

LION : Laser Interferometer On the moon

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Gravitational wave astronomy has now left its infancy and has become an important tool for probing the most violent phenomena in our universe. The LIGO/Virgo-KAGRA collaboration operates ground based detectors which cover the frequency band from 10 Hz to the kHz regime. Meanwhile, the pulsar timing array and the soon to launch LISA mission will cover frequencies below 0.1 Hz, leaving a gap in detectable gravitational wave frequencies. Here we show how a Laser Interferometer On the moon (LION) gravitational wave detector would be sensitive to frequencies from sub Hz to kHz. We find that the sensitivity curve is such that LION can measure compact binaries with masses between 10 and 100 M_{\odot} at cosmological distances, with redshifts as high as $z = 100$ and beyond, depending on the spin and the mass ratio of the binaries. LION can detect binaries of compact objects with higher-masses, with very large signal-to-noise ratios, help us to understand how supermassive black holes got their colossal masses on the cosmological landscape, and it can observe in detail intermediate-mass ratio inspirals at distances as large as at least 100 Gpc. Compact binaries that never reach the LIGO/Virgo sensitivity band can spend significant amounts of time in the LION band, while sources present in the LISA band can be picked up by the detector and observed until their final merger. Since LION covers the deci-Hertz regime with such large signal-to-noise ratios, it truly achieves the dream of multi messenger astronomy.

I. INTRODUCTION

The LIGO-Virgo-KAGRA (LVK) collaboration [1–3] now forms a network of gravitational wave observatories covering the Earth. Third generation ground based detectors such as the Einstein Telescope (ET) [4] and Cosmic Explorer (CE) [5, 6] are currently in the planning stage of development. These detectors are planned to push the lower frequency bound of Earth based gravitational wave detectors to their fundamental limits.

Newtonian noise, or gravitational gradient noise, forms a lower frequency bound of Earth based detection at about 1 Hz [7]. Meanwhile, with a proposed launch of 2034, the ESA’s LISA mission [8] will cover the μHz to sub-deci-Hz regime of the gravitational wave spectrum. The upper sensitivity bound of space based detectors is set by the interferometer arm length [9, 10]. These barriers create a gap of measurable frequencies which requires a different style of mission to fill. In this gap many interesting stellar phenomena go unrecorded and their immeasurable impact on the field of gravitational wave astronomy is lost [11]. Therefore, there is great interest in any gravitational wave detector capable of bridging this gap. Several missions, at various stages of development, are attempting to do this, but none is yet close to being launched [12, 13]. In this work we show a lunar gravitational wave observatory would be able to observe frequencies down to 0.7 Hz while simultaneously overlapping with the sensitive frequency range of Earth based detectors.

During the 90’s Wilson and La Fave published two papers on the idea of lunar interferometers, but as the field was still in its infancy, a lot of benefits and challenges went overlooked [14, 15]. A few other groups have suggested using seismometer arrays on both the Moon and other extraterrestrial solar bodies [16, 17]. Coughlin and Harms managed to put limits on the energy contained within the stochastic background across the frequency band 0.1-1 Hz using seismometers on the Moon from the Apollo missions as a detector. A recent proposal has now been submitted to launch many high sensitivity seismometers to the surface of the Moon to push this detection method to its limits [18]. If launched, these seismometers would enable a better understanding of the Moon’s seismic activity and so the true limits of seismic noise as discussed later in this paper. Aside from that, a paper has been submitted to arxiv recently discussing the concept of a lunar gravitational wave detector [19]. They focus largely on the astrophysical sources in their sensitivity band. Although their optimistic estimate of performance was excellent at low frequency, it relied upon the use of a freely floating test mass, a technology that has only been proposed and has no further development so far [20]. The conservative estimate they make is similar to the one we reach here, without focusing on the technical details needed to reach that. We also show significant differences in detector design. Still, it is very promising that two independent approaches can reach similar noise estimates.

In the following we discuss how a ground based long arm interferometer with Fabry-Pérot cavities could be constructed for use as a gravitational wave detector on the surface of the Moon. We will discuss the merits and potential design style of such a lunar observatory. We address this by constructing a feasible noise budget for a laser observatory based upon current gravitational wave detectors. We benefit from the lunar surface’s seismically quiet environment [21, 22], and its lack of atmosphere. Thus the limit on low frequency detection set by the Newtonian noise can be avoided. By means of this noise budget, we show that the sensitivity gap between the high frequency ground based detectors and low frequency space based detectors can be partially bridged. Furthermore, a detector built on the Moon with a sensitivity band also overlapping that of the Earth based network increases the size of the network by a factor of 60, improving the source localisation ability significantly.

Several stellar phenomena are expected in the frequency band exclusively covered by our proposed lunar detector and we discuss the impact their observations will have. A low frequency detector allows the tracking of merging binaries for much longer times [23], detecting binaries at much greater redshift [24], detecting heavier binaries [25], allows for better sky localisation [26], and detecting new types of astrophysical sources [27, 28]. Long standing questions about the origins of many sources could uniquely be resolved with a LION detector [29]. Furthermore, sub-Hertz detection allows for the probing of gravity in the strong field regime, testing general relativity to its limits [30–32]. Finding sources at very high redshifts leads directly to a better understanding of the early universe, where our current understanding is limited by our detection capabilities.

With the renewed interest in lunar missions from several major global powers [33–36], now is the ideal time for the gravitational wave community to begin considering what use the Moon can be in aiding our understanding of the cosmos.

Section II starts with the discussion of technical details, including detector parameters, noise contributions and the location and infrastructure. This is followed in Section III by a summarised noise budget. The science case in Section IV discusses the new possibilities that a lunar detector offers, while Section V gives an estimate about the mission cost and timeline.

Parameter	Value
Test Mass (kg)	1 267, 1 267, 698, 707
Suspension length (m)	3.54, 2.05, 1.66, 2.50
Temperature (K)	70
Laser Power (W)	250
Wavelength (nm)	2000
Arm Length (km)	40
Seismic	Earth Surface/1000

Table I. Overview of the key parameters of LION. All other values correspond to the Cosmic Explorer 2 design. The masses and suspension length are listed from test mass to top mass.

II. TECHNICAL DISCUSSION

The model for our suggested Laser Interferometer On the moon (LION) is based on the Cosmic Explorer 2 proposal. Our modifications are listed in Table I. These modification arise from the special conditions on the Moon and design choices made to optimise the frequency band of interest which we discuss below.

A. Location

The choice of the location for LION is predominately determined by the temperature map of the Moon. A crater near a lunar pole is considered by us to be a suitable position for several reasons; thermal stability, geometry, and shelter from solar radiation and dust [37–39]. A promising candidate site is the Shoemaker crater (88.1°S 44.9°E) at the Moon’s south pole. Hayne et al. [37] investigated the measurement data of the Lunar Reconnaissance Orbiter (LRO) mission launched in 2009 for three craters with about 50 km diameter. The shoemaker crater shows an average temperature of about 50K with a relatively small variation of minimal/maximal temperature 20 – 95K compared to other parts of the moon. It has a diameter of 50 km, introducing one of the limiting factors for the detectors: the arm length. The nearby Malapert mountain is a nearly perfect site to build solar panels and a communication equipment for data transfer [40]. Additionally, the surface appears to be nearly free of water frost, which could otherwise evaporate onto optics [37]. We assume the use of this crater for all future calculations.

B. Infrastructure

The vacuum on the surface of the Moon is three orders of magnitude better than that in the vacuum tubes in the aLIGO detectors [1, 41], and so no infrastructure will be built to house a vacuum. Only the optic support stations are needed to isolate the test optics and allow for their precise alignment controls.

For the detection of gravitational waves, coincidence data from two independent simultaneous instruments is required. This is solved in the ET detector and LISA by using a triangular shape with two interferometers in the arms [4, 42, 43]. Therefore, we propose to build LION in a triangular shape with an arm length of 40 km, limited by the dimensions of the crater.

C. Background Seismic

The seismic noise on the Moon arises from two main sources; meteorite impacts [44–47] and from the shallow seismic activity of the Moon [48]. Many of the sources of seismic activity on Earth do not exist on the Moon [49] such as moving cars and trains, winds, and the oceans tides. In particular, the oceans tides cause a large microseismic peak at 0.1-0.2 Hz which proves troublesome to all detectors seeking low frequency performance; a lunar site completely negates this [50]. Meanwhile, wind and ground conditions on the Earth tilts the detectors, polluting the measurements of inertial sensors with additional noise, which is directly injected into platform controls [51, 52]. The absence, or at the very least substantial reduction, of tilt would allow for a much more aggressive active platform control scheme to reduce motion in the test masses [53]. The control noise is currently one of the reasons the aLIGO detectors do not reach their design sensitivity at low frequencies.

The only direct seismic measurements on the Moon’s surface were performed during the Apollo missions [21, 44]. They concluded that the background seismic level was significantly below the sensitivity of their measurement devices (0.3 nm/ $\sqrt{\text{Hz}}$ at 1 Hz), and thus lower than anything on Earth’s surface. From this we can safely assume the seismic on

the Moon to be smaller by a factor of 1 000 than Earth’s surface seismic motion. However, the Russian operated Luna 27 will be launched in 2024 [54] with a more sensitive seismometer [55], possibly measuring an even lower boundary.

D. Newtonian Noise

Newtonian noise is caused by the movement of mass around the detector causing a change in the local gravitational field [49]. These largely come from two sources; the atmosphere and the ground. The lack of atmosphere on the Moon negates the former entirely. Reliable modelling of seismic Newtonian noise for the lunar surface is impossible without accurate measurements of the seismic activity and surface composition. On Earth the noise forms a noise cliff at approximately 1 Hz. Since the Moon has lower activity [45] and has a lower density on its surface it is assumed that this will occur at a lower frequency. Newtonian noise is therefore not plotted in the noise budget. A full study of the gradient noise would still be essential as more knowledge of the Moon’s activity is gained.

E. Suspension Systems

The limiting low frequency noise considerations are the residual of seismic activity and suspension thermal noise. Like in Earth bound detectors, a multistage seismic isolation system would be necessary. This will compose of a preisolation stage and several suspended masses each acting as a pendulum [56, 57]. In order to achieve the required seismic isolation the resonance frequencies of the pendula must be tuned to lower frequency than Cosmic Explorer. The gravity on the Moon’s surface is 1.62 m/s^2 , approximately a sixth of the gravity on Earth. Although the lower gravity of the Moon offers lower natural frequency by a factor of 0.4, longer suspensions with heavier test masses must still be included. As the gravity is weaker, the masses can be a factor of 6 larger than Cosmic Explorer without additional weight on the suspensions. Making such large test masses and coating them may prove difficult so we assume only a factor of 4 increase can be made. This leads to a test and penultimate mass of 1270 kg and another 2 stages with about 700 kg mass. Making the lengths of suspensions on average a factor of 3 longer allows for the whole system to fit in a 11m structure while reducing the noise to a level suitable for sub Hz measurements. Suspension systems are a limiting factor for the low frequency performance of all detectors with fundamental problems of how much weight can be suspended and resonance frequency. The lower gravity on the Moon provides help on both of these fronts. How far this can be developed will form the lower boundary of measurable frequencies, but ultimately it is a matter of engineering.

F. Thermal Noise

Thermal noise is a considerable problem for the low frequency response of any detector. The extremely low temperatures at the Moon’s south pole are a good start for achieving the necessary thermal noise suppression. However, a low mechanical loss is also a necessity for a low thermal noise [58]. The bulk material of the test masses at both LIGO and Virgo are fused silica, which due to a mechanical loss peak, has poor mechanical loss at cryogenic temperatures [59]. Research for alternative test mass materials is ongoing for use in the cryogenic interferometer of ET and other detectors [60–62].

The Cosmic Explorer proposal uses silicon ribbons to suspend their test masses and research is ongoing to design the next generation of suspensions [63]. The properties of the ribbons quoted in the Cosmic Explorer design is assumed when calculating the suspension thermal noise.

Likewise significant progress is needed to reduce both mechanical and optical losses of the test mass coatings to reach Cosmic Explorer’s design sensitivity. The progress of these development will be at the forefront of the efforts of next generation of gravitational wave detectors and their results will heavily influence the limits of a lunar interferometer.

G. Quantum Noise

Quantum noise is the predominant noise source at high frequencies for Earth bound interferometric gravitational wave detectors. While frequency independent squeezing is injected in current detectors [64–66] to reduce the shot noise, there are plans for a broadband noise reduction by using filter cavities [67] or EPR entanglement [68]. The proposed LION design uses the same optical configuration and laser power (250 W) as Cosmic Explorer including the injection of 15 dB squeezing and the application of filter cavities. We have not changed the corresponding parameters because the given design provides a promising noise performance already. A reduction of the radiation-pressure noise

at low-frequencies at the cost of high-frequency performance is possible though through the adjustment of laser power. The detector will be quantum noise limited above 2 Hz.

H. Seismic Shocks and Asteroid Impacts

Another cause of concern is asteroid impacts on the Moon. A large impact near the equipment could potentially lead both to saturated isolation equipment leading to damage to the controls as well as large mirror motion and loss of science mode. Reacquiring science mode is a difficult and time consuming process [69, 70], However, a similar problem is encountered on Earth with earthquakes. This problem is tackled at aLIGO with a combination of a specialised early warning system for incoming high activity seismic waves and alternative control schemes for high activity times [71]. A similar strategy could be copied for any lunar setup. Therefore, only a direct hit on the experiment would present a problem.

Based on the data of the still ongoing lunar reconnaissance orbiter, approximately 47 000 new impact sites had been detected in the area studied (6% of the lunar surface) in a 1241 day period [72]. This leads to an estimate of approximately 5 impacts within the detector area (a triangle with 40 km long sides) in a year. It is foreseen that this will prove to be a regular nuisance, but should still enable long stretches of observation. It is also unlikely that the optics will be hit directly as they will take up a small fractional area of the detector, leading to an estimate of direct hits once in a thousand years. Substance smaller impacts will be significantly under-counted by their very nature, and so it is likely a asteroid shielding solution of the optics will be needed.

I. Additional challenges

LION will face problems unique to its environment. Since the arms are not covered in tubes, Moon dust will eventual stick to the mirrors. Investigations in cleaning strategies on the Moon and the mars are likely to deliver the technologies to reduce this problem, as it is essential for many of the desired experiments and continued exploitation of these bodies [73, 74].

Furthermore, a mission of this style will require several large payloads to be transported to the Moon and positioned carefully, requiring assembly either by hand or robot. The feasibility of these strongly depends directly on the lunar missions in the coming decade. However, technology is reaching the stage where commercial missions to the Moon are becoming viable, a promising sign of things to come [75].

The total mass of the suspended optics is 4 000 kg, and the weight of a preisolation stage used at LIGO is 2 000 kg [50]. This would leave over 10 000 kg as remaining load for both the structure and auxiliary optics, if it was to be carried by the highest capacity rocket today. This would require at least 3 launches for total transport.

Gravitational wave detectors produce an high amount of data due to the number of sensors monitoring the numerous degrees of freedom. Furthermore, many systems will have to be operated from ground stations. A high bandwidth connection will be required to the site. Currently a record of 622 Megabits/s data transfer rate has been achieved by the Lunar Laser Communication Demonstration in orbit of the Moon [76]. With an encoding of 64bits per data point, we would be able to read out about 100 channels at a 100 kHz sample rate. While this may not encompass all of the data producing instruments, it should be sufficient for instrument readout of the main channel and diagnostics of auxiliary channels of interest to above the upper limits of LION's sensitive band.

With no need for a vacuum pump, and only small amounts of power needed for alignment controls and isolation, the main power consumption concerns are the telemetry, the high laser power, beam preparation and readout electronics, and the auxiliary sensors. In space missions the power supply is usually covered by a combination of advanced solar panels that reach an efficiency of 30% and Li-Ion batteries. While at the equatorial and mid-latitude regions of the Moon the long lunar nights set limitations for solar power supply, we take advantage of locating the interferometer in polar regions. As shown by [40] we receive up to 93 % of full or partial sunlight when placing the solar panels on mountains, for example the Malapert mountain, close to the chosen site. For 1.4 kW/m^2 of power provided by the sun and a pessimistic factor of 0.5 for the partial sunlight, we gain 0.2 kW/m^2 of solar power, making the power of the system very manageable with a solar panel array of a few tens of square meters.

III. NOISE BUDGET

We used the Gravitational Wave Interferometer Noise Calculator (gwinc) [77] software to estimate the noise budget of our proposed LION design shown in Figure 1. Cosmic Explorer (CE2 model, October 2020) was used as a base model, but with the changes discussed in the previous section and listed in Table I to match the design presented in

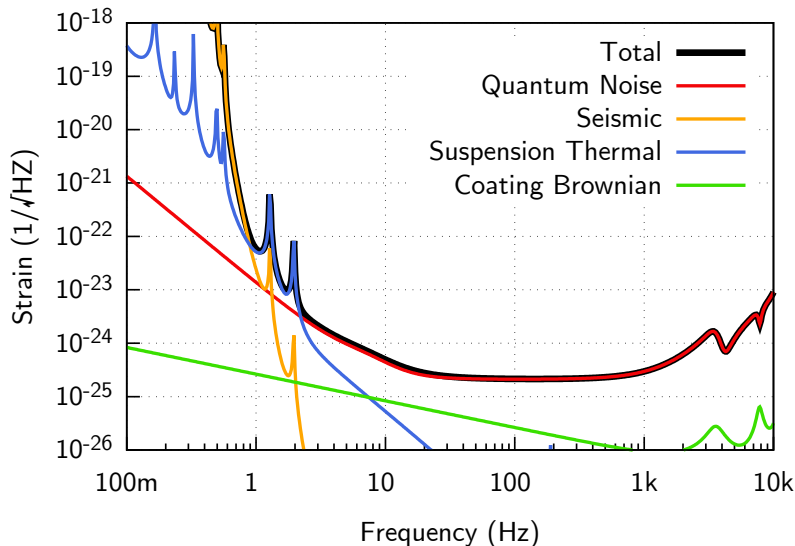


Figure 1. Noise budget for a gravitational wave detector operated on the Moon with an arm length of 40 km and optics with increased masses at a temperature of 70 K. The parameters used to create this are listed in Table I. The detector is quantum noise limited above 2 Hz and limited by thermal noise below this until it hits the seismic cliff at 0.8 Hz. The bandwidth of the detector is therefore approximately from 0.7 Hz to the kHz. Simulated with gwinc [77].

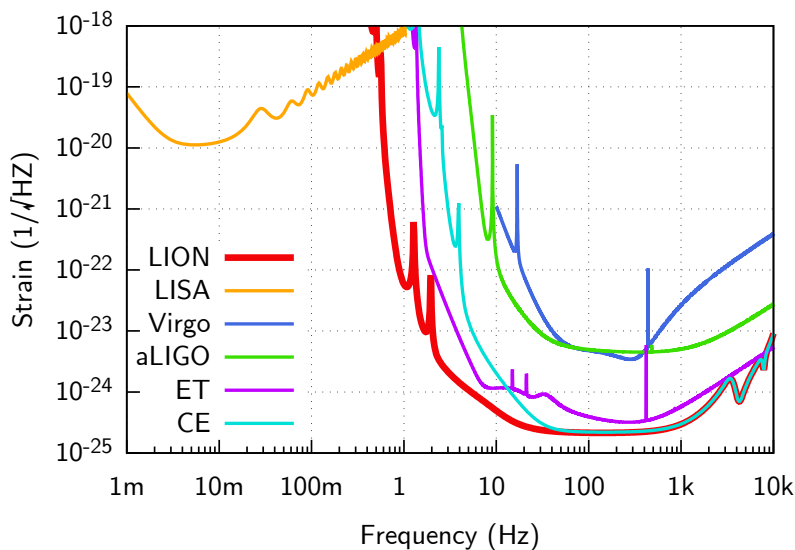


Figure 2. Comparison of the design sensitive of current and future gravitational wave detectors. Our proposed detector, LION, could extend the range of ground based detectors reducing the gap of measurable frequencies between Earth based and spaceborne missions. LION has the highest sensitivity in the detection band from below 30 Hz and is the only detector able to with sufficient sensitivity for detection between 0.7 Hz and 2 Hz.

this paper. The model is currently limited at low frequencies by the properties of the suspension system. Figure 2 shows the LION noise budget estimate and compares it with the performance of other current and proposed ground based detectors and the space based detector LISA. Although our estimate is based upon current technology and we possibly overestimate the Moon’s seismic activity, LION performs better than ET and Cosmic Explorer at frequencies below 30 Hz with detection capabilities down to 0.7 Hz. LION also manages to maintain performance comparable to Cosmic Explorer into the kHz regime.

IV. SCIENCE CASE

The LION sensitive band, from Figure 2, ranges between 0.7 Hz and several kHz with peak sensitivity at 10 Hz. Several investigations of sources in this frequency range have been conducted [78], showing the great interest in this band, a region where the current ground based network is blind to. In general, detecting in a lower frequency range opens the possibility for observing more massive black holes and thus allows to study gravity in the strong field regime [28]. This is a key element in the testing of general relativity in more extreme limits. Many new potential sources are predicted to exist in this band, for example, Type 1A supernovae, which have a gravitational wave frequency signature around 1 Hz. As discussed in [27], their observation may resolve the open question of their origins.

What makes LION unique, however, is its ability to cover a wide regime of frequencies and characteristic strains of merging binaries which cannot be explored with any other observatory. This forms the focus for this section.

A. An Approximation

We first give a few examples approximating the evolution in phase-space of the harmonics of the characteristic strain with the method of Peters et al.[79]. This has the advantage of allowing us to explore the evolution of the eccentricity, which is rather limited in more realistic waveforms based on computations of full general relativity. Once we have an idea of the evolution in phase-space of these systems, we will investigate in more detail the evolution of the full waveform and the computation of the signal-to-noise ratio following the method of Kaiser et al.[80], which we will describe in some detail. The scheme of Peters et al.[79] is based on an approximation of Keplerian ellipses. If we assume that the orbital parameters change slowly due to the emission of gravitational radiation, and that the gravitational waves are emitted at the integer multiples of the orbital frequency, at a distance D , the strain amplitude in the n -th harmonic can be described as

$$h_n = g(n, e) \frac{G^2 M_1 M_2}{D a c^4} \quad (1)$$

$$\simeq 1.6 \times 10^{-22} g(n, e) \left(\frac{D}{1 \text{ Gpc}} \right)^{-1} \left(\frac{a}{10^{-2} \text{ pc}} \right)^{-1} \left(\frac{M_1}{4 \times 10^4 M_\odot} \right) \left(\frac{M_2}{10 M_\odot} \right), \quad (2)$$

where we have normalised to parameters corresponding to an intermediate-mass ratio inspiral [IMRI, see e.g. 28, 30–32, 81], $g(n, e)$ is a function of the harmonic number n and the eccentricity of the source e . In Figure 3 we give an example of an IMRI and the inspiral of a binary of two stellar-mass black holes with masses $30 M_\odot$.

Another interesting example is shown in Figure 4. A system of two intermediate-mass black holes (IMBH) and an IMRI which, again, are only observable by LION at these distances and parameters. As we can see in the left panel, LION combined with LISA would allow us to do multi-bandwidth gravitational wave astronomy [see e.g. 25], since we can observe a source with LISA in the inspiral phase years before the final merger with a precision of at least seconds, which happens in the LION domain. This early warning would likely help to enhance the detection of the merger and ringdown with LION. Thanks to this, we would be in the position of breaking various degeneracies in the parameter extraction of the source. As before, we note that only LION is in this unique position.

As noted in [29], there is a need for a deci-Hertz gravitational wave observatory such as LION to understand the formation of compact binaries. This is something that LISA and LIGO/Virgo are not in the position of doing, as explained in [29].

B. Realistic waveforms and one comparison to LIGO

After our first exploration of the possible interesting systems for LION to observe, we now address with more realistic waveforms some examples. In particular, we employ the method of [84, 85], commonly referred to as IMRPhenomD, via the approach of [80]. The family IMRPhenomD approaches coalescing binaries by compounding a post-Newtonian approximation for the inspiral with a fully numerical relativistic solution for the merger and ringdown. This hybrid method allows us to quickly compute different waveforms. We also consider the approximation of [86], ENIGMA, which is a time domain, inspiral-merger-ringdown waveform model which allows consideration of moderately eccentric orbits, via the implementation of [87]. In particular, we display in Figure 5 four sources, with one of them only in the LISA regime as a reference point.

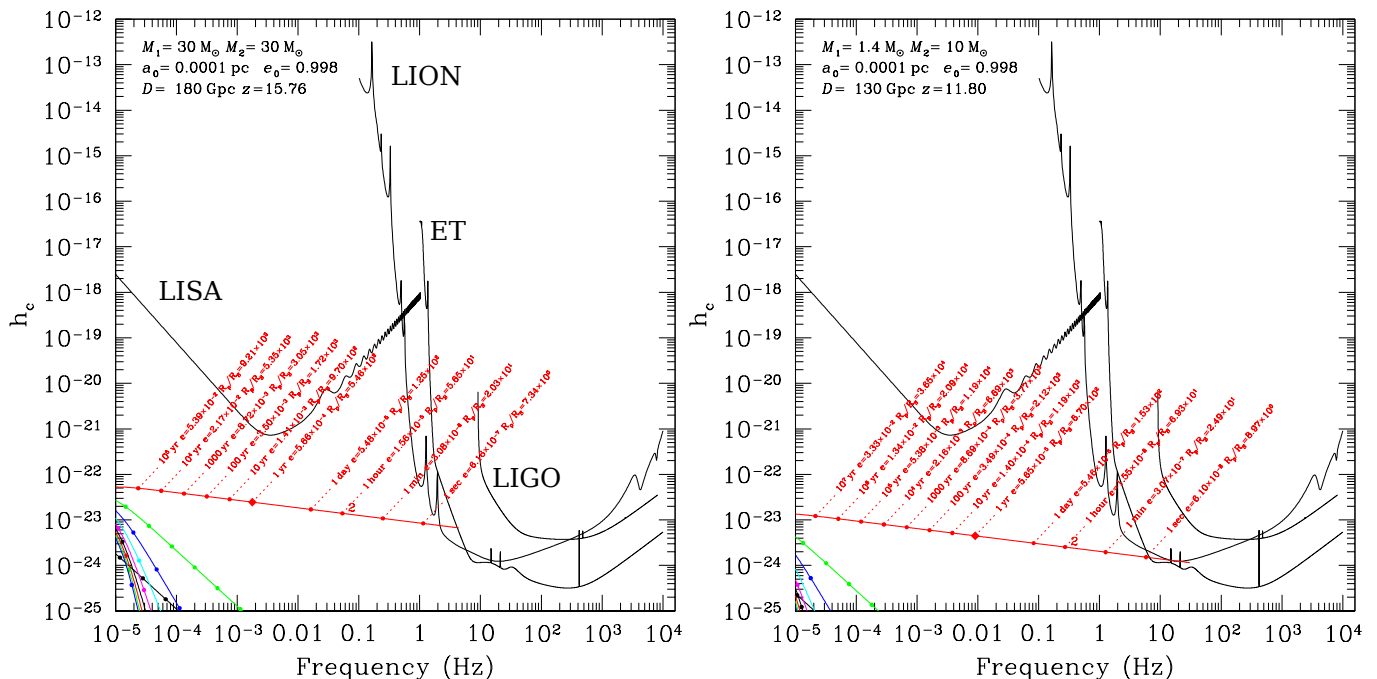


Figure 3. Evolution in frequency of the first harmonics (displayed in different colours) of two compact binaries in the approximation of Keplerian ellipses of [82]. We depict the characteristic, dimensionless amplitude as a function of the frequency in Hz. The initial dynamical parameters corresponding to the each source is summarised at the top, left corner of each panel (masses, initial semi-major axis and eccentricity and distance to the source D). From the left (lower frequencies) to the right (higher frequencies), we show the sensitivity curve of LISA [8], then LION, starting at about 1 Hz, the Einstein Telescope [83], and then LIGO. The upper, red harmonic corresponds to $n = 2$ in Equation 2, which means that the source has circularised. We also show different moments in the evolution of the harmonics, and add the information relative to the source at that moment; in particular the remaining time until merger, the eccentricity and the periastron distance R_p in Schwarzschild radii R_S . The left panel shows a binary of masses $M_1 = M_2 = 30 M_\odot$ at a distance of 180 Gpc, which corresponds to a redshift of $z = 15.76$. This is orders of magnitude distance further away than what LISA can hope to observe. The right panel shows the inspiral of a compact object of mass $1.4 M_\odot$ (e.g. a neutron star) onto a stellar-mass black hole of mass $10 M_\odot$ at a distance of 130 Gpc ($z = 11.80$). Even at this cosmological distance, the source spends one second in the LION domain. We note that no other detector is in the position of resolving these sources.

Probably the most remarkable system is a binary of two black holes of mass ratio $q = 18$ with the heaviest one having a mass of $100 M_\odot$ at a redshift of $z = 100$ (lowermost signal). This binary is only detectable by LION and shows the relevance of the detector.

We show in Figure 6 a binary of two IMBHs with equal mass and different eccentricities, as approximated with ENIGMA [86]. The case with eccentricity yields a slightly higher signal-to-noise ratio (SNR) as calculated in the approximation of [87] for chirping binaries.

Because IMRPhenomD features mass ratios up to 18 including spins, in Figure 7 we show the role of the spin s and q for two different systems, a binary of two IMBHs and a lighter one, with the mass of the heaviest black hole $18 M_\odot$, and $q = 10$. As expected, a mass ratio and positive spin value increases the characteristic strain as we approach the end of the evolution, which has an impact on the calculation of the signal-to-noise ratio.

C. Signal-to-noise ratio contour maps

To estimate the signal-to-noise ratio for different configurations and systems, we adopt the approach of [23] and assume that the noise is stationary, Gaussian and uncorrelated with the signal. If we envisage the waveforms as vectors in a Hilbert space [88], we can define a noise-weighted inner product as follows

$$\langle h' | h \rangle := 2 \int_0^\infty df \frac{\tilde{h}'(f)\tilde{h}(f)^* + \tilde{h}'(f)^*\tilde{h}(f)}{S_n(f)}. \quad (3)$$

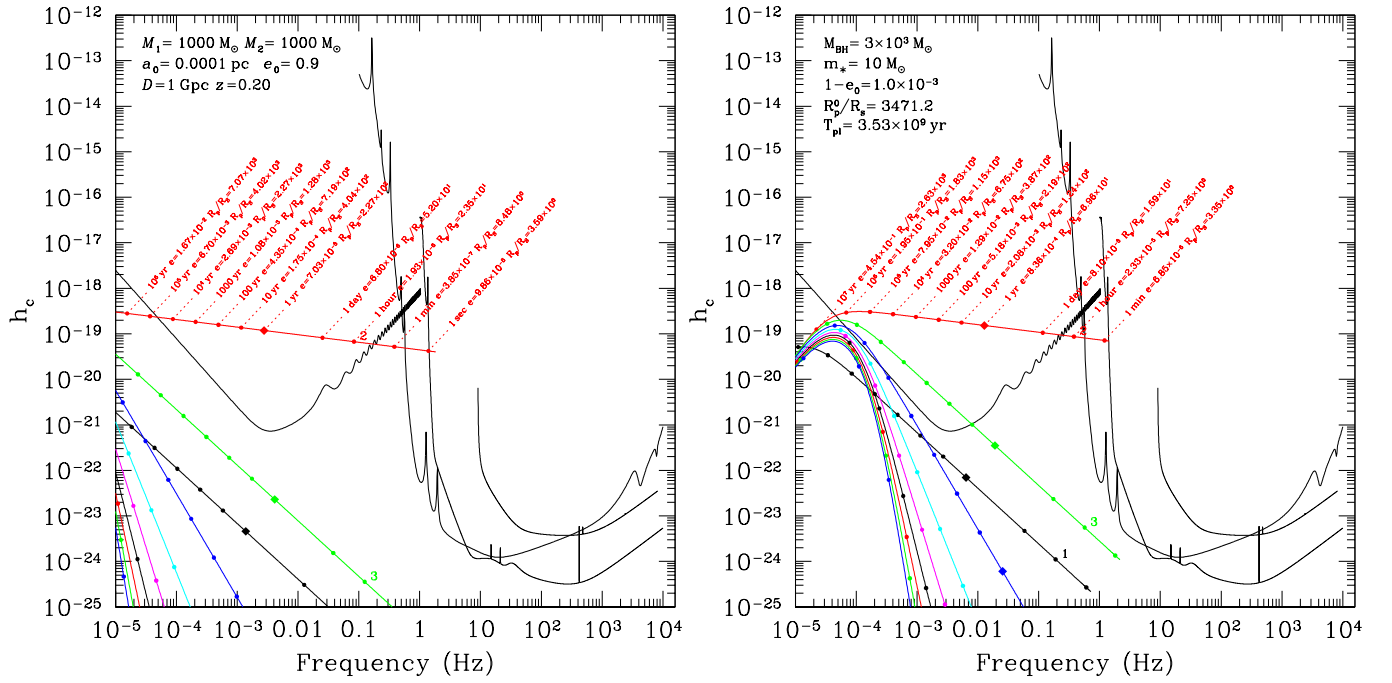


Figure 4. Same as in Figure 3 but for a binary of two intermediate-mass black holes (left panel) and an IMRI composed of an intermediate-mass black hole of mass $M_{\text{BH}} = 3000 M_\odot$ and a stellar-mass one of $m_* = 10 M_\odot$ (right panel). In the latter we also include information about the initial periastris distance R_p^0 , as well as the initial time for merger T_{pl} .

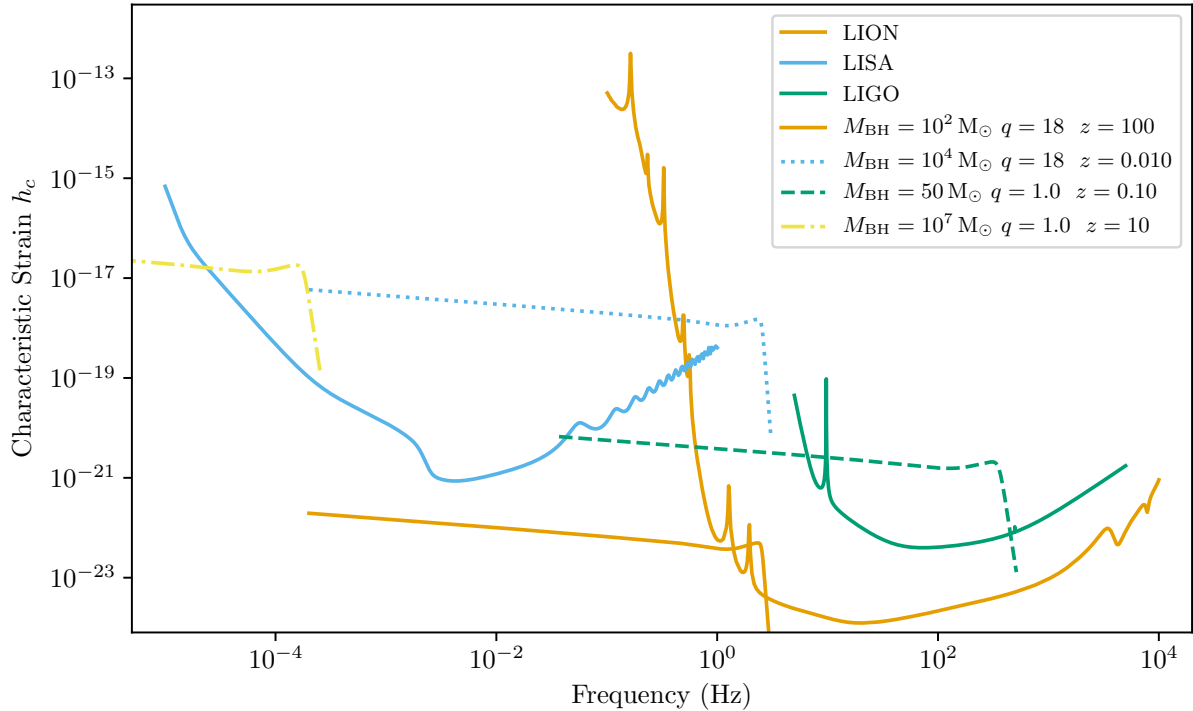


Figure 5. Evolution of four different signals with masses ranging between $10^7 M_\odot$ and $50 M_\odot$, different mass ratios q (in the legend we show the mass of the largest black hole) and the assumed redshift. We show three different observatories (LISA, LION and LIGO). The yellow, dash-dotted waveform corresponds to a system of $10^7 M_\odot$ at a redshift $z = 10$ with $q = 1$; the orange, solid waveform to a binary of $q = 100 M_\odot$, $z = 100$ and $q = 18$; the blue, dotted one to a system of $10^4 M_\odot$, $z = 10^{-2}$, $q = 18$ and the green, dashed curve represents a binary of mass $50 M_\odot$, $z = 0.1$ and $q = 1$.

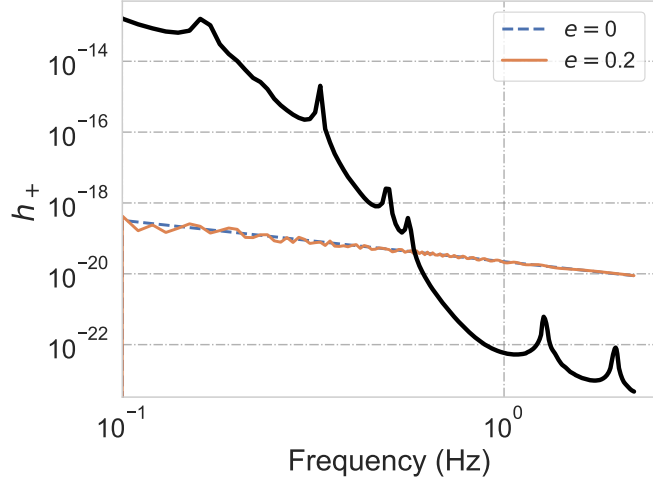


Figure 6. Evolution of the plus polarization h_+ for a binary of two IMBHs of masses $M_1 = M_2 = 10^3 M_\odot$ in the LION window (solid, black line). We consider two different eccentricities, one zero and the other $e = 0.2$ at the beginning of the evolution. As the systems evolve, the loss of angular momentum circularises the eccentric case, which converges towards the circular one. The binaries are assumed to be at a distance of 1 Gpc. For LION, the circular- and eccentric cases yield SNR ~ 1855 and 1875 , respectively, while for (advanced) LIGO the values are ~ 3.7 for the circular case, and 3.8 for the eccentric one.

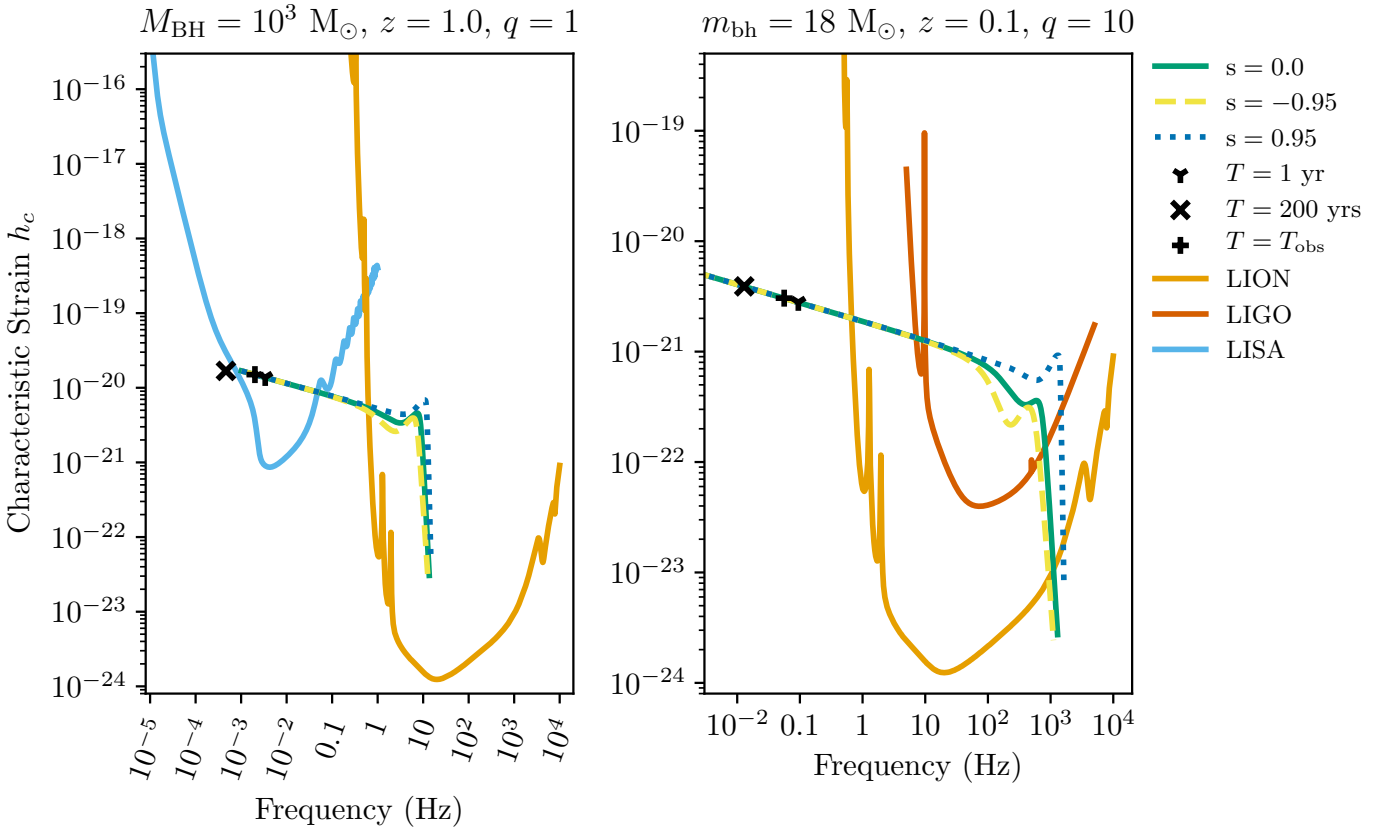


Figure 7. *Left panel:* A binary of two IMBHs of masses $10^3 M_\odot$ at a redshift $z = 1$ for different spin values (see legend on the right) at three different moments, namely 200 years before the coalescence, at the detector's (typical) observation time T_{obs} and 1 year before the coalescence. We display the sensitivity curve of LISA (blue, left one) and LION (orange, right one). *Right panel:* Evolution of the waveform for a binary of two black holes with $q = 18$ and the mass of the heaviest one $m_{\text{bh}} = 18 M_\odot$, at a redshift $z = 0.1$. As in the left panel, we pinpoint the same moments in the evolution, different spin configurations, the sensitivity curve of LION (orange, left one) and LIGO (red, right one).

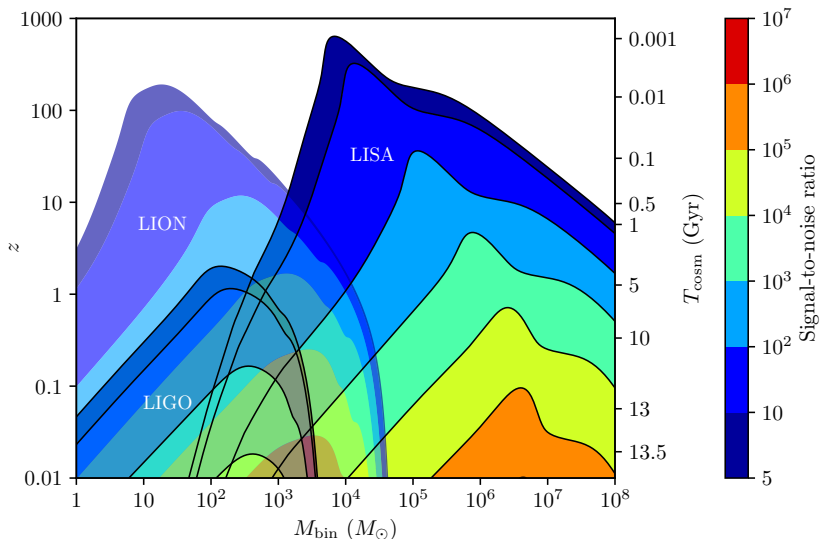


Figure 8. Contours of signal-to-noise ratio as a function of the total mass of the binary system M_{bin} in solar masses and redshift (and cosmological time, in Gyrs). We remark how LION covers a region of phase-space which is totally inaccessible to both LISA and LIGO, as shown with particular examples in Figure 5.

In the last equation we have introduced $\tilde{h}(f)$ as the Fourier transform of the time-domain waveform. Moreover, $S_n(f)$ is the one-sided noise power spectral density of the detector, following [89, 90], and see Section 2.3 of [80] for a summary and implementation. If we adopt the above-mentioned assumptions, the optimal signal-to-noise ratio (SNR) when filtering the data against h is given by

$$\rho = \sqrt{\langle h_+ | h_+ \rangle + \langle h_\times | h_\times \rangle}. \quad (4)$$

In Figure 8 we depict the SNR ρ as a function of the total mass of the binary M_{bin} and redshift for LION, but also LIGO and LISA for a reference point. We note that LION is in the position of extracting information about binaries with masses in the regime necessary to understand the formation and cosmical evolution of supermassive black holes [see, for a review 24], with SNRs values at redshift exceeding 100.

Finally, in Figure 9 we show how the SNR depends on the redshift, mass ratio and spin values for LION and compare it with LIGO as a reference. We note that, contrary to Figure 8, the contour map covers SNRs including values from 1.

D. Angular Resolution

We note that the frequency range of LION allows us to improve the angular resolution of source positioning in the sky, by adding a lunar detector to the LVK collaboration. The angular resolution $\Delta\Omega$ is proportional to the increase of the network area A , $\Delta\Omega \propto 1/A$ [26]. This means that an average Earth-Moon distance of 380 000km [91] increases the area A and improves the angular resolution by a factor of 60 compared to a purely Earth based network with maximum radius of 6000km.

This will not only help to enhance the sky mapping of these objects, but also opens a huge possibility to multi messenger astronomy, as we have seen, in particular in Fig. (8). The first counterpart observation GW170817 [92], showed, how much knowledge is gained when observing the emitted gravitational waves and electromagnetic radiation from an event. With the combination of improved sky location and knowledge about the time of the merger beforehand, the electromagnetic telescopes can be pointed to the sky location in time to ensure a simultaneous observation. This will significantly increase the upcoming Gravitational-wave Optical Transit Observer (GOTO) array's useful observations [93].

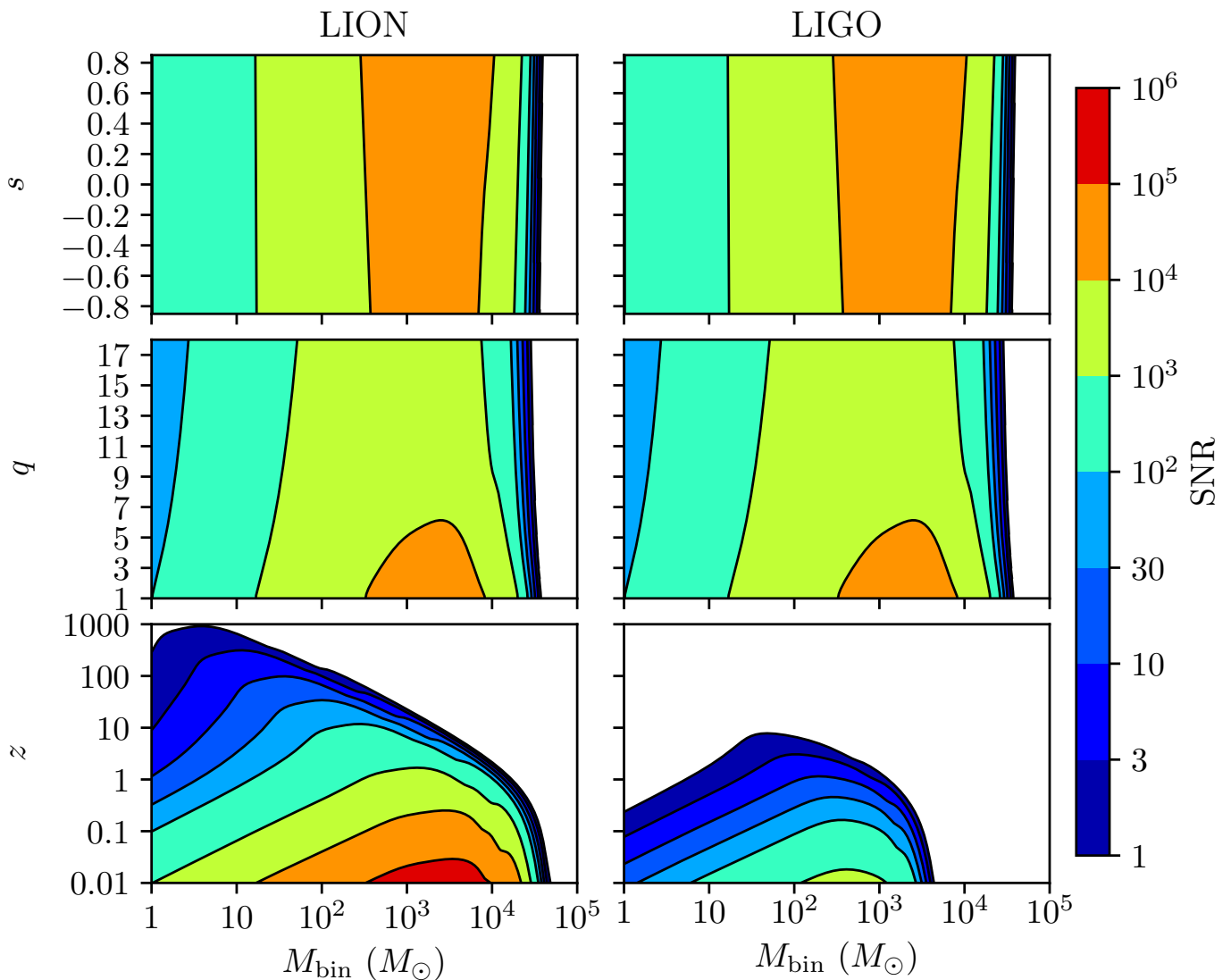


Figure 9. Mosaique of SNR contour maps to show its dependency with the redshift (bottom panels, as in Figure 8), the mass ratio q ranging between the values that IMRPhenomD allows for (mid panels, see text) and the spin (top panels). We show LION on the left column and LIGO on the right one.

V. COST AND TIMELINE

The costs for LION can be split into the sections of space operation, including the driving costs of launchers and landers, the communication with Earth, thus the ground segment, and the scientific resources. Three launches with the commercial Falcon Heavy by SpaceX currently cost 270M Euros [94], with additional costs for the landers themselves. Space qualification of equipment is often approximately 10 times more expensive than the qualification for ultra high vacuum. Thus, we estimate the infrastructure cost for Cosmic Explorer, without the need of a vacuum system, is 300M Euros [6]. With the additional cost of communication, landers, and automatic installation on the site, as well as all unmentioned human resources, we propose the mission with overall budget in the order of 1,500M Euros. Future discoveries of new technological requirements, or a significant improvement of the currently changing human spaceflight, however, can influence the cost level in any direction. We believe that this the right order of magnitude and it is similar to other proposed space based gravitational wave missions, [8, 42].

With an initial mission proposal by 2023 and a full design study based on new data about the Moon by 2030, simultaneous development of technologies along side Cosmic Explorer's second phase would enable us to begin space qualifying the necessary parts so that all technologies are space qualified by 2048. This would give time to build the missions in time for 3 launches in the middle of the decade, Assembling would be done robotically and it is hoped that

this will be completed within a couple of years. The mission lifetime is expected to be 10 years, with the possibility of 5 year expansion. It is expected that in this time components will wear out and limit operation. However, if there proved to be sufficient interest, LION can continuously be repaired and upgraded, making an advanced LION detector more likely than the need of disposal.

VI. CONCLUSION

We find that a detector built on the Moon with technology of the third generation detectors features a detection bandwidth between 0.7 Hz and 10 kHz with detection noise hitting a floor of $3 \times 10^{-24} \text{ m}/\sqrt{\text{Hz}}$ at 10 Hz. This is a conservative estimate which is limited by the thermal noise and residual seismic activity of the Moon. Since the actual seismic activity of the Moon is still uncertain and we only use an upper estimate of activity, a thorough test campaign is likely to improve the performance prediction. Nevertheless, LION would make an excellent complement to the existing network, with significant overlap of required technology development.

The unique detection band presents an opportunity to push the capabilities of gravitational wave astronomy and our understanding of physics. The ability to measure binaries of seed black holes to a redshifts of 100 and higher provides a unique glance at the cauldron where stars and galaxies were formed and would shed light on the question on how massive black holes assemble their mass and grow over cosmic timescales [see e.g. 24, for a review]. We also find that many of the sources present in the LISA band can be picked up in the LION band to observe final merger achieving the long held dream of multi messenger astronomy. Doing so will break many of the degeneracies of the parameter space so that we can better understand their formation channels [29]. In this regard, it can be envisaged as a true deci-Hertz bridge between space borne observatories and ground based ones. Moreover, having a much wider detection array at low frequencies is imperative for the coordination between electromagnetic and gravitational observations needed to glimpse the final stages of an inspiraling system with an optical telescope.

The Moon is perhaps one of the best available environments to operate a gravitational wave detector in our solar system. While we show in this paper that current or currently designed technology enables the low frequency detector, its installation on the lunar surface requires significant technological development. However, these lie not too far beyond the horizon of humanities progress. We believe that, once humanity starts exploiting the Moon for science and resources, a gravitational wave observatory is an excellent candidate for the first large scale infrastructure experiment on the lunar surface.

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AUTHOR CONTRIBUTIONS

The initial idea of LION was developed by the authors Bischof, Carter, Hartig and Wilken at a lecture week in 2018, where Amaro Seoane was supervising, run by the International Max Planck Research School for Gravitational Waves (IMPRS-GW). Bischof, Carter, Hartig and Wilken followed up the lecture week with a deeper exploration

of the required mission parameters, noise curves and technical discussion of the paper. The work on sources in the detection band was performed by Pau Amaro Seoane.

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- [1] LIGO Scientific Collaboration. Advanced LIGO. *Class Quantum Grav.* 2015 mar;32(7):074001. Available from: <https://doi.org/10.1088%2F0264-9381%2F32%2F7%2F074001>.
- [2] Caron B, Dominjon A, Drezen C, Flaminio R, Grave X, Marion F, et al. The virgo interferometer. *Class Quantum Grav.* 1997;14(6):1461.
- [3] Aso Y, Michimura Y, Somiya K, Ando M, Miyakawa O, Sekiguchi T, et al. Interferometer design of the KAGRA gravitational wave detector. *Phys Rev D.* 2013;88(4):043007.
- [4] Punturo M, Abernathy M, Acernese F, Allen B, Andersson N, Arun K, et al. The Einstein Telescope: a third-generation gravitational wave observatory. *Class Quantum Grav.* 2010 sep;27(19):194002.
- [5] Dwyer S, Sigg D, Ballmer SW, Barsotti L, Mavalvala N, Evans M. Gravitational wave detector with cosmological reach. *Phys Rev D.* 2015 Apr;91:082001. Available from: <https://link.aps.org/doi/10.1103/PhysRevD.91.082001>.
- [6] Reitze D, Adhikari RX, Ballmer S, Barish B, Barsotti L, Billingsley G, et al. Cosmic Explorer: The U.S. Contribution to Gravitational-Wave Astronomy beyond LIGO. In: *Bulletin of the American Astronomical Society.* vol. 51; 2019. p. 35.
- [7] Beker M, van den Brand J, Hennes E, Rabeling D. Newtonian noise and ambient ground motion for gravitational wave detectors. *J Phys Conf Ser.* 2012 jun;363:012004. Available from: <https://doi.org/10.1088%2F1742-6596%2F363%2F1%2F012004>.
- [8] Amaro-Seoane P, Audley H, Babak S, Baker J, Barausse E, Bender P, et al. Laser Interferometer Space Antenna. *ArXiv e-prints.* 2017 Feb;.
- [9] Essick R, Vitale S, Evans M. Frequency-dependent responses in third generation gravitational-wave detectors. *Phys Rev D.* 2017 Oct;96:084004. Available from: <https://link.aps.org/doi/10.1103/PhysRevD.96.084004>.
- [10] Schilling R. Angular and frequency response of LISA. *Class Quantum Grav.* 1997 jun;14(6):1513–1519. Available from: <https://doi.org/10.1088%2F0264-9381%2F14%2F6%2F020>.
- [11] Manchester RN, Hobbs GB, Teoh A, Hobbs M. The Australia Telescope National Facility Pulsar Catalogue. *Astron J.* 2005;129(4):1993–2006. Available from: <https://doi.org/10.1086%2F428488>.
- [12] Kawamura S, Nakamura T, Ando M, Seto N, Tsubono K, Numata K, et al. The Japanese space gravitational wave antenna—DECIGO. *Class Quantum Grav.* 2006;23(8):S125.
- [13] Phinney E, Bender P, Buchman S, Byer R, Cornish N, Fritschel P, et al. The Big Bang Observer. *NASA Mission Concept Study.* 2003;.
- [14] LaFave N, Wilson T. Lunar LIGO: A new concept in gravitational wave astronomy. In *Lunar and Planetary Inst.* 1993 02;24:841–842.
- [15] Wilson T, LaFave N. Lunar LIGO and gravitational wave astronomy on the Moon. In *Lunar and Planetary Inst.* 1994 03;.
- [16] Paik HJ, Venkateswara KY. Gravitational wave detection on the Moon and the moons of Mars. *Adv Space Res.* 2009;43(1):167 – 170. Available from: <http://www.sciencedirect.com/science/article/pii/S0273117708002342>.
- [17] Coughlin M, Harms J. 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.* 2014 Nov;90:102001. Available from: <https://link.aps.org/doi/10.1103/PhysRevD.90.102001>.
- [18] Harms J, Ambrosino F, Angelini L, Braitto V, Branchesi M, Brocato E, et al. Lunar Gravitational-Wave Antenna. *arXiv.* 2020;.
- [19] Jani K, Loeb A. Gravitational-Wave Lunar Observatory for Cosmology. *arXiv preprint arXiv:200708550.* 2020;.
- [20] Friedrich D, Nakano M, Kawamura H, Yamanaka Y, Hirobayashi S, Kawamura S. Juggled interferometer for the detection of gravitational waves around 0.1–10 Hz. *Class Quantum Grav.* 2014 nov;31(24):245006. Available from: <https://doi.org/10.1088%2F0264-9381%2F31%2F24%2F245006>.
- [21] Latham GV, Ewing M, Press F, Sutton G, Dorman J, Nakamura Y, et al. Passive Seismic Experiment. *Science.* 1970;167(3918):455–457. Available from: <https://science.sciencemag.org/content/167/3918/455>.
- [22] Latham GV, Ewing M, Press F, Sutton G, Dorman J, Nakamura Y, et al. Passive seismic experiment. *Apollo 16 Preliminary Science Report, NASA SP.* 1972;315.
- [23] Maggiore M. *Gravitational Waves: Volume 1: Theory and Experiments.* Gravitational Waves. OUP Oxford; 2008. Available from: <https://books.google.de/books?id=AqVpQgAACAAJ>.
- [24] Colpi M, Dotti M. Massive Binary Black Holes in the Cosmic Landscape. *Adv Sci Lett.* 2011 Feb;4:181–203.
- [25] Amaro-Seoane P, Santamaría L. DETECTION OF IMBHs WITH GROUND-BASED GRAVITATIONAL WAVE OBSERVATORIES: A BIOGRAPHY OF A BINARY OF BLACK HOLES, FROM BIRTH TO DEATH. *The Astrophysical Journal.* 2010 sep;722(2):1197–1206. Available from: <https://doi.org/10.1088/0004-637x/722/2/1197>.
- [26] Wen L, Chen Y. Geometrical expression for the angular resolution of a network of gravitational-wave detectors. *Phys Rev D.* 2010;81(8):082001. Available from: <http://dx.doi.org/10.1103/PhysRevD.81.082001>.
- [27] Mandel I, Sesana A, Vecchio A. The astrophysical science case for a decihertz gravitational-wave detector. *Class Quantum Grav.* 2018 feb;35(5):054004. Available from: <https://doi.org/10.1088%2F1361-6382%2Faa7e0>.
- [28] Amaro-Seoane P. Detecting intermediate-mass ratio inspirals from the ground and space. *Phys Rev D.* 2018 Sep;98(6):063018. Available from: <https://link.aps.org/doi/10.1103/PhysRevD.98.063018>.

- [29] Chen X, Amaro-Seoane P. Revealing the Formation of Stellar-mass Black Hole Binaries: The Need for Deci-Hertz Gravitational-wave Observatories. *Astrophys J.* 2017 Jun;842(1):L2. Available from: <https://doi.org/10.3847/2F2041-8213/2Faa74ce>.
- [30] Amaro-Seoane P. Relativistic dynamics and extreme mass ratio inspirals. *Living Rev Relativ.* 2018 May;21:4.
- [31] Amaro-Seoane P. The gravitational capture of compact objects by massive black holes. arXiv e-prints. 2020 Nov;p. arXiv:2011.03059.
- [32] Amaro-Seoane P, Gair JR, Freitag M, Miller MC, Mandel I, Cutler CJ, et al. Intermediate and extreme mass-ratio inspirals. *Astrophysics, science applications and detection using LISA. Class Quantum Grav.* 2007 Sep;24:113–+.
- [33] Mitrofanov I, Dolgoplov V, Khartov V, Lukjanchikov A, Tret'yakov V, Zelenyi L. "Luna-Glob" and "Luna-Resurs": science goals, payload and status. In: *EGU General Assembly Conference Abstracts.* vol. 16; 2014. p. 1.
- [34] Sibeck D, Angelopoulos V, Brain D, Delory G, Eastwood J, Farrell W, et al. ARTEMIS science objectives. In: *The ARTEMIS mission.* Springer; 2011. p. 27–59.
- [35] Xiao L. China's touch on the Moon. *Nat Geosci.* 2014;7(6):391.
- [36] Haruyama J, Sawai S, Mizuno T, Yoshimitsu T, Fukuda S, Nakatani I. Exploration of lunar holes, possible skylights of underlying lava tubes, by smart lander for investigating moon (slim). *Trans Jpn Soc Aeronaut Space Sci.* 2012;10(ists28):Pk.7–Pk.10.
- [37] Hayne PO, Hendrix A, Sefton-Nash E, Siegler MA, Lucey PG, Retherford KD, et al. Evidence for exposed water ice in the Moon's south polar regions from Lunar Reconnaissance Orbiter ultraviolet albedo and temperature measurements. *Icarus.* 2015;255:58 – 69. Lunar Volatiles. Available from: <http://www.sciencedirect.com/science/article/pii/S0019103515001335>.
- [38] Ingersoll AP, Svitek T, Murray BC. Stability of polar frosts in spherical bowl-shaped craters on the Moon, Mercury, and Mars. *Icarus.* 1992;100(1):40 – 47. Available from: <http://www.sciencedirect.com/science/article/pii/S001910359290016Z>.
- [39] Williams JP, Paige DA, Greenhagen BT, Sefton-Nash E. The global surface temperatures of the Moon as measured by the Diviner Lunar Radiometer Experiment. *Icarus.* 2017;283:300 – 325. Lunar Reconnaissance Orbiter - Part II. Available from: <http://www.sciencedirect.com/science/article/pii/S0019103516304869>.
- [40] Sharpe BL, Schrunk DG. Malapert mountain: Gateway to the moon. *Adv Space Res.* 2003;31(11):2467 – 2472. The Moon: Science, Exploration and Utilisation. Available from: <http://www.sciencedirect.com/science/article/pii/S0273117703005350>.
- [41] Williams DR. Williams DR, editor. Moon fact sheet. NASA; 2020.
- [42] Danzmann K, the LISA study team. LISA: laser interferometer space antenna for gravitational wave measurements. *Class Quantum Grav.* 1996 nov;13(11A):A247–A250. Available from: <https://doi.org/10.1088/2F0264-9381/2F13/2F11a/2F033>.
- [43] McNamara P, Vitale S, and KD. LISA Pathfinder. *Class Quantum Grav.* 2008 may;25(11):114034. Available from: <https://doi.org/10.1088/2F0264-9381/2F25/2F11/2F114034>.
- [44] Latham GV, Ewing M, Press F, Sutton G, Dorman J, Nakamura Y, et al. Apollo 11 passive seismic experiment. *Geochim Cosmochim Acta.* 1970 Jan;1:2309.
- [45] Nakamura Y. Shallow moonquakes: how they compare with earth-quakes. *Lunar and Planetary Science Conference Proceedings.* 1980 Jan;3:1847–1853.
- [46] Lognonné P, Feuvre ML, Johnson CL, Weber RC. Moon meteoritic seismic hum: Steady state prediction. *J Geophys Res Planets.* 2009 12;114(E12). Available from: <https://doi.org/10.1029/2008JE003294>.
- [47] Banerdt WB, Chui T, Griggs CE, Herrin ET, Nakamura Y, Paik HJ, et al. Using the Moon as a low-noise seismic detector for strange quark nuggets. *Nucl Phys B Proc Suppl.* 2007;166:203 – 208. Proceedings of the Third International Conference on Particle and Fundamental Physics in Space. Available from: <http://www.sciencedirect.com/science/article/pii/S0920563206010188>.
- [48] Watters TR, Weber RC, Collins GC, Howley IJ, Schmerr NC, Johnson CL. Shallow seismic activity and young thrust faults on the Moon. *Nat Geosci.* 2019 05;12:411–417. Available from: <https://doi.org/10.1038/s41561-019-0362-2>.
- [49] Beker M, Cella G, DeSalvo R, Doets M, Grote H, Harms J, et al. Improving the sensitivity of future GW observatories in the 1–10 Hz band: Newtonian and seismic noise. *Gen Relativ Gravit.* 2011;43(2):623–656.
- [50] Matichard F, Lantz B, Mason K, Mittleman R, Abbott B, Abbott S, et al. Advanced LIGO two-stage twelve-axis vibration isolation and positioning platform. Part 2: Experimental investigation and tests results. *Precis Eng.* 2015;40:287–297.
- [51] Lantz B, Schofield R, O'reilly B, Clark D, DeBra D. Requirements for a ground rotation sensor to improve advanced LIGO. *Bulletin of the Seismological Society of America.* 2009;99(2B):980–989.
- [52] Arai K, Collaboration T. Sensing and controls for power-recycling of TAMA300. *Class Quantum Grav.* 2002 mar;19(7):1843–1848. Available from: <https://doi.org/10.1088/0264-9381/19/7/383>.
- [53] Carter JJ, Cooper SJ, Thrift E, Briggs J, Warner J, Ross MP, et al. Particle swarming of sensor correction filters. *Class Quantum Grav.* 2020 sep;37(20):205009. Available from: <https://doi.org/10.1088/1361-6382/abb32a>.
- [54] Dacey J. The new race to the Moon. *Physics World.* 2019 jul;32(7):10–11. Available from: <https://doi.org/10.1088/2058-7058/32/7/14>.
- [55] Mitrofanov IG, Zelenyi LM, Tret'yakov VI, Dolgoplov VP. Science Program of Lunar Landers of "Luna-Glob" and "Luna-Resource" Missions. In: *Lunar and Planetary Science Conference. Lunar and Planetary Science Conference; 2011.* p. 1798.
- [56] Cumming A, Bell A, Barsotti L, Barton M, Cagnoli G, Cook D, et al. Design and development of the advanced LIGO monolithic fused silica suspension. *Class Quantum Grav.* 2012;29(3):035003.

- [57] Aston S, Barton M, Bell A, Beveridge N, Bland B, Brummitt A, et al. Update on quadruple suspension design for Advanced LIGO. *Class Quantum Grav.* 2012;29(23):235004.
- [58] Saulson PR. *Fundamentals of interferometric gravitational wave detectors.* World Scientific; 1994.
- [59] Schroeter A, Nawrodt R, Schnabel R, Reid S, Martin I, Rowan S, et al. On the mechanical quality factors of cryogenic test masses from fused silica and crystalline quartz. arXiv preprint arXiv:07094359. 2007;.
- [60] Penn SD, Sneddon PH, Armandula H, Betzwieser JC, Cagnoli G, Camp J, et al. Mechanical loss in tantala/silica dielectric mirror coatings. *Class Quantum Grav.* 2003;20(13):2917.
- [61] Hirose E, Sekiguchi T, Kumar R, Takahashi R, collaboration K, et al. Update on the development of cryogenic sapphire mirrors and their seismic attenuation system for KAGRA. *Class Quantum Grav.* 2014;31(22):224004.
- [62] Nawrodt R, Zimmer A, Koettig T, Schwarz C, Heinert D, Hudl M, et al. High mechanical Q-factor measurements on silicon bulk samples. In: *Journal of Physics: Conference Series.* vol. 122. IOP Publishing; 2008. p. 012008.
- [63] Cumming A, Cunningham L, Hammond G, Haughian K, Hough J, Kroker S, et al. Silicon mirror suspensions for gravitational wave detectors. *Class Quantum Grav.* 2013;31(2):025017.
- [64] Lough J, Schreiber E, Bergamin F, Grote H, Mehmet M, Vahlbruch H, et al. First demonstration of 6 dB quantum noise reduction in a kilometer scale gravitational wave observatory. arXiv. 2020;.
- [65] Acernese F, Agathos M, Aiello L, Allocca A, Amato A, Ansoldi S, et al. Increasing the Astrophysical Reach of the Advanced Virgo Detector via the Application of Squeezed Vacuum States of Light. *Phys Rev Lett.* 2019 Dec;123:231108. Available from: <https://link.aps.org/doi/10.1103/PhysRevLett.123.231108>.
- [66] Tse M, Yu H, Kijbunchoo N, Fernandez-Galiana A, Dupej P, Barsotti L, et al. Quantum-Enhanced Advanced LIGO Detectors in the Era of Gravitational-Wave Astronomy. *Phys Rev Lett.* 2019 Dec;123:231107. Available from: <https://link.aps.org/doi/10.1103/PhysRevLett.123.231107>.
- [67] Zhao Y, Aritomi N, Capocasa E, Leonardi M, Eisenmann M, Guo Y, et al. Frequency-Dependent Squeezed Vacuum Source for Broadband Quantum Noise Reduction in Advanced Gravitational-Wave Detectors. *Phys Rev Lett.* 2020 Apr;124:171101. Available from: <https://link.aps.org/doi/10.1103/PhysRevLett.124.171101>.
- [68] Ma Y, Miao H, Pang BH, Evans M, Zhao C, Harms J, et al. Proposal for gravitational-wave detection beyond the standard quantum limit through EPR entanglement. *Nat Phys.* 2017;13(8):776–780.
- [69] Staley A, Martynov D, Abbott R, Adhikari RX, Arai K, Ballmer S, et al. Achieving resonance in the Advanced LIGO gravitational-wave interferometer. *Class Quantum Grav.* 2014 nov;31(24):245010. Available from: <https://doi.org/10.1088/0264-9381/31/24/245010>.
- [70] Mullavey AJ, Slagmolen BJJ, Miller J, Evans M, Fritschel P, Sigg D, et al. Arm-length stabilisation for interferometric gravitational-wave detectors using frequency-doubled auxiliary lasers. *Opt Express.* 2012 Jan;20(1):81–89. Available from: <http://www.opticsexpress.org/abstract.cfm?URI=oe-20-1-81>.
- [71] Biscans S, Warner J, Mittleman R, Buchanan C, Coughlin M, Evans M, et al. Control strategy to limit duty cycle impact of earthquakes on the LIGO gravitational-wave detectors. *Class Quantum Grav.* 2018 jan;35(5):055004. Available from: <https://doi.org/10.1088/2F1361-6382/2F5aa4aa>.
- [72] Beckman M. Mission design for the lunar reconnaissance orbiter. In: *29th ANNUAL AAS GUIDANCE AND CONTROL CONFERENCE;* 2007. p. 1.
- [73] Kawamoto H, Uchiyama M, Cooper BL, McKay DS. Mitigation of lunar dust on solar panels and optical elements utilizing electrostatic traveling-wave. *J Electrostat.* 2011;69(4):370 – 379. Available from: <http://www.sciencedirect.com/science/article/pii/S0304388611000696>.
- [74] Mazumder MK, Sharma R, Biris AS, Zhang J, Calle C, Zahn M. Self-Cleaning Transparent Dust Shields for Protecting Solar Panels and Other Devices. *Part Sci Technol.* 2007;25(1):5–20. Available from: <https://doi.org/10.1080/02726350601146341>.
- [75] Chavers DG. NASA Lander Technologies Project Status. In: *AIAA SPACE 2016.* Aerospace Research Central; 2016. p. 5221.
- [76] Boroson DM, Robinson BS, Murphy DV, Burianek DA, Khatri F, Kovalik JM, et al. Overview and results of the lunar laser communication demonstration. In: *Free-Space Laser Communication and Atmospheric Propagation XXVI.* vol. 8971. International Society for Optics and Photonics; 2014. p. 89710S.
- [77] Adhikari R. Adhikari R, editor. *Gravitational Wave Interferometer Noise Calculator (GWINC),* Oct 2020. github; 2020. Available from: <https://git.ligo.org/gwinc>.
- [78] Gair JR, Mandel I, Miller MC, Volonteri M. Exploring intermediate and massive black-hole binaries with the Einstein Telescope. *Gen Relativ Gravit.* 2011;43.
- [79] Peters PC, Mathews J. Gravitational Radiation from Point Masses in a Keplerian Orbit. *Phys Rev.* 1963 Jul;131:435–440.
- [80] Kaiser AR, McWilliams ST. Sensitivity of present and future black-hole binary observations across the gravitational wave spectrum. arXiv e-prints. 2020 Oct;p. arXiv:2010.02135.
- [81] Konstantinidis S, Amaro-Seoane P, Kokkotas KD. Investigating the retention of intermediate-mass black holes in star clusters using N-body simulations. *Astronomy & Astrophysics.* 2013;557:A135.
- [82] Peters PC. Gravitational Radiation and the Motion of Two Point Masses. *Phys Rev.* 1964 Nov;136:1224–1232.
- [83] Sathyaprakash B, Abernathy M, Acernese F, Ajith P, Allen B, Amaro-Seoane P, et al. Scientific objectives of Einstein Telescope. *Class Quantum Grav.* 2012 Jun;29(12):124013.
- [84] Husa S, Khan S, Hannam M, Pürrer M, Ohme F, Forteza XJ, et al. Frequency-domain gravitational waves from non-precessing black-hole binaries. I. New numerical waveforms and anatomy of the signal. *PhRvD.* 2016 Feb;93(4):044006.
- [85] Khan S, Husa S, Hannam M, Ohme F, Pürrer M, Forteza XJ, et al. Frequency-domain gravitational waves from nonprecessing black-hole binaries. II. A phenomenological model for the advanced detector era. *Phys Rev D.* 2016 Feb;93(4):044007.

- [86] Huerta EA, Moore CJ, Kumar P, George D, Chua AJK, Haas R, et al. Eccentric, nonspinning, inspiral, Gaussian-process merger approximant for the detection and characterization of eccentric binary black hole mergers. *Phys Rev D*. 2018 Jan;97(2):024031.
- [87] Nitz A, Harry I, Brown D, Biwer CM, Willis J, Dal Canton T, et al.. AEI, editor. gwastro/pycbc: PyCBC Release v1.15.4. Zenodo; 2020.
- [88] Helstrom CW. *Statistical Theory of Signal Detection*. Pergamon Press, London; 1968.
- [89] Thorne KS, Hawking SW, Israel W. *Gravitational radiation*. Cambridge University Press; 1987.
- [90] Finn LS. Detection, measurement, and gravitational radiation. *Phys Rev D*. 1992 Dec;46:5236–5249.
- [91] Murphy TW. Lunar laser ranging: the millimeter challenge. *Rep Prog Phys*. 2013 jun;76(7):076901. Available from: <https://doi.org/10.1088%2F0034-4885%2F76%2F7%2F076901>.
- [92] Abbott BP, Abbott R, Abbott TD, Acernese F, Ackley K, Adams C, et al. GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. *Phys Rev Lett*. 2017 Oct;119:161101. Available from: <https://link.aps.org/doi/10.1103/PhysRevLett.119.161101>.
- [93] Dyer MJ, Steeghs D, Galloway DK, Dhillon VS, O'Brien P, Ramsay G, et al. The Gravitational-wave Optical Transient Observer (GOTO). arXiv. 2020;.
- [94] SpaceX. Musk E, editor. *FALCON USER'S GUIDE*. SpaceX; August 2020.