The case for dovetailing LIGO observations with next-generation facilities

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1 Executive summary

We summarize the science case for continued enhancement of the LIGO detectors [1] as engines for multimessenger discovery and pathfinders for next generation facilities. We argue that continuing to operate the LIGO detectors into the era of Cosmic Explorer will have the following benefits:

- Continuous operation of the LIGO detectors into the next-generation era will deliver an unbroken campaign of gravitational-wave observations that will maximize multimessenger observations as well as enhancing next-generation observations.
  - An $A^\sharp$ network could detect compact binary merger events past a redshift of 5, with a couple of BNS mergers per day, and one BBH merger every few hours. These observations will elucidate compact binary formation mechanisms and environments and probe strong-field gravity at unprecedented levels of accuracy.
  - Each improvement in sensitivity of the LIGO detectors expands the gravitational-wave discovery space potentially uncovering previously undetected sources such as nearly monochromatic signals from non-axisymmetric neutron stars or bursts of gravitational waves from supernova explosions.
  - The LIGO detectors envisioned for the 2030s provide an exceptional opportunity for coordinated multimessenger observing campaigns including Vera Rubin Observatory, IceCube and many other facilities around the globe and in space. The data can then be combined to improve measurements of the neutron star equation of state, to probe pre-merger distortions of neutron stars, and make sub-percent measurements of the Hubble expansion.
  - The continued operation of LIGO detectors during the next-generation era will be critical to ensuring precise localization of the loudest events identified by Cosmic Explorer. In fact, one 4 km $A^\sharp$ detector operating in conjunction with the proposed Cosmic Explorer observatory in its reference design (of one 40 km observatory and one 20 km observatory) will achieve the key science goals articulated in Ref. [2].
- *Research and development of instrumentation* to improve sensitivity is crucial to the long-term success of gravitational-wave astronomy [3]. The implementation and testing of improved technology in current LIGO detectors can reduce risk for next generation facilities.
- Continued operations of the LIGO detectors will *develop the workforce* needed to commission, characterize, and calibrate next generation detectors by working with real data and gaining first-hand experience with the common challenges of improving detector performance.

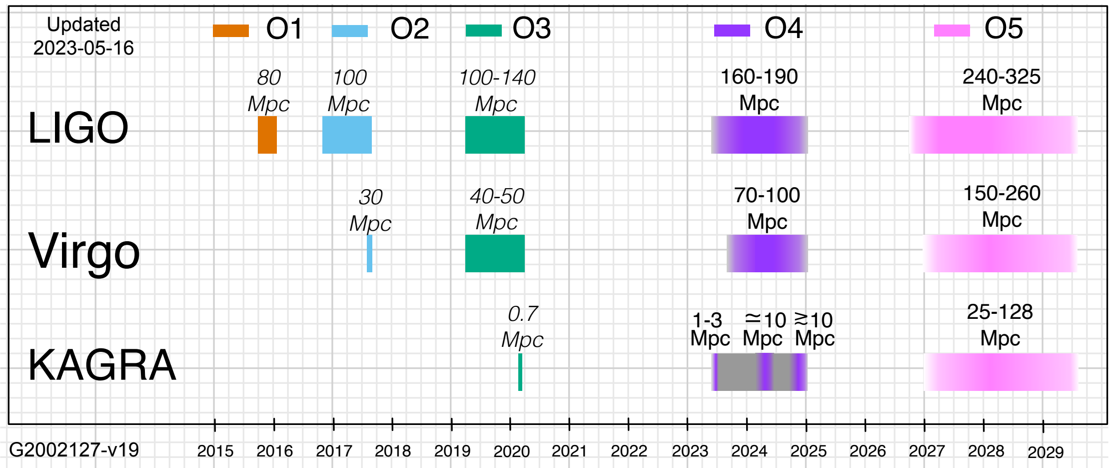

Figure 1: Past, present, and future observing plans for LIGO-Virgo-KAGRA gravitational-wave detectors. The fifth observing run (O5) will use the LIGO A+ detectors. The LIGO A$^\sharp$upgrade is conceived to come after O5 with further observing runs in the 2030s. The most recent version of this figure is maintained at `https://observing.docs.ligo.org/plan/`

2 Introduction

The LIGO Scientific Collaboration (LSC) is a self-governing organization dedicated to using gravitational wave detectors to understand gravity and observe the universe [4]. Founded in 1997, the collaboration has grown to more than 1,500 scientists from over 100 institutions around the world. The LSC coordinates research, development and operations activities among its member groups and uses data from the National Science Foundation's LIGO detectors at Hanford, Washington and Livingston, Louisiana. The LIGO Laboratory is the group within the LSC that constructs, manages, and operates the LIGO detectors and their associated facilities. The study of gravitational waves is enhanced through partnership with the European Virgo and the Japanese KAGRA Collaborations, collectively known as the LIGO-Virgo-KAGRA Collaborations (LVK). The Virgo detector [5] is located near Pisa in Italy while the KAGRA detector [6] is located in Kamioka, Japan.

Based on experience gained during the operations of the initial LIGO and Virgo detectors, the LVK organizes the development and operations of the detectors into observing runs that are separated by periods of detector improvement and maintenance. The LIGO-Virgo-KAGRA observing schedule from 2015 to 2030 is shown in Figure 1. The sensitivity of each detector is represented in terms of the average distance to which a binary-neutron-star merger may be detected at signal-to-noise greater than 8. The improvements in the LIGO detectors represent progression from the first phase of Advanced LIGO to the full implementation of the A+ design for O5.

The first direct observation of gravitational waves (GW150914) from a pair of colliding black holes in 2015 by the LIGO detectors [7] marked the beginning of observational gravitational-wave physics and astronomy. Since then, the catalog of gravitational-wave signals has increased to almost 100 mergers [8, 9, 10] including the landmark observation of the collision of two neutron stars by the LIGO and Virgo detectors (GW170817) [11] and the subsequent multimessenger observing campaign [12]. The fourth observing run O4, which started on 24 May 2023, promises to increase the number of detections to more than 300 mergers. While the number of detections is a simple metric by which to judge the success of the current gravitational-wave detectors, it is the deeper and broader scientific impact of these discoveries that reinforces the importance of continuing to observe the universe with gravitational waves. LIGO, Virgo, and KAGRA have collectively published 353 papers describing the detectors and the interpretation of the data taken so far. For each LVK paper there are tens to hundreds, sometimes even thousands, more papers published by scientists building on the initial results.

Recognizing the need to bridge the gap between O5 and initial operations of next generation gravitational-wave detectors, the LSC studied scenarios for upgrading the LIGO detectors beyond the A^+ program while taking account of the timelines of other projects (currently Virgo and KAGRA) and possible new facilities (e.g. Einstein Telescope and Cosmic Explorer). A number of upgrades extrapolating from current LIGO-Virgo room-temperate technology have been identified that could be available for installation by 2029 with the goal of continuing to operate the LIGO detectors into the mid-2030s and beyond. More information about this design, denoted $A^\sharp$, including an estimated timeline and cost, can be found in the LIGO Laboratory white paper [13] and the report from the LSC study [3].

In this white paper, we present an overview of the science case for the enhancement and continued operations of the LIGO detectors as engines for multimessenger discovery and pathfinders for next generation facilities. We argue that dovetailing the operations of the LIGO detectors with next-generation facilities will deliver exceptional scientific results over the next 20 years, will promote instrument science research that reduces risk for Cosmic Explorer, and will help grow the workforce essential to the success of next-generation facilities. We also note that the LIGO detectors are a cornerstone of multimessenger astronomy in the 2030s and that one 4 km LIGO $A^\sharp$ detector operating in conjunction with the proposed Cosmic Explorer in its reference configuration (of one 40 km detector, one 20 km detector) will achieve the key science goals articulated in the Cosmic Explorer Horizon Study Document [2].

3 International Gravitational-Wave Network

The LIGO-Virgo-KAGRA Collaboration is a landmark partnership that strengthens the global scientific effort in studying gravitational waves. By combining the data from multiple detectors, the LVK hopes to precisely locate the sources of gravitational waves, determine their properties, and infer the astrophysical processes involved. This collaboration facilitates data sharing, joint analyses, and the development of advanced detection techniques, leading to more comprehensive insights into the nature of the universe and the physics of extreme events.

The collective efforts of the LVK demonstrate the power of international collaboration in unraveling the mysteries of gravitational waves and opening new frontiers in astrophysics. At the same time, the need for more formal long-term cooperation has prompted the LVK to consider the formation of an organization that facilitates management and operations of the global detector network by delivering shared services and infrastructure necessary to maximize the science. The LVK is currently developing a broader organizational structure, called the International Gravitational-Wave Network (IGWN), that would allow member projects to: *a*) Formally share the costs of the development and operations of common infrastructure and services. *b*) Reduce the overhead associated with decision-making and management of common activities. *c*) Facilitate coordinated upgrades and synchronized observations to maximize gravitational-wave and multimessenger science.

Both LIGO and Virgo have studied detector improvements that could reach the limits of the current facilities in the form of $A^\sharp$ [3] and Virgo_nEXT [14]. In addition, the construction of the LIGO-India project [15] was recently inaugurated with the goal of operating a new LIGO detector in Aundha in the Hingoli district of Maharashtra by 2030. Construction of the LIGO Aundha Observatory (LAO) is funded by the Indian government with detector components supplied by LIGO Laboratory supported by the National Science Foundation. The LAO detector will initially operate at the A^+ sensitivity thus promising that a global network with exceptional observational capabilities will be operating in the 2030s.

4 Observational science with LIGO: the next 20 years

With continued investment and maintenance, the LIGO-Hanford, LIGO-Livingston, and LIGO-Aundha observatories can continue to operate into the 2040s [13]. The incremental upgrades envisioned in the $A^\sharp$ LIGO design can likely improve broadband instrumental strain sensitivity by a factor of two beyond the A^+ configuration.

A detailed study of the $A^\sharp$ instrumental design and its scientific potential has been performed in Ref. [3]. A factor-of-two improvement in LIGO strain sensitivity will enable precision observations of compact binary mergers, bolstering their utility as astrophysical probes and as test-beds of fundamental physics. It will furthermore expand the discovery space of gravitational-wave science, improving detection prospects for core-collapse supernovae, continuous waves from individual neutron stars, and a stochastic background of astrophysical or cosmological origin (or placing increasingly informative constraints on these processes). The scientific utility of $A^\sharp$ upgrades will carry over into the next-generation era as well, enhancing the localization capabilities of planned facilities like the Cosmic Explorer observatory. Finally, $A^\sharp$ instruments will act as pathfinders for such next-generation instruments; key technologies are shared by both the $A^\sharp$ and Cosmic Explorer designs, and their implementation into the current LIGO detectors will be a crucial step in delivering the technologies needed for future facilities.

Upgraded $A^\sharp$ detectors could begin observing the Universe towards the end of 2031. Research and development for $A^\sharp$ is already underway in the LSC [3], including work on improved optical coatings [16], high-stress glass fiber suspensions [17], upgraded suspension designs [18], lower loss squeezing [19], and improvements to other key technologies.

4.1 Observational science with $A^\sharp$

With an expected factor of two improvement in sensitivity over A^+, an $A^\sharp$ network could detect compact binary merger events with a total mass of around 100 $M_\odot$ past a redshift of 5, with a couple of BNS mergers and tens of BBH mergers per day. With annual BBH detection rates in the thousands, $A^\sharp$ would probe the BBH population with unprecedented precision. In addition to providing new clues about compact binary formation and astrophysical environments, measuring the evolution of the black hole mass spectrum with redshift should enable measurement of the Hubble expansion history at the percent level [20], with a probed redshift range complementary to the cosmic microwave background and local distance ladder measurements. Besides providing unprecedented access to the stellar-mass BBH population, the A$^\sharp$ upgrades will enable the detection of higher-order multipoles beyond the dominant quadrupolar mode with a signal-to-noise ratio ≥ 6 for up to a few tens of BBH mergers per year. This will significantly enhance the prospects for the detection of the nonlinear gravitational-wave memory effect [21] – a key prediction of General Relativity – and facilitate novel tests of the black hole dynamics as well as the no-hair theorem.

The multimessenger detection of the BNS GW170817 has provided us with the first constraints on the cold nuclear equation of state (EOS) of neutron stars from a gravitational-wave observation [22], and identified BNS mergers as the engine of (some) short gamma-ray bursts and the production site of heavy elements. The A$^\sharp$ sensitivity would allow enough signal-to-noise ratio to accumulate several minutes before the merger, thereby significantly increasing early warning times, and enabling multimessenger partners to pre-point their instruments to early localizations of candidate signals. This will afford additional science opportunities, such as possibly observing precursor flares, e.g. due to neutron crust shattering [23], or the early rise of the kilonova in the aftermath of the merger – a key target-of-opportunity for LSST at the Rubin Observatory [24]. Current EOS constraints from BNS observations provided by the measurements of the binary tidal deformability are fairly broad, but could be improved by at least a factor of two in an A$^\sharp$ detector network for a BNS at a distance of 100 Mpc. Complementary, improved sensitivity in the kHz regime will give access to the elusive post-merger regime for the first time [25], providing novel insights into the nuclear EOS.

The A$^\sharp$ detector network will expand the gravitational-wave discovery space, potentially uncovering previously undetected sources.

- Although core-collapse supernovae that occur close enough to Earth to be detected by the A$^\sharp$ detector network are expected to be rare, a detection would provide unique information about the astrophysics of the source [26]. The combination of gravitational wave, electromagnetic and neutrino observations of a supernova would provide the most complete picture ever of this highly energetic astrophysical phenomenon. The gravitational waves are emitted from deep inside the core, which cannot be explored electromagnetically, and observing them will allow us to discover the mechanism powering these explosions. The gravitational-wave signal will also allow us to measure the mass and radius of the proto-neutron star, the star's rotation and possibly the EOS. A network of A$^\sharp$ detectors operating through the 2030s would detect any rare nearby events that may occur in the decade before the next-generation detector era.

- The unprecedented sensitivity of the A$^\sharp$ detector network will provide valuable insights into long-lived, nearly monochromatic gravitational wave sources, including: non-axisymmetric neutron stars, r-mode superfluid oscillations of neutron stars, boson clouds surrounding black holes undergoing superradiance conditions, and searches for dark matter direct interactions [27]. Detection of even one long-lived source of gravitational waves would permit continuous observation and deeper understanding of the physics for such sources: neutron star EOS and dynamics, nuclear physics under extreme gravity and magnetic fields, tests of general relativity, particle physics, and possibly even unexpected discoveries. Depending on the nature of non-axisymmetric neutron star physics, it is possible that a few up to O(100) sources may be detectable, reaching limits on ellipticity $\sim 6 \times 10^{-10}$ [3]. The sky-localization for these sources is significantly better than binary mergers due to the much larger number of wave cycles accumulated in the detection band and the detectable sources are much closer (i.e., not at cosmological distances), thereby enabling improved electromagnetic observations and more insights as multi messenger astronomical sources. Continued operation of the $A^\sharp$ detector network can improve signal-to-noise of any sources–or sources just below threshold–as more data is accumulated.

- The expected $A^\sharp$ strain improvements will lead to improvements in the detector network sensitivity to the stochastic gravitational wave background, reaching normalized energy density $\Omega_{\rm GW} \sim 10^{-10}$ and enabling inference on both cosmological and astrophysical background models. High signal-to-noise (SNR) measurement of the stochastic background due to stellar-mass binary mergers will provide information about the high-redshift population of binaries, complementary to the individual detections. Potential detection of correlations between stochastic background anisotropy and electromagnetic tracers of structure (galaxy counts, gravitational lensing) would provide additional clues about formation and evolution of structure and of the binary populations [28].

4.2 LIGO is a cornerstone of multimessenger astronomy

The IGWN detectors envisioned for the 2030s provide an exceptional opportunity for coordinated multimessenger observing campaigns including Vera Rubin Observatory, IceCube and many other facilities around the globe and in space. Table 1 summarizes the expected detection rate of binary neutron star mergers within $z = 0.5$ by a variety of gravitational-wave detector networks. The kilonovae from mergers at larger redshifts are unlikely to be detectable in UVOIR telescopes except in exceptional circumstances. A network with at least three $A^\sharp$ detectors would detect thousands of mergers localized to $\leq 100\text{deg}^2$ (see Table 1) [29]. While such a network would detect these binaries at a ten times lower rate than networks using multiple Cosmic Explorers, the continued operations of the LIGO detectors, dovetailing with next-generation facilities, will already deliver measurements of the neutron star radius to a fraction of a km and the Hubble constant to a few percent [29], and refine the corresponding analysis approaches in the process. Analysis of $A^\sharp$ data will grapple with anticipated challenges associated with greater detector sensitivity (e.g. increased computational requirements, refining sky localization for early warning candidate alerts). Working with the more sensitive $A^\sharp$ detector network may also motivate new avenues of inquiry and novel analysis approaches that the community has not anticipated. The experience the community gains with continued operation of a 2G detector network will directly inform multimessenger analyses with next-generation GW detector data, and best prepare researchers to leverage this source-rich data.

4.3 Benefit of LIGO detectors during the next-generation era

The continued operation of 2G detectors during the next-generation era will be critical to ensuring precise localization of CE's loudest events. The signals from low-mass binary mergers (e.g., from binary neutron stars) will be in the detector band for an hour. The effects of Earth's rotation in this time can improve the precision of single-detector localization, but even for signals with a CE SNR ratio of 1000, binaries would at best be localized to 10 square degrees on the sky, and the typical SNR 1000 BNS will have multimodal localization regions of 1000's of square degrees [30]. Such loud signals, while rare, would have an SNR of 40 in 2G detectors at $A^\sharp$ design sensitivity. CE is expected to detect $\sim$5 BNS mergers per year with SNR > 300, which would have SNR > 12 in 2G detectors at $A^\sharp$ design sensitivity. Assuming a threshold SNR of 8, a network of 2G detectors at $A^\sharp$ sensitivity is expected to detect at least one BNS merger

Table 1: For the sub-population of binary neutron stars within $z = 0.5$, the table lists the number of detections per year for four detector networks with 90%-credible sky area $\Omega_{90} < 100$, 10 and 1 deg^2. The local merger rate has been assumed to be 320^{+490}_{-240} Gpc^{-3} yr^{-1} [31].

Metric	Ω_{90} (deg^2)		
Quality	≤ 100	≤ 10	≤ 1
3A$^\sharp$	$1.2^{+1.8}_{-0.9} \times 10^3$	$3.2^{+4.7}_{-2.5} \times 10^2$	$5.0^{+11.0}_{-5.0} \times 10^0$
CE20 + 2A$^\sharp$	$8.6^{+13.3}_{-6.4} \times 10^3$	$8.6^{+12.9}_{-6.8} \times 10^2$	$1.7^{+3.3}_{-1.5} \times 10^1$
CE40 + 2A$^\sharp$	$9.8^{+15.1}_{-7.3} \times 10^3$	$9.7^{+14.6}_{-7.6} \times 10^2$	$1.8^{+3.8}_{-1.6} \times 10^1$
CE40 + CE20 + 1A$^\sharp$	$1.4^{+2.1}_{-1.0} \times 10^4$	$3.4^{+5.3}_{-2.6} \times 10^3$	$9.7^{+15.7}_{-7.7} \times 10^1$

per day [3], and thus would critically contribute to the localization of at least as many mergers detected by a single CE instrument.

5 Instrument Science Research

Research and development of instrumentation to improve sensitivity is crucial to the long-term success of gravitational-wave astronomy [3]. While the LIGO Laboratory includes an instrument science research program [32] in addition to its core engineering, fabrication and commissioning capabilities. Research by the LSC and the wider GW community has repeatedly enabled LIGO to reach its target sensitivities [33, 34, 35, 36, 37]. Moreover, the implementation and testing of improved technology in current LIGO detectors can reduce risk for next-generation facilities, similar to how Advanced LIGO learned from the GEO 600 detector [38].

In the control band $\lesssim 10$ Hz and lower frequency band 10 Hz$-$30 Hz, development of larger test masses supported by improved seismic isolation and suspensions will be crucial to reducing noise and improving the stable operation of all future detectors.

The midfrequency band 30 Hz$-$1 kHz is especially crucial because this is where the noise floor of the most sensitive band of current [1] and all next-generation detectors is set. Coating thermal noise is a key limit in this band, and therefor an active area of research in the LSC [39]. Reduction of coating thermal noise from the current (O4) level is essential to achieving the science goals for A$^\sharp$ [3]. The A$^+$ (and Cosmic Explorer) design calls for a factor of 2 improvement in coating thermal noise over Advanced LIGO; A$^\sharp$ targets another factor of 2. Coordinated coating research is ongoing in the LSC, and across the international gravitational-wave community, with work on both amorphous [40] and crystalline coating solutions [41].

Quantum noise is important at both low and high frequencies in all interferometric gravitational-wave detectors. Below about 50 Hz, heavier masses and effective frequency-dependent squeezing [19] are needed to achieve the A$^\sharp$ noise target [3]. High power operation and phase squeezing become important to sensitivity above a few hundred Hertz. At higher frequencies, above 1 kHz, it dominates the noise, although coating thermal noise is not far below the expected quantum noise level and needs to be reduced in tandem to get the maximum benefit from squeezing advances. Development of higher laser power, along with the required power handling technology [42], and increases in squeezing need to be continued for improved sensitivity in future detectors. Variable reflectivity mirrors, both for the end mirror of the signal recycling cavity and the input mirror of the filter cavity, also promise increased sensitivity in the next generation [3]. Variable reflectivity allows for tuning of the high frequency optical noise against the thermal noise in the mid frequency band for overall sensitivity optimization.

6 Workforce development

Next-generation detectors will require a diverse, well-trained pool of researchers, engineers, and experts to maximize science potential. Continued observations with the current generation of detectors will give ideal preparation for future researchers to commission, characterize, and calibrate next-generation detectors by working with real data and gaining first-hand experience with the common challenges of improving detector performance.

Next-generation instruments will also require community development of data analysis methods well suited to the new challenges the data will present. Each major improvement to detector sensitivity has required the development of new analysis techniques to accommodate increased detection rates, understand detected sources, and be prepared for new discoveries. The anticipated sensitivity of next-generation detectors will take expected detection rates from a few to 100 events per day. Realization of the scientific potential of the next generation of detectors will require the community to be prepared to analyze data that is rich in novel and overlapping sources. Required improvements, including accurate waveforms, efficient algorithms, distributed computing approaches, and effective detector noise mitigation and data calibration, will all benefit from development and testing on real detector data.

Endorsements

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