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Astrophysics and fundamental physics with LISA

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Abstract

In this document we describe LISA - space-based gravitational wave observatory - and show its scientific capabilities in astrophysics and in fundamental physics. We also discuss the rich science return from possible simultaneous gravitational and electromagnetic observations.

Overview

The observation of gravitational waves (GWs) from merging black holes (BHs) by the LIGO-Virgo collaboration heralds an exciting new era of scientific discovery. We are now able to probe the universe in an entirely new way, having gained observational access to some of the most cataclysmic phenomena in nature. The LIGO-Virgo discoveries were revolutionary in three different ways: (i) they directly confirmed the existence of GWs as described by Einstein's General Relativity (GR); (ii) they established the existence of BHs in nature; and (iii) they also showed that BHs in nature can form binaries and merge.

At the same time, there is a flurry of activity aimed at taking the field to the next stage: low-frequency GW astronomy. The universe abounds with GW sources in the nHz to mHz frequency range, which is inaccessible to terrestrial instruments (ground-based detectors are sensitive in the few Hz to kHz range). Low-frequency sources include merging massive BHs (MBHs), compact objects captured by MBHs (EMRIs: extreme-mass-ratio inspirals), the early inspiral of LIGO-Virgo-type merging BHs, and about a hundred million galactic white-dwarf binaries, of which about twenty thousand will be detected and a handful are already known. Pulsar-timing arrays of radio telescopes are already searching for GWs at nHz frequencies, placing ever tighter upper limits on the GW strain in this band.

In 2016, the spectacular success of the European Space Agency (ESA) LISA Pathfinder mission has paved the way for the Laser Interferometer Space Antenna (LISA), the much anticipated flagship mission of low-frequency GW astronomy. LISA will target mHz frequencies and thus, in particular, systems involving BHs in the $10^4 - 10^7 M_\odot$ mass range. The LISA mission is currently in Phase A (feasibility and design study), which will lead to industrial production and to launch around 2034 (nominally), or even earlier if technical readiness is deemed satisfactory.

The knowledge of the LISA instrument has been built upon many years of LISA mission development studies through ESA's missions framework and upon the success of LISA Pathfinder. However, possibly unknown or new noise sources will play an important role in the definition of the LISA science performance and will be important for any attempt to extract GW signals from the raw data. This implies that the instrumental noise will need to be understood first by *very accurate simulations* and, second, estimated together with the GWs parameters in a *global fit procedure.*

LISA is an omnidirectional detector, so signals from all sources are present in the data stream simultaneously, overlapping in time and in frequency. The detection strategy depends on the astrophysical priors (parameter distribution) and on the available models for GW signals. The optimal techniques for detecting GW signals from coalescing binaries is matched filtering, where one searches for a signal of a known form by correlating it with the observed data. This implies that we should have a very accurate model for GW signals, as any inaccuracies will translate into bias in the parameter estimation. The waveform modelling effort, in turn, requires as input sufficient understanding of the relevant astrophysical processes at play. Finally, all of the above problems are, of course, strongly impacted by LISA's design features and mode of operation. We are in a situation where *the astrophysical, GW modelling, data analysis, and instrument design aspects of the mission are all strongly coupled to each other, and must be developed in close synergy.*

Science return from LISA

To describe the anticipated scientific outcome of the LISA mission, it is convenient to proceed by source category.

The strongest signals by far come from merging MBH binaries, with signal-to-noise ratios as high as a few$\times 10^4$. These will be seen as transients with the detectable part lasting between a few hours and a few months. LISA can see MBH mergers anywhere in the Universe, providing invaluable insights about their formation and early evolution, which is currently poorly constrained due mostly to lack of observational guidance. MBHs are thought to grow from high redshift 'seeds' via efficient accretion of cold gas and episodic coalescences with other MBHs following galaxy mergers. The nature of the seeds (i.e. the physical mechanism responsible for their formation as well as their initial mass, spin and redshift distributions) and the details of their growth are naturally reflected in the rates and properties of the MBH mergers that LISA will observe. LISA is the only instrument that can detect seeds close to the time of formation: electromagnetic probes, even the upcoming James Webb Space Telescope, will be limited to lower redshift, when the seeds can have grown significantly. Furthermore, electromagnetic observations measure luminosity, which is a combination of mass and accretion rate, while gravitational waves measure directly the mass of 'seeds', the parameter needed to distinguish models. Modelling those systems is a complex task, since numerical relativity can currently handle only moderate mass ratio (up to $\sim 1:20$) and not very high BH spin (up to ~ 0.8). Various (semi-)analytic models are built to match the numerical relativity results and could be extrapolated further. Given the high signal-to-noise ratio of GW signals from merging MBHs, we will be able to test GR with ultra-high precision (see separate letter describing testing GR with GWs).

Binaries of white dwarfs (WDs), are the most numerous sources in the LISA band: we expect $\sim 10^8$ of them in the Milky Way. They emit almost monochromatic signals, whose superposition at low frequencies (below a few mHz) form an unresolved stochastic GW foreground which stands above the instrumental noise. The signals are less numerous above a few mHz, where ~ 25000 sources can be individually resolved, with their sky position measured to within several degrees, and (for $\sim 1/3$ of sources) the distance measured to within $\sim 30\%$. For the latter, we can detect the frequency rate of change due to GW emission, mass transfer or the presence of a third body. Beyond the Galaxy, WD binaries can be detected out to the outskirts of the Local Group (~ 1 Mpc). In addition to WD binaries, LISA will detect a few tens of inspiralling binaries containing neutron stars. Detecting and characterizing ultra-compact binaries, and especially WD binaries, will provide unique astrophysical information about the uncertain stages of stellar binary evolution, the interior properties of compact objects, and about the optically elusive progenitors of type Ia supernovae (presumable sourced by merger of massive WD binaries). In addition, the characterisation of such a large number of WD binaries will allow us to trace and study the overall distribution and formation history of stars in our Milky Way, in its neighbouring galaxies and in other structures, like globular clusters and the stellar stream. The advantage over electromagnetic observations is that most WD binaries are faint optical emitters that may be detected only within a few kpc from the Sun, while one should be able to observe them through GWs out to the Andromeda galaxy for the more massive systems.

EMRIs are the result of the capture of a stellar remnant (like a BH or a neutron star) by MBHs in galactic nuclei. These sources will probe the environment in the heart of "quiet" galaxies like our own Milky Way. The captured stellar remnant will slowly inspiral around the MBH until the final plunge, spending $10^5 - 10^7$ orbits in close vicinity of the event horizon. The information about the spacetime of the central massive object will be encoded in the phase of the emitted GWs. EMRIs are therefore unique probes of the environment in the core of quiescent galaxies and will deliver ultra-precise tests of GR through the mapping of spacetime around MBHs, testing their BH nature (see separate letter describing testing GR with GWs). There has been great progress on modelling GW signal from EMRIs in the last few years but significant challenges remain. On the data-analysis side, EMRI signals are very hard to detect and characterize because of their complexity and their large parameter space. However, it was shown that one can detect them (for a signal-to-noise ratio above ~ 20, when embedded in a Gaussian instrumental noise) with extremely high parameter estimation precision. On the astrophysical side, rates have been estimated for the Milky Way, for which we have spectacular data, and significant work is under way to extend modelling to other galaxies.

LISA will also observe stellar-mass BH binaries similar to those detected by the LIGO-Virgo collaboration. But while the ground-based detectors usually observe a signal less than a second long, coming from the final merger, LISA will observe these binaries during the early stages of the inspiral, possibly detecting up to several hundred such systems. Some of these binaries, likely a few each year, will chirp through the LISA band in the course of the observation and will reappear in the band of ground-based interferometers several years later. These are multi-band sources for which ultra-precise parameter measurements can be performed, thus rendering them a unique laboratory both for testing GR (see separate letter describing testing GR with GWs) and for investigating their formation channel. Moreover, spatial and time localisation of their merger may be achieved at $\sim \text{arcmin}^2$ and $< 10\,\text{s}$ precision respectively weeks before merger, enabling the discovery of a possible electromagnetic counterpart.

LISA will detect stochastic GW signals from various sources: not only unresolved residuals from populations of astrophysical binaries (of which the galactic WD binary foreground is just an example), but possibly also, more interestingly, the stochastic signal from violent events occurring in the early Universe. Cosmological stochastic GW emission is a unique channel to probe the early universe, as GWs travel freely through spacetime, contrary to photons, which are tightly coupled in the primordial era. The detection of a signal from the early universe would grant invaluable tests of the underlying fundamental theory of particle physics. The LISA frequency band corresponds to energies in the early universe from about a few GeV to about 100 TeV; thus, LISA can probe energy scales beyond the Standard Model of Particle Physics, higher than those reached at colliders such as the LHC. This offers the possibility of complementary tests of physics beyond the Standard Model, in particular of the occurrence of a first-order electroweak symmetry breaking, with interesting connections with (e.g.) the problem of baryon asymmetry and dark matter formation scenarios. LISA can also test non-standard inflationary scenarios and their remnants such as primordial black holes and primordial magnetic fields.

LISA will also provide a possibility to infer cosmological parameters such as the Hubble constant and dark energy equation of state (please see also a separate letter describing cosmology with GWs). GW observations alone yield the luminosity distance which at low redshifts could be measured to better than few percents, and, at high redshifts is limited by weak lensing to a lower accuracy of about 5-10 percent. Determination of the redshift to the source requires an electromagnetic counterpart: either identification of the host galaxy or employment of statistical methods on the population of detected GW signals, or in the case of merging MBHs even the direct measurement of a coincident emission generated by the MBHs themselves.

Identification of the host galaxy to a merger event can occur in many different ways. For a nearby ($z < 1$) event with large MBHs and a high signal-to-noise ratio, the LISA error box in angle and redshift might contain a few thousand candidate galaxies, and the host might be identified from large scale optical morphology (such as tidal tails) as the site of a recent galaxy merger, although lengthy evolutionary timescales for binary MBHs can imply that by the time the MBHs merge the merger signatures in the galaxy have disappeared.

More typically, the error box contains of order ten thousand galaxies; in many cases the redshift is also very high, making optical identification difficult. In this case, for MBH mergers we may be aided by electromagnetic emission from the merging MBHs triggered by the merger process itself. One possibility is that dual jets are formed close to merger. This is supported by results of force-free simulations of merging MBHBs in an external magnetic field. Besides this effect, which is due to the twisting of magnetic field lines by the rapidly inspiralling MBHB, accretion also powers standard radio jets through the Blandford-Znajek effect, with luminosity dependent on the mass accretion rate. These jets can be observed in radio by upcoming radio facilities: the full SKA could reach μJy sensitivity on approximately $10\mathrm{deg}^2$ assuming 10 min integration time, which makes it an ideal instrument for simultaneous GW-EM observations. Such radio detection is in fact the most promising tool to detect counterparts of the highest redshift MBH mergers.

The candidates identified with SKA can then be followed up with optical/IR facilities, looking for spectral features in the galaxy host for redshift determination. The spectrograph MICADO on the extremely large telescope (ELT) will cover the wavelength range $1000 - 2400\,\mathrm{nm}$ (J to K band). Spectroscopic observations will be possible down to an apparent magnitude of $m_{ELT,sp} = 27.2$ for five hours of integration. This will allow the identification of lines such H_{alpha} (656nm) to $z \approx 2.6$,[OIII] (500nm) to $z \approx 3.8$, and [OII] (373nm) to $z \approx 5.4$. In addition to that, the Lyman break detection will enable precise photometric redshifts down to an apparent magnitude $m_{ELT,ph} = 31.3$ in J and H bands. Moreover, NIRCam (mounted on JWST) will have comparable performances down to lower wavelengths (600nm) in less than three hours of integration time.

Another distinctive signature to identify the host galaxy may come from responses of the material near the black holes' horizons to the merger event, which can lead to observable time-variable X-ray/UV emission from the MBHs, modulated by the binary period as the inspiral progresses. During the inspiral phase (i.e., prior to the merger) X-ray emission would be produced over a wide X-ray spectral band as thermal (soft) emission from the inner rim of the circumbinary disk surrounding the binary and/or as coronal (hard) emission from each of the black hole mini-disks within the cavity evacuated by the inspiraling black holes, as well as by shock-heated gas at the wall of the cavity. The X-ray emission is modulated with frequencies commensurate with those of the fluid patterns and of the gravitational chirp, providing the "smoking gun" to identify the X-ray source through a characteristic variability pattern. This gives in principle the exciting possibility of directly probing, for the first time, the behaviour of matter in the variable space-time induced by the merging black holes.

Within reasonable assumptions, Athena should be able to detect X-ray emission from sources at $z \leq 2$. After the merger, the X-ray monitoring of the LISA event error box may allow Athena to witness the re-birth of an Active Galactic Nucleus, or even the launch of a relativistic jet according to some theoretical predictions. This will provide a new window for exploring the origin of some of the most powerful and fundamental events in the Universe. LISA will provide sky localisation of a sizeable fraction of merged events to arc-minute precision, well within the Athena WFI (Wide Field Imager) field of view. Estimations show that LISA and Athena should be able to simultaneously observe about 30 events over ten years.

For LIGO-Virgo-type merging BHs and for nearby ($z < 0.5$) merging MBHs the host redshifts can be obtained from galaxy catalogs in a statistical sense. The technique is based on the assumption that galaxies are significantly clustered in the cosmic web. The direction and distance information inferred from analysis of GWs from merging BHs provides a 3D-"error box" for the location of the host galaxy. Depending on the redshift and the properties of GW signal, there are between a few hundreds and a few thousands of candidate hosts in this region of space. A galaxy redshift survey in the angular error box allows identification of candidate host galaxies and a 3D-map of their distribution. Because of galaxy clustering, the distribution of galaxy redshifts is highly nonuniform within the box and the distribution can be used to infer the redshift of the GW source. The error in the estimated source redshift is not eliminated, but is significantly reduced by adding this information from the actual spatial galaxy distribution in the direction of a source. A simple version of the technique was shown to yield a high precision estimate of Hubble's constant using EMRIs and a mock galaxies catalogs based on SDSS redshift data.

We want to mention another possible simultaneous observational program by Athena and LISA: observation of accreting white dwarf binaries. Between 5% and 10% of all white dwarfs are in binary systems and some fraction of those binaries show stable mass transfer ("AM CVn" systems). These short (< 30 min) period binaries are strong UV/X-ray and mHz gravitational waves emitters. Actually, HM Cnc (with orbital period of 5.4 min) and V407 Vul (9.5 min), are semi-detached AM CVn systems and currently in the loudest guaranteed LISA sources. Considering the predicted on-axis Athena sensitivity of $\sim 2 \times 10^{-16}\,\mathrm{erg\ s^{-1}cm^{-2}}$ in the 0.5-2 keV energy band in a typical 10 ks observation, we expect a few hundred systems with simultaneous X-ray and GW detection. Combined EM (from optical to X-ray)-GW observations of accreting DWDs would allow us to uniquely study fundamental physical processes, related to WD accretion physics and mass transfer stability.