Title: Gravitational Waves: The Birth of a New Area of Astronomy

Date: Oct 20, 2016 01:00 PM

URL: http://pirsa.org/16100061

Abstract: <p>On September 14th and December 26th, 2015, the Advanced LIGO detectors observed two gravitational wave signals, each from the merger of stellar-mass black holes. These two observations have given us the first glimpse in to the population of stellar mass black holes. In this talk I will discuss these first detections of gravitational waves including the non-detection of gravitational waves from the merger of binary neutron star and neutron star black holes systems. I will also describe the LIGO interferometers, their current state and the future of this exciting new field of gravitational-wave astronomy.</p>

Gravitational wave propagation

$$h(t) = Ae^{i(2\pi f t - \mathbf{k}\cdot\mathbf{r})}$$

Gravitational wave strength is given in strain:

$$h \sim \delta L / L$$

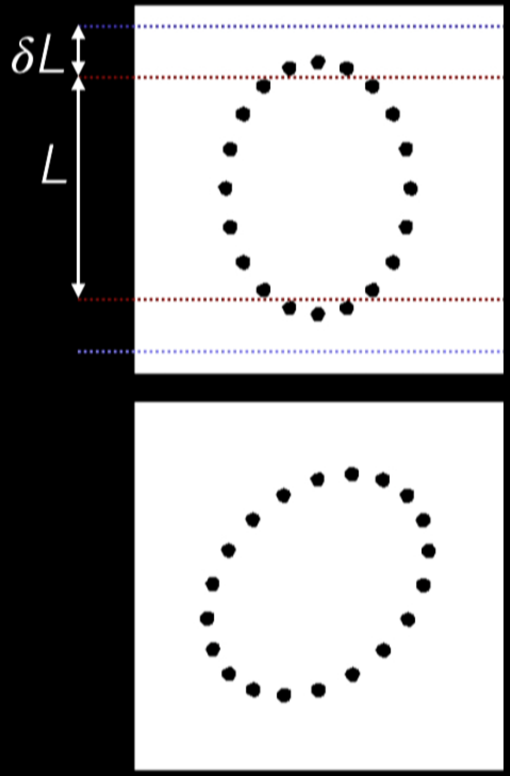
Typical strains from astrophysical sources are very small by the time they arrive at Earth:

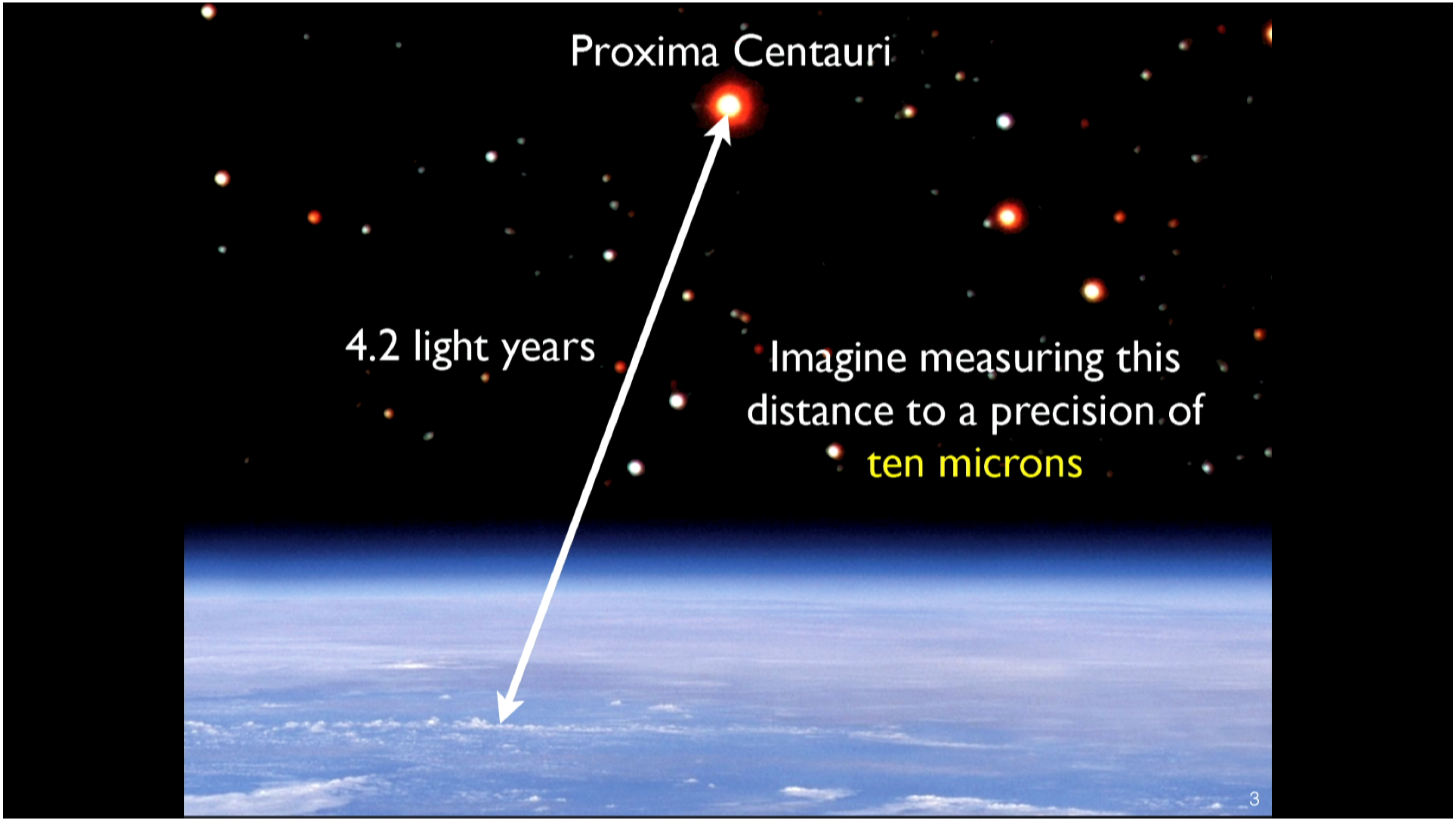
$$h \sim 10^{-21}$$

GW luminosity of recent BBH detections are huge. Peak luminosity:

$$L_{GW} \sim 10^{56}\ \mathrm{erg/s}$$

(GRB luminosity ~ 10^{49-52} erg/s)





Proxima Centauri

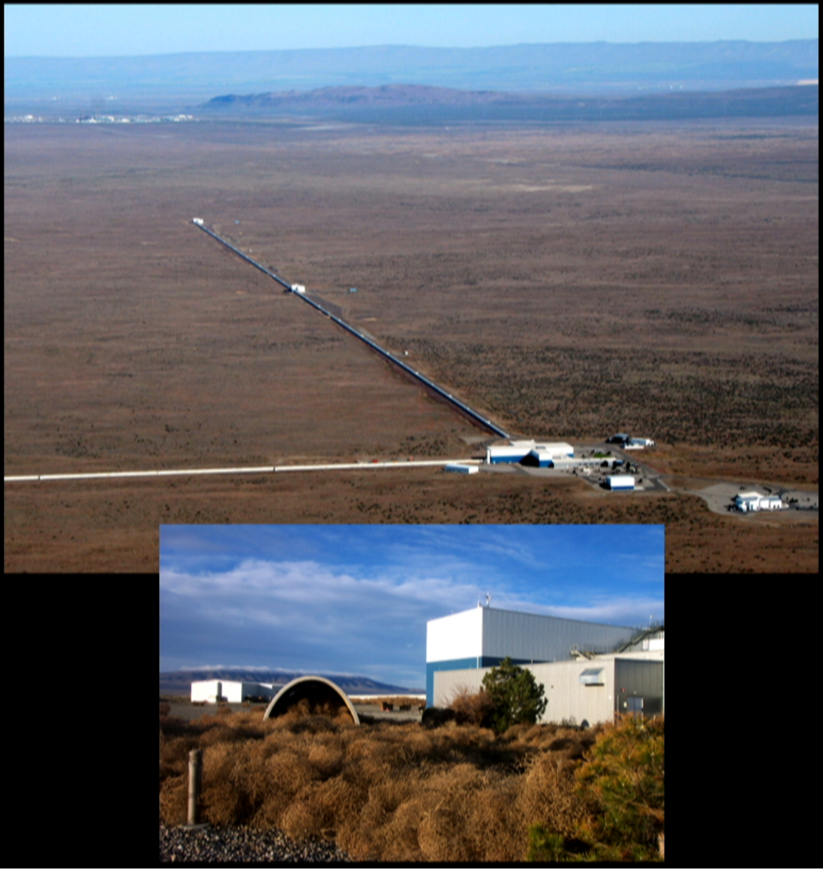
4.2 light years

Imagine measuring this distance to a precision of ten microns

LIGO

Laser Interferometer Gravitational-wave Observatory

LIGO-Hanford

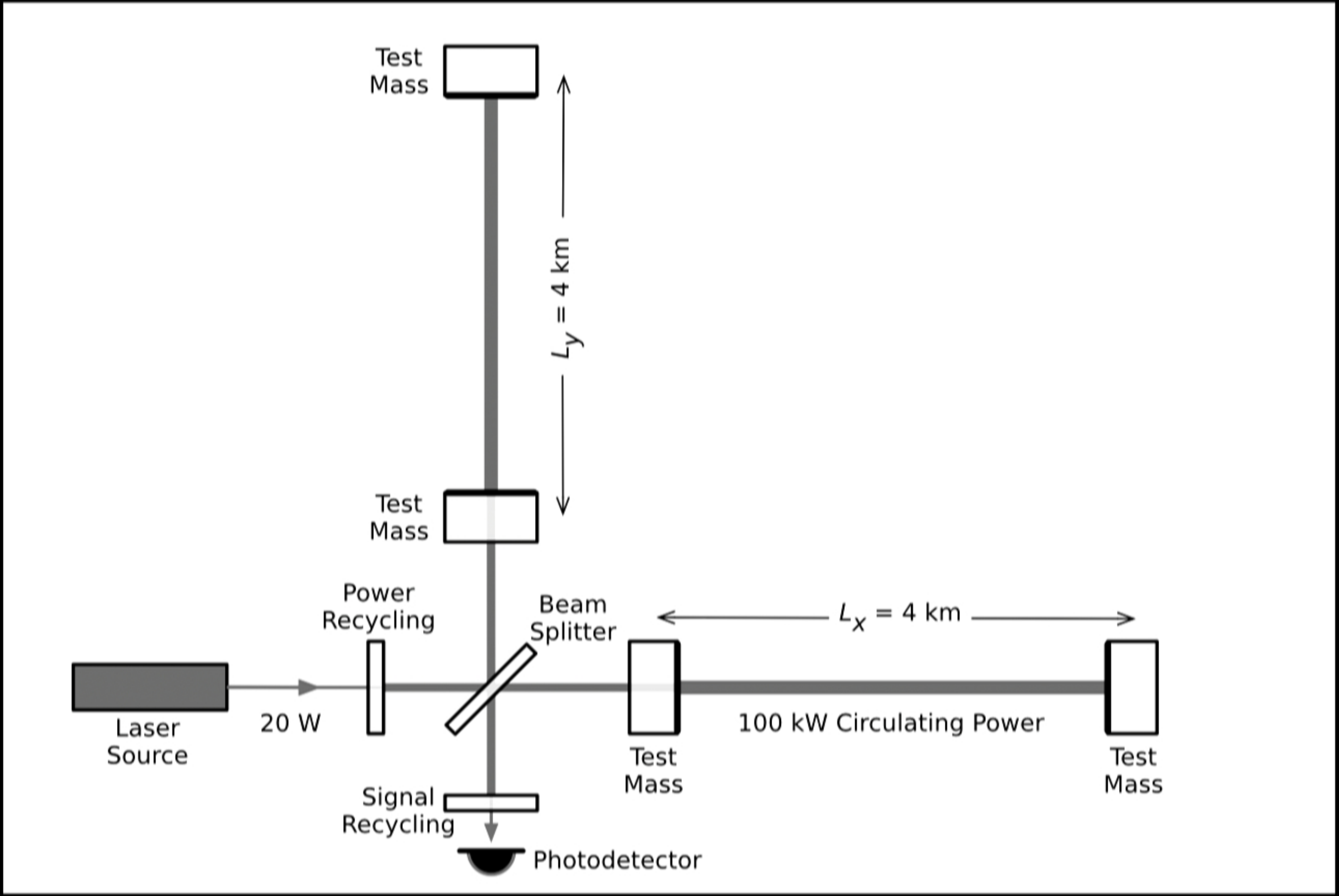


LIGO-Livingston

wave Observatory

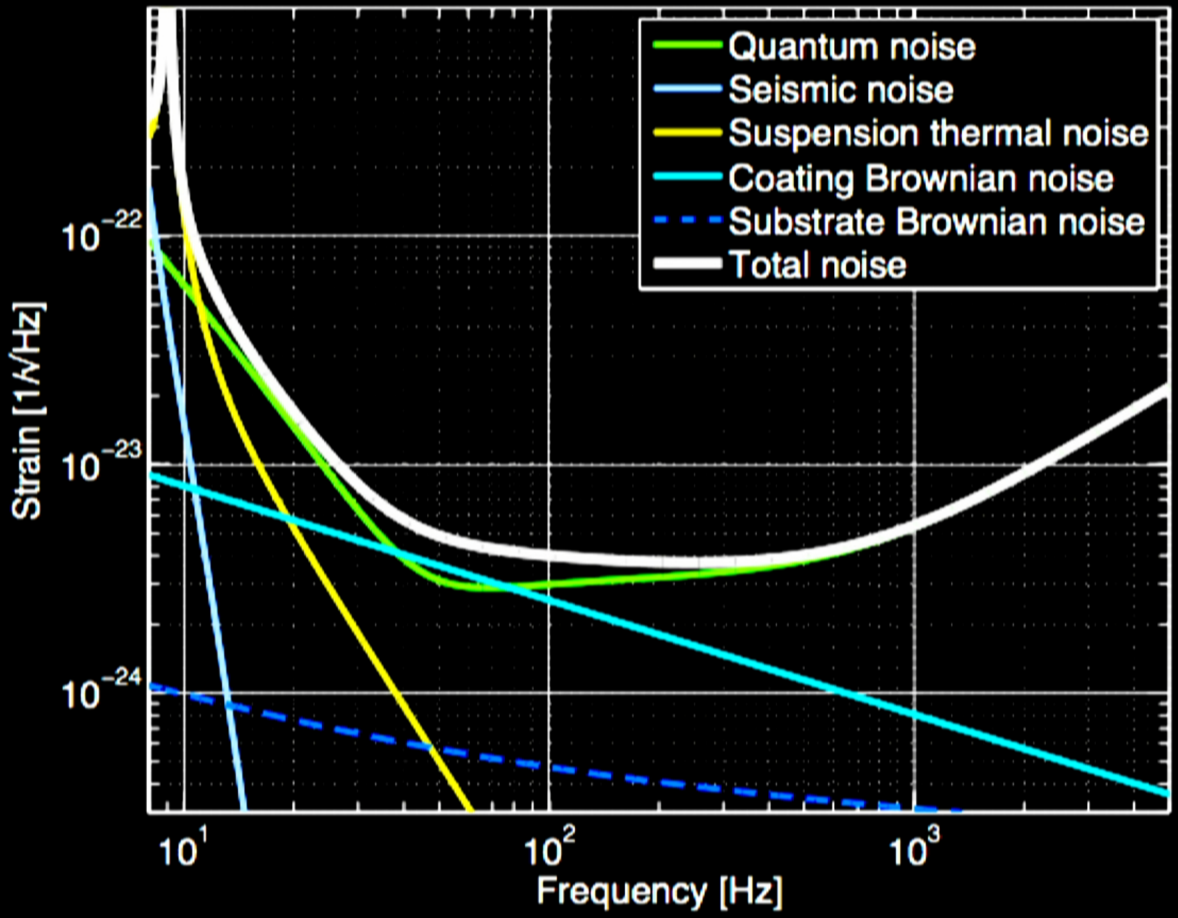
LIGO-Livingston

The design

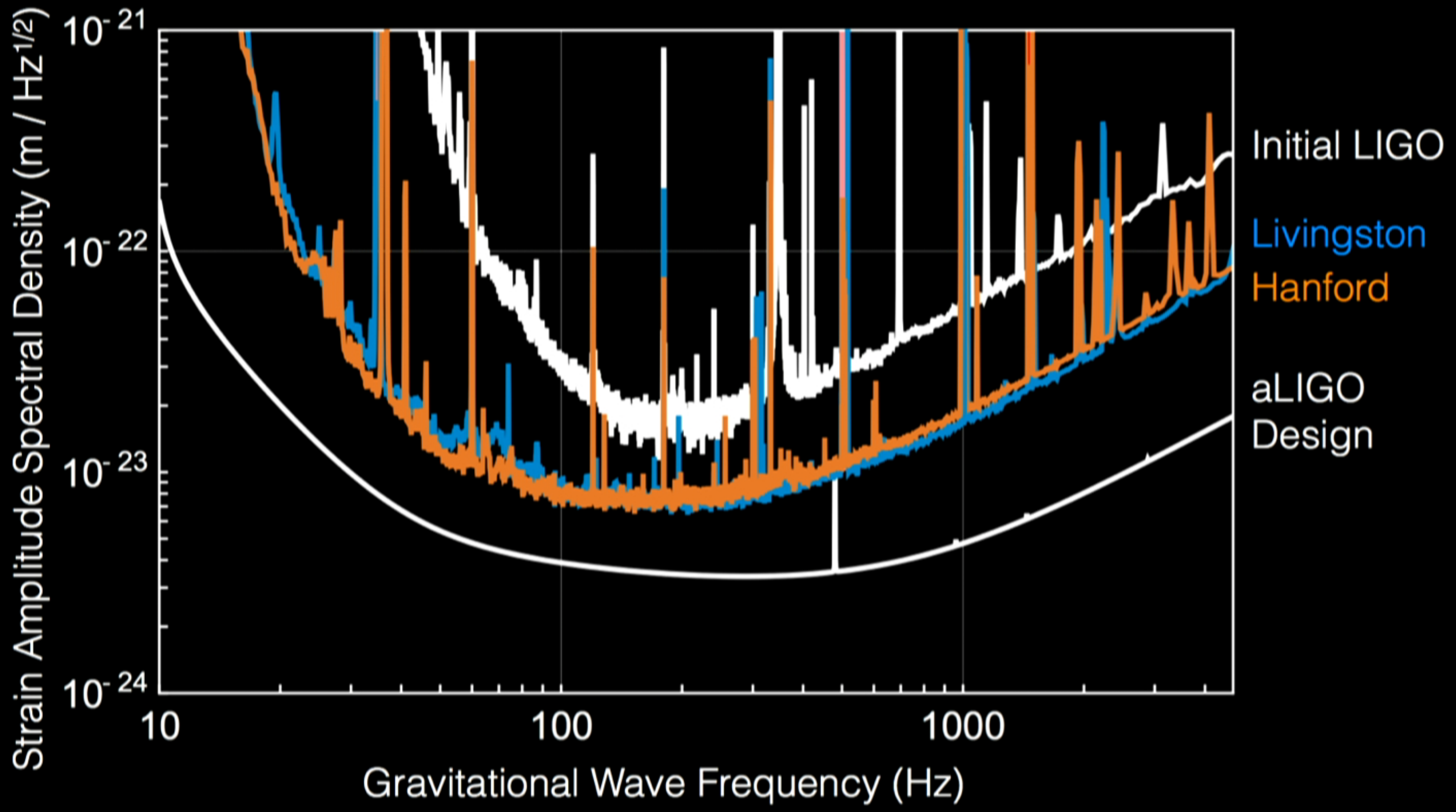


PRL 116, 131103 (2016)

Sensitivity: sources of noise

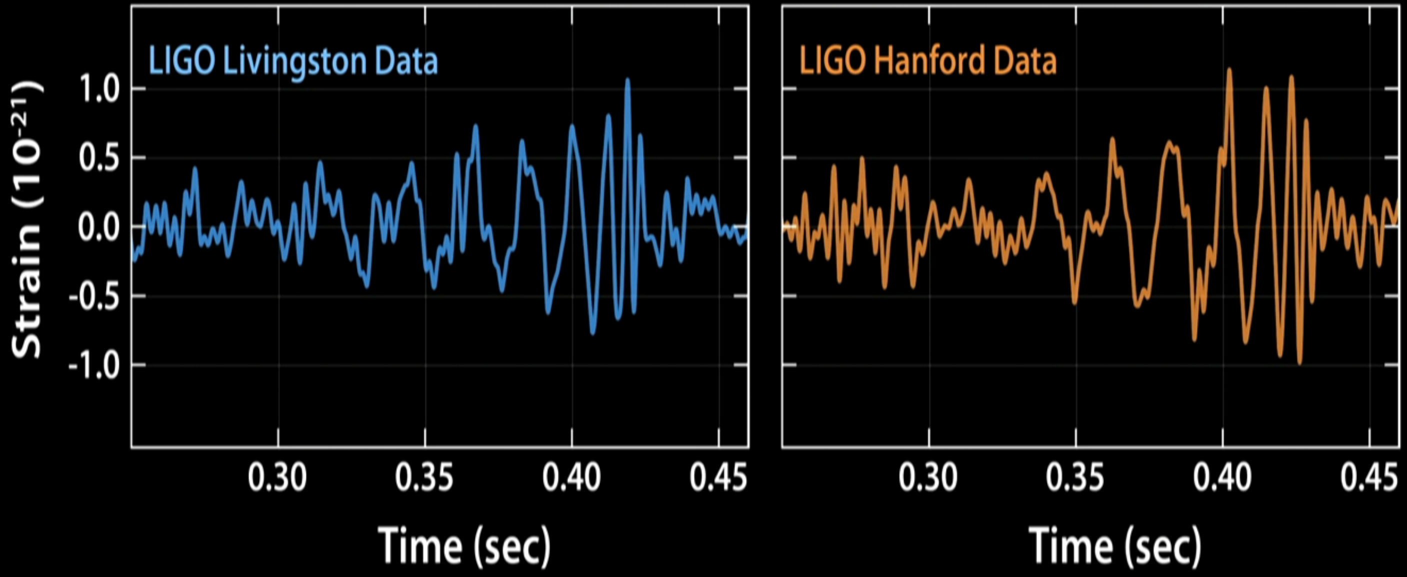


Sensitivity: past, present and future



PRL 116, 131103 (2016)

GW150914



PRL 116, 061102 (2016)

- Observed on September 14th, 2015 at 09:40:45 UTC
- First observed in LIGO-Livingston then 7ms later at LIGO-Hanford
- Over 0.2 seconds the signal increases in frequency and amplitude over ~8 cycles from 35Hz to peak amplitude at 150 Hz

How do we know 2 black holes collided?

Chirp mass:

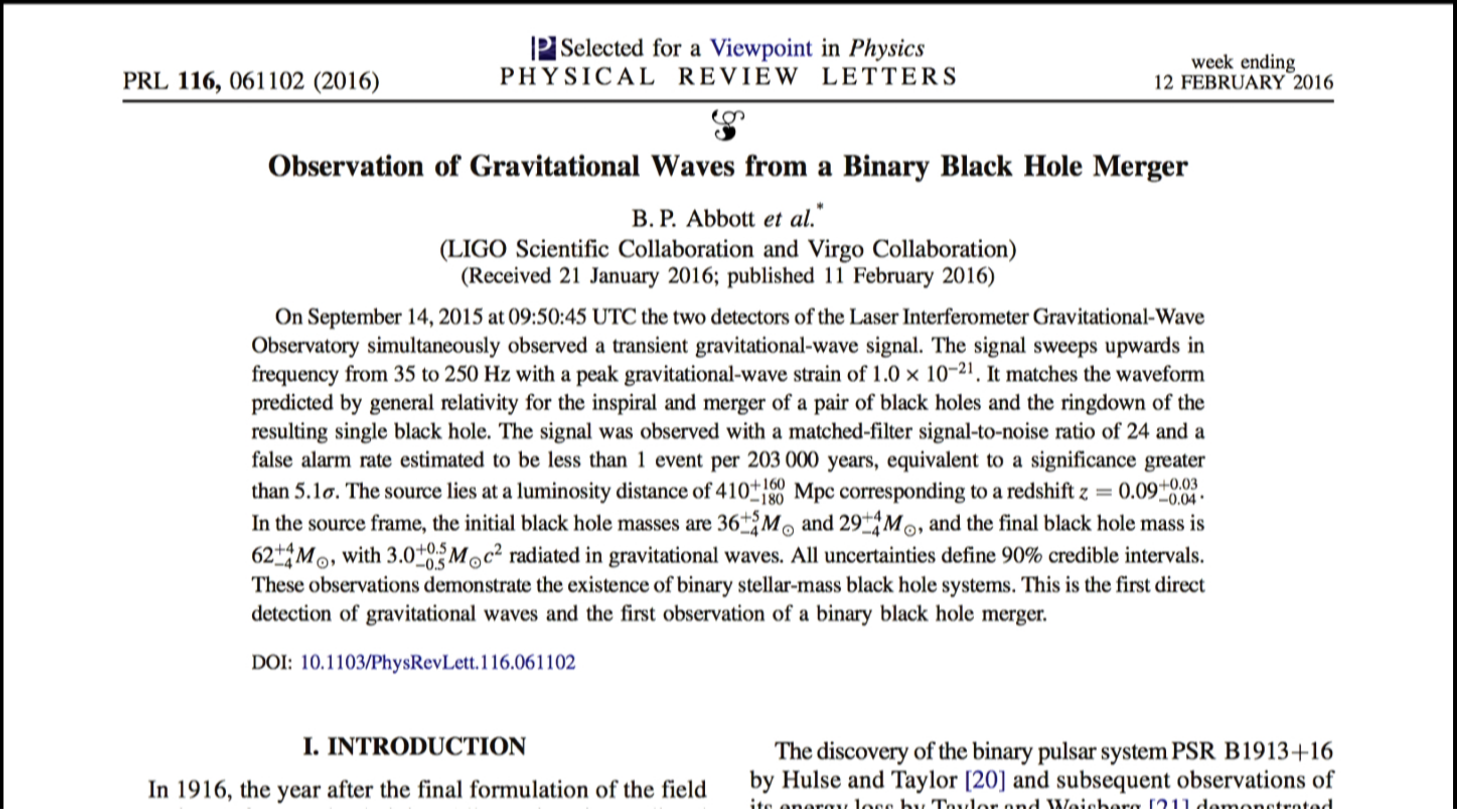
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

$\mathcal{M} \sim 30\ M_\odot$ implies total mass $M \gtrsim 70 M_\odot$ (detector frame)

Components must reach an orbital frequency of 75 Hz without touching. Equal Newtonian point masses orbiting at this frequency would be ~350 km apart

Black holes are the only known objects compact enough to be this close without touching

The big announcement…



PRL **116,** 061102 (2016)

Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW LETTERS

week ending
12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

I. INTRODUCTION

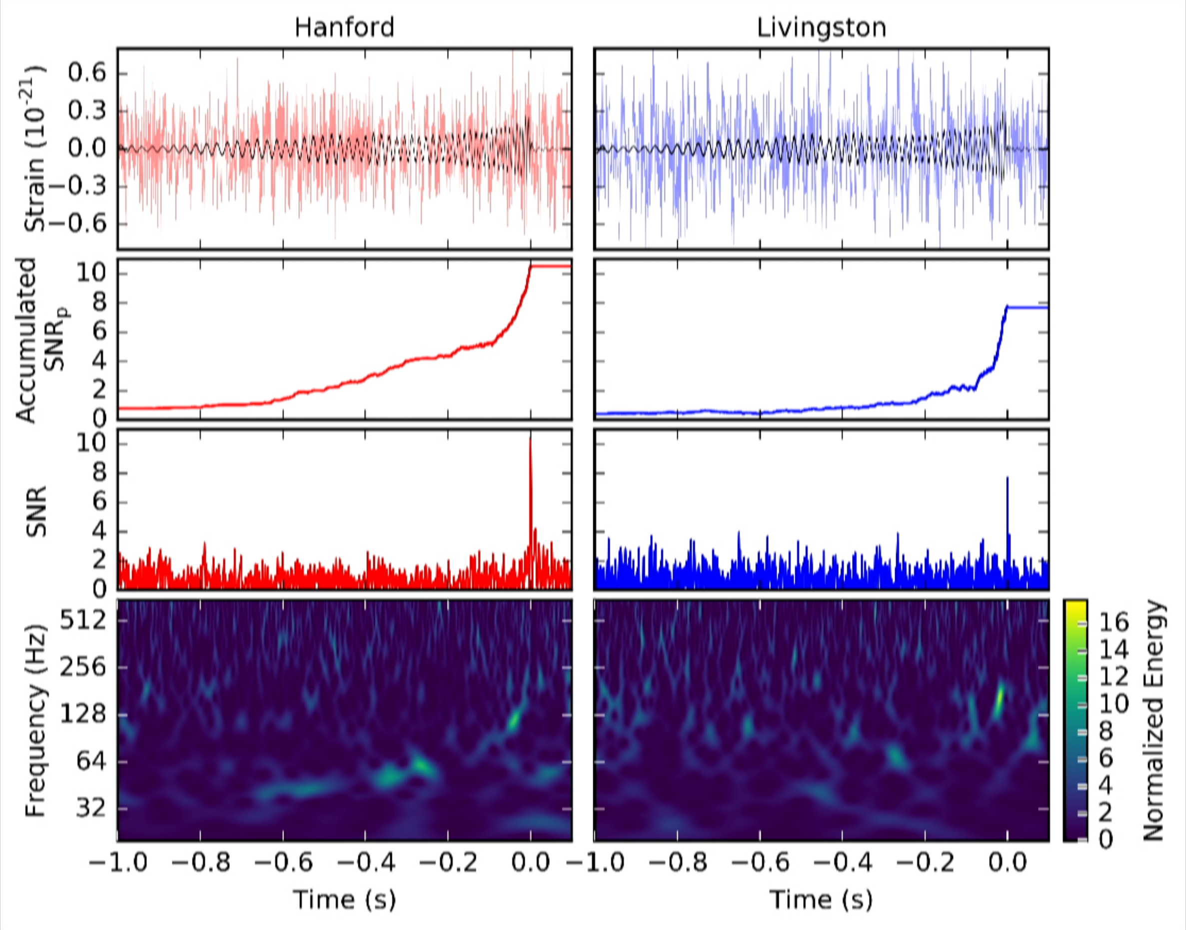
In 1916, the year after the final formulation of the field

The discovery of the binary pulsar system PSR B1913+16 by Hulse and Taylor [20] and subsequent observations of

The day after the announcement…

Image Credit: Calum Torrie et al.

GW151226



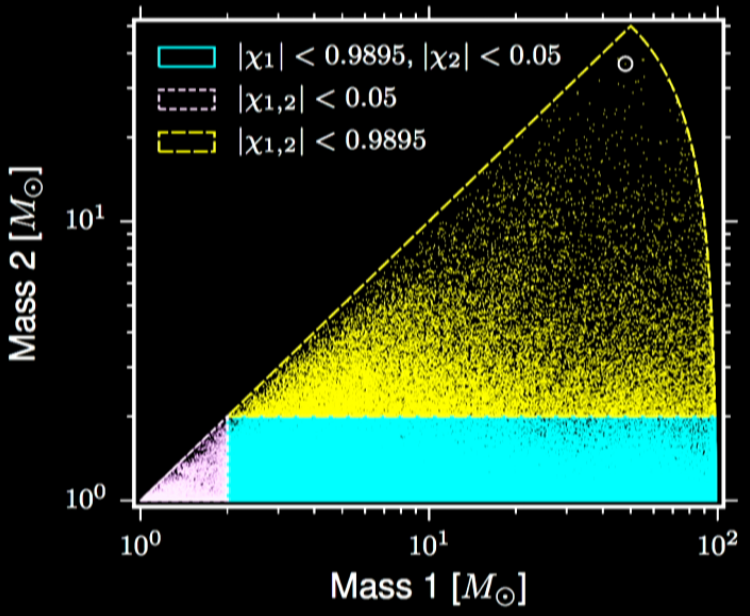
PRL 116, 241103 (2016)

To detect signals from compact-object binaries, we construct a bank template waveforms and matched-filter the data

$$\rho = \frac{\langle s|h\rangle}{\sqrt{\langle h|h\rangle}}$$

$$\langle a|b\rangle = 4\mathrm{Re}\int_{f_{\mathrm{low}}}^{f_{\mathrm{high}}} \frac{\tilde{a}(f)\tilde{b}(f)}{S_n(f)}\, df$$

Apply additional waveform-consistency tests to separate signal from noise



Allen,... , DAB, et al. Phys Rev D 85 122006 (2012)
Babak,..., DAB, et al. Phys Rev D 87 024033 (2013)
Usman,... DAB, et al. arXiv:1508.02357
Capano, et al. arXiv:1602.03509
Abbott, ..., DAB, et al. arXiv:1602.03839
DAB, et al., Phys. Rev. D 86 084017 (2012)

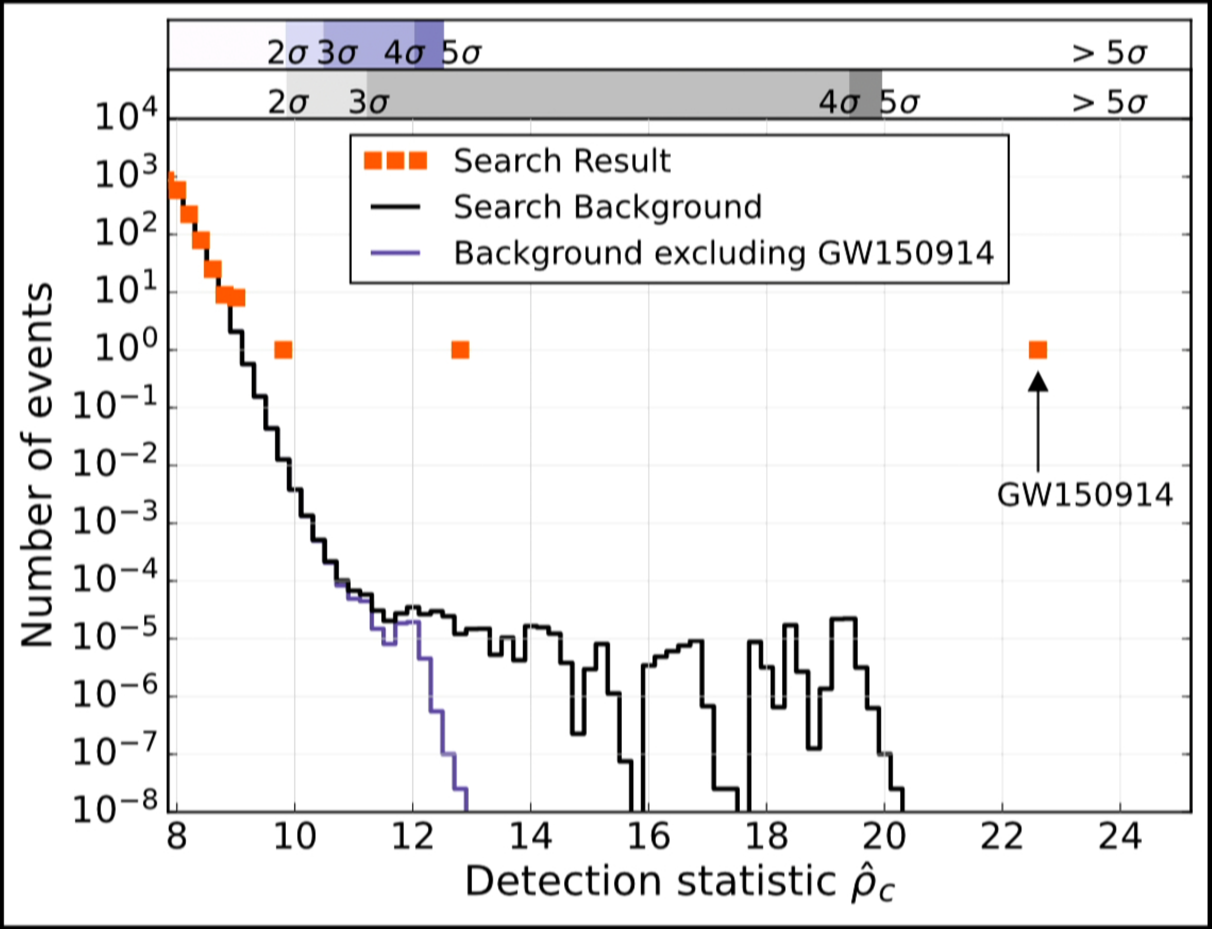
Calculating Significance

- Determined by rate at which detector noise produces an event with a detection statistic value equal to or higher than the candidate event
- Background set of data is created from coincident data from multiple detectors
- Slide the timestamps of one detector's data by many multiples of 0.1s and computing a new set of coincident events

Time shifted data

Usman et al., arXiv: 1508.02357 (2015)

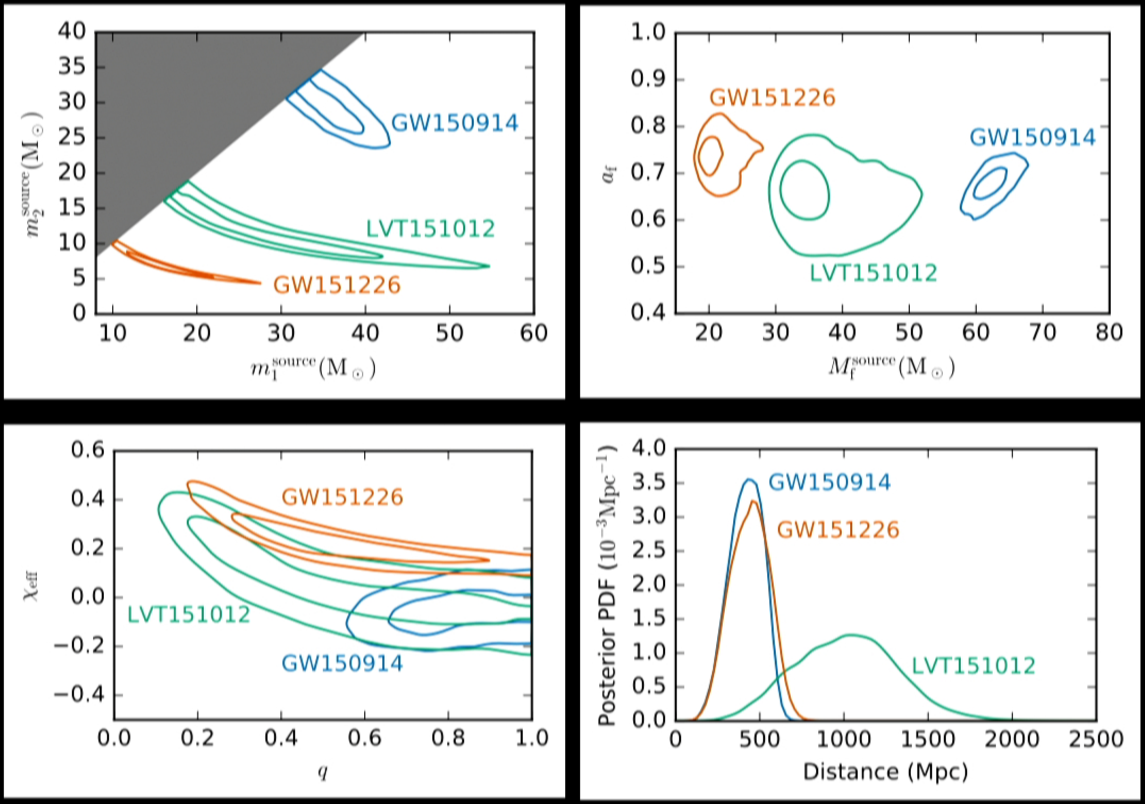
Results from the first observing run



Abbott et al. arXiv: 1606.04856 (2016)

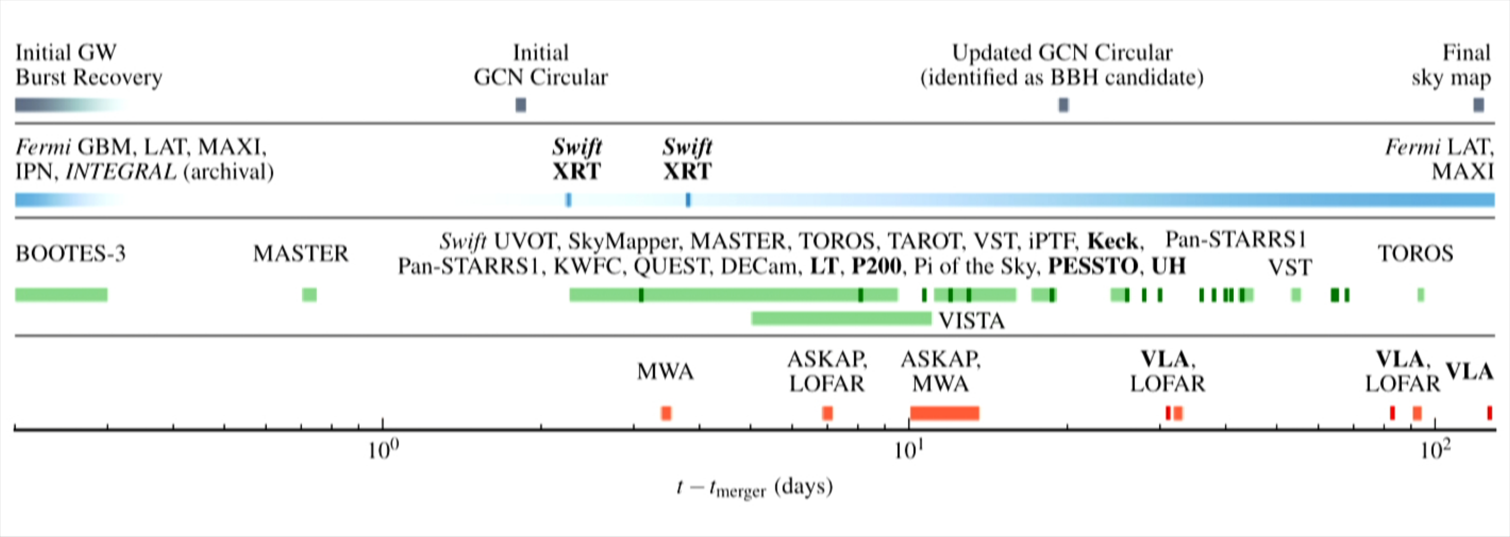
Parameters of the BBH systems

Posterior probability densities of the masses, spins and distance to the three events



Abbott et al. arXiv: 1606.04856 (2016)

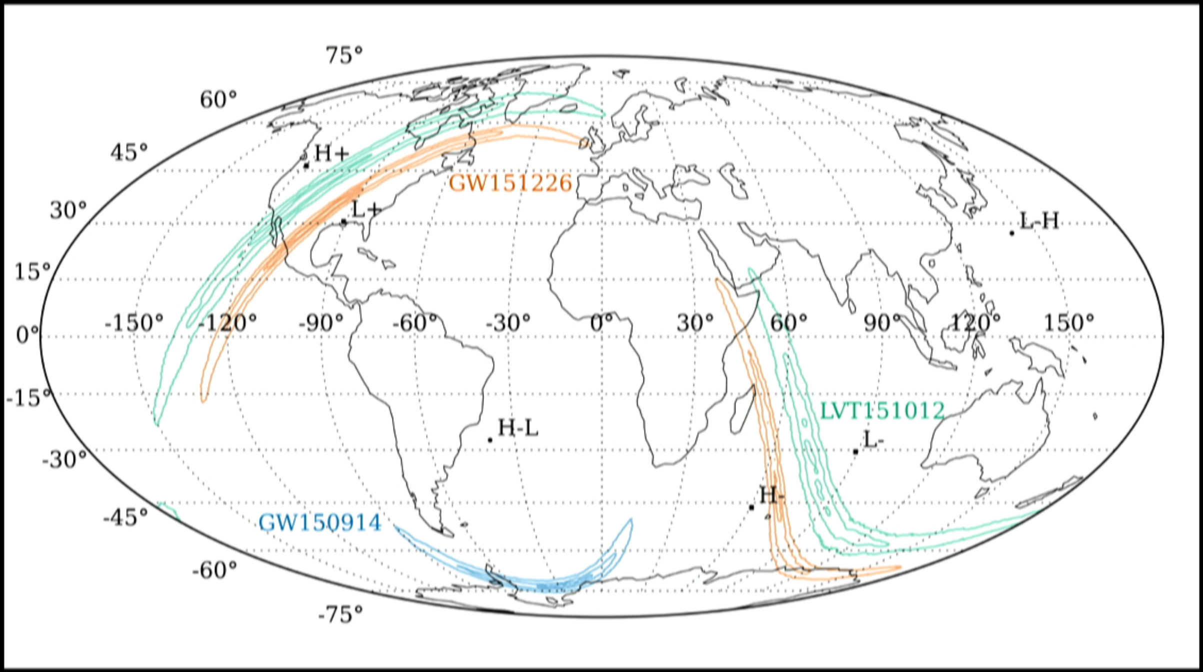
Electromagnetic Follow-Up



Timeline of observations of GW150914, separated by band and relative to the time of the gravitational wave event

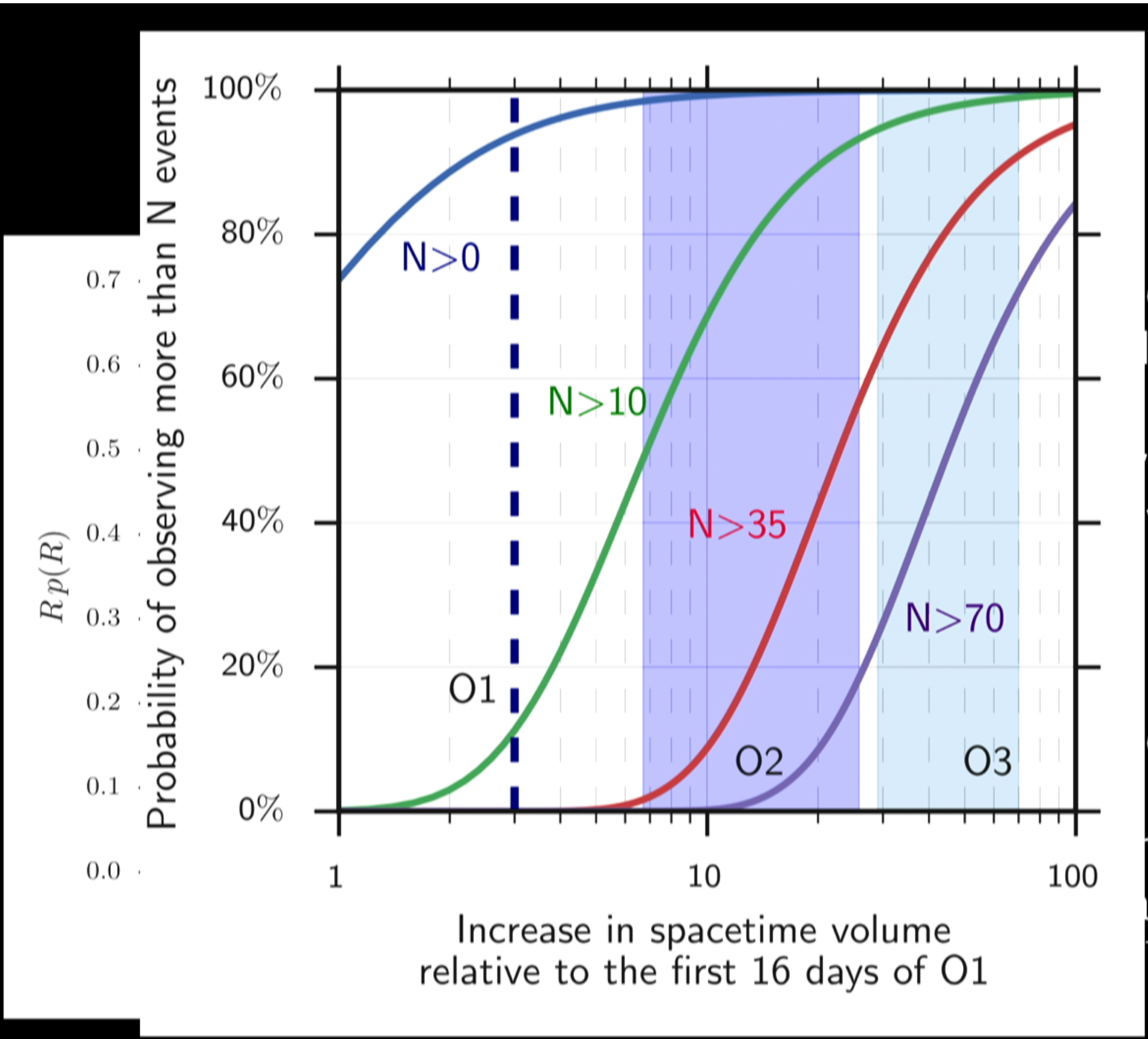
Abbott et al. ApJ 826, Number 1 (2016)

Localisation



Sky localization depends on:
- the location and orientation of the detectors
- time delay between signal arrival at spatially separated sites

Abbott et al. arXiv: 1606.04856 (2016)



Abbott et al. arXiv: 1606.04856 (2016)

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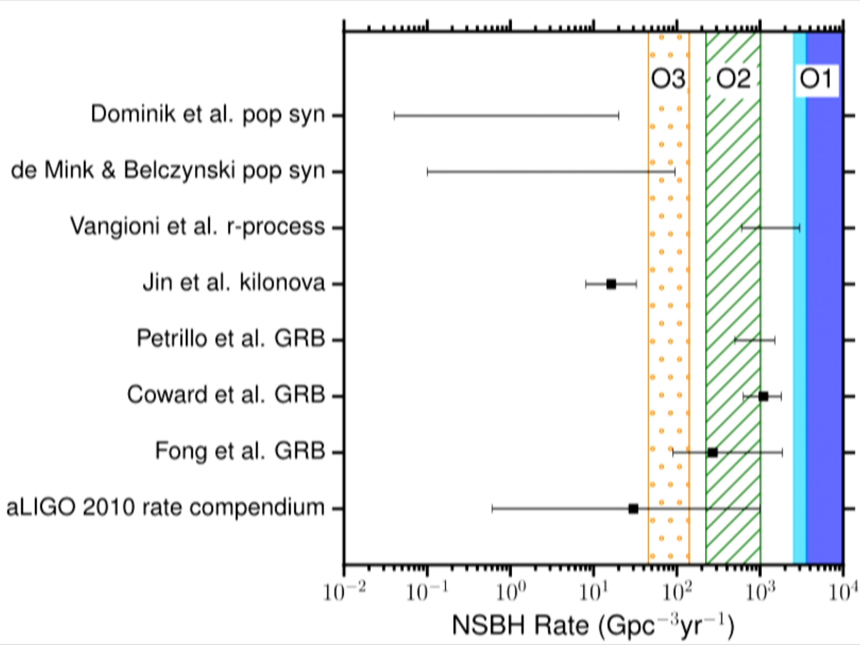
Searching for BNS and NS-BH systems

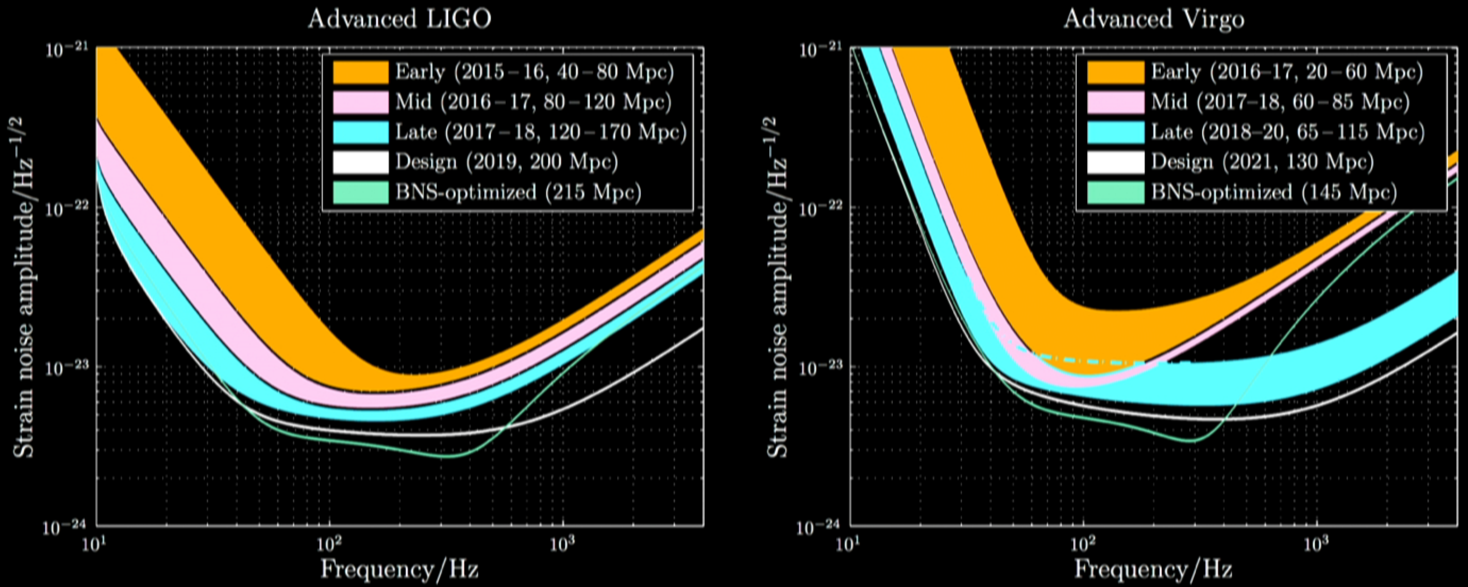
During O1 we looking for gravitational waves from binary neutron star (BNS) and neutron star - black hole (NS-BH) systems



- O1 90% upper limit NS-BH rate compared to other published rates
- Dark blue assumes 1.4-5 $M_\odot$ and light blue 1.4-10 $M_\odot$
- Constrain the merger rate of NS-BH systems with BH at least 5 $M_\odot$ to be less than 3,600 Gpc^{-3} yr^{-1} (assuming isotropic distribution of component spins)
- O2 and O3 BNS ranges are assumed to be 1-1.9 and 1.9-2.7 times larger than O1

Abbott et al., arXiv: 1607.07456 (2016)

Advanced LIGO's sensitivity was at the upper end of that predicted for the first observing run



Abbott et al. Living Reviews in Relativity **19**, 1 (2016)