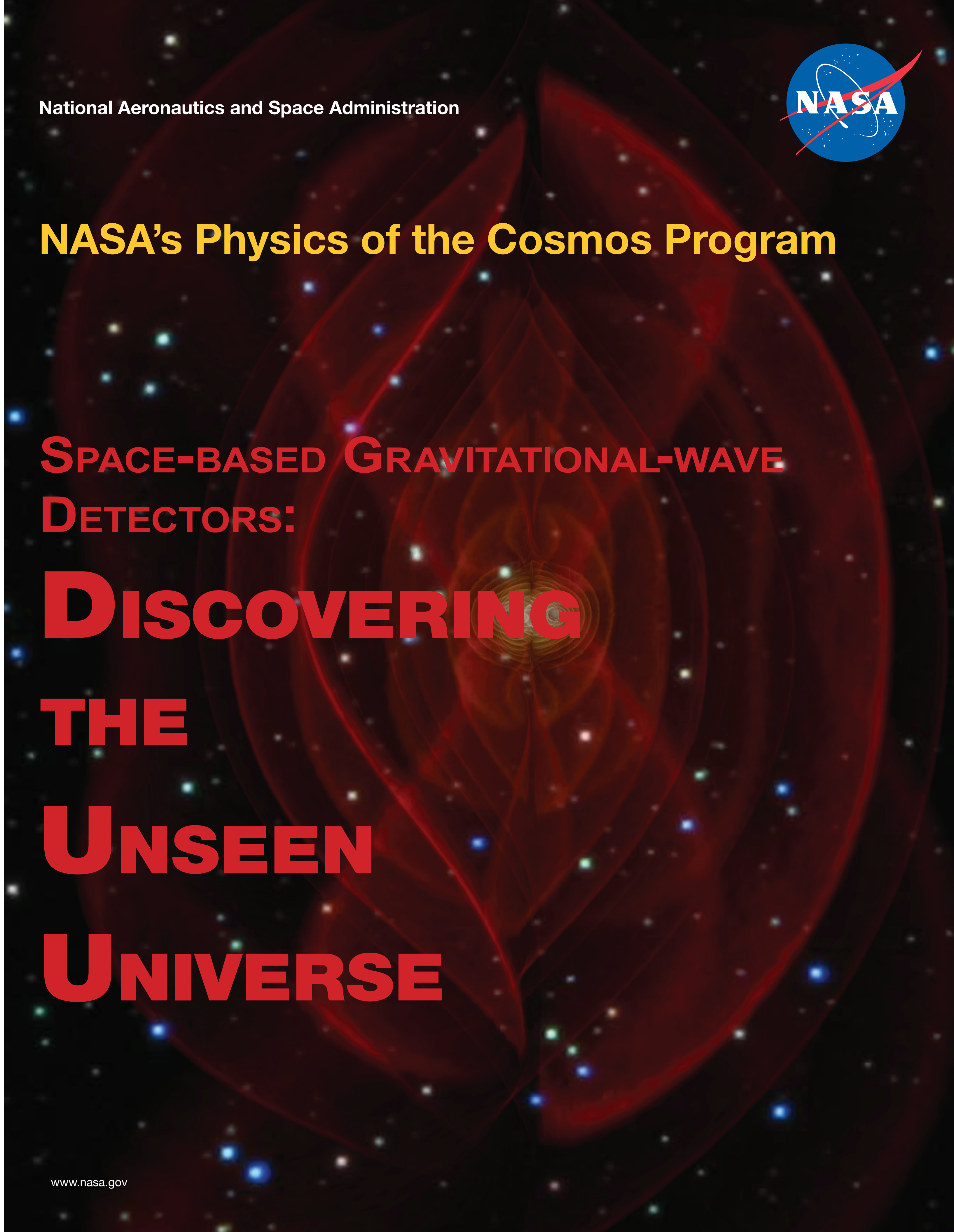


National Aeronautics and Space Administration

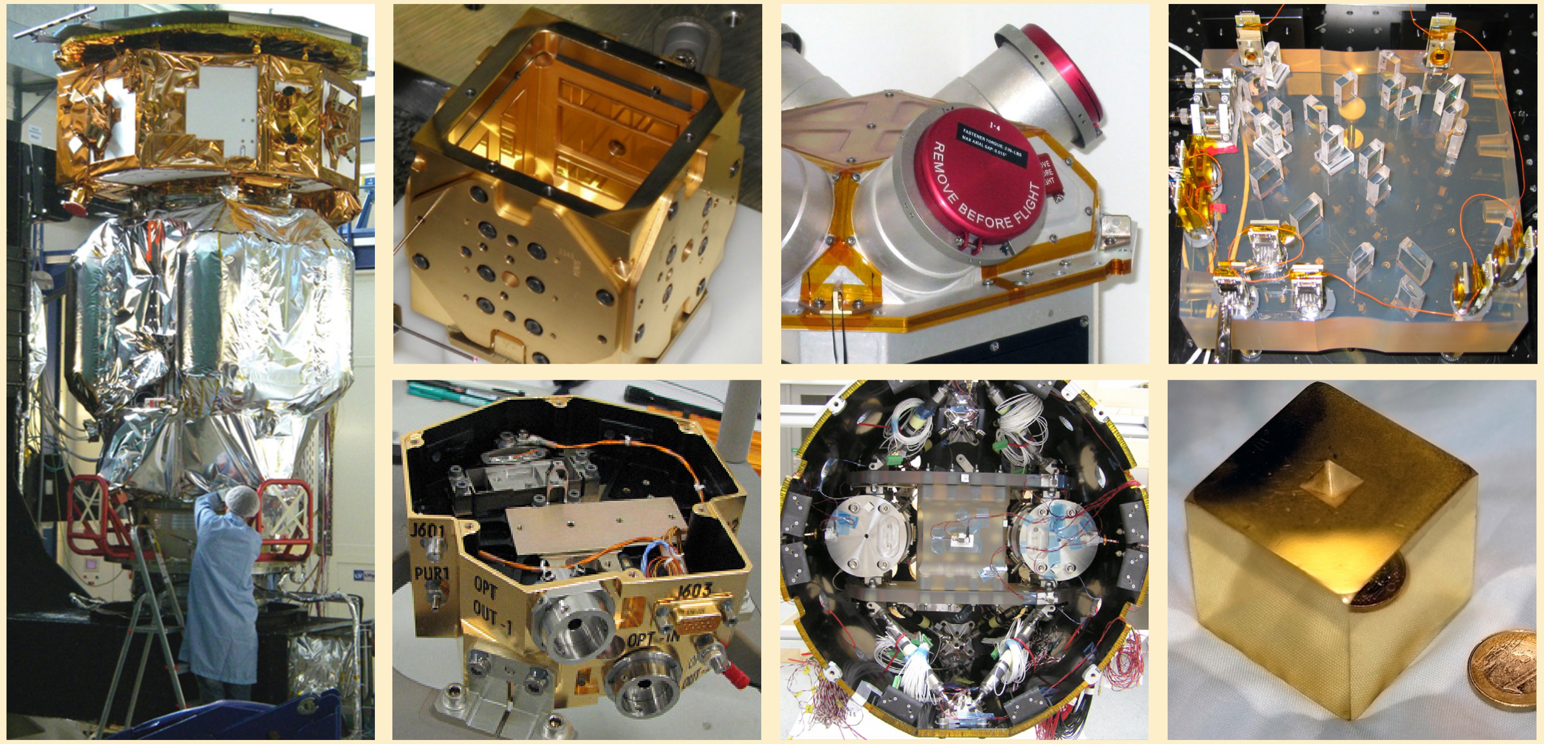
NASA's Physics of the Cosmos Program

# Space-based Gravitational-wave Detectors:

# Discovering the Unseen Universe

www.nasa.gov

## LISA Pathfinder Mission



*From the top left, clockwise: LISA Pathfinder spacecraft and propulsion module being prepared for thermal-vacuum test (Airbus Defence and Space/ESA), test-mass housing (CGS/ESA), colloid thruster (Busek/JPL), optical bench (University of Glasgow/STFC), gold-platinum test mass (Thales Alenia Space/ASI), thermal optical qualification model of the payload core assembly (Airbus Defence and Space/ESA), Acousto-Optic Modulator (RUAG/CNES).*

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 residual accelerations. Much of the flight hardware is directly usable in any gravitational wave mission. Future gravitational-wave missions will be able to use and improve the LISA Pathfinder flight hardware.

The frequency band accessible to a space-based gravitational-wave observatory has a rich collection of strong sources. For over two decades, NASA and ESA studied and developed a concept, called the Laser Interferometer Space Antenna (LISA), to operate in this band. In both the 2000 and 2010 Decadal Surveys, the National Research Council recommended a new start for LISA. However, budget restrictions forced NASA and ESA to separately explore lower cost variants of LISA considering science return, cost, risk, and technical readiness.

NASA has searched for low cost concepts that can carry out some of the NRC recommended science. These concept studies found that small cost reductions lead to large science reductions, but that a lower cost concept with acceptable risk and readiness exists. This LISA-like concept, called the Space-based Gravitational-wave Observatory Mid-Sized (SGO-Mid), can achieve almost all of the science recommended in the 2010 Decadal Survey. Baseline mission parameters are listed in the table to the left.

### Representative mission parameters for SGO-Mid

| Mission | |
|---|---|
| Frequency range | $10^{-4}$ to 1 Hz |
| Concept | Laser metrology between six drag-free test masses on three spacecraft |
| Orbits | Independent heliocentric orbits trailing Earth by 20° end of life |
| Configuration | Equilateral triangle with $10^6$ 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), exotic sources |
| Source localization | Arc-minutes to 1 deg, source dependent |

LISA-like concepts share the following common traits: three spacecraft orbiting the Sun in a naturally triangular constellation with million-kilometer separations, free-falling test masses isolated from their surrounding spacecraft by precision stationkeeping, interferometric laser metrology between the test masses to detect the apparent displacements caused by gravitational waves, and laser frequency noise subtraction in post-processing.

ESA has selected a gravitational-wave science theme for the third large mission in its Cosmic Vision Programme, called L3. Researchers in Europe have developed a LISA-like concept called Evolved LISA (eLISA). It is designed to use the technology developed for LISA Pathfinder shown above and is very similar to SGO-Mid. ESA has named a technical assessment team to review the design options for the L3 mission by 2016. ESA has initiated discussions with NASA about a role in the mission and invited NASA participation in the assessment team.

**European mission information:**
https://elisascience.org

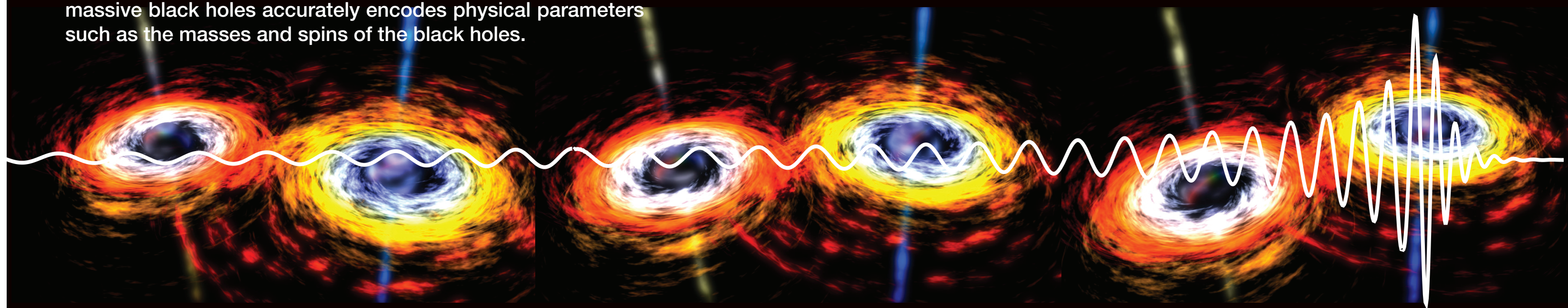
**NASA study final report:**
http://pcos.gsfc.nasa.gov/studies/gravitational-wave-mission.php

National Aeronautics and Space Administration

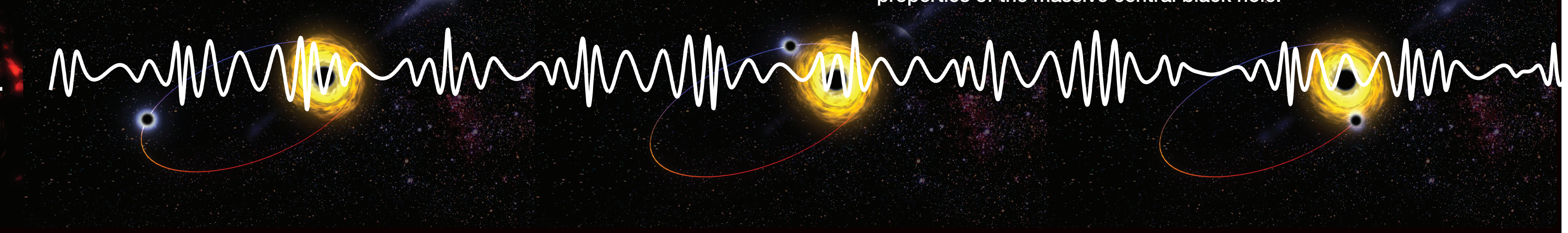
Goddard Space Flight Center
Greenbelt, Maryland

2014-10-195-GSFC

*Image credits: Cover: Three-dimensional numerical relativity simulation of gravitational wave emission from a pair of merging black holes with equal masses. Credit: Chris 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 and E. P. Shellard (string simulation); A. M. Srivastava (liquid crystals).*



The gravitational waveform from the coalescence of two massive black holes 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 supermassive 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.

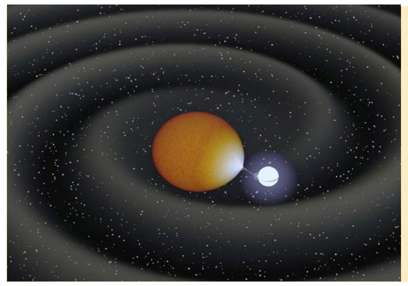
# Gravity is talking. We will listen.

"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**, distortions of space-time that propagate at the speed of light and are largely unaffected 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.

A space-based detector can target gravitational waves with frequencies between $10^{-4}$ and 1 Hz. A wide range of sources inhabit this band, including massive black holes merging at the centers of distant galaxies, compact objects spiraling into central galactic black holes, close binaries of compact stars in our galaxy, and, possibly, gravitational-wave relics from an extremely short time after the Big Bang.



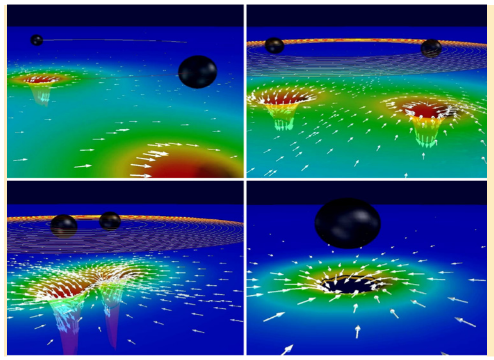
**A space-based gravitational-wave detector will study thousands of compact binaries and their place in our galaxy.**

**Such a detector will compile a catalog of several thousand individual systems and measure distances, 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 helium stars), predominantly from the millions of such systems in our galaxy, but also from more distant sources.

The strong signals 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**—systems that are either close 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 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.



**A space-based gravitational-wave detector will record the inspirals and mergers of binary black holes throughout the Universe.**

**Such a detector 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.**

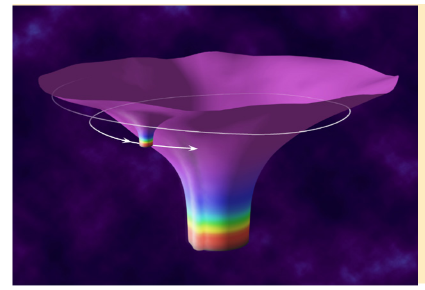
The centers of most galaxies are thought to harbor supermassive black holes—and as host galaxies merge, so do their enormous black holes.

A space-based observatory will be sensitive to gravitational waves from merging black holes with masses between $10^4$ and $10^7$ solar masses out to large redshifts (10–20). It will record waves from the final phase of their **inspiral** (months to years), from the violent, nonlinear **merger**—the most luminous event in the Universe, and from the **ringdown** phase as the two holes settle into a larger, single, rotating black hole.

These signals encode the masses, spins, and orbital parameters of black hole binaries, as well as their distances and sky positions. 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 dynamical, strong-field general relativity**.

Indeed, a space-based observatory will gather black hole parameters from tens to hundreds of mergers, shedding light on the formation and co-evolution of galaxies with their central 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 very massive stars or of heavier gas disks? Did black holes grow primarily by accretion or by mergers? A gravitational-wave observatory will answer these questions.

A mission design that includes more than one interferometer 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 this mission could identify a few host galaxies from optical counterparts in the ~10 deg$^2$ sky-position error boxes and determine their redshifts, it would constrain the redshift-distance relation. This would provide a calibration to the distance scale and Hubble constant an order of magnitude better than existing methods and with different systematics, since the main source of error is the weak lensing along the line of sight.



**A space-based gravitational-wave detector will map space-time around massive black holes by detecting the radiation of inspiraling compact stars.**

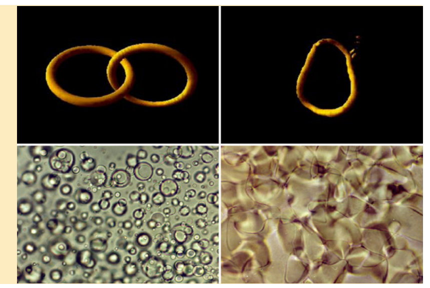
**Such a detector will measure black hole masses and spins to one part in 10,000 and test their Kerr nature to 0.1%**

Compact stellar objects in galactic nuclei can be scattered into orbits about the central black hole, where they are doomed to plunge into the central black hole by gravitational radiation after a long inspiral.

The gravitational-wave signals from these **extreme mass-ratio inspirals** embed a detailed map of the warped space-time that they traverse. If these events are frequent enough, a space-based observatory 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.

**A space-based gravitational-wave detector will search for the gravitational-wave signatures of the early Universe and for new physics.**

**Such a detector 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 might detect a stochastic background from such events, emitted at times between $3\times10^{-18}$ and $3\times10^{-10}$ seconds after the Big Bang, probing new physics not accessible with 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.