observation of

Gravitational Waves

and

the merger of two large mass stellar black holes

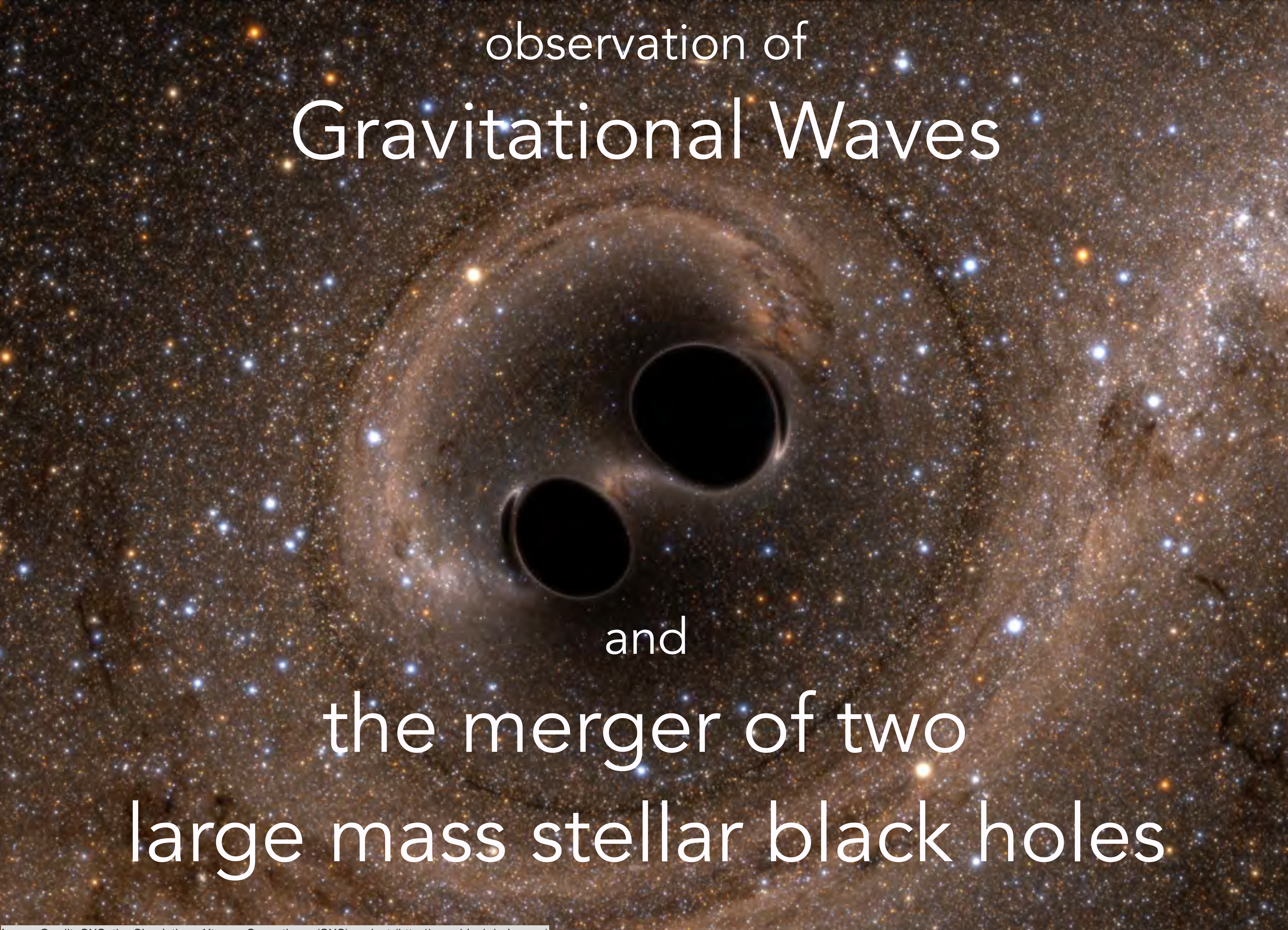
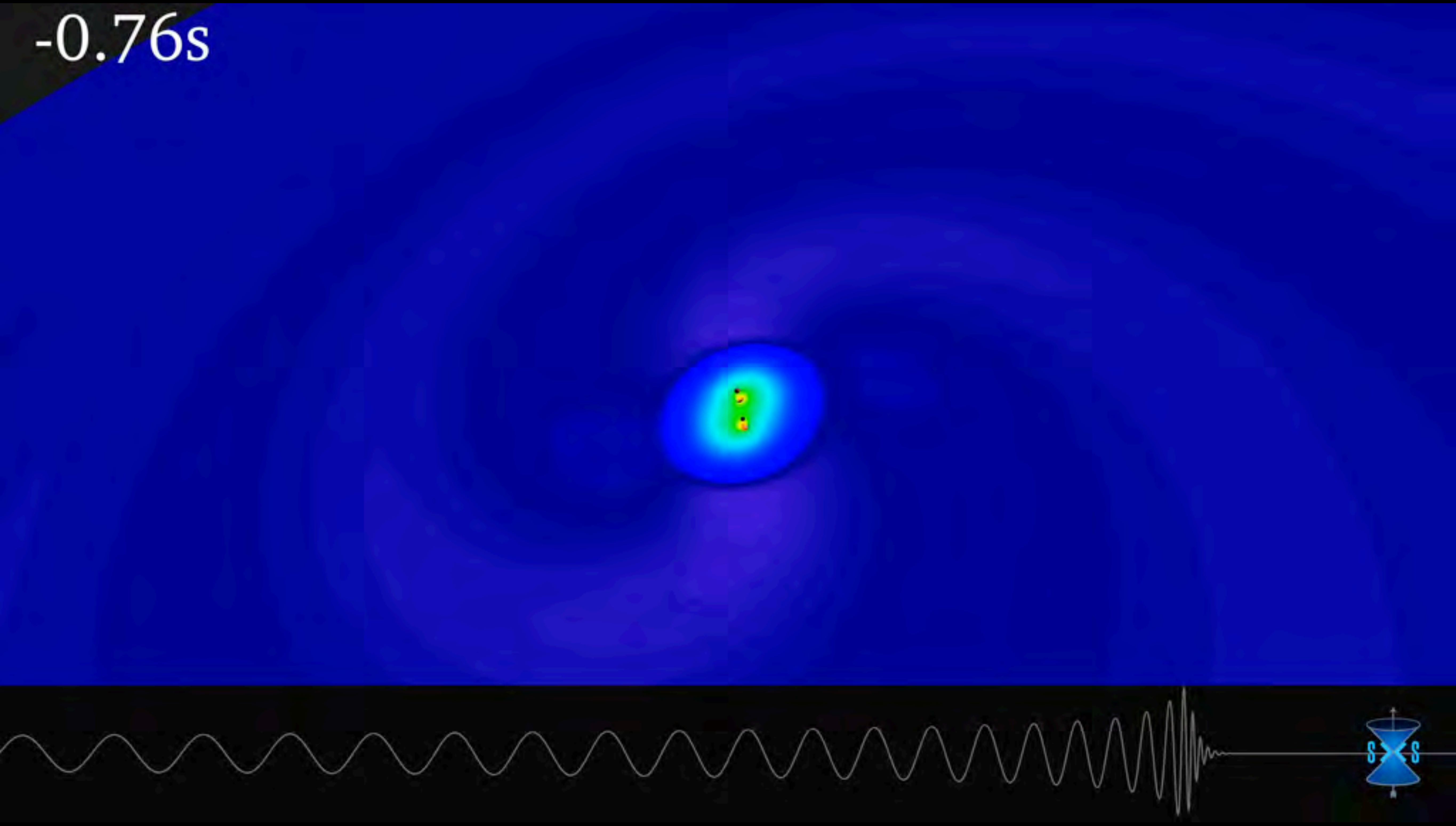


Image Credit: SXS, the Simulating eXtreme Spacetimes (SXS) project (http://www.black-holes.org)

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.



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

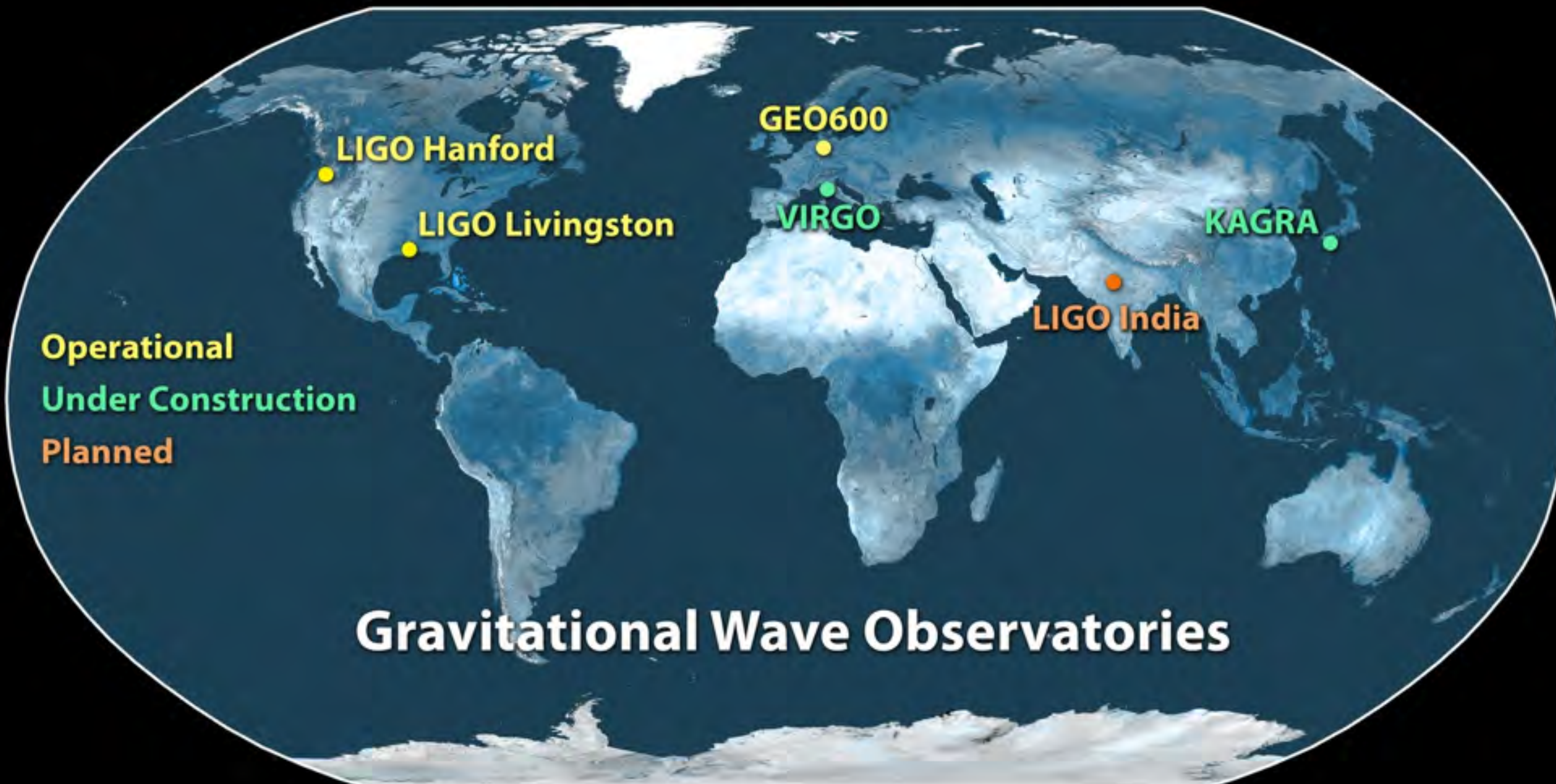


Image Credit: Caltech/MIT/LIGO Lab

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

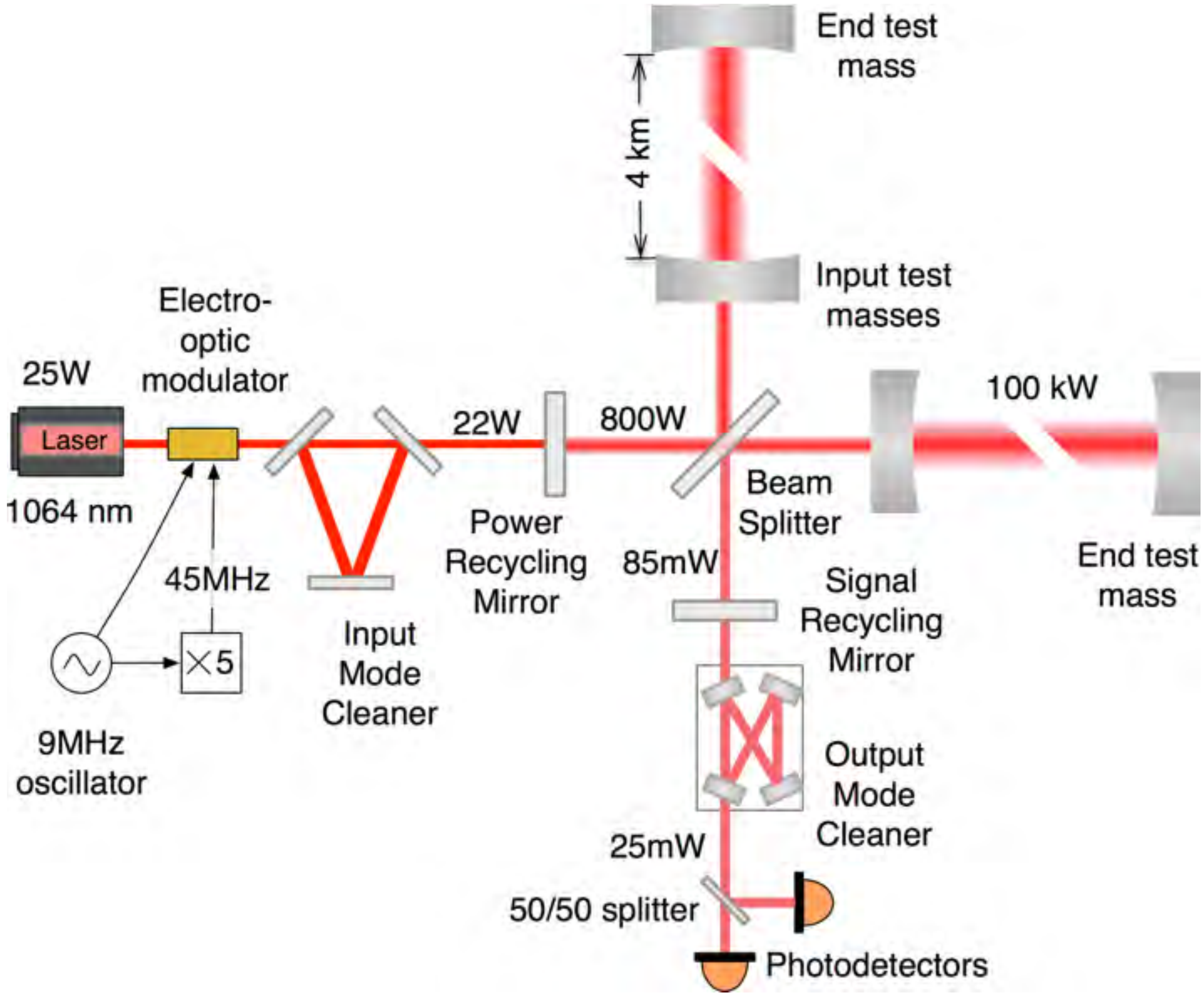
- Each interferometer consists of two 4 km long "arms" at right angles

- 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



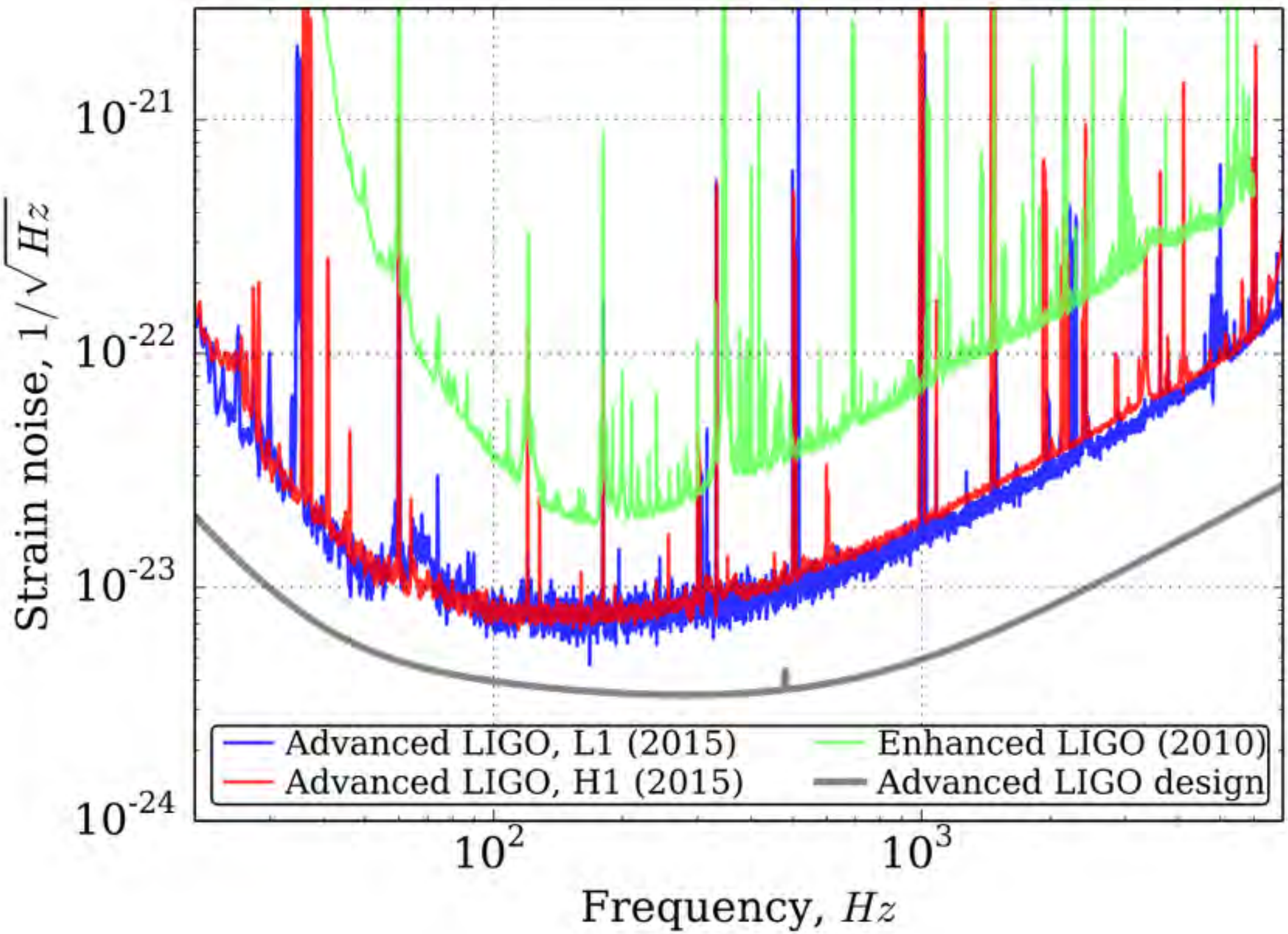
All of the components shown, except the laser and phase modulator, are mounted in the LIGO ultra-high vacuum system on seismically isolated platforms. Power levels at ca. 1/8 of design values.

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



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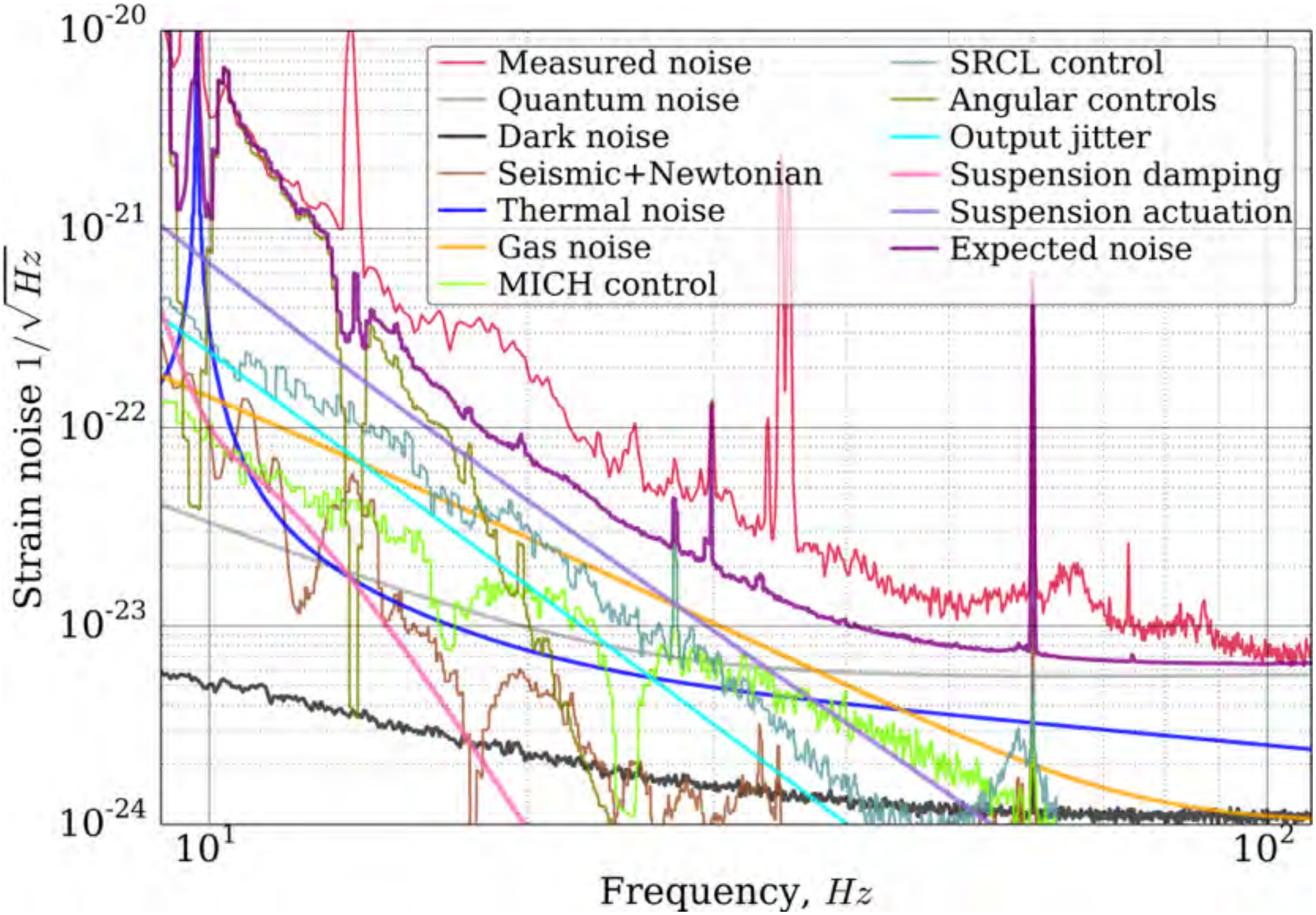
Some examples of noise sources are:

- **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 digitial electronics that are used to measure the signal itself.

advanced LIGO



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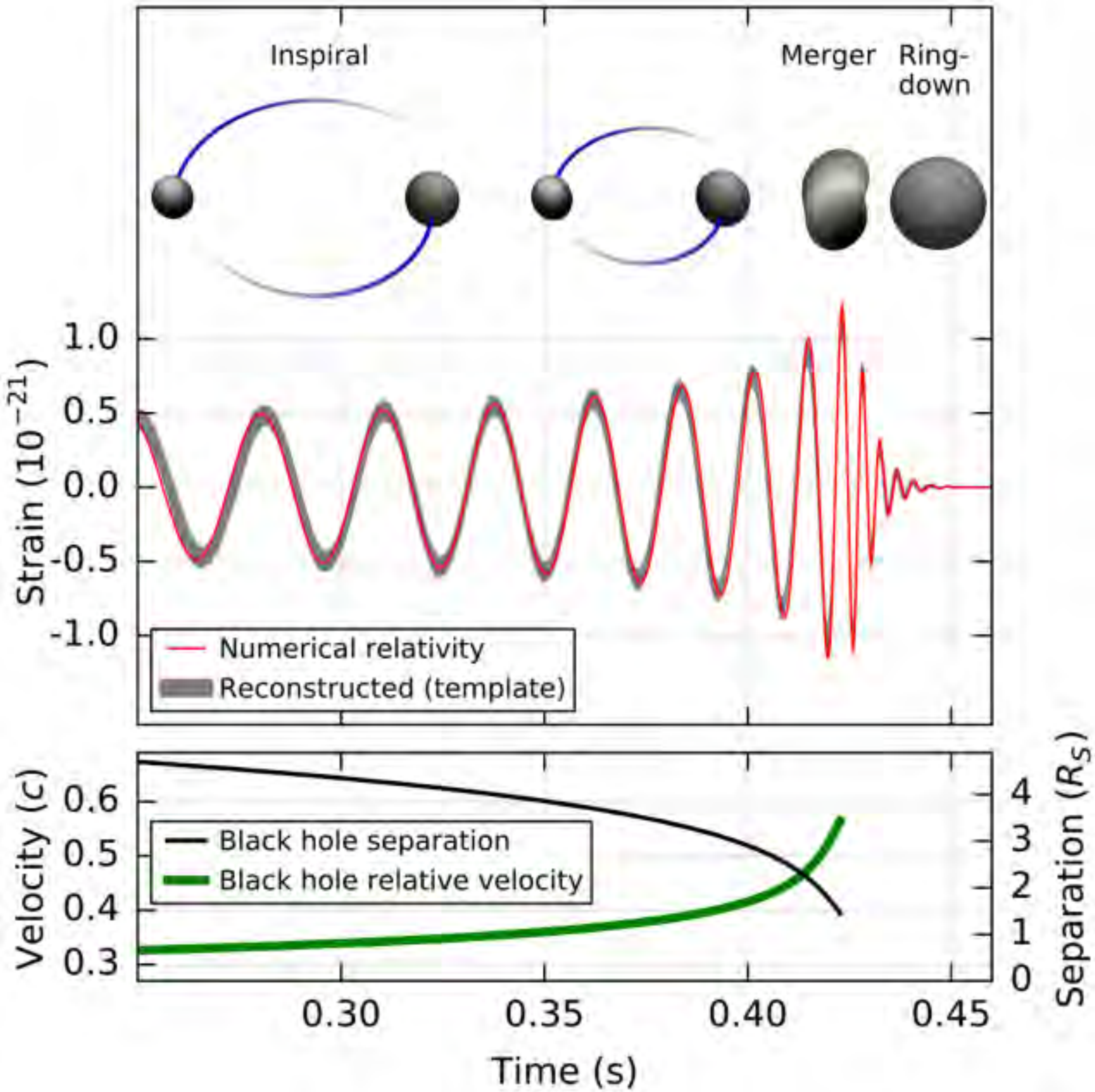

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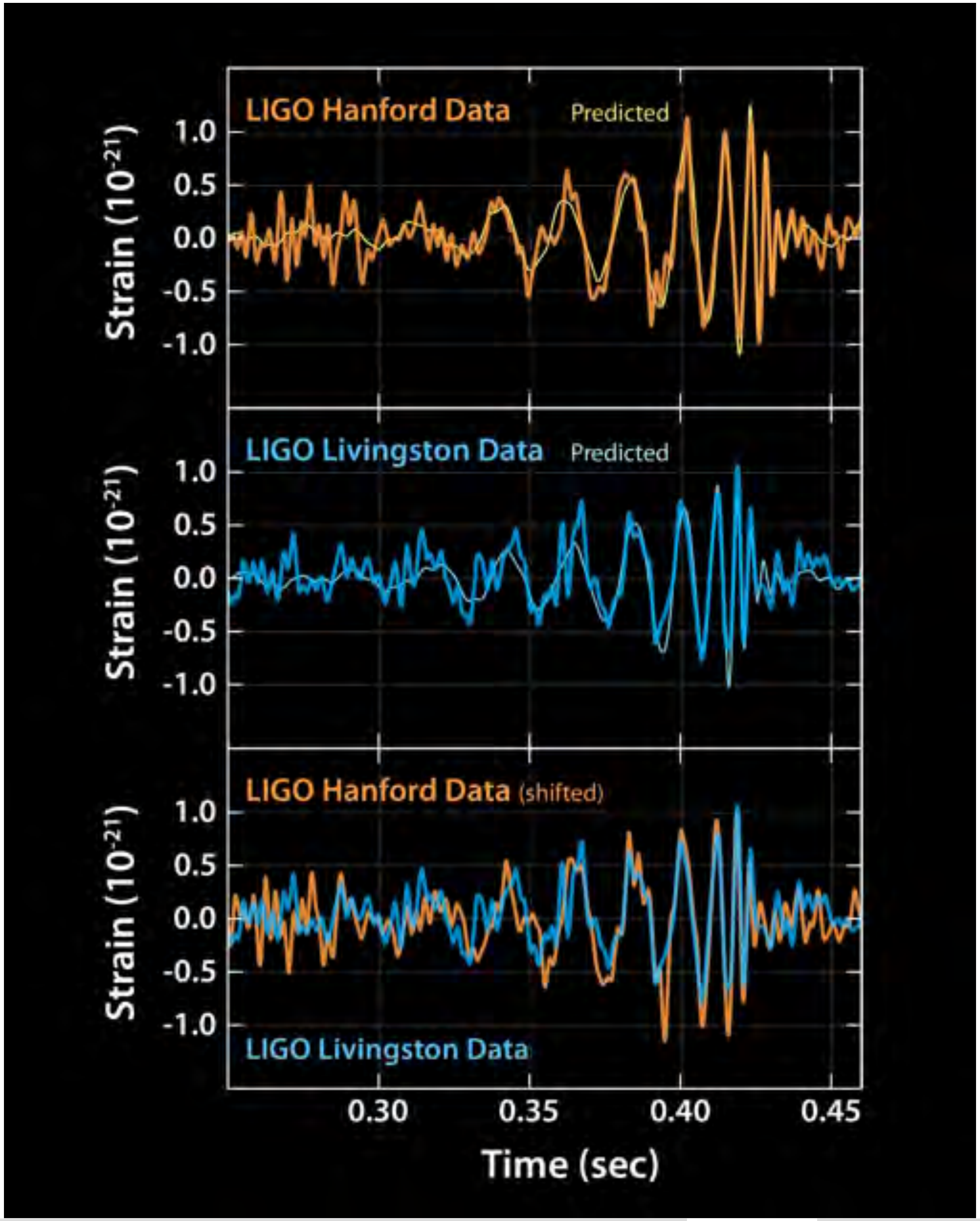

Strain represents the fractional amount by which distances are distorted

Image Credit: Caltech/MIT/LIGO Lab

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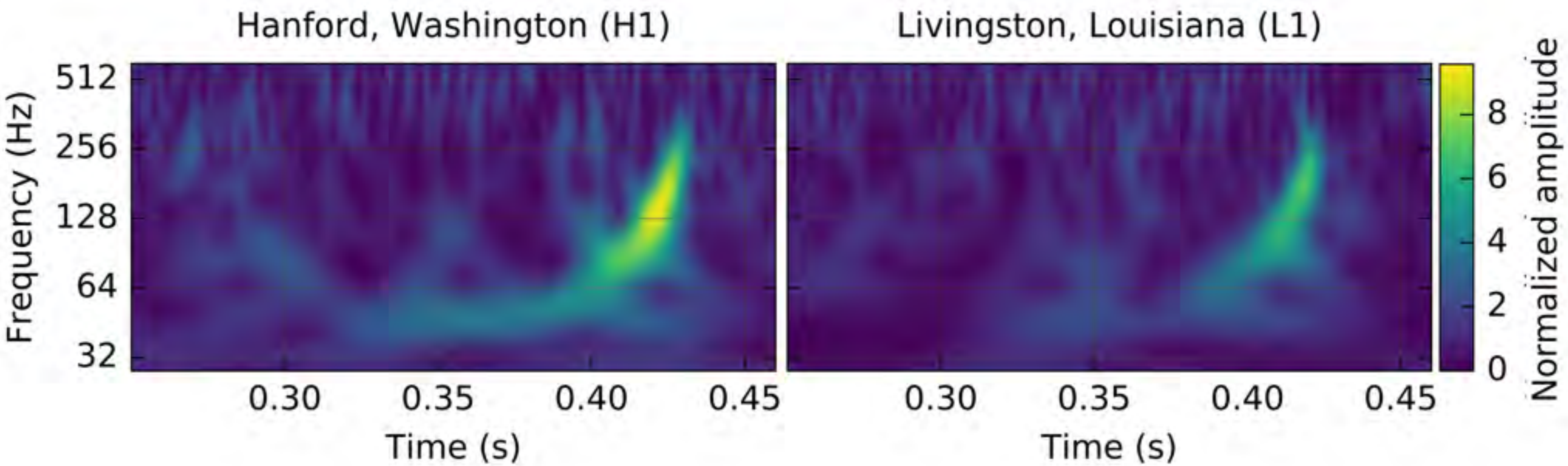
time-frequency representation of strain data



"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 $M \sim 30\ M_{sun}$
- sum of Schwarzschild radii $2GM/c^2$ >~210 km
- orbital frequency of 75 Hz for such M -> distance~350 km
- -> only possible for two black holes of $M \sim 30\ M_{sun}$

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

advanced LIGO

reconstructed source parameters for GW150914 (model calculations):

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

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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)

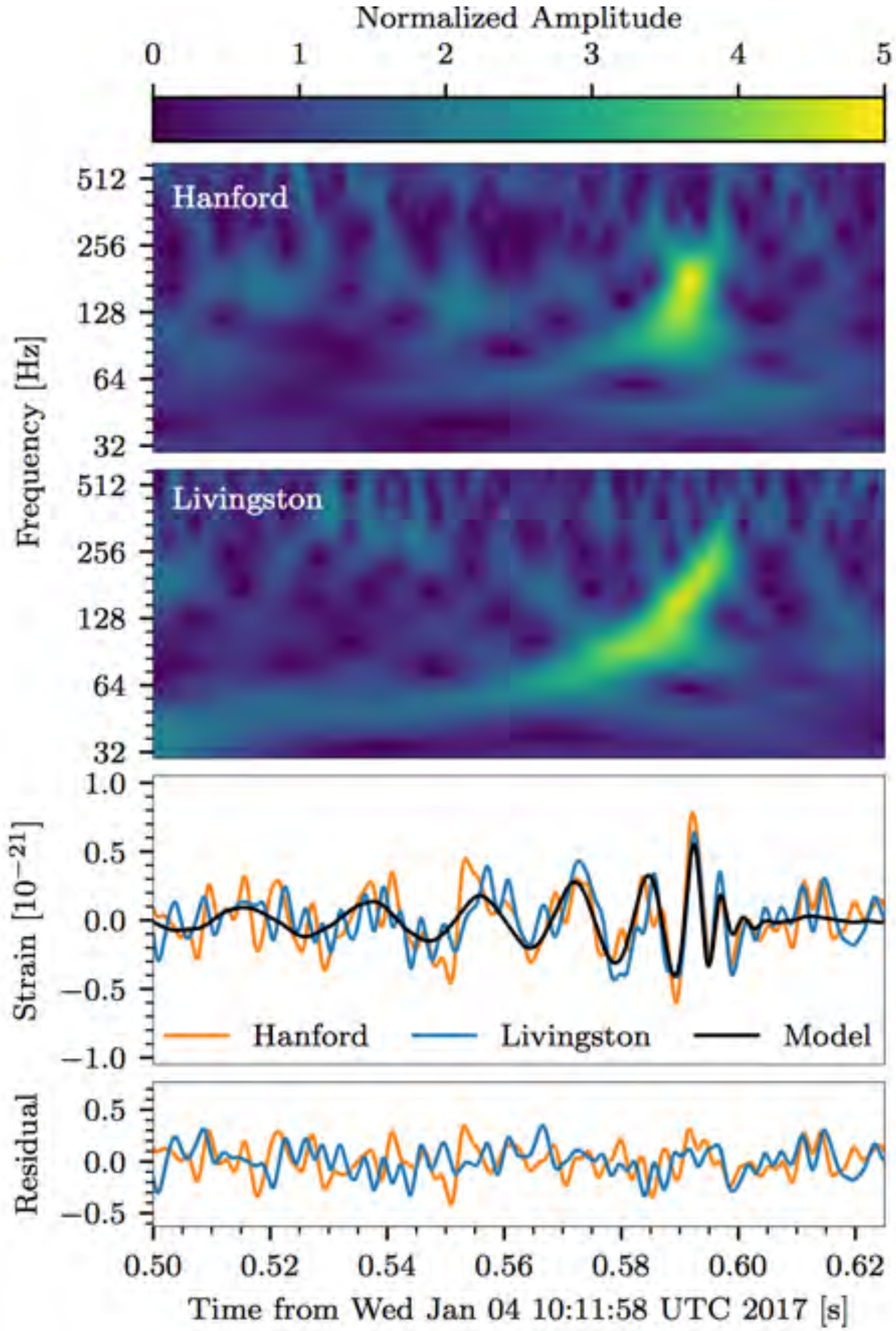
more data from advanced LIGO:

from LIGO 1st run: - 2 binary BH mergers
- 1 less likely candidate

LIGO 2nd run: - started Nov 30, 2016
- Jan 7, 2017:

GW170104:
Observation of a 50-Solar-Mass Binary Black Hole Coalescence

more data from advanced LIGO:



Primary black hole mass m_1	$31.2^{+8.4}_{-6.0}\ M_\odot$
Secondary black hole mass m_2	$19.4^{+5.3}_{-5.9}\ M_\odot$
Chirp mass $\mathcal{M}$	$21.1^{+2.4}_{-2.7}\ M_\odot$
Total mass M	$50.7^{+5.9}_{-5.0}\ M_\odot$
Final black hole mass M_f	$48.7^{+5.7}_{-4.6}\ M_\odot$
Radiated energy E_rad	$2.0^{+0.6}_{-0.7}\ M_\odot c^2$
Peak luminosity ℓ_peak	$3.1^{+0.7}_{-1.3} \times 10^{56}$ erg s^{-1}
Effective inspiral spin parameter χ_eff	$-0.12^{+0.21}_{-0.30}$
Final black hole spin a_f	$0.64^{+0.09}_{-0.20}$
Luminosity distance D_L	880^{+450}_{-390} Mpc
Source redshift z	$0.18^{+0.08}_{-0.07}$

(arXiv:1706.01812)

summary

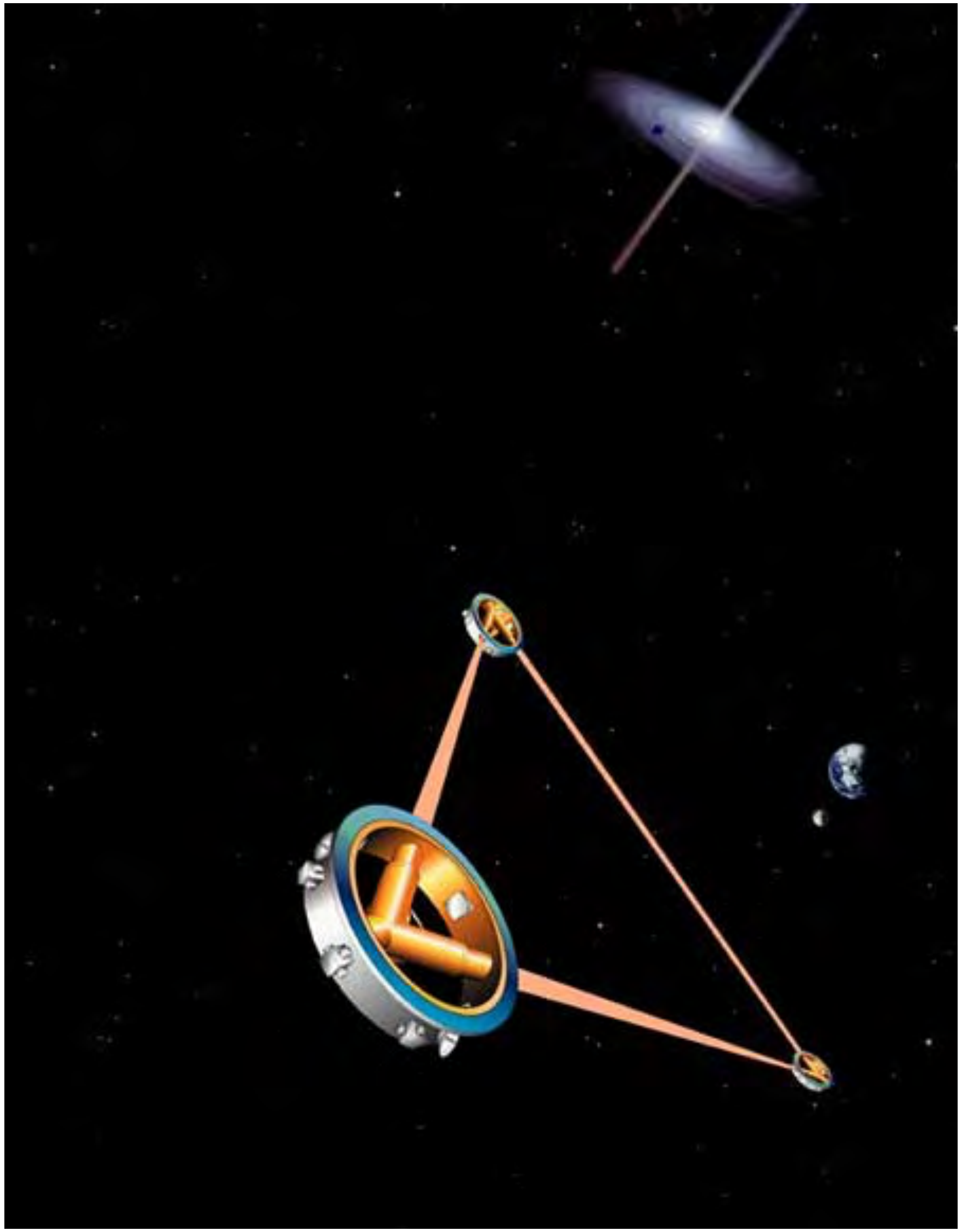
- first successful direct observation of gravitational waves
- first direct observation of stellar binary black hole merger
- first direct observation of massive black holes with $M>25M_{sun}$

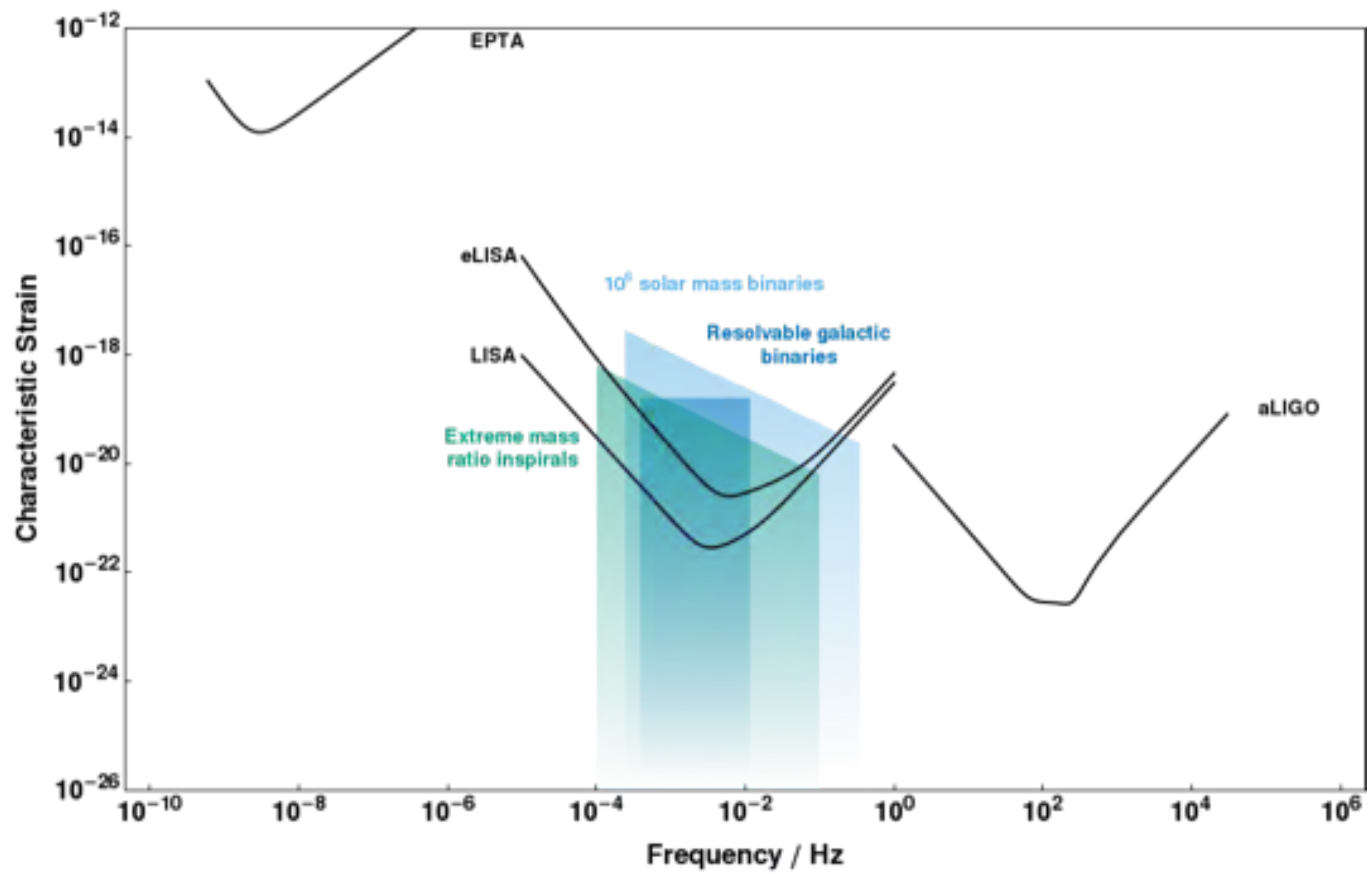
- important test of general relativity
- start of observational astronomy/astrophysics using gravitational waves as messengers

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

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