New Understanding from Binary Black Hole detections

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SUPA Lectures 2019

Outline

- Gravitational wave brief introduction
- The detections
  - The 1st detection - GW150914
  - The rest of the 1st observing run (O1)
  - The 2nd observing run (O2)
  - The current observing run (O3)
- Additional properties - populations
- Summary

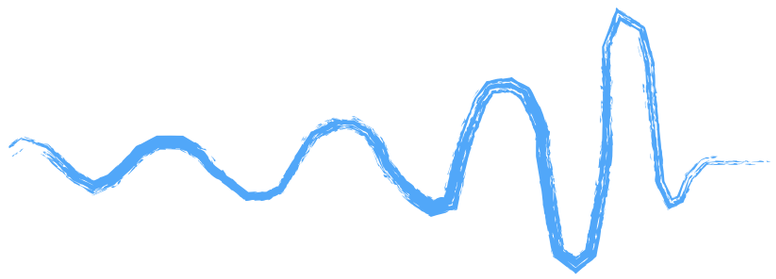
interspersed throughout are tutorial slides including some based on “The basic physics of the binary black hole merger GW150914” LIGO-Virgo Collaboration, arXiv:1608.01940 (2016)

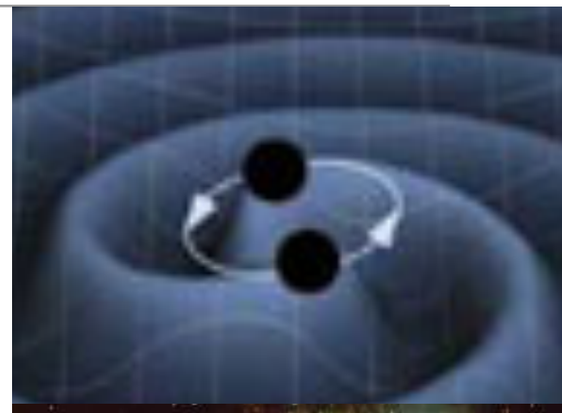
Gravitational wave basics

Just to warm you up

Astrophysical source types

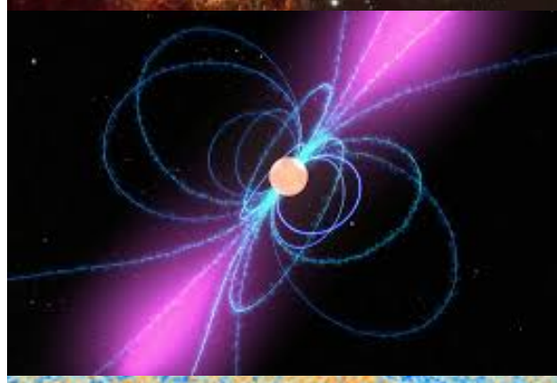
compact binary coalescence



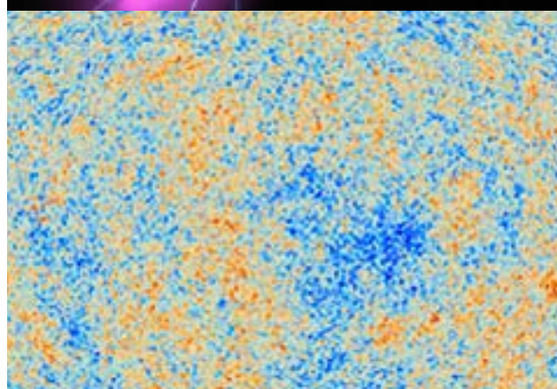


burst

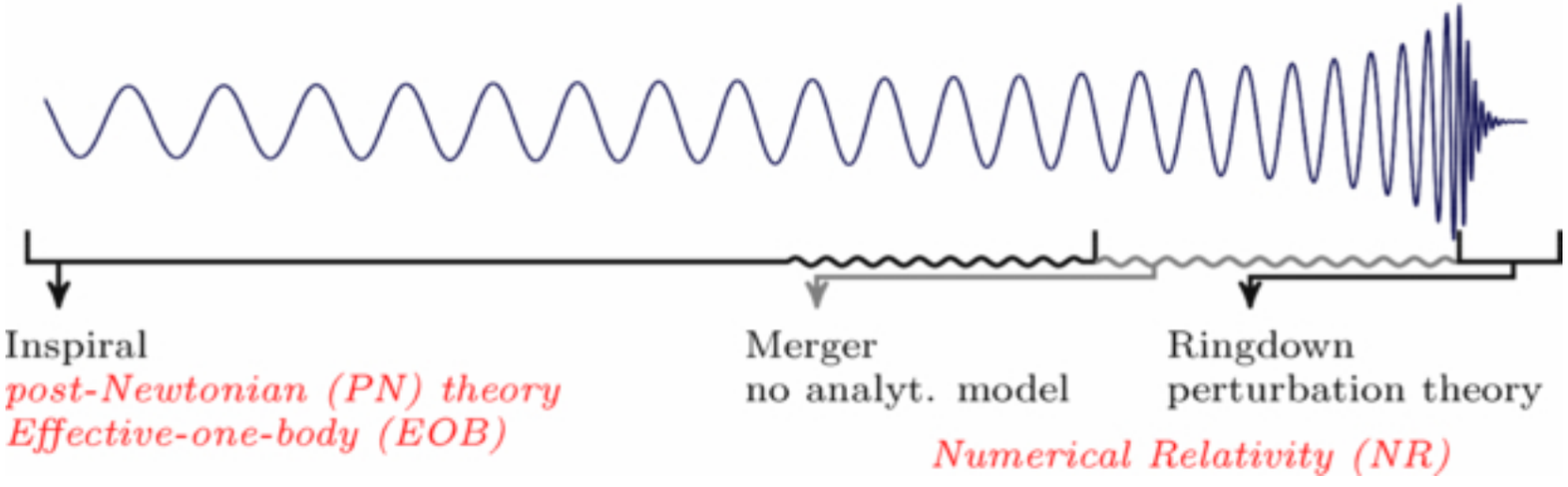
continuous

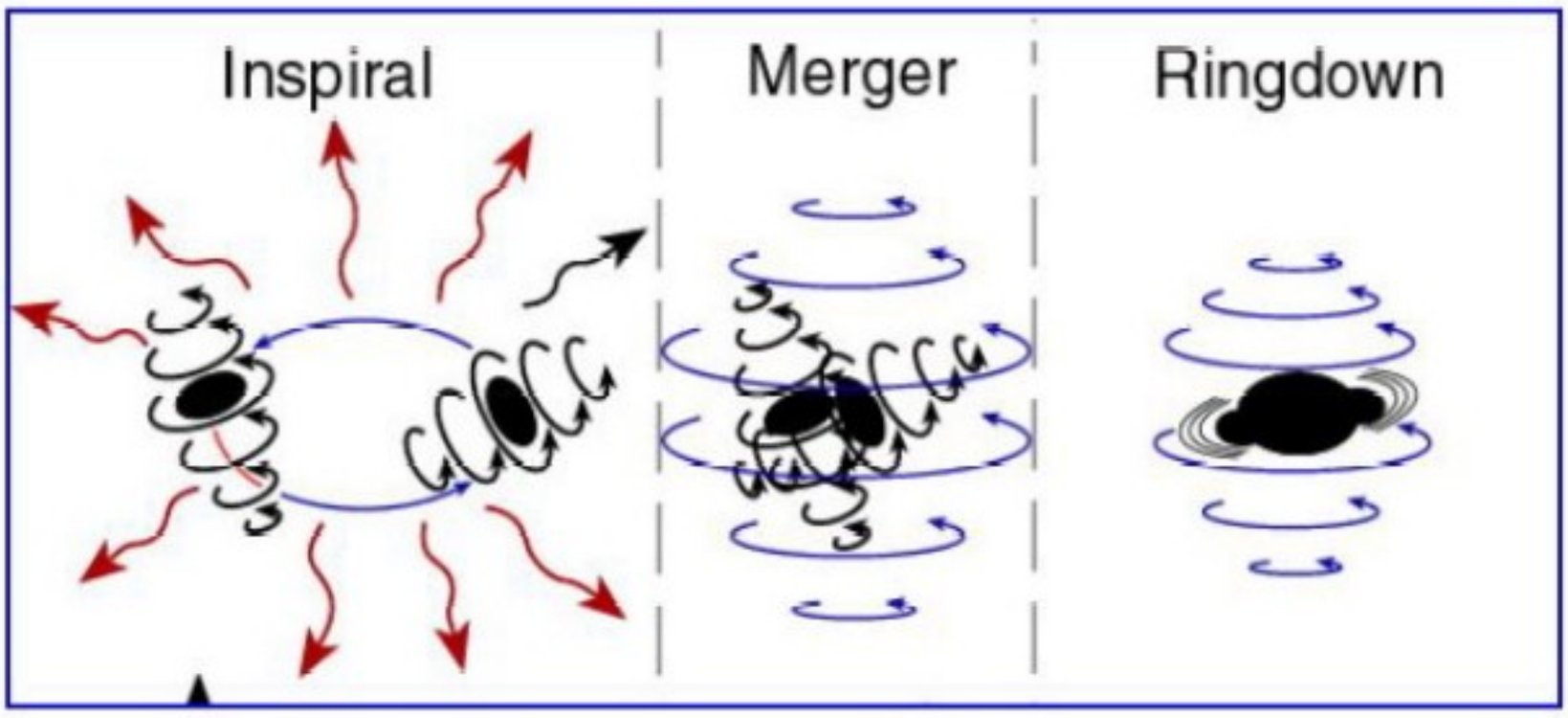


stochastic



Compact binary coalescence





Radiation from a binary

- First we calculate the quadrupole moment

$$Q_{ij} = \int \mathrm{d}^3x\,\rho(\mathbf{x})\left(x_i x_j - \frac{1}{3}r^2\delta_{ij}\right) = \sum_{A\in\{1,2\}} m_A \begin{pmatrix} \frac{2}{3}x_A^2 - \frac{1}{3}y_A^2 & x_A y_A & 0 \\ x_A y_A & \frac{2}{3}y_A^2 - \frac{1}{3}x_A^2 & 0 \\ 0 & 0 & -\frac{1}{3}r_A^2 \end{pmatrix},$$

- For a circular orbit where

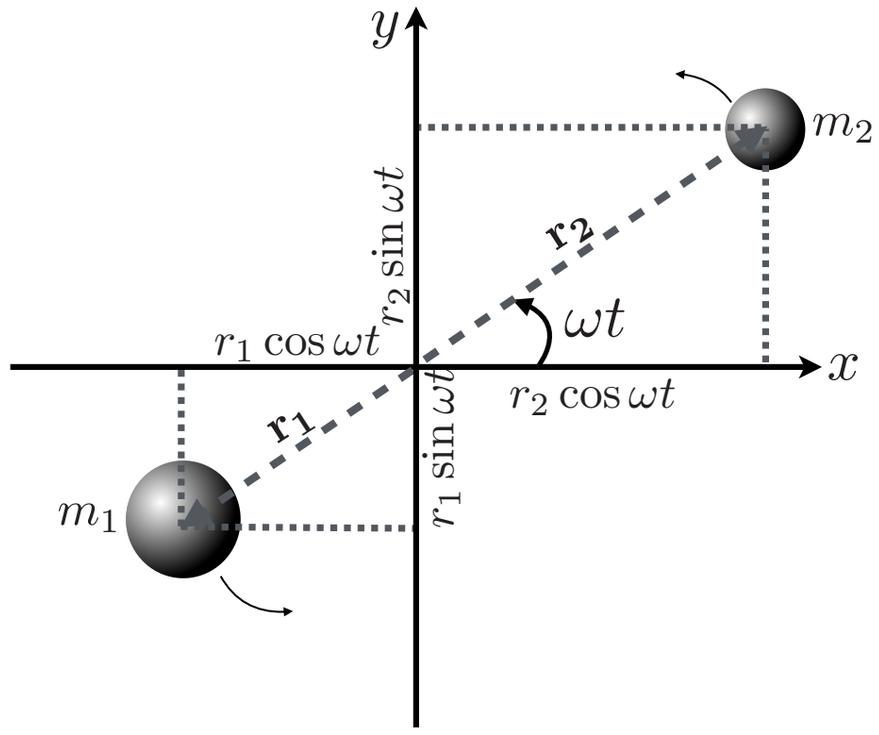
$$I_{xx} = \cos(2\omega t) + \tfrac{1}{3},\ I_{yy} = \tfrac{1}{3} - \cos(2\omega t),\ I_{xy} = I_{yx} = \sin(2\omega t) \text{ and } I_{zz} = -\tfrac{2}{3}$$

$$Q_{ij}^A(t) = \frac{m_A r_A^2}{2} I_{ij},$$

- Einstein found that the strain is then

$$h_{ij} = \frac{2G}{c^4 d_L}\frac{\mathrm{d}^2 Q_{ij}}{\mathrm{d}t^2},$$

- Where the individual masses are replaced by the reduced mass in defining Q_{ij}.



LIGO-Virgo Collaboration, arXiv:1608.01940 (2016)

Radiation from a binary

- Energy is then radiated according to the quadrupole formula

$$\frac{\mathrm{d}E_{\mathrm{GW}}}{\mathrm{d}t} = \frac{c^3}{16\pi G}\iint |\dot{h}|^2 \mathrm{d}S = \frac{1}{5}\frac{G}{c^5}\sum_{i,j=1}^{3}\frac{\mathrm{d}^3 Q_{ij}}{\mathrm{d}t^3}\frac{\mathrm{d}^3 Q_{ij}}{\mathrm{d}t^3} = \frac{32}{5}\frac{G}{c^5}\mu^2 r^4 \omega^6$$

$$\text{where } |\dot{h}|^2 = \sum_{i,j=1}^{3}\frac{\mathrm{d}h_{ij}}{\mathrm{d}t}\frac{\mathrm{d}h_{ij}}{\mathrm{d}t},$$

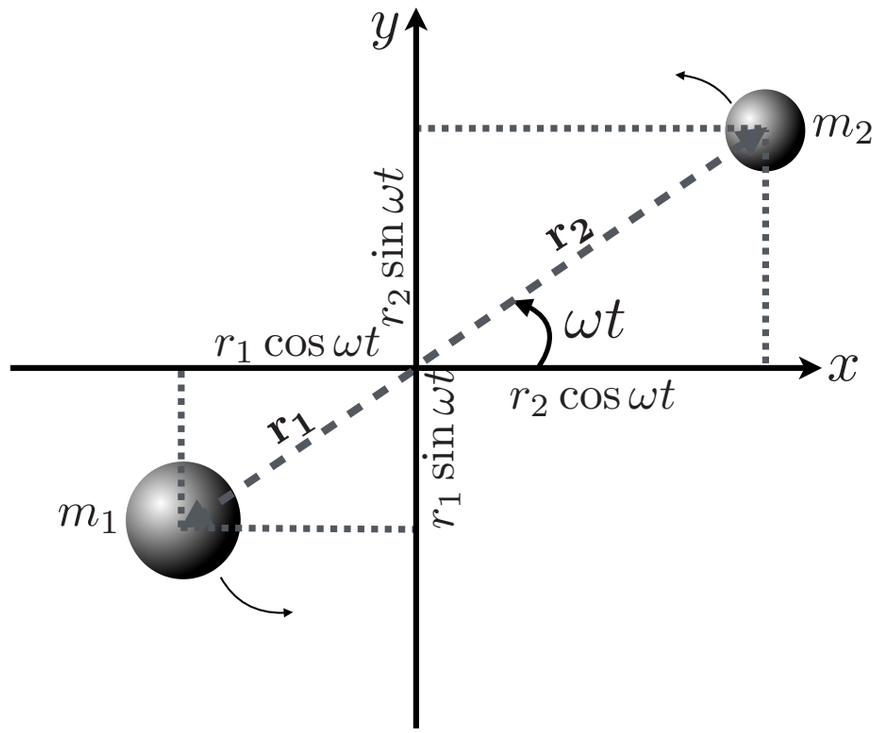
- This drains the orbital energy

$$\frac{\mathrm{d}}{\mathrm{d}t}E_{\mathrm{orb}} = \frac{GM\mu}{2r^2}\dot{r} = -\frac{\mathrm{d}}{\mathrm{d}t}E_{\mathrm{GW}}$$

- Which leads to a the evolution of the systems as an inspiral

$$\dot{\omega}^3 = \left(\frac{96}{5}\right)^3 \frac{\omega^{11}}{c^{15}} G^5 \mu^3 M^2 = \left(\frac{96}{5}\right)^3 \frac{\omega^{11}}{c^{15}} (G\mathcal{M})^5$$

- where $\mathcal{M} = \left(\mu^3 M^2\right)^{1/5}$ is the chirp mass

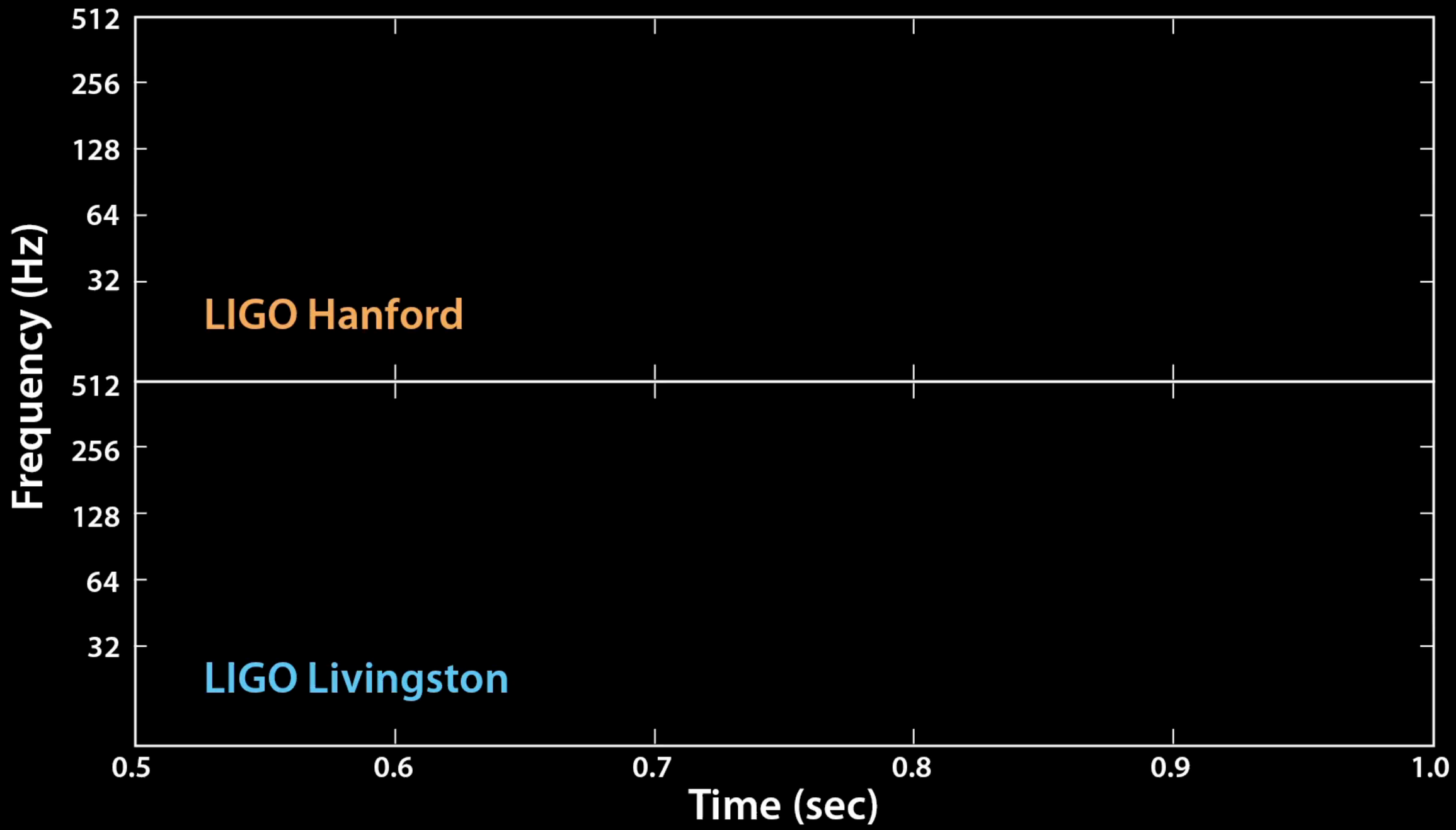


LIGO-Virgo Collaboration, arXiv:1608.01940 (2016)

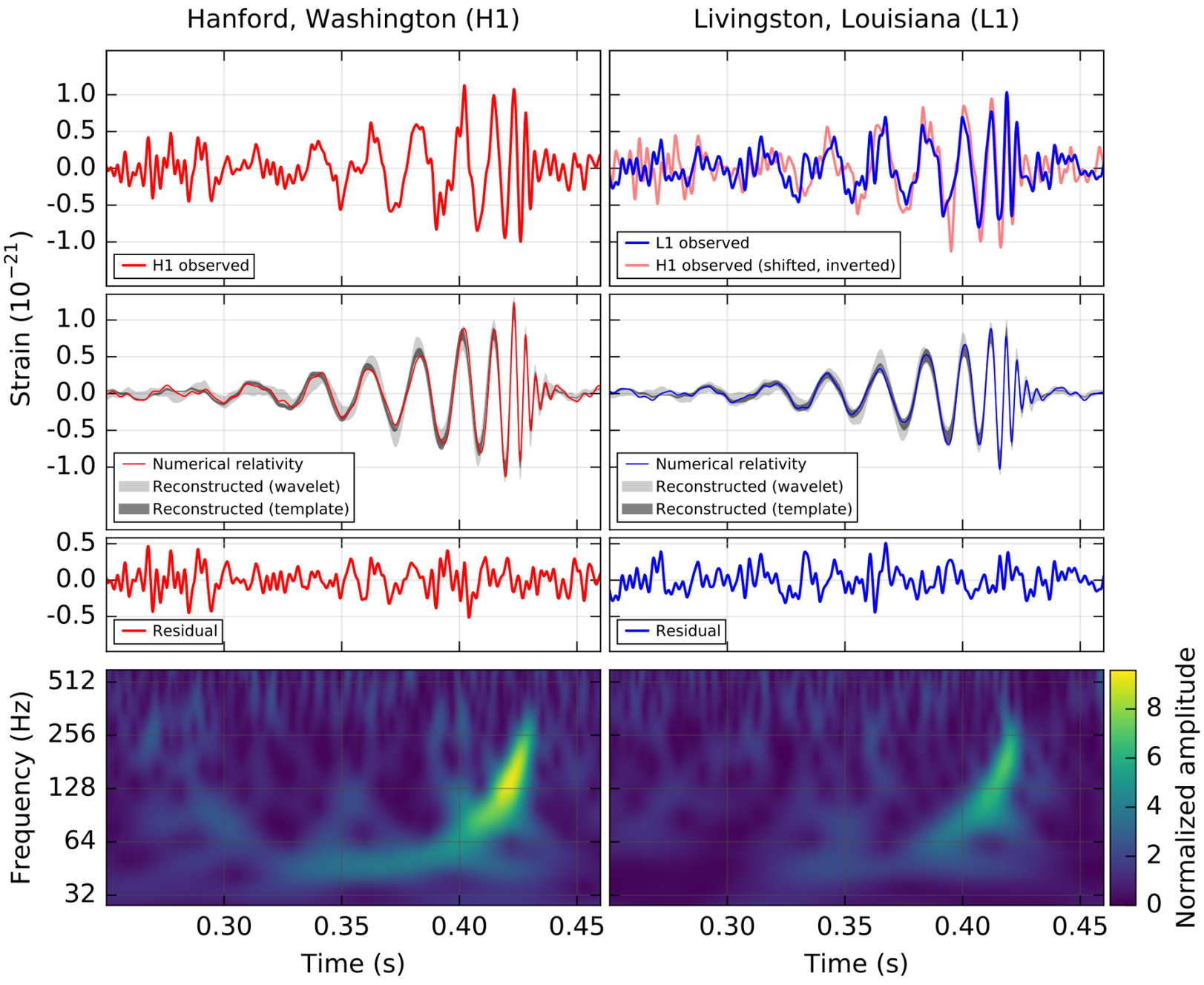
The 1st detection

GW150914

09:50:45 UTC,14th September, 2015



The data



LIGO-Virgo Collaboration, PRL **116**, 061102 (2016)

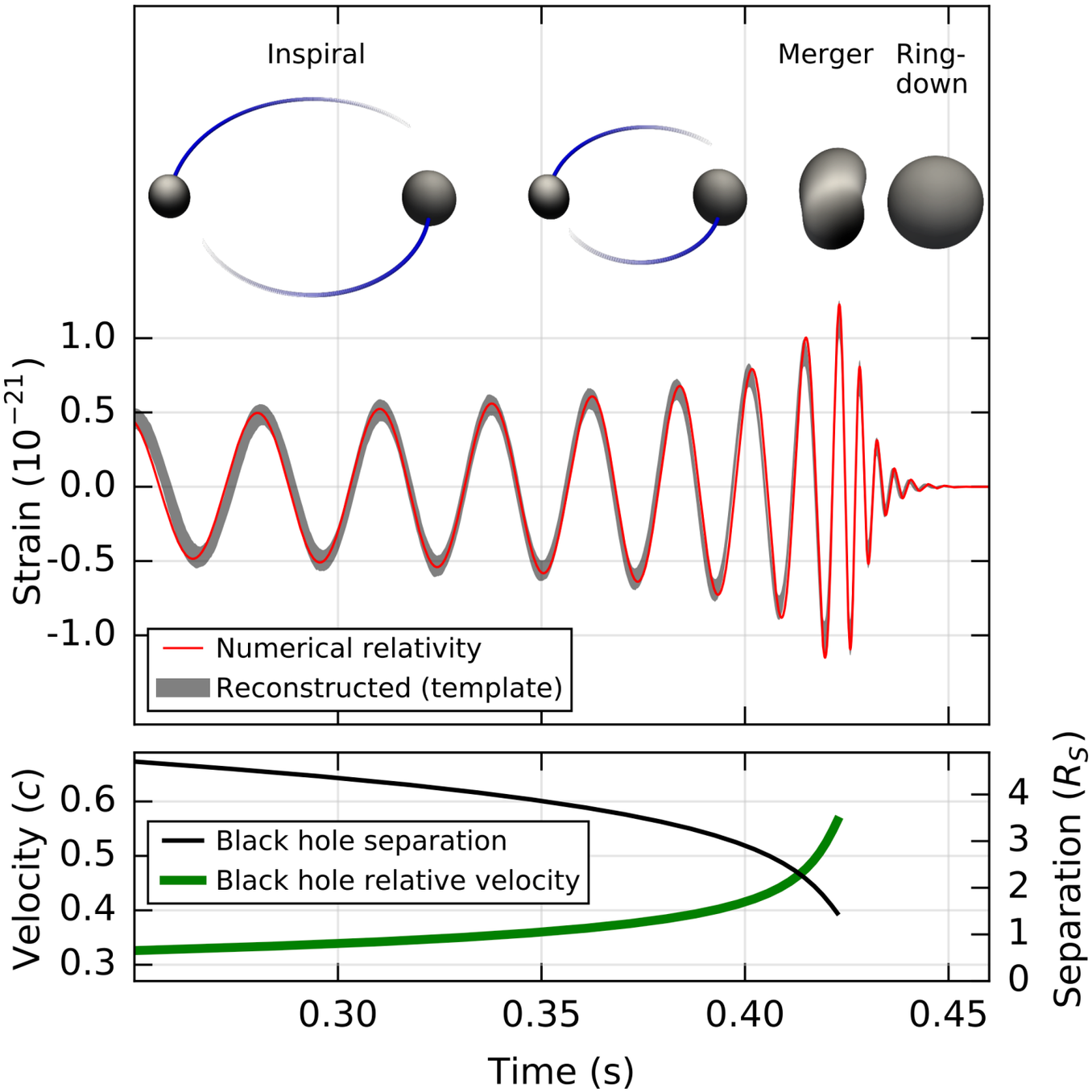
The data

The binary system

Credit: SXS Collaboration

A binary black hole?

- The first direct* detection of gravitational waves.
- The first unambiguous detection of a black hole.
- The first observation of a binary black hole.
- The most luminous event ever detected!
- Still the highest SNR BBH signal observed!



* the definition of “direct” in this case is subjective

LIGO-Virgo Collaboration, PRL **116**, 061102 (2016)

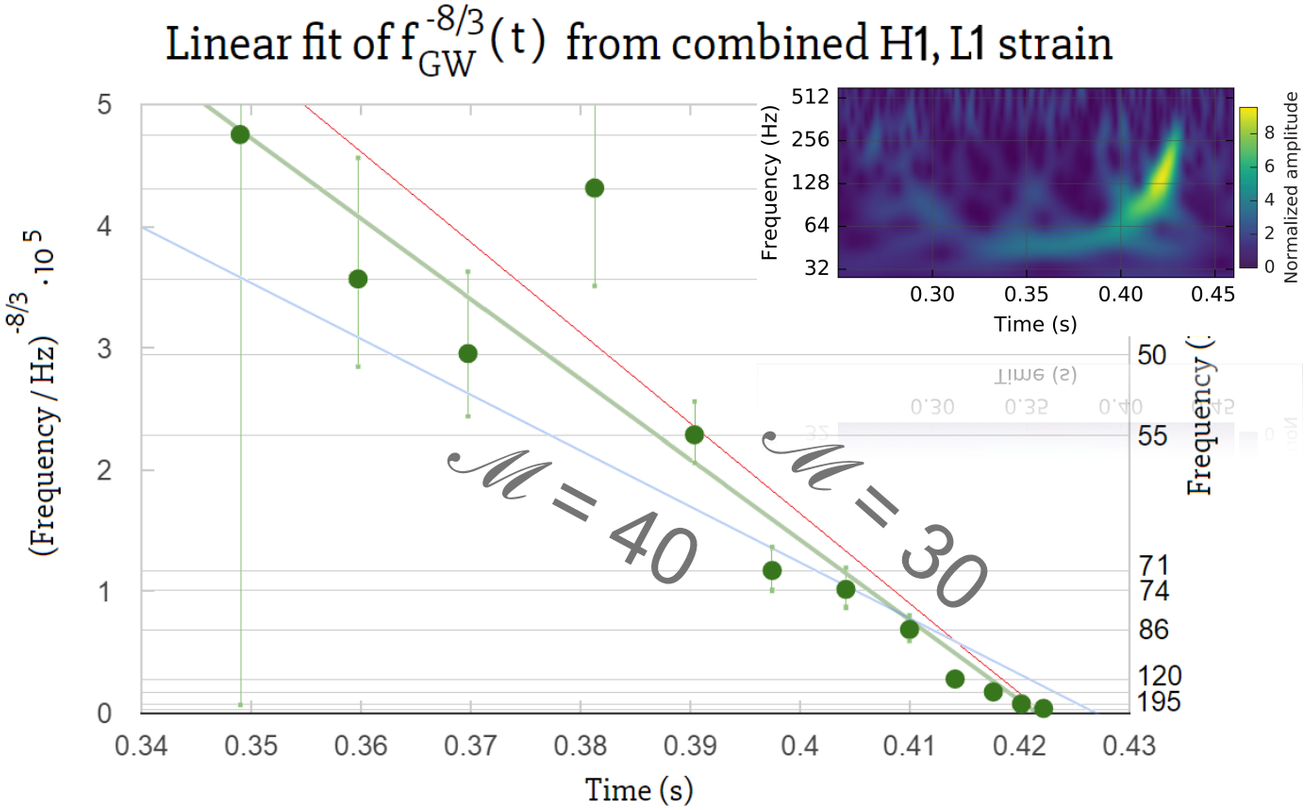
The mass scale

- We can rearrange the expression for frequency evolution to give

$$\mathscr{M} = \frac{c^3}{G}\left(\left(\frac{5}{96}\right)^3 \pi^{-8} \left(f_{\mathrm{GW}}\right)^{-11} \left(\dot{f}_{\mathrm{GW}}\right)^3\right)^{1/5}$$

- Then integrate to obtain

$$f_{\mathrm{GW}}^{-8/3}(t) = \frac{(8\pi)^{8/3}}{5}\left(\frac{G\mathscr{M}}{c^3}\right)^{5/3}(t_c - t)$$



- We use the value $\mathscr{M}$ = 30 for the remainder of this tutorial.

- We estimate the minimum mass of the lightest component later on.

LIGO-Virgo Collaboration, arXiv:1608.01940 (2016)

Proving compactness

- For an equal mass system the chirp mass implies that $m_1 = m_2 = 2^{1/5}\mathscr{M} = 35\,\mathrm{M}_\odot \qquad M = m_1 + m_2 = 70\,\mathrm{M}_\odot$

- For non-spinning objects with Keplerian orbit at the time of peak GW amplitude the orbital separation is

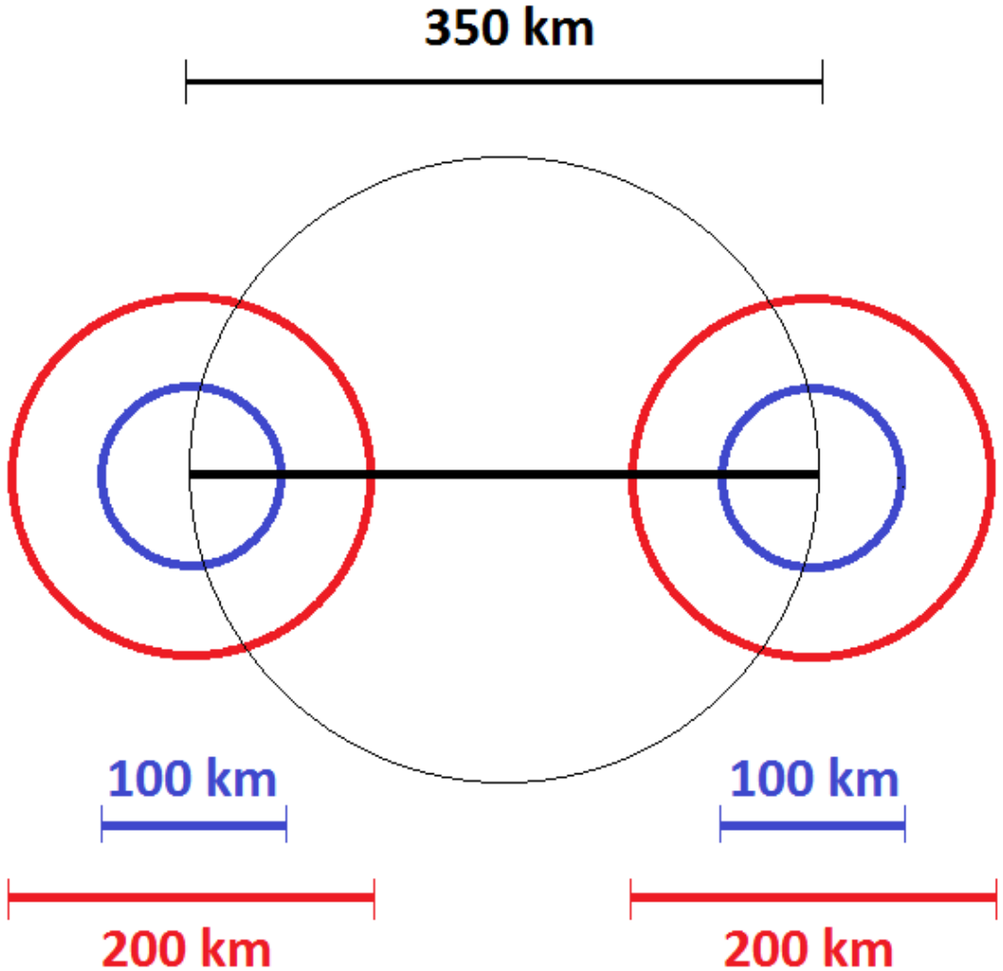
$$f_{\mathrm{GW}}\big|_{\mathrm{max}} \sim 150\ \mathrm{Hz}, \qquad R = \left(\frac{GM}{\omega^2_{\mathrm{Kep}}\big|_{\mathrm{max}}}\right)^{1/3} = 350\ \mathrm{km}$$

- Compared to normal stars this is tiny and although NSs could have this compactness NSs could not have this mass.

- The compactness ratio $\mathscr{R}$ is defined as the orbital separation divided by the sum of the smallest possible radii.

- The Schwarzchild radii of these objects is 103km allowing us to define the compactness ratio

$$\mathscr{R} = 350\,\mathrm{km}/206\,\mathrm{km} \sim 1.7$$



LIGO-Virgo Collaboration, arXiv:1608.01940 (2016)

Timeline of GW150914

- **1.3 billion years ago:** 2 black holes merge and release 3 $M_\odot$ of gravitational wave energy into the universe.
- **100,000 years ago:** these waves arrive at the edge of the milky way galaxy.
- **November 25, 1915:** Albert Einstein presents his General Theory of Relativity to the Prussian Academy of Sciences. GW150914 is 99 years, 9 months, and 20 days away
- **April 15, 1972:** at MIT Rai Weiss' Publication of Quarterly Progress Report No. 105 outlines the concept behind LIGO
- **1992:** The epoch of LIGO construction begins, leading to the realisation of the two observatories LIGO Livingston (LLO) and LIGO Hanford (LHO).
- **mid-late 90s:** Some of this audience are born.
- **2002:** The two initial LIGO detectors and the GEO 600 detector start their first period of scientific data taking, 'Science Run 1'.
- …

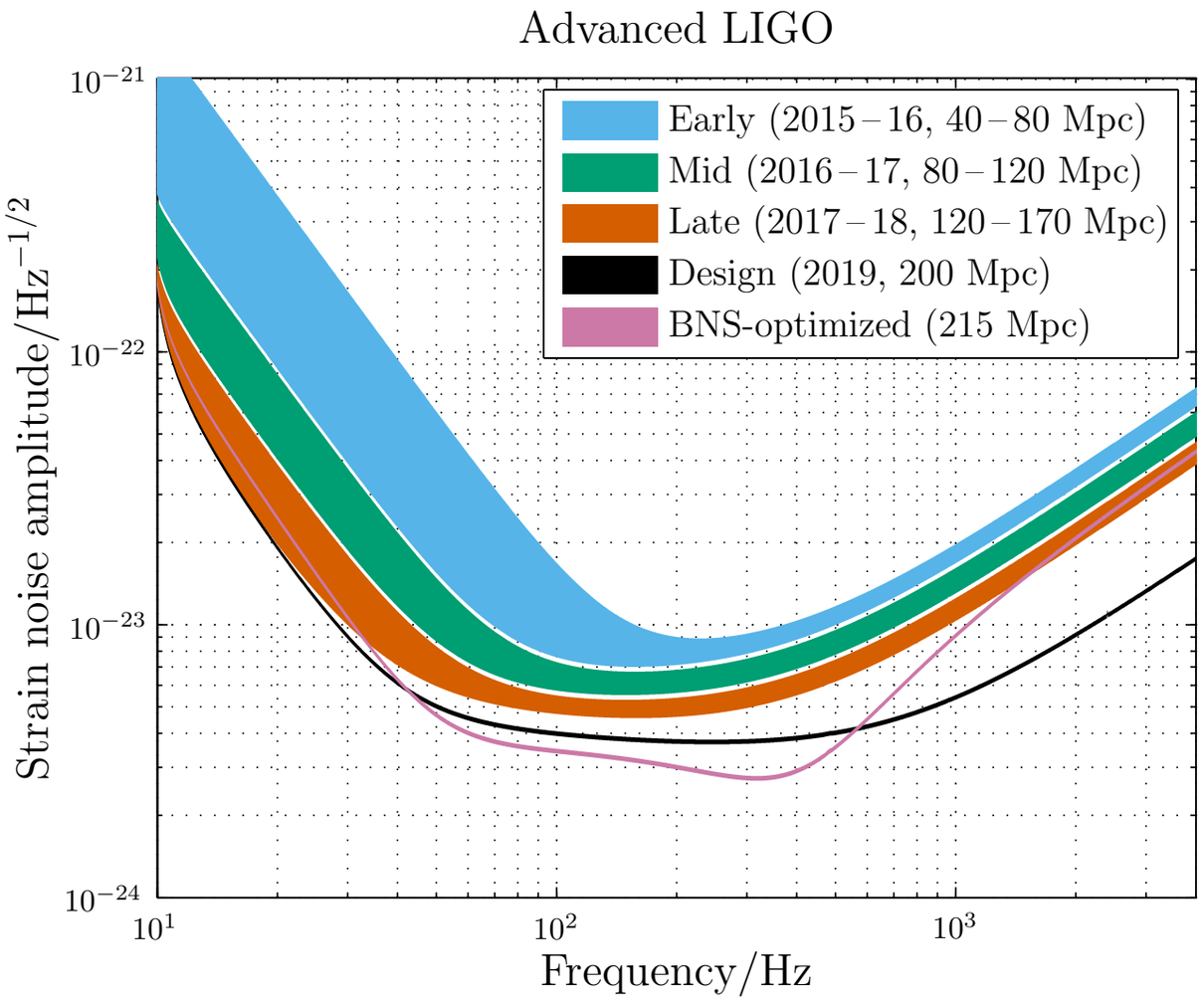
LIGO-Virgo Collaboration, arXiv:1602.03844 (2016)

The rest of the 1st observing run (O1)

GW151012 (formerly LVT151012), and GW151226

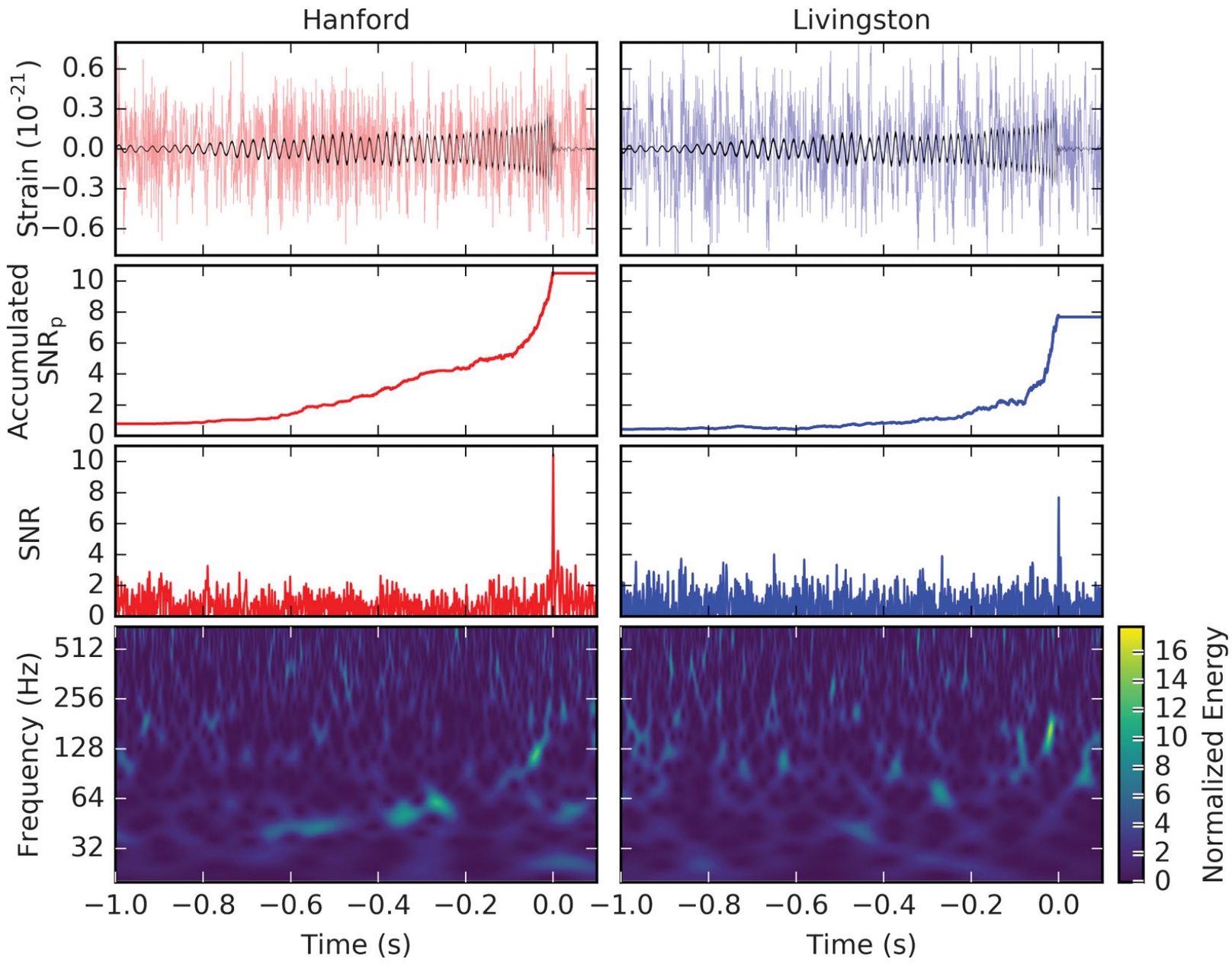
The O1 run (Sep 2015 - Jan 2016)

- Initial LIGO and Virgo successfully completed their operations with the S6/VSR2,3 runs in 2011.
- Advanced LIGO began operation in September 2015 with the first “Observing” run O1 spanning 12th Sep - 19th Jan.
- This accumulated 51.5 days of coincident data.



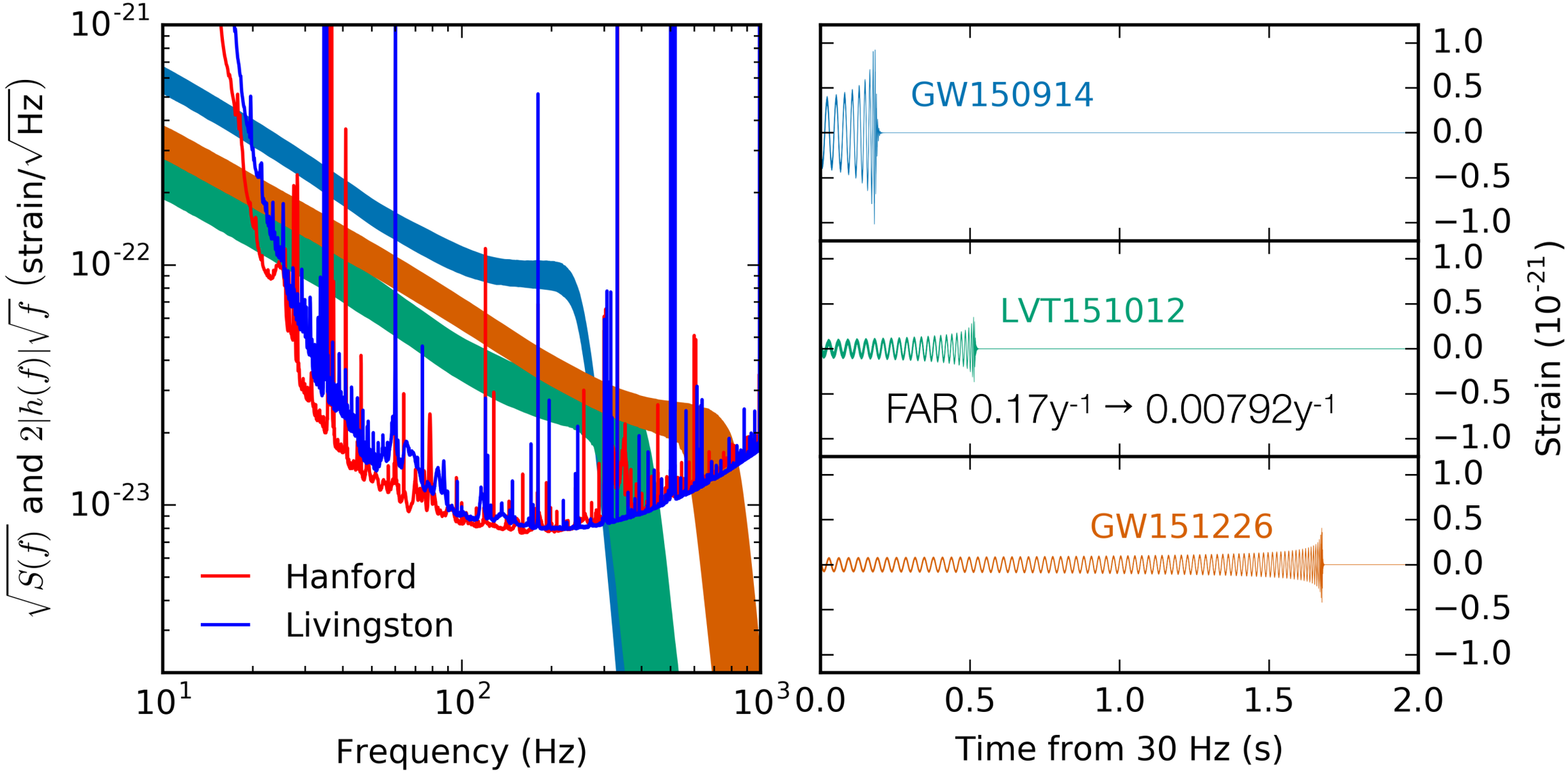
LIGO-Virgo Collaboration, Living Rev. Relativity **19**, (2016)

GW151226 (Boxing Day event)



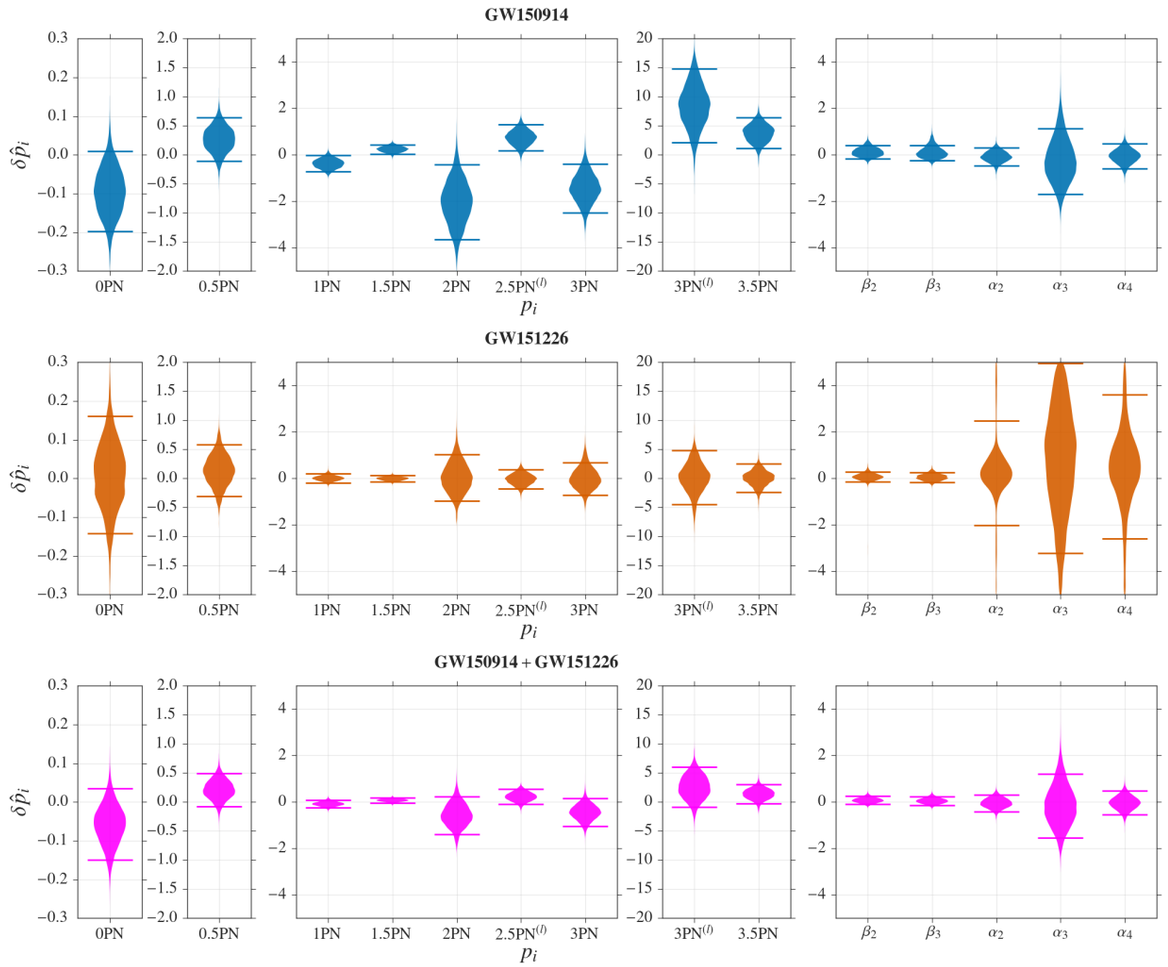
LIGO-Virgo Collaboration, PRL **116**, 241103 (2016)

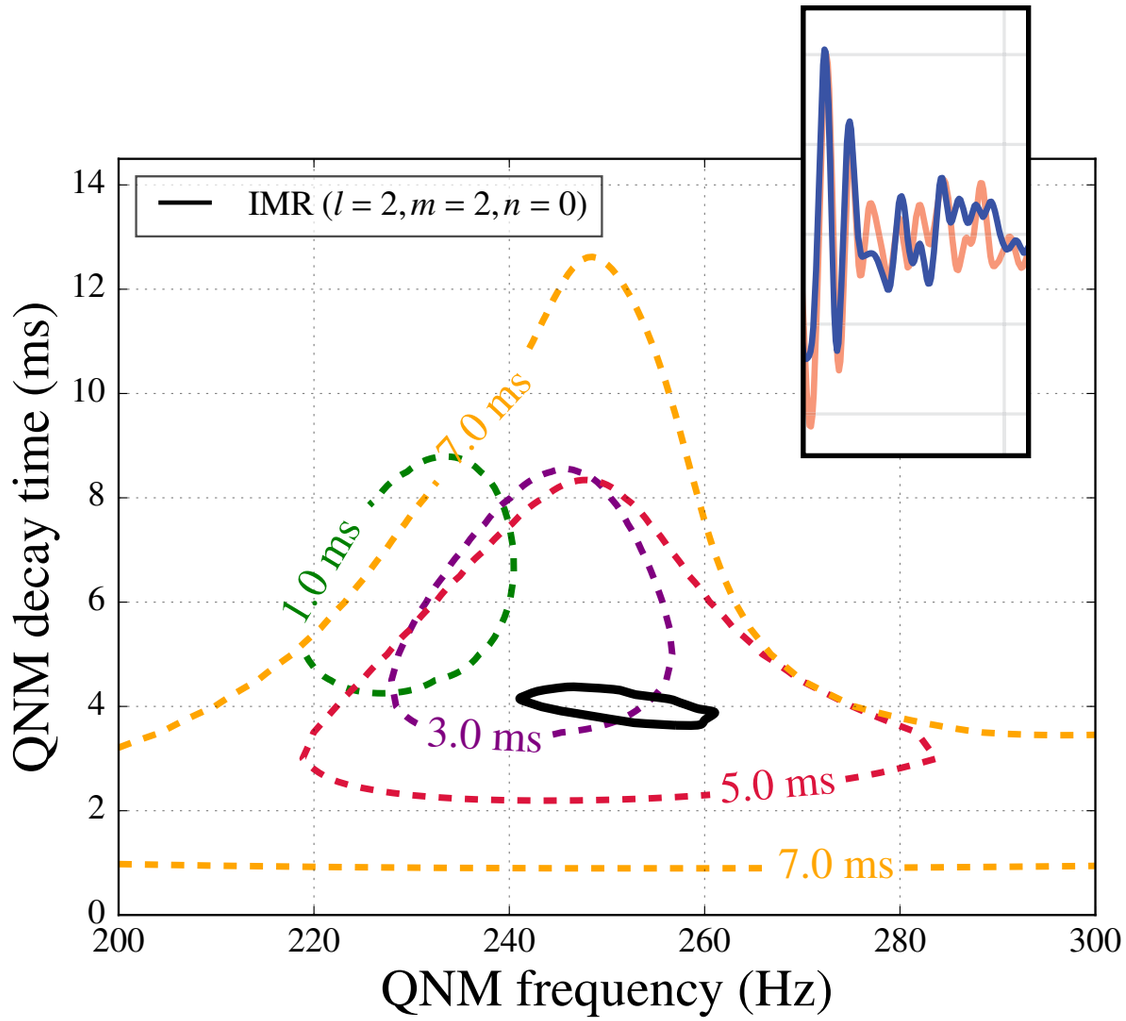
O1 Waveform comparison



LIGO-Virgo Collaboration, PRX **6**, 041015 (2016)

Is general relativity right?

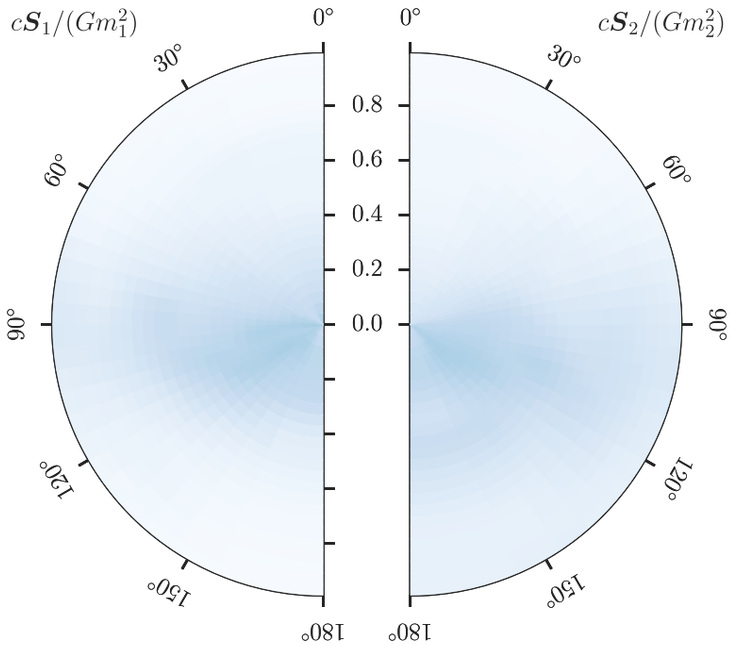




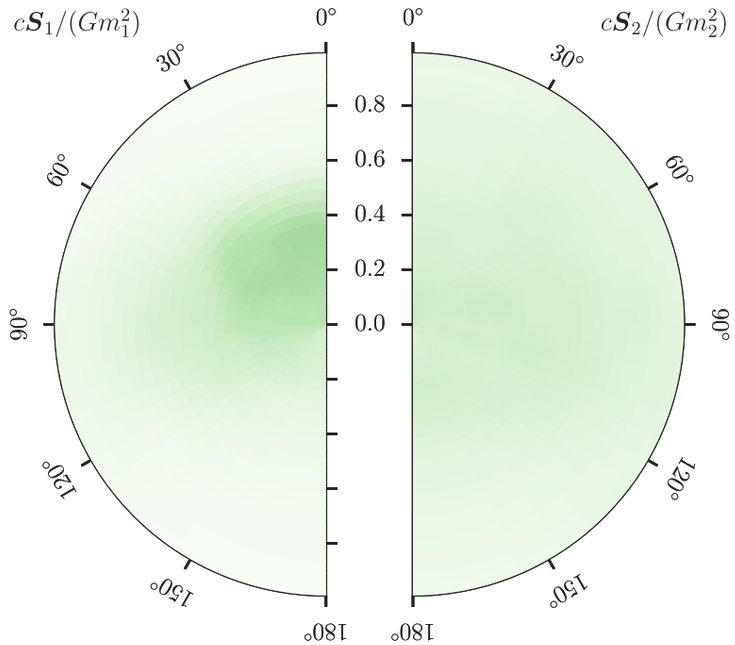
LIGO-Virgo Collaboration, PRX **6**, 041015 (2016)

O1 Spins

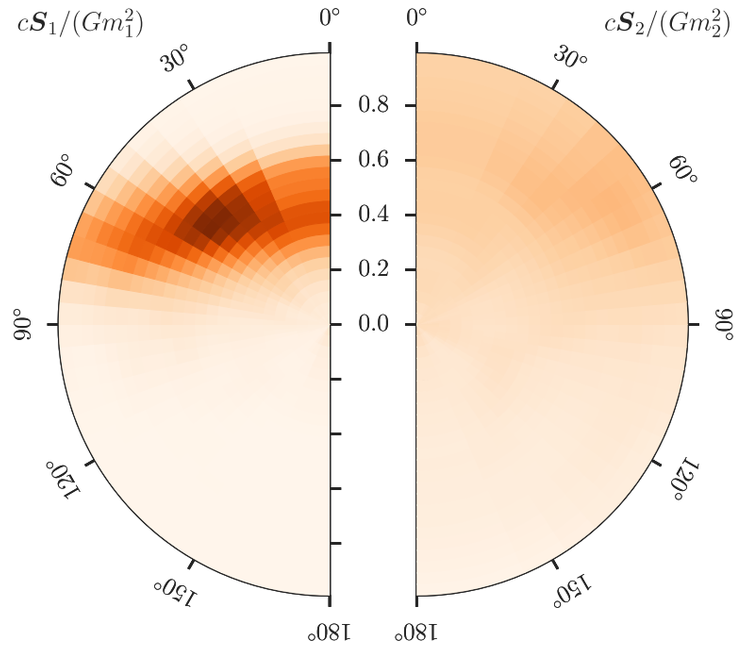
GW150914



GW151012



GW151226



LIGO-Virgo Collaboration, PRX **6**, 041015 (2016)

The 2nd observing run (O2)

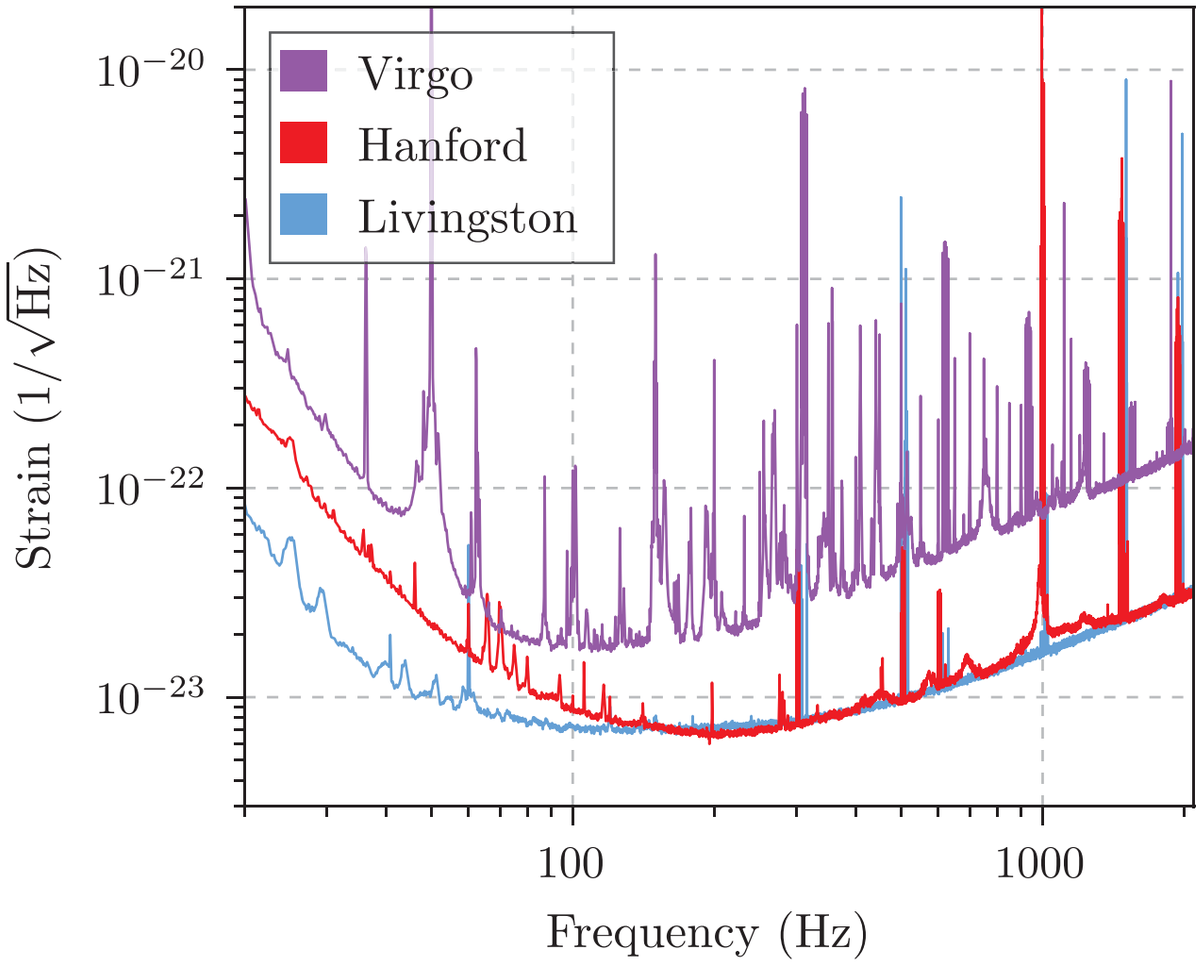
[ONLINE] GW170104, GW170608, GW170814, (the BNS GW170817),

and…

[OFFLINE] GW170729, GW170819, GW170818, and GW170823

The O2 run (Nov 2016 - Sep 2017)

- The Advanced LIGO O2 run began in November 2016 and ended in September 2017.
- Sensitivity was marginally improved but most importantly, Virgo joined in September 2017.
- From this data we have published 3 BBH detections and 1 BNS detection (GW170817).



LIGO-Virgo Collaboration, PRL **119**, 141101 (2017)

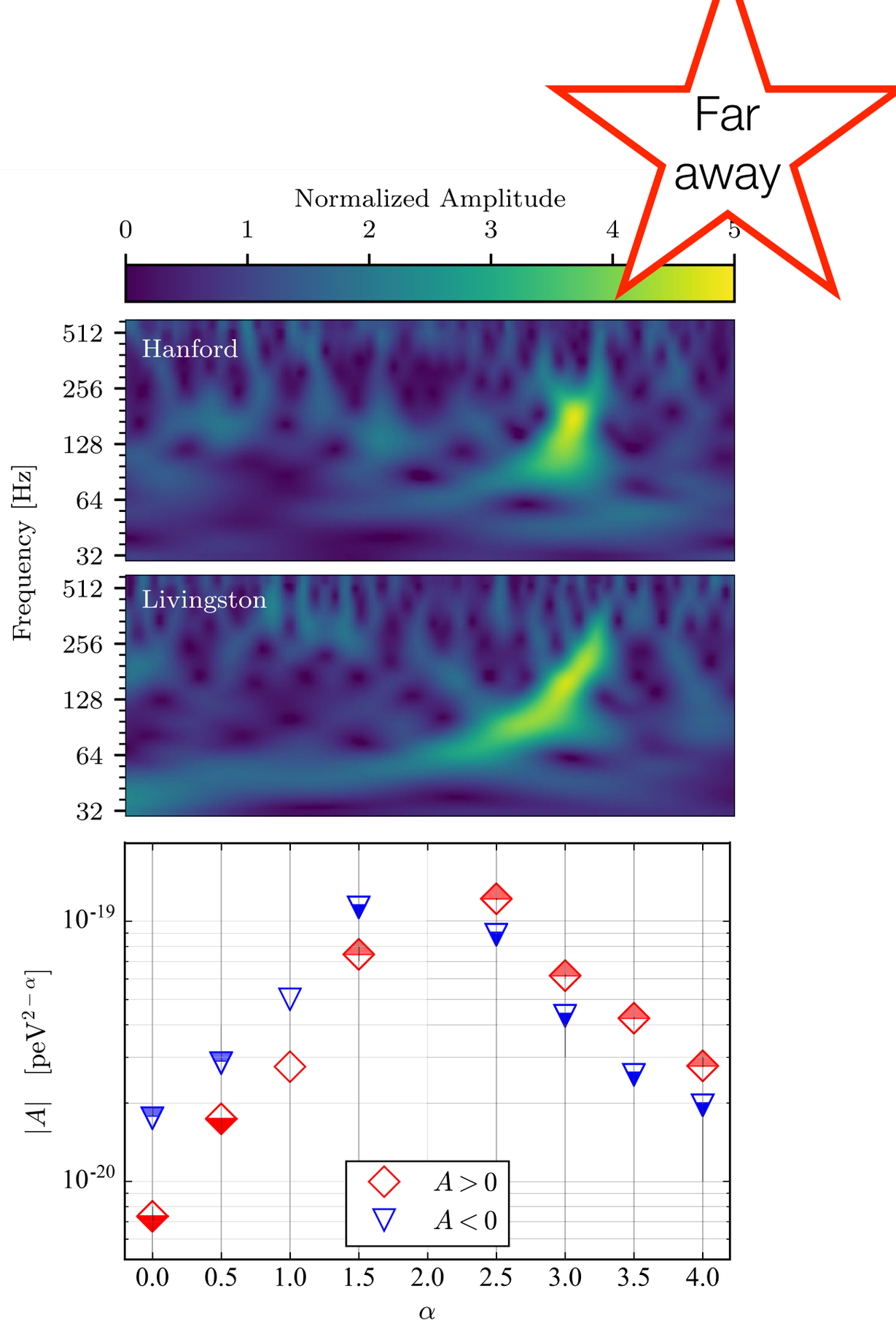
GW170104

- This event had component masses of $31^{+8.4}_{-6.0}$ and $19^{+5.3}_{-5.9}$ $M_\odot$.
- This event was at redshift 0.2 and had SNR 13.
- Combining this event with previous detections allows us to constrain the graviton mass and wavelength

$$m_g \leq 7.7 \times 10^{-23}\ \mathrm{eV}/c^2$$
$$\lambda_g > 1.6 \times 10^{13}\ \mathrm{km}$$

- Using a modified dispersion relation the group velocity of the GWs becomes

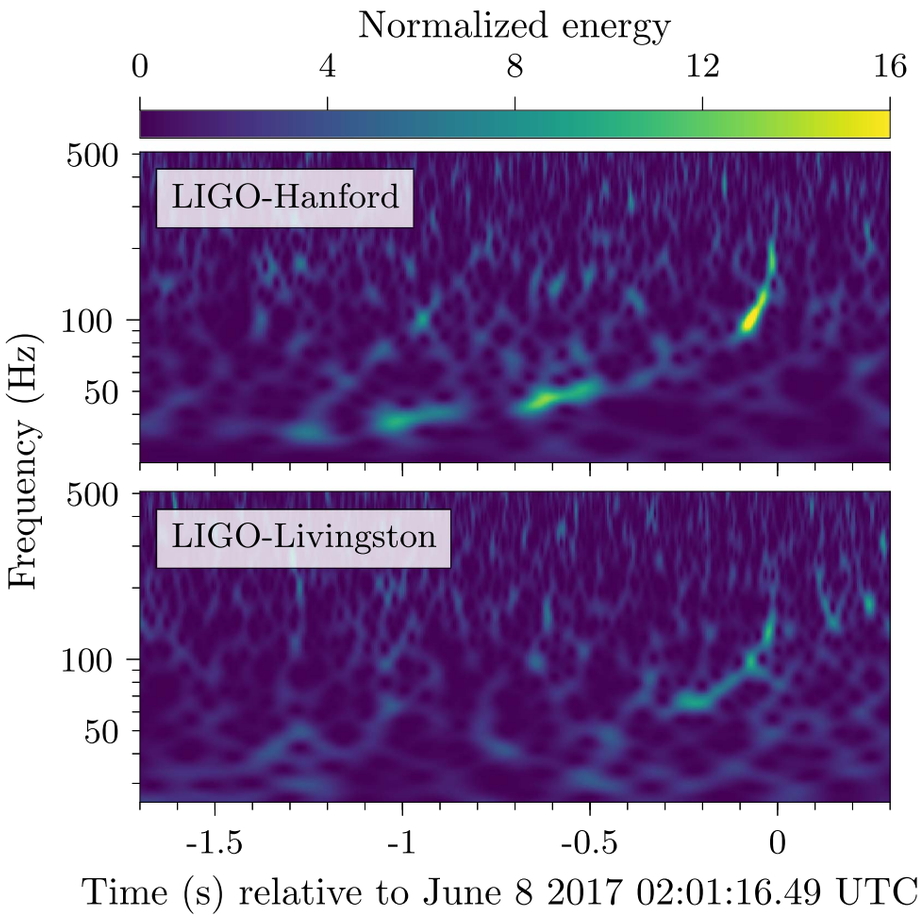
$$\frac{v_g}{c} = 1 + \frac{1}{2}(\alpha - 1) A E^{\alpha - 2}$$

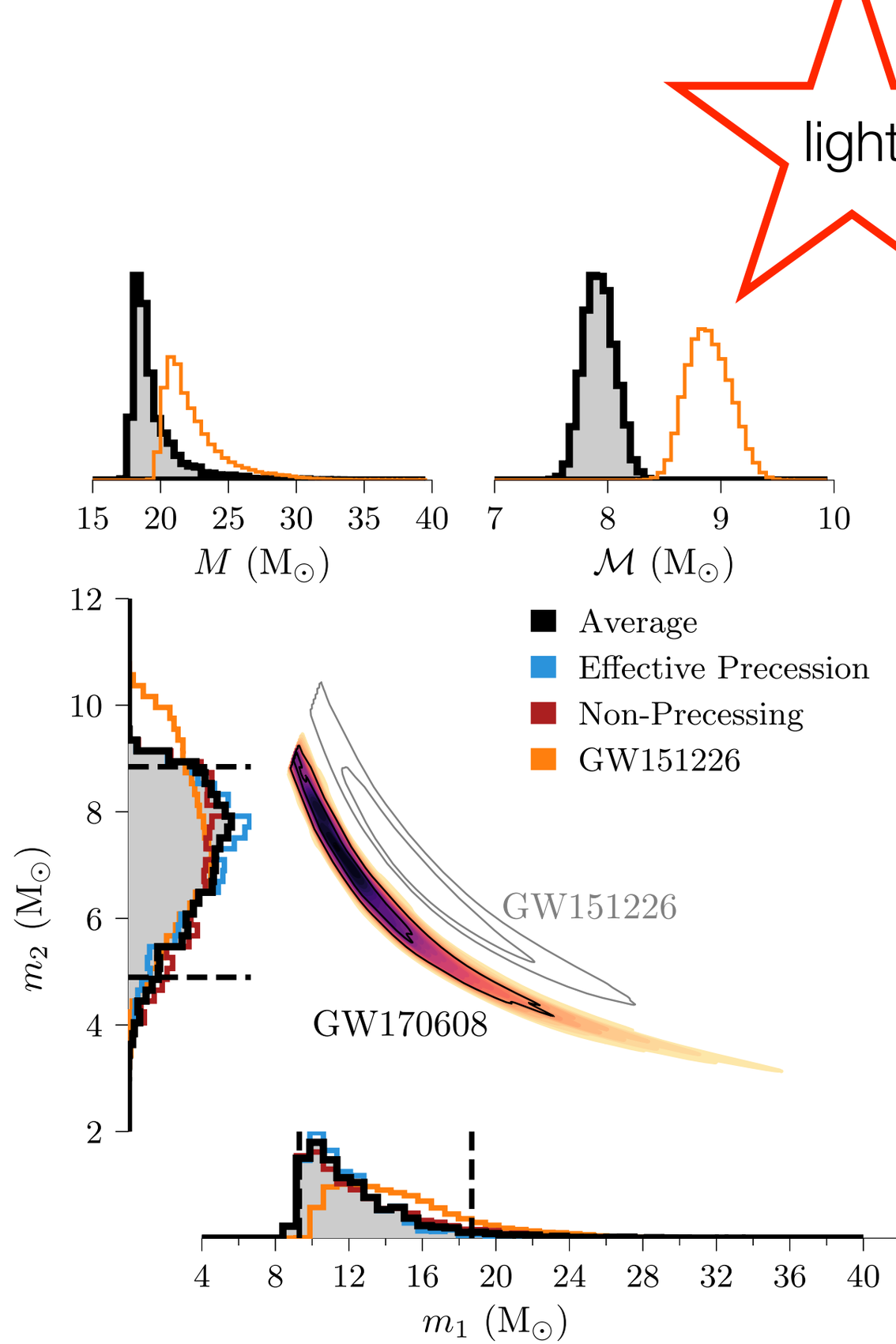


LIGO-Virgo Collaboration, PRL **118**, 221101 (2017)

GW170608

- This event had component masses of 12^{+7}_{-2} and 7^{+2}_{-2} $M_\odot$.
- This event was at redshift 0.07 and had SNR 13.

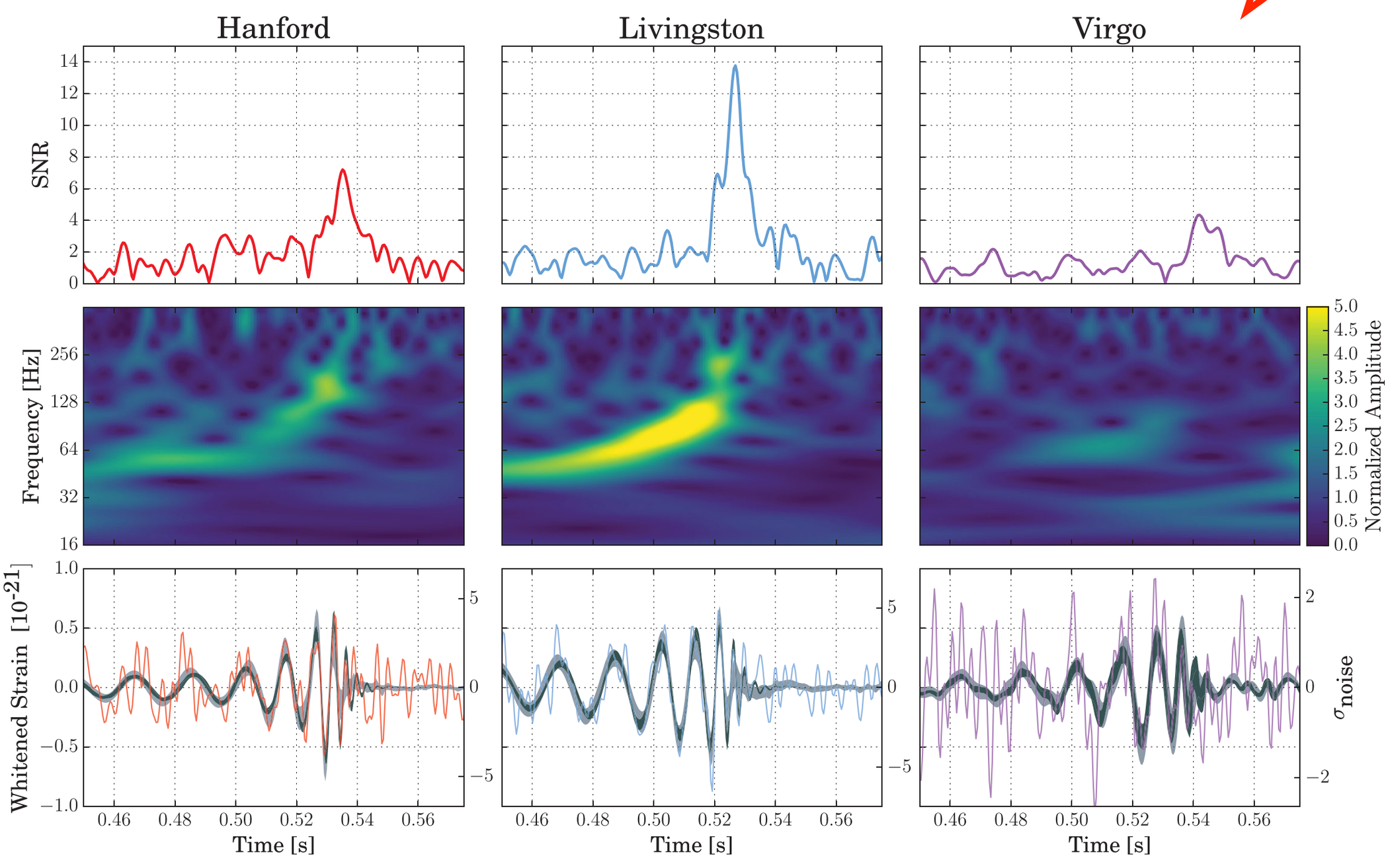




LIGO-Virgo Collaboration, ApJ Lett., 851, L35, (2017)

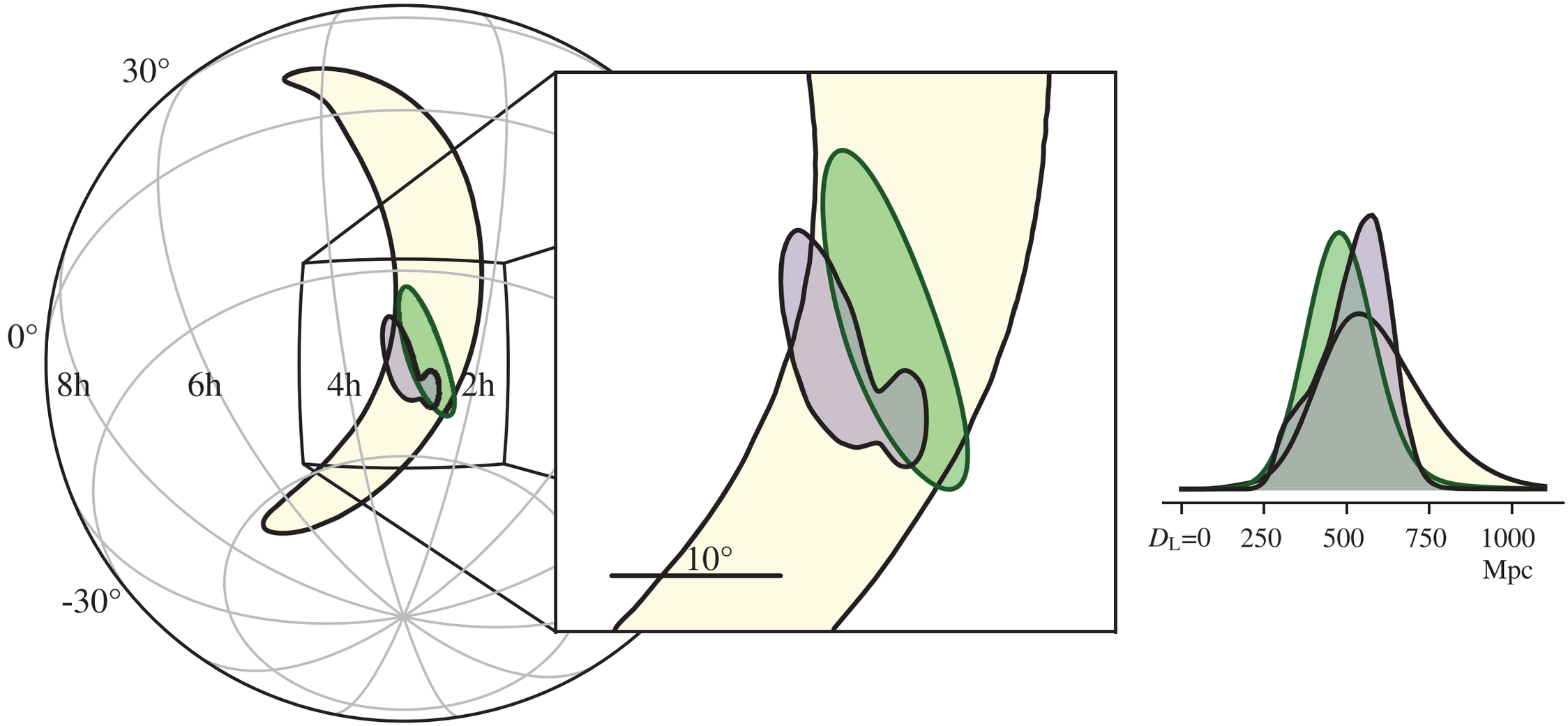
GW170814

LIGO & Virgo



LIGO-Virgo Collaboration, PRL **119**, 141101 (2017)

GW170814

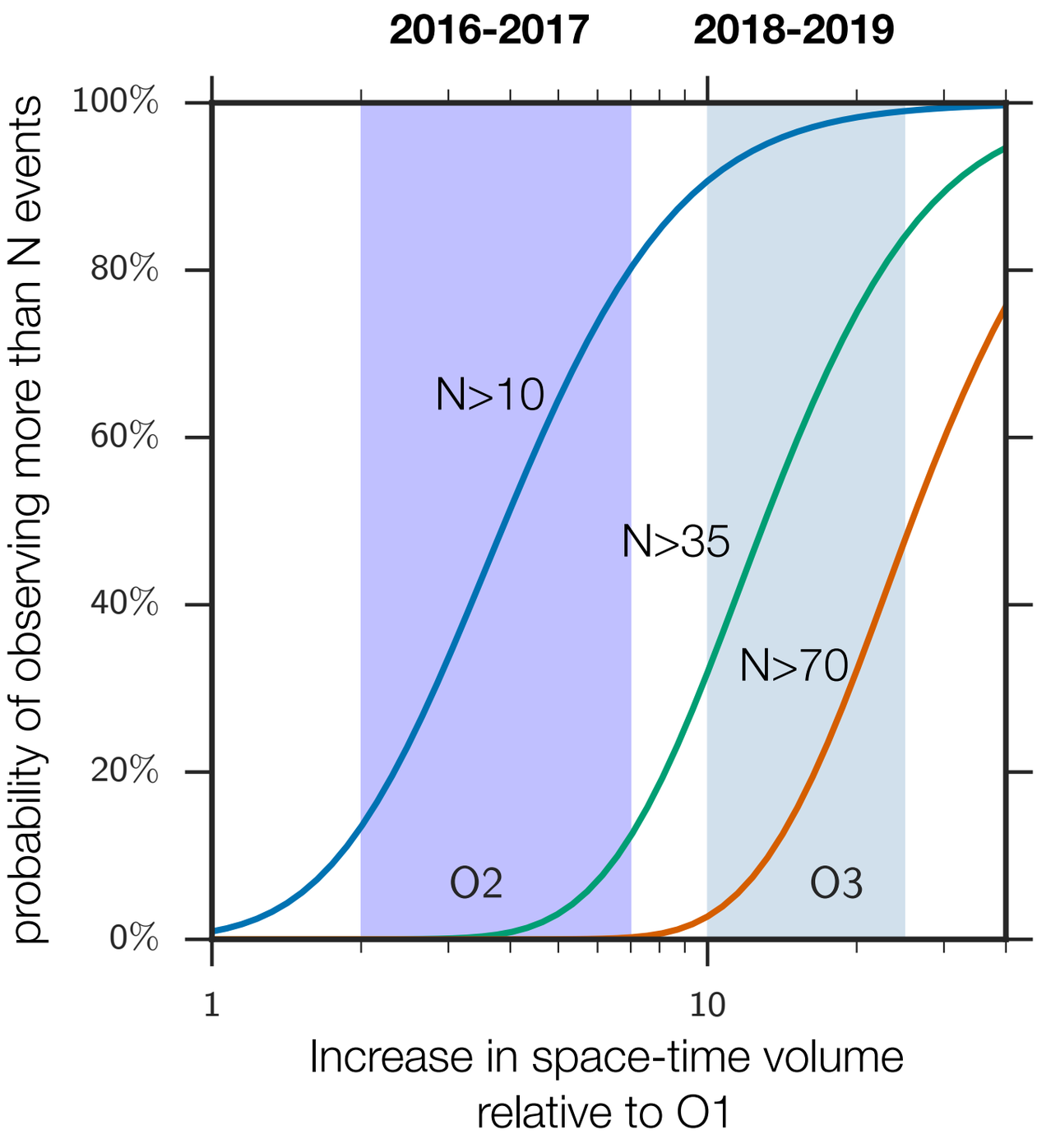


- This event had component masses of 31 and 19 $M_\odot$.
- This event was at redshift 0.2 and had SNR 13.

LIGO-Virgo Collaboration, PRL **119**, 141101 (2017)

What happens next?

- The first observing runs O1 and O2 are the first of many as the detectors improve in sensitivity.
- O3 will have ~50 times the sensitivity of O1.
- There **will be** many more detections.
- We must also not forget binary neutron stars, unmodelled transients, stochastic background, continuous signals, …



LIGO-Virgo Collaboration, PRX **6**, 041015 (2016)

Additional properties

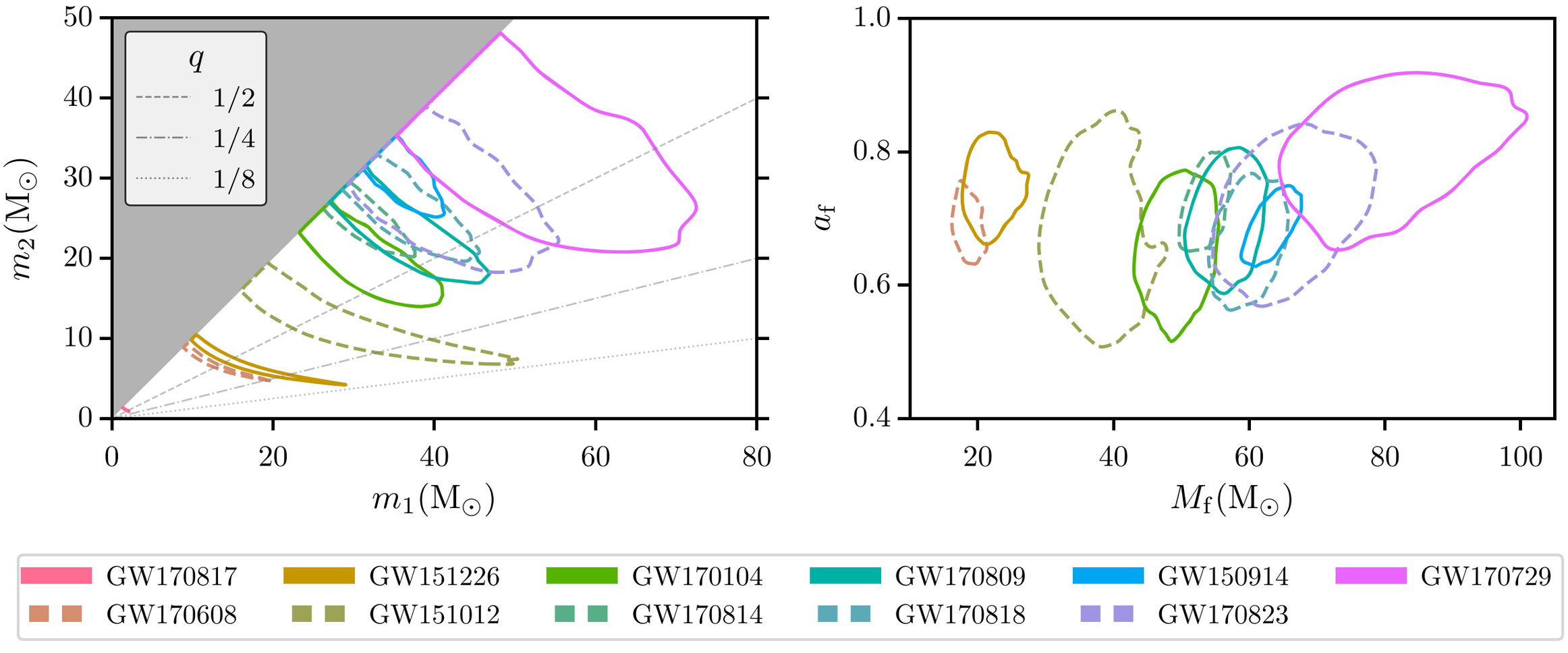
Characteristics of the ensemble

The big table of O1/O2 BBH properties

Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	$\chi_{\rm eff}$	$M_f/M_\odot$	a_f	$E_{\rm rad}/(M_\odot c^2)$	$\ell_{\rm peak}/({\rm erg\,s^{-1}})$	$d_L/{\rm Mpc}$	z	$\Delta\Omega/{\rm deg}^2$
GW150914	$35.6^{+4.7}_{-3.1}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.7}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.4}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4}\times10^{56}$	440^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	182
GW151012	$23.2^{+14.9}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.1}_{-1.2}$	$0.05^{+0.31}_{-0.20}$	$35.6^{+10.8}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.6^{+0.6}_{-0.5}$	$3.2^{+0.8}_{-1.7}\times10^{56}$	1080^{+550}_{-490}	$0.21^{+0.09}_{-0.09}$	1523
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.5}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7}\times10^{56}$	450^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$30.8^{+7.3}_{-5.6}$	$20.0^{+4.9}_{-4.6}$	$21.4^{+2.2}_{-1.8}$	$-0.04^{+0.17}_{-0.21}$	$48.9^{+5.1}_{-4.0}$	$0.66^{+0.08}_{-0.11}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-1.0}\times10^{56}$	990^{+440}_{-430}	$0.20^{+0.08}_{-0.08}$	921
GW170608	$11.0^{+5.5}_{-1.7}$	$7.6^{+1.4}_{-2.2}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.4}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.0}_{-0.1}$	$3.5^{+0.4}_{-1.3}\times10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	392
GW170729	$50.2^{+16.2}_{-10.2}$	$34.0^{+9.1}_{-10.1}$	$35.4^{+6.5}_{-4.8}$	$0.37^{+0.21}_{-0.25}$	$79.5^{+14.7}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5}\times10^{56}$	2840^{+1400}_{-1360}	$0.49^{+0.19}_{-0.21}$	1041
GW170809	$35.0^{+8.3}_{-5.9}$	$23.8^{+5.1}_{-5.2}$	$24.9^{+2.1}_{-1.7}$	$0.08^{+0.17}_{-0.17}$	$56.3^{+5.2}_{-3.8}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9}\times10^{56}$	1030^{+320}_{-390}	$0.20^{+0.05}_{-0.07}$	308
GW170814	$30.6^{+5.6}_{-3.0}$	$25.2^{+2.8}_{-4.0}$	$24.1^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.12}$	$53.2^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5}\times10^{56}$	600^{+150}_{-220}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1\times10^{56}$	40^{+7}_{-15}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.4^{+7.5}_{-4.7}$	$26.7^{+4.3}_{-5.2}$	$26.5^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.4^{+4.9}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7}\times10^{56}$	1060^{+420}_{-380}	$0.21^{+0.07}_{-0.07}$	39
GW170823	$39.5^{+11.2}_{-6.7}$	$29.0^{+6.7}_{-7.8}$	$29.2^{+4.6}_{-3.6}$	$0.09^{+0.22}_{-0.26}$	$65.4^{+10.1}_{-7.4}$	$0.72^{+0.09}_{-0.12}$	$3.3^{+1.0}_{-0.9}$	$3.6^{+0.7}_{-1.1}\times10^{56}$	1940^{+970}_{-900}	$0.35^{+0.15}_{-0.15}$	1666

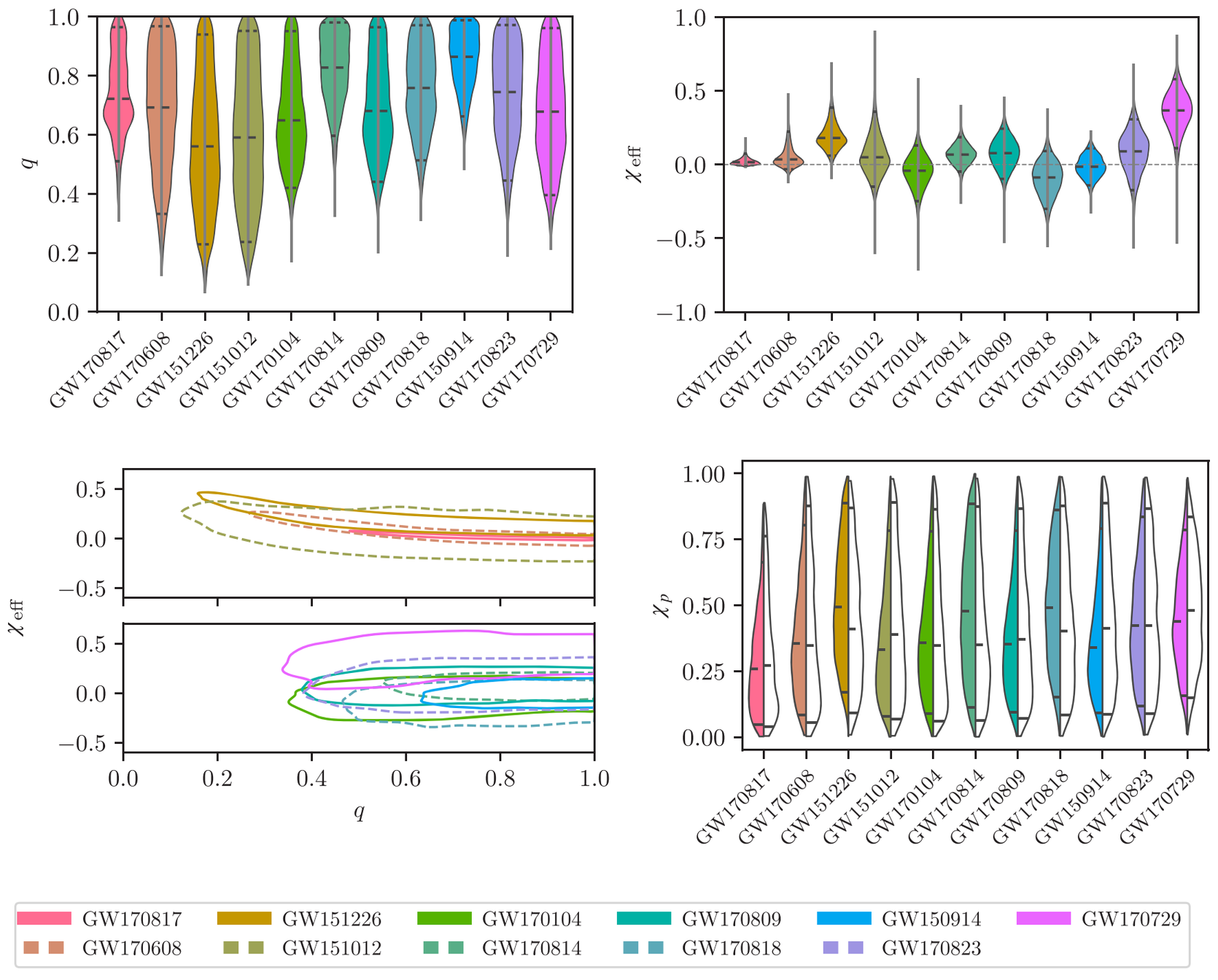
LIGO-Virgo Collaboration, PRX **9**, 031040 (2019)

Masses and spins



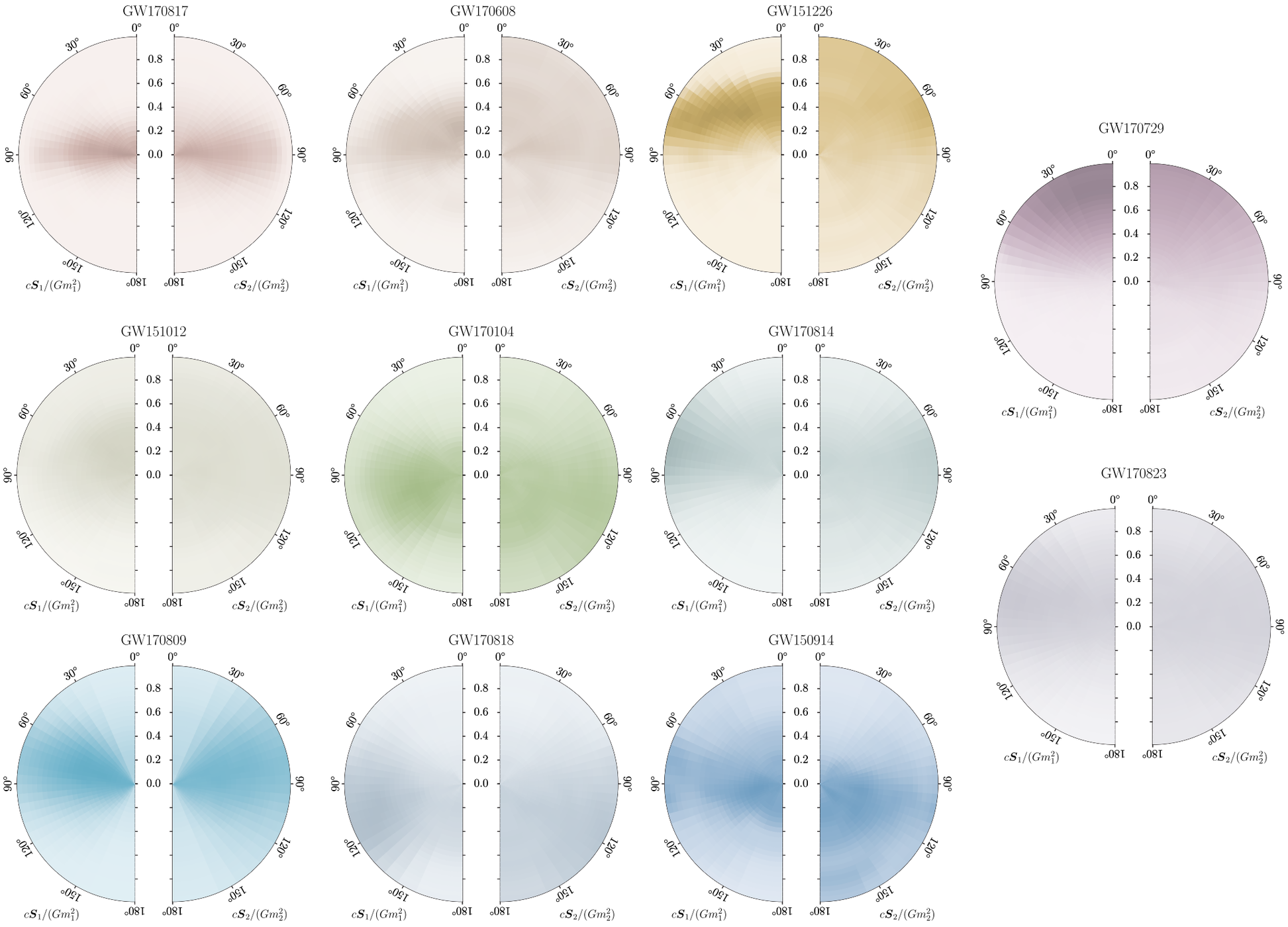
LIGO-Virgo Collaboration, PRX **9**, 031040 (2019)

Masses and spins



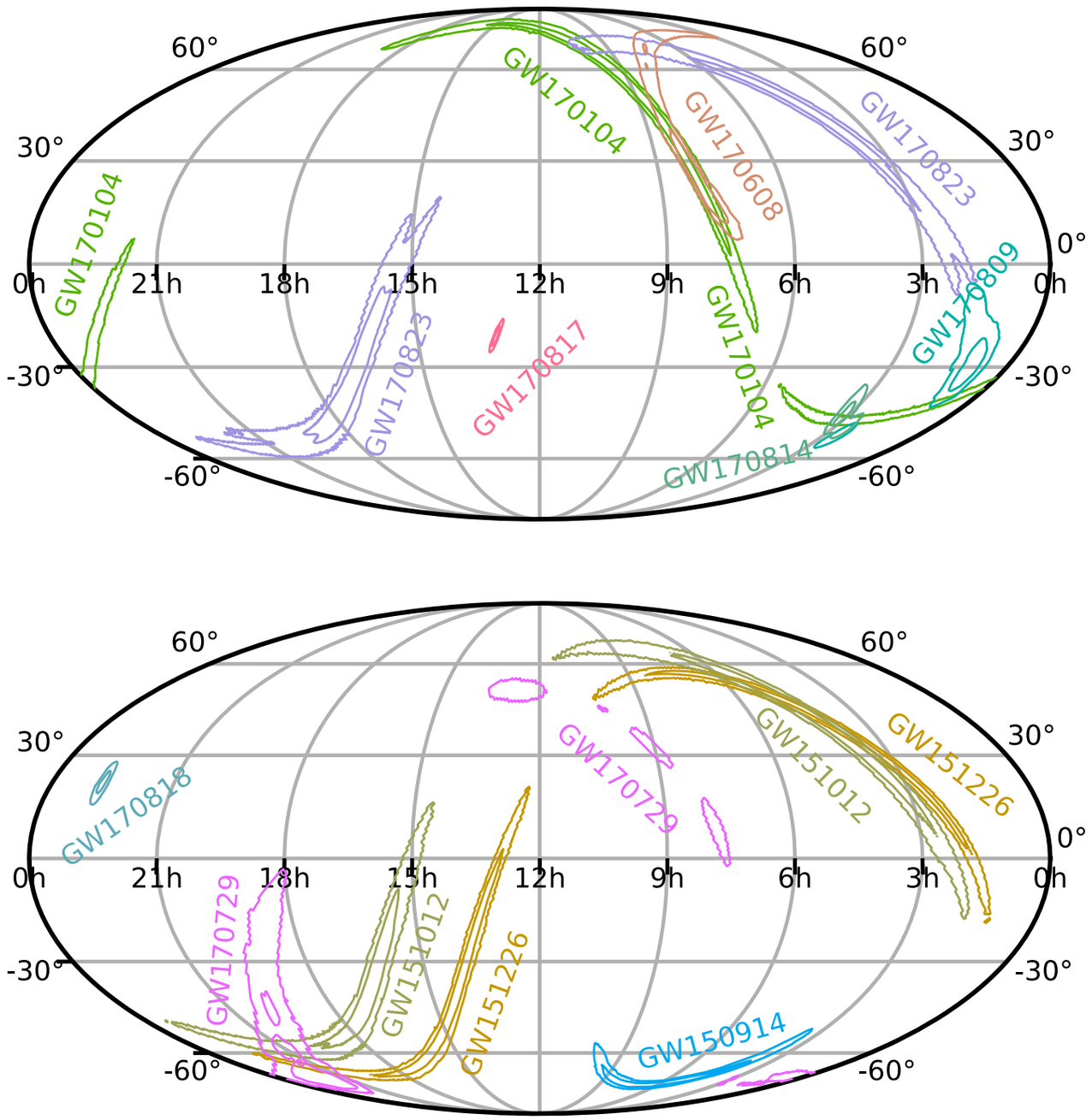
LIGO-Virgo Collaboration, PRX **9**, 031040 (2019)

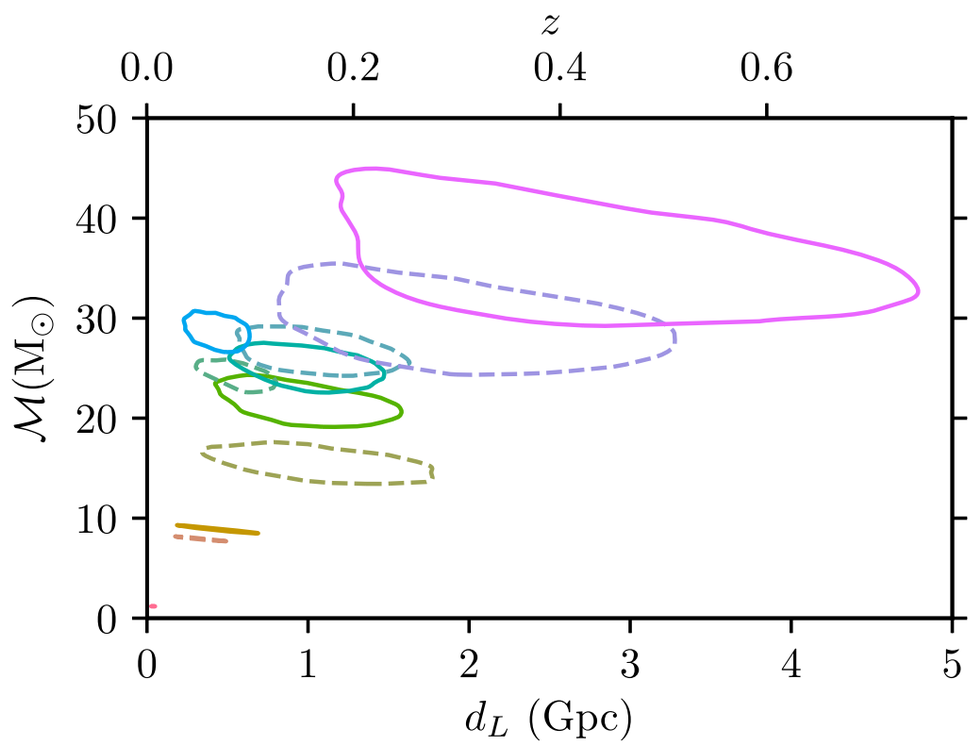
Spins



LIGO-Virgo Collaboration, PRX **9**, 031040 (2019)

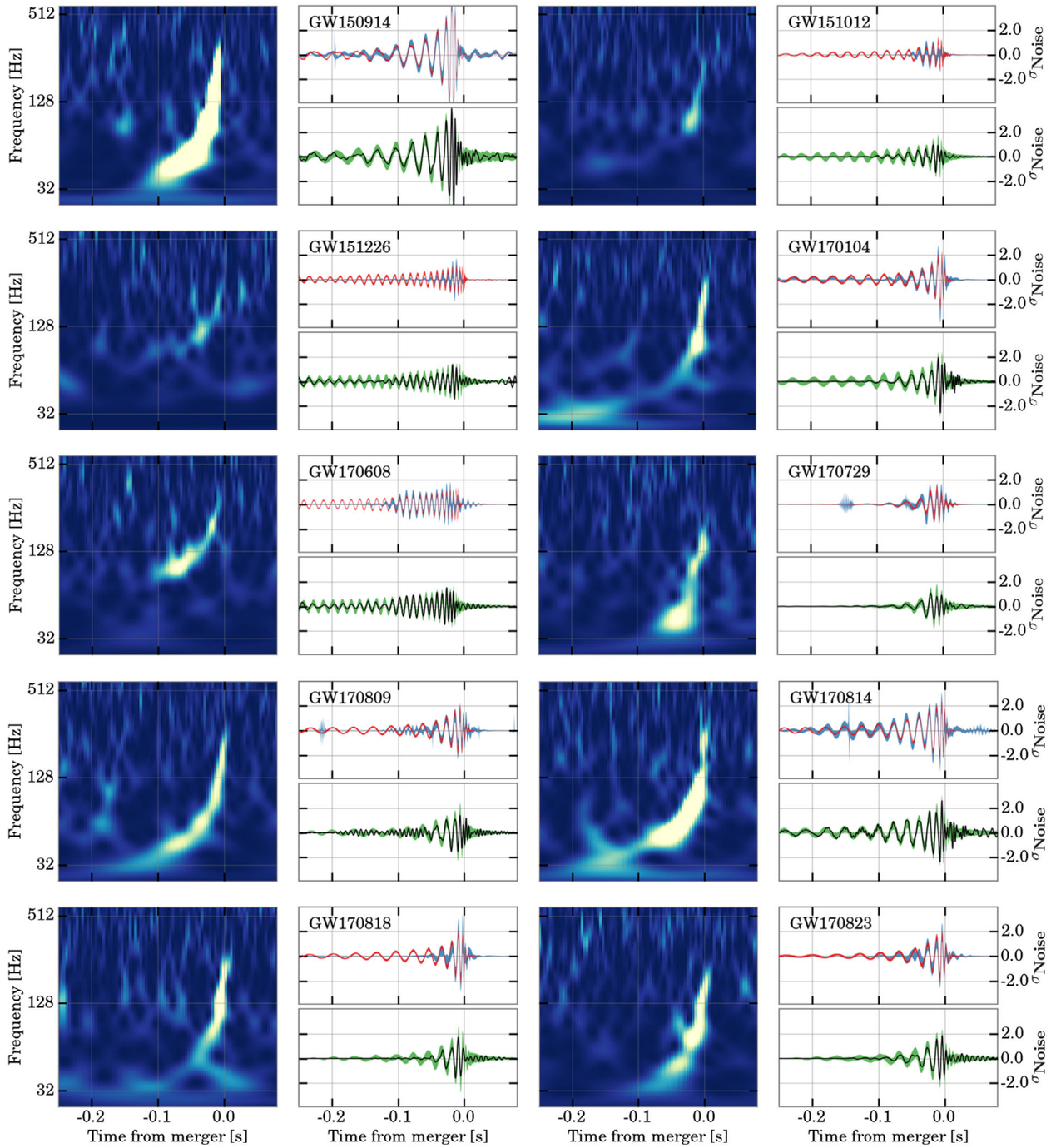
Sky localisation





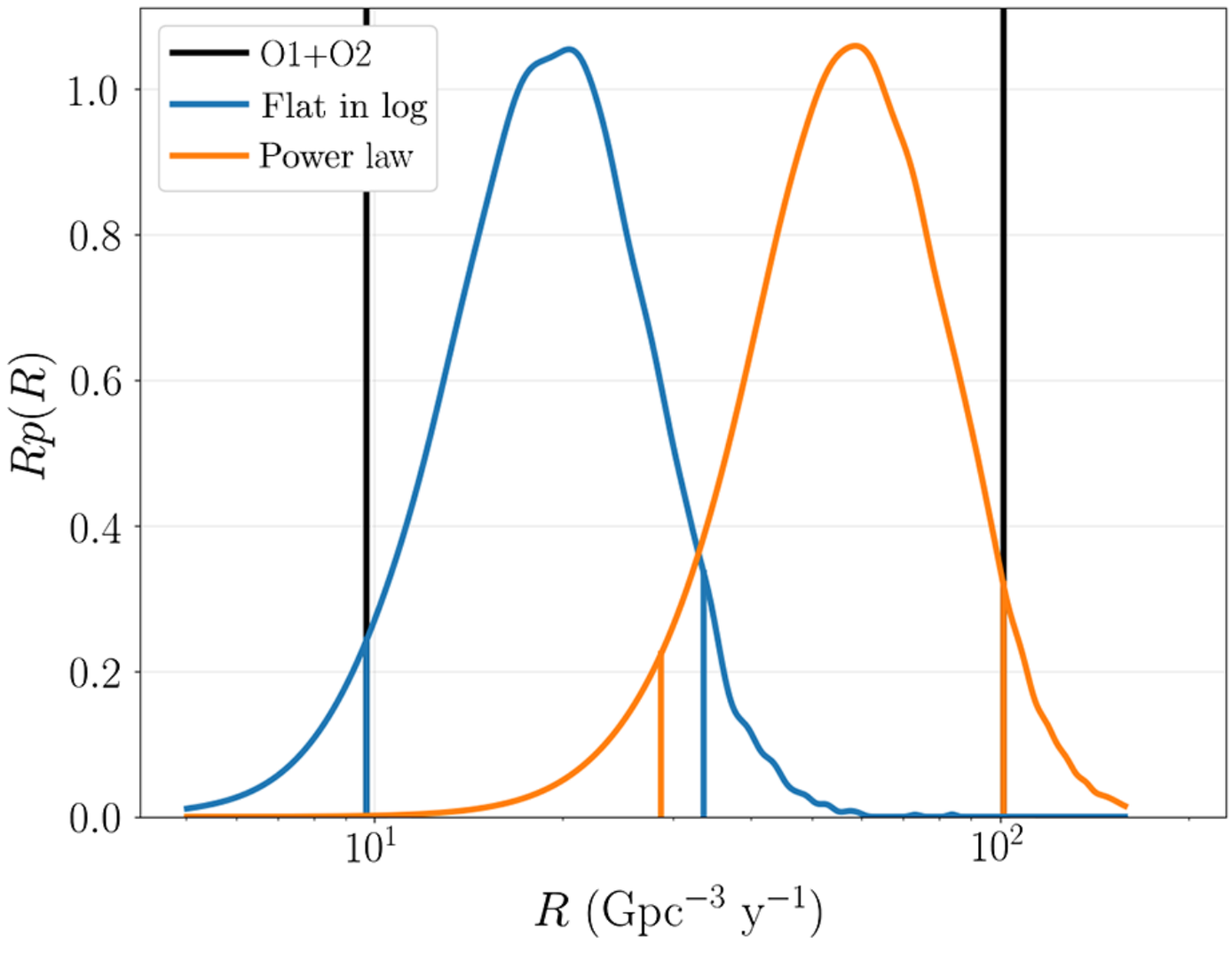
LIGO-Virgo Collaboration, PRX **9**, 031040 (2019)

Waveforms



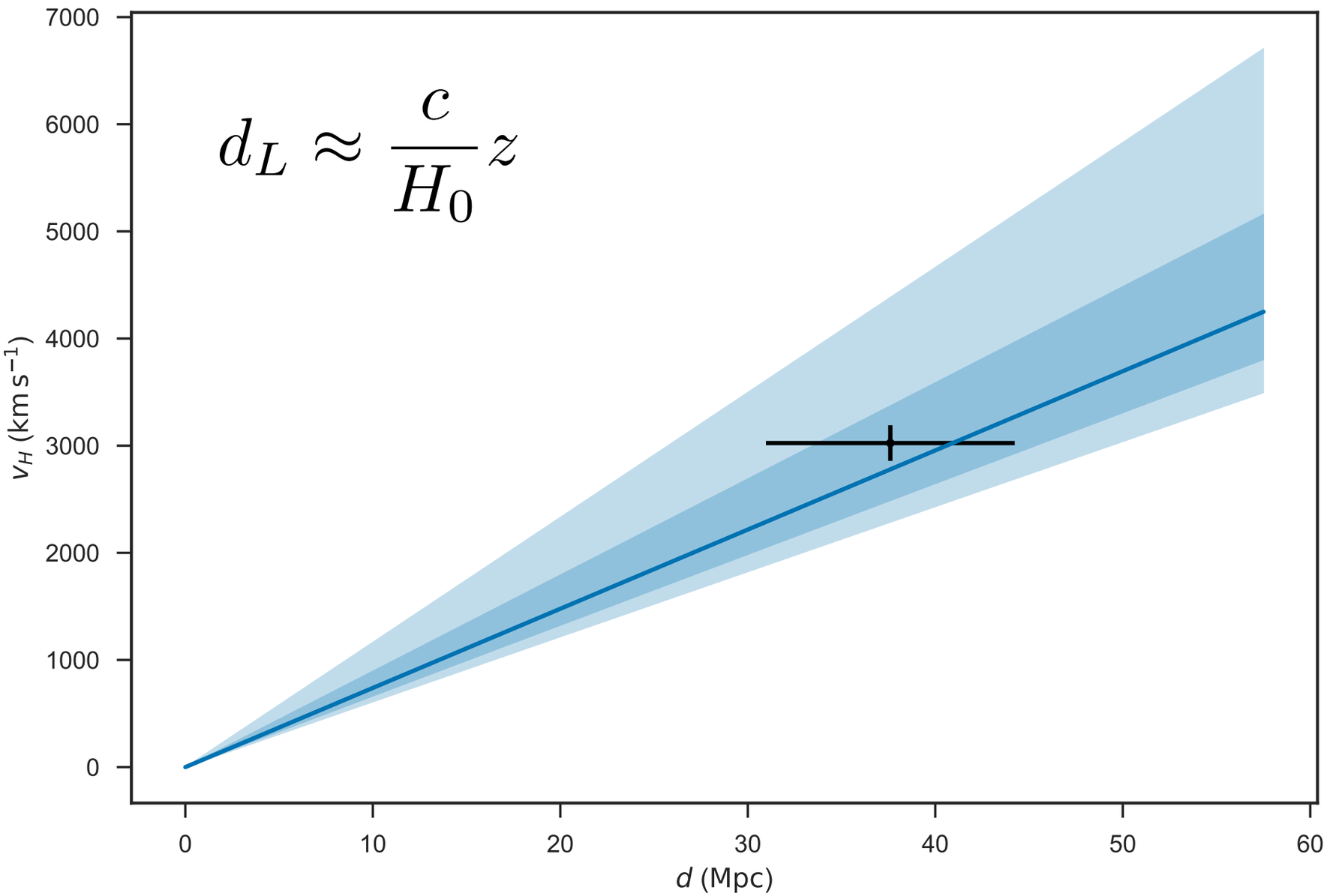
LIGO-Virgo Collaboration, PRX **9**, 031040 (2019)

Astrophysical Event Rate



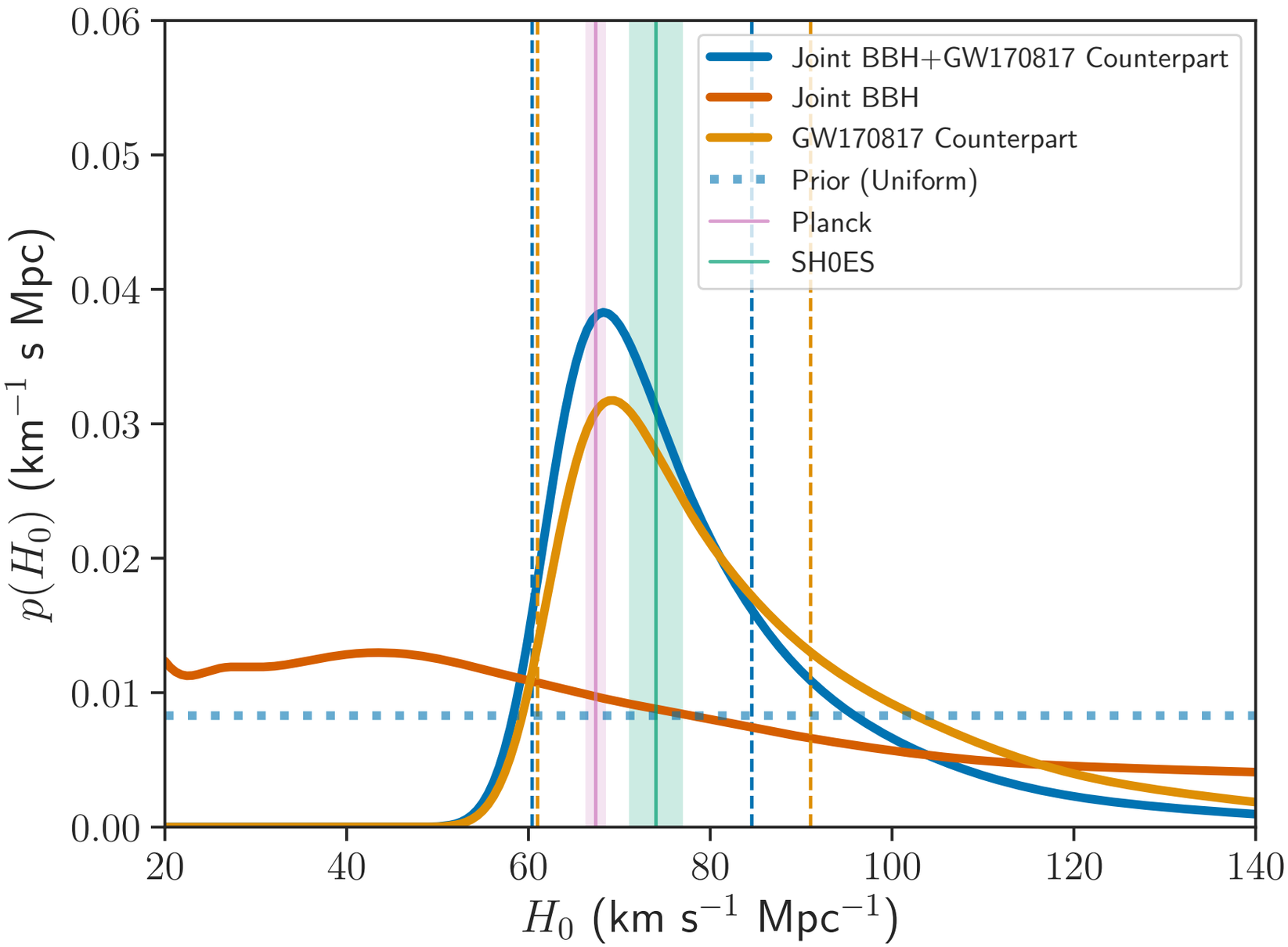
LIGO-Virgo Collaboration, PRX **9**, 031040 (2019)

Cosmology



Credit: Will Farr

The Hubble constant



LIGO-Virgo Collaboration, arXiv:1908.06060 (2019)

A distance limit

- The strain at the source can at most be ~1 at the Schwarzschild radius. Since the amplitude decreases as

$$h \sim R/d_L$$

- Therefore we can set an upper-limit on the distance based on the measured peak strain amplitude

$$d_L \leq 10^{21} \times 100\,\mathrm{km} \sim 3\,\mathrm{Gpc}$$

- This is very rough. See problems for an opportunity to refine it.

LIGO-Virgo Collaboration, arXiv:1608.01940 (2016)

A rough luminosity

- By Setting

$$\omega \sim c/r \text{ and } r \sim GM/c^2 \text{ and } M\omega \sim c^3/G$$

- By dimensional analysis of the quadrupole formula

$$L \sim \frac{G}{c^5} M^2 r^4 \omega^6$$

- We get the following universal approximation

$$L \sim L_{\text{Planck}} = c^5/G.$$

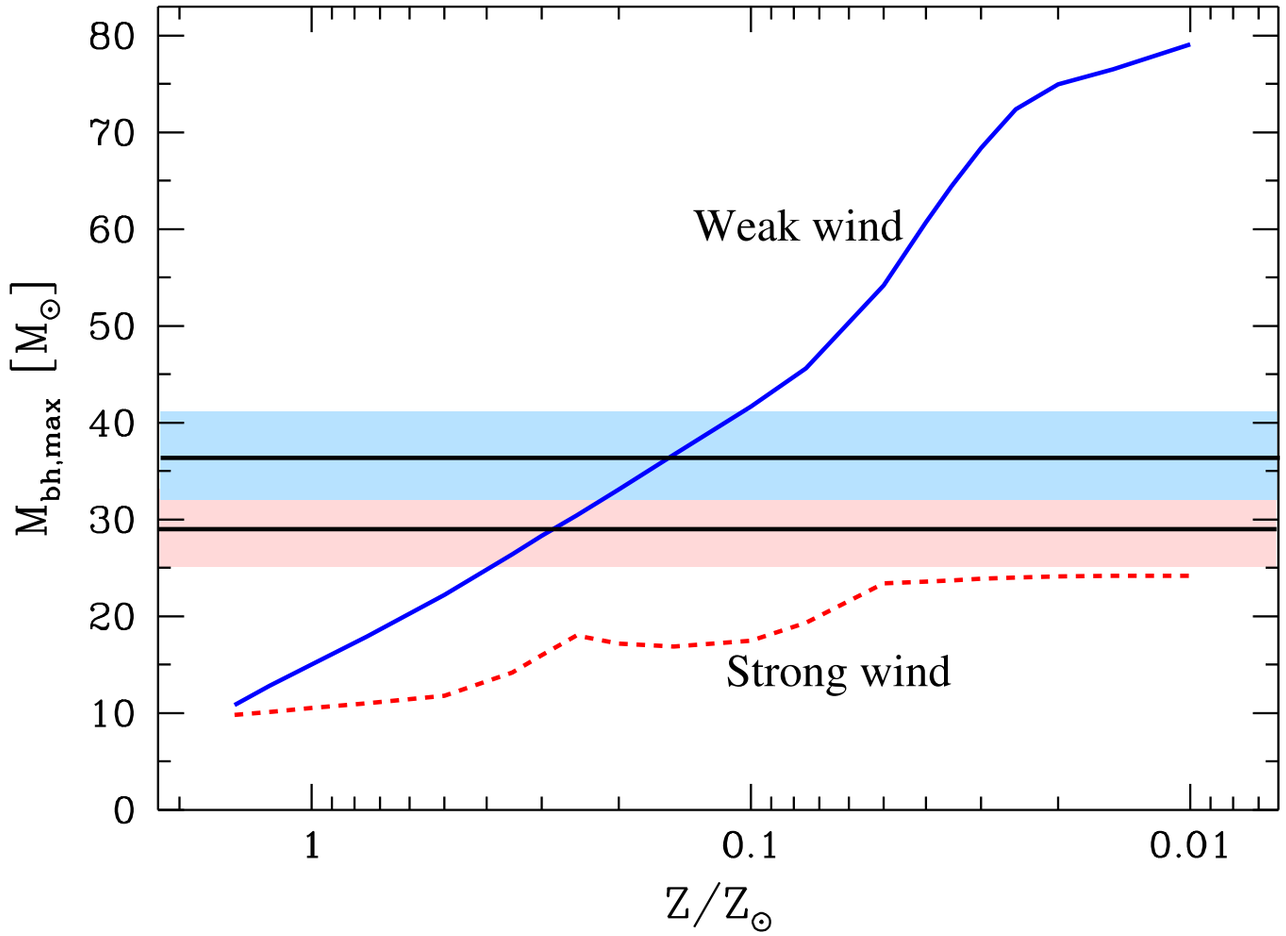
- Hence, to within factors of a few, all CBC events are equally luminous (3 x 10^{56} ergs/sec) since the mass sets both the characteristic energy and time scale of the event.

- However, a more slightly refined analysis gives $L \sim \frac{c^3 d_L^2}{4G} |\dot{h}|^2 \sim \frac{c^5}{4G} \left(\frac{\omega_{\text{GW}} d_L h|_{\max}}{c} \right)^2$

LIGO-Virgo Collaboration, arXiv:1608.01940 (2016)

What do the masses tell us?

- The most sensitive feature in determining the mass of a black hole is the metallicity of the star, Z.
- Low metallicity stars typically have less stellar wind allowing the progenitor star to maintain a higher mass.
- GW150914 comprised the heaviest known* black-hole (~35Msun) and indicates a possible low metallicity.



LIGO-Virgo Collaboration, ApJL **818**, 2 (2016)

The effect of spin

- We define the dimensionless spin parameter $\chi = \frac{c}{G}\frac{S}{m^2}$
- This modifies the gravitational radii (as well as orbital dynamics) such that the radius of an extremal Kerr black hole is

$$r_{\rm EK}(m) = \tfrac{1}{2} r_{\rm Schwarz}(m) = Gm/c^2.$$

- Hence we can get a lower limit on the Newtonian separation of 2 black holes

$$r_{\rm EK}(m_1)+r_{\rm EK}(m_2) = \frac{1}{2} r_{\rm Schwarz}(M) = \frac{GM}{c^2} \approx 1.5 \left(\frac{M}{\rm M_\odot}\right) \rm km.$$

- The orbital compactness (with eccentricity, unequal masses, spin) is

$$\mathscr{R} = \frac{r_{\rm sep}(M)}{r_{\rm EK}(M)} \leq \frac{R(M)}{r_{\rm EK}(M)} = \frac{c^2}{\left(GM\omega_{\rm Kep}\right)^{2/3}} \leq \frac{c^2}{\left(2^{6/5} G\mathscr{M}\omega_{\rm Kep}\right)^{2/3}} = \frac{c^2}{\left(2^{6/5}\pi G\mathscr{M} f_{\rm GW}\big|_{\rm max}\right)^{2/3}} \simeq 3.4\,,$$

LIGO-Virgo Collaboration, arXiv:1608.01940 (2016)

Really? Black-holes?

- We've shown that the system must have a compactness ratio <3.4.
- Therefore the Newtonian density scale is

$$\rho \geq \frac{m}{(4\pi/3)R^3} = 3 \times 10^{15} \left(\frac{3.4}{\mathscr{R}}\right)^3 \left(\frac{35\,\mathrm{M}_\odot}{m}\right)^2 \frac{\mathrm{kg}}{\mathrm{m}^3}$$

- This is less dense than NS densities but… again using the approximation

$$\omega \sim c/r \text{ and } r \sim GM/c^2 \text{ and } M\omega \sim c^3/G$$

- We can derive the following limit

$$\left(\frac{M_{\max}}{\mathscr{M}}\right) \simeq 3.4^{3/2} \times 2^{6/5} \simeq 14.4$$

- From which it follows that the max mass is 432$M_\odot$ with q=83. Leading to a lowest component mass of 5$M_\odot$, far greater than the max NS mass.

LIGO-Virgo Collaboration, arXiv:1608.01940 (2016)

Formation channels

- Possible BBH formation channels include:
  - Dynamical formation in a dense stellar environment (possibly assisted by gas drag in galactic nuclear disks).
  - Or isolated binary evolution
    - either the classical variant via a common-envelope phase (possibly from population III binaries).
    - or chemically homogeneous evolution in close tidally locked binaries.
- All of these channels have been shown to be consistent with the GW150914 discovery.
- The low masses of GW151226 are probably inconsistent with the chemically homogeneous evolution model.
- **A larger population (masses and spins) will help identify the correct channel(s)**.

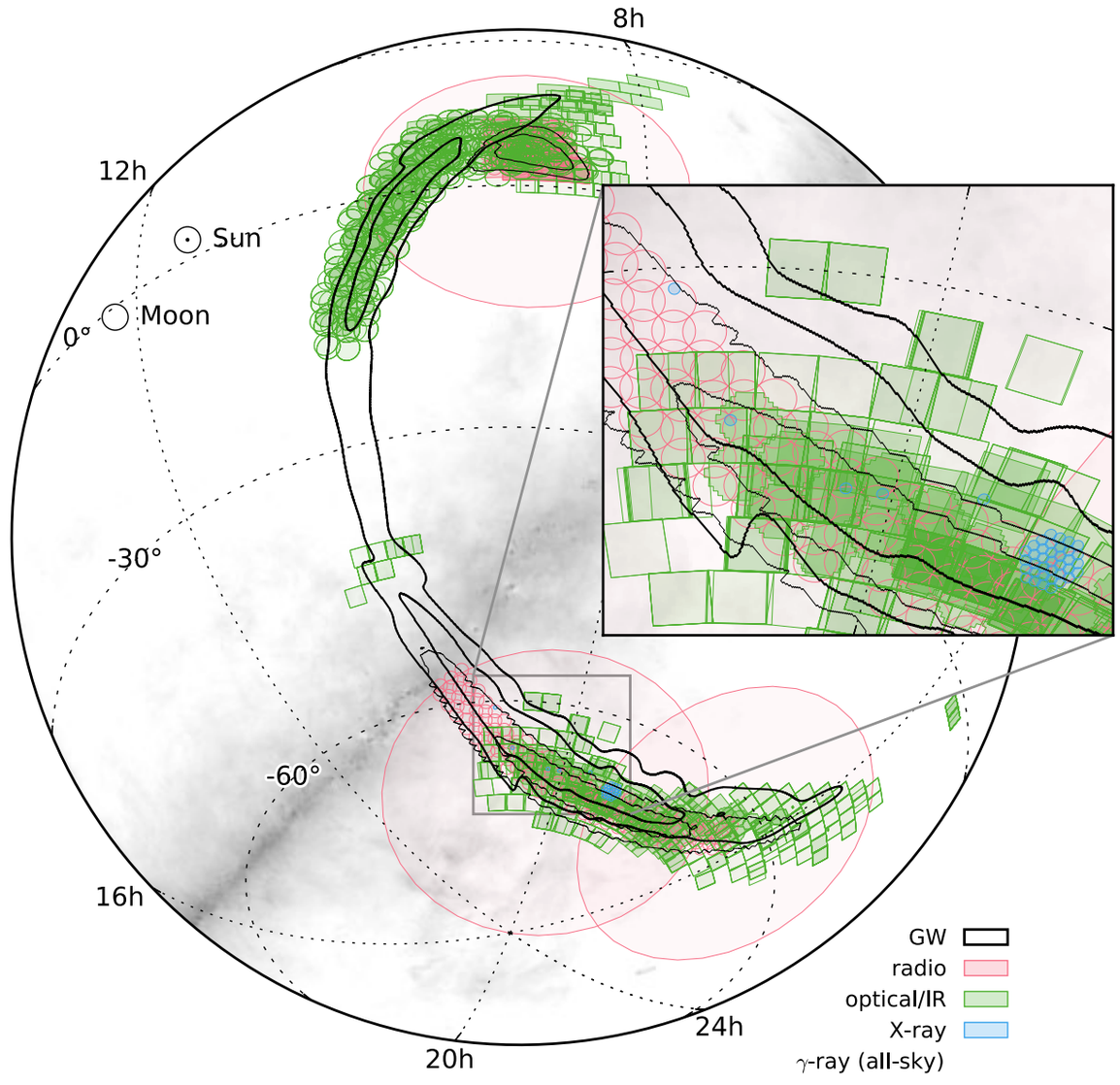
LIGO-Virgo Collaboration, arXiv:1606.04856 (2016)

Were there EM counterparts?

- The event time and location was shared with 63 teams of observers covering radio, optical, near-infrared, X-ray, and gamma-ray wavelengths with ground- and space-based facilities (**multi-messenger astronomy**).

- As this event turned out to be a binary black hole merger, there is little expectation of a detectable electromagnetic signature.

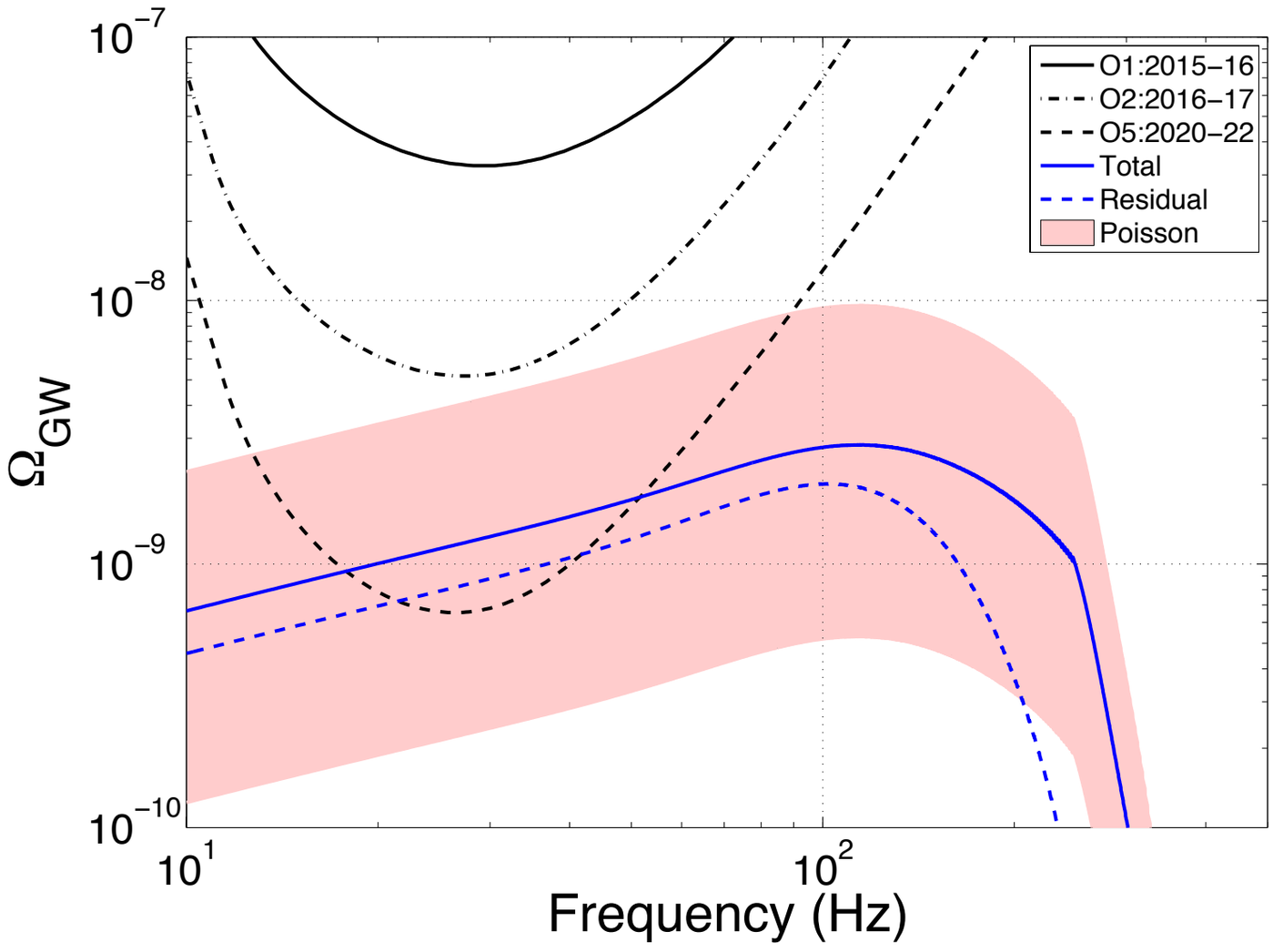
- There was a reported Fermi GBM trigger for GW150914 but…



LIGO-Virgo Collaboration, arXiv:1602.08492 (2016)

Too many to count

- The ensemble of all binary black hole mergers form an **astrophysical stochastic background**.
- This would inform us on the evolution of such binary systems over the history of th universe
- This has implications for spac based detectors (eLISA) and for ultra-low frequency waves detectable with pulsar timing arrays.



LIGO-Virgo Collaboration, arXiv:1602.03847 (2016)

Problems

1. Show that an asymmetric mass ratio would lead to a more compact system.

2. Derive an expression for the distance to a CBC event as a function of its frequency at peak strain and the peak strain.

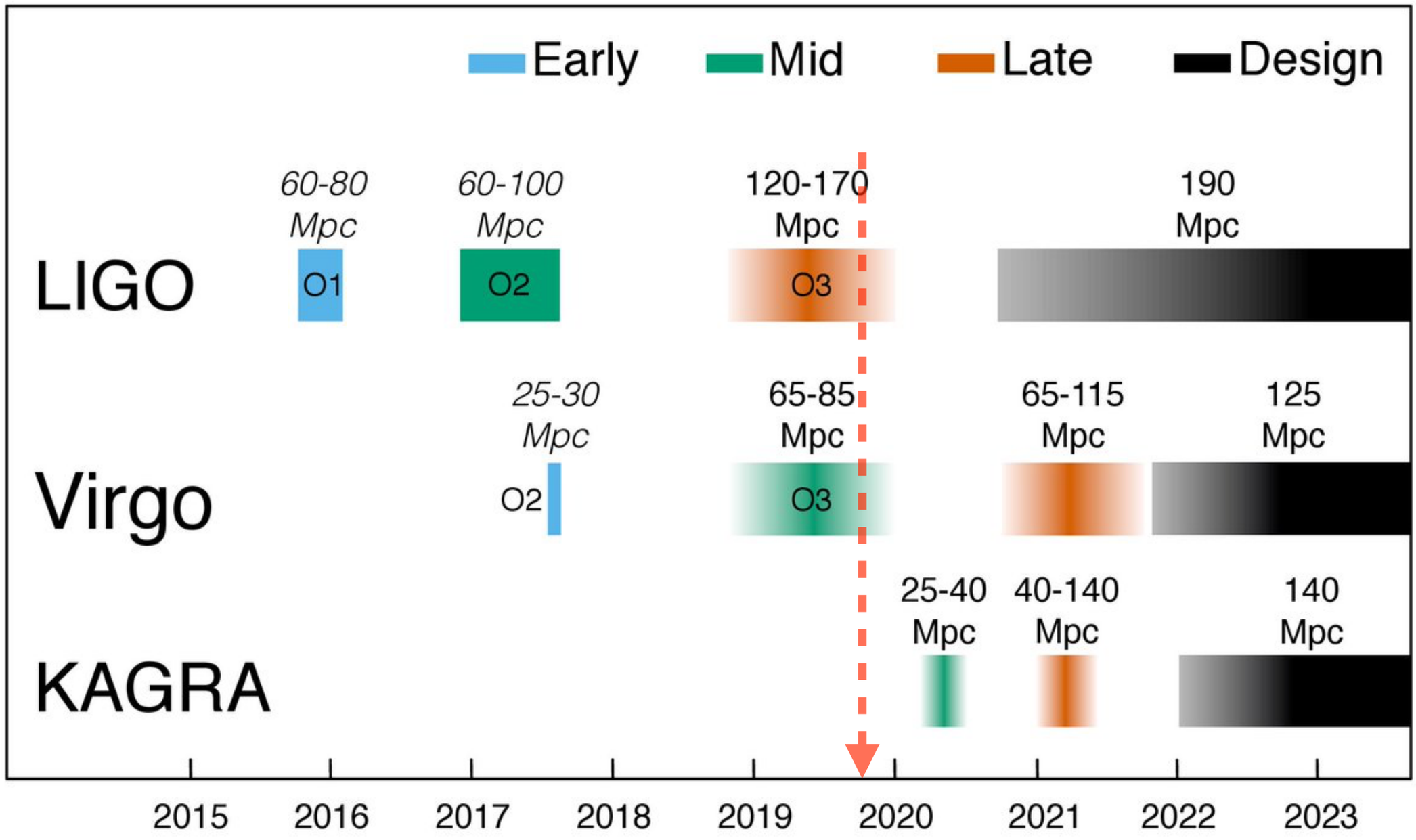
3. Show that ~$3M_{\odot}$ of energy were emitted during the merger of GW150914.

4. Repeat all calculations for GW151226 and LVT151012.

Conclusions

Extra things and a summary

What's happening now?



GraceDB [https://gracedb.ligo.org]

GraceDB — Gravitational-Wave Candidate Event Database

HOME | PUBLIC ALERTS | SEARCH | LATEST | DOCUMENTATION | LOGIN

Latest — as of 18 November 2019 08:07:59 UTC

Test and MDC events and superevents are not included in the search results by default; see the query help for information on how to search for events and superevents in those categories.

Query:

Search for: Superevent

Search

UID	Labels	t_start	t_0	t_end	FAR (Hz)	Created (UTC)
S191117j	ADVNO EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1258006119.454868	1258006120.454868	1258006121.454868	1.114e-18	2019-11-17 06:08:46 UTC
S191110af	ADVNO EM_Selected SKYMAP_READY DQOK GCN_PRELIM_SENT	1257462422.079116	1257462422.183200	1257462422.287284	2.499e-09	2019-11-10 23:10:59 UTC
S191110x	PE_READY ADVNO EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1257444539.210120	1257444540.210120	1257444541.210120	2.930e-11	2019-11-10 18:09:05 UTC
S191109d	PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1257296854.204590	1257296855.220703	1257296856.278186	1.537e-13	2019-11-09 01:07:46 UTC
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S190930t	ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253889264.685342	1253889265.685342	1253889266.685342	1.543e-08	2019-09-30 14:34:30 UTC
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S190923y	ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253278576.645077	1253278577.645508	1253278578.654868	4.783e-08	2019-09-23 12:56:22 UTC
S190915ak	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1252627039.685111	1252627040.690891	1252627041.730049	9.735e-10	2019-09-15 23:57:25 UTC
S190910h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1252139415.544299	1252139416.544448	1252139417.544448	3.584e-08	2019-09-10 08:30:21 UTC
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S190816i	PE_READY ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1249995888.757789	1249995889.757789	1249995890.757789	1.436e-08	2019-08-16 13:05:12 UTC
S190814bv	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1249852255.996787	1249852257.012957	1249852258.021731	2.033e-33	2019-08-14 21:11:18 UTC
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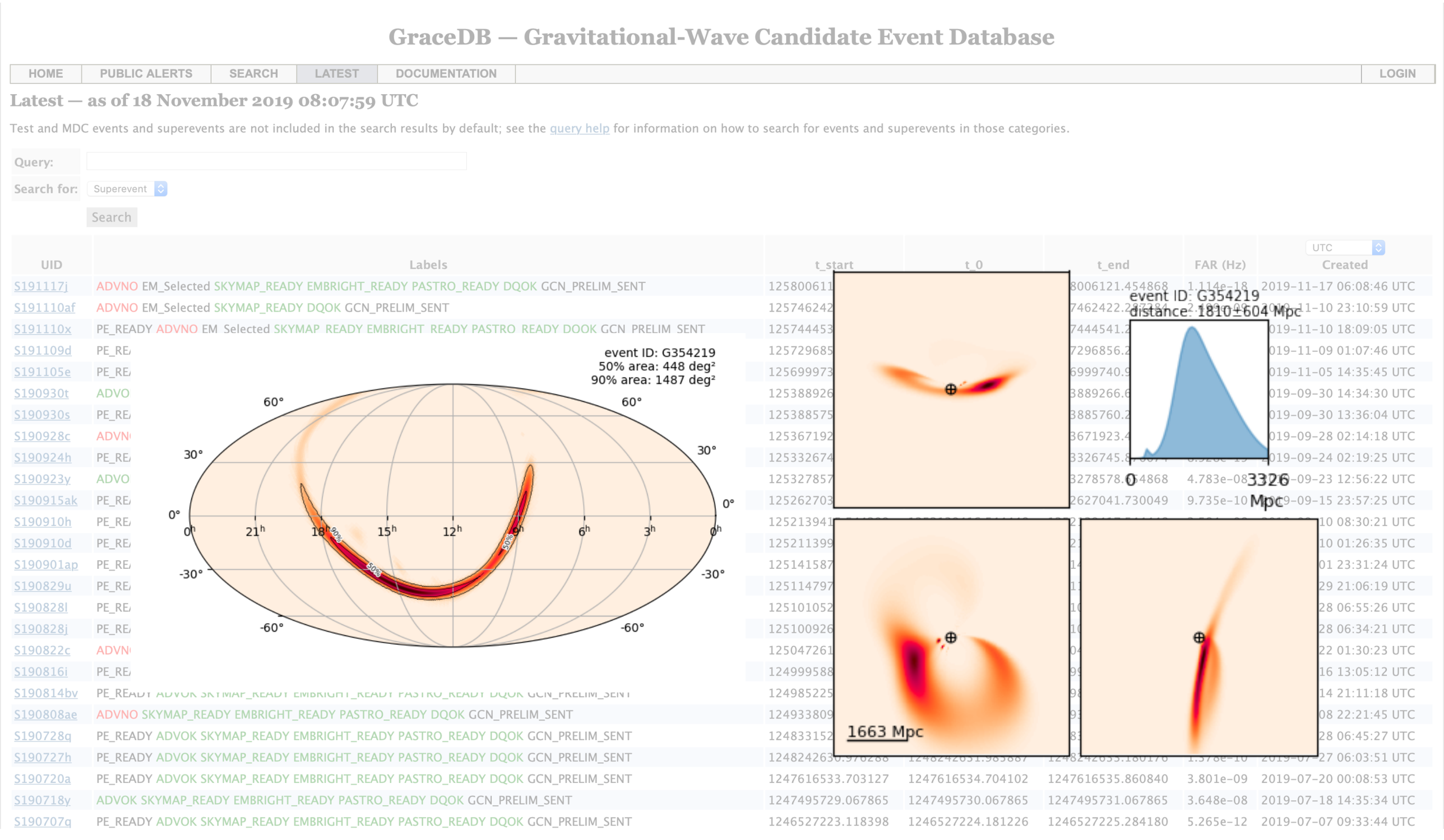
S190728q	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1248331527.497344	1248331528.546797	1248331529.706055	2.527e-23	2019-07-28 06:45:27 UTC
S190727h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1248242630.976288	1248242631.985887	1248242633.180176	1.378e-10	2019-07-27 06:03:51 UTC
S190720a	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1247616533.703127	1247616534.704102	1247616535.860840	3.801e-09	2019-07-20 00:08:53 UTC
S190718y	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1247495729.067865	1247495730.067865	1247495731.067865	3.648e-08	2019-07-18 14:35:34 UTC
S190707q	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1246527223.118398	1246527224.181226	1246527225.284180	5.265e-12	2019-07-07 09:33:44 UTC

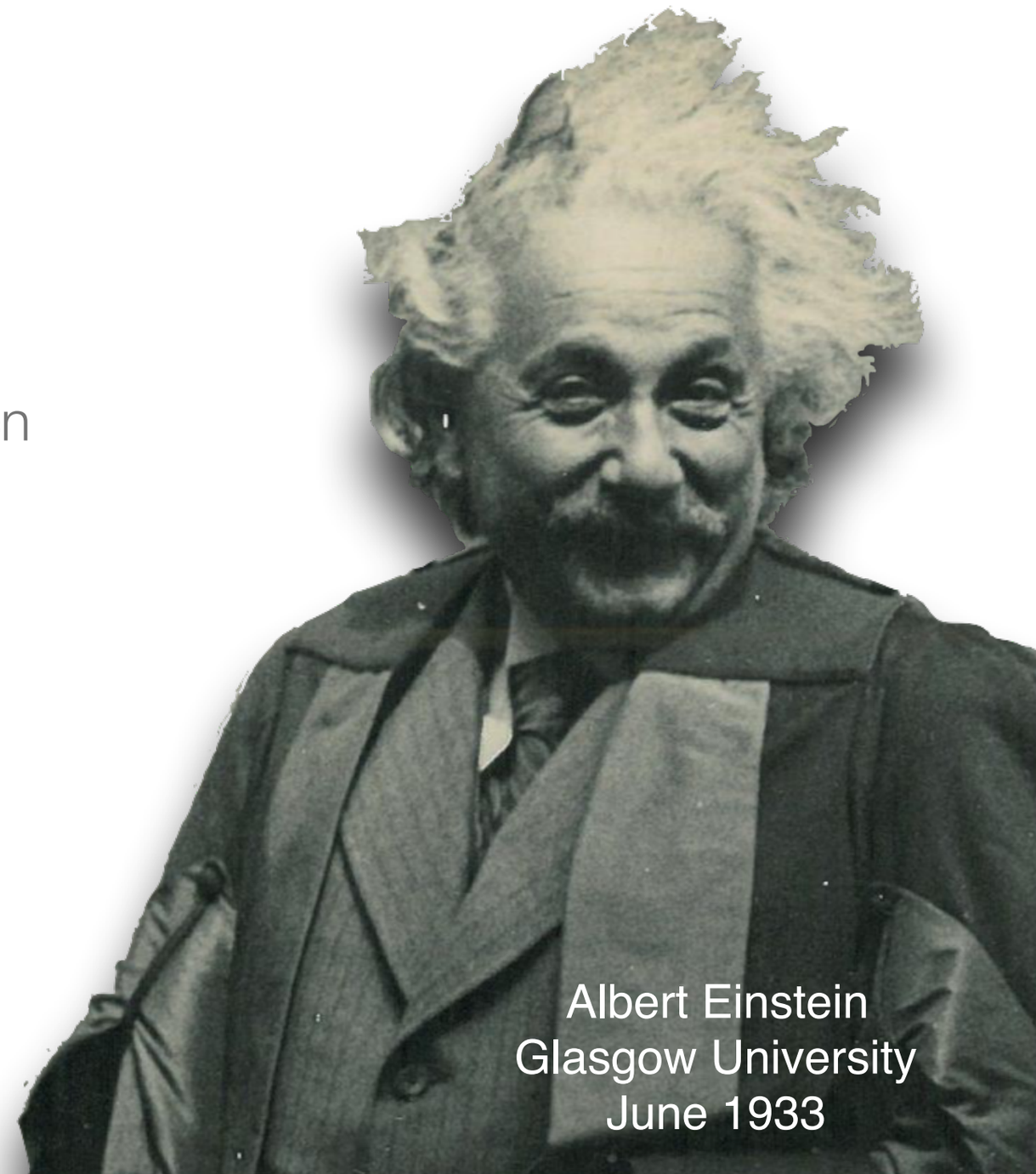
GraceDB [https://gracedb.ligo.org]



Mobile alerts

Summary

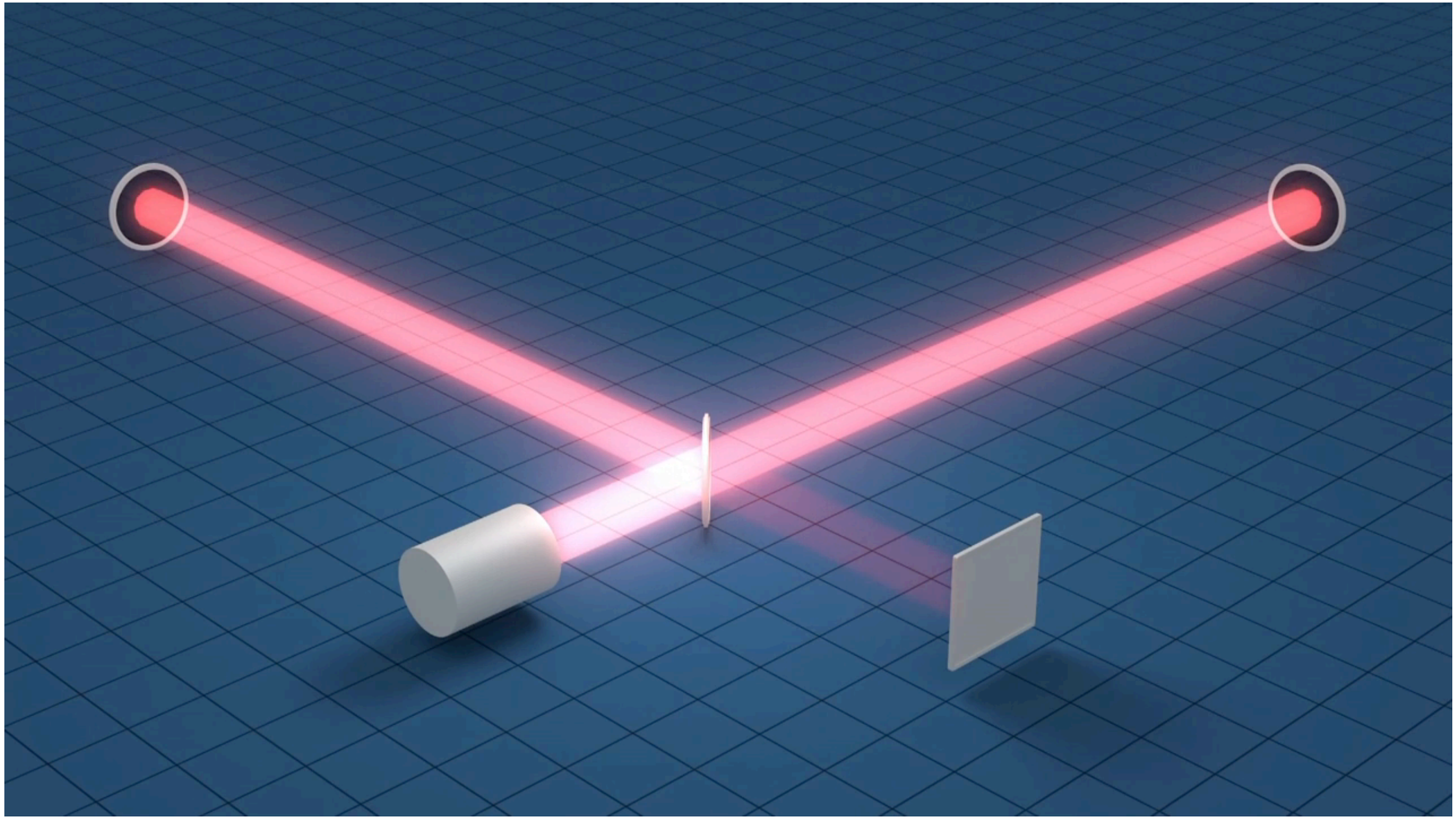
- As the director of LIGO Lab put it “We did it! We detected gravitational waves!” (Dave Reitze)
- Our very first discovery has provided the first observation of binary black holes.
- Our 9 additional BBH and a BNS detection has proved that it wasn’t a fluke!
- This is just the beginning of a completely new era of observational astronomy.
- We are in a uniquely exciting time for gravitational research (LISA PathFinder, LIGO India, Pulsar Timing Arrays).



Albert Einstein
Glasgow University
June 1933

Extra Slides

Interferometric detection



A global collaboration

- We have over 1000 members spread across 5 continents and over 100 institutions.

Glasgow’s role

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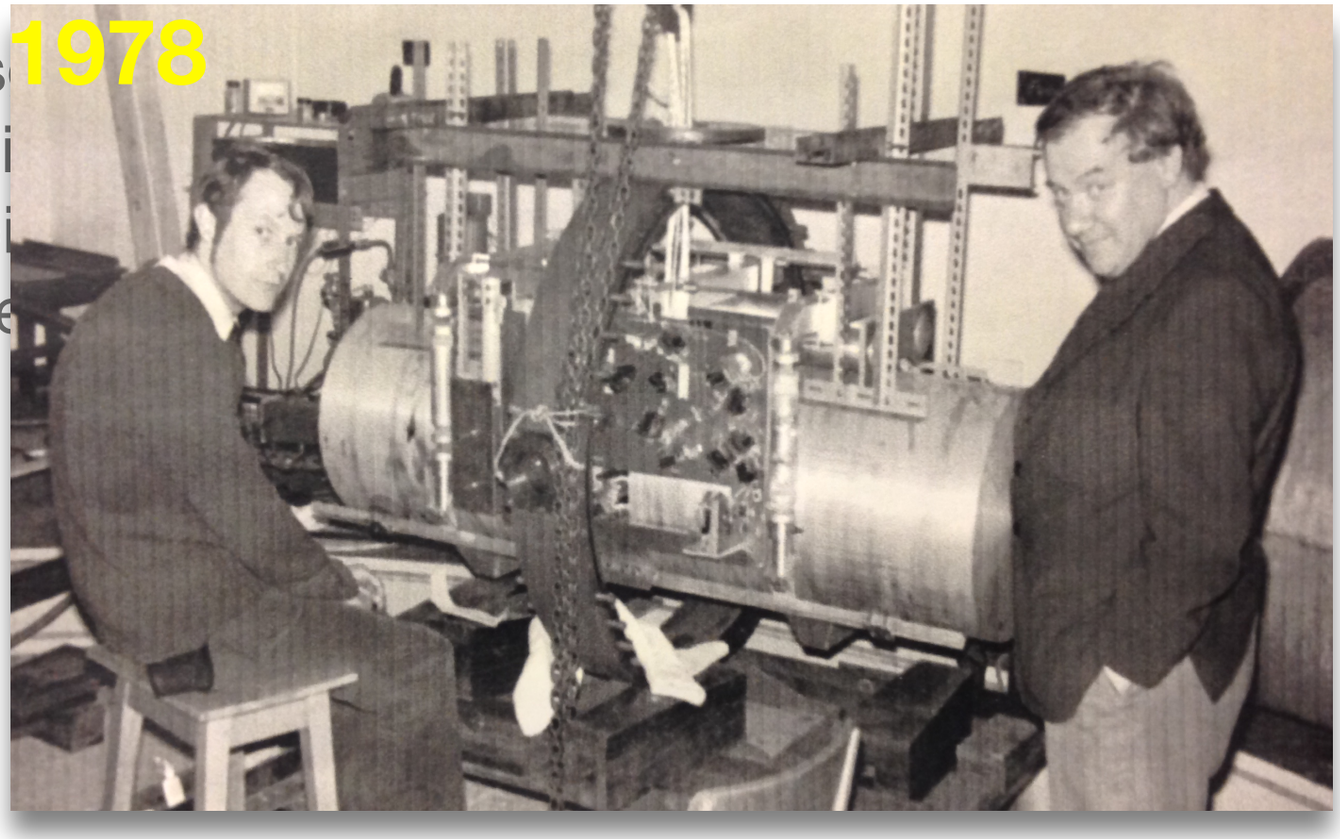
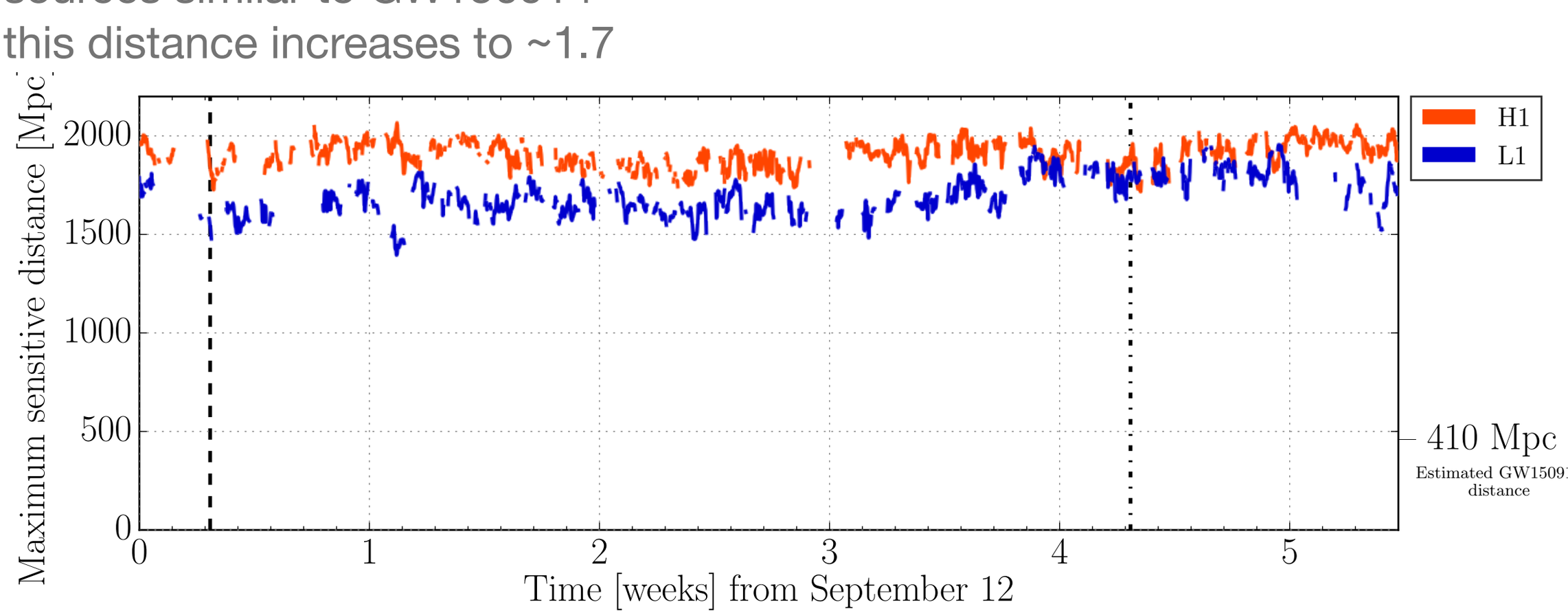


How far could we hear?

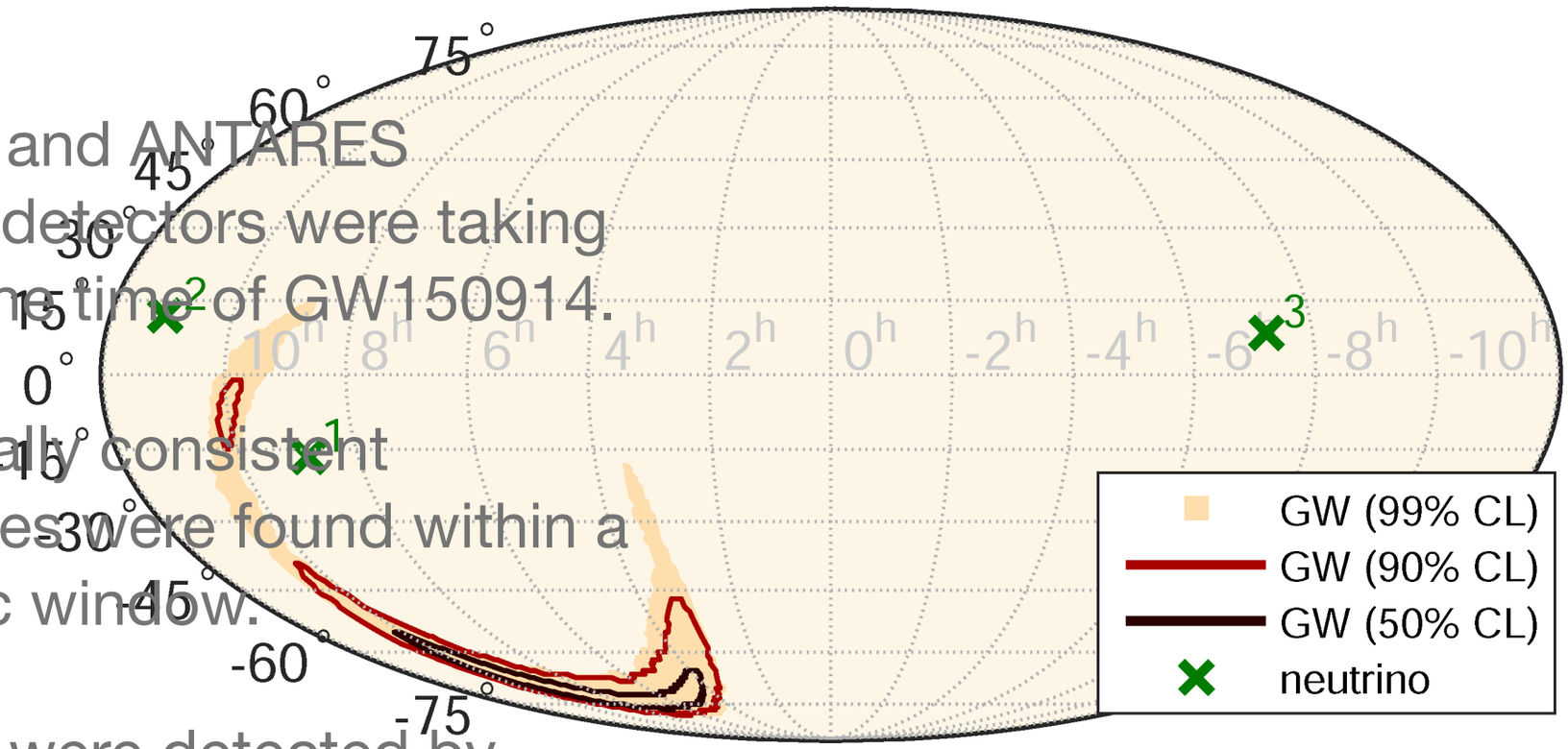
- Our nominal Figure of merit is the binary neutron star range which was ~70 Mpc for O1.
- Considering more massive sources similar to GW150914 this distance increases to ~1.7



LIGO-Virgo Collaboration, arXiv:1602.03844 (2016)

Any neutrinos?

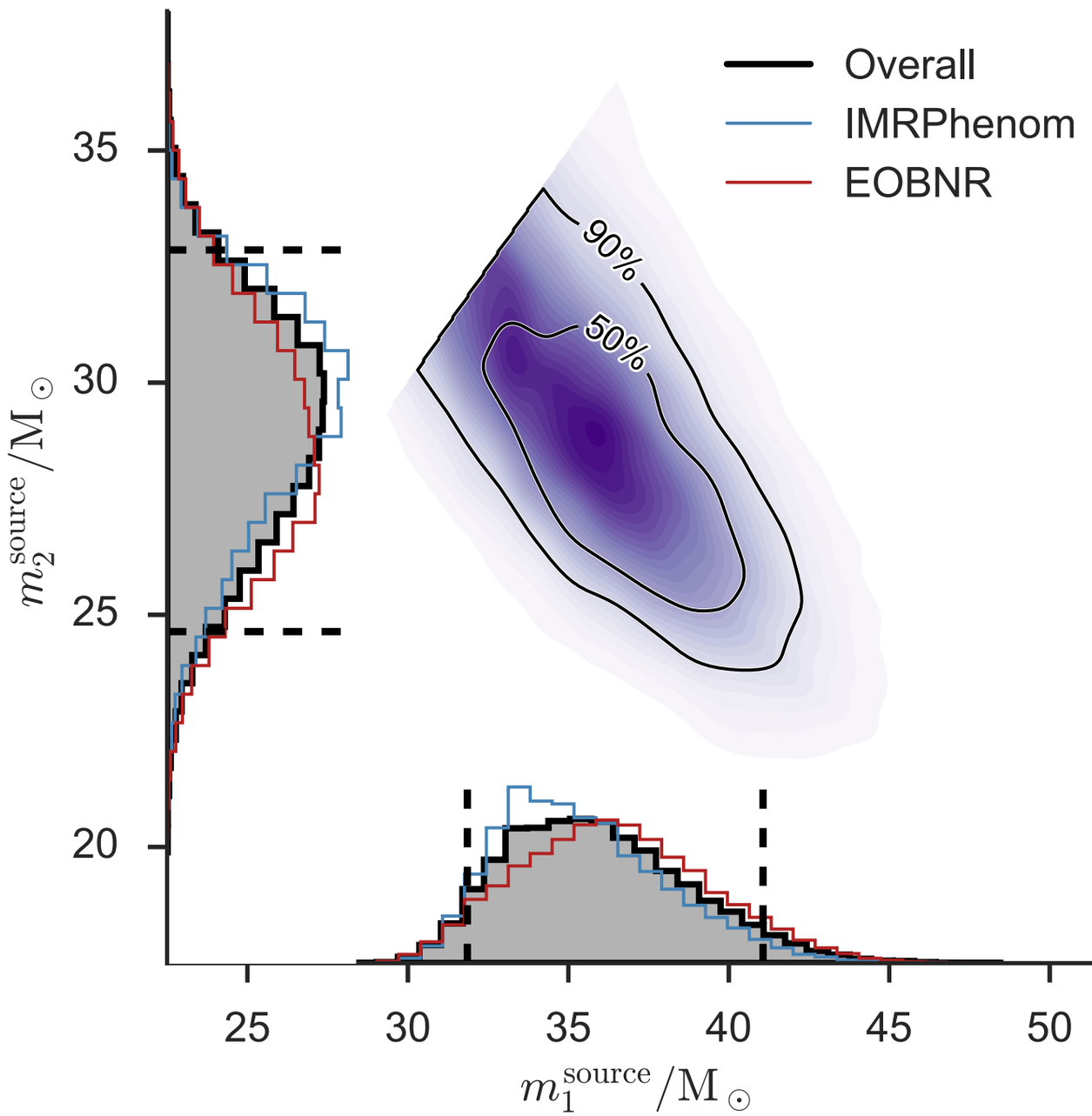
- IceCube and ANTARES neutrino detectors were taking data at the time of GW150914.
- No spatially consistent candidates were found within a ±500 sec window.
- 3 events were detected by IceCube but were consistent with the background.



LIGO-Virgo Collaboration, arXiv:1602.05411 (2016)

How heavy?

- The time evolution of the signa frequency tells us the “chirp mass” to ±10%.
- The component masses are estimated to be ~36 and 29 $M_\odot$.
- The result black hole has an estimated mass of 62 $M_\odot$.



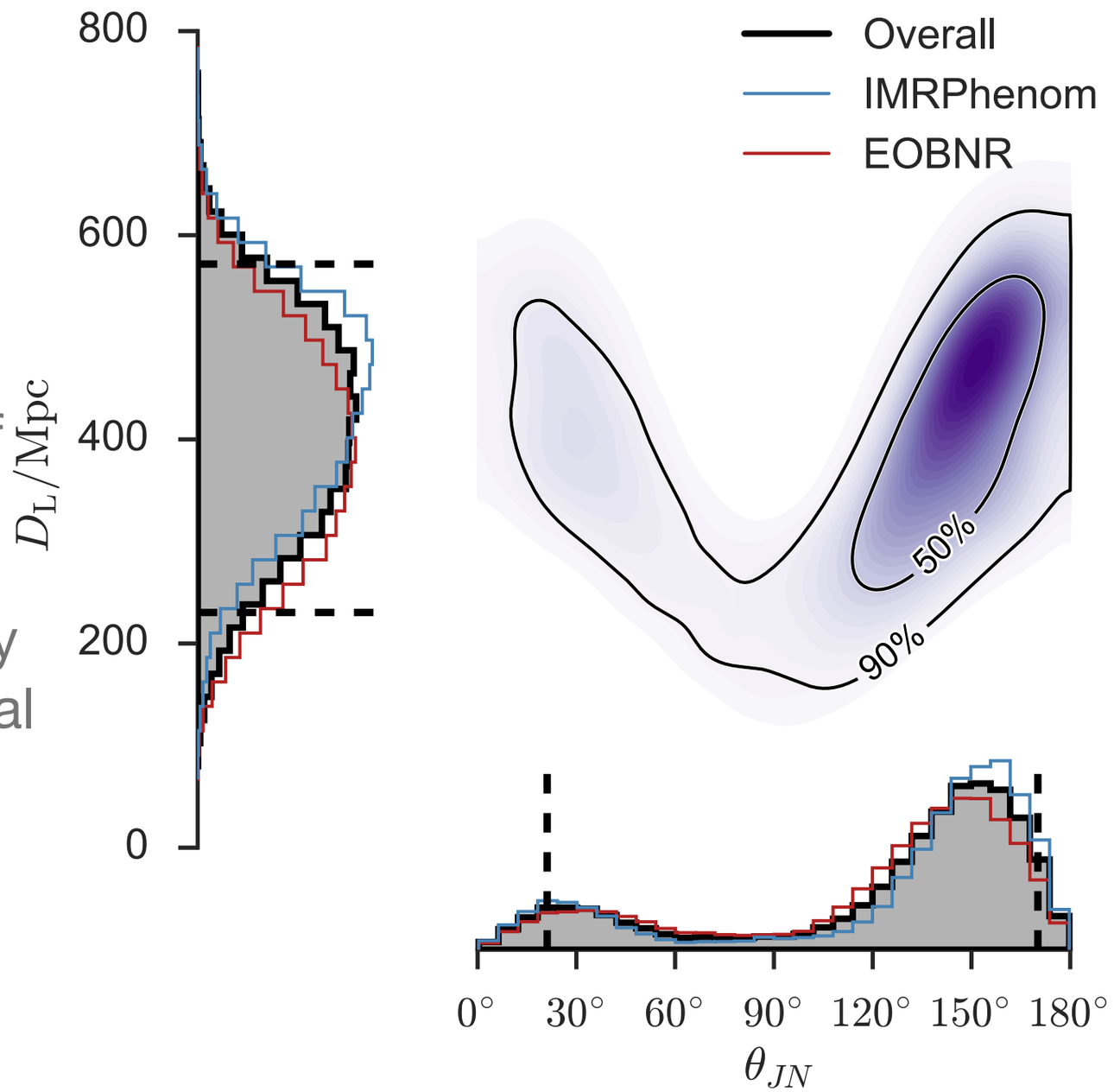
LIGO-Virgo Collaboration, arXiv:1602.03840 (2016)

How far?

- The measured amplitude is determined by 4 factors - the mass, distance, orbital inclination, and detector calibration.

- The corresponding redshift of the source is z~0.1.

- In principle we can use galaxy catalogues to identify potential host galaxies.



LIGO-Virgo Collaboration, arXiv:1602.03840 (2016)

Other companion papers

- In addition to the discovery paper, the second detection paper and the O1 results paper…
- There are 12 companion papers describing the, burst search, the BBH search, the system parameters, the astrophysical rates, implications, tests of GR, stochastic background, calibration, detector characterisation, neutrinos, the detectors, and EM follow-up.

papers.ligo.org

GW151226 - LIGO's Second Detection

- **"GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence"**
  Published in *Phys. Rev. Lett.* **116**, 241103 (2016) -- **Open access article**
- **"Binary Black Hole Mergers in the first Advanced LIGO Observing Run"**
  Accepted by *Phys. Rev. X*

GW150914 - LIGO's First Detection

Discovery Paper

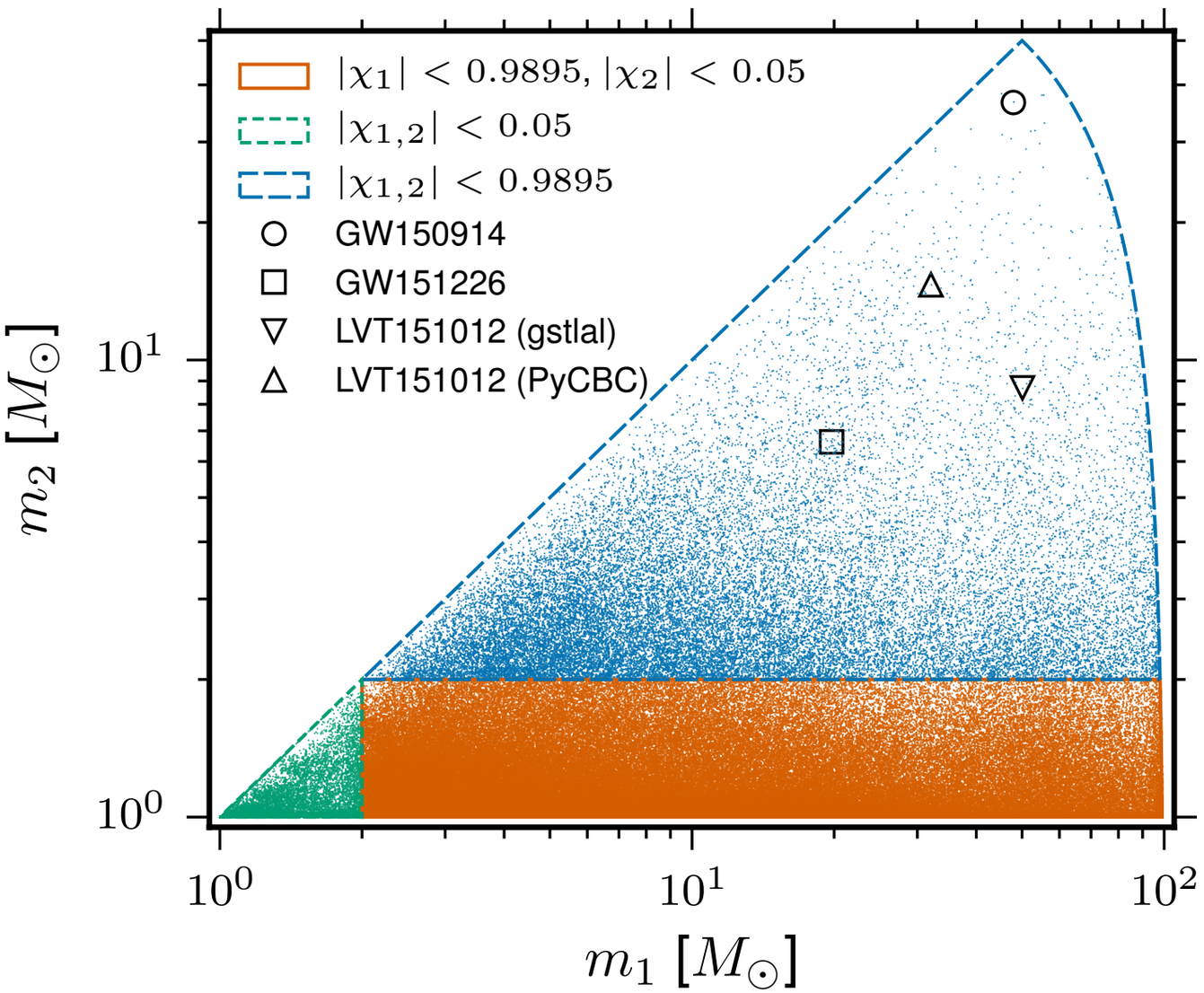
"Observation of Gravitational Waves from a Binary Black Hole Merger"
Published in *Phys. Rev. Lett.* **116**, 061102 (2016) -- **Open access article**

Related papers

- **"Observing Gravitational-wave Transient GW150914 with Minimal Assumptions"**
  Published in *Phys. Rev. D* **93**, 122004 (2016) -- **Abstract**
- **"GW150914: First Results from the Search for Binary Black Hole Coalescence with Advanced LIGO"**
  Published in *Phys. Rev. D* **93**, 122003 (2016) -- **Abstract**
- **"Properties of the Binary Black Hole Merger GW150914"**
  Published in *Phys. Rev. Lett.* **116**, 241102 (2016) -- **Open access article**
- **"The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914"**
  Accepted by *Astrophys. J. Lett.*
- **"Astrophysical Implications of the Binary Black-Hole Merger GW150914"**
  Published in *Astrophys. J. Lett.* **818**, L22 (2016) -- **Open access article**
- **"Tests of General Relativity with GW150914"**
  Published in *Phys. Rev. Lett.* **116**, 221101 (2016) -- **Abstract**
- **"GW150914: Implications for the Stochastic Gravitational Wave Background from Binary Black Holes"**
  Published in *Phys. Rev. Lett.* **116**, 131102 (2016) -- **Abstract**
- **"Calibration of the Advanced LIGO Detectors for the Discovery of the Binary Black-hole Merger GW150914"**
  Submitted to *Phys. Rev. Lett.*
- **"Characterization of Transient Noise in Advanced LIGO Relevant to Gravitational Wave Signal GW150914"**
  Published in *CQG* **33**, 134001 (2016) -- **Open access article**
- **"High-energy Neutrino Follow-up Search of Gravitational Wave Event GW150914 with ANTARES and IceCube"**
  Published in *Phys. Rev. D* **93**, 122010 (2016) -- **Abstract**
- **"GW150914: The Advanced LIGO Detectors in the Era of First Discoveries"**
  Published in *Phys. Rev. Lett.* **116**, 131103 (2016) -- **Abstract**
- **"Localization and Broadband Follow-up of the Gravitational-wave Transient GW150914"**
  Published in *Astrophys. J. Lett.* **826**, L13 (2016) -- **Open access article**

How do we search?

- Matched filters are correlated with the data to generate time-series of signal-to-noise ratio.
- Templates are placed in the 4-D space of component masses and (anti-)aligned spins.
- We have 2 independent search algorithms in order to verify any candidate signals.
- For GW150914 it was actually a search for un-modelled signals that found it.



LIGO-Virgo Collaboration, arXiv:1606.04856 (2016)

Matched filtering

$$x(t) = h(t - t_a) + n(t)$$

- For a signal in additive Gaussian noise
- The correlation of a template q with a dataset x is (in the frequency domain)

$$c(\tau) = \int_{-\infty}^{\infty} \tilde{x}(f)\tilde{q}^*(f)e^{-2\pi i f\tau}df$$

- For noise with zero mean, the mean and variance of the correlation are

$$\Sigma \equiv \bar{c}(\tau) = \int_{-\infty}^{\infty} \tilde{h}(f)\tilde{q}^*(f)e^{-2\pi i f(\tau - t_a)}df$$

$$N^2 = \overline{(c - \bar{c})^2} = \int_{-\infty}^{\infty} S_h(f)|\tilde{q}^*(f)|^2 df$$

- Where $S_h(f)$ is the noise spectral density
- This leads to the definition of the signal-to-noise ratio (SNR)

$$\rho^2 = \frac{\Sigma^2}{N^2}$$

Matched filtering

- Let us now define the noise weighted inner product

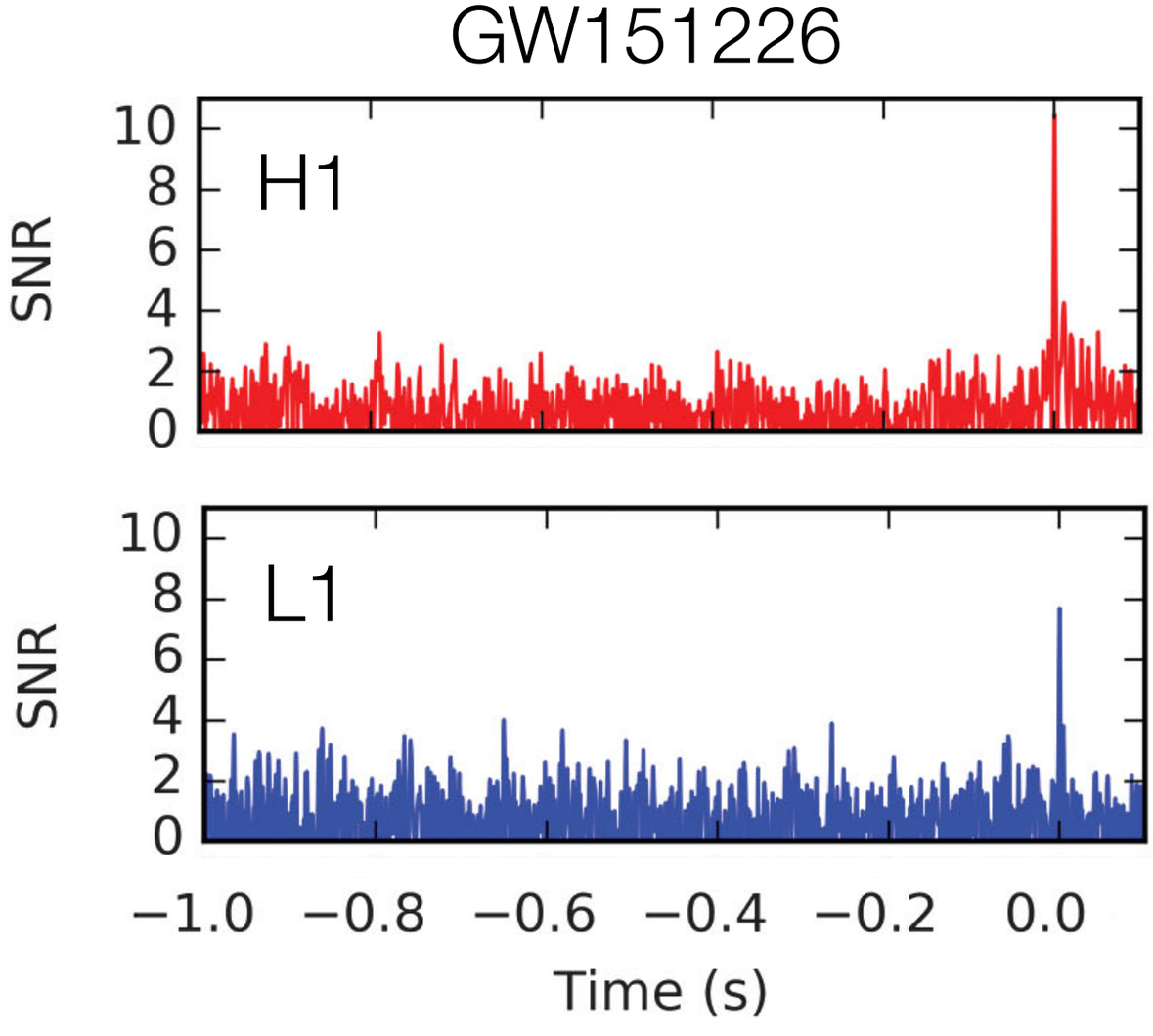
$$\langle a, b\rangle \equiv 2\int_0^\infty \frac{df}{S_h(f)}[\tilde{a}(f)\tilde{b}^*(f) + \tilde{a}^*(f)\tilde{b}(f)]$$

- This allows to us to rewrite the squared SNR as

$$\rho^2 = \frac{\langle h\, e^{2\pi i f(\tau - t_a)}, S_h\, q\rangle}{\sqrt{\langle S_h\, q, S_h\, q\rangle}}$$

- From which it is clear to see that the optimal filter is

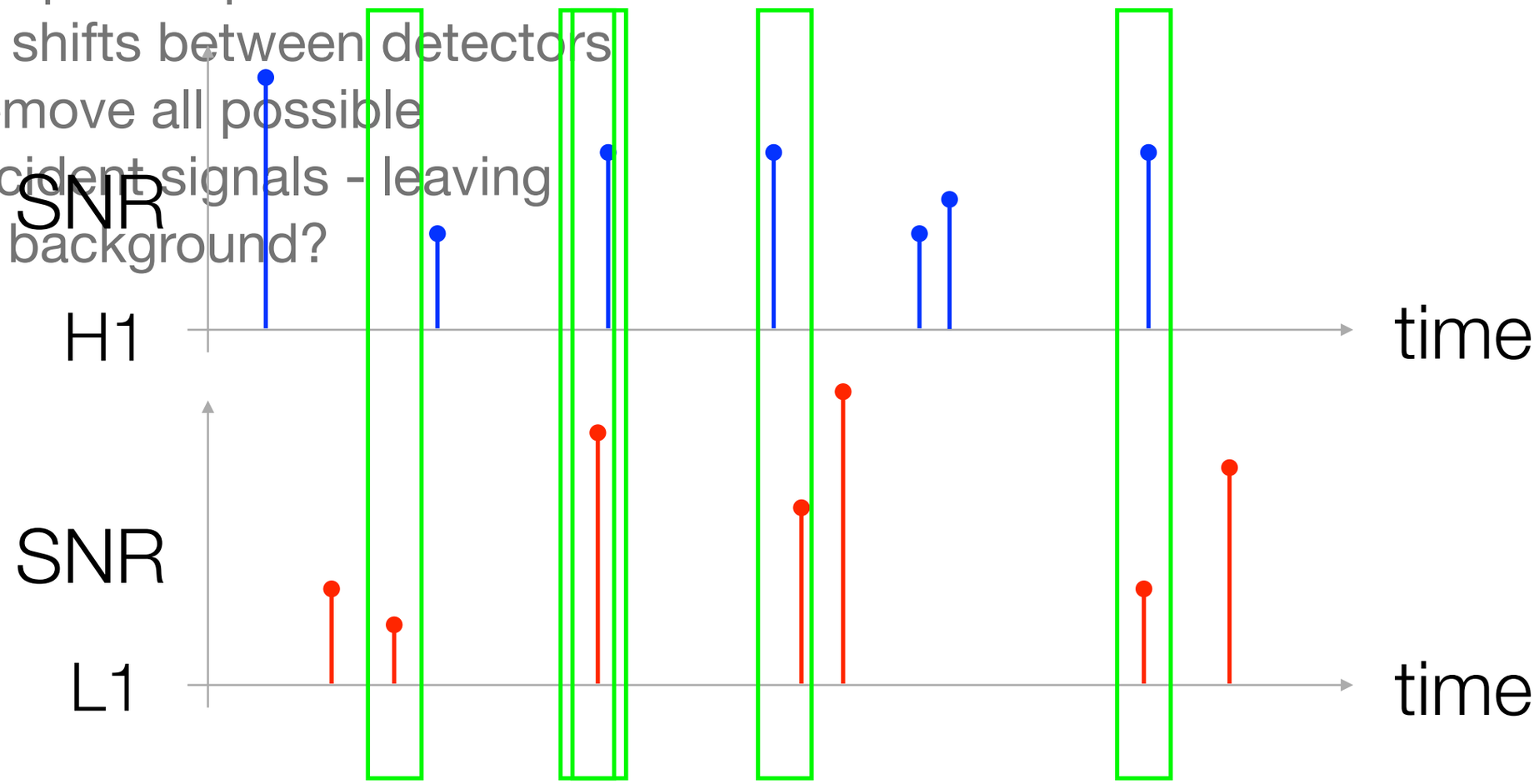
$$\tilde{q}(f) \propto \frac{\tilde{h}(f)e^{2\pi i f(\tau - t_a)}}{S_h(f)}$$



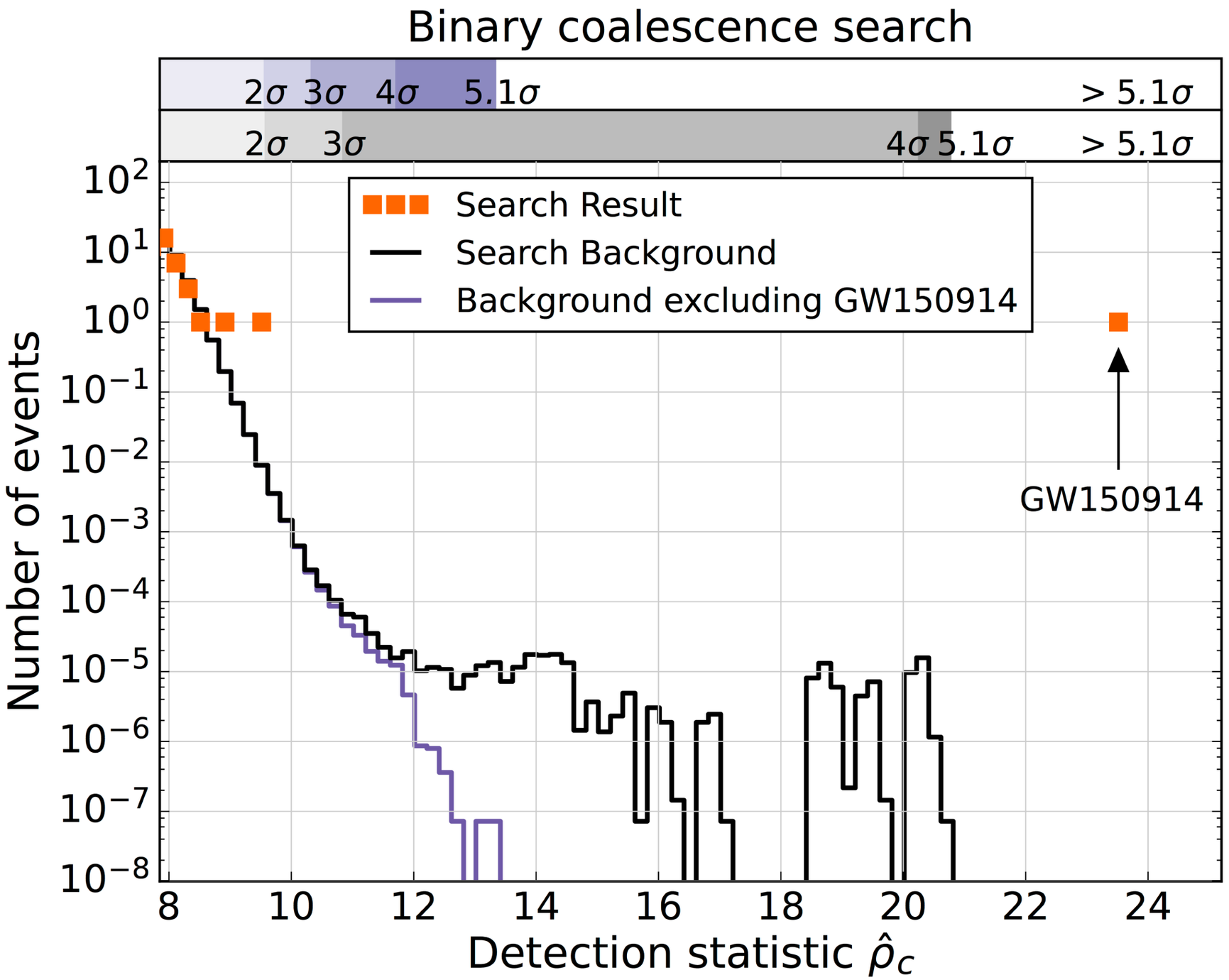
LIGO-Virgo Collaboration, PRL **116**, 241103 (2016)

How can we be sure?

- We use a method known as **time-slides** (or something mathematically equivalent).
- We impose repeated artificial time shifts between detectors to remove all possible coincident signals - leaving only background?

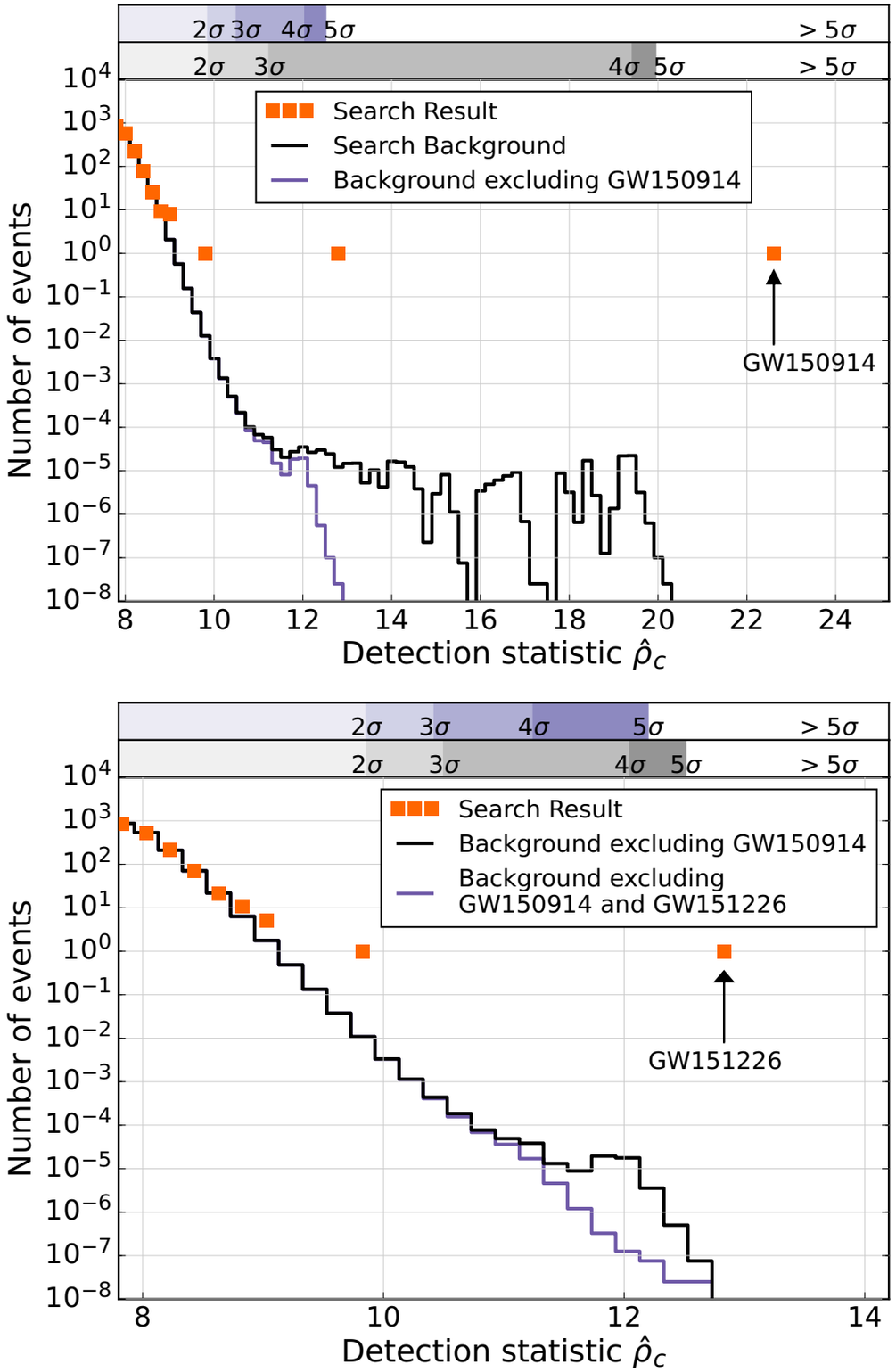


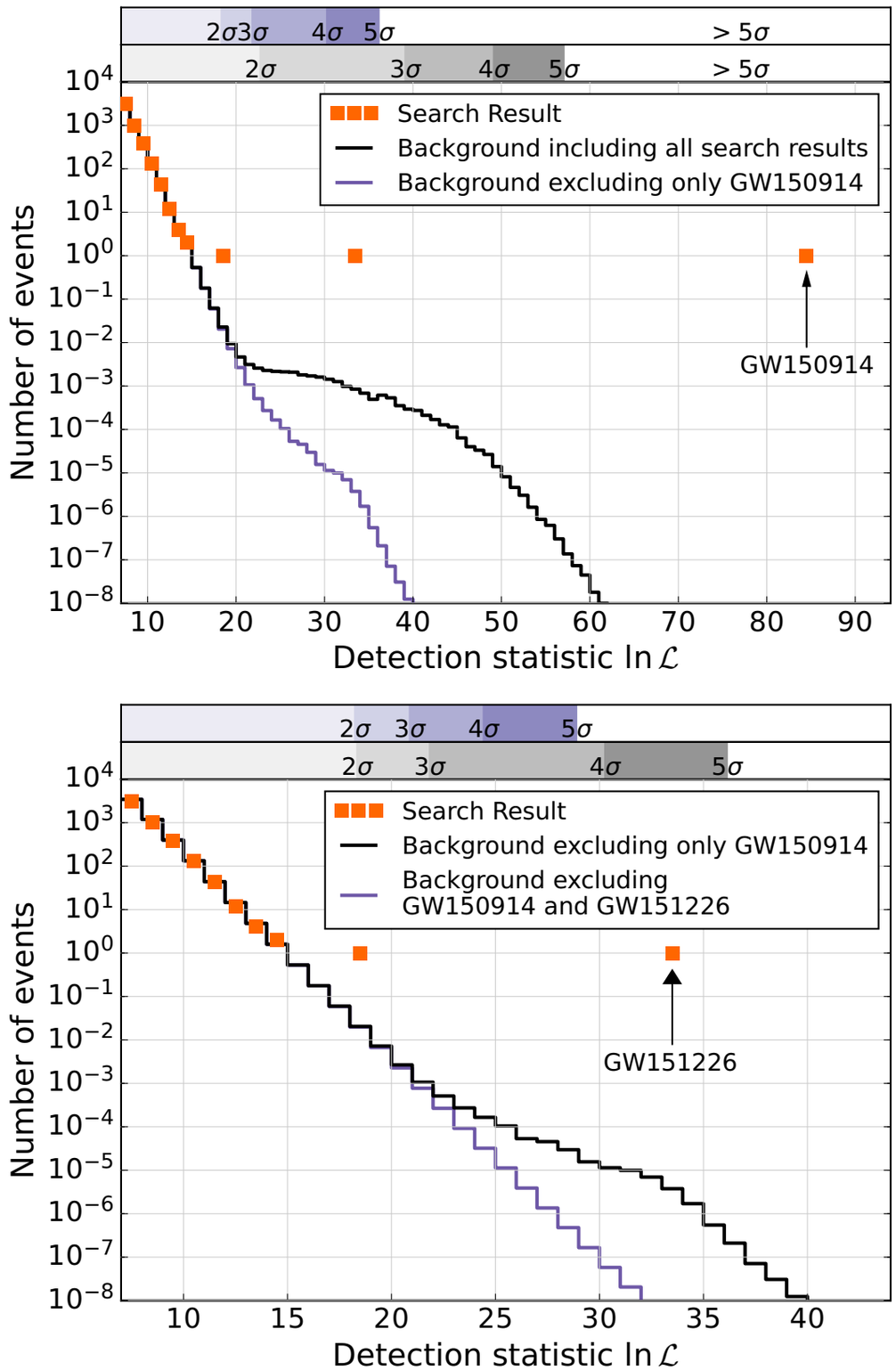
Are we sure?



LIGO-Virgo Collaboration, PRL **116**, 061102 (2016)

For both detections?

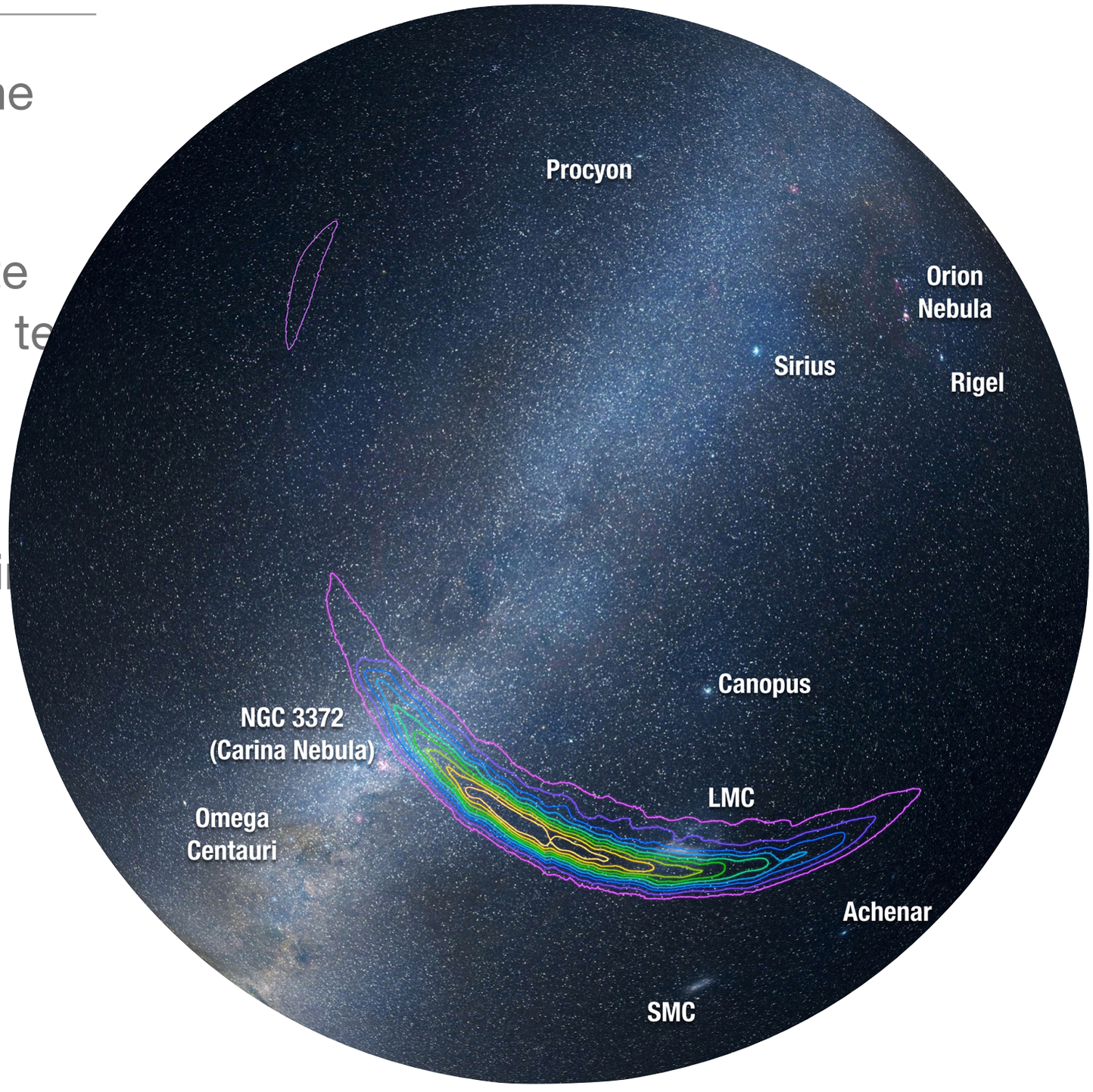




LIGO-Virgo Collaboration, arXiv:1606.04856 (2016)

Where was GW150914?

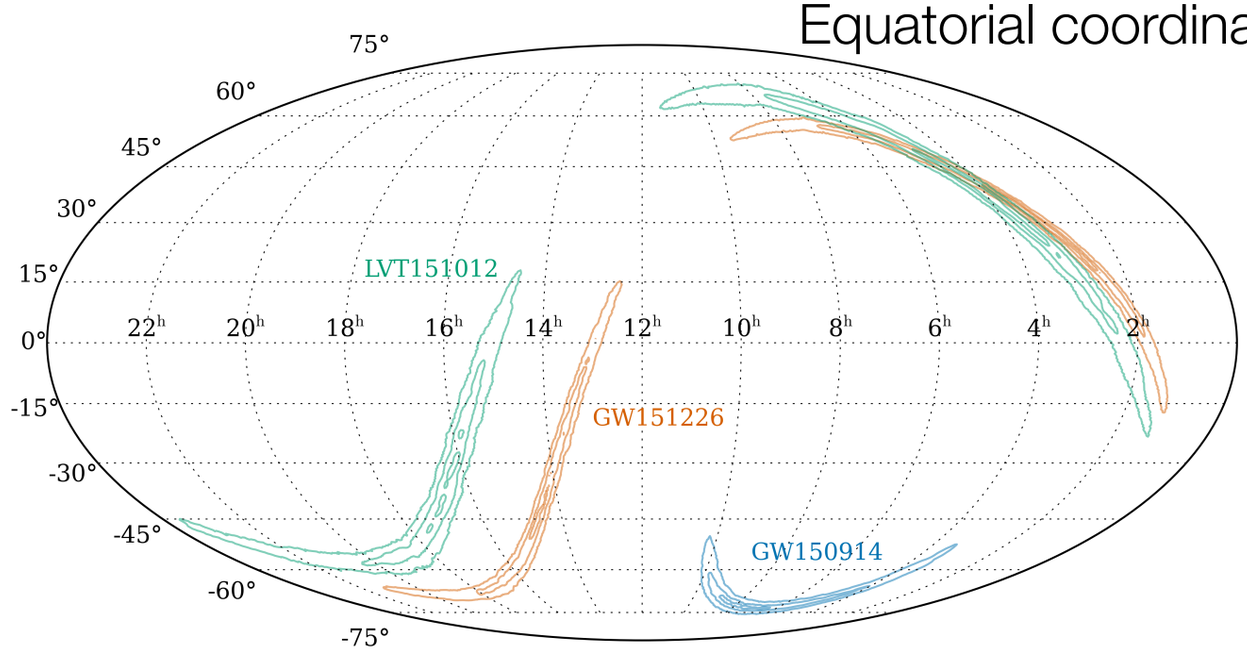
- Most likely somewhere in the southern hemisphere.
- We can very rapidly estimate the source sky location and te astronomers to point there telescopes.
- This is relevant to how we fi identified this signal. It was found with an **unmodelled** “burst” search.



Where were the others?

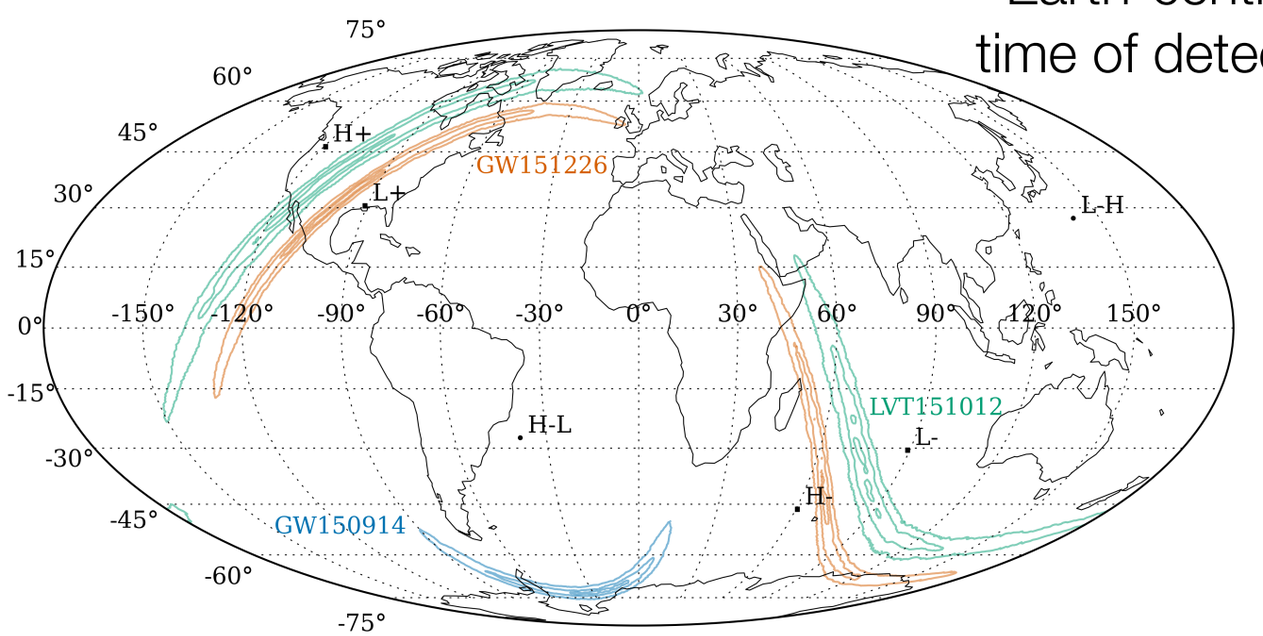
- Notice the typical scale of error-region, O(100s) square degrees for 2 detectors.
- GW150914, GW151226 and LVT151012 have 230, 850, 1600 sq deg error regions.

Equatorial coordinates



- It’s low number statistics but also notice the bias towards detection directly over/under the detectors.

Earth-centric at time of detections



How to measure parameters?

- We rely heavily on **Bayesian parameter estimation.**

likelihood

prior

posterior

$$p(\boldsymbol{\theta}|\boldsymbol{x}, I) = \frac{p(\boldsymbol{x}|\boldsymbol{\theta}, I)p(\boldsymbol{\theta}|I)}{p(\boldsymbol{x}|I)}$$

evidence

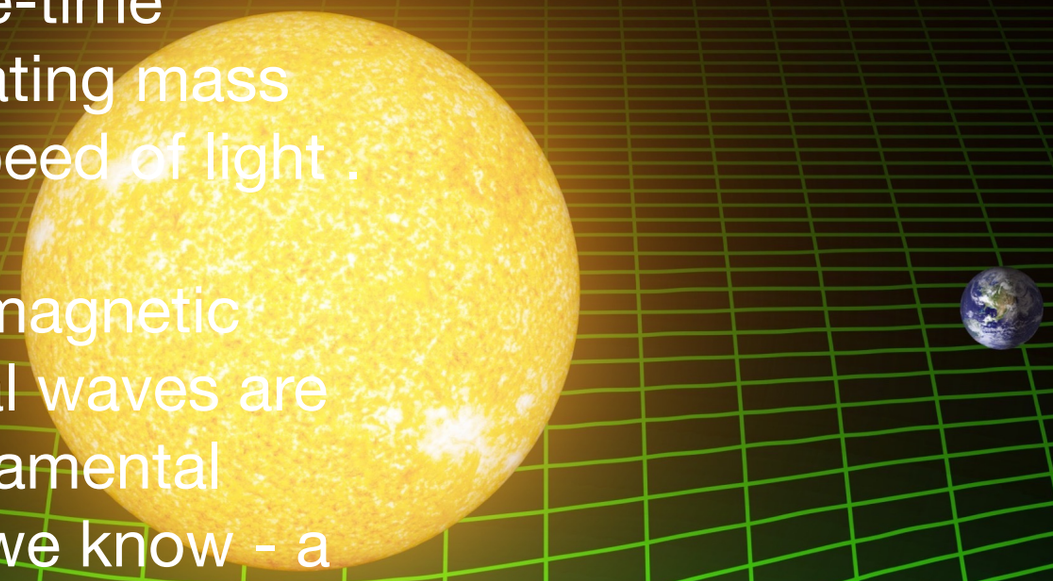
- We must make (motivated) assumptions regarding our noise distribution and the prior values of of the parameters.

$$\log p(\boldsymbol{x}|\boldsymbol{\theta}, I) = \exp\left[-\sum_{j=0}^{N-1} \frac{|\tilde{x}_j - \tilde{h}_j(\boldsymbol{\theta})|^2}{TS_h(f_j)}\right] + \text{const}$$

- In practice, obtaining posterior probability densities on system parameters is done via **Monte-Carlo techniques** (MCMC, nested sampling).

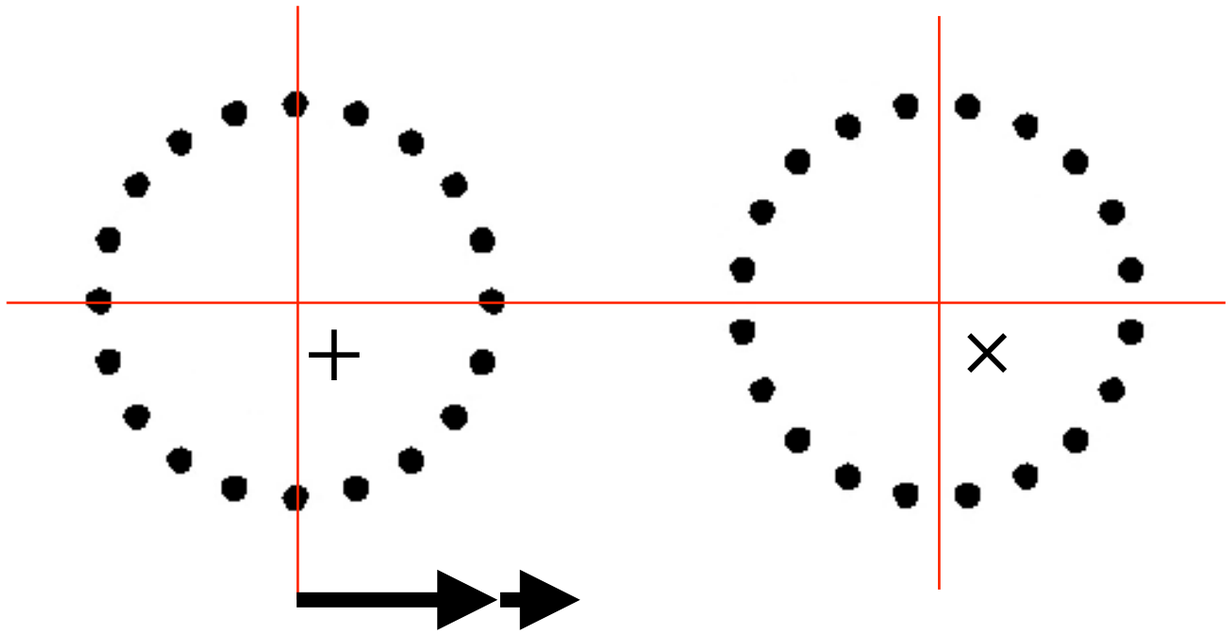
Gravitational waves

- “*Mass tells space-time how to curve and spacetime tells mass how to move*”
- 100 years ago Einstein theorised the existence of gravitational waves - tiny distortions in space-time caused by accelerating mass and travel at the speed of light .
- Apart from Electromagnetic waves, gravitational waves are the only other fundamental wave phenomena we know - a new window on the universe.



Measurable effects

- GWs are transverse waves composed of 2 polarisation states.

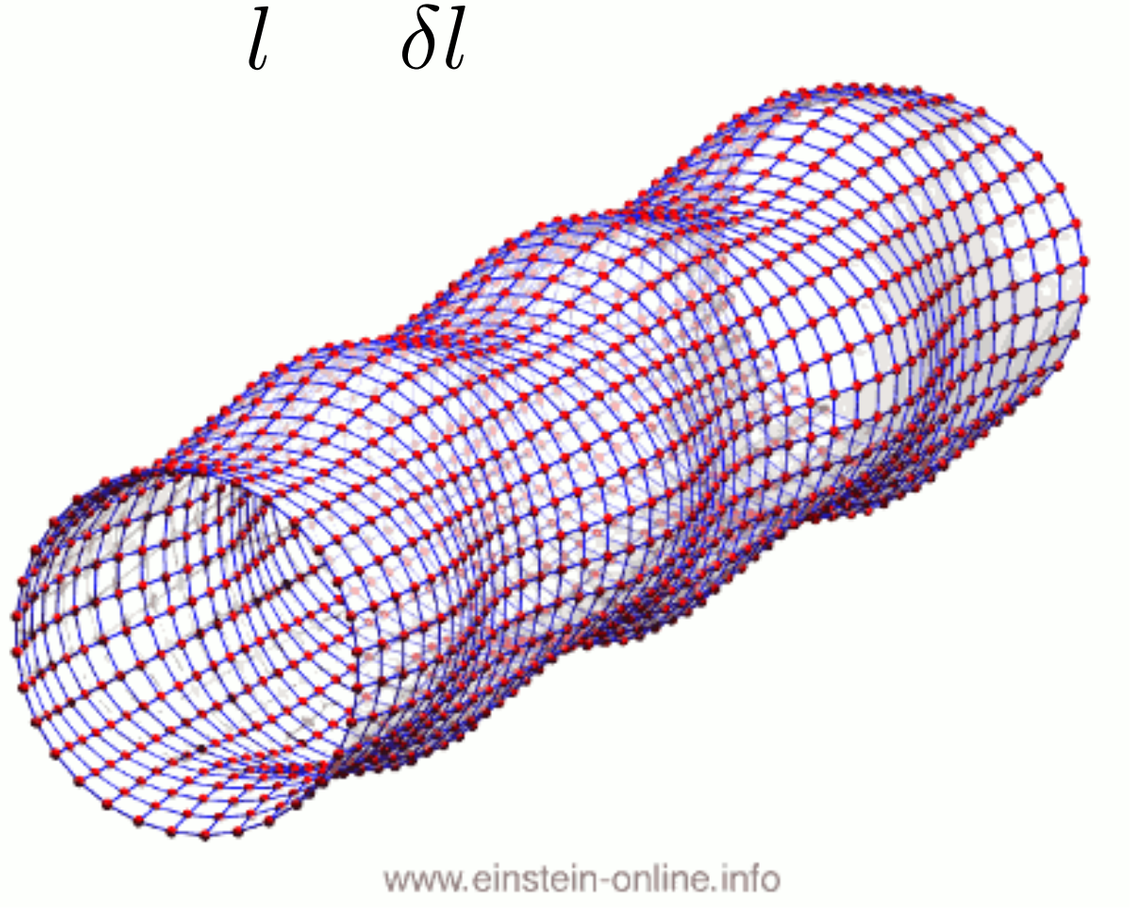


- Their effect is quantified by the dimensionless strain

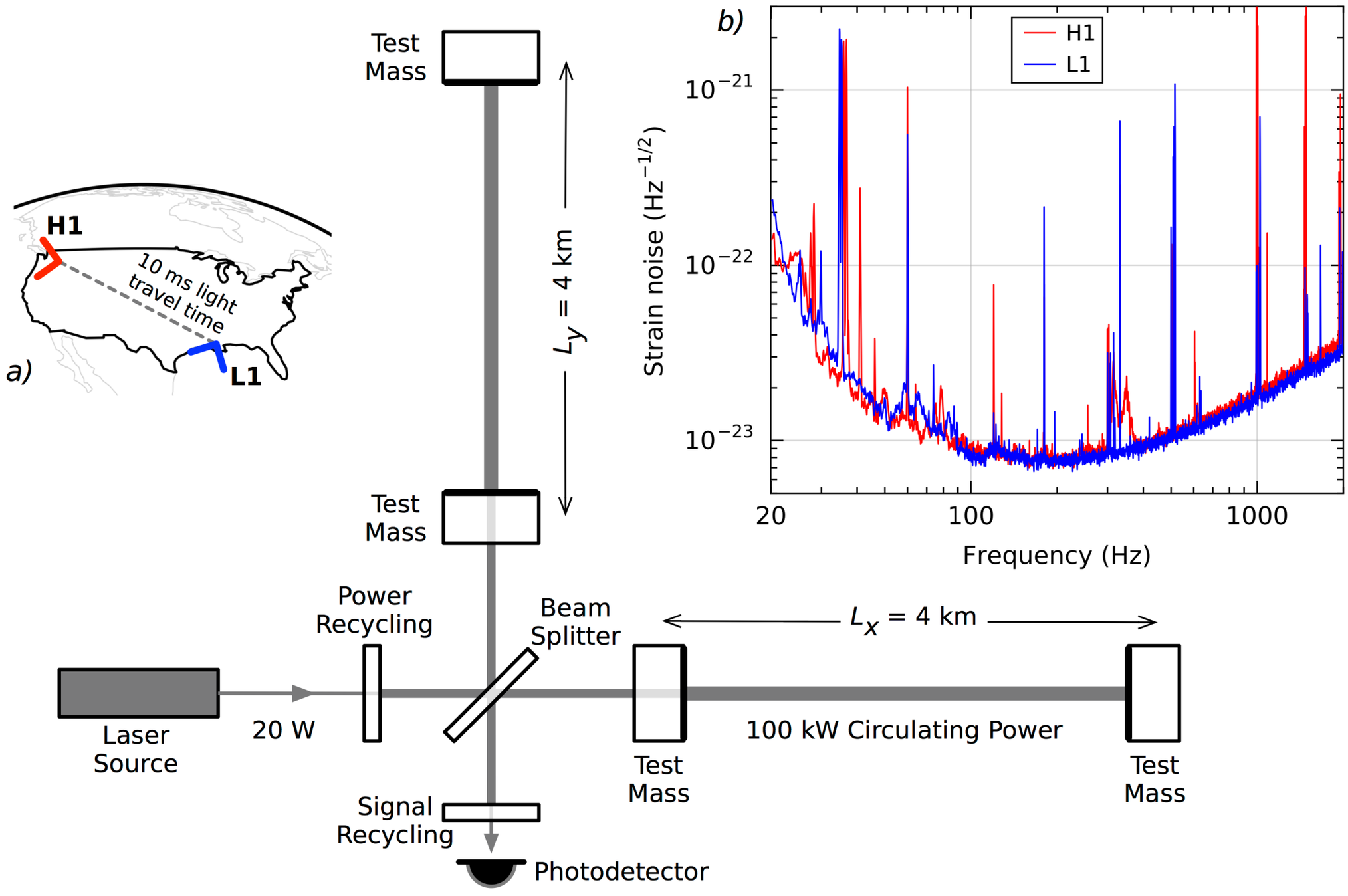
$$h = \frac{\delta l}{l}$$

- Typical levels of strain expected from astrophysical events is

$$\mathcal{O}(10^{-21})$$



Interferometric detection



LIGO-Virgo Collaboration, PRL **116**, 061102 (2016)

Interferometric detection

- An aerial view of the LIGO Livingston gravitational wave detector.

The global network

GEO600

Virgo

LIGO Livingston

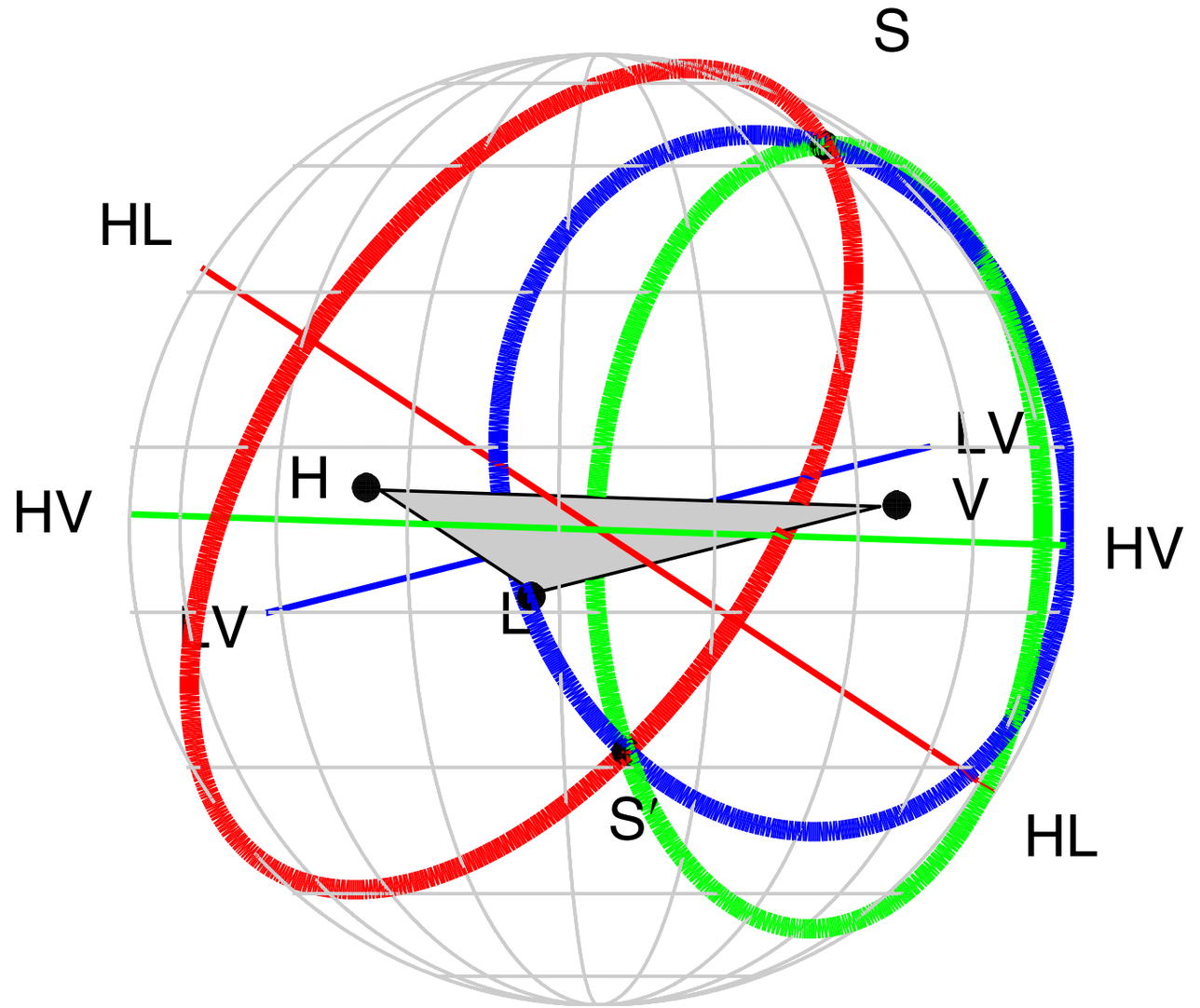
LIGO Hanford

LIGO-India

KAGRA

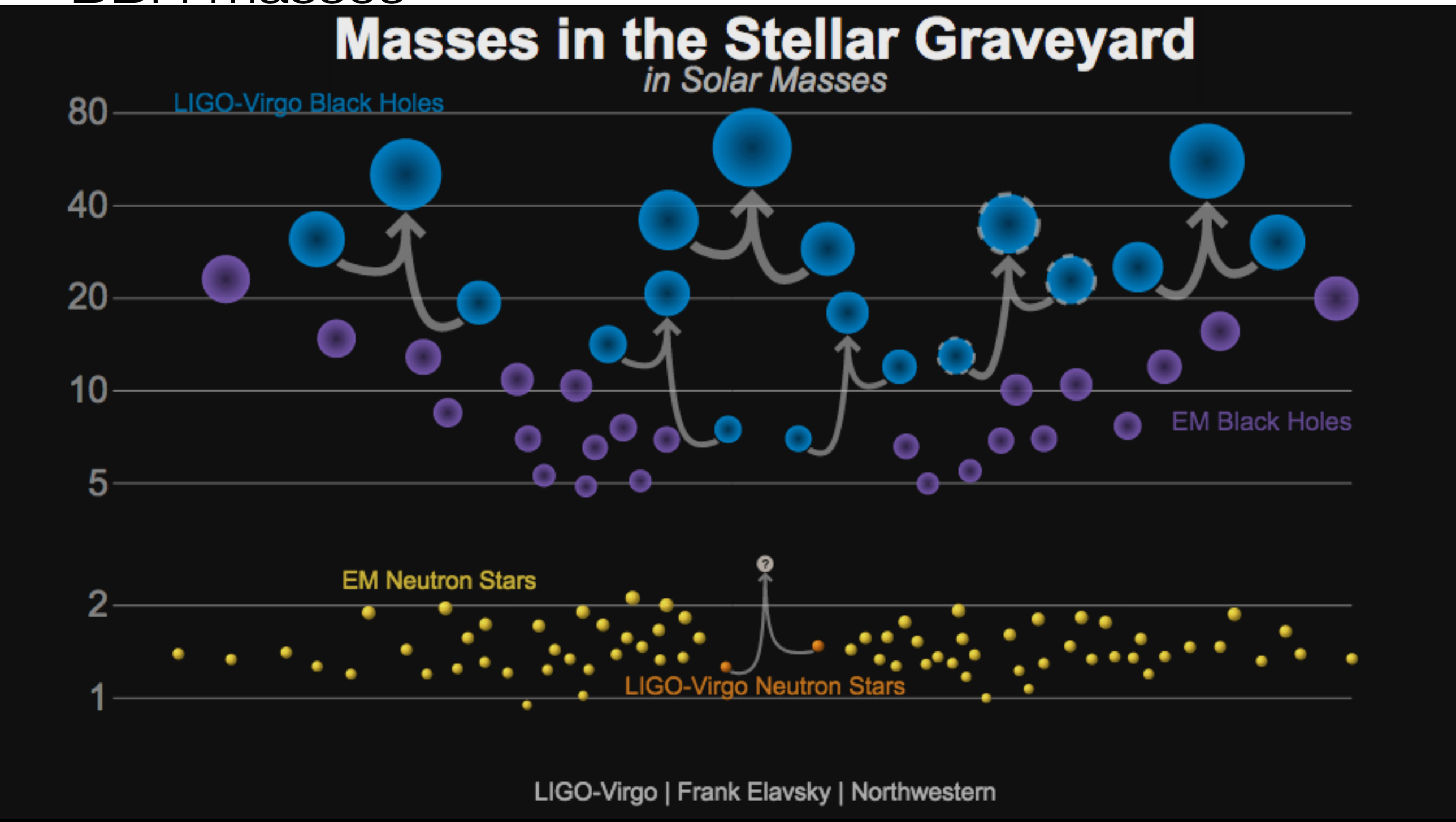
How can we locate it?

- Sky localisation information is key to GW multi-messenger astronomy.
- The time delay (with associated timing uncertainty) determines the bulk of the localisation ability.
- For four or more detectors there is a unique intersection region of all of the annuli.
- Additional antenna response modulation refine the estimate.



LIGO-Virgo Collaboration, arXiv:1304.0670 (2013)

BBH masses

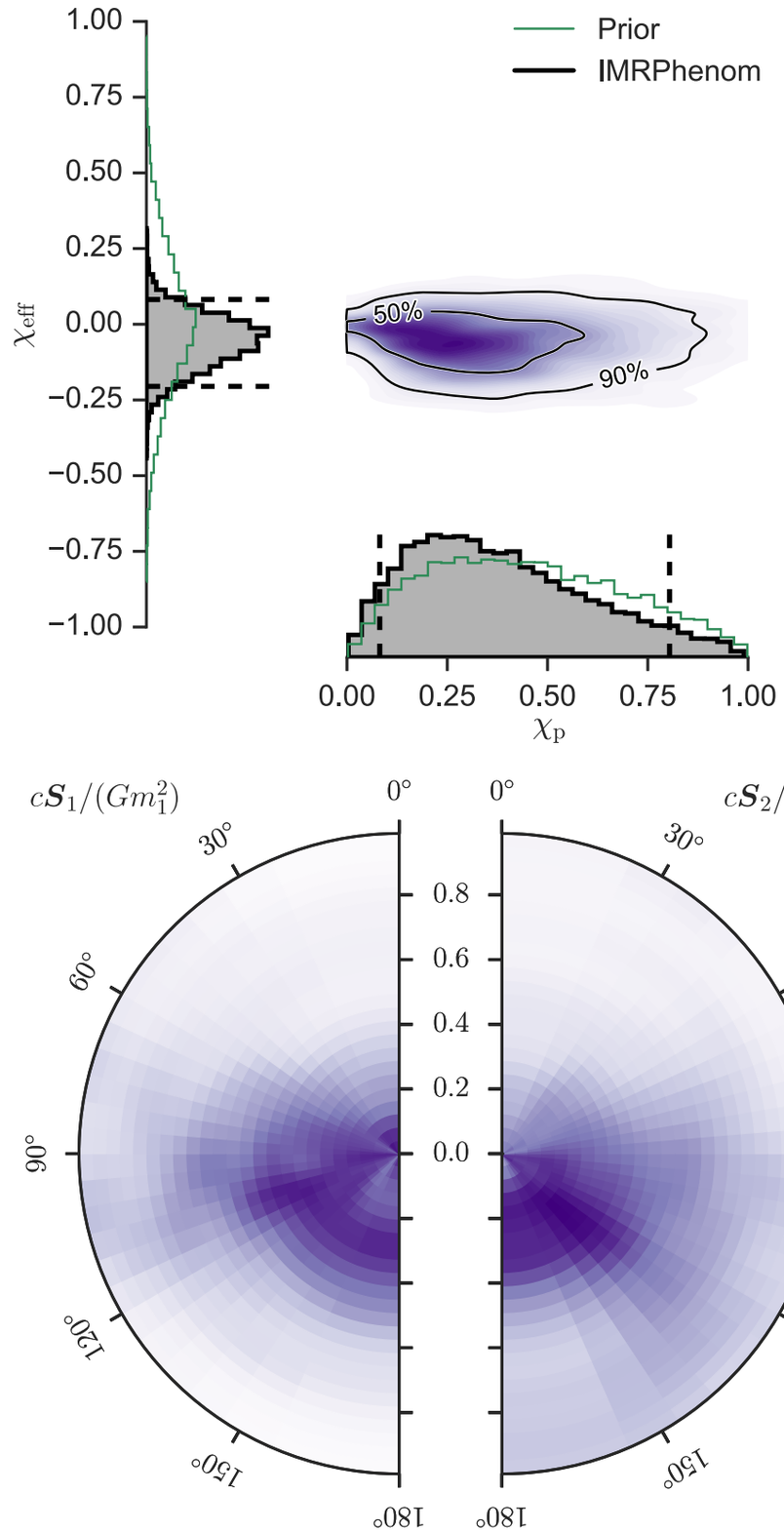

Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
80
40
20
10
5
EM Black Holes
EM Neutron Stars
2
1
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

GW150914 spin

- Spin affects the relativistic motion of the binary but has subtle influence on the waveform (extra/less cycles, modulation).

- The spin measurement for GW150914 suggests that the individual spins were either small, or they were pointed opposite from one another, cancelling each other's effect.

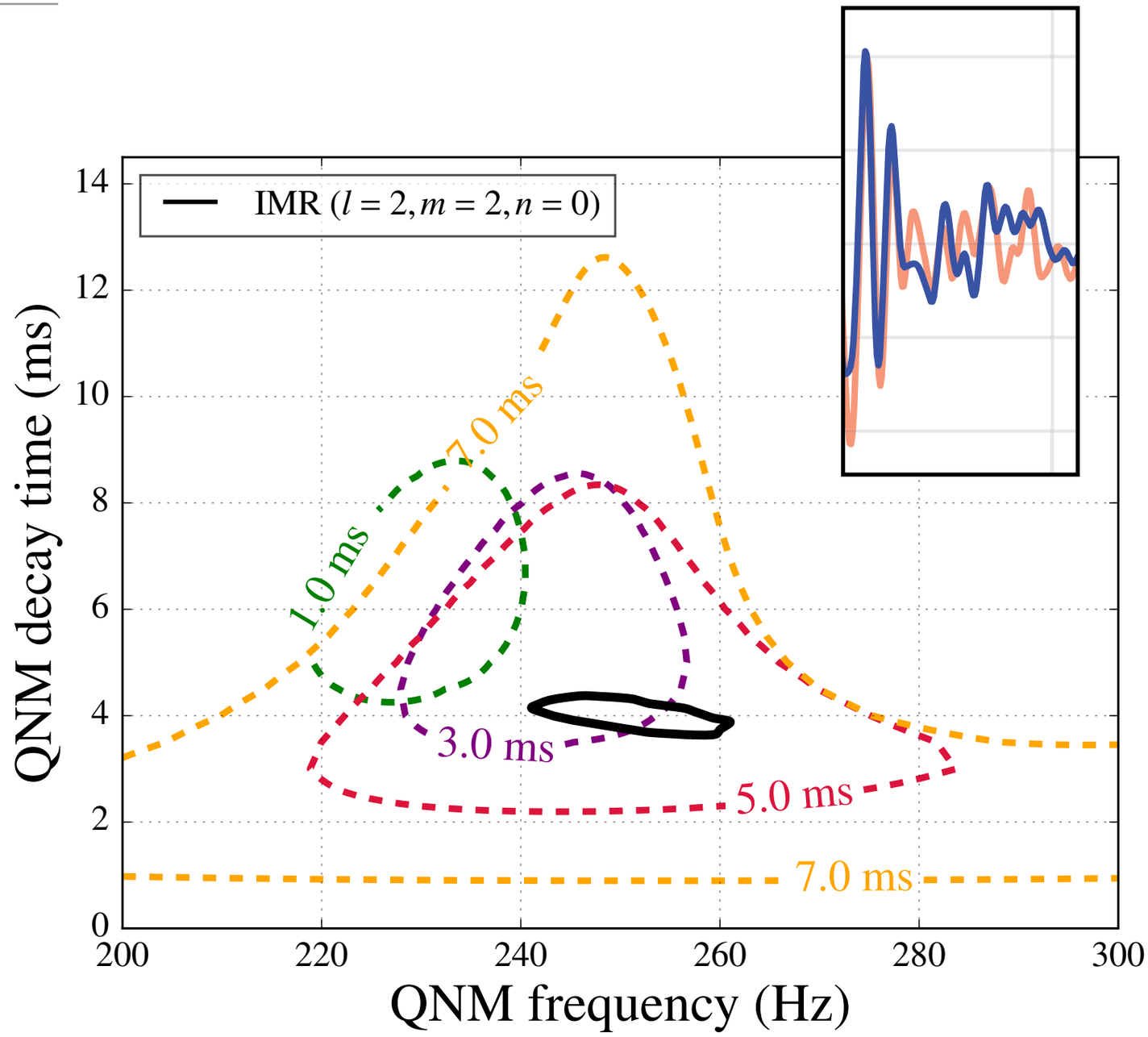
- Spin components in the orbital plane are poorly contained.



LIGO-Virgo Collaboration, arXiv:1602.03840 (2016)

Is general relativity right?

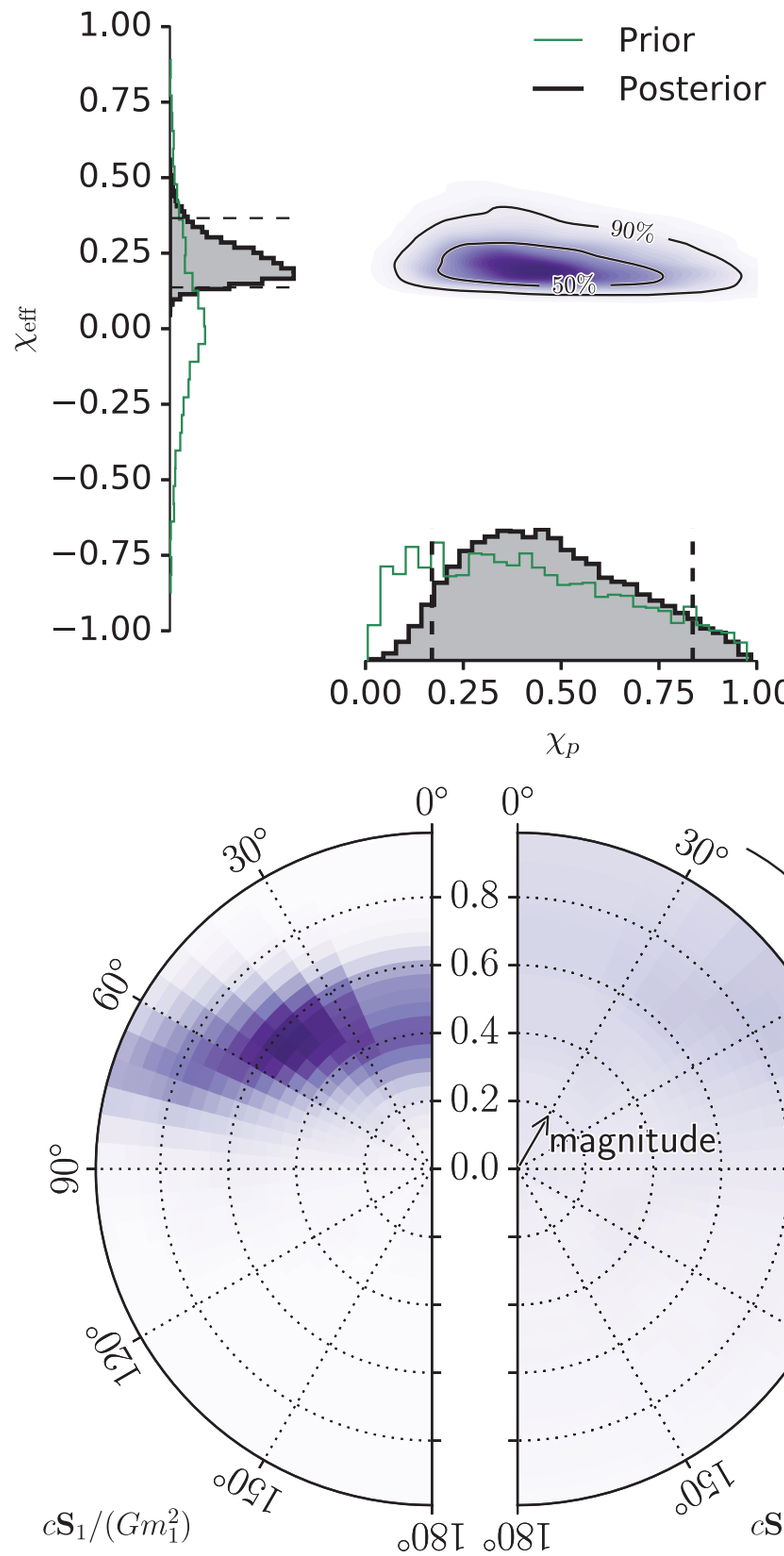
- We perform 3 main GR consistency tests.
- We test if the final mass and spin of the final black hole is consistent with predictions based on the inspiral.
- We test each post-newtonian expansion coefficient.
- We constrain the compton wavelength of the graviton to $<10^{13}$ km.
- **GR passes all tests**.



LIGO-Virgo Collaboration, arXiv:1602.03841 (2016)

GW151226 spin

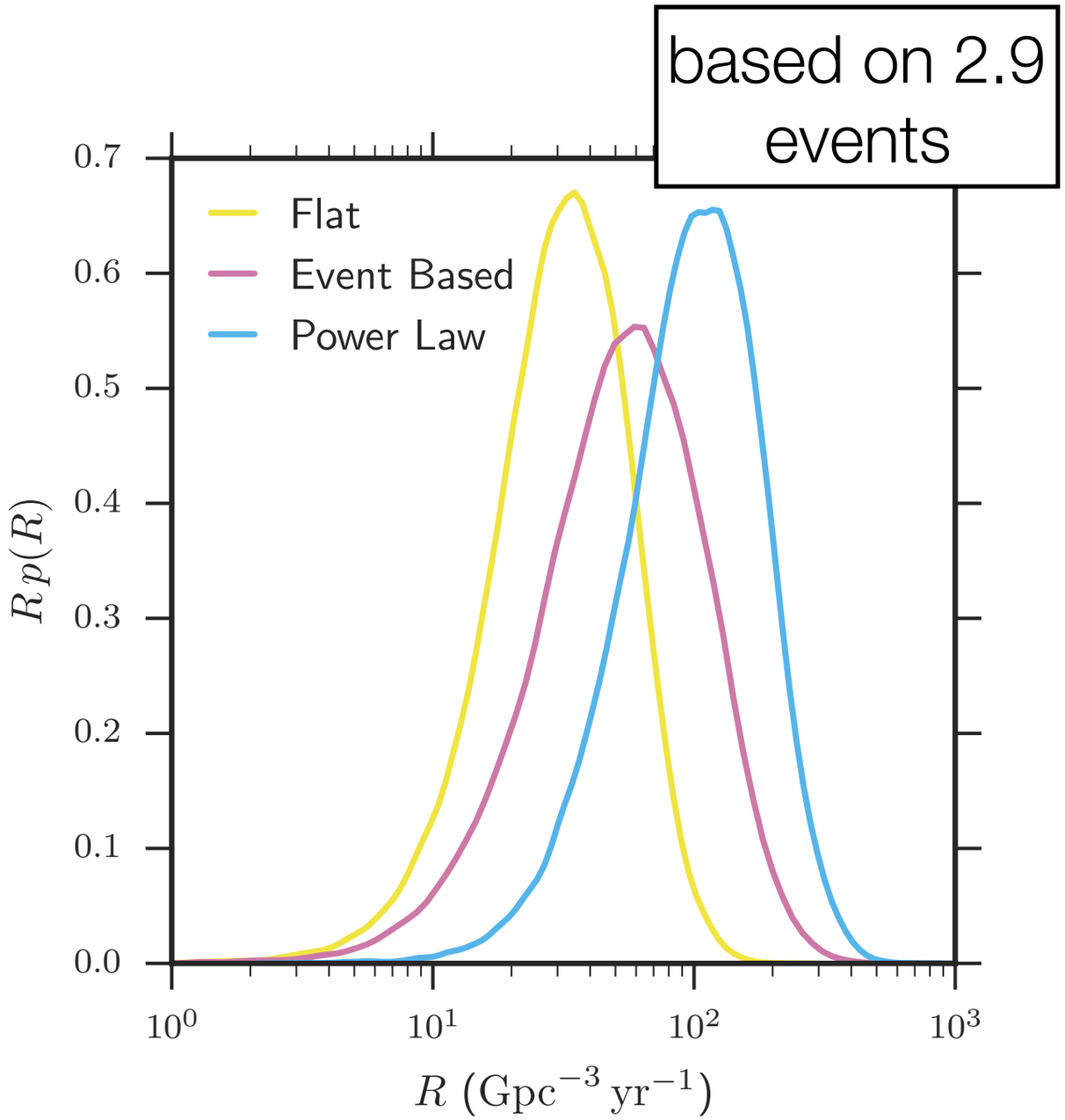
- At 99% confidence at least one of the components had non-zero spin.
- With 99% confidence we can also say the spin of that component was >0.2
- Again, the data are not informative regarding precession effects in the orbital plane.
- Spin can also give us an indication of the binary system formation mechanism.



LIGO-Virgo Collaboration, arXiv:1602.03840 (2016)

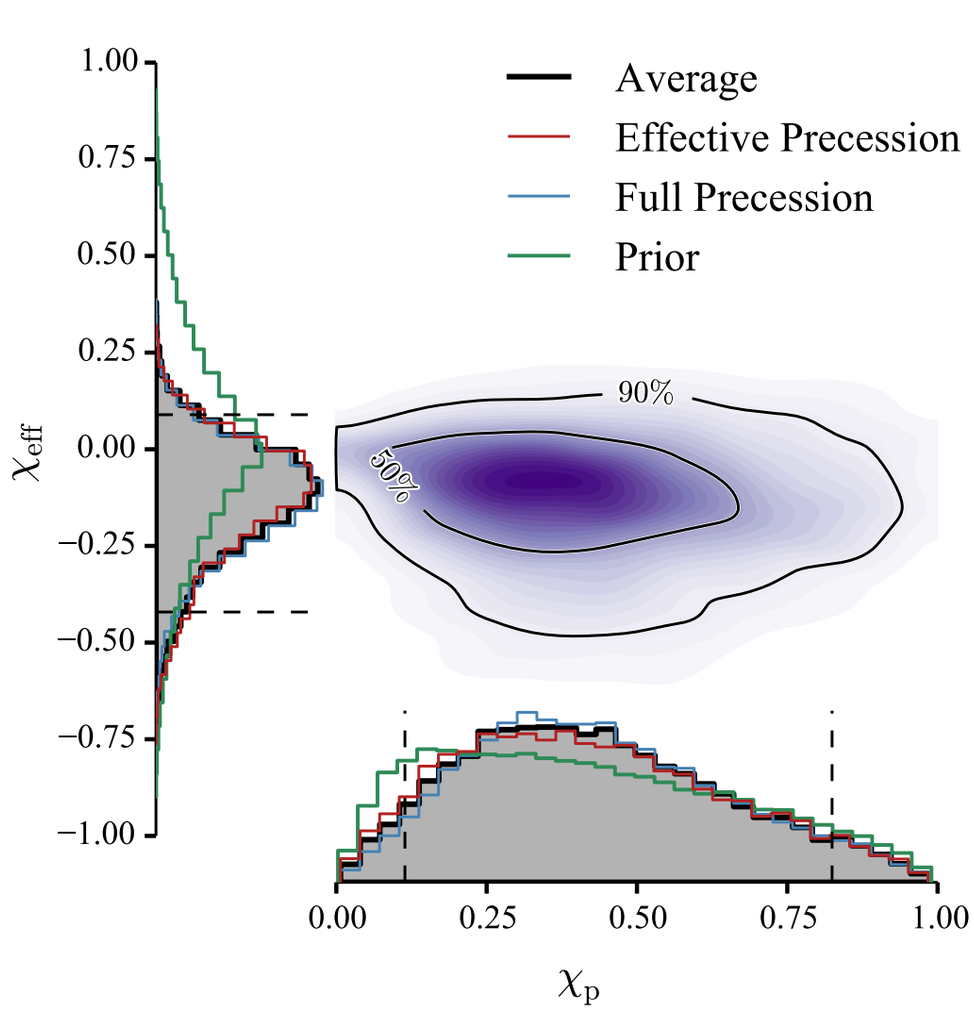
How common is this?

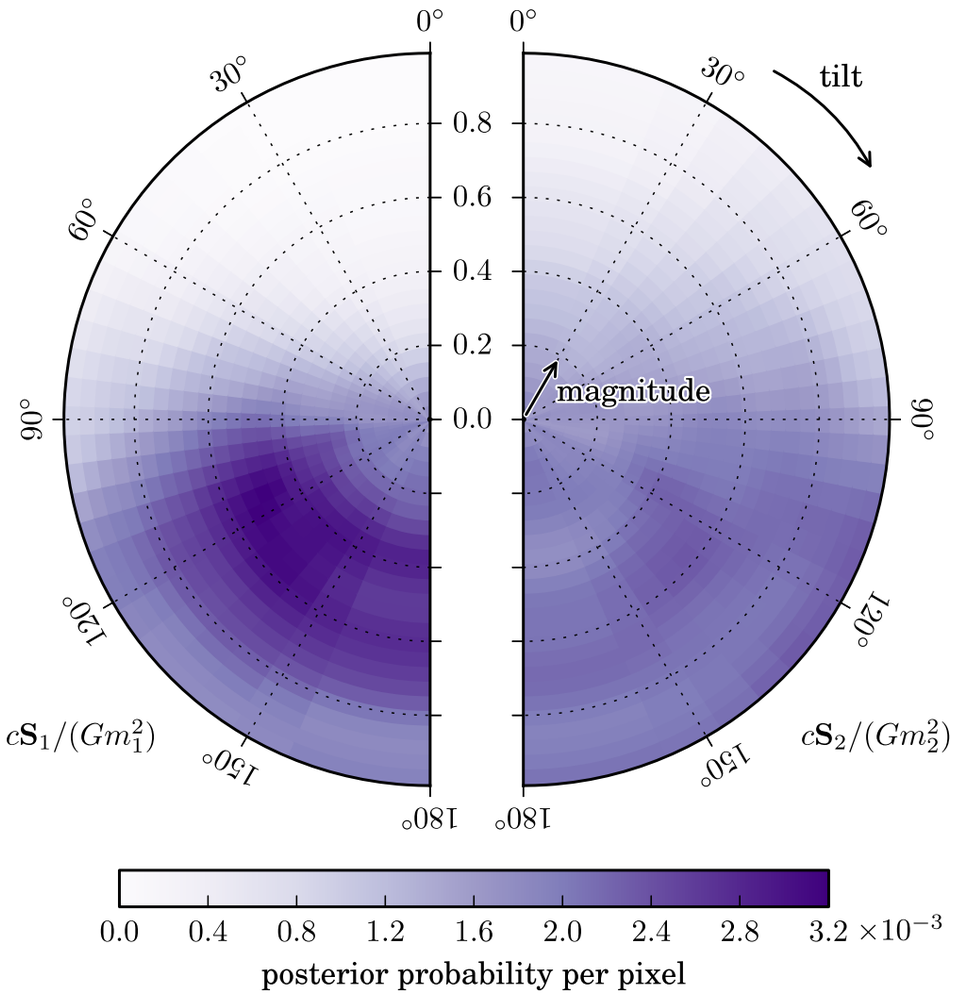
- We need to know how many events there are how sensitive our detectors were.
- We've only detected 6 event(s) (at present) and hence extrapolating the astrophysical event rate is hard.
- Uncertainties stem from Poisson counting noise, distance errors, calibration, and prior mass distributions.



LIGO-Virgo Collaboration, PRX **6**, 041015 (2016)

GW170104 spin

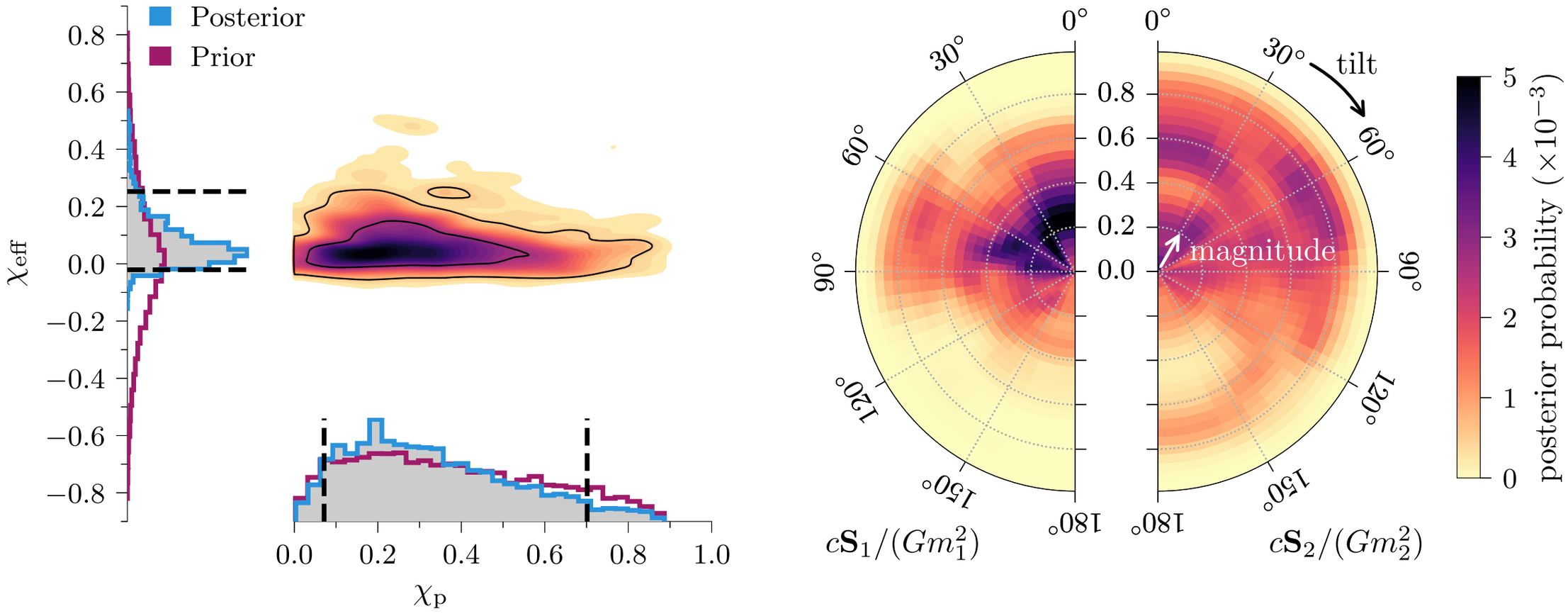




- The measurements disfavour a large total spin positively aligned with the orbital angular momentum, but do not exclude zero spins.

LIGO-Virgo Collaboration, PRL **118**, 221101 (2017)

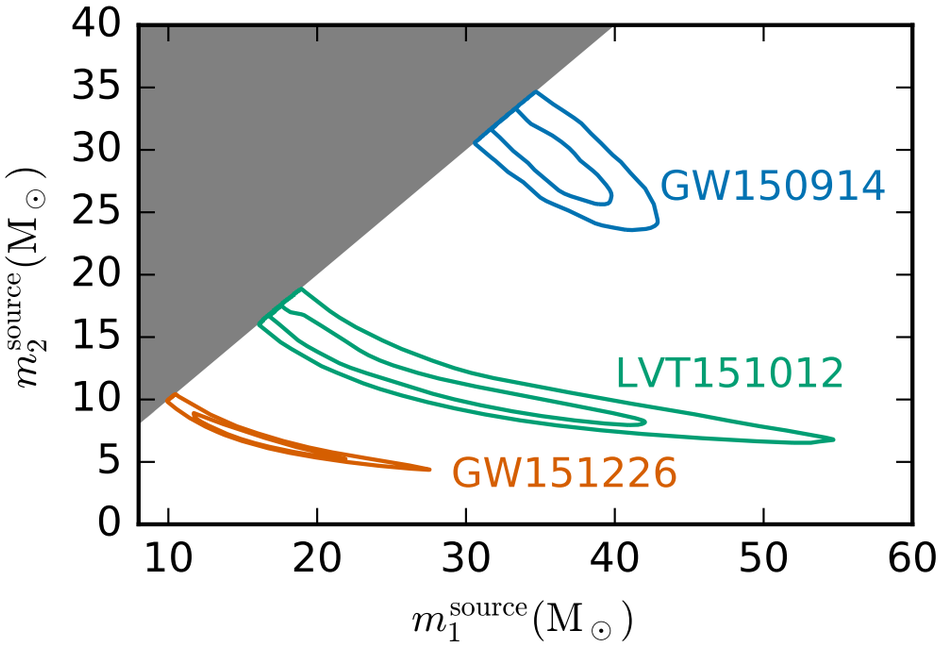
GW170608 spin

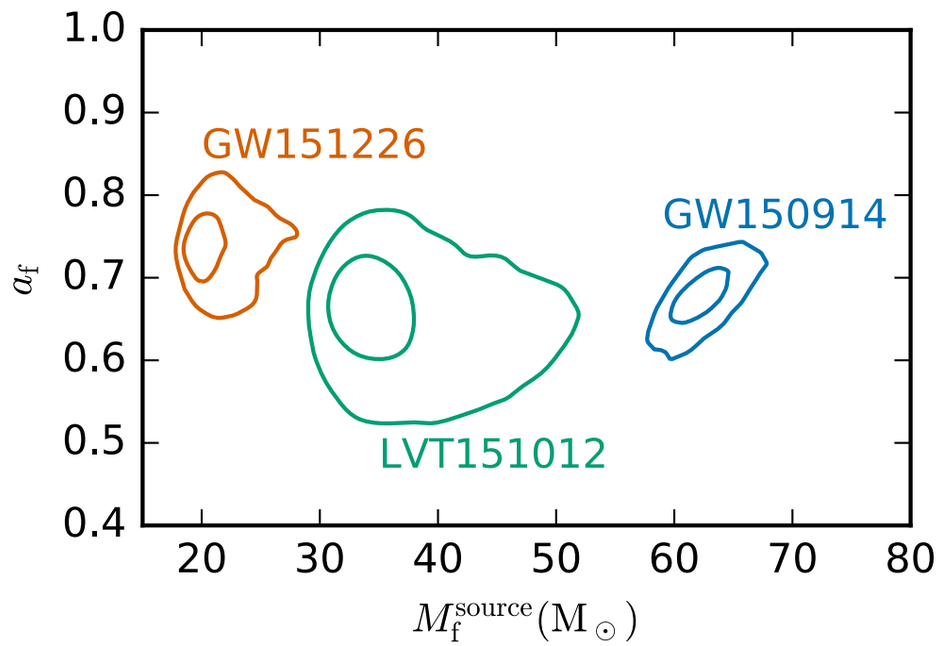


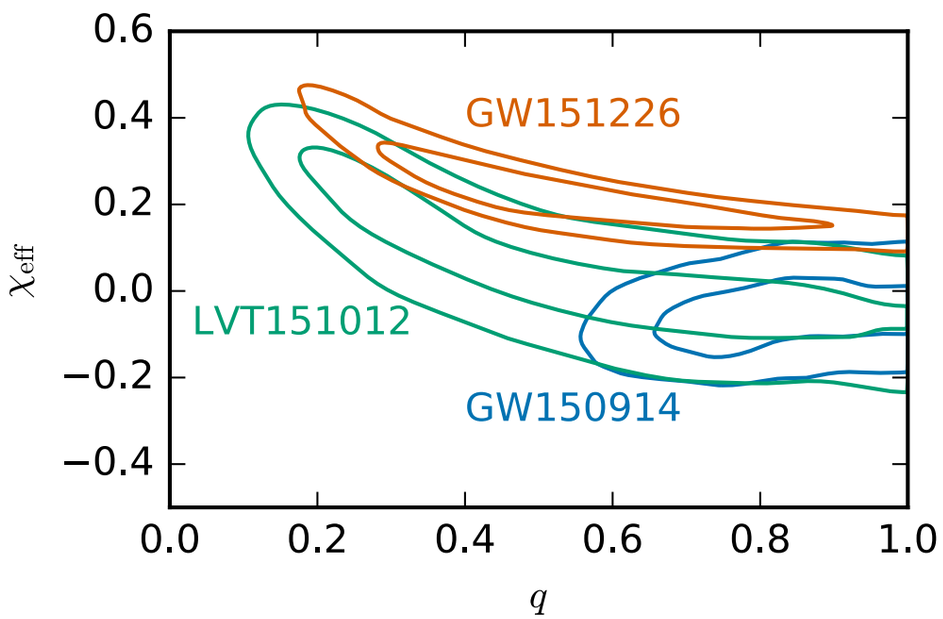
- In this case the data constrains the total effective spin to be small and likely positive. As with the others sources, we are insensitive to in-plane spin.

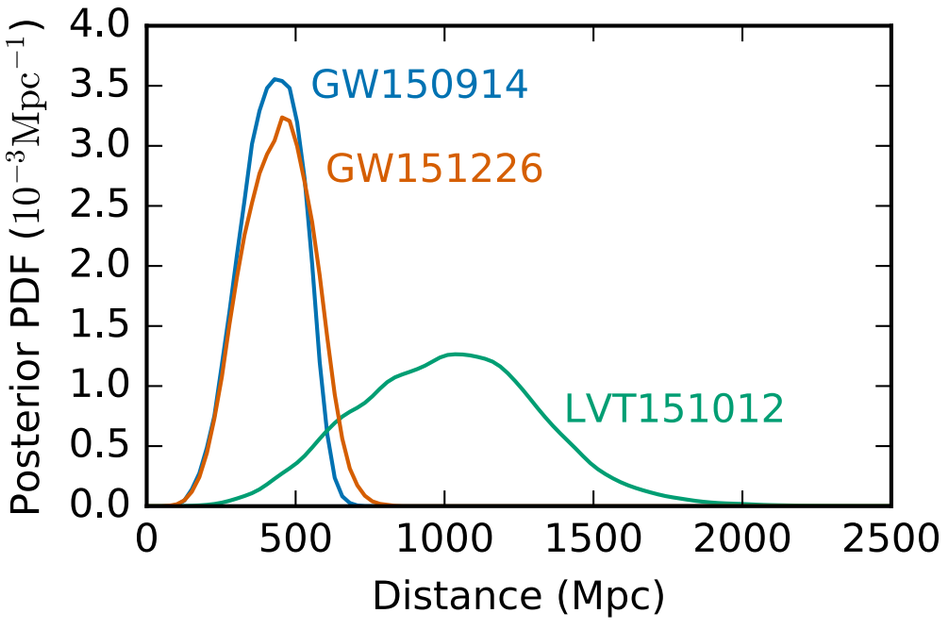
LIGO-Virgo Collaboration, ApJ Lett., 851, L35, (2017)

Source properties





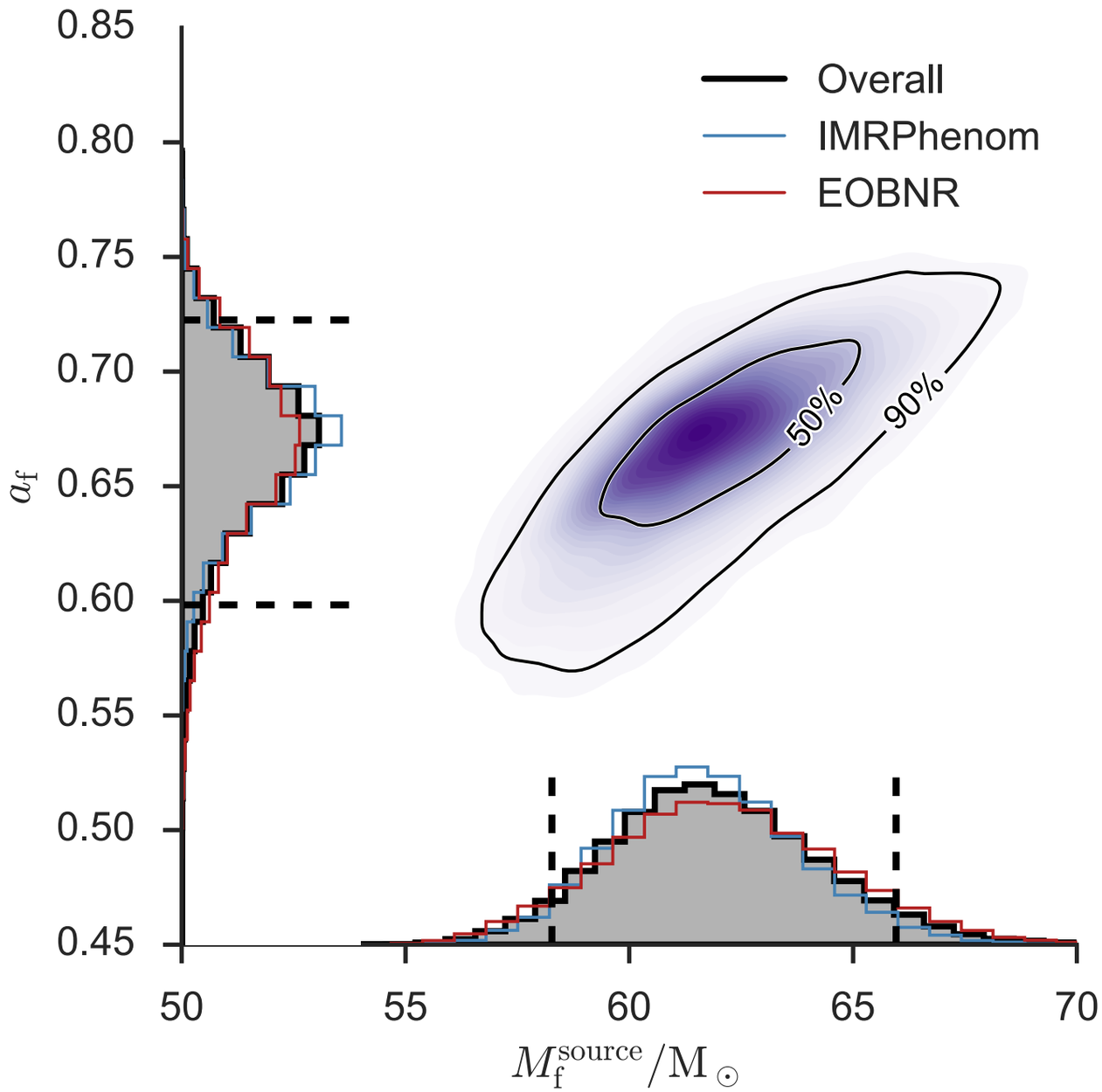




LIGO-Virgo Collaboration, PRX **6**, 041015 (2016)

What about the final black hole?

- The final black hole has a mass of 3 $M_\odot$ less than the sum of its components.
- It has a well constrained final spin of ~0.7.
- This is due to the fact that the final spin is mostly a function of the orbital angular momentum at merger.



LIGO-Virgo Collaboration, arXiv:1602.03840 (2016)