Binary black hole observations with Advanced LIGO

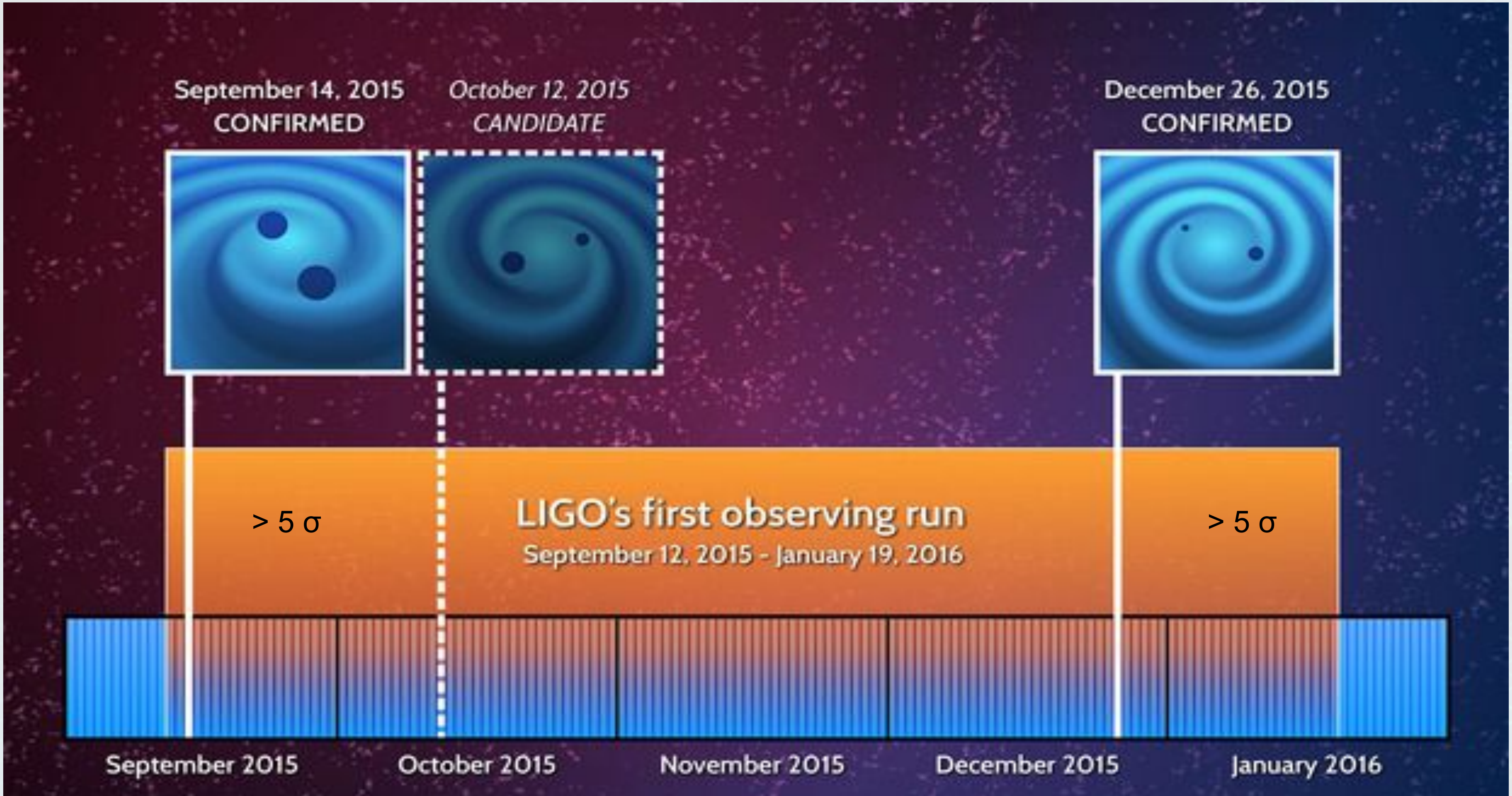
Chad Hanna (Penn State) on behalf of the LIGO Scientific Collaboration and the Virgo Collaboration.

LIGO - G1700996

Outline

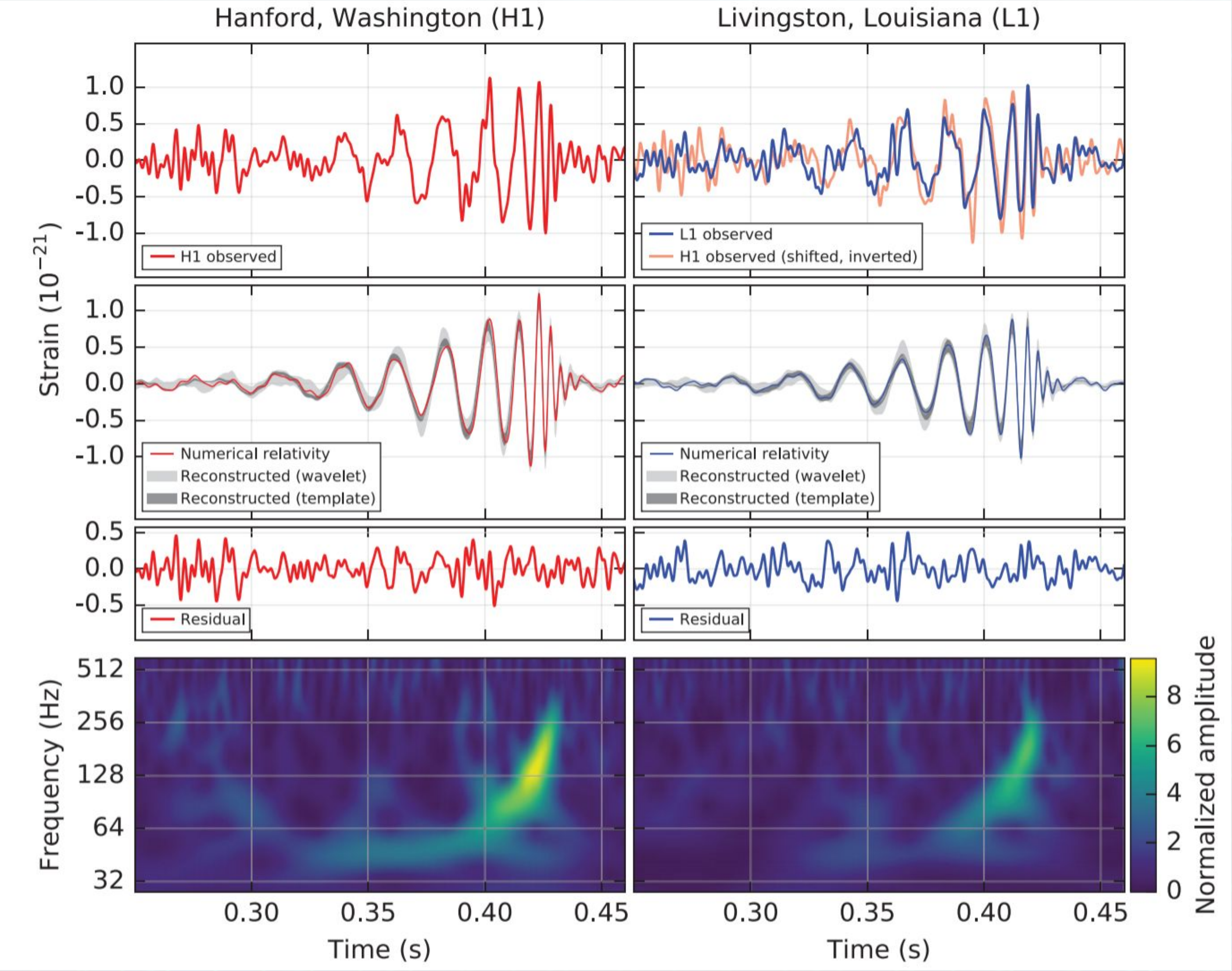
1. Binary Black Holes (BBH) in the first observing run.
    a. GW150914
    b. GW151226
    c. LVT151012
2. The distribution of masses
3. The distribution of spins
4. The distribution of amplitudes
5. Inference of the BBH coalescence rate
6. conclusion

BBH in LIGO's first observing run



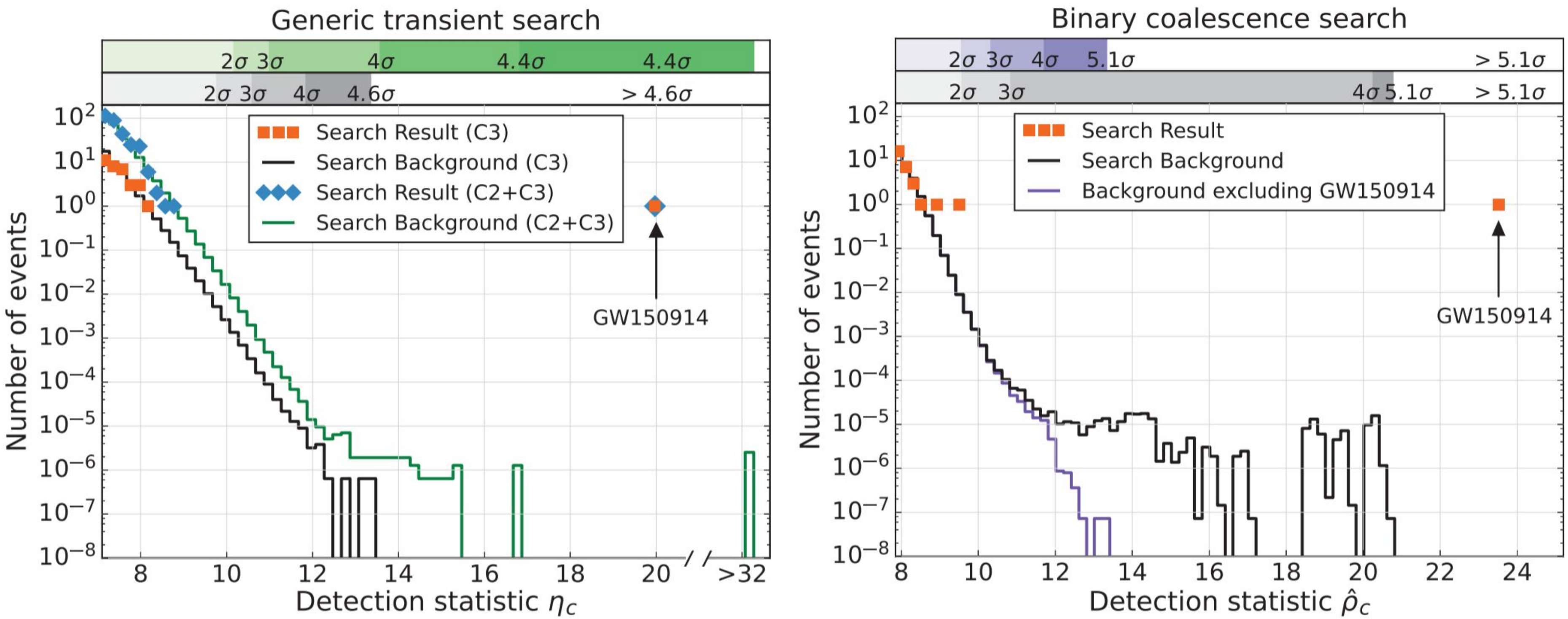
Credit LIGO

GW150914



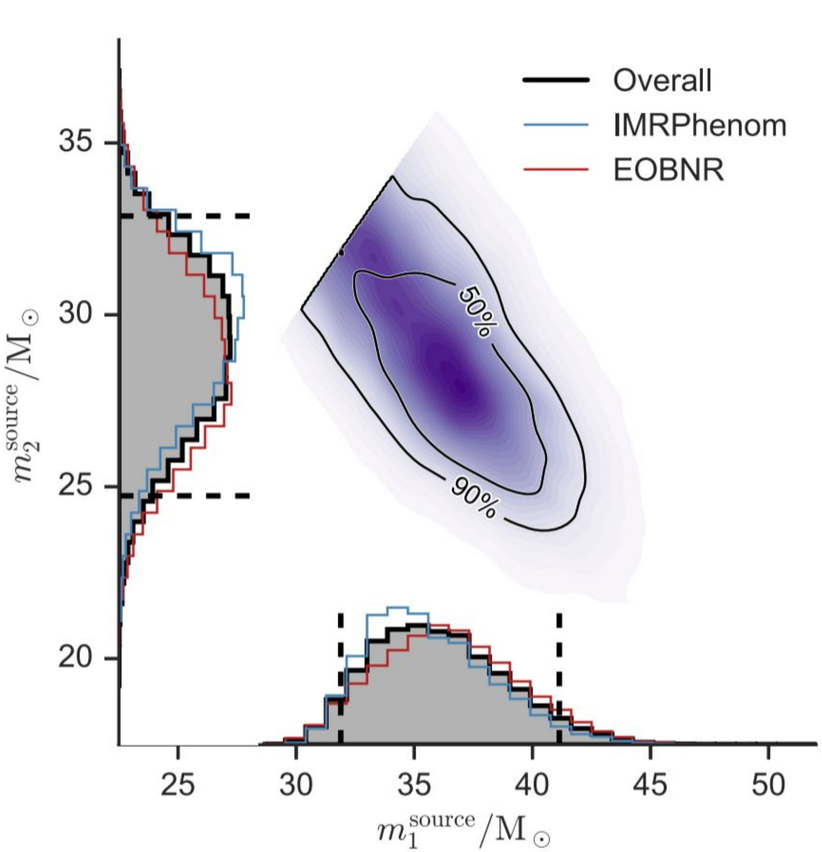
Phys. Rev. Lett. 116, 061102 (2016)

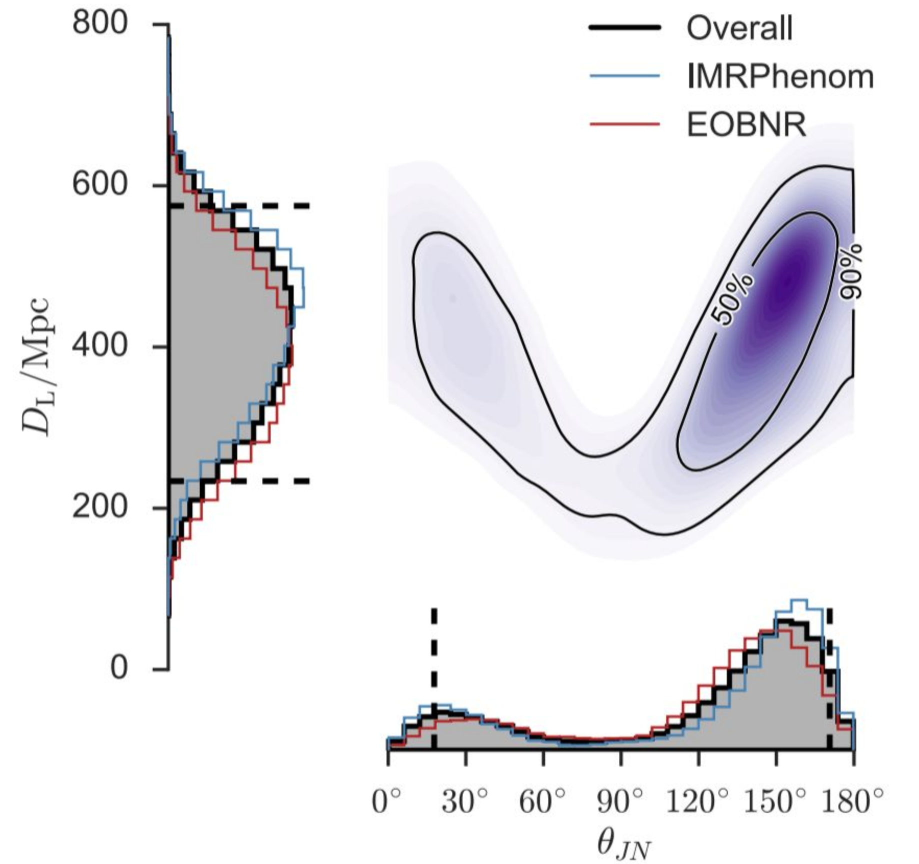
GW150914



Phys. Rev. Lett. 116, 061102 (2016)

GW150914

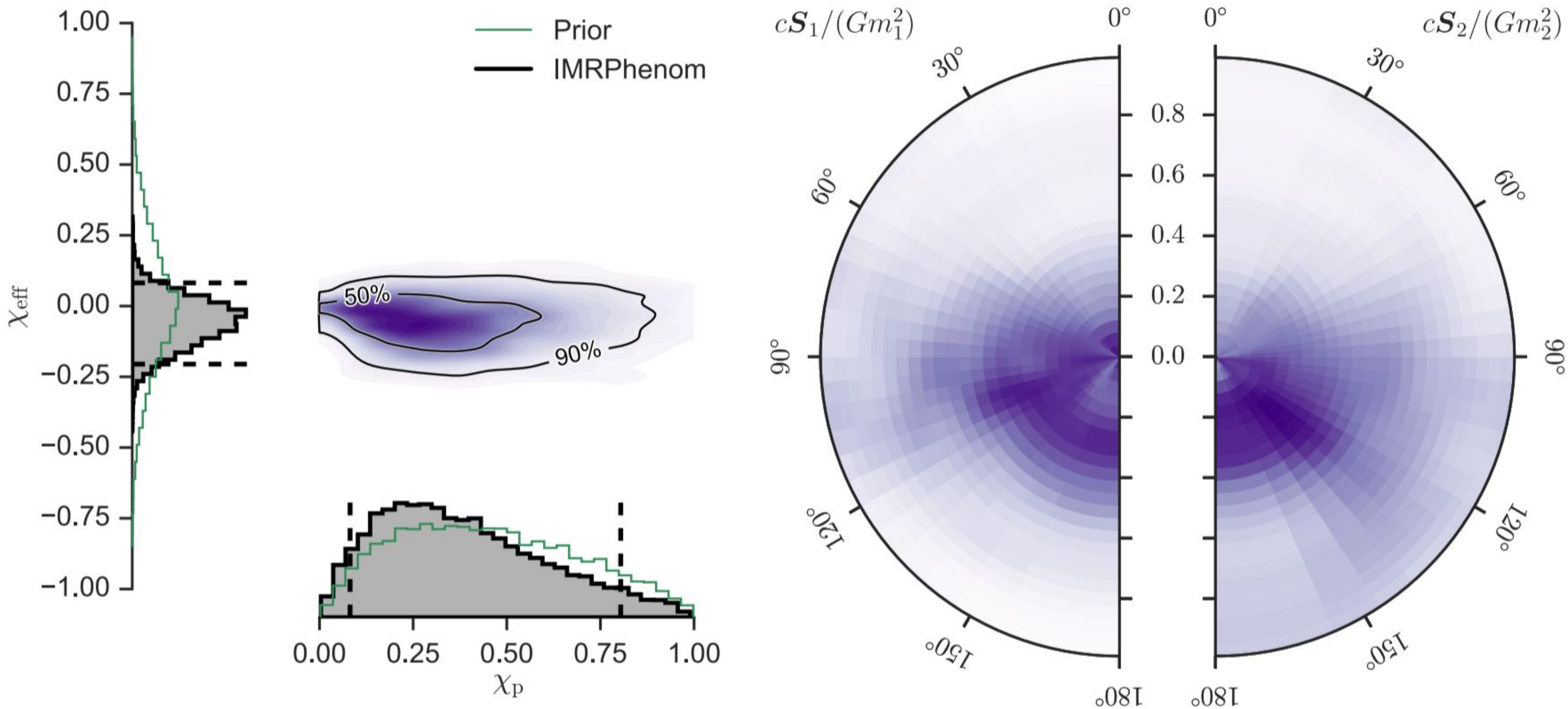




Primary mass $m_1^{\rm source}/{\rm M}_\odot$	$36.2^{+5.2}_{-3.8}$	Radiated energy $E_{\rm rad}/({\rm M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$
Secondary mass $m_2^{\rm source}/{\rm M}_\odot$	$29.1^{+3.7}_{-4.4}$	Peak luminosity $\ell_{\rm peak}/({\rm erg\ s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$
Chirp mass $\mathcal{M}^{\rm source}/{\rm M}_\odot$	$28.1^{+1.8}_{-1.5}$	Luminosity distance $D_{\rm L}/{\rm Mpc}$	420^{+150}_{-180}
Total mass $M^{\rm source}/{\rm M}_\odot$	$65.3^{+4.1}_{-3.4}$	Source redshift z	$0.09^{+0.03}_{-0.04}$

Phys. Rev. Lett. 116, 241102 (2016)

GW150914

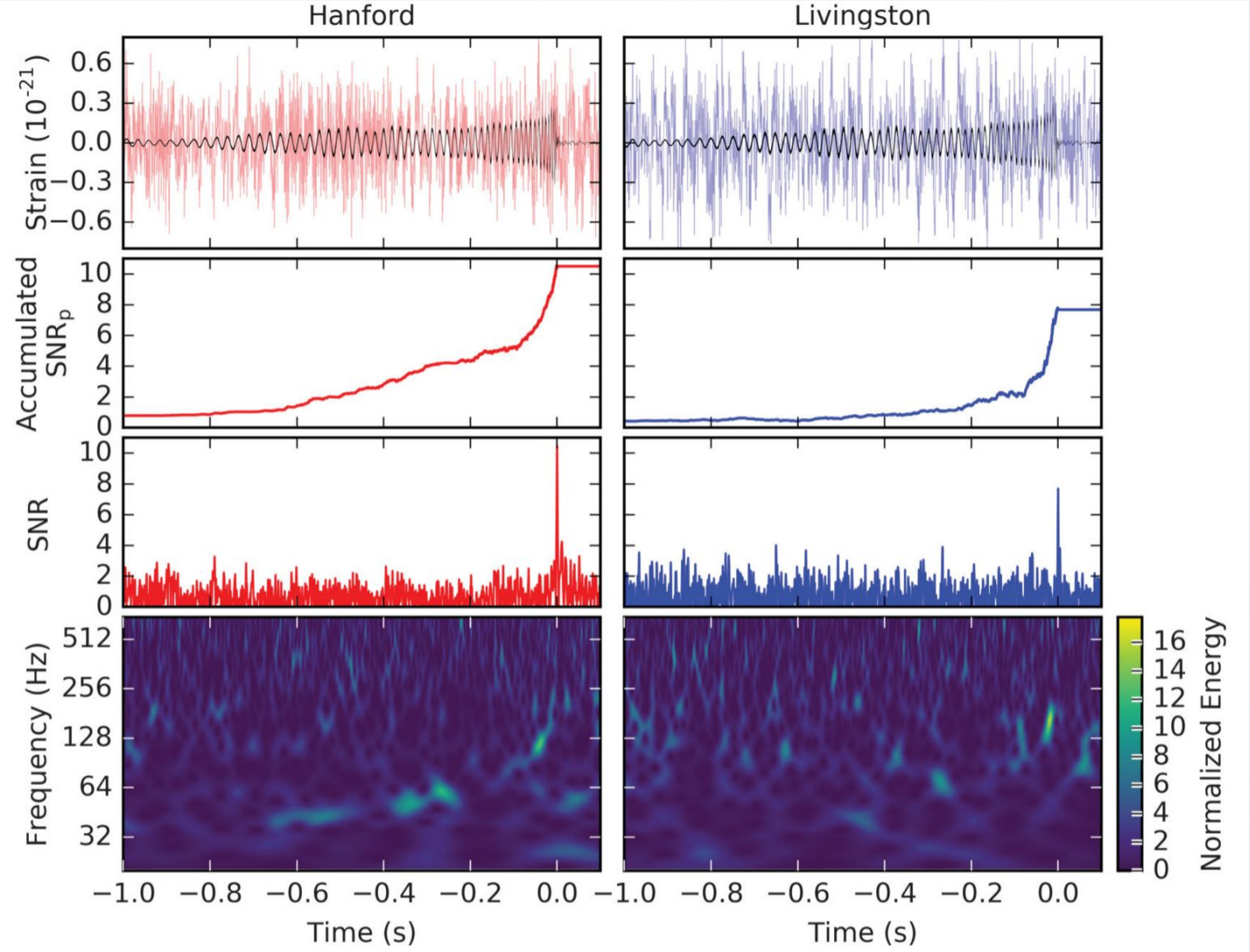


Effective inspiral spin χ_{eff} $-0.06^{+0.14}_{-0.14}$

$$\chi_{\mathrm{eff}} = \frac{c}{GM}\left(\frac{\boldsymbol{S}_1}{m_1} + \frac{\boldsymbol{S}_2}{m_2}\right) \cdot \frac{\boldsymbol{L}}{|\mathbf{L}|}$$

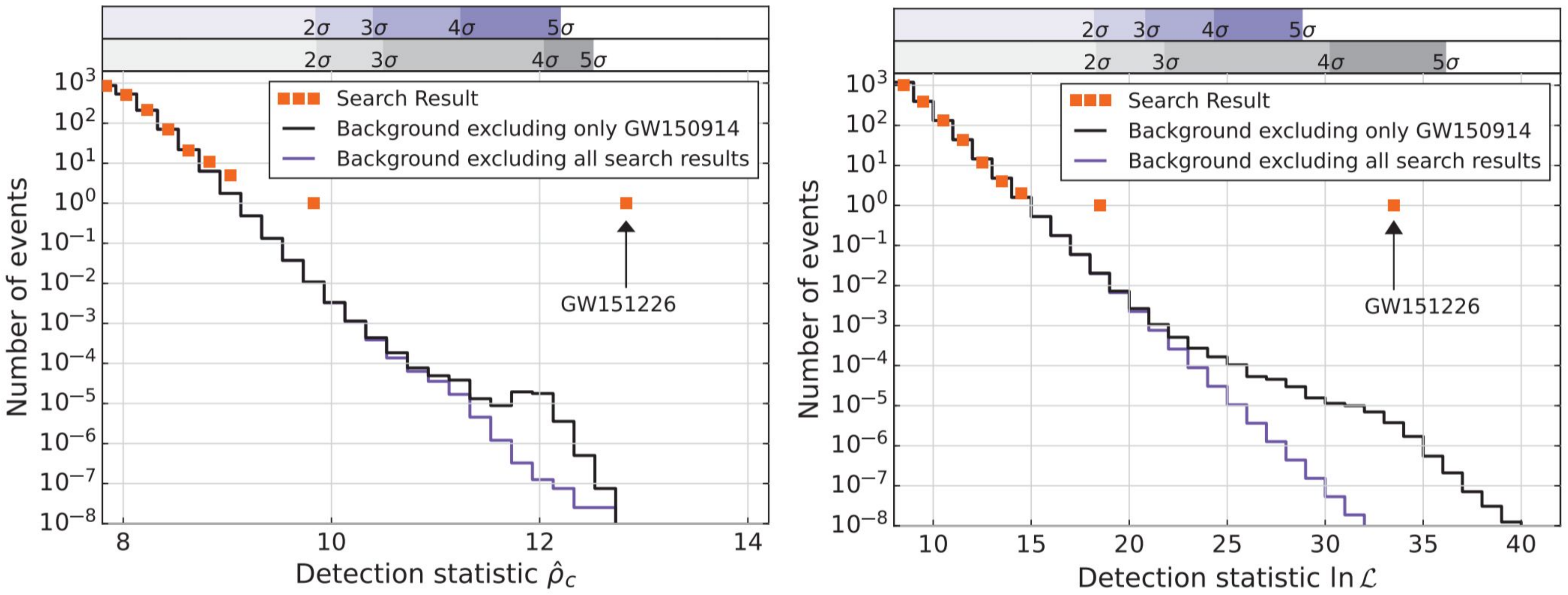
Phys. Rev. Lett. 116, 241102 (2016)

GW151226



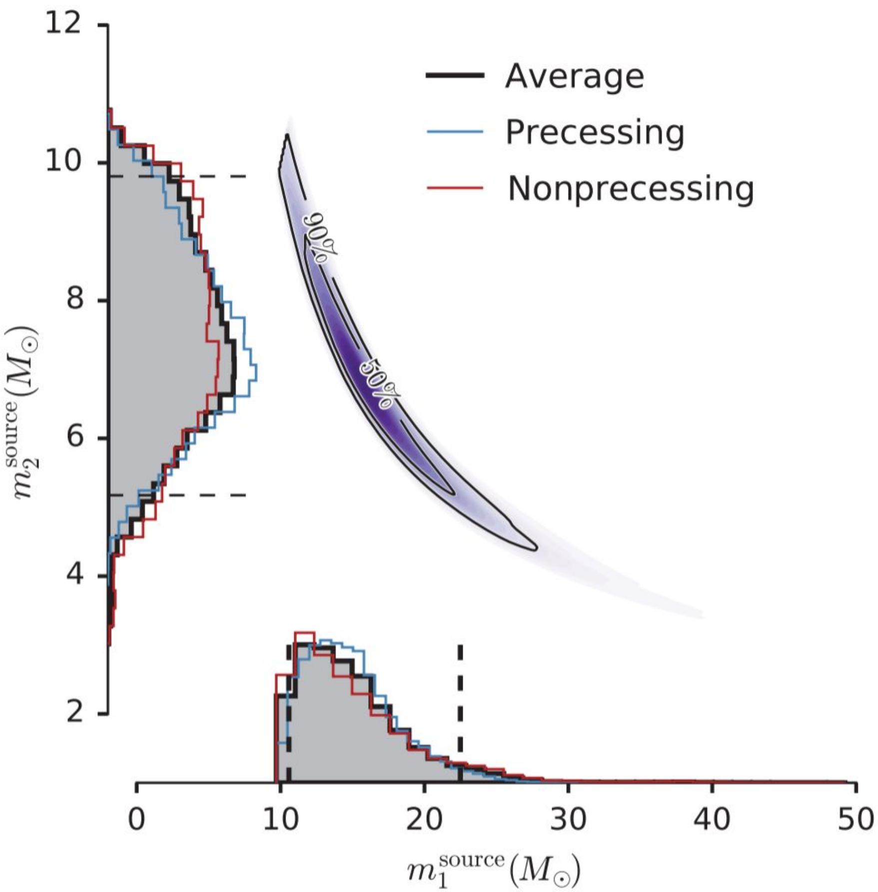
Phys. Rev. Lett. 116, 241103 (2016)

GW151226



Phys. Rev. Lett. 116, 241103 (2016)

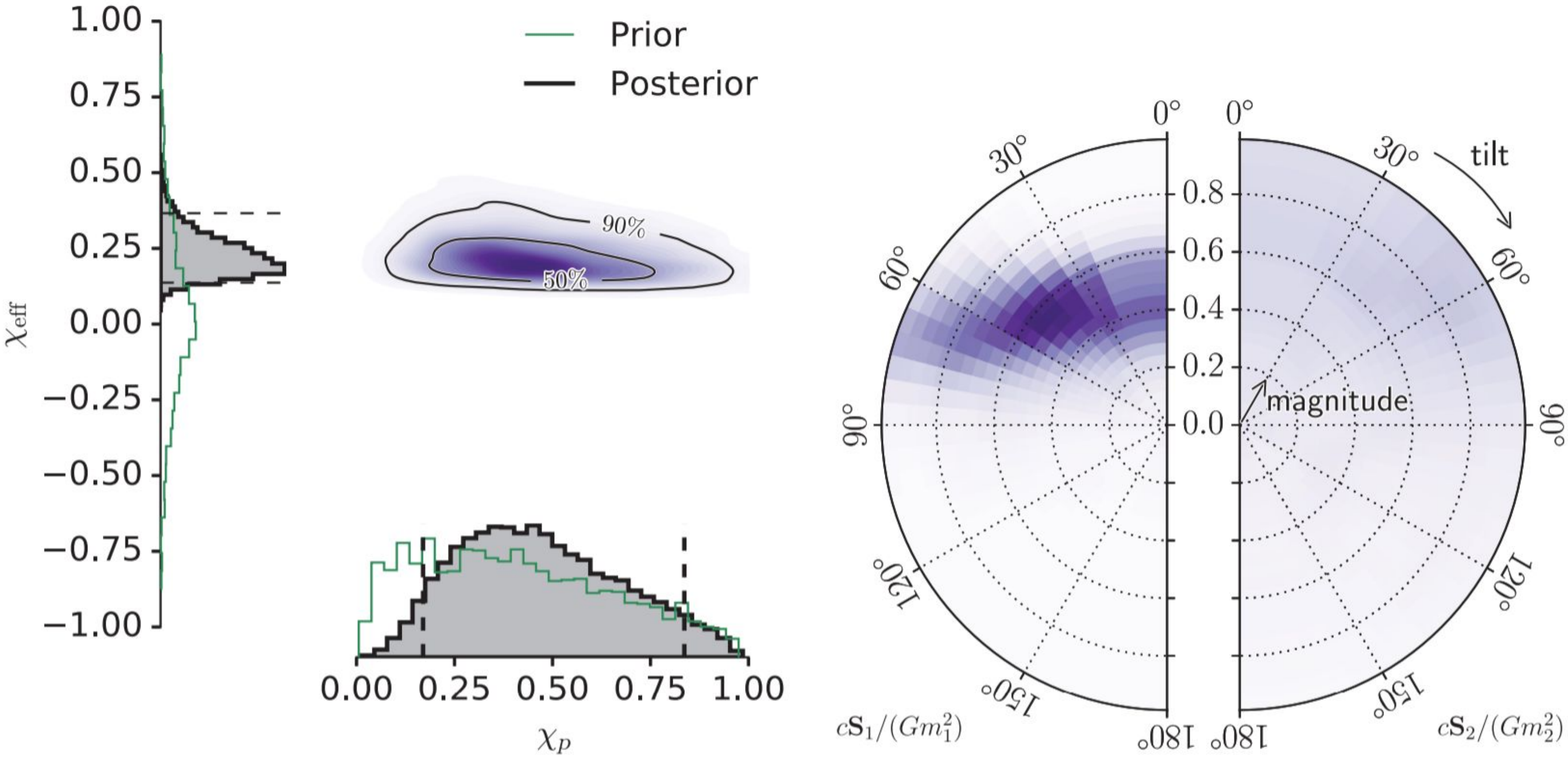
GW151226



Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$14.2^{+8.3}_{-3.7}$
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$7.5^{+2.3}_{-2.3}$
Chirp mass $\mathcal{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$8.9^{+0.3}_{-0.3}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$21.8^{+5.9}_{-1.7}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$1.0^{+0.1}_{-0.2}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$	$3.3^{+0.8}_{-1.6} \times 10^{56}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	440^{+180}_{-190}
Source redshift z	$0.09^{+0.03}_{-0.04}$

Phys. Rev. Lett. 116, 241103 (2016)

GW151226

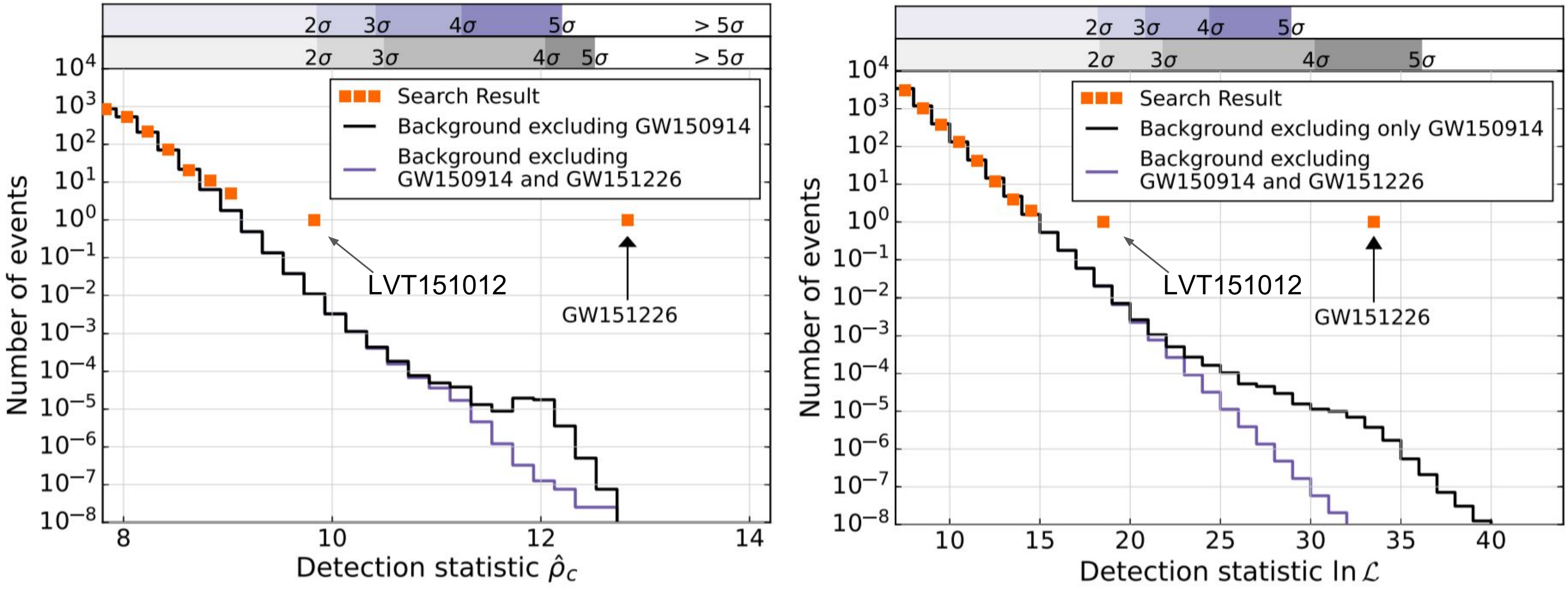


$$\chi_{\rm eff} = \frac{c}{GM}\left(\frac{\boldsymbol{S}_1}{m_1} + \frac{\boldsymbol{S}_2}{m_2}\right) \cdot \frac{\boldsymbol{L}}{|\mathbf{L}|}$$

Effective inspiral spin $\chi_{\rm eff}$ $0.21^{+0.20}_{-0.10}$

Phys. Rev. Lett. 116, 241103 (2016)

LVT151012

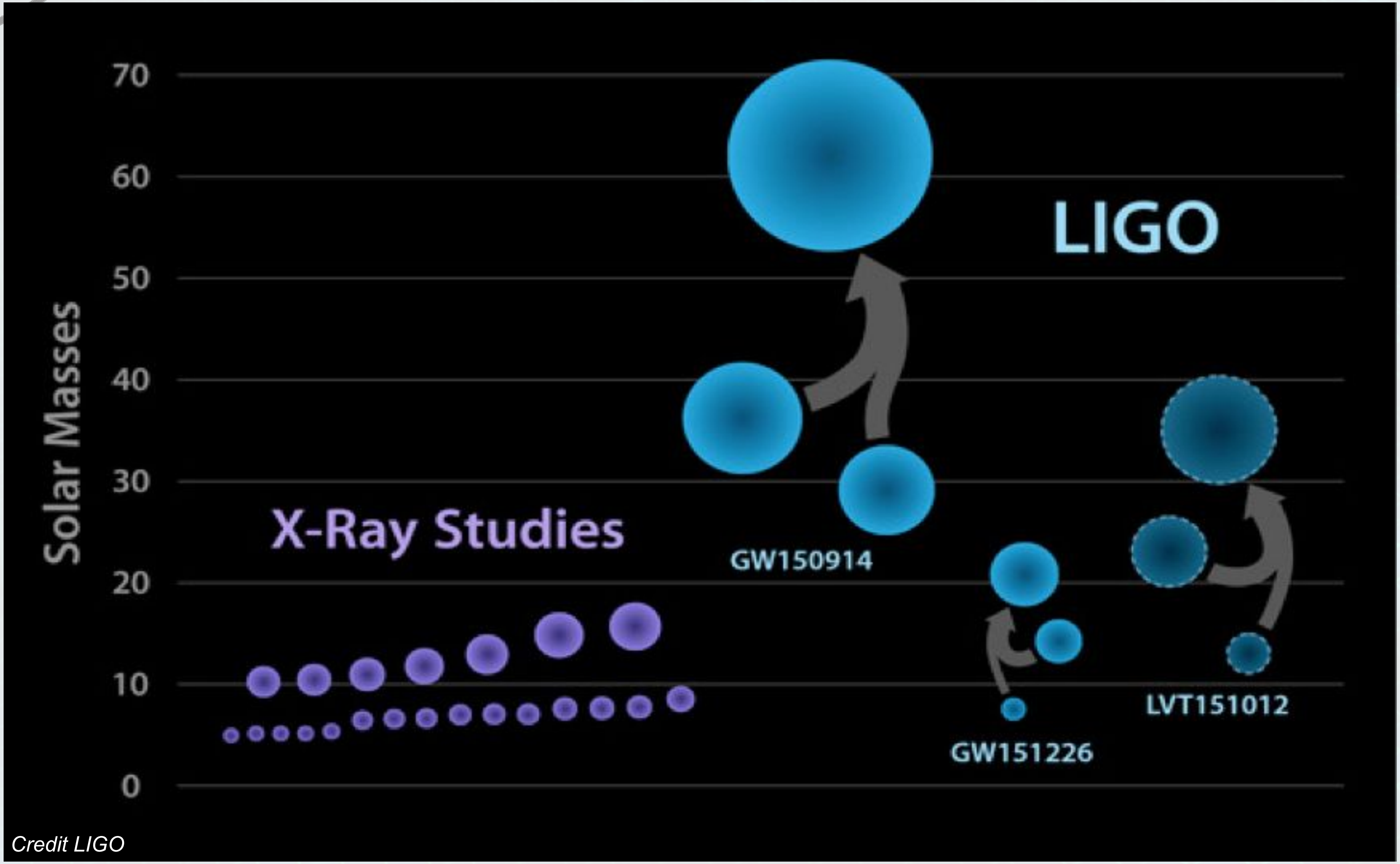


Phys. Rev. X 6, 041015 (2016)

LVT151012

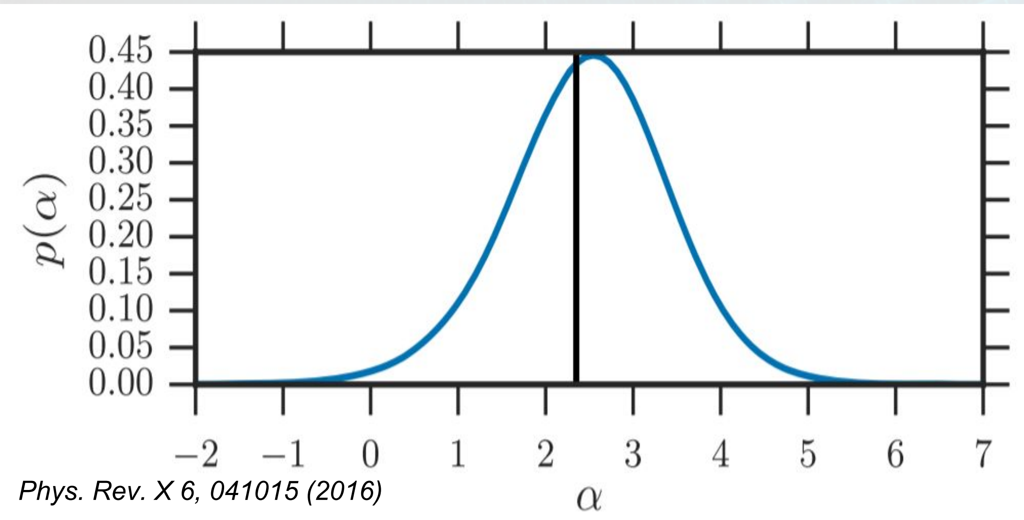
Primary mass $m_1^{\rm source}/{\rm M}_\odot$	23^{+18}_{-6}
Secondary mass $m_2^{\rm source}/{\rm M}_\odot$	13^{+4}_{-5}
Chirp mass $\mathcal{M}^{\rm source}/{\rm M}_\odot$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\rm source}/{\rm M}_\odot$	37^{+13}_{-4}
Effective inspiral spin $\chi_{\rm eff}$	$0.0^{+0.3}_{-0.2}$
Radiated energy $E_{\rm rad}/({\rm M}_\odot c^2)$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\rm peak}/({\rm erg\,s^{-1}})$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\rm L}/{\rm Mpc}$	1000^{+500}_{-500}
Source redshift z	$0.20^{+0.09}_{-0.09}$

Mass distribution

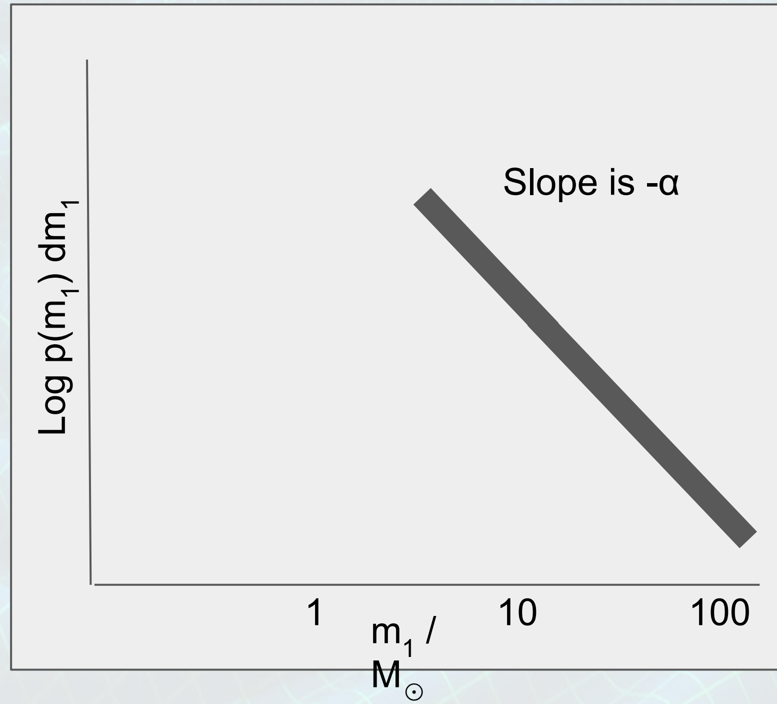


LIGO

BBH mass function



Phys. Rev. X 6, 041015 (2016)



$$p(m_1)\ dm_1 \propto m_1^{-\alpha}\ dm_1$$

The mass function may help us to tell the origin story of LIGO's black holes

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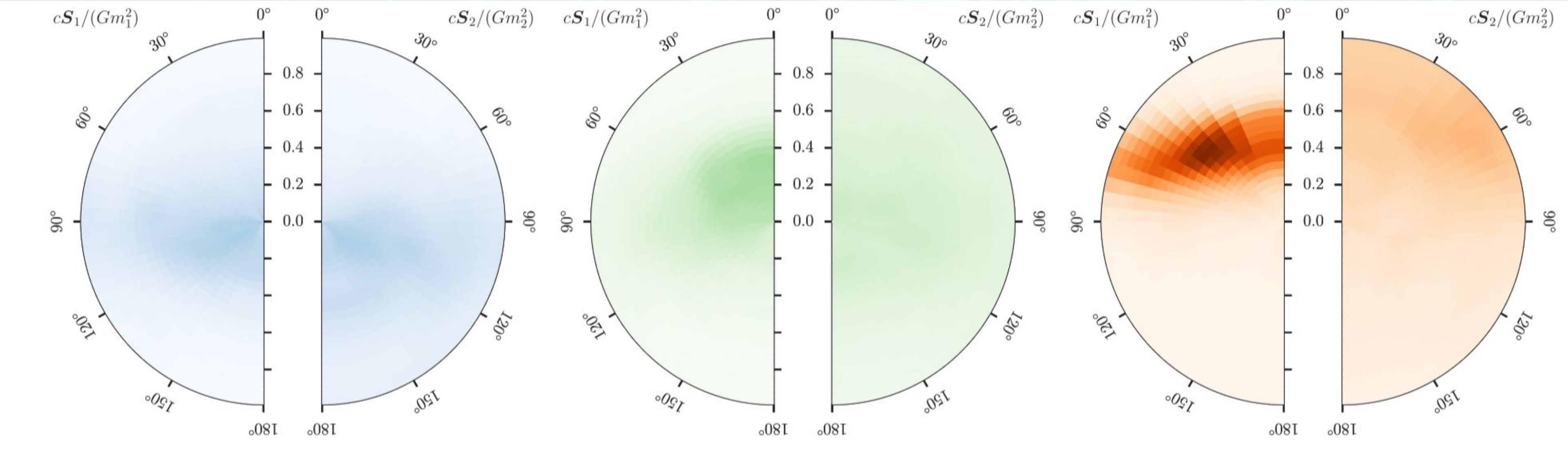
Spin distribution

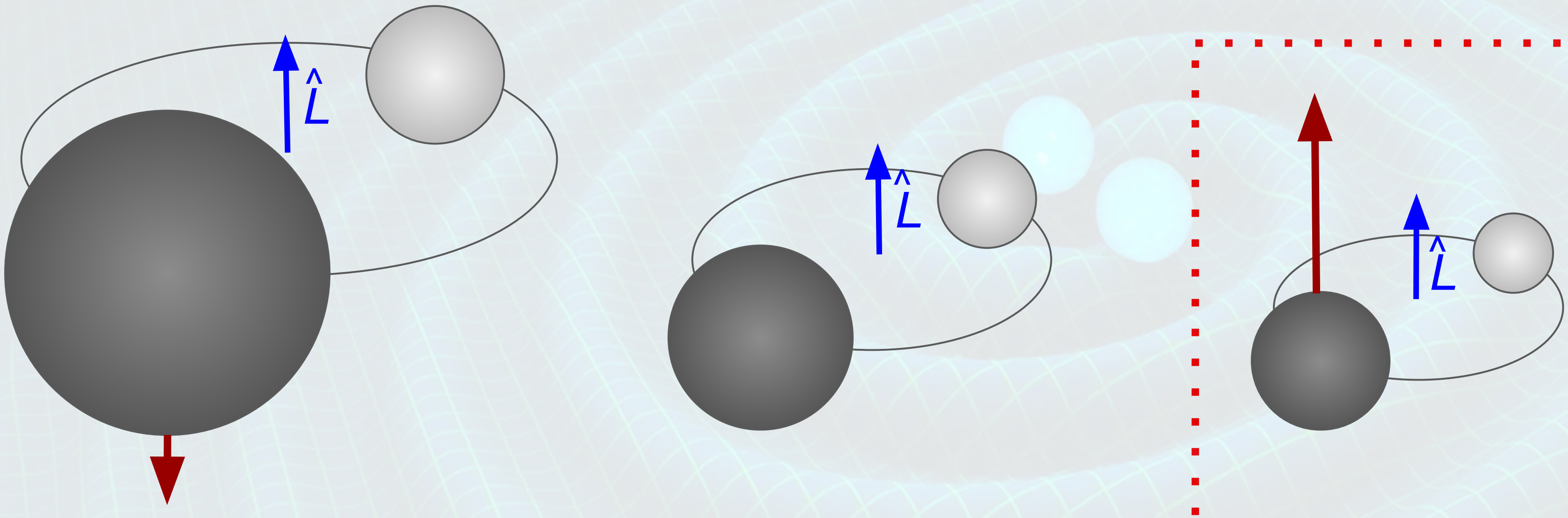


Phys. Rev. X 6, 041015 (2016)

GW150914 LVT151012 GW1512226

Spin distribution

Effective spin



GW150914
χ_{eff} = -0.06 [-0.14,0.14]

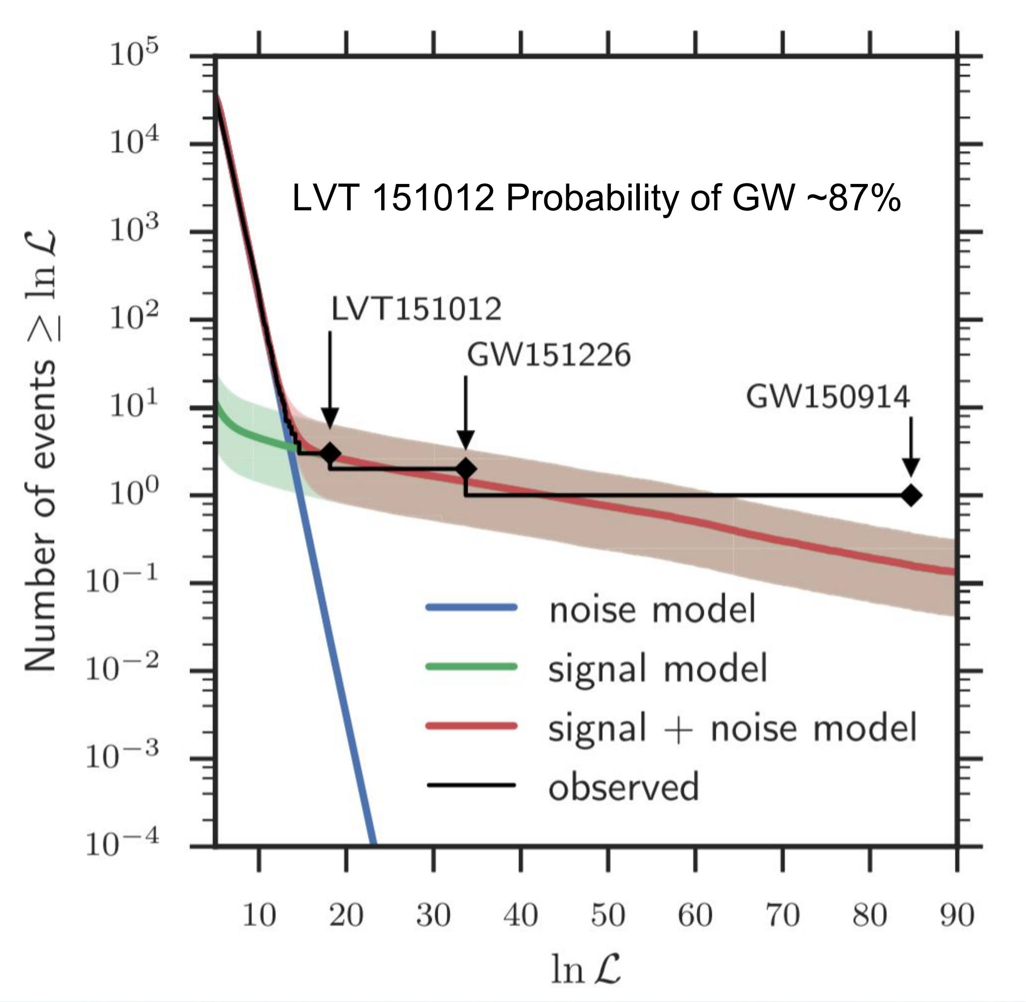
LVT151012
χ_{eff} = 0 [-0.2,0.3]

GW151226
χ_{eff} = 0.21 [-0.1,0.2]

$$\chi_{\text{eff}} = \frac{c}{GM}\left(\frac{\boldsymbol{S}_1}{m_1} + \frac{\boldsymbol{S}_2}{m_2}\right) \cdot \frac{\boldsymbol{L}}{|\mathbf{L}|}$$

Only GW151226 excludes χ_{eff} = 0 within the 90% confidence interval.

Amplitude distribution



Phys. Rev. X 6, 041015 (2016)

BBH Coalescence Rate

Mass distribution	$R/(\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1})$
GW150914	$3.4^{+8.8}_{-2.8}$
LVT151012	$9.1^{+31.0}_{-8.5}$
GW151226	36^{+95}_{-30}
All	55^{+103}_{-41}
Flat in log mass	31^{+42}_{-21}
Power law (−2.35)	97^{+135}_{-67}

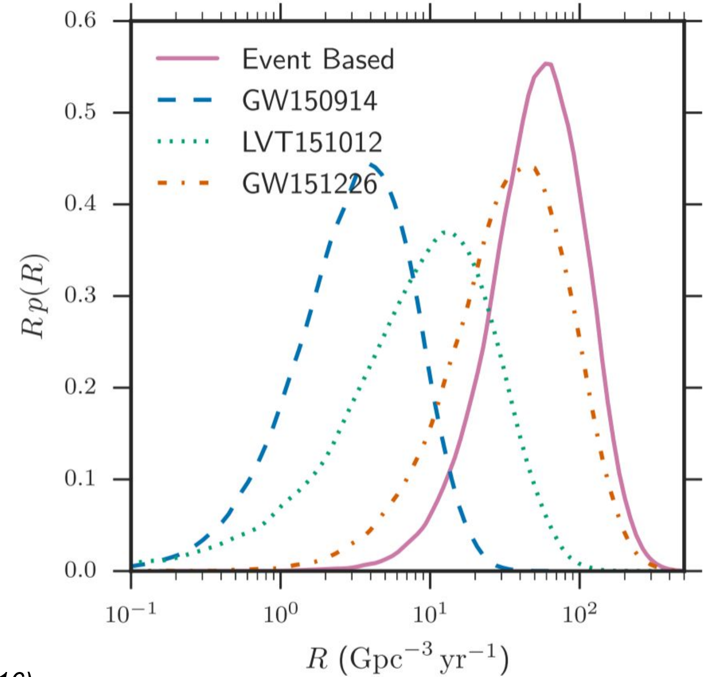
We use two canonical distributions for BBH masses:

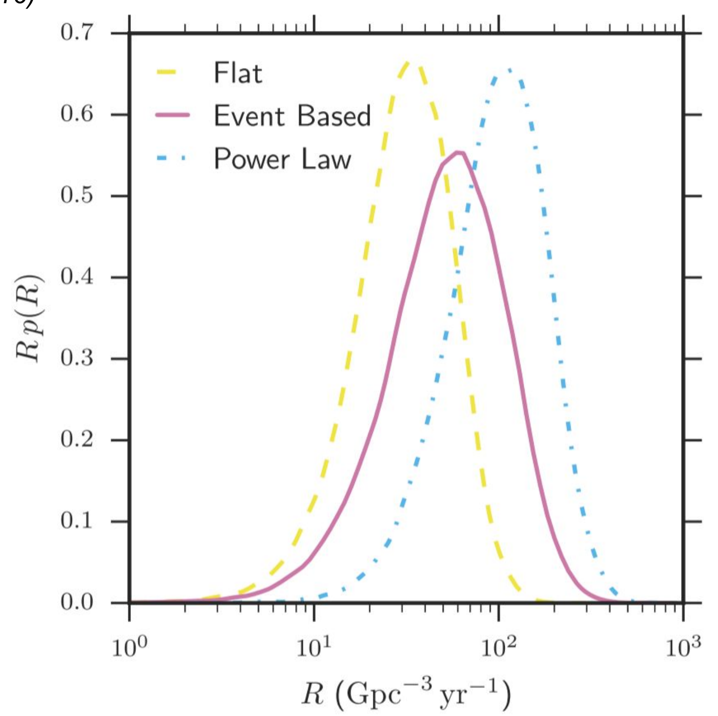
(i) a distribution uniform (flat) over the logarithm of component masses, $p(m_1, m_2) \propto {m_1}^{-1}{m_2}^{-1}$ and

(ii) assuming a power-law distribution in the primary mass, $p(m_1) \propto m_1^{-2.35}$, with a uniform distribution on the second mass.

We require $5M_\odot \leq m_2 \leq m_1$ and $m_1 + m_2 \leq 100M_\odot$.

Phys. Rev. X 6, 041015 (2016)





Conclusion

1. Advanced LIGO detected two definitive binary black hole mergers in its first observing run along with a third promising candidate
2. The black holes are heavier than known X-ray binary black holes
3. Two of the three black hole binaries are consistent with zero spin, one, GW151226 has a primary mass spin of at least 0.2
4. The mass distribution is consistent with a power law with slope -2.5
5. The binary black hole rate is still uncertain and model dependent but is plausibly in the range of a few to a few hundred mergers per year per gigaparsec cubed.
6. Advanced LIGO's second observing run begin at November's end 2016 and is ongoing through August 2017.

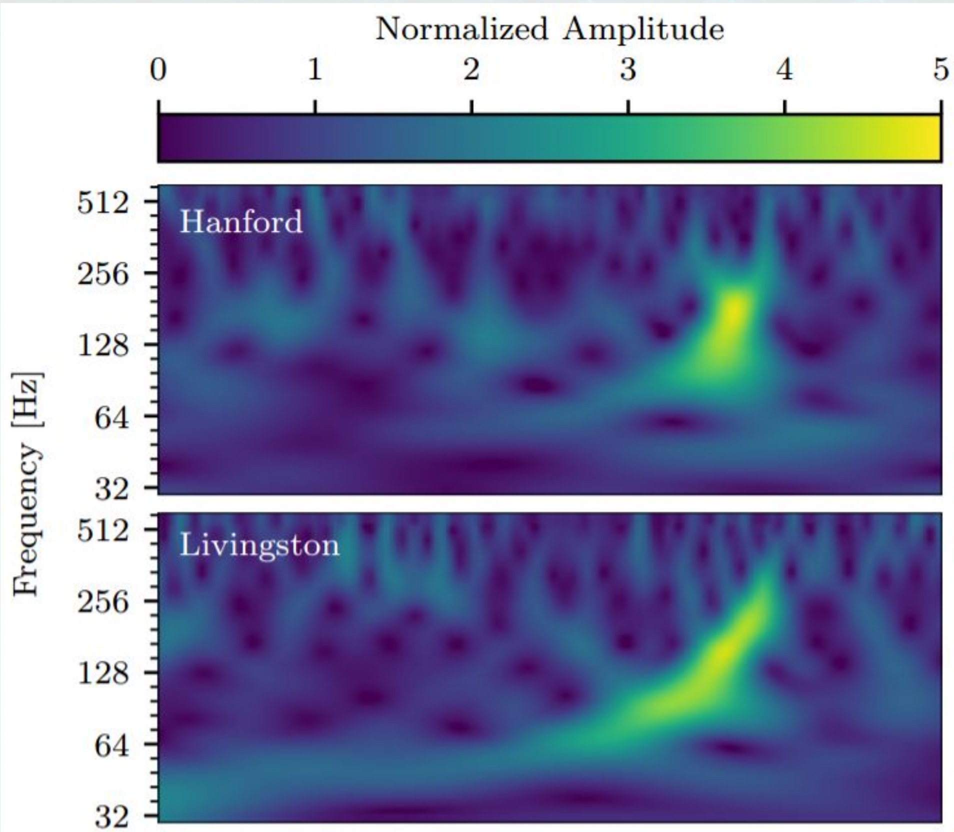
Introducing GW170104

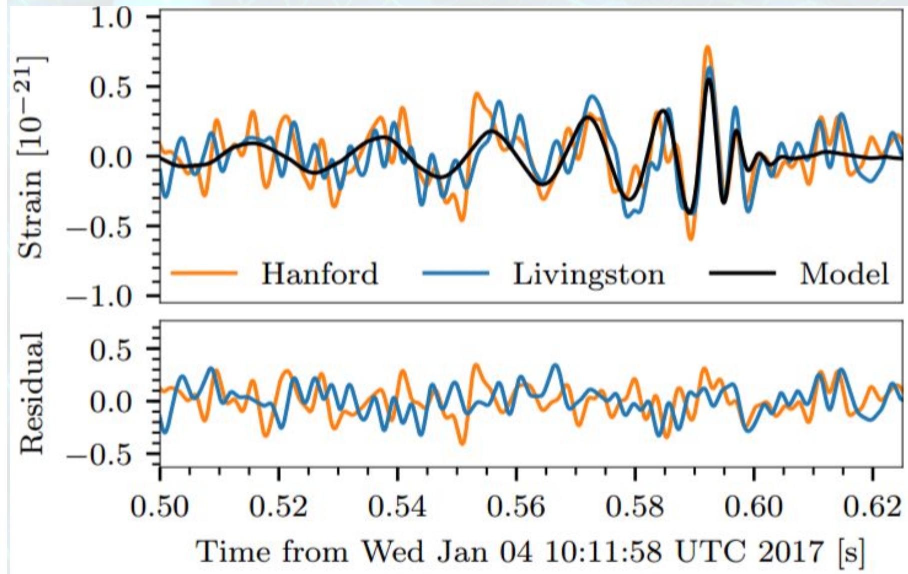
GW170104: Observation of a 50-solar-mass binary black hole coalescence at redshift 0.2

The LIGO Scientific Collaboration and the Virgo Collaboration

We describe the observation of GW170104, a gravitational-wave signal produced by the coalescence of a pair of stellar-mass black holes. The signal was measured on January 4, 2017 at 10:11:58.6 UTC by the twin advanced detectors of the Laser Interferometer Gravitational-Wave Observatory during their second observing run, with a network signal-to-noise ratio of 13 and a false alarm rate less than 1 in 70,000 years. The inferred component black hole masses are $31.2^{+8.4}_{-6.0}\,M_\odot$ and $19.4^{+5.3}_{-5.9}\,M_\odot$ (at the 90% credible level). The black hole spins are best constrained through measurement of the effective inspiral spin parameter, a mass-weighted combination of the spin components perpendicular to the orbital plane, $\chi_{\rm eff} = -0.12^{+0.21}_{-0.30}$. This result implies that spin configurations with both component spins positively aligned with the orbital angular momentum are disfavored. The source luminosity distance is 880^{+450}_{-390} Mpc corresponding to a redshift of $z = 0.18^{+0.08}_{-0.07}$. We constrain the magnitude of modifications to the gravitational-wave dispersion relation and perform null tests of general relativity. Assuming that gravitons are dispersed in vacuum like massive particles, we bound the graviton mass to $m_g \leq 7.7 \times 10^{-23}\ {\rm eV}/c^2$. In all cases, we find that GW170104 is consistent with general relativity.

Introducing GW170104

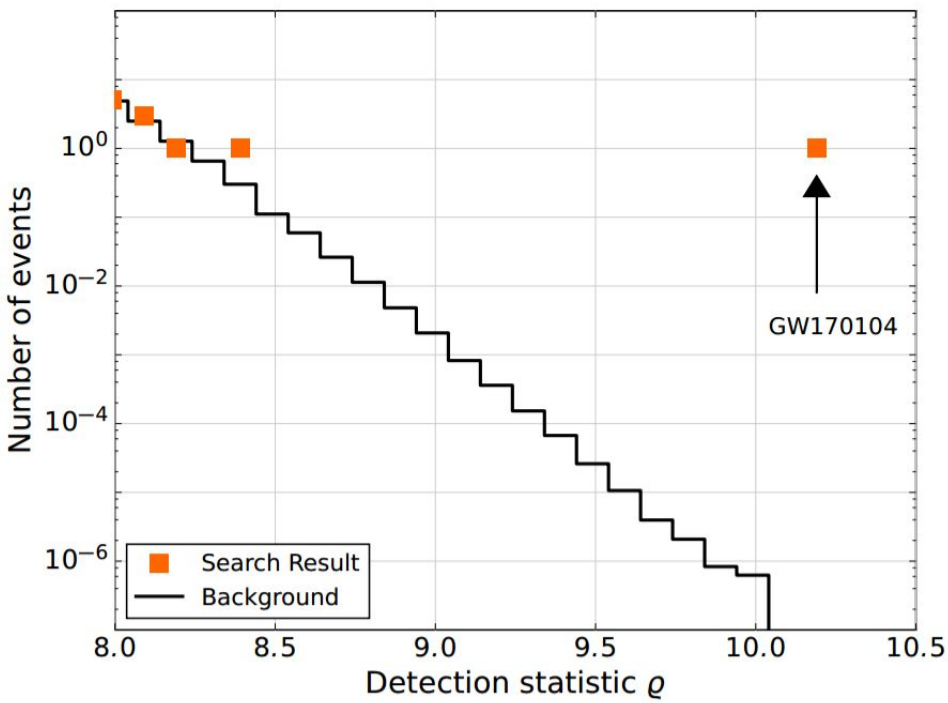


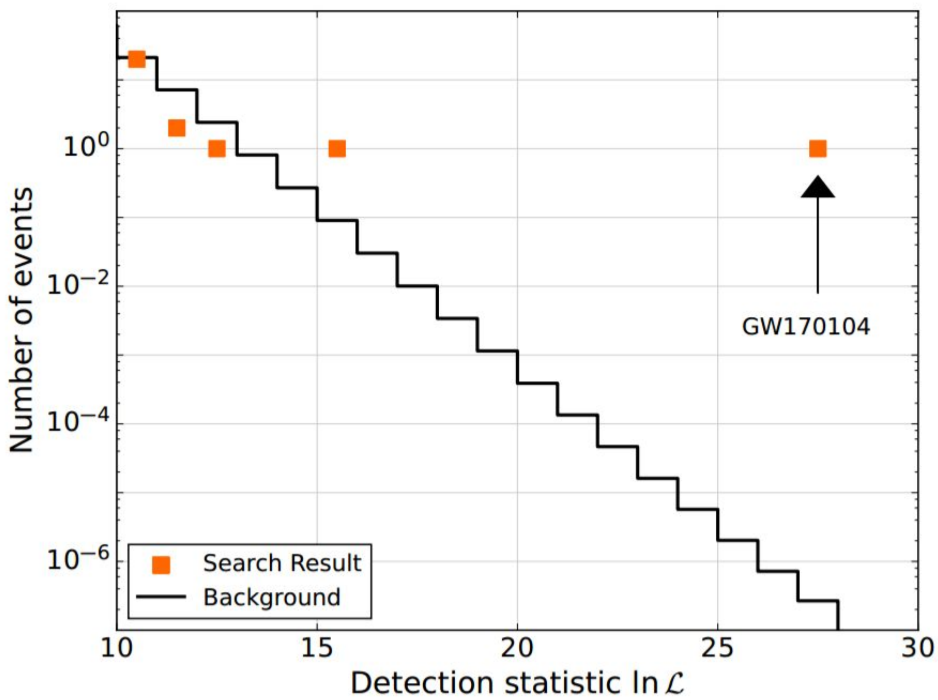


LIGO Scientific Collaboration and Virgo Collaboration to appear in PRL

Introducing GW170104

< 1 / 70,000 years!





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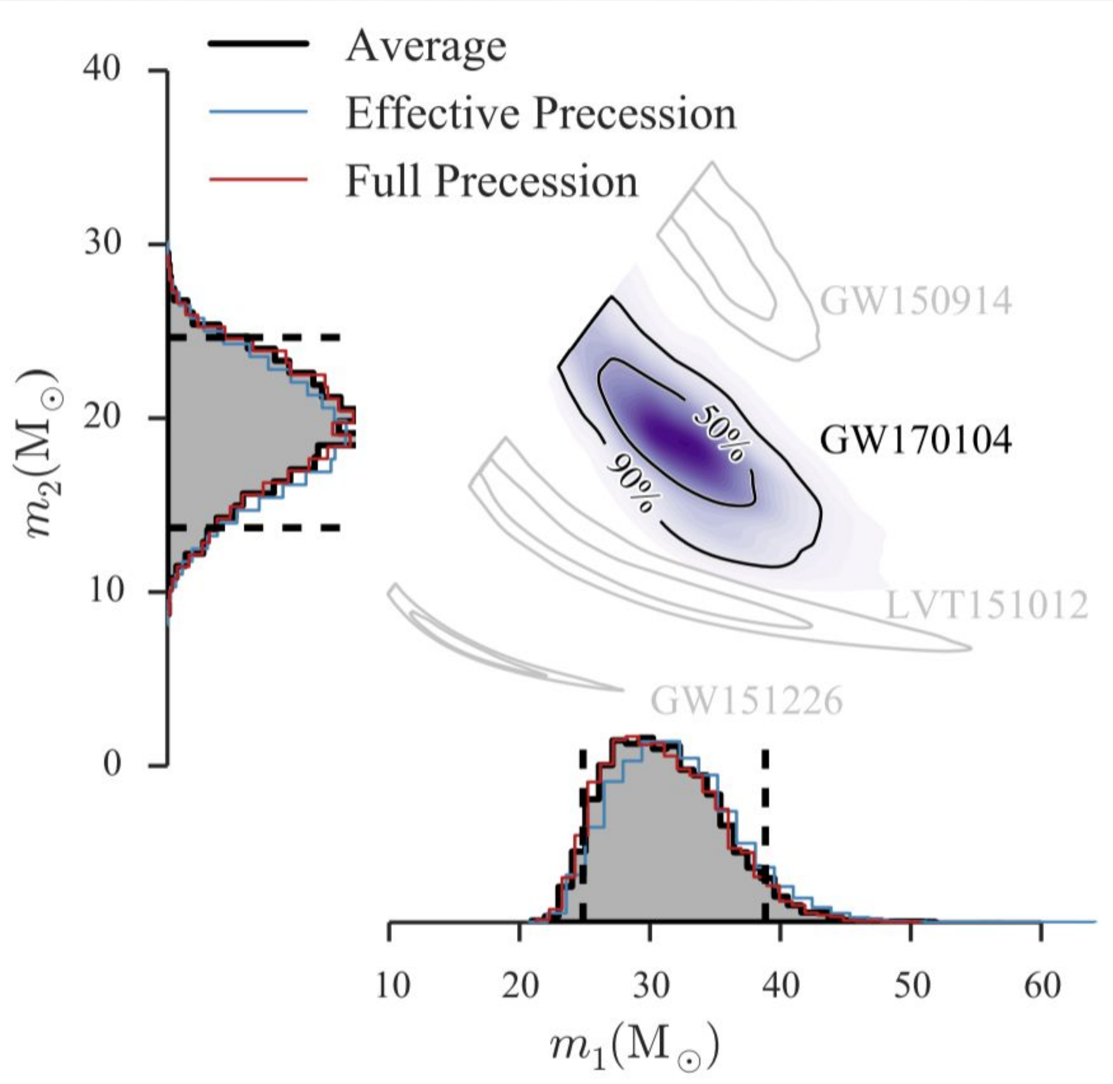
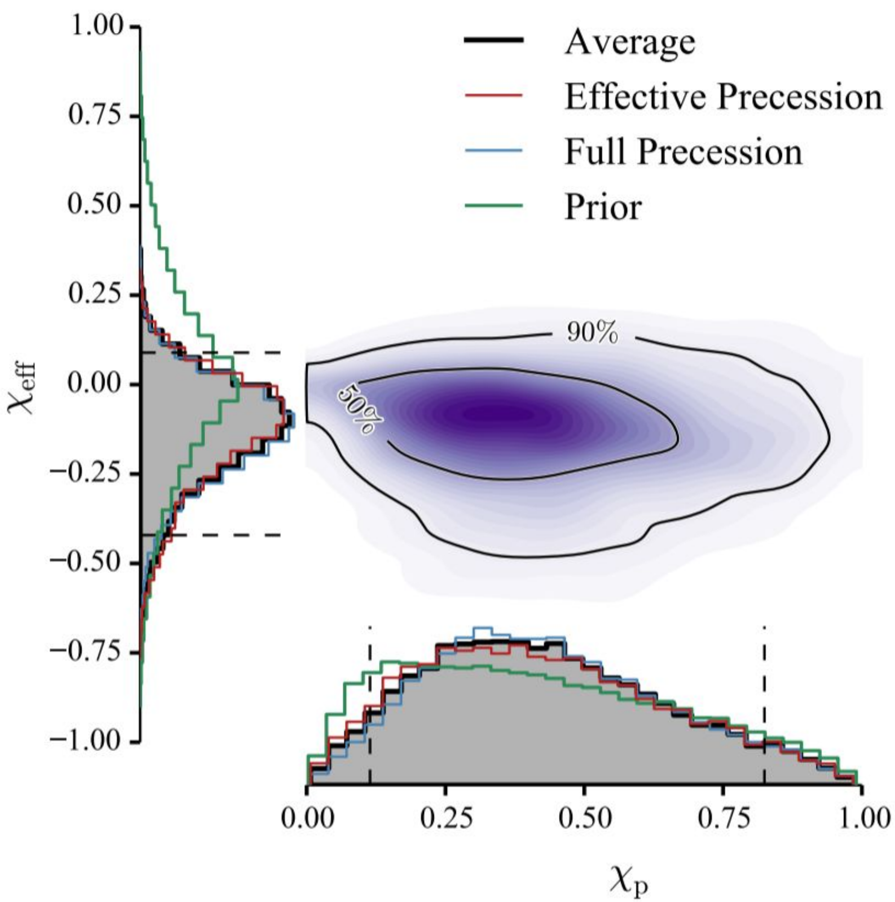
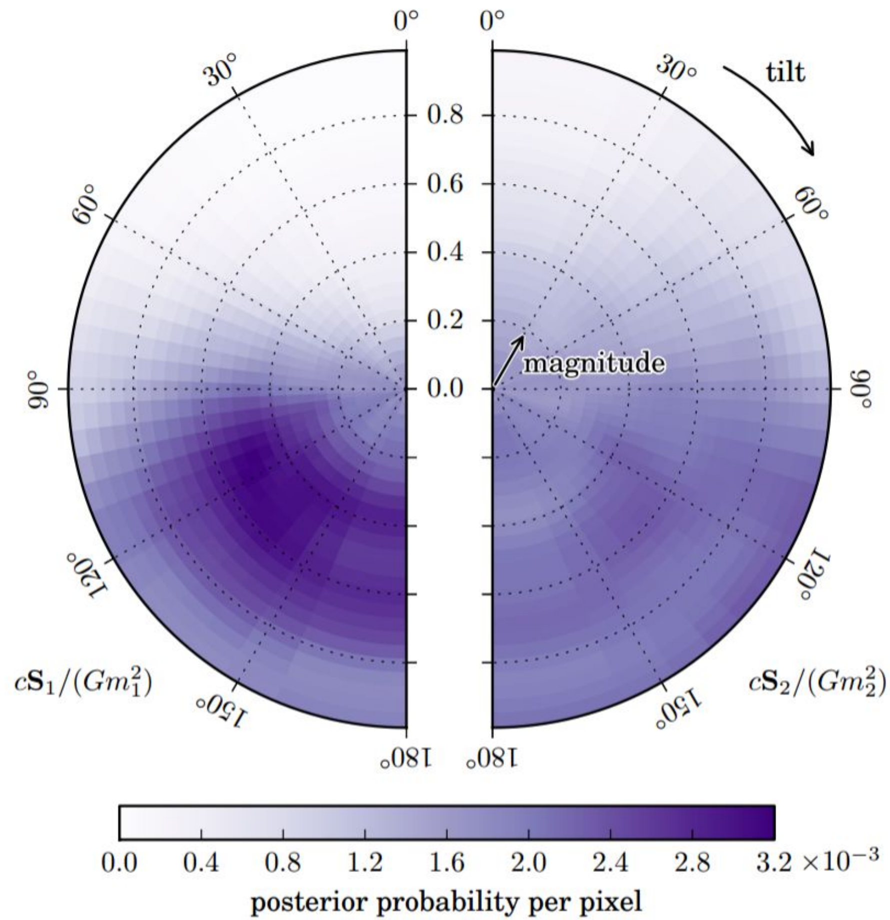
Introducing GW170104



LIGO Scientific Collaboration and Virgo Collaboration to appear in PRL

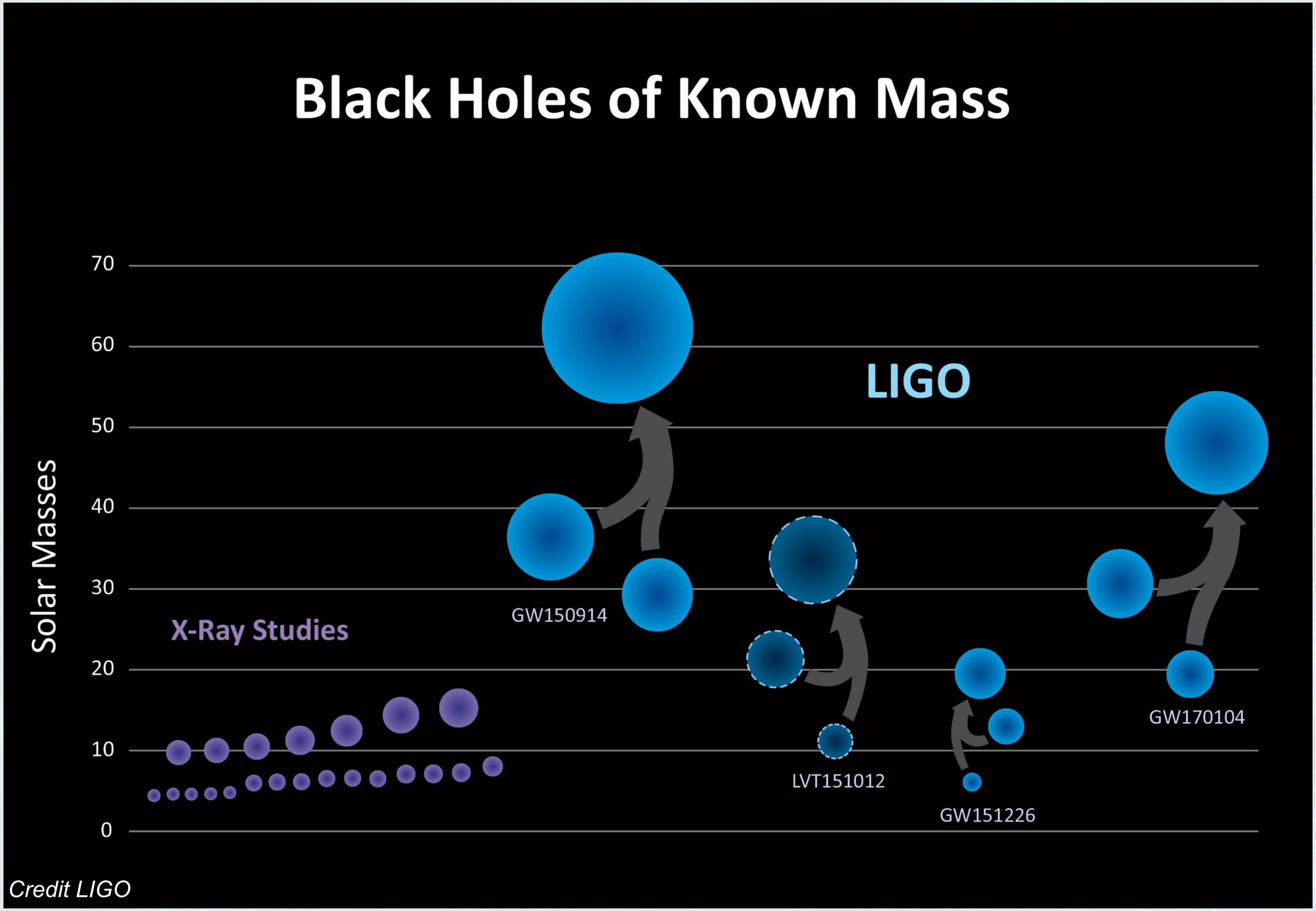
Introducing GW170104





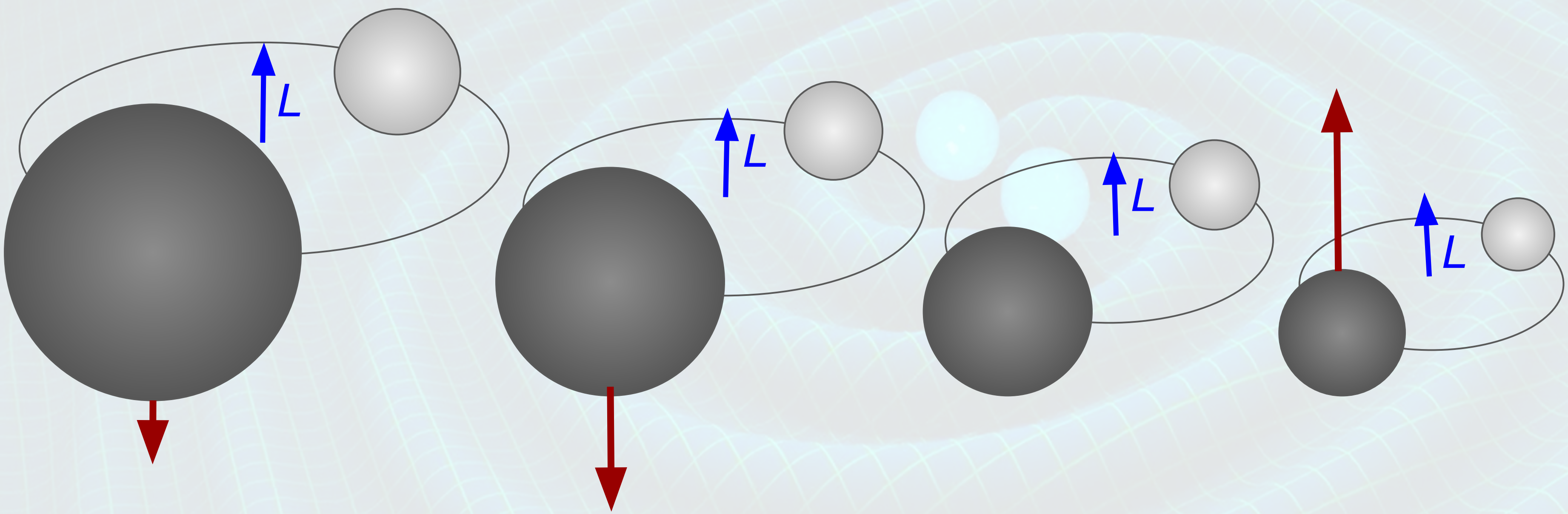
LIGO Scientific Collaboration and Virgo Collaboration to appear in PRL

Amongst the other LIGO BHs



Amongst the other LIGO BHs

Effective spin



GW150914 χ_{eff} = -0.06 [-0.14,0.14]

GW170104 χ_{eff} = -0.12 [-0.3,0.21]

LVT151012 χ_{eff} = 0 [-0.2,0.3]

GW151226 χ_{eff} = 0.21 [-0.1,0.2]

$$\chi_{\mathrm{eff}} = \frac{c}{GM}\left(\frac{\mathbf{S}_1}{m_1} + \frac{\mathbf{S}_2}{m_2}\right) \cdot \frac{\mathbf{L}}{|\mathbf{L}|}$$

Only GW151226 excludes χ_{eff} = 0 within the 90% confidence interval.

Introducing GW170104

Primary black hole mass m_1	$31.2^{+8.4}_{-6.0}\,\mathrm{M}_\odot$
Secondary black hole mass m_2	$19.4^{+5.3}_{-5.9}\,\mathrm{M}_\odot$
Chirp mass $\mathcal{M}$	$21.1^{+2.4}_{-2.7}\,\mathrm{M}_\odot$
Total mass M	$50.7^{+5.9}_{-5.0}\,\mathrm{M}_\odot$
Final black hole mass M_f	$48.7^{+5.7}_{-4.6}\,\mathrm{M}_\odot$
Radiated energy E_rad	$2.0^{+0.6}_{-0.7}\,\mathrm{M}_\odot c^2$
Peak luminosity ℓ_peak	$3.1^{+0.7}_{-1.3} \times 10^{56}\ \mathrm{erg\,s^{-1}}$
Effective inspiral spin parameter χ_eff	$-0.12^{+0.21}_{-0.30}$
Final black hole spin a_f	$0.64^{+0.09}_{-0.20}$
Luminosity distance D_L	$880^{+450}_{-390}\ \mathrm{Mpc}$
Source redshift z	$0.18^{+0.08}_{-0.07}$