International Centre for Theoretical Sciences
TATA INSTITUTE OF FUNDAMENTAL RESEARCH

LIGO Observations of Binary Black Holes

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On behalf of the LIGO Scientific Collaboration and Virgo Collaboration

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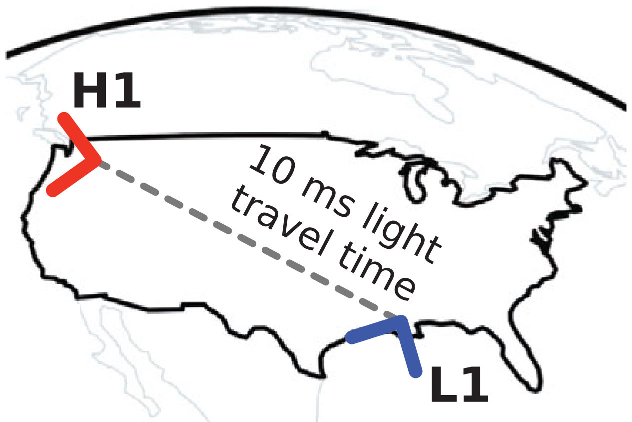
The first observational run of Advanced LIGO

- The first observing run (O1) of Advanced LIGO:
  12 Sep 2015 to 19 Jan 2016.

Fig. PRL 116, 061102 (2016)

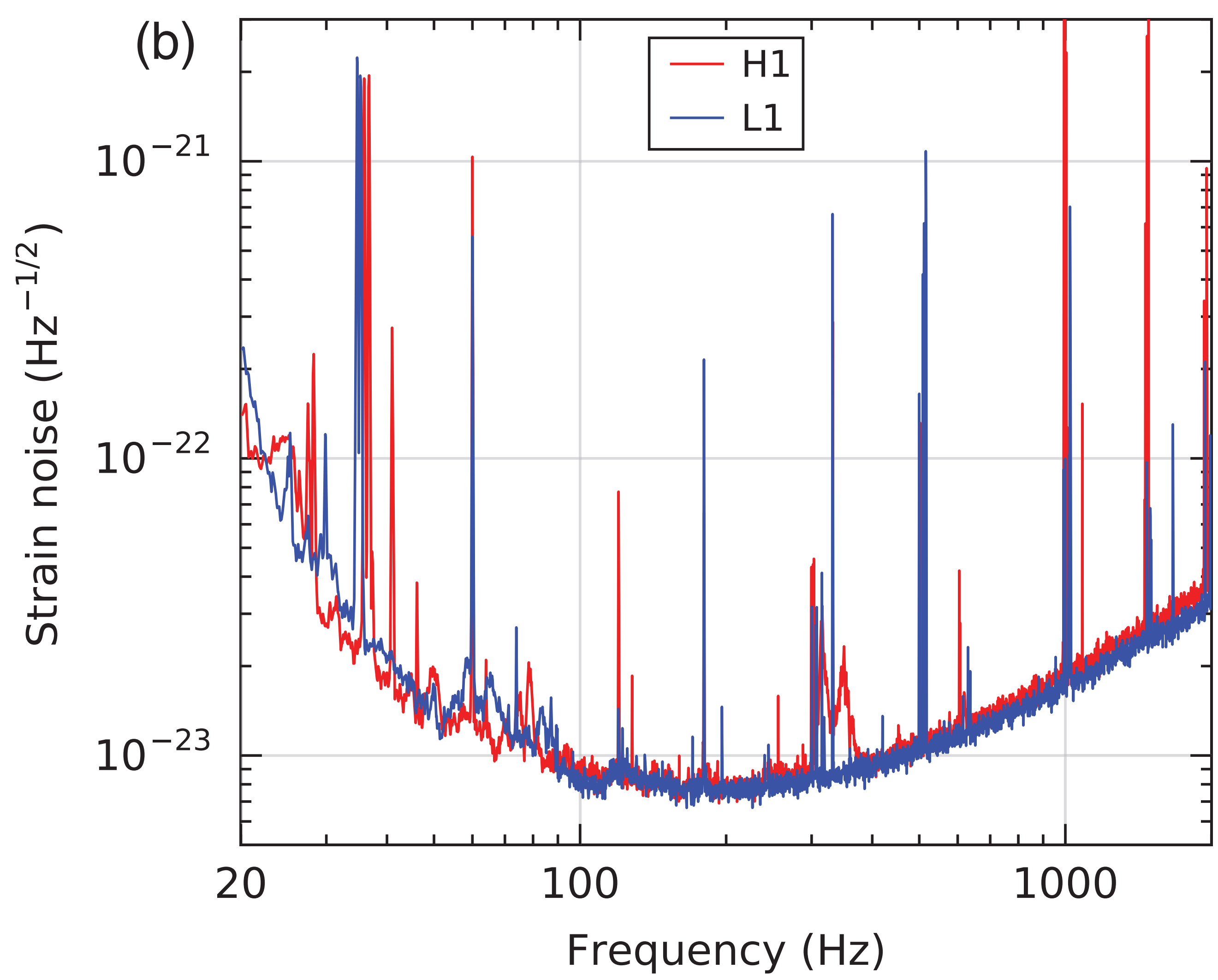


LIGO Observatories in Hanford and Livingston, USA

The first observational run of Advanced LIGO

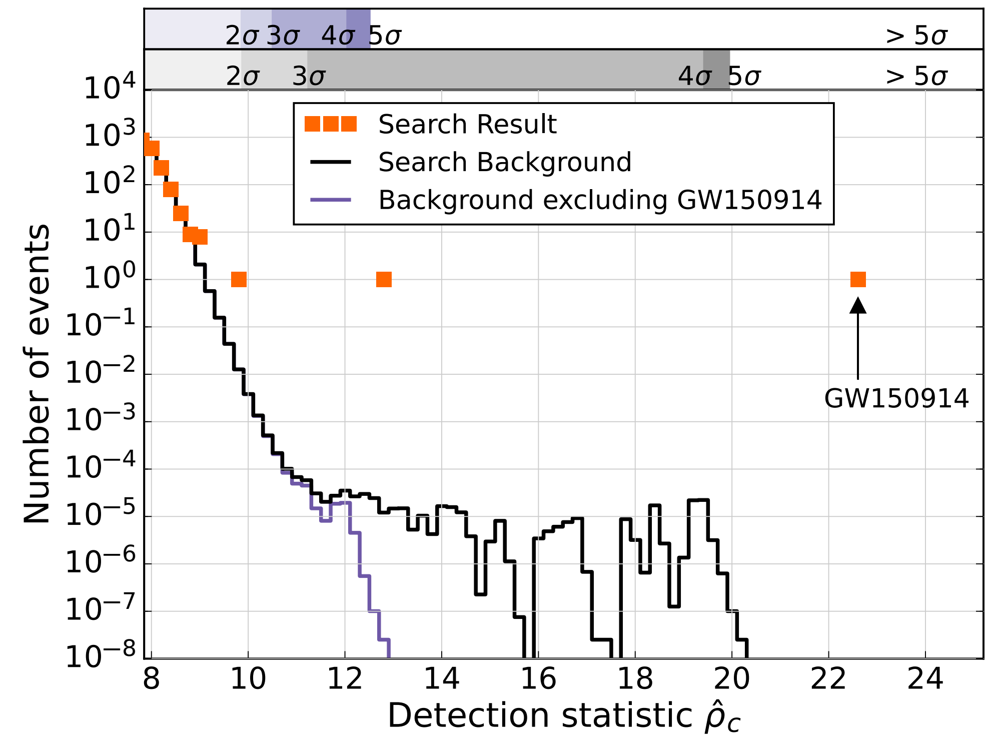
- The first observing run (O1) of Advanced LIGO
  12 Sep 2015 to 19 Jan 2016.
  - Unprecedented sensitivity to GWs in the frequency range 30 Hz to a few kHz.

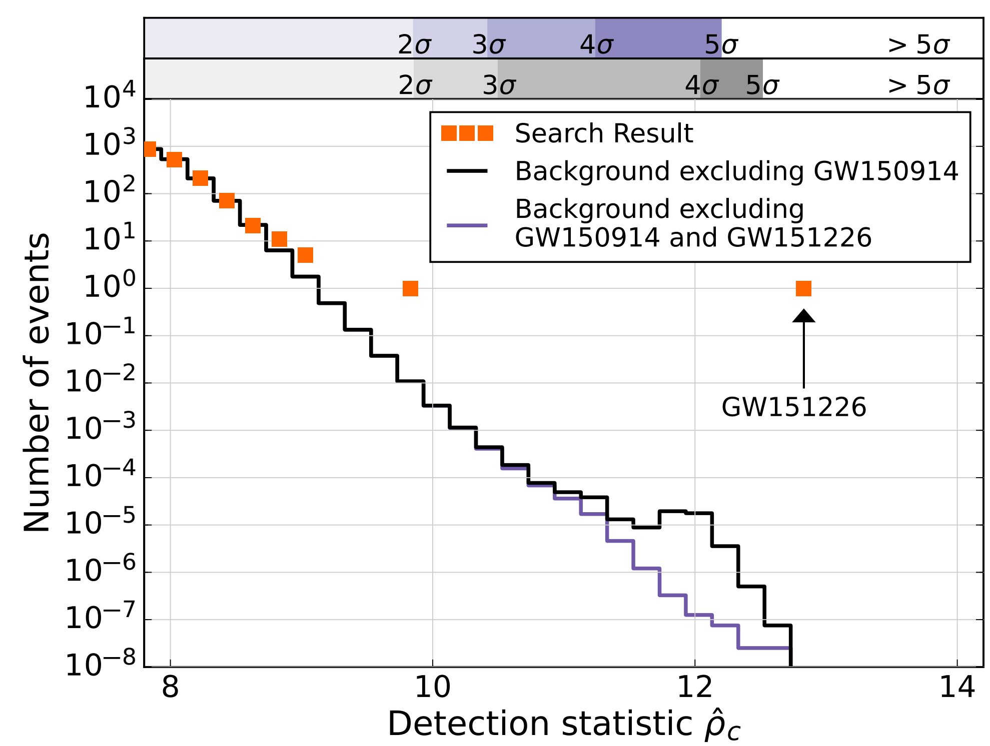
PRL 116, 061102 (2016)



Detection of gravitational waves from binary black holes

- The first observing run (O1) of Advanced LIGO **12 Sep 2015 to 19 Jan 2016.**
- Two confident (>5σ) detections of binary black holes: **GW150914, GW151226.** A third, less confident (~1.7σ) possible candidate **LVT151012.**
    - Detected by independent pipelines using CBC waveform models with similar confidence.
    - GW150914 was, in addition, confidently detected by a generic transient search pipeline.

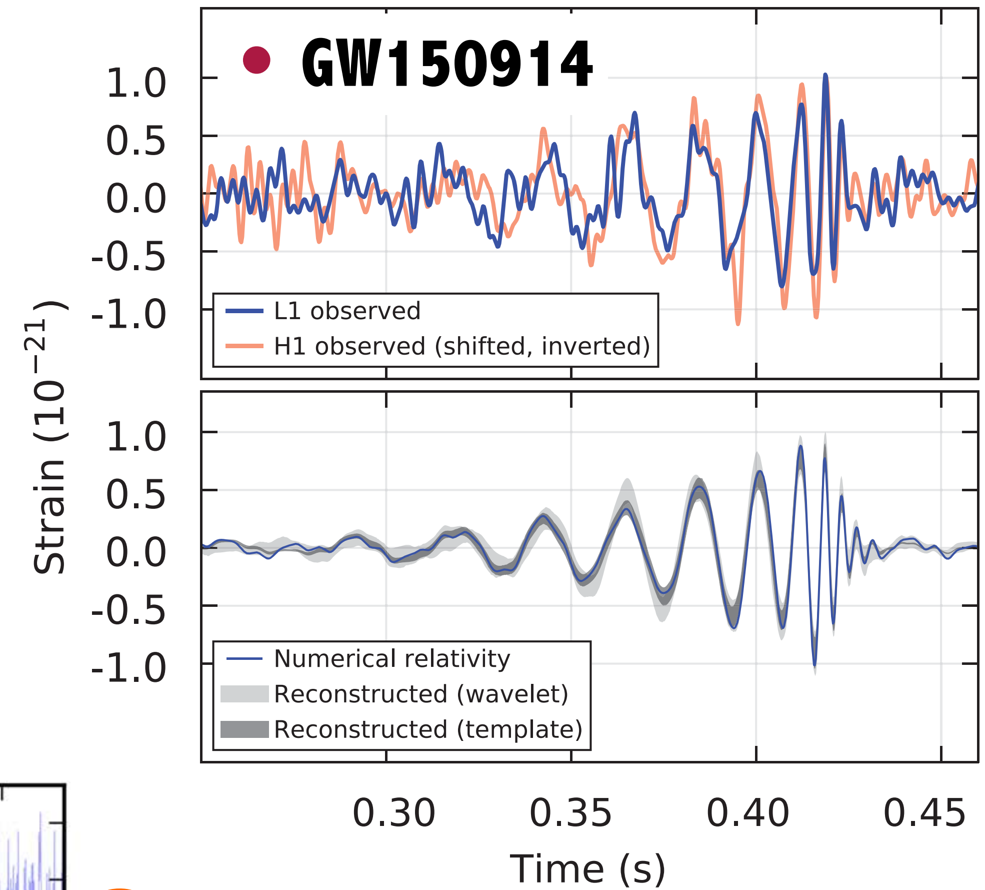




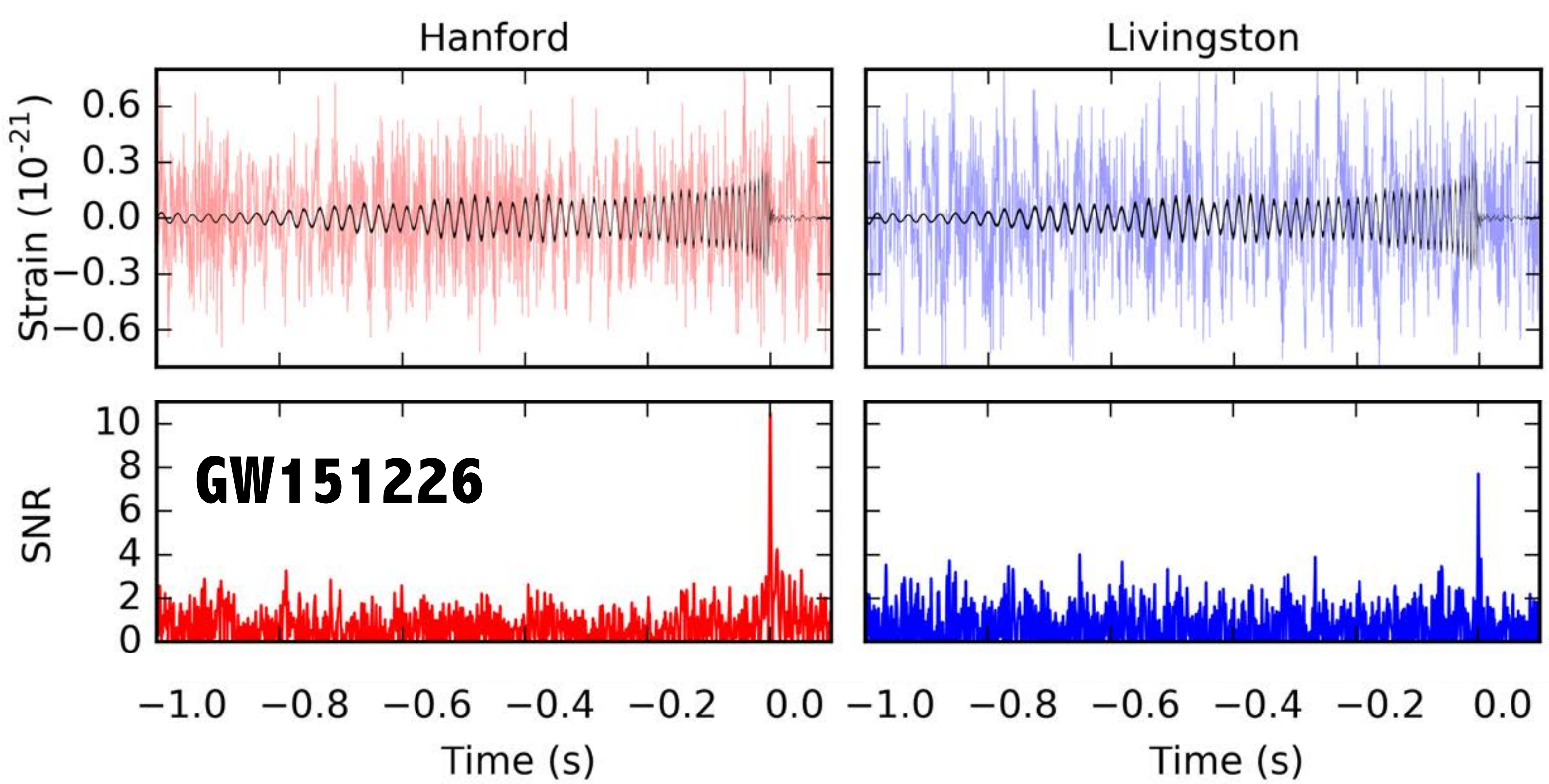
[arXiv:1606.04856]

Detection of gravitational waves from binary black holes

- **GW150914** Loud (SNR ~ 24), short-lived signal (duration ~ 0.2s) in the detector $\Longrightarrow$ massive binary.
- **GW151226** Weaker (SNR ~ 13) and longer (duration ~ 1s) signal in the detector $\Longrightarrow$ less massive binary.



PRL 116, 061102 (2016)

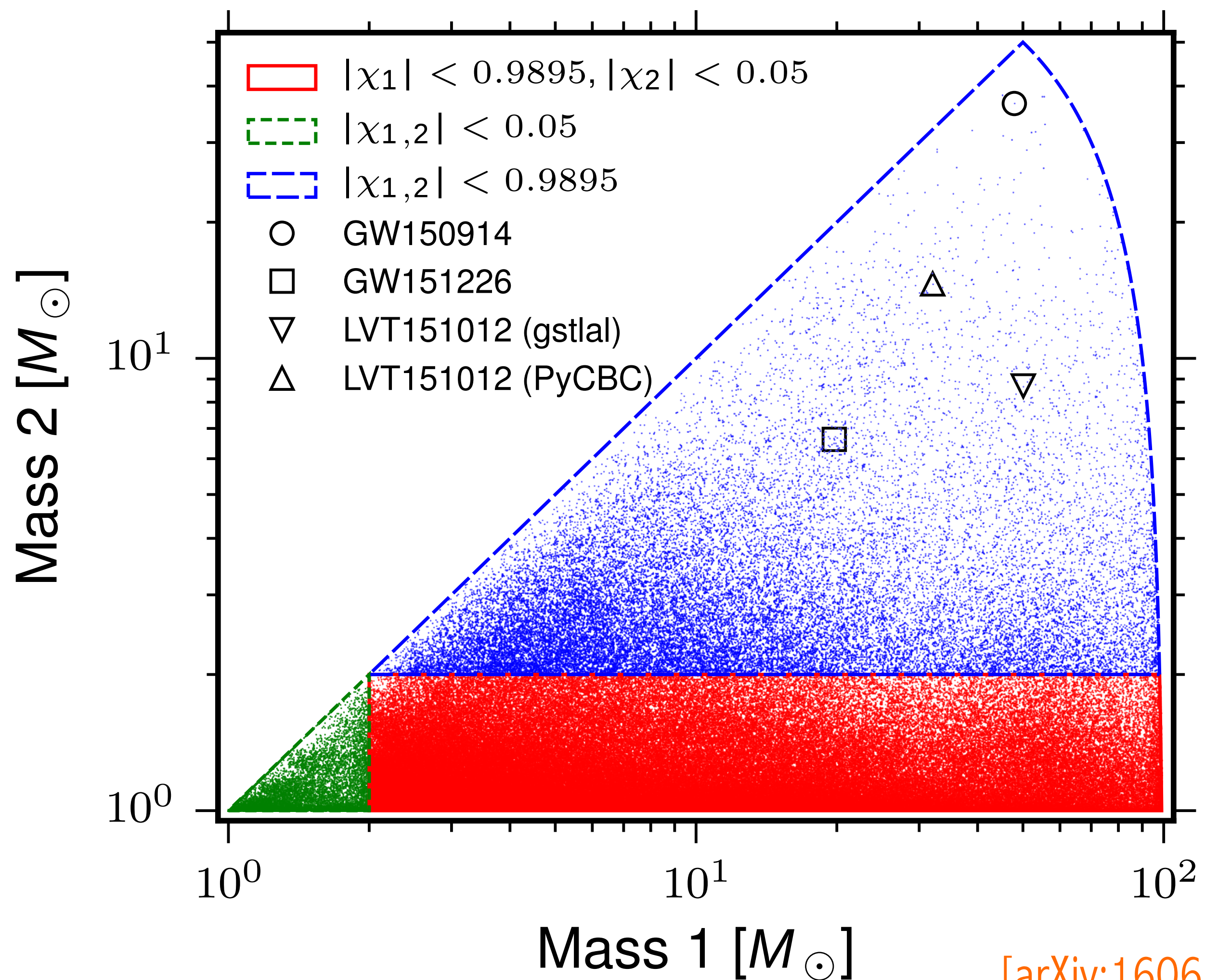


PRL 116, 241103 (2016)

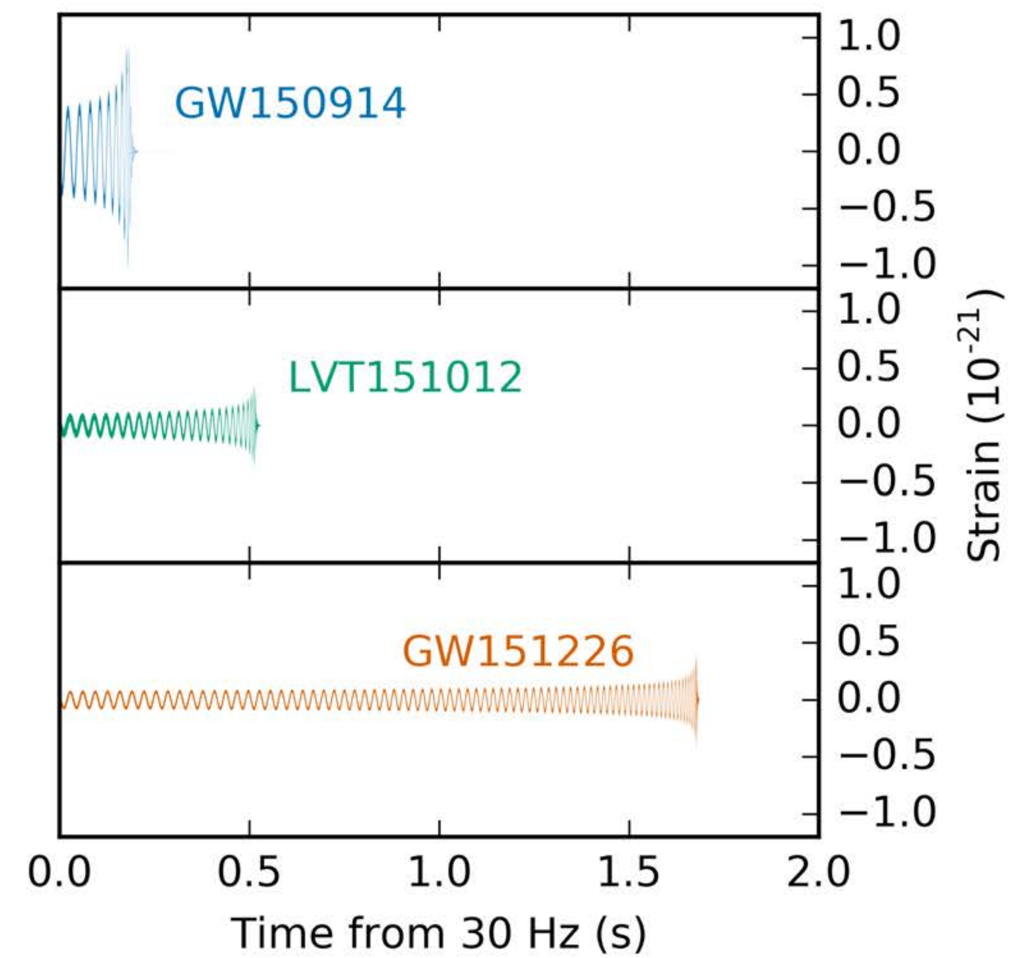
Searches for binary black holes in O1

- Two different matched-filter based searches employing GR based models of the expected signals from CBCs (including effects of aligned spins).

Search template bank



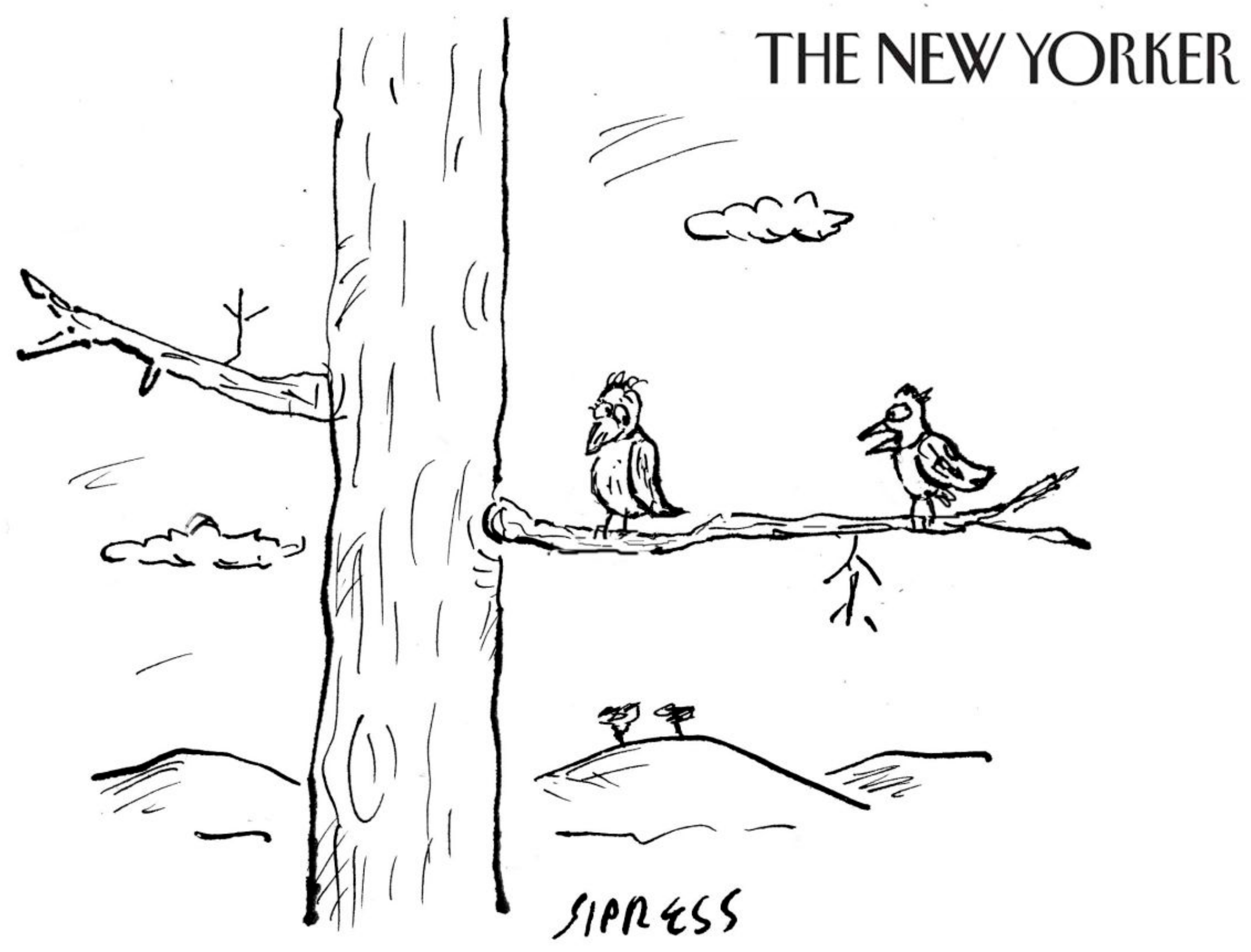
Most probable templates for the events



[arXiv:1606.04856]

Verification of the detector and data quality

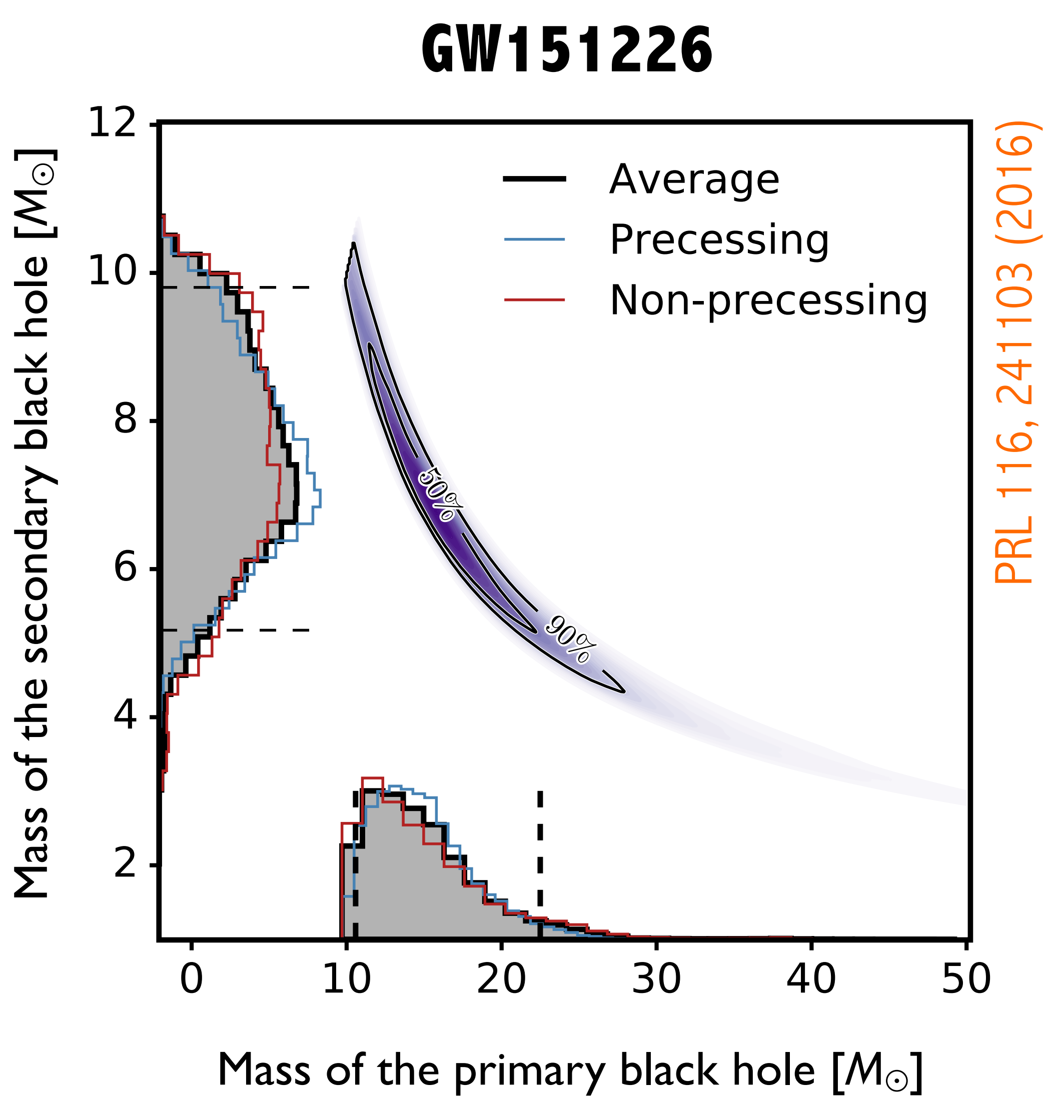
- Both the detectors were in a steady state of operation at the times around the events -- no evidence that these could be instrumental artifacts.
    - None of the environmental sensors recorded disturbances that could potentially explain the events.
    - Ruled out the possibility of "signal injections".

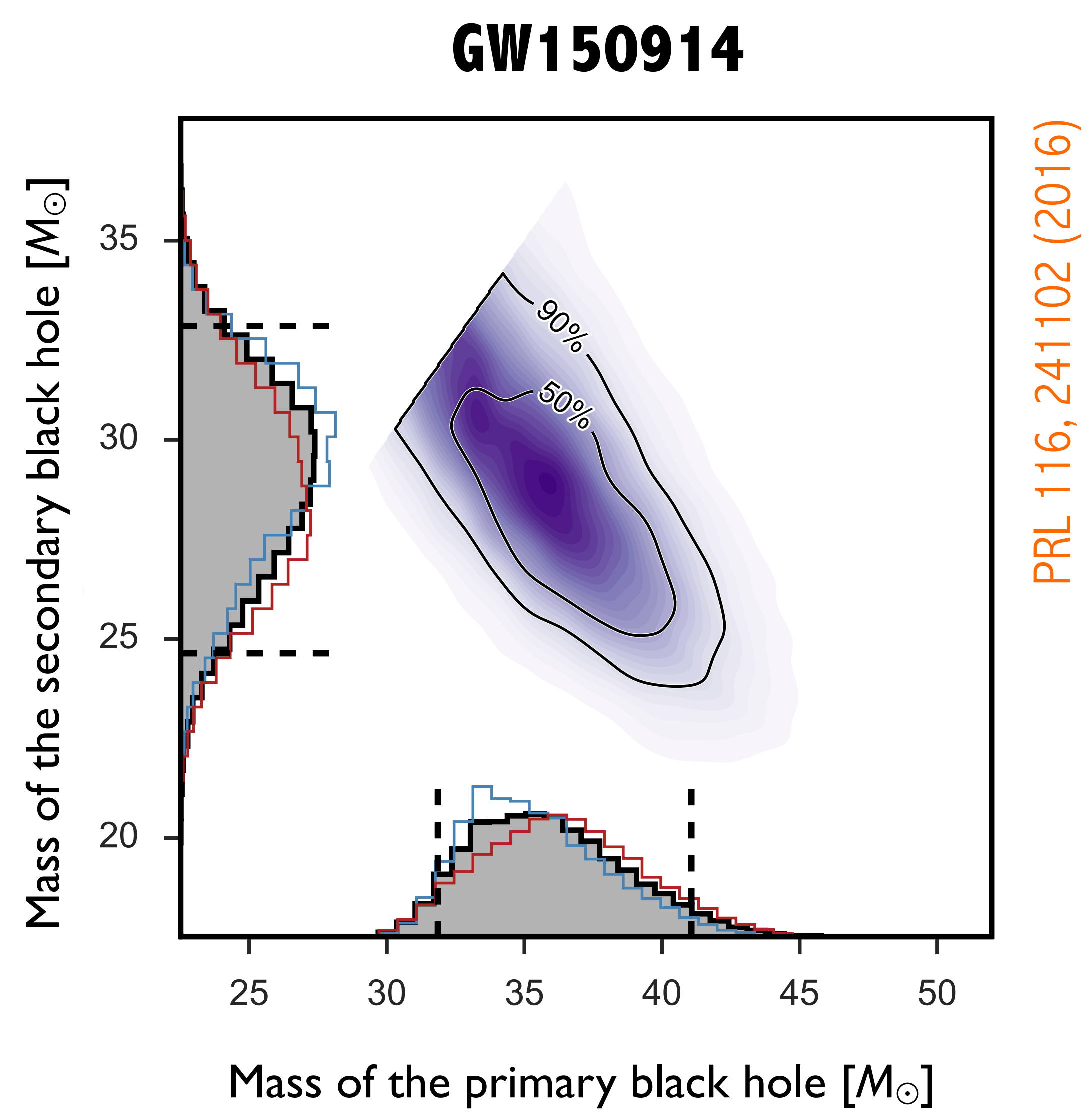


"Was that you I heard just now, or was it two black holes colliding?"

Estimating the parameters of the astrophysical source

- Posterior distributions of the component masses computed by comparing the data with theoretical templates (Bayesian inference).

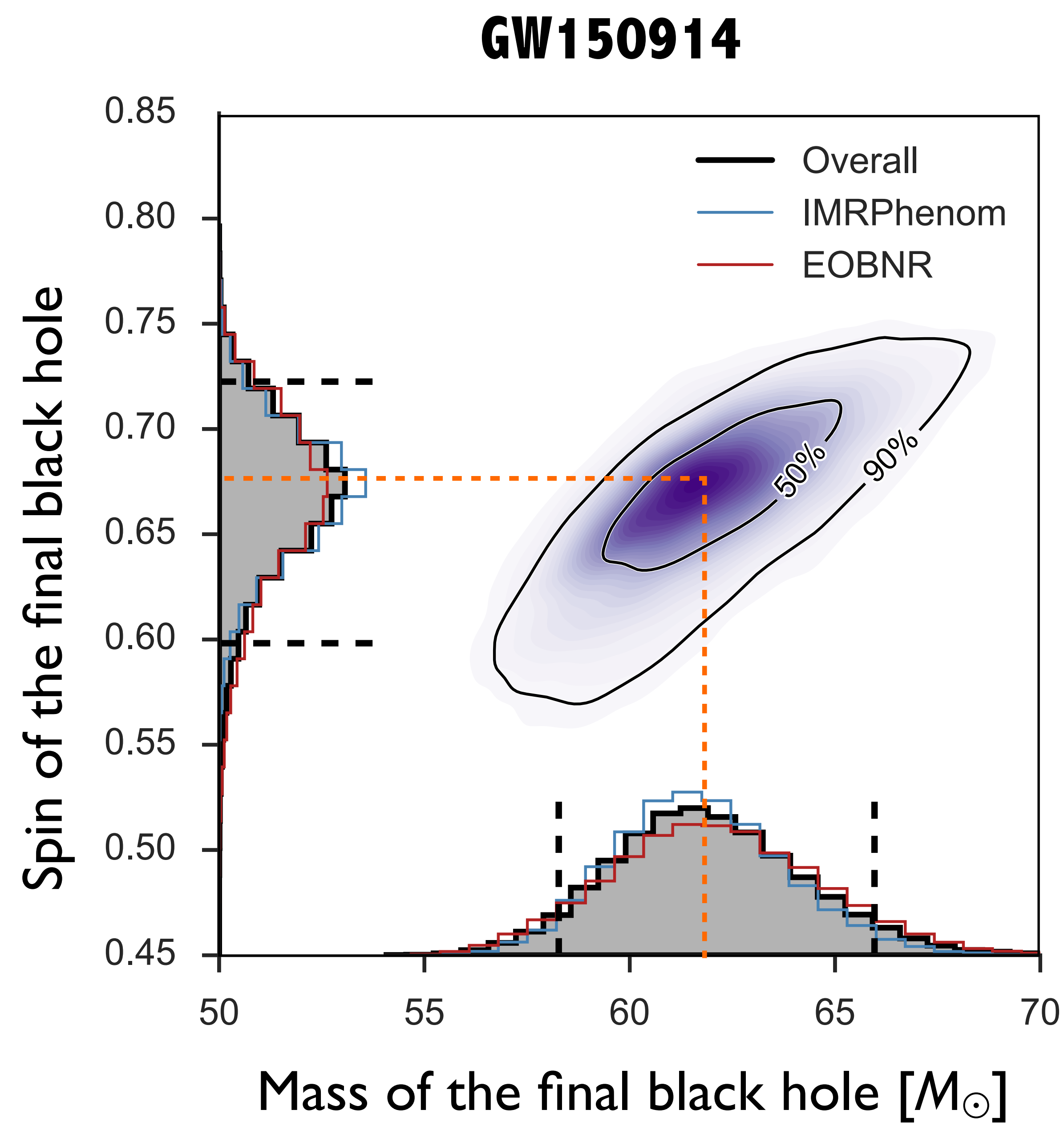




Estimating the parameters of the astrophysical source

- The individual spins are not well measured. However, the mass and spin of the final black hole can be inferred accurately using numerical-relativity simulations.

Event	GW150914	GW151226
Final mass $M_f^{source}/M_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$
Final spin a_f	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$



PRL 116, 241102 (2016)

Estimated source parameters

arXiv:1606.04856

Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
Significance	$>5.3\,\sigma$	$>5.3\,\sigma$	1.7σ
Primary mass $m_1^{\rm source}/{\rm M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\rm source}/{\rm M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Effective inspiral spin $\chi_{\rm eff}$	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\rm f}^{\rm source}/{\rm M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin $a_{\rm f}$	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\rm rad}/({\rm M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\rm peak}/({\rm erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4}\times 10^{56}$	$3.3^{+0.8}_{-1.6}\times 10^{56}$	$3.1^{+0.8}_{-1.8}\times 10^{56}$
Luminosity distance $D_{\rm L}/{\rm Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}

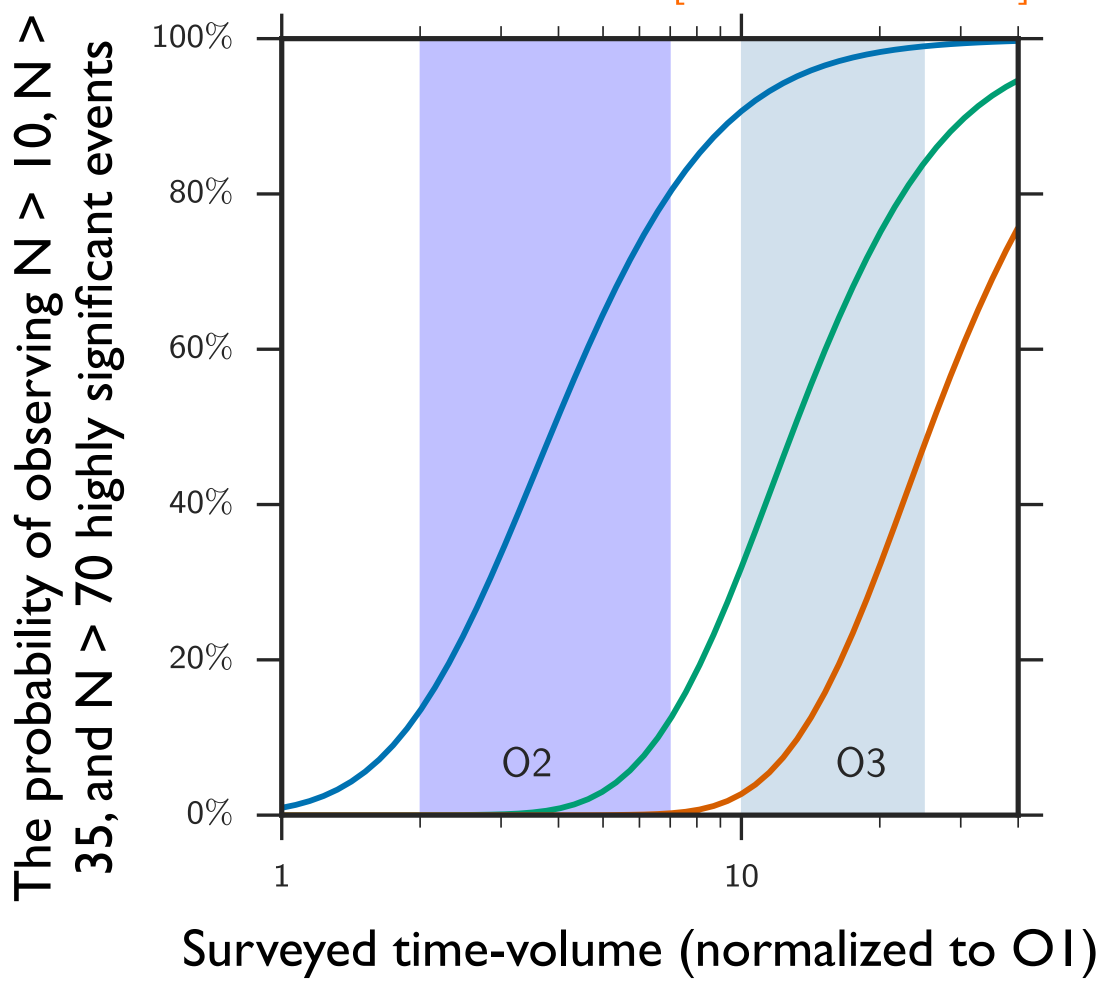
90% credible intervals including statistical & systematic errors

Observed signals are fully consistent with the predictions of GR.

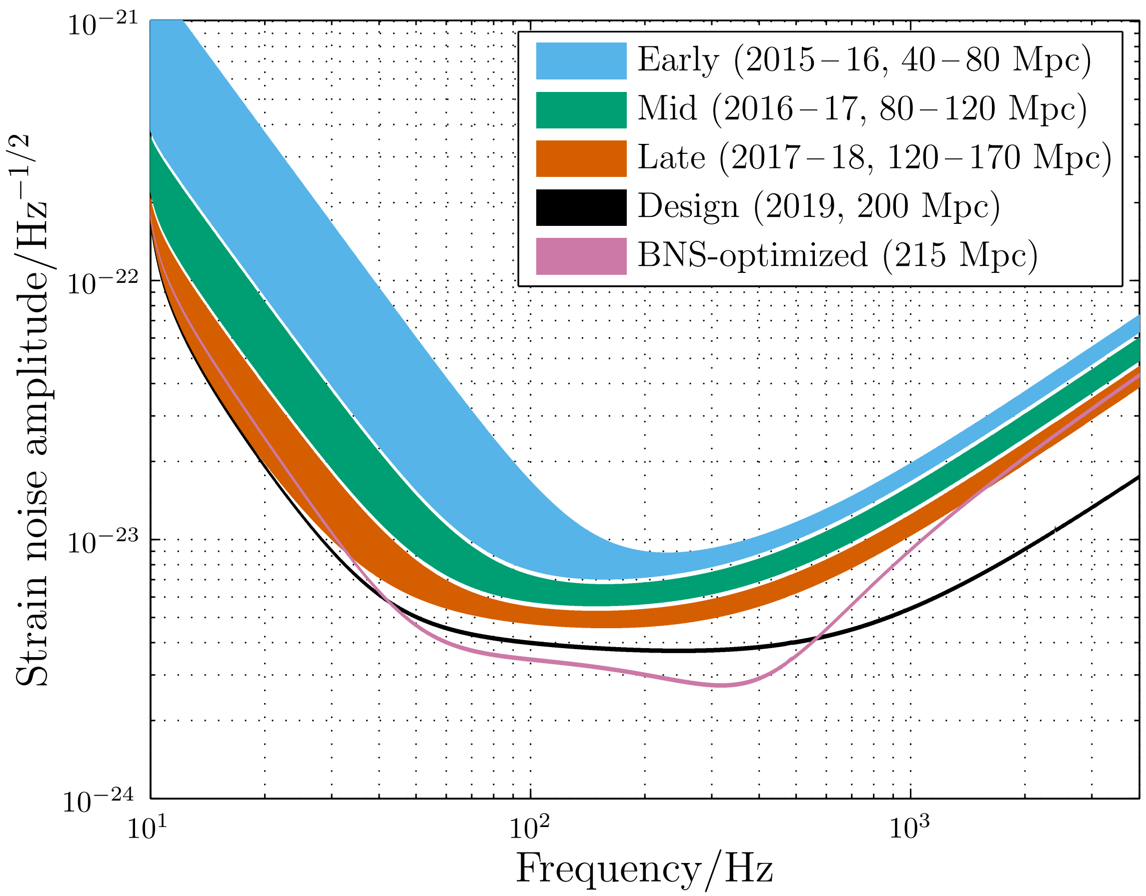
End of the era of gravitational-wave detection; beginning of gravitational astronomy

- Several detections expected in the upcoming observational runs. **Advanced Virgo** expected to join the network in a few months. **KAGRA** being commissioned. **LIGO-India** expected to join early next decade.

[arXiv:1606.04856]

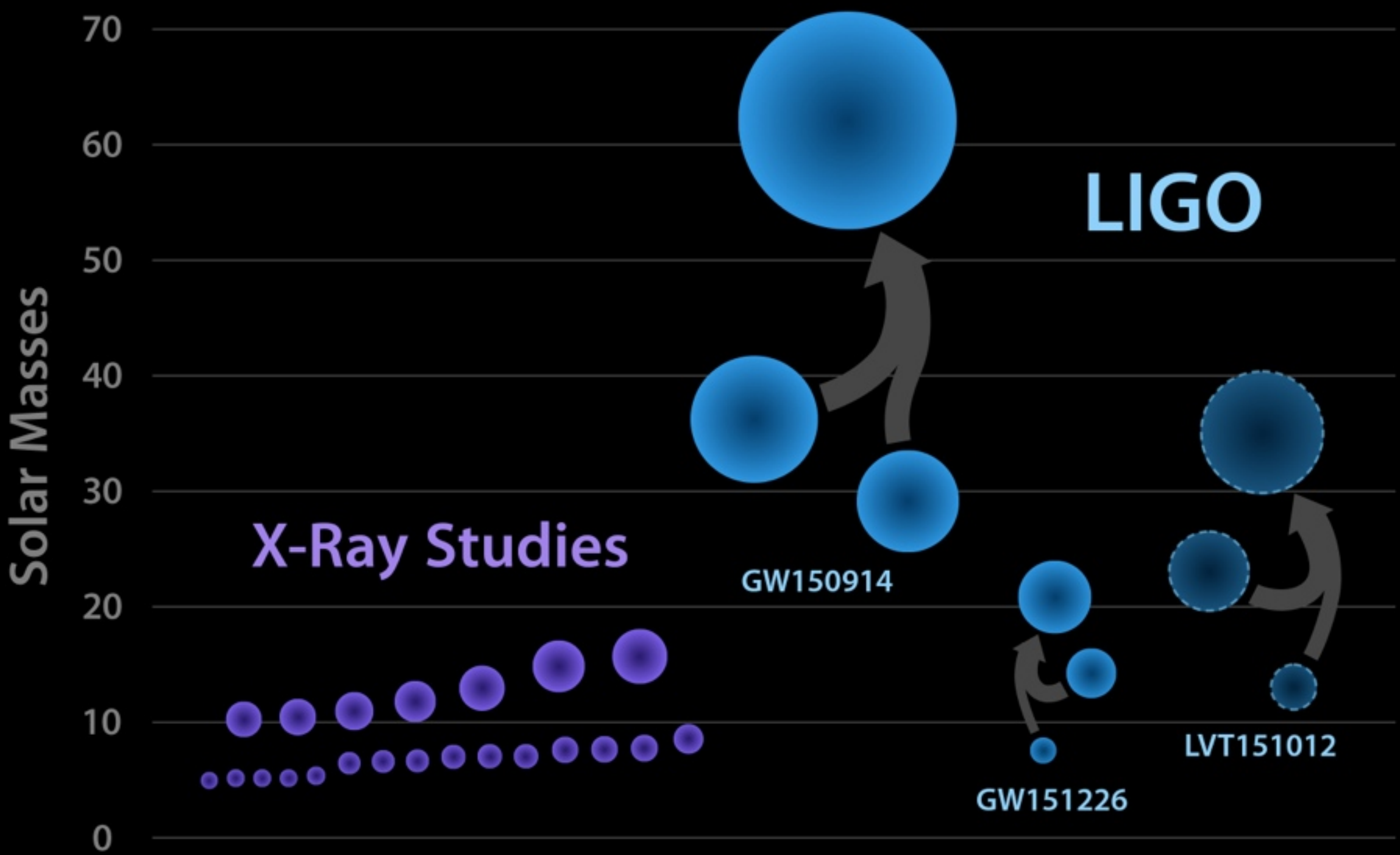


Estimated progress in the sensitivity of Adv LIGO



[arXiv:1304.0670v3]

Black Holes of Known Mass



http://ligo.caltech.edu