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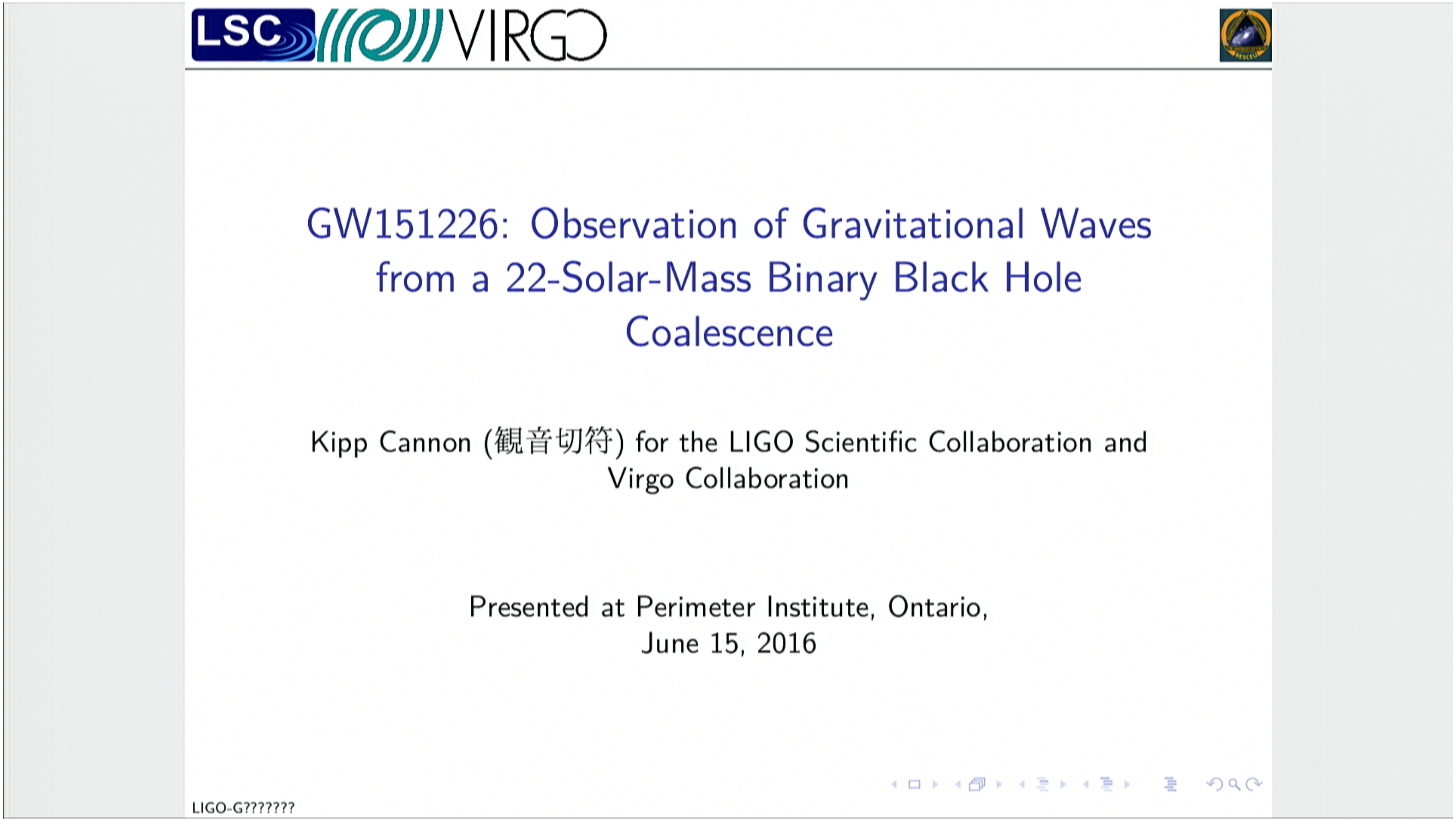
Abstract:



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

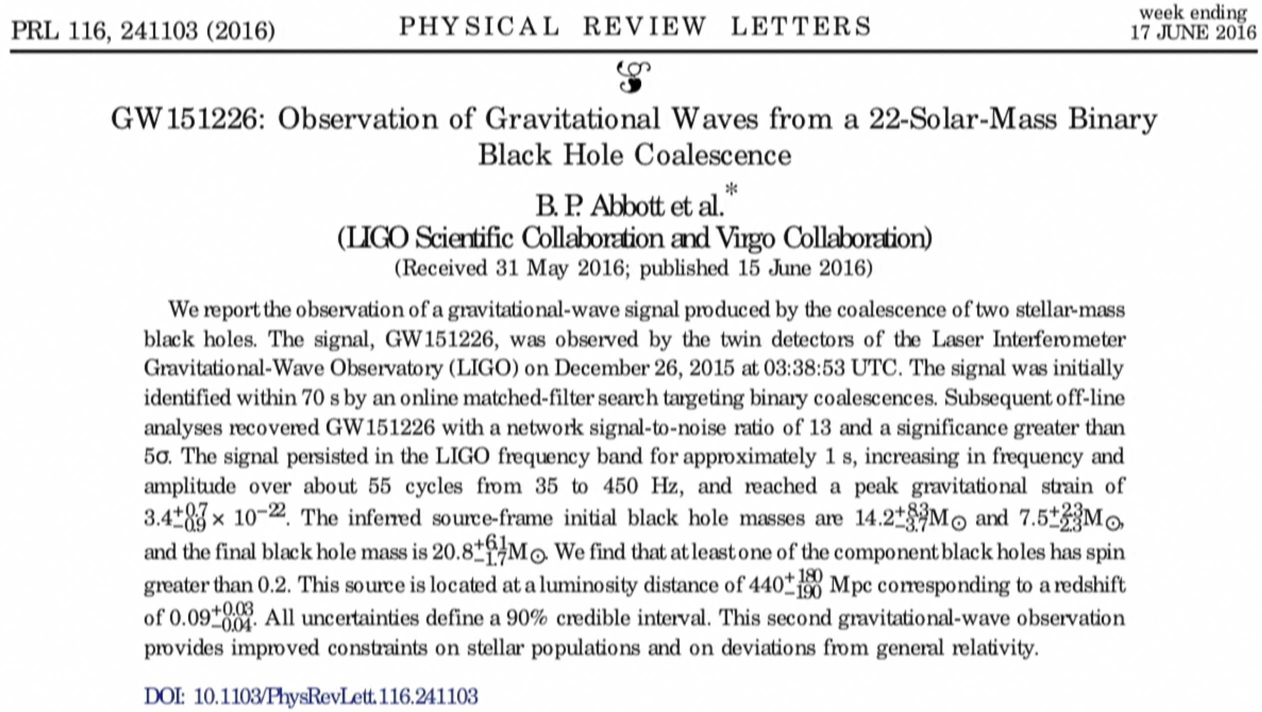
Kipp Cannon (観音切符) for the LIGO Scientific Collaboration and Virgo Collaboration

Presented at Perimeter Institute, Ontario,
June 15, 2016

LIGO-G???????

Links to Information

- Paper: https://dcc.ligo.org/P151226/public
- LIGO Open Science Center (LOSC): https://losc.ligo.org
- Includes links to companion papers, public release of LIGO strain data, plots, posters, audio files.



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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)

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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.

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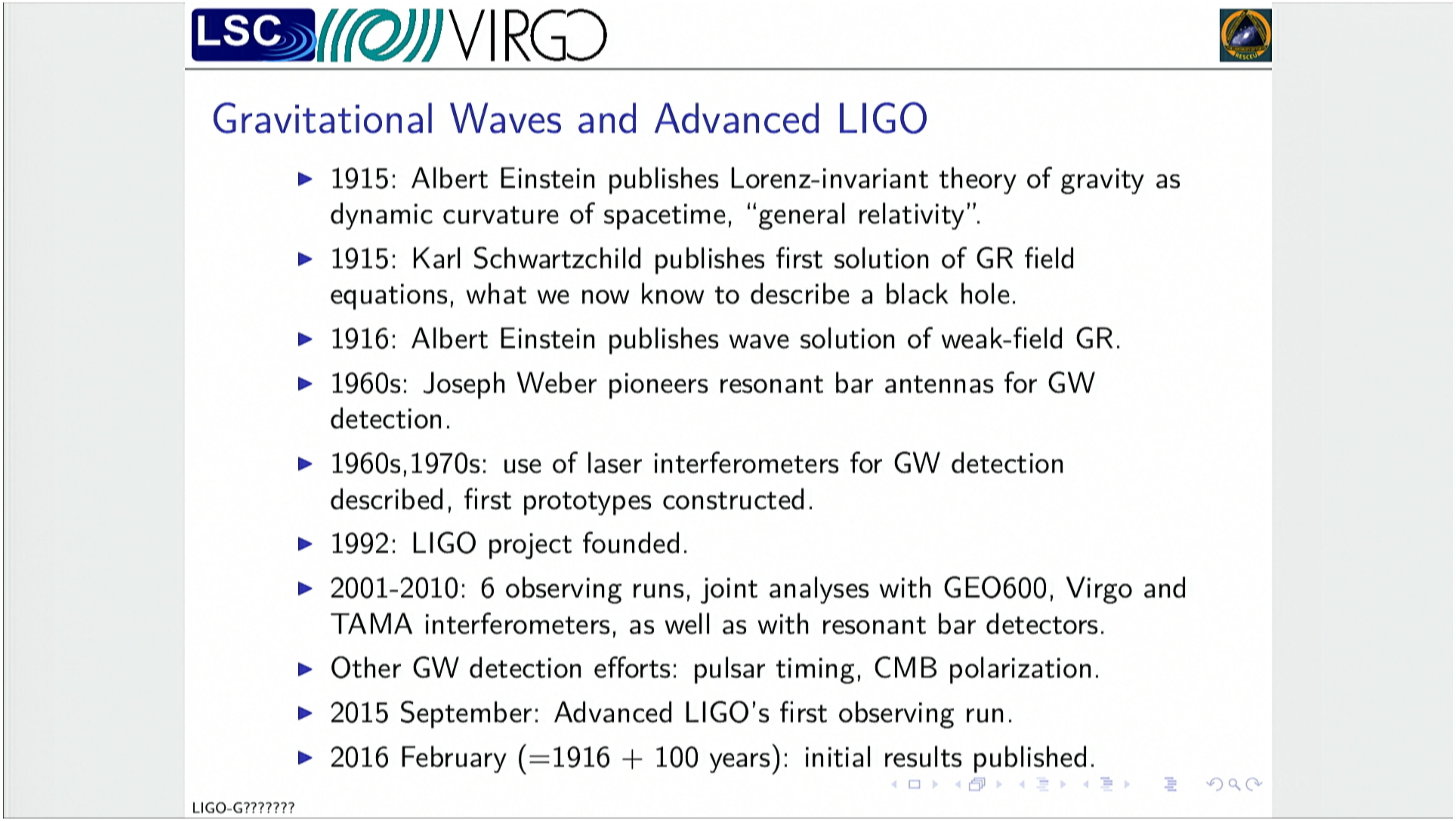
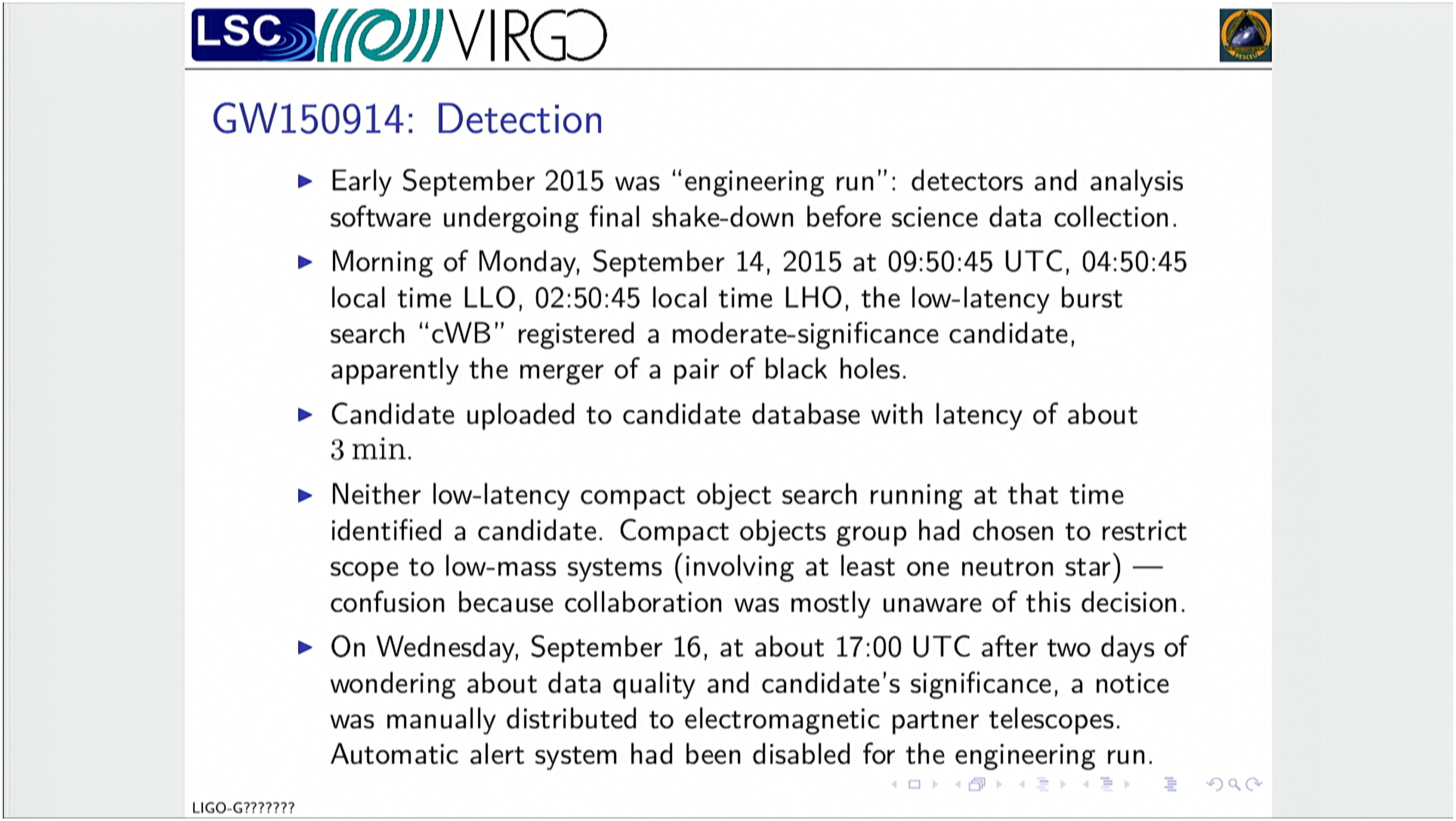


Gravitational Waves and Advanced LIGO

- 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.



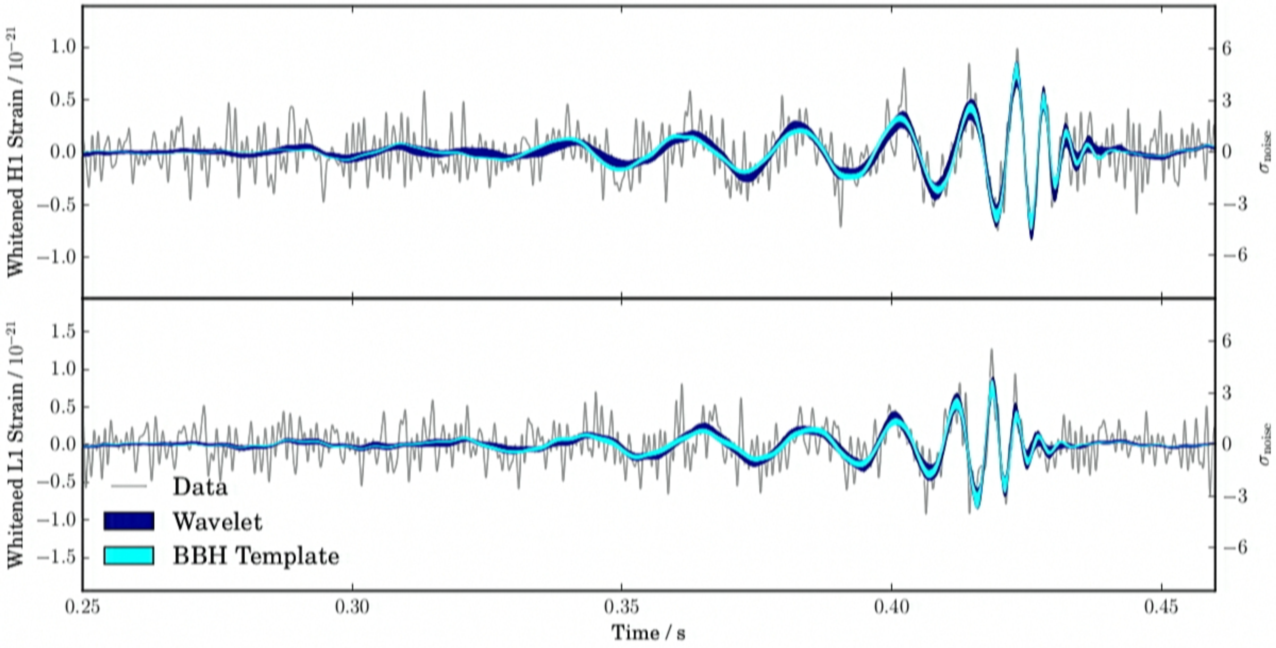
GW150914: Detection

- 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

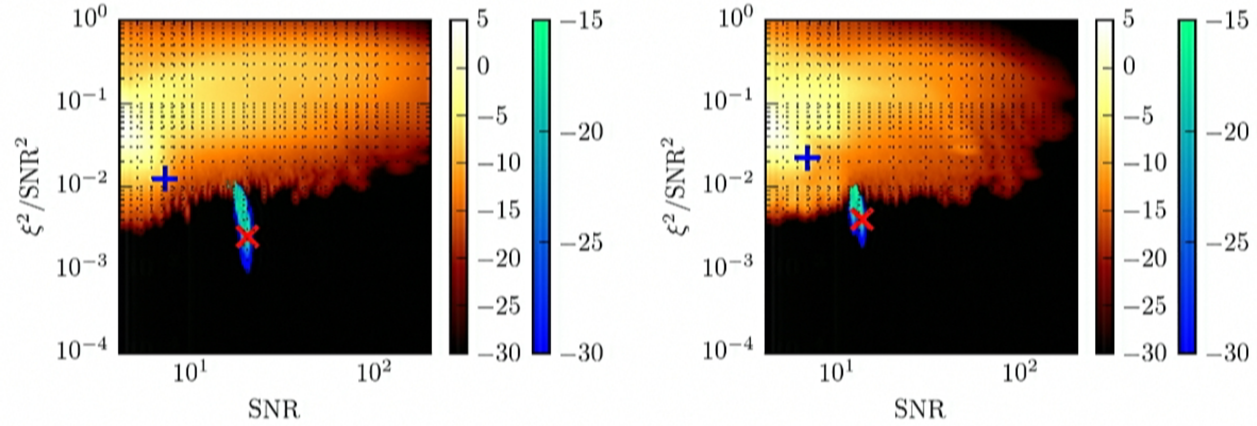
- 16 days of coincident data collection was required for compact object detection codes to estimate the candidate's false-alarm rate accurately enough to establish the candidate as a detection.
- During the 16 day period, a second binary black hole merger candidate was identified. False-alarm probability 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



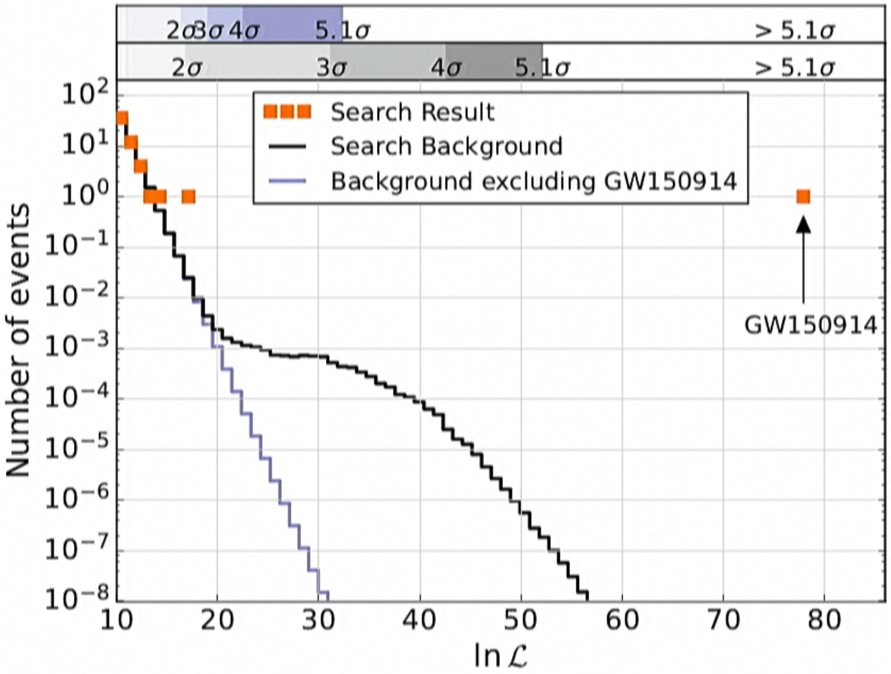
From LIGO-P1500218. Whitened time series. Times are relative to 09:50:45 UTC, vertical scale (on right) is standard deviations from the mean. Data, and 90% credible region from BBH parameter estimation reconstruction are shown.

GW150914: Detection



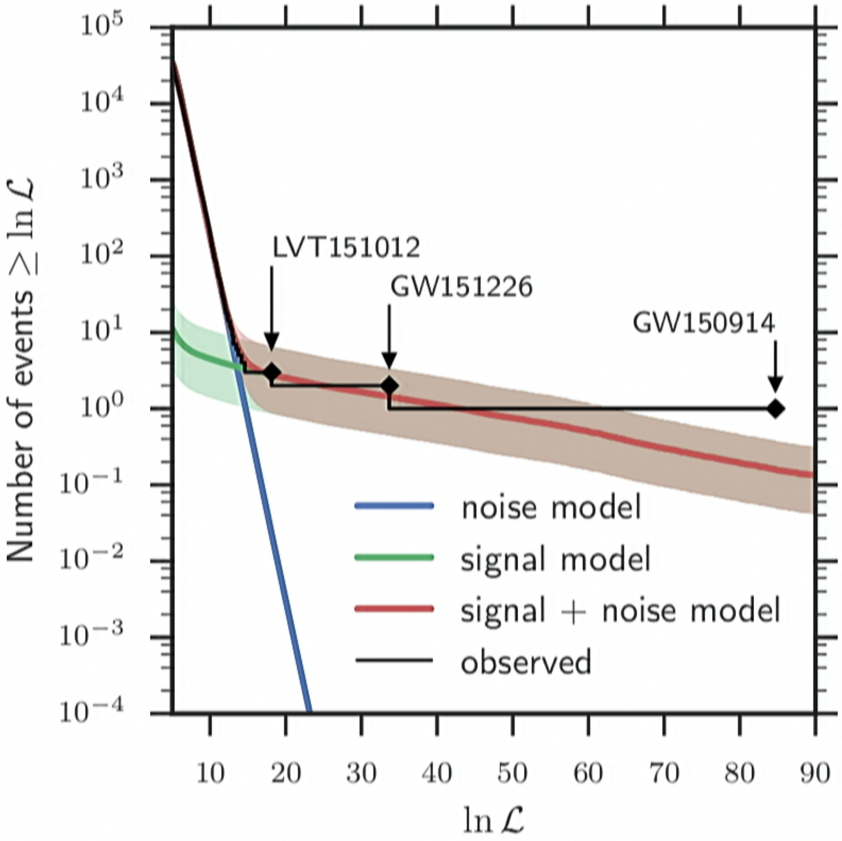
From LIGO-P1500269. Left = H1; right = L1. Horizontal axis is SNR, vertical axis is measure of magnitude of residual after subtraction of candidate from data — parallel and perpendicular components of data with respect to model waveform. Pink marker = first Monday; blue = second Monday. Orange = standard 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*. Blue = standard noise model; black = modified noise model; orange = observed events. Colour bars across top indicate statistical significance in "sigmas" for the two noise models.

GW151226: Detection



LIGO-G???????

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.

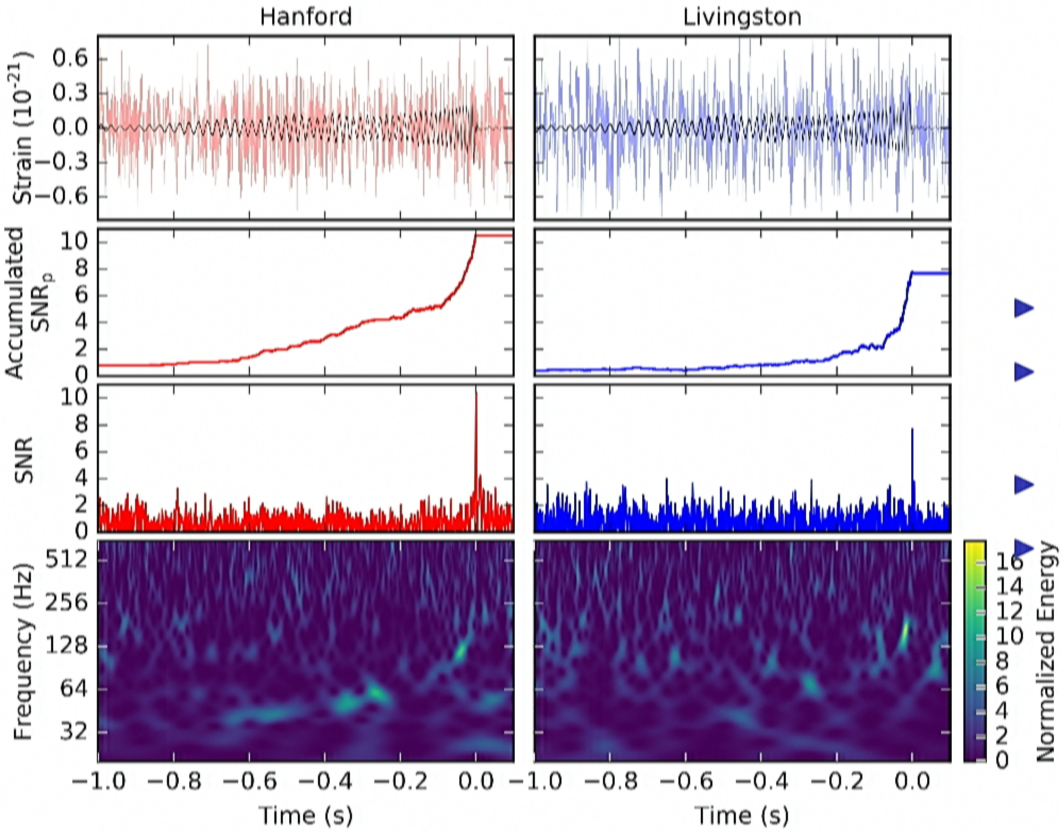
Cat found

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

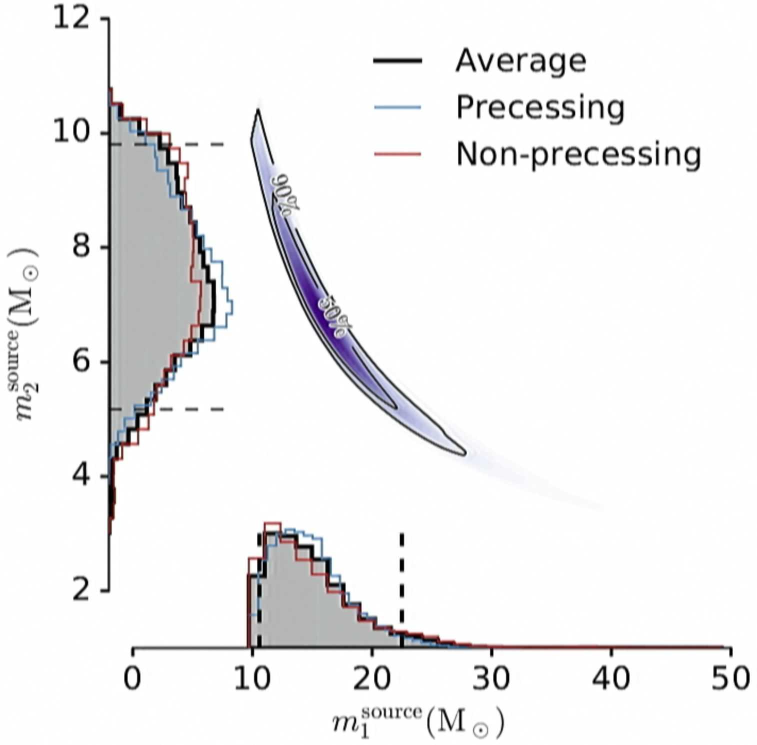
GW151226: Properties



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

From LIGO-P151226

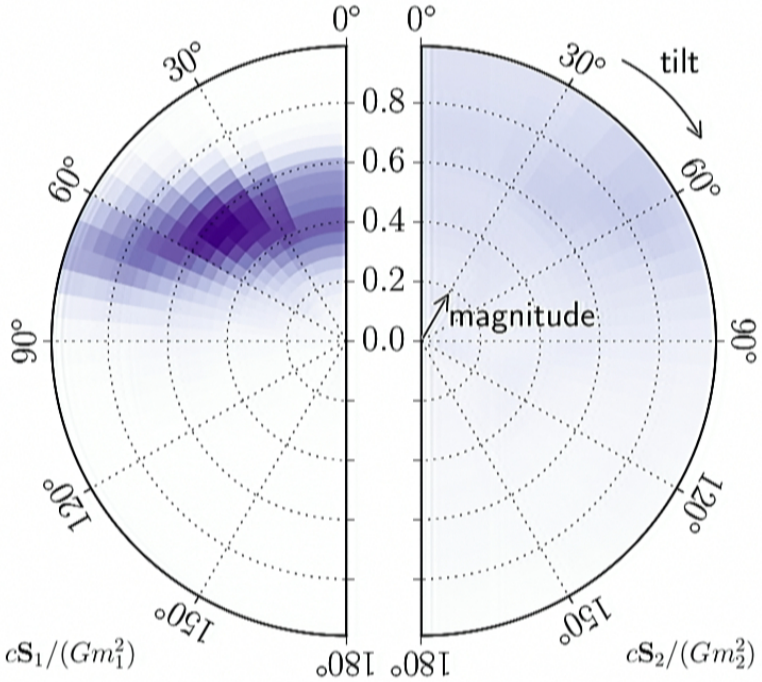
GW151226: Properties



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.

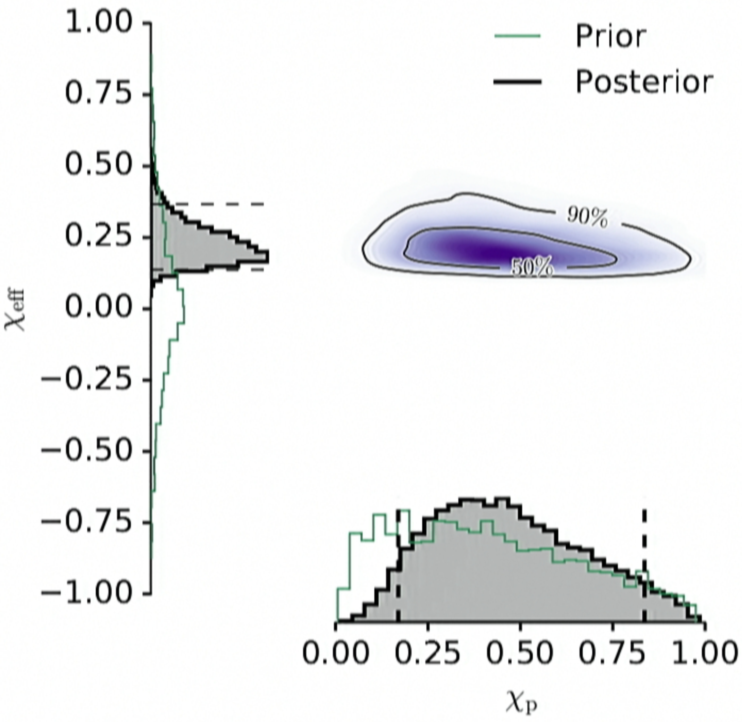
GW151226: Properties



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



From LIGO-P151226

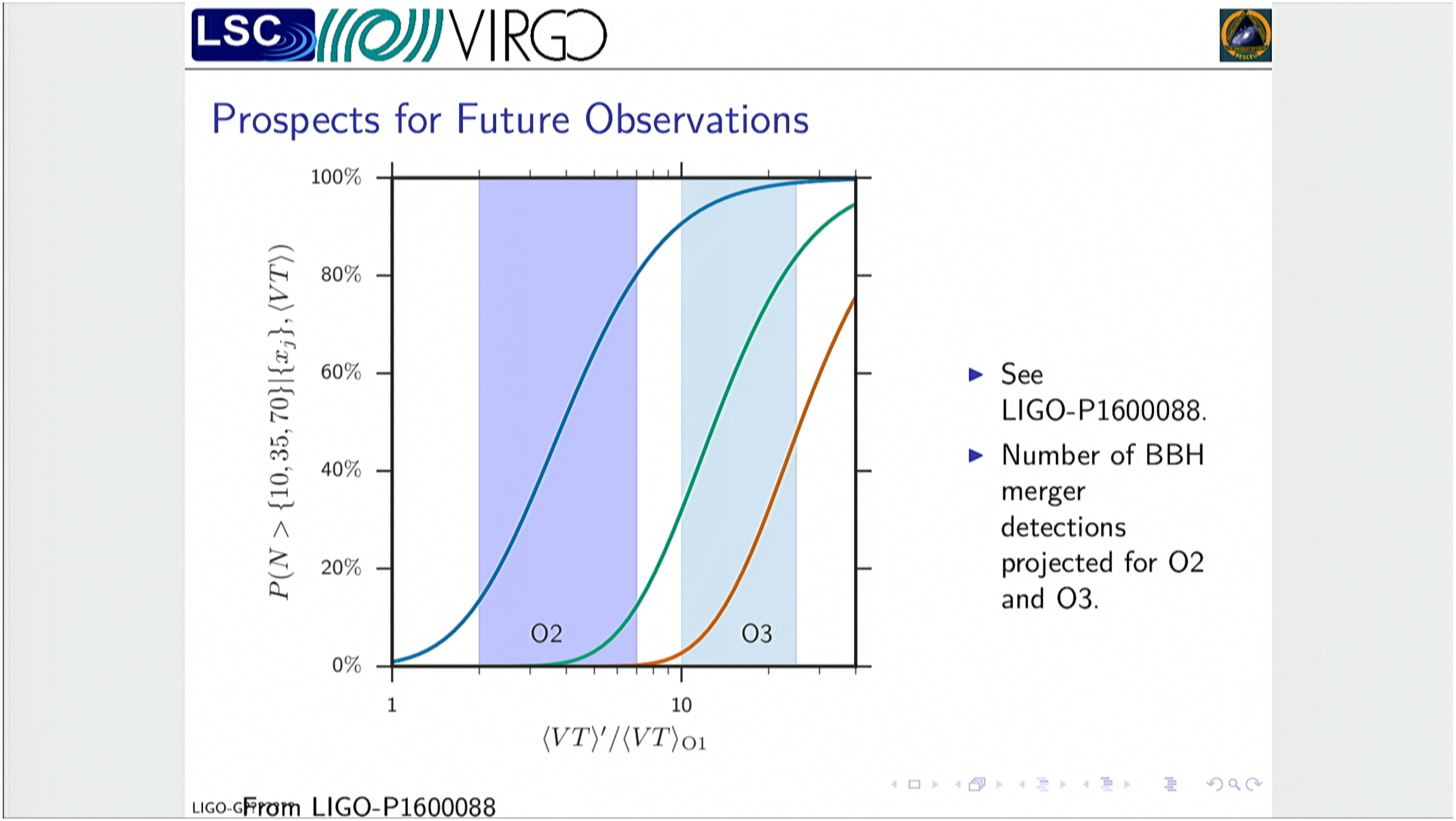
- Mass-weighted orbit-aligned spin (vertical) and in-plane spin (horizontal).

Constraining General Relativity

- GR is a non-linear theory, and the gravitational radiation from GW150914 has, in principle, carried information about back-scattering of GWs off of the spacetime curvature around the system, about the scattering of GWs off of themselves, about the coupling of the black hole spins to the orbital angular momentum and to each other, ...
- 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.

Binary Black Hole Merger Rate

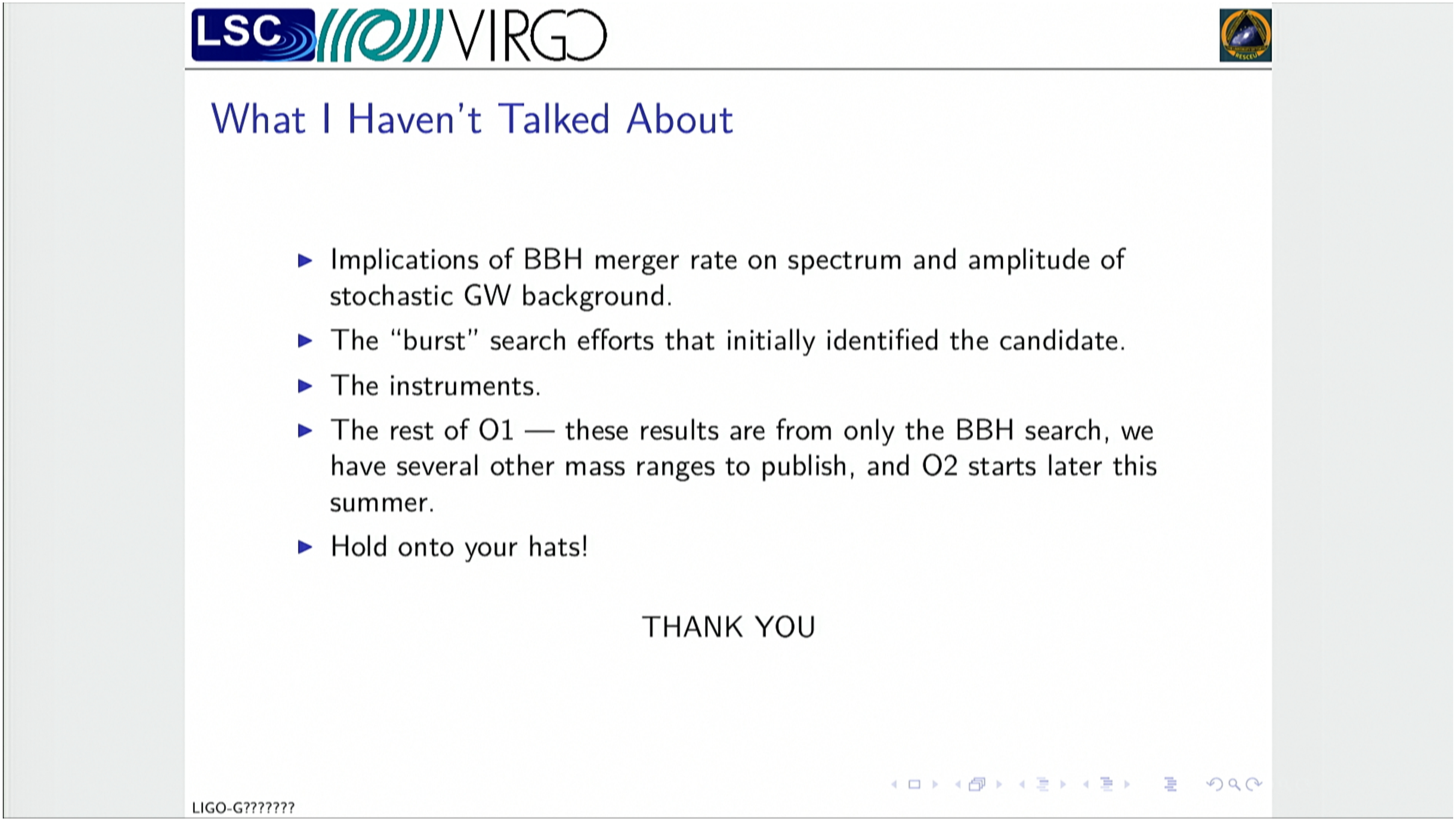
- The presence of the second candidate had a significant impact on the estimated number of detected signals in the data.
- See LIGO-P1500217.
- From the first 16 days we obtained a median and 90% credible interval of $4.8^{+7.9}_{-3.8}$ signals/experiment.
- The observation of GW151226 does not significantly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



Prospects for Future Observations

- See LIGO-P1600088.
- Number of BBH merger detections projected for O2 and O3.

LIGO-G 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 several other mass ranges to publish, and O2 starts later this summer.
- Hold onto your hats!

THANK YOU