Latest Results from Advanced LIGO's First Observing Run

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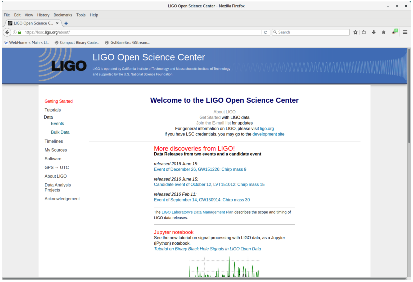
September 23, 2016

Links to Information

- LIGO Open Science Center (LOSC): `https://losc.ligo.org`
- Includes links to papers, LIGO strain data, plots, posters, audio files.
- Papers: `https://www.ligo.caltech.edu/page/publications`
- I will focus on "GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence" Phys. Rev. Lett. 116.241103, arXiv:1606.04855 [gr-qc]
- and "Binary Black Hole Mergers in the first Advanced LIGO Observing Run", arXiv:1606.04856 [gr-qc]



LIGO Open Science Center

LIGO is operated by California Institute of Technology and Massachusetts Institute of Technology and supported by the U.S. National Science Foundation.

Welcome to the LIGO Open Science Center

About LIGO
Get Started with LIGO data
Join the E-mail list for updates
For general information on LIGO, please visit ligo.org
If you have LSC credentials, you may go to the development site

More discoveries from LIGO!
Data Releases from two events and a candidate event

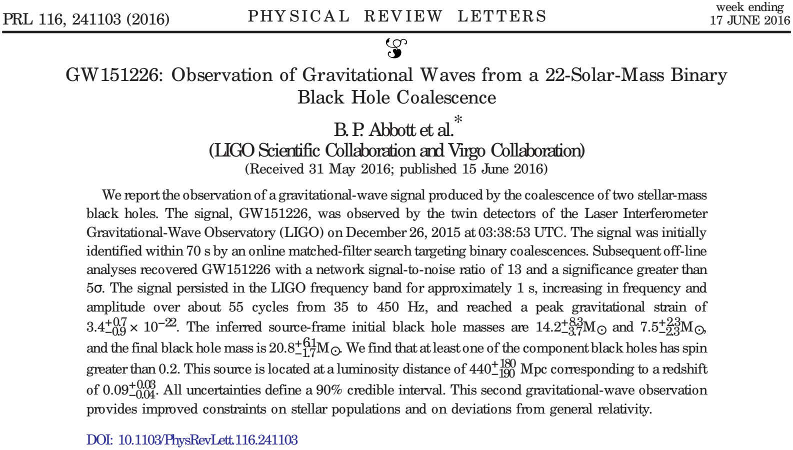
released 2016 June 15:
Event of December 26, GW151226: Chirp mass 9

released 2016 June 15:
Candidate event of October 12, LVT151012: Chirp mass 15

released 2016 Feb 11:
Event of September 14, GW150914: Chirp mass 30

The LIGO Laboratory's Data Management Plan describes the scope and timing of LIGO data releases.

Jupyter notebook
See the new tutorial on signal processing with LIGO data, as a Jupyter (iPython) notebook.
Tutorial on Binary Black Hole Signals in LIGO Open Data



PRL 116, 241103 (2016) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2016

GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence

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

(Received 31 May 2016; published 15 June 2016)

We report the observation of a gravitational-wave signal produced by the coalescence of two stellar-mass black holes. The signal, GW151226, was observed by the twin detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) on December 26, 2015 at 03:38:53 UTC. The signal was initially identified within 70 s by an online matched-filter search targeting binary coalescences. Subsequent off-line analyses recovered GW151226 with a network signal-to-noise ratio of 13 and a significance greater than 5σ. The signal persisted in the LIGO frequency band for approximately 1 s, increasing in frequency and amplitude over about 55 cycles from 35 to 450 Hz, and reached a peak gravitational strain of $3.4^{+0.7}_{-0.9} \times 10^{-22}$. The inferred source-frame initial black hole masses are $14.2^{+8.3}_{-3.7} M_\odot$ and $7.5^{+2.3}_{-2.3} M_\odot$, and the final black hole mass is $20.8^{+6.1}_{-1.7} M_\odot$. We find that at least one of the component black holes has spin greater than 0.2. This source is located at a luminosity distance of 440^{+180}_{-190} Mpc corresponding to a redshift of $0.09^{+0.03}_{-0.04}$. All uncertainties define a 90% credible interval. This second gravitational-wave observation provides improved constraints on stellar populations and on deviations from general relativity.

DOI: 10.1103/PhysRevLett.116.241103

DOI: `http://dx.doi.org/10.1103/PhysRevLett.116.241103`

Gravitational Waves and Advanced LIGO

- 1915: Albert Einstein publishes Lorenz-invariant theory of gravity as dynamic curvature of spacetime, “general relativity”.
- 1915: Karl Schwartzchild publishes first solution of GR field equations, what we now know to describe a black hole.
- 1916: Albert Einstein publishes wave solution of weak-field GR.
- 1960s: Joseph Weber pioneers resonant bar antennas for GW detection.
- 1960s,1970s: use of laser interferometers for GW detection described, first prototypes constructed.
- 1992: LIGO project founded.
- 2001-2010: 6 observing runs, joint analyses with GEO600, Virgo and TAMA interferometers, as well as with resonant bar detectors.
- Other GW detection efforts: pulsar timing, CMB polarization.
- 2015 September: Advanced LIGO’s first observing run.
- 2016 February (=1916 + 100 years): initial results published.

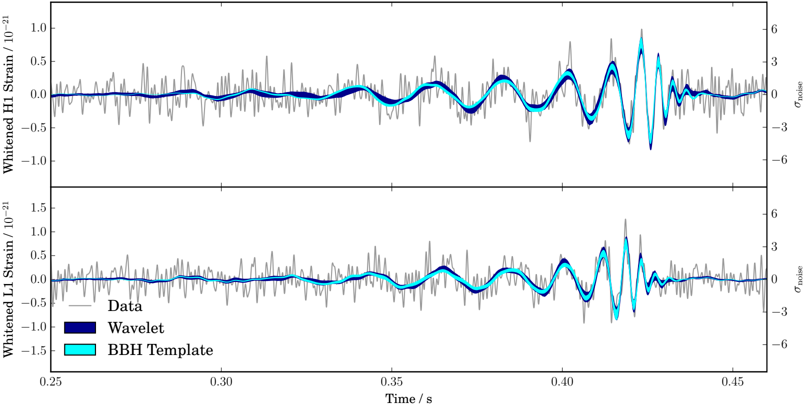
GW150914: Detection

- Early September 2015 was “engineering run”: detectors and analysis software undergoing final shake-down before science data collection.
- Morning of Monday, September 14, 2015 at 09:50:45 UTC, 04:50:45 local time LLO, 02:50:45 local time LHO, the low-latency burst search “cWB” registered a moderate-significance candidate, apparently the merger of a pair of black holes.
- Candidate uploaded to candidate database with latency of about $3\,\mathrm{min}$.
- Neither low-latency compact object search running at that time identified a candidate. Compact objects group had chosen to restrict scope to low-mass systems (involving at least one neutron star) — confusion because collaboration was mostly unaware of this decision.
- On Wednesday, September 16, at about 17:00 UTC after two days of wondering about data quality and candidate’s significance, a notice was manually distributed to electromagnetic partner telescopes. Automatic alert system had been disabled for the engineering run.

GW150914: Detection

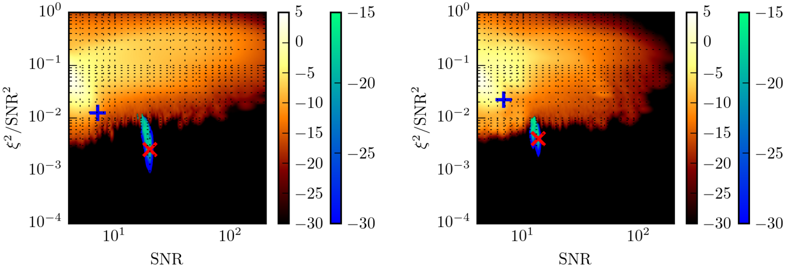
- 16 days of coincident data collection was required for compact object detection codes to estimate the candidate's false-alarm rate accurately enough to establish the candidate as a detection.
- During the 16 day period, a second binary black hole merger candidate was identified. False-alarm probability is a few percent: not significant enough for a detection claim on its own, more on this later.
- Second candidate was *also* on a Monday (October 12) — the two became known as "first Monday", and "second Monday".

GW150914: Detection



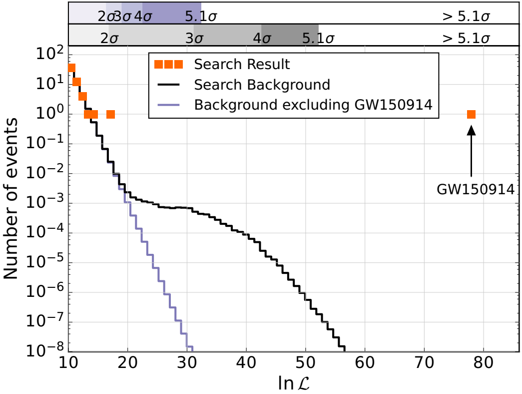
From LIGO-P1500218. Whitened time series. Times are relative to 09:50:45 UTC, vertical scale (on right) is standard deviations from the mean. Data, and 90% credible region from BBH parameter estimation reconstruction are shown.

GW150914: Detection



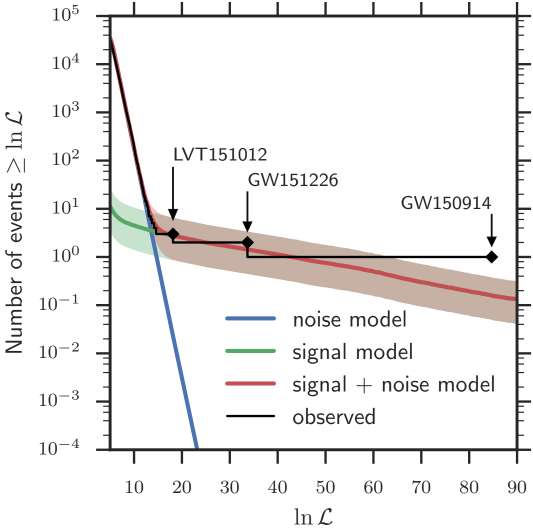
From LIGO-P1500269. Left = H1; right = L1. Horizontal axis is SNR, vertical axis is measure of magnitude of residual after subtraction of candidate from data — parallel and perpendicular components of data with respect to model waveform. Pink marker = first Monday; blue = second Monday. Orange = standard noise model (first Monday's significance is "off the charts"); blue/green = modified noise model assuming GW150914 is a sample drawn from the noise. **False-alarm probability** $\leq 1.4 \times 10^{-11}$.

GW150914: Detection



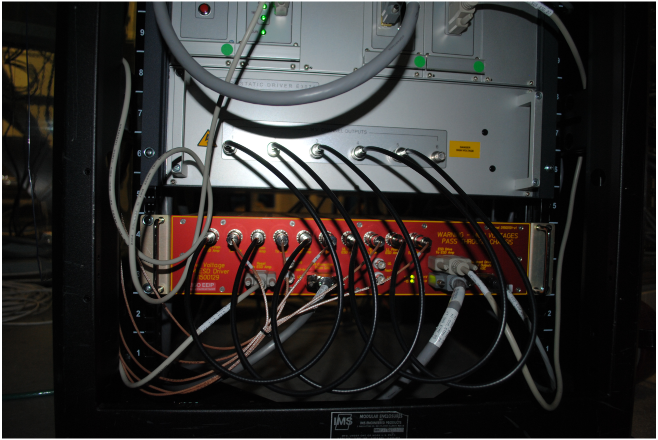
From LIGO-P1500269. Event count *binned by ranking statistic* (meaningless!). Blue = standard, black = modified noise model; orange = observed counts in bins. Bars across top indicate statistical significance in "sigmas" for the two noise models.

GW151226: Detection



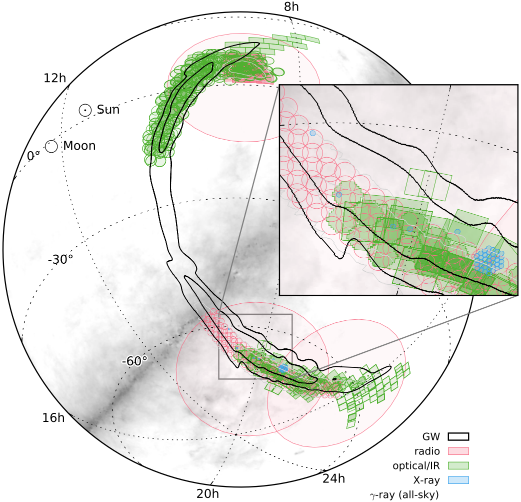
From LIGO-P1600088. Cumulative event count. Blue = noise model; black = observed counts (height above blue indicates significance); green = inferred signal model; red = signal + noise.

Importance of Low-Latency Analysis



- It's how we now know it wasn't artificial.

Importance of Low-Latency Analysis



- EM follow-up happened.
- Already O(10) non-collaboration papers on arXiv analyzing the results.

GW151226: Properties

- Interpreting the observation requires us to assume we understand the physics of the source.
- If our assumptions are incorrect, our interpretations can be incorrect.
- We employ two different phenomenological models calibrated to numerical relativity simulations to infer the source' properties.
- We also look for evidence of a departure from general relativity to constrain GR.

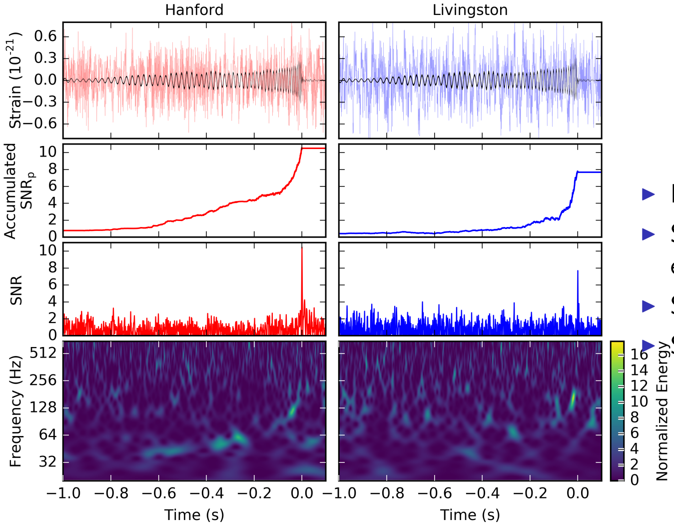
Cat found

Found in the rain was very cold and wet
I let him inside and tried to feed him. Male, not
very friendly.

Gray and black, found him on grand boulevard
and 8th street

Is he yours? Call 604-970-2105

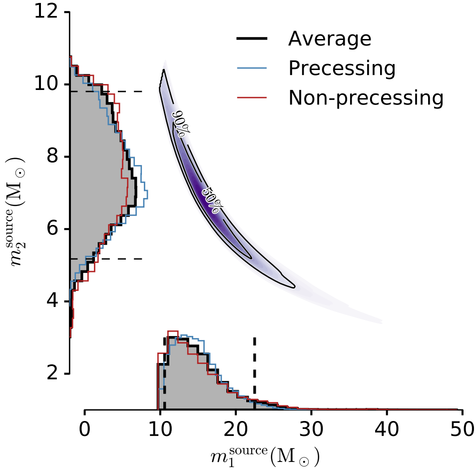
GW151226: Properties



- Filtered data.
- SNR integral vs. end time.
- SNR vs. time.
- Spectrogram.

From LIGO-P151226

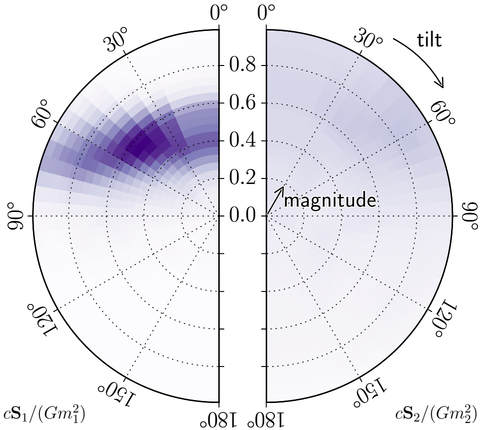
GW151226: Properties



From LIGO-P151226

- Source-frame masses: $14.2^{+8.3}_{-3.7}\,\mathrm{M}_\odot$, $7.5^{+2.3}_{-2.3}\,\mathrm{M}_\odot$.
- Differ from Earth-frame masses by about 10% due to red-shift: red-shift lowers frequency of received signal, makes signal appear to have come from higher-mass black holes.

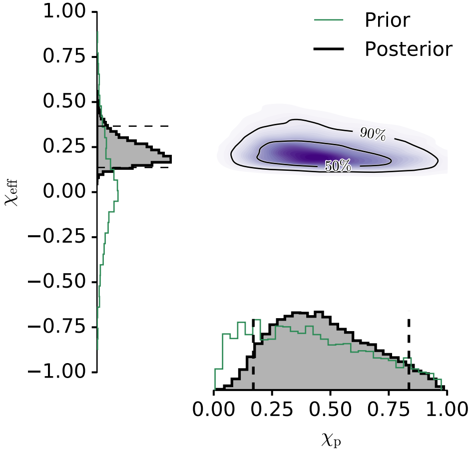
GW151226: Properties



From LIGO-P151226

- Spin magnitudes and angles from orbit axis.
- Prior is uniform in these co-ordinates.
- Primary hole (#1) is definitely spinning.
- No definitive evidence for or against spin-orbit alignment.

GW151226: Properties



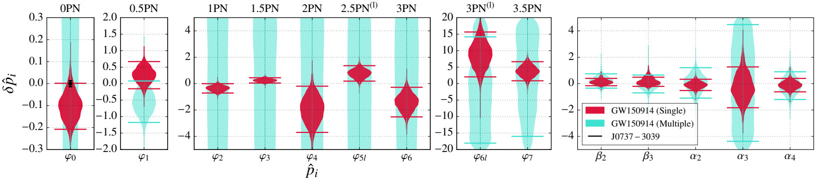
- Mass-weighted orbit-aligned spin (vertical) and in-plane spin (horizontal).

From LIGO-P151226

Constraining General Relativity

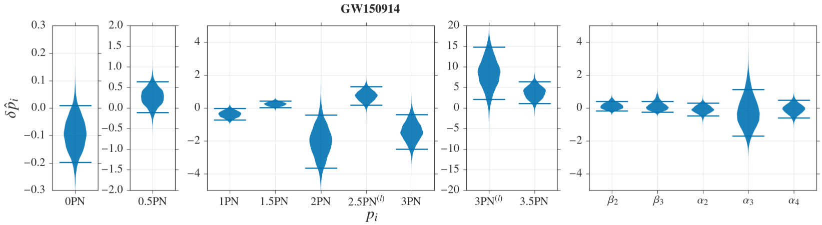
- At this time we lack the ability to directly connect our observations to the field equations of GR. We adopt a phenomenological waveform model that has been tuned to fit NR simulations, allow that model's parameters to vary and use GW150914 to infer posterior PDFs for the departures from the GR values.

Constraining General Relativity



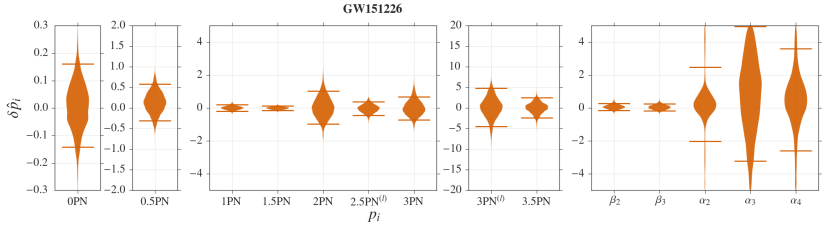
From LIGO-P1500213. Posterior PDFs for departures of parameters in "gIMR" phenomenological waveform model from GR values. Red = varying only that one parameter; cyan = allowing all parameters to vary. From left to right the parameters are related to higher-frequency, later, parts of the waveform. The components related to the merger and ring-down (right-most box) are best constrained. Only the φ_0 parameter (at far left) has been meaningfully constrained previously, via observations of the evolution of the double pulsar J0737-3039 (small black marker indicates constraint).

Constraining General Relativity



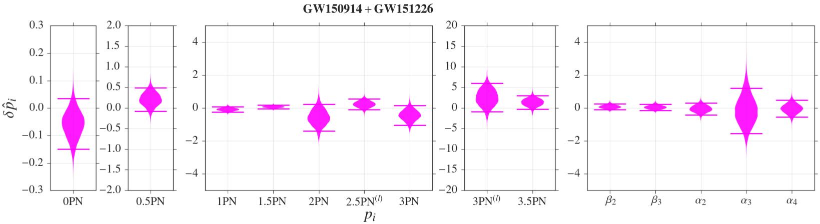
- See LIGO-P1600088.

Constraining General Relativity



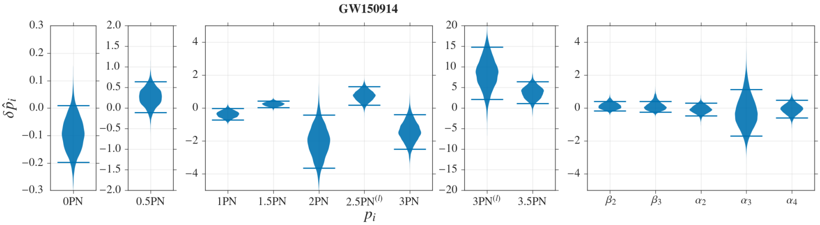
- See LIGO-P1600088.

Constraining General Relativity



- See LIGO-P1600088.

Constraining General Relativity



- See LIGO-P1600088.

Constraining General Relativity

- GR predicts only two polarization states for GWs.
- GW antennas are (generally) sensitive to a single polarization component.
- A network of antennas, each sensitive to a different polarization component, can be used to count the number of degrees of freedom in the wave field.
- LIGO has only two antennas that have been constructed to be as aligned with one another as is practical given the curvature of the Earth.
- No ability to constrain the number of polarization states, cannot even say there are 2 (LIGO-only data can be made consistent with a single polarization).
- Look forward to Virgo *and KAGRA* joining the network to enable this very important exploration of general relativity.

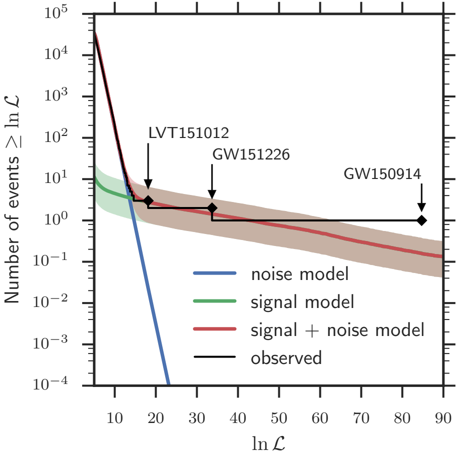
Binary Black Hole Merger Rate

- On Monday October 12 2015 a second candidate was identified.
- Found approximately 10 days after the fact with offline compact object search codes (low-latency BBH search was still not enabled).
- Low significance, false-alarm probability of 2%. Too quiet to be found with burst searches.
- Would have been disregarded except that in a world in which we believe we have built GW detectors and that sources of sufficient brightness exist in sufficient numbers for us to be detecting them, then this candidate is more correctly interpreted to be a signal.
- Has been designated LVT151012 (LIGO-Virgo Transient).
- Similar to GW150914: $(m_1, m_2) = (23^{+18}_{-5}, 13^{+4}_{-5})\mathrm{M}_\odot$ compared to $(m_1, m_2) = (36^{+5}_{-4}, 29^{+4}_{-4})\mathrm{M}_\odot$. Red shift ~ 0.2 compared to ~ 0.1.

Binary Black Hole Merger Rate

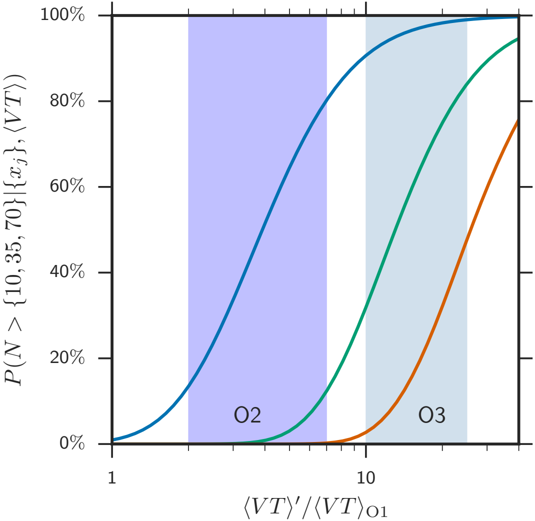
- The presence of the second candidate had a significant impact on the estimated number of detected signals in the data.
- See LIGO-P1500217.
- From the first 16 days we obtained a median and 90% credible interval of $4.8^{+7.9}_{-3.8}$ signals/experiment.
- The observation of GW151226 does not significantly alter the rate (lowers it a bit).

Binary Black Hole Merger Rate



- Horizontal axis is ranking statistic (log likelihood ratio).
- Vertical axis is number of events $\geq$ that threshold.
- GW150914 is an outlier.
- LVT151012 creates a consistent picture of a population of signals in the data.

Prospects for Future Observations



- Number of BBH merger detections projected for O2 and O3.

From LIGO-P1600088

What I Haven't Talked About

- Implications of BBH merger rate on spectrum and amplitude of stochastic GW background.
- The "burst" search efforts that initially identified the candidate.
- The instruments.
- The rest of O1 — these results are from only the BBH search, we have other mass ranges to publish.
- … and O2 starts soon …

THANK YOU