A Submission to the NSF MPSAC ngGW Subcommittee

Contents

1. Executive Summary

Cosmic Explorer (CE) is poised to propel another revolution in our understanding of the universe. Foundations have been laid by decades of National Science Foundation (NSF) investment and the work of a large community of scientists. Cosmic Explorer builds on the on-budget, on-time, breakthrough success of Advanced LIGO and the established and growing know-how of the gravitational-wave community.

Science Motivation – Gravitational-wave observations are revolutionizing humanity's understanding of the universe. The first direct detection of a binary black hole merger and the observation of a spectacular neutron-star merger were watershed moments in science, revealing the cosmos in a way no other probe can. Since in 2015, the NSF's LIGO and its partner observatory, the European Virgo, have detected over 90 merger events – revealing a bright gravitational-wave sky.

The NSF-funded Cosmic Explorer Horizon Study [1] describes a Next Generation (XG) ground-based gravitational-wave observatory: Cosmic Explorer. With more than ten times the sensitivity of Advanced LIGO, it will extend the reach of gravitational-wave observations towards the edge of the observable universe. Cosmic Explorer will ensure continued United States (US) leadership in gravitational-wave science, and in the international effort to build a Next Generation observatory network that will make transformative discoveries across physics, astronomy and cosmology. Cosmic Explorer will give scientists access to gravitational-wave signals from throughout the universe, reaching into regions that even the most powerful telescopes cannot explore and making discoveries that cannot yet be anticipated. Thanks to its extraordinary discovery potential, Cosmic Explorer will revolutionize the following areas:

Black Holes and Neutron Stars Throughout Cosmic Time. Cosmic Explorer's reach will encompass the entire observable population of binary systems of (stellar to light intermediate mass) black holes and neutron stars and provide a view of Cosmic Dawn complementary to that of the James Webb Space Telescope (JWST). It will teach us about the first stars through mergers of the black holes they left behind, chart the demographics and interactions of black holes and neutron stars across time and explore the physics underlying the birth, lives, and deaths of massive stars.

Multi-Messenger Astrophysics and Dynamics of Dense Matter. By observing many hundreds of neutron star mergers and measuring stellar radii to 100 m or better, Cosmic Explorer will probe the nature of high-density matter interacting via the strong force, thereby revealing the nuclear equation of state and its phase transitions in unprecedented detail. A plethora of multi-messenger observations will explain the production of the chemical elements that are the building blocks of our world, and explore the physics of the binary-merger engine powering gamma-ray bursts.

Novel GW Signals as New Probes of Extreme Astrophysics. Neutron stars and black holes, in isolation or in binary systems, can be sources of burst-like or continuous gravitational waves that have properties very different from the chirping signals already detected by LIGO and Virgo. Cosmic Explorer, especially in combination with observatories of other messengers, has the potential to use these yet undetected signals to reveal the physics behind a suite of extreme astrophysical phenomena that would otherwise remain unexplored.

Fundamental Physics and Precision Cosmology. Cosmic Explorer's expanded discovery potential will allow it to observe both loud and rare gravitational-wave events — probing the physics of the most extreme gravity in the universe and revealing unusual and novel objects. LIGO and Virgo are already detecting signals from merging systems that we do not fully understand. With its higher-fidelity detections, Cosmic Explorer will reveal the nature of these mysterious sources. It will illuminate the effects of dark matter in the cores of neutron stars, and its precision observations of black holes could help develop a viable theory of quantum gravity.

Dark Matter and the Early Universe. Cosmic Explorer will probe the nature of dark matter in ways – such as signatures in neutron star mergers or black hole superradiance – that are complementary to searches at high-energy colliders and underground direct-detection experiments. Cosmic Explorer will also provide a unique opportunity to observe the early universe via a cosmological stochastic gravitational-wave background.

Technical Description – Cosmic Explorer will achieve its unparalleled sensitivity using proven technology based on LIGO experience, while scaling up the detector's length from 4 to 40 km. The Cosmic Explorer design continues in the direction of the planned A$^\sharp$ upgrade to the LIGO detectors, guaranteeing increased technical readiness of Cosmic Explorer components. The reference concept presented in the Horizon Study is a 40 km observatory and a 20 km observatory, both located in the US, with a total estimated cost of $1.6B (2021 USD). Initial studies indicate that many locations that could accommodate facilities of this scale exist in the continental US. Site evaluation and identification will require broader and deeper studies that consider the environment and socio-economic impacts. Building partnerships with the local and Indigenous communities will be critical for ensuring that the presence of the observatory respects the cultural, environmental, socio-economic, political, and other aspects of its host communities. Assuming the project's design stage proceeds without unexpected delay and is continuously funded through the 2020s, Cosmic Explorer's first observing runs could take place in the mid-2030s — when the LIGO observatories are expected to be approaching their performance limit. This schedule will extend by decades the current trend of observations with increasing astrophysical reach.

Synergies With Partner and Multi-Messenger Observatories – The Horizon Study showed that although the reference concept can achieve Cosmic Explorer's science goals without other XG gravitational-wave detectors, its scientific output would be greatly enhanced by operating as part of an international network. Different configurations for Cosmic Explorer were examined in the Horizon Study, embedded in a global network that included the European Einstein Telescope, a potential detector in Australia, and the LIGO (A+) observatories. That work is extended here with the important outcome that Cosmic Explorer will be substantially more capable of addressing next-generation science objectives than planned upgrades to LIGO (A+, A$^\sharp$). As part of a multi-messenger network of international gravitational-wave observatories, astro-particle detectors, and telescopes across the electromagnetic spectrum, Cosmic Explorer will enable a synergistic, unique, view of astrophysical phenomena.

This White Paper responds to the call for submissions by the NSF Mathematical and Physical Sciences Advisory Committee (MPSAC) Subcommittee on Next-Generation Gravitational-Wave Observatory (ngGW). In §2, an overview of the key science objectives of Cosmic Explorer is presented. We expand on the revolutionary science that can be done with an order of magnitude greater sensitivity than A+, and with synergies between Cosmic Explorer, partner gravitational-wave observatories, and other multi-messenger observatories. In §3 the Cosmic Explorer concept is presented, highlighting its low-risk path to achieving these science objectives. §4 explores the impacts that Cosmic Explorer can have on science as a function of possible network configurations. In §5 an overview of the Cosmic Explorer project is given that includes the timeline, risks, costs, plans for identifying suitable sites, and opportunities presented by Cosmic Explorer to develop community partnerships and broaden participation. A summary and conclusion are given in §6.

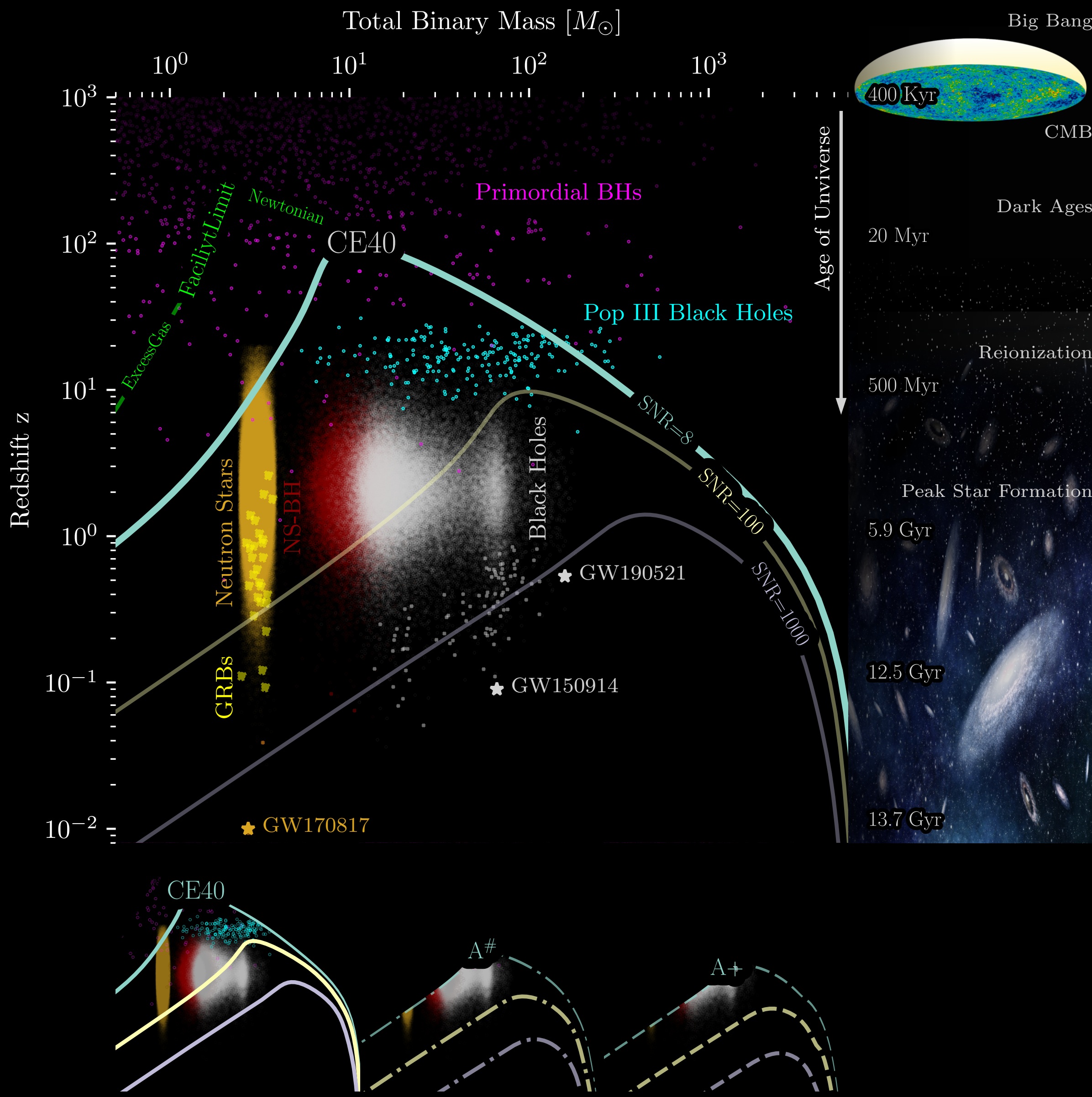

Figure 1: The reach of the Cosmic Explorer 40 km observatory for compact binary mergers as a function of total binary mass and redshift at various Signal-to-Noise Ratio (SNR) thresholds. Cosmic Explorer will push the cosmic horizon to the boundary of the population of binary neutron stars (gold), neutron star – black holes (red) and binary black hole mergers (white) (§2.1). The order of magnitude improvement in sensitivity enables observation of new populations of sources such as mergers from population III black holes (cyan) and potentially more speculative primordial black hole binaries (magenta). High-SNR signals will enable precision astrophysics (§§ 2.2 and 2.4). GW170817, GW150914, and GW190521 (stars) are highlighted along with the population of observed compact-object binaries (small dots) [2, 3]. The limit of the facility (see §3) is shown in green along with the ultimate limiting noise sources. A comparison to the reach of A$^\sharp$ and A+ is shown at the bottom.

2. Key Science Objectives

The Cosmic Explorer Observatory [1] Concept presented in the Horizon Study [1] will substantially expand the discovery horizon of current-generation ground-based gravitational-wave detectors (Advanced LIGO), even when compared to the planned upgrades of those detectors (A+ and A$^\sharp$; Figure 1). Specifically, Cosmic Explorer will open new discovery space across five major scientific areas—the Cosmic Explorer's key science objectives, highlighted in the "time-to-discovery" Figure 2. Cosmic Explorer science objectives are synergistic with the science goals of other observatories: The Decadal Survey on Astronomy and Astrophysics 2020 (Astro2020) report from the Panel on Particle Astrophysics and Gravitation has highlighted Cosmic Explorer as "*...central to achieving the science vision laid out in the survey's roadmap*" [4]. Likewise the Gravitational Wave International Committee's Science Book [5] states that "*A global next-generation gravitational wave observatory will propel the field of astrophysics and all foundational science research forward.*" There is tremendous opportunity for scientific discovery ahead, and world-wide momentum for ensuring that gravitational-wave astrophysics reaches its full potential over the next decade and beyond. Cosmic Explorer represents the investment required to capitalize on this opportunity, and to ensure that the US can retain, and strengthen, its leadership in this new field. In this Section, we describe Cosmic Explorer's key science objectives, emphasizing how the choice of observatory configuration (size and number) impacts each of them. In §4, we discuss in more details the impact of various Cosmic Explorer and international network configurations across the five science objectives.

2.1. Black Holes and Neutron Stars Throughout Cosmic Time

Gravitational-wave observations will continue to revolutionize our understanding of where and when compact objects such as neutron stars and black holes formed, providing unprecedented clues about the evolution and properties of their host galaxies. Several astrophysical formation scenarios have been proposed for compact binaries, each resulting in different distributions for the parameters (masses, spins, eccentricities) of the systems they form, as well as in different merger rate histories as a function of the redshift [6–20]. There already is some evidence that the variety of source properties observed so far is likely the result of multiple astrophysical formation channels [21–24]. While Advanced LIGO and Virgo have opened up this new frontier of observational astrophysics, they are also intrinsically limited in their sensitivity. In the A+ configuration, Advanced LIGO will be able to observe a 10–10 $M_\odot$ binary black hole (around the peak of the local mass function [25–27]) up to $z \sim 1$ (see Figure 1), at higher redshifts the SNR would be too low. The location of the peak of the mass function, and how it varies with redshift, contains crucial clues about binary evolution and the final stages of the life of massive stars [28–34].

With networks including two Cosmic Explorers, precise measurements of the merger rate, mass, and spin distribution of merging binaries across a large range of redshifts will make it possible to probe environmental impacts on compact binary yields, delay times between star formation and merger, and ultimately untangle the formation channels and their uncertain physics [35–43] (see Figure 2, top; Figure 4, upper left). For many thousands of loud sources every year, it will be possible to precisely measure the spins and masses of individual black holes in the binary [44], shedding light on poorly understood evolutionary processes such as mass transfer stability and efficiency in binary

[1] In the literature, the words "observatory", "detector" and "interferometer" are often used interchangeably. Herein an *observatory* is made up of a single *facility* and the gravitational-wave *detector* it hosts. The *detector* has many sub-systems, at the center of which is an optical *interferometer*. Applied to the Einstein Telescope (ET) — §4.1— triangular-xylophone concept, one facility hosts three detectors each of which is made up of two interferometers.

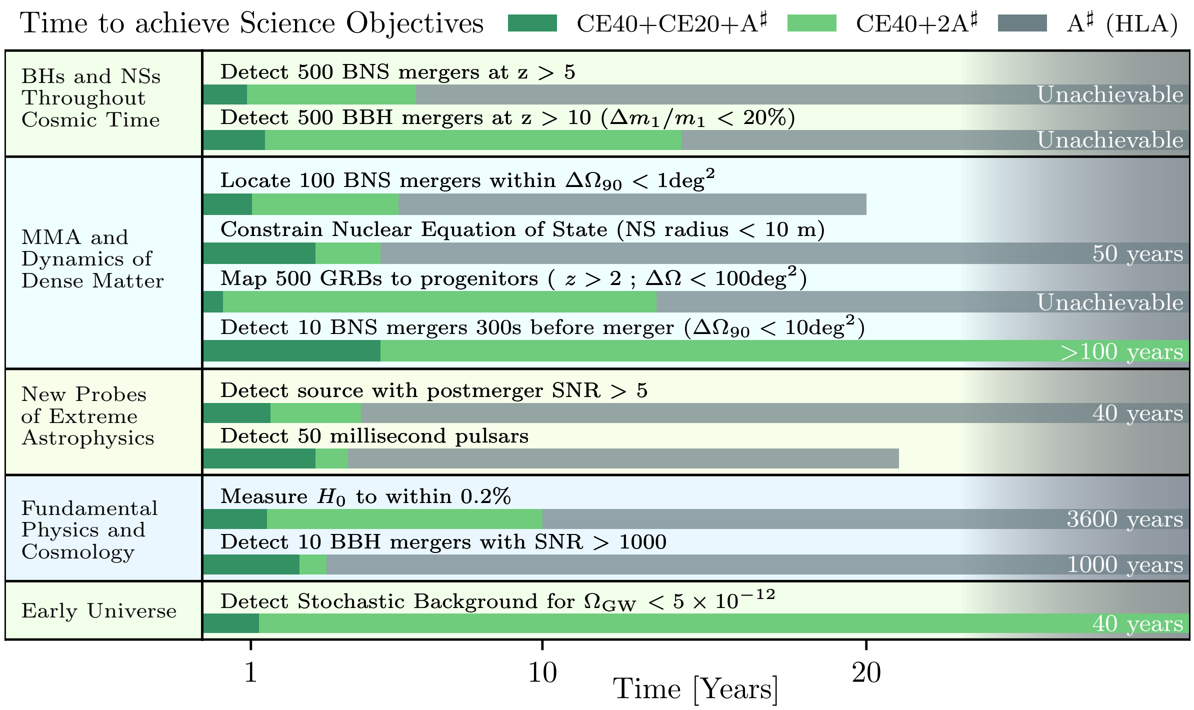

Figure 2: The time to make discoveries, grouped according to the key science questions they target (§2). A Cosmic Explorer 40 km observatory in a network either with a 20 km Cosmic Explorer and an A$^\sharp$ class observatory (dark green) or two A$^\sharp$ observatories (light green) are compared to a network of three A$^\sharp$ observatories (see also §4.2). The time to achieve the objective is given in cases which exceed the plot range. "Unachievable" indicates that the science goal is never achieved by the A$^\sharp$ detector network.

systems [45–49], mass ratio reversal [50–52], stellar winds and mass loss [53, 54], the sizes of the most massive stars, and more. Cosmic Explorer may be the only way in which these constraints can be placed at high redshifts [55]. Its sensitivity below 20 Hz will also enhance the measurability of orbital eccentricity [56], another strong indicator of binary formation pathways [57–59].

Constraining the black hole mass function above 50 $M_\odot$ would allow for a better understanding of the pair instability supernova mass gap (and of the nuclear physics processes that lead to it) [60, 61]; the rate of hierarchical mergers [62, 63]; and intermediate mass black holes (IMBH) [64]. A$^\sharp$ will observe a 100–100 $M_\odot$ IMBH merger at redshifts up to $z \sim 3$, and would therefore miss black hole mergers at higher redshifts (see Figure 1). This precludes probing the formation and merger of black holes created by Pop III stars, and other possible high-redshift channels, e.g., primordial black holes created during the inflationary epoch of the universe [19, 65, 66]. Little is known about Pop III stars (see [67] for a review), and while JWST might provide some information in the next few years [68], it will not directly resolve individual Pop III stars. Both primordial black holes and the remnants of Pop III stars might be the light seeds that formed supermassive black holes [64, 69–72], and thus Cosmic Explorer will shed light on one of the most pressing open questions in galaxy and structure formation. Because a network is required to accurately measure the mass of a distant source (see §4), two (and ideally three) XG observatories are needed in order to map the mass distribution of binary black holes at redshifts above 4 [35, 40, 42, 73].

Similar considerations can be made for neutron stars. Cosmic Explorer will provide access to neutron star binaries out to a high redshift (see Figure 1), and give us a clear picture of how their properties vary across cosmic history and galactic environments. By establishing the rate and distribution of neutron star mergers out to cosmological distances, Cosmic Explorer will also measure the time delay distribution between formation and merger [37], and map the history of chemical evolution in the universe beyond the reach of multi-messenger astronomy (see §2.2). However, it's only with two or more XG observatories that one will be able to precisely measure masses, distances and sky positions of thousands of binary neutron star sources per year (see Figure 4, upper left).

2.2. Multi-Messenger Astrophysics and Dynamics of Dense Matter

Neutron stars are among the most exotic objects in the stellar graveyard [74–78]. When paired with other neutron stars or black holes to form binaries, they emit chirping gravitational-wave signals followed by mergers that power some of the most energetic explosions in the universe [79–81]. The first binary neutron star merger detected in gravitational waves, GW170817, was observed in all the bands of the electromagnetic spectrum [79, 82]. It is a spectacular example of how gravitational-wave discoveries can impact our understanding of a rich variety of fields, ranging from nuclear and fundamental physics [83–88], to relativistic astrophysics [82, 89] and cosmology [90].

With an order of magnitude in sensitivity improvement relative to A+, Cosmic Explorer will extend the reach of multi-messenger astronomy to the high-redshift universe, unveiling binary neutron-star mergers around and beyond the peak of star formation, or a redshift of about 2 (inaccessible with 4 km observatories at $A^\sharp$ sensitivity; Figure 2). Events up to redshift 2 can be localized to better than $10\,\mathrm{deg}^2$ on the sky with a network of three XG observatories [91] (see Figure 4, upper right), offering an unprecedented opportunity to unveil the compact binary mergers that power gamma-ray bursts. A network including two Cosmic Explorer observatories would detect thousands of binary neutron star mergers per year with SNR > 100 (Figure 4, top left) determining their properties with unprecedented precision [92–94]. Measurements of neutron star tides across the masses in this sample will constrain their radii to better than 0.1 km — one part in 100 [95, 96] (Figure 4, top right). The resulting 0.01 km-level radius measurement for the common neutron-star equation of state would revolutionize our knowledge of high-density matter [97–100] (Figure 2). A network of XG observatories could localize nearby events to better than $1\,\mathrm{deg}^2$ on the sky (Figure 2, Figure 4), linking the properties of compact binary progenitors (masses, spins, and tides) to the properties of host galaxies and the diversity of merger outflows—from neutron-rich outflows contributing heavy element nucleosynthesis (e.g., [101–103]), to radio-to-X-ray emitting jets (e.g., [104–107]). In some cases, gravitational-wave observations of an in-spiralling system can provide the advance notice required to capture light from the moments closest to merger [108–110] (Figure 2).

After two neutron stars in a binary merge, oscillations of the hot, extremely dense remnant can produce "post-merger" gravitational radiation. This heretofore undetected signal probes a region of the phase diagram of dense matter that is inaccessible to collider experiments or direct electromagnetic observations, and where novel forms of matter such as deconfined quarks may appear [100, 111]. Cosmic Explorer will provide accurate measurements of the post-merger gravitational-wave frequencies for events with post-merger SNR > 5 [112, 113] (Figure 2). This will reveal dense-matter dynamics with finite temperature, rapid rotation and strong magnetic fields; shape theoretical models describing fundamental many-body nuclear interactions; and answer questions about the composition and interactions of matter at its most extreme [114–116]. Direct gravitational-wave observations of post-merger remnants will help determine the threshold mass for collapse of a rotationally supported neutron star, which has implications for the neutron-star mass distribution, predictions of electromagnetic counterparts [117, 118], and models of supernova engines [33].

In terms of its impact on the multi-messenger science of compact binary mergers highlighted in Figure 2, Cosmic Explorer is synergistic with space-based missions such as *Fermi* and *Swift*, the Nancy Grace Roman Space Telescope, and future NASA programs focused on the transient and time-variable universe [119–121]. From the ground, the Extremely Large Telescopes and the next generation Very large Array (ngVLA; [122]) will provide follow-up capabilities for Cosmic Explorer discoveries in the high-redshift universe ([121, 123–126]). The IceCube-Generation 2 neutrino observatory and Cosmic Explorer will help constrain emission models for high-energy neutrinos in nearby binary neutron star mergers [4, 127, 128].

2.3. Novel Gravitational-Wave Signals as New Probes of Extreme Astrophysics

Neutron stars and black holes, in isolation or in binary systems, can be sources of gravitational-waves signals that are very different from the chirping signals already detected by LIGO and Virgo. Cosmic Explorer, especially in combination with observatories of other messengers, has the potential to use these yet undetected signals to reveal the physics behind a suite of extreme astrophysical phenomena that would otherwise remain unexplored [129, 130]. Here we summarize several predicted "novel" signals, keeping in mind that exploratory research often brings surprises.

Spinning neutron stars produce quasi-periodic gravitational-wave signals that can last for millions of years [129–131]. These signals are due to mass quadrupoles supported by elastic or magnetic stresses, or due to current quadrupoles from long lived "r-mode" oscillations. Accreting neutron stars are especially driven to nonaxisymmetry by temperature gradients, magnetic bottling, and perhaps r-modes [130]. After accretion ends, these stars are believed to become "millisecond pulsars", spinning down at a minimum rate consistent with gravitational-wave emission from a quadrupole due to a young pulsar's magnetic field buried under accreted material [132]. Extrapolating from current searches such as in Ref. [133], Cosmic Explorer should detect multiple accreting neutron stars. It should also detect dozens of millisecond pulsars [132] (see Figure 2)—even without accounting for potential synergies with the Square Kilometre Array and ngVLA's future discoveries of several pulsars for every one currently known [123, 134]—in contrast to A$^\sharp$ which is likely to have one or two low-SNR detections. This will strongly test the hypotheses that the spins of accreting neutron stars are braked by gravitational wave emission and that millisecond pulsars are the same population observed after accretion [132, 135]. All-sky surveys for yet-unknown neutron stars may yield more than a hundred detections with Cosmic Explorer [136] compared to few or none with A$^\sharp$, and these stars will have arcsecond localization to guide followup searches for pulsars in radio and other electromagnetic wavebands. Long-lived gravitational-wave signals, particularly in tandem with electromagnetic observations, can provide information not only on the neutron star equation of state, but also the composition, spin, and magnetic field histories of some stars, and microphysics such as viscosity, thermal conductivity, and elastic properties of the crust [130, 131, 137].

Core-collapse supernovae generate bursts of gravitational waves from the dynamics of hot, high-density matter in their central regions. Cosmic Explorer will be sensitive to supernovae within the Milky Way and its satellites [138], with an expected rate of one over the planned 50-year lifetime of the facilities. A core collapse supernova detected by Cosmic Explorer will have an order of magnitude higher SNR than with A$^\sharp$, allowing much better waveform reconstruction and characterization of source properties [138]. The detection of a core-collapse event in gravitational waves would provide a unique channel for observing the explosion's central engine and the equation of state of newly formed ”protoneutron star”, allowing measurement of the progenitor core’s rotational energy and frequency measurements for oscillations driven by fallback onto the protoneutron star. This type of event can also be used to understand black hole formation [129], especially if ejection of the magnetosphere leads to a fast radio burst [139]. A nearby supernova explosion has the potential to provide a coincident neutrino detection, giving a spectacular multi-messenger event [129]. Some extreme supernovae, such as collapsars or with “cocoons”, may generate gravitational waves that may be barely detectable once per year with $A^\sharp$, but of order ten per year may be detectable with Cosmic Explorer [140–142].

Gravitational waves are also generated by other dynamic neutron-star events [130] such as magnetar gamma-ray flares (possibly accompanied by fast radio bursts) and pulsar glitches. Such impulsive, energetic events will excite the many normal modes of neutron stars, including the strongly gravitational-wave-emitting f-modes. Pulsar glitches may also be followed by weeks-long signals as crust and core readjust. Aided by the time and location of the electromagnetic trigger, upgrades to existing observatories can detect gravitational-wave signals only in the most optimistic scenarios [143], while with Cosmic Explorer detection is likely in a wider range of scenarios. Extrapolating from [144], with Cosmic Explorer f-modes with energies comparable to glitches of the Vela pulsar or common magnetar flares will be detectable to the galactic center, while energies comparable to magnetar giant flares will be detectable all over the galaxy and its satellites [145]. Detection of f-modes will independently measure the neutron star equation of state and masses of a population different from that seen in binary mergers, and combined with X-ray observations will yield information on internal magnetic fields [146], while a long post-glitch detection would add information on the viscosity of neutron-star matter. For these burst signals as well as supernovae, it is crucial to have multiple XG observatories to provide confidence through coincident detection. The location of most sources in the galactic plane makes it important to have a low latitude detector site [135, 147].

2.4. Fundamental Physics and Precision Cosmology

Thanks to its order-of-magnitude advance in sensitivity over current-generation gravitational-wave observatories, Cosmic Explorer will reveal the physics of strong-field gravity in unprecedented detail via two crucial pathways. First, in three years of operation, a network including the 40 km Cosmic Explorer observatory will detect $\gtrsim$ 10 pairs of merging black holes with a SNR greater than 1000 (the loudest such signal to date, GW200129_065458, had a SNR of 26.8) [2, 148], and hundreds of black hole merger events with post-inspiral SNR greater than 100 (see Figure 4). Second, Cosmic Explorer will detect waves from sources too rare for us to observe today: in each year of its operation, it will observe approximately 100,000 binary black holes — 1000 times the total number of gravitational waves observed to date from any source type [149, 150], providing far more opportunities to discover rare and interesting events. Together, these advances will enable Cosmic Explorer to shed light on the nature of gravity with incredible clarity, perhaps revealing physics beyond General Relativity (GR) [149, 151–155] the effects of which might be too subtle for current observatories to reveal (§4).

For example, unlike existing facilities, Cosmic Explorer will be sufficiently sensitive to detect the gravitational-wave memory effect, a permanent change in strain predicted by GR, with a single-event SNR greater than 5 [151, 154]. As another example, GR mandates that gravitational waves propagate at the speed of light; in the language of quantum field theory that means that the graviton, which mediates the gravitational interaction, must be massless. With a coincident detection of gravitational waves and gamma-ray bursts at redshifts of $z = 5$, Cosmic Explorer and its electromagnetic partner observatories will improve constraints on the graviton mass by three orders of magnitude [149]. Finally, while GR predicts only two gravitational-wave polarizations, more general theories of gravity allow for up to four additional vector and scalar modes [155]. A network of XG observatories will be able to find or place stringent upper limits on the existence of extra polarizations [156–158], and the inclusion of a 40 km Cosmic Explorer in this network will uniquely differentiate between the two scalar modes [153].

Cosmic Explorer will provide a novel and precise measurement of the cosmic expansion rate [159] with the potential to address the tension between the local cosmic expansion rate as determined by different experiments. Although gravitational-wave observations of binary black holes can be used to measure their luminosity distance, in the absence of additional information the redshift of the source must be inferred from cosmology. However, the combination of a luminosity distance measurement with an independent measure of redshift (either from an electromagnetic counterpart or with other approaches) can be used to probe cosmic expansion in ways that are independent of conventional measurements [160–164], such as using standard candles and the other elements of the cosmic distance ladder. Every year, many thousands of binary neutron star mergers observed by a XG network will have distance uncertainty less than 10% (see Figure 4, lower left), therefore Cosmic Explorer is well-positioned to improve our understanding of the tension in the local cosmic expansion rate as well as the dark energy equation-of-state [164–168], and provide an independent measurement of baryon acoustic oscillations [169]. A networks of two or more XG observatories will allow for precise localization of the binary mergers, and achieve sub-1% precision on H_0 in under a year (see Figure 2).

We finally note that this aspect of the Cosmic Explorer science is synergistic with the goals of the next-generation cosmic microwave background experiment CMB-S4 [4]. Indeed, as discussed in [170], studies of the primordial gravitational-wave background across a broad frequency range enabled by combining experiments such as CMB-S4 and Cosmic Explorer could better constrain cosmological parameters, and particularly the inflationary spectral index and the tensor-to-scalar ratio (see Figure 4).

2.5. Dark Matter and the Early Universe

Gravitational waves are an exciting new astrophysical probe of dark matter that is complementary to searches at high-energy colliders and underground direct-detection experiments and might reveal the nature of dark matter in several different scenarios. For instance, because of their strong gravitational fields and extreme densities, neutron stars might capture ambient dark matter over time through scattering off nucleons, or they might even produce dark matter, thanks to the exceptionally high energies achieved in binary neutron star mergers. If a neutron star were to contain dark matter, the dark matter would affect the neutron star's tidal deformability, previously noted as an indicator of nuclear equation of state in §2.2. The dark matter concentration would likely depend on the neutron star's age, mass, and environment in this scenario, leading to otherwise inexplicable variations in the tidal deformability [171, 172], and the collapse of neutron stars to black holes due to dark matter in their cores [173]. These variations will be accessible to Cosmic Explorer observatories, since they will detect many thousands of high-SNR binary neutron star mergers in which tidal deformability can be precisely inferred [150, 173].

Black hole superradiance is another possible mechanism by which dark matter might generate a gravitational-wave signature [174–177]. Critically, this mechanism only assumes a coupling through gravity, and as such would still be viable even if dark matter does not have any type of electroweak or strong interaction with baryonic matter. An ultra-light boson with mass in the range $\sim 10^{-13} - 10^{-12}$ eV would create a macroscopic "cloud" bound to a black hole, which reduces the mass and spin of the host black hole. The spin distribution of merging black holes can reveal, or rule out, the existence of these ultralight bosons [178, 179]. The large number of binary black holes with good spin measurement (see §2.1) implies even a single Cosmic Explorer could make a detection—or obtain useful upper limits—in less than a year ([38] and §4.2).

In addition, the cloud itself carries a large time-dependent energy density and sources nearly-continuous gravitational waves [180]. These signals can be observed with Cosmic Explorer as follow-up searches to rapidly rotating black holes formed in a merger, or with blind searches for continuous or stochastic waves from nearby black holes [181–183].

Recent studies also demonstrate that XG observatories can provide a unique opportunity to probe the early universe [184–187]. Standard slow-roll inflationary models are expected to produce a stochastic background with dimensionless energy density $\Omega_{\rm GW} \sim 10^{-17}$ [188, 189], which is too weak to be directly detected by ground-based gravitational-wave detectors. However, nonstandard inflationary and cosmological models can produce backgrounds due to processes such as preheating [190–192], first-order phase transitions [193–197], primordial black hole-seeding multifield inflation [198–200], and cosmic strings [201–205]—all with energy densities within the reach of Cosmic Explorer (see Figure 2 and bottom right of Figure 4). The detection of a cosmological stochastic background would obviously be of fundamental importance for our understanding of the early universe; and even a non-detection would allow for constraints on beyond-standard-model physics at energies orders of magnitude larger than those accessible with particle accelerators. A network of XG detectors with comparable sensitivity is needed to achieve this goal, as the foreground of resolvable sources must be precisely modeled to reveal the much fainter background [185, 206, 207].

3. The Cosmic Explorer Concept

The Cosmic Explorer reference concept presented in the Horizon Study [1] includes two widely-separated L-shaped observatories in the US, each housing one next-generation gravitational-wave detector (configurations "4020A" and "4020ET" in Table 1). This pair of observatories maximizes the scientific output with a 40 km arm length detector (ten times that of LIGO) that is unmatched for deep, broadband sensitivity, partnered with a second detector (20 km) to allow for source localization and polarization sensing, and to provide the capability of tuning its sensitivity to the physics of neutron stars after they have merged (see §§ 2 and 4). This concept also takes advantage of efficiencies associated with simultaneous construction (as well as commissioning and operation) of two sites within the US, as done by LIGO.

The heart of each Cosmic Explorer detector is a dual-recycled Fabry-Perot Michelson interferometer, operated at room temperature with a 1064 nm laser source, and quantum-enhanced by the injection of frequency-dependent squeezed vacuum states. Crucially, this is the same technology used by LIGO to reach unprecedented sensitivity in the O4 observing run. Relying on scaled-up, proven LIGO technology where possible, along with targeted technical advances, provides a straightforward approach to significant improvement with relatively low risk (leading risks are described in §5.5).

The expected gravitational-wave strain sensitivity of the initial Cosmic Explorer detectors is shown in Figure 3, together with an estimate of the ultimate performance of the A+ upgrade of the Advanced LIGO detectors. The 40 km Cosmic Explorer detector in its default broadband configuration reaches a strain sensitivity of about $2.5 \times 10^{-25} / \sqrt{\mathrm{Hz}}$ over a wide band, providing an order of magnitude improvement over Advanced LIGO A+ at 100 Hz, increasing to fifty times at 20 Hz. The 20 km arm length of the second detector in the reference concept was chosen as it provides a modest advantage over the 40 km detector in the 2 kHz to 4 kHz band when optimized for observing the final stages of binary neutron star mergers [1]. Two key factors deliver the superior sensitivity and increased bandwidth of Cosmic Explorer:

(i) Order-of-magnitude longer arms — The increased arm length provides a direct approach to significant sensitivity improvement with relatively low risk, while at the same time matching the gravitational-wave antenna size to the shortest expected signal wavelength [208]. As a result, one of the two dominant noise sources in Advanced LIGO A+, coating thermal noise, is reduced twenty-fold due to the larger optical beams and the longer arms [1, 209]. This leaves quantum vacuum fluctuations of the optical field as the dominant noise source over much of the observation band (although also reduced by the longer arms). The recent success of frequency-dependent squeezing technology [210, 211], with a 2× quantum noise reduction observed at the LIGO observatories, suggests that the 3× quantum noise reduction assumed for Cosmic Explorer is within reach.

(ii) Improved low-frequency isolation — Targeted isolation system improvements further reduce the noise at and below 20 Hz beyond the order-of-magnitude reduction that comes from arm length alone [212]. The test masses will be isolated from seismic disturbances with both passive and active systems scaled up from those in Advanced LIGO [213], and equipped with improved sensors [214]. A dedicated seismometer array will be used to measure the local seismic field, enabling the subtraction of noise introduced via the direct gravitational coupling of the ground motion to the test mass (known as "Newtonian noise" or "gravity gradient noise"). Finally, longer and heavier multiple pendulum suspensions will suppress environmental vibrations and the thermal noise from the suspension itself.

Facility Limit — The Cosmic Explorer facilities will constitute a major investment and are expected to have a 50-year lifetime. With this in mind, they will be designed to be flexible enough to support advancements in detector technology during this period. Two potential near-term upgrades are alternative coating materials, such as crystalline GaAs/AlGaAs [215], that could provide much lower coating thermal noise (especially relevant for the 20 km detector), and a combination of higher laser power and lower optical losses with high-fidelity squeezed states to reduce the quantum noise. Longer-term upgrades might include cryogenics or alternate optical configurations [216, 217]. Figures 1 and 3 highlight the Facility Limit, i.e., the sum of infrastructure-specific noise sources that would be common to all future detectors utilizing the Cosmic Explorer infrastructure, indicating that a 40 km facility could support an additional factor of five improvement in sensitivity relative to the Cosmic Explorer reference concept.

4. Impact of Network Configurations on Science Goals

The scientific potential of Cosmic Explorer is vast, and the science that can be anticipated is ground breaking on many fronts (see §2). Essential to fulfilling the majority of Cosmic Explorer's science objectives is the ability to localize sources in the sky, and to measure their properties, such as distances, redshifts, and/or masses. If two or more gravitational-wave observatories detect a compact binary, its sky location and orientation relative to the line of sight can be inferred from arrival time delays at different detectors, from signal strength consistency with the antenna patterns, and through

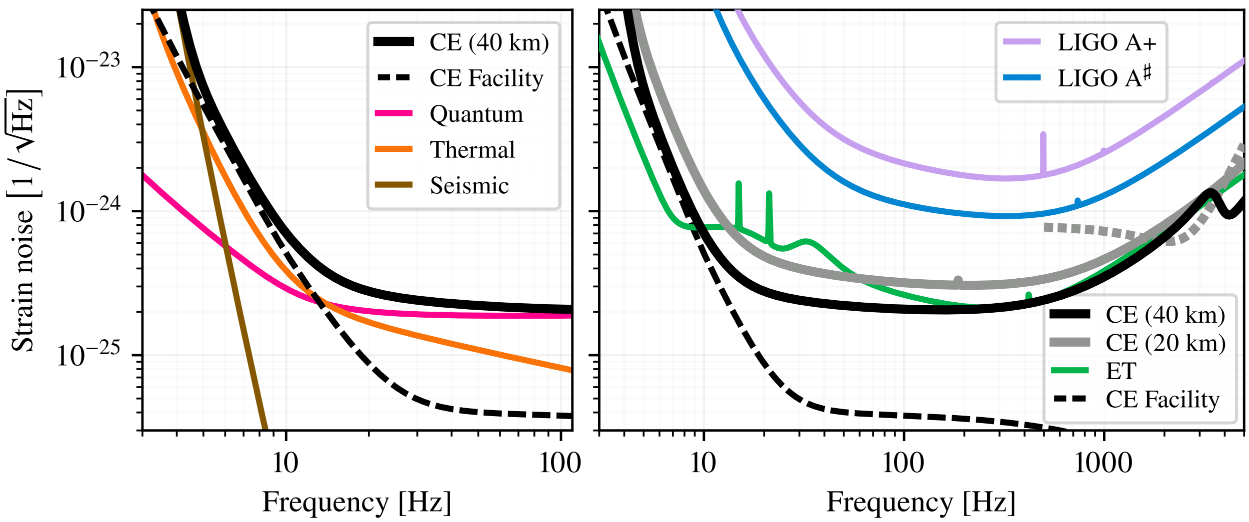

Figure 3: *Left:* Estimated spectral sensitivity (solid black) of CE and the known fundamental sources of noise that contribute to this total (other curves). *Right:* Comparison of spectral sensitivities of LIGO A+, LIGO A$^\sharp$, Einstein Telescope (a triangular arrangement of three detectors), and 20 km and 40 km versions of CE. The 20 km CE could be operated either in a broadband mode (solid gray) or a kilohertz-focused mode (dotted gray). The facility limit for a 40 km CE is indicated in dashed black. (Adapted from the CE Horizon Study [1].)

observation of both gravitational-wave polarizations. This significantly improves sky localizations and distance measurements. This section summarizes the scientific potential of a range of global gravitational-wave network configurations for which we have performed a dedicated trade-study that is intended to directly addresses the charge of the NSF MPSAC ngGW sub-committee [218].

4.1. Gravitational-Wave Observatory Network Configurations

The ngGW charge asks the subcommittee to consider XG US observatories as part of an international network, as well as potential upgrades to the current LIGO sites. Our models for each of these network nodes are described below, and the networks studied are shown in Table 1. This collection of network configurations is intended to be sufficient to serve the ngGW subcommittee's needs, without being unduly complex. We are aided by research indicating that the critical feature of a future network of gravitational-wave observatories is the number of XG detectors present, while their locations are of secondary importance [219].

Cosmic Explorer Observatories (CE A, CE B) — Since the locations of the CE observatories have yet to be determined, we selected two fiducial locations for CE; CE A off the coast of Washington state, and CE B off the coast of Texas. These locations are intentionally unphysical to avoid impacting our ability to find a home for CE (§5.3), but close enough to a wide range of potential sites to be representative from the point of view of gravitational-wave science. The CE A location is considered in both the 40 km and the 20 km lengths, while in this study the CE B location hosts only a 20 km observatory.

Existing LIGO Sites (LHO, LLO, LAO) — In order to focus on the science enabled by CE beyond what is possible in the current facilities, we model the LIGO detectors in an upgraded form (known as "A$^\sharp$", which has comparable sensitivity to the cryogenic "Voyager" configuration [220]) that approximately represents the limit to what is achievable in the LIGO facilities. Furthermore, in

Next Generation (XG) Observatories	Network Name	Detectors in the network
None	HLA	LHO, LLO, LAO
1 XG	20LA 40LA	CE A 20 km, LLO, LAO CE A 40 km, LLO, LAO
2 XG	20LET 40LET 4020A	CE A 20 km, LLO, ET CE A 40 km, LLO, ET CE A 40 km, CE B 20 km, LAO
3 XG	4020ET	CE A 40 km, CE B 20 km, ET

Table 1: We consider four classes of networks containing, zero to three next-generation (XG) observatories. Each network is given a name to facilitate comparisons. The HLA network, represents existing observatories and sets a baseline from which Cosmic Explorer return on investment can be assessed. CE40LA and CE20LA represent a single CE operating in the context of an upgraded 2G network. CE4020A is the CE reference configuration, operating with an upgraded LIGO Aundh in India (LAO), while CE40LET and CE20LET represent a single CE operating with LLO and ET. CE4020ET is the reference CE configuration operating with ET.

addition to the LIGO Hanford (LHO) and LIGO Livingston (LLO) detectors, we also consider LIGO India (LAO) in the A$^\sharp$ configuration, as it may be operational starting in the early 2030s.

Einstein Telescope (ET) — The Einstein Telescope is a planned XG gravitational-wave observatory in Europe [221]. It is currently envisioned as an underground triangular facility with 10 km arm length, housing six interferometers. The targeted timeline calls for first observations by the mid-2030s. The underground location, which is imperative in Europe, suppresses the expected seismic disturbances, thereby reducing the Newtonian noise that limits ground-based gravitational-wave facilities a low frequencies (cf. the difference between CE and ET below 8 Hz in Figure 3). While we are encouraged by ET's adoption into the European Strategy Forum on Research Infrastructure (ESFRI) road map, we present some network configurations that do not include ET to highlight the value of US investment even in the absence of our European collaborators.

4.2. Impact on Science Goals

The relative performance of different detector networks was assessed with the Fisher matrix approach using the GWBENCH open source software [42, 222]. Results reported here are broadly (within 20%) consistent with those found by other authors using the same approach [223–225]. In particular, we have confirmed that the Fisher results for the statistical uncertainty in the radius of neutron stars (e.g. $\Delta R_{\rm NS} \sim 100$ m) (Figure 4, top right panel) are consistent with the Bayesian inference of the same quantity (10 m for a combined population of ~ 300 events) reported in [97].

In Figure 4 we show the relative performance of networks with zero, one, two or three XG observatories (Table 1) with regard to the key science goals described in detail in §2. The various symbols that appear in that figure are as follows: $N_{\rm BNS}$, $N_{\rm BBH}$ and $N_{\rm IMBBH}$ are the number of binary neutron stars, binary black holes, and intermediate-mass black hole mergers, respectively; Δ followed by a symbol refers to the 1-sigma uncertainty in the quantity that follows it found using the Fisher matrix approach (except the sky position uncertain for which it is the 90% credible interval); Ω, D_L and z are the source's angular position on the sky, luminosity distance and redshift, respectively; m_1 is the mass of the primary companion of a binary; $R_{\rm NS}$ and $\tilde{\Lambda}_{\rm NS}$ are the radius and dimensionless

Figure 4: Polar histograms showing how Cosmic Explorer can accomplish the key science goals discussed in §2. *Top Left:* A XG network is critical to making high-fidelity observations (SNR > 100) of black hole and neutron star populations, while accurately measuring their masses, redshifts, and locations on the sky. *Top Right:* The HLA network cannot facilitate the electromagnetic follow-up of mergers at the highest redshifts accessible to the best telescopes while an XG network will routinely provide alerts to such mergers. XG observatories can make exquisite measurements of the radius of neutron stars and their tidal deformability, and they will detect dozens of post-merger signals from merger remnants. *Bottom left:* Precision tests of General Relativity are enabled by extremely high-fidelity events (SNR > 1000), and also by combining data from thousands of lower-SNR events. Additionally, tens of thousands of detections with accurate measurements of the distance allow for precision cosmology. *Bottom right:* Finally, the Cosmic Explorer network has abundant discovery potential with the ability to observe weak and rare signals, speculative sources, primordial backgrounds and an opportunity to discover physics beyond the Standard Model.

tidal deformability of a neutron star, respectively; Ω_{GW} denotes the energy density in stochastic gravitational-wave background relative to the closure density of the universe; and, finally, w_0 and w_a are the dark energy equation of state parameter and its variation in redshift, respectively.

In all cases, we take a network of three A$^\sharp$ detectors with no XG observatories as our baseline and show the improvements in various science outcomes obtained from networks containing one or more XG observatories. The addition of XG observatories to the global network provides a significant improvement in ability to achieve the science targets detailed in §2. At a minimum, we obtain a factor of ~10 improvement and, in many cases, XG detectors enable observations which are simply not possible with the A$^\sharp$ network, as shown in Figures 2 and 4.

A network of A$^\sharp$ detectors with no XG observatory provides moderate gains over the A+ network, allowing, e.g., observation and localization of binary neutron star mergers to redshift $z \approx 0.3$ and binary black hole mergers to $z \approx 2$. A single XG observatory greatly extends the reach of the network, with binary neutron mergers observable to the star formation peak at $z \approx 2$ and binary black holes observable to $z \gtrsim 10$, the epoch of the first stars in the universe, as shown in Figure 1 and discussed in §2.1. This will vastly increase the rate of signals, as well as enabling observations of nearby events with unprecedented fidelity. Consequently, for science goals which require the observation of new signals, such as continuous waves from pulsars (§2.3), or of new features in signals, such as post-merger waveform following a binary neutron star (§2.2), a single XG observatory is transformational. The expected observing time required to achieve these science goals is reduced by at least an order of magnitude with a single CE observatory complementing the A$^\sharp$ network. Similarly, the number of binary neutron star and binary black hole mergers observed at SNR > 100 will increase by an order of magnitude, enabling precision measurements of neutron star radii (§2.2) and comparisons between observations and GR predictions (see §2.4).

Several science goals require the accurate localization of sources, both on the sky and in distance/redshift, and consequently mass. For example, a source at redshift $z = 10$ observed in a single XG observatory would be essentially unlocalized in the sky, and have a distance uncertainty of $\sim 50\%$. This leads to an uncertainty of ± 4 in the redshift measurement and, due to the mass–redshift degeneracy in gravitational-wave observations, a 40% uncertainty in the mass measurement, rendering a detailed study of the binary black hole population at high redshifts impossible. For events that lie beyond the A$^\sharp$ horizon, accurate localization and mass/redshift measurements can only be achieved with a network of two or more XG observatories. A second XG observatory enables, at least partial, localization of large numbers of events and provides a substantial improvement in the gravitational-wave measurement of the Hubble constant and other cosmological parameters (§2.5). A two XG network also enables precision localization of nearby binary neutron stars. A network of three XG detectors enables good localization of the majority of sources, with tens of thousands of binary neutron star signals each year localized to better than $10\,\mathrm{deg}^2$, thereby enabling multi-messenger follow-up observations (see §2.2 and Figure 4). A three XG network can also improve constraints on the binary inclination angle relative to the line of sight, and hence the luminosity distance measurement (§2.1 and §2.4). Multiple XG observatories also improve the confidence in detection of poorly modeled sources (§2.3), enable polarization measurements that are relevant for tests of GR (§2.4) and the inference the presence of dark matter in neutron star cores or detect primordial stochastic backgrounds (§2.5).

5. The Cosmic Explorer Project

While the primary objective of Cosmic Explorer is to answer deep scientific questions in fundamental physics, nuclear physics and astrophysics, an undertaking of this scale has impacts well outside of the scientific community. If Cosmic Explorer is to be be funded by US taxpayers, it must serve the needs of the nation in a broad sense, be cognizant of and responsive to potentially impacted communities, and be designed to maximize the return on taxpayer dollars. This section broadens the view of Cosmic Explorer relative to the scientific and technical highlights presented in §2 and §3 with information about the Cosmic Explorer Project, cost estimates and timeline (§§ 5.1 and 5.2), the process of finding potential homes for CE (§5.3), education and equity efforts (§5.4), and known project risks (§5.5).

The Cosmic Explorer Project was organized in 2021 following the completion of the Cosmic Explorer Horizon Study [226, 227], and currently has over 40 members with a wide range of expertise. In addition, CE has international partners (Australia, Canada, Germany, UK) and a broad community in the CE Consortium. In Fall 2022, the Project organized the development of seven proposals to the NSF to fund the first three years of the Cosmic Explorer conceptual design. The Project also organized the writing of this white paper.

5.1. Cost Estimates

The Cosmic Explorer observatories are envisioned as largely above-ground, L-shaped facilities [1]. This choice is in line with currently-operating observatories, but different from the KAGRA detector in Japan and the planned Einstein Telescope in Europe. In the US context, where large relatively flat areas with low population densities can be found (see §5.3), building above ground maximizes scientific return on investment by avoiding tunneling costs and the complexity of underground construction, installation and operation.

Design and Construction costs — The initial cost estimate for the Cosmic Explorer reference concept consisting of a 40 km observatory and a 20 km observatory is approximately \$1.6B (2021 USD), as published in the Horizon Study [1]. The Horizon Study also presents estimates for two 20 km observatories (\$1.3B), a single 40 km (\$1.0B) and a single 20 km (\$0.7B). These estimates are based on extrapolating actual costs from LIGO construction, the Advanced LIGO upgrade, and the work of professional civil engineering and metallurgy consultants. Cost drivers for a Cosmic Explorer observatory are: arm length, beamtube material and diameter, and location-dependent civil-engineering costs. Many of the costs associated with arm length are simply proportional to the length (e.g., the beamtube and its enclosure, the roads along the beamline, electrical utilities along the beamline, the slab supporting the beamtube), and largely location independent (within 10% of the national average). The cost of excavation and transportation is generally not proportional to the length of the facility, and highly dependent on topography and geology (e.g., depth to rock). Notably, the cost of the detectors installed in the observatories is not a leading driver (estimated at approximately 28% of the total). A full breakdown of this cost estimate is given in [1].

Maintenance and Operations Costs — Again drawing from the CE Horizon Study, yearly maintenance and operations costs for the CE reference concept (2 observatories) were estimated at \$60M (2021 USD) [1]. This estimate is based on LIGO experience, and includes the observatory facilities, vacuum systems, and detector hardware. It also includes management, community engagement, and the data analysis and curation required to make CE data available and accessible to the scientific community and the public. Notably, this estimate does *not* include university research or

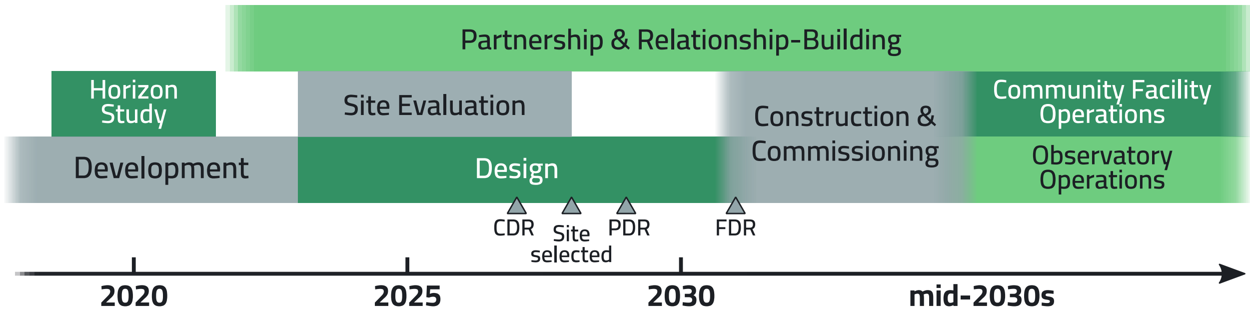

Figure 5: Cosmic Explorer top-level timeline showing a phased approach to design and construction. Following the NSF Research Infrastructure Guide [228], the design stage has 3 major milestones: conceptual design review (CDR), preliminary design review (PDR, budget is final), final design review (FDR). The timeline shown here assumes an aggressive funding model, leading to construction in the early 2030s and operation in the mid-2030s. While the initial mandate is expected to be for 20 or 25 years, the facility may operate for 50+ years [1]. The eventual divestment stage is not indicated.

development efforts towards future CE upgrades, and it assumes a model in which much of the data analysis (beyond that needed to issue astronomical alerts) happens in the scientific community (and is separately funded). To respond directly to the ngGW subcommittee's charge, we compute "maintenance and operations costs for the first ten years" as \$670M in 2023 USD. If we assume 3% inflation for all future years and compute operation costs from 2035 to 2045, the total is \$1.1B in then-year dollars.

5.2. Timeline

The timeline for Cosmic Explorer spans multiple decades and takes place in distinct stages. The development stage for Cosmic Explorer began in 2013, and culminated in the publication of the Cosmic Explorer Horizon Study in 2021 [1]. The design and site-selection stage is expected to start this year (2023) and continue for 8 to 10 years. Expedient funding will allow CE construction in the early 2030s, and *initial observations in the middle of the next decade*. Figure 5 graphically summarizes this timeline.

In parallel with these technical efforts, work on partnership and relationship building at all levels will be of ever increasing importance. In addition to bringing scientists into the CE community, the CE project will be building relationships with local and Indigenous communities at potential observatory host locations (see §5.3). Work with all of the communities that are engaged with and/or impacted by Cosmic Explorer, from local to global, will continue throughout the life of the project. Even in the final stage of Cosmic Explorer, the divestment stage, close partnerships with local and Indigenous communities will be critical to ensuring that this project is completed in a way that facilitates the creation of future major facilities by the NSF and other agencies.

5.3. Site Evaluation and Community Partnerships

Construction on the scale of the Cosmic Explorer observatories is not only technically challenging, but requires proactive attention to potential social, cultural, and economic impacts during all stages of its existence, from design to divestment.

During the CE development stage, many physically promising locations in the United States that could plausibly accommodate a 20 km or 40 km baseline observatory were algorithmically identified using publicly available topological and land use data. Several of these locations were followed up with additional publicly available data, such as land ownership, current and traditional Indigenous connection to land, proximity to cities and seismicity, as well as earthquake, flood and wind hazard. Fundamental physical requirements for a Cosmic Explorer observatory include quiet ground motion and other favorable ambient environmental conditions, modest weather disturbances, minimal susceptibility to natural disasters, and low human-induced noise. Optimal locations would also have access to a number of strategic infrastructures — such as roads, rail, airports, and cities — to support all phases of the project, from construction (i.e., delivery of vacuum pipes and large equipment) to commissioning and operation.

Cosmic Explorer presents an opportunity to broaden participation and build research competitiveness and STEM capacity in states that have traditionally been awarded less NSF support; a number of plausible locations are in EPSCoR jurisdictions [229]. Furthermore, cost estimates made for the CE Horizon Study indicate that excavation will not be the leading cost driver for locations with favorable geology and topography – meaning that there is flexibility to choose locations that do not have the lowest excavation costs if they excel in other areas, such as social and environmental consideration [1].

Beyond the physical features of a location, decades of LIGO operations have also highlighted the importance of the social context of an observatory. Cosmic Explorer has the unique opportunity to prudently conceptualize community engagement and to respectfully work within the local and global socio-cultural context. In today's social and legal context (e.g., [4] and references therein), an investment in establishing robust and sustained relationships with local and Indigenous communities will be fundamental to the evaluation of each location's potential for housing an observatory.

In parallel with the design stage of Cosmic Explorer, a deeper, broader, and more culturally aware study of potential locations in the US will be required. In anticipation of near-term funding, work has begun to assemble a team with diverse expertise in gravitational-wave experiment and computation, astrophysics, geology, geography, and sociology. Project leadership has initiated work with consultants in law and economics to develop an integrated, interdisciplinary approach to location evaluation that supports CE's scientific goals while simultaneously identifying areas of relevance to, and potential synergies with, Indigenous and other local communities.

Identifying and evaluating the most promising locations for Cosmic Explorer observatories will take place in concert with developing protocols and best practices for large-scale projects to be in partnership with local and Indigenous communities. This work will draw on expertise from traditional knowledge (as appropriate), physics, geology, Geographic Information Systems (GIS), and sociology to incorporate both quantifiable (e.g., topology and seismology) and go/no-go information (e.g., protected lands or historical lands) into the evaluations that identify initial locations of interest. Results from subsequent assessment steps will be used to refine the collection of viable locations toward a set of well characterized candidates in the late 2020s (see §5.2).

5.4. Broadening Participation and Cultivating a Thriving Community

The Cosmic Explorer Project is committed to equity advancing values emphasized in the NSF 2022–2026 Strategic Plan [230] and the report from the Astro2020 Panel on the State of the Profession and Societal Impacts [4]. The CE Directors' Office provides central leadership and integration into CE structure and culture through the Director of Equity, Diversity, and Inclusion (EDI), prioritizing core structures for leadership composition and advancement, mentorship, education, and community engagement. CE efforts to broaden participation support recruiting, training, and mentoring professionals and students through a multi-generational project. Coordination across CE Project institutions includes facilitating training with external experts, developing mentoring structures connected to recruiting, hiring, retention, and promotion for CE members and leadership, and development of the CE code of conduct and ombuds office. Project leadership also facilitates partnerships between institutional Research Experiences for Undergraduates (REU) and Bridge programs to bring research opportunities to undergraduate and graduate students. These efforts serve the need of the nation by contributing to the development of the STEM workforce, and directly address a Project risk associated with the multi-generational nature of Cosmic Explorer (see §5.5).

The University of Washington Center for Evaluation and Research for STEM Equity (CERSE) collaborates with CE leadership to design and execute project consulting, including collection and analysis of demographic data and advising on organizational development. The Cosmic Explorer Project is connected to the broader community through the Gravitational Wave International Committee (GWIC), the Multimessenger Diversity Network (MDN), the Gravitational Wave Early Career Scientists (GWECS), and the GW Allies to facilitate the sharing of resources and best practices. CE community engagement encompasses contributions to STEM workforce development, connections to the broader astrophysics community, and to communities near potential CE host locations (see §5.3).

5.5. Risks and Mitigation Strategies

A project of the scale and complexity of Cosmic Explorer will have a number of risks at each phase of development. The Project will manage these with well-established practices, leveraging experience from LIGO and its upgrades. An initial assessment of risks and mitigations can be found in §11.4 of the CE Horizon Study [1]. In general, CE has been conceived to minimize risk for the infrastructure by evolving from the successful LIGO design, and minimizing risk for the CE detector by planning on re-scaling the LIGO designs to the greater CE length (see §3) with two observatories sharing common design and management teams. The two observatory teams will profit from the same synergy seen in LIGO. With that basis, we discuss some leading risks below.

A leading technical risk for both the 40 and 20 km instruments is in making the larger diameter optics to the required optical performance, although preliminary contacts with vendors indicate that CE optics should only require a modest investment in retooling. There are also technical risks associated the interferometer control and stability associated with scaling-up to CE (e.g., frequency control bandwidth limits due to arm length, parametric instabilities in large mirrors, etc.). Though these are known challenges and incremental relative to proven technology, research during the CE conceptual design phase is planned to mitigate the associated risks.

Mitigation of management and non-technical risks is also important to CE success. In particular, site identification and preparation for CE will not only require that technically suitable locations be found, but also the development of enduring relationships with the local and Indigenous communities (see §5.3). The significant duration of CE requires that the engaged scientific and engineering team be multi-generational; to ensure this, CE involves a range of teaching institutions distributed across the US, and the team will maintain a vigorous program of research involving students throughout the Project duration and into the observing epoch (see §5.4).

Lastly, there is the risk of missing significant added science that is enabled by other gravitational-wave observatories (most notably Einstein Telescope; see §4.1), or complementary photon and particle observatories (see §2). We address these external risks by maintaining close relationships with these projects, communicating our plans and capabilities, and helping to demonstrate to funding agencies the synergistic potential of observing with CE as part of a global multi-messenger network.

6. Summary and Conclusion

Gravitational waves are generated by physical processes that are vastly different from those that generate other forms of radiation and particles. Measuring these minute distortions in space allow us to access regions of the universe that cannot be observed in any other way. Thanks to wise investments in the field of gravitational-wave science, made by the NSF on behalf of the nation, the detection of gravitational waves has become a reality and we (the agency, the scientific community and the nation) are now in a position to contemplate the long-term future of this field.

In this white paper we have presented the Cosmic Explorer observatory concept, developed over the last 10 years with continuous input from the scientific community, and documented in the NSF-supported Cosmic Explorer Horizon Study [1]. The Cosmic Explorer reference concept consists of two observatories, one with 40 km-long arms, and one with 20 km-long arms. This is the configuration that emerged from the Horizon Study as optimal in terms of scientific return on investment and was corroborated in the dedicated trade-study performed for this white paper. The scientific goals of Cosmic Explorer reach into multiple areas of physics and astronomy. Cosmic Explorer will detect millions of events each year from throughout the observable universe. It will map the population of compact objects across time, shed light on the nature of ultra-dense matter, trace the origins of the elements that are the building blocks of our world, and reveal physics of the most extreme gravity in the universe. And, in recognition of all that is yet to be discovered, we note that it would be a profound anomaly in astronomy if nothing unexpected came from Cosmic Explorer's vast improvement in sensitivity.

The Cosmic Explorer Project is preparing for entry into the observatory design stage. The conceptual and preliminary design phases (next 8–10 years) will see the development of detailed instrument, vacuum system and facility designs, as well as accurate cost and schedule estimates. Site identification and evaluation will also be underway during this period, along with economic, environmental and socio-cultural impact studies. Establishing partnerships with local and Indigenous communities will be fundamental to the evaluation of a location's potential for housing a Cosmic Explorer observatory. Mutually respectful, culturally relevant relationships that center trust, process, and community interests are as much a part of the outcome as is the technological achievements and knowledge to be gained [231, 232]. Cosmic Explorer's order-of-magnitude sensitivity improvement over LIGO A+ relies on proven technology and decades of experience with the LIGO observatories. While the facility design will accommodate a wide variety of potential upgrades, the initial detector will profit from the $A^\sharp$ development, ensuring readiness with limited R&D and low risk. Assuming the Cosmic Explorer design stage starts soon and is continuously funded through the 2020s, Cosmic Explorer's first observing runs could take place in the mid-2030s.

True to its name, Cosmic Explorer will extend humanity's gravitational-wave sense to cosmic distances. It will renew the US' leadership in gravitational-wave science and form the cornerstone of the next-generation global observatory network.

Acronyms

CE Cosmic Explorer. 1, 2, 4–20
ET Einstein Telescope. 4, 13, 16, 19
GR General Relativity. 8, 9, 15
IMBH Intermediate Mass Black Hole. 5
JWST James Webb Space Telescope. 1, 5
MPSAC Mathematical and Physical Sciences Advisory Committee. 2, 12
ngGW Next-Generation Gravitational-Wave Observatory. 2, 12, 17
ngVLA next generation Very large Array. 7
NSF National Science Foundation. 1, 2, 12, 16–18, 20
SNR Signal-to-Noise Ratio. 3, 4, 6–9, 14, 15
US United States. 1, 4, 10, 12, 16, 18–20
XG Next Generation. 1, 2, 5, 6, 8–10, 12–15

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