LIGO's Black Holes

Daniel Holz

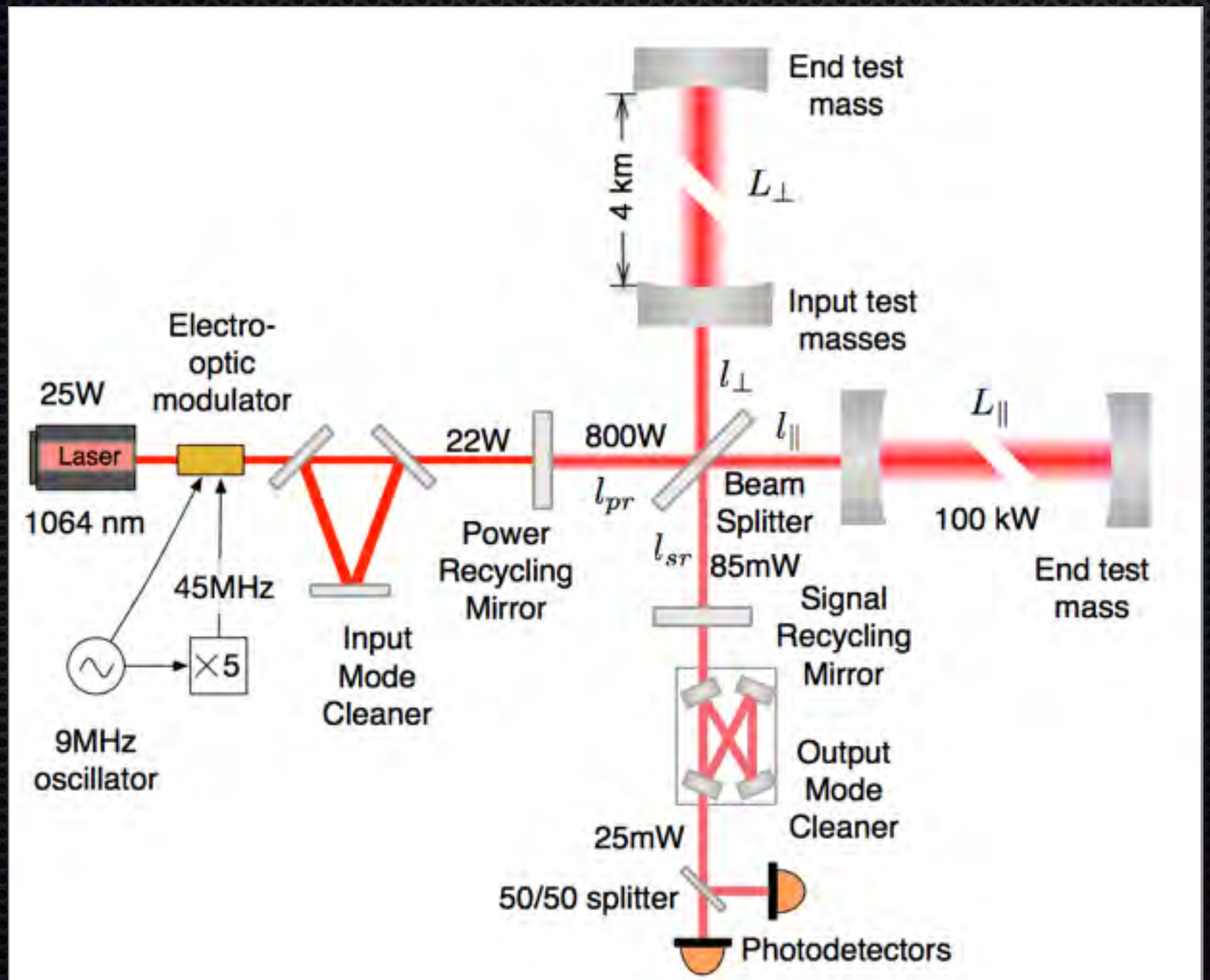
The University of Chicago

What do gravitational waves do?

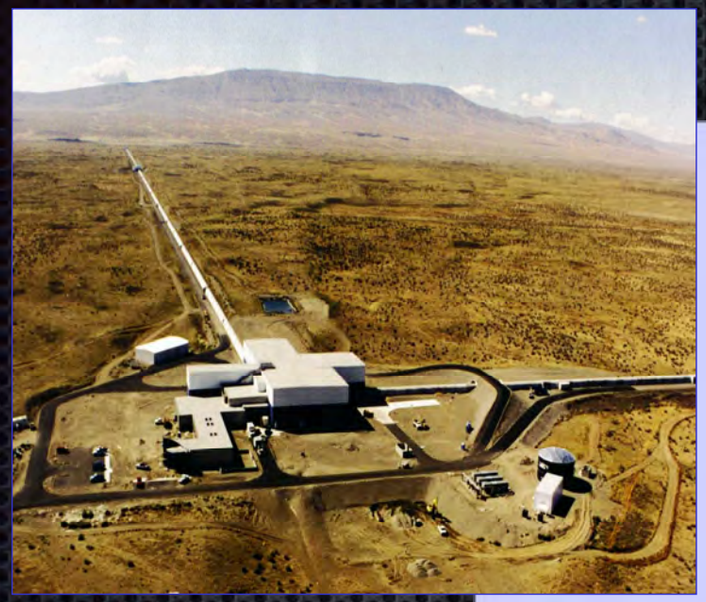
- Consider a ring of non-interacting masses floating in empty space:

- Distances between the masses oscillate as gravitational wave passes
- Amplitude of wave measured by the strain, which is the fractional change in length: $h = \Delta L / L$

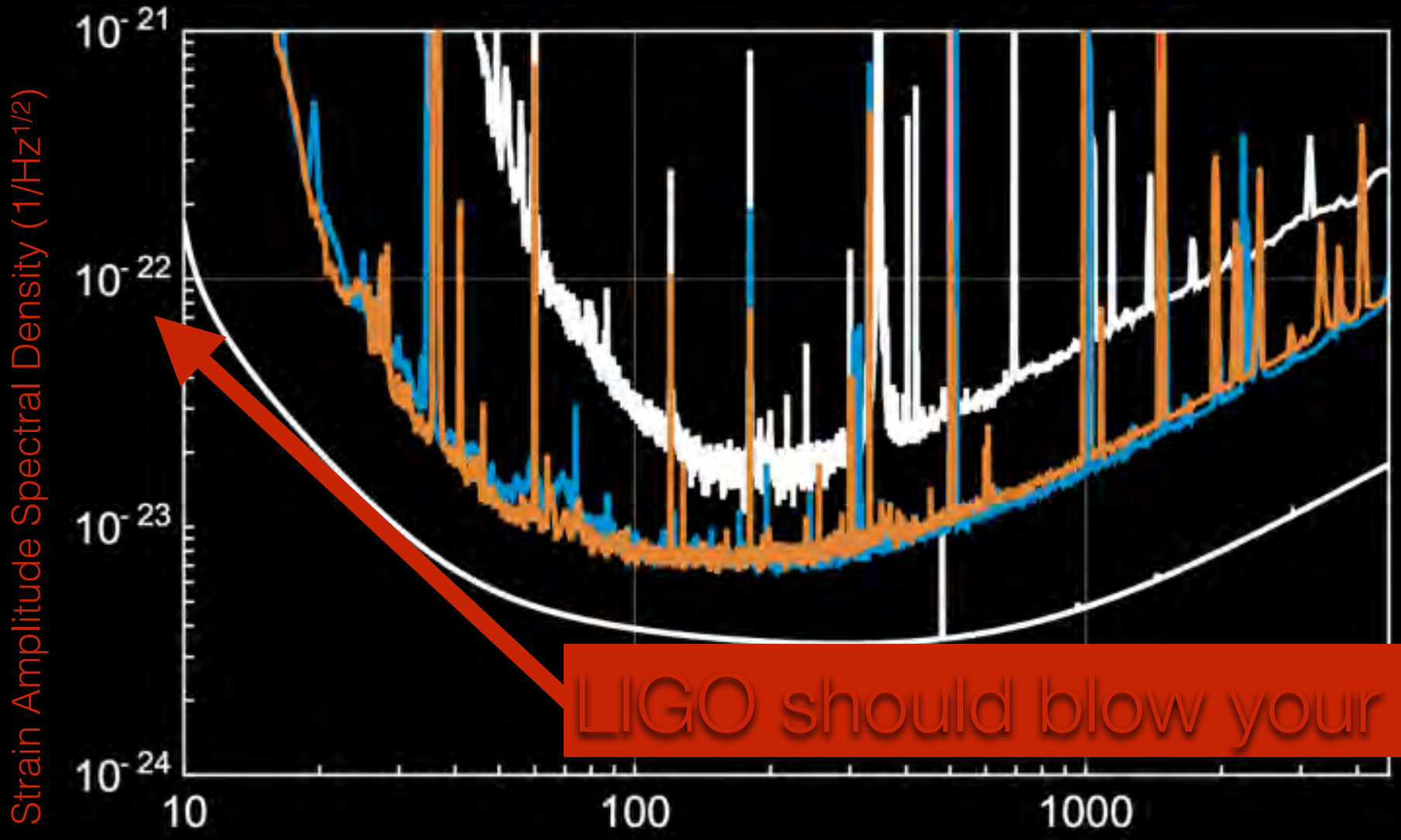
LIGO: Laser Interferometer Gravitational wave Observatory



LIGO: Laser Interferometer Gravitational wave Observatory

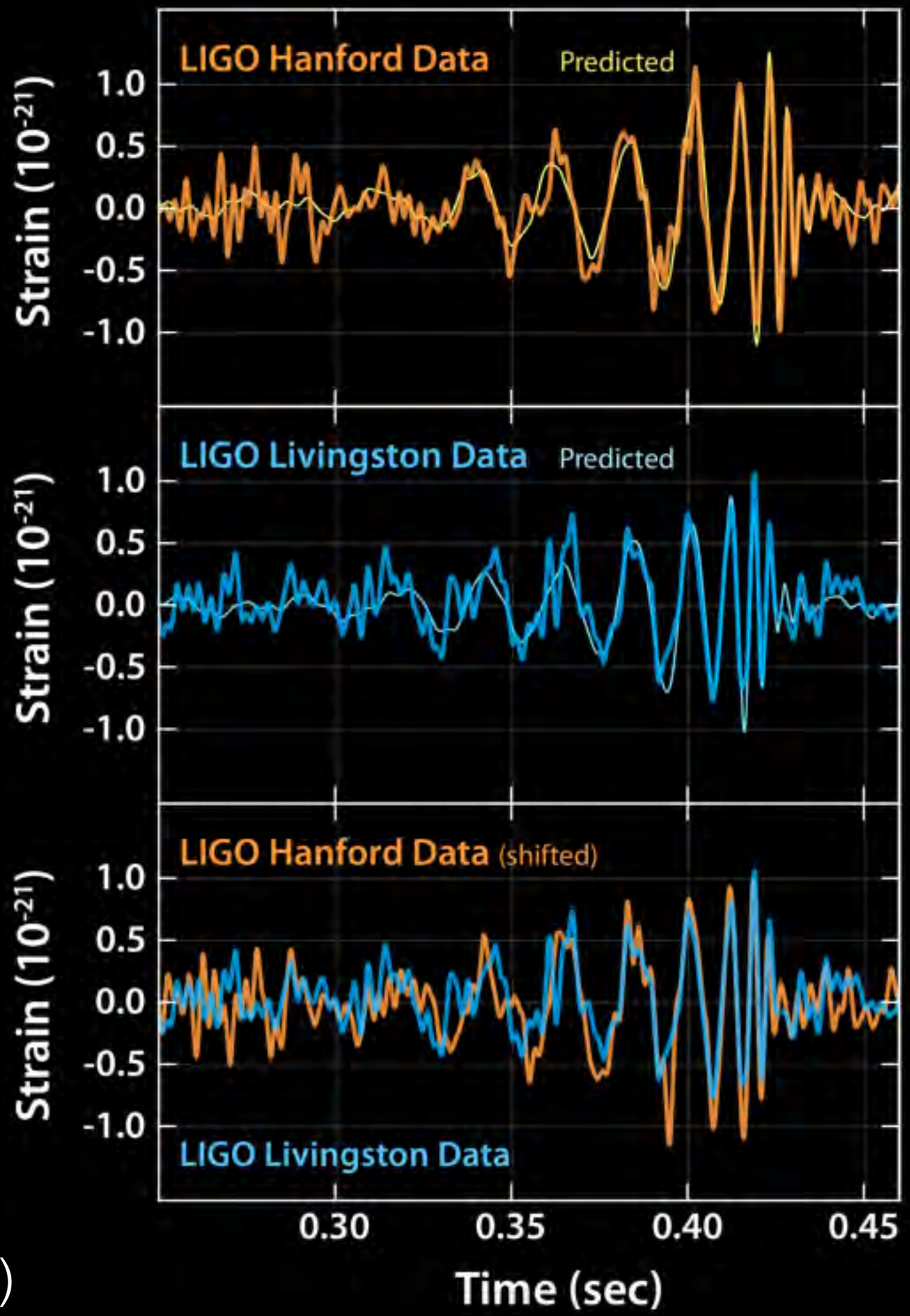


LIGO is amazing

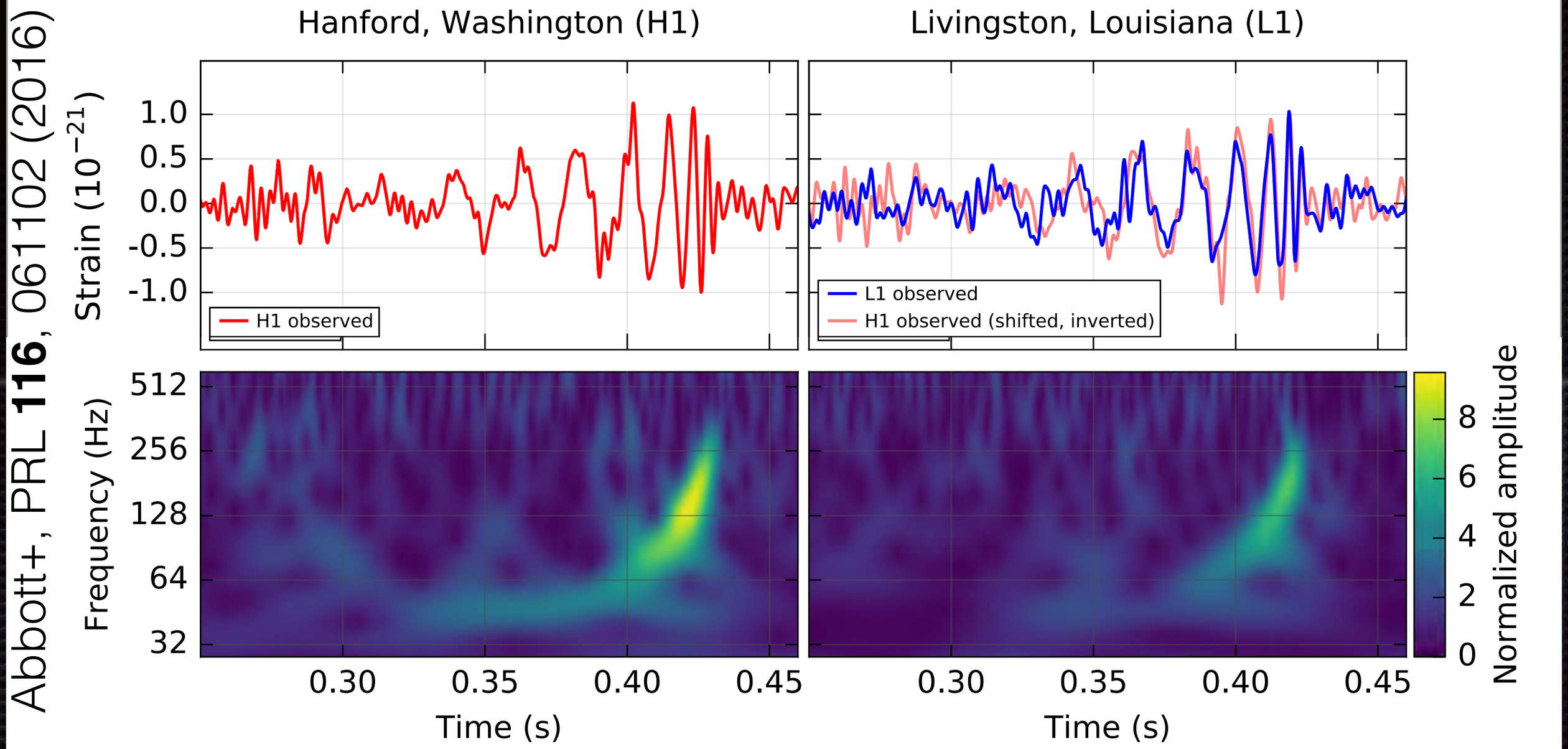


Abbott+, PRL **116**, 131103 (2016)

Observation of Gravitational Waves from a Binary Black Hole Merger

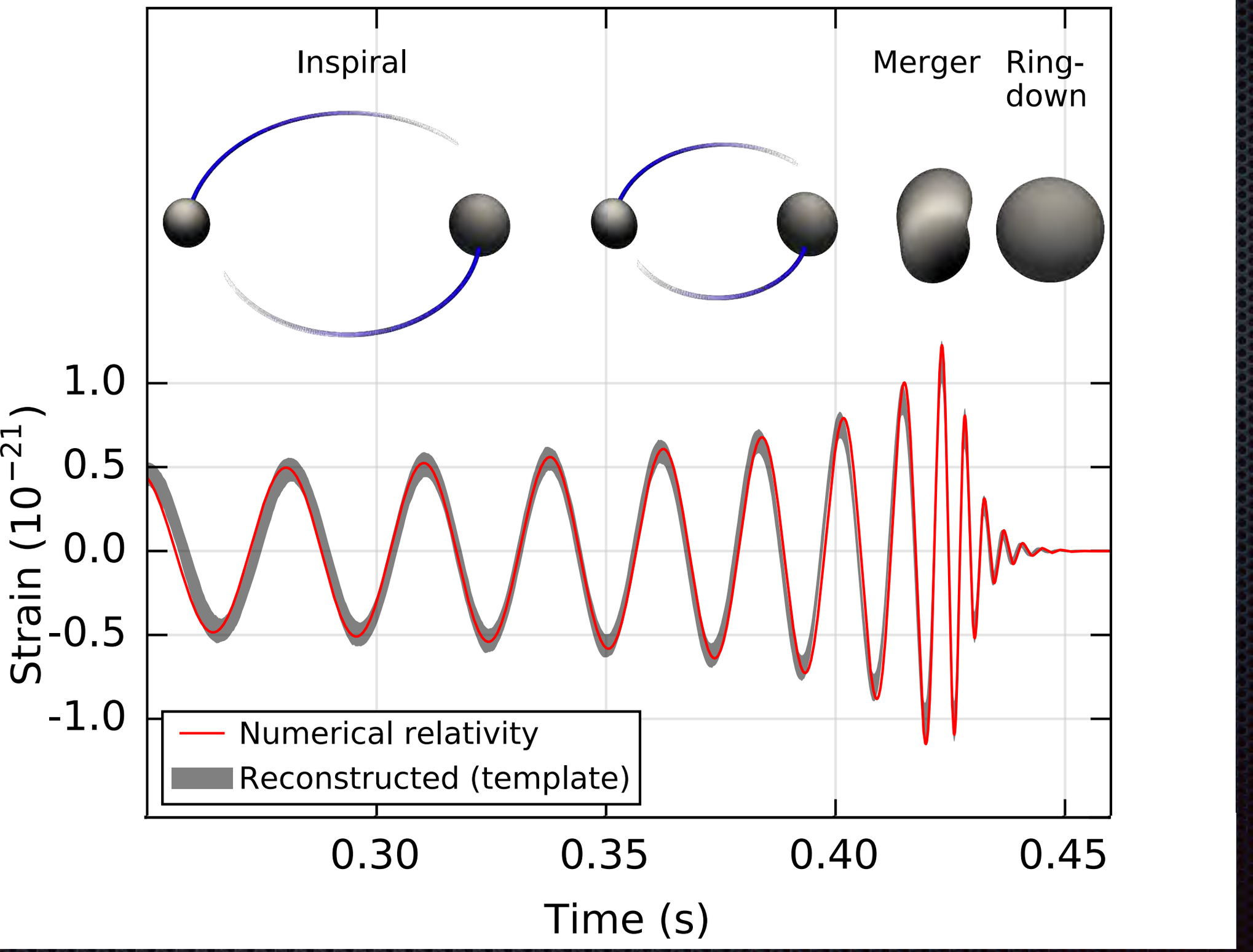


Abbott+, PRL **116**, 061102 (2016)



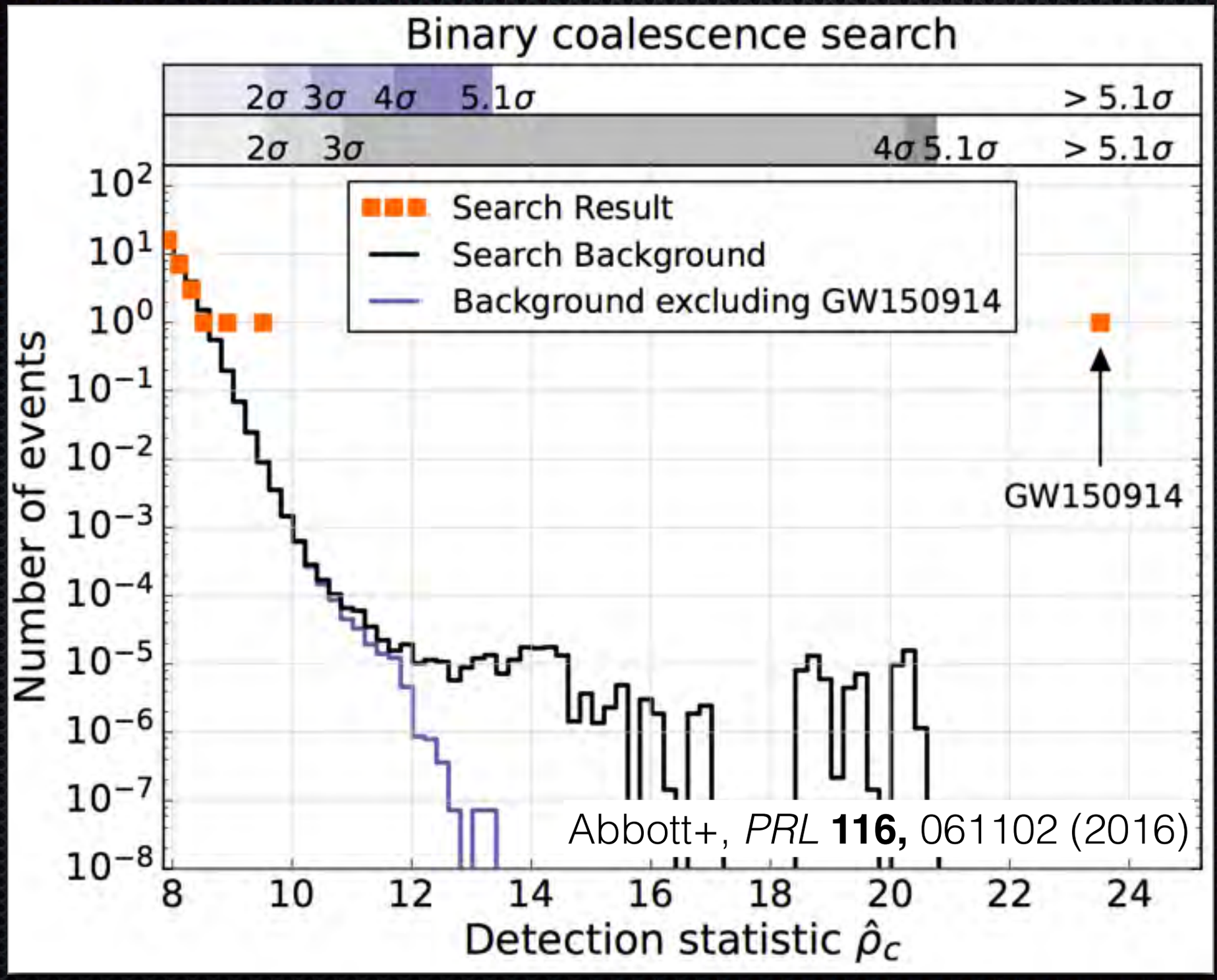
- See a loud chirping waveform in both detectors
- Waveform is roughly same amplitude in both detectors, shifted by 7 msec
- Waveform peaks at ~150 Hz

Abbott+, PRL **116**, 061102 (2016)



- Inspiral, merger, and ringdown of a binary black hole

Is GW150914 noise? No!



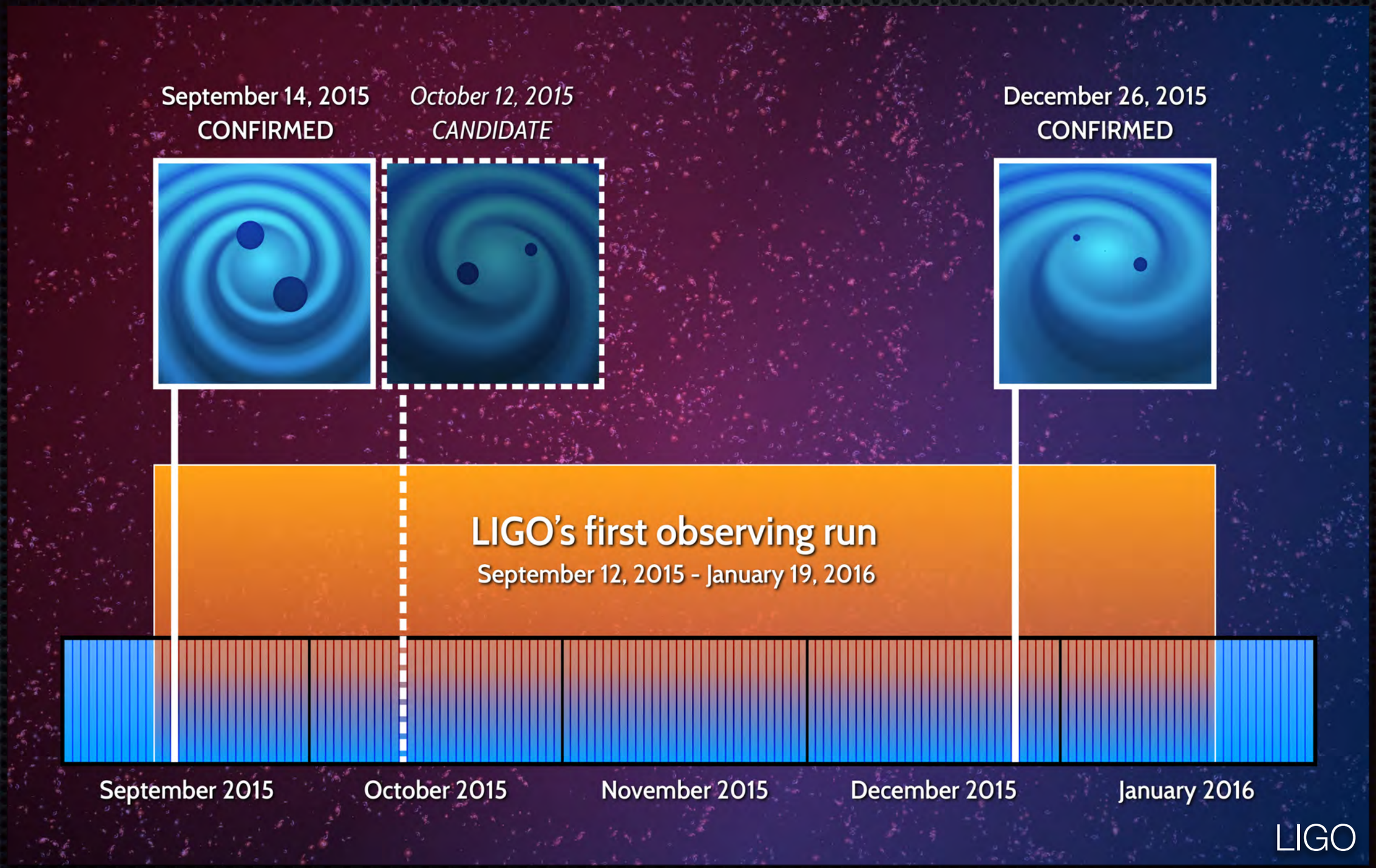
- The false alarm rate is <1 event per 200,000 years

O1: First science run

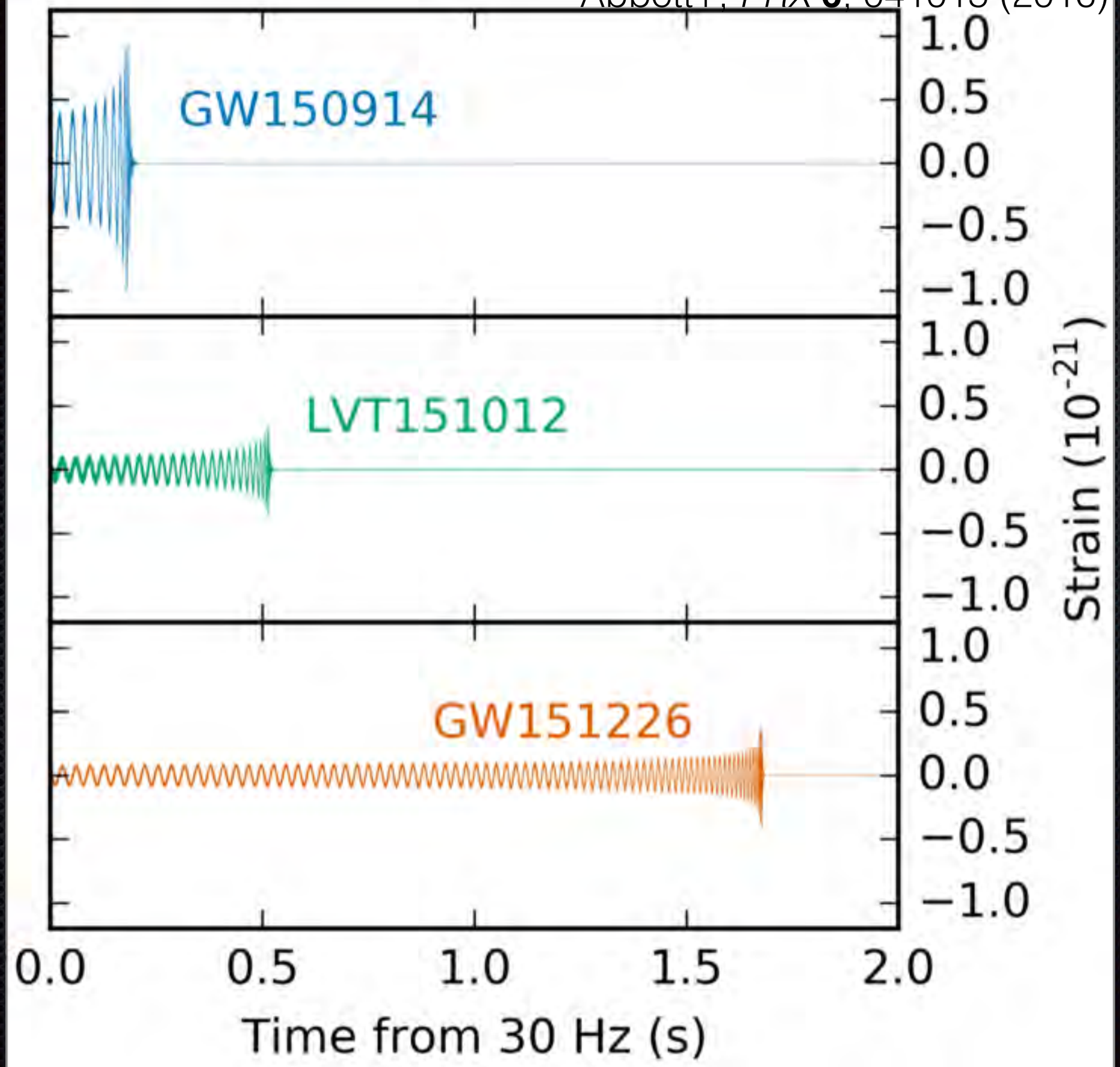
- September 12, 2015 to January 19, 2016
- ~50 days of good quality, coincident data
- Total of 2.87 events:
  - GW150914, GW151226, LVT151012
- >20 collaboration papers


LIGO

O1: 2.9 interesting sources

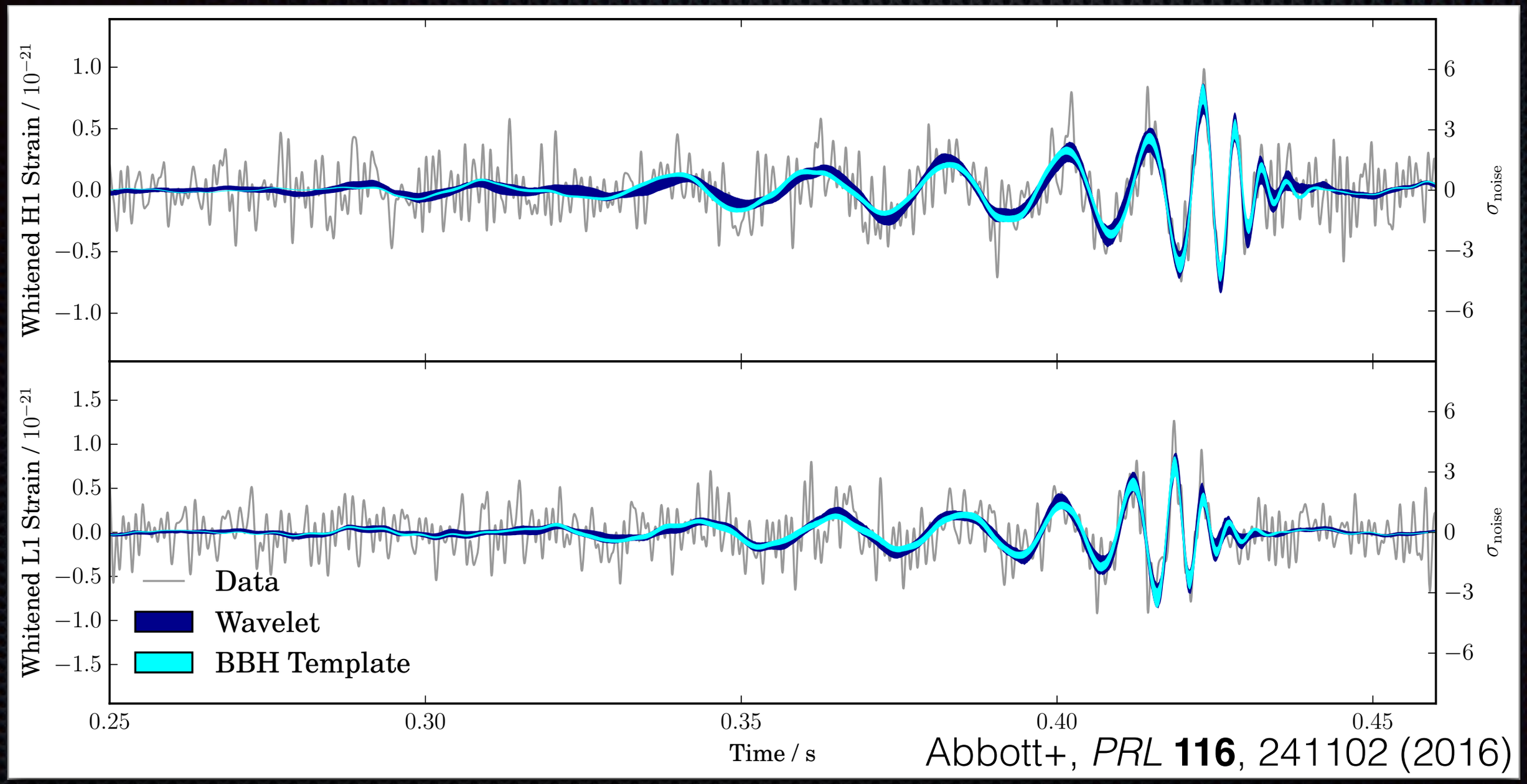


Abbott+, *PRX* **6**, 041015 (2016)



Does general relativity work?

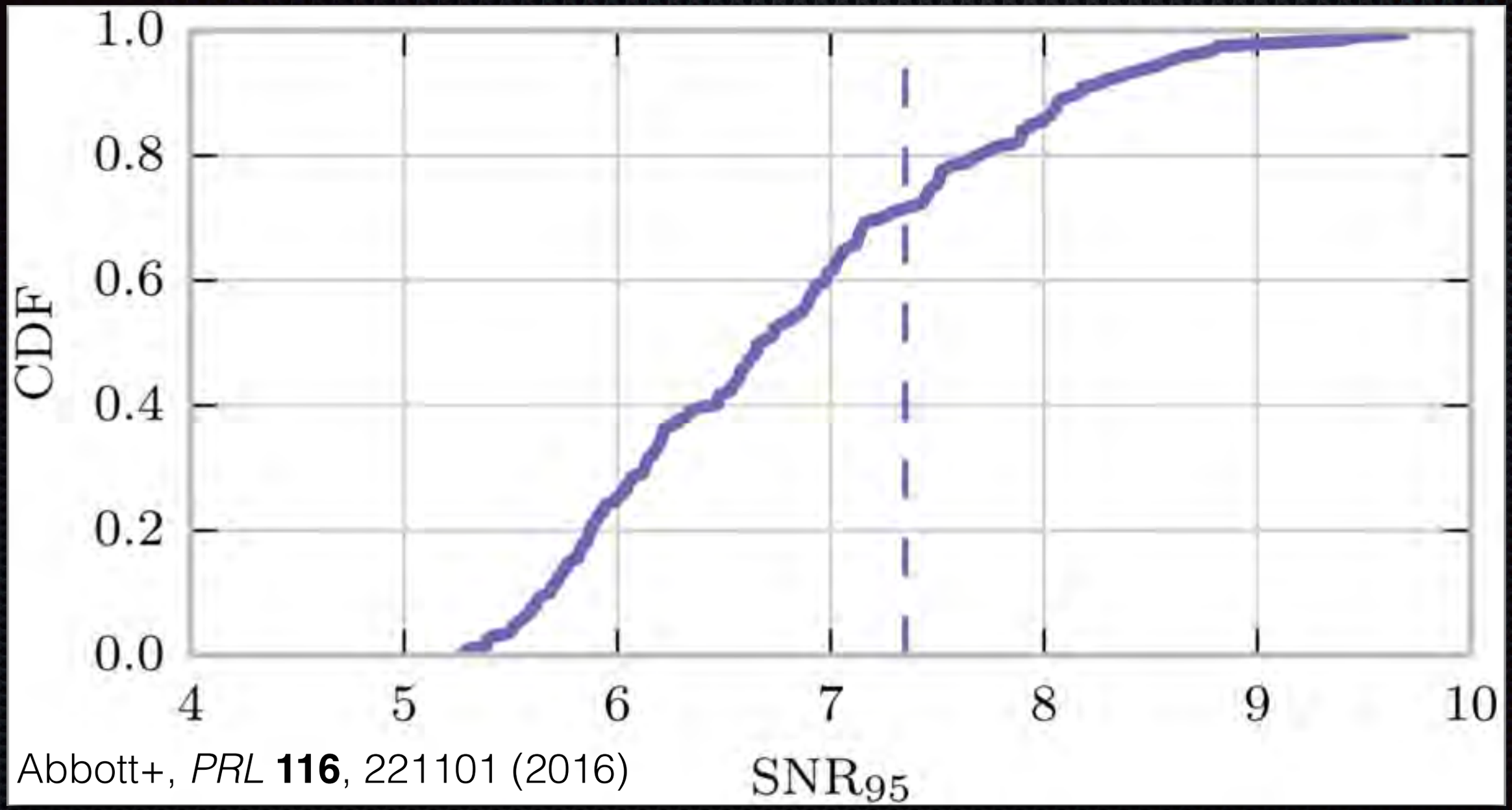
Are they really black holes? Yes!



Abbott+, *PRL* **116**, 241102 (2016)

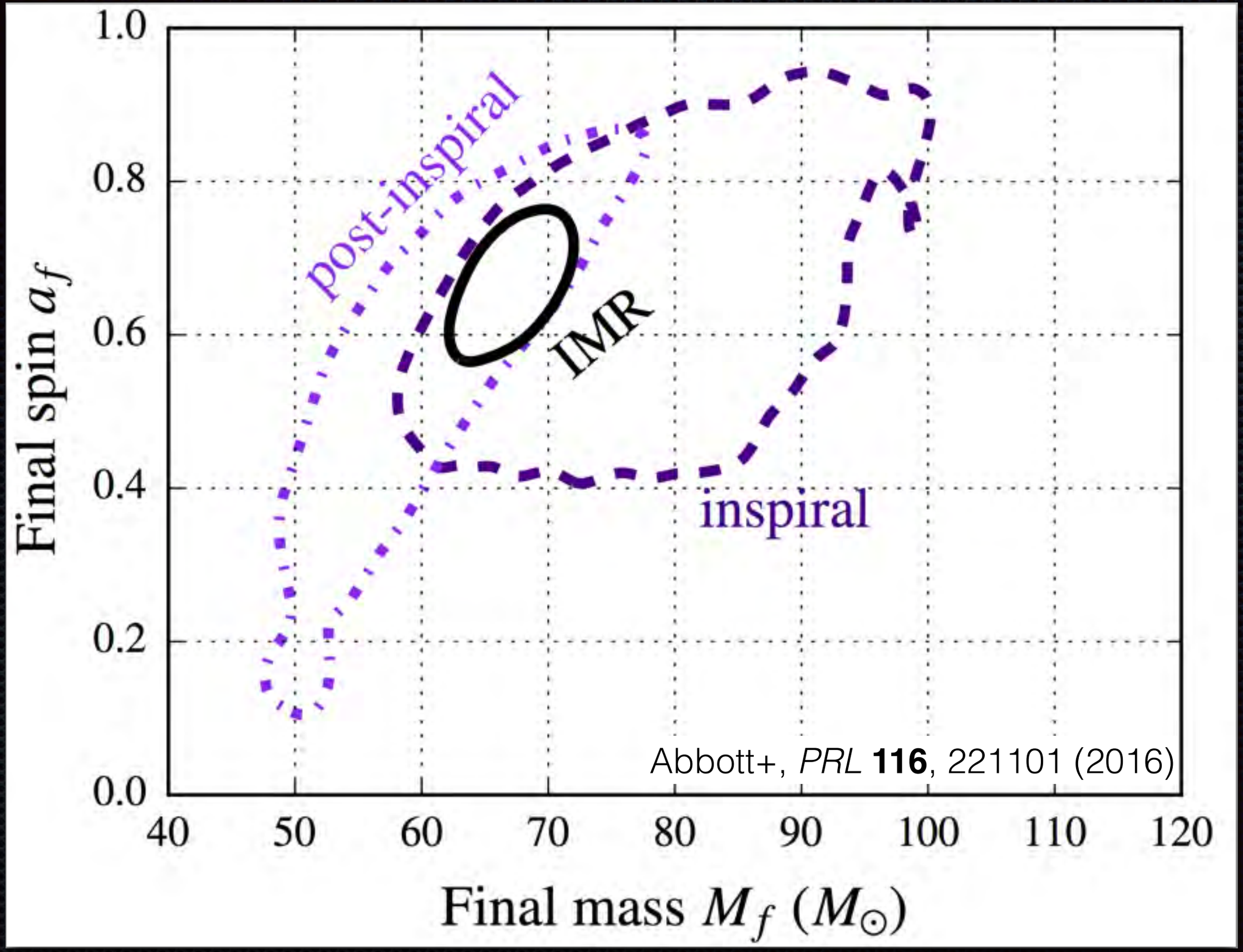
- Whitened data
- Wavelet is unmodeled sine-Gaussian (no general relativity)
- BBH template is general relativity
- Agreement between Wavelet and GR!

Does general relativity work? Yes!

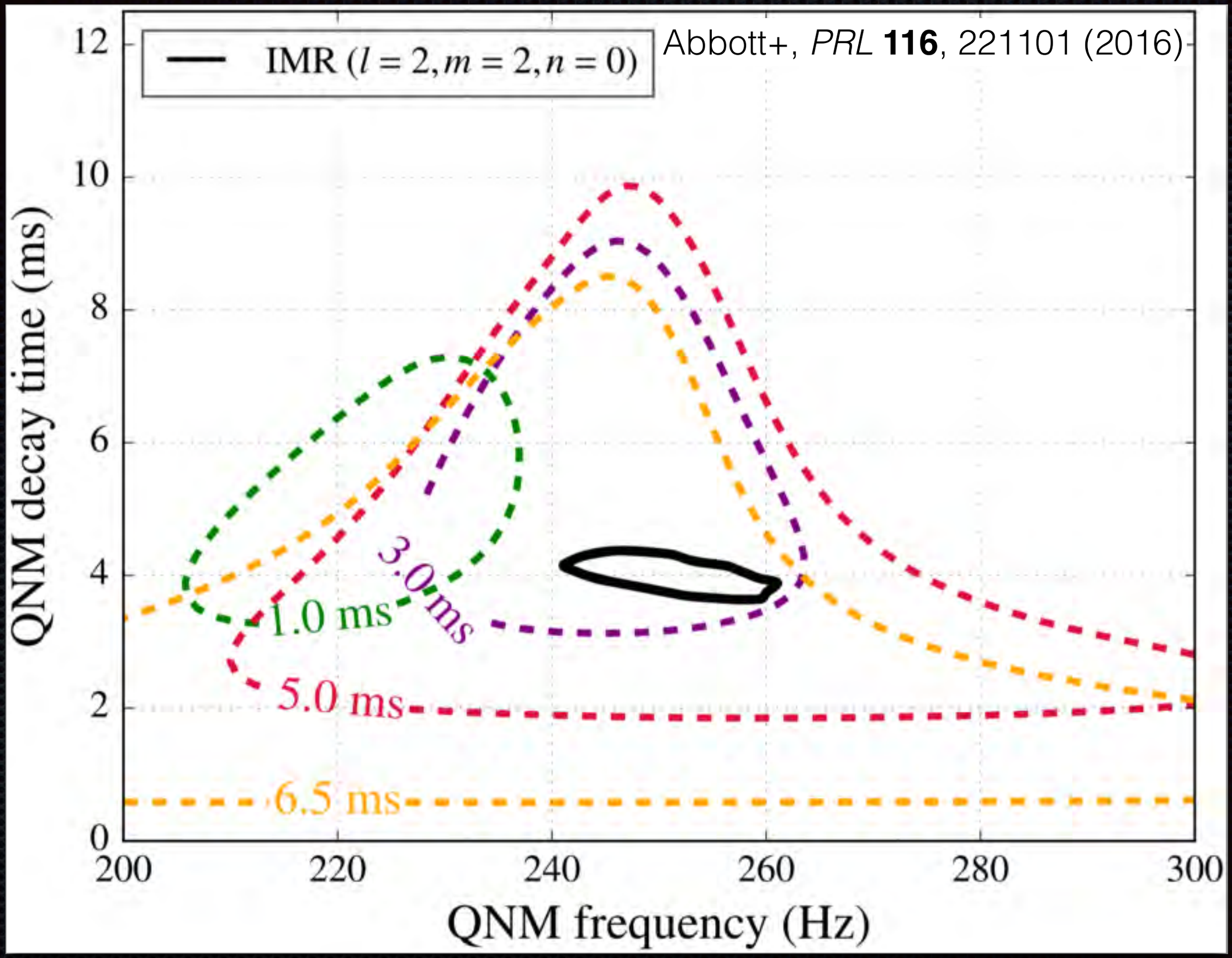


Abbott+, *PRL* **116**, 221101 (2016)

- Subtract best-fit waveform from the data
- Search for an “unmodeled” source
- Nothing is left but noise: GR describes the signal!



- Inspiral is consistent with merger+ringdown

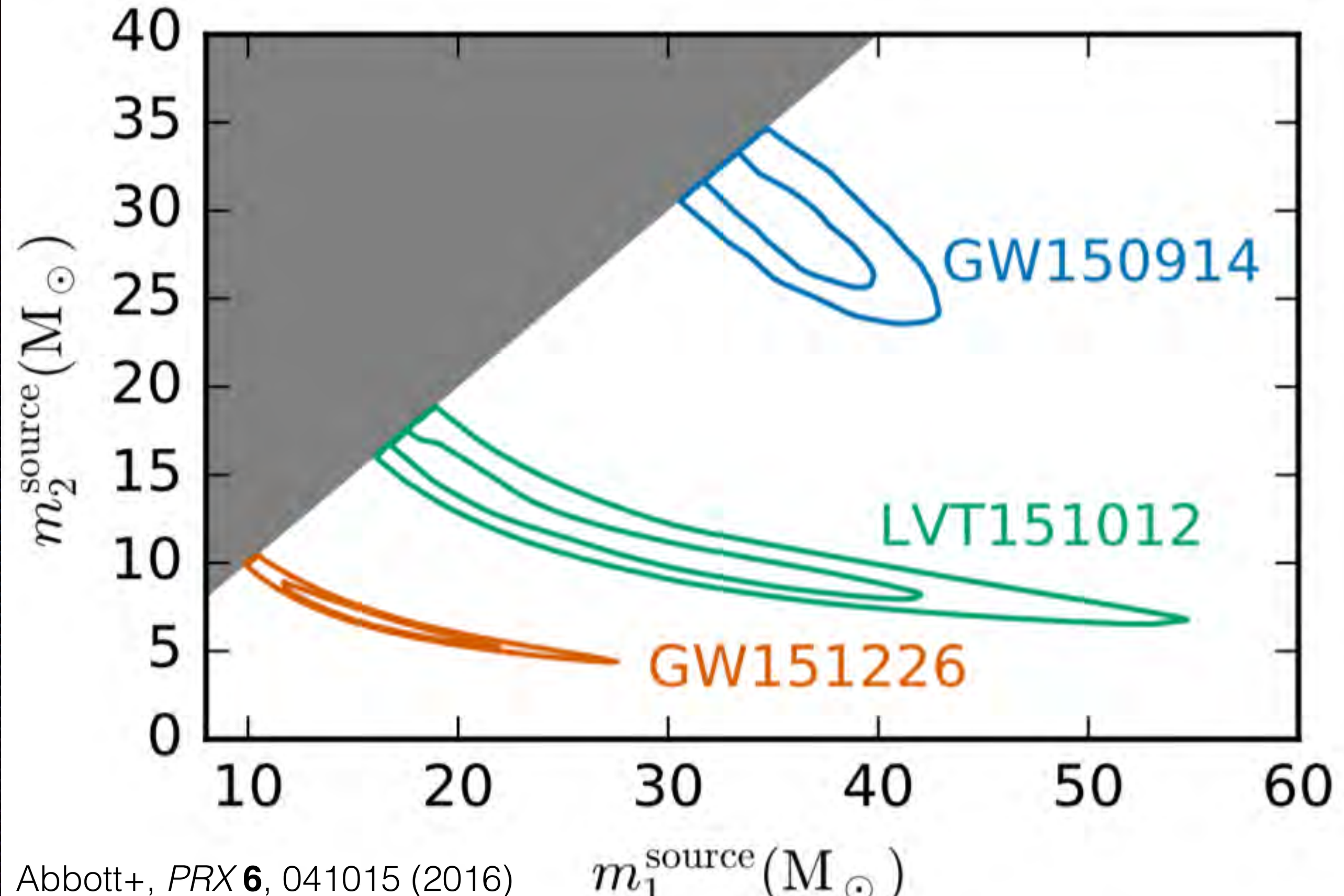


Abbott+, *PRL* **116**, 221101 (2016)

- Weak evidence for ringdown

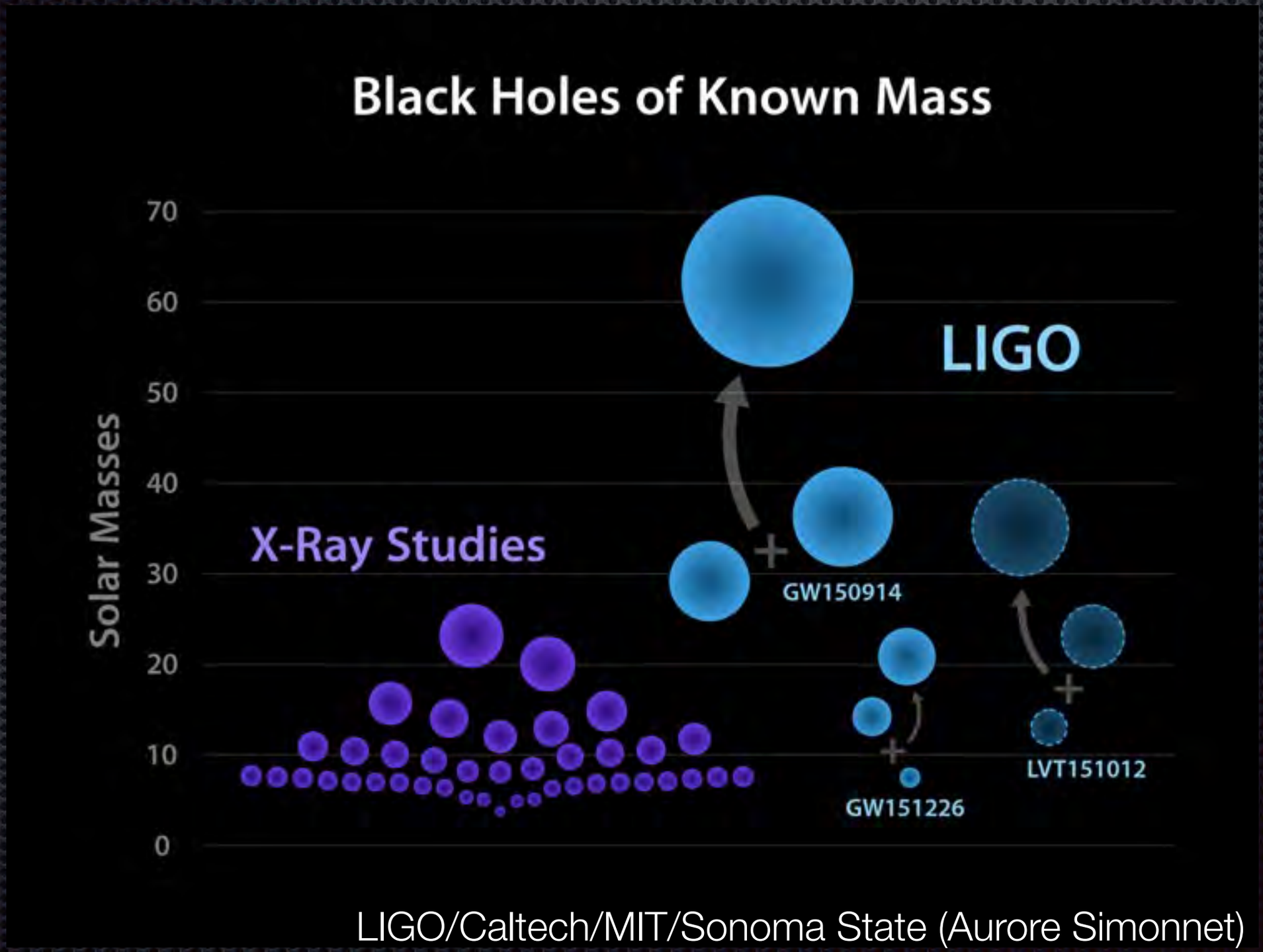
What has been detected?

Black hole masses



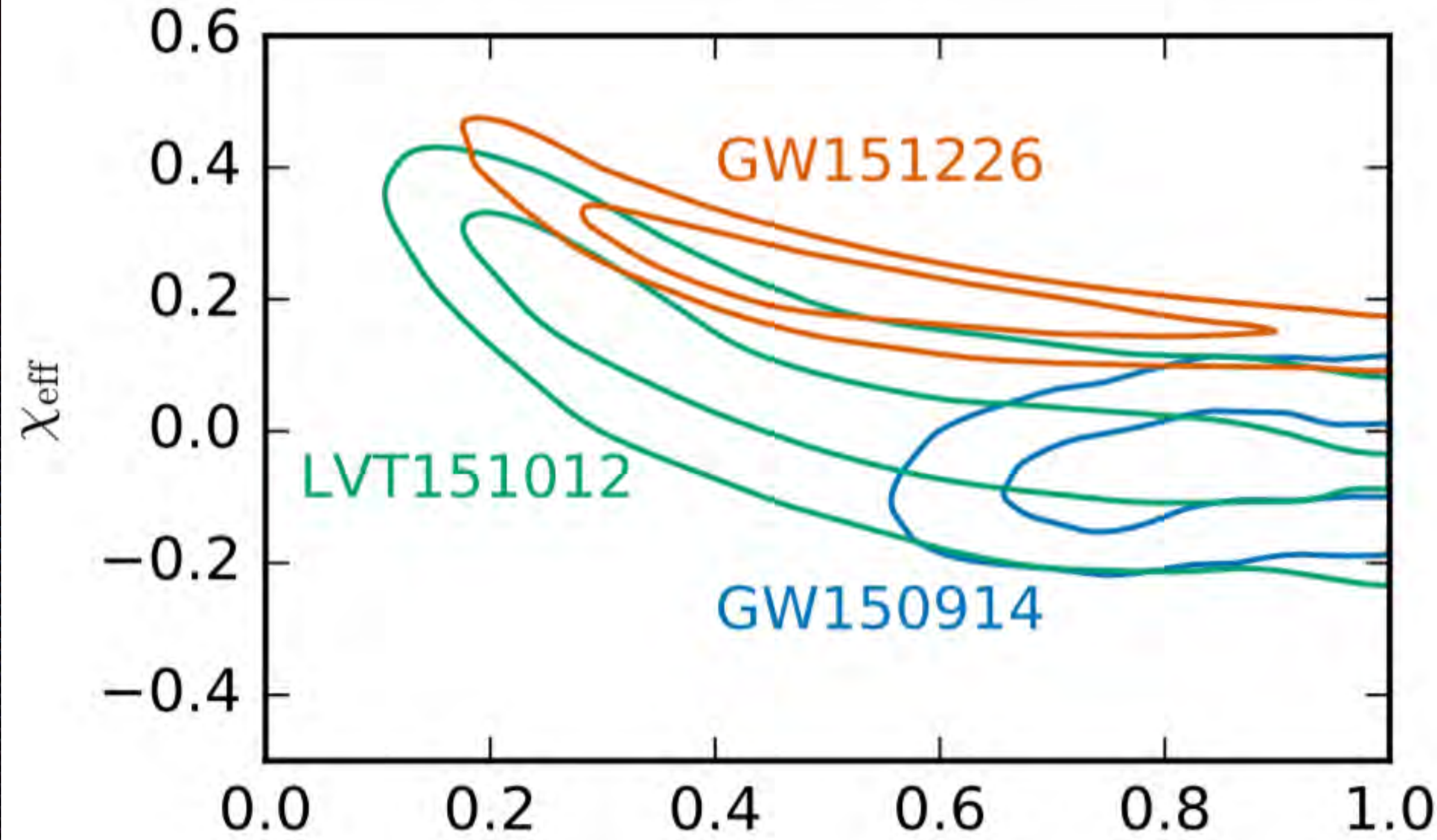
Abbott+, *PRX* **6**, 041015 (2016)

The masses of all known stellar black holes



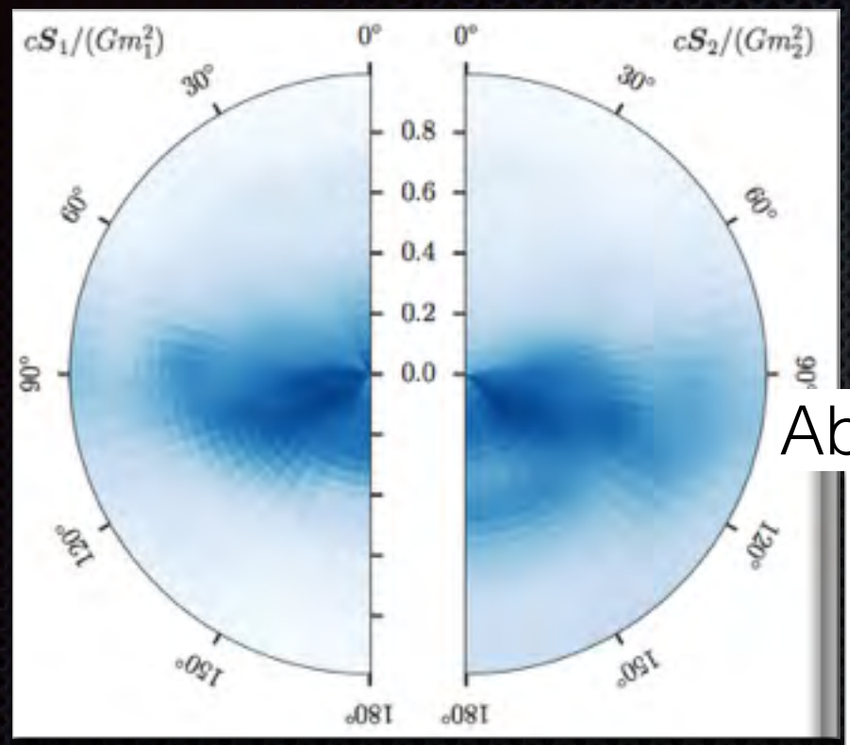
LIGO/Caltech/MIT/Sonoma State (Aurore Simonnet)

Black hole spins/mass ratios



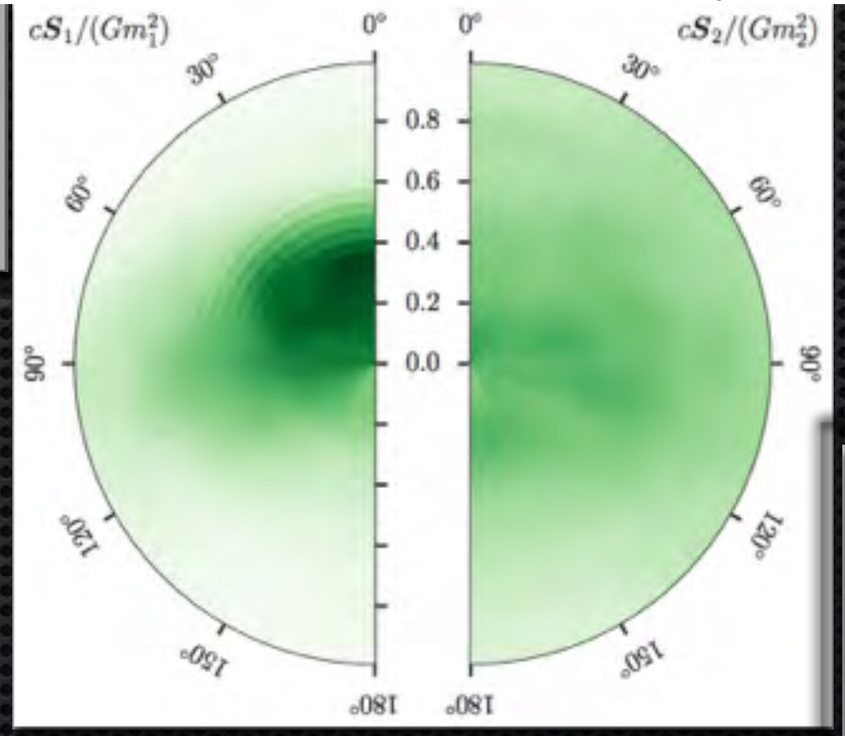
Abbott+, *PRX* **6**, 041015 (2016)

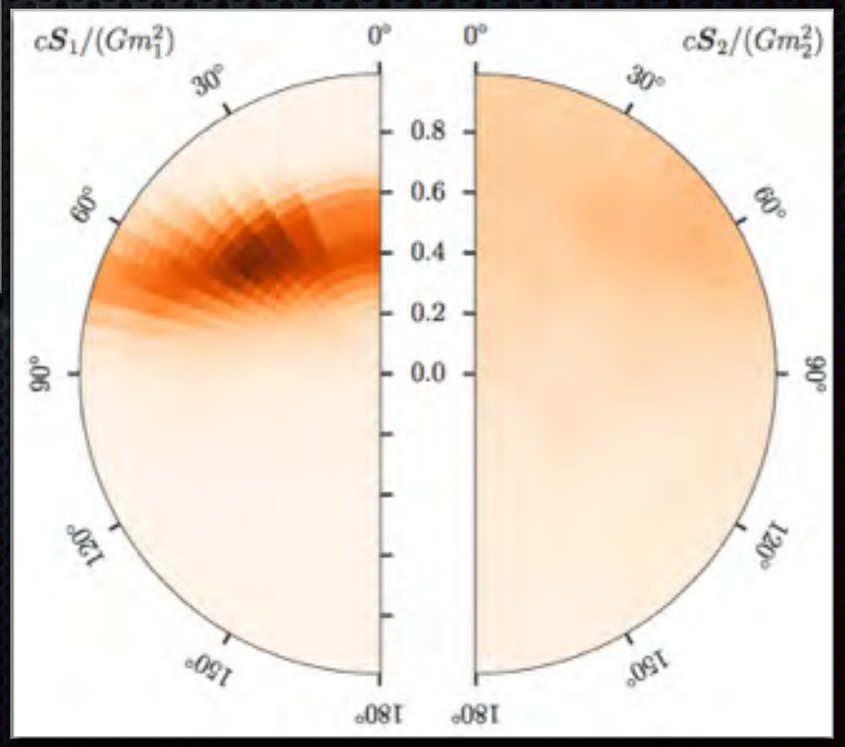
Spins of the three events



Not all BHs in the Universe are extremal Kerr!

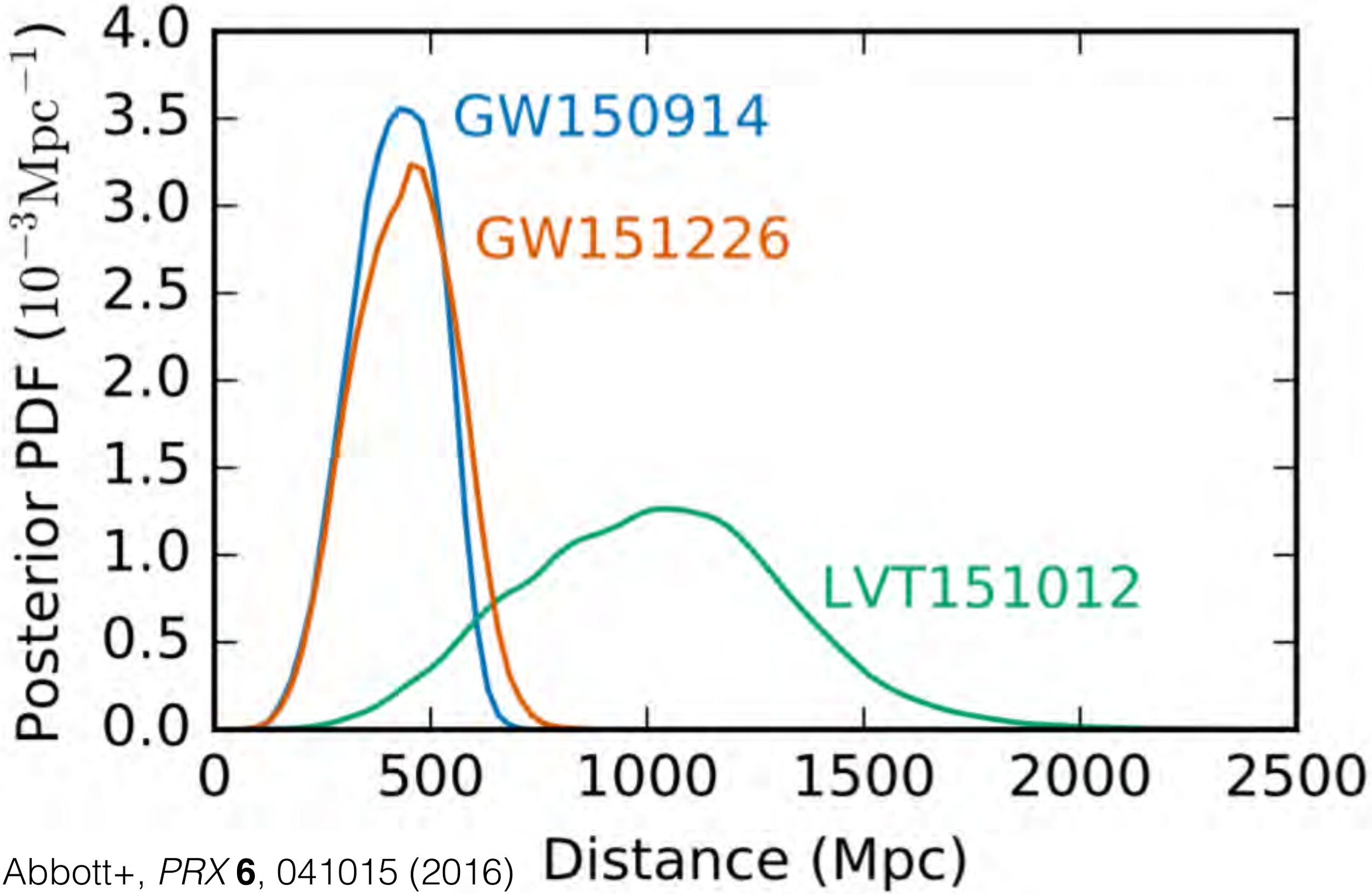
Abbott+, *PRX* **6**, 041015 (2016)





Not all BHs in the Universe are Schwarzschild!

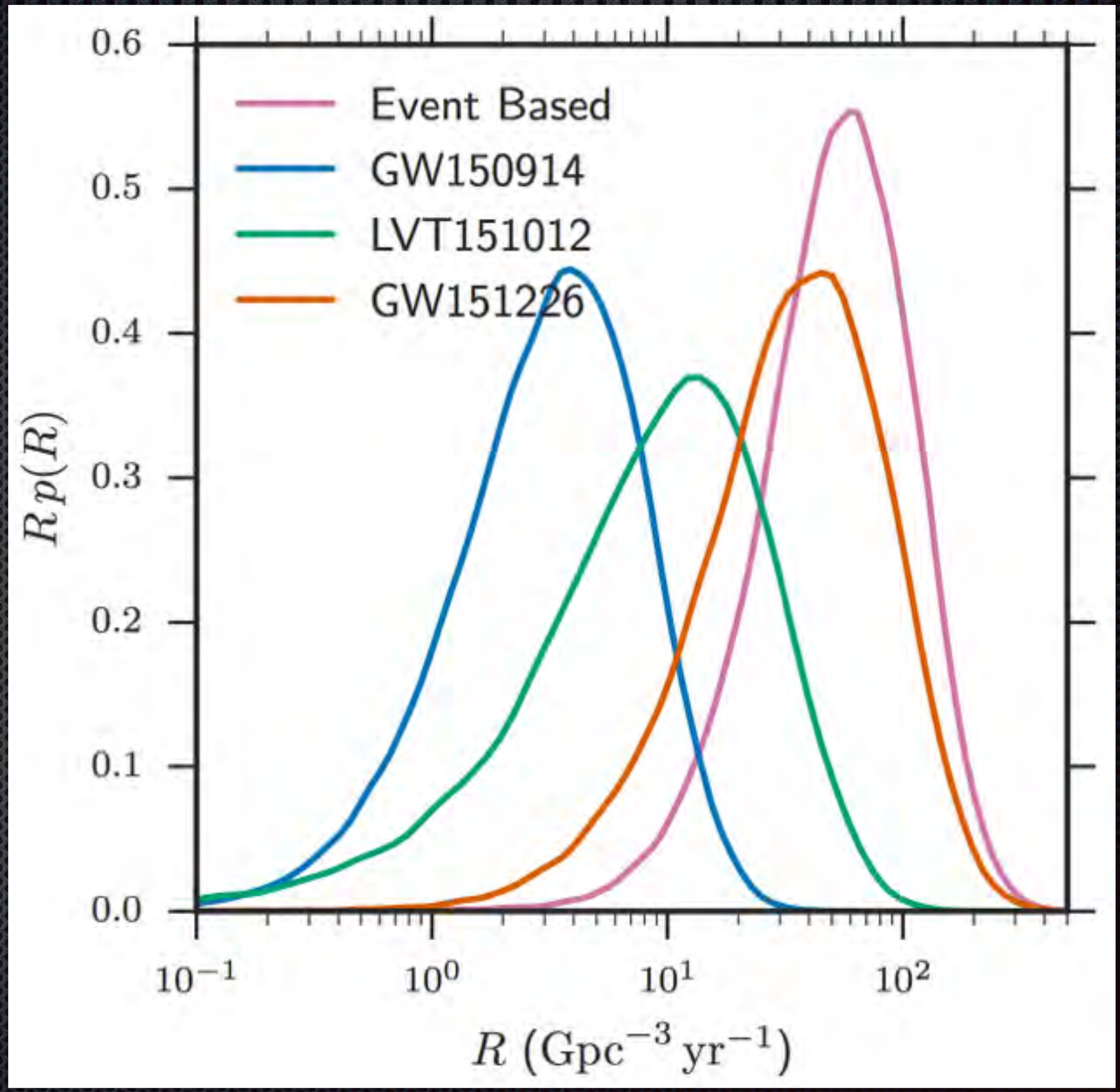
Black hole distances



Abbott+, *PRX* **6**, 041015 (2016)

BBH event rate density

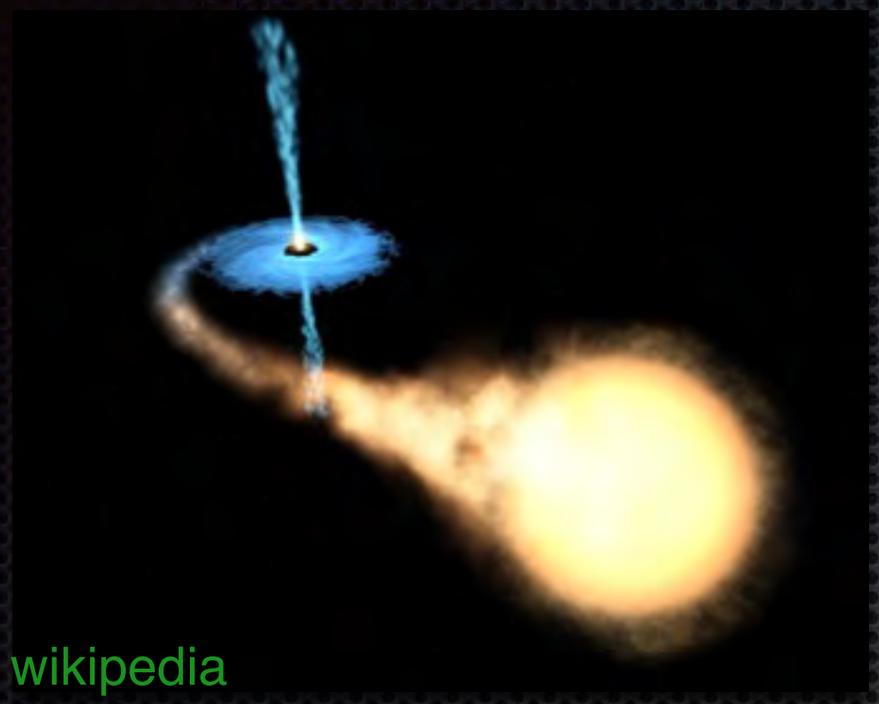
- Combined rate of $\lesssim 10\,\mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$ is excluded
- Will improve rapidly with additional observations



Abbott+, *PRX* **6**, 041015 (2016)

How does the Universe make these black holes?

Two formation channels



wikipedia

Isolated

- Progenitors stars form in binary
- Mass transfer, supernovae, common-envelope (or homogeneous evolution? Pop III?)

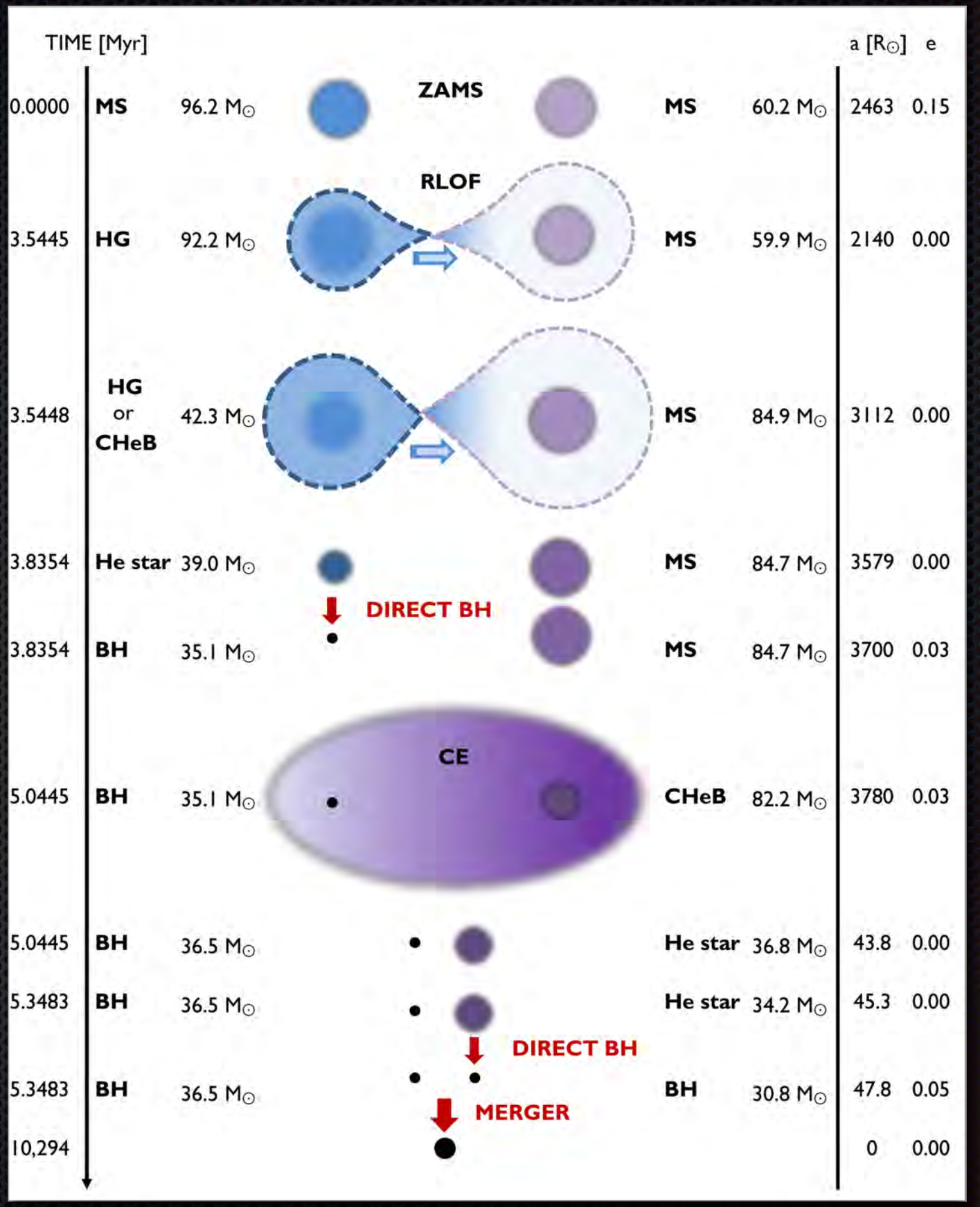
Dynamical

- Black holes segregate towards center
- Dynamical interaction: black holes form binaries, three body interactions harden and (sometimes) eject binaries

AURA/STSci/NASA

How did the Universe make these black holes?

- Example of a binary similar to GW150914, from birth, through evolution, to merger
- Lots of complicated astrophysics!



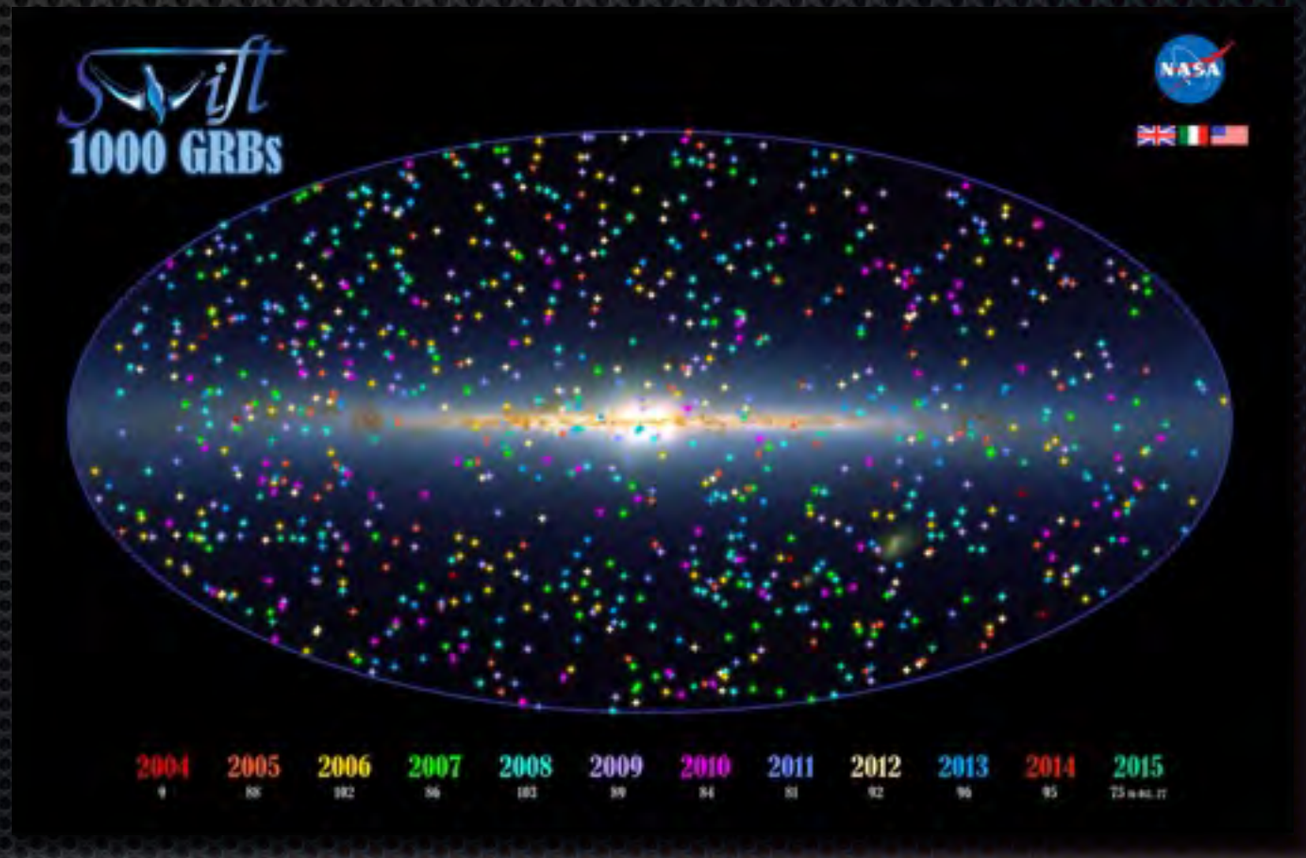
Belczynski, DH, Bulik, & O'Shaughnessy, *Nature* (2016)

Can we see these sources?

Do counterparts exist?

Binary neutron stars/neutron-star black holes

- Gamma-ray bursts
- X-ray bursts
- Optical afterglows/ kilonovae
- Radio counterparts
- ?

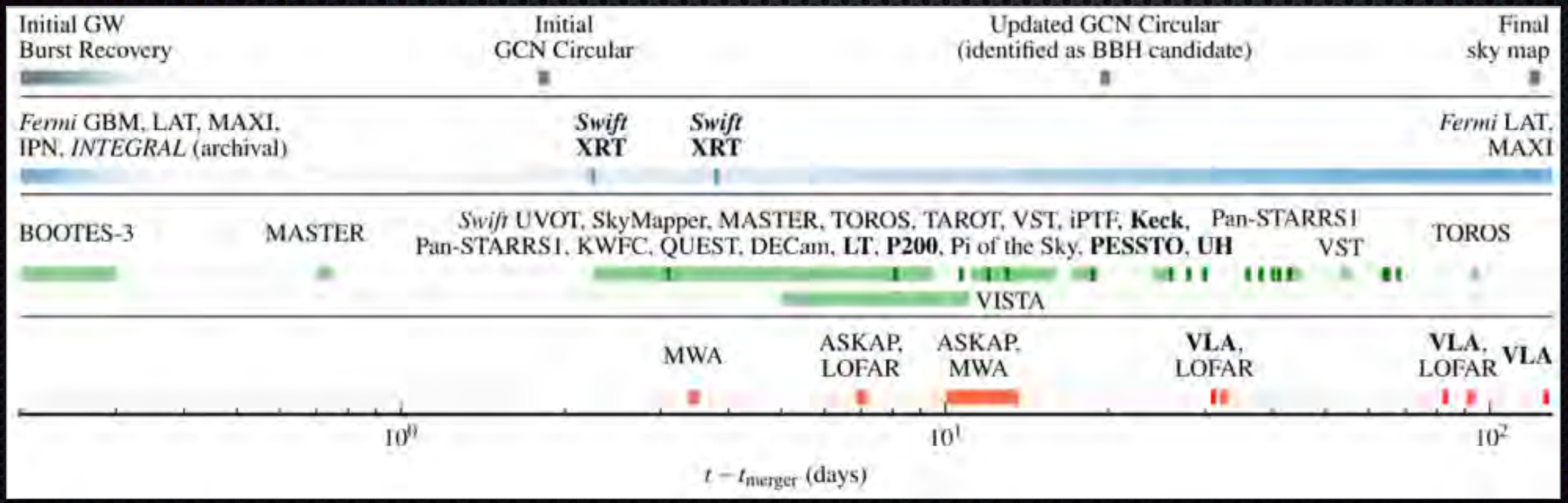


Do counterparts exist?

Binary black holes

?

Looking for counterparts to GW150914

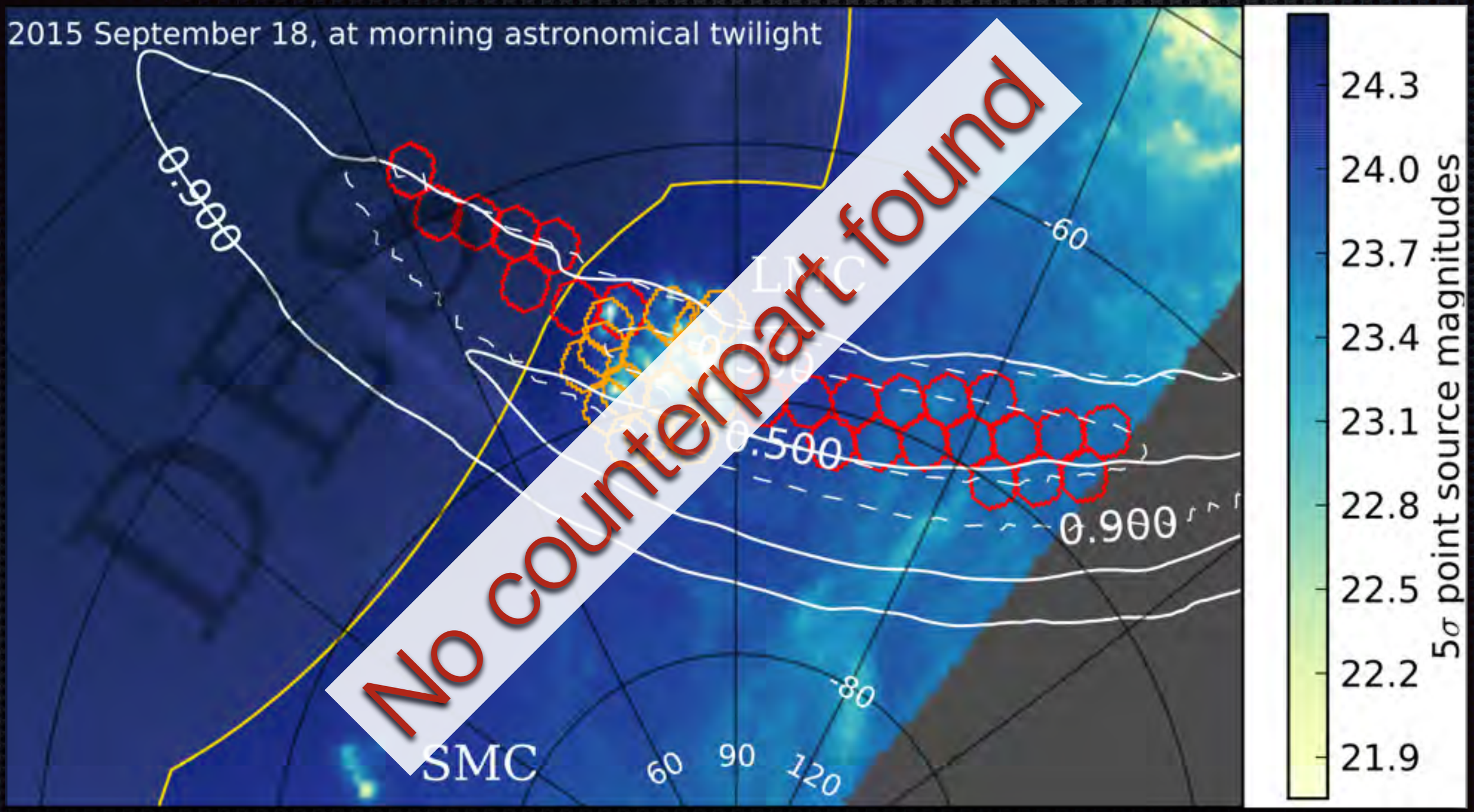


- Alert sent within 48 hours (for first GW event ever, and during engineering run)
- Over 20 EM partners responded

Abbott+ *ApJL* **826**, L13 (2016)

DECam follow-up

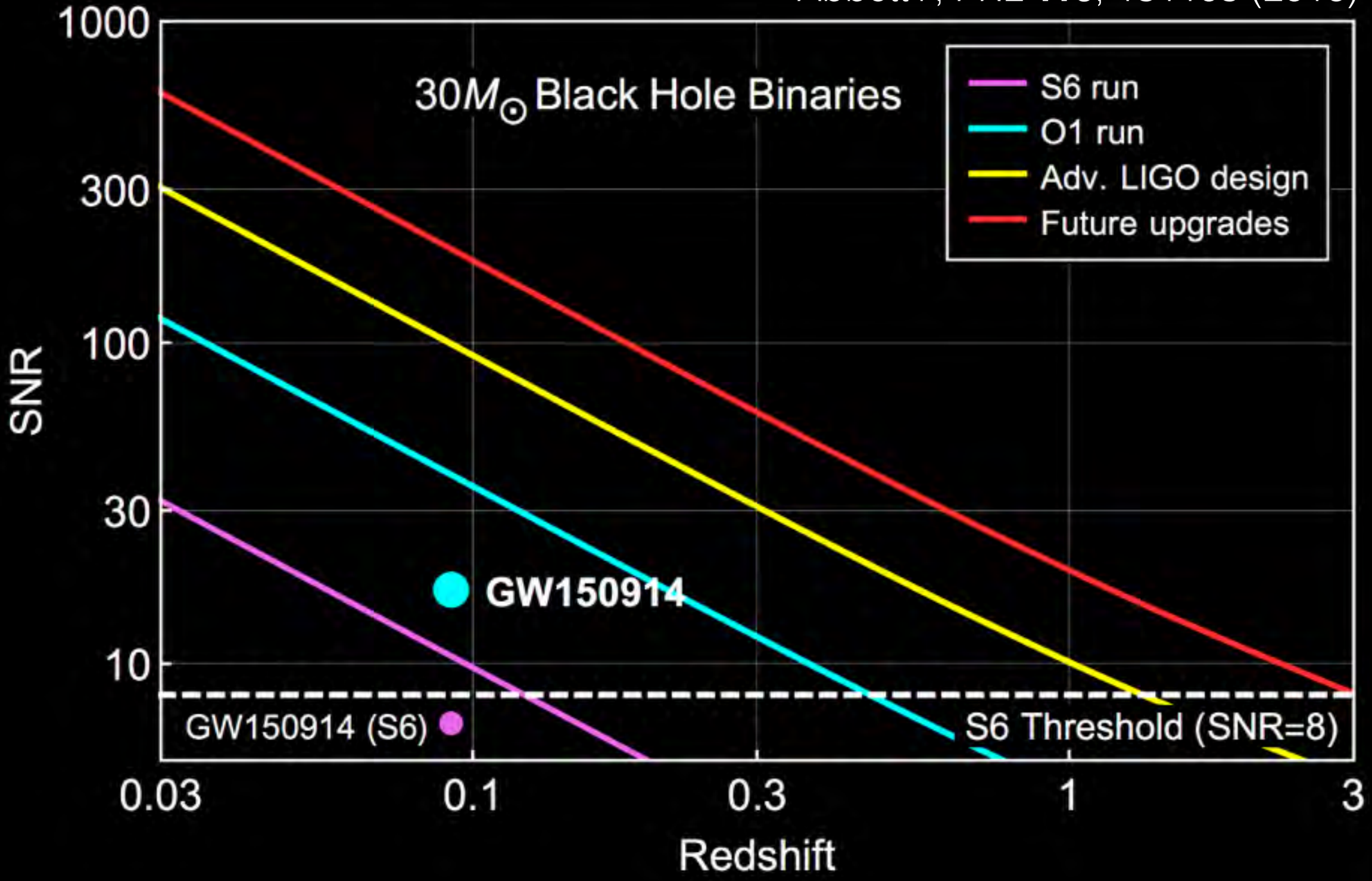
Soares-Santos+, *ApJL* 2016
Annis+, *ApJL* 2016
Cowperthwaite+, *ApJL* 2016



- Covered ~100 deg^2 to ~22 mag (*i* and *z* band)
- Covered ~38%/11% of initial/final probability map

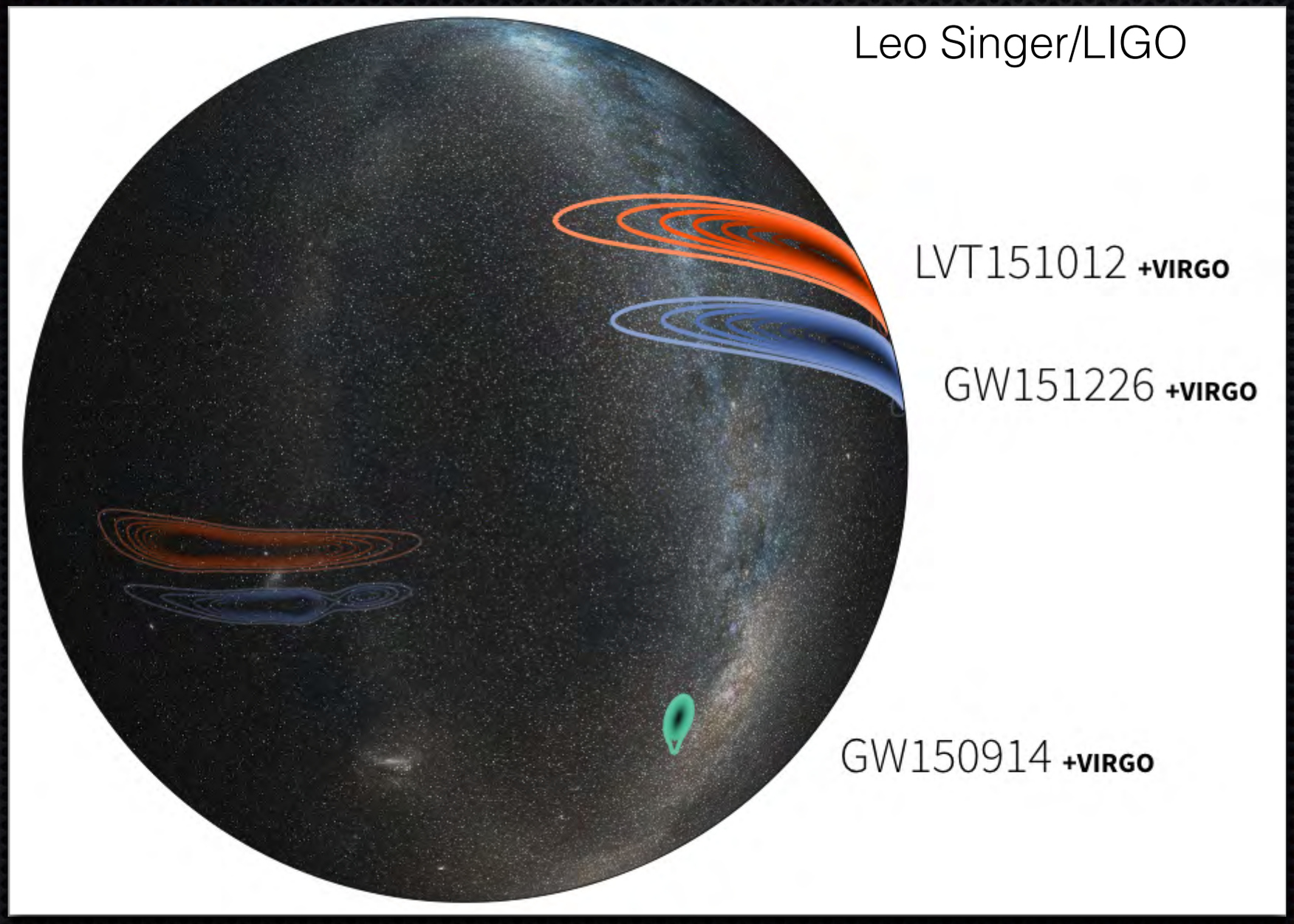
What happens next?

Abbott+, *PRL* **116**, 131103 (2016)



- We rapidly go from detecting none, to detecting a handful, to detecting a large fraction of all the BBHs in the Universe

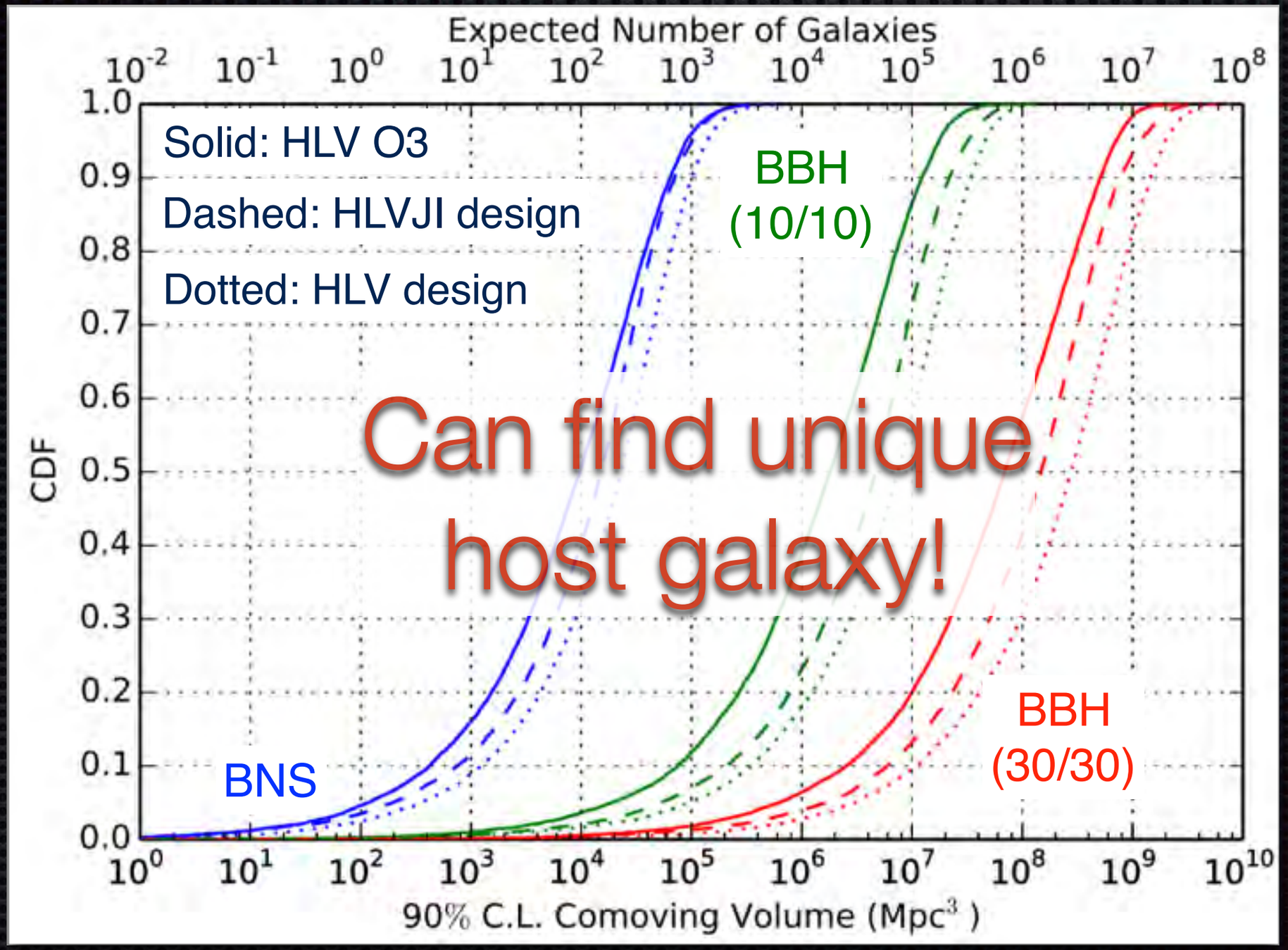
Sky areas will get smaller



- Virgo, and other additional detectors, would dramatically improve localization

Finding the one

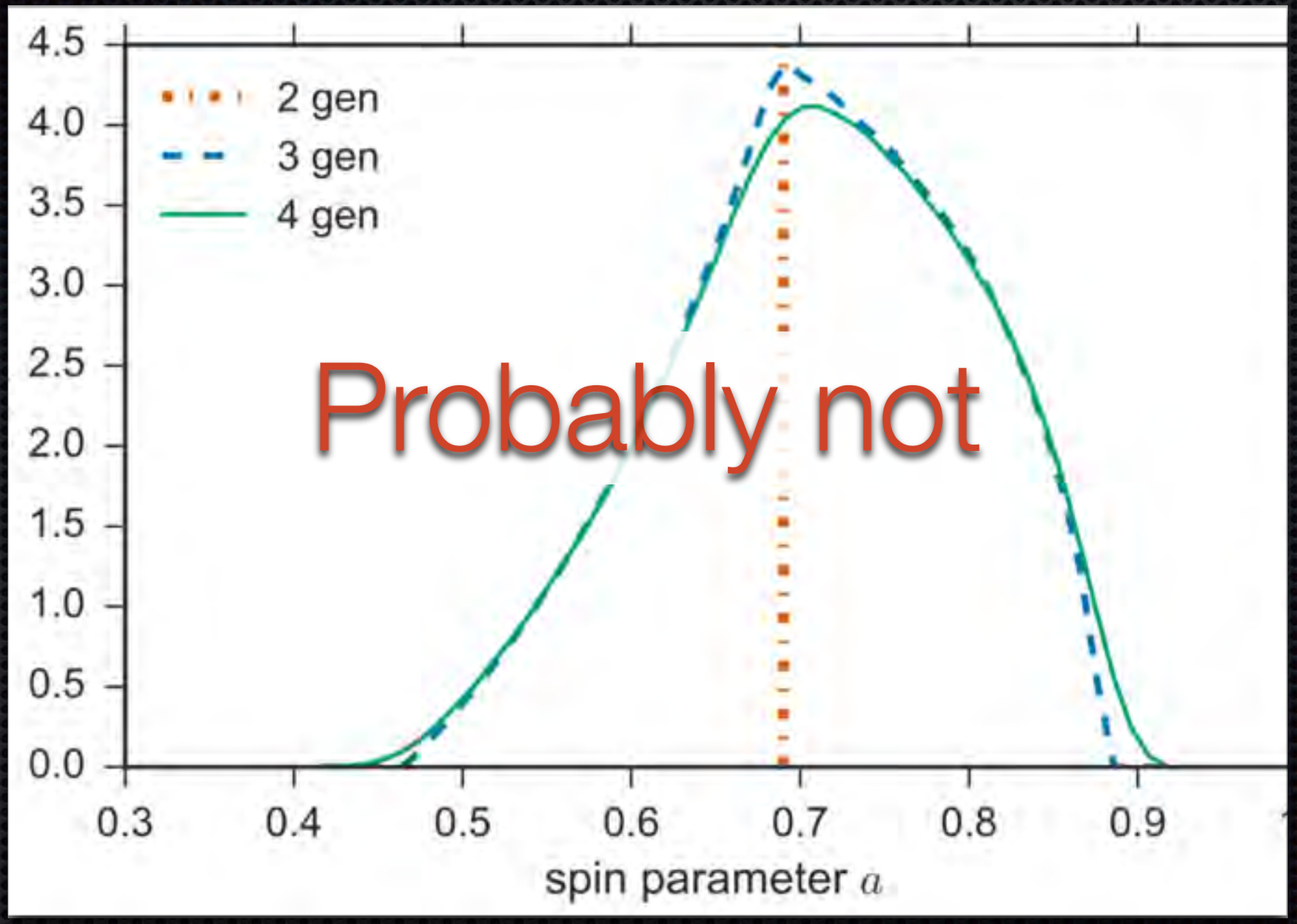
Chen & Holz, *ApJ* in press (2017)



- Low latency 3D localization: sky location + distance
- Some sources are very well localized

Are the LIGO BHs made from smaller BHs?

Fishbach, DH, & Farr, *ApJL* in press (2017)



- Orbital angular momentum dominates
- Universal distribution of final black hole spin, robust to changes in initial spins, mass ratio, number of mergers, etc.

Where is GW astro headed?

- tens or hundreds of detections
- mass/mass ratio distribution
- spin/spin alignment distribution
- rate/evolution with redshift

- constrain models of BH formation/evolution
- NSs? mass gap? EOS?
- EM counterparts?
- host galaxy properties?
- standard sirens/H_0?
- test gravity with high-SNR golden events
- stochastic background?
- supernovae?
- surprises?!