LIGO OBSERVERS
Merging BLACK Holes

"Observation of Gravitational Waves from a Binary Black Hole Merger"

B. P. Abbott et al.*
(LIGO Scientific Collaboration and Virgo Collaboration)

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PRL 116, 061102 (2016)

- What is a Gravitational Wave?
- What is logo?
- Event reconstruction and parameters
- What did we learn?

references:

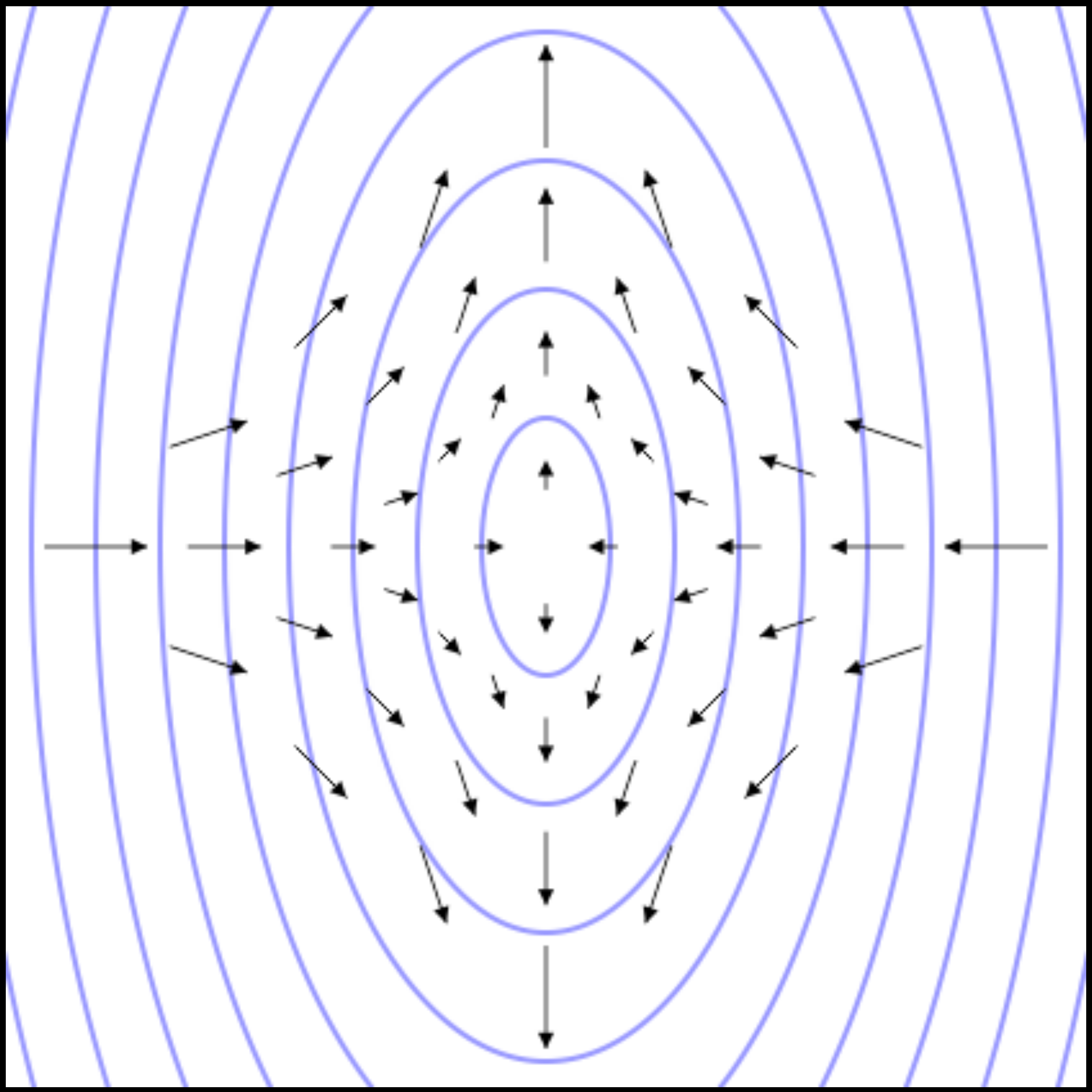
https://physics.aps.org/articles/v9/17

https://www.ligo.caltech.edu/page/detection-companion-papers

https://www.ligo.caltech.edu/gallery

and other sources I shamelessly plundered

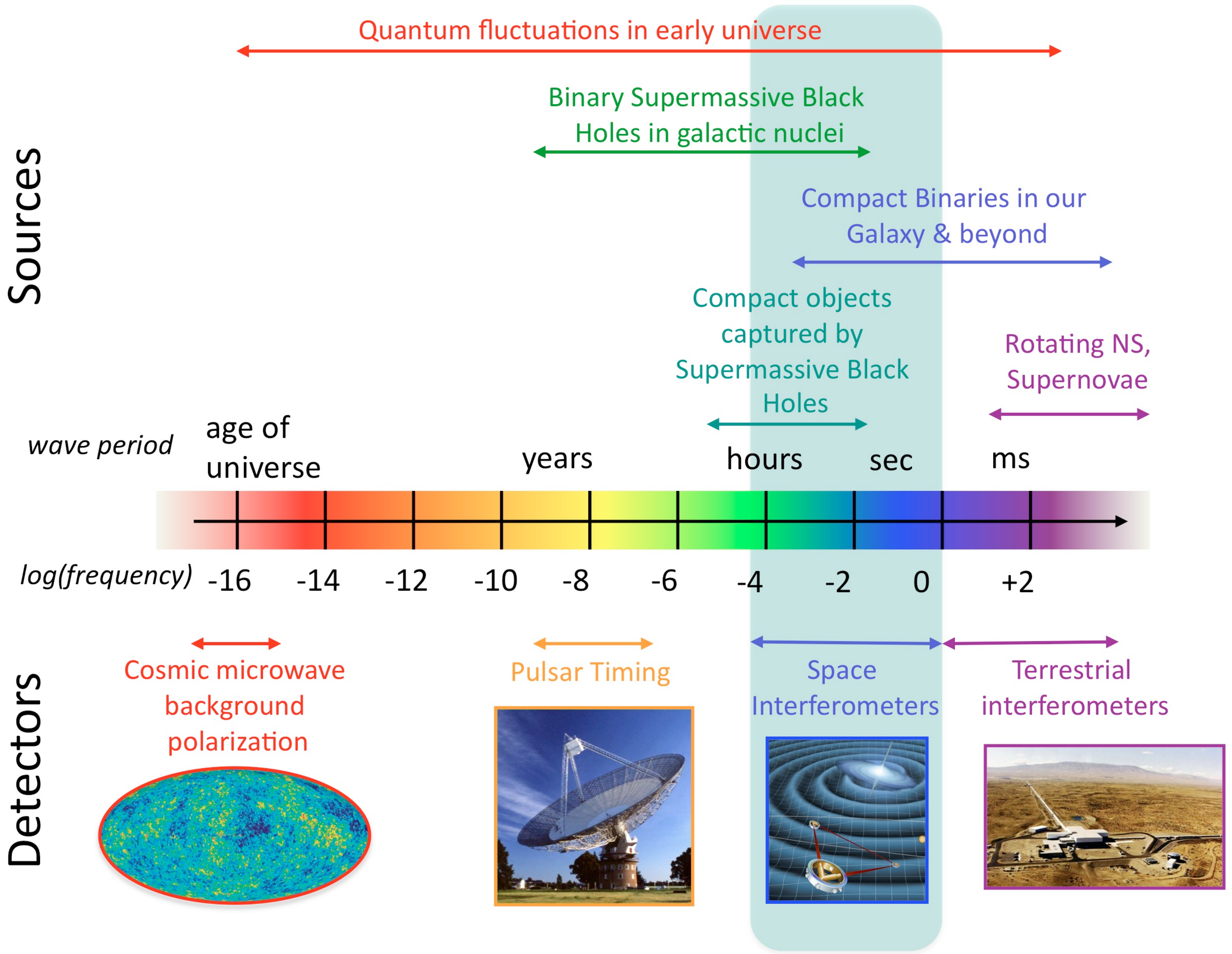
Quadrupole transverse wave
travels at speed of light



Two polarizations: +,x
this is +; x is rotated 45^0

Hard to calculate energy of wave in GR, and therefore hard to know if this was a real effect.
Consensus at Chapel Hill 1957 conference was yes.

The Gravitational Wave Spectrum



LIGO Interferometer, Hanford

An interferometer like LIGO consists of two "arms" (each one 4km long) at right angles to each other, along which a laser beam is shone and reflected by mirrors (suspended as **test masses**) at each end. When a gravitational wave passes by, the stretching and squashing of space causes the arms of the interferometer alternately to lengthen and shrink, one getting longer while the other gets shorter and then vice-versa. As the interferometers' arms change lengths, the laser beams take a different time to travel through the arms – which means that the two beams are no longer "in step" (or in **phase**) and what we call an **interference pattern** is produced. This is why we refer to the LIGO detectors as "interferometers".

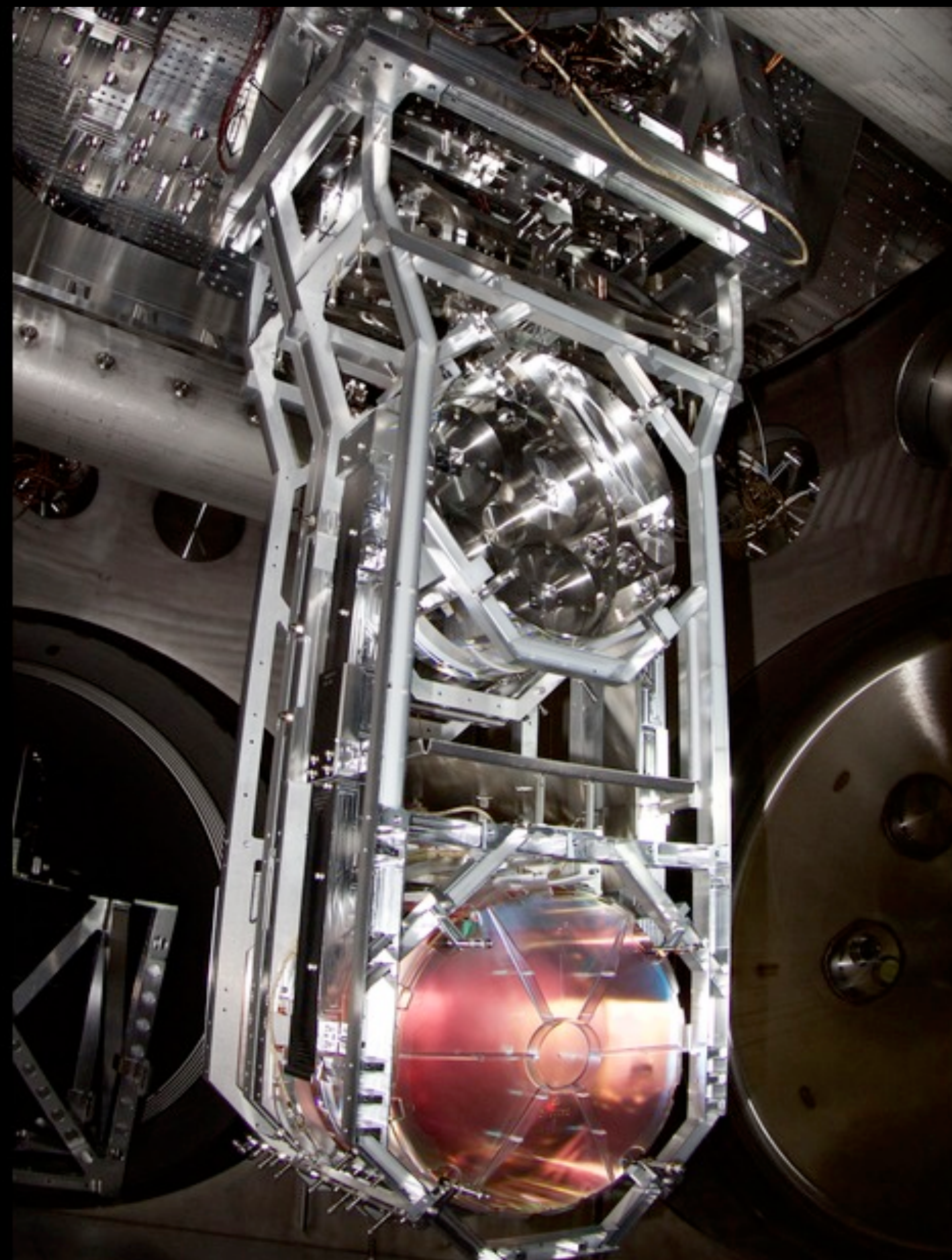
The difference between the two arm lengths is proportional to the strength of the passing gravitational wave, referred to as the **gravitational-wave strain**, and this number is mind-bogglingly small. For a gravitational wave typical of what we can detect, we expect the strain to be about **1/10,000th the width of a proton**! However LIGO's interferometers are so sensitive that they can measure even such tiny amounts.

Size of effect: h=strain

$$\Delta L = h\,L = 10^{-21}\,(4\ \text{km}) = 4\times10^{-16}\ \text{cm}$$

100 reflections of 1064 nm laser

4 element suspension provides inertial damping



The photo shows one of LIGO's test masses installed as the 4th element in a 4-element suspension system. "Test masses" are what LIGO scientists call the mirrors that reflect the laser beams along the lengths of the detector arms. The 40 kg test mass is suspended below the metal mass above by 4 silica glass fibers.

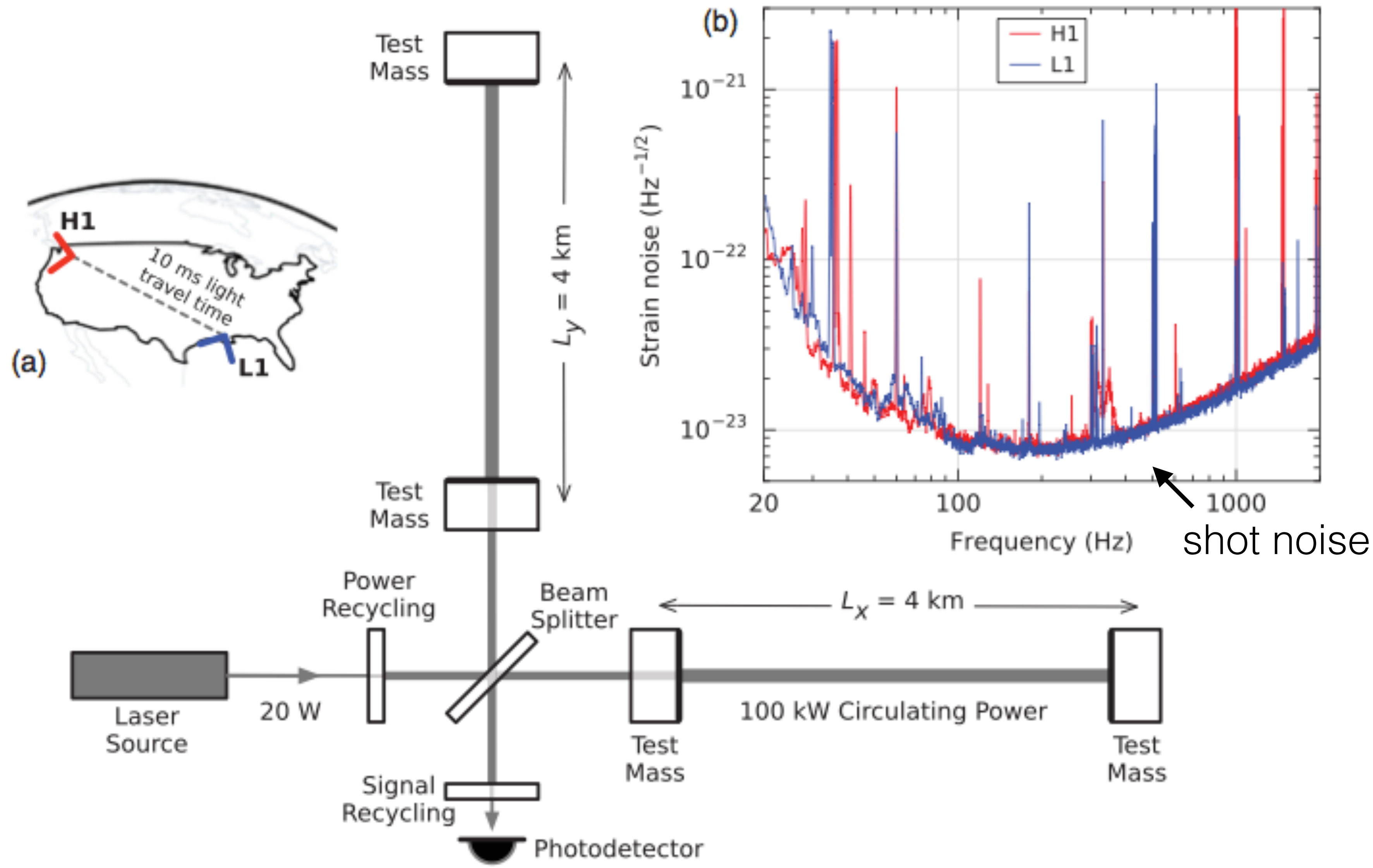


FIG. 3. Simplified diagram of an Advanced LIGO detector (not to scale). A gravitational wave propagating orthogonally to the detector plane and linearly polarized parallel to the 4-km optical cavities will have the effect of lengthening one 4-km arm and shortening the other during one half-cycle of the wave; these length changes are reversed during the other half-cycle. The output photodetector records these differential cavity length variations. While a detector's directional response is maximal for this case, it is still significant for most other angles of incidence or polarizations (gravitational waves propagate freely through the Earth). *Inset (a):* Location and orientation of the LIGO detectors at Hanford, WA (H1) and Livingston, LA (L1). *Inset (b):* The instrument noise for each detector near the time of the signal detection; this is an amplitude spectral density, expressed in terms of equivalent gravitational-wave strain amplitude. The sensitivity is limited by photon shot noise at frequencies above 150 Hz, and by a superposition of other noise sources at lower frequencies [47]. Narrow-band features include calibration lines (33–38, 330, and 1080 Hz), vibrational modes of suspension fibers (500 Hz and harmonics), and 60 Hz electric power grid harmonics.

http://ligo.org/science/Publication-SqueezedVacuum/index.php [☆]

Caves [5, 6] showed that replacing coherent vacuum fluctuations entering the antisymmetric port with correctly phased squeezed vacuum states decreases the “in- phase” quadrature uncertainty, and thus the shot noise, below the quantum limit.

[6] http://journals.aps.org/prd/pdf/10.1103/PhysRevD.23.1693

from Caves [6]

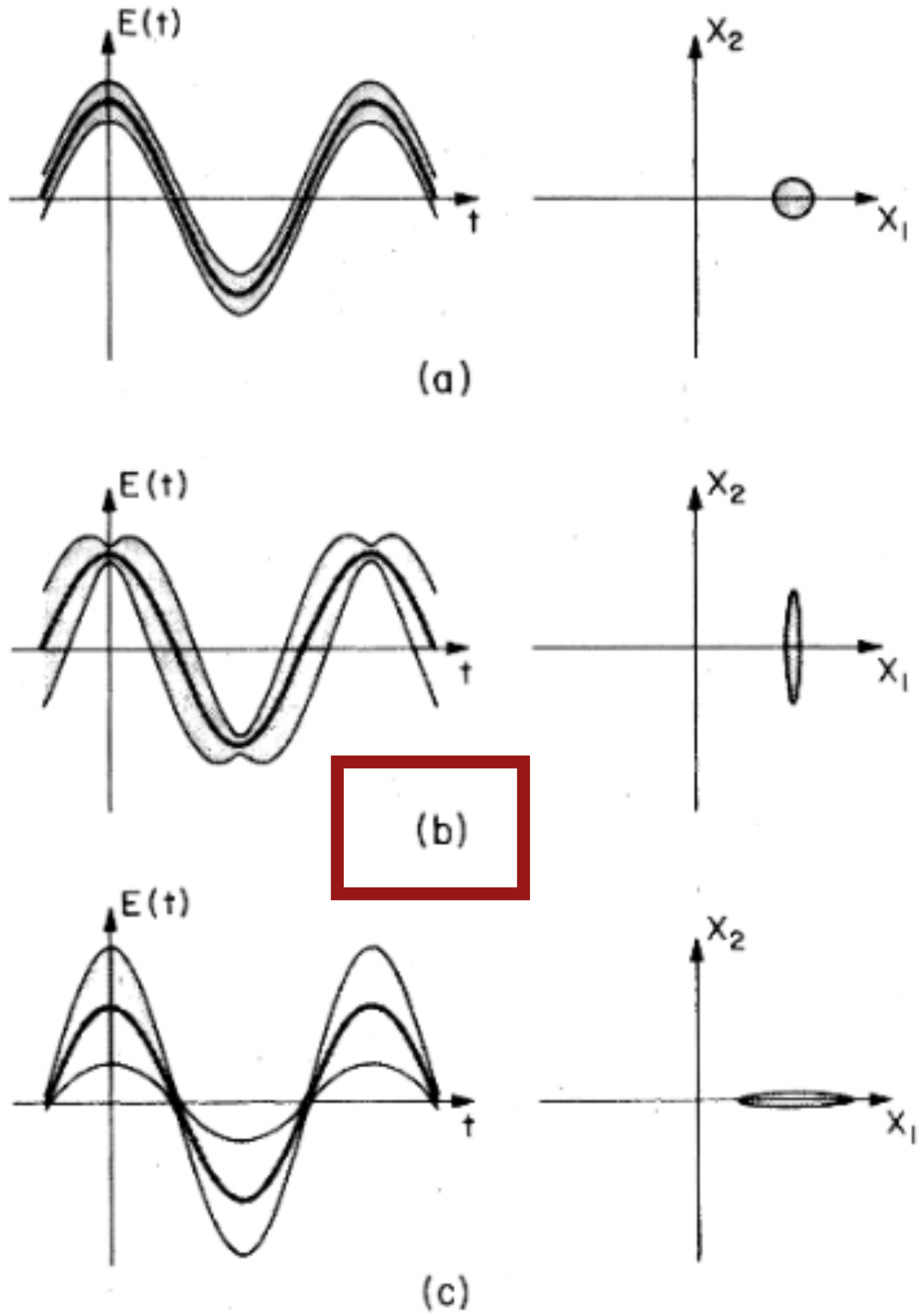


FIG. 2. Graphs of electric field versus time for three states of the electromagnetic field. In each graph the dark line is the expectation value of the electric field, and the shaded region represents the uncertainty in the electric field. To the right of each graph is the corresponding "error box" in the complex-amplitude plane.

lates with frequency 2ω. This situation is depicted in Fig. 2 for two cases: the case where the coherent excitation of the mode appears in the quadrature phase that has reduced noise [Fig. 2(b)] and the case where the coherent excitation appears in the quadrature phase that has increased noise [Fig. 2(c)].

[☆]

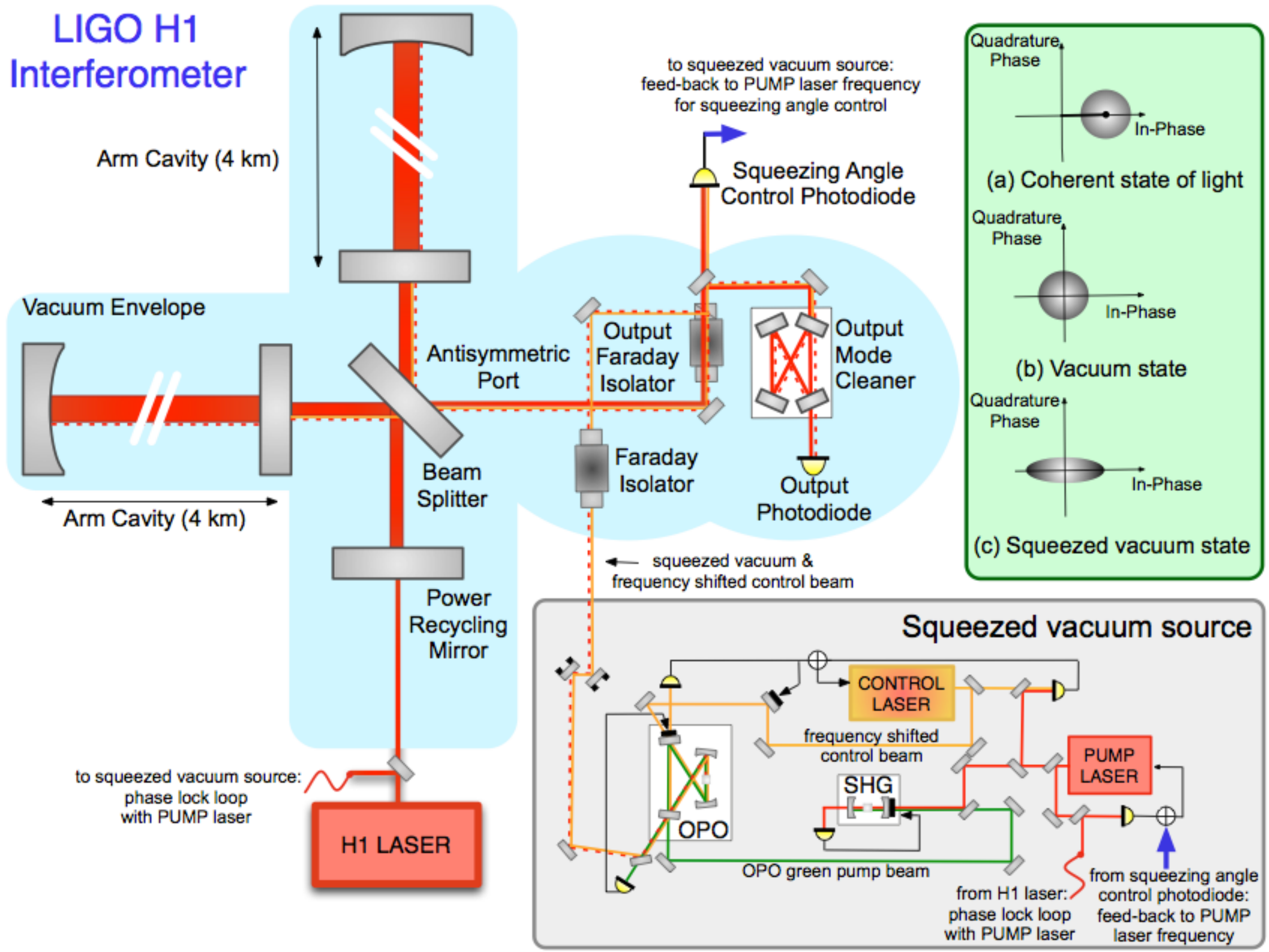
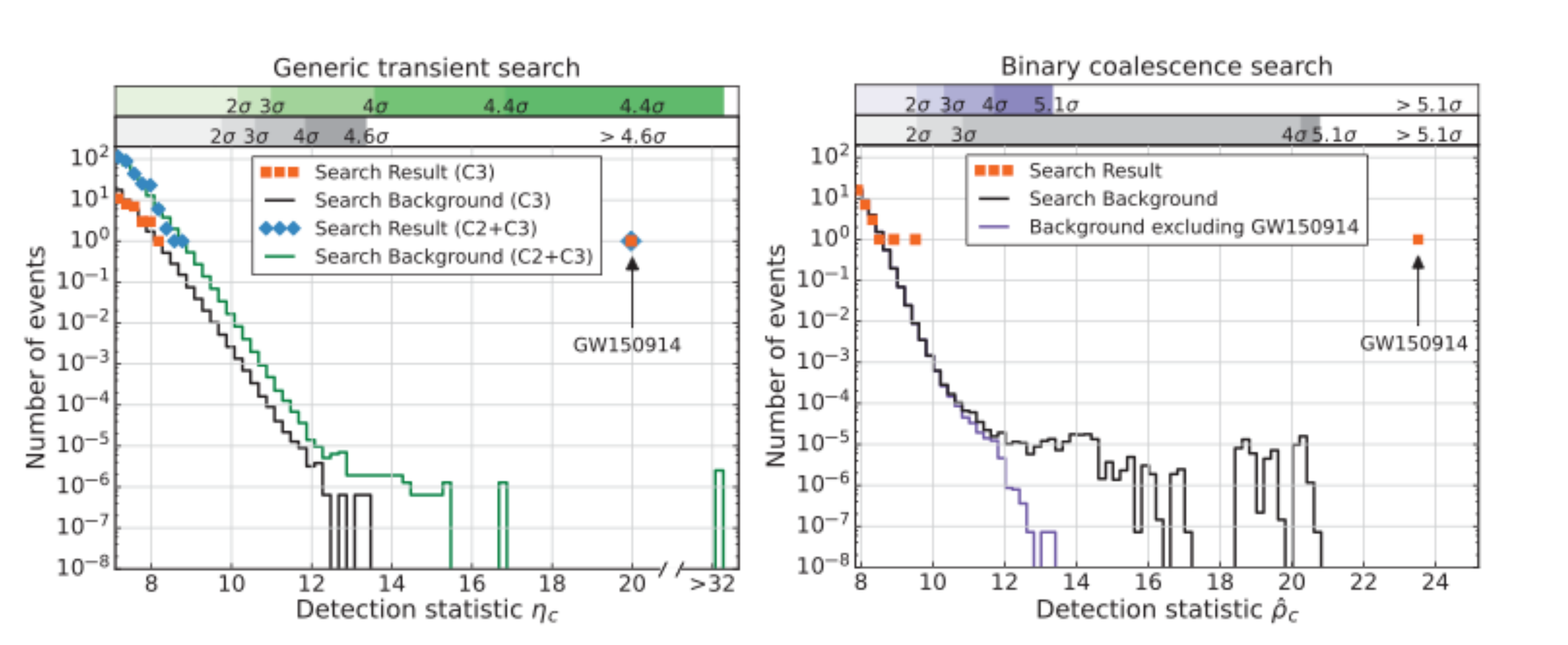


FIG. 1. Simplified layout of the H1 interferometer with squeezed vacuum injection. The interferometer layout is described in the text, together with the main squeezer components (shown in the grey box). The green box shows a simplified representation of coherent states and squeezed states in the "in-phase" and "quadrature phase" coordinates.



The waveform is consistent with a black hole binary system whose component masses are 36 and 29 times the mass of the Sun.

Moreover, no binary system other than black holes can have component masses large enough to explain the observed signal. (The most plausible competitors would be two neutron stars, or a black hole and a neutron star.) The binary is approximately 1.3 billion light years from Earth, or equivalently, at a luminosity distance of 400 megaparsecs (redshift of $z \sim 0.1$).

masses & spins

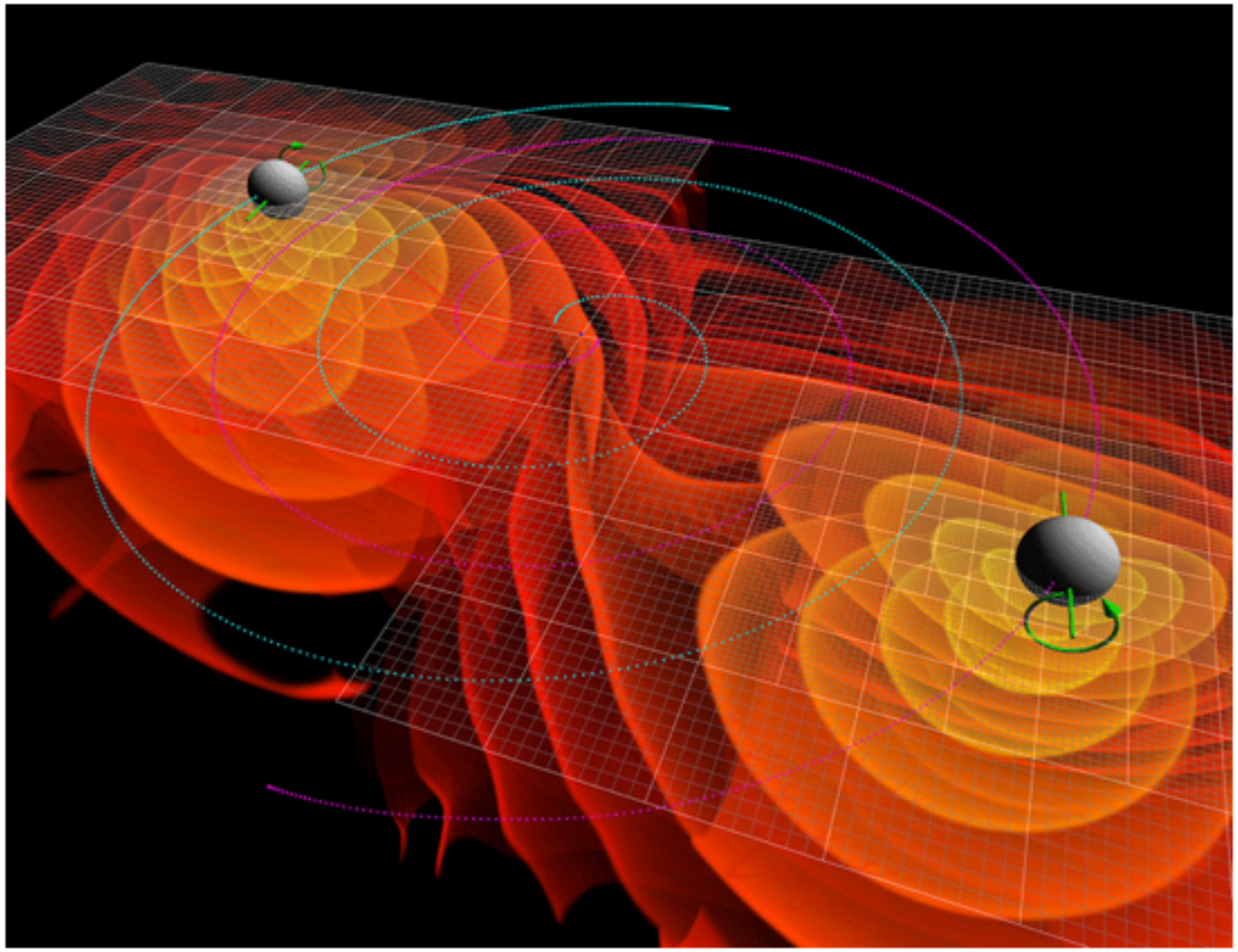
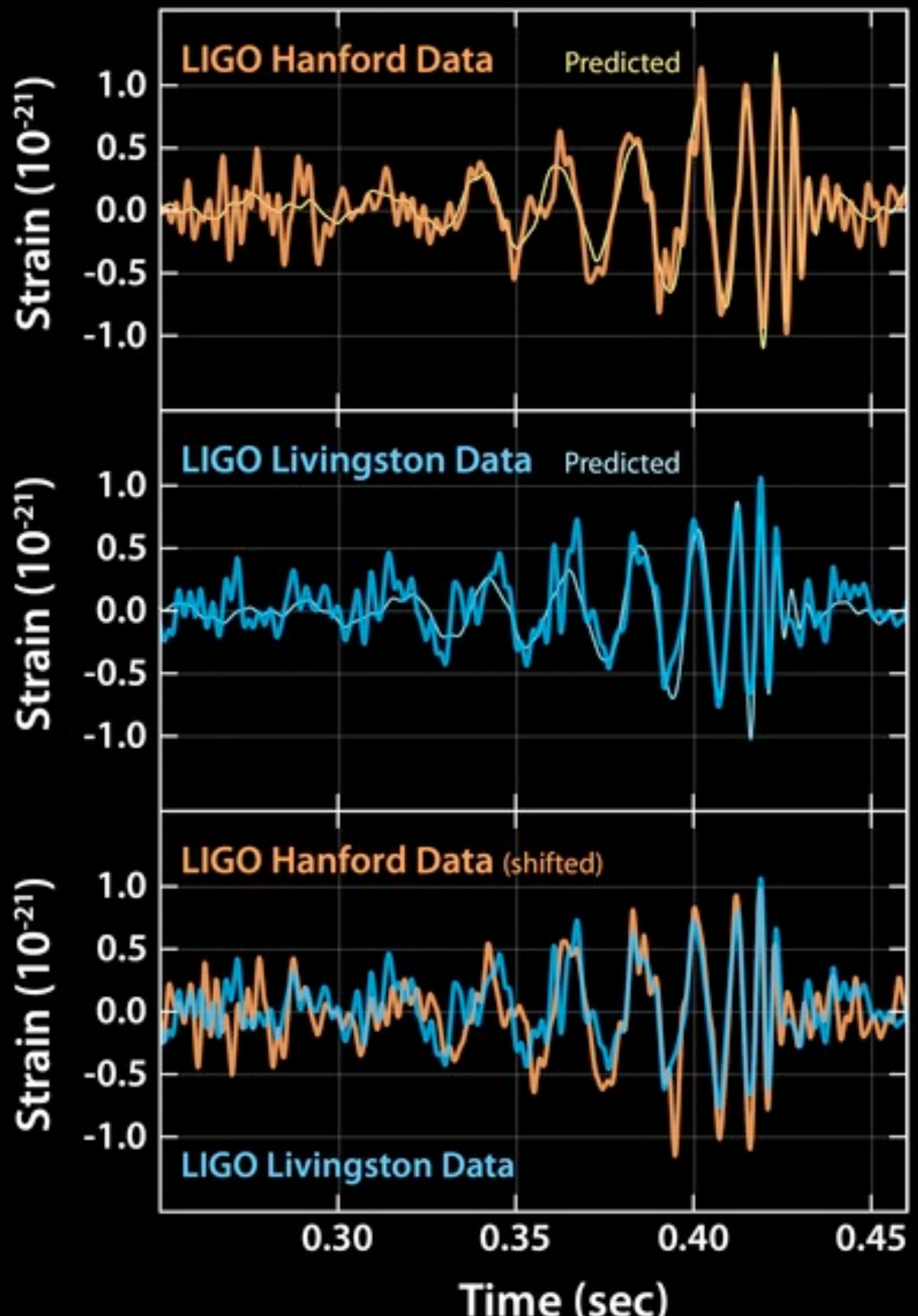
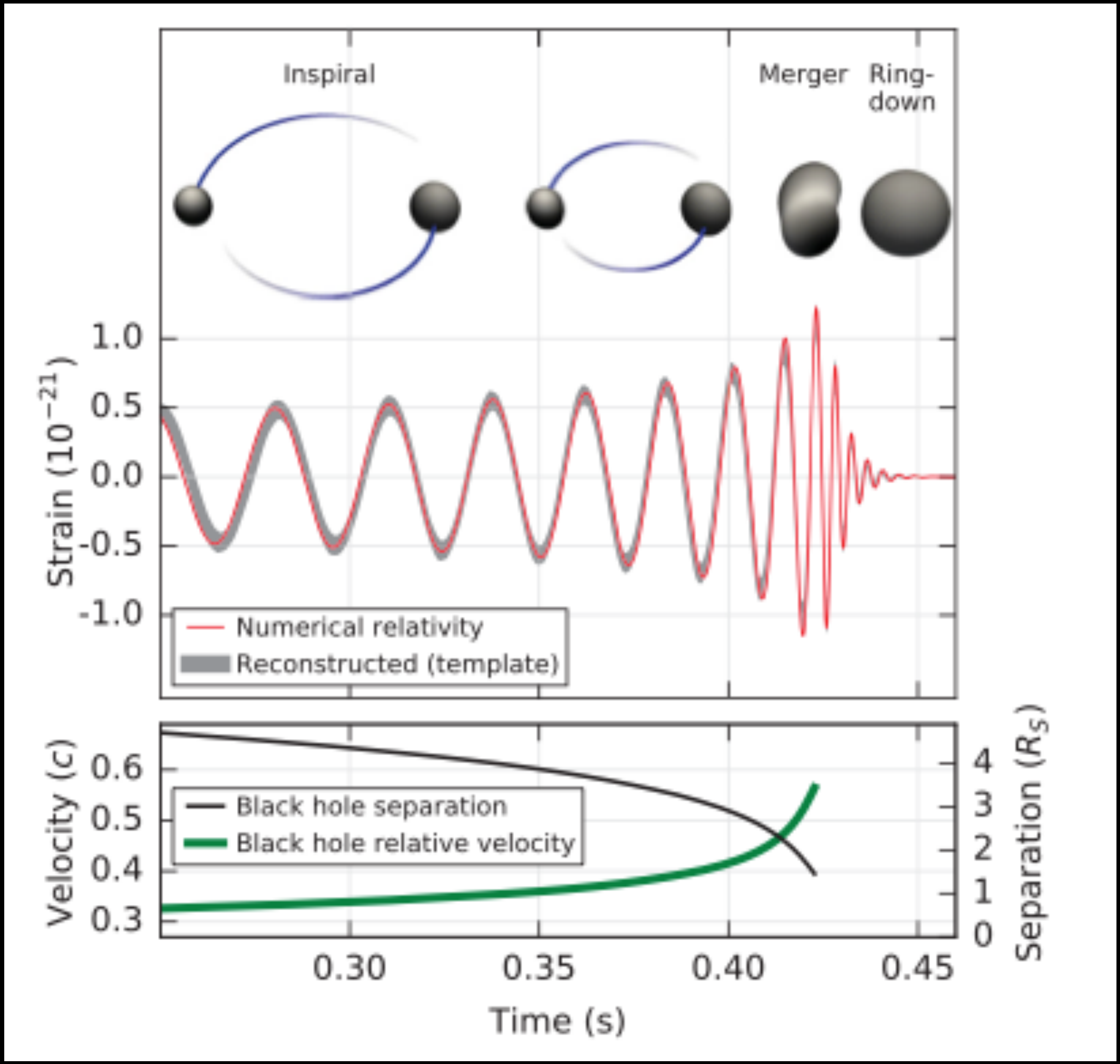


Figure 1: Numerical simulations of the gravitational waves emitted by the inspiral and merger of two black holes. The colored contours around each black hole represent the amplitude of the gravitational radiation; the blue lines represent the orbits of the black holes and the green arrows represent their spins. (C. Henze/NASA Ames Research Center)


LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)

Numerical modeling



$A_{GW} \sim 1/D_L$

In general relativity, gravitational radiation is fully described by two independent, and time-dependent polarizations, h_+ and $h_\times$. Each instrument k measures the strain

$$h_k = F_k^{(+)} h_+ + F_k^{(\times)} h_\times \,, \quad (1)$$

a linear combination of the polarisations weighted by the antenna beam patterns $F_k^{(+,\times)}(\alpha, \delta, \psi)$, which depend on the source location in the sky and the polarisation of the waves [22, 23]. During the inspiral and at the leading order, the GW polarizations can be expressed as

$$h_+(t) = A_{\rm GW}(t)\left(1 + \cos^2 \iota\right) \cos \phi_{\rm GW}(t) \,, \quad (2a)$$

$$h_\times(t) = -2A_{\rm GW}(t) \cos \iota \sin \phi_{\rm GW}(t) \,, \quad (2b)$$

During the inspiral, the phase evolution $\phi_{\rm GW}(t; m_{1,2}, \boldsymbol{S}_{1,2})$ can be computed using post-Newtonian (PN) theory, which is a perturbative expansion in powers of the orbital velocity v/c [24]. For GW150914, v/c is in the range ≈0.2–0.5 in the LIGO sensitivity band. At the leading order, the phase evolution is driven by a particular combination of the two masses, commonly called the chirp mass [25],

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

where f is the GW frequency, $\dot{f}$ is its time derivative and $M = m_1 + m_2$ is the total mass. Additional parameters

$$\chi_{\rm eff} = \frac{c}{G}\left(\frac{\boldsymbol{S}_1}{m_1} + \frac{\boldsymbol{S}_2}{m_2}\right) \cdot \frac{\hat{\boldsymbol{L}}}{M} \,,$$

The approximate location is shown on this sky map of the southern hemisphere. The colored lines represent different probabilities for where the signal originated: the purple line defines the region where the signal is predicted to have come from with a 90 percent confidence level; the inner yellow line defines the target region at a 10 percent confidence level.

The gravitational waves were produced by a pair of merging black holes located 1.3 billion light-years away.

A small galaxy near our own, called the Large Magellanic Cloud, can be seen as a fuzzy blob underneath the marked area, while an even smaller galaxy, called the Small Magellanic Cloud, is below it.

Researchers were able to home in on the location of the gravitational-wave source using data from the LIGO observatories in Livingston, Louisiana, and Hanford, Washington. The gravitational waves arrived at Livingston 7 milliseconds before arriving at Hanford. This time delay revealed a particular slice of sky, or ring, from which the signal must have arisen. Further analysis of the varying signal strength at both detectors ruled out portions of the ring, leaving the remaining patch shown on this map.

From the signal, the researchers were also able to perform two consistency tests of general relativity and put a bound on the mass of the graviton—the hypothetical quantum par- ticle that mediates gravity. In the first test, they used general relativity to estimate the black hole remnant's mass and spin from the pre-merger parameters. They then also determined the remnant's mass and spin from the oscillations in the wave produced by the final black hole [6]. They found that the values inferred from these oscillations agreed with those they had calculated. The second test was to analyze the phase of the wave generated by the black holes as they spiraled inward towards one another. This phase can be written as a series expansion in v/c, where v is the speed of the orbiting black holes, and the authors verified that the coefficients of this expansion were consistent with the predictions of general relativity. By assuming that a graviton with mass would modify the phase of the waves, they determined an upper bound on the particle's mass of 1.2×10^{-22} eV/c^2, improving the bounds from measurements in our Solar System and from observations of binary pulsars. These findings will be discussed in detail in later papers.

Department of Physics & Astronomy
University of New Mexico

Physics and Astronomy Colloquium

A Galactic Scale Gravitational Wave Observatory

Presented by Maura McLaughlin, WVU

Pulsars are rapidly rotating neutron stars with phenomenal rotational stability that can be used as celestial clocks in a variety of fundamental physics experiments. One of these experiments involves using an array of precisely timed millisecond pulsars to detect perturbations due to gravitational waves. We are now entering a new era of gravitational wave astrophysics, with the first direct detection of gravitational waves from a black hole binary system with LIGO. The gravitational waves detectable through pulsar timing will most likely result from an ensemble of black hole binaries which are much more massive than the LIGO source. I will describe the efforts of the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), a collaboration which monitors an array of over 40 millisecond pulsars with the Green Bank Telescope and Arecibo Observatory. The most recent limits on various types of gravitational wave sources will be presented, and I will show how these limits are already constraining models for galaxy formation and evolution. I will then describe the dramatic gains in sensitivity that are expected from discoveries of millisecond pulsars, more sensitive instrumentation, improved detection algorithms, and international collaboration and show that detection is possible before the end of the decade.

4:00 pm, Friday, February 19, 2016
Room 125, Dane Smith Hall
Southwest corner of Las Lomas and Yale, Albuquerque, New Mexico