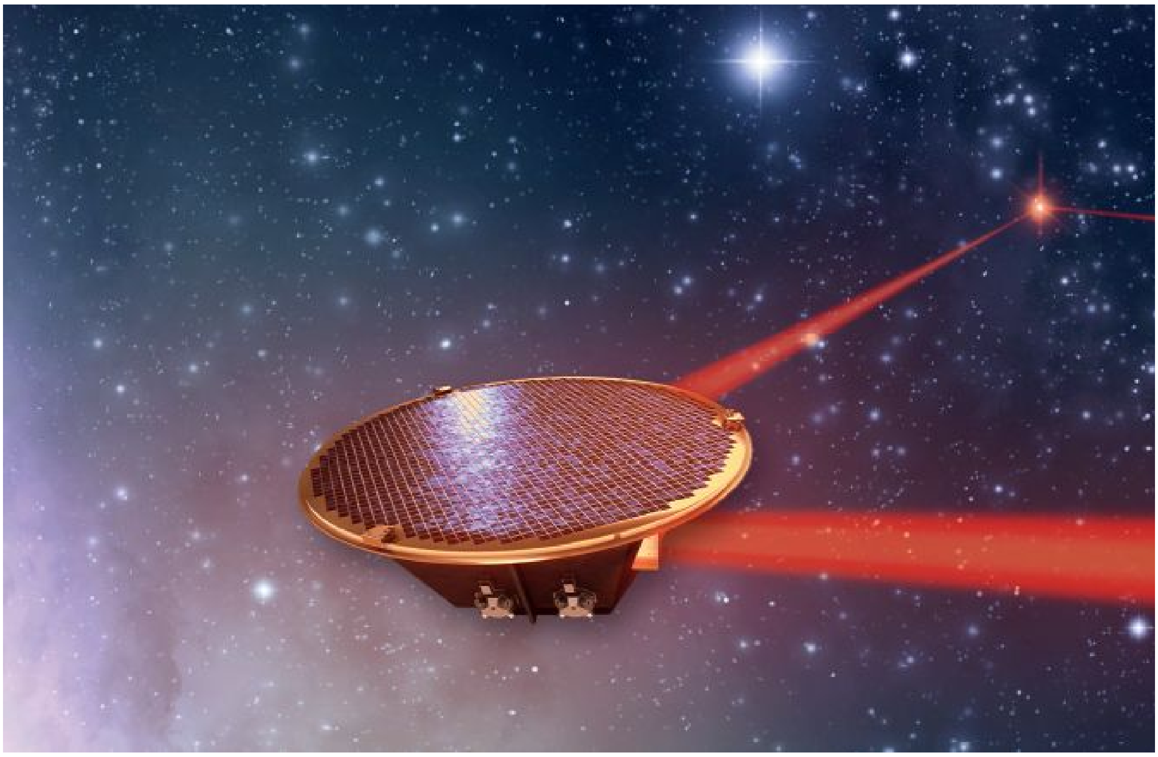
eLISA: Gravitational waves from Space
An Astronomy/Physics facility



A proposal for the KNAW committee for future large-scale facilities

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Frontpage: Artist impression of eLISA. Credit Simon Barke.

Summary

Gravitational waves are ripples in the fabric of space-time predicted by Einstein's General Theory of Relativity. They are emitted by objects with a strong, varying gravitational field, such as black hole binaries and mergers, and possibly by processes in the very early universe. The European Space Agency's L3 flagship mission (ESA L3), planned for a launch in 2034, will be the first space mission aimed at detecting gravitational waves. It will consolidate the leading position of Europe in this field. The mission builds on a strong heritage in Europe of gravitational wave research on the ground, as well as the technology development for the LISA Pathfinder mission that has been successfully launched last year. The main scientific aims of the mission are: i) to unravel the role of astrophysical black hole mergers in the formation of structure in the universe, ii) to measure the properties of black holes in great detail; iii) use that to test General Relativity; iv) to probe the physics of the very early universe and v) to study the ultra-compact binaries in our Milky Way.

We have formed an eLISA-NL consortium to prepare for the gravitational wave space mission. Its aim is to secure NL participation in the mission and thus enable influence on the mission design and access to (proprietary) data for Dutch scientists. It consists of scientists from 10 universities and research institutes for the scientific exploitation and five technology institutes that want to participate in development and construction of the mission. We have identified a number of possible hardware contributions and will work with ESA and the eLISA consortium to define the final contributions.

The eLISA project provides a unique opportunity to strengthen Dutch technology for high-precision space application, for new collaborations between research institutes and with industry and to exploit synergy between the Physics and Astrophysics communities in the Netherlands. By participating in eLISA the Netherlands ensures its role as a leading country in the field of Gravitational Wave (Astro)Physics.

Key words

Gravitational waves; fundamental physics; astrophysics; black holes; early universe, gravity;

Proposal

A. SCIENCE AND TECHNICAL CASE

eLISA: A new facility to open the gravitational wave window in space

The European Space Agency (ESA) has an ambitious agenda called "Cosmic Vision" for its scientific space programme in the next (two) decades. In December 2013, a senior review committee has advised ESA to select the scientific themes to be addressed by their future large, flagship missions. The third one, planned for a launch in 2034, is a mission addressing the science of Gravity and Gravitational Waves. The ESA Gravitational Observatory Advisory Team (GOAT)[1] has recently recommended ESA to go ahead with development of a mission that is based on the technique of laser interferometry [12], for which we will use the name eLISA. NASA has expressed the desire to contribute to this mission rather than develop a competing mission.
The current proposal concerns the Dutch contribution to that mission that is needed for Dutch scientists to be involved in the final design and design trade-offs, for Dutch labs and industry to benefit from this high-precision project and finally for Dutch scientists to have access to the data from the mission. The mission will consist of three spacecraft which exchange laser beams that are used to measure the distances between the spacecraft to atomic precision (picometre). Passing gravitational waves will be detected because they cause periodic changes in the spacecraft distances ("arms"). In order to achieve the picometre precision, the spacecraft contain free floating test masses that are protected from all external influences. Precision control of the spacecraft ensures that they accurately trace the free floating path of the test masses, only influenced by Gravity. The LISA Pathfinder mission that will test the most crucial technologies of the mission, was launched in December and will perform its tests in the course of 2016[2].

A.1 Science Case

Introduction: Gravitational waves

Gravitational waves (GWs) are ripples in the fabric of space-time travelling at the speed of light, which only weakly interact with matter and travel largely undisturbed over cosmological distances (Fig. 1). Their signature is a fractional squeezing of space-time perpendicular to the direction of propagation, with an amplitude $h = \Delta L/L$ on the order of 10^{-20}. These minute signals make them extremely difficult to detect. When detected, the GWs give direct information about their sources and can be used as a new window on the Universe and as a tool to study the fundamental nature of Gravity and of black holes. Below we give a brief summary of the science that can be done with eLISA, which is largely based on existing documents in which more details and extensive references to the scientific literature can be found [1][2][3]

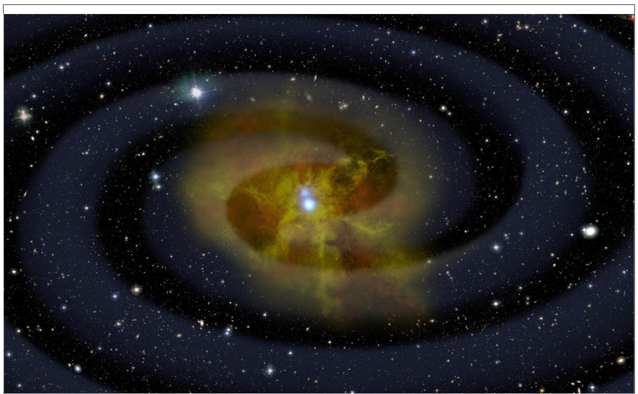


Figure 1: Artist impression of a super-massive black hole merger. Credit: NASA

1.1 Science with eLISA

Electromagnetic observations of the Universe, plus theoretical modelling, suggest that the richest part of the GW spectrum falls into the frequency range accessible to a space interferometer, from about 0.1 mHz to 100 mHz. In this band, important first-hand information can be gathered to tell us how binary stars formed in our Milky Way; to test the history of the Universe out to redshifts of order z ~ 20; to probe gravity in the dynamical strong-field regime and on the TeV energy scale of the early Universe.

1http://www.cosmos.esa.int/web/goat
2http://sci.esa.int/lisa-pathfinder/

1.1.1 Astrophysical Black Holes

eLISA observations will probe massive black holes over a wide, almost unexplored, range of redshift and mass, covering essentially all important epochs of their evolutionary history (for a detailed review see [4]). eLISA probes are coalescing massive binary black holes, which are the loudest sources of gravitational waves in the Universe. They are expected to appear at the 'cosmic dawn', around a redshift of z ~ 11 or more, when the first galaxies started to form. Coalescing binary black holes at a redshift as remote as z ~ 20 can be detected with eLISA, if they exist. eLISA will also explore black holes at the peak of the star formation in the Universe, at redshifts of z ~ 3 to z ~ 1.5. According to the currently favoured paradigm about the formation of structure (i.e. galaxies and galaxy clusters) in the Universe, regions of higher-density cold dark matter in the early Universe form self-gravitating haloes, which grow through mergers with other haloes and accretion of surrounding matter. Ordinary matter (baryons) and massive black holes are thought to follow the same process of hierarchical clustering. The black holes in the centres of galaxies may be formed early on as small seeds of only 100-1000 times the mass of the Sun, perhaps as remnants of the first generation of stars. Alternatively, the seeds may be much larger (10^3 – 10^5 times the mass of the Sun) and formed from collapse of large clouds or runaway mergers of smaller objects. These seeds evolve over time through phases of intense accretion when they show up as Quasars, and through mergers with other massive black holes after the merger of their parent galaxies, to form the super-massive black holes that we see at the present time.

eLISA will measure the masses of black hole mergers throughout the complete evolution of the Universe, from the early mergers that occurred billions of years ago and produced GWs that have travelled through the Universe unaltered for billions of light years, to the recent mergers that occur nearby. These measurements will thus directly probe the mass growth of the black holes, their initial mass and thus their origin. The signal-to-noise ratio of the GW detection of the merger are in general very high (Fig. 2). In addition, the eLISA measurements will measure the spin of the black holes to high precision, which is a tracer of the previous accretion history: high for coherent accretion from a thin accretion disk, or much lower if the accretion took place in many randomly oriented accretion episodes.

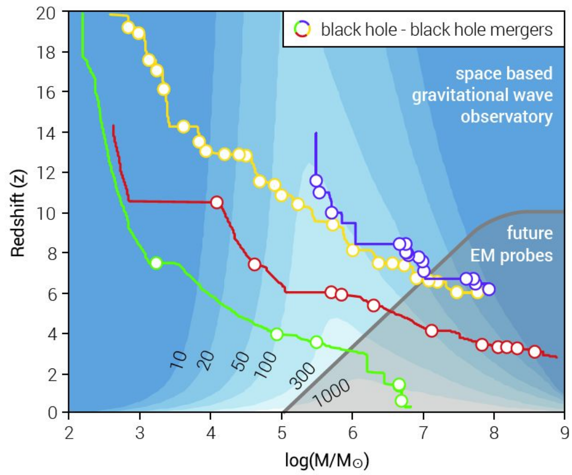


Figure 2: Redshift (distance and look-back time) versus mass for 4 example black holes that show their merger history (coloured lines). Only the massive black holes in the relatively nearby Universe can be studied by current and future electro-magnetic facilities (bottom right). A space gravitational wave mission would be sensitive to the whole range; the background colour scale indicating the signal-to-noise ratio of detections ranging from 10-1000. From [1]

Finally, the eLISA measurements will probe the three stages that describe the merger of two black holes: inspiral of the two black holes to get closer and closer together, merger and the "ringdown" of the newly formed black hole that initially is highly distorted and thus provide detailed information about the merger process itself (in addition to the critical tests of the theory of General Relativity as described below). The predicted rate of detectable GW mergers in the eLISA band ranges from 10—100 per year, depending on the theoretical assumptions.

1.1.2 Extreme mass-ratio inspirals and the physics of dense environments

The existence of super-massive black holes in the centres of galaxies creates a very interesting hierarchy between this central object and much lower mass, but much more numerous objects surrounding it. These other objects can be stars of different types and mass, but also compact objects such as white dwarfs, neutron stars and stellar-mass black holes. This leads to the interaction between the super-massive black hole and the other compact objects, that may be captured and may

gradually spiral into the super-massive black holes. These so-called *extreme-mass ratio inspirals* (EMRIs) provide a unique tool to probe both the very high object densities in the centres of galaxies as well as their central super-massive black hole (for a detailed review see [5]).
The low-mass objects act as a test mass in the potential of the super-massive black hole and thus allow measurement of the mass and spin of the latter to very high accuracy. They will shed light on the local population of quiescent or dormant super-massive black holes due to their favourable GW frequency, this is particularly true to those at the low-mass end of the super-massive black hole mass range (10^5—10^6 times the mass of the Sun). That is exactly the range in which the black hole at the centre of our Milky Way is found, and also the range that is most difficult to study using electro-magnetic probes. The masses of the low-mass objects (predominantly stellar-mass black holes) can also be determined accurately and thus provide a unique view of their mass spectrum and provide tests of the theories that describe the stellar dynamics in galactic nuclei.

1.1.3 Testing General Relativity

The GW measurements made by eLISA will probe the most extreme and violent manifestations of Gravity and thus are probably the best way to test the fundamental nature of Gravity (see [1][2] for detailed reviews). In particular, GWs test the theory of Gravity in the limit of very high velocities (approaching the speed of light) and very strong space-time deformations. The two key factors that make eLISA a very good instrument to test our current understanding in the form of Einstein's General Relativity are the high signal-to-noise detections and the long duration of up to a year, of the inspiral and merger of the two black holes. This complements the (most likely) earlier tests of General Relativity using GWs from ground-based detectors such as LIGO/Virgo and the Einstein Telescope. In the inspiral phase of the detection, the measurements can be examined for evidence of a massive graviton as predicted by several alternative Gravity theories, that would show up as a frequency dependent phase shift. In addition, the inspiral phase can be compared in great detail with predictions from General Relativity using numerical relativity simulations and thus expose any hints of incompleteness of General Relativity. The merger and ringdown phases can be used again to test GR, because the accurate determinations of the masses and spins of the two black holes during inspiral, together with numerical relativity simulations to predict the signature of the merger and the properties of the final remnant and compared directly with the observations. Finally, the properties of the ringdown, in General Relativity, are completely determined by the pre-merger binary and the mass and spin of the final black hole, again providing a consistency check for General Relativity. In the ringdown phase, so-called quasi-normal modes of the black hole can be used to determine the Kerr-ness of the black hole and distinguish against exotic black-hole alternatives such as boson stars and gravastars.
EMRIs also can serve as tools for testing General Relativity, as they probe the space-time curvature around the super-massive black hole. Sufficiently high signal-to-noise ratio EMRIs can test the no-hair theorem and again check the consistency of the black hole space-time with that described by General Relativity in contrast to many alternative theories.

1.1.4 Cosmology on the TeV energy scale

GWs produced very early in the evolution of the Universe form a fossil radiation, unaltered because of their weak interaction with other forms of mass and energy (see Fig. 3 and [6] for a detailed review). For the most promising formation scenarios, their wavelength is set by the apparent horizon scale at the time they are formed and thus their current (redshifted) frequency is directly linked to the time at which they were formed. For the typical eLISA frequencies of about 0.1mHz, this corresponds to the time when the energy of the Universe was in the TeV range and thus the age of

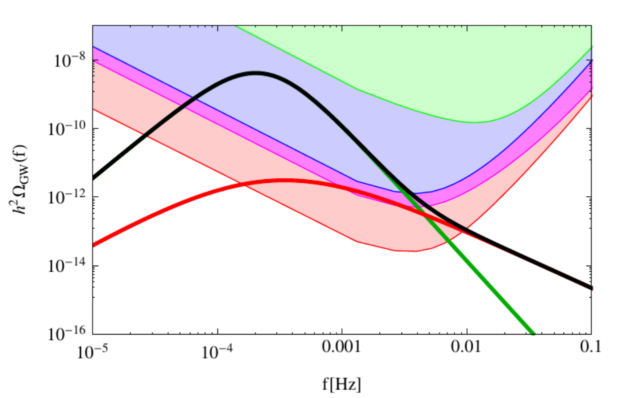


Figure 3: Simulated signal from cosmological first-order phase transition compared to different eLISA configurations. From [6]

the Universe some 10^{-17} – 10^{-10} s. At these times and energies, new physics such as first order phase transitions, supersymmetry and extra dimensions may show up. In addition, in phase transitions the formation of cosmic strings could happen, that later decay emitting GWs.

1.1.5 Ultra-compact binaries

Last but not least, close to home in our own Milky Way several million ultra-compact binaries are expected to exist that radiate GWs in the eLISA band (see Fig. 4 and [7] for a detailed review). By far the most numerous will be white dwarf binaries, the remnants of the vast majority of low- and intermediate-mass stars, but a small subset will contain neutron stars and stellar-mass black holes. Already now, we know some 50 ultra-compact binaries, typically close to the Sun, and several of these have sufficiently strong GWs that they will be detectable by eLISA. These so-called *verification sources* can be used early on in the commissioning and operations of the mission to validate the performance of the instrument. In the next decades, several more verification binaries are expected to be discovered by wide-field transient surveys such as PannSTARRS, ZTF, BlackGEM and ultimately LSST. Based on the observed binaries and theoretical models, eLISA is expected to individually detect and determine the periods of several thousand currently unknown ultra-compact binaries. The remaining millions of binaries will form a stochastic GW foreground. These results will constrain the outcome of the common-envelope phase in the evolution of binary stars, that not only determines the properties of the close white dwarf binaries, but plays a fundamental role in the formation of all compact binaries, also those leading to X-ray binaries, Gamma-ray burst and type Ia supernovae. Also, the GW measurements will directly probe the physics at the moment the two white dwarfs (or the white dwarf and the neutron star/black hole) come so close together that material starts to be transferred from one object to the other. Depending on the details of the physics, the nuclear reactions and the tidal interaction, the two objects may merger producing a violent explosion or a new, more massive, object, or the system may evolve into a stable mass-transfer phase producing interacting binaries known as AM CVn systems or ultra-compact X-ray binaries. Currently it is unknown what the branching ratios of these processes are due to our lack of understanding of the tides and (magneto)hydrodynamics of the onset of mass transfer. A subset of several hundred binaries will have sufficiently strong signals that accurate sky position, inclination and distances can be measured. These can be used to measure the 3D distribution of these systems in the Milky Way and relate them to their parent populations. Finally, eLISA will be able to test dynamical interactions in globular clusters that may enhance the formation of ultra-compact binaries and if so, would show up as excess GW emission from the clusters compared to the Galactic disk.

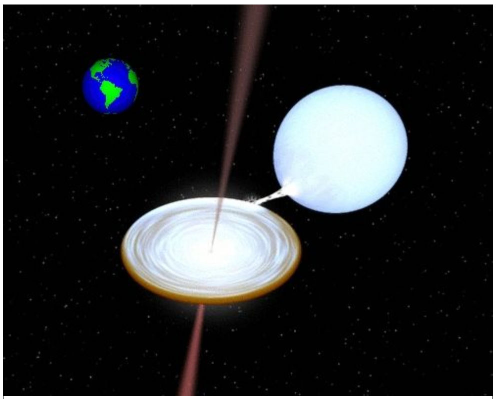


Figure 4: Artist impression of an ultra-compact binary with the Earth to scale.

1.2 Dutch scientific interest in the mission

The eLISA-NL science community includes scientists interested in all the scientific areas covered by the eLISA mission, but there are several topics where we have specific interest or particular expertise that gives us a special or leading role. Already now, several of us (Nelemans, Rossi) are actively involved in providing scientific input the the ESA Gravitational Observatory Advisory Team which is evaluating mission profiles.

1.2.1 Compact binaries

The Netherlands is playing a leading role in the scientific topic of ultra-compact binary systems as eLISA sources. The population models that are currently used worldwide in order to estimate the numbers and properties of the eLISA ultra-compact binaries are based on the models developed by Nelemans, Verbunt and Portegies Zwart and extended later by the RU group. These provide models of the population of white dwarf (and neutron star and black hole) binaries in the Milky Way and can be readily used to calculate the expected number of sources detectable by any low-frequency GW detector. These models are calibrated against the observed ensemble of ultra-compact binaries, and efforts at the RU have made significant contributions to the knowledge about this population by detailed studies of individual binaries and wide-field surveys to find more. A new approach in the last years has been to assess the number of binaries for which both GW and optical measurements and the science this enables (RU). Currently, a detailed investigation of the influence of tidal effects on the evolution of white dwarf binaries and their relevance for eLISA is undertaken as a collaborative effort of UL and RU. The neutron star binaries are studied using radio and X-ray facilities at ASTRON, SRON and UvA. Finally, the UL group is one of the leading groups studying the dynamics and compact binaries in globular clusters. This large number of activities in the Netherlands have led to a leading role in the field of ultra-compact binaries: Nelemans is the chair of the ultra-compact binaries science working group and is coordinating the relevant sections in all the eLISA documents.

1.2.2 Fundamental theory of Gravity and Black Hole tests

There is a diverse expertise in the Netherlands on (testing) the fundamental theory of Gravity, with theoretical groups (RU, RUG) working on the fundamental properties of Gravity and Quantum Gravity and experimental work, both in physics and in astronomy aimed at testing the predictions of General Relativity. The theoretical work focusses on alternative theories of Gravity, their consistency and ability to describe the experimental data. The experimental tests of General Relativity are done either in accreting strong-gravity environments or using GWs and performing tests of the General Relativity predictions or fitting parametrized forms of a general theory of Gravity to the data. In addition, there are studies of the fundamental properties of black holes done in the Netherlands. On the one hand studies using astronomical observations of accreting black holes (UvA, SRON) and on the other hand, specifically relevant for eLISA, studies of efficient descriptions of EMRIs (Nikhef, UL). Finally, the SRON group is searching for intermediate-mass black holes to test models of super-massive black-hole formation.

1.2.3 Early Universe

The Netherlands has a strong and growing group of theoretical physicists and astronomers working on the very early Universe, where the seeds are formed for the formation of structure in the later phases. It is also the place where new physics, like Inflation and phase transitions can occur. The Dutch theoretical cosmology groups (UL, UU, UvA, RUG, Nikhef) have recently joined forces in the FOM program on Cosmology with the aim to boost their cohesive research efforts, attract new talent and build new and sustainable bridges to the Dutch astronomy community to support and strengthen the cosmology research efforts in the Netherlands. Researchers at UU are investigating properties of relic gravitational waves produced during cosmic inflation, and in particular how quantum loops affect their evolution, which is currently poorly understood. On the interface between theoretical physics and astronomy, people at RUG study the nature of quantum space-time and its effects on black holes. These explorations show that black hole mass grows due to mini wormholes over billions of years. This novel effect beyond General Relativity turns the gravitational wave signal with redshift into a subtle probe of Planck scale phenomena.

1.2.4 Structure formation

Many astronomers in the Netherlands have a research topic that is related in some way or another to the formation of structure and galaxies in the Universe. This is a very broad research topic that ranges from theoretical and numerical studies of structure formation (UL), via detailed investigations of the role of stellar, hydrodynamic and radiation feedback on galaxy formation (RUG, UL, RU) to multi-wavelength studies of galaxies and their stellar and gas content at different redshifts (e.g. ASTRON). At UL theoretical models for the formation of the first black hole seeds are developed (including the leading model for formation from direct collapse of gas in proto-galaxies) . At RUG state-of-the-art models for the formation, growth and merging of massive seed black holes in the early universe, z ~5-20 are developed. These models use advanced numerical tools like adaptive mesh refinement codes. The intermittent accretion flow of gas onto massive black holes is computed and the many mergers between proto-galaxies and their central black holes are followed. These efforts are leading in the world and help to determine the history of the gravitational wave signal due to massive binary black holes. Within the eLISA consortium, Rossi (UL) is leading on-going efforts to theoretically determine their initial mass distribution and infer the observational consequences

1.3 Relation with other facilities/methods

Gravitational waves can be detected by a range of instruments and experiments. These all differ in one crucial property of the GWs that they can detect: their frequency or wavelength. Much as in the case of different electro-magnetic wavelengths, these different GWs probe very different sources or different aspects of the same sources and thus are complementary rather than alternatives. Because GWs are produced by bulk motion, the rule of thumb is: source size = wavelength and wavelength = detector size. In addition, a number of electro-magnetic facilities provide synergy with the GW detectors.

The (advanced) Virgo and LIGO detectors are ground-based detectors that have sizes of order kilometres and thus are sensitive to high-frequency GWs from very small objects, such as merging neutron stars and stellar-mass black holes. The American LIGO detector has recently started observing again, after an upgrade of the hardware and the ongoing “Observing run 1” has shown that the detectors are stable and can already detect sources to larger distances that the earlier version of the detector. In the spring the detectors will be further tuned and upgraded to reach even larger sensitivities. The Italian/French/Dutch advanced Virgo detector is currently integrated and will join LIGO in the second observing run, late this year.
On the other end of the GW spectrum are the **Pulsar Timing Array** experiments, that use the distances between the Earth and several radio pulsars as “detector” and thus are sensitive to very low-frequency GWs from extremely large objects, such as revolving pairs of super-massive black holes that are on their way to merge at much higher frequencies in the eLISA band. The most recent observing campaigns have reached sensitivities that are beginning to probe the predicted range of GW strengths in their very low-frequency band. The Netherlands (ASTRON) is part of the European Pulsar Timing Array (EPTA).

For the future, there are plans to build a new ground-based detector, the **Einstein Telescope**, that will be another huge improvement over the sensitivities of the advanced LIGO and Virgo detectors. In order to reach these measurement accuracies, the detector will be larger and underground. Given the time line of the eLISA mission, the Einstein Telescope will likely be the complementary detector at the time and there will be strong synergies between the detectors, both in terms of different measurements related to the same scientific questions (e.g. the test of General Relativity and the detailed measurements of black holes) as well as in some cases observations of the same (binary) objects, that are first seen orbiting around each other in the eLISA band and then several years later seen merging in the Einstein Telescope band. There is a separate proposal describing the Dutch contributions to the Einstein Telescope.

Related in a different way are **electro-magnetic facilities** that will complement the GW detections of the same sources. These can take the form of fairly independent studies of the same systems, in particular compact binaries and super-massive black-hole binaries. For these objects a large range of facilities are relevant from the radio band (LOFAR, VLA, SKA in the future), via submillimeter/infrared (ALMA, Herschel, Euclid), optical (VLT, wide-field survey instruments like BlackGEM, ZTF and LSST in the future) to X-rays (Chandra, XMM-Newton, Astro-H, Athena in the future). Secondly, there are very interesting possibilities of joint observations of the GW sources, both for white dwarf binaries in our Milky Way to electro-magnetic counterparts of the GW signal of super-massive black-hole mergers. For these the same electro-magnetic facilities will be used. The electro-magnetic observations typically give orthogonal information to the GW data (in particular, the distance, ejecta studies and a very accurate position yielding the possibility to do studies of the local environment).

Finally, the **Event Horizon Telescope** is a project to use electro-magnetic radiation to probe the horizon of a black hole by spatially resolving the image of the immediate surroundings of a black hole that is accreting material. By using very long-baseline interferometry, it is possible to resolve scales comparable to the black-hole horizon for the one in the centre of the Milky Way and M82. The Event Horizon Telescope is currently under development and may provide the first resolved images in the next 5 years

A.2 Technical case

2.1 General description of the eLISA mission

The following general description is based on the mission concept presented in the Gravitation Universe white paper[]. The eLISA mission consists of 3 drag-free spacecraft forming a triangular constellation with arm lengths of 1-5 million km and laser interferometry between "free-falling" test masses[3]. The interferometers measure the variations in light travel time along the arms due to the tidal deformation of space-time by gravitational waves. The mission has three spacecraft, one 'mother' at the vertex and two 'daughters' at the ends, which form a single Michelson interferometer configuration (Figure 5). The spacecraft follow independent heliocentric orbits without any station-keeping and form a nearly equilateral triangle in a plane that is inclined by 60° to the ecliptic. The constellation follows the Earth at a distance between 10° and 30°. Celestial mechanics causes the triangle to rotate almost rigidly about its centre as it orbits around the sun, with variations of arm length and opening angle at the percent level. The unique feature of the eLISA interferometry is the use of 'Time-Delay Interferometry' (TDI), which synthesises a virtual balanced arm length interferometer in postprocessing. This almost completely removes the laser frequency noise and allows construction of several independent measurement variables by combining the laser phases from the end points with different time delays.

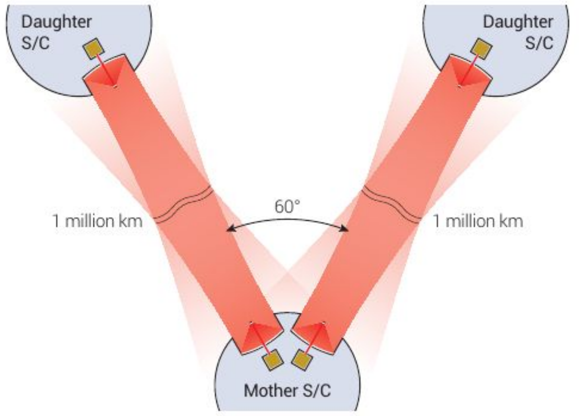


Figure 5: eLISA configuration with one mother and two daughter spacecraft in a triangular shape, exchanging laser beams to form a two-arm Michelson interferometer.

The payload consists of four identical units, two on the mother spacecraft and one on each daughter spacecraft. Each unit contains a Gravitational Reference Sensor (GRS) with an embedded free-falling test mass that acts both as the end point of the optical length measurement, and as a geodesic reference test particle. A telescope transmits light from a laser at along the arm and also receives a small fraction of the light sent from the far spacecraft. Laser interferometry is performed on an optical bench placed between the telescope and the GRS. The eLISA Metrology System (the "phase meter") is the opto- electronical subsystem that actually measures the picometre displacements of the test masses in the three spacecraft, and therefore of vital importance for the mission. The accurate determination of the position is done with precise phase measurements of the heterodyne interferometric signals that are generated with the laser beams that are sent between the spacecraft. On the optical bench, the received light from the distant spacecraft is interfered with the local laser source to produce a heterodyne beat note signal between 5 and 25 MHz, which is detected by a quadrant photodiode. The phase of that beat note is measured with very high precision by an

3The Gravitational Universe Advisory Team is currently investigating different arm length options.

electronic phasemeter (μrad phase differences with 1000 of seconds stability of the 1024 nm wavelength laser beams). Its time evolution reflects the laser light Doppler shift from the relative motion of the spacecraft, and contains both the macroscopic arm length variations on time scales of months to years, and the small fluctuations with periods between seconds and hours that represent the gravitational wave science signal. The measurement of relative spacecraft motion is then summed with a similar local interferometer measurement of the displacement between test mass and spacecraft. This yields the desired science measurement between distant free-falling test masses, removing the much larger motion of the spacecraft, which contains both thruster and solar radiation pressure noise. A simplified schematic of the LISA Metrology System is shown below (Fig. 6).

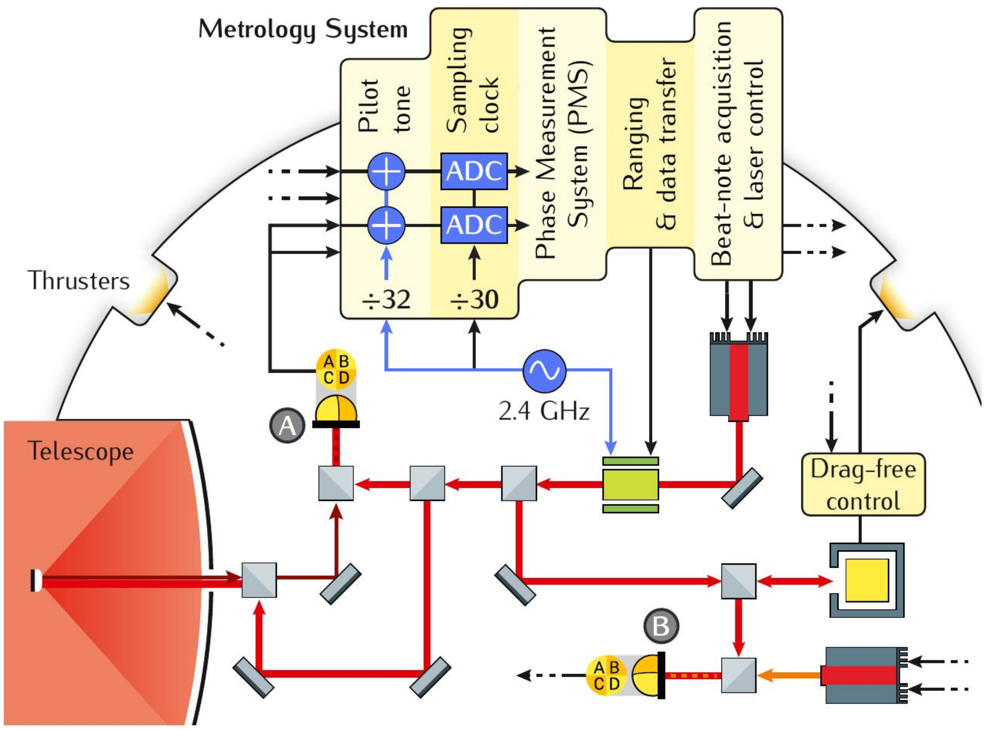


Figure 6: Simplified functional overview of the LISA Metrology System for one laser link. Quadrant photodiodes are used to enable Differential Wavefront Sensing (DWS) to get not only the position but also the alignment information for the distant spacecraft (detector A) and the proof mass (detector B). This requires a multitude of phase measurement channels. The alignment information with respect to the incoming beam for both, proof mass and spacecraft, is used in the Drag-free Attitude Control System (DFACS). All interactions between systems are shown as black arrows, where dashed lined arrows also go to the PMS. From Final Report Lisa Metrology system (ESA ITT AO/1-6238/10.NL/HB)

The spacecraft are actively controlled to remain centred on the test masses along the interferometric axes, without applying forces on the test masses along these axes. This 'drag-free control' around the shielded geodesic reference test masses uses the local interferometry measurement as a control signal for an array of micro-Newton spacecraft thrusters, with the residual spacecraft jitter reaching the nm/√ Hz level. These thrusters also control the spacecraft angular alignment to the distant spacecraft by detecting the laser beam wavefront with 'differential wavefront sensing' with nrad/√ Hz precision. Other degrees of freedom are controlled with electrostatic test mass suspensions. The only remaining degree of freedom is then the opening angle between the arms at the master spacecraft, which varies smoothly by roughly 1.5° over the year, and can be compensated for either by moving the two optical assemblies against each other or by a steering mirror on the optical bench.

The test masses are cubes, made from a dense non-magnetic (for instance Au-Pt) alloy and shielded by the GRS. The GRS core is a housing of electrodes, at several mm separation from the test mass, used for nm/√ Hz precision capacitive sensing and nN-level electrostatic force actuation on all non-interferometric degrees of freedom. The GRS also includes fibres for UV light injection for photoelectric dis-charge of the test mass, and a caging mechanism for protecting the test mass during launch and then releasing it in orbit.

2.2 LISA Pathfinder

On December 3, 2015, the ESA LISA Pathfinder mission was successfully paunched from French Guyana. It is a very important technology demonstration mission for the ESA L3 mission, to which SRON has contributed. It will test the GRS technology, part of the metrology system and the drag-free control of the spacecraft. It is currently on its way to the first Lagrange point between the Earth and the Sun, where it will perform detailed measurements of the distances between two test masses using laser interferometry similar to what will be used in the eLISA mission. If successful, the LISA Pathfinder measurements will retire a significant fraction of the risks for the eLISA mission.

2.3 Potential Dutch hardware/software contributions

In the past year we have identified a number of potential Dutch hardware contributions to the eLISA mission. These are concentrated in several of the subsystems at the heart of the mission:

- The **Phase meter** is the device that measures the phase of the light in the interferometer in order to measure the displacement of the test masses in the three spacecraft and thus is in the heart of the mission. Nikhef and SRON, are planning to use their expertise on Virgo hardware (Nikhef) and space hardware (SRON) to work together with the Albert Einstein Institute in Hannover on the phase meter.
- There are several **opto-mechanic mechanisms** planned to be part of the optical bench of the mission that make sure that the exchange of laser light between the different satellites will be successful. TNO has developed several of these mechanisms in the past years in order to demonstrate that the exchange of lasers between satellites 5 million kilometres apart is feasible.
- The light of the laser will be received by a **telescope** before being directed into the optical bench for interferometry. TNO and NOVA are involved in the design and testing of the telescopes. Both are involved in the development of Active Optics technology to further improve the accuracy of the alignment of the beam and the pointing accuracy of the laser beams.
- NOVA will contribute to the **overall system engineering** of the instrument hardware and to the full error budget analysis to assure that the science requirements are fully taken into account in the hardware and software specifications. Some solutions may require a hybrid solution in hardware and data acquisition and calibration software.
- Finally, the laser group of Twente University is developing a **laser** that has the potential to be used in space, due to its compactness and stability as well as advantages for building redundant systems and thus safer operation in the form of integrated optics.

2.4 How ESA science missions work

For this proposal it is important to know how space missions in Europe are organised, developed and financed. In general, ESA provides and pays the satellite and the telescope, together called spacecraft and consortia based in the ESA member countries provide and pay for the instruments, generally referred to as payload. The money for the ESA funded parts of the mission comes from the mandatory contributions of the member states to the ESA science programme. The ESA agreement is that most of these contributions are returned to the member states as contracts to their industry or knowledge institutes for providing hardware. The funding for the payload is generally provided by the national funding agencies. In case of the eLISA mission, the separation between spacecraft and payload is not completely obvious and will be determined in the near future by negotiations between ESA, a committee of representatives of the member states and the eLISA consortium. Therefore it is at present not completely clear which potential Dutch contributions will be be ESA funded and for which national funding will be needed. We will play an active role in the ESA payload committee and the eLISA consortium to try to optimise the definition of the payload for the Dutch hardware contributions. Below, we will indicate for each of the potential contributions what the likely and preferred part of the mission is that they are part of.

The second important aspect of space missions is their planning and time line. Below in section C we give details of the time line and the necessary actions in the next years, but here we already want to mention the most important phases: in the next years the mission and the consortium will be finalized. Then the technology for the mission will need to be developed, both for the spacecraft and the payload. Only after the technology has been sufficiently developed can the final mission be approved and implemented. This means that despite the launch and bulk of the financing necessary in the rather far future, this project already now is gaining momentum.

2.5 Status of potential Dutch hardware contributions

The status of the different potential Dutch hardware contributions is quite diverse and only a short description will be given here. For several contributions we indicate the Technology Readiness Level (TRL). The TRL is a measure of technical maturity of instruments or sub-systems, as used by ESA and other Space Agencies. It ranges from 1 to 9, with 1 being only the basic concept, and 9 the level of instrumentation that has actually flown on a spacecraft. In the early phase of a space mission development program, technology should be at level 4 or higher.

2.5.1 Phase meter

Nikhef has a strong scientific motivation (expressed elsewhere) to contribute to eLISA. Nikhef is involved in the search for GW and has gained extensive expertise in developing technology for the Advanced Virgo laser interferometer. Especially it's expertise on angular alignment of core optics and adaptive optics such as phase cameras can be applied for eLISA. Nikhef has designed and produced all RF and DC quadrant photodiode modules necessary to sense and control the alignment between the optics of Advanced Virgo. Phase cameras provide accurate images of the spatial distribution of amplitude and phase of the laser fields, and are of paramount importance for the active compensation of the aberrations of the transmissive optics of the interferometer.

Nikhef proposes, in collaboration with AEI Hannover, to deliver frontend opto-electronics of the eLISA phase meter, including sensors, trans-impedance amplifiers, heat management in vacuum, and digital demodulation. To deliver flight hardware and ground support equipment for the phase meter, a close collaboration with SRON is crucial.

2.5.2 Mechanisms

The different opto-mechanic mechanisms developed by TNO are

- *In-field pointing mechanism (IFPM, Fig. 7)* is a mechanism to correct for small changes in the angle between the arms in the triangle. It is part of the optical bench and consists of a mirror guided by a Haberland hinge, a nanometer-resolution encode and piezostepper actuators. It is already at quite high technology readiness level (5) and needs little further technology development. Due to its position on the optical bench it could be classified as payload, but due to its function for the overall configuration it would be preferably classified as spacecraft. That would also make sense because the alternative technology, i.e. to physically adjust the angle between the two telescope tubes, clearly classifies as spacecraft.

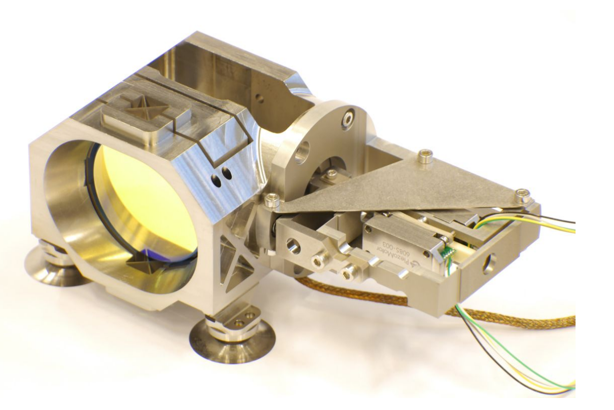


Figure 7: Picture of the IFPM . The IFPM consists of a mirror guided by a haberland hinge, a nanometer-resolution encoder and piezostepper actuators. The IFPM can do beam steering by steering a single mirror ±2.5° with extremely high accuracy. Picture TNO.

- *Point Ahead Angle Mechanism (PAAM)* is a mechanism to correct the direction of the transmitted light due to the time delay in the interferometry arms. The PAAM concept is based on a piezo-stack actuated rotatable mirror, whose extreme dimensional stability is achieved by manufacturing a monolithic Haberland hinge mechanism. Extreme thermal stability is realized by placing the thermal centre on the surface of the mirror. The mechanism is already at mature technology readiness (6) and little costs are needed for further development. Similarly to the IFPM, it would preferably be classified as spacecraft.

- *Fiber Switching Unit Actuator (FSUA)* is the actuator of the Fiber Switching Unit. Its aim is to allow the optical bench to switch between two separate laser sources, one a redundant backup for the other. The lasers, and fiber feeds to the optical bench should be separate to give the maximum possible levels of failure robustness. It is a high technology readiness (5-6) and needs little technology development. It would be part of the payload.
- *Active Aperture Mechanism (AAM)* is a mechanism to move a small optical aperture in-plane. This is a small TNO project, executed as subcontractor for a large Aibus/Astrium GmbH project. It is in the early phases of development, at low technology readiness level (2), but would need only limited further development. Classified as payload.

2.5.3 Telescope

- Design work for the telescope is needed, because the currently foreseen off-axis telescope still has to be optimized. This clearly would be part of the spacecraft and whether this is a viable Dutch contribution depends a lot on the choices for the telescope provider (potentially a US contribution).
- *LISA Telescope Assembly-structure testing* is a current TNO activity for testing the stability of the structure that holds the telescope primary and secondary mirrors. The telescope is exposed to cold space on one side and the warm spacecraft on the other side. In a dedicated thermal vacuum chamber the thermal position deviation of this large structure is tested. It is at high technology readiness level and because the telescope is most likely classified as spacecraft, its testing would naturally also be classified as such.

2.5.4 System level

- NOVA has a strong scientific motivation to contribute to eLISA. This is expressed in its involvement in VIRGO and Electro-Magnetic follow-up studies of gravitational waves, such as BlackGEM. NOVA has extensive experience in technology development and development of scientific instrumentation that is used in the James Web Space Telescope, the European Extremely Large Telescope and other large facilities. NOVA key expertise is in the translation of science requirements to technical specifications and in system engineering regarding the trade of between extremely accurate passive components and active controlled systems with the required calibration methods. Furthermore NOVA intends to contribute its expertise in design, manufacture and test of these integrated systems.

2.5.5 Laser

- U Twente is developing a stable, hybrid-integrated semiconductor external waveguide laser that may serve as a laser for eLISA. Its technology is well developed in a laboratory environment, but not yet space qualified. For the further development significant funding is needed. However, it most likely would be ESA funded as spacecraft.

2.6 Challenges and risks

There are a number of challenges and risks that we are facing and that need attention in the next few years, even though the launch of eLISA is still far in the future

- *Securing the optimal Dutch hardware contributions to eLISA.* Determining the exact division of the payload components between the different partners in the hardware consortium and fitting these to the available expertise and budgetary boundary conditions will be a complex puzzle. This is even more so, because for the eLISA mission, the division between payload and spacecraft is not obvious. This means an additional ingredient to the puzzle of the payload division. There is a baseline that has been agreed between ESA and a number of the member states from the NGO proposal several years ago. Nevertheless, changes to that plan will be necessary, to accommodate new parties (such as the Netherlands, Portugal and Belgium) as well as the new time line for the mission with a launch in 2034. ESA has announced the plan to convene a "payload definition" committee, with representatives from all interested member states, to solve this puzzle. The Netherlands will be represented in this committee and together with the whole eLISA-NL consortium we will work towards securing optimal division between payload and spacecraft and a good payload contributions for the Netherlands.

- *Realising technology development* of the Dutch hardware components, and similarly important, *consolidating of the new collaborations* between the different eLISA-NL hardware partners that are needed to make the Dutch contribution a success. Once the outlines of the Dutch hardware contribution appear, it will become clear which technology development is needed for these contributions. Because some of these contributions, in particular the one to the phasemeter, concern new collaborations, it will be a challenge to find the optimum organisational structure as well. These challenges are exacerbated by the time line of these technology developments. Because of several reasons, the ESA Gravitational Observatory Advisory Team, has recommended an early start of the development of the mission, with the aim to demonstrate technology readiness already in the early 2020s. Especially for SRON, this is a challenging time line, because of the ongoing efforts for the ESA L2 Athena mission. For that reason NOVA will step in to undertake technical R&D studies to make sure that technical readiness is reached in time. We will play an active role in the payload definition committee as well as in the eLISA consortium board to ensure that the time line of the technology development is compatible with the Dutch boundary conditions. In conclusion we need to undertake several technical R&D project between 2017 and 2021 to assure that technical readiness is achieved before the Netherlands makes firm commitments to payload contribution. Finding funding for the R&D activities is still a challenge. We will further discuss funding opportunities with the Netherlands Space Office (NSO) and NWO, as well our own organisations
- *LISA Pathfinder failure.* Although Pathfinder has been successfully launched, the most crucial parts of the technology demonstration, i.e. the GRS, the metrology system components and the dragfree control will only be tested when the test masses are released and the interferometry system is switched on. The test mass release is scheduled for mid February 2016 and the in orbit operations are planned to start early March 2016. It will likely take several months before the first results become known. Obviously, if one of the subsystems would show serious problems this could impact the schedule of the ESA L3 mission.

B.3 EMBEDDING

3.1 Place in (international) landscape of facilities

The ESA L3 mission is one of the flagship missions of the Cosmic Vision program and the only space GW mission planned worldwide. It is part of a suite of GW detectors and experiments aimed at uncovering the different frequency bands of the GW spectrum (see sect. 1.3). Its scientific aims cover major open questions in astronomy and physics, as identified in many national and international strategic plans [8][9][10][11].

Within the Netherlands the GW efforts are part of the emerging field of astroparticle physics, which is coordinated by the Committee for Astroparticle physics in the Netherlands (CAN)[4]. This field bridges the scientific disciplines of Astronomy and Physics and deals, apart from GWs, with Cosmic Rays, Gamma-rays, Neutrino's and Dark Matter. FOM has supported these topics with several FOM programmes and NWO-EW recently awarded a multidisciplinary Astroparticle Physics program (WARP). Since 2011 we yearly organise a Dutch Gravitational Wave meeting in which the different groups involved in GW research meet and report on their ongoing activities.

4 http://www.astroparticlephysics.nl/

The eLISA-NL consortium will coordinate the Dutch participation in the eLISA mission and will be open for Dutch scientists, guaranteeing national access to the early (proprietary) data and guaranteed science return awarded to the payload consortium.

The eLISA activities have had and will have strong **synergy** with the activities related to the ground-based detectors **Virgo** and in the future **Einstein Telescope**. This has been the case in the FOM programme Gravitation Physics and will continue in the future. The synergy will work on three different aspects

- There is already synergy between the *hardware* developed by Nikhef for the Virgo detectors and the proposed hardware contribution to the phasemeter.
- There is significant synergy between the data analysis efforts between Virgo, Einstein Telescope and eLISA.
- There will be synergy between the science of Virgo, Einstein Telescope and eLISA, in particular in some of the fields that have specific Dutch scientific interest: i) testing GR (which can be done for different objects and object classes between the two facilities), ii) compact binaries (where the source population of eLISA and the LIGO/Virgo and Einstein Telescope mergers are the same) and iii) Early Universe science (where the two different frequency ranges probe different energy scales)

We also foresee synergy with the **Pulsar Timing Array** (PTA) activities, not so much on the hardware, but on the scientific exploration of super-massive black hole populations. In particular, with PTAs the high-end of the super-massive black hole mass distribution will be studied at low redshifts. As mentioned before, by combining PTA GW observations with eLISA, super-massive black-hole binaries will be studied at different evolutionary stages when probing different parts of the GW spectrum.

A PTA will test General Relativity in the radiative regime by investigating the polarisation properties of GWs and constraining the mass of the graviton. Also, by measuring GWs from cosmic strings the Early Universe will be probed at different energy scales compared to eLISA and LIGO/Virgo.

3.2 How does the facility match with strengths of Dutch research?

The science of eLISA aligns very well with several strengths of Dutch research, both in astronomy, physics and in instrumentation.

NOVA is the national top research school in Astronomy, rated “exemplary” in the most recent evaluation round. It coordinates the Dutch astronomy research and graduate education and is the knowledge institute that develops high-tech astronomical instrumentation. Its research is focused in three networks and the eLISA science features prominently in Network 1 (origin and evolution of galaxies from high redshift to the present) and Network 3 (Astrophysics in extreme conditions). The eLISA-NL consortium has members from all three networks. On the instrumentation side, NOVA has been involved in space instrumentation and data management (JWST, Gaia, Euclid) and has had (co-)PI roles in several optical/IR instrument for the European Southern Observatory VLT telescope, such as X-Shooter, Sphere, Matisse. It is the PI institute for the future E-ELT Metis instrument.

Nikhef is the National Institute for Subatomic Physics that coordinates the particle physics and most astroparticle physics activities in the Netherlands. In particular it coordinates all activities for the Virgo experiment and the Einstein Telescope. The GW group and the Detector R&D groups were awarded the highest rankings in the last international evaluation of the NWO institutes (2011).

As described above, the *cosmology community* in the Netherlands is currently actively building a new cohesive structure to stimulate and foster collaborations between the physicists and astronomers.

SRON is the Netherlands Institute for Space Research and was given the highest ranking by the most recent international evaluation in 2011. SRON’s mission is to bring about breakthroughs in international space research. The institute develops pioneering technology and advanced space instruments, and uses them to pursue fundamental astrophysical research, Earth science and exoplanetary research. As national expertise institute SRON advises the Dutch government and coordinates – from a science standpoint – national contributions to international space missions. SRON has a long time heritage in the development of space instrumentation, with recent PI and co-PI roles in missions like Herschel-HIFI, ASTRO-H, and Athena-XIFU. Development of electronics flight hardware is well in line with the expertise present at SRON. Besides the formal aspects of the development of flight hardware (Space Systems Engineering, Qualification, Product Assurance, Quality Assurance), the current expertise at SRON in high-frequency Digital Signal Processing has substantial overlap with the core read-out electronics of eLISA.

The science of eLISA features prominently in the new Dutch science agenda (wetenschapsagenda[5]), in particular questions 129 "What is the nature of Gravity, Space and Time and what can we learn from black holes?", 127 "What is the origin, history and future of the Universe?", 131 "What is the origin and evolution of galaxies, stars and planets?" and 132 "How can we use telescopes and space missions to understand the Universe and explore the Solar System?". These feature in three of the 16 example routes: "Building blocks of matter and the nature of space-time", "The origin of life, on Earth and in the Universe" and "Big data: searching patterns in large data files".

C.4 ORGANISATION AND FINANCES

4.1 Organisation

The project is closely connected to the European eLISA consortium, that has submitted the "Gravitational Universe" white paper to ESA which led to the selection of the L3 mission. The eLISA consortium also contains most of the partners of the LISA Pathfinder consortium and will form the L3 payload consortium. This consortium consists of a hardware section, a data analysis working group and six science working groups, one of which is led from the Netherlands. Since several years, there is a representative of the Netherlands on the consortium board and one of the board meetings has taken in Amsterdam.

The Dutch eLISA-NL consortium also consists of a hardware section and scientists. There are close contacts between the eLISA-NL partners and several other European institutes and companies that will contribute to the mission hardware, in particular with the Albert Einstein Institute in Hannover, Astrium and Airbus. Within the eLISA-NL consortium Gijs Nelemans (RU) and SRON have taken on the coordinating role of the potential Dutch hardware contribution. With TNO, SRON, Nikhef, UTwente and NOVA on board all the necessary expertise is present in the eLISA-NL consortium for a significant hardware contribution to the mission. At the same time, we are still actively looking for other partners that want to join the efforts.

On the science side, the eLISA-NL consortium is strongly connected to the scientific community through NOVA and Nikhef, thus reaching the astronomy and particle physics communities. In addition, the theoretical physics and cosmology community is also involved and currently, all six universities with physics or astronomy groups are represented in the eLISA-NL consortium.

The eLISA-NL consortium so far has had its scientific exchanges via the science working groups of the eLISA consortium and via the Dutch Gravitational Wave meetings. A series of meetings focussed on the potential Dutch hardware contributions has taken place since December 2013.

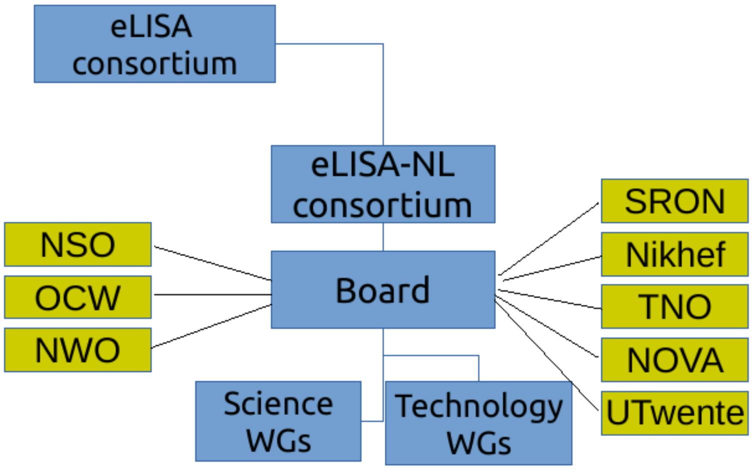
In the near future, we plan to move to a slightly more formal structure in the eLISA-NL consortium, in order to be ready to contribute to the payload definition, the proposal in response to the call for mission and the formation of the final eLISA payload consortium.

Structure of organisation

We envision an organisation that consists of science and technology groups, coordinate by an eLISA-NL consortium board. The main tasks of the consortium board will be to interface with the European eLISA consortium with ESA, with the different institutes and universities that take part in the eLISA-NL consortium as well as with the funding agencies. It will also coordinate the scientific and

5 https://vragen.wetenschapsagenda.nl/home

technology groups. In addition, the board will coordinate the outreach and communications of the eLISA-NL consortium, including setting up an eLISA-NL website. Below is a schematic structure of the consortium



4.2 Finances

Based on the different possible hardware contributions we have made a rough estimate of the costs for the development and construction of the different possible hardware contributions. For development cost, we used estimates for the R&D development in the next 5 years that is needed to bring the items to sufficient technological matureness that they can be included in the mission design (phase A). It is not yet clear which parts will in the end be realised as Dutch hardware contributions, but these numbers should give some indication to the cost of the project. In the appendix the origin of these rough estimates is given, together with an overview of the technological matureness of the items. For the exploitation of the project we do not need to budget running cost as these are all included in the ESA budget. Of course there will be significant cost associated with the scientific exploitation of the mission, but these will have to be brought in by the scientist that want to use the data. Below we give a very rough estimate, based on the number of senior scientists in the consortium (27), assuming they will each have 1-2 PhD students or post-docs.

Costs

Note, all estimates are on top of modest in kind contributions of institutes and the range given includes margin and uncertainties in the final items that will consist the Dutch hardware contribution.

1. Technology development: ~4-6M€
2. Construction (Dutch contribution): ~20-55M€
3. Exploitation (science exploitation): ~8M€

Business case.

The technology development will be partly paid by ESA, but part of if will have to be obtained by the consortium from Dutch funding opportunities (see sect. 2.6), such as NWO-G or NL technology development funds. For the construction of the Dutch hardware contributions part will be ESA funded, part will have to be financed from the Roadmap. In the most ambitious case, where all the potential contributions are realised, additional sources of funding (either from government or industry) will have to be found. Finally, as described above, the science exploitation will have to be brought in via national (NWO, Universities) and European (EU, ERC) budgets and grants.

D.5 FURTHER DEVELOPMENT

The next steps the process needed in the coming years to realise this facility are the following.

1. We will have to play a very active role in *payload definition.* This will be dome by a newly formed ESA committee, in which we will have one or two representatives. The main aim of our efforts is to optimise the definition of the division of spacecraft (ESA funded) and payload (member state funded) items. In addition, this committee will already make an inventory of the possible division of the payload subsystems between the member states.
2. Based on the outcome of the payload definition committee, we have to *secure Dutch hardware contributions in consortium* in such a way that we will optimally use the Dutch expertise and at the same time ensure effective collaboration and interfaces between the different payload consortium partners.
3. In parallel we have to *make a technology development plan for NL* and obtain funding for it within the Netherlands and streamline the interactions between the different eLISA-NL partners and the overall coordination of the hardware section of the eLISA-NL consortium.
4. This also means that we will have to move to a *more mature organisation of eLISA-NL consortium* that will be ready to represent the Dutch involvement in eLISA, for the people in the consortium, toward the (inter)national partners and to the funding agencies and the public in the Netherlands.
5. On a longer time scale we need to consolidate the NL contributions and obtain funding for it, work towards optimal calibration and data analysis and towards the science exploitation of the mission.

The **time line** for the facility is:

- Payload definition: 2016
- Call for mission: 2016
- Payload consortium consolidation: 2018
- Technology development: 2016-2024
- Mission adoption: 2024
- Construction: 2025-2034
- Scientific operations: 2034-2036/39

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