Global strategies for gravitational wave astronomy
Report from the Dawn IV workshop; Amsterdam August 30-31 2018

April 22, 2019

Contents

1 Preface

The workshop *Dawn IV: Global strategies for gravitational wave astronomy* took place August 30-31, 2018 in Amsterdam, the Netherlands. 100 physicists and astronomers attended to plan a global approach for third generation ground-based gravitational wave detectors.

By the time of the Dawn IV workshop, the LIGO and Virgo collaborations had announced the detection of gravitational waves from six binary black hole (BBH) mergers [1, 2, 3, 4, 5, 6] and four more three months afterward [7]. The results from the most recent observing run, O2, included the first gravitational wave signal detected by a global network of three detectors, which allowed for novel tests of general relativity in the strong field limit [6]. The detection of gravitational waves from a binary neutron star merger just three days later, GW170817 [8], in coincidence with a gamma ray burst [9], opened the era of multi-messenger astronomy with gravitational waves [10]. A successful electromagnetic follow-up campaign identified the host galaxy [11] and enabled observations across the electromagnetic spectrum, resulting in new measurements of fundamental physics [12]. In the interim, the 2017 Nobel Prize in Physics was awarded to Rainer Weiss, Kip Thorne, and Barry Barish for their contributions to the first observation of gravitational waves from the binary black hole merger GW150914.

Since the end of O2 in late August 2017, the LIGO and Virgo detectors have undergone an intense period of instrumentation upgrades and commissioning to continue pushing the detectors' astrophysical reach toward design sensitivity [13, 14]. Currently the Advanced LIGO, Advanced Virgo and GEO detectors are preparing to begin the third observing run O3 of the advanced detector era in spring 2019 [15]. KAGRA is completing installation of its underground, cryogenic detector and plans to join O3 as well in late 2019 [16]. The expected rate of confident detections of gravitational waves from compact binary mergers is as high as once per week during O3 with Advanced LIGO and Advanced Virgo, with roughly 10x uncertainty. A higher event rate in O3 is expected to quickly grow the catalog of known stellar remnant masses, spins, and distribution in the Universe. Further upgrades will allow the Advanced LIGO+ (A+) and the Advanced Virgo+ (AdV+) detectors to nearly double the detector design sensitivity by 2024 [17]. The evolution of the world-wide detector network will also include LIGO India, currently planned to be operation mid-2025 as a third A+ detector.

Results from the past three years have firmly established gravitational-waves as a new branch of astronomy. Excitement from scientists and the general public world-wide has further fueled the exploration of ideas and plans for the next generation of terrestrial gravitational detectors: the third generation, or 3G. A major goal of Dawn IV was to strategize across the global gravitational-wave astronomy community on how to build the most scientifically fruitful future detector network possible.

During the two-day workshop, members of the scientific organizing committee led sessions and discussions spanning the current status of the field, designing and evaluating designs for 3G detectors, and organizing a global community strategy for realizing next generation detectors:

- A survey of progress in the field (Section 3)
- Designing the 3G detectors (Section 4)
- The roadmap to 3G detectors (Section 5)

Recommendations and action items based on discussions are provided at the end of each section and summarized in the executive summary.

In contrast to previous Dawn meetings (Dawn I, Dawn II, Dawn III), which focused more on the U.S.-based LIGO gravitational-wave detectors, Dawn IV had a truly global scope. Attendees represented Australia, Belgium, France, Germany, Hong Kong, Hungary, India, Italy, Japan, the Netherlands, Spain, Switzerland, the United Kingdom, and the United States, with 54% affiliated with institutions in Europe, 38% in the United States, and 8% in Asia and Australia.

This report represents the views of those participants at the workshop and other interested colleagues who reviewed the document and endorsed it [1].

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[1] These individuals are listed in Appendix A.

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2 Executive summary

The dawn of the detection era in September 2015, the first GW detection with a global network of three advanced detectors in August 2017, and the subsequent detection of the merger of two neutron stars with gravitational and electromagnetic radiation increased global interest in future, third generation (3G) gravitational wave detectors.

As a consequence of previous Dawn workshop recommendations, the Gravitational Wave International Committee (GWIC) has taken the lead in organizing the global vision for 3G science. Additionally, the Gravitational Wave Agencies Correspondents (GWAC) has facilitated international funding agency communication surrounding future large-scale terrestrial detectors. The GWIC 3G subcommittees, especially the Science Case Team, have made progress building an internationally coordinated science case and a global synergistic plan for 3G observatories.

Research and development for detector upgrades and future detectors is already well underway. Recently, the NSF has funded the A+ project in the U.S., with participation from OzGrav and funding from ARC in Australia. The STFC in the U.K. is also expected to support the A+ project with in-kind funding contributions. The NSF-Moore funded Center for Coating Research (CCR) is also exploring coating options for A+. Toward 3G detectors, a collaborative proposal to study the science-driven requirements of a 3G network and assess the costs for large-scale above-ground detectors (such as Cosmic Explorer) was funded by the NSF. With a science case already well established for the Einstein Telescope (ET) design, studies of future ET sites are in progress.

The future global 3G detector network

In order to maximize the scientific output of the global network of detectors, we propose as a future goal a network of three 3G detectors; potentially an Einstein Telescope in Europe, a Cosmic Explorer in the US, and a third 3G detector in a location that maximizes the sky localization ability of the network. Given the likely US and Europe locations for two of the detectors, a site in the southern hemisphere appears optimal.

In order to achieve a global network of 3G detectors, the GW community needs to be well coordinated to have clear, coherent input to the variety of coming international roadmapping exercises. GWIC should continue to provide a framework to enhance 3G profile and accelerate interaction between international projects and global agencies.

To that end, below are major recommendations and action items contained in this report.

General Recommendations

- GWIC should found an international Umbrella Organization by the Dawn V meeting in Spring 2019 to coordinate international research and development for 3G and detector upgrade plans.
- The ground-based GW community should prepare to respond to calls for input to roadmaps. Specifically for the US Astro2020 Decadal Survey, we should respond through the submission of i) a coordinated set of science white papers, and if required by the Astro2020 charter ii) roadmaps for development of mid-scale technologies and programs to enable 2.5 and 3G detectors. A proposal should also be included in the 2021 European Strategic Forum for Research Infrastructures (ESFRI) roadmap.
- A Dawn V meeting should be held when the GWIC-led 3G subcommittee report is expected to be released to the community. The focus should be the 3G subcommittee report and its use for informing international funding agencies, including the the US Astro2020 Decadal Survey and the 2021 ESFRI roadmap in Europe.

Designing the 3G detectors

- Exploring the astrophysical science gain of a third 3G facility and placement in the southern hemisphere should be a top priority for GWIC.
- We recommend that the 3G science case evaluate the science contribution from below 10 Hz versus above 10 Hz for each item, to help inform detector requirements, and for 500 Hz to 4 kHz, potentially from 2G and 2.5G detectors with shorter baselines of 3-4 km.

The roadmap to 3G detectors

- The GW community should address the development of software and computing hardware in parallel with the instrumentation and science development.
    - The GW community should invest in funding and planning for the employment of computer scientists to support the infrastructure needed for 3G data analysis.
- The 3G community should adopt the following common strategies:
    - Establishment of a common research and development program within the U.S. and Europe to facilitate the exchange of information and optimize the global expenditure of efforts.
    - As part of a broader global research and development effort, investment in more global resources devoted to characterization of coatings at cryogenic temperatures, such as a dedicated, internationally resourced coatings center.
    - Global coordination of prototype engineering and scaled tests for 3G detectors, including beam tube construction, vacuum technologies, and excavation and construction methods.
    - Development of a long term plan that balances observing with installation and commissioning breaks to make use of current generation facilities as a testbed for 3G technologies.
- The 3G community should continue to explore paths from the current organization of largely independent projects toward a global unified endeavor, with the objective to optimize the use of financial and human resources, and to maximize the science from a 3G network.
- The GW, EM, and neutrino communities should coordinate to identify key joint science targets for multi-messenger studies.

Lastly, we recognize that the GW community is currently dependent on a single optic coating facility (LMA) for detectors present and future, and a single source for any critical component is viewed as a potential risk to the whole community. In addition to the recommendations for enabling a next-generation global detector network above, we also highly recommend the re-establishment of the coating capabilities in hardware and staffing once offered by CSIRO in Australia to mitigate this present risk and as a significant contributor to broader ongoing research efforts.

3 Survey of progress

3.1 Progress on action items in the Dawn III report

The Dawn III workshop *What Comes Next for LIGO: Planning for the post-detection era in gravitational-wave detectors and astrophysics* took place on July 6-7, 2017 in Syracuse, NY [18]. This meeting focused on addressing strategic questions about the future of gravitational-wave astrophysics, and resulted in recommendations summarized in the Dawn III report [19].

Highlights of progress from Dawn II to Dawn III

A series of achievements occurred prior to the Dawn III meeting that stemmed from recommended outcomes of the Dawn II meeting. The Gravitational Wave International Committee (GWIC) took the lead in organizing and fostering studies of 3G detectors, detector networks, and science. Additionally, the Gravitational Wave Agencies Correspondents (GWAC) played an increasingly impactful role in facilitating international funding agency communication. The Center for Coating Research was established to organize international research aimed at the LIGO A+ upgrade and beyond. Progress was made toward achieving frequency-dependent squeezing in time for A+, and toward UK participation in LIGO A+.

Major changes in the field between Dawn III and Dawn IV

The second observing run (O2) overall resulted in a number of detections, with discoveries of gravitational waves from the mergers of ten stellar remnant binary systems reported by the LIGO and Virgo collaboration to date [1, 2, 3, 4, 5, 6, 7]. Additionally, the LIGO and Virgo collaboration achieved a global 2G detector network during O2, which made multiple detections, including the first triple detection of a binary black hole merger, GW170814 [6], and the observation of gravitational waves from a binary neutron star (BNS) merger, GW170817 [8]. The latter discovery was the first example of multi-messenger astrophysics with gravitational waves. The presence of the Virgo detector in the LIGO-Virgo detector network enabled the sky localization that drove a successful electromagnetic follow-up campaign [10]. GW170817 transformed the interaction between GW community and the broader scientific community, establishing gravitational wave observations as a key component of modern astronomy.

Progress toward future detectors

The Dawn III report made six recommendations addressing global progress toward future detectors, including 2.5 G designs that are upgrades to current second generation detectors, such as A+; and 3G designs such as the Einstein Telescope and Cosmic Explorer. Each of these recommendations is quoted below along with a summary of progress.

"A+ should be implemented, and the team developing the upgrade concept should submit a proposal as soon as possible."

The A+ project [17] was recently funded by the National Science Foundation in the U.S., extending the reach and project lifetime of the LIGO detectors. A partner proposal is currently under review by the STFC in the UK, providing significant in-kind contributions to LIGO A+. The Australian OzGrav consortium is participating in A+, and has received funding for A+ squeezing. The Virgo Collaboration has developed a two-phase plan for AdV+, and is working with funding agencies on its realization.

"Essential A+ research and development must continue, in order to be ready to inform the A+ final design."

Several options for coatings are being explored by the NSF-Moore funded Center for Coating Research (CCR), including ideal glass, stabilized, and nanolayer coatings. A 300m scale filter cavity that would enable frequency-dependent squeezing is now considered the baseline for the A+ design. The LIGO laboratory and partners are currently exploring thermally-controlled adaptive lenses designed to reduce mode mismatch loss.

"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."

This was a primary goal of the Dawn IV meeting; see Section 5.7 for discussion. Additionally, seismic isolation and suspensions are under development for cryogenic silicon as well as large room-temperature silica mirrors. Testing of 2 micron lasers and development of light squeezing at 2 microns, needed for silicon mirrors, is underway. Multiple groups around the world are also investigating alternative interferometer topologies.

"The lifetimes of the present 3- and 4-km installations should be soberly assessed to help in determining timelines for 3G facilities."

According to a LIGO Laboratory study the current LIGO facilities are expected to last until the mid-2040s with two major caveats: 1) the vacuum system is refurbished, which is underway for LIGO sites, and 2) funds are found to keep the remainder of the infrastructure from obsolescence. ∼10M USD are required beyond nominal vacuum system maintenance.

"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."

A collaborative proposal to study the science-driven requirements of a 3G network, and perform a cost assessment for long above-ground detectors such as Cosmic Explorer was funded by the NSF (MIT, Penn State, Syracuse, CSU Fullerton, Caltech).

"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 GWIC 3G subcommittees, especially the Science Case Team, have made significant progress addressing this recommendation. This Dawn IV meeting intended to further deliver on this recommendation.

The 3G science case

The GWIC 3G sub-committee has been charged to deliver the first draft of a 3G science case document by December 2018, which will undergo internal review and revision in early 2019. The GWIC 3G Science Case Team has since been formed, and issued an open call to the international community to help develop the science case. This call 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. The Dawn III report highlighted five priorities for building the global 3G science case. These are quoted below, along with a summary of progress.

"Access to a global network capable of resolving the polarization states of gravitational wave signals in addition to the position and distance to sources is of critical importance for tests of General Relativity."

The observation of multiple BBH signals and one BNS merger demonstrated the capability and value of a global 3-detector network. GW170814 demonstrated that the signal's polarization is consistent with GR. More than three detectors are required to test non-GR polarizations. KAGRA and LIGO-India are keenly awaited. Additionally, GW170817 helped constrain the propagation speed, and this helped rule out many alternative theories of gravity.

"The much improved sensitivity of 3G detectors will necessitate the development of more accurate models to decode the ringdown phase of black holes and establish whether the sources are Kerr black holes or something more exotic."

Theoretical efforts are underway to understand the dynamics of the merged horizon and to generalize the no hair theorem to BBH systems.

"Concomitant with detector improvements, the 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."

Numerical and analytical relativity efforts have been split between BBH and BNS (matter), but NR and AR groups are coordinating to increase the parameter space for BBH simulations.

"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."

We are working on improved waveform models, now that we have analyzed GW170817 and reported the first measurement of NS radii. We need to understand the model systematics and include the postmerger part of the signal in our analysis and here too some progress has been made within the LVC.

"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 x T) that is now used. Examples might include metrics that emphasize the localization and discovery potential of a detector network."

Some proposed ideas are currently under investigation, as reported in Section 4.4.

Building an international collaboration of 3G efforts

Discussion during the Dawn III meeting resulted in one recommendation on the governance structure of a global 3G detector effort, which is quoted below along with a summary of progress.

"Global community building for internationally coordinated science case, and detector design/development." The Dawn IV meeting and report are steps toward this global planning. See also Section 5.8 for recommendations on the future of Dawn meetings.

3.2 Global timelines and constraints

3.2.1 Europe

Physicists and astrophysicists from European countries participate in a number of GW infrastructures on the ground (GEO, LIGO, Virgo) and in space (LISA).

As a guidance for the future, it should be kept in mind that it took 30 years from the 1989 Virgo proposal, to the forthcoming 2019 O3 run, a run with a projected sensitivity above 60 MPC for BNS detection (double O2 sensitivity).

The scientific history of Virgo passed from the acceptance of the proposal in 1993-1994, the start of construction in 1997, the start of science runs and the operation together with LIGO as a single observatory in 2007, the Advanced Virgo approval in 2009 and of course the 2017 detections. The scientific landmarks were accompanied by institutional landmarks, starting with the foundation of the EGO consortium by CNRS and INFN in 2000 to host the Virgo antenna, the joining of Netherlands in 2006 and Spanish, Polish and Hungarian groups in 2010, Belgium and Germany in 2018. The total cost of the endeavor, including the operation budget during these years is close to half a billion Euros.

The Advanced Virgo + (AdV+) program will take the next 10 years, and will develop, in parallel with LIGO A+ and KAGRA, in two phases. The first phase upgrades will include frequency dependent squeezing, Newtonian noise cancellation, and signal recycling and will conclude with an observing run with a projected BNS range above 160 Mpc (roughly three times O2 sensitivity) in the mid-2020s. This phase has been approved by the agencies and a design document is in the process of review for the release of the construction funds, on the order of 10 million Euros.

Then, phase 2 will demand better mirror coatings as well as larger beams and test masses which are projected to yield a BNS range around 260 Mpc (four times O2 sensitivities), circa 2026-2027, with an extra cost (∼10-20 million Euros) depending on whether only the end mirrors will be changed or the change will include the input mirrors as well. The approval of this phase should happen before 2021 in order to keep the above schedule.

There has also been a continuum of participation from Europe in the LIGO instruments. Groups in the UK and Germany made critical material contributions to LIGO, and important intellectual and technical contributions to the instruments also came from LIGO Scientific Collaboration groups in Belgium, Hungary, Italy, and Russia. Additionally, Virgo groups in Europe have made indirect contributions to the LIGO program from the inception in the 1980s through to the current LIGO A+ upgrade. There is a growing commonality of research and engagement between LIGO and Virgo instruments and there is substantial, broad European engagement in GEO600, Virgo, LIGO, KAGRA and next generation GW detectors.

In parallel, the third generation (3G) European project under the name of Einstein Telescope is in the middle of its second decade since its conception. The idea was formulated in 2004, within the EU-funded ILIAS project, was studied in detail in an EU funded Design Study (2008-2011), followed by further studies between 2012 and 2018 funded by different sources, including EU and APPEC.

The founding workshop inaugurating the ET collaboration occurred in April 2018 at the EGO/Virgo site. The ET collaboration is currently preparing a proposal to be included in the European Strategic Forum for Research Infrastructures (ESFRI) roadmap with submission deadline April 2020, for inclusion in the ESFRI roadmap of 2021. This procedure is crucial for European country acceptance of the ET project.

There are currently 3 candidate sites for the location of ET and the final site selection is expected by 2022-2023, time when the TDR will be also ready. By 2023 the ET project should be approved and the excavation could start by 2025 with an end of the construction of the civil infrastructure towards 2030-2031 and a start of installation, commissioning and operation after 2032. The sensitivity goal for ET is an increase of a factor 10 with respect to the AdV+ sensitivity, covering thus the largest part of the visible Universe for binary black hole mergers with a projected investment cost of between 1 and 2 billion Euros.

On the detector/technology side: a) the AdV+ Phase II will tackle the technological risks of ET; b) the interlinked sensor network monitoring and mitigating noise of the interferometers is at the avant-garde of the technology of *smart infrastructures*; c) the environmental studies can become a source of innovation in the domains of geological and atmospheric monitoring (early warnings, earth, cloud and sea behavior); d) given that the 3G civil-infrastructure is a large part ($> 90\%$) of the cost, there are technological innovation synergies to be developed with other fields, such as high energy physics, with the same concerns of civil infrastructure; e) GW computing is also at the forefront of recent developments in big data analytics and machine learning.

It is important that the parallel efforts to advance the sensitivity of the Virgo instrument be closely coordinated with the ET development. There is interaction at all levels: personnel, infrastructure, proposals, and funding. It is also vital that the global 3G organization and activities complement the timeline and processes in Europe imposed by the European funding agencies, which arrive sooner than those elsewhere. We are pleased to note that the European scientific community and funding agencies continue to give a high priority to the development of gravitational-wave field [20].

3.2.2 The United States

Upon the completion of the successful O2 observing run late August 2017, the LIGO Hanford (H1) and Livingston (L1) detectors have been undergoing a series of improvements aimed at increasing sensitivity (as measured by binary neutron star, or BNS, inspiral range) to 120 Mpc or greater. All major upgrades have been installed; both H1 and L1 are presently being commissioned. The joint LIGO-Virgo O3 run is scheduled to start in April 2019 with an approximate duration of one year.

Upon the completion of O3, further detector improvements and commissioning will begin in early 2020 with the goal of achieving the Advanced LIGO target design sensitivity of approximately 175 Mpc BNS inspiral range before the start of the O4 run in early 2021. O4 is anticipated to last approximately 18 months and is expected to be jointly carried out with Virgo and KAGRA.

The NSF recently awarded the LIGO Laboratory a US $20.5M grant to carry out a series of improvements on H1 and L1 (A+) that will yield sensitivity enhancements of up to 1.6/1.9 for BBH/BNS sources, greatly enhancing the number of detections to 20-300/1-13 BBH/BNS events per month. Major improvements include the implementation of frequency-dependent squeezing, new test masses with coatings having lower thermal noise, and balanced homodyne readout[2]. Additional funding of approximately US $13M is being sought from the Science and Technology Facilities Council in the UK. The Australian Research Council has supplied in-kind funding for squeezing lasers. The A+ upgrade program will be carried out in parallel to the O3 and O4 runs. The first A+ run is expected to commence sometime in 2024.

Plans are being vigorously pursued for two future detectors with longer time horizons – LIGO Voyager and Cosmic Explorer. Voyager is intended for the existing LIGO Observatories, with an aim to reach the existing facility sensitivity limits, and can deliver a 3x improvement in BNS inspiral range over A+. It will take advantage of new technologies currently being researched, including silicon mirrors operated at 123 K temperatures, and high power 1.5-2 mm wavelength lasers with squeezed light injection. Longer term, the

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[2] Details of the A+ program can be found in the Dawn III workshop report[19].

Cosmic Explorer design proposes a 40 km arm length interferometer to be housed in a new observatory facility. Both the Voyager and Cosmic Explorers designs are still very much in the concept stage, with construction at least ten years away. In addition to its science gains, Voyager will serve as technology testbed for Cosmic Explorer.

3.2.3 Australia

There is no doubt that siting a 3G facility in Australia would be an optimal choice for the global array. However, the astrophysical science gain of a third detector is not yet quantified, nor is the strategic advantage of siting that third detector in Australia over elsewhere. Evaluating and clarifying these issues should be a top priority.

The Australian Decadal plan for Astronomy, 2016-2025, states that "Mid-scale investment in large international (GW) facilities will provide the tools for Australian discoveries in these areas." There is therefore a prospect for Australian community support for mid-scale Australian investment in an international facility that could be sited in Australia with an Australian mid-scale investment of \$10s of millions.

Given this quantum of funding, OzGrav has setup a working group to develop the science case and conceptual design for an onshore 'high frequency' detector with a total price tag of under \$100M, that could be operational within 10 years, while prototyping 3G technology. Input from other nations in the Asian region and elsewhere may be crucial. Such a detector may lay the foundation for a future full bandwidth 3G node.

3.2.4 Asia

Here we report on the status and plans in India, China, Korea, Taiwan, and Japan. In India, there has been intense activity to realize LIGO India. LIGO India is the combination of an infrastructure contributed by India and an Advanced LIGO Detector contributed by the US National Science Foundation. LIGO India will be operated with the US LIGO detectors by the US-India LIGO Laboratory. It is expected to come on line in the mid-2020's. In China, two space-based gravitational-wave detector projects have been proposed: TianQin and Taiji. The former is an international project and plans to launch in 2035. Other than the space projects, a possibility of a large-scale ground-based detector (Asia-Australia Gravitational-wave Observatory, AAGO) has been discussed among China and Australia. In Korea and Taiwan, researchers will actively join the upgrade of KAGRA, but so far there is no concrete plan for participation in 3G detectors.

In Japan, the gravitational wave community agrees that DECIGO will be the next main project after KAGRA. DECi-hertz Interferometer Gravitational-wave Observatory (DECIGO) is a future Japanese space-based gravitational-wave antenna that will target the detection of an early-universe stochastic gravitational wave signature imprinted by inflation. DECIGO's design consists of four clusters of spacecraft; each cluster contains three spacecraft with three Fabry-Perot Michelson interferometers. The DECIGO group will first try to launch B-DECIGO, a small-scale, simpler version of DECIGO with the sensitivity slightly worse than that of DECIGO, yet good enough to provide frequent detection of gravitational waves [21]. The B-DECIGO mission will complement the sensitive frequency bands of future gravitational wave detectors and verify key technologies for DECIGO. The DECIGO group has been refining the design of B-DECIGO, and broadly proposing B-DECIGO as a promising future mission. It should also be noted here that the ET-KAGRA (ELiTES) collaboration has made a big contribution in the construction of KAGRA and we will keep it toward the construction of ET. A number of people from Japan have joined the ET collaboration.

3.2.5 APPEC Roadmap

The European Astroparticle Physics Strategy 2017-2026 was launched by APPEC in January 2018 in Brussels [20]. APPEC is the Astroparticle Physics European Consortium, a consortium of 19 funding agencies, national government institutions, and institutes from 17 European countries, responsible for coordinating and funding national research efforts in astroparticle physics.

Apart from promoting cooperation and coordination, a crucial APPEC activity is to formulate, update and realise the European astroparticle physics strategy. Key ingredients in the new strategy are the 21 recommendations addressing, in addition to the scientific issues, crucial organisational aspects as well as important societal issues such as gender balance, education, public outreach and relations with industry. By acting coherently on these recommendations, Europe will be able to exploit fully the tantalising potential for new discoveries in good international collaboration.

In the new APPEC strategy, gravitational-wave research is one of the top priorities:

"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."

In December 2017, the APPEC General Assembly decided to proceed with implementing their recommendations for Gravitational Waves and make progress in the next 1-2 years in good collaboration with relevant bodies and scientists. More specifically, it was decided to define a collective approach from the agencies, research organizations and scientists towards:

- full exploitation of the current 2nd generation detectors Adv. Virgo and Adv. LIGO (including upgrade strategies and plans)
- the preparations for Einstein Telescope and to pave the way for an ESFRI application in 2020
- a collective European position in the global developments in GW policies.

During the DAWN meeting APPEC's General Secretary Job de Kleuver invited GWIC, the ET-collaboration and other to suggest topics where APPEC could be supportive with respect to the further developments of 3G GW.

3.2.6 Gravitational waves in the US Astro2020 Decadal Survey

The US astronomical and astrophysical communities participate in an exercise every ten years (a 'Decadal Survey') to survey the state of astronomy and astrophysics, identify frontier areas, and evaluate the future plans for facilities and missions in the coming decade. The Astro2020 Decadal Survey is commissioned by NASA, NSF, and DOE and carried out by a committee convened by the US National Academy of Sciences. The final report will carry tremendous weight in deciding funding priorities for large and mid-scale astronomy and astrophysics programs in the coming decade.

The recent detections of gravitational waves by LIGO and Virgo, and in particular the BNS merger GW170817, highlights the deep engagement between the astronomical and gravitational-wave communities. The Astro2020 decadal includes, for the first time, a request for input from the ground-based gravitational-wave community on the status and plans for these detectors. While no ranking is anticipated, it is valuable to inform the Astro2020 committees of the complement to other domains that GW detectors will provide, and the GW community welcomes any feedback from the Astro2020 Survey on planning for the future.

The ground-based community is preparing to participate. The first phase of the Astro2020 Decadal, the call for science white papers, has already begun [22]. At least three of the eight thematic areas have scientific overlap with gravitational waves: i) formation and evolution of compact objects, ii) cosmology and fundamental physics, and ii) multi-messenger astronomy and astrophysics. A detailed timescale for the carrying out the survey have not yet been established, however it is expected take 2 years to complete the survey process and release the report.

A call for new facilities, missions, and/or project proposals will come at some point in 2019. These proposals require not only a description of the science targets but also a detailed cost and technical assessment which will undergo an independent cost and technical evaluation. Although funding for a US 3G design has recently been awarded, the study is just beginning and it is unlikely that the US ground-based community will be sufficiently prepared to submit a 3G proposal on the Astro2020 time scale. However, the community does plan to submit documents both to inform the planning efforts underway.

3.3 Communication between funding agencies

As part of the work of its 3G Subcommittee GWIC identified an important role, overseen by the GWIC Chair, associated with communication with (and among) funding agencies. In particular, this is intended to enable GWIC representatives to:

- identify and establish a communication channel with funding agencies who currently or may in the future support ground-based GW detectors
- communicate as needed to those agencies officially through GWIC on the scientific needs, desires, and constraints from the communities and 3G projects structured in a coherent framework
- serve as an advocacy group for the communities and 3G projects with the funding agencies

GWIC and its members have worked to identify relevant funding agencies and funding agency bodies for this purpose, which includes both individual national agencies and relevant formal or informal agency groupings. In the case of national agencies the expected normal communication routes apply, with research groups and collaborations communicating directly with their individual funders. However at a more strategic level there are several groupings (partially overlapping) of international funders, or in some cases senior scientific officials with whom communication channels are desirable and/or appropriate.

These include:

1. International groupings of relevant funding agency representatives exist in the form of the 'Gravitational Waves Agency Correspondents' (GWAC). GWAC is an informal body of representatives of funding agencies covering ground and space-based gravitational wave projects and science, initially formed in 2015 at the initiative of the US National Science Foundation.
2. The 'Astro-particle Physics International Forum' (APIF) is convened under the aegis of the OECD-Global Science Forum, and comprising of officials of funding agencies for the purpose of facilitating a globally coherent response to the scientific opportunities in astro-particle physics. For more information see the APIF Final Report [23].
3. In Europe the 'Astro-particle Physics European Consortium' (APPEC), a consortium of agencies with responsibility for funding particle astrophysics. APPEC appoints a Scientific Advisory Committee drawn from the European scientific community to maintain a scientific roadmap for particle astrophysics, may choose when appropriate to create financial instruments to support strategic areas, and can act via influence to support projects in non-financial actions (see Section 3.2.1 above for more details).
4. The 'Group of Senior Officials' (GSO), on Global Research Infrastructures. The GSO was established and active from 2011 onward to informally explore cooperation opportunities in Global Research Infrastructures (GRIs). Participating countries are represented on the GSO by "government officials and experts in the areas of international research facilities and international relation". For more information see [24].

GWIC has received formal invitations from various of these bodies - specifically APPEC and GWAC - to present the status and planning activities of the broad gravitational wave community that it represents. GWIC representatives (S. Rowan, D. Shoemaker, D. Reitze and M. Punturo) attended telecons with presentations to GWAC (Nov 2016 and Feb 2018) and made presentations in person (S. Rowan, M. Punturo, J. van den Brand) to the APPEC General Assembly, Barcelona (Dec 2017).

Presented in each case was the status of community planning along with some recommendations to GWAC/APPEC for possible support actions. In those presentations, GWIC communicated the status of 3G subcommittee activities, as summarized in this report. GWIC reported that the Australian Research Council (ARC) committed approximately AUD 600K to support participation of Australian scientists in global 3G preparatory activities, but noted that elsewhere that 3G coordination efforts are 'funding limited', i.e. limited largely to working through telecons and e-mail.

GWIC recommended that:

- GWAC/APPEC should consider and identify support mechanisms for the community in its respective regions to participate in the 3G activities which are essential to feed into the ongoing major international roadmapping and landscaping exercises;

- GWAC endorse and support a joint Dawn/ET workshop in 2018 to advance coordination of Euro-US community-agency planning;
- GWAC consider playing a role in collaborating with scientists in the study and definition of possible governance schemes in the 3G detector era.

In response:

- NSF awarded the grant for US participation in 3G efforts.
- APPEC have indicated they would welcome further detail from the community as to what support could be appropriate to consider for 3G activity.
- This meeting ('Dawn IV') has been held in Europe for the first time and expanded with enhanced Europe-US-Australia-Asian attendance.

GWAC expressed particular interest in iterating with GWIC on governance models for the 3G network, and it was agreed to iterate with GWAC on the governance report before finalizing its contents.

Lastly, the 11th GSO Meeting was held on May 21-25 2018, hosted by United States (NSF and DOE) at NSF's National High Magnetic Field Lab (Maglab) at Florida State University. Activities included a visit to LIGO Livingston Observatory (LLO). At LLO the GSO additionally received a presentation on GW activities with an offer to hear more about GW global infrastructure planning at a future meeting.

Elements of the GWIC 3G study will inform the case for the inclusion of the Einstein Telescope on the ESFRI Roadmap in Europe and the preparation of science papers for the upcoming US Astro2020 Decadal Survey. The intent is that preliminary report(s) would be circulated for comment and input among the relevant communities and stakeholders for appropriate iteration before the finalizing of a combined report in mid-2019. GWIC, with the community, should give careful consideration to the path after that in advocacy for the report recommendations.

3.4 The 3G science case

The GWIC 3G Committee has charged the 3G Science Case Team (SCT) to develop and identify the most compelling science themes for the next generation of gravitational wave detectors and to deliver the science case document by the end of 2018. To meet the charge, a team of international experts in the various fields pertinent to the 3G science case was formed in June 2017. In response to an open call issued in July 2017 to join the effort to develop the science case we received an overwhelming response; as of mid-2018 the Science Case Consortium consisted of more than 250 members from all over the world. A consortium wide consultation led to identifying nine working groups to help develop the science case. These are: (1) Extreme Gravity and Fundamental Physics, (2) Neutron Stars, (3) Supernovæ, (4) Compact Binaries, (5) Seed Black Holes, (6) Cosmology, (7) Multi-messenger Observations, (8) Waveform Modelling, and (9) Detector Neworks. The consortium of scientists have helped draft the science case that is currently being refined.

Based on the reports and prioritisation identified by the working groups, the SCT has come up with five principal science themes for the 3G detectors. These are questions of fundamental importance and are uniquely addressed by the next generation of gravitational-wave detectors. With the next generation of detectors we can:

- Explore new physics in gravity and in the fundamental properties of compact objects
- Determine the physics of densest, hottest matter in nature
- Understand the physics of the most powerful phenomena in the Universe
- Reveal the complete population of binary black holes, star remnants and seeds to supermassive black holes, throughout the Universe, and
- Uncover the first moments of our Universe, probe its dark sectors and relevant particle physics.

Several theoretical and data analysis challenges must be mitigated in order to accomplish the science goals of 3G detectors. These include needs for (a) accurate (analytical and numerical) modeling of gravitational wave sources to meet the demands imposed by vastly increased signal strengths and complexity of waveforms, b) new analysis algorithms and search strategies to deal with the vastly increased number of sources (both in number and variety), (c) theoretical progress in both general relativity and alternative theories of gravity to delineate how gravitational wave observations could be used to discriminate between different theories of gravity and (d) understanding what detector networks, strain sensitivity, tradeoff between low and high-frequency sensitivity for different science objectives.

For example, many physical effects known to be present in the dynamics of compact binary systems are not modeled accurately enough. These include precession of the orbit due to black hole spins, higher modes of radiation beyond the quadrupole, eccentric orbits with higher harmonics, etc., and these effects would need to be controlled well for both unbiased measurement of source parameters as well as tests of general relativity. To test alternative theories of gravity we need to compute how the emitted signals differ from those in general relativity and if it is necessary to look for signatures that are not just small deviations from general relativity but qualitatively different features, for example polarization of the waves different from general relativity or deviation in the orbital evolution. In the case of supernovæ, it is difficult to predict the amplitude and phase evolution of the signal but knowledge of the signal duration and its spectral energy distribution is vital for signal extraction and source characterization. In particular, characteristics of the signal related to the supernova mechanism (asymmetry, rotation, role of neutrinos, etc.) will help in discriminating between different supernova models.

As we develop the science case for the next generation of gravitational wave detectors it is equally important to evaluate the sensitivity and bandwidth requirements, network configurations, and measurement capabilities of different potential detector networks. Such an evaluation is currently ongoing but this activity will need to be further strengthened and expanded to help in a comprehensive understanding of not only what science is enabled by a given choice of detector configuration, geometry and networks but also what science is lost or compromised because of the choice we make.

3.5 Recommendations

Recommendations from Section 3; a survey of progress in the field:

- The ground-based GW community should organize clear, coherent input to the variety of forseen international roadmapping exercises. We should prepare a coordinated set of 3G science white papers and a proposal for a mid-scale technology development program to research key technologies for 3G in response to the Astro2020 Decadal Survey and the 2021 European Strategic Forum for Research Infrastructures (ESFRI) roadmap.

- GWIC should continue to provide a framework to enhance 3G profile and accelerate interaction between international projects and global agencies.

- Exploring the astrophysical science gain of a third 3G facility and placement in the southern hemisphere should be a top priority for GWIC. We note the capability and commitment of Australia's science community and funding agencies to a detector there.

- LIGO-India scientists must be involved in planning and execution of the A+ upgrade program. This will be very useful for training purposes as LIGO-India is expected to come online in the A+ configuration, and will benefit LIGO-India and the world-wide network going forward.

- The gravitational wave community should undertake a planning exercise to will to stage the implementation of Voyager and Cosmic Explorer in the A+/AdvVirgo+ era and appropriately update the 'observing scenarios' document [15] into the next decade.

- We recommend that the GWIC and the ET collaboration work together to communicate where APPEC could be supportive with respect to further developments of 3G GW.

- The GWIC 3G Science Case Team (SCT) should deliver a first draft of the science case document by the end of 2018, including an evaluation of the capabilities of different detector networks composed of 2G, 2.5G, and 3G detectors.
- GWIC 3G science case should inform the case for the inclusion of the Einstein Telescope on the ESFRI Roadmap in Europe, and the preparation of science papers for the upcoming US Decadal Survey.
- GWIC, with the community, should give careful consideration to the path after the science case document is circulated for comment and input among the relevant communities and stakeholders (before mid-2019) in advocating for the report recommendations.

4 Designing the 3G detectors

4.1 The global 3G detector network

The next generation of gravitational-wave detectors will be developed and built in an environment with rich scientific precedent and complex global interactions and this context will impact their design and governance. However, the primary objective of the community is clear; to maximize the scientific output of the global network of detectors.

A potential network of 3G detectors which realizes this goal is also relatively easy to identify (e.g., an Einstein Telescope in Europe [25], a Cosmic Explorer in the US [26], and a third 3G detector in a location that maximizes the sky localization ability of the network; potentially in Australia). And yet, the path from the present to that objective must be justified in the context of the realities of limited funding and time. See Sections 5.6 and 5.7 for discussion of the path forward toward this goal.

In this section we discuss 3G observatory design using an initial set of instrumentation and detector technologies. However, our ultimate goal is to build 3G observatories with a many-decade lifetime to accommodate a range of technologies which we foresee as possible.

The following subsections describe the current conceptual designs for future detectors and the design trade-offs that are under consideration. Performance metrics, which will be necessary to optimize the network and the detectors of which it is comprised, are also presented, along with some preliminary conclusions drawn from them.

4.2 Basic concepts for 3rd generation detectors

Third generation (3G) instruments, such as Einstein Telescope (ET) and Cosmic Explorer, will take advantage of the latest technological developments, as well as a new facility to extend detector baselines from 3-4 km to 10s of km.

The ET concept relies on a triangular shaped facility, with 10 km long arms and three co-located instruments. Each instrument comprises of two detectors each, in a xylophone configuration in which one detector maximizes the sensitivity at low frequency, while the other detector maximizes the high frequency performance. The output of the two detectors are then combined to provide a broadband sensitivity. The main advantage of a triangular facility is the ability of resolving the polarization of gravitational waves without the need of additional facilities; the main drawback is the complexity of installing and commissioning multiple instruments in the same facility.

The main advantage of the xylophone configuration is to decouple technologies that are difficult to coexist in a single detector, like, for example, cryogenics ($\sim$20K) and high power operations. The ET xylophone concept calls for a low frequency cryogenic detector, with low circulating power, and a high frequency room temperature detector with high circulating power.

Even for the xylophone concept the main drawback is complexity, as the two types of detectors have very different characteristics and they require dedicated commissioning efforts (in other words, lessons learned from one detector are not necessarily relevant for the other).

The Cosmic Explorer concept relies on an L-shaped configuration with 40 km arms. Increasing the arm length beyond the existing 4 km facilities is crucial to take advantage of the scaling of fundamental noise with length [26]. Arms of 40 km length appear to be optimal; this length leads to a first null in sensitivity at 3.75 kHz, and an arm length longer than 40 km would reduce the useful detector bandwidth and negatively impact some science goals [27].

The Cosmic Explorer approach provides the highest sensitivity in the 100 Hz region. In the absence of ET, two Cosmic Explorer instruments would be needed to resolve the polarization of gravitational waves.

The potential of the 3G detector network and the criteria to optimize its science performance is an active area of research. The 3G detectors aim to improve the sensitivity over the 2G network by more than a factor of 10, with their astrophysical reach targeting cosmological distances. Coupling this fact with the co-location of multiple detectors in the original ET design, it emerged from Dawn IV that the typical detector sensitivity curve is not anymore a representative figure of merit. The astrophysical reach for binary systems can be more accurately represented by redshift vs. source mass, as illustrated in Figure 4.2, showing how ET and Cosmic Explorer cover a wide range of binary sources.

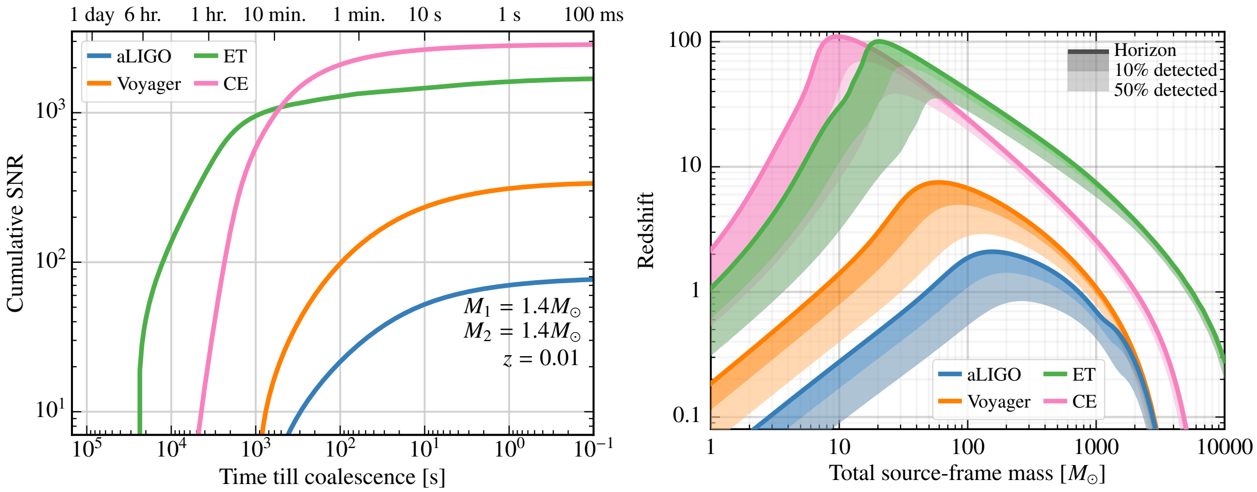

Figure 1: Accumulated SNR for 2G and 3G detectors vs time till merger (left). Cosmological reach of 2G and 3G detectors for CBC (right). *Credit: Evan Hall and John Miller (MIT)* [28].

The ET and Cosmic Explorer original designs where motivated by the historical context in which they evolved:

- ET was designed to be a stand-alone 3G underground facility, encompassing multiple detectors in a 10km triangular baseline to best extract polarization information from the gravitational wave sources;
- Cosmic Explorer was designed to complement ET, by extending the astrophysical reach for binary neutron star systems. To take advantage of the scaling of noise sources with length, Cosmic Explorer was designed as an L-shaped, 40km detector.

Both ET and Cosmic Explorer designs are currently evolving to take into account the needs of a global detector network. Moreover, exploration of the scientific advantages and positioning of a third 3G gravitational-wave detector has begun. This third detector could draw from both ET and CE designs to complement and complete a 3G network able of precision pointing.

As noted in Section 5.6, 2.5G detector designs that leverage new technologies to extend the reach of existing facilities are also under development and may serve as a bridge between 2G and 3G detectors. For example, LIGO Voyager would extend LIGO detector sensitivity beyond A+ by including lower loss mechanical coatings operating at room temperature for 1064nm light and broadband squeezing enhancement. The current LIGO Voyager concept [29] calls for a new wavelength of the laser light (1550 nm - 2 um) and new materials (silicon optics, amorphous Silicon coatings) which would require cryogenic operations at 123 K.

4.3 Science gained at low frequencies vs. observatory requirements

Third Generation detectors target not only to increase the strain sensitivity in the detection band covered by current instruments, but moreover to push down into the sub-10 Hz band, as well. The main advantages of an improved low-frequency cut-off are enhanced capability for source parameter estimation (in particular mass and spin parameters), improved sensitivity for intermediate mass black hole mergers of up to several thousands solar masses at cosmological distances, and in general a longer duration for inspiraling sources to stay 'in-band'. For instance GW170817 would have been inside the ET-band for nearly a day and would have accumulated an SNR of 8 already 3-4 hours before the merger, thus in principle allowing enhanced early warning for multi-messenger partners. Moreover, longer duration of in-band signals might also help with sky-localisation due to the rotation of the detector antenna patterns.

Improved low-frequency sensitivity will also be advantageous to the observation of non-CBC sources, but as no such signals have yet been observed it is not clear how these will it is currently not clear how strongly these will influence the 3G science case. Therefore we recommend to analyse for each item in the 3G science case to evaluate the contribution from sub-10 Hz sensitivity versus what science can be done with sensitivity only above 10 Hz.

Improving the detector performance to deliver sub-10Hz sensitivity, comes with significantly more stringent requirements for 3G infrastructures and detector technologies, and might require longer commissioning and noise hunting periods. It is important to note that the sub-10Hz band differs in two aspects from higher frequency bands: 1) At high frequencies the sensitivity is limited only by a very small number of noise sources, often completely dominated by quantum noise. However at the low frequency end we have to battle a cocktail of many noise sources including Newtonian noise (seismic and atmospheric), radiation pressure noise, suspension thermal noise, seismic noise, as well as a myriad of technical noises, such as control noises and scattered light. 2) While for all frequencies above 10 Hz the targeted sensitivity improvement from 2G to 3G is about an order of magnitude, below 10 Hz we require improvements by factors from 100s to millions. Such large factors cannot always be achieved by parameter tweaking of current systems, but in some cases might require disruptive change and new concepts (such as for instance the xylophone concept which allows to reduce feedback and control noises).

We recommend the development of more holistic noise models including not only fundamental noises, but also to develop and take into account simplified estimates of technical noise sources.

4.4 Performance metrics

The effort to bring gravitational-wave astronomy into a new era with a set of third-generation detectors is already well under way, and design studies are proceeding with two main thrusts. On one hand, the gravitational-wave community is identifying a list of science goals for the third-generation network, attempting to answer questions around neutron stars, the history of star formation, cosmological evolution, strong gravity, and other areas. On the other hand, the community is also considering what the third-generation ground-based gravitational-wave network will look like: how many facilities to build, where to locate and orient them, and what kind of detectors to put inside them.

The parameters characterizing the third-generation network should be chosen to best achieve the science goals. In order to provide a quantitative link between the network parameters and the science goals, a series of metrics (equivalently, figures of merit) should be established to evaluate the performance of a fiducial third-generation network. Figure-of-merit studies for gravitational-wave networks have already been undertaken [30, 31, 32, 33, 34, 35] in some cases using figures of merit to optimize detector placement/configuration and in other cases exploring the figure-of-merit performance of a few plausible network configurations.

There has been a preliminary exploration of the performance of a large number of potential three-detector networks, consisting of various combinations of Voyager, Einstein Telescope, and Cosmic Explorer, with random facility locations and orientations around the globe. A large, randomized ensemble enables us to exhaustively analyze the parameter space of possible three-detector networks. In this preliminary study, the figures of merit under configuration are sky localization, signal-to-noise ratio, and luminosity distance uncertainty for BNSs at redshift 0.3, along with the signal-to-noise ratio of an unmodeled (white in strain) high-frequency source. For each network realization, the figures of merit are computed using an ensemble of sources distributed isotropically in sky location and inclination. The sky localization and luminosity distance uncertainties are computed via Fisher matrix. For each figure of merit, both the median and the best 1% of the events are computed.

Already several conclusions can be drawn from this preliminary study:

1. The single largest predictor of network performance is the composition of the network: even when the facility locations and orientations are randomized, different classes of networks naturally cluster together when plotted according to their figure of merit performance.

2. Generally, networks of three third-generation detectors outperform networks of one third-generation detector supplemented with two second-generation detectors, particularly for localization and distance uncertainty.

3. Networks which achieve good figure-of-merit performance when optimized according to the median event also achieve good performance when optimized for the best 1% of events, and vice versa.

This study has several natural extensions, such as including other figures of merit such as mass uncertainty and polarization selectivity, and a wider variety of networks, including networks with more or fewer than three detectors [28].

4.5 Recommendations

Recommendations from Section 4; designing the 3G detectors:

- The GWIC 3G science case subgroup should carefully evaluate the contribution from sub-10Hz sensitivity for each science target, as pushing detector sensitivity below 10 Hz requires significantly steeper infrastructure investment.
- The GW community should develop more holistic noise models including not only fundamental noises, but also to develop and take into account simplified estimates of technical noise sources.
- Work on performance metrics for 3G networks (as well as combined 2.5G and 3G networks) should continue with high priority, and inform the 3G science case, instrument design, and site selection.

5 The roadmap to 3G detectors

5.1 The roadmap between A+/Adv+ and 3G

The A+ and adVirgo+ upgrades for 2G detectors, now in progress, follow an attractive incremental model: rapidly and opportunistically applying select new technology, as it becomes available, to escalate the observing horizon in stages. We expect this current round of upgrades to improve compact binary detection rates by about a factor of five with respect to baseline 2G instruments, enabling an array of new insights into GW source populations and properties. They will also increase the accessible astrophysics, relativity and cosmology information that can be derived, by registering nearby events at extremely high SNR. They can further open up a significant new portfolio of multi-messenger opportunities in concert with next-generation electromagnetic space and survey instruments. Enhanced '2G+' observations may even foreshadow some of the novel discovery spaces, highlighted elsewhere in this report, that are eagerly anticipated for 3G-class instruments. Finally, these incremental enhancements can lay firm groundwork for future 3G designs, vetting aspects of the new technology in the most stringent, realistic context currently possible.

The incremental upgrade approach has limits, however. One is the constraint to maintain compatibility with legacy systems and infrastructure; new topologies, footprints, and even wavelengths may be effectively off the table. Less obvious, but potentially more serious, is the growing imperative to minimize interruptions to observing. Upgrades require downtime. The explosive discoveries of the last three years, particularly the multi-messenger astronomy revolution triggered by GW170817, have raised global pressure to keep observing. Indeed, LIGO and Virgo's triumphs of sky localization and parameter reconstruction now extend this expectation to the full network of operating (or operable) instruments worldwide. Funding agencies have begun reflecting this revised focus in their mission oversight. As a result, the palette of improvements that could be installed and commissioned within an 'acceptable' observing hiatus of roughly one year may be effectively exhausted with A+ and AdV+.

On the other hand, the substantial leap to 3G – in funding, innovation, and time – must be bridged. A bold confluence of favorable economics and empowered, sweeping vision may yet arise to propel us. We can certainly hope, but we cannot plan on it. If gradual improvement of existing assets is problematic, another stepwise path is needed.

Perhaps the most obvious place to look is our own history. The leap from the most advanced prototype to initial LIGO was two orders of magnitude. It is of course conceivable that some key technological obstacles cannot be fully retired without direct tests on the most sensitive available interferometer, at the largest available scale. These issues must somehow compete for time on current-generation instruments. However, from the standpoint of sponsor investment, many of the more prominent risks for the 3G designs outlined above, as for the initial instruments 25 years ago, have less to do with technology than with economy.

Focusing nonetheless first on technologies, the path to 3G requires:

1. The development of enabling technologies: mirror substrates, mirror coatings, light sources, suspensions and cryogenics
2. Testing in engineering facilities
3. Integration into scalable prototypes

1. Enabling technologies
The development of high quality, massive mirror substrates especially for non-1 micron wavelength and non-room temperature operation (eg silicon substrates at 123 K) will be a technically challenging and expensive development requiring close collaboration with industry. A dedicated, internationally resourced, Center is likely to be required. The development of low optical and mechanical loss coatings is of a similar scale (see next section). The recent funding in the US of the Center for Coatings Research has focused the community and with European investment likely to follow as well, this program is in reasonable shape. A major risk factor is the availability of large area coating facilities. While there are significant technical hurdles to overcome to deliver suitable light sources (lasers and squeezers) and low noise suspensions and cryogenic systems the research and development can probably be undertaken in existing research laboratories.

2. Engineering tests

As in the early days of LIGO and Virgo, before Hanford, Livingston or Cascina, we can model and optimize methods to construct 3G machines, explore specific engineering risks, and accurately predict costs by scaled engineering demonstrations. These can include tests of beam tube construction, preparation and pumping strategies; samplings of candidate excavation and construction methods; tests of seismic isolation, suspensions, refrigeration and thermal control; simulations of light scattering and optical damage; and myriad other topics. As for initial LIGO and Virgo, before any 'observing' instruments existed, such focused tests can both direct the design, and bound the cost and risk associated with facility construction, paving the way for responsible 3G investment; KAGRA has followed this path. Once again this should be organized as coordinated global effort.

3. Integration into scalable prototypes

In the next 7 years the global 2G+ array is planned to mature into a 5 detector network along with GEO600. Depending on the science output it is conceivable that a well organized community could dedicate one or 2 of these detectors to proving 3G technology on the kilometer scale. Potentially, different subsystems could be trialled in different detectors whilst delivering low frequency and high frequency, limited bandwidth detectors. It is of course crucial to fully understand the noise anatomy of 2G+ detectors, especially at low frequencies.

Using the template above, we would need to have completed step 1 by mid-2020's, with steps 2 and 3 by early 2030's to enable final design of the first detectors to go into the 3G facilities by the mid-2030's.

5.2 Coatings: roadmap to readiness

5.2.1 Background

Because of the universality of coating thermal noise as a limit to performance of all the ground-based detectors, and the significant technical challenges posed, it is one focus of the community. Thermal noise limits the mid-band design sensitivity of current detectors (aLIGO and adVirgo), enhanced versions of current detectors (A+ and AdV+), 2.5G cryogenic detectors (Voyager and KAGRA), and 3G detectors (Einstein Telescope-Low Frequency, or 'ET-LF', and Cosmic Explorer or 'CE'). In all these cases, the thermal noise is fundamentally connected to the mechanical and optical properties of the dielectric mirror coatings. While A+ and AdV+ will operate at room temperature with 1.06 μm lasers, the designs of the 2.5G and 3G detectors are still evolving, so therefore are the requirements on the mirror coatings. For definiteness in the following discussion, we assume that Voyager will operate at 123 K with a 2 μm laser, ET-LF will operate at 20 K with a 2 μm laser, and that Explorer will operate at a temperature and wavelength that emerges as most advantageous given the experience with the enhanced 2G and 2.5G detectors.

The power spectral density of thermal noise is proportional to the operating temperature of the mirrors, the mechanical loss angle of the mirror coatings at that temperature, and the thickness of the mirror coating [36]. For all cases, a reduction in the mechanical loss by approximately a factor of 4 compared to the current technology (Ti:tantala/silica) will be adequate to meet thermal noise requirements. Another consideration is that the required number of layers in the mirror decreases as the index difference between the layers increases, so that high-index contrast materials will reduce the thermal noise even if the mechanical loss is unchanged. The situation in ET-LF is somewhat different, in that the thermal noise is dominated by the mirror suspension, which must be able to extract the thermal load imposed by the optical power absorbed in the mirror; in this case the optical absorption plays a key role in the thermal noise performance, and must be held in the range of 1 ppm.

In addition to meeting these requirements on mechanical loss, the mirrors also must meet optical specifications (absorption, scatter, figure error) even more stringent than those for current detector designs. These are near the state of the art but attainable for conventional ion-beam-sputtering (IBS) deposition of amorphous oxide mirrors; if other types of materials and deposition methods emerge as necessary to meet the mechanical loss requirements, significant tool development will be necessary.

Mechanical loss in amorphous materials is generally known to result from coupling of elastic energy into low energy excitations of the materials, generally thought of as two-level systems (TLS) in an effective double-well potential in some appropriate configuration coordinate. These TLS typically involve motions of several dozen atoms, and different TLS are responsible for losses at different temperatures (low barrier heights at low temperatures, higher barriers at higher temperatures). Reducing the mechanical loss thus requires reducing the density of TLS with the barrier heights pertinent to the operating temperature of the system. It is important to note that a process that reduces the losses for one temperature may increase it for another, if the distribution of TLS is reduced at one barrier height at the expense of increasing it at another.

5.2.2 Current approaches to low-noise mirrors

Approaches to reducing the mechanical loss fall into several categories: improved processing of conventional amorphous oxide or doped amorphous oxide materials, alternative amorphous materials – typically semiconductors like amorphous silicon (a-Si) or silicon nitride (SiN), or crystalline semiconductor mirrors.

Amorphous oxides
Empirical results for amorphous oxide mirrors deposited by IBS show that the mechanical loss at room temperature is reduced by post-deposition annealing, and that the reduction is greater at higher annealing temperatures. The maximum annealing temperature is limited by crystallization of the film. One approach under investigation is to chemically frustrate crystallization through introduction of an appropriate dopant into the coating to increase the temperature at which crystallization occurs. Another empirical observation is that low deposition rates often correlate with reduced losses. A promising result combining these two approaches, low-rate deposition of Zr:tantala with an electron-cyclotron-resonance (ECR) sputtering system followed by high-temperature annealing produced a film with the 4-fold reduction in mechanical loss at room temperature necessary for A+ and AdV+ mirrors, though to this point the results vary from run to run so reproducibility is not yet established. It is also not yet clear whether this low-rate method is scalable to deposition of complete mirrors meeting optical specifications. It should also be noted that cryogenic loss measurements are not available, and changes in room-temperature losses and cryogenic losses often are anti-correlated, so implications of this material to cryogenic 2.5G and 3G detectors is not yet clear.

A more speculative approach to suppressing crystallization and thus allowing higher annealing temperatures is to geometrically frustrate crystallization through the use of nano-layers, with each quarter-wave layer consisting of alternating layers of two materials with several nm thickness, thinner than the critical size for nucleation of crystallites. Suppression of crystallization has been observed in titania/silica nanolayers. Concerns such as homogeneity and scattering in the nanolayers has not yet been characterized.

Until recently, progress in reducing mechanical losses has been based on empirical studies alone. Recently, there has been progress in theoretical tools to guide the empirical work. Molecular dynamics methods enable calculation of the atomic structures that correspond to the energy spectrum of TLS in amorphous materials. Theoretical results correctly predict empirical data for the temperature dependence (at cryogenic temperatures) of losses in model systems like silica, and the trend in loss vs Ti-doping in tantala. Obtaining results accurate for room temperature losses requires computation of larger structural motifs corresponding to higher barrier TLS; extension to these regimes is currently under development. These methods also have suggested dopants whose promise has been borne out experimentally, e.g. Zr in tantala. Closely related are experimental methods to determine atomic structure in amorphous films via electron or X-ray diffraction techniques. These serve both as tests to inform the structural models, and can be correlated against experimental data to directly establish relations between structure and mechanical loss. A "virtuous circle" of theoretical modeling, atomic structure characterization, and macroscopic property measurements (in particular mechanical loss) has reached the stage where the methods mutually reinforce and speed developments in the respective methods.

A theoretical concept that has emerged is that of an ultra-stable glass, i.e. one that has an atomic structure of low internal energy with greatly reduced density of TLS, which is inaccessible to conventional annealing processes on realistic time scales, but can be reached through vapor deposition due to the enhanced atomic mobility of the surface layer during deposition. According to this picture, deposition at elevated temperatures (to increase surface mobility) and at low rates (to give longer times for surface atoms to explore the energy landscape) should lower the density of TLS.

The first empirical example of such an ultrastable inorganic material, elevated temperature deposition of amorphous silicon with two-order-of-magnitude reduction in cryogenic mechanical losses compared to room-temperature deposition, indicates the physical reality of the concept. This result both shows that a-Si is a promising material for long-wavelength mirrors (though unacceptable levels of optical absorption, discussed below, remain an issue), and motivates the search for ultrastable amorphous oxides suitable for 1μm operation. The first systematic effort at elevated temperature deposition of an oxide, amorphous tantala, yielded lower losses at room temperature than obtained with conventionally deposited films, but the losses converged to similar values after annealing; results for cryogenic losses of these films are not yet available. Recent results for amorphous alumina show lower cryogenic losses even after annealing than in room-temperature deposited films, which appears, subject to further verification, the first example of an ultrastable amorphous oxide. It is also a promising material for a low-index layer in a cryogenic mirror, since its mechanical loss is almost an order of magnitude lower than silica at cryogenic temperatures. These studies are in an early stage; further work (theoretical and empirical) is necessary to establish whether the ultrastable glass concept is a route to a low-noise cryogenic mirror.

Semiconductor materials

The results for the mechanical loss of amorphous silicon deposited at elevated temperatures show that a mirror consisting of a-Si as a high-index layer together with silica as a low index layer would meet the thermal noise requirements for cryogenic detectors. The issue that remains in this case is the optical loss, which is more than an order of magnitude higher than typical requirements. This absorption is associated with 'dangling bonds' in silicon atoms that are three-fold rather than four-fold coordinated. As such, this mechanism is not intrinsic, and depends strongly on deposition conditions and post-deposition processing. For example, low deposition rates, post-deposition annealing and annealing in hydrogen can all reduce the absorption significantly, and are topics of active current research. The absorption cross-section decreases with increasing wavelength, resulting in a strong preference for 2 μm vs 1.5 μm wavelength operation, and probably eliminating this material for use at 1 μm. It is also worth noting that the best results for cryogenic losses in a-Si have been obtained with films fabricated by evaporation rather than sputtering. Verification of these results in sputtered films is important, since meeting optical quality requirements is not practical via evaporative deposition methods.

Silicon nitride is another material widely used in the semiconductor industry with potential for low-noise mirrors. Low-pressure chemical vapor deposition (LPCVD) produces films with adequate mechanical loss that together with silica low-index layers could form a mirror meeting ET-LF or Voyager thermal noise specifications. IBS deposited silicon nitride has been also produced with a 1.8 reduction of mechanical losses at room temperature with respect the titania doped tantala. The issue again is excess optical absorption, which currently would be more than order of magnitude too large to meet specifications, but, with further development, have the potential, unlike amorphous silicon, for use with 1μm lasers. Another possible concern is the high Young's modulus that makes the material more suited to silicon or sapphire rather than silica substrates.

Multi-material coatings

In this sense, the problem for semiconductor materials is the converse of that for oxide materials: the mechanical properties are adequate, but the optical absorption is too high. A general approach that can address this problem is the use of multi-material coatings, in which the top layers, where the optical intensity is highest, consist of materials with low optical absorption but too large mechanical loss, while the lower layers consist of materials with low mechanical loss but too large optical absorption. In this way, the limitations of the types of material can be traded off against each other. Examples exist of multi-material coatings based on demonstrated material properties that could meet the requirements of ET-LF.While the additional complexity of depositing such multi-material coatings could pose a fabrication challenge, especially if the optimal deposition method differs for the different materials involved, it remains an important option if simpler material combinations fail to meet requirements.

Crystalline coatings

Epitaxially grown coatings consisting of alternating layers of high and low index layers of crystalline materials present an alternative method that avoids the mechanical loss issues associated with TLS in amorphous materials. The best developed of these materials are AlGaAs/GaAs mirrors grown by molecular beam epitaxy (MBE) on GaAs substrates and then transferred by wafer-bonding methods to mirror substrates such as silica or silicon. The mechanical and optical losses measured in small cavities with mirrors made in this fashion appear adequate for 2.5G and 3G detectors.

The issues with respect to applying these as general solutions for gravitational wave interferometry are related to scaling. One scaling issue is associated with developing the infrastructure necessary for fabrication of $\tilde{4}0$ cm (or larger) diameter optics: growth of the necessary GaAs crystal substrates, and development of MBE and wafer-bonding tools meeting the optical homogeneity requirements. An order of magnitude estimate of the cost of that effort is ∼$40M. The other issue is related to MBE growth, in which an areal density of discrete defects generally appears. While these defects can be avoided in experiments with small beams by alignment in small cavities, this would not be the case with beam sizes characteristic of full-scale detector configurations. The optical scatter, absorption, and elastic loss associated with these defects are not yet well characterized, nor is their anticipated density known. Samples with several inch diameters are currently being characterized to better understand these issues, which presumably should be clarified before the investment in scaling the tooling is seriously considered.

A less well-developed approach is the use of GaP/AlGaP crystalline coatings. These have the advantage of being able to be grown directly onto silicon, removing the need for transferring the coating between substrates. Initial measurements of the cryogenic mechanical loss of these coatings appear very promising for use in cryogenic gravitational wave detectors. However, significant work on refining deposition parameters and reducing optical absorption is likely to be required.

5.2.3 Current research programs

There are several current and planned programs devoted to developing low-thermal-noise mirror coatings suitable for enhanced 2G, 2.5G, and 3G detectors. Participants are involved in all aspects of coating research, including various deposition methods, characterization of macroscopic properties at room and cryogenic temperatures, and atomic structure modeling and characterization. The recent incorporation into the project of several groups involved in coating deposition is particularly important, as the costs and time delays associated with commercial deposition of research coatings have been significant impediments to rapid progress.

LIGO Scientific Collaboration

There are approximately 10 U.S. university research groups participating in various aspects of coating research. In late 2017, a more coordinated effort and additional funding for these groups were initiated under the Center for Coatings Research (CCR), jointly funded by the Gordon and Betty Moore Foundation and the NSF. Work in the U.S. also importantly includes that in the LIGO Laboratory. These efforts are complemented by groups not formally affiliated with the CCR, notably that by the large optical coating group at U. Montreal. Other major LSC coatings research programs are those in GEO (U. Glasgow, U. Strathclyde, U. Hamburg, U. Hannover). The efforts of these groups are coordinated through biweekly telecons of the LSC Optics Working Group.

Virgo

There are again 10 European universities involved in various aspects of the Virgo Coatings Research and Development Project, including new material research, metrology and more recently simulation. The proposal has been submitted to the EGO Council. Funding should come in 2019. The ViSIONs project, providing additional support for six of the French institutions, including the Laboratoire des Matériaux Avancés (LMA), was approved in June 2018 and it is focused on the studying the relation between the physical properties of sputtered or evaporated materials and the structural and macroscopic properties of the deposited films. LMA is the only facility currently operational that is capable of producing coatings of the size and optical quality required for gravitational-wave interferometers. Nevertheless LMA has already started improving the uniformity of coating deposition in order to meet the challenges of the A+ and AdV+ detectors. The AdV+ project contemplates the possibility to use end cavity mirrors of 55 cm diameter. Therefore LMA has developed its own plan to upgrade their coaters and tools to deal with such increase of diameter and weight.

5.2.4 Timelines and outlook

Timelines

By far the most pressing timeline is for the enhanced 2G detectors. In the case of A+, allowing for a one-year pathfinder after the coating material and process are identified, the required research to identify a suitable mirror coating should be completed by May 2020. This timeline implicitly assumes that the coating will be a sputter-deposited amorphous doped oxide, perhaps deposited at an elevated temperature, a slower than conventional rate and/or with a higher than conventional annealing temperature. It is unlikely that there is time in such a schedule to identify coatings and develop the required equipment for a process with more significant deviations from current deposition methods.

In recognition of the fact that meeting the enhanced 2G detector timeline requires doing basic research on a development schedule, the efforts of the LSC community are of necessity focused on these mirrors. That said, it is also recognized that the community shouldn't put itself again in such a situation, so a portion of the current research effort is devoted to establishing approaches to mirrors for 2.5G and 3G detectors. It is difficult to set research timelines for this effort, since the funding and construction schedules for these systems are not yet established. Another open question is the deposition process that will be required for the 2.5G and 3G mirrors; the further that process is from conventional IBS, the longer it is likely to take to develop suitable tooling. It seems that in any plausible scenario at least five years are available for research into the best approach to mirrors meeting 2.5G requirements. Results for these 2.5 G mirrors will, in turn, inform choices with respect to 3G mirrors. It is therefore too soon to argue for a large investment in scaling deposition tools alternative to elevated-temperature IBS for 2.5G and 3G mirrors. That said, as the funding trajectories and interferometer architectures become better defined, it will be important to regularly re-evaluate the current understanding of potential mirror technologies, and make critical decisions, especially with respect to deposition tools with long development times and requiring major financial investments.

Outlook

The additional funding provided by the CCR for U.S. efforts in coating research, combined with the previously existing NSF support, leave these efforts with reasonably adequate funding in the near future. It would be helpful to add another deposition group to the effort, as there is currently more capacity for characterization of properties other than cryogenic mechanical losses than for synthesis. It is also important that the LIGO Laboratory continue with at least its current effort level, as their contribution to high-throughput mechanical loss characterization, optical scatter and homogeneity measurements, and their overall coordination of sample fabrication, distribution, and characterization is important to the LIGO Scientific Collaboration efforts.

In GEO, there is growing capacity for depositing coatings at Strathclyde, UWS and Hamburg. These coatings can be produced at a rate faster than it is possible to characterize their properties at cryogenic temperatures, and thus more resources devoted to such characterization are desirable. Currently, a novel type of ion-beam sputtering is being developed and tested at Strathclyde. While this is a promising research route, there are also plans to set up a large chamber with an industry ion source which should be capable of producing large and uniform coatings. This is an important priority in gaining access to more coating facilities which are suitable for the deposition of large, high-quality coatings. Initiating studies of GaP/AlGaP crystalline coatings, using hardware now installed in an MBE chamber at Gas Sensing Solutions Ltd, is also planned. This is an important parallel research direction to the development of amorphous coatings.

In Virgo, the activities are progressing at the pace compatible with the funding available from other projects. LMA and University of Sannio are able to provide high quality coatings at a rate higher than the existing characterization capability in Virgo coating research and development. The project ViSIONs takes care of only one specific aspect of the research, that is the impact and the understanding of deposition parameters on the coatings properties.

At present, there is only one group, LMA, capable of depositing coatings of a size and quality suitable for gravitational wave interferometers. While French CNRS through EGO is fully committed to continue supporting LMA as a research and coating facility for future gravitational wave detectors, a single source for any critical component is viewed as a potential risk to the whole community. There was a second system capable of such depositions, though subsequently defunded, at CSIRO in Australia. It seems prudent to re-establish this program, both to provide a second source for full-scale coatings, and as a significant contributor to the ongoing research efforts.

While there is a good level of coordination within the LSC coating research programs, and within the Virgo collaboration, the interaction between LSC and Virgo groups has been less effective. Current efforts underway to establish an agreement on how to manage these interactions to enable more efficient exchange of information will be invaluable in generating synergy between the programs, and avoiding unnecessary duplication of efforts.

5.3 Vacuum systems

A vacuum workshop sponsored by the NSF will be held at the LIGO Livingston Louisiana site between January 28 to February 1, 2019. The workshop brings vacuum experts from the large baseline interferometric gravitational wave detector projects together with accelerator and plasma vacuum experts. The purpose of the meeting is to discuss methods to reduce the costs of the 3rd generation gravitational wave detector beam tube systems while still meeting the vacuum requirements. The concepts and ideas brought forward may also be useful in other large vacuum systems. The first of such meetings is intended to outline a program of research and development. For more information, see LIGO document G1801704 [37].

5.4 Computing requirements

Gravitational wave signals from compact binary coalescences (CBCs) are a primary science target for 3G detectors. Matched filtering is one of the main techniques employed for both CBC detection and parameter estimation. This powerful method is the optimal linear filter for signals buried in Gaussian, stationary noise. A problem with matched filtering is that it is extremely phase sensitive, and thus requires very accurate waveform models (templates). At present, these templates are constructed by combining both analytical and numerical relativity. As we increase the parameter space to include more asymmetric mass systems, and higher order physical effects such as extra harmonics and eccentricity, the importance of numerical relativity will grow. As a consequence, so too will the required investment in computing.

Currently, to cover the parameter search space, more than 10^5 templates need to be generated. As GW parameter estimation uses Bayesian inference, between 10^6-10^7 templates need to be generated to extract accurate astrophysical information. In both cases, each template is cross-correlated with the data and a Likelihood value is calculated. Each likelihood involves the evaluation of a discretized, noise-weighted inner product. The array sizes involved in describing both the discretized data and templates can be very large, with the array length being a direct function of the low-frequency cutoff of the detector. As we move towards better low frequency performance in 3G detectors, the signals will have a longer duration in the detector, and will therefore require larger array sizes to digitize the templates. The waveform generation and the likelihood calculation constitute the main computational bottleneck for matched filtering.

There are two possibilities for increasing the efficiency of GW astronomy, especially if the analysis becomes time-critical (e.g. an alert needs to be sent to EM and neutrino facilities). In the first case, we can rely on improvements in computer hardware. However, we are already seeing the time gap between jumps in technology beginning to lengthen, with a prediction that the well known Moore's law will come to an end 2025. In fact, as the cost of silicon chip fabrication increases, it may even be sooner than that. Furthermore, to offset the slowdown, a lot of current effort is being invested into multi-core chips using multithread technology. This suggests that to take advantage of future hardware, algorithms for GW astronomy might also need to be written in a multithreaded fashion, something that may be beyond the capabilities of the GW astronomers and require professional programmers.

The second option is to improve the convergence of our Bayesian inference algorithms. A problem is that, in most cases, "off the shelf" algorithms do not work for GW astronomy without serious modification. In most cases, it is possibly faster and simpler to develop specific GW algorithms. However, algorithmic development is a slow process and is difficult to do while also trying to analyse real-time data. As a consequence, this is something that may require dedicated effort.

While it is difficult to predict the computational hardware and power that will be available in the 3G era, in the short to mid-term, the community should keep itself abreast of developments in both hardware and software. We should keep in mind that not every new technology will be useful for GW astronomy, and some useful technologies may require too much effort for too small a return. The community should be prepared to conduct cost-benefit exercises for those technologies that we believe to be pertinent. And for those technologies that we decide to adopt, in order to fully maximize their impact, the community should be prepared to invest in employing expertise beyond the capabilities of GW astronomers, e.g. computer scientists, professional programmers.

5.5 Community outreach and engagement

Engaging a broader community beyond the gravitational wave community will be necessary to build support for and maximize the science potential of 3G detectors. Multi-messenger astronomy with gravitational waves is a natural synergistic base from which to grow interest and train a future generation of multi-messenger astrophysicists invested in next-generation gravitational wave science.

3G detectors will provide rich multi-messenger science targets for electromagnetic follow-up of individual events as well as cross-correlation of GW and EM source catalogs. For 3G detectors with the design sensitivity of ET or CE, the gravitational wave signal from a binary neutron star merger like GW170817, detected in 2017 at 40 Mpc from Earth, would be detectable at great distances; over a redshift of z=1. With such sensitivity, 3G detectors could provide thousands of high-SNR gravitational wave events with certain electromagnetic counterparts. Additionally, 3G detectors would identify many more binary black hole and neutron star-black hole merger events where possible exotic electromagnetic counterparts could be thoroughly explored.

The electromagnetic facility landscape in the 2030's is expected to be rich with high energy, UV-Optical-IR, and sub mm–Radio observations on Earth and in space. Several neutrino experiments are anticipated to be observing in the coming decades as well. The design and timeline of 3G gravitational wave detectors will likely influence the observing scenarios of these planned facilities and space missions, and vice versa. The GW community should coordinate with the EM and neutrino communities on multi-messenger science opportunities and identify a small number of clear and convincing joint science targets that could be used to promote the usefulness of 3G detectors and future EM and neutrino facilities in multi-messenger studies. The GW community should also continue to be a strong presence at meetings organized by the EM and neutrino communities to both provide information on our developing plans and to collect ideas for maximizing joint multi-messenger science.

5.6 The path forward for science on this scale

Central for going forward is the strength and breadth of the science case for 3G and to convince a broad scientific community of the important contributions that 3G can make to fields ranging from fundamental physics, astrophysics, astronomy, cosmology and cosmography, to nuclear science.

Attention must be paid to carefully define a subset of most convincing examples, such as the capability of detecting GWs from all coalescing binaries in the Universe; the importance for cosmology such as new and independent access to the history of the EOS parameter of Dark Energy; the capability for precision tests of gravity under extreme circumstances; and access to the Dark Ages and perhaps signals of the early universe.

A global path forward must be defined, where every new phase must be associated with a new scientific target. Realizing design sensitivities and proceeding towards A+ and AdV+ will allow the GW community to produce increasingly better GW data on important observables such as the equation of state of neutron stars, tests of general relativity, and mapping the cosmology of the local universe, while at the same time reducing the risks of key technology for 3G. The next step will be to realize ET, as the most mature proposed 3G detector in concept and design, with a proposed design that suits the constraints of the European-funded/sited project. We expect that ET will for the first time provide access to the entire universe in GWs and provide a driving force and test bed for 3G technologies. In parallel, we should strive to realize two additional detectors, taking advantage of common design and execution, with one likely in the US and then an additional site to be determined but responsive to the best resulting network performance.

The global path forward must feature an Umbrella Organization to show the global interdependencies, and to demonstrate to funding agencies how investments are leveraged: research and development, upgrades, ET/Voyager, etc. The GW community must define such an Umbrella Organization for Global 3G to address the research needs of the world-wide scientific communities, and to combine the best available knowledge, human capital and resources in one specific scientific area with multi-source funding. The Umbrella Organization can start in a 'loose' way, but should encourage global research and development, develop the science case, and evolve into a structured vehicle later.

In the path forward to 3G science on a global scale it is important to consider the viewpoint of different continents and countries. The status of GW, and 3G GW should be monitored in each country.

Important general questions are:

What is the composition of your community?
How do we grow our global community?

Focusing on ET given its advanced state, EU countries must ask questions such as:
Is ET on your national roadmap?
When will there be an opening, and will you pursue that?
What is needed to be on your national roadmap?
Science case, technical plans, ...?
What is needed to pave the way in your country to support an ESFRI request?
If so, then what is needed from the GW collaborations, APPEC, GWIC, your own scientists?

For ET and submission to ESFRI, the near-term governance strategy must be defined. In addition the budget should be updated where besides investment cost, the operating costs deserve careful consideration. For 3G and in particular Einstein Telescope, the existing expertise at CERN on managing global research on the largest scale represents a valuable resource. Moreover there is strong overlap of 3G science and CERN's scientific program. CERN is willing to allow access to its technical expertise on vacuum and control systems, underground construction, and cryogenic technology.

5.7 Common strategies

There is unanimity that a global 3G network is best for the science and optimal to leverage investments around the world in GW science. It is also recognized that close coordination of the planning is needed to best realize our goal.

However, the determination of the roadmap toward the realization of a global network of 3G GW observatories must be based on the current status of the efforts. We have the ET project which has been funded over the last 10 years and has a well-explored conceptual design. We have CE which is has several years of conceptual design but is just getting started in a more substantive study of science goals and technology solutions. We also have a community consensus that a third detector, placed to optimize the science, is needed, but without a specific concept behind it.

There are many advantages to an approach with identical detectors with a coordinated timeline, e.g.,

- Minimization of the human and conceptual efforts and of the global costs
- Unified research and development effort
- Single design
- Single global management for design/operations
- Best assurance of optimization of science

Advantages to uncoupled efforts can also be found:

- Time efficient: each project can optimally benefit of the continental opportunities.
- Better matching with the continental/regional constraints.
- Possibly easier to be initially funded.

Our challenge is to find the best path from the current uneven level of development of the three concepts to a complete and synergistic network in the 2030s. Factors which we need to consider are

- The readiness of observatory concepts and their documentation.
- The differences in the observatory concepts: scientific goals (e.g., one-location polarization measurement) and implementation (e.g., surface or underground).
- The timelines of funding (study and full) in various continents.

- The variety of development paths in various continents.

In the near term, it appears best to pursue the following approach:

1. Push the ET project through its next steps
    - The roadmap of the ET project has a well-prescribed path because of the complex European environment.
    - The current ET design is solid enough to be submitted to the ESFRI roadmap.
    - The triangular ET geometry will be proposed, as it seems to guarantee the best science exploitation for a network composed of a single 3G detector and few 2.5 detectors [28]; this could be an optimal choice if the 3G observatories (ET, CE, third 3G detector) will be realized at different times
2. Push the development of the CE concept
    - Present the Science Case and a sketch of observatory and instrument configurations to the Astro 2020 Decadal study
    - Complete the current NSF-funded study of 3G detectors
    - Form a conceptual design which assumes multiple 3G detectors, and considers network performance of several global design solutions including the baseline ET concept, and looks at one- and two-detector CE implementations
    - Define a roadmap for CE responding to US and other countries' needs and constraints
    - Seek opportunities for adequate peer review (e.g., at the Mid-Decadal review)
    - Pursue funding sources for CE funding in parallel with the above activities.
3. Plan for a tightly-coupled unified coordination and governance of the global network
    - Start with the establishment of a Coordinating Organization now
    - Have all development globally draw from common studies of the science that can be achieved with a 3G network, and from studies of network configurations and capabilities, to guide each of the projects toward the best use of the available global resources
    - Define and jointly develop common enabling technologies
    - Adapt, as possible, the design options to optimize for the science and the use of global human and financial resources
    - Push toward to a common governance, as the projects become more advanced.

5.8 The evolving role of Dawn meetings

Motivation for and origin of the Dawn meetings

The first Dawn workshop was held in May 2015, in Silver Spring, MD, as aLIGO construction was coming to a close. The subtitle for the meeting was "What comes next for LIGO?". It was not yet known how sensitive the instruments might be let alone when they might detect the first GW signal. However, detections could come at any moment so it was certainly time to consider the future. In fact, the first detection of GWs, GW150914, from the first detection of a BBH merger was only 4 months away. Compared to Europe where the ET design study had been completed in 2011, the US was woefully behind in defining the next generation ground-based GW detector and in planning how to achieve it. The goal of the Dawn workshop was to take the first steps to ameliorate this deficiency by gathering together leading experts in all relevant topics to make recommendations on how to proceed. This led to a report that was shared with NSF.

Major recommendations of Dawn I - III

The initial Dawn workshop was followed by two others in the US. The reports from these workshops tended to follow similar themes but evolved as the detection era progressed. Near term instrumental recommendations focused on the urgency of research to improve optical coatings, the implementation of squeezing, and Newtonian noise cancellation. Eventually, the A+ concept became mature leading to recommendations that it go forward. Research on the ultimate technologies for existing facilities (Voyager) and on concepts for new facilities (CE) was advocated. The importance of preparing for multi-messenger astronomy was recognized with recommendations on interacting with the broader astronomical community. This led naturally to the importance of a worldwide network of ground-based GW detectors working together and thus to an ever increasing focus on international interactions. Finally, there were recommendations on the need in the US for an external advisory group (such as HEPAP is for particle physics) and for a NRC study to develop the science case and the instrumental requirements for a 3G GW detector network and for cooperation internationally among GW funding agencies.

Current status of major recommendations

The dawn of the detection era in September 2015, the addition of Advanced Virgo to the GW detection network in August 2017, and the almost immediately thereafter detection of the first BNS merger in GWs and EM radiation gave enhanced reality and urgency to ramping up research on detector improvement. Frequency-independent squeezing has been installed in aLIGO in preparation for O3. NSF funded a Center for Coatings Research while frequency-dependent squeezing was demonstrated. The progress in these essential components led to the US and Australian funding their contributions to A+ with the UK contribution likely to follow. NSF has also funded the CE design study involving both instrumental design and science-case studies, as well as a future GW detector vacuum workshop to be held in Feb 2019 at LIGO Livingston. While there is no formal advisory committee or NRC study, GWIC has taken on the role of coordinating the development of a roadmap for the hoped for 3G network. Finally, NSF has taken the lead in organizing the GW funding agencies into GWAC who meet annually and receive Dawn reports (via NSF) and oral presentations by GWIC.

Evolution from US to global focus

As the Dawn workshop discussions progressed toward an increased focus on planning for 3G instruments, so did the realization that a global approach was essential. While tentative in Dawn I, Dawn II and III had full sessions on long term planning by the international community and building international collaboration respectively. A recommendation from the latter session was to hold the next Dawn workshop in Europe, possibly connected to an ET workshop. While Dawn IV was not connected to ET, it was held in Europe and had many European participants. This new location was reflected in the change of subtitle from “What comes next for LIGO?” to “Global strategies for GW astronomy”.

It must be pointed out that the timescale disparity between ET (considering site selection) and CE (in its conceptual design phase) represents a significant challenge to the development of a global 3G effort. While it is currently reasonable for each 3G design to proceed at its own pace, at some point in the not-to-far future, decisions will be needed. It is crucial that such decisions be made with the “ideal” 3G science case in hand so that the tradeoffs between achieving transformative science goals and what can actually be built are well understood.

Options for the future of Dawn Workshops

The first Dawn workshop preceded the discovery era in GW astronomy. It set the framework for the future Dawns. These workshops developed a series of recommendations ranging from a ramped up research effort in coatings to a study to map out the parameters for 3G. Many of these recommendations have been realized. Does this mean that the need for such workshops has ended? Options include ending the series, merging with another meeting, keeping the current approach of flexible response to circumstances, or ramping up an advisory role by collecting input from other relevant meetings (acting as a clearinghouse). Discussion seemed to favor the flexible response option. The clearinghouse concept was thought to be insufficiently forward looking. One aspect of the discussion that seemed popular was to use the Dawn workshops to foster the connection between the global research community and the funding agencies. The presence of many representatives of the funding agencies at this meeting yielding interaction and discussion was regarded very positively. There was no consensus on how to accomplish the goal of a more explicit connection. Suggestions included attaching the Dawn workshops to GWADW (but may not have the right people), to APPEC (to make it easy for some funding agency staff), or having the funding agencies organize the workshops (unrealistic).

Who is the Dawn community?

Up to this point, the Dawn workshop agendas have been constructed primarily by LSC members, especially those in the US. With the increasing global focus, it is time to implement somehow the broader 3G community into future iterations of the Dawn workshops. However, any rigid, formal community structure centered on 3G is regarded as too premature to consider. Even the possibility of an "interest group" such as those preceding the formation of the LSC and LISA collaborations did not generate much enthusiasm. On the other hand, some loose structure among those interested in 3G would prove useful to promote the GWIC 3G report and 3G more generally to the broader scientific community and to potential funders, to foster refinement and updating of the 3G science case, and to foster communication (and, perhaps eventually, coordination) among 3G researchers.

Proposal for Dawn V to focus on GWIC 3G report

The recognized importance of the GWIC 3G report, expected to be released for community comment in mid 2019, meant that a suggestion to focus Dawn V on issues related to the report was met with great enthusiasm.

Recommendation: That the Dawn V Workshop focus on issues related to the GWIC 3G report. That it be held after the report is released for community comment but before it becomes final. The precise date and location are TBD.

Beyond Dawn V

The sense of this (Dawn IV) workshop among the participants was that the meetings have significant value. Especially true this time was enhanced participation of researchers and funding agency staff due to the European location. While there was significant discussion on the future of Dawn, no consensus was reached beyond the recommendation for Dawn V where this matter should be raised again.

5.9 Recommendations

Recommendations from Section 5; the roadmap to 3G detectors:

- A Dawn V meeting should be held ahead of mid-2019, when the GWIC-led science case is expected to be released for community. The focus should be the science case and its use for informing international funding agencies, including the US Astro2020 Decadal Survey and the ESFRI roadmap in Europe.
- The global path forward must feature an 'umbrella organization' to coordinate international research and development and detector upgrade plans. We strongly recommend GWIC establish such an organization ahead of Dawn V.
- The 3G community should adopt the following common strategies as part of a coordinated global research and development effort:
  - Global coordination of prototype engineering and scaled tests for 3G detectors, including beam tube construction, vacuum technologies, and excavation and construction methods.
  - The global GW community should produce a long term plan that balances observing with installation and commissioning breaks to make use of current generation facilities as a testbed for 3G technologies.
  - Coatings research and development programs within the U.S. and Europe should collaborate closely.
  - Investment in more global resources devoted to characterization of coatings at cryogenic temperatures, such as a dedicated, internationally resourced coatings center.
- Computing approaches must be mapped out to be ready for 3G data when available:
  - The GW community should carefully evaluate software and computer hardware solutions which will be most suitable for 3G data analysis over the course of decades.

  - We highly recommend investment in funding and planning for the employment of computer scientists to support the infrastructure needed for 3G data analysis.
  - The numerical and analytical relativity community should work to generate faster waveforms and log-likelihoods ahead of the 3G era so that these aspects of data analysis are not limiting.
  - The community should invest in more convergent Bayesian Inference algorithms for PE, which is vital when PE becomes time critical, and difficult to do while also analysing data.
- For developing coatings to enable the 3G sensitivity requirements:
  - In the U.S. we recommend adding another coatings deposition group to the coatings research and development effort, and the LIGO Laboratory continue with at least its current coatings research and development and coordination efforts, which are vital to broader global efforts.
  - In Europe, a large chamber with an industry ion source capable of producing large and uniform coatings in addition to ion-beam sputtering capabilities being developed and tested at Strathclyde is an important priority in gaining access to sufficient coating facilities suitable for the deposition of large, high-quality coatings.
- As noted in the Executive Summary, we also highly recommend the re-establishment of a facility such as CSIRO in Australia. At present, there is only one group, LMA, capable of depositing coatings of a size and quality suitable for gravitational wave interferometers. While French CNRS through EGO is fully committed to continue supporting LMA as a research and coating facility for future gravitational wave detectors, a single source for any critical component is viewed as a potential risk to the whole community. The CSIRO facility would provide a second source for full-scale coatings, and as a significant contributor to current ongoing research efforts.
- The GW community should continue to make efforts to evaluate 3G detector construction cost and opportunities for cost reduction.
- A GWIC subcommittee (TBD) should explore ways to use the Dawn workshops to enhance communications among the funding agencies (GWAC), the agencies' awareness of developments toward 3G, and the communication between funders and researchers in the global context.
- The GW, EM, and neutrino communities should coordinate to identify a small number of clear and convincing joint science targets that could be used to promote the usefulness of 3G detectors and future EM and neutrino facilities in multi-messenger studies.
- The GW community should create a roadmap for the evolution of global governance, with the goal of a common governance, to be realized as the projects become more advanced.

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