Overview and progress on the Laser Interferometer Space Antenna mission

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Overview and progress on the Laser Interferometer Space Antenna mission

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At a Lorentz Center workshop, Chiara Caprini, Antoine Petiteau and Elena Maria Rossi gave a series of presentations about the Laser Interferometer Space Antenna (LISA) mission, the instrument, and the associated science in cosmology and astrophysics.

This Comment is an overview of the question and answer session that followed the talks given by Chiara Caprini, Antoine Petiteau and Elena Maria Rossi at a recent Lorentz Center workshop.

LISA Pathfinder (LPF) was launched to assess the readiness level of some key technologies for LISA. What were its achievements and what will LISA inherit from LPF? LPF was launched in 2015 by the European Space Agency (ESA) to demonstrate key technologies for LISA. Its main objective was to show that it is indeed possible, in a space environment, to measure the distance between free-falling test masses to picometre accuracy, as required for the future LISA mission. The first results[1] showed that we were able to successfully estimate the quality of the free fall and the impact of various spurious forces, and that the requirements for LISA were quickly achieved. The latest results[2] even exceeded these requirements. These excellent results pushed the LISA mission forward, as it moves towards its official adoption at the end of 2023, with a launch expected in 2034.

LISA will be a constellation of three drag-free satellites in a near-equilateral, 2.5-million-km, triangular formation[3] (Fig. 1). The three spacecraft will continuously exchange infrared laser beams. Each spacecraft will be equipped with two movable optical sub-assemblies (MOSAs), two laser sources (one for each MOSA), a phasemeter, and an onboard computer (for online data treatment, data storage, spacecraft control and so on).

LISA will measure the relative proper motion of free-falling test masses in order to detect gravitational waves (GWs) from a variety of astrophysical sources. Contrary to ground-based detectors, where we observe tiny variations in the phase difference (otherwise constant) of two interfering laser beams, LISA will use heterodyne interferometry[3]. The test-mass–test-mass distance will split up into three interferometric measurements: the inter-spacecraft signals monitor the spacecraft-to-spacecraft distance; the test-mass signals record the spacecraft-to-test-mass distance; lastly, the reference signals compare the phase of both lasers hosted on each spacecraft. These measurements will ultimately be combined to recover the differential motion of all pairs of test masses.

In addition to GW signals, various noises will couple into our measurements. The so-called test-mass acceleration noises represent spurious forces on the test masses, that is, deviations from their free-falling condition. They are of various origins (actuation noise, Brownian motion, magnetic or electrostatic forces and so on) and have been measured by LPF[2], whose gravitational reference sensor will be similar to that of LISA. Other noises have their origin in the metrology system and will be reduced on the ground by various algorithms, gathered in the initial noise-reduction pipeline[4–8].

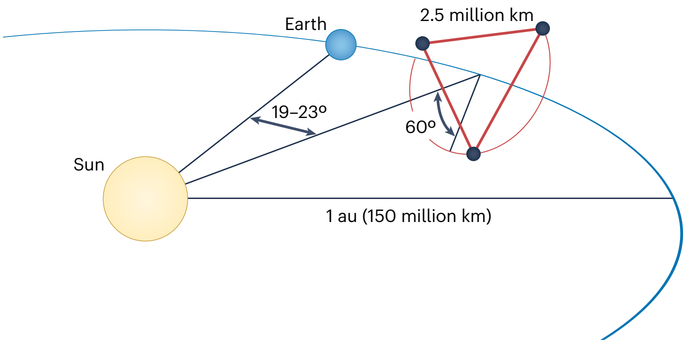

Fig. 1 | LISA orbital scheme. The constellation plane will be tilted by about 60° with respect to the ecliptic, and its centre of mass will trail or lead the Earth by about 20° on its heliocentric orbit. Figure adapted from ref. [3], courtesy of Simon Barke.

What will the mission duration be? How does one make sure that the required performance is maintained during this time? The nominal observation duration has been set to 4.5 years (with a potential extended mission up to 10 years, mainly limited by the amount of available propellant on board)[3]. Due to scheduled maintenance periods, orbital maneuvers and possibly unscheduled failures, scientific data will only be collected with a limited duty cycle that yields 4 years of data for the nominal observation run. We refer to the periods when no useful data is collected as data gaps, and we expect scheduled gaps of about 3.5 hours every week (alternatively, we could also choose to perform maintenance operations on a biweekly basis, resulting in a 7-hour-long gap every two weeks)[9]. In general, the data analysis pipelines must be able to handle data gaps. However, protected periods, during which no maintenance or orbital maneuvers are allowed, can be requested when valuable events are foreseen, such as binary black hole merger events.

Moreover, since LISA will evolve in a space environment, the performance of its components will degrade over the mission time (due to cosmic rays, extreme temperature variations and so on). To ensure accurate performance, critical systems must be space-qualified, and a high level of redundancy will be implemented (for example, duplicated electronic systems, lasers, thrusters and star trackers). A direct consequence of the degradation of all instrumental components, noise properties will change over time; requirements are actually set on the end-of-life condition. As many sources expected in the LISA band are long-lived (months to years), these non-stationarities must be accounted for in analysis algorithms.

Finally, we expect that instrumental artifacts, or glitches, will appear in our measurements. These glitches were observed and characterized by the LPF[10], and ongoing studies will try to assess their impact on available data analysis.

How will LISA data analysis be organized? ESA will only be able to reach the LISA spacecraft once a day. Therefore, the data will be stored on board the spacecraft until connection with Earth can be established again. During contact time, critical housekeeping data and scientific data at a sampling rate of 4 Hz are downloaded as 'level-0' data. The scientific measurements will be processed through noise-reduction pipelines (for example, laser noise and spacecraft jitters will be suppressed as part of the time-delay interferometry (TDI) post-processing algorithm) to produce a 24-hour segment of so-called level-1 data. The daily telemetry will last for about 8 hours, during which live measurements will also be streamed to Earth (in parallel to the stored data) in order to perform an online fast analysis (low-latency alert pipeline). We estimate that this low-latency alert pipeline will be able to issue alerts about an hour after a GW has reached the constellation.

These level-1 data will be analysed by several deep-analysis pipelines to detect GW signals and extract the source parameters. Some will analyse 24-hour segments, while others must re-process longer segments of data (months to years) to refine estimations for long-lived sources. Contrary to current ground-based detectors, LISA measurements are signal-dominated, cannot provide a direct estimation of the noise and contain multiple GW signals simultaneously. Thus, to account for the uncertainty in the noise and distinguish between different GW signals, we envision a 'global fit' approach, in which the GW signals and the noise are simultaneously estimated[11] (Fig. 2), such that we can provide an analysis marginalized over the noise parameters. The results of all these pipelines are gathered in the 'level-2' data. Official source catalogues will be regularly compiled and released as 'level-3' data.

What are the astrophysical sources LISA expects to see and what can we learn from them? LISA will be sensitive to GWs with frequencies from 10^{-4} Hz to 1 Hz. As shown in Fig. 3, we expect several types of sources in this frequency band.

Supermassive black-hole binaries (SMBHBs) with masses between 10^4 and 10^7 $M_\odot$ are regarded as the loudest sources. They are expected to stay in the LISA band for hours to months. The detection rate of these sources ranges between 10 and 300 events per year. We hope that these detections will tell us about the formation and evolution of galaxies. Solar-mass compact binaries on the other hand are the most numerous sources. These are persistent sources, with some of them staying in band for the whole duration of the mission with typically a slow frequency evolution. Tens of thousands white dwarf binaries (WDBs) with periods less than ~20 min will be individually resolved. Through electromagnetic (EM) observations, several such WDBs have already been identified and will be used for instrument calibration. Most WDBs with longer periods will instead form a prominent stochastic background of unresolved sources, or confusion noise. Black hole binaries with total mass approaching or exceeding 100 $M_\odot$ will be first observed by LISA and, some years later, with ground-based detectors; this is called multi-band detection. (We currently expect to observe only a few of these black hole binaries due to the reduced population rates, based on recent data from LIGO and VIRGO.)

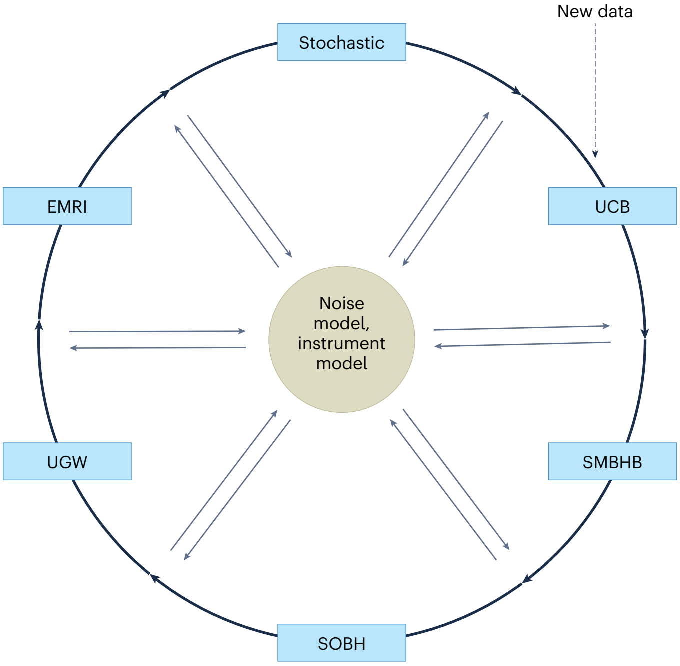

Fig. 2 | Schematic view of the global fit approach. The approach includes stochastic GW sources, supermassive black-hole binaries (SMBHBs), extreme mass-ratio inspirals (EMRIs), stellar origin black hole binaries (SOBHs), galactic ultra-compact binaries (UCBs), and unmodeled GWs (UGWs). The residuals from each source analysis block are passed along to the next analysis. New data are incorporated into the fit during the mission. The noise and instrument models are updated on a regular basis. Figure adapted with permission from ref. [11], APS.

Through the observations of solar-mass compact binaries we can learn a lot about astrophysics at different scales, such as their tidal interaction, stellar binary evolution, accretion physics, galactic star formation history, galactic structure and so on. This is particularly interesting because with GW observations, we can also peer through dust regions of our Galaxy, which are inaccessible to optical observations. Thus, LISA has the potential to challenge our understanding of various astrophysical phenomena.

Another exciting class of sources are extreme mass ratio inspirals (EMRIs), which constitute a stellar-mass object, such as a black hole, neutron star or white dwarf, orbiting around a single SMBH. They can be viewed as test particles probing the innermost and highly curved region around SMBHs. Such sources will stay in the LISA band for years, and the detection rate is estimated at ~1–10^3 events per year. Through EMRIs, we can also study the content of galactic nuclei.

Closely related sources are intermediate mass ratio inspirals (IMRIs), for which the mass ratio of the heavy to lighter object is 10 to 1,000. Both the astrophysics behind possible formation channels and their inspiral dynamics are currently not well understood. Therefore, observations of such systems will provide very valuable information about the formation and growth of intermediate-mass black holes (IMBHs) in galactic nuclei, as well as details of stellar dynamics in those systems.

LISA will also be able to detect planets orbiting white dwarf binaries via a periodic Doppler modulation of the GW signal of the binary caused by the exoplanet. Current exoplanet searches are mainly limited to our solar neighbourhood, but such searches extend to anywhere in

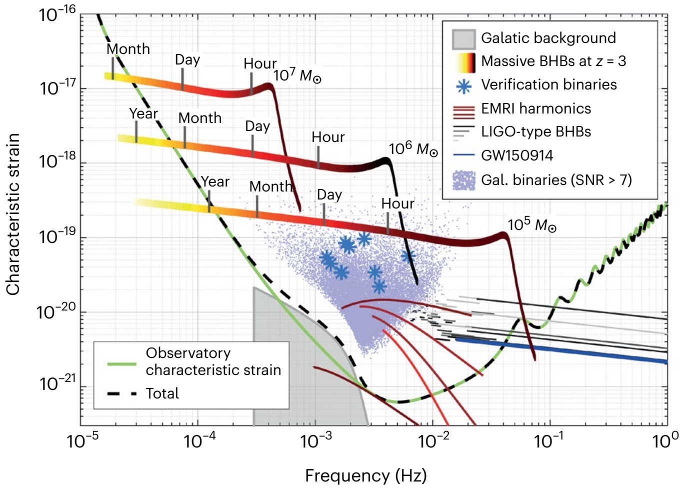

Fig. 3 | Expected GW sources in the LISA frequency range. LISA will be sensitive to GWs with frequencies from 10^{-4} Hz to 1 Hz. Figure reproduced from ref. [3]. courtesy of Martin Hewitson.

our Milky Way[12]. Similarly, brown dwarfs orbiting around WDBs can be detected using the same principle. This could provide new information on the missing link between planets and stars, as brown dwarfs are expected to be more abundant than planets by a factor of 30–150.

What is the role of LISA in probing black hole physics? The first binary black hole merger was observed by ground-based GW detectors that operate in the hectohertz waveband[13]. Such a waveband is sensitive to black holes of several to hundreds of solar masses. On the other hand, the millihertz waveband of LISA is optimal to observe binary black holes of a few thousands to tens of millions of solar masses. These systems represent a totally different population of black holes and have not yet been observed with GWs. Indeed, the EM observations for those SMBHBs are not conclusive, and leave important open questions concerning their evolutionary paths in the cosmos and the very nature of the spacetime around them. These represent some of the questions that would be targeted by LISA.

LISA will detect SMBHBs with the phenomenal signal-to-noise ratios (SNRs) of up to several thousands enabling high-precision measurements of these merging black holes. The GW signals contain characteristic features about the properties of the emitting black holes. The so-called Kerr hypothesis states[14] that all astrophysical black holes — from the viewpoint of mathematics — have exactly the same spacetime structure, simply rescaled by their mass, and with only one extra macroscopic degree of freedom, that is, their spin. The importance of the Kerr hypothesis cannot be overstated, and LISA provides an unprecedented avenue to test it through the ringdown part of the GWs. In the ringdown signal, we can measure, in addition to the fundamental quasinormal modes, the higher modes to a remarkable precision (current data analysis challenges include up to eight modes), which will enable a new era of black hole spectroscopy, analogous to spectroscopy in atomic physics.

As pointed out earlier, another unique class of black hole systems to be discovered by LISA are the so-called EMRIs. The trajectory of its stellar-mass object depends on the spacetime shaped by the SMBH. These stellar-mass objects probe deep into the strong-field regime of the curved spacetime and will therefore inform us about the very nature of SMBHs and the properties of their event horizons, thus testing the Kerr hypothesis. The GWs emitted by EMRIs have a rich mode structure and by observing various of these extra modes, LISA's observations have the ability to distinguish the Kerr black hole spacetime predicted by the general relativity (GR) from its modified alternatives or black hole mimics[15].

Can LISA test general relativity? The possibility to detect low-frequency GWs with LISA will not only open a new window for testing our models of various astrophysical phenomena, but will also provide us with the opportunity to perform new tests of gravity[15]. This includes the already-mentioned test of the Kerr hypothesis. A violation of this hypothesis might occur if the observed compact object lacks a horizon, as is the case for some exotic alternatives arising if one includes quantum effects or beyond-the-standard-model particle physics. Another intriguing possibility are non-Kerr compact objects that are still black holes, but are described by a modification of GR[16]. LISA has the possibility to detect GW signals from black hole binary mergers and EMRIs in a completely different mass range compared to the black holes observed by ground-based detectors. This is important for testing the strong-gravity regime, because different theories of gravity predict non-negligible modifications of the Kerr solution at different mass ranges. Thus, by combining the observational constraints from ground-based detectors and LISA we can explore a plethora of possible deviations from Einstein's gravity.

LISA will also be able to probe the propagation of GWs, thereby providing a clean test of their kinematics. Some alternative theories of gravity modify the dispersion relation that connects the GW wavelength to its frequency. This could lead to frequency-dependent, polarization-dependent, direction-dependent propagating velocities of GWs observable by gravitational-wave detectors. Such observations will provide stringent constraint on the properties of modified gravity, such as the mass of the graviton, the Lorentz symmetry violations, and decays of gravitons into other particles. In some cases LISA can provide constraints orders of magnitude better compared to ground-based detectors.

What can LISA teach us about cosmology? Measuring GWs with LISA can help us to probe various stages of the evolution of the Universe starting shortly after the Big Bang up to present times[17]. Potential GW sources in the early Universe might lead to the production of a stochastic gravitational-wave background (SGWB) created by the superposition of many independent sources with too low SNR and/or too small correlation scale (with respect to the detector resolution) to be individually resolved. The detection of such a SGWB will allow us to probe the Big Bang at extremely early times, between inflation and Big Bang nucleosynthesis, which is inaccessible through EM radiation. LISA can also be used to probe the late-time expansion of the Universe and determine the Hubble constant, since GWs are analogous to standard candles in astrophysics and can test the expansion of the Universe.

Another intriguing possibility is to set constraints on primordial black holes (PBHs), formed during the early stages of the evolution of the Universe through density fluctuations and not through core-collapse like standard astrophysical black holes. PBHs still constitute a viable dark matter alternative. It turns out that second-order scalar field perturbations can give rise to both PBHs and a SGWB detectable by LISA. The PBH masses are compatible with the hypothesis that they constitute the entirety of dark matter; in this case, their existence can be tested by LISA through the associated SGWB signal.

Some theories predict that phase transitions related to grand unification, which might have occurred in the very early times after the Big Bang, might leave a network of cosmic strings in the Universe. This process would produce a SGWB within the LISA sensitivity band. Moreover, LISA can also provide tests of scenarios beyond the standard model of particle physics, complementary to particle colliders.

What is the richness and what are the challenges in observing the SGWB? As discussed in the previous questions, the SGWB is the superposition of numerous independent sources (of different types) with relatively low SNR from both cosmological and astrophysical origin. The former is more intriguing from the fundamental physics point of view because its (non)detection will answer many open questions about the early Universe, at epochs that we cannot access via EM observations.

Detecting a SGWB is challenging, though, as one cannot rely on the usual match-filtering techniques. As a consequence, detailed knowledge of the instrumental noise is required to distinguish the stochastic signal from the noise. For ground-based detectors, this is done by cross-correlating the outputs of the different detectors. Since the noise is uncorrelated between detectors, the SGWB signal appears as a common source. In LISA, however, we cannot rely on this technique as only one GW detector in the millihertz frequency range will be operating (the Chinese Taiji/TianQin mission might overlap with LISA, in which case we might use the correlation between the two detectors). In addition, the LISA data are expected to be signal-dominated. Thus, we will not be able to measure and calibrate the noise of the instrument as easily as with ground-based detectors. One of the techniques that has been used to measure the noise is to look for TDI null channels, which have suppressed sensitivity to GW signals but still carry some information on the instrumental noise[18,19].

Several sources of stochastic background, with similar spectral shapes, might emit in the LISA band. As a consequence, another challenge to analyse this type of GW signal is to distinguish one type of SGWB from another[20]. Typically, though, the different sources will create signals with different spectral shapes, nominally allowing us to differentiate between models. Signals will be overlapping in frequency space, and the question of how to simultaneously analyse two or more SGWBs is still an open problem. One model-agnostic approach is to divide the LISA frequency band into several bins[21] and fit a simple power law in each bin. Bins in which the signal can be approximated with a power law are merged, and the combination of different power law signals from different bins will lead to the emergence of more complicated spectral shapes. Note that in each bin, the SGWB will be a combination of astrophysical and cosmological signals.

What are the differences between data analysis for LISA and other existing and future ground-based detectors? Are there synergies between the different detectors? How do you see the future of GW astronomy? As mentioned above, the LISA data analysis will have significant differences with the techniques used to analyse the current and future LIGO, Virgo, Kagra (LVK) data. Indeed, if ground-based detectors will detect more and more events as their sensitivities improve, they will still have less frequent events than LISA, and data from ground-based detectors will remain dominated by the instrumental noise. Detecting and analysing GW signals represent a challenge for the LVK community due to the small SNR of these sources. On the contrary, millions of Galactic binary inspirals are expected in the LISA band, the vast majority of which will have faint signals. This comes at the cost of additional efforts to identify and disentangle individual events.

The estimation of the noise is easier for current ground-based detectors, as signal-free data is regularly available. For LISA, one will have to rely on more sophisticated techniques to evaluate the noise, such as fitting it alongside the signals in a global fit, or computing TDI null streams that increase the SNR. Some of these approaches might also be used in the future planned ground-based detector Einstein Telescope (ET), which will have a similar triangular design. However, an important difference is that ET will consists of three real Michelson-like interferometers, whereas LISA relies on TDI to synthesize Michelson measurements as a first processing step.

Because most signals in current ground-based detectors are short-lived (less than a second), the properties of the instrument can be considered stationary over the duration of the analysis. This is not true for LISA, as we expect long-lived signals (for example, SMBHB mergers can be visible up to several months in the LISA band and EMRIs could be visible for over a year); as a consequence, algorithms will have to account for these non-stationarities.

Data collected by LISA can be analysed and combined with observations from other instruments. We not only expect such synergies with high-frequency ground-based GW detectors, but also with pulsar timing observations. With the timing of an array of millisecond pulsars, we can observe sources emitting GWs in the nanohertz frequency range, such as SMBHBs and cosmological backgrounds. A few dozens of millisecond pulsars are currently monitored by various pulsar-timing arrays (PTAs); we think that the sensitivity necessary to detect realistic signals has now been reached. A correlated signal has been detected, and investigations are ongoing to determine whether the signal originates from GW emissions or not[22–25].

In addition to the necessary technical advances and overcoming data analysis challenges, higher sensitivity of future space-borne and ground-based detectors will pose new challenges for the waveform modelling community[15]. For instance, current GW templates do not account for eccentric systems; they are still limited in the number of higher modes included; they are all constrained to general relativity (full numerical simulations are very scarce for alternatives theories of gravity); lastly, templates often do not fully take into account environmental effects.

To conclude, the next era of GW astronomy is very promising. With many detectors covering a wide frequency range, ranging from the nanohertz (with PTAs) to the megahertz (with ground-based detectors), we can aim for multi-band astronomy. As an example, LISA will be able to see the inspiral phase of stellar-mass black hole binaries years before they merge in the LVK band[26]. Synergies between GW detectors and other EM or even neutrino observatories are of great interest. Several big instruments in the EM spectrum are expected to start their observations by the time LISA flies. This is the case of the European X-ray space observatory Athena[27] and the radio telescope Square Kilometer Array (SKA). Our understanding of the Universe will be stretched beyond our imagination, so stay tuned and expect the unexpected!

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Competing interests

The authors declare no competing interests.