Invited Paper

Achieving a cosmological reach: from Advanced LIGO to the next generation of terrestrial gravitational wave detectors

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ABSTRACT

Following a decade of unprecedented success through LIGO and Virgo's observations of compact binary coalescences, gravitational wave astronomy is now recognized as a key tool in our continued efforts to understand the Universe and our place within it. Far from resting on their laurels though, the gravitational wave community is forging ahead with major plans for the future. The proposed "ultimate terrestrial gravitational wave detector facility" *Cosmic Explorer* recently received a boost with significant funding from the NSF to proceed with a conceptual design. This paper surveys the current state-of-the-art ground-based gravitational wave detector facilities, and their planned near-term upgrades. After motivating the next-generation Cosmic Explorer concept with a discussion of the key science targets, this paper describes some of the unique technical challenges it faces, including a focus on the ongoing optical design of Cosmic Explorer's 40 km-scale laser interferometers.

Keywords: Gravitational waves, laser interferometry

1. INTRODUCTION

The Advanced LIGO detectors have brought about an astrophysics revolution in the years since the first observing run O1 began. The first detection of gravitational waves from a binary black hole (BBH) system[1] was followed up by several more BBH detections in O1 and O2, before the breathtaking gravitational wave multi-messenger neutron star inspiral and coalescence event GW170817.[2] Groundbreaking discoveries have continued ever since in O3 and O4, including another likely neutron star inspiral event,[3] the most massive BBH system on record,[4] asymmetric BBHs[5,6] and host of other sources.[7,8] These observations provide far more than just a mere catalog of curiosities; they allow us to probe general relativity in the strong field regime,[9] make independent measurements of the Hubble parameter,[10] and understand formation of large-scale structure in the universe, to name just a few of the big-picture science products of gravitational wave observations.

These successes and science payoffs have been achieved in large part because of a constant drive within the gravitational wave physics research community for better instrument performance. This paper discusses the rationale behind continued improvements of existing gravitational wave detector facilities, including the near term plans for upgrades to the LIGO detectors. It introduces the science case for the US "next generation" gravitational wave detector facility concept Cosmic Explorer (CE), as a major leap forward from the current generation of detectors. With CE sufficiently motivated, the paper discusses some of the key challenges that lie ahead for the optical design of the 40km-scale CE interferometers, and how these challenges differ from the current 4km-scale LIGO detectors.

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2. CURRENT STATE-OF-THE-ART INTERFEROMETERS

The current international gravitational wave detector network consists of the two Advanced LIGO detectors[11] (one in Livingston, Louisiana, and one in Hanford, Washington), the Advanced Virgo detector[12] in Cascina, Italy, and the KAGRA detector[13] in Kamioka, Japan. All of these interferometers are configured as dual recycled Fabry-Perot Michelson interferometers, with km-scale Fabry-Perot arms formed by test-mass mirrors which are elaborately suspended to isolate them from ground motion.

The major limiting noise sources of these detectors are similar, and are shown for Advanced LIGO in the A+ (O5) configuration in the left panel of Fig. 1. Quantum noise (the combination of shot noise and quantum radiation pressure noise) limits across much of the detection band. At the frequencies of peak sensitivity, around 100 Hz, mirror coating Brownian thermal noise is also a significant limiting noise source. Towards lower frequencies, a combination of seismic noise, suspension thermal noise, longitudinal and angular controls noise, and direct gravitational coupling of local density fluctuations (Newtonian gravity noise) limits the sensitivity. Lurking below these noise sources is residual gas pressure noise, arising from random interactions between the laser beam and the few molecules present in the evacuated beam tubes. More details on the O3 sensitivity and noise budget of the Advanced LIGO detectors can be found in Ref.[15]

The LIGO and Virgo interferometers are above-ground and operate at room temperature, in contrast to KAGRA which is located underground in the Kamioka mine and operates with test-mass mirrors cooled to cryogenic temperatures. KAGRA's underground location has potential for better seismic and Newtonian noise performance, and its cryogenically cooled test masses are projected to experience reduced thermal noise.

As illustrated in Fig. 2, at the time of writing we are partway through observing run O4, during which the Advanced LIGO detectors have so far been the only interferometers producing science data. The detectors are operating in a new configuration, using frequency dependent squeezed light to enhance the quantum noise performance across the entire frequency band.[16] The inclusion of frequency dependent squeezed light required the installation of a 300 m so-called filter cavity, which provides a frequency dependent phase shift for the squeezed vacuum field such that the shot noise is reduced at high frequencies where it limits the sensitivity, while quantum radiation pressure noise is reduced at low frequencies where it would otherwise limit the sensitivity.

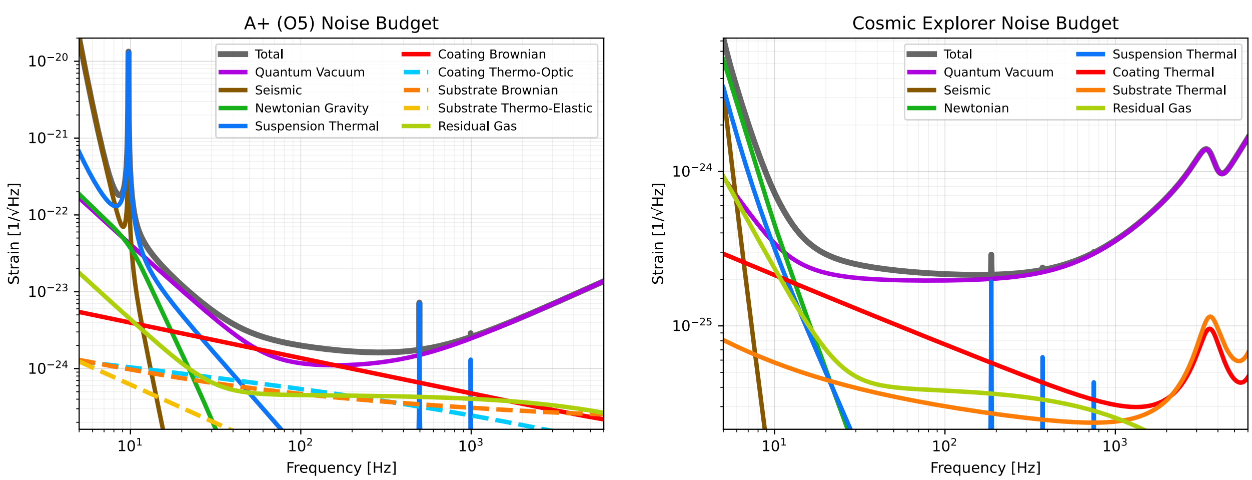

Figure 1. The projected strain sensitivities of the Advanced LIGO detectors in the A+ (O5) configuration, and of the initial Cosmic Explorer 40 km detector, including contributing noise sources across the detection band. These sensitivity curves were produced using GWINC.[25]

3. NEAR TERM UPGRADES TO LIGO DETECTORS

The latest upgrades to Advanced LIGO ahead of the O4 run, namely the addition of a low optical-loss readout chain and frequency dependent squeezing, comprise part of a broader upgrade known as A+.[17] The remaining elements will be installed and commissioned ahead of and during O5, as illustrated in the timeline shown in Fig. 2. These upgrades include the replacement of the test mass mirrors with those coated with advanced low-mechanical loss materials (lowering the coating Brownian thermal noise), and a change of the readout scheme to balanced homodyne detection.[18]

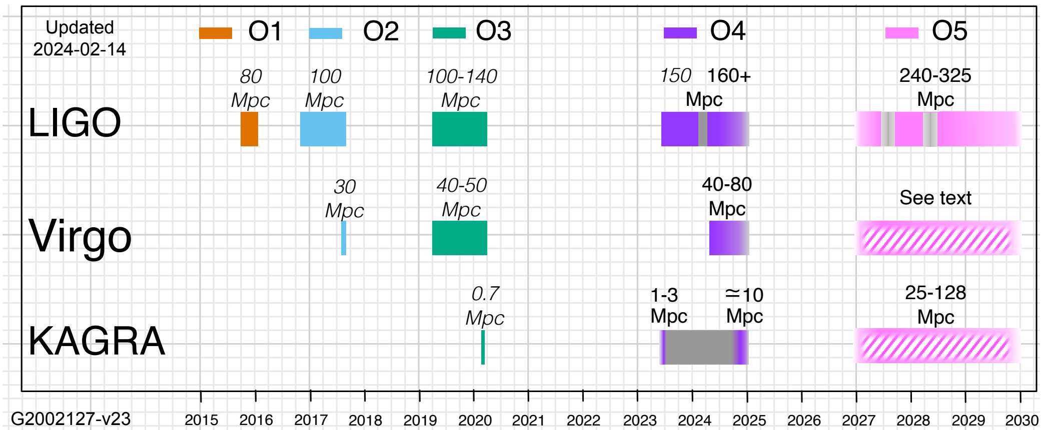

Figure 2. The proposed timeline for observing runs O4 and O5 with target binary neutron star inspiral ranges in megaparsecs, reproduced from Ref.[14]

A review of possible post-O5 upgrades to the LIGO observatories identified two leading concepts: A$^{\#}$ and Voyager, with A$^{\#}$ being recommended as the baseline due to its greater technical readiness.[19] The A$^{\#}$ concept relies on 1.5 MW of circulating light power (up from the 0.8 MW target in A+) and 10 dB of broadband effective squeezing to improve high-frequency sensitivity; reduced coating thermal noise to improve mid-frequency sensitivity; and upgraded suspensions and improved length and alignment controls to improve low-frequency sensitivity. As shown in Tab. 1, A$^{\#}$ is also planned to make use of larger and heavier test masses to improve the coating thermal noise, quantum radiation pressure noise, and suspension thermal noise performance.

Parameter	A+ (O5)	A$^{\#}$ (O6)	CE
Arm length (km)	4	4	40
Laser wavelength (nm)	1064	1064	1064
Mirror mass (kg)	40	100	320
Total suspension length (m)	1.6	1.6	4
Total suspension mass (kg)	120	400	1500
Mirror diameter (cm)	34	46	70
Arm power (MW)	0.8	1.5	1.5
Detected squeezing (dB)	6	10	10
Newtonian Rayleigh wave suppression (dB)	0	6	20

Table 1. Comparison of key interferometer parameters for near-term LIGO upgrades A+ and A$^{\#}$, as well as with the first envisaged 40 km CE interferometer.

The Voyager concept, relying instead on more novel technologies like cryogenic operation with crystalline silicon test masses, remains a contemporary topic of study.[20] Table 1 shows a comparison of some key detector parameters between the O5 configuration A+, and the proposed post-O5 upgrade A$^{\#}$, as well as the next-generation 40 km Cosmic Explorer detector concept.

As described in more detail in the post-O5 study report,[19] the baseline A$^{\#}$ sensitivity is limited at around 100 Hz almost equally by residual gas pressure noise, quantum noise, coating Brownian and substrate Brownian noise. While one can envisage possible improvements to tackle some of these noises, residual gas pressure noise represents a *facility limit*, in that there is no reasonable way to reduce this significantly in the existing LIGO facilities. To make significant improvements beyond $A^{\#}$ sensitivity, we must therefore consider an entirely new facility which can offer extended limits to future detector performance.

4. THE U.S. CONCEPT FOR A NEXT GENERATION GRAVITATIONAL WAVE DETECTOR: COSMIC EXPLORER

The detector concept that is now known as Cosmic Explorer (CE) was first described in the literature by Dwyer *et al* in Ref.,[21] and by name in Ref.[22] The basic idea presented was to achieve the bulk of a tenfold sensitivity enhancement through a tenfold increase in the length of the interferometer arms. In simple terms, gravitational waves produce a strain effect on spacetime, so a larger baseline gives a larger distance change between test masses for the same gravitational wave amplitude[*]. The instrument noise on the other hand remains unchanged, or even in some cases, such as mirror coating Brownian noise, is reduced. Thus, the detector sensitivity generally improves with the length of the facility. The cosmological reach of such a detector was strong enough motivation to explore the feasibility of the concept further, leading to the publication of a 2021 Horizon Study with NSF support.[23] The Horizon Study covered the science case for CE, as well as a reference concept for the detectors themselves, along with an analysis of alternative design options (number and scale of detectors), and a parametric cost estimate for the project.

Around the same time, the 2020 Decadal Survey on Astronomy and Astrophysics gave a resounding endorsement of CE, stating that such a next-generation gravitational-wave observatory in the United States is "central to achieving the science vision laid out in the survey's roadmap".[24] Buoyed by the enthusiasm from the scientific community, the next step towards realizing CE has begun: conceptual design of the observatories. A collection of proposals, coordinated under the CE project umbrella, were submitted to the NSF in 2022 to carry out this conceptual design phase, including site search and selection, an indigenous partnership program, and the interferometer and facility design. Many of these are now funded at this time, and the conceptual design is consequently proceeding at pace.

The science case laid out in the Horizon Study was broadly separated into three themes: Black holes and neutron stars throughout cosmic time; Dynamics of dense matter; and Extreme gravity and fundamental physics. Perhaps the clearest motivation for pursuing such a detector concept comes from the first theme: at CE's nominal sensitivity, it will be able to detect effectively *every* stellar mass binary black hole merger in the observable universe. This corresponds to a cosmological reach back to redshifts of 100 for $10\,M_{\odot}$ BBHs, potentially shedding light on the existence of population III black holes, and even primordial BBHs. CE will also observe the vast majority of neutron star inspiral systems, and allow precision measurements of the merger and ring-down phase, giving unique insight into the behavior of matter under extreme gravity and at extreme pressures. A full discussion of the groundbreaking science that can be done with CE is beyond the scope of this paper, but more details can be found in the CE Horizon Study and references therein.[23]

5. OPTICAL DESIGN CHALLENGES FOR COSMIC EXPLORER

One of the most appealing facets of the CE concept is that it does not rely on any new unproven technology to reach cosmologically significant sensitivity. It relies instead largely on an increase in scale to boost the gravitational wave signal and thereby make more and higher fidelity measurements. As such, CE is a relatively low risk concept for a future observatory. However, the scaling up in length does bring some unique challenges: one can not simply scale up the entire LIGO optical layout and expect to meet our sensitivity targets.

The first challenge encountered is that the free spectral range of the arm cavities for a 40km detector is 3.75 kHz – ten times smaller than for Advanced LIGO. For CE this frequency, at which gravitational waves from certain source locations cannot be detected, is close to the upper end of the scientifically interesting frequency band. Arm cavities are used to increase the stored light power in the interferometers, increasing the signal produced by interactions between the light and gravitational waves. However, this increased storage time also imposes a *bandwidth* limitation on the optical response of the detector to gravitational waves. The

[*]The caveat is that this simple picture is only really valid in the long-wavelength approximation for the gravitational wave with respect to the interferometer arms. For this reason, 40 km is actually optimal for the type of gravitational wave sources targeted by CE. For more detail, see Ref.[21] and Ref.[23]

resonant sideband extraction technique is used to mitigate this narrow banding effect via the additional of a partially reflective mirror at the output of the Michelson interferometer known as the signal extraction mirror.[26] Assuming the same arm cavity finesse[†] for CE as Advanced LIGO, the narrow banding effect of the arms occurs at frequencies as low as a few Hz. To recover a useful detector bandwidth, CE therefore requires a 10 times higher reflectivity signal extraction mirror than Advanced LIGO. This in itself does not pose a major challenge for the optical design of CE, but there are other consequences of the long arms and low free spectral range that do.

5.1 Short signal extraction cavity

As noted in Ref.[26] the addition of a signal extraction mirror at the interferometer output produces another optical resonance. In the case of CE this resonance can lie within the detection band, leading to a loss of sensitivity around the frequencies of interest for neutron star merger signals.[27] To retain sensitivity at these frequencies, the optical design must keep the total length of the signal extraction cavity, formed between the detector arm cavity input mirrors and the signal extraction mirror, below about 200 m. Advanced LIGO's signal extraction cavity length is 55 m, so it is clear that a 10 times scale up to CE will not be feasible, since a 550 m signal extraction cavity will drastically impact the detector sensitivity in the middle of the scientifically interesting band. Moreover, the 40 km arms beget a minimum diffraction limited laser beam spot size on the test mass mirrors that is around twice as large as the beams in Advanced LIGO. The challenge of reducing the beam size between the arms and the signal extraction mirror is therefore greater, assuming the same beam size at that mirror in CE as in Advanced LIGO, and with little room for extension of the signal extraction cavity length.

5.2 High circulating power and the degradation of quantum enhancement techniques

The 10 times lower free spectral range of the CE 40 km arm cavities with respect to those of Advanced LIGO presents additional challenges in terms of higher-order spatial mode resonances. With CE assuming a broadband 10dB suppression of quantum noise via the injection of frequency dependent squeezed vacuum states, higher-order mode resonances present a possible mechanism for misrotation of the squeezed state within narrow regions of the detection band. This leads to an unwanted enhancement of the quantum noise, potentially spoiling the detector sensitivity to gravitational waves at these frequencies.

This is currently an active topic of simulation studies, but the best understood solution is to keep coupling of the fundamental Gaussian mode to higher-order spatial modes as low as possible, by keeping the interferometer within narrow tolerances on misalignments, mode mismatches, and higher-order wavefront mismatches. The presence of interferometer imperfections can become power dependent, however in the case of high circulating light powers, due to absorption of the laser light and resulting thermal distortions in the substrates and surface figures of the test mass mirrors.[28] Thus the challenge is to satisfy the requirement for 1.5 MW circulating light power in the interferometer arms, without jeopardizing the benefits of squeezed light enhanced quantum noise performance. To this end, studies are ongoing into next-generation thermal compensation systems that can maintain a well-matched interferometer even at record high circulating power levels. Development of advanced wavefront actuators, along with complementary mode sensing and control (MSC) schemes is identified as a critical R&D pathway through $A^{\#}$ design and implementation, all the way through to CE. In general, the $A^{\#}$ interferometers in the LIGO 4 km facilities will allow tests of many of the concepts planned for CE, reducing risk and impacting the design in a timely way.

5.3 Corner layout selection

The opportunity to design an entirely new facility brings with it the chance to rethink the interferometer layout, considering topologies different to those of the current generation of interferometers. Moreover, some of the aforementioned additional constraints for a 40 km-scale interferometer push the design in different directions. The CE optical design team has therefore been considering a range of exotic topologies at this early stage, with a view to down-selecting to a few of the most promising candidates for more detailed study. A range of these potential topologies are shown in Fig. 3, loosely grouped by some shared key characteristics.

[†]The ratio of frequency separation of successive resonances (free spectral range) to the width of resonances

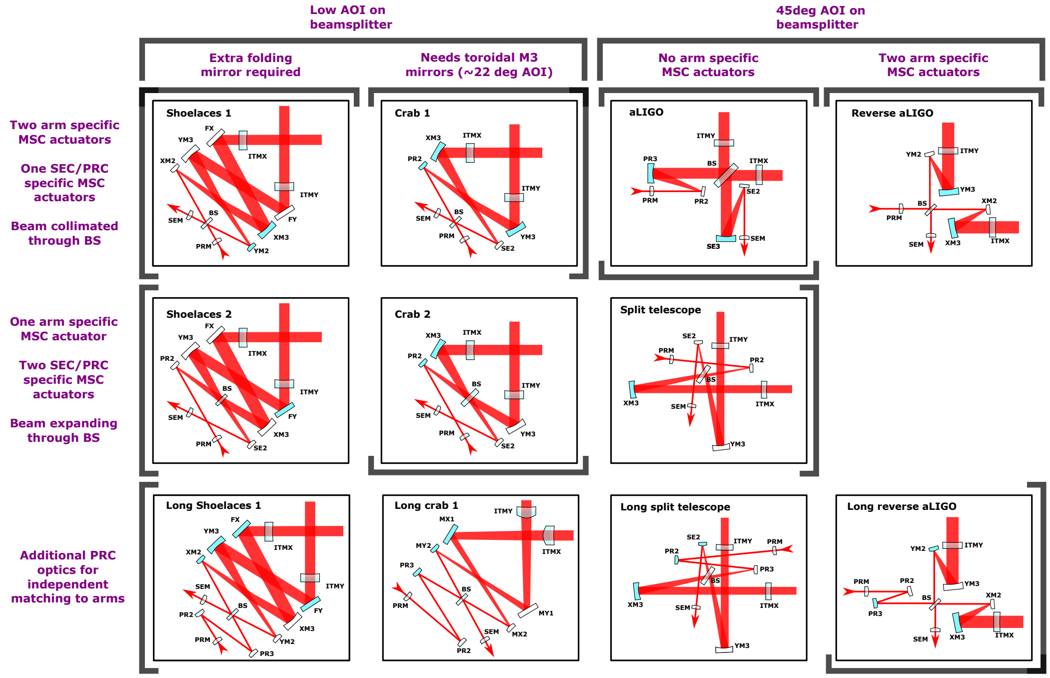

Figure 3. A range of considered optical layouts for the CE corner interferometer, grouped in terms of shared features including number and location of mode sensing and control (MSC) actuation points.

The minimum beam radius at the mirrors of a 40 km Fabry-Perot arm cavity illuminated with 1064 nm light is around 12 cm, requiring 70cm diameter cavity mirrors to maintain tolerable clipping losses. For the Advanced LIGO-like topology this would require a beamsplitter that is larger still, due to the projection of the beam onto the beamsplitter normal effectively stretching the intensity distribution in the interferometer plane. A 1 m-scale beamsplitter poses technical risks that motivated consideration of topologies which could allow smaller beam sizes at the beamsplitter location. All other topologies shown in Fig. 3 share the common feature of having a beam size at the beamsplitter that is significantly smaller than at the arm cavity mirrors.

The most striking departure from the layouts of the current generation of detectors is seen in the six topologies with low angle of incidence (AOI) on the beamsplitter. This was identified as a possible advantage over the conventional 45° angle of incidence designs currently employed because of the more symmetric optical paths through the beamsplitter substrate taken by the beams traveling between the power recycling mirror and the X-arm, and between the Y-arm and the signal extraction mirror. In the presence of absorption-induced thermal lensing in the beamsplitter, it is more feasible to achieve a successful compensation in the case of low angle of incidence.

The middle row of topologies and the ‘long split telescope’ design share the common feature of having a rapidly diverging beam through the beamsplitter. This has been shown to place unrealistically tight tolerances on the beamsplitter placement in order to maintain sufficiently good mode matching between the two interferometer arms, and so these topologies are disfavored. The lower row of topologies all include additional optics in the power recycling cavity. In these topologies, actuation of the curvature of the mirrors between the beamsplitter and the input test masses (ITMs) can be used to control the mode matching of the arms to each other, as well to as to the signal extraction cavity. Actuation of the additional power recycling cavity optics can then be used to match the power recycling cavity to the arm cavities. The preference is for additional optics in the power recycling cavity rather than the signal extraction cavity because the power recycling cavity does not have as strict overall length limitation as the signal extraction cavity, and higher optical losses incurred by the additional intra-cavity reflections have a much smaller impact on the detector sensitivity when they occur in the power recycling cavity.

These are just some of the considerations that go into making a decision about which topologies to pursue at the next stages of optical conceptual design for the CE interferometers. These next stages include the choice of modulation frequencies for length, alignment and wavefront sensing and control, the design of a laser frequency stabilization and lock acquisition scheme, and design of the frequency dependent squeezed light injection path. The optical design also must interface with the vacuum system design and layout, and be as flexible as possible to allow for future upgrades to the initial interferometers after the first CE observing runs. Correspondingly, the CE facility will be planned to accommodate a range of topologies, both to retain flexibility in the initial detector design, and to provide future upgrade paths for detectors installed in the CE observatory. All of these design tasks rely on a plethora of simulation studies and optimization procedures, which are currently being developed by CE optical design team members across the globe.

6. OUTLOOK

The LIGO and Virgo detectors have opened a new window to the universe through the observation of gravitational waves from compact binary systems. A tenfold increase in detector scale, as proposed for the Cosmic Explorer interferometers, increases the science reach of gravitational wave detectors to encompass the entire observable universe for stellar mass binary systems. This increase in scale brings with it interesting challenges for the optical design of these interferometers, which are now being addressed through the conceptual design process. Developing Cosmic Explorer from a concept to real detectors operating at design sensitivity promises to be an exciting endeavor, as we push the envelope of what can be achieved in precision metrology through quantum-enhanced laser interferometry for decades to come.

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