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EXECUTIVE SUMMARY from the LSC-Virgo White Paper on Gravitational Wave Data Analysis and Astrophysics (July 2017 edition)

The LSC-Virgo Data Analysis Council
including the LSC-Virgo Data Analysis Working Groups
and the Detector Characterization and Calibration Working Groups

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1 Overview and Executive Summary

Gravitational wave (GW) searches and astrophysics in the LIGO Scientific Collaboration (LSC) and Virgo collaboration are organized into four working groups. The **Compact Binary Coalescence (CBC)** group searches for signals from merging neutron stars or black holes by filtering the data with waveform templates. The **Burst** group searches for generic gravitational wave transients with minimal assumption on the source or signal morphology. The **Continuous Waves (CW)** group targets periodic signatures from rotating neutron stars. The **Stochastic Gravitational-Wave Background (SGWB)** group looks for a gravitational wave background of cosmological or astrophysical origin. Joint teams across two or more working groups exist where the science suggests overlap between sources or methods. In addition, the **Detector Characterization (DetChar)** group collaborates with the detector commissioning teams and works to improve searches by identifying and mitigating noise sources that limit sensitivity to astrophysical signals.

The *LSC-Virgo White Paper on Gravitational Wave Data Analysis and Astrophysics*, which is updated yearly, describes the astrophysical search plans of the LSC-Virgo working groups. This document is its executive summary. It includes a mission statement and summary of scientific priorities for each search group, as well as statements from the Detector Characterization and Calibration teams.

The Advanced Detector Era (ADE) is the epoch of Advanced LIGO and Advanced Virgo science data acquisition, which began in September 2015 and has (as of July 2017) already yielded the first direct observations of gravitational waves by the Advanced LIGO detectors [Phys. Rev. Lett. (PRL) 116, 131103 (2016), PRL 116, 241103 (2016), PRL 118, 221101 (2017)]. Table 1 shows the past and planned schedule of observing runs, as provided by the LSC-Virgo Joint Run Planning Committee, which includes representatives from the laboratories, the commissioning teams and search groups.

Epoch	Run Duration	Run Name	$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) LIGO	Virgo	Binary Neutron Star (BNS) Range (Mpc) LIGO	Virgo	
2015–16	4 months	O1	20 – 30	–	68 – 78	–	actual
2016–17	8 months	O2	30 – 60	20 – 40	70 – 90	20 – 40	in progress
2018–19	12 months	O3	75 – 90	40 – 50	120 – 170	60 – 85	projected

Table 1: Plausible observing schedule and expected sensitivities for the Advanced LIGO and Virgo detectors. The O1 Burst range is for $\sim 150\,$Hz signals, from [Phys. Rev. D 95, 042003 (2017)] . The O1 BNS range is from [Astrophys. J. Lett. 832, L21 (2016)]. The O2 LIGO BNS range is from public status updates on the ligo.org web site. Projected sensitivity for Virgo in the last month of O2 and for LIGO and Virgo in O3 will be strongly dependent on commissioning progress [Living Rev. Relativity 19 (2016), 1].

Current LSC-Virgo scientific priorities are summarized in Table 2, by search group, in three categories:

- **Highest priority:** searches most likely to make detections or yield significant astrophysical results.
- **High priority:** promising extensions of the highest priority goals that explore larger regions of parameter space or can further the science potential of LIGO and Virgo.
- **Additional priority:** sources with lower detection probability but high scientific payoff.

Computing needs and resource allocations are derived from the science priorities presented in this table. Scientific motivations, details on methods and the strategy for result validation are provided in the **activity plans** included in the full version of this white paper.

We note that the LSC and Virgo Collaboration have adopted a *Multiple Pipeline Policy* [LIGO-M1500027], which calls for astrophysical results to be validated with a different analysis, using independent methods and tools when possible. In some cases this may require the same data to be analyzed by more than one pipeline for the same science target.

	LSC-Virgo Astrophysics Search Working Group			
	Burst	CBC	CW	SGWB
Highest priority	All-sky search for generic GW transients, both in low latency for multi-messenger follow-up and offline	Detecting the coalescence of neutron star and black hole binaries and measuring their parameters	All-sky search for isolated neutron stars, both as a *quick-look* on owned resources and as a deep/broad search on Einstein@Home	Searches for an isotropic stochastic GW background
	Parameter estimation for the astrophysical interpretation of detected burst events	Characterizing the astrophysical distribution of compact binaries	Targeted search for high value, known pulsars	Directional searches for stochastic GW backgrounds
	Search for GW bursts triggered by outstanding GRB alerts	Responding to exceptional CBC detections	Directed searches for the most promising isolated stars (Cas A, Vela Jr etc.)	Search for very long transients (~ 10 hr $-$ days)
	Searches triggered by outstanding astrophysical events (a galactic supernova, neutron star transients, an exceptional high energy neutrino alert)	Multi-messenger astronomy with compact binaries	Directed searches for X-ray binaries Sco X-1 and XTE J1751$-$305	Data folding for efficient SGWB searches
	Search for cosmic string kinks and cusps	Searching for CBC-GRB coincidences		Searches for non-Gaussian GW backgrounds
		Testing General Relativity with compact binaries		Data quality and detector characterization studies
High priority	Searches triggered by high energy neutrinos, extra-galactic supernovae, and GRB observations	All sky search for spinning binary neutron star systems (deep and low latency)	Targeted search for other known pulsars	Long transient follow-up of CBC and burst candidates
	Burst search for intermediate mass ratio and eccentric black hole binary systems	Matched filter search for intermediate mass black hole binary systems	Directed searches for other isolated compact stars and X-ray binaries	
	All-sky search for long bursts of > 10 s duration			
Additional priority	GRB-triggered search for long-duration bursts and plateaus	Exploring effects of detector noise on parameter estimation	All-sky search for isolated compact stars (alternative approaches)	
	Hypermassive neutron star follow-up	Searching for sub-solar mass CBC signals	All-sky search for CW signals from binary systems	
	Burst searches triggered by radio transients and by SGR/SGR-QPO	Developing searches for CBC signals with generic spins	Spotlight deep sky-patch search	
	Burst tests of alternative gravity theories **		Search for continuous-wave transients	
			Search for supernova post-birth signals **	

Table 2: Science priorities of the LSC and Virgo Collaboration, for the four astrophysics search groups: Burst, Compact Binary Coalescences (CBC), Continuous Waves (CW), and Stochastic Gravitational-Wave Background (SGWB). The targets are grouped into three categories (highest priority, high priority, additional priority) based on their detection potential. There is no additional ranking within each category in this table. Critical for accomplishing these science priorities are the detector characterization and calibration activities described in this document.
** Future searches under development, not included in current activity plans.

1.1 Searches for Generic Transients, or Bursts

The mission of the Burst group is to detect gravitational wave transients, or *bursts*, and to gain new information on populations and emission mechanisms of the associated astrophysical objects, as well as to test theories of gravity. Central to the Burst group philosophy is the assumption of minimal information on the source, so that searches for gravitational wave bursts typically do not require a well-known or accurate waveform model and are robust against uncertainties in the gravitational wave signature. Burst searches are, therefore, sensitive to gravitational wave transients from a wide range of progenitors, ranging from known sources such as binary black-hole mergers (in particular the most massive and loudest ones) to poorly-modeled signals such as core-collapse supernovae as well as transients that are currently unknown to science. We refer to this as the “eyes wide open" approach.

For example, the complexity of supernovae makes it difficult to reliably map the dynamics of a core-collapse into a gravitational wave signal. The merger of precessing intermediate-mass black holes ($\geq 100\,\mathrm{M}_{\odot}$) produces gravitational wave transients which appear as short, sub-second bursts in the data. Long gamma-ray bursts could be associated with a gravitational wave transient lasting more than 10 seconds. Since robust models are not available for many plausible sources, we also need data analysis methods that are able to detect emission mechanisms that have not been envisioned yet.

The Burst group implements a variety of methods to identify instances of statistically significant excess power, localized in the time-frequency domain. To discriminate between gravitational waves and noise fluctuations, the analysis requires the signal to appear coherently in multiple detectors. The confidence of a candidate event is established by repeating the analysis on many instances of background, obtained by shifting the data from different detectors with non-physical delays. In a few special cases when an accurate signal model is available, such as for cosmic string cusps or neutron star ring-downs, a search can be done using matched filtering with a bank of templates.

Although burst search algorithms are designed to detect a wide range of signals, their tuning and interpretation benefit from considering how they perform for plausible astrophysical signals. Therefore, the group's science program involves an active collaboration with the theoretical astrophysics, source modeling and numerical relativity communities.

Many gravitational wave burst sources should also be observable in more traditional channels, from Earth-based astronomical data, through sensitive gamma-ray/X-ray satellite detections, γ-ray, visible and radio burst to neutrino signals. Knowledge of the time and/or sky position of the astrophysical event producing a gravitational wave burst can be used to increase the sensitivity of a triggered burst search compared to an untriggered, all-sky search, and the association with a known astrophysical event may be critical in establishing our confidence in a gravitational-wave burst detection. Most importantly, joint studies of complementary data enable scientific insight that cannot be accessed through gravitational waves or other messengers alone. Therefore, in addition to searches using only the gravitational wave 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.

Once a significant source of GWs is found, its characterization – identification and localization – brings the most precious information about the onset of the violent phenomena at the origin of the GWs emission. The GW signal is encoding the source parameters (mass, orientation, and matter bulk motion) and given the various possible sources covered by Burst searches, GW signal characterization must be as generic as possible and also customized using the state-of-the-art knowledge of each possible Burst source.

1. **Highest priority**

   The Burst group is focused on an *eyes wide open* approach to detecting gravitational wave transients.

To maximize its discovery potential, the Burst group employs a strategy of multiple searches, overlapping in parameter space to allow for cross-validation of search outputs. Highest priority goals for the analysis of advanced detector data include:

- a statement on the transient gravitational wave sky, with population studies if we have several detections, a rare-event detection significance if we have one candidate or an upper limit on the rate of gravitational wave bursts if there is no detection;
- deployment of multiple analyses for cross-validation of the all-sky search results, including verifying the significance of any observed events, across a wide parameter space. This is especially important for events that are not matched to a specific source model;
- the astrophysical interpretation of any detected signals, leveraging signal characterization and parameter estimation;
- a prompt analysis, trigger production and sky localization, to enable the electromagnetic and neutrino follow-up of gravitational wave transients;
- prompt reports on astrophysically significant events, such as nearby gamma-ray bursts, soft gamma repeater hyperflares, galactic supernovae, exceptional bursts of low (MeV) energy neutrinos, or exceptional high (GeV–EeV) energy neutrinos;
- a dedicated search for gravitational wave bursts originating from cosmic strings.

2. **High priority**

   - The Burst group has recently extended the parameter space of the all-sky search to include longer duration transients (≥ 10 s) which may originate from various astrophysical sources such as long gamma-ray bursts, bridging the gap with continuous wave sources. Long-duration burst searches share similar complexities with their short-duration counterparts. Given the size of the parameter space covered by the long-duration search, multiple analyses are deployed to cross-validate the results.
   - The Burst group pursues, with the burst analysis approach, some classes of compact binary coalescence sources that are not well covered by the current waveform template banks. These include intermediate mass binary black holes, binary black holes with eccentric orbits and intermediate mass ratio inspirals.
   - Finally, the Burst group pursues multi-messenger searches for gravitational wave bursts in conjunction with signatures such as generic gamma-ray bursts, fast radio transients, low- and high-energy neutrino observations, and electromagnetic observations of nearby core-collapse supernovae. The Burst group uses information on the astrophysical event to reduce the parameter space over which searches must be performed, leading to a reduction in the false alarm rate and, consequently, an improvement in search sensitivities.

3. **Additional priority**

   Additional priorities include the search for gravitational waves in association with neutron star transients (eg. pulsar glitches, type I X-ray bursts and soft gamma ray repeater flares) and testing alternative theories of gravity with gravitational wave bursts.

Several of these science targets – intermediate mass black hole binaries, gamma-ray bursts (GRBs), electromagnetic followup – overlap with the CBC group, while others – long transient and cosmic string – overlap with the stochastic group. Joint teams are working together across the three groups on these targets.

1.2 Searches for Signals from Compact Binary Coalescences

On September 14, 2015, one-hundred years after gravitational waves were first predicted, the Advanced LIGO experiment detected gravitational waves from the merger of two black holes. This discovery was followed by a second confirmed binary black hole detection on December 26, 2015. As of this writing (July 2017), the second observing run (O2) has already yielded the discovery of a third strong event, GW170104, firmly establishing the existence of stellar-mass binary black hole mergers as a primary source population for Advanced LIGO and Advanced Virgo. Additional events are expected as analysis of O2 data continues. Furthermore, we anticipate discovery of entirely new source classes such as coalescing binary systems containing neutron stars within the next few years. The Compact Binary Coalescence group aims to discover additional compact binary mergers and to use the gravitational wave signals to advance our understanding of fundamental physics and astrophysics.

The range of scientific activities pursued by the CBC group requires us to prioritize our goals. In the regime of increasing detection frequency over the coming observing runs, we must strike a balance between exploitation of established classes of sources and preparing for detection of new source classes. Achieving these goals requires the group to prioritize the continued research and development of our tools and methods for source detection, estimation of parameters, inference of rates and populations, probing fundamental physics and modeling of waveforms with analytical and numerical relativity. We will continue to develop our search pipelines to improve their sensitivity to quiet sources by improvements in detection statistics, understanding of the noise background and rigorous understanding of data quality. We expect a tremendous human effort will be required to develop, deploy, run and interpret the results of low-latency and offline searches in the context of evolving detector sensitivity and data quality. Additionally, the compact binary coalescence group maintains an active collaboration with a broader community to enhance the impact of our discoveries on theoretical astrophysics and the electromagnetic and astroparticle observing communities. With this in mind we have outlined the following projects which cover the current goals of the group.

1. **Highest priority**

    - **Responding to exceptional events**. We must be prepared to detect and respond to novel sources of extraordinary scientific importance. We define these as sources that yield significant new astrophysics and would warrant a rapid stand-alone publication. These would naturally include the first detection of binary neutron-star, neutron-star black-hole binary or intermediate mass binary systems. We also anticipate examples in which measurement of a source's parameters (e.g. masses and spins) could provide significant constraints on its formation channel or our understanding of stellar evolution (e.g. the possible existence of gaps in the black hole mass distribution, minimum or maximum neutron star mass). Other examples could include sources which are exceptionally loud and allow us to measure the source physics with unprecedented precision, thereby providing exceptional constraints on general relativity, or, for binaries containing a neutron star, measurement of the nuclear equation of state (see below).
    - **Producing a catalogue of detected compact binaries**. We will produce a summary of all compact binaries detected during each observing run in order to provide a reference for the astrophysics community with details of the detected source's physical parameters, notable properties, and waveform estimates. This requires a good understanding of systematic errors, including waveform modelling errors. We will continue to reduce our sources of systematic errors by improving our waveform modeling with comparison to numerical relativity simulations. The catalog completeness will be improved by including uncertain signals along with their estimated p-value.
    - **Characterizing the astrophysical distributions of compact objects**. As the number of de-

tections increases, we will begin to build a picture of the astrophysical distribution of compact binaries in terms of their masses and spins. This will set novel empirical constraints on the astrophysics of binary evolution. To accurately learn these distributions we need the ability to infer the physical properties of our detected sources and estimate their distribution taking into account the selection effects of our detectors and pipelines.

- **Testing general relativity**. The final stages of compact binary coalescence provide a unique window into the behavior of gravity in the strong field, high-velocity regime. We will continue to develop the range of tests we are able to perform on our detections, ensuring their robustness through comparison to numerical relativity simulations where possible. We will develop methods of combining multiple detections to place better constraints on the theory, and test specific predictions from general relativity such as the no-hair and area theorems.
- **Multimessenger astronomy and astrophysics**. The observation of an electromagnetic or neutrino counterpart to a gravitational wave signal will be of huge astrophysical importance to the field, so we will continue to pursue multi-messenger astronomy by providing alerts to our observing partners. This requires the continued development of low-latency pipelines for detection and localization of sources, and the infrastructure associated with collating and distributing information about detection candidates.
- **Gamma-ray bursts**. The coincident detection of a gravitational wave with a gamma-ray burst ranks among the highest impact discoveries possible in the compact binary field. We will continue performing a deep coherent search for gravitational waves focussed on the sky position of any known gamma-ray bursts, and pursue joint searches for gravitational wave and GRB signals.
- **Probing the properties of matter in the extremes of physical limits**. Binary coalescences involving neutron stars are a unique laboratory for studying the behaviour of matter at super-nuclear densities and pressures. We will develop methods of constraining the neutron star equation of state by measuring its observable effects on the inspiral, merger and post-merger phases of the coalescence signal, and apply these to forthcoming neutron star merger observations.

2. **High priority**

High priority activities are those which are less certain to produce a significant result in the near term, but where the potential payoff would be high.

- **Intermediate mass black hole binaries & intermediate mass-ratio inspirals**. A goal of the compact binary coalescence group is to search for intermediate mass black hole binaries. Especially at the highest masses, the success of any search will be sensitive to the effects of higher order modes and precession in the waveforms. An extension of the intermediate mass black hole binaries research is the development of searches for intermediate-mass ratio inspirals and waveforms to describe them.
- **Eccentric binaries**. Eccentric binary systems are another potential class of source where the searches and waveforms are less mature. Templated searches and unmodeled searches can be combined to allow for more robust searches over a range of eccentricity.
- **Spinning binary neutron stars**. Searching for neutron star binaries with significant component spin is also a high priority. Although neutron stars in binary systems have been observed to have small spin, some isolated neutron stars are known to spin significantly. If neutron stars with significant spins do exist in binary systems, then opportunities to detect them could be lost without a dedicated search.

3. **Additional priority**

   Building more accurate noise models for parameter estimation techniques can dramatically mitigate the effects of non-stationary, non-Gaussian noise on the fidelity of parameter inference. It is a priority to conduct a simulation campaign to study improved noise models for parameter estimation.

   The compact binary parameter space searched in higher priorities is not complete. It covers a plausible range of physical parameters based on observation and stellar evolution models. However, there are other interesting but less plausible parameter spaces which would have a dramatic impact if discovered. For example, given additional resources, we would consider searching for compact objects below one solar mass. It is possible that neutron stars or black holes could exist with masses down to fractions of a solar mass and be in detectable binary systems. Additionally, although parameter estimation techniques use waveforms that account for orbital precession, detection searches do not presently include precession effects in the templates. Work is ongoing to develop such a search, and with additional resources, we would conduct a precessing binary search in the future.

1.3 Searches for Continuous-wave Signals

The LSC/Virgo Continuous Waves (CW) Group aims to measure gravitational wave signals that are long-lived, nearly sinusoidal and extremely weak, believed to be emitted by rapidly rotating neutron stars in our galaxy. These stars can emit gravitational radiation through a variety of mechanisms, including elastic deformations, magnetic deformations, unstable r-mode oscillations, and free precession, all of which operate differently in accreting and non-accreting stars. Long-term simultaneous gravitational wave and electromagnetic observations of a galactic neutron star would support a rich astrophysical research program.

For known pulsars with measured spin frequencies, frequency derivatives and distances, energy conservation allows setting an upper limit on gravitational wave strain amplitude, known as the *spindown* limit, albeit with significant uncertainties due to poorly understood neutron star astrophysics. Previous searches in LIGO and Virgo data have obtained 95% confidence upper limits well below the spindown limits for several pulsars, including the Crab Pulsar and Vela. As interferometer sensitivities improve in the Advanced Detector Era, several dozen more known pulsars will become spindown-accessible, primarily at spin frequencies below 100 Hz. For suspected neutron stars with unknown spin frequencies, indirect upper limits based on estimated age or on estimated accretion rates can also be derived. Such indirect limits are more optimistic for non-accreting stars, but accreting neutron stars are more likely to be emitting near their limits.

Because there is so much astrophysical uncertainty in continuous gravitational wave emission and because electromagnetic astronomers have detected only about 2500 of the O(10^{8-9}) neutron stars believed to populate our galaxy, the CW group has established a broad program to search for gravitational wave emission from five distinct source categories, ordered below by decreasing *a priori* information known about the sources: 1) known pulsars with well-measured timing; 2) other known or suspected isolated neutron stars with limited or no timing information; 3) known or suspected binary neutron star systems; 4) unknown isolated stars in any direction; and 5) unknown binary stars in any direction.

This ordering of categories corresponds to ordering by source strain sensitivity. Targeted searches using known ephemerides from radio, X-ray or γ-ray timing measurements can achieve strain sensitivities limited only by the intrinsic detector sensitivity and observation time spans with minimal trials factor corrections. Directed searches using known sky locations but having no *a priori* frequency information (e.g., Cassiopeia A) are degraded by trials factors that depend on the band size searched and on the assumed age of the source (which affects the number and range of higher-order spin derivatives to be searched). The sensitivity achievable with all-sky searches is still further limited by the need to make sky-location-dependent corrections for Doppler modulations of detected source frequency due to the Earth's motion (daily rotation and orbital motion). The number of sky points to search to maintain accurate demodulation grows rapidly with coherence time used in the search (time scale over which the signal is assumed to follow a precise phase model). The effect is severe enough to preclude all-sky searches using coherence times equal to the full observation spans of data runs. Adopting semi-coherent summing of data makes the computational problem tractable, but sacrifices additional sensitivity beyond that from the trials factor of exploring a larger parameter space. Directed searches for suspected neutron stars in binary systems with unknown source frequency must make similar sensitivity tradeoffs, and all-sky searches for sources in unknown binary systems define the current extreme in sensitivity tradeoff for tractability.

In the case of known objects, we have identified sources that seem to be the most promising, and should priorities need to be set because of limited resources (labor or computing), those sources will receive the highest priority. With these considerations in mind, the CW group plans a comprehensive search program in the Advanced Detector Era for all of these source categories, with the following priorities:

1. **Highest priority**
   - Targeted searches for the Crab and Vela pulsars as well as other stars for which the spindown limit is likely to be beaten to within a factor of two. High-interest stars likely to fall in this category include PSR J0537−6910 and PSR J1813−1246, among many others, as detector sensitivities improve. These analyses will include searching at the stellar spin frequency and twice that frequency.
   - Directed search for Cassiopeia A which is the youngest known neutron star in the galaxy, but for which the spin frequency is unknown. (This choice of primary source is under reconsideration; Vela Jr. may be more promising, under some astrophysical assumptions.)
   - Directed searches for the X-ray binaries Scorpius X–1, Cygnus X–3, PSR J1751–305 and 4U 1636-536. The first two are especially bright in X-rays, and in the torque-balance model, GW luminosity scales with X-ray luminosity. For the latter two objects there is evidence for sharp X-ray periodicities that may indicate an r-mode oscillation.
   - All-sky searches for unknown isolated stars. These searches necessarily suffer from degraded strain sensitivity relative to what can be achieved in the targeted and directed searches, but they cast a very wide net, offering a reasonable prospect of discovery.

2. **High priority**
   - Targeted searches for known pulsars for which the spindown limit is unlikely to be beaten, according to conventional theory, but which are extreme astrophysical objects of great interest.
   - Directed searches for young supernova remnants other than Cassiopeia A, including Supernova 1987A, for sources near the galactic center, for sources in nearby globular clusters and for unidentified γ-ray sources with pulsar-like spectra.
   - Directed searches for additional X-ray binaries.

3. **Additional priority**
   - All-sky searches for unknown binary stars. Because of the additional unknown orbital parameter space to search, these searches are most computationally demanding and must make the greatest tradeoffs in strain sensitivity for tractability.
   - All-sky searches for unknown isolated stars, using alternative algorithms.

For every type of search, the CW group supports at least two independent methods (pipelines). This redundancy provides greater robustness against incorrect assumptions in signal modeling and against non-optimum handling of instrumental artifacts. The robustness against incorrect signal modeling is especially important for accreting sources, such as Scorpius X–1, where the time span over which the coherence of the signal model can be safely assumed is uncertain. In fact, that time scale is likely to vary in response to fluctuations in accretion rate.

There is some overlap in the CW search space with searches carried out in the Burst and Stochastic working groups. Long-lived transients may also present as short-lived CW sources. A small joint subgroup with members from both the CW and Burst groups is carrying out work in this area. CW sources with deterministic but unknown phase evolution, such as from a neutron star in a binary system with uncertain parameters, may be detectable via the "radiometer" method in use by the Stochastic group. Tradeoffs among search methods for such sources are being explored in a joint CW/Stochastic mock data challenge focused on the search for Scorpius X-1.

1.4 Searches for Stochastic Backgrounds

A stochastic gravitational-wave background (SGWB) is formed from the superposition of many events or processes that are too weak and/or too numerous to be resolved individually. The prime objective of the SGWB group is to measure this background, which can arise from cosmological sources such as inflation, cosmic strings, and pre-Big-Bang models or from astrophysical sources such as compact binary coalescences, supernovae, and neutron stars. The measured rate of binary black hole (BBH) mergers indicates that, at design sensitivity, Advanced LIGO may detect an astrophysical background. This detection will be of great interest as a probe of the evolution of the Universe since the beginning of stellar activity. Meanwhile, the detection of a cosmological background would be a landmark discovery of enormous importance to the larger physics and astronomy community. The stochastic searches are built on the cross-correlation infrastructure, which was originally designed to carry out searches for an isotropic stochastic background, but has been adapted to also search for directional and transient SGWB signals.

Although no SGWB was detected during O1, results from the isotropic search constrain the energy density of the stochastic background to be $\Omega_0 < 1.7 \times 10^{-7}$ at 95% confidence. When advanced detectors reach design sensitivity, we expect to be sensitive to an energy density as low as $\Omega_0 < 6 \times 10^{-10}$. The isotropic search has been extended to include a test for GR by searching for a background of non-tensor polarizations. This extension provides a tool for model selection between a tensor and non-tensor background signal, as well as an estimate of the background energy density from tensor, vector, and scalar polarizations. It is also important to estimate the individual contributions of distinct sources of the background, since the true background may not be fully described by a single power law. Independent methods have been developed to consider all physically allowed spectral shapes using a either a mixing matrix deconvolution or Bayesian parameter estimation. Bayesian parameter estimation techniques are also used to estimate or constrain the average chirp mass and merger rate of the binary black hole population. Significant model development will be necessary for understanding and interpretating the observational results. Additionally, a fully-Bayesian analysis for an isotropic SGWB is being developed using BayesWave. This analysis is capable of estimating noise power spectra and modeling glitches in the data, allowing a simultaneous estimate of both detector noise and GW background contributions to observed data in a fully-Bayesian manner.

The directional searches provide a method of distinguishing between different stochastic sources using sky maps of gravitational-wave power. The group employs both a radiometer algorithm and a spherical harmonic decomposition to generate sky maps (and strain spectra) that can be used to identify cosmological or local anisotropies as well as point sources. The spherical harmonic decomposition provides an estimate of the energy density of the SGWB from extended sources over the sky. It will also be applied to search for an anisotropic GW background estimated from pulsars in the galactic plane. The broadband radiometer measures the background energy density from point-like sources over the sky, and provides an important tool for GW astronomy when there is significant uncertainty in the phase evolution of a continuous-wave signal. As an application, a narrowband radiometer has been used to search for gravitational waves from Scorpius X-1, the Galactic Center, and SN 1987A. Using a compressed data set folded over a sidereal day, the radiometer can be applied to perform an unmodeled search for persistent sources over all frequencies and sky locations. Directional searches are performed separately for multiple spectral indices in standard LIGO analyses but it may be possible to deconvolve the skymaps to constrain backgrounds of multiple spectral components. Exploration studies are being performed, initially considering two or three power-law spectral indices. We also investigate models of SGWB anisotropies, which we can test against our results. Continuous-wave (CW) sources with deterministic but unknown phase evolution, such as a neutron star with unknown spin period, may be detectable either via the stochastic radiometer or via methods being developed in the CW group. The Stochastic group continues to develop these searches, in consultation with the CW Group.

It may be possible for neutron stars to emit transient gravitational waves on time scales lasting hours to weeks. Moreover, exotic models allow for the possibility of a seemingly persistent signal to start or stop during an observing run, also leading potentially to very long transient signals. The Stochastic group has developed a cross-correlation pipeline to search for very long-lived gravitational-wave transients on these time scales. Applications of this search include the ability to establish whether an apparently persistent source, e.g., observed in a stochastic background search, exhibits variability in time; and an understanding of the behaviour of detector artefacts on timescales of days to weeks. There is overlap between the very long transient search and searches being carried out in the Burst and Continuous Waves search groups.

It has been demonstrated that data compressed using sidereal folding can be used to facilitate extremely efficient searches over long observing times. The stochastic group is producing a combined extended folded data set for the O1 and O2 observing runs. This data set will be utilised by the all-sky all-frequency radiometer, by the very-long transient search, and by the galactic pulsar search.

The traditional stochastic searches share a common assumption of a Gaussian and stationary background. However, a background from unresolvable binary BH mergers, for example, is likely to be detected first by the Stochastic group even though it will not be stationary and is unlikely to be Gaussian. Non-Gaussian stochastic background signals have been studied using software injections and analyses on mock data. A search for an astrophysical background from unresolved compact binary coalscences is being pursued in conjunction with the CBC group. The joint activity will develop and implement a Bayesian search strategy that is optimally suited to handle the non-stationarity of the expected background from BBH mergers.

The Stochastic group is actively involved in detector characterization efforts, with overlap with the Detector Characterization (DetChar) group. For example, the SGWB group relies on magnetic field measurements to estimate and mitigate contamination due to Schumann resonances. There are also plans to study how intermittent signals from (instrumental, environmental, or astrophysical) transients may bias stochastic analyses using software injections. The group has also developed and maintains a stochastic data-quality monitor to track search sensitivity in real time and to identify problematic sources of noise.

1. **Highest priority**

   The Stochastic group places highest priority on activities that are essential for detecting and interpreting the stochastic background. The isotropic analysis is the original *raison d'être* for the SGWB working group, and the detection of a stochastic background is the SGWB group's most compelling scientific deliverable. We include in the **isotropic searches** recent and planned extensions including a search for non-GR polarizations, parameter estimation and model development, and a fully-Bayesian search for an isotropic power-law background. The standard **directional searches** employ both a radiometer algorithm and a spherical harmonic decomposition to generate sky maps (and strain spectra) that can be used to identify cosmological or local anisotropies as well as point sources. Extensions to the directional searches include an all-sky all-frequency radiometer search for unmodeled persistent GW signals, a search for an anisotropic background from Galactic pulsars, and component separation using narrowband maps. Models of anisotropic backgrounds will provide a detailed picture of an observable background. The **search for very long transients** assesses the temporal distribution of the SGWB. The production of a combined extended **folded data set** facilitates the application of the very-long transient search, the all-sky all-frequency radiometer and the galactic pulsar search. The **non-Gaussian searches** will address the possible non-stationarity of an astrophysical background. **Data quality and detector characterization studies** are essential to the understanding and interpretation of results for all of the group's activities.

2. **High priority**

We assign high priority to a software injection study on intermittent transients, to investigate how such signals may bias the stochastic analyses.

1.5 Characterization of the Detectors and their Data

The detector characterization teams are largely separate for LIGO and Virgo, but there are some common tools and ongoing exchange of ideas.

1.5.1 LIGO

LIGO's sensitivity to gravitational-wave signals is limited by noise from the instruments and their environment. Continued detection of signals of high significance, the vetting of candidate signals, and the accuracy of parameter estimation is *crucially* dependent on the quality of the data searched and the collaboration's knowledge of the instruments and their environment. The LIGO Detector Characterization group (DetChar) is focused on working together with the astrophysical search groups and the detector groups to (i) deliver the data quality information necessary to clean the data sets, veto false positives, and allow candidate follow-up for gravitational-wave searches; and (ii) characterize the Advanced LIGO detectors to help to identify data quality issues that can be addressed in the instruments to improve future instrument and search performance.

The priorities in this white paper have three major focuses: 1) contributing key work to the current O2 observing run and search results, 2) supporting the upgrade of the detectors during the commissioning break, and 3) preparing for future observing runs. The highest priorities for finishing the current observing run are maintaining key tools, monitoring data quality issues in the detector, vetting GW event candidates, and producing data quality products through the end of O2. During the commissioning break, an additional priority is conducting on-site and off-site investigations of interferometer and environment behavior to support the upgrade effort. The highest priorities in preparing for future observing runs are automation of key tools and commonly performed tasks, improvement of monitors of known data quality features, and development of data quality for very low-latency EM alerts. Other high priorities are characterization of interferometer subsystems and auxiliary channels before O3, and curating data quality information for public data releases.

In parallel, the are a number of research and development tasks which have the potential to enhance the detector characterization mission. The highest priorities are investigation of which instrumental artifacts have the most severe impacts on each astrophysical search, development of existing machine learning and citizen science methods to identify the causes of noise transients, and the integration of various detector characterization tools into a central framework with common data formats. Longer-term goals are development of new methods, or improvement of existing methods, for noise identification and mitigation. This includes exploration of machine learning techniques and transient noise identification methods. All new methods should be performance tested with a data set and performance goals outlined by the DetChar group.

Search Data Quality: LIGO data contain non-Gaussian components such as noise transients and quasi-periodic lines that adversely affect the astrophysical searches. Transient noise in the detector data can mimic or mask transient signals from Compact Binary Coalescences and more generic Burst sources, interfering with detection and the accuracy of the source parameters recovered. To minimize these negative effects, LIGO data must be cleaned of transient data quality issues. The primary forms of data quality information that must be delivered to the astrophysical search groups are: *state segments* that indicate which data should be analyzed, based on the state of the instrument and its calibration; *veto segments* that indicate periods of poor quality data; and *data quality triggers* that identify short durations where the data are likely to contain a non-astrophysical disturbance. Searches will use state segments to identify data suitable for analysis. Searches will use veto segments and data quality triggers to either ignore problematic data or to reduce confidence in any search triggers associated with these times. For continuous-wave and stochastic background searches, frequency bins that are contaminated by non-astrophysical disturbances must be identified and removed, and low-level, broadband contamination from correlated magnetic noise must be mitigated.

Automation of Data Quality assessment: With the anticipated signal rate for O3, and the need for low-latency data to support multi-messenger astronomy, the Detector Characterization group must develop automated approaches to identify the causes of instrumental problems and to provide data quality information in low-latency with minimal human supervision. This will be the main focus of the group during this period, with partners in the astrophysical search groups collaborating on both identifying pipeline needs and sensitivities to data defects.

aLIGO Instrument Characterization: The Detector Characterization group works with the detector commissioning and engineering groups to identify and resolve issues in the aLIGO subsystems related to glitch and noise contamination and auxiliary channel signal fidelity and robustness. This work has led to early data quality improvements and helped to train a wider pool of scientists who are familiar with the instruments. Continued work aims to facilitate aLIGO detections by ensuring that the detectors are well understood and that instrumental fixes for data quality issues are aggressively pursued. While the detectors are being upgraded, the DetChar group will provide commissioners with off-site assistance in any needed investigations as well as characterize changes in instrumental subsystems.

1. **Highest priority.** The highest priority of the LIGO Detector Characterization group is to provide timely data quality information to the LSC-Virgo search groups that designate what data should be analyzed, remove egregious data quality issues, and identify time periods and frequencies of poor data quality. Automation is central to success in this activity.

2. **High priorities.** Complement and collaborate on commissioning to help identify sources of data defects that limit sensitivity to transient and continuous wave (CW) gravitational wave sources. Use non-interferometer auxiliary sensors to find, quantify, and mitigate coupling between the gravitational wave strain data and the environment. Maintain and extend the software infrastructure required to provide needed data quality information to online searches.

3. **Additional Priorities.** Develop improved methods to uncover the causes of the noise transients which most impact the searches, with the goal of mitigating them or producing vetoes. Pursue exploration of well-motivated new approaches to data quality issues.

To accomplish these priorities, the LIGO Detector Characterization group requires:

- astrophysical search group participation to report sensitivities in the analysis pipelines to data defects
- data quality experts to identify data defects and investigate their source
- code developers to support and build key infrastructure and develop specific modules to recognize and flag data defects
- instrument characterization experts to quantify the sensitivity of the instrument to the environment, establish coupling coefficients between the gravitational wave data, the instrumentation, and the environment, and to identify mitigation strategies where needed

1.5.2 Virgo

Noise mitigation, spectral lines identification, glitch reduction and data quality vetoes are the main tasks of the Virgo detector characterization group. Responsibilities include working with the commissioning team to track down any limitation to the detector's sensitivity, working with the calibration team to maintain the calibration and timing accuracy to an acceptable level for GW searches, and providing noise information and vetoes to the data analysis groups and commissioning team. During past science runs and commissioning periods, the Virgo detector characterization team has provided several investigation and monitoring tools, and data quality vetoes which impacted positively both commissioning activity and astrophysical searches.

Search Data Quality: A new Virgo data quality model has been developed and is currently implemented. This model defines workflows and procedures the group will follow to provide data quality products to searches. In particular, emphasis is made to produce and deliver search-specific data quality vetoes. On top of this, a new and ambitious online architecture is being implemented to provide vetoes to online search pipelines. We have developed with LIGO a common data quality segment database, to benefit the Burst and CBC groups, and it has been moved to production. Additional data quality needs specific to the CW and Stochastic search groups include the identification of noise source contributions to spectral lines or non-stationary and non-linear features. For this, we use automatic spectral lines identification tools already well tested, and a line database.

Early Advanced Virgo Characterization: The Virgo detector characterization team will begin noise and glitch studies on each commissioned sub-system as soon as they come online, in close collaboration with sub-system hardware coordinators and commissioners. A system of shifts has been organized. Periodically, a team of two shifters is on watch. They study transient and spectral noise using analysis tools developed by the group.

1. **Highest priority**
   The highest priority of the Virgo Detector Characterization team is to find and mitigate sources of noise and to provide data quality information to the LSC-Virgo search groups in order to reduce the impact of the remaining noises.

2. **High priority**
   Our current high priorities are the development of useful tools for commissioning and an early characterization of each sub-system of Advanced Virgo in order to reduce the need for vetoes in future searches. This will imply a coherent system of monitoring web pages, a spectral line database catalogue, identification of non stationary lines and a software infrastructure to provide useful online data quality information.

3. **Additional priority**
   Additional priorities for Virgo detector characterization are to develop improved methods to uncover the paths and the sources of the noise transients which most impact the searches, and to implement automated noise classification tools.

1.6 Data Calibration

1.6.1 LIGO Calibration

LIGO calibration includes all work to produce the calibrated strain time series that is used by all astrophysical analyses. This necessary work includes:

- creating accurate models of the detector to calibrate the data
- maintaining the necessary infrastructure and performing the physical measurements needed to calibrate the detector models

- tracking and correcting for time-varying changes in detector configuration and performance
- providing an error budget on the calibration that astrophysical analyses use to establish uncertainties in measured quantities
- producing a calibrated detector time series in low-latency for multi-messenger astronomy
- providing infrastructure to re-calibrate the detector data with improved measurements and correcting problems with the low-latency calibration
- providing scientific support for the collaboration's astrophysical analyses on matters of detector calibration and its accuracy.

Since the calibration of the detector changes in response to its day-to-day environmental and physical state, and in response to planned commissioning changes that improve its sensitivity, calibration of the data is an ongoing task that requires continuous activity both during and between observing runs.

1.6.2 Virgo Calibration

During the Virgo science runs, the calibration measurements have been automated and extended to have some redundant data. 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 outputs are then used (i) in the frequency-domain calibration, resulting in the Virgo sensitivity curve, (ii) in the time-domain calibration, resulting in the GW strain digital time series and (iii) for the hardware injections. Independent cross-check of the reconstruction has been done systematically during VSR4 using a photon calibrator.

The methods used for Virgo will still apply for AdV after some tuning for the new configuration. Simulations have been carried on for the a priori most challenging measurements, i.e. the measurement of the mirror actuation response. They confirm that the Virgo methods can still be applied, putting some constraints on the minimum force to be applied on the AdV arm mirrors. In parallel a conceptual design of the new photon calibrator to be developed for AdV is being finalized before the setup is built and then installed. Critical calibration activities are:

1. development and improvement of instrumental measurements (in particular with the digital demodulation electronics of the photodiode readout),
2. prototyping and installation of a photon calibrator,
3. development of online tools to monitor the Virgo timing permanently,
4. upgrade the GW strain [h(t)] reconstruction method after the study of the impact of some parameters that were neglected during the Virgo era.

1.6.3 LIGO and Virgo Hardware Injections

Hardware injections are simulated gravitational wave signals added to LIGO and Virgo strain data by physically actuating on the test masses. They provide an end-to-end validation of our ability to detect gravitational waves: from the detector, through data analysis pipelines, to the interpretation of results. The hardware injection group is tasked with the development, testing, and maintenance of hardware injection infrastructure.

This includes on-site software to carry out the injections at specified times. We also work with the search groups to maintain the software that generates gravitational waveforms suitable for injection.

Each data analysis group works with the hardware injection team, in different ways: Burst and CBC groups provide transient waveforms and determine suitable injection rates, the CW group selects the parameters for neutron star signals, which persist throughout the observing run, and the SGWB group typically carries out one or two ≈ 10 min injections during each observng run. The search groups analyze hardware injections during science and engineering runs to identify and solve problems as they come up, and the results of these studies are reported back to the hardware injection team so that adjustments can be made.

1.6.4 LIGO Timing Diagnostics

Traceable and closely monitored timing performance of the detectors is mission critical for reliable interferometer operation, astrophysical data analysis and discoveries. The advanced LIGO timing distribution system provides synchronized timing between different detectors, as well as synchronization to an absolute time measure, UTC. Additionally, the timing distribution system must provide synchronous timing to subsystems of the detector. Timing distribution system's status is monitored, and periodically tested in-depth via timing diagnostics studies.

Critical timing tasks include:

1. verifying traceable performance of the timing distribution system,
2. verifying the validity and accuracy of the recorded time-stamp,
3. verifying the accuracy of the distributed timing signals,
4. expanding the capabilities of data monitoring tools related to timing,
5. availability of timing diagnostics for various subsystems,
6. measuring and documenting the timing performance,
7. reviewing the physical/software implementation and documentation of the timing distribution and timing diagnostics components.