GRAVITATIONAL WAVE DETECTION FROM SPACE

Philippe Jetzer

University of Zürich

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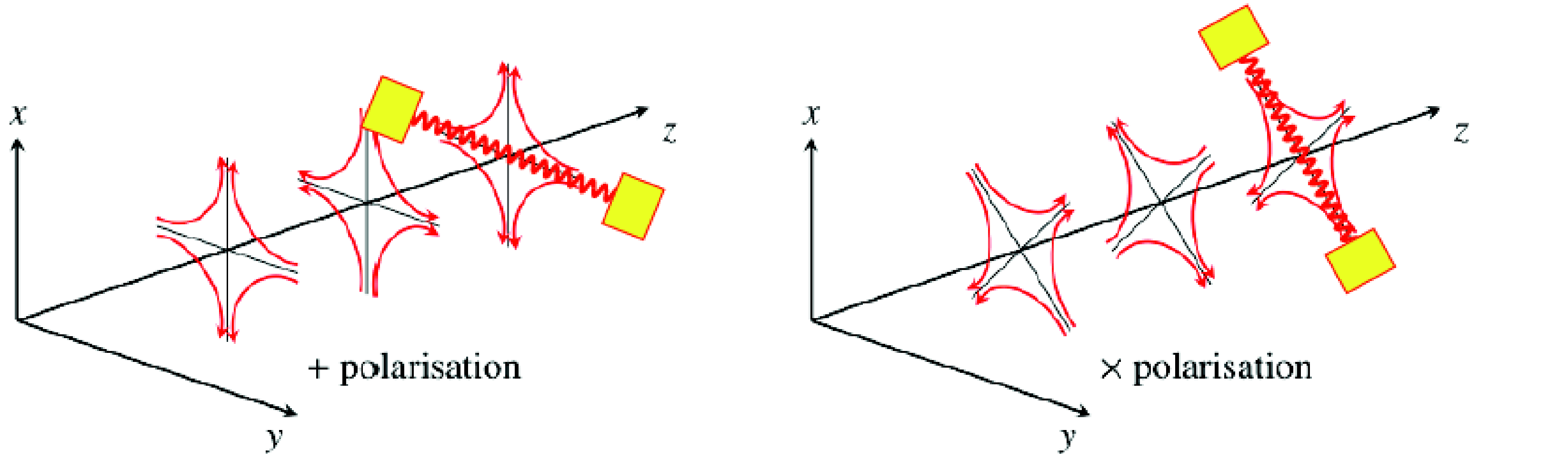
Understanding gravitational waves

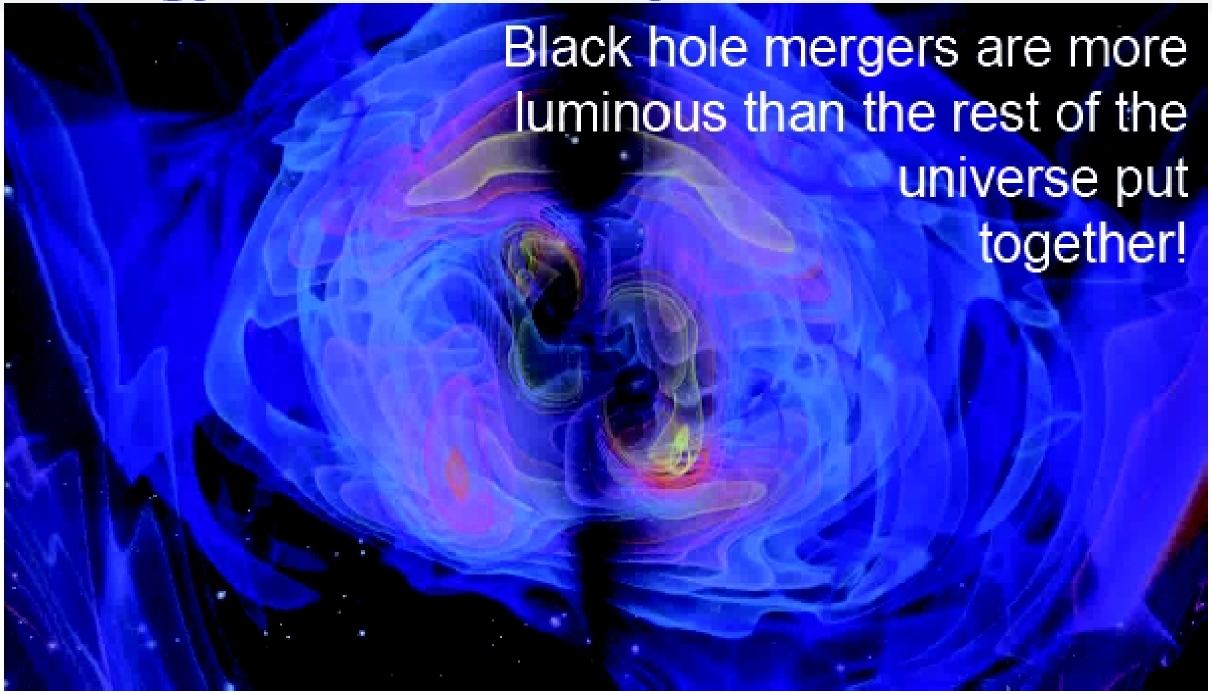
- **Strong analogies with EM radiation**
  - Two transverse polarisations
  - Move at speed of light, follow geometrical optics
  - Same behaviour with gravitational lensing, cosmological redshift
- **Like light, GW phase and polarisation follows source motions**

  Measuring degree of circular polarisation gives ***binary orbit inclination.***
- **Signal phase encodes large-scale source dynamics.**



But GWs *are* different …

- **Coupling of GWs to matter is very different from EM.**
- **Very weak, $h << \varphi/c^2 = GM/rc^2$**
  - This leads to $\delta L/L \sim h \sim 10^{-21}$ to 10^{-24}.
  - $h \sim 1/r$
- **Weakness negligible scatter, absorption: perfect messengers!**
- **Have huge energy flux; luminosity scale is $c^5/G \sim 3.6 \times 10^{59}$ erg/s.**



- **LISA is a mission to detect and observe gravitational waves**
  - Gravitational waves are predicted by any “reasonable” theory of gravity, yet not directly detected.
  - Gravitational waves are a tool for astronomers, astrophysicists and cosmologists
- **LISA will address important questions in fundamental physics, astrophysics and cosmology.**
  - Precision tests of GR
  - Nature of objects in the center of galaxies
  - History and evolution of galaxies
  - Structure formation in the Universe

- *Does gravity travel at the speed of light ?*
- *Does the graviton have mass?*
- *How does gravitational information propagate: Are there more than two transverse modes of propagation?*
- *Does gravity couple to other dynamical fields, such as, massless or massive scalars?*
- *What is the structure of spacetime just outside astrophysical black holes? Do their spacetimes have horizons?*
- *Are astrophysical black holes fully described by the Kerr metric, as predicted by General Relativity?*

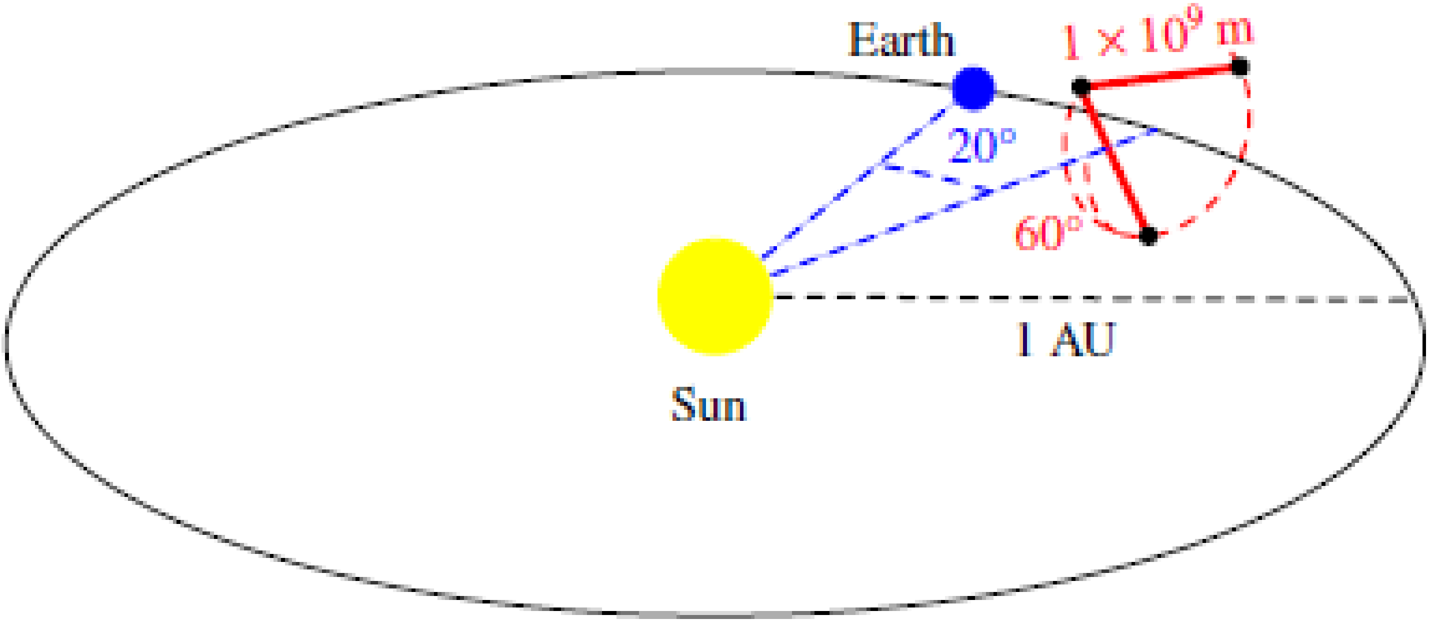
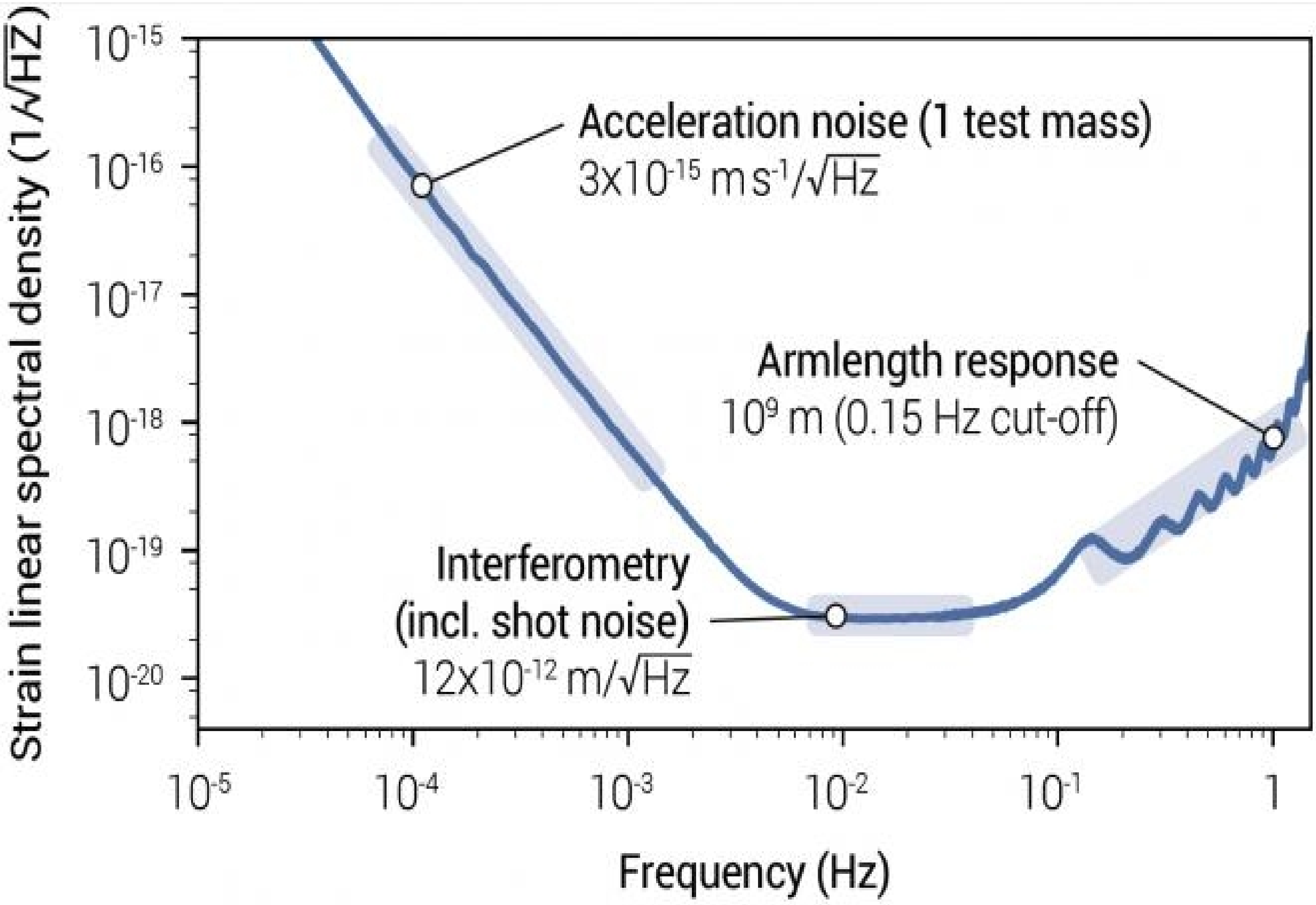


Figure 1: The eLISA orbits: The constellation is shown trailing the Earth by about 20 degrees (or 5×10^{10}km) and is inclined by 60 degrees with respect to the ecliptic. The trailing angle will vary over the course of the mission duration from 10 degrees to 25 degrees. The separation between the spacecraft is $L = 1 \times 10^9$ m.

eLISA - Sensitivity



Science Objectives

Through the detection and observation of gravitational waves:

- Trace the formation, growth, and merger history of massive black holes
- Explore stellar populations and dynamics in galactic nuclei
- Test General Relativity with observations
- Probe new physics and cosmology
- Survey compact stellar-mass binaries and study the structure of the Galaxy

Event Rates and Event Numbers

Frequency band	1×10^{-4} Hz to 1 Hz, (3×10^{-5} Hz to 1 Hz as a goal)
Massive black hole mergers	$10\ \mathrm{yr}^{-1}$ to $100\ \mathrm{yr}^{-1}$
Extreme mass ratio inspirals	$5\ \mathrm{yr}^{-1}$ to $50\ \mathrm{yr}^{-1}$
Galactic Binaries	~ 3000 resolvable out of a total of ~ 30×10^6 in the *eLISA* band

Figure 5: Artist impression of a detached double white dwarf binary (left) and an interacting binary in which a neutron star accretes material from a white dwarf donor. The Earth is shown to set the scale. Courtesy BinSim by Rob Hynes.

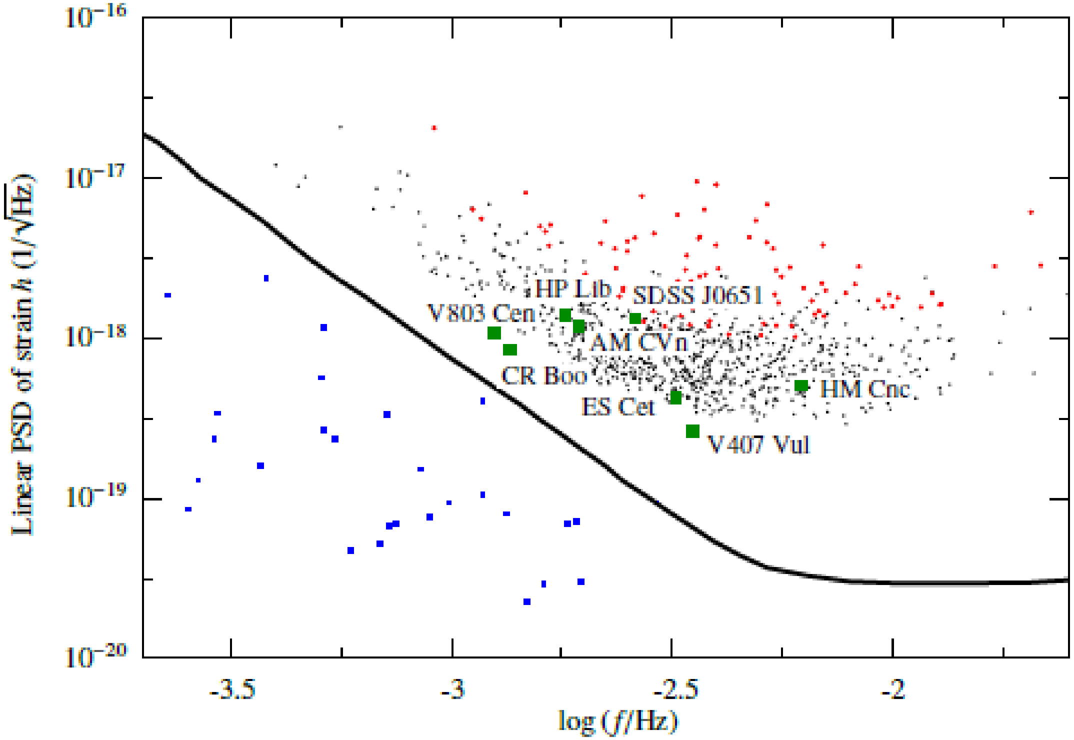


Figure 6: Strain amplitude spectral density versus frequency for the verification binaries and the brightest binaries,expected from a simulated Galactic population of ultra-compact binaries. The solid line shows the sensitivity of eLISA. Verification binaries are indicated as green squares with their names indicated, blue squares are other known binaries. Strongest 100 simulated binaries are shown in red, strongest 1000 as black dots. The integration time for the binaries is two years. Based on Brown et al. (2011), Roelofs et al. (2006, 2010) for the known binaries and Nelemans et al. (2004) for the simulation.

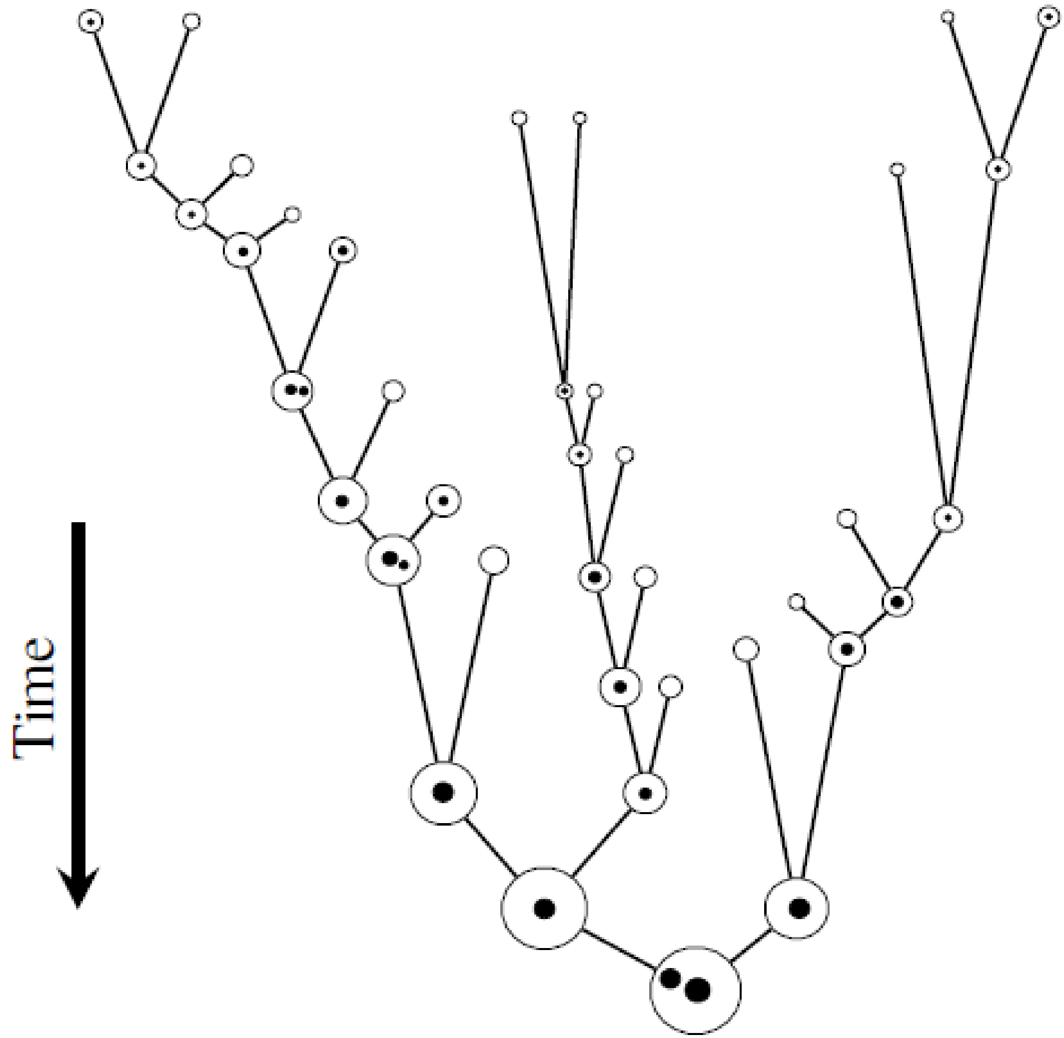


Figure 13: A cartoon of the merger-tree history for the assembly of a galaxy and its central black holes. Time increases along the arrow. Here the final galaxy is assembled through the merger of twenty smaller galaxies housing three seed black holes, and four coalescences of binary black holes.

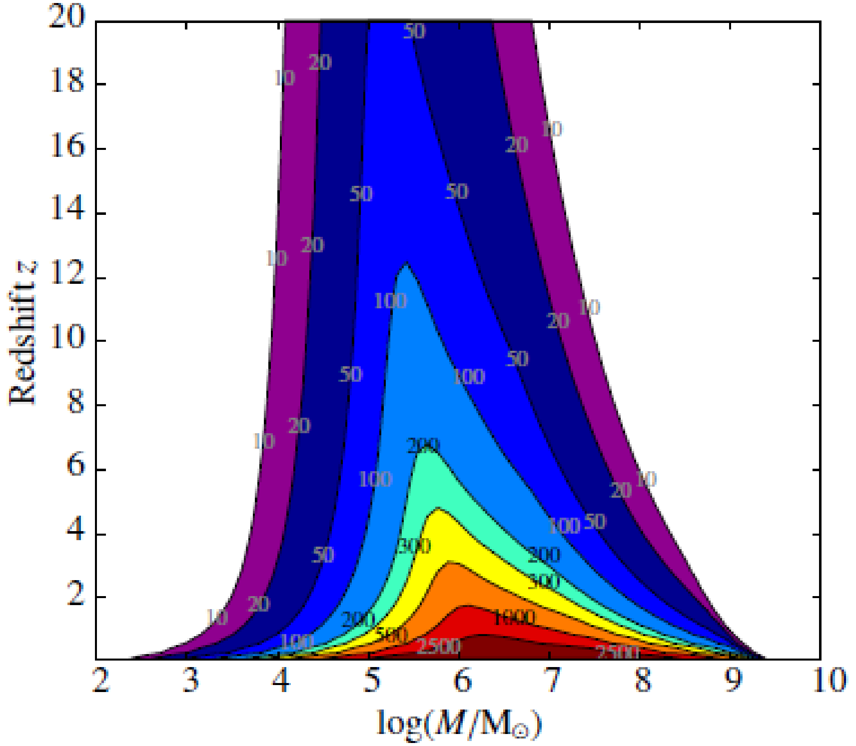
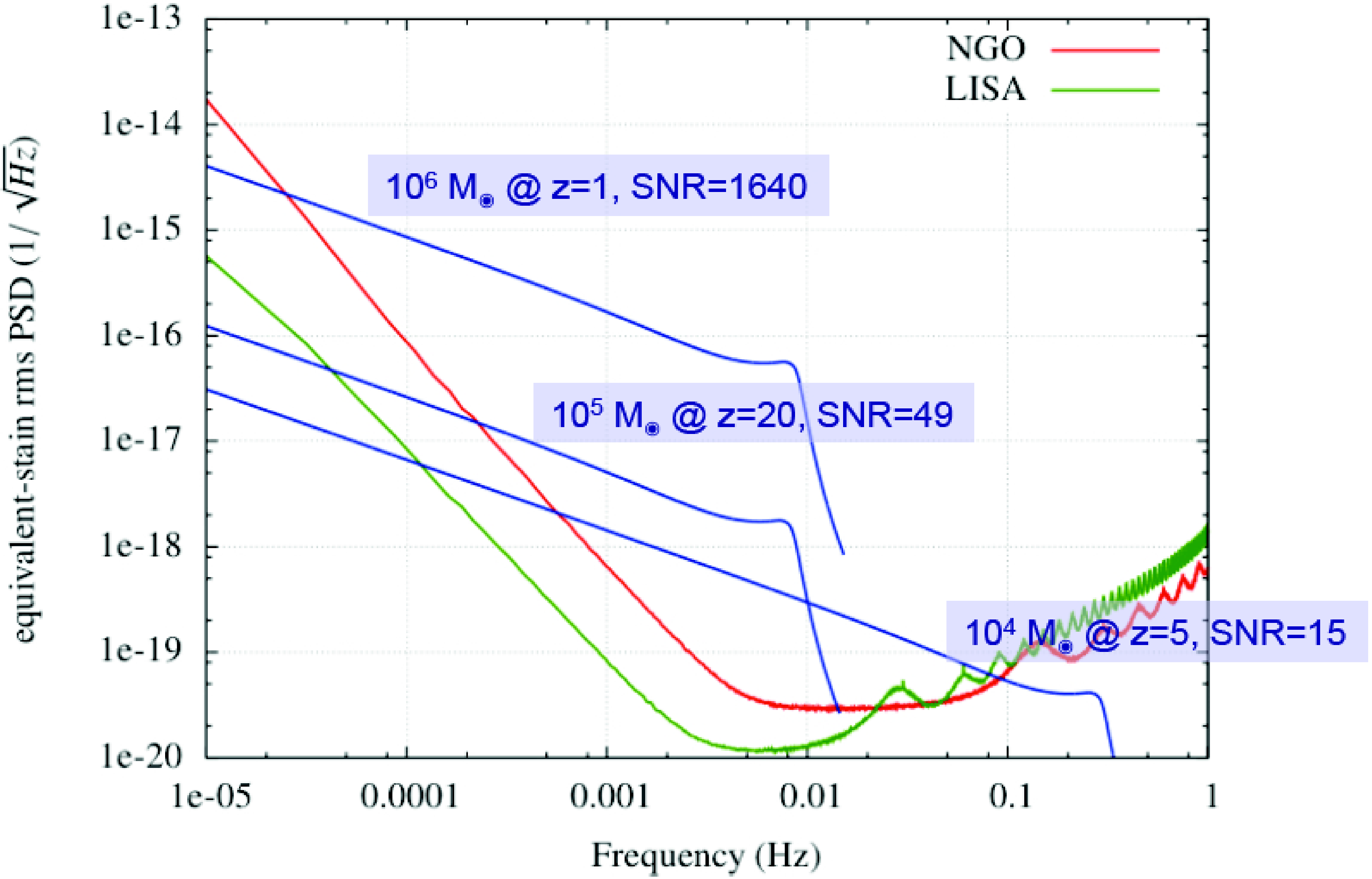


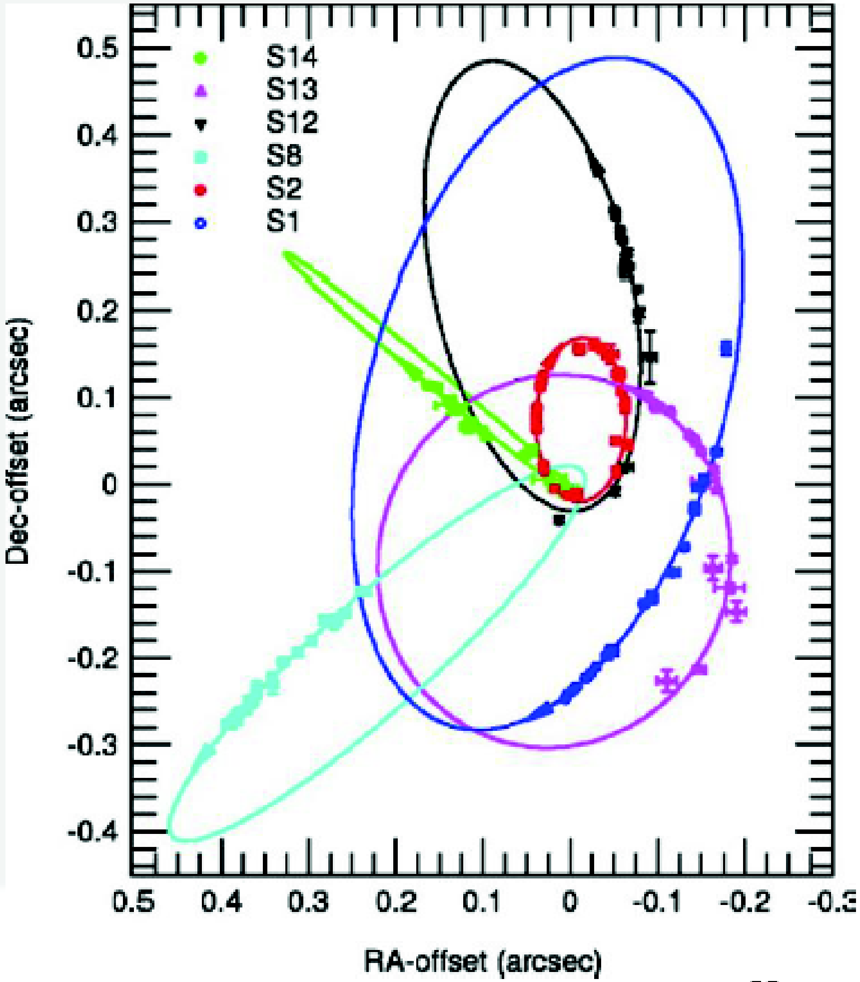
Figure 16: Constant-contour levels of the sky and polarisation angle-averaged signal-to-noise ratio (SNR) for equal mass non-spinning binaries as a function of their total mass M and cosmological redshift z. The total mass M is measured in the rest frame of the source. The SNR is computed using PhenomC waveforms (Santamaría et al., 2010), which are inclusive of the three phases of black hole coalescence (in jargon: inspiral, merger, and ring-down, as described in the text).

Sensitivity and BH Science of NGO



Extreme Mass-Ratio Inspirals: EMRIs

- **Stellar-mass BH capture by a massive BH: dozens per year to z~0.7.**
- **We have measured the mass of the GC BH using a few stars and with at most 1 orbit each, still far from horizon.**
- **Imagine the accuracy when we have 10^5 orbits very close to horizon! GRACE/GOCE for massive BHs.**
  - Prove horizon exists.
  - Test the no-hair theorem to 1%.
  - Measure masses of holes to 0.1%, spin of central BH to 0.001.
  - Population studies of central and cluster BHs.
  - Find IMBHs: captures of 10^3 M_o BHs.



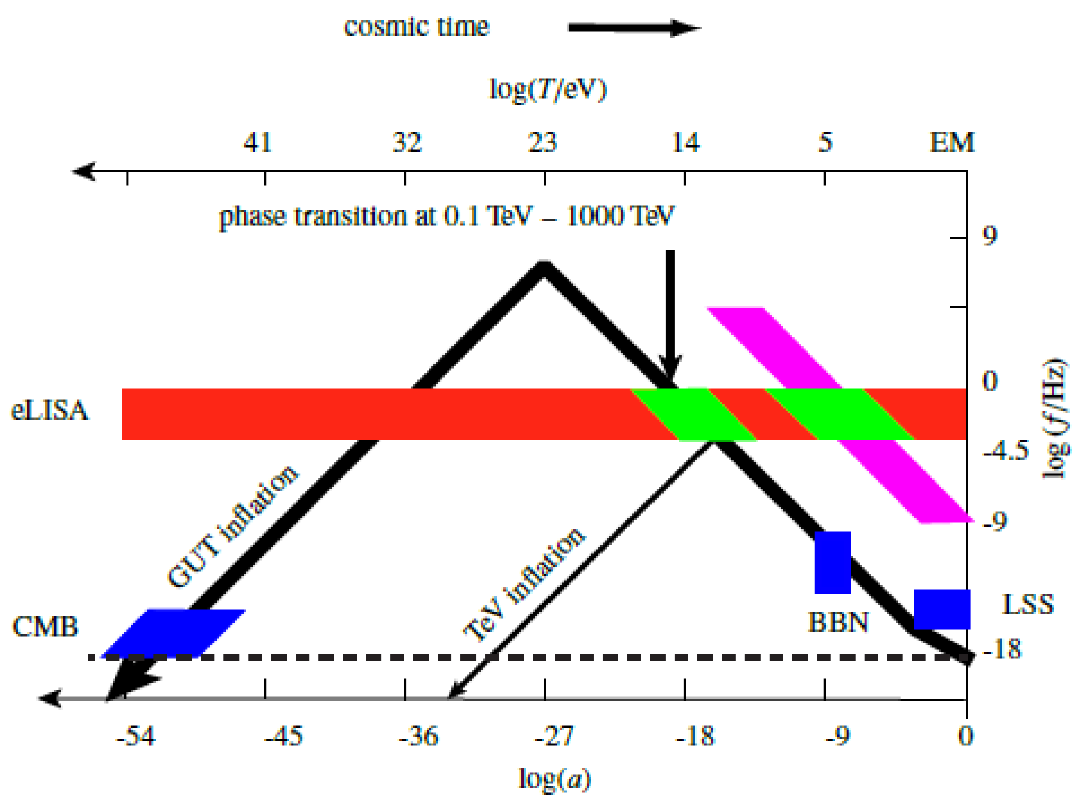
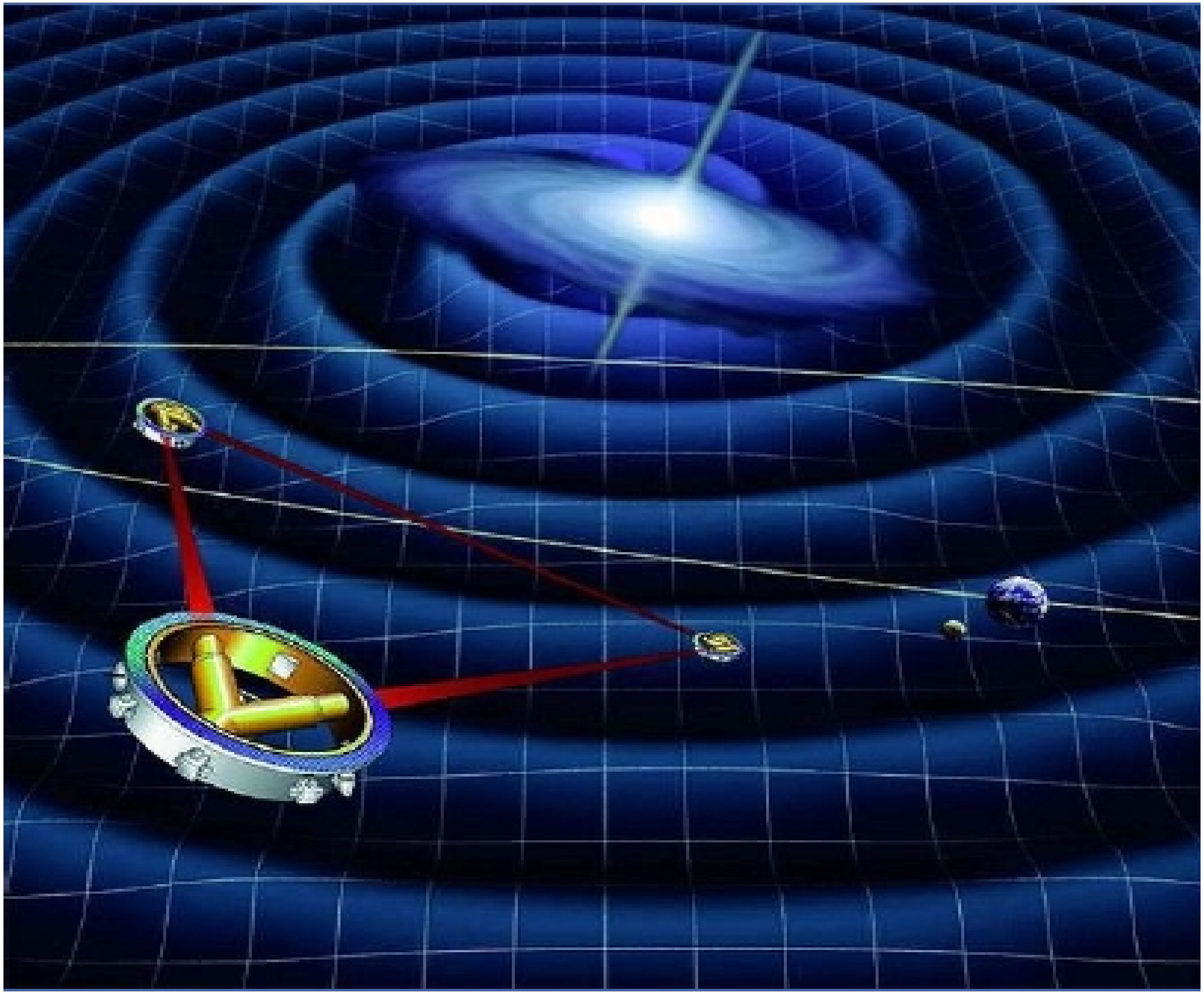
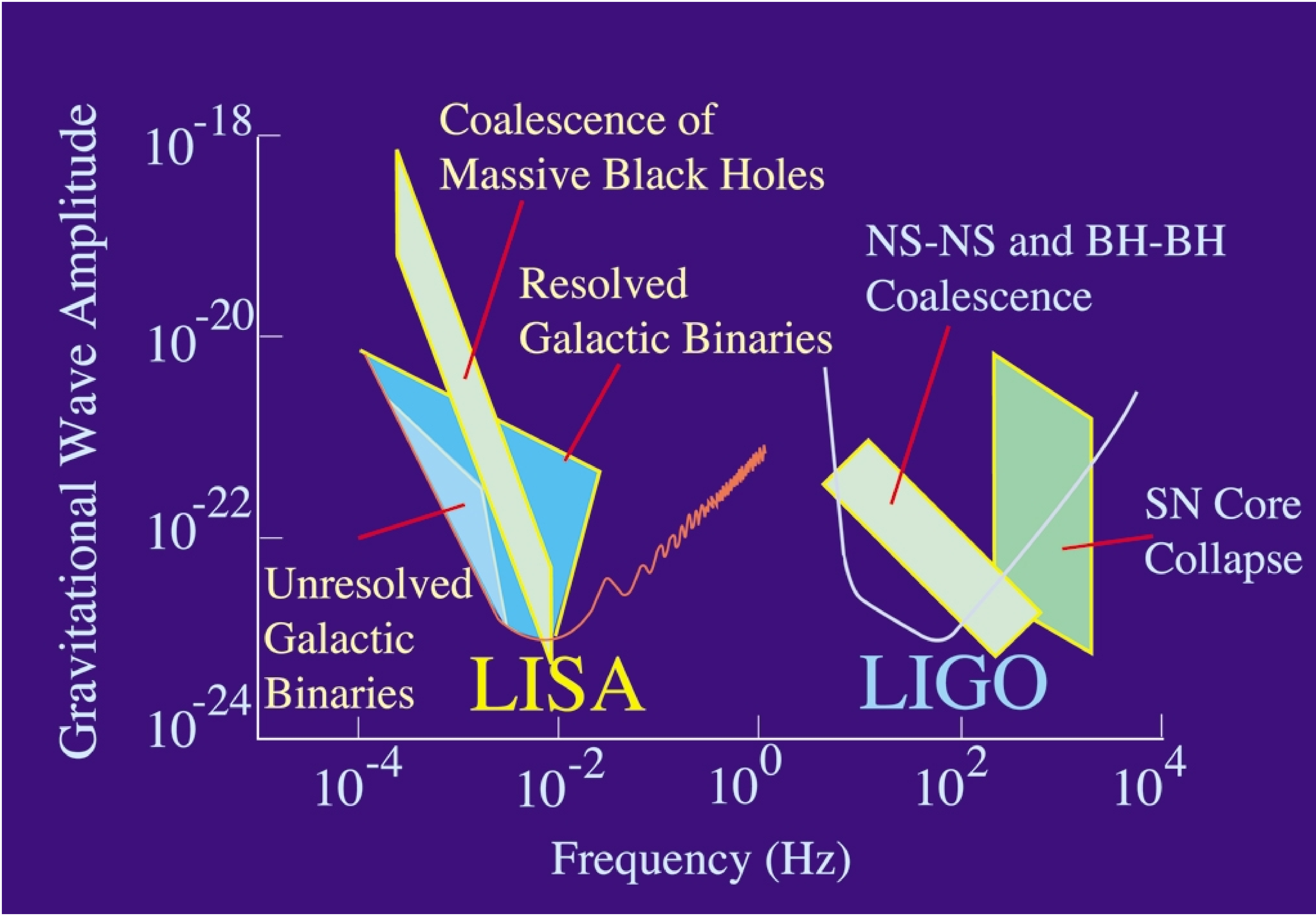


Figure 25: The observed (redshifted) frequency of wave-generating phenomena is shown as a function of cosmic scale factor a, with the present epoch at the right. The redshifted Hubble rate (horizon scale) is shown in black for a standard Grand Unified Theory (GUT) and a lower temperature Terascale (TeV) inflationary cosmology. Blue regions are accessible to electromagnetic (EM) observations: the Universe since recombination (right box) and cosmic microwave background (CMB) fluctuations (left box). The red bar shows the range of cosmic history accessible through eLISA from processes within the horizon up to about 1000 TeV.

LIGO (Laser Interferometer Gravitational wave Observatory) Handford (USA).

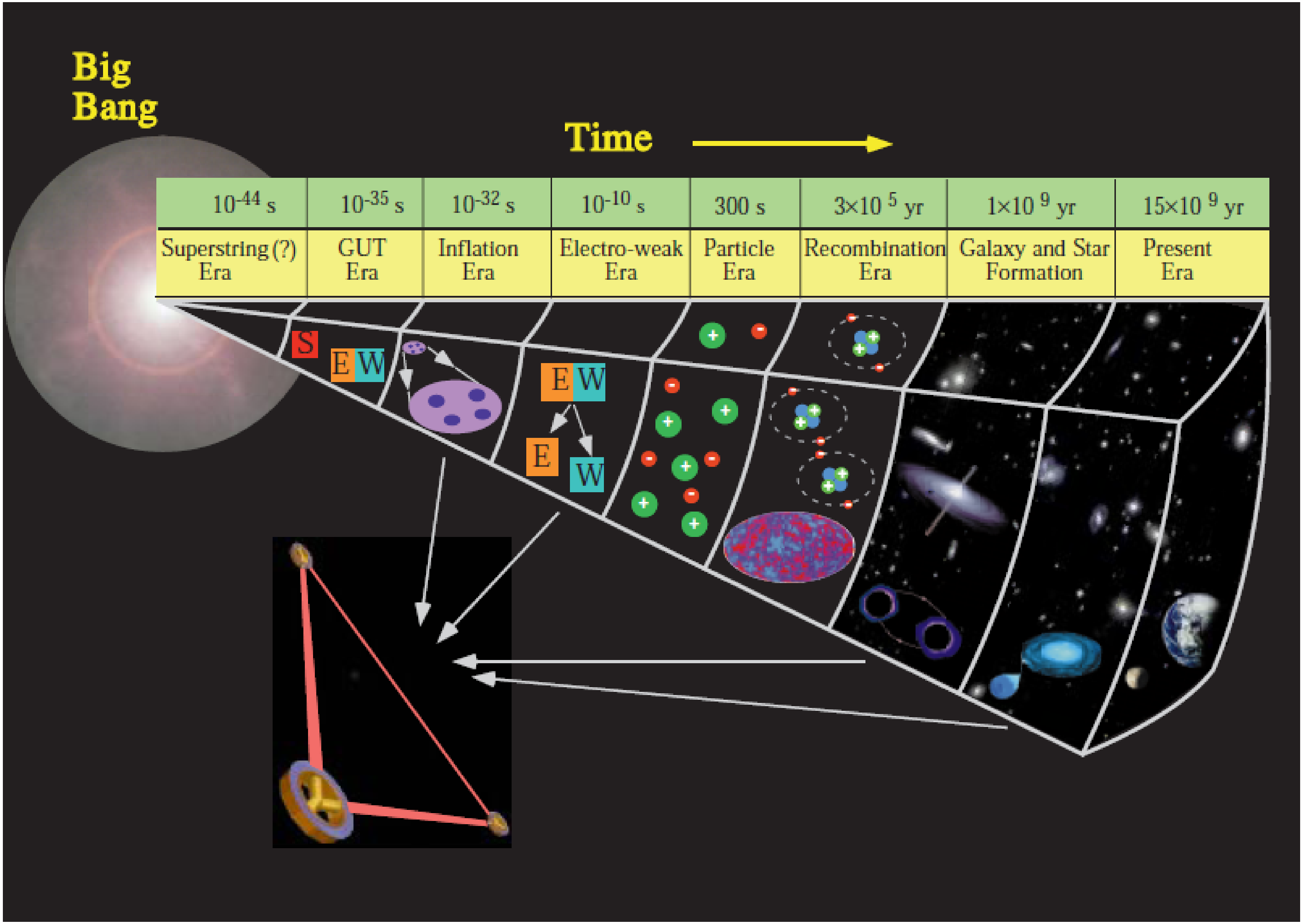


LISA (Laser Interferometer Space Antenna)



Gravitational Wave Amplitude
10^{-18}
10^{-20}
10^{-22}
10^{-24}
Coalescence of
Massive Black Holes
Resolved
Galactic Binaries
Unresolved
Galactic
Binaries
NS-NS and BH-BH
Coalescence
SN Core
Collapse
LISA
LIGO
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
Frequency (Hz)

VIDEO eLISA

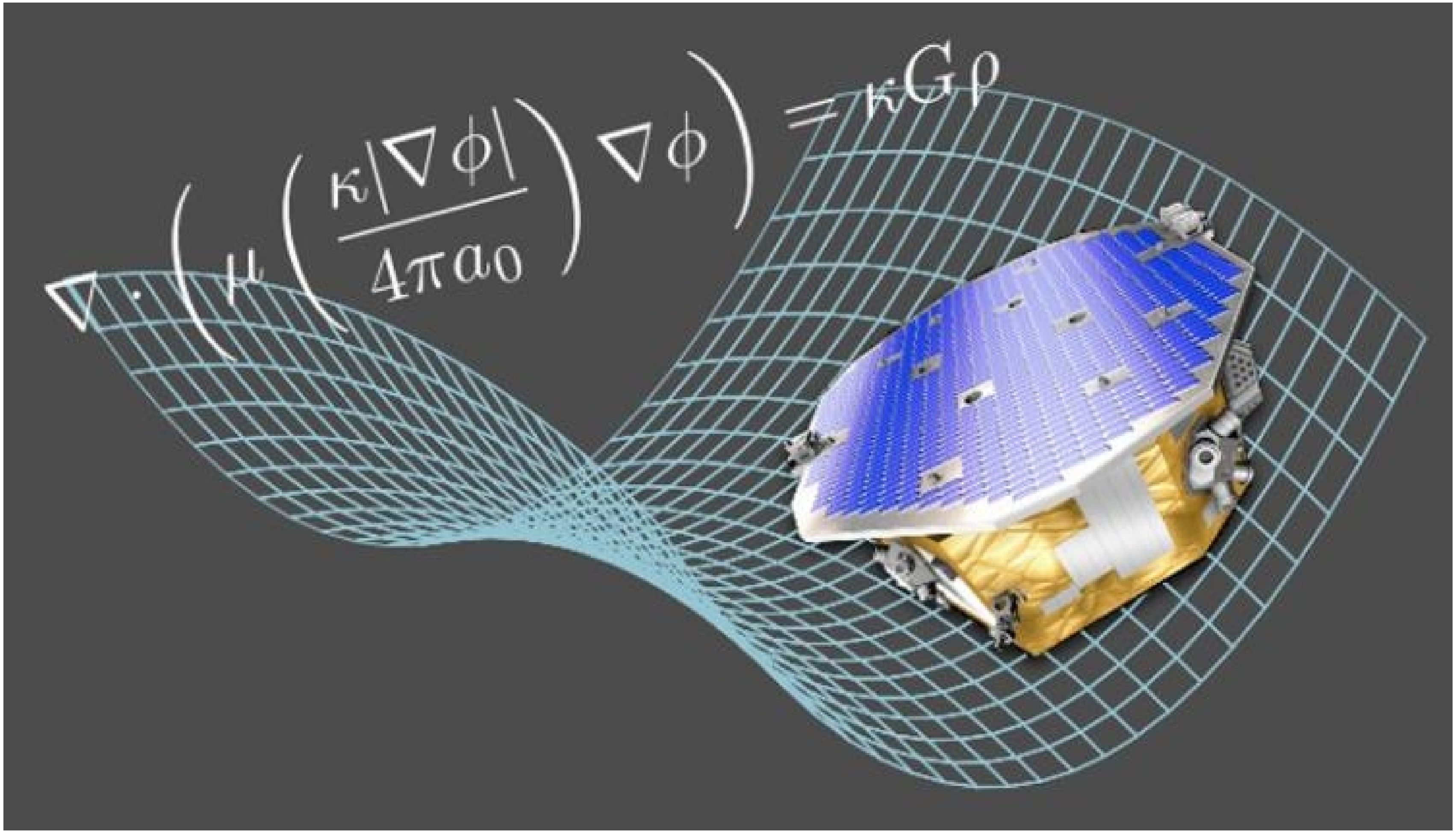

Big Bang
Time
10-44 s
10-35 s
10-32 s
10-10 s
300 s
3×10 5 yr
1×10 9 yr
15×10 9 yr
Superstring (?) Era
GUT Era
Inflation Era
Electro-weak Era
Particle Era
Recombination Era
Galaxy and Star Formation
Present Era
S
E W
E W
E
W

Introduction

- LISA Pathfinder is a technology verification mission for LISA
  - LPF was approved by ESA to demonstrate the concept of low frequency gravitational wave detection in space
- The LISA Pathfinder will test in flight:
  - Inertial sensors
  - Interferometry between free floating test masses
  - Drag Free and Attitude Control System (DFACS)
  - Micro-Newton propulsion technology
    - Field Emission Electric Propulsion (FEEP)
    - Colloidal thrusters (provided by NASA - JPL)
- The basic idea of LISA Pathfinder is to squeeze one arm of the LISA constellation from 5 million km to a few tens of cm!

LISA Pathfinder
launch in 2015


IABG


$\nabla \cdot \left(\mu \left(\frac{\kappa |\nabla \phi|}{4\pi a_0} \right) \nabla \phi \right) = \kappa G \rho$