Cosmic Explorer and next-generation ground-based gravitational-wave astronomy

Philippe Landry on behalf of the Cosmic Explorer Project
Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, ON M5S 3H8

Cosmic Explorer is the United States' planned contribution to the global network of next-generation ground-based gravitational wave observatories. With ten times the sensitivity of the LIGO detectors, Cosmic Explorer will survey compact binary mergers out to cosmological distances, precisely localize the sources of many kilonovae and gamma-ray bursts, and potentially discover new sources of gravitational waves. A next-generation observatory network that includes Cosmic Explorer will have a transformative impact on astrophysics, fundamental physics, nuclear physics and cosmology.

1 Introduction

The existing global network of gravitational wave detectors has made several pathbreaking discoveries since its first observing campaign debuted in 2015. These include the first-ever direct detection of gravitational waves, which originated from a binary black hole merger;[1] the first multimessenger observation of a binary neutron star coalescence, whose gravitational waves were accompanied by radiation across the electromagnetic spectrum;[2] and the discovery of compact objects from both high- and low-mass gaps in the known black hole mass spectrum.[3,4] Comprising two LIGO detectors in the United States,[5] Virgo in Italy,[6] and recently augmented by KAGRA in Japan,[7] this observatory network serves as a window on the gravitational universe in the frequency band from tens of Hz to a few kHz, with sensitivity to gravitational wave strains of $O(10^{-25})/\sqrt{\text{Hz}}$. The strain sensitivity achieved by LIGO during its third observing run (O3), and its projected sensitivity after the scheduled A+ technology upgrade later this decade,[8] are plotted as a function of gravitational wave frequency in Fig. 1.

Following a period of upgrades and commissioning, LIGO, Virgo and KAGRA will resume operating in spring 2023. During this fourth observing run (O4), the network is projected to achieve three times the sensitivity of its O3 benchmark.[8] Because the amplitude of a gravitational wave falls off like $1/r$ with distance from the source, a threefold sensitivity improvement translates to a threefold increase in the detector's reach, or a nine-fold increase in the spacetime volume it probes. Thus, O4 promises an order of magnitude more compact binary coalescence detections than O3. The detection rate will increase further in subsequent observing campaigns, as the LIGO detectors leverage the improvements to suspension systems, mirror coatings and squeezed light technology planned as part of the A+ upgrade.

Although all of the gravitational waves detected to date have been from compact binary coalescences, they are far from the only source of gravitational radiation in the universe. In the LIGO–Virgo–KAGRA frequency band, we expect continuous, monochromatic gravitational waves from asymmetries on rotating neutron stars and bursts of gravitational waves from core-collapse supernovae. At higher frequencies, we anticipate gravitational waves from the oscillations of binary neutron star merger remnants. And, at lower frequencies, a stochastic background of gravitational waves is predicted, both from unresolved astrophysical sources and from

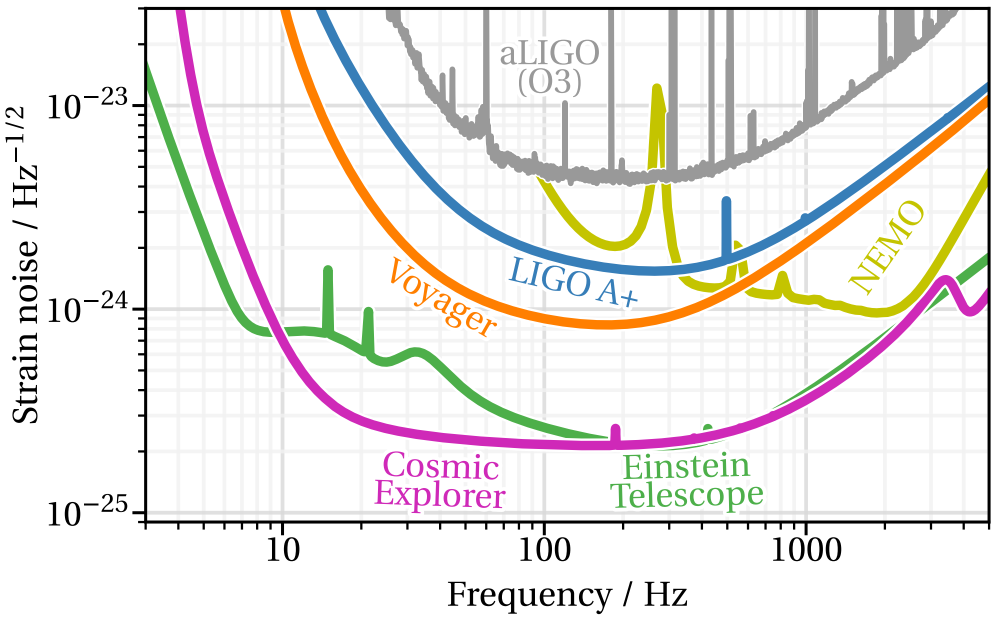

Figure 1 – Strain sensitivity of existing and proposed ground-based gravitational wave detectors, from the Cosmic Explorer Horizon Study.[9] Cosmic Explorer aims to achieve an order-of-magnitude improvement in broadband sensitivity compared to LIGO A+, a scheduled upgrade to the LIGO detectors that will bring them beyond their original design sensitivity.

perturbations of cosmological origin.

A serendipitous discovery of gravitational waves from one of these sources is possible, but unlikely, with the current detector network. Moreover, for compact binary coalescences, the network's reach will be limited to nearby mergers (redshifts $z \lesssim 2$) even after the A+ upgrade. In the face of these limitations, the desire to fully explore the few Hz to few kHz discovery space out to cosmological distances has motivated the development of concepts for a new generation of ground-based gravitational wave observatories. These next-generation observatories will have ten times the sensitivity of LIGO A+, enabling them to probe all the merging stellar-mass compact binaries in the universe, precisely localize nearby binary neutron star coalescences—sometimes with early warning of merger—for follow-up by electromagnetic astronomers, confidently detect postmerger binary neutron star signals, and possibly make the first discovery of gravitational radiation from a supernova or rotating neutron star. The United States' planned contribution to this global effort is an observatory called Cosmic Explorer.[9]

2 Next-generation gravitational wave astronomy

The Cosmic Explorer observatory is envisioned as two widely separated L-shaped surface interferometers located in the United States. It is intended to function as part of a global next-generation detector network that will be operational in the mid-to-late 2030s. The Cosmic Explorer detectors will share the same basic design as the existing 4-km LIGO interferometers, but will be scaled up in length L by an order of magnitude. Because the basic strain resolution of the interferometer scales like L^{-1}, the tenfold increase in arm length ensures the factor of ten gain in broadband sensitivity relative to LIGO A+, whose mature technology Cosmic Explorer will initially employ. However, innovations in mirror coatings and cryogenic technology (to reduce thermal noise), lasers and squeeezed light (to reduce high-frequency quantum noise), as well as suspensions and control systems (to mitigate environmental noise) will be adopted as they become available, helping to push the sensitivity envelope even further. Because the core design is essentially a scaled up version of LIGO, Cosmic Explorer promises a big science upside with relatively low technical risk.

A detailed vision for Cosmic Explorer and the science it will enable is laid out in the Cosmic Explorer Horizon Study.[9] The reference design presented there calls for one interferometer to have 40-km arms, and the other to have 20-km arms. This is because the free spectral range (i.e. the frequency corresponding to the light travel time in the arms) of the 40-km detector degrades its sensitivity around 3.7 kHz, where postmerger binary neutron star signals are expected. A shorter detector, with a higher free spectral range, is more sensitive to high-frequency gravitational waves. However, the longer detector has better broadband sensitivity for peering deep into the cosmos. Thus, a heterogeneous detector network is beneficial for maximizing Cosmic Explorer's science return. The tradeoffs associated with different design choices and detector networks are weighed in the Horizon Study; it also reports a rough cost estimate for the project.

Cosmic Explorer will do its best science if it is embedded in a global next-generation detector network. Fortunately, the mature European concept for a next-generation observatory, Einstein Telescope,[10] is on the path towards funding. It is meant to be operational on the same timescale as Cosmic Explorer, and its site selection process is already well underway. Einstein Telescope uses a different design than Cosmic Explorer to achieve a comparable sensitivity profile: it is conceived as a triangular interferometer with 10-km sides, built underground to reduce low-frequency noise. The long baseline between American and European detectors will allow for precise triangulation of sources on the sky. Of course, an additional next-generation detector located in the southern hemisphere would be especially advantageous for source localization. Although not a full-scale next-generation detector, there is an Australian concept for a 4-km intereferometer, called NEMO,[11] specially designed to target high-frequency postmerger binary neutron star signals. If funded, it could observe in tandem with Cosmic Explorer and Einstein Telescope in the mid-2030s. In addition, the LIGO–Virgo–KAGRA network, augmented by LIGO-India[8] and possibly operating beyond A+ sensitivity (e.g. in the proposed Voyager configuration[12]), may remain active through the 2030s, helping to localize the closest sources. Besides ground-based gravitational wave detectors, the space-borne LISA observatory[13] is scheduled to launch and begin taking data on a similar timescale. While it is sensitive to much lower (mHz) frequencies, there are opportunities for multi-band observations with LISA and Cosmic Explorer as wide compact binaries evolve towards merger.

What will the advent of these next-generation facilities mean for gravitational-wave astronomy? Let us consider their impact in the context of compact binary coalescences. With ten times the sensitivity of LIGO A+, Cosmic Explorer's reach for binary black hole mergers will extend to the edge of the gravitational-wave universe. Its detection horizon for binary black holes is plotted in Fig. 2, as compared against the theorized redshift distribution of such systems: the horizon lies well beyond $z = 10$, where the first stellar-origin black holes are thought to have formed. Hence, Cosmic Explorer will be sensitive to universe's very first compact binary mergers. For binary neutron stars, also shown in Fig. 2, virtually the entire population of mergers is contained within the detection horizon; Cosmic Explorer's merging neutron star survey will be remarkably complete. All told, a global next-generation detector network that includes Cosmic Explorer is expected to detect half a million or more compact binary coalescences per year.[9] Such a rich dataset will be transformative for astrophysics, cosmology and fundamental physics.

3 Key Cosmic Explorer science

Cosmic Explorer's unprecedented Hz-to-kHz strain sensitivity, coupled with its potential for precise source localization when embedded in a global next-generation observatory network, make it an ideal vehicle for advancing our understanding of the cosmos. Cosmic Explorer is poised to have the highest scientific impact in three broad areas: the evolution of the populations of stellar-mass black holes and neutron stars throughout cosmic history; the dynamics and structure of the dense and neutron-rich matter found in neutron stars; and the basic understanding of

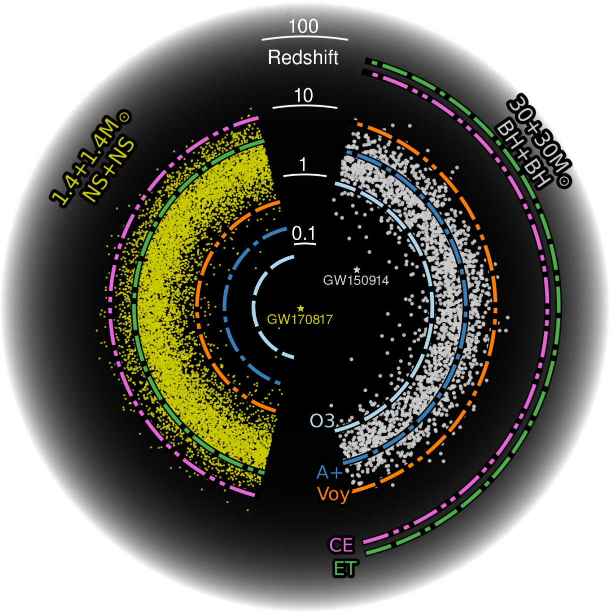

Figure 2 – Cosmic Explorer's detection horizon for binary black hole and binary neutron star mergers, from the Cosmic Explorer Horizon Study.[9] The binary black hole horizon lies well beyond the redshift at which the first stellar-origin black holes are thought to have formed. Nearly the entire merging neutron star population is contained within the detection horizon for binary neutron stars.

gravity and fundamental physics in extreme conditions. Below, we examine Cosmic Explorer's key science targets in each of these areas.

Besides enumerable science targets, the most exciting aspect of Cosmic Explorer is its wide discover aperture: the promise that it will discover something completely unexpected by virtue of its tenfold broadband sensitivity improvement. Similar order-of-magnitude gains in electromagnetic astronomy have led to major discoveries, such as pulsars and fast radio bursts. We anticipate the same kinds of surprises with next-generation gravitational wave astronomy.

3.1 Black holes and neutron stars throughout cosmic time

Thanks to its deep cosmological reach, Cosmic Explorer is well-placed to answer key questions about the astrophysical origin of compact objects and their evolution over cosmic history. As shown in Fig. 3, a single 40-km Cosmic Explorer detector will be able to observe compact binary mergers of $O(M_\odot)$ to $O(100\,M_\odot)$ in total mass past $z = 10$. The ability to resolve these extremely distant sources is critical for learning about the black-hole remnants of the very first stars, known as Population III stars.[14] Measuring the remnant black holes' mass distribution will constrain the initial mass function of Population III stars, which is an important input in modeling how the first galaxies formed.

Cosmic Explorer's measurement of the black-hole merger rate at high redshift will also shed light on the formation of supermassive black holes in the early universe: did they form directly from the collapse of hydrogen clouds, or hierarchically, from repeated mergers of stellar- and intermediate-mass black holes? Determining whether the black-hole remnants of Population III stars act as seeds for the formation of supermassive black holes has important implications for galactic evolution.[15]

More locally, Cosmic Explorer's survey of binary black hole mergers will be complete beyond the peak of star formation at $z = 2$ if it is embedded in a next-generation network. Similarly, its survey of binary neutron stars will capture one out of every two mergers at that redshift. This means that the mass, spin and redshift distributions of black holes and neutron stars will be resolved in great detail. Such measurements will be incredibly powerful for distinguishing

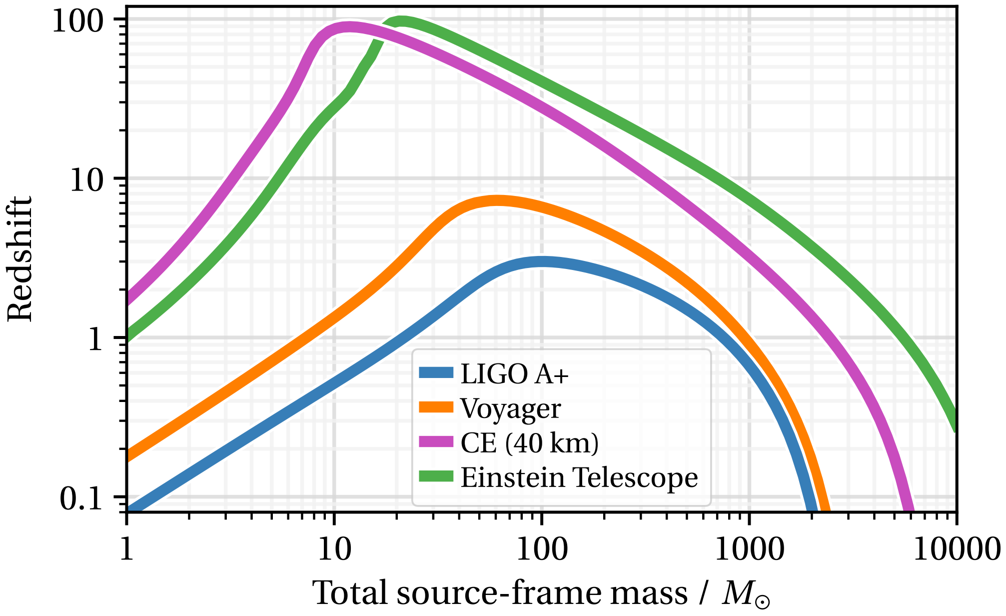

Figure 3 – Cosmic Explorer's detection horizon for compact binary coalescences as a function of binary mass, from the Cosmic Explorer Horizon Study.[9] The detection horizon initially increases with mass, peaking at $z \approx 100$ for 10 $M_\odot$ binaries, as heavier binaries produce larger-amplitude gravitational waves. Thereafter, the detection horizon decreases because heavier binaries merge at lower, less sensitive frequencies, and the most distant mergers are redshifted out of band.

subpopulations originating from different formation processes, such as isolated binary evolution vs dynamical assembly in dense stellar environments, and assessing their relative contributions to the merging compact object population.[16]

3.2 Dynamics of dense matter

The unprecedented depth and breadth of Cosmic Explorer's sensitivity curve will also advance our knowledge of the internal structure and composition of neutron stars, whose cores contain the densest matter in the universe. Fig. 4 illustrates the phase diagram of quantum chromodynamics in terms of temperature and density; understanding the fundamental properties of matter in all regimes of the diagram is an important goal for nuclear physics. Tidal signatures in the gravitational waves from inspiralling binary neutron stars probe its high-density, zero-temperature region. As part of a next-generation network, Cosmic Explorer will detect hundreds of binary neutron star mergers with signal-to-noise ratios in excess of 100 per year.[17] The loudest of these mergers will precisely constrain the neutron star tidal deformability, which is strongly correlated with the neutron star radius, a proxy for the repulsive nuclear interactions that determine the stellar structure. These observations will determine the neutron star radius to within 100 m across the neutron star mass spectrum,[18] a major improvement over current km-scale uncertainties.

Besides characterizing cold dense matter in neutron stars before merger, Cosmic Explorer will probe the finite-temperature ultra-dense matter found in neutron star merger remnants. This is a highly uncertain region of the phase diagram that is virtually impossible to access experimentally. Thanks to its high-frequency sensitivity, particularly in the proposed 20-km configuration, Cosmic Explorer will confidently detect dozens of postmerger gravitational wave signals per year.[19] The loudest of these will permit a measurement of the peak postmerger oscillation frequency, which is sensitive to thermal, rotational and magnetic corrections to neutron star structure.[20]

Neutron star mergers also eject neutron-rich material that powers the r-process nucleosyn-

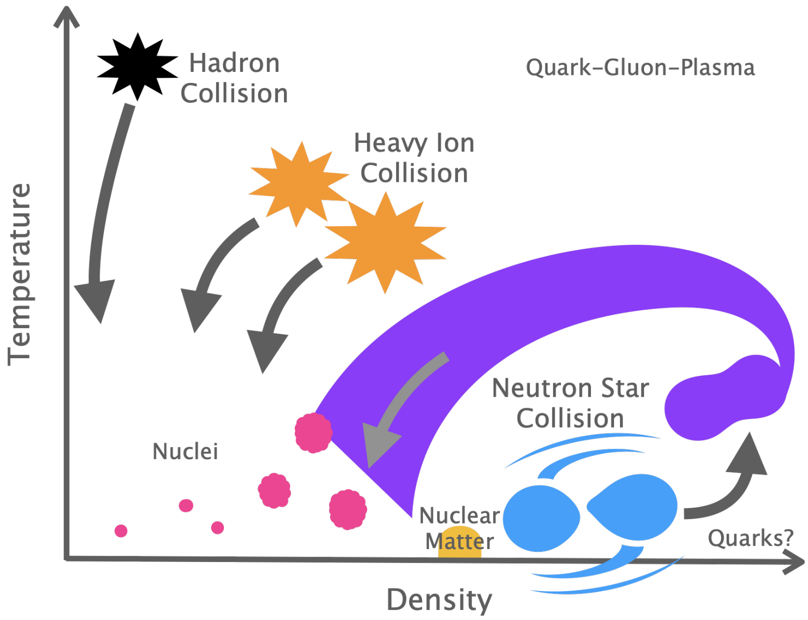

Figure 4 – Binary neutron star mergers as probes of the phase diagram of quantum chromodynamics, from the Cosmic Explorer Horizon Study.[9] Gravitational waves from the inspiral stage of a binary neutron star coalescence encode information about the structure of matter at high density and low temperature. Postmerger gravitational waves from the oscillations of the merger remnant probe matter at ultra-high density and finite temperature. The neutron-rich matter ejected by the merger powers heavy-element nucleosynthesis.

thesis of heavy elements, like gold and platinum, and produces a radioactive afterglow known as a kilonova. A next-generation network including Cosmic Explorer will be a boon to multi-messenger astronomy because of its ability to localize dozens of binary neutron star mergers per year to within 0.1 deg^2 on the sky inside the horizon of searches for kilonovae,[17]. Systematic studies of gravitational wave-localized kilonovae will link their properties to those of the binary neutron star progenitors, allowing for better constraints on compact binary mergers' contribution to heavy element nucleosynthesis over cosmic history. Moreover, since the next-generation network's binary neutron star survey will be complete past $z = 0.5$,[9] all detected short gamma-ray bursts within this horizon will have an associated gravitational wave counterpart, often with a precise sky localization—and sometimes with advance warning of merger.[17] This will provide insight into the mechanism for launching the relativistic jets that generate gamma-ray bursts.

3.3 Extreme gravity and fundamental physics

Cosmic Explorer will detect hundreds of thousands of binary black hole mergers per year, some of which will be extremely loud, with signal-to-noise ratios of thousands.[9] A simulation of the recovered waveform for one such example is shown in Fig. 5. These exceptionally loud events will be excellent testbeds for our theory of gravity. Precision tests of inspiral evolution and the ringdown of remnant black holes will constrain alternatives to general relativity in the strong-field regime.[21]

The completeness of Cosmic Explorer's survey of nearby compact binary coalescences will also permit systematic searches for outliers in the black hole and neutron star populations. These outliers could be exotic compact objects like boson stars,[22] black holes with axion clouds,[23] or dark-matter-admixed neutron stars[24]. They would distinguish themselves at the population level due to their unusual masses, spins or tidal properties.

Additionally, the cosmological reach of a next-generation network involving Cosmic Explorer will be able to test competing theories of dark energy. Besides measuring the Hubble constant locally with standard sirens (i.e. mergers with identified electromagnetic counterparts), the dark

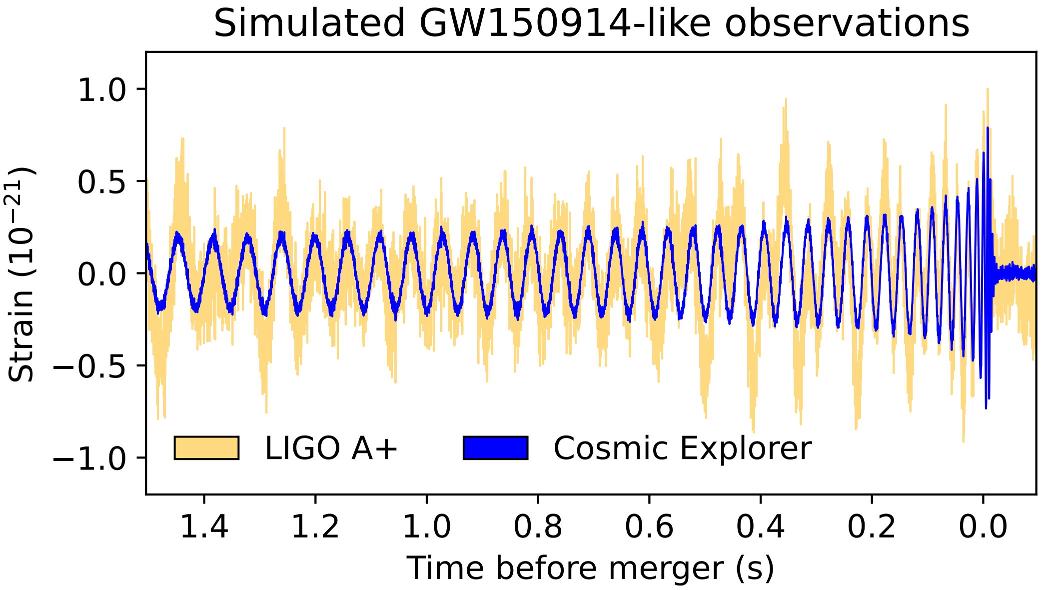

Figure 5 – The gravitational waveform of a binary black hole merger like GW150914 as seen by Cosmic Explorer vs LIGO A+, from the Cosmic Explorer Horizon Study.[9] GW150914, the first gravitational wave discovery, was detected by LIGO with a signal-to-noise ratio of 24, but the loudest binary black hole merger observed by a next-generation network including Cosmic Explorer each year will have a signal-to-noise ratio above 2700.

energy equation of state will be constrained via mergers at large redshift.[25] Precise sky localizations will allow for dark siren cosmology, where the source is statistically associated with a host in the absence of an electromagnetic counterpart. Even without these localizations, it will be possible to do cosmography with redshifted features in the astrophysical distributions of compact objects.[26]

4 Outlook

The advent of Cosmic Explorer and other next-generation observatories will be a gamechanger for ground-based gravitational wave astronomy, and will hugely impact related areas of science, like astrophysics, fundamental physics, nuclear physics and cosmology. The order of magnitude scale-up of the LIGO design envisioned by Cosmic Explorer will lead to unmatched capabilities for gravitational wave survey completeness, reach and precision.

The science case and reference design discussed here were released as part of the Cosmic Explorer Horizon Study in 2021. The Cosmic Explorer project is now in its conceptual design stage, which involves a site search and the elaboration of a technical design, plus research and development of next-generation instrumentation and data analysis techniques. The site search is a critical, multi-year process that needs to consider many factors, both physical and social, about candidate sites. The conceptual design stage will lead into site selection and, assuming the project is funded, construction towards the end of the decade. According to this timeline, the first observations with Cosmic Explorer could potentially occur in the mid-to-late 2030s. With Einstein Telescope also coming online on that timescale, the global next-generation ground-based gravitational wave observatory network can then begin fulfilling its incredible science potential.

Acknowledgments

P.L. thanks his Cosmic Explorer Horizon Study co-authors for their input on this manuscript. P.L. is supported by the Natural Sciences & Engineering Research Council of Canada (NSERC).

References

1. B. P. Abbott et al. *Phys. Rev.* D, 93(12):122003, 2016.
2. B. P. Abbott et al. *Phys. Rev. Lett.*, 119(16):161101, 2017.
3. R. Abbott et al. *Phys. Rev. Lett.*, 125(10):101102, 2020.
4. R. Abbott et al. *Astrophys. J. Lett.*, 896(2):L44, 2020.
5. J. Aasi et al. *Class. Quant. Grav.*, 32:074001, 2015.
6. F. Acernese et al. *Class. Quant. Grav.*, 32(2):024001, 2015.
7. Y. Aso et al. *Phys. Rev.* D, 88(4):043007, 2013.
8. B. P. Abbott et al. *Living Rev. Relativ.*, 21(1):3, 2018.
9. M. Evans et al. *arXiv*, arXiv:2109.09882, 2021.
10. M. Punturo et al. *Class. Quant. Grav.*, 27(8):084007, 2010.
11. K. Ackley et al. *Publ. Astron. Soc. Aust.*, 37:e047, 2020.
12. R. X. Adhikari et al. *Class. Quant. Grav.*, 37(16):165003, 2020.
13. P. Amaro-Seoane et al. *arXiv*, arXiv:1702.00786, 2017.
14. J. P. Ostriker and N. Y. Gnedin. *Astrophys. J. Lett.*, 472:L63, 1996.
15. J. E. Greene, J. Strader, and L. C. Ho. *Annu. Rev. Astron. Astrophys.*, 58:257–312, 2020.
16. I. Mandel and A. Farmer. *Phys. Rep.*, 955:1–24, 2022.
17. S. Borhanian and B. S. Sathyaprakash. *arXiv*, arXiv:2202.11048, 2022.
18. D. Finstad, L. V. White, and D. A. Brown. *arXiv*, arXiv:2211.01396, 2022.
19. V. Srivastava et al. *Astrophys. J.*, 931(1):22, 2022.
20. A. Bauswein, H.-T. Janka, K. Hebeler, and A. Schwenk. *Phys. Rev.* D, 86(6):063001, 2012.
21. N. Yunes, K. Yagi, and F. Pretorius. *Phys. Rev.* D, 94(8):084002, 2016.
22. V. Cardoso and P. Pani. *Living Rev. Relativ.*, 22(1):4, 2019.
23. R. Brito et al. *Phys. Rev.* D, 96(6):064050, 2017.
24. J. Bramante, T. Linden, and Y.-D. Tsai. *Phys. Rev.* D, 97(5):055016, 2018.
25. H.-Y. Chen, P. S. Cowperthwaite, B. D. Metzger, and E. Berger. *Astrophys. J. Lett.*, 908(1):L4, 2021.
26. S. R. Taylor and J. R. Gair. *Phys. Rev.* D, 86(2):023502, 2012.