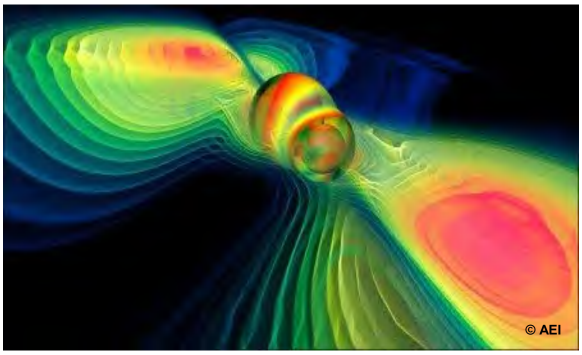
LISA

Mission Objectives

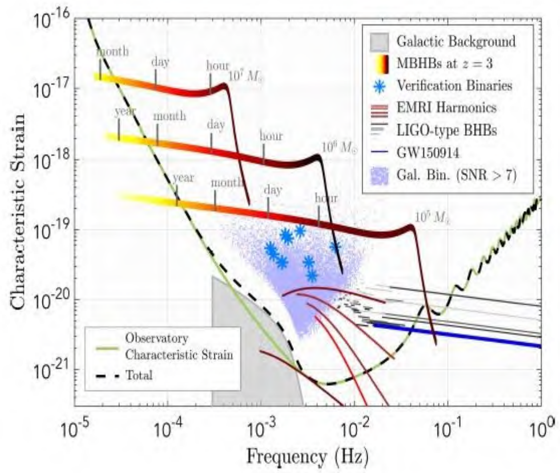
The ESA space science mission **LISA** (**L**aser **I**nterferometer **S**pace **A**ntenna) is meant to detect low-frequency gravitational waves from space after 2035, and characterize their sources with high accuracy. **Gravitational waves** (GW) are vibrations of space-time caused by fast temporal variations of the spatial distribution of very large masses like e.g. the coalescence (merger) of stellar-mass or supermassive black holes. GW propagate in space with the speed of light, and exhibit a temporal vibrational pattern (frequency gradient) characteristic of their source. The **GW frequencies** observable with LISA range from a few 10^{-5} to about 1 Hertz. This makes it possible to observe very massive GW sources (masses larger than 10^4 to 10^7 solar masses). By contrast, ground-based GW observatories like LIGO in the USA and Virgo in Italy are sensitive to considerably higher frequencies, i.e. some 30 to a few 10^3 Hertz. Thus, they observe different sources than LISA in the mass range below a few 100 solar masses. Hence, LISA will be complementary to these ground-based observatories.



GW become noticable as tiny periodic changes of any distances on Earth and in space. The alternation of lengths (**amplitudes of GW**, or strain) caused by the GW emitted by characteristic sources amount to typically only about 10^{-21}. This corresponds to only a tenth of a millionth millionth millionth percent! Hence, a measurement rod or distance of four kilometers equal to that of the LIGO detectors will be stretched and expanded respectively by merely a few hundredth of a femtometer, or, in other words, a hundredth of the diameter of the nucleus of a hydrogen atom (proton).

The most important scientific goals of LISA are:

- The study of the formation and evolution of compact binary stars in the Milky Way with orbital periods of a few minutes only; some of these binaries can be used as calibrations sources since they radiate very regular GW of constant frequencies.
- Tracing the origin, growth, and the history of successive mergers of massive black holes (BH, more than a few 1,000 solar masses) at very large distances in the early universe; in this way, the growth of supermassive BHs of 10^7 solar masses and more as they can be found in the centers of galaxies shall be reconstructed.
- Probing the dynamics of stellar BHs in the dense nuclear stellar clusters in the centers of galaxies by means of the inspirals of star-like bodies into much more massive BHs (EMRIs – Extreme Mass Ratio Inspirals).



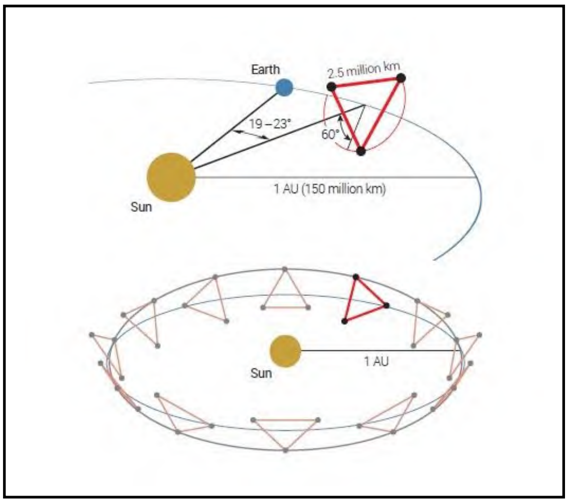
- An enhanced understanding of the astrophysics of stellar mass BHs the kind of which were detected as BH-BH mergers since 2015; these BHs orbit each other on successively tighter orbits, loose their orbital energy by radiation of GW, and leave the LISA frequency band months and years before merger only to become observable by ground-based GW antennas a few minutes or seconds before coalescence; thus, stellar BH-BH mergers can be predicted.
- Exploration of the fundamental nature of gravitation and BHs as well as the expansion of the universe (determination of the Hubble constant).
- Understanding of the stochastic GW backgrounds and their implications for the early universe as well as the background of high-energy cosmic (particle) rays in the TeV-range.
- Detection of GW bursts and unforeseen, hitherto unknown GW sources.

Of utmost importance for the research conducted by LISA is the so-called **multi-messenger astronomy**. This implies that (post-incident) observations of GW events and permanent GW sources will be carried out, covering, if feasible, the whole range of the electromagnetic spectrum from gamma and X-rays, over the UV, visual and infrared radiation, to the domain of radio waves, and over a time interval as long as possible. Finally, the search for neutrino emissions shall also be included. By this means, the most comprehensive data base shall be provided to support the astrophysical interpretation of GW sources and their nature.

The LISA Mission and its Scientific Payload

The minuscule amplitudes of a transmitted GW can only be detected by means of highly sensitive laser interferometry. The **laser interferometer** of LISA will be configured by three identical spacecraft which will form a nearly equilateral triangle with edges of 2.5 million kilometers on each side. This configuration is tilted by 60 degrees w.r.t. the ecliptic (orbital plane of the Earth), and will trail Earth on its orbit at a distance of about 50 to 65 million kilometers (drift orbit). At the same time, the whole configuration will rotate about itself once per year, in this way being able to locate permanent sources of GW with high accuracy by using triangulation, i.e. by determining their positions (directions) in the sky.

An important feature of the layout of the spacecraft and the LISA interferometer is the slight “breathing” of the configuration, i.e. the variations of the ideally equilateral triangle of the interferometer as a consequence of orbital dynamics of the spacecraft. This causes the arm lengths to alter quasi periodically by ±35,000 kilometers, and the inner angles of the triangle by approximately ±0.9 degrees. This requires active compensation and corrections as well as a special calibration of the measurement data on ground (TDI, s. below).



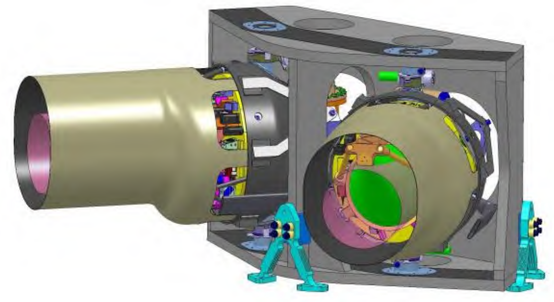
On board of each of the spacecraft two telescopes will be mounted to virtually span the laser triangle. Each of these telescopes is attributed a reflective test mass like the ones that were already used during the technology demonstration mission LISA Pathfinder (2015 – 2017). These **test masses** will be free-floating while in operational mode, and provide the mirrors at the ends of the respective interferometer arms. External disturbances exerted onto the spacecraft, for example by the radiation pressure of the sunlight, magnetic fields, or varying gravitational forces will be largely eliminated by the spacecraft structure, or compensated via a so-called “**Drag-Free Attitude Control System**“ (DFACS) and cold-gas micro-newton propulsion. These external and also internal interfering signals (“noise”) disturbed the GW signals considerably if no appropriate measures are taken to suppress or characterize them. The effects to consider comprise cosmic particle radiation that accounts for the electrostatic charging of the test masses, the electric noises of the measurement electronics, intensity and frequency fluctuations of the laser light, and other disturbances within the measurement device like the Brownian molecular motion in the residual gas inside the ultra-high vacuum around the test masses, as well as a coupling between the changes of moving parts angles into optical pathlength variations (Tilt-To-Length Coupling).

The payload concept of LISA plans for two **telescopes** per spacecraft with free apertures of about 30 centimeters each. These serve as transmit and receive telescopes for the interferometer and the laser beam between the spacecraft which uses a wavelength of 1,064 nanometers. The **Nd:YAG lasers** foreseen as light sources will have output powers of approximately 2 watts. **Optical Benches** (OB) are rigidly fixed to each of the telescopes. They contain the (“scientific”) interferometer actual optics and the photodiodes for signal detection to measure the phases of the received laser beam by means of a complex **Phasemeter System** (PMS) with very high accuracy.

Moreover, a “**Gravitational Reference System“** (GRS) is firmly connected to each of the telescope units; each GRS contains one of the **test masses** (TM) inside a vacuum enclosure. The TM provide the mirrors at the end of each of the interferometer arms. These cube-shaped, gold-coated TM are manufactured from a special gold-platinum alloy, exhibit an edge length of 46 millimeters and a mass of nearly 2 kilograms each. The designs of GRS and TM including the complex mechanism to lock the TMs safely during launch, and to sensitively release, position, and re-grab the TM have already been successfully tested with LISA Pathfinder. Another critical function is the monitoring and contactless control of the electrostatic charge of the TM via UV (ultraviolet) light (“**Charge Management**“). Combined with the necessary low-noise control and detection electronics (i.a. the PMS) the elements described above make up the “**Moving Optical SubAssembly**“ (MOSA). The telescope, OB and GRS will be tracked via a moveable mounting such that the laser connection to the opposite spacecraft and telescope is permanently preserved. However, a direct back reflection of the laser beam over 2.5 million kilometers is not possible even though the beam divergence is very low since the very low radiation energy reaching the opposite detector (a few 10^{-10} watts only) and the by far insufficient length of coherence prevents this; thus, a “fresh” beam will be re-transmitted by the receiving spacecraft using high-fidelity phase coupling.

In order to achieve the high precision of the phase measurement LISA utilizes heterodyne interferometry. This method uses the phase information from a beat frequency (beat-note) in the Gigahertz range, and compares it to a “local oscillator”. Hence, the measurement will be transformed from the high laser radiation frequency (3×10^{14} Hertz) into the microwave regime which makes electronic measurement much easier to perform. This measurement principle has already been or is still being very successfully applied with LISA Pathfinder and LIGO.

Owing to the slight tilts of the spacecraft and telescopes with respect to each other in the interferometer the challenge to generate the beat-notes is due to the fact that the wavefront of the incident laser beam arrives at a small tilt angle. Moreover, this angle will permanently and systematically alter during the duration of the mission. The tilt has to be compensated before the beat-notes can be generated by means of a reference laser beam. To this end a so-called “**Differential Wavefront Sensing**“ (DWS) will be applied.



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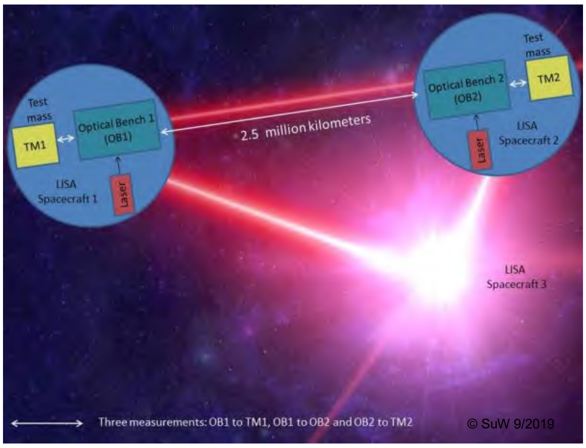
Furthermore, thorough elimination of the laser frequency noise is needed to fulfil the precision requirements of LISA. In an interferometer with two equally long arms the frequency noise cancels out exactly when both beams are superposed. If, however, the arm lengths are different as will be the case with LISA a procedure called “**Time Delay Interferometry**“ (TDI) needs to be deployed. In this procedure the detected laser signal is compared with a reference beam which is equivalent with the one that has been originally emitted. In this way, the frequency noise can be eliminated completely via post-processing, and also take into account the relative motions of the spacecraft with respect to each other at velocities of a few meters per second (Doppler effect).

Finally, each distance measurement between the free-floating TM of each two spacecraft will be decomposed into three partial measurements. To begin with, the distance of the TM to its telescope will be measured for the first spacecraft; subsequently, the distance between this telescope and the one on the opposite spacecraft is determined, i.e. the long leg between the two spacecraft with a light travel time of more than eight seconds; and finally, the distance between the telescope and TM on the second spacecraft. This tripartite measurement will be carried out permanently in both directions between all three spacecraft leading to 3 x 2 x 3 = 18 measurements in total which have to be taken into account. The extensive post-processing takes into account all known sources of errors and measurements, as well as further effects in order to be finally able to extract the GW signals from the processed data.



LISA has been selected as the **L3 mission in ESA's space science programme** in 2017. It will be developed and built by ESA in close collaboration with NASA, and with payload contributions from more than ten European countries. A scientific LISA Consortium is significantly contributing to this development, and, in addition, will establish the science data processing and archiving. The German contribution to LISA consists mainly of the management and the system engineering of the Interferometric Detection System (IDS) and the provision of the phasemeter central to the payload of LISA by the **Max Planck Institute for Gravitational Physics / Albert Einstein Institut (AEI)** in Hanover. Moreover, the AEI will deliver a critical opto-mechanical mechanism in cooperation with partners from the Netherlands. In addition, the AEI also supports the mission by consulting ESA and the LISA Consortium with many issues regarding the mission and payload system design. Finally, **Karsten Danzmann** of the AEI is the **Principal Investigator** of the mission. The contribution of the AEI to LISA is significantly supported by grants given by DLR on behalf of the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

LISA: Mission Characteristics

- Begin of development: 2017 (first studies from 1993)
- Launch date: August 2035
- Launcher: Ariane 6.4
- Launch location: Kourou, French Guiana
- Mission duration: of min. 6.25 years (incl. 4.5 years nominal operation) / 6 years of possible mission extension
- Orbit characteristics: heliocentric drift orbit (Earth distance > 50 million km)
- Operations center: ESOC, Darmstadt, Germany (mission operations) ESAC, Madrid, Spain (science operations)
- Launch mass of (3) crafts: 8,300 kg
- Dimensions (single craft): 4.8 m x 3.0 m x 1.1 m
- Mass of payload: 830 kg (per spacecraft)
- Electrical power consumption (spacecraft and payload): 2,300 W (full payload operation)
- Telemetry rate (config.): ~270 kbit/s (X-band, downlink)

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