The Detection of Gravitational Waves:
What we've learned, and where we go from here

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For the LIGO Scientific Collaboration and the Virgo Collaboration

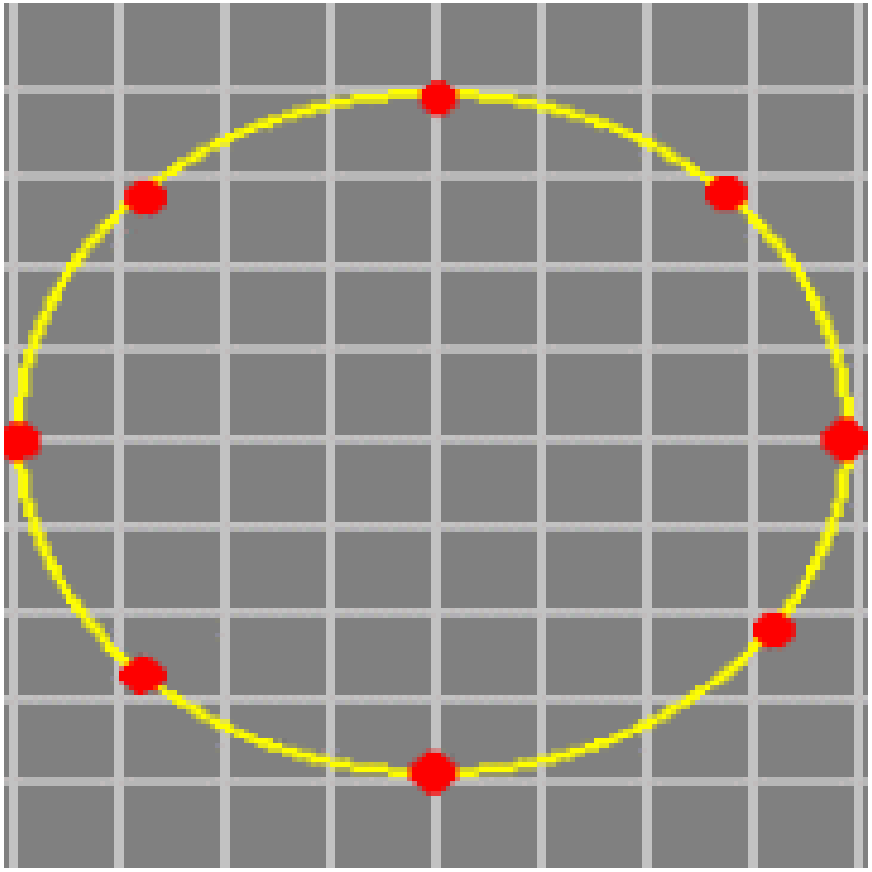
Outline

- Interferometers as an implementation of Pirani's thought experiment
- Advanced LIGO as an exemplary interferometer
- What we've discovered so far
- What's next for instruments and for science

Pirani's seemingly simple thought experiment

"By measurement of the relative accelerations of several different pairs of particles, one may obtain full details about the Riemann tensor. One can thus very easily imagine an experiment for measuring the physical components of the Riemann tensor."

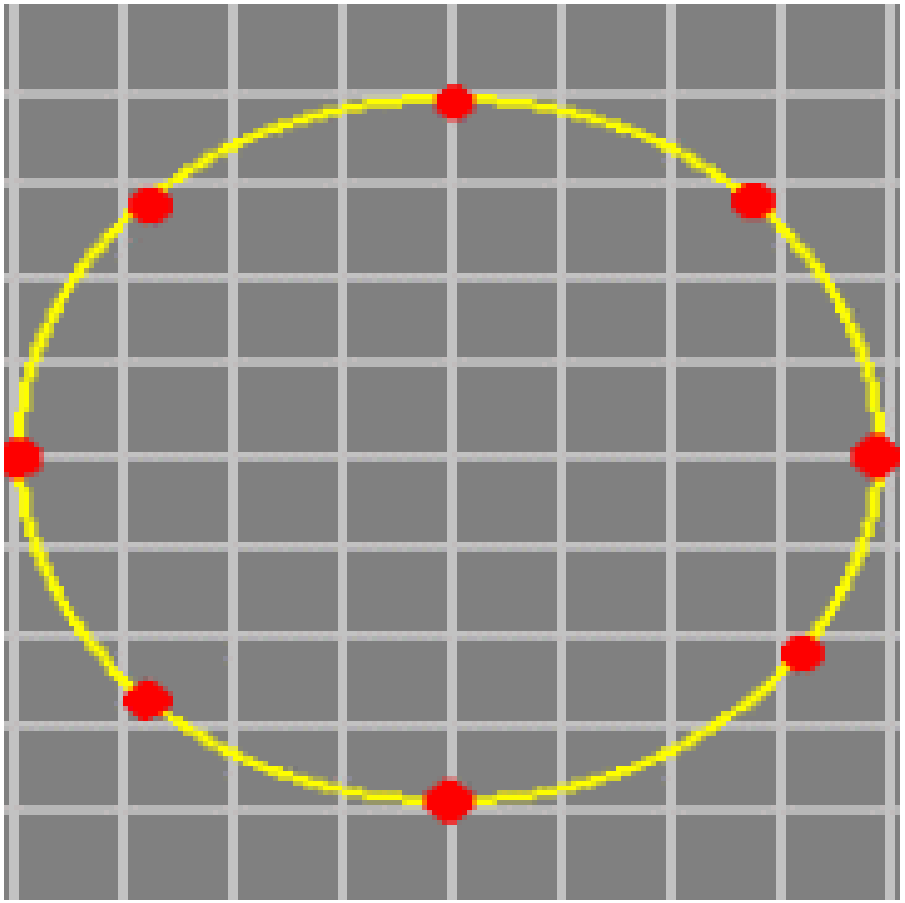
Pirani's "several different pairs of particles"



"…the relative accelerations of several different pairs of particles"

Neighboring test masses exhibit genuine relative motions.

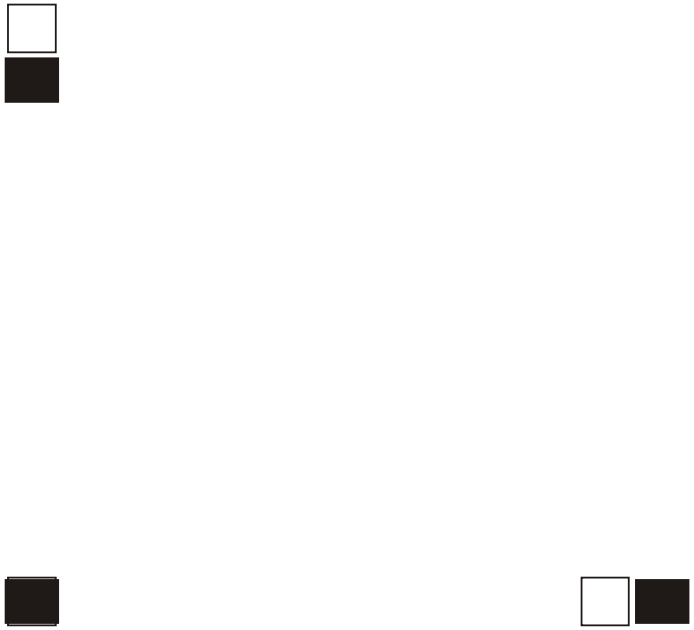
"Just" need to find a way to implement the measurement, with sufficient sensitivity.



… to implement the measurement, with sufficient sensitivity.

- How to implement the measurement?
- How to make it sensitive enough? N.B.: Relative motions of test masses turned out to be at the level of $\Delta L/L \sim 10^{-21}$!

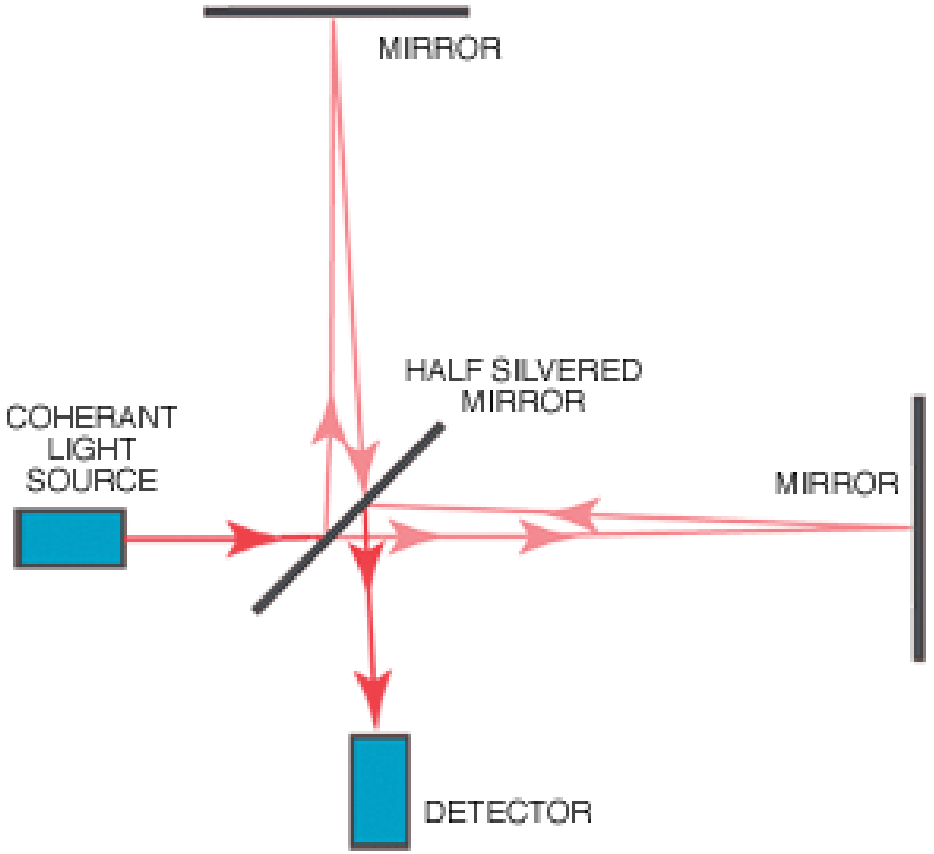
Measuring the round trip light travel time between pairs of particles



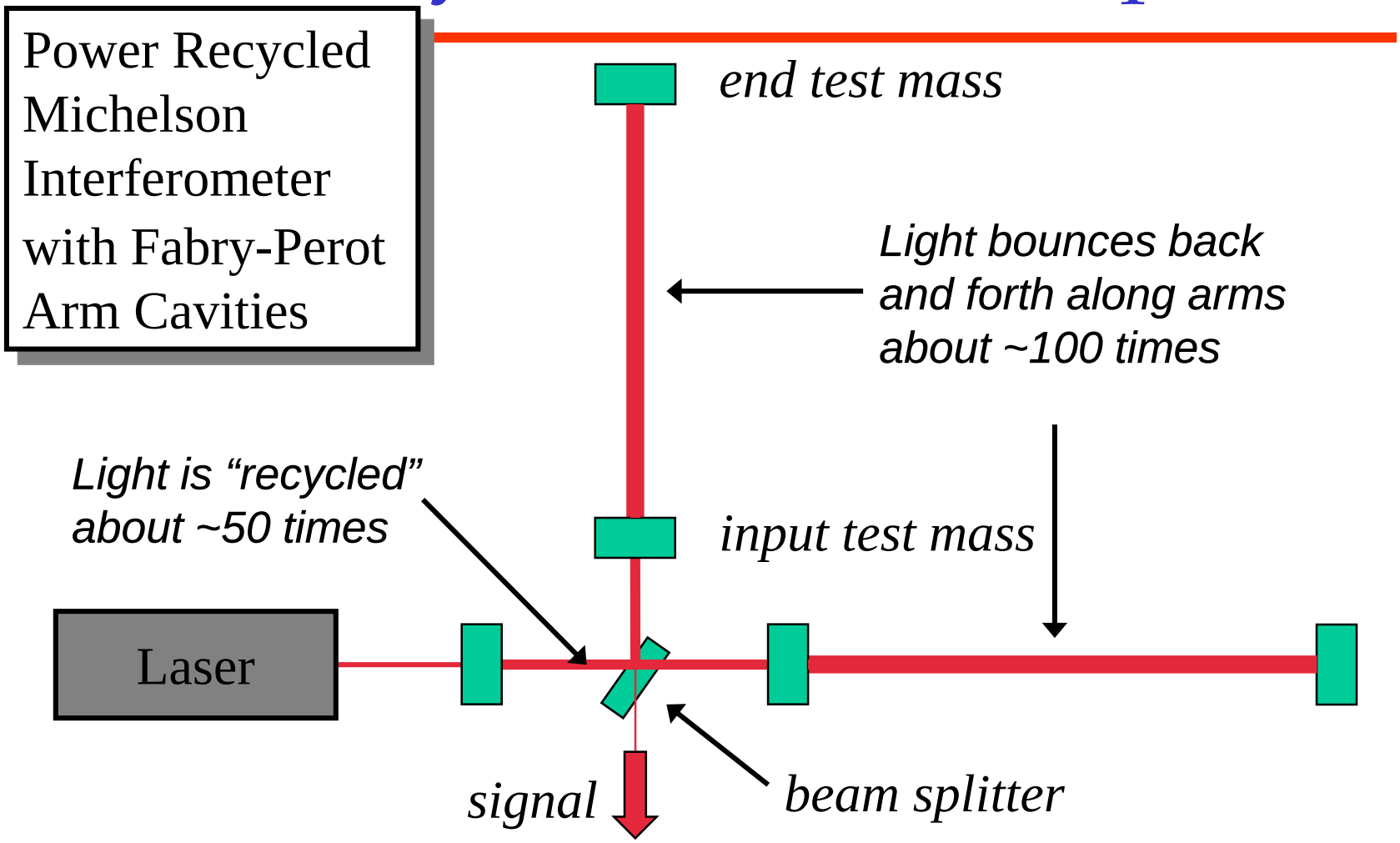
Pairs of particles can be separated by
~ the wavelength of the gravitational wave. (Big interferometers have multi-km separations.)

Measurement of the relative accelerations of several different pairs of particles

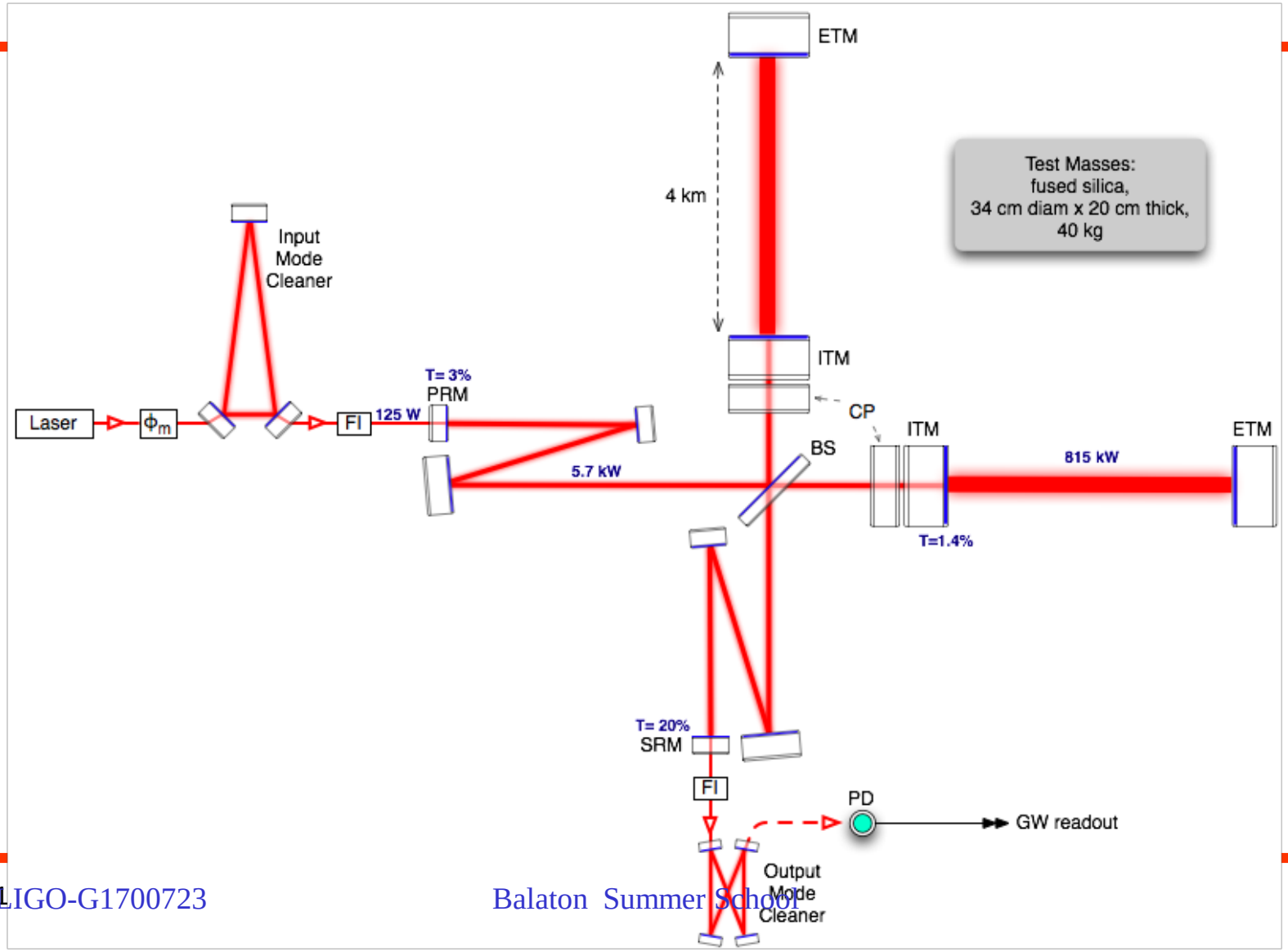
Via a Michelson interferometer



To achieve the required sensitivity, need cleverer optics

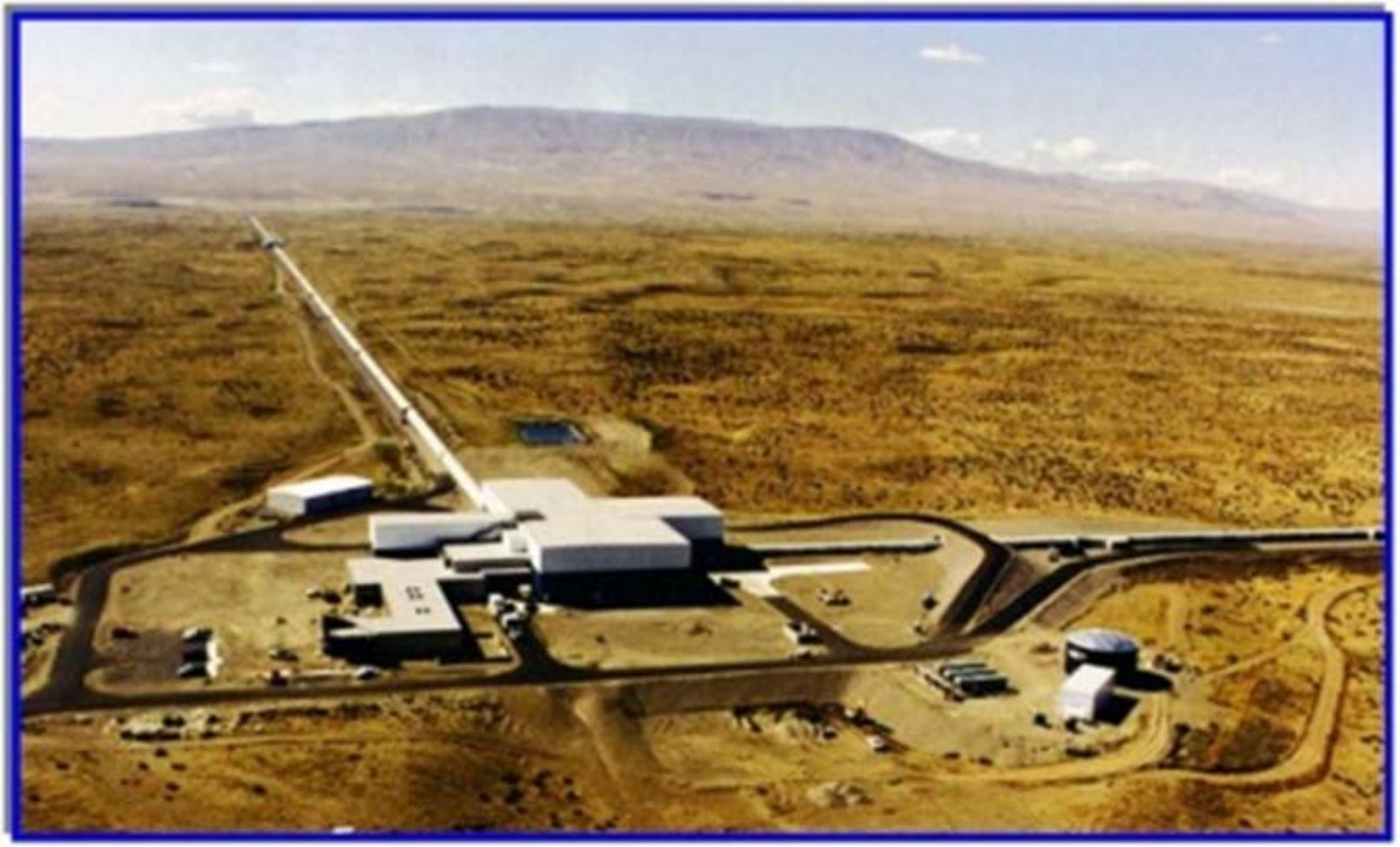


The design has many refinements



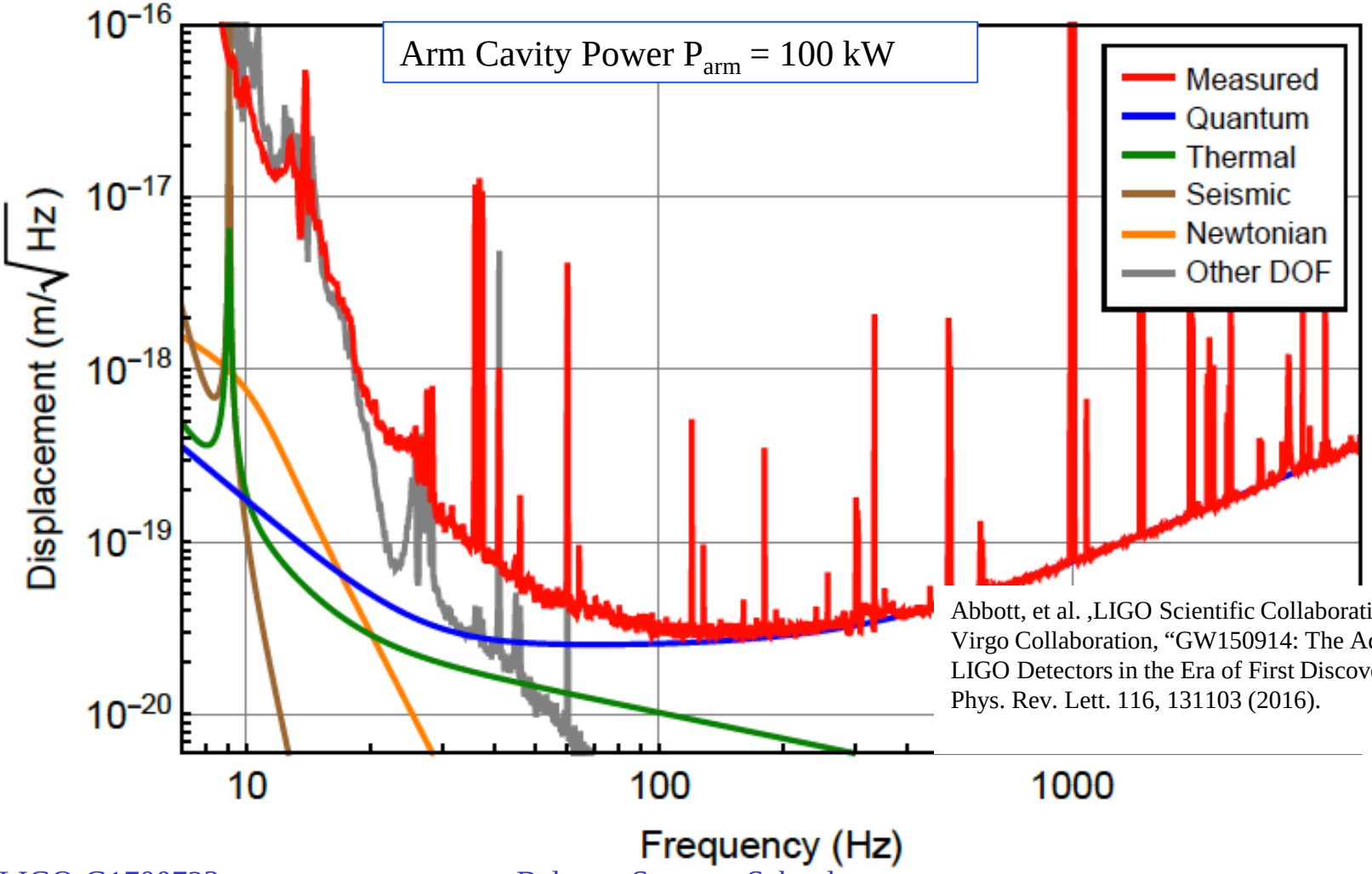
LIGO Observatory at Livingston, LA

LIGO Observatory at Hanford, WA



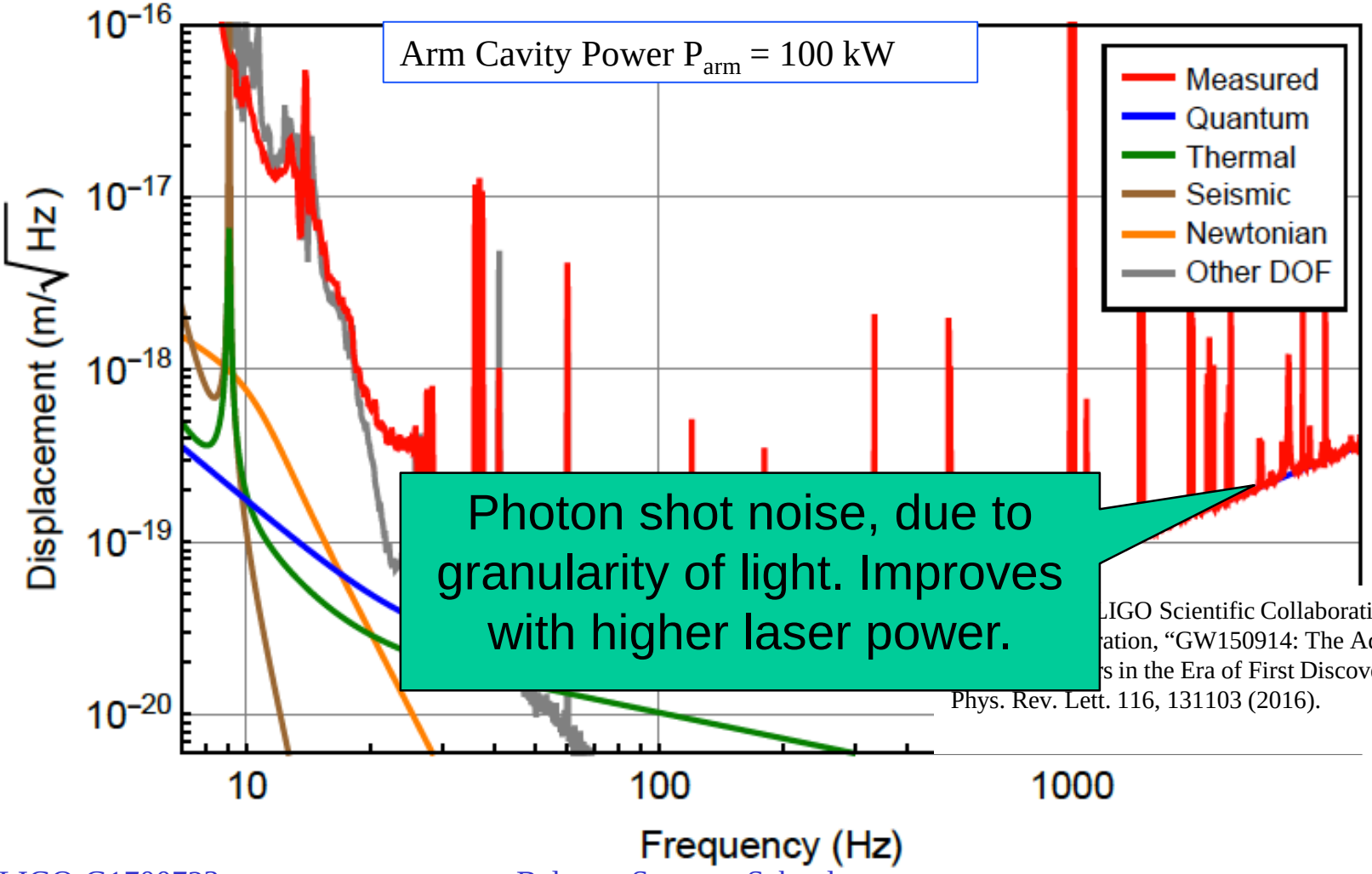
VIRGO
EGO

Advanced LIGO detector sensitivity in 2015



Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, "GW150914: The Advanced LIGO Detectors in the Era of First Discoveries", Phys. Rev. Lett. 116, 131103 (2016).

Advanced LIGO detector sensitivity in 2015



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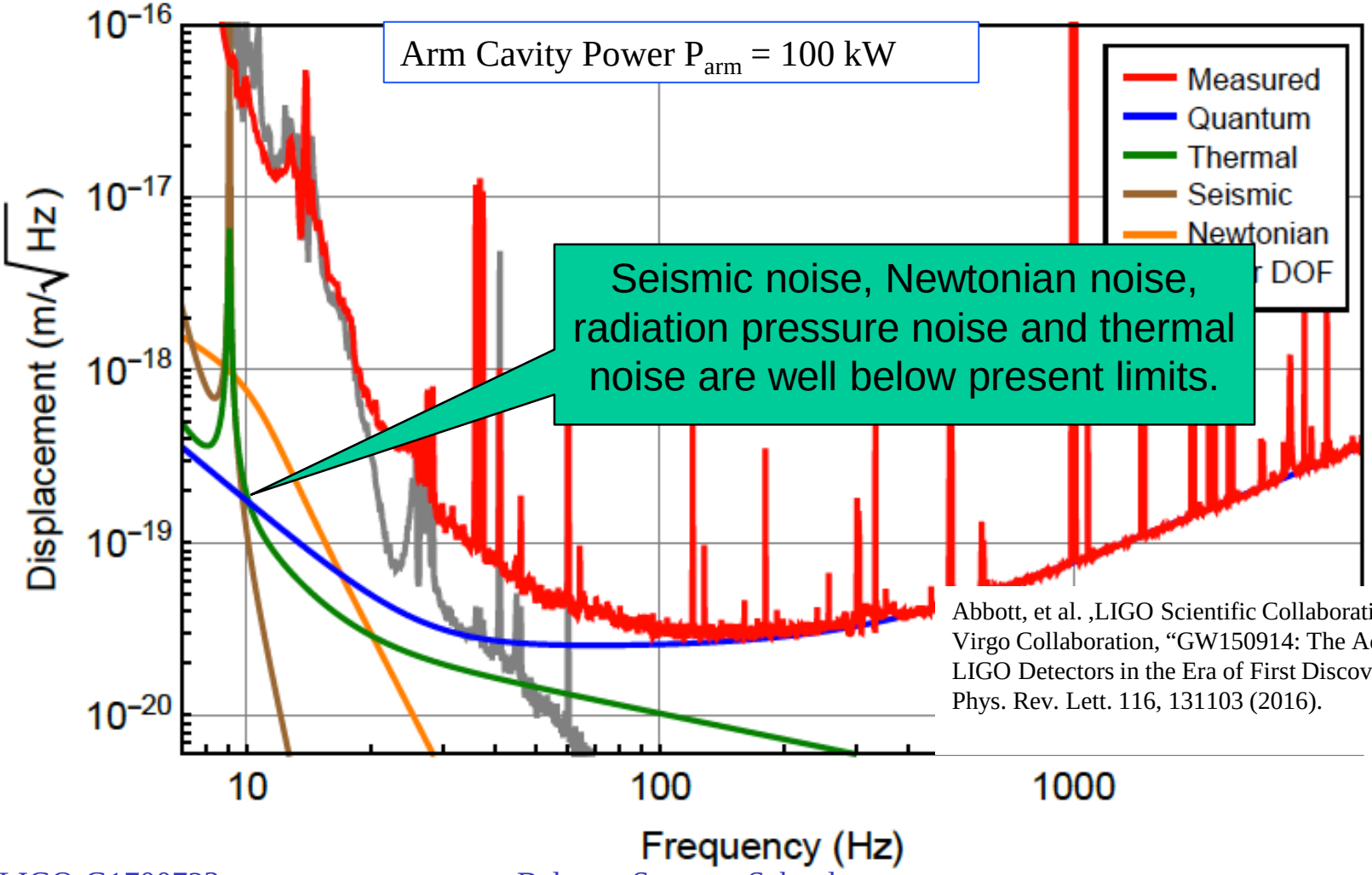

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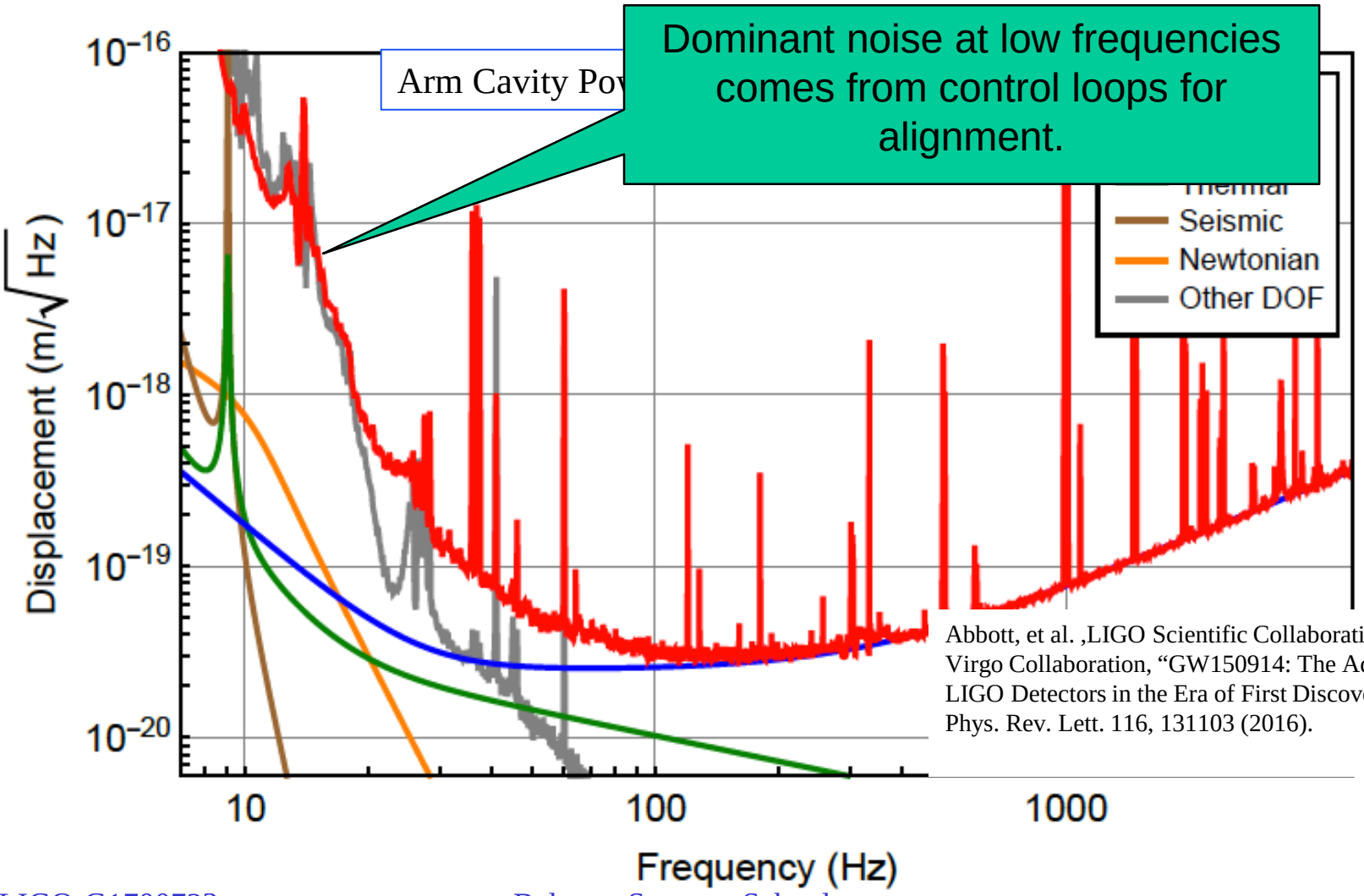


Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, "GW150914: The Advanced LIGO Detectors in the Era of First Discoveries", Phys. Rev. Lett. 116, 131103 (2016).

What is interesting about gravitational waves?

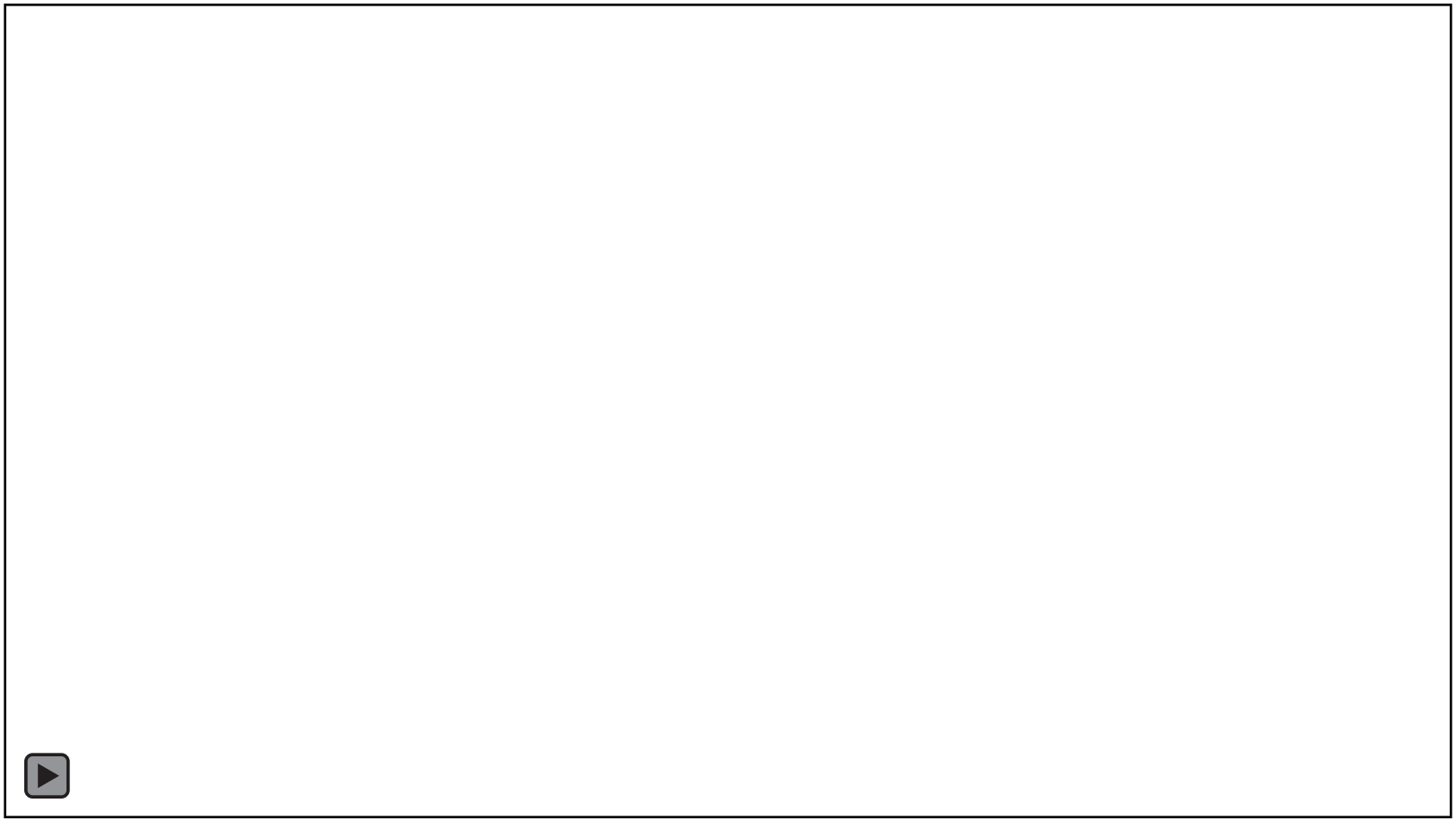
- Embody gravity's obedience to the principle "no signal faster than light"
- Travel through otherwise opaque matter
- Can be generated by pure spacetime
  - Black holes
  - Early universe fluctuations

Thus, gravitational waves can reveal, like nothing else can, the dynamics of strongly-curved spacetime.

What kinds of things might we see? Might we learn?

- Binaries of neutron stars and black holes
  - Study black hole spacetime
  - Learn neutron star equation of state
  - What is the engine of gamma ray bursts?
- Stellar core collapse
  - Dynamics that lead to supernova
- Rotating neutron stars
  - What mechanisms can make neutron stars lumpy?
- Early universe dynamics

Here's how two black holes generate gravitational waves



Gravitational waveform lets you read out source dynamics

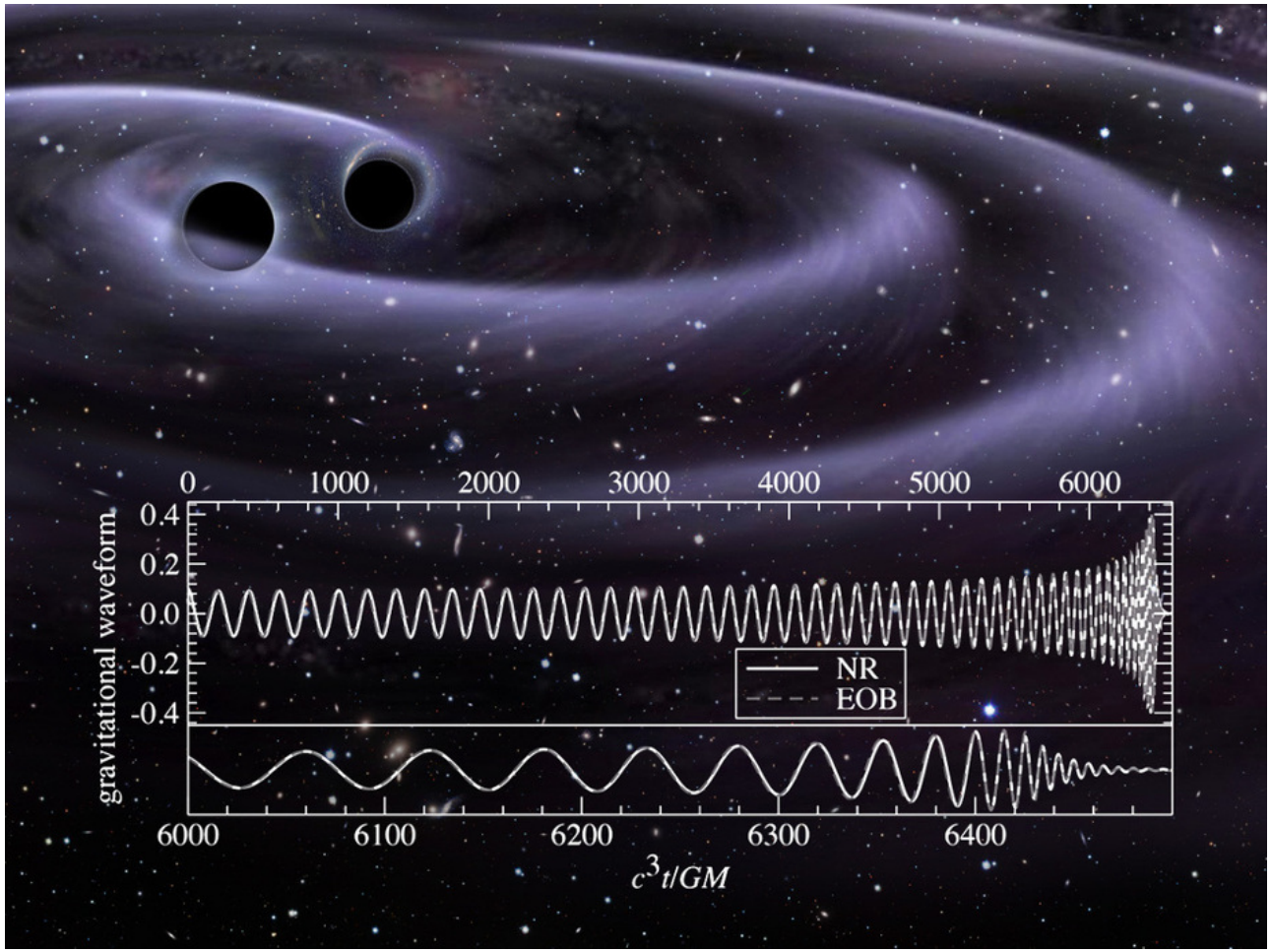
The evolution of the mass distribution can be read out from the gravitational waveform:

$$h_{\mu\nu}(t) = \frac{1}{R}\frac{2G}{c^4}\ddot{I}_{\mu\nu}(t - R/c)$$

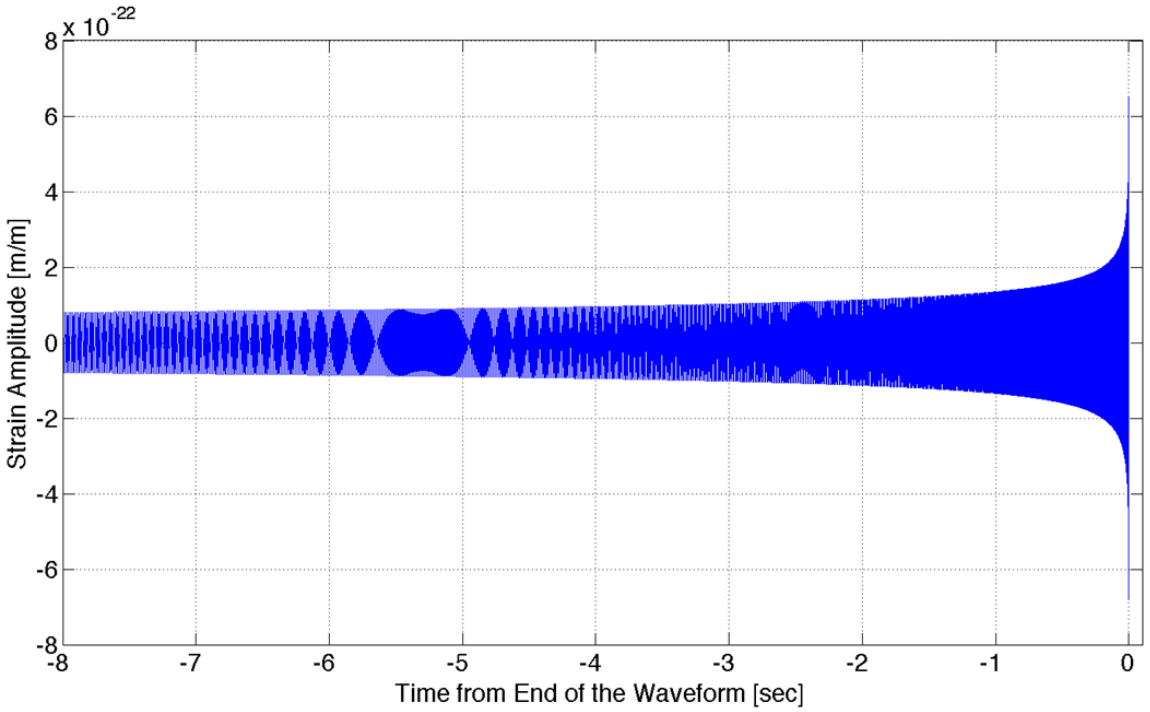
Coherent relativistic motion of large masses can be directly observed from the waveform!

$$I_{\mu\nu} \equiv \int dV\left(x_\mu x_\nu - \delta_{\mu\nu} r^2/3\right)\rho(r).$$

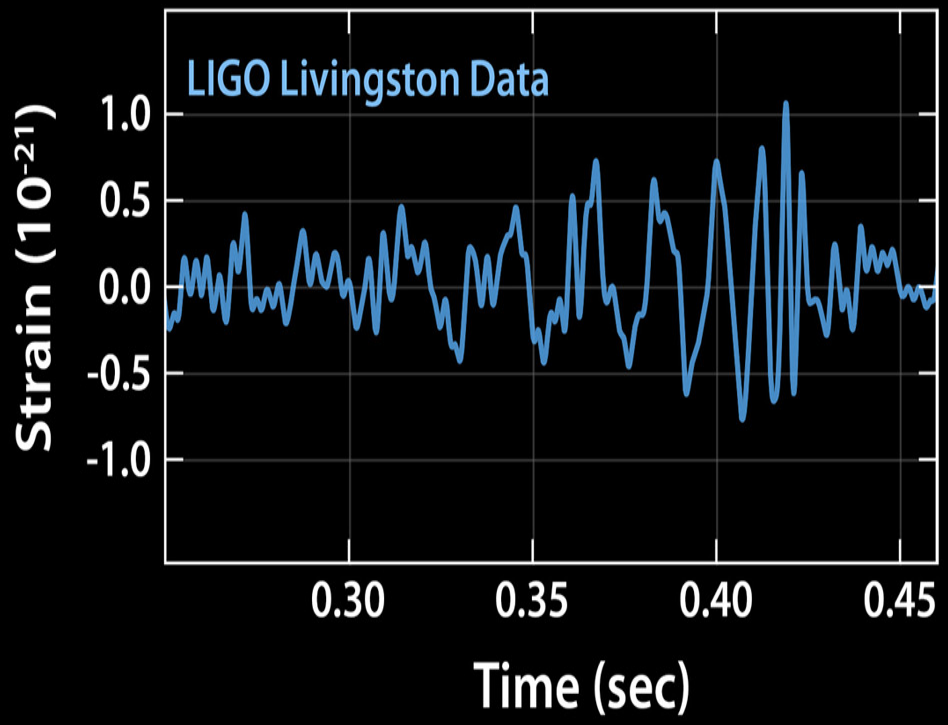
Pattern of oscillations from black hole inspiral and merger



Orbital periods of stellar-mass binaries are in the audio band!



2015 Sept 14 09:50:45 UTC



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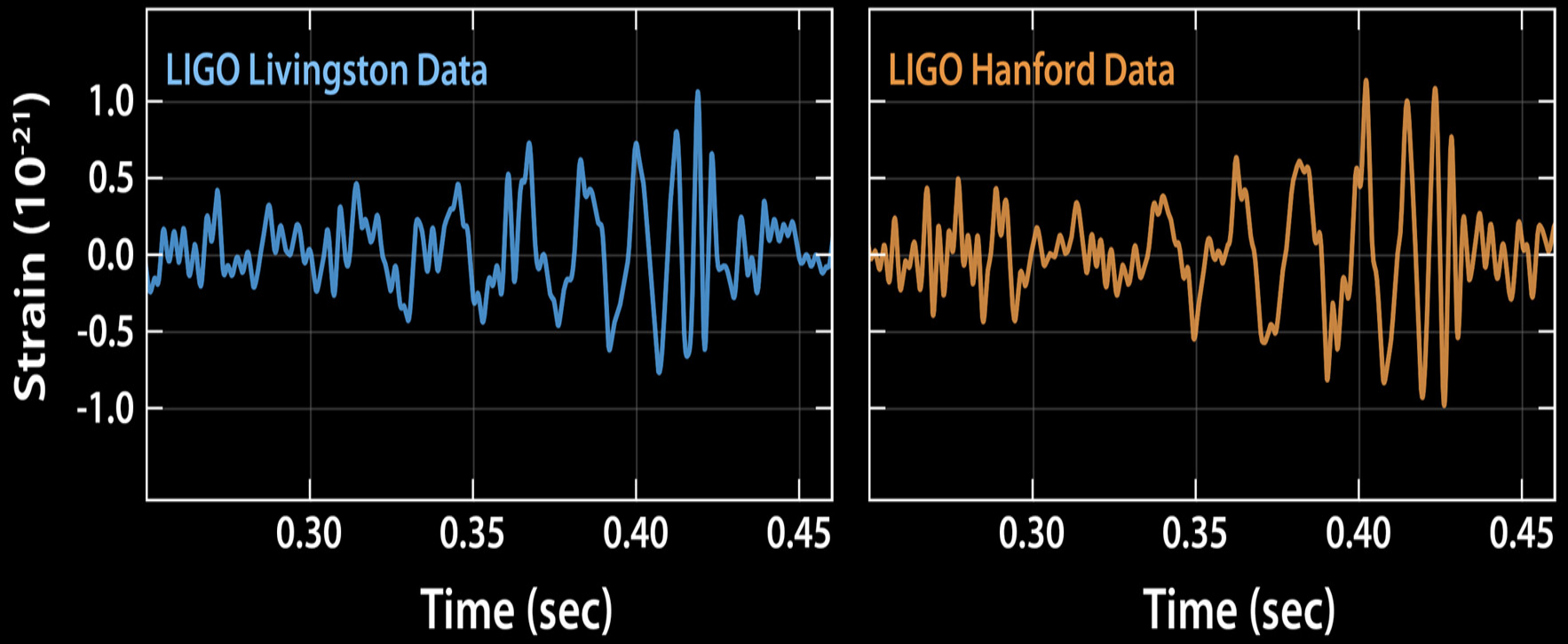

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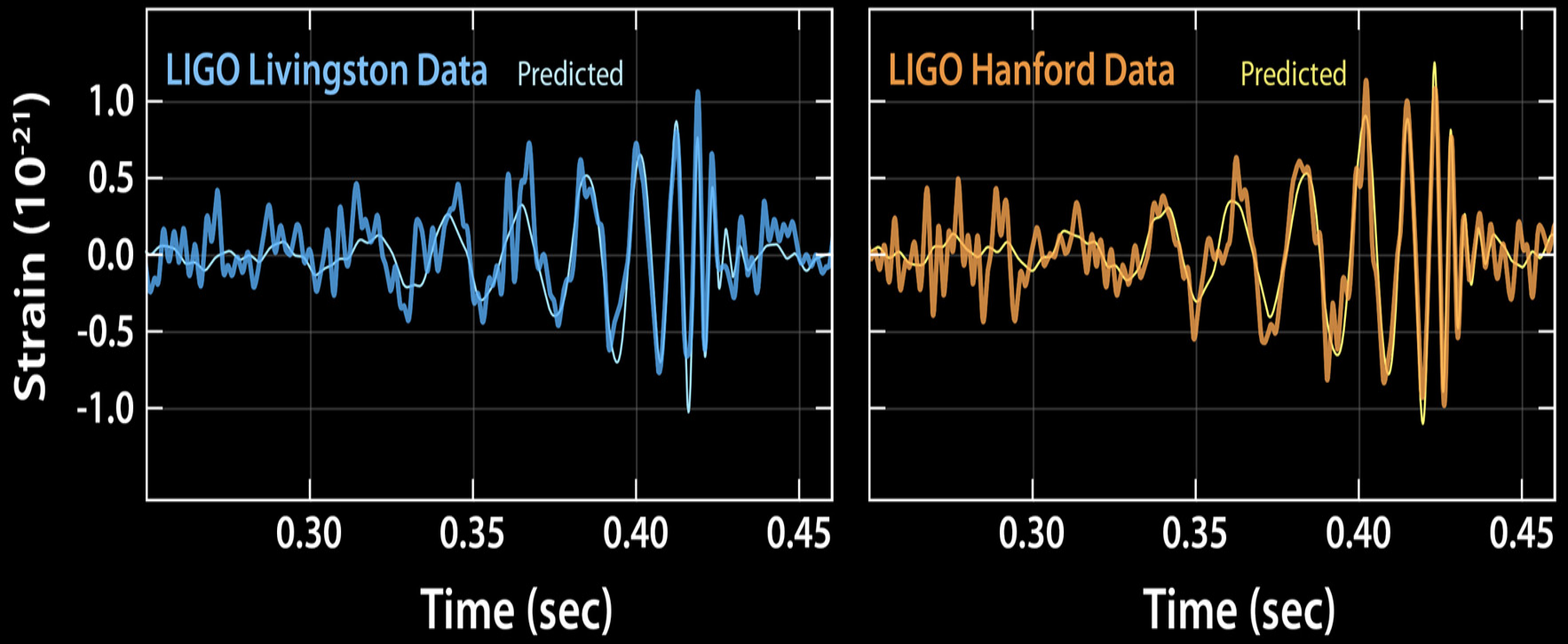
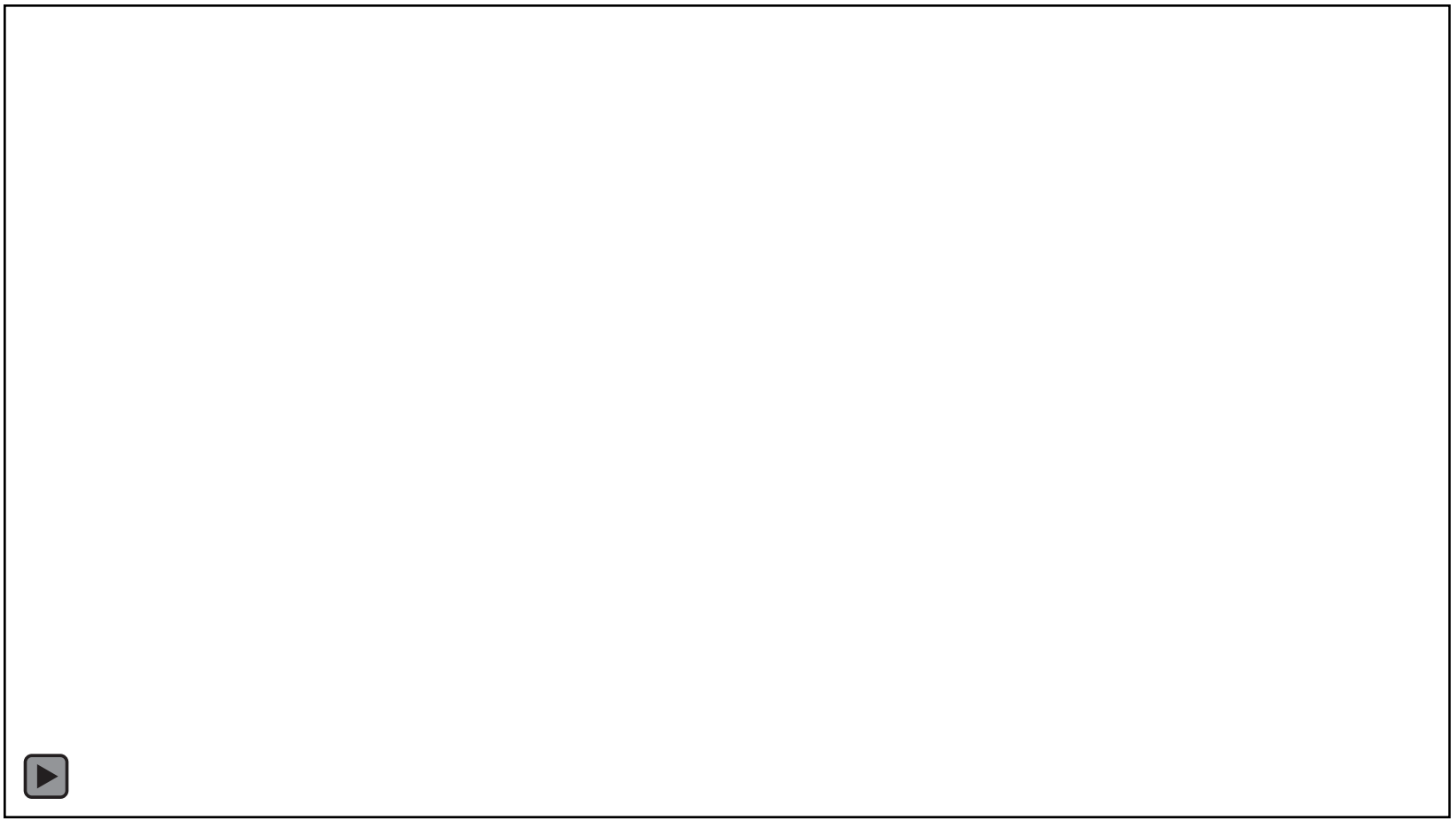
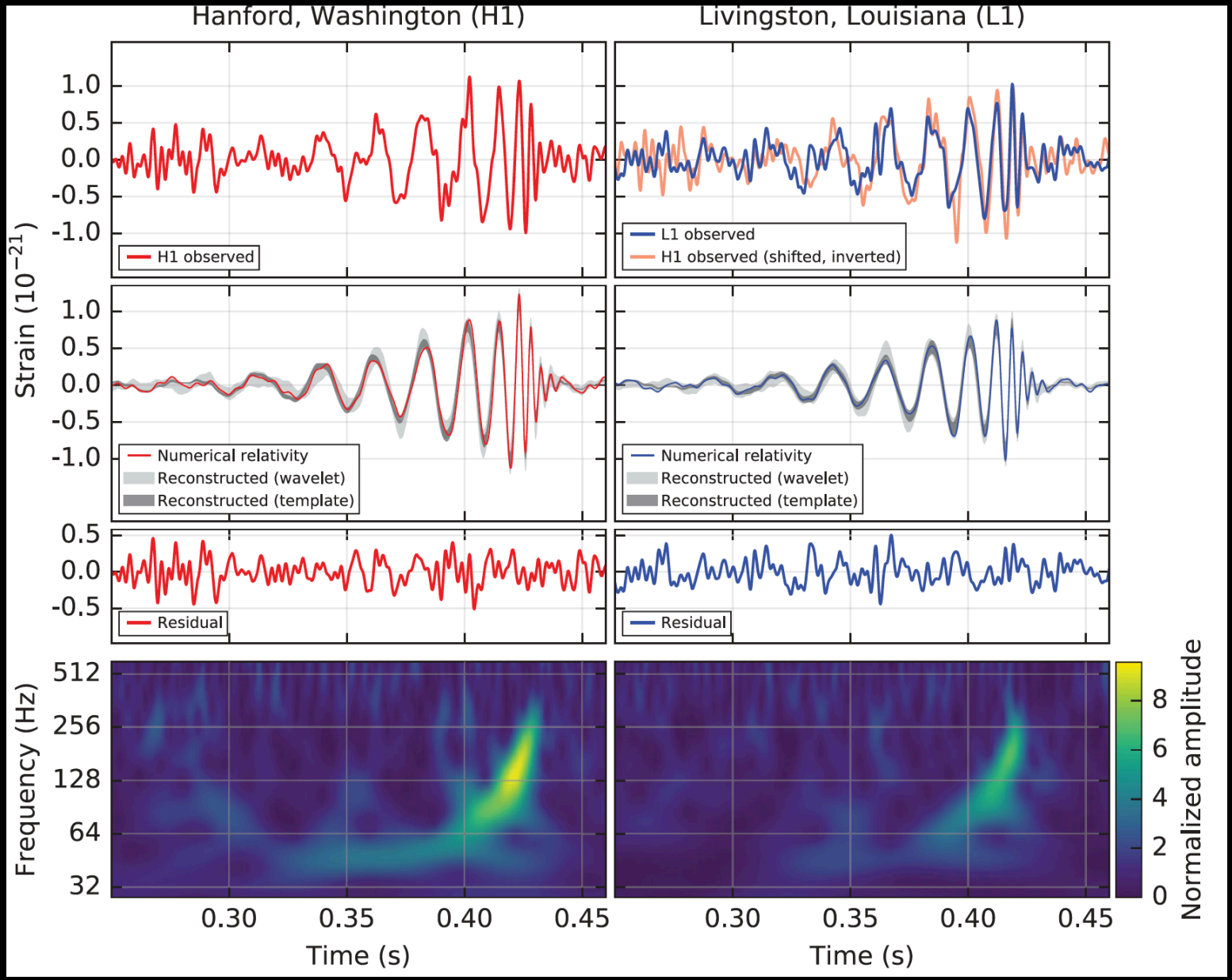


Listen to the signal



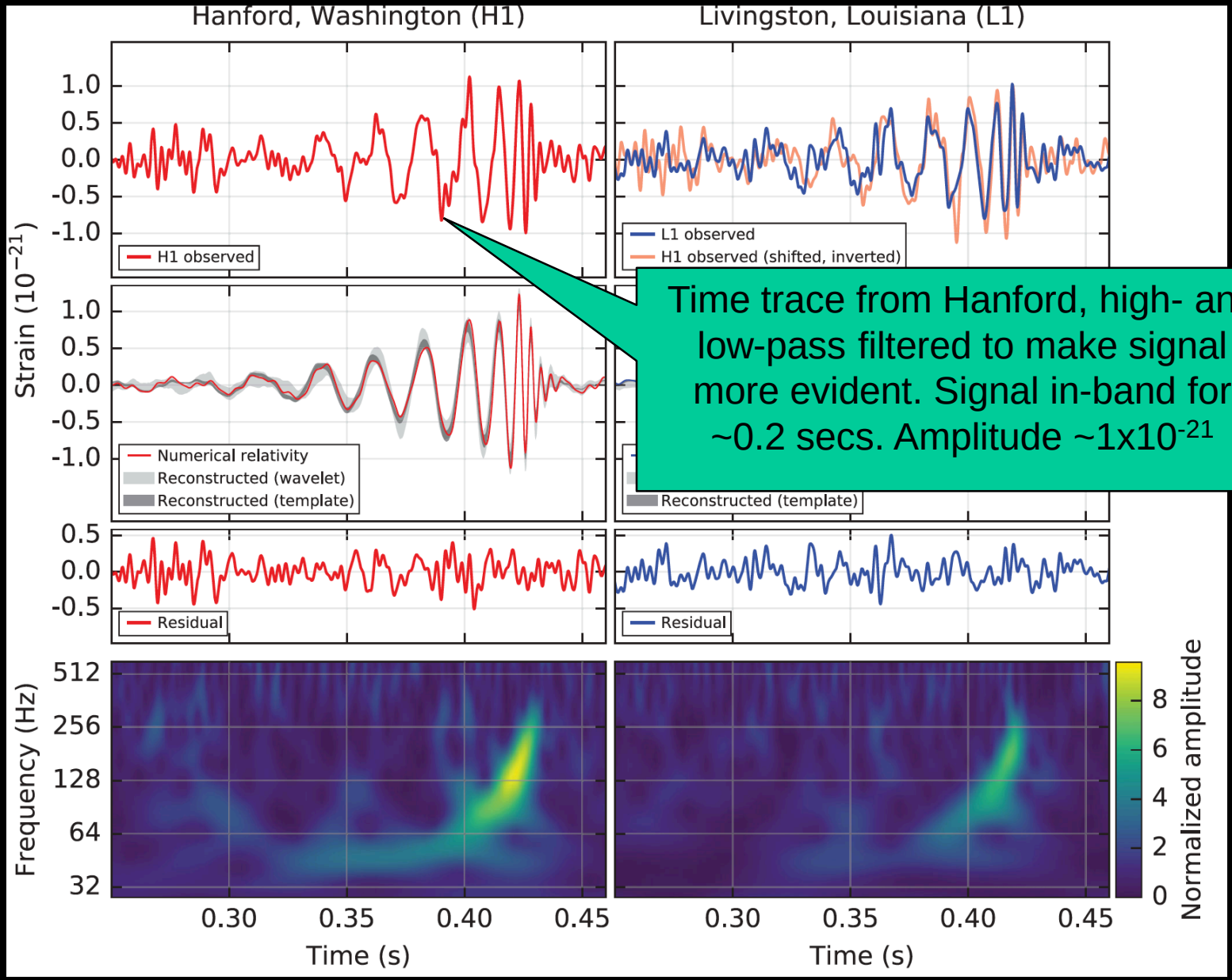


LIGO-G1600128

B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett. 116, 061102 (2016)

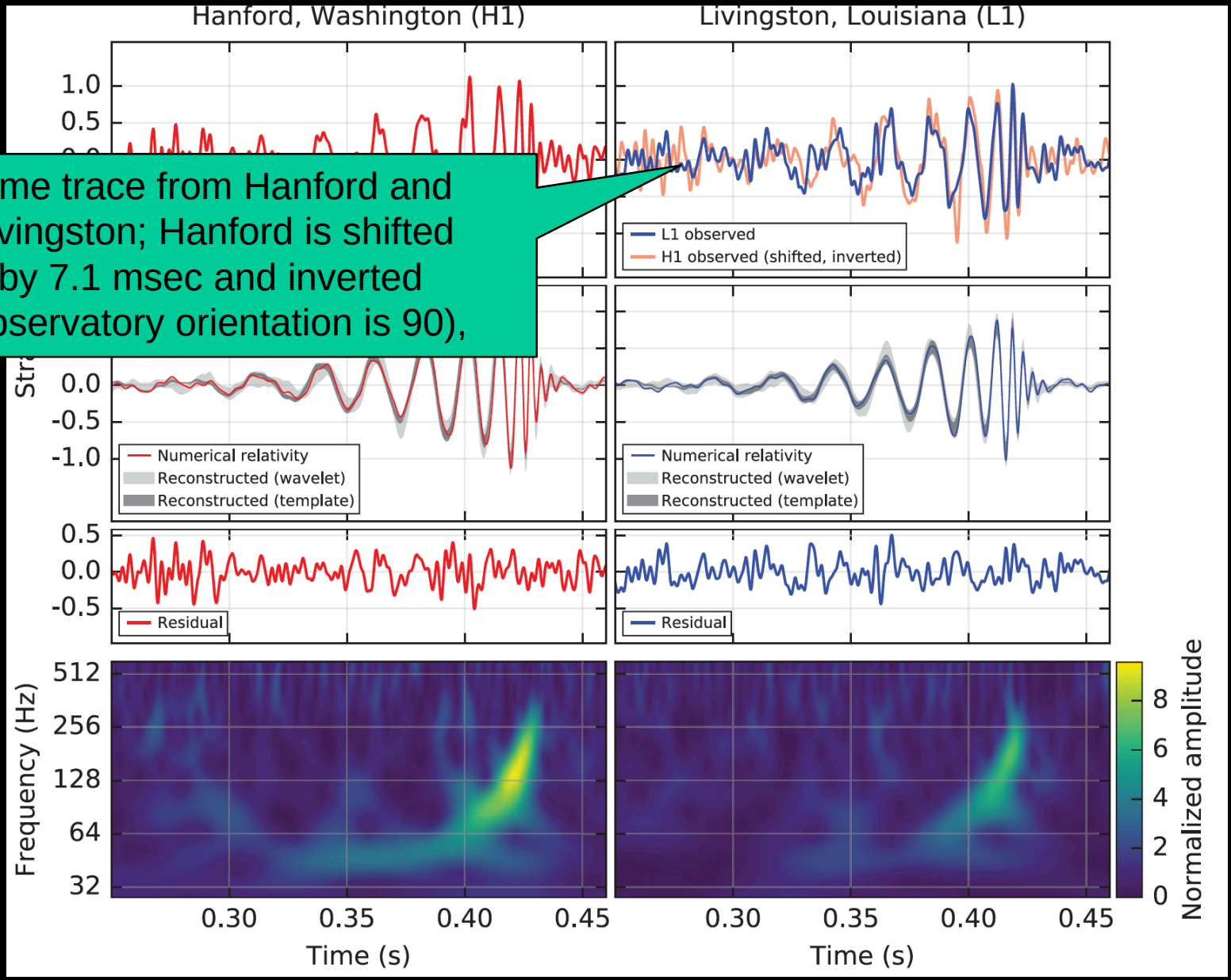
What was momentous about the discovery of GW150914?

- First reception ("direct detection") of gravitational waves.
- First observation of the existence of binary black holes.
- Demonstration that predicted waveform matches what nature produces.



LIGO-G150122

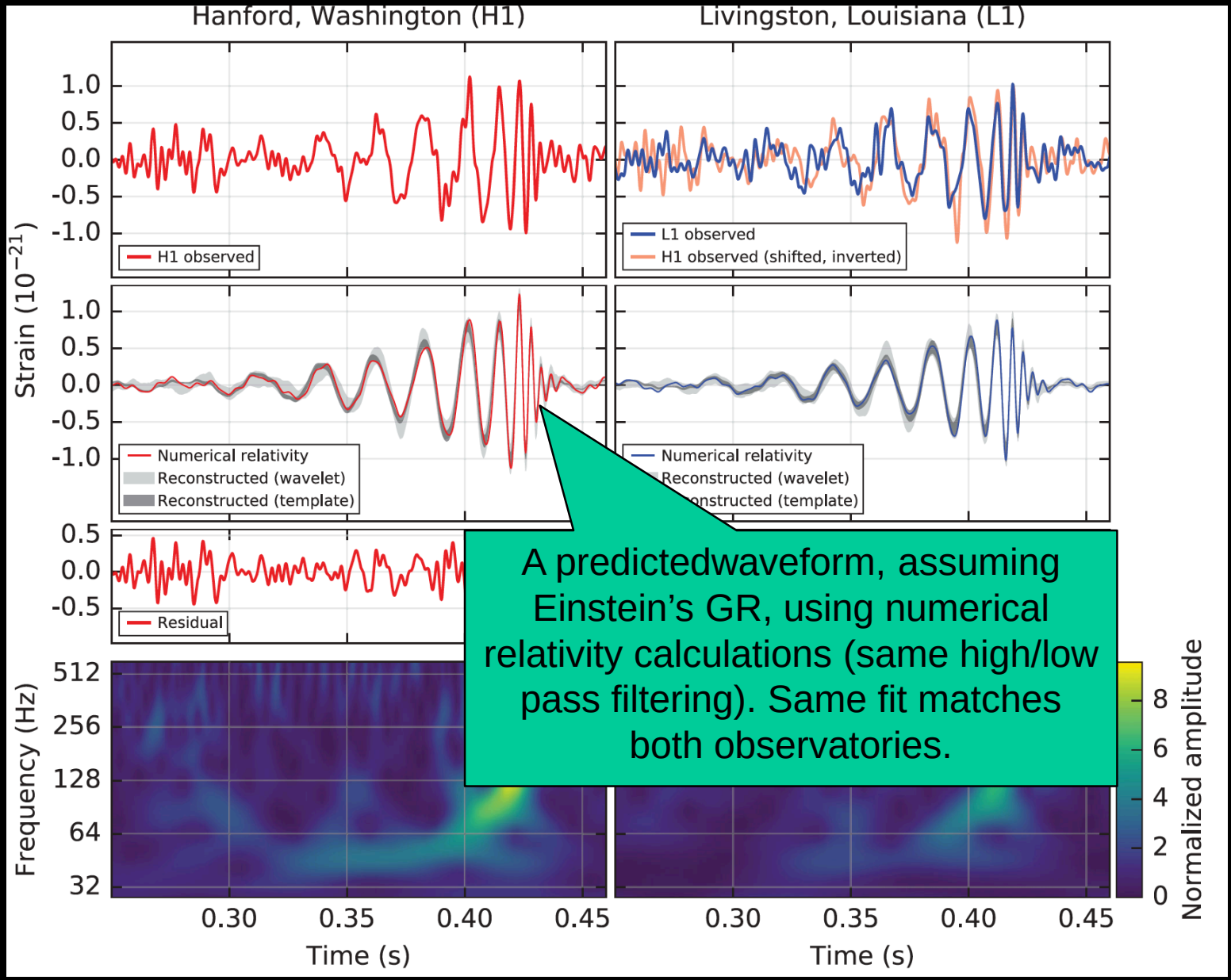
B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett. 116, 061102 (2016)



Time trace from Hanford and Livingston; Hanford is shifted by 7.1 msec and inverted (observatory orientation is 90),

LIGO-G1600128

B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett. 116, 061102 (2016)



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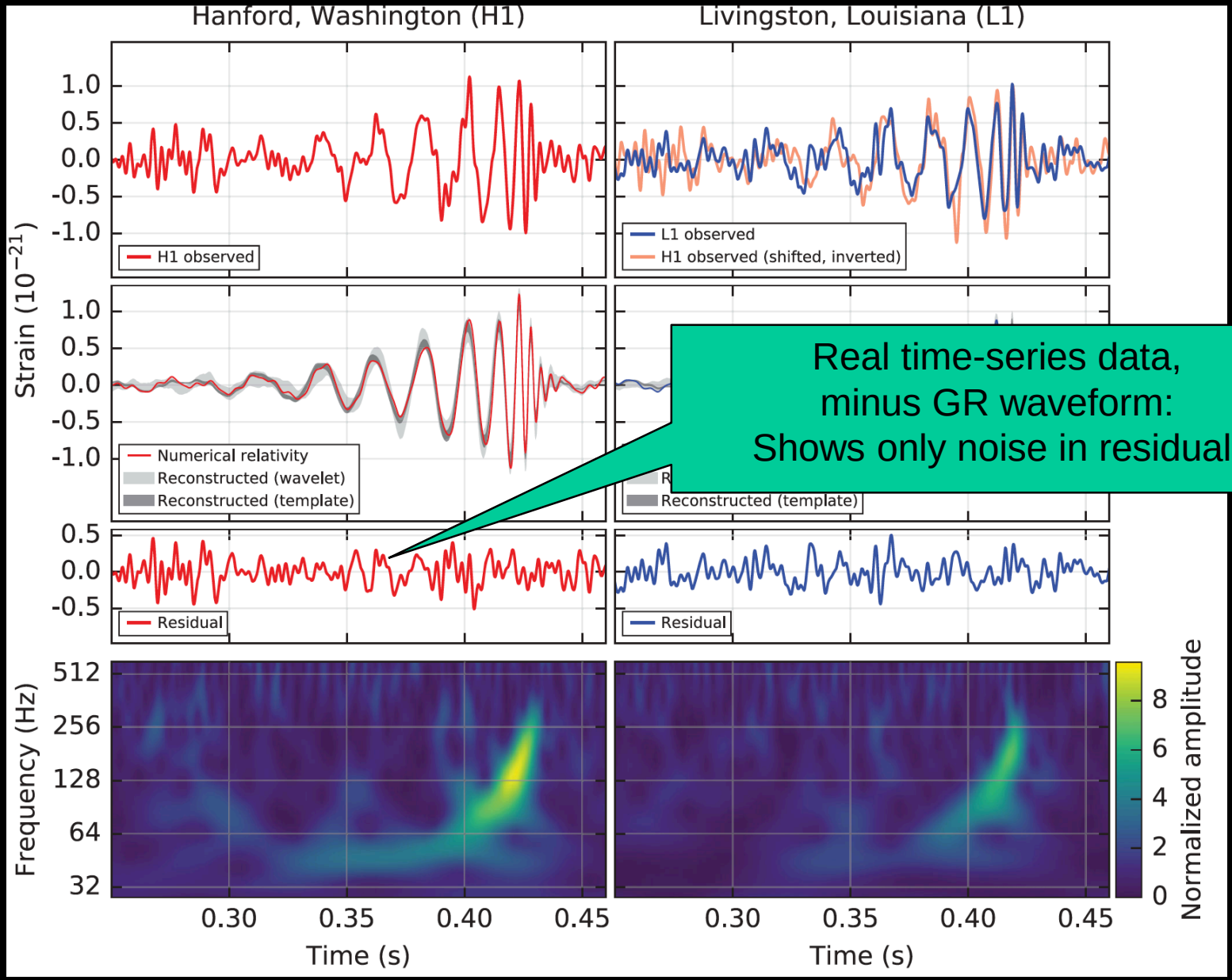

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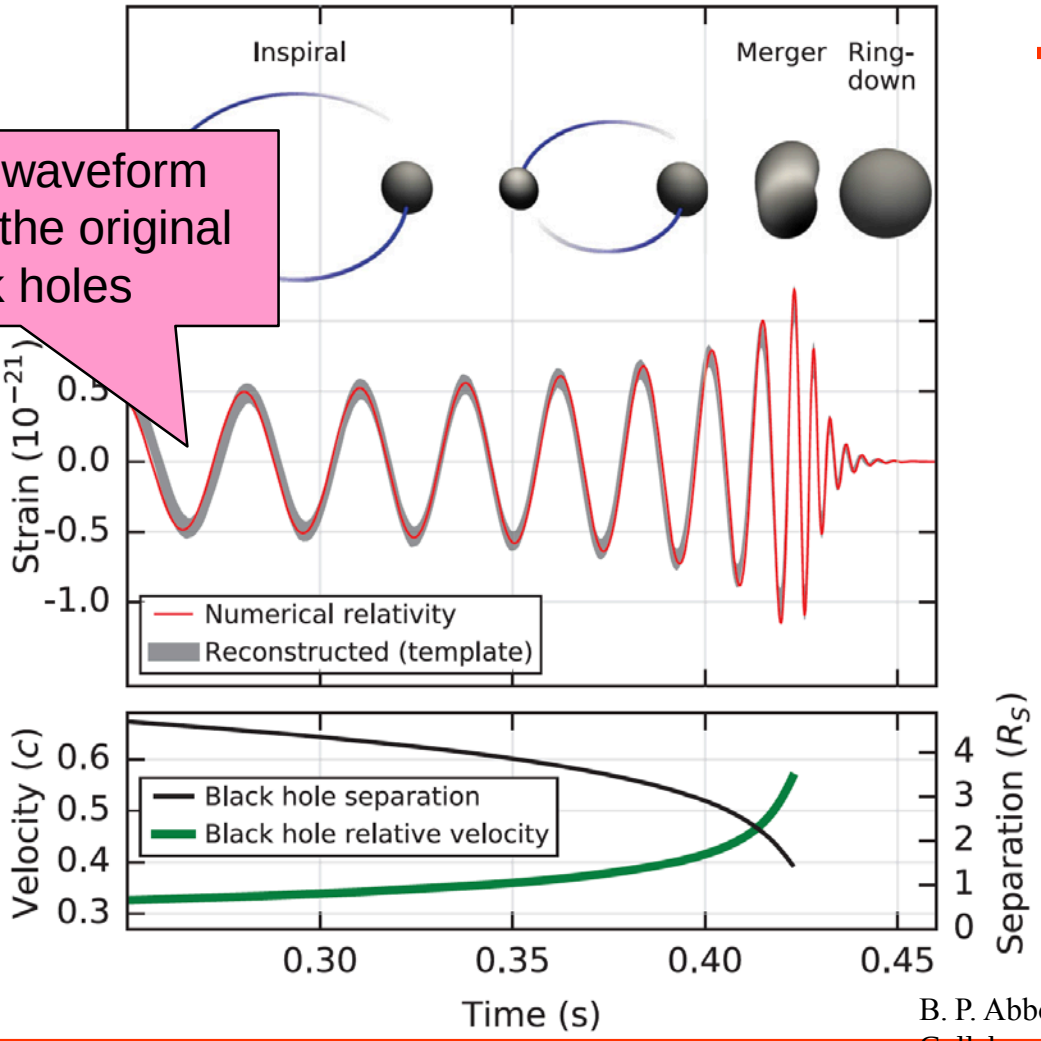
How do we learn from h(t)?

Early part of waveform from orbits of the original two black holes



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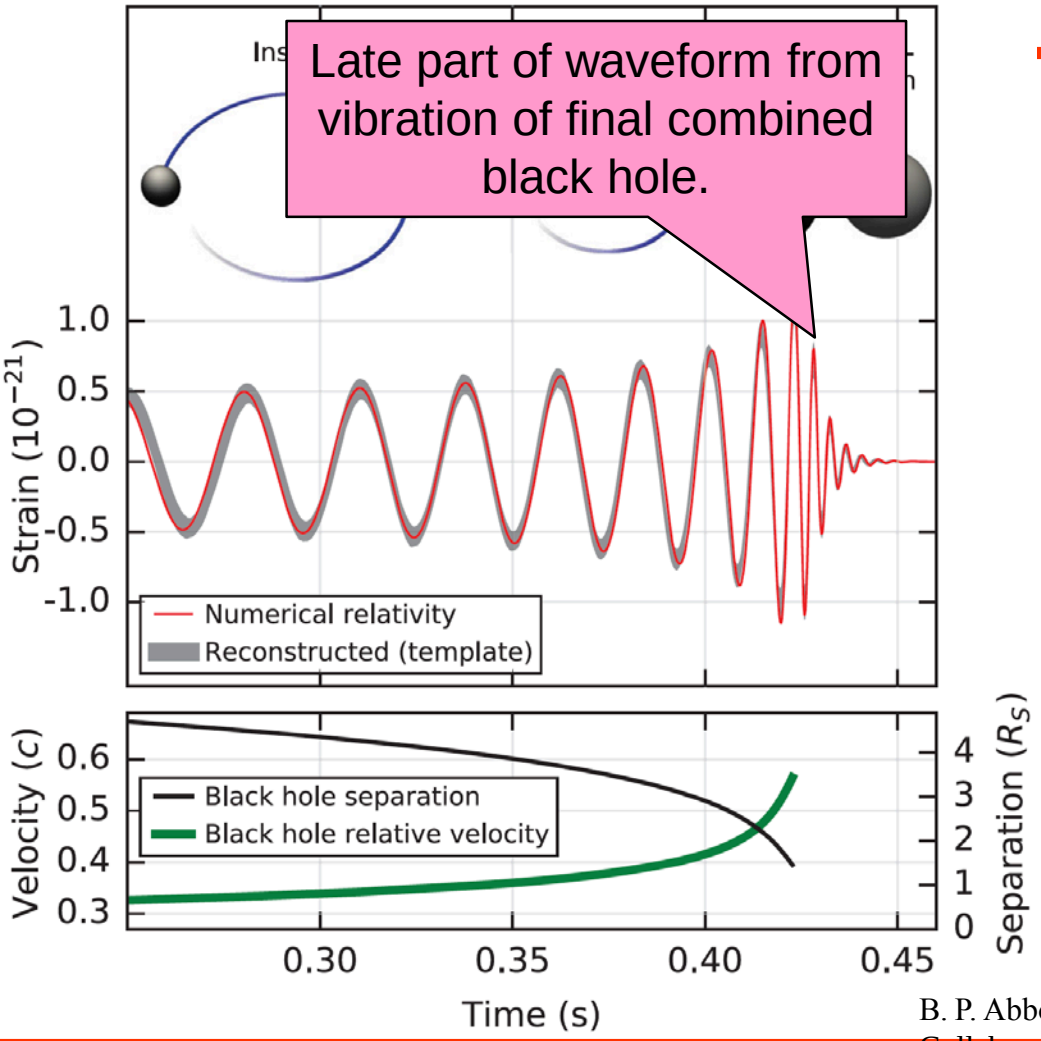

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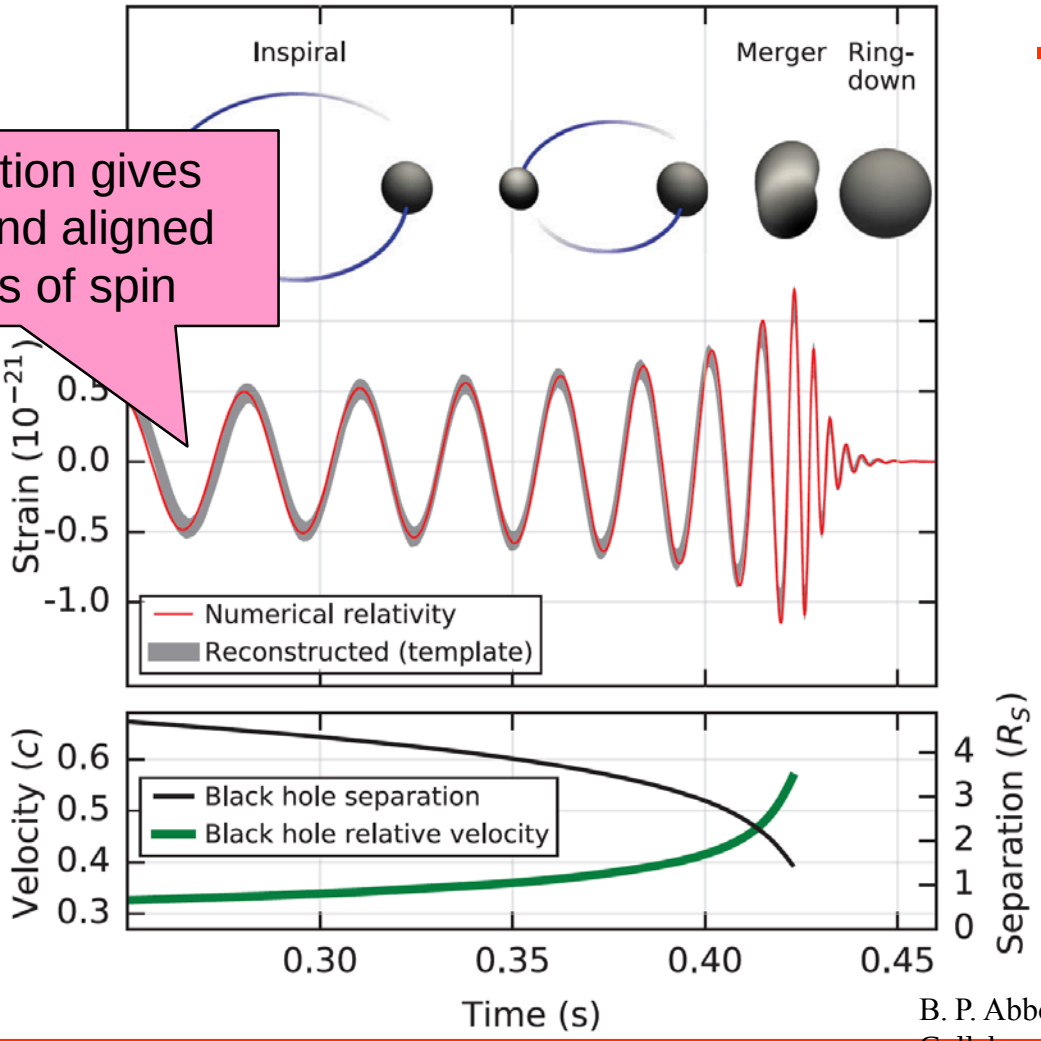
How do we learn from h(t)?

Phase evolution gives chirp mass and aligned components of spin



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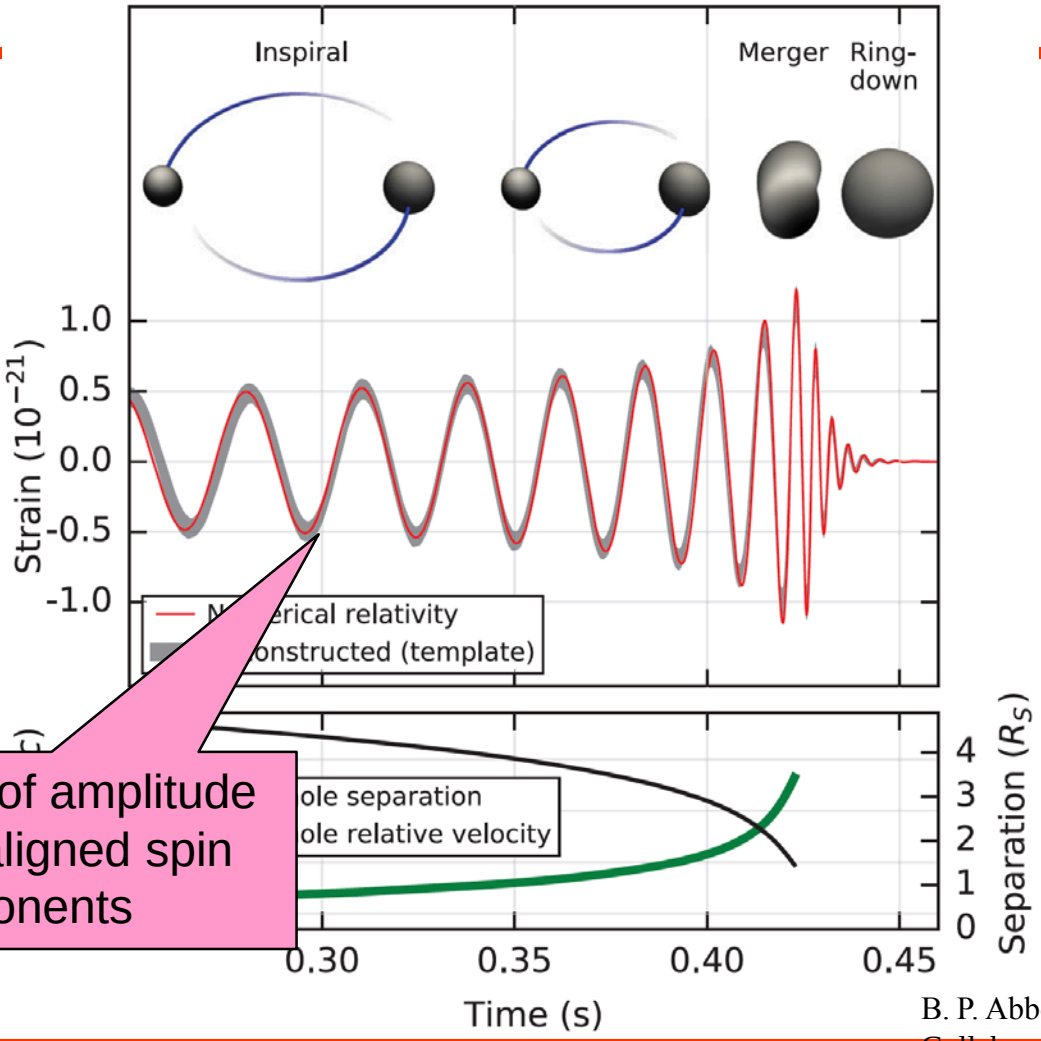

Modulation of amplitude gives nonaligned spin components

B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett. 116, 061102 (2016)

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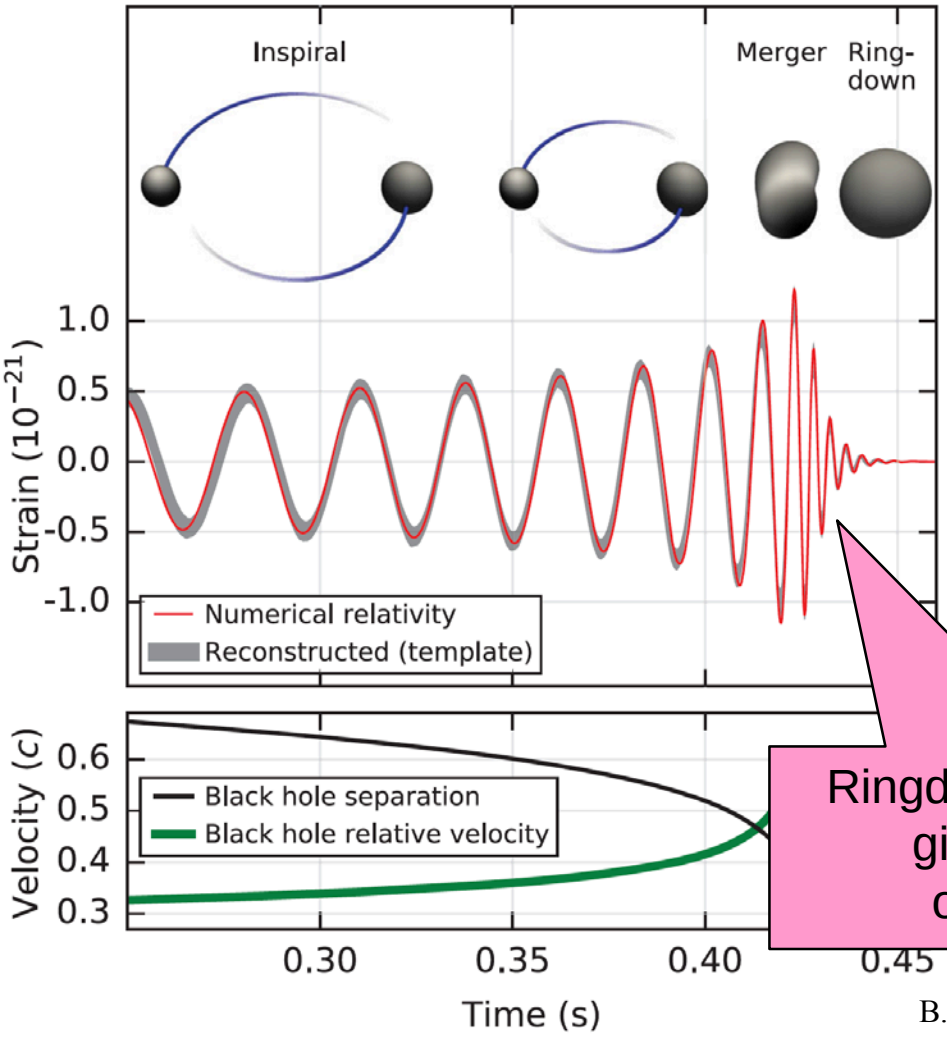


Ringdown frequency and *Q* give mass and spin of final black hole

B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett. 116, 061102 (2016)

General relativity works!

It took analytical relativity and numerical relativity to predict the waveform from a coalescing binary.

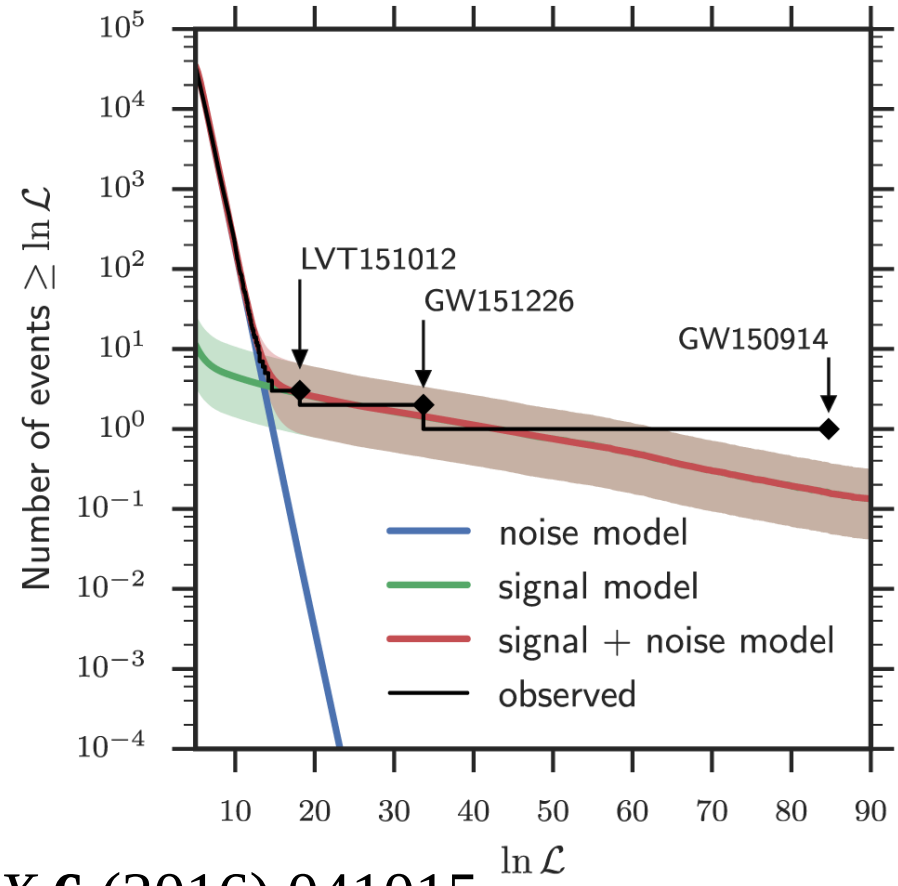
The best fit waveforms leave no significant residual – they work!

Future observations will provide more stringent comparisons, tighter tests of GR.

Astrophysical implications

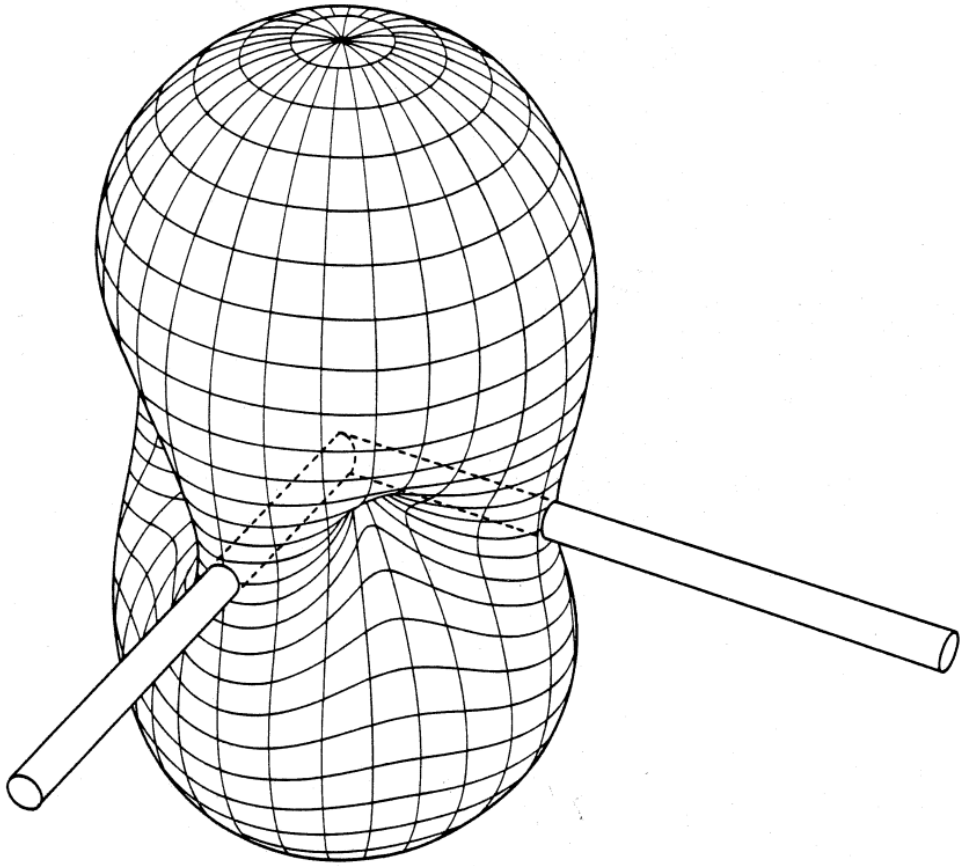
Observed rate of binary black hole events is within the range that had been predicted.

Now though, we know it through measurement.



Abbott et al, *Phys. Rev. X* **6** (2016) 041015

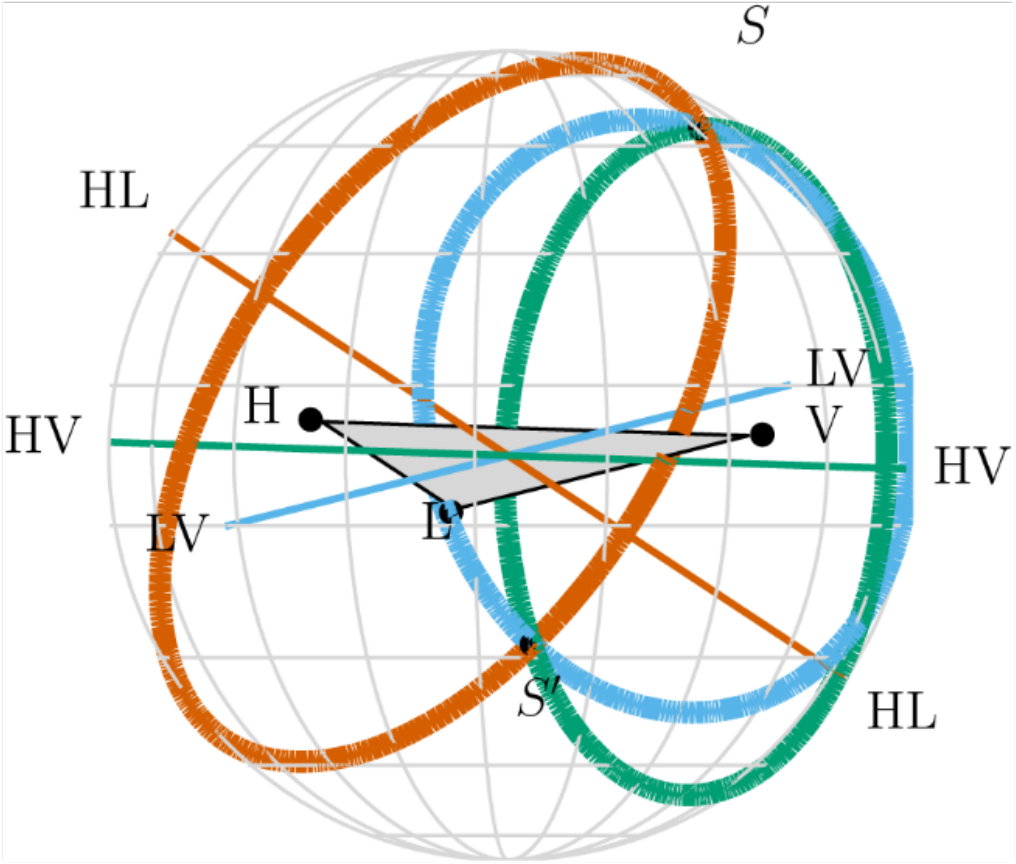
An interferometer has almost omni-directional sensitivity



Abbott, et al., Living Rev. Relativity, 19, (2016), 1

To find the direction to a source, triangulate with a global network

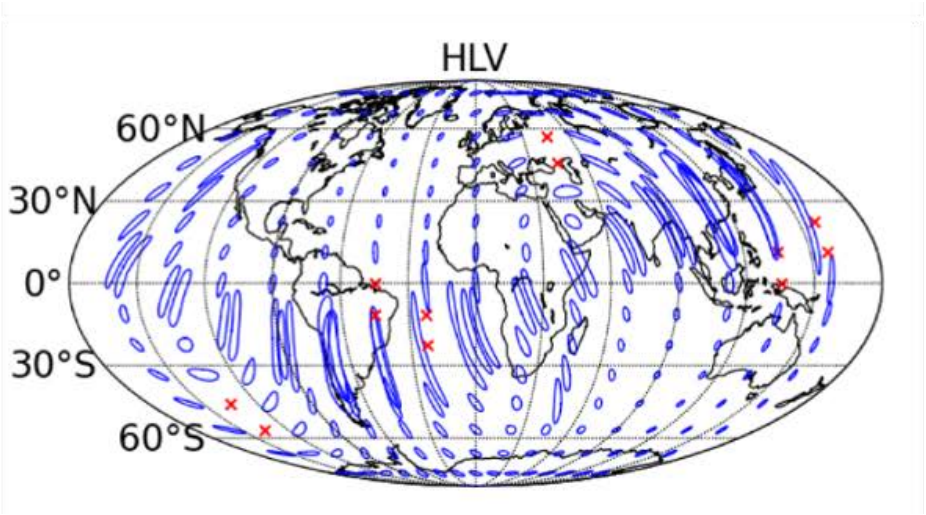
… here, illustrated with LIGO and Virgo.



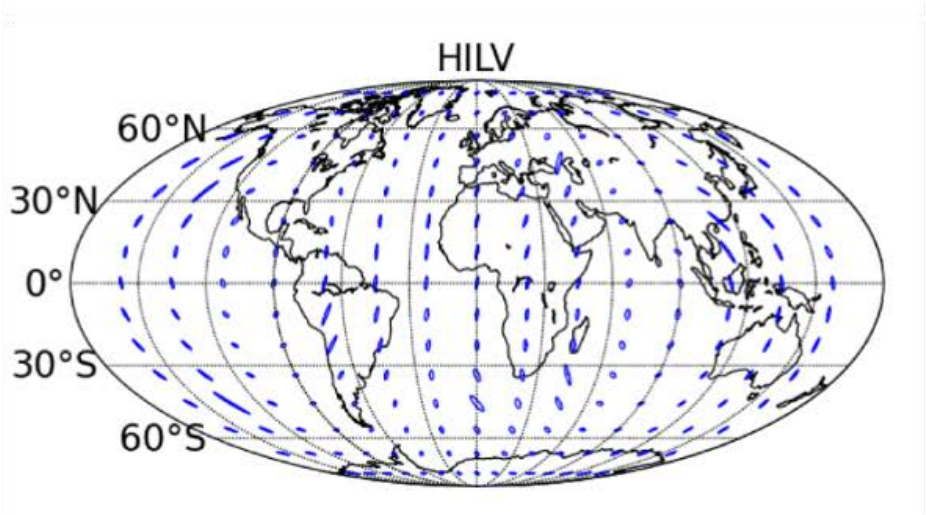
Abbott, et al., Living Rev. Relativity, 19, (2016), 1

Future evolution of the global network

Error boxes without LIGO-India

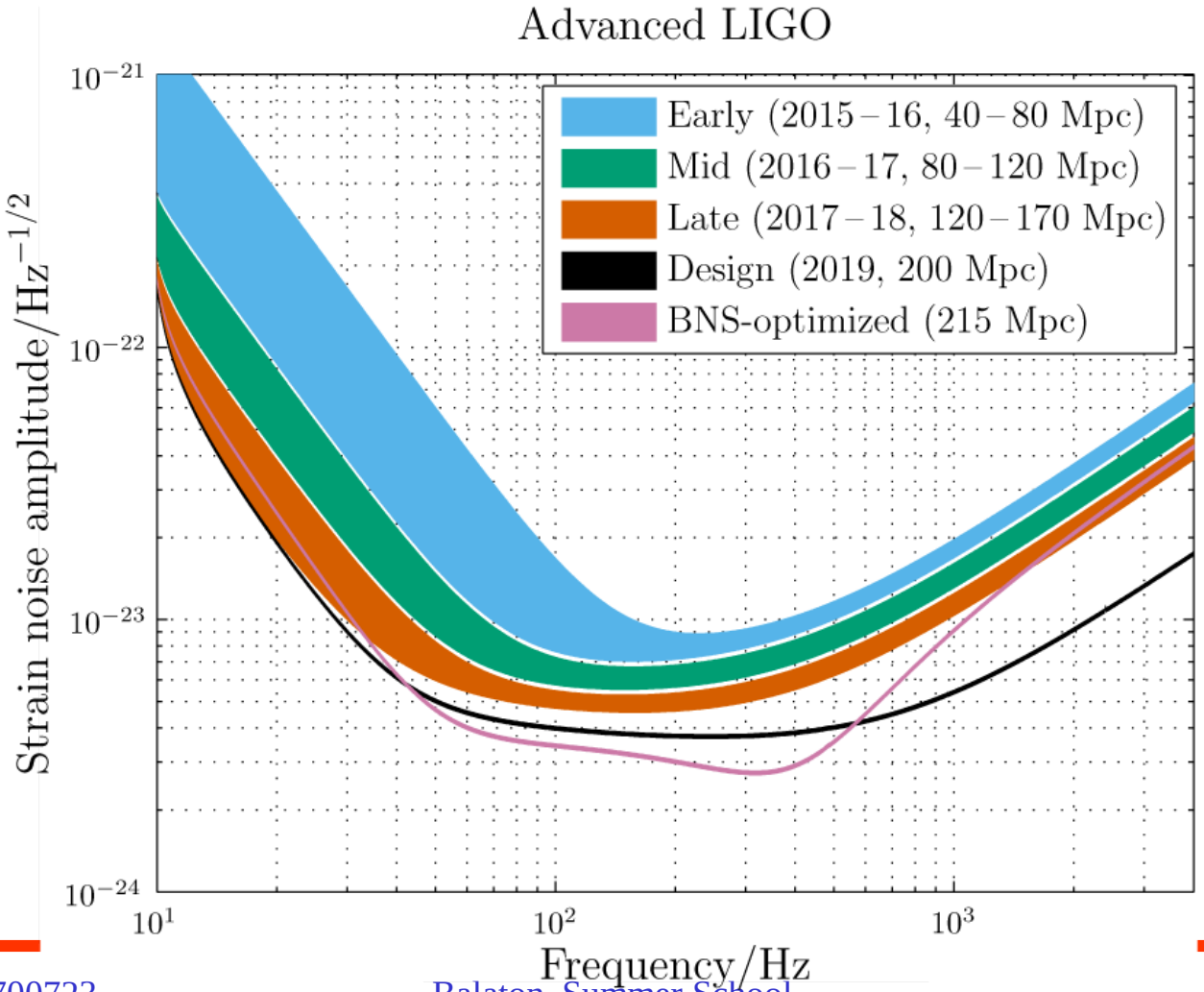


Error boxes with LIGO-India



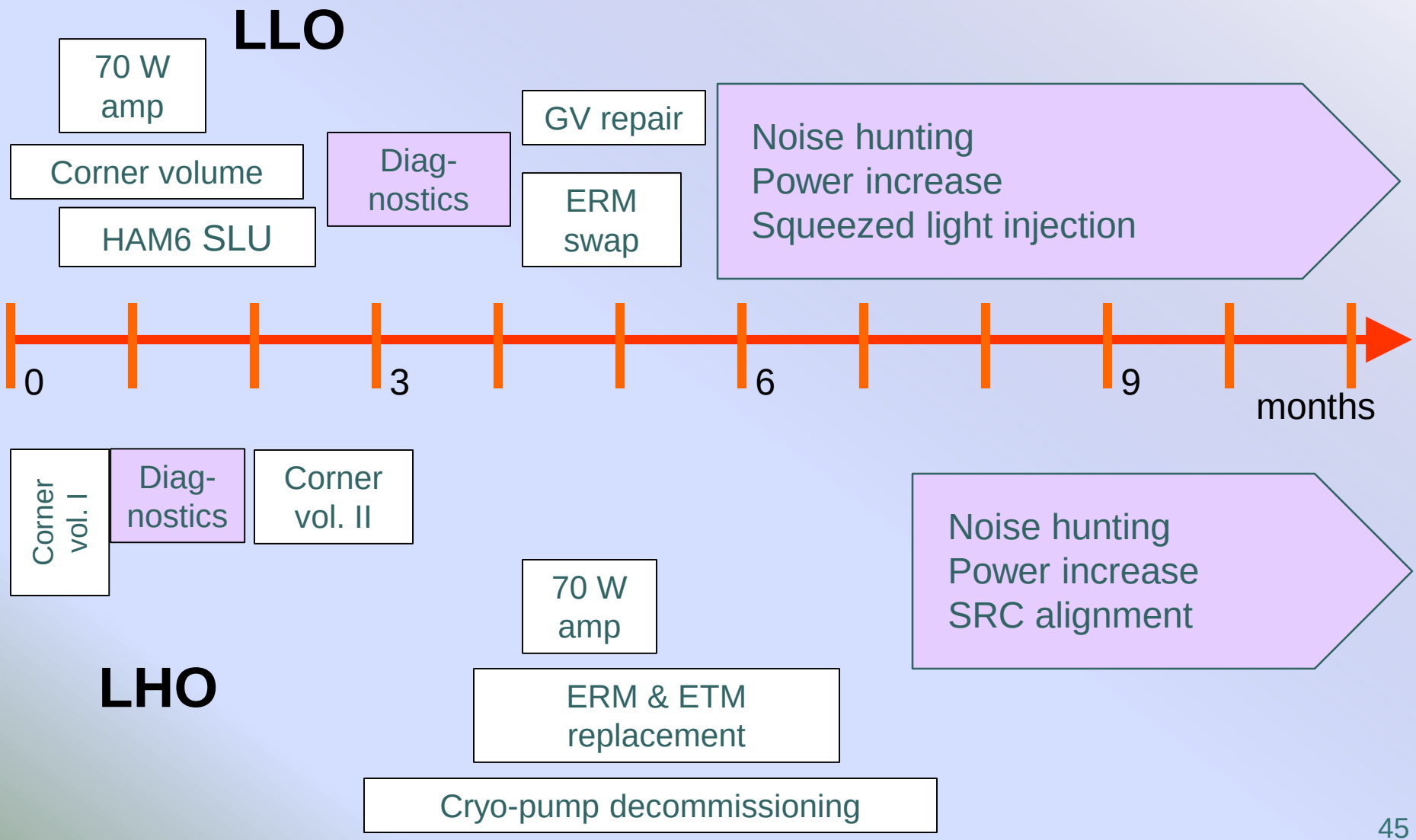
Abbott, et al., Living Rev. Relativity, 19, (2016), 1

LIGO now in O2. (Virgo is just joining now.) O3 aims at "Late" sensitivity



Abbott, et al., Living Rev. Relativity, 19, (2016), 1

Scheduling overview



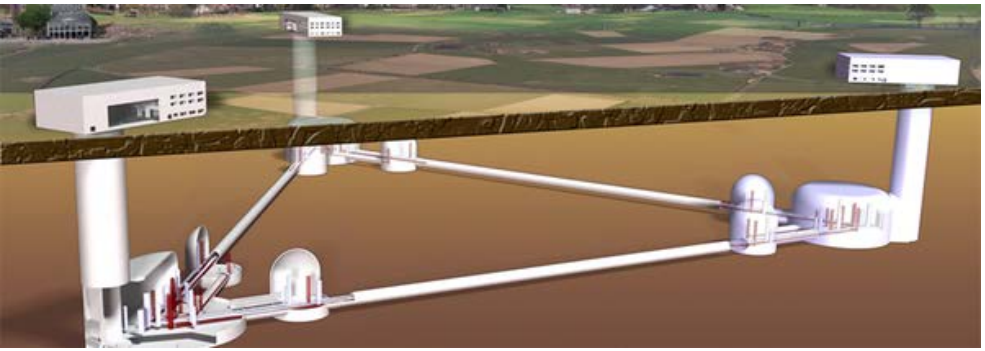
Future science reach for the global network

Epoch			2015 – 2016	2016 – 2017	2017 – 2018	2019+	2022+ (India)
Estimated run duration			4 months	6 months	9 months	(per year)	(per year)
Burst range/Mpc		LIGO	40 – 60	60 – 75	75 – 90	105	105
		Virgo	—	20 – 40	40 – 50	40 – 80	80
BNS range/Mpc		LIGO	40 – 80	80 – 120	120 – 170	200	200
		Virgo	—	20 – 60	60 – 85	65 – 115	130
Estimated BNS detections			0.0005 – 4	0.006 – 20	0.04 – 100	0.2 – 200	0.4 – 400
90% CR	% within	5 deg^2	< 1	2	*> 1 – 2*	*> 3 – 8*	*> 20*
		20 deg^2	< 1	14	*> 10*	*> 8 – 30*	*> 50*
	median/deg^2		480	230	—	—	—
searched area	% within	5 deg^2	6	20	—	—	—
		20 deg^2	16	44	—	—	—
	median/deg^2		88	29	—	—	—

Abbott, et al., Living Rev. Relativity, 19, (2016), 1

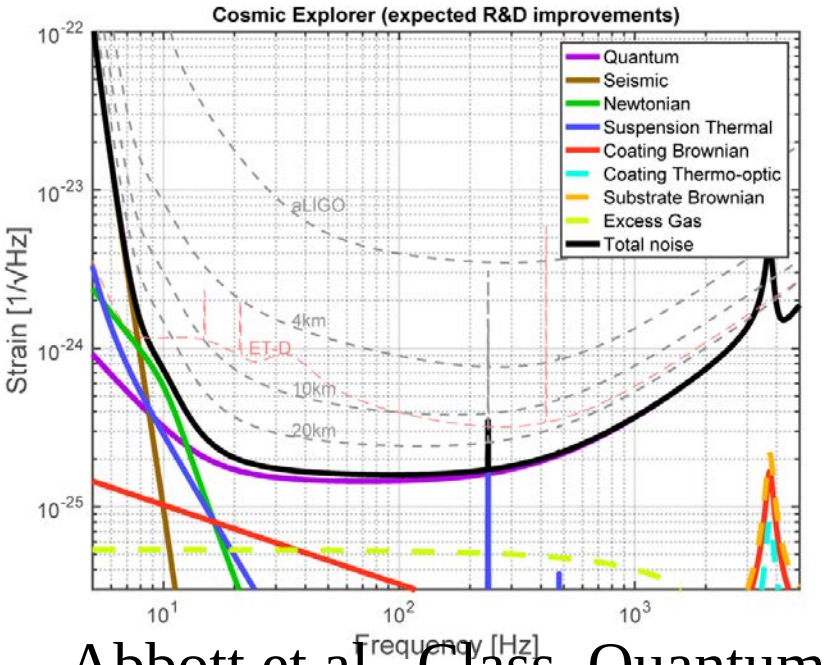
Visions of 3rd generation detectors

Schematic of the Einstein Telescope, a proposed 10-km underground detector.



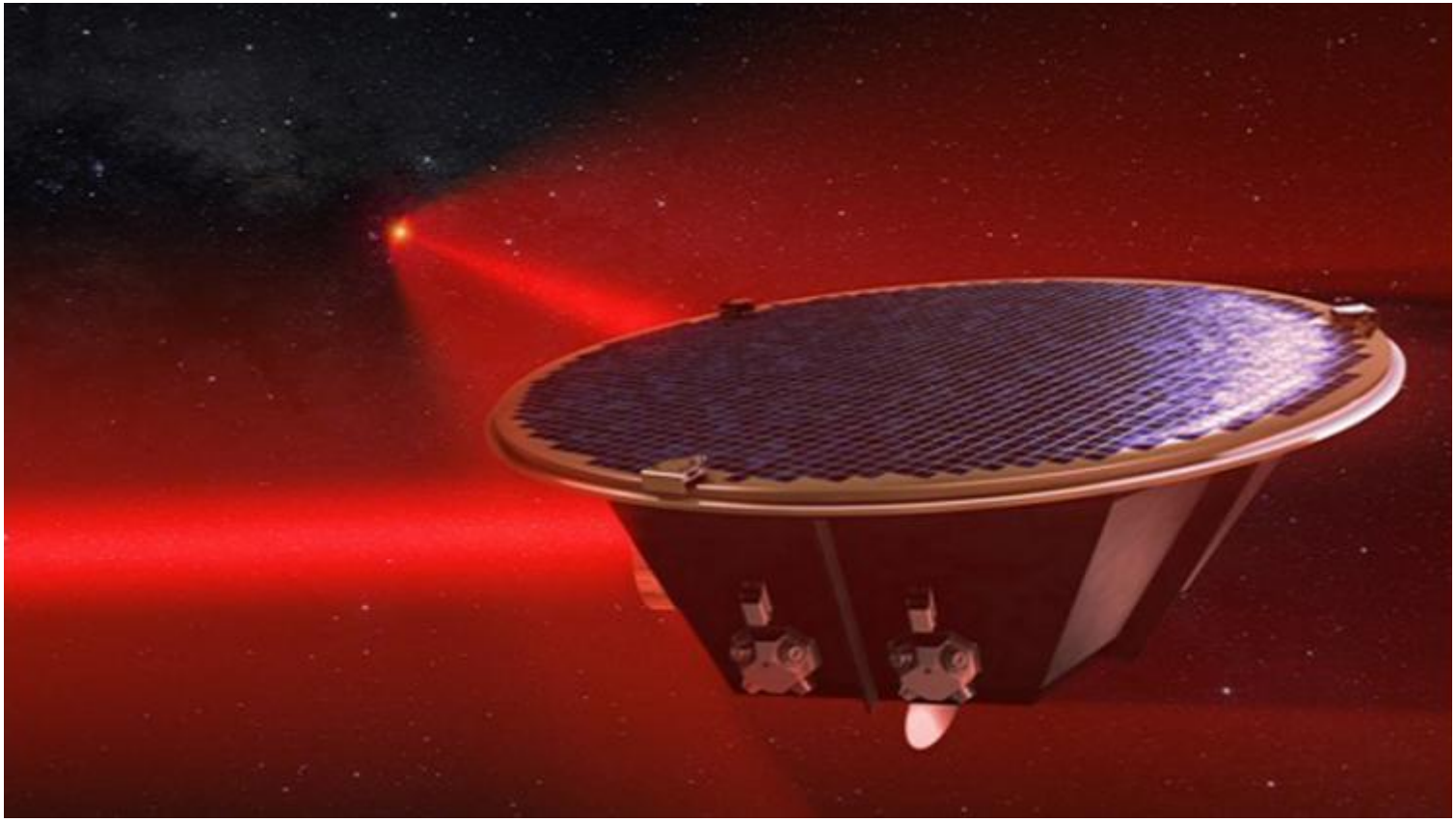
Source:
https://www.aei.mpg.de/18498/03_Einstein_Telescope

Noise spectrum of Cosmic Explorer, a proposed 40-km above-ground detector.



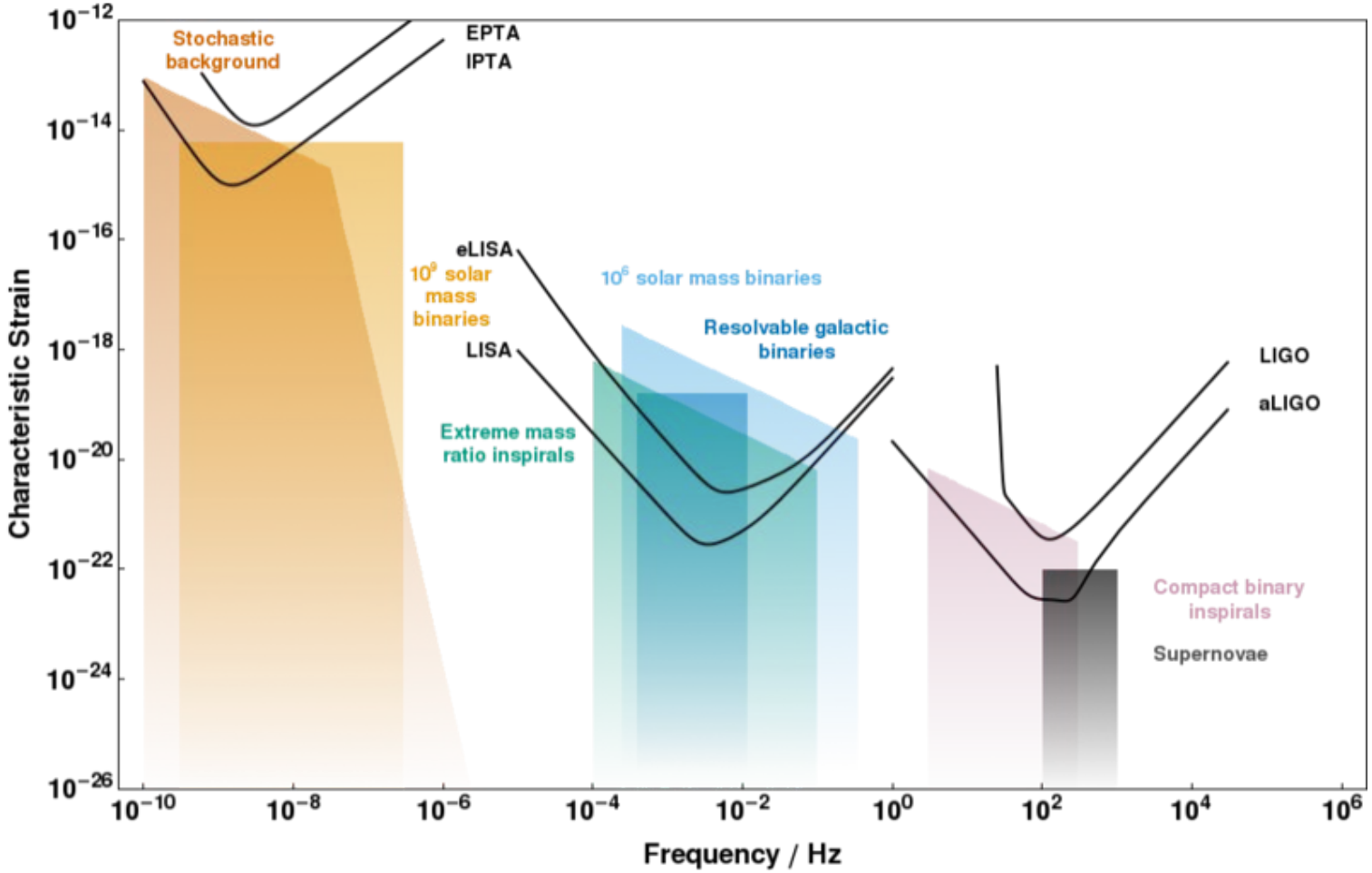
Abbott et al., Class. Quantum Grav. **34** (2017) 044001

LISA, a space-based detector, has just been selected for launch in 2034



Source: https://www.elisascience.org/

There's a broad spectrum of gravitational waves to explore



Source: http://rhcole.com/apps/GWplotter/