Snowmass2021 - Letter of Interest

A deci-Hz Gravitational-Wave Lunar Observatory for Cosmology

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
■ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
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Abstract: We are proposing Gravitational-wave Lunar Observatory for Cosmology (GLOC) [1] – a first of its kind fundamental physics experiment on the surface of the Moon. The experiment would access gravitational-waves (GWs) in the frequency range of deci-Hz to 5 Hz, a challenging regime for all Earth-based detectors and space missions. We find that such a lunar-based experiment can survey $\gtrsim 70\%$ of the observable volume of our universe without significant background contamination. This unprecedented sensitivity makes GLOC a powerful cosmic probe for Dark Energy, Dark Matter and physics beyond the Standard Model. In particular, it will independently trace the Hubble expansion rate up to redshift $z \sim 3$, provide the strongest limits on the sub-solar Dark Matter candidates and test ΛCDM cosmology up to $z \sim 100$. Furthermore, it will have a unique access to GWs from Type Ia supernovae, thus aiding calibration of the standard candles.

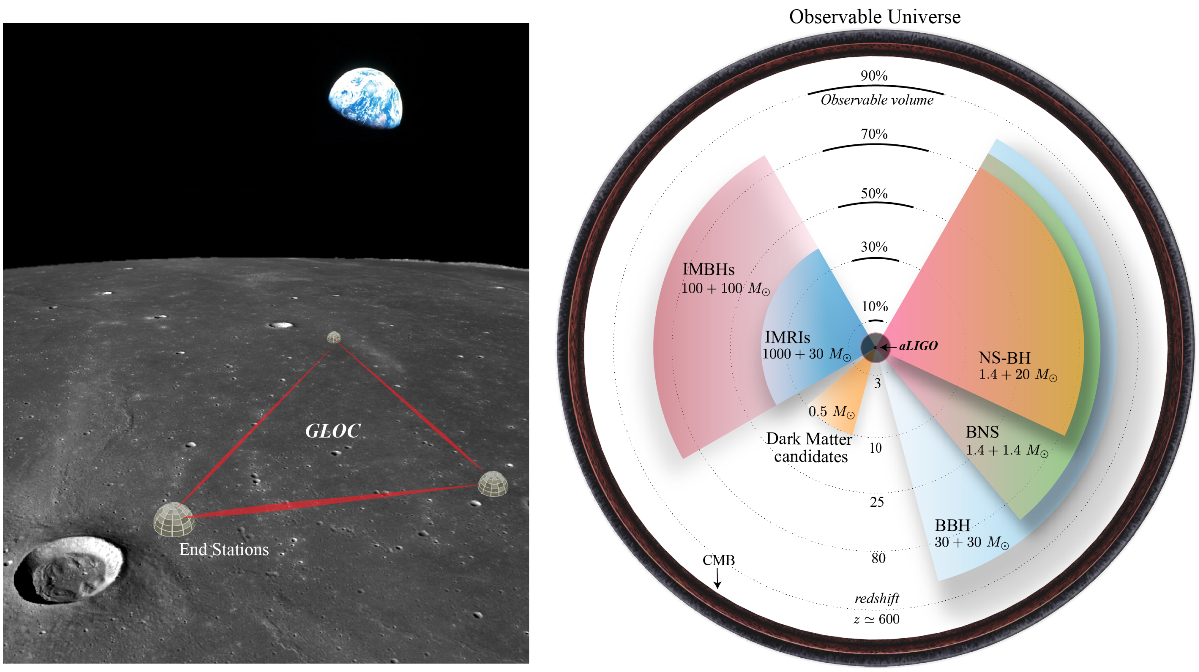

Figure 1: **Concept design and cosmological reach of GLOC.** Left: Three end stations on the surface of the Moon forming the full triangular-shape GLOC detector. Right: Cosmological reach of GLOC in comoving coordinates. The concentric circles represent the percentage fraction of the comoving volume of the observable universe ($V_{\rm obs} = 1.22 \times 10^4\ {\rm Gpc}^3$) out to a given cosmological redshift, with the outermost being the CMB [2]. The highlighted slices refer to the horizon redshifts in GLOC. For reference, the circle in the center represents the maximum reach of aLIGO at its design sensitivity for a 100 solar mass binary [3].

Motivation. One of the most challenging frequency range to measure gravitational waves (GWs) is from deci-Hz to 1 Hz. This range tends to be too low for all the proposed Earth-based gravitational-wave detectors (like Einstein Telescope [4] and Cosmic Explorer [5]) and too high for the space mission LISA [6], although DECIGO [7] and other concepts [8, 9] are currently being studied to detect deci-Hz GWs. The universe offers a rich set of astrophysical sources in this regime [10], whose observations will open unique tests of general relativity and physics beyond the Standard Model [9]. Here, we are proposing a lunar-based detector whose primary goal is to access this deci-Hz GW regime [1]. With the advent of NASA's Artemis and Commercial Crew programs, the time is ripe to consider fundamental physics experiments on the 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 during sunrise is comparable to the currently implemented 8 km ultra high vacuum (10^{-10} torr) at each of the LIGO facilities [11, 12]. The seismometers left from the Apollo missions suggests that at low-frequencies ($0.1{\sim}5$ Hz), the seismic noise on the Moon is three orders of magnitude lower than on Earth [13]. Seismic noise is a fundamental limitation for the low-frequency sensitivity of GW detectors on Earth (for example, aLIGO, has seismic wall at $\lesssim 10$ Hz). The presence of vacuum just above Moon's solid terrain provides a great benefit in extending the LIGO interferometer length at minimal cost. Unlike a similar setup on Earth, a lunar-based detector is only weakly affected by environmental factors or human activities. 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 the next page, we list the top science targets of a lunar-based detector:

(1) Unprecedented Cosmological Probe. As shown with Fig. 1, the detector would have a rare advantage of accessing GWs across five orders of magnitude in mass - from sub-solar dark matter candidates ($\sim 10^{-1}\ M_{\odot}$) [14] to stellar mass binaries ($\sim 10^{1-2}\ M_{\odot}$) to intermediate-mass black holes (IMBHs, $\sim 10^{3-4}\ M_{\odot}$) [15]. Across this mass-range, GLOC's sensitivity would probe $30 - 80\%$ (redshifts $z\sim 10 - 100$) 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 $z\sim 70$ [16], even one such detection will violate ΛCDM cosmology [17].

(2) Type Ia Supernovae Progenitors. One of the strongest science cases of GLOC is towards studying Type Ia supernovae (SNe) mechanisms. The access to low-frequency sensitivity ($0.1\sim 1$ Hz) enables a direct discrimination between the single [18, 19] and double degenerate (mergers of two white dwarfs) scenarios of Type Ia SNe. 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.

(3) Dark Matter Search. GLOC can put the tightest bounds on a putative population of sub-solar dark matter objects ($0.1 - 1\, M_{\odot}$) [14]. 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 [20]. 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 ($z \sim 10$).

(4) Multi-Messenger Probe for Neutron Star Equation of State. A binary neutron star (BNS) at $z \sim 2$ would be in the GLOC band for an entire orbital period of the Moon, while a nearby BNS (like GW170817 [21]) would be in-band for almost three months. This allow GLOC to constrain BNS to $\lesssim 10^{-2}\ \mathrm{arcmin}^2$. 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 SNR in GLOC is about an order of magnitude higher than Earth-based detectors, thus providing some of the strongest tests of general relativity.

(5) Multi-Band Dark Energy Sirens. For a relatively light binary black hole (BBH) like GW151226 [22], GLOC would start measuring its inspiral a day before the merger. A multi-band observation [23] of these BBHs between GLOC and a LIGO-like detector on Earth can reduce the sky-location error to $1\ \mathrm{arcsec}^2$, 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 [24]. Furthermore, combining these high redshift dark sirens with GW lensing would constraint cosmological parameters to increased precision [25].

(6) First Stars and Pair-instability Supernova. The enhanced low-frequency sensitivity permits GLOC to survey mergers of black holes in the so-called "pair-instability" mass-gap ($60 \sim 120\ M_{\odot}$) [26] and IMBHs practically across the entire universe. Such cosmological reach is crucial for connecting IMBHs with the Pop-III remnants [27] and the seeds of super-massive black holes [28, 29].

(7) Internal Structure of Gamma Ray Bursts' Jets. A gravitational-wave detector sensitive slightly below 1 Hz would be able to probe the acceleration process and the internal angular profile of the ultra-relativistic jets powered by the central engines of GRBs [30,31]. Such observations can remove degeneracies between different jet models, and thus constrain estimation of both multi-messenger astronomical events and of cosmological standard candles [32].

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