The Observation of Gravitational Waves from a Binary Black Hole Merger by LIGO

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About 1.3 billion years ago...

As massive objects move around, the curvature of space changes

Information about the changing spacetime curvature propagates out at the speed of light as gravitational waves

The physical effect of a gravitational wave is to stretch and squeeze spacetime by a strain proportional to

$$h \sim \frac{G}{c^4}\frac{E_{\rm NS}}{r}$$

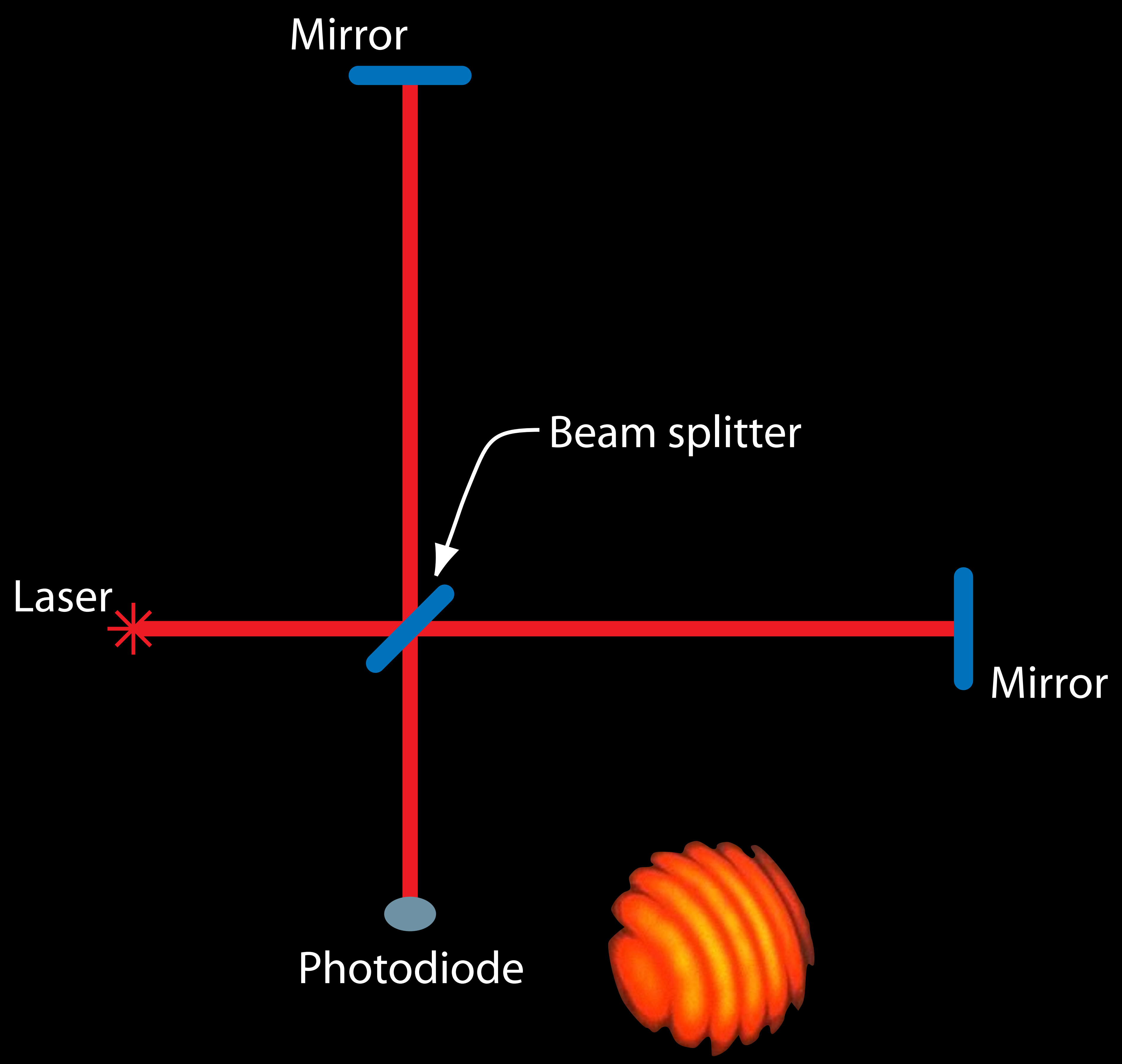
For typical astrophysical sources

Imagine measuring this distance to a precision of ten microns

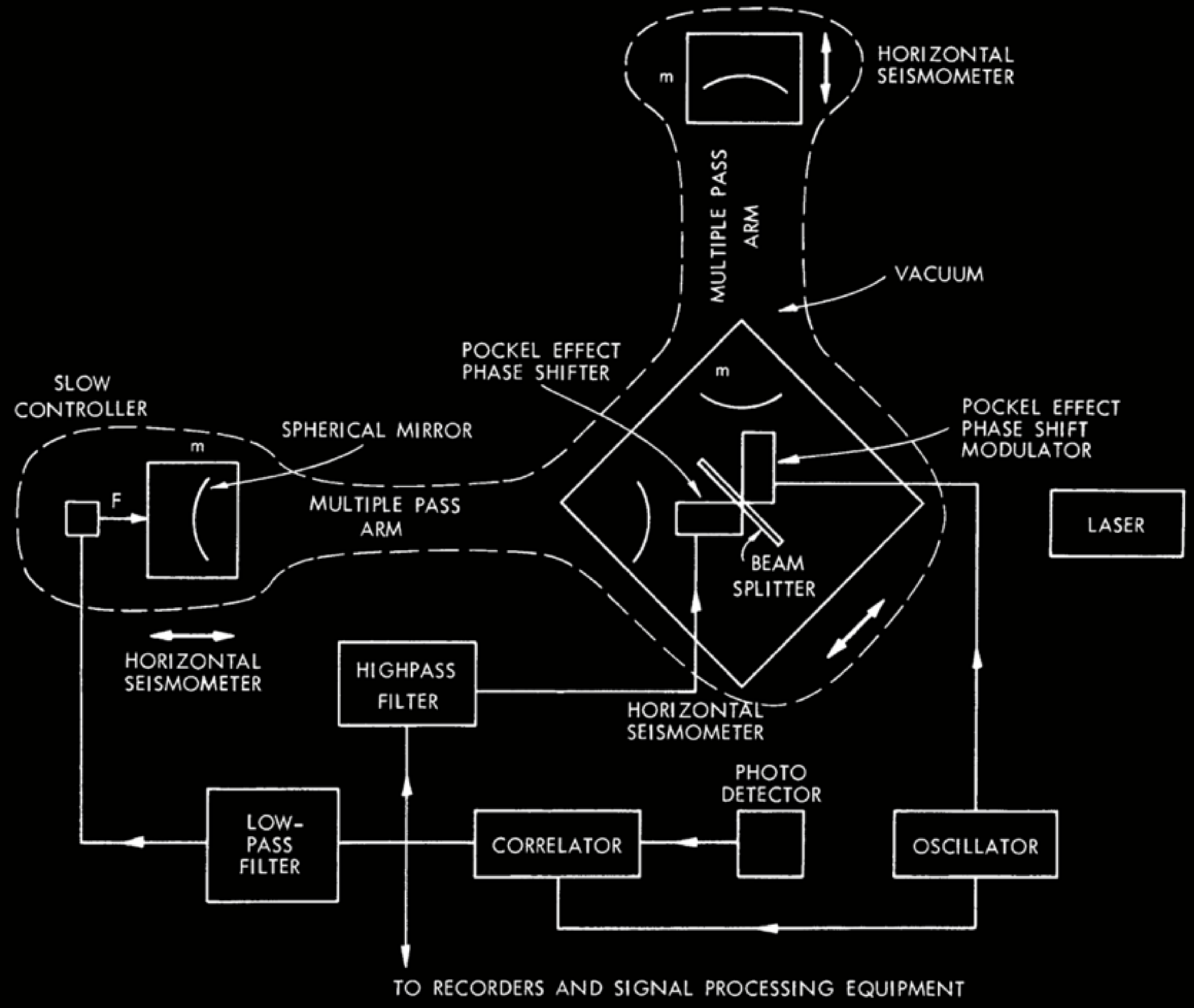
However, the energy radiated in gravitational waves is enormous

$$L_{\mathrm{GW}} \sim \left(\frac{c^5}{G}\right)\left(\frac{v}{c}\right)^6\left(\frac{R_{\mathrm{S}}}{r}\right)^2 \sim 10^{59}\mathrm{erg/s}$$

Solar luminosity L ~ 10^{33} erg/s
Gamma Ray Bursts L ~ $10^{49\text{-}52}$ erg/s

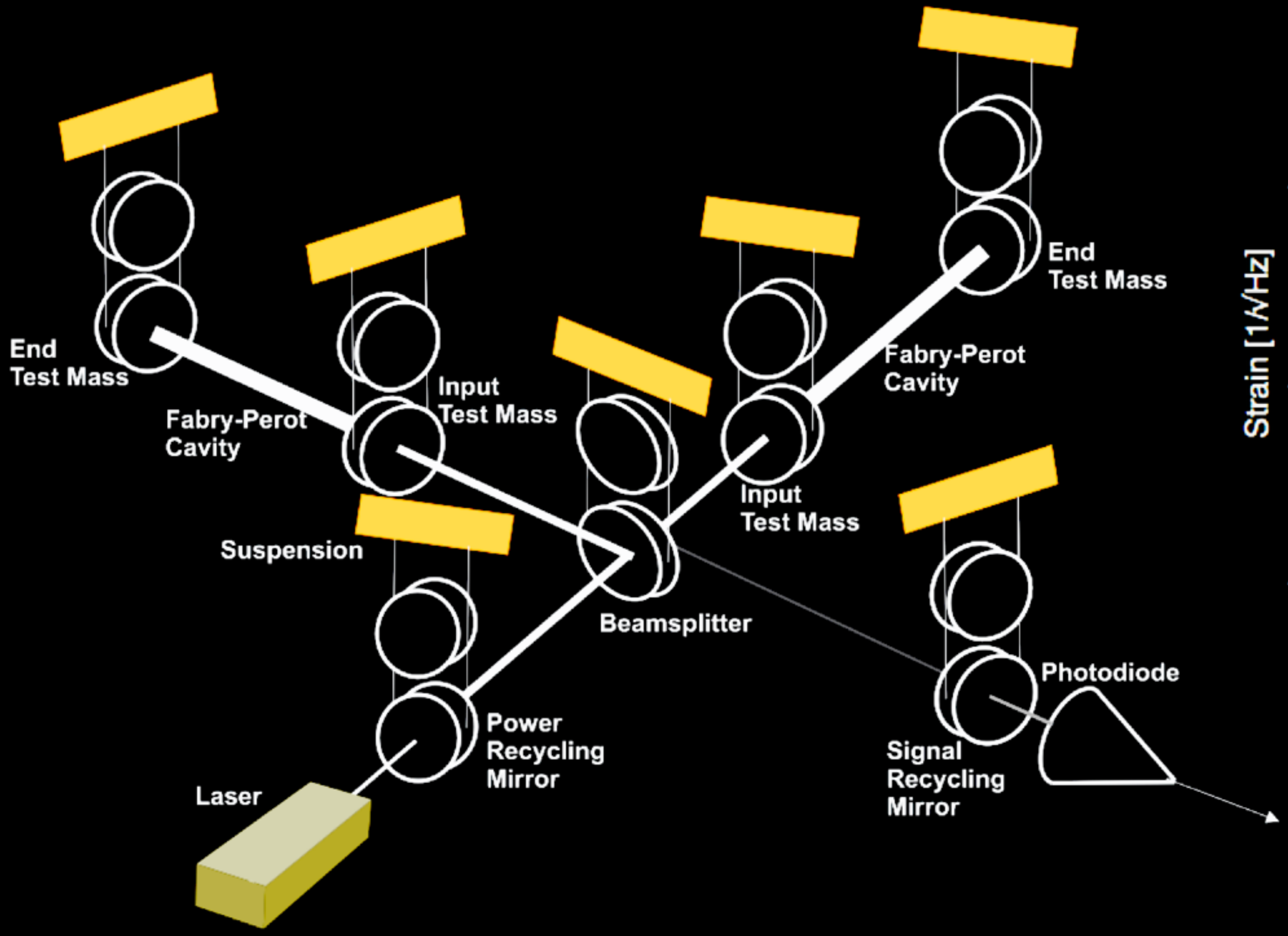


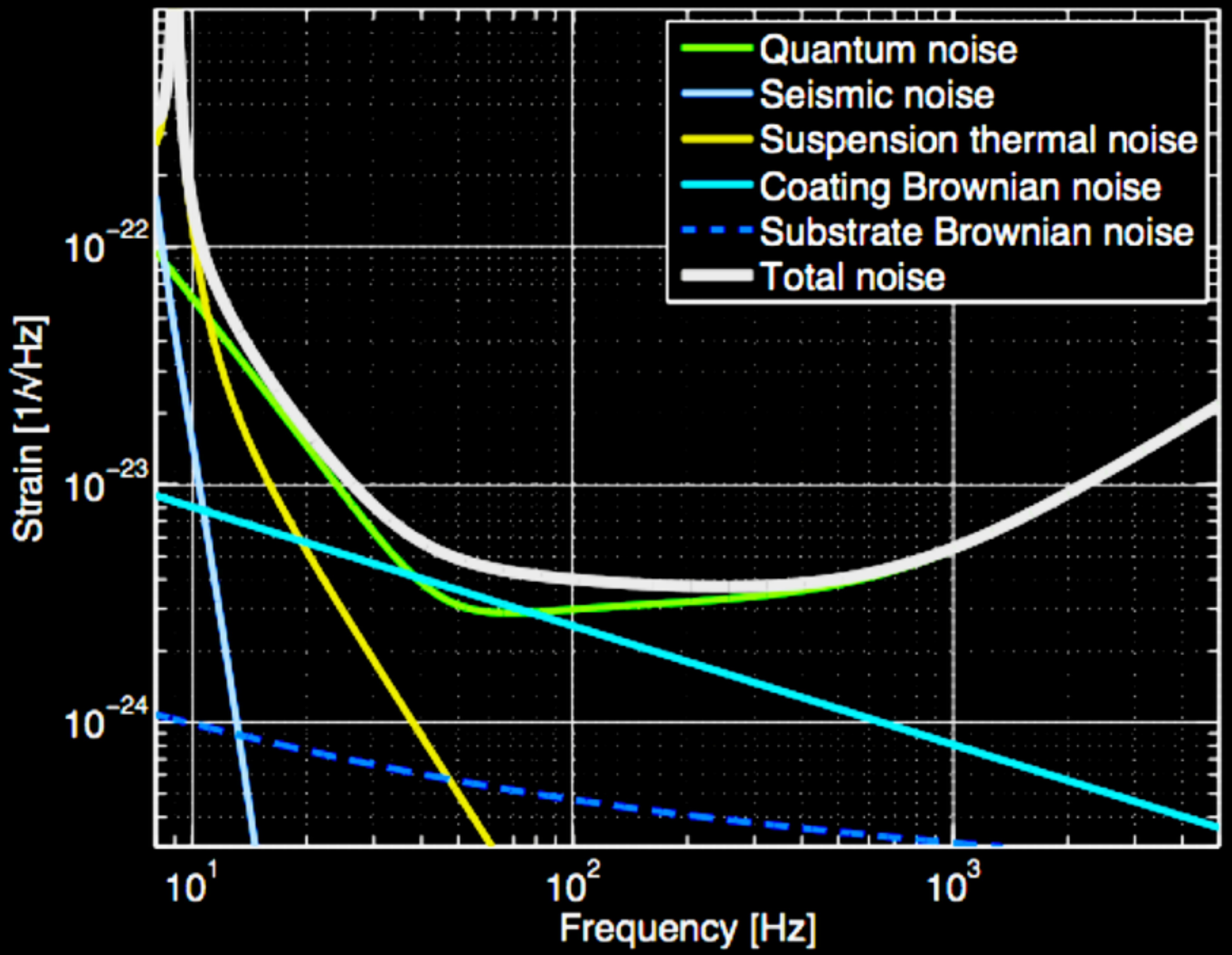
Michelson interferometer

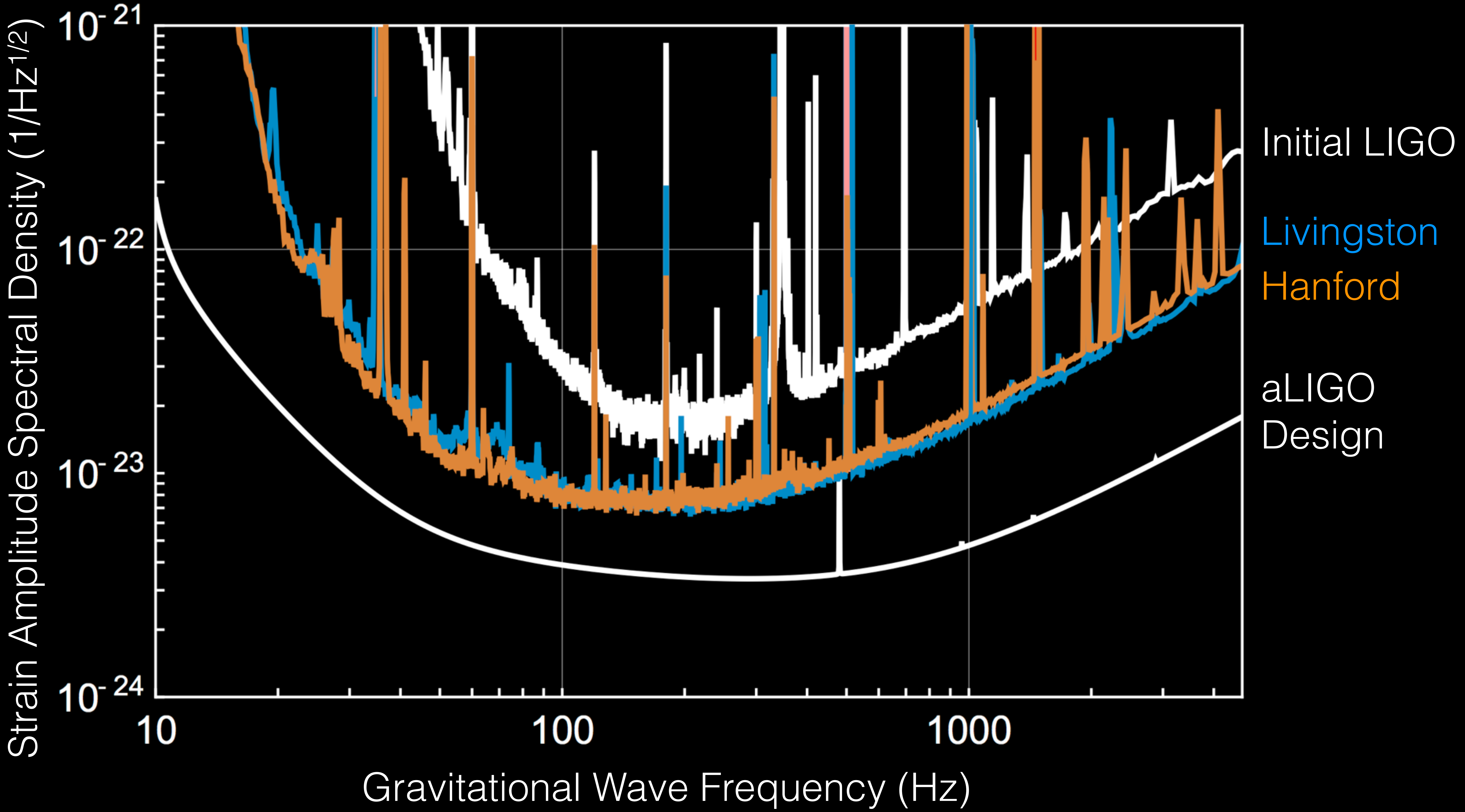


Weiss' 1972 design study

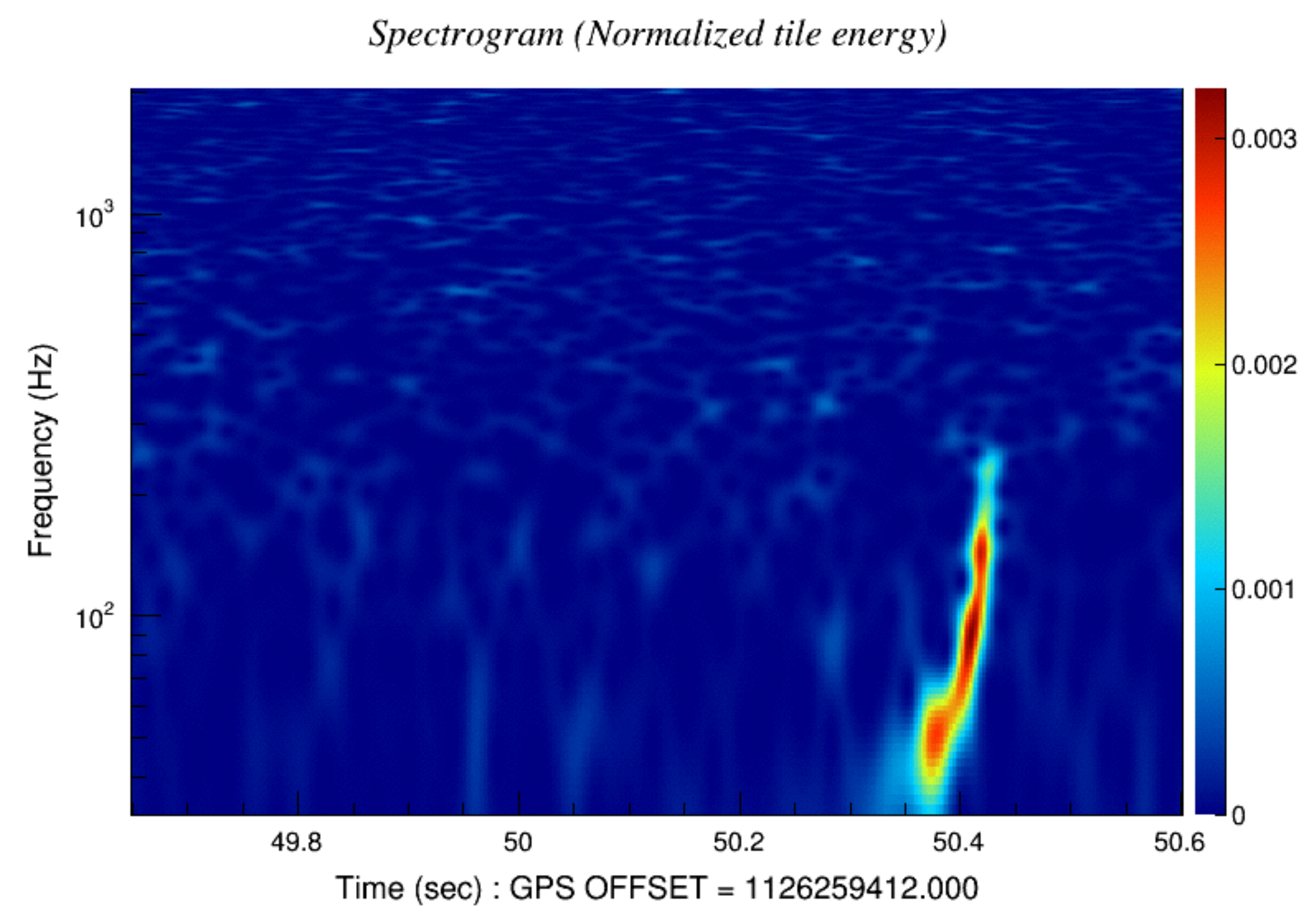
Advanced LIGO

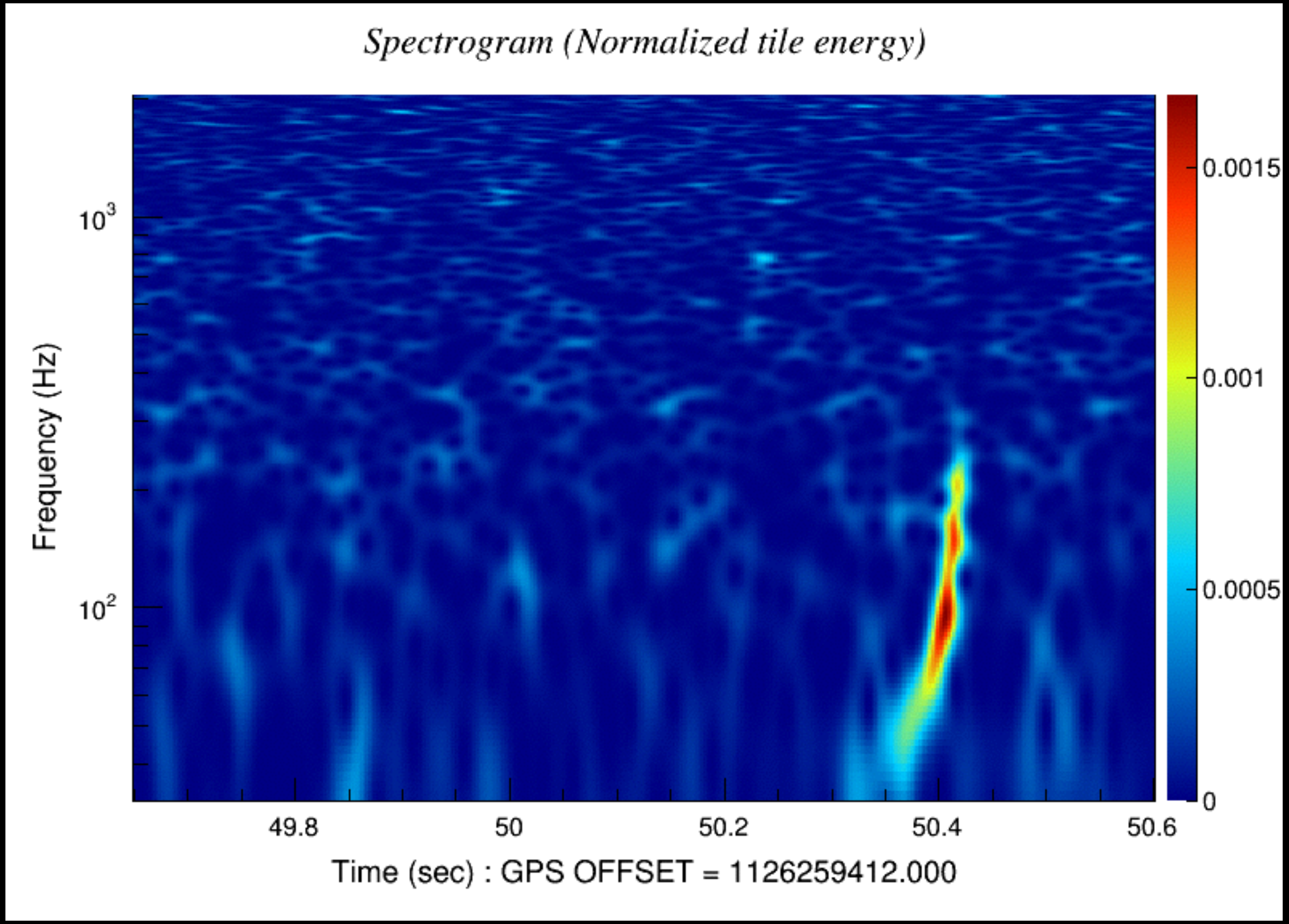


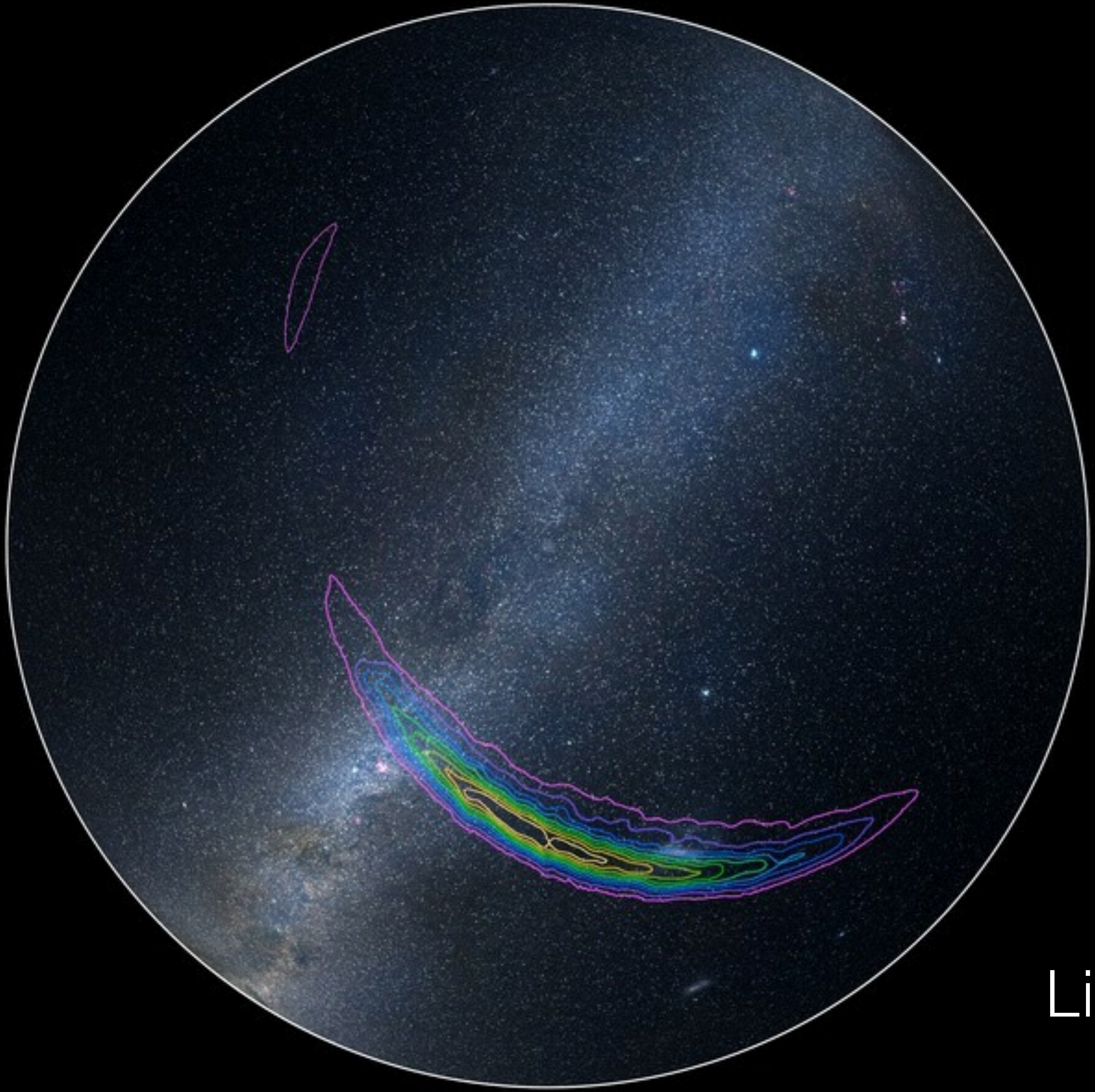



Strain Amplitude Spectral Density (1/Hz$^{1/2}$)
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10
100
1000
Gravitational Wave Frequency (Hz)
Initial LIGO
Livingston
Hanford
aLIGO
Design

Transient signal with signal-to-noise ratio ~ 24 identified within three minutes by low-latency coherent wave burst search

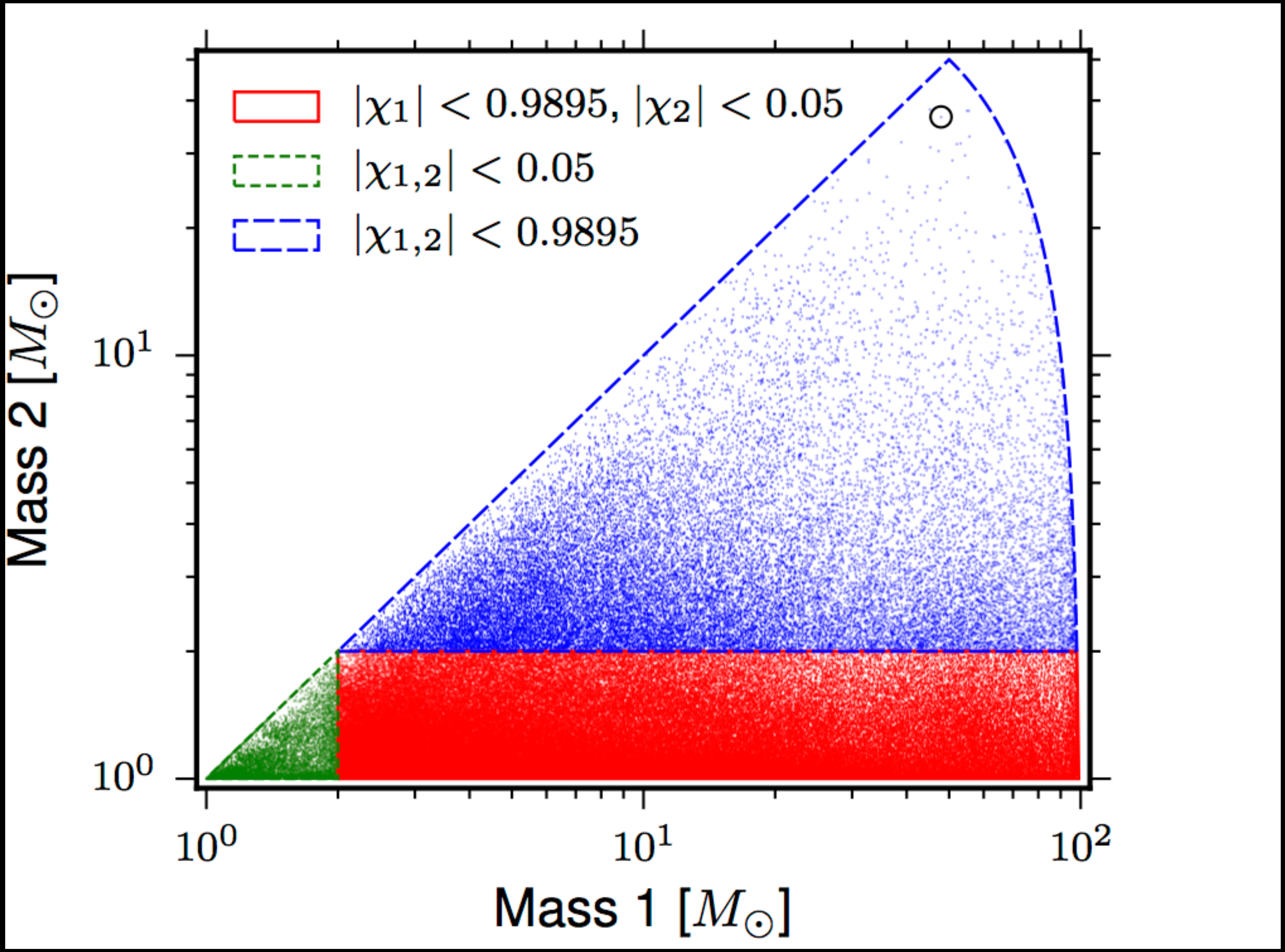






Probable location of merger

Limited by two-detector network



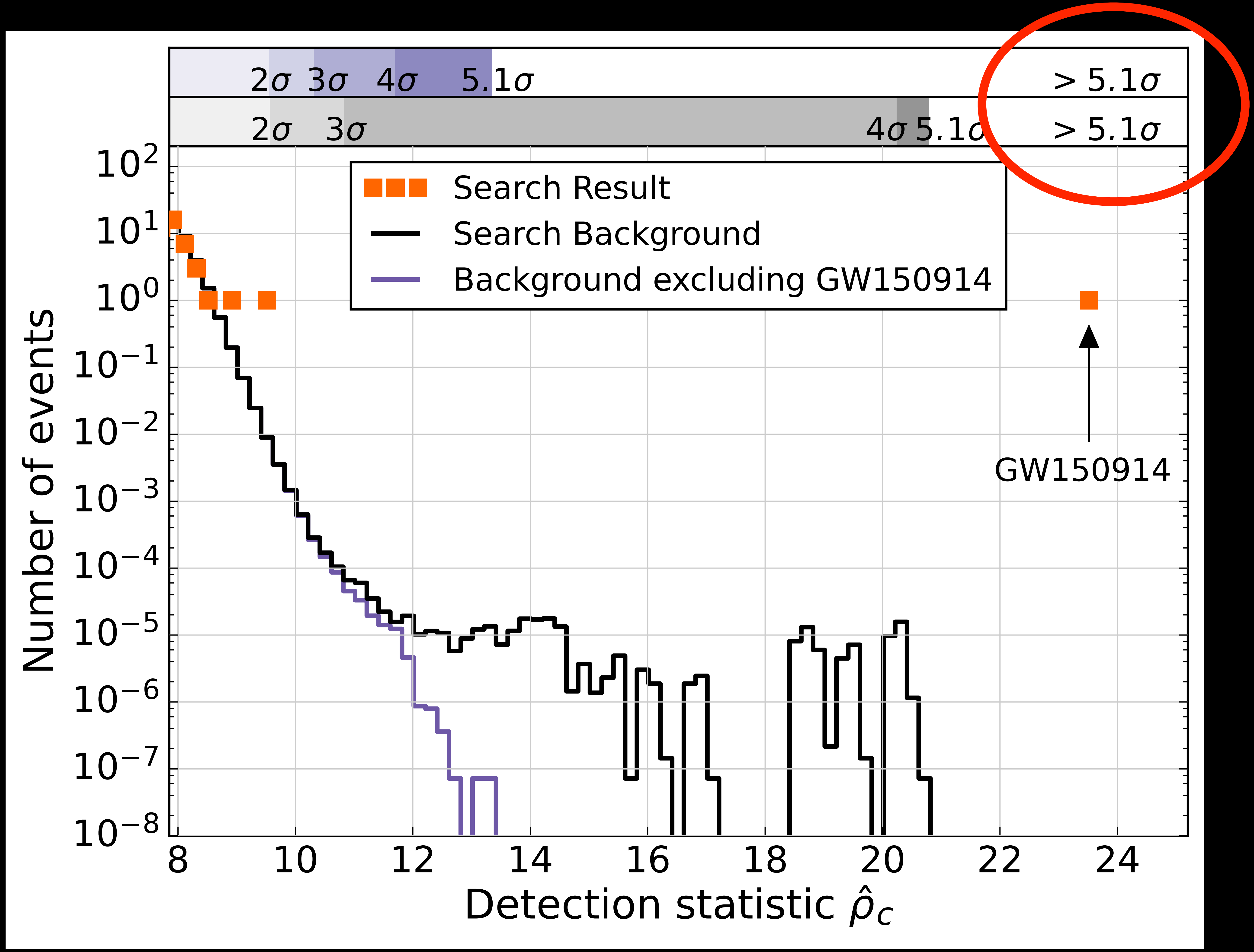
To detect signals from compact-object binaries, we construct a bank template waveforms and matched-filter the data

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

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

Apply additional waveform-consistency tests to separate signal from noise

Significance of the Signal

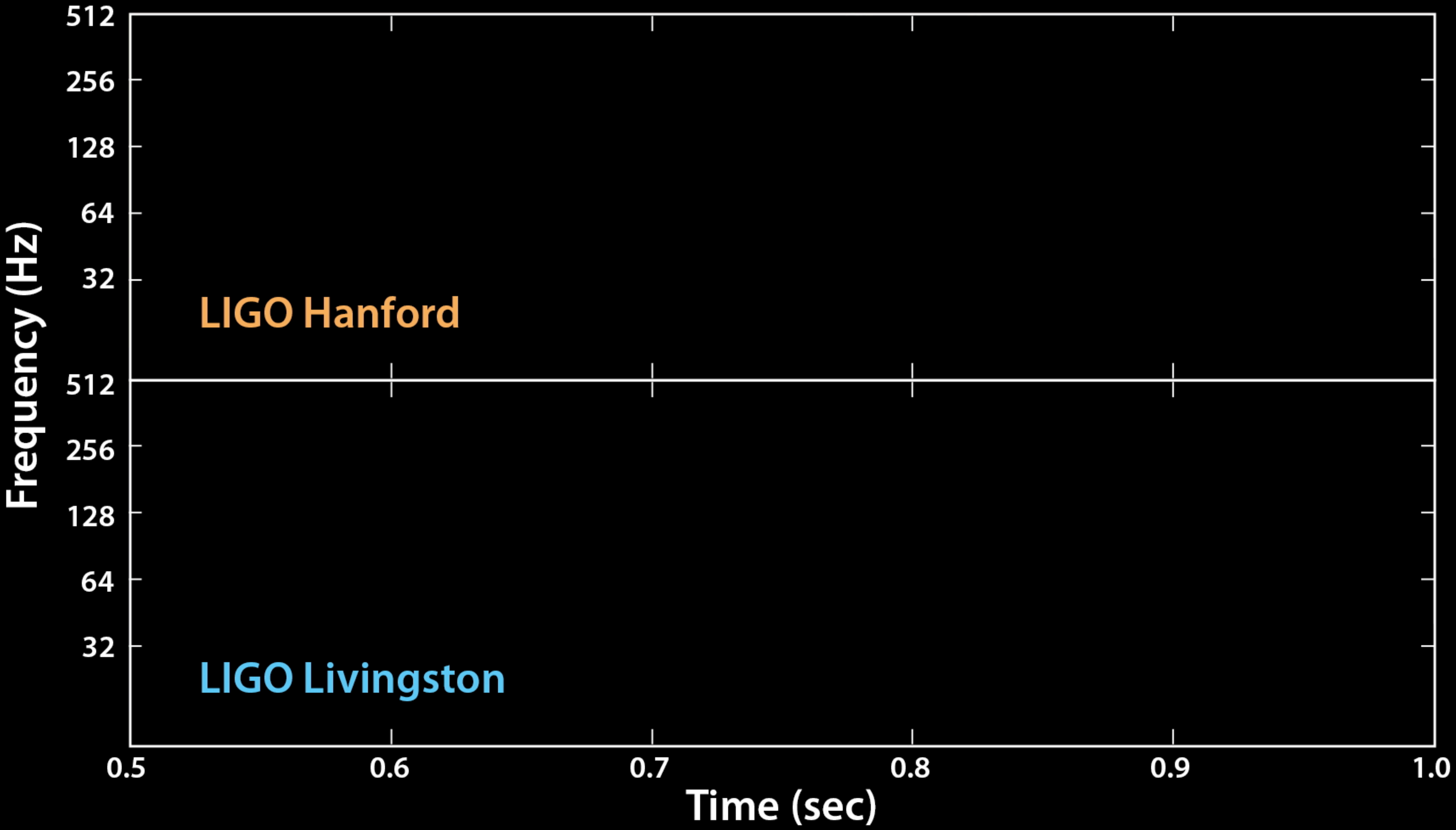


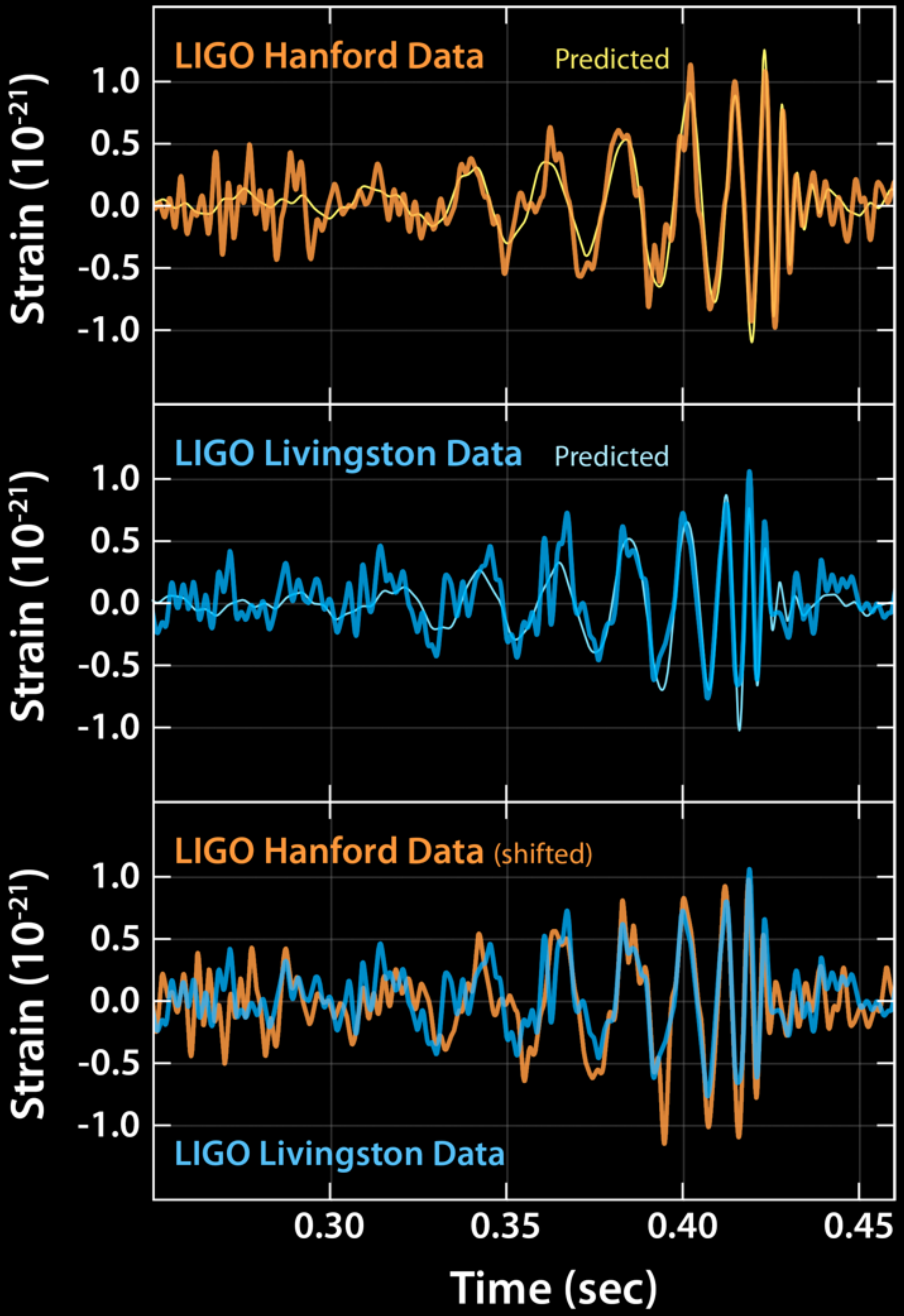
- Matched filter search for signals from compact-object mergers in data taken between Sep 12 and Oct 20, 2015

- Approximately 250,000 templates

- Measure the noise background by introducing artificial "time-shifts" and re-analyzing these data

- False alarm rate < 1 in 203,000 yr


512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)



GW150914

- Observed September 14, 2015 09:50:45 UTC
- The signal is seen first by the Livingston detector and then 7ms later at Hanford
- Over 0.2 seconds, the signal increases in frequency and amplitude in about 8 cycles from 35 Hz to a peak amplitude at 150 Hz

- Use this to measure the "chirp mass"

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

- From this we can bound the total mass $M = m_1 + m_2 \gtrsim 70 M_\odot$
- The components must reach an orbital frequency of 75 Hz without touching each other
- Black holes are the only known objects compact enough to do this

Use Bayesian analysis to measure source parameters

$$\text{Primary mass} = 36^{+5}_{-4}\, M_\odot$$

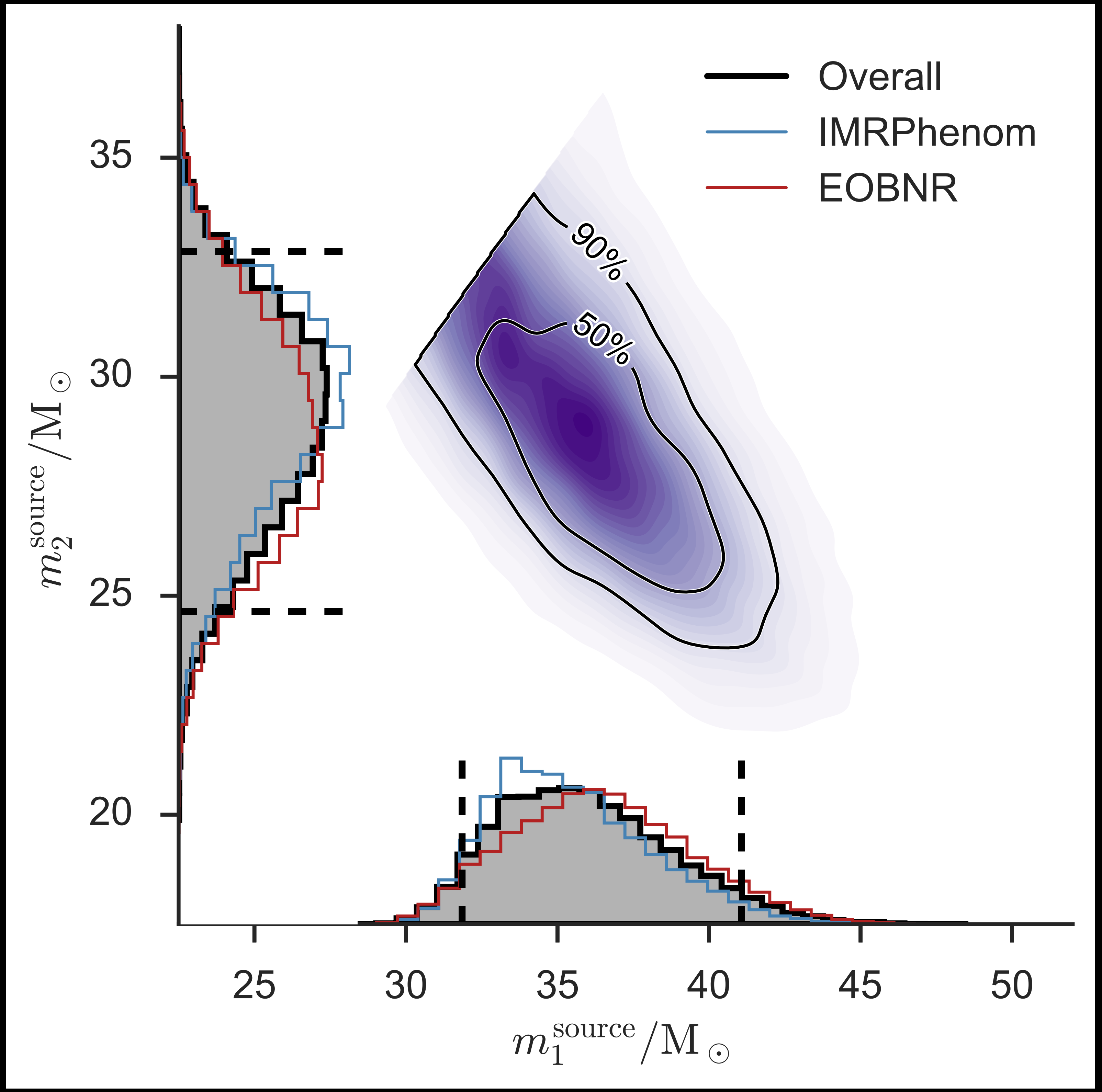
$$\text{Secondary mass} = 29^{+4}_{-4}\, M_\odot$$

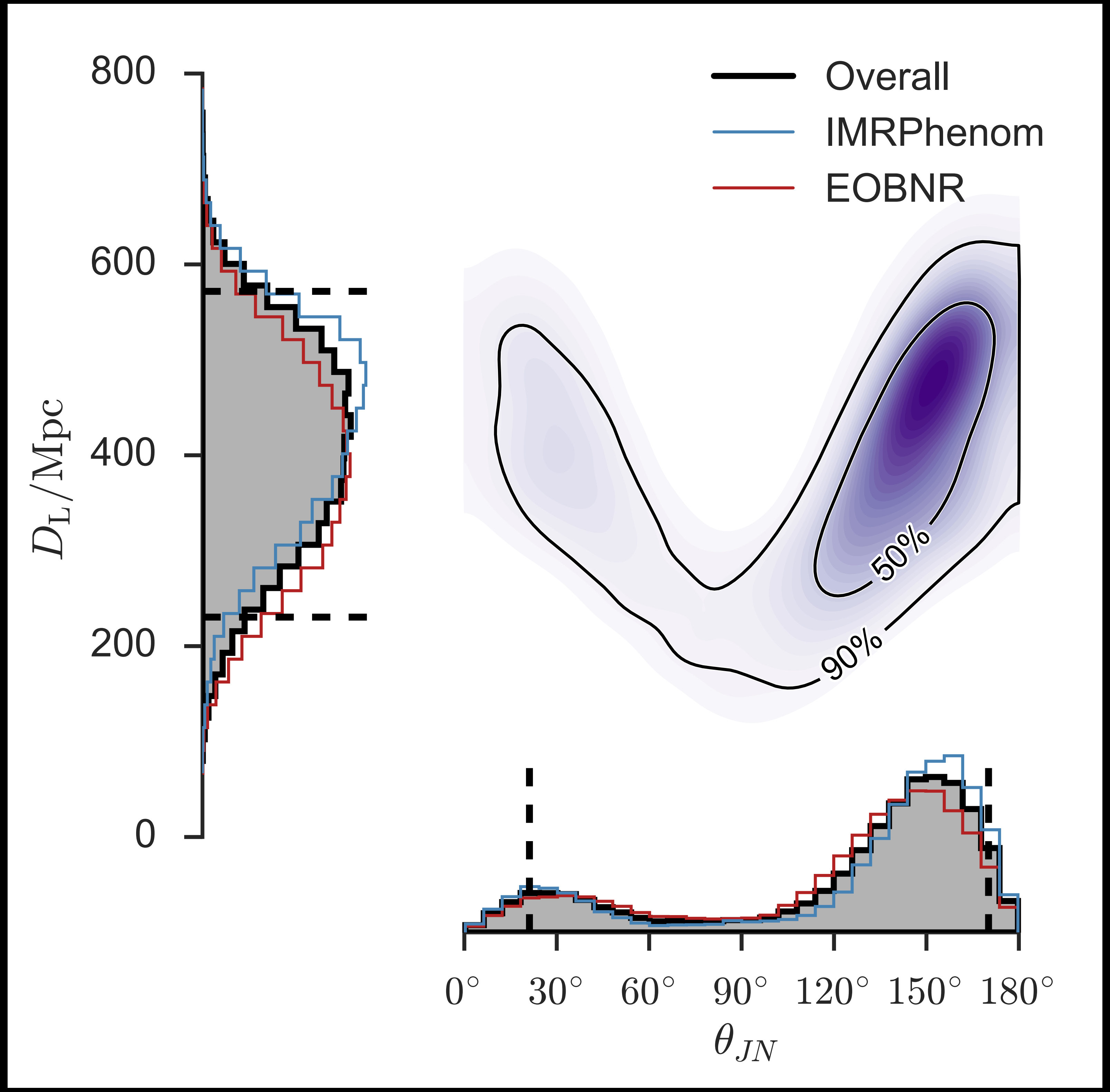
$$\text{Luminosity Distance} = 410^{+160}_{-180}\,\text{Mpc}$$

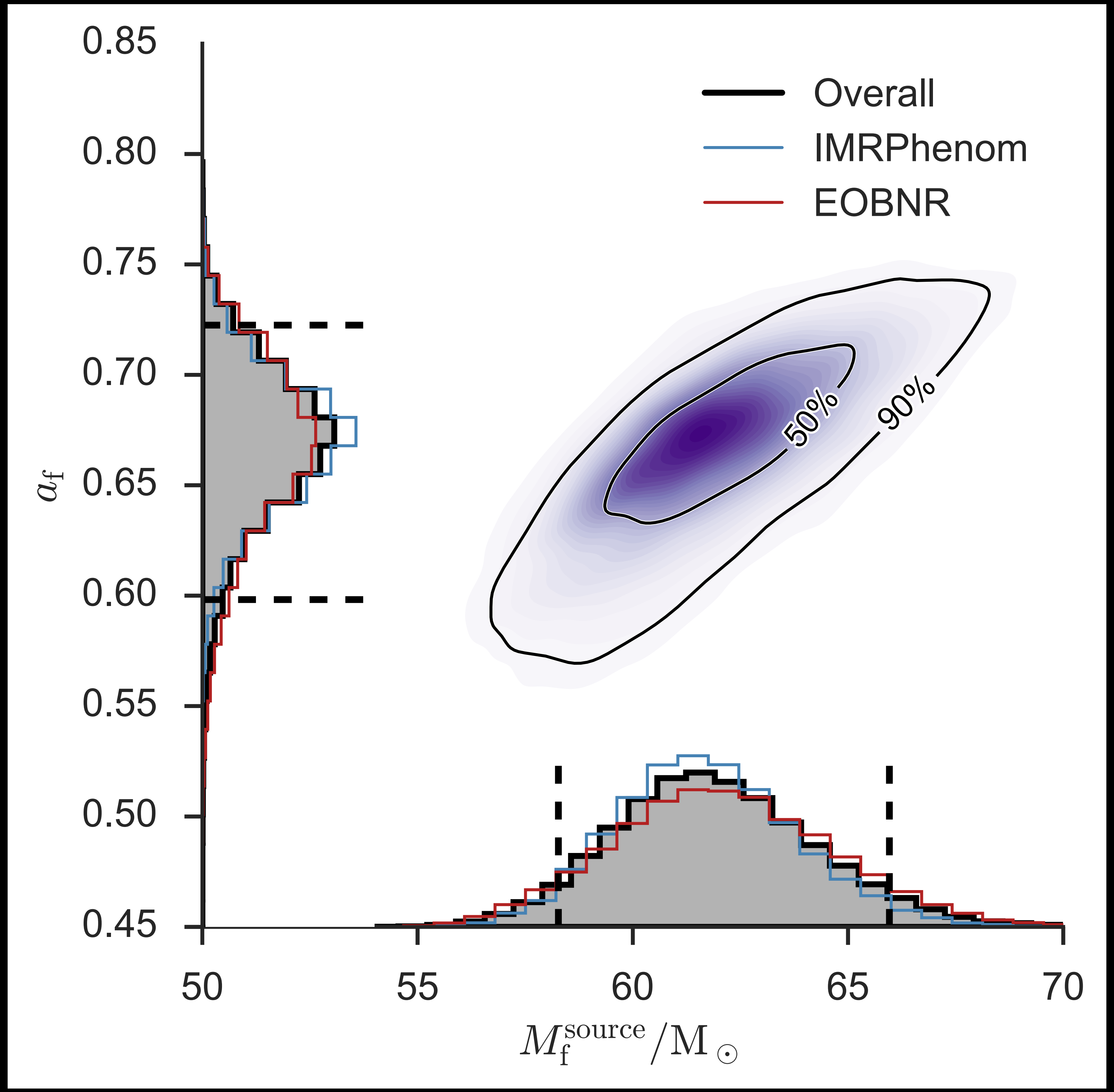
$$\text{Source redshift } z = 0.09^{+0.03}_{-0.04}$$

$$\text{Final black hole mass} = 62^{+4}_{-4}\, M_\odot$$

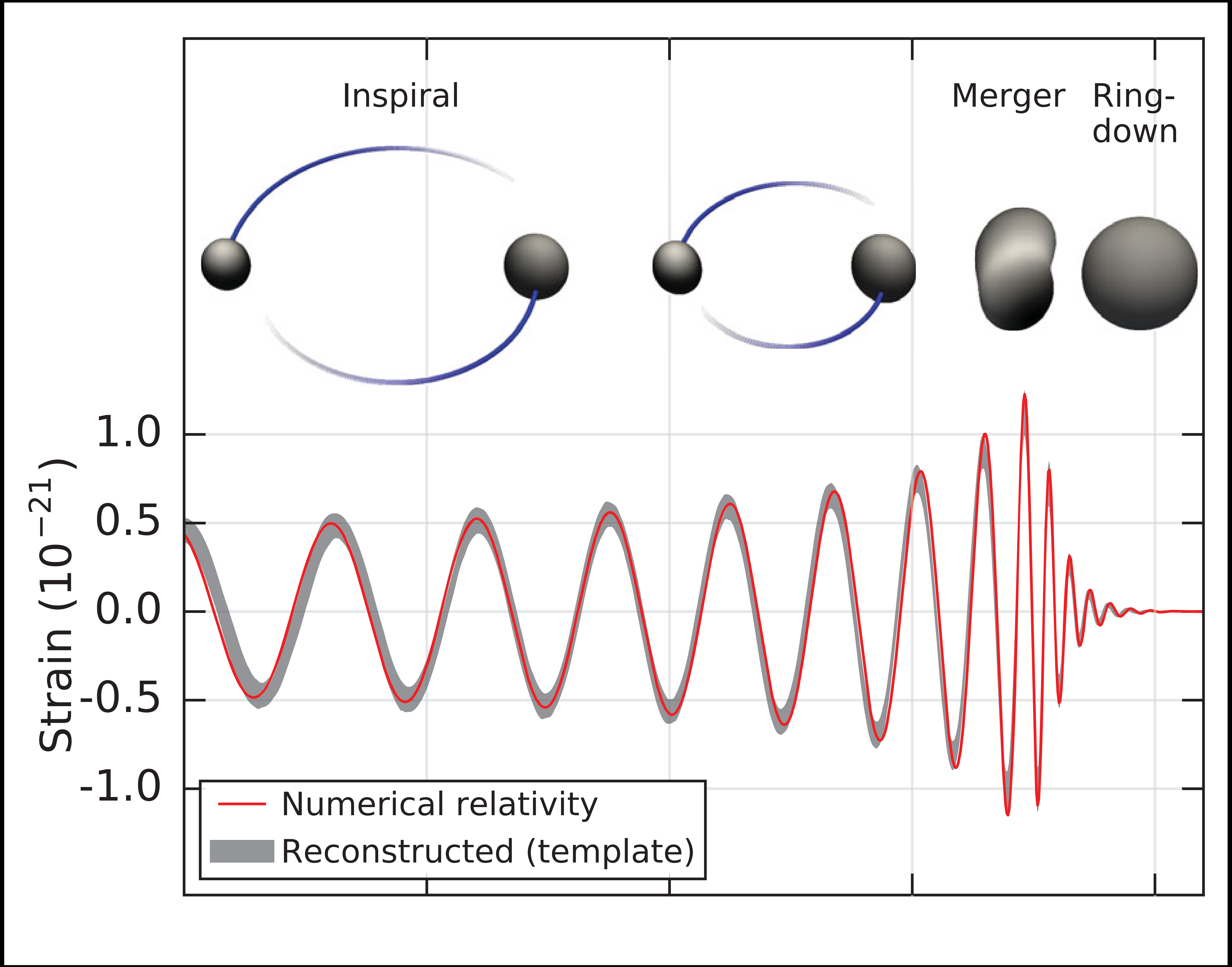
$$\text{Final black hole spin}z = 0.67^{+0.05}_{-0.07}$$



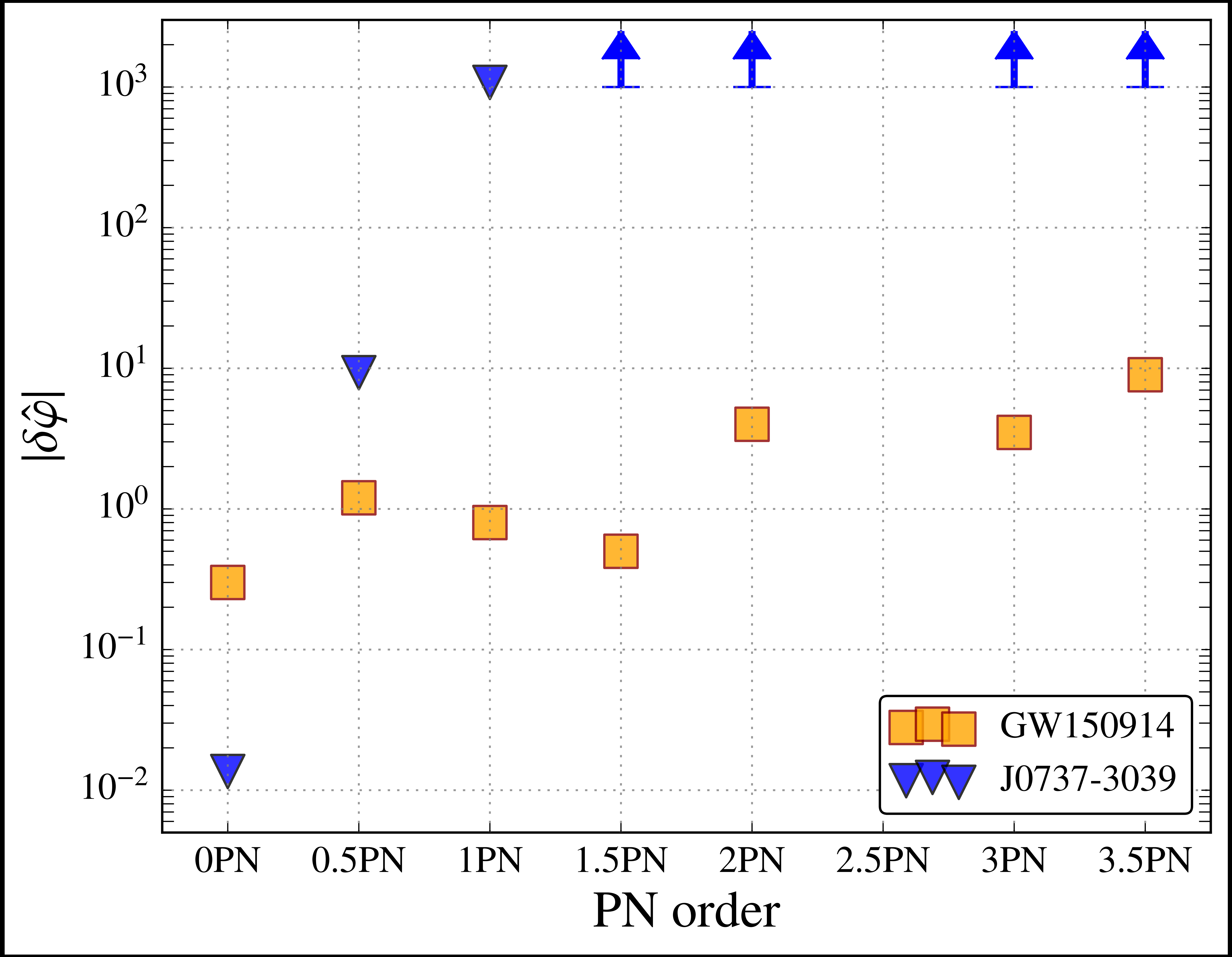





-0.76s



- Full numerical relativity waveform fits very well to measured signal
- No evidence for deviation from the merger of two Kerr black holes described by General Relativity
- NR simulations give radiated energy $3M_{\odot}c^2$

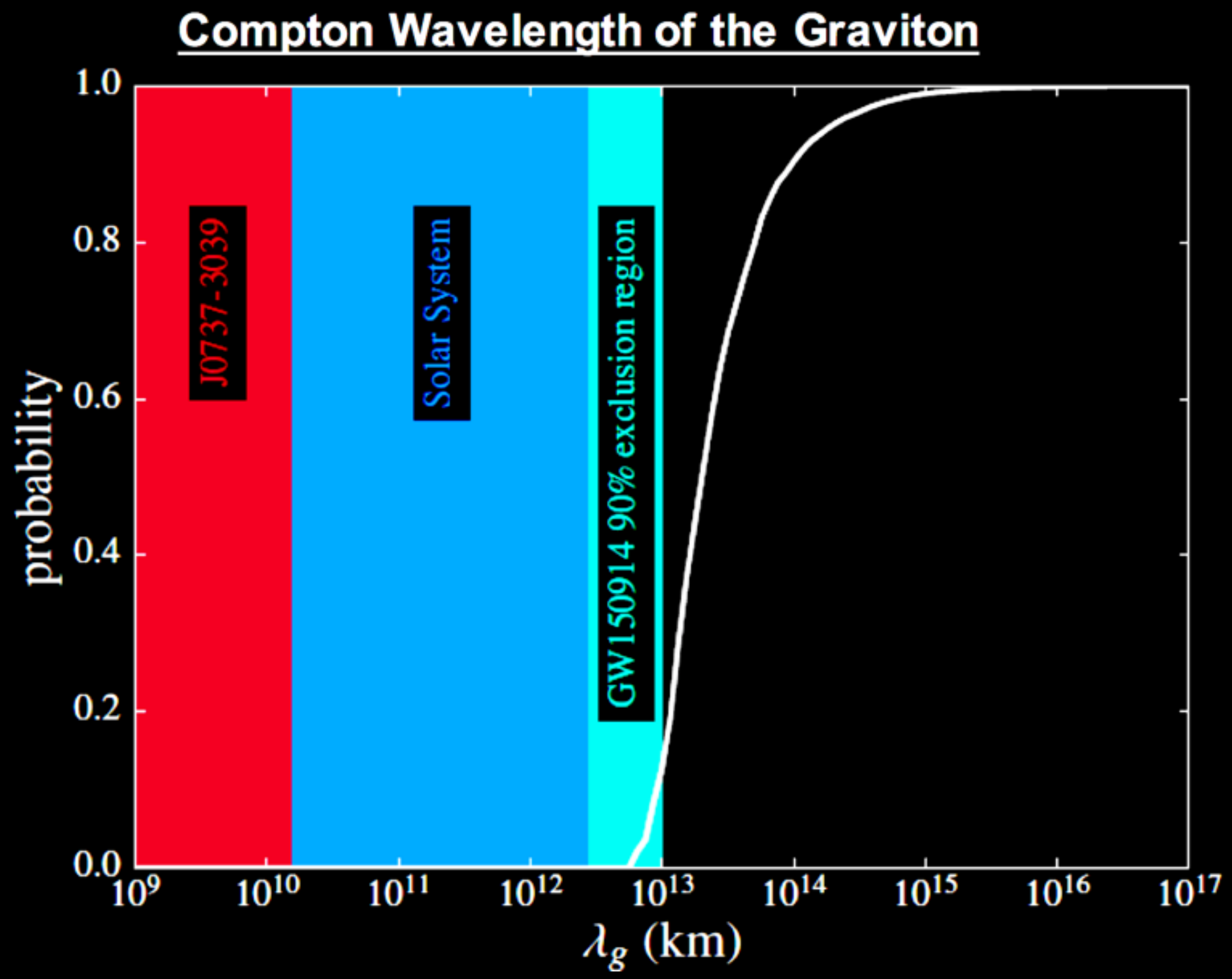


- Measure deviation of post-Newtonian parameters from those predicted by GR

$$\Psi(f) = \sum \phi_k (\pi M f)^{\frac{k-5}{3}}$$

$$\phi_k \rightarrow \phi_k (1 + \delta\varphi_k)$$

- GW150914 is the first observation of a binary black hole merger...
- ...and is the best test of GR in the strong field, nonlinear regime
- We find no evidence for disagreement with General Relativity

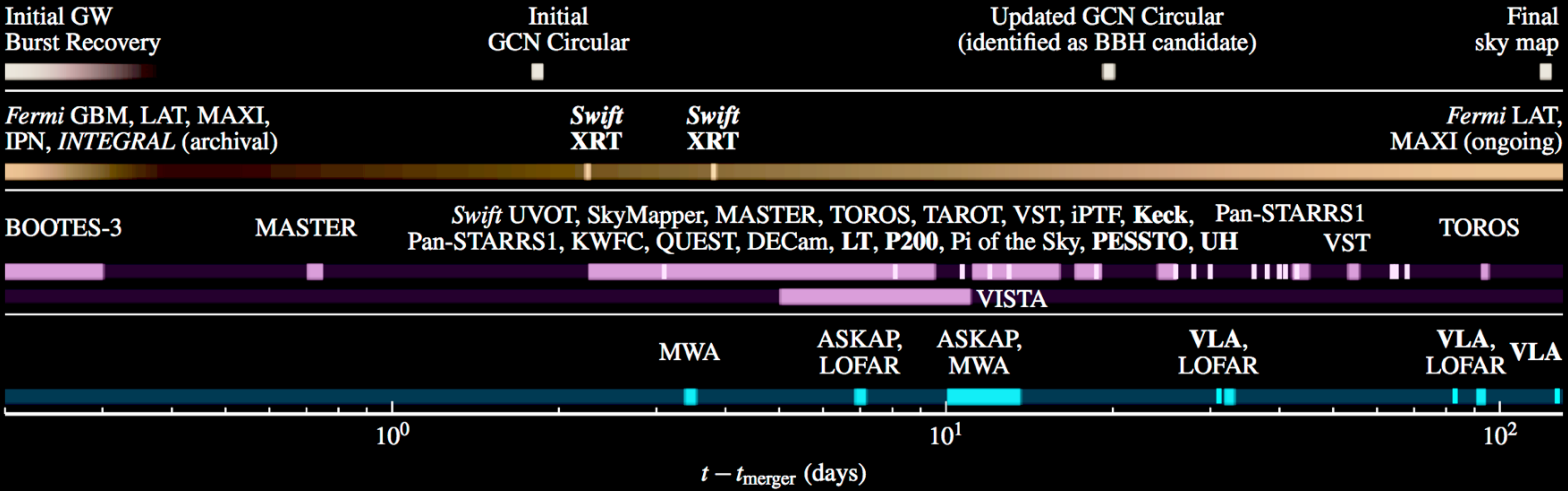


$$\lambda_g > 10^{13}\,\mathrm{km}$$

$$m_g < 1.2 \times 10^{-22} eV/c^2$$

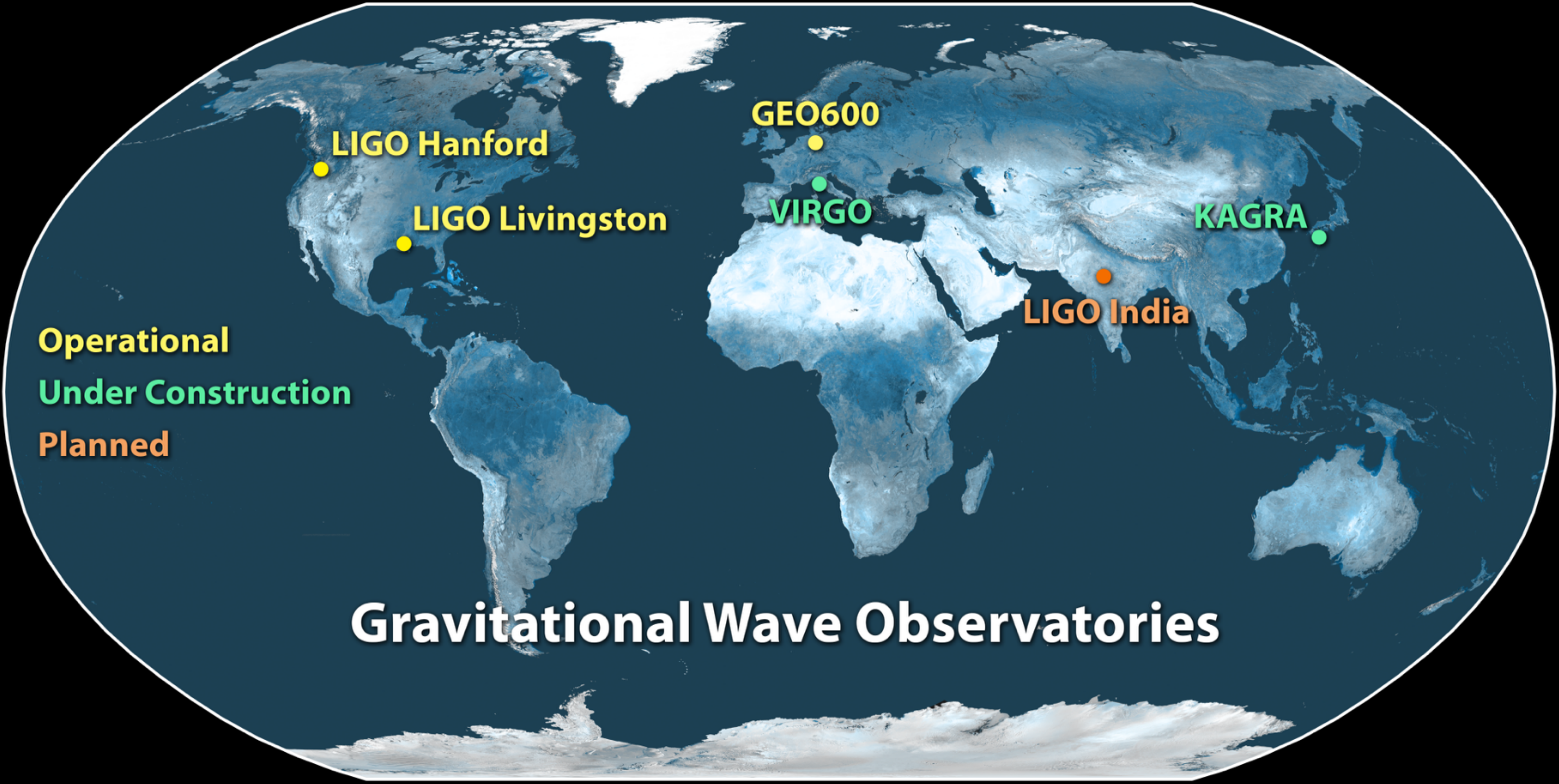
- GW150914 has important implications for massive star formation
- Black holes larger than 25 solar masses exist
- Black hole binaries exist and merge within a Hubble time
- Merger rates implied by the detection are 2 - 400 Gpc^3 / yr
- Black holes this massive likely formed in a low-metallicity environment (less than half the solar metalicity)

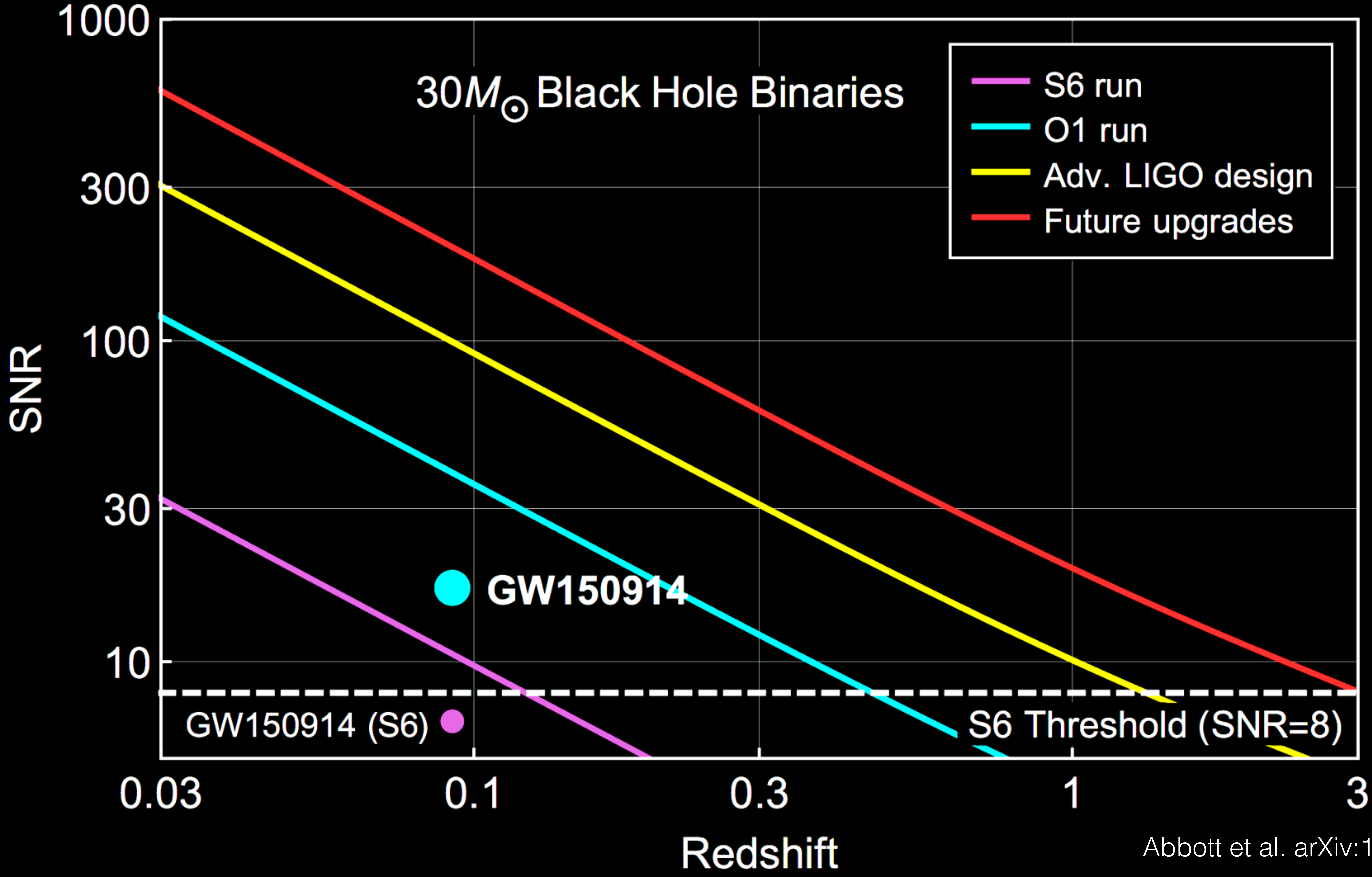
Follow-up by a wide variety of electromagnetic observing partners



Abbott et al. arXiv:1602.08492

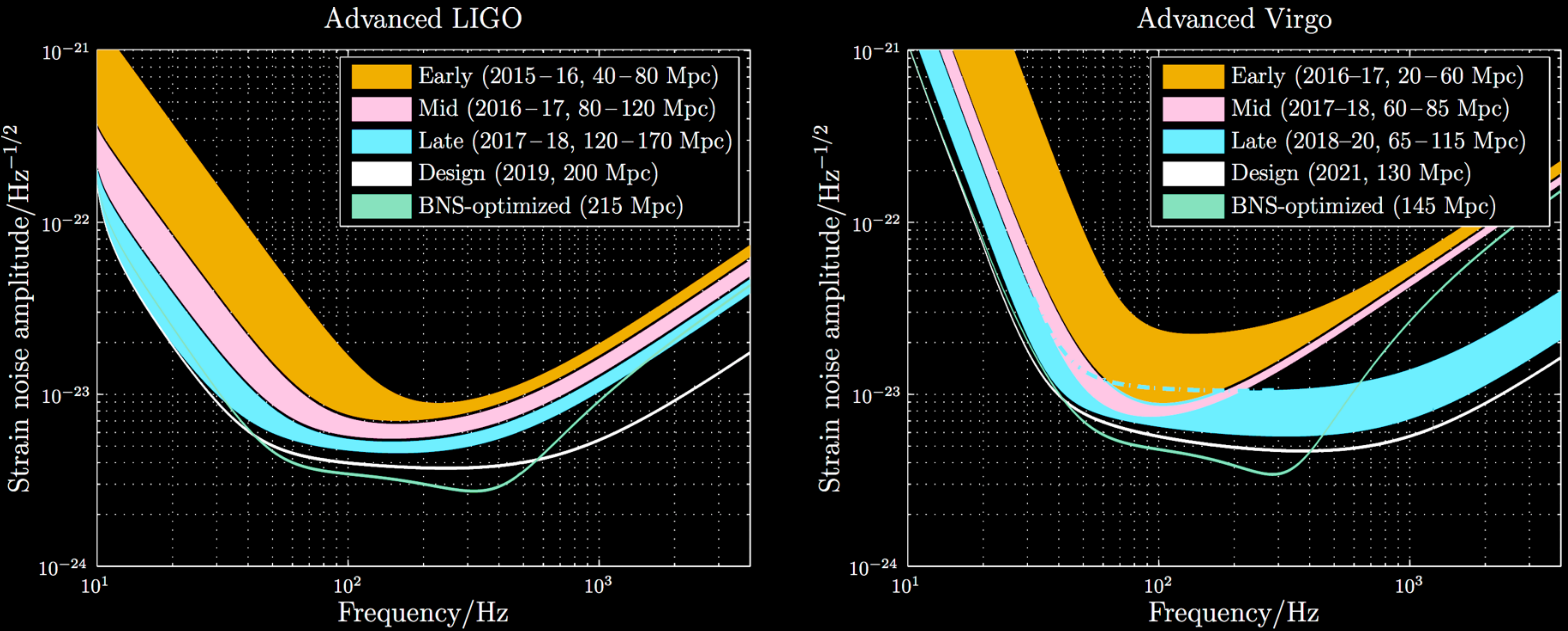
Gravitational Wave Observatories



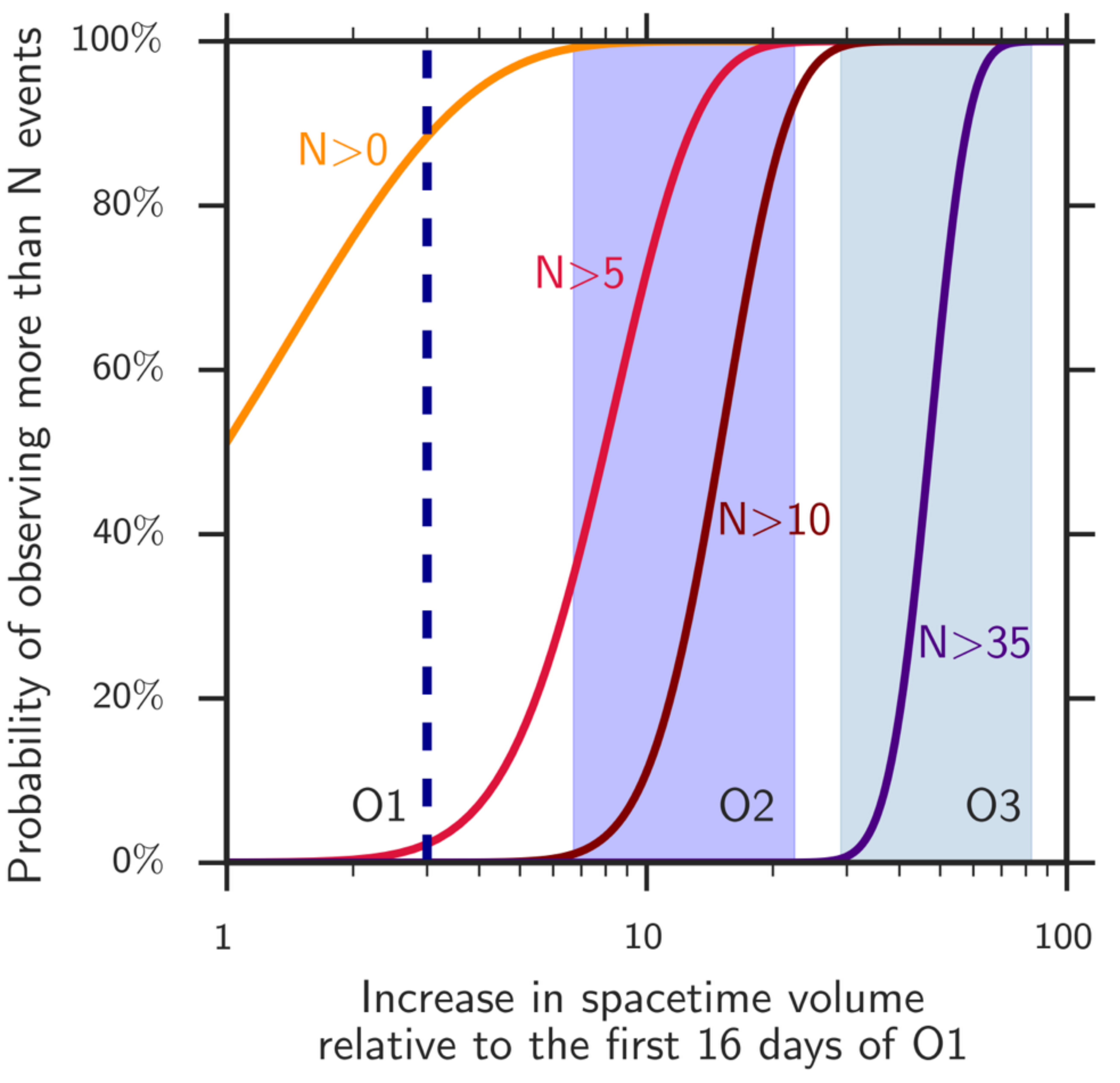


Abbott et al. arXiv:1602.03838

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



Abbott et al. arXiv:1304.0670

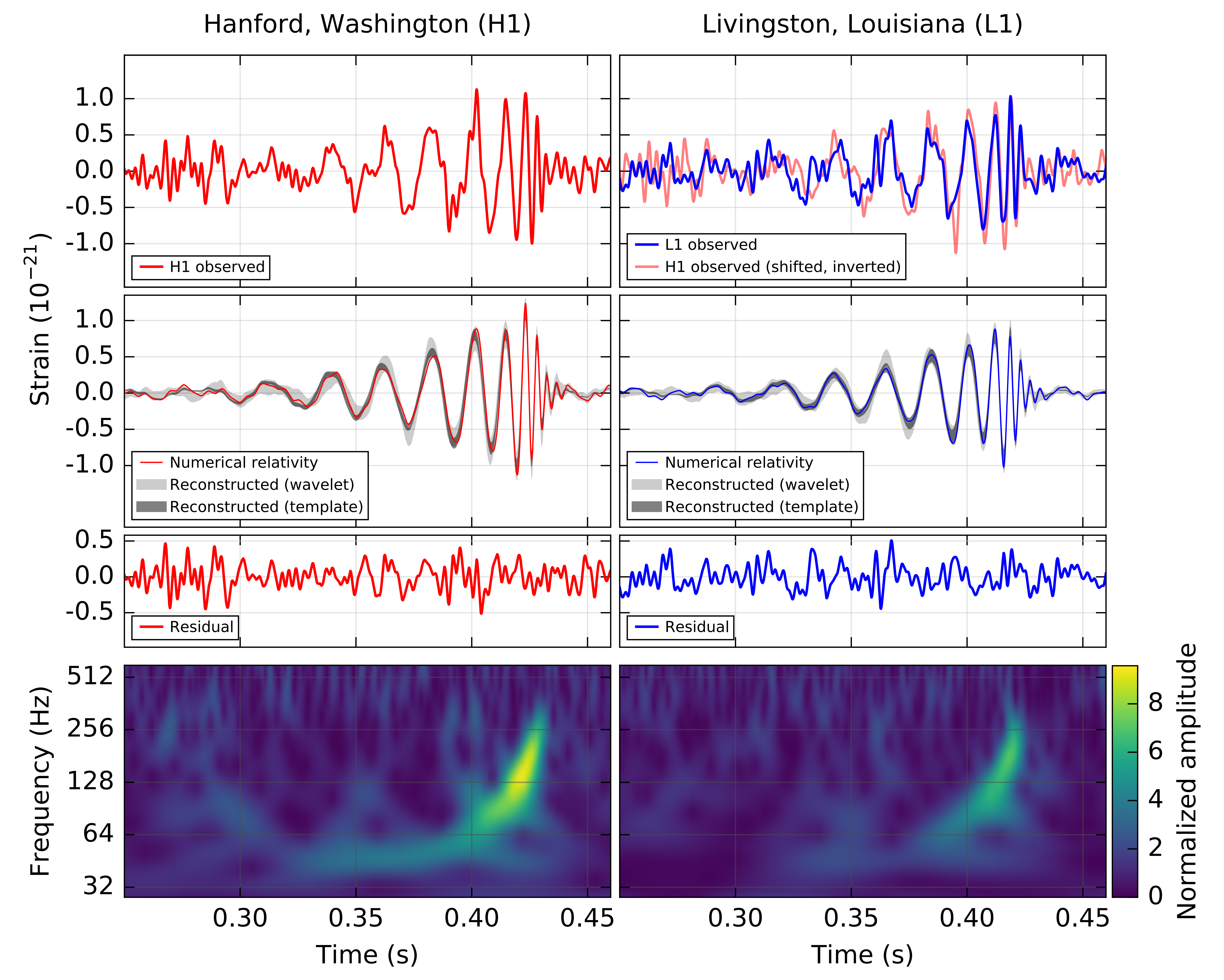


- Rates 2 - 400 Gpc^{-3} yr^{-1}
- This is only the beginning of gravitational-wave astronomy
- Lots more physics and astrophysics too explore

- LIGO has made the first measurement of gravitational-wave amplitude and phase

- A merging binary black hole system has been seen for the first time

- LIGO will resume the search for gravitational waves in the Fall of 2016; Virgo will join in



Abbott et al. PRL **116** 061102 (2016)

The LIGO Scientific Collaboration

LSC

TRINITY UNIVERSITY

UNIVERSITY OF MARYLAND

Andrews University

WASHINGTON STATE UNIVERSITY

CALIFORNIA STATE UNIVERSITY FULLERTON

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

SONOMA STATE UNIVERSITY

indigo

MONTCLAIR STATE UNIVERSITY

University of Glasgow

Australian National University

WHITMAN COLLEGE

AMERICAN UNIVERSITY WASHINGTON, DC

UNIVERSITY OF THE WEST of SCOTLAND UWS

TEXAS TECH UNIVERSITY

清華大学 Tsinghua University

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Max Planck Institute for Gravitational Physics ALBERT EINSTEIN INSTITUTE

UNIVERSITY OF STRATHCLYDE

MICHIGAN

CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut Canadien d'astrophysique théorique

Università degli Studi del Sannio

NASA GODDARD SPACE FLIGHT CENTER

ICTP SAIFR

THE UNIVERSITY OF WESTERN AUSTRALIA

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ACU

UNIVERSITY OF CAMBRIDGE

THE UNIVERSITY OF CHICAGO

MONTANA STATE UNIVERSITY

THE UNIVERSITY of MISSISSIPPI

THE UNIVERSITY OF ADELAIDE AUSTRALIA

SOUTHERN UNIVERSITY Agricultural & Mechanical College

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

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CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

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INPE

UF UNIVERSITY of FLORIDA

Georgia Institute of Technology

Korean Gravitational-Wave Group

LSU LOUISIANA STATE UNIVERSITY

ACIGA

University of Southampton

CHARLES STURT UNIVERSITY

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