

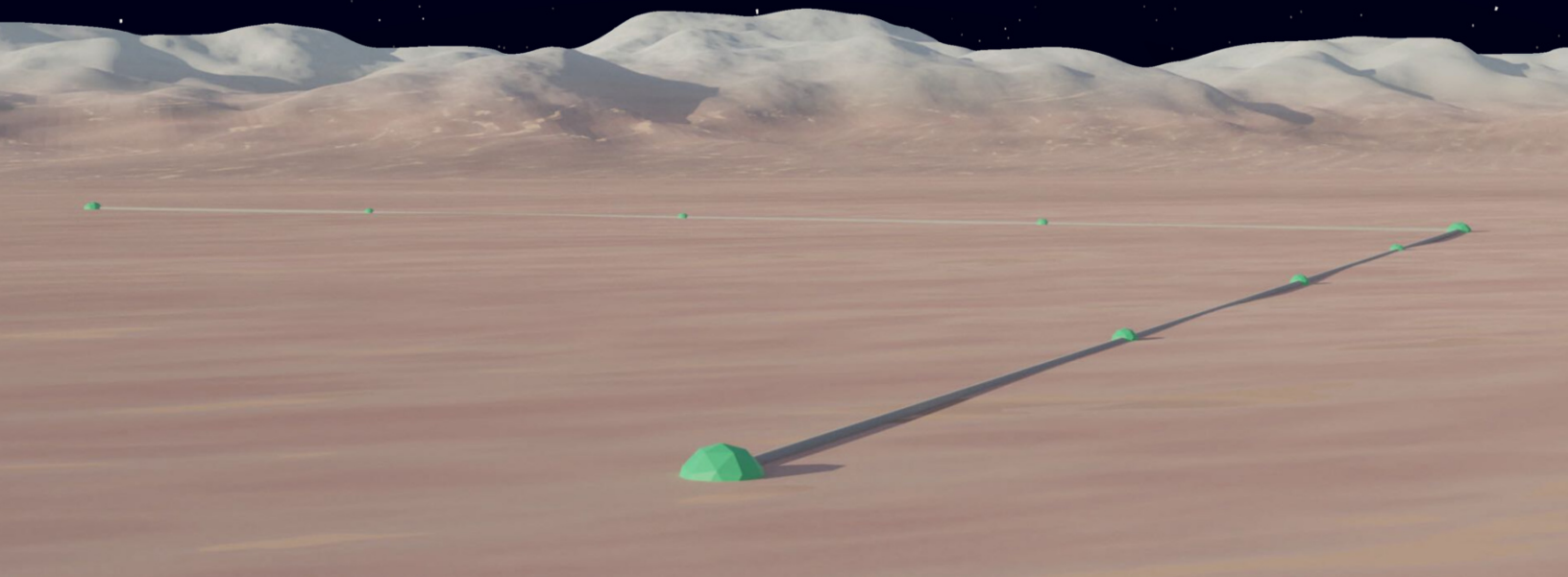


Comments and feedback are invited on this Horizon Study. For the next revision, feedback is most useful if received by July 15, 2021. Please submit feedback via the web form at <https://cosmicexplorer.org/horizon-study-feedback> or via email to ce-questions@cosmicexplorer.org

A Horizon Study for

Cosmic Explorer

Science, Observatories, and Community



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Cover Image

The cover image shows an artistic rendering of Cosmic Explorer [credit: Evan Hall (MIT)] beneath a numerical-relativity simulation of a binary black hole emitting gravitational waves [credit: Nils Fischer, Harald Pfeiffer, Alessandra Buonanno (Max Planck Institute for Gravitational Physics), Simulating eXtreme Spacetimes (SXS) Collaboration].



This study was funded by the National Science Foundation.

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Summary and Purpose

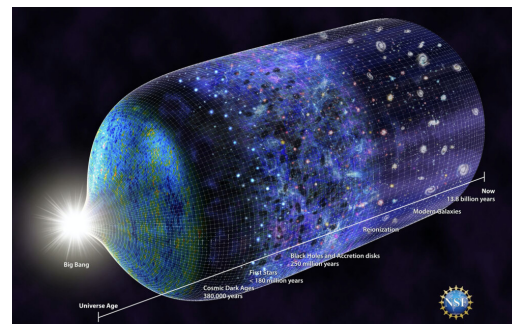
1 Executive Summary

Gravitational-wave astronomy has revolutionized humanity's view of the universe. Investment in the field has rewarded the scientific community with the first direct detection of a binary black hole merger and the multimessenger observation of a neutron-star merger. Each of these was a watershed moment in astronomy, made possible because gravitational waves reveal the cosmos in a way that no other probe can. Since the first detection of gravitational waves in 2015, the National Science Foundation's LIGO and its partner observatory, the European Union's Virgo, have detected over fifty binary black hole mergers and a second neutron star merger—a rate of discovery that has amazed even the most optimistic scientists.

This Horizon Study describes a next-generation ground-based gravitational-wave observatory: **Cosmic Explorer**. With ten times the sensitivity of Advanced LIGO, Cosmic Explorer will push the gravitational-wave astronomy towards the edge of the observable universe ($z \sim 100$). The goals of this Horizon Study are to: describe and evaluate design concepts for Cosmic Explorer; to plan for the United States' leadership in gravitational-wave astronomy; and to envisage the role of Cosmic Explorer in the international effort to build a “Third-Generation” (3G) observatory network that will make discoveries transformative across astronomy, physics, and cosmology.

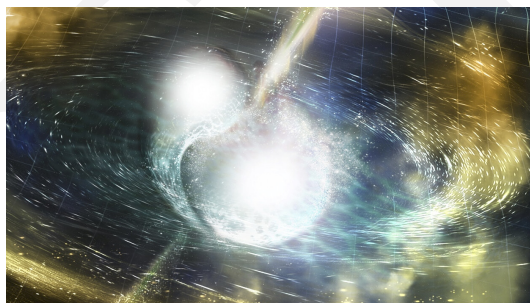
Major discoveries in astronomy are driven by three related improvements: better sensitivity, higher precision, and opening a new observational window. Cosmic Explorer promises all of these. The nature of gravity means that with a one order-of-magnitude sensitivity improvement over current detectors Cosmic Explorer will see gravitational-wave sources across the history of the universe. With its unprecedented sensitivity, Cosmic Explorer will make discoveries that cannot yet be anticipated, especially since gravitational waves reach into regions of the universe that electromagnetic observations cannot explore. With Cosmic Explorer, scientists can use the universe as a laboratory to test the laws of physics and study the nature of matter. In addition to Cosmic Explorer's extraordinary discovery potential, this Horizon Study focuses on three key science areas in which Cosmic Explorer will make a particularly dramatic impact:

Black Holes and Neutron Stars Throughout Cosmic Time. Understanding how the universe made the first black holes, and how these first black holes grew, is one of the most important unsolved problems in astrophysics. Cosmic Explorer will detect gravitational waves from binary black holes and neutron stars out to the edge of the visible universe, providing a view of Cosmic Dawn complementary to what is expected from the James Webb Space Telescope. Cosmic Explorer will be able to see evidence for the first stars by detecting the mergers of the black holes they leave

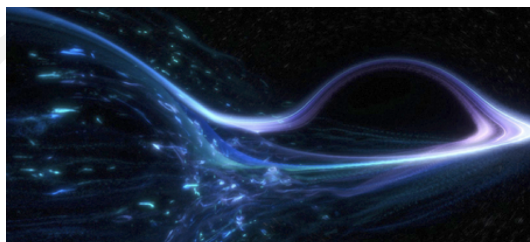


behind. The millions of mergers detected by Cosmic Explorer will map the population of compact objects across time, detect the first black holes that contributed to seeding the universe's structure, explore the physics of massive stars, and reveal the processes that create black holes and neutron stars.

Dynamics of Dense Matter. While a quantitative theory of nuclei, neutron-rich matter and deconfined quark matter has begun to emerge, understanding the nature of strongly interacting matter is an unsolved problem in physics. By observing many hundreds of loud neutron star mergers and measuring their radii to 100 m or better, Cosmic Explorer will probe the phase structure of quantum chromodynamics, revealing the nuclear equation of state and its phase transitions. Cosmic Explorer's ability to detect and study the hot, dense remnants of neutron star mergers will provide an entirely new way of mapping out the dense, finite-temperature region of the quantum chromodynamics phase space, a region that is currently unexplored. A plethora of multimes-senger observations will map heavy-element nucleosynthesis, explain the build-up of the chemical elements that are the building blocks of our world, and explore the physics of the binary-merger engine powering short gamma-ray bursts.



Extreme Gravity and Fundamental Physics. Cosmic Explorer's increased discovery aperture will allow it to observe both loud and rare gravitational-wave events—events that will reveal physics of the most extreme gravity in the universe as well as events from unusual and novel objects. LIGO and Virgo are already detecting events that we do not fully understand. With its higher-fidelity detections Cosmic Explorer will reveal the nature of these mysterious sources. Cosmic Explorer will be able to look for the effects of dark matter in the cores of neutron stars and probe the nature of dark energy by looking for its imprint in gravitational-wave signals from the cosmos. Cosmic Explorer's precision observations of black holes could help develop a viable theory of quantum gravity.



Cosmic Explorer's order-of-magnitude sensitivity improvement will be realized using a dual-recycled Fabry–Pérot Michelson interferometer, the technology employed by all current gravitational-wave detectors. Cosmic Explorer's increased sensitivity comes primarily from scaling up the detector's length from 4 to 40 km. This increases the amplitude of the observed signals with effectively no increase in the detector noise. From the topographical and geological point of view, many sites exist that could accommodate a Cosmic Explorer design with a 40 km detector at facilities in the continental United States. When selecting sites, partnership with the local and regional communities, and Indigenous Peoples will be of utmost importance to ensure respect for cultural, environmental, socio-economic, political, and other impacts of hosting a Cosmic Explorer observatory. Hazards including earthquakes, floods, storms, and fires must also be considered, especially with the view of a long-lived facility and a changing environment.

There are many design choices that could realize some or all of Cosmic Explorer’s wide range of scientific opportunity. The reference design considered in this Horizon Study is a 40 km detector and a 20 km detector, both located in the United States, with a total estimated cost of \$1892M (2030 USD). Alternative configurations of two 20 km detectors a single 40 km detector are estimated to cost \$1468M (2030 USD) and \$1180M (2030 USD), respectively. If the MREFC preliminary design phase begins in the mid 2020s, then Cosmic Explorer’s first observing runs could take place in the early 2030s. As the field moves forward, it will be essential to engage the broadest possible set of scientific stakeholders in Cosmic Explorer’s science to define its operational parameters. This includes defining Cosmic Explorer’s scientific priorities and the best detector technologies, network design, and operational parameters needed to realize this science.

This Horizon Study includes a preliminary trade study that illustrates how the range of observational science possible with Cosmic Explorer depends on the number of detectors, their characteristics, their locations, and cost are varied (summarized in Table 1.1). Different configurations for Cosmic Explorer are explored, each embedded in a variety of global networks including the Einstein Telescope, the Japanese KAGRA observatory, the LIGO-India detector, Voyager (a possible upgrade of the LIGO facilities using some of the 3G technologies), a potential detector in Australia, and the existing second-generation (2G) observatories. The community is encouraged to use this as a launch point to engage as Cosmic Explorer’s design parameters are developed in the coming years.

This Horizon Study describes a Cosmic Explorer project organization that follows the model successfully employed by LIGO: two US-based Cosmic Explorer facilities constructed in one project, followed by a transition to an operations organization. The project will be managed using well-established methods for addressing technical, managerial and political risks. The Cosmic Explorer timeline spans multiple decades and will take place in distinct stages: concept development; observatory design and site preparation; construction and commissioning; initial operations; operations at nominal sensitivity; observatory upgrades; and operations. The Cosmic Explorer facilities are intended to be long-lived, allowing the potential for future detector upgrades with technologies yet to be discovered.

The operations stage will embrace daily operations, production of observation data, and low-latency astrophysical searches to produce astronomical alerts. Given the substantial investment and broad community support that will be required to realize a US third-generation gravitational-wave observatory, Cosmic Explorer is planned to be an Open Data facility in its operations phase. In this model, the Cosmic Explorer project is responsible for detector operations, calibration, curation of the detector data streams, and dissemination of detector data and rapid alerts to the scientific community. Cosmic Explorer will generate a data set that provides a unique, rich, and deep view of the universe over its lifetime. An open data approach will facilitate scientific collaboration, maximize the scientific community’s investment in the project, as well as supporting scientists from small institutions and historically underrepresented institutions.

Gravitational-wave astronomy is global. The United States can address a much larger number of scientific questions if Cosmic Explorer is operated as a leading part of a world-wide network

of observatories. As part of a multimessenger network of international gravitational-wave observatories, astro-particle detectors, and telescopes across the electromagnetic spectrum, Cosmic Explorer will precisely localize and study the nature of a multitude of sources. Laboratory and accelerator studies of heavy ions and rare isotopes will help Cosmic Explorer determine the physics of dense matter. Gravitational-wave observations are generated by physical processes that are vastly different from those that generate other forms of radiation and particles and can see into regions of the universe that cannot be observed in any other way. It would be a profound anomaly in astronomy if nothing new and interesting came from Cosmic Explorer's vast improvement in sensitivity.

With foundations laid by decades of National Science Foundation investment and the work of a large community of scientists, Cosmic Explorer is poised to propel another revolution in our understanding of the universe. The community is invited to join the effort to define, shape, and realize Cosmic Explorer: the future of gravitational-wave astronomy.

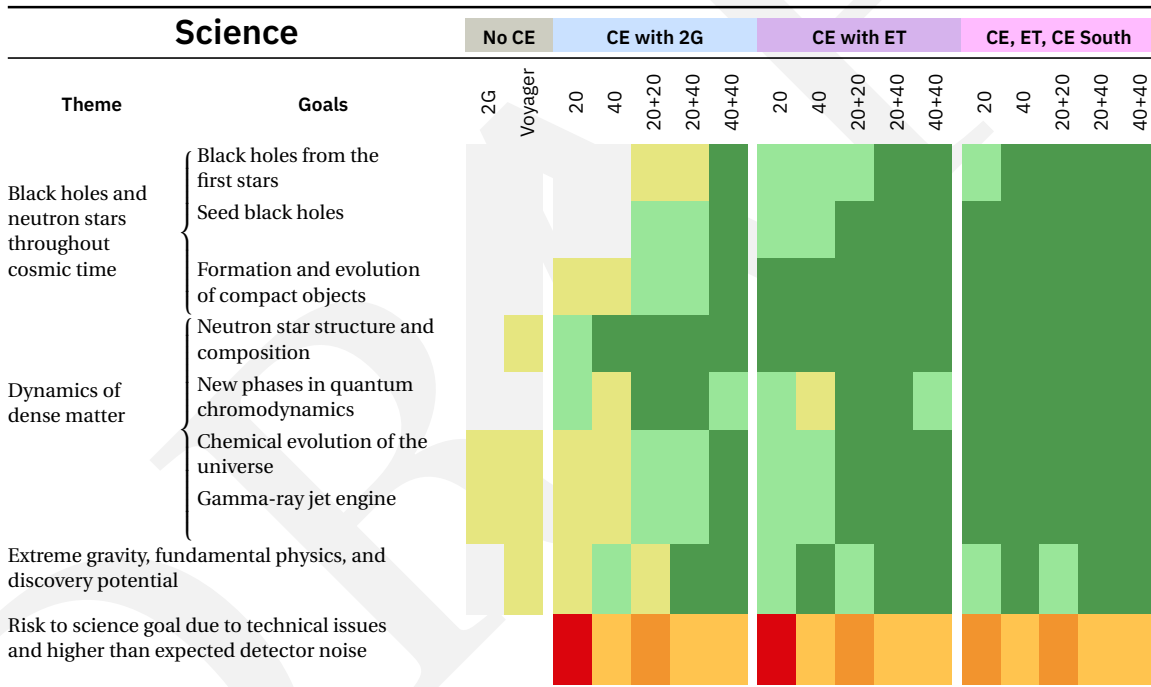


Table 1.1: This graphic indicates the level to which key science goals can be achieved by different Cosmic Explorer configurations; details can be found in §7.2.1. A US Cosmic Explorer consisting of one 20 km detector, one 40 km detector, or a pair of detectors of 20 or 40 km length are evaluated against a background network that includes second-generation (2G) gravitational-wave observatories, the EU Einstein Telescope (ET) and a 20 km Cosmic Explorer-like detector located in Australia (CE South). Yellow indicates that this network can begin to explore the science goal, light green indicates that the network can achieve a good understanding, and dark green indicates that the network can realize the full science potential. Longer, more sensitive detectors are generally better, and a network is required for many science goals. For example, studying black holes from the first stars requires a 40 km detector that can see black holes at $z \gtrsim 10$ in a network that can measure both gravitational-wave polarizations to accurately measure the hole's redshift. The exception to the rule is the observation of neutron star post-merger signatures to probe finite-temperature quantum chromodynamics, where tuning one 20 km detector allows better narrow-band tuning for this source. This study is a starting point for community input to the design of Cosmic Explorer.

2 Purpose and Scope

The LIGO observatories are continuing to extend their astrophysical reach into new discovery space, but in the coming decade they will reach the limits imposed by their facility size and lifetime. These observatories will be replaced by a new generation of gravitational-wave observatories, known as third-generation (3G) or next-generation observatories, with longer baselines and new infrastructures. The international community's vision for next-generation science is detailed in white papers published by the Gravitational Wave International Committee,¹ and plans toward a next-generation gravitational-wave observatory in Europe, Einstein Telescope, are well underway.²

This Horizon Study is part of the development stage of a major facility project,³ the US-based next generation gravitational-wave observatory known as Cosmic Explorer (CE). The purpose of this document is to provide a clear vision of the science enabled by CE, a reference concept for the CE instrument and its evolution, and initial cost estimates for its construction and operation. It is intended to inform the scientific community, and the agencies which fund that community, with the goal of providing a foundation for further development of CE in those communities while spurring action toward CE's construction. This document, together with reports from the Gravitational Wave International Committee (GWIC),^a will form the point of departure for the process leading to the design stage of the Cosmic Explorer Project.³

The major science themes that will be addressed by Cosmic Explorer and their associated goals are presented in §§3–5. §6 presents a consideration of the type of detection technology to be used, including a discussion of alternative technologies, and presents a reference concept based on ground-based laser interferometric detection technology, which is well suited for achieving the science goals.

Given that funding for the next generation of detectors must be directed so as to maximize the resulting scientific output, this Horizon Study presents a preliminary trade study for CE in §7. This trade study documents the impact of design and funding choices on the scientific output of CE, and in particular on the key science goals presented in §5. Of particular interest are the overall length of the CE arms, since this is the primary cost driver, and the possibility of building multiple observatories in the US. The community is encouraged to use this trade study as a launch point to engage in the development of Cosmic Explorer's design parameters.

With the key scientific objectives and overview of the CE design in hand, the rest of the document focuses on the technology needed to achieve Cosmic Explorer. The technical design concept, along with site and infrastructure requirements, is presented in §8. A data-management plan, and the human and computational resources needed to deliver open data and multimes-

^ahttps://gwic.ligo.org/3Gsubcomm/documents/GWIC_3G_Community_Networking_Report_Sep_2020.pdf

senger alerts are presented in §9, along with a survey of the broader computing requirements and analysis costs.

The plans presented in this Horizon Study can only be successful with continued input from and strong endorsement by the scientific community, as well as early engagement with local communities, including Indigenous Peoples, at potential observatory locations. The vision of Cosmic Explorer as part of diverse local and global communities, and its anticipated role as part of the global gravitational-wave network, are presented in §10.

§11 presents a cost estimate for CE construction and operation, along with a timeline and management outline for the project. This includes a discussion of technical and project management risk, based on risk management strategies employed by LIGO and other large projects. The timeline starts with ongoing research and development work, and lays out a path to astrophysical observation with CE. Both Initial and Advanced LIGO were delivered on time and on budget and CE will benefit greatly from the experience earned through the LIGO project. The management plan and cost-budget schedule presented here is based upon the successful Advanced LIGO management model, taking into account the lessons learned. Finally, conclusions are reported in §12.



Science Objectives

3 Overview

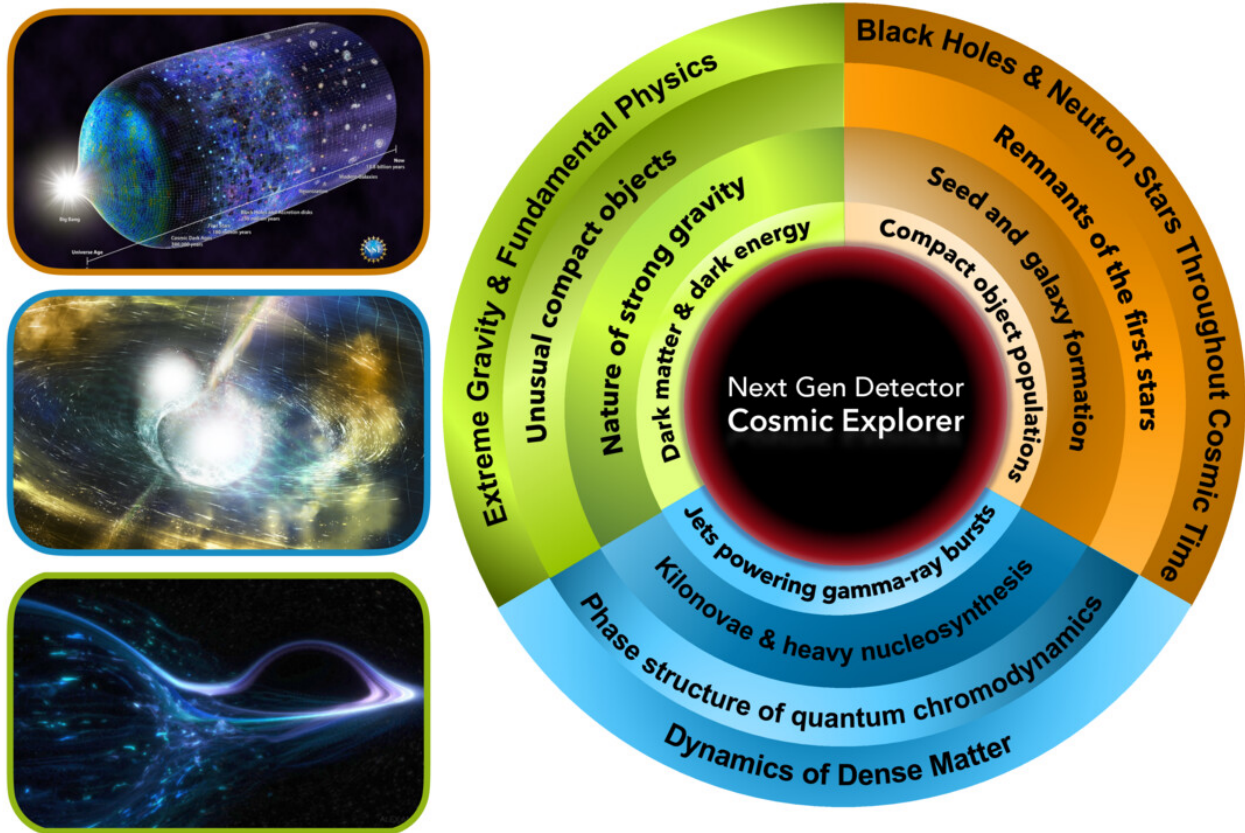


Figure 3.1: Central science themes and objectives that will be addressed by Cosmic Explorer. Cosmic Explorer’s greatly increased sensitivity over today’s detectors provides access to significantly more sources, spread out over cosmic time, as well as high-fidelity measurements of strong, nearby sources. Sections 5.1–5.3 provide a more detailed description of the science enabled by Cosmic Explorer. Credits for images to left, from top to bottom: N.R.Fuller, National Science Foundation; Aurore Simonnet, Sonoma State University; Alex Andrix.

The gravitational-wave discoveries by Advanced LIGO and Advanced Virgo have opened a new window on the universe. There is significant international interest in and mobilization toward developing a next generation of ground-based gravitational-wave observatories that would be capable of observing gravitational waves throughout the history of star formation and exploring the workings of gravity at its most turbulent and extreme. Broad and detailed community studies of the potential for a network of such observatories (and its synergy with other types of

gravitational-wave observatories and electromagnetic and astroparticle observatories) have been organized by the Gravitational-Wave International Committee (GWIC) and summarized in a series of white papers.¹ The science case for a next-generation network, extensively described in the GWIC 3G Science Case Report along with a series of 2020 Astro Decadal Survey white papers,⁴⁻⁸ is highly compelling, and the Einstein Telescope team has independently developed a science case for their planned facility.⁹

Through our study we have identified **three central scientific themes**, similarly inspired by the broader community, that Cosmic Explorer will address (illustrated in Fig. 3.1):

1. **Black Holes and Neutron Stars Throughout Cosmic Time**, §5.1
2. **Dynamics of Dense Matter**, §5.2
3. **Extreme Gravity and Fundamental Physics**, §5.3

Additionally, we discuss the broad and deep discovery aperture of Cosmic Explorer and its potential for observing unexpected phenomena, §5.4.

Associated with each scientific theme are a number of key objectives. Some of these are achievable by a single Cosmic Explorer observatory operating on its own, while others will require an additional observatory or a network to achieve. Similarly, some objectives are guaranteed, based on Cosmic Explorer’s expected performance and what we have already learned about gravitational-wave science, while others are not certain but would provide extraordinary or even revolutionary outcomes. Fig. 3.2 shows the key science objectives for Cosmic Explorer arranged on axes corresponding to these considerations.

A “trade study” of how effectively different visions of Cosmic Explorer could address these science themes, along with a resulting science-driven design concept for Cosmic Explorer, are presented later in §7 and §8. A science traceability matrix describes the measurements required to accomplish the science goals, and the instrument requirements needed to achieve these measurements. This study relies on knowledge (e.g., event rates and observations of gravitational-wave sources) that was not available when today’s detectors were designed. In contrast, Cosmic Explorer’s ultimate design will be informed by what the existing observatories have discovered, and will continue to discover, about the gravitational-wave universe. The science traceability matrix reveals that addressing Cosmic Explorer’s science goals will require detectors with a strain sensitivity of $6 \times 10^{-25} / \sqrt{\text{Hz}}$ at 10 Hz and $2 \times 10^{-25} / \sqrt{\text{Hz}}$ at 100 Hz; compared to Advanced LIGO this an order of magnitude sensitivity improvement at 100 Hz and opens the low-frequency gravitational-wave band for observation. This leap in sensitivity between the 2G and 3G detectors, shown in Fig. 3.3 and Fig. 3.4, will expand humanity’s gravitational-wave access from the first nearby discoveries to the majority of stellar-mass black hole and neutron star coalescences in the universe. The current status of the 2G detectors and path toward the next generation is outlined below in §4.

Cosmic Explorer Science Themes

- Black Holes and Neutron Stars Throughout Cosmic Time
- Dynamics of Dense Matter
- Extreme Gravity and Fundamental Physics
- Discovery Potential

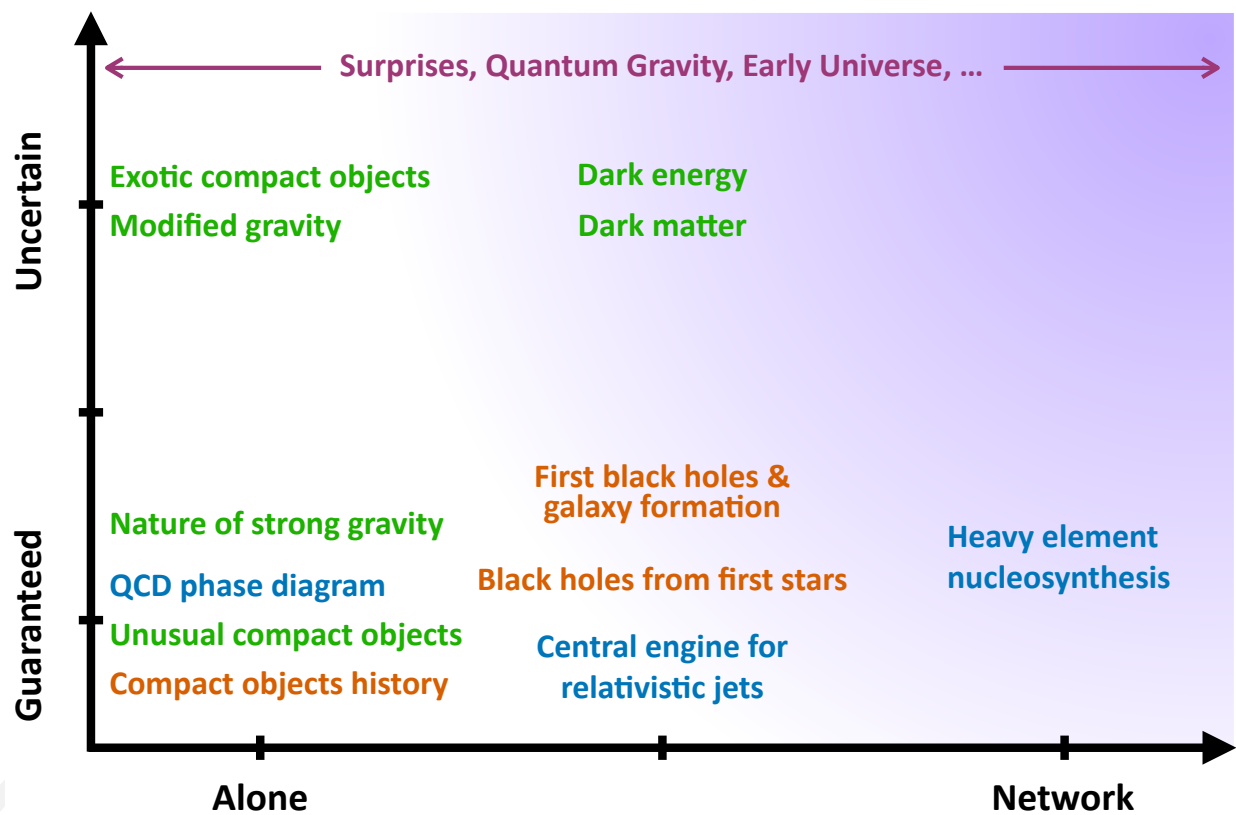


Figure 3.2: The key science objectives for Cosmic Explorer’s central themes, located on axes that qualitatively assess the likelihood of observing gravitational waves related to those objectives, ranging from guaranteed to uncertain, and the number of detectors required to achieve those objectives, ranging from Cosmic Explorer alone, through Cosmic Explorer with a small or second-generation network, to Cosmic Explorer as part of a full third-generation network. The “Discovery Potential” objectives in purple are uncertain and span the space from alone to requiring a full network.

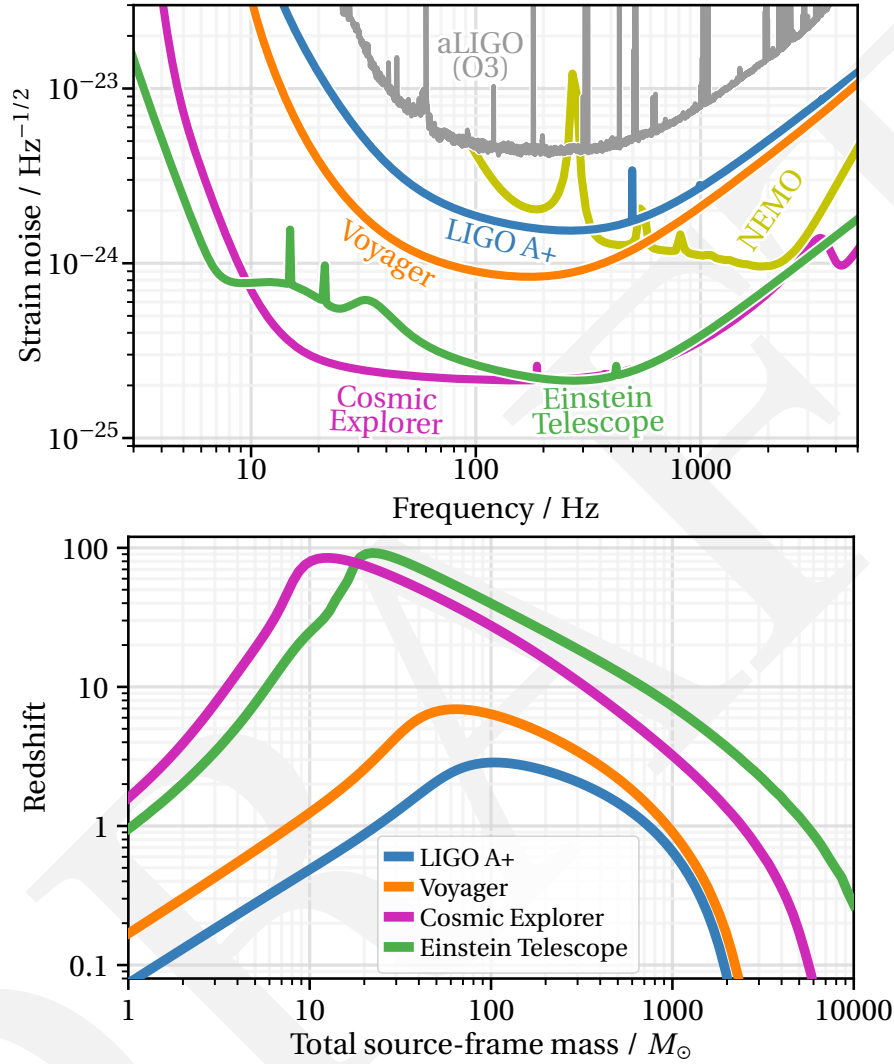


Figure 3.3: *Top*: Amplitude spectrum of the detector noise as a function of frequency for Cosmic Explorer (CE), the current (O3) and upgraded (A+) sensitivities of Advanced LIGO, LIGO Voyager, NEMO, and the three paired detectors of the triangular Einstein Telescope. At each frequency the noise is referred to the strain produced by a source with optimal orientation and polarization. *Bottom*: Maximum redshift (vertical axis) at which an equal-mass binary of given source-frame total mass (horizontal axis) can be observed with a signal-to-noise ratio of 8.¹⁰ Different curves represent different detectors. For binary neutron stars (total mass $\sim 3M_{\odot}$), CE will give access to redshifts larger than 1, where most of the mergers are expected to happen. For binary black holes, it will enable the exploration of redshifts of 10 and above, where mergers of black holes formed by either the first stellar population in the universe (Pop III stars) or by quantum fluctuations shortly after the Big Bang (primordial black holes) might be found.

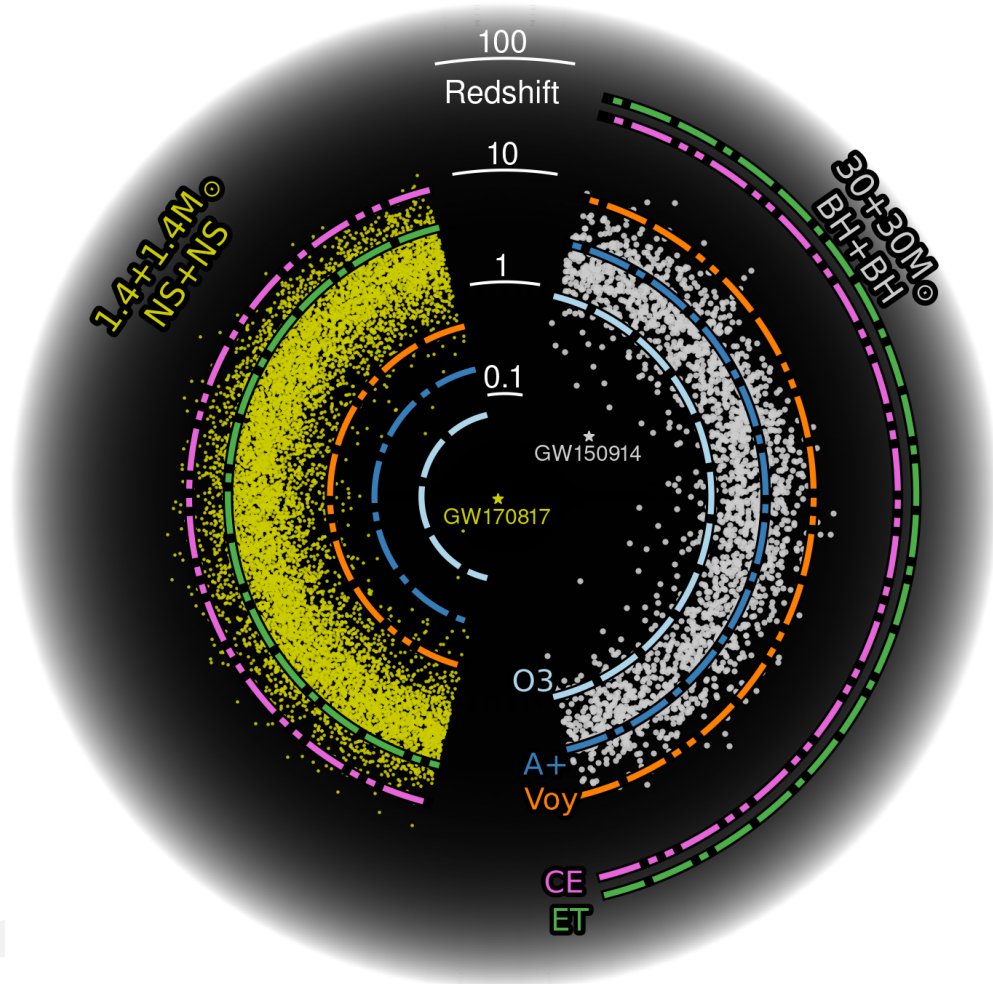


Figure 3.4: Astrophysical horizon of current and proposed future detectors for compact binary systems. As in the bottom of Fig. 3.3, the lines indicate the maximum redshift at which a detection with signal-to-noise ratio 8 could be made. The detectors shown here are Advanced LIGO during its third observing run (“O3”), Advanced LIGO at its anticipated sensitivity for the fifth observing run (“A+”), a possible cryogenic upgrade of LIGO called Voyager (“Voy”), the Einstein Telescope (“ET”), and Cosmic Explorer (“CE”). The yellow and white dots are for a simulated population of binary neutron star mergers and binary black hole mergers, respectively, following Madau and Dickinson [11] with a characteristic binary merger time of 100 million years.

4 Status of Ground-Based Gravitational-Wave Observatories

A century after Einstein's prediction of gravitational waves, Advanced LIGO¹² debuted this new “sense” for humanity by observing coalescing binary systems of black holes^{13–15} with up to tens of solar masses¹⁶ and enabling tests of relativity in the strong gravity regime.¹⁷ In 2017, LIGO and its European partner Virgo¹⁸ inaugurated an era of gravitational-wave multimessenger astronomy by discovering a binary neutron star merger with a gamma-ray-burst counterpart,¹⁹ and rapidly sharing its source location with the broader astronomical community, triggering observations of the system across the electromagnetic spectrum.²⁰ The scientific goldmine opened by these observations has connected binary neutron star mergers with short gamma-ray-bursts and equated the speed of gravity to very precisely that of light,²¹ provided a gravitational-wave measure of the local Hubble constant,²² given strong clues about the origin of heavy elements,²³ and probed the properties of ultra-dense nuclear matter.^{19,24}

These initial successes of the Advanced LIGO Project were the result of forty years of research and development, including prototypes of increasing scale and the first generation LIGO detectors, and strong international collaborations. These efforts delivered the technology and engineering needed to build the second-generation detectors. They also trained the early-career scientists and engineers who envisioned, built, and are operating these observatories, and fostered a community that is searching for gravitational-wave sources and extracting astrophysical information from these observations.

The LIGO and Virgo observatories have continued to increase their reach and discovery rate, revealing populations of astrophysical events^{25–28} and routinely issuing alerts to the broader astronomical community.²⁹ At its 2018 sensitivity, this network was reporting observations of tens of black hole mergers and of order one merger involving a neutron star per year.³⁰ At the time of writing, the 2G observatory network is being strengthened by the Japanese KAGRA observatory³¹ and by an enhancement to Advanced LIGO known as A+. ³² A planned joint US-India detector, LIGO-India,³³ has received in-principle approval from the Indian government and progress has been made toward selecting and acquiring a site. Additionally, progress has been made toward “Voyager” technology to possibly maximize the potential of the existing LIGO facilities by implementing cryogenic silicon optics and suspensions and reducing quantum and Newtonian (gravity gradient) noise.^{34,35} Options for lasers, photodiodes, and electro-optics for Voyager's planned 2 μm operating wavelength as well as cryogenic engineering solutions to cool the suspended optics have been identified and will soon be tested in an upgrade to the Caltech 40-m prototype³⁶ and the European ETpathfinder prototype.³⁷ LIGO and its partners are

providing dramatic and deepening insights into the populations and lifetimes of black holes and the inner workings of neutron stars. However, these 3–4 km detectors can offer only a glimpse of the full gravitational-wave universe.

Three next-generation observatory concepts have emerged. In Europe, plans have solidified for the Einstein Telescope or ET. The first ET Design Report was published in 2011 and updated in 2020.² It describes a single-site observatory with 10 km-long arms located 200–300 m underground to reduce seismic motion and Newtonian noise, with low-frequency detectors operated at cryogenic temperatures (10–20 K) to reduce thermal noise (especially the Brownian motion of molecules in the optics and their coatings) and high-frequency detectors using very high laser power and frequency-dependent squeezed light to reduce the impact of the laser light’s quantum noise. In 2021, a proposal was submitted to include ET in the 2021 update of the European Strategic Forum for Research Infrastructures (ESFRI) roadmap. If that proposal succeeds, ET will enter a preparatory phase with construction possible by 2026 and observations by 2035.³⁸ An Australian-led project, NEMO,³⁹ envisions a 4 km-baseline detector with excellent sensitivity targeting the higher frequency band (1–3 kHz) associated with gravitational-waves from the postmerger phase of neutron stars. Cosmic Explorer^{40,41} is the planned United States contribution to the next-generation gravitational-wave observatory network and the focus of this study.

With that introduction to the detectors, we now turn to a discussion of the scientific opportunities of broad interest that will be opened by Cosmic Explorer.

5 Key Science Questions

The key science questions to be addressed by Cosmic Explorer are presented below. The gravitational-wave spectrum is rich with sources, and many more scientific opportunities will be explored by the third generation network than described here. This selection was made for the purposes of clarity and to focus on the most compelling science that will be accessible with Cosmic Explorer.

5.1 Black Holes and Neutron Stars Throughout Cosmic Time

Cosmic Explorer can detect merging stellar-mass black holes mergers that happened when the universe was less than 500 Myrs old. This immense reach will reveal for the first time the complete population of stellar-mass black holes in binaries, starting from an epoch when the universe was still assembling its first stars. Cosmic Explorer will detect hundreds of thousands of black-hole mergers each year, measuring their distances, masses and spins. These observations will reveal the black-hole merger rate, the underlying star formation rate, how both have changed throughout cosmic time, and how both are correlated with galaxy evolution.

5.1.1 Remnants of the First Stars

The first stars formed when the universe was only a few hundred million years old. With no previous generation of stars to process the primordial gases of the universe, these stars, known as Population III or “Pop III” stars, were almost entirely composed of hydrogen and helium.⁴² Due to their pristine composition, they are believed to have been extremely massive, with masses more than a hundred times that of the sun.⁴³ Despite intensive observational efforts, to date

Box 5.1: Key Science Question 1

How have the populations of black holes and neutron stars evolved over the history of the universe?

Cosmic Explorer will detect gravitational waves from black holes and neutron stars in binaries to redshifts of ~ 10 and above, allowing us to:

- Shed light on Population III stars through the black holes they might have left behind;
- Measure the properties of the first black holes and their role in galaxy formation;
- Characterize the populations of compact objects and their evolution.

there are no claims of detection of Pop III stars. Since the rate at which stars burn their nuclear fuel increases dramatically with their mass, it is plausible that no Pop III stars have continued to emit light long enough to be observed in the local universe. The James Webb Space Telescope⁴⁴ should be able to observe the very first galaxies formed in the universe, which only contained Pop III stars,⁴⁵ and study their role in the epoch of reionization, but not individual Pop III stars.⁴⁶

After burning their nuclear fuel, Pop III stars, like other stars, may collapse to form compact objects such as black holes. If the mass of Pop III stars is above $\sim 230 M_{\odot}$, they should not trigger a pair instability supernova (PISN) – an explosion that entirely destroys the star, leaving no compact object behind – but instead directly collapse into a black hole with minimal mass loss. Less massive stars might leave behind black holes below the PISN mass gap, i.e., with masses up to $\sim 60 M_{\odot}$.^{47–50} Depending on the initial mass distribution (mass function) of Pop III stars, we expect to find black holes in the early universe with masses of tens to hundreds of solar masses, possibly with a mass-gap between ~ 60 and $\sim 150 M_{\odot}$ due to PISN.⁵¹ Detecting and characterizing the black holes generated by Pop III stars can thus be a powerful method to study the properties of their progenitor stars, including masses and composition. Knowledge of the mass function of the first generation of stars in the universe could change our understanding of how galaxies formed (see next subsection).

Unfortunately, both existing X-ray telescopes, and those currently proposed for the 2030s (e.g., the Lynx⁵² and Athena⁵³ X-ray observatories) would only be able to detect and measure the mass of supermassive black holes, hence leaving totally unexplored a region of the mass spectrum that is likely to have been populated by Pop III stars. The LISA gravitational-wave detector⁵⁴ will also not be sensitive to black holes in that mass range at redshifts of 10 or more. By contrast, Cosmic Explorer can detect stellar mass black holes to redshifts beyond 10, if they merge in binary systems, and is the most promising tool for investigating the life and death of the first generation of stars.

5.1.2 Seed Black Holes and Galaxy Formation

Supermassive black holes (SMBHs), with masses of millions to billions of solar masses, are known to exist at the center of most galaxies, and to significantly impact the evolution, energetics and dynamics of their host galaxies.^{55,56} The study of galaxy formation is thus intimately related to understanding how and when the central black holes formed, which is an area of extremely intense research.

A key open question is: how did supermassive black holes form so early in the history of the universe? Compelling evidence shows that SMBHs of billions of solar masses already existed at redshift of $\gtrsim 7.6$,⁵⁷ when the universe was only 670 million years old. The relatively short time scale over which SMBHs were produced challenges our understanding of how black holes form and grow. The two main scenarios that have been suggested to explain the presence of high-redshift SMBHs are (1) direct collapse of hydrogen clouds into black holes, followed by gas accretion, and (2) repeated mergers of smaller black holes through gravitational runaway processes.⁵⁸

If the first black holes in the universe were the remnants of the first generation of stars, as mentioned above they could have masses up to a few hundred solar masses. Repeated mergers of black holes, starting from tens or hundreds of solar masses, passing through the regime of intermediate-mass black holes (IMBHs, in the mass range $\sim[10^2, 10^5] M_\odot$), could eventually result in SMBHs of billions of solar masses. The LIGO and Virgo observatories have detected gravitational waves from the merger of two heavy black holes, GW190521, whose merger gave birth to a black hole of $\sim 150 M_\odot$ at redshift of ~ 0.8 . The merger product might represent the first-ever detection of an intermediate-mass black hole, though a light one. Advanced detectors will observe more of these systems in the next few years, and start measuring their merger rate and mass distribution. Advanced detectors or their upgrades (Fig. 3.3 bottom), however, will not be able to detect a $100\text{--}100 M_\odot$ IMBH at redshifts larger than 3. By contrast, Cosmic Explorer will be able to observe them to redshifts larger than 10. Measuring the mass function and merger rate of heavy and intermediate-mass black holes at those redshifts would directly illuminate their role in the formation of SMBHs.

5.1.3 Formation and Evolution of Compact Objects

LIGO and Virgo have detected black holes with masses as light as $2.5 M_\odot$ (if indeed the lighter component of GW190814 is a black hole⁵⁹) and as heavy as $150 M_\odot$.⁶⁰ While most of the black hole binaries seem to have small spins (or, more precisely, a small projection of the mass-weighted total spin along the orbital angular momentum, χ_{eff} ^{61,62}), some systems show large spins, or spins which are misaligned with the orbit.⁶³ It is unlikely that this variety of parameters can be the result of a single astrophysical formation channel.^{30,64} In fact, different formation scenarios are expected to result in different distributions for the masses and spins of the black holes. The two channels which are usually expected to produce most black hole binaries are isolated formation in galactic fields^{65,66} and dynamical encounters in dense environments (e.g., globular clusters,^{67,68} nuclear star clusters, and the disks of active galactic nuclei^{69,70}). The former is expected to form black holes with masses that track the stellar initial mass function, while the latter could produce heavier black holes, due to the possibility of repeated in situ mergers.^{71–74} Other parameters of the environment, e.g., the metallicity, also strongly affect the mass of the resulting compact objects.⁷⁵ Similarly, the magnitude and orientation of the spins in the binary will depend on where the system formed, and on the details of the supernovae explosions that created the black holes.⁷⁶ Gravitational-wave observations measuring these parameters can aid in understanding where black hole binaries formed, providing precious clues about the evolution and properties of their environments, and thus of galaxies and their surroundings.

While LIGO and Virgo have opened up this new frontier of observational astrophysics, they are also intrinsically limited in their sensitivity. Even in their A+ configuration, the current LIGO facilities will not be able to observe black hole binaries at redshifts larger than 3.^a While still enabling significant understanding of the local universe, they will not be able to say anything

^aThis is for $50\text{--}50 M_\odot$ binary black holes. For lighter and heavier systems the horizon will be smaller, as seen in Fig. 3.3.

Box 5.2: Key Science Question 2

What is the structure and composition of neutron star matter?

Cosmic Explorer will measure gravitational radiation from binary neutron star coalescences and provide the precise source localizations required for multimessenger astronomy, allowing us to:

- Explore new regions in the phase diagram of quantum chromodynamics;
- Map heavy element nucleosynthesis in the universe through counterpart kilonovae and distant mergers;
- Reveal the central engine for the highly relativistic jets that power short gamma-ray bursts.

about how efficient the production of black holes was, or what their properties were, earlier in the history of the universe. This is of fundamental importance, since the merger rate in different channels is expected to be rather similar up to redshifts of ~ 2 , and have different high-redshift behaviors. Searches for the stochastic signal produced by unresolved sub-threshold binaries will give hints about their high-redshift distribution, but with large uncertainties (compare, e.g., Refs. [77] and [78]). Understanding how the rate and sites of production of black hole binaries evolved across the age of the universe will provide hints about, for example, the evolution of the star formation rate, a quantity which is hard to measure at high-redshift using photons.¹¹ More importantly, advanced detectors, and the proposed upgrades such as Voyager, would entirely miss black hole mergers at redshifts larger than ~ 7 .⁷⁸ This will preclude probing the formation and merger of black holes created by Pop III stars, as described above, and other possible high-redshift channels, e.g., primordial black holes created during the inflationary epoch of the universe. It is only with next-generation detectors like CE that we will be able to understand the efficiency and characteristics of each formation channel that generates black hole binaries, anywhere in the observable universe.

Similar considerations can be made for neutron stars. The discovery of GW190425,⁷⁹ a binary neutron star system much heavier than known galactic systems suggests that the astrophysical properties of neutron stars might be more diverse than what has been observed in the Milky Way. Next-generation observatories will provide access to neutron star binaries all the way to redshift ~ 10 , and give us a clear picture of how their parameters vary across cosmic history and galactic environments.

5.2 Dynamics of Dense Matter

Neutron stars are made of the densest known matter in the universe and can support incredibly large magnetic fields. The merger of two neutron stars is so cataclysmic that it can produce the brightest electromagnetic emission in the cosmos and trigger the formation of heavy elements like gold and platinum. Six decades after the discovery of neutron stars, we still do not understand how matter behaves at the extreme densities and pressures attained in their cores, or how they

can generate magnetic fields a million times stronger than those created on Earth. Cosmic Explorer will detect $\sim 8 \times 10^4$ binary neutron star mergers per year out to a redshift of 4, of which ~ 10 are expected to have signal-to-noise ratios above 300. The dense-matter science these observations will enable is highlighted in Box 5.2.

5.2.1 Neutron Star Structure and Composition

Neutron stars are excellent astrophysical laboratories for ultra-dense matter. Subtle signatures of the stellar interior are encoded in the gravitational waves emitted when neutron stars coalesce,^{80–83} allowing us to probe the fundamental properties and constituents of matter in a phase that is inaccessible to terrestrial experiments.⁸⁴ The matter in neutron star cores is so dense that it cannot be described in terms of individual nucleons. It reaches equilibrium as a neutron-rich fluid and may even transition to deconfined quarks at the highest densities.⁸⁵ The phase structure of dense matter is shown schematically in Fig. 5.1.

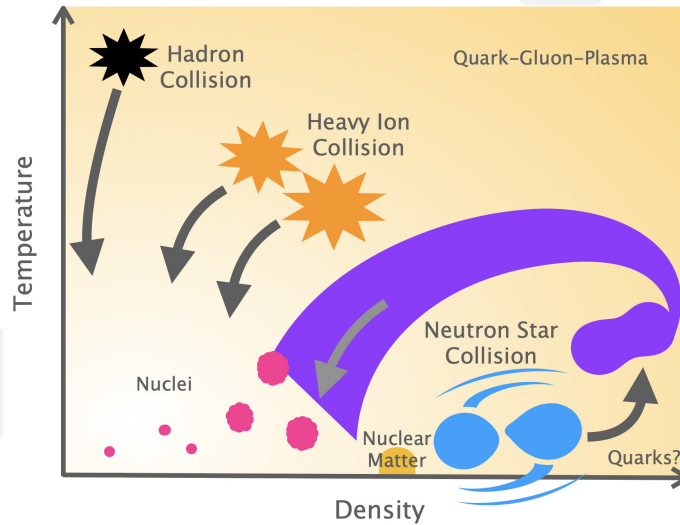


Figure 5.1: Schematic QCD phase diagram. At low densities and temperatures, matter is arranged into nuclei. As the density increases, the nuclei disintegrate into a sea of interacting neutrons and protons, so-called nuclear matter. Terrestrial collider experiments probe dense nuclear matter at high temperature, as it “melts” into a quark-gluon plasma and recombines. In contrast, the compressed cores of neutron stars hold supranuclear-density matter in a cold neutron-rich equilibrium. At the highest densities, phase transitions involving strange particles or quark matter may occur. Gravitational-wave observations of neutron stars explore this low-temperature, high-density phase from inspiral and a unique high-temperature, high-density region of the phase diagram after the stars collide. The kilonova counterpart to a neutron star merger traces the r-process nucleosynthesis that transforms neutron-star matter into heavy nuclei.

As we enter the Cosmic Explorer era, our understanding of neutron star matter will be informed by current- and near-future observations including gravitational waves,^{86–90} x-ray spectra,⁹¹ bursts,⁹² and pulsar profile modeling.^{93–96} Together, these are expected to yield $\sim 5\%$ errors on neutron star radii for dozens of sources.

Cosmic Explorer’s precision measurements of tidal deformabilities across the neutron-star mass spectrum will constrain the neutron-star radius better than 0.1 km—one part in 100—for hundreds of systems per year, revolutionizing our knowledge of the equation of state (EOS) that characterizes the ultradense matter in inspiralling neutron stars. These observations will enable us to distinguish between competing first-principles models for ultra-dense matter⁹⁷ and resolve the nature of the phase transition to quark matter,⁹⁸ if it occurs in neutron-star cores. Gravitational-wave astrophysics may also emerge from the dynamic excitation of oscillations in the component neutron stars, yielding new insight on their structure and composition.^{99–103}

Cosmic Explorer may also observe gravitational waves from spinning neutron stars; quasi-periodic signals lasting for millions of years.¹⁰⁴ Their emission requires nonaxisymmetry, which could be supported by elastic stresses in the crust, deformations due to magnetic fields, thermal asymmetries or unstable oscillations driven by accretion.^{105–107} Cosmic Explorer may reveal if gravitational waves explain the spin-down rates of millisecond pulsars,¹⁰⁸ and the corresponding ellipticities are within direct detection reach. Gravitational-wave emission could also explain the relatively low spins of accreting neutron stars in low-mass x-ray binaries.^{109–111} Observing these long-lived gravitational waves would provide additional insight into the formation and thermal, spin and magnetic field evolution of neutron stars.^{107,112}

5.2.2 New Phases in Quantum Chromodynamics

After a binary neutron star merges, oscillations of the hot, extremely dense remnant produce postmerger gravitational radiation. This heretofore undetected signal probes the unexplored high-density, finite-temperature region of the QCD phase diagram. As indicated in Fig. 5.1, this region is inaccessible to collider experiments and difficult to observe directly with electromagnetic astronomy. This is where novel forms of matter are most likely to appear.^{113–116} Cosmic Explorer is well-suited to observing postmerger gravitational waves:^{117–119} it is expected to detect ~ 100 postmerger signals every year in a 3G network.

Measurements of the dominant postmerger gravitational-wave frequency^{120–128} will reveal dense-matter dynamics with finite temperature,¹²⁹ rapid rotation¹³⁰ and strong magnetic fields.¹³¹ These observations will shape theoretical models describing fundamental many-body nuclear interactions and answer questions about the composition of matter at its most extreme, such as whether quark matter is realized at high densities.^{116,132,133} Direct gravitational-wave observations of postmerger remnants will also help determine the threshold mass for collapse of a rotationally supported neutron star,^{124,134–137} which has implications for the neutron-star mass distribution,¹³⁸ compact binary formation scenarios¹³⁹ and predictions for electromagnetic emission from neutron star mergers.¹⁴⁰

Massive stars undergoing core-collapse supernova also generate gravitational waves from the dynamics of hot, high-density matter in their central regions. Searches for supernova and various other burst-like sources are well-developed,^{141–144} and Cosmic Explorer’s anticipated sensitivity to supernovae within the Milky Way galaxy yields expected observation rates of twice per century.¹⁴⁵ Detecting these waves would provide a channel for observing the explosion’s

central engine¹⁴⁶ and the equation of state of newly formed protoneutron star.¹⁴⁷ The results could be spectacular, with signal-to-noise ratios over 1000 for sources at the galactic center (8 kpc), leading to estimates of the progenitor core's rotational energy and frequency measurements for oscillations driven by fallback onto the protoneutron star.^{148,149} Given that the facility life of Cosmic Explorer is expected to be around 30 years, detection of a galactic supernovae is certainly possible during the lifetime of the facility.

5.2.3 Chemical Evolution of the Universe

Stellar nucleosynthesis is responsible for the transformation of primordial hydrogen and helium into the light elements, but a different process must be invoked for elements heavier than iron. The observation of GW170817 and its electromagnetic counterpart established binary neutron star mergers as a key site of heavy element nucleosynthesis.¹⁵⁰ The matter ejected during a merger is hot, dense and neutron-rich, perfectly suited for sustaining rapid neutron capture (r-process) nuclear reactions. These reactions give rise to an optical and infrared afterglow—a kilonova—that can last for days or weeks.¹⁵¹ However, important questions about this picture remain to be answered: is binary neutron star nucleosynthesis the sole, or merely dominant, source of heavy elements in the universe?¹⁵² How do the binary's properties affect the quantity and composition of the ejected matter? Moving beyond a single example of a multimessenger neutron-star merger will be essential for decoding the missing links in the universe's chemical evolution.

As part of a third-generation network, Cosmic Explorer will localize ~ 20 binary neutron star mergers in the nearby universe to within ~ 0.1 deg.² every year, enabling the electromagnetic follow-up needed to connect the gravitational-wave and kilonova observables to the ejected matter. Distances and sky localizations for nearby neutron-star and neutron-star/black-hole mergers will identify their host galaxies, allowing the connection between compact binaries and their environment to be closely probed.^{153,154} In some cases, early warning of a system likely to produce matter outside the merger remnant can give electromagnetic observatories the advance notice required to capture the earliest moments of the kilonova.¹⁵⁵ Cosmic Explorer will also record essentially all neutron star mergers out to redshift 1, so even poorly localized events can be connected with independently identified kilonovae from surveys like the Vera C. Rubin Observatory's LSST and the Roman Space Telescope.¹⁵⁶ The James Webb Space Telescope,¹⁵⁷ the Extremely Large Telescope,¹⁵⁸ the Giant Magellan Telescope¹⁵⁹ and the Thirty Meter Telescope (TMT),¹⁶⁰ will allow us to characterize the nature of the merger through deep imaging and spectroscopy. Precise measurement of the source properties from the inspiral signal will break degeneracies in kilonova models, helping to pin down the rates of specific nuclear reactions. We will learn about the feedback of neutron-star merger nucleosynthesis on stellar and galactic evolution,¹⁶¹ as well as the conditions under which matter is present in the circumbinary environment.¹⁶² By observing of the rate and distribution of neutron star mergers out to cosmological distances, Cosmic Explorer will also map the history of chemical evolution in the universe beyond the reach of multimessenger astronomy.

5.2.4 Gamma-Ray Jet Engine

Gamma-ray bursts are the most energetic electromagnetic phenomena in the universe. Although the connection between the short-duration subclass of these bursts and neutron-star mergers was confirmed by the multimessenger observation of GW170817,¹⁶³ the fundamental mechanism that produces this high-energy emission remains to be understood. The features of short gamma-ray burst light curves and spectra suggest that they originate in highly relativistic outflows of matter from the postmerger remnant.¹⁶⁴ However, the central engine powering these relativistic jets is still a matter of debate: is it an accreting black hole, or a strongly magnetized, rotating neutron star (magnetar)?^{165,166} As part of a third-generation gravitational-wave detector network, Cosmic Explorer will address this question by identifying the gravitational waves associated with all the observable gamma-ray bursts originating in neutron star mergers, thanks to its complete coverage of the binary neutron star population out to a redshift of 1. Future gamma- and X-ray observatories, such as the Einstein Probe,¹⁶⁷ eXTP,¹⁶⁸ ECLAIRs,¹⁶⁹ ATHENA,¹⁷⁰ THESEUS¹⁷¹ and TAP,¹⁷² will be critical to increasing the reach for multimessenger follow-up of gravitational-wave sources. Besides the central engine, this will lead to insight into the structure of the jet,¹⁷³ the time delay between merger and prompt emission,^{174,175} and the nature of afterglow emission.¹⁷⁶ Gravitational-wave information will also distinguish binary neutron star from neutron-star black-hole coalescences, revealing possible phenomenological differences in their gamma-ray emission.^{177,178}

The subset of Cosmic Explorer's well-localized binary neutron star mergers that produce a long-lived neutron star remnant will teach us about the origin and geometry of the ultra-strong magnetic fields supported by magnetars.¹⁷⁹ The existence of magnetars is known from electromagnetic observations,¹⁸⁰ but the amplification mechanism that allows their magnetic fields to grow so strong is a mystery.¹⁸¹ Electromagnetic follow-up of these special events will allow magnetohydrodynamic simulations of magnetic field amplification and jet creation to be put to the test. Better knowledge of the magnetic fields neutron star matter can support may shed light on a wide range of photospheric emission, including radio and gamma-ray pulses.¹⁸²

5.3 Extreme Gravity and Fundamental Physics

Cosmic Explorer will reveal the physics of the strongest gravity in the universe in unprecedented detail, thanks to two crucial dividends from Cosmic Explorer's tremendous advance in sensitivity over current-generation gravitational-wave observatories. First, in three years of operation, a single 40-km Cosmic Explorer observatory would likely detect at least one signal from merging black holes with a signal-to-noise ratio greater than 2700 (the loudest such signal to date, GW150914, had a signal-to-noise ratio of 24). Figure 5.2 illustrates the impact of Cosmic Explorer's tremendous sensitivity gain by simulating the raw, unfiltered gravitational-wave strain data a GW150914-like gravitational wave would produce in Cosmic Explorer (and, for comparison, in Advanced LIGO+).

Second, Cosmic Explorer will detect waves from sources too rare for us to observe today: in

Box 5.3: Key Science Question 3

What is the nature of the strongest gravity in the universe, and what does that nature reveal about the laws of physics?

Cosmic Explorer’s observations of loud and rare gravitational waves will reveal the (potentially new) physics of the most extreme gravity in the universe, allowing us to:

- Probe the nature of strong gravity with unprecedented fidelity;
- Discover unusual and (if they exist) novel compact objects impossible to detect today;
- Probe the nature of dark matter and dark energy.

each year of its operation, Cosmic Explorer will observe approximately 100 000 binary black holes — 2,000 times the total number of gravitational waves observed to date from any source.^{63,183}

Together, these advances will enable Cosmic Explorer to reveal the nature and nonlinear behavior of the strongest gravity in the universe with incredible clarity, perhaps revealing physics beyond general relativity whose effects are too subtle for us to recognize today. This will open a wide window on fundamental physics. Through possible effects on the gravitational waves it observes, Cosmic Explorer has the potential to shed light on longstanding mysteries in physics, including the unknown natures of dark matter and dark energy. Cosmic Explorer will also reveal the precise nature of the sources of its many observations, giving away the presence of rare black-hole and neutron star binaries and (if they exist) novel imposters that mimic these conventional binaries.

Realizing just one of these potential discoveries would revolutionize our understanding of extreme gravity and fundamental physics.

5.3.1 Nature of Strong Gravity

General relativity describes gravity as curvature of a 4-dimensional spacetime.¹⁸⁴ Gravitational-wave detectors are unique in their ability to probe regions of strong spacetime curvature: Observations of gravitational waves, beginning with GW150914 *et seq.*,^{13,19,25,185} and parallel developments in accurate numerical simulations¹⁸⁶ of binary black-hole coalescences, are giving us a first glimpse of strong spacetime curvature, including constraints on the nature and behavior of strong gravity.^{183,187–192}

Detectors on Earth are sensitive to gravitational waves from stellar-mass black holes, which, near their horizons, have stronger spacetime curvature than any other object we have observed. And because the gravitational waves emitted by coalescing binary black holes depend only on the warped vacuum spacetime surrounding the black holes’ horizons, these waves present the cleanest opportunity to probe strong gravity’s fundamental nature. Making the most of this opportunity is crucial not only for understanding extreme gravity in isolation, but also for understanding its role when combined with matter and electromagnetic fields (as with neutron-star mergers¹⁹).

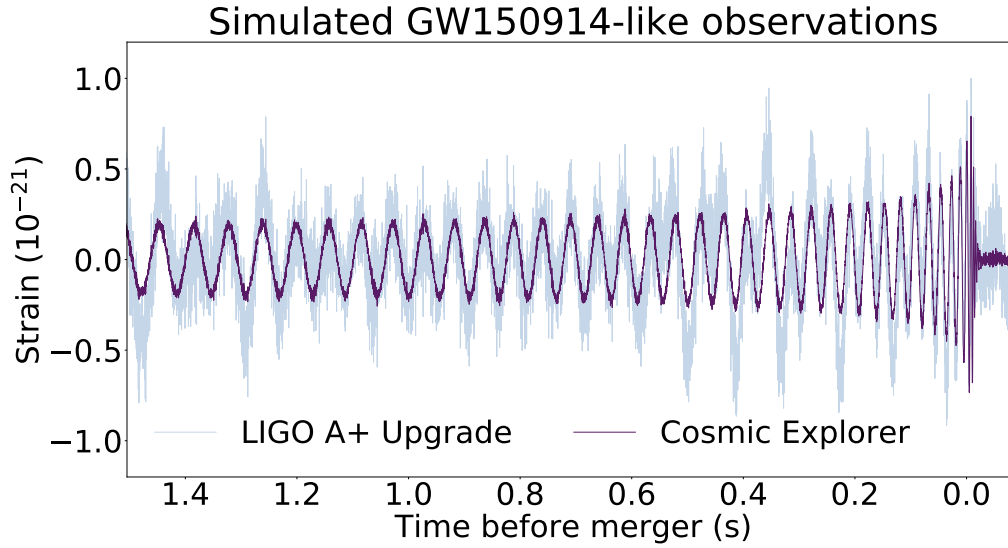


Figure 5.2: Simulated gravitational-wave detector strain measurements for a GW150914-like signal from two merging black holes. The strain is shown as a function of time for the signal superimposed on both simulated Cosmic Explorer noise (CE, blue) and simulated Advanced-LIGO+ noise (A+, gray). The strain data is not filtered or postprocessed; Cosmic Explorer will be so sensitive that the gravitational waveform is clearly visible in the unprocessed data.

So far, although there are many proposed alternatives, all observational and experimental tests are consistent with general relativity.^{17,183,187,188,192–194} In particular, the loudest signal from merging black holes to date, GW150914, is in good agreement with general relativity.¹⁹⁵ The observation of GW150914 is consistent with the “No-Hair Theorem”¹⁹¹ at about the $\sim 10\%$ level, meaning that to this confidence, the remnant left behind from the merger is a Kerr black hole. GW170817, a precisely located binary-neutron-star coalescence¹⁹ accompanied by electromagnetic counterparts,¹⁹⁶ constrained the graviton mass to $< 4.7 \times 10^{-23} \text{ eV}/c^2$, provided tight constraints on possible violations of Lorentz and parity invariances, and constrained the gravitational wave speed to light speed within about one part in 10^{16} and thereby ruled out a number of alternative gravity theories that were invoked to explain dark energy.

Cosmic Explorer will test general relativity at unprecedented precision, with the potential to discover physical effects beyond general relativity that are too subtle for current-generation instruments to measure. For instance, general relativity has a massless exchange boson (i.e., the graviton); with coincident detection of gravitational waves and gamma-ray bursts at redshifts of $z \sim 5$, Cosmic Explorer and its electromagnetic partner observatories would constrain the graviton mass three orders of magnitude better than current observatories. General relativity also is Lorentz invariant, although its experimental confirmation is not as robust¹ as the tremendous accuracy achieved in particle physics,¹⁹⁷ and it is parity invariant, although some quantum-gravity theories (e.g., Ref. [198]) predict parity violations. As another example, general relativity satisfies the equivalence principle and has two tensor polarizations for gravitational waves. But alternative theories that, motivated by the low-energy limit of quantum gravity, introduce additional degrees of freedom (such as a scalar field), violate the equivalence principle and lead

to additional gravitational-wave polarizations—while modifying compact-binary gravitational-wave emission.^{199–201} Discovering even one such violation of general relativity, however small, would revolutionize our understanding of fundamental physics.

5.3.2 Unusual and Novel Compact Objects

Cosmic Explorer’s high-fidelity observations of stellar-mass coalescing objects, together with its cosmological reach, will present an excellent opportunity for exploring the nature of merging compact objects. Cosmic Explorer will detect large numbers of merging stellar-mass black holes and neutron stars throughout the universe. These detections will likely include uncommon mergers too rare for even upgraded detectors in the current observatories, such as black holes with extremal spin, the inspiral of a neutron star into an intermediate-mass black hole,^{202,203} or a binary black hole with enough surrounding matter to produce an electromagnetic counterpart. Measuring the properties of these rare mergers could revolutionize our understanding of the nature of compact objects.

Cosmic Explorer will also explore with unprecedented clarity whether some compact binaries might contain objects other than black holes and neutron stars. All observations so far are consistent with coalescing black holes and neutron stars, but Cosmic Explorer will probe whether new types of compact binaries²⁰⁴ exist (e.g., so-called “great impostors”,²⁰⁵ gravastars,^{206–209} boson stars^{210,211} quark stars,²¹² Planck stars²¹³), as they could have different tidal properties or quasi-normal modes of oscillation. If they do exist, it remains an open question by how much (or how little) the gravitational waves they emit differ from the waves emitted by conventional black-hole and neutron-star binaries.^{195,214} At minimum, Cosmic Explorer’s enormously increased sensitivity and throughput will allow detailed tests of the Kerr black hole paradigm,^{215–218} a necessary prerequisite for recognizing other kinds of novel compact objects.^{204,219} There are, however, black hole mimickers whose inspiral and quasi-normal mode spectrum might be similar to black holes in general relativity but exhibit post-merger signals such as echoes of the ringdown signal due to modified structure of the horizon. And if novel compact objects exist but are rare, Cosmic Explorer’s cosmic reach will greatly increase our potential to observe them.

5.3.3 Dark Matter and Dark Energy

More than half a century since the first discovery of the cosmic microwave background, our understanding of the history of the universe is in crisis. Dark matter—one of the major factors that governs the dynamics of the universe—has remained elusive decades after its gravitational influence on baryonic matter was discovered. On the largest scales, the universe’s expansion is driven by the invisible dark energy whose nature we do not yet comprehend and whose value appears to be too small to be consistent with vacuum energy. The current rate of expansion of the universe determined by supernovae is in stark contrast with the value deduced from the cold-dark-matter models that agree with the spectrum of the fluctuations in the cosmic microwave background.

In response to this crisis, the astronomical community is making a substantial, ongoing effort to probe the dark sectors (i.e., dark matter²²⁰ and dark energy²²¹). Gravitational-wave observations present a unique opportunity for synergistic, complementary efforts to better understand dark matter and dark energy. Confirming that the universe appears the same in the gravitational-and electromagnetic-waves would reinforce our degree of belief in cosmological models (in the Bayesian sense), but any departure between the two would be tremendously consequential.

Dark Matter Approximately 85% of the mass in the universe is thought to consist of dark matter.²²² Despite compelling evidence for the existence of dark matter from galaxy rotation curves, gravitational lensing, and the cosmic microwave background, its fundamental nature remains a mystery.²²³

To date, the only observational evidence for dark matter is via their passive gravitational influence on visible matter. Gravitational waves are an exciting new astrophysical probe of dark matter, complementing searches at high-energy colliders and underground direct-detection experiments,^{224,225} that might reveal the nature of dark matter in several different scenarios.²²⁶ Cosmic Explorer's greatly improved sensitivity and cosmic reach will enable it to investigate these scenarios. For instance, because of their strong gravitational fields and extreme densities, neutron stars might capture ambient dark matter over time through scattering off of nucleons^{227,228} or might even produce dark matter, thanks to the exceptionally high energies achieved in binary neutron star mergers.²²⁹ If a neutron star were to contain dark matter, the dark matter would affect the neutron star's internal structure and hence its tidal properties.²³⁰ The dark matter concentration would likely depend on the neutron star's age, mass, and environment in this scenario, leading to variations in the neutron-star tidal deformability, their maximum mass throughout the population and even implosion of neutron stars when dark matter form mini black holes at their cores.

There are other possibilities where dark matter might be observable with gravitational waves. Ultra-light bosonic dark matter could become self-gravitating on its own, forming a novel compact object whose properties differ from those of a neutron star.^{214,231–233} A significant concentration of ultra-light bosonic dark matter in the vicinity of a black-hole binary could spin down the black holes through superradiance^{234–237} to spins below values that are characteristic of the black-hole and boson stars. The spin distribution of detected black holes therefore might reveal the existence of ultralight bosons.^{238–240} The cloud itself would produce continuous gravitational waves when it oscillates or a burst of gravitational waves when it collapses.^{211,226,238,241} In the former case, level transitions or annihilations in the boson cloud are predicted to emit the continuous gravitational waves monochromatically, with frequency determined by the boson and binary masses.²²⁶ Searches for ultralight dark matter particles via the clouds they create around black holes only assume a coupling through gravity; this type of search would still be viable even if dark matter does not have any type of electroweak or strong interaction with baryonic matter.

Dark Energy More than two thirds of the total energy in the observable universe is dark energy. The accelerating expansion of the universe reveals the ubiquitous nature of dark energy on the largest length scales, but the nature of dark energy remains one of the biggest outstanding mysteries in physics.

Since dark energy interacts only through gravitational interactions, a number of modified theories of gravity beyond general relativity have been proposed as explanations of dark energy. These theories include effects that Cosmic Explorer and its partner gravitational-wave and electromagnetic-wave observatories might detect, if they exist (e.g., Ref. ²⁴² and the references therein, and more broadly, the discussion of the nature of gravity above). For instance, some theories of gravity beyond general relativity predict differences in the observed gravitational-wave and electromagnetic-wave luminosity distances caused by gravitational-wave damping. Cosmic Explorer's cosmic reach puts it in a strong position to search for these effects.

But whether or not Cosmic Explorer observes effects beyond general relativity, its gravitational-wave observations of binary black holes²⁴³ at cosmological distances will be standard sirens. Like standard candles (such as type Ia supernovae), gravitational waves from merging compact binaries provide a reliable measure of distance; specifically, the luminosity distance can be inferred by comparing the observed waves to theoretical model gravitational waveforms (e.g., using the technique of matched filtering²⁴⁴). Combining the standard-siren distance with a measure of redshift (either from an electromagnetic counterpart or through statistical methods) will provide measurements of the cosmic expansion history that are independent from conventional measurements using standard candles and the other elements of the standard cosmic distance ladder,^{1,245–247} improving our understanding of the dark energy equation of state beyond what would be possible with electromagnetic observations alone (e.g., Fig. 9 of Ref. [248]).

5.4 Discovery Potential

Historically, major discoveries in astronomy have been facilitated by three related improvements in detector technology: deeper sensitivity, new band of observation and higher precision. Improved sensitivity helps sample larger volumes and more complete surveys thereby enabling the discovery of rare events that otherwise don't make the cut, e.g., Type Ia supernovae that eventually led to the discovery of the recent accelerated expansion of the universe. Opening a new frequency window has been critical to identifying entirely new classes of sources—the cosmic microwave background, quasars and gamma-ray bursts are just the tip of the iceberg examples. Increased precision has also often helped discover subtle physical effects or phenomena, e.g., the discrepancy in the Hubble constant inferred from Type Ia supernovae and the Planck mission.

A deeper, wider and sharper observational window: Cosmic Explorer will at once make progress in sensitivity, bandwidth and precision, catalyzing unprecedented discovery potential. Gravitational-

wave observations will be deeply penetrating and signals are generated by physical processes that are vastly different from those that generate other forms of radiation and particles. It would be a profound anomaly in astronomy if nothing new and interesting came from Cosmic Explorer’s vast improvement in sensitivity.

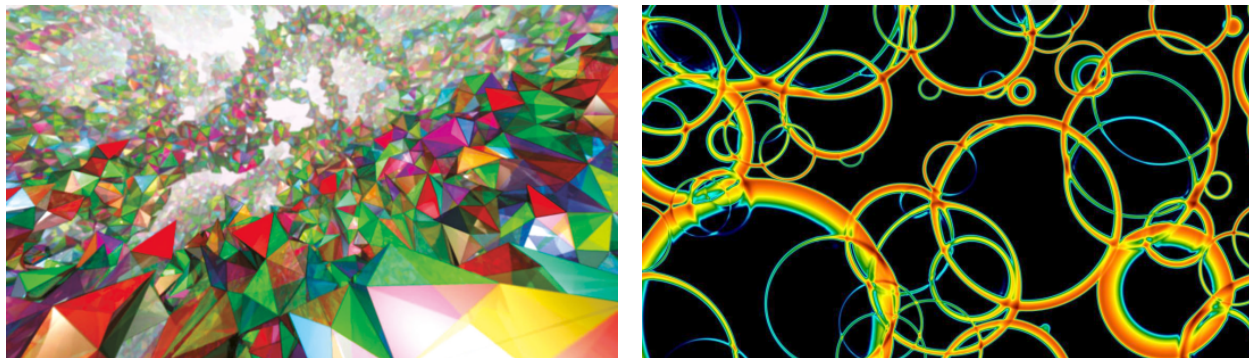


Figure 5.3: Cosmic Explorer’s discovery potential is enabled by increased sensitivity, greater bandwidth and precision measurement. The left image (credit: AEI/Milde Marketing/Exozet) shows an artist’s conception of quantum nature of spacetime that could be reflected in the structure of black hole horizon, and the right image (credit: D. Weir, University of Helsinki) shows bubble collisions in the early universe that could produce stochastic backgrounds detectable by a pair of Cosmic Explorer detectors.

Compared to current detectors, Cosmic Explorer will peer far deeper into the universe and considerably widen the observed frequency range, especially to low frequencies. Because gravitational-wave observatories are sensitive to amplitude, which falls off inversely with the distance from the source, a factor ten increase in strain sensitivity is equivalent to a factor ten increase in the *diameter* of a telescope. Cosmic Explorer will thus have dramatically greater discovery potential in a similar way to the “discovery aperture” opened by much larger and more advanced telescopes. Many or most new telescopes that greatly expand humanity’s view of the cosmos end up being known for a different and more dramatic discovery than what was predicted in their science cases. The phenomenon of serendipitous discovery has been discussed in articles on exploration of the unknown and serendipitous astronomy,^{249,250} some prominent examples being the cosmic microwave background, the discovery of pulsars, Cygnus X-1, and fast radio bursts.

Opportunities for new discoveries Gravitational radiation results from coherent motion of bulk matter and there likely are fewer ways for it to be generated than electromagnetic radiation. However, the gravitational-wave spectrum has already proven to be source rich, with many bright emitters. The fact that we know very little about much of the universe’s energy budget promises discoveries of either completely unexplored or highly speculative, but plausible, sources and phenomena. Examples include axionic clouds around black holes, dark matter in the form of sub-solar primordial black hole binaries, stochastic backgrounds from early-universe phase transitions, quantum gravity signatures in the fine structure of black hole horizons or modified boundary conditions. Moreover, gravitational waves allow us to peer into systems that cannot

Box 5.4: Key Science Question 4

What discoveries might be possible with improved sensitivity, bandwidth and precision measurement?

Cosmic Explorer will have greater sensitivity and bandwidth and measure sources with exquisite precision and help in discoveries in astronomy and fundamental physics:

- Do quantum gravity effects manifest in the structure of black hole horizons?
- What could primeval phase transitions reveal about the energy scales in the Standard Model?
- How would gravitational wave observations help explore new particles and fields?

be observed with electromagnetic astronomy e.g., probe the dense regions of the earliest epochs of the universe, directly observe the core-collapse supernova mechanism and explore the nature of dense matter in the interior of neutron stars (see, Fig. 5.3).

5.4.1 Quantum Gravity

General relativity and quantum theory, the two founding pillars of modern physics, have both been vindicated time and again by high precision laboratory experiments, astronomical observations and cosmological measurements. Yet, there is no satisfactory theory of quantum gravity to date, but, more critically, general relativity is at odds with the fundamental principles of quantum theory that physical states obey unitary evolution. The latter is brought to bear in the bizarre behavior of black holes that are formed by collapse of matter in pure quantum states and yet when they evaporate by Hawking radiation, which is purely thermal, the observed states are mixed quantum states and information is irretrievably lost.²⁵¹ This information paradox that arises in semi-classical gravity is largely suspected to be cured by a quantum theory but every proposal for a quantum theory of gravity violates one or more of the basic tenets of general relativity, e.g., the local Lorentz violation, or its predictions, e.g., the existence of additional polarizations in the radiative field [201].

It is largely expected that black holes could reveal violations of general relativity in the form of failure of the no-hair theorem as a result of quantum effects near black hole horizons.^{252,253} As another example of how Cosmic Explorer might help address open questions in quantum gravity, recently, “there has been a striking realization that physics resolving the black hole information paradox could imply postmerger gravitational wave echoes”.^{254–257} These echoes have not yet been observed, but Cosmic Explorer’s extremely high sensitivity could reveal them, should they exist.

The vast cosmological distances, redshifts in excess of $z \sim 20$, over which gravitational waves travel will severely constrain violation of local Lorentz invariance and the graviton mass.²⁰¹ Such violations or a non-zero graviton mass would cause dispersion in the observed waves and hence help to discover new physics predicted by certain quantum gravity theories. At the same time, propagation effects could also reveal the presence of large extra spatial dimensions that lead to

different values for the luminosity distance to a source as inferred by gravitational wave and electromagnetic observations^{248,258}) or cause birefringence of the waves predicted in certain formulations of string theory.^{259,260} The presence of additional polarizations predicted in certain modified theories of gravity, instead of the two degrees of freedom in general relativity, could also be explored by future detector networks.^{201,261}

5.4.2 New particles and fields

The vast horizon of Cosmic Explorer will help either discover or set stringent limits on the existence of particles and fields on a variety of different scales. The composition of dark matter is largely unknown but it could be composed, at least in part, of ultralight bosons such as QCD axions,²⁶² dark photons or other light particles,²⁶³ spanning a wide mass range of masses,^{262,263} from 10^{-33} eV to 10^{-10} eV. In particular, the Compton wavelength of ultralight bosons in the mass range 10^{-20} eV– 10^{-10} eV corresponds to the horizon size of black holes of mass $10 M_{\odot}$ – $10^{10} M_{\odot}$. Although these ultralight fields may not interact with other Standard Model particles, the equivalence principle implies that their gravitational interaction with, for instance, black holes, could have observable consequences. For example, bosonic fields whose Compton wavelength matches the horizon scale of an astrophysical black hole could form bound states (often called ‘gravitational atoms’) around black holes and extract their rotational energy and angular momentum via the mechanism of superradiance.^{264,265} This would result in a Bose-Einstein condensate that acts as a source of continuously emitted gravitational waves. Cosmic Explorer would have access to the higher end of the mass range from 10^{-13} eV to 10^{-10} eV, which correspond to QCD axions.

After LIGO’s first discovery of stellar black holes with unusually large masses,²⁶⁶ primordial black holes were proposed as viable candidate sources and they would also constitute at least a fraction of the dark matter. Searches for subsolar mass black holes have not produced any detections so far, leading to some of the best upper limits²⁶⁷ on the fraction of dark matter in black holes of mass 0.2 – $1.0 M_{\odot}$. The existence of subsolar black holes is considered to be a definitive proof that they were produced in the primordial universe as stellar evolution cannot produce black holes below about $3 M_{\odot}$. Cosmic Explorer and partner observatories will constrain the fraction of dark matter in such black holes at the level of 10^{-5} of the total budget.

5.4.3 Stochastic Gravitational-Wave Backgrounds

A stochastic gravitational-wave background is expected to arise due to the superposition of individually unresolvable gravitational waves of both astrophysical and cosmological origin. The astrophysical backgrounds of stellar-mass compact binary mergers that are the targets of current ground-based gravitational-wave detectors (e.g., Refs. [268–273]) will be nearly entirely resolvable with the next generation observatories, but residual unresolvable signals can contaminate the measurements of much weaker cosmological backgrounds.^{274–276} While this poses a computational challenge, recent methods²⁷⁷ demonstrate that Cosmic Explorer can

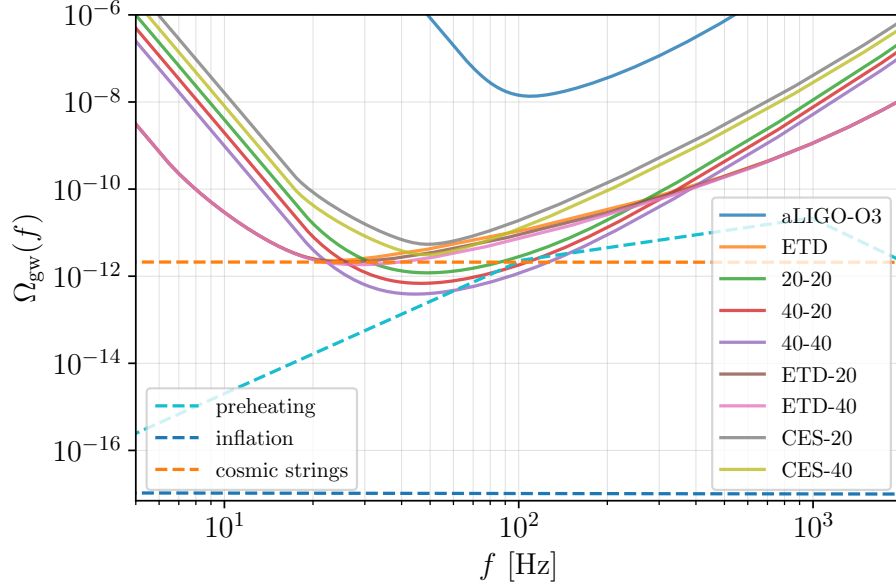


Figure 5.4: Sensitivity of Cosmic Explorer detector networks to stochastic gravitational-wave background compared to that of the three Vs in the Einstein Telescope (ET-D). 20-20, 40-20 and 40-40 correspond to two CE detectors in the US with the numbers indicating the arm length in kilometers. ETD-20, ETD-40 correspond to the sensitivity of an ET array when combined with a CE in the US. Likewise, CES-20 and CES-40 correspond to the sensitivity of a 20 km CE in Australia and a CE in the US. A stochastic background with energy density $\Omega_{\text{gw}}(f)$ calculated at a reference frequency of 300 Hz would be detected at a SNR of 3 after one year of observing if it crosses the curve for that network.²⁸³ The expected backgrounds for cosmic strings ($G\mu = 1 \times 10^{-11}$, with fiducial model parameters from Ref. [284]), preheating (for hybrid inflation occurring at 10^9 GeV as calculated in Ref. [285]) and standard slow-roll inflation²⁸² are shown in dashed lines.

provide a unique opportunity to probe the early universe with gravitational waves. Standard slow-roll inflationary models are expected to produce a stochastic background with dimensionless energy density $\Omega_{\text{GW}} \sim 10^{-17}$,^{278,279} too weak to be directly detected by all but the most ambitious space-based gravitational-wave detectors.^{280,281} However, nonstandard inflationary and cosmological models can produce backgrounds due to processes like preheating, first-order phase transitions, and cosmic strings,²⁸² all with energy densities within the reach of Cosmic Explorer (see Fig. 5.4).

Particle Production and Preheating Following inflation, the universe must undergo a period of particle production during which the inflation field couples to other particle species into which it eventually decays. If this process occurs non-perturbatively, it is called *preheating* (see Refs. [286, 287] for reviews). While the amplitude of the background generated during this process of particle production is expected to be independent of the temperature scale at which it occurs, standard inflationary models predict that it will peak at $f \sim 10^7 - 10^8$ Hz, well beyond the frequency band of Cosmic Explorer.^{288,289} However, for hybrid inflation occurring around $\sim 10^9$ GeV, the background from preheating peaks in the band of ground-based detectors with an energy density of $\Omega_{\text{GW}} \sim 10^{-11}$, which is probable with Cosmic Explorer.^{285,290,291} Even a

non-detection of such a background could be used to constrain the physics and temperature scale of particle production in the early universe.

Cosmic Strings Cosmic strings are one-dimensional topological defects produced in spontaneous symmetry breaking phase transitions following inflation.²⁹² When a string folds upon itself, it produces a loop, which oscillates under its tension, emitting gravitational waves in a series of harmonic modes.^{293–295} Cusps and kinks are formed when cosmic string loops intersect.^{296,297} These string features emit higher frequency bursts of gravitational radiation²⁹⁸ whose superposition creates a stochastic gravitational-wave background accessible to ground-based gravitational-wave detectors.^{299,300} The spectrum of the background depends on the cosmic string tension, $G\mu$, and the loop model, among other parameters.^{301,302} The current generation of ground-based gravitational-wave detectors has placed the most stringent upper limit on the string tension to date, $G\mu \lesssim 4 \times 10^{-15}$,¹⁴³ and Cosmic Explorer will allow us to probe tensions that are several orders of magnitude smaller, offering a window into beyond-the-standard-model physics at the highest energies.

Electroweak Phase Transition Phase transitions in the early universe, such as the decoupling of the electromagnetic and weak forces, can also produce a stochastic gravitational-wave background under some modifications of the Standard Model if they are strongly first order,^{303–306} i.e., if there is a discontinuity in the first derivative of the free energy during the transition. In this scenario, gravitational waves are emitted due to the collision of bubbles of the new phase^{307,308} and due to the anisotropic stresses generated by magnetohydrodynamical turbulence and discontinuities in the shocked plasma surrounding the expanding bubbles.^{309–312} A first-order electroweak phase transition also has implications for electroweak baryogenesis, which could provide an explanation for the cosmic baryon asymmetry.³¹³ The peak frequency of the stochastic background energy density spectrum depends on the energy scale of the transition, with a transition occurring at 10^9 GeV producing a background peaking in the frequency band of ground-based gravitational-wave detectors.^{278,314} Such a background is expected to have an amplitude of $\Omega_{\text{GW}} \sim 10^{-12 \pm 2}$, within the range of Cosmic Explorer.^{315,316} The detection of a cosmological stochastic background by Cosmic Explorer would represent the accomplishment of one of the most ambitious goals of gravitational-wave astronomy, and even a non-detection would allow for constraints on beyond-the standard-model physics at energies orders of magnitude larger than those accessible with particle accelerators.



Observatories

6 A Science-Driven Design for Cosmic Explorer

Achieving the science goals laid out in §3 requires a gravitational-wave observatory capable of reliably measuring the strain from mergers in the band between a few hertz and a few kilohertz with a sensitivity of approximately $3 \times 10^{-25} / \sqrt{\text{Hz}}$. This strain sensitivity guarantees that remnant mergers from the first stars are still observable (Fig. 6.1, adapted from Ref. [78]). The upper limit of the frequency band is dictated by the highest frequency signals expected from the lightest known compact objects: neutron stars. The lower edge of the frequency band of any terrestrial detector is dictated by the seismic motion of the Earth’s surface. Pushing the seismic cut-off lower has scientific benefits: namely the observation of heavier binary systems and longer merger early-warning times. The observatory cost on the other hand increases rapidly with the size and complexity of the seismic isolation system and the need to avoid local gravitational disturbances (“Newtonian noise”). The residual motion of the isolation system is eventually subdominant to Newtonian noise, which is the coupling of seismic and atmospheric fields to the detector through direct Newtonian gravity. Since seismic and Newtonian noise are displacement noises, the low-frequency strain sensitivity can also be improved by lengthening the detector arms.

Since gravitational-wave detectors are essentially antennas, the highest frequency of interest also sets the ideal scale of the antenna: a few tens of kilometers for signals at a few kilohertz. This happens to be about ten times the size of existing detectors. Thus, a detector with the same displacement sensitivity as current gravitational-wave interferometers will naturally gain strain sensitivity when scaled up, requiring only modest improvements over current detector technology.

6.1 Design Concept for Cosmic Explorer

The interferometric technology used in current gravitational-wave detectors such as Advanced LIGO and Virgo is the most mature and it forms the basis for the Cosmic Explorer detector concept. In addition to the discussion of interferometric technology in §6.2.1, in this section we also briefly discuss potential alternative technologies: space-based interferometers in §6.2.2, atom interferometers in §6.2.3, and torsion pendulum detectors in §6.2.4.

The scale of the facility required to achieve the science goals outlined in §3 represents a major investment. We therefore plan for this facility to have a lifespan of about 50 years and the flexibility to host a number of iterations of detector designs. This will allow funding agencies to capitalize on future research and development breakthroughs, should the operational life-span of CE be extended beyond the initial mandate (which is expected to be 20 years). In this

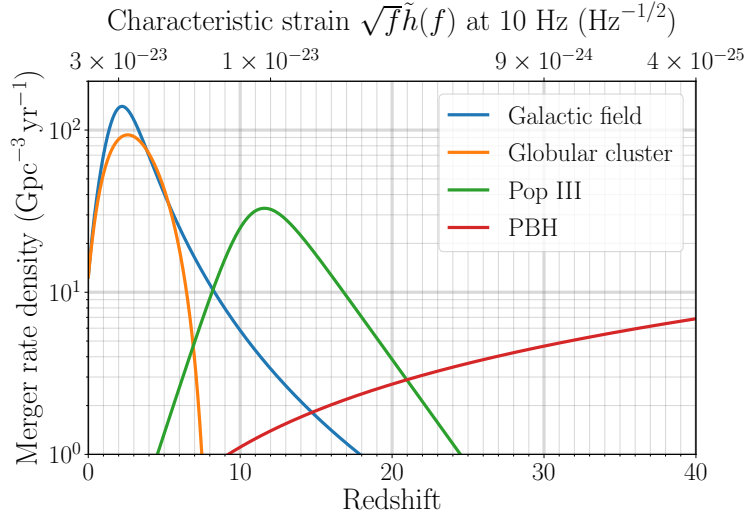


Figure 6.1: Merger rate densities of a few representative populations of compact objects as a function of redshift. Galactic field and globular cluster formation are expected to produce both binary black holes (BBHs) and binary neutron stars, while the other channels will only produce BBHs. The curves for galactic field, globular cluster and Pop III formation are taken from Ng et al.,⁷⁸ and are based on population synthesis analyses by Refs. [317–319]. The primordial black hole (PBH) merger rate is taken from Refs. [320, 321]. The top axis gives the characteristic strain calculated at 10 Hz (as measured in the detector frame) of an optimally oriented 30–30 M_{\odot} BBH placed at the corresponding redshift indicated on the bottom axis. Here the characteristic strain is defined as $\sqrt{f}|\tilde{h}(f)|$, where $\tilde{h}(f)$ is the Fourier transform of the gravitational-wave signal. The strain does not follow a simple linear trend with redshift due to (1) the non-linear relation between luminosity distance and redshift³²² and (2) the fact that if the source is far enough, what will be observed at 10 Hz are the merger and the ringdown.

document we focus on one of these detector concepts, chosen to minimize risk while leveraging the output of the active global instrument research community.

The technology to be installed when the Cosmic Explorer observatories are built features the lowest possible technical risk to achieve the most readily accessible science goals. The corresponding detector is largely a scaled-up version of current room-temperature, fused-silica-based interferometers, with some incremental improvements in non-critical technologies (see §8.3). This will be followed by a sequence of planned upgrades that incorporate currently less developed technologies as they become available (see §8.1). In addition to the planned upgrade path to achieving the CE target sensitivity and science goals, a second path involving 2 μm lasers and cryogenic silicon mirrors (a.k.a. “Voyager technology” or simply “2 μm technology”) is discussed as risk mitigation should the incremental approach based on current technology encounter unexpected challenges. Beyond its role as risk mitigation for the Cosmic Explorer science goals presented here, 2 μm technology may present an opportunity for maximizing the output of the Cosmic Explorer observatories in the future. While 2 μm technology is much less mature than the currently deployed 1 μm technology, this technology, or some other future detector technology that has not yet been conceptualized, is expected to eventually allow the CE observatories to push toward the fundamental physical limits of the facility (see §8.4).

6.2 Proposed Alternative Detector Concepts

Here we list a number of potential alternative technologies for detecting gravitational waves: ground-based laser Interferometry (which we choose as the technology for the CE reference concept), space-based interferometry, atom interferometry and torsion bars. We also look at the cryogenic silicon-based upgrade proposal Voyager for the currently existing LIGO observatories. A comparison of low-frequency terrestrial gravitational wave detection methods was also given by Harms et al.³²³

6.2.1 Ground-Based Laser Interferometry

All direct detections of gravitational waves to date have been made with laser interferometers, more specifically Michelson interferometers enhanced with optical cavities in a so-called “dual-recycled Fabry–Pérot Michelson” (DRFPMI) configuration. Astrophysically sensitive laser interferometers of this type are the result of a global R&D effort spanning four decades: whereas early laboratory prototypes in the 1980s achieved peak strain sensitivities of about $10^{-19} / \sqrt{\text{Hz}}$ at kilohertz frequencies,³²⁴ the current kilometer-scale detectors achieve peak strain sensitivities better than $10^{-23} / \sqrt{\text{Hz}}$ down to several tens of hertz.

The Cosmic Explorer reference concept (§8.1) adopts the DRFPMI interferometer as the working technology. This design builds on the success of the existing DRFPMI research program, aiming to extend the sensitivity of this class of laser interferometers by one more order of magnitude, achieving peak strain sensitivities better than $10^{-24} / \sqrt{\text{Hz}}$ down to 5 Hz. This sensitivity improvement is due to a combination of longer interferometer arm cavities, realizable in the 2030s at new facility, and a set of technology improvements that can be achieved in the 2020s and 2030s.

Other laser interferometer topologies have been proposed for gravitational wave detection.^{325,326} However, none of these topologies will achieve cosmological reach unless, as with the Cosmic Explorer DRFPMI design, a combination of longer facilities and technology improvements is assumed. Moreover, these interferometer topologies are still in the laboratory prototyping phase: compared to the DRFPMI program, any program needed to realize these alternate topologies carries more risk and cannot leverage as much existing R&D. The Cosmic Explorer facility however would be able to accommodate a corresponding upgrade should one of these topologies turn out to be beneficial. This is particularly true for an above-ground facility like Cosmic Explorer, where significant changes to the observatory’s vertex and end stations are possible.

6.2.2 Space Missions

In parallel with the development of ground-based interferometers, gravitational-wave interferometry is also being pursued for implementation in space, with a science program that is largely complementary to that of ground-based gravitational-wave interferometers. The first

anticipated space mission, LISA,³²⁷ is scheduled to launch in 2034, and other missions include TianQin,^{328,329} Taiji³³⁰ and DECIGO.^{331,332} Going into space has the advantage of much longer laser path lengths (2.5 million kilometers, in the case of LISA), as well as the absence of terrestrial force noise. On the other hand, laser power limitations and diffraction loss limit the achievable arm power, and hence the shot noise sensitivity of space-based laser interferometers is less than terrestrial detectors. These characteristics make space missions most suitable for detections in the sub-hertz band. Space missions will detect the mergers of intermediate-mass and supermassive black holes, but will observe stellar-mass systems only in their early inspiral phase. Notably, space missions will not observe neutron-star postmerger signals. On the other hand, space missions will be able to observe some stellar-mass systems early in their inspiral phase, in some cases years before they are observed in terrestrial detectors. Such joint observations can potentially set tighter limits for some tests of general relativity.

6.2.3 Atom Interferometry

Atom interferometers have been proposed as tools to detect gravitational waves via gradiometric measurement.^{333–337} In a typical proposed setup atom interferometers are used as interferometric inertial references, taking the place of test masses in conventional gravitational-wave interferometers. Two or more such atom interferometers are separated along a baseline and interrogated by a common laser. Pulses from that laser serve as splitter, mirrors and recombiner for the individual atom interferometers, and additionally pick up a phase modulation due to a gravitational wave passing the baseline. This puts challenging constraints on the laser phase front that need to be overcome to achieve interesting sensitivities.

Even with orders-of-magnitude improvements in atomic flux and with baselines exceeding 10 km, the audio-band strain sensitivity of these gradiometers is limited by atomic shot noise to a level that does not surpass the sensitivity already achieved by laser interferometers. Instead, the proposed sensitivity improvement over ground-based laser interferometers occurs in the decihertz band, where the direct seismic noise coupling is suppressed because the atom clouds are in freefall. As such, an atomic gradiometer operating at the shot-noise limit is sensitive primarily to compact binaries in the range $[10^3, 10^4] M_\odot$, potentially extending to redshifts of a few.

Though the direct seismic noise is suppressed, atomic gradiometers are still sensitive to seismic and atmospheric fluctuation through direct Newtonian coupling in much the same way as laser interferometers. This Newtonian noise drives many of the proposed experiments to assume underground operation over a long (kilometer-scale) baseline, along with other techniques such as noise subtraction with auxiliary sensors and the use of dozens of atom interferometers to exploit the different spatial correlation properties of gravitational waves and Newtonian noise. Even so, mitigating Newtonian noise at decihertz frequencies, which is a prerequisite for shot-noise-limited operation of the instrument, will require a challenging research program due to the greater strength of geophysical noise below 1 Hz and the greater number of processes that produce it.^{338,339}

6.2.4 Torsion Pendulums

Laser interferometry can be used to search for gravitational-wave-induced fluctuation in the angle between two bars, suspended from their center of mass as torsion pendulums. Such a torsion bar antenna design offers some cancellation of mechanical noise. The characteristic length scale of the detector is set by the size of the bars, which in the TOBA proposal^{340,341} is 10 m; this proposal additionally assumes cryogenic operation underground. The detector sensitivity is of the order $10^{-20} / \sqrt{\text{Hz}}$, which is several orders of magnitude less sensitive than ground-based detectors. Torsion bar detectors are also affected by Newtonian noise, although the coupling geometry is slightly different. Interestingly, this might make torsion bar detectors the most promising local sensors for directly measuring Newtonian noise, potentially assisting Newtonian noise mitigation in other gravitational-wave detector designs.

6.2.5 Voyager

Voyager is the name for a proposed cryogenic silicon upgrade intended to maximize the reach of the existing LIGO facilities.³⁴ Efforts toward Voyager are currently pioneering the research and development needed for cryogenic silicon and 2 μm gravitational-wave technology. The implementation of Voyager in the LIGO facilities would lead to increased gravitational-wave detection rate and significantly improved astrophysics. However, the unproved nature of the optics needs extensive development. The 4 km baseline would also constrain the future. Voyager will not reach the era of first stars or achieve the full set of goals envisioned for CE (see Table 7.3). Voyager would be a demonstration of technology that could be used to upgrade Cosmic Explorer, yielding important performance information in detectors significantly more sensitive than other possible technology prototypes.

7 Optimizing Design Performance Versus Cost

In this section we explore a range of Cosmic Explorer designs and the impact of design choices on the scientific output of CE and the 3G network. The objective of this exploration is to ensure that resources expended in construction of the CE facility are put to good use, i.e., to optimize the science-per-dollar spent on CE.

We start by creating a science traceability matrix, shown in Table 7.2, that maps the three primary science objectives described in §3 to the observations needed to realize the science objective in terms of a specific measurement and its requirements. Measurement requirements are then mapped to the instruments and instrument requirements. We then identify a reference configuration for CE (see Box 7.1) that can achieve all of these requirements, and discuss a number of variants of this configuration (see §7.1). These variants differ principally in the length and number of CE facilities in the US, since these are the primary cost drivers. This is followed by a presentation of the impact of these alternative on CE's ability to achieve its key science goals. A summary of the results of this section is given in Table 7.3.

Box 7.1: Cosmic Explorer Reference Concept.

The Cosmic Explorer concept consists of two widely-separated L-shaped observatories in the United States — one with 40 km long arms and another with 20 km arms.

This concept maximizes the scientific output as the 40 km detector can be optimized for deep broadband sensitivity, while the 20 km detector is capable of tuning its sensitivity to the physics of neutron stars after they have merged. To enable accurate source localization and coverage and to ensure sufficient transient noise rejection, the observatories should not be co-located. To ensure that wave polarizations can be well distinguished, the observatories should not be parallel.

Two US observatories would accomplish the majority of the CE science independent of additional international next-generation gravitational-wave observatories — though CE would reach its maximum potential as part of a next-generation network. This concept would also take advantage of efficiencies associated with parallel construction (as well as commissioning and operation) of two sites within the US, as done by LIGO.

Facility capabilities differ more than might be expected by a simple arm-length scaling of the signal's strength. In particular, the free spectral range of long-arm facilities ($c/2L_{\text{arm}} \approx 3.7 \text{ kHz}$ for a 40 km detector) begins to limit the flexibility of the observatories to target high-frequency signals such as the postmerger phase of neutron-star mergers. The frequency of postmerger

gravitational waves varies substantially within current matter uncertainties and with the masses of the merging stars.³⁴² As we better understand the population of neutron-star mergers and the properties of dense matter, we can tune the sensitivity of a shorter 20 km detector for optimal postmerger physics,^{39,119} for example by focusing on frequencies characteristic of a hadron-quark phase transition.¹³² To compare facilities, we include reference tunings optimized for inspiral and postmerger observation.

7.1 Alternate Configurations

This section describes variants which differ somewhat from the reference configuration of two L-shaped observatories, one with 40 km long arms and another with 20 km arms (see Box 7.1). For the reasons discussed in the following sub-sections, the variants involving one or two observatories of either 20 km or 40 km are carried forward into the subsequent trade-study discussion in §7.2.

7.1.1 Shorter Arms (10, 20 and 30 km) and Optical Tunings

Reducing the length of the interferometer arms is a clear means of reducing the cost of a CE facility. As the reference concept was chosen for maximum scientific output, this cost reduction must come at the expense of scientific output.

Table 7.1 shows the scalings of fundamental noises as the detector length L is varied. In all cases, the strain-referred noise from the geophysical and thermal sources is the same or worse as L is reduced. The shot noise, which is the dominant noise source near and above 100 Hz, is shaped not only by the length of the detector, but its optical configuration. For a given length L , we identify two optical configurations of interest. First, we identify a “compact-binary optimized” configuration, where the detector’s shot noise is tuned to give the best sensitivity below 1 kHz, where stellar-mass binaries inspiral and merge. Second, we identify a “postmerger optimized” configuration, where the detector’s shot noise is tuned to give the best sensitivity around 2–3 kHz, at the expense of sensitivity below 1 kHz; this configuration will best capture late-time signals from the aftermath of neutron star mergers. It is possible to convert the detector from one configuration to the other by replacing a small number of optical components, with no facility modification required.

The compact-binary optimized and postmerger optimized detector configurations are shown in Fig. 7.1 as a function of arm length. Evidently, for $L = 40$ km there is only a modest difference between the two configurations. However, for a 20 km facility the difference is significant, showing a clear tradeoff to be made between the science goals. It is noteworthy that the 30 km option appears to be “the worst of both worlds” in that it cannot be tuned to high frequencies, and its sensitivity at low frequency is not as good as a longer facility.

We stress that for a given detector length, the tradeoff between these two optimized configurations is *not* built into the facility and thus not a long-term choice. We expect to periodically

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.³⁴³ 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.

switch detector configurations (e.g., observe in compact-binary mode for a year, then observe in postmerger mode the following year), since this requires only minor modifications to the detector and does not require facility modification. Furthermore, the postmerger optimized sensitivity shown in Fig. 7.1 is only one of a continuum of options available: in a 20 km facility, for instance, any frequency between 1 and 3 kHz can be targeted, and the target frequency can be changed between observing runs.

7.1.2 Multiple Interferometers

The current reference concept for Cosmic Explorer includes two facilities that are geographically separated while still being located in the United States. While the reference maximizes the scientific output of CE, alternate configurations may involve one, two or three detectors which may or may not be colocated.

One Large CE versus Two Smaller CEs It is apparent that a 40 km facility will cost more than a 20 km facility, and one might imagine that two of the smaller facilities can be built for a price similar to that of a single larger detector. (This is not true; see §8.5.) The merits of a longer detector lie in the scaling of various noises with length (see Table 7.1), while those of multiple detectors lie in the freedom to sample different gravitational-wave polarizations and to geographically separate the detectors to improve localization of sources. For CE, where the arm-length approaches the wavelength of the gravitational waves of interest for some science goals, the bandwidth of the detector is also an important consideration. Thus, the impact of choosing a single detector over a pair of detectors will be different for different science goals.

As a simplified example in which bandwidth is not a major concern, consider two 10 km facilities versus a single 20 km facility. Since quantum shot noise will dominate in most of the

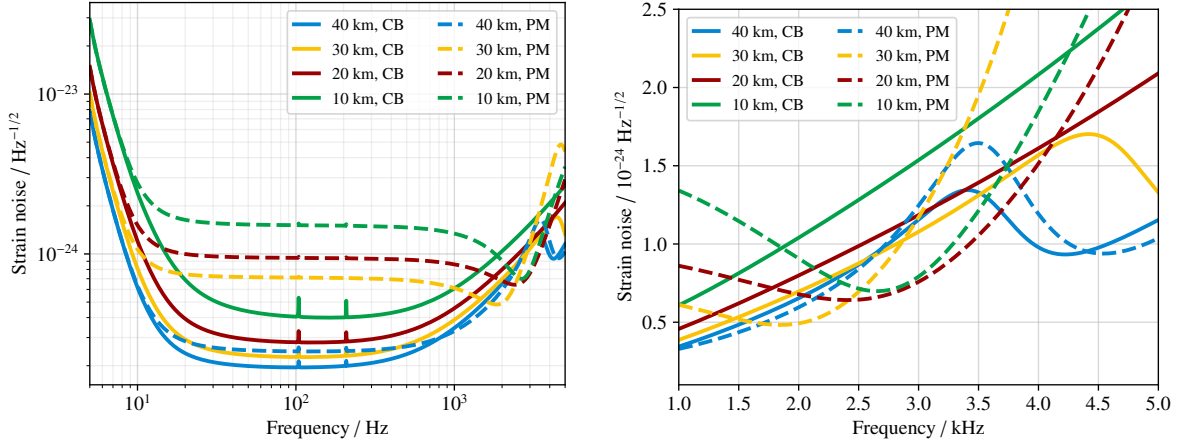


Figure 7.1: Amplitude spectrum of the detector noise as a function of frequency for the four Cosmic Explorer lengths considered in this comparative performance study. PM denotes the postmerger optimized configuration and CB denotes the compact-binary optimized configuration. The plot on the left shows the broadband sensitivity and the plot on the right shows the benefits of the postmerger optimized configurations at high frequencies.

detection band, from Table 7.1 we can see that these two configurations will give similar results (i.e., both a factor of $\sqrt{2}$ more sensitive than a single 10 km facility). At lower frequencies, where quantum radiation pressure, coating Brownian noise, and Newtonian noise are dominant, the longer detector will provide superior performance. This consideration, combined with the fact that cost is not simply proportional to arm length, drives us to consider long detectors, and is the reason why the CE reference concept revolves around matching the detector to the gravitational-wave wavelength relevant to our science goals. This is a significant change in perspective from that which motivated the initial LIGO observatory and detector designs, where the best effort in instrumentation determined what science could be accomplished. We can now invert the logic, as is done in most more mature fields of science, and ask what detectors are needed for the science we want to accomplish.

This brings us back to the original question: one large observatory, or two smaller ones? In section §7.2 we consider combinations of 20 km and 40 km observatories and the merits of each depend on the science question being answered. However, broadly speaking, two 20 km observatories can do more than a single 40 km observatory (see Table 7.3), though as previously noted a single 40 km observatory is somewhat less expensive than a pair of 20 km observatories (see Table 11.1).

Two Interferometers in a Single Vacuum Envelope Given the expense of building a CE observatory, one might expect that housing multiple interferometers in the same vacuum envelope would allow for greater sensitivity and flexibility with relatively little added cost. Putting both a 20 km and a 40 km CE in the same beamtubes, for instance, appears to yield an observatory capable of simultaneously optimizing compact-binary and postmerger science. The Initial LIGO Hanford Observatory did, in fact, operate with two interferometers in the same beamtubes,

albeit for different reasons.

Unfortunately, this approach requires that the clear aperture of the beamtubes be large enough to put the interferometer optics side-by-side with enough separation to avoid mechanical and optical interactions between the detectors. This, in turn, requires that the beamtube diameter be roughly doubled to house two interferometers, which leads to a number of practical and economical challenges.

The immediate practical issue is that CE already requires the largest pipe diameter and vacuum hardware (e.g., gate valves) commonly made, so a special process would be required to produce many kilometers of larger diameter pipe and special orders would be required for all beamtube related hardware. The second issue is that the pipe wall thickness required to support atmospheric pressure must increase with diameter, so maintaining the same safety margin would require twice as much material, or a more sophisticated manufacturing process (e.g., stiffening rings, corrugated pipes, etc.). These factors combined would increase the cost of the vacuum system by more than a factor of 2, making separate vacuum systems a clearly superior approach. Using separate vacuum systems also avoids potential optical interactions between the interferometers: a problem which plagued the initial LIGO Hanford Observatory.

One approach that could work is to “time multiplex” the vacuum system. That is, to build an observatory that can operate as either a 20 km *or* a 40 km CE by building mid-stations (20 km from the vertex) capable of housing test-masses. The mid-station mirrors could be installed when dense matter science motivates the 20 km postmerger-optimized configuration and removed when the 40 km compact-binary optimization is more favorable. The advantages of this configuration are relatively small, but so is the additional expense, so it may be the best option if only one observatory can be built.

Side-by-Side Interferometers While the previous discussion makes it clear that putting multiple interferometers in the same vacuum envelope will not reduce cost, there remains the possibility of placing two interferometers side-by-side in the same observatory. This approach could potentially save some fraction of the civil engineering cost of CE (28% of the total) relative to building two separate observatories. It also has the advantage of reducing the overall project footprint, and thus its impact on the land and environment.

The disadvantages of this approach are clear: both detectors will measure the same gravitational-wave polarization, there is no additional sky-localization information offered by the second detector, and local disturbances will appear in both detectors make coincident detection a less powerful tool. This would result in a significant compromise on the science goals: much like having only a single detector, CE would be dependent on the rest of the next-generation network in order to deliver definitive answers (see Table 7.3).

Three-Detector Triangle Another option is to build a single triangular facility comprised of three side-by-side detectors, which is the baseline design of the Einstein Telescope. Such a facility is sensitive to both the $+$ and \times polarization of incoming gravitational waves. As a rough

metric, we can compare the signal-to-noise performance of such a three-detector triangular facility to two single-detector L-shaped facilities with nonparallel arms—these two facilities jointly are also sensitive to both polarizations.

For a circularly-polarized overhead signal, a three-detector triangular facility of length L on a side collects the same signal-to-noise ratio as two L-shaped single-detector facilities each with arm length $L' = \frac{8}{9}L$ and oriented at 45° relative to one another, assuming in both cases the detectors are shot-noise limited with the same bandwidth, and otherwise have identical parameters.^a This means that instead of laying out a triangular facility with total arm length $3L$, similar performance could be achieved by laying out two L-shaped facilities with total arm length $4 \times \frac{8}{9}L \approx 3.6L$. Additionally, since each detector in the triangular facility requires a separate vacuum envelope, the triangular facility would require $6L$ of vacuum tube, while the two L-shaped facilities would require only $3.6L$. The relative expense of these options will depend on the details of the sites and local construction costs, but it is unclear that the 20% decrease in total arm length saved by building a triangle (relative to two L's) will ever be sufficient to outweigh the added expense of manufacturing, housing, and operating almost twice as large of a vacuum envelope and an extra interferometer. (In CE, the vacuum system makes up 37% of the cost, the detector 24%, and the civil work 28%, which suggests that a triangular facility would cost roughly 20% more than two L-shaped facilities with the same sensitivity.)

In light of the above, it is clear that building a three-detector triangular facility is not advantageous relative to two co-located L-shaped facilities, except possibly in an environment where excavation costs entirely dominate the facility cost, which is not the case for CE. Furthermore, with two L-shaped facilities there is the clear advantage that the facilities can be separated by a long baseline, as with the current LIGO facilities, and thereby achieve better sky localization than a single triangular facility. This option is also favorable in that it only requires two interferometers to be built and operated, rather than three interferometers as in the triangular design, thereby reducing maintenance and operations costs.

^aSuppose the triangular facility has a side length of L , so that each of the three detectors has an arm length L and an opening angle of 60° . If a circularly polarized signal with strain amplitude $h_+ = h_\times \equiv h$ is incident from directly overhead, then the total signal-to-noise ratio of the triangular facility is $\rho_\Delta(L) = \frac{3}{2}\rho(L)$, where

$$\rho(L) = \left(4 \int df \frac{h^2}{n(L)^2} \right)^{1/2} \quad (7.1)$$

is the signal-to-noise ratio that would be accumulated by a single detector also of length L with 90° opening angle, and $n(L)$ is the strain noise amplitude spectral density of such a detector.

Conversely, two L-shaped facilities of length L' oriented at 45° relative to one another would collect a total signal-to-noise ratio of $\rho_{\perp\vee}(L') = \sqrt{2}\rho(L')$. Assuming that the detector parameters, including the bandwidth, are the same in both the triangular and L-shaped cases, and assuming the signal occurs in a frequency range dominated by shot noise, the detector noises are related by $n(L') = (L'/L)^{1/2}n(L)$.³⁴³ Equality of the signal-to-noise ratios $\rho_\Delta(L)$ and $\rho_{\perp\vee}(L')$ is then achieved for $L' = \frac{8}{9}L$. Thus, two L-shaped detectors are slightly more sensitive than three detectors in a triangular facility of the same length.

Table 7.2: Science traceability matrix for the science goals identified for Cosmic Explorer in this Horizon Study. This matrix illustrates the flow-down of Cosmic Explorer’s high-level science goals, through the measurement objectives and requirements needed to accomplish these goals, to the necessary instruments and instrumental requirements to achieve these goals. The requirements chosen here are the minimum set needed to fully realize each goal. We emphasize that this study is a starting point for community input to the final design of Cosmic Explorer and encourage the community to provide input to expand and refine Cosmic Explorer’s science traceability matrix.

Science Objectives	Measurement Objectives	Measurement Requirements	Instruments	Instrument Requirements
Black holes and neutron stars throughout cosmic time.	Observe black holes formed by Population III stars.	Detect tens of binary black hole mergers at $z > 10$ and measure their redshifts better than 20%.	A network of two 3G detectors.	5×10^{-25} strain sensitivity at 10 Hz, increasing to no more than 2×10^{-25} strain up to 50 Hz.
	Determine if supermassive black holes at $z \sim 8$ are built from hierarchical mergers of smaller black holes.	Detect thousands of binary black hole mergers at $z > 8$ and measure their redshifts better than 25% and source frame mass better than 10%.	A network of two 3G detectors.	1×10^{-24} strain sensitivity at 10 Hz, increasing to no more than 3×10^{-25} strain at 500 Hz.
	Determine the formation and evolution channels of black holes and neutron stars formed at $z < 4$.	Detect tens of thousands binary black hole mergers up to redshift of 4 and measure their redshifts to better than 25% and source frame mass to better than 10%.	A network of two 3G detectors.	1×10^{-24} strain sensitivity at 10 Hz, increasing to no more than 3×10^{-25} at 500 Hz.
Dynamics of dense matter.	Measure the structure and composition of neutron stars.	Measure the neutron star radius to within < 100 m across the full mass range of neutron stars and all plausible nuclear equations of state.	One 3G detector.	3×10^{-25} strain sensitivity from 20 Hz to 400 Hz, rising to no more than 6×10^{-25} at 1.5 kHz.
	Explore the high density, finite temperature phase space of quantum chromodynamics.	Detect neutron star post-merger remnants with a signal-to-noise ratio > 8 with measurement of merging object’s masses to better than 1%.	One 3G detector.	1×10^{-24} strain sensitivity at 1–3 kHz and 5×10^{-25} strain sensitivity from 20 Hz to 1 kHz.
	Trace the chemical evolution of the universe using multi messenger observations of neutron star mergers.	Detect and localize neutron star mergers to 1 deg^2 and 1% in distance at least two minutes prior to merger.	A network of two 3G detectors and electromagnetic observatories.	5×10^{-25} strain sensitivity from 20 Hz to 2 kHz in two widely separated detectors, multi-detector network to localize signals out to distances at which telescopes can observe counterparts.
	Connect the properties of binary neutron star mergers to the physics of the relativistic jets powering short gamma-ray bursts.	Detect mergers, localize sources, and measure binary inclination to within 1% for neutron star mergers out to $z \sim 2$.	A network of two 3G detectors and gamma-ray burst satellites.	5×10^{-25} strain sensitivity from 20 Hz to 2 kHz in two widely separated detectors, multi-detector network to measure inclination and polarization out to $z \sim 2$.
Extreme gravity, fundamental physics, and discovery potential.	Study the nature of strong gravity, search for unusual or novel compact objects, explore the implications of quantum gravity, and probe dark matter and dark energy.	Open the largest possible discovery space in gravitational-wave strain sensitivity with a network that is sensitive to both polarizations of the gravitational-wave signal.	A network of two or more 3G detectors to validate the detection of novel sources.	2×10^{-25} or better strain sensitivity across the widest possible frequency band.

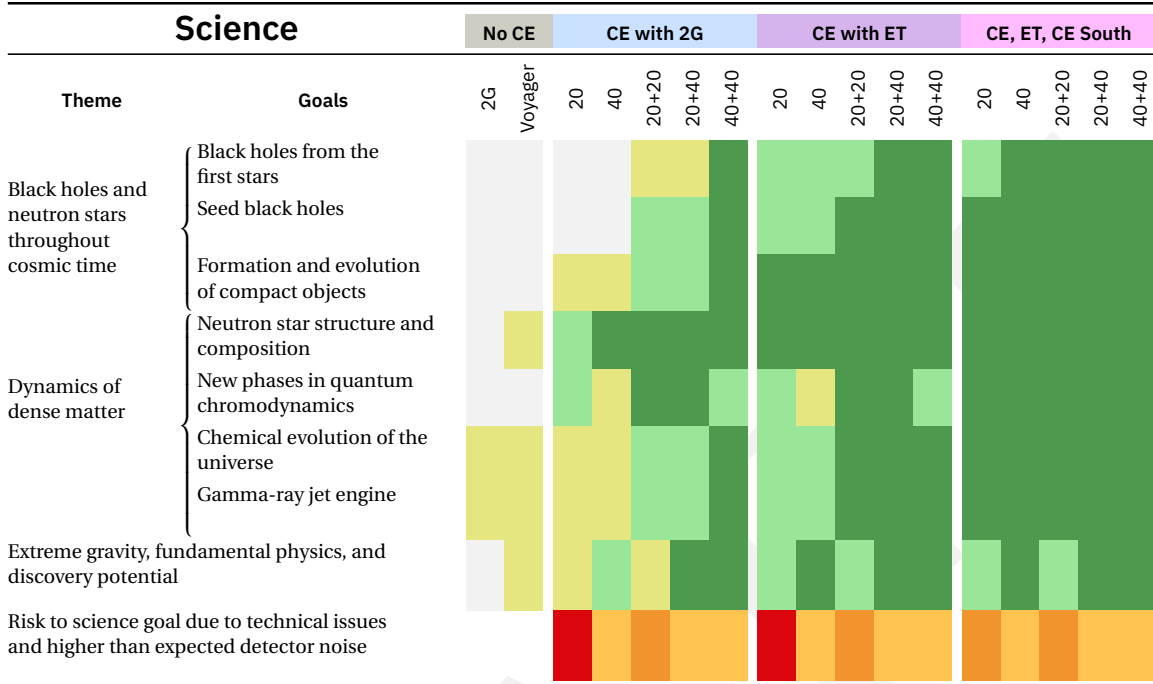


Table 7.3: This graphic indicates the level to which key science goals can be achieved by a variety of Cosmic Explorer configurations. A US Cosmic Explorer consisting of one 20 km detector, one 40 km detector, or a pair of detectors of 20 or 40 km length are evaluated against a background network that includes second-generation (2G) gravitational-wave observatories, the EU Einstein Telescope (ET) and a 20 km Cosmic Explorer-like detector located in Australia (CE South). For each goal, yellow indicates that this network can begin to explore the science, light green indicates that the network can achieve a good understanding of the science goal, and dark green indicates that the network can fully realize the goal. Longer, more sensitive detectors are generally better, and a network is required for many science goals. For example, studying black holes from the first stars requires a 40 km detector that can see black holes at $z \gtrsim 10$ in a network that can measure both gravitational-wave polarizations to accurately measure the hole’s redshift. The exception to the rule is the observation of neutron star post-merger signatures to probe finite-temperature QCD. The higher bandwidth of the 20 km detector allows for better narrow-band tuning for this particular source, but one detector in this configuration is sufficient. Detailed descriptions of the metrics that determine the criteria shown can be found in §7.2.1. We emphasize that this study is a starting point for community input to the final design of Cosmic Explorer. Detailed descriptions of the metrics that determine this flow-down matrix can be found in §7.2.1.

7.2 Trade-Study Outline

The optimization of CE design in the context of a variety of potential future global gravitational-wave detector networks is a complex task. The process used to perform this optimization is referred to herein as a “trade study” since we are looking for tradeoffs which are likely to maximize the scientific output of CE both in the near-term and integrated over the lifetime of the facility. This section gives a brief outline of the trade study, while leaving a full technical description to the literature.^{344–347}

The trade study considers the performance of CE design variants both in the context of the existing 2G detector network, and in the presence of representative next-generation facilities. Specifically, nine detector locations are considered in this study: the five 2G detector sites, including LIGO India (Hingoli, India), and four representative sites for the 3G detectors. Since the locations of future detectors are unknown, we choose locations which we expect are plausible based on geophysical considerations, knowing that the exact location of a detector has little impact on network performance.³⁴⁵ The Einstein Telescope’s reference location is set to be the same as Virgo, while the three possible Cosmic Explorer locations C, N, and S are set to be sites in Idaho (USA), New Mexico (USA), and New South Wales (Australia). The spread of these locations around Earth is shown in Fig. 7.2. The right-hand plot in Fig. 7.2 provides a graphical summary of 2G and 3G detector generations and design concepts considered at each location. The Cosmic Explorer sensitivity curves used in the trade-study are shown in Fig. 7.1. For the sake of brevity, we include results for only 20 km and 40 km Cosmic Explorer configurations although the results are available, and will be made public online, for other arm lengths.

Many different performance metrics are used in the trade-study to capture network perfor-

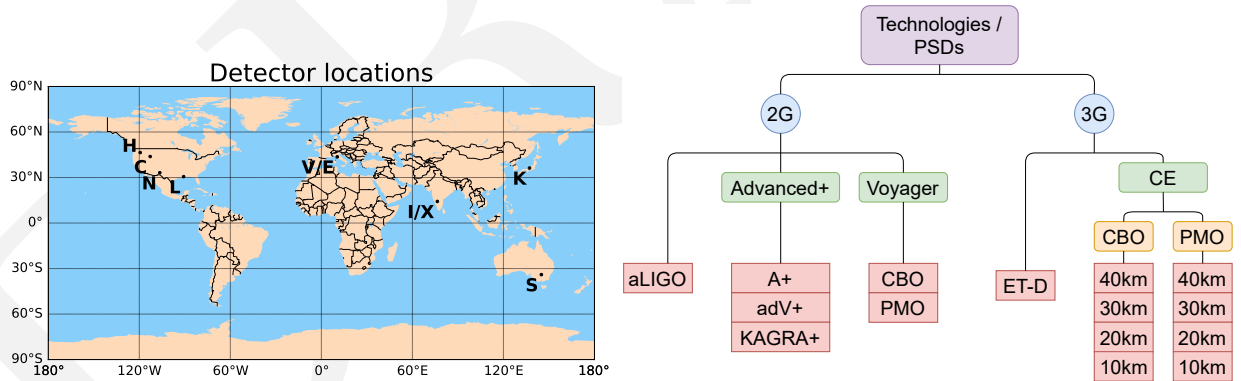


Figure 7.2: The left plot shows detector locations considered in this trade study while the right plot is a graphical summary of the choices available for installing detectors of different arm lengths and sensitivities at various locations. The Advanced+ and Voyager detectors are located at the 5 existing sites (labeled H, L, V, K and I). Since its actual future location is unknown, but certainly in Europe, the Virgo site is used as our reference location for the Einstein Telescope. Cosmic Explorer facilities are considered at three possible locations, two in the US (C and N), and one in Australia (S). For each instance of CE in the US, a variety of configurations are considered (encoded as different power spectral densities, PSDs, and shown on the right side, under the green CE label). These include arm lengths from 10 to 40 km and compact-binary or postmerger optimizations (CBO or PMO).

mance and its impact on scientific output.^{344–347} A key ingredient in almost all performance metrics is the rate of events expected to be observed by different detector networks as a function of redshift. Based on observations so far, the local (i.e., $z \ll 1$) merger rates inferred for the population of binary neutron stars (BNS) and binary black holes (BBH) are^{240,348} $\mathcal{R}_{\text{BNS}} = 320 \text{ Gpc}^{-3} \text{ yr}^{-1}$ and $\mathcal{R}_{\text{BBH}} = 23.8 \text{ Gpc}^{-3} \text{ yr}^{-1}$. Fig. 7.3 plots the cosmic merger rate as a function of redshift¹¹ and time delays and metallicity as treated in Ng et al..⁷⁸

Box 7.2: Questions addressed by the trade study, and their answers in brief.

In addition to a general science-per-dollar optimization, we also use the trade study as a means of answering the following frequently asked questions:

- Is it better to build one large CE, or two smaller ones?
Two 20 km observatories are broadly advantageous relative to a single 40 km observatory, but also somewhat more expensive (see §7.1.2). Better still is the reference configuration of one 40 km and one 20 km observatory (see Table 7.3).
- Should a second CE be built in the US, internationally, or both?
Having a long separation between observatories is favorable for localizing and characterizing gravitational-wave sources, so if only two CE observatories are built it is best for the second to be located far away (e.g., in Australia). However, two observatories in the US can be separated by a sufficient distance to precisely localize a large number of sources, making most of the key science goals accessible (see Table 7.3).
- Would a triangular Einstein Telescope-like design make sense for CE?
A triangular configuration is not advantageous in places where above-ground construction is feasible (e.g., US and Australia, see §7.1.2).
- To what degree are our key science goals dependent on the global detector network?
This question drives much of the complexity of our trade study, and the answer is graphically captured in Table 7.3. The short answer is: much of the key science can be done with the reference CE configuration (one 40 km and one 20 km observatory), while a network of three or more next-generation detectors offers solid answers to all of our key science questions.

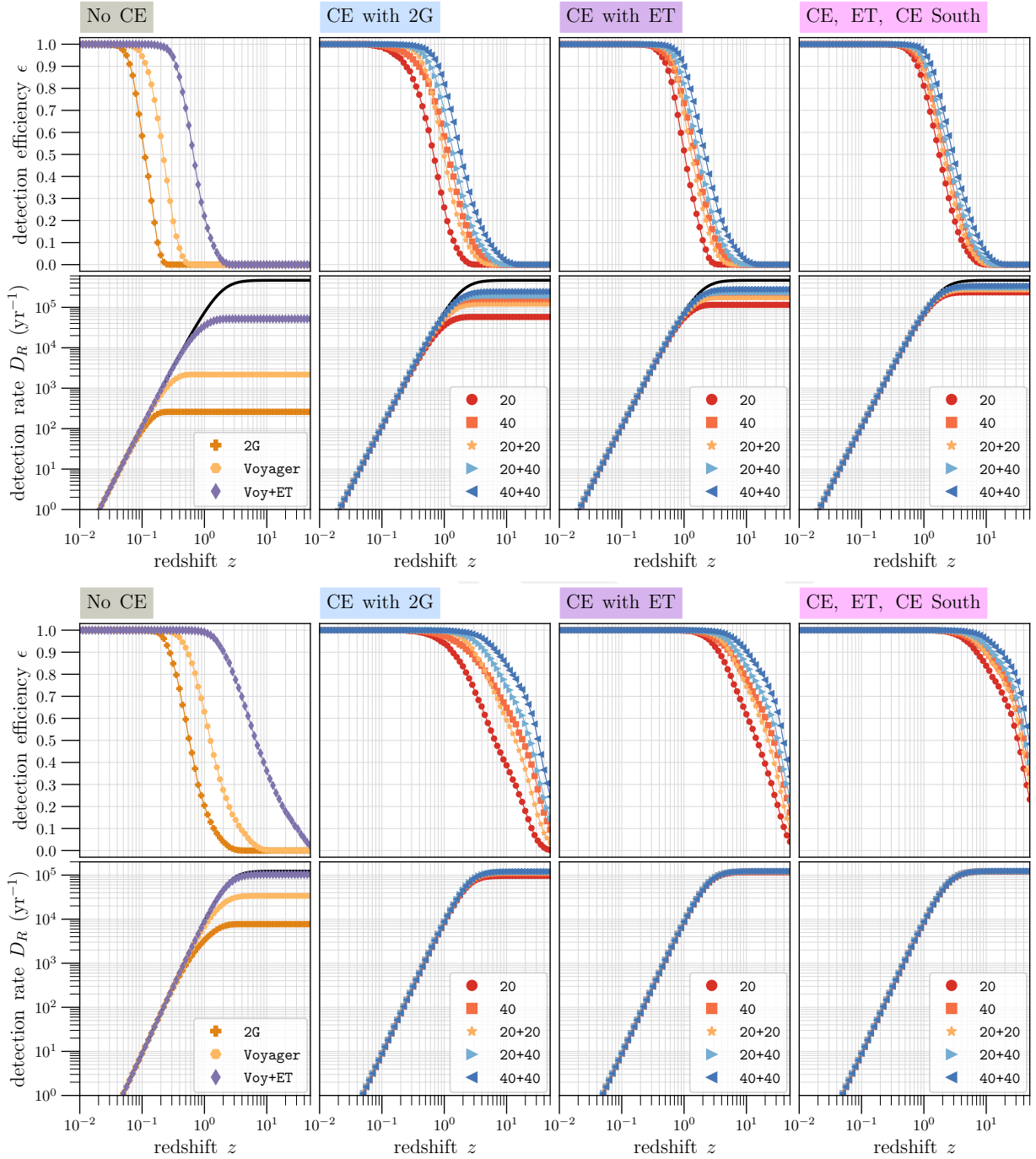


Figure 7.3: The detection efficiency (top and third rows) and the cumulative detection rate (second and fourth rows) of signal-to-noise ratio greater than 10 events for various detector networks for binary neutron stars (top two panels) and binary black holes (bottom two panels). For a given redshift z , the detection efficiency ϵ is defined as the fraction of the number of detected sources to the total number of sources (shown as solid, black lines in the third and bottom rows) out to that distance. The networks are exactly as in Table 7.3.

7.2.1 Impact on Key Science Goals

The key science goals for CE are described in §5. In order to assess the impact of CE design choices on our capacity to accomplish these science goals, we identify a set of performance metrics for each science goal and then evaluate the capability of CE, in the presence or absence of other detectors, to achieve the stated goals. Box 7.2 summarizes the main conclusions of this study with respect to the CE design. Box 7.3 summarizes the key observation rates for Cosmic Explorer.

Box 7.3: Observation Rates for Compact Binaries with Cosmic Explorer.

Cosmic Explorer’s ability to detect large numbers of compact binaries out to large cosmological distances is driven by the low-frequency sensitivity of the 40 km detector. In one year of observations, such a detector will:

- Observe 800 000 binary neutron star mergers (one every 40 seconds),
 - including 80% of all mergers within $z = 1$, allowing association with EM transient surveys,
 - of which 10 will have $\text{SNR} > 300$, providing access to postmerger physics,
 - for thousands will provide distance and sky localization with more than 10 minutes of early warning,
 - and will observe half of all mergers out to $z = 10$, allowing association with gamma-ray bursts and charting the history of supernovae and merger time delays;
- Observe 100 000 binary black hole mergers (one every 5 minutes),
 - of which 8 will be nearby ($z < 0.1$) with median SNR of 600 and $\text{SNR} > 2700$ for the loudest 10% of sources,
 - and 1200 will be at cosmological distances $z > 2$ (inaccessible to current networks whose most distant sources are $z \sim 1$) and have median SNR of 20 (i.e., with SNR similar to GW150914 in Advanced LIGO).

7.2.2 Black Holes and Neutron Stars Through Cosmic Time

Remnants of the First Stars The most sensitive astronomical telescopes (e.g., JWST) will be sensitive to objects at a maximum redshift $z \sim 30$, some 100 Myr after the Big Bang, while the first stars in the universe could have formed even earlier, a mere 30 Myr after the Big Bang or $z = 70$. The network of CE and ET will be sensitive to such redshifts and beyond. Binaries of black hole remnants of first stars could be observed by the 3G network. The metric needed to decisively infer that the observed sources are remnants of first stars is to accurately measure their redshift. This can be done either using the whole population of detected sources, and showing that it contains a high-redshift merger peak; or by proving that individual sources have merged at redshifts higher than what is expected from other astrophysical channels.

The first approach was followed by Ng et al.⁷⁸ where it was shown that a network of 2 CE and one ET could reveal a peak of mergers from Pop III remnants at redshift of ~ 12 (see also Fig. 6.1 above). Given the computational cost of that type of analysis, here we use a simpler figure-of-merit based on individual sources. Specifically, we focus on the fraction of events merging at redshifts $z \geq 10$ with fractional redshift uncertainty smaller than some threshold. As shown in Fig. 6.1, the peak of mergers from Pop. III remnants is expected to happen at $z \sim 12$ (though significant uncertainty exists). Meanwhile, the main two late-universe populations, formation in galactic fields or dynamical formation in globular clusters,^b do not contribute significantly to the total merger rate for redshifts above ~ 8 . Our rough figure-of-merit is thus the fraction of BBH sources for which the statistical uncertainty is smaller than 20 %. This is an uncertainty for which the posterior distribution for the redshift of a black hole that merges at the lowest redshift we consider, i.e., 10, would exclude $z < 8$ at a 1σ level. For black holes whose true redshift is higher than 10, this criterion is conservative in the sense that even an uncertainty larger than 20 % could be sufficient to exclude $z < 8$. We find that no network without at least two 3G detectors can satisfy our criterion. A network with only one 3G detector (Einstein Telescope or Cosmic Explorer) could *detect* some sources at $z \geq 10$, but the associated redshift uncertainty would be too large to definitively prove the merger didn't happen at smaller redshifts. A network with one Einstein Telescope and one 40 km Cosmic Explorer optimized for compact binaries detection^c would detect roughly 20 sources per year that satisfy our criterion. That number more than doubles (~ 57 sources) if the network is augmented to also include a 20 km compact-binary-optimized Cosmic Explorer, due to the superior resolving power of a 3-site network. Adding a CE South brings the number of viable sources to ~ 95 . This highlights that Cosmic Explorer is required if one wants to both access mergers of black holes from the first stars (or, at even higher redshifts, primordial black holes) and also precisely measure their redshift.

In Table 7.3 we mark in yellow networks that yield at least one viable source per year, and in light (dark) green networks that give access to at least 10 (50) viable sources per year.

Black Hole Seeds and Galaxy Formation If supermassive black holes at $z \sim 8$ were built from hierarchical mergers of smaller black holes at higher redshifts we should detect lighter black hole mergers at higher redshifts and heavier ones at lower redshifts. This requires not only the capability of measuring the redshift of a BBH source, but also its source-frame mass. We stress that precise measurement of the source-frame mass does in turn require a precise measurement of the source redshift. This is because what GW detectors measure are redshifted mass parameters, which are $(1 + z)$ times larger than the astrophysically interesting source-frame quantities.²⁷⁸ Therefore, we expect that larger networks will do better at measuring source-frame

^bOther formation channels have been proposed, e.g., nuclear star clusters, young star clusters and mergers in the disk of active galactic nuclei. Here we focus on globular clusters and galactic fields merely because they have been extensively studied in the literature.

^cFor all science goals involving populations of compact binaries, low frequency sensitivity is more important than sensitivity above ~ 500 Hz. Therefore, the postmerger-optimized setting is not thoroughly discussed here.

masses.^{349,350}

Our figure-of-merit to quantify the ability of a network to track the growth of black holes across cosmic history will be the fraction of sources for which the source-frame chirp mass and the redshift can be measured at least as well as what the LVK has reported for GW190521. This source is one of the most interesting found to date in advanced detector data, being composed of two very heavy stellar mass black holes, one of which might lie in the pair instability mass gap (see §5.1). Its formation pathway is not certain, but it might be the result of previous-generation black hole mergers.³⁵¹

We would like our 3G network to be able to characterize similar sources with equal or higher precision, at high redshifts, from 4 to 10. Quantitatively, this requires a 1σ uncertainty on the estimation of the source-frame chirp mass of $\sim 10\%$ or better, and a 1σ uncertainty on the estimation of the redshift of $\sim 25\%$ or better.

We find that at least two 3G detectors are needed. A network made by two 20 km CEs (both compact-binary-optimized) will provide access to ~ 250 viable sources per year. This is 4 times the number of BBHs detected in LIGO-Virgo data in the first three observing runs. Networks which can more precisely resolve the two polarizations of gravitational-wave signals can yield significantly higher numbers of sources that satisfy our criterion. An Einstein Telescope and a 40 km compact-binary-optimized Cosmic Explorer would detect ~ 1300 viable sources per year, while the best network we consider (ET, CE South and two 40 km compact-binary-optimized CEs, i.e. ET plus three CE detectors) would yield nearly 5000 sources per year.

In Table 7.3 we mark in yellow networks that can detect at least 100 viable sources per year, and in light (dark) green networks that give access to at least 500 (2500) viable sources per year.

Formation and Evolution of Compact Objects While the extremely high redshift universe will teach us about primordial black holes and black holes from the first generation of stars, most of the black holes in the universe are produced and merge at redshifts smaller than 4. To characterize the evolution and formation channels of these black holes one needs a large number of black hole binaries with precise measurement of redshifts and intrinsic parameters. We use the same figure-of-merit of the previous section, namely 1σ uncertainty on the estimation of the source-frame chirp mass of $\sim 10\%$ or better, and a 1σ uncertainty on the estimation of the redshift of $\sim 25\%$ or better. However, we only consider sources up to redshift of 4.

As one might expect, even networks without a Cosmic Explorer can yield some viable sources per year, for example a network of 3 Voyager detectors can detect ~ 170 viable sources per year. While a single 40 km Cosmic Explorer with Advanced Plus detectors can find ~ 500 viable sources per year, that number becomes 20 000 if two 20 km CEs are used. This highlights that when the BBHs of interest are at redshifts of few, instead of > 10 , having two 20 km CE detectors is more beneficial than having a single larger detector. In turn this is due to the superior polarization resolving power of larger networks. The same pattern is observed even when ET is included. A network of ET and a 40 km CE finds 33 000 sources per year, while a network of ET and two 20 km CEs finds 48 000. Adding a CE South increases the number of viable sources by less than

10 %.

In Table 7.3 we mark in yellow networks that can yield at least 250 viable sources per year, and in light (dark) green networks that give access to at least 2500 (25 000) viable sources per year.

7.2.3 Dynamics of Dense Matter

Neutron Star Structure and Composition Cosmic Explorer’s ability to probe the structure and composition of neutron star matter is tied to the precision with which the 3G detector network can measure masses and tidal deformabilities from inspiral gravitational waves. In order to achieve a milestone in our knowledge of the dense-matter equation of state at zero temperature, which encodes the details of neutron-star internal structure, masses and tidal deformabilities must be measured precisely enough to constrain the stellar radius to within 0.1 km across the full neutron-star mass spectrum.

The measurability of masses and tidal deformabilities is essentially dictated by the inspiral signal-to-noise ratio. The number of binary neutron star detections made with signal-to-noise ratio above 100, a rough threshold for an informative tidal signature in the measured waveform, is plotted along the inspiral axis of Fig. 7.4 for the different networks considered in the trade study. Operating in a 2G background network, a 40 km Cosmic Explorer detector will observe ~ 300 binary neutron star mergers per year with signal-to-noise ratio in excess of 100. A single 20 km Cosmic Explorer is less well suited to these measurements, but could nonetheless make ~ 100 such loud detections per year if optimized for the inspiral signal. Two 40 km Cosmic Explorers operating in tandem would provide the best constraints on the zero-temperature equation of state. The inclusion of a 20 km Cosmic Explorer or Einstein Telescope in place of the second 40 km detector leads to more modest improvements in performance relative to the single-3G detector network.

Hence, the zero-temperature equation of state science can be maximized with a 40 km Cosmic Explorer detector, although a 20 km detector also performs very well in this area. In Table 7.3 we mark in light (dark) green networks that are expected to detect at least 10 (100) binary neutron star inspirals with signal-to-noise ratio above 100 per year. Networks marked in yellow meet this inspiral signal-to-noise ratio criterion at a rate of 1–10 per year.

New Phases in Quantum Chromodynamics Cosmic Explorer’s capacity to map the phase structure of quantum chromodynamics with neutron-star merger observations will depend on the 3G detector network’s sensitivity to the postmerger signal. In order to break new ground in our understanding of the equation of state in the finite-temperature regime, postmerger gravitational waves must be captured above a signal-to-noise threshold of 8 for several neutron-star mergers, so as to permit measurements of the dominant postmerger frequency.

In contrast to the inspiral gravitational waves, the postmerger signal is better captured by a 20 km Cosmic Explorer detector than a 40 km detector because it can be tuned for increased sensitivity in the relevant kHz frequency range. Using a signal-to-noise ratio threshold of 8, Fig. 7.4 shows the yearly number of postmerger observations per network along the postmerger axis. A

postmerger-optimized 20 km detector will observe the gravitational waves from the remnant of a binary neutron star merger 60–70 times per year, whether operating in a 2G background network or with Einstein Telescope. A single 40 km Cosmic Explorer in a 2G background network would likely miss half of those signals. The optimal performance is achieved when pairing the 20 km postmerger-optimized Cosmic Explorer with a second Cosmic Explorer detector of either 20 km or 40 km; we can then expect ~ 110 postmerger detections (~ 140 if Einstein Telescope is also in the network) per year. Although the trade study shows that a network of two 40 km Cosmic Explorer detectors may nominally return ~ 70 postmerger observations per year, such a network has a greater risk of missing the postmerger signal altogether because its high-frequency sensitivity is not tunable and the precise value of the dominant postmerger frequency depends on the uncertain neutron star equation of state.

Thus, a 20 km postmerger-optimized detector is a must for Cosmic Explorer to map the QCD phase diagram into the finite-temperature regime. In Table 7.3 we mark in light (dark) green networks that are expected to detect at least 50 (100) postmerger signals per year. Networks marked in yellow are expected to detect more than one postmerger signal per year.

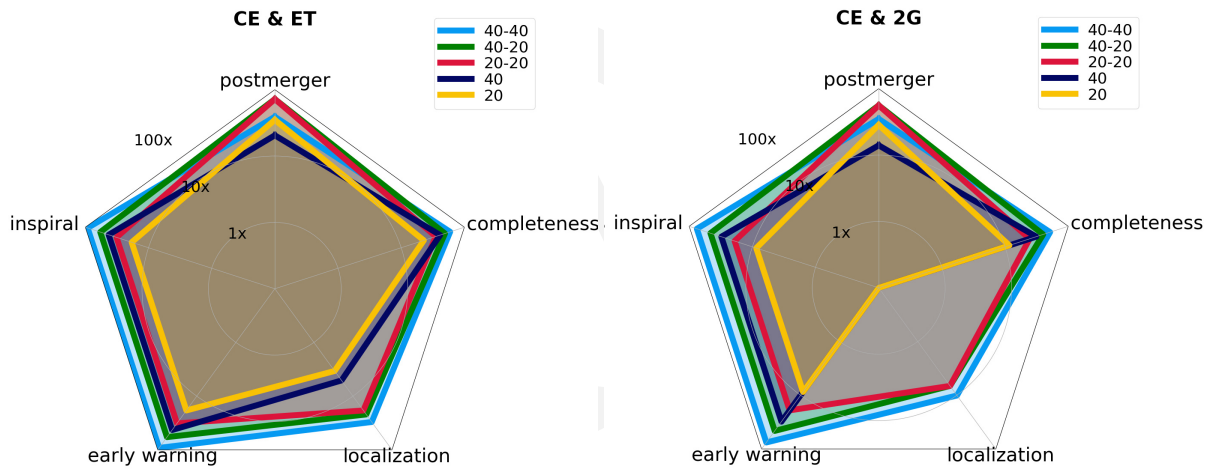


Figure 7.4: Comparative performance of different Cosmic Explorer configurations across five metrics relevant to the Dynamics of Dense Matter science goals. The left-hand plot assumes that the background network includes Einstein Telescope; the right-hand plot adopts a 2G background network. The radial axes are log-scaled and normalized to minimum performance requirements for advancing science. Postmerger performance is measured via the number of postmerger signals detected above a signal-to-noise ratio threshold of 8, normalized to two detections per year. The inspiral metric is the number of binary neutron star mergers detected with signal-to-noise ratio greater than 100, a threshold for useful tidal information in the signal; it is normalized to 10 detections per year. The early warning metric is the number of signals which reach an inspiral signal-to-noise ratio of 10 at least 2 min before merger, normalized to 10 per year. Localization performance is assessed via the number of binary neutron star mergers measured with uncertainties of 1% in distance, 1% in inclination and 1 deg^2 in sky location, normalized to 1 per year. The completeness metric is the percentage of all binary neutron star mergers detected out to redshift $z \sim 2$, normalized to 1%.

Chemical Evolution of the Universe The chemical evolution of the universe can be traced by observing hundreds of neutron-star mergers out to cosmological distances. The complete picture will be built up from multimessenger observations of the sources, particularly prompt electromagnetic observations over the entire spectrum accessible to ground- and space-based telescopes. The key to rapid electromagnetic follow-up is precise localization of the sources, preferably before merger. The ability of the detector network to localize the source to within 1 deg^2 on the sky while measuring the luminosity distance to within 1% will, therefore, determine how well this science goal can be achieved. Additionally, since the signal can last for hours in the sensitivity window of Cosmic Explorer it will be possible to provide alerts about an imminent merger several minutes ahead of time so that electromagnetic telescopes have enough time to point themselves at the source and hence obtain data on the prompt emission of electromagnetic waves in the aftermath of the merger. The inspiral and postmerger signal-to-noise ratios are also important for connecting the binary and remnant properties to kilonova models. The comparative performance of different Cosmic Explorer configurations across these metrics is shown in Fig. 7.4.

The primary driver of localization performance is the number of 3G detectors in the network. The yearly rate of binary neutron star mergers localized to 1 deg^2 in sky area and 1% in distance is plotted along the localization axis in Fig. 7.4 for the different networks in the trade study. A single Cosmic Explorer embedded in a 2G background network will not be able to localize the vast majority of neutron-star mergers well enough to enable accurate electromagnetic follow-up. Rather, two Cosmic Explorer detectors working in conjunction—and preferably partnered with Einstein Telescope, whose especially good low-frequency sensitivity is advantageous for localization—are required. For this metric, the optimal three-detector network of two 40 km Cosmic Explorers and Einstein Telescope is expected to localize ~ 30 binary neutron star mergers precisely every year. Adding a fourth 3G detector in the southern hemisphere, such as a 20 km Cosmic Explorer, increases this number to ~ 50 per year, as the large detector baseline is particularly advantageous for localization. Nonetheless, even without Einstein Telescope or a 3G detector in the southern hemisphere, a 40 km Cosmic Explorer paired with a 20 km one would ensure a dozen such detections per year.

Early warning of the merger correlates strongly with the inspiral signal-to-noise ratio, which builds up as the coalescence progresses. Louder signals reach a detection threshold signal-to-noise ratio of 10 sooner. For the same reason as it was favored for constraining the zero-temperature equation of state, a 40 km Cosmic Explorer detector in the network is most helpful for early warning. Operating alongside Einstein Telescope or a second Cosmic Explorer detector, we can expect $\mathcal{O}(1000)$ binary neutron star mergers with greater than 2 min of early warning per year with such a configuration. As can be seen from the early warning axis of Fig. 7.4, a 20 km Cosmic Explorer operating in a 2G background network or with Einstein Telescope will nonetheless provide 2 min of early warning for several hundreds of binary neutron star mergers per year.

Consequently, the optimal detector network for this science goal would involve two 40 km Cosmic Explorer detectors, preferably with a third 3G detector such as Einstein Telescope.

However, any network with three 3G detectors performs quite well in terms of both localization and early warning. If one of those detectors is a 20 km postmerger-optimized Cosmic Explorer, the odds of joint pre- and postmerger gravitational wave and electromagnetic observations are increased, as the loss in localization and early warning capabilities is modest (a decrease of approximately one third) relative a network whose Cosmic Explorers are all in the 40 km configuration. Networks in Table 7.3 colored in light (dark) green will localize at least one (five) binary neutron mergers to within 1% in distance and 1 deg^2 in sky area per year, and also give 2 min of early warning of merger for 100 signals on a yearly basis. Yellow networks cannot achieve the localization criteria, but still reach the early warning performance target.

Gamma-Ray Jet Engine The properties of the gamma-ray burst ensuing after a binary neutron star merger are largely determined by the remnant, which forms the central engine for launching and driving relativistic jets. The nature of the remnant can be revealed by the observation of postmerger gravitational waves. In order to better understand the physics of the jets and the gamma-ray emission, pre- and postmerger gravitational waves must be associated with gamma-ray observations. This will require good coverage of the population of merging neutron stars out to the horizon $z \sim 2$ of future gamma-ray observatories, so as to provide a reasonably complete gravitational-wave catalog for identifying counterparts. Additionally, to break degeneracies in emission models, it is crucial to measure the source inclination precisely. The inspiral and postmerger signal-to-noise ratios are also important for connecting the binary and remnant properties to jet models; the postmerger observations, in particular, call for the presence of 20 km Cosmic Explorer in the network, as discussed above. The tradeoffs in performance between these different metrics are shown in Fig. 7.4 as a function of different Cosmic Explorer configurations.

The detector horizon for binary neutron star mergers is tied to the arm length; the 40 km Cosmic Explorer configuration captures more of the population out to cosmological distances compared to the 20 km configuration. The fraction of the $z \lesssim 2$ population of merging binary neutron stars captured by each detector network in the trade study is plotted along the completeness axis of Fig. 7.4. Operating with a 2G background network, we can expect a 40 km detector to provide a gravitational-wave association for one out of every three detected gamma-ray bursts, versus one in 10 for a 20 km detector. Moreover, a single 40 km detector outperforms two 20 km ones. The optimally performing configuration for the completeness metric, two 40 km Cosmic Explorers in conjunction with Einstein Telescope, would detect the gravitational waves from 60% of the neutron-star mergers with $z < 2$.

A 40 km Cosmic Explorer detector also delivers more precise inclination measurements, as well as better source localization in general, as described above. To reliably break the distance-inclination degeneracy for neutron-star mergers out to cosmological distances, more than one 3G detector is necessary. However, to ensure that postmerger gravitational waves can be associated with a fraction of the gamma-ray bursts, one of these detectors would ideally be a 20 km postmerger-optimized Cosmic Explorer.

Thus, balancing the need to observe pre- and postmerger gravitational waves for a large

fraction of the binary neutron-star population out to redshifts of $z \sim 2$, we conclude that a 20 km Cosmic Explorer paired with a 40 km one is the optimal configuration for this science goal. Two 40 km detectors would perform less well for the postmerger observations, while two 20 km detectors would capture less of the distant neutron-star merger population. The presence of Einstein Telescope in the network would enhance its performance, especially in terms of source localization. The light (dark) green networks in Table 7.3 will measure source inclination to within 1% for one (five) or more binary neutron star mergers per year, and also capture 10% of the total population merging neutron stars out to $z \sim 2$. The inclination performance target will not be met by the networks colored in yellow.

7.2.4 Extreme Gravity and Fundamental Physics

The Nature of Strong Gravity Gravitational-wave observations of merging black holes encode the nature of the strongest gravity in the universe — the gravity near the horizon of a stellar-mass black hole. Observations of merging black holes with current-generation detectors are giving us a first look at the nature and behavior of strong gravity. So far, all of these observations are consistent with general relativity’s picture of two (initially Kerr) black holes merging into a remnant Kerr black hole, within the experimental noise and theoretical uncertainty of the form of the emitted gravitational waves.

But evidence of new, revolutionary physics has often been first evident in small deviations from conventional expectations. How much we can learn about strong gravity from a gravitational-wave observation thus depends on the strength of the gravitational-wave signal compared to detector noise. The higher the signal-to-noise ratio of an observation, the clearer is the resulting view of the underlying gravitational physics, and the greater potential for discovery.

A Cosmic Explorer detector will give us a solid opportunity far beyond the first look that even the best current-generation detector network could give. For instance, in each year of its operation, a single, 40 km, Cosmic Explorer detector would observe roughly 8 merging black holes that are approximately at least as close to Earth as GW150914 (redshift $z < 0.1$), the loudest gravitational-wave observation from merging black holes so far, with half having signal-to-noise ratios greater than about 600 and the top 10% having signal-to-noise ratios greater than 2700. In contrast, half the observations with a second-generation network using A+ (Voyager) technology would have a signal-to-noise ratio greater than about 70 (150), with the top 10% of signals having signal-to-noise ratios greater than about 280 (610).

A 40-km Cosmic Explorer detector in a network including at least one other next-generation detector would be especially favorable for revealing the nature of strong gravity. In a network with three 3G detectors (two 40 km Cosmic Explorers and one Einstein Telescope), for instance, the top 10% of binary black holes closer than $z = 0.1$ would have signal-to-noise ratios greater than 4100. Also, including more than one next-generation interferometer enables better measurement of the gravitational waves’ polarization, including any potential scalar or vector polarizations that would indicate physics beyond general relativity. A network of next-generation detectors that each have arm lengths no longer than 20 km would be almost as favorable but would not

be quite as sensitive a probe of the nature of gravity, because the 20-km detector's sensitivity is not quite as good in the most sensitive frequency band.

Unusual or Novel Compact Objects Third-generation detectors have the potential to unmask novel objects, including objects potentially masquerading as black holes or neutron stars, by providing precise strain measurements that can be compared with theoretical predictions. Voyager would be capable of giving us a first look at rarer compact binaries, and it also has the potential to give a first look at novel compact objects, if they not only exist but are also sufficiently nearby to be in Voyager's range and sufficiently distinct from black holes and neutron stars that they do not require the signal-to-noise ratios that only detectors in next-generation observatories can achieve. Even a single next-generation observatory would give a much more solid picture of rare, conventional compact binaries: one Cosmic Explorer detector would observe all of the binary-black-hole mergers in the observable universe (about 100 000 observations per year) and would observe nearby mergers with very high signal-to-noise ratios, which corresponds to a greater opportunity to recognize an observation as being unusual.

Similar considerations as for probing the nature of strong gravity apply here: a Cosmic Explorer with 40 km instead of 20 km arms, as part of a network with more than one next-generation detector, would be especially favorable. The 40-km arm length would deliver the highest signal-to-noise ratios, which would enable us to better recognize unusual or novel compact binaries. More than one next-generation detector would be especially favorable for finding unusual or novel compact binaries, because they would increase our confidence in observations of faint unusual or novel compact binaries, and because they would provide polarization information not accessible to a single detector.

Dark Matter and Dark Energy The strength that any signature that dark matter or dark energy might have on gravitational-wave observations is unknown. Current-generation detectors have so far not found signatures of dark matter, and they lack the cosmic reach to provide insight into dark energy through cosmic variations in the observed population of compact objects.

To look for such potential effects, a 40-km Cosmic Explorer as part of a network with multiple next-generation detectors would be most favorable. A 40-km detector would have the highest sensitivity, which would have the best potential to reveal subtle signatures of dark matter, dark energy, or quantum gravity. And a network with more than one next-generation detector will be necessary to observe some of the proposed effects, such as additional gravitational-wave polarizations or standard sirens that rely on multimessenger observations. While some of the proposed effects, such as gravitational-wave echoes, would not necessarily require a network with more than one next-generation detector, such a network would still increase our confidence in detecting faint imprints that dark matter, dark energy, and quantum gravity might have on gravitational-wave observations.

8 Technical Overview and Design Choices

The LIGO and Virgo instruments have opened a new window on the universe, but they are, like Galileo’s first telescope, just sensitive enough to observe the brightest sources. Today the Advanced LIGO detectors see signals roughly weekly; when the recently funded “A+” upgrade is mature in 2025, it will deliver roughly ten detections per week. The key science questions presented in §3 are only answerable by making observations with significantly higher fidelity over a wider frequency band, and by observing more distant sources. As described in §6, this requires new facilities with longer baselines and detectors with an order of magnitude greater sensitivity in the audio frequency band. This section provides a technical overview of the Cosmic Explorer observatory that can deliver that sensitivity, including the sites, infrastructure, and vacuum systems. It also outlines the key technologies that will require research and development to enable the CE science goals. Finally, the key drivers of project costs are discussed.

8.1 Reference Detector Concept

The Cosmic Explorer reference detector concept (see Box 7.1) is that of a dual-recycled Fabry–Pérot Michelson interferometer (DRFPMI) scaled up to use 40 km or 20 km long arms. The longer arm length will increase the amplitude of the observed signals with effectively no increase in the noise. Although there are areas of detector technology where improvements will lead to increases in the sensitivity and bandwidth of the instrument relative to the existing LIGO detectors, the dominant improvement will come from the order-of-magnitude increase in length.

The interferometers installed in the Cosmic Explorer observatories will evolve as the technologies and science evolve. The first two decades of Cosmic Explorer evolution are sketched Fig. 11.1. Like LIGO and Advanced LIGO, CE’s sensitivity is expected to improve with time thanks to technology upgrades and commissioning effort. Unlike the LIGO detectors, there are parts of the CE nominal design which may not be installed before the CE observatories begin collecting data. These “planned upgrades” include: low-loss readout of high-fidelity squeezed states of light (see §8.3.5), adding seismometer arrays capable of removing noise from gravitational disturbances (known as “Newtonian Noise”, see §8.3.9), and improved sensors for seismic isolation relative to what is expected to be available at the time of construction (see §8.3.8).

In order to minimize risk and allow for Cosmic Explorer observations to begin as soon as possible, the initial CE configuration is expected to use the technology developed for the “A+” upgrade to Advanced LIGO in the new larger facilities, along with a few advances to modestly improve the low frequency sensitivity. This provides a straightforward approach to significant

improvement using tested technology with relatively low risk. The planned upgrades will then proceed when possible given availability of new technologies and when maximally beneficial to the scientific output of the observatories. That is, the upgrades can all be performed in parallel at one or both observatories, or sequentially at one observatory at a time to avoid long downtimes.

To further mitigate risk, a second technology capable of achieving (and possibly surpassing) the target sensitivity of CE has also been identified. This “backup concept” uses technology currently being developed for the LIGO Voyager detector, consisting of a 2 μm laser and cryogenic silicon test masses, and will only be required if a major problem is encountered with scaling up current technology. In addition to its role as risk mitigation, research is ongoing to understand if the 2 μm design also offers a path to higher laser power and thus sensitivity beyond the CE target.

8.1.1 Overview

A simple Michelson interferometer measures the strain of a passing gravitational wave by measuring the difference in time for light to traverse two more-or-less perpendicular arms, at the end of which are mirrors serving as test masses. So that these test masses are free from external horizontal forces in the frequency band of interest, they are suspended from pendulums (which also isolate them from seismic noise as discussed further below). The relative phase accumulated by the light in each arm is modulated by a passing gravitational wave and the ensuing power modulation at the antisymmetric port is measured with photodetectors. Practically, the common mode rejection of a Michelson interferometer provides some suppression of laser frequency and intensity noises.

The DRFPMI, shown in Fig. 8.1, improves on the simple Michelson interferometer in several ways. First, input test masses are added to each arm to make Fabry–Pérot cavities. This increases the power stored in the arms, which decreases the quantum shot noise. Second, a “power recycling mirror” added to the symmetric port further increases the power stored in the interferometer and provides passive filtering of laser noise. Finally, a “signal extraction mirror” added to the antisymmetric port forms a “signal extraction cavity”. The bandwidth of the interferometer can be tuned to enhance the sensitivity relevant for a particular science case by simply changing the reflectivity of this mirror as is shown in Fig. 8.2.

The other major subsystems of the interferometer are described in the following sections. §8.1.2 explains how quantum noise is reduced by injecting “squeezed vacuum states”, first reflected off of another optical cavity for broadband noise reduction, into the antisymmetric port of the interferometer. The choice of optics and coatings is discussed in §8.1.3. §8.1.4 describes how the optics are suspended to isolate them from seismic noise. The generation and stabilization of the main laser beam before injection into the symmetric port of the interferometer and the readout of the signal at the antisymmetric port is described in §8.1.5. §8.1.6 describes the mitigation of the noise caused by Newtonian gravity fluctuations, and §8.1.7 discusses computing and control systems. Fig. 8.1 shows this reference concept including these major subsystems and Table 8.1 presents the key design parameters. The estimated spectral sensitivity of Cosmic

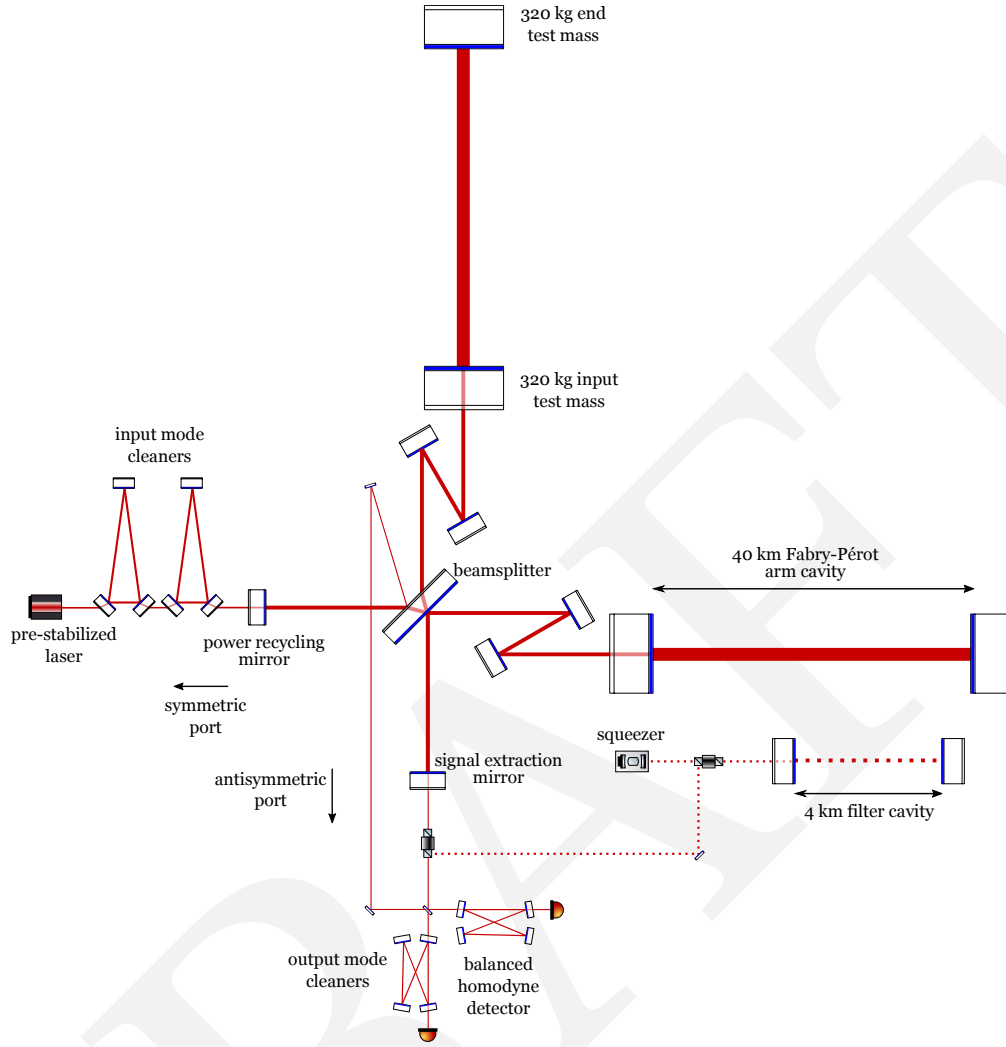


Figure 8.1: Simplified optical layout of the Cosmic Explorer reference detector concept for the 40 km implementation. The input and end test masses form the two arm cavities which, together with the beamsplitter, power recycling mirror, and signal extraction mirror, comprise the core of the dual-recycled Fabry–Pérot Michelson interferometer as described in §8.1.1. As described in §8.1.5, the light carrying the gravitational wave signal is spatially filtered and read out from the antisymmetric port by a balanced homodyne detector comprised of two photodiodes and output mode cleaners; a high power laser is injected into the symmetric port of the interferometer after passing through two input mode cleaners which assist in producing a frequency and intensity stabilized beam with a spatially clean mode. The squeezer generates squeezed vacuum states which are reflected off of a filter cavity and injected into the antisymmetric port to provide broadband quantum noise reduction as described in §8.1.2.

Explorer and the limitations to it that are imposed by the known fundamental noise sources are shown in Fig. 8.3.

8.1.2 Quantum Noise Reduction

Quantum vacuum fluctuations entering the antisymmetric port of the interferometer will be the dominant limit to the sensitivity of Cosmic Explorer above 20 Hz. Quantum mechanics requires

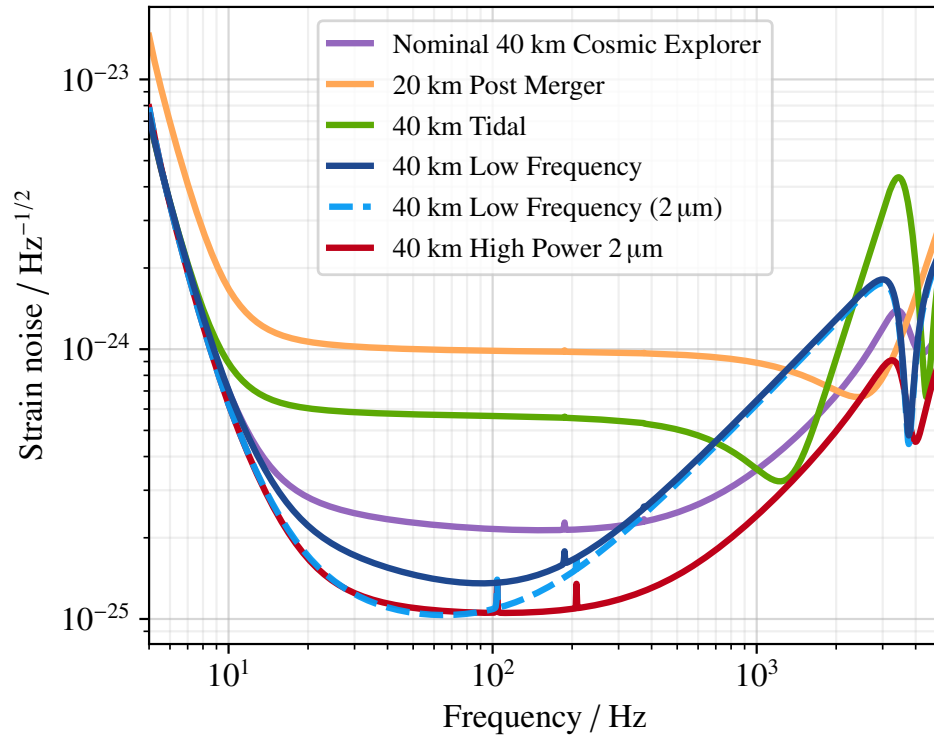


Figure 8.2: Examples of strain sensitivities targeting different science cases obtained by varying the reflectivity of the signal extraction mirror.

every mode of the electromagnetic field to have a minimum zero-point energy. These vacuum fluctuations enter any open port of the optical system.^a Radiation pressure noise dominates at low frequencies where fluctuations in the vacuum field amplitude quadrature beat with the main laser field to produce a fluctuating radiation pressure force on the mirrors. At higher frequencies, it is the beating of the vacuum field fluctuations in the orthogonal phase quadrature with the main laser field, shot noise,^b that directly limits the accuracy with which the phase can be measured.^{352–354}

While Heisenberg’s uncertainty relation dictates the fundamental limit below which the vacuum fluctuations cannot be reduced, fluctuations in one quadrature can be reduced at the expense of increasing the fluctuations in the orthogonal quadrature, leading to “squeezed states.”³⁵⁵ As with Advanced LIGO,³⁵⁶ Cosmic Explorer will use a nonlinear crystal pumped with a laser at twice the frequency of the main laser, known as a degenerate optical parametric oscillator, to produce the correlations necessary to generate such squeezed vacuum states and inject them into the antisymmetric port. In this way, radiation pressure noise can be reduced

^aVacuum fluctuations entering the symmetric port contribute noise to the common mode, rather than the differential mode which carries the gravitational wave signal.

^bThis shot noise arising from the beating of the vacuum fluctuations entering the antisymmetric port with the main laser is a truly intrinsic phase noise of the optomechanical system. It is distinct from the related technical noise, also referred to as shot noise, where phase noise is produced by excess light incident on a photodiode beating with vacuum fluctuations.

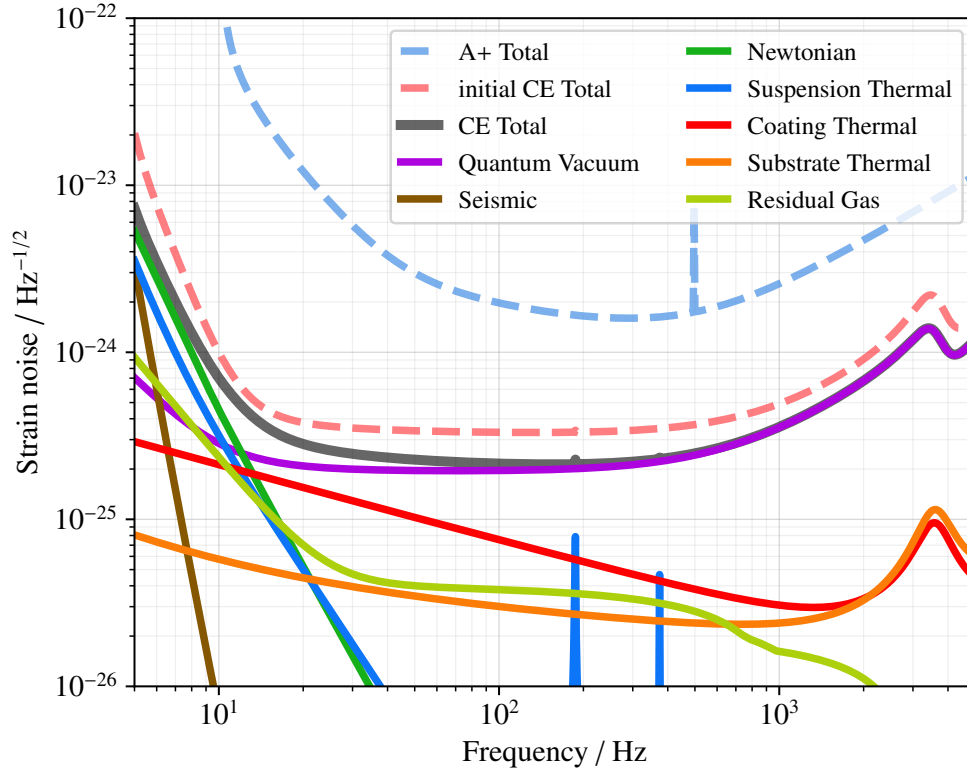


Figure 8.3: Estimated spectral sensitivity (solid black) of Cosmic Explorer and the known fundamental sources of noise that contribute to this total (colored curves). The design sensitivity of LIGO A+ is also shown in dashed blue and the initial sensitivity of Cosmic Explorer is shown in dashed red.

by injecting states with decreased uncertainty in the amplitude quadrature, at the expense of increased phase uncertainty and shot noise. Similarly, shot noise can be reduced by injecting states with decreased uncertainty in the phase quadrature at the expense of increased amplitude fluctuations and radiation pressure noise. However, since radiation pressure dominates at low frequencies and shot noise dominates at high frequencies, injecting squeezed vacuum with a fixed ratio of amplitude to phase uncertainty necessitates a tradeoff between reducing quantum noise at high and low frequencies.

The frequency dependence required to achieve broadband quantum noise reduction can be achieved by reflecting the squeezed vacuum state generated by the parametric oscillator off of an extra optical cavity detuned from resonance, known as a filter cavity, before it is injected into the interferometer.^{353,357,358} Cosmic Explorer will use such a 4 km long filter cavity to produce a frequency dependent squeezed state that rotates from amplitude squeezing at low frequencies to phase squeezing at high frequencies at the appropriate rate to achieve 10 dB of broadband quantum noise reduction. The realizable net amount of noise reduction is dependent on the optical losses in the system, which are expected to improve as upgrades are made to the detector

Quantity	Units	LIGO A+	initial CE	CE	CE (2 μm)
Arm length	km	4	40	40	40
Material		Silica	Silica	Silica	Silicon
Test mass	kg	40	320	320	320
Temperature	K	293	293	293	123
Wavelength	μm	1	1	1	2
Arm power	MW	0.8	1.5	1.5	3
Squeezed light	dB	6	6	10	10
Susp. length	m	1.6	4	4	4
Susp. mass	kg	120	1500	1500	1500
Final stage blade		No	Yes	Yes	Yes
Rayleigh wave suppr.	dB	0	6	20	20
Body wave suppr.	dB	0	0	10	10
Susp. point at 1 Hz	$\text{pm}/\sqrt{\text{Hz}}$	10	1	0.1	0.1
BNS horizon redshift		0.19	4.2	8.3	11.7
BBH horizon redshift		2.7	34	41	41
BNS SNR, $z = 0.01$		75	900	1260	1460
BNS warning, $z = 0.01$	min	4	94	103	103

Table 8.1: Key design parameters and astrophysical performance measures for the LIGO A+ and 40 km Cosmic Explorer detectors. The astrophysical performance measures assume a $1.4\text{--}1.4M_{\odot}$ binary-neutron-star (BNS) system and a $30\text{--}30M_{\odot}$ binary-black-hole (BBH) system, both optimally oriented. “BNS warning” is the time before merger at which the event has accumulated a signal-to-noise ratio (SNR) of 8.

8.1.3 Optics and Coatings

Cosmic Explorer will use large 320 kg test masses made into highly reflective mirrors through the use of thin-film coatings consisting of alternating layers of high and low refractive-index materials. The substrates and coatings for Cosmic Explorer will use the existing technology for LIGO A+ scaled up to the larger test mass size. The desire to make massive test masses stems from the desire to reduce quantum radiation pressure noise and, as a practical matter, they must be wide enough to accommodate the large diameter beams of a nearly diffraction limited 40 km long arm cavity.

The test mass substrate is fused silica, chosen for its low mechanical loss at room temperature, and correspondingly low thermal noise, and low absorption of $1\text{ }\mu\text{m}$ light. The low refractive-index layers of the coatings will be silica; the high index layers are yet to be determined. These coatings must have low mechanical loss to reduce their thermal noise, yet this thermal noise is still a significant source of noise at middle frequencies. The desire to reduce this noise is one factor motivating the use of cryogenics as an alternative technology as discussed in §8.1.8.

8.1.4 Seismic Isolation and Suspensions

Each of the four Cosmic Explorer test masses will be suspended by a quadruple pendulum in order to isolate them from seismic disturbances.³⁵⁹ The suspensions provide passive $1/f^8$ filtering of seismic noise above their mechanical resonance frequencies. Even so, the suspensions themselves will be suspended from inertial seismic isolation systems which provide additional active and passive suppression of seismic noise.³⁶⁰

In order to minimize thermal noise, the final suspension stage is monolithic. Each silica test mass is suspended from another silica mass, the penultimate mass, by silica fibers.³⁵⁹ The top two masses of the suspensions are maraging steel and are suspended by steel wires.

In order to reduce the vertical suspension resonances, and thus both the vertical seismic and suspension thermal noises which couple into the arm length due to the Earth's curvature, each of the first three stages is suspended from steel blade springs attached to the stage above. Unlike the LIGO suspensions, however, an additional set of silica blade springs are added for the final stage instead of bonding the suspension fibers directly to the penultimate mass.

The inertial seismic isolation systems which reduce the seismic motion of the optical tables to which the suspensions are attached are similar to those of Advanced LIGO³⁶⁰ but with refined inertial and position sensors. It is assumed that incremental improvements will allow CE to initially achieve a threefold improvement over Advanced LIGO at 10 Hz and a tenfold improvement at 1 Hz. Novel six-dimensional inertial isolators with optical readout will be used to achieve an additional threefold improvement at 10 Hz and tenfold improvement at 1 Hz to achieve the final CE sensitivity. The status of this technology is described in §8.3.8.

8.1.5 Input and Output

The laser source for Cosmic Explorer begins with a 1 μm seed laser, which produces around 1 W of light. This is then amplified by a two-stage amplifier to the full input power of about 140 W, the amount needed to reach the goal of 1.5 MW arm power with expected optical loss. Together with some laser intensity and frequency stabilization and some cleaning of the spatial mode of the laser, this comprises the pre-stabilized laser.³⁶¹ The light from the pre-stabilized laser is then sent through two triangular cavities known as input mode cleaners to provide further laser frequency stabilization and cleaning of the spatial mode. The light exiting the input mode cleaners is then injected into the main interferometer at the back of the power recycling mirror.

The gravitational wave signal is imprinted on the light exiting the interferometer from the signal extraction mirror. This signal is measured using a balanced homodyne detector with a local oscillator derived from a few hundred milliwatts of light extracted from the beamsplitter. The spatial mode and frequency content of the signal and local oscillator are cleaned by two bow-tie cavities known as output mode cleaners before being detected with high quantum-efficiency photodiodes.

8.1.6 Newtonian Noise Mitigation

Fluctuations in the gravitational attraction between the test masses and the environment, known as “Newtonian noise”,³³⁹ are a significant low frequency noise source for Cosmic Explorer.

Seismic waves are one source of Newtonian noise. CE will initially suppress noise from Rayleigh surface waves by a factor of two in amplitude. After planned upgrades, CE will suppress Rayleigh waves by a factor of ten and will additionally suppress the Newtonian noise from body waves by a factor of three. A combination of several techniques may be employed to achieve these goals. One technique is to use seismometer arrays to estimate the seismic field near the test masses and to subtract its effects from the gravitational wave strain data.³⁶² Another approach is to directly reduce the coupling of seismic waves to the test mass by modifying the density of the material below each mass³⁶³ or intentionally deflecting or dissipating them with architected materials or seismic metamaterials.^{364–369} These techniques are discussed in detail in §8.3.9.

Cosmic Explorer is also affected by Newtonian noise due to density fluctuations in the atmosphere at infrasonic frequencies. The reference concept does not include any suppression of Newtonian infrasound noise, since it is unknown if the technology needed to do so would be mature by the 2040s, and this is the dominant source of Newtonian noise.

8.1.7 Computing and Controls

Holding the detector at its stable, astrophysically sensitive operating point requires feedback control on a large number of degrees of freedom, such as the relative distances and angles between the suspended optics. Additionally, bringing the detector to its operating point requires a multi-step locking scheme. Following an evolution of the controls systems used for LIGO,³⁷⁰ CE will use a hybrid digital and analog real-time data acquisition and controls system, along with automated supervision of the detector locking. The digital system will also provide near real time calibration and astronomical alerts.

Because of environmental conditions and the time required for the locking process, current gravitational-wave interferometers have roughly 75 % availability; the CE designs will strive to improve upon this. The greatest improvement in observing time will likely come from reducing the time required to achieve lock, e.g., with a fully deterministic locking scheme, and from improving the instrument’s robustness to the environmental disturbances, particularly from high seismicity and wind.

8.1.8 2 μm Cryogenic Silicon as an Alternative Technology

In order to mitigate risk in the event that the LIGO A+ technology cannot achieve the CE design sensitivity and to retain the possibility of surpassing this goal in the future, it is prudent to continue research into the technology being developed for LIGO Voyager, namely cryogenic silicon test masses and a 2 μm laser.

One risk associated with the nominal 1 μm technology is potential roadblocks to achieving the required 1.5 MW power in the arm cavities. The presence of point-like particles in the test mass coatings which absorb the laser power and thermally deform the mirrors has been an obstacle to achieving the design power in Advanced LIGO.³⁷¹ While progress has been made in addressing this issue, which must also be solved for A+ to reach its sensitivity goal, it is not expected to be a significant issue for the cryogenic silicon technology due to the high thermal conductivity of silicon. Other thermal effects may also limit the achievable arm power for the 1 μm technology. The power absorbed in the test mass substrates, for instance, causes a thermally induced lens which must be corrected.³⁷² While research is still needed into methods of correcting this lens, the magnitude of the effect should be smaller with the 2 μm technology.

Another motivation for research into the 2 μm technology is the fact that coating Brownian noise is a non-negligible noise source from roughly 10 to 100 Hz for the 1 μm technology. Even if the thermal effects associated with this technology are overcome and more power can be stored in the arm cavities, the presence of this noise may prevent the 1 μm technology from significantly improving its sensitivity beyond the current design. The importance of coating Brownian noise is already visible in the “low frequency” tuning shown in Fig. 8.2 where it limits the sensitivity of the 1 μm technology while the 2 μm technology is still limited by quantum noise. Furthermore, while both technologies achieve similar performance with the long arms of Cosmic Explorer, the 1 μm technology becomes less attractive for arms significantly shorter than 20 km.

8.2 Site and Facility

Several important factors must be considered when identifying sites suitable for hosting a Cosmic Explorer facility. The site must satisfy the requirements described in §8.2.1 in order to reach design sensitivity, and sites with favorable topography can significantly decrease the cost of civil engineering work needed to accommodate the beamtubes as is discussed in §8.5.1. Other site selection considerations are discussed in §8.5.3.

The CE building design and construction can be based upon those used for LIGO, with future research into considerations such as aerodynamic building shapes, wind fences, and other vibration reduction engineering such as berms. Operating the existing LIGO observatories has taught us much about how to not only mitigate noise couplings but also to design facilities that have more immunity to environmental noise. As much as possible, equipment and personnel that cause vibration, acoustic, infrasound, and electromagnetic disturbances should be located far from the most sensitive equipment, for example in out-buildings near to the corner and end stations. In addition to the buildings housing the CE detector infrastructure, CE will require laboratories, warehouses, mechanical and electrical workshops, and offices, as well as meeting spaces for users and visitors. These buildings should be close enough to allow access to the CE site, but far enough away that they do not significantly couple anthropogenic noise into the detector. Access roads will be needed, and access to rail would be advantageous, especially for

delivery of the vacuum pipe.

8.2.1 Site and Facility Requirements

Ambient seismicity Ground motion directly impacts the sensitivity of Cosmic Explorer, particularly due to seismically induced fluctuations in the local gravitational field. This gravitational influence on the detector test masses cannot be screened or shielded, though it can be partially ameliorated with data subtraction techniques, by altering the properties of the ground near the test masses, and by selecting a low-seismicity site. The current estimate of the Cosmic Explorer sensitivity assumes a Rayleigh-wave-dominated ground motion with amplitude $1 (\mu\text{m}/\text{s}^2)/\sqrt{\text{Hz}}$. Based on US seismic surveys, this ground acceleration target is not particularly onerous, and the overall seismicity at the site is likely to be dominated by local machinery above 5 Hz. A dedicated seismic survey for Cosmic Explorer must establish both the overall ground motion amplitude above 5 Hz, as well as the partitioning of the field into its bulk and surface wave components.

Additionally, experience from existing long-baseline laser interferometers shows that high seismicity negatively impacts the controllability of the instrument, leading to downtime and decreased sensitivity. It is therefore important to survey the ground motion down to 10 mHz.

Ambient infrasound Acoustic waves also impact the Cosmic Explorer sensitivity by generating local gravity fluctuations. The Cosmic Explorer sensitivity model assumes an ambient acoustic spectrum of $1 \text{ mPa}/\sqrt{\text{Hz}}$, which is in line with the median spectrum from long-term global infrasound surveys. A dedicated infrasound survey for Cosmic Explorer must be careful to disentangle the effect of wind confusion noise.

Geotechnical issues Any potential site will require a geotechnical investigation to assess its suitability and to arrive at a precise cost estimate for the construction of a CE observatory. In addition to standard civil-engineering aspects, this assessment will need to evaluate the potential for seismic engineering as discussed in 8.3.9.

Ambient environment Longer term measurements of the environment are required than were made for LIGO in order to determine the frequency with which periods of excess noise arise from the weather (for example wind and thunderstorms) or from anthropomorphic origins (such as cars and trains). Susceptibility to natural disasters such as flooding, earthquakes, or hurricanes must also be evaluated.

Environmental stewardship 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 of the ecosystem might range from interference with migratory or mating patterns, to the extinction of local flora and fauna, to the introduction of damaging invasive

species, as well as other possibilities. Since various forms of chemical or thermal pollution can cause such problems, as can negligent construction or waste disposal practices, 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 caution with respect for the environment is essential throughout the lifetime of the facility, it is especially important during the initial construction phase and during facility decommissioning at the end. During the operations phase the potential for harm is less but still requires careful monitoring.

8.2.2 Vacuum System

Beamtube diameter	48 in (122 cm)
Beamtube thickness	$\frac{1}{2}$ in (13 mm)
Beamtube material	mild steel
Beamtube BRDF	10^{-3} sr^{-1}
Hard close gate valves	10, partitioning into 10 km sections
Soft close gate valves	32, partitioning into 2 km subsections
2000 L/s ion pumps	40, one for each subsection
Roughing pumps	40, one for each subsection
non-evaporable getters	distributed throughout
6 in pumping ports	one every 250 m
Baffle aperture	100 cm
Baffle BRDF	10^{-3} sr^{-1}

Table 8.2: Reference parameters for the Cosmic Explorer vacuum system for a 40 km facility. Fig. 8.4 shows a schematic of how the vacuum system is broken up into 10 km subsections.

As with all interferometric gravitational-wave detectors, ultra high vacuum (UHV) is necessary in the Cosmic Explorer arms and in the chambers that contain the detectors core optics. This vacuum system is responsible for shielding the interferometer from acoustic noise and thermal noise from the atmosphere (by removing the air), and for absorbing any laser light which is scattered out of the interferometer. While the vacuum techniques developed for the LIGO detectors are adequate for CE, there is room for improvement and value engineering (see §8.3.1). Nominal parameters of the CE vacuum system are given in Table 8.2.

The vacuum practices used with the test mass chambers of CE will need to be improved relative to that of current LIGO facilities to reduce pumpdown times after in-chamber detector work. Besides increased pumping capacity, it may be necessary to bake the test mass chambers to ensure adequate protection from condensation on the cryogenic mirrors. For both the chambers and beamtubes, the hydrogen pumping speed can easily be augmented by titanium sublimation or non-evaporable getter pumps relative to current LIGO.

Residual gas pressure requirements The pressure requirements in the beamtubes and in the test mass chambers are determined by two different processes. Fluctuations of the gas column density in the beamtubes induces a phase noise when the light scatters off of the residual gas molecules,³⁷³ while the residual gas in the chambers exerts a force noise directly on the test masses.^{374,375} The gas force noise has a $1/f^2$ frequency dependence and is important at low frequencies, while the gas scattering noise is constant in frequency up to a cutoff frequency determined by the time for a molecule to cross the beam; see Fig. 8.3.

The vacuum system requirements for the partial pressures of each species are broken up into a set of requirements that must be met and a set of goals to strive for. The requirements on the beamtube pressures are that the gas scattering noise is at least a factor of five below the design sensitivity, and the requirements on the chamber pressures are that the gas damping noise is at least a factor of three below the design sensitivity. The goals on the pressures in both the beamtubes and chambers are that the residual gas noise is a factor of ten below the design sensitivity at all frequencies. In the absence of a malfunction or poor vacuum practice, such as leaks in the vacuum system or inadequate cleaning of vacuum components, achieving the low partial pressures necessary to meet these requirements will be most challenging for hydrogen, water, nitrogen, and oxygen. We thus allow these four species to saturate these requirements with each contributing one quarter to the total. Hydrocarbons need to be kept to a level that they do not contaminate the mirror and cause excess optical loss. These pressure requirements and goals are summarized in Table 8.3.

UHV beamtubes The vacuum tubing for Cosmic Explorer will be separated into 10 km sections, which are independently pumped. Each section is further divided into 2 km subsections for outgassing and leak hunting as shown in Fig. 8.4. The LIGO beamtubes are also independently pumped in 2 km sections. The ends of the 10 km sections will require fully capable gate valves but the 2 km subsections need only the equivalent of light weight shutters to aid in the initial commissioning and operational leak checking. These shutters can be allowed to leak between subsections by as much as 10^{-3} L/s and do not have to bear atmospheric loads. We call this a “soft” close valve which should be significantly lower in cost than the “hard” close valves used at the ends of the 10 km sections. The soft close valves could be magnetically actuated and will not require penetrations in the vacuum envelope.

Test mass chambers Each test mass suspension will be enclosed in a UHV chamber. One possibility to consider is for the bottom two stages of the suspension (consisting of the test mass and penultimate mass) to be separated from the upper stages so that the stages can be accessed separately and in order to separate materials with high outgassing from the test masses. The feasibility of doing this in a manner that both withstands atmospheric loads and maintains the necessary vibration isolation needs to be investigated. Even if this can be accomplished, achieving the goal pressures in the chambers will be more challenging than in the beamtubes since high temperature bakes are not possible in order to protect the components housed in

Species	Req / torr	Beam tubes		Req / torr	Chambers	
		Goal / torr	LIGO Achvd / torr		Req / torr	Goal / torr
He	1.3×10^{-9}	3.4×10^{-10}			8.8×10^{-10}	7.9×10^{-11}
H ₂	3.3×10^{-10}	8.3×10^{-11}	3.4×10^{-9}		3.1×10^{-9}	2.8×10^{-10}
Ne	1.8×10^{-10}	4.5×10^{-11}			3.9×10^{-10}	3.5×10^{-11}
H ₂ O	3.0×10^{-11}	7.6×10^{-12}	2.3×10^{-12}		1.0×10^{-9}	9.4×10^{-11}
O ₂	2.1×10^{-11}	5.3×10^{-12}	2.0×10^{-13}		7.8×10^{-10}	7.0×10^{-11}
N ₂	1.9×10^{-11}	4.7×10^{-12}	1.0×10^{-13}		8.3×10^{-10}	7.5×10^{-11}
Ar	6.7×10^{-12}	1.7×10^{-12}	9.0×10^{-14}		2.8×10^{-10}	2.5×10^{-11}
CO	5.8×10^{-12}	1.4×10^{-12}	2.0×10^{-12}		3.3×10^{-10}	3.0×10^{-11}
CH ₄	4.8×10^{-12}	1.2×10^{-12}	2.2×10^{-11}		4.4×10^{-10}	4.0×10^{-11}
CO ₂	2.8×10^{-12}	6.9×10^{-13}	4.0×10^{-13}		2.7×10^{-10}	2.4×10^{-11}
Xe	6.3×10^{-13}	1.6×10^{-13}			1.5×10^{-10}	1.4×10^{-11}
100 u H _n C _m	8.9×10^{-14}	2.2×10^{-14}			1.8×10^{-10}	1.6×10^{-11}
200 u H _n C _m	1.7×10^{-14}	4.2×10^{-15}			1.2×10^{-10}	1.1×10^{-11}
300 u H _n C _m	6.2×10^{-15}	1.5×10^{-15}			1.0×10^{-10}	9.2×10^{-12}
400 u H _n C _m	3.1×10^{-15}	7.6×10^{-16}			8.8×10^{-11}	7.9×10^{-12}
500 u H _n C _m	1.7×10^{-15}	4.3×10^{-16}			7.9×10^{-11}	7.1×10^{-12}
600 u H _n C _m	1.1×10^{-15}	2.8×10^{-16}			7.2×10^{-11}	6.5×10^{-12}

Table 8.3: Cosmic Explorer residual gas requirements and goals. The requirements are that the total gas scattering noise is a factor of five below the design sensitivity and that the total gas damping noises are a factor of three below the design sensitivity. The goals are that the total residual gas noise is a factor of ten below the design sensitivity everywhere. See text for details. The pressures achieved in the Advanced LIGO beamtube are also shown for comparison.³⁷⁶

the chambers and since they will need to be opened periodically to make modifications to the detector. The other core optics, such as the beamsplitter, will also be housed in UHV chambers though the requirements on these are not as stringent.

Requirements due to scattered light Light scattered out of the interferometer can scatter off the beamtube and reenter the interferometer. In this way, motion of the beamtube can be converted to noise on the light circulating in the interferometer and thus noise at the gravitational-wave readout. The presence of this coupling sets a requirement on the diameter of the beamtube that as the arm length is increased and the interferometer beams grow in size. Calculations show that 120 cm diameter beamtubes with 100 cm baffle apertures are sufficient to keep noise due to scattered light a factor of ten or more below the nominal sensitivity of Cosmic Explorer.^{377,378} See §8.3.13 for a broader discussion of the scattered light mitigation research required for CE.

8.3 Enabling Technologies

The reference detector concept for Cosmic Explorer is largely based on the evolution of technology currently deployed in LIGO and other gravitational-wave detectors. Clearly, this evolution of

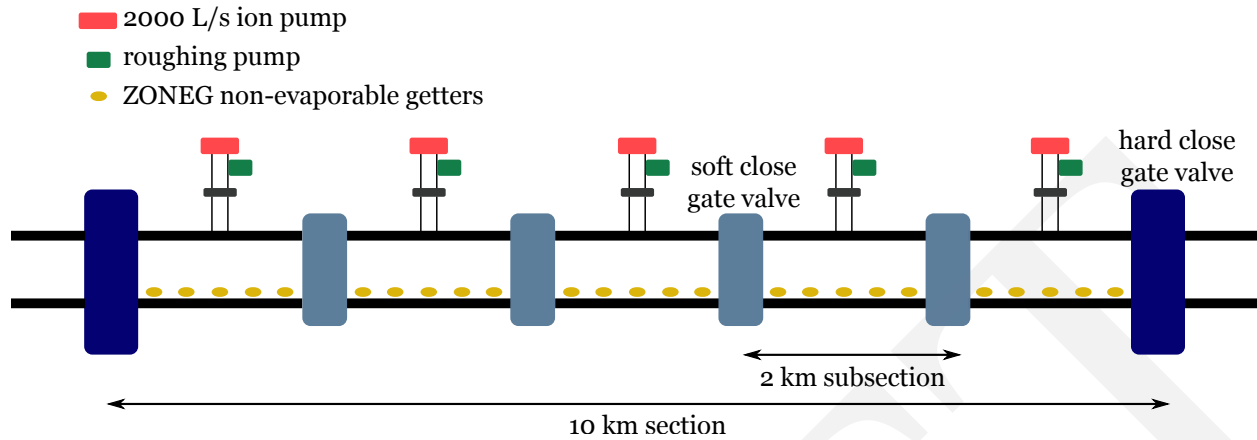


Figure 8.4: Schematic of a 10 km beamtube section. Each 10 km section can be pumped and serviced independently. The ends of the section are determined by commercial 48 in (122 cm) gate valves with elastomer O-rings that can withstand an atmospheric pressure from either side. The 2 km subsections are separated by soft-close gate valves used for separating regions with small pressure differences during some bake operations and for diagnostics. 6 in pumping ports (not shown) are located every 250 m and can be used for leak hunting and diagnostics or while pumping down.

Technology	2G	CE facility	initial CE	CE	CE (2 μ m)
Ultra-High-Vacuum Systems	Green	Yellow			
Large, High-Purity Mirror Substrates			Orange	Orange	Red
Low-Loss Mirror Coatings	Yellow		Yellow	Yellow	Orange
Optical Wavefront Control				Orange	Red
High-Fidelity Squeezed States of Light				Orange	Red
High-Power Ultrastable Laser	Green		Orange	Orange	Red
Low-Noise Suspensions			Orange	Orange	Red
Inertial and Position Sensors			Orange	Orange	Red
Seismic Arrays and Engineering	Green	Yellow	Orange	Orange	Red
Environmental Monitoring	Green		Yellow	Yellow	Orange
Low-Noise Cryogenics			Orange	Orange	Red
Low-Noise Control Systems	Yellow		Orange	Orange	Red
Calibration Techniques			Orange	Orange	Red

Table 8.4: Summary of required research and development activities for Cosmic Explorer. The columns in the table indicate whether the activity involves primarily the near-future second generation (2G) detectors, i.e., A+, the CE facility, the initial Cosmic Explorer sensitivity (initial CE), the target Cosmic Explorer sensitivity (CE), or a realization of the target sensitivity using the 2 μ m technology (CE (2 μ m)). Technology readiness is indicated by green (ready), yellow (nearly ready), orange (requiring modest research), and red (requiring significant research).

technology will not happen without direction, effort and funding. This section identified areas where research and development are required to realize the target Cosmic Explorer sensitivity.

The timeline for Cosmic Explorer, which includes a collection of planned upgrades, is con-

structured so as to follow the expected technology development over the next two decades. Development areas are enumerated in Table 8.4 and discussed in the following sections, along with the research required to advance them. To ensure the continuity of gravitational-wave astronomy, it is critical that these development efforts are well supported while the current generation of observatories are still operational. In addition to ensuring that CE will achieve its full potential, many of the technologies required for CE may also be used to enhance existing observatories. This research will take place in collaboration with other projects like ETpathfinder³⁷ and the Caltech 40 m prototype.³⁶

8.3.1 Research on Reducing the Cost of Ultra-High Vacuum Systems

Roughly 37% of the cost of CE resides in the ultra high vacuum (UHV) system needed for the beamtubes and vacuum chambers. While the vacuum technology used in the LIGO could be used to meet the goals for CE ongoing research indicated that significant cost savings may be available, and as such LIGO vacuum technology serves as a backup strategy should new techniques not be realized. In particular, the research described below aims to develop technology that could meet the CE requirements and reduce the cost of UHV systems from the estimate of around \$520 million for duplication of the LIGO approach to less than \$340 million.

Techniques to eliminate high temperature bakes The outgassing of adsorbed water is a well established problem in UHV technology. The binding energy of the water to the surface has a broad distribution with a peak around 1 eV (10^4 K). The time it takes a water molecule to evaporate from the surface at a fixed temperature is exponentially dependent on the binding energy. The molecules with low binding energy evaporate quickly while the tightly bound ones can take years (even centuries) to evaporate. The distribution of binding energies leads to a $1/t$ dependence in the outgassing rate of gas species at a fixed temperature as a function of time t . Gases that do not adsorb, such as nitrogen and oxygen, usually pump out of a system exponentially while water remains as a long term contributor to the residual gas pressure. A standard method to remove the water from a system is to heat the walls (“bake”) to increase the evaporation rate. For example, in LIGO the beamtubes were heated to 150 °C for three weeks while the water was pumped out of the system with 6000 L/s cryopumps placed every 250 m along the tube. The overall bakeout costs were \$9 million in 1994 dollars for 16 km of tubing and, as discussed in §8.5, would conservatively cost \$62 million for the 80 km of tubing required for a 40 km CE in 2021 dollars. This cost was dominated by the electricity needed for the bake and motivates research to establish if there are more economical methods.

One method is to use lower temperature bakes with modest pumping capacity for longer durations. Modeling suggests that this could reduce the water outgassing to levels that meet the CE requirements in the beamtube. Another technique to reduce the cost of the beamtube bakes is to use a moving external heater with dry flush gas to remove water from a tube. The process would take place before the tube is evacuated and involves passing the dry gas through the tube while heating the tube to between 145 to 200 °C with a movable external ring oven about a meter

long. The gas density and flow rate are adjusted to keep the water entrapped in the gas from diffusing back as the oven is slowly moved from one end of the tube to the other in the direction of the gas flow. The temperature of the tube in the short region under the ring heater can be significantly higher than in a full bake which reduces the emission time of the tightly bound water and allows shorter dwell time for the ring heater at each point along the tube. It would take about 14 days to complete the bake for one 2 km subsystem. CERN is looking into a system using inductive rather than radiative heating.

A test planned for LIGO (and important for both LIGO and CE) is the ability to back fill a large vacuum system that has been under UHV conditions with a dry gas and recover UHV conditions without a bake—a situation that might occur after an accident or necessary repair is made. Modelling indicates that with dry gas filters now available it should be achievable.

Mild steel instead of stainless steel beamtubes Low carbon steel is between 1/3 to 1/4 of the cost of stainless steel with comparable mechanical properties. For many years it has not been considered a satisfactory material for UHV due to some faulty measurements in the 1950s. Standard production techniques now produce carbon steel with between 1/300 to 1/1000 of the entrapped hydrogen and comparable water outgassing than most stainless steels.³⁷⁹ Recent preliminary measurements at CERN and NIST have provided additional evidence for the low hydrogen outgassing but more research is needed to verify these findings and to develop the practical techniques necessary to use mild steel in UHV.

Beamtube coatings Coating the interior of the beamtubes with a material that has a low binding energy for water would reduce the time needed to bake the beamtubes. Ongoing research by metallurgists indicates that the dark oxide that forms on carbon steel (magnetite Fe_3O_4) may have a lower binding energy for water and this should be tested. This coating, similar to “gun bluing”, could be generated on both the internal and external surfaces of the beamtubes to both lower binding energies and prevent oxidation (rust). It may also be worth looking into using hydrophobic silicon coatings.

Soft-close gate valves for leak hunting As described in §8.2.2 and shown in Fig. 8.4, each beamtube is broken up into 10 km long sections separated by hard close gate valves, and each of these is further broken up into five 2 km subsections separated by soft close gate valves. 48 in (122 cm) diameter gate valves for UHV service are commercially available from VAT and other sources. They cost between \$150 to \$200 k and are able to seal a vacuum system from atmospheric leakage to better than 10^{-7} L/s as well as to withstand the atmospheric pressure load. However, in the event that a leak develops in the a beamtube, an uninterrupted 10 km segment will make finding the problem challenging. Experience from LIGO shows that 2 km sections are manageable for leak-hunting, and development of less expensive soft-close valves which are used only in the event of a leak could result in significant cost savings for the CE project.

Nested system In the event that the water outgassing cannot be reduced sufficiently to meet the CE requirements it becomes useful to investigate another option. There are engineering and operational advantages to separating the functions of maintaining a space against the atmospheric pressure load and reducing the residual gas to the levels of UHV. One promising concept uses a nested vacuum system with an outer shell of carbon steel tubing and an inner tube of thin wall aluminum.³⁸⁰ If the research shows the nested system is favored, it will be useful to develop an annular soft close valve that separates the inner and outer systems for outgassing and UHV operations and opens quickly in the event of a pressure increase in the outer system.

8.3.2 Large, High-Purity Mirror Substrates

Cosmic Explorer requires large and high-quality optical substrates for the main interferometer mirrors (a.k.a. test masses). The Cosmic Explorer test masses will be much heavier than the current Advanced LIGO mirrors (320 kg instead of 40 kg) in order to reduce quantum radiation pressure noise, suspension thermal noise, and all technical force noises. Furthermore, due to the larger diffraction-limited beam size, the Cosmic Explorer mirrors must have a diameter of more than 50 cm in order to hold round-trip optical losses from aperture effects to the parts-per-million level.³⁴³

Large silica optics The fused silica test masses used for CE will be roughly twice the diameter of those in Advanced LIGO (70 cm instead of 34 cm), again to reduce diffraction loss from the large beams. Such large volume masses are thought to be achievable with excellent optical properties. However, a careful engineering design, specification, and characterization of the optics will need to be carried out as with Advanced LIGO.³⁸¹ The GWIC 3G R&D report¹ calls out the importance of the homogeneity of the index of refraction for silica optics, and this may be significant for the CE beamsplitters and input test masses.

Large silicon optics The material of choice for the 2 μm technology test mass substrates is silicon for the reasons outlined in Ref. [34]. Silicon has low Brownian noise at cryogenic temperatures (unlike fused silica), its thermoelastic noise vanishes at 123 K where its coefficient of thermal expansion goes to zero, and this temperature is compatible with high optical power. The diameter of the silicon mirrors for CE will be at least to 80 cm since 2 μm diffraction limited beams are larger than 1 μm beams. There is currently no production process which can produce substrates of this size of sufficient purity for CE (see §8.4). Furthermore, there is some evidence that polishing silicon surfaces can increase their optical absorption.³⁸² Further work is required develop a production process compatible with CE requirements and to test whether a silicon surface can be polished to the specifications without resulting in surface absorption.

Polishing and surface figure Scattered light continues to be a significant source of noise for the current generation of gravitational-wave detectors. Continued improvements in surface

polishing of large optics would help to reduce the level of scattered light from the optical surfaces. Estimates of the noise expected from scattered light for CE suggest that the required surface polish is comparable to that already achieved in Advanced LIGO for spatial scales below a few cm.³⁷⁸ However, due to the larger CE beam size, it is necessary to ensure that this level of surface roughness can be achieved up to spatial scales of several tens of cm. See §8.3.13 for a broader discussion of the scattered light mitigation research required for CE.

8.3.3 Low-Loss Mirror Coatings

1 μm Coatings Current Advanced LIGO coatings are alternating layers of SiO_2 and $\text{Ti:Ta}_2\text{O}_5$ (nearly quarter wavelength) Bragg stacks. Research is underway to improve upon the mechanical loss and optical properties of these for A+. The Cosmic Explorer 1 μm technology will require A+-like low-mechanical-loss coatings, scaled to the larger CE substrates, and with excellent purity to minimize scattering and absorption. CE will benefit from the current research aimed at improving the A+ coatings. Because the room-temperature mechanical loss of the current high-index of refraction material SiO_2 is quite low, significant effort is focused on identifying a high-index material with lower mechanical loss. For example, doped germanium seems to be a promising coating for A+, offering a 30% reduction in coating thermal noise.³⁸³ Because coating thermal noise will be a contributing noise source for CE, additional gains beyond the state of the art in the coming years will be of great benefit.

Anomalous absorption from small defects in the Advanced LIGO test mass coatings has proven to be a major challenge and limitation to both the sensitivity of the instruments, via degradation of the cavity buildup, and the lifetime of the optics as the absorbers increase with time.³⁷¹ Research must be undertaken to solve this problem for CE, and is currently a major focus for A+ coatings.

2 μm Coatings The 2 μm coating technology will build off research and development toward LIGO Voyager and shows promise to offer improved thermal noise performance over the 1 μm technology. The baseline assumed is “Voyager” coatings, scaled to 80 cm diameter and operated at 123 K. While it is expected that this area will benefit from significant further research, promising candidates for such coatings have already been identified, including amorphous SiO_2/Si ³⁸⁴ and crystalline $\text{GaAs}/\text{AlGaAs}$.³⁸⁵ Development efforts are also needed toward scaling up from the current state-of-the-art of 20 cm and 34 cm for crystalline $\text{GaAs}/\text{AlGaAs}$ ³⁸⁵ and amorphous coatings, respectively.

Conductive Coatings Silica is an insulator and as such charge can build up on its surface. This has been an issue in Advanced LIGO, so it will be important to limit the amount of charge that is able to build up on the CE optics.³⁸⁶ With R&D underway on slightly conductive overcoatings and with the experience of charge control in LIGO to fallback on, charge is not expected to be a major issue for CE.

8.3.4 Optical Wavefront Control

Even at the sub-parts-per-million level of optical absorption achieved in the current Advanced LIGO mirror coatings, thermal lensing induced by the high laser power circulating in the arm cavities (1.5–3 MW for CE) will lead to significant changes of the optical mode in the interferometer. In addition, any anomalous absorption from small defects (see §8.3.3) will make the problem significantly worse. If not corrected, the resulting wavefront distortions lead to excess scattering in the arm cavities, limit the power build-up, and degrade the interferometer contrast at the readout port. In addition, the distorted optical modes will no longer match the output mode cleaner cavity, nor the mode of the non-classical squeezed vacuum injected from that dark port to reduce the interferometer quantum noise (see §8.3.5)—unsqueezed quantum vacuum will leak into the interferometer, reducing the sensitivity gain from squeezing the quantum noise.

In order to achieve the mode-matching requirements and the high levels of frequency dependent squeezing in CE, active wavefront control actuators for the readout optics leading to the output mode cleaner, for the squeezed vacuum injection optics and filter cavity, as well as on the test masses themselves will be indispensable. New technologies are under development for active wavefront control and mode-matching for the A+ upgrade. These have direct applicability to CE with its even stricter optical loss requirements.

8.3.5 High-Fidelity Squeezed States of Light

Squeezed states of light are used to reduce quantum noise in currently operational gravitational-wave detectors and this technology will also be used in Cosmic Explorer; initially at modest levels of noise reduction with planned upgrades expected to bring CE to its target sensitivity (see §8.1.2). The production of frequency-independent squeezing is employed in the current Advanced LIGO³⁵⁶ and Advanced Virgo³⁸⁷ detectors, and has reached 6 dB of noise reduction in GEO600.³⁸⁸ Frequency-dependent squeezing has been observed by reflecting squeezed light off of filter cavities as described above,^{389,390} and a 300 m filter cavity is now being installed at the LIGO sites for the A+ upgrade. These two demonstrated technologies set the baseline 6 dB of frequency-dependent squeezing for the initial CE target. Research and development is needed to reach the required 10 dB of frequency-dependent squeezing, down to about 10 Hz, for the final CE design and to demonstrate this also at 2 μ m laser wavelength.

The level of noise reduction by squeezing, in decibels, is limited to $10 \log_{10}(2\theta_{\text{rms}} + \Lambda)$, where θ_{rms} is the RMS average phase noise of the squeezed field, and Λ is the total effective optical loss experienced by the field, in both cases accounting for all mechanisms starting from the generation of the field, its propagation through all optical elements of the detector, and its conversion to current in the photodiode. 10 dB of noise reduction can be achieved assuming baseline values of $\theta_{\text{rms}} \lesssim 10$ mrad and $\Lambda \lesssim 8\%$. The effective squeezing losses have some broadband contributions as well as some frequency dependent contributions due to the optical cavities of the interferometer and quantum filter cavity. Here it is assumed that the contributions to the total loss are mostly broadband: 1 % from the squeezer, 2 % from the Faraday isolators, 1 %

from the photodiodes, 1 % from the output mode cleaner, 1 % from the pickoff mirrors, and 1 % from mode mismatch; finally, frequency-dependent cavity effects contribute an additional 1 %, thereby totalling 8 % total loss. The following paragraphs provide an overview of the R&D needed to achieve these loss levels, and hence a broadband squeezed light noise reduction of 10 dB.

Squeezer design The existing design of in-vacuum squeezers used by Advanced LIGO,^{391,392} which yields 2 % internal cavity losses, is nearly sufficient for the Cosmic Explorer requirements, and only incremental improvements are needed. The current dominant losses in 1064 nm squeezers are: the finesse of the optical parametric oscillator cavity, which can be lowered if more pump light is used;^c the transmissivity of the mirror that injects the coherent control field, which can be lowered if other, reasonable controls needs are engineered; the anti-reflection coating losses of the nonlinear crystal (which generates the optical correlations needed for a squeezed state), which will improve with time and can be assigned more strict specifications; and the internal optical loss of this crystal, which as yet are subdominant to the others mentioned while crystal fabrication can be expected to improve. Altogether, 1 % losses or better should be achievable.

Research to demonstrate squeezing at 2 μm , where the same design constraints apply, is ongoing.³⁹³ The main differences are related to the eventual coating performance and crystal losses achievable at the longer wavelength.

Low-loss Faraday isolators Low-loss Faraday isolators are now used in Advanced Virgo,³⁹⁴ and are planned for the A+ upgrade of LIGO. These demonstrate ~ 1 % loss per pass of the squeezed light. The current design of a filter cavity requires a minimum of four total passes through Faraday isolators. An additional fifth pass is used in Advanced LIGO to add optical isolation, but can be addressed assuming isolation is improved and other integrative requirements on scatter can be addressed. Nevertheless, some improvement is required to bring the isolator losses down to a total of 2 % given the four required isolator passes.

High Quantum-Efficiency Photodetection Achieving 1 % loss from photodiodes requires photodiode quantum efficiencies $\gtrsim 99$ %. While this level of quantum efficiency has already been achieved for 1 μm light, it is a serious challenge for 2 μm light requiring significant R&D, but there are no known fundamental obstacles to achieving this performance.³⁴ Promising candidate technologies are described in Ref. [34] and include extending the InGaAs detectors used for 1 μm light as well as developing HgCdTe and InAsSb detectors.

An alternative method is to add parametric amplification, with strict requirements on its efficiency, to the output of the interferometer, possibly by adding another squeezer unit.^{352,395,396}

^cThe nonlinear interaction strength, which sets the level of squeezing, is enhanced by the cavity finesse; however, the cavity loss is also enhanced by the finesse. Thus, the finesse can be lowered to reduce the loss while keeping the same level of squeezing if the pump power is increased at the same time. The requirements on phase noise are therefore the same since the level of anti-squeezing is not increased.

This amplifies both the optical signal and quantum noise, preserving the signal-to-noise ratio, and lower quantum efficiency photodiodes may then be used without penalty. The integration requirements of such an optical parametric amplifier, and its pump light, have so far not been fully studied. However, the balanced homodyne readout of the “A+” upgrade to LIGO shares a number of requirements that are likely to translate to the parametric amplified readout scheme.

Filter cavity The low-frequency design and high-mass mirrors of CE give it a very low “standard quantum limit” (SQL) crossover frequency where the quantum noise has equal contributions from photon shot noise and quantum radiation pressure noise. This leads to the CE filter cavity needing a very long storage time and narrow bandwidth, while also being low-loss. This could be achieved with a 4 km-long filter cavity with a finesse of ~ 4000 , assuming the current benchmark losses of 80 ppm total in a 4 km long cavity set by the LIGO arm mirrors. A 4 km filter cavity length is necessary to prevent the loss-induced dephasing of the cavity from limiting the allowable injected squeezing.³⁹⁷

The additional design constraints for controlling squeezing with a 40 km interferometer can be alleviated given more research into the scheme proposed in Ref. [398], which uses the filter cavity itself as a low-noise phase reference for the squeezed light.

Constraints due to the Integration of Subsystems In Advanced LIGO, some of the interferometer alignment controls are sensed at the antisymmetric port using 1 % “pickoff mirrors”. Additionally, the filter cavity also picks off 1 % for alignment control. For Cosmic Explorer, these pickoffs should ideally be avoided or reduced, which will impact the overall controls design of the instrument. This will require research given that the alignment sensing and controls need to achieve the low frequency sensitivity goals of CE.

Additionally, there are integrative constraints for the squeezer and filter cavity between the total optical isolation, the length and alignment noises which must be suppressed, and the sensing noise injected by the control systems. Improved seismic isolation and its resulting lowered RMS noise will reduce controls authority needs and offset the requirements imposed by the lower frequency sensitivity of the CE detectors. A more detailed design study is required.

Core Optics Optical losses in an interferometer can limit the enhancement due to squeezing independent of other aspects of the system.³⁹⁹ In Cosmic Explorer the loss in the signal extraction cavity (see Fig. 8.1) plays a direct role in limiting the high-frequency sensitivity of the detector and thus the postmerger science it can perform. Above the detector bandwidth, the low transmission of the CE signal extraction mirror causes a large enhancement of losses within the signal extraction cavity, approximately $4\epsilon_{\text{SEC}}/T_{\text{SEM}}$ where T_{SEM} is the transmissivity of the signal extraction mirror and ϵ_{SEC} is the loss in the signal extraction cavity. While these resonantly-enhanced losses reach their maximum above the instrument bandwidth, they are sufficiently large that the losses within the signal extraction cavity must be minimized, so they do not degrade the detector performance within the signal band. This includes all of the anti-

reflection coatings of vertex optics such as the input test masses, compensation plates, and beamsplitter. Additionally, there is loss in the high-reflection coatings of the telescope optics within the signal extraction cavity. While compensated in other optics, the refractive index inhomogeneities in the substrate of the beamsplitter cannot currently be compensated using surface polishing, due to the non-normal incidence of the beam, and must be analyzed to consider its contribution to the squeezing losses.

At high frequencies, the resonant “dips” in the 20 km instrument noise at 2–4 kHz, which depend on the instrument length, signal extraction cavity length, and signal extraction mirror transmissivity, have a complex relationship to the internal cavity losses. Full optimization of the squeezing level for postmerger signals requires a careful analysis not only of the instrument response, but also of the losses to squeezing, as the two mostly, but not entirely, align at those high frequencies. Furthermore, it is the loss in the signal extraction cavity that limits both the depth of these dips and the frequencies to which they can be tuned, so it is especially important to the 20 km science case that these losses be kept low.

Mode Matching The squeezed states used in Cosmic Explorer will interact with a sequence of optical cavities: the squeezer’s optical parametric amplifier, the filter cavity, the interferometer, then finally the output mode cleaner. Each cavity modifies the incident squeezed states, but only in its respective resonating fundamental Gaussian mode. Mode mismatch between the cavities causes coherent constructive and destructive interference between the fundamental and higher order modes, but this usually causes specific frequency dependence,³⁹⁷ depending on the layout of the cavities. Mismatch with the interferometer degrades squeezing only at high frequencies above the response pole of the interferometer. The filter cavity is only affected by mismatch losses within its bandwidth, mimicking cavity losses. The output mode cleaner mismatch is broadband, but is the easiest to directly measure and remedy.

If loss of $< 2\%$ in squeezing due specifically to mismatch is desired at all frequencies, then the practical goal is to require $< 0.5\%$ mismatch between any two elements. This will require the optical design of the output optics and squeezer to be extremely mindful not only of curvature mismatch, but astigmatism and higher order aberrations as well. The overall curvature mismatch can be corrected using active wavefront control,^{400,401} as is planned for LIGO. Research is needed into control and mitigation of astigmatism in the telescope designs, particularly since wavefront control requires larger beams, and that exacerbates the effect of nonzero-angle of incidence on differential curvature. The ability to independently measure and quantify wavefront errors in-situ using auxiliary beams and detectors should also be improved.

The need for higher-order aberration correction may prove necessary to match the squeezer beam to the interferometer, given that the interferometer has contrast defect and distortion from heating. More modeling is necessary to establish those needs. The astronomy community has created active correction optics, which prove the principle, but integrating them in Cosmic Explorer may require an appropriate beam expansion telescope to match the range and scale of the actuators to the beam — a different regime than the current curvature actuators.

8.3.6 High-Power Ultrastable Laser

The laser frequency and intensity noise requirements for CE and the optical topologies required to achieve them are currently under active research. In this work we have assumed that the laser frequency and intensity noise are kept low enough to not contribute significantly to the overall detector noise budget. A baseline for achieving this is a combination of a pre-stabilized laser and two suspended modecleaners (as in Fig. 8.1 and §8.1.5).

CE will require a ~ 140 W $1\text{ }\mu\text{m}$ laser to reach the nominal 1.5 MW arm power given the expected optical loss. This level of output power has already been demonstrated in stabilized continuous-wave lasers.⁴⁰² However, the stabilization requirements will likely require additional work. If the alternative $2\text{ }\mu\text{m}$ technology were employed, a significantly higher laser power of ~ 280 W would be needed to reach the nominal 3 MW of arm power. The technology available at $2\text{ }\mu\text{m}$ is much less advanced than $1\text{ }\mu\text{m}$ technology, and considerable research and development toward ultrastable $2\text{ }\mu\text{m}$ laser sources⁴⁰³ and their high power amplification is needed.

8.3.7 Low-Noise Suspensions

As described in §8.1.4, each of the four test masses will be suspended by quadruple pendulum suspensions similar to those currently employed by LIGO. The suspension design determines the magnitude of both the seismic noise and the suspension contribution to the total thermal noise. The reference concept for both technologies is a 4 m tall suspension chain of total mass 1500 kg. It is believed that such suspensions can be achieved and supported by scaling up current Advanced LIGO systems.

Increasing the mechanical compliance of the suspensions—in all six degrees of freedom—is key in reducing seismic and thermal noises. More compliant suspensions produce lower frequency mechanical resonances, and displacement noises are passively filtered above these frequencies. Furthermore, similar to the thermal noise of the substrates and coatings discussed in §§8.3.2 and 8.3.3, the mechanical loss of the suspension material determines the magnitude of the suspension thermal noise, and this loss is reduced for more compliant suspensions.

Developing highly stressed suspensions is critical for two reasons. First, this provides the opportunity to increase the suspension compliance. Second, it increases the fundamental and harmonic frequencies of the high- Q transverse vibrational (“violin”) modes of the suspensions, which degrade the sensitivity in a narrow ($\sim 1/Q$) band around the mode frequencies, thus reducing the number of modes in the detection band. The development status of highly stressed materials for the two technologies is discussed below.

Silica The gravitational wave community has much experience with manufacturing highly stressed fused silica suspension fibers using a fiber pulling technique.⁴⁰⁴ Tapered fibers are used in order to reduce thermoelastic noise at the ends of the fiber where the most bending, and therefore the most loss, occurs. The end radius is chosen to give the appropriate stress where the two contributions to thermoelastic loss—one from thermal expansion and one from

the temperature dependence of the Young modulus—cancel. A smaller radius is chosen to maximize the stress along the length of the fiber. The maximum stress in the Advanced LIGO silica fibers is 800 MPa,³⁵⁹ which provides a safety factor of about six for the breaking stress of fibers realized at the time the LIGO suspensions were designed.⁴⁰⁵ Recent advances in these fabrication techniques allow for fibers to be manufactured with working stresses of 1.2 GPa, which provides a safety factor of about three.⁴⁰⁶ While these fiber fabrication techniques are mature, no fused silica blade springs have been manufactured to date, and this is a critical area of R&D necessary to meet CE’s low frequency sensitivity goals. The current design for both stages of the silica technology calls for 1.2 GPa fiber stress and 800 MPa blade spring stress.³⁷⁸

Silicon Since the alternative silicon realization of CE operates at the zero-crossing of the thermal expansion coefficient, it is not possible to cancel the thermoelastic noise as is done for the fused silica fibers. Therefore, silicon suspensions would use silicon ribbons with dimensions chosen to maximize the stress along the entire length of the ribbon. Silicon ribbon fabrication is not well developed and the experiments most relevant to manufacturing suspensions find that the tensile strength of ribbons depends on the surface treatment and edge quality with average breaking stresses measured ranging from 100 to 400 MPa, and individual samples observed as high as 700 MPa.^{407,408} Silicon blade springs have yet to be developed. While larger stresses have been observed in other applications, the silicon based backup-concept for CE assumes 400 MPa of stress in both the fibers and blade springs.³⁷⁸

8.3.8 Inertial and Position Sensors

Cosmic Explorer will benefit greatly from research and development into low-noise inertial and position sensors in multiple degrees of freedom. These sensors will enable improvements in seismic isolation and suspension control, both of which enhance the low-frequency sensitivity of CE and improve its output for science goals that depend on source localization, early warning, and/or high-redshift compact binary sources.

As described in §8.1.4 above, the initial CE seismic isolation reference concept assumes a moderate improvement over current technology: $0.1 \text{ pm}/\sqrt{\text{Hz}}$ at 10 Hz, which is threefold better isolation than Advanced LIGO, and $1 \text{ pm}/\sqrt{\text{Hz}}$ at 1 Hz, which is tenfold better than Advanced LIGO.³⁷⁸ Promising technologies to achieve this include combining the mechanics of a conventional geophone (GS13) with an interferometric proof mass readout.⁴⁰⁹ The noise below 1 Hz is residual ground motion that comes from the inclusion of a position sensor signal to lock the suspension point to the ground on long timescales (a technique known as “blending”). Additionally, the horizontal inertial sensing is susceptible to contamination from ground tilt, and should therefore be paired with low-noise tiltmeters.⁴¹⁰ This is motivated by studies at LIGO Hanford that have shown that ground tilt couples significantly to the strain readout of the interferometer even after active seismic isolation.⁴¹¹ Lowering the tilt coupling, along with mitigating Newtonian noise fluctuations from the atmosphere, is an important motivator for carefully designed buildings.⁴¹² Further research in all of these areas is warranted.

Subsequent upgrades are planned to achieve a more significant isolation improvement: an additional threefold improvement at 10 Hz and tenfold improvement at 1 Hz. A number of efforts are underway to meet this challenge worldwide. Some promising technologies involve a monolithic proof mass assembly to reduce thermal noise and optical displacement sensors to reduce readout noise. van Heijningen et al. demonstrated a monolithic accelerometer combined with an interferometric readout that reached a noise floor of $8 \times 10^{-15} \text{ m}/\sqrt{\text{Hz}}$ above 30 Hz, and they expect that the performance could reach $10^{-15} \text{ m}/\sqrt{\text{Hz}}$ above 10 Hz.⁴¹³ A proposed superconducting niobium upgrade to this system would reduce eddy current damping and greatly improve suspension thermal noise allowing, in principle, $10^{-15} \text{ m}/\sqrt{\text{Hz}}$ above 1 Hz.⁴¹⁴ Development of novel six-dimensional inertial isolators with optical readouts is also progressing,⁴¹⁵ and the use of such systems within the existing LIGO facilities and Advanced LIGO isolation infrastructure has been explored.⁴¹⁶ These sensors have the additional benefit of being capable of sensing tilt. Moreover, the improved low-frequency noise of the inertial sensors leads to less reliance on the low-frequency position sensor signal, thereby lessening the contamination from residual ground motion.

8.3.9 Seismometer Arrays and Seismic Engineering

Without mitigation, Newtonian noise from seismic waves would limit the low-frequency sensitivity of Cosmic Explorer. As stated in §8.1.6, Newtonian noise produced from surface seismic waves will need to be suppressed by a factor of two through careful facility design, and by a factor of 5 through sensor based noise cancelation. A combination of several techniques can be employed to achieve these goals, which were mentioned in §8.1.6, outlined in Ref. [378], and briefly discussed below.

Low-density materials Newtonian noise may be reduced by lowering the overall material density near the test mass.³⁶³ This is achieved as part of the facility design by having recesses (e.g., a basement) or low-density building materials (e.g., Geofoam) near/under the test masses, and/or by locating the test masses well above the ground level (e.g., on the second floor).

Seismic metamaterials and architected structures Seismic waves can be deflected or dissipated before they reach the test masses with intentionally designed structures. Seismic metamaterials are architected structures that can reduce surface wave propagation, which utilize above ground resonators, buried resonators, inclusions, and/or exclusions.^{364–369} While more detailed studies will need to be conducted to ensure the feasibility of employing this technology, the CE facility is expected to incorporate at least the simplest of these techniques into its design.

Seismometer array subtraction Newtonian noise can be subtracted from the detector's strain data by estimating the local seismic field with an array of seismometers.³⁶² A recent proof of

principle experiment demonstrated a tenfold suppression in the range 10–20 Hz,⁴¹¹ though more research is needed to meet the Cosmic Explorer requirements. The installation of a seismometer array capable of reducing Newtonian noise in CE by a factor of 5 is one of CE's planned upgrades. The above mentioned techniques largely rely on modeling wave propagation through homogeneous media. Future studies on wave propagation through inhomogeneous media, such as stratified soil, natural topological structures, etc., will need to be conducted to ensure that these techniques are capable of reaching design sensitivity in a given seismic noise environment.

8.3.10 Environmental Monitoring

Monitoring of non-gravitational-wave disturbances from the environment, using an array of instruments located at the sites as well as information from global monitoring, has been critical for ground-based gravitational-wave observatories to date. The main purposes of environmental monitoring are localizing and mitigating sources of noise, assuring that the contribution of ambient environmental noise is kept below the background noise of the detectors or subtracted from the detector strain data, and validating candidate gravitational-wave signals by ruling out potential sources of terrestrial origin.⁴¹⁷

For CE, Newtonian noise will place more stringent requirements on acoustics, particularly infrasound (sound at frequency less than 20 Hz).³⁷⁸ CE will thus require a more careful measurement and reduction strategy for infrasound than needed by today's detectors. Ideally, Cosmic Explorer will employ sensors that measure the atmospheric pressure down to $0.1 \text{ mPa}/\sqrt{\text{Hz}}$ at 10 Hz, and can disentangle the acoustic field from turbulent pressure fluctuations. Subtraction of infrasonic Newtonian noise with sensor arrays faces a number of uncertainties,³³⁹ and as such the CE sites should be selected, and facilities constructed, so as to minimize infrasonic noise.

Requirements for the facility magnetic spectrum and coupling to the CE electronics and sensitive equipment have not yet been set. However, magnetic coupling in current detectors has required significant monitoring and mitigation, so we expect this to also be the case for CE. For example, Schumann resonances, electromagnetic resonances between the Earth's surface and the ionosphere that are excited by lightning, will require careful measurement and perhaps subtraction.⁴¹⁸

8.3.11 Low-Noise Cryogenics

A centerpiece of the CE 2 μm backup-concept, as well as Einstein Telescope and Voyager, is the use of crystalline silicon at cryogenic temperatures for the test masses and the lowest stages of the suspensions. The Japanese detector KAGRA, currently under construction, will use cryogenics and sapphire test masses to achieve similar objectives. Kagra and ET will operate at below 20 K, while the Voyager technology proposed for the CE backup concept targets 123 K. The Voyager operating temperature was chosen because it not only offers some reduction of thermal noise, but is also a zero crossing value for the thermal expansion coefficient of crystalline silicon⁴¹⁹

and thus eliminates two major limitations to performance: thermoelastic noise and thermal aberrations from light absorption within the optics.

A challenge for the cryogenic operation of Cosmic Explorer will be to accurately (± 2 K)³⁷⁸ hold the optics and suspensions at their target temperature without introducing additional noise through vibrations, acoustics, or Newtonian noise coupling. Techniques under consideration, but requiring more study, to control deviations from the target temperature include: using the vibrational eigenmodes of the test masses as temperature sensors;⁴²⁰ and injecting small localized heat modulation to the test masses and minimizing the induced displacement. For both, thermal radiation could likely be used to actuate the temperature.

It is likely that a radiative cooling approach such as that envisioned for Voyager³⁵ would be used for CE. This involves a moveable heat link that comes into contact with the test mass only during initial cool down, to speed up heat extraction, and then radiative cooling only to maintain the test mass and suspension temperature during operations. However, there are open questions such as: What are the key drivers of the overall heat budget?; What temperature, length (tens of m?), and material/coating properties will the radiation shields that stop the cold optics from seeing the warmer tube and environment require?; Will each core optic and suspension require a dedicated cryostat? What is the most promising cryogenic technology (e.g., pulse-tube cryocoolers in phase opposition (such as in ET) or Gifford-McMahon) to use?; How will the vibrations be isolated?; and what techniques (such as helium gas cool-down or retractable contacts) will be used to provide high cool-down speeds? These questions will be addressed in more detail in the design phase of the CE project, and in light of Voyager technology research developments.

8.3.12 Calibration Techniques

The current generation of detectors operates with frequency-dependent systematic errors roughly at a level of a few percent in amplitude and a few degrees in phase, and timing errors of tens of microseconds or less.^{421–424} These are small enough that the estimation of the astrophysical parameters for even the loudest systems is limited by the detector noise, rather than the calibration systematic error and statistical uncertainty.^{425–430} The high signal-to-noise ratio of observations (sometimes in the thousands) that will be made with Cosmic Explorer, along with the expected improvement in theoretical waveform accuracy (see §9), will require a similarly improved accuracy and precision of CE's calibration in order to maximize the accuracy of the information extracted. This is particularly important when using the data for tests of General Relativity: calibration errors might be mistaken for a deviation from the expected signal morphology within General Relativity, and hence yield false positives. In the simplest view, the overall calibration systematic error together with statistical uncertainty for CE is required to be at a lower level than those for the second generation detectors,⁴²⁵ i.e., $\lesssim 1\%$ in amplitude and $\lesssim 1^\circ$ in phase. On the other hand, multimessenger observations with CE and a next-generation optical telescope such as the Vera Rubin Observatory would result in an estimate of the Hubble constant with a 0.2 % uncertainty over five years.⁴³¹ Across CE's most sensitive frequency band,

more stringent calibration accuracy and precision may be required (a careful reassessment of the exact requirements is still needed). Research and development is required to extend the techniques of today to reach these stringent requirements.

The calibration standards for current detectors involve using power-modulated laser light, so-called photon calibrators^{432,433} to produce the displacement fiducials. By accurately measuring the response of relevant control loops using photon calibrators and the suspension length actuators, the unknown calibration parameters are inferred and the frequency-dependent reference calibration model is produced.⁴²¹ Photon calibrators and the suspension length actuators are also used to inject sinusoidal calibration lines with high signal-to-noise ratio in order to monitor time-dependent calibration factors. After constantly accounting for the time-dependent factors, the systematic error and statistical uncertainty in the calibration model, and equivalently in the calibrated strain data, are quantified using a collection of wide-band measurements.⁴²¹ While calibration of the detectors using observations of binary neutron star coalescences and ensembles of compact binary inspirals has been demonstrated, it is unlikely, even for 3G detectors, that astrophysical calibration will surpass the accuracy of direct physical standards.^{434,435}

For CE, improvements in the accuracy and precision of photon calibrator methods, and/or research into alternative calibration methods, such as direct gravitational calibrators (Newtonian calibrators),^{436,437} laser frequency modulation,⁴³⁸ and the free-swinging Michelson method,^{439,440} are promising. Improvements to the accuracy and precision of the photon calibrators to the required levels should be possible through anticipated improved NIST laser power standards in the coming years.⁴⁴¹ Similarly, Newtonian calibrators are currently being designed and tested that are expected to meet the requirements.^{442,443} An absolute uncertainty of 0.17 % may be achieved by combining photon and Newtonian calibrators.⁴⁴² In addition, research and development are needed to push the desired level of calibration error and uncertainty towards low frequencies ($\lesssim 20$ Hz) and high frequencies ($\gtrsim 2$ kHz), and to reduce the latency of high-quality calibration. Studies are also needed to model the detector response more accurately, e.g., modeling the complete response of the Fabry–Pérot arm cavities rather than using the single-pole approximation,^{425,444–446} and accounting for the difference between the full Fabry–Pérot arm cavity response and the motion of the mirrors.⁴⁴⁷ The long-wavelength approximation in Michelson response also needs to be taken into consideration.⁴⁴⁶ These factors will become important in the era of CE for studying nuclear equation of state and testing those aspects of General Relativity that have signatures at high frequencies. It appears that the currently-foreseen needed precision in calibration can be delivered in a timely manner for Cosmic Explorer.

8.3.13 Scattered Light Mitigation

Noise from light that is scattered out of the main laser beams has been a persistent issue for current gravitational-wave detectors.^{448,449} While scattered light reduction was included in the design of the advanced detectors, much effort has been devoted to diagnosing and fixing light scattering issues after installation.^{417,450,451} Scattered light effects, which are often driven by seismic motion, will be particularly important to address in order to ensure the excellent low-

frequency performance of Cosmic Explorer. It is thus important that a scattered light mitigation design that incorporates the best practices and lessons learned from the 2G experience be developed for Cosmic Explorer. Three main areas of concern are discussed below.

Light scattered from the coated test masses can reflect off of moving elements, such as the beam tube walls and baffles, and recombine with the main cavity laser mode giving rise to additional phase noise in the readout.⁴⁵² For this reason, baffles were installed at various points along the beam tubes of the 2G detectors to deflect and absorb scattered light. Light scattering from the test masses has two main sources: roughness of the coated surfaces, which is responsible for most of the scattering at small angles; and point defects on the surfaces that show up as “bright spots” and are responsible for most of the scattering at large angles. The noise contribution to Cosmic Explorer surface roughness scattering can be estimated following Sec. 2.2 of Ref. [377]. Setting a noise requirement that is a factor of ten below the CE design sensitivity at all frequencies, and assuming a beam tube diameter of 120 cm (as discussed in §8.2) and baffles with a black nickel coating with bidirectional reflectance distribution function (BRDF) of 10^{-3} sr^{-1} ,⁴⁵³ gives an upper limit requirement on the surface roughness power spectral density (over spatial scales that scatter into the tube) with functional form $S(\nu) = (0.03 \text{ nm}^2 \text{ mm}) / (1 \text{ mm} \times \nu)$,³⁷⁸ where ν is the inverse of the spatial scale. For point defects, which have a roughly flat BRDF over angle, even assuming a high mirror BRDF of 10^{-4} sr^{-1} , point scattering into the baffled arms is an insignificant noise source for Cosmic Explorer.³⁷⁸

A related and potentially important consideration is light from the main cavity mode being clipped by the moving baffles in the beam tubes, leading to modulated diffraction that causes phase noise in the readout. Several approaches to this problem are being investigated, including modal simulations and analytic solutions. While progress is being made, no firm estimates have yet been produced.⁴⁵⁴

Additionally, an evolution and front-loading of the stray light control work done for the 2G detectors will be needed for Cosmic Explorer. In Advanced LIGO, for example, it was necessary to incorporate dozens of types of baffles and beam dumps that were specifically designed, using ray tracing and hardware design software, to intercept important stray light.⁴⁵⁵ For some already installed baffles, work was also required to improve their seismic isolation and dampen resonantly enhanced motion.⁴¹⁷ Significant design work is called for to identify and eliminate scatter and stray beams associated with the many optical and mechanical components of CE, along with continued R&D into low-scatter materials and coatings that could reduce the levels of stray light.

8.4 Silicon Upgrades

As mentioned in §8.1.8, in addition to its role risk mitigation, the prospect of using the $2 \mu\text{m}$ cryogenic silicon technology with higher arm powers than are called for in the nominal design is a strong motivation for continued R&D into this technology. Here we briefly examine the limits to which this technology can be pushed, and then show that it could be used to approach the

sensitivity limits imposed by the Cosmic Explorer facility.

Since, as with Voyager, the cryogenic CE test masses would be radiatively cooled, a strict limit on the achievable arm power is imposed by the requirement that the power absorbed in the test masses does not exceed the radiative cooling power.³⁴ Assuming the coatings have 1 ppm absorption, the total absorbed power is determined by the power absorbed in the input test mass (ITM) substrates, which in turn depends on the absorption of the silicon crystal.

There are two methods of producing silicon crystals³⁴ and, as discussed in §8.3.2, producing the large 80 cm diameter silicon CE test masses is one of the most challenging tasks for the 2 μ m technology. The magnetically stabilized Czochralski (MCZ) method can produce the largest crystals—up to 45 cm in diameter today. This is the baseline design for Voyager. The float zone technique has only realized crystals up to 20 cm in diameter, but they are more pure than MCZ crystals and therefore have lower absorption. Since it will likely be necessary to bond multiple silicon crystals together to make the CE test masses anyway, it is reasonable to again consider float zone silicon. Silicon absorption of 5 ppm/cm has been measured at 1550 nm wavelength⁴⁵⁶ and can be taken as a starting point for the substrate absorption of a float zone CE test mass.

The emissivity of the test mass barrel can likely be made nearly 1 either by coating it with a high emissivity coating or with a broadband anti-reflective coating. The emissivities of the HR and AR optical coatings are unknown at this time. Assuming emissivities of 0.95, 0.75, and 0.9 for the barrel, HR, and AR surfaces, respectively, a Cosmic Explorer using float zone silicon could reasonably achieve 12 MW arm power while satisfying the heat budget. Thermal lensing in the ITM substrates⁴⁵⁷ would likely not be an issue at this power.

Such an interferometer would be roughly a factor of two more sensitive than the nominal design from about 30 to 300 Hz. The noise budget for such an interferometer is shown in Fig. 8.5. The high frequency sensitivity is not significantly improved by going to higher power because it is dominated by loss in the signal extraction cavity (SEC), which is enhanced by the arm cavity finesse \mathcal{F} . The finesse is increased in proportion to the arm power so as to satisfy the heat budget by reducing the power absorbed in the ITM substrates. Since, as with the other quantum noises, SEC loss is inversely proportional to the square root of arm power at high frequencies, the total scaling is $\sqrt{\mathcal{F}/P_{\text{arm}}}$ and it is effectively constant when the power is increased in this manner, while the other quantum noises, dominant below ~ 300 Hz, are reduced as $P_{\text{arm}}^{-1/2}$.

The ultimate limits to the achievable sensitivity of any future detector that a given facility can support are usually taken to be the sum of the residual gas and Newtonian noises. If we add to this list 500 ppm SEC loss, the broadband sensitivity of a high power interferometer shown in Fig. 8.5 reaches this limit below ~ 10 Hz, where it is limited by Newtonian noise, and above ~ 600 Hz, where it is limited by SEC loss. It is possible to find a “mid-frequency” tuning, similar in spirit to the low-frequency tuning of Fig. 8.2, which reaches a peak sensitivity of $7 \times 10^{-26} \text{ Hz}^{-1/2}$ around 100 Hz at the expense of sensitivity above about 400 Hz. It is not possible to find tunings with a resonant dip at higher frequencies due to SEC loss. Therefore, improving the high frequency sensitivity ($\gtrsim 600$ Hz) beyond that shown in Fig. 8.5 requires some combination of reducing SEC loss below 500 ppm, reducing the silicon substrate absorption, reducing the coating absorption (which may become necessary), and increasing the emissivities of the test masses.

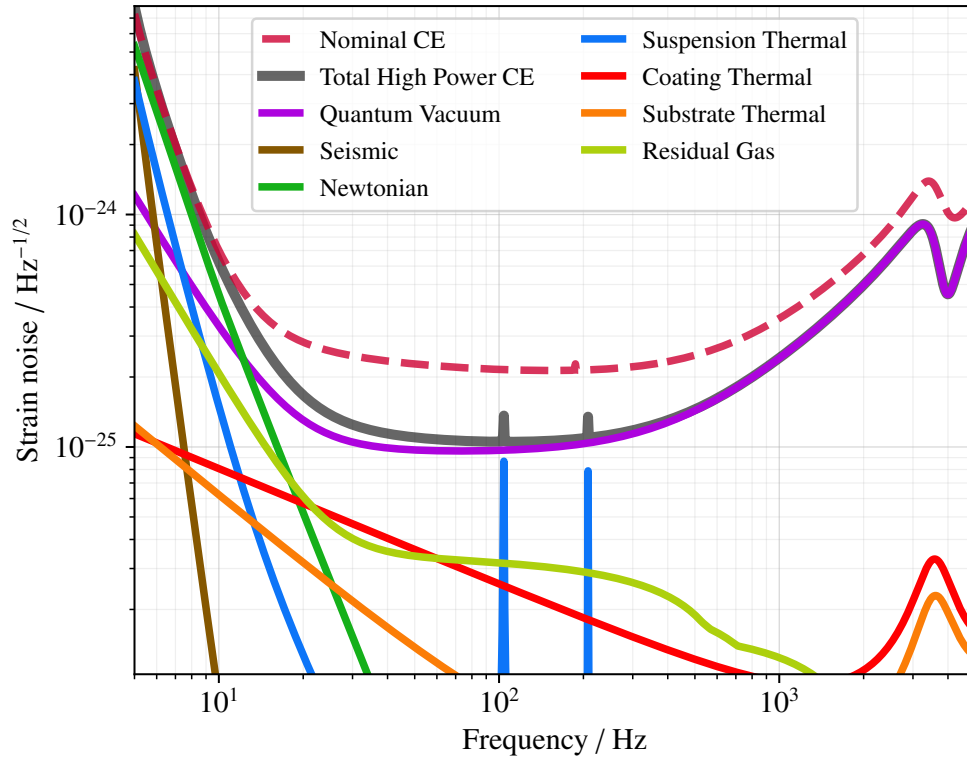


Figure 8.5: Noise budget for a high power silicon Cosmic Explorer with 12 MW arm power.

8.5 Cost Drivers

The initial cost estimate for CE presented in §11.1 is based on actual costs from LIGO construction, the Advanced LIGO upgrade, and the work of professional civil engineering and metallurgy consultants. The exercise of developing this cost estimate brought to the fore a set of cost-drivers which impact the technical design and scientific output of a Cosmic Explorer observatory. The following sections describe the primary cost-drivers and their relationship to CE performance: arm length, beamtube material and diameter, and observatory location. Notably, the cost of the detectors installed in the Observatories is not a major cost driver.

8.5.1 Arm Length

The length of an observatory's arms is the most fundamental feature in determining its potential scientific output (see Table 7.1 in Box 7.1). As such, arm length is generally increased in the measure possible to the optimal length dictated by the science goals and thus automatically becomes the principal cost-driver for any gravitational-wave observatory.

Many of the costs associated with arm length are simply proportional to the length. Examples of this are: the road which goes along the beam-line and provides access to the beamtube, the electrical utilities which run alongside the beamtube, the slab which supports the beamtube, the beamtube enclosure, and the beamtube itself. All of these civil engineering costs are largely

location independent (generally within 10 % of the national average, and often a few percent lower than the average for the reference sites considered for CE). The total of all of the above, including the beamtube and associated vacuum equipment (e.g., ports, valves, pumps, etc.), is roughly 40 % of the cost of a 40 km facility.

The cost of excavation and transportation is not included in the above list of civil engineering costs because it is highly location dependent, and generally not proportional to the length of the facility. In order to have a concrete example, consider a large dry lakebed (e.g., the Bonneville Salt Flats along interstate 80 west of Salt Lake City, UT). The surface at such a location follows the geoid almost perfectly: meaning that it follows the curvature of the Earth and has constant altitude. The arms of a gravitational-wave observatory must, however, be straight lines since laser beams do not curve with the Earth's geoid. The curvature of the Earth is such that the elevation at the center of a 40 km long straight line is 30 m lower than the ends. Preparing such a site would require excavating almost 10 million cubic meters of soil, and transporting it more than 10 km on average (i.e., from the center to the ends), at a cost of very roughly \$100 million (highly dependent on geology). For a “flat” site like this, the volume of excavation required grows with arm length squared, and the transportation distances grow with length, such that the total cost grows with arm length to the third power (i.e., a 40 km facility would cost *8 times* that of a 20 km facility).

The flat-site example drove significant interest in finding sites which minimize excavation and transportation costs.⁴⁵⁸ Such sites are slightly bowl-shaped with an elevation profile roughly 30 m higher at the ends than in the middle. There are a number of wide “valleys” that fit this description in the western states, and picking a location and orientation well can vastly reduce excavation and transportation costs. However, this search for topographically favorable sites clearly showed that the number of advantageous and available sites decreases rapidly with arm length, meaning that excavation costs for a 20 km observatory may be less than a few percent of the total observatory cost, while for a 40 km observatory they are likely to remain near 10 % of the total simply because there are fewer 40 km sites to choose from.

8.5.2 Beamtube Material and Diameter

The lasers which propagate along the arms of a gravitational-wave detector must travel in ultra-high vacuum to avoid the noise associated with polarizable atoms and molecules traversing the laser beams (see Box 7.1). This fundamental performance driver is the reason that the LIGO facilities are among the largest ultra-high vacuum systems ever built. The cost of this vacuum system, utilizing the research described in §8.3.1, will be roughly 37% of the cost of a CE facility, and approximately one third of that is required to produce the beamtubes, making the choice of beamtube material and size an important cost driver.

As discussed in §8.2.2, a wide variety of factors come into play when designing a vacuum system. While CE could reuse the LIGO vacuum system design with only minor modifications, ongoing research into the vacuum properties of steel suggest that mild carbon steel will provide superior performance at lower-cost.⁴⁵⁹ This is the material used by the oil industry for pipelines,

so it is well characterized and readily available in a range of diameters up to 48 in (122 cm). The standard pipeline wall-thickness of $\frac{1}{2}$ in (13 mm) is sufficient to support the atmospheric load without stiffening rings (required in the current LIGO design), making manufacturing relatively simple. (Note: Shifting to thinner walls to save material actually increases cost, since this requires a non-standard process at the foundry.)

Scattered light is a potentially limiting technical noise source for gravitational-wave detectors, as observed in LIGO and Virgo. The ratio of tube diameter to laser beam size in existing facilities is, however, large enough that scattering in the arms is not limiting. Initial estimates of scattering in the CE arms indicate that 48 in beamtubes are sufficient to ensure that this technical noise will not be important for both the 1 and 2 μm realizations of CE.^{377,378} Calculations of scattering in the CE arms are ongoing with the objective of developing a detailed baffling strategy for CE, based on the baffles currently used in LIGO.

8.5.3 Choice of Site

As mentioned above, the location of an observatory can have a significant impact on its cost. In addition to topography and geology, which determine the type of excavation (i.e., digging, or blasting) and the amount of transportation required, there are a variety of other factors that must be considered. A few prominent features are listed below, informed by the experience with LIGO-US and LIGO-India site identification.

Local Community A CE observatory will inevitably have a significant impact on the landscape, environment and the local community. As such *the local community must be included in any site selection process from the beginning*. This issue is of paramount importance for CE and §10.2 is dedicated to it.

Environmental Impact The long L-shaped footprint of a CE facility may have environmental impacts on resident and migratory animal populations. When searching for potential CE sites one should expect that many topographically favorable locations will be eliminated by environmental constraints (e.g., sage grouse leks in Idaho), and that some construction costs will be expended to accommodate animal populations (e.g., wildlife bridges).

Land Acquisition Sites which are favorable for CE are vast open spaces with relatively flat terrain, and as such they tend to be either very remote, already in use (as national parks, military facilities, etc.), or both. In some cases, this can facilitate land acquisition for CE (e.g., if the land is federally owned), or make it unfeasible (e.g., if the space is a national monument). Land acquisition may also be difficult in areas that are mostly private land due to the length of the CE arms, which may cross many individual plots.

A potential site could be unsuitable if the land cannot be acquired or its acquisition would greatly increase the cost of the project. Though Cosmic Explorer will be a surface facility, atten-

tion must be paid to, e.g., severed mineral rights, to avoid underground activity that negatively impacts the instrument performance.

Natural Hazards Certain potential sites could be disqualified due to unacceptably high probability of catastrophic natural disaster (flood, fire, etc.). In addition to consulting the historical record (e.g., the 100-year flood level), the potential impact of climate change on the suitability of a location must also be considered.

Surrounding Infrastructure. Some otherwise promising sites may be disqualified if they are hard to access or frequently rendered inaccessible (e.g., due to inclement weather). The absence of anthropogenic noise sources (e.g., industry, wind farms) must be assured for the lifetime of CE. Not all potential sites will be located close enough to critical infrastructure (e.g., roads, utilities) required to construct and operate the facility, and building such infrastructure may be prohibitively expensive.

Proximity to cities In addition, while some candidate sites tend to be remote, they must be sufficiently close to social infrastructure (hospitals, schools, etc.) to sustain an effective workforce.

9 Data Management, Analysis, and Computing

9.1 Data Management Plan

Given the substantial United States Federal Government investment and broad community support that will be required to realize a U.S. third-generation gravitational-wave detector, Cosmic Explorer is planned to be an Open Data facility. To realize this goal, both the construction and operations budgets must contain sufficient funding to support personnel and computing for the rapid release of high-quality, calibrated gravitational-wave strain data and alerts for events of interest. Development of Cosmic Explorer will include the creation of a Data Management Plan that will describe the technical implementation of user access mechanisms throughout the lifecycle of Cosmic Explorer, guidelines for the use of data products, and publishing rights. The full data management plan will be developed in consultation with input from U.S. and international stakeholder funding agencies, the instrument development team, and the broader scientific community. Although there are significant differences in the type and scale of the data sets, the data policies of the NSF/DOE Vera C. Rubin Observatory and NASA's Fermi Gamma-Ray Space Telescope provides an excellent baseline for Cosmic Explorer's data management plan. This Horizon Study outlines the following principles for Cosmic Explorer's data management plan:

1. The data management plan should maximize the science output of the funding agencies and science community's investment in the project.
2. There should be no reserved science; all types of scientific endeavors are open to all individuals and membership of any group or collaboration does not convey exclusive rights to any particular area of research.
3. Open data facilitates scientific collaboration, enriches research and advances analytical capacity to inform decisions.
4. Open data supports and ensures access for junior scientists.
5. Open data supports scientists from small institutions and historically underrepresented institutions.

To achieve these goals, the Cosmic Explorer data set will be released as open data as quickly as possible (i.e., as close to real time as possible) once construction ends and operations begin.

Cosmic Explorer will generate a data set that provides a unique, rich, and deep view of the universe over its lifetime. However, in comparison to e.g., the Rubin Observatory data set, the volume of Cosmic Explorer's data is remarkably small considering its scientific potential. Almost all of the scientific information from an interferometric gravitational-wave detector is contained in a one-dimensional time series, with calibration information and additional metadata that describes these data. Whereas the Rubin Observatory is expected to generate ~ 20 terabytes of data each night, the size of Cosmic Explorer's primary data set will be ~ 20 gigabytes per day. An additional ~ 2 terabytes of control and monitoring data will be recorded each day for a single interferometer. The size of alert data packets containing timing, sky location, and source properties (e.g., masses and spins) for detected compact-object mergers is less than 1 gigabyte per day, assuming of order one hundred alerts per day. We anticipate no significant technical challenges to releasing these data to the user community in real time.

The challenges of realizing open data for Cosmic Explorer include i) ensuring that project construction costs have sufficient funding for the human resources needed to develop the infrastructure to deliver open data to the community, and ii) that the operation budget has sufficient funds to calibrate, clean and release the gravitational-wave time series with appropriate detector metadata and as quickly as possible. Funding will be needed for personnel to develop, deploy, and manage the generation of astronomical alerts for compact-object mergers, and to provide support to the user community. Given the critical nature of these tasks, they should not be subject to a separate entity supported by third-party funding or separate grants; they should be included in the construction and operation budgets, as appropriate.

Open release of alerts required to accomplish the key science goals described in this Horizon Study and the real-time release of the cleaned, calibrated gravitational-wave strain will allow the broadest possible use of the Cosmic Explorer facility, while keeping the scope of the project at a reasonable level. All data will be released with a liberal open license. Re-use, re-distribution, and production of derivatives will be allowed and encouraged. To aid in the use of Cosmic Explorer data by the public, all software developed for and data produced by Cosmic Explorer will be publicly released and thoroughly and clearly documented. All data will use standard, open formats whenever such formats exist. §9.2 and §9.3 discuss the requirements for computing expected to be with the scope of the project, as well as the broader scope of computing that will be pursued by the wider community.

9.2 Requirements for Open-Data and Analysis

To deliver the science goals described in §5.1–§5.3, the Cosmic Explorer project will need to provide:

1. Management and curation of the detector data throughout the lifecycle of the project.
2. Near-real time production of a calibrated, cleaned gravitational-wave strain data set with metadata describing the quality of these data.

3. Production of low-latency alerts for the merger of compact-object binaries.
4. Operation and support of a Cosmic Explorer Data Access Center for dissemination and support of open data.
5. Periodic publication of catalogs describing the events observed in a given period.

Data management and the production of low-latency analysis required to deliver alerts and prepare the data product releases for the community will be in scope for the project—neither of these tasks present significant computational challenges, as described below. Approximately ten FTEs will be needed to perform tasks related to data preparation, alert generation, data curation, and user community support during the operations phase of the project.

The bandwidth of the control systems required to operate Cosmic Explorer does not differ significantly from that of Advanced LIGO. Similar to Advanced LIGO, the cost of the digital detector control systems is not expected to be a significant fraction of the cost of the instrument. Since the number of Cosmic Explorer control and data channels is also similar to that of Advanced LIGO, we expect data rates of 2 Tb per day of detector operation. Storage and dissemination of data of this scale is a solved problem with current technology.

Although the sensitivity of Cosmic Explorer will be an order of magnitude better than that of Advanced LIGO at 100 Hz and two orders of magnitude better at 10 Hz, Cosmic Explorer's detector noise increases rapidly below 10 Hz; at 3 Hz the detector is five orders of magnitude less sensitive than it is at 10 Hz. For a broad-band source such as inspiraling compact objects, there is very little signal-to-noise below 7 Hz; over 99.5% of the signal-to-noise lies above 7 Hz. A binary neutron star waveform starting at this frequency lasts 77 minutes from the time that it enters the detector's sensitive band to coalescence. For a waveform of this length, the Doppler frequency modulation due to the diurnal and orbital motion is $(\Delta f/f) \sim 10^{-8}$ and can be neglected in search algorithms.⁴⁶⁰ Several search algorithms already exist that can search for waveforms of this length in a computationally efficient manner.^{461–463} A matched filter search for binary neutron stars with component masses between 1 and $3 M_{\odot}$ using current data-analysis algorithms only requires a factor of three times more template in its bank than required by Advanced LIGO.⁴⁶⁴ Again, this is a scale of computing that is accessible by current technology; implementing searches for the rapid identification of compact-object merger events will be straightforward a decade from now.

The computational cost of parameter measurement scales with the number of sources observed. While this is expected to increase by three orders of magnitude with respect to Advanced LIGO, there already exist algorithms that can measure the parameters of e.g., a binary neutron star (sky location, masses, and spins) within 20 minutes for Advanced LIGO using 32 cores of a current processor.^{465–467} Although Cosmic Explorer will detect events at a significantly higher rate than Advanced LIGO, the time-frequency volume of these events is relatively sparse in the data set and so Cosmic Explorer data analysis is not confusion limited (as is the case, e.g., for LISA white dwarf sources). Since the signal processing techniques are linear, there are no major obstacles to performing in-house measurement of binary parameters for the generation

of alerts.⁴⁶⁸ Increasing the speed of parameter estimation from detection to time-to-release for catalogs over present-day analysis primarily requires development of data-analysis pipelines to automate tasks currently performed by humans, e.g., hand-checking of convergence for detected events.

While the computational challenges are straightforward and the necessary algorithms are already being explored, there is still significant algorithm, code, and infrastructure development needed to realize the scientific potential of Cosmic Explorer; these developments will allow a richer and more efficient approach to low-latency analysis in the Cosmic Explorer era. Adopting the open data paradigm for Cosmic Explorer will: allow greater access to data; opening possibilities to build upon and create new research from publicly accessible data and alerts; facilitate research across disciplines and foster new collaborations; help to ensure universal participation in Cosmic Explorer's science without barriers that can prevent the participation of underrepresented groups; and ensure compliance with funding agency mandates.

9.3 Additional Computational Resources

An open data model for Cosmic Explorer leaves the community free to pursue a wide range of science goals using human and computational resources that they obtain through the normal process of obtaining research funding and computational resources. These projects include but are not limited to: searches for sources of gravitational waves beyond compact-object mergers; low-latency analysis for gravitational waves e.g., from core collapse supernovae; re-analysis of events or data using new waveform models; analysis of populations of events; and comparison of signals to numerical models of sources.

Searches for unmodeled transient sources with Cosmic Explorer are likely to be challenging but will not require significant computational resources. The most computationally challenging search for gravitational-wave sources will be the all-sky search for continuous waves from pulsars. The scale of this search is set by the need to grid over pulsar frequency, the pulsar's spin down rate, and the sky location of the source (due to the Doppler modulation induced the Earth's motion over the integration period). Although the computational cost of this search does not depend on the detector sensitivity, broad parameter space searches for continuous gravitational waves are likely to remain bound by computational power due to the extremely fine grid needed to search the target signal space. At fixed computational power, the development of more sensitive search algorithms and the use of new computing hardware is pivotal in fully exploiting the improved reach of Cosmic Explorer.

A significant effort will be needed to develop waveforms that will be accurate enough for third-generation gravitational wave detectors. The accuracy necessary to avoid biasing interpretation of an observation scales with the square of the observation's signal-to-noise-ratio. While the loudest observations of merging black holes and neutron stars to date have signal-to-noise ratios of ≈ 30 , Cosmic Explorer's observations will include detections of gravitational waves from merging black holes and neutron stars with signal-to-noise ratios in the thousands. These

loud signals are among the most critical for realizing our science objectives, and interpreting them without bias will require inspiral-merger-ringdown waveform models substantially more accurate than today's state of the art.^{469,470}

Additionally, most current neutron star merger simulations are still not carried out with realistic microphysics, and full explorations of the parameter space of neutron star mergers are extremely challenging computationally. These issues are illustrated, for example, in the disagreement between multimessenger constraints on the lower limit of the neutron star radius that use different numerical simulations of neutron stars merging in GW170817. Also note that only a handful of high-accuracy neutron star merger waveforms exist today—and these are not accurate enough for Cosmic Explorer.⁴⁷¹

Significant progress needs to be made over the next decade to ensure that waveforms of sufficient accuracy and that span a large enough parameter space are in hand to deliver the promise of Cosmic Explorer's science case. For instance, achieving sufficiently accurate gravitational waveforms (which approximate, phenomenological waveform models must be calibrated and validated against) will likely require next-generation numerical-relativity codes that will take full advantage of the high-performance computing facilities that will be available in the 2030s.

An artistic rendering of a futuristic transit station. The main structure is a large, white, geodesic dome with a triangular pattern, partially covered in green vegetation. To the left, a smaller, similar structure is visible on a grassy hill. The foreground is a wide, flat, grey-tiled platform. The sky is blue with scattered white clouds. A large, white, diagonal watermark reading 'DRAFT' is overlaid across the entire image.

Community, Organization, and Planning

Artistic visualization of a CE end station by Cal State Fullerton undergraduate Vikki Brown.

10 Cosmic Explorer at the Local and Global Scales

The Cosmic Explorer project will develop observatory designs with a multi-dimensional approach that creates synergy with its respective local, scientific, and global communities. This includes designing the physical and virtual infrastructure to serve Cosmic Explorer's broad community integration and engagement goals, and developing interpersonal relationships among members of these communities. Early and ongoing engagement with communities connected with Cosmic Explorer, from local to global, will be crucial to the project's success.

In 2020 the GWIC 3G Community Networking Subcommittee published a report^a that identifies potentially interested scientific communities for third-generation gravitational-wave projects. The GWIC report also outlines a communication and outreach plan for engaging the relevant communities, and delivers concrete recommendations for next-generation gravitational-wave projects. This section describes specific actions already taken toward these recommendations, and plans for realizing others in the future.

The report also identifies engagement with the public as a key area of focus for the coming observatories, just as it has been for the existing observatories. Crucially, however, Cosmic Explorer will need to undertake an even more thorough effort to identify and reach out to all communities with potential interest in the observatory, particularly local communities who will be impacted by its presence, and to build positive and mutually beneficial relationships with them. This section also describes key elements of this important effort.

10.1 Community Integration and Engagement

As Cosmic Explorer is a new astrophysical observatory, there is an opportunity to reimagine the human-focused portion of the observatory, by designing the facility to strengthen the interaction between everyone who uses and visits it while highlighting the contribution of the local community to the Cosmic Explorer effort. This will extend the model used for the current observatories, which have implemented community engagement plans⁴⁷² and built science education centers in Louisiana^b and Western Australia^c that draw significant local and global public interest. We here propose that Cosmic Explorer should build upon this model to facilitate an even tighter integration between scientists and the public.

In designing a facility that brings scientists and the public together, Cosmic Explorer can look to other scientific installations, such as Fermilab's Wilson Hall, which combines staff offices

^ahttps://gwic.ligo.org/3Gsubcomm/documents/GWIC_3G_Community_Networking_Report_Sep_2020.pdf

^b<https://www.ligo.caltech.edu/LA/page/Science-Education-Center>

^c<https://gravitycentre.com.au>

with public gathering spaces. Beyond purely scientific outreach activities, Wilson Hall hosts cultural activities, such as art exhibitions, embedding itself in the fabric of the local community. Additionally, the architecture of the Fermilab facility itself is designed intentionally to conserve and restore the surrounding environment.^d Another example of a successful meeting and exhibition space is the ‘Imiloa Astronomy Center in Hawaii,^e which presents the astronomical knowledge of the local Native Hawaiian community alongside the astronomical observatories in Hawaii, and emphasizes the community presence by (for example) translating all materials into the local Indigenous language.^{473,474,f} By looking to these examples, the Cosmic Explorer facility can be a place for scientific workshops, community activities, teach-ins (such as the work of Karletta Chief in the Navajo Nation^g) and exhibitions happening under one roof in a welcoming environment.

10.2 Building Strong Relationships with the Local Community

The Cosmic Explorer concept is based on observatories on the grandest of scales. These observatories’ activities will not happen in a vacuum: they will impact the landscape in which they are built and will change the lives of people in nearby communities. The Cosmic Explorer project will address issues surrounding observatory impact on the land, environment, and host community carefully, intentionally, and as an opportunity to build a mutually beneficial long-term relationships with its host communities.

Cosmic Explorer cannot be built and operated without ongoing local consent, which could be revoked if the project does not actively work to maintain a positive relationship with the local communities. To that end, Cosmic Explorer will integrate Indigenous leadership (elders and community leaders) and local community leaders at large into the leadership structure of Cosmic Explorer, to ensure there is continuous engagement around future directions of the project. This integration could, for example, take the form of a community-based oversight committee, representative of the project’s hosts, neighbors, and other local communities, with decision making power (e.g., veto power) over any project decision that impacts the land, environment or community. Additionally, the Cosmic Explorer project will include funding dedicated to community engagement and furthering the inclusion of Indigenous people in the project and the broader scientific community. This support might include, for example, funding scholarships for undergraduate students and fellowships for graduate students and postdoctoral scholars drawn from local demographic and Indigenous populations.

These actions reflect Cosmic Explorer’s need to prioritize community involvement in a fundamentally new way than previous physics and astronomy projects. Having multiple members from local communities serving on the leadership boards of the project — including Indigenous

^d<https://history.fnal.gov/history-fermi.html>

^eimiloahawaii.org

^f<http://www.ifa.hawaii.edu/info/vis/visiting-mauna-kea/saturday-night-programs/malalo-o-ka-po-lani.html>

^gFor an example of such a teach-in, see https://youtu.be/KV5Q-i_ae88

leadership, local community groups, and others — will be necessary during all stages of the project. The Cosmic Explorer project must start by building respectful and meaningful relationships from the outset, evolving into permission for land use, continuing integration and collaboration during commissioning and operations, and importantly ensuring accountability for agreements throughout the lifetime and decommissioning of the observatories.

10.2.1 Indigenous Communities

All lands within the United States are the ancestral home lands of Indigenous Peoples,⁴⁷⁵ and as scientists, we acknowledge that the scientific community has a long and continuing history of inflicting trauma on Indigenous populations. Examples specific to astronomy include the Mt Graham International Observatory, the Kitt Peak National Observatory,⁴⁷⁶ and the Thirty-Meter Telescope.⁴⁷⁷ More generally, academia in the United States has been advanced at the expense of Indigenous wellbeing, including through the land-grant system^{478,479} and unethical experimentation.⁴⁸⁰ As Cosmic Explorer's site-selection process begins, the Cosmic Explorer project will first learn the history of each potential site. The project will then connect with networks of tribal councils and leaders to learn what is the most respectful way to engage. If permission to engage is given, the project will work to build and maintain a relationship with the community.

Building these relationships will be a core driver in the way the project engages with the local community.⁴⁸¹ A community's willingness to host an observatory will depend critically on the relationships built and the competency the project demonstrates around the community's heritage, ancestry, values, and culture. The Cosmic Explorer project schedule will include the time to learn together about how an observatory could achieve a mutually beneficial relationship consistent with the community's priorities. The Cosmic Explorer project management and site selection teams will make a conscious effort to gain local public acceptance and support for its observatories, particularly in the wake of the unification of Native communities to protect against the Dakota Access Pipeline and demonstrations in opposition to the construction of the Thirty Meter Telescope.^{477,482} These teams will work to understand the full spectrum of views around the local impact of the Thirty Meter Telescope, including those of the astrophysics community, the local Hawaiian community, and those in both communities, in order to understand how the disconnect arose. These teams will also study previous examples of the impact of large astronomical facilities, and large government and industrial facilities more broadly, on local Indigenous communities.

The Cosmic Explorer team will invest in internal and external development with respect to Indigenous Peoples. We envision that this will include, but not be limited to, the following:

- The Cosmic Explorer project will demonstrate to the Indigenous community its commitment to understanding their culture and cultural practices.
- The project will conduct cultural impact studies that involve the local Indigenous community as part of any site-selection process, with the goal of ensuring that the project is

aware of and respectful toward locations of cultural significance at the earliest possible stage of the process.

- Indigenous communities often have protocols — e.g., practices of respect and ceremony at physical locations. As the Cosmic Explorer project is a guest in local host communities, the project will learn about these practices and create space for their perpetuation.
- As part of developing lasting and mutually beneficial relationships, the Cosmic Explorer project will seek out opportunities to integrate Indigenous wisdom into its research plans, such as in the case of environmental monitoring. Indigenous cultures have *millennia* of history and experience specific to their ancestral land and the environment, making this a clear opportunity for working together to build mutual respect and trust.⁴⁸³
- Cosmic Explorer will invite the involvement of its Indigenous hosts more broadly in order to highlight their presence at the observatory. The exact nature of this involvement will depend on the host community's needs and values but may include, for example, language preservation—e.g., using Indigenous names for parts of the observatory and notable discoveries, and translating descriptions of discoveries into Indigenous languages.^{474,484–486}
- Cosmic Explorer will work to eradicate anti-Indigenous rhetoric from the gravitational-wave community and ensure that it is not creating a hostile environment for anyone in the local community seeking to engage or for Indigenous scholars who join the gravitational-wave astrophysics community.
- Cosmic Explorer will elevate anti-racist work around Indigenous communities in the gravitational-wave community, including improving cultural competency, researching how to utilize language that is respectful of Indigenous communities and their relationship to land, and building on relationships and partnerships that are already in place. These actions should lead to a collaborative environment that is intentionally structured to avoid the perpetuation of racist practices.
- As a commitment to the stewards of the lands, Cosmic Explorer must be in continuous dialogue about what procedures match the practices of the host Indigenous community. For example, during the construction phase, how and where to put the land once it is moved must be mutually agreed upon.⁴⁸³ During the planning and decommissioning phases, dialogue on what returning the land must look like to the host community must be discussed, budgeted, and fully achieved. The Cosmic Explorer project must ensure that nothing is abandoned and everything is accounted for.

Taken together, the above points show the necessity of the Cosmic Explorer community developing positive relationships with local communities with historically longstanding land tenure.

10.2.2 The Local Community at Large

The Cosmic Explorer project will work to cultivate a positive relationship with additional groups in local communities, importantly starting before site selection, and continuing through the lifetime of the project. The success of the project will rely on the members of the community being invested and involved in CE. Members of the community will be integral to the project as members of the CE staff, collaborators on local projects, educational partners, and colleagues in local governance. Cosmic Explorer will engage with local communities at forums including public libraries, local government offices, schools, colleges and universities.

Throughout the site selection process, Cosmic Explorer will reach out to local educational institutions and develop partnerships to integrate participation of their students, scientists, and educators with CE science and outreach. This partnership may include science education research, sharing science and technology development with the public, and outreach to a broad audience in the surrounding regions, following examples such as the Southern University/LIGO partnership in Louisiana.^h

In parallel, Cosmic Explorer will initiate conversations at other local hubs such as public libraries and community centers, starting during the site identification process and continuing during the project and observatory lifetime, to build and maintain local relationships.

10.3 Cosmic Explorer as Part of the Scientific Community

The Cosmic Explorer project will only succeed with wide and explicit engagement and support by all levels of the scientific community. As the project moves forward, it will work to ramp up the frequency and depth of this engagement and support.

10.3.1 In the Gravitational-Wave Community

In the context of completing this Horizon Study, preliminary steps toward integrating Cosmic Explorer into the gravitational-wave community are already underway, including the following:

- Cosmic Explorer's membership in the Gravitational-Wave International Committeeⁱ (GWIC). This membership enables Cosmic Explorer to participate in the coordination of projects covering ground interferometers, space interferometers, and pulsar timing arrays. Membership also enables Cosmic Explorer to provide updates to GWIC and to the Gravitational-Wave Agencies Correspondents^j (GWAC) to inform the funding agencies covering the broad scope of gravitational-wave research.
- Presentations and outreach to communities, including those at the LIGO-Virgo-KAGRA Collaboration meetings;

^h<https://www.subr.edu/subhome/73>

ⁱ<https://gwic.ligo.org>

^j<https://www.nsf.gov/mps/phy/gwac.jsp>

- Organization of a one-day meeting in Summer 2020 between the teams associated with Einstein Telescope, NEMO and Cosmic Explorer;
- Organization of the First Cosmic Explorer Meeting, a five-day remote conference that was held in October 2020 with broad community participation to discuss the technical design and the science case for CE;
- Formation of the Cosmic Explorer Consortium⁴⁸⁷ in October 2020 to provide an open and efficient way for members of the broader physics and astronomy communities to contribute to the conceptualization, design, and future use of CE. Already the consortium has more than 300 members and has begun two monthly remote meetings, one devoted to instrumental research and development and another devoted to astrophysics; and
- Participation in discussions, plenaries, and technical talks at international Dawn Meetings.

10.3.2 In the Physics Community

The Horizon Study team has worked to raise the profile of Cosmic Explorer within the wider physics community through the following:

- Participation in discussions, plenaries, and technical talks at American Physical Society meetings;^{488,489}
- Invitations through the APS Division of Gravity to join the Cosmic Explorer Consortium and research meetings;
- Participation in the DOE Snowmass2021 effort through committee leadership (Adhikari and Sathyaprakash) and through a Letter of Interest:
 1. “Cosmic Explorer: The Next-Generation U.S. Gravitational-Wave Detector”, S. Ballmer, P. Fritschel, Cosmic Explorer, LIGO Laboratory⁴⁹⁰

10.3.3 In the Astronomy Community

The Horizon Study team has worked to raise the profile of Cosmic Explorer within the wider astronomy community through the following:

- Participation in the Astro2020 Decadal Survey through two white papers:
 1. D. Reitze et al., “Cosmic Explorer: The U.S. Contribution to Gravitational-Wave Astronomy beyond LIGO”, *Bull. Am. Astron. Soc.* **51**, 035 (2019)
 2. D. Reitze et al., “The US Program in Ground-Based Gravitational Wave Science: Contribution from the LIGO Laboratory”, *Bull. Am. Astron. Soc.* **51**, 141 (2019)

10.3.4 In the Scientific Community

The Horizon Study team has worked to raise the profile of Cosmic Explorer within the wider scientific community through the following:

- Launching a Cosmic Explorer website^k to increase visibility and opportunities for engagement in the CE community;
- Communicating Cosmic Explorer science with the public through social media about upcoming meetings, science goals, and opportunities;
- Discussing Cosmic Explorer at SACNAS conferences, which includes scientists across all STEM disciplines;
- Amplifying the Cosmic Explorer Plans in Science Magazine: A. Cho, “Giant detectors could hear murmurs from across universe”, *Science* **371**, 1089–1090 (2021).

10.3.5 Current and Future Work

This Horizon Study document serves as a reference to communicate plans and gather input and feedback. Through the current NSF funding supporting this study, the Cosmic Explorer team has already initiated efforts toward education and public outreach. All of the PIs have made Cosmic Explorer a focal point in their presentations to the public, and many of them have begun incorporating Cosmic Explorer technology and science into their classes. The project has strong engagement by graduate students and has been engaging undergraduate researchers in small but increasing numbers. These students have presented their research at their universities and in public settings.

Beyond the initial phases described above, this document will be employed to re-engage and expand discussions with members of the gravitational-wave, physics, astronomy, scientific affinity groups, and Indigenous leadership communities, including the LIGO, Virgo, and KAGRA Scientific Collaborations, Einstein Telescope, LISA, DECIGO, NanoGrav, CMBS4, the APS Division of Gravitational Physics, AAS, the DOE Snowmass, the APS Forum on Diversity & Inclusion, AAS Committee on the Status of Minorities in Astronomy, SACNAS, AISES, to name a few. Building on the preliminary phases of community engagement described above, the Cosmic Explorer project will begin to operationalize recommendations from the Horizon Study, expecting that engagement with the broader communities will increase steadily as the Cosmic Explorer Project moves forward.

10.4 Developing a Global Gravitational-Wave Network

The discussion in §§ 3–5 and 5.4 of the observational science that is possible with the next generation of gravitational-wave observatories illustrates the great value added were these

^k<https://cosmicexplorer.org/>

detectors to operate in concert as a global network.

Presently, the Einstein Telescope and Cosmic Explorer are the candidate next-generation observatories in Europe and the U.S. Assuming that CE and ET are realized, they could naturally form the basis of the 3G network, as Advanced LIGO and Advanced Virgo do now for the 2G network. Should other facilities of suitable capability come online, they too could participate. An effective 3G network would be a coordinated partnership that seeks to leverage the investments in each independent observatory to create great value added. Optimally, it would consist of three (or more) 3G detectors, geographically distributed on the globe to provide good localization of sources on the sky.

When envisioning international partnerships for Cosmic Explorer, we will learn from the success of the LIGO Laboratory and the LIGO Scientific Collaboration (LSC). It and the Virgo, KAGRA and GEO600 detector groups participate in a Joint Run Planning Committee to coordinate observing runs. These partnerships have been crucial for extracting the most information possible from the first observations of gravitational waves, and especially the sky localization that enabled multi-messenger astronomy.

The ground-based gravitational-wave community has recognized the imperative to form a globally coherent effort, and has made some progress toward that outcome. One of the deliverables of this Horizon Study has been to contribute to this goal. A series of NSF-supported meetings^{494–498} began in 2015 to start planning for the future. These meetings have helped guide the development of the LIGO interferometers, specifically establishing “A+” as an upgrade to the 4 km detectors.

They have served as valuable forums for discussion of further improvements to the present 4km baseline LIGO observatories, and to discuss CE and other next-generation observatories. There has been significant worldwide participation. We anticipate that the Dawn meetings will continue as an important planning resource. In addition to facilitating communication between the CE and ET projects, they helped cultivate ideas for an Australian detector that would focus mostly on studies of the coalescence phase of neutron stars (NEMO³⁹).

In parallel, the Gravitational-Wave International Committee (GWIC)⁴⁹⁹ chartered a subcommittee to study detector astrophysical and instrumental science.⁵⁰⁰ Hundreds of scientists worldwide participated in providing in-depth analyses of the observational science and discussions of the instrumental opportunities and challenges. The documents were improved by reviews from both experts in the field and by members of the Gravitational-Wave Agencies Correspondents (GWAC)^l and are publicly available on the GWIC web pages.^m This GWIC 3G endeavor enriched and updated the CE and ET science cases, and helped prioritize and focus the instrumental development. GWIC remains actively engaged in coordinating the world-wide effort and will sponsor further collaborative activities.

There remains a strong incentive for each of the major projects to form consortia which are focused internally. Einstein Telescope has formed a Consortium⁵⁰¹ which is providing technical

^l<https://www.nsf.gov/mps/phy/gwac.jsp>

^m<https://gwic.ligo.org/3Gsubcomm/documents.shtml>

and scientific support for its proposal, and the Cosmic Explorer Consortium is also active [See section 10.1]. However, the experience with the first-generation observatories – Virgo, LIGO, and now KAGRA – demonstrates the synergy, efficiency, and scientific value of close coordination at all levels. Recognizing this, the CE and ET efforts are coordinated through exchange of members in their organizing committees, and via informal interactions at meetings in our field: Dawn, GWADW, Amaldi, GWPAW.

The CE team greatly values closer links between the CE and ET projects, and as early as is feasible. This will allow common technical developments, minimize independent parallel work, and could possibly lead to economies of scale. In the longer term, it is clear that the greatest scientific return will come from joint planning for running and upgrades and from joint analyses of data. The nature of this global governance is yet to be determined, but value in significant coordination is clear.

Historically, the gravitational wave community has built strong partnerships across many institutions, mainly in North America, Europe, Australia, Japan and India. Into the 2030s, we will expect to see a shift into a more developed and connected global scientific community. Cosmic Explorer will facilitate opportunities for broader geographic participation so that scientists across Africa, the Americas, Asian, and Pacific Island nations can be welcomed into the global gravitational-wave community.

10.5 Cultivating a Respectful, Healthy and Thriving Scientific Community

Innovation excels when diverse minds across many axes of identity can thrive. The Cosmic Explorer project will work to address all axes of diversity; among these are gender spectrum, race/ethnicity, (dis-)ability, socio-economic status, and sexual orientation. In order to support each of these communities, Cosmic Explorer will ensure continuous and comprehensive efforts are made to do the necessary anti-oppressive work. As the project builds capacity around each axis of diversity, it will understand how people may intersect multiple groups. Cosmic Explorer will build competency on what impacts each demographic and work to be actively anti-sexist, anti-racist, anti-ableist, and anti-homophobic, in every aspect of the project's work, ensuring that each population has access to participation and is represented and respected for their contributions. This requires comprehensive yearly planning, continuous engagement and regular assessment on whether those goals are achieved.

As Cosmic Explorer continues to ensure fruitful engagement with its global partners, it will continue to invest in learning respectful cultural practices and designing our workflows and schedules based on this. Beyond seeking input from the physics and astronomy communities, Cosmic Explorer will seek to learn best practices from different organizations that have setup thriving diverse global institutions. The project will also ensure support exists to engage with outside consultants and facilitators to help grow our awareness around the most effective ways to do this.

11 Cosmic Explorer Project

This section presents cost estimates, a project timeline, an operations model, and an outline of the project management that would be brought to bear in the project phase of Cosmic Explorer.

11.1 Cost Estimates

The cost estimate for CE presented here is based on actual costs from LIGO construction and the Advanced LIGO upgrade. Since the CE observatories are significantly longer than LIGO, we have revised the estimated civil engineering costs with the guidance of a professional civil engineering consultant (Eric Riegel, TruE Consulting), and we have engaged a professional metallurgy consultant (Dan Henkel, Rimkus) to help us find approaches to beamtube construction that simultaneously reduce cost and increase performance. The technical impact of design-choice cost-drivers is discussed in §8.5.

Adapting the historical LIGO construction and upgrade costs to CE required a few extrapolations: costs which depend on the length of the observatory must be scaled appropriately, design changes due to lessons learned and research which has been done since LIGO was built must be incorporated, and inflation and shifts in the market prices of materials must be accounted for. The CE cost estimate was broken down into four top-level categories: civil engineering, vacuum system, detector, and project costs. Each of these estimates include materials and labor, as well as management and design costs (see Table 11.1).

The civil engineering costs were estimated *ab initio* by our civil engineering consultant, Eric Riegel, in consultation with LIGO engineers (including Fred Asiri, the civil engineer in charge of the original LIGO construction). These estimates were cross-checked against scaled LIGO costs. Civil engineering accounts for 28% of the total estimated project cost (see Table 11.2).

The vacuum system cost estimate is based on recent work done by Rainer Weiss as part of the *NSF Workshop on Large Ultrahigh Vacuum Systems for Frontier Scientific Research Instrumentation*⁵⁰² (NSF award 1846124). This estimate was, in turn, based on extrapolation from LIGO costs, along with updates for current material prices and new technologies. Vacuum systems account for 37% of the total estimated project cost.

Experience from the Advanced LIGO upgrade was used to estimate the cost of design, construction, and installation of a CE detector. Adjustments were made for sub-systems which will be significantly different, such as the mirror suspension system, and for systems which were not part of the Advanced LIGO upgrade (e.g., the squeezed light source). The detectors and their sub-systems account for 24% of the total estimated project cost.

Cosmic Explorer Cost Estimates, \$(M) 2030 USD

Observatory Costs	20 km	40 km	Project Level Costs	
<i>Management</i>			<i>Project Wide</i>	
Civil Engineering	14	28	Management	25
Vacuum System	20	37	Coordination	6
Detector	18	18	Computing	12
<i>Total</i>	<i>52</i>	<i>83</i>	<i>Total</i>	<i>43</i>
<i>Site Specific Design</i>			<i>Common Design</i>	
Civil Engineering	3.1	3.1	Civil Engineering	18
Vacuum System	0.9	0.9	Vacuum System	8
Detector	1.1	1.1	Detector	6
<i>Total</i>	<i>5.0</i>	<i>5.0</i>	<i>Total</i>	<i>32</i>
<i>Realization</i>			Project Level Total	74
Civil Engineering	136	278	Contingency	
Vacuum System	205	373	20 km Observatory	116
Detector	183	183	40 km Observatory	184
<i>Total</i>	<i>524</i>	<i>834</i>	Project Level	15
Observatory Total	581	922		
Grand Total for Reference Concept (2 Observatories)			1892	

Table 11.1: Cost estimate for the Cosmic Explorer Project reference concept (one 40 km and one 20 km observatory), in millions of 2030 US dollars. The cost estimate includes design, materials, construction, installation and project management for the civil engineering (buildings, roads, etc.), the vacuum system, and the detector. The cost of alternate configurations can be estimated by adding the associated observatory costs to the project-level costs (e.g., \$1,468 M for two 20 km observatories, or \$1,180 M for a single 40 km observatory).

The project-level costs, including management, were estimated based on the Advanced LIGO experience. This estimate includes separate management estimates for each of the other cost categories, as well as project-level costs such as computing and communication, travel and shipping between observatory locations (collectively labeled “Coordination” in Table 11.2). The project-level and management costs account for 11% of the total estimated project cost.

Some significant uncertainties remain to be resolved in this cost estimate. An essentially irreducible uncertainty of roughly 20% results from changes in the market prices of raw materials, especially steel for the vacuum system. Furthermore, a more complete design of the facility, vacuum system and detector will be required to improve the cost estimates for these components. Finally, about half of the cost of civil engineering is in excavation and site dependent costs that introduce some uncertainty in the civil engineering portion of the estimate. These uncertainties will be addressed as the Cosmic Explorer timeline becomes clearer, the design phase progresses, and the site selection process converges.

11.2 Timeline

The Cosmic Explorer timeline spans multiple decades and takes place in distinct stages: development; observatory design and site preparation; construction and commissioning; initial operations; planned upgrades; operations at nominal sensitivity; future observatory upgrades and operations.

Development The development stage for Cosmic Explorer began in 2013, and has resulted in many relevant publications within the gravitational-wave community. This stage will continue after the completion of this document and its endorsement by the scientific community that Cosmic Explorer will serve. This phase is one in which the community engagement work must expand in scope as described in §10, our understanding of the key science goals discussed in §5 will deepen, and the enabling technology discussed in §8.3 can be further developed by the instrument community.

As noted in §10, building competence around, and relationships with, Indigenous Peoples is a long-term endeavor that will be critical to the success of CE and must commence as soon as possible. This work can, and must, begin before a site is selected and may begin even before any specific sites are considered by making contact with national Indigenous Peoples organizations (e.g., SACNAS). By opening the conversation with national Indigenous Peoples organizations, the relationship building process can expand to include learning about Indigenous communities, and eventually reaching out to specific community leaders and seeking permission to engage in a dialog about potential locations for a Cosmic Explorer observatory.

The technical development described §8.3 is also important to ensuring that the investment in Cosmic Explorer facilities is most effectively utilized, and the CE science goals are achieved. Development of the technologies summarized in Table 8.4 will require planning and funding, roughly at the level of \$15 M over 4 years.⁴⁰

Observatory Design and Site Preparation The project begins with dedicated funding for Cosmic Explorer design and passes through all phases of the MREFC process.^{3a} In addition to the design

^a<https://www.nsf.gov/bfa/lfo/>

Top-Level Costs	\$(M) 2030 USD	Percent
Civil Engineering	524	28
Vacuum System	706	37
Detector	448	24
Management, Design, Project	214	11
Grand Total (2 Observatories)	1892	100

Table 11.2: Top-level cost breakdown for Cosmic Explorer, excluding operating costs, in millions of 2030 US dollars and including 20% contingency. Inflation is computed in then-year USD for a project starting in 2027 and completing in 2035 with a typical ramp up and ramp down, which is numerically equivalent to 2030 USD assuming a 2.3% average inflation rate.

phases for the CE observatories (conceptual, preliminary, final), this preparatory stage will include prototype construction for the CE vacuum system and a nationwide search for and research about potential observatory sites. This will result in the selection of observatory construction locations (“site selection”): a process that we expect will be led by the relevant funding agencies. Two or more years will be required to build relationships with local communities and to obtain the necessary permits for construction, making it imperative that this work be done in parallel with technical and civil design efforts. The total time estimated for this phase of the project is 5 years.

Construction and Commissioning While some overlap between design and construction is possible, the vast majority of the technical and civil designs will need to have finished their final design phases before funds can be appropriated for construction. The civil works required for a Cosmic Explorer observatory will require at least two years, and potentially more depending on the particulars of the site. Installation of the detector and subsystem commissioning can occur to some degree in parallel with civil works (i.e., as soon as the corner and end buildings are finished). However, commissioning of each detector will require at least two years, making the estimated time for this phase of the project 5 years.

First Operations Phase Once the CE detectors are operational, the project will transition to the Operations Stage. This will follow the successful model developed by LIGO: interleaved commissioning and observation, with observation periods growing in duration as the detector matures. In parallel with detector operations, preparations for the planned upgrades will be underway, as described in section §8.1. The duration of this phase depends on commissioning progress, upgrade readiness, and the success of the observation campaigns, and as such is somewhat flexible: 5 years is a plausible duration. By this phase, we expect that the community-focused aspect of the facility (§10.1) will also be operational; depending on the nature of the facility, this could include the arrangement of exhibits, workshops or other programs of community interest.

Upgrade Phase The upgrade of the CE detectors to their nominal configuration will bring increased sensitivity and full access to the key science goals described in §5. Some upgrades (see §8.1) can be performed with relatively little disruption of observation (e.g., seismometer array installation), while other may require significant down-time (e.g., upgrading seismic isolation systems). To allow for installation and commissioning of the new sub-systems, interleaved with observation, this phase may last as long as 4 years. The upgrades of the CE observatories may, depending on the needs of the scientific community, happen simultaneously or sequentially.

Second Operations Phase The second operations phase envisioned in this Horizon Study will presumably occur in the presence of other next-generation gravitational-wave detectors, and as such will result in ground-breaking high-fidelity access to gravitational-wave sources from throughout the universe. The duration of this phase is not specified here.

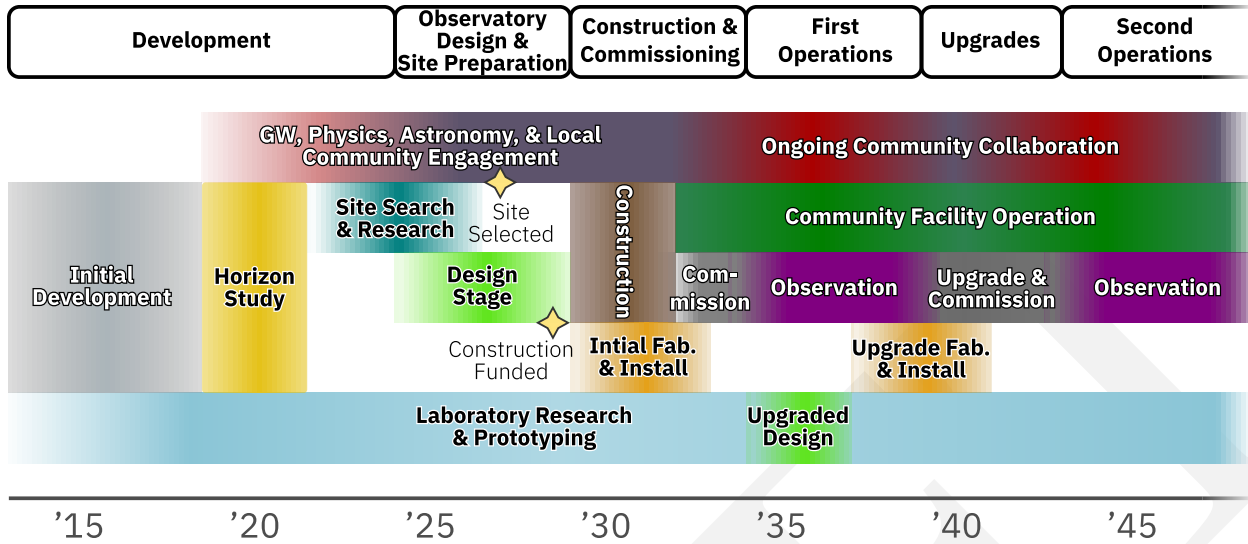


Figure 11.1: A top-level timeline showing a phased approach to Cosmic Explorer, as described in §11.2. The eventual divestment from the facility is not indicated.

Future Work Though the commitment to fund Cosmic Explorer will likely be based on a 20-year duration, the Cosmic Explorer facilities are intended to be long-lived, with a nominal 50-year lifetime. While this is too far into the future for meaningful speculation about particular technologies, the CE facility design allows for improvements in fundamental noises, such as quantum and thermal noise, well beyond the CE target sensitivity (see Fig. 8.5). As such, the CE observatories will accommodate continuous improvements to detector technology and scientific output.

Eventually the CE facility will reach the later stages of its life cycle and be divested. It is thus important to begin planning from the outset, as recommended for large facilities,³ to engage the scientific and local communities in divestment decisions and to anticipate costs. Some questions to be considered are whether the facilities could live on with new stewardship or be dismantled and cleaned up and how these decisions could strengthen the relationships fostered with the local community.

11.3 Operations Model

Following the successful example of LIGO (LIGO-G1300748), the Cosmic Explorer construction project will have a well-defined scope which leads into the commissioning and then operations phases. The hand-off could be defined as the point at which all installation at the Observatory is complete, and acceptance of the subsystems following a successful stand-alone test campaign has been completed. The first goal of the operations and maintenance phase would be to commission the instruments to reach a useful initial astrophysical sensitivity and sufficiently robust operations, along with the ability to produce high-quality and well-calibrated astrophysical data and alerts to the broader astronomical community. Achievement of this goal leads into a phase of alternating periods of observations and detector improvements, following the successful

model employed by the current gravitational-wave network.

We anticipate an open data model for Cosmic Explorer in which strain data and astronomical triggers would be released immediately to the public (see §9.1). The data distribution and associated computing infrastructure will thus be key aspects of the operations model.

The organizational and staffing model for accomplishing the Cosmic Explorer Operation and Maintenance is provided below, based on the LIGO Laboratory Operations for the Advanced LIGO Phase (M1300188). There will be persons who play roles in several groups, and many will change their focus according to the phase of activity (repairs, upgrades, commissioning, observing).

1. A *detector group*, consisting of engineers and scientists who specialize in various detector subsystems and electronics. This group will be responsible for maintaining, testing, documenting, and repairing controlled detector configurations with a focus on optimizing data quality and uptime. This group will also be responsible for operating the detectors.
2. A *commissioning group*, largely scientists, will commission and test the instruments and establish new detector configurations, with a focus on improving their performance.
3. A *systems engineering group*, largely engineers, will set technical standards and approved changes in controlled configurations, with a focus on system trades.
4. A *calibration and data quality group* of scientists and engineers will ensure the data are ready for astrophysical interpretation. These individuals will work with commissioners to find and resolve sources of instrumental and environmental noise, and will vet the data to correct, mark, and/or edit data as needed to allow the subsequent analysis to be made by the scientific community.
5. An *observation coordination group* of scientists will plan and coordinate observations with the gravitational-wave and astronomical network and interface with the broader scientific community on issues related to observations.
6. An *analysis, data, and computing group*, focused on the cybersecurity, computing, low-latency analysis for astronomical alerts, maintaining catalogs of observations, curating and disseminating open data, and running a “Help Desk” to facilitate the use of CE by the broader scientific community.
7. A *facilities group*, responsible for maintaining the physical infrastructure of the observatories. Staffing will include significant vacuum expertise, and civil, electrical, and grounds engineers and technical support.
8. A *management group*. Each site will have a lightweight management and business group, enabling safety, procurements, shipping, human resources support, and top-level direction. For the target configuration of two Cosmic Explorer Observatories, one of the two

observatory sites will carry management common to the two sites to minimize costs and maximize synergy between the sites.

9. An *community engagement and integration group* responsible for promoting integration of the CE observatories into the local community, arranging programs and exhibits at the community-focused facility, and with engaging the public at large. This includes building and maintaining synergistic relationships with local Indigenous Peoples, publishing broadly accessible versions of high-impact scientific results which inspire community engagement, and translating these materials into Indigenous languages.

External advisory committees will be established to (1) aid in technical management and evolution of the observatories, (2) coordinate with the greater scientific community and help guide the timing and trades of observation vs. commissioning, and (3) ensure that each observatory maintains healthy relationships with local communities, including Indigenous Peoples.

The scope for the operations of Cosmic Explorer can be estimated based on extrapolation from the LIGO Laboratory operations. As described above, significant staff will be required to properly operate, maintain, and incrementally commission the detectors. The two-detector configuration of CE would profit, as LIGO does, from some economy of scale for technical and management staff; the single detector approach would allow some reduction but not a factor of two. The vertex and end stations are expected to be similar in size and complexity to the LIGO buildings. The first detector to be installed will be comparable in electronic, mechanical, and optical systems, and will require staff comparable to LIGO's to maintain it. The vertex and end-station vacuum systems for the initial detector will also be similar to LIGO; if the 2 μm technology requiring cryogenics is used, there will be some increased operating complexity. The vacuum system will be 5 to 10 times greater in length and volume, but a great majority is passive once installed. There will be greater maintenance needs to inspect and maintain the tube, foundation, and protective cover. There will be some increase – roughly a factor three – in the staffing and operating expenses for this larger vacuum system and civil infrastructure, bringing them to roughly 40% of the total operations cost (see Table 11.3).

A significant difference in project scope for Cosmic Explorer compared to Advanced LIGO is the staffing associated with delivering Cosmic Explorer data and alerts to the scientific community. In an Open Data model, data will be need to be calibrated and conditioned to the point that it can be interpreted for observational science without expert knowledge of the instrument and the data imperfections, robustly documented, archived, and served to the scientific community. Operations staff will also have responsibility the production and dissemination of low-latency alerts for known multimessenger sources. These activities will require a dedicated group of people whose sole job is preparing data and performing initial analysis.

It is assumed that the research and development of new detectors will be supported by proposals to funding agencies; the staff at the CE observatories would be members of groups proposing for upgrades and new detectors, complemented by many in the greater scientific community.

Yearly Operations Cost Estimates	\$(M) 2030 USD	Percent
Facilities	22.0	30
Vacuum Systems	9.4	13
Detector	20.6	28
Analysis, Data, and Computing	8.8	12
Management	7.0	9
Community Engagement	5.7	8
Grand Total (2 Observatories)	73.5	100

Table 11.3: Estimated yearly operations costs for Cosmic Explorer with two observatories, based on Advanced LIGO and scaled for CE facility sizes, in millions of 2030 US dollars. Operations costs for a CE project with a single observatory would be roughly 30% less. This estimate is for observatory operations *only* and does not include research for instrument upgrades.

11.4 Risk Management

Successful risk management starts with a careful examination of the project requirements and the construction and engineering responses in place to meet them. This examination leads to a good understanding of potential risk factors and their impact on the project. It is a common practice among large projects to establish a “risk registry” for perceived problem areas so that potential major issues are identified early and resolved, and that the project remains on schedule. For example, the Risk Registry for Advanced LIGO is publicly available.^b We expect to follow this practice. Also, for the aLIGO project, a Risk Management plan was created and is available from the LIGO DCC.^c This plan and lessons learned will serve as a guide to Cosmic Explorer. In the next two subsections we present the main technical and management risk factors that will form the starting point of Cosmic Explorer’s risk management plan.

11.4.1 Technical Risk

Unproven technology (*cf.* §8.3) and the land acquisition for a large site constitute the largest technical risk factors for the project. Cosmic Explorer will rely on the proven room temperature fused-silica-optic technology of Advanced LIGO operating at a wavelength of 1064 nm; fortunately, the success of Advanced LIGO establishes that this technology is extremely mature. As with LIGO, the Cosmic Explorer sensitivity will continue to improve through a series of planned upgrades.

The main technical risk factors are fairly limited. The ones we have identified so far are:

1. *Risk of acquiring site(s) with adequate space and no excess noise that could compromise interferometer sensitivity and performance* (*cf.* §8.2.2). Finding appropriate site(s) that have not only adequate space for Cosmic Explorer, but also provide a low seismic noise background for the observatory is key to the Cosmic Explorer design. Initial surveys of North America suggest that it is possible to find adequate sites, and a detailed site

^b<https://dcc.ligo.org/LIGO-M080359>

^c<https://dcc.ligo.org/LIGO-M060045>

survey as part of a design study can guarantee that the current seismicity of candidate sites is acceptable. But acquiring the required continuous piece of land from potentially numerous previous owners can be difficult and poses an obvious project risk. Thus the land acquisition will have to be managed carefully. Possible urban encroachment on the site(s) over the lifespan of the observatory also will have to be managed.

2. *Risk associated with the vacuum system (cf. §8.2.2).* An adequate vacuum system is clearly technologically feasible. However, the significant increase in required vacuum volume compared to the Advanced LIGO detectors makes the vacuum system the driving cost factor for the project. A more cost-effective vacuum system construction is desired, and requires additional research.

To mitigate the project risk ahead of construction it is essential that a vacuum system prototype is built at the engineering design stage. Ideally this prototype would be constructed by the company that will get the contract for the vacuum system. It would also be useful to prototype a test mass chamber due to its complexity. Prototypes similar in spirit were constructed as part of initial LIGO.

3. *Risk associated with larger test masses not achieving design specifications.* While almost all technology from Advanced LIGO could be directly installed in a larger facility, the longer arm lengths do require an increase in optics size compared to Advanced LIGO, pushing the capability of current coating facilities. Together with issues related to small absorbers in the test-mass mirror coatings encountered in Advanced LIGO, this puts the manufacturing capability of optics for Cosmic Explorer at a critical spot. Achieving the optics and coatings design specifications is essential for reaching the design circulating laser power (1.5 MW) and thermal noise. Addressing this risk will require a significant investment in proof-of-principle optics as part of a design study (cf. §8.3).
4. *Risks associated with a 20 km detector.* Since the strain sensitivity is proportional to arm length, almost all noise sources are a factor of 2 less stringent for the 40 km compared to the 20 km. The losses in the signal extraction cavity limit the high frequency sensitivity, specifically they reduce the depth of the resonant dip in the post-merger tuned configuration. Since the high frequency sensitivity is the key science driver for a 20 km Cosmic Explorer detector, there is also added technical risk for this 20 km post-merger tuning configuration arising from any excess signal extraction cavity loss. The low frequency optimized tuning is not limited by the excess noise in the signal extraction cavity. Thus, we realize that the overall risk of having a single 20 km detector is significantly higher than a single 40 km detector. The technological challenges and the corresponding risk to CE detectors are discussed in (cf. §8.3).
5. *Risk due to an inadequate number of electromagnetic follow-up observatories.* Part of Cosmic Explorer's scientific promise is to provide sky localization and early warning for neutron star merger events. Thus the availability of a sufficient number of well-performing

satellites, observatories and telescopes (x-ray, optical, radio, neutrino) is critical for reaping the full scientific benefit from Cosmic Explorer. Scheduling observation runs to maximize overlap with followup assets can mitigate that risk.

6. *Environmental risks:* As a facility designed for a 20+ year life span, rare but violent events such as floods, violent storms and earthquakes pose a significant but hard to predict risk for the project. The site selection, facility and instrument design will have to accommodate these risk factor.
7. *Malicious risks:* Sufficient site security, in the form of video monitoring, digital surveillance and physical barriers (locked entrances and fencing), will be needed to protect against both unintentional accidents and intentional sabotage. Infrastructure such as power lines, the vacuum system and the computer grid may be tempting targets for bad actors.

We have also identified the backup technology being developed for the LIGO Voyager detector consisting of cryogenic silicon optics operating at a wavelength of 2 μm which could be installed after the initial observing phase if it is found that the Advanced LIGO technology cannot reach the sensitivity goals (*cf.* §8.1.8). This technology could also be used to surpass the nominal CE sensitivity in the future (*cf.* §8.4).

11.4.2 Management Risk

The management risk for a large project like Cosmic Explorer is to a large extent related to the deployment and organization of human resources to address the technical and engineering challenges of the project. This includes adequate financial backing and coordination to ensure that resources and scheduling are adequate to the task.

As described in §11.6, Cosmic Explorer project management will be accomplished using standard project management practices. A team of project management professionals will be tightly integrated into the project engineering and systems integration group. The use of monitoring software (e.g., Primavera, used by aLIGO) and a carefully-developed resource-loaded schedule will help to identify areas which may have significant risk. The risk registry described in §11.4 will be critical in managing problem areas and their potential effects on project costs and schedule.

For Cosmic Explorer, there is potential for significant management risk in at least three areas: (1) publicity risk associated with site acquisition; (2) where new technology is required to achieve performance goals (*cf.* §8.3); and (3) where international partnerships may be established as part of the core Cosmic Explorer project and the wider 3G network.

1. The construction of Cosmic Explorer requires the acquisition of a large, continuous. L-shaped piece of land. While for most of this land the construction impact will be limited to allowing a path for the vacuum system, this land acquisition will impact local land owners and Indigenous communities. Thus, especially in the age of social media, a genuinely

trustworthy relationship with local communities is absolutely essential for the success of the project. The ground work for such a relationship needs to be laid early on in the project, ahead of the actual site acquisition.

2. As described earlier (*cf.* §11.4.1), Cosmic Explorer will require significant new developments in large-scale, high performance vacuum systems; in seismic isolation of the test masses; in test mass suspensions; and in the use of much larger test masses. Crucially, the research and development needed to address the technical risk requires significant expertise, both scientific and engineering. Through the lifespan of Initial and Advanced LIGO the NSF has invested in building up that technical, scientific and engineering expertise in the form of the LIGO laboratory staff scientists and engineers, as well as associated research groups across the country. That pool expertise forms a national asset, the loss of which would set back Cosmic Explorer significantly. It is thus of particular importance to sustain this expertise during the transition from current detectors (Advanced LIGO, A+) to Cosmic Explorer.
3. International partnerships can present difficult complexities in several ways, including: the length of time needed to put them into place; the probable need for negotiations between high levels of government; differing costing protocols between countries (making cost assessments difficult to compare); ensuring that a single management structure has adequate authority; and differing work rules. Similar issues can arise also between states and funding agencies within the U.S., though they are usually more easily managed.

When envisioning international partnerships for Cosmic Explorer, we will learn from the success of the LIGO Scientific Collaboration (LSC). The LSC has data sharing and data analysis agreements, through MOUs, with Virgo and KAGRA. Also, the GEO collaboration with its GEO600 detector, and OzGrav are members of the LSC. Through this mechanism, leaders from the LIGO, Virgo, KAGRA, and GEO600 detector groups participate in the Joint Run Planning Committee to coordinate observing runs. These partnerships have been crucial for enabling and extracting the most information possible from the first observations of gravitational waves and especially the sky localization enabling multimessenger astronomy.

11.5 Synergies with Programs at U.S. Funding Agencies

Cosmic Explorer's unique capabilities to explore extreme gravity and to search for new physics complement the priorities and planned missions of several funding agencies in the United States. (A comprehensive description of the "European Strategy for Particle Physics" is available in the 2020 Physics Briefing Book.²²⁴)

1. NSF: The Divisions of Astronomy⁵⁰³ (AST, \$250M 2019 CP) and Physics⁵⁰⁴ (PHY, \$285M 2019 Actual), and the Office of Polar Programs⁵⁰⁵ (OPP, \$398M 2019 Actual) all make large investments in the study of black holes, stellar evolution, nuclear physics, dark energy and

dark matter. Instruments such as LIGO, IceCube, EHT and optical and radio telescopes located at many sites around the world, including the South Pole.

2. DOE: The DOE program⁵⁰⁶ in High Energy Physics (HEP, \$1.01B 2019 request) comprises: the Energy Frontier, the Intensity Frontier and the Cosmic Frontier. The intellectual basis for the program is described in the 2014 “P5” report.⁵⁰⁷ The overall science focus is on the Higgs boson, neutrino mass, dark matter, cosmic acceleration and “exploring the unknown.” The “Cosmic Frontier” program (\$75.5M 2019 request) supports the ongoing Fermi/GLAST, AMS, HAWC, DES and eBOSS experiments. It is constructing the Rubin Observatory and DESI for research into dark energy, and LZ and SuperCDMS-SNOLab for dark matter searches. Via the SPT-3G it explores the CMB to study cosmic acceleration and neutrino properties (with NSF). There is also an extensive program in cosmic-ray and gamma-ray research (AMS, HAWC). Nuclear Physics programs of the Office of Science, such as the Facility for Rare Isotope Beams (FRIB), actively develop connections to nuclear astrophysics.⁵⁰⁸
3. NASA: The Astrophysics Program⁵⁰⁹ (\$1.496B 2019 request) plays the lead role in eight operating missions (e.g., Hubble, FGST, NICER, TESS, JWST), and five in development (e.g., Webb, WFIRST). It is a partner in the development of Euclid and LISA. The NASA Physics of the Cosmos program focuses on dark matter and dark energy, the evolution of galaxies and stars, and matter and energy in extreme environments. The LISA program⁵¹⁰ in GW research is closely tied to LIGO/Virgo, and possibly to Cosmic Explorer and the European Einstein Telescope.⁵¹¹

11.6 Cosmic Explorer Project Roadmap

In proceeding with the Cosmic Explorer Project, we will draw on the successful experience and expertise of the LIGO Lab and the lessons learned during LIGO’s planning, construction, and operation. The LIGO Lab now has a long history of delivering on time and on budget, has been well operated and managed, and has delivered important scientific discoveries. At the same time, the LIGO Lab has consistently received high ratings for its leadership and management. As a result of these attributes, morale within the LIGO Lab has generally been very high. We recognize this quality as one of the greatest assets to any project and one which must be preserved for Cosmic Explorer.

We also recognize that the CE Project is significantly larger in scale and will require greater sophistication in the Project organization, and a larger breadth of participation and support in the project.

In planning the next steps for the Project, three resources have been of particular value:

- The NSF Major Facilities Guide (MFG).³

- The book chapter on “Planning, managing, and executing the design and construction of Advanced LIGO”⁵¹² by David Shoemaker, who led the Advanced LIGO Project. This chapter was written with future projects in mind to provide experience, generalizations, and lessons learned from both Initial and Advanced LIGO.
- Advice and experience shared by the management and staff of LIGO, other gravitational-wave observatories world-wide, and other large-scale scientific facilities.

The Cosmic Explorer Project will proceed along the guidelines provided in the Major Facilities Guide. In broad outline, these are to:

- collect feedback from the broad scientific community on the match of the Cosmic Explorer concept and capability with their needs and interests, using the Horizon Study as a basis for discussion. In this process the parties (individuals and institutions) interested in engaging substantively in the next Project phases can be identified. Partnership arrangements and international participation will be informally explored.
- collect feedback from the NSF, and address any specific shortcomings to ensure that the NSF can correctly consider the Project; feedback on next steps will be welcome.
- cast the Horizon study into the form of a Project Execution Plan, and start to address those elements most in need of refinement. Several of these elements follow.
- establish the core of a Project Office, and within it a system engineering activity.
- establish a plan to create an accurate, detailed, costed baseline project description that provides the project performance goals, the technical aspects of the facility, its estimated cost and the time required for completion. This will become the *Reference Design* for the project. This essential document provides the point of departure for measuring progress accurately and for assessing cost, schedule and technical performances.
- establish an orderly process for implementing project changes even at an early conceptual phase, and maintain an accurate record of them as they occur.
- identify potential critical and near-critical paths through the schedule. Ensure that early effort is allocated to assess these activities to firm up estimates, and explore mitigation where possible.
- develop a plan for identifying and managing risk (*cf.* §11.4)
- research and document “lessons learned” during the construction of LIGO, aLIGO and A+, as well as from observatories constructed outside the U.S. (GEO, KAGRA, LIGO India, Einstein Telescope) and other large facilities (e.g., the Thirty Meter Telescope).

- draft a Scope Management Plan and explore scope contingency responses to anticipate means to explore savings from potential de-scoping options, and find decision points for exercising options.
- establish robust means of communication with the external physics and astronomy communities and the public.
- collaborate with other relevant Projects (e.g., Einstein Telescope) to leverage technical and scientific opportunities whenever possible.
- establish and maintain a strong community engagement and integration program with the objective of building synergistic relationships with local communities at potential Observatory sites, including Indigenous Peoples.

These activities will be focused (and iteratively tuned) with a target of creating a technical development roadmap with estimates of funding and more detail on the magnitude of the challenges associated with technical development work. A goal will be to support a critical review by mid-decade to enable a detailed engineering design study.

The pace and character of this followup activity will depend on the funding available to the Project. Seeking that funding will be one of the first activities to follow the completion of the Horizon Study.

12 Conclusion

This Horizon Study has described the path forward for realizing Cosmic Explorer, a next-generation, ground-based gravitational-wave observatory in the United States. By drawing on two decades of international effort to scale up the proven technology that has enabled humanity's first observations of gravitational waves, Cosmic Explorer will extend our gravitational-wave vision to the farthest reaches of the universe.

In this study, we have described a science-driven design for Cosmic Explorer and have considered how to optimize the design performance versus the cost. We presented a technical overview of the detectors and a roadmap to the research and development required to achieve them. We have further examined the organization, planning, and community engagement that will be necessary to design, build, and operate Cosmic Explorer.

During the next few years, we will welcome feedback from the National Science Foundation, the National Research Council, and from the gravitational-wave community; their guidance and endorsement will be critical to the success of the next generation of gravitational-wave science in the United States. We aspire for this study to prepare the way, through the next two decades, for the ultimate design, construction, and operation of Cosmic Explorer.

Continued funding to develop enabling technologies, grow the CE community and build relationships with potential observatory host communities is crucial to preparing the CE Project for critical review in the mid-2020s. If CE is determined to be technically ready, of interest and timely, we expect that a thorough design study will begin, leading to a complete design and construction plan that will be funded in the late-2020s.

Once operational, its cosmic reach and exquisite sensitivity will enable Cosmic Explorer to revolutionize our understanding of the universe while continuing the United States' leadership in gravitational-wave science. Cosmic Explorer will observe black holes and neutron stars throughout cosmic time, probe the nature and behavior of the densest matter in the universe, and explore the universe's most extreme gravity and open questions in fundamental physics. As part of an international next-generation gravitational-wave network, Cosmic Explorer would couple these advances in gravitational-wave astronomy with the future of electromagnetic and particle astronomy.

Acknowledgements

We would like to thank the National Science Foundation for supporting this study through the collaborative awards NSF–1836814, NSF–1836779, NSF–1836702, NSF–1836809, and NSF–1836734. We also thank the Australian Research Council, who provided funding through grant CE170100004, as well as the MathWorks, Inc., and the Heising-Simons foundation. We would also like to thank the members of this study’s advisory panel, Patrick Brady, Kathryn Daniel, Gabriela González, Vicky Kalogera, Harald Lück, David Reitze, Sheila Rowan, and Jim Yeck, for their advice and helpful suggestions throughout the study. Furthermore, we are very grateful to the gravitational-wave community and especially the Gravitational-Wave International Committee, both for their work toward the next generation of gravitational-wave observatories and for their feedback on this study.

Finally, the PIs on the grants that funded this work are deeply grateful to the graduate student and postdoctoral scholar co-authors who worked tirelessly to make this Horizon Study a reality.



This study was funded by the National Science Foundation.

Abbreviations

2G	Second generation of gravitational-wave detectors
3G	Third generation of gravitational-wave detectors
A+	LIGO A+ upgrade
AAS	American Astronomical Society
AISES	American Indian Science and Engineering Society
APS	American Physical Society
BBH	Binary black hole
BNS	Binary neutron star
CBO	Compact-binary-optimized detector configuration
CE	Cosmic Explorer
DECIGO	Decihertz Gravitational-Wave Observatory
DOE	Department of Energy
ET	Einstein Telescope
EOS	Equation of state
GWAC	Gravitational-Wave Agencies Correspondents
GWADW	Gravitational-Wave Advanced Detector Workshop
GWIC	Gravitational-Wave International Committee
GWPAW	Gravitational-Wave Physics and Astronomy Workshop
IMBH	Intermediate-mass black hole
KAGRA	Kamioka Gravitational-Wave Detector
LIGO	Laser Interferometer Gravitational-Wave Observatory
LISA	Laser Interferometer Space Antenna
LSC	LIGO Scientific Collaboration
LVK	LIGO–Virgo–KAGRA Collaboration
MREFC	Major Research Equipment and Facilities Construction (NSF account)
NEMO	Neutron-Star Extreme Matter Observatory
NSF	National Science Foundation
PISN	Pair-instability supernova
PMO	Postmerger-optimized detector configuration
QCD	Quantum chromodynamics
SACNAS	Society for Advancement of Chicanos/Hispanics and Native Americans in Science
SMBH	Supermassive black hole
UHV	Ultrahigh vacuum

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DISSENT

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