GRAVITATIONAL WAVES AND MULTI-MESSENGER ASTRONOMY

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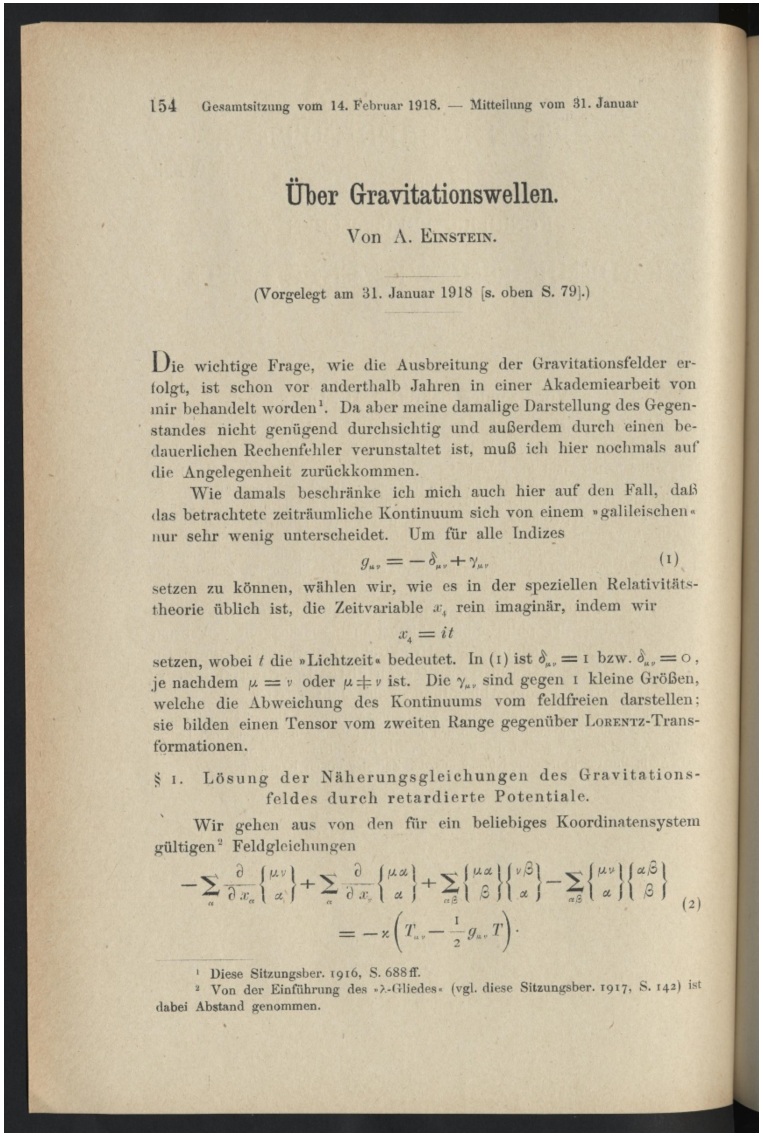
Gravitational Waves

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

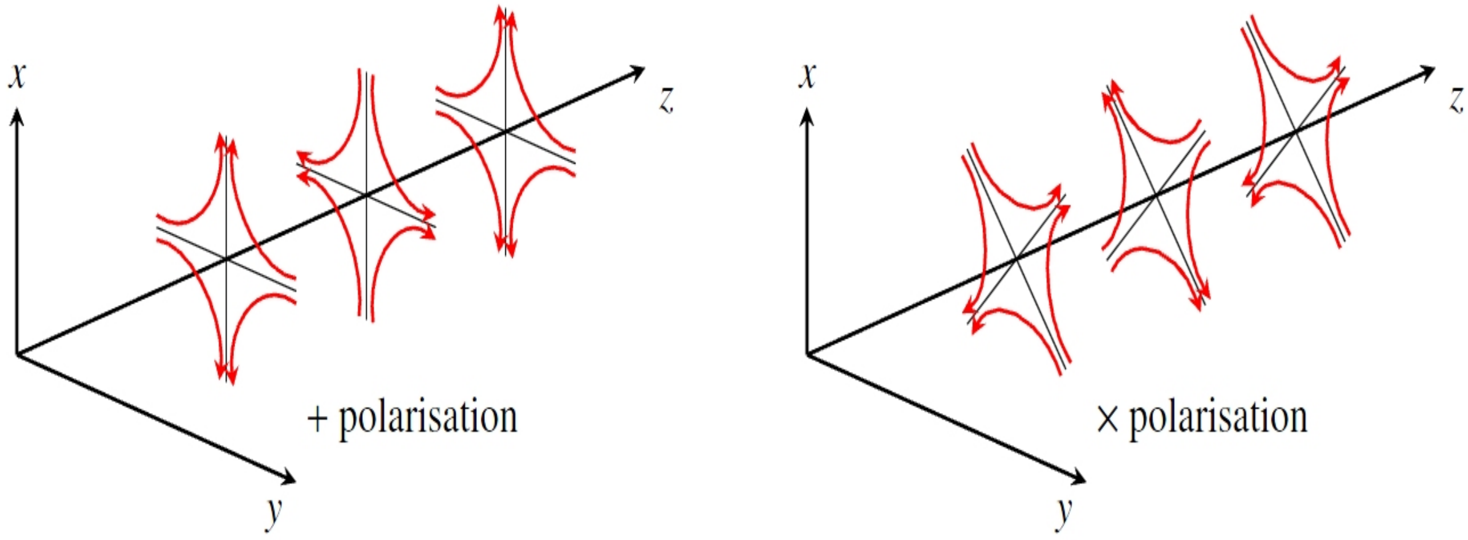
$$-\sum_{\alpha} \frac{\partial}{\partial x_\alpha} \begin{Bmatrix} \mu\nu \\ \alpha \end{Bmatrix} + \sum_{\alpha} \frac{\partial}{\partial x_\nu} \begin{Bmatrix} \mu\alpha \\ \alpha \end{Bmatrix} + \sum_{\alpha\beta} \begin{Bmatrix} \mu\alpha \\ \beta \end{Bmatrix} \begin{Bmatrix} \nu\beta \\ \alpha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

[1] Diese Sitzungsber. 1916, S. 688 ff.

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

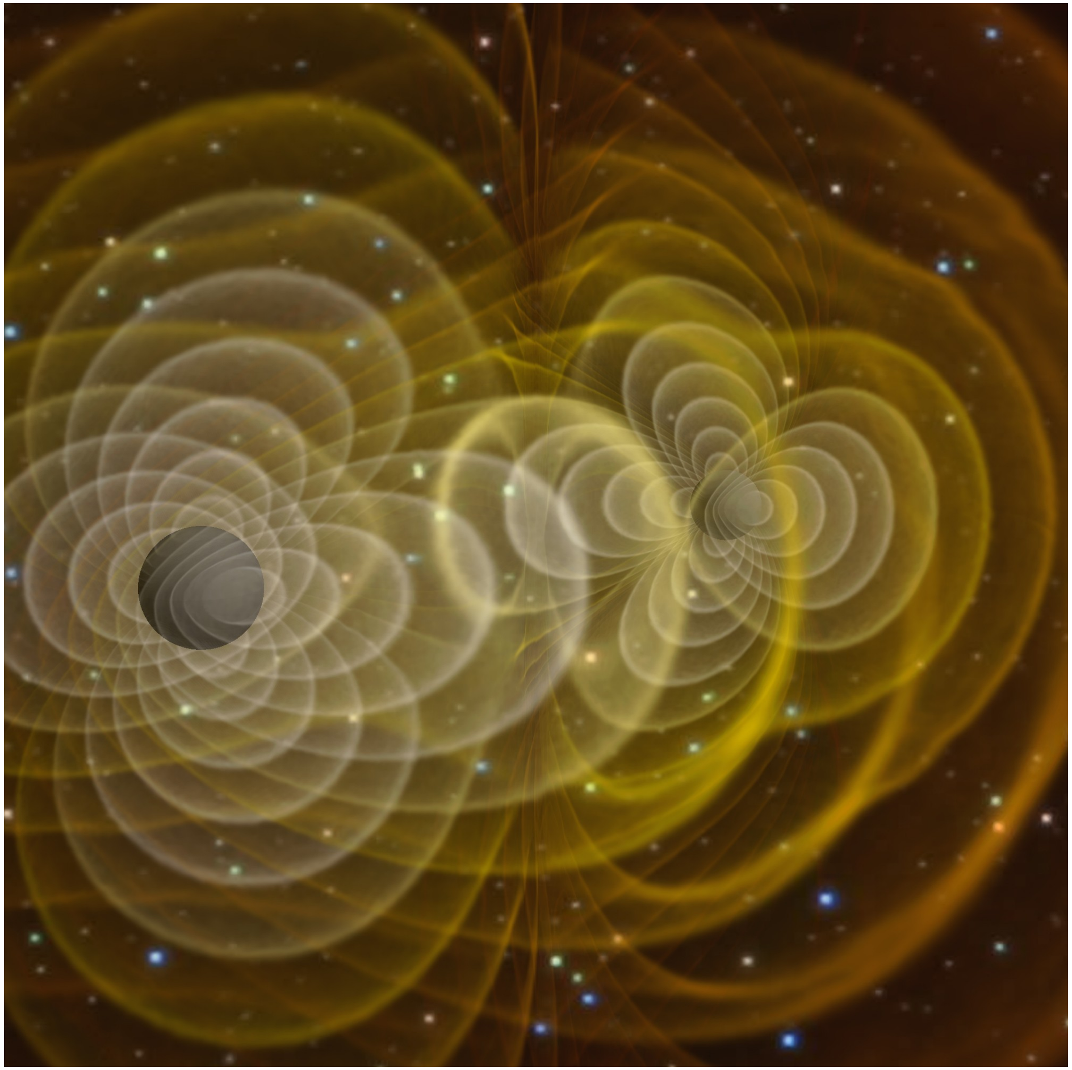
Understanding Gravitational Waves

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



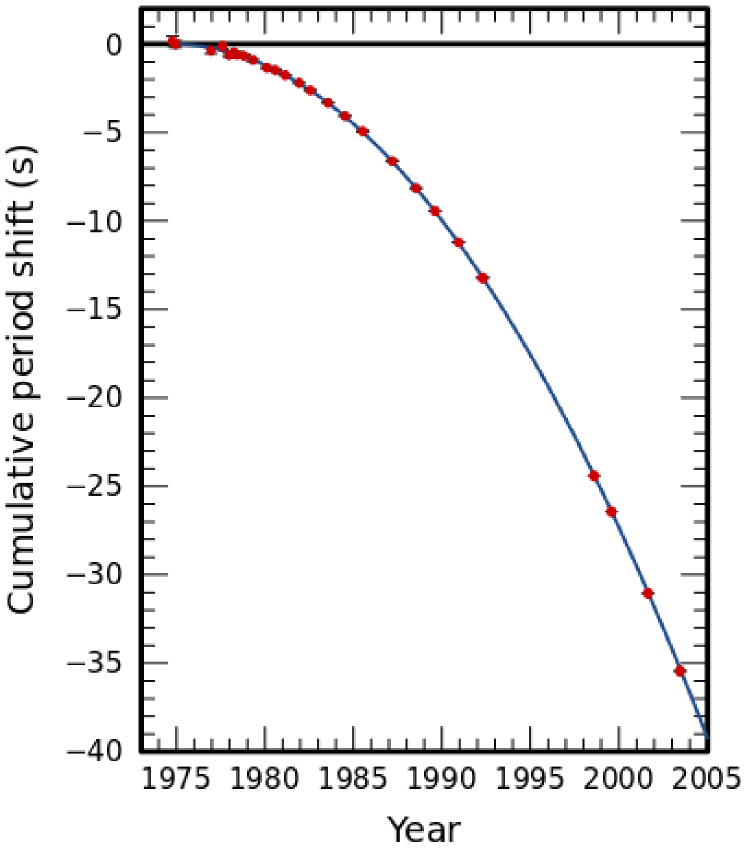
...but GWs *are* different...

- 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

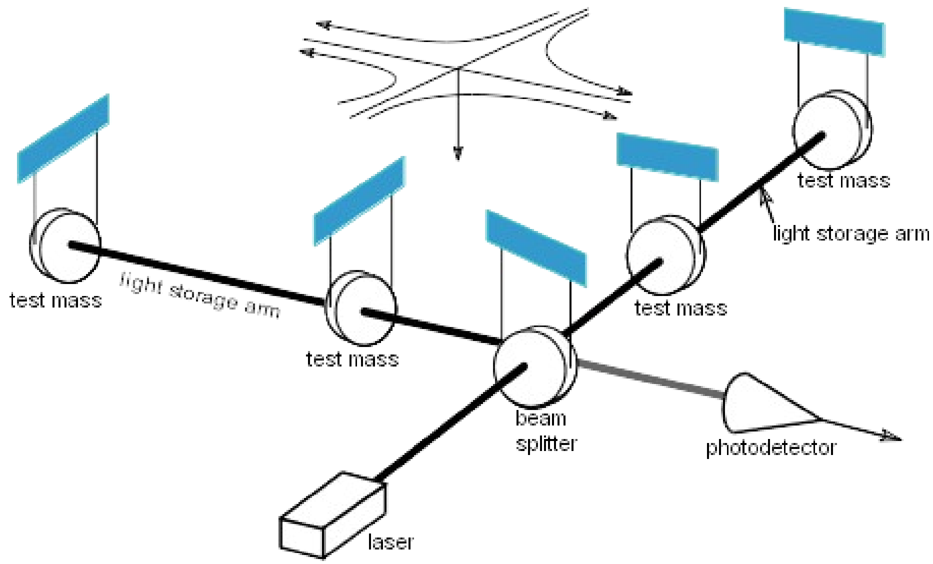


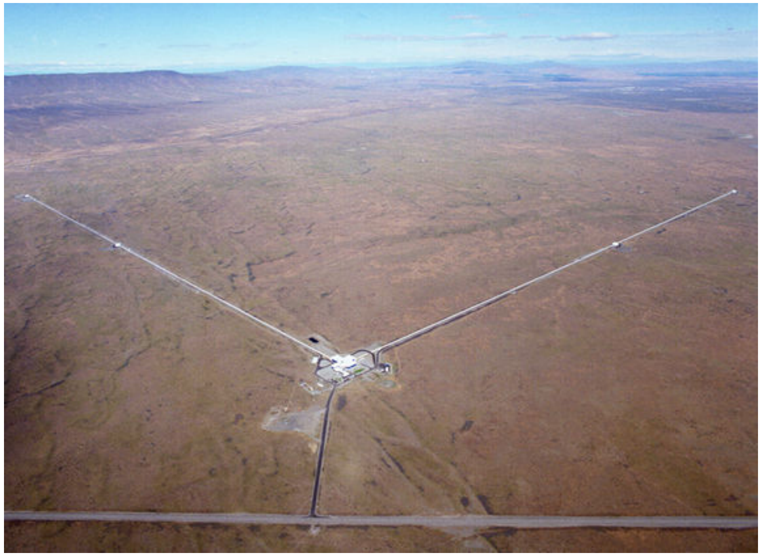
Evidence:
Hulse – Taylor Binary Pulsar discovered in 1974

- 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.

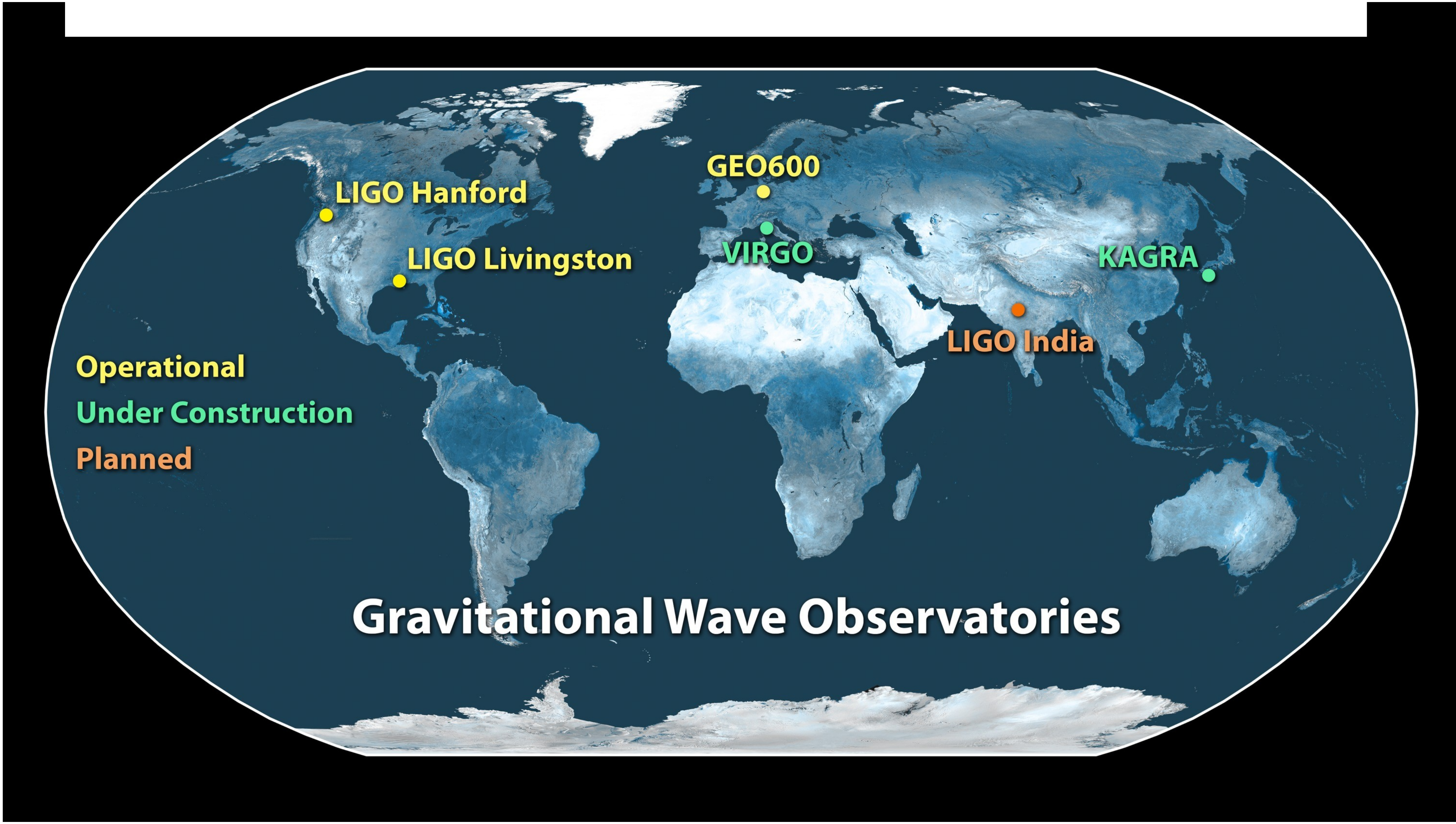


Existing Ground Based GW Detectors

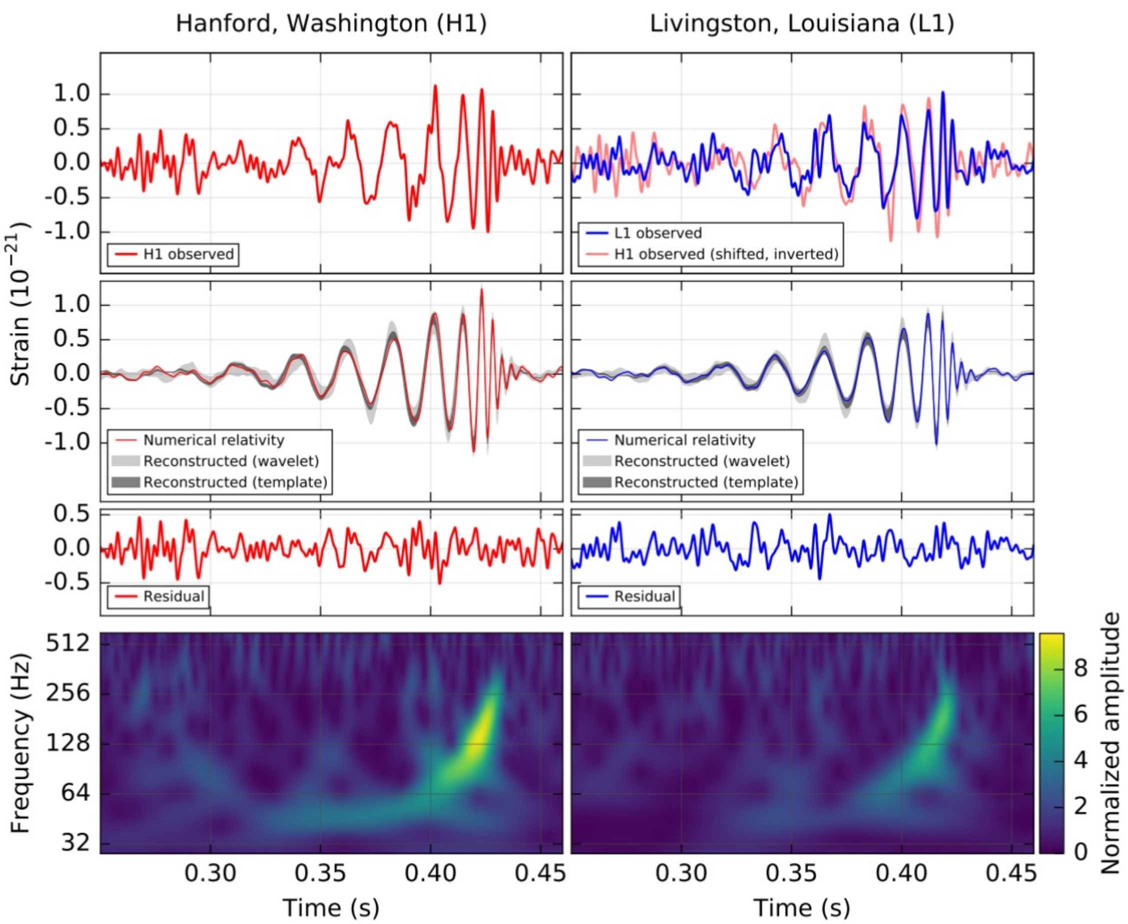


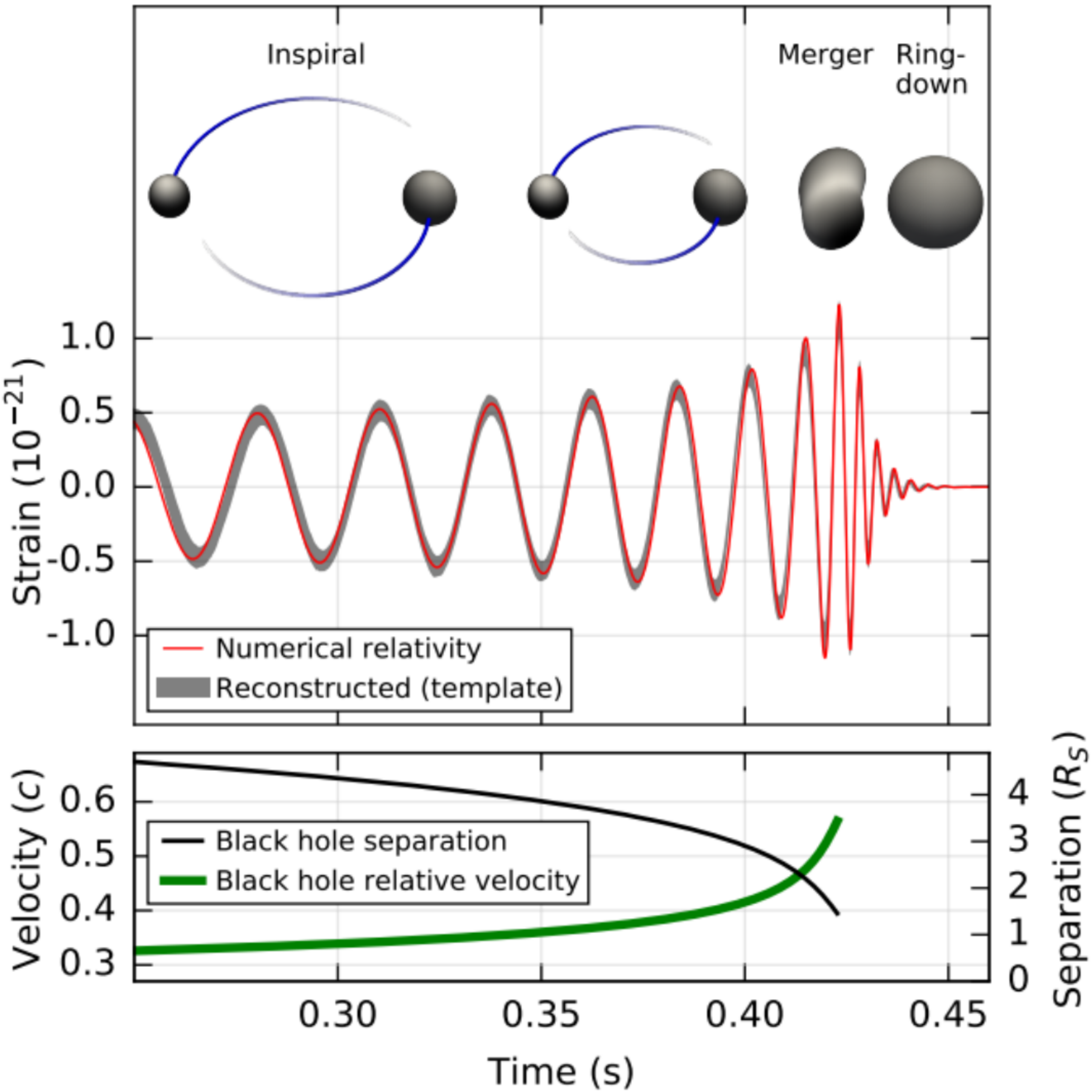


Existing/ Planned Ground Based GW Detectors

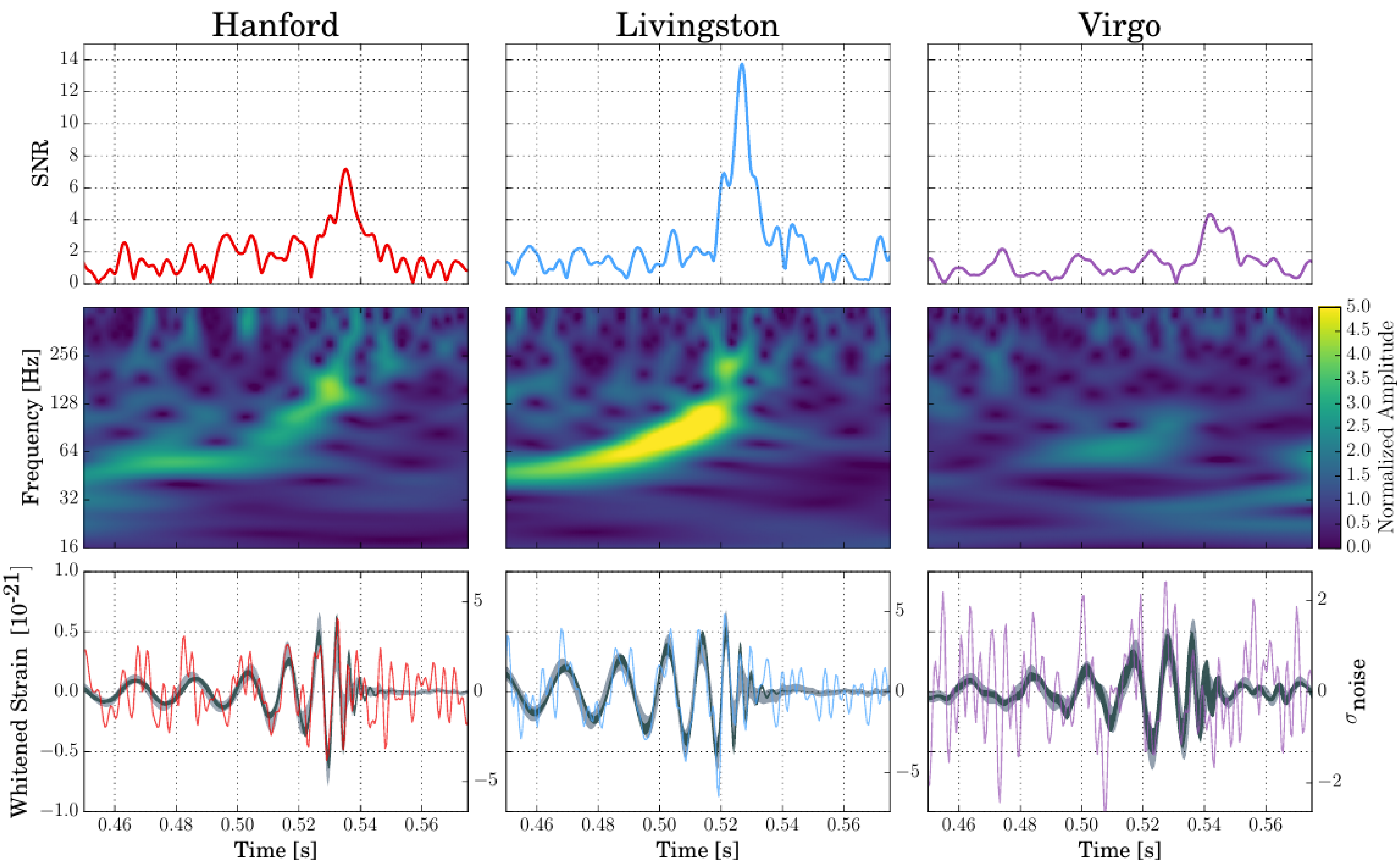


Gravitational wave signal of 14 September 2015

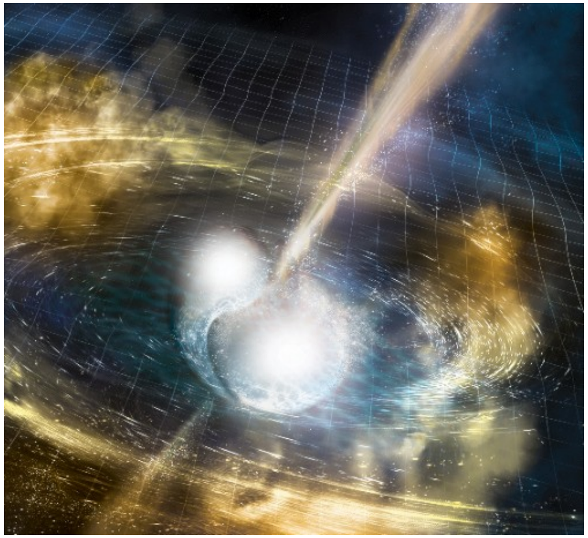




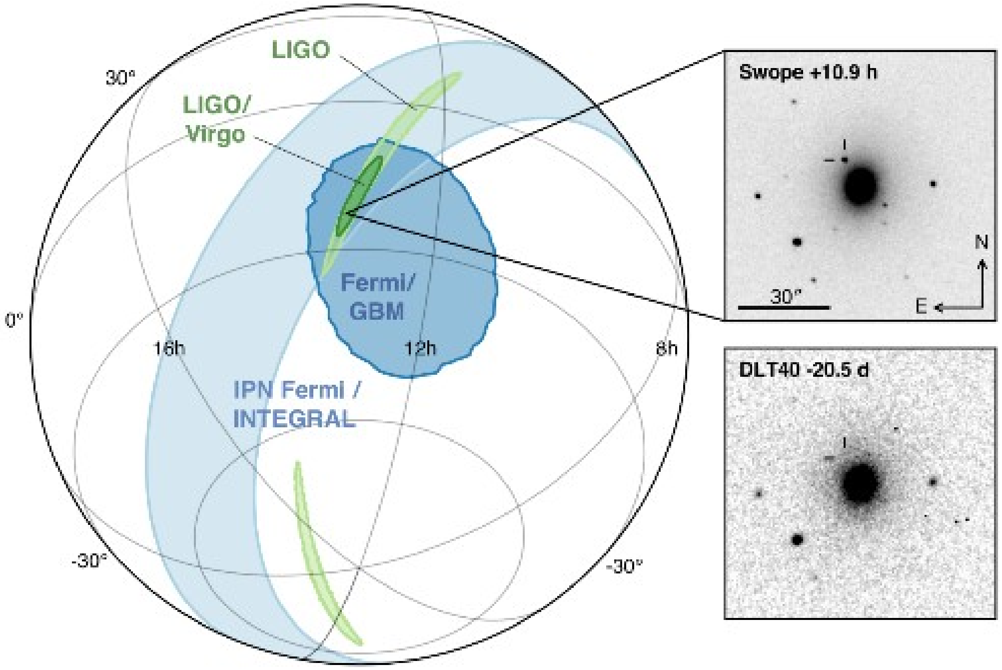
Inspiral
Merger
Ring-down
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
4
3
2
1
0
0.30
0.35
0.40
0.45
Time (s)



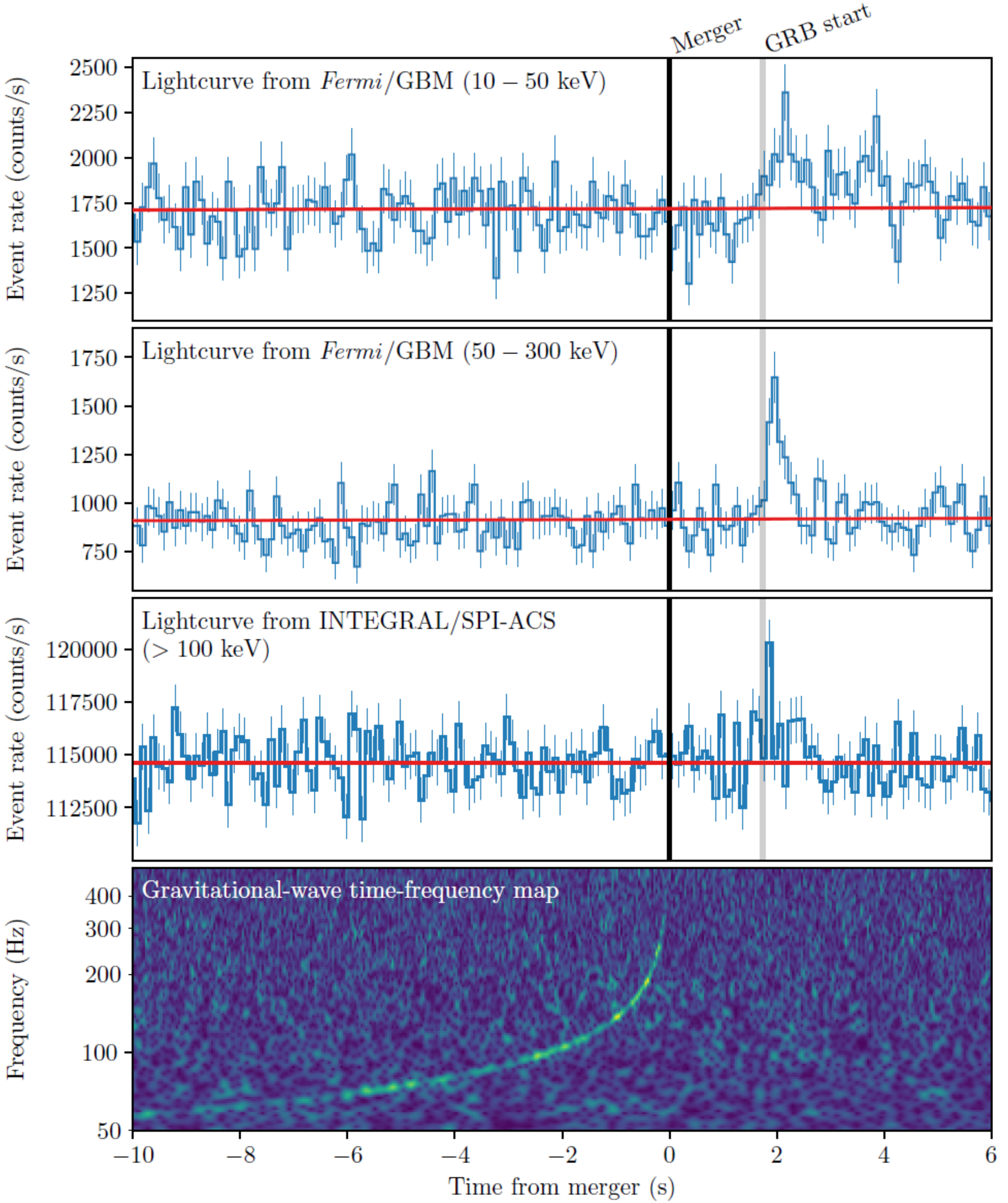
Event of 14 August 2017: 30 + 25 solar masses, final mass 53 solar masses



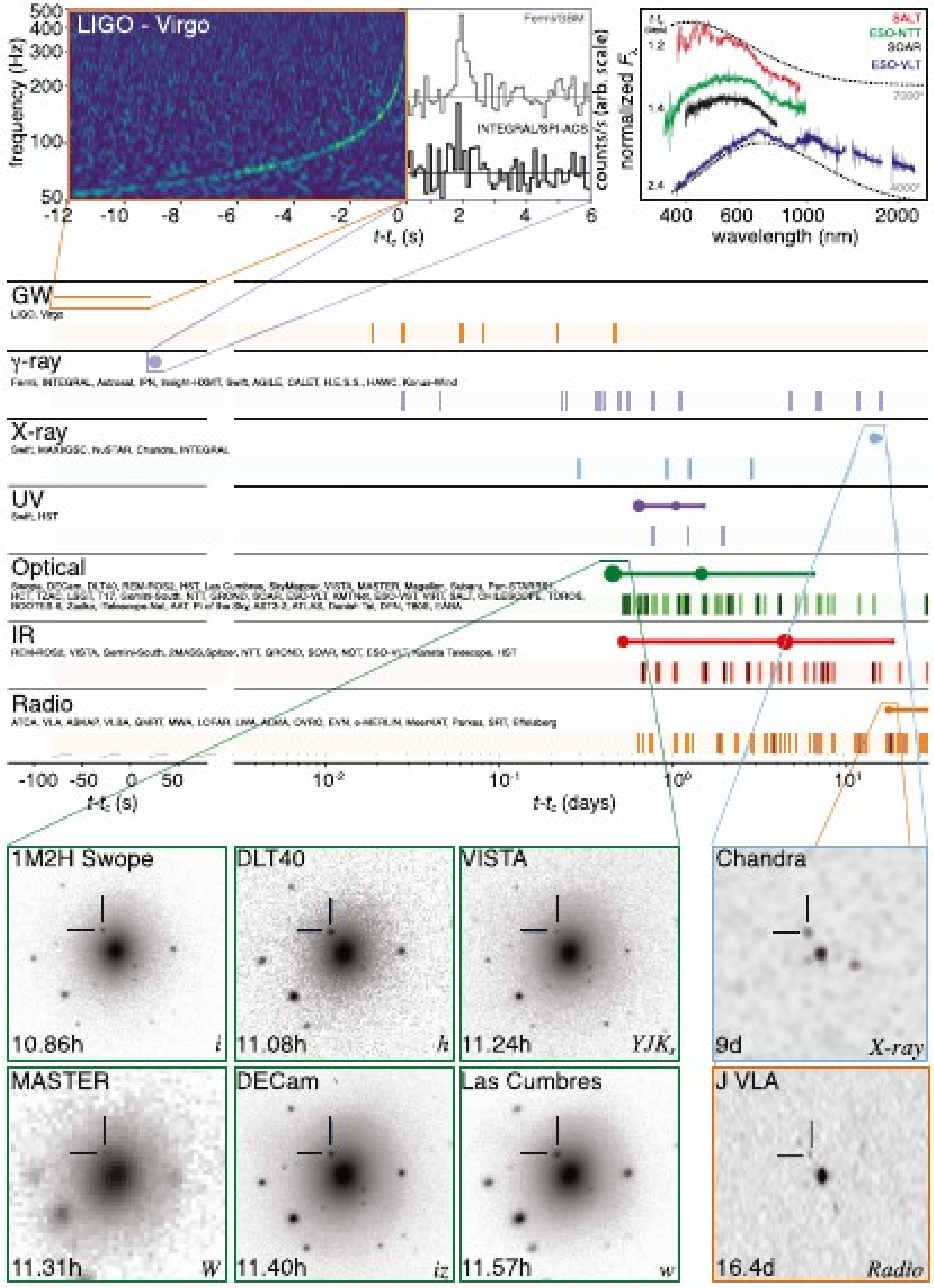
Artist’s illustration of two merging Neutron stars.



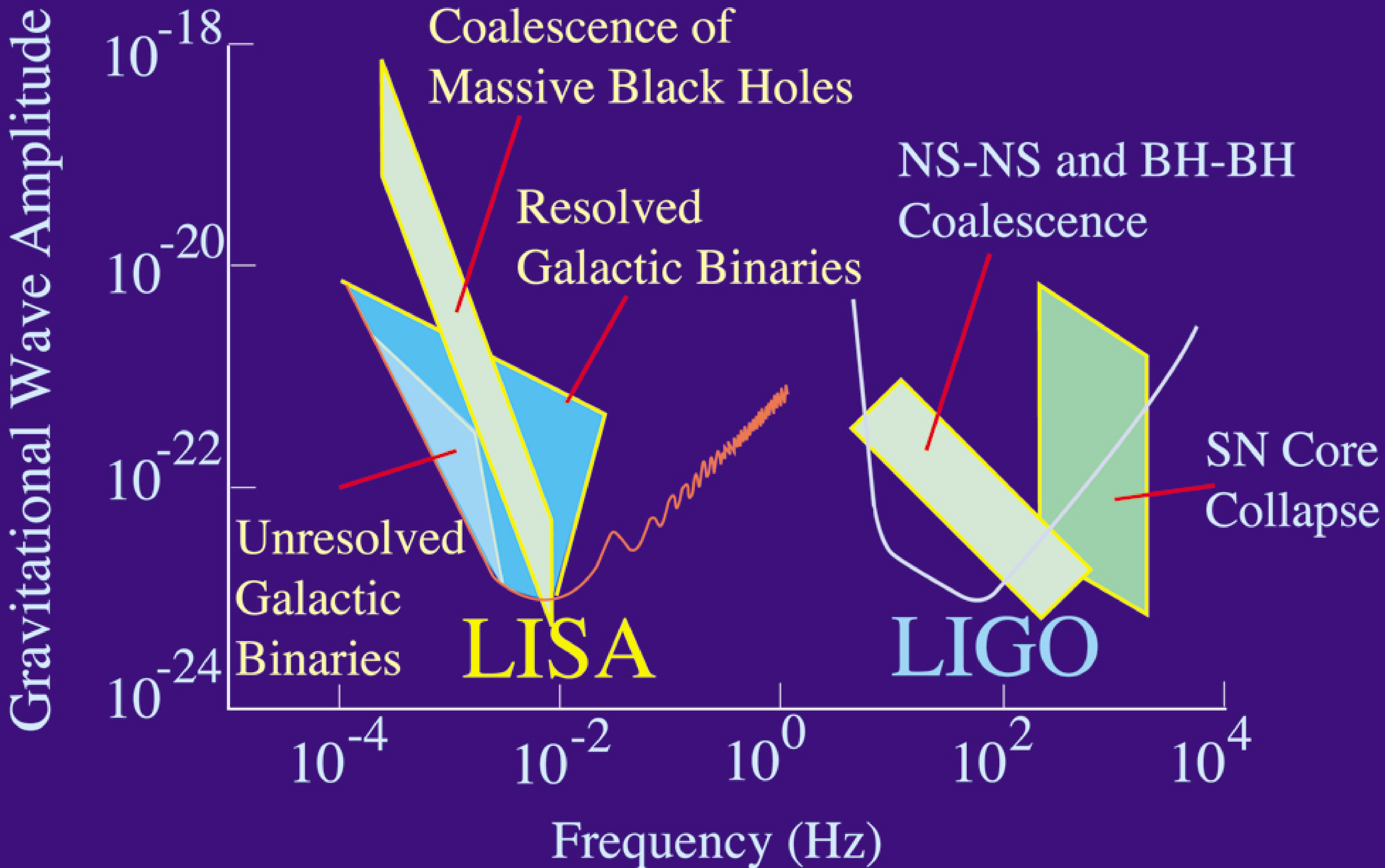
Discovery of the optical image by the Swope Telescope.
Host galaxy NGC 4993.
Top: 10.9 hr after the merger.
Bottom: 20.5 days before.



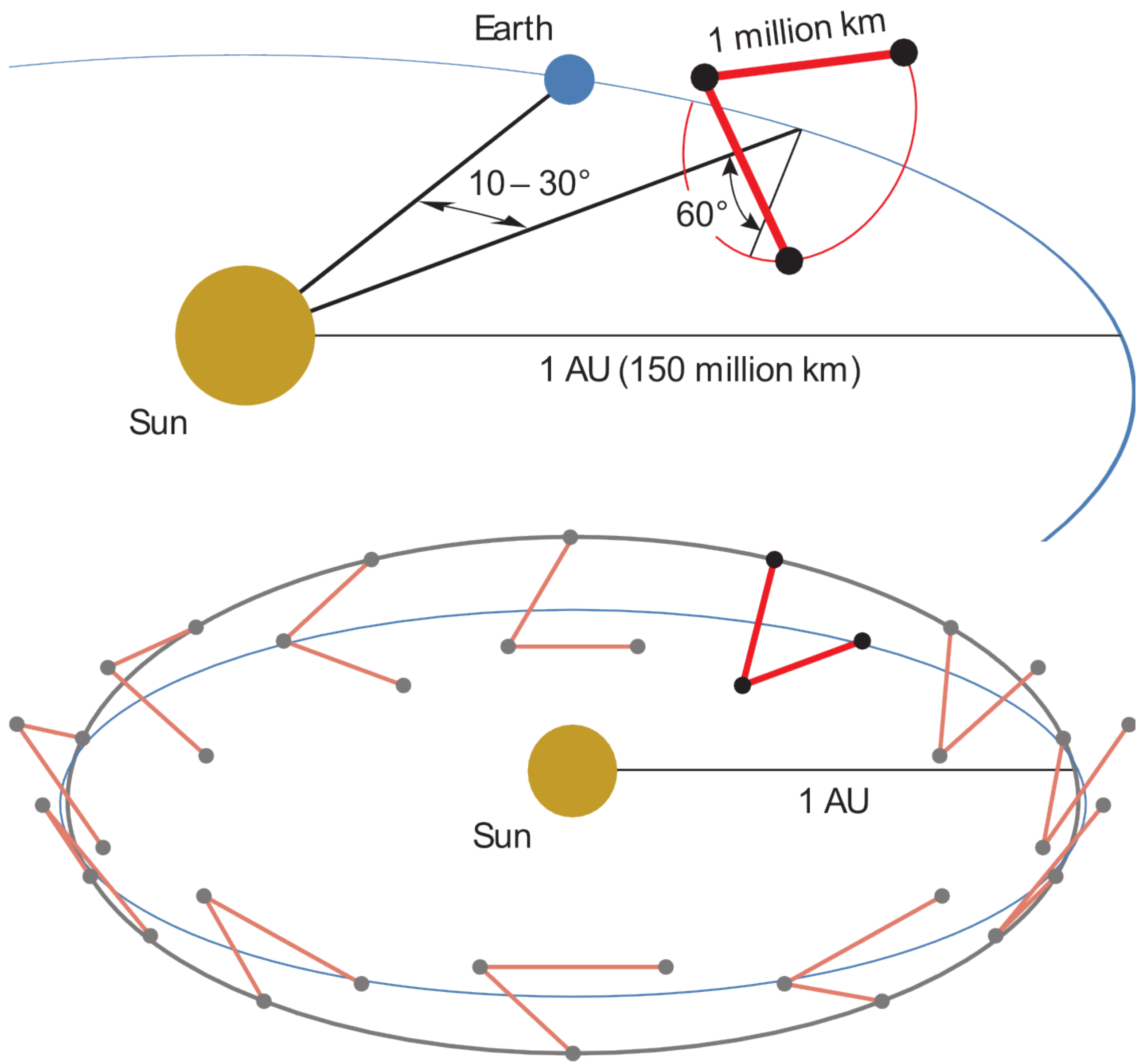
Merger
GRB start
Lightcurve from Fermi/GBM (10 – 50 keV)
Lightcurve from Fermi/GBM (50 – 300 keV)
Lightcurve from INTEGRAL/SPI-ACS
(> 100 keV)
Gravitational-wave time-frequency map
Event rate (counts/s)
Frequency (Hz)
Time from merger (s)



Time line of the discovery of GW170817 in the various electromagnetic bands.

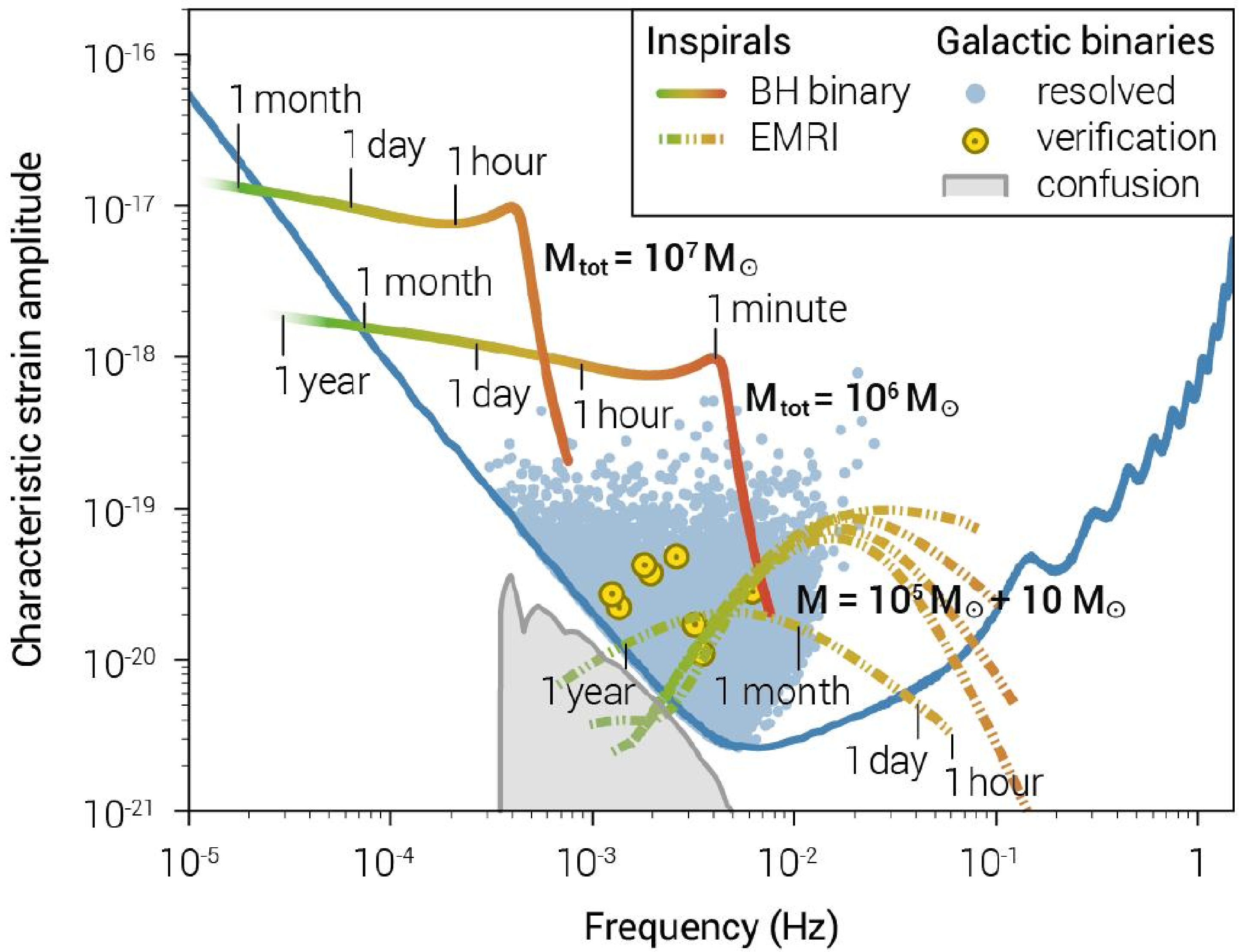


Gravitational Wave Amplitude
10^{-18}
10^{-20}
10^{-22}
10^{-24}
Coalescence of
Massive Black Holes
Resolved
Galactic Binaries
Unresolved
Galactic
Binaries
LISA
NS-NS and BH-BH
Coalescence
SN Core
Collapse
LIGO
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
Frequency (Hz)



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

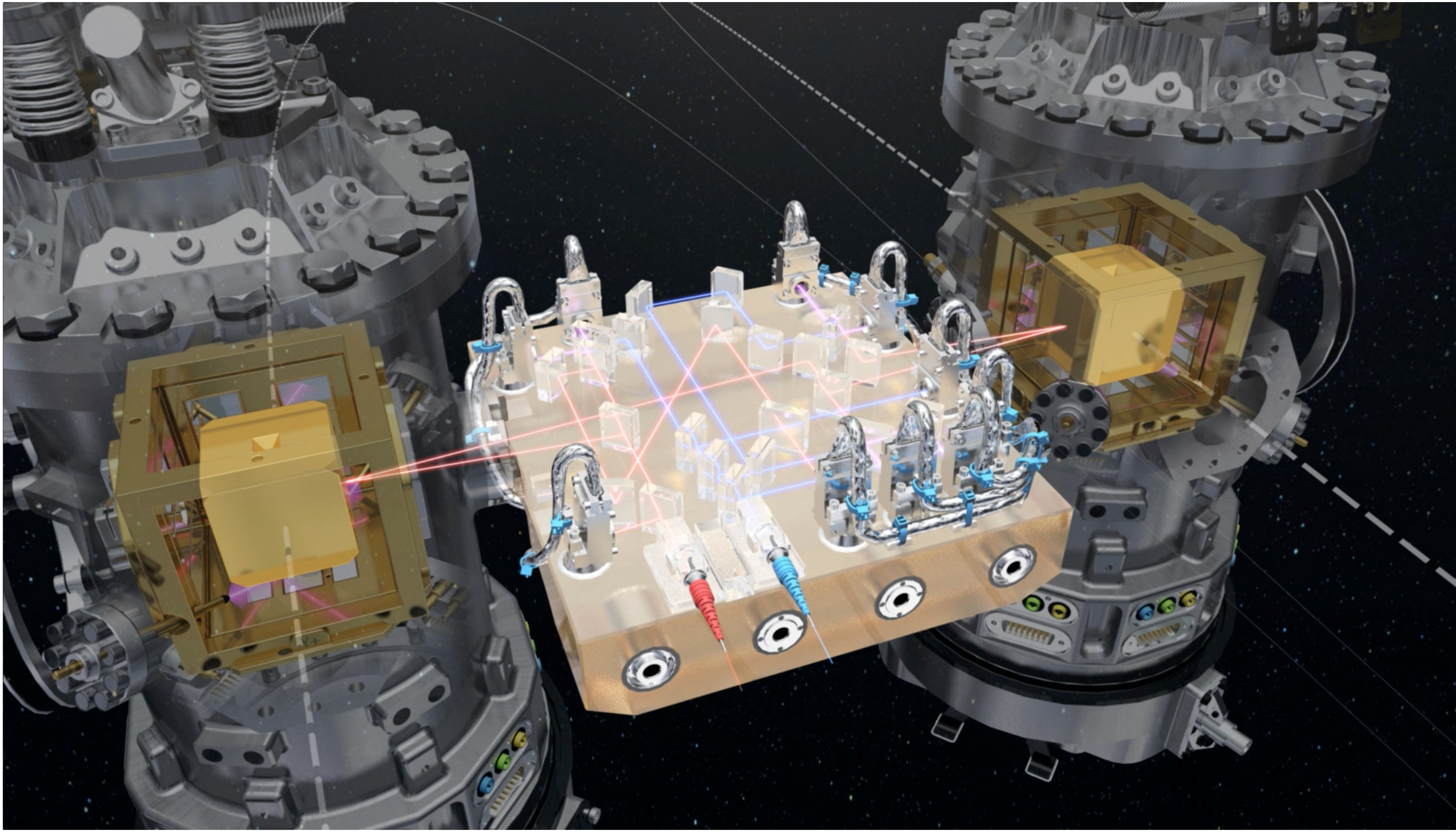
LISA sensitivity and Black Hole science



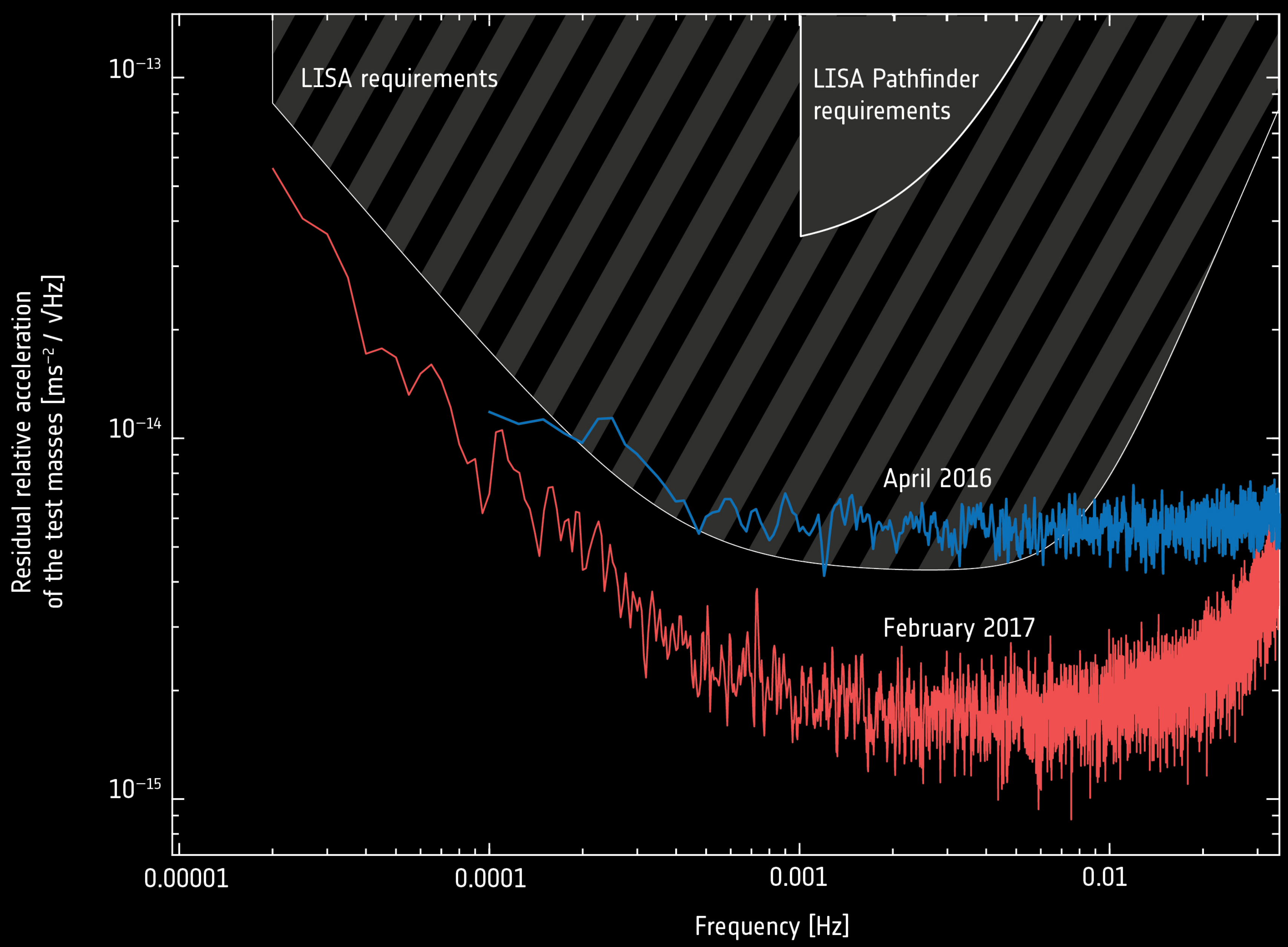
LISA PATHFINDER (ESA MISSION)

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



LISA requirements
LISA Pathfinder requirements
April 2016
February 2017
10^{-13}
10^{-14}
10^{-15}
Residual relative acceleration of the test masses [ms^{-2} / √Hz]
0.00001
0.0001
0.001
0.01
Frequency [Hz]

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