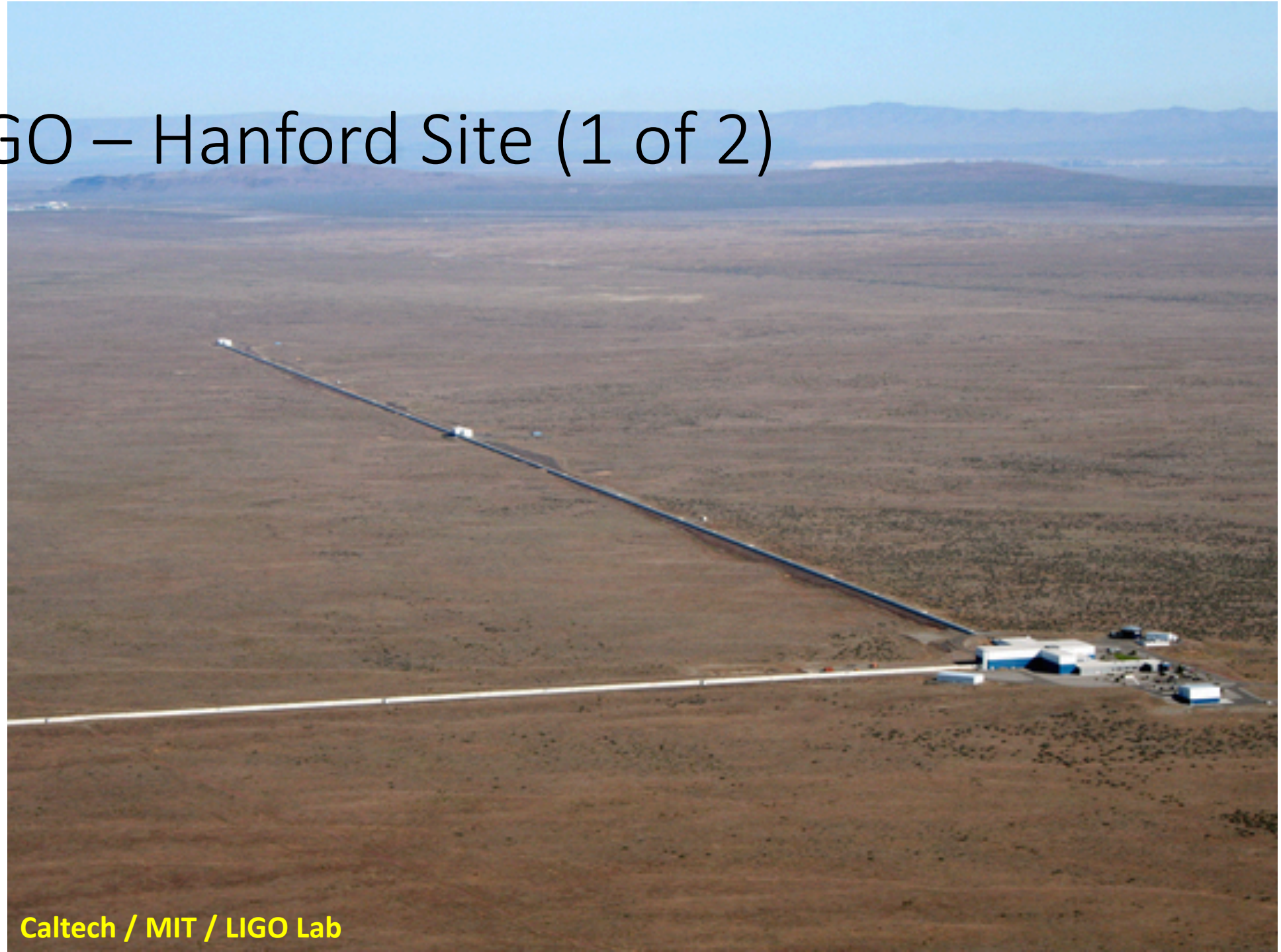
Gravitational Waves

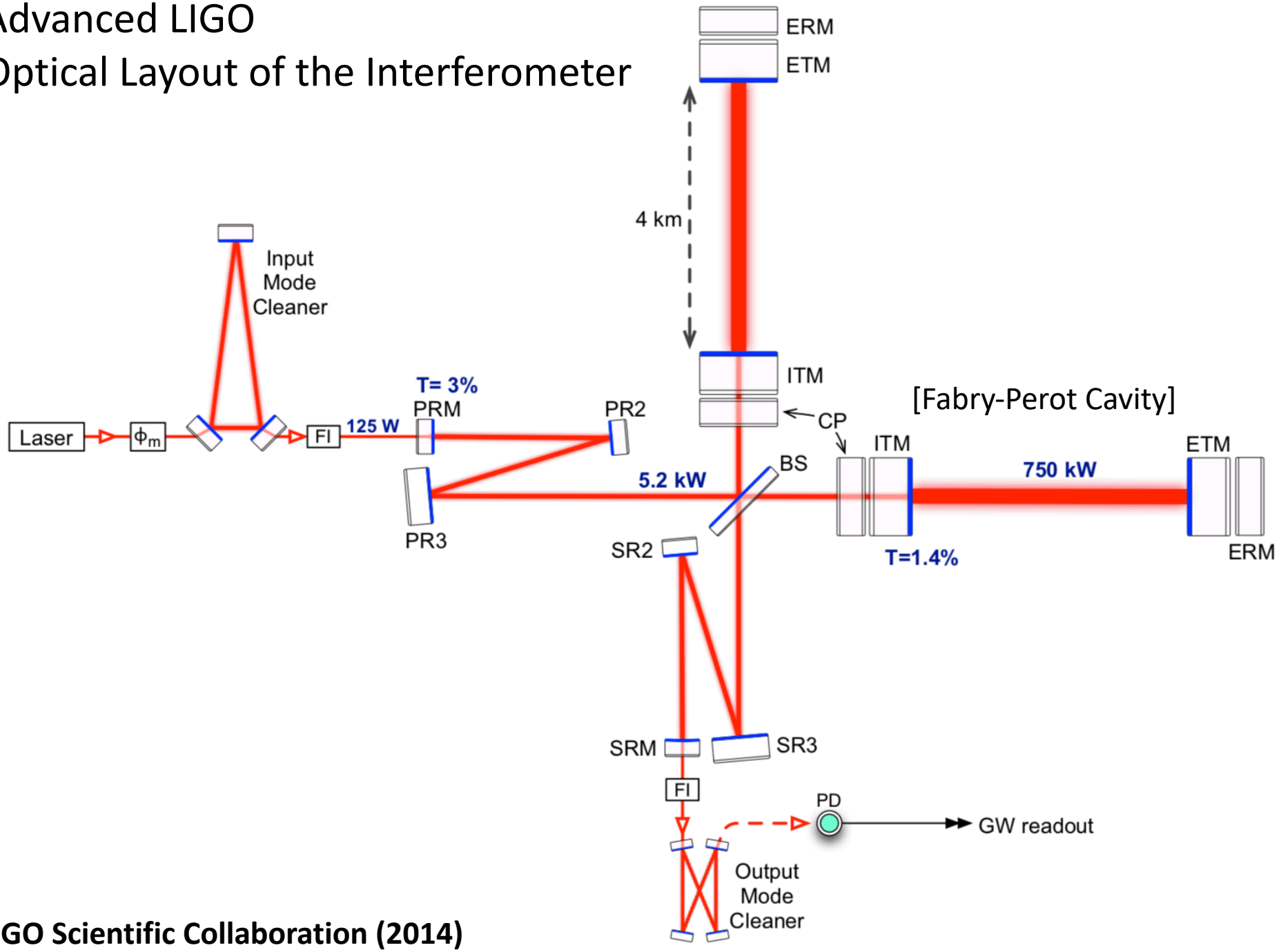
Supplement to Lecture XV

October 23, 2019

LIGO – Hanford Site (1 of 2)



Advanced LIGO
Optical Layout of the Interferometer



LIGO Scientific Collaboration (2014)

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

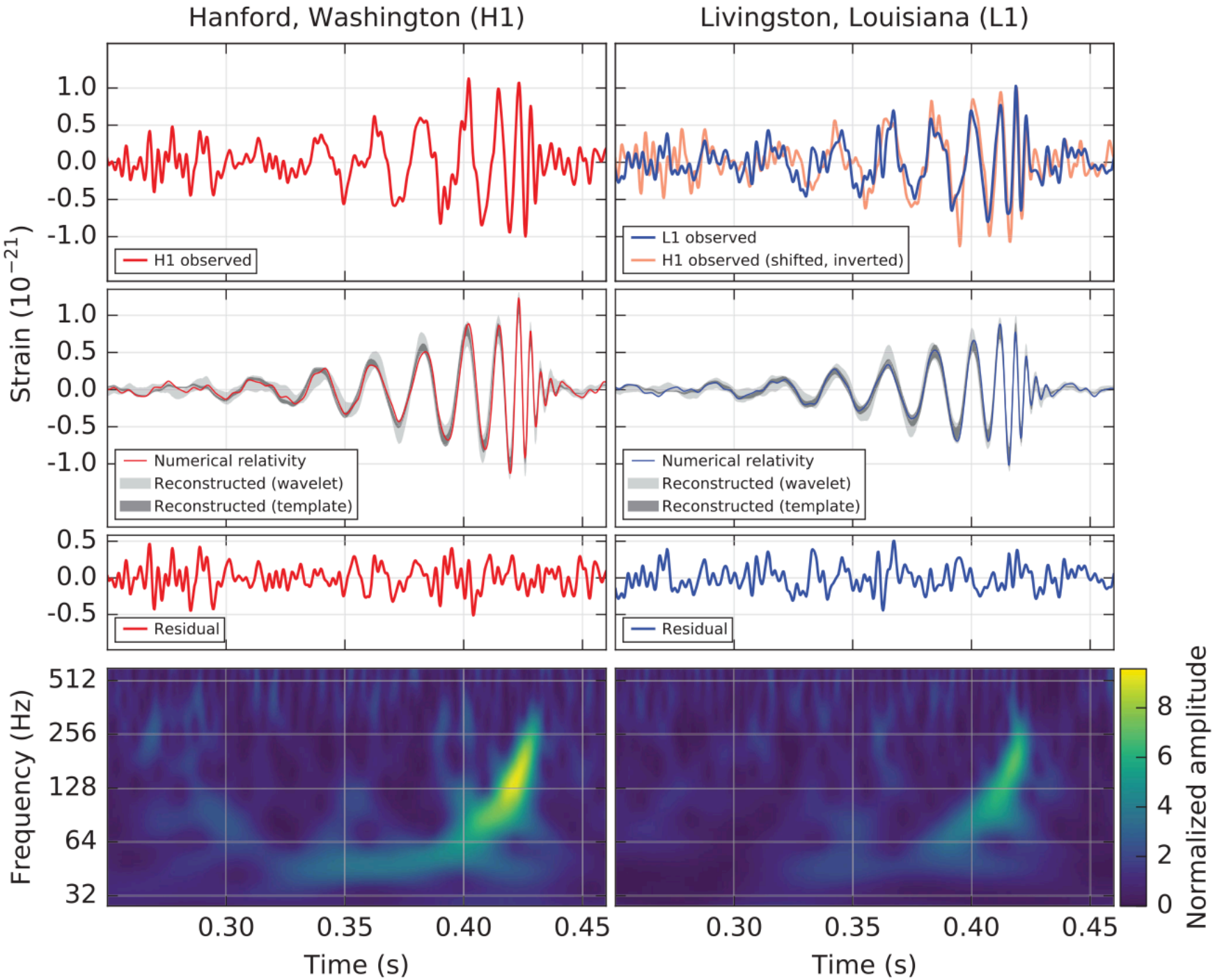
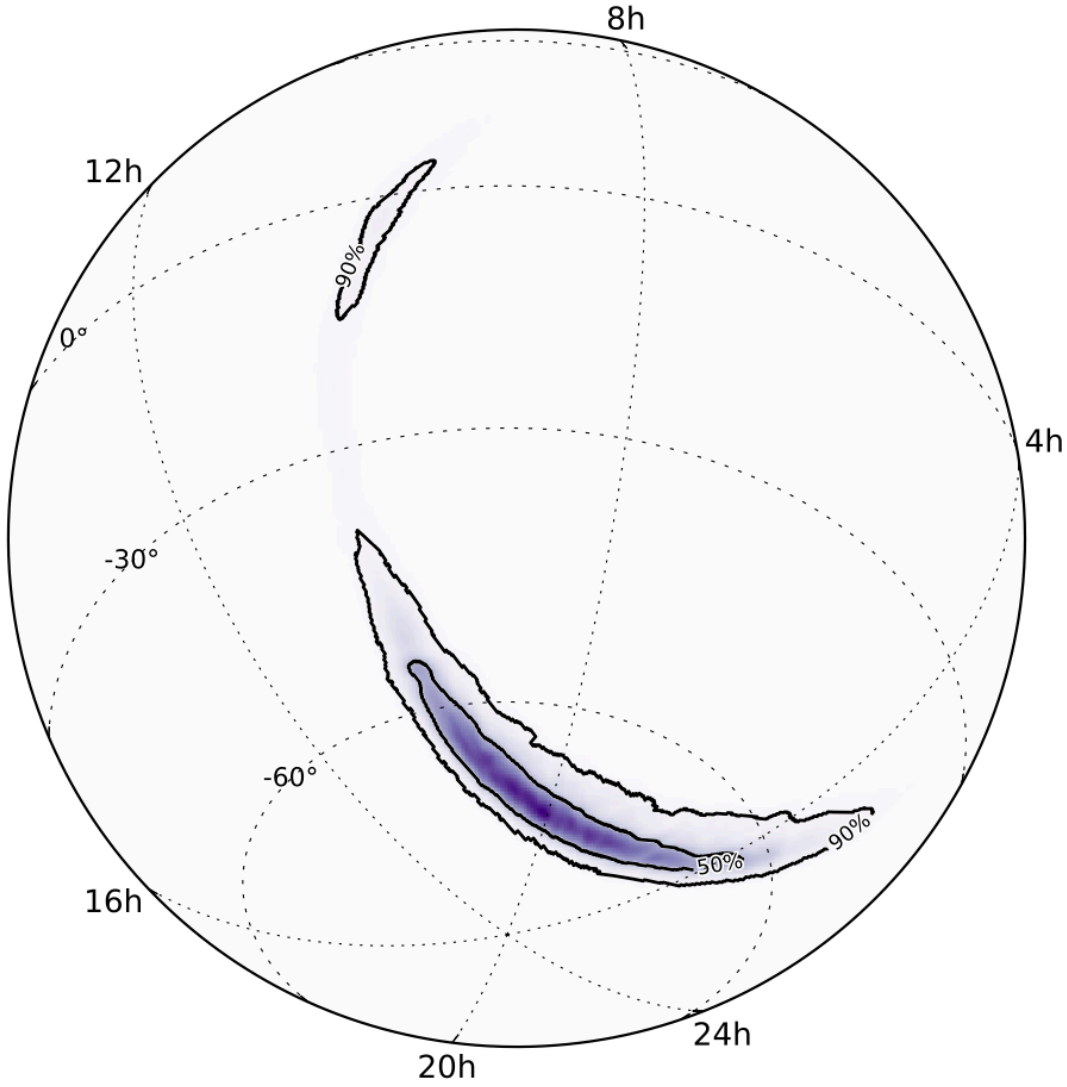

Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
0.30
0.35
0.40
0.45
Time (s)
Normalized amplitude
0
2
4
6
8

TABLE I. Source parameters for GW150914. We report median values with 90% credible intervals that include statistical errors, and systematic errors from averaging the results of different waveform models. Masses are given in the source frame; to convert to the detector frame multiply by $(1+z)$ [90]. The source redshift assumes standard cosmology [91].

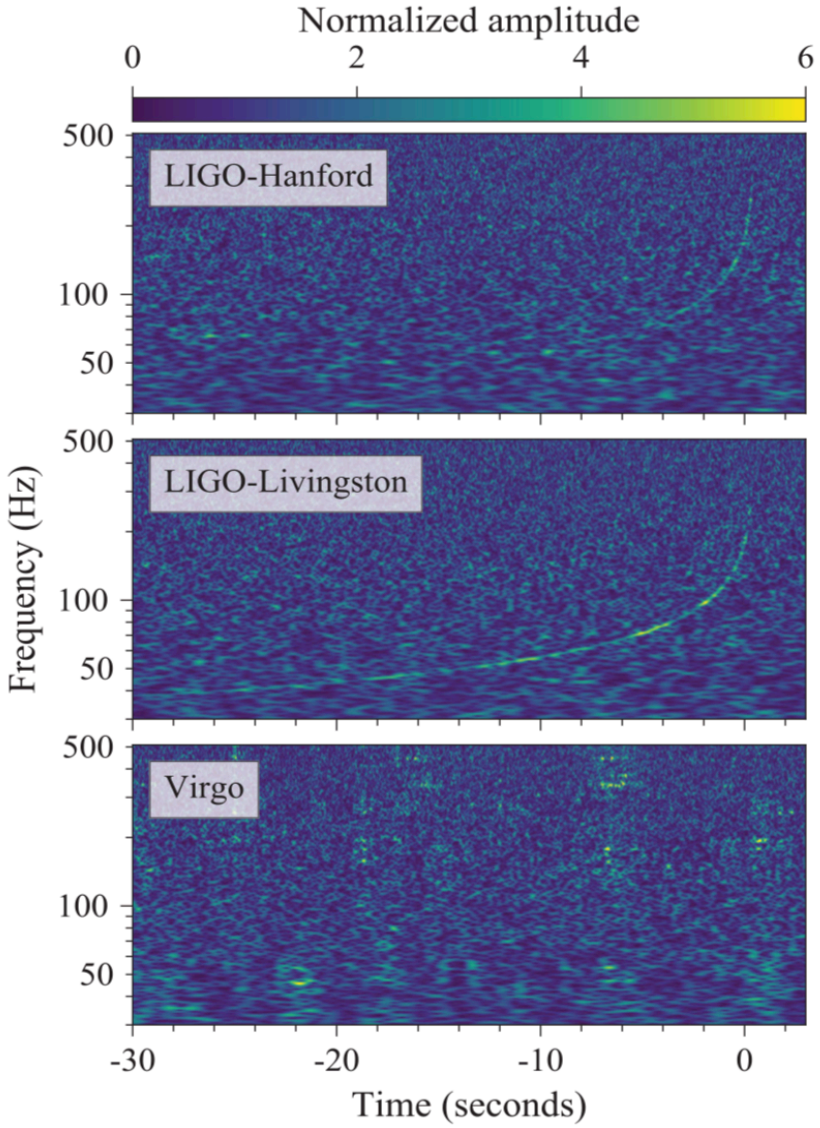
Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

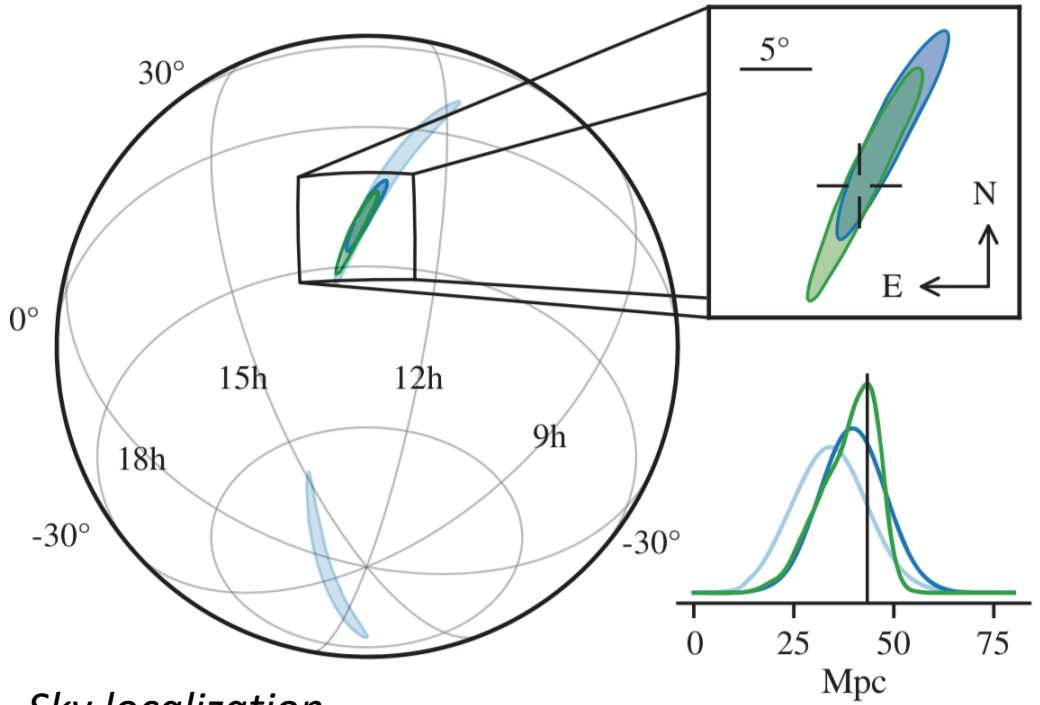


The estimated total energy radiated in gravitational waves is $3.0^{+0.5}_{-0.5} M_\odot c^2$. The system reached a peak gravitational-wave luminosity of $3.6^{+0.5}_{-0.4} \times 10^{56}$ erg/s, equivalent to $200^{+30}_{-20} M_\odot c^2/\mathrm{s}$.

GW 170817

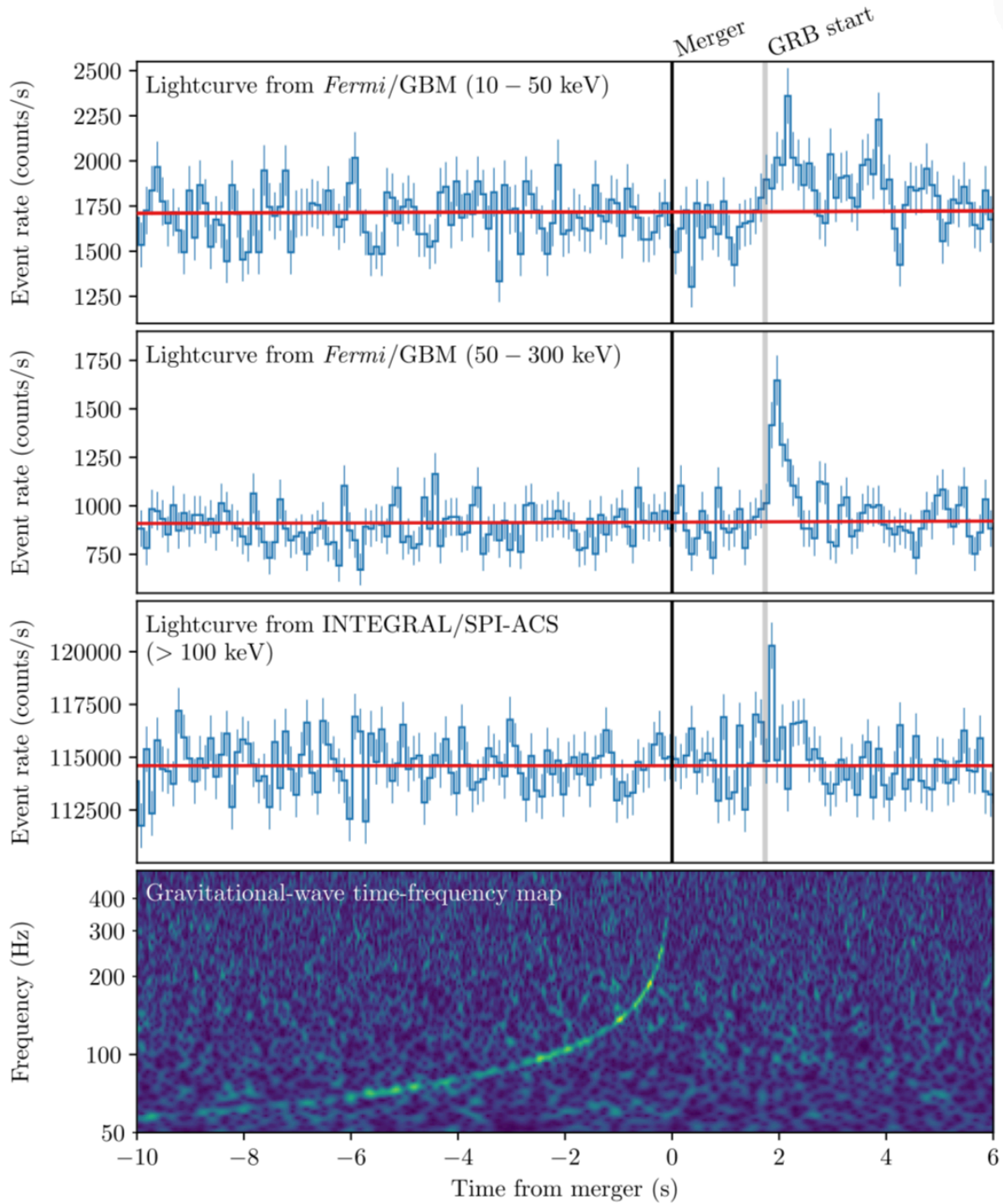
(LIGO + Virgo Collaborations 2017)





Sky localization

$$m_{\mathrm{T}}^{2/5}\mu^{3/5} = 1.188^{+0.004}_{-0.002} M_{\mathrm{Sun}}$$

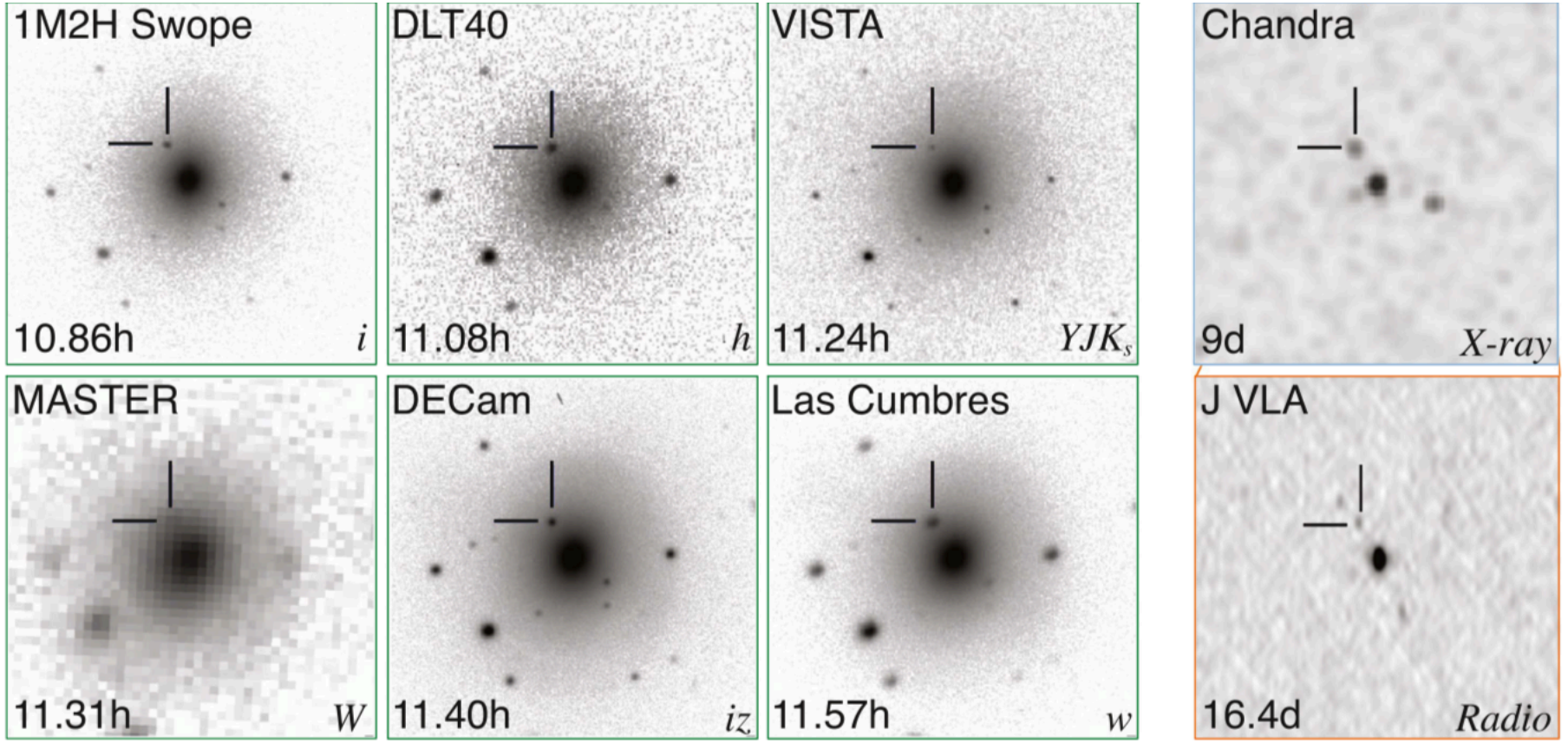


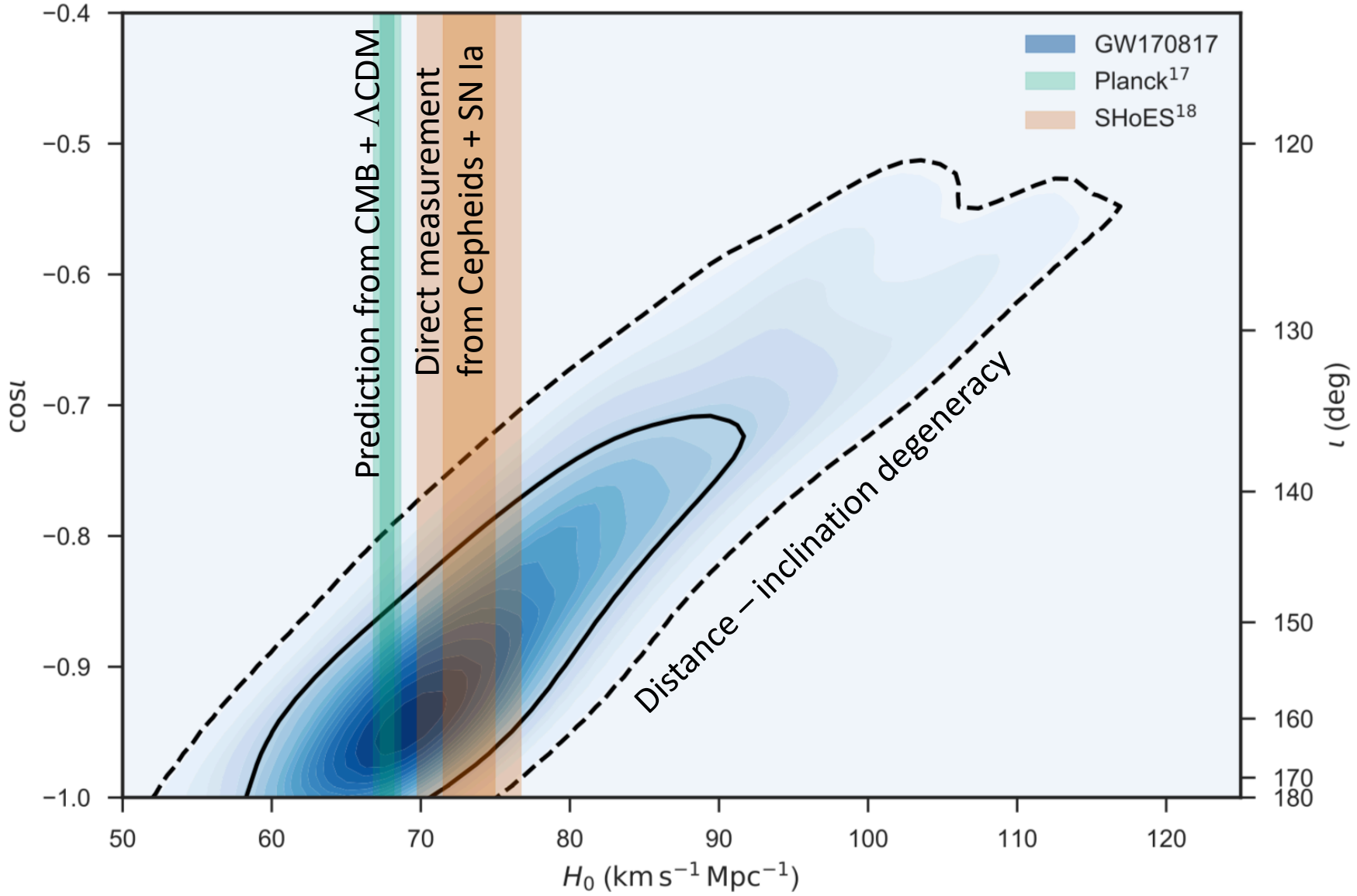
Gamma Ray Burst Coincident with GW Event

(LIGO, Virgo, Fermi-GBM, INTEGRAL Collaborations, 2017)

Multi-Wavelength Electromagnetic Observations of GW170817

(Many Collaborations, 2017)



Host galaxy is NGC 4993, z = 0.0097

H_0 from 1 Gravitational Wave Source