https://doi.org/10.1038/s44453-025-00021-w

The moon as a gateway to discovery: how lunar gravitational-wave detection advances science across disciplines

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Lunar gravitational-wave detection aims at bridging the critical 0.1–1 Hz frequency gap, enabling the study of astrophysical and cosmological signals inaccessible to current detectors. By combining the advances in seismology, optics, and metrology, it will transform the Moon into a multidisciplinary laboratory, simultaneously advancing our understanding of the Universe and the science of the Moon itself.

The detection of gravitational waves (GWs) in 2015 by the Laser Interferometer Gravitational-wave Observatory (LIGO) has transformed astrophysics, opening an entirely new observational window into the Universe. Since then, the LIGO collaboration, together with Virgo and KAGRA, has detected numerous signals from black hole and neutron star mergers, providing new insights into compact-object populations and the behavior of gravity under extreme conditions. Meanwhile, the international Pulsar Timing Array (PTA) community has recently reported compelling evidence for a signal in the nano-Hertz band, likely originating from a cosmic population of supermassive black hole binaries or early Universe quantum fluctuations. This offers a first glimpse of GWs on intergalactic scales and opens a new window into galaxy evolution and early Universe dynamics.

However, LIGO/Virgo/KAGRA are subject to strong seismic noises and hence limited to the $10–10^3$ Hz frequency range, which is ideal for stellar-mass binaries, but insensitive to the GWs below ~10 Hz. PTAs, on the other hand, are sensitive to nano-Hertz GWs, suitable for detecting the most massive black holes, but lacking sensitivity above 10^{-6} Hz because the timing residual is much smaller. Next-generation observatories aim to extend this reach. The Einstein Telescope (ET) in Europe and Cosmic Explorer (CE) in the United States will improve strain sensitivity by an order of magnitude and extend the low-frequency limit of ground-based interferometers to roughly 1 Hz, but the sensitivity at even lower frequencies will still be limited by seismic noise. In space, the Laser Interferometer Space Antenna (LISA) mission, scheduled for launch around 2035, will operate in the milli-Hertz (mHz) band, and the sensitivity decays significantly above 0.1 Hz due to photon short noise.

Therefore, a critical frequency gap between 0.1 Hz and 1 Hz remains beyond the reach of both terrestrial and space-based missions. Many intriguing sources—including the seeds of supermassive black holes, the precursors to LIGO/Virgo/KAGRA events, supernovae, and quantum fluctuations in the early Universe—emit GWs in this band. Detecting them may help us answer questions such as why do black holes form, how does matter tangle with spacetime, or how did our universe come into being. Bridging this “mid-frequency desert” requires new strategies and environments free from previous limitations. The Moon, being seismically quiet, atmosphere-free, thermally stable, and relatively close to Earth, offers precisely such a platform Fig. 1.

Lunar seismology

The idea of using the Moon itself as a GW detector dates back to the Apollo era. In the late 1960s, Joseph Weber proposed that celestial bodies could act as resonant detectors, vibrating globally in response to passing GWs. The underlying theory is the same as an elastic body driven into oscillation by an external force. In the case of the Moon, the external force comes from the tidal field induced by GW, and the oscillation results in a detectable global seismic signal at the entire surface of the Moon. Interestingly, if the frequency of the time-varying tidal field matches any of the fundamental oscillation modes of the Moon, called the “normal modes”, the Moon will vibrate even more violently. This is a resonance that can greatly amplify the outputs of lunar seismometers.

During the Apollo 12–17 missions, seismometers deployed on the Moon recorded moonquakes, allowing scientists such as Dyson, Press, Chitre, Duennebier, and Latham to analyze whether global oscillations could reveal GW signatures. Although no detections were made, these studies established the theoretical understanding of the Moon’s response to GWs in the mid-frequency band[1].

Modern proposals have revived and expanded upon this concept. A leading example is the European-led Lunar Gravitational-Wave Antenna (LGWA[2]), proposed to be deployed in the 2030s, which envisions deploying an array of cryogenic seismometers in the permanently shadowed regions (PSRs) at the lunar south pole. These areas offer natural thermal stability and mechanical quietness, which are essential for ultra-sensitive measurements. The project’s pathfinder mission, Soundcheck, is designed to validate these PSR conditions and the required cryogenic isolation technology.

In a more immediate future, China’s Chang’e-7 mission (planned for ~2026) will carry a seismograph to characterize the lunar seismic environment, thereby paving the way for future observatories[3,4]. Furthermore, other international programs like the US Artemis and Commercial Lunar Payload Services (CLPS) are also expected to deploy seismometer payloads. The prospect of lunar seismic GW detection is also driving instrument innovation, prompting designs for seismometers that could achieve LGWA-level sensitivities while operating at the Moon’s ambient surface temperature[5]. Ultimately, the potential establishment of a comprehensive lunar seismometer network opens the exciting possibility of cross-correlating data from multiple instruments. This capability could allow scientists to constrain the mid-frequency-band gravitational-wave background, a signal potentially originating from the very beginning of the Universe[6].

This convergence of global interest has, in turn, stimulated a new wave of theoretical studies. Researchers are updating models of the Moon’s response to GWs using state-of-the-art lunar structural models[7–11]. New, more advanced numerical methods, such as finite-element simulations, are adopted to account for the Moon’s highly heterogeneous subsurface and interior structures[12].

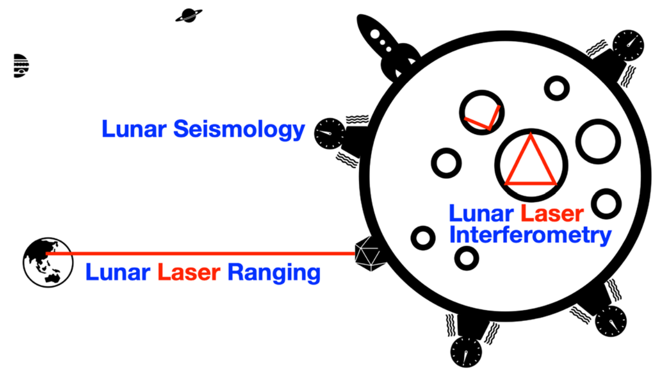

Fig. 1 | Schematic diagram of proposed lunar gravitational-wave detection methods. Lunar Seismology: an array of seismometers measures the Moon's global vibrations induced by gravitational waves. Lunar Laser Interferometry: a long-baseline laser interferometer, either equilateral triangle or L-shaped, is constructed in a lunar crater to detect spacetime distortions as changes in its arm length. Lunar Laser Ranging: a laser linkage precisely measures the Earth–Moon distance, seeking subtle, cumulative changes caused by the resonant interaction between the Earth–Moon system and passing gravitational waves.

Lunar laser interferometry

The technique of laser interferometry, proven by LIGO, measures spacetime distortions through phase shifts in laser beams reflected over long baselines. Extending this concept to the Moon offers the potential for excellent sensitivity in the mid-frequency band. Besides the absence of atmosphere or ocean tide, another significant benefit stems from the lunar landscape. Whereas Earth's curvature presents a formidable obstacle to long-baseline interferometry, requiring massive tunneling projects, the Moon's natural craters transform this challenge into an opportunity, providing pre-existing bases for interferometers with arm lengths up to ~100 km.

Interest in lunar interferometers emerged in the early 1990s. Stebbins & Bender explored a "lunar LISA", in which lunar-surface-based optical stations would form kilometer-scale arms, while Wilson & La Fave analyzed practical challenges such as thermal extremes, dust, and alignment stability. Though premature at the time, these studies established that the Moon's environment offered unmatched advantages for mid-frequency interferometry.

With modern optics and photonics—such as ultra-stable lasers, precision cavities, and vibration isolation systems—now mature, lunar interferometry is transitioning from concept to engineering reality. The Gravitational-wave Lunar Observatory for Cosmology (GLOC) proposes a triangular array with ~40 km arms, capable of detecting signals from seed black holes and cosmological backgrounds[13]. The Laser Interferometer On the Moon (LION) envisions a similar geometry but with expanded bandwidth into the kilohertz regime, enabling continuous observation from inspiral to merger for compact binaries[14]. The most recent design, the Laser Interferometer Lunar Antenna (LILA), incorporates advantages from an earlier strainmeter-based concept[15] and adopts a modular approach: deploying shorter-baseline prototypes before expanding to tens of kilometers[16]. Moreover, LILA integrates quantum-enhanced metrology and advanced strainmeter lasers to achieve good sensitivity down to 10^{-3} Hz.

Lunar Laser Ranging

Lunar Laser Ranging (LLR)—the measurement of the Earth–Moon distance via laser reflections—has provided some of the most stringent tests of general relativity for many decades. The technique involves sending laser pulses from Earth to retroreflectors placed by the Apollo and Luna missions; the time-of-flight of these photons reveals the Earth–Moon separation with centimeter, and now millimeter, precision. For GW detection, passing waves are expected to induce tiny perturbations in the Earth–Moon distance or in the geometry among multiple reflectors. Differential timing between reflectors could reveal long-wavelength GWs in the micro-Hertz to milli-Hertz regime[17].

Technological advances have dramatically increased sensitivity. High-power continuous-wave lasers, next-generation retroreflectors, and adaptive optics systems are expected to achieve sub-millimeter ranging and possibly tens of micrometers precision in differential measurements[18]. Although LLR's sensitivity in the 0.1–10 Hz band remains below that of interferometric or seismometer-based methods, it provides an essential complementary channel for detecting very low-frequency or broad-band GWs.

Cross-disciplinary synergy

For decades, seismology, laser interferometry, and laser ranging advanced largely independently, with minimal intersection with theoretical physics. Now, however, the quest to detect GWs on the Moon is fusing these distinct disciplines into a new, cohesive field of research, as we have detailed above.

This fusion is fueled, in large part, by the technological advances in seismology, laser interferometry, optics, and precision metrology. For example, the seismometers proposed for LGWA and Chang'e incorporate either cryogenic sensors or low-noise electronics derived from decades of terrestrial seismology and planetary missions such as InSight. By significantly lowering instrument noise, these seismometers directly enhance the detection capability for weak accelerations, thereby narrowing the gap between the projected sensitivity to GW and the actual signal strength. The interferometers—LILA, LION, and GLOC—build directly on technologies developed for LIGO and LISA, including ultra-stable lasers, precision optical cavities, and advanced vibration isolation. Freed from the disturbances of Earth's atmosphere and ocean tides, these lunar interferometers will realize their full potential to detect GW in the 0.1 Hz band. Meanwhile, LLR benefits from new high-power lasers and precision timing systems, transforming it from a geodetic experiment into a potential GW observatory.

Conversely, the progress from lunar GW research will also feed back into these disciplines. Sensitive seismometers will yield unprecedented data on the Moon's internal structure, crustal composition, and thermal evolution, advancing our understanding of lunar physics so that questions such as whether the lunar core is liquid or solid might finally be answered. Laser interferometers and ranging systems will refine optical metrology and time-transfer standards, aiding both Earth-based and deep-space navigation. The cryogenic and quantum sensing technologies required for lunar observatories could revolutionize precision measurement, quantum communication, and space engineering.

In this symbiotic framework, the Moon becomes both an astrophysical observatory and a cross-disciplinary testbed. Lunar exploration, once a symbol of human achievement, now promises something even more profound: new hope for detecting the faintest ripples in spacetime, and a new way to understand our Moon, our Universe, and our own potential.

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Received: 17 October 2025; Accepted: 26 November 2025;
Published online: 07 January 2026

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Acknowledgements

The author is supported by the National Key Research and Development Program of China (Grant No. 2024YFC2207300).

Author contributions

X.C.: Conceptualization, Data Analysis, Investigation, Writing—original draft.

Competing interests

The author declares no competing interests.

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