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Review Article

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Lunar Gravitational-Wave Detection

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Abstract
A new era of lunar exploration has begun bringing immense opportunities for science as well. It has been proposed to deploy a new generation of observatories on the lunar surface for deep studies of our Universe. This includes radio antennas, which would be protected on the far side of the Moon from terrestrial radio interference, and gravitational-wave (GW) detectors, which would profit from the extremely low level of seismic disturbances on the Moon. In recent years, novel concepts have been proposed for lunar GW detectors based on long-baseline laser interferometry or on compact sensors measuring the lunar surface vibrations caused by GWs. In this article, we review the concepts and science opportunities for such instruments on the Moon. In addition to promising breakthrough discoveries in astrophysics and cosmology, lunar GW detectors would also be formidable probes of the lunar internal structure and improve our understanding of the lunar geophysical environment.

Keywords Gravitational waves · Lunar science · Seismometers · Laser interferometry

1 Introduction

The Moon offers a unique geophysical environment for fundamental physics experiments as well as astrophysical observatories (Silk et al. 2023). The permanently shadowed regions (PSRs) at the lunar poles offer the coldest areas in our solar system (Williams et al. 2019), the far side especially during lunar nights might be among the most quiet radio locations in our solar system (Alexander et al. 1975), and seismic vibrations are expected to be several orders of magnitude smaller in a range of frequencies compared to Earth (Lognonné et al. 2009). This opens exciting opportunities for breakthrough observations with electromagnetic observatories and gravitational-wave (GW) detectors (Koopmans et al. 2021; Silk et al. 2021; Harms et al. 2021).

Lunar GW detection has been under consideration since Apollo 17 when the Lunar Surface Gravimeter developed under the coordination of Joseph Weber was deployed on the

S. Katsanevas is deceased.

Extended author information available on the last page of the article

Moon to observe lunar surface vibrations generated by passing GWs (Giganti et al. 1977). The experiment did not reach its targeted performance, but even if it had, we know today that it would not have been sensitive enough to detect GW signals. Lunar vibrations caused by GWs are expected to be several orders of magnitude weaker than those that the instrument was designed to observe. The main motivation to take such an experiment to the Moon was that with the extremely low level of seismicity observed with previously deployed Apollo seismometers (Nakamura et al. 1981), Weber who had done similar measurements on Earth already (Forward et al. 1961) had reason to suspect that GW signals could be detected on the Moon.

A lunar GW detector would complement a future network of terrestrial and space-based GW detectors. Next-generation terrestrial detectors have been proposed including the Einstein Telescope in Europe (Steering 2020) and the Cosmic Explorer in the US (Evans et al. 2021). Construction of these research infrastructures is expected around 2035 with a targeted lifetime of at least 50 years. The space-borne detector LISA is an approved mission orbiting the Sun expected to be launched in the second half of the 2030s (Bayle et al. 2022). It has a nominal lifetime of four years, but with potential to be extended to a mission of 10 years. Such a network would open opportunities for multiband observations between GW detectors, where especially a decihertz detector on the Moon would make an enormous impact (Sesana 2016; Sedda et al. 2020; Grimm and Harms 2020). If technological hurdles concerning deployment and operation of GW detectors on the lunar surface can be overcome, the Moon might take a key role for the exploration of our Universe through GW observations.

2 Current and Future Facilities for GW Science

2.1 Current Terrestrial Laser-Interferometric GW Detectors

A global network of currently four long-baseline, laser-interferometric gravitational-wave (GW) detectors is operative consisting of Virgo (Acernese et al. 2014), the two LIGO detectors (Aasi et al. 2015), and KAGRA (Akutsu et al. 2019). A fifth detector is under construction in India (Souradeep 2016). Breakthrough observations have been made including the first detection of GWs by LIGO, GW150914 (van den Brand et al. 2016), and the multi-messenger campaign following the merger event GW170817 of two neutron stars (Abbott et al. 2017; LIGO Scientific Collaboration et al. 2017a). Our understanding of compact-binary populations has greatly improved over the past years (Abbott et al. 2021), and the astrophysical processes governing the emissions of electromagnetic signals of neutron-star mergers are much better understood (Abbott et al. 2017b; McCann et al. 2018).

The current detectors are undergoing regular technological upgrades. Recent changes include the implementation of frequency-dependent squeezing, increase of laser power, and the installation of seismic and acoustic monitoring systems for noise cancellation (Cahillane and Mansell 2022; Muciaccia et al. 2023). The laser-interferometric system of a GW detector is very complex and requires many months of commissioning time to benefit from the latest technological upgrades. Much of the effort goes into the isolation of a detector from its environment. The vacuum system, seismic isolation, stray-light control, and environmental monitoring are the most important measures to mitigate environmental disturbances (Zucker and Whitcomb 1996; Acernese et al. 2010; Fiori et al. 2020; Soni et al. 2020; Romero-Rodríguez et al. 2022). An increasingly important technology to mitigate the impact of environmental disturbances is active noise mitigation or noise cancellation (Matichard et al. 2015; Driggers et al. 2019; Harms 2019), where sensor data are being used to correct for the

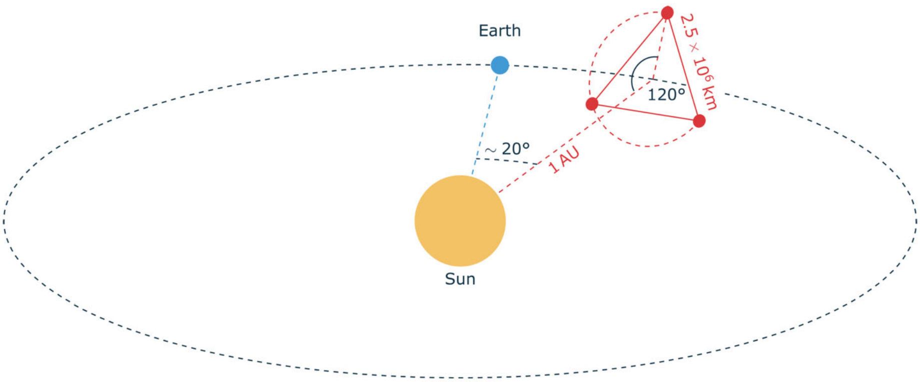

Fig. 1 Schematics of LISA orbits. The constellation is trailing the Earth by about 20° and inclined against the ecliptic by 20°. This orbital arrangement allows the constellation to be stable without further station keeping manoeuvres

disturbance either via feedback or feedforward control, or by subtracting a noise model from the GW data in post-processing. Through technology upgrades and continuous commissioning of a detector, the facility performance approaches its infrastructural limitations, which makes it harder to improve its sensitivity. At some point, new detector facilities are required to enable new breakthrough science. At low frequencies, performance limitations are linked to environmental disturbances, which are orders of magnitude weaker on the Moon.

2.2 The Laser Interferometer Space Antenna - LISA

LISA is a space-borne gravitational wave detector and is a mission of the European Space Agency (ESA) with NASA as an international partner (Bayle et al. 2022; Thorpe et al. 2019; Amaro-Seoane et al. 2017).

LISA is a constellation of three satellites, 2.5 million km apart, that orbits the Sun in an Earth-like orbit. The constellation trails the Earth by about 20° or 55 million km and is inclined by 60° with respect to the ecliptic (Fig. 1). The shape and orientation of the constellation ensures that no station-keeping manoeuvres have to be undertaken during the lifetime of the mission, which is projected to be approximately 10 years (including a possible extension of the mission lifetime).

The absence of anthropogenic and other low-frequency noise sources present on Earth, such as seismic, tides, or weather systems in the chosen orbits enables LISA to be sensitive to a band of frequencies between 0.1 mHz and 1 Hz; see figure 2.

The relatively long arm length (or inter-spacecraft distance) allows to employ a comparatively low displacement sensitivity of about 15 $\mathrm{pm}/\sqrt{\mathrm{Hz}}$ but comes at a price. The usual interferometric schemes, such as a Michelson interferometer employed by most terrestrial detectors, have to be modified for such long arm lengths. Firstly, the direct reflection of the laser at an end-mirror is not feasible. Sending the laser through a 30 cm telescope (the largest feasible size for this mission) will cause diffraction to widen the laser beam to many kilometers and only a fraction, about 10^{-9} of the emitted laser light, will be received by the other spacecraft. Direct reflection being impractical, LISA employs a transponder scheme, where a laser in the receiving spacecraft is phase-locked (with a suitably chosen frequency offset) to the incoming beam before sent out again (see Fig. 3).

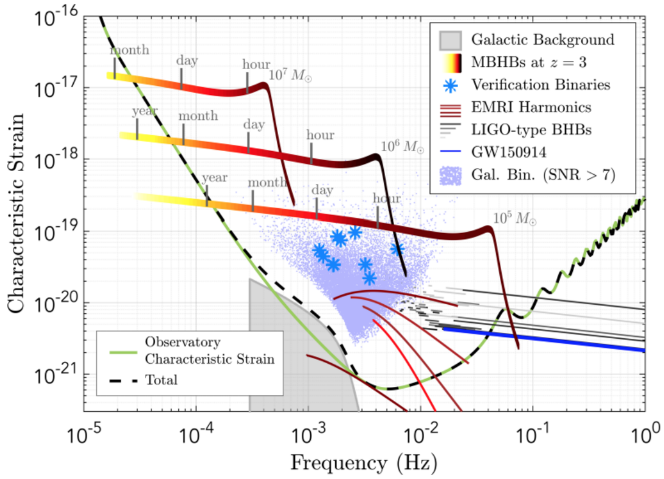

Fig. 2 Sensitivity of LISA as characteristic strain (figure from Amaro-Seoane et al. 2017)

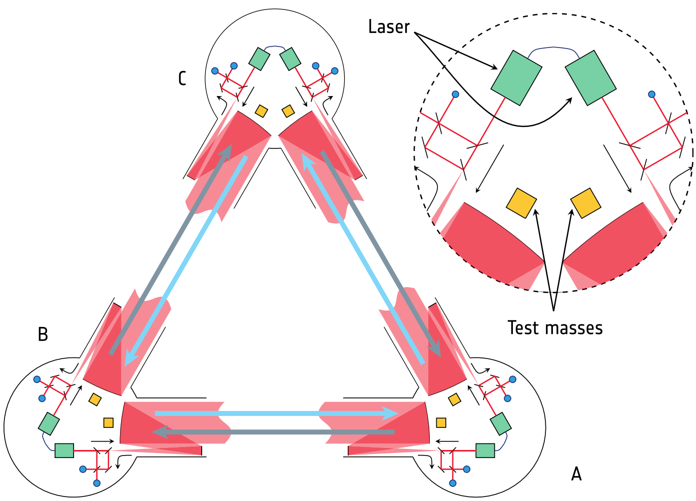

Fig. 3 Measurement principle of LISA (figure from Bogenstahl et al. 2017)

Secondly, LISA uses free-falling test masses as fiducial end-points of the arms, instead of optical mirrors. Those test masses are cubes with a side of 46 mm and a mass of 1.96 kg, made out of a Au-Pt metallic mixture that provides reduced magnetic susceptibility to the test mass. The position of those test masses inside the spacecraft is measured interferometrically with respect to an optical bench that also supports the interferometric measurement of the inter-spacecraft distance (see Fig. 4).

The demonstration of free-fall for the test masses (by limiting stray forces on the test-masses) was one of the key contributions of the LISA Pathfinder technology demonstrator, in orbit from December 2014 to June 2017. The distance ($\approx$ 38 cm) between the two test masses on LISA Pathfinder was measured interferometrically and the performance of the

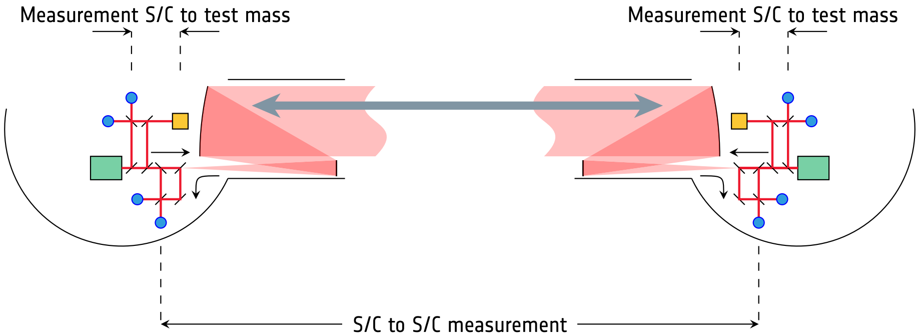

Fig. 4 Tri-partition of the measurement in a LISA arm (figure from Bogenstahl et al. 2017)

differential acceleration between the test masses was demonstrated to be smaller than 2 $\mathrm{fm/s^2}/\sqrt{\mathrm{Hz}}$ (Armano et al. 2016).

The science objectives of LISA are aligned with the low-frequency performance of the constellation. The science of the LISA mission is extremely broad and diverse and has been studied and described in a series of white papers (Littenberg et al. 2019; Caldwell et al. 2019; Colpi et al. 2019; Cutler et al. 2019; Baker et al. 2019; Natarajan et al. 2019; Berry et al. 2019; Cornish et al. 2019; McWilliams et al. 2019; Berti et al. 2019; Bellovary et al. 2019). The sources range from galactic binaries nearby in our own Galaxy (Littenberg et al. 2019) to sources all across the Universe: massive black hole mergers in the range from $10^4\ M_\odot$ to $10^7\ M_\odot$ (Colpi et al. 2019; Bellovary et al. 2019), and extreme-mass ratio inspirals (Berry et al. 2019), where neutron stars or stellar-size black holes fall into massive black holes at the center of galaxies, as well as possible observations of a stochastic cosmological background. The science ranges from the astrophysics of binary evolution (Sesana et al. 2020), galaxy formation and black holes to fundamental physics (Arun et al. 2022; Berti et al. 2019) and cosmology (Boileau et al. 2022, 2021; Corman et al. 2021; Caprini et al. 2020; Caldwell et al. 2019).

2.3 Einstein Telescope and Cosmic Explorer

Infrastructural limitations like site conditions and detector size set important constraints on the sensitivities that can be reached with a detector. With increasing lifetime of a detector facility, technological upgrades enabling new breakthrough observations become more complex and more difficult to implement. At some point, new infrastructure is needed to overcome these constraints. A new generation of terrestrial GW detectors has been proposed with the Einstein Telescope in Europe (Steering 2020) and the Cosmic Explorer in the USA (Evans et al. 2021). Figure 5 shows conceptual drawings of the two facilities.

The Einstein Telescope is proposed as an underground detector in the shape of an equilateral triangle with 10 km arm length. Each vertex of the triangle is the center station of a pair of interferometers; one optimized for low-frequency observations (ET-LF) between about 3 Hz and 50 Hz, and one optimized for high-frequency observations (ET-HF) from about 50 Hz to a few kHz. The ET-LF interferometers will be operated at cryogenic temperatures and with lower power laser beams. The high-frequency interferometers will be operated with up to a few megawatts of power in the interferometer arms. While the underground environment will help to reduce the ambient seismic and atmospheric noise, ET-LF interferometers require additional mitigation of environmental noise to reach the sensitivity target (Badaracco and Harms 2019; Amann et al. 2020).

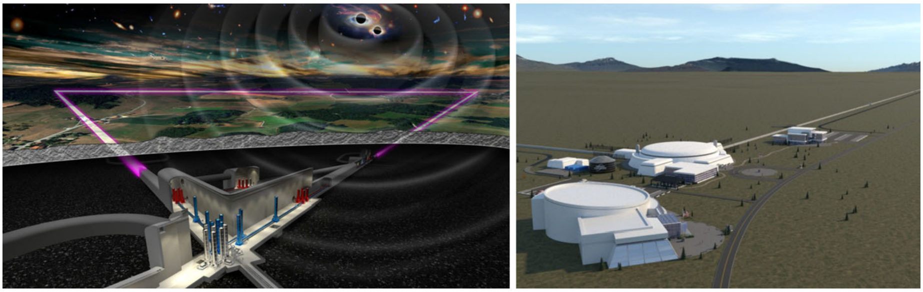

Fig. 5 Artistic conceptions of next-generation terrestrial detector facilities. The Einstein Telescope (left) is a proposed underground facility in Europe to host future-generations of GW detectors with 10 km arm lengths in an equilateral triangle (image credit: Marco Kraan, Nikhef). The Cosmic Explorer (right) is the US proposal for two next-generation detectors located at the surface with 20 km and 40 km arm lengths (image credit: Angela Nguyen, Virginia Kitchen, Eddie Anaya, California State University Fullerton)

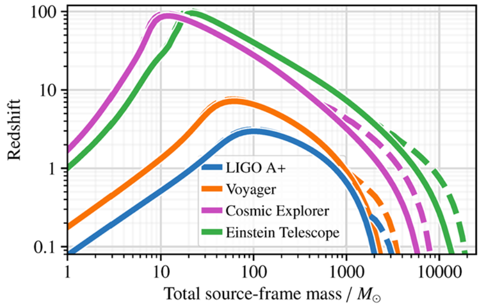

Fig. 6 Detection horizons as a function of total source-frame mass of the compact binary. Dashed lines indicate detection horizons when higher-order modes of the GW signal are included. Terrestrial GW detectors have their best detection capabilities in the mass range 10 – 100 $M_\odot$. The plot is taken from (Hall 2022)

The reference design of the Cosmic Explorer foresees two surface detectors in the US; one with 40 km arm length, the other with 20 km arm length. The option to have the vertices and ends of the interferometers underground is under consideration. As surface detectors, the Cosmic Explorer will not match the low-frequency sensitivity of the Einstein Telescope, but its longer arms make it superior at higher frequencies. The low-frequency end of its observation band will ultimately be set by gravitational noise of the ambient fields and limitations in the ability to estimate this noise using environmental data. Assuming that the gravitational noise can be reduced to a level comparable to what is predicted for underground sites (Hall et al. 2021), the targeted observation band is approximately 8 Hz – few kHz.

Figure 6 shows the detection horizons of Einstein Telescope and Cosmic Explorer as a function of total source-frame mass of compact binaries. These would vastly exceed the horizons even of the most ambitious upgrades of current detector facilities like the proposed Voyager (Adhikari et al. 2020). Einstein Telescope would detect almost all of the 10^5 binary black-hole mergers expected to occur per year in our Hubble volume and see a fraction of about 10% – 20% of the 10^6 expected binary neutron-star mergers (Maggiore et al. 2020). Such detection statistics will enable breakthrough science and lead to exciting possibilities also for multi-messenger astronomy with electromagnetic and neutrino counterparts of GW sources. High impact is expected especially in cosmology and astrophysics, and paradigm shifting discoveries like the first signs of quantum gravity, detection of a primordial black-hole population, or the observation of a primordial stochastic GW background are conceivable (Agullo et al. 2021; Ng et al. 2022; Sharma and Harms 2020).

2.4 Some Examples of Electromagnetic Observatories Possibly Operating in the Coming Decades

Multi-messenger observations are the new frontier to unveil the most energetic processes associated with white dwarfs (WD), neutron stars, black hole collisions, and stellar explosions. Over the next decades more sensitive and complementary observations, ranging from radio to the very high-energy gamma rays and gravitational waves, will aim at 1) investigating the Universe along its cosmic history up to the dark ages to address open questions about the nature of dark matter and dark energy, 2) probing the nature of matter under extreme conditions, 3) unveiling the physics governing energetic transients, and 4) testing new fundamental physics through extreme astrophysical phenomena. This section gives an overview of some of the major electromagnetic observatories which are expected to play a key role in the future exploration of the Universe in synergy with gravitational-wave detectors.

The Vera C. Rubin Observatory, which is expected to start operations in 2024, will revolutionize time-domain astrophysics. It will perform the so called Legacy Survey of Space and Time (LSST), an unprecedentedly sensitive, ten-years long survey of the optical sky. LSST will observe over 10 million transients every night. The 8.4 m Simonyi Survey Telescope at the Rubin Observatory and its 3200-megapixel LSST Camera are designed to provide an exceptionally wide field of view (9.6 sq.degrees) with a better than 0.2 arcsecond sampling. The telescope's compact configuration will allow it to rapidly slew across the sky, making LSST capable of surveying the entire southern sky every three nights in six optical bands, ranging from 320 to 1050 nm. The camera will feature solid state detectors with over three billion pixels, providing extremely high quality data. The Rubin observatory will offer target-of-opportunity (ToO) capabilities which enable the early discovery and characterization of the optical counterpart of gravitational-wave sources. For binary-neutron star (BNS) and neutron star/black hole (NSBH) mergers it will detect both the kilonovae and Gamma-Ray Burst (GRB) afterglows (Andreoni et al. 2022). Furthermore, it is expected to detect about 1000 well-sampled tidal disruption events (TDEs) per year. The LSST will observe hundreds of thousands of well-measured Type 1a supernovae (SNe 1a), replicating the current generation of SN 1a cosmology experiments several hundred times over different directions and regions across the sky (Hambleton et al. 2022).

A new generation of 30 – 40 m class telescopes, such as the Thirty Meter Telescope (TMT, Fenchuang 2022), the Giant Magellan Telescope (GMT, Fanson et al. 2022), and the Extremely Large Telescope (ELT, Tamai et al. 2022) will provide unprecedented tools to characterize transients, unveiling the physics of stellar explosions and extreme objects such as black holes. ELT will deliver spectroscopic and high-resolution imaging data at sensitivities never before reached. It will allow us to follow up and characterize the optical and near infrared emission of gravitational-wave sources giving detailed information on the spectral properties and temporal evolution also for the fainter and more distant sources. It will unveil properties of the host galaxies and the local environment of the source. Furthermore, characterizing a sufficiently large sample of SNe 1a detected by LSST, ELT will give insights into the nature of the progenitors of thermonuclear explosions. Despite their crucial role in modern cosmology, it is still unclear whether the explosion is triggered by the merger of a binary system of WDs or is rather due to accretion of material from a non-degenerate companion onto the WD. Supernovae 1a are standard candles providing precise measurements of distances and thus measurements of the expansion rate of the Universe. The inspiral and mergers of binary WDs are expected to be detectable through gravitational waves in the decihertz band, providing another complementary measurement of the source distance. Thus, multi-messenger observations of these events are vital to both understand the progenitors of SN 1a and to solve the tension on the Hubble constant estimate (see e.g., Maselli et al. 2020).

Wide field-of-view (FoV) γ-ray and X-ray satellites are key instruments operating in synergy with GW detectors and making it possible to detect the short GRB prompt and afterglow emissions associated with BNS mergers (see e.g. Ronchini et al. 2022). Instruments such as the Soft X-ray Imager (SXI, 0.3 – 5 keV, FoV of 0.5 sr) on board of the mission concept THESEUS (Amati et al. 2021) are also important to probe the thermonuclear explosions of massive WDs associated with SN Ia. SXI is expected to detect the thermonuclear shock breakout, the interaction between the SN and the matter bound in the system, and the interaction between the SN ejecta and the circum-binary environment. THESEUS will also sample the soft X-ray light curves of more than 50 TDEs per year. The simultaneous observation of the hard X-ray by the X/Gamma-rays Imaging Spectrometer (XGIS, 2 keV – 10 MeV), and the infrared by the InfraRed Telescope (IRT) can provide information on the geometry and jet orientation (Mereghetti et al. 2021; Report 2021). A more sensitive satellite such as Athena plays a key role in the characterization of high-energy transients enabling the observations of BNS mergers and GRBs afterglows also at late times and when they are seen by an observer not aligned to the jet-axis. Athena is expected to constrain the jet geometry and orientation, to help understanding the rate of BNS which are not able to produce a jet (choked jets), and to probe the fundamental physics of particle shock-acceleration. It is able to detect X-ray emission from the sub-relativistic jet giving rise to the kilonova emission. Athena is also expected to detect the possible high-energy emission from massive BH coalescences, to study the nature of stellar disruption and subsequent accretion onto supermassive black holes during TDEs, and to detect the X-ray emission from accreting WD binaries (Piro et al. 2022).

The Cherenkov Telescope Array (CTA) is the next generation ground-based observatory for detecting very-high energy gamma-rays (Acharya et al. 2013). It consists of an array of more than 100 telescopes located both in the northern and southern hemispheres. CTA is expected to bring dramatic advances in our understanding of the origins and production of non-thermal particles in the Universe thanks to its unique capabilities; it will be 10 times more sensitive than any existing instrument, it will feature a wide energy range (from 20 GeV to 300 TeV), an excellent angular resolution approaching one arcminute, a large field of view of several tens of square degrees, and a rapid slewing time suitable to swiftly catch the early emission from transients such as gamma-ray bursts.

Going to the longer wavelengths, the Square Kilometre Array (SKA) aims at exploring transient radio signals with unprecedented sensitivity, giving access to the physics of extreme phenomena such as exploding stars, compact object mergers, and ultra-relativistic jets from accreting black holes. In its first years of operation, it is expected to detect TDEs and Fast Radio Bursts (FRBs) at rates ranging from 1 to 1000 per week (Fender et al. 2015). The SKA will significantly increase our ability to detect GRB afterglows by following-up several hundred of GRBs in the high frequency bands. It will also be able to routinely detect "orphan afterglow" emission, from the population of GRBs whose relativistic jets are not pointed towards the Earth (Burlon et al. 2015).

2.5 European Space Agency Lunar Exploration Roadmap

In this section, we present the lunar exploration opportunities offered by ESA, the research payloads and the technology demonstrators currently planned for a flight to the Moon, and the available means to mature the design and the technology of a future gravitational-wave detector.

2.5.1 The Terrae Novae Programme and the Underlying Process

The Terrae Novae programme secures Europe's role in space exploration. Managed by the ESA Human and Robotic Exploration Directorate (HRE), it is a comprehensive programme of human and robotic exploration missions and activities for Low Earth Orbit (LEO), the Moon and Mars. The programme cornerstones are

- Sustained presence in LEO: Extend the International Space Station (ISS) operations with new infrastructure allowing enhanced science in LEO, at the same time promoting commercial exploration services, which will allow access to LEO in the post-ISS era.
- Exploring farther: Continue delivering modules for sending ESA and NASA astronauts to the Moon. This includes ESA contributions (I-HAB and ESPRIT modules) to the first research station orbiting around the Moon, the Lunar Gateway.
- Moon robotic exploration: Fly research and technology demonstrators to the Moon surface in missions of opportunity with international partners and start the construction of the European Argonaut (formerly known as EL3). ESA will land multiple scientific payloads to probe the lunar environment, study its interior and prepare for its sustainable exploration.
- Mars robotic exploration: Continue gathering data from the Trace Gas Orbiter; start the construction of a European lander to take the Rosalind Franklin rover to the surface of Mars; cooperate with NASA on Mars Sample Return to return to Earth physical samples from another planet.

The Terrae Novae programme relies on two pillars, the Science in Space Environment (SciSpacE) programme and the Exploration Preparation Research and Technology (ExPeRT) programme. SciSpacE defines the science and the applications to be developed using a variety of ground and space platforms. On the other hand, the ExPeRT programme integrates, coordinates and manages the development of studies and technologies for future exploration missions to LEO, Moon and Mars destinations. The SciSpacE programme has three main research areas:

- Physical sciences;
- Life sciences;
- Moon and Mars sciences.

The research topics to be developed in LEO, beyond LEO (Lunar Gateway) and in robotic exploration missions around and on the Moon and Mars are defined in a bottom-up approach. Over 300 scientists were involved in a wide consultation process of the scientific community, which produced 16 white papers reflecting the interests and recommendations on focus areas across a broad range of disciplines that could be addressed within the capabilities of the Terrae Novae programme. The White Papers are streamlined to identify priorities that will drive future Announcements of Opportunities (AOs) for missions. This process is currently ongoing with the involvement of the scientific community and ESA advisory bodies (HESAC, PSWG and LSWG).

2.5.2 Science on the Moon

ESA is currently flying research payloads and technology demonstrators to the lunar surface on missions of opportunity with international and commercial partners. Plans until 2025 are defined and summarized below:

- The Exospheric Mass Spectrometer will land with NASA-CLPS (2022) on the Moon surface. The ion trap mass spectrometer will be used to detect lunar volatiles.
- Landcam-X technology will be installed on board a commercial lander (2023). The camera will be tested to improve precision and safety of future lunar landings.
- The MoonLIGHT laser retroreflector with its automatic pointing mechanism will be launched with NASA-CLPS (2024). The corner cube reflector will be used to perform Lunar Laser Ranging (LLR) experiments from the Earth. The MoonLIGHT ranging measurements will contribute to improve general relativity tests and will be used to study the Moon interior.
- An energetic neutral atoms and ions detector will be placed on the lunar surface with CNSA (2024).
- An Exospheric Mass Spectrometer will also be installed on-board the LUPEX rover in collaboration with JAXA (2024/25).
- Lunar Pathfinder will test commercial communication and navigation services around the Moon (2025).
- PROSPECT will reach the lunar surface with NASA-CLPS (2025). From the PROSPECT payload, ProSEED will drill beneath the surface in the South Pole region of the Moon and extract samples that will be then analyzed in the ProSPA chemical laboratory.

In a mission of opportunity, the availability of resources is negotiated among the international partners. Typical figures allocated to the payload for mass, volume and power consumption are 5 kg, 5 dm^3, and 10 W, respectively. Single integrated units are typically preferred and easier to accommodate. Meanwhile, the construction of Argonaut has been approved. With a total mass of delivered cargo of 1500 kg, Argonaut will be compatible with different mission types: cargo, science rover, sample return stage, scientific/technology demonstration packages, in-situ resources, production equipment, power generation equipment, etc.

Future missions in lunar orbit or at the Moon surface will be defined based on the scientific priorities identified for the program and will be selected from the ongoing and future AOs. The following investigations have been proposed in the Fundamental Physics and Astrophysics White Papers:[1]

- Einstein's Equivalence Principle tests through lunar laser ranging experiments to the Moon.
- Tests of de-coherence models in quantum mechanics with entangled photons distributed on the Earth-to-Moon baseline.
- Studies of the origins of primordial fluctuations and primordial black holes using radio interferometry and gravitational wave detectors.
- Studies of the cosmic-ray distribution in the solar system through measurements of fluxes and spectra on board space probes.
- Surface magnetic fields and long-wave radio emissions from the corona using radio telescopes.
- Plasma physics studies relying on small plasma packages, UV and ENA imagers, and transponders for radio science experiments.

Gravitational-wave physics and astronomy are topics of interest both for the Fundamental Physics and the Astrophysics White Papers.

[1] The SciSpacE White Papers are available at https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Research/The_SciSpacE_White_Papers.

2.5.3 A Path to a Gravitational-Wave Project on the Moon

ESA can offer several means to incubate study ideas, elaborate preliminary mission concepts and advance mission-critical technology to an adequate technology readiness level (TRL).

As first, Topical Teams are working groups that include experts from European universities, research entities, and industries focusing on selected research topics in the areas of interest for the HRE programme. Within a Topical Team contract, ESA provides support for meetings and workshops. A Topical Team can be used to incubate ideas and develop them toward a mission concept.

At the next level, a Concurrent Design Facility (CDF) study might help defining mission design aspects. The ESA CDF infrastructure gathers teams of scientists and engineers from different disciplines and with different expertise to work together, in close coordination, with the purpose of completing complex designs.

Both a Topical Team and a CDF study could be considered to advance the mission concept of a Lunar GW antenna and the pathfinder missions that might be required for site survey. This preliminary study phase could help the team to consolidate the mission concept and prepare for future ESA Announcement of Opportunities.

3 Lunar GW Detection

In the following sections, we present the three main concepts proposed for lunar GW detectors, i.e., (1) the inertial measurement of lunar vibrations produced by GWs (Sect. 3.2), (2) the long-baseline, laser-interferometric measurement of seismic strain produced by GWs (Sect. 3.3), and the long-baseline, laser-interferometric measurement of GW strain with suspended test masses (Sect. 3.4). We include discussions about the lunar GW response (Sect. 3.1) and the cleaning of data from the seismic background (Sect. 3.5).

3.1 Lunar GW Response

Weber suggested that GWs could be detected by observing the induced vibrations of the elastic bodies (Weber 1960). Later, formalisms were developed to apply the theory to planetary bodies, e.g., through generation of seismic waves (Dyson 1969) or by excitation of quadrupolar normal modes (Ben-Menahem 1983). A planet's GW response in terms of normal modes depends on radial inhomogeneities of the shear modulus. In the case of the Preliminary Reference Earth Model (PREM) (Dziewonski and Anderson 1981) there are two major shear-modulus discontinuities: at the surface and at the core-mantle boundary. A similar structure is predicted by the Weber lunar model (Weber et al. 2011). Comparing the two models, the surface value of the Earth's radial shear modulus (270 GPa) on basalt surface bed-rock of PREM is two orders of magnitude larger than the lunar surface regolith in the first upper km (0.65 GPa). The lunar GW response at lower frequencies is not significantly affected by the surface layer, while at high enough frequencies, the low shear modulus means that the GW response will be reduced compared to Earth. From preliminary models (Garcia et al. 2019), it can be expected that the transition happens somewhere in the decihertz band with possible resonant effects in the lunar GW response.

To calculate the lunar response using the normal mode theory we use a non-rotating 1D lunar model (Weber et al. 2011) and a Green tensor formalism (Ben-Menahem 1983; Majstorović et al. 2019). The induced GW response is written as

$$s(\mathbf{r},t) = \int_{-\infty}^{t} \int_{V} \mathbf{G}(\mathbf{r},\mathbf{r}';t-t') \cdot \mathbf{f}(\mathbf{r}',t')dV'dt' \tag{1}$$

where in transverse-traceless gauge the force term is defined as the gradient of the shear modulus (Dyson 1969)

$$\mathbf{f}(\mathbf{r},t) = -\frac{\partial \mu}{\partial r}\mathbf{e}_r \cdot \mathbf{h}(\mathbf{r},t) \tag{2}$$

and $\mathbf{h}(\mathbf{r},t)$ is the metric perturbation of the space-time.

Considering the GW source as an infinite monochromatic wave with pulsation ω_g, $\mathbf{h}(\mathbf{r},t) = \Re\left\{h_0 \boldsymbol{\epsilon} e^{i(\omega_g t - \mathbf{k}_g \cdot \mathbf{r})}\right\}$ in the long-wavelength regime, we neglect the $(\mathbf{k}_g \cdot \mathbf{r})$ term.

The Green tensor depends on the eigenfunctions computed for the lunar model. After some computation, the induced response for a given mode k (degree l and order m) to an infinite monochromatic GW is written (Majstorović et al. 2019) as

$$\mathbf{s}_k(\mathbf{r},t) = h_0 \mathbf{s}_k(\mathbf{r}) \bar{g}(t) \delta_{l,2} f^m(e,\lambda,\nu)\zeta_k, \tag{3}$$

where the associated displacement eigenfunctions are

$$\begin{aligned}\mathbf{s}_k(\mathbf{r}) = \hat{\mathbf{e}}_r U_k(r) Y_{lm}(\theta,\phi) + \hat{\mathbf{e}}_\theta \left(\kappa^{-1} V_k(r) \partial_\theta P_{lm}(\cos\theta)\right) \\ + \hat{\mathbf{e}}_\phi \left(\kappa^{-1} V_k(r) \tfrac{1}{\sin\theta} P_{lm}(\cos\theta) \partial_\phi e^{im\phi}\right)\end{aligned} \tag{4}$$

with Y_{lm} the real spherical harmonic functions and P_{lm} the associate Legendre polynomials of degree l and order m. θ and ϕ are respectively the colatitude and longitude of a point at the Moon surface.

The source-time function defines the resonance with the seismic mode of eigenfrequency ω_k

$$\bar{g}(t) = \frac{1}{2\pi}(i\nu)^{-1} \frac{1}{\gamma_k + i(\omega_g - \omega_k)} e^{i\omega_g t} \tag{5}$$

and the pattern function $f^m(e,\lambda,\nu)$ depends on the polarization and incidence angles of the GW. Finally, the function ζ_k depends on the radial interior model and is written

$$\begin{aligned}\zeta_k = \mu(a) a^2 \left(U_k(a) + \frac{3}{\sqrt{6}} V_k(a)\right) \\ - \int_r \frac{\partial \mu}{\partial r} \left(U_k(r) + \frac{3}{\sqrt{6}} V_k(r)\right) r^2 \mathrm{d}r,\end{aligned} \tag{6}$$

where a is the Moon mean radius, U_k and V_k are the mode eigenfunctions for the radial and tangential displacements, and γ_k is the decay rate of the eigenmode.

Similar theoretical computation was done for the Earth by (Coughlin and Harms 2014a,b,c) later extended to a laterally heterogeneous Earth's model considering normal mode coupling by (Majstorović et al. 2019).

From equation (1) we see that the lunar induced response depends on the metric perturbation, the GW frequency, GW incidence angles and the 1D lunar model (from which we derive normal mode displacement eigenfunctions and eigenfrequencies). By considering the resonance regime ($\omega_g = \omega_k$) we can calculate the lunar response shown in Fig. 7 for a seismometer placed at a distance of about 170 km from the lunar pole. The radial response is strongly suppressed since the GW propagation direction is parallel to the Moon's polar axis.

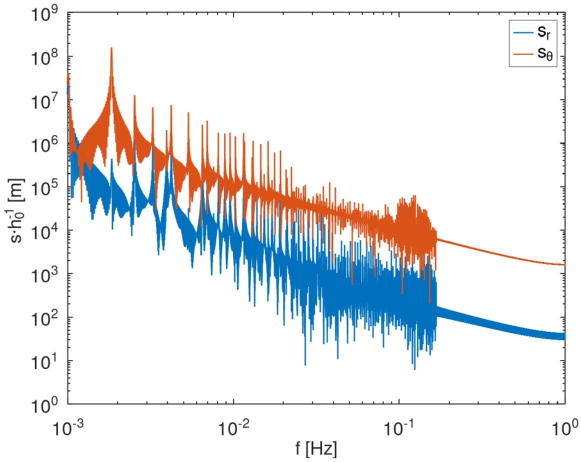

Fig. 7 Lunar GW response calculated by summing 229 quadruple normal modes and for a sensor location close to the lunar north pole ($\theta = 0.1$, $\phi = 0.1$). The GW propagates parallel to the lunar rotation axis. The response is calculated from a 12 h long time series sampled at 0.5 s. As expected, the GW response s_r along the radial direction is suppressed near the poles

Numerical simulations implementing topography and regional geological models will be necessary for a more accurate GW response model in the decihertz band. For example, such a model must be able to reproduce the observed effects on moonquake waveforms, from which very high Q-factors around a few 1000 of the ground medium were inferred (Garcia et al. 2019).

3.2 The Lunar Gravitational-Wave Antenna (LGWA)

The first upper limits on a GW power spectrum published in 1961 were obtained in the range 0.3 mHz – 4.5 mHz by measuring the deformation of the Earth produced by GWs with a Benioff strain seismograph (Forward et al. 1961). This experiment was carried out by a group of physicists from University of Maryland (Forward, Zipoy, Weber) together with seismologists from Caltech (Smith, Benioff). To overcome the sensitivity limitations set by the terrestrial background of seismic and atmospheric noise, Weber went on to develop high-precision laboratory-scale experiments known as resonant-bar antennas operating in the kHz range. He also proposed the development of a seismometer to observe the normal modes of the Moon excited by GWs, which was deployed in 1972 by the crew of Apollo 17 (Giganti et al. 1977). The Lunar Surface Gravimeter, as it was called, did not reach the expected performance due to a design error, and today we know that even a working instrument would not have reached the sensitivity to observe GWs.

Nonetheless, it was well known from other seismic experiments during the Apollo era that the seismic background on the Moon is several orders of magnitude lower than on Earth in the range 0.1 Hz to a few Hz (Coughlin and Harms 2014c). The instrument noise of the seismometers limited these searches, and models of the seismic background formed by moonquakes and meteoroid impacts predict that several orders of seismometer sensitivity improvements are possible before meeting limitations from a continuous seismic background (Lognonné et al. 2009; Harms 2022).

The concept for an array of high-precision seismic sensors suitable for GW detection on the Moon was proposed under the name LGWA (Harms et al. 2021). It consists of four seismic stations deployed in a PSR. Starting from an ambient temperature of less than 40 K, as can be found in some permanently shadowed regions (PSRs) at the lunar north and south poles, a sorption cooler will bring the payload to 4 K (Wu et al. 2017) so that niobium, a superconducting material with high mechanical quality (Bilenko et al. 2002), can be used

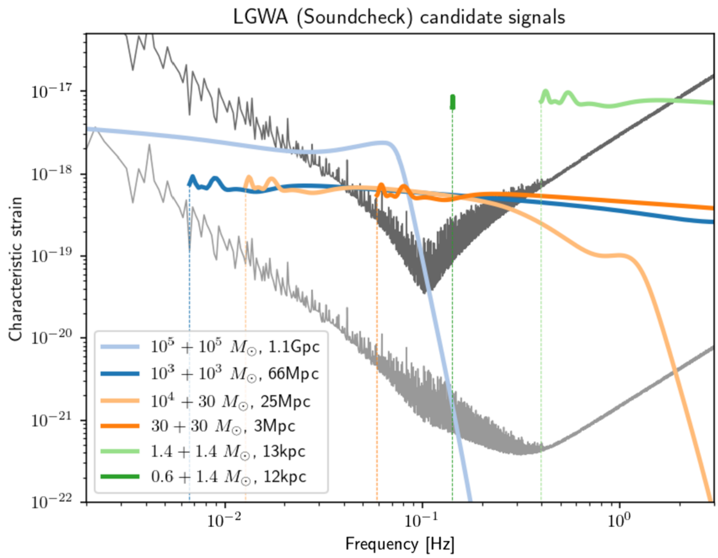

Fig. 8 Characteristic strain noise of LGWA (light gray) and its precursor mission LGWA Soundcheck (dark gray) compared with a few examples of signal spectra. Here, an observation time of 2 months is assumed for all signals. The amplitude modulation of the GW signals due to the rotation of the Moon is visible for signals with slow frequency evolution. The distance of each signal is chosen to yield an SNR of about 9 in LGWA Soundcheck. The plot was produced with GWFish (Dupletsa et al. 2022)

for the proof mass and actuators (van Heijningen et al. 2022). The use of superconductors for the proof mass and for the coil actuators will reduce damping and therefore thermal noise in the system.

The LGWA sensitivity model is shown in Fig. 8 (light gray) together with the sensitivity model of LGWA Soundcheck (dark gray). LGWA Soundcheck was proposed as an explorer of the seismic environment inside a PSR and as a technology demonstrator. The spectra of a few example signals are displayed assuming an observation time of 2 months for each signal. The distances of the signals are chosen so that the signal-to-noise ratio (SNR) of observations with LGWA Soundcheck is about 9. The aim is to achieve a displacement sensitivity of 10^{-12} m/Hz$^{1/2}$ from 0.1 Hz to 1 Hz with LGWA Soundcheck, and 10^{-13} m/Hz$^{1/2}$ at 0.1 Hz and 2×10^{-15} m/Hz$^{1/2}$ at 1 Hz with the LGWA array. Below 0.1 Hz, the LGWA sensitivity is fundamentally limited by thermal noise of the proof-mass suspension, while the seismic background is expected to limit the sensitivity above 0.1 Hz together with the noise of the laser-interferometric readout of the proof-mass displacement (van Heijningen et al. 2023). In Sect. 3.5, a technique to reduce the noise from the seismic background is described, which makes use of an optimal, frequency-dependent combination of data from the four seismometers. A careful analysis of achievable noise-reduction factors still needs to be done based on a geological model of the deployment site.

3.3 The Lunar Seismic and Gravitational Antenna (LSGA)

The LSGA project aims for a measurement of strain deformations of the Moon produced by GWs and geophysical signals (Katsanevas et al. 2020). A laser interferometer whose optics are mounted on the lunar surface is proposed to observe GW signals. A more detailed analysis of the geophysical signals is proposed to be achieved with a network of optical fibers

(Hilweg et al. 2022). The mounts of the laser optics can be adapted from laser retroreflectors, which are being developed independently for a CLPS mission launch (Intuitive Machines n. 3, or IM-3) to the Reiner Gamma site (59W, 7N) in 2024 (dubbed CP11), under a NASA-ESA MoU.

Laser retroreflector system description. It consists of three main subsystems: (1) the bare 10 cm diameter, high-quality optical retroreflector MoonLIGHT (Moon Laser Instrumentation for General relativity/Geophysics High accuracy tests); (2) MPAc (MoonLIGHT Pointing Actuators, a customized dual gimbal) during system deployment; (3) ADC (Actuated Dust Cover) to protect MoonLIGHT's optical face from the accumulation of regolith dust. This overall retroreflector system will support Lunar Surface Laser Ranging with a laser deployed on the Moon, as opposed to the standard LLR (Lunar Laser Ranging) up until now performed by ground laser stations located on the Earth and targeting the existing Apollo 11, 14, 15 and Lunokhod 1, 2 reflectors. MoonLIGHT-MPAc-ADC will also support standard LLR for the test of General Relativity including measurements of possible time variations of the gravitational constant, test of the Weak and Strong Equivalence Principle, inverse-square-law deviations, measurements of the beta parameter of the parameterized post-Newtonian formalism (through the Nordtvedt parameter), and geophysics (composition of deep lunar interior) on the 2024 CP11 CLPS mission. The accuracy is ten fold increased with respect to the Apollo/Lunokhod reflectors. Delivery of the first MoonLIGHT-MPAc-ADC proto flight model (PFM1) is currently foreseen by the end of 2023. In parallel and following the PFM1 delivery, a second PFM will be built by ESA and INFN for new opportunities and studies for new applications, like GW detection on the Moon (like this proposal), a Geophysical package for ESA's Argonaut, Lunar Geophysical Network (LGN) activities. The current CP11 reflector system is required to have an accuracy of equal or less than 3 degrees, although its design can be customized to be capable of 1 degree.

Potential sources of uncertainty and mitigation strategies for the reflector. The heritage that is being acquired through the 2024 CP11 mission (delivery of the PFM1 to IM-3 foreseen in August 2023) represents a significant risk reduction in reflector performance. The availability of a PFM2 is a further risk reduction. All three subsystems have margins for improvement beyond the CP11 baseline. The pointing accuracy can be improved if needed (equal or less than 3 degrees is enough for CP11). The current optical accuracy of MoonLIGHT is: wave/10 in total retro-reflected flatness, and 0.2 arcseconds in the dihedral angle offsets. Improvements for GW detection are possible with extra funding (like for example the flatness of the three back reflecting surfaces and the flatness of the total retro-reflected laser wavefront).

Given its direct inheritance from Apollo 11, 14, and 15, fully exposed optics that work on the surface of the Moon for more than 55 years on the Moon, MoonLIGHT and its basic mounting components/design (Suprasil 1 and/or 311, Aluminum and KEL-F plastic) will resist lunar surface radiation for decades. The same applies to the thermal excursion heritage: Apollo reflectors, which are not too far from the equator, are expected to experience a thermal range of about 300 K based on in situ Apollo temperature measurements and detailed orbit thermal measurements (by DIVINER on LRO). The only Apollo optical performance variation observed in 50 years of LLR observations was a slow reduction of their laser return intensity (due to slow regolith dust deposition over the reflectors), which according to LLR station measurements and associated studies is estimated to be about a factor of 10 in 50 years. But this effect has been compensated by laser station improvements over the same time. If coping with dust accumulations will be needed given the specific deployment scheme (for example a rover) the ADC will have to be considered.

3.4 The Gravitational-Wave Lunar Observatory for Cosmology (GLOC)

Current GW detectors like LIGO and Virgo implement sophisticated isolation and active mitigation techniques to reduce the impact of the environment on the GW measurement (Matichard et al. 2015,?; Fiori et al. 2020). Proposed next-generation detectors like Einstein Telescope and Cosmic Explorer will push the observation band to lower frequencies, which will increase the role of environment disturbances (Amann et al. 2020; Hall et al. 2021). The coupling between environment and detector happens through many different mechanisms. For example, it can be mechanical coupling through the suspension systems, stray light entering the main beam path, direct gravitational coupling to acoustic and seismic fields, magnetic fluctuations, etc. Environmental disturbances also affect the operation of the laser interferometer, where a complex control system must align the suspended optics to bring the interferometer to its most sensitive state and keep it there (Allocca et al. 2020). The Gravitational-wave Lunar Observatory for Cosmology (GLOC) was proposed as a triangular, laser-interferometric concept with suspended optics (Jani and Loeb 2021). It will profit from the quiet lunar environment to simplify the interferometer control and isolation systems, and to exploit the natural high-quality vacuum at the lunar surface. In this way, it might be possible to overcome low-frequency sensitivity limitations known from terrestrial detectors and extend the observation band to decihertz frequencies.

The strain sensitivity goal of 10^{-23} $\mathrm{Hz}^{-1/2}$ at 1 Hz will nonetheless require seismic isolation. Assuming a baseline of 10 km, the differential displacement of the two suspended test masses of an interferometer arm will have to be less than 10^{-19} $\mathrm{m/Hz}^{1/2}$ at 1 Hz, which requires about 5 orders of magnitude attenuation with respect to ground motion (Harms 2022). This can in principle be achieved with a staged suspension systems coupled with ultra-sensitive seismometers or strainmeters. However, there is no known material and proposed suspension technology that would produce low enough suspension thermal noise to reach the sensitivity goal at 1 Hz (Harms et al. 2013; Harms and Mow-Lowry 2017). Furthermore, while the interferometer control of GLOC would likely be significantly simpler than what is needed for terrestrial detectors, there are intrinsic effects that need to be counteracted like radiation pressure and strong enhancement of vibrations at the suspension resonances. Such controls are known to inject considerable noise into the system at low frequencies (Andric and Harms 2021).

A possible advantage of GLOC over space-based concepts is that the lifetime of space-based detectors is limited by orbital dynamics eventually making it impossible to maintain a satellite configuration with established laser links. There is no known hard limit to the lifetime of GLOC. The expected science return of GLOC would be much more impactful than of LGWA and LSGA and be close to previously proposed space-based detector concepts like Big Bang Observer (Phinney et al. 2003) and DECIGO (Kawamura et al. 2021). GLOC would be able to observe most types of GW sources from a wide range of compact object masses out to high redshift. It would have an immense impact on cosmology and observe astrophysical sources with high signal-to-noise ratio to enable high-precision tests of general relativity and precise measurements of the properties of compact stellar objects.

3.5 Seismic Background-Reduction Techniques

Even though the lunar environment has an extremely low level of seismic noise, a significant seismic background might still be present in lunar GW measurements in particular due to meteorite impacts. The LGWA seismic array will be exploited to estimate and subtract the seismic background to meet the LGWA sensitivity requirements. Similar techniques might also find applications in GW concepts like LSGA and GLOC.

With this goal in mind, we can make use of the experience gained in terrestrial GW interferometers for what concerns the cancellation of a gravitational-noise background produced by density variations in the environment of a detector associated with seismic and atmospheric fields (Harms 2019; Trozzo and Badaracco 2022). It is predicted to affect the sensitivity of terrestrial GW detectors in their low-frequency band (2–30 Hz), and it is predicted to be important even for future underground GW detectors like the Einstein Telescope, where the gravitational noise is anticipated to be significantly reduced (Badaracco and Harms 2019; Amann et al. 2020). Gravitational noise is widely believed to establish a practical lower frequency limit for terrestrial GW detectors (Harms et al. 2013).

Coherent noise cancellation is an effective way to clean GW data from environmental noise (e.g., see Driggers et al. 2012, 2019) and was proposed to overcome sensitivity limits in future GW detectors (Cella 2000; Driggers et al. 2012). Wiener filters are a possible choice for the optimal processing of environmental data for noise cancellation (Coughlin et al. 2014). In the case of NN cancellation, seismic sensors will be placed around the detector test masses to provide the information for a coherent estimate of the NN associated with the seismic field. In the case of Wiener filtering, the information is encoded in the correlations between the seismic sensors and with the detector data. To maximise the noise-cancellation performance, one needs to *optimize the array configuration*, which means to find the sensor locations and orientations that minimize the residual noise in the GW data. A study of this nature has already been performed for the GW detector Virgo (Badaracco et al. 2020).

To find the optimal array, one can use recorded seismic data and numerical simulations of the seismic field; in particular, we need to evaluate the cross power spectral density (CPSD) between seismometers. For optimizations of surface seismometer arrays, the domain of this function is a four-dimensional space (the coordinates of two points on the surface). This poses a challenge to the optimization algorithm especially for larger numbers of seismometers. With seismic data from N sensors, we will be able to evaluate $N \times N$ two-point spatial correlations. A technique is required to create a surrogate model of the Wiener filter based on the observed CPSDs, e.g., using Gaussian Process Regression. One can use the surrogate model to estimate the residual of the noise cancellation for an arbitrary number of seismometers in an arbitrary array configuration, whose optimum can then be found.

In the case of lunar GW detectors, the available seismic data from a lunar site will be none or very few before the detector is being deployed. In this case, based on a geological and topographic model of the site, one can employ numerical simulations of the CPSD (Andric and Harms 2020). The results of such simulations can either directly enlarge the set of observed CPSDs, or they can be used in a more sophisticated optimization algorithms as priors of a Bayesian optimization (Andric 2022). Such hybrid optimization schemes, i.e., based on data and simulations, will also be necessary for the Einstein Telescope and are currently under development.

Also for LGWA, the optimal array configuration for background reduction needs to be determined. Lunar seismic data from PSRs are not available yet. Numerical simulations of the seismic field combined with seismic measurements in lunar analogues, e.g., volcanic landscapes, will be fundamental to determine effective array configurations.

4 Lunar Science

4.1 Seismic Exploration of the Moon and Mars

The Moon and Mars are the only two terrestrial bodies other than Earth for which seismological studies have been performed. For the Moon, this has been made thanks the deployment of a network of 4 passive seismometers operated as one of the sensors of the Apollo Lunar Surface Experiment (ALSEP). See (Lognonné and Pike 2015; Lognonné and Johnson 2015; Garcia et al. 2019; Nunn et al. 2021) for a general overview of Apollo instruments (Lognonné and Pike 2015; Nunn et al. 2021) and results (Lognonné and Pike 2015; Garcia et al. 2019). After two unsuccessful attempts (Anderson et al. 1977; Lognonné et al. 1998), Mars has been seismically explored by the SEIS instrument (Lognonné et al. 2019) onboard NASA InSight mission (Banerdt et al. 2020).

More than 13000 Moonquakes have been recorded over the 7.7 years of the Lunar Network operation, most of them being Deep Moonquakes or impacts, with the exception of 30 shallow moonquakes (Nakamura et al. 1981); see among other (Frohlich and Pulliam 1999; Kawamura et al. 2017) for the deep moonquakes seismicity; see (Oberst 1987) for shallow moonquakes and (Lognonné et al. 2009; Gudkova and Zharkov 2004; Gudkova et al. 2015) for impacts.

Slightly more than 1300 Marsquakes have been recorded over the 4 years of InSight operation (Marsquake Service 2023); see (Giardini et al. 2020; Clinton et al. 2020; Ceylan et al. 2022) for more on Mars seismicity.

For the Moon, and because of the four-station network configuration, the internal structure has been constrained from mostly arrival differential travel times of direct waves (e.g. (Lognonné et al. 2003; Gagnepain-Beyneix et al. 2006) for the mantle, crustal conversions (Vinnik et al. 2001) and located impacts (Lognonné et al. 2003; Gagnepain-Beyneix et al. 2006; Chenet et al. 2006) for the crust and core reflected phase (Weber et al. 2011; Garcia et al. 2011) for the core.

For Mars and because of the single station configuration, the use of secondary phases, such as PP, PPP, SS, SSS was necessary for mantle inversion (Khan et al. 2021; Drilleau et al. 2022). The crust below InSight landing site has been characterized by receiver function (Lognonné et al. 2020; Knapmeyer-Endrun et al. 2021) but also by surface wave analysis (Kim et al. 2021; Beghein et al. 2022; Kim et al. 2023) following the recording of two very large impacts (Posiolova et al. 2022) and the largest M = 4.7 marsquake (Kawamura et al. 2022). Last but not least, the core has also been detected thanks ScS phases (Stähler et al. 2021).

With respect to GW detection from the Moon, one of the most critical points related to lunar structure is the extremely low rigidity of the lunar subsurface, with shear velocities ranging from 50 m/s to 125 m/s in the first 15 m (Tanimoto et al. 2008) and increasing deeper toward an average of 500 m/s in the first km (Garcia et al. 2011) associated with a globally distributed cover of regolith. On the other side, the low seismic activity of the Moon will be beneficial to all GW detectors: most of the moonquakes have indeed amplitudes smaller than a few 10^{-10} m and furthermore, the Apollo records were flat most of the time, despite their sensitivity of $0.5 \cdot 10^{-10}$ m in ground displacement at 0.5 Hz.

4.2 Space Qualified Very Broadband and Long-Period Seismometer Performances

To date, only the Apollo Long Period seismometer (Bates et al. 1979) and the InSight very broadband (VBB) seismometer (Lognonné et al. 2019) have successfully flown. A comparison is shown in Fig. 9. The noise floor was about $2 \cdot 10^{-10}$ m/s^2/Hz$^{1/2}$ and 10^{-10} m/s^2/Hz$^{1/2}$ for the Apollo Z sensor and InSight VBBZ, respectively, at 0.5 Hz, but with a much better resolution for InSight. In 2025, the FarSide seismic suite (Panning et al. 2022) will operate a vertical VBB, which is a spare unit of InSight with an improved displacement transducer but a lower mechanical gain due to its vertical configuration. A new VBB based on optical sensing (de Raucourt et al. 2022) is now in development for future missions, including Argonaut, Artemis or LGN (Weber et al. 2020), with a targeted noise of $5 \cdot 10^{-12}$ m/s^2/Hz$^{1/2}$ in

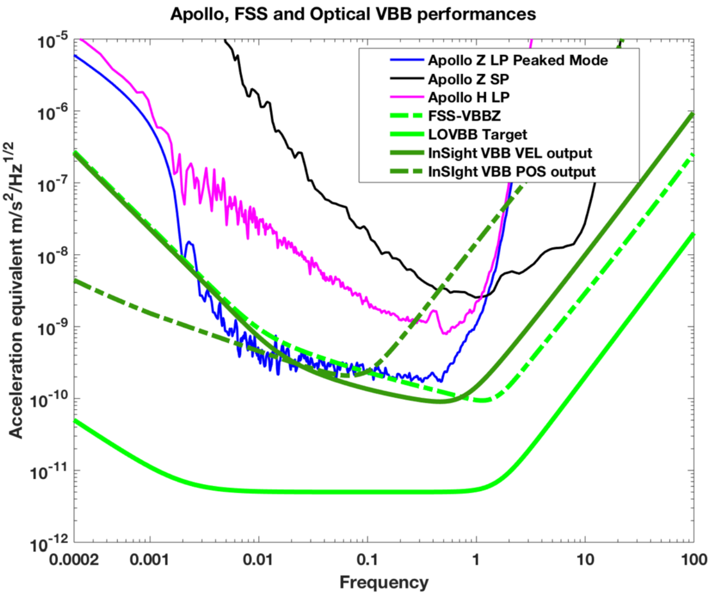

Fig. 9 Comparison in acceleration spectral density of the self noise of the Apollo sensors, of the InSight VBB sensor for both the Velocity and the POS, tidal outputs, and the future Lunar VBB

the 0.01 Hz–1 Hz bandwidth ($1.5 \cdot 10^{-13}$ m/Hz$^{1/2}$ at 1 Hz). It has first reached TRL4 in the frame of the H2020 PIONEERS project (Mimoun et al. 2019) and TRL 6 is now targeted by mid 2025 through CNES funding. At 1 Hz, the proof mass Brownian noise is the major source of noise, while the other sources of noise, including those of the interferometric reading, are about $5 \cdot 10^{-13}$ m/s^2/Hz$^{1/2}$. Larger proof masses with higher Q could therefore in principle be considered, if such a laser-optical VBB was used for active seismic mitigation of lunar GW detectors.

4.3 Distributed Acoustic Sensing (DAS)

Use of extended fibre optic cables as seismic antennas in various applications onshore and offshore has increased significantly in the last decade (Jousset et al. 2018; Landrø et al. 2022; Bouffaut et al. 2022; Nishimura et al. 2021; Taweesintananon et al. 2021). For Lunar applications (Landrø et al. 2022; Sollberger et al. 2016) seismic fibre optic cables are attractive due to low weight and long range, which opens for the possibility of designing a lunar seismic gravitational antenna (LSGA).

The basic principle for all DAS (distributed acoustic sensing) is illustrated in Fig. 10, where an acoustic source is creating a stretch in an optic fibre. In a fibre (telecommunication fibre or specially designed fibre) there are always impurities or inhomogeneities that act as optical scatterers (illustrated by the orange sphere in Fig. 10) that will move a small distance ΔL which can be found by measuring the optical phase difference between two signals recorded by the interrogator, that is $\Delta L = c\Delta t$ where c is the speed of light in the fibre and Δt is the time delay between the two signals.

Recently there has been a rapid improvement in DAS-interrogation. First, the signal to noise ratio versus distance has improved significantly, which makes it possible to measure signals 100 to 150 km into a fibre optic cable. A practical example is shown in Fig. 11,

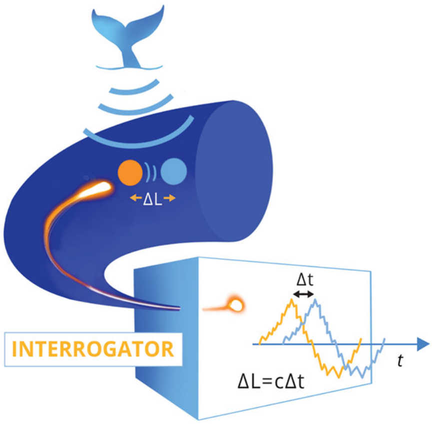

Fig. 10 The acoustic wavefield originating from the acoustic source modulates the fiber. The light propagating inside the fiber, which is backscattered due to inhomogeneities of the glass, is thus reflected from positions being shifted in space by the acoustic wavefield. This is indicated by the orange and light blue sphere. A DAS interrogator can reconstruct this acoustic wavefield present at each location along the fiber by detection of the change/modulation to the phase of the backscattered light, illustrated by the two shifted curves in the interrogator box, also color-coded to see the relation to the two spheres that are shifted by the acoustic signal generated by the whale. Figure from Landrø et al. (2022)

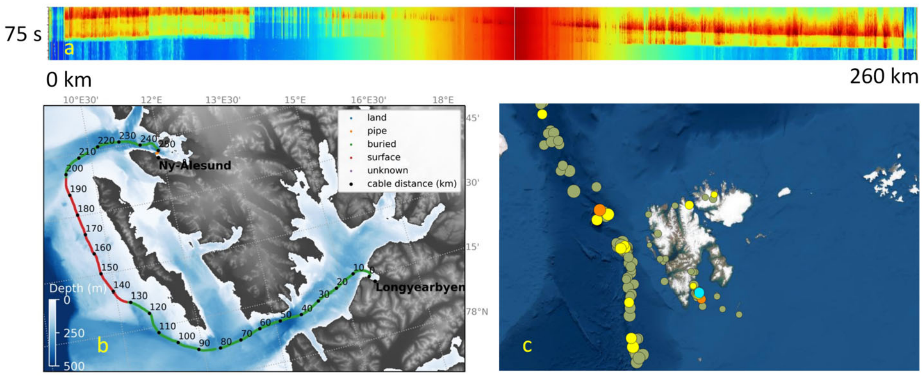

Fig. 11 a) DAS-recording (x-axis denotes distance along fibre in km from Ny Ålesund and y-axis shows 75 seconds of data) of an earthquake south of Svalbard. The first event is the P-arrival and the second is the S-arrival. In the present example we have used one interrogator in Ny Ålesund and another in Longyearbyen and spliced the two plots together. The signal to noise ratio is gradually decreasing and at the middle of the cable (approximately at 130 km) we observe that the earthquake signal is hardly visible. b) the path for the trenched fibre optic cable and c) the earthquake position (blue circle) south of the fibre optic cable

where a recent earthquake (August 2022) south of Svalbard was recorded by two DAS-interrogators.

Second the sensitivity has increased, enabling a strain sensitivity better than 10^{-10}. It is expected that new interrogators in the future will push this limit further. The strain sensitivity for frequencies above 1 Hz depends on the gauge length (the length over which coherent phase changes are sampled, see Fig. 10) and the distance from the interrogator to the observation point on the fibre. For instance a gauge length of 10 m and a distance of 10 km yields a strain sensitivity of 10^{-11} and a gauge length of 40 m for the same distance yields a strain sensitivity of approximately 10^{-12}. If the fibre distance is increased to, for instance, 50 km, these numbers drop by a factor of 10, approximately. (Landrø et al. 2022) show that good quality DAS-data can be acquired as low as 10 mHz (and probably lower), which is essential for LSGA-applications. There are several experiments that should be carried out on earth in Lunar-like environments prior to installing DAS-fibres on the Moon. Challenges are related to issues like coupling to the ground. In Fig. 11 the variation in signal strength along the fibre is partly caused by weak coupling to the seabed. Various types of fibres should also be tested in order to determine an optimal Lunar DAS-fibre.

4.4 Seismic Background

Despite the Apollo seismic passive experiment, very little is known about the micro-seismic lunar noise. Records from the Apollo Long period seismometer suggest that the recorded noise was likely instrument self noise on the vertical axis (Lognonné and Johnson 2015), meaning that an upper limit was set for the vertical noise at about $2 \cdot 10^{-10}$ m/s^2/Hz$^{1/2}$ in the 0.1–0.5 Hz bandwidth. This translates into a ground displacement noise of 20 pm/Hz$^{1/2}$ at 0.5 Hz. Horizontal seismic noise was reported with amplitudes five times larger at 1 Hz (10^{-9} (m/s^2)/Hz$^{1/2}$) and rising as $1/f$ towards lower frequencies. This appears most likely to be tilt noise with a non-seismic origin. Last but not least, the lack of atmosphere of the Moon will prevent from surface pressure noise and from associated gravitational fluctuations as are present on Earth (Fiorucci et al. 2018).

The true micro-seismic background noise of the Moon has therefore not yet been recorded by seismometers. The FarSide Seismic Suite, with an expected 20 times better sensitivity than Apollo peaked mode at 1 Hz (Panning et al. 2022) might measure the noise better above 0.5 Hz but likely not below 0.5 Hz, but future seismometers on Artemis might reach that microseismic noise floor (Weber et al. 2020). A background noise associated with impacts has been proposed based on the extrapolation of Apollo peaked-mode seismic data toward smaller amplitudes (Lognonné et al. 2009), and will likely be mostly related to short periods surface waves trapped in the very low velocity subsurface. Simulations predict a root-mean-square (rms) of background noise that lies 50% of the time below 75 fm and 90% of the time below 0.5 pm based on minute-long stretches of time series (Lognonné et al. 2009). These values correspond to the square-root of the integrated spectral densities within the simulated measurement band. Assuming a flat displacement spectrum of the impact signals (Daubar et al. 2018) and for simplicity a bandwidth of 1 Hz of the ground-displacement spectrum, this translates into a background smaller than $5 \cdot 10^{-14}$ m/Hz$^{1/2}$ at 1 Hz 50% of the time. Confirming such low noise will be critical for future lunar GW projects.

Seismic waves in the decihertz band are expected to be strongly scattered by subsurface heterogeneities and will have relatively low horizontal phase or group velocities (about 40 m/s at 5 Hz and possibly 100 – 150 m/s at 1 Hz). These phase velocities for a 50 fm/Hz$^{1/2}$ displacement noise amplitude on the horizontal axes (not considering potentially important contributions from ground tilt and assuming equal displacement spectra along the horizontal and vertical directions), will lead to seismic strain of about $2 - 3 \cdot 10^{-15}$ Hz$^{-1/2}$ at 1 Hz. Background mitigation will require seismic measurements very close to the GW sensors with self noise low enough to prevent noise injection in the process.

4.5 Lunar Geology

The naked eye view of the Moon shows two different types of terrains: the darker Maria volcanic plains and the brighter Highlands, which are topographically higher and rugged. The Highlands constitute about 85% of the total surface of the Moon.

The application of the geological principles to study the observations made with orbital and landed robotic and crewed missions to the Moon since the 1960's has brought to the identification of two main processes which shaped the surface of the Moon since its formation: volcanism and impact cratering. The Maria are the expression of primarily basaltic flows which filled the topographic lows, overlapping the lighter terrains. Over the Maria, physiographic features like ridges, domes, fissures, and caves skylight support the hypotheses of the volcanic origin of these terrains. Craters are everywhere on the Moon, but rough Highlands have a remarkably higher crater density than the Maria. Impact cratering on the airless Moon happens at hypervelocity and the resulting structures, the craters, witness the effect of impactors at all scales. The craters on the Moon range from 175 km in diameter down to the micrometer scale of micro-impact of space debris, resulting in a continuous abrasion of all exposed material.

The continuous meteoritic bombardment generates a layer of crushed and melted rock called the regolith. In the Apollo era, we had direct access to the regolith, and samples of the regolith can be studied on Earth. The mean grain size of lunar regolith ranges from 40 to 800 μm, with most of the material falling between 45–100 μm (Heiken et al. 1991). The thickness of the regolith ranges from about 5 m on Maria to about 10–20 m on the highlands. However, seismic data from geophysical observations from Apollo 15 seismometers suggest that the first layer of the Moon is made by a highly scattering media a few kilometers up to 20 km thick, referred to as the mega-regolith (Latham et al. 1972). This is consistent with the presence of craters tens of kilometers in diameter, contributing to fracturing the first kilometers of the lunar crust. The compositional diversity between the Maria and the Highlands also implies a lateral variability of the regolith. From the gravitational wave detection perspective, knowing the site-specific geology can be critical in deploying instrumentation on the surface. A geologic model can also drive numerical models simulating the acoustic response of the regolith.

5 Gravitational-Wave Science

Considering all proposed concepts, lunar GW detection might cover an observation band from 1 mHz to a few Hz and open the decihertz band to GW observations (Harms 2022). Several studies have highlighted the importance of a decihertz observatory (Jani and Loeb 2021; Sedda et al. 2020; Mandel et al. 2018; Isoyama et al. 2018; Harms et al. 2021). Considering a network of lunar GW detectors, additional scientific studies can be carried out. For example, antipodal pairs of GW detectors at the two lunar poles would form an ideal network for the search of stochastic GWs exploiting correlations between two detectors (Coughlin and Harms 2014a). It was also pointed out that a distribution of vibration sensors over the surface of the Moon would enable detailed measurements of the GW polarization and interesting tests of general relativity (Wagoner and Paik 1976; Bianchi et al. 1996). In this section, we will briefly outline some of the main science goals of lunar GW detection.

5.1 Populations of Compact Binaries in the Local Universe

Compact binary systems composed of white dwarfs (WDs), neutron stars (NSs) and black holes (BHs) populating our local Universe – from our Solar neighbourhood, through the Milky Way out into the Local Group, up to hundreds of Mpc away for the most massive binaries – are among the sources observable by lunar GW detectors. These detectors have the potential to extend observations in the mHz frequency band of missions like LISA (Amaro-Seoane et al. 2017), TianQin (Luo et al. 2016) and Taiji (Ruan et al. 2020) to the mid-frequency band (about 0.05 Hz – 1 Hz) where mergers of WD binaries occur or to create a bridge to the high-frequency observations of terrestrial GW detectors.

Compact stellar remnant binary systems are guaranteed GW sources as some have are already been discovered with electromagnetic (EM) telescopes. The most famous example of such a binary being the first discovered binary pulsar (Hulse and Taylor 1975), which via measuring its orbital decay over three decades led to the first indirect evidence for GWs (Weisberg and Taylor 2005) and paved the way forward for the field of GW astronomy. Discoveries of many more systems consisting of a NS/WD with another compact companion down to orbital periods as short as several minutes followed since then (Kupfer et al. 2018). Some of the shortest period and better characterised of the known binaries have been even proposed to use for testing space-based GW detectors and maximising their scientific output (e.g. Stroeer and Vecchio 2006; Kupfer et al. 2018; Littenberg 2018; Finch et al. 2022). Therefore known binaries are also called *verification binaries* in the GW literature. Some of these verification binaries can be detected with LGWA (Harms et al. 2021). Furthermore, known binaries offer a new opportunity to study the astrophysics of compact binaries using both their GW and EM radiation (e.g. Marsh 2011; Korol et al. 2017; Breivik et al. 2018; Tauris 2018; Littenberg and Cornish 2019).

From a theoretical perspective, compact binaries are expected to be several orders of magnitude more abundant than currently observed by EM telescopes, with binaries composed of two WDs being the most abundant in the Milky Way and its immediate neighbourhood. Their formation involves up to several mass transfer episodes; at least one of these episodes has to be unstable leading to a *common envelope*, a phase during which binary can shrink dramatically (Paczynski 1976; Webbink 1984; Livio and Soker 1988; de Kool et al. 1987; Ivanova et al. 2015). Even though this is one of the least understood phases in binary evolution, the fact that we do observe close double compact objects and mergers is a strong indication that something like a common envelope phase takes place. Thus, the demographics of compact binaries observed via GW radiation will provide opportunities to learn new physics and answer key scientific questions related to formation and evolutionary processes of tight binary systems. Besides the common envelope physics, this includes questions related to the stability and efficiency of mass and angular momentum transfer, tides, accretion onto compact objects, as well as details of their destruction in supernovae explosions (for a review see Amaro-Seoane et al. 2023).

At frequencies < 1 mHz, binary population synthesis simulations predict $\mathcal{O}(10^7)$ double WDs, followed by $\mathcal{O}(10^5)$ NSWDs in the Milky Way alone (Amaro-Seoane et al. 2023). Studying these binary populations with EM facilities has proven to be technically challenging due to the compact size of these binaries and WD/NS stars themselves, and so GW detectors – characterised by different selection effects – are ideally suited for discovering and characterising them in bulk (Rebassa-Mansergas et al. 2019; Korol et al. 2022). Importantly, GW selection effects enable the study of double compact objects with weak EM signatures at unprecedentedly large distances throughout the Milky Way, including its most massive satellites and possibly reaching out as far as the Andromeda galaxy, which is otherwise impossible with EM telescopes (Korol et al. 2018; Roebber et al. 2020; Wilhelm et al. 2021; Keim et al. 2023).

5.2 Mergers of Massive BHs and AGNs

Based on high spatial resolution observations (van der Marel 1994; Kormendy and Richstone 1995), it is now accepted that at the center of every galaxy (perhaps with the exception of irregular galaxies) lies a BH heavier than about 10^6 $M_\odot$. The best evidence for this was provided by the microarcsecond angular resolution images of SgrA*, at the Milky Way center, and of the nucleus of M87, the giant elliptical at the heart of the Virgo cluster, obtained by the Event Horizon Telescope at millimetric wavelengths (Event Horizon Telescope Collaboration et al. 2019, 2022).

Virtually no galaxy goes undisturbed during its lifetime, and in fact galaxies often experience episodes of strong interaction with their neighbors, or even mergers (Barnes and Hernquist 1992). In the Local Universe, interacting pairs of galaxies abound, as displayed for instance by the spectacular HST imagery archived in the Hubble Heritage repository .[2] These legacy snapshots witness the onset of dynamical friction, when the distances between the galaxies central SMBHs are still tens to hundreds of kpc. Radio observations can resolve binary SMBHs down to separations of parsecs in radiogalaxies at $z \sim 0.1$ (Rodriguez et al. 2006; Deane et al. 2014).

From the above follows that super-massive nuclear BHs (SMBH) at the centers of interacting galaxies will become dynamically bound and form close orbits in binary (or multiple) systems. SMBH in binary systems represent a large fraction of the totality of SMBHs in the Universe (Volonteri et al. 2002). Loss of energy via gravitational radiation will cause the orbits to shrink and the binary SMBH system to coalesce in a few million years of the binary "hardening" (Begelman et al. 1980; Komossa and Zensus 2016; Valtonen et al. 2021).

Galactic interaction may trigger star formation in the vicinity of the orbiting SMBH, and nuclear activity when the SMBHs are at less than a parsec distance from one another. This is in fact considered to be a major channel of nuclear activity ignition so that it has been speculated that a large fraction of, or virtually all, AGN should contain a binary SMBH at their centers.

Search for evidence of binary central motion in AGN at all wavelengths from radio to gamma-rays in the form of periodic signals in their light curves has yielded appealing and suggestive results, although the significance is generally not robust, e.g. (Ackermann et al. 2015). The most convincing case appears to be that of OJ287, a blazar source at $z = 0.306$, that shows maxima with a rest-frame period of approximately 9 years in its optical light curve. This was however evenly and densely sampled only in the latest 25 years (Valtonen et al. 2021). The model that describes the binary SMBH system in the nucleus of OJ287 suggests a distance between the two BHs of $\sim$0.1 pc and a remaining lifetime of 10^4 years before merger.

The final inspiral and merger of binary SMBHs should produce a gravitational signal of sub-Hz frequency, that the future LISA mission and – with higher S/N – the perspective lunar GW experiments could detect from any cosmological distance.

5.3 The Case of SN 1a Progenitors

Type 1a Supernovae (SN 1a) play a crucial role in modern cosmology. In addition to providing the first evidence that the Universe is accelerated by some sort of dark energy, they recently led to a tension with the value of the Hubble constant derived from modelling of the Cosmic Microwave Background (CMB) (Cappellaro 2022, for a review). Yet, and despite of their importance, the nature of their progenitors is still unclear.

SNe Ia are believed to originate from white dwarfs (WD) which, due to mass transfer in close binary systems, grow above the Chandrasekhar limit ($\sim 1.4\,M_\odot$) and then are incinerated by a thermonuclear explosion in degenerate matter conditions. This idea dates back

[2] https://hubblesite.org/.

to the early 1970s (Whelan and Iben 1973) but the actual nature of the secondary stars is still undetermined. Two alternative scenarios have been proposed: the donor can be a main sequence or a red giant star (the single degenerate scenario, or SD), or another WD (the double degenerate scenario, or DD), which would lose orbital momentum via gravitational waves (GW) radiation and eventually merge.

The evidence collected so far in favour of one or the other option is all indirect. As examples of relevant results we can list: i) the presence (Patat et al. 2011) or absence (Sand et al. 2021) of signatures of circumstellar gas surrounding the progenitor that favour SD and DD, respectively; ii) the failed search for a surviving companion of historical SN Ia in our Galaxy, favoring DD (Ruiz-Lapuente et al. 2019); iii) the failed search of a precursor star in pre-explosion archival images (Graur et al. 2014) favoring DD; iv) the search for candidate DD systems that did not find a sufficient number of short period, massive WDs to account for the observe SN Ia rates (Napiwotzki et al. 2020) favoring SD, or otherwise sub-Chandrasekhar explosions; v) the distribution of delay time from star formation to explosion derived from statistics of SN Ia rate that tends to favor the DD scenario (Maoz et al. 2012), although the strength of this argument is debatable (Greggio and Cappellaro 2019).

The bottom line is that, after decades of research, none of the results are conclusive and, in some cases, the findings appear to be even in contradiction. The new era of gravitational wave (GW) astronomy opens a new avenue for obtaining independent and direct insights to nature of the SN Ia progenitor, which remains an open question in modern astrophysics (Livio 2001). This is because the binary systems from which SN Ia originate are GW sources (cf. Sect. 5.1).

In the case of SD systems, mass transfer to the accreting WD occurs when the secondary donor star fills its Roche lobe. This sets a lower limits for the separation between the two stars and the orbital period (of the order of 10 minutes). In this configuration the GW emission is weak and does not affect significantly the binary evolution. On the other end, loss of orbital momentum via GW emission causes the shrinking of DD system orbital radius. Because of the small tidal radius of WDs, this allows a minimum orbital period (P) of a few seconds and a stronger GW signal. In fact, the GW emission grows with the GW frequency, and hence is proportional to P^{-1}.

We have to consider that at frequency of 10^{-2} Hz the merging time for DD systems is $\sim 10^4$ yr. Hence, the Galaxy needs to host few tens WDs with mass $>= 0.7\, M_\odot$ orbiting with this frequency to allow for 1–5 SN per thousand years. If these systems are not found, either SD dominate the census of progenitor systems or SN Ia can originate from system of smaller mass. We notice that whereas the Sub-Chandrasekhar scenario is not the favoured option to explain the majority of SN Ia (Mazzali et al. 2007), it is gaining support also in accounting for the observed SN Ia diversity (Flörs et al. 2020).

Detectors like LGWA would be able to probe the $10^{-2} - 1$ Hz GW spectral range. The analysis of mass and orbital period distribution of DD systems would allow for accurate prediction of the SN rate that can be compared with observations.

One may envisage that the ultimate proof of the DD-SNIa connection would be the observation of the merging event followed by the detection of its electromagnetic (EM) counterpart. However, one has to consider that the chance of observing a DD merging is of the order of the SN Ia rate, hence one in a few centuries in the Galaxy. In addition, while in special cases one may expect that the SN explosion, and hence the appearance of the EM source following a few seconds after the merger (Pakmor et al. 2022), more conventional scenarios allow for a long delay between the merger and the explosion, ranging up to 10^4 yr (Shen et al. 2012). This implies that, even in the case such a rare event of a WD merger of appropriate mass occurs and its GW emission is detected, it may not be associated to a

SN Ia EM event, and hence it would not provide the long sought and much desired smoking gun.

This is why, in the current state of affairs, the comparison between the known rate of SNe 1a and the rate of GW sources with the properties expected for the merging of DD systems is probably one of the most promising tools to solve this key question.

5.4 Core-Collapse Supernovae and Jets

The acceleration of a jet to relativistic velocity is an interesting source of gravitational waves: Jet-GWs (Segalis and Ori 2001; Piran 2002; Sago et al. 2004; Birnholtz and Piran 2013; Leiderschneider and Piran 2021; Piran 2022). This is a memory type signal whose amplitude satisfies:

$$h \approx \frac{4G\mathcal{E}}{c^4 r} \approx 10^{-24}\left(\frac{\mathcal{E}}{10^{51}\ \mathrm{erg}}\right)\left(\frac{100\mathrm{Mpc}}{r}\right). \tag{7}$$

where G is Newton's constant, $\mathcal{E}$ is the jet's energy, c is the speed of light and d the distance to the source. The rise time and the corresponding typical frequency are determined by the longer of the acceleration time or the duration of the jet. Such signals arise from any source in which a relativistic jet is accelerated. AGNs and GRBs are, of course, the classical sources that first come to mind. However, the first are quasi steady state sources (on human time scale) whose typical frequencies are far too low. The second are typically too far and their signals are typically to weak to be detected.

Core collapse SNe (CCSNe) jets are within the frequency range and are possibly sufficiently nearby to be within the expected sensitivity of Moon GW detectors. Such jets were inferred recently to take place in several powerful SNe (Piran et al. 2019). These jets are hidden as they are choked while propagating in the exploding star. However, they deposit their energy in the stellar envelope in powerful cocoons. In some directions, that are not too far from the jet axis, a low-luminosity GRB can be observed as the cocoon breaks out from the envelope (Kulkarni et al. 1998; MacFadyen et al. 2001; Tan et al. 2001). This was noted already for the first low luminosity GRBs 980425. However, the existence of such jets can be inferred even when we do not observe the low-luminosity GRB. The cocoon ejecta escapes with large velocities (Pais et al. 2023) reaching up to 100,000 km/sec in SN 2017iuk (Izzo et al. 2019; Nakar 2019). Those velocities are far higher than typical velocities seen in regular GRBs. The high velocity material spreads around the exploding SN (Piran et al. 2019; Pais et al. 2023) absorbing some of the light of the SNe producing very broad absorption lines. Such lines have been observed already in SN 1997ef (Mazzali et al. 2000) but their origin remained mysterious for more than two decades (Piran et al. 2019). The lines disappear after a few days as the fast material spreads and becomes optically thin. Hence, they have been observed only in a few cases when the SN followup was initiated rather quickly. The existance of such hidden jets is supported by other evidence for jets in SNe (Totani 2003; Mazzali et al. 2005; Maeda et al. 2008; Taubenberger et al. 2009; Grichener and Soker 2017).

Piran et al. (Piran et al. 2019) estimated that the typical energies of these CCSNe jets are of order 10^{51} ergs or even higher. This energy is typically insufficient to explode the SN. However, it is an important component in the overall energy budget. Jet-GWs are the only way to directly observe these jets. With typical distances of a few tens of Mpc as compared to a few Gpc for long GRBs and a few hundred Mpc for a nearby short GRB, SNe-Jets are prime candidate sources for detectable Jet-GWs. In fact, estimates suggest that the Jet-GWs from a powerful CCSNe may be stronger and easier to detect than the GWs that arise from the SN collapse itself.

5.5 Tidal Disruption of WDs

Main sequence or giant stars nearby stellar black holes (BH) or super-massive black holes (SMBH) have been observed to be disintegrated or disrupted during their passage at the periastron; these are the so-called Tidal Disruption Events (TDEs). The disrupted star undergoes extreme acceleration that stretches the lighter star along the line of gravitational force and squeezes it along the perpendicular directions; hence the star is flattened in an elongated pancake shape, aligned to the plane of its orbit around the compact star (Carter and Luminet 1982). These TDEs are mainly transient phenomena that lasts for days to months and observed at multi-wavelength by EM observatories (see e.g. Rossi et al. 2021, and references therein). A catalog of observed TDE candidates can be found here .[3]

TDE requires that the passage of the lighter star near the compact object lie within the tidal radius (so called Roche or Hill radius) (Hills 1976) written as

$$R_t \approx R_* \left(\frac{M_c}{M_*}\right)^{1/3}, \tag{8}$$

where (R_*, M_*) are the radius and mass of the lighter star and M_c is the mass of the compact star. The strength of the TDE is defined as the penetration parameter

$$\beta_p = \frac{R_t}{R_p}, \tag{9}$$

while R_p is the periastron radius.

For a TDE, three conditions have to be satisfied: (i) $\beta_p \geq 1$, which can be achieved if the star approaches the BH [4] in a highly eccentric or parabolic trajectory. For a given M_*, (ii) $R_t > R_*$, and $R_{\mathrm{BH}} > R_*$; where R_{BH} is event horizon of BH, otherwise the whole BH enters into the star, and (iii) $R_t > R_{\mathrm{BH}}$ otherwise, the BH would engulf the entire star at once (Maguire et al. 2020).

The disrupted star results in debris, in which most of the matter is dispersed away from the BH but a smaller part of the stellar matter form closed orbits (Rees 1988) that results in the EM radiation via various processes. In addition, a burst-like GW signal is also generated because the quadrupole moment of the star due to the tidal deformation varies in time as it makes the closest approach towards the BH. Since the GW strain increases with the M_* and decreases with the R_* for a given β_p, hence a WD or an NS will have stronger GW signals with higher frequencies as well compared to a main-sequence or giant star (Kobayashi et al. 2004). However, a WD-BH TDE is more likely than a NS-BH TDE because NSs are around 10^8 times denser than WDs, so they often result in mergers without a TDE. Another reason is that WDs are much more prevalent in the universe compared to NSs (Shapiro and Teukolsky 1983).

The most relevant feature of the WD-BH TDEs is that the associated GW frequencies lie in the deci-Hz band which is between the observation bands of by LISA, 10^{-1} Hz and lower, and that of the ground based GW detectors above 10 Hz (Casalvieri and Ferrari 2006). Hence, the deci-Hz sensitivity of lunar GW detectors fills this *observational gap* and opens up future possibilities to detect Intermediate Mass Black holes (IMBHs) and to probe the spin of the responsible BH for the TDE (Gezari 2014). For establishing the detection of a

[3] https://tde.space/.

[4] From here until the end of this section, 'BH' stands for all kinds of black holes including Supermassive and intermediate mass black holes.

WD-BH TDE, the EM-counterparts for the GW signal will be of great importance, since during the disruption the WD is subjected to extreme pressure causing a sharp increase in the temperature, triggering explosive nuclear burning for $\beta_p \geq 3$ (Rosswog et al. 2009), which is seen as a transient increase in the luminosity followed by an slow decay. Fast X-ray transients and optical Type-Ia supernovae-like events are also the possible observational manifestations of a WD-BH TDE (Haas et al. 2012). EM signatures may also include observations of jets due to the Blandford-Znajek process (Lam et al. 2022).

5.6 GW Cosmology

By accessing GW signals in a frequency range from 0.1 – 1 Hz with a sensitivity of $\sim 10^{-21}$ in strain measurement, lunar GW detector concepts like LGWA and GLOC could potentially survey black holes across several orders of magnitude in mass to cosmological distances. The enhanced low-frequency sensitivity permits the survey of primordial and intermediate-mass black holes (IMBHs) practically across the entire universe. Such cosmological reach is crucial for connecting IMBHs with the Pop-III remnants (Madau and Rees 2001) and the seeds of supermassive black holes (Gair et al. 2009; Pacucci and Loeb 2020). Furthermore, the cosmological reach of lunar GW detectors at their peak sensitivities is not expected to have any astrophysical foregrounds from the white dwarf binaries (Robson et al. 2019). Thus, any GW signal with redshifted frequency $f_{\rm det} = (1 + z)\, f_{\rm src} \gtrsim 0.2$ Hz could be identified in the data without contamination.

As an illustration, we show in Fig. 12 the cosmological reach of GLOC for various binaries consisting of neutron stars and black holes of several orders of masses. While we do not expect observations of such binaries beyond $z \sim 30$ (Loeb and Furlanetto 2013), even one such detection would violate ΛCDM cosmology (Koushiappas and Loeb 2017; Ng et al. 2022).

One of the strongest science cases of lunar GW astronomy program is towards studying Type 1a supernovae (SNe) mechanisms. The access to 0.1 – 1 Hz enables direct discrimination between the single (Falta et al. 2011; Seitenzahl et al. 2015) and double degenerate (mergers of two white dwarfs) scenarios of Type 1a SNe. 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.

Lunar GW detectors can put the tightest bounds on the speculative population of sub-solar dark matter objects ($0.1 - 1\, M_\odot$) (Shandera et al. 2018). 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 (Abbott et al. 2019). The deci-Hz reach of lunar GW detectors allows us to measure the dark matter density of such exotic objects to 30% of the entire observable volume of the universe ($z \sim 10$).

For stellar black hole binaries, lunar GW detectors would start measuring the inspiral phase a day before the merger. A multi-band observation (Jani et al. 2019) of these black holes binaries between the Moon and earth-based GW detector on Earth can reduce the sky-location error to the angular scale of a single galaxy. This opens a new population of high redshift dark sirens to independently measure the evolution of the Hubble parameter as a function of redshift (Schutz 1986). Furthermore, combining these high redshift dark sirens with GW lensing would constraint cosmological parameters to increased precision (Congedo and Taylor 2019).

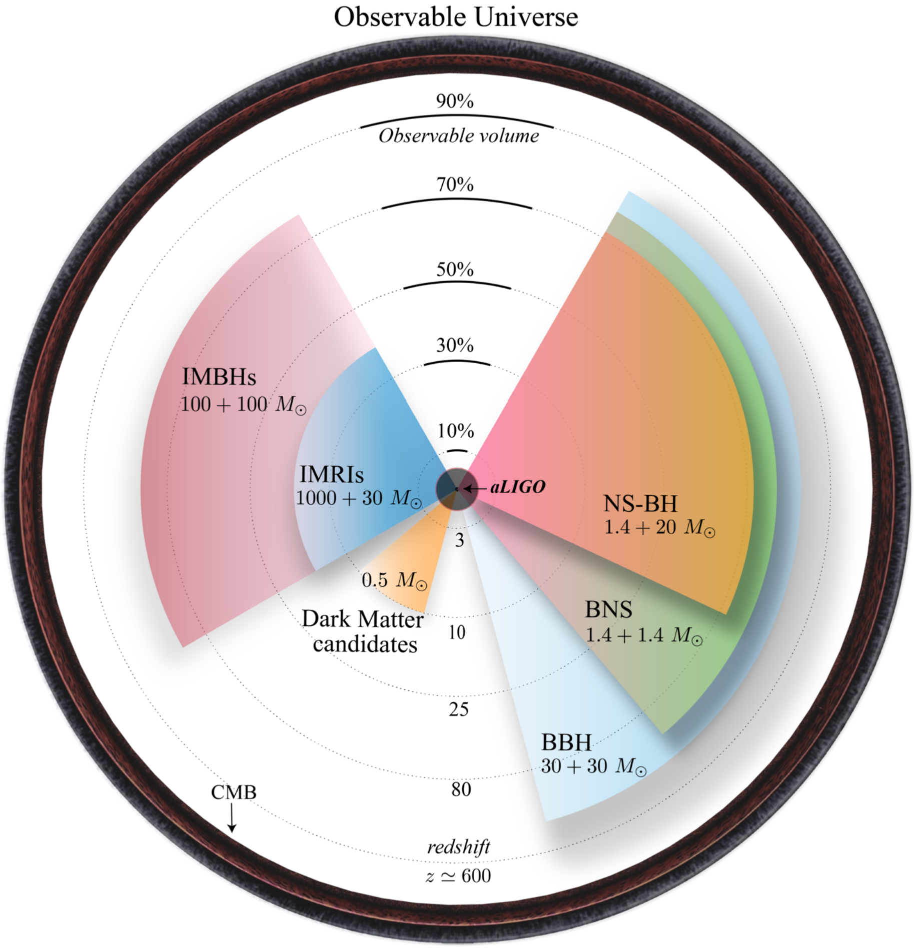

Fig. 12 Cosmological reach of a lunar GW detector concept GLOC in comoving coordinates. The concentric circles represent the percentage fraction of the comoving volume of the observable universe ($V_{\text{obs}} = 1.22 \times 10^4$ Gpc^3) out to a given cosmological redshift, with the outermost being the cosmic microwave background. The highlighted slices refer to the reach of GLOC in units of redshift. For reference, the circle in the center represents the maximum reach of Advanced LIGO at the design sensitivity for a 100 solar mass binary. The plot was adapted from Jani and Loeb (2021)

6 Conclusion

In this article, we provided an overview of the proposed concepts for lunar GW detectors and discussed some of the key technologies to realize the instruments. We highlighted the unique properties of the Moon that enable an exclusive contribution of lunar GW detection to the field including the Moon's extremely low background of seismic disturbances, and the low-temperature, thermally stable conditions of the Moon's permanently shadowed regions. The Moon can either be used as an antenna for GWs and a sensor reads out its deformations caused by the fluctuating spacetime, or it can serve as an ultra-quiet environment for a long-baseline laser interferometer similar in design to the current detectors on Earth.

Having access to the frequency band 0.1 Hz – 1 Hz, lunar GW detectors will be able to observe GW sources that LISA or future terrestrial GW detectors cannot see. These sources include intermediate-mass black-hole binaries at the cosmic dawn and beyond, mergers of white-dwarf binaries in our local universe, tidal disruption events, and low-frequency signals from supernovae and jets. Some of these sources will emit electromagnetic (EM) counterparts, and the association of GW and EM signals can teach us more about the environment of these sources and provide ground-breaking insight into source mechanisms, e.g., revealing the nature of SN-1a progenitors.

Lunar GW detectors will also play a crucial role in what is known as multiband GW observations. A neutron-star binary can be detected months before its merger, which can then be observed with terrestrial GW detectors and EM observatories. An early warning of the upcoming merger can be issued together with a precise sky-localization. Similarly, an intermediate-mass black-hole binary can be observed first in the millihertz band with a LISA-type detector and later its merger in the decihertz band with a lunar GW detector for high-precision waveform analyses.

Finally, the deep connection that is established by lunar GW detection between observations of the universe through GWs and of the Moon through its seismic properties is an immense and unique opportunity for an inter-disciplinary science case. In fact, the present article is an early product of this collaboration.

7 Dedication to Stavros Katsanevas

ISSI Forum on Lunar Gravitational-wave Detection, 5–6 Oct, 2022. Stavros Katsanevas was a Greek-French physicist born in Athens in 1953. He was director of the European Gravitational Observatory, former director of the AstroParticle and Cosmology (APC) laboratory, and former chairman of the Astroparticle Physics European Consortium (APPEC). He spearheaded the inter-disciplinary approach to gravitational-wave research and conceived, under the aegis of the NASA Artemis mission, a lunar project for the detection of gravitational radiation that uses the Moon itself as a detector.

The launch of the Artemis program by NASA, aimed at following up the Apollo missions and setting up the conditions for cis-lunar colonization, stirred a lot of interest and enthusiasm in the European community, and sparked ideas and proposals to foster various areas of science from astroparticle to biophysics, from seismology to condensed matter physics.

With characteristic vision and scientific foresight, Stavros caught this opportunity to conceive a gravitational detection experiment that used the Moon itself as a detector and adopted Engineered Fiber Distributed Acoustic Sensors (EFDAS) to offer sensitivity to the signal. With his holistic approach to science, he went a step further and involved the astrophysicists to identify the multi-wavelength characteristics of the potential gravitational wave emitters and the electromagnetic facilities that would optimize their detection and monitoring. Ultimately, this should lead to establish a fully-fledged multi-messenger observational program from the Moon.

This ISSI Forum was part of these efforts and was intended as a kickoff of the possible European collaborations in GW Lunar projects and activities. Very sadly, Stavros left us less than two months after the Workshop, after having dedicated to this, and a multitude of other projects, up to the last minute of his very creative and intellectually rich life.

However, the seeds Stavros has sown bear a solid promise to bring EFDAS to the Moon and all the technology involved in gravity waves detection using lunar experiments. Most importantly, he spearheaded progress in new physical and technological avenues, both experimental and theoretical. He then contributed to establish a network of scientists dedicated to the manifold aspects of research development and exploitation of the lunar environment, and saw into it that this team and its projects could start and grow in a coordinated and choral way and could play a dominant role in the global lunar race.

The baton of this concept has been passed on to us, his colleagues, friends and followers, who will endeavour to further it into completion and implementation.

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Declarations

Competing Interests The authors declare no conflict of interests.

References

Aasi J et al [LIGO Scientific Collaboration] (2015) Advanced LIGO. Class Quantum Grav 32(7):074001. https://doi.org/10.1088/0264-9381/32/7/074001

Abbott BP [LIGO Scientific Collaboration, Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration, The DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF, AST3, CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, SKA South Africa/MeerKAT] (2017a) Multi-messenger observations of a binary neutron star merger. Astrophys J Lett 848(2):12. https://doi.org/10.3847/2041-8213/aa91c9

Abbott BP et al [LIGO Scientific Collaboration, Virgo Collaboration] (2016) Observation of gravitational waves from a binary black hole merger. Phys Rev Lett 116:061102. https://doi.org/10.1103/PhysRevLett.116.061102

Abbott BP et al [LIGO Scientific Collaboration, Virgo Collaboration] (2017) GW170817: observation of gravitational waves from a binary neutron star inspiral. Phys Rev Lett 119(16):161101. https://doi.org/10.1103/PhysRevLett.119.161101. arXiv:1710.05832 [gr-qc]
Abbott BP et al [LIGO Scientific Collaboration, Virgo Collaboration] (2017b) Estimating the contribution of dynamical ejecta in the kilonova associated with GW170817. Astrophys J Lett 850:L39. https://doi.org/10.3847/2041-8213/aa9478. arXiv:1710.05836 [astro-ph.He]
Abbott BP et al [LIGO Scientific Collaboration, Virgo Collaboration] (2018) GW170817: measurements of neutron star radii and equation of state. Phys Rev Lett 121:161101. https://doi.org/10.1103/PhysRevLett.121.161101
Abbott BP et al [LIGO Scientific Collaboration, Virgo Collaboration] (2019) Search for subsolar mass ultracompact binaries in Advanced LIGO's second observing run. Phys Rev Lett 123(16). https://doi.org/10.1103/physrevlett.123.161102
Abbott R et al [LIGO Scientific Collaboration, Virgo Collaboration, KAGRA Collaboration] (2021). GWTC-3: compact binary coalescences observed by LIGO and Virgo during the second part of the third observing run. arXiv e-prints. https://arxiv.org/abs/2111.03606
Acernese F et al (2010) Measurements of Superattenuator seismic isolation by Virgo interferometer. Astropart Phys 33(3):182–189. https://doi.org/10.1016/j.astropartphys.2010.01.006
Acernese F et al (2014) Advanced Virgo: a second-generation interferometric gravitational wave detector. Class Quantum Grav 32(2):024001. https://doi.org/10.1088/0264-9381/32/2/024001
Acernese F et al [Virgo Collaboration] (2023) Advanced Virgo plus: future perspectives. J Phys Conf Ser 2429(1):012040. https://doi.org/10.1088/1742-6596/2429/1/012040
Acharya BS et al [CTA consortium] (2013) Introducing the CTA concept. Astropart Phys 43:3–18. https://doi.org/10.1016/j.astropartphys.2013.01.007
Ackermann M et al (2015) Multiwavelength evidence for quasi-periodic modulation in the Gamma-ray blazar PG 1553+113. Astrophys J 813(2):41. https://doi.org/10.1088/2041-8205/813/2/L41. arXiv:1509.02063 [astro-ph.HE]
Adhikari RX et al (2020) A cryogenic silicon interferometer for gravitational-wave detection. Class Quantum Grav 37(16):165003. https://doi.org/10.1088/1361-6382/ab9143
Agullo I, Cardoso V, del Rio A, Maggiore M, Pullin J (2021) Potential gravitational wave signatures of quantum gravity. Phys Rev Lett 126:041302. https://doi.org/10.1103/PhysRevLett.126.041302
Event Horizon Telescope Collaboration, Akiyama K, Alberdi A, Alef W, Asada K, Azulay R, Baczko A-K, Ball D, Baloković M, Barrett J et al (2019) First M87 Event Horizon Telescope results. I. The shadow of the supermassive black hole. Astrophys J 875(1):1. https://doi.org/10.3847/2041-8213/ab0ec7. arXiv:1906.11238 [astro-ph.GA]
Event Horizon Telescope Collaboration, Akiyama K, Alberdi A, Alef W, Algaba JC, Anantua R, Asada K, Azulay R, Bach U, Baczko A-K et al (2022) First Sagittarius A* event horizon telescope results. I. The shadow of the supermassive black hole in the center of the Milky Way. Astrophys J 930(2):12. https://doi.org/10.3847/2041-8213/ac6674
KAGRA Collaboration, Akutsu T et al (2019) KAGRA: 2.5 generation interferometric gravitational wave detector. Nat Astron 3(1):35–40. https://doi.org/10.1038/s41550-018-0658-y
Alexander JK, Kaiser ML, Novaco JC, Grena FR, Weber RR (1975) Scientific instrumentation of the Radio-Astronomy-Explorer-2 satellite. A&A 40(4):365–371
Allocca A, Bersanetti D, Casanueva Diaz J, De Rossi C, Mantovani M, Masserot A, Rolland L, Ruggi P, Swinkels B, Tapia San Martin EN, Vardaro M, Was M (2020) Interferometer sensing and control for the advanced Virgo experiment in the O3. Sci Run Galaxies 8(4). https://doi.org/10.3390/galaxies8040085
Amann F et al (2020) Site-selection criteria for the Einstein telescope. Rev Sci Instrum 91(9):094504. https://doi.org/10.1063/5.0018414
Amann F, Bonsignorio F, Bulik T, Bulten HJ, Cuccuru S, Dassargues A, DeSalvo R, Fenyvesi E, Fidecaro F, Fiori I, Giunchi C, Grado A, Harms J, Koley S, Kovács L, Losurdo G, Mandic V, Meyers P, Naticchioni L, Nguyen F, Oggiano G, Olivieri M, Paoletti F, Paoli A, Plastino W, Razzano M, Ruggi P, Saccorotti G, Sintes AM, Somlai L, Ván P, Vasúth M (2020) Site-selection criteria for the Einstein telescope. Rev Sci Instrum 91(9):094504. https://doi.org/10.1063/5.0018414
Amaro-Seoane P, Audley H, Babak S, Baker J, Barausse E, Bender P, Berti E, Binetruy P, Born M, Bortoluzzi D, Camp J, Caprini C, Cardoso V, Colpi M, Conklin J, Cornish N, Cutler C, Danzmann K, Dolesi R, Ferraioli L, Ferroni V, Fitzsimons E, Gair J, Gesa Bote L, Giardini D, Gibert F, Grimani C, Halloin H, Heinzel G, Hertog T, Hewitson M, Holley-Bockelmann K, Hollington D, Hueller M, Inchauspe H, Jetzer P, Karnesis N, Killow C, Klein A, Klipstein B, Korsakova N, Larson SL, Livas J, Lloro I, Man N, Mance D, Martino J, Mateos I, McKenzie K, McWilliams ST, Miller C, Mueller G, Nardini G, Nelemans G, Nofrarias M, Petiteau A, Pivato P, Plagnol E, Porter E, Reiche J, Robertson D, Robertson N, Rossi E, Russano G, Schutz B, Sesana A, Shoemaker D, Slutsky J, Sopuerta CF, Sumner T, Tamanini N, Thorpe I, Troebs M, Vallisneri M, Vecchio A, Vetrugno D, Vitale S, Volonteri M, Wanner G, Ward H, Wass P,

Weber W, Ziemer J, Zweifel P (2017) Laser Interferometer Space Antenna. ArXiv e-prints, arXiv:1702.00786 [astro-ph.IM]

Amaro-Seoane P, Andrews J, Arca Sedda M et al (2023) Astrophysics with the Laser Interferometer Space Antenna. Living Rev Relativ 26:2. https://doi.org/10.1007/s41114-022-00041-y. arXiv:2203.06016 [gr-qc]

Amati L, O'Brien PT, Götz D, Bozzo E, Santangelo A, Tanvir N, Frontera F, Mereghetti S, Osborne JP, Blain A, Basa S, Branchesi M, Burderi L, Caballero-García M, Castro-Tirado AJ, Christensen L, Ciolfi R, De Rosa A, Doroshenko V, Ferrara A, Ghirlanda G, Hanlon L, Heddermann P, Hutchinson I, Labanti C, Le Floch E, Lerman H, Paltani S, Reglero V, Rezzolla L, Rosati P, Salvaterra R, Stratta G, Tenzer C (2021) Theseus consortium: the THESEUS space mission: science goals, requirements and mission concept. Exp Astron 52(3):183–218. https://doi.org/10.1007/s10686-021-09807-8. arXiv:2104.09531 [astro-ph.IM]

Anderson DL, Miller WF, Latham GV, Nakamura Y, Toksöz MN (1977) Seismology on Mars. J Geophys Res 82(28):4524–4546. https://doi.org/10.1029/JS082i028p04524

Andreoni I, Margutti R, Salafia OS, Parazin B, Villar VA, Coughlin MW, Yoachim P, Mortensen K, Brethauer D, Smartt SJ, Kasliwal MM, Alexander KD, Anand S, Berger E, Bernardini MG, Bianco FB, Blanchard PK, Bloom JS, Brocato E, Bulla M, Cartier R, Cenko SB, Chornock R, Copperwheat CM, Corsi A, D'Ammando F, D'Avanzo P, Datrier LEH, Foley RJ, Ghirlanda G, Goobar A, Grindlay J, Hajela A, Holz DE, Karambelkar V, Kool EC, Lamb GP, Laskar T, Levan A, Maguire K, May M, Melandri A, Milisavljevic D, Miller AA, Nicholl M, Nissanke SM, Palmese A, Piranomonte S, Rest A, Sagués-Carracedo A, Siellez K, Singer LP, Smith M, Steeghs D, Tanvir N (2022) Target-of-opportunity observations of gravitational-wave events with Vera C. Rubin observatory. Astrophys J Suppl Ser 260(1):18. https://doi.org/10.3847/1538-4365/ac617c. arXiv:2111.01945 [astro-ph.HE]

Andric T (2022) Providing priors to Bayesian array optimization for the Sardinian candidate site of the Einstein Telescope. Nuovo Cimento C 45(6):183. https://doi.org/10.1393/ncc/i2022-22183-7

Andric T, Harms J (2020) Simulations of gravitoelastic correlations for the Sardinian candidate site of the Einstein Telescope. J Geophys Res, Solid Earth 125(10):e2020JB020401. https://doi.org/10.1029/2020JB020401

Andric T, Harms J (2021) Lightsaber: a simulator of the angular sensing and control system in LIGO. Galaxies 9(3). https://doi.org/10.3390/galaxies9030061

Armano M et al (2016) Sub-femto-g free fall for space-based gravitational wave observatories: LISA pathfinder results. Phys Rev Lett 116(23):231101. https://doi.org/10.1103/PhysRevLett.116.231101

Arun KG, Belgacem E, Benkel R et al (2022) New horizons for fundamental physics with LISA. Living Rev Relativ 25(1):4. https://doi.org/10.1007/s41114-022-00036-9. arXiv:2205.01597 [gr-qc]

Badaracco F, Harms J (2019) Optimization of seismometer arrays for the cancellation of Newtonian noise from seismic body waves. Class Quantum Grav 36(14):145006. https://doi.org/10.1088/1361-6382/ab28c1

Badaracco F, Harms J, Bertolini A, Bulik T, Fiori I, Idzkowski B, Kutynia A, Nikliborc K, Paoletti F, Paoli A, Rei L, Suchinski M (2020) Machine learning for gravitational-wave detection: surrogate Wiener filtering for the prediction and optimized cancellation of Newtonian noise at Virgo. Class Quantum Grav 37(19):195016. https://doi.org/10.1088/1361-6382/abab64

Baker J, Haiman Z, Rossi EM, Berger E, Brandt N, Breedt E, Breivik K, Charisi M, Derdzinski A, D'Orazio DJ, Ford S, Greene JE, Hill JC, Holley-Bockelmann K, Key JS, Kocsis B, Kupfer T, Madau P, Marsh T, McKernan B, McWilliams ST, Natarajan P, Nissanke S, Noble S, Phinney ES, Ramsay G, Schnittman J, Sesana A, Shoemaker D, Stone N, Toonen S, Trakhtenbrot B, Vikhlinin A, Volonteri M (2019) Multimessenger science opportunities with mHz gravitational waves. Bull Am Astron Soc 51(3):123. https://doi.org/10.48550/arXiv.1903.04417. arXiv:1903.04417 [astro-ph.HE]

Banerdt WB, Smrekar S, Banfield D, Giardini D, Golombek M, Johnson C, Lognonné P, Spiga A, Spohn T, Perrin C, Stähler S, Antonangeli D, Asmar S, Beghein C, Bowles N, Bozdağ E, Chi P, Christensen U, Clinton J, Collins G, Daubar I, Dehant V, Drilleau M, Fillingim M, Folkner W, Garcia R, Garvin J, Grant J, Grott M, Grygorczuk J, Hudson T, Irving J, Kargl G, Kawamura T, Kedar S, King S, Knapmeyer-Endrun B, Knapmeyer M, Lemmon M, Lorenz RD, Maki J, Margerin L, McLennan S, Michaut C, Mimoun D, Mittleholz A, Mocquet A, Morgan P, Müller N, Murdoch N, Nagihara S, Newman C, Nimmo F, Panning MP, Pike WT, Plesa A-C, Rodriguez S, Rodriguez-Manfredi J-A, Russell CT, Schmerr N, Siegler M, Stanley S, Stutzman E, Teanby N, Tromp J, van Driel M, Warner N, Weber R, Wieczorek M (2020) Initial results from the InSight mission on Mars. Nat Geosci 13:183–189. https://doi.org/10.1038/s41561-020-0544-y

Barnes JE, Hernquist L (1992) Dynamics of interacting galaxies. Annu Rev Astron Astrophys 30:705–742. https://doi.org/10.1146/annurev.aa.30.090192.003421

Bates JR, Lauderdale WW, Kernaghan H (1979) ALSEP termination report. Technical Report 1036, National Aeronautics and Space Administration

Bayle J-B, Bonga B, Caprini C, Doneva D, Muratore M, Petiteau A, Rossi E, Shao L (2022) Overview and progress on the Laser Interferometer Space Antenna mission. Nat Astron 6:1334–1338. https://doi.org/10.1038/s41550-022-01847-0

Begelman MC, Blandford RD, Rees MJ (1980) Massive black hole binaries in active galactic nuclei. Nature 287(5780):307–309. https://doi.org/10.1038/287307a0

Beghein C, Li J, Weidner E, Maguire R, Wookey J, Lekić V, Lognonné P, Banerdt W (2022) Crustal anisotropy in the Martian lowlands from surface waves. Geophys Res Lett 49(24):2022–101508. https://doi.org/10.1029/2022GL101508

Bellovary J, Brooks A, Colpi M, Eracleous M, Holley-Bockelmann K, Hornschemeier A, Mayer L, Natarajan P, Slutsky J, Tremmel M (2019) Where are the intermediate mass black holes? Bull Am Astron Soc 51(3):175. https://doi.org/10.48550/arXiv.1903.08144. arXiv:1903.08144 [astro-ph.HE]

Ben-Menahem A (1983) Excitation of the Earth's eigenvibrations by gravitational radiation from astrophysical sources. Nuovo Cimento C 6(1):49–71. https://doi.org/10.1007/BF02511372

Berry C, Hughes S, Sopuerta C, Chua A, Heffernan A, Holley-Bockelmann K, Mihaylov D, Miller C, Sesana A (2019) The unique potential of extreme mass-ratio inspirals for gravitational-wave astronomy. Bull Am Astron Soc 51(3):42. https://doi.org/10.48550/arXiv.1903.03686. arXiv:1903.03686 [astro-ph.HE]

Berti E, Barausse E, Cholis I, Garcia-Bellido J, Holley-Bockelmann K, Hughes SA, Kelly B, Kovetz ED, Littenberg TB, Livas J, Mueller G, Natarajan P, Shoemaker DH, Shoemaker D, Schnittman JD, Vallisneri M, Yunes N (2019) Tests of general relativity and fundamental physics with space-based gravitational wave detectors. Bull Am Astron Soc 51(3):32. https://doi.org/10.48550/arXiv.1903.02781. arXiv:1903.02781 [astro-ph.HE]

Bianchi M, Coccia E, Colacino CN, Fafone V, Fucito F (1996) Testing theories of gravity with a spherical gravitational wave detector. Class Quantum Grav 13(11):2865–2873. https://doi.org/10.1088/0264-9381/13/11/003

Bilenko IA, Ju L, Paget D, Blair DG (2002) Niobium flexure suspension design for high Q sapphire test masses for future gravitational wave detectors. Meas Sci Technol 13(8):1173. https://doi.org/10.1088/0957-0233/13/8/302

Birnholtz O, Piran T (2013) Gravitational wave memory from gamma ray bursts' jets. Phys Rev D 87(12):123007. https://doi.org/10.1103/PhysRevD.87.123007. arXiv:1302.5713 [astro-ph.HE]

Bogenstahl J, Tröbs M, d'Arcio L, Diekmann C, Fitzsimons ED, Hennig JS, Hey FG, Killow CJ, Lieser M, Lucarelli S, Perreur-Lloyd M, Pijnenburg J, Robertson DI, Taylor A, Ward H, Weise D, Heinzel G, Danzmann K (2017) Design and construction of a telescope simulator for LISA optical bench testing. In: Cugny B, Armandillo E, Karafolas N (eds) International conference on space optics — ICSO 2012, vol 10564. SPIE, Bellingham, p 105643. https://doi.org/10.1117/12.2309066. International Society for Optics and Photonics, https://doi.org/10.1117/12.2309066

Boileau G, Christensen N, Meyer R, Cornish NJ (2021) Spectral separation of the stochastic gravitational-wave background for LISA: observing both cosmological and astrophysical backgrounds. Phys Rev D 103(10):103529. https://doi.org/10.1103/PhysRevD.103.103529. arXiv:2011.05055 [gr-qc]

Boileau G, Jenkins AC, Sakellariadou M, Meyer R, Christensen N (2022) Ability of LISA to detect a gravitational-wave background of cosmological origin: the cosmic string case. Phys Rev D 105(2):023510. https://doi.org/10.1103/PhysRevD.105.023510. arXiv:2109.06552 [gr-qc]

Bouffaut L, Taweesintananon K, Kriesell HJ, Rørstadbotnen RA, Potter JR, Landrø M, Johansen SE, Brenne JK, Haukanes A, Schjelderup O et al (2022) Eavesdropping at the speed of light: distributed acoustic sensing of baleen whales in the Arctic. Front Mar Sci 994. https://doi.org/10.3389/fmars.2022.901348

Breivik K, Kremer K, Bueno M, Larson SL, Coughlin S, Kalogera V (2018) Characterizing accreting double white dwarf binaries with the Laser Interferometer Space Antenna and Gaia. Astrophys J 854(1):1. https://doi.org/10.3847/2041-8213/aaaa23. arXiv:1710.08370 [astro-ph.SR]

Burlon D, Ghirlanda G, van der Horst A, Murphy T, Wijers RAMJ, Gaensler B, Ghisellini G, Prandoni I (2015) The SKA view of Gamma-Ray bursts. In: Advancing Astrophysics with the Square Kilometre Array (AASKA14), p 52. https://doi.org/10.22323/1.215.0052

Cahillane C, Mansell G (2022) Review of the advanced ligo gravitational wave observatories leading to observing run four. Galaxies 10(1):36. https://doi.org/10.3390/galaxies10010036

Caldwell R, Amin M, Hogan C, Holley-Bockelmann K, Holz D, Jetzer P, Kovitz E, Natarajan P, Shoemaker D, Smith T, Tamanini N (2019) Astro2020 science white paper: cosmology with a space-based gravitational wave observatory. Bull Am Astron Soc 51(3):67. https://doi.org/10.48550/arXiv.1903.04657. arXiv:1903.04657 [astro-ph.CO]

Cappellaro E (2022) Supernovae and their cosmological implications. Nuovo Cim Riv Ser 45(8):549–586. https://doi.org/10.1007/s40766-022-00034-1

Caprini C, Chala M, Dorsch GC, Hindmarsh M, Huber SJ, Konstandin T, Kozaczuk J, Nardini G, No JM, Rummukainen K, Schwaller P, Servant G, Tranberg A, Weir DJ (2020) Detecting gravitational waves from cosmological phase transitions with LISA: an update. J Cosmol Astropart Phys 2020(3):024. https://doi.org/10.1088/1475-7516/2020/03/024. arXiv:1910.13125 [astro-ph.CO]

Carter B, Luminet J (1982) Pancake detonation of stars by black holes in galactic nuclei. Nature 296:211–214
Casalvieri C, Ferrari ASV (2006) Gravitational signals due to tidal interactions between white dwarfs and black holes. Mon Not R Astron Soc 365:929–938. https://doi.org/10.1111/j.1365-2966.2005.09773.x
Cella G (2000) Off-line subtraction of seismic Newtonian noise. In: Casciaro B, Fortunato D, Francaviglia M, Masiello A (eds) Recent developments in general relativity. Springer, Berlin, pp 495–503. https://doi.org/10.1007/978-88-470-2113-6_44
Ceylan S, Clinton JF, Giardini D, Stähler SC, Horleston A, Kawamura T, Böse M, Charalambous C, Dahmen NL, van Driel M, Durán C, Euchner F, Khan A, Kim D, Plasman M, Scholz J-R, Zenhäusern G, Beucler E, Garcia RF, Kedar S, Knapmeyer M, Lognonné P, Panning MP, Perrin C, Pike WT, Stott AE, Banerdt WB (2022) The marsquake catalogue from insight, sols 0–1011. Phys Earth Planet Inter, 106943. https://doi.org/10.1016/j.pepi.2022.106943
Chenet H, Lognonné P, Wieczorek M, Mizutani H (2006) Lateral variations of lunar crustal thickness from the Apollo seismic data set. Earth Planet Sci Lett 243:1–14. https://doi.org/10.1016/j.epsl.2005.12.017
Clinton JF, Ceylan S, van Driel M, Giardini D, Stähler SC, Böse M, Charalambous C, Dahmen NL, Horleston A, Kawamura T, Khan A, Orhand-Mainsant G, Scholz J-R, Euchner F, Banerdt WB, Lognonné P, Banfield D, Beucler E, Garcia RF, Kedar S, Panning MP, Perrin C, Pike WT, Smrekar SE, Spiga A, Stott AE (2020) The marsquake catalog from InSight, sols 0–478. Phys Earth Planet Inter 310:106595. https://doi.org/10.1016/j.pepi.2020.106595
Colpi M, Holley-Bockelmann K, Bogdanović T, Natarajan P, Bellovary J, Sesana A, Tremmel M, Schnittman J, Comerford J, Barausse E, Berti E, Volonteri M, Khan FM, McWilliams ST, Burke-Spolaor S, Hazboun JS, Conklin J, Mueller G, Larson S (2019) The gravitational view of massive black hole mergers. Bull Am Astron Soc 51(3):432
Congedo G, Taylor A (2019) Joint cosmological inference of standard sirens and gravitational wave weak lensing. Phys Rev D 99(8):083526. https://doi.org/10.1103/physrevd.99.083526
Corman M, Escamilla-Rivera C, Hendry MA (2021) Constraining extra dimensions on cosmological scales with LISA future gravitational wave siren data. J Cosmol Astropart Phys 2021(2):005. https://doi.org/10.1088/1475-7516/2021/02/005. arXiv:2004.04009 [astro-ph.CO]
Cornish N, Berti E, Holley-Bockelmann K, Larson S, McWilliams S, Mueller G, Natarajan P, Vallisneri M (2019) The discovery potential of space-based gravitational wave astronomy. Bull Am Astron Soc 51(3):76. https://doi.org/10.48550/arXiv.1904.01438. arXiv:1904.01438 [astro-ph.HE]
Coughlin M, Harms J (2014a) Upper limit on a stochastic background of gravitational waves from seismic measurements in the range 0.05–1 Hz. Phys Rev Lett 112:101102. https://doi.org/10.1103/PhysRevLett.112.101102
Coughlin M, Harms J (2014b) Constraining the gravitational wave energy density of the universe using Earth's ring. Phys Rev D 90:042005. https://doi.org/10.1103/PhysRevD.90.042005
Coughlin M, Harms J (2014c) Constraining the gravitational-wave energy density of the universe in the range 0.1 Hz to 1 Hz using the Apollo seismic array. Phys Rev D 90:102001. https://doi.org/10.1103/PhysRevD.90.102001
Coughlin M, Harms J, Christensen N, Dergachev V, DeSalvo R, Kandhasamy S, Mandic V (2014) Wiener filtering with a seismic underground array at the Sanford Underground Research Facility. Class Quantum Grav 31(21):215003. https://doi.org/10.1088/0264-9381/31/21/215003
Cutler C, Berti E, Holley-Bockelmann K, Jani K, Kovetz ED, Larson SL, Littenberg T, McWilliams ST, Mueller G, Randall L, Schnittman JD, Shoemaker DH, Vallisneri M, Vitale S, Wong KWK (2019) What can we learn from multi-band observations of black hole binaries? Bull Am Astron Soc 51(3):109. https://doi.org/10.48550/arXiv.1903.04069. arXiv:1903.04069 [astro-ph.HE]
Daubar I, Lognonné P, Teanby NA, Miljkovic K, Stevanović J, Vaubaillon J, Kenda B, Kawamura T, Clinton J, Lucas A, Drilleau M, Yana C, Collins GS, Banfield D, Golombek M, Kedar S, Schmerr N, Garcia R, Rodriguez S, Gudkova T, May S, Banks M, Maki J, Sansom E, Karakostas F, Panning M, Fuji N, Wookey J, van Driel M, Lemmon M, Ansan V, Böse M, Stähler S, Kanamori H, Richardson J, Smrekar S, Banerdt WB (2018) Impact-seismic investigations of the InSight mission. Space Sci Rev 214(8):132. https://doi.org/10.1007/s11214-018-0562-x
de Kool M, van den Heuvel EPJ, Pylyser E (1987) An evolutionary scenario for the black hole binary A0620-00. A&A 183:47–52
de Raucourt S, Lognonné PH, Chabaut G, Gabsi T, Guattari F, Kawamura T, Nebut T, Pont G, Robert O, Tillier S, Yana C, Banerdt WB, Garcia R, Neal C, Panning M (2022) Technological evolution of the very broad band seismometer: insight, far side seismic suite and future missions with optical VBB. In: IAC-22, vol 2022, pp 22–321273001
Deane RP, Paragi Z, Jarvis MJ, Coriat M, Bernardi G, Fender RP, Frey S, Heywood I, Klöckner H-R, Grainge K, Rumsey C (2014) A close-pair binary in a distant triple supermassive black hole system. Nature 511(7507):57–60. https://doi.org/10.1038/nature1345410.48550/arXiv.1406.6365. arXiv:1406.6365 [astro-ph.GA]

Driggers JC, Evans M, Pepper K, Adhikari R (2012) Active noise cancellation in a suspended interferometer. Rev Sci Instrum 83(2):024501. https://doi.org/10.1063/1.3675891
Driggers JC, Harms J, Adhikari RX (2012) Subtraction of Newtonian noise using optimized sensor arrays. Phys Rev D 86:102001. https://doi.org/10.1103/PhysRevD.86.102001
Driggers JC et al [LIGO Scientific Collaboration Instrument Science Authors] (2019) Improving astrophysical parameter estimation via offline noise subtraction for Advanced LIGO. Phys Rev D 99:042001. https://doi.org/10.1103/PhysRevD.99.042001
Drilleau M, Samuel H, Garcia RF, Rivoldini A, Perrin C, Michaut C, Wieczorek M, Tauzin B, Connolly JAD, Meyer P, Lognonné P, Banerdt WB (2022) Marsquake locations and 1-d seismic models for Mars from insight data. J Geophys Res, Planets 127(9):2021–007067. https://doi.org/10.1029/2021JE007067
Dupletsa U, Harms J, Banerjee B, Branchesi M, Goncharov B, Maselli A, Oliveira ACS, Ronchini S, Tissino J (2022) GWFish: a simulation software to evaluate parameter-estimation capabilities of gravitational-wave detector networks. Astron Comput 100671. https://doi.org/10.1016/j.ascom.2022.100671
Dyson FJ (1969) Seismic response of the Earth to a gravitational wave in the 1-Hz band. Astrophys J 156:529. https://doi.org/10.1086/149986
Dziewonski AM, Anderson DL (1981) Preliminary reference Earth model. Phys Earth Planet Inter 25(4):297–356
ET Steering Committee (2020) Einstein Telescope design report update 2020. Available from European Gravitational Observatory. Document number eT-0007B-20. https://apps.et-gw.eu/tds/ql/?c=15418
Evans M, Adhikari RX, Afle C, Ballmer SW, Biscoveanu S, Borhanian S, Brown DA, Chen Y, Eisenstein R, Gruson A, Gupta A, Hall ED, Huxford R, Kamai B, Kashyap R, Kissel JS, Kuns K, Landry P, Lenon A, Lovelace G, McCuller L, Ng KKY, Nitz AH, Read J, Sathyaprakash BS, Shoemaker DH, Slagmolen BJJ, Smith JR, Srivastava V, Sun L, Vitale S, Weiss R (2021) A horizon study for cosmic explorer. Science, Observatories, and Community. https://arxiv.org/abs/2109.09882
Falta D, Fisher R, Khanna G (2011) Gravitational wave emission from the single-degenerate channel of type ia supernovae. Phys Rev Lett 106:201103. https://doi.org/10.1103/PhysRevLett.106.201103
Fanson J, Bernstein R, Ashby D, Bigelow B, Brossus G, Burgett W, Demers R, Fischer B, Figueroa F, Groark F, Laskin R, Millan-Gabet R, Park S, Pi M, Turner R, Walls B (2022) Overview and status of the Giant Magellan Telescope project. In: Marshall HK, Spyromilio J, Usuda T (eds) Ground-based and Airborne Telescopes IX. Society of Photo-Optical Instrumentation Engineers (SPIE) conference series, vol 12182, p 121821. https://doi.org/10.1117/12.2631694
Fenchuang L (2022) Thirty Meter Telescope (TMT) project status. In: Marshall HK, Spyromilio J, Usuda T (eds) Ground-based and Airborne Telescopes IX. Society of Photo-Optical Instrumentation Engineers (SPIE) conference series, vol 12182, p 121821. https://doi.org/10.1117/12.2631546
Fender R, Stewart A, Macquart JP, Donnarumma I, Murphy T, Deller A, Paragi Z, Chatterjee S (2015) The transient universe with the square kilometre array. In: Advancing Astrophysics with the Square Kilometre Array (AASKA14), p 51. https://doi.org/10.22323/1.215.0051
Finch E, Bartolucci G, Chucherko D, Patterson BG, Korol V, Klein A, Bandopadhyay D, Middleton H, Moore CJ, Vecchio A (2022) Identifying LISA verification binaries amongst the Galactic population of double white dwarfs pp 2210–10812. arXiv e-prints, arXiv:2210.10812 [astro-ph.SR]
Fiori I, Paoletti F, Tringali MC, Janssens K, Karathanasis C, Menéndez-Vázquez A, Romero-Rodríguez A, Sugimoto R, Washimi T, Boschi V, Chiummo A, Cie?lar M, De Rosa R, De Rossi C, Di Renzo F, Nardecchia I, Pasqualetti A, Patricelli B, Ruggi P, Singh N (2020) The hunt for environmental noise in Virgo during the third observing run. Galaxies 8(4). https://doi.org/10.3390/galaxies8040082
Fiorucci D, Harms J, Barsuglia M, Fiori I, Paoletti F (2018) Impact of infrasound atmospheric noise on gravity detectors used for astrophysical and geophysical applications. Phys Rev D 97:062003. https://doi.org/10.1103/PhysRevD.97.062003
Flörs A, Spyromilio J, Taubenberger S, Blondin S, Cartier R, Leibundgut B, Dessart L, Dhawan S, Hillebrandt W (2020) Sub-Chandrasekhar progenitors favoured for type Ia supernovae: evidence from late-time spectroscopy. Mon Not R Astron Soc 491(2):2902–2918. https://doi.org/10.1093/mnras/stz3013. arXiv:1909.11055 [astro-ph.HE]
Forward RL, Zipoy D, Weber J, Smith S, Benioff H (1961) Upper limit for interstellar millicycle gravitational radiation. Nature 189(4763):473–473. https://doi.org/10.1038/189473a0
Frohlich C, Pulliam J (1999) Single-station location of seismic events: a review and a plea for more research. Phys Earth Planet Inter 113:277–291
Gagnepain-Beyneix J, Lognonné P, Chenet H, Lombardi D, Spohn T (2006) A seismic model of the lunar mantle and constraints on temperature and mineralogy. Phys Earth Planet Inter 159:140–166
Gair JR, Mandel I, Sesana A, Vecchio A (2009) Probing seed black holes using future gravitational-wave detectors. Class Quantum Grav 26:204009. https://doi.org/10.1088/0264-9381/26/20/204009. arXiv:0907.3292 [gr-qc]

Garcia RF, Gagnepain-Beyneix J, Chevrot S, Lognonné P (2011) Very preliminary reference Moon model. Phys Earth Planet Inter 188:96–113

Garcia RF, Khan A, Drilleau M, Margerin L, Kawamura T, Sun D, Wieczorek MA, Rivoldini A, Nunn C, Weber RC, Marusiak AG, Lognonné P, Nakamura Y, Zhu P (2019) Lunar seismology: an update on interior structure models. Space Sci Rev 215:50. https://doi.org/10.1007/s11214-019-0613-y

Garcia RF, Khan A, Drilleau M, Margerin L, Kawamura T, Sun D, Wieczorek MA, Rivoldini A, Nunn C, Weber RC, Marusiak AG, Lognonné P, Nakamura Y, Zhu P (2019) Lunar seismology: an update on interior structure models. Space Sci Rev 215(8):50. https://doi.org/10.1007/s11214-019-0613-y

Gezari S (2014) The tidal disruption of stars by supermassive black holes. Phys Today 67:37–42

Giardini D, Lognonné P, Banerdt WB, Christensen U, Clinton J, van Driel M, Stähler S, Böse M, Garcia RF, Khan A, Panning MP, Perrin C, Banfield D, Beucler E, Charalambous C, Euchner F, Horleston A, Jacob A, Kawamura T, Kedar S, Mainsant G, Scholz J-R, Smrekar S, Spiga A, Agard C, Antonangeli D, Barkaoui S, Barrett E, Combes P, Conejero V, Daubar I, Drilleau M, Ferrier C, Gabsi T, Gudkova T, Hurst K, King FKS, Knapmeyer M, Knapmeyer-Endrun B, Llorca-Cejudo R, Lucas A, Luno L, Margerin L, McClean J, Mimoun D, Murdoch N, Nimmo F, Nonon M, Pardo C, Rivoldini A, Rodriguez-Manfredi J-A, Samuel H, Schimmel M, Stott AE, Stutzman E, Teanby N, Warren T, Weber R, Wieczorek M, Yana C (2020) The seismicity of Mars. Nat Geosci 13:205–212. https://doi.org/10.1038/s41561-020-0539-8

Giganti J, Larson J, Richard J, Tobias R, Weber J (1977) Lunar surface gravimeter experiment. Final report. Technical report, University of Maryland Department of Physics and Astronomy, College Park, Md

Graur O, Maoz D, Shara MM (2014) Progenitor constraints on the type-Ia supernova SN2011fe from pre-explosion Hubble Space Telescope HeII narrow-band observations. Mon Not R Astron Soc 442:28–32. https://doi.org/10.1093/mnrasl/slu052. arXiv:1403.1878 [astro-ph.GA]

Greggio L, Cappellaro E (2019) Correlation of the rate of type Ia supernovae with the parent galaxy properties: light and shadows. A&A 625:113. https://doi.org/10.1051/0004-6361/201834932. arXiv:1903.05412 [astro-ph.HE]

Grichener A, Soker N (2017) Core collapse supernova remnants with ears. Mon Not R Astron Soc 468:1226–1235. https://doi.org/10.1093/mnras/stx534. arXiv:1610.09647 [astro-ph.HE]

Grimm S, Harms J (2020) Multiband gravitational-wave parameter estimation: a study of future detectors. Phys Rev D 102:022007. https://doi.org/10.1103/PhysRevD.102.022007

Gudkova TV, Zharkov VN (2004) Mars: interior structure and excitation of free oscillations. Phys Earth Planet Inter 142:1–22

Gudkova T, Lognonné P, Miljković K, Gagnepain-Beyneix J (2015) Impact cutoff frequency – momentum scaling law inverted from Apollo seismic data. Earth Planet Sci Lett 427:57–65. https://doi.org/10.1016/j.epsl.2015.06.037

Haas R, Shcherbakov RV, Bode T, Laguna P (2012) Tidal disruptions of white dwarfs from ultra-close encounters with intermediate-mass spinning black holes. Astrophys J 749(2):117. https://doi.org/10.1088/0004-637x/749/2/117

Hall ED (2022) Cosmic explorer: a next-Generation ground-based gravitational-wave observatory. Galaxies 10(4). https://doi.org/10.3390/galaxies10040090

Hall ED, Kuns K, Smith JR, Bai Y, Wipf C, Biscans S, Adhikari RX, Arai K, Ballmer S, Barsotti L, Chen Y, Evans M, Fritschel P, Harms J, Kamai B, Rollins JG, Shoemaker D, Slagmolen BJJ, Weiss R, Yamamoto H (2021) Gravitational-wave physics with cosmic explorer: limits to low-frequency sensitivity. Phys Rev D 103:122004. https://doi.org/10.1103/PhysRevD.103.122004

Hambleton KM, Bianco FB, Street R, Bell K, Buckley D, Graham M, Hernitschek N, Lund MB, Mason E, Pepper J, Prsa A, Rabus M, Raiteri CM, Szabo R, Szkody P, Andreoni I, Antoniucci S, Balmaverde B, Bellm E, Bonito R, Bono G, Botticella MT, Brocato E, Bucar Bricman K, Cappellaro E, Carnerero MI, Chornock R, Clarke R, Cowperthwaite P, Cucchiara A, D'Ammando F, Dage KC, Dall'Ora M, Davenport JRA, de Martino D, de Somma G, Di Criscienzo M, Di Stefano R, Drout M, Fabrizio M, Fiorentino G, Gandhi P, Garofalo A, Giannini T, Gomboc A, Greggio L, Hartigan P, Hundertmark M, Johnson E, Johnson M, Jurkic T, Khakpash S, Leccia S, Li X, Magurno D, Malanchev K, Marconi M, Margutti R, Marinoni S, Mauron N, Molinaro R, Moller A, Moniez M, Muraveva T, Musella I, Ngeow C-C, Pastorello A, Petrecca V, Piranomonte S, Ragosta F, Reguitti A, Righi C, Ripepi V, Rivera Sandoval L, Stassun KG, Stroh M, Terreran G, Trimble V, Tsapras Y, van Velzen S, Venuti L, Vink JS (2022) Rubin observatory LSST transients and variable stars roadmap. ArXiv e-prints. https://doi.org/10.48550/arXiv.2208.04499. arXiv:2208.04499 [astro-ph.IM]

Harms J (2019) Terrestrial gravity fluctuations. Living Rev Relativ 22(1):6. https://doi.org/10.1007/s41114-019-0022-2

Harms J (2022) Seismic background limitation of lunar gravitational-wave detectors. Phys Rev Lett 129:071102. https://doi.org/10.1103/PhysRevLett.129.071102

Harms J, Mow-Lowry CM (2017) Suspension-thermal noise in spring–antispring systems for future gravitational-wave detectors. Class Quantum Grav 35(2):025008. https://doi.org/10.1088/1361-6382/aa9e28

Harms J, Slagmolen BJJ, Adhikari RX, Miller MC, Evans M, Chen Y, Müller H, Ando M (2013) Low-frequency terrestrial gravitational-wave detectors. Phys Rev D 88:122003. https://doi.org/10.1103/PhysRevD.88.122003

Harms J, Ambrosino F, Angelini L, Braito V, Branchesi M, Brocato E, Cappellaro E, Coccia E, Coughlin M, Ceca RD, Valle MD, Dionisio C, Federico C, Formisano M, Frigeri A, Grado A, Izzo L, Marcelli A, Maselli A, Olivieri M, Pernechele C, Possenti A, Ronchini S, Serafinelli R, Severgnini P, Agostini M, Badaracco F, Bertolini A, Betti L, Civitani MM, Collette C, Covino S, Dall'Osso S, D'Avanzo P, DeSalvo R, Giovanni MD, Focardi M, Giunchi C, van Heijningen J, Khetan N, Melini D, Mitri G, Mow-Lowry C, Naponiello L, Noce V, Oganesyan G, Pace E, Paik HJ, Pajewski A, Palazzi E, Pallavicini M, Pareschi G, Pozzobon R, Sharma A, Spada G, Stanga R, Tagliaferri G, Votta R (2021) Lunar gravitational-wave antenna. Astrophys J 910(1):1. https://doi.org/10.3847/1538-4357/abe5a7

Harms J, Angelini L, Coughlin M, Currie D, Dell'Agnello S, Jani K, Katsanevas S, Kawamura T, Loeb A, Lognonné P (2021) Lunar gravitational-wave detection. Decadal Survey on Biological and Physical Sciences Research in Space 2023-2032

Heiken GH, Vaniman DT, French BM (1991) Lunar sourcebook, a user's guide to the Moon. Cambridge University Press

Hills JG (1976) The tidal breakup and capture of stars by black holes in globular clusters. Astrophys Lett 17:95

Hilweg C, Shadmany D, Walther P, Mavalvala N, Sudhir V (2022) Limits and prospects for long-baseline optical fiber interferometry. Optica 9(11):1238–1252. https://doi.org/10.1364/OPTICA.470430

Hulse RA, Taylor JH (1975) Discovery of a pulsar in a binary system. Astrophys J 195:51–53. https://doi.org/10.1086/181708

InSight Marsquake Service (2023) Mars seismic catalogue, InSight mission; V13 2023-01-01. ETHZ, IPGP, JPL, ICL Univ. Bristol. https://doi.org/10.12686/a19. https://www.insight.ethz.ch/seismicity/catalog/v13

Isoyama S, Nakano H, Nakamura T (2018) Multiband gravitational-wave astronomy: observing binary inspirals with a decihertz detector. B-DECIGO. Progr Theor Exp Phys 2018(7):073E01. https://doi.org/10.1093/ptep/pty078

Ivanova N, Justham S, Podsiadlowski P (2015) On the role of recombination in common-envelope ejections. Mon Not R Astron Soc 447(3):2181–2197. https://doi.org/10.1093/mnras/stu2582. arXiv:1409.3260 [astro-ph.SR]

Izzo L, de Ugarte Postigo A, Maeda K, Thöne CC, Kann DA, Della Valle M, Sagues Carracedo A, Michałowski MJ, Schady P, Schmidl S, Selsing J, Starling RLC, Suzuki A, Bensch K, Bolmer J, Campana S, Cano Z, Covino S, Fynbo JPU, Hartmann DH, Heintz KE, Hjorth J, Japelj J, Kamiński K, Kaper L, Kouveliotou C, KruŻyński M, Kwiatkowski T, Leloudas G, Levan AJ, Malesani DB, Michałowski T, Piranomonte S, Pugliese G, Rossi A, Sánchez-Ramírez R, Schulze S, Steeghs D, Tanvir NR, Ulaczyk K, Vergani SD, Wiersema K (2019) Signatures of a jet cocoon in early spectra of a supernova associated with a γ-Ray Burst. Nature 565(7739):324–327. https://doi.org/10.1038/s41586-018-0826-3. arXiv:1901.05500 [astro-ph.HE]

Jani K, Loeb A (2021) Gravitational-wave lunar observatory for cosmology. J Cosmol Astropart Phys 2021(06):044. https://doi.org/10.1088/1475-7516/2021/06/044

Jani K, Shoemaker D, Cutler C (2019) Detectability of intermediate-mass black holes in multiband gravitational wave astronomy. Nat Astron 4:260–265. https://doi.org/10.1038/s41550-019-0932-7. arXiv:1908.04985 [gr-qc]

Jousset P, Reinsch T, Ryberg T, Blanck H, Clarke A, Aghayev R, Hersir GP, Henninges J, Weber M, Krawczyk CM (2018) Dynamic strain determination using fibre-optic cables allows imaging of seismological and structural features. Nat Commun 9(1):1–11. https://doi.org/10.1038/s41467-018-04860-y

Katsanevas S, Bernard P, Giardini D, Jousset P, Mazzali P, Lognonné P, Pian E, Amy A, Apostolatos T, Barsuglia M, Chardonnet C, Montagner J-P, Olivetto C, Perlmutter S, Piran T, Pottie P-E (2020) Lunar seismic and gravitational antenna. In: Ideas for exploring the Moon with a large European lander. ESA, p 1. https://ideas.esa.int/servlet/hype/IMT?documentTableId=45087607031744010&userAction=Browse&templateName=&documentId=a315450fae481074411ef65e4c5b7746

Kawamura T, Lognonné P, Nishikawa Y, Tanaka S (2017) Evaluation of deep moonquake source parameters: implication for fault characteristics and thermal state. J Geophys Res, Planets 122(7):1487–1504. https://doi.org/10.1002/2016JE005147

Kawamura S et al (2021) Current status of space gravitational wave antenna DECIGO and B-DECIGO. Prog Theor Exp Phys 2021(5):05A105. https://doi.org/10.1093/ptep/ptab019

Kawamura T, Clinton JF, Zenhäusern G, Ceylan S, Horleston AC, Dahmen NL, Duran C, Kim D, Plasman M, Stähler SC, Euchner F, Charalambous C, Giardini D, Davis P, Sainton G, Lognonné P, Panning M, Banerdt WB (2022) S1222a - the largest marsquake detected by insight. Geophys Res Lett 49:2022–101543. https://doi.org/10.1029/2022GL101543

Keim MA, Korol V, Rossi EM (2023) The large magellanic cloud revealed in gravitational waves with LISA. Mon Not R Astron Soc 521(1): 1088–1098. https://doi.org/10.1093/mnras/stad554 arXiv:2207.14277 [astro-ph.GA]

Khan A, Ceylan S, van Driel M, Giardini D, Lognonné P, Samuel H, Schmerr NC, Stähler SC, Duran AC, Huang Q, Kim D, Broquet A, Charalambous C, Clinton JF, Davis PM, Drilleau M, Karakostas F, Lekic V, McLennan SM, Maguire RR, Michaut C, Panning MP, Pike WT, Pinot B, Plasman M, Scholz J-R, Widmer-Schnidrig R, Spohn T, Smrekar SE, Banerdt WB (2021) Upper mantle structure of Mars from insight seismic data. Science 373(6553):434–438. https://doi.org/10.1126/science.abf2966

Kim D, Davis P, Lekić V, Maguire R, Compaire N, Schimmel M, Stutzmann E, Irving JCE, Lognonné P, Scholz J-R, Clinton JF, Zenhäusern G, Dahmen NL, Deng S, Levander A, Panning MP, Garcia RF, Giardini D, Hurst K, Knapmeyer-Endrun B, Nimmo F, Pike WT, Pou L, Schmerr NC, Stähler SC, Tauzin B, Widmer-Schnidrig R, Banerdt WB (2021) Potential pitfalls in the analysis and structural interpretation of seismic data from the Mars InSight mission. Bull Seismol Soc Am 111(6):2982–3002. https://doi.org/10.1785/0120210123

Kim D, Stähler SC, Ceylan S, Lekic V, Maguire R, Zenhäusern G, Clinton J, Giardini D, Khan A, Panning MP, Davis P, Wieczorek M, Schmerr N, Lognonné P, Banerdt WB (2023) Structure along the Martian dichotomy constrained by Rayleigh and love waves and their overtones. Geophys Res Lett 49:2022–101666. https://doi.org/10.1029/2022GL101666

Knapmeyer-Endrun B, Panning MP, Bissig F, Joshi R, Khan A, Kim D, Lekić V, Tauzin B, Tharimena S, Plasman M, Compaire N, Garcia RF, Margerin L, Schimmel M, Stutzmann E, Schmerr NC, Bozdağ E, Plesa A-C, Wieczorek MA, Broquet A, Antonangeli D, McLennan SM, Samuel H, Michaut C, Pan L, Perrin C, Smrekar SE, Johnson CL, Brinkman N, Mittelholz A, Rivoldini A, Davis PM, Lognonné P, Pinot B, Scholz J-R, Stähler SC, Knapmeyer M, van Driel M, Giardini D, Banerdt WB (2021) Thickness and structure of the Martian crust from InSight seismic data. Science 373:438–443. https://doi.org/10.1126/science.abf8966

Kobayashi S, Laguna P, Phinney ES, Mészáros P (2004) Gravitational waves and X-ray signals from stellar disruption by a massive black hole. Astrophys J 615(2):855. https://doi.org/10.1086/424684

Komossa S, Zensus JA (2016) Compact object mergers: observations of supermassive binary black holes and stellar tidal disruption events. In: Meiron Y, Li S, Liu F-K, Spurzem R (eds) Star clusters and black holes in galaxies across cosmic time, vol 312, pp 13–25. https://doi.org/10.1017/S1743921315007395

Koopmans LVE, Barkana R, Bentum M, Bernardi G, Boonstra A-J, Bowman J, Burns J, Chen X, Datta A, Falcke H, Fialkov A, Gehlot B, Gurvits L, Jelić V, Klein-Wolt M, Lazio J, Meerburg D, Mellema G, Mertens F, Mesinger A, Offringa A, Pritchard J, Semelin B, Subrahmanyan R, Silk J, Trott C, Vedantham H, Verde L, Zaroubi S, Zarka P (2021) Peering into the dark (ages) with low-frequency space interferometers. Exp Astron 51(3):1641–1676. https://doi.org/10.1007/s10686-021-09743-7

Kormendy J, Richstone D (1995) Inward bound—the search for supermassive black holes in galactic nuclei. Annu Rev Astron Astrophys 33:581. https://doi.org/10.1146/annurev.aa.33.090195.003053

Korol V, Rossi EM, Groot PJ, Nelemans G, Toonen S, Brown AGA (2017) Prospects for detection of detached double white dwarf binaries with Gaia, LSST and LISA. Mon Not R Astron Soc 470(2):1894–1910. https://doi.org/10.1093/mnras/stx1285. arXiv:1703.02555 [astro-ph.HE]

Korol V, Koop O, Rossi EM (2018) Detectability of double white dwarfs in the local group with LISA. Astrophys J 866(2):20. https://doi.org/10.3847/2041-8213/aae587. arXiv:1808.05959 [astro-ph.HE]

Korol V, Hallakoun N, Toonen S, Karnesis N (2022) Observationally driven Galactic double white dwarf population for LISA. Mon Not R Astron Soc 511(4):5936–5947. https://doi.org/10.1093/mnras/stac415. arXiv:2109.10972 [astro-ph.HE]

Koushiappas SM, Loeb A (2017) Maximum redshift of gravitational wave merger events. Phys Rev Lett 119(22). https://doi.org/10.1103/physrevlett.119.221104

Kulkarni SR, Frail DA, Wieringa MH, Ekers RD, Sadler EM, Wark RM, Higdon JL, Phinney ES, Bloom JS (1998) Radio emission from the unusual supernova 1998bw and its association with the γ-ray burst of 25 April 1998. Nature 395(6703):663–669. https://doi.org/10.1038/27139

Kupfer T, Korol V, Shah S, Nelemans G, Marsh TR, Ramsay G, Groot PJ, Steeghs DTH, Rossi EM (2018) LISA verification binaries with updated distances from Gaia Data Release 2. Mon Not R Astron Soc 480(1):302–309. https://doi.org/10.1093/mnras/sty1545. arXiv:1805.00482 [astro-ph.SR]

Lam ATL, Shibata M, Kiuchi K (2022) Numerical-relativity simulation for tidal disruption of white dwarfs by a supermassive black hole. https://doi.org/10.48550/ARXIV.2212.10891. https://arxiv.org/abs/2212.10891

Landrø M, Bouffaut L, Kriesell HJ, Potter JR, Rørstadbotnen RA, Taweesintananon K, Johansen SE, Brenne JK, Haukanes A, Schjelderup O et al (2022) Sensing whales, storms, ships and earthquakes using an Arctic fibre optic cable. Sci Rep 12(1):1–10. https://doi.org/10.1038/s41598-022-23606-x

Landrø M, Johansen S-E, Schmitz N, Amundsen H (2022) Using das-fibres for lunar seismic imaging. European Lunar Symposium

Latham G, Ewing M, Dorman J, Lammlein D, Press F, Toksőz N, Sutton G, Duennebier F, Nakamura Y (1972) Moonquakes and lunar tectonism. Moon 4(3-4):373–382. https://doi.org/10.1007/BF00562004

Leiderschneider E, Piran T (2021) Gravitational radiation from accelerating jets. Phys Rev D 104(10):104002. https://doi.org/10.1103/PhysRevD.104.104002. arXiv:2107.12418 [astro-ph.HE]

Littenberg TB (2018) Gravitational wave sources as timing references for LISA data. Phys Rev D 98(4):043008. https://doi.org/10.1103/PhysRevD.98.043008. arXiv:1805.03589 [astro-ph.IM]

Littenberg TB, Cornish NJ (2019) Prospects for gravitational wave measurement of ZTF J1539+5027. Astrophys J 881(2):43. https://doi.org/10.3847/2041-8213/ab385f. arXiv:1908.00678 [astro-ph.IM]

Littenberg T, Breivik K, Brown WR, Eracleous M, Hermes JJ, Holley-Bockelmann K, Kremer K, Kupfer T, Larson SL (2019) Gravitational wave survey of galactic ultra compact binaries. Bull Am Astron Soc 51(3):34

Livio M (2001) Type Ia supernovae and their implications for cosmology. In: Livio M, Panagia N, Sahu K (eds) Supernovae and Gamma-Ray bursts: the greatest explosions since the Big Bang, vol 13, pp 334–355. https://doi.org/10.48550/arXiv.astro-ph/0005344

Livio M, Soker N (1988) The common envelope phase in the evolution of binary stars. Astrophys J 329:764. https://doi.org/10.1086/166419

Loeb A, Furlanetto SR (2013) The first galaxies in the universe. Princeton University Press, Princeton

Lognonné P, Johnson CL (2015) Planetary seismology. In: Schubert G (ed) Treatise on geophysics, 2nd edn. vol 10. Elsevier, Oxford, pp 65–120

Lognonné P, Pike WT (2015) Planetary seismometry. In: Tong VCH, Garcia RA (eds) Extraterrestrial seismology. Cambridge University Press, Cambridge, pp 36–48. https://doi.org/10.1017/CBO9781107300668.006

Lognonné P, Zharkov VN, Karczewski JF, Romanowicz BA, Menvielle M, Poupinet G, Brient B, Cavoit C, Desautez A, Dole B, Franqueville D, Gagnepain-Beyneix J, Richard H, Schibler P, Striebig N (1998) The seismic OPTIMISM experiment. Planet Space Sci 46(6–7):739–747. https://doi.org/10.1016/S0032-0633(98)00009-9

Lognonné P, Gagnepain-Beyneix J, Banerdt WB, Chenet H (2003) A new seismic model of the Moon: implication in terms of structure, formation, and evolution. Earth Planet Sci Lett 211:27–44. https://doi.org/10.1016/S0012-821X(03)00172-9

Lognonné P, Le Feuvre M, Johnson CL, Weber RC (2009) Moon meteoritic seismic hum: Steady state prediction. J Geophys Res, Planets 114(E12). https://doi.org/10.1029/2008JE003294

Lognonné P, Le Feuvre M, Johnson C, Weber RC (2009) Moon meteoritic seismic hum: steady state prediction. J Geophys Res 114:12003. https://doi.org/10.1029/2008JE003294

Lognonné P et al (2019) SEIS: The seismic experiment for internal structure of InSight. Space Sci Rev 215:12. https://doi.org/10.1007/s11214-018-0574-6

Lognonné P et al (2020) Constraints on the shallow elastic and anelastic structure of Mars from InSight seismic data. Nat Geosci 13:213–220. https://doi.org/10.1038/s41561-020-0536-y

Luo J, Chen L-S, Duan H-Z, Gong Y-G, Hu S, Ji J, Liu Q, Mei J, Milyukov V, Sazhin M, Shao C-G, Toth VT, Tu H-B, Wang Y, Wang Y, Yeh H-C, Zhan M-S, Zhang Y, Zharov V, Zhou Z-B (2016) TianQin: a space-borne gravitational wave detector. Class Quantum Grav 33(3):035010. https://doi.org/10.1088/0264-9381/33/3/035010. arXiv:1512.02076 [astro-ph.IM]

MacFadyen AI, Woosley SE, Heger A (2001) Supernovae, jets, and collapsars. Astrophys J 550(1):410–425. https://doi.org/10.1086/319698. arXiv:astro-ph/9910034 [astro-ph]

Madau P, Rees MJ (2001) Massive black holes as Population III remnants. Astrophys J 551:27–30. https://doi.org/10.1086/319848. arXiv:astro-ph/0101223 [astro-ph]

Maeda K, Kawabata K, Mazzali PA, Tanaka M, Valenti S, Nomoto K, Hattori T, Deng J, Pian E, Taubenberger S, Iye M, Matheson T, Filippenko AV, Aoki K, Kosugi G, Ohyama Y, Sasaki T, Takata T (2008) Asphericity in supernova explosions from late-time spectroscopy. Science 319:1220. https://doi.org/10.1126/science.1149437. arXiv:0801.1100

Maggiore M, Broeck CVD, Bartolo N, Belgacem E, Bertacca D, Bizouard MA, Branchesi M, Clesse S, Foffa S, García-Bellido J, Grimm S, Harms J, Hinderer T, Matarrese S, Palomba C, Peloso M, Ricciardone A, Sakellariadou M (2020) Science case for the Einstein telescope. J Cosmol Astropart Phys 2020(03):050. https://doi.org/10.1088/1475-7516/2020/03/050

Maguire K, Eracleous M, Jonker PG et al (2020) Tidal disruptions of white dwarfs: theoretical models and observational prospects. Space Sci Rev 216:39. https://doi.org/10.1007/s11214-020-00661-2

Majstorović J, Rosat S, Rogister Y (2019) Earth's spheroidal motion induced by a gravitational wave in flat spacetime. Phys Rev D 100:044048. https://doi.org/10.1103/PhysRevD.100.044048

Mandel I, Sesana A, Vecchio A (2018) The astrophysical science case for a decihertz gravitational-wave detector. Class Quantum Grav 35(5):054004. https://doi.org/10.1088/1361-6382/aaa7e0

Maoz D, Mannucci F, Brandt TD (2012) The delay-time distribution of type Ia supernovae from Sloan II. Mon Not R Astron Soc 426(4):3282–3294. https://doi.org/10.1111/j.1365-2966.2012.21871.x. arXiv:1206.0465 [astro-ph.CO]

Marsh TR (2011) Double white dwarfs and LISA. Class Quantum Grav 28:094019. https://doi.org/10.1088/0264-9381/28/9/094019. arXiv:1101.4970 [astro-ph.SR]

Maselli A, Marassi S, Branchesi M (2020) Binary white dwarfs and decihertz gravitational wave observations: from the Hubble constant to supernova astrophysics. A&A 635:120. https://doi.org/10.1051/0004-6361/201936848. arXiv:1910.00016 [astro-ph.HE]

Matichard F, Lantz B, Mason K, Mittleman R, Abbott B, Abbott S, Allwine E, Barnum S, Birch J, Biscans S, Clark D, Coyne D, DeBra D, DeRosa R, Foley S, Fritschel P, Giaime JA, Gray C, Grabeel G, Hanson J, Hillard M, Kissel J, Kucharczyk C, Le Roux A, Lhuillier V, Macinnis M, O'Reilly B, Ottaway D, Paris H, Puma M, Radkins H, Ramet C, Robinson M, Ruet L, Sareen P, Shoemaker D, Stein A, Thomas J, Vargas M, Warner J (2015) Advanced LIGO two-stage twelve-axis vibration isolation and positioning platform. Part 1: design and production overview. Precis Eng 40:273–286. https://doi.org/10.1016/j.precisioneng.2014.09.010

Matichard F, Lantz B, Mason K, Mittleman R, Abbott B, Abbott S, Allwine E, Barnum S, Birch J, Biscans S, Clark D, Coyne D, DeBra D, DeRosa R, Foley S, Fritschel P, Giaime JA, Gray C, Grabeel G, Hanson J, Hillard M, Kissel J, Kucharczyk C, Roux AL, Lhuillier V, Macinnis M, O'Reilly B, Ottaway D, Paris H, Puma M, Radkins H, Ramet C, Robinson M, Ruet L, Sareen P, Shoemaker D, Stein A, Thomas J, Vargas M, Warner J (2015) Advanced LIGO two-stage twelve-axis vibration isolation and positioning platform. Part 2: experimental investigation and tests results. Precis Eng 40:287–297. https://doi.org/10.1016/j.precisioneng.2014.11.010

Mazzali PA, Iwamoto K, Nomoto K (2000) A spectroscopic analysis of the energetic type Ic hypernova SN 1997EF. Astrophys J 545(1):407–419. https://doi.org/10.1086/317808. arXiv:astro-ph/0007222 [astro-ph]

Mazzali PA, Kawabata KS, Maeda K, Nomoto K, Filippenko AV, Ramirez-Ruiz E, Benetti S, Pian E, Deng J, Tominaga N, Ohyama Y, Iye M, Foley RJ, Matheson T, Wang L, Gal-Yam A (2005) An asymmetric energetic type Ic supernova viewed off-axis, and a link to Gamma ray bursts. Science 308(1284–1287). https://doi.org/10.1126/science.1111384. arXiv:astro-ph/0505199

Mazzali PA, Röpke FK, Benetti S, Hillebrandt W (2007) A common explosion mechanism for type Ia supernovae. Science 315(5813):825. https://doi.org/10.1126/science.1136259. arXiv:astro-ph/0702351 [astro-ph]

McWilliams ST, Caldwell R, Holley-Bockelmann K, Larson SL, Vallisneri M (2019) Astro2020 decadal science white paper: the state of gravitational-wave astrophysics in 2020. ArXiv e-prints. https://doi.org/10.48550/arXiv.1903.04592. arXiv:1903.04592 [astro-ph.He]

Mereghetti S, Balman S, Caballero-Garcia M, Del Santo M, Doroshenko V, Erkut MH, Hanlon L, Hoeflich P, Markowitz A, Osborne JP, Pian E, Rivera Sandoval L, Webb N, Amati L, Ambrosi E, Beardmore AP, Blain A, Bozzo E, Burderi L, Campana S, Casella P, D'Aí A, D'Ammando F, De Colle F, Della Valle M, De Martino D, Di Salvo T, Doyle M, Esposito P, Frontera F, Gandhi P, Ghisellini G, Gotz D, Grinberg V, Guidorzi C, Hudec R, Iaria R, Izzo L, Jaisawal GK, Jonker PG, Kong AKH, Krumpe M, Kumar P, Manousakis A, Marino A, Martin-Carrillo A, Mignani R, Miniutti G, Mundell CG, Mukai K, Nucita AA, O'Brien PT, Orlandini M, Orio M, Palazzi E, Papitto A, Pintore F, Piranomonte S, Porquet D, Ricci C, Riggio A, Rigoselli M, Rodriguez J, Saha T, Sanna A, Santangelo A, Saxton R, Sidoli L, Stiele H, Tagliaferri G, Tavecchio F, Tiengo A, Tsygankov S, Turriziani S, Wijnands R, Zane S, Zhang B (2021) Time domain astronomy with the THESEUS satellite. Exp Astron 52(3):309–406. https://doi.org/10.1007/s10686-021-09809-6. arXiv:2104.09533 [astro-ph.IM]

Mimoun D, Garcia RF, Lognonné PH, De Raucourt S, Kawamura T, Giardini D, Schmelzbach C, Karatekin O, Dehant VMA, Wassermann JM, Bernauer F, Bonnefois JJ, Igel H, Guattari F, Wilhelm A, Cadu A, Tillier S (2019) H2020 PIONEERS study: planetary instruments based on optical technologies for an iNnovative European exploration using rotational seismology. In: AGU fall meeting abstracts, vol 2019, pp 23–02

Nakamura Y, Latham GV, Dorman HJ, Harris J (1981) Passive Seismic Experiment, Long Period Event Catalog, Final Version (1969 Day 202-1977 Day 273, ALSEP Stations 11, 12, 13, 14, 15, and 16). Technical report, University of Texas Institute for Geophysics

Nakamura Y, Latham GV, Dorman HJ, Harris JE (1981) Passive seismic experiment long-period event catalog, final version. Technical Report UTIG Technical Report No. 18, Galveston Geophysics Laboratory of the University of Texas at Austin, Marine Science Institute

Nakar E (2019) Heart of a stellar explosion revealed. Nature 565(7739):300–301. https://doi.org/10.1038/d41586-019-00043-x

Napiwotzki R, Karl CA, Lisker T, Catalán S, Drechsel H, Heber U, Homeier D, Koester D, Leibundgut B, Marsh TR, Moehler S, Nelemans G, Reimers D, Renzini A, Ströer A, Yungelson L (2020) The ESO supernovae type Ia progenitor survey (SPY). The radial velocities of 643 DA white dwarfs. A&A 638:131. https://doi.org/10.1051/0004-6361/201629648. arXiv:1906.10977 [astro-ph.SR]

Natarajan P, Ricarte A, Baldassare V, Bellovary J, Bender P, Berti E, Cappelluti N, Ferrara A, Greene J, Haiman Z, Holley-Bockelmann K, Mueller G, Pacucci F, Shoemaker D, Shoemaker D, Tremmel M, Urry CM, Vikhlinin A, Volonteri M (2019) Disentangling nature from nurture: tracing the origin of seed black holes. Bull Am Astron Soc 51(3):73. https://doi.org/10.48550/arXiv.1904.09326. arXiv:1904.09326 [astro-ph.HE]

Ng KKY, Chen S, Goncharov B, Dupletsa U, Borhanian S, Branchesi M, Harms J, Maggiore M, Sathyaprakash BS, Vitale S (2022) On the single-event-based identification of primordial black hole mergers at cosmological distances. Astrophys J Lett 931(1):12. https://doi.org/10.3847/2041-8213/ac6bea

Nishimura T, Emoto K, Nakahara H, Miura S, Yamamoto M, Sugimura S, Ishikawa A, Kimura T (2021) Source location of volcanic earthquakes and subsurface characterization using fiber-optic cable and distributed acoustic sensing system. Sci Rep 11(1):1–12. https://doi.org/10.1038/s41598-021-85621-8

Nunn C, Pike WT, Standley IM, Calcutt SB, Kedar S, Panning MP (2021) Standing on Apollo's shoulders: a microseismometer for the Moon. Planet Sci J 2(1):36. https://doi.org/10.3847/PSJ/abd63b

Oberst J (1987) Unusually high stress drops associated with shallow moonquakes. J Geophys Res 92(B2):1397–1405. https://doi.org/10.1029/JB092iB02p01397

Pacucci F, Loeb A (2020) Separating accretion and mergers in the cosmic growth of black holes with x-ray and gravitational-wave observations. Astrophys J 895(2):95. https://doi.org/10.3847/1538-4357/ab886e

Paczynski B (1976) Common envelope binaries. In: Eggleton P, Mitton S, Whelan J (eds) Structure and evolution of close binary systems. IAU Symposium, vol 73 Dordrecht, Reidel, p 75

Pais M, Piran T, Lyubarsky Y, Kiuchi K, Shibata M (2023) The collimation of relativistic jets in post-neutron star binary merger simulations. Astrophys J Lett 946:L9. https://doi.org/10.3847/2041-8213/acc2c5 arXiv:2211.09135 [astro-ph.He]

Pakmor R, Callan FP, Collins CE, de Mink SE, Holas A, Kerzendorf WE, Kromer M, Neunteufel PG, O'Brien JT, Röpke FK, Ruiter AJ, Seitenzahl IR, Shingles LJ, Sim SA, Taubenberger S (2022) On the fate of the secondary white dwarf in double-degenerate double-detonation type Ia supernovae. Mon Not R Astron Soc 517(4):5260–5271. https://doi.org/10.1093/mnras/stac3107. arXiv:2203.14990 [astro-ph.SR]

Panning M, Kedar S, Bowles N, Calcutt S, Drilleau M, Garcia R, Kawamura T, Lognonné P, Mimoun D, Nunn C, Pike WT, Portela-Moreira D, de Raucourt S, Weber R, Wilhelm A (2022) Farside Seismic Suite (FSS): first-ever seismology on the farside of the Moon and a model for long-lived lunar science. In: European planetary science congress, pp 2022-672. https://doi.org/10.5194/epsc2022-672

Patat F, Chugai NN, Podsiadlowski P, Mason E, Melo C, Pasquini L (2011) Connecting RS Ophiuchi to [some] type Ia supernovae. A&A 530:63. https://doi.org/10.1051/0004-6361/201116865. arXiv:1104.0506 [astro-ph.SR]

Phinney et al (2003) The Big Bang observer: direct detection of gravitational waves from the birth of the universe to the present. NASA Mission Concept Study

Piran T (2002) Gamma-Ray bursts - a primer for relativists. In: Bishop NT, Maharaj SD (eds) General relativity and gravitation. World Scientific, Singapore, pp 259–275. https://doi.org/10.1142/9789812776556_0013

Piran T, Nakar E, Mazzali P, Pian E (2019) Relativistic jets in core collapse supernovae. Astrophys J 871(2):25. https://doi.org/10.3847/2041-8213/aaffce. arXiv:1704.08298 [astro-ph.HE]

Piran T (2022) Jet gravitational waves. In: Brink L et al (eds) Looking Beyond the Frontiers of Science. World Scientific, Singapore, pp 291–311. https://doi.org/10.1142/9789811263699_0035 arXiv:2210.02740 [astro-ph.He]

Piro L, Ahlers M, Coleiro A, Colpi M, de Oña Wilhelmi E, Guainazzi M, Jonker PG, Namara PM, Nichols DA, O'Brien P, Troja E, Vink J, Aird J, Amati L, Anand S, Bozzo E, Carrera FJ, Fabian AC, Fryer C, Hall E, Korobkin O, Korol V, Mangiagli A, Martínez-Núñez S, Nissanke S, Osborne J, Padovani P, Rossi EM, Ryan G, Sesana A, Stratta G, Tanvir N, van Eerten H (2022) Athena synergies in the multi-messenger and transient universe. Exp Astron 54(1):23–117. https://doi.org/10.1007/s10686-022-09865-6. arXiv:2110.15677 [astro-ph.HE]

Posiolova LV, Lognonné P, Banerdt WB, Clinton J, Collins GS, Kawamura T, Ceylan S, Daubar IJ, Fernando B, Froment M, Giardini D, Malin MC, Miljković K, Stähler SC, Xu Z, Banks ME, Beucler E, Cantor BA, Charalambous C, Dahmen N, Davis P, Drilleau M, Dundas CM, Durán C, Euchner F, Garcia RF, Golombek M, Horleston A, Keegan C, Khan A, Kim D, Larmat C, Lorenz R, Margerin L, Menina S, Panning M, Pardo C, Perrin C, Pike WT, Plasman M, Rajšić A, Rolland L, Rougier E, Speth G, Spiga A, Stott A, Susko D, Teanby NA, Valeh A, Werynski A, Wójcicka N, Zenhäusern G (2022) Largest recent impact craters on Mars: orbital imaging and surface seismic co-investigation. Science 378(6618):412–417. https://doi.org/10.1126/science.abq7704

Rebassa-Mansergas A, Toonen S, Korol V, Torres S (2019) Where are the double-degenerate progenitors of type Ia supernovae? Mon Not R Astron Soc 482(3):3656–3668. https://doi.org/10.1093/mnras/sty2965. arXiv:1809.07158 [astro-ph.SR]

Rees M (1988) Tidal disruption of stars by black holes of 10^6–10^8 solar masses in nearby galaxies. Nature 333:523–528. https://doi.org/10.1038/333523a0

Robson T, Cornish NJ, Liu C (2019) The construction and use of LISA sensitivity curves. Class Quantum Grav 36(10):105011. https://doi.org/10.1088/1361-6382/ab1101

Rodriguez C, Taylor GB, Zavala RT, Peck AB, Pollack LK, Romani RW (2006) A compact supermassive binary black hole system. Astrophys J 646(1):49–60. https://doi.org/10.1086/50482510.48550/arXiv.astro-ph/0604042. arXiv:astro-ph/0604042 [astro-ph]

Roebber E, Buscicchio R, Vecchio A, Moore CJ, Klein A, Korol V, Toonen S, Gerosa D, Goldstein J, Gaebel SM, Woods TE (2020) Milky way satellites shining bright in gravitational waves. Astrophys J 894(2):15. https://doi.org/10.3847/2041-8213/ab8ac9. arXiv:2002.10465 [astro-ph.GA]

Romero-Rodríguez A, Martínez M, Mir LM, Yamamoto H (2022) Determination of the stray light-induced noise from the baffle in the cryogenic trapping area of advanced Virgo in O5. Galaxies 10(4). https://doi.org/10.3390/galaxies10040086

Ronchini S, Branchesi M, Oganesyan G, Banerjee B, Dupletsa U, Ghirlanda G, Harms J, Mapelli M, Santoliquido F (2022) Perspectives for multimessenger astronomy with the next generation of gravitational-wave detectors and high-energy satellites. A&A 665:97. https://doi.org/10.1051/0004-6361/202243705. arXiv:2204.01746 [astro-ph.HE]

Rossi EM, Stone NC, Law-Smith JAP et al (2021) The process of stellar tidal disruption by supermassive black holes. Space Sci Rev 21:40. https://doi.org/10.1007/s11214-021-00818-7

Rosswog S, Ramirez-Ruiz E, Hix WR (2009) Tidal disruption and ignition of white dwarfs by moderately massive black holes. Astrophys J 695(1):404–419. https://doi.org/10.1088/0004-637x/695/1/404

Ruan W-H, Guo Z-K, Cai R-G, Zhang Y-Z (2020) Taiji Program: Gravitational-Wave Sources. Int J Mod Phys A35:2050075. https://doi.org/10.1142/S0217751X2050075X

Ruiz-Lapuente P, González Hernández JI, Mor R, Romero-Gómez M, Miret-Roig N, Figueras F, Bedin LR, Canal R, Méndez J (2019) Tycho's supernova: the view from Gaia. Astrophys J 870(2):135. https://doi.org/10.3847/1538-4357/aaf1c1. arXiv:1807.03593 [astro-ph.SR]

Sago N, Ioka K, Nakamura T, Yamazaki R (2004) Gravitational wave memory of Gamma-Ray burst jets. Phys Rev D 70:104012. https://doi.org/10.1103/PhysRevD.70.104012. arXiv:gr-qc/0405067

Sand DJ, Sarbadhicary SK, Pellegrino C, Misra K, Dastidar R, Brown PJ, Itagaki K, Valenti S, Swift JJ, Andrews JE, Bostroem KA, Burke J, Chomiuk L, Dong Y, Galbany L, Graham ML, Hiramatsu D, Howell DA, Hsiao EY, Janzen D, Jencson JE, Lundquist MJ, McCully C, Reichart D, Smith N, Wang L, Wyatt S (2021) Circumstellar medium constraints on the environment of two nearby type Ia supernovae: SN 2017cbv and SN 2020nlb. Astrophys J 922(1):21. https://doi.org/10.3847/1538-4357/ac20da. arXiv:2108.11407 [astro-ph.HE]

Schutz BF (1986) Determining the Hubble constant from gravitational wave observations. Nature 323(6086):310–311. https://doi.org/10.1038/323310a0

Sedda MA, Berry CPL, Jani K, Amaro-Seoane P, Auclair P, Baird J, Baker T, Berti E, Breivik K, Burrows A, Caprini C, Chen X, Doneva D, Ezquiaga JM, Ford KES, Katz ML, Kolkowitz S, McKernan B, Mueller G, Nardini G, Pikovski I, Rajendran S, Sesana A, Shao L, Tamanini N, Vartanyan D, Warburton N, Witek H, Wong K, Zevin M (2020) The missing link in gravitational-wave astronomy: discoveries waiting in the decihertz range. Class Quantum Grav 37(21):215011. https://doi.org/10.1088/1361-6382/abb5c1

Segalis EB, Ori A (2001) Emission of gravitational radiation from ultrarelativistic sources. Phys Rev D 64(6):064018. https://doi.org/10.1103/PhysRevD.64.064018. arXiv:gr-qc/0101117 [gr-qc]

Seitenzahl IR, Herzog M, Ruiter AJ, Marquardt K, Ohlmann ST, Röpke FK (2015) Neutrino and gravitational wave signal of a delayed-detonation model of type Ia supernovae. Phys Rev D 92(12):124013. https://doi.org/10.1103/PhysRevD.92.124013. arXiv:1511.02542 [astro-ph.SR]

Sesana A (2016) Prospects for multiband gravitational-wave astronomy after GW150914. Phys Rev Lett 116:231102. https://doi.org/10.1103/PhysRevLett.116.231102

Sesana A, Lamberts A, Petiteau A (2020) Finding binary black holes in the Milky Way with LISA. Mon Not R Astron Soc 494(1):75–80. https://doi.org/10.1093/mnrasl/slaa039. arXiv:1912.07627 [astro-ph.GA]

Shandera S, Jeong D, Gebhardt HSG (2018) Gravitational waves from binary mergers of subsolar mass dark black holes. Phys Rev Lett 120(24):241102. https://doi.org/10.1103/physrevlett.120.241102

Shapiro SL, Teukolsky SA (1983) Black holes, white dwarfs, and neutron stars: the physics of compact objects. Wiley, New York

Sharma A, Harms J (2020) Searching for cosmological gravitational-wave backgrounds with third-generation detectors in the presence of an astrophysical foreground. Phys Rev D 102:063009. https://doi.org/10.1103/PhysRevD.102.063009

Shen KJ, Bildsten L, Kasen D, Quataert E (2012) The long-term evolution of double white dwarf mergers. Astrophys J 748(1):35. https://doi.org/10.1088/0004-637X/748/1/35. arXiv:1108.4036 [astro-ph.HE]

Silk J, Crawford I, Elvis M, Zarnecki J (2021) Astronomy from the Moon: the next decades. Philos Trans R Soc A, Math Phys Eng Sci 379(2188):20190560. https://doi.org/10.1098/rsta.2019.0560

Silk J, Crawford I, Elvis M, Zarnecki J (2023) The next decades for astronomy from the Moon. Nat Astron 7(6):648–650. https://doi.org/10.1038/s41550-023-02000-1

Sollberger D, Schmelzbach C, Robertsson JO, Greenhalgh SA, Nakamura Y, Khan A (2016) The shallow elastic structure of the lunar crust: new insights from seismic wavefield gradient analysis. Geophys Res Lett 43(19):10–078. https://doi.org/10.1002/2016GL070883

Soni S et al [LIGO Scientific Collaboration] (2020) Reducing scattered light in LIGO's third observing run. Class Quantum Grav 38(2):025016. https://doi.org/10.1088/1361-6382/abc906

Souradeep T (2016) LIGO-India. Reson 21:225–231. https://doi.org/10.1007/s12045-016-0316-6

Stähler SC, Khan A, Lognonné P, Banerdt WB, Giardini D, Ceylan S, Drilleau M, Duran A, Garcia R, Huang Q, Kim D, Lekić V, Samuel H, Schimmel M, Schmerr N, Sollberger D, Stutzmann E, Xu Z, Antonangeli D, Davis P, Irving J, Kawamura T, Knapmeyer M, Maguire R, Marusiak A, Panning MP, Perrin C, Plesa A-C, Rivoldini A, Schmelzbach C, Zenhäusern G, Beucler E, Charalambous C, Clinton J, Dahmen N, van Driel M, Plasman M, Horleston A, Pike WT, Smrekar S, Gudkova T (2021) Seismic detection of the Martian core. Science 373(6553):443–448. https://doi.org/10.1126/science.abi7730

Stroeer A, Vecchio A (2006) The LISA verification binaries. Class Quantum Grav 23(19):809–817. https://doi.org/10.1088/0264-9381/23/19/S19. arXiv:astro-ph/0605227 [astro-ph]

Tamai R, Koehler B, Cirasuolo M, Biancat-Marchet F, Tuti M, González Herrera J-C, Ramsay S (2022) Status of the ESO's ELT construction. In: Marshall HK, Spyromilio J, Usuda T (eds) Ground-based and Airborne Telescopes IX. Society of Photo-Optical Instrumentation Engineers (SPIE) conference series, vol 12182, p 121821. https://doi.org/10.1117/12.2631613

Tan JC, Matzner CD, McKee CF (2001) Trans-relativistic blast waves in supernovae as Gamma-Ray Burst progenitors. Astrophys J 551(2):946–972. https://doi.org/10.1086/320245. arXiv:astro-ph/0012003 [astro-ph]

Tanimoto T, Eitzel M, Yano T (2008) The noise cross-correlation approach for Apollo 17 LPSE data: diurnal change in seismic parameters in the shallow lunar crust. J Geophys Res 113:08011. https://doi.org/10.1029/2007JE003016

Taubenberger S, Valenti S, Benetti S, Cappellaro E, Della Valle M, Elias-Rosa N, Hachinger S, Hillebrandt W, Maeda K, Mazzali PA, Pastorello A, Patat F, Sim SA, Turatto M (2009) Nebular emission-line profiles of type Ib/c supernovae - probing the ejecta asphericity. Mon Not R Astron Soc 397:677–694. https://doi.org/10.1111/j.1365-2966.2009.15003.x. arXiv:0904.4632

Tauris TM (2018) Disentangling coalescing Neutron-Star-White-Dwarf Binaries for LISA. Phys Rev Lett 121(13):131105. https://doi.org/10.1103/PhysRevLett.121.131105. arXiv:1809.03504 [astro-ph.SR]

Taweesintananon K, Landrø M, Brenne JK, Haukanes A (2021) Distributed acoustic sensing for near-surface imaging using submarine telecommunication cable: a case study in the Trondheimsfjord, Norway. Geophysics 86(5):303–320. https://doi.org/10.1190/geo2020-0834.1

THESEUS Assessment Study Report (2021) THESEUS: transient high-energy sky and early universe surveyor. https://sci.esa.int/documents/34375/36249/Theseus_YB_final.pdf

Thorpe JI, Ziemer J, Thorpe I, Livas J, Conklin JW, Caldwell R, Berti E, McWilliams ST, Stebbins R, Shoemaker D, Ferrara EC, Larson SL, Shoemaker D, Key JS, Vallisneri M, Eracleous M, Schnittman J, Kamai B, Camp J, Mueller G, Bellovary J, Rioux N, Baker J, Bender PL, Cutler C, Cornish N, Hogan C, Manthripragada S, Ware B, Natarajan P, Numata K, Sankar SR, Kelly BJ, McKenzie K, Slutsky J, Spero R, Hewitson M, Francis S, DeRosa R, Yu A, Hornschemeier A, Wass P (2019) The Laser Interferometer Space Antenna: unveiling the millihertz gravitational wave sky. Bull Am Astron Soc 51: 77. https://doi.org/10.48550/arXiv.1907.06482

Totani T (2003) A failed Gamma-Ray Burst with dirty energetic jets spirited away? New implications for the Gamma-Ray Burst-supernova connection from SN 2002ap. Astrophys J 598:1151–1162. https://doi.org/10.1086/378936. arXiv:astro-ph/0303621

Trozzo L, Badaracco F (2022) Seismic and Newtonian noise in the GW detectors. Galaxies 10(1):20. https://doi.org/10.3390/galaxies10010020

Valtonen MJ, Dey L, Gopakumar A, Zola S, Komossa S, Pursimo T, Gomez JL, Hudec R, Jermak H, Berdyugin AV (2021) Promise of persistent multi-messenger astronomy with the blazar OJ 287. Galaxies 10(1):1. https://doi.org/10.3390/galaxies10010001. arXiv:2112.10102 [astro-ph.HE]

van der Marel RP (1994) On the stellar kinematical evidence for massive black holes in galactic nuclei expected with the Hubble Space Telescope. Astrophys J 432:91–94. https://doi.org/10.1086/187519

van Heijningen JV, Gatti A, Ferreira EC, Bocchese F, Badaracco F, Lucas S, Perali A, Tavernier F (2022) A cryogenic inertial sensor for terrestrial and lunar gravitational-wave detection. Nucl Instrum Methods Phys Res A 1041:167231. https://doi.org/10.1016/j.nima.2022.167231
van Heijningen JV, ter Brake HJM, Gerberding O, Chalathadka Subrahmanya S, Harms J, Bian X, Gatti A, Zeoli M, Bertolini A, Collette C, Perali A, Pinto N, Sharma M, Tavernier F, Rezvani J (2023) The payload of the lunar gravitational-wave antenna. J Appl Phys 133(24):244501. https://doi.org/10.1063/5.0144687
Vinnik L, Chenet H, Gagnepain-Beyneix J, Lognonné P (2001) First seismic receiver functions on the Moon. Geophys Res Lett 28:3031–3034
Volonteri M, Haardt F, Madau P (2002) Modelling the merging history of binary SMBHs in hierarchical models of galaxy formation. Astrophys Space Sci 281(1):501–504. https://doi.org/10.1023/A:1019573531536
Wagoner R, Paik H (1976) Proceedings of international symposium on experimental gravitation, Pavia. Roma Accademia Nazionale dei Lincei, Roma
Webbink RF (1984) Double white dwarfs as progenitors of R Coronae Borealis stars and type I supernovae. Astrophys J 277:355–360. https://doi.org/10.1086/161701
Weber J (1960) Detection and generation of gravitational waves. Phys Rev 117:306–313. https://doi.org/10.1103/PhysRev.117.306
Weber RC, Lin P-Y, Garnero EJ, Williams Q, Lognonné P (2011) Seismic detection of the lunar core. Science 331(6015):309–312. https://doi.org/10.1126/science.1199375
Weber RC, Neal C, Banerdt B, Beghein C, Chi P, Currie D, Dell'Agnello S, Garcia R, Garrick-Bethell I, Grimm R, Grott M, Haviland H, Kawamura T, Kedar S, Lognonne P, Nagihara S, Nakamura Y, Nunn C, Ostrach L, Panning M, Petro N, Schmerr N, Siegler M, Watters T, Wieczorek M, Zacny K (2020) Artemis: enabling the lunar geophysical network. In: Lunar surface science workshop. LPI contributions, vol 2241, p 5063
Weisberg JM, Taylor JH (2005) The relativistic binary pulsar B1913+16: thirty years of observations and analysis. In: Rasio FA, Stairs IH (eds) Binary radio pulsars. ASP conference seriess, vol 328, p 25
Whelan J, Iben I (1973) Binaries and supernovae of type I. Astrophys J 186:1007–1014. https://doi.org/10.1086/152565
Wilhelm MJC, Korol V, Rossi EM, D'Onghia E (2021) The Milky Way's bar structural properties from gravitational waves. Mon Not R Astron Soc 500(4):4958–4971. https://doi.org/10.1093/mnras/staa3457. arXiv:2003.11074 [astro-ph.GA]
Williams J-P, Greenhagen BT, Paige DA, Schorghofer N, Sefton-Nash E, Hayne PO, Lucey PG, Siegler MA, Aye KM (2019) Seasonal polar temperatures on the Moon. J Geophys Res, Planets 124(10):2505–2521. https://doi.org/10.1029/2019JE006028
Wu Y, Zalewski DR, Vermeer CH, Holland HJ, Benthem B, ter Brake HJM (2017) Baseline design of a sorption-based Joule-Thomson cooler chain for the METIS instrument in the E-ELT. Cryogenics 84:37–52. https://doi.org/10.1016/j.cryogenics.2017.04.003
Zucker ME, Whitcomb SE (1996) Measurement of optical path fluctuations due to residual gas in the LIGO 40 meter interferometer. In: Proceedings of the seventh Marcel Grossman meeting on recent developments in theoretical and experimental general relativity, gravitation, and relativistic field theories

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