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The LSC-Virgo white paper on gravitational wave data analysis

Science goals, status and plans, priorities

(2012-2013 edition)

The LSC-Virgo Data Analysis Working Groups, the Data Analysis Software Working Group, the Detector Characterization Working Group and the Computing Committee

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1 Foreword by the DAC Chairs

As for the previous editions, the data analysis white paper annually describes the goals, status, and plans of the data analysis teams in the LSC and Virgo. The document is revised and updated every year in the summer, and finalized by early fall. This is the document for 2012-2013. It is intended to facilitate:

- the understanding of the science that we are doing
- the identification of "holes" in our science plan and of tasks that demand more manpower
- the prioritization of our objectives
- the identification of areas when manpower should be shifted to and/or removed from
- the exploitation of synergies among the work carried out in different search groups
- an harmonious exploitation of common resources

Since the understanding of artifacts in our data is an essential part of the analysis work (allowing us to reduce the false alarm rate and increase our confidence that we have the tools to reliably interpret the output of the detector), we begin with a section on Detector Characterization. 'Detector characterization' is a term that indicates a variety of activities at the boundary between the detector and the data analysis. These activities are aimed at supporting the experimental effort by understanding the detector sensitivity performance to various types of signals and spotting critical artifacts that degrade it. They are also aimed at supporting the data analysis efforts by providing lists of "safe" vetoes for times and for triggers produced by the search pipelines which can be correlated with malfunctioning of known origin in the instrument and hence that can be discarded as not being of astrophysical origin. This section also includes information on the calibration procedures and expected calibration accuracy in the upcoming runs.

Since data analysis work both drives and is constrained by the computing environment and facilities where it develops, the last section of this document describes the development and maintenance of software tools and the management of software and computing resources.

The data analysis activities are organized in four groups which, broadly speaking, map into four different search approaches, depending on the different signals: compact binary coalescence signals, burst signals, continuous wave signals and stochastic backgrounds. This classification is historical in origin and as the searches that we carry out evolve, becoming more ambitious and broader, the boundaries between the different signals and the boundaries between the different search techniques become somewhat blurred and this distinction is only indicative.

The continuous waves (CW) and stochastic background searches are different with respect to the burst and CBC searches in that weeks to months of data have to accumulated before a meaningful search can be performed: the sensitivity scales with the inverse of the noise level (in sqr Hz) and with the square root of the effective length of the data used, counting all detectors separately. Hence these searches are going to be largely offline and do not require the development of the close-to-real-time trigger releases that are so crucial to transient signal searches. EM-follow-up observations of the sources of a continuous wave signal would surely take place if we detected a CW signal. However for a standard CW signal such follow-up study is likely not going to prove so crucial for enhancing the detection confidence, and could likely be carried asyncrounously with respect to the GW observation. So for this year EM follow-ups are still not going to be a focus area for the non-transient signals searches.

As of this year, in order to more effectively identify the best science deliverables (what papers we should be writing), to leverage the broadest spectrum of ongoing efforts, to avoid redundancy and to coordinate different efforts with overlap, the CBC and burst groups have formed teams that take responsibility for broad scientific topics. While the four search groups continue to maintain overall control and responsibility, we expect that the new teams will play a significant role in a healthy cross-group dialogue and promotion of good science. Any search carried out within either the CBC or burst group should also be discussed within the relevant team to ensure that it is tuned optimally with respect to the broader scientific context and/or more searches connected to similar scientific questions are considered jointly and planned in the same paper, when it makes sense. The burst group has identified 8 science focus areas: all-sky all-times searches, GRB triggered searches, joint gw-high energy neutrino searches, supernovae triggered searches, GWs as probes of neutron star physics, other EM counterparts and follow-up observations, binary black hole searches and finally signals from non standard sources. The CBC group has identified the science focus areas based on the binary components masses: neutron star-neutron star binaries, neutron star - black hole binaries, stellar mass black hole binaries and intermediate mass black hole binaries.

These science focus areas map directly on the searches and observational papers that we want to write. In practice, in order to support such goals all groups need to develop specific capabilities and tools. Examples of such capabilities and tools, common to both burst and CBC searches, are good data-quality information, reliable event significance assessment and parameter and rate estimation. Additionally the CBC group requires accurate waveforms. Close to real-time trigger generation capabilities are also among the science goals for all transient searches and these require a non trivial data management infrastructure and streamlined analysis pipelines down to the very final significance assessment steps. The development of such capabilities and the testing and qualification of our searches in turn requires that we can carry out large scale simulations of our searches including fake signal injections. All these tools need to work coherently to contribute to the main focus goals.

A certain amount of independent and somewhat unfocused research is of course important since breakthroughs often emerge unexpectedly from investigations. Surely the most difficult task for the chairs of the search groups is to strike the right balance between focus/goal - driven research and scientific liveliness and freedom of research in the Collaboration.

2 Characterization of the Detectors and Their Data

A thorough characterization of the LIGO, Virgo, and GEO600 detectors and their data is a critical requirement for making confident detections in the coming years. This includes the identification and reduction of (stationary, non-stationary, transient and periodic) noise coupling into the detector outputs, accurate and stable calibration and timing, and careful monitoring of the interferometer state.

In the years 2012-2013 the first subsystems of Advanced LIGO will be operating and ready to test, while heavy installation and commissioning of other subsystems will continue. The Virgo collaboration will begin its installation of Advanced Virgo. During this period GEO600 will be the only operational interferometric gravitational-wave detector. It will provide single-detector astrowatch coverage while undergoing incremental upgrades in the GEO-HF program. Meanwhile nearly all gravitational-wave searches on data sets from the initial detectors will be completed.

This will be a particularly important era for detector characterization. Noise transients, upconversion, spectral features and lines had important negative impacts on searches for gravitational waves with the initial detectors. A collaboration-wide effort in detector characterization is required to ensure that these disturbances are mitigated in the advanced detectors to allow and hasten the first detections. Detector characterization efforts should be prioritized on work that directly i) improves the sensitivity, calibration, or performance of the detectors or ii) improves the sensitivity or false alarm rate for LSC-Virgo gravitational-wave searches.

In many ways it makes sense to coordinate detector characterization efforts and share experience between LIGO, Virgo and GEO600. We describe in Subsection 2.1 the LSC-Virgo-wide priorities for the characterization of the detectors and data. However these detectors also have important differences in topologies and technologies and are at different stages of their installation schedules, so they require detector-specific planning. The detector characterization efforts specific to the LIGO, Virgo, and GEO600 are described separately in Subsections 2.2, 2.3, and 2.4, respectively.

2.1 LSC-Virgo-wide detector characterization priorities

The LSC and Virgo detector characterization groups have the following overall priorities for 2012-2013.

- **Characterize Advanced LIGO, Advanced Virgo, and GEO-HF subsystems as they come online.** In the past much of our characterization has been done by looking at artefacts in the detector outputs and trying to reconstruct their cause from the thousands of interferometer channels. Characterizing the systems during their construction gives us the unique opportunity to identify and fix issues with glitch and noise performance, channel signal fidelity and robustness, etc., and maximize our knowledge of the systems at an early stage and in simpler pieces. This will serve a dual role of training a wider pool of scientists who are familiar with the instruments. Both should lead to better understood and more sensitive detectors and expedite detections. However it should be noted that the actual coupling of noise to the detector output signals can only be investigated once the interferometers are assembled and the first locks have been achieved.

- **Improve upon the physical environmental monitoring (PEM) systems from the initial detectors.** The PEM systems are critical for identifying and removing noise couplings as well as following up detections, e.g. by ruling out external causes for putative signals. This includes instrumenting the sites with sensitive devices placed in key locations, calibrating the output of all sensors into physical units, evaluation of the levels with which external disturbance couple into the detectors and their subsystems, and a thorough documentation.

- **Strengthen the relationship between detector/commissioning scientists and detector characterization scientists.** It is important to have a strong relationship and excellent communication between the instrumentalists/commissioners and the detector characterization groups in order to identify and quickly resolve data quality issues and expedite the time required to achieve high quality data. This can be achieved through cooperation on noise investigations, engineering runs, glitch shifts, and regular communication in both directions about issues with data quality and artefacts that are observed. This can also be improved by more direct involvement by commissioners in the detector characterization groups.

- **Develop and implement the infrastructure needed to ensure high data quality in low latency.** Low-latency and accurate knowledge of calibration, detector state, data quality flags, vetoes, timing, etc., will allow us to better assess the data quality of the advanced detectors and will enhance the science that can be done with low-latency searches by improving false-alarm rates and confidence.

- **Provide data quality support for all ongoing collaboration gravitational-wave searches.** In 2012-2013 we expect a small number of searches to continue on the collected S6/VSR2,3,4 data sets. We will work to ensure that these have accurately calibrated, well-understood, and high quality data.

- **Press for a breakthrough in glitch reduction/veto techniques.** Searches for short duration and/or unmodelled gravitational-wave signals with the initial detectors were limited by a background of transient noise glitches present in the instrumental outputs. A breakthrough is needed to ensure that the sensitivity of these searches will be limited by the stationary noise of the detectors in the advanced detector era. To identify more effective techniques we will reuse the S6/VSR2,3,4 data sets to test diverse inputs and more advanced algorithms. Our goal is significantly higher efficiency (>90% after current category 3 data quality) for low additional deadtime ($\approx$10%).

- **Document the detector characterization work that had an impact on initial detectors and searches.** This includes contributing to analysis papers, writing an overview detector characterization paper for LIGO S6, and GEO S6 (following the lead of the Virgo VRS2,3 paper [28]), and completing papers describing methods that had an impact on detector/search sensitivity. This documentation should help us better assess the work that has been done and identify areas to improve for the advanced detector era.

- **Develop/implement improved detector characterization tools, techniques, and figures of merit.** A number of tools that were successful during the initial detector era can be improved upon. This includes continued work on the GEO, LIGO, Virgo collaborative summary pages, veto algorithms such as hveto, use-percentage veto and bilinear-coupling veto, figures of merit that give a truer indication of the range of the instruments taking into account non stationary and non Gaussian behavior, systems to record vital information about channels and their status, data viewing tools, and spectral features, coherence, and line monitors. Many of these improved tools can be deployed at GEO600 to test how they work on an operational detector and to interact with commissioning.

- **Transfer characterization knowledge and experience into automated tools and machine learning approaches.** A long-time goal of detector characterization is to take more of what we have learned and encode it in automated tools.

2.2 LIGO Detector Characterization

2.2.1 Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is an NSF-funded project with the mission of directly detecting gravitational waves from astrophysical sources. LIGO has completed six periods of scientific running, S1-S6, over the past decade, amassing several years of coincident observation with its detectors at design sensitivity, and often in coincidence with its international partners GEO600 and Virgo. LIGO is in the midst of a major upgrade, called Advanced LIGO, that will increase the strain sensitivity of each interferometer by more than a factor of 10 and the volume of the universe observable by gravitational waves by a factor of 1000. Advanced LIGO is expected to make the first gravitational-wave detections and begin an era of gravitational-wave astronomy.

The LSC detector characterization group [1] directly supports LIGO's mission because a thorough characterization of the detectors is required to confidently detect gravitational waves. Gravitational-wave searches require accurately calibrated data with precise timing. The collaboration's ability to make detections and the level at which upper limits for gravitational-wave emission are set depend critically on detector performance characteristics, such as the overall level of the noise-limited detector spectrum, the probability distribution of transients in the detector output, the degree to which the noise components are stationary, and lines and features that are present in the data. Detector characterization is also an important aid to the commissioning process. Characterization efforts identify issues and provide clues to commissioners, who use these to improve the instruments.

Detector characterization is carried out by a variety of scientists focused on different problems. Commissioners operate at the cutting edge of detector characterization, modifying the detector systems to increase their performance in terms of noise, lines, and robustness. Their investigations may focus on interferometer-based detector characterization, such as investigation of noise sources, lines and features, or environmental disturbances. Members of the analysis groups also make important contributions to detector characterization. They often direct their efforts toward impediments to astrophysical searches, such as coherent or accidentally coincident glitches that pollute compact binary and burst searches, features that could blind searches for periodic or stochastic background sources, or wandering line features that could mimic a pulsar.

During intense commissioning, it is difficult to evaluate the long-term performance of the instruments. Science and engineering runs serve as testing grounds for interferometer stability and for rapid communication between commissioning, detector characterization, and data analysis groups. As experience has accumulated, tools to evaluate the search backgrounds and instrument stability have improved and the latency of diagnostic feedback has decreased dramatically. Rapid feedback useful for noise and transient mitigation and commissioning is becoming routine.

However, even after years of commissioning and detector characterization the data recorded for scientific analysis contains unforeseen artifacts that decrease the sensitivity of or even blind some searches if left unchecked. For that reason, the detector characterization group has a strong effort to identify and remove non-astrophysical artifacts from the recorded data. For transient searches this is done using data quality flags and vetoes. For periodic and stochastic searches, times and/or specific frequency ranges are identified and removed from the analyses. These efforts have led to improved upper limits in the searches performed to date.

As new artifacts are found, new characterization methods are developed. If the artifacts persist, the group works to automate the relevant methods for more rapid detection of problems. For initial LIGO, the online monitoring systems included the Data Monitoring Tool (DMT)[2] with a number of targeted monitors, the controls system software (EPICS)[3], and search-oriented monitors such as the trigger generators Omega [4] and KleineWelle [5] for the burst search, and daily iHope [7] for CBC, as well as a variety of customized tools written in e.g., python, C++, and Matlab. It also included a human element, namely the attentiveness and active data exploration by interferometer operators and scientific monitors (scimons). For the advanced detector era, we plan to build upon this experience, and as much of this work as possible should be automated.

The LSC Detector Characterization community has a broad membership, including full-time commissioners, full-time data analysts, and many in between.The DetChar working group concentrated most of its effort in the initial detector era on providing online characterization tools and monitors and on providing characterization (most directly data quality flags and vetoes, and diagnostic information) of interferometer data in science runs for astrophysical analysis. Every search working group has active DetChar members, and information flows in both directions, to mutual benefit. *The Det Char group has few members exclusively or even mostly dedicated to the group. This brings a beneficial diversity of ideas, but reduces efficiency with respect to full-time members. A goal of our group is to recruit more members that commit a substantial amount of their time to the group. The latest LSC-Virgo MOU includes a less-restrictive publication policy for detector characterization work that supports this goal.*

In the following subsections, we describe the requirements on detector characterization for our collaboration to achieve its scientific goals during the advanced detector era (2.2.2), the LIGO-specific priorities for detector characterization (2.2.3), status and plans for data run support (2.2.4), and software infrastructure (2.2.5), as well as the activities and priorities of the different working groups, noise transients (2.2.6), spectral features (2.2.7), calibration (2.2.8) and timing (2.2.9).

2.2.2 Overview Requirements to Achieve aLIGO Science

The primary goal of LIGO detector characterization over the next few years is to ensure that the Advanced LIGO data is accurately calibrated and of high enough quality that the collaboration is prepared to make confident detections by the first science runs of aLIGO, which could start as early as 2014. The following requirements for detector characterization in the advanced detector era are driven by the science requirements of the search groups described in further sections of this whitepaper. Here we present the requirements but do not get into the specifics of how they will be addressed until Subsection 2.2.3.

1. **Provide an accurate calibration, timing, and state information for the gravitational-wave channels.** It is imperative that the gravitational-wave channels for aLIGO have strain calibration and timing accuracy that meets the requirements for confident detections and that the state of the detectors is accurately recorded to signal what data should be analyzed.

2. **Remove egregious data quality problems in the detectors.** Neutron star binary coalescence signals are the most likely source to be detected by aLIGO. Owing to their minutes-long waveforms, BNS searches are expected to be relatively robust against short and quiet noise transients. However, loud transients or dramatic non-stationarity could complicate or blind a potential detection. To maximize detections, BNS searches require that egregious data quality problems are identified and removed in the detectors.

3. **Provide a well-understood and documented physical environmental monitoring system.** Among the most important requirements for both improving the detectors and following up potential signals is a well-monitored and understood physical environment at the detector sites. Only a suite of well understood environmental monitors will allow us to say with confidence that potential coincident signals did not arise from anthopogenic, terrestrial, atmospheric, etc, external effects.

4. **Remove the majority of short duration transients in the detector outputs.** The initial LIGO detectors exhibited a high rate of non-Gaussian noise transients (glitches). These acted to increase

the background in (and therefore decrease the senisitivity of) searches for shorter duration, less well modelled waveforms such as burst sources, and higher mass CBC systems (BHBH and NSBH). If aLIGO has a similar glitch rate these searches will require a significant reduction (possibly $> 90\%$ of single-detector noise transients above SNR 8). The best way to achieve this is through mitigations in the detector, but improved data quality products such as flags and vetoes will also be required.

5. **Provide high data quality with low latency.** Providing this information is necessary to carry out sensitive low-latency searches, including searches with electromagnetic followup. High data quality includes accurate calibration, timing, and information about the interferometer state, as well as the removal of as many data artefacts as possible by automated means.

6. **Remove lines or spectral features that limit continuous-wave and stochastic background searches.** For continuous waves and stochastic searches the detector characterization group should identify and help remove any lines or spectral features found coherent in the instruments and/or occurring at frequencies targeted by the searches.

2.2.3 Priorities for LIGO Detector Characterization

In this section we set priorities for detector characterization during the upcoming year by choosing activities that will ensure that the requirements listed above will be met by the first aLIGO science run in late 2014.

1. **Characterize the Advanced LIGO subsystems as they are brought online.** [*Supports requirements 2,3,5 above.*] We will investigate the data quality of aLIGO subsystems as they are deployed. Investigations will include,

   - checking the channel fidelity (are the channels recorded above ADC noise over their useful frequency range, do the signals saturate during nominal operation?)
   - identifying artefacts (glitches, lines, features) and helping to reduce them
   - contributing to the "noise budget" (a tool for understanding of the various noise contributions) for each subsystem
   - helping to document information about auxiliary channels and calibrate them into physical units
   - recording accurate and authoritative information about the state of each subsystem and of the entire interferometer.

   This work is aimed at identifying and fixing problems early - which is preferable to waiting for the first locks of the full interferometers in ca. 2014 and then trying to sort the myriad of artefacts present in the detector output back to their individual sources. This “ground up” approach is, we believe, an improvement over the “top down" approach that was typically used in Initial LIGO. It allows each subsystem to be carefully studied and “checked off" as well-behaved and understood during commissioning, which should result in a much cleaner output once the complete detectors are made operational. And it will train a larger number of detector characterization group members familiar with the individual subsystems. It should be noted however, that many data quality issues, such as complicated noise couplings, will only become apparent when the full interferometers are operating so we expect characterization in the later phases of commissioning and running (2014 and beyond) to also be extremely important.

2. **Upgrade the LIGO Physical Environmental Monitoring Systems for Advanced LIGO** [*Primarily supports requirement 2, but supports all goals above.*] The LIGO PEM system must be taken apart for aLIGO installation, affording an opportunity for redistribution of the sensors, system upgrades,

and channel renaming based on lessons learned in initial LIGO. In addition, changes associated with aLIGO will require redeployment of sensors to new coupling sites, installation of new sensors in new rooms and on new vacuum chambers, as well as redeployment of sensors made redundant by seismic sensors in the active isolation system. Plans for this PEM upgrade are laid out in the aLIGO PEM Upgrade document [6]. Associated with the upgrade are a number of hardware and software projects for LVC members, detailed in the upgrade document and listed here.

Hardware

- power meters for roof radio monitors
- RF monitors at the main modulation frequencies for inside the LVEA
- an RF spectrum monitoring system that sweeps from a few kHz to a couple of GHz
- 1 Hz to 10,000 Hz RF monitor
- an electrostatic field monitor
- several coil magnetometers
- a sky observation system
- an upgraded cosmic-ray detection system
- infrasound monitors

Software

- updated dead channel monitor
- channel snapshots
- statistical channel monitor
- channel location and calibration web page
- direction to source finder using propagation delays
- code to search for “pulsars" in selected auxiliary channels using modified all-sky and/or specific pulsar search code
- modified stochastic code to search for signal between aux channels
- significance figure of merit for Carleton DARM-aux coherence line monitor
- 1Hz (and other) comb monitor

3. **Participate actively in the aLIGO engineering runs.** [*Supports all requirements above.*] In the upcoming years the LIGO Scientific Collaboration plans to have a series of engineering runs to test important software infrastructure, establish procedures for software release/maintenance during aLIGO, perform detector characterization early using real subsystem data, and measure progress of the analysis groups toward key science goals. The duration of these runs and the role played by the real interferometer data is expected to increase steadily from 2012 through 2014. In the detector characterization group we will work toward having key investigations completed and critical software (calibration, timing, state, data quality monitoring, etc.) implemented and tested in these engineering runs. We expect these periods will provide excellent opportunities to observe the longer term stability of the interferometer and its subsystems than is often possible during heavy commissioning.

4. **Develop improved methods to uncover the causes of and veto noise transients.** [*Supports requirement 2,4,5 above.*] During S6 we had some success using burst and CBC search algorithms [5] to

parameterize glitches in the detector outputs and a large number of auxiliary channels and then using automated tools such as UPV [10] and hveto [9] to generate "veto" segments based on statistical correlation. To achieve requirement 5 above we will need to improve upon the performance of these algorithms. Promising avenues of research that should be followed are:

- Improved glitch parameterization that works well over a broad parameter space in frequency, duration, and SNR, and runs on the detector outputs and all high-sample-rate auxiliary channels.
- Investigations of the utility of other physical inputs (thank glitch parameters) as an indicator of glitches in the detector output. For example mean values or RMS of slow auxiliary channels (e.g. alignment).
- Extending veto techniques by straightforward refinement, or using methods such as multivariate classifiers, bilinear coupling indicators, etc.
- Data mining techniques that identify connections between times subject to glitches and the values of a wide array of control and monitoring signals. This will allow the exploration of the possibility that saturation of error signals in control systems causes extra sensitivity to environmental disturbances, as well as other mechanisms that can cause time-varying couplings between control channels and the gravitational wave output.

Further discussion of this goal is in Section 2.2.6.

5. **Provide data quality support to search groups for remaining S6 analyses and engineering run analysis.** It is important that the detector characterization group provide support for data quality issues in all remaining iLIGO analyses, and support analyses that are performed on the aLIGO engineering runs.

6. **Continue to document the detector characterization work that has had an impact on the LIGO detectors and searches.** This includes contributing to S6/VSR2,3 analysis papers, writing an overview detector characterization paper for LIGO S6, documenting the PEM system, and completing papers describing methods had an impact on iLIGO or early aLIGO data.

2.2.4 Data Run Support

For most of the engineering runs and all of the science runs, LSC policy has been to staff the control rooms around the clock with one operator per interferometer and at least one scientist (scimon) per observatory. The scimons have been responsible for monitoring the quality of the data, carrying out investigations, and making decisions on when to take science data *vs.* when to make adjustments / repairs, in consultation with the operator on duty and the local run coordinator, when appropriate.

In 2009 the LSC approved a policy of a 7-day minimum stay for scientific monitors. This resulted in improved data monitoring in S6. We will critically evaluate the performance of the scimon system and develop a plan to be used in the Advanced LIGO runs. Relatedly, having a detector characterization expert at the Hanford Observatory for extended periods of time over the past years has proved critical to the understanding of many artefacts, especially those related to the coupling of the physical environment. Because longer stays have proven beneficial, we will investigate programs, such as long-term fellowships, to encourage even longer stays of scimons and other LSC scientists at the Observatories.

Another important aspect of data run support is injection of simulated astrophysical signals into the detector hardware to validate data analysis pipelines with high confidence. LIGO Laboratory and LSC scientists have provided the human resources to set up the injection infrastructure and carry out the injections. We will use the experience with initial LIGO, including the results of “blind" injection exercise, to plan for future runs.

Although there will be no science runs in the upcoming year, there will be engineering runs. We will use these periods to test data monitoring systems and interactions with the searches, and to gain an early understanding of the artefacts in each of the subsystems. This will require a close communication between commissioning teams and detector characterization groups, a relationship we would like to foster.

2.2.5 Software Infrastructure

Over the years, many tools have been developed for on- and off-line monitoring of detector status and data quality. Many of these software tools (EPICS[3], DTT[8] and DataViewer) are used interactively in the Observatories' control rooms by operators, commissioners and scientific monitors, and have proved to be essential to operations and commissioning. These tools were developed by the LIGO Laboratory, and we expect these tools to be maintained, and improved when appropriate, for Advanced LIGO operations.

The Data Monitoring Tools system, or DMT[8], is used as a background-process environment for continuous monitoring. The DMT system provided many critical functions in S6, including the online production of calibrated strain files that are were used for low-latency analyses, online production of data quality information that was used for selecting appropriate data to run on and vetoing noise transients in those analyses, and continuous graphical monitoring of the data and the environment displayed in the control room. Although programs used by the DMT system were written by scientists in many different institutions, the maintenance of the infrastructure is done by the LIGO Laboratory.

Data quality monitoring involves reviewing the results produced by monitors such as those run in DMT, veto selection programs such as hveto [9] and UPV [10], noise transient monitoring, coherence and line monitoring, results of data analysis such as search background, and other scripts running in the LIGO Data Grid clusters at the Observatories. This review is done continuously during science runs by scientific monitors at a basic level, and periodically at a deeper level by members of the Glitch and Spectral features subgroups. These investigations result in the diagnosis, identification, and sometimes fixing of artefacts in the gravitational wave channel, which reduce the background for the searches of astrophysical signals in the data. For aLIGO we are working to bring all of these types of monitors together on a single easily digestible page (with many sub-pages) for each detector, called a LIGO summary page (with GEO and Virgo pages available from the same system).

The DetChar group compiles information from its investigations to create a repository of data quality (DQ) information for each run. The information is used to form time intervals which are flagged with data quality flags, which are incorporated into a database (which also has the information on which times are in nominal science mode). The database can be queried by the astrophysical search programs, as well as by members of the group diagnosing problems in the data. The database infrastructure was first used in S5, and was significantly revamped for S6 by the LSC Software Working group (7). This resulted in a reliable system where flags are introduced online by well tested DMT monitoring programs, and offline by the DetChar group and by scimons. For aLIGO we plan to move monitoring of critical state information of the interferometers and their subsystems to the front-end systems. This will enable the production of low-latency and authoritative state information that can be used automatically by searches, and downstream monitors.

For detector characterization it is important that collaboration members have easy and reliable access to the LIGO data, including the gravitational wave channels and the many auxiliary channels (and their archived trends). For most of the initial LIGO era access to LIGO data from outside the observatory control rooms required signficant effort - and this was an impediment to engaging more collaboration members in detector characterization. This situation was greatly improved in 2010 with the LIGO Laboratory's development of a secure network data server, NDS2. This system now reliably serves raw, archived, and trend data, and is robust enough for use by the entire collaboration. However, because Advanced LIGO is significantly more complex than initial LIGO, it will have many more channels, and in the era leading to first detections demand for served data will be greater. It is critical for detector characterization work in aLIGO that NDS2 be supported to reliably serve all raw, archived and trend data available on frames to a large number of users.

For aLIGO we also require data viewing and signal processing tools to read the data served by NDS2 and make a variety of plots or results ranging from quick looks at timeseries and spectra to more complex analyses. The tools currently under active use and development are the Matlab-based graphical user interface LIGO Data Viewer, ligoDV [11], a script-based Matlab interface, mDV [12], and a python interface to the NDS server, pynds. In 2011 a new web-based data viewer, ligoDV-web (`ldvw.ligo.caltech.edu`), has been developed. This service has made it possible to access LIGO data through a web browser on your desktop, laptop, tablet or smartphone, and only requires users to have a valid ligo.org username and password for authentication.

Despite the critical importance of Detector Characterization, there are only two collaboration members with near full time dedication to detector characterization software (one dedicated to NDS2 and DMT, and another dedicated to ligoDV and ligoDV-web), and only a few other members partially dedicated to developing and maintaining software tools. To thoroughly characterize the more complex Advanced LIGO detectors and enable the first detections, the detector characterization group requires a more robust software infrastructure and human resources to support it.

Software priorities This section describes priorities for detector characterization software work over the next few years. In general we want to build on the successful software infrastructure from S6 and expand it to meet the demands of searches in the Advanced detector era. These activities will be coordinated with the Software Working Group, as described in Section 7.

1. Implement and test glitch parametrization software that can run online and continuously on the detector output and auxiliary channels and generates output that is improved (in sensitivity, particularly at low frequencies, SNR and frequency accuracy) with respect to the triggers that were produced in S6. Prepare to process hundreds of fast channels per detector from 1Hz to 6kHz.

2. Develop and implement a LIGO daily report system inspired by the GEO summary pages.

3. Develop and implement Online Detector Characterization (ODC) channels to be deployed in the aLIGO front-end systems that will monitor key aspects of the interferometers and their subsystems and provide critical and authoritative information about the interferometer state.

4. Produce software to monitor the first subsystems of Advanced LIGO that will form the foundation for data quality flags in the first runs.

5. Continue development of the LIGO segment database to increase input and output speed, robustness and to improved user interface tools.

6. Develop a new trigger database appropriate for the storage of short-duration veto information. This should be able to store parameters such as central time, duration, central frequency and SNR.

7. Continue development of new and improved Channel Information System (CIS) `cis.ligo.org` containing channel names, sample frequencies, editable descriptions, links to appropriate subsystem models, and other information.

8. Continue refinement of veto production algorithms and test these improvements on aLIGO subsystem data.

9. Migrate data quality and veto flags that proved useful in S6 and are likely to be useful in Advanced LIGO to on-line production.

10. Automate and improve upon current data quality flag and veto segment performance validation tools. For Advanced LIGO these should be capable of running daily (and on longer timescales) for all data quality and vetoes and report individual and cumulative efficiency, deadtime, used percentage and safety with respect to hardware signal injections.

11. Improve the current dead channel monitor with a lower false alarm, integrated reporting, and more direct ties to the segment database.

12. Continue development of NDS2, and data access/viewer/processing tools such as ligoDV, ligoDV-Web, pynds, to ensure easy and reliable access to LIGO data and standard signal processing techniques for detector characterization.

13. Maintain appropriate reduced data sets for Advanced LIGO to be used for detector characterization and for data analysis. This includes data from engineering runs.

2.2.6 Noise Transients

The largest detector characterization subgroup, the Glitch Group[13], carries out studies of interferometer noise transients, or "glitches". Composed of experimentalists and analysts, the working group has broad expertise, and its work is closely coupled to the burst and CBC searches.

The goals of the Glitch Working Group are:

- To identify the times of brief transients in the data taken during engineering and science runs that will affect the astrophysical searches.
- To investigate the causes of these transients using information from auxiliary instrumental and environmental channels and other information such as logbook entries.
- To work with commissioners and experimentalists to confirm the suspected causes of transients and attempt to mitigate them by changes to the instrument.
- To produce data quality flags or other information that can be used by the astrophysical searches to reduce the effect of any transients that are impossible or impractical to mitigate.
- To provide information to experimentalists and builders of future detectors to achieve interferometer noise that is stationary and Gaussian.

In the coming years, there will be short engineering runs dedicated to studying the data quality of the different Advanced LIGO subsystems as they are installed. We expect this activity will start in 2012 with pre-stabilized laser, input mode cleaner, small chamber seismic isolation, small suspensions in L1 and large suspensions and arm cavities in H2. We expect, with the LIGO Laboratory's help, to take full advantage of the possibility to exercise data monitoring tools, as well as get an early understanding of the artifacts in each of the building blocks of the very complex gravitational wave detectors.

The priorities for the coming year are:

- Participate in commissioning of the aLIGO subsystems. Identify glitches in subsystem channels that would/will affect the interferometer in future science runs, with special focus on rare glitches.
- Participate in engineering runs. When instrumental data is used as a fake gravitational wave channel, provide data quality information for the astrophysical searches on the fake data.

- Develop the ability to run burst-like searches on many auxiliary instrumental and environmental channels in real time. Improve these searches and their tuning to provide the most useful information to glitch hunters.
- Automate production of graphical visualization of the data products needed for evaluating data quality and identifying transients.
- Devise improved ways to diagnose problems arising from data acquisition, data sampling and/or imperfect timing in digital control systems.
- Tune and improve currently existing code, and develop new approaches, for finding and diagnosing data quality problems. Test this on S6 data as well as the new data that is coming in.

The first and foremost goal for the advanced detector eta is to enable the astrophysical searches to make confident detections. This requires a deep cleaning of the background by understanding nearly all of the glitches that are of concern to the astrophysical searches, and either mitigating them or creating data quality flags that identify them with good accuracy. There are a number of sub-goals that will facilite requires better ways to analyze the auxiliary channels that provide information about the state of the instrument and the environment, since it is this information that predicts the occurence of glitches.

2.2.7 Spectral Features

Another working group of the LSC Detector Characterization group is charged with investigating spectral features of the gravitational wave spectral noise density, which is especially important for the searches of gravitational waves from rotating stars and stochastic background. Many of the spectral features are due to environmental disturbances, including seismic activity, high wind, acoustic noise, and electromagnetic interference. Some sources are natural, but many are also anthropogenic, including sources from observatory infrastructure, e.g., nearby motors and HVAC systems. A wide variety of environmental channels have been commissioned and are monitored in initial, enhanced and advanced LIGO, but unusual artifacts typically require detailed on-site investigations and eventually mitigation, work carried out by scientists from the observatories and from LSC institutions, as part of commissioning. Acoustic mitigation has played an especially critical role in lowering interferometer noise floors[23]. The retrofitting of LLO vacuum chambers with feed-forward, hydraulic pre-actuators led to dramatic improvement in L1 duty cycle, allowing the interferometer to ride out the passage of trains without lock loss. Nonetheless, significant increase in gravitational wave channel noise is seen during such a passage and in general during high seismic noise times, due to not very well understood upconversion of the noise into the gravitational wave band (40Hz-6kHz). Environmental disturbances may also, of course, be manifested through linear couplings to the interferometer as direct glitches or lines, for sources with characteristic frequencies in the LIGO band of sensitivity. There have been extensive studies during S5 and S6 to understand better the sources of steady-state environmental couplings, particularly lines; these studies are now extending to advanced LIGO subsystems.

The list of high priority activities related to characterizing spectral features in 2012-2013 are::

- Continue to analyze and investigate noise lines affecting data quality in S6 data, including summarizing frequency line issues in S6 for a data quality paper.
- *Noise budget for subsystems*: Measure the environment about advanced LIGO subsystems to identify periodic signals so as to develop a catalog of potential noise lines that could enter these sub-systems. Conduct noise injection tests to measure the transfer function of different environmental noise sources.

- *List of lines and line monitors in subsystems*: Apply the existing noise line finding tools in order to characterize the noise environment of advanced LIGO sub-systems. Use seismometers, accelerometers, microphones, magnetometers, voltage line monitors and other devices to map out noise, and how it couples into advanced LIGO subsystems. Use existing line finding tools, such as Fscan (a pulsar search code, applied to auxiliary channels), coherence (which calculates the coherence between the gravity wave channel and auxiliary channels), and NoEMI (Noise Event Miner, developed at Virgo).
- *Investigate coherence of environmental channels with the different subsystems*: Use the coherence tool to monitor the coherence between various signals. The Stochastic Transient Analysis Multi-detector Pipeline (STAMP) also allows for the long-term monitoring of the coherence between different channel pairs. These tools will be used to monitor noise signals in subsystems, producing an executive summary for each system. There will also be a need to study non-linear frequency up-conversion of noise; STAMP, as well as bicoherence code, will be used to study up-conversion of noise in subsystems.

As various advanced LIGO subsystems come on-line the software for spectral line identifications and interchannel correlations can be applied; this will serve as a means to identify noise in the subsystems, and prepare the routines for application on advanced LIGO h(t) data when it becomes available.

2.2.8 Calibration

Calibration of the LIGO interferometers is a task critical to the success of the data analysis algorithms, and the confidence associated with their results. As such, the LSC created in its bylaws a Calibration committee, separate from the DetChar group, although there are still many common members and activities.

Calibration of a detector is a complex task that involves instrumental hardware measurements, detector modeling, computer programs, and extensive validation and review. The Calibration Committee responsible for this essential work includes LIGO Laboratory and other LSC scientists, along with a dedicated Calibration Review Committee which provides advice and vetting of this work. The Calibration Committee's results are posted and documented on a web page[14] available to the Collaboration, as well as recorded in the electronic logs, software repositories, and LIGO documents[15].

The calibration procedure has evolved in sophistication since the S1 run, most notably in automation, modeling, and redundant validation methods, with calibration provided both in the frequency domain (a frequency-indexed response function to be applied to the Fourier transform of the gravitational wave channel) and in the time-domain (a derived digital time series, "h(t)", representing strain as a function of time, which LIGO started to generate in S4)[16, 17]. Starting with the S6 run, the time domain data has been the main calibration product. The generation of the time domain data is complex enough a job that needed a dedicated team for calibration and another one for the review. The Calibration Committee is therefore co-chaired by a time-domain chair and an experimental chair. There are also some efforts to calibrate the detector data at higher frequencies, near the 4-km cavities' free spectral range at 37 kHz, where the detectors are, in principle, comparable in sensitivity to gravitational waves as in the baseband near 100 Hz.

Estimation and reduction of the errors in the calibration data products has been a major effort in recent years, and these investigations will continue. An alternative method of calibration using auxiliary laser pressure actuation ("photon calibrator") and interferometer laser frequency modulation developed and implemented in the S5 run, have also been used during S6. In S5 the various methods agreed to within 10%. In the S6 run, we have had calibrations by the coil calibration, the photon calibration, and other methods, with agreement at 10%-20% level. Understanding the origin of these differences is essential for the development of more accurate calibrations.

The scope of the calibration itself was expanded during and after the S5 run to include the timing of the LIGO data. If the interferometer model used for calibration is incorrect, it could skew the timing of LIGO data even if the clock system is working perfectly. See §2.2.9.

Production and analysis of the time-dependent calibration coefficients is an essential tool for calibration validations. They can be used to estimate the systematic and statistical uncertainties of the calibration as well as the time offset changes. These studies will be continued in the future. Development of on-line tools to monitor the time-dependent calibration factors, and more generally h(t) data quality, is essential.

As the necessity of the analysis using the data from multiple gravitational wave projects increases, so does the urgency to share the information about the calibration of various gravitational wave detectors transparently. There has been a very fruitful exchange of ideas and methods with the scientists performing the calibration from Virgo and GEO. Also important is an exchange of ideas about the review process. Though there hasn't been much communication between the calibration reviewers from different projects, it is desired that more communication channel is established by the end of the S6 run. In collaboration with Virgo and GEO, the calibration team will also work on improving h(t) generation techniques, and the development of pre-processed h(t) products such as whitened, cleaned, and coherent data streams.

The Calibration Committee's membership has been augmented in recent years by the graduate students and the scientists alike from several LSC institutions. The work load necessary for the calibration of LIGO instruments increased drastically both in hardware- and software-related tasks since S1, and the participation of motivated persons from broad backgrounds proved highly successful and indeed indispensable for satisfying the goal of the Calibration and the Calibration Review Committee, i.e. the timely delivery of the vetted calibration. In addition, for students this provide valuable instrumental training. It would be highly desirable to sustain this broad participation.

The work of the calibration team is currently focused on preparations for the advanced detector era. New independent techniques are being developed to produce h(t) data with second and sub-second latencies (during S6 the latency was 1 minute). These techniques include moving the generation of h(t) to the front end of the interferometer (CDS), and a gstreamer-based algorithm. In addition, on-line tools to monitor the quality of the data produced on the fly, and the development of pre-processed h(t) products (e.g. whitened, cleaned, and coherent data streams) are being developed.

2.2.9 Timing

Traceable and closely monitored timing performance of the GW detectors is mission critical for reliable interferometer operation, astrophysical data analysis, and discoveries. For example, (a) timing jitter of digitization of the GW signal could directly contribute to the noise level degrading the astrophysical reach of the LIGO interferometers, (b) coincident and coherent observation using the network of GW detectors is only possible if the absolute timing of the data streams agree within a high degree of accuracy, (c) a network of interferometric GW detectors can only recover both the polarization and sky direction information for a detected event if the absolute timing of their data-streams are known, and (d) multimessenger astronomy with external observatories also require traceable and accurate absolute timing.

The Timing Stability Working Group (TSWG) includes scientists from both the LSC and the LIGO Laboratory. The group shall be responsible for (a.) the availability and diagnostics of timing information and signals provided for various subsystems (e.g., LSC, OMC, etc.), (b.) measuring and documenting the timing performance of mission critical digital subsystems such as LSC and OMC DAQs, (c.) in close collaboration with the Calibration team (also see 2.2.8), the end to end timing and phase calibration measurements of the detectors (e.g., through the photon calibrator[21], characterization of analog modules, etc.), and (d.) the documented review and certification of the physical/software implementation and verification of the availability of precise documentation of timing related parts of mission critical subsystems. While it is quite likely that issues with the timing performance of subsystems are discovered by the timing team, it is the responsibility of the subsystems to address the problem; the timing team is responsible only for the certification that the issue was indeed eliminated.

The construction, testing and diagnostics tasks have already provided fertile ground for undergraduate and graduate student research involvement and diversity in the program is strongly encouraged for the future.

The next challenge in timing diagnostic is long term. Several projects will be executed in preparation of the advanced detector era, such as:

- Further develop and test injection techniques to determine accurate timing through direct test mass excitations
- Augment and expand the capabilities of data monitoring tools related to timing and phase calibration
- Enhance the availability of timing diagnostics capabilities provided for various subsystems
- Measure and document the timing performance of mission critical digital subsystems
- Measure and document the end to end timing and phase calibration measurements of the detectors (e.g., through the photon calibrator, characterization of analog modules, etc.)
- Review and certify the physical/software implementation and verify of the availability of precise documentation of timing related parts of mission critical subsystems

2.3 GEO Detector Characterization

2.3.1 Introduction

GEO 600 is currently the only operating laser interferometer gravitational wave observatory in the world. Foreseeing this period of single interferometer operation, an upgrade program called GEO-HF was begun in 2008 [24]. This upgrade was designed in an incremental fashion such that the majority of the time can be operated in an astrowatch mode where the interferometer is set to low noise operation for nights and weekends. Figure 1 shows the results of the first phases of this upgrade program along with some projections for the future stages. In the coming years there will be a handful of multi-week long interruptions of astrowatch to carry out installations; otherwise most of the commissioning work will be carried out using short, daytime interruptions. Even when heavy commissioning is occurring, and the interferometer is operating smoothly, we are able to achieve a 70% duty cycle for astrowatch observations.

Aside from this astrowatch role, GEO 600 plays a special role in the gravitational wave research community because of the regime in which its sensitivity lies. Figure 1 shows that GEO 600 now has comparable high-frequency sensitivity to what Virgo achieved in its last science run and will soon be comparable and surpass the last sensitivities of both LIGO detectors in this regime. This sensitivity warrants round the clock operation, when the interferometer is not being used for commissioning purposes, as well as maintenance of this sensitivity to enable possible serendipitous detection of rare, loud events. However, the sensitivity to compact object binary coalescences is approximately an order of magnitude worse than what the LIGO and Virgo interferometers obtained for over two years of science operation. For this type of event, there is no chance of improving the upper limits to the population densities already set by the few-kilometer-scale interferometers. For this reason a balance is struck between data taking in astrowatch mode and carefully scheduled commissioning to improve detector sensitivity. This also provides a degree of flexibility for prototyping new techniques that is not enjoyed at the larger interferometers. Combined with the observational potential which results in the maintenance of the sensitivity, this accessibility gives GEO 600 a special niche in the gravitational wave research community. Taking this viewpoint *GEO 600 can be seen to be the sum of a working detector and a prototype of an observatory.* This brings the advantage of allowing tests of stability and long term implementation of prototyped techniques which cannot be investigated at smaller prototype interferometers where the duration of any given experimental setup is comparatively short.

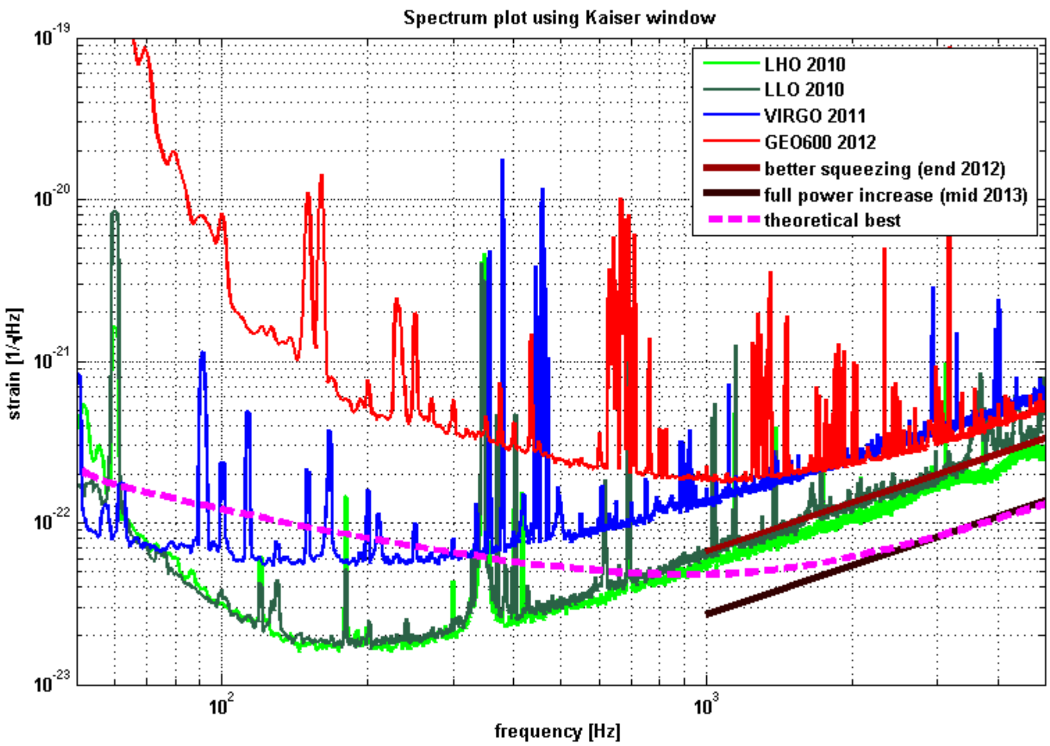

Figure 1: Recent interferometer sensitivities and GEO 600 projections. The improvements to the high-frequency sensitivity due to better squeezing and the power increase scheduled over the next year are depicted by the brown and dark brown guidelines showing only the rising part of the shot noise curve. A more accurate shot noise curve after the two upgrades, combined with the predicted level of thermal noise then results in the "theoretical best" curve.

The primary goal of the GEO detector characterization group is to utilize and maintain the easy access observatory nature of GEO 600 for characterization purposes. This goal has two main facets. The first is to aid in the commissioning process to improve the sensitivity of astrophysical searches carried out using GEO 600 data. The second is to provide implementation support for and/or develop advanced characterization techniques that require an operating interferometer. The rest of this section describes a few directions which the group is taking to achieve this goal.

2.3.2 Commissioning Tools

Currently the commissioning at GEO 600 is focused on improving both the high-frequency (above 1 kHz) and mid-frequency (between 100 Hz and 1 kHz) sensitivity. In parallel to the effort to lower the stationary noise floor of the interferometer, there is work devoted to reducing the number of loud transient signals in the detector output. All these lines of work naturally have positive consequences for GEO 600's observational potential. One of the aims of the GEO detector characterization group is to aid this commissioning process by providing views on many aspects of the interferometer through both established and novel means.

For example, the signal output of the GEO 600 interferometer contains an element of unexplained noise. Figure 2 is a recent noise budget that shows the discrepancy in the few hundreds of Hz band. Recently the work to search for this noise component has been started again. Two important pieces of information are known about a noise source in this frequency range. The first is that it has a dependency on the amount of

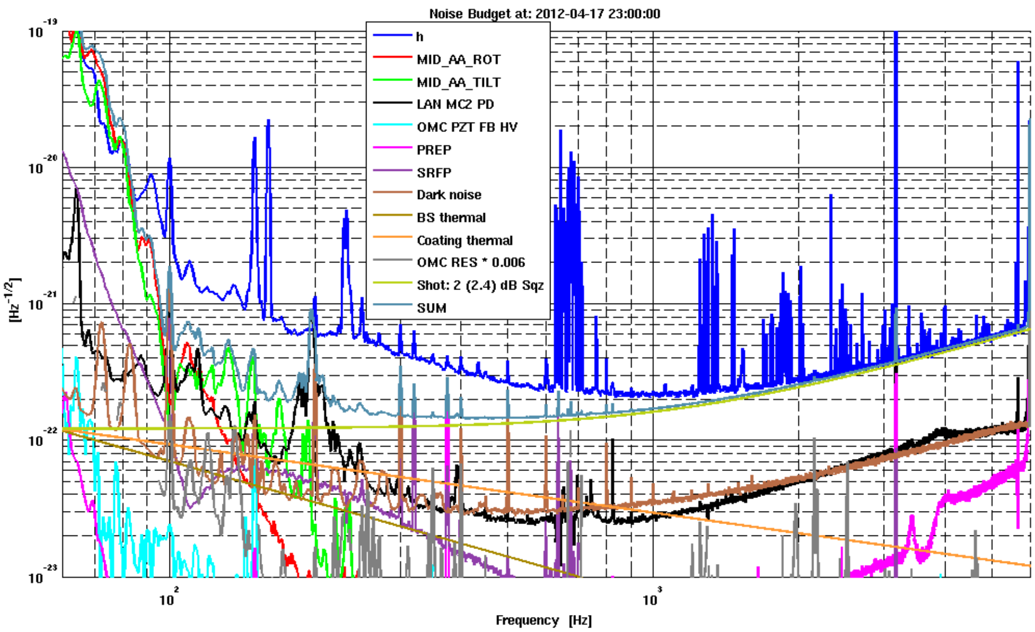

Figure 2: Recent noise budget for GEO 600. The blue curve shows a recent sensitivity curve. The gray-blue curve labeled "SUM" is the incoherent sum of all the noise contributions shown below it. We see that in the region from 85 Hz to 950 Hz the predicted sensitivity does not match the actual sensitivity.

power sent to the interferometer. The second is that this power dependent component is very non-stationary.

The non-stationarity of the noise component described above makes it very difficult to characterize via conventional means like calculating power spectra. Listening to the detector output is always a powerful tool but difficult to quantify and distinguish subtle changes. One of the current objectives of the GEO detector characterization team is to develop methods which are able to better characterize this non-stationary noise component. An example of this work is an effort to utilize data analysis pipelines such as Omega [25] and GSTLAL excess power [26] to display noise properties instead of triggers.

Projects such as this one can be described as data analysis for commissioning purposes. It is the commissioning that generates the questions which drive these analyzes. If these analyzes are successful then we will come full circle and they will start to drive the direction that the commissioning work takes. For the case of the mid-frequency noise investigations, the work of the characterization group at GEO 600 has already led to opening a new program of searching for scattered light in the interferometer. These types of projects makes up the bulk of the GEO detector characterization activities.

2.3.3 Interferometer Overview Monitoring

Another area of GEO detector characterization, which can also be seen as a type of commissioning tool, is that of interferometer overview monitoring. This consists of providing wide overviews of many different aspects of a running interferometer. These overview monitors are run constantly and save their history in an organized fashion that is easy to browse, normally as web pages. The first instances of such overview monitors were developed at the Virgo and GEO 600 interferometers. Recently, within the GEO detector characterization group a new implementation of these pages have been developed which makes it easy to

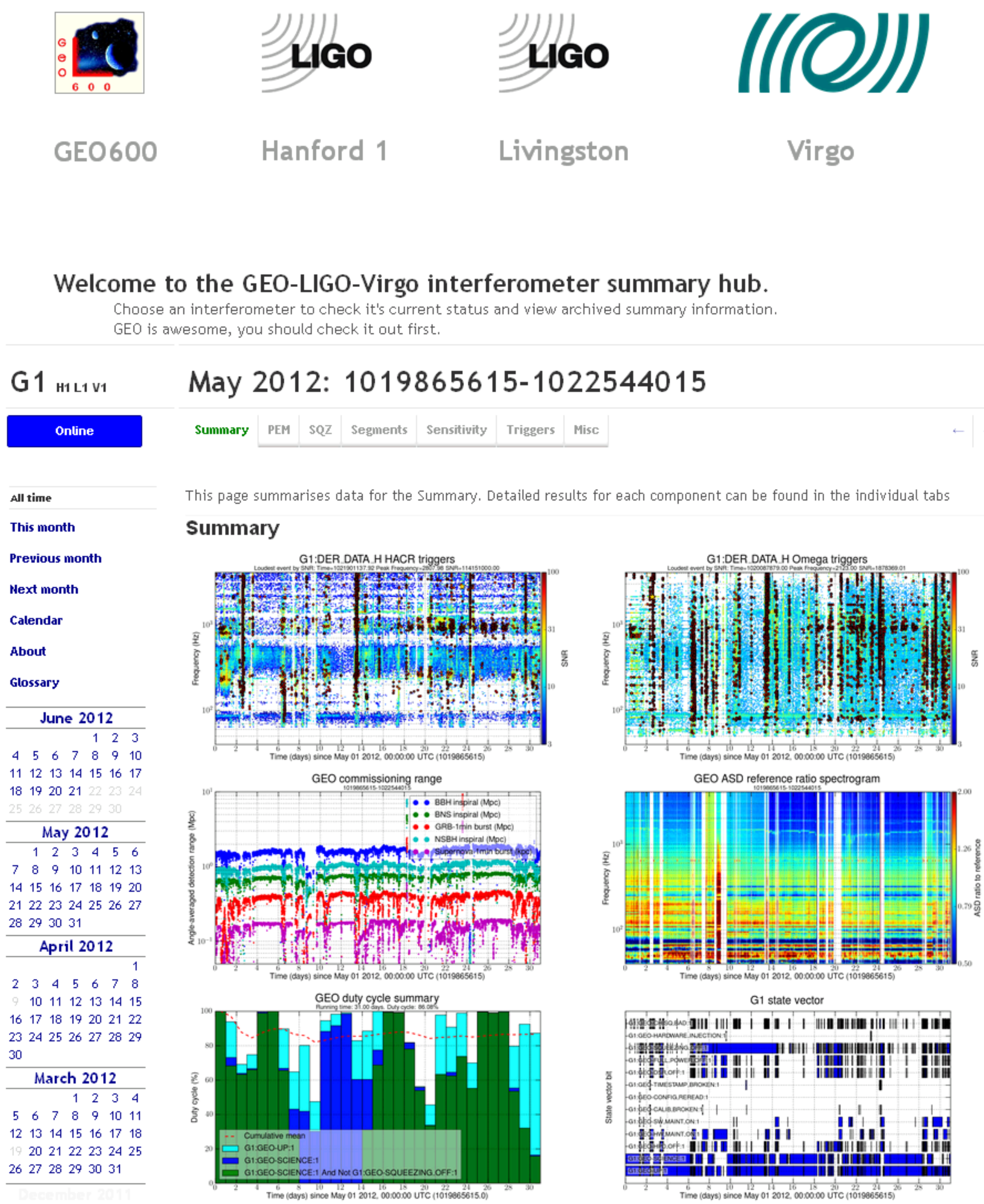

Figure 3: Interferometer summary pages. The very top section shows the hub which branches out to individual interferometers. It is shown here to emphasize the new feature of the code which is that it can be used to easily generate summary pages for any interferometer. Just below is an example of part of a monthly summary page from GEO 600.

generate these pages for all the different interferometers with a unified look and feel. Figure 3 shows two example pages from this work [27].

For these universal summary pages there are a few active areas of advancement. Since the universal pages are new, we are still thinking of ways to improve their organization. However, a larger area of expansion is in the content of the pages. As we grow in our understanding of how best to monitor gravitational wave interferometric detectors, these overview pages should evolve. The GEO detector characterization group will continue to improve the universal summary pages. This includes both the organization of the pages and exploring novel ways for monitoring that can then be added as content to these pages.

2.3.4 Advanced Techniques

The last category for work within GEO detector characterization is to investigate advanced characterization techniques. Since we are currently the only operating interferometer we would like to support the development of techniques that require such an environment.

We can again illuminate this type of characterization work by describing an example from ongoing work within the group. Recently we have been developing a new type of line monitor which follows both the amplitude and phase of a given line. This tool then can be used to generate a "noise-free" instance of the line. It is also very fast and can measure the line parameters in real-time. Because of this tool's real-time capabilities we are planning to use this tool in the control scheme of GEO 600. Possible usages range from feed-forward control to subtract power line harmonic coupling to mirror motion, to adaptive feedback loop shapes which either enhance or subtract lines.

For techniques such as this which can benefit from demonstration on an operating interferometer, the GEO detector characterization team can provide some implementation and development support depending on how well it fits the aims of GEO 600's role in the community. Although the tool used in this example was developed by a part of the GEO detector characterization group, this does not have to be the case. We invite people with ideas to discuss them with us!

2.3.5 Summary

Another way to state the primary goal of the GEO detector characterization group is that it is to aid and contribute to the goals of the GEO 600 operation as a whole. As mentioned earlier, the GEO 600 overarching goals are two-fold. In one direction this is to make use of the advanced detector installation and commissioning time for serendipitous discovery. The other objective is to contribute in some way to the advanced detector era. These objectives will remain central to GEO 600 into this era when the GEO 600 sensitivity is surpassed at all frequencies. We find that for both of these goals, the solution to achieving each one takes us down pathways of commissioning and characterization which are often times very much overlapping, interactive, and not easy to distinguish.

Indeed, when closely inspecting the examples given in this section, they can each be classified at the same time as contributing to both objectives as well as lying on both pathways. Taking the non-stationary noise characterization work as an example, it is a project that was driven by a commissioning problem but utilizes tools from the analysis/characterization community. Its success rests on the contribution of ideas from both points of view. In addition to the possibility of increasing the chances of serendipitous discovery by helping to increase the mid-frequency sensitivity of GEO 600, this project will also contribute to characterization in the advanced era.

All the examples mentioned here and most of the work within the GEO detector characterization group share this very intertwined nature. It is our goal to bring the resources of the analysis community to the instrument, and thus balance observational sensitivity, as well as insight into future commissioning advances, as in no other place in the world.

2.4 Virgo Detector Characterization

2.4.1 Introduction

As already been stressed, the search for gravitational signals requires a careful monitoring of the detector's response and the mitigation of the main sources of noise, both internal and due to the environment. In Virgo, the detector characterization relies upon a robust data acquisition system (DAQ) that has been designed to collect all data from Virgo sub-systems (including all probes that monitor the detector environment) and to provide data access to various processes/actors with minimal latency (down to few seconds for data viewer dataDisplay for example). The DAQ system was also thought to generate monitoring information about each sub-system. In Virgo, detector characterization is carried out by different actors involved in different groups that are highly interconnected:
- the commissioning group which has a dedicated team of people who track down any sources of noise that couple with the dark fringe (GW channel),
- the calibration team which measures and checks that control loops are well modelised and monitored to maintain the calibration and timing accuracy to an acceptable level for GW searches,
- and the Virgo data quality (VDQ) and Noise groups which study the quality of the data to provide useful information anf vetoes to the data analysis groups and useful feedback and investigation tools to the commissioning team for noise mitigation.

To accomplish the detector characterization tasks, different processing algorithms and tools have been developed over the last years and most of them have been exercised during the past science runs (VSR1-VSR4). These tools are described in section 2.4.2 and most of them will remain in place for Advanced Virgo. In section 2.4.3, the plans of the different actors for Advanced Virgo are presented. Most of the results obtained during VSR1, VSR2 and VSR3 science runs are summarized in [28], while more details about Virgo detector characterization for Advanced Virgo can be found in the Virgo Data Analysis Report [29] and in the VDQ and noise groups strategy documents [30][31].

2.4.2 Detector monitoring, detector characterization tools and online processing

Since many years, several diagnostics tools have been developed to provide information to Virgo commissioners, people on shift and detector characterization experts. Most of these tools acquire data from the Virgo DAQ system (either from files written on disk or from shared memories), and generate results and web pages with latency that varies from few seconds up to few days, depending on the necessity to accumulate enough statistics and/or the necessity of a very prompt information. Most of the information generated during the four Virgo scientific runs has been archived (in plain files stored on disk or in databases). Command line tools have been developed to help the Scimons (scientists on shift in the control room) to get more rapidly and easily the needed information. An online vetoes production has been also developed to help fast follow-up decision for candidates selected by low-latency data analysis pipelines and to improve the significance of events found by offline analyses [32]. For Advanced Virgo, a reorganization and several improvements of those tools is planned, as explained in the following.

1. **Detector Monitoring System (DMS):** since the beginning of the Virgo interferometer's commissioning, several online detector monitoring algorithms have been implemented. The aim of such algorithms is to provide information (mainly as quality flags) used to set alarms in control room and to monitor various parts of the interferometer and each software process involved in the DAQ or interferometer's controls [33][34]. Technically, the detector monitoring implementation uses the same software tools as the DAQ system. All the detector monitoring algorithms use the same input and output software interface [35] and the same configuration syntax [36]. Moreover, the quality tests done within each detector monitoring algorithm can depend on the interferometer's locking state provided

by the automation system. The quality flags generated by those algorithms are used to create a summary quality flag representing the general detector's quality. In addition, each algorithm generates an xml file containing the flags values used to build red and green flags to inform operators in control room about the interferometer's behavior:
https://pub3.ego-gw.it/itf/qcmoni/V5/index.php

For Advanced Virgo, the DMS is going to be upgraded to simplify the generation of quality flags, to better interface with data analysis and to provide in control room easy tools for alarms and detailed monitoring.

2. **Channels Database:** a mySQL database is automatically and periodically updated by a dedicated online process to store information about each data channel available from the DAQ. A web interface has been developped to allow any user to fill a description field associated to each channel. A command line is available to get rapidly and easily the information on any channel. More details and documentation are available in https://wwwcascina.virgo.infn.it/DataAnalysis/chDBdoc

3. **MonitoringWeb:** a tool based on web display, VEGA scripts [37] and bash scripts has been set up some years ago to generate periodically updated web pages. It has been upgraded in 2010 to provide more features, a standardization of the scripts and an automatic daily archive of the information. This monitoring tool provides, in a set of web pages, the status of each detector's subsystem but also the status of the DAQ, online processing and online GW searches [38]. It includes also a set of plots showing the noise budget of the detector and a set of spectrograms computed over week, day and hour scales [39] in order to monitor the spectral behavior of several interesting signals. Archives and current pages are available in https://wwwcascina.virgo.infn.it/MonitoringWeb.
Some noise monitoring web pages are generated with dedicated scripts that make plots from information stored directly in mySQL databases. See https://wwwcascina.virgo.infn.it/MonitoringWeb/Noise.

   For Advanced Virgo, it is foreseen to add a summary page providing the main figures of merits (horizon, glitch rate, etc...) and an automatic GW event summary page built for each GW event and providing the main information about the detector, its environment, the data quality information and the noise condition. In addition, we plan to add monitoring pages for hardware injections, data storage, data transfer and defective probes.

4. **Noise budget:** this tool, using model or measured transfer functions, produces information and plots, periodically updated, which summarize various noises contributions to the sensitivity curve:
https://wwwcascina.virgo.infn.it/MonitoringWeb/NoiseBudget

   Current implementation allows daily archives as well as the possibility to follow the noise budget evolution on a short time scale of a few minutes. For Advanced Virgo, this specific page of MonitoringWeb will be adapted to the noises of the new detector and will be improved in its short time scale display.

5. **Data visualization:** since the beginning of the Virgo interferometer's commissioning, dataDisplay [40] provides an easy way to display data online or offline. It allows to follow with a few seconds latency in control room the changes made on the interferometer or to do some trivial data processing (FFT, histograms, band pass filtering, ...). This software allows to combine signals and to do several types of plots: time plots, spectra, coherence, transfer functions, 1D or 2D distributions, time-frequency plots, etc...

   For Advanced Virgo, dataDisplay will be upgraded to improve its speed, to cleanup its code and to allow more signal processing features.

6. **Calibration and h-reconstruction:** the calibration of the Virgo interferometer is necessary in order to perform precise data analysis. The "standard" calibration had been automated and extended to have some redundant measurements during the first science run, in 2007. It includes measurement of the absolute time of the Virgo data, measurement of the transfer function of the dark fringe photodiode readout electronics, measurement of the mirror and marionette actuation transfer functions and monitoring of the finesse of the arm cavities. The calibration methods [41] developed for Virgo have been automatized as much as possible.

   The calibration output are then used in the frequency-domain calibration to provide the Virgo sensitivity curve, and in the time-domain calibration to provide the h(t) strain digital time series.

   The last calibration campaign to prepare VSR4, and the calibration monitoring during the run, have shown that the actuation responses have been stable at the level of the percent during a one-year period, from June 1010 to September 2011 [42].

   An independent method, developed to calibrate the mirror actuation gain, uses the radiation pressure of a secondary laser to push on the input mirrors and is in operation since 2007. It is used to determine the sign of h(t), defined as the sign of L_x-L_y where L_x and L_y are the lengths of the north and west arm cavities. Improvements on the calibration of this system have been performed [43] and this system has then been used to estimate the errors of h(t) below $\sim 500Hz$ with a completely independent method compared to the standard calibration. No discrepancies were found larger than the systematic errors of this system, of the order of 8% in amplitude and 30 μs in timing. More information and the calibration and reconstruction notes can be found at:
   https://workarea.ego-gw.it/ego2/virgo/data-analysis/calibration-reconstruction

7. **Hardware injections:** in order to perform coherent hardware injections simulating gravitational wave signals in the LIGO-Virgo detectors network, a system has been setup in 2009, based on the GPS time and using the calibration of the timing system. It was successfully used during VSR2, VSR3 and VSR4 for hardware and blind injections of gravitational-wave like signals. It should be possible to keep the same architecture for Advanced Virgo.

8. **Transient triggers generation:** Different algorithms are generating triggers with a low latency (less than a minute) and web pages are generated automatically in the MonitoringWeb system.

   Kleine Welle (KW): this algorithm is a computational method that finds transients in a time series by applying dyadic wavelet transforms (Haar basis) to look for excess energy regions in timescale decompositions [44]. Pre-processed whitened data is passed to the dyadic wavelet transform, then a threshold is applied on the energy of individual pixels. This step identifies the statistical outliers. The nearby pixels are clustered on the time-frequency plane and the significance is determined from their known distribution. Kleine Welle is the only transient finder algorithm able to process all auxiliary channels (more than 800 channels) on a few nodes accessing data available in shared memories of the DAQ, but might be replaced by Omicron for Advanced Virgo.

   Omega tools: a very useful tool for glitches investigations and glitchiness monitoring is the Omega burst search algorithm running online (Omega-online). Omega-online reads data from disk with a latency of few minutes. A web interface provides figures of merit using the omega triggers stored in ASCII files. Those various results and time-frequency plots are available at
   https://wwwcascina.virgo.infn.it/MonitoringWeb/Bursts.
   For significant triggers, an other process, Omega-scan, runs over several auxiliary channels and provides interesting information about possible origin of the trigger. Omega-scan results of all loud triggers are available in a centralized web page for further human investigation. Omega-online and Omega-scans are tools developed by LIGO and that we adapted to the Virgo needs.

For Advanced Virgo an improved version of Omega, called Omicron, is developed in Virgo. Omicron may be about 10 times faster than Omega and our aim is to use it on hundred of auxiliary channels, providing thus triggers more reliable than KW and an easy way to build vetoes or to investigate rapidly on loud glitches. First tests have shown that about 80 computing cores (twenty 4-cores machines) will be needed to run online over about 800 channels.

MBTA: MBTA is a Compact Binary Coalescence (CBC) search algorithm running online on LIGO and Virgo data. It is based on matched-filtering technics applied on separate frequency bands, the results being recombined coherently. This algorithm provides Virgo triggers helpful to monitor in real time the glitches most similar to a CBC GW signal, to check the efficiency of data quality vetoes against such glitches and to categorize the DQ vetoes for CBC offline analyses.

WDF: the Wavelet Detection Filter looks for transient signals in a wavelet based map. The input data pass trough a whitening filter. A wavelet transform is applied to the whitened data and a set of wavelet coefficient are selected following a thresholding criteria with respect to the noise background. The highest values for wavelet coefficients are supposed to be linked to the transient signal. The result is built summing all the squared coefficients and dividing this value by the noise RMS. In principle, this is proportional to the SNR of the transient signal. After a selection using a fixed threshold the events are clusterized in time. The filter gives indication also on the frequency content of the trigger (frequency and time information is provided by the maximum value of wavelet coefficient). The online report is given at: https://pub3.virgo.infn.it/MonitoringWeb/Noise/html/index.php?callContent=10
The last hour five loudest events are automatically analyzed to check their features in time and time-frequency domains, using a set of auxiliary channels.
https://pub3.virgo.infn.it/MonitoringWeb/Noise/html/index.php?callContent=34

9. **Glitches identification:** this work is done mainly by using transient search algorithms like Omega-online or KleineWelle. The Omega-scan tool is also heavily used to find hints of coincident glitches in auxiliary channels. During runs, glitch shifts are organized. A list of loudest triggers found by online GW analyses and not DQ flagged is established and studied to identify glitch families. Such glitch shifts give also the opportunity to strengthen the relationship with the commissioning team. Logbook information is also used to define, offline, some DQ segments that flag bad quality data periods and/or to understand various noise increases. A web interface has been set up to allow Scimons to create DQ segments for any event that could affect the data quality. Investigation on glitches origin and on the noise coupling path are done in collaboration with the commissioning team. We especially investigate the possible correlation between the GW channel and all the auxiliary channels.

   For Advanced Virgo, some automatic glitch classification tool may help to accelerate such investigation work. We will also improve the organization of the glitch shifts, including more tools providing automatized information for fast checks.

10. **KW-based vetoes:** KleineWelle (KW) transient search algorithm is useful to seek for statistically significant coupling between glitches in the dark fringe and any auxiliary channels. For this investigation veto algorithms UPV (Use Percentage Veto) and hVeto (hierarchical Veto) are run on each of the KW trigger lists over a daily period or a weekly period. They select and rank the channels that show a statistically significant excess of glitches in coincidence with the dark fringe glitches. Usually only triggers that pass all online DQ vetoes are considered in this study. When feasible and when the coupling between the dark fringe and a channel is persistent, a DQ flag based on this particular auxiliary channel is created. For all the other selected channels, KW-based veto segments are generated and used in the burst and CBC searches.

    More details are available in https://wwwcascina.virgo.infn.it/DataAnalysis/KW/Veto/

11. **Data quality and veto generation:** using the same basic libraries as the DAQ system, a set of DQ monitors generates online DQ flags which are collected by a specific process (SegOnline) which produces DQ segments, stores them in a database (VDB) and, in parallel, transfers them in the LIGO database (segdb). Additional flags are produced offline and a reprocessing of the online DQ flags is done whenever needed. Offline and online production include several cross-checks to validate the DQ segment lists for the search groups. On a weekly basis, we study the effect of the DQ vetoes on the triggers produced by the online burst and CBC GW searches. Statistical information such as efficiency, use percentage and dead-time of each DQ flag is computed online every week. In collaboration with the burst and CBC groups, each DQ flag is assigned a category which tells how the DQ flag should be applied by the GW search pipelines.

    The online DQ flags are permanently monitored in https://wwwcascina.virgo.infn.it/MonitoringWeb/DQ and the various reprocessings results are available from https://wwwcascina.virgo.infn.it/DataAnalysis/DQ

12. **Vetoes safety:** we validate the safety property of all the DQ flags and KW-based vetoes using loud hardware injections. The probability that a veto does not suppress any genuine GW event is computed considering the totality of the data since the start of a run. Different thresholds applied on this probability allow to detect when a veto becomes unsafe. In addition various tools are provided to monitor the data quality flags and to help glitch investigations.

    More details are available in https://wwwcascina.virgo.infn.it/MonitoringWeb/DQ/safety

13. **Spectral lines identification:** NoEMi (Noise Event Miner) framework is looking for frequency lines in the dark fringe, h(t) and a subset of the auxiliary channels. It implements some of the algorithms developed for the CW search to extract, with a maximal one day latency, the peaks (Frequency Events or EVF) in a frequency spectrum. From the persistence distributions of the peak maps, NoEMi identifies the noise lines and looks for coincidence between channels. The lines are compared with those already extracted in the previous iterations, in order to track the non-stationary lines (lines whose frequency changes with time). NoEMi produces every day a set of summary plots of the peak maps and a list of identified lines published on the Virgo monitoring pages [45]. The tool raises an alarm if noise lines are found close to the Doppler band of some known pulsars. The peak maps and line parameters are stored into a MySQL database and can be accessed through a web user interface [46], which allows data filtering, plotting and addition of user-defined meta-data.

    There are currently two instances of NoEMi running on Virgo data: a "low resolution, fast update" one, with a 10 mHz frequency resolution, which updates the lines database every 2 hours, and a "high resolution, slow update" one with a 1 mHz frequency resolution and an update once a day.

14. **Coherence:** the coherence between dark fringe channel and all auxiliary channels is computed on 5 minutes chunks of data, decimated to 1 kHz (using a 8th order Butter-worth filter). A web page with two tables is generated. The first table is a list of all channels analyzed: each entry in the table is a link to a plot of the corresponding coherence. The second table shows for each frequency bin a list of the 10 channels which gave the largest coherence.
    Results are in https://pub3.virgo.infn.it/MonitoringWeb/Noise/html/index.php?callContent=407

    For Advanced Virgo the coherence results will be archived in a database to allow queries and plots production on older data set. Coherence monitor will also be used jointly with NoEMi to better identify the source of noise for spectral peaks.

15. **Non stationarity:**

    NonStatMoni: This online monitor computes RMS over various frequency bands of the dark fringe signal. Such RMS value is a time domain signal whose spectrum at low frequency gives indication of

the slow evolution of the dark fringe in different frequency bands. Its results are stored in the trend data.
https://wwwcascina.virgo.infn.it/MonitoringWeb/Noise/NonStatMoni

BRMSMoni: it computes for a set of channels, the RMS over a set of frequency bands. In addition, it can compute the amplitude of a spectral line at a given frequency. Its results are stored in the trend data and can be used to determine the level of noise in a control loop (looking for instance at the 1111Hz line injected in the laser frequency control loop) or to follow the level and type of seismic activities on the site: https://wwwcascina.virgo.infn.it/MonitoringWeb/Environment

16. **Non linear coupling investigation:** the “Regression” project aims at measuring the linear couplings and some classes of non-linear ones among a primary "target" channel (e.g. h(t) or dark fringe) and a set of auxiliary channels (environmental or instrumental channels). This information can then be used for commissioning and noise hunting activities, as well as for cleaning non Gaussian noises from h(t) by numerical subtraction of the measured correlation with the auxiliary channels.

    We are developing and testing two different procedures:

    - a procedure based on a forward-regression orthogonal estimator applied to non-linear system identification to subtract environmental noise to the dark fringe output. A Volterra series expansion is employed and the model results linear in the parameter. In this way, the identication algorithm can be the same as in the linear case, and orthogonal least squares method can be used. The identification accuracy is improved by filtering the error in a specified frequency region. A good point of the method, developed by S.A Billings et al., is that a ranking of the auxiliary channel significativity can be given.

    - a procedure based on a coherent analysis of the target and auxiliary channels. It consists in a linear regression or Wiener-Kolmogorov filter which predicts the target channel part correlated to auxiliary channels. Considering as input the mixing of more auxiliary channels, it is possible also to characterize bilinear (or higher order) couplings to the target channel, for instance up-conversion of low frequency noise to side-bands of strong spectral lines. The algorithm is based on a chi-square minimization to find the optimal prediction, whose last step selects the most relevant auxiliary channels for the prediction by applying a regulator to the ranked list to avoid increasing prediction noise due to un-useful auxiliary channels.

17. **Databases:**

    Segments database (VDB): this tool, based on a mySQL v5 server, allows to archive all the DQ segments generated in Virgo and to keep trace of any change. It also contains all basic segments, such as the Science mode and hardware injection periods, as well as the Scimon information generated by shifters. VDB provides useful facilities to perform requests and logical operations on DQ segments lists, by anyone in LIGO, GEO and Virgo:

    - The VDB Web UI: this is the Web interface used to query and combine together DQ segments archived into the database. In particular a dedicated section about data quality and science mode segments list has been developed. In this section it is possible to use several features like showing each single DQ list with its properties or combine together several segments lists, by using user defined logical expressions.
    - The VDBtk_segments.exe: that is the command line tools for the DQ segments lists. This extends the functionalities available in the Web UI, in particular it is used to upload DQ segments list into VDB or to combine them with logical operators.

- The API's of the VDB library: using only the two functions *VDB_set_online* and *VDB_segments_download*, you can download online DQ segments within your data analysis code if you linked it to the VDB library.

For Advanced Virgo, an upgrade of VDB is under way, with a large cleanup of the mySQL tables and an optimization of the DQ segments access. Users requirements and software requirements documents are going to be written and an associated upgraded is foreseen also for the VDB library, the web interface and the command line tool VDBtk_segment. In addition, access tools in python for offline and online DQ segments will be added. We will also focus on the strategy to adopt and the tools to be developed for the synchronization with the LIGO database segdb or the use of VDB by LIGO.

Lines database (LinesDB): lines identified by NoEMi are stored in a mySQL database which can be accessed through a web interface. The database is updated in real time by NoEMi and is filled offline with user-defined information (type of instrument used in the measurement, general information on the line and its noise source, etc...) once the source of the disturbance is understood. The identification of the noise lines found in VSR2-VSR4 data started just after the end of VSR4. Out of the O(1000) lines found in each run, 90% have already been identified and less than 100 lines still require investigation. The lists of identified lines are used to veto fake candidates in the stochastic and CW searches.

Triggers databases: some of the transient search algorithms (for instance WDF) stores triggers in mySQL databases. This allows to archive triggers in a well controlled way and to provide a standard interface to access to those triggers. For Advanced Virgo, we plan to generalize the use of databases to all transient search algorithms.

2.4.3 Advanced Virgo plans

Virgo science runs have demonstrated the importance of time periods at the frontier between commissioning and science run:
- noise hunting campaigns before data taking starts (for instance mitigation of seismic and acoustic sources of noise, that can generate spurious signals mostly by modulating the position of elements that scatter light inside the interferometer cavities),
- a pre-run period for online vetoes tuning,
- a commissioning time dedicated to the careful calibration of the instrument.
The organization of those time periods will be also a mandatory item of the detector characterization plans. Before we reach these after-commissioning time periods, the reduction of the environmental noise for Advanced Virgo is mandatory to reach the Advanced Virgo target sensitivity. This goes along with an upgrade of the monitoring sensors. In parallel to this effort, an upgrade of the calibration methods and of the injection tools may be needed. Finally, the detector characterization groups (VDQ and Noise groups) are defining the upgrades of the monitoring tools and developing new ideas to better identify the limiting sources of noise and to suppress their effects in GW searches.

All those projects and the strategy adopted are briefly described below.

1. **Data quality monitoring and glitch shifts**

   Most of the tools that monitor the detector are in place and already fully integrated in the DAQ system. Improvements are though foreseen, especially to better handle the flow of data quality information which is generated during science runs and to provide useful inputs to GW searches. Most of the foreseen improvements have been mentioned for each tool described in section 2.4.2.

   The organization of the glitch shifts and the interactions with Scimons and commissioning team will be also one of the main items we plan to improve for Advanced Virgo.

2. **Calibration, h-reconstruction and injections**

   The calibration methods developed and automatized for Virgo should be still valid for Advanced Virgo calibration. However, Siesta simulations are on-going to check whether the methods used for the mirror actuation calibration will still be sensitive enough with the new optical configuration. The estimation of the minimum force to be applied on the mirrors for calibration might put constraints on the design of the electro-magnetic mirror actuators of Advanced Virgo.

   The Virgo calibration is presently using the same actuators as those used to control the interferometer. The possibility of using an external actuator to produce the excitation signal, the photon calibrator, is under evaluation for Advanced Virgo. Plans to improve the photon calibration setup for Advanced Virgo have been described in the section 14.6 of the Advanced Virgo Technical Design Report [47].

   The current h-reconstruction method is expected to work for the first steps of Advanced Virgo, without signal recycling cavity. Studies are then needed to update it to the interferometer with the signal recycling.

   The architecture used to generate coherent hardware injections in the LIGO-Virgo network should be kept for the injections in Advanced Virgo.

3. **Environmental noise**

   Environmental noise coupling to the Virgo interferometer has been a primary issue along the detector commissioning and during all science runs. Eventually, residual noise had impact on GW signal searches. Based on this experience, Advanced Virgo detector design adopts strategies to reduce coupling and mitigate sources of environmental noise. We also foresee to upgrade and improve the environmental noise monitoring sensors network. We briefly describe below the environmental noise mitigation strategies and monitoring sensors upgrades.

   Noise mitigation strategies:

   Our goal in Advanced Virgo is to reduce environmental noise in the GW channel below the design sensitivity by at least a factor 10. To achieve this ambitious goal, we plan to work both on reducing the coupling of the disturbance to the interferometer and reducing the emitted noise and limiting noise transmission paths. Detector design strategies to reduce environmental noise coupling briefly consist in:

   - Reducing vibration noise coupling by:
     - minimizing beam paths in air and through ground connected optics, thus adopting in-vacuum suspended optical benches and replacing Brewster windows with cryogenic vacuum traps;
     - implementing an optimized in-vacuum suspended baffles system to absorb stray light from core optics;
     - minimizing diffused light at injection and detection ports, by adopting for example low diffusing optical components;
     - accurately designing new components (one example: new cryo-traps design will minimize re-coupling of vibrations from liquid Nitrogen bubbling).
   - Reducing electromagnetic noise coupling by:
     - adopting lower strength magnet actuators on core optics (to couple less environmental magnetic fields);

  - assuring negligible EM coupling at new project components like Ring Heater thermal compensation device and new sensitive electronics.

On the other hand, strategies are defined to create a quieter environment at critical locations. We have defined more stringent seismic and acoustic noise requirements for the injection (INJ) lab (which will host in-air benches), the detection (DET) lab and experimental halls.

The planned actions are:

- to improve INJ and DET lab acoustic isolation, as well as labs air cleanliness quality by adopting dedicated clean room low noise HVAC systems;
- to relocate and/or silence more offending sources: for example vacuum scroll pumps will be confined in acoustically isolated rooms and seismically isolated;
- for electronics racks which cannot be segregated, but need, for operation reasons, to remain in the experimental halls, to reduce acoustic emission from cooling fans (which is the major noise source) and reduce fans number by optimizing heat dissipation, and to seismically isolate racks;
- to move most offending power transformers at some distance to minimize stray magnetic fields in the experimental areas close to the core optics. To this end, a DC distribution system will be implemented to serve at least part of the electronics. In addition, care will be taken to adopt power supplies with low stray field emission, i.e. implementing toroidal shaped transformers type.
- to partially replace the current large noisy UPS generator with a smaller less noisy UPS system dedicated to electronics close to magnetic noise sensitive area. This should further reduce stray magnetic fields.

Monitoring sensors upgrades:

The upgrade for Advanced Virgo will require also an improvement of the environmental monitoring network, following two major requests: on one hand a larger number of sensors are required due to the higher complexity of the interferometer, on the other hand the higher sensitivity of the antenna will require a more severe rejection of the environmental noise that implies a general improvement of the sensitivity of the monitoring network.

The first request mainly comes from the installation of the Signal Recycling tower and from the installation of the suspended optical benches placed at the output ports of the ITF. The tower will be equipped with a set of temperature probes for the suspension monitoring and a couple of accelerometers to monitor the tower vibration at medium frequency. The suspended optical benches, required for the seismic and acoustic isolation of the detection optics, also need additional probes with respect to the Virgo/Virgo+ case, for a careful acoustic and seismic monitoring. Moreover Virgo infrastructure counts a number of devices (e.g. water chillers, air compressors) which follow on/off cycles driving high currents at the start-up. They are potential sources of noise transients. In addition to mitigating them, we plan to monitor their on/off status by adding simple current probes in the fast monitoring system.

The second request implies the adoption of more sensitive probes, whenever possible, or the use of less noisy conditioning electronics to optimize the probe response to the environmental noise. For most sensors, in particular for episensors, PZT accelerometers and microphones, an improvement of the sensitivity can be easily obtained by increasing the output gain, if the standard environmental noise level allows this operation without saturating the electronic. This should be possible if all the foreseen actions, required for the noise mitigation, are effective.

The area surrounding the Virgo observatory site is subject to slow but steady modifications. Noisy activities such as wind turbines, speedways, caves, have been installed or are being proposed for installation at a few km from the site. Preserving the site noise climate is important for Advanced Virgo and an agreement has been signed between EGO and the local authorities to regulate noisy installations in the observatory surrounding area. We propose also a set of outdoors environment probes to monitor potential external noise sources and to monitor variations of the site noise climate.

More details can be found in https://wwwcascina.virgo.infn.it/EnvMon

4. **Data quality for GW searches**

For Advanced Virgo, we do not plan to do large upgrades of the software architecture used to generate online DQ flags or KW-based vetoes. The main improvements will concern glitch investigations and new vetoes developments. We focus in priority on the Omicron trigger generator, the VDB upgrade, the glitch classification and the various tools used to monitor glitches or to estimate vetoes performances and categorization. An additional important point will be the involvment of the VDQ group in the upgrade of environment monitoring, defining types and location of any probes useful for the development of efficient vetoes.

Also, tools for investigating on noise non linear coupling are under development and could help us to determine which set of auxiliary channels should be used to veto glitches or to mitigate the associated noise source. Related to this developement, short time scale non-stationary lines are considered also as one of the main sources of glitches to be investigated and for which tools should be developed.

We also plan to improve the identification of glitch families to determine which are the main characteristics of glitches which could be combined to give a weight to GW triggers instead of vetoing time period as we do now. Being able to replace the vetoes categorization by such a number or more globally by a veto performance indicator would simplify the use of vetoes in data analyses. A reflexion in this direction has been started within the GWOLLUM project linked with the Omicron trigger generator.

The veto safety assessment has also to be improved. To compute the safety probability, we assume currently that hardware injections and veto segments are randomly distributed in time. This is not the case for hardware injections (done each 5 seconds in a series of 10) and not always the case for the veto segments.

We will need also to define which information is mandatory to be used by online analyses when producing GW events or by scientist on shift when deciding about GW event candidate to be sent for follow-ups by satellites and telescopes. The production of online DQ flags is mainly motivated by our ability to select good candidates for such low latency analyses and follow-up. This reflexion is linked to the glitch classification and the use of a statistical estimator to weigh triggers to replace vetoes categorization but this is a longer term priority.

A document describing the VDQ strategy for the coming years is in preparation. This document lists the current tools available and their foreseen improvements. It describes also the current projects, the needs and requirements for various aspects of the glitch investigations, online vetoes production, monitoring tools and commissioning help. This document will be subject to discussions and comments and should be released during the summer 2012. It is accompanied by a web page listing the various tools and projects linked to detector characterization activities and that we plan to update regularly: https://wwwcascina.virgo.infn.it/DataAnalysis/DQ/dqtools.html

The Noise group is also defining in a document its strategy for Advanced Virgo. In addition to the upgrades of the NoEMi tool and the Lines database, the NMAPI [48] framework, which provides web interfaces to databases, will be upgraded. More precisely here is a list of on going projects in the noise group for Advanced Virgo:

- Centralised DataBase: we plan to have a centralised database to store and retrieve all Noise monitor results having a transparent access via a web interface. The aim is to increase the interoperability and communication between applications within this environment and NMAPI via the use of the Connections Database (CDB).
- Upgrade NMAPI to D-NMAPI: we foresee to upgrade NMAPI to a distributed version of the application (Distributed NMAPI) which will distribute the computational work on different computing nodes improving the performance of NMAPI.
- Non-linear coupling identification: new algorithms for detector characterization have been proposed that focus on the identification of non linear coupling of noise sources with the dark fringe. We plan to integrate these algorithms into NMAPI.
- Glitch characterization: the aim is to produce a catalogue of transient noise event waveforms (using cWB or WDF pipeline) and archive them in a Database. We plan also to do some tests and comparison between transient events found by CW pipeline cleaning procedure and the ones found by WDF and Omega pipelines.

Last but not least, data analysis groups are common between LSC and Virgo but detector characterization is more independently carried on as it deals with the specificities of the detector and its environment. Nevertheless exchange of knowledge and use of common tools like Omega-online, KW, UPV, hVeto were fruitful and we plan to intensify such relationship for the preparation of advanced detectors era. The Engineering Runs are part of our development plans. They will especially be used for testing all new developments related to the low latency CBC search (MBTA) and online processing before real data are generated by Advanced Virgo.

3 Searches for signals from compact binary coalescence

3.1 Overview of searches

The inspiral and merger of a compact binary system generates gravitational waves which sweep upward in frequency and amplitude through the sensitive band of the Earth-based detectors [218]. The detection of gravitational waves from these astrophysical sources will provide a great deal of information about strong field gravity, dense matter, and the populations of neutron stars and black holes in the Universe. The scientific program of the LSC/Virgo Compact Binary Coalescence (CBC) Group is designed to identify GW signals from compact binary sources in the detector data, estimate the waveform parameters with confidence in the correctness and validity of the results, and use these signals for the study of gravity and the astrophysics of the sources [218].

The immediate goal of the CBC group is to make the first detections of gravitational waves from compact binary systems with data from the LIGO and Virgo detectors, through computational methods that are as close as possible to optimal (that is, making full use of the detectors' sensitivities), and to develop robust and unbiased methods to gain confidence that the detections are not false alarms due to detector noise fluctuations. Once signals have been identified, there is a need for the accurate recovery of parameters in order to perform detailed studies of both gravitational-wave astrophysics and fundamental physics.

This section of the white paper lays out the goals of the CBC group. We begin with a brief recap of past searches performed on the data taken by the first generation of detectors during the LIGO S1-6 and Virgo VSR1-4 science runs, as well as a description of the ongoing analyses on these data sets. Then, in Section 3.3 we provide a brief overview of the analysis techniques and strategies that have been developed before discussing, in Section 3.4 the various sources that will be targetted in the advanced detector data.

3.2 Searches for Binary Coalescences in the S1-6 and VSR1-4 data

The CBC group has now completed searches for binary coalescence with total mass between $2\mathrm{M}_{\odot}$ and $25\mathrm{M}_{\odot}$ (including binary neutron stars with component mass as low as $1\mathrm{M}_{\odot}$ using its flagship *ihope* pipeline and all Initial LIGO/Virgo data. The results have been published in a series of papers: S1 [59], S2 [60], S3 and S4, [63], S5+VSR1 [66, 67, 53] and S6+VSR2/3 [58]. No detections were made, but a 90% confidence upper limit on the rate of binary neutron star coalescence of $1.3 \times 10^2 \mathrm{Mpc}^{-3}\mathrm{Myr}^{-1}$ was determined using this data.

A low-latency search was performed in addition to the *ihope*-based search using the triple-coincident data from S6/VSR3. Using the *MBTA* pipeline a latency of around three minutes from data recording to sky localisation was achieved, and the resulting triggers were sent for electromagnetic followup by several telescopes [145].

A number of additional searches have been performed for: binary black hole systems in S2 [61]; spinning black hole and neutron star binaries in S3 [64]; the ringdown of black holes formed after coalescence of binary systems, in S4 data [65], binary black hole systems in S5 data [55].

Finally, we have conducted searches for gravitational waves associated to short gamma ray bursts in S5-VSR1 [54], S6-VSR2/3 [93] as well as for two GRBs whose localizations overlapped nearby galaxies: 051103 [57] and 070201 [62].

There are several ongoing searches for gravitational waves using the data taken by the initial LIGO and Virgo detectors that we describe briefly below.

3.2.1 Inspiral–Merger–Ringdown of black hole binaries

A search using LIGO S6 and Virgo VSR2/3 data has been performed for binaries with total mass M between $25 - 100 M_{\odot}$, using EOB-NR templates. There have been numerous innovations in the high mass search, in an attempt to improve its sensitivity and to keep up with the ever improving knowledge of the waveforms emitted by these systems.

A further search of S5/S6-VSR2 data over a restricted parameter range (mass ratio below 4:1) is in progress to test a specific astrophysical binary formation scenario. This "focused highmass" search may obtain upper limits a factor 3-4 better than existing limits on BBH merger rates, due to the greatly reduced number of templates and the use of recent developments in search techniques.

3.2.2 Parameter estimation

Accurate parameter estimation on detection candidates is crucial for the astrophysical interpretation of search results. It can also be used as part of follow-up studies, providing another mechanism for understanding signal consistency. During S6, the CBC group has significantly advanced the readiness of Bayesian parameter estimation tools. Multiple tools using different sampling techniques had been developed and successfully compared with each other. These tools were applied to a number of triggers from the low-mass and high-mass pipelines, including the Big Dog event. A full-author list paper describing the parameter-estimation tools developed by the CBC is nearing completion. It will include examples of the performance on S6 hardware and/or software injections.

3.2.3 Search at times of IPN GRBs

The preferred progenitor scenario for short-hard gamma ray bursts (GRBs), is the merger of a neutron star or black hole-neutron star binary system. This motivates a search for gravitational waves using LIGO S6 and Virgo VSR2/3 data for CBC signals associated with GRB events. Searches for GRBs identified by Swift and Fermi have been completed on the S5-6 and VSR1-3 data. The interplanetary network (IPN) is also able to detect and localize GRBs, manual followup is required to analyze the IPN data to compute a sky localization. A list of IPN GRBs detected during S5-6 and VSR1-3 has been produced and a CBC search for gravitational waves associated to the short IPN GRBs is well underway.

3.2.4 Sub-threshold GRB followup

In addition to an EM-triggered search of LIGO data it is also possible to follow up S6 triggers by looking in archived data from GRB missions. We will use sky location and distance information from parameter estimation to run a targeted followup of S6 CBC events searching for sub-threshold high-energy electromagnetic counterparts to NS/NS and NS/BH mergers in Fermi GBM and RXTE ASM data.

3.2.5 Ringdown search:

For high mass binary coalescences ($M \gtrsim 100 M_{\odot}$) , the majority of the power received by the LIGO and Virgo detectors will be from the ringdown part of the coalescence. Therefore, the search for coalescencing binary systems can be done looking for the final ringdown which has a known and simple waveform (a damped sinusoid), whose parameters (frequency and damping time) can be related to the final black hole mass and spin. The uncertainty in the theoretical predictions for how the inspiral, merger and ringdown phases couple into a single waveform governed by a single set of source parameters (masses and spins) leads us to pursue such a ringdown-only search. In addition to binary coalescence, other mechanisms for strongly perturbing an astrophysical black hole can also result in an observable ringdown.

This search is being run on the S5/VSR1 (H1,H2,L1) and S6/VSR2-3 (H1,L1,V1) data using an improved and re-tuned analysis. The analysis is nearing completion and a results paper is in preparation.

3.3 Analysis techniques and strategies

Here, we outline the major parts of the analysis that is required to identify gravitational wave signals from CBC in the detector data as well as to characterize the signal and extract the relevant gravitational and astro-physics.

3.3.1 Data quality

The method of matched filtering upon which the CBC searches are based is optimal in the case of stationary Gaussian noise. However, the noise of the real detectors deviates in several ways from this simple model. The noise power spectra of the detectors changes over minute and hour timescales. Also, there are a large number of glitches in the data, which are non-Gaussian transients typically on sub-second time scales.

The Detector Characterization group has the responsibility for understanding these non-ideal characteristics of the detector. For example, the Glitch sub-group may produce flags which predict the occurences of glitches in the data. The CBC Data Quality group is responsible for studying:

What kind of data quality issues are the advanced detectors likely to have? How do each of these data quality issues affect each of the CBC searches? The length of the templates is probably the primary determining factor in what DQ issues a search needs to worry about. The binary neutron star search is likely to be most affected by non-stationarity like slow changes in the PSD over time, and non-stationary lines. Binaries containing black holes have shorter templates which will be more affected by glitches. All searches should also have a way of cutting out very loud glitches from the data so they don't corrupt the PSD or the filters. Software must also be developed to simulate expected types of data quality issues, and recolored S6 and VSR2-3-4 data as well as engineering run data also provide excellent tests of our understanding of how realistic data affects the search.

Find the best way to incorporate DQ information into the search, using vetoes or incorporating the information into the likelihood ranking. DQ information should be incorporated in a more sophisticated way than just putting integer second vetoes around the glitch. We need a good map from the glitch characteristics (its frequency, Q, and amplitude) to the time and SNR of the inspiral triggers it will cause. The same goes for non-stationarity, or long-lived rumbliness. We should have both some improvements on the traditional veto method, and some developments of folding in the DQ information to the ranking statistic or feeding it into a classifier.

Improve signal-based vetoes based on likely behaviors of the instrument. In Gaussian noise and in a single detector, the SNR is the optimal statistic. Searches in real data require signal-based vetoes, but which of these vetoes are used and how they are tuned depends entirely on how the noise deviates from Gaussian. We must evaluate our various chi-squared and other signa-based tests and optimizing their tuning, and come up with other signal-based vetoes as well. Another ability that should be developed is to matched filter for known glitch classes, so we can ask "does this look more like an inspiral, or more like this known type of glitch". This would most likely only be a last resort if there were a significant type of glitch that could not be eliminated by any other type of method.

Develop measures of the effect of data quality issues on the search sensitivity (and the improvement when vetoes are applied). The most important thing is testing. We need to rigorously evaluate how well our search is doing. Then we use that to tune our use of DQ information - whichever way makes the search most sensitive is the way that we use. This interacts with efforts to improve background estimation. It's easy to miss things that hurt you at the 1/1000 year level if you've only got background out to the 1/100 weeks level. We also should try to know what things in the single-detector background are going to hurt the full search. This information must be fed back to the detector characterization group for investigation and mitigation.

High-priority goals for the next year

- Develop software to simulate data with simplified models of data quality issues. Examples are non-stationary PSDs, jitter lines and lines with sidebands, scattered light, and simple glitch models.
- Develop an understanding of how simple models of glitches or non-stationarity affect the CBC search, especially in the case of advanced detector noise curves.
- Prototype tools to rigorously evaluate the sensitvity of the search in real data.
- Develop and test methods to remove very loud glitches in the data so that they have no effect on the power spectrum estimation or matched filtering.
- Participate in Engineering Runs using real data (from previous runs and from advanced detector subsystems). Attempt the improve the search for simulated signals in this data, and to make confident detections of these simulated signals.

Goals for the advanced detector era

- Understand in detail how all important types of glitches and data quality issues affect the search.
- Given an event or detection candidate in imperfect data, be able to very confidently determine whether it was caused by a data quality issue. It should be possible to detect even in data with glitches if we can prove that these glitches could not have caused the trigger.
- Develop the ability to use low-latency data quality information in the online search.
- Optimally use data quality information in ranking event candidates rather than using on/off integer second vetoes. This will most likely involve likelihood or multivariate classifier methods.
- Have simple-to-use software that rigorously evaluates the sensitivity of the search in imperfect data, with and without data quality information applied. This will make it very simple to determine whether some new data quality flag, method, or tuning of the search is an improvement.
- Achieve a much better cleaning of the search background, and approach as closely as possible the Gaussian limit.

3.3.2 Gravitational waveforms emitted during binary coalescence

Gravitational waves emitted from compact binaries with total mass $\sim 1 - 10^3\,M_\odot$ are considered prime detection candidates and could potentially yield the most information about their sources and the underlying laws of gravity, as accurate waveform models are available. These waveforms can be used as templates for a matched filtering search which can extract weak signals buried in noise. The waveforms are also used in injection studies, which are important for assessing detection efficiency and estimating the false alarm rate of candidate events. Lastly, after detections are made, the waveforms will be used within Bayesian inference pipelines, which will measure the probability distribution for source parameters such as the masses, spins and sky location, see sec. 3.3.8, as well as possibly fundamental gravity parameters, see sec. 3.3.9.

Waveforms calculated within the post-Newtonian framework are thought to provide accurate representations of the adiabatic inspiral when the two bodies are relatively widely separated [89, 102]. Numerical relativity has achieved simulations which cover the late portion of the inspiral, the merger of the two bodies, and the ringdown as the merged body settles into a final steady state, with excellent agreement among different groups and independent codes [198, 79, 106, 199, 143, 135].

The final ringdown phase can also be described by black hole perturbation theory [86]. Analytic waveform models have been developed which combine insights from post-Newtonian theory, numerical relativity and black hole perturbation theory to describe the entire inspiral-merger-ringdown (IMR) evolution: these include the Effective-One-Body (EOB) framework [100, 101, 103, 104, 115, 190, 189, 215] as well as phenomenological or hybrid approaches [70, 72, 207, 200].

Waveform development remains a very active area of research, as analytic waveform models are frequently improved through the inclusion of new and better descriptions of physical effects such as spin couplings and precession, higher harmonics of the orbital frequency, tidal deformability of neutron stars in binaries, memory effects, eccentricity as well as non General Relativity effects.

Furthermore, numerical simulations until recently have mostly focused on non-spinning or spin-aligned binaries of comparable component masses [187]. However, these simulations are being pushed to more difficult cases of extreme mass ratios, large spin magnitudes and generic, precessing spin configurations. As more simulations are performed, analytic IMR models are re-calibrated so as to have the best possible agreement with all of the available simulations.

The continued development of new and improved waveform models is an important goal for the CBC working group, also in collaboration with numerical and analytical relativists. More accurate waveform models will increase the chances of detection and improve the quality of science that can be done with those detections. The development of many waveform models will also allow us to gauge systematic errors by examining the differences between models.

Recently, the LALSimulation library has been developed within LAL to generate any of the available waveform families for use as search templates, injected signals or within Bayesian inference pipelines. Work is in progress to homogenize the use of all available waveforms in order to generate them through a single interface, making it very easy for a data analysis pipeline to try many different waveform families. This will facilitate studies for which waveforms are most appropriate for any given source or parameter range. It is also important to make the waveform-generation routines as fast as possible. This is especially important for Bayesian inference pipelines, which must typically generate millions of waveforms, and for low-latency search pipelines, see sec. 3.3.6.

High-priority goals for the next year

- Finalize a common interface for all data analysis codes to generate waveforms. This interface should be as simple and intelligible as possible, but flexible enough to generate all available waveforms.
- Determine which waveform parametrizations, in particular the conventions for orientation angles for precessing binaries, will allow Bayesian inference codes to converge as quickly as possible.
- Improve upon existing waveforms to include more physical effects
  1. Implement a new merger-ringdown model, the implicit-rotating source (IRS) [78, 151], for use with any EOB inspiral model or as a stand-alone alternative to ringdown searches.
  2. Improve upon the existing spin-aligned EOB model (SEOBNRv1) by including sub-dominant modes, spin terms in the radiation-reaction sector at higher PN order and calibrating it to spin magnitudes larger than 0.6.
  3. Complete the implementation of a new spinning, precessing EOB model (SEOBNRv2).
  4. Improve upon the existing spinning, precessing inspiral model to allow for more spin couplings, higher order precession equations and the ability to use non-orbit-averaged precession equations.
  5. Implement several new spinning, precessing inspiral models including the CBWaves waveform model [114] for eccentric binaries and a new frequency-domain model [71].

6. Improve upon the existing TaylorF2 frequency-domain inspiral waveforms to allow for higher harmonics of the orbital frequency, spin couplings and tidal terms.
7. Improve the PhenSpin model [200] of phenomenological IMR waveforms describing precessing spinning systems by extending the region of parameter space in which they are tested against numerical simulations.
8. Implement an improved non-precessing spin IMRPhenom [70, 72, 207] waveform model including higher harmonics.

Note that comparisons between the analytical IMR models and a large set of numerical waveforms is planned to take place within the NRAR collaboration. These comparisons will be used to improve the IMR models.

Goals for the advanced detector era

- Seek further waveform speedup, especially through use of GPUs.
- Include eccentric waveforms, memory terms and all possible physical effects not included in waveform models currently available in LAL.
- Work with the various source groups to determine the best available waveforms for each source.
- Perform studies to quantify the level of systematic bias from waveform uncertainties due to the inclusion or omission of higher harmonics of the orbital frequency, tidal effects, eccentricity and other physical effects.
- Waveforms may be also modified by the effects due to soft neutron star equations of state (which affect the waveform at frequency larger than 450Hz [214]). Inclusion of such effect requires some more analytical modeling.
- Review and validate all waveform implementations to ensure they are correct and consistent with the literature.

3.3.3 "Streaming" analysis pipelines

Since 2008 the LSC has been preparing a "stream-based" CBC pipeline that aims to ultimately reduce the latency of compact binary searches down to $\lesssim 10$ seconds despite the challenges presented with longer duration signals in the advanced detector era. This will be a gradual process with the first advanced detector science runs likely having $\lesssim 1$ minute latency. Rapid CBC searches combined with rapid detector characterization, source localization and candidate event alerts will facilitate the LSC and Virgo's role as a member of the broader transient astronomy community and will hopefully enable the association of transient GW events with transient electromagnetic events.

One of the projects that aims to achieve this goal is known as GstLAL, which is a library that relies on the open source signal processing / multimedia library Gstreamer and the gravitational wave analyis library LAL. Gstreamer provides the infrastructure to quickly create and deploy stream-based analysis work flows that handle processing GW detector data with near real-time performance. LAL provides the waveform generation codes, simulation engine, and many other tools that have been developed by the LSC and Virgo. In addition to creating a software library, a substantial amount of new algorithm development was necessary to enable this project [109, 110].

In addition to the low latency CBC search that GstLAL provides, the project also maintains an "off line" pipeline that allows one to analyze older data efficiently using the same tools developed for the low latency analysis.

Engineering runs engineering runs are designed to ramp up critical analysis systems as Advanced LIGO and Virgo are being constructed and commissioned. The GstLAL CBC search participated in the first advanced detector engineering run and will continue to participate in biannual engineering runs for the foreseeable future. The GstLAL CBC search development will continue towards the goal of meeting the science metrics established by the CBC group for low latency analysis.

High-priority goals for the next year

- Test full advanced detector search that includes the challenges of long filters (10 Hz = $\sim$ 30 min for 1,1 $M_{\odot}$) and the challenges of template number (about 200,000 without including the effects of spin).
- Provide search latencies that are no worse than S6 ($\leq$ 2 min) despite the increase in filter length.
- Provide a filter length independent search latency so that filters which are 30 min long have results at the same time as filters that are 1 min long.
- Online detection level false alarm probability estimation with 5 sigma confidence capability at the time the event is reported.
- Deal with (i.e. continue to operate usefully, though not necessarily optimally, despite) data drop outs, data corruption and data glitches that are inherent in a low latency analysis.
- Report events greater than some significance threshold to gracedb reliably so that the astronomical alert system can take over.

Goals for the advanced detector era

- Expand the signal parameter space to include the effects of spin, merger, ring down and any other effects that are critical for detection of CBC signals.
- Further reduce the latency associated with CBC searches.
- Sub-solar-mass search - The GstLAL CBC effort will analyze S5 data for compact binaries with component masses less than 1 solar mass. This is a yet unsearched dataset for such systems and also offers a unique opportunity to test advanced detector algorithms and technology due to the similarities to an advanced detector neutron star search (i.e. long waveforms and large template numbers).

3.3.4 Multi-Band pipelines

The Multi-Band Template Analysis (MBTA) is a low-latency implementation of the standard matched filter that is commonly used to search for CBC signals. It divides the matched filter across two frequency bands (or more). Thus the phase of the signal is tracked over fewer cycles, meaning sparser template banks are needed in each frequency band, and a reduced sampling rate can be used for the lower frequency band, reducing the computational cost of the FFTs involved in the filtering. The full band SNR is computed by coherently combining the matched filtering outputs from the two frequency bands.

MBTA was used during S6/VSR3 to perform an online CBC search as part of the EM follow-up program. It delivered triggers with a latency of a few minutes, the most significant of which leading to alerts being issued.

The developments and investigations needed to upgrade the MBTA pipeline and search in view of the advanced detector era are briefly described below.

- Technical improvements

  - Simplify the software installation procedure.
  - Improve the robustness of the pipeline and its error reporting.
  - Investigate the possibility to use multithreading, which would leverage the increased number of cores per machine expected in the future, and would make it easier to balance the load between processes.
  - Upgrade the pipeline to work with four detectors (or more).

- Improving the latency

  As templates get longer with the increased bandwidth expected in advanced detectors, some actions are needed to keep the latency low. A trade-off can be found between computing efficiency and latency by adusting some configuration parameters:

  - Reduce the size of the FFT in each of the frequency bands
  - Increase the overlap between successive FFTs
  - Increase the number of frequency bands

- Optimizing the sensitivity

  Several possibilities need to be explored.

  - In case of detectors with different sensitivities, the observed volume may be optimized by adjusting the various single detector thresholds, possibly in an adaptive way.
  - It should also be possible to increase the efficiency by implementing a low threshold search hierarchically, triggered by the observation of a loud trigger in at least one detector.
  - The possibility to implement an additional step based on a coherent search across detectors should also be investigated.
  - The search configuration needs to be optimized as a function of the detectors noise spectra. Especially, there is a trade-off to be found to choose the low frequency bound ot the search - lowering if allows to increase the SNR but also requires a denser template bank, thus increasing the probability of a false alarm. One can also consider configuring the search with an extra frequency band at very low frequency, used in a hierarchical way to add to the SNR of a trigger detected in the other frequency bands.
  - The consistency tests - the chi2 cut at the single detector level and the mass cut at the coincidence step - need to be tuned and optimized for the sensitivities and glitchiness of the advanced detectors.
  - The trigger clustering step needs to be optimized to avoid trigger "pile-up" when the trigger rate increases (due to the larger template bank and/or detector glitchiness).
  - Investigations are needed to understand if the sensitivity to sources with significan spin can be improved by using spinning templates.

- Assessing the parameter estimation capabilities of the pipeline

  It is important to understand how close one can get to the instrinsic timing accuracy of the detectors - depending on their bandwidth - since timing accuracy translates into sky localization ability.

  The question of spin also needs to be looked at from this perspective. Adding a second search step with spinning templates might be worthwhile to pass on more accurate timing information to the sky localization software.

3.3.5 FFT based pipelines

Offline analysis in the CBC relies heavily on the *ihope* pipeline. This pipeline [91] performs matched filtering of data in the frequency domain, relying on the fast Fourier transform (FFT), and it and its predecessors have been widely used in several published or forthcoming CBC analyses setting upper limits in both blind searches and triggered searches [53, 55, 58, 66, 67, 54, 50].

As the advanced detector era approaches, this pipeline must be maintained and developed to accomodate longer templates and larger template banks necessitated by the improved detector noise profile, as well as continue to support a variety of different waveform families as appropriate for different potential sources. In each of these cases, it must provide a sensitive search with an accurate characterization of candidate event significance.

To deal with these new challenges, several different strategies are being employed or developed:

- Larger template banks, with each template significantly longer, will be necessary for binary neutron stars in the advanced detector era. As this will increase the computational cost of such searches, the computational power of graphical processing units (GPU) is being investigated for use in such searches, as well as an investigation of how the changing the low-frequency cutoff (and hence the template length) affects the recovered signal-to-noise ratio, to determine how much longer templates should be.
- The current pipeline looks for coincidence between detectors of at least two events above threshhold. When such a coincidence is found, candidate triggers are followed up with a second stage of the search that employs a variety of signal consistency tests to winnow the candidate triggers to a set that is quasi-Gaussian and can be evaluated for statistical significance. Though computationally cheaper than some alternatives, this approach can complicate event significance estimation. So alternate pipelines being developed are:
  - Single-stage pipelines that apply signal consistency vetoes to all triggers.
  - The use of exact mass coincidence between detectors, rather than the ellipsoidal algorithm currently used (and which in particular would need to be extended to higher-dimensional parameter spaces when spin-effects of sources must be considered).
  - Coherent pipelines have proven more sensitive in triggered searches [54, 50] and are also being explored for all-sky searches. As a naive implementation is computationally very expensive, alternatives in both the formulation of the search as well as the possible speedup such a search might receive when implemented on a GPU are both being investigated.
- Finally, experience with the S6 science run has shown that more robust PSD estimation and automatic excision of glitches could be beneficial, and strategies for doing so are under investigation.

Several of the developments above require alternate choices to those presently made in the ihope pipeline, and the integration of new software into that pipeline. Taken together with the need to investigate alternative event significance and rate estimation techniques (section 3.3.7) and possibly filter against other templates (section 3.3.2) these plans all necessitate effort to ensure that our pipeline becomes more flexible, so that the different software components may be assembled as needed by scientific goals. To that end, many of the near term projects described below are focused on improving that flexibility.

High-priority goals for the next year

- Investigation of alternative statistics and vetoes to improve the sensitivity of triggered coherent searches.

- Simplify the post-processing (pipedown) to unify the database format so that new statistics are easier to test. Expected by the end of the summer of 2012. Also add the ability to use multiple criteria for matching injections to events to all three of inspiral, ringdown, and IMR branches.
- Integrate pipedown with the single-stage ihope pipeline (summer or early fall) and add the ability to cluster, calculate false-alarm rates, and rank and plot events across multiple databases.
- Investigate the efficieny improvement by using exact-match coincidence rather than ellipsoidal, in both non-spinning and aligned-spin systems.
- Development of a GPU capable pipeline. There are extensions to both the existing ihope and coherent PTF pipelines to leverage GPU computation of FFT, and also ongoing work through the PyCBC project to develop a toolset and pipeline that can perform all of the computationally intensive portions of the search (the matched filtering) on the GPU. In addition the GWTools project is nearing completion of an OpenCL based toolkit capable of many of the components of an FFT-based inspiral search, with upcoming plans to extend the toolkit to (for instance) spinning waveform templates.
- In addition to the ongoing development of PyCBC as a toolkit, there is also a concrete plan to have a code capable of a bank simulation by the end of the summer of 2012, and a single-stage pipeline utilizing PyCBC by the end of 2012.

Goals for the advanced detector era

- New pipelines developed above, as well as perhaps some low-latency pipelines described elsewhere in this whitepaper (sections 3.3.3 and 3.3.4) will need to be compared against the existing pipelines to ensure that their performance and in particular event significance estimation are consistent with the established pipelines.
- Changes described above to the pipelines should also, in the first half of 2013, be tested on both old engineering run data (from ER1 and ER2) as well as forthcoming engineering runs.
- While the FFT-based pipelines do not aim to be a replacement for low-latency pipelines, their latency nevertheless should be improved so that as advanced detectors are taking data, the previous day's data can be analyzed for both detector characterization and significance calculation for any candidate events from the previous day. In other words, these pipelines should be capable of delivering believable significance estimates of candidate events with a latency of one day.
- Likewise, during the S6 run FFT-based pipelines were used to provide daily summaries of CBC search performance for detector characterization [91]. Similar CBC-centric detchar tools should be available as aLIGO/AdV sub-systems come online to allow for comprehensive characterization of the detectors.

3.3.6 Electromagnetic followup of gravitational wave events

Compact binary mergers involving at least one neutron star (cf. Sections 3.4.1 & 3.4.2) are (1) expected to produce electromagnetic (EM) radiation at a variety of wavelengths and timescales [173, 174, 179] and (2) thought to be the progentiors of some short γ-ray bursts [90, 85, 224, 84, 178]. As such, they are the most promising sources for joint EM+GW observations and a key science goal for the LVC.

In S6/VSR2,3 the LVC performed its first low-latency search for joint EM+GW radiation [56]. The search focused on triply coincident triggers generated by the MBTA pipeline (cf. Section 3.3.4). These triggers were then passed to GraCEDb, where an automated process applied data quality vetoes and performed sky localization, at this point having incurred a total latency of about 3 minutes. From there, surviving triggers were then passed on via the LVAlert protocol to the LUMIN and GEM [340] processes where tilings were produced and viewtimes were determined for each partnering telescope. In the end a single trigger with a false alarm rate of ∼once every six days was sent out for imaging.

High-priority goals for the next year

- Use a standard file format and coordinate system for skymap output.
- Continue exploring improvements to sky localization latency and accuracy.
- Work to provide mass estimates as quickly as possible, in order to determine, e.g., whether or not a neutron star was involved in the binary.
- Work to provide distance estimates as early as possible, to help determine, e.g., which telescopes may be suited to followup the event.
- Investigate a "tiered" approach to parameter estimation (particularly sky localization): Provide initial skymap and parameters from the matched filter output with a latency of ∼minutes and provide updates as the dedicated parameter estimation codes converge.

Goals for the advanced detector era

- Assess the errors in sky localization introduced by using non-spinning templates for spinning systems.
- Maintain and update GraCEDb and LVAlert to provide a clearinghouse for all relevant GW trigger information, including that from electromagnetic observatories, neutrino detectors, etc.
- Determine which potential electromagnetic counterparts are most promising given the latencies of trigger generation and sky localization as well as the expected rate of serendipitous EM transients.
- Provide an interpretation of the significance of joint EM+GW observations. Investigate incorporating these results into those from the offline pipelines.
- Work jointly with the Burst group to determine a plan for dealing with simultaneous (and perhaps contradictory) Burst and CBC skymaps.

3.3.7 Event significance and rate estimation

The confidence with which a CBC trigger is believed to be due to a true GW signal is determined through estimation of the background of events due to detector noise (the false alarm rate, FAR) and measurement of the efficiency of the analysis pipeline to simulated signals in detector noise. In addition to the determination of the statistical significance of individual GW candidate events, the ensemble of events output from a CBC pipeline are used to infer the properties of the underlying astrophysical population of sources, primarily the event rates of different source classes. The current state for the ihope pipeline can be summarised as:

- The FAR is estimated using 100 time-slides over a ∼6-week analysis time. This enables us to achieve values down to $\sim 0.2\,\mathrm{year}^{-1}$.
- Extending time-slides to $\mathcal{O}(10^6)$ slides over ~ 4 months of data (performed for the blind injection challenge with a new coincidence code) enabled the accuracy of FAR estimation to be improved to $\sim 10^{-4}\,\mathrm{year}^{-1}$.

- Detection efficiencies are estimated with injection runs made uniformly over distance, using information from one "loudest event" per analysis. This has been deemed adequate to set upper limits with a few$\times 10\%$ systematic uncertainty (comparable to calibration errors).
- Signal-background separation based on ad-hoc tuning to background and injection triggers have been found to be both time and effort-consuming.

Ongoing studies and developments fall under headings as follows: background estimation for confident detection; astrophysical rate estimation; and event ranking methods to better separate signal from background.

Background estimation

- A new coincidence code is being integrated into the ihope framework for a single-stage pipeline, enabling more than the current limit of $\sim 10^4$ time-slides to be routinely carried out.
- The use of continuous time shifts (all possible coincidences) for background estimation. This technique estimates FARs to a level that would require millions of time-slides but with a much lower computational cost. Issues to address include accounting for non-independence of trials across parameter space and time, and determining the best method for combining single-template FAR distributions.
- Time-slide-less methods for FAR estimation. These are based on separately estimating the total rate of coincidences, and the fraction of events louder than a given candidate. This has been implemented for gstlal based online and offline CBC pipelines [107] and a similar approach using all possible trigger pairs within a range of parameter space is under development for ihope/fft triggers.
- A detailed comparison of several different FAR estimation methods for the 2-detector case, using a month of S5 data with fake signals [119].
- Calculating the combined significance of more than one candidate event, in the case of several possible GW signals.

Rate estimation

- The potential systematic uncertainties of the loudest-event statistic due to finite statistics. This involves the improvement of the "Lambda" [92, 88] calculation including quantifying its uncertainty (this relates strongly to improved FAR and efficiency estimates).
- The application, improvement, and possible replacement of the loudest-event statistic in the detection era. This includes the combination of results from many disjoint analysis times and over many distinct classes of source (*e.g.* mass bins). Ongoing investigations into statistical bias in rate estimation schemes and the replacement of the loudest-event statistic with a more general approach utilising all loud triggers.
- Improving computational efficiency and accuracy of the estimated sensitive volume by optimizing injection placement. This is done whilst balancing the cost with limiting effects such as noise non-stationarity, calibration and inaccuracy of prior astrophysical parameter distributions.
- Quantifying selection biases for pipelines, from both model assumptions and pipeline implementation factors. This includes modeling injection results with analytic and phenomenological expressions.

Automated methods/trigger ranking

- Multivariate statistical classifiers (MVSCs) can improve the separation of signal from background in multi-dimensional spaces, for instance the parameter space of CBC triggers. A specific multivariate classifier known as a random forest of bagged decision trees was developed for use in the S6 high-mass search. Several technical issues were identified and addressed, but not before the S6 highmass search was completed. The technique is now being applied for the S5 and S6 ringdown searches and can be further developed for Advanced-era searches. MVSCs can also be used to incorporate DQ information into search results (see section 3.3.1).
- Another approach for ranking triggers in high-dimensional parameter spaces is to approximate the N-dimensional likelihood distribution with lower-dimensional distributions: the "likeliness" code includes all (relevant) combinations of 2-dimensional slices. This approach could help extend the likelihood estimation used in gstlal [107] by allowing individual dimensions to be used repeatedly. `lalapps_likeliness` could also be incorporated into ihope's "pipedown" post-processing.

3.3.8 Accurate estimation of source parameters

In past few years the CBC group has been developing tools of increasing complexity to carry out Bayesian inference – model selection and parameter estimation – of the detection candidates. Being able to accurately estimate the parameters of coalescing binary systems – masses, spins, distance, location in the sky, etc – and to compare alternative hypotheses, are essential elements for studies in astrophysics, cosmology and fundamental physics that are enabled by GW observations.

Studies targeted at investigating specific science questions and/or developing techniques focused on GW data analysis have converged during the last year into a single library, LALInference, part of the LSC Analysis Library. LALInference provides the functionalities for CBC Bayesian inference, building on the LAL infrastructure – I/O, data conditioning, waveform generation etc – and offers a range of independent algorithms for the stochastic sampling of the parameter space, which is at the heart of the numerical implementation of techniques for Bayesian inference. LALInference is built around two main strategies to walk around the parameter space: Markov-chain Monte-Carlo (MCMC) methods [204, 205, 220, 221, 201, 225] and Nested Sampling [212, 126, 504], with a number of flavours of both techniques. It is essential that multiple techniques continue to be pursued at this stage in order to validate the algorithms and pipelines, explore trade-offs in terms of efficiency and accuracy while we prepare for the science runs with advanced detectors.

High-priority goals for the next year

- As part of the technical work to validate the algorithms and codes, it is necessary to investigate the performance of Bayesian sky localisation and evaluate the trade-offs in terms of accuracy and speed between the "fast" sky localisation approach – Timing++ – and the slower Bayesian estimation approach.
- In the area of sky localisation, it is also important to address whether Bayesian codes could provide sky localisation information on shorter time-scales, *e.g.* by running a Bayesian follow-up on triggers for which the mass (and other intrinsic) parameters have been fixed to the values returned by the detection template, and therefore reduce the total parameter space to sample. Work is already in progress in this area (REF?).
- It is essential to fully track the developments in the waveform approximants that are used for analyses, and made available within LAL, see Section 3.3.2 and provide Bayesian inference functionalities for all of them. In particular, the following are the first priority items for the coming period:

  - Complete the validation of the Bayesian parameter estimation pipelines for inspiral signals describing binaries with spins, and considering the sub-classes (that are astrophysically motivated) of (i) aligned angular momenta and non-precessing binaries, (ii) one single spin and (iii) fully precessing binaries.
  - Complete the validation of the Bayesian parameter estimation pipelines for sufficiently high-mass systems in which merger and ring-down contribute appreciably to the total recovered signal-to-noise ratio, restricted at present to non-spinning binaries and non-precessing systems, and extending it to more general spin configurations as the relevant waveform approximants become available.

- Some work has already been done to explore whether one can use the Bayes factor as a figure of merit to establish confidence in detection candidates, see *e.g.* [432]. Further investigations in this area are ongoing, using archived S6 timeslide data.

- The results of Bayesian inference depend both on the likelihood function *and* the priors used in the analysis. Work is needed to investigate suitable priors to use in the analysis and the effects of difference choices on the results.

- As the engineering run effort continues, it is important to include the Bayesian follow-up stage in the plan, in order to ensure readiness for the first science run.

- Several generic infrastructure improvements are needed: (i) Standardise post-processing tools to produce the final results of the analysis, (ii) investigate and introduce standard "convergence tests" for both MCMC and nested sampling to diagnose the reliability of the results, and include them in the post-processing script, and (iii) fully integrate the Bayesian follow-up pipeline in the EM follow-ups and access to triggers using GraCEDb.

Goals for the advanced detector era

Here we list a number of further improvements that are essential to be delivered on the time scale of the first advanced detector science run, or science investigations that are needed in order to be fully prepared for the science exploitation of advanced instrument data.

- Investigate the effects of the presence of short (shorter than the signal duration) glitches in one or more instruments on the quality of Bayesian inference, see Section 3.4.1.

- Improve the speed of the Bayesian analysis, coming from more efficient waveform computations (de facto, the improvements covered within the waveform sub-working group) and new waveform/likelihood parameterisation to improve the efficiency to move around parameter space. As part of this work, dedicated implementations on GPUs should be explored.

- Use interpolated waveforms, SVD or reduced basis decomposition, selected sampling for long waveforms produced by low-mass systems and lower frequency cut-off.

- Track the work in the "testing of the strong-field dynamics" area, see Section 3.3.9, with the goal of providing the necessary infrastructure.

- Investigate the impact on parameter estimation of higher harmonics in the waveforms used to construct the likelihood function.

- Include tidal terms into several waveform families for neutron star binaries, and investigate the ability of measuring tidal effects.

- The ability to reconstruct broader information about the astrophysics of sources and their populations, formation rates, binary formation channels, depends directly on the quality of parameter estimation, and of course the underlying binary population(s). Investigations are needed in order to address the issue of providing quantitative statements on broader astrophysical questions starting from a collaction of detected sources.
- Waveform accuracy ultimately determines the quality of parameter estimation. The sources of errors in the description of a waveform can be categorised into two classes: (i) errors coming from the approximations entering the evaluation of the gravitational waveform itself, and (ii) errors produced by the calibration process. Some studies have been carried out to address some of these issues (see *e.g.* [**?**]), but more detailed analyses are required. In particular, we need to address the impact of systematic biases introduced by waveform uncertainties, and the effect on parameter estimation accuracy coming from marginalising over (realistic) waveform errors.

3.3.9 Investigating the strong field dynamics of gravity

The most stringent tests of the dynamics of general relativity (GR) to date are set by measurements of the orbital parameters of the binary pulsar system PSR J0737-3039 [105, 153]. The *compactness* $GM/(c^2R) \simeq 4.4 \times 10^{-6}$, with M the total mass, R the orbital separation, and the typical orbital velocity $v/c \simeq 10^{-3}$ of this system, place it in the relatively weak-field regime. By contrast, for an inspiralling binary at the last stable orbit, the compactness is $1/6$ and the velocity is $1/\sqrt{6}$ in units of c. Therefore, the emission of gravitational waves during the coalescence of compact binary systems is, in the foreseeable future, the only phenomenon allowing empirical access to the full dynamics of GR. This characteristic allows for unprecedented tests of the non-linearity of GR [226] and, for systems involving at least one neutron star, measurements of the behaviour of matter in one of the most extreme situations. The LIGO/Virgo collaboration has recently started investigating these things.

Detecting deviations from general relativity during the inspiral phase

Binary neutron star systems A first effort to detect deviations from GR has recently been started by the LIGO/Virgo collaboration; a full pipeline – named TIGER – focused on binary neutron star (BNS) systems is well into development and indications about the accuracy of GR tests are already available. BNS were chosen as, in these systems, higher harmonics, spin interactions and precession are believed to be unimportant, although finite size effects do become important late in the inspiral. This allows the use of frequency domain templates in the analysis. As for the "standard" detection methods, TIGER requires the estimation of a *background* for the detection statistics (the Bayesian *odds ratio* in the case of TIGER). The background is computed by running the pipeline over many GR signal. The distribution of odds ratios defines the efficiency, per given false alarm probability, of the detection of departures from GR. A series of tests in simulated gaussian noise show that, with the current setup, a wide variety of deviations from GR can be detected [159, 160]. With as few as 15 detections, deviations of $\sim 10\%$ in the 1.5 PN coefficient – the "tail" term – are picked unambiguously even when aligned spins are considered. The same holds for deviation of $\sim 20\%$ in the 2 PN coefficient. These PN orders are, to date, still uncharted territory. If no deviations are detected, however, TIGER can constrain each of the PN coefficient to $\sim 1\%$ [159]. Recently it was shown [188], using the singular value decomposition of the Fisher matrix, that certain linear combinations of the PN phasing coefficients can be estimated with much better accuracy as opposed to the estimation of the original phasing parameters. A Bayesian formulation of the problem using this new set of parameters may tighten the constraints that can be put on possible deviations from GR. Note that also non-PN deviations can be detected [160], but the nature of the deviation cannot be pinpointed and a different approach is required, e.g. the parametrised-post Eistenian (PPE) model [228].

Binary black hole systems Being a pure space-time process, the coalescence of binary black holes (BBH) is the ideal setting to perform tests of GR. However, for BBH higher harmonics, spin interactions and precession are very important and, for a reliable test, they must be included in the analysis. Since no waveforms encompassing all the aforementioned effects is yet mature or fast enough, first investigation relied on phenomenological models [69] considering only aligned spins. For these systems, preliminary studies indicate that deviations $\sim 1\%$ in any of the known PN coefficient can be detected.

High priorities for next year

- Full integration within the parameter estimation infrastructure.
- Preliminary studies have been performed in simulated gaussian noise. Whether the results still hold in the presence of non-gaussianities is yet to be tested. TIGER will be tested in real (e.g. S5) or real-like (e.g. ER) noise.

Longer term goals

- Tests of GR using systems containing black holes require waveforms that include all the known dynamical effects of GR. Current testing capabilities are limited by the availability of waveforms including fully precessing spins. Furthermore, since the bottleneck of TIGER is the computation of the background over $O(10^5)$ simulated events, the waveform models and the parameter estimation infrastructure will necessarily have to be fast.
- A large class of alternative theories of gravity predicts the existence of additional GW polarisations [226]. With exception of few efforts within the LSC, the detector response to these polarisations is not taken yet into account within current pipelines, but dedicated functions are already available. The detection of these polarisations would immediately rule out GR as the theory of gravity. However, waveforms that produce such additional states are not yet available and will have to be implemented.
- Ringdown signals from massive systems can also be used to test the no-hair theorem and the nature of the remnant metric, e.g. [144]. A concrete testing infrastructure similar to TIGER might be implemented.

Constraints on alternative theories Several modifications to GR waveforms during the inspiral stage have been worked out, see Table I in [112] for a list. For many theories, interesting bounds on non-GR parameters can be set by Advanced LIGO/Virgo. Fisher Information Matrix based studies suggest that interesting bounds can be put on the dipolar radiation [74] and on the mass of the graviton [75]. For simplistic massive graviton models, Bayesian studies also suggest that current limits based on Solar System observations can be improved using GW observations[118, 112]. Subsequently, efforts towards understanding the constraints on their additional parameters are needed. Note that TIGER is able to constrain only theories predicting changes in any of the PN coefficients, but it is unsuitable for non-PN orders. For the latter, the development of theory-specific waveforms is necessary.

Long term goals

- Development of GW waveforms for alternative theories and full integration within the LSC parameter estimation framework.
- Analyses of GR signals both in gaussian noise and real-like noise and assessment of expected sensitivity to non-GR parameters.

Measuring the equation of state of neutron stars During the coalescence of BNS systems, finite size effects become important when the orbital frequency is ≥ 200Hz. Therefore, modifications to the waveform due to tidal deformations are just outside the most sensitive band of the detectors. The exact shape of the tidally distorted GW signal depends on the details of the equation of state (EOS) of the neutron stars. According to [214], Advanced LIGO/Virgo should not be able to determine the NS equation of state (EOS), except for the most extreme cases. No realistic systematic study is available yet, however, preliminary studies based on Bayesian model selection techniques indicate that Advanced LIGO/Virgo should be able to at least detect the signature of matter effects. Whether this can be extended to a statement over the EOS is yet unclear. However, this provides a mechanism to discriminate among systems containing at least a NS, without relying in model dependent mass cuts. For BNS-based tests of GR, Sec. 3.3.9, this is an important feature.

Long term goals

- Implementation of realistic GW waveforms including matter effects.
- Analyses of binary neutron star systems signals both in gaussian noise and real-like noise and assessment of the measurability of the EOS.

Measurement of the Hubble constant The determination of the Hubble parameter H_0 is still one of the most critical issues in cosmology, with repercussions on a wide range of fields in physics ranging from the determination of the abundances of light elements in the early Universe, the content of weakly interacting particles and therefore about the nature of dark energy. The exact value of the expansion rate today is still a matter of debate. Its current accepted value lies in the range $60 - 75$ km s^{-1} Mpc^{-1}, e.g. [147]. The ingredients required for the measurement of the cosmological parameters are a *luminosity distance* and the corresponding *redshift*. Canonical measurements of the Hubble constant – and any other cosmological parameter – require the determination of the so-called *cosmic distance scale ladder*. On the contrary, GW give a direct measurement of the luminosity distance, e.g. [208], thus bypassing completely the need for the distance calibrations. However, GW provide no information about the redshift of a source (but see [172]). Many different methods have been proposed to obviate to this deficiency:

- If short-hard Gamma-ray Bursts (GRBs) are the result of the coalescence of binary systems containing at least a NS, the simultaneous observation of a GRB and a GW could provide the redshift of the source. With this method H_0 can be measured to $\sim 13\%$ with 4 events and to $\sim 5\%$ with 15 events [181].
- If one knows (or estimates) the mass function of neutron stars, it provides with a statistical measurement of the redshift. Using this method, H_0 should be measured to $\pm 10\%$ using ~ 100 observations of BNS systems [216]. This method amounts to a modification to the prior probability distribution for the mass parameters during the parameter estimation process.

- The measurement of the extrinsic parameters of a GW event provides a 3-dimensional error box in the sky. By cross-correlating with a galaxy catalogue, one can obtain a statistical measurement of the redshift of the source. In this case H_0 can be estimated to $\sim 5\%$ after 25 observations [209, 117]. This method can be used provided the use of the redshifts and sky positions of known galaxies as prior distributions during the parameter estimation process.

High priorities for next year

- Implementation of the necessary infrastructure for the use of redshifts and sky positions of known galaxies as prior distributions within the parameter estimation framework.

3.3.10 Engineering runs

A series of both software and hardware engineering runs is planned in the lead up to the first science runs of the advanced detectors. These are described in greater detail in another section of the white paper. The main goals of these runs are:

- Assist in commissioning of upgraded detector subsystems as they become available.
- Aid in commissioning and detector characterization of the instrument as a whole when primary construction is complete.
- Commission data analysis computing and services.
- Commission searches to be ready for the first science runs
- Establish a strong communication channel between low latency gravitational-wave analyses and electromagnetic instruments for fast follow-up of candidates.

Engineering Run 1 The initial advanced detector engineering run took place between January 18, 2012 and February 15, 2012. Since no full detector subsystems were available at the time, mock noise was used to simulate the two (then anticipated) Hanford detectors, the Livingston detector, and the Virgo detector. This mock noise used colored Gaussian noise derived from the high power, zero detuned advanced LIGO configuration sensitivity, and the corresponding projected advanced Virgo sensitivity. Injected signals included a blind population of double neutron star binaries and black hole neutron star binaries produced within predicted realistic event rates [164].

The gstlal CBC pipeline participated in ER1, utilizing the low latency network to distribute the analysis over several computing nodes. Several inferences about the presence of gravitational waves from the injected source populations were made to high confidence. The Multi-Band Template Analysis pipeline was also run online during this period, and established detection level confidence in several events, including blind injections.

Engineering Run 2 The second advanced detector engineering run will take place between July 11, 2012 and August 8, 2012. Injected source populations will be similar to ER1, but also include higher mass signals such as black hole binaries. Both the MBTA and gstlal-based pipelines are scheduled to analyze this data in near real time. Pipelines analyzing the data were expected to report significant triggers with a latency of a few minutes or less.

The most important goal of this run is to drive closer coupling of data analysis to the instruments as they are constructed and commissioned as well as better understanding the impact of non-stationary and non-Gaussian data. To this end, and to best involve the ongoing detector characterization efforts, best effort will be made to analyze data including instrumental artifacts. Primarily, this will involve the real-time recoloring of the new prestabilized laser systems to resemble advanced detector strain. This data will be broadcast and analyzed just as it was in ER1. A secondary plan would instead use recolored S6 data. The simulated advanced Virgo detector will use recolored VSR3 data.

Future Engineering Runs Engineering runs are scheduled to take place roughly every six months until the first advanced observational run. Some goals related to CBC activities:

- Commission data analysis pipelines to be ready for the first observational runs.
- Commissioning of source localization and parameter estimation.
- Refinement of source rate estimation techniques.
- Provide near real-time detector characterization including feedback from low latency CBC analyses and online monitors.
- Commission detection and follow-up procedures and integrate event archiving and curation systems (GraceDB).

3.4 Binary Coalescence Sources

We have split the parameter space of compact binary coalescence sources into five regions for the purpose of this paper. These are

- Neutron Star–Neutron Star Binaries
- Neutror Star–Black Hole Binaries
- Stellar mass Black hole–Black hole binaries
- Intermediate mass Black hole binaries
- Gravitational wave counterparts to GRBs

There are significant overlaps in the IMBBH and GRB analyses between the CBC and burst sections. The IMBBH sources and science are described below, while the GRB analysis is described in the burst section of the white paper.

3.4.1 Neutron star–neutron star binaries

The coalescence of binary neutron star (BNS) systems is expected to be a primary source of gravitational waves for ground-based detectors, emitting gravitational radiation with a characteristic chirp signal in the instruments' most sensitive band (approximately $10\mathrm{Hz}$–$1000\mathrm{Hz}$). Unlike BH binaries, BNS systems have been observed in the Milky Way, which establishes them as the most certain GW source. Population synthesis models also predict the existance and rate of coalescence of BNS systems, and together these yield an likely estimate of the rate of such sources between $0.01\mathrm{Mpc}^{-3}/\mathrm{Myr}$ and $10\mathrm{Mpc}^{-3}/\mathrm{Myr}$, but possibly as high as $50\mathrm{Mpc}^{-3}/\mathrm{Myr}$ [51]. A primary goal of the initial observations with the advanced detectors is to constrain these rates, which translate to a detection rate of between $0.4\mathrm{yr}^{-1}$ and $1000\mathrm{yr}^{-1}$.

During the initial detector era the CBC group has used the flagship *ihope* detection pipeline, which takes advantage of the post-Newtonian approximation for the waveform to matched-filter the data for potential signals [91]. The improved sensitivity of the advanced detectors at low frequencies (10Hz to 40Hz) will lengthen the detectible portion of the signal from 25 s to several minutes, increasing the computational cost of the search. Therefore, improvements to the *ihope* pipeline, as well as investigation of alternative detection pipelines is a high priorty for the CBC group.

The possible range of neutron star masses and radii is determined by the equation of state, the formation process of the initial NS and its subsequent evolution. The large uncertainties in these quantities mean that the precise possible mass range is not well known. Electromagnetic observations of neutron stars in a range of binary systems show a range of masses with a mean close to the canonical value of $1.4\,\mathrm{M}_{\odot}$, but with outliers as low as 0.7 and as high as $2.7\,\mathrm{M}_{\odot}$ [155]. However, neutron stars in binary systems with another neutron star may have a tighter mass distribution of $1.35 \pm 0.14\,\mathrm{M}_{\odot}$ [152].

After the masses, the angular momenta of the neutron stars have an effect on the inspiral waveform at 1.5 post-Newtonian order and above. The size of this effect depends on the spin frequencies and orientations of the compact bodies with respect to each other and the orbital angular momentum. Of neutron stars in compact binaries, one star is expected to have been recycled by accreting matter from its companion before supernova, which will lead to appreciable spin. The fastest example of such a system is the binary J0737-3039, with spins of 44Hz and 0.36Hz, of which the slower would have a negligible effect on the gravitational wave signal [162]. Although in terms of dimensionless spin, these are small compared to expectations for black holes, the loss of signal to noise ratio in a non-spinning search could be appreciable [94], and requires development of searches and template bank placements by the CBC group.

As the upper mass limit for neutron stars is not well known, another problem is determining whether the objects in a compact binary are neutron stars or black holes. The matter in a neutron star will respond to the tidal field of the companion body, slightly altering the phase evolution of the inspiral signal, which may be an observable effect with advanced detectors [214, 146]. If observable, this would allow the categorisation of objects into NS or BH, shedding light on the highest mass of a NS vs lowest mass of a BH.

From a gravitational wave astrophysics point of view, the component masses and spins of the binary can be inferred from the data by solving the inverse problem to find the values that produce the observed phase evolution. In order to do this with maximum precision, the CBC group has developed parameter estimation algorithms which produce probability distributions for the parameters of interest. These algorithms are computationally expensive, so further development and efficiency improvements are needed to analyse the longer signals for the advanced detectors.

Science of the first detections

Advanced detector observations of BNS coalescence will give us access to information previously unobtainable with electromagnetic astronomy. Using only the first few detections, we can place constraints on the astrophysical event rates, which in turn inform estimates of the population of binary neutron stars and their formation processes [166]. If we are lucky, we could confirm BNS mergers as a progenitor of short GRBs if prompt emission is detected electromagnetically, although it is more likely that the beamed high-energy photons will not be visible and followup observations must be made with optical and radio instruments.

Science in the regular detection era

Once the advanced detectors have acculumated tens of confirmed signals, we will have accumulated enough information to begin to probe the statistical distribution of BNS systems. Of special interest are the mass and spin distributions, which can further constrain modes of production of BNS systems, in addition to the more accurate rate determination. The measurement of inclination angles coupled with electromagnetic observations will provide vastly improved constraints on the electromagnetic beaming angle of short GRBs [197]. We should be able to detect, or at least limit the tidal deformability of the neutron stars involved, yielding insights into the internal structure and equation of state of neutron stars, and possibly observe their tidal disruption prior to merger. Likewise, detection or constraint of deviations from general relativity in the dynamical regime will become possible, which could help to eliminate alternative theories of gravity. Determining the mass and equation of state will consequently allow the radius of the neutron star to be determined.

The GWs from compact object mergers have an absolute amplitude at the source that is known from first principles, and comparison with the amplitude measured at the antenna as well as with red shifts of possible host galaxies gives a set of possible Hubble parameters; repeated observations provides a Millikan oil drop like iterative refinement of the value of the Hubble parameter.

Projects Prior to First Detections

This is work that must be completed or will be completed prior to the first detections in the advanced detector era. *Input required as indicated*

- Quantify efficiency improvement in detecting BNS inspirals using only BNS templates (not entire low mass bin)
- How can we handle waveforms that last tens of minutes in our data? (*Waveforms, searches, PE, DQ, ER*)
- What are the component mass ranges for a binary neutron star search, based on the available astrophysics?
- How important is spin for binary neutron star searches in the advanced detector era? (*Waveforms, searches, PE*)
- What latency (h(t), DQ, coincident triggers, background estimation) do we need, and how can we achieve it? (*EM, searches, DQ*)
- Is it possible and desirable to perform a coherent analysis? (*searches*)
- Can we really detect a signal before merger? With what forewarning time? (*searches, EM*)
- What electromagnetic transients (in addition to short GRBs) are suitable for following up with a targetted search? (*EM*)
- What is the best way of estimating the astrophysical rate of BNS with multiple detections (and false alarms)? What are the requirements on false alarm and efficiency measurements? (*Rates*)
- Decide whether to perform HW injections, what population to use? (*searches*)
- Automate followup procedures (*DQ, PE*)
- Determine how to search the parameter space for early/design advanced detector runs, taking into account detector noise spectra, length and number of templates. Exercise pipelines on Software Engineering Runs.

Projects For Early Detection Era

This is work whose products will become necessary in or be completed in the era of the first few detections.

- What have we learned about the astophysical rate of BNS? (*Rates*)
- Are GWs the progenitor of short GRBs? (*GRB*)
- What data products are to be released upon detection?

- Can we see evidence of tidal effects in the inspiral phase, to what level of accuracy? (*waveforms, PE, testingGR*)
- Can we see evidence of tidal disruption at high frequencies ($> 400\text{Hz}$)? In what systems? (*waveforms, PE, testingGR*)

Projects For Regular Detection Era

A list of topics for investigation. This is work whose products will become necessary in or be completed in the era of regular detections.

- Develop an event database for astrophysics.
- What is the astrophysical rate of BNS? (*Rates*)
- Can we constrain the equation of state of NS?
- How can we estimate background in the presence of multiple signals? (*Rates*)
- Can we see evidence of deviations from post-Newtonian expansion in the inspiral phase? (*testingGR*)
- What alternative theories of gravity can we constrain? (*testingGR*)
- What cosmology can we perform? (*Rates,testingGR*)
- What is the neutron star mass function? (*Rates*)

3.4.2 Neutron star–black hole binaries

Neutron-star, black-hole (NSBH) systems are thought to be efficiently formed in one of two ways, either through the the stellar evolution of field binaries, or through dynamical capture of a neutron star by a black hole. Though no NSBH systems are known to exist, both mechanisms are known to be efficient at forming comparable binaries [134, 206, 157, 83]. Rates for the occurance of, and even the existence of, these systems are unknown, although they are estimated to be 0.03 Mpc^{-3} yr^{-1} from population synthesis of field binaries [52]. Current dynamical simulations of globular clusters predict nearly no NS-BH mergers [122], however new formation channels have been proposed that might allow higher rates [156]. The rate of short GRBs has also been estimated as > 0.01 Mpc^{-3} yr^{-1} from observations [178, 196], however it is not known what fraction of short GRBs will be NSBH mergers as opposed to BNS mergers.

The mass distribution of NSBH systems is not well known as no systems have been observed. However, it is possible to place estimates on the mass ranges by looking at other observed systems. From mass measurements of over 50 pulsars, it can be observed that, in general, the mass of the pulsar is very consistent with a value of $1.35M\odot$ [166, 152]. However a few pulsars have been observed with larger masses, up to $2.74 \pm 0.22M\odot$ [166], although the mass distribution for NSs is tighter for those in binaries with other NSs [152], which would presumably apply to NSs in binaries with stellar mass BHs. BH masses can be estimated through observation of ∼20 x-ray binaries where it has been possible to measure the black hole's mass. Their masses vary between ∼4 and ∼20 solar masses, however this may not be reflective of the mass distribution for NSBH systems [166]. We should prioritize these ranges of NS and BH masses in our searches, however it may be possible for NSBH systems outside of these expected mass ranges to exist and it is important to remember this when implementing NSBH searches in the advanced detector era.

The spin distribution of black holes in NSBH systems is not well known, some black holes observed in x-ray binaries have very large dimensionless spins (>0.7), while others could have much lower spins (∼0.1) [169, 166]. At birth the spin period of a neutron star is believed to be in the range of 10 to 140 ms, which corresponds to dimensionless spins ≤ 0.04 [166], depending on the equation of state (EOS) of the NS. However, these natal spin periods are expected to die off significantly in the long time between the formation of the neutron star and the merger of the two objects. It is possible for neutron stars to be spun up to much higher spins that will persist until merger [140], for example a ~ 1 ms pulsar has a dimensionless spin of 0.4. However it is unlikely for a field NSBH system to be spun up by accretion as the BH would form first.

Searches for these objects have so far have been done during S5/VSR1 and S6/VSR2-3 within the context of the non-spinning, low mass CBC search [66, 67, 53, 58]. However, as aLIGO and aVirgo will be sensitive to lower frequencies [137, 49], it may be more important to include the effects of spin for these objects [68, 96].

Numerical relativity simulations of these systems have been performed [128, 202] and show that certain combinations of mass, spin, and NS equation of state (EOS) parameters can cause the neutron star to tidally disrupt before coalescence. Therefore these systems could power the central engines of short GRBs or produce other types of prompt or delayed EM counterparts.

Science of the first detections

With the first observation of GWs from the merger of a NSBH system, we may be able to provide the first direct evidence for the existence of NSBH binary systems. To do so, we will need to be able to confidently distinguish the purported NSBH GW signal from a BBH, or even BNS, GW signal. This will require us to investigate how confidently we could make such a statement, either through the use of only GW information (including information extracted from including higher harmonics [76] or precession effects), or from the identification of an EM counterpart.

Science of order 10 detections

Once detections of NSBH GW signals are routine, there are more scientific questions we can hope to answer. One of the first pieces of information we will have access to is the observed rate of NSBH coalescences. We will also directly have access to a measurement of the mass and the spin distribution of both the BH and NS.

Extracted information will allow us to probe different formation models by investigating how well the predicted distributions agree with the theoretical distributions. From this we may be able to determine if the majority of NSBH systems form as field binaries or through dynamical capture. This may also be possible from measurements of the eccentricity of the binary as it enters the sensitive band of the detectors. Conventional models from globular clster interactions lead to binaries with wide separations [134], which would circularize before entering the detectors' sensitive bands [195, 194]. However exceptional mechanisms that allow relativistic capture may lead to measurable eccentricities in the sensitive band of the detector. This analysis would require the development of waveforms that accurately model the eccentric binary evolution [97].

The observation of the spin distribution of the BH would provide information about two aspects of the formation of the NS for field binary NSBH systems. The alignment of the BH spin with the orbital angular momentum would tell you about the size of the kick imparted on the compact objects during their formation [150, 141, 77, 136, 129, 149, 227]. Whereas the size of the spin of the BH would provide information on the amount of accretion the BH experienced [169].

As with BNS systems, finite size effects may become measurable with collections of observations. This would aid in making a statistical NS radius and EOS measurement [193, 168]. Investigation is needed to understand if this kind of study is easier with NSBH signals than with BNS signals, NSBH systems will merge at lower frequencies, and thus these finite size effects may be easier to observe with NSBH mergers.

The identification of an electromagnetic counterpart could provide several insights. The estimated parameters from many of these systems, along with EM counterparts or lack-there-of, would allow us to test the predictions of numerical relativity for which configurations of the BH mass, spin, and NS EOS produce accretion disks that power short GRBs [128, 202]. Additionally, galaxy host identification of EM counterparts can allow us to better constrain their formation process, as with (the possibly identical) short GRB events [84]. For example for short GRBs, host galaxy information has been used to constrain their typical age; host galaxies also let us constrain the size of the kicks imparted on the binary from SN [77, 141].

In the absence of a detection of NSBH GW signals, we could place scientifically interesting constraints on the rate of NSBH coalescences. The absence of NS-BH detections will also constraint the fraction of short GRBs powered by NS-BH mergers.

Technical issues

In addition to solifidying the scientific statements we could make, there are many technical challenges that will need to be overcome associated with various stages of searching for NSBH GW signals. The open questions that need to be addressed for NSBH searches are as follows: *Input required as indicated*

- What parameter space should we search?
  - Should we restrict to the “estimated” masses above or broaden our search windows?
  - How much does the NSBH parameter space overlap that of other sources?
  - Should we search the full range of spins mentioned above? Is it okay to neglect NS spin?
- What waveforms should we use?
  - How accurate are the waveforms? (*Waveforms*)
    - NSBH waveform are very different between approximants, especially in the high mass ratio limit. We need to investigate and quantify by how much?
    - When waveforms do vary which one should we trust/use?
    - Can we compare with numerical relativity waveforms? Are such waveforms available over the full NSBH parameter space.
    - Are time-domain waveform implementations stable when integrated for long times? At what sampling frequencies is this true?
  - Should we use spinning/precessing filters? (*Searches*)
    - How sensitive at fixed FAR are our search pipelines to NSBH signals if non-spinning template waveforms are used?
    - How sensitive at fixed FAR are our search pipelines to NSBH signals if aligned-spin template waveforms are used?
    - Can an efficient precessing NSBH pipeline be deployed? (e.g., physical template family [191])
    - How do these search strategies compare fixed FAR and computational cost?
  - How fast are the waveforms? (*Waveforms, PE*)
    - For parameter estimation we will want the waveform generation to be faster than the filtering done with them.
- How do we search? (*Searches*)
  - What priors do we use on these searches? (BH and NS masses and spins)
  - Can these waveforms be compressed to reduce computational cost [109, 108, 110, 127, 139]?
  - At fixed computational cost, at fixed FAR, is it better to do a coincident or a coherent search?
  - How will this change between low-latency and offline searches?

- How accurately can we estimate parameters? (*Waveforms, PE*)
  - Sky localization:
    - How accurate can we be after 3 hrs, 6 hrs, 1 day, and 7 days?
    - How does ignoring spin affect sky localization?
  - Mass estimation:
    - Do precessional effects help?
    - (How quickly) Can we can we distinguish between NSBH and BBH signals?
    - How well can we measure the spin magnitudes/orientations of the BH and the NS.
- Event significance and rate estimation (*Rates*)
  - To confidently claim a NSBH detection we will be required to confidently estimate very low false alarm rates. This is not an NSBH specific problem though and is likely a more pressing issue for BNS searches, where the first detection is most likely to be made.
  - To be able to place reliable limits on NSBH merger rates we will require large-scale simulation campaigns to evaluate the search sensitivity. Given the potentially very large cost of performing a NSBH search, it is vital to be able to do this efficiently.
- DetChar and DQ requirements: (*DQ, searches*)
  - How important are phase and amplitude calibration for determining masses, spins, and sky locations?
  - What types of glitches would NSBH filters be susceptible to?

3.4.3 Stellar mass black hole–black hole binaries

The main feature of this source is the large space of possible intrinsic parameter values (component masses and spins) due to wide uncertainties in current astrophysical knowledge. This presents challenges in carrying out and optimizing our searches and interpreting their results; but also opportunities to extract significant new information about the sources, well beyond that provided by EM observations, and to distinguish between astrophysical models of stellar collapse and binary evolution.

There are no known stellar-mass binary black holes; their existence is predicted from population syntheses of field populations, and through dynamical modeling of dense stellar clusters. For massive field progenitors, the common envelope and mass-transfer phases which are required in order to produce BBH merging within a Hubble time [180, 81] may lead to strong correlations between the properties (spins and masses) of the components of field binary black holes. Binary black holes may also be formed dynamically, either in dense globular clusters [122, 123, 183] or galactic nuclei. The components of such binaries have generally evolved in isolation, thus the component properties may be largely independent of each other and of the orbital parameters. Binaries formed near galactic nuclei may also have significant orbital eccentricity [182].

The mass distribution of Galactic stellar mass BH has been estimated in [124, 186, 171]. X-ray observations constrain the mass of a few BH to lie in the range $5 \leq M_\bullet/\mathrm{M}_\odot \leq 20$, which has been confirmed with dynamical mass measurements for 16 black holes. An apparent lack of BH masses in the range 3–5 $\mathrm{M}_\odot$ [124] (though, see [154]) has been ascribed to the supernova explosion mechanism [80, 131].

The most massive observed stellar mass black holes are found in extragalactic high-mass X-ray binaries, IC10 X-1 and NGC300 X-1, both with BH masses in the $20 - 30\,\mathrm{M}_\odot$ range and with Wolf-Rayet star companions [211, 113]. These systems are likely to be field stars that formed in low-metallicity environments. Population synthesis based on recent stellar wind models allows for isolated black hole masses up to $\sim 80\,\mathrm{M}_\odot$ [131, 82], though common envelope binary evolution [121] can have a strong influence, reducing the maximum expected component mass, at low metallicity, to $\sim 60\,\mathrm{M}_\odot$ and total mass to $\lesssim 100\,\mathrm{M}_\odot$ [120]. There is no direct observational limit on BBH mass ratios; for a minimum mass of $3\,\mathrm{M}_\odot$ we have $1 < q \lesssim 25$. Current models of isolated binary evolution favor $q \lesssim 4$ [120], though future studies may lead to the re-assessment of such priors.

X-ray observations of the spins of accreting black holes in binary systems, while technically challenging, indicate a fairly uniform distribution over the entire range $0 \leq a \equiv S/m^2 \leq 1$ [175, 210, 170, 161, 133, 116, 158]. Indications that spin-orbit misalignment in field binaries may be small come from observations of the microquasar XTE J1550-564 [213], and population synthesis models of Fragos et al. [129].

The estimated rates of BBH coalescence have large uncertainties: current estimates are between 1×10^{-4} and $0.3\,\mathrm{Mpc}^{-3}\mathrm{Myr}^{-1}$, with a best estimate of $0.005\,\mathrm{Mpc}^{-3}\mathrm{Myr}^{-1}$, for systems consisting of two $10\,\mathrm{M}_\odot$ black holes [51]. Observations from initial LIGO and Virgo have placed an upper limit about a factor of 4 larger than the "high" rate estimate [58].

Science of the first detections

The first detection from this source would prove the existence of a previously unobserved type of binary and constitute a major discovery. Given the large parameter space, the first few confident detections could begin to distinguish between astrophysical models of compact object populations. At least one intrinsic source parameter will be well measured (chirp mass, in the low-mass limit); depending on the measured values, nonzero rates could be estimated to within a factor of a few, while upper limits in regions of parameter space where *no* detections are made would be significantly improved, potentially ruling out classes of model or allowing us to tune the parameters of population synthesis models [185]. If one of the first few detections has moderately high SNR, we may find strong evidence for at least one spinning component, independently establishing the existence of black hole spin in GR.

Science of order(10) detections

With several detections we begin to establish an observational distribution over chirp mass, and, possibly, spin or mass ratio, further constraining models of BBH populations [98]. Some of the louder signals could give indications for or against precessing component spins, and/or allow component masses to be well estimated, allowing us to test competing models of binary formation, and possibly test the hypothesis of a "mass gap" [131] between neutron stars and low-mass BH. Rare signals could also be seen outside the main mass distribution. As the mass distribution carries information about most input physics, even the approximate answer provided by order(10) detections will allow us to rule out many alternatives [167, 184], allowing inferences on the environments (metallicity) of star formation and stellar winds, on mechanisms of stellar collapse and binary evolution (supernova kicks, mass transfer episodes) and possibly on kicks from BBH mergers for dynamically formed binaries.

A more speculative aim is to test the validity of our waveform models based on PN expansion, numerical relativity in the strong-field regime and BH perturbation theory. Establishing a deviation from the predictions of GR, for example the Kerr description of BH, would be a major discovery, though requiring many technical challenges to be brought under control.

Overall search issues and strategy

Given the very large parameter space of signals, the BBH search will naturally tend to split into several parameter regions, and possibly into independently-tuned pipelines using different filter waveforms and methods. We then need to determine in which regions different searches or pipelines are more efficient, considering also false alarm rates (FARs), and use this information to plan the search as a whole.

As in present searches, we may calculate separate FAR estimates for each parameter region or pipeline. This can lead to a trials factor problem where false alarms from templates corresponding to a-priori less favoured signals, for example at high mass ratio, penalize the significance of likely first detections. We will study strategies for ranking candidates in order to improve the prospects of first detection, given weak astrophysical priors, while not excluding the possibility of finding unexpected signals.

After the first few detections, the scientific focus is likely to shift to making astrophysical deductions on rates and parameters from a broad range of searches. Bayesian inference will find a natural application in combining information from several pipelines with varying efficiencies over parameter space. The overall search plan in this era is likely to be constrained by computational cost, for instance in measuring the search efficiencies over the parameter space, or in accurately determining the parameters of spinning signals.

Waveforms and search algorithms (*Waveforms, Searches*)

The main goal here is appropriate choice and placement of templates over the parameter space. Where should the boundary between using inspiral-only templates and IMR templates be, given the differences in search sensitivity and computational cost? Should we search with templates including the effects of spin or higher signal harmonics? How should templates be placed in higher-dimensional parameter space, or when the metric may not be analytically computable? An alternative to current geometrical placement methods is the "stochastic" template bank [138]: a near-term goal is to further develop this method and evaluate its possible benefits.

Aligned-spin waveforms / searches : Recently, IMR waveforms for aligned-spin systems have been developed [207, 215], and the metric for aligned-spin inspiral signals has been calculated [94]. Further work is required to implement aligned-spin search pipelines: outstanding questions include IMR template placement, choice of waveform model over parameter space, and comparisons with the non-spinning search.

Precessing waveforms / searches : Precession effects from mis-aligned spins may be common for BBH [148, 183]. Detecting precessing systems involves several challenges. Past attempts at searching for precessing inspiral signals involved a large increase in the number of template degrees of freedom, leading to higher FARs [219, 99], though some highly precessing signals may gain enough SNR to offset this increase. Future studies should develop improved methods to describe [96] and search for precessing signals, and quantify the potential benefits from an optimized precessing search.

The current phenomenological precessing IMR waveform family [200] is only tuned on a very small region of the parameter space: significant work is needed to develop more generally valid models, intersecting with efforts in numerical relativity and analytical relativity (NRAR) to simulate and describe precessing systems. Such developments are important to fully realize the potential of parameter estimation on BBH.

Waveforms including higher harmonics : EOBNR waveforms for non-spinning systems incorporating modes other than $l = 2$, $m = 2$ have recently been developed [189]. Higher harmonics are expected to play a significant role for asymmetric systems ($q \gg 1$), though such sources are not favoured by current models of binary evolution. Ongoing studies should determine how well existing dominant-mode templates fit these more realistic waveforms, and over what parts of parameter space they could influence detection prospects.

Systems with orbital eccentricity : While most BBH are expected to have negligible eccentricity in the detector's sensitive frequency band, some coalescences occuring in high-density environments may retain significant eccentricity [182]. For these systems we may study whether a templated search can be effectively carried out [97, 111] or an unmodelled search is preferable.

Data Quality (*DQ*)

The wide range of BBH waveforms (ranging from minutes to fractions of a second in duration) presents severe challenges in understanding and mitigating the effects of non-Gaussian transients in data. Future studies will model such transients, quantify their effects on the BBH templates, and develop methods to better use data quality information in BBH searches, either by category vetoes or by modifying the ranking of triggers to account for the likely "glitchiness" of data.

Event significance and rate estimation (*Rates*)

To make confident first detections it will be necessary to reliably estimate very small FARs; several methods for improving the precision of background estimation are under current investigation. Signal-background discrimination is a significant challenge for BBH due to the strongly-varying response of templates over the parameter space to detector artefacts. Multivariate classifiers have been investigated for this task: it remains an open question how best to make use of such techniques.

BBH searches may have significant overlaps with NSBH or unmodelled burst searches, as well as within the BBH parameter space itself, thus a strategy is needed (*e.g.* [87]) to evaluate the significance of candidates for which several pipelines may be sensitive.

To infer astrophysical rates over the BBH parameter space and determine the implications for astrophysical models, we require accurate measures of search sensitivity. Priorities here include improving computational efficiency when simulating large numbers of signals, and developing more powerful methods to draw astrophysical inferences from the results of our searches.

Estimation of source parameters (*PE*)

The information gained from accurate estimates of source parameters will be crucial to answer astrophysical questions. If we are able to measure BBH component masses, the possible "mass gap" between $3-5\,\mathrm{M}_\odot$ can be investigated. Distinguishing between precessing *vs.* spin-aligned BBH will also have strong astrophysical implications. Studies are in progress to determine the expected accuracy of such measurements in the Advanced era, and point to areas where further development is needed.

Testing strong-field dynamics of GR (*testingGR*)

Uncovering deviations from predicted GR waveforms with BBH signals is an exciting possibility, but presents many challenges due to systematic uncertainties in waveform models, the large parameter space of possible GR signals, and instrumental noise artefacts. Studies have been carried out [160], and more are needed, to determine what statements can be made in the Advanced detector era.

3.4.4 Intermediate mass black hole binaries

Gravitational-wave sources:

Intermediate-mass black holes (IMBHs) with a mass between ~ 100 and $\sim 10^4$ solar masses occupy the mass range between stellar-mass and massive black holes (see [176] for a detailed review). There is growing but still ambiguous evidence for IMBH existence, including observations of ultra-luminous X-ray binaries (e.g., [125]). A number of formation mechanisms have been proposed, which may lead to the existence of IMBHs of a few hundred solar masses in globular clusters. Such IMBHs are likely to form binaries which can be hardened through dynamical interactions to the point of merging through gravitational-wave radiation reaction. If IMBHs in this mass range are generic, then Advanced LIGO and Virgo can detect gravitational waves from their coalescence [51]. Compact binary mergers involving IMBHs can be divided into two categories:

(i) *Mergers of IMBH binaries.* Two intermediate-mass black holes can merge either if two are born in the same cluster [130], or if their globular-cluster hosts merge [73]. Another potential source is the merger of two lighter seeds of massive black holes [132], though these are likely to occur at too high a redshift to be detectable by advanced detectors. The rate of IMBH binary (IMBHB) mergers is not well understood, largely because of the uncertainty in the occupation number of IMBHs in globular clusters; [130] predict up to one detection per year by advanced detectors. An approximate upper limit can be obtained by assuming that no globular cluster should have more than $O(1)$ such IMBHB mergers; a space density of ~ 1 globular cluster per Mpc^3 with a typical age of 10 Gyr yields a rate similar to the one quoted above. Typical spins and eccentricities are uncertain. Given the IMBH mass range and the low-frequency noise spectrum of advanced detectors, gravitational waves where the inspiral portion of the IMBHB waveform are likely to be below the low-frequency sensitivity cutoff, with the detectable signal is dominated by the short merger and ringdown phases [192].

(i) *Intermediate-mass-ratio inspirals.* If an IMBH exists in an environment where it is surrounded by neutron stars and stellar-mass black holes, such as a globular cluster, intermediate-mass-ratio inspirals (IMRIs) of compact objects into IMBHs become likely sources of gravitational waves [95]. Advanced LIGO and Virgo could detect tens of such events per year [164]. The dominant capture mechanism is likely to involve gradual binary hardening via three-body interactions, meaning that the binary eccentricity will be very low in the GW detector band [164]. Spins of IMBHs that grow primarily through such minor mergers should not exceed ~ 0.3 [163]. For systems with very asymmetric mass ratios, the power emitted during the merger and ringdown portions of the waveform will be suppressed, so the late inspiral may dominate the signal-to-noise ratio.

Waveforms:

For IMBHBs, accurate waveform including merger and ringdown are critical. Several waveform families already exist, such as PhenomIMRB & EOBNR (see Section 3.3.2) but more waveform accuracy studies are needed specifically for waveforms covering the IMBHB parameter space.

Accurate waveforms for IMRIs are particularly difficult, because the PN approximation is expected to fail for binaries that spend so many cycles close to the ISCO, while the IMRI mass ratio is not extreme enough for the mass-ratio expansion to be accurate [165]. EOBNR waveforms may be accurate in this regime; other approaches include hybrid waveform families [142]. Waveform accuracy studies are made difficult by the absence of accurate numerical-relativity waveforms at IMRI mass ratios, although there have been promising recent advances in numerical simulations of IMRIs [177].

In the future, waveforms including precessing spins, inspiral-merger-ringdown phases, higher harmonics, and possibly eccentricity will be highly desirable for the development of searches and interpretation of search results.

Detection and parameter estimation:

The following are some of the special challenges presented by the detection and parameter estimation of binaries involving IMBHs, and the available avenues of addressing them:

- The low frequency of sources involving IMBHs places a greater emphasis on low-frequency detector performance. (*DQ, Searches*)
- The short signal duration of IMBHB sources, and the possible semblance of IMRIs to instrumental artifacts, lead to stringent data quality requirements (see Section 3.3.1). (*DQ, Searches*)
- Can template-bank-based inspiral-merger-ringdown searches [55] be extended to higher masses? (*Searches, Waveforms*)
- The parameter space spanned by the IMBHB sources can be also explored with (coherent) burst searches (see Section 4.4.7), which do not rely on accurate GW waveforms.
- The relative sensitivity and utility of ringdown-only searches (e.g., [65]) requires further study. (*Searches*)
- Is a dedicated search necessary for IMRIs?
- The accuracy of parameter inference, including mass and spin measurements, needs to be explored in this mass range (see Section 3.3.8). This includes challenges with parameter estimation when using templates with potentially significant systematic uncertainties (for IMRIs) and technical developments necessary to run parameter-estimation tools on triggers provided by burst searches. NINJA-style studies can lead to improved confidence in the ability to accurately infer IMBHB parameters. (*PE, Waveforms*)

IMBH Science:
A single detection of a $100+\ M_\odot$ system could provide the first unambiguous confirmation of the existence of IMBHs. This alone would be a major discovery.

Further detections could allow us to investigate the prevalence of IMBHs in globular clusters and cluster dynamics.

IMBHs could provide particularly exciting ways of testing general relativity (see Section 3.3.9). For example, independent measurements of the IMBH mass quadrupole moment from IMRI gravitational waves would probe the IMBH spacetime structure [95, 203]. Ringdown studies of IMBHs could similarly test whether IMBHs are really Kerr black holes [144].

4 Searches for general burst signals

The mission of the LSC-Virgo Burst Analysis Working Group (also known as the *Burst Group*) is a broad search for short duration gravitational wave (GW) transients, or *bursts*. A variety of astrophysical sources are expected to produce such signals, as summarized in Sect. 4.1. Sophisticated models are available for certain sources, but in most cases the amplitude and waveform of the GW signal are highly uncertain; for this reason, a burst source requires robust detection methods. While initially the Burst Group focused on signals much shorter than 1 second, with little or no assumption about their morphology [229], it is now also pursuing longer signals and the incorporation of available signal waveform knowledge, to seek specific targets in addition to unknown phenomena and mechanisms of emission and propagation. Sect. 4.2 summarizes recent GW burst search results, while Sect. 4.3 describes the methods used in our searches.

In Sect. 4.4 we describe the Burst Group scientific goals and plans over the next 3 years, as we prepare for the advanced detector era, including a discussion of top priorities and a timeline of our preparations. While this document includes all ongoing or planned burst analyses and investigations, the Burst Group remains open to new, scientifically motivated activities that will support its goals; the analysis techniques and tools that we will continue to refine over the next few years will form the foundation of burst data analysis in the Advanced LIGO/Virgo era.

In some cases, an overlap in astrophysical targets and methods exists with other LSC-Virgo groups. Such cases include short-duration gamma-ray bursts and the merger and ringdown of binary compact objects, which are pursued by both the Burst and CBC (Sect. 3) Groups. Longer duration transients ($\sim$minutes or longer) may also be pursued using methods developed by the Stochastic (Sect. 6) and Continuous Waves (Sect. 5) Groups. The Burst Group will coordinate with other analysis groups in areas of common interest, to ensure the best possible scientific results.

4.1 Gravitational-wave Burst Sources & Science

The Burst Group targets a broad range of astrophysical systems and phenomena that potentially emit GW bursts. The primary goal of searches with the initial LIGO, GEO and Virgo detectors was to make a first detection, but along the way first astrophysically relevant observational limits on the GW emission from targeted sources were made.

The list of potential burst sources does not change from the initial to the advanced detector era. However, due to the ~ 10 times greater distance reach and ~ 100 times greater energy sensitivity of advanced detectors, the chance of detection and the potential for parameter estimation and the extraction of interesting fundamental physics and astrophysics increases. For this, GW burst data analysis strategies in the advanced detector era will need to take into account more information from theoretical/computational astrophysical source models. In turn, more and higher-fidelity source modeling input will be required. We must actively approach the modeling community to encourage the development of improved models for use in advanced detector searches. Most important for parameter estimation and physics extraction will be to have a theoretical understanding *for each source* of the mapping between signal characteristics (e.g., frequency content, time-frequency behavior) and physics parameters. This includes knowledge of potential degeneracies that may be broken by complementary information from electromagnetic (EM) or neutrino observations. For this, multi-messenger modeling input and observations will be necessary.

Searches for GW bursts in the advanced detector era will be a combination of untriggered, all-sky searches and externally triggered localized searches. Untriggered, all-sky searches (see Sect. 4.4.1) have the greatest potential of finding electromagnetically dark sources (see Sect. 4.1.4) and may discover unexpected sources (see Sect. 4.1.8). They also provide triggers for follow-up studies of candidate events with EM observations (see Sect. 4.4.6). Externally triggered searches will have electromagnetic and/or neutrino counterpart observations. Strategies must be developed for the extraction of physics at the post-detection stage combining EM, neutrino, and GW information. Hence, it will be important to continue to work with our external partners and to extend collaborations from trigger exchange to, for example, full data sharing and joint analysis, parameter estimation and physics extraction wherever it facilitates better scientific output.

While we can expect to learn more astrophysics about known sources (even non-detections, translated into improved upper limits, will have important consequences for astrophysics) and potentially constrain aspects of fundamental physics (e.g., the nuclear equation of state), we must be ready for the unexpected. This may be a detected signal from a known source (e.g, with an EM or neutrino counterpart) that is completely different from model predictions, or a high-significance event that is detected with unexpected characteristics and with no EM or neutrino counterpart. We must develop strategies of how to handle both scenarios.

In the following, we discuss key burst sources that are likely to be focal points of data analysis efforts in the advanced detector era and briefly discuss science possibilities and potential.

4.1.1 Gamma-Ray Bursts

Gamma-ray bursts (GRB) are intense flashes of gamma rays that are observed approximately once per day, isotropically distributed across the sky. GRBs are divided into two classes by their duration [230, 231]. Long GRBs ($\gtrsim 2\,\mathrm{s}$) are associated with star-forming galaxies of redshifts of $z \lesssim 9$ and core-collapse supernovae [232, 233, 234, 235]. Short GRBs ($\lesssim 2\,\mathrm{s}$) have been observed from distant galaxies of different types. Most short GRBs are believed to be due to the merger of neutron star (NS-NS) or neutron star – black hole (NS-BH) binaries [236, 237], while a few percent may be due to extragalactic SGRs [238, 239].

Short GRBs: NS-BH, NS-NS Coalescence and Postmerger Evolution

Post-Newtonian theory predicts a distinctive GW chirp signal from the inspiral stage of NS-NS or NS-BH coalescence, so that the detection of such a signal associated with a short GRB would provide "smoking gun" evidence for the binary nature of the GRB progenitor. Recent analytic and computational work suggests that constraints on the nuclear equation of state (EOS) are possible by matched filtering of advanced detector data from the intermediate to late inspiral of NS-NS and NS-BH binaries [240].

Interesting science potential is not restricted to the inspiral phase. In the NS-NS case, the merger signal as well as the GW emitted in the postmerger evolution reveal the mass and spin of the system, whether black hole formation is prompt or delayed, and may also place constraints on MHD spindown and the nuclear EOS. The postmerger signal (which cannot be templated) may also provide information on whether a short GRB is powered by a millisecond hypermassive neutron star or by a black hole – accretion disk system. However, most of the postmerger GW emission will occur at frequencies of $1 - 4\,\mathrm{kHz}$. With an expected energy emission of up to $\sim 10^{-3} - 10^{-2}\, M_{\odot}c^2$, these signals will most likely be detectable only for nearby ($D \lesssim$ few $\times\, 10\,\mathrm{Mpc}$) events. It will therefore be worthwhile to perform a targeted search on the postmerger evolution for the most nearby events.

The majority of nearby NS-NS/NS-BH coalescence events are likely to be gamma-weak or silent due to the expected beaming of the prompt emission, but more isotropically emitted precursors or afterglows (e.g., [241, 242, 243, 244, 245, 246, 247]) are expected in bands from radio to X-ray. Discovering the EM counterpart of a NS-NS/NS-BH merger will be a major breakthrough. Joint EM-GW observations of short GRBs in the advanced detector era have great science potential and will provide answers to many open astrophysics questions connected to short GRBs and binary mergers (e.g., [248, 237, 236]).

Long GRBs and Engine-Driven Supernovae

The question of the long GRB central engine is one of the major unsolved problems in relativistic astrophysics. There is overwhelming evidence from EM observations that long GRBs are related to massive star death and core-collapse supernovae [249] (see also Sect. 4.1.2), but the precise nature of this relationship is unclear. Central engine scenarios either involve a very rapidly spinning (millisecond period) magnetar or a stellar-mass black hole with an accretion disk. Relativistic GRB outflows may be powered by neutrino pair annihilation in polar regions or extraction of spin and/or accretion energy via magnetohydrodynamic processes (or a combination of these).

The early GW and neutrino signals expected from a long GRB will be similar to those of a rapidly spinning core-collapse supernova before explosion [250]. Hence, long GRBs should be approached with similar modeling input as supernova searches. During the GRB stage, GW emission may come from accretion disk instabilities (clumping, fragmentation) [251, 252, 253] or nonaxisymmetric magnetar deformation [254, 251]. The most extreme of these models predict emitted energies in GW of order $0.1\,M_{\odot}c^2$ which advanced detectors may be able to constrain to many tens to hundreds of Mpc (depending on the frequency of the GW emission) [255]. For nearby GRBs ($D \lesssim$ few Mpc), engine scenarios may be constrainable, but much more theoretical modeling will be necessary to establish signal shapes characteristic of particular central engine models.

An interesting class of objects between long GRBs and regular core-collapse supernovae are hyper-energetic type-Ib/c supernova explosions that do not produce an observed GRB, but exhibit late time energy input into the ejecta by a central engine seen in radio observations (e.g., [256, 249]). Engine-driven supernovae occur considerably more frequently in the local universe than long GRBs and may be extreme core collapse events with plausibly strong GW emission. An engine-driven supernova within a few tens of Mpc would be an interesting science target for advanced detectors.

Current and future searches for long GRBs rely on external triggering by the prompt gamma emission observed by satellites. As in the case of short GRBs, joint EM-GW observations may help answer pressing questions regarding the central engine and progenitors of long GRBs.

Additional long GRB science opportunities are in joint searches for GW and high-energy neutrinos (HENs) from GRBs. HENs are expected to be generated by interactions of accelerated protons in relativistic shocks in GRBs [257, 258, 259, 260, 261, 262, 263, 264, 265, 266, 267] and may be observable by HEN detectors. Of particular interest to joint GW+HEN searches are so-called *choked* GRBs (e.g., [268, 261]). These EM weak/silent systems may arise if the central engine turns off before the jet can escape from the star. In this case the jet stalls ("chokes"). While no gamma ray emission can be observed from such systems, HENs generated in the jet earlier on can escape if the envelope is not too thick [269]. Afterglow X-ray/optical radiation are also potentially observable. An important component in probing the structure of such joint GW+HEN sources is the connection between the time-of-arrival of GW and HEN signals [270].

Low luminosity GRBs [271, 272, 233, 273, 274, 275, 276, 277] have sub-energetic gamma ray emission and form a sub-class of long GRBs. While they are more difficult to detect via gamma-ray observations, they are more populous than conventional GRBs [274, 276]. Due to the higher event rate, the overall GW and neutrino flux from these sources may be comparable or even surpass that of conventional GRBs [278, 279, 280].

Other phenomena expected to produce simultaneous HENs and GWs include short-hard GRBs [257], core-collapse supernovae [263], and soft gamma-repeaters [281, 282, 283].

4.1.2 Core-Collapse Supernovae and Accretion Induced Collapse

Massive star collapse does not immediately lead to a supernova explosion. Within half a second of collapse, the inner stellar core reaches nuclear density. There the nuclear EOS stiffens, leading to a rebound of the inner core (core bounce) into the still-infalling outer core material. This results in the formation of the supernova shock that initially moves out quickly in mass and radius, but soon is decelerated, then stalls due to the dissociation of heavy nuclei and neutrino losses. The shock must be revived (by the core-collapse supernova mechanism), but how precisely this occurs is currently uncertain [284]. It has been argued [285] that GW from a galactic core-collapse supernova could help constrain the mechanism.

Core-collapse supernovae, no matter how precisely they explode, are expected to involve a wealth of processes leading to the emission of GW [250]. Based on all-sky search results from the initial detectors [286, 287], advanced detectors can be expected to detect core-collapse supernovae emitting $10^{-10} - 10^{-9}\, M_\odot c^2$ ($10^{-8} - 10^{-7}\, M_\odot c^2$) at $100\,\mathrm{Hz}$ ($1000\,\mathrm{Hz}$) throughout the galaxy. This is well within what is predicted by current simulations (see, e.g., [250, 288] for reviews). More optimistic predictions based on analytic models suggest GW energies of up to $\sim 0.1\, M_\odot c^2$ [251]. Advanced detectors are likely to be able to constrain these models out to tens of Mpc. Improved modeling, in particular full 3D models that provide signal predictions for both polarizations, will be necessary to fully exploit the improved sensitivity that advanced detectors will offer.

The rate of nearby core-collapse supernovae is known only to a factor of $\sim$two. Galactic events are expected once or twice per century and the rate for the entire local group, including Andromeda, is roughly two to four per century [289, 290]. The rate increases dramatically at a $3 - 5\,\mathrm{Mpc}$ where star forming galaxies produce $\sim$0.5 core-collapse supernova per year [267, 291]. Within $10\,\mathrm{Mpc}$ the core-collapse supernova rate is $\sim 1/\,\mathrm{year}$. While the expected event rate is moderate, the physics that may be learned from a detection of GW from a core-collapse supernova goes far beyond constraining emission and explosion mechanisms. Supernovae are cosmic laboratories for high-energy-density gravitational, plasma, nuclear, and particle physics. In particular, it may be possible to extract information on the nuclear EOS directly from GW observations [292]. Combining information carried by neutrinos with that carried by GW may allow more robust parameter estimation and physics extraction, but the details of how these data can be combined are unknown and must be worked out.

Current constraints on core-collapse supernova GW emission come from all-sky blind burst searches [286]. Sensitivity improvements (by factors of order unity) can be expected from a targeted all-sky search using information from models and, in particular, from a search that uses EM triggers for extragalactic supernovae. Such searches are in development, with emphasis on finding ways to handle the large uncertainties on the time of core collapse and onset and end of GW emission inherent to an EM triggered search.

Low-energy neutrinos are emitted copiously in core collapse, and such triggers will provide much better timing than EM triggers (e.g., [293]). Current initiatives to collaborate with neutrino observatories will need to be intensified in the advanced detector era. Triggering by neutrinos will be trivial for any Milky Way or Magellanic cloud event. More distant events in galaxies of the local group (e.g., in Andromeda) will lead to only very few events in current and near-future neutrino detectors [294, 295] and a joint GW-neutrino search for sub-threshold triggers may increase the detection efficiency by up to a factor of two [296].

An interesting challenge to be ready for is the detection of GW and neutrinos from a galactic core collapse event with no EM counterpart. This could be either an "unnova" (an event that leads to a weak explosion or no explosion at all [297] and in which a black hole is formed after $\sim 1 - 2\,\mathrm{s}$ of GW and neutrino emission), or it could be a EM-obscured supernova. Unnovae or obscured supernova may make up $\sim$50% of all core collapse events [298].

Accretion-Induced Collapse (AIC) of Massive White Dwarfs

AIC occurs when a white dwarf (WD) is pushed over its Chandrasekhar mass limit and conditions (central density, temperature, composition) favor collapse rather than thermonuclear explosion. AIC may occur in binary WD merger events or by accretion from a companion star. Their occurrence rate is probably multiple orders of magnitude smaller than that of regular core collapse (e.g., [299]). AIC will proceed like a normal core-collapse event, but unlike ordinary massive stars, AIC progenitors are quite likely rapidly spinning. Hence, AIC is likely to give a strong GW signal from core bounce. In addition, postbounce long-lasting nonaxisymmetric rotational instabilities are plausible [299, 251].

AIC are expected to lead to EM-subluminous supernova explosions and we may be faced with a strong GW and neutrino signal with a weak EM counterpart. Being able to differentiate the AIC case from the black-hole forming regular core-collapse case will be important.

4.1.3 Neutron Stars

Isolated neutron stars in our galaxy may be sources of detectable GW burst via a number of processes.

Phase-transition Induced (Mini-)Collapse of Neutron Stars
Recent work on core-collapse supernova and neutron star modeling suggests that a QCD hadron-quark phase transition in a (proto-)neutron star could lead to the emission of GW by ringdown oscillations following a "minicollapse" of the neutron star and its stabilization at a higher-density equilibrium [300, 301]. If no stabilization occurs, a black hole will form and black hole quasinormal modes will emit GW as the hole rings down to an axisymmetric equilibrium [250]. In the former case, typical GW frequencies will be $1-3\,\mathrm{kHz}$, while in the latter emission will be predominantly at frequencies $\gtrsim 4-6\,\mathrm{kHz}$.

Given the high-frequency emission of this class of sources, advanced detectors will still be limited to nearby ($D \lesssim$ few kpc) [286, 302] events, but there are a number of accreting neutron stars in X-ray binaries that should be monitored for such high-frequency GW emission. Provided high-SNR detection, information on the nuclear EOS and object mass could be gained.

Soft Gamma Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs)
SGRs and AXPs emit short-duration X-ray and gamma-ray bursts at irregular intervals, and (rarely) giant gamma-ray flares with luminosities up to $10^{47}\,\mathrm{erg/s}$ [303]. SGRs/AXPs are most likely strongly magnetized neutron stars (magnetars) that experience recurring dynamical events in their crust or magnetosphere, which lead to the observed outbursts, though the details of the outburst mechanism remain to be understood.

If magnetar outbursts/giant flares are due to magnetic-stress induced crust quakes (e.g., [304, 305]) and if crust and core are efficiently coupled in magnetars, SGRs/AXPs will emit GW via the excitation of the magnetar's non-radial oscillation modes [306, 307, 308, 309, 310, 311, 312, 313]. The pulsating X-ray tail of SGR1806−20 also revealed the presence of quasi-periodic oscillations (QPOs) [314, 315, 316] that were plausibly attributed to seismic modes of the neutron star, thus suggesting associated GW emission [317, 318].

Together with glitching radio pulsars, bursting magnetars are the closest known potential sources of GW. Less than two dozen Galactic SGRs and AXPs have been identified, at distances from $\sim 1.5\,\mathrm{kpc}$ to $\sim 50\,\mathrm{kpc}$. SGRs 1806-20, 1900+14, and 1627-41 are located in our Galaxy near the galactic plane, between 6 and $15\,\mathrm{kpc}$ distance. Another, SGR 0526-66, is located in the Large Magellanic Cloud, about $50\,\mathrm{kpc}$ away. Two others, SGR 0501+4516 and SGR 0418+5729, are located opposite the galactic center and may be an order of magnitude closer to us ($\sim 1\,\mathrm{kpc}$) than the other known Galactic SGRs .

A network of advanced detectors will probe the energetics of magnetar outbursts several orders of magnitude below the typical electromagnetic energy output of giant SGR flares, constraining an unexplored and interesting region [319, 310, 320, 311, 312, 306]. If provided with reliable GW emission models that go beyond analytic estimates (i.e., ringdowns), advanced detectors may be able to constrain the outburst mechanism by putting astrophysically interesting upper limits on emitted energies.

Pulsar Glitches
Pulsar spin evolution is well modeled by assuming magnetic dipole braking is the dominant mechanism for the spin-down. However, some pulsars occassionally exhibit sudden step jumps, called *glitches*, in the rotation rate, followed by an exponential decay back to (almost) the pre-glitch rate.

There exist two main candidates for the mechanism behind pulsar glitches. One suggestion is that glitches may be due to starquakes where the equilibrium configuration of the solid crust of the neutron star deforms as the pulsar spins down. The energetics of the more frequent 'glitchers', however, are indicative of a superfluid core rotating more or less independently of a solid crust. The crust experiences a magnetic torque and spins down, leading to differential rotation between the superfluid and the crust. The superfluid rotates by means of vortices, which are normally 'pinned' to the outer crust. It has been suggested (eg. [321]) that once the differential rotation reaches a critical value, an instability sets in, causing a dramatic un-pinning of the superfluid vortices. This transfers angular momentum from the superfluid component to the crust and causes the observed temporary spin-up.

There are a variety of mechanisms for GW emission associated with pulsar glitches, the details of which depend strongly on the glitch mechanism. For superfluid-driven glitches, there may be an incoherent, band-limited stochastic burst of GW due to an 'avalanche' of vortex rearrangement [322] which will occur during the rise-time of the glitch ($\leq 40\,\mathrm{s}$ before the observed jump in frequency). A possible consequence of this vortex avalanche is the excitation of f-mode oscillations in the neutron star in the frequency range $1-3\,\mathrm{kHz}$, leading to quasi-sinusoidal GW emission over timescales of $50-500\,\mathrm{ms}$. In the case of starquake-driven glitches, it also seems reasonable to expect that the neutron star f-modes may be excited.

Given the relatively low energy associated with the change of angular velocity in a typical glitch ($\sim 10^{42}\,\mathrm{erg}$) and the high frequency of emission, advanced detector searches will be limited to nearby sources, such as the Vela pulsar ($\sim$300 pc). However, the scientific benefit of a high-SNR detection is enormous, and may directly probe the highly uncertain mechanics of pulsar glitches.

The excited post-glitch pulsar may also emit GW at r-mode frequencies (of order tens of Hz for most glitching pulsars). The time decay constant for a quasi-sinusoidal GW ring-down at r-mode frequencies is likely dominated by damping from the viscous boundary layer between the outer crust of the neutron star and its fluid core. According to the model proposed by Levin and Ushomirsky [323], the expected time constants are of order 10^4 seconds or shorter for neutron stars in the frequency band of terrestrial GW detectors. Methods are underdevelopment to search for such long-duration bursts.

4.1.4 Mergers of Black Hole Binary Systems

The coalescence of binary compact objects consisting of neutron stars (NS) and/or black holes (BH) are the most promising sources for detection by LIGO and Virgo. Sources consisting of binary black holes (BBH) and intermediate mass black hole binaries (IMBBHB) are discussed in details in the CBC sections of this white paper (Sect.3.4.3 and Sect. 3.4.4). and they are a subject of the Burst Group research as well (see Sect. 4.4.7).

Current approaches to the detection of GWs from binary black holes expect the binary to have a circular orbit by the time it enters the frequency band of ground-based detectors. However, black hole binaries may form through various scenarios, for example, by dynamical interactions in galactic nuclei containing a supermassive black hole (SMBH), or in globular clusters [324]. If stellar-mass or intermediate-mass black holes form a dense population around SMBHs, the probability of close encounters of two black holes could be high [325]. Such encounters may lead to the formation of binary black hole systems. The initial eccentricity e of such binary system is likely to be close to unity and remain large all the way to the merger. The merger may happen within hours, and such short lived systems are expected to have a unique GW signature: a series of short bursts. There are no accurate eccentric binary black hole waveforms with $e > 0.05$ available at this time and the burst searches may be the only way to detect and study binary sources with high eccentricity.

The advanced detectors will provide an exciting opportunity for the first detection and study of GW signals from BBH mergers, with sensitive ranges of up to several Gpc for some systems. The expected detection rates [326] vary dramatically between 1 and a few thousand BBH mergers per year, with possibly $\sim$30 events/year for lighter (total mass $< 100 M_{\odot}$) BBH systems and $\sim$1 event/year for heavier IMBBH systems (total mass $> 100 M_{\odot}$). Observations of BBH and IMBBH binaries in a wide parameter space and measurements of their parameters will have important consequences for theories of the formation and growth of supermassive black holes and the dynamics and evolution of globular clusters [327].

4.1.5 Cosmic (Super-)String Cusps and Kinks

Cosmic strings are one-dimensional topological defects that may have formed during one of the early symmetry-breaking phase transitions in the universe [328]. Superstrings are the supposed basic constituents of matter in fundamental string theory or M-theory, which is at present the leading contender for a unified theory of all fundamental interactions including gravity. Both cosmic strings and superstrings are still purely hypothetical objects. There is no direct observational evidence for their existence even though they may produce a variety of astrophysical signatures. One of the most promising ways of detecting the presence of cosmic strings and superstrings is via their GW emission. This is the primary mechanism of energy loss from strings, so strings are believed to contribute significantly to the cosmological GW background.

An important role in the emission of GWs is played by the presence of cusp features on strings resulting from an oscillating loop. At such points the string reaches the speed of light for a brief moment and a burst of GWs is emitted, with strong beaming in the direction of the string's motion. This yields a characteristic GW signature which depends on the reconnection probability, the size of the loop, and the string tension $G\mu$ [329, 330, 331]. This last parameter is crucial to characterize a string network and its evolution. The best current constraint is given by the CMB observations of WMAP: $G\mu < 2.1 \times 10^{-7}$ (68% C.L.) [332].

The GW waveform is well-modeled by a power law in frequency ($\sim f^{-4/3}$) with a frequency cutoff given by the angle between the cusp feature and the line of sight. This allows a templated search with a better efficiency than the standard all-sky burst search.

A second type of GW signal is expected from cosmic strings, originating from a string kink produced after the reconnection of two string segments. As for cusps, the kink signal obeys a power law in frequency ($\sim f^{-5/3}$) but with a smaller strain amplitude, which disfavors detection. However, recent studies (e.g., [333]) show this might be compensated for by a higher production rate. A kink search would be a straightforward extension of the current LIGO-Virgo analysis.

4.1.6 Exotic Theories of Gravity and Matter

An intriguing possibility is that gravity may be better described by a theory other than General Relativity. Although General Relativity has withstood all tests at the post-Newtonian level so far, the direct detection of gravitational waves will provide an opportunity for new tests including probing the regime of validity of alternative theories of gravity [334, 335, 336, 337]. The possibility of such alternative theories could, in turn, help unravel outstanding problems in astrophysics, including dark energy and dark matter, and even provide clues to reconciling gravity and quantum mechanics [338]. The LSC-Virgo network provides a unique opportunity to study the detailed properties of gravitational radiation.

Alternative theories of gravity may result in a difference between the speed of light and the speed of propagation of gravitational waves [339]. Coordinated electromagnetic and gravitational wave searches could place constraints on the propagation speed of gravitational waves.

Alternative metric theories of gravity also predict extra polarization states, in addition to the "plus" and "cross" polarization modes of Einstein gravity. Indeed, every other known viable metric theory of gravity predicts more than two polarization states [339], and the most general gravitational wave can have up to six polarization states [334, 335]. For instance, Brans-Dicke theory and other scalar-tensor theories predict an additional scalar transverse polarization state. This will have an impact on multi-detector coherent gravitational wave searches because the linear combination of data streams that maximizes the gravitational wave content depends on the number and type of additional polarization states. If the direction of the gravitational wave is known in advance then disentangling which polarization states are present in a signal is straightforward [335], provided there are at least as many detector data streams as polarization modes. This is the case for externally triggered searches, and for searches where the gravitational wave triggers have sufficiently large signal-to-noise that triangulation can be used to pinpoint the sky-location. For all-sky searches new techniques need to be developed to separate out the expanded set of polarization states. On the other hand, if the scalar mode is the dominant component of the signal—as might arise from stellar core collapse to a proto-neutron star and/or the birth of a black hole—then a search for *only* the scalar mode is interesting, and can be implemented effectively even with only two or three detectors.

Evidence for the the existence of extra polarization states would be fatal for General Relativity. A non-detection, however, may not rule out alternative theories of gravity because the strength of the extra polarization states depends on the source and emission mechanism. The emission mechanism can also be different in alternative theories of gravity. In particular, different multipole moments (such as the dipole) contribute to the radiation.

4.1.7 Bursts with memory

The possibility for a gravitational-wave burst to settle in a non-zero strain has been identified in the mid-1970's [ref Zel'dovich, Braginsky, Thorne]. Such a DC effect in gravitational-wave radiation, a "memory", may provide a distinct companion to the transient part of the radiation from several astrophysical systems. This includes bursts from core-collapse supernovae [ref Thorne, Ott] as well as merging binary systems [ref Favata]. This effectively zero-frequency strain signal presents challenges in detecting it with ground-based interferometers due to the low frequency seismic wall the instruments are subject to.

4.1.8 Unknown Unknowns

Blind burst searches allowing for any kind of signal time-frequency content are the only way in which completely unexpected signals that do not have EM/neutrino triggers can be found. The dramatic increase of the volumetric reach of advanced detectors will lead to a corresponding increase of the possibility of discovering an unexpected event. A strategy and/or protocol of how to handle such an event and how to communicate with outside theorists should be established for the advanced detector era.

4.2 Recent Observational Results

In the past year, the LSC-Virgo Burst Group published the results of six searches, as well as one full-collaboration methods paper.

S6/VSR2+3 EM followup method [340]. During S6/VSR2+3, low-latency analysis pipelines for burst and inspiral signals were used to identify GW candidates and reconstruct their sky locations. The event coordinates were then sent to a network of optical, radio and X-ray observatories during two observation periods (17 December 2009 to 8 January 2010, and 2 September to 20 October 2010), with a latency of about 30 minutes. Simulations show the median sky area for reconstructed signals with signal-to-noise ratio at the detection threshold is between 10 and 100 square degrees, and the correct portion of the sky would be observed for a strong event with 50% or greater probability with a few wide-field pointings. The results of observations made through this work are expected to be published within the next year.

GRB 051103 [341]. On November 3 2005, one day before the start of S5, a short duration gamma-ray burst was detected and localized to the outskirts of M81, estimated to lie at 3.6 Mpc from the Earth. At that time, the 2 km Hanford detector (H2) and the 4 km Livingston detector (L1) were recording data with BNS horizon distances of $\sim$4 Mpc and $\sim$8 Mpc, respectively. If the progenitor was a compact binary coalescence in M81, the inspiral GW signal from GRB 051103 should have been detected in LIGO data. The event was analyzed by the matched-filtering pipeline used to search for inspiral signals from short GRBs in S5/VSR1 data, and also by the burst analyses used for GRBs and SGR flares in S5/VSR1 data. None of these analyses yielded a GW detection. These measurements rule out with $> 95\%$ confidence the possibility that this GRB was due to compact binary coalescence in M81, under the assumption that the electromagnetic emission is beamed within a cone angle of $\sim 50°$. The lowest 90% confidence upper limit on the isotropically emitted GW burst energy is $\sim 10^{51}$ erg, well above what might be expected from an SGR giant flare. If the host galaxy was indeed M81, this suggests GRB051103 was a giant flare from a magnetar, which is consistent with some circumstantial evidence from the electromagnetic spectrum. If confirmed, this would be the most distant magnetar flare ever observed and only the second such event seen in another galaxy.

S5/VSR1 IMBBH [342]. As discussed in Sect. 4.1.4, the gravitational-wave signal from the merger and ringdown of intermediate mass black hole coalescences lies in the most sensitive frequency band of LIGO-Virgo. A first search for IMBBH mergers has been conducted on S5/VSR1 data, focusing on systems with a total mass of 100 to 450 $M_\odot$ and mass ratios between 1:1 and 1:4. The standard unmodelled search pipeline [343] is augmented with an elliptical polarization constraint to improve rejection of background glitches. No potential GW signal candidates were observed and an upper limit on the rate of IMBBH mergers has been set at 0.6 Mpc^{-3} Myr^{-1}, averaged across all search masses, with a 90% confidence level.

S6/VSR2+3 all-sky [287]. The all-sky search for GW bursts in S6/VSR2+3 was completed using the coherent analysis pipeline employed for S4 and S5/VSR1 [343, 344, 345, 286]. The analysis had a livetime of 207 days between July 7, 2009 and October 20, 2010, when at least two of the three LIGO-Virgo detectors are in coincident operation, and searched for transients of duration < 1 s over the frequency band 64-5000 Hz, without other assumptions on the signal waveform, polarization, direction or occurrence time. The thresholds were tuned for a false alarm rate of 1 event every 8 years. No candidate GW events were found, and we set a frequentist upper limit on the rate of GW bursts of 1.3 events per year at 90% confidence, by combining this search with the S5/VSR1 analysis. We also present upper limits on source rate density per year and Mpc^3 for sample populations of standard-candle sources. Typical sensitivities of the search in terms of the root-sum-squared strain amplitude for these waveforms lie in the range $(5 - 100) \times 10^{-22}\text{Hz}^{-1/2}$.

S6/VSR2+3 SWIFT followup [346]. The feasibility of rapid multi-wavelength follow-ups of GW burst candidates is demonstrated in this analysis of two candidate GW transient events recorded in S6/VSR2+3, whose reconstructed sky locations were observed by the SWIFT observatory. SWIFT's observations yielded no evidence for an unusual electromagnetic signal in coincidence with either event. Additional simulation studies combined realistic X-ray signals with simulated GWs originating from nearby galaxies. The results from this hypothetical source population were compared with real background distributions, showing that coincident X-ray sources could dramatically increase our confidence in a GW observation.

S6/VSR2+3 GRB [347]. During the S6/VSR2+3 run GCN notices reported approximately 150 GRBs detected by satellite-based gamma-ray experiments at times when two or more GW detectors were operating. A search for GW bursts using the same coherent analysis method used for S5/VSR1 [348, 349, 350] yielded no candidate event. We set 90% confidence upper limits on the GW amplitude associated with each GRB, or lower bounds on the distance in the assumption of a fixed GW energy emission. The median distance exclusion for short-duration signals in the detectors' sensitive band ($\sim 150\,\text{Hz}$) is 17 Mpc $(E/0.01\text{M}_\odot\text{c}^2)^{1/2}$, where E is the energy emitted in circularly polarized GWs from face-on rotating systems. We also place distance exclusions on binary progenitors, with median distances of $\sim 7\,\text{Mpc}$ for NS-NS systems and $\sim 15\,\text{Mpc}$ for NS-BH systems. New features introduced to this GRB search include the ability to target poorly localized GRBs (from e.g., the Fermi satellite), a more powerful, weighted binomial population detection method, and a novel population-based GRB-rate exclusion statement.

S5/VSR1 GW+HEN Antares [351]. Cataclysmic cosmic events such as gamma-ray bursts can be plausible sources of both GWs and high energy neutrinos. A new search for coincident GW bursts and high energy neutrinos used 216 neutrino triggers collected by the ANTARES neutrino telescope in its 5-line configuration from January to September 2007. The GW analysis follows that used for the S6/VSR2+3 GRB burst search [348], with an on-source time window based on astrophysical expectations for the relative delay between neutrino and GW emission [270] in GRBs. No significant coincident events were observed, and we place limits on the density of joint high energy neutrino and GW emission in the local universe. In particular, simulations based on models of the maximum expected GW emission from collapsing stars indicate that such sources would have to have been at least ∼10 Mpc away from the Earth.

4.3 Methods Used in Burst Searches

This section describes how the Burst Group searches for GW transient signals without knowing their form, select good-quality data, evaluate the background rate of false triggers from detector noise fluctuations, and estimate the sensitivity of its searches.

4.3.1 Signal Extraction

Despite rapid progress in relativistic astrophysics, there is still significant uncertainty in predicted waveforms for most GW burst sources (see Sect. 4.1). Therefore, the Burst Group implements a variety of methods to find transients in the data that are inconsistent with the baseline noise level, and rely heavily on coincidence between multiple detectors to discriminate between GWs and noise fluctuations. A *search pipeline* generally consists of one or more signal processing algorithms, post-processing tools and diagnostics criteria. The analysis pipeline produces a set of *triggers* which, if they pass all significance tests and consistency checks, are considered to be candidate GW burst events.

In a few special cases when an accurate signal model is available, such as for cosmic string cusps or neutron star or black hole ringdowns, a search can be done using matched filtering with a bank of templates. Otherwise, GW bursts can be identified in the detector output data as excess-power localized events in the time-frequency (TF) domain. To obtain a TF representation of data a number of transformations are used, including windowed Fourier transforms, discrete wavelet decompositions (Symlets, Meyer wavelets) [352] and continuous wavelet transforms (Q-transform) [353]. These transformations are actively used in the burst search algorithms. At the same time, the Burst Group is open to other promising approaches such as the Hibert-Huang Transform (HHT) adaptive time-frequency decomposition [354], and the fast Wilson-Daubechies transform. A few other methods which do not start with a TF representation have been implemented in past burst searches, including a change-point analysis of bandpassed data [355] and a cross-correlation analysis using pairs of detectors [356].

Access to detector networks is especially important for the detection of GW bursts, as the identification of a consistent signal in multiple instruments increases the significance of a candidate event and distinguishes it from instrumental and environmental artifacts. Also, data from multiple detectors allow to reconstruct the two GW polarizations and determine the direction to the source. For these reasons, the Burst Group has developed multi-detector search algorithms which can be classified as *incoherent* or *coherent*. Incoherent algorithms [355, 353, 357, 358] identify excess-power events in individual detectors; a time coincidence is then required between events in different detectors. This is particularly useful for detector characterization and the study of enviromental and instrumental artifacts (see Sect. 4.3.2). Coherent algorithms are based either on cross-correlating pairs of detectors [359, 360, 361] or on a more general coherent network analysis approach [343, 348]. In these methods, a statistic is built as a coherent sum over the detector responses, which, in general, yields better sensitivity, at the same false alarm rate, than individual detector statistics.

Several coherent approaches have already been adopted in past analyses, including a constrained likelihood method for untriggered searches [362, 343, 363] and a likelihood method for triggered searches [348]. In preparation for the analysis of advanced detector data, these methods are being upgraded and tested both on initial detector data and engineering runs. The Burst Group is also exploring a Bayesian formulation of a coherent network analysis [364], already used in the analysis of initial detector data [365], and on maximum entropy methods [366]. In addition, the Burst Group is investigating dedicated coherent algorithms which may use partial information about burst sources and incomplete source models, for targeted searches that address the science goals described in Sect. 4.4.

The prompt detection of GW signals and estimation of source coordinates enables coincident observations with other astronomical instruments, which can significantly increase the confidence of detection [367]. Such measurements may not only aid the first detection of GWs but also they will give us fundamentally new information about the sources and their distribution. The Burst Group has made significant progress in the development of source localization methods, which were extensively tested during the Position Reconstruction Challenge and used during the S6-VSR2/3 run [340]. The source localization problem will remain a high priority of the Burst Group in preparation for advanced detector network. LIGO, Virgo and other ground-based GW detectors have a linear response to the GW strain at the detector sites. The inferred GW strain at each detector site thus amounts to the greatest information that GW detector observations can provide for the purpose of astrophysical interpretation. Even in the absence of an electromagnetic counterpart an inferred waveform can provide basic information about a source and its dynamics. With an electromagnetic counterpart the accessible physics and astrophysics expands exponentially. Waveform inference is thus a basic desideratum of GW detection and the pursuit of robust and reliable reconstruction algorithms that provide the collaboration this capability is one of the Burst Group priorities (see also Sect. 4.3.6).

The Burst Group strategy in the advanced detector era is to support both an incoherent pipeline, with a coherent network follow-up, and a coherent network analysis pipeline. Future needs for hardware computing infrastructure will need to be evaluated during the transition years. The Burst group will benefit from an effort to make the software user-friendly for all group members, with search codes packaged as common tools for all to run and configure for customized analyses, with reduced overhead for learning how to use the code, and a standardized output from all pipelines. The development of new software will be coordinated with DASWG; the group encourages making best possible use of existing and validated code. We remain open to better ways to do things but aim to avoid unnecessary duplication of effort, maximize efficiency, recognize practical development of new tools.

4.3.2 Detector Characterization

Data quality plays a key role in burst searches, where the false alarm rate is dominated by noise transients, or "glitches", which can happen with similar morphology in multiple detectors and pass the coherence tests developed for the identification of GW candidates. Glitches represent the ultimate limit to the sensitivity of the burst search and to the confidence in a possible detection.

In a coordinated effort of Burst and CBC Group members, the Glitch Group and the Virgo Data Quality (VDQ) Group study the correlation of the rate and strength of single detector transients to trends and transients in the sensing and control systems that maintain the interferometers in their operating condition, as well as monitors of the physical environment in which the interferometers sit: vibration, sound, magnetic and electric fields, power line voltages, and others. These studies have led to the identification of times likely to be contaminated by non-GW effects, which the Burst Group uses to veto event candidates found by the GW channel analyses. Based on their duration and character, we distinguish between *data quality* vetoes and *event-by-event* vetoes [368, 369].

Data Quality (DQ) vetoes are long time intervals (typically several seconds), during which auxiliary signals indicate that an interferometer was out of its proper operating condition. The vetoes are constructed from the DQ flags identified by the Detector Characterization group and the VDQ group. Different flags have different correlation with transients in the GW channel, thus we developed a categorization system for DQ flags to be used as vetoes:

- Category 1 vetoes define which data can be safely analyzed by the search algorithms; they remove features that could affect the power spectrum.

- Category 2 vetoes define the *full* data set, where to search for detection candidates. They remove times when the detector is unambiguously misbehaving with a well-understood physical coupling. They introduce a small dead time (a few percent) and have high efficiency for removing single-detector outliers.

- Category 3 vetoes define the *clean* data set to be used to set an upper limit in the case of no detection. They identify times with an excess of single-detector triggers in the GW channel, but the correlation is not unambiguous and they may introduce up to 10% dead time. If a detection candidate is found at these times, flag is taken into account in the event followup, as described in Sect. 4.3.7.

- Category 4 flags specifically tag the times where hardware injections were performed. In most searches they are to be used as Category 1 vetoes since they might affect the PSD computation.

- Category 5 data quality are advisory flags: there is no obvious correlation with single detector transients, but they are known detector or environmental features.

The classification of DQ flags into vetoes is based on their correlation with single-detector triggers [370, 365]: they are not tuned on multi-detector outputs, but once the tuning is complete, their effectiveness is tested on coherent network analysis triggers.

Event-by-event vetoes are short intervals (typically 100 ms or shorter) that mark individual transients in an interferometer's output with a coincident transient in one or more diagnostic signal. They are identified with extensive statistical studies of coincidence between single detector triggers in auxiliary channels and event candidates, with a software package which considers many possible veto conditions in a hierarchical classification process. The vetoes are ranked on the basis of the significance of their correlation with GW triggers, and their significance is re-evaluated in subsequent iterations, after each condition is applied. Their safety is tested against hardware injections [371].

While there is overlap in personnel and activities between the Detector Characterization group and the Burst Group, the Burst Group is explicitly responsible for applying DQ flags and vetoes to burst analyses based on information provided, interfacing with the Detector Characterization group to assess the impact of DQ on the searches, and identifying which artifacts are creating the greatest problems in burst analyses.

Preparations for the advanced detector era are building upon these techniques and definitions developed in previous science runs, with the currently existing approaches serving as a baseline which will be improved for future runs. Any target-of-opportunity externally triggered analyses using GEO astrowatch data currently being collected will be supported by the detector characterization activities and employ these basic strategies as well. However, despite the intense detector characterization effort in previous science runs, the burst search sensitivity in initial detector data was still dominated by glitches. As we prepare for the advanced detector era, new, more sophisticated techniques need to be developed and implemented for an effective mitigation of non-Gaussian noise transients, with a target of at least 90% cleaning of single detector triggers in future runs. Close collaboration between the Detector Characterization group, VDQ Group, Burst and CBC working groups, and the instrumental commisioners will be critical in meeting these objectives.

Online analysis will remain an area of focus in the advanced detector era, partially in order to enable rapid feedback to commisioners. This facilitates improved data quality for future data in addition to mitigating the effect of current problems in burst analyses. As in offline analysis, the implementation in S6/VSR2-3 serves as a performance baseline which will be built upon. In the previous science runs, the Burst Group collaborated with the Detector Characterization group and the VDQ group for a prompt and documented definition of DQ flags and veto criteria to enable online analysis. Single-interferometer triggers were produced online and time-frequency plots, as well as histograms and correlograms, were available with a latency of

2-3 minutes. These plots were available for commissioning and science monitoring, and used for the identification of DQ flags. A standardized set of data quality flags were produced with low latency and were available for online analysis; additional studies and a periodic revision of vetoes and their categorization was performed for the offline burst analysis, as the understanding of each detector improved. The offline vetoes were tested against coherent WaveBurst multi-detector triggers, especially relevant for understanding the background in the burst analysis.

As data from advanced detector subsystems, e.g. the PSL (pre-stabilized laser), become available the engineering runs will be increasingly useful as testbeds for detector characterization techniques (as well as gaining an understanding of the subsystems themselves). This will include prototyping improved burst online trigger generators running over expanded sets of auxiliary channels, as well as developing new and improved DQ/veto algorithms.

4.3.3 Background Estimation

The key to a burst search is discrimination between GW signals and *false alarms*, or background noise fluctuations which pass the analysis selection criteria. The False Alarm Rate (FAR) or, alternatively, the False Alarm Probability (FAP) for the observation time, depends on the detector noise properties and on the full set of analysis selection criteria. The FAR is typically estimated with an *off-source* resampling of the observation data, equivalent to switching off any GW signals.

In a network of detectors with independent noise, the off-source resampling is performed by *time shifting* the data of detectors relative to each other by more than the maximum light travel time between the sites. This voids the coincidence conditions for any GW signal which may be present in the data and provides a reliable estimate of the accidental background if the noise properties vary over time scales longer than the time shifts. This procedure is repeated many times with different time shifts, so that each resample can be considered independent from the others. The sum of the resampled observation times should exceed the inverse of the target FAR by at least a factor of a few. If there is a known trigger time for the possible GW, the background estimation can take advantage of it by defining off-source samples within a single detector.

The significance of event candidates found in the *on-source* (unshifted) analysis can be evaluated by comparison with the distribution of the accidental background, typically quantified with statistics that describe the strength or quality of the signal. For an objective assessment of the FAR, we adopt a *blind* statistical procedure, where we use the off-source data, without examining the on-source data, to tune the procedures to compute the test statistics and their thresholds. Once the on-source has been disclosed, a second set of independent off-source resampling can be drawn to re-evaluate the false alarm rate. This avoids possible biases from over-fitting to the first off-source sample.

This method has a few caveats. The time shift analysis cannot discriminate between GW signals, other foreground signals or correlated noise sources at different detectors. Moreover, if accidental events are not consistent with a Poisson point process, it is not obvious how to evaluate the uncertainty of the empirical off-source distribution, which propagates into the FAR uncertainty. Another problem with the time-shift method occurs if strong signal events in the detectors produce accidental coincident events in off-source resamples and induce a positive bias on the FAR estimates. This effect is mitigated in coherent network analyses: the stringent consistency checks between detector responses makes them more robust against this bias than incoherent analyses. Up to this point we have seen no evidence that signal injections in the data can affect the result of coherent burst searches.

4.3.4 Simulations

The Burst Group uses software signal injections in the data to tune its analyses, assess their *detection efficiency*, once all selection criteria are fixed, and interpret the results against different signal models. In the analysis of initial LIGO-Virgo data, simulated signals were added to the data at pseudo-random times, spanning the expected range of signal properties (frequency, duration, etc.), but without attempting to exhaust all plausible signals, as the robustness of the signal extraction methods allows to extrapolate to other signals.

The detection efficiency is evaluated as a function of waveform and amplitude, averaged over random sky positions, for all-sky burst searches, or at the fixed sky position of an astrophysical event which triggered the search. Results are also interpreted using models of galactic and extragalactic mass distributions. The standard set of simulated waveforms has been expanded over time, to improve the astrophysical interpretation, e.g. including elliptically polarized signal models and random distribution of the inclination angle of the source with respect to the line of sight.

Systematic effects of calibration uncertainties on the detection efficiency are estimated with injections of signals with suitably mis-calibrated amplitude and phase (or time). These tests can be performed on subsets of the observation time to limit the computational load, since typically a few-days subset is representative enough of the detection efficiency through a data run.

While the basic simulation machinery used in the analysis of initial LIGO-Virgo data is well-established, exploratory work is being done for a more flexible simulation mechanism in the advanced detector era. Also, work is in progress to expand the set of waveforms and include modeled or astrophysically motivated signals.

4.3.5 Hardware Signal Injections

We inject simulated signals into the interferometer hardware from time to time as an end-to-end test of the detector, data acquisition system and data analysis pipelines. By comparing the reconstructed signal against the injected one, we check the detector calibration. Hardware signal injections are also useful for establishing the safety of vetoes, i.e. testing the limits on the cross-coupling of loud GW signals into auxiliary data channels that might be used to define vetoes.

4.3.6 Burst Parameter Estimation

The detection of an un-modeled burst of gravitational wave radiation will present the astrophysics community with a wonderful mystery to solve: What produced the signal? Answering this question will require an assessment of the degree of confidence that one process or another was at work, and learning as much as possible about the underlying dynamics of the system from the gravitational wave data.

The process of characterizing gravitational wave signals for modeled systems such as binary black hole mergers is fairly straightforward and well understood (see for instance [372]). Physical parameters such as the mass and spin of the component black holes affect the waveforms in a known way, and by comparing the parameterized waveforms to the data it is possible to develop posterior probability distributions for the model parameters. The problem of parameter estimation for a general burst signal is more difficult. At first sight the question may seem ill-posed since the signal extraction and search techniques generally do not use physically parameterized models. For example, the output of burst search may be a list of best-fit wavelet amplitudes for the reconstructed signal, from which it is possible to derive physical quantities such as the duration, rise and decay times, peak frequency, frequency band containing 90% of the power, etc.. The choice of physical quantities is flexible, and can be tailored to address particular astrophysical questions. In addition to characterizing the time-frequency and energy content of the signal, the coherent network techniques adopted by the Burst Group allow to estimate the source sky location and reconstruct the waveform with its polarization, as discussed in Sect. 4.3.1.

The goal of burst parameter estimation is to go beyond finding best fit point estimates for the quantities that characterize a signal, and to produce full posterior probability distributions for the parameters. It is only when the spread in the parameter estimates are available that it becomes possible to meaningfully compare the predictions of different astrophysical models. This is a high priority item for the Burst Group in the advanced detector era. So far only preliminary studies have been conducted with techniques described in this sections, but the expectation for the advanced era preparation is these techniques will be incorporated in the science team activities described in Sect. 4.4.

Examples of ongoing burst parameter estimation efforts include Bayesian techniques where wavelets are used to model both the network-coherent gravitational wave signals and instrument glitches [373] and full posterior distributions characterizing the signals and glitches are produced, incorporating Bayesian model selection, and providing odds ratios for the detection and non-detection hypotheses. An additional benefit of using Bayesian inference in the analysis is that it is easy to incorporate priors, including strong priors on the signal morphology that can be used to produce targeted searches. For instance, there are ongoing efforts to incorporate information from numerical simulations of core collapse supernovae and the resulting gravitational waveform catalogues, using a Principal Component analysis and Markow Chain Montecarlo based reconstruction [292] or Nested Sampling. This type of Bayesian inference for parameter estimation and waveform reconstruction in targeted searches will be pursued as waveform catalogues become available, with coordination to take place within the science teams.

4.3.7 Be Prepared to Detect a GW Signal with Confidence

Establishing high confidence in the detection of a GW transient remains the most challenging problem for the Burst Group in the Advanced Detection Era. Burst searches are not tied to a specific source model, and therefore they are more affected by non-stationary noise than templated searches. In the analysis of data from the initial generation of GW interferometers, the Burst Group has adopted several tests to assess whether a candidate event should be considered a GW detection, including consistency tests among coincident signals from different interferometers, extensive detector characterization studies, to exclude instrumental and environmental transients, and background studies to establish the significance of observed candidate events. There have been significant improvements in the burst algorithms during the analysis of the initial data, and yet, they are not sufficient for a confident detection of expected GW signals. During the data runs of initial detectors there were two blind burst injections, which have been promptly discovered and reconstructed by the burst algorithms. However, due to excessive non-stationary background noise the burst search could not identify these events as GW signals with high confidence.

In preparation for the analysis of data from advanced detectors, and to solve the extremely hard problem of non-stationary background noise, the Burst Group has identified several directions of research aiming a confident detection of low rate GW transients.

Coherent network analysis: this approach has proven very effective in searches of initial data; it require further development to fully utilize capabilities of future advanced detector networks.

Inclusion of models into burst searches: one of the main priorities in the burst analysis, the inclusion of models (which may not be accurate) helps to divide assorted un-modeled events into wide weakly-modeled classes with significantly reduced background. For example, such classification of burst triggers into different polarization states has been already used in the analysis of initial detector data. Other models targeting particular classes of burst signals can be also developed and used in the analysis. Such weakly-modeled algorithms are quite computationally intensive and also a development of robust source models will require a close collaboration with a wider astrophysical community.

Improved statistical analysis is required to combine different runs and searches in order to establish a significance of observed candidate events. For example, during the S6/VSR2+3 burst analysis there were 4 different time epochs and four different network configurations with significantly different rates of background events, for a total of 16 analysis configuration. All these configurations need to be combined in a single measurement with a clear statement of statistical significance of the candidate events. Such statistical approaches based on likelihood, false alarm density, and other methods are under development in the Burst and CBC groups. They need to be implemented and tested, and perhaps other, more advanced statistical algorithms, need to be developed.

Advanced background studies need to be performed for better understanding of low rate non-stationary tails in the background rate distributions. Burst searches are capable to accumulate hundreds of years of effective live time of the background sample (thousands of time lags). However this is not sufficient for an accurate estimate of the false alarm rates. New approaches for accumulation of million lags need to be developed.

Detector characterization studies is one of the most important activities in the Burst Group. Burst Group members actively participate in detector characterization studies (as part of the LSC Detector Characterization group) and the burst algorithms are used for identification of data quality flags and vetoes. During the analysis of initial detector data, the burst group also developed a "detection checklist" - a follow-up procedure for candidate events. We will continue to work with members of other LSC working groups to improve the identification of spurious events in the detectors. New DC approaches need to be developed to make a breakthrough in this area and to dramatically improve the efficiency of the data quality selection cuts and vetoes.

Best use of the initial detectors data set: We do not need to wait for advanced detector data to improve and test advanced analysis algorithms, new statistical procedures and novel data quality methods which are required for a confident detection of burst GW signals. All this work can be done on the existing data set, before a data from advanced detectors is collected. Detection challenges and tests of confident detection approaches can be performed as a part of the software engineering run plan.

Efficient use of trigger event properties and source distribution: Beyond perfecting our GW search methods, it is also crucial to understand and incorporate information from other messengers in the analysis. The anticipated source distribution based on the available galaxy catalogs is a good example where we can significantly enhance our sensitivity by weighting results with the probability distribution of potential sources. For external triggers, trigger properties beyond source direction (e.g. source distance for GRBs or neutrino energy for HEN searches) can be an important addition to the information used in the analyses.

4.4 Science Goals

The Burst Group's fundamental goals are to detect gravitational-wave transients and use them to test theories of gravity, to learn new things about astrophysical objects, and to enable statistical analyses of source populations and emission mechanisms. The group aims to extract a broad range of science results from early data of the advanced gravitational wave detector network, building on our online and offline analysis experience and the data analysis infrastructure developed for the initial detectors. The analysis for S6/VSR2+3 "first science targets" is complete, and the remaining papers on other S6/VSR2+3 searches are expected over the next year or so. In the meantime the focus of the group is shifting to preparations and infrastructure developments for the advanced detector era.

Although many Burst Group search algorithms are designed to detect a wide range of signals, the tuning and interpretation of the searches can benefit from considering how they perform for realistic astrophysical signals. Therefore, part of the group's science program involves actively collaborating with the theoretical astrophysics, source modeling and numerical relativity communities.

Many of the plausible gravitational-wave sources introduced in Sect. 4.1 should be observable in more traditional channels. Directly relevant astrophysical observations are abundant, ranging from Earth-based astronomical data, through sensitive GRB/X-ray satellite detections, to neutrino signals. Knowledge of the time and/or sky position of the event increases the sensitivity of an externally triggered burst search compared to an untriggered all-sky search. The association with a known astrophysical event may be critical in establishing our confidence in a candidate GW burst detection. Perhaps most importantly, joint studies of the complementary data can enable scientific insight that cannot be accessed through gravitational waves or other messengers alone. Therefore, in addition to searches using only the GW data, a significant part of the Burst Group's science program involves connecting with other observations and working closely with the astronomy and astrophysics communities to extract as much science as possible from our data and searches.

First Science Targets

We plan to be able to perform rigorous and sensitive core analyses on "day one" of the advanced detector era, including being ready to detect and fully characterize a GW signal when it arrives. Specifically, the Burst Group is committed to deliver the following:

1. An all-sky statement on generic gravitational wave bursts: upper limits if there is no detection, a rare-event detection significance if we have one candidate, or population studies if we have several detections.
2. Prompt analysis for electromagnetic followup of early detections.
3. Prompt reports on interesting astrophysical triggers, such as GRBs, SGRs, and supernovae.

In preparation, the group will pursue necessary ingredients such as data access, data quality, simulations, interpretation and statistics, and improved background estimation, as detailed in Sect. 4.3 and summarized in Sect. 4.3.7.

Science Teams

Beyond simply detecting gravitational-wave bursts, we wish to study specific astrophysical sources such as black hole mergers, core collapse supernovae, perturbed neutron stars, eccentric binaries, gamma-ray burst engines, cosmic string cusps, joint emitters of GWs and neutrinos, as well as test alternate theories of gravity. To achieve these goals the Burst Group is organised into eight science teams:

- **All Sky - All Time:** The most general search for transient GW signals (and starting point for some analyses aimed at more specific signals).
- **Gamma-Ray Bursts (GRB):** GWs associated with gamma-ray burst triggers.
- **High Energy Neutrinos (HEN):** GWs coincident with high energy neutrino events.
- **Supernova (SN):** GW search triggered by optical or low-energy neutrino observations.
- **Neutron Star Physics (NS):** GWs from isolated neutron stars, particularly searches triggered by SGRs, pulsar glitches.

- **Other Electromagnetic Counterparts (EM):** GWs associated with EM counterparts (X-ray, UV, optical, radio) using searches triggered by EM events other than the specific sources mentioned above, or else triggered by GW events and followed up with EM observations.
- **Binary Black Holes (BBH):** Searches for GWs from IMBBH, eccentric BBH. Close ties with the CBC group.
- **Exotica:** Alternative theories theories of gravity, cosmological defects (cosmic strings), bursts with memory.

These teams are based on science targets and sources rather than analysis methods, and are the "home base" for coordination of all activities in their areas. In particular, each team has the primary responsibility for formulating the science case for their work, and proposing analysis methods and a coherent publication strategy to achieve those scientific goals. Each team should lay out a timeline with milestones for being ready for the first advanced detector data, using the engineering runs schedule to plan on testing, review accomplishments and report to the whole group.

New searches or teams will be embraced by the group once they have proven their potential with astrophysical motivation and a viable implementation plan. The team should consider the likely signals; what astrophysical interpretation(s) should be pursued for a non-detection or for a detection; the suitability of existing analysis tools and techniques; what specific improvements need to be made; and what new tools or techniques (if any) need to be developed. Simulations and astrophysical input will help decide whether a specific source requires a targeted analysis or a different tuning and interpretation of the standard all-sky and externally triggered searches.

4.4.1 [ALL-SKY] Search as Broadly as Possible for Gravitational Wave Bursts

There is strong astrophysical motivation to search for burst-like gravitational-wave signals using ground-based laser interferometers [374]. The emphasis has historically been on astrophysical systems for which the resulting burst waveforms are either poorly modeled or unknown, including, but not limited to, the merger phase of binary coalescence and core-collapse supernovae. In recent years numerical relativity calculations have offered significant information on the waveform accompanying binary mergers [375], as well as important new information on the features of signals accompanying core-collapse [250, 376]. Burst sources with well-modeled waveforms include emission from neutron star ringdowns following a pulsar glitch, black hole ringdowns or cosmic string cusps (see Sect. 4.1.3 and 4.1.5).

Typical signals predicted by these models last from less than a millisecond to hundreds of milliseconds, with signal power in the frequency range from 50 Hz to few kHz. Various models of gravitational-wave emission from core-collapse supernovae [250] and gamma-ray burst progenitors [377] may result in signals lasting up to several seconds. Although the best sensitivity of ground-based interferometers is achieved around $\sim$150 Hz, first generation instruments remain sensitive to within a factor of $\sim$10 over most of their frequency band (60–6000 Hz). Given the broad spectrum of astrophysical sources, signal morphologies and their uncertainties and the possibility of unanticipated sources, it is of paramount importance for the burst search to provide an eyes-wide-open approach capable of detecting the widest range of signals.

Our approach relies on generic search methods and on minimal assumptions about the signal morphology. The search analyzes as much of the available data as possible from times when two or more detectors are running well, and no assumption is made on the direction and the source(s) of gravitational-wave bursts. This kind of untriggered burst search is often referred to as *all-times, all-sky*, or simply *all-sky*[1]. The search is traditionally tuned in such a way that a very low number ($\ll 1$) of background events is expected over

[1] It should be noted that many of the model-dependent searches are effectively "all-times, all-sky" ones with the difference, of course, that they optimize their sensitivity to specific waveform models.

the duration of the observation. Thus, any signal events (foreground) resulting from this analysis constitute detection candidates for which further and exhaustive investigation is performed (see Sect. 4.3.7). The immediate result of this search is a statement on the rate and strength of gravitational-wave bursts at the instruments. We can also give an astrophysical interpretation to the results through order-of-magnitude estimates of the reach (distance to which a signal could be detected) for certain astrophysical models.

The main all-sky searches on first-generation LIGO-Virgo data are now complete [287]. A near-term goal for the all-sky search is to **re-analyse the S5-6/VSR1-4 data sets** using a set of simulated signals extended to comprehensively to cover both known astrophysical models (including for example supernovae, ringdowns, cosmic strings, and inspirals) as well as realistic signal parameter distributions (source inclination and signal polarisation, sources distributed according to the galaxy distribution in the local universe). This re-analysis will produce rigorous astrophysical interpretations of the GW burst content of first-generation detector data. It will also serve as a powerful test of our upgraded pipelines in preparation for the advanced detector era.

In addition to the short-duration search, the group is **expanding analysis coverage to signals that last up to several seconds or minutes**, with tailored modification to existing all-sky algorithms or new cross-correlation techniques. Some of these efforts are pursued jointly with the Stochastic Group (Sect. 6).

In the longer term, our primary task is **prepare for low-latency searches in the advanced detector era**. The Burst Group has a goal of fielding two independent all-sky pipelines, as was the case in S6/VSR2,3. The critical challenge for the all-sky search is background rejection, as discussed in Sect. 4.3.7. Another important technical challenge is to develop methods for background estimation at the levels required for a confident detection (i.e., equivalent to millions of time lags). The S5-6/VSR1-4 data and the Engineering Runs will be vital for testing and validating our pipelines.

Historically, many pieces of burst analysis infrastructure and techniques were first developed in the all-sky search, and later applied in other more specialised searches. We expect this pattern to continue. In particular, we intend to **investigate the feasibility of reusing all-sky event data for specialised searches** (e.g., triggered searches) in the advanced detector era. This approach has significant advantages over writing purpose-built analysis pipelines for specialised searches, particularly minimising duplication of effort. It also allows the specialised searches to take advantage of the low-latency nature of the all-sky search. Increased sharing of tools between group members will also naturally lead to improved interoperability between tools and collaboration between Group members.

4.4.2 [GRB] Look for GW Transients Associated with Gamma-Ray Bursts

Note: This science team encompasses GRB searches in both the Burst and CBC Groups.

LIGO and Virgo have a long history of searching for GWs associated with GRBs [378, 379, 380, 381, 360, 349, 382, 341, 347]. In the early advanced detector era, the detection of a GRB-GW event would provide compelling support for the associated GW signal. And, as discussed in Section 4.1, the GW signals would provide valuable insights into GRB progenitor models. Eventually, GRB-GW observations may provide important connections to cosmology (see Section 3.3.9).

The search strategy is based on looking for a GW coincident in time and sky direction with the external GRB trigger. The burst search algorithm is applied to both long and short GRBs. The current search pipeline [348] is based on a coherent network algorithm designed to be sensitive to generic or weakly modelled gravitational wave transients. The CBC analysis focuses primarily on short GRBs. It is a coherent matched-filter search (see [347] and Sect. 3.3.5) for low-mass binary inspirals, which are a likely progenitor of this GRB class. The burst analysis is complementary to the CBC search, providing the ability to detect or constrain any gravitational wave emission that does not match the inspiral waveform. Even non-detections can be significant; for example, the analyses of GRB 070201 [379] and GRB 051103 [341] supported the hypothesis that the event progenitors were not compact binary mergers in the target galaxies, and were more likely to be giant flares.

GRB triggers are collected primarily from the GRB Coordinate Network (GCN, [**?**]), and from the Third Interplanetary Network (IPN, [383]). While GCN notices are distributed in real time, the localization of IPN GRBs requires manual effort by IPN scientists and therefore these triggers are obtained via collaboration with the IPN with a time lag of months to years. As a result, GCN and IPN GRBs have been analysed separately. The analysis of all GCN GRBs during S6/VSR2-3 has been completed [347]. Near- term goals are to **complete the ongoing analyses of IPN GRBs from S5/VSR1 and S6/VSR2-3, and GCN GRBs from Astrowatch periods**. Ongoing collaboration between LIGO/Virgo and the IPN should streamline IPN trigger generation in the advanced detector era, assuming continuing operation of the IPN network and support of operations.

Additional GRB triggers are generated by analysis of data from the *Swift* satellite for candidate GRBs which are below the nominal *Swift* trigger threshold. Since GW signal strength does not necessarily follow GRB luminosity, such a search is worthwhile, as relatively nearby GRBs may be included in this sample. Indeed, this sample could be enriched in a suspected local population of low luminosity GRBs [384, 385]. **Completing the ongoing analysis of sub-threshold *Swift* triggers** is another near-term goal of the GRB team.

In addition to the search for signals from individual GRBs, one can search collectively over a population of GRB triggers, to infer properties of the population of astrophysical sources as a whole rather than any one member [386]. This strategy has been successfully used to improve upper limits on GW emission from GRBs [360].

In looking ahead to the advanced detector era, a few issues stand out. Most fundamentally, there must be operating GRB satellites. Since current missions will be at or past their anticipated lifespan as Advanced LIGO/Virgo approach their best sensitivities, this is far from assured. Another issue is the handling of GRB trigger data. Ideally, it should be treated in a manner which is fully coordinated and compatible with other astrophysical observers. The collaborations should **prepare for low-latency GRB-triggered searches**, with a goal to be ready to provide GW observational information which can be included in a public GRB trigger notice with a latency sufficiently short so as to be relevant to follow-up observers. Options for the low-latency searches include either the launching of dedicated algorithms which make use of the known GRB time and location, or to simply compare GRB triggers with lists of GW triggers resulting from all-sky, all-time pipelines. Refinements of existing pipelines are foreseen. Specifically, for the CBC case the searches will need to incorporate longer templates and, due to GRB beaming, may specialize to face-on CBC orientations. Infrastructure will need to be developed to automatically launch search codes upon receipt of a valid GRB trigger.

4.4.3 [HEN] High-Energy Neutrino Multimessenger Analyses

Many of the most violent and interesting phenomena producing GW transients are also thought to be sources of high energy neutrinos (HENs) [387, 388, 389, 390, 391, 392, 351]. These non-thermal, tera-electronvolt neutrinos are thought be produced in relativistic outflows driven by central engines also responsible for GW emission [393, 394, 395, 396, 397, 398, 399, 400]. Both long and short gamma ray bursts (GRBs), core-collapse supernovae with fast rotating cores, and highly magnetized neutron stars (magnetars) are thought to produce GWs and HENs that may be detectable out to relevant distances [392].

There are multiple scientific benefits of simultaneously observing GWs and high energy neutrinos from a common source:

- **High-confidence detection** – Both GWs and neutrinos are weakly interacting messengers, and so far there has been no confirmed detection of either sources of cosmic origin. The combined information from GW and HEN observatories can greatly enhance our confidence in a joint detection [387, 388, 389, 390, 391, 392, 351, 401]. In particular, a comparison [391] of joint GW+HEN searches using advanced GW detectors and the completed km^3 IceCube detector to the reach of independent searches using the same detectors concluded that, while the main advantage of joint searches is increased sensitivity for the actual detection of sources, joint searches will provide better constraints than independent observations if, upon non-detection they result in an increased exclusion distance by at least a factor $\sim f_b^{1/3}$ compared to independent searches, where f_b is the neutrino beaming angle. This study derived the first observational constraints on common GW-HEN sources using initial LIGO, Virgo, and IceCube data, and also projected population constraints from joint searches with advanced GW and HEN detectors.

- **New probe of the depths of violent astrophysical phenomena** – GWs and HENs both carry information from the depth of their source that is, to a large extent, complementary to the information carried by electromagnetic radiation. While the GW signature of cosmic events is characteristic of the dynamics of their central engine , a HEN flux is reflective of the presence of hadrons in the relativistic outflow generated and driven by the central engine. Detecting both messengers from a common source would provide the unique opportunity to develop and fine tune our understanding of the connection between the central engine, their surrounding, and the nature of the outflows. For example, it has recently been demonstrated [269] that the energy-dependence of the onset time of neutrino emission in advancing relativistic jets can be used to extract information about the supernova/gamma-ray burst progenitor structure. Together with observed GWs, this would provide information on the inner density of the progenitor beneath the shock region ($\sim 10^{10}$ cm for mildly relativistic jets). In favorable conditions, very few neutrinos, in coincidence with a GW signal, would be sufficient to provide important information, and/or to differentiate between progenitor types.

- **Prospect of common sources dark in gamma rays** – The emission of HENs is tightly connected to the presence of high energy photons (gamma rays) in the outflow. There are specific cases where the source optical thickness is large and prevents the gamma-rays to escape from the source. One of the most interesting prospects of joint GW - high energy neutrino searches are common sources that are dark in gamma rays. One of the prominent such sources are choked GRBs [395, 402, 403] or low-luminosity GRBs [271, 272, 233, 273, 274, 275, 276, 277]. These sources are difficult to detect with electromagnetic observatories, and hence provide an exciting opportunity to joint GW - HEN searches that can discover them and/or constrain their population [390, 391, 401]. Further, it is plausible that previously unanticipated sources or mechanisms can be discovered and studied with joint searches.

Currently operating HEN observatories include IceCube [404], a cubic-kilometer detector at the South Pole, and ANTARES [405] in the Mediterranean sea. ANTARES is proposed to be upgraded to cubic-kilometer detector (called KM3NeT) in the coming years [406]. A third HEN detector is operating in lake Baikal and has been proposed to be upgraded [407].

There have been coincident data taking periods between initial GW and HEN detectors in the last few years, providing datasets that have already been used to derive population constraints on joint sources [391, 351]. This includes the first coincident search for GWs and HENs, using the S5/VSR1 data and the partial ANTARES detector in its 5-string configuration [351]. The analysis uses the directional distribution and the time of arrival of HENs to trigger a GW follow-up analysis, similar to the analysis used for GW follow-up searches of GRBs.

Near-term goals for the HEN team include **analysis of the joint S5/VSR1 and IceCube data**. The baseline analysis [408, 401] takes into account the significance of the GW and HEN signals, calculated based on the excess energy in the GW datastream (see e.g. [409]) and the reconstructed neutrino energy and neutrino flux (i.e. number of coincident neutrinos). The analysis also takes into account the directional probability distributions of the GW and HEN signals, as well as the *a priori* source distribution using the observed distribution of blue luminosity in the universe[2]. A parallel search is performed where the blue-luminosity distribution is ignored in order to search for sources not connected to blue luminosity, e.g. galactic sources. The joint search will use the coincidence time window derived in [390]. It will consider individual signal candidates, as well as an ensemble of weak, sub-threshold signals that could not be detected individually. In the case of no detection, results will be used to obtain upper limit estimates of multimessenger GW+HEN sources.

Another exciting future direction is to **search high energy neutrinos in coincidence with longer GW transients**, lasting from seconds to weeks. Such GW transients may be emitted, e.g., by collapsars, some of which may produce long GRBs. For long GRBs the central engine is active for at least the duration of the prompt gamma-ray emission [390]. GW emission can be even longer, e.g., due to a rotationally unstable protoneutron star remaining after core-collapse [410]. A specific GW search pipeline, called STAMP, has been developed to search for such second-week-long transient GW events with no prior assumption on GW frequency and temporal evolution [411]. A joint GW-high energy neutrino search is ongoing using this pipeline and neutrino data from the partially completed IceCube.

The joint **analysis of ANTARES 12-line and LIGO-Virgo S6-VSR2/3 data** is also under preparation. A layer of improvement to the baseline analysis has been developed and is currently in testing. It consists of a modification of the GW event generation algorithm which allows the full use of all GW data (currently restricted periods when three GW detectors are operating).

The advanced detector era holds the exciting promise of the detection of gravitational waves and high energy neutrinos. The expected sensitivity of multimessenger searches was recently surveyed by Bartos *et al.* [391]. Bartos *et al.* derived the first observational constraints on common sources of GWs and high energy neutrinos with initial LIGO and Virgo GW data (S5/VSR1 science runs), and neutrino data from the partially completed IceCube detector with 40 strings. They used these results to calculate projected constraints for common GW-neutrino sources obtainable with advanced LIGO-Virgo and the full IceCube detector with 86 strings. They also compared the estimated reach of joint GW+HEN searches using advanced GW detectors and the completed km^3 IceCube detector to the reach of independent searches using the same detectors. Studies indicate that multimessenger searches with advanced detectors will be able to probe some of the most interesting parameter space for GRBs, including choked GRBs [391]. The search algorithms developed for current detectors will also be applicable in the advanced detector era. For example, the baseline GW+HEN LIGO-Virgo-IceCube analysis method [408, 401] can readily incorporate multiple coincident neutrinos in the analysis, a tool that will be crucial given the highly increased neutrino frequency expected from, e.g., the full IceCube detector.

Advanced searches will also be able to build on some of the search parameters developed for earlier searches. For example, the maximum time difference between the arrivals of the observed GW trigger and HEN events [390], one of the key parameters of the joint GW+HEN search algorithm, will be usable for advanced searches as well. Here, a too small time window might exclude some potential sources, while a too large time window would unnecessarily increase the false alarm rate and the computational cost.

Low-latency joint GW+HEN searches will constitute an interesting new direction for the advanced detector era. Both GW and HEN detectors and their implemented event reconstruction algorithms will be able to provide low latency events that in turn can be used in low-latency joint searches. As both GWs and HENs can arrive prior to the onset of electromagnetic emission from sources such as GRBs, joint GW+HEN events may be primary targets for electomagnetic follow-up searches.

In short, GW+HEN observational results have already proved to produce exciting scientific results

[2]I.e. the analysis assumes that the source distribution follows the blue-luminosity distribution of galaxies.

[391, 351], while the projected constraints [391] and expectations (e.g., [269]) suggest that multimessenger GW+HEN searches will be a fruitful direction of research during the advanced detector era.

4.4.4 [SN] Supernovae as Astrophysical Triggers

Core collapse supernovae are interesting candidates as gravitational-wave sources and can be studied in conjunction with both neutrino and optical messengers (see Sect. 4.1).

Most optical triggers carry the burden of a large uncertainty on the derived event time (order of several hours or more), making the GW data analysis task challenging. Well-known sky locations are a significant aid to the analysis. **A near-term goal is completion of the optical supernova search in initial detectors data**, which is underway and might be able to constrain the most extreme core collapse models. The enhanced reach of advanced detectors will be able to constrain a more significant swath of the model space.

Supernova triggers from detectors sensitive to low energy (tens of MeV) neutrinos can be used in GW searches as well. For example, a core-collapse supernova near the galactic center is expected to produce a large flux of ~ 8000 detected neutrinos in the Super-Kamiokande detector [412] with a pointing accuracy of 4°. Unlike photons, which can take up to $\sim$day to break out, neutrino bursts and gravitational waves mark the moment of core collapse, and are expected to be coincident in time to < 1 s. The expected strong neutrino signal for a galactic core-collapse supernova would provide excellent timing and good pointing, thus allowing an improved sensitivity gravitational-wave burst search, similar to that employed for GRBs. For extragalactic supernovae, the neutrino signature would in general provide timing but not pointing. At the distance of Andromeda the expected flux of detected neutrinos in Super-Kamiokande would fall off to $\mathcal{O}(1)$. In this case, joint neutrino-GW time-coincident searches would substantially increase detection probability and decrease the false-alarm rate. With cooperation from Super-K and other detections, we hope to participate in joint GW-neutrino supernova searches. However, the agreements are still under negotiation at the time of writing.

In the case of a supernova GW detection, likely from a Galactic supernova accompanied by a neutrino signal, the urgent question will be "what can the signal teach us about the physics underlying core collapse?" This question is best approached with model selection and parameter estimation algorithms. We are developing two methods for supernova model selection, using the nested sampling[413] and the MCMC algorithms. **A near term goal is to prepare and characterize these for the realistic aLIGO supernova detection scenario.**

4.4.5 [NS] GWs as probes of Neutron Star Physics

Isolated neutron stars in our galaxy may be sources of detectable GW burst via a number of processes, as discussed in Sect. 4.1.3. Searches for GWs from these systems are carried out in coordination with the Stochastic (Sect. 6) and Continuous Waves (Sect. 5) Groups as appropriate.

Triggers from Magnetars

Current externally triggered searches look for GWs associated with bursts from magnetar candidates – soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs) – following two distinct search strategies. The first strategy looks for GW emission associated with the prompt gamma-ray burst from individual magnetar bursts and giant flares. An emphasis is placed on GW emission from the damping of f-modes in the magnetar which may be excited in the burst, but the entire detector band is searched up to 3 kHz. This strategy has been used to analyze over 1400 electromagnetic SGR and AXP triggers, including the 2004 giant flare [361, 319]. The second strategy looks for the collective signature of weak GW bursts from repeated flares from a single SGR source, stacking the GW data to dig deeper into the noise at the expense of additional but plausible model dependence. This strategy was used to analyze the 2006 SGR 1900+14 storm [414].

Pulsar Glitches as External Triggers

Investigations into excitations of pulsars (post-glitch) and accreting millisecond pulsars (post-flare) have shown that gravitational waves emitted at r-mode frequencies are a potential source for second and third generation gravitational wave detectors.

A search strategy has been formulated with members of the Continuous Waves working group to search for these long-lasting transient signals. Trial runs on simulated data have shown the search strategy capable of identifying the presence of long transient signals at strengths estimated by previous feasibility studies. The next step is to perform a comprehensive characterisation of the search using both simulated data and data acquired by interferometers. Efforts will also be made to translate the outputs from search codes into astrophysically interesting constraints on the source parameters.

Triggers from the low mass X-ray binary (LMXB) Sco X-1

The Rossi X-ray Timing Explorer (RXTE) mission was been extended to the end of 2010 and observations overlapped with the S6/VSR2/VSR3 run. Multi-messenger observations of Sco X-1 allow us the opportunity to search for correlations between the X-ray and potential GW emission. An exploratory cross-correlation analysis between RXTE and LIGO has been performed using S5 coincidence data. In addition to this ongoing analysis a second approach is under way where both RXTE and LIGO-VIRGO time-series data are analyzed to generate trigger lists using existing search pipelines developed for gravitational-wave burst detection. LIGO-VIRGO data is analyzed by a coherent network analysis pipeline and RXTE data by a single detector pipeline based on the excess power method. Masking the sky around Sco X-1 using a coincidence analysis can improve the detection confidence, and therefore enable us to set upper limits on GWs correlated with astrophysical events encoded in RXTE data.

4.4.6 [EM] Other Electromagnetic Counterparts and Follow-up Observations

The previous subsections described several scenarios in which astrophysical systems are expected to emit electromagnetic (EM) radiation along with GW bursts, and the substantial benefits of joint observations. Here, we consider other EM counterparts where the nature of the source is unclear, and/or where the EM signature is present but was not initially detected by surveys.

Radio burst triggered GW searches

Bursts of radio waves have been detected by various radio telescopes, but their origin remains mysterious. Some, such as the remarkable "Lorimer Burst" [415], are now thought to have a terrestrial origin [416], but not *all* observed bursts can be discarded in that way. Since energetic events which produce detectable GWs are likely to feed some of the released energy into EM emission, radio transient counterparts are quite possible. The radio transient either could be short and prompt, or else an afterglow rising and peaking days, weeks or months later (depending on radio frequency band). A short transient would result from coherent emission, e.g. from some plasma excitation, while a radio afterglow could be synchrotron emission from an expanding jet or fireball.

Prompt radio bursts are natural candidates for joint analysis with GW data, especially because there are theoretical models in which various mechanisms give rise to a prompt pulse of radio emission from some putative gravitational wave sources, e.g. compact binary coalescence scenarios or cosmic string cusps [417]. Therefore, the Burst Group science program includes GW burst searches targeting the times and sky locations of reported radio bursts recorded by radio telescopes such as Green Bank [418], Arecibo, Nasu, ETA, LWA, and potentially others.

An interesting aspect of follow-up of radio triggers is that for each event we will have the dispersion measure. This will provide an independent measure of the distance, allowing us to better predict when the gravitational wave should have arrived at our detectors and also to estimate the absolute gravitational-wave luminosity of a detected event.

Tasks for this area include:

- Identify interesting radio transients, taking into account whether they appear to be truly astrophysical
- Consider the detectability of possible GW sources that could have produced the radio transients
- Develop search techniques with appropriate coherent/coincident analysis conditions
- Complete searches
- Consider what conclusions can be drawn from positive and negative search results
- Formulate a good plan for joint radio-GW searches in the advanced detector era

EM follow-ups of GW event candidates

Telescopes cannot cover the whole sky at all times with good sensitivity. Current EM survey projects typically have lengthy cadence times, or are considerably less sensitive than their more directed counterparts [419]; therefore it is quite possible that the EM signature from an interesting event will be missed because no telescope of an appropriate type is looking in the right direction at the right time. The GW detector network, on the other hand, is effectively an all-sky monitor for highly energetic astrophysical events. Thus there is a strong motivation to point optical, X-ray and/or radio telescopes in response to potential GW triggers and thereby attempt to catch an associated transient EM signal which would otherwise be missed. For example, because the gamma rays from GRBs are believed to be beamed (and because even the Fermi Gamma-ray Burst Monitor covers only half the sky), there may be short-lived "orphan afterglows" from nearby GRB progenitors which are going undetected [237]. If such an event is detected by the network of GW interferometers, then the reconstructed sky position can in principle be used to point one or more telescopes and catch the afterglow before it fades away.

Other possible sources of joint EM/GW emission include decaying neutron star matter ejected during merger [420, 421, 246] and supernovas [251]. Some more details on these sources and their expected observational signatures can be found in [422, 419, 423].

Like externally triggered GW searches, GW-triggered EM follow-up observations can be beneficial in two ways. First, they would help establish the event as astrophysical in nature, effectively increasing the reach of the interferometer network in the case of a low-signal-to-noise-ratio event that might not otherwise stand out from the background. Additionally, having an associated EM signal increases the astrophysical information that can be mined from a GW event [424, 425, 426]. Note that both prompt and delayed follow-up observations are appropriate to catch different possible light curves.

During the S6/VSR2+3 run, we successfully implemented and operated a program of rapid electromagnetic follow-up observations using several ground-based optical telescopes—most with fields of view of 3 square degrees or more—plus the LOFAR radio telescope, and the XRT (X-ray) and UVOT (UV/optical) instruments on the *Swift* satellite [340]. The EVLA also followed up some event candidates weeks later [427]. Observations were triggered by both burst and CBC [340] event candidates. Although the total live time of the project was only about 7 weeks and only 9 triggers were followed up during that time, it was successful as a demonstration of the methods and basic capabilities, and a great learning experience to build on for the advanced detector era. As of June 2012, results from the *Swift* follow-up analysis have been released [346] while the analysis of ground-based optical and radio images is not quite done.

Tasks for this area include:

- Complete analysis of S6/VSR2+3 image data
- Publish the S6/VSR2+3 results paper
- Validate low-latency trigger generation with coherent WaveBurst
- Consider whether to also run Omega Pipeline for low-latency trigger generation
- Make sure there are useful diagnostics for proper operation
- Evaluate latency and robustness to gaps, glitches, etc.
- Evaluate and apply low-latency data quality and veto cuts
- Set up background estimation procedures
- Choose standard format for sky maps (HEALPix, maybe?)
- Check correctness of sky maps at advertised probability level
- Assess position reconstruction error regions for different signal types and amplitudes
- Try to find ways to improve precision of position reconstruction
- Quantify effects of calibration uncertainties
- Package event information to send with alert
- Set up standard communication protocol with observers
- Develop and improve methods for joint analysis with X-ray, radio, etc.

Search for EM counterparts in archival data

In addition to the rapid-response EM followup mentioned above, there is also a wealth of all-sky high-energy photon survey data which can be searched offline for EM counterparts to GW events. Joint search pipelines are currently being run and refined to search specifically for S6/VSR2+3 GW-triggered EM counterparts in Fermi GBM (20 keV$-$40 MeV) and RXTE ASM (1$-$10 keV) archival data. This is done in coordination with scientists from both missions. The search targets prompt gamma-ray emission from GBM which may be below threshold for public reporting to the GCN, as well as x-ray afterglow signals in the ASM.

4.4.7 [BBH] Explore Binary Black Holes in a Wide Parameter Space

Burst searches are usually un-modeled or weakly modeled to be open to the broad spectrum of sources discussed in Sect. 4.1. For example, a coherent all-sky burst search COHERENTWAVEBURST is effectively a matched filter operating on a vaste parameter space of generic burst waveforms. In general, it can be sensitive to a wider class of CBC sources (see for details Sect. 4.1.4) than dedicated inspiral template searches (Sect. 3), and immune to a possible discrepancy between theory and nature. However, it comes at the price of reduced search sensitivity and increased false alarm rates.

The goal of the burst BBH searches is to explore as wide as possible the parameter space of BBH sources which may not be accesible by the inspiral CBC searches due to the luck of complete or accurate template banks. In principle, the existing all-sky pipelines can be used for such searches, but their performance is significantly affected by a non-stationary nature of the detector noise. For these reasons the burst group is developing weakly-modeled searches tuned for specific source signatures, but preserving the robustness of the un-modeled burst search. For example, a dedicated search for intermediate mass (100Mo-400Mo) binary black holes [428] conducted by the burst group on the initial LIGO and Virgo data used the all-sky burst search COHERENTWAVEBURST enhanced with the elliptical polarization constraint.

In preparation for the first detection of BBH sources in a wide range of BBH parameters with arbitrary spin configurations and possible high eccentricities, the burst BBH working group identifies the following science targets, pursued in collaboration with the other working groups.

Detection with confidence. Most of anticipated BBH signals are expected to have relatively short duration (few seconds or less) and can be easily confused with the instrumental/environmental artifacts (glitches). Identification and rejection of such false events is a serious challenge in the burst analysis. Therefore, advances in the detector characterization (Sect. 2.2,2.3,2.4) and data regression are critical for the burst BBH searches. To improve the BBH detection efficiency and reduce false alarm rate, the BBH searches employ model constraints. The group will improve existing constraints on the GW polarization states and develop new robust BBH constraints based on the time-frequency pattern recognition. A special concern is a production of large background samples (by at lest a factor of 10 compared to the S5/S6 burst analysis) and better estimation of the false alarm rates, Background production is very CPU intensive and require the development of efficient analysis algorithms.

Development and validation of astrophysical waveforms. An ongoing collaborative effort with the CBC group is studying the use of the full coalescence BBH waveforms, including the inspiral, merger, and ringdown phases. The same set of phenomenological and EOBNR waveforms [70, 103, 429, 430] is being analyzed by burst search methods, inspiral and ring-down matched filtering to compare their detactability across the BBH parameter space. We will also pursue the development of the faithful BBH waveforms (with high spin and eccentricity [431, 325]) covering the BBH parameter space as wide as possible. Studies of such waveforms will help to devise new detection techniques and provide important guidance for the interpretation of search results. The astrophysical BBH waveforms will be used to quantify the reach of the BBH searches and in the parameter estimation studies.

Coordinate reconstruction. Sky localization is a challenging problem for the BBH analysis, particularly for sources with high masses. Such BBH sources are expected to produce a signal at low frequency where the triangulation capabilities of detector networks are affected by the diffraction limit: (λ/d 1, where λ is the GW wavelength and d is the network base length. For these reasons it is important to develop coherent network reconstruction algorithms which use advantage of the antenna polarization coverage. The burst BBH working group concentrates on the un-modeled (robust) sky localization in close coordination with the CBC group (Sect. 3) and the astrophysical follow up effort (Sect. 4.4.6).

Waveform reconstruction and source parameter estimation. In preparation for a detection, the working groups need to improve parameter estimation techniques (as discussed in Sect. 4.3.6). One of the main priorities of the BBH working group is a weakly-modeled reconstruction of the BBH waveforms, Such analysis can identify the polarization state of the BBH system and determine such source parameters as the binary inclination angle and eccentricity. The reconstructed waveforms can be compared to known models for extraction of other source parameters (component masses, etc.). Progress towards waveform reconstruction has already been made via coherent techniques, but more progress is needed to compare a candidate to waveform parameters. Bayesian [432] and MCMC [433] techniques are currently being explored by the CBC Group as well as members of the Burst Group. We are open to exploration of new techniques which may prove useful for reconstruction of BBH waveforms.

4.4.8 [EXOTICA] Beyond Standard Theories and Sources

A prototype analysis looking for cosmic (super)string signatures has been performed on S4 data [434]. The near term goals include the completion of the S5/6-VSR1/2/3 analysis which has been in progress. If no detection is made, it is expected to set upper limits on $G\mu$ about 10 times more stringent than the current CMB constraints. Another factor of 10 or more may be expected from searches in the advanced detector era, especially since signals from string cusps are strongest at low frequencies where the sensitivity improvement is expected to be the greatest.

Search strategies for alternative theories of gravity have already started being investigated within the

Burst group. The goals for the next year include defining of such strategies for scalar gravitational-wave bursts, exploring how existing all-sky search methods like coherent-WaveBurst can be modified in order to be sensitive to scalar waves and quantifying search sensitivity to models by software injections of candidate signal morphologies. We will also explore ability to constrain the mass of the graviton. We will examine the application of such methods to LSC-Virgo data already in hand and the possibility to complete and publish the results from an end-to-end search.

A search for bursts with memory may complement searches for generic bursts or from binary systems. An effort to assess and define such a search is in the nascent stage. We expect to address the feasibility of such a search by quantifying the expected sensitivity for the various scenaria where memory may be present. We will also explore how to adopt existing general burst-search methods as well templated search methods like the one used in the search for cosmic (super)strings in order to look for memory in our data. The emphasis will mainly be for the advanced detector era, but any significant progress in terms of methods and proof-of-concept work using data already in hand may lead to publication.

5 Searches for continuous-wave signals

UPDATED

Rapidly rotating neutron stars are the most promising sources of continuous-wave (CW) gravitational signals in the LIGO and Virgo frequency band.[3] These stars are expected to emit gravitational radiation through a variety of mechanisms, including elastic deformations [439, 440, 442], magnetic deformations [441, 445], unstable r-mode oscillations [443, 439, 444], and free precession [449], all of which operate differently in accreting and non-accreting stars. We present a review of these emission mechanisms in [438]. Indirect upper limits on gravitational wave emission inferred from photon astronomy are more optimistic for non-accreting stars, but according to present theories accreting neutron stars are more likely to be emitting at or near the indirect limits.

The sources for which we search fall into four broad categories: non-accreting known pulsars for which timing data is available, non-accreting known stars without timing data, unknown isolated stars, and accreting stars in known binary or stars in unknown binary systems. For each type of source, we know or can infer properties of the source population; and for particular stars, there are indirect upper limits on gravitational wave emission which LIGO or Virgo must beat in order to claim a novel result. From our point of view, each type of object presents a distinct data analysis challenge which is directly constrained by more conventional astronomical observations. In particular, as most of our searches are computationally limited, their sensitivities are directly dependent on the constraints that come from conventional astronomy. As a result of our computational limitations we support a variety of search codes, each optimised for a different portion of parameter space. Where possible these code share common libraries and are cross-checked on fake signals injected into the detectors.

The breadth of investigation is fundamental to our search method. Given the large uncertainties in neutron star demographics (only $\sim$2000 of 10^8-10^9 neutron stars in the galaxy have been detected), evolution, and structure, we cannot confidently predict which type of source will provide our first continuous-wave discovery. Prudence demands an eyes-wide-open approach and enough flexibility to exploit unexpected waveform models. That said, however, we do adhere to certain priorities in allocating resources (scientists and computers) to different searches. Specifically, we place the highest priority on targeted searches for known pulsars (especially those for which the spindown limit is achievable – see below) and on all-sky searches for unknown isolated pulsars.

The merging of LSC and Virgo CW efforts has revealed strong and well-developed programmes from both groups. An ongoing task is to combine these effectively, maximising both the return on time already invested in developing codes and the science delivered by new joint ventures. Our state right now is one of transition, where we are evaluating the scientific justification and available manpower for these searches, while balancing the importance of redundancy against current resources.

An important new element in this evaluation is the recent creation of simulated data with several thousand software injections for pulsars at randomly chosen sky locations and with frequencies and frequency derivatives spanning our search ranges (see section 5.7.1). These standardized data sets should enable us to compare with more statistical precision and more systematically the sensitivity and robustness of the various pipelines in detecting pulsars in blind searches or in reconstructing source parameters in targeted searches. The outcomes of these comparisons are expected to lead to the abandonment (or at least de-prioritization) of some search pipelines.

[3] We use the term "neutron star" broadly, keeping in mind that some such stars may contain quark matter or other exotica.

5.1 Non-accreting pulsars

UPDATED

We include in this source type all objects for which pulsations are observed in radio, X-ray, or other electromagnetic radiation, with the exception of accreting millisecond pulsars. Photon astronomy can tell us precisely the sky positions, frequencies, and frequency changes of these objects, meaning that our analyses need search only a small parameter space and are not computationally limited (see section 5.1.1 below). Photon astronomy also sets an upper limit on the gravitational wave strain we could see from a known pulsar, assuming that all of the observed spindown is due to gravitational waves. In terms of the distance D, gravitational wave frequency $f_{\rm gw}$ and its time derivative $\dot{f}_{\rm gw}$, this indirect limit is [438]

$$h_{\rm IL} = 8.1 \times 10^{-25} \left(\frac{1\,{\rm kpc}}{D}\right) \left(\frac{-\dot{f}_{\rm gw}}{10^{-10}\,{\rm Hz/s}} \frac{100\,{\rm Hz}}{f_{\rm gw}}\right)^{1/2} \left(\frac{I}{10^{38}{\rm kgm}^2}\right)^{1/2}. \tag{1}$$

Here I is the star's moment of inertia, as estimated by theory but not directly observed, and could be higher than the fiducial value by a factor of up to 3. For most pulsars the distance D is determined by combining their observed radio dispersion measure with a model of the galactic H II distribution and is uncertain to at least 20%. Analysis of the LIGO full S5 data and the Virgo VSR2 data has beaten this indirect "spindown limit" by a factor of 7 for the Crab pulsar (59.45 Hz) and by $\sim$40% for the Vela pulsar (22.38 Hz). Other pulsars for which the spindown limit may be reached in S6/VSR2/VSR4 include PSRs J0205+6449 (30.45 Hz), J1833-1034 (32.33 Hz), J1813-1749 (44.74 Hz), J1913+1011 (50.59 Hz), J1952+3252 (55.69 Hz), J0737−3039A (88.11 Hz) and J0537−6910 (123.95 Hz) [446].

The discussion above assumes gravitational wave emission from a triaxial neutron star, with the electromagnetic and gravitational wave components rotating as one unit. The astrophysical return from detecting such emission would be the first ever measurement of the difference between the two (equatorial) components of the inertia tensor. This in turn would give important information on the strength and strain profile of the solid phase of the star (the crust, or possibly a solid core) and/or information on the nature of the internal magnetic field.

While this form of gravitational wave emission is the simplest and most plausible, it is by no means the only possible wave generation mechanism. Other emission mechanisms include free precession, excited modes of oscillation of the fluid, and the spindown of a multi-component star. The astrophysical returns from detection of such wave generation could be considerable, potentially giving information on asymmetries in the inertia tensor, the viscosity of the fluid, and the internal structure of the star. However, the observational challenge is correspondingly greater, as the gravitational wave emission no longer occurs at twice the spin frequency. This means that searches for such waves require careful thought in order to pick out a range of parameter space (i.e., the wave frequency and its time derivatives) that is both astrophysically reasonable and computationally feasible to search over. As described below (5.1.2), such a search has already been carried out for the Crab pulsar, concentrating on a small patch of parameter space centred on (twice) the observed spin frequency. Clearly, a more comprehensive search over an enlarged parameter space and for more pulsars is needed to fully exploit the science potential of targeted searches.

Targeted searches are those for gravitational wave emission from pulsars of known position, rotation frequency, spindown rate, and binary orbital parameters where necessary. This additional information greatly reduces the size of the parameter space over which we must search, and allows us to perform a fully coherent search for signals over all the available data. Timing accuracy is sufficient to maintain coherence both during and between science runs, and the relative phasing of the interferometers is also sufficiently well determined for us to be able to combine data from all runs and all detectors coherently, resulting in the lowest signal sensitivities achievable by LIGO and Virgo.

Three different pipelines are in current use for targeted searches: 1) a time-domain Bayesian method used in previous LIGO searches; 2) a new Fourier-domain method with Wiener filtering and deconvolution of amplitude modulation; and 3) a new matched filter method based on the $\mathcal{F}$-statistic and (new) G-statistic. These three methods are described below.

5.1.1 Time domain Bayesian method

UPDATED

The time-domain Bayesian method has been applied successfully to data from the first five LSC science runs [435, 436, 455, 453, 454] and to the Virgo VSR2 run. It is also currently being used for searches in S6 VSR3 and VSR4 data. A detailed discussion of the method can be found in [452], with the implementation of the inclusion of binary system parameters in [456].

The method is designed to carry out robust signal extraction and optimal parameter estimation, rather than perform well in a large parameter space search. Its primary purposes are

- to perform searches for signals from known pulsars and,
- to determine the astrophysical parameters of candidate sources.

The current method comprises a heterodyne and filtering stage to extract interferometer data in a tracked 1/60 Hz band centered on the expected gravitational wave signal, followed by a Bayesian parameter estimation stage. This second stage delivers an upper limit to the strain amplitude of any signal and an estimation of the signal's parameters, should one be detected, in the form of marginal posterior probability distributions for the signal parameters. The method has successfully determined the parameters of the injected signals in all our science runs. The most computationally intensive part of the search is the heterodyning and downsampling of the raw data. Currently this takes about 25 min per pulsar per detector per day of data. We will investigate a new method of computing the tracked 1/60th Hz band by combining short Fourier transforms rather than by heterodyning the timeseries. This should give a very significant speed-up when processing multiple targets.

We have strong links with the radio groups at University of Manchester (Jodrell Bank), ATNF (Parkes), MPIfRA (Effelsberg), Nancay, Arecibo, HartRAO, Hobart and NRAO (Green Bank) who have generated timing solutions for our pulsar candidates over the LIGO and Virgo observing runs, and checked that no glitches have occurred in these pulsars. These collaborations have provided data for the S5 targeted searches and are currently generating timing solutions for an even wider range of targets in S6/VSR2/3/4 and beyond. We have initiated a collaboration with Frank Marshall (RXTE) to be able to target promising X-ray objects. This collaboration has provided useful discussions and timing information for the young X-ray pulsar PSR J0537−6910, which is another pulsar for which we could soon beat the spindown limit. We are also compiling timing data on new γ-ray pulsars discovered with the Fermi satellite.

Of the pulsars for which we have accurate timing, the Crab pulsar is both the youngest, and the most rapidly spinning-down, candidate within our sensitivity range. The relatively large amount of intrinsic timing noise for this pulsar is tracked and corrected for within our search method [455, 456]. We have published the results of a search for gravitational waves from the Crab pulsar using data from the first nine months of S5 until the time that a large timing glitch was observed in the Crab pulsar [453] (also see §5.1.2.) A follow-on search for 116 pulsars in the full S5 data set included the Crab and enabled us to beat the spindown limit by a factor of 5.6 using uniform priors over the unknown parameters. Astrophysically motivated priors on the inclination and polarisation angles allowed us to further beat the spindown limit by an extra factor of 1.3. This result has allowed us to constrain the amount of the pulsar spindown power budget released by gravitational radiation to be less than about 2%.

Results from a search for the Vela pulsar in VSR2 data have been obtained for both uniform and restricted priors on its orientation. These results beat the spin-down limit for Vela and have been published [506], along with results from the other two targeted pipelines described below.

In 2012 we will complete the search in full S6 and VSR2/VSR4 data sets for all accessible known pulsars with available precise timing.

We have started a programme to search for known pulsars not only at the nominal $2f_{\rm rot}$ frequency, but also at $f_{\rm rot}$ (using the model described in [505]), and potentially in the vicinity of $(4/3)f_{\rm rot}$ for *r*-modes, as part of a broader effort to widen the parameter space in targeted searches. An upgrade to the current MCMC parameter estimation code has been implemented that makes use of the nested sampling algorithm [504]. In addition to providing marginal posterior probability distributions for signal parameters this will provide a signal vs. noise odds ratio that can be used as a detection statistic. The algorithm will also be more robust when applied to wider band searches. A methods publication describing and characterising the nested sampling algorithm, the odds ratio and its use for deriving limits simultaneously from $f_{\rm rot}$ and $2f_{\rm rot}$ searches is planned for the coming year.

5.1.2 Narrowband Searches for Known Pulsars

UPDATED

We know of several physical mechanisms that could cause the frequency of a neutron star's emitted gravitational waves to differ slightly from the typically assumed $2f_{\rm rot}$, with $f_{\rm rot}$ being the rotation frequency. Using estimates of the maximum frequency difference the $\mathcal{F}$-statistic search method has been used to searched a small frequency and frequency derivative parameter space for the Crab pulsar with nine months of data from the S5 run [453]. This search has also been performed on 28 days of S6 and VSR2 data.

The nested sampling parameter estimation code developed for the targeted known pulsar search can also be extended to search narrow frequency bands. We will compare both the $\mathcal{F}$-statistic search and the nested sampling approach to the searches. The $\mathcal{F}$-statistic search's template coverage will provide confidence that the entire parameter space is covered, whereas the nested sampling method naturally provides signal parameter estimates and upper limits. Using estimates of the frequency parameter space required we will perform narrowband searches for the current selection of known pulsars in S6/VSR2/3/4 data. This will allow some previously poorly timed pulsars to be including in the analysis.

In the longer term, these narrowband search method will be explored as a follow-up step to semi-coherent all-sky searches.

5.1.3 Signal Fourier 5 components method

UPDATED

The signal Fourier 5 components targeted search starts from the short FFT database (SFDB) which contain data after a time-domain cleaning which allows to efficiently remove short time domain disturbances[460]. Schematically, from the SFDB a small (fraction of Hertz) band is extracted and transformed in to the time domain, keeping the original sampling rate. Doppler, spin-down and Einstein effects are then corrected by means of a resampling procedure which, for a given search direction, makes the Doppler correction effective for all the frequencies and under-samples the data at a much lower rate (e.g. 1Hz). After these corrections, a further cleaning step is applied in order to remove outliers appearing in the small frequency band considered. At this point the data 5-vector is computed as well as the matched filters with the signal templates (1 matched filter if polarization parameters are known, 2 matched filters if they are unknown). The outputs of the matched filters are used to build a detection statistics. See [461] for more details. The corresponding p-value is then computed in order to establish how much the data are compatible with pure noise. If no significative evidence of a signal is obtained, an upper limit to the signal amplitude is determined. This method has been applied, together with the other two coherent pipelines, for the search of CW signals from the Vela pulsar in the VSR2 data [506] beating the spin-down limit by a factor of about 1.6.

Recently the method has been extended to allow a coherent analysis of different datasets, coming from the same or different detectors [462]. Moreover, a new method for computing upper limits in the frequentist framework has been developed which overcomes some problems of the standard frequentist methods [463]. We are currently analyzing VSR4/S6 data and have obtained preliminary results for Vela (VSR4) and Crab (VSR2/VSR4/S6, both separate and joint analysis). The review of the network extension of the 5-vector method is going to start. There are three more low frequency pulsars for which the spin-down limit could be approached (even if probably not beaten, at least for the standard value of the momentum of inertia). For one of these, J0205+6449, we have obtained from astronomers an updated ephemeris covering the VSR4 time span, and the analysis will be done soon. For the other two it is possible that astronomers will provide ephemerides covering VSR4 too.

We plan to have by the end of the year a mature paper draft describing Vela, Crab and one or more other low frequency pulsars. Then we plan to extend the analysis method to 1*f frequency and apply it to the Crab search. We are also working on a detailed statistical characterization of the 5-vector method and a full comparison with other coherent pipelines which will be described in a methodological paper to be ready by the first trimester of the coming year.

5.1.4 Narrow-band search with the signal Fourier 5 components method

UPDATED

Due to the use of a resampling procedure for Doppler correction, the 5-vector method described in the previous section can be also used for narrow-band searches. We have started to work on the development of a full method for such kind of search, which assumes a known source direction and a possible small mismatch between two times the EM frequency and the GW frequency. Important points will be the tests on software and hardware injections and the setting of a procedure for computing upper limits. We plan to have a fully tested and reviewed method by the second trimester of next year.

5.1.5 Time domain matched-filter method using the $\mathcal{F}$ and G statistics

UPDATED

Assuming that other parameters of the gravitational wave signal, *i.e.*, the amplitude, the phase, polarization and inclination angles are unknown, matched filtering is realized by computing the $\mathcal{F}$-statistic [492]. If the computed value of the $\mathcal{F}$-statistic is not significant, we derive an upper limit on the gravitational wave signal. From current observations of the Vela nebula the polarization and inclination angles can be estimated to a very good accuracy [493]. We use this knowledge to improve our search. This required derivation of a new optimum statistic called the G-statistic. In our analysis we take into account non-Gaussianity and non-stationarity of the noise.

We can apply these methods to target various interesting known pulsars. In particular they have been applied to the analysis of VSR2 data for the Vela pulsar, for which the spindown limit was beaten in VSR2. For this analysis we are using updated ephemeris data provided by radio-astronomers (Hobart & HartRAO) Another obvious target is the Crab pulsar, for which about 2.5 months of data would allow to go below the current upper limit at $2f_{\rm rot}$, at the Virgo design sensitivity. The search for emission at $f_{\rm rot}$ will be also performed.

The status of the search for Vela in VSR2 data was described at the 2010 GWDAW meeting [469]. Final results for VSR2 data beat the spin-down limit for Vela and have been published [506], along with results from the other two targeted pipelines described below.

We are currently applying our pipeline to search for Vela and other known pulsars in VSR2/VSR4/S6 data sets. In particular we are searching for Vela in VSR4 data and for Crab in VSR2/VSR4/S6 data and we plan to search for pulsars J0205+6449 (30.45 Hz), J1833-1034 (32.33 Hz), J1813-1749 (44.74 Hz) in VSR4 data. We will complete this search in 2012 providing sufficiently accurate ephemeris is available.

We have also started to search for Crab pulsar at once the spin frequency assuming the model described in [505] and we plan a similar search for J1813 -1749 (44.73). We expect to finish this search in 2012.

5.2 Non-pulsing non-accreting neutron stars and favorable directions

UPDATED

This type includes point sources, such as central compact objects in supernova remnants, as well as highly localized regions, such as the innermost parsec of the galactic center. Photon astronomy can provide sky positions for these objects, but since no pulses are observed, the external measurements cannot provide us with frequencies or spindown parameters. Since we must search over many frequencies and spindown parameters, sky-survey positional errors (such as from ROSAT) are too large: we require arcminute accuracy or better to keep down the computational cost of a long integration time and thus a deep search. Although no f and $\dot{f}$ are observed for these objects, we can still define an indirect limit we need to beat. If we assume an object has spun down significantly from its original frequency and that this spindown has been dominated by gravitational wave emission, we can rewrite Eq. (1) as

$$h_{\rm IL} = 2.3 \times 10^{-24} \left(\frac{1\,{\rm kpc}}{D}\right) \left(\frac{10^3\,{\rm yr}}{\tau_{\rm sd}}\right)^{1/2} \left(\frac{I}{10^{38}\,{\rm kg\,m^2}}\right)^{1/2} \tag{2}$$

in terms of the age a, which can be inferred in various ways.

Initial LIGO can beat this upper limit for several objects of this type, including the youngest – the object in supernova remnant Cas A ($\tau_{\rm sd} = 326\,{\rm yr}$, $h_{\rm IL} = 1.2 \times 10^{-24}$) – and the closest, Vela Junior ($D > 200\,{\rm pc}$, though the precise value is uncertain). Several more objects have indirect limits attainable with advanced LIGO, including the remnant of Supernova 1987A ($h_{\rm IL} = 3.2 \times 10^{-25}$). However this putative neutron star is only 25 years old and would require a search over a large parameter space including six or seven frequency derivatives. Searches over small sky areas (single “pixels”) are computationally the same as searches for known point sources, and for several of these (such as the galactic center) even initial LIGO could beat indirect limits. We recently completed a search for Cassiopeia A [494] and have begun searching for other interesting locations on the sky, such as star-forming regions and globular clusters, as described below. We are collaborating with several photon astronomers on constructing more complete target lists of point sources and small areas, both for initial and advanced LIGO (see section 5.2.7).

The first search for a source with no timing (Cas A) used the $\mathcal{F}$-statistic code with a single integration of $\mathcal{O}(10)$ d. Our estimate of computational cost and sensitivity [495] shows that this is enough to start beating indirect upper limits on some sources. For young sources even such a short integration time requires up to the second frequency derivative; thus metric-based methods and code for tiling parameter space in multiple dimensions are important to reduce the computational cost. In the near future we will try hierarchical searches (see other searches below) which will require algorithm and code development to adapt to the needs of this search. We are also evaluating the potential of resampling methods to reduce not only the computational cost for a given search, but also the cost's scaling with integration time. This, combined with hierarchical methods, will allow us to search a significant fraction of the S5/S6 data sets (and future sets of comparable length) rather than $\mathcal{O}(10)$ d.

A similar but deeper search was carried out for Calvera, which is an X-ray source originally detected by ROSAT and confirmed with Swift and Chandra measurements. Until fall 2010 it had no detected optical or radio counterpart and was thought to be an isolated neutron star, possibly a millisecond pulsar beaming away from us, but relatively close – O(100 pc) away.

A fully coherent search using a barycentric resampling method based on interpolation in the time domain was carried out for Calvera over the 90-360 Hz band [497], assuming an age of O(10^6) years which severely restricts the spindown range to be searched. Because the sky location was known, the search benefitted dramatically in reduced computational cost from the resampling step during preprocessing. Preliminary upper limits were obtained in summer 2010, but the subsequent observations of pulsations in X-rays [496] outside the sensitive LIGO band deterred pursuing publication. Nonetheless, the search served as a useful benchmark for directed, deep searches for old objects and as a proving ground for the barycentric resampling method.

5.2.1 Coherent directed searches

UPDATED

The coherent search for Cas A is being updated to S6 data and extended to of order ten non-pulsing candidate neutron stars in supernova remnants. As of June 2012 the list consists of the objects in remnants G15.9+0.2, G18.9-1.1, G65.7+1.2, G111.7-2.1 (Cas A), G189.1+3.0 (IC 443), G266.2-1.2 (Vela Junior; worth two searches), G330.2+1.0, G347.3-0.5, and G350.1-0.3, plus the possibly-empty remnant G1.9+0.3 which is the youngest in the galaxy and small enough to search with one sky position. The update includes the SSE2 enhancements to floating-point instructions on Intel processors, resulting in nearly a factor 3 speed-up over the standard F-statistic code according to preliminary runs. These preliminary runs also confirm that the sensitivities of these coherent searches, integrating over time spans from 5 days to 5 weeks, will beat the indirect limits for the above objects using S6 data. Production runs should begin in summer 2012, followed by post-processing in the fall, with the observational results paper review to begin in 2013.

In addition, a search based on time domain resampling [497], following the template placement method of the Cas A search [494], is being carried out for isolated stars in globular cluster NGC 6544. A pilot run over a 1-Hz band has been carried out recently and the preliminary results are being validated before proceeding to a wide-band search in summer and fall 2012. The associated software development is based on an Einstein@Home implementation of the resampling algorithm. Code development is being coordinated with the E@H team, to permit a common code base for a variety of future searches.

5.2.2 Searches for sources near the galactic center

UPDATED

The galactic center is a location where one might expect to find a large number of unknown, young neutron stars. Standard electromagnetic observations have identified only a small fraction of all pulsars thought to be present near the galactic center. The dispersion and scattering of the signal by interstellar material between potential sources and the Earth significantly reduces the depth of such observations. The current estimate of the total number of pulsars present in the galactic center (the inner $2\,\mathrm{deg} \times 0.8\,\mathrm{deg}$ of the galaxy) is 10^6 (Muno et al). Some of those objects could be promising sources of CW gravitational wave signals. Searching in the direction of the galactic center involves searching over a small sky-region but over large frequency and spindown ranges.

The entire S5 data has been scanned using the `Einstein@Home` infrastructure. This search is meant to be more sensitive over a different region of parameter space – it searches a larger range of spindowns and a narrower frequency band – and uses a larger data set.

A single sky position is used for this search, a single template pointed directly to the galactic center; the frequency band is 77-496 Hz, for which the search can beat the indirect spindown limit for an age assumed to be greater than 200 years. The data searched is from S5, using only H1 and L1 detectors. The range of spindowns is specified by the spindown age via $\tau = f/\dot{f}$, where f is the gravitational wave frequency of a neutron star. The search uses 630 11.5-hour segments semi-coherently.

Production running finished over a year ago. The analysis of the results is concluded, unfortunately resulting in no statistically significant detection. For the September LV meeting we expect to present upper limit results and for the March meeting a final draft of the observational paper. The review of this analysis has not started and it should asap.

5.2.3 Supernova 1987A using the cross-correlation technique

UPDATED

As described elsewhere, the semi-coherent excess power methods are more robust than the fully coherent searches. This is because they demand phase coherence of the signal only over the coherent integration time, which is much shorter than the total observation duration. This reduction in the minimum coherence time has the added advantage of significantly reducing the computational cost. It is possible to reduce this coherence time even further by using cross-correlations between data from multiple detectors. In the case when we correlate coincident data from two detectors, the minimum coherence time is just the light travel time between the two detectors. In the general case, we can correlate data streams collected at arbitrary times from two distinct detectors, and also from the same detector at distinct times. The details of this method, which is a generalization of methods used previously in the stochastic "radiometer" search [513, 486], can be found in [480]. The main feature of this generalization is the presence of a free parameter, the minimum coherence time required of the signal, which can be tuned depending on the desired sensitivity, robustness and computational cost.

The starting point for this search is a set of SFTs of duration $T_{\rm sft}$ covering a total observation time $T_{\rm obs}$ followed by: i) a choice of the minimum coherence time $T_{\rm coh-min}$ which is used to create pairs of SFTs, ii) a computation of the cross-correlation statistic for each pair for a given set of pulsar parameters, and iii) calculating a weighted linear combination of the various cross-correlations, with the weights chosen to maximize the sensitivity exactly as in the PowerFlux or the weighted Hough searches. Many of the existing standard CW searches can be viewed as special cases of this scheme. The standard PowerFlux search corresponds to considering only self correlations of the SFTs, a full coherent search corresponds to considering all possible SFT pairs, and the hierarchical search is an intermediate case with $T_{\rm obs} \gg T_{\rm coh-min} \gg T_{\rm sft}$. This is however a computationally inefficient way of calculating the coherent statistic, for which it is better to use the existing $\mathcal{F}$-statistic, so we expect that the cross-correlation is useful only with $T_{\rm coh-min}$ either comparable or lesser than $T_{\rm sft}$.

One object to which this semi-coherent method can be applied in a directed search is a neutron star in the supernova remnant SN1987A. [481] In searching for such a young object, searching over frequency derivatives can be prohibitive because of the need to search over higher derivatives. It turns out that the search space can be narrowed by using a physical model for the frequency evolution: $\dot{nu} = Q_1\nu^5 + Q_2\nu^n$. The first term is the usual term due to gravitational wave emission while the second term represents all other effects (ideally, for electromagnetic braking, one would expect a braking index of $n = 3$ but this is not observed in practice). With this model, and using $T_{\mathrm{coh-min}} \approx 1$ hr, it turns out that the computational cost becomes manageable.

A pipeline to perform a cross-correlation search for isolated neutron stars has been written and tested and undergone significant review. Some testing has been done with S5 data. In the coming year, the search will be applied to S5 and/or S6 data with an eye towards producing a publication within the year. Future development will involve a reorganization of the search pipeline as detailed in section 5.4.2. It is hoped that completion of this directed (semi-targeted) search will be useful in developing an all-sky search based on cross correlation.

5.2.4 Semi-targeted search using stroboscopic resampling

UPDATED

In general, the correction of the Doppler effect due to Earth motion depends on the source sky direction and frequency. Since the parameters are often unknown, a large computational effort is required to correct for any possible direction and emission frequency. A correction technique independent of the frequency is used in a pipeline based on stroboscopic resampling. The antenna proper time is accelerated or slowed down by deleting or duplicating in a timely manner single samples of the digitized signal in order to keep the reference clock synchronized with the source clock, within an accuracy given by the inverse of the sampling frequency f_s (several kilohertz) [458]. The removal (or the duplication) of the samples takes place typically each few seconds. The list of samples to be removed or duplicated (named *mask*) is thus not huge and can be easily computed by simple geometrical consideration. As detailed in [458] the mask corresponding to a given direction is provided by the times when the antenna crosses one of the equi-phase parallel planes fixed in the space, perpendicular to the wave vector and each at a distance c/f_s from the next one. Each "crossing time" is computed by the scalar product of the antenna velocity and the wave direction (in practice by a few operations each second of data).

The maximum phase error due to the non-perfect synchronization is given by $2\pi f_0/f_s$ where f_0 is the signal expected frequency and f_s is the sampling one. As a reminder, a phase error around a few tenths of rad is small enough to guarantee that almost all the signal energy is recovered around the main frequency. It is thus important to resample the data working at the Virgo data acquisition frequency (20 kHz) in order to use the method effectively up to several hundred Hz. This frequency independence makes the method very appealing for sources where the direction is well fixed, but the emission frequency is uncertain (semi-targeted search). The pulsar spindown is taken into account by properly shifting the equi-phase target plane during the acquisition time. As a consequence, a single mask requires specifying both the direction and the spindown value of the source. The Einstein delay and the Shapiro effect can be also easily computed without any significant additional computational cost.

We have developed an analysis pipeline and are applying it to VSR2 data. The Earth ephemeris is computed by using the Roma 1 group PSS routine. In just a few minutes the ephemeris and Einstein delay data are computed and stored for the entire VSR2 period with a sampling time of a few seconds (enough to approximate Earth motion with enough accuracy).

Starting from the ephemeris, another routine computes the masks for a set of directions and spindown values. The computation time was tested not to exceed a few 10^{-8} of the integration time, per each mask (i.e., per each direction and spindown).

In parallel the antenna data, already cleaned from non-stationary events by usual PSS techniques, is pass-band filtered around the signal expected frequency. The bandwidth must be large enough to contain all the sidebands produced by Doppler and spindown. Several tens of operations per sample are necessary in the data filtering. The final cost will be evaluated after implementation, but we expect to work with a computing time around 10^{-4} – 10^{-3} of the integration time.

During the signal decimation, different masks can be applied in parallel to the filter output (at signal sampling frequency). Very light buffers are produced at the downsampling frequency (inverse of the filter band) for FFT spectral analysis. Usual statistical analysis for peak identification will be adopted in the final step of the pipeline.

Since the Doppler correction (computation of masks and their parallel application in decimation of the filtered data) is negligible, the optimization strategy for the semi-targeted search is straightforward. We need only choose the width of the pass-band filter ("slice"). Indeed this choice determines the downsampling factor, thus the length of the buffers governing the FFT computation time. Finally we must multiply the time required for the previous operation (filtering and parallel FFTs) times the number of slices required to cover all of the interesting detection band. The optimization of the pass-band filter width, obtained minimizing the total computation time, depends on the analysis to be performed. Many tests have been performed on simulated data assuming different antenna orbits, spindown values, sampling frequencies and source frequencies. In all cases, the expected phase-locking and peak reconstruction accuracy has been found. Similar tests have been performed injecting signals in the VSR1 data. All the results are described in Torre's graduation thesis [482], or (more in summary) in [483]. The resampling of the data requires less than 10^{-5} of the investigated time (for a single direction and spindown on a few Hz band), that is negligible with respect to the time required to read the HF stream (of the order of 10^{-4}). A method to read the data and apply the resampling technique directly to the down-sampled data (making negligible the computing time for reading data) is in progress.

A methods paper was recently published in Phys. Rev. D [499].

The amplitude modulation will be taken into account using a matched filtering in the frequency domain, in a way similar to the one developed by the Rome group. We are currently implementing a full pipeline for this purpose, and testing it on hardware injections in VSR2 data.

After the validation of the pipeline we plan to apply it to the observation of the supernova remnant RX J0852.0-4622. There is a Ph. D. student dedicated to this (Oriella Torre), which should discuss her thesis at the end of 2012. We expect to be able to finalize the main steps of the activity (not including internal reviews) in time for this.

5.2.5 Semi-targeted searches for "transient CW signals"

UPDATED

In the last year the transient gravitational waves search code [500] has been tested to recover signals with timescales in the order of $10^2 - 10^4$ s that can be associated with neutron star glitches and X-ray bursts. The signals were injected in gaussian simulated noise at the ET level. Their timescales were estimated assuming an energy dissipation model that proposes the existence of a viscous boundary layer at the crust-core interface by [509], that rules the timescale of the signal. Given that the r-mode's frequency is known with a precision of 20%, searches are carried out in a frequency band defined by this uncertainty. This means that for young pulsars like the Vela Pulsar ($f_{mode} \sim 15$ Hz) a $f_{band} \sim 3$ Hz was used, while for faster spinning stars like 4U 1608$-$522 ($f_{mode} \sim 825$ Hz) a $f_{band} \sim 165$ Hz was used. In this work, two different kind of sources were considered:

- **young glitching pulsars** (like the Vela Pulsar and PSR J0537-6910) with viscosity damping timescales $\sim 10^2$ s, and

- **millisecond pulsars** from which two sub-classes of sources can be distinguished: *glitching millisecond pulsars* (like PSR J1824 -2452 and HETE J1900.1 -2455) with timescales $\sim 10^4$, and *Type I Bursts* from accreting millisecond pulsars (like 4U 1608 -522) for which timescales are $\sim 10^4$ s.

The injected signals were constructed, considering observed parameters of these pulsars ($f_{\rm spin}$, distance, $\Delta\nu/\nu$ during the glitch) and assuming the same neutron star EoS parameters as in [509].

In the case of pulsar glitches an assumption that the E_{mode} = E_{glitch} was done, and in a similar way, for the Type 1 Bursts E_{modes} = E_{burst} was assumed. It was found out that if the Levin and Ushomirsky dissipation model [509] is considered, the detectability of gravitational waves associated with glitches in young pulsars is not plausible with 3rd generation gravitational waves detectors. On the other hand, millisecond pulsars that glitch are a more promising transient sources for the future gravitational waves detectors using this technique. In this context a study of signal recovery based on signal-to-noise ratios based on this techinique was done. Signals with SNR $\sim$ 10 ($h_0 \sim 10^{-26}$ and timescales $\sim 10^4$ s) where tested and recovered.

Motivated by these results, a relation was set between the energy of the glitch and the energy of the gravitational wave, the proportionality of which is modulated by the timescale of the signal. With this in mind, the amount of energy that is transferred from the glitch to the gravitational wave was parameterised. This parameter (β) is proportional to the duration of the signal, and it was found that the signal duration needed in order to recover a signal for young pulsars is out of the scope of a transient signal search and is more likely to be tested with a CW search.

In the coming year we plan to assess to what extent gravitational wave observations could place constraints on the stellar parameters, including the strength of dissipative processes in the star.

5.2.6 Directed search using $\mathcal{F}$-statistic

UPDATED

Another directed-search pipeline is under development, building upon already implemented all-sky search code that employs the $\mathcal{F}$-statistic method (Sect. 5.3.8). Novel usage of graphical processor unit (GPU) solutions, framework and dedicated libraries promise that a search for GWs from astrophysically motivated sources over a large frequency and frequency derivative will dramatically reduce computational costs, as well as allow for much greater flexibility in comparison to what is possible in all-sky searches. Additionally, the pipeline will serve as a testing ground for new theoretical methods of parameter space optimization and hardware/software implementation techniques.

5.2.7 Other targets

UPDATED

We are collaborating with several astronomers on constructing lists of interesting targets for further directed searches, i.e., targets where LIGO and Virgo can beat the indirect limits on gravitational-wave emission. Apart from Cas A there are of order ten candidate non-pulsing neutron stars with indirect limits on h_0 beatable with S5 or S6/VSR2 coherent and semi-coherent searches. There are also several small, young supernova remnants (such as SN 1987A) and pulsar wind nebulae where the neutron star is not seen. Other small sky regions (further discussed below) also can be targets of this type of search. Examples include regions of massive star formation such as the galactic center and massive young clusters containing magnetars such as Westerlund 1. Globular clusters are not likely to contain young neutron stars, but some old neutron stars are known to possess planets and debris disks. Frequent perturbations in the dense environment of a cluster core could trigger bombardment episodes, and a star with an impact-related deformation counts as rejuvenated for purposes of a gravitational-wave search. Considering interaction timescales, most of the best targets are nearby, dense clusters such as NGC 6544. However 47 Tuc's interaction timescale is short enough to make it an attractive target even though it is further away; and furthermore the first GLAST/Fermi results show considerable high-energy diffuse emission which is likely related to neutron star activity in the relatively recent past.

It is useful to maintain ties because X-ray and gamma-ray astronomers are beginning to find many point source neutron star candidates, and thus it is likely that the interesting target list for LIGO will expand substantially even before advanced LIGO. Examples include Fermi point sources and HESS TeV gamma-ray sources that are followed up with Chandra and XMM-Newton X-ray observations, yielding pulsar wind nebulae and sometimes the neutron stars themselves.

A paper describing an interesting list of targets in in preparation and will be submitted for publication this year. As the advanced detector era approaches, these studies will be extended.

5.3 All-sky searches for isolated neutron stars

UPDATED

These are objects which have not been previously identified at all, and thus we must search over various possible sky positions, frequencies, and frequency derivatives. They are believed to constitute the overwhelming majority of neutron stars in the Galaxy, but most of them are not believed to be good sources for LIGO or Virgo. It has been argued, based on the observed supernova rate and inferred population of neutron stars in the Galaxy, that the indirect limit on the strongest signal from this population is no more than

$$h_{\rm IL} = 4 \times 10^{-24} \left(\frac{30\,{\rm yr}}{\tau} \right)^{1/2}, \tag{3}$$

where τ is the mean time between supernovae in the Galaxy. The latest and most detailed derivation of this upper limit is given in [438]. Note, however, that a more recent simulation analysis finds significantly lower expectations that depend on the assumed source frequency and ellipticity [479].

It is useful here to briefly explain the computational challenge that must be overcome for these searches. The parameter space for blind searches for weak signals from unknown isolated neutron stars is very large. The number of templates N_p, required to cover the entire sky, a large frequency band, and a range of spin-down parameters and using data which spans a duration T, is roughly proportional to T^5. The computational cost therefore scales as $\sim T^6$. In fact, for any reasonable volume of parameter space, N_p becomes so large that using our existing coherent integration code and using the full computational power of our largest computational platform `Einstein@Home` running for a few months, it is not possible to consider values of T larger than a few days. Even if we were able to speed up our coherent demodulation algorithm by, say, a factor of 100, T would increase only by a factor of $100^{1/6} \approx 2.2$. On the other hand, we require T to be a few months to have a realistic chance of detection. The situation is, naturally, even more demanding for neutron stars in binary systems.

For this reason, different methods using a combination of coherent and semi-coherent techniques have been designed. The basic idea is to break up T into smaller segments which are analysed coherently, and to stitch together these segments using a semi-coherent technique. Outlier candidates are then followed up. The sophistication and automation of the follow-ups have improved in recent analyses and offer the promise of lowering detection thresholds significantly in some search pipelines.

Five all-sky pipelines are currently in use for carrying out all-sky searches: 1) a quick-look semi-coherent method known as PowerFlux using incoherent sums of strain spectral power from many 30-minute "Short Fourier Transforms" (SFTs), 2) a multi-interferometer Hough transform method starting from 30-minute SFTs, 3) a hierarchical algorithm using `Einstein@Home`, based on phase-preserving demodulation over many ∼day long intervals, followed by a semi-coherent step (see below), 4) a hierarchical method, developed in Virgo, based on the alternation of coherent and incoherent steps; and 5) an $\mathcal{F}$-statistic-based search also developed on Virgo data. It is likely that the use of one or more of these pipelines will be discontinued in the next 1-2 years, following the systematic comparisons using standardized simulated data sets, as described above.

In addition, two new methods are under development that offer greater robustness against uncertainty in the source model: 1) a "loosely coherent" method [474] using the PowerFlux infrastructure; and 2) a cross-correlation method [480] which provides a smooth bridge between semi-coherent and coherent methods, with the possibility of parameter tuning to improve sensitivity over semi-coherent methods while maintaining robustness.

5.3.1 PowerFlux method

UPDATED

For a monochromatic, constant-amplitude sinusoidal wave in Gaussian noise, summing the strain power from M short Fourier transforms improves the sensitivity (strain value for a fixed signal-to-noise ratio) by a factor $M^{1/4}$. In contrast, a coherent search based on a single Fourier transform over the entire M intervals gives a sensitivity that improves like $M^{1/2}$. One strong advantage of the semi-coherent methods is their robustness against unknown source phase disturbances, such as from frequency glitches due to starquakes.

The searches we must perform are more complicated than simple power sums. Frequency and amplitude modulations that depend on source direction are relatively large. The frequency modulations arise from the motion of the detectors with respect to the source, with components due to the Earth's rotation ($v/c \sim 10^{-6}$) and to its orbital motion ($v/c \sim 10^{-4}$). The amplitude modulation arises from the changing orientation of the interferometer arms with respect to the source direction as the Earth rotates. As a result, an all-sky search requires a set of finely spaced templates on the sky with varying corrections for these modulations. In general, the number of templates required for a given coverage efficiency scales like the square of the source frequency.

Within the last few years, we have explored three related methods for incoherent strain power summing: StackSlide [447], Hough [470, 437], and PowerFlux [471]. These methods take different approaches in summing strain power and in their statistical methods for setting limits, but their performances are quite similar. Because PowerFlux has been found to yield somewhat better efficiency than the other two methods for most frequency bands, it has been chosen as the quick-look semi-coherent algorithm used on data from the S5 and S6 science runs. An article based on applying all three methods to the S4 data was published in early 2008 [472] in Physical Review D.

In short, PowerFlux computes from many thousands of 30-minute SFTs an average strain power corrected for antenna pattern and with weighting based on detector noise and antenna pattern. Its signal estimator is direct excess strain power for an assumed source direction and polarization, using one circular polarization projection and four linear polarization projections. PowerFlux, like Hough or StackSlide, corrects explicitly for Doppler modulations of apparent source frequency due to the Earth's rotation and its orbital motion around the Solar System Barycenter. Source frequencies are searched with ∼0.56 mHz spacing and limits presented separately for 0.25 Hz bands.

A short publication based on an improved PowerFlux search over the first 8 months of S5 data was published in Physical Review Letters in early 2009 [473]. These results cover the frequency range 50-1000 Hz and negative spindown as large as 5×10^{-9} Hz/s. The present PowerFlux program permits deeper searches for coincident candidates among multiple interferometers than in S4 and applies tighter coincidence requirements between candidates in the H1 and L1 interferometers, which allows setting lower SNR thresholds for followup of candidates.

A series of major improvements to computational efficiency were made to facilitate a PowerFlux run over the full S5 data while keeping memory requirements within the bounds of LIGO processors and keeping total computational time for the first-pass search within a half-year. A two-interferometer power sum was used, together with coincidence between H1 and L1, to push deeper into the noise than before.

In parallel, a "loosely coherent" follow-up was added directly to PowerFlux, one that allows for slow drifts or modulations in phase from one SFT epoch to the next [474]. It offers the possibility of a "controlled zoom" of interesting candidates and reduces the chances of missing a true signal because it doesn't quite fit the template for a long coherent search. Upper limits for the 50-800 Hz band based on a search of the full 2-year S5 data were produced, and outliers followed up with the new loose coherence step. These results were published in 2012 [476].

Preliminary S6 results have been obtained, with follow-up of outliers in progress. A large number of spectral artifacts seen in S6 data (associated with the output mode cleaner) make this follow-up more laborious than expected. A novel "universal" statistic [477] has been developed to cope with the large number of non-Gaussian S6 bands in both H1 and L1 data. Other recent improvements included a coherent IFO-sum option for each SFT to gain further SNR [478]. Publication of final S6 results is expected in the coming year.

5.3.2 Hough transform method

UPDATED

As in the PowerFlux method, the weighted Hough transform method (used already to analyze the S4 data [472]) takes into account the detector antenna pattern functions and the non-stationarities in the noise. This algorithm allows to combine data from different interferometers, to perform a multi-interferometer search.

For the analysis of the full S5 data, many new features have been included into the Hough search code, such as dynamical selection of data depending on SFT noise floors and sky-positions, splitting of sky patches with frequency dependent size, creation of a top list of candidates, internal follow-up using the full data, and a chi-square test [484] to reduce the number of candidates and consequently increase the sensitivity of the search. Separate analyses of the first and second calendar years of S5 data have been carried out, and coincidence of outliers between years 1 and 2 has been imposed as a filter on outliers to be followed up. This has also allowed to use a lower threshold compared to previous searches for candidate selection permitting deeper searchers .

Full-S5 Hough preliminary results have been presented to the collaboration in spring, including all sky upper-limits. A publication is under preparation and it will be submitted for publication in the coming year.

5.3.3 `Einstein@Home` Searches

UPDATED

Overview: `Einstein@Home` is a public distributed-computing project in which users contribute the spare CPU cycles on their computers for gravitational wave searches. Thus far, it has been used in the blind wide parameter space searches for CW sources. It was launched in February 2005, and since then it has built up a user-base of over 200 000 active users; it currently delivers more than $\sim$ 200 Tflops of continuous computing power. This is by far the largest computational platform available to the LSC and it is also one of the largest public distributed projects of its kind in the world. The project is targeted towards making a detection and not on setting precise upper limits. So far it has analysed LIGO data from S3, S4 and S5.

The analyses on S3 and S4 have been completed, a report and final results from the S3 search were posted on the `Einstein@Home` web page, and a paper on the S4 results has been published in PRD [489]. A similar search was run on S5 data (S5R1), and the paper presenting these results published in PRD [490].

S5 R3/R5/R6 postprocessing: The second S5 analysis was based on a greatly improved search pipeline, which eliminates the main problem limiting the sensitivity in previous `Einstein@Home` searches: this search was based on a Hierarchical search pipeline, consisting of individual $\mathcal{F}$-statistic searches on $N_{\text{stack}} = 84$ data "segments" spanning no more than $T_{\text{stack}} = 25$ h each. Each of these segments contains at least 40 h of data from H1 and L1 (the multi-IFO coherent analysis is another significant improvement). The results from these $\mathcal{F}$-statistic stacks are then combined in a second stage using the Hough algorithm. As both of these steps are performed on a participating host computer *before* sending back the results, the optimal threshold on the $\mathcal{F}$-statistic stacks can be used, avoiding the limiting sensitivity bottleneck and are expected to substantially improving sensitivity with respect to the previous search method. After an initial shorter "test" run ("S5R2") with this pipeline, lasting for about 3 months, a further improved setup was launched as the 3rd `Einstein@Home` run on S5 data (codename "S5R3"), designed to run for about a year. The S5R3 run analysed only data from roughly the first year of S5. A follow-on `Einstein@Home` run (S5R5) was launched in Jan 2009, covering a frequency range up to 1kHz. S5R5 uses a mostly identical pipeline to the previous (S5R3) run, but include 121 new segments of data from the second half of S5. The search setup also takes account of the speedup of the science application by nearly a factor of 2, and an increase of more than 30% in participating hosts. S5R5 covered the frequency range 50-1000 Hz, with the follow-up S5R6 run covering the 1000-1190 Hz band for the same data segments. These run have finished as well as the post-processing and follow-up. The observational paper is complete and is expected to be posted on the arxiv by July.

S5GC1 search: A significant improvement to the hierarchical search comes from exploiting global correlations in source parameter space [491]. An engineering run (S5GCE) to test this improvement was completed in spring 2010, and a new production run (S5GC1) over the full S5 data has recently completed. Post-processing is stalled and it is not clear what is the most scientifically meaningful way to use this data.

S6 Bucket search: A production run over the most sensitive S6 data (in the "bucket") begun in 2011, where the relatively low frequencies (50-450 Hz) permit searching with a longer coherence time (90 segments of 60 hours each) and up to spindowns corresponding to an age of 600 years. The run completed, and a similar run was launched in 2012 which returns candidates ordered according to a different statistic from used in the first bucket search. In particular, the results are ranked according to a "line veto" statistic that, broadly speaking, decreases the significance of candidates with signal-inconsistent average multi versus single-IFO F-stat values (see 5.3.5). This run will end in November 2012. Of interest is going to be the comparison between the candidates of the current and previous bucket run. We expect the latter to be more sensitive. We expect the systematic post processing to begin in 2013.

Data selection and run set-up procedures: The best exploitation of the limited computing resources for a given parameter space is an optimization problem that depends on the noise level of the data and on their gaps relative to all the usable detectors. Up to now each `Einstein@Home` run has required an ad hoc iterative study of the set-up parameters. The team is trying to quantify through figures of merit the relevant choice parameters and to set up automatic procedures to define run parameters. Part of the data selection and preparation procedures also involves characterizing the effects of the Rome time-domain cleaning on LIGO data and making it possible for this cleaning to be incorporated in our automatic procedures. This is part of the effort.

Speed-up of the F statistic search: Incorporate the resampling-based code developed by Chris Messenger in the `Einstein@Home` hierarchical pipeline. Progress has been made in 2011-2012 on this. We foresee using the resampling technique in the next E@H run.

Sliding coherence scheme We're studying a novel hierarchical search technique for all-sky surveys for continuous gravitational-wave sources. The present work proposes to break the data into subsegments shorter than the desired maximum coherence time span (size of the coherence window). Then matched-filter outputs from the different subsegments are efficiently combined by sliding the coherence window in time: Subsegments whose timestamps are closer than coherence window size are combined coherently, otherwise incoherently. Compared to the standard scheme at the same coherence time baseline, data sets can be longer by about 50-100

Signal-based veto procedures: Based on the final results of ongoing post processing efforts, signal-based vetoes will be incorporated in the hierarchical `Einstein@Home` pipeline allowing to discard spurious disturbances from the "top list" of returned candidates hence ultimately improving the sensitivity of the search. As explained in the S6-bucket search paragraph this step has indeed been incorporated in the 2012 E@H run. Study of the impact on sensitivity is foreseen in 2012 as the results come in.

Local maxima, clustering of correlated candidates, detection tests over portions of the parameter space Based on the final results of ongoing post processing efforts, identification of correlated candidates will be studied and possibly incorporated in the hierarchical `Einstein@Home` pipeline allowing to save follow-up cycles. For the same purpose, i.e. identification of interesting regions in parameter space, we will also investigate the application of standard hypothesis testing methods, for example the Bayes ratio. No significant progress has been made on this in 2011-2012. It is not one of our highest priority items, and we'll get to it depending on manpower.

Longer coherent integration time baselines Currently we are not able to perform searches with a coherent time baseline longer than about 60 hours. The reasons are twofold: 1) the hierarchical search software cannot handle spindown orders greater than one, and 2) we do not know how to set up template grids with integration times in this range. Both problems are being studied. In 2011-2012 the GCT search code routines were modified to allow the use of 2nd order spindown to expand the population of sources that we can search for, but not to allow for significantly longer coherent observation times. This item remains on our to-do list.

Sensitivity estimates and comparisons We maintain and develop an analytical framework to estimate the sensitivity of the complex search procedures that the `Einstein@Home` performs as well as other searches, most notably the Powerflux search. Such framework successfully predicted the S5R5/R6 $h_0^{90\%}$ ULs.

Automatic follow-up procedures: Based on the final results of ongoing optimization studies for a hierarchical search (see below), automatic follow-up procedures will be implemented in the `Einstein@Home` core code in the long term, ultimately permitting improved sensitivity (cf Sec. 5.3.4).

Support and maintenance: The Einstein@Home servers and project require continual maintenance in the form of software updates, message board interaction with users, publicity, maintenance of server hardware, maintenance, repair and extension of the BOINC libraries, bug tracking and elimination, etc.

Automatization of work-unit generator for different searches: Currently much work and specialized expertise is required in order to set up a new BOINC project, or even to prepare and launch a new run in an existing project such as Einstein@Home. Some of the key steps required are a "workunit generator" that needs to be implemented (coded in C++ against the BOINC library), together with a validator and an assimilator. The science application needs to be installed on the server, together with various setup steps required on the server in order to prepare the scheduler and the database. Work has now begun on a project to make this increasingly easier and more "user-friendly", allowing users to set up new runs or even whole projects "on the fly".

GPU optimizations for E@H: An effort is underway (in collaboration with NVIDIA) to leverage the potentially large computing power gained from optimizing our E@H science codes to benefit from the massively parallel capabilities of modern graphic chips (GPUs), currently mostly aiming at NVIDIA cards using the CUDA software library.

Relation to the "Grid":

BOINC is a general computing platform that is able to leverage huge computing power from a pool of heterogeneous computing resources in a fault-tolerant and robust way. In this it achieves an important goal that is also part of various "grid" initiatives. If one can create a flexible and simple interface, similar to that of condor, say, to this powerful infrastructure, one could leverage the massive pool of LSC computing clusters or other "grid" resources in a more transparent and flexible way than is currently possible.

5.3.4 Followup-searches to confirm or veto CW signal candidates

UPDATED

Better theoretical understanding and the development of software tools is required in order to deal efficiently with the follow-up of interesting candidates from incoherent search pipelines. A methods paper on the optimization of a single-stage hierarchical search has been published. A fully coherent follow-up method has been developed based on a non-grid based approach using a Mesh Adaptive Direct Search algorithm (NOMAD). A methods paper describing this follow-up procedure and its performance is in preparation. A follow-up pipeline has been implemented and applied to candidates from the S5R5 Einstein@Home search. In the coming year the follow-up procedure will be extended including addition of higher-order spindowns. We will further investigate moving the coherent follow-up step onto the hosts participating in the Einstein@Home search. v

5.3.5 Instrumental line-veto statistics for wide-parameter searches

One of the standard methods of CW data analysis is the multi-detector $\mathcal{F}$-statistic. In a typical search, the $\mathcal{F}$-statistic is computed over a range in frequency, spin-down and sky position, and the candidates with highest $\mathcal{F}$ values are kept for further analysis. However, this detection statistic is susceptible to a class of noise artifacts, strong monochromatic lines in a single detector. Conventionally, these artifacts are removed manually in post-processing. By assuming an extended noise model - standard Gaussian noise plus single-detector lines - we can use a Bayesian odds ratio to derive a generalized detection statistic, the line veto (LV-) statistic. In the absence of lines, it behaves similarly to the multi-detector $\mathcal{F}$-statistic, but it is much more robust against line artifacts, reducing the need for manual removal in post-processing.

As explained in the S6 bucket search paragraph, this statistic has been implemented directly on the Einstein@Home clients in order to improve the sensitivity of the search. Namely, by avoiding saturation of the top-list of candidates returned by triggers from line artifacts, the detection threshold is effectively lowered. In 2012-2013 by studying the incoming results we will characterize the gained sensitivity improvement on real data.

5.3.6 Hierarchical Hough search

UPDATED

The All-Sky search, as already described in the 2011 WP [459, 460, 464, 468] for unknown neutron stars, is carried out in the Rome group with the "Frequency Hough Transform method", a transformation from the time/observed frequency plane to the source frequency/spin-down plane. A detailed method paper (following a previous one in which the basis of the method were outlined) is in preparation and will be finished by this summer. We are now concentrating on the Virgo low frequency region, from 10 to 128 Hz, where the good Virgo sensitivity gives the opportunity to exploit a band never analyzed before for All-Sky searches. The review of the method has started in Dec. 2011 and it is now well under way. We discussed with the reviewers the whole procedure, from the creation of the FFTs Data Base, where an important tool is the data cleaning procedure we use to remove short spikes in time to reduce the noise level, peak-maps creation (the algorithm that we use is different from used in earlier LIGO searches, as we select only local maxima and not all data above threshold) up to the Hough algorithms. The analysis of VSR2 and VSR4 data is now running, actually we are completing a few tests to tune all the search parameters and to decide how to parallelize the jobs submission. The study of the procedure for the noise lines identification and veto, on both VSR2 and VSR4 data, has been completed. This is a very important part of the analysis, as all noise candidates identified and removed at this stage would have produced heavy artifacts in the analysis. The effectiveness of the procedure has been verified, making use of the deep noise study carried on with the NoEMi tool (presentation at the Virgo week in February and at the recent LVC meeting in Caltech). Another part of the procedure we have recently developed, after some tests, are the "Coarse" and "Fine" Grid steps: the "Coarse" step identifies candidates and the "Fine" step (which uses a refined grid on spin-down and Sky parameters) is immediately run to store all the candidates with refined parameters. We have also completed the work to submit the analysis under the Grid environment, with scripts to submit and control the status of the jobs. The procedure runs on small frequency bands, from 2 Hz at 10 Hz up to small fractions of Hz at 128 Hz. It is also parallelized on the two Sky parameters.

Plans: we are now running the search under Grid. This step will end by July and we will begin the study of candidates, identification and removal of artifacts (even if O(100) were removed with the veto we still expect to see many). Depending on the results, we will evaluate if a paper with separate results from the two runs, at least in some sub-bands, will be appropriate. Our estimation is that this work will be our main goal up to May 2013. In parallel to this we will start the submission of jobs for the high frequency part of the spectrum. We have also begun the study of the generalization of the Hough transform procedure to include the second spin-down parameter, in view of the Advanced Detectors Era.

5.3.7 Coincidences and Followup of hierarchical Hough candidates

In parallel to this, we are now developing the procedure to do coincidences among the candidates that we will find with VSR2 and VSR4 data. Coincidences allows to strongly reduce the false alarm probability Coincidences are imposed on a parameter space of 4 parameters: frequency, spin-down and the two Sky coordinates. We have already studied the effect of the window in the parameter space on the number of expected candidates and the results have shown that it is very important to run the "Fine" grid search before doing the coincidences. Given the fact that the two runs are not parallel in time, of particolar importance is the spin-down estimation (needed for the estimation of the source frequency). The Follow-up procedure will be applied only on candidates that survive after the veto and the coincidences. We still have to design the details of the follow-up procedure. This work will be our main goal from May 2013, and we estimate to finish by the end of the year 2013. The time needed to follow-up candidates will clearly depend on how many candidates will survive and also on how much time we will need to study and fully understand the features of all the found candidates, to safely reject those due to noise.

5.3.8 $\mathcal{F}$-statistic all-sky search

UPDATED

Another analysis method currently used for all-sky searches is based on the $\mathcal{F}$-statistic [492]. It consists of a coherent stage over 2-day data segments, each covering a 1-Hz bandwidth and a follow up procedure of searching for coincidences among the candidates obtained in the coherent stage. We search the band from 100Hz to 1kHz, and we assume the minimal spindown time of 1000 yr. We use a constrained optimal grid with minimal match MM = $\sqrt{3}/2$. The constraints are such that we need to resample the data only once for each sky position and such that we can use the FFT to calculate the F-statistic. Our guiding principle in the choice of a segment to analyze will be the quality of the data. The data for analysis is narrow-banded and cleaned using the procedures described in section 5.1.5. We set a threshold of 40 for twice the value of the $\mathcal{F}$-statistic above which we shall register the parameters of the candidates. Finally we search for coincidences among the candidates from different segments. We collaborate on the coincidence analysis with the LSC Einstein@Home team. We also plan to do a search using the above method in the subspace of the parameter space defined by the spin down parameter equal to 0. For this subspace we are analyzing 25000 2-day 1Hz band sequences.

VSR1 production run is complete. 20419 narrowband data segments were coherently searched with the F-statistic and 4.21×10^{10} candidates were obtained. We have applied a vetoing procedure to the candidates. Firstly we have identified periodic interferences in the data, and then we have applied three vetos to the candidates. Firsly we removed candidates in a narrow band around the identified lines, secondly we applied stationary line veto known from the Einstein@Home searches, and finally we removed candidates close to the poles in equatorial coordinates. As a result 3.19×10^{10} candidates remained. We have preliminary imposed upper limits on amplitude of gravitational wave for 1-Hz bands analyzed assuming normality of the noise. Our best upper limits reach 3.2×10^{-24}. Currently we have completed the code to search for coincidences and we are now testing it with software injections. The final stage of our analysis will be determination of sensitivity of our search through software injections in the bands analyzed.

A paper describing the all-sky search is expected to be submitted for publication in the coming year. In the longer term the search pipeline will be applied to the full VSR2 and VSR4 data, with improvements based on the global correlations code used in `Einstein@Home`.

5.3.9 Loosely coherent search

UPDATED

A new method called "loose coherence" is based on the notion of allowing slow drifts or modulations in phase from one SFT to the next, as described above for following up PowerFlux outliers. But, in principle, the method could be applied from scratch in a dedicated pipeline to identify those outliers. A stand-alone program is in development to permit "blob" searches for narrow regions in frequency, frequency derivative and sky location. A test implementation was completed demonstrating expected gain computational efficiency [475]. Further development is underway to develop the code into a practical search tool. It is not yet clear whether or not this approach can be applied to a full-sky search.

5.3.10 Cross-correlation search

UPDATED

The cross-correlation method has been described previously. The plan for S5 is to use it in a directed search but it could in principle also be used for an all-sky search complementing the existing semi-coherent searches. The current plan is to use this technique for all-sky and binary searches only in S6.

5.4 Accreting and unknown binary neutron stars

UPDATED

For this class of source the gravitational radiation is thought to be powered by ongoing or previous accretion onto the neutron star. In this scenario, first proposed by [450], the neutron star achieves an equilibrium state whereby the angular momentum fed to it through accretion is balanced with the angular momentum radiated away through gravitational waves. This argument and its history is summarized in [438]. The resulting indirect limit can be put in terms of X-ray flux F_x and spin frequency $f_{\rm rot}$ as

$$h_{\rm IL} = 5 \times 10^{-27} \left(\frac{300\,{\rm Hz}}{f_{\rm rot}}\right)^{1/2} \left(\frac{F_x}{10^{-8}\,{\rm erg\,cm^{-2}\,s^{-1}}}\right)^{1/2}. \quad (4)$$

At present we divide the known accreting neutron stars into two groups: the low-mass X-ray binaries (LMXBs) and the accreting millisecond X-ray pulsars (AMXPs). Sources from both groups consist of a neutron star in orbit around a lower mass companion object from which it is accreting matter. From a data analysis perspective the key difference is that for the majority of the $\sim$85 known LMXBs the spin frequency of the neutron star is unknown but thought to lie in the range $\sim$200 Hz – 1 kHz and for the 7 known AMXPs the spin frequency (equal to the pulsar frequency) is known to high accuracy. This difference makes searches for the LMXBs a far more challenging task that of the AMXPs. Note that there are 10 LMXBs for which type-I thermonuclear bursts are seen from which the spin frequency can be constrained to within $\sim$1 Hz.

Another important difference comes from the indirectly measured time-averaged accretion rates which are typically at, or within a factor of a few of, the Eddington limit for the LMXBs. The AMXPs exhibit accretion rates lower by a factor of 10 – 100 in comparison. This difference, according to Wagoner's arguments, makes the LMXBs likely to be stronger gravitational wave emitters than the AMXPs.

To date we have published a single coherent analysis on the accreting neutron star in the LMXB Sco X-1 using S2 data [438]. This was an exercise in wide multi-dimensional parameter space matched filtering and due to the rapid increase of search templates with observation time, the search was computationally limited to an observation time of only 6 h. Sco X-1, although the brightest X-ray source in the sky and consequently, also likely to also be the brightest continuous gravitational wave source, is typical of the LMXBs. As such it is clear that incoherent hierarchical search strategies need to be developed in order to maximise the search sensitivity, given the volume of parameter space we need to search and the computational resources. In this spirit, an incoherent search approach, based on the "radiometer" cross-correlation technique developed within the stochastic background group was applied to S4 data to set an upper-limit on radiation from Sco X-1 [513]. This result was recently updated with an S5 search, which also included a search in the directions of the galactic center and SN1987A [486]. At present there is an ongoing study into the relative merits of each of the possible search strategies available within the LVC for targetting Sco X-1. A paper comparing and contrasting the methods, including the sideband, cross-correlation, twospect and radiometer searches is underway. We estimate that results will be available within a year and publication submission estimated towards the end of 2013.

Finally, we are exploring new methods to carry out an all-sky search for unknown neutron stars in binary systems. Because the unknown orbital parameters increase the parameter space enormously, it is expected that only relatively insensitive methods using short coherence times will be feasible.

5.4.1 Sideband search for known binary systems

UPDATED

The GWs from a continuously emitting source in a binary system will be received at a ground–based detector as a frequency and amplitude modulated signal. For known binary sources such as the low–mass X–ray binaries (LMXBs) we can remove the effects of the detector motion and maximize over the unknown amplitude modulation parameters through barycentric corrections and the use of the $\mathcal{F}$-statistic. The remaining time dependent frequency modulation, due to the binary Doppler motion of the source, allows us to decompose the signal into the infinite sum of frequency modulated sidebands. Under the conditions that the observation time is $\gtrsim 3$ orbital periods and that there is negligible drift in the intrinsic spin frequency of the source (i.e $\dot{\nu} \lesssim T^{-2}$ where T is the observation time) this sum is truncated leaving $M \sim 4\pi f_{\rm gw} a \sin i/c$ frequency resolvable sidebands where $f_{\rm gw}$ is the intrinsic GW frequency and $a \sin i/c$ is the orbital semi-major axis projected along the line of sight and normalised by the speed of light. Each of the sidebands is uniformly separated from the next by $1/P$ where P is the orbital period, and any orbital eccentricity acts only to redistribute power amongst existing sidebands.

By computing the $\mathcal{F}$-statistic for a given sky position and for a long enough observation time, a signal of adequate amplitude could be extracted by incoherently summing together the $\mathcal{F}$-statistic at each sideband frequency [487, 488]. This is equivalent to convolving the detection statistic frequency series with a "comb" of unit amplitude spikes separated in frequency by the inverse of the orbital period. The incoherent summing makes this a non-optimal strategy, but one that can have greater sensitivity to GW signals than a matched–filter approach because its observation length is not computationally limited. When using this approach, the parameter space resolution (and hence the number of search templates) is significantly reduced. It should also be noted that the sensitivity of this search to GWs scales with $T^{-1/2}$, as with a coherent search (and unlike other incoherent searches), however, the sensitivity also scales as $M^{-1/4}$ (M is the number of sidebands) and hence high frequency, large orbit sources will be harder to detect with this method.

Of the LMXBs it is those of unknown spin frequency to which this search is most suited. This includes the Z and atoll sources (rather than the accreting millisecond X-ray pulsars) which have known sky position, and for some, a reasonably well known orbital period. The remaining orbital parameters, semi-major axis, time of passage through the ascending node, eccentricity etc. are generally quite poorly known. This scenario suits this search, as the sensitivity is relatively insensitive to all orbital parameters except for the orbital period.

The search code and associated pipeline are complete, and preliminary results have been obtained from S5 data. However, the expected sensitivity of this search will only become astrophysically interesting (i.e., will start challenging accretion balance upper-limits) for advanced LIGO and specifically for Sco X-1.

As written above, the method assumes constant frequency over the observation. But it can be extended to the case of changing frequency, e.g. due to fluctuating accretion rate, with semi-coherent methods. A natural choice to investigate in this context is the stack-slide method, which could use coherent integration lengths of order two weeks [447].

The code review for the sideband search is nearing completion and the associated results paper describing the exploratory S5 search for Sco X-1 is in an early draft stage. A complementary accompanying methods paper is at a mature draft stage and is expected to be submitted for publication this year. The results paper will follow this and we aim fr submission early next year.

5.4.2 Cross-correlation searches for known binary systems

UPDATED

The cross-correlation search described in section 5.2.3 can also be applied to a search for binary systems at known sky locations, such as Sco X-1. The parameter space is three-dimensional, consisting of the gravitational wave frequency and the two unknown binary orbital parameters (e.g., projected semimajor axis and binary orbital phase), so a semi-coherent cross-correlation search with a short coherence time should allow a search using a manageable number of templates. This search should allow the use of more data than in the fully-coherent short-time search done in [438], and a more sensitive search than the incoherent cross-correlation search done in [486].

We will reorganize the cross-correlation code written for isolated neutron stars, described in section 5.2.3, and apply it in a search for radiation from Sco X-1. The search will initially be performed on S6/VSR2 data, with an eye towards having the pipeline fully developed by the time advanced detectors come on line.

5.4.3 Polynomial search for unknown binary systems

UPDATED

As discussed above, searches for unknown binaries present formidable computing challenges. The orbital movement of the neutron star around the center of gravity of the binary system may induce large and rapidly changing frequency modulations of the gravitational wave. The frequency $f_{\rm ssb}$ detected in the solar system barycenter may be modeled as

$$f_{\rm ssb} = f_{\rm gw}\gamma\left(1 - \frac{\vec{v}\cdot\vec{n}}{c}\right) \tag{5}$$

with $f_{\rm gw}$ the frequency of the gravitational wave in the neutron-star rest frame, γ the Lorentz contraction factor, $\vec{v}$ the velocity of the neutron star with respect to the solar system barycenter, and $\vec{n}$ a unit vector in the direction of the source. Similarly, the change in frequency per unit time may be modeled by

$$\frac{df_{\rm ssb}}{dt} = f_{\rm gw}\gamma\left(1 - \frac{d\vec{v}}{dt}\cdot\frac{\vec{n}}{c}\right) + \frac{df_{\rm gw}}{dt}\gamma\left(1 - \frac{\vec{v}\cdot\vec{n}}{c}\right). \tag{6}$$

Assuming that the movement of the neutron star can be described adequately by Keplerian orbits, the phase of the gravitational wave depends on 6 extra parameters (e.g., the phase in the orbital, the orbital period, the mass of the accompanying star, the eccentricity, and the angles of the major and minor axes with respect to $\vec{n}$). For short orbital periods, the derivative of the detected frequency df/dt will be completely dominated by the Doppler shift. As an extreme example, for a neutron star orbiting an object with the same mass in a circular orbit with a period of 5000 s, $df_{\rm ssb}/dt$ may be as large as $0.002 \times f_{\rm gw}/s$.

In order to accommodate such large frequency shifts, a new search algorithm is being developed. An extension of the coherent search method with extra parameters to describe the orbital motion of the neutron star is not computationally feasible (for coherence times in the order of 1 h, the extra number of parameter values needed to cover all likely Keplerian orbits exceed a factor of 10^9). A hierarchical search method like the stack-slide or Hough transform methods as discussed in Ref. [447] is also not promising, since the short FFT database must have a time length below about 25 s in order to keep the strength of the gravitational wave in 1 bin. As an alternative, we propose to apply a set of filters that describe the phase of the gravitational wave as a third-order polynomial in time (and hence the frequency as a second-order polynomial in time). The presence of the gravitational wave may be detected by looking for the correlation of the data with these filters. The polynomial shape of the filters facilitates the analysis (a large reduction in filter parameters is obtained by relying on the fact that translating the polynomial filter in time or in frequency will give another polynomial filter in the same parameter set) and renders a complete scan over years of data computationally feasible. The filters should be coherent over the time that they are applied, implying that third-order derivatives of the frequency of the gravitational signal should be small. For binary systems with orbital periods of the order of 4000 s, the coherence time is limited to about 500 s for this reason. However, for such waves the frequency could spread over hundreds of frequency bins in a 500 s Fourier transform, hence the proposed set of filters should give a sizeable improvement over stack-slide or Hough-transform techniques that start from a short FFT base. Searches for binary systems with larger orbital periods may be applied with a larger coherence time.

If a correlation between a filter and the data exceed a threshold and constitutes a hit, then for the hit the frequency is known as a function of time. Therefore, hits between data stretches can be correlated easily. We are currently developing this analysis strategy and the algorithms. Analysis of the Virgo and Ligo data with this set of filters could set an upper limit on the existence of gravitational waves within a parameter range that is not currently covered by other analysis techniques, i.e., waves with frequency derivatives df/dt up to 2 mHz/s and d^2f/dt^2 up to 10^{-6} Hz/s^2.

For this search, the code has been implemented and has been tested on simulated data with white noise. The results have been published in the thesis of S. van der Putten[510]. The code has been adapted to be able to deal with both Ligo's (MakeFakeData) and Virgo's (SIESTA) codes for simulated data, and first tests have been done to test the merging of simulated data with real data and to read in and process real data. This year, a methods paper should be published (based on simulated data) and the software to analyze real data should be validated.

5.4.4 TwoSpect search for unknown binary systems

UPDATED

The TwoSpect search is a hierarchical method under development for detecting unknown continuous wave sources from binary systems. The goal of the TwoSpect search is to probe regions of the large parameter space of pulsars in binary systems without exhausting the existing computational resources available. It seems unlikely that the search will have the sensitivity to make a detection in S5 or S6/VSR2 data, but since accreting neutron stars in binary systems are the best candidates to have large ellipticities, carrying out a search is prudent.

The TwoSpect method relies on computing two successive power spectra of the calibrated strain data channel, hence the name TwoSpect. First, we take a power spectrum of the time series data, where the coherence time for the first power spectrum depends on the region of parameter space we wish to cover. For shorter-period binary systems, we use a shorter coherence time for each SFT. We make these choices to ensure the signal remains in one bin during most of each SFT interval. We then demodulate the SFTs based on the sky location, correcting for the Earth's daily and annual motions. The SFTs are noise- and antenna-pattern-weighted in the same manner as for the PowerFlux algorithm. The initial power spectra are mean-subtracted within search bands to ensure that the powers computed in the second-stage spectra are distributed as a χ^2 distribution with two degrees of freedom. The second spectra are taken over a long observation time, e.g., 1 year, for each bin in the first set of spectra. The resulting frequency- by-frequency plot is matched against templates which are either rough approximations of a CW signal from a binary system (less computations required) or a more detailed approximation (more computations required). This two-stage pipeline acts as a filter to find the best candidates for a deeper search. We also use a spectrum folding algorithm known as Incoherent Harmonic Summing (IHS) developed by the radio pulsar community. This algorithm can provide a threshold filter for deciding whether or not to carry out a template calculation for a putative set of source parameters.

The first production run on S6 data began in early spring 2012 and is expected to run for several months on the LIGO computing clusters. Simultaneously, a detailed review of the computer code and associated scripts will begin in summer 2012. The computer code implements the algorithm described in the published article [501].

In parallel, a study will be carried out in the coming year of optimizing the TwoSpect method for directed searches for known LMXB's and unknown binaries in globular clusters, for which elimination of the IHS step should be feasible and should improve sensitivity.

5.5 Search for Non-Sinusoidal Periodic Waves

UPDATED

Our searches for continuous waves focus mainly on waveforms that are nearly sinusoidal, with smooth modulations in frequency and amplitude. But in the the spirit of keeping eyes wide open, it is reasonable to look for other periodic gravitational waveforms, such as periodic pulses similar to the radio pulses that led to the original electromagnetic discovery of pulsars. In the Fourier domain these non-sinusoidal waveforms could contain many frequency harmonics, no one of which has sufficient power to be detectable in a conventional CW search.

A number of algorithms can be applied to detect such waveforms, including incoherent harmonic summing [502] and the Gregory-Loredo method [503]. We have begun to explore the use of the Gregory-Loredo method, which has been used previously in radio, X-ray and gamma ray astronomy to search for non-harmonic periodicity in time-series. It is designed to be efficient in detecting pulsating signals in sparse-sampled data. We will study the tradeoffs in detection efficiency *vs.* computational cost for non-sinusoidal pulses when applied to the high-duty-factor LIGO and Virgo data. Initial exploratory studies are being carried out in the Matlab environment. If the method proves to be promising, it will likely be implemented in the offline DMT environment, to increase computational efficiency.

Because the method is computationally intensive, it will likely be applied only in directed searches at interesting points on the sky, such as the galactic center and globular cluster cores, where high stellar density might lead to periodic transients. We are also testing the added computational cost and particularly the best approaches to this detection method to account for modulations due to the Earth's motion (Doppler effect, antenna pattern).

It should be noted that the Gregory-Loredo method may also prove useful in detector characterization to identify periodic instrumental glitches or periodic non-stationarities. A DMT implementation of the search code could be applied straightforwardly for such glitch searching in online, real-time detector monitoring.

5.6 Sidereal periodicity studies

UPDATED

We found a sidereal periodicity in the VSR2 h-reconstructed power. Applying the same method of analysis to the Ligo antennas (with the S6 data) we also found the sidereal peak, but in this case it is accompanied with an anti-sidereal one.

Recently we have found that an artifact due to an annual periodicity can explain the sidereal and anti-sidereal doublet found in the two LIGO antennas. Anyway this artifact cannot explain the Virgo sidereal effect. A procedure to avoid the artifact has been developed, but it is not completely satisfactory. We are waiting for more Virgo data (in runs of at least six months).

For more information see [508].

5.7 Support infrastructure

UPDATED

There is important infrastructure needed to support the various CW searches. New software injections will be an important element in evaluating the performance of search pipelines. Systematic detection and identification of instrumental or environmental spectral lines, particularly wandering lines, has been and will continue to be necessary to eliminate outliers in many searches. Other spectral artifacts with apparent sidereal behavior can also lead to outliers. In this section we describe ongoing and planned work to address these support needs.

5.7.1 Software injections

UPDATED

An important new element in evaluating search pipeline performance is the creation of simulated data with several thousand software injections for pulsars at randomly chosen sky locations and with frequencies and frequency derivatives spanning our search ranges. These standardized data sets should enable us to compare with more statistical precision and more systematically the sensitivity and robustness of the various pipelines in detecting pulsars in blind searches or in reconstructing source parameters in targeted searches. The outcomes of these comparisons might well lead to the abandonment (or at least de-prioritization) of some search pipelines.

We created 3000 parameter files for artificial pulsars and generated signals from these over the period of S6. The signals have been added to a replica of the S6 frames and distributed to the LSC clusters. These reference software injections will be used to compare and contrast the performance of search pipelines. Several injections have already been extracted using the known pulsar pipeline and PowerFlux. This process is expected to continue over the coming year with additional search pipelines.

In preparation for the advanced detector era engineering runs are being performed to simulate detector data. In the first such run, ER1, two simulated pulsars were created and injected into the dataset. These have been successfully extracted using the known pulsar search method. Similar injections will also be performed in the successive engineering runs.

5.7.2 CW detector characterization

UPDATED

The CW Group has a strong interest in monitoring (and mitigating) instrumental spectral lines (see the detector characterization chapter) with low latency. In preparation for S6 the nascent “F-Scan” infrastructure developed during S5 for generating high-resolution spectrograms to detect wandering lines visually was automated and expanded to auxiliary channels and to Virgo channels. These spectrograms and data files proved invaluable in quickly spotting and tracking down instrumental lines in S6 data. The F-Scan output has also been mined for spectral coincidences between interferometers and between strain and auxiliary channels. Further improvements included dedicated F-scans for bands relevant to special pulsars, such as the Crab and Vela. An F-Scan version with further enhancements is being run on H1 and L1 PSL data currently and will be run on H2 One Arm Test data in summer 2012.

In addition, the offline auxiliary-channel coherence studies used in following up on S4 and S5 pulsar candidate outliers have continued for S6/VSR2 analyses. Special attention has been given to narrow spectral bands around a half dozen known pulsars for which the spindown limit may be accessible in S6/VSR2/VSR4 and to bands containing outliers coincident between H1 and L1. A new technique using spectral correlations is also under development.

On the Virgo side, a new infrastructure called NoEMi has been developed for identifying/mining stationary or slowly wandering spectral lines. It was run offline on VSR2 data, and in real-time on VSR3 and VSR4 data. During science runs NoEMi publishes daily summary pages, with plots and lists of the found noise lines, on the Virgo monitoring web pages. In particular, for the objectives of the CW targeted search, noise lines found at the same frequencies of the known pulsars are highlighted in the summary pages. More details on NoEMi can be found in [507].

Lines found by NoEMi are stored in a database which is made accessible via a web interface. The database allows to add user-defined information (metadata) to each identified line.

NoEMi will be used as the main noise line monitoring tool for the Advanced Virgo, LIGO and GEO detectors. NoEMi will run on the "local" computing centers (thus distributing the computing load and storage requirements) and send the formatted data to a centralised (cluster of) databases. As a preliminary test-bench of the upgraded framework, NoEMi has been installed and run at Caltech on the full S6 LIGO data and was recently commissioned at Hanford to run daily on the H2 One Arm Test data in summer 2012.

Because of sidereal modulation of CW source amplitudes (as seen by the interferometers), it is good to be aware of instrumental or environmental effects that could lead to apparent sidereal artifacts. Ongoing investigations have indeed revealed apparent artifacts in both strain and auxiliary environmental channel. Further analysis will be carried out of the full S6/S6/VSR2/VSR4 data sets to quantify the effects of these artifacts on CW searches.

In addition, the Gregory Loredo method will be used in the coming year to investigate instrumental artifacts that lead to periodic transients, and spectral correlation methods (different from spectral coherence) will be used for studying environmental contamination of the strain channels.

6 Searches for stochastic backgrounds

6.1 Sources of Stochastic Gravitational-wave Background

A stochastic gravitational-wave signal is formed from the superposition of many events or processes, which are too weak and too numerous to resolve individually, and which therefore combine to produce a confusion-limited background. The stochastic gravitational-wave background (SGWB) can arise from cosmological sources such as inflation, cosmic strings, and pre-Big-Bang models. Alternatively, it can arise from astrophysical sources such as compact binary coalescences, supernovae, neutron stars, etc.. One of the prime objectives of the Stochastic Working Group is to measure the SGWB.

Using tools developed to search for the stochastic background, the group has expanded its scope. For example, we have utilized the stochastic radiometer (see below) to produce the current best upper limits on strain from Sco X-1, a nearby low-mass X-ray binary. We are also investigating long-lived gravitational-wave transients. Long-lived gravitational-wave transients from rotational instabilities in neutron stars and accretion disks may be detectable with the Stochastic Transient Analysis Multi-detector Pipeline (STAMP) described below. The unifying feature of current stochastic analyses is that the signal we seek to measure is long-lived and difficult or impossible to model in the time domain.

6.2 Stochastic Search Method

The stochastic search method has evolved from a search for an isotropic SGWB (see section 6.2.1). S5 LHO-LLO-VSR1 isotropic and directional analyses have been published, while S5 long transient analyses remain in progress. S6-VSR23 analyses are in progress and the S5 H1-H2 analysis is in review. We are continuing to develop and extend the stochastic formalism, for example, to estimate the parameters of models of the stochastic background.

6.2.1 Isotropic Search

A stochastic background of gravitational waves (GWs) is expected to arise as a superposition of a large number of unresolved sources, from different directions in the sky, and with different polarizations. It is usually described in terms of the logarithmic spectrum:

$$\Omega_{\rm GW}(f) = \frac{1}{\rho_c}\,\frac{d\rho_{\rm GW}}{d\ln f}\,, \tag{7}$$

where $\rho_{\rm GW}$ is the energy density of gravitational waves, ρ_c is the critical density of the Universe, and f is the frequency. The effect of a SGWB is to generate correlations in the outputs s_A, s_B of a pair of GW detectors, which can be described for an isotropic background in the Fourier domain by

$$\langle \widetilde{s}_A^*(f)\,\widetilde{s}_B(f')\rangle = \frac{1}{2}\delta(f-f')\,\gamma_{AB}(f)\,S_{\rm gw}(f) \tag{8}$$

where $\tilde{s}_A$ and $\tilde{s}_B$ are the Fourier transforms of the strain time-series of two interferometers ($A \neq B$).

The raw correlation depends on the (one-sided) power spectral density $S_{\rm gw}(f)$ the SGWB would generate in an interferometer (IFO) with perpendicular arms, as well as the observing geometry. The geometrical dependence manifests itself via the overlap reduction function [519], which can be written as

$$\gamma_{AB}(f) = d_A^{ab}\,d_B^{cd}\,\frac{5}{4\pi}\iint d^2\Omega_{\hat{n}}\,P^{\rm TT}_{abcd}(\hat{n})\,e^{i2\pi f\hat{n}\cdot(\vec{r}_2-\vec{r}_1)/c} \tag{9}$$

where each IFO's geometry is described by a response tensor constructed from unit vectors $\hat{x}$ and $\hat{y}$ down the two arms

$$d^{ab} = \frac{1}{2}(\hat{x}^a\hat{x}^b - \hat{y}^a\hat{y}^b)\,, \tag{10}$$

$\vec{r}_{1,2}$ is the respective interferometer's location and $P^{\rm TT}_{abcd}(\hat{n})$ is a projector onto traceless symmetric tensors transverse to the unit vector $\hat{n}$ (see [520], p. 10).

We deploy a cross-correlation method to search for the stochastic GW background, following [521]. In particular, we define the following cross-correlation estimator:

$$Y_{AB} = \int_{-\infty}^{+\infty} df \int_{-\infty}^{+\infty} df' \; \delta_T(f-f') \; \tilde{s}_A(f)^* \; \tilde{s}_B(f') \; \tilde{Q}_{AB}(f') \,, \tag{11}$$

where δ_T is a finite-time approximation to the Dirac delta function, and $\tilde{Q}_{AB}$ is a filter function. Assuming that the detector noise is Gaussian, stationary, uncorrelated between the two interferometers, and uncorrelated with and much larger than the GW signal, the variance of the estimator Y_{AB} is given by:

$$\sigma^2_{Y_{AB}} = \frac{T}{2} \int_0^{+\infty} df \, P_A(f) P_B(f) \mid \tilde{Q}(f) \mid^2 \,, \tag{12}$$

where $P_i(f)$ are the one-sided power spectral densities (PSDs) of s_A and s_B, and T is the measurement time. Optimization of the signal-to-noise ratio leads to the following form of the optimal filter [521]:

$$\tilde{Q}_{AB}(f) = N_{AB} \, \frac{\gamma_{AB}(f) S_{GW}(f)}{P_A(f) P_B(f)} \,, \text{ where } S_{GW}(f) = \frac{3H_0^2}{10\pi^2} \, \frac{\Omega_{GW}(f)}{f^3} \,. \tag{13}$$

$S_{GW}(f)$ is the strain power spectrum of the stochastic GW background to be searched. Assuming a power-law template spectrum with index α, $\Omega_{GW}(f) = \Omega_\alpha (f/100 \text{ Hz})^\alpha$, the normalization constant N_{AB} is chosen such that $\langle Y_{AB} \rangle = \Omega_\alpha T$. The signal-to-noise ratio for a pair of interferometers for an ideal measurement of length T in stationary noise can be written as

$$\text{SNR} = \frac{3H_0^2}{10\pi^2} \left(2T \int_0^\infty df \gamma^2_{AB}(f) \frac{\Omega^2_{GW}}{f^6 P_A(f) P_B(f)} \right)^{1/2} \tag{14}$$

where H_0 is the present value of the Hubble expansion rate. The largest contribution to this integral comes from the frequency region where $P_{A,B}$ is minimum, which is between 50Hz and 150Hz for initial LIGO.

In order to handle gaps in the data, data non-stationarity, and for purposes of computational feasibility, the data for an interferometer pair are divided into many intervals of equal duration (typically 1-3 minutes), and Y_I and σ_{Y_I} are calculated for each interval I. The loss in duty-cycle due to the finite interval size is of order 1 minute for each analyzable data segment (which is typically several hours). The data in each interval are decimated from 16384 Hz to 4096 Hz and high-passed filtered with a 40 Hz cut-off. They are also Hann-windowed to avoid spectral leakage from strong lines present in the data. Since Hann-windowing effectively reduces the interval length by 50%, the data intervals are overlapped by 50% to recover the original signal-to-noise ratio. The effects of windowing are taken into account as discussed in [523].

The PSDs for each interval (needed for the calculation of $Q_I(f)$ and of σ_{Y_I}) are calculated using the two neighboring intervals. This approach avoids a bias that would otherwise exist due to a non-zero covariance between the cross-power and the power spectra estimated from the same data. Furthermore, by comparing σ_I calculated using the neighboring intervals with σ'_I calculated using the interval I, we identify intervals containing large noise transients and reject them from the analysis. In addition to this stationarity cut, we impose some data-quality flags (such as 30-sec before lock-loss), a large-σ cut (rejecting particularly noisy time-periods), and we ignore frequency bins which are determined to contain instrumental correlations. The intervals that pass all the data-quality cuts are averaged with $1/\sigma_I^2$ as weights, yielding the final estimates of Y and σ_Y.

6.2.2 Directional Search

The analysis described above is designed to search for an isotropic SGWB. It is also possible to search for anisotropies in the GW background. One way to approach the problem is to define a sky-position dependent optimal filter. As discussed in [524], one can write:

$$Q(t,f,\hat{\Omega}) = N(t,\hat{\Omega}) \, \frac{\int d\hat{\Omega}' \, \gamma(t,f,\hat{\Omega}') \, A(\hat{\Omega},\hat{\Omega}') \, H(f)}{P_1(f) \, P_2(f)}, \tag{15}$$

where $A(\hat{\Omega},\hat{\Omega}')$ reflects the anisotropy in the GW spectrum across the sky. For point sources, one chooses $A(\hat{\Omega},\hat{\Omega}') = \delta^2(\hat{\Omega},\hat{\Omega}')$. Note, also, that the overlap reduction function γ is now dependent on the sky-position, as well as on the sidereal time t. Following the procedure analogous to the one outlined in the previous Section leads to an estimate of Y and σ_Y for every direction on the sky—i.e. a map of the GW background. However, this map is blurred by the antenna patterns of the interferometers. The problem of deconvolving the antenna pattern from this map is described in [514, 528]; (see more below).

6.2.3 Mapping

The methods described in 6.2.1 and 6.2.2 are optimal under the assumption that the background is either isotropic or dominated by point sources, but neither addresses the question of estimating the actual spatial distribution of a stochastic background. A method that does this is described in this section.

The spatial distribution $\mathcal{P}(\hat{\Omega})$ of the strain power of stochastic background can be expanded with respect to any set of basis vectors on the sphere:

$$\mathcal{P}(\hat{\Omega}) = \mathcal{P}_\alpha \mathbf{e}_\alpha(\hat{\Omega}) \,, \tag{16}$$

Defining $C(f,t)$ as the cross-power between the output of the two detectors,

$$C(f,t) = \frac{2}{\tau} \, \tilde{s}_1^*(f,t)\tilde{s}_2(f,t) \,, \tag{17}$$

one can show that its expectation value is given by

$$\langle C(f,t) \rangle = H(f)\gamma_\alpha(f,t)\mathcal{P}_\alpha \,, \tag{18}$$

with $H(f)$ the strain power spectrum of the stochastic background. The $\gamma_\alpha(f,t)$ are basis dependent geometric factors that can be pre-calculated and play the role of the overlap reduction function in the isotropic analysis. The covariance matrix of $C(f,t)$ is given by

$$N_{ft,t't'} = \langle C_{ft} C^*_{f't'} \rangle - \langle C_{ft} \rangle \langle C^*_{f't'} \rangle \tag{19}$$

$$\approx \delta_{tt'} \delta(f-f') P_1(f,t) P_2(f,t), \tag{20}$$

with P_1 and P_2 the strain noise power spectra of the two detectors.

Assuming Gaussian noise, the likelihood for measuring a specific cross-power $C(f,t)$ is

$$p(C_{ft}|\mathcal{P}_\alpha) \;\propto\; \exp\left[-\frac{1}{2}((C^*_{ft} - \langle C^*_{ft}\rangle) N^{-1}_{ft,f't'} \right. \\ \left. (C_{f't'} - \langle C_{f't'} \rangle) \right] \tag{21}$$

where $\langle C_{ft} \rangle$ is given by 18 and repeated ft and $f't'$ indices are summed and integrated over—e.g., $\sum_t \int_{-\infty}^{\infty} df$..

Now one can ask for the $\mathcal{P}_\alpha$ that maximize this likelihood. They are given by

$$\hat{\mathcal{P}}_\alpha = (\Gamma^{-1})_{\alpha\beta}\, X_\beta \tag{22}$$

where

$$X_\beta = \sum_t \tau \int_{-\infty}^{\infty} df\, \gamma_\beta^*(f,t)\, \frac{H(f)}{P_1(f,t)P_2(f,t)}\, C(f,t)\,, \tag{23}$$

$$\Gamma_{\alpha\beta} = \sum_t \tau \int_{-\infty}^{\infty} df\, \gamma_\alpha^*(f,t)\, \frac{H^2(f)}{P_1(f,t)P_2(f,t)}\, \gamma_\beta(f,t)\,. \tag{24}$$

The matrix inversion in Eq.22 in practice requires a regularization scheme because the interferometer pair can be insensitive to particular background distributions. Note that if one restricts the basis set to either just an isotropic component or just a point source at a given location, one will get exactly the analysis described in 6.2.1 and 6.2.2 respectively.

While this algorithm in principle would work in any basis, a basis with a natural resolution cut-off will reduce the required number basis vectors and thus simplifies the required matrix inversion. One obvious such basis is formed by spherical harmonics, which is what we currently use to construct gravitational-wave sky maps.

6.2.4 Multi-baseline: LIGO/VIRGO joint search

As shown in [521], the optimal method for combining more than two detectors is to make pairwise correlation measurements, and then combine these results in the same way measurements from different times are combined: average the point estimates Y with a relative weighting of σ^{-2}, or equivalently in the mapping formalism, sum up the X_β and the Fisher matrices $\Gamma_{\alpha\beta}$. As discussed in [522] the inclusion of the LIGO-Virgo pairs can enhance the sensitivity of the global GW detector network to an isotropic background of gravitational waves, particularly at frequencies above 200 Hz. The improvement in the low frequency range is small owing to the overlap reduction factor in Eq. (14). Furthermore, the addition of a third instrument with comparable live time and sensitivity improves both the resolution and sensitivity of the mapping algorithm, effectively simplifying the regularization problem mentioned in Section 6.2.3.

6.2.5 H1H2 Isotropic Search

The isotropic search outlined above is usually applied to the non-collocated interferometers (such as the two 4-km interferometers at Hanford and Livingston), in order to minimize the instrumental correlations. However, the overlap reduction for this interferometer pair is significant above 50 Hz. Hence, the collocated pair of Hanford interferometers could potentially lead to a result $\sim 10\times$ more sensitive than the S5 isotropic stochastic result. (The advantage of co-located interferometers is expected to be less during the advanced detector era, since the overlap reduction function is relatively large at the low frequencies where the aLIGO interferometers are expected to be most sensitive.) However, co-located interferometers are also more susceptible to instrumental correlations. The Stochastic Group has developed two methods to handle this problem.

One approach relies on the coherence, defined as

$$\Gamma_{XY}(f) = \frac{|P_{XY}(f)|^2}{P_{XX}(f)P_{YY}(f)} \tag{25}$$

where P_{XY} is the cross-power spectrum between channels X and Y, and P_{XX} and P_{YY} are the two power spectra. As discussed in [526], it is possible to estimate the instrumental correlations between interferometers 1 and 2 by

$$\Gamma_{instr,12} \approx \max_i(\Gamma_{1Z_i} \times \Gamma_{2Z_i}) \tag{26}$$

where Z_i are the numerous environmental channels, including microphones, seismometers, accelerometers, power-line monitors etc. As discussed in [526], this method can be used to identify frequency bands in which the instrumental correlations between two interferometers are large. These bands could then be removed from the isotropic stochastic search. Moreover, the method can be used to estimate the residual contamination in the "good" frequency bands.

The second approach relies on time-shifting one GW channel with respect to the other. Since the stochastic GW background is expected to be broadband, its coherence time is much shorter than $\sim$1s, so the GW correlations between the two channels are expected to disappear at 1s time-shift. However, narrow-band features (of width $\sim$ 1 Hz) are expected to survive 1s time-shift. Hence, this method can also be used to identify narrow-banded instrumental correlations. The two methods agree well.

6.2.6 Searching for Long-Lasting Transients

The Stochastic Group has developed a pipeline called STAMP (Stochastic Transient Analysis Multi-detector Pipeline) for the study of long gravitational-wave transients lasting from $\mathcal{O}(\mathrm{s})$ to weeks. STAMP utilizes frequency-time (ft)-maps (spectrograms) of cross-power created from two or more spatially separated detectors (e.g., H1 and L1). It extends the principle behind the narrowband radiometer [513, 524, 525] in order to consider signals with shorter durations and/or more complicated spectral content.

STAMP can call on a variety of pattern recognition algorithms in order to identify structure in ft-maps. Current analyses utilize a density-based track search algorithm favored for its speed and effectiveness. Other available algorithms include burstCluster (borrowed from the Burst Group's Flare Pipeline), Radon, Hough, locust, and box search algorithms. STAMP searches can be externally triggered (e.g., using long GRB triggers). It is also possible to perform an untriggered "all-sky" analysis, though, it is expected to be computationally expensive. Work is underway to address these computational challenges.

STAMP is also used for detector characterization purposes. Instead of cross-correlating two gravitational-wave channels, we cross-correlate one gravitational-wave channel with a physical environmental monitoring channel to look for noise that is coherent in the gravitational-wave channel. This "STAMP-PEM" technique has been used to investigate airplane/helicopter noise, chiller-pump "Crab" noise, and noise from lightning and thunder [529]. Work is ongoing to apply STAMP-PEM to Advaced LIGO commissioning data in order to find correlations between PEM sensors and sensing channels (eventually DARM).

6.3 Results and Plans

6.3.1 Status of S5/S6 Searches

Isotropic Search (published): The Stochastic Group finished the isotropic search with LHO-LLO interferometer pairs using the S5 data. The final results is a new 95% upper limit on the gravitational-wave energy density $\Omega_0 < 6.9 \times 10^{-6}$ for a frequency independent spectrum ($\alpha = 0$) in the band 41-169 Hz. This result is 10 times more sensitive than the previous upper limit based on S4 data [511], and it is more sensitive than the Big-Bang Nucleosynthesis bound and the Cosmic Microwave Background bound in the LIGO frequency band. The result was published in Nature [527], including the implications of the new result for the models of early-universe cosmology, for cosmic (super)string models and for pre-big-bang models.

Radiometer and Spherical Harmonics (published): The Stochastic Group has analyzed the S5 data set with both the radiometer and the Spherical Harmonics decomposition analysis described in sections 6.2.2 and 6.2.3. The results were published in Physical Review Letters [514]. The radiometer analysis produced maps of the GW sky 30 times (in strain power) more sensitive than those produced using the S4 data [513], as well as targeted narrow-band limits on GW radiation coming from Sco X-1 and the Galactic Center. It also confirmed the previously published isotropic result. The second directional analysis produced the first spherical-harmonic decomposition map of the gravitational-wave sky, similarly to what is done in the field of Cosmic Microwave Background. This method targeted complex source distributions on the sky, and has been summarized in a method paper published in Physical Review D [528]. The S6-VSR23 update may be part of a single paper with the isotropic result depending on whether there is sufficient new material to warrant separate papers.

S5+VSR1 Isotropic Search (published): The Stochastic Group also conducted a joint LIGO-VIRGO stochastic search, using the shared S5+VSR1 data (data acquired between May 18, 2007 and October 1, 2007). Although the LIGO-VIRGO interferometer pairs are less sensitive than the LIGO 4-km interferometer pair to the isotropic stochastic background at frequencies below 800 Hz, above 800 Hz the LIGO-VIRGO pairs are similar or even more sensitive than the LIGO-LIGO pairs. Moreover, the LIGO-VIRGO pairs have different zeroes in the overlap reduction function, which can improve the overall network sensitivity even at lower frequencies. This paper was recently published in Physical Review D [515]

S6+VSR23 Isotropic and Directional Searches: The strain sensitivity of the LIGO 4-km interferometers (H1 and L1) is improved compared to S5, though, the coincidence time is limited by the relatively low duty cycle, especially early in the run. Virgo sensitivity, meanwhile, did not match the VSR1 levels around 100 Hz. The isotropic limit for S6+VSR23 is expected to be less than a factor of two improved compared to the S5 result. Despite these mixed results, we expect to update our isotropic and directional searches with some interesting improvements. By adding Virgo to the directional analyses, we expect to be able to improve the angular resolution of the directional search due to the longer baseline between the LIGO and VIRGO sites. Also, work is ongoing to investigate stochastic signals from extended patches of sky such as the Virgo and Coma clusters.

Isotropic Search using colocated Hanford Interferometers: The isotropic searches performed up to date have used non-collocated interferometer pairs because of the reduced chances of environmental correlations. The LHO interferometer pair, however, could potentially be $\sim 10\times$ more sensitive to stochastic GW background due to the more favorable overlap reduction function. However, the collocated interferometer pair also suffers from instrumental correlations, because the two interferometers share the same environment and the same sources of instrumental noise.

The Stochastic Group developed two methods to estimate and suppress the instrumental correlations, as discussed above in more detail. The group has applied these methods to the S5 data, and the results indicate that the PEM-coherence and the time-shift approaches identify well the grossly contaminated frequency bands, which are then removed from the analysis. Moreover, the PEM-coherence approach can be used to estimate the residual contamination in the "good" frequency bands. The co-located interferometer (H1H2) analysis was performed in two frequency bands: low-frequency (80-160 Hz) and high-frequency (460-1000 Hz). The H1H2 paper draft is mature and discussions are underway with the stochastic review team to ascertain the best way to publish these results.

Non-Gaussian Search The group is exploring the possibility of searching for non-Gaussian SGWB also known as the "popcorn noise". The basic formalism for this search has been developed for co-located, white detectors. Preliminary tests of the formalism have been successfully performed, however the extension of this method to realistic interferometer pairs is still under investigation. The hope of the group is to perform the non-Gaussian search using all of S5 data, thereby improving on the sensitivity to non-Gaussian stochastic signals as compared to the standard isotropic search.

Stochastic Intermediate Data and Stochastic Folded Data: Since several searches rely on similar quantities (such as strain cross and power spectral densities of different interferometers), the group has produced Stochastic Intermediate Data (SID), stored in the frame format, and containing the commonly used quantities calculated for segments throughout the S5 run. More recently, the intermediate data has been stored in Matlab .mat files in order to speed up input/output time for STAMP searches. In addition to simplifying the standard stochastic searches, the SID frames also find use in detector characterization studies and in searches for GW transients on minute or hour time-scales. In particular, the SID frames combined with the new algorithms searching for long-lasting transients have led to a new S6 data quality flag identifying transients due to passing airplanes.

The filter functions used in any long-duration stochastic search have a symmetry—they have a period of one sidereal day. One can use this symmetry to "fold" cross-spectral data from each day on top of each frequency bin of each sidereal time segment. That way effectively one has to analyze one sidereal day long data, as compared to few hundreds to a thousand days of data over a science run, thus saving huge amount of computation time. In addition, the folded data is highly portable—the whole dataset can be loaded in a desktop computer's memory and can be stored in a DVD. A MATLAB based pipeline was developed to fold "Stochastic Intermediate Data (SID)" to one sidereal day, which was applied to fold the whole S5 data. All the existing and new long duration analyses can now be performed on the folded data. However, rigorous validation of the results has to be done before making the data available for different analyses, which the group proposes to do in the coming months.

Searches for Long-Lasting Transients (STAMP) The Stochastic Group has developed the infrastructure necessary for searching transient GW signals on the time scales of minutes, hours or longer. This Stochastic Transient Analysis Multi-detector Pipeline (STAMP) uses intermediate data, i.e. time-frequency maps of the cross-correlation between two interferometers with resolution of $1\ \mathrm{s} \times 1$ Hz. The time-frequency map is then parsed in search of different types of GW signals, which appear as clusters of significant pixels. Several different pattern recognition algorithms were developed, but current searches favor the density-based track search algorithm for its speed and effectiveness. The Stochastic Group is also drawing from experiences of other groups (such as the Burst Group) performing searches for short duration transients.

Current STAMP searches that are in progress include

- search for long-lived GWs from long GRBs
- search for long-lived GWs coincident with high-energy neutrinos
- an all-sky (untriggered) search for long-lived gravitational waves

Several other projects are in an exploratory phase, including a search for r-modes and other signals associated with isolated neutron stars.

6.4 Stochastic Group's Plans for Advanced Detector Era

Advanced detectors are expected to have about $10\times$ better strain sensitivity than the initial interferometric detectors, as well as to extend the sensitive band from 40 Hz down to 10 Hz. Furthermore, the number of detectors operating in a worldwide network is expected to increase, eventually including sites LIGO-Hanford, LIGO-Livingston, Virgo, GEO-HF (at high frequencies), KAGRA (Japan), and potentially LIGO India. These significant strain sensitivity improvements and the increase in the number of available detector pairs that could be cross-correlated will enable real breakthroughs in the searches for the SGWB and for long-lasting transients. We summarize below the scientific targets and the corresponding searches that the Stochastic Group plans to perform in the advanced detector era.

6.5 Modeling of the stochastic background

The Stochastic Group is developing a catalog of cosmological and astrophysical sources of the SGWB. While many SGWB models have been proposed in the literature, most of them have not been systematically studied in terms of their accessibility to future GW detectors. It is therefore critical and timely to perform a systematic study of these models and identify specific science questions in the framework of these models that could be addressed by the second-generation GW detector network. Furthermore, as the GW community is beginning to conceive the design of the third-generation detectors, it is also important to identify the SGWB science targets that could be pursued by these detectors, thereby influencing the design requirements for such detectors. The Group has already studied some of the proposed models. For example, a study of the SGWB due to coalescences of binary neutron stars and/or black holes has shown that the isotropic stochastic search can be used to constrain the rate and average chirp mass of such binaries. Similarly, stochastic searches can be used to probe the equation of state in magnetars, or to probe the parameter space in cosmic (super)string models.

This effort is closely linked with the development of the parameter estimation techniques. While traditional stochastic isotropic searches were limited to estimating the amplitude of the stochastic background (for a specific assumed spectral shape), the new techniques can be used to estimate additional model parameters. The parameter estimation techniques can be used to constrain parameters in generic models (such as the power index in the power-law spectral form), or to constrain fundamental parameters in SGWB models, as identified in the systematic SGWB model studies.

6.6 Parameter estimation

Current work on stochastic parameter estimation has focused on estimating the parameters of simple (two-parameter) models including generic power-law models and models of the SGWB from binary neutron stars and binary black holes [517]. In the case of an SGWB from compact binary coalescences, stochastic measurements can be combined with transient measurements (of individual coalescences) to gain more information about the source of an observed stochastic background [517].

Future work will explore a wider variety of models including those characterized by more than two parameters. Exploring the higher-dimensional likelihood functions may require the application of numerical integration tools such as nested sampling [518] and/or Markov Chain Monte Carlo. The group is exploring publicly available (open source) code for these calculations. Another focus of future work will be combining information from other sources (such as transient GW detections) in order to disentangle different sources of the SGWB.

6.6.1 Searches for Isotropic Stochastic Gravitational-Wave Background

Isotropic stochastic GW background will be one of the prime targets of the Stochastic Group in the advanced detector era. This is especially true since recent work has shown that the stochastic background from compact binary coalescences may be detectable by advanced LIGO [516]. The flagship search targeting this background will be the multi-baseline cross-correlation search, using non-collocated GW detectors. It is likely that this search will be the limiting case of the anisotropic search discussed below. The improved detector strain sensitivities and the increased number of baselines will improve the sensitivity of the detector network to the level of $\Omega_{GW} \sim 10^{-9}$ or better. The code/pipeline for these searches already exists and has been applied to S4/S5 LIGO data [511, 512, 527]. Minor adjustments will be needed to apply it to advanced detector data such as extending the sensitive band down to 10 Hz and creating a new high-pass filter.

Another isotropic stochastic search could be performed using the colocated H1-H2 detector pair (in the case when H2 does not move to India). As discussed above, due to the shared location/environment, this detector pair is much more susceptible to instrumental and environmental correlations, which could potentially compromise the stochastic GW background measurement. Substantial efforts have been made in the past to perform this search with S5 data. While the S5 search is not completed yet, two conclusions can already be made. First, at high frequencies (above 400Hz) the instrumental/environmental correlations are small and can be effectively identified and removed from the analysis. Consequently, isotropic stochastic search at these frequencies should be possible with aLIGO H1 and H2, providing sensitivity of order $\Omega_{GW} \sim 10^{-5}$ at 1 kHz (a factor of $\sim 100\times$ improvement over the S5 result which is not yet published). This analysis will be of particular interest for astrophysical models of stochastic background, which are expected to peak at few hundred Hz or 1 kHz. Second, at frequencies below 300Hz, the environmental contamination may be substantial, and it might not be possible to completely identify and remove it. While the S5 analysis will give important information about this when it is completed, it is clear that the analysis method could be improved to make better use of the PEM channels—currently only the PEM channel contributing the most to cross-correlation is used in the analysis, which is clearly not the optimal use of available information. Depending on the available manpower in the coming years, the Stochastic Group is interested in pursuing such improvements in the method.

6.6.2 Searches for Anisotropic Stochastic Gravitational-Wave Background

Anisotropic stochastic searches have already been performed on S4 data [513] and S5 data [514]. This includes both the radiometer searches that target point-sources on the sky, and the spherical-harmonic decomposition search which is capable of searching for complex spatial distributions in the GW sky. Both of these methods also produce the isotropic result as a limiting case, so could be combined with the isotropic search discussed above. The improved strain sensitivities of detectors, as well as the larger number of detector baselines, will lead to at least 100-fold improvement in the sensitivity to anisotropies in the stochastic GW background as compared to the S5 result (which is yet to be published). Additional improvements are expected by extending the frequency band of the search down to 10 Hz. The increased number of detector baselines will also significantly improve the angular resolution of the search.

The radiometer search can be used to target specific point-like sources, as was done in the case of Sco-X1 and the galactic center with S4/S5 data. Another detailed study is needed to determine which sources would be suitable targets for such searches (especially since the new band 10-40 Hz will be opened), as well as to understand the relative advantages and disadvantages as compared to Continuous-Waves searches. However, it is also possible that the simplicity of the method will drive these targeted searches despite of possible improved sensitivity than the CW searches.

Finally, we note that the current anisotropic searches average over the two GW polarizations. The algorithm could be extended to estimate the two polarization components. Depending on the available manpower, a detailed study could be made to add this functionality to the search code/pipeline and to quantify its performance using a series of signal simulations/injections.

6.7 Mock Data

The Stochastic Group is implementing infrastructure for generating simulated/mock data gravitational wave frames (*.gwf files) containing various SGWB signatures, such as from a population of BNS/BBH pairs, from cosmic strings, as well as generic backgrounds of tunable amplitude and spectral index. The mock data frames are processed using the standard stochastic analysis. The group is investigating the applicability of existing pipelines and detectability of the signal in the advanced detector era as well as the parameter estimation accuracy using the simulated data sets.

6.7.1 Searches for Long-Duration Transients

As discussed above, STAMP ("Stochastic Transient Analysis Multi-detector Pipeline") is a pipeline devoted to the study of long $\gtrsim 1\,\mathrm{s}$ gravitational-wave (GW) transients [536]. The pipeline is designed to be flexible, so that it could be used to search for a variety of different astrophysical signals. Consequently, multiple searches (and multiple papers) are being planned for the advanced detector era including triggered searches using isolated neutron stars, GRBs, supernovae as well as an untriggered search.

The STAMP code suite is at a mature stage. Most of the infrastructure is already complete, and numerous checks have been performed. The first analyses (targeting GRBs and high-energy neutrinos) are underway. We expect the key STAMP infrastructure review to be completed in 2012-2013.

6.7.2 Computation for stochastic searches

The Stochastic Group currently relies on Matlab for most analyses, and many users still use Matlab 2007a. As part of our preparation for Advanced LIGO, we have begun to test that our pipelines will continue to work with the most recent version (currently Matlab 2012a). Based on these tests, we believe Matlab will continue to suit our needs during the Advanced LIGO era.

While we expect Matlab to play a central role in the near future for stochastic analyses, we are also investigating new directions. Some interest has been expressed in developing stochastic pipelines in C++ or python in order to facilitate potentially time-consuming calculations. It is likely that such work will be driven if necessary by computational needs.

6.8 Detector characterization for stochastic searches

The long integration time used in the stochastic analysis can reveal noise noise lines. Common noise lines at two sites can occur due to similar equipment in the laboratory, or common timing in the data acquisition systems. A strong line in on interferometer, along with a large random fluctuation in the other, can also produce a signal at a specific frequency in the stochastic search pipeline. In the advanced detector era the coherence between pairs interferometers' output will be calculated in real time. In this way noise lines that would affect the stochastic search (and by extension, also the CW search) can be identified during the science runs, and possibly even be addressed and fixed in the laboratory.

Efforts will also be made to investigate possible noise correlations between the LIGO Hanford and Livingston sites. While the possibility of correlated noise is low, there are possible mechanisms. Special attention will be given to electromagnetic sources. The correlations between the coil magnetometers at the LIGO sites will be monitored. If any common signals are found, special attention will be given to seeing if there is similar noise in the interferometers' output. Data from radio frequency (RF) monitors at the sites will also be studied. There may be RF frequencies that are common between sites (e.g. 10 MHz signal generator syncing signals). Audio frequency RF will also be monitored. A very possible source of inter-site correlations are GPS synced DAQ system issues; studies will be done (monitoring many auxiliary channels) to determine if this noise is present and affecting the stochastic search. It should be noted that this search for inter-site noise correlations can commence immediately and need not depend on H1 and L1 being in science mode.

The STAMP pipeline has been demonstrated to be a good tool to search for long duration noise transients in interferometer data [529]. The STAMP pipeline will be applied to interferometer control signals and physical and environmental monitoring channels as aLIGO sub-systems come on-line. This noise search effort will be done in collaboration with the detector characterization group.

7 LSC Computing and Software

The LIGO instruments deliver about 1TB/day of data. Even with only about 1% of this data in the gravitational-wave strain channel (the rest consists of detector and environment monitoring information) LIGO data analysis is a formidable computing challenge. Binary inspiral, burst and stochastic searches can utilize many Tflops of computing power to analyze the data at the rate it is acquired. *LIGO's scientific pay-off is therefore bounded by the ability to perform computations on this data.*

The LSC has adopted commodity computer clusters as the solution that meets its computational needs most cost effectively. Compute centers are geographically distributed at several sites around the world; this approach has the advantage that it puts resources close to the university researchers who are analyzing the data. Grid middleware allows for relatively easy access to data and computing power. If local resources are inadequate or a poor match, a researcher can access additional resources on the grid.

The LSC also developed the Einstein@Home project to leverage an alternative distributed computing paradigm for its most formidable computing challenge, the search for gravitational waves from isolated pulsars. The pulsar analysis puts reduced demand on quick turn-around and has low data flow, but requires PFlops of computing power. The analysis engine that underlies Einstein@Home utilizes much of the standard LSC software infrastructure described below; BOINC [4] is used to distribute work to thousands of volunteered personal computers world-wide.

7.1 Current status

The LIGO Data Grid (LDG) is the combination of computational and data storage resources, grid computing middleware and LSC services which, together, create a coherent data analysis environment for gravitational-wave science. With resources located at LIGO Laboratory centers (Caltech, MIT, LHO and LLO) and LSC institutions (UWM, Syracuse, and 3 sites in the EU managed by the GEO-600 collaboration), the LDG is a true distributed facility.

The LIGO Data Grid currently offers the minimal services required on a fully functional data grid. The LDG continues to see growth in the number of users, higher demand for the resources, and construction of more sophisticated workflows. It is essential, therefore, to provide support of the LDG infrastructure, to provide user support and documentation, and to create the new services that gravitational-wave scientists will require. These services include: improved resource monitoring service and a resource brokering service to ensure that optimal use is made of LDG resources at all times; a metadata service to provide collation, distribution and access to the scientific results of searches; and a virtual organization management service to facilitate access control of LDG resources.

We anticipate evolution of the usage model as the community gains experience, so we are committed to a modular approach which allows us to remain light on our feet and to implement solutions which enable the best gravitational-wave science. A detailed description of the program of work on the LIGO Data Grid follows.

7.2 Activities in support of LDG Operations

1. **Hardware and Operating System Maintenance** The LDG clusters are all commodity clusters as this offers the most GFLOPs/dollar of capital investment. Using Linux requires an investment to track, and in some cases work around, this developing operating system. These are the traditional system-administration roles independent of grid activities.

[4] `http://boinc.berkeley.edu`

2. **Grid Middleware Administration** Each local cluster must maintain an evolving set of middleware in as stable a fashion as possible. The primary means to do this is the LDG Server software, discussed below. This software is rapidly evolving and requires effort to configure, support and maintain, independent of the effort required to create and maintain the LDG Server package itself.

3. **Data Distribution and Storage** The LDG currently uses the commercial SAM-QFS mass storage software from Oracle, commodity storage in the compute nodes, Linux based RAID servers, and the LIGO Data Replicator (LDR) to store and distribute data. Input data is common to the majority of analysis pipelines, and so is distributed to all LDG centers in advance of job scheduling.

4. **Reduced Data and Calibrated Data Products** The Initial LIGO raw full-frame data files contain 13 to 15 thousand channels, including the gravitational-wave channel. For Advanced LIGO the number of channels is expected to increase by an order of magnitude. Within the LIGO Data Analysis Systems (LDAS) at the observatories, a Level 1 Reduced Data Set (RDS) is generated that contains on the order of 300 channels (some of which are downsampled) that are the most useful for analysis and detector characterization. The Level 1 RDS files are about 20% the size of the raw frames, facilitating their distributed storage on cluster disk space for rapid I/O and for transfer to downstream LDG clusters. An even smaller Level 3 RDS is generated that contains just the gravitational-wave channel and instrument status information. Within the RDS infrastructure, LDAS also generates calibrated strain data using code from the LSC Algorithm Library, which it distributes as a separate set of frames files that are used for most offline analyses.

5. **Certificate Authority and User Accounts** LIGO uses X.509 certificates for authentication of users on the LDG. Several international Grid Certificate Authorities (CAs) supply user certificates, including DOEGrids CA in the USA. The LSC provides a simplified script interface for DOEGrids CA users within LIGO. RA agents are required to verify certificate requests to the CA and then approve them. LDG user accounts are requested via a web interface; these are also verified, and approvals are sent to each LDG site where local admins add the accounts.

6. **LIGO Data Grid Client/Server Bundles** LSC staff leveraged experience and built upon the Virtual Data Toolkit (VDT) to create the LIGO Data Grid Client and Server packages. The server bundle enables LSC administrators to easily deploy standard grid services and middleware such as Globus GRAM and GridFTP across the LDG. The client bundle provides quick one-stop installation of all the software needed to gain access to the LDG resources by users in the LSC. Moreover, the LDG Client bundle provides scripts specific to the LDG to simplify certificate requests and other activities that users perform. Over the past year, the LSC has worked with the VDT team to migrate the LDG Client and Server to use native packaging for Linux platforms. The LSC now maintains these bundles in the LSCSOFT repositories for easy installation and configuration on the LDG. A Mac OS client suite is maintained in order to support the increasing number of scientists using this platform to access LDG resources. The LSC continues to collaborate with the VDT team to provide feedback on their software and distribution mechanisms.

7. **User Support** The LDG predominantly uses Condor for job queue management. As the analysis workflows for this new branch of astronomy are evolving rapidly, significant effort is required to work closely with the Condor development team to ensure efficient use of the LDG clusters. This feedback has been productive, with many timely bug fixes and feature enhancements being provided, however this requires significant effort from LDG administrators to isolate and troubleshoot issues that are particular to gravitational-wave data analysis. Compared with our High Energy Physics colleagues, the workflows that are being developed on the LDG are not yet as mature or stable, causing a significant

burden on cluster administrative staff. Since the LDG users are generally scientists and not grid experts, staff are required to offer performance tuning in terms of GFLOP/s, job scheduling efficiencies, memory utilization, file management, and general debugging support for intermittent job failures.

8. **LIGO VO Support for OSG** Provide primary support for OSG usage of LIGO VO resources, continue to fulfill the responsibilities of OSG point of contact, security contact, and support center for LIGO, and handle any issues that arise for OSG users, OSG administrators and the OSG Grid Operations Center (GOC) while using LIGO facilities; regular participation in OSG Operations, OSG Integration, and OSG Support Center telecons. Maintain and administer the Virtual Organization Membership Service (VOMS) and LIGO Accounts Management System (LAMS) used to track users with Grid certificates approved to use LIGO Data Grid resources.

7.3 Data Analysis Software Development Activities

A suite of software tools are supported, developed and released by the LSC for the purpose of analyzing data from gravitational-wave experiments. These data analysis software projects are developed under the umbrella of the *Data Analysis Software Working Groups* (DASWG). Many of these projects have evolved into full scale software projects which enable most of the large scale analysis efforts within the LSC, thus requiring substantial effort to maintain them. Moreover, the LSC and the international community of gravitational-wave astronomers have embraced the grid-computing model and its associated technologies placing further demands on the software tools developed by DASWG.

1. **Data Monitoring Tools** The Data Monitoring Toolbox or DMT is a C++ software environment designed for use in developing instrumental and data quality monitors. About 50 such monitor programs have already been developed by members of the LIGO Scientific Community. DMT monitors are run continuously while LIGO is in operation, and displays produced by these monitors are relied on to give the operators immediate quantitative feedback on the data quality and interferometer state. In addition to their on-line use, the monitors and the software infrastructure they are based on have many offline applications including detector characterization, data quality determination and gravitational wave analysis. To facilitate the use of the DMT environment and monitors offline, the majority of the DMT package has been ported to the LSC offline processing clusters. Porting and packaging the DMT for offline use will continue to be supported.

2. **GLUE** The Grid LSC User Environment (GLUE) provides workflow creation tools and metadata services, written in Python, which allow LSC scientists to efficiently use grid computing resources within and external to the LIGO Data Grid. Analysis of data from gravitational-wave detectors is a complicated process typically involving many steps: filtering of the data from each individual detector, moving trigger data to a central location to apply multiple instrument coincidence tests, investigating auxiliary channels, and coherent combination of data from all detectors in the network. The description of these complicated workflows requires a flexible and easy to use toolkit to construct a virtual representation of the workflow and then execute it on a single cluster, across the entire LIGO Data Grid, or on external compute resources such as the OSG. The GLUE pipeline module provides this facility and is used by numerous LSC-Virgo data-analysis pipelines. GLUE is integrated with Pegasus workflow planner, allowing scientists to better manage the workflows generated using the pipeline module. Direct generation of Condor workflows is also supported. GLUE also provides an extensive suite of metadata management tools. The ligolw module provides a toolkit for generating and manipulating LIGO light-weight XML documents (LIGOLW XML). These documents are used to store many data products, from detector data quality and metadata information to the scientific products of searches. GLUE also provides the server tools to manage the extensive detector state metadata

generated by the LIGO, Virgo and GEO detectors, as well as client tools used by LSC-Virco scientists to access these data.

3. **LSC Algorithm Library Suite** The LSC Algorithm Library Suite (LAL) is a collection of C language routine libraries that form the engine of the computationally-intensive data analysis programs. LALSuite routines are used in LAL Applications (collected in the LALApps package) which are programs that perform specific data analysis searches, and the LAL-Python interface (PyLAL) that provides access to LAL routines within the Python language. LALSuite contains (i) general purpose data analysis routines that provide common data analysis tools (e.g., routines to perform time-domain filtering, Fourier and spectral analysis, differential equation integrators), astrometric tools (e.g., routines for converting between sky coordinate systems and time systems), and gravitational-wave specific tools for signal simulation and data calibration; (ii) routines for reading and writing data in standard LIGO data formats; and (iii) implementations of search-specific gravitational data analysis algorithms. Enhancements are planned to improve the I/O routines to interface with LDR data catalogs directly and to leverage Grid tools to directly access data stored remotely. Also planned are significant improvements to the interface of the core analysis routines to make these routines easier to integrate into other software.

   C language applications for performing specific searches are contained in the LALApps package which is freely available under the GPL. This package provides a set of stand-alone programs that use LAL routines to perform specific pieces of a search pipeline. The programs can be strung together to form a data analysis workflow: a sequence of steps that transform the raw interferometer output into a set of candidate events. These applications continue to be enhanced and new ones developed.

   PyLAL is a Python module that includes extension modules that link against LAL, thereby making LAL routines available within the Python scripting environment. PyLAL thus provides a mechanism for rapid data analysis application development, for data exploration and graphing, and for performing quick follow-up analyses. As PyLAL matures, many more LAL routines will be incorporated so that significant aspects of the data analysis pipelines will be written in Python.

4. **MATLAB Applications** The MATLAB software suite is a commercial product which is widely used within the LIGO Scientific Collaboration (and the broader gravitational wave detection community beyond) for on-line and off-line data analysis, detector characterization, and operations. The MATLAB Applications package (MatApps) is a collection of gravitational-wave data analysis tools for use within the MATLAB environment that were written by the LSC members in support the analysis of LIGO, Virgo, and GEO data. This software is now maintained as part of the LSC MATLAB Applications (MatApps) project. Many of the contributions to MatApps are complete analysis tools developed by individual scientists and, as a result, there was considerable duplication within the repository. Recent initiatives seek to streamline the repository, better document its contents and share this knowledge with the MatApps community in order to minimize the duplication of efforts and increase ease of use. Streamlining has taken the form of migrating MatApps from a CVS to an SVN and flattening the repository structure for better intuitive use; this effort is ongoing. Improving the communication within MatApps includes the creation of a MatApps wiki, where users (including MatApps leadership) are continually developing the documentation content, and the creation of a MatApps discussion email list where users ask questions of the community at-large. A pilot newsletter has been issued and will be used in the future to communicate general information that may affect a user's interaction with MatApps (outages, new features in the latest MATLAB release, etc.). Better user support efforts are ongoing and include the creation of a dedicated RT tracking system for users to seek assistance with MatApps. Finally, MatApps intends to further reduce duplication of efforts by integrating more with other software projects within the LSC (e.g. LAL/LALApps, PyLAL, GLUE). Specifically, im-

provement to I/O routines can be made by interfacing with LDR and LDAS data catalogs. Through these streamlining and communication efforts, the collaboration will significantly increase the verifiability and maintainability of this analysis software, while simultaneously reducing the barrier to the development of analysis software by individual researchers, educators and students.

5. **LIGO Data Analysis Systems Software** The LIGO Data Analysis Systems (LDAS) includes an important software component which provides (among other things) a frame API for interacting and reducing gravitational-wave frame data, a diskcache API for tracking the location of tens of millions of files mounted on hundreds of filesystems, a job management service for running frame and diskcache API jobs, and the maintenance of a C++ library for interacting with frame data. LDAS RDS and calibrated strain data generation, the data finding service provided by GLUE, and the data replication publishing service provided within LDR are among the software components that use LDAS software services.

6. **Support and Release of Software** The LSC now releases a unified build of the LSCSoft bundle for use by the LSC and other gravitational-wave scientists. This release method will be enhanced to include better support of platforms other than the cluster operating systems selected by the CompComm and DASWG.

   A well defined LSCSoft Software Release Protocol [5] has been developed over the past two years and is currently in use. This protocol requires that inclusion of new or modification/updating of existing packages in the LSCSoft bundle must be approved first by the Software Change Control Board (SCCB). These packages are then built, by the repository maintainers, for the officially supported operating systems [*Scientific Linux 6.1 Debian 6.0 Squeeze and MacOS X Snow Leopard*].

   These packages [*rpm*'s for Scientific Linux, *deb*'s for Debian] are maintained in `YUM` [for Scientific Linux] and `APTITUDE` [for Debian] repositories at UWM. The external *MacPorts* repository is used for MacOS X. These comprise *Testing* and *Production* repositories. The Scientific Linux build process leverages modern virtualization technologies, i.e., a testbed of Virtual Machines at UWM [*Xen, VMWare, VirtualBox*] which are used for building & testing the built the software before publishing it to the testing repositories and announcing their availability to the DASWG email list. For the Debian packages, a similar process [but without using virtualization technologies] is carried out by the Debian Team at Hannover Univ., which also maintains a mirror of the UWM repository. Once the testing phase ends, and if no errors are found in the packages, they are moved to the production repositories upon approval by the SCCB. The corresponding announcement of the official release is then made to DASWG email list.

   The next step in this project is to deliver fully functional virtual-machine images to downstream users. Initially, virtual machines will include the full LSCSoft bundle and LDG client installed and configured to provide a fully integrated environment for analysis. It is further anticipated that users may wish to have custom configured virtual machines with selected software and applications installed. An interface will be developed to allow users to request such VMs which will be automatically built and delivered to them. In the long term, this approach will allow the LSC to maximally leverage Cloud Computing technologies and may provide a route to reduce the total cost of computing for gravitational-wave astronomy.

7.4 Intermediate-term development activities

The distributed LDG relies on a number of grid services to allow robust, efficient operations. A minimal subset are currently deployed on the LDG. The full set is outlined here along with estimated personnel

[5] `https://www.lsc-group.phys.uwm.edu/daswg/wiki/SoftwareReleaseProtocol`

requirements to support, enhance and deploy them where appropriate.

1. **Problem Tracking and Support** Robust operation of the LDG requires detailed problem tracking to insure that services are maintained and that security issues are quickly and efficiently addressed. There is already web based problem tracking facilities. This service needs to be extended and integrated with the LDG monitoring services. Over the next year, the informal knowledge base that exists in mailing lists and sprinkled throughout web pages and wikis will be harvested to develop a powerful and extensible help system. Furthermore, problem reporting and tracking will be simplified.

2. **Authentication and Authorization** The LSC relies on the Grid Security Infrastructure (GSI) from the Globus toolkit to authenticate users. GSI authenticates using X.509 certificates, which are currently obtained from a number of nationally operated grid certificate authorities from countries in which LSC member institutions reside. User access is provided at each site via hand-maintained grid map files. Users access standard unix accounts which are provisioned by hand by administrators. This approach does not scale sufficiently for the LDG. The OSG is using the VOMS-GUMS-PRIMA model for this purpose. The LSC has deployed these tools to share resources with OSG, but needs to explore all technologies that meet the collaboration's needs.

   Within the next year, this model will change substantially. Using the centralized authentication and authorization infrastructure currently being developed in the LSC and LIGO lab, short-lived X.509 certificates and proxy certificates will be supplied by MyProxy backed by LIGO.ORG CAs. MyProxy will leverage the existing centralized authentication infrastructure (in particular the LIGO.ORG and LIGO-GUEST.ORG kerberos realms) to link these certificates to user's identity in the LIGO.ORG LDAP. This will allow the capability for fine-grained access control and for automatic and uniform account provisioning on the LDG. Over the next several years, LIGO will be seeking TAG-PMA accreditation for the LIGO CAs to allow LIGO users to seamlessly interact with other scientific grids such as OSG.

   These developments are part of a larger effort, known as the Auth Project, which is described in more detail in 7.5.

3. **Monitoring Services** While the current LDG infrastructure is working well, it lacks of a fully deployed monitoring/information system. Having easy access to current information about the health of the LDG would allow us to prevent problems and/or troubleshooting issues much more effectively. Moreover, having access to historical data about usage and health of the LDG would facilitate decision making when the time comes to enhance or adjust the LDG. It is clear that aLIGO will require a considerable growth in the current computational infrastructure that will benefit from a fully functional monitoring service.

   One type of information inherent to grid computing models describes the status of clusters, their processes, their services, the status of jobs on the cluster, and the status of connectivity between clusters. In order to maximize the throughput, users and job submitting agents need to have access to this information. The LDG currently uses Ganglia to obtain snapshots of the status of clusters at different locations and then reports them to a central Ganglia metadata server. Enhancing monitoring services by including new tools to collate the information collected and to provide a consolidated Grid friendly interface is an essential step to improve efficiency.

   A prototype information service, the LSC Grid Information Service (LSCGIS), has been deployed which uses standard cluster monitoring tools and scripts to gather the required information and then exposes it via a RESTFul web service. This LDG-customized project can be enhanced by integrating it together with more general tools such as *Nagios*, for a finer metadata gathering. While this information is currently used to prevent/fix problems, it is clear that it can also be used to feed information into analysis pipelines or workflows to make them aware of available infrastructure and to make them more intelligent. The prototype LSCGIS should will continue to be evolved to address all of these possibilities.

4. **LIGO Data Replicator** The LIGO Data Replicator (LDR) replicates bulk interferometer data files to LIGO Data Grid (LDG) computing sites, as well as the Virgo site in Cascina, Italy (CSC). LDR provides a metadata catalog for gravitational wave data files (typically with extensions .gwf and .sft) that in conjunction with other tools allows LIGO and Virgo scientists and their codes to discover data and other files within the LDG. Replication begins when data is *published* into the LDR network at a site. Publishing implies that relevant metadata about a file is entered into the local metadata catalog that is part of LDR and that a mapping from the logical filename (LFN) to an access path (typically a URL) or physical filename (PFN) is created in the local replica catalog (LRC). By the end of the LIGO S6 science run the LDR metadata catalog contained metadata information on more then 35 million files and each RLS replica catalog is expected to hold between 1 and 50 million mappings, depending on the data sets replicated to each site. Currently LDR is deployed at the LIGO Hanford observatory (LHO), LIGO Livingston observatory (LLO), Caltech (CIT), Massachusetts Institute of Technology (MIT), Syracuse University (SYR), University of Wisconsin-Milwaukee (UWM), Albert Einstein Institute Hannover (HAN), Cardiff University (CDF), and Birmingham University (BHM), as well as the Virgo site CSC. The CDF and BHM deployments leverage the "LDR as a service" model where only a GridFTP server is deployed at the site and the rest of the LDR logic and tools are hosted at UWM and provided as a service to the site. Investigations and testing continue to ensure scalability and performance meet the demands for the post enhanced LIGO era, especially since data from both the Virgo and GEO instruments will continue to be published, replicated, and discovered using LDR even as the LIGO instruments turn off after S6. Specific directions include tightly integrated web based monitoring to further ease the administrative burden, as well as migrating the LRC to a web services and more robust server platform.

5. **Data Quality and Segment Database** The lightweight database daemon (LDBD) provides a client and server framework for scientific meta-data services. LDBD is built on top of the existing LIGO authentication and authorization services, with a relational database back-end (DB2). This framework is designed to be extensible; the first application using it is the interferometer data quality service (Segment Database). Tools have been developed for low latency discovery and archival of Science and DQ segments for the S6 online and offline analysis. Two production servers at Caltech and a development server at Syracuse are currently providing critical metadata services for the LSC and Virgo collaborations.

   This S6 data-quality service is currently being enhanced to better meet the needs of online data-analyses and control-room work through a combination of improvements to the existing database infrastructure and the implementation of new, related data-quality services and APIs. In addition to scalability and reliability improvements, these will deliver metadata at lower latencies and higher rates, and enable the development of more powerful, integrated client tools. For example, core DQ flag generation is being moved to the Online Detector Characterization system (section 2.2.5) to avoid timing errors and enable offline data analyses to access critical data-quality information directly in frames. Additional (expensive or otherwise offline-generated) DQ flags will continue to be inserted into the SegDB from other sources. Specific improvements include simplifying and improving the performance of the Segment Database by allowing trigger metadata to be stored in a dedicated trigger database supporting sub-1Hz resolution and additional metadata. Critically, a consistent API between these data-quality services will facilitate the implementation of more powerful client tools that can access and synthesize information from the segment database, conlog, and trigger database.

6. **Event Database and Archival Project** The gravitational-wave candidate event database (GraCEDb) is a prototype system to organize candidate events from gravitational-wave searches and to provide an environment to record information about follow-ups. A simple client tool is provided in Glue to submit a candidate event to the database.

   An entity submits an event to Gracedb using the client tool in Glue or via the web interface. At the time of submission, the following things happen: 1) A unique ID is assigned to the candidate event. This UID is reported to the entity submitting the candidate event. The UID takes the form GXXXX, where XXXX is a number with a minimum of four digits. Extra digits will be used as needed. The UID is intended for internal use only. 2) The submitter, the search group, the search type that generated the event are recorded. 3) A web area is created to hold information about the candidate event and any follow-ups that are performed. These directories are accessible via web browsers and by logging into any of the submit machines at UWM, in particular hydra.phys.uwm.edu:/archive/gracedb/data/GXXXX. The general directories have the same permissions as /tmp in a Unix file system, so any LVC users can add content under that directory. The use of directories based on ligo.org usernames is encouraged to keep things organized. 4) A wiki page is created to allow easy entry of information about the candidate event. 5) An alert is published to the corresponding node in the LVAlert system; subscribers to that node receive the alert and initiate follow-ups. Alerts are also sent to the gracedb@ligo.org mailing list.

   As with the DQ and Segment Database, the database lacks robust monitoring and fail-over solutions. The production database is backed up, but no hot spare exists. An automated fail-over solution must be developed, along with replication of event information to redundant off-site systems. In the intermediate term, production-level support will be provided for the LSC and Virgo collaborations through the end of the S6 run and during the era that VSR3 and GEO-HF will be operating.

   LARS will be a collection of tools and services that provides archival storage for LIGO. A prototype has been delivered. The user tools are simple programs that are intended to allow LIGO scientists to catalog and share search results. Users may add descriptions and locations of search results to a simple database. This database may be queried by others to discover result locations. Individual results may be narrowed within a search by specifying a description in the result's LALCache. When found, query results may be listed or data may be presented to the user in a local directory, if sshfs is available. Work has started to leverage cli.globus.org services to provide transparent and efficient transport and distribution of data products by users. When implemented, we anticipate LARS will become an important tool for scientists.

7. **Multi-Site Scheduling and Brokering** The ability to plan, schedule, and monitor large workflows simultaneously across multiple LDG sites is becoming increasingly necessary in order to load balance across the computational resources distributed throughout the LDG and to support ever larger workflows which cannot easily or always be serviced within time constraints at a single LDG site. A number of intermediate-term development activities are focused on supporting LIGO data analysis workflows across multiple LDG sites as well as other "grid" sites external to LDG.

   One such activity focuses on leveraging the "Grid Universe" available with the Condor High Throughput Computing system and in particular "Condor-C", the Condor Grid type. Currently Condor manages most LDG computational resources (Linux clusters) at a site level. That is, each Linux cluster resource is its own Condor pool and jobs submitted to be run and managed at any single site only run within that same Condor pool. When properly configured, however, the jobs submitted at one site and into one Condor pool may migrate and be run and managed by a remote Condor pool, with the results and output being staged back to the original submission site as if the jobs had ran at the submitting site. An earlier attempt by Condor to support this type of migration of jobs was the Condor "flocking" mechanism. This newer approach known as Condor-C promises to scale better. LDG staff are evaluating Condor-C throughput and scaling behavior and providing feedback to the Condor team, as well as working to understand how best to abstract the details of Condor-C job submission and management away so that LDG users do not have to manage the details themselves.

While Condor-C provides the "plumbing" to allow jobs to flow between clusters, LSC-Virgo workflows must be written to take advantage of the transport mechanisms Condor-C provides. One approach to solving this problem is leverages the Pegasus workflow mapping engine. GLUE has the ability to output LSC-Virgo workflows in the abstract directed acyclic graphs (DAX) format (this is now the standard format used by CBC workflows). The Pegasus workflow planner can then be used to render these "abstract" workflows to "concrete" Condor DAGs. The actual management of the workflow is handled by Condor DAGMan. At present, Pegasus translates CBC workflows to Condor DAGs consisting of standard and vanilla Condor universe jobs targeted for a single LDG cluster. Pegasus provdes services such as bundling short running jobs into larger jobs and better management of input and output data products. LDG scientists are currently investigating Pegasus' ability to render workflows as Condor-C jobs which would allow execution across multiple LDG sites connected with Condor-C.

Pegasus can plan also plan workflows for execution across sites that do not run Condor pools as well as into sites that do run Condor pools. LDG staff are evaluating Pegasus and working to understand how to tune Pegasus to schedule LIGO workflows across non-LSC sites (such as the OSG) most efficiently.

Finally, the use of pilot servers to provide a simple interface for the users that want to submit jobs on the LDG, but have them run on other resources including those available to the Virgo collaboration. An existing test system will be duplicated and extended to provide efficient resource sharing across the LDG.

8. **Test and Build** To ensure the successful analysis of LIGO-Virgo data, it is increasing important to automate the validation of LIGO software and infrastructure. With continuous advancements in scientific analyses and computing technology, LIGO's software and computing infrastructure is growing in size and complexity. This trend is driving the need for more automated validation.

   As a result, automated build and test systems such as the NSF-sponsored Metronome framework can be of enormous benefit to LIGO. Such automated testing is also critical to the validation of changes to LDG system architecture, operating systems, and runtime environment. However, regression testing a distributed software stack is a computationally demanding task—an apparently harmless update of one component can cause subtle failures elsewhere in the system. And in the event of a critical security patch to one or more components, regression validation of the entire system absolutely must happen very quickly.

   Enabling an automated testing solution tailored to the needs of LIGO's distributed computing environment, will help ensure that changes to LIGO code or to LDG system architecture, operating systems, and runtime environment do not cause unexpected and undesirable changes to scientific results. Additional testing resources would also support testing the reproducibility of past results in the face of such changes. Automated test and build is essential to enable higher-quality software and prevent "bitrot" as LIGO scales past the capabilities of largely manual software and infrastructure validation processes.

9. **gstLAL** gstLAL in a software project to wrap the GW data analysis machinery of LALSuite in GStreamer "elements". GStreamer is a free C library that provides the infrastructure required to build complex realtime and non-realtime digital signal processing pipelines. GStreamer is primarily

intended to be used in multimedia applications for the desktop, but it is of high quality with many features and easily satisfies our own needs for data analysis pipelines.

Using gstLAL, a prototype application is being developed to search for the gravitational-waves from collisions of very low-mass primordial black holes. The PBH templates used by the search are up to 30 minutes long, and so the completion of this search will serve as a technology demonstrator for Advanced LIGO, proving that we have the software infrastructure required to handle the long templates in the flagship binary neutron star search. At present the PBH trigger generator program runs, but many problems remain to be solved before a full PBH search can be completed, for example how to perform background estimation with such long templates and how to practically construct banks of such long templates. These problems are outside the scope of gstLAL itself but the further development of gstLAL will be driven by their solution.

7.5 Preparing for the advanced detector era

Work on the requirements for the hardware, software and services needed for gravitational-wave astronomy in the Advanced Detector Era (ADE) has been ongoing for several years now. A number of discussions and presentations have allowed the CompComm and DASWG to build a task list and determine the approximate FTE count to meet the needs.

Towards the end of 2010, a proposal was prepared to support the continued operations of the LIGO Data Grid, including software support, enhancement, and release. In addition, in 2011 a plan was presented for a sequence of engineering runs to test this infrastructure.

Following a table of tasks and FTE requirements, this section gives a summary of the engineering run plans, followed by more details of the larger projects that will need to be completed in order to leverage the advanced detectors for maximal scientific productivity.

7.5.1 Engineering Runs

In 2011, a sequence of engineering runs was planned that would:

- Test important software and computing infrastructure.
- Establish run procedures for the Advanced Detector Era.
- Test detector characterization using real subsystem data.
- Measure progress on software for key science goals.

The runs were named and tentatively scheduled for dates within this time frame:

- ER1: January - February 2012. (Complete)
- ER2: July - August 2012. (Ongoing)
- ER3: January - February 2013.
- ER4: Coincident with advanced detectors coming online in 2013.
- ER5: Coincident with advanced detectors coming online in 2014.
- ER6: Coincident with advanced detectors coming online in 2014.

	Task	Support	Programming	Architect	FTE total
Applications	DQ pipelines	TBD	TBD	TBD	TBD
	Low-latency analysis	TBD	TBD	TBD	TBD
	Offline analysis	TBD	TBD	TBD	TBD
	Simulations	TBD	TBD	TBD	TBD
	Other applications	TBD	TBD	TBD	TBD
	Open Data Workshops	TBD	TBD	TBD	TBD
	Task	Support	Programming	Architect	FTE total
Data Handling and Analysis Software	Architect	0	0	0.5	0.5
	Software R&D	0	0.5	0.5	1
	Support	0.6	0	0	0.6
	I/O Libraries	0.2	0.8	0	1
	Low-latency tools	0.5	0.5	0.5	1.5
	MatApps	0.3	0.7	0	1
	Service Clients	0.2	0.4	0	0.6
	LDAS	0.3	0.7	0	1
	LAL Suite (LAL, Glue, Pylal)	0.6	1.4	0	2
	DMT	0.4	1.4	0.2	2
	NDS	0.2	0.2	0	0.4
	LIGO DV	0.3	0.7	0	1
	Open Data Software Support	TBD	TBD	TBD	TBD
	Open Data Documentation	TBD	TBD	TBD	TBD
	Task	Support	Programming	Architect	FTE total
Data Handling and Analysis Services	Architect	0	0	0.5	0.5
	Middleware R&D	0	0.5	0.5	1
	Support	0.6	0	0	0.6
	Build & Test	0.4	0.3	0.3	1
	Workflow Service	0.4	0.3	0.3	1
	OSG/EGEE Integration	0.6	0.2	0.2	1
	Monitoring	0.4	0.2	0.2	0.8
	LDR	0.5	1.3	0.2	2
	DQ Database	0.5	1.2	0.3	2
	GRaCEDb	0.5	1.2	0.3	2
	Open Data Web Services	TBD	TBD	TBD	TBD
	Auth/Roster	0.5	1.2	0.3	2
	h(t) production	0.2	0.4	0.1	0.7
	RDS generation	0.2	0.4	0.1	0.7
	Open Data Support Services	TBD	TBD	TBD	TBD
	Open Data Cleaning	TBD	TBD	TBD	TBD
	Task	Support	Programming	Architect	FTE total
Data Center Operations	UWM-WebS	0.6	0.2	0.2	1
	UWM-Tier2	1	0	0	1
	SYR-Tier2	1	0	0	1
	LLO	1.5	0	0	1.5
	LHO	1.5	0	0	1.5
	MIT	1	0	0	1
	CIT	3	0	0.5	3.5
	Open Data Centers	TBD	TBD	TBD	TBD
	Totals	18	14.7	5.7	38.4

Table 1: A list of tasks and FTE requirements for LIGO Data Grid operations and software/service design, development, release and support. The support activity includes administration, help desks, packaging, testing, release. The architect activity refers to high-level architecture development. Notice that the applications layer is considered separately from core operations and support activities. All open-data activities remain TBD until the plan is formulated and accepted.

This schedule is timed to allow groups to report on milestones/metrics at the following LIGO-Virgo meeting. The runs will also become longer and more integrated with interferometer data as the advanced detector subsystems come online. After the last run, the software infrastructure will be in place and have been tested to prepare for the first ADE science run.

As of the writing of this white paper, ER1 has been completed. It ran from January 18 to February 15 2012. The goals for ER1 were to deploy improved low-latency data transfer and access tools, test the mock-data-challenge signal generation infrastructure, establish science metrics for analyses, and test the DAQ at Livingston, and to encourage detector characterization on existing sub-system data there.

Both the low-latency transfer (LLD) and bulk transfer (LDR) networks were run. Simulated H1, H2, L1, and V1 data was generated using the noise curves for high power aLIGO and advanced Virgo. Burst injections were done at known times every $10,000$s, and blind compact binary signals were injected at about the best-guess astrophysical rate, uniformly distributed in space.

Low latency analysis was done by the cWB, gstlal-inspiral, and MBTA pipelines. A list of gravitational-wave (injection) candidates was prepared by gstlal-inspiral in advance of unblinding which reported three with 5-σ confidence. After the injections were unblinded on 15 March, performance reports were prepared for the three pipelines and it was shown that the gravitational-wave (injection) candidates identified by gstlal-inspiral were indeed blind injections.

The next engineering run, ER2 (scheduled for July 11 to August 8, 2012) is in progress at time of writing. Its goals are to deploy prototype h(t) system for LIGO, deploy prototype low-latency detector characterization environment at the LIGO sites, test connection to Transient Alert Network (GCN), harden existing services, and benchmark further searches.

There is also the goal (for ER2 or the next run) to recolor real subsystem data (e.g., from the PSL which currently is running for H1 and L1) to generated the fake mock-data-challenge-data. In this way, real detector characterization activities can be connected with the astrophysical searches of the data.

The proposal for ER3 is to run from January 23 to February 20, 2013. After this, the runs will hopefully coincide with the detectors coming on line. In this way, the engineering runs will begin to bring together the software and detectors in complete end-to-end tests in preparation for the first ADE science run.

7.5.2 Software

A list of critical software development areas follows below. Most of these are tied to existing DASWG projects. A number of efforts are under way to prototype GPU enabled analysis codes, to wrap existing libraries for use in python (and other languages), and to develop standalone software toolkits for data analysis. Over the next 12 months, the LSC will review these prototyping activities, establish formal software projects or merge with existing projects, and sunset activities that are duplicating existing capabilities.

1. **I/O Libraries** Because of the volume of data involved and the complexity of the algorithms we use to process it, searches for gravitational waves can quickly transform from problems of astrophysics and astronomy to problems of data management. Experience has taught us that the ease and speed with which data analysis challenges are solved is often closely related to the quality of the software libraries used to read and write data products, and so the selection of an I/O library is an important step in the development of a search for gravitational waves. Libraries with well-designed interfaces and robust bug-free internals allow us to spend more time doing science and less time solving I/O problems.

   Today, our searches rely on a combination of I/O libraries developed in-house and libraries maintained by third parties. Libraries developed in-house provide the benefit of being under our control — bugs that affect us are fixed when we need them to be, and we choose when to change software interfaces and file formats — but suffer by requiring people within the collaborations to do the design and maintenance work, people who often do not have a great deal of experience engineering and maintaining complex software projects and whose time is principally allocated to other tasks. Libraries developed externally, on the other hand, are often designed and maintained by people with greater software engineering experience, but sometimes see interface changes occur at times that are not convenient for us.

We have seen a trend within the collaboration to transition from in-house libraries to libraries developed externally. For example, much of our XML I/O now relies on professionally-maintained XML parsers like expat instead of the metaio library developed in-house. In the future, this trend should continue. Whenever a new I/O challenge presents itself every effort should be made to research existing solutions, and use them when possible. In particular, we foresee a growing need for the network transport of many different types of data including astronomical alerts, audio-frequency time-series data in both realtime and non-realtime, database queries and other kinds of remote procedure calls. An enormous variety of technologies has already been developed for solving problems of these types and more. It is important to use those existing solutions whenever possible to allow the expertise and time of their designers and maintainers to streamline our own work, and to help drive the development of those projects so that gravitational wave astronomy can contribute to technological progress in other areas as well.

2. **Low-latency tools** It is not yet clear whether or not a network of ground-based gravitational-wave antennas can be used to successfully provide alerts of transient events to non-GW observatories, there is a significant probability that useful alerts will continue to flow the other way for many years into the advanced detector era. However, one of the challenges facing the search for GWs from binary neutron star collisions in the advanced detector era is the length of the template waveforms required by the search and the number of them. Advanced LIGO BNS templates might be up to 30 minutes in length and be more than an order of magnitude more numerous than the 45 s long templates used by Initial LIGO. The increase in the BNS search's computational complexity indicates the need for a new approach to the problem of matched-filtering, in particular the desire is to develop techniques that allow data to be processed in small chunks *less* than the length of a single template. We have been addressing this need by developing a new software project named gstlal. See `http://www.lsc-group.uwm.edu/daswg/projects/gstlal.html`. Although the development of this technology is motivated by the need to reduce the memory requirements of the analysis pipeline, a side-effect of the effort has been the creation of a suite of data analysis software tools that allow the creation of pipelines in which the time delay between data going in and answer coming out is short.

   The data analysis machinery used by gstlal continues to reside within the lalsuite of libraries (see below). gstlal wraps the lalsuite machinery in GStreamer "elements". GStreamer is a free C library providing the infrastructure required to assemble digital signal processing pipelines, and although it is primarily used to implement multimedia recording and playback on desktop computers, the GStreamer library is of very high quality and easily satisfies all of our own needs for such a library. By using it, not only do we leverage the design experience of GStreamer's developers, but the bug fixes and feature enhancements we have provided back to the project can now be found in Nokia cell phones where GStreamer provides the multimedia playback software, making the gstlal project one of the few places where GW data analysis can be said to have provided industrially-relevant spin-off technology.

   A prototype application has been constructed using the tools provided by gstlal to search LIGO and Virgo data for GWs from compact object collisions. Because gstlal-based applications also have access to all the machinery of GStreamer, they are easily interfaced to network protocols, sound cards and multimedia file formats, and so in the future gstlal might be useful for outreach activities. For example, one could imagine writing software to demonstrate what GWs sound like, allow users to add simulated GWs to simulated detector data streams to hear how different detector configurations make it easier or harder to find different GWs, and so on.

3. **Low-latency data distribution (lldd)** Rapid analysis of data from the global gravitational-wave network requires aggregation of the gravitational-wave strain channels at a central processing location. The low-latency data distribution network is being developed to meet this need. A prototype system was developed, released, and deployed during the past year. It has been used during ER1 and ER2 to allow low-latency transient searches to deliver gravitational-wave triggers to a central database in under a minute after data acquisition. The same system will be used at the observatories to deliver raw interferometer data to the clusters for rapid detector characterization activities. Over the next 12 months, the `lldd` software package will be enhanced to provide improved monitoring and more robust data transfers. Performance results from ER2 will be used to prioritize the next development activities with the goal of a mature low-latency distribution network by the start of ER4.

4. **MatApps** With Advanced LIGO comes the prospect of the first direct detection of gravitational waves and the beginning of the field of gravitational wave astronomy. As a consequence, real-time data analysis will have increased importance as will rapid prototyping of code and visualization of results. While MATLAB is not the only choice users have to achieve these goals, MatApps intends to support this effort by building its infrastructure through coordination and communication with the MATLAB-using community. Coordination needs to be developed between MATLAB-rich repositories that exist outside of MatApps (e.g. LigoDV) to promote ease of code development and to reduce duplication of efforts. Communication is the foundation of user support in MatApps. While we will continue to address individual user questions and concerns, we want to develop the MatApps community to be a clearinghouse of best practices to achieve computational speed and ease of use. We also intend to communicate MATLAB knowledge through documentation. MATLAB is a powerful tool for use in the grid computing environment and we intend to promote its use in this way by keeping complete documentation in a centralized location and offering training to those who wish to gain experience. MathWorks, the author of MATLAB, often updates MATLAB several times a year and we intend to streamline our vetting of new versions and updating documentation about any issues or other considerations so that users may take advantage of the latest features. These new initiatives, combined with our ongoing efforts, will help scaffold the increased demand for data analysis results that Advanced LIGO will introduce.

5. **LAL Suite (LAL, Glue, Pylal)** The LAL Suite of tools has grown beyond its initial scope to include I/O libraries, time and frequency series analysis tools, and domain-specific functionality that enables scientists to access and analyze gravitational-wave data. The development model adopted during the first generation LIGO science runs was deliberately agile. It allowed the developers, largely the same group as the user base, to be remarkably fleet-footed. The LAL Suite user base continues to expand. Indeed, the software has been used by scientists involved in the LISA mock data challenge demonstrating the utility of the software beyond LIGO. It is timely, as advanced instrumentation is installed in the LIGO facilities, to rework and retool LAL Suite to meet the decade-long scientific campaign that lies ahead by providing LSC scientists as well as the wider community of gravitational-wave astronomers with a toolbox for performing gravitational wave data analysis and simulation.

   As LAL Suite developed organically without an imposed final design, the code is not as clean, or general, as it could be. Therefore one of the first steps in improving the sustainability of LAL Suite for the future is to ensure that it has a clean, and easy to understand API (Application Programming

Interface). Another effect of the organic development of LAL Suite is that there are numerous functions that are no longer used and that there are many functions that perform similar tasks. The code base will be simplified by unifying these similar functions, thereby decreasing the amount of code redundancy.

While having a clean code base will greatly improve the maintainability and sustainability of the code, another critical aspect is adequate documentation of the software. The LAL code has now been restructured, but unfortunately the documentation has not; therefore the documentation sectioning does follow the current structure of LAL Suite. The documentation will be unified and restructured to improve the clarity and usefulness.

LAL Suite was originally written using the C89 standard, as at the time the C99 standard had been approved but there where no shipping compilers that supported the standard to an acceptable level. This is no longer the case. C99 provides many improvements and features to the C language which will help in the maintenance of LAL Suite. The adoption of the C99 standard has already started in several minor, but key, areas: the first of which is the use of the C99 fixed-width integer datatypes. The C89 standard did not define the size of the integer datatypes, and therefore they are platform and compiler dependent. As LAL Suite is used on multiple platforms with different compilers, a way was needed to ensure that the integer datatypes were consistent across the different platforms. This led to custom code that determined the size of the various integer datatypes and made the appropriate typedefs. The C99 standard provides fixed width integer datatypes that are of the same size regardless of platform and compiler. Using these greatly simplifies the code base which leads to increased maintainability.

There are many functions in LAL that are very similar and only differ in the datatype on which they operate. This leads to a lot of similar code that needs to be maintained consistently so that errors are not introduced by updating one function and not another. Ways in which this duplicated code can be reduced will be investigated.

Another key feature that is provided by the C99 standard is support for complex numbers and complex arithmetic. Currently LAL defines is own complex datatype as a structure with two floating point fields. While this accomplishes the task of representing complex numbers, it complicates matters as helper functions need to be written to perform simple arithmetic. This greatly complicates the code base, and a transition to the built in complex type will alleviate a lot of problems. The C99 complex type is however not entirely a drop in replacement for the current LAL complex structure therefore, so an in depth study will be done in order to determine the optimal way to transition to the native C99 complex datatypes.

The ability to simulate the gravitational wave strain that would be produced from various types of astrophysical sources, e.g., coalescing compact binaries, continuous waves from distorted pulsars, random gravitational-wave noise from the early universe, is an important feature of the LAL libraries. However, the simulation software is currently integrated into individual searches, and is not exposed in a general, well documented, and easy-to-use API. This situation is unsatisfactory: one of the major functions that LAL Suite should perform is to provide the community with vetted software for gravitational waveform simulation. Therefore, one of the significant goals is to extract the routines that perform gravitational wave simulation from the individual search packages and combine them into a LALSimulation library. The routines will be re-implemented where necessary so that they have a common and useful interface. They will also be carefully documented community vetted so that their correctness is assured. This library will be the primary contribution of LAL Suite to the community of scientists outside of the LSC.

While it is important to have a clean and well-documented code base, it is also important that this code base is tested on a regular basis to ensure that the code works as expected, and that no code modifications lead to unexpected changes in behavior. One way towards achieving this is to implement unit tests which aim to isolate each part of the code and shows that each of these "units" behaves as expected. Ideally every function inside the LAL libraries should have a test associated with it, therefore individual functions can be regularly tested to ensure correct behavior. Unit tests best work when the library functions perform one simple task that can be easily tested; many of the core library functions are now being written to perform such single tasks, and are therefore amenable to effective unit testing. The unit tests will be developed for these routines within the existing testing environment. Testing of individual functions is a step in the right direction but to ensure that the code works as expected complete workflows need to be tested in addition to the unit tests. Therefore an investigation into a build and test systems, such as Metronome, will be made to determine how complete LAL Suite workflows can be tested on a regular basis.

Increasingly, programs are being writing in scripting languages, such as python, as these provide a quick and easy method to accomplish tasks. We are finding that we are frequently needing to access many of the LAL Suite functions within such scripting languages. To date, required functions have been manually wrapped by hand as needed, an approach which clearly will not scale and a task that will need to be done for each scripting language that needs access to these functions. SWIG (Simplified Wrapper and Interface Generator), is a tool that can be used to automate the generation of bindings and one of the main advantages is that once things are setup bindings for any supported language can be automatically created. It will therefore be investigated how SWIG can be used to automate generation of language bindings.

6. **DMT** With the upgrade of the Ligo Control and Data System (CDS) for Advanced LIGO the reference platform for the DMT will formally move from Solaris to Linux. In fact, because of the enormous offline computing power available from the Linux clusters, much of the recent DMT development has been tested on both Linux and Solaris insuring relatively simple porting to the new platform. Further development and rigorous testing will still be necessary for the online components, especially those involved in distributing online data to all the processes. Although at present, the plan is to leave the frame broadcasting mechanism much the same as for initial ligo, the opportunity to receive data more quickly by way of an direct connection to the CDS data network should be evaluated.

   Additional DMT software development will also be needed to monitor and characterize the new and more complex aLIGO interferometry.

   The use of the same operating system online and offline, provides the opportunity to unify the packaging and distribution of the online and offline DMT software. Already, much work has been done to unify the packaging of all software from the DMT/GDS package used by CDS DMT-online and DMT offline.

7. **NDS** The version 2 Network Data Server (NDS2) allows Ligo-Virgo collaboration members to access current and archived Ligo data remotely. The network protocol uses Kerberos to allow nearly transparent authentication by the Ligo-Virgo scientists while preventing access by unauthorized persons. Offline and online NDS2 servers are currently running at Caltech and LHO, respectively, with the offline server making all Ligo raw data acquired since the start of S5 available. The NDS2 client code has been interfaced to matlab, octave, python, C and C++. An example client application is the ligoDV viewer, described in the following section.

   This year the server and client have advanced considerably. The focus of recent development has been to:

- Improve server reliability: preventing hangups when requested data are temporarily not available or the server is swamped with requests.
- Improve error reporting and fail-over: Produce more meaningful error status returns and allow successful return of partial data if some channel is unavailable.
- Improve portability: Client interfaces have been added for several interpretive languages (matlab, octave and python) and building and packaging has been developed and tested on many platforms (centos, debian, solaris, Mac).

We expect that use of data from the NDS2 server will increase significantly in the future. NDS2 provides an exceptionally fast and convenient means to fetch data for real-time analysis. It may also provide a distribution mechanism for the proposed Open Data Initiative.

Future improvements will include ports to additional platforms (e.g. Windows) and improved dynamic data finding by the server.

8. **ligoDV** The LIGO Data Viewer (ligoDV) project `https://wiki.ligo.org/LDG/DASWG/LigoDV` is aimed at increasing the accessibility of LIGO data and standard data processing algorithms to all scientists within the LSC. It currently consists of two primary sub-projects, ligoDV and ligoDV-web, described below.

   The primary software tool in the project, ligoDV, is a Matlab-based graphical user interface that allows LSC members to connect to LIGO data servers, specifically the network data servers NDS and NDS2, and retrieve data. Furthermore it provides a platform for applying mathematical manipulations such as filters, Fourier transform, coherence, transfer functions and others to this data and finally exporting and/or plotting the results. The package is essentially operating system independent, since it consists of a collection of m-files that require only a graphics-capable Matlab installation and NDS2 client. Owing to the portability of the NDS client, ligoDV is also location independent allowing users to query data and do studies while at meetings or anywhere with an Internet connection. The ligoDV user-base has grown over the past few years and it is now used widely within the LSC. This in turn has aided detector characterization, commissioning and data analysis studies by lowering the hurdles required to access LIGO data.

   LigoDV has been in active development for most of the last year and a new version has been released with the following improvements.

   - Saving of configuration data specifying server, time intervals and channel selection.
   - Detailed documentation has been developed covering installation and usage. The program GUI now includes buttons that link to the appropriate section of the wiki.ligo.org describing how to use that function.
   - On line notification when a new version is available.
   - Improved error messages and pop-up error windows.
   - Improved filter module that allows viewing the combined response of several filters.
   - Minor changes to the user interface to streamline operation.

   In addition there have been a number of requests for enhancements to ligoDV.

   The following are the development priorities for ligoDV in the coming year.

   - Extend the configuration operations to include filter specification and plot products.

- Use the new SWIG/Java bindings to NDS2 to remove the need for Matlab/C interface to be compiled for each version of Matlab on each operating system. This also includes using a local database to cache channel lists for faster access.
- Continue expanding filtering options to add pole/zero specification and the ability to import Foton filter definitions.
- Add Omega-scan as a new plot product.
- Continue to refine the user interface with the goal being to simplify operation by disabling or hiding options not pertinent to the processes defined.
- Improve channel list handling to work with the millions of channels available in the aLIGO era.

The continued development of ligoDV will lead to a much improved tool. This will benefit the detector characterization and analysis work remaining for Enhanced LIGO. It will also be a central component of the Advanced LIGO detector characterization program that will be actively monitoring data during the establishment of the first Advanced LIGO subsystems (DetChar priority 1 in Section 2.2.3.

LigoDV-web is a new product in development `https://ldvw.ligo.caltech.edu`. As we saw more users of LigoDV, it became obvious that the our biggest impediment to expanding the user base is the cost/availability of Matlab and the installation of the NDS2 client on desktop systems that are not running a reference operating system. While there have been vast improvements in the portability of the NDS2 client it can still be a challenge to install. There will always be a significant fraction of the LSC that can benefit from a web-based client that has essentially no accessibility barriers to allow quick-look studies of the data.

LigoDV-web is a Java based thin-client model product that has no installation requirements except a modern browser with javascript enabled. It uses the NDS2 client to access data and will provide most of the products available in LigoDV. It is fully integrated with the ligo.org Shibboleth authentication so that LSC-Virgo users can gain access to the site using their logo.org credentials. It provides quick easy access to all available data (raw, online, RDS, trend) on most Internet appliances including smart phones, tablets and computers. Furthermore, the channel list retrieval, databasing, data retrieval, calculations, and plot generation are all done server-side such that users need only specify a plot, wait, and then see it appear in their browser - at which point it has also been archived and they can share it as a link with others.

The development priorities for LigoDV-web over the next year are as follows.

- Continue development of the infrastructure to improve robustness, speed and improve the user experience.
- Allow users to export data products such as spectra and time series in formats that are easily read into other code such as python or Matlab for further analysis.
- Prefiltering data to ameliorate frequency leakage for data with a very large dynamic range (such as strain data).
- New plot products such as histograms, coherence and transfer functions.
- Automatic updating plots of online data.
- Offline processing of requests that require too much time for browsers to wait.

7.5.3 Services

1. **Network Data Simulator** It will be important to continually test and assess the data analysis infrastructure for the advanced detector era as it is developed. A new project will be established to simulate the data streams from the network of gravitational-wave detectors and deliver it to analysts by the same means they can expect during future observing runs. This will allow users to develop their analysis tools with knowledge of the key infrastructure and an operational testbed against which to test. A key component of this project will be to run regular and long-lived mock data challenges of increasing complexity which will allow the collaborations to efficiently benchmark analysis codes against each other. This project will be initiated in the coming year. Details should be available by mid 2011.

2. **Monitoring** The main advantage of having a customized solution to provide LDG metadata is that it can be integrated, redesigned and reconfigured at will, with almost any other tools designed to gather information about complex infrastructures. The LSCGIS prototype can be integrated with less flexible tools such as Nagios, ReSS (Re_source Selection Service, used by OSG), BDII, Relational DataBases, etc., which can help to improve the information service. Implemented as a RESTFul Web Service, LSCGIS is flexible and scalable enough that it can even use web technologies such as Google Maps API, PHP dynamic server scripting, be displayed in Internet enabled cellphones, etc.

   Under the umbrella of this project several studies are being carried out to choose among the best Grid monitoring technologies and to integrate them in a customized monitoring environment for LDG. The **OSG ReSS** is particularly interesting since it can also be integrated with Condor-G, which could be useful once LDG transitions from a Data Grid towards a Computational Grid, with the aid of other Grid technologies.

   Also, studies about integration of Identity Management technologies (Kerberos, MyProxy, LIGO Auth Project, etc.) with Monitoring services are being considered. We are convinced that no a single solution will be enough to cover all the needs of a complex VO such as LSC/VIRGO and that the integration of several customized proposals will be the best approach to keep the computational infrastructure as flexible and scalable as possible. Besides, intelligent workflows will need of all the best available information gathering and customized solutions in order to retrieve useful and relevant LDG metadata and use it as input for the analysis pipelines.

3. **LIGO Data Replicator (LDR)** Initial and enhanced LIGO have clearly demonstrated the need for bulk replication of interferometer data sets to computing centers around the world during the advanced detector era. The growing development of “real time” or stream based analysis in addition to file based analysis does not diminish the need for robust replication of curated interferometer data sets to computing sites for efficient consumption by data analysts and their codes.

   The experience gained during the LIGO S6 science run with data replication provided as a service (“LDR as a service”) to the Cardiff University and Birmingham University groups demonstrated that the software as a service (SAS) model for bulk data replication in the advanced interferometer era is not only viable but preferred. Individual computing sites are simply not staffed at a level that allows deep knowledge at each local site of all the necessary details for robust and continuous replication of data. Instead, the LDR as a service model demonstrated the efficiency of requiring at a computing site only a standards-based interface to local site storage (usually GridFTP) and then locating the rest of the necessary logic and tooling at a centrally managed collaboration facility, where local experts can monitor and tune the replication network over time.

   Of course moving all of the LDR functionality except for the interface to local site storage to one physical facility carries the risk that the entire replication network could fail if that one central facility should be cut off from the internet or go down for whatever reason. In the advanced detector era, hence, LDR as a service must evolve so that it leverages the necessary tools and infrastructure to provide a high availability service with failover capabilities supported by a small but expertly staffed geographically distributed set of data centers.

The S6 and earlier science runs have also demonstrated that data discovery, as provided most recently by the server tool LDRDataFindServer and the client tool ligo_data_find, should be to some extent decoupled from bulk data replication. While the server tool needs to be able to consume state information from the replication service, it need not be tightly coupled to the replication service and should be capable of consuming information about the location of data files from many sources in a "pluggable" fashion, and then delivering that information via a variety of standardized interfaces and APIs to various data analysis tools and other services.

4. **GRaCEDb** The current Gracedb/Lumin system is excellent prototype service accepting a number of injected event streams (MBTAOnline, Omega, Ringdown etc) and a small number of event subscribers (ROTSE, LOFAR, QUEST, TAROT, SWIFT etc).

   As we move to the era of Data Challenges and eventually Advanced LIGO, the set of pipelines reporting events will change with time, with new pipelines, modifications to existing pipelines, and changes in personnel leading to "black-box" code. The LIGO event system should have a well-defined protocol for working with the pipelines that create event triggers, so that streams can be added and throttled in a well-defined way. On the other side, the set of subscribers to LIGO events will grow, and the upgraded system should streamline the process of adding subscribers and handling the individual requirements.

   The current event model is an "imperative", where LIGO software decides what each follow-up telescope should do. As the number of subscribers grows, this individual attention will become an undue burden on LIGO staff. Furthermore, we expect stiff competition for robotic follow-up facilities, as new, prolific event streams come on line (LOFAR, LSST, etc). It will become more difficult to get the best facilities if LIGO expects to take immediate, imperative control of the telescope. The new model will need to shift to *informational* rather than *imperative*, meaning the subscriber gets what LIGO has observed, and decides what to do. Thus the telescope scheduling code (much of Lumin) will be run and modified by the event subscriber rather than the event author.

   Past events are also important, for studies of correlation with other event streams. Already astronomical events are being collected into repositories (PTF, Galex, CRTS, SWIFT, etc), and interoperability of these archives will be needed for these important scientific studies. The International Virtual Observatory Alliance has already defined a standard event representation (VOEvent), and many authors and subscribers are exchanging these standard packets. The LIGO event distribution system would be well-positioned for the future by adopting VOEvent.

   Currently, Lumin delivers messages by a protocol customized for each subscriber, and as the number of subscribers grows, this will be more and more difficult. Therefore the event distribution from LIGO should adopt a standard transport protocol. Some requirements for this may include buffering and reliable delivery, strong security (preferably linked to the LIGO Auth system), integrity signatures, indication of presence and readiness, broadcast, multiple implementations, and widespread adoption.

   In addition to delivering LIGO observations to follow-up facilities (Gracedb and LoocUp), LIGO is acting as a follow-up facility for external triggers from other observatories. These two sides of the same coin could be unified by handling *all* relevant astronomical event streams in the same way, whether they are from LIGO or not.

5. **Rapid Event Distribution** As noted in section 3.3.6, the science return of LIGO will be greatly improved if GW detections are backed up with afterglow detection in electromagnetic bands, especially if the follow-up observations are undertaken as soon as possible after the detection.

Rapid event release is well elaborated by the NASA GCN system [550], which has been sending rapid, electronic notices of gamma-ray bursts, and other phenomena, for nearly 20 years. The GCN is now one of many providers of astronomical events, and LIGO will become such a supplier itself in the era of Open Data.

The VOEvent format [551] has become an international standard for reporting and rapid follow-up of astronomical transients. There will be LIGO services that allow publication of gravitational-wave events and receipt by subscribers within seconds. Subscribers may selectively subscribe to event feeds, query past events, and investigate possible event correlations (e.g., GRBs and neutrino events).

The effort here is to ensure that LIGO has the requisite tools to send information about candidate events from GraCEDb to partnering astronomers for follow up. The LSC will develop/deploy simple client tools that allow rapid distribution via TAN (formerly NASA GCN), SkyAlert, and other mechanisms as needed.

6. **Identity Management** Moving into the advanced detector era, the size of the gravitational wave community (which includes the LIGO Laboratory, the LIGO Scientific Collaboration (LSC), Virgo and other collaborators) will continue to grow. Having centralized identity management for members of the community will be essential for a satisfactory user experience, for effective resource administration and for computer security. LIGO Laboratory and the LSC have initiated a joint effort called the Auth (Authentication and Authorizations) Project to develop a unified identity management infrastructure to serve the needs of the community. The project is currently funded on grid operations funding from the Physics at the Information Frontier award **PHY-0600953**. It focuses on four areas - core infrastructure to collect and store user information and create credentials, web services, grid services and general computing and shell access.

   The core infrastructure includes a custom MySQL database with PHP user interface to collect and store user information, two Kerberos realms (LIGO.ORG and LIGO-GUEST.ORG) to provide single sign-on (SSO) authentication to community members and collaborators, an LDAP directory service to provide authorization information and a second to provide user directory information, and an Internet2 product called Grouper which allows creates easy and flexible organization of LDAP entries into groups with an ability to delegate group management. Group membership forms the basis for all subsequent authorization decisions (eg members of the LSC Computing Committee group can view and edit the minutes of the LSC Computing Committee meeting).

   Web services leverage Internet2's Shibboleth software for authentication and authorizations. This integrates with Kerberos to provide an SSO web solution with fine-grained authorization capabilities to LIGO and LSC web services. We currently provide our own Shibboleth Identity Provider (IdP) service because too few community members participate in InCommon (or other Shibboleth federations) to make using external IdPs feasible, but our plan is to start leveraging external IdPs as they become more ubiquitous. The use of Shibboleth is starting to spread throughout LSC web resources and should be generic in the advanced detector era.

   Grid services will leverage MyProxy, a product developed at NCSA, to provide transparent grid access to the community leveraging Kerberos authentication. MyProxy will issue short-lived X.509 certificates and proxy certificates underwritten by the LIGO.ORG Certificate Authorities (CAs). Distribution of Grid Map Files with the MyProxy generated user credentials will be handled by an in-house product. At present, the LIGO CAs are in operation, and detailed planning documents for the rest of the infrastructure have been written. In the advanced detector era, the grid services will be fully deployed and operational. Based on extensive discussions with the grid CA community, we expect the LIGO.ORG CAs to be accredited by TAGPMA by that time as well.

General computing and shell services will leverage kerberos via SSH or PAM for login. Account provisioning will be serviced by LDAP and NSSwitch, with LDAP transparent proxy overlays to augment the LSC managed information with site-specific information. This model, which is intended for major community compute centers but not individual community institution workstations and laptops, is currently deployed for LHO and LLO general computing.

As well as the four major areas, there are a number of other IdM related services that the Auth Project provides support and development for, including mailing lists, request tracking systems, version control systems, special needs environments such as LIGO control room CDS systems, and others. A more comprehensive description of the plans and activities is available at the project wiki (`https://www.lsc-group.phys.uwm.edu/twiki/bin/view/AuthProject/WebHome`).

7.6 Open Data

LIGO has a mandate from the NSF to broadly disseminate data products from the LIGO gravitational wave (GW) detectors, including the full calibrated strain data sets, to the wider community of scientists (amateur and professional) and students, as laid out in the LIGO Data Management Plan [547].

This plan identifies two phases of data release. In phase 1, the detectors are evolving towards design sensitivity and the understanding of instrumental artifacts is in its early stages; detections are expected to be rare. In this phase, data release to the wider research community makes the most sense for validated gravitational wave data surrounding confirmed discoveries, and important non-detections where detectable gravitational waves might plausibly have been expected. A small number of example data releases have already been made for an injected event [549] and a significant non-detection [548]. LIGO will continue to build these data releases, creating a catalog.

In phase 2, the performance of the detectors and the understanding of their noise characteristics will have grown, and detections are expected to be more frequent. During this phase the entire body of gravitational wave data, along with associated information about the data quality, will be released to the wider research community.

Prototyping of open data releases will continue over the next 12 months. Several new staff will be hired to prototype the gravitational-wave object catalog(s), the web services framework for open data access, and the procedures for data curation.

8 Virgo computing and software

In 2012, the computing model for Advanced Virgo has been updated [552]. The data flow for Advanced Virgo will double ($\sim$2 TB / day). This especially means the storage facility at the Virgo site (Cascina), sized to store the equivalent of 6 months of data, needs to be upgraded. Data analysis workflows have been also expanded. Virgo collaboration is taking advantages of the Italian and French national computing centers. The role of Cascina fully dedicated to data acquisition, low latency GW searches, detector characterization with fast feedback to commissioning, commissioning support and data distribution is better defined. All other activities that require large computing resources or access to large volume of raw-data must be carried out in the other Virgo computing centers or on the LSC clusters. The CCIN2P3 and CNAF computing centers provide permanent data storage facilities and large computing resources for offline data analysis and reprocessings. In addition to these main computing resources, Virgo laboratories host clusters that are used for offline GW searches. These clusters, as well as CNAF and CCIN2P3 can be used through the Virgo GRID Virtual Organization.

Since the beginning of Virgo, no logical separation between online and offline software has been chosen in order to avoid the duplication of library developments. Many GW search developments have been designed to run online as soon as possible. One drawback of this strategy is the still limited number of Virgo pipelines running offline in CCIN2P3 and CNAF. In order to improve the use of CNAF and CCIN2P3, we plan to revise our computing model; this especially means to improve data transfer, data access (streamlined data recall of old data has been required by commissioning team as well as data analysists), and provide a more uniform framework (including support) for Virgo software management at CNAF and CCIN2P3.

In section 8.2 we describe the current projects/services and section 8.6 is focusing on the future efforts for Advanced Virgo.

8.1 Organization

The Virgo data analysis software (VDAS) group has been set up in 2010 to help and support data analysis activities in Virgo and to manage the computing resources. It includes software developments support, data transfer monitoring, data access support and management of the relations with the LSC and EGO. The EGO computing department is an important actor which provides infrastructures, manpower and support. They are in charge of the IT architecture, installation and the maintenance of all computing equipment on site. Data transfer from Cascina to CCIN2P3 and CNAF is carried out by the EGO computing department. The EGO software group contributes to Virgo software developments for the control of the detector and its characterization. Every year a “Virgo computing needs” document is prepared for discussions with the computing centers and the EGO directions. This gathers all requests from data analysis groups.

8.2 Current status

The Virgo detector is now getting upgraded at Cascina. Cascina computing equipments will also been upgraded to match AdV requirements for data storage, data access and data processing at Cascina. But most of the current Virgo computing and software architecture will remain the same. AdV computing plan still needs to be completed. A first draft has been released, but few technical requirements are still missing. Data analysis groups needs are still to be better defined. This is needed to start working on the bulk data transfer new developments and improve the data access, both remotely and at the computing centers. The use of GRID at CNAF and CCIN2P3 will be generalized.

8.2.1 Computing at the EGO/Virgo site

DAQ Virgo acquired about 12 MByte/s of raw data, which are stored on a hierarchy of circular buffers, ultimately allowing to keep about 5 months of data at the site. A separation is in place, at network and disk level, between the computers and applications critical for Virgo operation and monitoring, and the rest of the computing/user environment. DAQ system is also feeding GW workflow that analysis with minimal latency Virgo data as well as LIGO detector data transfered at Cascina thought the low latency data transfer system. The DAQ system is getting upgraded (see AdV TDR [553]) to match with the expected data flow increase.

Detector control and monitoring A number of real time machines and workstations are dedicated to run the control and data monitoring algorithms, with an high level of automation and web reporting. Most of the actions are either automatic or run via an interface which also takes care of tracking and reporting the actions in log files. Some improvements and upgrades are foreseen for AdV.

Online processing A number of real time processes take care of formatting the acquired data and of performing a first processing, including the production of online h(t) and the basic data quality assessment. More information about this and the previous activities is available at `http://wwwcascina.virgo.infn.it/WebGUI.htm`

Data logging and transfer Data are automatically indexed (with Frame File Lists produced), and transferred at the computing centers of CNAF (Bologna) and CCIN2P3 (Lyon) for permanent storage using SRB (Lyon) and bbFTPPro (Bologna). This bulk data transfer service is going to be upgraded for AdV, using more powerful technology such as LCG-GRID (grid-ftp) that would provide better book-keeping information and allow a direct GRID data access at CNAF and CCIN2P3.

Low latency searches and detector characterization processing A cluster of about 100 nodes including 32 dual processors and 64 dual-core dual processor machines, is available for online analysis as well as for detector characterization algorithms on the most recent data. These machines receive either data from the online processing, thus with a very small latency (a few seconds), or read data from the raw data buffer, with a larger latency (a few minutes). The farm needs to be upgraded for AdV. Technical requirements about new material to purchase need to be written in collaboration with the data analysis and detector characterization teams. For a more detailed description of the online algorithms, see Virgo detector characterization and low latency CBC sections.

8.2.2 Computing at CCIN2P3 (Lyon, France)

The CCIN2P3 (`http://cc.in2p3.fr/`) is the computing center of the Institut National de Physique Nucleaire et des Particules funded by the CNRS, and is used by the Virgo Collaboration since 2000.

It serves as official repository of the Virgo data since 2000. All data are stored in high mass storage system (HPSS) that provides quasi unlimited storage capacity (in 2012 more than 16 PByte of data are stored in HPSS. Virgo data amounts to 790 TByte). A large enough cache disk space and a software interface is used to get a transparent data access. As soon as data are produced or transfered to Lyon they are declared in the SRB (Storage Resource Broker) catalogue that allows a remote access to the data from the laboratories of the Virgo Collaboration.

The CCIN2P3 also provides large computing facilities, based on about 15000 Linux processors whose efficiency use is higher than 90%. The CCIN2P3 operates an LHC Computing Grid (LCG) Tier-1 center.

Jobs can be submitted either via a batch queue system (GE) or via LCG Grid. Virgo runs at CCIN2P3 GW burst and pulsar searches. Data quality investigations and the h(t) reprocessing are also performed at CCIN2P3.

8.2.3 Computing at CNAF (Bologna, Italy)

The CNAF (`http://www.cnaf.infn.it`) is the main computing center of the Istituto Nazionale di Fisica Nucleare and serves as repository of two year's worth of the most recent Virgo data. It also provides a large computing facility, consisting of a collection of Linux workstations (about 13000 processors). Jobs can be launched either via GRID or via a standard batch scheduler system.

In 2011, Virgo data have been migrated to a new storage system that keeps on spinning media the most recent data or most recently accessed data and migrates the older data on tapes automatically. Virgo runs at CNAF mostly pulsar searches, and up to now has used only a small fraction of the total CNAF power. It plans to run in Bologna also the other offline searches.

Both at CNAF and CCIN2P3 remote access to data is possible but latency can be very inconvenient when data are not in the cache disk. This must be improved for AdV.

8.3 Virgo software

The Virgo data analysis software is organized in a hierarchy of libraries, from the very basic ones which allow to format and to access frame data, to very specialized ones for the searches, with, as already underlined a strong connection to the online control of Virgo (management and library sharing)

8.3.1 Basic software

Data are formatted and accessed with the `Frame` library. Data visualization is possible using the `dataDisplay` software, which is capable of reading data from the online and offline, also from geographically distance places. Simulation of the detector and the sources is possible with the `siesta` software, which can be programmed with "cards" which describe objects and their relation, and outputs data in frame format. Interactive work with frame data is possible with the `vega` software, which is `ROOT` linked with various Virgo libraries. `Cm` is a task-to-task communication protocol based on TCP-IP used by all online running processes in Virgo. It is also used to transfer frames with low latency to LSC clusters. Many other packages, developed for the online control of Virgo are also used in some Virgo GW search workflows.

8.3.2 Search software

A low latency workflow `MBTA` has been developed in Virgo. It makes use of the `inspiral` library for templates, signals and template grids. It analyzes Virgo and LIGO detectors data in coincidence at Cascina during science runs.

The Burst group has developed a comprehensive C++ `BuL` library which hosts most of the Virgo specific search algorithms, as well as utilities and service routines which allow to build pipelines running on real or simulated data. It also includes modules dedicated to signal processing and data noise generation. Burst search Virgo workflow are built on top of `BuL`. They also include matlab and python based post-processing functions.

The Pulsar group has developed a comprehensive package, mostly based on Matlab or Matlab compiled routines. More information is available at `http://grwavsf.roma1.infn.it/pss/`

The Stochastic Background Group has developed a specific search and simulation library `SB`, documented at `http://wwwcascina.virgo.infn.it/DataAnalysis/Stochastic/software/SB/index.html` which leverages also on the noise library `NAP`

8.3.3 Detector characterization software

A C++ package called `NAP` is dedicated to some noise analysis, from the computation of basic statistics to more sophisticated approaches, like AR and ARMA modeling, as well as multi-coherence and non-linear analysis. More information is available at `http://wwwcascina.virgo.infn.it/DataAnalysis/Noise/nap_index.html`.

Other projects dedicated to detector characterization are also organized around specific software. For instance `NoEMi` is a software project dedicated to the identification of the spectral lines. `NMAPI` is a framework to generate web pages from information stored in databases. `GWOLLUM` is a new framework based on Omega and other utilities, to both generate Omega-like trigers and study the performance of data quality vetoes. Many other packages like `SegOnline` or `BRMS` are used for generating data quality information. Many veto algorithms (`UPV`, `hVeto`, `BCV`), originally developed in the LSC, are now part of the Virgo detector characterization software.

8.4 Virgo software management

In Virgo, all packages are managed, configured and build by `CMT` (`http://www.cmt.org`). A simple requirements file describes the build options, and more importantly the dependences with other packages. Each Virgo C or C++ software project is made of a package that comprises at minimum one folder `cmt/`

that contains the requirements file. Note that the use of CMT to manage a package does not prevent to use other tools like autoconf.

All Virgo packages are archived in the Cascina CVS repository accessible by any LSC/Virgo users through a pserver whose address is :pserver:<user>@cvs.ego-gw.it:/cvsroot All packages can be installed using CMT directly from the CVS archive. The most stable version of data analysis packages are also available from the standard Virgo Common Software distribution available at http://wwwcascina.virgo.infn.it/sDoc/VirgoReleases/current.html.

8.5 Services

8.5.1 Data transfer

The data transfer between Cascina, CNAF and CCIN2P3 is performed via a bulk replication engine developed by the EGO computing department. It consists of a modular software written in Python that is currently using two different transfer technologies: bbftpPro for CNAF and SRB for CCIN2P3. While satisfactory for point-to-point data transfer, this solution is not optimal for distributing data on request, hence for AdV another solution based on GRID is under study. The plans are to exploit more fully the range of middle-ware available by the GRID development, thus improving the data access in computing centers. Data transfer between Cascina and LSC clusters (Hannover) is performed using LDR tools. A server at Cascina has been equipped with all required LSC software.

8.5.2 Databases

Many databases are now used in Virgo. The first one VDB is dedicated to segments and data quality information (vetoes). It is a MySQL database used through many interfaces: web, command line and library API. VDB is currently upgraded for AdV to be able to contain millions of segments. The user interface requires also improvements such that VDB is queried directly by search workflows. VDB is developed through the Virgo Data Quality project that is the main provider of segments. VDB is available at https://vdb.virgo.infn.it/main.php.

Another important database is LineDB is the database that contains all information about Virgo spectral lines. This tools is developed jointly with NoEMi. Trigger databases are also now available and some are integrated in the NMAPI framework. LineDB is available at https://pub3.virgo.infn.it/MonitoringWeb/Noise/html/index.php?callContent=408.

8.5.3 Virgo software package release

Part of the Virgo software packages are released few times a year as tarbal and rpms. These release are installed at CNAF, but not at CCIN2P3. In Lyon packages are installed by users from the CVS archive in a common zone (THRONG_DIR/pro/).

8.5.4 Virgo problem report system

The SPR system to report problems for both software and hardware has been recently upgraded. It's now based on MantisBT. That especially allows to use the Cascina Active Directory authentication system. Any user can submit problems at http://sprserver.ego-gw.it/mantisbt/my_view_page.php.

8.6 Preparing for the advanced detector era

While most of the Virgo software and computing infrastructure will remain unchanged for AdV, we have identified few projects that need urgently to be upgraded:

- Data transfer: the current technology must be upgraded to interface with GRID and the book-keeping databases.
- Remote data access: raw-data older than 6 months are available only in computing centers. Currently the remote data access is penalized by the storage on tapes of the data in computing centers. Remote access for data visualization requires a quicker access to data than what is currently possible.
- Data access in computing center: currently bookkeeping is done manually with all possible source of errors. The new data transfer system needs to provide better data management in computing centers and provide users with up-to-date information about the location of the files and their content.
- GRID: the use of GRID has been promoted in Virgo since many years. A Virgo Virtual Organization has been defined in the LHC Computing Grid (LCG) organization (`http://lcg.web.cern.ch/lcg/`). Few groups (mainly pulsar group) is routinely running jobs over the GRID, inside the Virgo VO, both at the two TIER1 computing centers of CNAF and at several TIER2 sites. However we still need to generalize the use of GRID on all Virgo clusters. All Virgo workflows should be made compliant with GRID data access.
- Software management and packages release: Alternative to CMT might be useful. In any case we want to avoid the use of native tools like autoconf which does not provide enough control of the package dependencies. We also need to think how to improve the installation of Virgo and LSC software at Virgo computing centers and on users laptop.
- CVS to SVN migration: this should be done in the next year.
- Authentication: a unique identity recognized on both Virgo and LSC web pages, based on GRID certificate would simplify the communication of information between the LSC and Virgo.

Concerning GW workflow, advanced detector data analysis preparation has already started through the Engineering Runs organized jointly with the LSC. It will allow to test all new framework and upgrades of existing tools.

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