GRAVITATIONAL WAVES: A NEW WINDOW TO EXPLORE THE UNIVERSE

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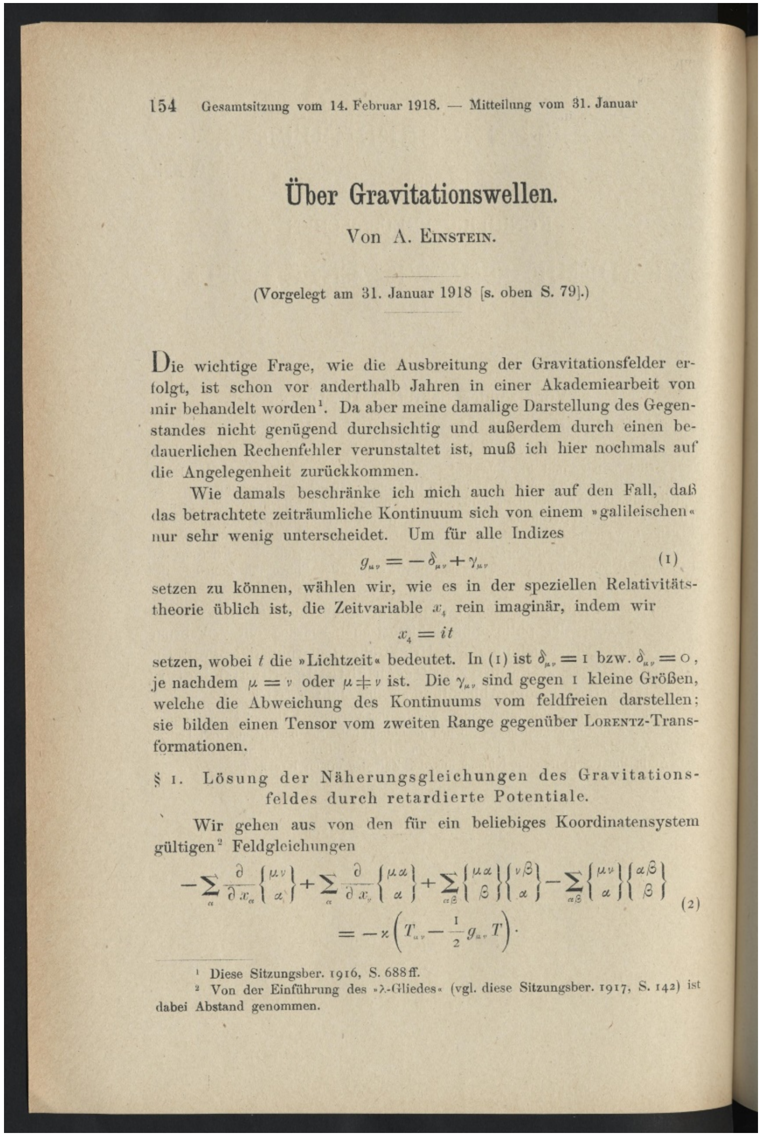
Gravitational Waves

2 December 1915:
Einstein completes General Relativity
(A. Einstein,
Sitz. Ber. Preuss. Akad. Wiss. Berlin,
- December 1915, 844-847)

June 1916:
Gravitational Waves are predicted
(A. Einstein,
Sitz. Ber. Preuss. Akad. Wiss. Berlin,
- June 1916, 688-696
- January 1918, 154-167)



154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

Über Gravitationswellen.

Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

Wie damals beschränke ich mich auch hier auf den Fall, daß das betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

setzen zu können, wählen wir, wie es in der speziellen Relativitätstheorie üblich ist, die Zeitvariable x_4 rein imaginär, indem wir

$$x_4 = it$$

setzen, wobei t die »Lichtzeit« bedeutet. In (1) ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$ ist. Die $\gamma_{\mu\nu}$ sind gegen 1 kleine Größen, welche die Abweichung des Kontinuums vom feldfreien darstellen; sie bilden einen Tensor vom zweiten Range gegenüber Lorentz-Transformationen.

§ 1. Lösung der Näherungsgleichungen des Gravitationsfeldes durch retardierte Potentiale.

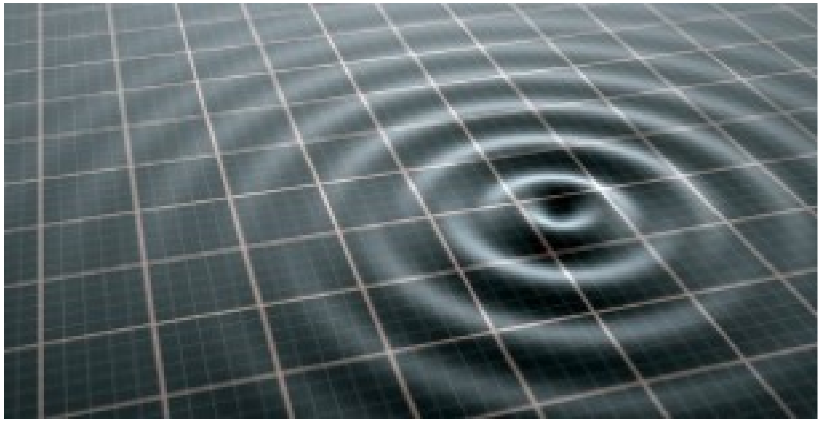
Wir gehen aus von den für ein beliebiges Koordinatensystem gültigen[2] Feldgleichungen

$$-\sum_\alpha \frac{\partial}{\partial x_\alpha} \begin{Bmatrix} \mu\nu \\ \alpha \end{Bmatrix} + \sum_\alpha \frac{\partial}{\partial x_\nu} \begin{Bmatrix} \mu\alpha \\ \alpha \end{Bmatrix} + \sum_{\alpha\beta} \begin{Bmatrix} \mu\alpha \\ \beta \end{Bmatrix} \begin{Bmatrix} \nu\beta \\ \alpha \end{Bmatrix} - \sum_{\alpha\beta} \begin{Bmatrix} \mu\nu \\ \alpha \end{Bmatrix} \begin{Bmatrix} \alpha\beta \\ \beta \end{Bmatrix} = -\varkappa \left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T \right). \qquad (2)$$

[1] Diese Sitzungsber. 1916, S. 688ff.
[2] Von der Einführung des »λ-Gliedes« (vgl. diese Sitzungsber. 1917, S. 142) ist dabei Abstand genommen.

Gravitational Waves

Gravitational waves are solutions of the linearized Einstein Field Equations:

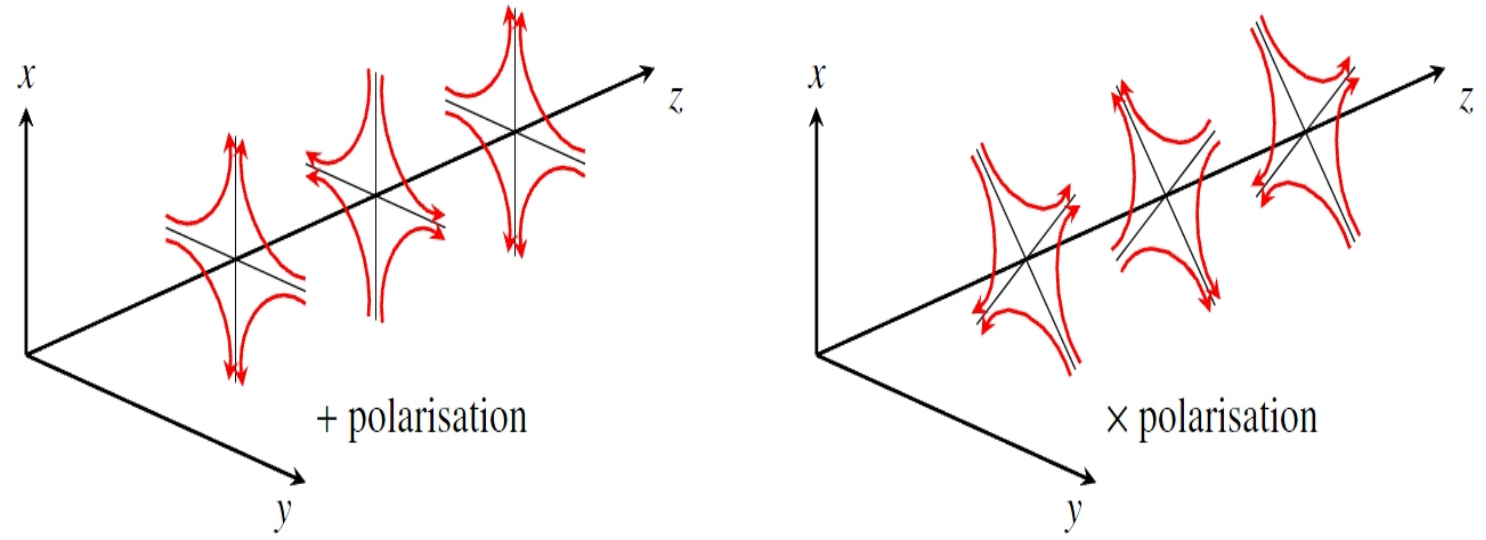


$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \quad \text{with} \quad |h_{\mu\nu}| \ll 1$$

$$G\left[g_{\mu\nu}\right] = \Box h_{\mu\nu} = 0\,, \qquad \Box = \nabla^2 - \frac{1}{c^2}\partial_t^2$$

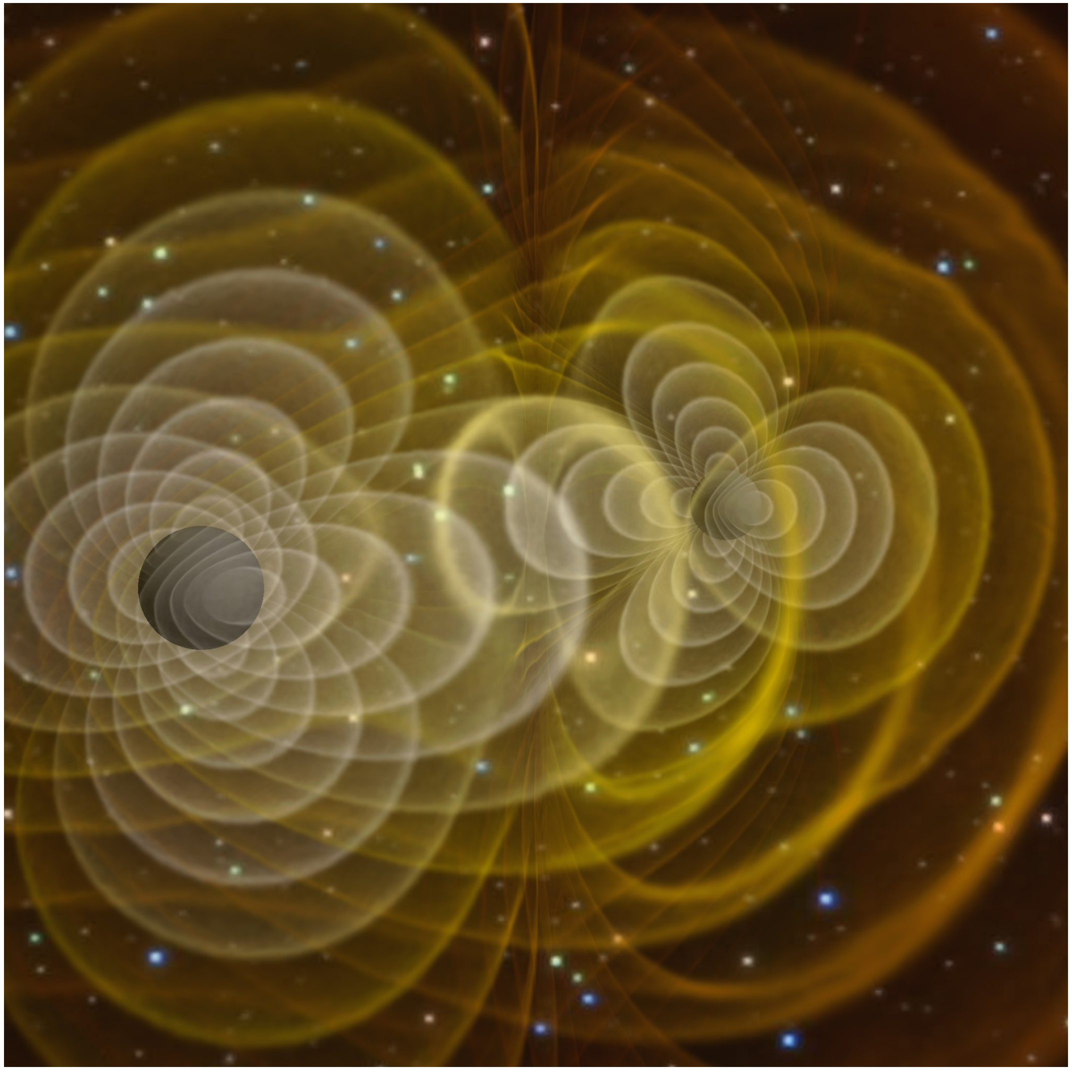
Understanding Gravitational Waves

- Strong analogies with EM radiation
  - Two transverse polarisations
  - Move at the speed of light, follow geometrical optics
  - Same behaviour with gravitational lensing, cosmological redshift

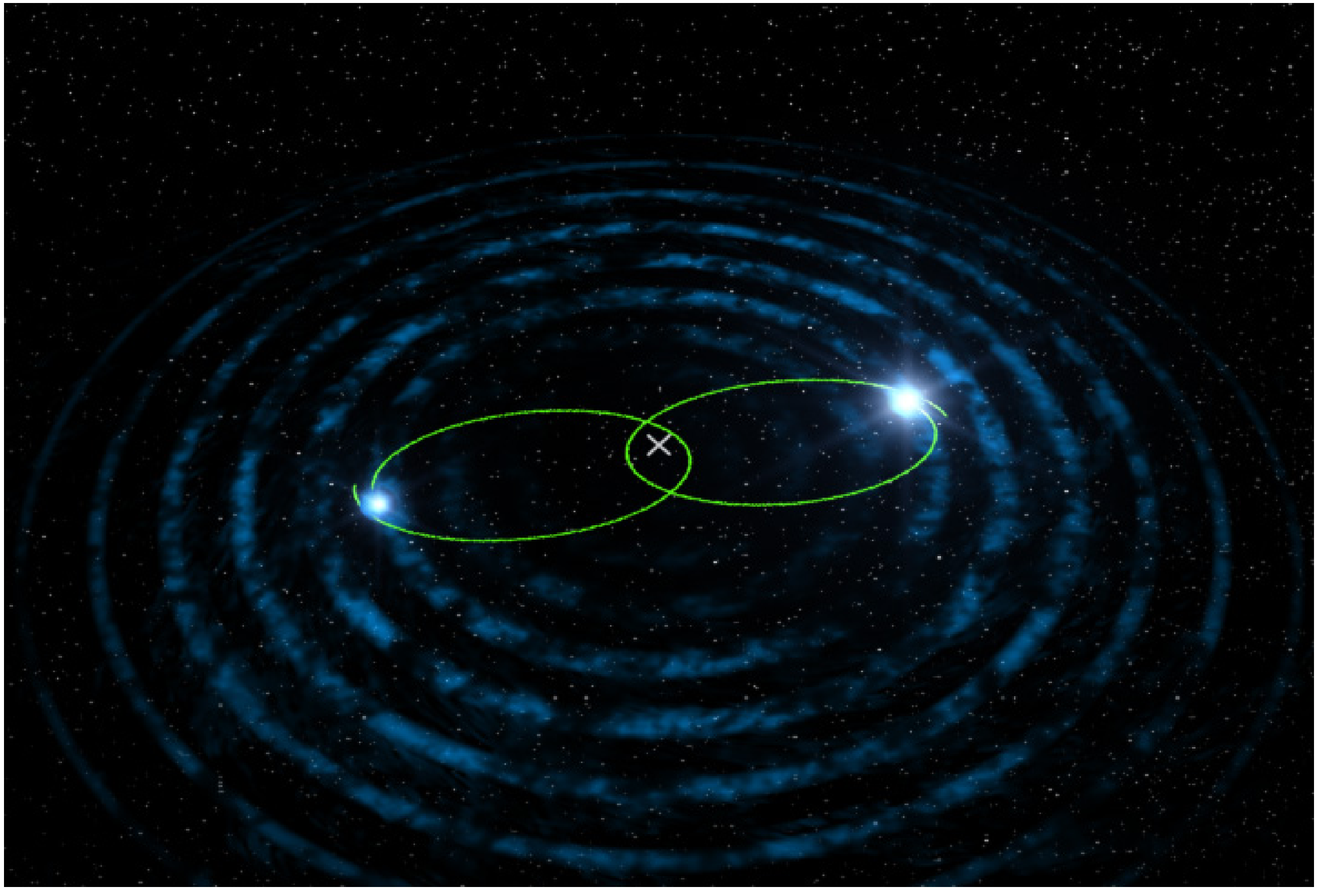


...but GWs *are* different...

- Coupling of GW to matter is very different from EM
- Very weak
  - $h \approx \delta L / L \approx 10^{-21} \ldots 10^{-24}$
  - $h \approx 1 / r$
- Weakness
  - negligible scatter, absorption
  - perfect messengers!
- Huge energy flux
  - luminosity scale is $(c^5/G) \approx 3.6 \cdot 10^{59}$ erg/s

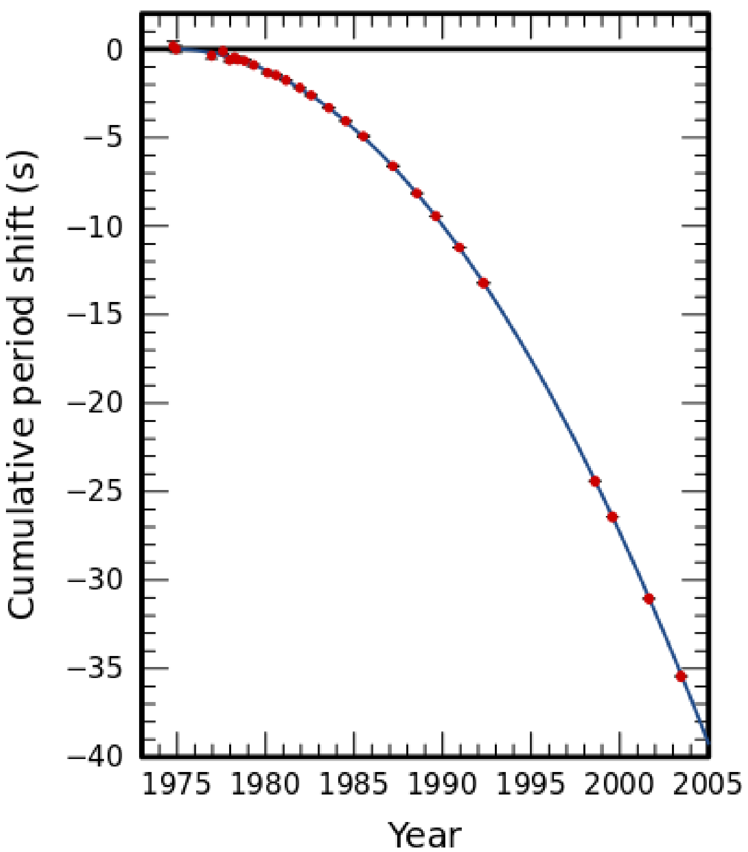


Evidence:
Hulse – Taylor Binary Pulsar discovered in 1974

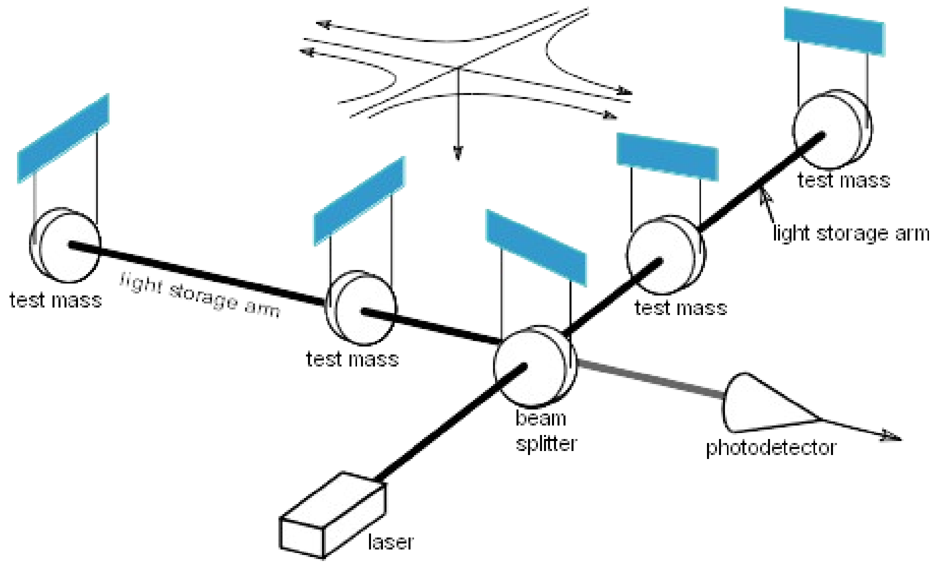


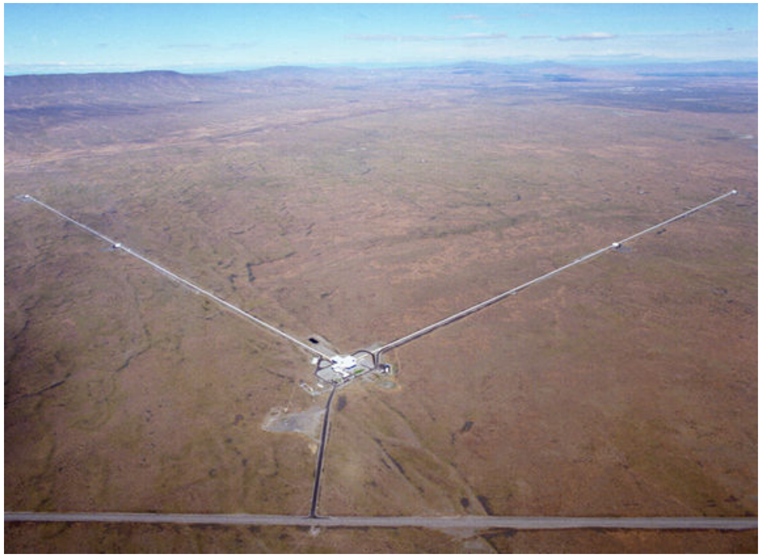
Evidence:
Hulse – Taylor Binary Pulsar discovered in 1974

- Orbital decay of PSR 1913 + 16 binary pulsar systems
  - from data points represent the cumulative shift of periastron time measured whereas the parabola curve shows the same quantity predicted by the General Relativity.
- Mass of both pulsars of about 1.4 solar masses.
- Orbital period: 7.75 hours.

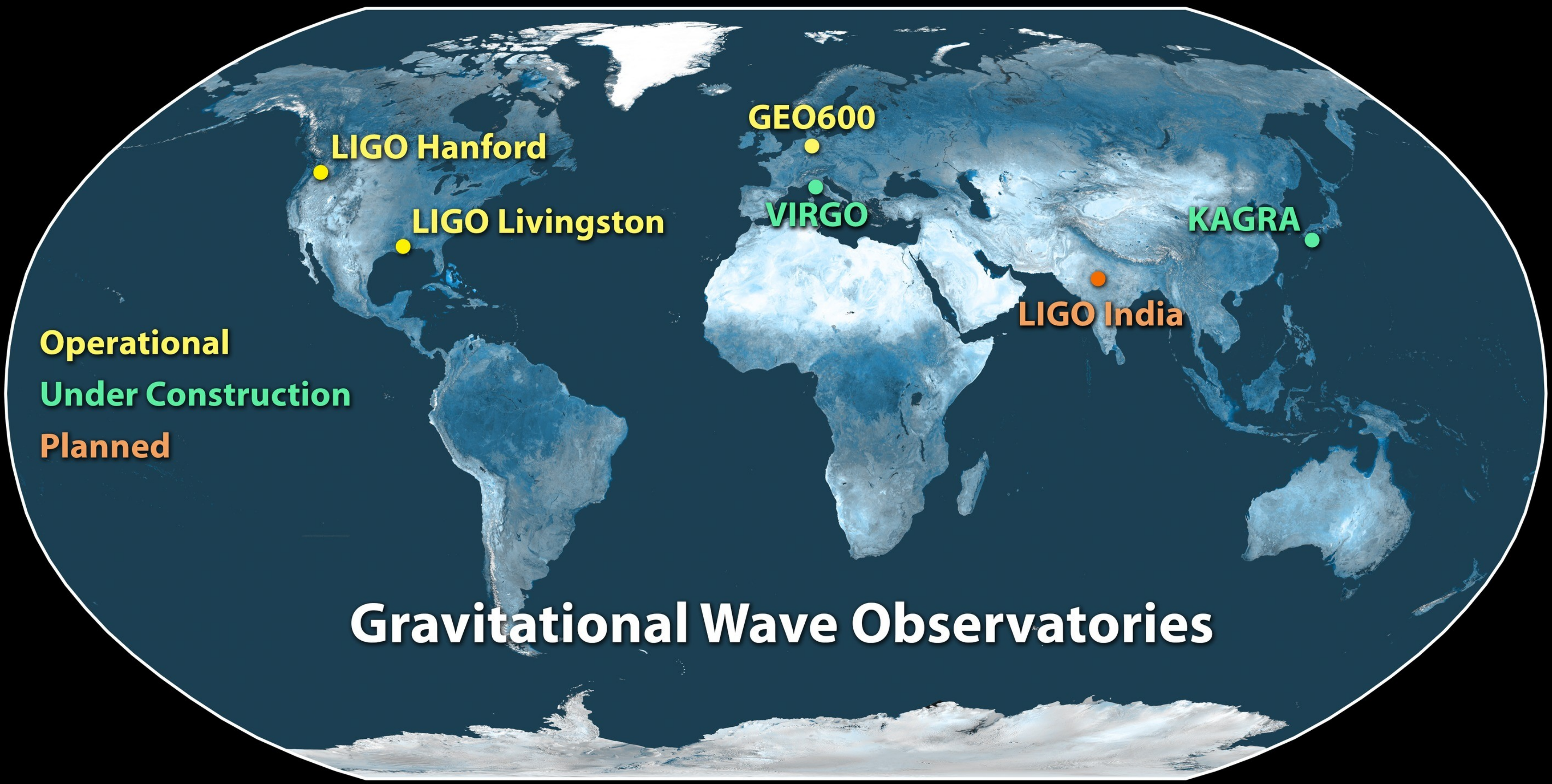


Existing Ground Based GW Detectors

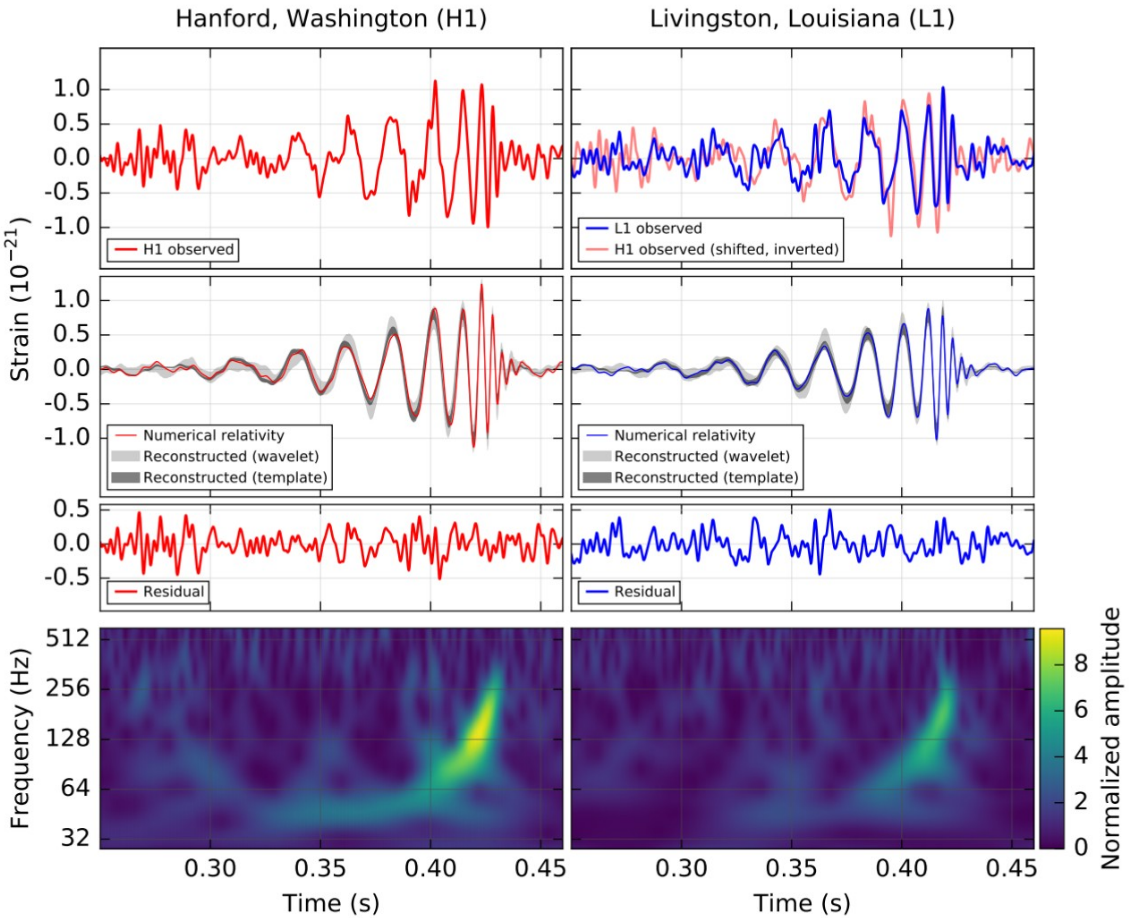


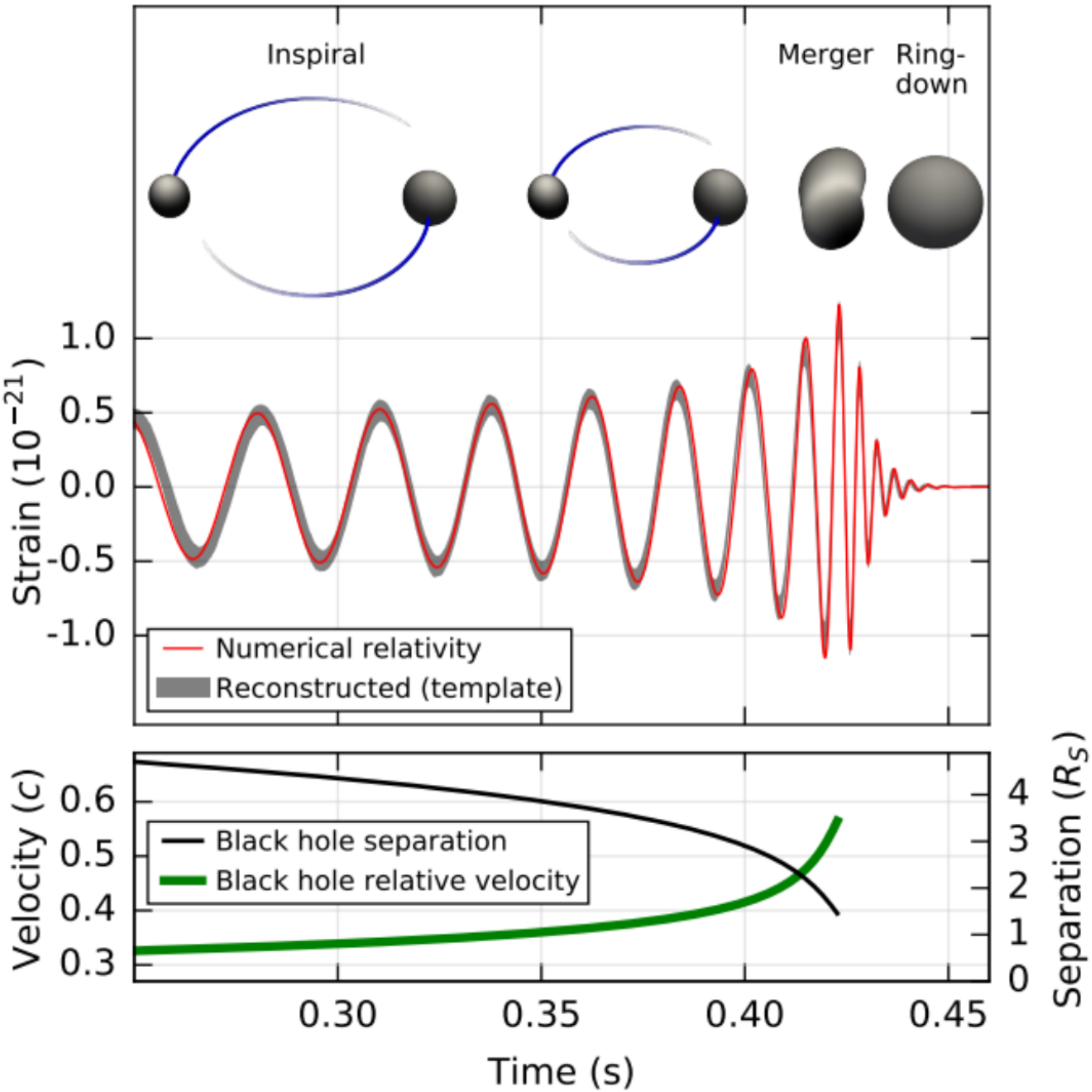


Existing/ Planned Ground Based GW Detectors

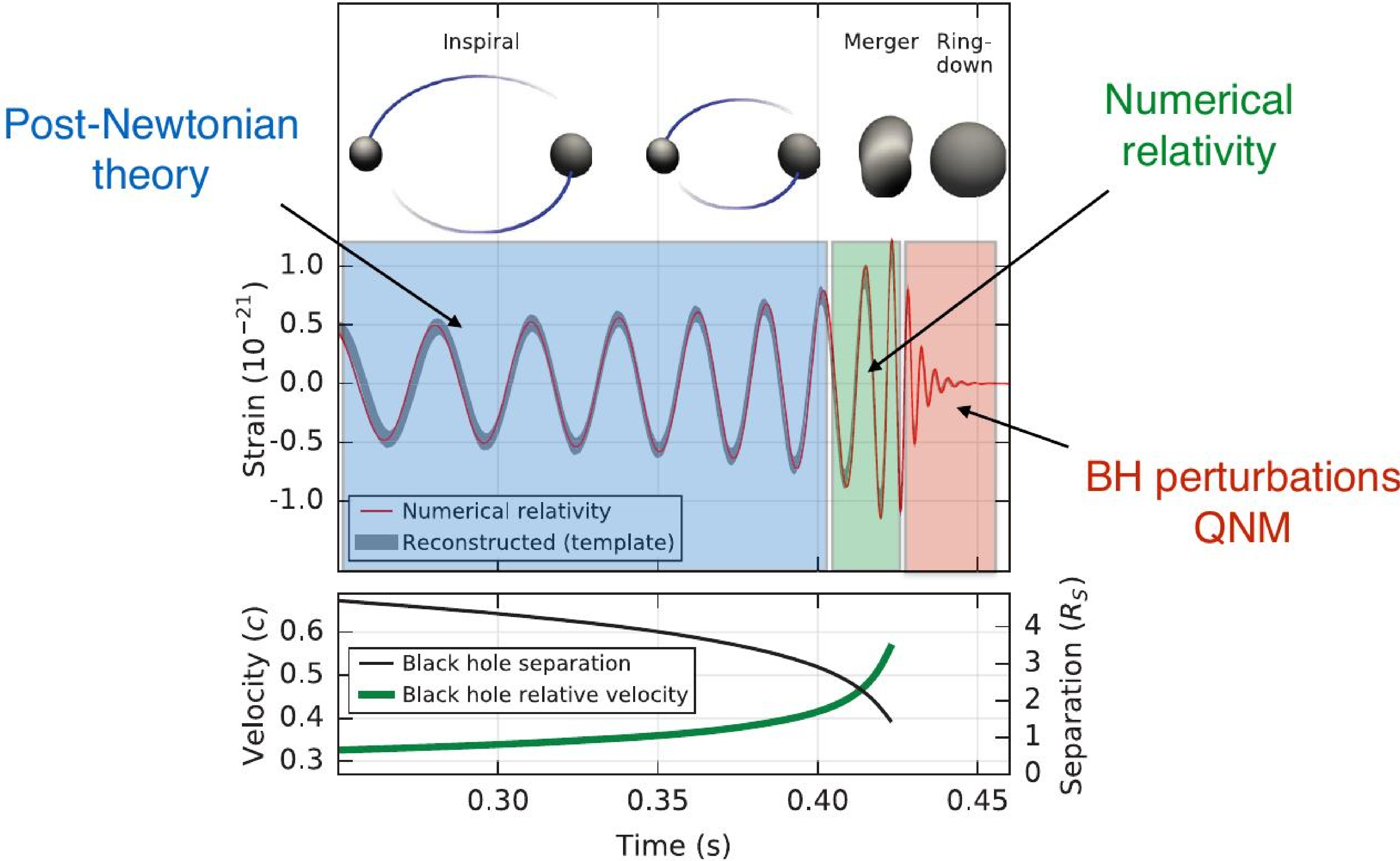


Gravitational wave signal of 14 September 2015





Inspiral
Merger
Ring-
down
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
4
3
2
1
0
0.30
0.35
0.40
0.45
Time (s)



Post-Newtonian theory
Numerical relativity
BH perturbations QNM
Inspiral
Merger
Ring-down
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
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Velocity (c)
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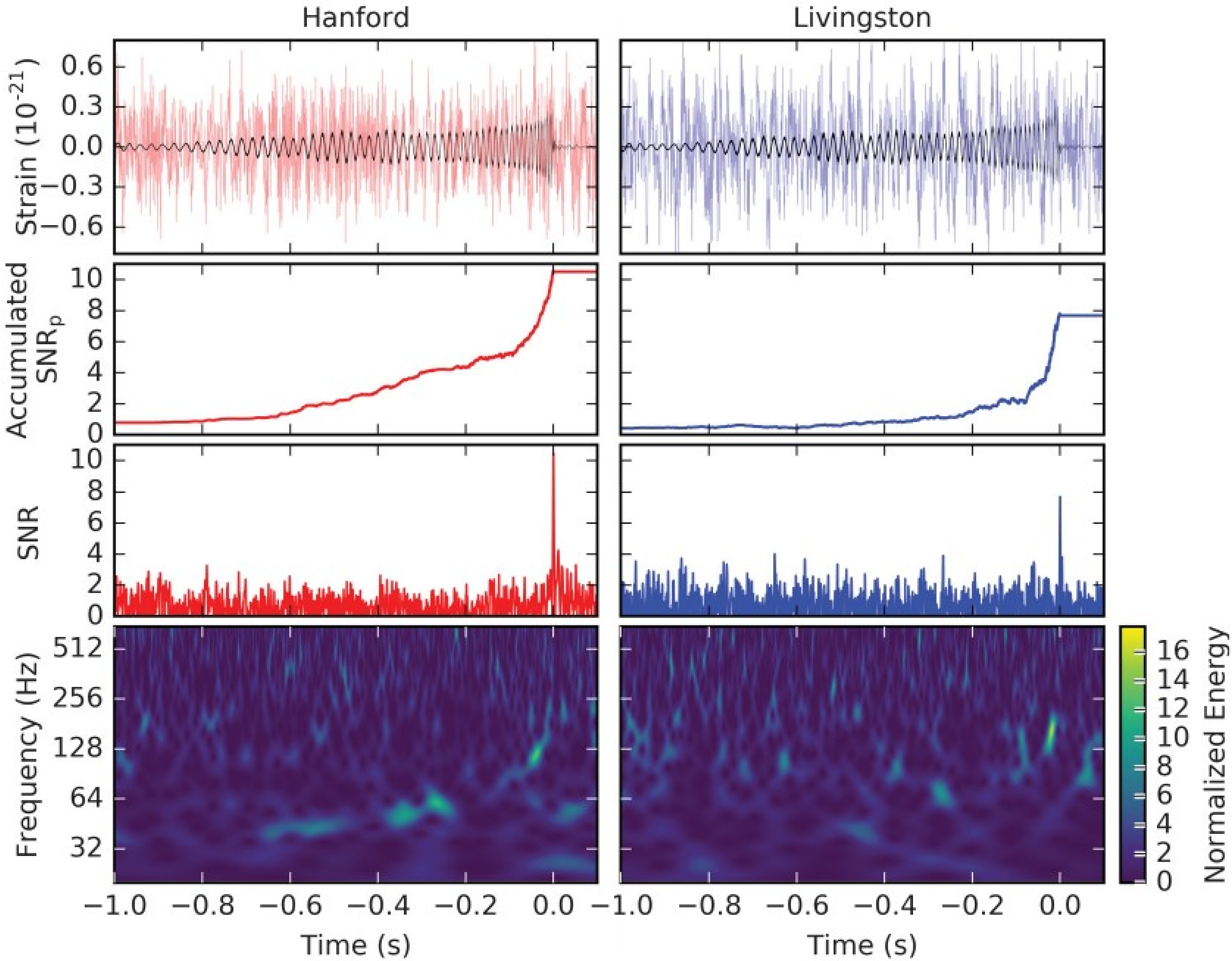


GW151226 observed by the LIGO Hanford (left column) and Livingston (right column) detectors, where times are relative to December 26, 2015 at 03:38:53.648 UTC.

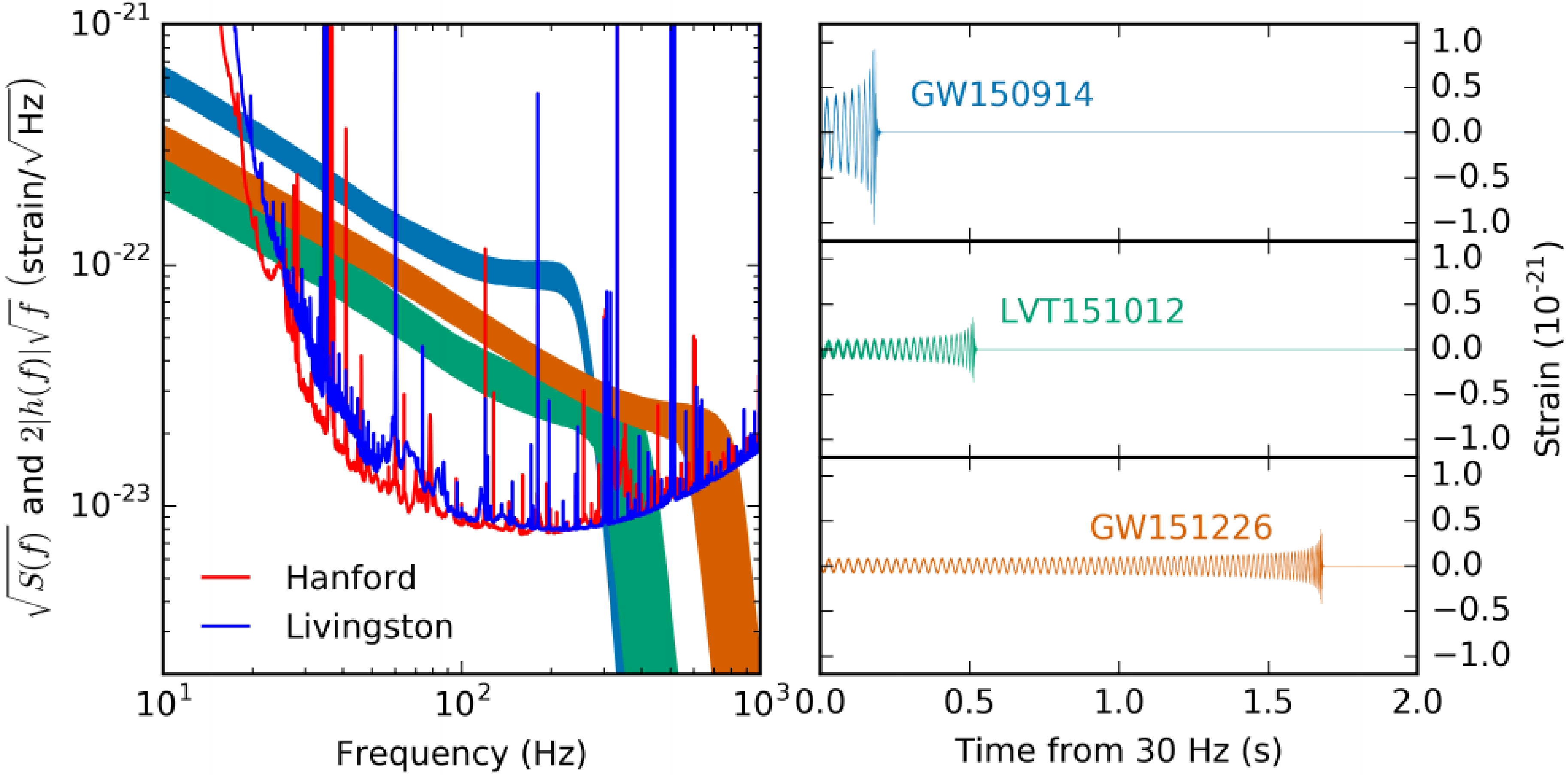
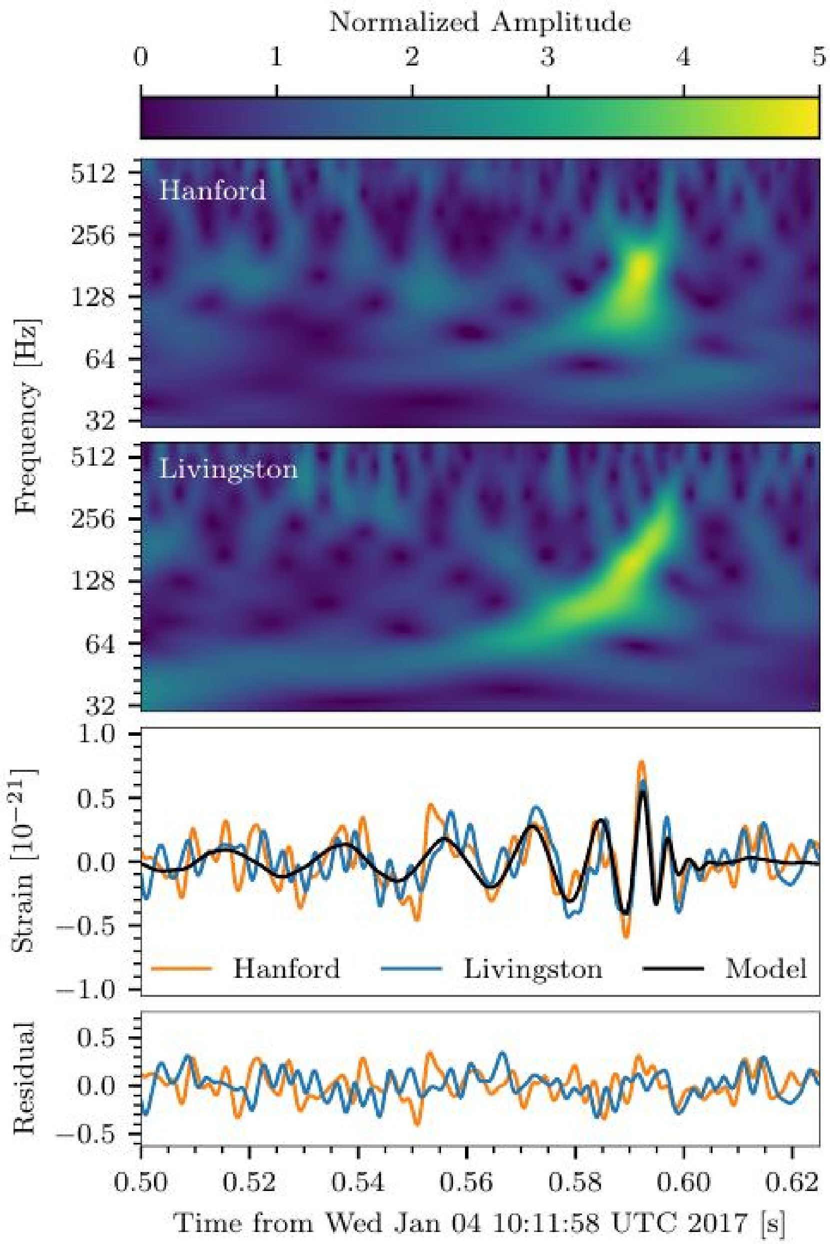


FIG. 1. Left: Amplitude spectral density of the total strain noise of the H1 and L1 detectors, $\sqrt{S(f)}$, in units of strain per $\sqrt{\text{Hz}}$, and the recovered signals of GW150914, GW151226 and LVT151012 plotted so that the relative amplitudes can be related to the SNR of the signal (as described in the text). Right: Time evolution of the waveforms from when they enter the detectors' sensitive band at 30 Hz. All bands show the 90% credible regions of the LIGO Hanford signal reconstructions from a coherent Bayesian analysis using a non-precessing spin waveform model [45].

Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate $\mathrm{FAR/yr^{-1}}$	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\,\sigma$	$> 5.3\,\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathscr{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_{f}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

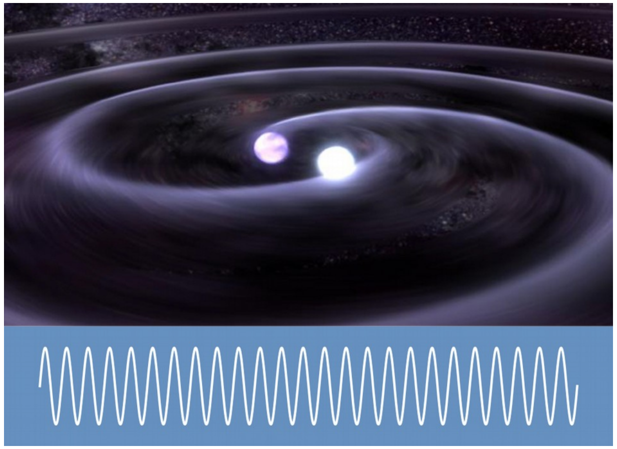
4 January 2017: third event 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2

Coalescence of a 31.2 and a 19.4 Solar mass BH, giving rise to a 48.7 Solar mass Black Hole.

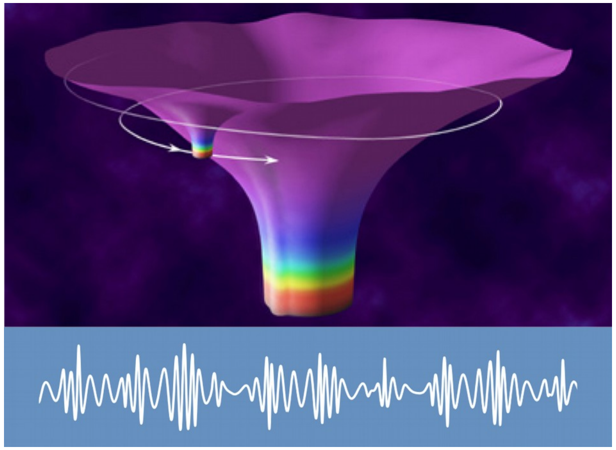


Different Sources – Different Signals

Binary White Dwarfs,
Neutron Stars,
Stellar Black Holes

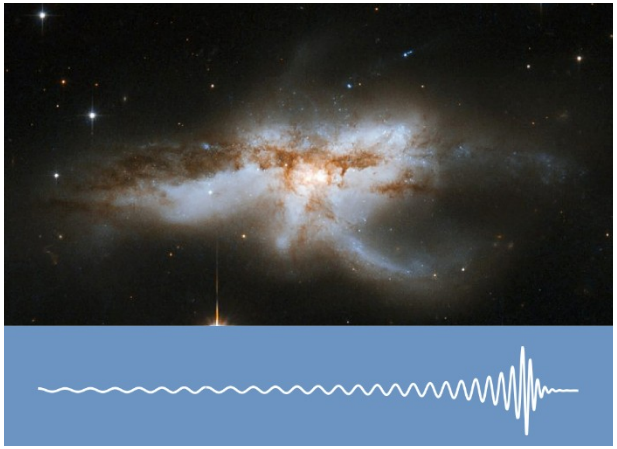


Extreme
Mass-Ratio
In-Spirals (EMRI)

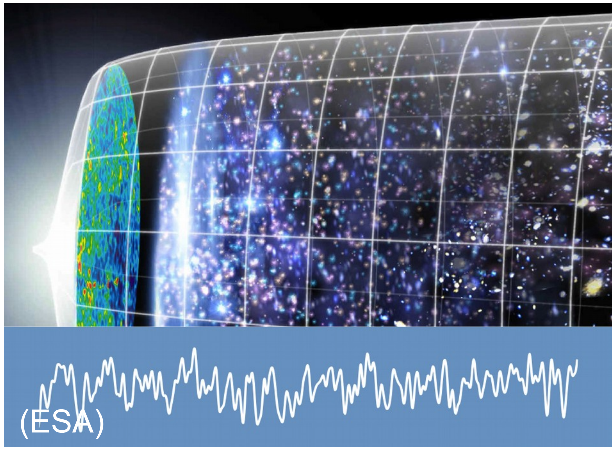


Different Sources – Different Signals

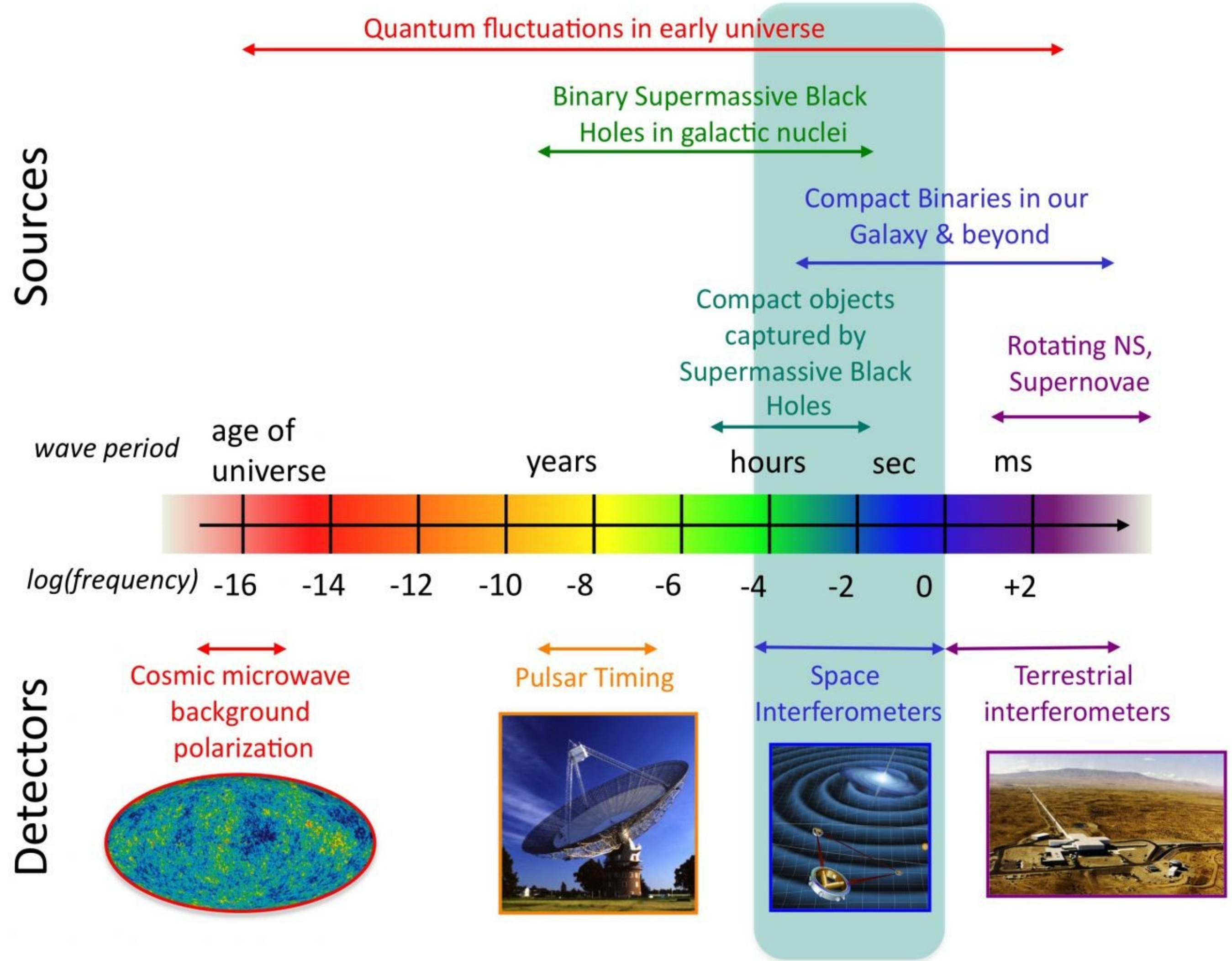
Coalescence of Supermassive Black Holes

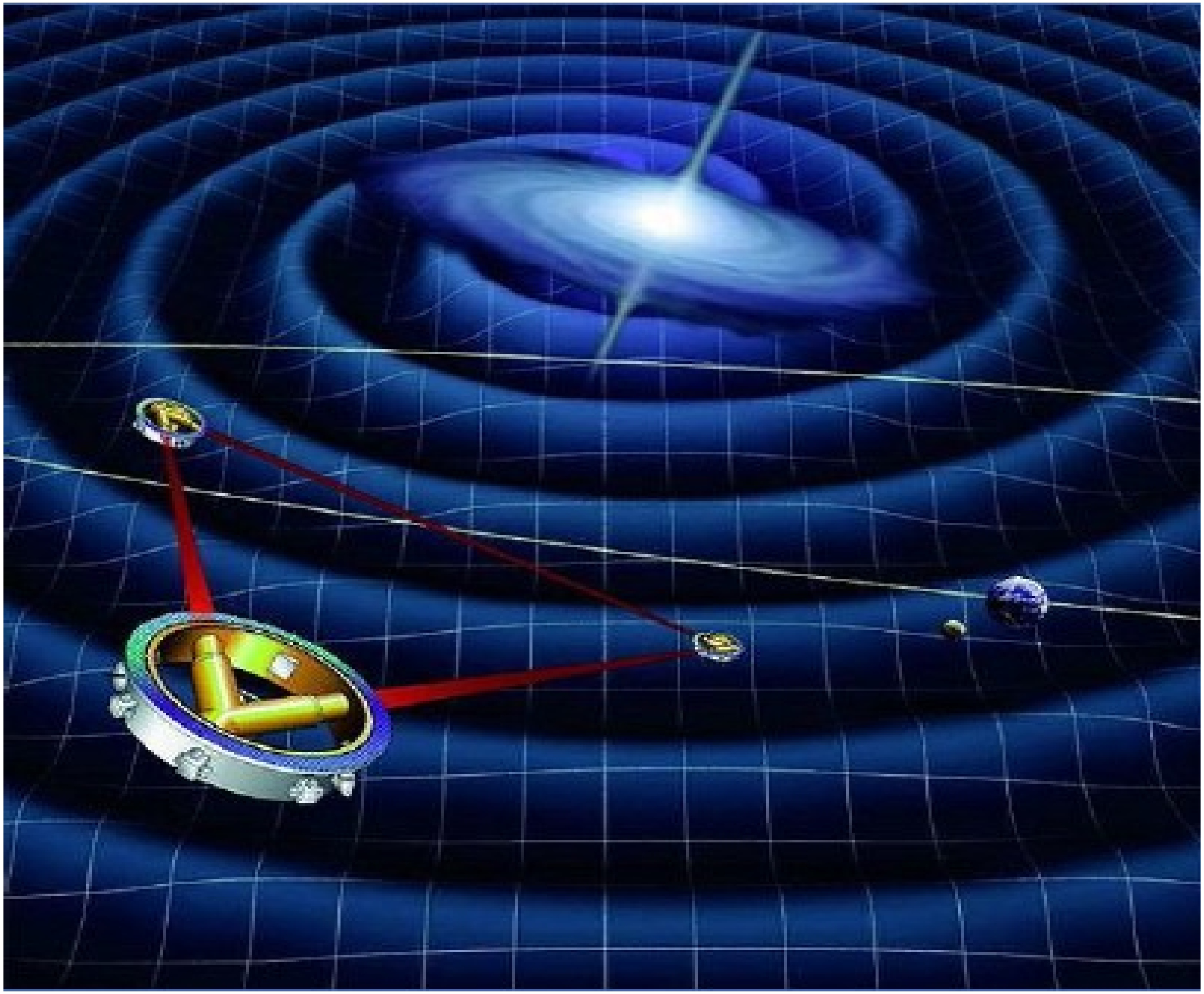


Primordial Gravitational Waves

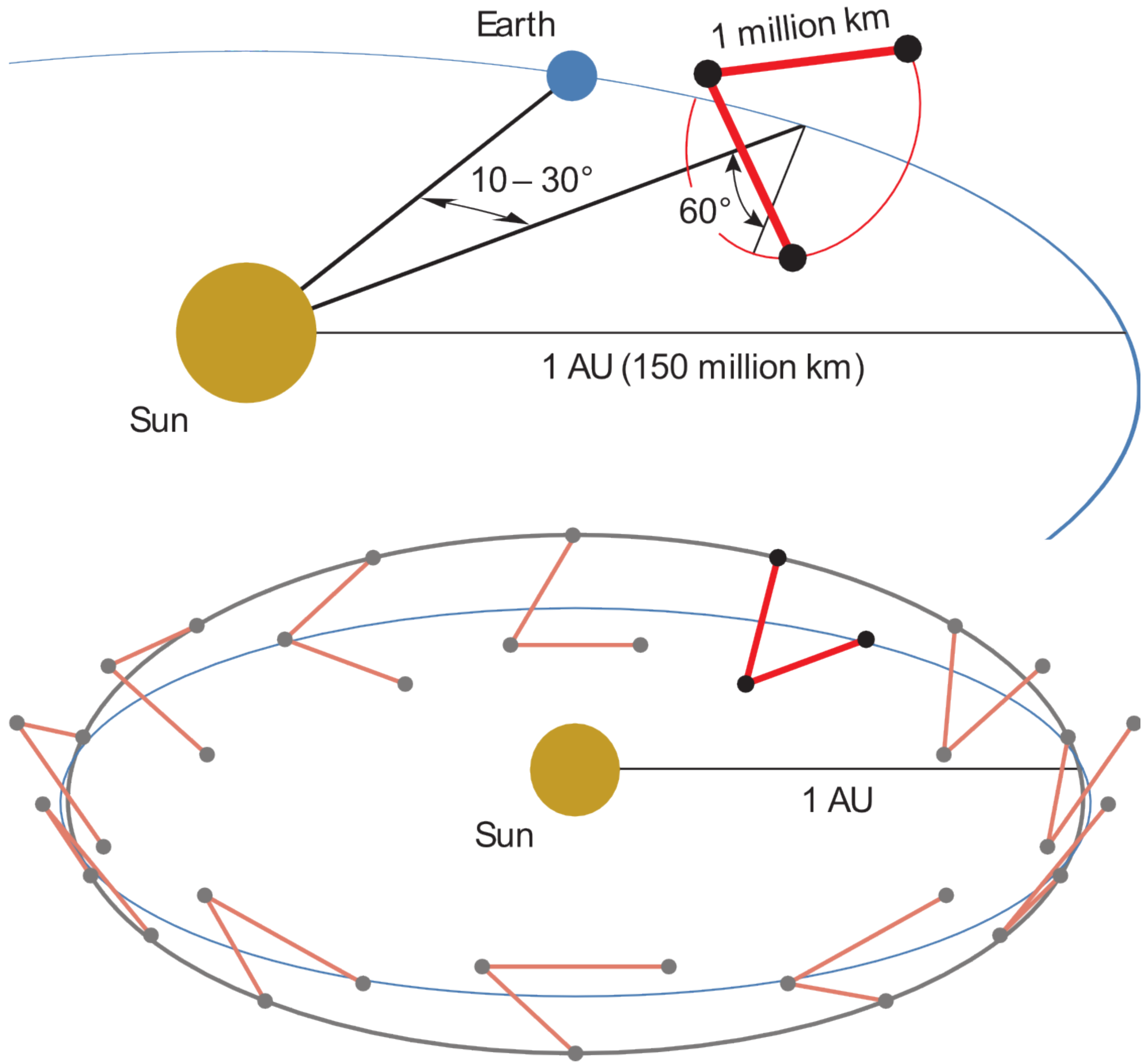


The Gravitational Wave Spectrum

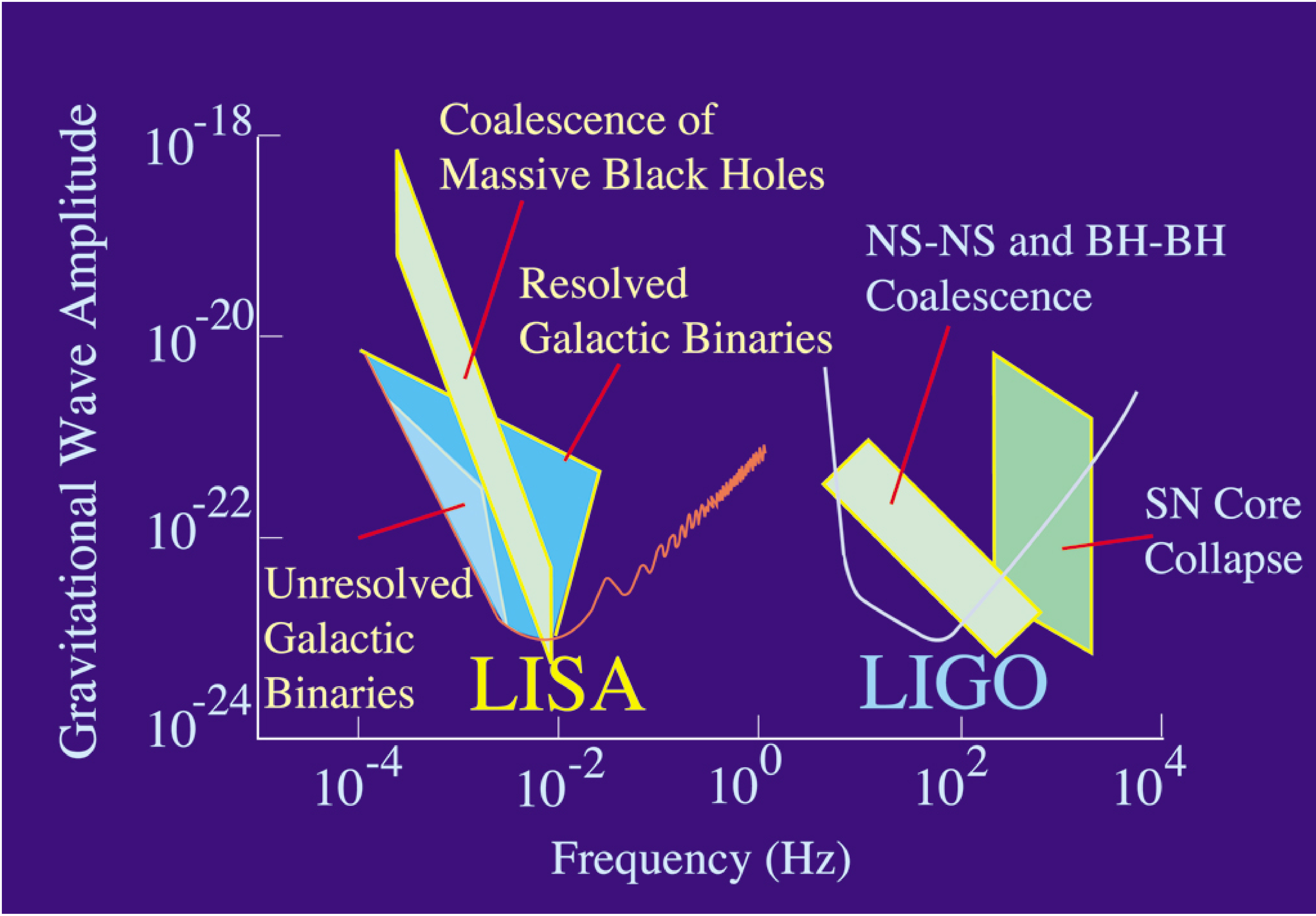




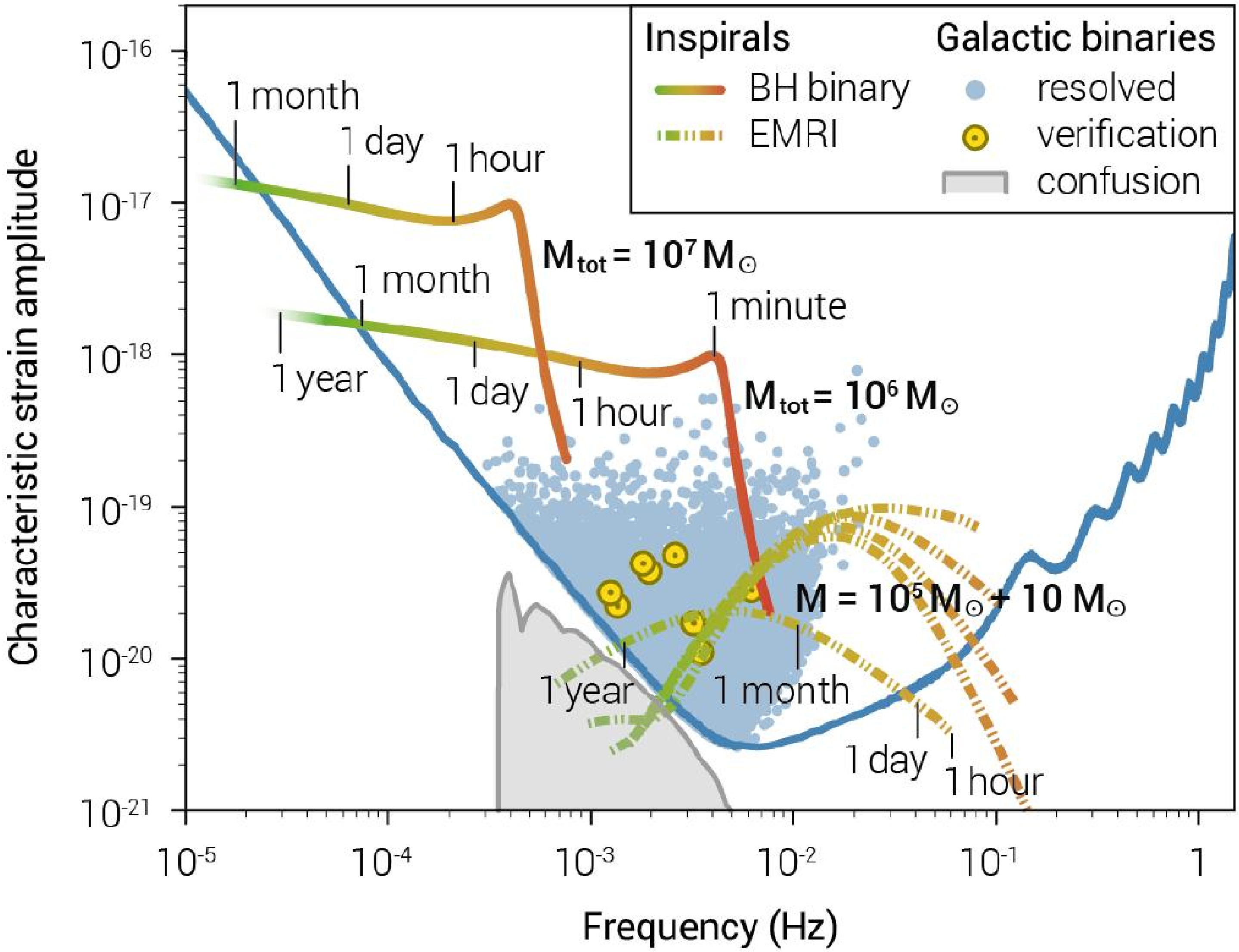
LISA (Laser Interferometer Space Antenna)



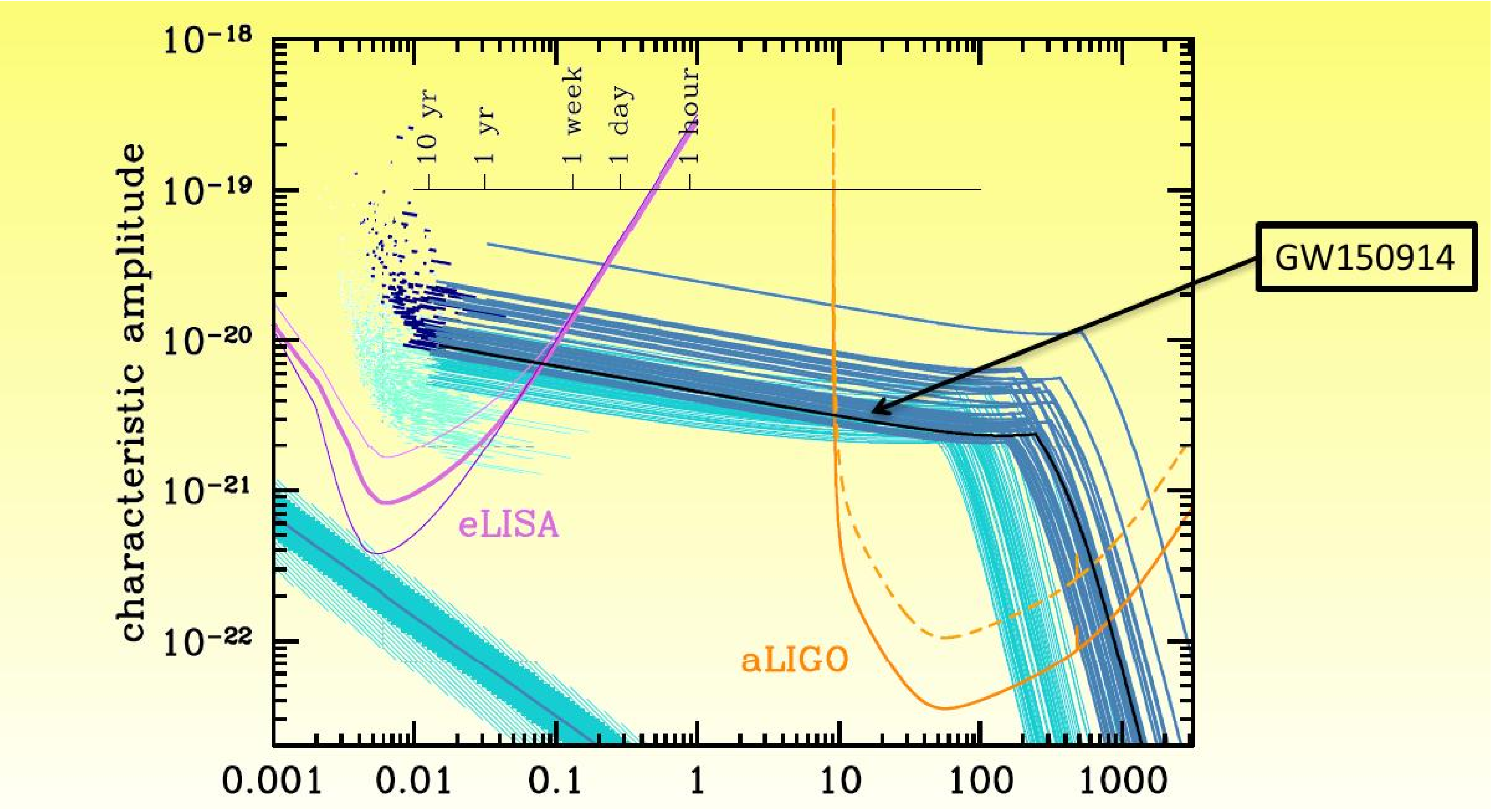
Earth
1 million km
10 – 30°
60°
1 AU (150 million km)
Sun
Sun
1 AU


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)

LISA sensitivity and Black Hole science

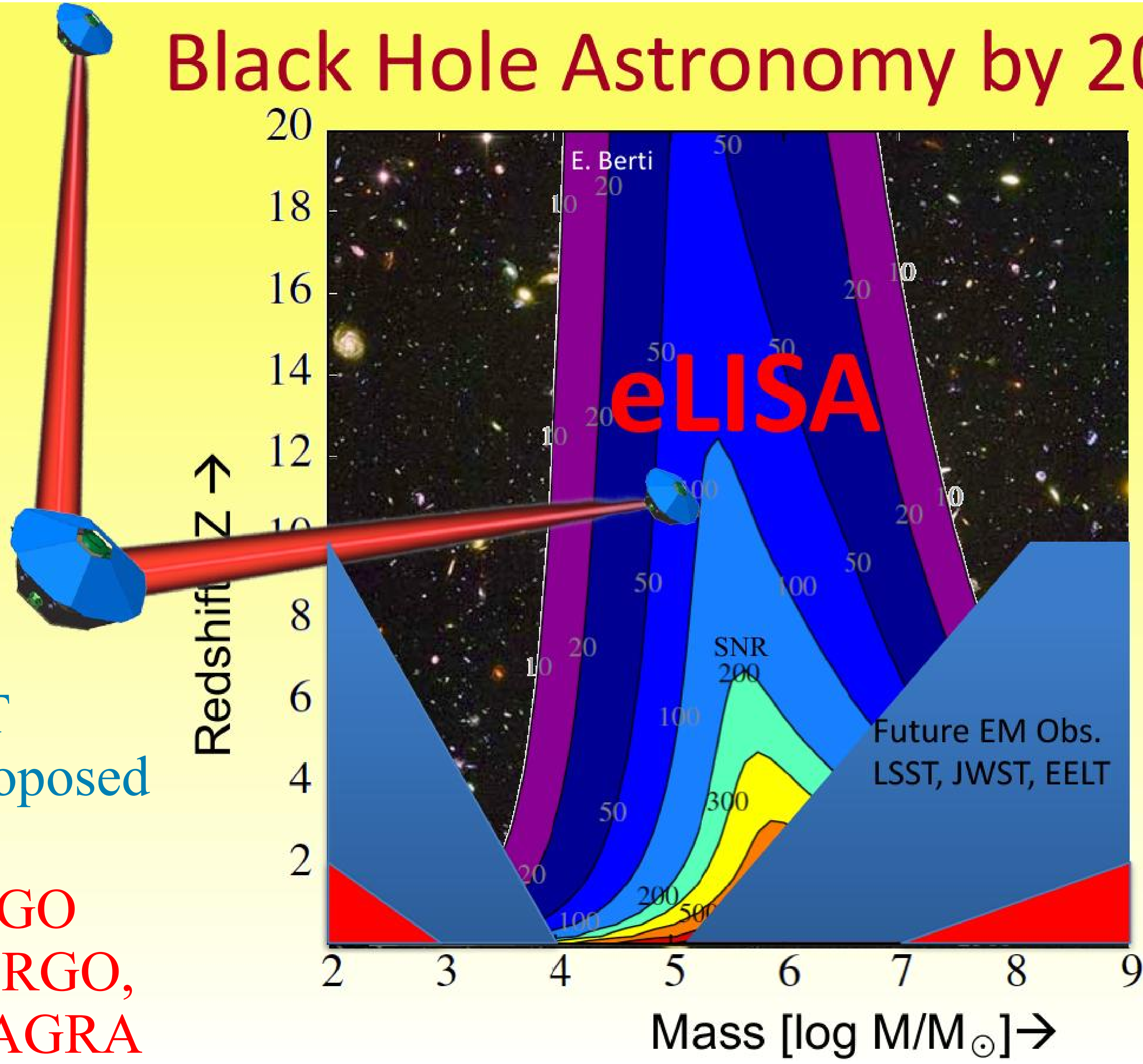


LISA: 1st LIGO event "predicted" 10 years in advance



Frequency (from Sesana 2016)

Black Hole Astronomy by 2030



ET proposed

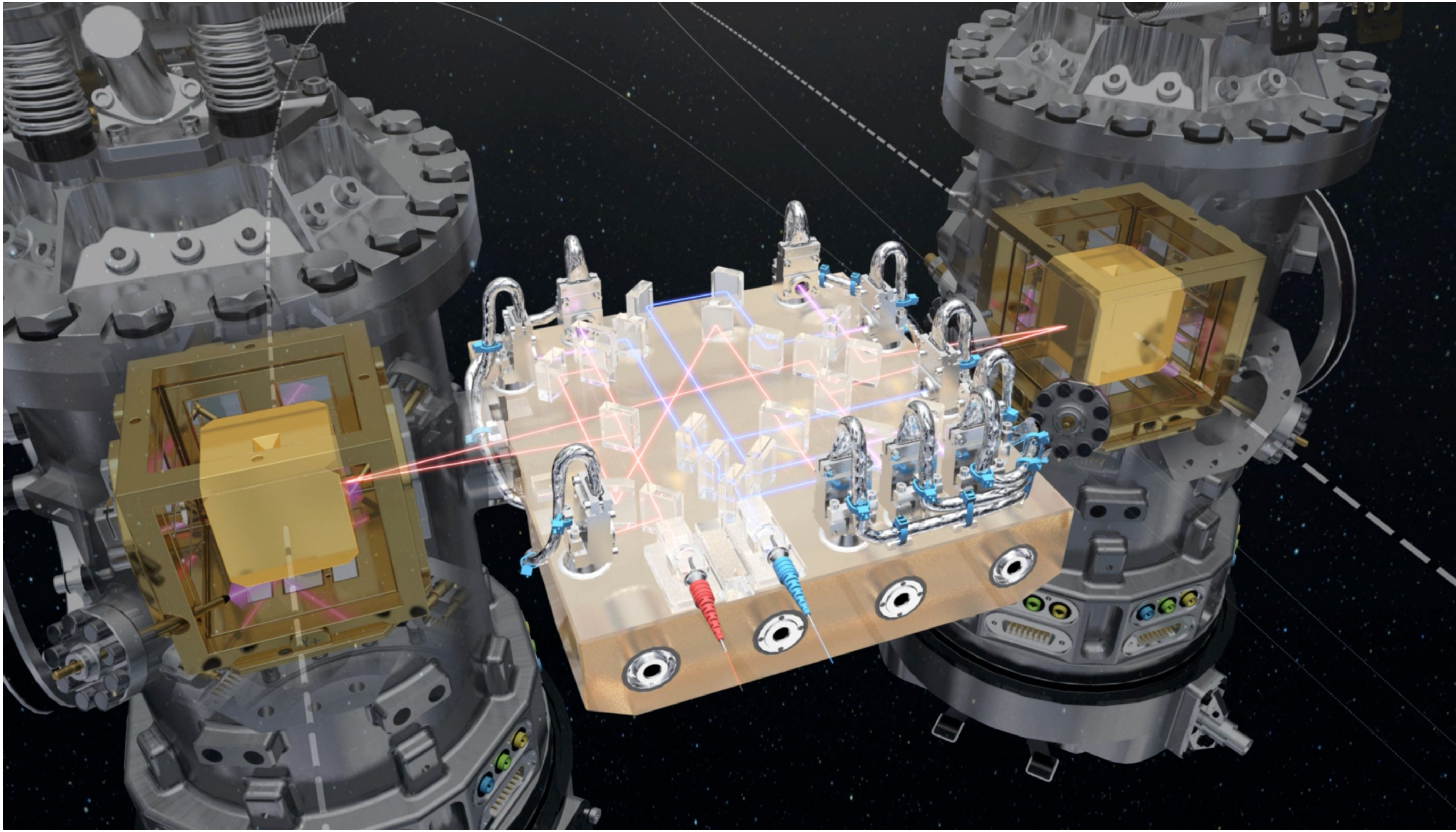
LIGO VIRGO, KAGRA

SKA, Pulsar Timing

LISA PATHFINDER (ESA MISSION)

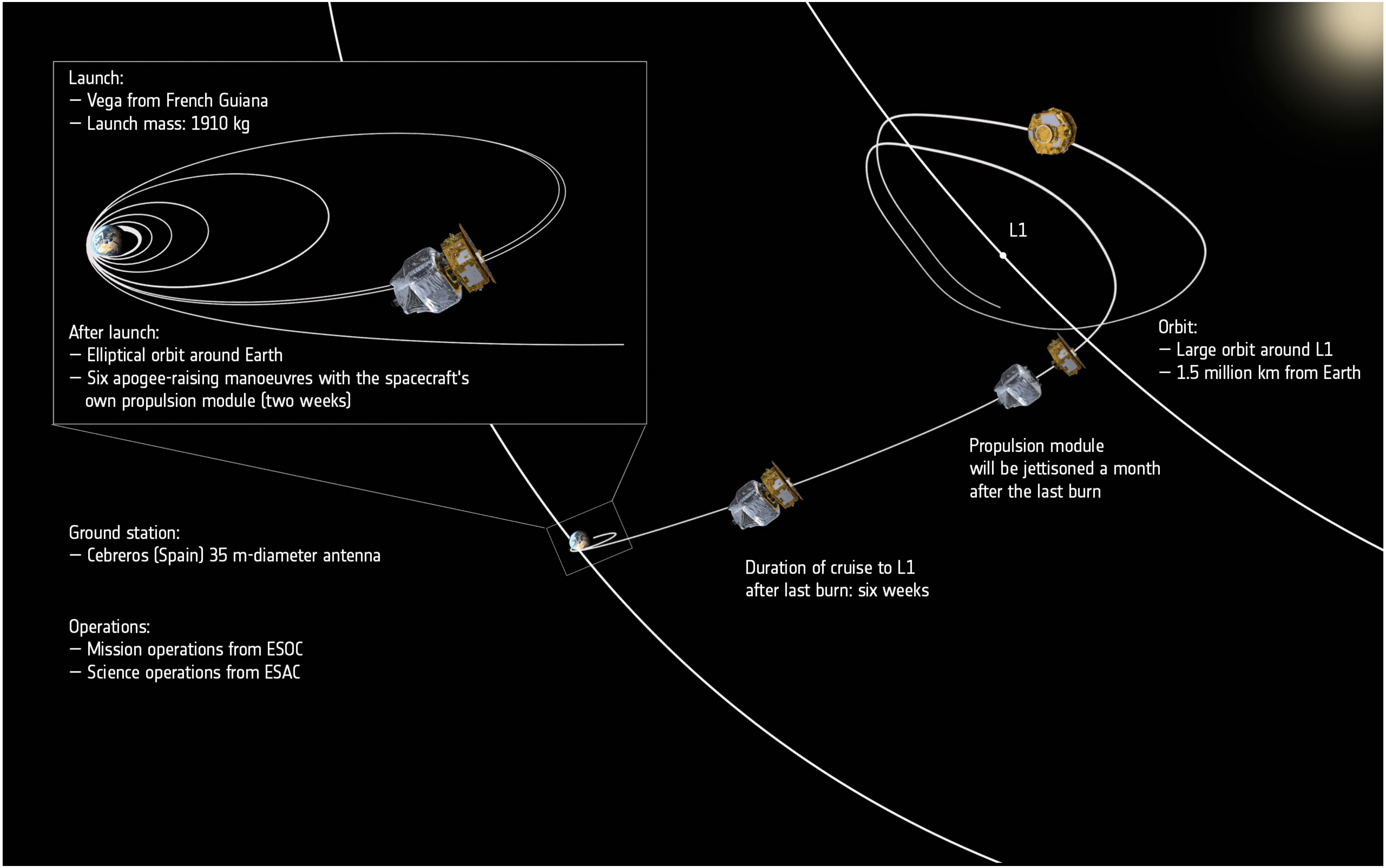
Launch: 3 December 2015 - End mission: 18 July 2017

- LISA Pathfinder is the first step in the observation of gravitational waves from space
- LISA Pathfinder provides us with:
  - A better understanding of the physics of the forces acting on a free-falling test mass
  - Industrial experience in the development, manufacture, and testing of technologies required for GW detection
  - Data analysis algorithms and tools dedicated to the analysis of the system as a whole
  - Essential experience in the commissioning of a LISA-like mission
- LPF essentially shrinks one arm of LISA from ~million km down to ~40cm
  - Giving up the sensitivity to gravitational waves
  - Maintaining the instrument noise which could dominate the GW signal

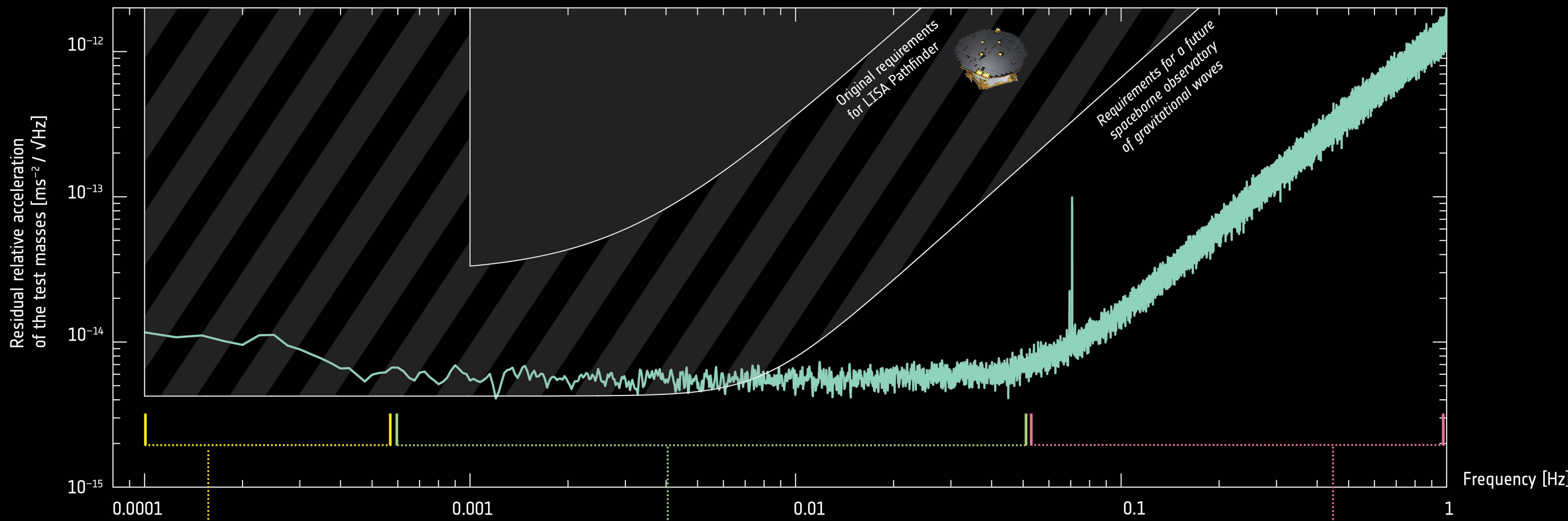


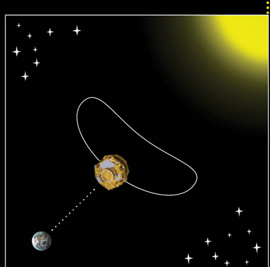
Floating test masses: 46 mm gold-platinum cubes

Launch of LISA Pathfinder on 3 December 2015


Launch:
– Vega from French Guiana
– Launch mass: 1910 kg
After launch:
– Elliptical orbit around Earth
– Six apogee-raising manoeuvres with the spacecraft's own propulsion module (two weeks)
Ground station:
– Cebreros (Spain) 35 m-diameter antenna
Operations:
– Mission operations from ESOC
– Science operations from ESAC
L1
Orbit:
– Large orbit around L1
– 1.5 million km from Earth
Propulsion module will be jettisoned a month after the last burn
Duration of cruise to L1 after last burn: six weeks

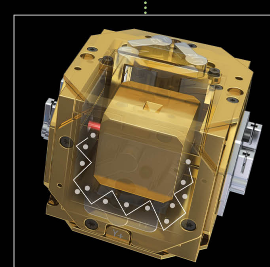
➔ LISA PATHFINDER EXCEEDS EXPECTATIONS





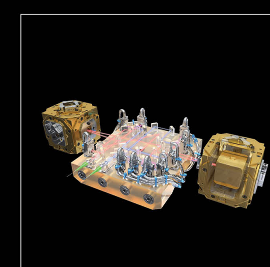
Centrifugal force

The rotation of the spacecraft required to keep the solar array pointed at the Sun and the antenna pointed towards Earth, coupled with the noise of the startrackers produces a noisy centrifugal force on the test masses. This noise term has been subtracted, and the source of the residual noise after subtraction is still being investigated.



Gas damping

Inside their housings, the test masses collide with some of the few gas molecules still present. This noise term becomes smaller with time, as more gas molecules are vented to space.

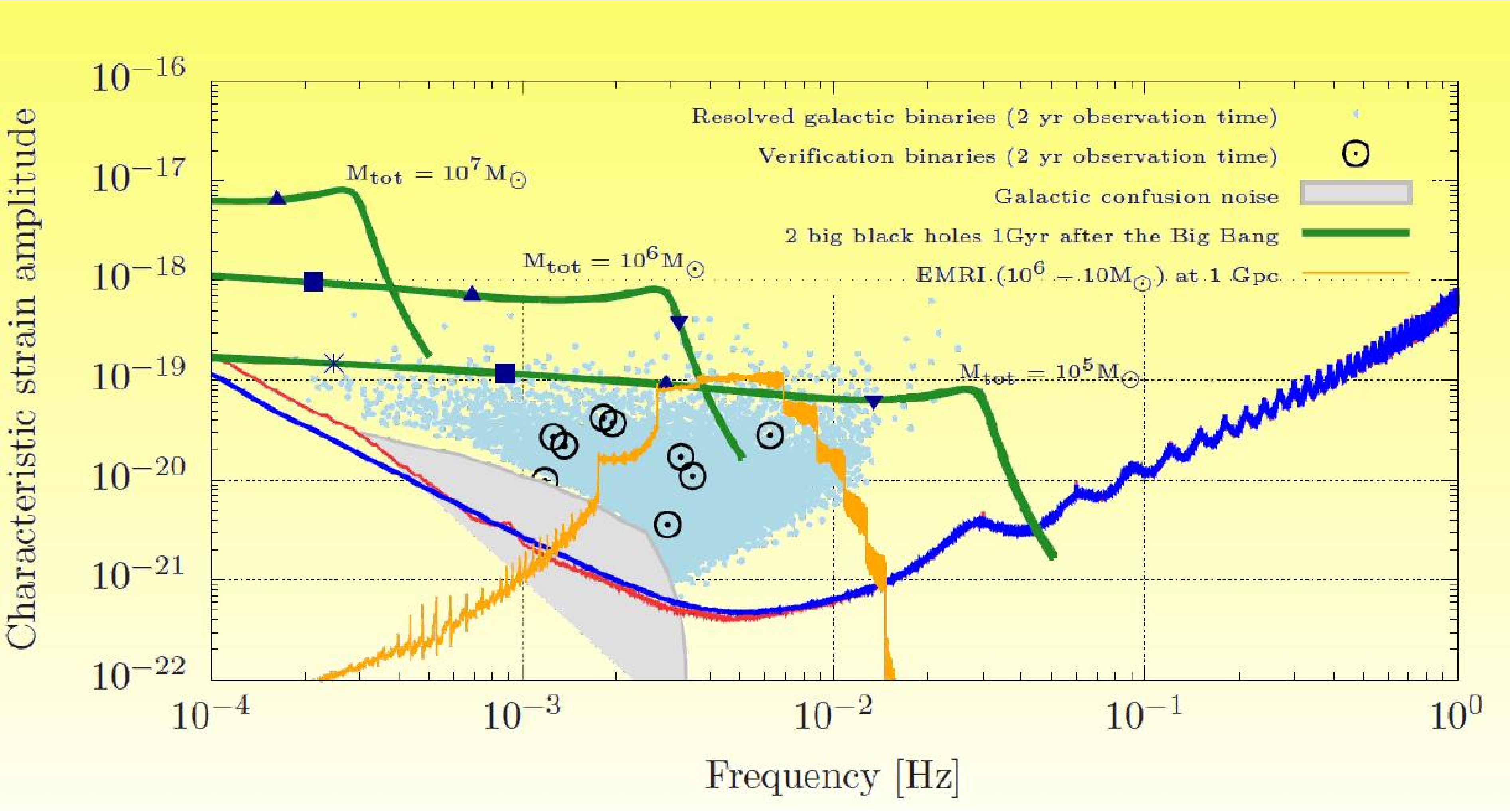


Sensing noise

The sensing noise of the optical metrology system used to monitor the position and orientation of the test masses, at a level of 35 fm / √Hz, has already surpassed the level of precision required by a future gravitational-wave observatory by a factor of more than 100.

Spacecraft: ESA/ATG medialab; data: ESA/LISA Pathfinder Collaboration

LISA Sensitivity with current Pathfinder performance

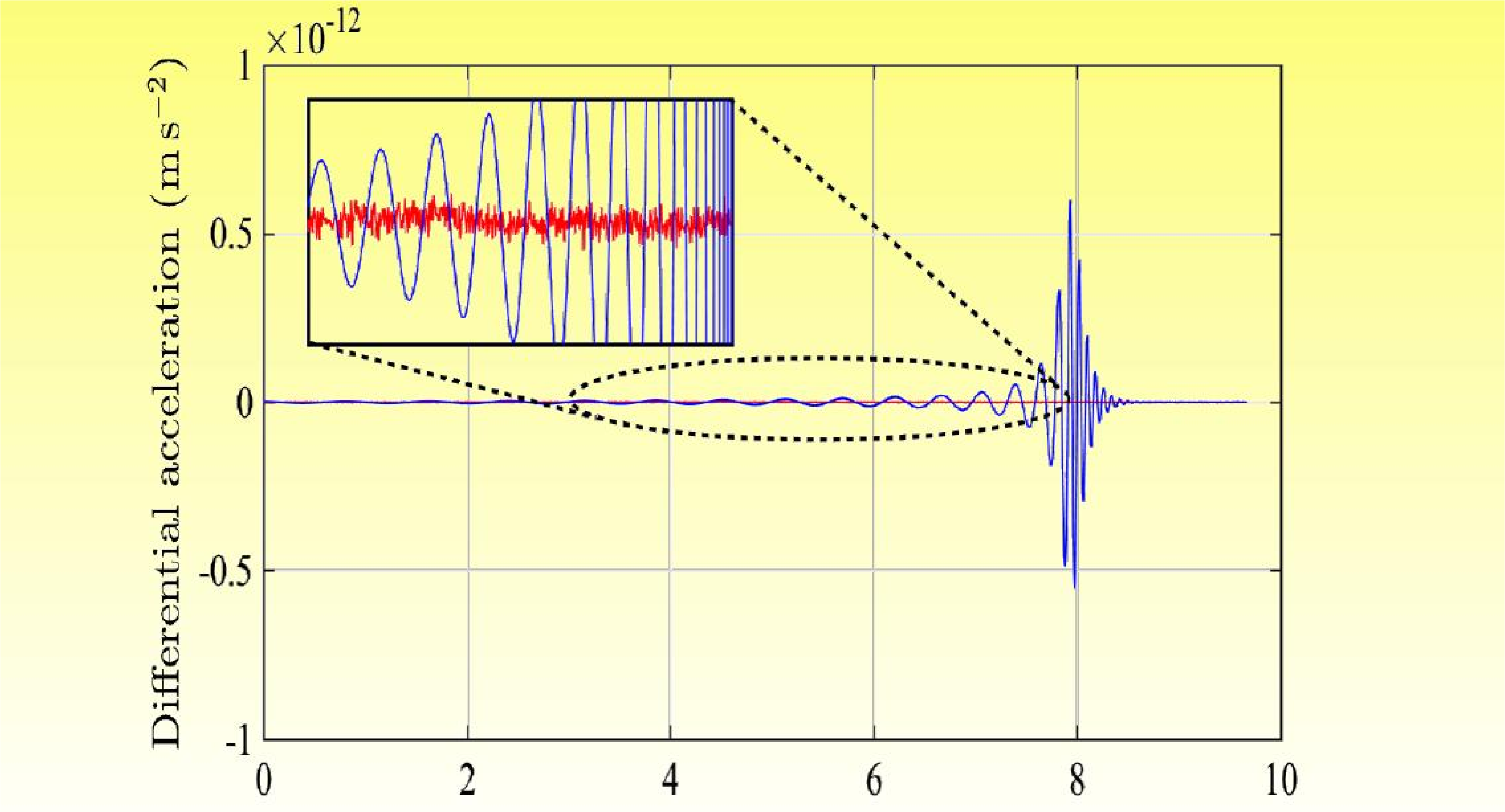


* 1 year; ■ 1 month; ▲ 1 day; ▼ 1 hour before coalescence

Black Hole merger for above noise for LISA:

10^5 Solar Mass BH binary merger at z=5

In red: Pathfinder instrumental noise



Time (in hours) (Petiteau 2016)

Within ESA's Cosmic Vision plan:

The Gravitational Universe was identified in 2013 as the Theme for the L3 Large-class mission

On 20 June 2017 LISA has been selected as the third (L3) Large-class mission in ESA's Science programme. Following this selection the mission design and costing can be completed and will be then proposed for "adoption" (early 2020s) before construction begins.

Currently launch is foreseen for 2034, however could be also anticipated.

The LISA Consortium includes also NASA participation.

GRAVITATIONAL WAVE ASTRONOMY HAS STARTED