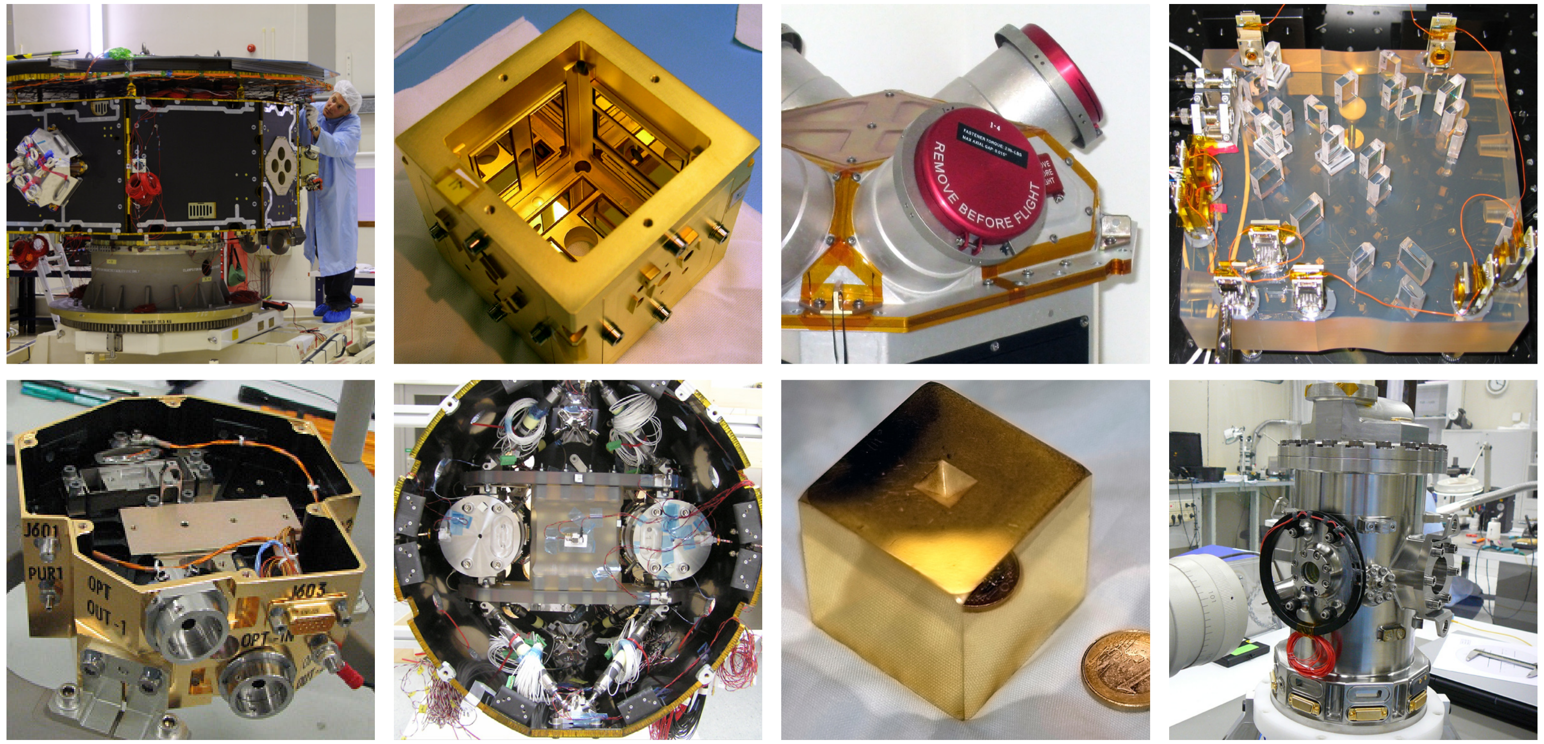
LISA Pathfinder Mission



LISA Pathfinder, an ESA-led technology mission, will demonstrate that test masses can be maintained in a condition very close to free fall, as needed to measure gravitational waves, and will confirm our understanding of their spurious accelerations. Much of the flight hardware is directly usable in any GW mission. Future gravitational-wave missions will be able to use and improve the LISA Pathfinder flight hardware.

From the top left, clockwise: side view of LISA Pathfinder sciencecraft (Astrium/ESA), test-mass housing (Thales Alenia Space/INFN), colloid thruster (Busek/JPL), optical bench (University of Glasgow/STFC), vacuum enclosure (Carlo Gavazzi Space), platinum-gold test mass (Thales Alenia Space/ASI), payload qualification model (Astrium/ESA).

The low-frequency band (0.0001–1 Hz) of the gravitational wave spectrum hosts a rich collection of astrophysical sources. The Laser Interferometer Space Antenna (LISA) was studied and developed by NASA and by ESA, the European Space Agency, as the reference mission to cover this science for over 20 years. Although highly ranked in the 2010 National Academies Decadal Survey for its compelling science, tight budgets have forced NASA and ESA to consider lower cost reformulations of this mission concept. The two agencies have conducted separate mission studies that considered various options according to cost, risk, and technical readiness. For NASA, the studies also looked at the ability to address the science goals endorsed by the Decadal Survey. In Europe, the study concentrated on a mission concept for the first large mission in ESA's Cosmic Vision long-term plan.

NASA study final report:
http://pcos.gsfc.nasa.gov/studies/gravitational-wave-mission.php

ESA assessment study report:
http://elisa-ngo.org/resources/documents/document-yellow-book

Representative mission parameters for eLISA/NGO and SGO-Mid

Frequency range	10^{-4} to 1 Hz
Measurement concept	Laser metrology between six drag-free test masses on three spacecraft
Mission	
Orbits:	Independent heliocentric orbits trailing Earth by 20° end of life
Configuration:	Equilateral triangle with 106 km arms, inclined at 60° to the ecliptic
Duration:	Two years science operations
Science Payload (on each spacecraft)	
Lasers:	Two 2-W, 1064 nm frequency pre-stabilized to 280 Hz/√Hz
Test masses:	Two 46 mm, 2-kg Au-Pt cubes
Telescopes:	Two 20–25 cm dia, f/1.5, λ/30
Science	
Data Volume:	Approx 12 Gb/year
Sources:	Massive black hole binaries (MBHBs), compact galactic binaries, extreme mass-ratio inspirals (EMRIs)
Source localization	Arc-minutes to 1 deg, source dependent

Both studies concluded that small reductions in cost result in large reductions in science return. Nonetheless, they found it possible to define a mission with acceptable risk and science return at lower cost than the baseline LISA. One of the missions studied by NASA is known as Space-based Gravitational-wave Observatory (SGO-Mid). The ESA mission, the New Gravitational-wave Observatory (NGO), or evolved-LISA (eLISA), is similar. Representative mission parameters are listed in the table. Both mission concepts are largely scaled-down versions of the original LISA mission concept.

The three spacecraft are launched together and cruise to a solar orbit, where they settle into a triangle with million-km arms. Gravitational waves are measured by using laser interferometry to monitor the distance fluctuations between freely falling reference masses. Very high precision, low-noise thrusters keep the spacecraft hovering around the masses, protecting them from external disturbances while allowing them to respond to gravitational waves.

National Aeronautics and Space Administration

Goddard Space Flight Center
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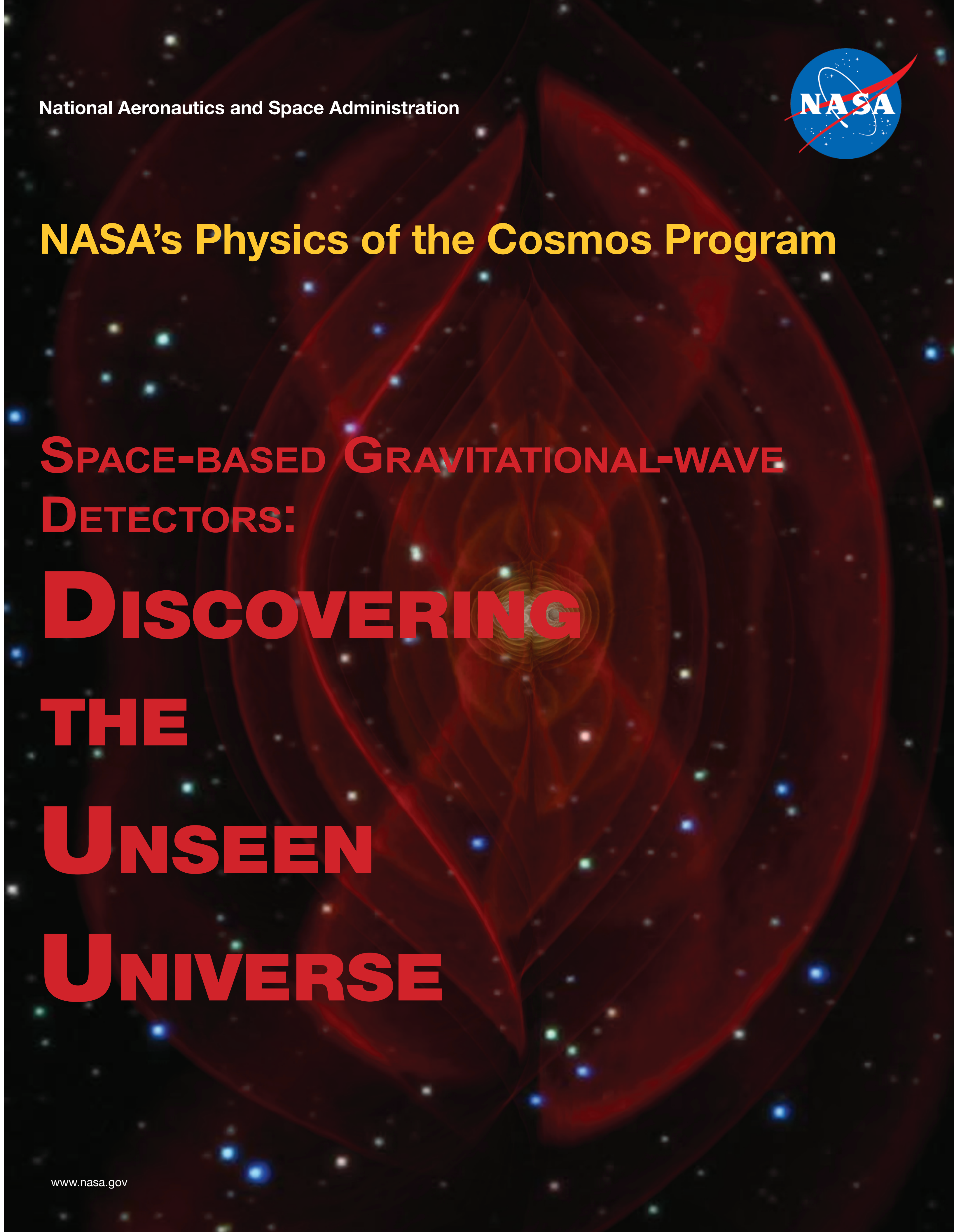
NP-2012-12-361-GSFC

Image credits: Cover: Three-dimensional numerical relativity simulation of gravitational wave emission from a pair of merging black holes with equal masses. Credit: Henze, NASA; Pages 2–3: Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Potsdam, Germany, and Milde Science Communication (LISA animation stills); S. Phinney (mass-transferring Galactic binary); Caltech/Cornell numerical-relativity group (black-hole binary simulation); R. Battye & E. P. Shellard (string simulation); A. M. Srivastava (liquid crystals).



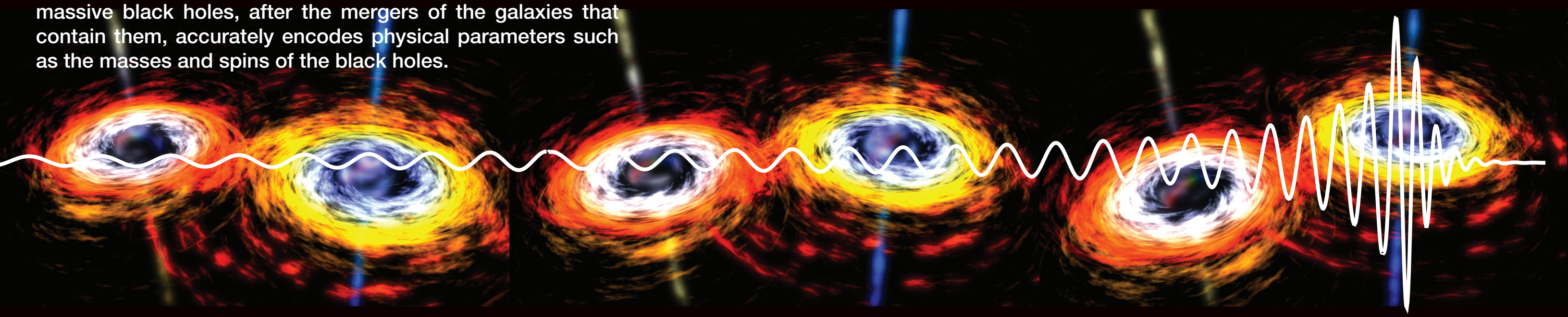
National Aeronautics and Space Administration

NASA's Physics of the Cosmos Program

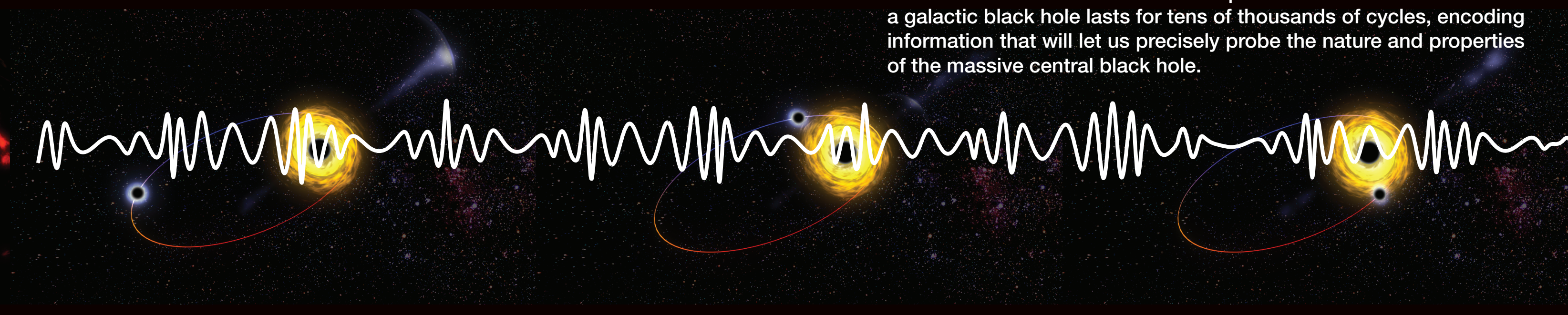
Space-based Gravitational-wave Detectors:

Discovering the Unseen Universe

www.nasa.gov



The gravitational waveform from the coalescence of two massive black holes, after the mergers of the galaxies that contain them, accurately encodes physical parameters such as the masses and spins of the black holes.



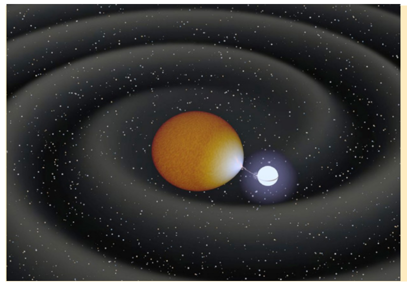
The waveform from the eccentric inspiral of a stellar remnant toward a galactic black hole lasts for tens of thousands of cycles, encoding information that will let us precisely probe the nature and properties of the massive central black hole.

Gravity is talking.
We will listen.

> “A low-frequency gravitational-wave observatory would open an entirely new window on the cosmos by measuring ripples in space-time caused by many new sources. [...] It would be unprecedented in the history of astronomy if the new gravitational-radiation window does not reveal new, enigmatic sources.”
>
> National Academy of Sciences Astro2010 Decadal Report

Einstein’s theory of general relativity predicts that accelerated masses produce **gravitational waves**, perturbations of spacetime that propagate at the speed of light and are virtually undisturbed by intervening mass. Their measurement will add a new sense to our perception of the Universe, providing rich and unique information about its behavior, structure, and history.

Space-based detectors will target gravitational waves of frequency between 10^{-5} mHz and 1 Hz. This band is inhabited by a **wide range of sources**, such as: the massive black holes merging at the centers of distant galaxies; the inspirals of compact objects into central galactic black holes; the binaries of compact stars in our Galaxy; and, possibly, the gravitational-wave relics from an extremely short time after the Big Bang.



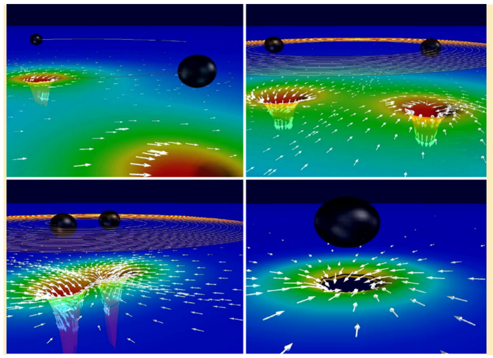
Space-based gravitational-wave detectors will study thousands of compact binaries and their place in the Galaxy.

They will compile a catalog of several thousand individual systems, and will measure distances and accurate orbit and mass parameters for hundreds of short-period systems.

The dominant gravitational-wave contribution in the low-frequency band comes from **short-period binaries of compact stellar objects** (white dwarfs, neutron stars, black holes, and naked He stars), predominantly from the millions of such systems in our Galaxy, but also from more distant sources.

The accumulated signal from a few known **verification binaries** will stand out as the only sources in the entire field with known optical counterparts, and will provide the first validation that the observatory is operating correctly. In addition, a sufficiently sensitive mission will individually observe **several thousand unknown binaries**, those closest to us or with frequencies above 3 mHz (i.e., orbital periods shorter than 10 minutes).

This **Galactic census** will give us unprecedented insight into the evolution of close binary systems and of the progenitors of some types of supernovae, neutron stars, and black holes. It will also provide rich information about tidal interactions and other non-gravitational effects that are associated with the internal physics of the stellar remnants.



Space-based gravitational-wave detectors will record the inspirals and mergers of binary black holes throughout the Universe.

They will observe tens to hundreds of coalescing massive black-hole binaries, measuring their masses to an accuracy of 0.1%, sky positions to a few degrees, and luminosity distances to a few tens of percent.

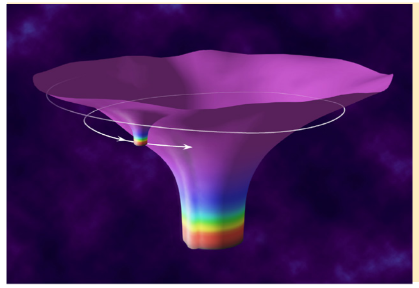
Most galactic centers are thought to harbor supermassive black holes—and as host galaxies merge, so do their central black holes.

Space-based observatories will be sensitive to gravitational waves from the coalescences of black holes with masses between 10^4 and 10^7 solar masses, out to large redshifts (10–20). They will record waves from the final phase (months to years) of their gravitational-radiation–driven **inspiral**; from their violently nonlinear **merger**, the most luminous event in the Universe; and from the **ringdown** phase as the two holes settle into a single, rotating black hole.

These signals encode the masses, spins, and orbital parameters of the binaries, as well as their distance and sky position. Recent breakthroughs in the numerical simulation of black-hole mergers make it possible to compare the measured waves with theoretical models, providing the first detailed **test of strong-field general relativity**.

Indeed, space-based observatories will infer black-hole parameters from tens to hundreds of coalescences, shedding light on the formation and co-evolution of galaxies and their nuclear black holes, and testing the hypothesis of galaxy and black-hole growth by **hierarchical mergers** and accretion. Did the first massive black holes arise from the collapse of supermassive stars, or of heavier gas discs? Did black holes grow mostly by accretion, or by mergers? Gravitational-wave observatories will answer these questions.

Some missions’ designs (those with more than one interferometric readout) would also measure **absolutely calibrated luminosity distances** to the binaries, with precisions of a few percent for close systems in the absence of lensing. If a few host galaxies can be identified from optical counterparts in the ~10 deg² sky-position error boxes, and their redshifts determined, LISA will constrain the redshift–distance relation, calibrating the distance scale and Hubble constant an order of magnitude better than existing methods, with different systematics, since the main source of error is the weak lensing along the line of sight.



Space-based gravitational-wave detectors will map spacetime around massive black holes by detecting the radiation of inspiraling compact stars.

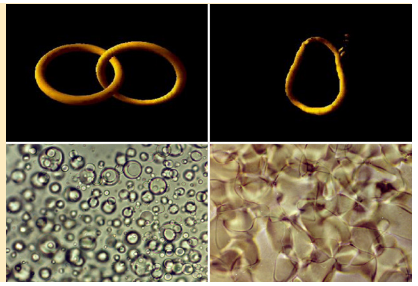
They will measure black-hole masses and spins to one part in 10^4, and test their Kerr nature to 0.1%.

Compact stellar objects in galactic nuclei can enter a region of phase space where their further evolution is dominated by gravitational-wave emission; after a long inspiral, they are doomed to plunge into the central black hole.

The gravitational-wave signals from these **extreme mass-ratio inspirals** encode a detailed map of the warped spacetime that they traverse. If these events are sufficiently frequent, space-based observatories will be able to verify whether galactic centers host rotating black holes, or other exotic objects. These signals will also yield a census of the **masses and spins of galactic black holes**, and of the species of compact objects in the galactic center.

Space-based gravitational-wave detectors will search for the gravitational-wave signatures of the early Universe and for new forms of “dark physics.”

They could detect the stochastic signal from first-order phase transitions, as well as the backgrounds, bursts, and periodic signals from cosmic superstring loops.



The low frequency gravitational-wave band spans the Tera-scale frontier of the early Universe, where phase transitions of new forces of nature or extra dimensions of space may have caused explosive bubble growth and efficient gravitational-wave production. Space-based detectors may detect a stochastic background from such events, emitted at times between 3×10^{-18} and 3×10^{-10} s after the Big Bang, probing new physics in complement to particle accelerators. They will also be sensitive to the radiation from topological defects such as the cosmic superstrings predicted in some versions of string theory.