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LISA Science and multi-messenger astronomy

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Abstract. We discuss the prospects of the space-based mission LISA to detect gravitational waves from space, which following the superb performance of the LISA Pathfinder satellite has been approved by ESA as an official mission in June 2017. An overview of the main scientific goals of LISA is given and some possible multi-messenger aspects are presented as well, in particular for the study of the Milky Way through the gravitational radiation from Galactic binaries, some of which can also be observed by electromagnetic radiation.

Key words. Gravitational waves – Galaxy: structure — Cosmology: observations

1. Introduction

With the first direct detections by the LIGO and VIRGO observatories of gravitational waves (GWs) from merging black holes in 2015 (Abbott et al. 2016, 2018) and the subsequent multi-messenger observation of colliding neutron stars in 2017 (Abbott et al. 2017), the field of gravitational wave astronomy has been firmly established. On Earth, GW observations are limited to black holes with masses no larger than a few tens that of the Sun, producing high-frequency GW signals in the ground-based detectors. Sources with much larger masses, such as the mergers of massive black holes at the centers of galaxies, generate signals at much lower frequencies, and are thus undetectable with interferometric instruments on Earth.

The proposed LISA mission is a space-borne gravitational wave observatory with an interferometer arm-length of 2.5 million km, providing a much longer baseline compared to the few kilometers of the ground-based observatories (LISA collaboration 2013, 2017). LISA will enable us to discover parts of the universe that are invisible by other means, such as supermassive black holes, the gravitational-wave relics of the Big Bang, and other, as yet unknown, objects. LISA will enhance our knowledge about the beginning, evolution and structure of our Universe and provide highly accurate tests of the theory of general relativity in an entirely new regime. The observatory also has the potential to uncover hints about the nature of quantum gravity, thus contributing to fundamental physics. LISA builds on the success of LISA Pathfinder (LPF), which completed its mission in July 2017 after twenty years of technology development (Armano et al. 2016, 2018).

2. Scientific objectives of the LISA

LISA will detect and study low-frequency GWs in the range from about 0.1 mHz to 1 Hz, and thus complement ground-based gravitational observatories. LISA will enable the detection of GWs from massive black hole coalescences (typically 10^6 – 10^7 $M_\odot$) within a vast cosmic volume encompassing all ages, from the cosmic dawn to the present, across the epochs of the earliest quasars and of the rise of galaxy structure. The merger-ringdown signal of these loud sources enables tests of Einstein's General Theory of Relativity (GR) in the dynamical sector and strong-field regime with unprecedented precision. Indeed, alternative gravity theories would influence the dynamics of such mergers in a distinct way, and hence LISA is expected to either directly observe the imprints of certain alternative theories on GW data or to put severe constraints on them. LISA will map the structure of spacetime around the massive black holes that populate the centers of galaxies using stellar compact objects (such as black holes or neutron stars) as test particle-like probes, producing a very clean GW signal which LISA will be able to measure with high precision. The same signals will also allow us to probe the population of these massive black holes as well as any compact objects in their vicinity. A stochastic GW background or exotic sources may probe new physics in the early Universe. Added to this list of characteristic LISA sources are the newly discovered LIGO/VIRGO heavy stellar-origin black hole mergers, which will emit GWs in the LISA band from several years up to a week prior to their merger, enabling coordinated observations with ground-based interferometers and electromagnetic telescopes. The vast majority of signals will come from compact galactic binary systems (white dwarfs) in the mHz frequency range, which will allow us to map their distribution in the Milky Way and illuminate stellar and binary evolution.

LISA will map the spacetime around astrophysical black holes, yielding several precision tests of GR in an entirely new regime. These have the potential to uncover hints about the nature of quantum gravity, as well as enabling measurements of properties of the universe on the largest scales. LISA will also contribute to fundamental physics; in particular it will be possible to detect or put strong constraints on the primordial gravitational wave background, which like the cosmic microwave background is a leftover from the Big Bang. Several processes occurring at very high energies in the primordial Universe can produce a stochastic background of gravitational waves. The detection of this relic radiation would have a profound impact both on cosmology and on high energy physics. Any fossil radiation of gravitational waves, if not washed away by inflation and later phase transitions, would have decoupled from matter and energy at the Planck scale. LISA could therefore directly probe cosmological epochs before the decoupling of the cosmic microwave background, which currently provides our closest view of the Big Bang. The LISA frequency band of 0.1 mHz to 100 mHz corresponds to 0.1 to 100 TeV energy scales in the early Universe, at which new physics is expected to become visible. The Large Hadron Collider (LHC) has been built to investigate the physics operating at this energy scale, which in 2012 led to the remarkable discovery of the Higgs boson, completing the particle spectrum of the Standard Model. It is the final confirmation that spontaneous symmetry breaking is the mechanism at play in electroweak physics, and is the first example of a fundamental scalar field playing a role in a phase transition that took place in the very early Universe. These findings further motivate the search for a cosmic background of gravitational waves. LISA would have the sensitivity to detect a relic background created by new physics active at TeV energies, assuming that more than a modest fraction of the energy density of the Universe is converted to gravitational radiation at the time of production.

3. Multi-messenger observations with LISA

Following the observation of the Neutron stars coalescence by LIGO/VIRGO, besides gravitational waves a lot of observations in many wavelength of the electromagnetic spectrum have been carried out. This marks the beginning of the multi-messenger astronomy. In the following runs of LIGO/VIRGO (which will soon be joined by KAGRA) many more such events are expected. Similarly, one expects also for LISA that some of the gravitational wave events might be observed in some bands of the electromagnetic spectrum. Much will depend

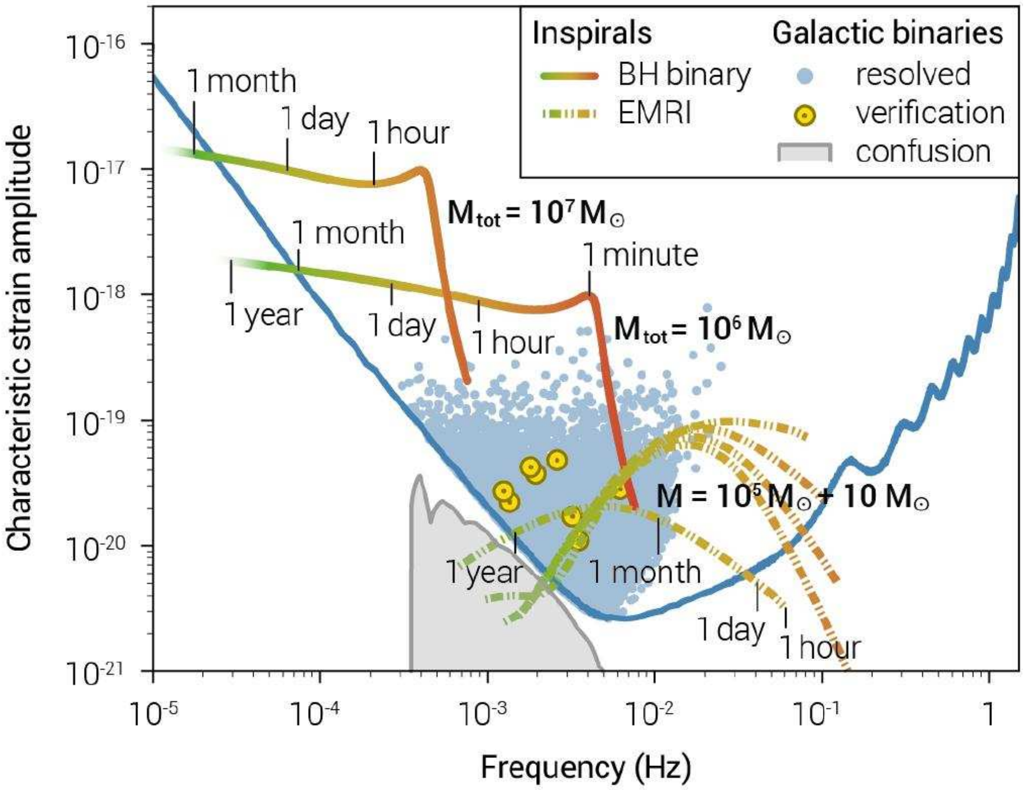

Fig. 1. Figure from ref. (LISA collaboration 2017). The figure shows some examples of gravitational wave astrophysical sources in the frequency range of LISA, compared with the sensitivity curve of LISA. The data is plotted in terms of unit-less "characteristic strain amplitude". The tracks of two massive black hole binaries, located at $z = 3$ with equal masses ($10^7 M_\odot$ and $10^6 M_\odot$), are shown. The source frequency (and SNR) increases with time, and the remaining time before the plunge is indicated on the tracks. An equivalent plot is shown for an EMRI source at 200 Mpc, with 5 harmonic frequencies evolving simultaneously. Several thousand galactic binaries, with SNRs above 7, will be resolved after 1 year of observation. Some binary systems are already known, and will serve as verification signals. Millions of other binaries result in a "confusion noise" that varies over the year. The average level is represented as grey shaded area.

on the environment the supermassive black holes are embedded. For supermassive black holes one expects these to be surrounded by a circumbinary disk from which material can accrete on the black holes, and thus be sources of X-ray. If such, then one might speculate to observe the X-ray signal before merging and then be able, in case of a sufficient precise sky localization, to allow many telescopes to observe the very moment of the merger. However, only the closer coalescing events might be observed by X-ray satellites such as Athena or the X-ray telescope (XRT) on the proposed NASA satellite Transient Astrophysics Probe (TAP). Such satellites might detect the counterparts of supermassive coalescing black holes only up to a few z (Dal Canton et al., 2019). Clearly, such an observation would allow to study the behaviour of matter in the variable space-time surrounding the merging black holes.

Another possible multi-messenger window might arise from the detection with LISA of some 10^5 ultra-compact double white dwarf (DWD) binaries across our galaxy, including regions that are hardly accessible to electromagnetic observations. It has been argued that thanks to the large number of DWD detections it will be possible to use them as tracers of the Milky Way potential (Korol et al., 2019). Combining its results with Gaia and LSST observations a much more accurate Galaxy model, including bulge, disc and halo, could be constructed. This way a better Galactic rotation curve could be inferred and thus also determine more accurately the dark matter content.

Joint gravitational wave detections of stellar mass black holes, of the mass as seen so far by LIGO and VIRGO, by ground based observatories and LISA should be feasible and could open new opportunities for fundamental physics and astronomy (Gerosa et al., 2019). This would open the multi-band gravitational wave astronomy. LISA observations could then be used to predict with great accuracy mergers of such black holes detectable with the ground based observatories such as LIGO/VIRGO and the proposed ET (Einstein Telescope) in future.

Finally, we mention that gravitational lensing of the gravitational wave signal might occur and thus allow to get more information on the coalescing black holes. Moreover, the long path length to high redshift gravitational wave standard sirens could be used to probe the large-scale structure of the Universe. Thus the detection of strongly-lensed gravitational wave sources could provide an additional tool for cosmography (Sereno et al. 2010, 2011). In particular, time-delay measurements coupled with high calibration accuracy and annual motion of the space-based observatory will enable a better localization of the coalescing binaries. Lensing amplification will help further to find the host galaxies. Since most of the optical depth for lensing is provided by intervening massive galactic halos, the detection of multiple events will provide information on evolution and formation of large-scale structure, constraints on cosmological parameters, and tests of competing theories of gravity.

4. Conclusions

After the very successful technological mission LISA Pathfinder, LISA has been approved as an official mission by ESA and shall be launched hopefully before 2034, ideally being operational at the same time as the X-ray satellite Athena. LISA will be complementary to the ground based gravitational wave observatories and open a completely new window in the exploration of the Universe including multi-band gravitational wave and multi-messenger observations.

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