GRAVITATIONAL-WAVE LUNAR OBSERVATORY FOR FUNDAMENTAL PHYSICS

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Observations from the world's first successful gravitational-wave (GW) experiment - LIGO - has shown the far reaching impact this new window of the universe has on fundamental physics, astronomy and cosmology[1]. Several large-scale experimental facilities and space-missions are being suggested to probe the universe across the GW spectrum. Prominent proposals within 2030s include *Einstein Telescope* [2], an European initiative for 10 km underground interferometers and the ESA-led space mission *Laser Interferometer Space Antenna* (LISA)[3].

One of the most challenging frequency range to measure GWs is from deci-Hz to 1 Hz. This range tends to be too low for all the proposed Earth-based GW detectors and too high for the space missions. The universe offers a rich set of astrophysical sources in this regime[4], whose observations will be critical for testing General Relativity and probing physics beyond the Standard Model[5].

Here, we show that a lunar-based GW detector would be ideal to probe the deci-Hz regime. We suggest the acronym **GLOC**[6] - *Gravitational-wave Lunar Observatory for Cosmology*, as the detector could survey an unprecedented 80% of the entire observable volume of our universe. With the advent of NASA's Artemis III Program, such a sustainable base on the Moon for fundamental physics can be envisioned in the timeline of other large-scale experiments proposed in the field.

Why Moon?

The Moon offers a natural environment for constructing a large-scale interferometer as a GW detector. The atmospheric pressure on the surface of the Moon is comparable to the currently implemented 8 km ultra high vacuum (10^{-10} torr) at each of the LIGO facilities[7]. The seismometers left from the Apollo missions suggests that at low-frequencies (<0.5 Hz), the seismic noise on the Moon is expected to be two orders of magnitude lower than on Earth[8]. Seismic noise is a fundamental limitation for the low-frequency sensitivity of GW detectors on Earth (for example, LIGO, has seismic wall at around 10 Hz). The deci-Hz frequencies are too high to pursue with space missions like LISA, as they are fundamentally limited by the laser shot noise.

The presence of vacuum just above Moon's solid terrain provides a great benefit in extending the LIGO interferometer length at minimal cost. The extended arm-length allows measurement of lower GW frequencies (higher wavelength). Unlike a similar setup on Earth, a lunar-based detector is only weakly affected by environmental factors such as winds or lightening. This would ensure continuous operation of

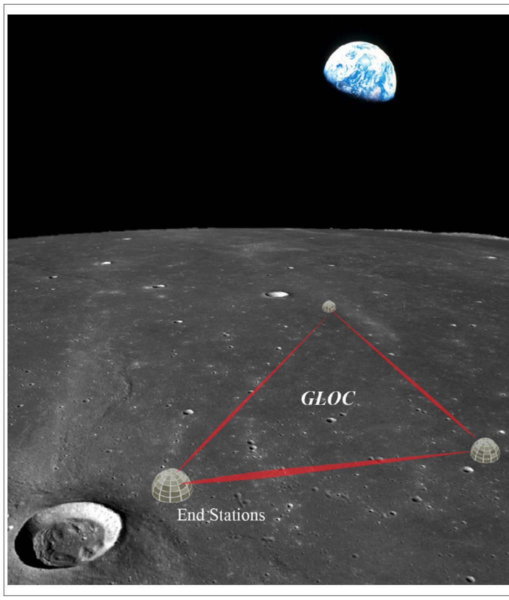

Figure 1: Concept design of GLOC. Three end stations on the surface forming a triangular GW detector. Image of Moon's surface adapted from Lunar Reconnaissance Orbiter (NASA/GSFC/ASU) and Earthrise from the Apollo archives.

the lunar-detector. The Moon-quakes occur at much lower frequencies[9] and thus should not impact the GW sensitivity at the deci-Hz range.

An additional advantage is that the Moon is not corrupted by any unpredictable noise from human activities. In case of a lock-loss in the interferometer, a lunar-based detector can be brought back online from a control center on Earth. In the event of a serious hardware failure, parts of the detector can be replaced and repaired by astronauts. The benefit of performing on-request maintenance is not available for space-based GW detectors, making the Moon a better long-term investment. In addition, future space-missions like LISA are limited in their lifetime (typically a few years), after which the gravitational perturbation from solar system objects will disrupt their geometry. In contrast, a lunar-based detector can operate and be steadily improved for decades.

Concept Design

We adopt a triangular geometry for GLOC, instead of the L-shaped design of LIGO (see Fig 1). The final experimental setup would essentially consist of three end station that will house the optics, primarily the laser, a mirror and a suspension system. The end stations can be designed as dorm shaped compartments that are temperature controlled and isolated from the rest of the detector. Each end station can be separated by few tens of km, essentially dictated by the site-selection. An ideal location would be a large lunar crater, providing a flat land for at least two end stations and a higher elevation to place the third station.

A prototype of GLOC can be achieved through the first set of Artemis missions. This will constitute monitoring a set of physical and environmental sensors. Similar to the LISA Pathfinder[10] and the 40 meter LIGO[11], this prototype will be critical in providing a fundamental noise budget of the GW detector on the lunar-surface.

Probing the Earliest Universe

As shown with Fig. 2, the lunar-based detector would have a rare advantage of accessing GWs across five orders of magnitude in mass - from sub-solar dark matter candidates to stellar mass binaries to intermediate-mass black holes. Across this mass-range, GLOC's sensitivity would probe 30-80% (redshifts z~10-100) of the entire observable volume of the universe. This provides an unprecedented cosmological probe that extends beyond the reach of any electromagnetic telescope other than the cosmic microwave background (CMB) experiments. While we do not expect stellar objects to exist beyond z~70, even one such detection will violate standard cosmology[12].

Searching for the Dark Matter

GLOC can put the tightest bounds on a putative population of sub-solar dark matter objects[13]. There are no known astrophysical phenomena that can create detectable GWs at such low-masses, however, primordial black holes or dark matter within neutron star cores offer possible scenarios. The deci-Hz reach of GLOC allows us to measure the dark matter density of such exotic objects to 30% of the entire observable volume of the universe.

Dark Energy Sirens

For binary black holes (BBHs), GLOC would start measuring its inspiral a day before the merger. A multi-band observation of these BBHs between GLOC and a LIGO-like detector on Earth can reduce the sky-location error to 1arcsec^2 (at z~3) namely the angular scale of a single galaxy. These are the tightest constraints on the source location in GW astronomy, allowing to identify the potential host galaxy without electromagnetic counterparts. This opens a new population of high redshift dark sirens to independently measure the evolution of the Hubble parameter as a function of redshift[14].

Explosion Mechanisms of Supernovae

One of the strongest science cases of GLOC is towards studying Type Ia supernovae (SNe) mechanisms. The access to low-frequency sensitivity enables a direct discrimination between the single and double degenerate scenarios of Type Ia SNe[15]. A joint observation of such an event with GWs and electromagnetic signals can be used to constrain the unknown masses and explosion mechanism of the white dwarfs. This can potentially reduce the error budget in using SNe as standard candles. Further, such multi-messenger observations could constrain cosmological parameters to sub-percent precision.

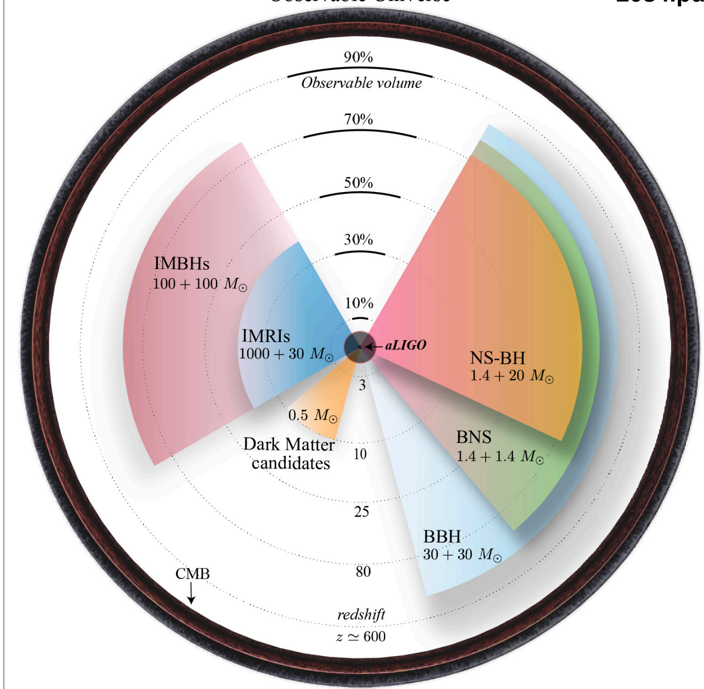

Figure 2: Cosmological reach of GLOC in comoving coordinates. The concentric circles represent the percentage fraction of the comoving volume of the observable universe out to a given cosmological redshift, with the outermost being the CMB. The highlighted slices refer to the horizon redshifts in GLOC. For reference, the circle in the center represents the maximum reach of LIGO at its design sensitivity for a 100 solar mass binary.

Multi-messenger Astrophysics

A binary neutron star (BNS) would be in the GLOC band for an entire orbital period of the Moon, while a nearby BNS would be in-band for almost three months. This allow GLOC to constrain BNS to 0.01arcmin^2. The sky-localization alert for BNSs can be sent days in advance, allowing readiness of high-latency electromagnetic followups with reach up to high redshifts. Furthermore, the overall signal-to-noise-ratio in GLOC is about an order of magnitude higher than Earth-based detectors, thus providing some of the strongest tests of general relativity.

References: [1] B. Abbott et al., Physical Review X 9 (2019) [2] M. Punturo et al., Proceedings, 14th Workshop on Gravitational wave data analysis (GWDAW-14): Rome, Italy, January 26-29, 2010, Class. Quant. Grav. 27, 194002 (2010). [3] P. Amaro-Seoane et al., arXiv e-prints , arXiv:1702.00786 (2017) [4] I. Mandel, A. Sesana, and A. Vecchio, Classical and Quantum Gravity 35, 054004 (2018). [5] M. A. Sedda, C. P. L. Berry, K. Jani, et al (2019), arXiv:1908.11375 [6] K. Jani and A. Loeb, (2020) arXiv:2007.08550 [7] LIGO Scientific Collaboration, Classical and Quantum Gravity 32, 074001 (2015) [8] P. Lognonne, Journal of Geophysical Research, 114 (2009) [9] H. Hanada et al. in International Association of Geodesy Symposia (Springer Berlin Heidelberg, 2005) pp. 163– 168. [10] Danzmann, K., Nature Phys 11, 613–615 (2015). [11] Weinstein, A., Classical and Quantum Gravity, Volume 19, Issue 7, pp. 1575-1584 (2002). [12] S. M. Koushiappas and A. Loeb, Physical Review Letters 119 (2017) [13] S. Shandera, D. Jeong, and H. S. G. Gebhardt, Physical Review Letters 120 (2018) [14] B. F. Schutz, Nature (London) 323, 310 (1986). [15] D. Falta et al., .Physical Review Letters, 106:201103 (2011)