

observation of
Gravitational Waves

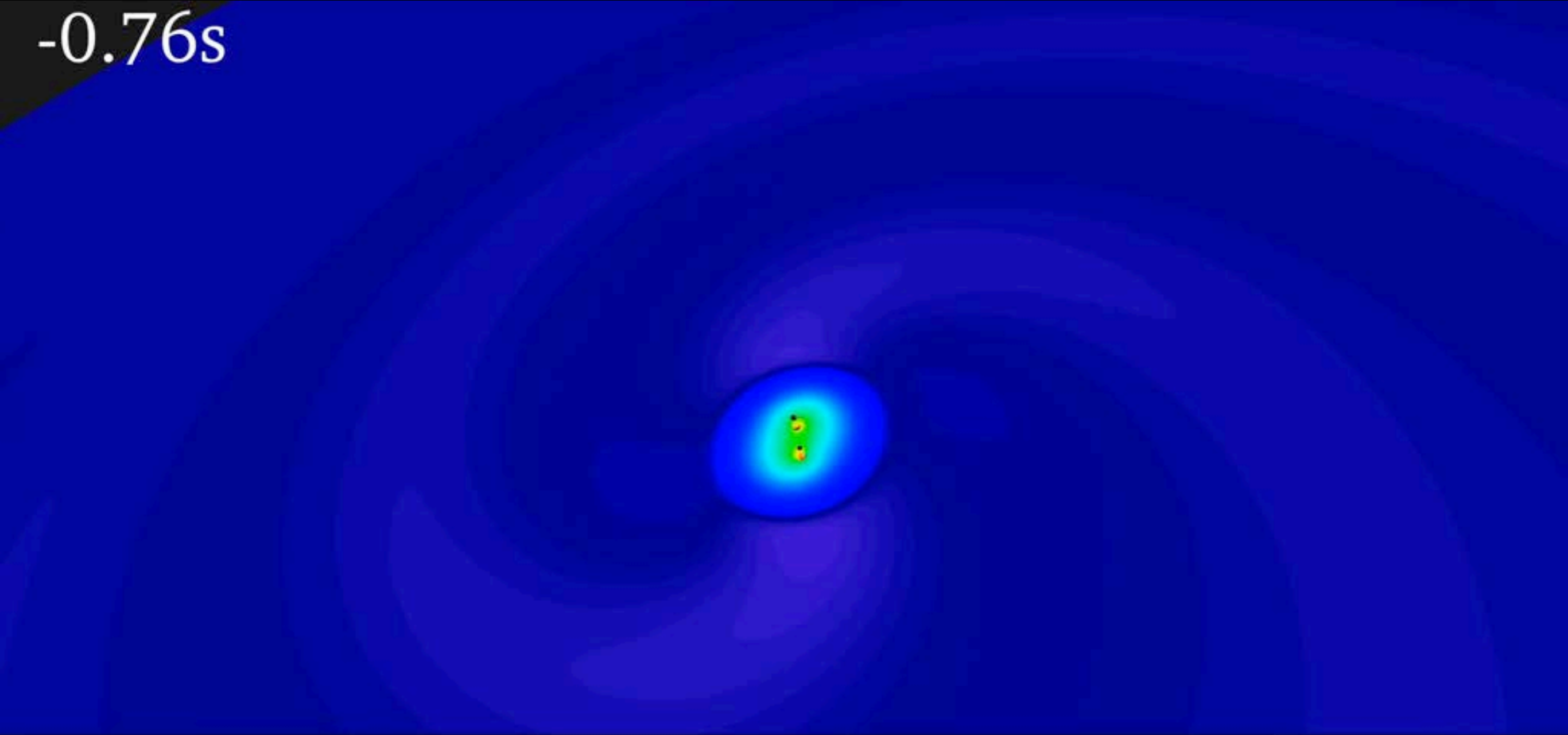
and
the merger of two

large mass stellar black holes

Gravitational Waves

- Gravitational waves are "ripples" in space-time
- their existence was predicted by Einstein in 1916, when he showed that accelerating massive objects radiate waves of distorted space
- these ripples travel at the speed of light, carrying information about their cataclysmic origins, as well as about the nature of gravity itself
- produced by some of the most violent events in the cosmos, such as the collisions and mergers of massive compact stars
- also in 1916, Karl Schwarzschild showed that Einstein's work permitted the existence of black holes
- on September 14, 2015, the Laser Interferometer Gravitational-wave Observatory (LIGO) observed gravitational waves, produced by two merging massive black holes, each of ~ 30 sun masses, in a galaxy about 1.3 billion light years apart.

-0.76s



Animation created by SXS, the Simulating eXtreme Spacetimes (SXS) project (<http://www.black-holes.org>)

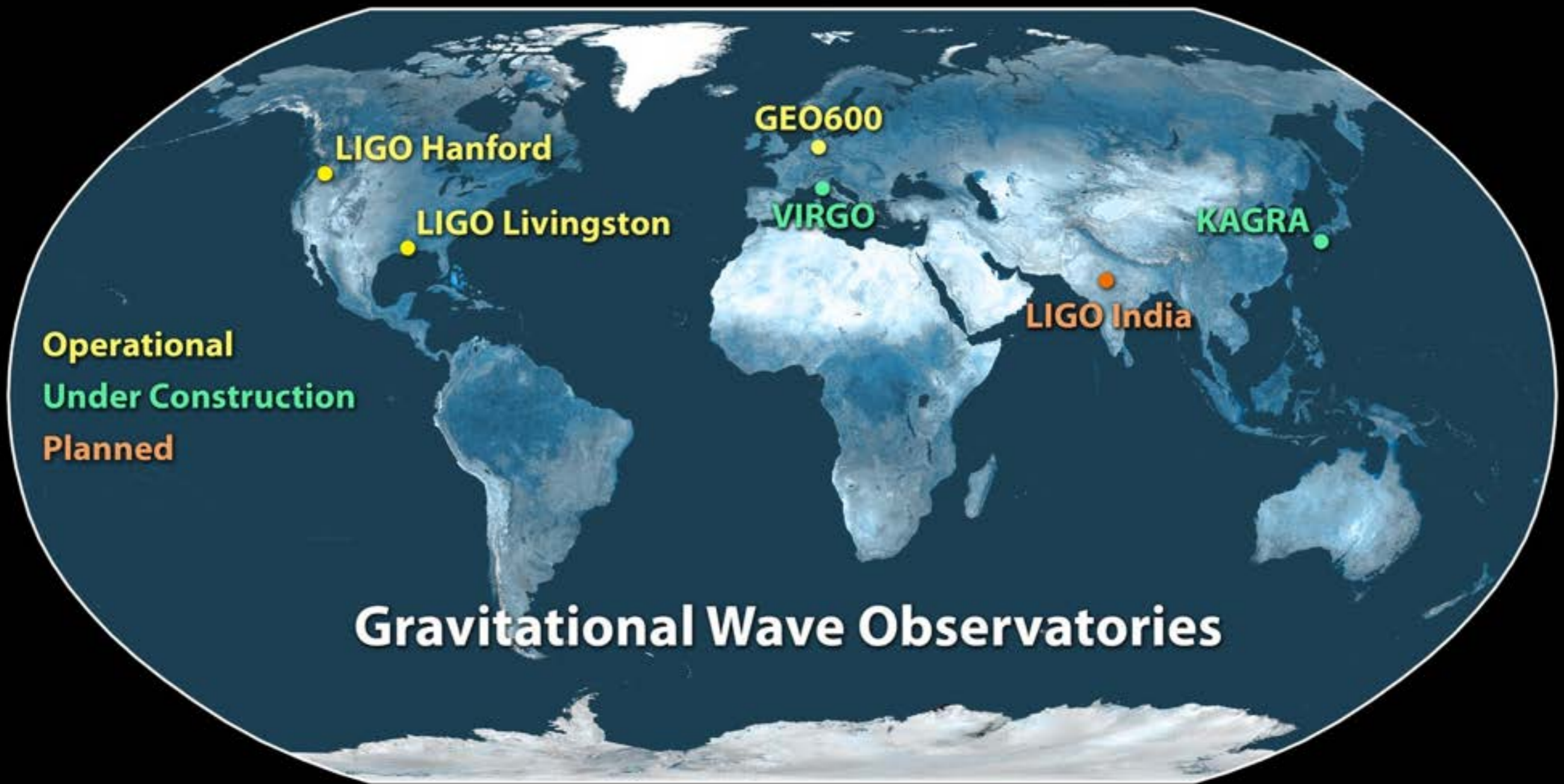


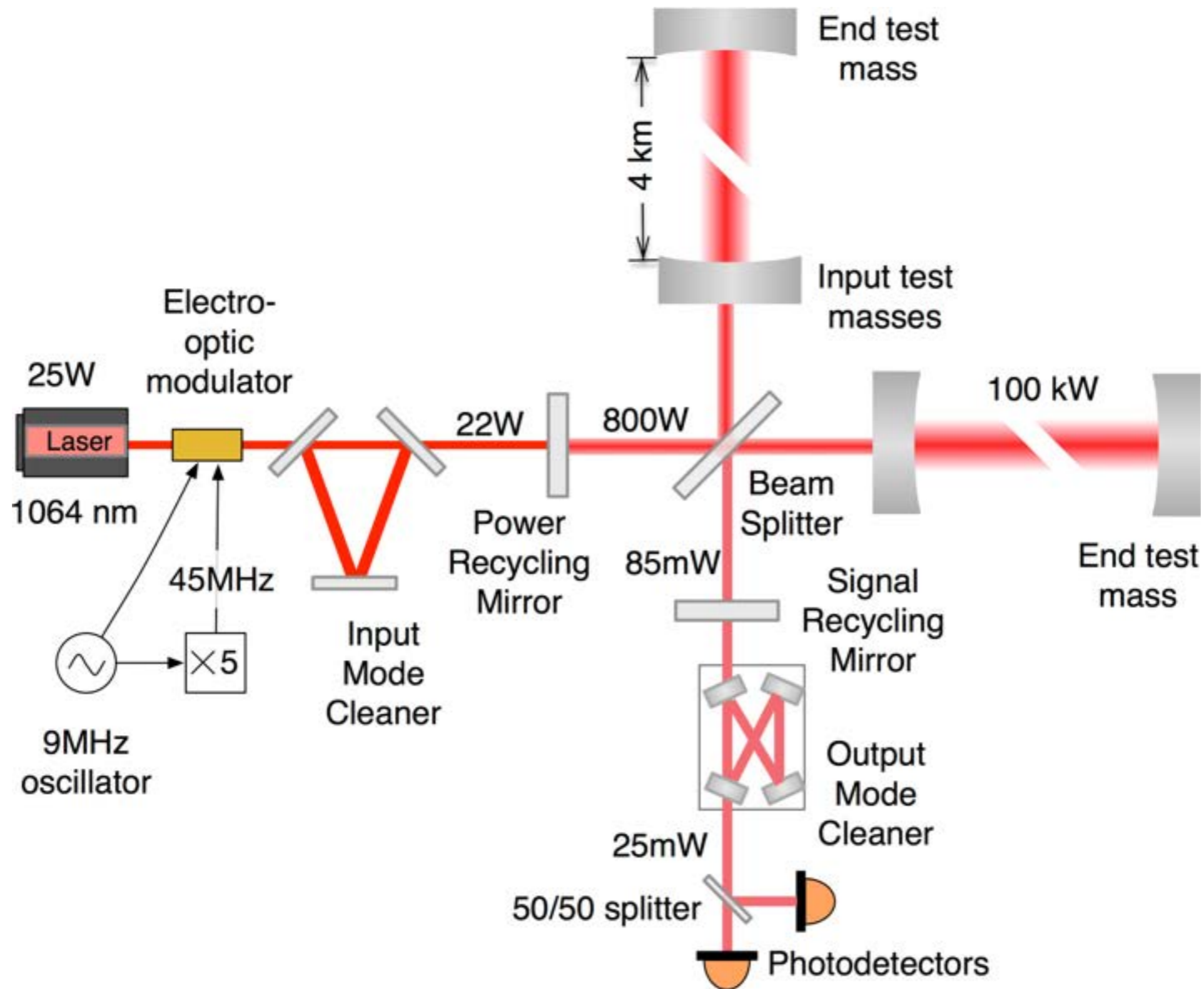
Image Credit: Caltech/MIT/LIGO Lab

advanced LIGO

- LIGO is the world's largest gravitational wave observatory
- two giant laser interferometers located thousands of kilometers apart: one in Livingston, Louisiana and the other in Hanford, Washington
- Each interferometer consists of two 4 km long "arms" at right angles
- a laser beam is shone and reflected by mirrors (suspended as test masses)
- a gravitational wave causes the arms of the interferometer alternately to lengthen and shrink, one getting longer while the other gets shorter
- the difference in length (strain) LIGO is sensitive to is down to 1/10.000 of the diameter of a proton - after upgrade to *advanced LIGO* in 2014 (advanced power recycling, signal recycling, new optical elements and suspensions)



advanced LIGO



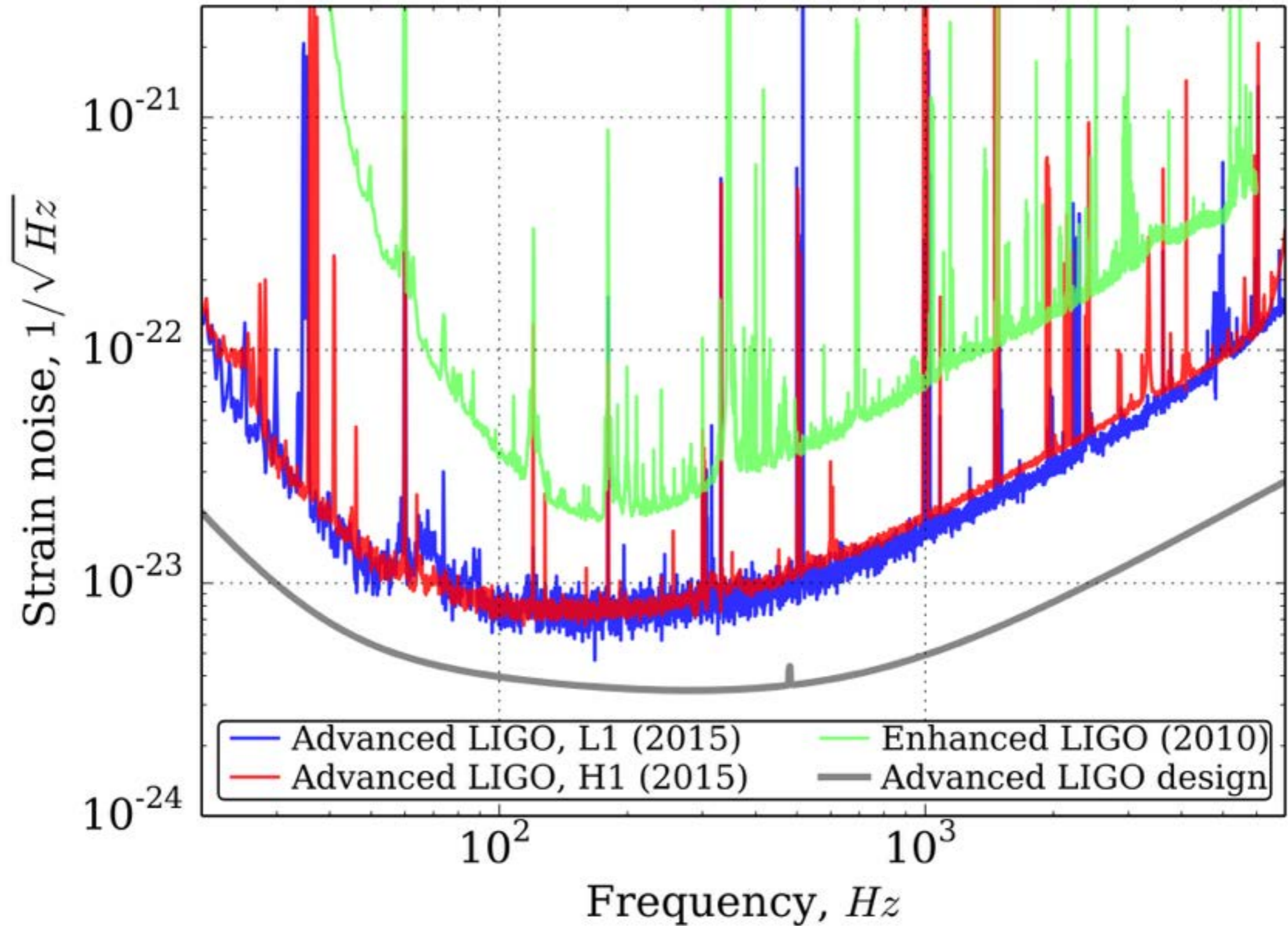
All of the components shown, except the laser and phase modulator, are mounted in the LIGO ultra-high vacuum system on seismically isolated platforms. Power levels at ca. 1/8 of design values.

advanced LIGO

Table 1. Main parameters of the Advanced LIGO interferometers. PRC: power recycling cavity; SRC: signal recycling cavity.

| Parameter | Value |
|-------------------------------------|-----------------------------|
| Arm cavity length | 3994.5 m |
| Arm cavity finesse | 450 |
| Laser type and wavelength | Nd:YAG, $\lambda = 1064$ nm |
| Input power, at PRM | up to 125 W |
| Beam polarization | linear, horizontal |
| Test mass material | Fused silica |
| Test mass size & mass | 34cm diam. x 20cm, 40 kg |
| Beam radius ($1/e^2$), ITM / ETM | 5.3 cm / 6.2 cm |
| Radius of curvature, ITM / ETM | 1934 m / 2245 m |
| Input mode cleaner length & finesse | 32.9 m (round trip), 500 |
| Recycling cavity lengths, PRC / SRC | 57.6 m / 56.0 m |

advanced LIGO

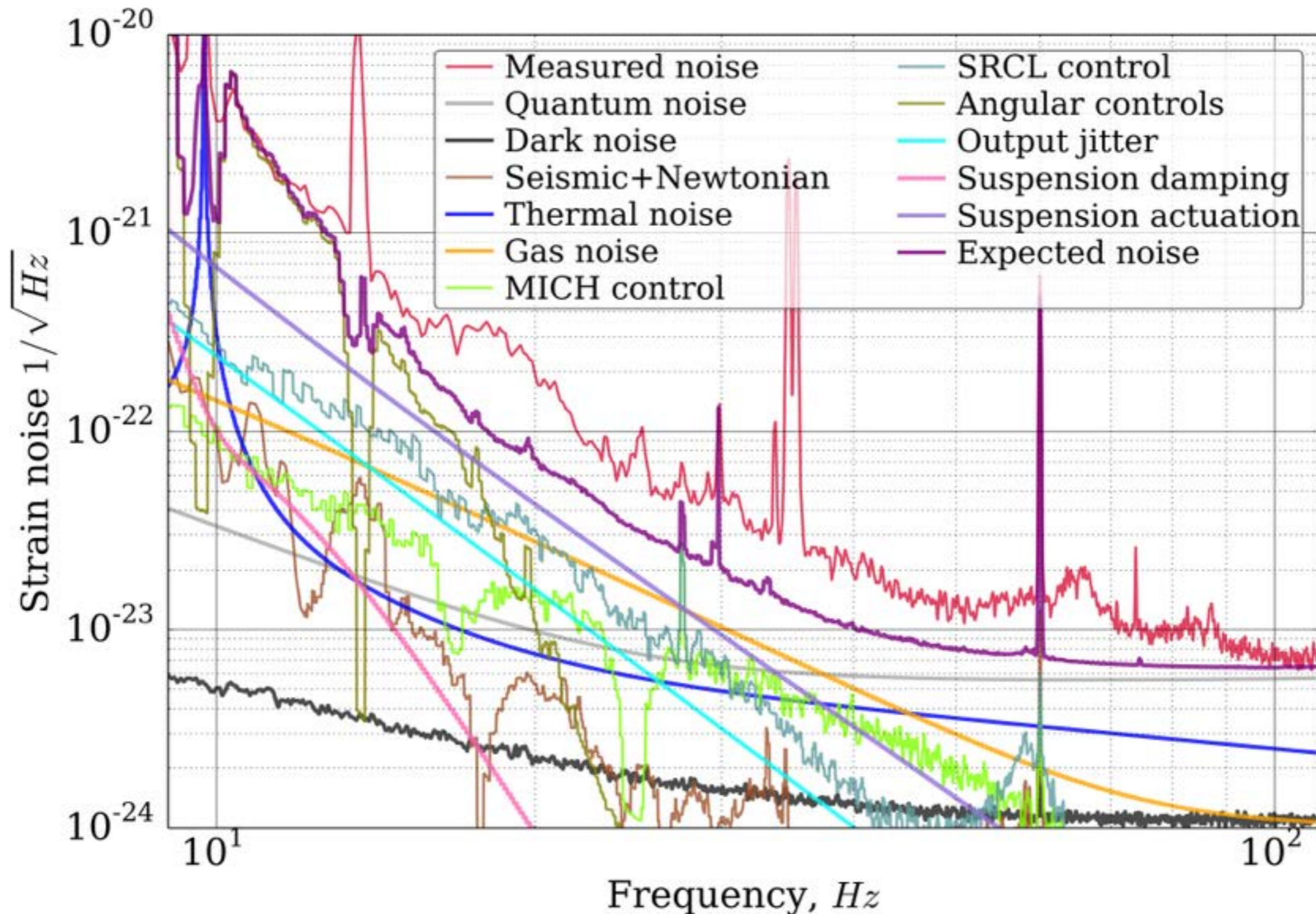


advanced LIGO

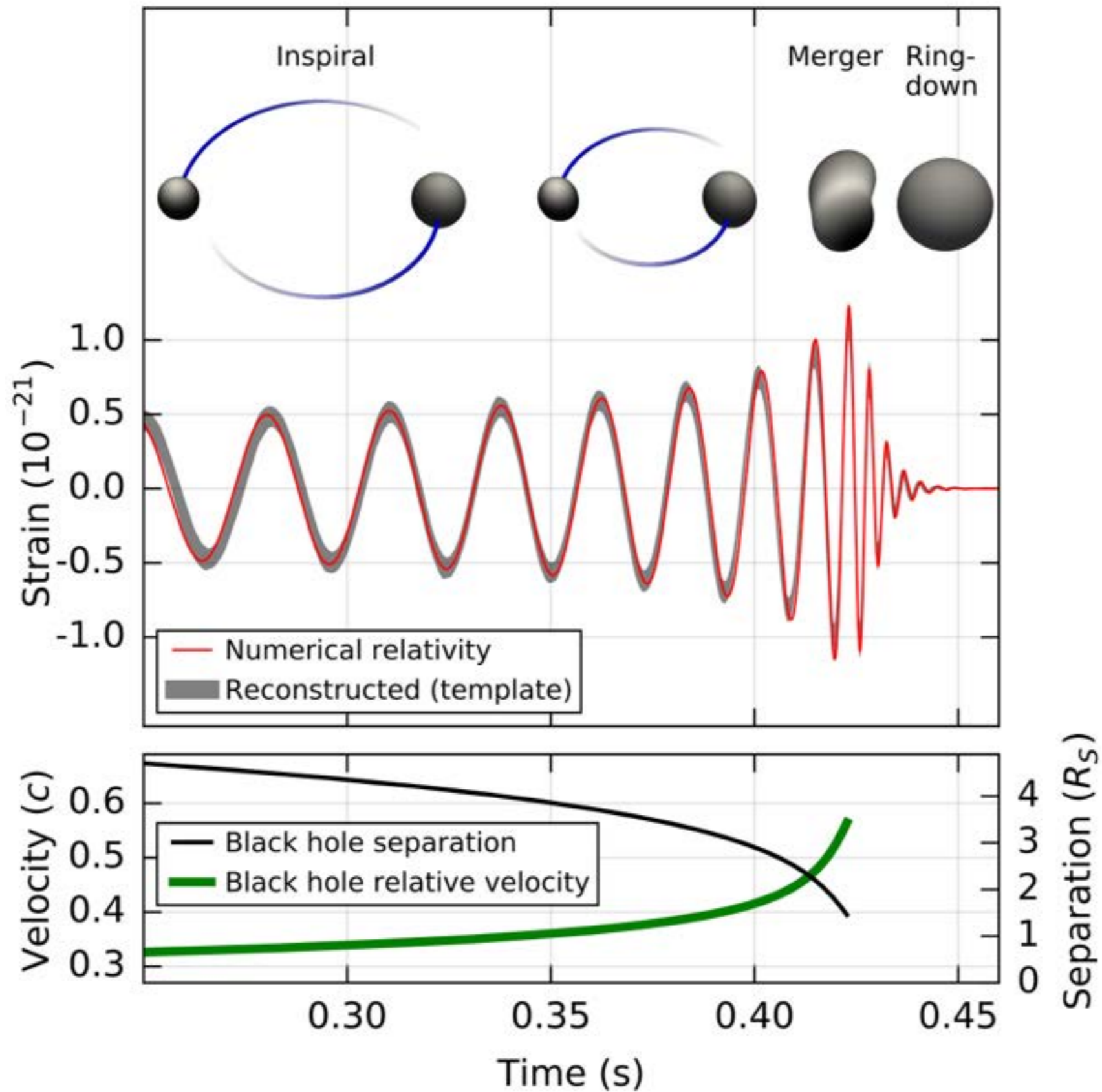
Some examples of noise sources are:

- **Seismic noise**, due to the motion of the mirrors from ground vibrations, earthquakes, wind, ocean waves, and human activities such as vehicle traffic.
- **Thermal noise**, from the microscopic fluctuations of the individual atoms in the mirrors and their suspensions.
- **Quantum noise**, due to the discrete nature of light (composed of photons) and the statistical uncertainty from the "[photon counting](#)" that is performed by the photodetectors.
- **Gas noise**, from the interactions of the residual gas particles in the vacuum enclosure with the mirrors and the laser light.
- **Charging noise**, from the interaction of static electric charges on the glass mirrors with the metal of the vacuum enclosures and the mirror supports.
- **Laser noises**, for example small variations in the laser intensity and frequency.
- **Auxiliary degree-of-freedom noise**, due to the control of the position and alignment of the various mirrors in the detectors, and the slight cross-coupling between those mirrors and the measurement of the gravitational wave signal.
- **Oscillator noise**, generated by the [radiofrequency modulation](#) of the laser light, which is necessary for the control of the interferometer.
- **Beam jitter**, or slight variations in the position and angle of the laser beam in the detector, which can generate noise if they misalign the laser beam with respect to the optical cavities.
- **Scattered light**, generated by tiny imperfections in the mirrors of the interferometers, which can redirect a small fraction of the laser light towards the walls or other components of the instruments. If this light recombines with the main beam it will generate a spurious signal in the readout photodetectors.
- And finally, **electronics noise**, which is generated by the analog and digital electronics that are used to measure the signal itself.

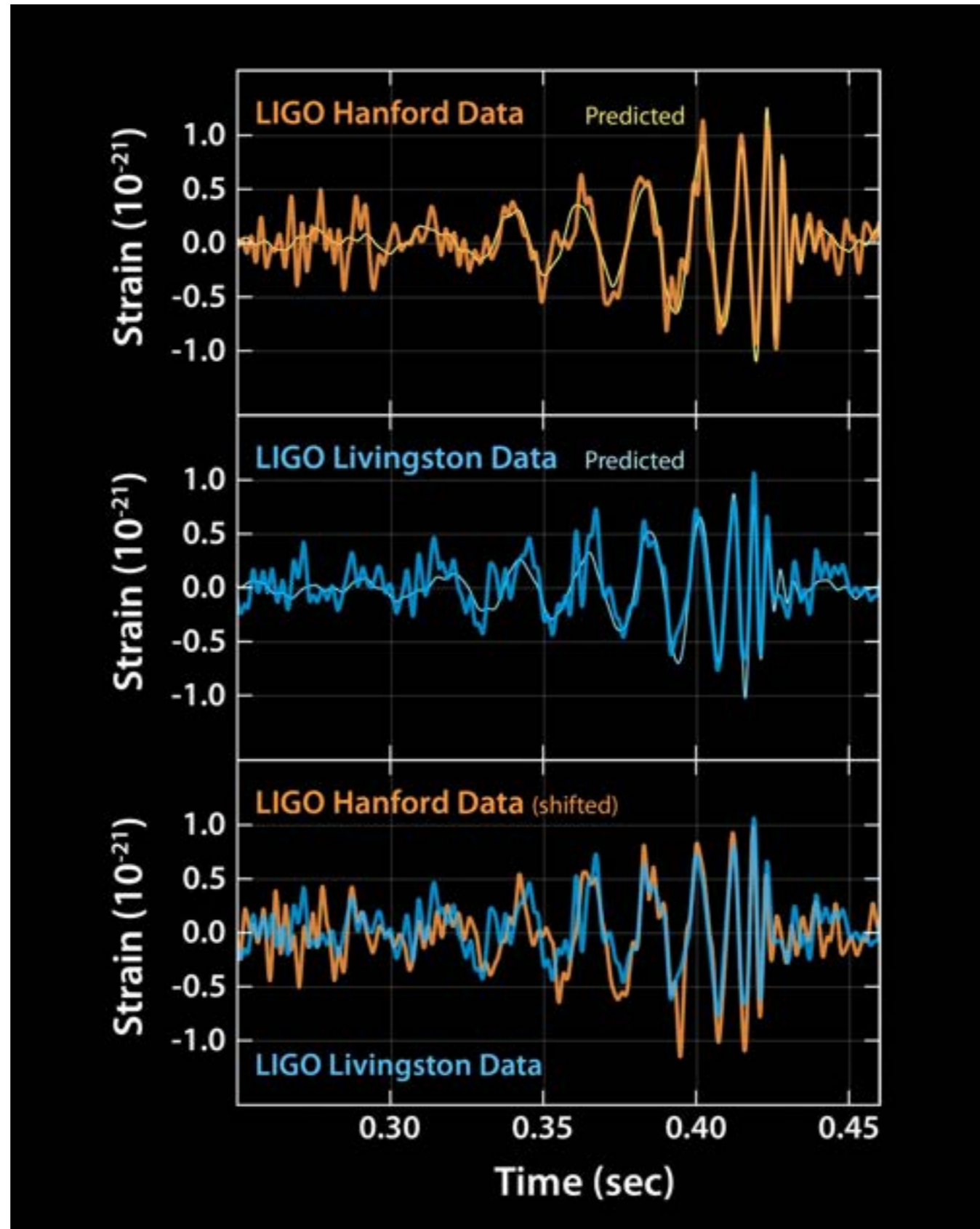
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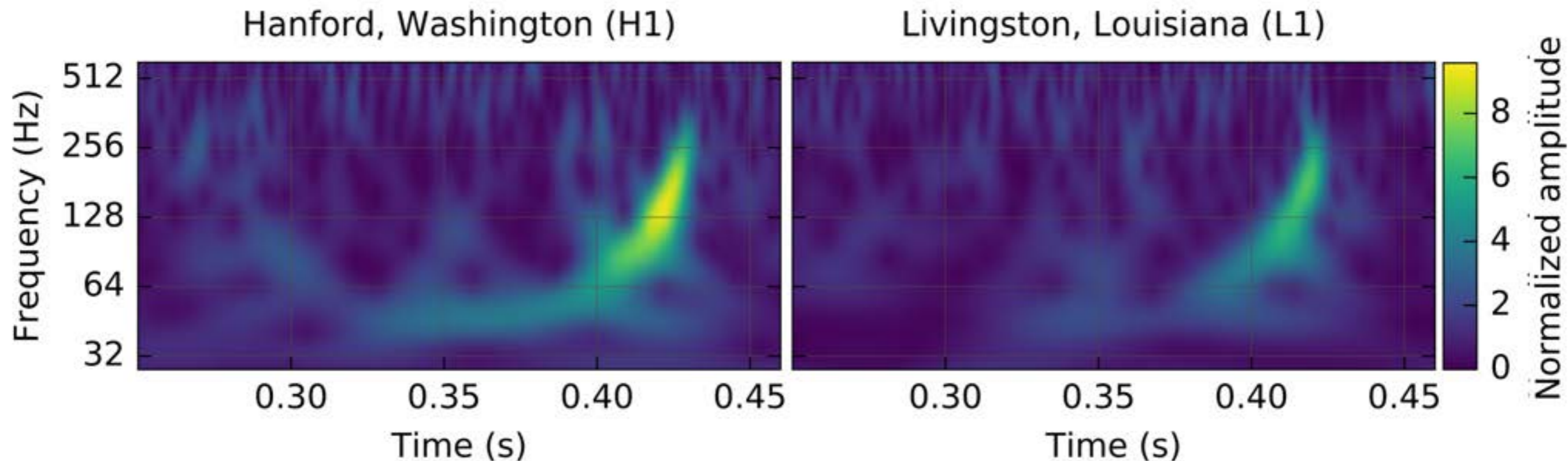


Strain represents the fractional amount by which distances are distorted

Image Credit: Caltech/MIT/LIGO Lab

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time-frequency representation of strain data



"Chirp"-Mass:

$$M = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G} \left[\frac{5}{96} \pi^{-8/3} f^{-11/3} \dot{f} \right]^{3/5}$$

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signal numerics:

- within 0.2 s, 8 cycles with increasing freq. 35 - 150 Hz
- "chirp" mass $M \sim 30 M_{\text{sun}}$
- sum of Schwarzschild radii $2GM/c^2 > \sim 210 \text{ km}$
- orbital frequency of 75 Hz for such $M \rightarrow$ distance $\sim 350 \text{ km}$
- \rightarrow only possible for two black holes of $M \sim 30 M_{\text{sun}}$

- decay wave form after peak consistent with damped oscillations of a BH relaxing to stationary configuration

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reconstructed source parameters for GW150914
(model calculations):

| | |
|---------------------------|---------------------------------|
| Primary black hole mass | $36_{-4}^{+5} M_{\odot}$ |
| Secondary black hole mass | $29_{-4}^{+4} M_{\odot}$ |
| Final black hole mass | $62_{-4}^{+4} M_{\odot}$ |
| Final black hole spin | $0.67_{-0.07}^{+0.05}$ |
| Luminosity distance | $410_{-180}^{+160} \text{ Mpc}$ |
| Source redshift z | $0.09_{-0.04}^{+0.03}$ |

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some other numerics:

- strain noise at 100Hz: $\sim 10^{-23}$
- max. observed signal: $\sim 10^{-21}$
- interferometer length: 4000 m
- strain sensitivity: $10^{-23} \cdot 4000\text{m} \sim 10^{-19}\text{m}$
- proton size: $\sim 1 \text{ fm} = 10^{-15} \text{ m}$

- laser wavelength: 1064 nm

- phase sensitivity: 10^{-10} (dark fringe limit)

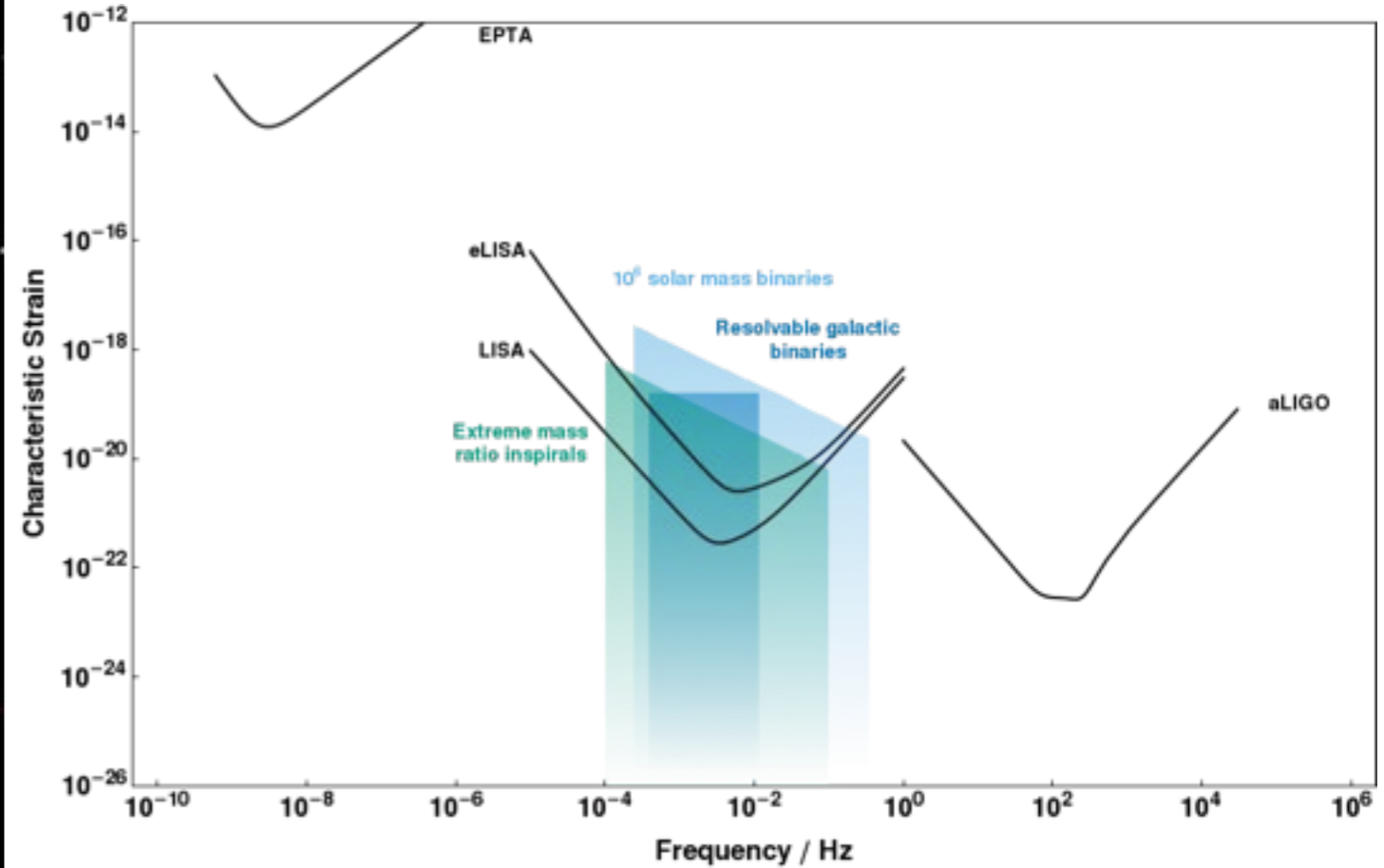
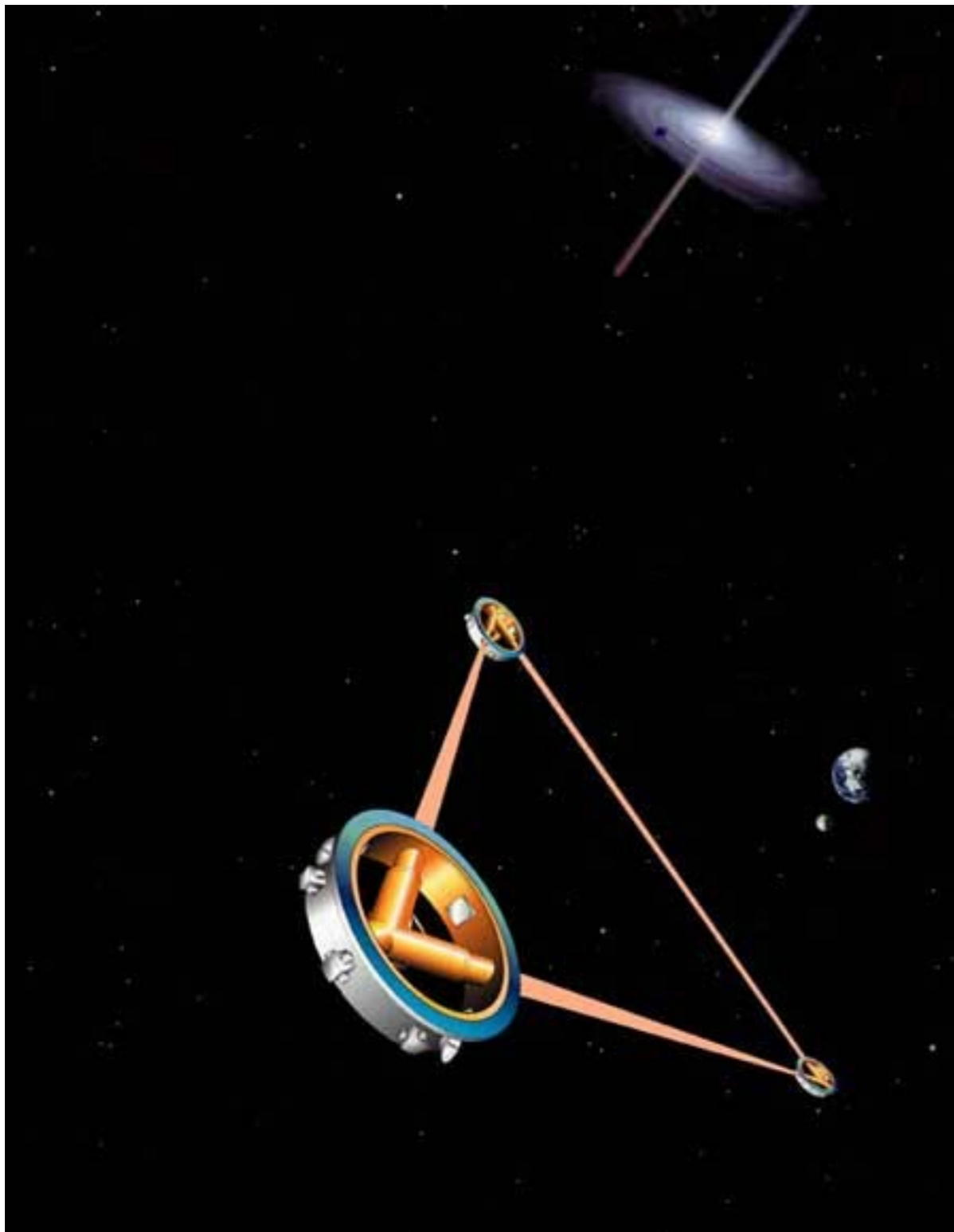
summary

- first successful direct observation of gravitational waves
- first direct observation of stellar binary black hole merger
- first direct observation of massive black holes with $M > 25M_{\text{sun}}$
- important test of general relativity
- start of observational astronomy/astrophysics using gravitational waves as messengers

outlook

- analysis of full data sample
- full commissioning of advanced Ligo
- more detectors (VIRGO (3km), KAGRA (3km), 3rd LIGO)

Future: (Evolved) Laser Interferometer Space Antenna: (e)LISA



- LISA: joined NASA & ESA project
- 2011: NASA quits participation
- eLISA: ESA revised mission concept
- 2015: launch of LISA pathfinder
- 2034: tentative launch eLISA

arm lengths: 5 million km (LISA)
 1 million km (eLISA)

Literature

Advanced LIGO

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www.ligo.caltech.edu

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<http://www.ego-gw.it/public/virgo/virgo.aspx>

<http://www.geo600.org>