THE GRAVITATIONAL UNIVERSE

SCIENCE THEME
ADDRESSED BY
THE **eLISA** MISSION
OBSERVING THE UNIVERSE
IN
- **LOW FREQUENCY GRAVITATIONAL WAVES** -
SELECTED BY ESA FOR L3

THE GRAVITATIONAL UNIVERSE
A science theme addressed by the *eLISA* mission observing the entire Universe

https://www.elisascience.org/whitepaper/

MONICA COLPI
DEPARTMENT OF PHYSICS G. OCCHIALINI, UNIVERSITY OF MILANO BICOCCA
eLISA Consortium Board

TEONGRAV MEETING, ROMA, 4 FEBRUARY 2014

GRAVITY HAS IS OWN MESSENGER

GRAVITATIONAL WAVES

PERTURBATIONS OF THE CURVATURE OF SPACE-TIME
PROPAGATING AS WAVES AT THE SPEED OF LIGHT

●

EMITTED BY ACCELERATED ASTRONOMICAL BODIES
amplitude - phase - polarization of the wave follow the source motion

●

CARRY ENERGY AND MOMENTUM
INFORMATION
ON THE PHYSICAL PROPERTIES OF THE ASTRONOMICAL SOURCES AND OF SPACE-TIME ITSELF

●

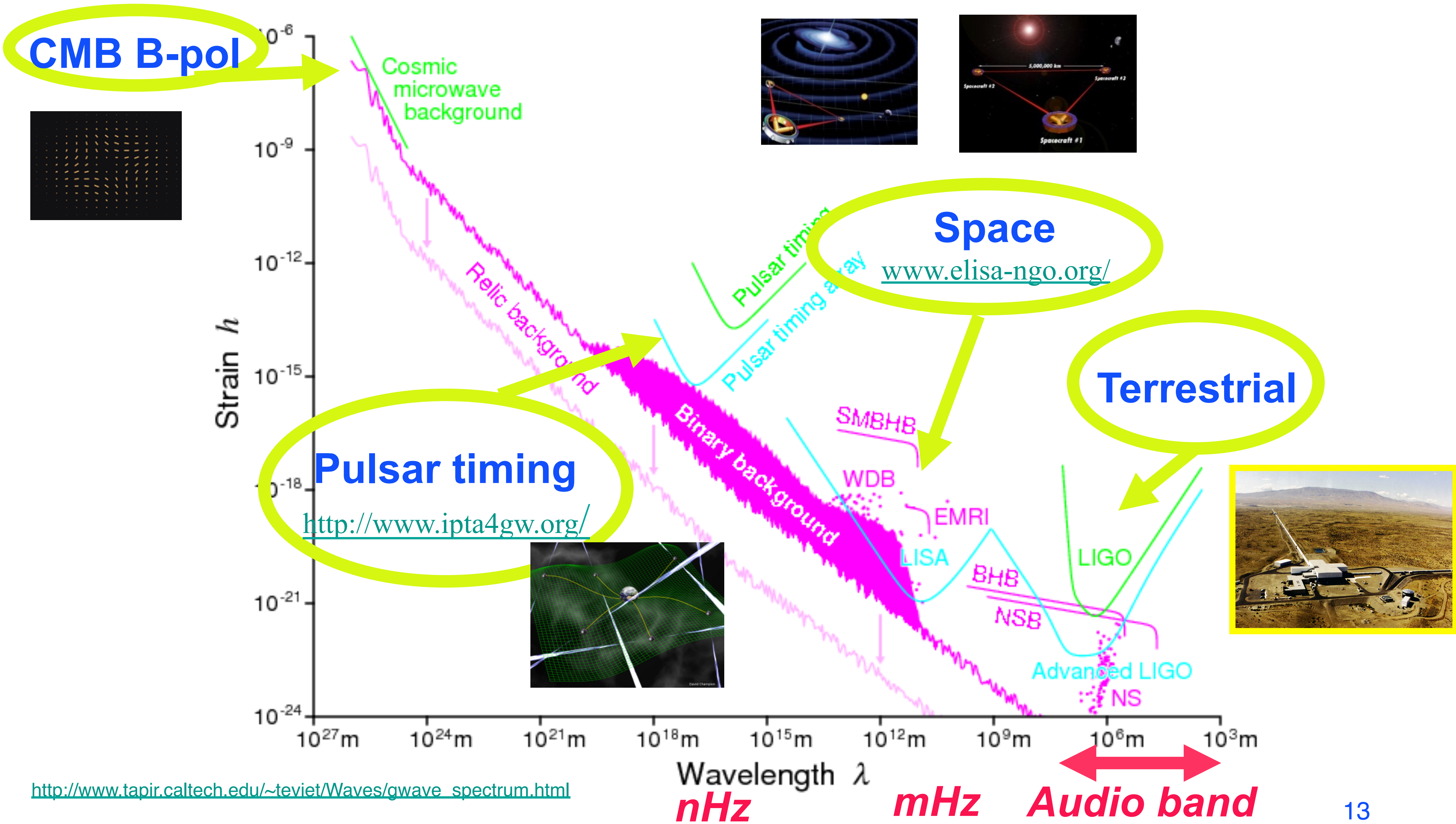
SPACE-TIME IS STIFF - ASTRONOMICAL SOURCES ARE **"COMPACT OBJECTS"**

●

THEY TRAVEL ALMOST UNDISTURBED THROUGH SPACE-TIME
cosmological redshift and lensing

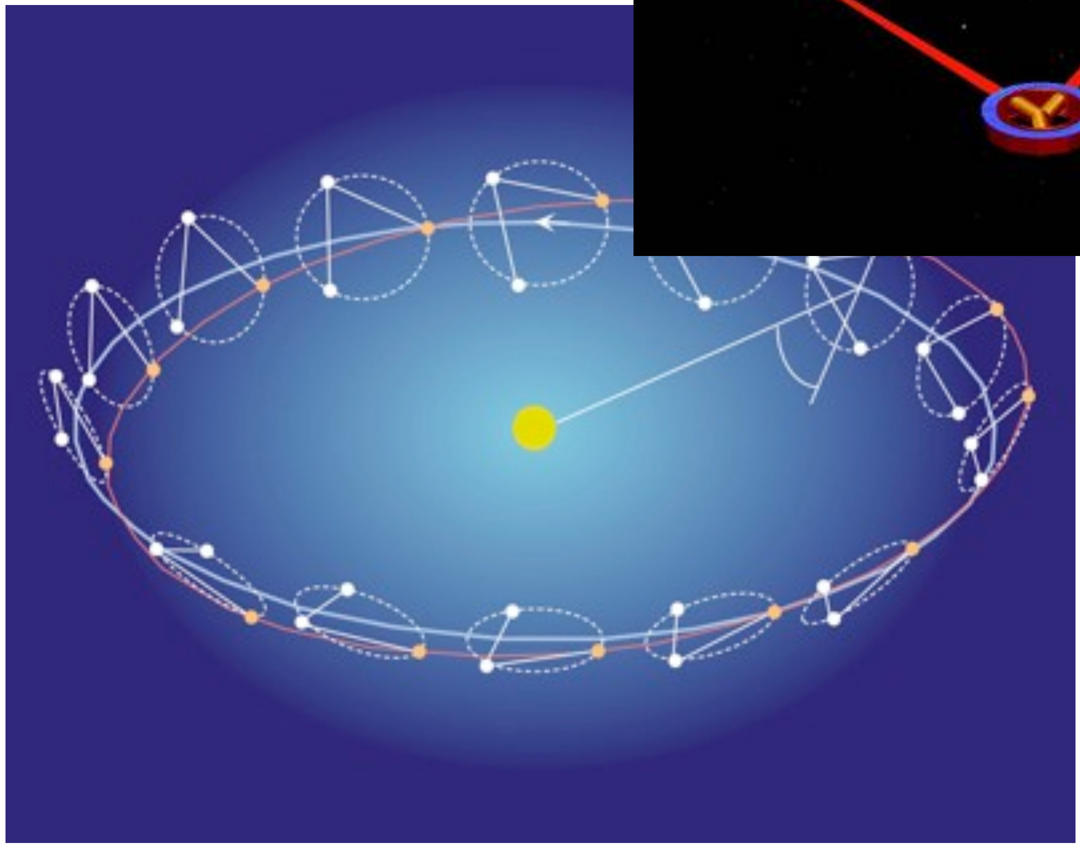
●

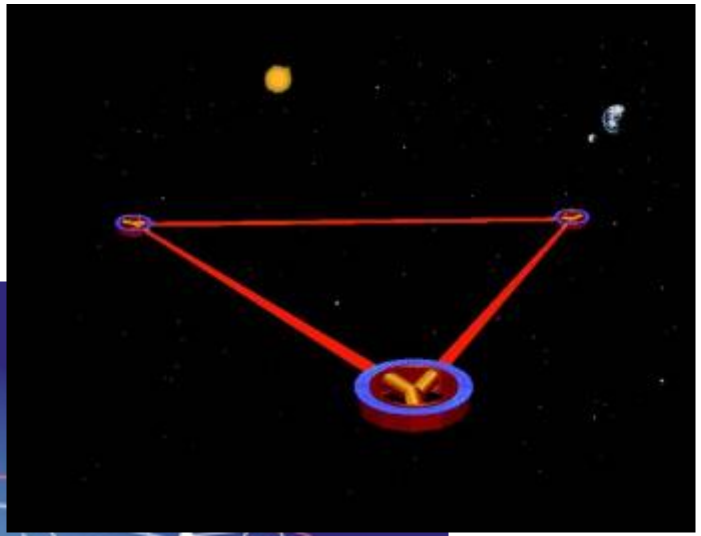
UNIQUE MESSENGERS
TO EXPLORE THE "entire" UNIVERSE



http://www.tapir.caltech.edu/~teviet/Waves/gwave_spectrum.html

Laser Interferometer Space Antenna
mature concept
LISA, NGO, eLISA





* FIRST MISSION CONCEPT STUDIES START IN THE 80s @ JILA
Laser Antenna for Gravitational radiation Observation in Space (LAGOS)

* LISA was proposed to ESA in early 90s first to the then M3-cycle, later as Cornerstone mission to the Horizon 2000 Plus

* The later LISA
3 Spacecrafts in triangular constellation
long baseline (5 Mkm)
cartwheel heliocentric orbit
appear in 1997
joint formulation study
ESA - NASA

* ESA Cosmic Vision 2015-2025 programme in 2005
LISA was identified as a potential candidate for L1

* more than 2000 papers have been published on LISA

comments on this story

Stories by subject

- Policy
- Space and astronomy

Stories by keywords

- European Space Agency
- L-Class missions
- LISA
- IXO
- ESJM-Laplace

This article elsewhere

Blogs linking to this article

Published online 22 March 2011 | *Nature* **471**, 421 (2011) | doi:10.1038/471421a

News

Europe makes do without NASA

US budget crisis forces European Space Agency to abandon plans for joint mission.

Eugenie Samuel Reich

The European Space Agency (ESA) is pushing ahead without NASA support for its next big science mission, as the ongoing US budget crunch and competing priorities impose serious constraints on the US space agency (see *Nature* **471**, 278; 2011). ESA last week told leaders of three large, or 'L-class', missions that are competing for funding to revise their proposals by leaving out the substantial US contribution that had previously been assumed.

"The decision was made very reluctantly," says David Southwood, director of science and robotic exploration at ESA. "NASA could not meet our timetable to launch."

most recent | commented

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  26 April 2011
- Ants team up to stay dry
  26 April 2011
- Nuclear agency faces reform calls
  26 April 2011
- Telescope will track space junk
  22 April 2011
- China hopes research centre can quell food-safety fears
  22 April 2011

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  08 March 2011
- ESA on countdown to flagship mission selection

esa space science

European Space Agency

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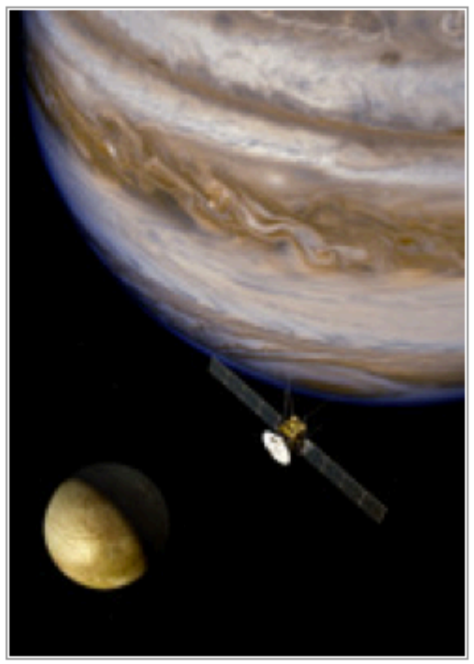
Science missions...

News



Artist's impression of JUICE

JUICE is Europe's next large science mission

2 May 2012

PR 13 2012 - Jupiter's icy moons are the focus of Europe's next large science mission, ESA announced today.

The Jupiter Icy moons Explorer – JUICE – was selected over two other candidates: NGO, the New Gravitational wave Observatory, to hunt for gravitational waves, and ATHENA, the Advanced Telescope for High-Energy Astrophysics.

JUICE is the first Large-class mission chosen as part of ESA's Cosmic Vision 2015-2025 programme.

It will be launched in 2022 from Europe's spaceport in Kourou, French Guiana, on an Ariane 5, arriving at Jupiter in 2030 to spend at least three years making detailed observations.

17-May-2012

More about ESA's Cosmic Vision...
- Defining the Cosmic Vision
- Missions beyond imagination

Related articles
- ESA's Cosmic Vision workshop 2004
- Plans for the future
- How a mission is chosen

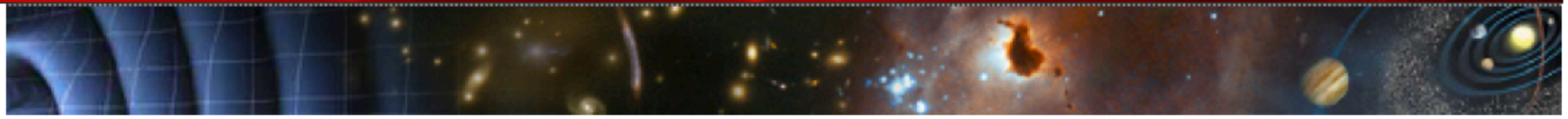
Related links
- More on Cosmic Vision 2015-2025

Cosmic Vision 2015-2025: ESApod
- Cosmic Vision

courtesy by Karsten Danzmann

SCIENCE PORTAL | SCIENCE & TECHNOLOGY | RESEARCH

esa **Cosmic Vision 2015-2025** Science Programme European Space Agency



Cosmic Vision 2015-2025
- Cosmic Vision
- Candidate Missions
- M-class Timeline
- L-class Timeline

The Four Themes
- Planets and Life
- The Solar System
- Fundamental Laws
- The Universe

News

Cosmic Vision Brochure

CHEOPS

EChO

17-Mar-2013 14:21:42 UT

Call for White Papers for the definition of the L2 and L3 missions in the ESA Science Programme

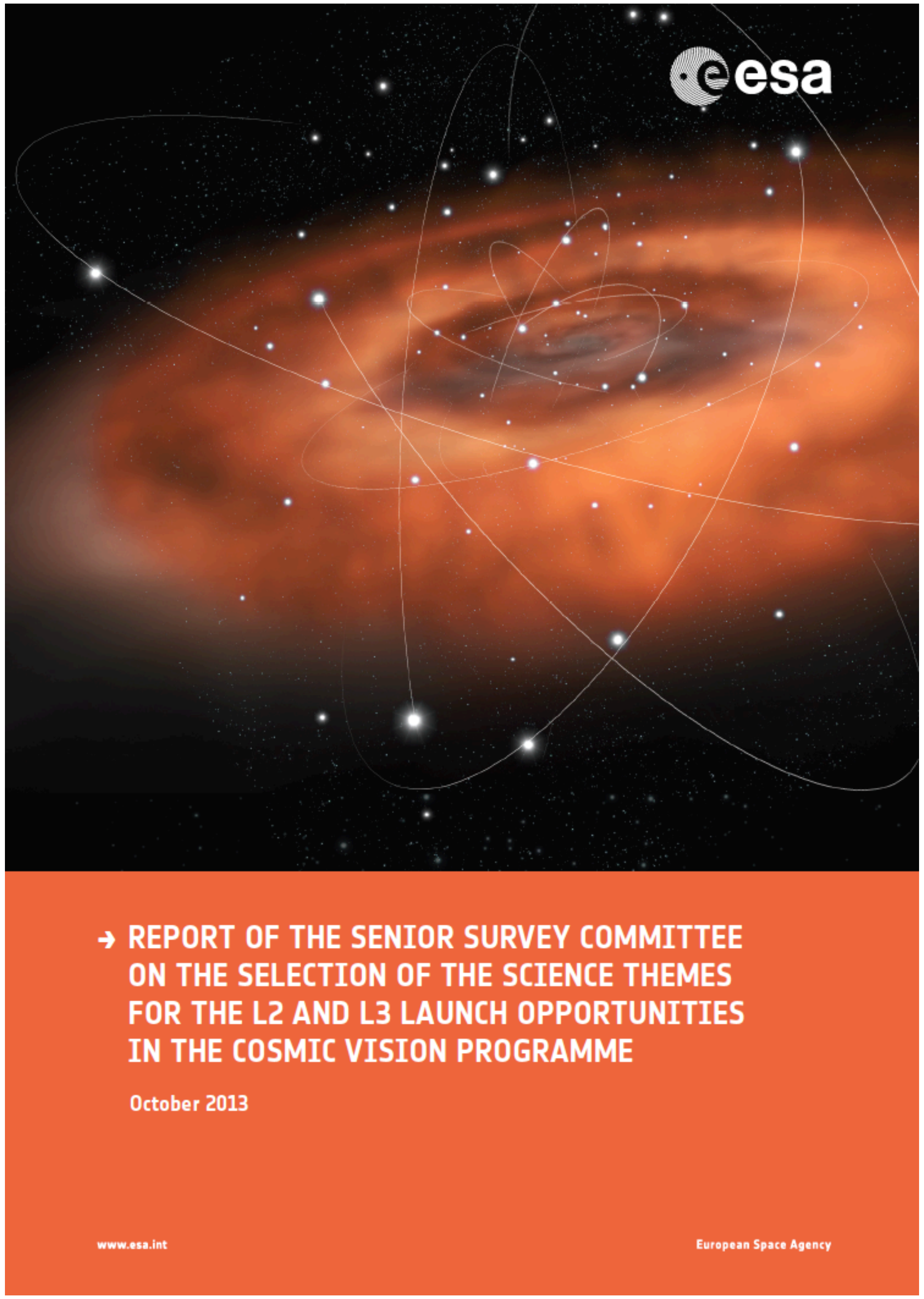
05 Mar 2013

The Director of Science and Robotic Exploration intends to define, in the course of 2013, the science themes and questions that will be addressed by the next two Large (L-class) missions in the Cosmic Vision 2015-2025 plan, "L2" and "L3", currently planned for a launch in 2028 and 2034, respectively. This process starts with a consultation of the broad scientific community, in the form of the current Call, soliciting White Papers to propose science themes and associated questions that the L2 and L3 missions should address. The submission deadline for White Papers is 24 May 2013, 12:00 CEST (noon).

Print this

DOCUMENTATION
- Call for White Papers for L2 and L3

SELECTED THEMES 28 OCTOBER 2013



Prepared by the Senior Survey Committee:

Dr. Catherine Cesarsky (CEA, Chair)

Prof. Willy Benz (Bern University)

Dr. Sergio Bertolucci (CERN)

Prof. Giovanni Bignami (INAF)

Dr. Thérèse Encrenaz (Meudon Observatory)

Prof. Reinhard Genzel (MPE)

Dr. Jason Spyromilio (ESO)

Prof. John Zarnecki (Open University)

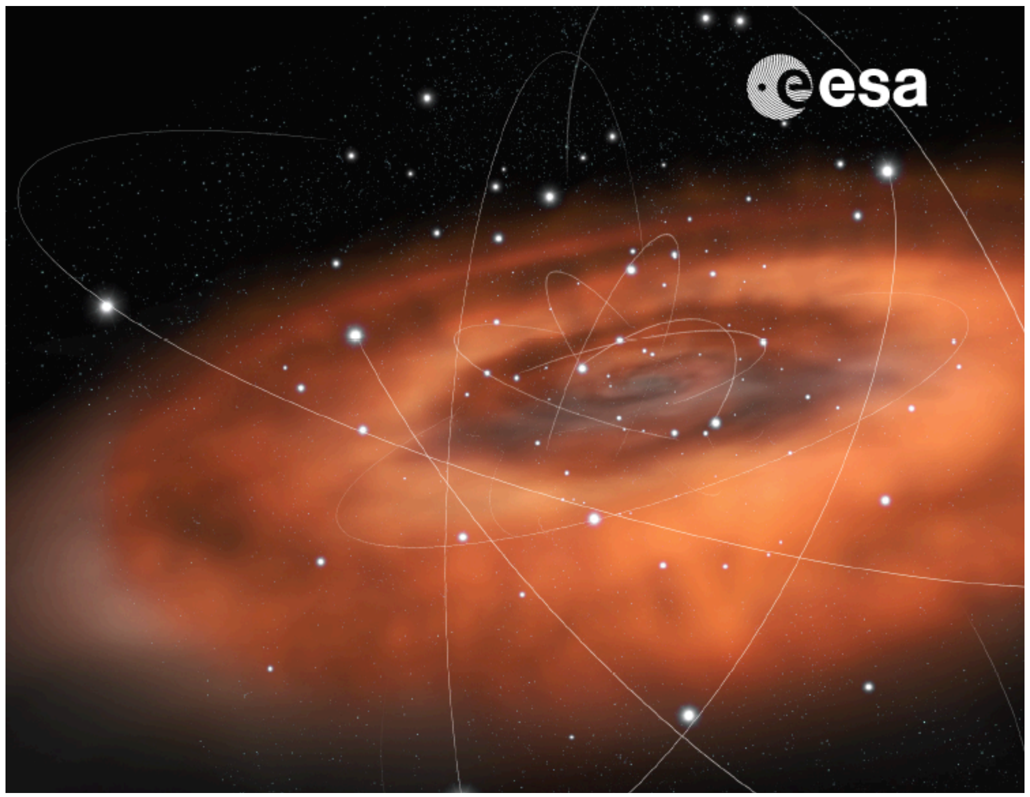
Cover image: An artist's impression of the environment at the centre of our Galaxy, the Milky Way

Credit: ESA – C. Carreau

Layout: Sapienza Consulting, United Kingdom

This report is available online at http://sci.esa.int/ssc_report

eLISA has been SELECTED
28 October 2013



THE HOT and ENERGETIC UNIVERSE
L2
2028

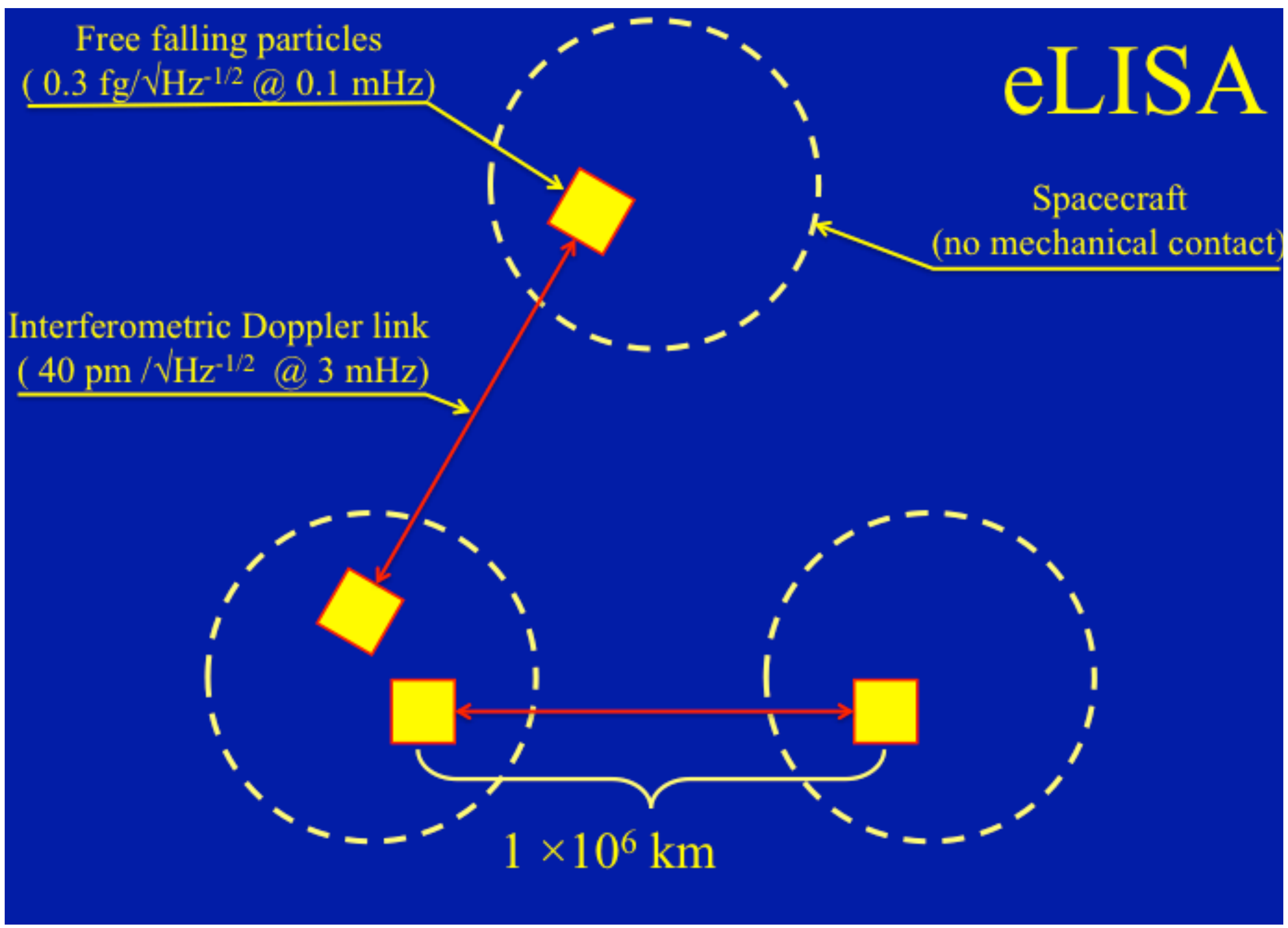
THE GRAVITATIONAL UNIVERSE
L3
2034

PLAnetary Transits and Oscillations of stars (PLATO)

evolvingLISA

eLISA is a constellation
of the three spacecraft shielding each a drag-free geodesic reference test mass

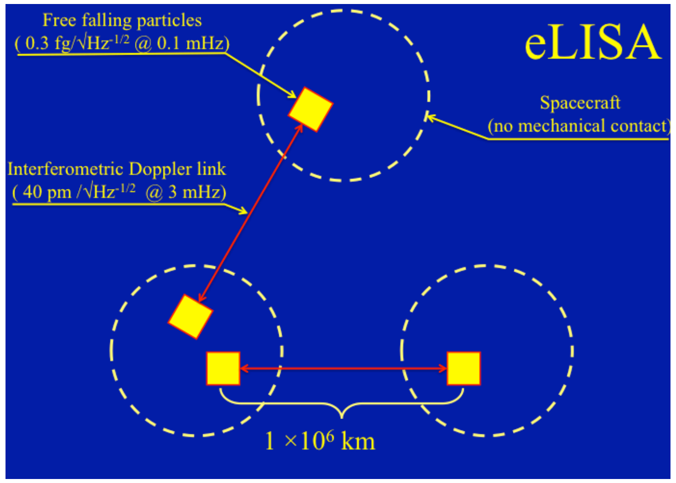
being perturbations in the metric of spacetime, gravitational waves require
for their detection a "geometrical measurements"
Doppler shifts on two electromagnetic beams traveling from one test particle to the other



the gravitational wave h(t)
induces
a relative change in the
distance between two freely
falling test-masses

$$\delta s = h(t) L_{\mathrm{arm-lenght}}$$

eLISA: EXPLORING THE LOW-FREQUENCY GRAVITATIONAL WAVE UNIVERSE



$$f_{\rm gw} = \omega_{\rm gw}/(2\pi) = [10^{-4} - 1]\,{\rm Hz}$$

$$\lambda_{\rm gw} = c/f_{\rm gw} = [2\times 10^{-3} - 20]\,{\rm AU}$$

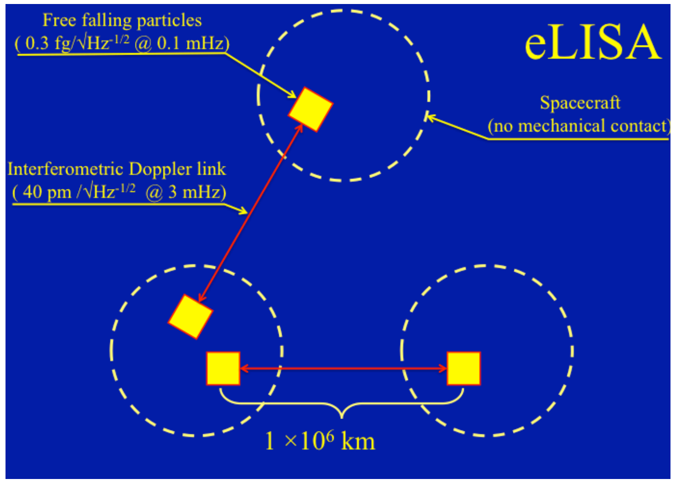
timescales of minutes to hours

$$L_{\rm arm-lenght-eLISA} = 10^6{\rm km} = 0.66\times 10^{-2}\,{\rm AU}$$

$$L_{\rm arm-lenght} \ll \lambda_{\rm gw}$$

$$L^{\rm optimal}_{\rm arm-lenght} = \frac{c}{4 f_{\rm gw}} \sim 0.5\left(\frac{10^{-3}{\rm Hz}}{f_{\rm gw}}\right)\ {\rm AU}$$

eLISA: EXPLORING THE LOW-FREQUENCY GRAVITATIONAL WAVE UNIVERSE



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$$L_{\rm arm-lenght-eLISA} = 10^6{\rm km} = 0.66 \times 10^{-2}\,{\rm AU}$$

LIGO-VIRGO
ground-based

$$f_{\rm gw} = \omega_{\rm gw}/(2\pi) = [10 - 10^4]\,{\rm Hz}$$

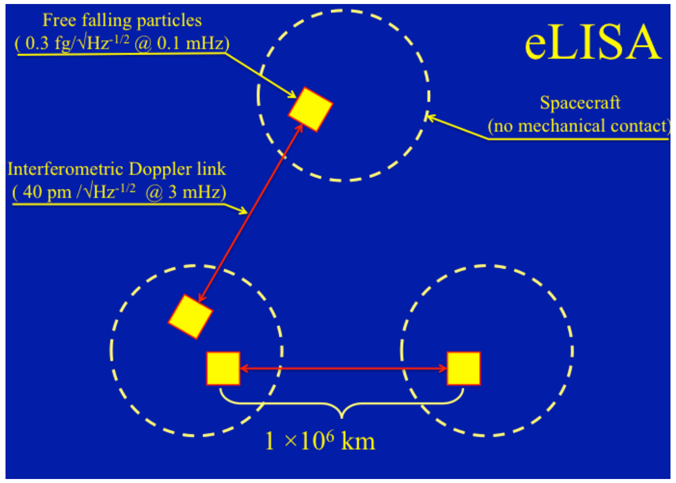
$$\lambda_{\rm gw} = c/f_{\rm gw} = [30 - 10^4]\,{\rm km}$$

$$L_{\rm arm-length-Virgo} = 4\,{\rm km}$$

$$L_{\rm arm-lenght} \ll \lambda_{\rm gw}$$

$$L^{\rm optimal}_{\rm arm-lenght} = \frac{c}{4 f_{\rm gw}} \sim 0.5 \left(\frac{10^{-3}{\rm Hz}}{f_{\rm gw}} \right) \;{\rm AU}$$

eLISA: EXPLORING THE LOW-FREQUENCY GRAVITATIONAL WAVE UNIVERSE



$$f_{\text{gw}} = \omega_{\text{gw}}/(2\pi) = [10^{-4} - 1]\,\text{Hz}$$

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$$L_{\text{arm}-\text{lenght}-\text{eLISA}} = 10^6\text{km} = 0.66 \times 10^{-2}\,\text{AU}$$

LIGO-VIRGO
ground-based

$$f_{\text{gw}} = \omega_{\text{gw}}/(2\pi) = [10 - 10^4]\,\text{Hz}$$

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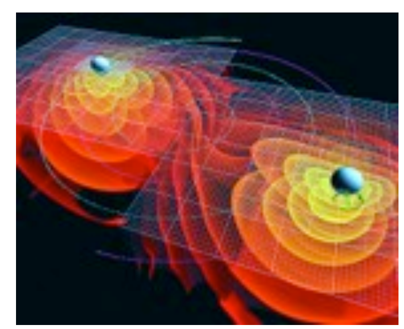
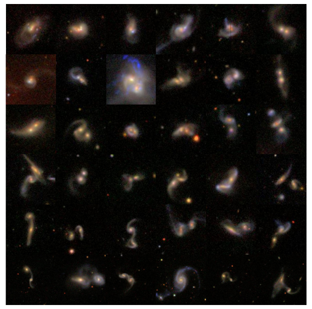
$$L_{\text{arm}-\text{length}-\text{Virgo}} = 4\,\text{km}$$



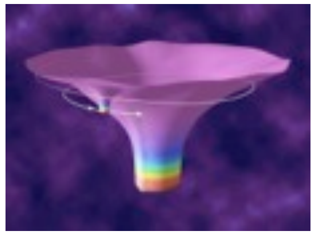
$$f_{\text{gw,ISCO}} \simeq 2.2 \left(\frac{10^6_{\odot}}{M}\right) \text{mHz}$$

eLISA as an OBSERVATORY in SPACE to explore the universe
0.1 mHz - 1 Hz
SELECTION OF "SOURCES"



MASSIVE BLACK HOLE MERGERS

$$10^4\,M_\odot - 10^7\,M_\odot$$



EXTREME MASS RATIO INSPIRALS

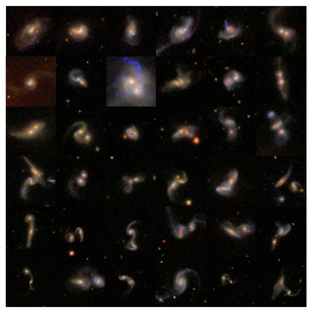
$$10\,M_\odot \ \text{into} \ 10^7\,M_\odot$$

ULTRA COMPACT BINARIES IN THE MILKY WAY
OF ALL FAVLORS

STOCHASTIC SIGNALS FROM THE BIG BANG

THE UNKNOWN

eLISA as an OBSERVATORY in SPACE to explore the universe
0.1 mHz - 1 Hz
SELECTION OF "SOURCES"



MASSIVE BLACK HOLE MERGERS

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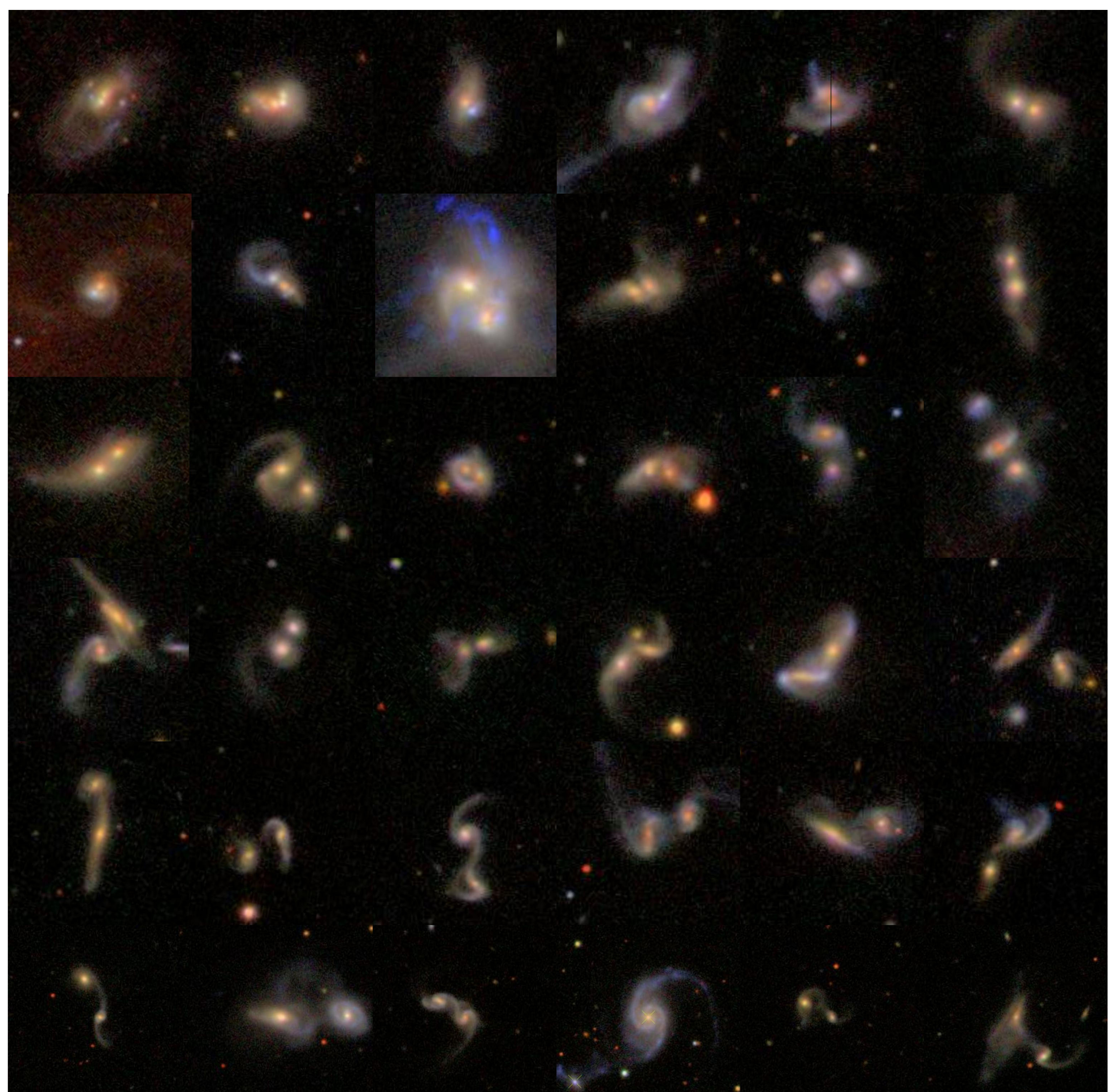
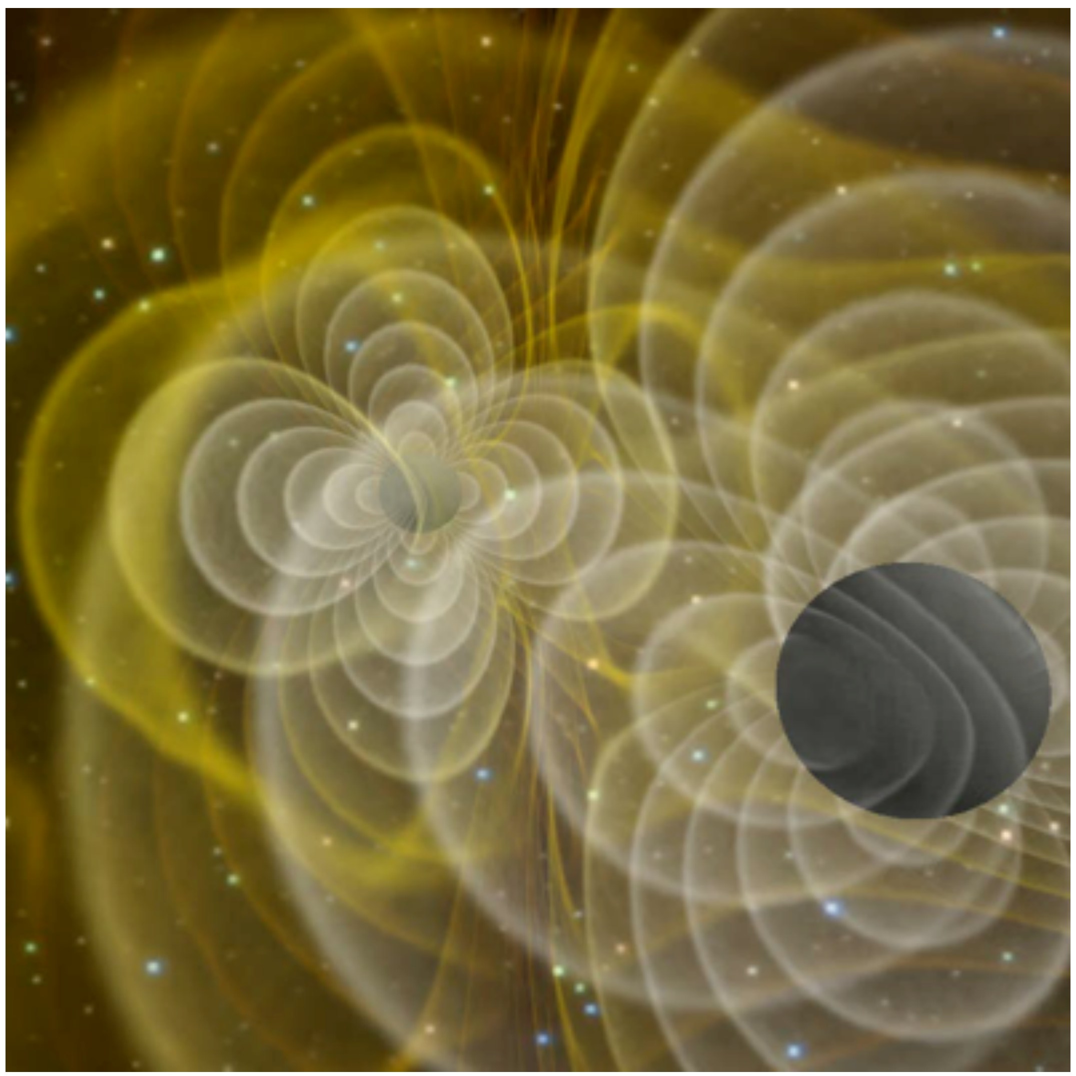
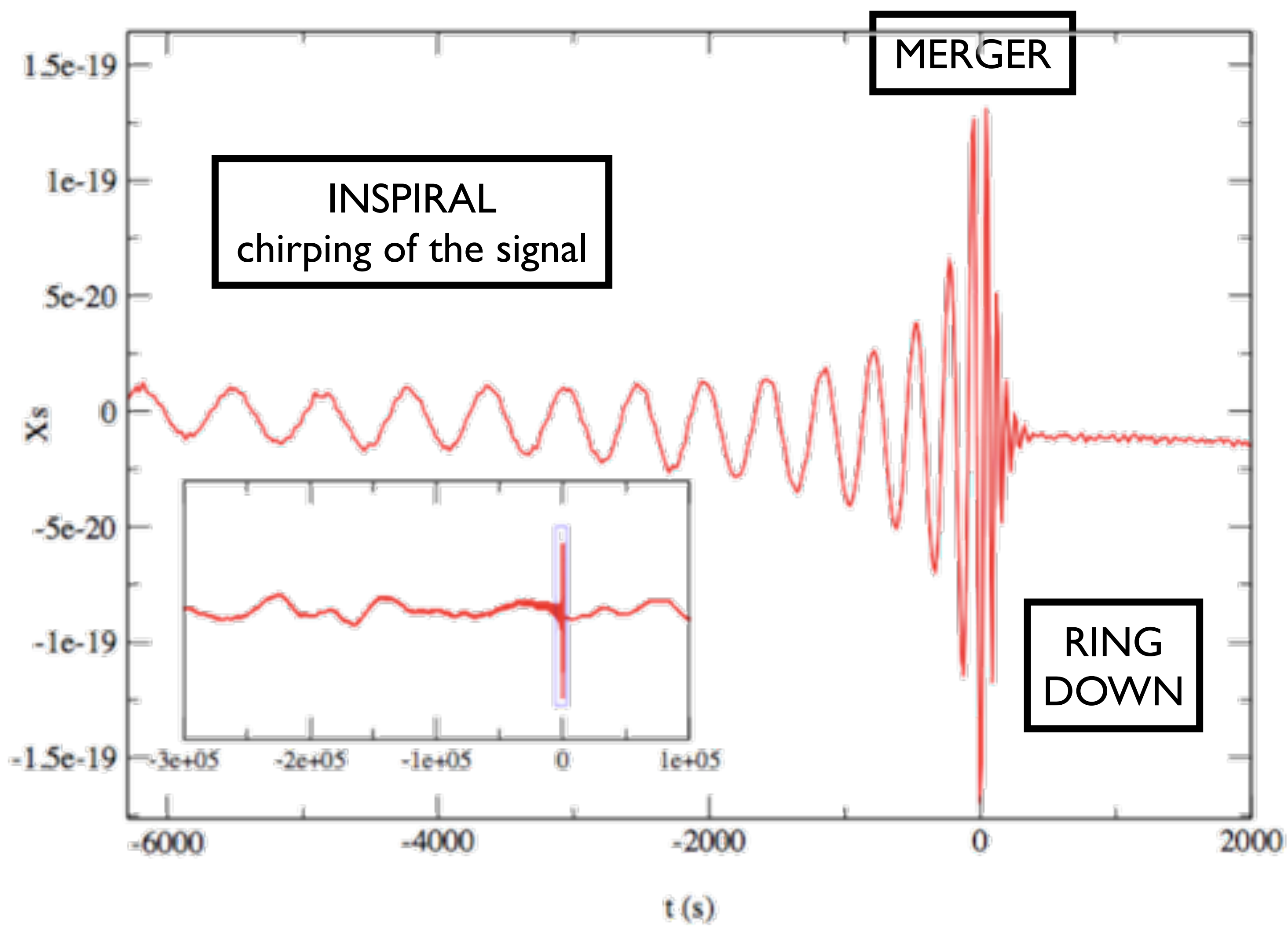


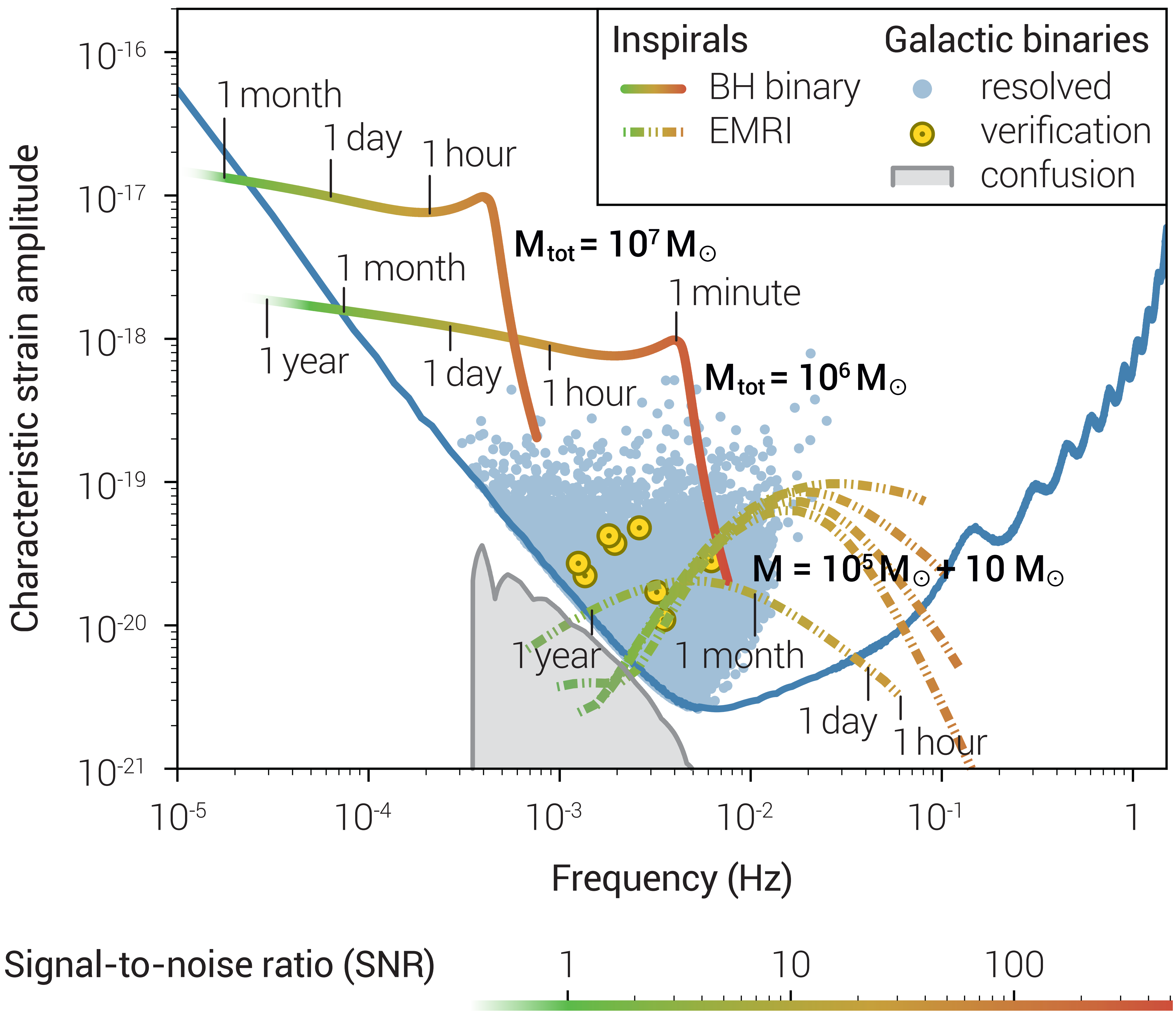
BINARY BLACK HOLES
INSPIRAL - MERGER - RING-DOWN

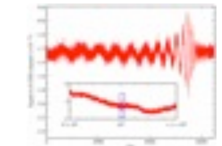
17 parameters determine the waveform
THE SPIN INTRODUCES A LOT OF STRUCTURE IN THE WAVEFORMS
this helps in determining the physical parameter of the sources with high accuracy





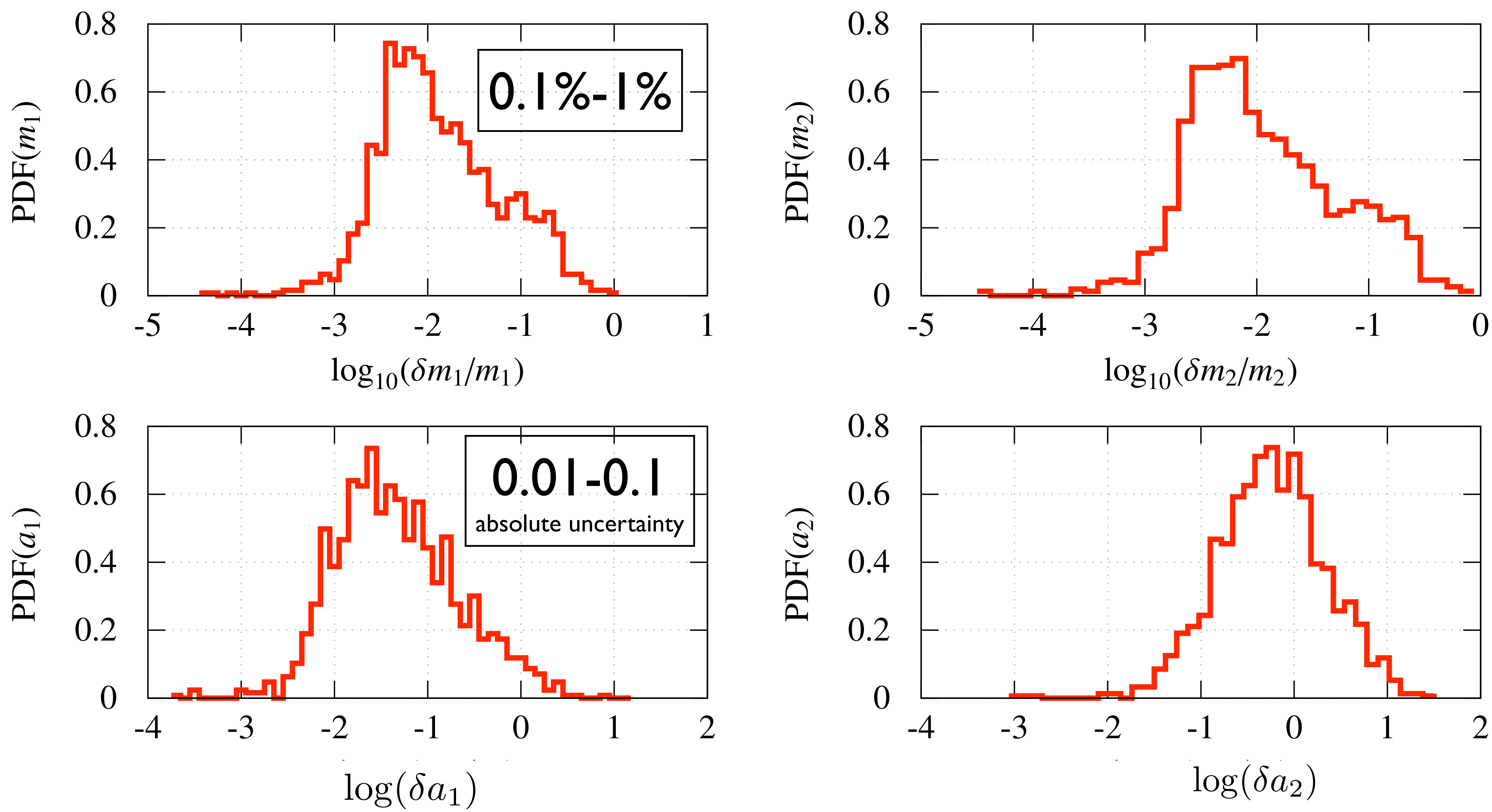
black hole
black hole
inspiral and
merger
z=3





PARAMETER ESTIMATION: redshifted MASS & SPIN

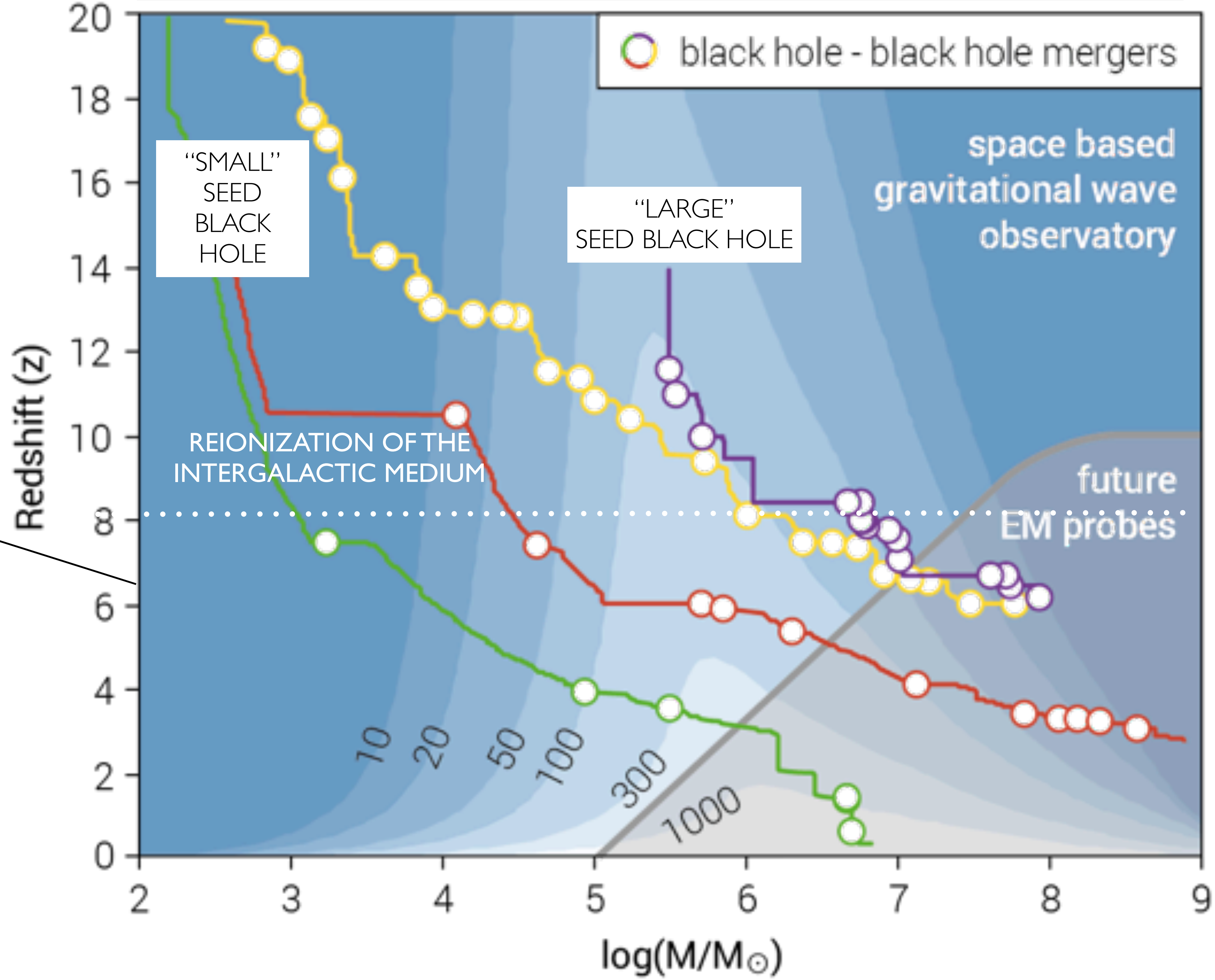
ERROR DISTRIBUTION IN THE PARAMETER ESTIMATION



SPIN MEASURE DEVOID BY SYSTEMATIC ERRORS
AND IMMUNE FROM UNCERTAINTIES INTRODUCED
BY MODELING OF THE SOURCE SPECTRUM/SHAPE OF IRON LINE

ALL BLACK HOLES TRANSIT ACROSS THE eLISA BAND
WE WILL PROBE THE EXISTENCE OF "SEED"

ULASJ1120
@
z=7.08

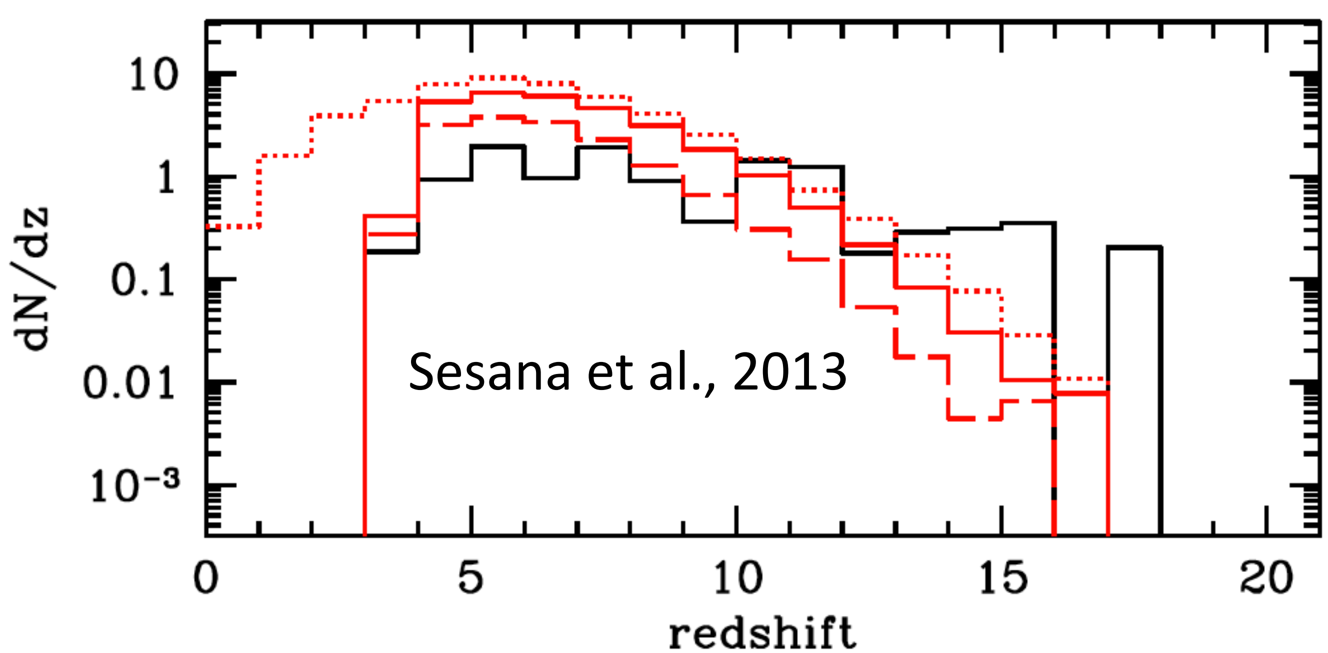


EVENT RATES OF BLACK HOLES MERGERS

10-100 mergers/year

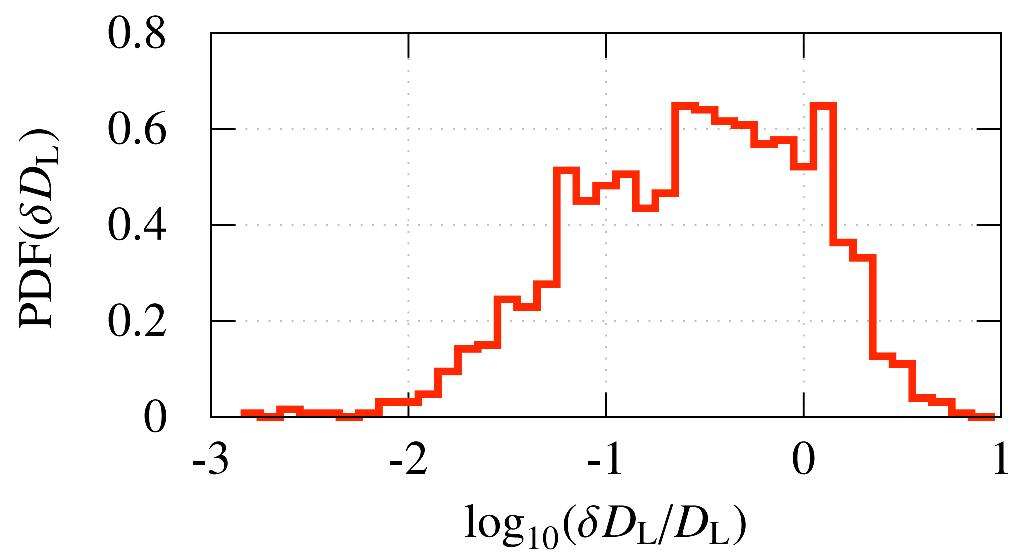
I. from semi-analytical models clustering of dark matter halos without tracing the dissipation of the baryonic component

II. using cosmological hydrodynamical simulations which have shown the importance of clod flows to feed black holes

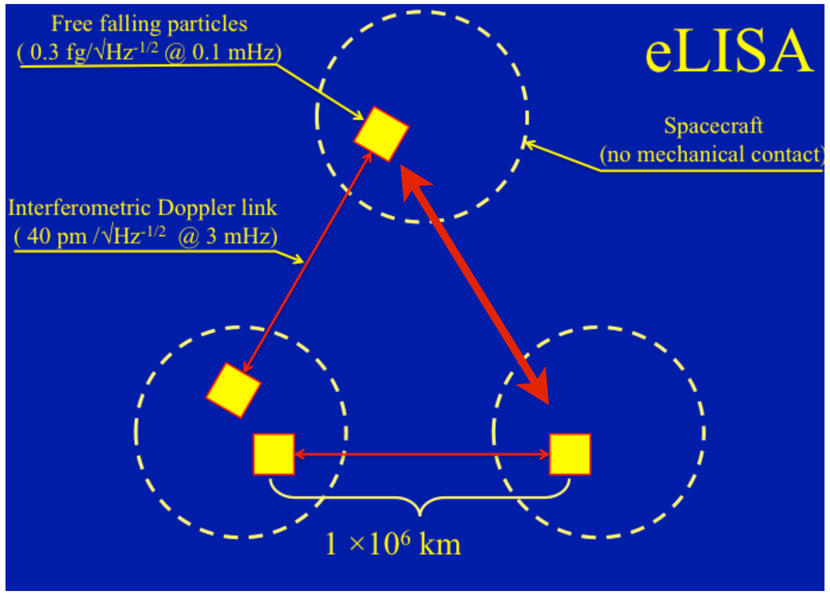


COALESCING BLACK HOLES ARE STANDARD CANDLES

LUMINOSITY DISTANCE



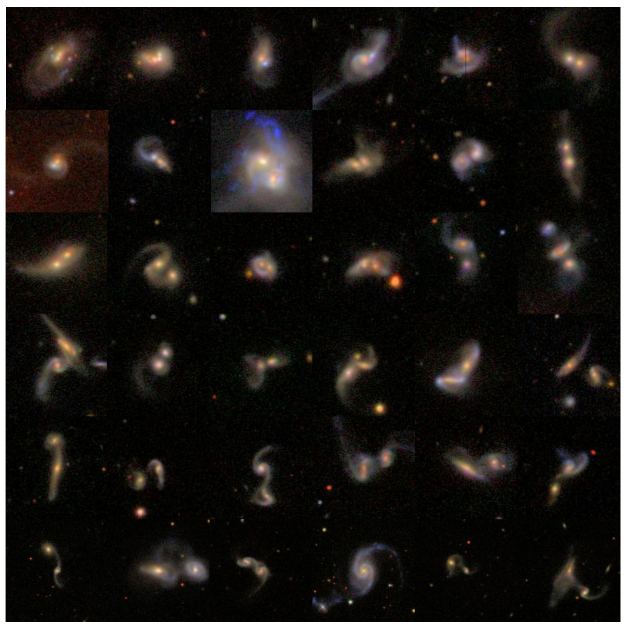
a third link



eLISA

key science question will be addressed

MASSIVE BLACK HOLE MERGERS $10^4\,M_\odot - 10^7\,M_\odot$



when did the first black holes appear and how do they form ?

how did black holes assemble and evolve from cosmic dawn to the present?

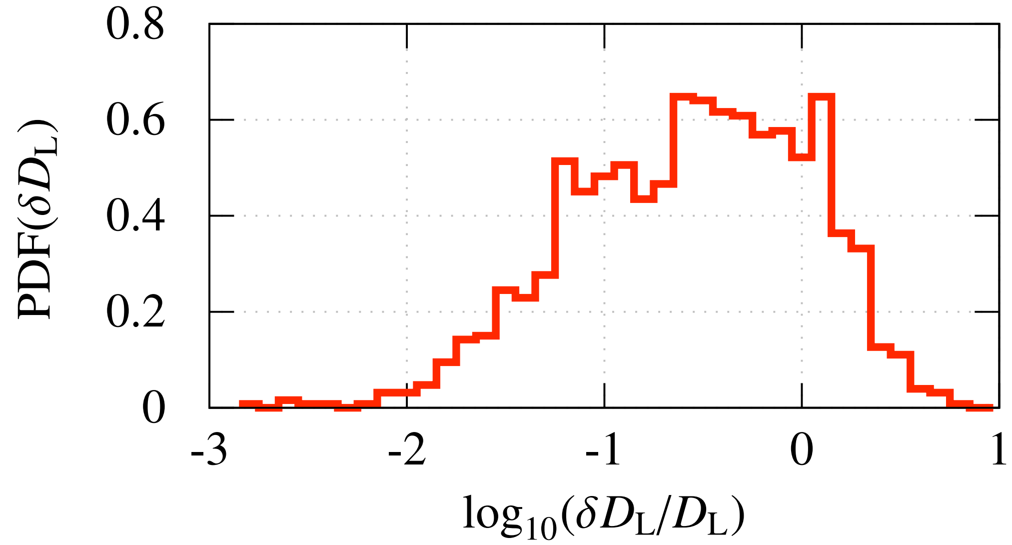
what role did black hole play in cosmic re-ionization galaxy evolution and structure formation?

\

eLISA will make the largest and deepest survey of MASSIVE BLACK HOLE MERGERS in the UNIVERSE

COSMOGRAPHY

LUMINOSITY DISTANCE - COSMOGRAPHY



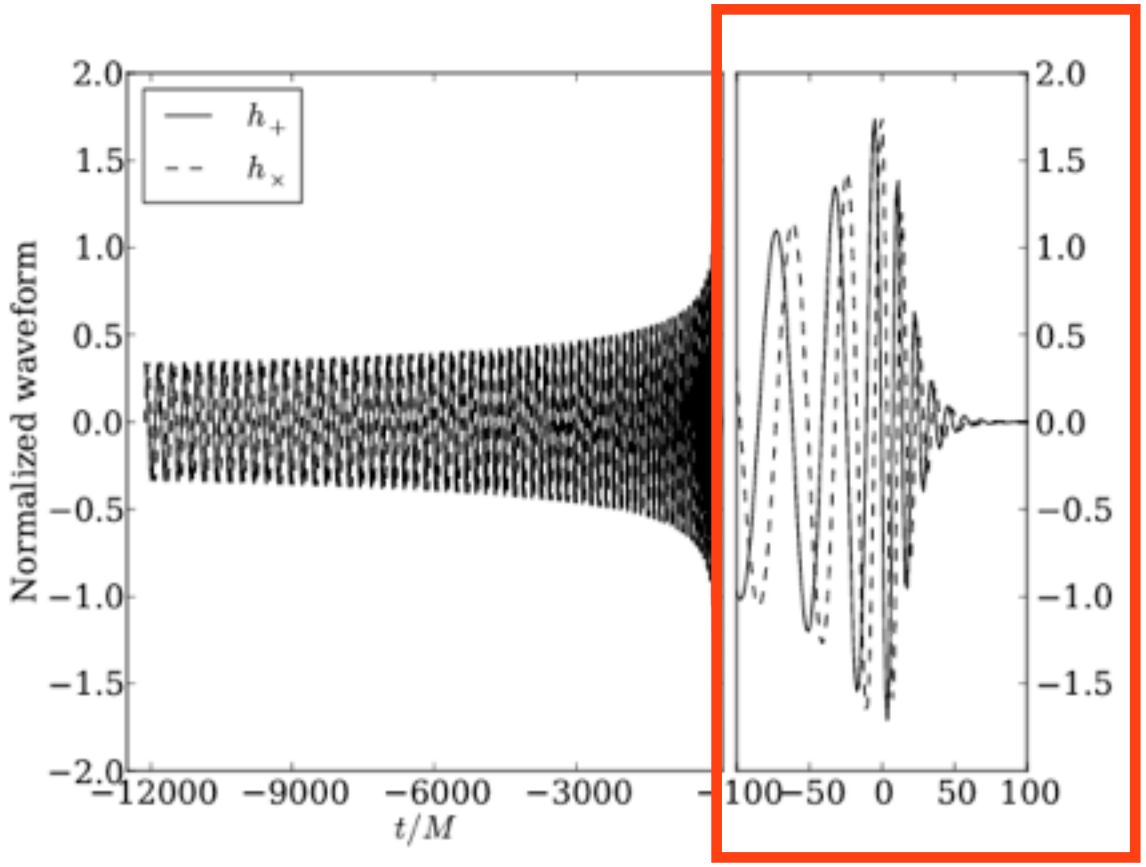
IDENTIFICATION OF AN ELECTROMAGNETIC COUNTERPART
INDEPENDENT MEASURE
REDSHIFT OF THE SOURCE

THIS WOULD LEAD TO AN INDEPENDENT MEASURE OF THE COSMOLOGICAL PARAMETERS
immune by systematic errors
(expected major improvements in the data analysis)

eLISA IS A FULL SKY MONITOR
SKY LOCATION ACCURACY IS TYPICALLY
IN THE RANGE OF 10-1000 SQUARE DEGREES

TEST of GENERAL RELATIVITY IN THE STRONG FIELD REGIME DYNAMICAL SECTOR

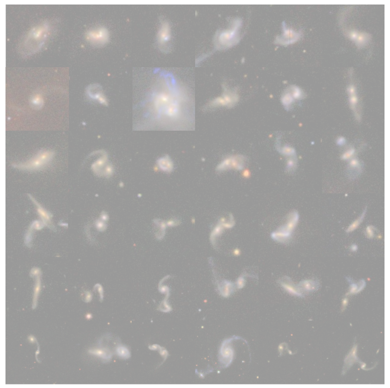
BLACK HOLE "SPECTROSCOPY"



WE CAN UNIQUELY IDENTIFY A BLACK HOLE
HAVING "NO-HAIR"
FROM THE SPECTRUM OF ITS
RING-DOWN RADIATION
CHECKING CONSISTENCY WITH THE ENTRIE SHAPE OF THE
WAVEFORM

eLISA

ASTROPHYSICS

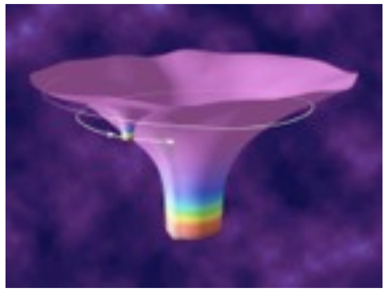


MASSIVE BLACK HOLE MERGERS $10^4\, M_\odot - 10^7\, M_\odot$

when did the first black holes appear and how do they form ?

how did black holes assemble and evolve from cosmic dawn to the present?

what role did black hole play in cosmic re-ionization galaxy evolution and structure formation?



EXTREME MASS RATIO INSPIRALS $10\, M_\odot$ into $10^7\, M_\odot$

how is the stellar dynamics in galactic nuclei ?

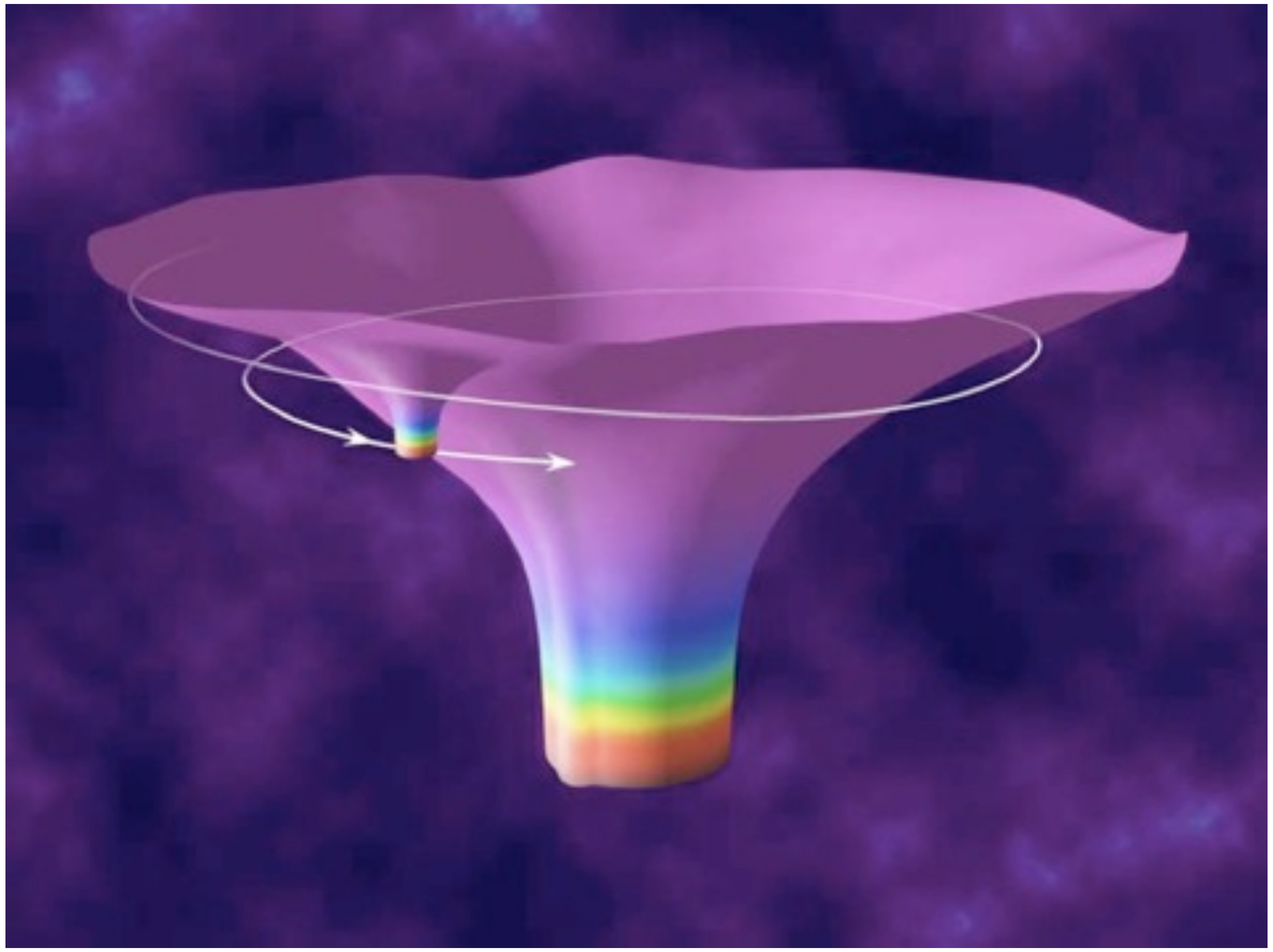
what is the role of mass segregation and relaxation in determining stellar populations around central black holes?

ULTRA COMPACT BINARIES

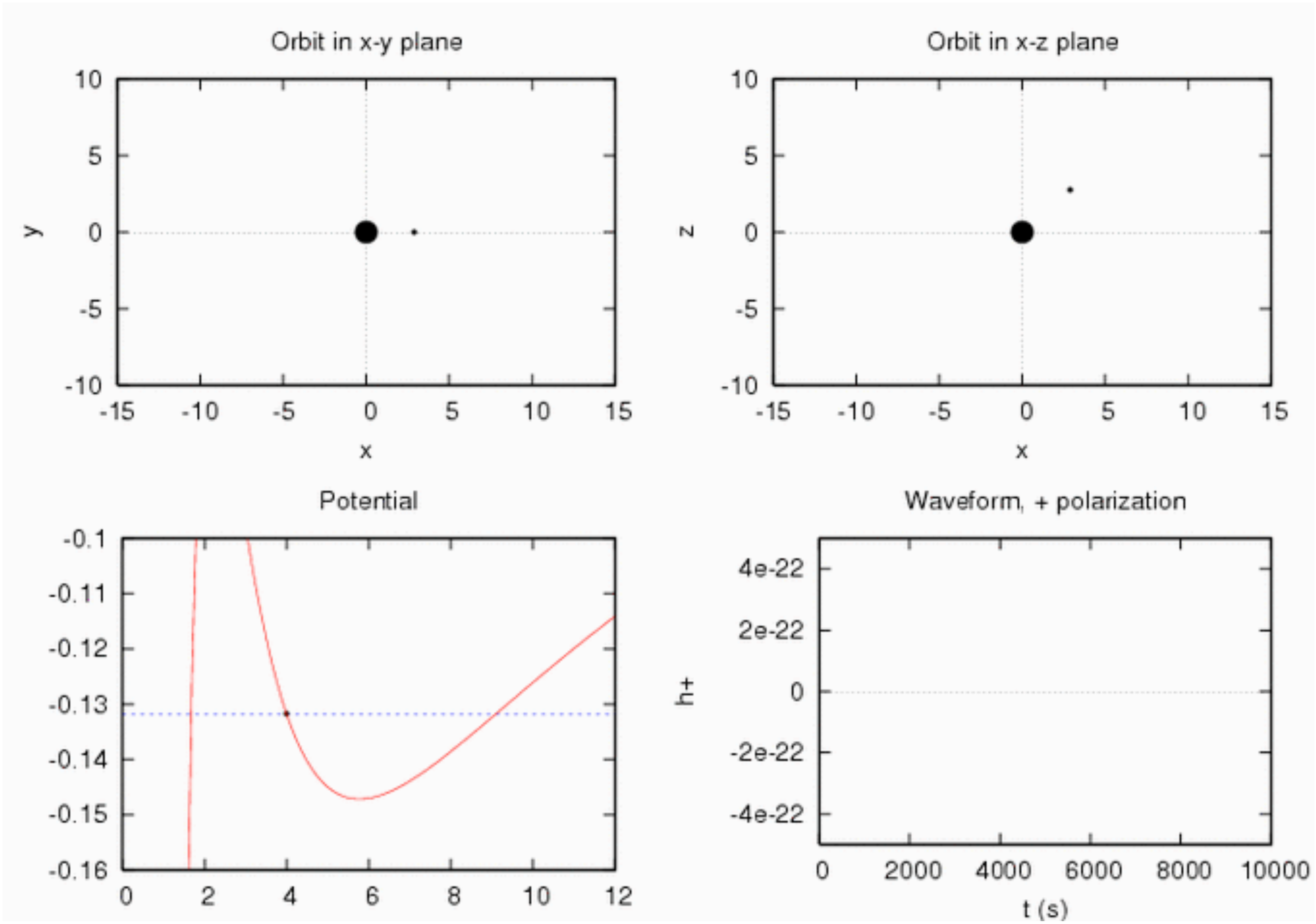
what is the explosion mechanism of type Ia supernovae?

what is the formation and merger rate of compact binaries in the Milky Way?

EXTREME
MASS RATIO INSPIRALS



EXTREME MASS RATIO INSPIRALS: PRECISION PROBES OF KERR SPACE TIMES



THE WAVEFORM ENCODES THE GEOMETRY OF THE SPACETIME

MASS MOMENTS AND CURRENT MULTIPOLES DETERMINE THE GEOMETRY OF THE SPACE-TIME

IF A BLACK HOLE HAS NO HAIR then ALL MOMENTS DEPEND ON MASS AND SPIN only

FRACTIONAL ACCURACY OF MASS AND SPIN AT THE LEVEL OF 0.01%-0.1%

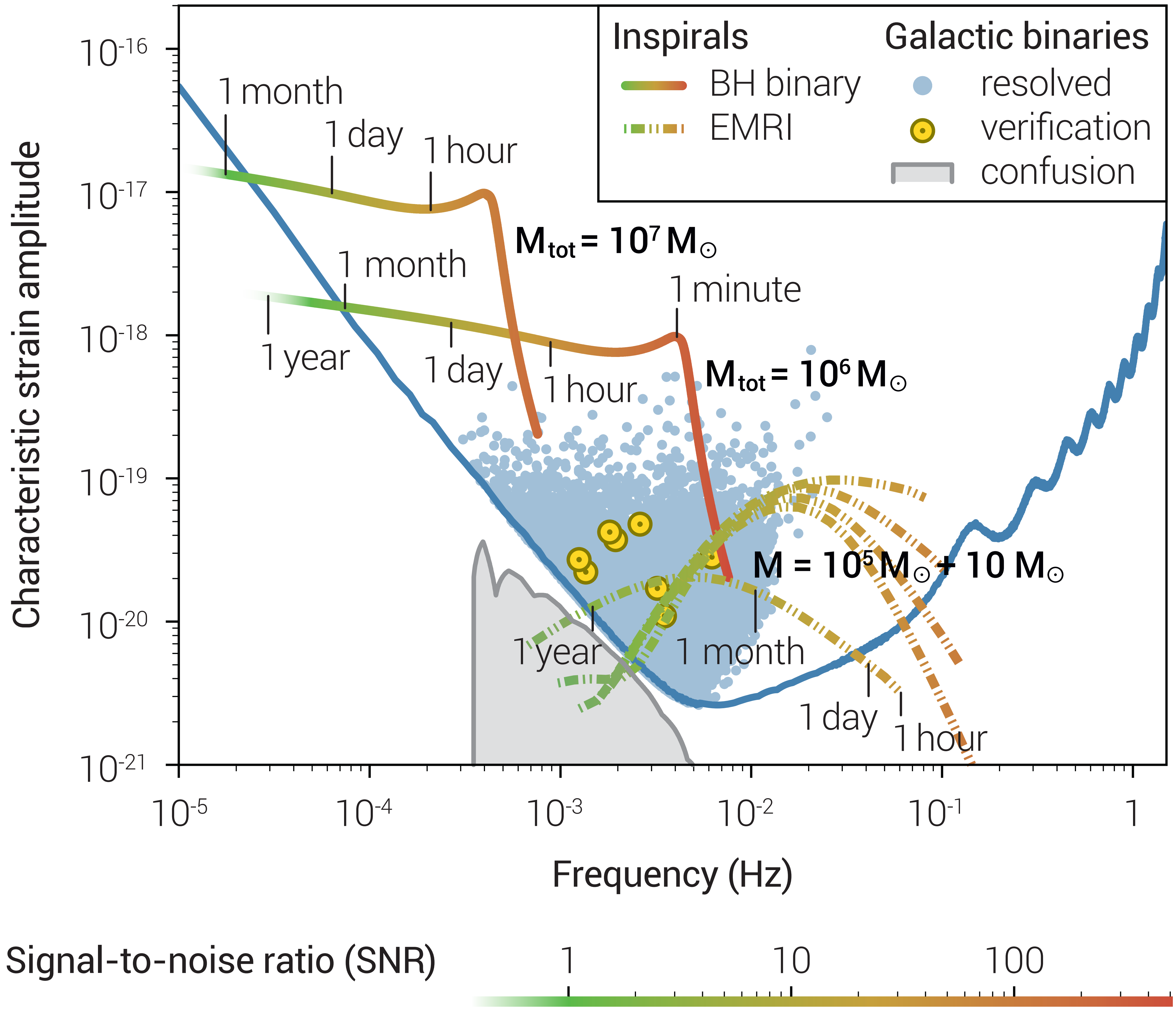
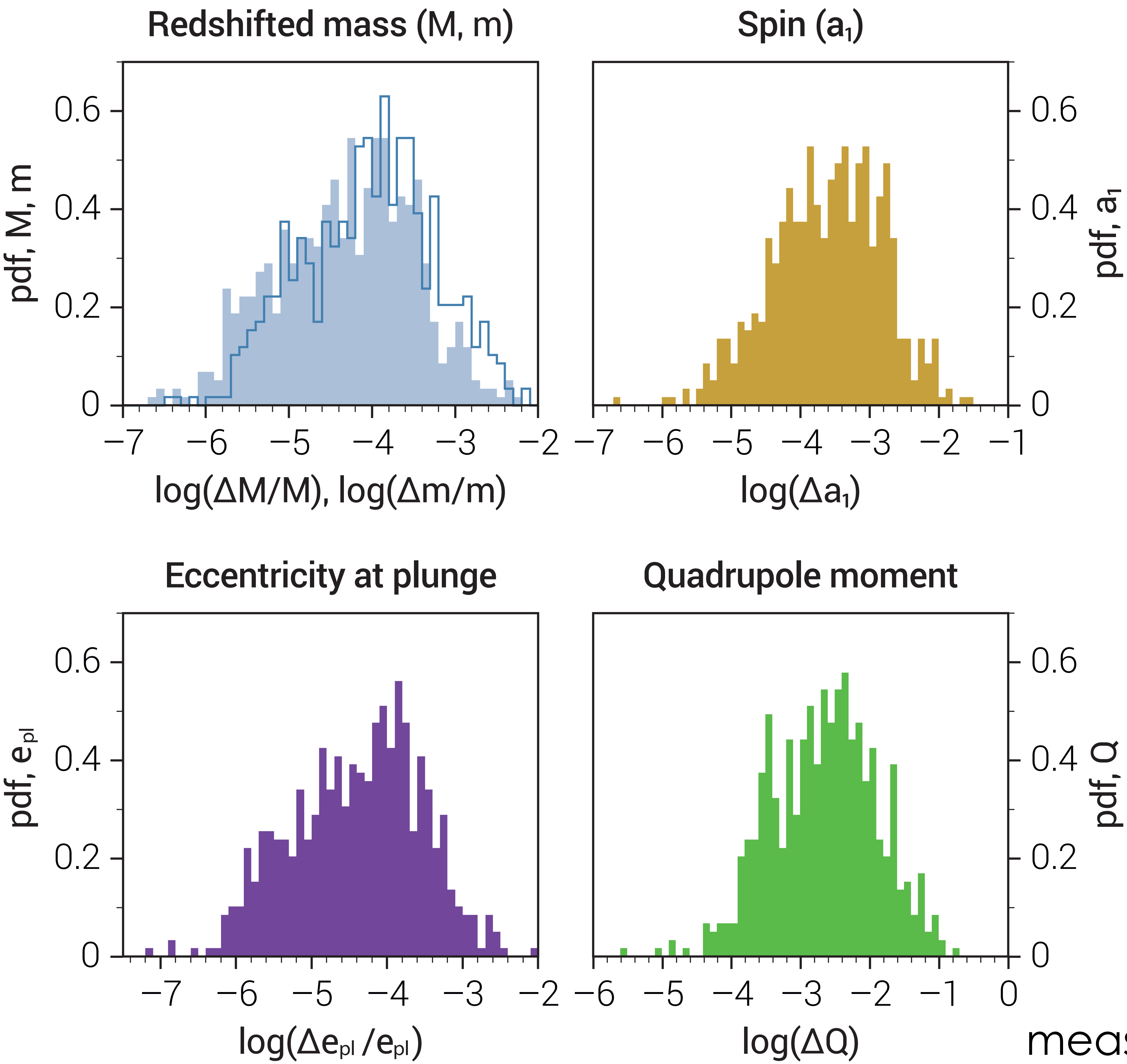


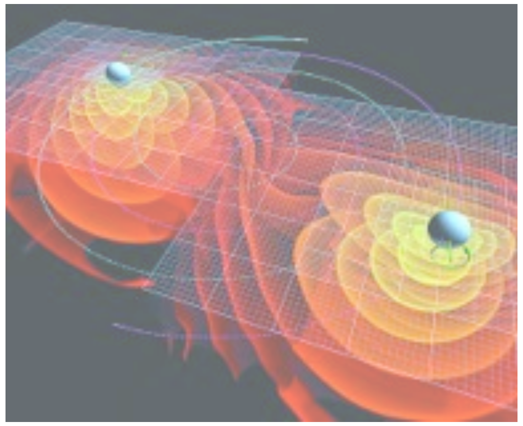
Figure 13: Examples of gravitational wave astrophysical sources in the frequency range of eLISA, compared with the sensitivity curve of eLISA.

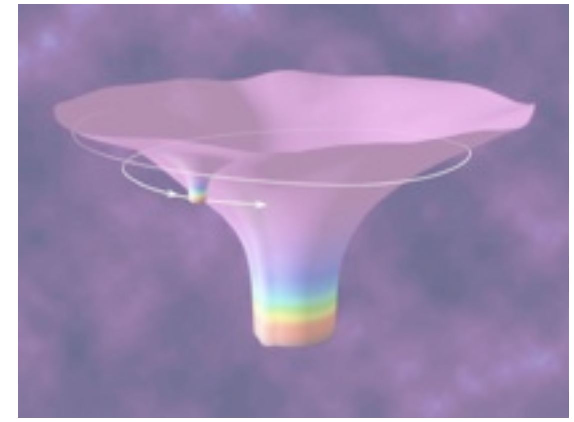


measurable deviation of the quadrupole moment of the source from the Kerr value

EMRI's SOUND

RATHER THAN **"seeing"** THE SOURCES
THROUGH THEIR ELECTROMAGNETIC
RADIATION,
eLISA WILL **"hear"** THE UNIVERSE
BY CAPTURING THE VIBRATIONS OF THE
FABRIC
OF SPACETIME ITSELF

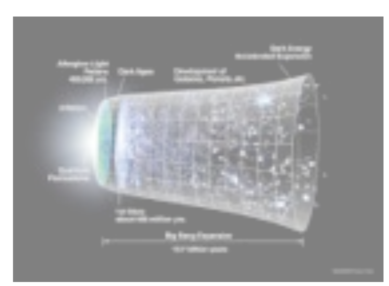




THE BEAUTY
OF
COALESCING BINARY BLACK HOLES
EXTREME MASS RATIO INSIPIRALS
IS IN THE SIMPLICITY

COLLISION OF PURE SPACETIMES

UNIVERSE SEEN THROUGH GRAVITY “ONLY”

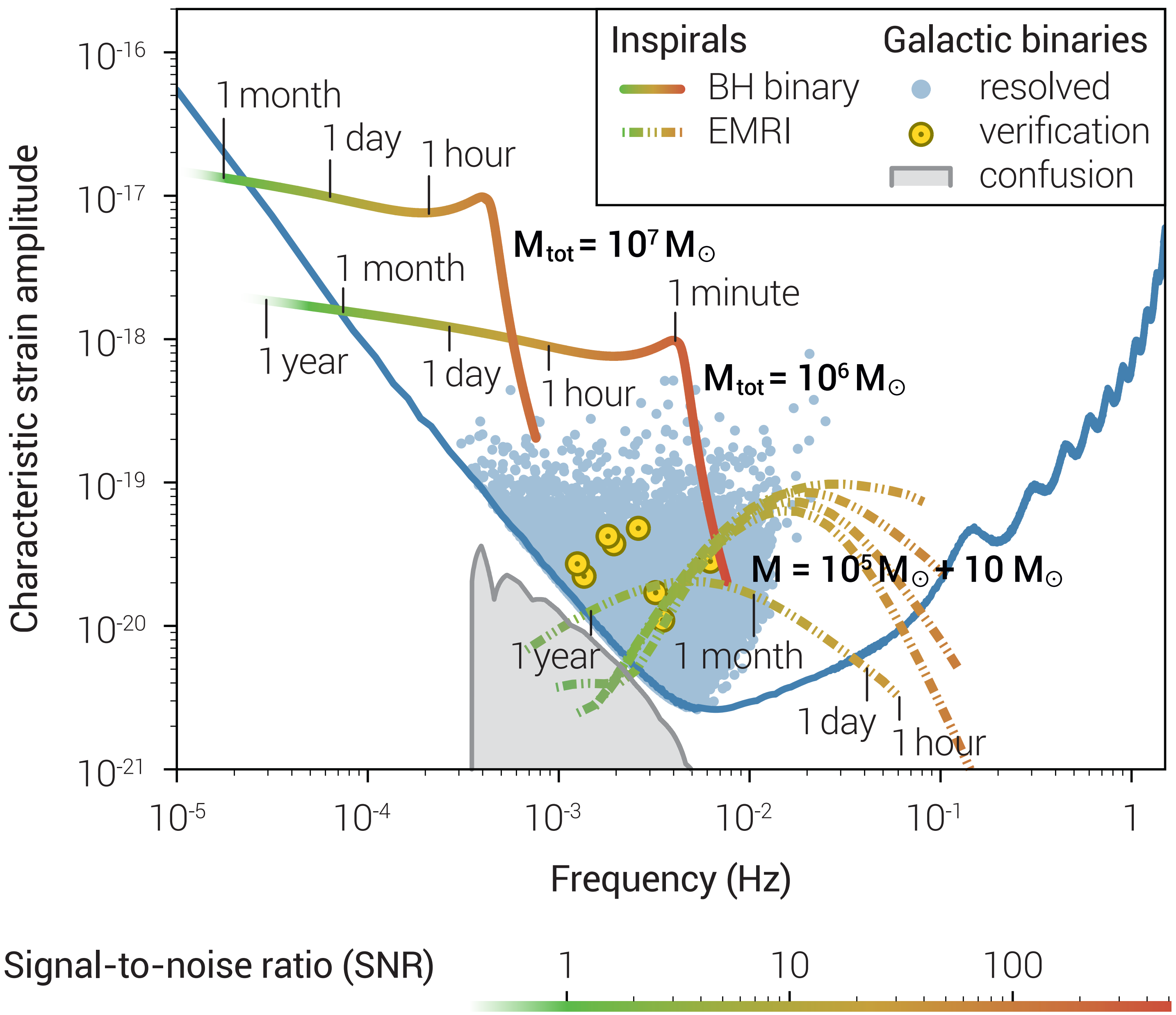


MILKY WAY

ULTRA COMPACT BINARIES AS VERIFICATION SOURCES

MAPPING THE INVISIBLE "STAR BINARIES": 1000 WHITE DWARFS NEUTRON STARS AND BLACK HOLES

****IMPACT ON THE ASTROPHYSICS OF TYPE Ia SUPERNOVAE****



WHITE DWARFS WITH ORBITAL PERIODS LESS THAN A FEW MINUTES

HUGE DISCOVERY SPACE

- Massive Black Holes (10^4 to 10^8 $M_\odot$)
  - Look back before re-ionisation, Black Hole mergers at $z \geq 20$, if they exist
  - How did Black Holes form? How important were cold gas flows?
  - What were the Black Hole seeds? When did they appear?
  - What role did Black Holes play in re-ionisation, galaxy evolution and structure formation?
  - What is the precise luminosity distance to loud standard siren black hole binaries?
  - What is the distance – redshift relation and the evolution history of the universe?
  - Does the Graviton have mass?
- Extreme Mass Ratio Inspirals, EMRIs (1 to 10 $M_\odot$ into 10^4 to 5 x 10^6 $M_\odot$)
  - How is the stellar dynamics in dense galactic nuclei?
  - How does dynamical relaxation and mass segregation work in dense galactic nuclei?
  - What is the occupation fraction of black holes in low-mass galaxies?
  - How large are deviations from Kerr Metric, and what new physics causes it?
  - Are there horizonless objects like boson stars or gravastars?
  - Are alternatives to GR viable, like Chern Simons or scalar tensor theories or braneworld scenarios?
- Ultra-Compact Binaries in Milky Way
  - What is the explosion mechanism of type Ia supernovwe?
  - What is the formation and merger rate of compact binaries?
  - What is the endpoint of stellar evolution?
- Stochastic Signals
  - Directly probe Planck scale epoch at 0.1 TeV to 100 TeV before decoupling of microwave background
  - Were there phase transitions and of which order?
  - Probe Higgs field self coupling and potential, and search for supersymmetry.
  - Are there warped sub-millimetre extra-dimensions?
  - Can we see braneworld scenarios with reheating temperatures in the TeV range?
  - Do topological defects like Cosmic Strings exist?

eLISA

ASTROPHYSICS
FUNDAMENTAL PHYSICS
COSMOLOGY
“at the same time”

addressing the key question of
ESA’s COSMIC VISION

Table 6.4.: *Main parameters and constraints of the constellation for a typical science orbits.*

Parameter	nominal value	actual value/deviation	
Arm length	10^6 km	$\delta L_{max} = 18.31 \times 10^3$ km	$\delta L_{max} = -30.66 \times 10^3$ km
Relative velocities	0 m/s	$\delta v_{max} = 7.06$ m/s	
Trailing angle	10°	$\Phi_{max} = 19.81°$	$\Phi_{min} = 9.34°$
Inner angle	60°	$\alpha_{max} = 61.59°$	$\alpha_{min} = 58.44°$

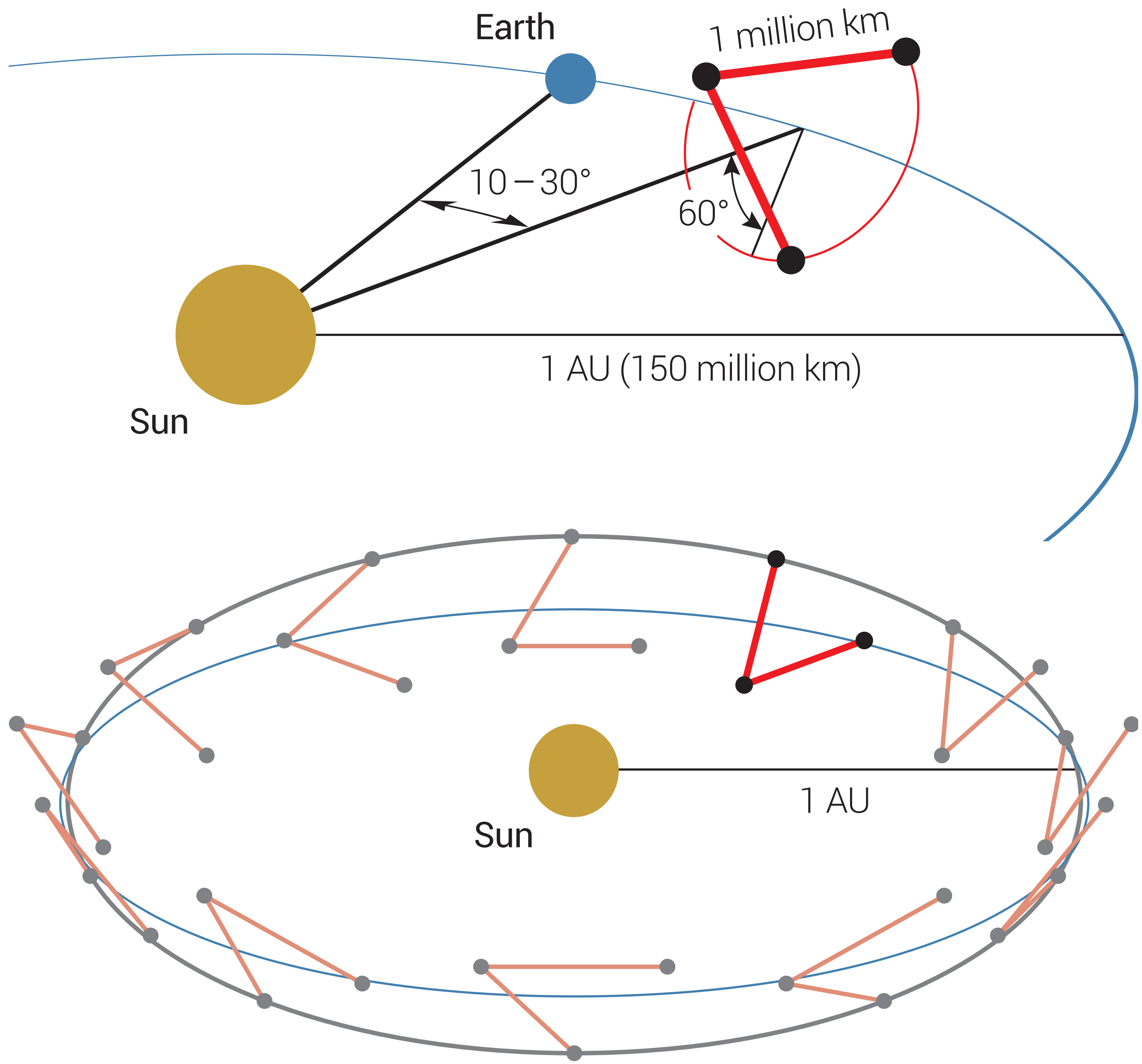


Figure 10: eLISA Orbits. The three eLISA-NGO spacecraft follow the Earth as an almost stiff triangle, purely due to celestial mechanics.

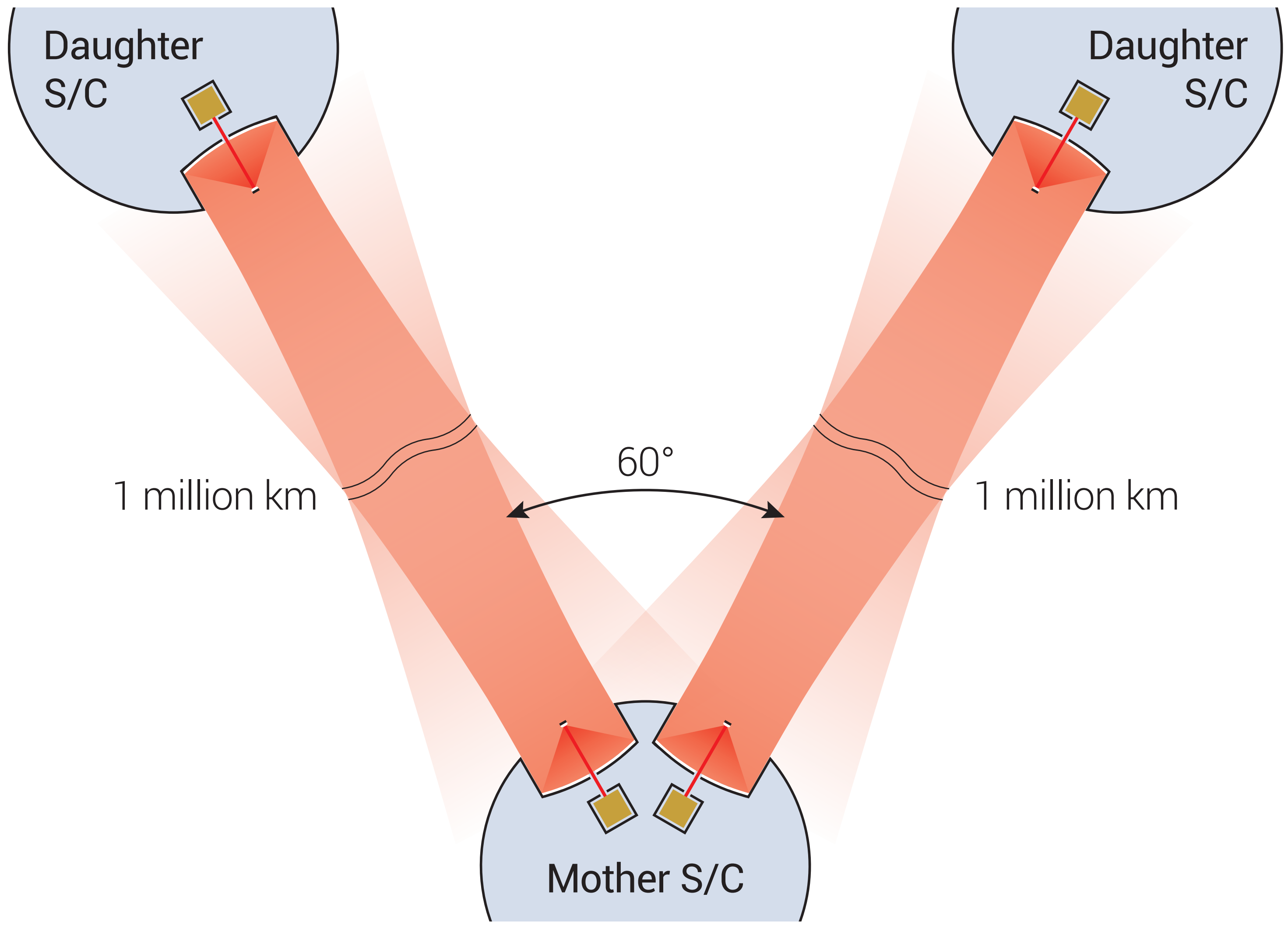


Figure 9: eLISA configuration (not to scale). One mother and two daughter spacecraft exchanging laser light form a two-arm Michelson interferometer. There are four identical payloads, one at the end of each arm, as shown in Figure 11.

Drag-free control

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/$\sqrt{\text{Hz}}$ 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/$\sqrt{\text{Hz}}$ 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 payload consists of four identical units, two on the mother spacecraft and one on each daughter spacecraft (Figure 11). 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 with 20 cm diameter transmits light from a 2 W laser at 1064 nm 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.

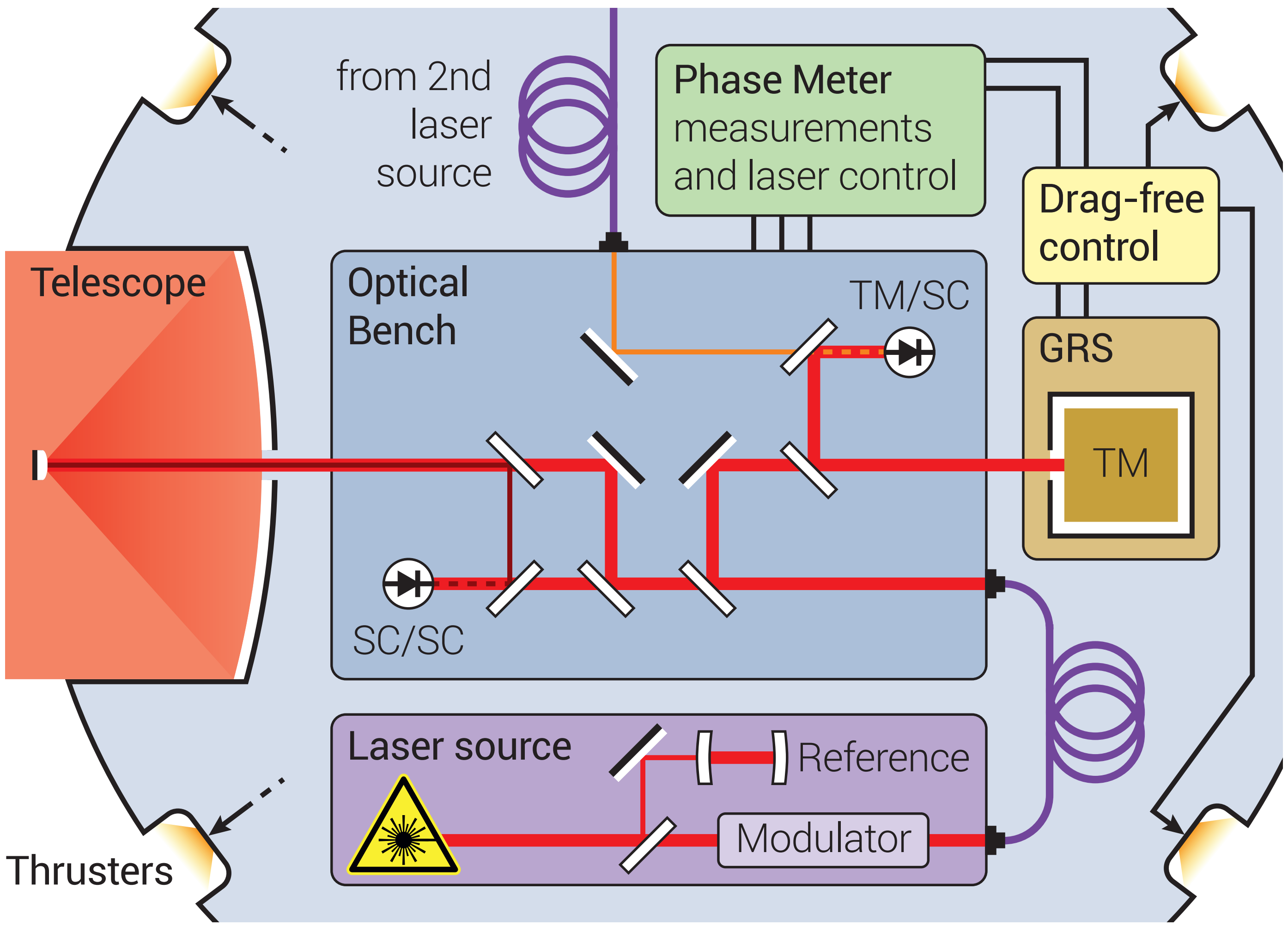


Figure 11: eLISA payload. Each payload unit contains a 20 cm telescope, the test mass enclosed inside the Gravitational Reference Sensor (GRS) and an optical bench hosting the interferometers. (Auxiliary reference interferometer omitted for clarity, see [15] for details.)

GRS contains a test mass
(46x46x46 cm cube of gold and platinum of 2 kg)
the spacecraft is kept centered on the test mass using a drag fee technique in which the position of the mass is sensed

the spacecraft adjusts its position with respect to the test mass using micro-thrusters

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 μcycle/$\sqrt{\text{Hz}}$ precision by an electronic phasemeter. 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 times cales of months to years, and the small fluctuations with periods between seconds and hours that represent the gravitational wave science signal.

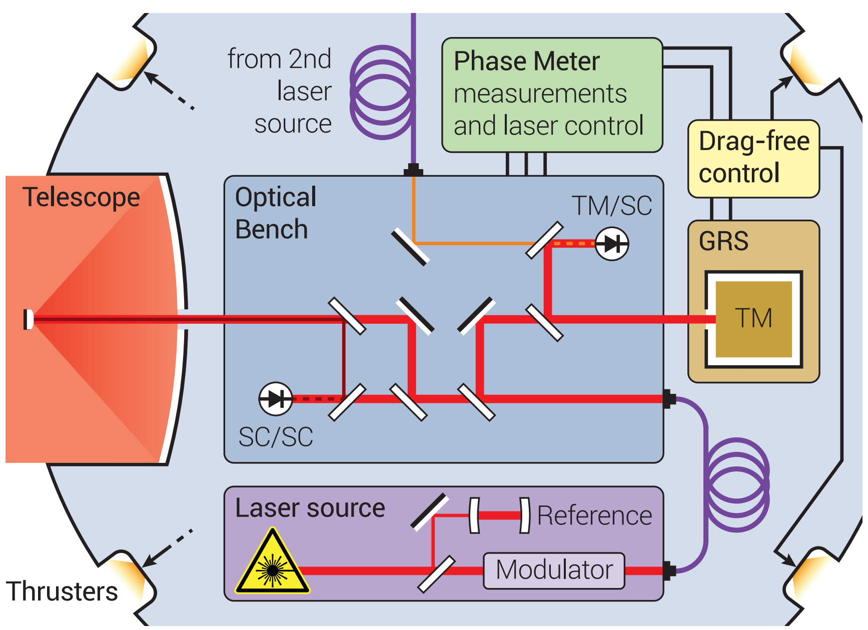


Figure 11: eLISA payload. Each payload unit contains a 20 cm telescope, the test mass enclosed inside the Gravitational Reference Sensor (GRS) and an optical bench hosting the interferometers. (Auxiliary reference interferometer omitted for clarity, see [15] for details.)

optical bench contains all interferometers

science (measuring distances between the optical benches of the SC when about 100 pWatt enter the optical bench from the distant SC)

test mass (position of the mass relative to OB)

reference interferometer
(frequency noise of the primary laser relative to the secondary)

optical truss
(stability of the telescope structure)

interference is referenced to the internal proof mass that freely falls “unattached “ to the SC