Supplementary Material for the NSF MPSAC ngGW Subcommittee

COSMIC EXPLORER

Requested Supplementary Material

I am writing on behalf of the NSF MPSAC ngGW Subcommittee. Thank you and your team for submitting your white paper on the Cosmic Explorer detector concept.

I am following up with a request for some additional information. Our Subcommittee would greatly appreciate having further input from you as we work through our charge.

First, a few questions:
(1) In the set of networks you are using LLO (A# configuration) in some configurations. Can you please let us know why you made this choice instead of LHO?

(2) Although there has been progress with better coatings, it is not clear there will be better coatings that will let A+ achieve its design sensitivity. What would your path forward be if the coatings quality did not work out as hoped/anticipated? Similar question, if laser power could not be raised to levels significantly higher than those currently used in aLIGO?

(3) What are your thoughts on the impact of climate change on your design or the site selection? Although we realize that quantitative answers on these or associate cost implications are difficult, we invite your input on this important matter.

We note that the Subcommittee has thoughts and potential answers to these questions, but we welcome your input as we consider them.

Second, we request that you provide us quantitative data for 5 more potential ngGW detector networks. We would appreciate having the data in the form of polar histograms as in your Figure 4. The additional network configurations of interest are:
4020L# , 40L#H# , 40L+H+ , 20L+H+ , 20L+A+
Above "L" corresponds to LLO, "H" to LHO, "A" to LAO, "+" to A+ sensitivity, "#" to A# sensitivity. We hope that producing new network configurations is not a prohibitive burden to your team, but please let me know if it is.

Could you let me know when you may be able to provide us with the histograms and the (short, a few sentences) answers to the questions? You may decide to send this additional information asynchronously.

Cosmic Explorer: Supplementary Material for the NSF MPSAC ngGW Subcommittee
Technical Report CE–P23000xx–vN
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Contents

The Cosmic Explorer (CE) team is grateful to the Next-Generation Gravitational-Wave Observatory (ngGW) subcommittee for the opportunity to answer questions about the CE white paper. In §1 we discuss the first 3 questions posed by the subcommittee. The work to produce data for additional network configurations is ongoing, and the results will appear as Section 2 in a subsequent version of this note. In the meantime, we refer the subcommittee to the technical report detailing the results presented in our white paper with all the relevant tables and figures [1].

The CE team welcomes any request for clarification or iteration on this response, as well as any additional questions the subcommittee would like us to consider.

1. Response to Questions 1–3

1.1. Question 1: Configuration Choice

In the set of networks you are using LLO ($A^\sharp$ configuration) in some configurations. Can you please let us know why you made this choice instead of LHO?

In picking configurations to study, we assumed that the number of CE+LIGO facilities operating in the US would always be two. Essentially, shutting down both LIGO sites seems disadvantageous if we have only one CE, and we (tacitly) assumed that operations costs for three observatories would be prohibitive. The result is that CE observatories essentially **replace** LIGO observatories in the network configurations we studied.

To make comparisons as meaningful as possible, we decided to use fiducial locations for CE observatories that are near the LIGO observatories they replace (i.e., CE-A near LHO and CE-B near LLO). In all configurations with one CE, we removed LHO and used the CE-A location (just off the west coast). This choice was arbitrary; we could have removed LLO and used the CE-B location (in the Gulf of Mexico). However, earlier studies indicate that this choice is not important to the result, but rather that the number of next-generation observatories and the area of the network (always a triangle for the configurations we presented) are the important factors [2, 3]. Thus, in order to minimize the number of configurations presented (to avoid confusion), we did not present networks with one CE and LHO.

1.2. Question 2: Technical Risks and Mitigation Strategies

This two part question addresses technical risks and mitigation strategies for CE. In the following sections we discuss the two technical areas (coating thermal noise and circulating power) separately, and in terms of the impact the realization of these risks might have on CE in its initial instantiation. For both coating thermal noise and laser power, however, we want to stress that we expect upgrades to the detectors will occur in the anticipated 50-year lifetime of the CE observatories, as they have in all gravitational-wave observatories to date. We think it likely that there will be progress on these technical fronts in the coming years, and certainly in the coming decades, in part due to the large overlap with the envisioned LIGO $A^\sharp$ upgrade, and in part due to the significant R&D efforts going on in Europe to support the Einstein Telescope.

In addition to more incremental options, a potential long-term mitigation strategy would be to adopt elements of the Voyager and ET-LF concept in a cryogenic interferometer. While we do not believe that this technology will be at a sufficient technical readiness level for implementation in the initial CE detectors, we plan to pursue CE observatory infrastructure compatible with 2 μm light, providing the ability to 'fall back' to cryogenics to help manage coating thermal noise (CTN) and power-related limitations – or for later upgrades that give even greater reach. We note, however, that ensuring 2 μm compatibility may have an impact on the beamtube size and thus will be subject to value engineering.

1.2.1. Coating Quality

Although there has been progress with better coatings, it is not clear there will be better coatings that will let A+ achieve its design sensitivity. What would your path forward be if the coatings quality did not work out as hoped/anticipated? ...

The impact of coating technology on CE sensitivity is shown in Fig. 1, and the resulting change in horizon for CE is shown in Fig. 3. From these figures it is clear that even with current technology CE will have access to a wide range of science targets. Indeed, one of the key advantages of the long-arm-cavity design approach behind Cosmic Explorer is that CTN scales as $L^{-3/2}$ for constant arm cavity geometry (i.e., constant g-factor) [4, 5]. For the same reason, the CE 20 km configuration is more vulnerable to CTN than the 40 km configuration.

A clear mitigation strategy for CTN in case better coatings are not available is to change the arm cavity g-factors to make larger beam spots and thus lower CTN (which scales inversely to the beam size). For the 40 km configuration, which has $w = 12$ cm spots in the nominal configuration, as much as a factor of two increase in beam size (and thus a factor of two reduction in CTN) seems achievable. This would require larger optics (120 cm diameter) and larger beamtubes (150 cm diameter), both of which could significantly increase cost. Larger spot sizes would also result in a less stable optical configuration (arm cavity g^2-factor ~ 0.94, for comparison aLIGO has g^2-factor ~ 0.84), potentially resulting in alignment and thermal control challenges.

The 20 km CE configuration could also achieve a factor of two reduction in CTN relative to the

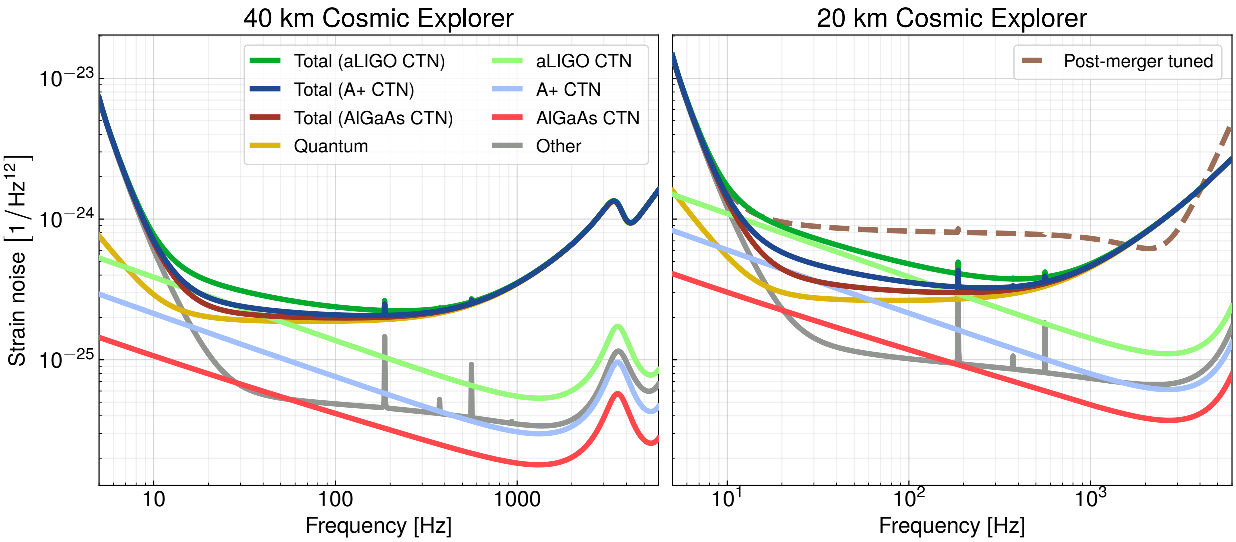

Figure 1: Cosmic Explorer sensitivity with different coatings. Curves are shown for “aLIGO CTN” (i.e., coatings currently in operation), the expected A+ thermal noise (which is also the nominal value for CE), and for the AlGaAs coatings targeted for A$^\sharp$. The “Post-merger tuned curve” is the baseline 20 km interferometer tuned for post-merger physics which is not sensitive to the coating thermal noise. However, mitigating CTN for the broadband tuning with larger beam sizes could compromise the performance of the post-merger tuning (see §1.2.1)

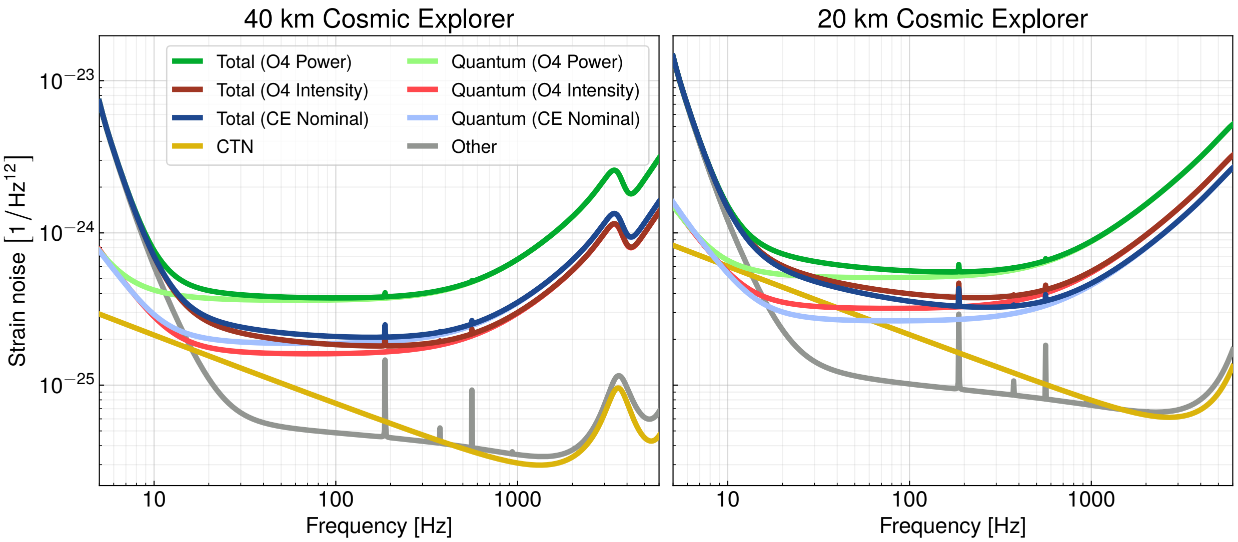

Figure 2: Cosmic Explorer sensitivity with different arm powers. The arm power for LIGO in O4 is approximately 400 kW. Since CE has larger beams than LIGO, the arm power for the same intensity on the mirrors is $400\,\mathrm{kW} \times (12\,\mathrm{cm}/5.3\,\mathrm{cm})^2 = 2\,\mathrm{MW}$, which is higher than the nominal CE design of 1.5 MW (see §1.2.2).

nominal by increased beam sizes, with similar technical and cost implications. However, in order to achieve its post-merger science goals the 20 km CE needs to be tunable to high-frequency signals, as shown in Fig. 1, which requires a comparatively short signal extraction cavity. Increasing the 20 km interferometer beam sizes would make the output telescope requirements more challenging, and potentially incompatible with the stringent optical loss requirements. The result could be a 20 km instrument that would gain little from a post-merger tuning, and would have a sensitivity in the kilo-hertz band comparable to that of the nominal 40 km CE (as seen in the broadband tuning noise curves shown in Fig. 1).

1.2.2. Laser Power

... Similar question, if laser power could not be raised to levels significantly higher than those currently used in aLIGO?

With regard to the power level assumed for our CE models (1.5 MW in the arms, as for A$^\sharp$), we computed sensitivity curves for CE which use the current power level in Advanced LIGO (~400 kW), and the current **intensity** on the test masses (Fig. 2). We show both current-power and current-intensity cases because, roughly speaking, for issues caused by uniform optical absorption the power is relevant, while for issues caused by point absorbers, the intensity is relevant [6]. Note that while for CE we assume higher power than currently used, CE has larger beams on the test masses (by ~5× in area for CE 40 km), so the intensity of the nominal CE 40 km is actually comparable to or lower than current detectors. Moreover, point-absorber free optics have been delivered to LIGO, after a significant improvement in the coating production techniques developed by the vendor in collaboration with LIGO.

Mitigation strategies for reduced power are limited. Some amount of re-optimization may be available in terms of the interferometer optical parameters (e.g., signal extraction cavity bandwidth),

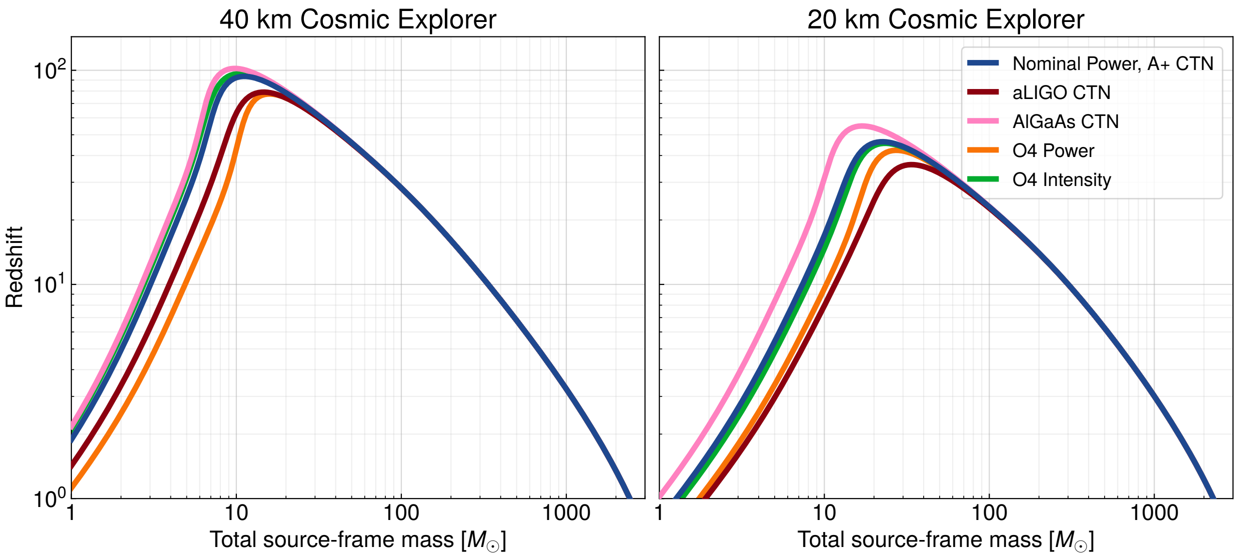

Figure 3: Horizon redshifts at which the SNR of a detector is 8 for optimally oriented, non-spinning, equal mass binaries for the scenarios shown in Figs. 1 and 2. Potential technical limitations are discussed in §§ 1.2.1 and 1.2.2 and their astrophysical implications are discussed in §1.2.3.

but the most direct route is to enhance the detection efficiency and thus enable higher levels of squeezing. At present, going beyond the 10 dB squeezing target is considered more challenging than operating at 1.5 MW, but we will explore in this direction as warranted by progress in existing interferometers.

1.2.3. Astrophysical Implications

A complete and quantitative discussion of the potential impact of CTN and laser power challenges would require running full network analyses of these technical variants of CE. However, even without that some qualitative evaluation of the impact on CE science is available.

As shown in Fig. 3, CTN and laser power limitations mainly impact the horizon redshift of systems with a total source-frame mass below ~20 $M_\odot$. That is an astrophysically interesting region of the black hole mass function as it corresponds to black holes near the peak of the mass function measured by existing detectors in the local universe. Furthermore, current data indicates a dearth of compact objects with masses between 2 $M_\odot$ and ~10$M_\odot$. Because it is expected that different astrophysical formation channels evolve in different ways as a function of metallicity (and thus redshift), precise measurment of the low-mass end of the black hole mass function plays a role in CE science. The impact on the horizon redshift for the 40 km CE configuration is relatively minor (e.g., the horizon remains beyond $z \sim 10$ for total source-frame masses above ~ 5 $M_\odot$, left panel of Fig. 3), while the 20 km configuration (right panel in Fig. 3) exhibits greater vulnerability to high CTN levels and laser power limitations.

In addition to high-redshift science, some CE science targets depend on access to the large number of sources expected to be present at the peak of star formation (i.e., $z \sim 2$). Since the horizon redshift of the 40 km configuration remains beyond $z \sim 4$ even for a 1.4 – 1.4 $M_\odot$ binary neutron star (BNS), the primary impact of CTN and power limitations will be on the signal-to-noise ratio (SNR) of the detected signals. Laser power limitations in particular would impact the SNR of tidal and post-merger signals from BNS systems (as can be seen in the "O4 Power" sensitivity curve in Fig. 2, left panel). Here again, the 20 km configuration would suffer somewhat more from technical limitations, with the horizon for BNS systems only approaching the peak of star formation. As noted earlier, the post-merger configuration of the 20 km CE could be compromised by CTN mitigation strategies, and laser power limitations could have a similar impact (i.e., SNR reduced by as much as a factor of two relative to the nominal 20 km CE parameters).

1.3. Question 3: Climate Change

What are your thoughts on the impact of climate change on your design or the site selection? Although we realize that quantitative answers on these or associate cost implications are difficult, we invite your input on this important matter.

We recognize the importance of both accounting for the impact of climate change in our design process and considering CE's impact on the environment. As such, climate change is a focus of the recently funded NSF proposal "Collaborative Research: Identifying and Evaluating Sites for Cosmic Explorer[1]." Climates in the United States are diverse and each location has a unique forecast over the projected lifetime of CE. Our site identification process includes a location specific evaluation of these factors and takes into account for both location feasibility and facility design.

Our procedure for site identification considers the long-term suitability of potential observatory locations. This includes a thorough investigation of potential developments around the location that could alter the environment. Such developments include proposed future activities (e.g., mining or industrial expansion), urban encroachment, and the impact of climate change. The risk associated with catastrophic natural disasters (e.g., floods, fires, earthquakes), which may become more likely as the climate changes, will also be estimated from publicly available data. Climate resilience will be a key design feature for CE, starting with location specific assessment and continuing through the broader project design for each location.

The site identification project will also produce information about the related question of CE's impact on climate change. We will assess CE's carbon footprint for the full lifecycle of these facilities and pursue pathways to minimize and offset it. We are open to and will consider options that allow CE to share space with an energy producer, such as a solar farm. As with many aspects of CE, the ongoing example of LIGO's experience with practices such as adopting renewable power sources and seeking means to reduce power use in operations will provide guidance in the design of future CE observatories.

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[1] NSF Awards 2308985, 2308986, 2308987, 2308988, 2308989, 2308990

Acronyms

BNS binary neutron star 7, 8

CE Cosmic Explorer 4–8

CTN coating thermal noise 4, 5, 7, 8

ngGW Next-Generation Gravitational-Wave Observatory 4

SNR signal-to-noise ratio 7, 8

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Cover art. *Rendering of a Cosmic Explorer observatory:* Edward Anaya, Virginia Kitchen, Angela Nguyen, and Joshua R. Smith (CSU Fullerton). *Rendering of gravitational-wave emission from a black hole binary:* scientific contact by Ed Seidel; simulations by Max Planck Institute for Gravitational Physics (Albert-Einstein-AEI); visualization by Werner Benger, Zuse Institute, Berlin (ZIB) and AEI; the computations were performed on NCSA's Itanium Linux Cluster.

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