NSF MPS AC Subcommittee
on
Next-Generation Gravitational-Wave Detector Concepts

Report, March 2024

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Report from the NSF MPS AC Subcommittee
on
Next-Generation Gravitational-Wave Detector Concepts

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I. Executive Summary

The breakthrough detection of gravitational waves (GW) in 2015 by the Laser Interferometer Gravitational-Wave Observatories (LIGO) initiated a new field in physics and astronomy, providing a novel way to observe the Universe by "listening" to the ripples of spacetime. That detection and the follow-up observations using improved capabilities of the LIGO detectors yielded remarkable achievements worthy of the Nobel prize. The LIGO detectors reached unprecedented sensitivity and revealed the existence of stellar-scale black holes more massive than expected and neutron-star mergers emitting both gravitational waves and light signals (multi-messenger signals) across the entire spectrum while at the same time providing additional confirmation of Einstein's theory of general relativity. Building on this success, the U.S. science community has begun to plan for the next generation of gravitational-wave (ngGW) detectors, with capabilities ten times better than those of the latest incarnations of LIGO.

The LIGO facilities do not operate in isolation. In fact, there is a worldwide network of detectors, including Virgo in Europe, KAGRA in Japan, and a variant of LIGO under construction in India (LIGO-India). Many of the GW detections after 2015 crucially involved Virgo data, and multi-messenger astronomy (MMA) primarily relies on the availability of multiple detectors at well-separated locations. In addition, there is ongoing planning for the Einstein Telescope (ET), a next-generation detector in Europe, and the achievement of high-priority scientific goals in the future will greatly benefit from a worldwide detector network. Thus, any discussion of ngGW detectors in the U.S. must be carried out in the context of their place in an evolving, well-coordinated international network.

With this in mind, the NSF Mathematical and Physical Sciences Advisory Committee (MPSAC), at the request of the MPS Assistant Director, established the Next Generation Gravitational-Wave (ngGW) Detector Concept Subcommittee to identify network configurations that can operate by the mid-2030s at approximately a factor of 10 better than the design sensitivity of LIGO A+, to provide an overview of their potential astrophysical scientific outcomes, and to recommend optimal ngGW concepts under different potential constraints. Established in January 2023, the Subcommittee received input from the GW science community through white papers, heard presentations from the leaders of key observatories, and met regularly to discuss science priorities and formulate recommendations.

We find that a next-generation detector network with such a significant sensitivity improvement will have a transformative impact on the nascent field of GW physics and astronomy by leading us into the era of precision GW and multi-messenger astrophysics. The discovery potential is tremendous in several cutting-edge research areas, specifically: probing black-hole formation and evolution back to the beginnings of star and galaxy formation and potentially to the early moments of our Universe, enabling a profound, quantitative exploration of quantum chromodynamics and neutron-rich matter, critically contributing to the resolution of the Hubble tension in cosmology, and revealing new physics through the exploration of dark matter and dark energy. The scientific impact extends well beyond GW astrophysics to fundamental physics, particle physics, and nuclear physics. Reaching this unprecedented detector sensitivity will also lead to major technology advancements in advanced electronics, materials science, quantum sensing, and quantum information science, further strengthening the US STEM workforce and economic development.

Among the white papers submitted to the Subcommittee, the detector concept that can deliver the required sensitivity improvement is that of the Cosmic Explorer (CE) consisting of two L-shape detectors, each with 40km and 20km arms (CE40 and CE20, respectively). Based on all considerations per the Subcommittee's charge, we provide the following recommended list of worldwide ngGW network configurations that deliver a sensitivity an order of magnitude better than the LIGO A+ design sensitivity, accounting for possible external constraints, specifically the availability of non-US detectors, ET and LIGO-India:

- **CE40, ET, LIGO-India**
- **CE40, ET**
- **CE40, CE20, LIGO-India**
- **CE40, CE20**

We find that, for all the above network configurations, maintaining the operation of one of the LIGO detectors during the ngGW era does not significantly contribute to the ngGW science goals. This, combined with cost considerations, leads us to recommend that the LIGO facilities be phased out at the onset of science operations of the CE observatory. Still, continuous operation of the LIGO facilities until CE science runs begin is important for scientific discovery, training early-career researchers, and laying the path to the CE sensitivity levels. We reaffirm the Post-O5 report[i] and recommend that advancements target A$^\sharp$ technology and operations as an important intermediate step toward the ngGW era.

II. Introduction

Opening a brand-new scientific field is not the expected result of even the most breakthrough discoveries. However, the 2015 discovery of the first binary black hole (BBH) merger by NSF's LIGO did exactly that. One century after Einstein published his theory of General Relativity (GR) and its natural consequence of the potential existence of GW, the new field of GW physics and astronomy was fully launched, enabling us to probe the Universe in a completely new way. GW emissions represent a completely different messenger that carries information about physics and cosmic sources that cannot be discovered and studied in any other way. In 2017, just two years after the 2015 LIGO discovery, the discovery of the first double neutron-star (NS) merger, coupling electromagnetic (EM) and GW observations, launched GW-EM MMA and demonstrated its ability to provide answers to decades-long questions. They triggered EM observations that demonstrated that gravity and light have the same speed to 15 decimal points and that many of the heaviest elements in the universe (to say nothing of the priciest, such as gold and platinum) are produced when NS merge. These and other discoveries have revolutionized how we explore the physical world and the cosmos, have verified the predictions of general relativity for GW in exquisite detail at the extremes of gravity where natural objects move at half the speed of light and have uncovered new mysteries about black hole (BH) formation.[ii]

The LIGO project started several decades ago, proposing what seemed to be an impossible experiment to detect GW from astrophysical phenomena. NSF supported the vision, even though it was known that it was going to take a long time and substantial investment in both an initial and an advanced phase. Since the first discovery in 2015, the sensitivity of the LIGO detectors has improved with the hard work of scientists and engineers and the installation of new cutting-edge quantum optics designs. The rate of discoveries has accelerated: the first four months of data collection produced three detections, whereas the four months between October 2023 and January 2024 have produced 28 detections.[iii] And there is more to discover: the expected sensitivity (which may take a few years to achieve) will observe events in a volume almost 10 times as large. This will likely include GW sources other than the coalescence of binary systems, including ones we haven't imagined yet.

NSF has been at the center of the development and transformation of GW discoveries and the MMA field. It has achieved this by having supported not only the development, design, construction, and operation of the LIGO facilities through two phases but also by supporting the generations of scientists and engineers engaged in the LIGO Scientific Collaboration (LSC, comprising 60 U.S. institutions).[iv] In fact, opening up this new field would have been impossible without NSF's visionary, consistent, and long-term investment in large-scale GW facilities at a time when GW detections seemed incredibly difficult, if not impossible. As the First Report[v] of the MPSAC Subcommittee on Facilities and Major Research Infrastructure remarked: "… [LIGO] is a remarkable story of NSF's decisions, championed by MPS, to invest in a true long-shot project whose success has made the U.S. the world's leader in gravitational wave science." NSF's success with GW is proof that fundamental, transformative scientific success cannot be achieved without long-term, steadfast commitment and investment.

NSF's strategic vision has been rewarded in multiple ways, levels, and fronts aligned with the Foundation's mission, well beyond "… promoting progress in science".[vi] Reaching the kind of unprecedented sensitivity needed for detecting GW sources routinely required innovation in multiple areas of science and engineering. The exquisite precision of the detectors measures sub-nuclear length differences between arms more than two miles long: this is the joint effort of physicists and optical, electric, mechanical, and vacuum engineers. Signals are extracted from instrumental and terrestrial noise with advanced data analyses and high-performance computing, requiring the development of new technologies and large, robust teams of scientists and engineers capable of bridging new and old technologies and applying them in innovative ways. NSF's investment has produced an excellent, highly competitive STEM workforce that, over the years, brought their innovative, problem-solving capabilities to industry. This has, in turn, translated into economic development for the nation and broad, robust U.S. industrial and scientific leadership.[vii]

In parallel, the GW discoveries have captured the public's imagination and fueled new generations of STEM-oriented students. BH collisions, extreme gravity, ultra-dense NS matter, and the production of gold and platinum upon their mergers have attracted hundreds of interviews of LIGO scientists and engineers, thousands of press articles around the world, a wide-reaching citizen-science project, and a never-ending engagement with education programs at all levels. The LSC as a whole has been honored with multiple international prizes, and dozens of LIGO scientists and engineers have received awards for their specific contributions. Most notably, in 2017, the Nobel Prize in Physics was awarded to long-time LIGO leaders Barish, Thorne, and Weiss.

Throughout the decades before and since the first GW discovery made by LIGO, U.S. leadership in the nascent field of GW astrophysics has been undeniable. At the same time, the LIGO project has opened significant opportunities for international partnerships through the LSC and its alliance with the other international ground-based GW detector collaborations (Virgo and KAGRA). Most recently the NSF shared LIGO equipment with India for the development of the future LIGO-India detector. Through these partnerships, the U.S., NSF, and LSC have benefited from detector technology development and sharing, data analysis development and operations, and overall mutual intellectual exchanges.

The world has ambitious plans for the future of GW science. Maintaining the U.S. position at the forefront of discovery will require strategic and decisive action. NSF investment in the current LIGO facilities enables important upgrades that will bring us to the target sensitivity with currently approved funding (referred to as A+). Further small- or mid-scale upgrades of these same facilities will provide for additional gains in sensitivity. However, the European science community is already targeting a leap in GW-detector sensitivity and is planning for a completely new ngGW observatory, the Einstein Telescope. The Einstein Telescope has been included among the priority infrastructures for breakthrough research in the European Strategic Forum on Research Infrastructures (ESFRI[viii]) in 2021. The existing LIGO facilities have fundamental limits associated with their size, and no level of investment in them will allow the U.S. to complement and expand the ET sensitivity. For the U.S. to remain relevant in this exciting, fast-growing field of GW astrophysics for decades to come, it is imperative that we consider U.S.-based ngGW detector options with a target sensitivity of ~10 times better than that achieved by the A+ stage.

III. Charge & Process

Charge: Following a request by the National Science Foundation Assistant Director of the Mathematical and Physical Sciences Directorate, the Mathematical and Physical Sciences Advisory Committee (MPSAC) established a Next Generation Gravitational Wave Detector Concept Subcommittee (ngGW Subcommittee or "the Subcommittee") to assess and recommend a set of concepts for new GW observatories in the U.S. Consideration of a ngGW detection network is also a direct response to the recommendations of the Astro2020

Decadal Survey, which described it as a central component of the future of astronomy and astrophysics.

The ngGW Subcommittee's charge can be found on the Next-Generation Gravitational Wave Observatory Subcommittee page on the NSF website.[ix] The overarching goal for this Subcommittee is to identify configurations that can operate by the mid-2030s at approximately a factor of 10 better than the sensitivity of LIGO A+ and to recommend optimal ngGW concepts under different potential constraints. The Subcommittee's work has been based on input from the scientific community. The expectation is that the ngGW Subcommittee findings will inform future NSF deliberations and that an optimal concept will mature into an MREFC-scale detection network.

Process: The ngGW Subcommittee membership was finalized by the end of January 2023. Its work began by preparing and issuing a call for white papers, inviting community submissions that address the Subcommittee's specific charge, overarching goal, and as many of the deliverables identified in the charge as possible. The call for white papers was issued on April 13, 2023. The call for white papers can be found on the under the Subcommittee page on the NSF website.[x]

The following white papers were received by June 12, 2023:[xi]

- "Cosmic Explorer"
- "The case for dovetailing LIGO observations with next-generation facilities"
- "LIGO Voyager"
- "A Roadmap for the LIGO Observatories in the Era of Cosmic Explorer"
- "Fundamental properties of Gravitational Waves that could lead to surprises": Rainer Weiss, Emeritus Professor of Physics MIT. This was not a white paper, but rather thoughtful suggestions shared with the Subcommittee.

The ngGW Subcommittee also solicited input from the community by inviting presentations from current GW projects. These presentations provided additional sources of information and further opportunities for the subcommittee members to ask questions. The presentations took place between May - July 2023. The Subcommittee heard presentations from:

- Einstein Telescope (Harald Lück, Leibniz University Hannover, Max Planck Institute and Deputy Spokesperson of ET Scientific Collaboration)
- KAGRA (Shinji Miyoki, University of Tokyo, Institute for Cosmic Ray Physics)
- LIGO (Patrick Brady, University of Wisconsin-Milwaukee and LSC Spokesperson; David Reitze, University of Florida and Executive Director of LIGO Laboratory)
- LIGO-India (Sendhil Raja, Raja Ramanna Center for Advanced Technology)
- LISA (Guido Müller, Director of Max Planck Institute for Gravitational Physics)
- Virgo (Gianluca Gemme, INFN Genova, Virgo Spokesperson)

The presentations are available online through the NSF website.[xii]

The Subcommittee also had regular one-hour meetings (typically weekly) to discuss the detectors' capabilities, science potential, network configurations, response to other charge considerations, recommendations, and write the report. Based on the information gathered from the white papers and presentations, as well as additional specific information requested from the current project groups and the NSF, the Subcommittee identified the following priority science objectives:

1. Black Holes and Neutron Stars across the Universe
2. Physics of Dense Matter and Multi-Messenger Astrophysics
3. Cosmology Probes and the Dark Sector
4. Fundamental Physics and Novel Sources

For each science objective, the Subcommittee considered many different ngGW network configurations and their potential for achieving every key scientific goal within each objective. These assessments were made using metrics provided through white papers, follow-up communications, and research literature. The Subcommittee also assessed the technical risks of the detector technologies needed to achieve sensitivity an order of magnitude greater than the sensitivity of LIGO A+, as well as timelines and costs. The recommended set of ngGW network configurations takes into account constraints outside the NSF's and U.S. control.

The Subcommittee made a first presentation of their status to the NSF MPSAC during the public meeting on November 8, 2023. In early March 2024, the Subcommittee shared a first draft of the report with the NSF MPSAC in advance of the public presentation to the MPSAC at their meeting on March 26 - 27, 2024.

IV. Science Discovery Potential for ngGW Facilities

In the early 1990s, when the NSF and Congress were poised to decide whether or not to proceed with the construction of LIGO, they faced opposition from influential voices in the scientific community who argued that LIGO would not discover anything new and would (if it even succeeded) only verify the existence of GW, a fact already established by observations of the Hulse-Taylor binary pulsar. The contrast between then and now could not be more stark. While the initial detection in 2015 did verify the existence of GW, it and the subsequent observations of waves from inspiraling BBH and NS went much further. The LIGO-Virgo observations initiated the new field of GW and related MMA, attracting some of the brightest young scientists to these fields and generating enormous public interest.

Yet perhaps more importantly, this success made it clear that this is only the beginning. The next generation of improved GW detectors has the potential, particularly when operated as a network with other worldwide detectors, to answer some of the most pressing questions in physics and astronomy. They will elucidate the formation and evolution of BH across the universe and through cosmic time, with important implications for stellar structure and evolution. They will study the nature of ultra-dense matter in NS, advancing our understanding of the basic interactions of elementary particles. They will measure the expansion rate of the universe, with the potential to resolve current conundra and tensions in cosmology. They will test GR in the extreme gravity regime close to BH. As is often the case when new observation capabilities become available, there is also the potential to discover something entirely new and unexpected, such as compact objects that are neither BH nor NS, falling outside the purview of strict GR. Often, major breakthroughs come from such unexpected discoveries.

Below, we summarize in more detail the anticipated science potential of ngGW detectors based on our current knowledge. We draw from recent reviews and white papers (including all submitted to our Subcommittee) and summarize the most salient points here.[xiii] [xiv] [xv] [xvi] [xvii] [xviii]

Black Holes and Neutron Stars across the Universe

The first GW detection at the beginning of the First Observing Run (O1) with Advanced LIGO not only opened up a new window onto the Universe but also started a revolution in compact-object astrophysics. GW150914 confirmed decades-old predictions that BBH form in nature and merge at a significant rate and surprised us by revealing the most massive (at the time) stellar-scale BH. In just a few years, we transitioned from knowing each BBH merger by its individual name to having an observational sample that has grown by ~100. We are now able to study the BBH population out to cosmological distances, constrain theoretical predictions, and address questions regarding their collective properties as a function of redshift and metallicity and their origins and evolution. At present, answering these questions is hampered by the limited precision of BH characterization and the limited reach in distance (~8Gpc) of our current detectors.

The discovery of the double NS merger (GW170817) associated with a separately detected short gamma-ray burst (GRB) proved transformational for MMA and the study of matter at the most extreme densities. Subsequent NS merger discoveries revealed surprising NS properties clearly different from those measured with high accuracy through radio pulsar timing and the existence of mixed mergers (NS-BH). Moreover, even with just a handful of NS mergers, their relatively high astrophysical rate, coupled with that of BBH mergers, is challenging astrophysical models and our physical understanding of core-collapse supernovae, leading to the formation of NS and BH. Still, our current detectors are too limited to enable NS population studies and mature MMA. Even when we reach A+ sensitivity, a sample of only ~10 NS mergers is expected.

With ngGW detectors, we will enter a new era in the study of NS, “low-mass” BH, and MMA: an era of precision measurements and complete observational samples across the Universe. For the stellar-mass BH population, theoretical predictions imply that we will be able to detect mergers all the way out to the beginning of star formation. Thousands of these detections will be at a signal-to-noise ratio (SNR) exceeding 100, enabling a level of precision that will allow to not only measure BH masses, spins, and mass ratios with high precision but also track the evolution of these properties through cosmic times parallel to galaxy evolution and metallicity increases. We will observationally probe and quantify physical correlations and features in BH properties that connect to their evolutionary origins and possibly evolve through time. With such large BH populations and the capability to reach out to the onset of star formation, we will uniquely probe BH formed from the first-generation (zero-metallicity, Population III) stars. Measuring the BH mass function at those early times can reveal information about Population III stars that we cannot obtain any other way in the coming decade. Such observational probes will challenge theoretical population models at a quantitative level that EM observations have never reached.

Questions around intermediate-mass black holes (IMBH, 100-10,000 solar masses) have persisted in astrophysics for approximately half a century. Firmly proving their existence in varied environments and understanding their origins are key challenges in their own right. Moreover, their connection to cosmological questions and whether they can provide the seeds for the growth of supermassive BH is becoming an increasingly pressing question, especially as recent EM observations reveal the existence of supermassive BH at higher and higher redshifts. Although we have evidence that ~100 solar mass BH can form through BBH mergers, the expanded frequency coverage of ngGW detectors will discover mergers involving IMBH-scale BH at a population level and high enough redshifts coupling them to the evolution of supermassive BH.

The impact of ngGW detectors on NS astrophysics will be transformative, opening up the era of NS population studies. Hundreds of very high-SNR detections will enable precise mass and spin measurements across cosmic scales, allowing us to assess the currently emerging differences with the Galactic binary pulsar population. Our knowledge of this population will grow in parallel due to advances in radio observatory capabilities.

Physics of Dense Matter and Multi-Messenger Astrophysics

Astrophysical systems, such as isolated NS and NS in binary systems, experience extreme internal and surrounding matter conditions that are impossible to reproduce on Earth. Their observation therefore provides a unique way to investigate properties of gravity, density, temperature, energy, and magnetic fields far from the range accessible by nuclear physics experiments on Earth.

For many years, these astrophysical objects were observed only through their EM radiation, but their interiors or regions closest to them are obscured with this type of observation. Unveiling the state of matter inside NS, where intense gravity compresses matter to several times the density of an atomic nucleus, thus remains an open challenge for physics.

GW, interacting weakly with matter and thus traveling almost unimpeded, are a powerful new tool for exploring previously inaccessible regions. Because the properties of matter within the interiors of NS give rise to specific imprints on the GW signals, they now offer a tremendous opportunity to probe nuclear physics in unexplored regimes by obtaining tight constraints on their nature and structure.

Indeed, the first observations of GW from the merger of a NS binary, GW170817, obtained by LIGO and Virgo in 2017, allowed us for the first time to measure the tidal deformation that each star's gravitational field induces on its companion. As this deformation is directly dependent on the nuclear equation of state (EOS), these observations already operate under some constraints. The tidal deformability determines the amount of NS matter disrupted at the merger, which gives rise to the sub-relativistic and relativistic ejecta powering different EM counterparts.

The GW170817 discovery was followed by a massive EM follow-up campaign, which led to the detection of almost the entire spectrum of EM signatures, from gamma rays to radio. This event marked the dawn of MMA, including GWs, showing us the tremendous potential of this emerging observational field. GW and EM multiwavelength observations have solved the mystery of the progenitors of short GRBs, allowing us to demonstrate relativistic jet formation in the merger of binary NS systems and to reveal its structure, with a significant impact on relativistic astrophysics. Optical emission from the sub-relativistic ejecta has revealed evidence of the nucleosynthesis of heavy elements, pointing to the merger of NS as one of the main channels of formation of such elements in the Universe. Direct measurement of the distance from the GW signal, together with the recession velocity of the host galaxy from EM observations, demonstrated a new means of measuring (still with large uncertainties) the local expansion rate of the Universe.

Although the current GW detectors have already achieved significant results for the physics of dense matter, a tenfold improved sensitivity of GW detectors will provide the required capabilities to firmly address the long-standing open questions on the nature of matter at nuclear densities.

Such detectors will be able to bring the detections of NS and NS-BH binaries from a few per year of the current detectors to tens of thousands, reaching distances well beyond the peak of the star-formation rate density, enabling population studies along the cosmic history. The improved high-frequency sensitivities will make it possible to study the closest NS with unprecedented precision, to measure tidal deformability with an order of magnitude higher accuracy, and to access NS interiors through the observations of merger and post-merger GW signals. These will allow us to determine the EOS and also to understand the strong interaction theory by investigating regimes where quantum effects become important. While progress has been made in developing a quantitative theory of nuclei, neutron-rich matter, and deconfined quark matter, the nature of strongly interacting matter remains a tantalizing enigma in physics. With the observation of numerous NS mergers and the ability to accurately measure star radii to 100 meters or better, we anticipate a profound exploration of quantum chromodynamics' (QCD) phase structure, offering an unprecedented avenue for charting the dense, finite-temperature realm within the phase space of QCD.

Multi-messenger observations will become routine. While the number of GW signals with associated short GRB is limited to a few, even at the design sensitivity of the current detectors, almost all short GRB will have a detectable GW counterpart. The precision of parameter estimation for the progenitor system and the merger remnant, together with the information from the broadband EM observations, will unveil the physics governing the sub-relativistic neutron-rich ejecta and relativistic ones. The next-generation detectors operating in synergy with innovative EM observatories, such as the Vera Rubin Observatory, the JWST, and ELT, will enable us to study heavy-element formation at its production site and to understand how binary NS contribute to the cosmic abundances over time. Together with gamma-ray and X-ray observatories, tens to hundreds of joint detections per year are expected to probe short GRB physics, unveiling the formation, structure, and composition of relativistic jets and how compact objects accelerate particles and produce huge amounts of energy in a short amount of time.

Another potential GW signal of interest is that from a core-collapse supernova (CCSN), which is expected to be a burst of a few seconds' duration immediately following core bounce. An observation would provide insight into the currently poorly-understood CCSN explosion mechanism and will also elucidate the properties of the compact remnant, e.g., EOS of a proto-NS or rotation of a BH remnant. However, the specific nature of the GW signal is not cleanly predicted. There are large model uncertainties and also potentially intrinsic physical variances, such that matched-filter searches cannot be used. Furthermore, expected strains are typically broadband and small. CCSN GW emission may only be detectable with current networks within distances less than the extent of the Milky Way and, for some CCSN GW signal models, much less than 10kpc. Within this range, the expected CCSN event rate is less than a few per century.

An exciting possibility is a coincident detection of GW with the prompt neutrino-burst signal from a CCSN. Such a multi-messenger detection would offer highly enhanced opportunities for both astrophysics and particle physics, including a potentially improved understanding of neutrino mass, as well as an early alert of an impending EM supernova due to the prompt nature of both the neutrino and GW emission. The current understanding of the expected neutrino signal, while still suffering from order of magnitude uncertainties, is more precise than the GW predictions. The distance sensitivity of most current neutrino detectors is the entire Milky Way or somewhat beyond, with Super-K's reach extending to a few hundred kpc. Next-generation neutrino detectors, including Hyper-K, DUNE, JUNO, and IceCube-Gen2, which will be operational within the ngGW time frame, will improve neutrino-signal statistics but will have distance sensitivity still limited to the Local Group. With ngGW facilities, our sensitivity to a GW signal from a CCSN could robustly extend to the edges of the Milky Way for many models, rendering, for the first time, a multi-messenger CCSN detection in neutrinos and GW highly probable. While the CCSN event rate in that range is still only a few per century, there is still a reasonable probability of observing an event during the ngGW era—and even a single nearby CCSN event observed in GW, neutrino, and EM channels will be a scientific event of enormous impact. In addition to the core-collapse signal, the GW signal of a possible nascent NS (remnant of the explosion) is expected to be detectable to our closest galaxy neighbors.

Cosmology Probes and the Dark Sector

In the past three decades, cosmology has seen the emergence of a standard model characterized by an exquisite alignment between theoretical predictions and observational data, a feat unimaginable in earlier times. However, our current understanding of the universe remains incomplete, with dark matter and dark energy being crucial yet not fully understood elements. Dark matter, vital in the dynamics of cosmic perturbations, remains mysterious. Similarly, dark energy, dictating the late-time expansion of the universe, is a puzzle we have yet to solve. Adding to these enigmas are emerging tensions and inconsistencies among various measurements, hinting that our standard model of cosmology might be incomplete. The most prominent of these is the discrepancy in the Hubble constant measurements, contrasting direct observations with values inferred from the Cosmic Microwave Background and Large Scale Structure.

GW observations have opened a novel and promising avenue for cosmological exploration. They emerge as a unique tool for measuring the Hubble constant, independent of traditional astronomical methods. GW from binary mergers, like those involving NS or BH, provide critical information about the luminosity distance and sky position of these events. As "standard sirens," these GW sources, when coupled with redshift estimations, unlock the potential to refine measurements of cosmological parameters, including the Hubble constant.

Measuring the Hubble constant requires having a redshift for the event, and there are two broad methods for accomplishing this:

- Bright Siren Method: EM counterparts, such as kilonovae or GRB from mergers involving NS, can pinpoint a merger's location and its host galaxy. Spectroscopic data from these galaxies provide the necessary redshift information, enhancing the precision of H0 measurements.

- Dark Siren Method: For mergers without detectable EM counterparts, like those involving only BH, sky localization plays a crucial role. The "statistical dark siren" approach aggregates H0 estimates from galaxies within the event's localization volume. Among these, "golden dark siren events," with highly precise localization, promise even more accuracy by identifying unique host galaxies.

The incorporation of two next-generation detectors in the GW observational network would open a new era in precision cosmology. These advanced detectors are poised to measure the Hubble parameter with unprecedented accuracy, a small fraction of a percent, using both of the methods described above, potentially resolving the Hubble tension or providing convincing evidence of new physics beyond the standard cosmological model.

Binary neutron star (BNS) mergers offer a unique insight into nuclear physics. The intrinsic mass scale of NS, imprinted in the tidal interactions during a merger, if coupled with knowledge of the nuclear EOS, can directly reveal the redshift from GW observations. This method, reliant on the accurate determination of tidal deformability, could also provide measurements of the Hubble constant of similar accuracy with the incorporation of two next-generation detectors in the GW observational network.

This approach not only refines measurements of the Hubble constant but also maps the expansion history of the universe up to high redshifts with considerable precision. To achieve such constraints, ngGW detectors have become indispensable. While this method offers an independent avenue to chart the universe's expansion, it's important to note that the constraints it provides, although valuable, are anticipated to be less stringent compared to those expected from forthcoming dark energy surveys.

GW provide a means to investigate proposed new particles, such as axions, which are suggested as solutions to the strong-CP problem in QCD. Not limited to axions, any ultralight boson within the appropriate mass range could form 'gravitational atoms' around rotating black holes. These 'gravitational atoms' are capable of emitting distinct GW signals. While current detectors have already demonstrated the capability to detect boson cloud systems around young spinning black holes in our galaxy, the advent of a network incorporating two next-generation observatories promises to enhance these detection capabilities significantly, potentially improving sensitivity by a factor of 10 to 20. This advance opens new avenues in probing aspects of particle physics and dark matter that are otherwise inaccessible through conventional observational methods.

In recent decades, the concept of primordial black holes (PBH), formed shortly after the Big Bang, has gained traction as a potential component of dark matter and a seed for supermassive black holes. The abundance of PBH might be set by processes happening during the very early Universe when the primordial density fluctuations responsible for the structure we see in the Universe were created. Thus, a detection of PBH could provide a new window into this poorly constrained epoch. Although various experiments have constrained their abundance, certain mass ranges of PBH could significantly influence GW observations (~10-50 solar masses). These PBH, arising from early Universe overdensities and expected to have small spins and low clustering, could form binary systems detectable as high-redshift merging events. This is in contrast to BH formed from Population III stars, whose merger rate decreases at very high redshifts. The ability to detect BH at high redshifts will not only enhance our understanding of the early universe but also refine the constraints on PBH abundance by orders of magnitude compared to current limits. By distinguishing the redshift evolution patterns of PBH and Population III mergers, one could measure the PBH fraction of dark matter with unprecedented precision, potentially reshaping our understanding of cosmic history and dark matter composition.

Fundamental Physics and Novel Sources

General relativity (GR) is widely regarded as our “standard model” for gravity. During the 110 years since Einstein completed the theory, it has been tested numerous times using laboratory experiments, observations centered on the solar system, timing of binary pulsars, and, most recently, the direct detections of GW. It has passed every test with flying colors.

Yet there is a significant current of thought that asserts that GR, in the form defined by Einstein's equations, may not be the last word on gravity. This has emerged from a number of conundra that have to date defied resolution. Two come from observational astronomy: the apparent existence of "dark matter," which affects the rotation curves of galaxies, gravitational lensing, and the large-scale structure of the universe, yet which has only weak interactions with the elementary particles of the standard model; and "dark energy," a hypothetical substance that is responsible for the observed accelerated expansion of the universe. GR alone cannot account for these phenomena. Because no candidate elementary particle to act as dark matter has been detected to date, and because there is very little agreement on the nature of the dark energy, a substantial industry has emerged in devising "modified gravity" theories that agree with GR in the realms where precision tests exist, yet depart from it at larger scales in order to account for one or both of the dark matter and dark energy phenomenologies gravitationally. A third conundrum comes from pure theory: the apparent incompatibility of GR with quantum mechanics. Despite decades of research by thousands of investigators, it is hardly an exaggeration to say that we are no closer to a satisfactory quantum theory of gravity today than we were in the 1940s when a tiny handful of GR theorists began to think about quantizing Einstein's theory.

The detection of gravitational radiation from inspiralling compact objects has opened a new realm of strong-gravity, dynamical tests of GR, with the hope of testing these modified gravity theories. In fact, when the detection of GW and EM signals from the event GW170817/GRB170817 verified that the speeds of gravitational and EM waves are the same to extremely high precision, it killed or severely constrained a large number of modified gravity theories.

A next-generation network of detectors, by detecting binary inspiral signals with higher SNR and by detecting many more sources at modest SNR, thereby driving down statistical uncertainties, could make significant improvements in tests of GR. Bounds on the parameters that govern the shape of gravitational waveforms could be improved by two orders of magnitude, as could bounds on the graviton mass. Significant tests could be performed regarding the existence of additional modes of polarization of the waves beyond the two predicted by GR. With improved SNR, it will be possible to detect multiple "ringdown" modes of oscillation of the final object produced by a merger, thereby testing whether that object is truly a black hole of GR (obeying the so-called "no-hair theorems") or possibly an exotic horizonless object predicted by some alternative theory of gravity. Other exotic objects could potentially be detected, such as BH surrounded by clouds of light bosons or non-GR compact objects that store GW temporarily and then release them as "echoes." It should be pointed out that a number of these tests, including bounding the graviton mass and testing the nature of spacetime around compact objects, will be performed with higher precision by the space-based LISA interferometer.

Detection of a stochastic background of GW originating in the early universe would also be possible. While a background of waves generated during the standard inflationary epoch will be too weak to be detected, waves from non-standard processes such as cosmic strings could be detectable. Searches for such background signals could provide additional constraints on exotic physics or cosmological models.

If all that resulted from these observations were additional confirmations of GR, that would still be a laudable achievement. By contrast, the verified detection of a violation of GR, however unexpected it might be, could be transformative, providing clues about dark energy, dark matter, or even quantum gravity. A difficulty is that few modified gravity theories provide compelling "targets" where GW tests might be interesting or crucial since, by design, they tend to deviate strongly from general relativity on either large cosmological scales or unattainably small Planck scales.

As a result, while the tests of fundamental theory described here are important scientific goals, our view is that they do not *drive* the selection of optimal network configurations. All the configurations considered will yield improved tests of fundamental theories, some better than others, but we could identify no configuration that was so "sweet" as to be qualitatively more effective than any other.

V. Survey of Individual Detectors & Concepts

There is no single metric to measure the sensitivity of GW detectors, but the main sensitivity figure of merit is the noise amplitude spectral density as a function of frequency, which determines the astrophysical reach to different sources (for example, mergers of IMBH need lower noise at lower frequencies, and last cycles of mergers of NS need lower noise at higher frequencies).

For each configuration, the strain noise is assumed to be limited by "fundamental" sources, namely seismic noise, thermal noise, and quantum noise.

- The amplitude of the seismic noise is mostly determined by ground noise, the seismic isolation provided by seismic isolation systems and mirror suspensions, and arm length. Newtonian noise (NN), i.e., a direct gravitational coupling of mass fluctuations around the mirrors caused by seismic movements or atmospheric sources (wind, sound), cannot be decoupled. NN can only be reduced by measuring the seismic or acoustic field and subtracting the calculated effect.
- The amplitude of the thermal noise is mostly determined by the substrate and coating material of the mirrors, the laser-beam size on the mirrors, the operating temperature of the mirrors, and the arm length.
- The quantum noise is mostly determined by the circulating laser power, the weight of the mirrors, and the quantum vacuum squeezing. The overall shape of the noise spectral density also depends on the arm cavity parameters and the signal recycling configuration, if used.

The facilities also have limits, mostly due to the vacuum systems (beam tubes and vacuum chambers) and civil infrastructure.

A measure of detector sensitivity often used is the distance at which an inspiralling pair of two NS with masses of 1.4 solar masses each can be seen at an SNR of eight, averaged over sky localization and binary orbit inclination. This is called the “BNS range”. The distance for detecting BBH, in general, is larger, depending on their mass, but it also depends critically on the detector noise in the frequency band before the BBH merger frequency, so it is not a simple scaling from the BNS range.

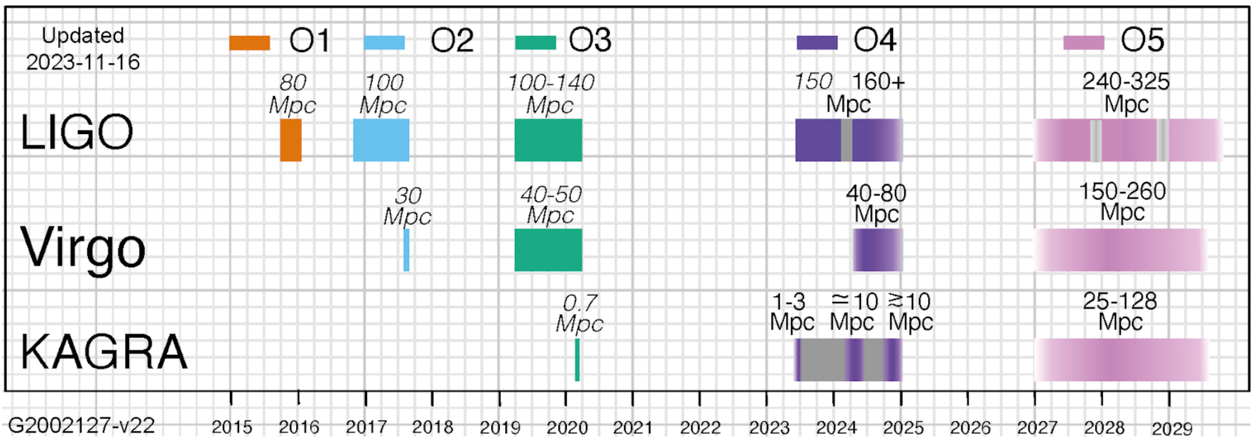

Figure 4.1: Timelines of planned observation runs. This figure was taken from the LIGO, VIRGO and KAGRA Observing Run Plans[xix] at the time of the report writing. It is updated periodically. The distances in Mpc indicate the average distance at which a BNS merger is detected with a signal-to-noise ratio of 8.

The **Advanced LIGO detectors (aLIGO)** began installation in 2010 and had an 80Mpc BNS range in 2015 when the first GW was detected in the LIGO-Virgo O1. The aLIGO design sensitivity was ~170Mpc, and the sensitivity increased to 100-140Mpc in the Third Observing Run (O3) in 2019-20. The LIGO-Virgo catalog of published events[xx] in O1-O3 has ~ 90 events, including two BNS mergers, two NS-BH mergers, and 83 BBH mergers, with masses between 5 and 100 solar masses.

The frequency-dependent squeezing currently being used in the Fourth Observing Run (O4) started in May 2023, with the LIGO observatories operating with a 160Mpc BNS range. In the first nine months of O4 (O4a), there were 81 significant detection candidates, all BBH mergers except for two possible NS-BH mergers.

The **A+ upgrade** was funded in 2018 and consisted mostly of frequency-dependent squeezing, higher power, and better mirror coatings. The A+ upgrade could reach a BNS range of 325Mpc by the end of the decade in the planned Fifth Observing Run (O5). Possible future upgrades in the same LIGO facilities are A$^\sharp$ and Voyager.[xi] [i]

The **A$^\sharp$ detector** would use the same laser wavelength and substrate material as A+ but would use larger test masses, improved suspensions, seismic isolation, increased squeezing, and better optics coatings if available. The BNS range of A♯ would be 400-600Mpc, depending on coatings and configuration.

The **Voyager** concept uses 2μm laser wavelength, larger test masses, higher power, and low temperature (123K) operation. Depending on the configuration, the Voyager BNS range would be 600-800Mpc.

The committee received one white paper for a ngGW observatory concept in the U.S., **Cosmic Explorer** (CE), with two facilities of 20km and 40km long, respectively (CE20 and CE40). CE increases the arm length compared to existing LIGO facilities by a factor of 5-10, which roughly translates into a reduced effect of most noise sources by the same factor. Similarly to current and future concepts in existing facilities, the optical configuration can be optimized for high-frequency, low-frequency, or wideband operation.

In Table 4.1, we present the expected timeline for LIGO A+, with possible timelines for Voyager, CE40, and CE20 (all depending on CE-funding start dates). Notice that without A♯ or Voyager, there would be a considerable gap without any commissioning, which could result in a serious loss of personnel and experience.

	Now-2025	2025-2030	2030-2035	2035-2040
LIGO A+	O4	O5		
LIGO A♯	R&D, Proposal	Procurement, Installation	Commissioning, Operation (6yrs after funding)	Operation
Voyager	R&D, Proposal	R&D, Proposal, Procurement	Installation, Commissioning, Operation (3.5yrs after funding)	Operation
CE	R&D, Design	Site selection, Design (Concept, preliminary and final reviews)	Construction	Commissioning, Operations (~5yrs after funding)

Table 4.1: Timelines for possible future U.S. detectors considered in this report (except for A+, which is the current LIGO detector). In each case, operations (observing mode) follow after a period of commissioning, which can last one or more years.

In Table 4.2, we show the main parameters of detector configurations in current and future facilities. The circulating power in A+ has not been achieved yet but is expected to be achieved in the near future.

	A+	A♯	Voyager	CE20	CE40
Arm length	4km	4km	4km	20km	40km
Laser Wavelength	1µm	1µm	2µm	1µm	1µm
Arm power	0.75MW	1.5MW	4.0MW	1.5MW	1.5MW
Squeezed light at 1kHz	6dB	10dB	10dB	10dB	10dB
Mirror Substrate	Silica	Silica	Silicon	Silica	Silica
Mirror mass	40kg	100kg	200kg	320kg	320kg
Mirror Temperature	Room temp.	Room temp.	123 K	Room temp.	Room temp.
NN Suppression	0dB	6dB	6-20dB	20dB	20dB
Coating noise level	A+	A+/2	A+/2	A+	A+

Table 4.2: Key parameters of current (A+) and future detector concepts (from CE white paper and post-O5 report)

While the sensitivity of the 4km detectors (A♯ or Voyager) will be close to the limits imposed by technology, physics, and infrastructure constraints, the initial version of CE is based on a conservative design using existing proven technologies. The increase in sensitivity is largely achieved by increasing the length. Therefore, significant further improvements of 4km detectors beyond A♯ or Voyager are not to be expected, while the CE versions outlined here represent only the beginning of an evolution in which Voyager technologies or other currently prototyped technologies can be used for later improvements.

We summarize the sensitivity curves of the baseline designs for the detectors of different evolutionary stages from the currently achieved state (O4) to the ngGW detectors in Figure 4.2, including a figure with the aLIGO design sensitivity curve divided by 10 as a reference, noting that the CE design (as well as the European ET design) has a larger improvement ratio at low frequencies (most relevant to BBH mergers) and a smaller improvement ratio at higher frequencies (most relevant to late stages of BNS mergers).

These detectors can be tuned to optimize their sensitivity to various science objectives, as indicated in Figure A1.2 in Appendix A1 for the “advanced” generation up to Voyager and in Figure 4.3 (or Figure A1.1 in Appendix A1) for CE. For more technical details on the different evolution stages, also see the public Instrument White Paper 2022/23.[xxi]

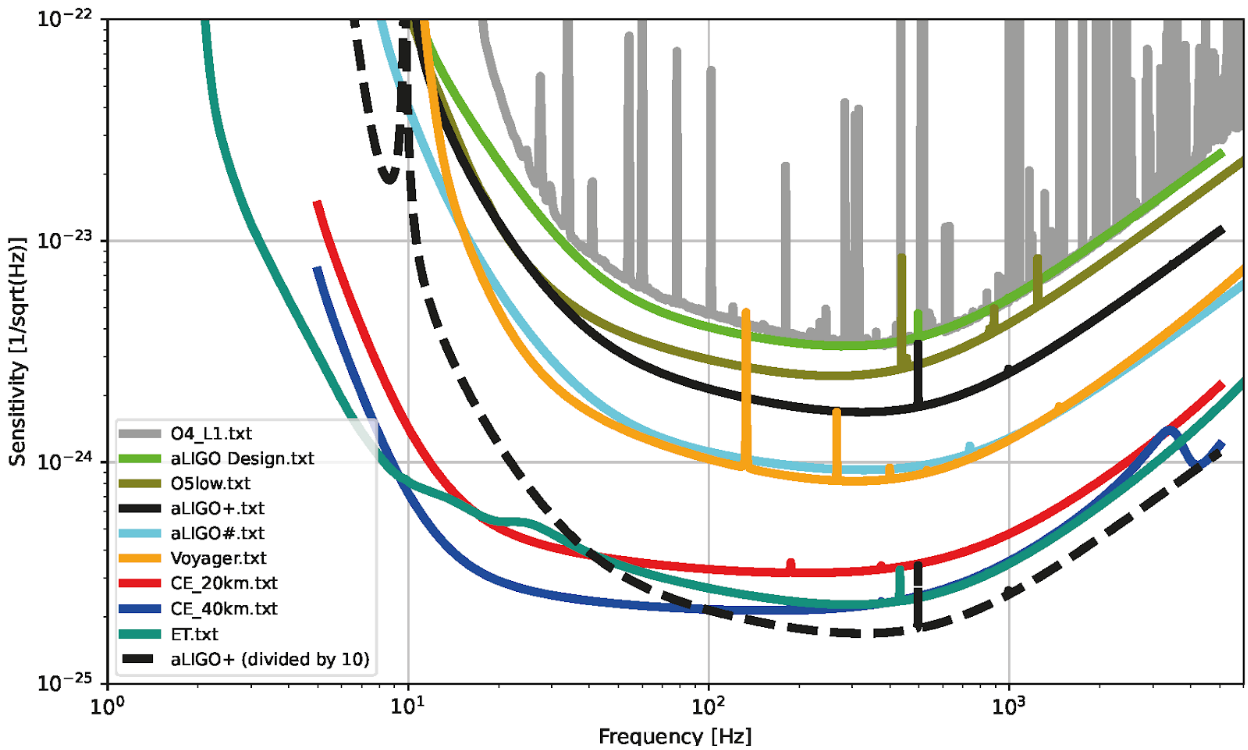

Figure 4.2: Amplitude Spectral Densities of the gravitational-wave-strain equivalent noise for various observatory designs. Note that the plot can only be indicative because the observatories and detectors in network configurations do not all respond to a certain type of gravitational wave in the same way. The responses differ depending on the incidence angle and polarization of the gravitational wave. Information on the sources for these curves can be found in Appendix A1.

In the following sections, we summarize the CE20 and CE40 concepts, including R&D needed, risks, timeline, and cost.

- **Two U.S.-based ngGW concepts:**

    - **CE40**

The concept is a dual-recycled Fabry-Perot Michelson interferometer with 40km arms, operated with suspended test masses at room temperature, probed with a 1µm-wavelength laser, and quantum-enhanced by the injection of frequency-dependent squeezed light (same configuration as A+). In its broadband configuration (see Figure 4.2), it reaches a strain sensitivity of $2.5\text{x}10^{-25}\text{Hz}^{-1/2}$ over a wide frequency band (20-500Hz), roughly 10 times the expected sensitivity of A+.

Some differences in technology with respect to A+ are larger optics, with suspensions and seismic isolation adapted to larger optics; subtraction of gravity gradient noise; higher circulating power; and higher squeezing level. Some of these technologies may be tested in A$^♯$ (if funded and implemented in time). A leading technical risk is manufacturing the larger diameter optics to the required optical performance, including low coating loss (A+

coatings extrapolated to 40km and larger test masses satisfy CE thermal noise requirements).

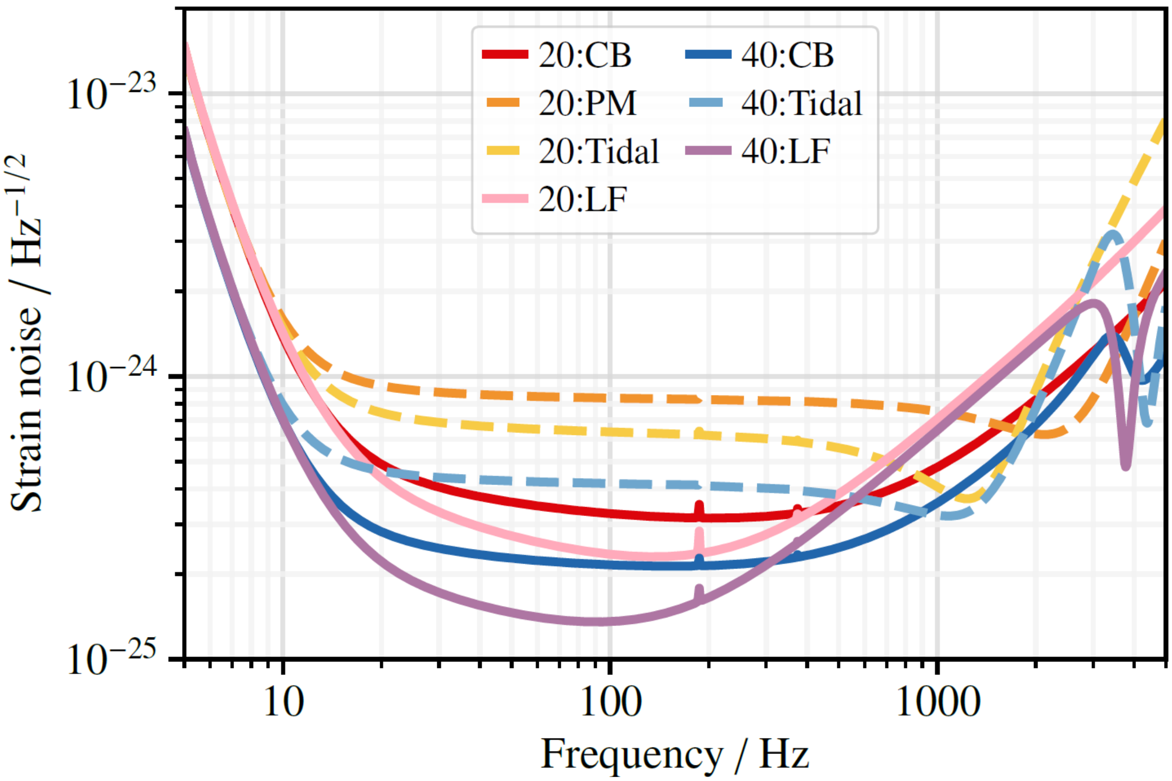

Figure 4.3: Amplitude Spectral Densities of the gravitational-wave-strain equivalent noise for various CE designs and tunings.[xxii] By changing the reflectivity and the tuning of the Signal Extraction Mirror, low- and mid-frequency performance can be traded against high-frequency performance. The compact binary (CB) configuration is the design sensitivity of the respective (40km or 20km) observatory. Each detector can be tuned to observe with a high-frequency optimized sensitivity post-merger optimized (PM) or binary neutron-star tidal (Tidal) and a low-frequency optimized sensitivity (LF).

Other technical risks involve an increase in the complexity of the frequency control and parametric instabilities due to longer lengths and larger mirrors. R&D on these topics and A♯ will help minimize these risks.

From the submitted white paper, the estimated cost for a single 40km observatory is $1.0B (2021 USD), with maintenance and operation costs of $30M/yr (half of the total for two CE detectors in 2021 USD). The timeline estimates 8-10 years from site evaluation to completing the final design review and 4–5 years for construction and commissioning.

- **CE20**

The CE 20km concept is essentially the same as the one described above for CE40, but with 20km arms, possibly tuned to have a ~3x better sensitivity at frequencies near the merger frequency of NS (see Figure 4.3, A4.1). Technology, risks, and timelines are similar to those for CE40. The cost estimate is \$0.7B, and operation costs are \$30M/yr (2021 USD).[xxiii]

There are some differences in technical challenges and risks between CE20 and CE40.

For detectors as large as CE, the earth's curvature is already beginning to have an impact on construction costs. With 40km-long arms, the distance between the straight line of the laser beam (and consequently the vacuum tubes) and the earth's surface (if it were to follow the geoid) is 30m in the center of the arms. Although a suitable bowl-shaped surface topography can minimize earthworks, it restricts the choice of suitable locations. In this regard, arm length has a disproportionate impact on construction costs. Many fundamental noise sources scale favorably with length (see Appendix A1), which makes CE40 less risky than CE20. However, negative scalings that add risk to CE40 include the frequency control bandwidth, which scales inversely with arm length, and the closer spacing of parametric instabilities, which scales inversely with mirror size. The minimum mirror size for a 40km setup exceeds that for a 20km configuration, with low technical risks in substrate and coating quality and homogeneity. Alignment stability requirements for a 40km configuration are higher than for a 20km setup. With longer arms, the line width of the arm cavities gets narrower, which causes increasing issues with the signal extraction cavity. Suppressing higher-order modes becomes increasingly important with increasing arm length, as the associated frequencies tend to move into the most sensitive detection band. The free spectral range for 40km arm length is 3.75kHz, close to the BNS merger frequency.

- **Other U.S.-based/connected detectors/concepts that could support the U.S. ngGW network:**

  - **LIGO A+**

This is the upgrade of aLIGO, funded in 2018. This included the implementation of frequency-dependent squeezing (already in place), test masses with lower coating loss (this is currently in progress for implementation in 2025 for O5), and other changes (larger beam splitter, balanced homodyne readout). Current planning has O5 running through the end of 2028. The technological risks are low, with coating thermal noise research already in an advanced state.[xxiv] [xxv]

  - **LIGO A$^\sharp$**

The first post-O5 upgrades should be designed to be available for installation at the start of 2029 (depending on funding), with operation continuing through the mid-2030s. A post-O5 study group recommended a concept known as A$^\sharp$.[i] The A$^\sharp$ design would offer roughly a factor of two improved strain sensitivity at low frequencies (below 50Hz) and high frequencies (above 300Hz). The former involves improved seismic isolation, larger test masses, and improved test mass suspensions. The latter involves higher laser power (and accompanying improvements in thermal compensation and parametric instability suppression) and increased squeezing. Lower thermal noise beyond what is planned for A+ for large test masses is challenging R&D.[xxvi]

A+ and $A^\sharp$ can be realized with different optimization strategies (signal extraction reflectivity and tuning, filter cavity length, coatings, etc.), leading to various sensitivity curves, as shown in Figure A4.2. Therefore, the sensitivity curves shown in Figure 4.1 and the resulting scientific cases can only be indicative.

The total cost of the $A^\sharp$ upgrade is expected to be within the NSF Mid-scale RI-2 range, up to $100M.[xxvii]

- **Voyager**

The Voyager concept – 200kg crystalline silicon test masses at 123K, 2μm laser wavelength, 4MW arm power – holds promise for its inherent power-handling capability and low thermal noise, but its underlying technologies are less mature than those of $A^\sharp$. Several coating options are considered.[i] Costs are estimated to be slightly above $100M if both sites were upgraded to Voyager technology.

The sensitivity of CE40 and CE20 can be improved further from the design considered in this report by adopting cryogenic operations (with different laser wavelengths and different mirror substrates) such as the ones proposed for Voyager. If that upgrade were to be considered, Voyager could serve as a pathfinder to test technologies in a km-scale detector.

- **Non-U.S.-based detectors/concepts that could support the U.S. ngGW network:**

For quality sky localization of short-duration signals a network of multiple detectors is needed. The pointing capabilities of the network scale with the area spanned by the network detectors.

- **LIGO-India**

The LIGO-India detector will mostly be a copy of the LIGO detectors, applying some of the lessons learned during the U.S. LIGO operations. As it is located in Aundha in the Hingoli district of Maharashta, it is sometimes called LIGO A, but as this can easily be confused with A for “advanced LIGO,” we will use LIGO-India here. LIGO-India was initially planned as a copy of aLIGO, but the current plan is to upgrade it to the A+ status. It will be set up in collaboration with LIGO Lab, Caltech, and MIT. Site acquisition has been completed. The infrastructure and vacuum system for implementing frequency-dependent squeezing will be built from the beginning and is included in the funded costs of ~$300M, covering civil infrastructure, the vacuum system, and installation. Construction of the LIGO-India Observatory is funded by the Indian government with detector components supplied by LIGO Laboratory, supported by the NSF. The detector size is limited by neighboring villages and a lake and cannot be extended.

With the planned detector design, a BNS reach of 100-140Mpc can be achieved (the latter value is comparable with O3 sensitivity and can be reached if the money for the squeezer can be found). All further upgrades will require additional funding. The scheduled timeline currently goes from May 1, 2023 - Apr. 30, 2030, with the aim to participate in O5. Funding for the operating costs has yet to be applied for.

- **KAGRA**

KAGRA is a Japanese GW detector with an arm length of 3km built underground in the Kamioka mine in the Gifu prefecture. It is a power-recycled Fabry-Perot Michelson interferometer (it will include later resonant sideband extraction) using sapphire mirrors in the arm cavities to be cooled to 20K. Currently, most optics are still operated at room temperature. It uses long suspension chains for seismic isolation starting at the upper floor of a two-story cavern system, with the mirrors at the lower floor. In O5, planned for 2027, the KAGRA collaboration aims to achieve a BNS range > 100Mpc. At present there is no post-O5 plan for KAGRA operations.

- **Einstein Telescope (ET)**

The Einstein Telescope is the European counterpart to CE, aiming for 10 times better sensitivity than the design sensitivity of the aLIGO/Virgo Detectors (see Figure 4.1). The basic design has three nested detectors with 10km arms in the shape of an equilateral triangle, built underground at a depth of about 200-300m. Each detector consists of two interferometers. The first is optimized for low frequencies (3-30Hz), with silicon arm-resonator mirrors cooled to ca. 20K and suspended by long low-frequency suspension chains. This interferometer is operated at a laser wavelength of 1550nm at a relatively low arm cavity power of about 20kW. The other interferometer, aiming at high frequencies (30-10000Hz), uses second-generation technologies, including fused silica optics operated at room temperature and a laser wavelength of 1064nm, reaching 3MW in the arm cavities. Both use frequency-dependent squeezing with 10dB of effective squeezing for quantum noise reduction.

VI. Survey of Potential ngGW Network Configurations

As has already been demonstrated, breakthroughs in GW science are not possible without the availability of multiple GW detectors operating at different locations around the globe. This is needed not only for detection confidence through time coincidence at two different detectors but also for drastically improving the constraints on the source sky location, separating the signal's polarization modes for improved tests of GR, and enabling discoveries of previously undetected signals (e.g., stochastic backgrounds).

As we look towards achieving a leap in GW sensitivity improvement of a factor of ~10 better than A+, we consider a variety of network configurations that include at least one or both CE detectors. We do so because, without a CE detector, there is no possibility of reaching this level of sensitivity improvement. We examine the science potential of such network configurations that also include any one or two of the current LIGO detectors and the LIGO-India detector, each with either A+ or $A^\sharp$ sensitivities, and the ET detector. We consider the 10km arm ET triangular shape design for our quantitative metrics assessment. An updated evaluation of the ET science case is given by Branchesi et al. (2023)[xxviii] where different designs are considered (one-site triangular-shape detector versus two-site L-shape detectors). Although the ET capabilities somewhat improve considering the two L-shape detectors, the differences are not significant enough to affect our considerations.

Different networks are anticipated to reach different sensitivities across the frequency range of ground-based detectors and therefore have capabilities that will enable achieving all, some, or none of the science potential summarized in Section 2. It is important to assess these capabilities quantitatively, so we adopt the evaluation of ngGW science potential reflected in the CE white paper. We consider science objectives, and six science goals are identified within each objective. For each goal, the CE team identifies a specific metric and evaluates it, given (i) a network configuration with a specific frequency-dependent sensitivity curve and (ii) an adopted astrophysical model for GW sources across the Universe. For our Subcommittee work, we consider the metrics for what we consider *critical* goals in each science objective; by "critical", we mean science goals that qualitatively change the scientific landscape.

We also note that all results are obtained for just one astrophysical model for the distribution of GW sources across the Universe and the properties (e.g., masses). The absolute numerical results for each metric are directly dependent on this one model and are expected to be uncertain by a few to several factors. However, our purpose is a comparative study between networks, their capabilities, and their scientific potential. Therefore, we are mainly interested in the relative values of the metric values and not their absolute values.

In what follows, we summarize our conclusions when considering the metrics for 15 network configurations provided by the CE team[xxiii] [xxix] (see also: Appendix A2). We provide our conclusions for two general cases:

- **A.** Considering networks that comprise detectors directly connected to U.S. funding and contributions (i.e., without considering the existence of the ET detector)
- **B.** Considering network options that include the ET detector.

Science Objective: Black Holes & Neutron Stars across the Universe

The current sample of BH and NS mergers has already uncovered a rich set of questions we can answer as the sample grows, extending to higher and higher redshifts. Correlations between the physical properties of compact objects, their dependence on redshift, and features in population characteristics potentially carry critical information about their origins. With ngGW detectors, we expect to probe the complete population of stellar-scale BH and a major fraction of NS binaries. Such big samples open up a large range of science opportunities and key science goals include: (i) Precision measurements of NS and BH physical properties, which require large numbers of very high-SNR BNS (hundreds) and BBH (thousands) detections, (ii) Settling the questions of whether primordial BH and BH formed from Population III stellar populations exist, which requires significant number (tens) of BBH detections at very high redshifts with quality distance measurements, and (iii) Settling the question of whether intermediate-mass (100 - 10,000 solar masses) BH exist, which requires the detection of a significant number (hundreds) of BBH with quality mass measurements.

For *all* of these goals combined, we find:

- **A.** We need *both* CE detectors (**CE40**, **CE20**). The third detector can be *any* of the *existing **LIGO** detectors or* **LIGO-India** (at either **$A^{\sharp}$** or **A+** sensitivity), although neither is critical.
- **B.** We *must* have **CE40**, as this SO cannot be achieved with CE20 alone, but we do not need to have both CE detectors. The third detector can be *any* of the *existing **LIGO** detectors or* **LIGO-India** (at either **$A^{\sharp}$** or **A+** sensitivity), although neither is critical.

Science Objective: Dynamics of Dense Matter and Multimessenger Astrophysics

A major science deliverable for any ngGW network we would consider, is to conclusively uncover the behavior of matter at densities higher than that of nuclei (i.e., the NS EOS). Two reliable measurements that can provide such constraints are high-accuracy measurements of the tidal deformability parameters and radii for a significant number of BNS detections. These measurements could be complemented by the “aspirational” science goal of measuring the post-merger GW signal for at least a handful of NS merger events. Using these three metrics for this science objective, we find:

- **A.** We need to have *both* CE detectors (**CE40, CE20**) for this science and especially for the detection of the post-merger signal. Having **LIGO-India** as the third detector brings some benefits, while in the absence of **LIGO-India,** having **LIGO** as a third detector provides only marginal, if any, benefits.
- **B.** We can achieve most goals with **CE20,** although **CE40** provides more reliability. Having **LIGO-India** as the third detector brings some benefits, while in the absence of **LIGO-India,** having **LIGO** as a third detector provides only marginal, if any, benefits.

To pursue multi-messenger science, sky localization capabilities are paramount. There is a range of different science goals that are unreachable now but will be targeted in the ngGW era. The overarching science goal is to have multi-messenger characterization of NS mergers as far back as the earliest times as possible. At a minimum, for breakthrough science, we would need a major sample of GW sources detected with high-quality localization (<~ 10sq.deg) out to the peak of star formation (redshift of about 2). For higher redshifts, things become more difficult, but we could use time and sky-location coincidence with GRB with less stringent localization accuracy. For the nearby Universe (redshift below

0.1), we can also hope for multi-wavelength EM detections coupled to GW detections, and ngGW networks should deliver a healthy sample of those too. When using these metrics we find:

- **A.** We need to have *both* CE detectors (**CE40, CE20**) *and* **LIGO-India** is critically needed as the third detector, preferably with **A$^\sharp$** sensitivity (although **LIGO-India A+** would be desirable compared to having no third detector or a third detector in the same continent as the CE detectors).
- **B.** We can achieve most goals with **CE20,** although **CE40** provides much higher reliability. Having **LIGO-India** as the third detector will add a major advantage. On the other hand, in the absence of **LIGO-India**, having **LIGO** as a third detector provides only marginal, if any, benefits.

Science Objective: Cosmology Probes and the Dark Sector

Although we would not consider measuring the Hubble constant as the primary science goal driving the ngGW investment, it would be a very important cosmology science goal for providing an independent constraint complementing the EM measurement methods. For the GW detections to be competitive, Hubble-constant constraints should reach ~1%. Such constraints can be obtained through either the bright- or dark-siren methodology, and we would need large samples of them to reach this level of Hubble-constant accuracy. When considering these cosmology metrics, we find:

- **A.** We need to have *both* CE detectors (**CE40, CE20**) *and* **LIGO-India** is important as the third detector, preferably with **A$^\sharp$** sensitivity. In the absence of **LIGO-India**, having a **LIGO** detector as the third detector in the network would help with pursuing some of these science goals.
- **B.** We can achieve all of these science goals with **CE20.** Having **LIGO-India** as the third detector will be a great advantage, but in its absence, having a **LIGO** detector as the third component could be advantageous too.

Beyond Hubble-constant constraints, GW observations open up new opportunities for probing the nature of dark matter or dark energy through different types of measurements, some connected to only hypothesized, yet potentially exciting, sources and physical processes. When considering relevant metrics, network requirements throughout demand:

- **A.** Both **CE40** and **CE20** are needed for most science goals, and in fact, for a couple, even *two* **CE40** detectors would be needed. The third detector can be *any* of the *existing* ***LIGO*** *detectors or* **LIGO-India** (at either **A$^\sharp$** or **A+** sensitivity), although it does not appear that either is critical.
- **B.** We can pursue some of these science goals with **CE20,** but **CE40** would allow us to achieve all of them. The third detector can be *any* of the *existing* ***LIGO*** *detectors or* **LIGO-India** (at either **A$^\sharp$** or **A+** sensitivity), although neither is critical.

Science Objective: Fundamental Physics and Novel Sources
With ngGW facilities, there are significant opportunities to perform precision tests of GR. The results are likely to be incremental in nature, with more advanced detectors yielding more precise tests. Furthermore, the space-based mission LISA is expected to yield more stringent tests of GR in many respects (notably in bounding the graviton mass). However, we note that the detection of gravitationally lensed BNS events is an exciting prospect, which can lead to tests of the polarization modes of GW. At the same time, there is no compelling reason to anticipate a measurement of a violation of GR. Accordingly, we assess that this science objective is *not a primary driver for our network recommendations*. When assessing the science metrics available to us, we find that achieving this science requires having **CE40** (and **CE20** in the absence of ET); also, having either **LIGO-India** or **LIGO** would bring advantages for different goals in this science objective.

VII. Broader Impacts & Opportunities

An NSF-supported ngGW facility should plan to have continued broader impacts and provide a wide range of opportunities to the scientific community, building on LIGO's strong record. In what follows, we highlight several key ways NSF could fulfill its broad mission to fund big facilities, like CE, with tangible benefits to society.

Community investments. Aiming for the successful operation of a CE facility at design sensitivity will require prompt action, starting with investments in LIGO detector advancements and CE-related R&D. Expert groups across the U.S. science and engineering community will need support to overcome the technical challenges and develop detailed plans of all aspects of the project to mitigate risks and ensure timely progress. Critical technology development will be needed in instrumentation (e.g.,
new mirror coatings, improved seismic isolation systems, more powerful laser systems, and improvements in vacuum tube systems) and in data analysis and computing (e.g., advances in machine learning will be needed to more efficiently analyze the huge volumes of data that are expected to result). All these advances are transferable to non-GW communities.[xxx] This investment will greatly benefit the continued development of STEM talent strengthening the U.S. workforce and fueling economic development. Regarding selection, assessment, and management of such a major research facility, we echo the recommendations of the MPSAC Subcommittee on Facilities and Major Research Infrastructure.[xxxi]

Environmental impacts. We are pleased that the CE team plans to seriously consider the facility's environmental impacts:
"Throughout the construction of Cosmic Explorer, very careful attention will be given to preserving the local environment—both its living ecosystems and its
non-living components. Possible alterations to the ecosystem might include interference with migratory or mating patterns, the extinction of local flora and fauna, or the introduction of damaging invasive species. Such problems can be caused by chemical or thermal pollution, negligent construction, or waste disposal practices. Therefore, a thorough

environmental impact study will be necessary to identify, constrain, and remediate such effects. This will be done with the active participation of the local community as well as state and federal governing agencies.

While respect for the environment is essential throughout the lifetime of the facility, it is especially important during the initial construction phase and facility decommissioning. During the operations phase, the potential for harm is smaller but still requires careful monitoring."

It will also be important to carefully measure the properties of various candidate sites prior to site selection. Issues that will need to be considered are: seismic noise, including the overall amplitude for noise above 5Hz, as well as the individual low-frequency noise bulk and surface wave components. Ambient infrasound measurements will also need to be conducted, wind measurements, traffic and other human-generated noise sources, and weather/disaster assessments.

Workforce development. There is tremendous opportunity for investment in the scientific workforce in the U.S. It is vital to be able to recruit, train, and retain a scientific workforce. A strong STEM workforce will not only advance GW science for years to come, but is also a necessary component to being globally competitive. Workforce needs will extend beyond the immediate scientific workforce, including technical support and administrative and financial support.
We recommend support of observatory-based outreach programs following LIGO's exemplary impacts in the Louisiana and Washington areas. Any new facility is likely to be sited in a rural area, which means that the local population will likely be under-resourced and also may be indigenous or have a high percentage of indigenous residents. STEM education lags in most rural and tribal areas, and input from Observatory personnel can be extremely important to ensuring the development of a local workforce. It is also important to have the support of the local community to avoid misunderstandings concerning acceptable land use policies and to avoid building in areas with cultural significance. Strong partnerships with the local community and indigenous groups will be essential for the success of the construction phase of the project.

Going beyond public outreach, we also recommend that REU and Bridge programs led by scientists staffing the new Observatory are supported, to continue to inspire undergraduates from a wide range of backgrounds to major in STEM fields.

U.S. leadership. The European GW science community, with support from their funding agencies, is further ahead in their planning for their ngGW facility (ET). As LIGO is approaching its currently-targeted design sensitivity (A+), it is imperative that the U.S., the current leader in this nascent field of GW astrophysics with breakthrough discoveries, seriously plan for our ngGW facility in a carefully-considered multi-step, multi-faceted way. The U.S. should invest in the current LIGO facilities and advance them to their maximum potential in a way that mitigates risks and leads us to the ngGW era through the most secure path possible.

Multi-agency, Private-Philanthropic-Government partnerships. Although most of the funding for any new GW observatory is expected to come from the NSF and international partners, many large, U.S.-based private foundations have contributed significant funds to ground-based astronomical observatories. Examples include the Keck Foundation (Keck Telescopes), the Charles and Lisa Simonyi Fund (Rubin Observatory), Gordon and Betty Moore Foundation (Thirty Meter Telescope), the Carnegie Institution for Science, and the Cynthia and George Mitchell Foundation (Giant Magellan Telescope). Moreover, both ngGW science and technology align with DOE-HEP interests and expertise.[xxxii] [xxxiii] We strongly encourage the NSF to pursue such partnerships when planning for ngGW facilities.

International partnerships. As has been demonstrated already, GW astrophysics is a global science, relying greatly on international partnerships for its success. Even if operating detectors are based in one country, data analysis, computing, and science breakthroughs require close international collaboration. We recommend that efforts for international coordination start early in the process with other projects relevant to the ngGW era (e.g., ET, LIGO-India) and also with other international organizations facilitating such partnerships. The Gravitational Wave International Committee (GWIC[xxxiv]) is one such organization. Since its formation in 1997, GWIC has facilitated international collaboration and cooperation in the construction, operation, and use of the major GW detection facilities worldwide. It is associated with the International Union of Pure and Applied Physics (IUPAP) as its Working Group WG.11. Through this association, GWIC is connected with the International Society on General Relativity and Gravitation (IUPAP's Affiliated Commission AC.2), its Commission C19 (Astrophysics), and another Working Group, the AstroParticle Physics International Committee (APPIC). In April 2021, GWIC released studies relevant to ngGW detectors, including a special volume on science, related scientific efforts in MMA, computing needs, R&D, governance structures, and a roadmap, all elements that are important to plan for when such a major global effort is undertaken.

VIII. Recommendations

Based on the materials available, we conclude that the only U.S. detector concept that can reach the target sensitivity of ~10x better than that of the LIGO A+ design is that of Cosmic Explorer, consisting of two possible detectors (CE40 and CE20). Considering a timeline of ~10 years focuses our attention on the first stage of Cosmic Explorer, which does not require cryogenics technology.

We considered multiple important factors when arriving at our recommendations for ngGW networks under different external constraints. First and most critically, we considered the potential for impact on key scientific problems, the possibility of providing definitive answers to major questions, and the potential for scientific discoveries, especially those not yet predicted. When assessing science impact, we considered worldwide networks that include non-U.S. detectors expected to be operational during the ngGW era (~2030 and beyond), specifically ET and LIGO-India. Since their construction and operation at their targeted sensitivities are not under NSF's control, we considered them as uncertain external constraints, and we make recommendations for ngGW networks under different options for these external constraints. Additionally, we considered technical risk and readiness, the existence of a realistic path toward reaching the targeted sensitivity within a reasonable timeline, the overall associated cost, and the projected MREFC funding levels (to the best of our current knowledge).

Based on all considerations per the Subcommittee's charge, we provide the following recommended list of worldwide ngGW network configurations that deliver a sensitivity an order of magnitude better than the LIGO A+ design sensitivity, accounting for possible external constraints:

- **CE40**, **ET**, **LIGO-India** (Network #1)
- **CE40**, **ET** (Network #2)
- **CE40**, **CE20**, **LIGO-India** (Network #3)
- **CE40**, **CE20** (Network #4)

We note that the availability of the LIGO-India detector in the network is important for MMA and, in fact, critically important in the absence of ET. For all the recommended configurations, maintaining the operation of one of the LIGO detectors does not improve MMA science and does not affect the other science cases. This, combined with cost considerations, leads us to recommend that the LIGO facilities be phased out by the time the CE wide-band sensitivity (of one or two detectors depending on the network choice) is better than that of the aLIGO detectors.

In Table 7.1 we summarize our recommendations for ngGW networks under different external constraints posed by non-U.S. detectors.

	CE40	CE20	ET	LIGO-India	LIGO
Network #1	✓	X	✓	✓	X
Network #2	✓	X	✓	X	X
Network #3	✓	✓	X	✓	X
Network #4	✓	✓	X	X	X

Table 7.1: Recommendations for ngGW networks under four different external constraints regarding the construction and operation of non-U.S. detectors, ET, and LIGO-India. All detectors are assumed to reach their targeted best sensitivity during operations ($A^\sharp$ for LIGO-India and LIGO), but the recommendations remain unchanged if sensitivities remain closer to A+ levels.

To reach CE sensitivities, it is imperative to invest in ngGW R&D through intermediate sensitivity steps developed in the LIGO detectors to mitigate risks is imperative. We reaffirm the post-O5 report[i] and recommend that advancements target A♯ technology and operations until the ngGW era. In summary, continuous operation of the LIGO detectors until CE science runs begin is important for maximizing the probability of detecting rare but important events, for maintaining and advancing talent in early-career researchers, for developing the needed technology, and for achieving the intermediate sensitivity on the path to the CE design sensitivity.

We further recommend that the selection of institutions for the management, development, and operation of CE facilities be decided following the recommendations of the MPSAC Subcommittee on Facilities.[xxxi] We recommend that strong partnerships with local communities and indigenous groups at the observatory site(s) are developed early, that attention is given to preserving the local environment, both its living ecosystems and its non-living components, and that CE education and public outreach programs are supported. We encourage the NSF to seek funding partnerships with non-profit foundations, relevant industry, and international partners and to pursue close integration with international ngGW funding agencies, observatories, and with the GWIC to advance effective and optimal coordination of the global effort.

IX. Conclusion

Though a roughly year-long process, our ngGW Subcommittee has included a wide variety of inputs from across the entire GW community (U.S. and worldwide), has worked on careful analysis of different factors, and responded to the charge presented to us by the NSF MPSAC. Considering all factors identified in the charge and possible external constraints, we recommended ngGW network configurations that can operate at a sensitivity approximately an order of magnitude greater than that of LIGO A+ in the next decade. The science potential of the ngGW detectors is tremendous and will transform the nascent field of GW astrophysics to a well-established field of physics and astronomy, delivering new multi-messenger sources and breakthrough discoveries in compact-object astrophysics, cosmology, fundamental physics, and potentially uncovering phenomena we have not even considered yet.

Appendices

A1. Detector Sensitivities

The sensitivity curves in Figure 4.1 are taken from the following sources:

O4: L1 sensitivity as of start of December 2023
A+: https://post-o5.docs.ligo.org/-/sensitivity-curves/-/jobs/2363204/artifacts/strain/Aplus.txt and as in LIGO-T2200384–v2
A+: https://post-o5.docs.ligo.org/-/sensitivity-curves/-/jobs/2363204/artifacts/strain/Aplus.txt and as in LIGO-T2200384–v2
POSTO5: https://git.ligo.org/post-o5/sensitivity-curves/-/jobs/2363204/artifacts/browse/strain
$A^\sharp$: https://dcc.ligo.org/public/0186/T2300041/001/Asharp_strain.txt
Voyager: https://post-o5.docs.ligo.org/-/sensitivity-curves/-/jobs/2363204/artifacts/strain/Voyager_intermediate.txt
CE: https://dcc.cosmicexplorer.org/CE-T2000017/public

Many fundamental noise sources scale differently with the length of a detector. The following table shows the most important of these (from CEHS):

Noise	Scaling	Remarks
Coating Brownian	$1/L^{3/2}$	Fixed cavity geometry
Substrate Thermo-Refractive	$1/L^2$	Fixed cavity geometry
Suspension Thermal	$1/L, 1$	Horizontal, vertical noise
Seismic	$1/L, 1$	Horizontal, vertical noise
Newtonian	$1/L$	
Residual Gas Scattering	$1/L^{3/4}$	Fixed cavity geometry
Residual Gas Damping	$1/L$	
*Quantum Shot Noise	$1/L^{1/2}$	Fixed bandwidth
*Quantum Radiation pressure	$1/L^{3/2}$	Fixed bandwidth

Table 7.1: Scalings of fundamental noises with arm length L, referred to astrophysical strain.[387] The test mass radii of curvature are varied to hold the arm cavity geometry fixed. In the case of the quantum shot and radiation-pressure noises (*), the given scalings are for a fixed detector bandwidth, but these noises could instead be optimized in a number of different ways — hence the "compact-binary optimized" and "postmerger optimized" curves in Fig. 7.1.

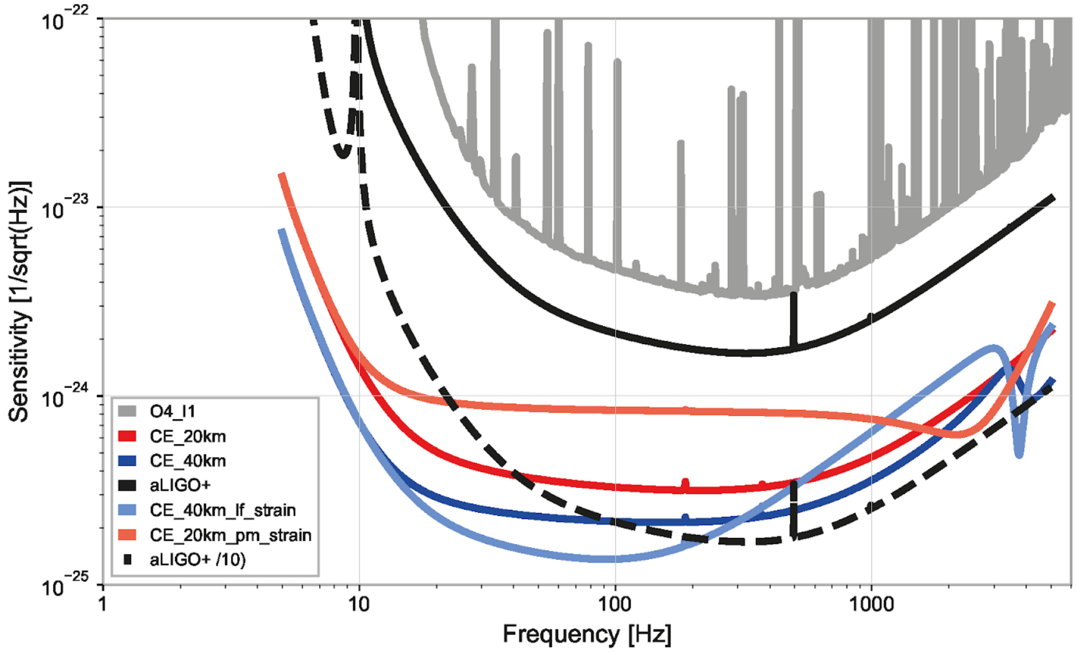

Figure A1.1: Amplitude Spectral Densities of the gravitational-wave-strain equivalent noise for various CE options (data from CE-T2000017) in comparison to O4, A+ and A+/10 sensitivities.

Note that the sensitivity of CE40 can be tuned to a ca. 2x better sensitivity around 100Hz at the cost of high-frequency performance, while the sensitivity around the merger frequency of BNSs

can be improved for CE20 at the cost of other frequencies by detuning and changing the reflectivity of the signal extraction mirror. Shown only for comparison are the sensitivity curves of L1 @ O4 and aLIGO+.

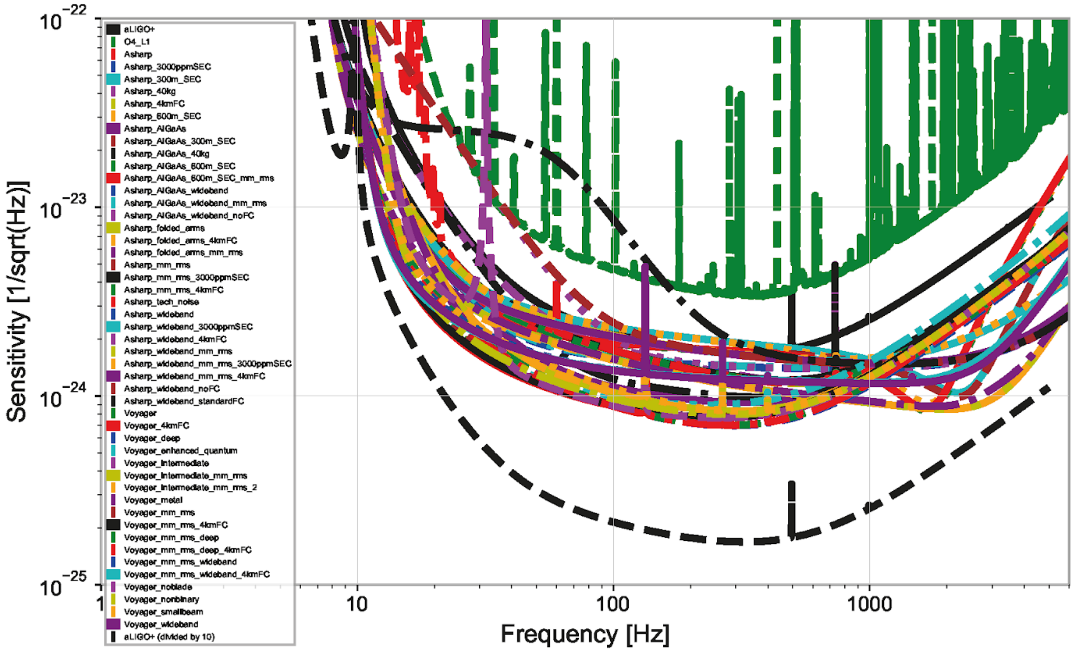

Figure A1.2: Amplitude Spectral Densities of the gravitational-wave-strain equivalent noise for various "advanced" observatory designs, showing the flexibility of possible designs.

A2. ngGW Science Metrics

In what follows we append the tables with science metrics for every science goal identified by the CE team for ngGW network configurations considered in the CE white paper and in Gupta et al. (2023). The quantitative data were provided by the CE team to the Subcommittee when requested, following the submission of white papers.

The networks considered in the study: Below "L#" corresponds to LLO, "H#" to LHO, "A#" to LAO, which are all assumed to be in A# sensitivity.

No. XG	Name	Detectors
0	H#L#A#	LLO, LHO, LAO
1	20L#A#	CE-A 20km, LLO, LAO
1	40L#A#	CE-C 40km, LLO, LAO
2	20L#ET	CE-C 20km, LLO, ET
2	40L#ET	CE-C 40km, LLO, ET

2	4020A#	CE-C 40km, CE-A 20km, LAO
3	4020ET	CE-C 40km, CE-A 20km, ET

New networks to be considered are as below. "+" to A+ sensitivity, "#" to A# sensitivity.
In this Table CE-C coordinates are: (42.790437, -87.062837) with x-arm 250.824degs CCW relative to local east

No. XG	Name	Detectors
1	20L+H+	CE-C 20km, LLO, LHO
1	20L+A+	CE-A 20km, LLO, LAO
1	40L+H+	CE-C 40km, LLO, LHO
1	20L#H#	CE-C 20km, LLO, LHO
1	40L#H#	CE-C 40km, LLO, LHO
2	4020L+	CE-C 40km, CE-A 20km, LLO
2	4020L#	CE-C 40km, CE-A 20km, LLO
2	4040L#	CE-C 40km, CE-A 40km, LLO

Black holes and Neutron Stars throughout the Universe

Network	Precision inference of BNS mergers: NBNS/Hereyr, SNR>100	Pinning down primordial black holes: NBBH/yr, z>25, dz/z<0.2	BNS mass function to Cosmic noon: NBNS/yr, z>1, dz/z<0.2, dm1/m1<0.3	Illuminating Pop-III remnants: NBBH/yr, z>10, dz/z<0.1	Masses of IMBH: NIMBBH/yr, z>3, dm1/m1<0.2	Precision inference of BBH mergers: NBBH/yr, SNR>100
H#L#A#	0	0	0	0	6	17
20L#A#	39	0	0	0	150	1300
40L#A#	220	0	0	9	190	5000
20L#ET	120	8	0	38	840	3700
40L#ET	350	17	7	110	870	7500

4020A#	350	3	22	74	510	6900
4020ET	480	28	81	360	890	9500
New networks requested by the MPSAC ngGW Subcommittee						
20L+H+	28	0	0	0	48	1200
20L+A+	37	0	0	0	100	1200
40L+H+	230	0	0	0	88	4800
20L#H#	31	0	0	0	130	1300
40L#H#	230	0	0	1	180	4900
4020L+	340	3	0	32	500	6800
4020L#	350	3	0	39	530	6800
4040L#	640	9	5	98	580	10500

Multi-messenger Astrophysics and Dynamics of Dense Matter

Network	NS radius, NBNS/yr, dR<100 m	Tidal deformability: NBNS/yr, d\tilde\Lambda<50	Post-merger detections per 5 years	Mapping GRBs to progenitors: NBNS/yr, z>2, d\Omega<100 deg^2	Localization at SFR peak: NBNS/yr, 0.1<z<2, d\Omega<10 deg^2	Multiband EM counterparts: NBNS/yr, z<0.1, dOmega<1 deg^2
H#L#A#	0	0	0.15	0	260	1
20L#A#	20	330	1.8	19	780	6
40L#A#	72	1300	1	37	890	6
20L#ET	280	1500	3	6200	6000	26
40L#ET	450	2600	2.3	25000	9200	47
4020A#	320	1900	3.4	3700	3900	32
4020ET	740	3100	5	66000	27000	71

New networks requested by the MPSAC ngGW Subcommittee						
20L+H+	4	320	1.5	0	0	0
20L+A+	0	320	1.5	0	85	0
40L+H+	36	1300	1.0	0	1	0
20L#H#	20	320	1.7	0	7	0
40L#H#	64	1300	1.2	0	8	0
4020L+	140	1800	3.3	0	95	0
4020L#	180	1800	3.4	0	210	1
4040L#	270	2900	2.8	2	430	4

Fundamental Physics and Cosmology Relative rate of strong lensing detections per year are followed by number of lensed detections per year in parentheses, the latter are used in the polar plots.

Network	Bright siren cosmology: NBNS/yr, dDL<0.1, d\Omega<10 deg^2	Hubble Constant inference: dH0/H0 in units 0.01/x	Dark siren cosmology: NBBH/yr, dDL<0.1, d\Omega< 1 deg^2	Precision Tests of GR: RSS post-inspiral SNR	Number of lensed detections per year	Constraining graviton mass, NBNS/yr, z>5
H#L#A#	14	x=1	69	1900	1	0
20L#A#	63	2	290	5300	11	0
40L#A#	71	2.4	350	8100	65	84
20L#ET	1100	5.2	2200	7800	47	0
40L#ET	1600	5.8	3300	9900	91	340
4020A#	790	4.9	1300	9500	87	580
4020ET	4800	7.5	6800	11000	110	880
New networks requested by the MPSAC ngGW Subcommittee						
20L+H+	0	-	1	5200	62	0

20L+A+	4	1.5	43	5300	61	0
40L+H+	0	-	2	8200	160	160
20L#H#	5	3.2	13	5400	64	0
40L#H#	7	3.6	19	8300	170	180
4020L+	18	3.2	120	9700	210	640
4020L#	60	3.4	180	9700	210	640
4040L#	95	3.8	350	12000	290	2600

Dark Energy, Dark Matter and Novel Sources

Network	Dark energy parameter dw0 in units of 2/x	Detection of DM assisted NS implosions, NBBH/yr	Number of detectable pulsars in 1 yr	High-z formation channels: NBBH/yr, z>10, dz/z<0.2, dm1/m1<0.2	Sensitivity to Omega_GW in units of 2e-10/x, in 1 yr, SNR=3	Distance to detectable axion clouds in 1 yr0 (Mpc)
H#L#A#	x=1	0	1	0	x=1	0.3
20L#A#	16	1200	3	6	3.7	0.9
40L#A#	30	4600	5	35	6.5	1.5
20L#ET	44	4200	5	65	76	1.1
40L#ET	66	8000	11	140	97	1.8
4020A#	66	6300	9	110	35	1.8
4020ET	100	9700	21	230	110	2.1
New networks requested by the MPSAC ngGW Subcommittee						
20L+H+	9.2		3	3	3.3	0.9
20L+A+	8.7		3	0	1.8	0.9
40L+H+	19		5	24	5.7	1.4
20L#H#	13		3	5	6.8	1.0

40L#H#	28		5	30	11	1.6
4020L+	38		9	79	210	1.6
4020L#	45		9	85	210	1.8
4040L#	60		20	129	400	1.5

References

[i] Fritschel, P. et al. 2022, `Report from the LSC Post-O5 Study Group', https://dcc.ligo.org/public/0183/T2200287/002/T2200287v2_PO5report.pdf

[ii] Kalogera et al. 2021, `The Next Generation Global Gravitational-Wave Observatory: The Science Book', https://gwic.ligo.org/3Gsubcomm/docs/GWIC_3G_Science_Book.pdf

[iii] LIGO/Virgo/KAGRA Public Alerts, https://gracedb.ligo.org/superevents/public/O4/

[iv] LIGO Scientific Collaboration, https://www.ligo.org/about.php

[v] MPS AC Subcommittee on MPS Facilities and Major Research Infrastructure, Report 1, 2002, https://www.nsf.gov/mps/advisory/mpsac_subcommittee_reports/MPS_Facilities_and_Major_Research_Infrastructure_Report_1.pdf

[vi] NSF Mission and Vision, https://www.nsf.gov/pubs/2014/nsf14002/pdf/02_mission_vision.pdf

[vii] LIGO's Impact on Science and Technology, https://www.ligo.caltech.edu/page/science-impact

[viii] ESFRI 2021 Roadmap Update, https://www.esfri.eu/latest-esfri-news/new-ris-roadmap-2021

[ix] MPS AC Subcommittee on Next-Generation Gravitational-Wave Observatory, https://www.nsf.gov/mps/phy/nggw.jsp

[x] MPS AC ngGW Subcommittee Call for White Papers, https://www.nsf.gov/mps/phy/nggw/WhitePaperCall2.pdf.

[xi] Link to web page containing white papers (**link forthcoming**)

[xii] Link to website containing presentations (**link forthcoming**)

[xiii] Reitze, D., et al. 2019, `Cosmic Explorer: The U.S. Contribution to Gravitational-Wave Astronomy beyond LIGO', https://arxiv.org/abs/1907.04833

[xiv] Srivastava, V., et al. 2019, PRD, 100, 043026, `Detection Prospects of Core-Collapse Supernovae with Supernova-Optimized Third-Generation Gravitational-Wave Detectors, https://journals.aps.org/prd/abstract/10.1103/PhysRevD.100.043026

[xv] Ballmer, S., et al. 2021, `Snowmass2021 Cosmic Frontier White Paper: Future Gravitational-Wave Detector Facilities, https://arxiv.org/abs/2203.08228

[xvi] Scholberg, K. 2012, `Supernova Neutrino Detection', Annual Review of Nuclear and Particle Science, Vol. 62:81-103, https://www.annualreviews.org/doi/10.1146/annurev-nucl-102711-095006

[xvii] Nakamura, K., et al. 2016, `Multi-Messenger Signals of Long-term Core-Collapse Supernova Simulations: Synergetic Observation Strategies', MNRAS, Volume 461, Issue 3, 3296, https://academic.oup.com/mnras/article/461/3/3296/2608524

[xviii] Evans, M., et al. 2021, `A Horizon Study for Cosmic Explorer: Science, Observatories, and Community', https://arxiv.org/abs/2109.09882

[xix] LIGO, Virgo, and KAGRA Observing Run Plans, https://observing.docs.ligo.org/plan/

[xx] Gravitational-Wave Transient Catalog by the LIGO/Virgo/KAGRA Collaboration, https://gwosc.org/eventapi/html/GWTC/

[xxi] LSC Instrument Science White Paper, 2022-2023, https://dcc.ligo.org/public/0185/T2200384/002/Instrument_Science_White_Paper_2022.pdf

[xxii] Srivastava, V., et al. 2022, `Science-driven Tunable Design of Cosmic Explorer Detectors', ApJ, 931, 22, https://iopscience.iop.org/article/10.3847/1538-4357/ac5f04

[xxiii] Cosmic Explorer White Paper (**link forthcoming**)

[xxiv] McGhee, G.I., et al. 2023, ` Titania Mixed with Silica: A Low Thermal-Noise Coating Material for Gravitational-Wave Detectors', PRL, 131, 171401, https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.131.171401

[xxv] Vajente, G., et al. 2021, 'Low Mechanical Loss TiO_2: GeO_2 Coatings for Reduced Thermal Noise in Gravitational-Wave Interferometers', PRL, 127, 07110, https://doi.org/10.1103/PhysRevLett.127.071101

[xxvi] Cole, G.D. et al. 2023, `Substrate-Transferred GaAs/AlGaAs Crystalline Coatings for Gravitational-Wave Detectors', Appl. Phys. Lett. 122, 110502
[xxvii] Link to LIGO presentation to the Subcommittee (**link forthcoming**)
[xxviii] Branchesi, M., et al. 2023, `Science with the Einstein Telescope: A Comparison of Different Designs', JCAP, 07, 068, 191, https://iopscience.iop.org/article/10.1088/1475-7516/2023/07/068
[xxix] Gupta, I., et al. 2024, ` Characterizing Gravitational-Wave Detector Networks: From A♯ to Cosmic Explorer', https://arxiv.org/abs/2307.10421
[xxx] LIGO Technology, https://www.ligo.caltech.edu/page/ligo-technology
[xxxi] MPS AC Subcommittee on MPS Facilities and Major Research Infrastructure, Report 2, 2003, https://www.nsf.gov/mps/advisory/mpsac_subcommittee_reports/2nd_facilities_report_2023-12-01.pdf
[xxxii] Asai, S., et al. 2023, ` Exploring the Quantum Universe: Pathways to Innovation and Discovery in Particle Physics', Report of the 2023 Particle Physics Project Prioritization Panel, https://www.usparticlephysics.org/2023-p5-report/
[xxxiii] Butler, J.N., et al. 2023, `Report of the 2021 U.S. Community Study on the Future of Particle Physics (Snowmass 2021) Summary Chapter', https://arxiv.org/abs/2301.06581
[xxxiv] Gravitational-Wave International Committee, gwic.ligo.org