What Comes Next for LIGO? Planning for the post-detection era in gravitational-wave detectors and astrophysics

Report from the DAWN-III Workshop, Syracuse, NY, July 6-7, 2017

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1 Preface

The workshop *"Dawn III - What comes next for LIGO"* took place on July 6-7, 2017 in Syracuse, NY, gathering about 40 gravitational wave scientists from around the world to continue planning for the post-detection era in ground-based gravitational-wave detectors and astrophysics.

At the time of the workshop, three gravitational-wave events from binary black hole coalescences had been confirmed [1, 2, 3, 4], and the second Advanced LIGO observing run was in full swing. In the weeks following the workshop, Virgo joined the run, additional binary black hole coalescences were detected and a new watershed moment took place on August 17, 2017, with the detection of a binary neutron star merger in coincidence with a gamma ray burst and extensive electromagnetic followup [5, 6, 7, 8, 9]. August 2017 will be remembered as the inaugural month of gravitational-wave enabled, multi-messenger astronomy, and the future of this new kind of astronomy will depend critically on the next generation of gravitational-waves detectors.

The two-day program of this workshop focused on the global strategy for third-generation (3G) gravitational-wave observatories and detectors and their science case, with emphasis on the coordination between the European effort proposing to build an observatory, detailed by the *Einstein Telescope* design study, and the U.S. proposal of a similar class observatory, named *Cosmic Explorer*. The workshop consisted of three sessions devoted to different aspects of planning for the future of the GW field:

- Session A: progress since the last meeting on strategic activities and technology;
- Session B: the 3G science case;
- Session C: building international collaboration on 3G efforts.

Each session included several presentations followed by a moderated discussion, affording participants ample opportunity to pose questions, make comments and suggestions. The sessions were organized and led by the members of the Scientific Organizing Committee: Beverly Berger and David Shoemaker (Session A), Matt Evans and B. Sathyaprakash (Session B), Harald Lueck and Sheila Rowan (Session C). The main conclusions and recommendations from the workshop are summarized in the Executive Summary of this report (§2). The remaining sections of this report summarize the discussions that took place in each session. Presentation materials from the workshop are publicly available online [10].

This report is a public document, designed to be shared with all parties interested in these strategic questions, and it represents the views of those participants at the workshop and other interested colleagues who reviewed the document and endorsed it[1].

Laura Cadonati and Albert Lazzarini, on behalf of the Scientific Organizing Committee and the workshop participants.

[1]These individuals are listed in Appendix A

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2 Executive Summary

The 2017 DAWN-III Workshop focused on the global strategy for third-generation (3G) gravitational-wave observatories and detectors and their science case, with emphasis on the coordination between the European effort of the Einstein Telescope (ET) design study, and the U.S. proposal of Cosmic Explorer (CE). The workshop consisted of three sessions devoted to different aspects of planning for the future of the GW field: progress since the last meeting on strategic activities and technology, the 3G science case, and building International collaboration on 3G efforts.

Progress since the last meeting on strategic activities and technology

The 2017 DAWN-III Workshop began with review of the key recommendations from the previous workshop followed by an overview of progress since the 2016 workshop. There has been progress on a number of fronts:

- *The GWIC initiative to organize and foster 3G studies has begun in earnest.* During the past year the interaction between the Gravitational Wave International Committee (GWIC) [11] and the Gravitational Wave Agencies Correspondents group (GWAC) [12], has increased, leading to a dialog on how to coordinate activities beyond the national scale.
- *The LIGO A+ upgrade to Advanced LIGO is under design;* it incorporates frequency-dependent squeezing, informed by laboratory demonstration of the approach. The US will be joined by the UK and Australia in developing a coordinated proposal for this initiative.
- *In support of the A+ effort, coating research has started to ramp up* with the establishment of the Center for Coating Research (CCR) in the US and collaboration among the CCR and international partners.

The review of recent progress in strategic activities and technology development highlighted the following priorities and recommendations for continued progress along the roadmap for ground-based GW observations?

- **A+ should be implemented**, and the team developing the upgrade concept should submit a proposal as soon as possible.
- **Essential A+ R&D must continue**, in order to be ready to inform the A+ final design.
- **The timelines, potential sensitivities, and realistic costs of the ultimate instrumentation of existing 2G facilities** (e.g., Voyager in the US) must be understood in order to make a credible science case for new 3G facilities.
- **The lifetimes of the present 3- and 4km installations should be soberly assessed** to help in determining timelines for 3G facilities.
- **An engineering study to establish scaling relations and to identify potential cost reductions** should begin as soon as proposed 3G concepts are sufficiently precise to allow it.

- **Communication must be maintained among planners of 3G instruments** (e.g., ET and CE) to ensure that the gravitational wave community has a common science case, a synergistic plan for the observatories, and a coherent message. The 3G science case is the first priority.

The 3G science case

The second session of the workshop focused on the status the 3G science case, and highlighted the following priorities:

- **Access to a global network capable of resolving the polarization states** of gravitational wave signals is of critical importance for tests of General Relativity.
- **The much improved sensitivity of 3G detectors** will deliver high-SNR events from which it may be possible to decode the ringdown phase of black holes, in order to establish whether they are Kerr black holes or something more exotic.
- Concomitant with detector improvements, **the numerical relativity community must continue to develop and deliver waveforms that cover a greater parameter space than is available today**, in particular covering less massive systems, with much longer waveforms, and eccentric systems.
- To access the nuclear equation of state (EOS) under super-nuclear densities attainable in neutron stars and understand how a binary neutron star (BNS) merger might begin to inform the EOS, **techniques need to be developed and tested that can derive neutron star radii from the data**. This requires further development of codes capable of producing GR waveforms when taking into account matter effects.

Building International collaboration on 3G efforts

The final session of the workshop was devoted to considering how the nascent international GW community might best organize itself into a governance model that could sustain the coordinated, design, development and deployment of a global array of 3G detectors to be operated as a single coherent network. We reviewed existing international organizations in physics and astronomy which range from the most binding options involving intergovernmental treaty arrangement (e.g., CERN) to the least binding, a model of which would be today's *collaboration of collaborations* which work together to operate LIGO and Virgo. How the world community organizes itself in the next few years may determine the long range future of the field. The recommendations from this session were that **the community should begin now the process of global planning to ensure community-wide buy-in of the science case and how to support it with a 3G network: what is needed is a global ownership of the design(s), and the implementation plan, including validated cost estimates, plans for risk mitigation, and the overall development schedule.**

3 Review of progress since the last DAWN meeting: strategic activities and technological progress

3.1 Recommendations from previous DAWN reports

To begin the third annual discussion of the future of ground-based gravitational-wave (GW) detection, it is useful to review the recommendations made in previous DAWN reports.

The first set of recommendations concerned LIGO A+, an upgrade of Advanced LIGO focusing on the addition of frequency-dependent squeezing and improved optical coatings:

1. *LIGO and its partners should proceed to implement LIGO A+ as soon as possible.* In the ensuing time since that recommendation was made a team composed of LIGO Laboratory and UK partners who contributed to Advanced LIGO has been exploring a concept for A+. At the time of this writing, a LIGO A+ proposal has been recommended for funding by NSF, and one is under review by the STFC in the UK, providing significant in-kind contributions to LIGO A+. In addition, the Australian OzGrav consortium is exploring ways to participate in A+, and at the time of this writing has received funding for A+ squeezing.
2. *LIGO-India should come online in the LIGO A+ configuration to match the US LIGO configurations expected at that time.* In response to this recommendation, there is currently a verbal commitment from LIGO-India to implement the same upgrades as the US instruments. The source of funding for this is being sought.

Previous reports noted the crucial importance of *improved optical coatings* to LIGO A+ and recommended a focused, coordinated effort to produce optical coatings with lower thermal noise. In response to this recommendation, a consortium of LSC institutions led by Stanford developed a proposal to the NSF for the LSC Center for Coatings Research. At the time of the DAWN-III Workshop, a decision on the proposal was still pending, though the NSF Physics Division recognized coating research as a high priority. The proposal has now been funded and the ramped-up program of research is underway. The Center is distributed across the globe including long-standing LSC groups active in coating research, while adding coatings experts not previously associated with GWs. In addition, modeling improvements and experimental coordination allow exploration of parameter space to search for candidate coatings.

It has long been recognized, and recommended in previous DAWN reports, that to go forward to the third generation era of GW detectors (3G) requires *global coordination.* A major first step in the global effort has been taken up by the **Gravitational Wave International Committee (GWIC)** in establishing subcommittees to explore various aspects of the path to 3G facilities including the science case, identification of highest priority 3G R&D, potential facility designs, and governance issues. A collaborative proposal to the NSF has been submitted by five institutions (MIT, Penn State, Syracuse, Fullerton, Caltech) to study the science-driven requirements of a 3G network, and perform a cost assessment for long above-ground detectors such as Cosmic Explorer (CE). In addition, progress has been made to deepen and strengthen the collaboration between those promoting US 3G concepts and those in Europe involved in updating the Einstein Telescope (ET) designs.

On a shorter timescale, previous DAWN reports recommended that both funding agencies, through the **Gravitational Wave Agencies Correspondents (GWAC)**, and science teams, through GWIC, coordinate on research for near- and mid-term upgrades such as A+. Progress here has been significant: GWIC's 3G planning process was presented to GWAC in October 2016, NSF is currently coordinating with the UK's STFC on review of the A+ proposal, and GWAC has requested regular updates from GWIC on the progress of 3G planning. Additional detail is provided in §3.2.

Past DAWN recommendations urged that GWAC request or encourage GWIC to provide international coordination of critical 3G technologies. GWIC's ongoing 3G planning process is, of course, international so that participants are regularly informed of developments. The development of the 3G science case by GWIC starts from the assumption that *the network is the detector*. This means that the strongest science case will require facilities whose signals when combined allow the fullest science to be extracted. While this does not preclude different facility designs, it does foster coordinated development of essential technology.

Finally, two past recommendations focused on sending information about candidate events (triggers) to electromagnetic (EM) partners. These partners were connected to the LSC and Virgo through Memoranda of Understanding (MoUs). The first recommendation was to send along with the existence and time of the trigger as much information as possible including skymaps, significance, distance, and likely event category. Note that the workshop was held before the detection of the first binary neutron star (BNS) merger and before the identification of several more binary black hole (BBH) mergers. The next LIGO-Virgo observation run, O3, will deliver low-latency public triggers of likely events. In the age of public GW triggers, the recommendation was made to continue MoUs with EM partners who wish to target particular sources or science.

3.2 Status of strategic activities

In the Fall of 2016, GWIC appointed a **3G subcommittee**, chaired by D. Reitze and M. Punturo, with five main components. Leading the way is the development of the science case, chaired by V. Kalogera and B. Sathyaprakash; the status of the science case development will be discussed later in this report. The remaining components are development of methods to coordinate the ground-based GW community, organizing and facilitating links among planned 3G facilities' associated GW communities and with other GW and non-GW communities relevant to their development and science, agency interfacing and advocacy by (at a minimum) developing communication channels, and investigating potential governance schemes for a global 3G effort. In 2017, S. Rowan reported on GWIC 3G at all major GW-related conferences and to APPEC, a consortium of 17 funding agencies, national government institutions, and institutes from 14 European countries, responsible for coordinating and funding European national research efforts in astroparticle physics [13]. On the funding agencies front, GWAC is an informal NSF initiative to create a direct channel of communication between funding agencies to coordinate the use of existing and to explore new funding opportunities for the gravitational wave science community. Some twelve funding agencies in North and South America, Europe, and Asia are currently members, and all agencies that include or contemplate GW funding are welcome to join. In the past year, GWIC and GWAC began coordination on research for near- and mid-term upgrades such as A+.

The charge of the R&D Coordination group in the GWIC 3G subcommittee is to develop and facilitate coordination mechanisms in the domain of technical development among the current and future planned and anticipated ground-based GW projects, including identification of common technologies and R&D activities as well as comparison of the specific technical approaches to 3G detectors. The subgroup itself will not engage in R&D. Rather, the goal is coordination to optimize the focus on crucial topics and to avoid redundancy of effort. Topics of international focus will be optical coatings and their substrates (silica, silicon, sapphire, ...) for both optical and thermal-noise performance, cryogenics to reduce thermal noise, facility issues (arm length, installation above or below ground, vacuum systems, ...), Newtonian and other low frequency noise, suspensions, lasers, squeezers, etc. To this end, it will be necessary to consider both design-independent R&D (probably the highest priority) but also design-dependent R&D, especially if the latter leads to down-selection of a single, optimal design.

It is interesting to look at the progress of ET, the *Einstein Telescope* concept developed for implementation in Europe. A great deal of progress was made on both the technical aspects and the coherence of the work among those groups focusing on ET while the study was funded. However, a certain time elapsed where there was much less activity and coherence. The missing component in the ET effort was the 'glue', that is the commonality of effort among the European groups in achieving ET. In the past, this glue had been provided by a single funded proposal. Unfortunately, recent efforts to obtain similar multi-national funding from the EU F2020 program have failed twice. The ET community is hopeful that APPEC will facilitate funding for a coordinated approach to update the original ET design and to proceed with making it a reality.

It is now time to consolidate the strategic approach to 3G. The starting point is the projection of (upgraded) 2G instruments as they would become in the 2020s and the science that could be expected from them. The case that must be made then is the additional science that one could obtain from the investment in 3G instruments. The main driver for the 3G effort should be the science case. In parallel, an engineering study to establish scaling relations and to identify potential cost reductions should begin as soon as feasible. The most interesting scientific opportunities would then inform the compromises (based on the engineering study) that would be inevitable in going from the ideal instruments to ones that could actually be built. The science would also determine the ideal case for how many instruments there should be and where they should be. Furthermore, the governance model should be driven by the optimal (science driven in equilibrium with reality) choice of instruments: the best governance structure will be driven by the need to achieve the 3G goal as determined by the science case. The astronomical community should be brought in to help make the science case, engineers need to be involved as early as possible to weigh in on what is feasible, and funding agency coordination should be sought now. We note the value to LIGO success of the single management for the two LIGO sites, and this should be considered for the 3G epoch in some form.

3.3 Technological progress: recent research highlights

The past year has seen progress on several fronts in the technology for advanced, ground based detectors, as summarized in this section.

3.3.1 Low frequency noise mitigation

A coordinated effort to address low frequency noise is essential for Advanced LIGO to reach design sensitivity. Challenges include scattered light, length-angle cross couplings, characterization of thermal and magnetic effects in the suspensions, and electrostatic charging of the optics. Some improvements have been made including better baffling and absorbers to reduce scattered light at LLO and an apparently effective method to mitigate charging. At the time of the Workshop, plans were underway to switch out end-test-masses (ETMs) to operate with improved coatings and replacement of the end reaction masses. These changes are part of the ongoing activities prior to O3.

3.3.2 Seismic isolation and suspensions

In addition to the headline changes to coatings and introduction of squeezing, the target A+ performance has stimulated developments in other areas. In particular, the reduction of seismic noise in A+ is pursued by using seismic arrays for Newtonian noise subtraction, implementing tilt sensors on the current internal seismic isolation system (ISI), increasing the diameter of the beam splitter and associated changes to the suspension, developing monolithic suspensions with thinner fibers to reduce the bounce/roll modes, improved analysis of stray light to aid mitigation, and understanding laser damage thresholds and contamination control. For 3G instruments, Newtonian noise mitigation could influence the site selection and the seismic array could become significantly more significant (e.g., by becoming 3-dimensional). Seismic noise reduction will require improved sensors with better tilt-horizontal coupling and noise performance, a study of sources of upconverted noise, new control strategies, and even implementation of some proposals for new configurations to reduce seismic noise. The suspensions need to be designed for either cryogenic silicon or large room-temperature silica mirrors; sensors and actuators that can operate at low temperatures need development; associated development items are establishing the ability to fabricate suspensions capable of handling heavy payloads, and determining how best to commission a cryogenic detector (KAGRA's experience here will be invaluable).

Collaboration is the key ingredient to achieve these technologies. Examples would be LIGO-India beginning operations in the A+ configuration, collaborations (already existing) with KAGRA to learn from their cryogenic experience, engagement with the worldwide array of mid-scale prototypes (Caltech, AEI, Glasgow, Gingin), and taking advantage of opportunities for sensor (including low frequency torsion pendulums) development with SWG/Nikhef, KAGRA, and ANU as a few examples.

3.3.3 Coatings

The installation of frequency-dependent squeezing in Advanced LIGO will make the current level of coating thermal noise dominant in a band around 100 Hz. To fully profit from the reduction in quantum noise requires reduction of thermal noise by a factor of 2. Several options are being explored by the NSF-Moore funded Center for Coating Research (CCR). Several avenues currently being explored include ideal glass, stabilized, and nanolayer coatings. The growth of the coating collaboration with the addition of experts in various techniques for making coatings, the ability to characterize four samples at once in a new Caltech facility, and the increasing importance of computer modeling allow progress to be made in these diverse areas. It was also noted that A+ will likely require stabilized, annealed amorphous coatings. Looking further ahead, Voyager (the possible step between A+ and CE) may require coatings appropriate for other laser wavelengths and substrate materials, e.g., 1550 nm and silicon respectively. An important milestone from the past year was the direct measurement of coating thermal noise at MIT, which allowed characterization of trial coatings.

3.3.4 Squeezing for LIGO and Virgo

Frequency independent squeezing is now being added to both Advanced LIGO detectors, to reduce the quantum shot noise due to the uncertainty in the arrival time of photons to the dark port diode. In Advanced LIGO the squeezed light source is placed within the ultra-high-vacuum envelope, and it is currently being commissioning to be ready for O3. Virgo is collaborating with AEI to add an in-air squeezer to Advanced Virgo on a similar timescale. Given known sources of optical loss in advanced detectors, the theoretical maximum squeezing enhancement is limited to 6 dB. Extra loss and phase noise set a more realistic target of 3 dB for O3 (equivalent to a laser power enhancement of a factor of 2). When operating at full power, advanced detectors will be limited by quantum radiation pressure noise below 100 Hz. In this scenario, frequency independent squeezing would only be able to decrease quantum shot noise, at the expense of increasing quantum radiation pressure noise (Heisenberg principle). Frequency dependent squeezing is needed to achieve a broadband reduction in quantum noise. Audio-band frequency dependent squeezing has been demonstrated in a table-top experiment at MIT [14], by reflecting the squeezed beam off a filter cavity. Suspended filter cavity prototypes are currently being commissioned at MIT and NAOJ. A three-hundred meter scale filter cavity is now considered the baseline for A+, with the goal of achieving broad-band reduction of quantum noise and take full advantage of improved coating design. To achieve higher levels of squeezing, optical loss needs to be reduced. Mode mismatch is one of the main loss mechanisms. A research program is underway to use thermally-controlled adaptive lenses to mode match everywhere wavefront sensing is measured, so as to reduce mode mismatch loss. Balanced homodyne readout is the typical readout scheme used in table-top, quantum noise limited experiments, and its application in large scale interferometers is under study. Alternative interferometer topologies are also investigated: the speed-meter concept is under testing in the Glasgow group; an additional concept, Einstein-Podolsky-Rosen entanglement – frequency dependent squeezing without a filter cavity – is also being developed for testing in GEO. Regarding other wavelengths that are plausible candidates for future detectors, squeezing at $2\,\mu$m has recently been demonstrated at ANU. Looking forward, it is clear that the goal of 6-10 dB of squeezing is very challenging and will not be achievable unless it becomes a top priority; filter cavities for squeezing and balanced homodyne readout are within reach but require finalizing the control scheme and understanding all of the relevant noise couplings; experimental results are needed to validate alternative topologies for application in large scale detectors.

3.3.5 Technical challenges for the design of CE

Unlike aLIGO, for CE, the choice of the length of the signal recycling cavity (SRC) affects the response of the detector to GWs. The aLIGO scheme for frequency control (locking the laser frequency to the average arm length using Pound-Drever-Hall reflection locking) will not work for CE's ten times longer arms. The questions of the test mass size and precision of radius of curvature and surface figure can be very difficult to resolve. Specific design issues for these questions were presented and contrasted with the 'easier' case of aLIGO.

The Free Spectral Range of a 40 km instrument may require some changes in length readout and control. In general, the technology of aLIGO will work for CE with extrapolations; relatively few things require new inventions. Clearly the mirror fabrication technology needs improvements for smoothness and the ability to deliver performance over a larger surface. Crystalline coatings which may address thermal noise are currently possible over 20 mm; this will undergo tests at 75 mm soon. More tantalum in the coatings shows (in initial measurement) some improvement. SiO was noted to be a possible ingredient in 2 micron coatings. Seismic isolation and suspension development are likely to be cost drivers for the overall detector components. This will be a 'push-back' on potential science case requests for better low-frequency sensitivity, and a current difference in the conceptual designs for CE and ET.

3.4 The big questions

For multiple detectors, we clearly have different kinds of top-level siting/funding constraints that will drive us to different solutions. How can we best enjoy economies of scale, and show unanimity, given that 'richness'? The most important thing is that the 3G detectors be operating together and have comparable sensitivities. How can we accommodate multiple observatories and funding? This is an important element in our undertaking due to our need to have a closely coordinated program constrained by diverse national interests. One element of our history we must not neglect is the common management of the two LIGO sites and the ability to distribute the resources freely between them as needed; this was critically important to the success of the LIGO/aLIGO instruments.

Progress toward 3G requires that we choose the most optimistic projections for where our field will be in the late 2020's to show what the 3G version will deliver beyond that projection. Science will change during the 10- to 20-year time period of gestation of the 3G projects, and it is important to work on the science goals to make them initially robust. We would like to leave the meeting with a community statement on the US development path; a definition of the role of the Voyager detector concept in the context of the 3G planning; timelines for 3G which can speak clearly and forcefully to the community and funding agencies. Lastly, we need a community approach (codified in a statement) to talking about the virtues of different designs which is constructive for all the approaches.

3.5 Conclusions and Recommendations

The review of recent progress in strategic activities and technology development led the participants to commend the progress that has been made on recommendations in previous DAWN reports. Highlights include GWIC's leadership in organizing and fostering the 3G studies, GWAC's increasing role in facilitating funding agency communication, the establishment of the Center for Coating Research to organize the US and international research aimed at the LIGO A+ upgrade and beyond, progress toward implementing frequency-dependent squeezing in time for A+, and the likely UK participation in LIGO A+.

The discussion in this session identified the following priorities and recommendations for continued progress towards A+:

- **A+ should be implemented**, and the team developing the upgrade concept should submit a proposal as soon as possible.
- **Essential A+ R&D must continue**, in order to be ready to inform the A+ final design.
- **The timelines, ideal sensitivities, and realistic costs of the ultimate instrumentation of existing 2G facilities** (e.g., Voyager in the US) must be understood in order to make a credible science case for new 3G facilities.
- **The lifetimes of the present 3- and 4-km installations should be soberly assessed** to help in determining timelines for 3G facilities.
- **An engineering study to establish scaling relations and to identify potential cost reductions** should begin as soon as proposed 3G concepts are sufficiently precise to allow it.
- **Communication must be maintained among planners of 3G instruments** (e.g., ET and CE) to ensure that the gravitational wave community has a common science case, a synergistic plan for the observatories, and a coherent message. **The 3G science case is the first priority.**

4 The 3G Science case

The second session of the meeting focused on the science case for future generation detectors, with a review of the role of the GWIC science case team in fostering a solid science case, as well as broad science topics relevant for 3G detectors: tests of General Relativity, extreme gravity, nuclear equation of state, and stellar evolution. This section summarizes the main conclusions of this session, with a list of take-home messages and action items identified during the discussion.

4.1 Role of the GWIC science case team

As mentioned in §3, in early 2017 GWIC formed a sub-committee on *Third Generation Ground-based Detectors* with the charge to examine the path to the *development of a network of future ground-based gravitational-wave observatories.* The GWIC 3G sub-committee will work with the global community to (a) explore and develop the science case for the next generation of observatories, (b) coordinate key research and development themes and programs that will lead to technological breakthroughs needed to achieve design goals and (c) recommend frameworks to efficiently manage and operate the next generation gravitational-wave detector network. In particular, the committee has been charged to deliver a science case document by December 2018. The 3G sub-committee appointed an international Science Case Team of 18 members, jointly co-chaired by Vicky Kalogera (Northwestern) and Bangalore Sathyaprakash (Penn State and Cardiff University). An open call to the international community to help develop the science case attracted more than 200 researchers worldwide and still growing. The science case is being studied by nine working groups, each co-chaired by two or three members of the science case team. Figure 1 illustrates how the science case team is organized.

A study carried out in Europe for the Einstein Telescope project has already demonstrated that the gravitational-wave window is rich in sources that can inform us about extreme gravity and fundamental physics, relativistic astrophysics and cosmology. LIGO and Virgo have already begun to make a big impact in astrophysics and fundamental physics. For example, the discovery of GW170817 has proven that binary neutron star merger produce gamma-ray bursts, adding a clue to a decades-long puzzle in astronomy. Consistency of the speed of gravitational waves and electromagnetic radiation has ruled out a large class of alternative theories of gravity proposed to explain the problem of dark energy.

Advanced detectors at their design sensitivity will detect thousands of binary black holes and hundreds of binary neutron stars each year. These data sets will provide an invaluable insight into dynamical spacetimes and structure of neutron star cores and a new tool for measuring cosmological parameters. Next generation of detectors will have a far larger distance reach and detect signals with a vastly greater signal-to-noise ratio. The 3G Science Case Team will explore the full gamut of science questions that can be addressed by the next generation of gravitational-wave detectors. In order to cast a wide net on the possible scientific benefits the study will deliberately avoid reference to any specific detector design or detector network, instead the focus will be to come up with a compelling list of science questions and how they might be resolved by future gravitational-wave observations and multimessenger astronomy. More specfcially, the highest priority areas of the science case

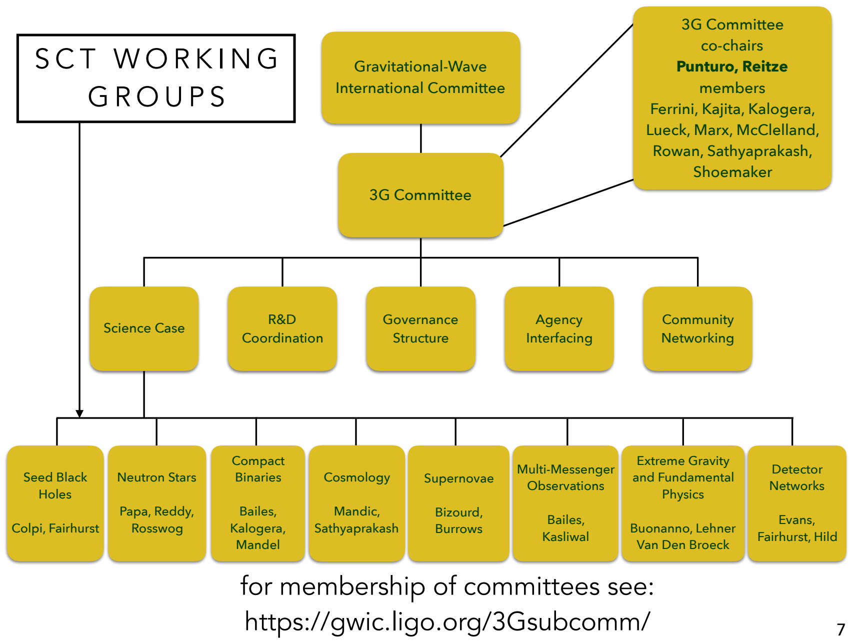

Figure 1: Structure of the 3G sub-committee and various working groups of the science case team.

include:

- understanding if nature's black holes are truly black holes of general relativity and exploring the existence of other compact objects in nature,
- testing strong field gravity and horizon dynamics during black hole mergers,
- deciphering the equation of state and structure of dense neutron star cores,
- mapping the demographics of light black hole seeds and their growth throughout the Universe,
- reconstructing the formation and cosmological evolution of binary black holes and neutron stars and their populations,
- detecting transient GW signals from supernovae and other explosive phenomena and hence shed light on the mechanism of gravitational collapse and core bounce, and
- measuring the Hubble parameter and the dark energy equation of state with standard sirens.

In addition, the Science Case Team will also examine (a) the progress that will be needed in waveform modeling, data analysis, and computing, to facilitate the best possible use of 3G data, (b) the detector networks that will be required to accomplish the science goals and (c) what multi-messenger observations of GW sources could help transform our understanding of the Universe.

4.2 Tests of General Relativity

The exploration of General Relativity (GR) and alternative theories of gravity with GW observations is following two main approaches: checking the consistency of the GW signal with expectations from GR and targeted tests for specific theories. While LIGO has already set important bounds with past detections [5, 15], 3G detectors can significantly improve these bounds.

Deviations from GR can affect the GW signals by altering the generation of GWs, and/or their propagation. In the latter case, the magnitude of the deviation from GR increases with the distance of the detected event. 3G detectors will be therefore able to contribute significantly to this aspect, by detecting events further away. An example is to test for a modified relation dispersion that affects that GW propagation, as done in [3].

In general, it is useful to associate alternative theories of gravity to their leading Post-Newtonian (PN) phase order. In this approach, constraints on different PN orders are informed by different frequency content [16]: the lower the PN order, the lower the corresponding frequency band of the detector that is important. In particular, the low-frequency content is dominated by negative PN orders - science in this regime requires designs with good low-frequency sensitivity.

An alternative approach is to test for evidence of dipole radiation, which is not expected by GR, but it is present in modified theories of gravity. In these scenarios, some energy will be lost to dipole radiation, and systems will inspiral faster than predicted by GR. Preliminary studies have already shown how future ground and space detectors would be able to constrain this energy loss [17]. Depending on the leading PN order of the particular theory, LISA, ET and CE would contribute in different ways.

Additional insight in alternative theories of gravity is a measurement of the GW polarization, as some theories predict up to 6 polarizations. For this particular problem, only a network of sensitive detectors would allow meaningful constraints [5].

Finally, detectors sensitive enough to decode the ringdown phase of black holes will help distinguishing between Kerr black holes and more exotic objects [18, 19]. Accomplishing this is extremely challenging with 2G detectors, and 3G instruments are needed. Some controversy still exists over what happens near the event horizon of BH [20, 21, 22, 23, 24]. Ideas for how to test this are relatively new, but more experience needs to be acquired.

A realistic expectation in the near future is that 2G detectors will keep providing tighter bounds, and possibly rank alternative theories of gravity. With 3G detectors we will be able to impose more significant bounds, but for real progress we also need models and numerical simulations of alternative theories of gravity that give us specific predictions for merger and ringdown, and spin precession. The null test of GR also require understanding equation of state effects and eccentricity, which can be important for events at high SNR, when the statistical uncertainty is small.

It should be noted that 3G detectors are not guaranteed to measure a deviation from GR. Still, some constraints, such as the graviton mass, are interesting scales, theoretically. It is unclear whether the broader community will find other scales compelling.

4.3 Extreme gravity

Numerical Relativity (NR) has achieved tremendous successes in the past decade, but challenges do remain for the community. NR is about solving the Einstein's Field Equations numerically without any approximation. This is a very challenging problem, since GR equations have hundreds of terms depending on formulations. The quest for solutions is more than 50 years old; since the first breakthroughs in 2005 [25, 26, 27], it took 12 years of solid, hard work to compute accurate gravitational waveforms in the late inspiral and merger dynamics of black hole binary (BBH) systems. Today there are several groups and multiple NR codes[2], and thanks to this community, NR is used to calibrate models, has produced large waveform catalogs [28, 29, 30], and plays an important role in interpreting LIGO observations [31, 32]. The various NR codes use independent approaches and calculations, but their results now agree very well [33], and residuals are small compared to current and near-future (5-10 years timescale) needs of the GW data analysis community [34].

There are however important areas of improvement necessary to optimize the extraction of gravitational wave science, especially at the ET/CE scale:

- There are still several sources of error in the NR waveforms, mostly dominated by the GW waveform extraction to infinity, but there are also paths to improvement, such as perturbative extraction.
- The extraction of higher waveform modes is already of particular importance for parameter estimation (e.g., GW150914) and tests of GR, and it will be even more important to extract science from the expected loud signals at the ET/CE scale (SNR$\sim$1000).
- Today NR provides accurate waveforms in the LIGO/Virgo band for system with total mass $\mathrm{M}_T > 50\mathrm{M}_\odot$, but smaller mass systems have a longer in-band signals, and for $\mathrm{M}_T < 30\mathrm{M}_\odot$ hybrid waveforms are needed, to track the full coalescence. For eccentric system there is not much available today, but we should expect a lot of progress in the next 5 years.

To conclude, future needs include a broader parameter space, improved efficiency of simulation and accuracy, as the interferometer sensitivity improves and statistical errors decrease. For non-GR simulations there are no simulations at the moment. Some proposals motivated by low-energy limits of quantum gravity, merit more attention. In summary, science in the ET/CE scale requires lots of modes, high accuracy, inclusion of more physics (eccentricity), and higher mass ratio.

The discussion highlighted how NR can also help discriminating between a classical and quantum black hole, by producing simulations that account for effective field theory, which would produce a quantum black hole, as well as tests of no-hair/multimode ringdown for classical black holes. These questions will become relevant at the ET/CE scale, but the simulations will take a very sizable efforts, so the work should start now.

4.4 Nuclear physics/ Neutron star radius from GW observations

Binary neutron star mergers lead to late-time gravitational wave signals that are very different from binary black hole mergers. At early stages of their evolution, when the

[2] SXS (SpEC), RIT (LazEv/ETK), GSFC(Hahndol/ETK), GT (Maya/ETK), AEI (CCATIE/ETK), Jena/Cardiff/Palma/Vienna (BAM), AEI/Palma (Llama/ETK), UIUC (Lean/ETK), etc.

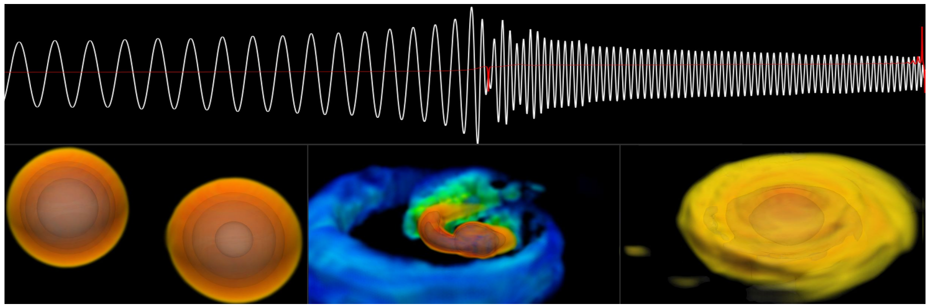

Figure 2: The diagram shows the anatomy of a binary neutron star signal: after a long inspiral, during which the two neutron stars can be essentially treated as point particles, the two bodies merge to form a black hole or a short- or long-lived neutron star, sorrounded by a torus that produces electromagnetic radiation. The nature of the post-merger signal, in particular the spectral features, depend most critically on the neutron star equation of state.

tidal interaction between the component bodies is small, gravitational waves from binary neutron stars are indistinguishable from binary black holes. As the companion bodies come closer together, the tidal field of one of the bodies induces a quadrupole deformation in the other body. Orbital rotation of the stars leads to a variation of the quadrupole and hence modifies the phase and frequency evolution of emitted gravitational waves (see Fig. 2). The modification depends on the neutron star equation of state and masses and spins of the bodies.

The central densities of neutron stars can be up to ten times larger than the nuclear saturation density and during the merger and coalescence of a pair of neutron stars the maximum density could rise even further. In fact, the behaviour of bulk matter at such high densities is not very well understood. The uncertainty in theoretical understanding comes from the many-body problem with strong interactions. The description of bulk neutral matter in terms of hadrons, such as protons and neutrons, may need to be expanded to accomodate new particles that are formed at these energies, such as hyperons, pions, and kaons. Indeed, the appropriate degrees of freedom describing cold matter at very high density may no longer be hadrons but the quarks and gluons themselves, in some form of quark matter.

During the inspiral phase neutron stars are well described by the ground state of matter, i.e. with a "cold" equation of state. The temperatures reached in the coalescence as a result of the strong shocks will be significant and of the order of $\sim 10^{10}$–10^{12} K. Yet observed characteristics of neutron star mergers may be able to constrain the ground state of dense neutral matter. However, building accurate waveform models from the post-merger phase will be key to making the necessary measurements and inferring the supra-nuclear equation of state.

An interesting feature that has emerged from studies of BNS coalescences is the formation of a hyper-massive remnant which oscillates and emits gravitational waves on fairly long timescales. The presence or absence of such post-merger oscillations, as well as their characteristic frequency and duration, varies with the cold equation of state. However, they are additionally sensitive to other physical characteristics, such as thermal properties, magnetic fields, particle production, and so forth. The precise details of the signal are not easy to predict. However, the signal from such a post-merger oscillation could be directly visible in a third generation detector, which should help probe the equation of state.

4.5 The first stars and galaxies through a GW lens

The first stars, known as Population III (Pop III) stars, were formed during the epoch of reionization, at red-shift $z \sim 6-20$. These stars have never been observed, but are expected to be very massive, up to an possibly beyond $100\,\mathrm{M}_\odot$, and are a potential source of massive black holes in the early Universe. Pop III binary systems will produce black hole binaries (BBH) with a distribution of merger times, the majority of which are expected to be on the scale of cosmic evolution (billions of years), but the number of Pop III remnant mergers at low red-shift is not known. Third generation GW detectors will have sufficient sensitivity to measure mergers of BBH from Pop III stars as a function of red-shift and thus the potential to separate them from other BBH populations. While a single 3G detector will be capable of detecting such sources from throughout the Universe, a network of 3G detectors may be necessary to provide accurate measurements of the distances and masses of these sources.

While we have some understanding of the formation mechanisms and environments of first stars, the mass distribution of Pop III stars is poorly constrained, as is the range of red-shifts at which they formed. While GW events offer a unique means of improving our understanding of both of these features of Pop III stars, at high red-shift mass and distance are inexorably linked in GW signals; the observed mass $M_{obs} = (1+z)M_{source}$, and the measured distance is $D_L = (1+z)D_c$ where D_c is the co-moving distance to the source. Cosmological models can be used to compute $z(D_c)$, but the resulting red-shift estimate will only be as accurate as the measurement of D_L, and thus the mass of the source will be limited by the distance measurement. Accurate source localization on the sky and measurement of both GW polarizations improve distance measurements, pointing to the necessity of the network of 3G detectors.

4.6 Figures of Merit and Detector Design

The DAWN-II report included a recommendation to develop new metrics to guide future detector design: *Detector performance is a multi-dimensional consideration. The community should identify a set of performance metrics for future planning, beyond the single space- time volume metric ($V \times T$) that is now used. Examples might include metrics that emphasize the localization and discovery potential of a detector network.*

Progress on this in the past year was focused on compact binary coalescences. Historically, we have quantified a detector's sensitivity in terms of the *binary neutron star inspiral range*, defined as the effective radius of the average detection volume of a GW detector (assuming a detection threshold of SNR = 8) for uniformly distributed and randomly oriented binary neutron star systems. Other metrics could be potentially more relevant to compact-binary systems science target [35]. Amongst them are:

- Horizon: maximum distance at which a given source could be detected assuming optimal orientation and location

- Response distance R_x: luminosity distance at which x% of the sources would be detected, for sources placed isotropically on the sky with random inclinations/orientations, but with all sources placed at exactly this distance.
- Average distance: average luminosity distance of the detected sample.

The discussion which followed highlighted the need for more science target oriented figures of merit, or *'performance metrics*. In particular, science targets which rely on more than just detection of CBC sources and/or on non-CBC sources, are not represented by these extensions of the standard *range* metric.

4.7 Conclusions and Recommendations

The second session of the workshop focused on the status the 3G science case, and highlighted the following priorities:

- **Access to a global network capable of resolving the polarization states** of gravitational wave signals is of critical importance for tests of General Relativity.
- **The much improved sensitivity of 3G detectors** will deliver high-SNR events from which it may be possible to decode the ringdown phase of black holes, to establish whether they are Kerr black holes or something more exotic.
- Concomitant with detector improvements, **the numerical relativity community should continue to deliver waveforms that cover a greater parameter space than is available today**, in particular covering highly spinning, less massive systems, with much longer waveforms, and eccentric systems.
- To access the nuclear equation of state (EOS) under super-nuclear densities attainable in neutron stars and understand how a binary neutron star (BNS) merger might begin to inform the EOS, **techniques need to be developed and tested that can derive neutron star radii from the data**. This requires further development of codes capable of producing GR waveforms when taking into account matter effects.

5 Building international collaboration on 3G efforts

As noted in §3, previous DAWN reports emphasized that to deliver on the promise of the science of the gravitational waves field, international collaboration and co-operation is needed at the level of both scientific projects and funding agencies. The third session of the DAWN-III workshop was dedicated to presentations and perspectives:

- on the models for operating and governing large-scale scientific projects with an international footprint;
- on lessons learned from other large scale astronomy-type facilities;
- on the cross-funding-agency activities in Europe targeted at planning for international astro-particle physics developments;
- on the status of design planning for 3G observatories stemming from activities in Europe and the USA.

5.1 Models for governance of scientific megaprojects

The session opened with a presentation from Gary Sanders, from the Thirty Meter Telescope (TMT) and the GWIC 3G governance subgroup, with a perspective on models for governance of very large science projects. This served as a stimulus to understand the landscape of how project governance needs to match the vision of a community and funding agencies for a particular field of science.

The model for governance of projects starts with their originators: is the project driven bottom–up by a single institution or by a set of institutions in a particular country? Or is it driven top–down, with international funding agencies as originators, with peer consultation and with each agency organizing its supported community and guiding the communities into collaboration?

Canonical options for global project governance were examined, ranging from the most binding options (intergovernmental treaty organisation like CERN) to the least binding options (minimally coordinated, separate, but related, existing executive organizations such as the current LIGO and Virgo arrangements). A key consideration in making choices around governance is the vision, both from the community and supporting agencies for the future of the field: are we planning for just the next set of detectors or for a longer future? For a single world-wide gravitational wave laboratory with multiple sites, with unified management and perhaps only one detector design, or for an option that suits diverse designs deployed at different sites but co-ordinated operation? Such considerations strongly influence any proposed governance model. High Energy Physics has been through this phase change, but in our field it is now another point of inflection – previously we went from small science to Big Science, and now we are facing a step from Big to Global.

During the discussion it was noted that the International Linear Collider (ILC) represents an example of how the community and agencies moved forward via the entities of International Committee for Future Accelerators (ICFA) and Funding Agencies for Large Colliders (FALC), which are the equivalent of GWIC and GWAC. The process started with ICFA producing a 20 page document describing the science, with references for deeper information. Then ICFA formed the Central Design Group, which enabled down-selects and the establishment of a conceptual design. FALC then developed funding for the study and established the charter. This was a 5.5 year process that ensured balance in representation, and also required a couple of years to setup.

5.2 Astroparticle Physics in Europe: via our new roadmap towards more collaboration and coordination

At the time of the DAWN-III meeting, the Astro-Particle Physics European Consortium (APPEC), which is the grouping of European agencies supporting astro-particle physics, including gravitational waves, was engaged in the writing of an updated roadmap for the field. The APPEC General Secretary, Job de Kleuver, presented the strategic objectives of the APPEC: to coordinate European Astroparticle Physics, to develop and update long term strategies via a roadmap, and to express collective views on astroparticle physics in international fora. APPEC can do this via:

- coordination between existing/developing national activities;
- convergence of future large scale projects/facilities;
- organizational advice for implementation of large facilities;
- common calls funded by a (virtual) common pot.

For very large projects, APPEC serves the need for a collective European view and global coordination. The latest version of the APPEC roadmap was recently launched in January 2018 and it states: *With its global partners and in consultation with the Gravitational Wave International Committee (GWIC), APPEC will define timelines for upgrades of existing as well as next-generation ground-based interferometers. APPEC strongly supports further actions strengthening the collaboration between gravitational-wave laboratories. It also strongly supports Europe's next-generation ground-based interferometer, the Einstein Telescope (ET) project, in developing the required technology and acquiring ESFRI status. In the field of space-based interferometry, APPEC strongly supports the European LISA proposal.*

GWIC was invited to for a first discussion with the representatives of APPEC at its General Assembly in December 2017: APPEC has tools it can use to support European gravitational wave 3G activities such as the organization of common calls for ET R&D (as has been done in the past); and organization of political support towards the preparation of inclusion of ET on the European Strategy Forum on Research Infrastructures (ESFRI) roadmap in 2019/2021. APPEC has endorsed ET in Europe and recommends developing common strategies (on European or global level) on topics like: open access and open data policies, computing needs, socio economic impact and the value of international collaboration.

5.3 Lessons from Australia's participation in the Square Kilometre Array

The OzGrav Director, Matthew Bailes, presented lessons learned in the formation of large science projects from Australia's participation in the Square Kilometre Array (SKA).

The key message was that science needs to drive the technological solutions. Global partnerships can be essential but governance needs early attention for the success of large scale international projects, and it is desirable to make site selection choices as early as possible. There remains a strong scientific case for sites located in Australia/the far east along with detectors in Europe/North America.

5.4 Status of planning and design for 3G detector concepts

The status of planning and designs for 3rd generation detector concepts in Europe and the United Status was examined.

Matt Evans presented a concept for Cosmic Explorer – a US led design concept for a 3G observatory. At the time of the meeting a proposal for a conceptual CE design study was in preparation (now submitted to the NSF). Meeting participants discussed the options for consideration in designing a global 3G observatory network. A network design should consider first what the optimal number of detectors would be – driven by our new knowledge from recent detections feeding into a 3G network science case. Other considerations include location, whether there is a role for existing, perhaps upgraded 2G detectors, etc.

The 3G science case, under development by a 3G subcommittee of GWIC, should provide input into the Cosmic Explorer concept. Cosmic Explorer conceptual work will be coordinated within the LSC, and with international partners in Europe and Australia through GWIC and GWAC. Preliminary budget estimates suggest this doesn't fit within a single agency like NSF – it is more probably global, more than just informal international or regional collaborations. The discussion suggested that a science case needs to define "the" ideal array, with consideration of how ET or CE fit in there, and other designs as well. Science is unquestionably a global solution, whereas the multiple instruments have to and can accommodate different boundary conditions.

There was a consensus that the vision of the GW community for new observatory infrastructures is a long term vision of facilities for the future.

5.5 Conclusions and Recommendations

The international GW community should begin the process of global planning and establishing community-wide buy-in of the requirements and approach to meeting them with a 3rd generation network of detectors. The scientific motivation must be clear, strong, and widely appreciated by the public, the broader scientific community, and by government funding agencies. It is essential to work together globally early enough to build global ownership of the design (or designs) and its implementation plan including a clear understanding of a validated cost estimate with a plan for cost risk mitigation. In the U.S., the timescale for having sufficient information available would be the next DAWN Workshop, at which time the NSF may consider beginning the process of developing a charter for an independent external study.

The Gravitational Wave Agencies Correspondents (GWAC[12]) was established informally by the NSF in 2015 after the first DAWN workshop in order to provide an inter-agency forum within which a direct channel of communication between funding agencies may be used to coordinate the use of existing funds and to explore new funding opportunities for the gravitational wave science community. The Gravitational Wave International Committee (GWIC[11]), was formed by the leaders of the various projects in 1997 to facilitate international collaboration and cooperation. These two entities, one representing the funding agencies and the other representing the major GW projects, represent the appropriate international forum within which to forge new consortia and to plan for future large-scale projects. **The GWAC and GWIC should engage to coordinate an international R&D effort in the critical technologies for next generation ground-based GW**

detectors. There are different modalities for successful progress on this front. **The suggestion of a future following on meeting hosted in Europe covering 'DAWN' topics but hosted in Europe by APPEC should be given consideration.**

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Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H. E. S. S. Collaboration, LOFAR Collaboration, LWA, Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN, Fireball Network, ATLAS, Time Resolution Universe Survey, RIMAS, RATIR, and South Africa/MeerKAT. Multi-messenger Observations of a Binary Neutron Star Merger. *Astrophysical Journal Letters*, **848**:L12, 2017.

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