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

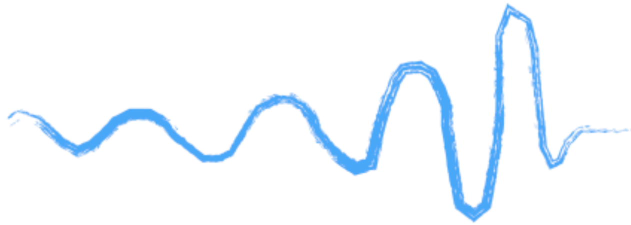
interspersed throughout are tutorial slides including some based on “The basic physics of the binary black hole merger GW150914” LIGO-Virgo Collaboration, arXiv:1608.01940 (2016)

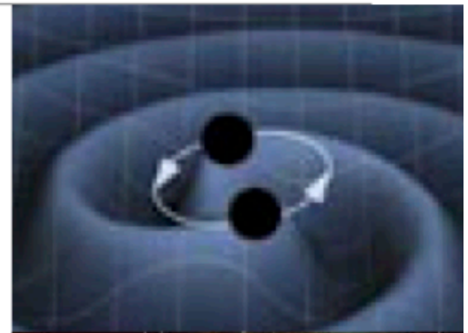
Gravitational wave basics

Just to warm you up

Astrophysical source types

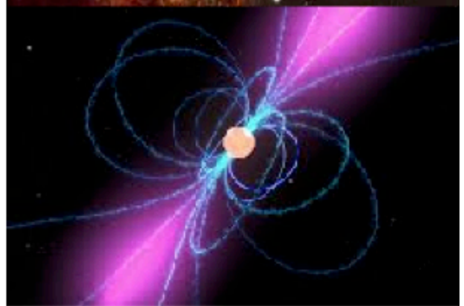
compact binary
coalescence



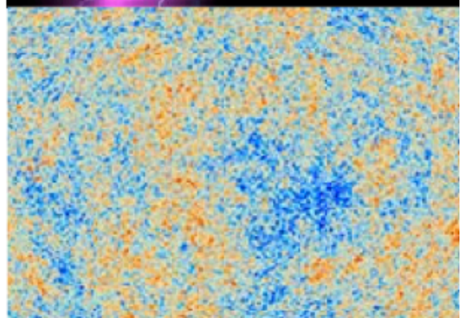


burst

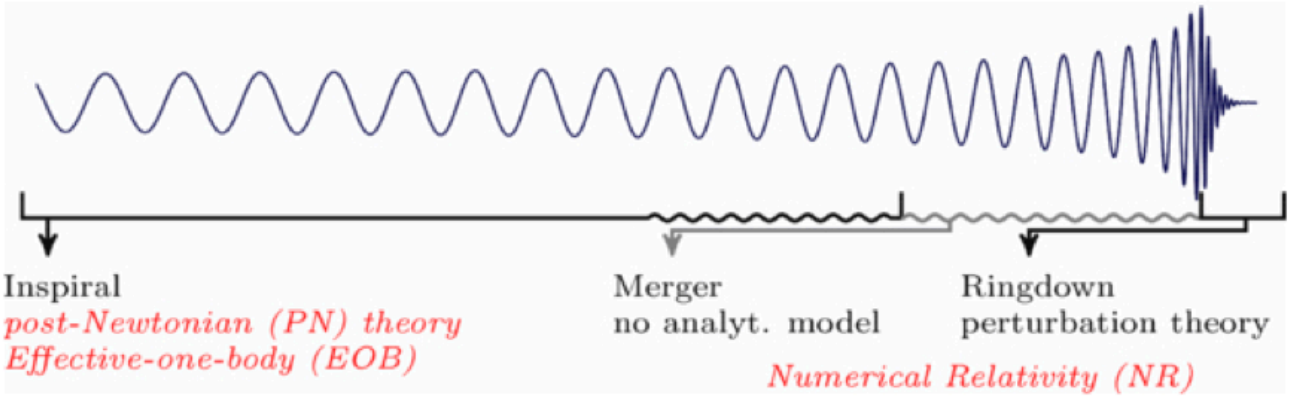
continuous

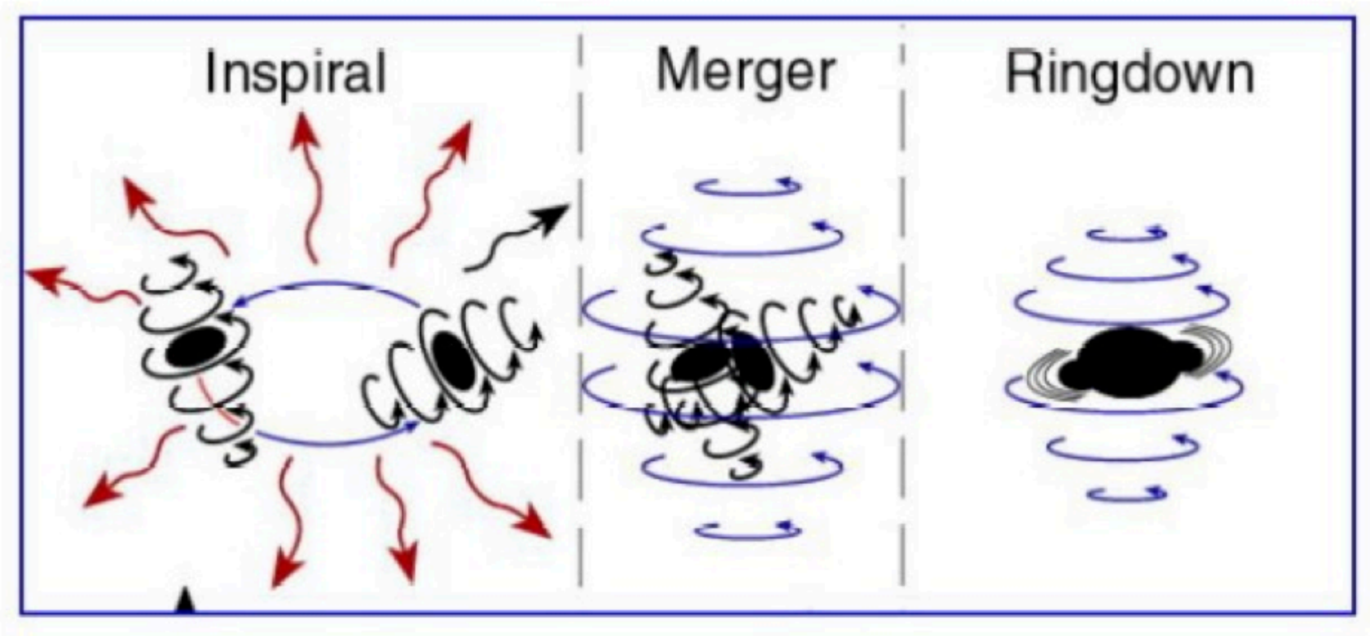


stochastic



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

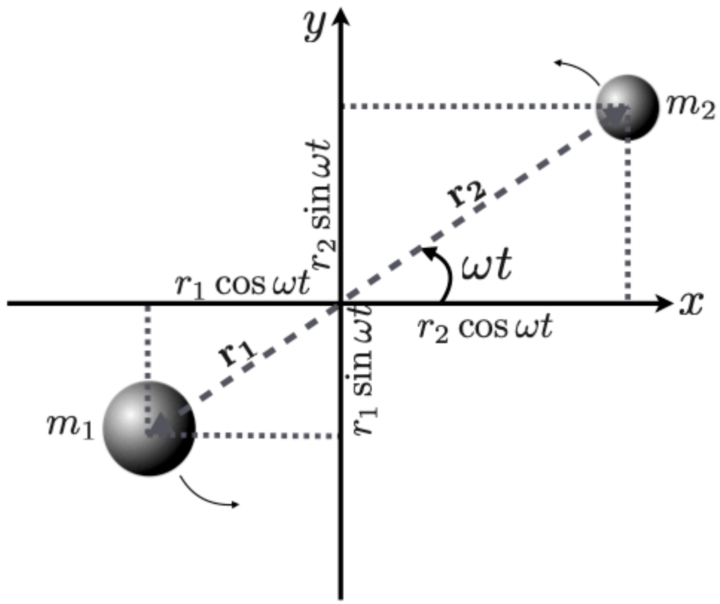
$$I_{xx} = \cos(2\omega t) + \tfrac{1}{3},\ I_{yy} = \tfrac{1}{3} - \cos(2\omega t),\ I_{xy} = I_{yx} = \sin(2\omega t) \ \text{and}\ I_{zz} = -\tfrac{2}{3}$$

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

- 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

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

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

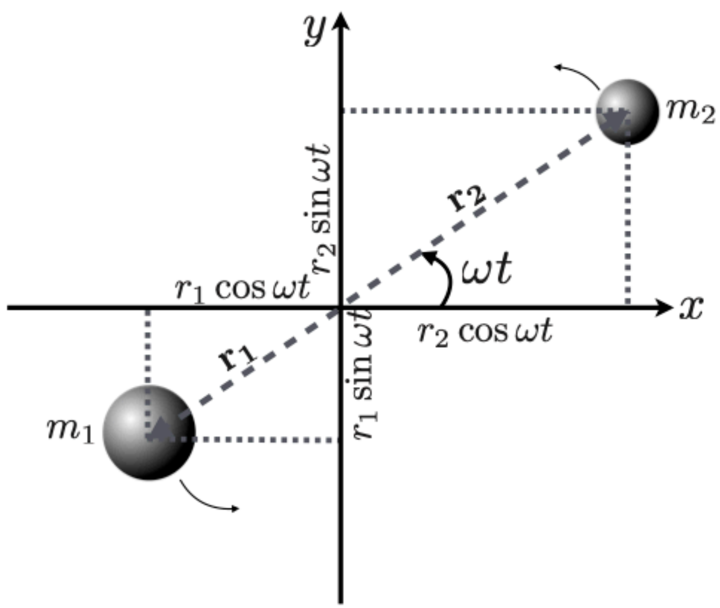
- This drains the orbital energy

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

- 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

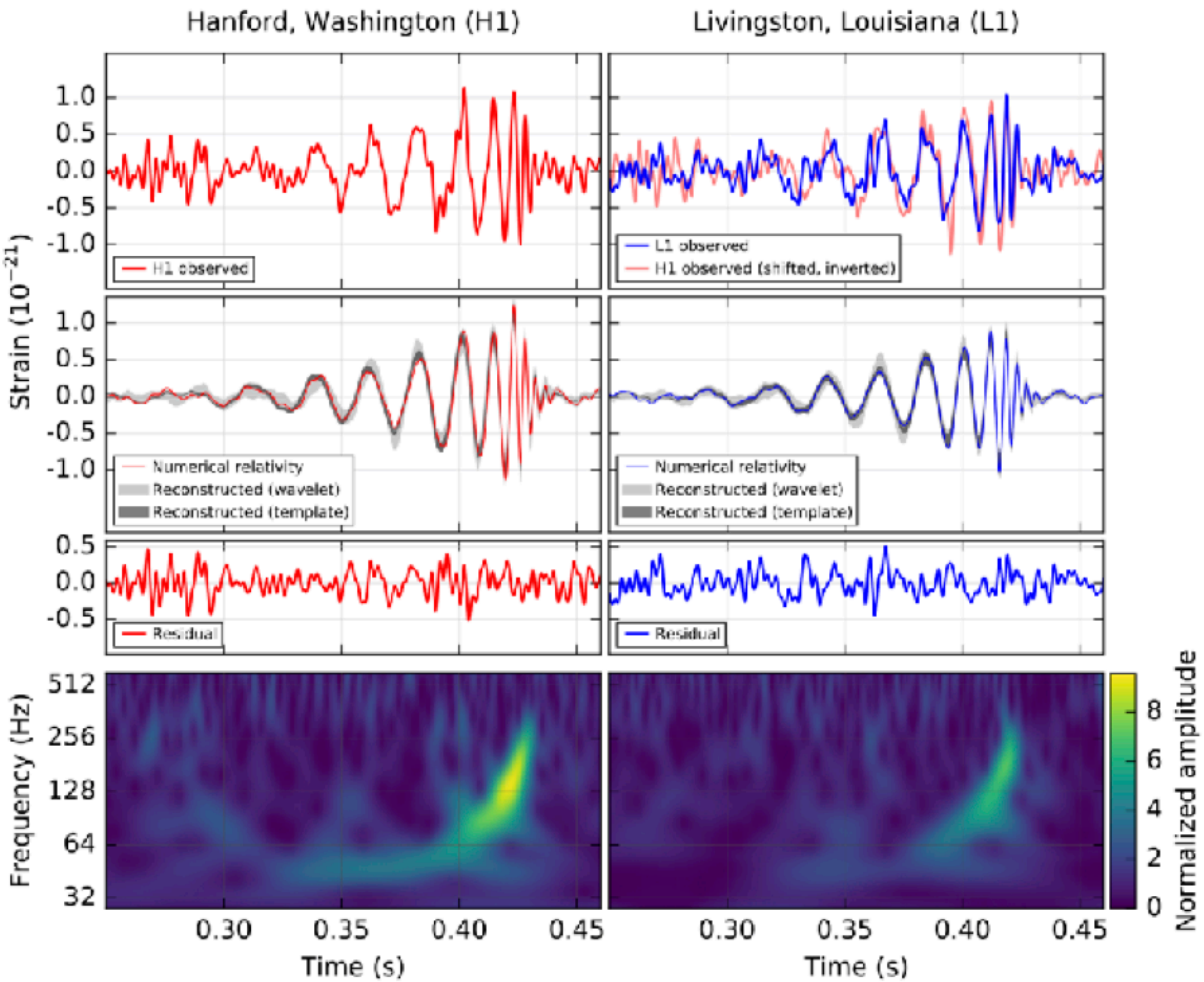


LIGO-Virgo Collaboration, arXiv:1608.01940 (2016)

The 1st detection

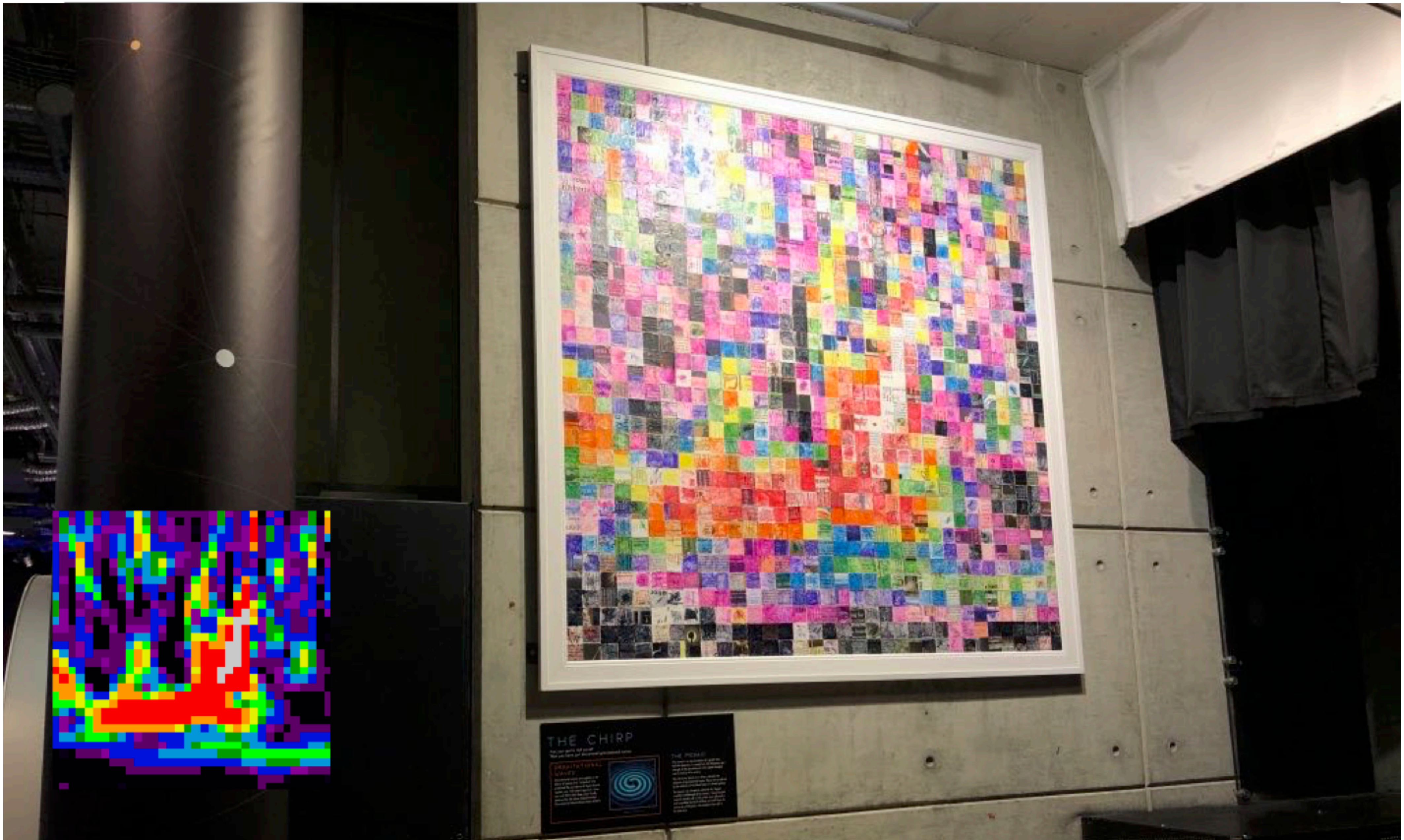
GW150914

The data



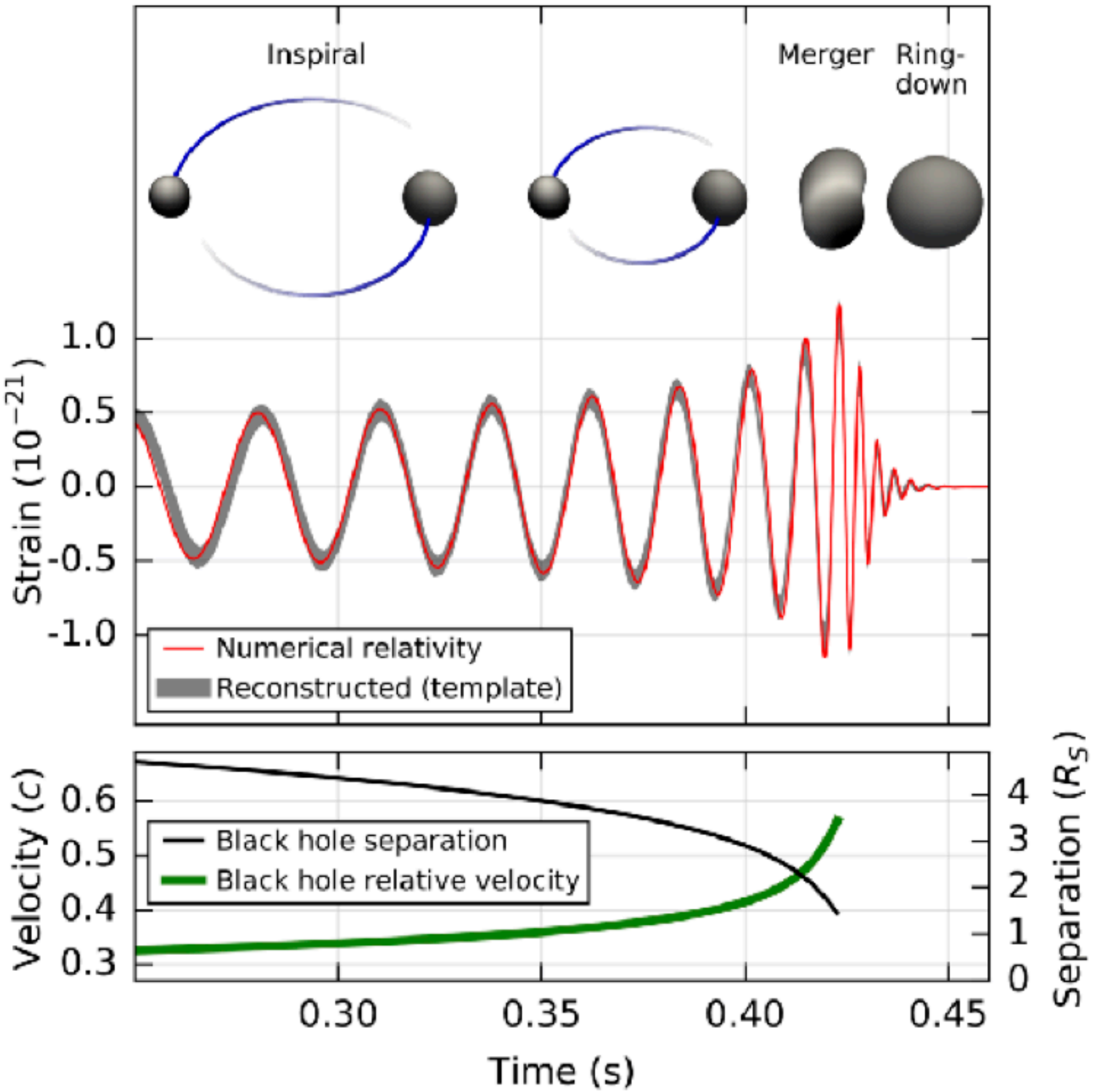
LIGO-Virgo Collaboration, PRL **116**, 061102 (2016)

The data



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)

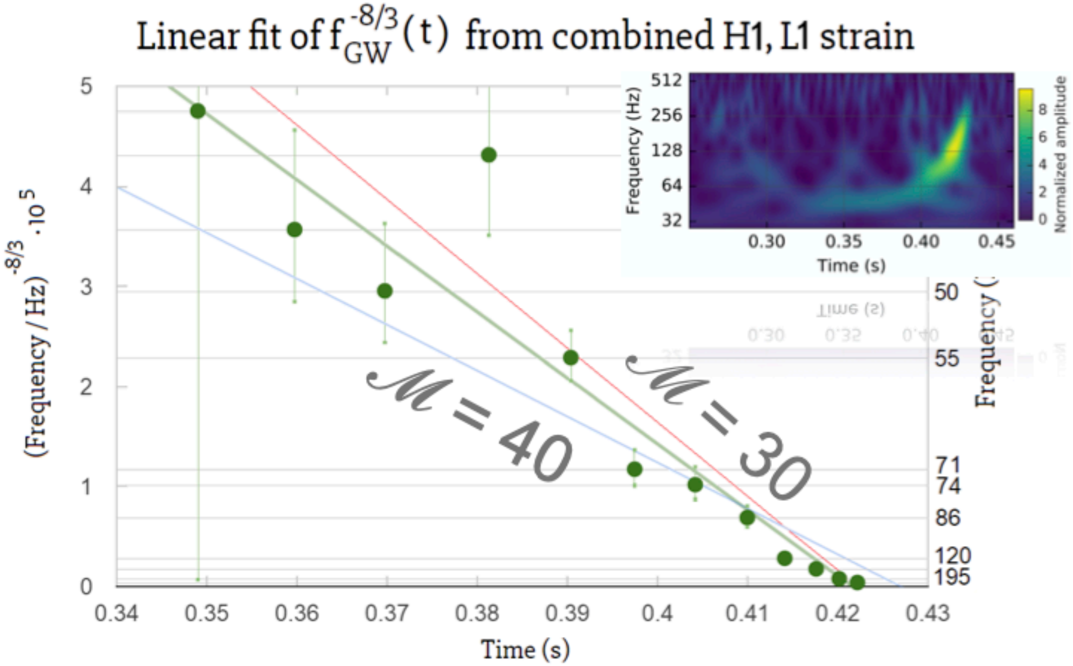
The mass scale

- We can rearrange the expression for frequency evolution to give

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

- Then integrate to obtain

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



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

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

LIGO-Virgo Collaboration, arXiv:1608.01940 (2016)

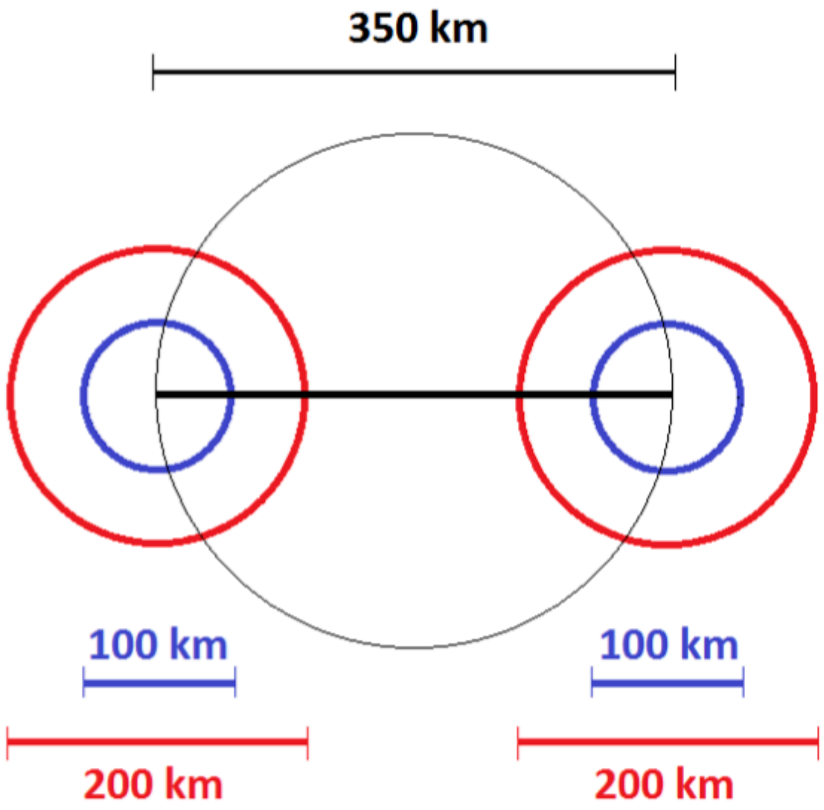
Proving compactness

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

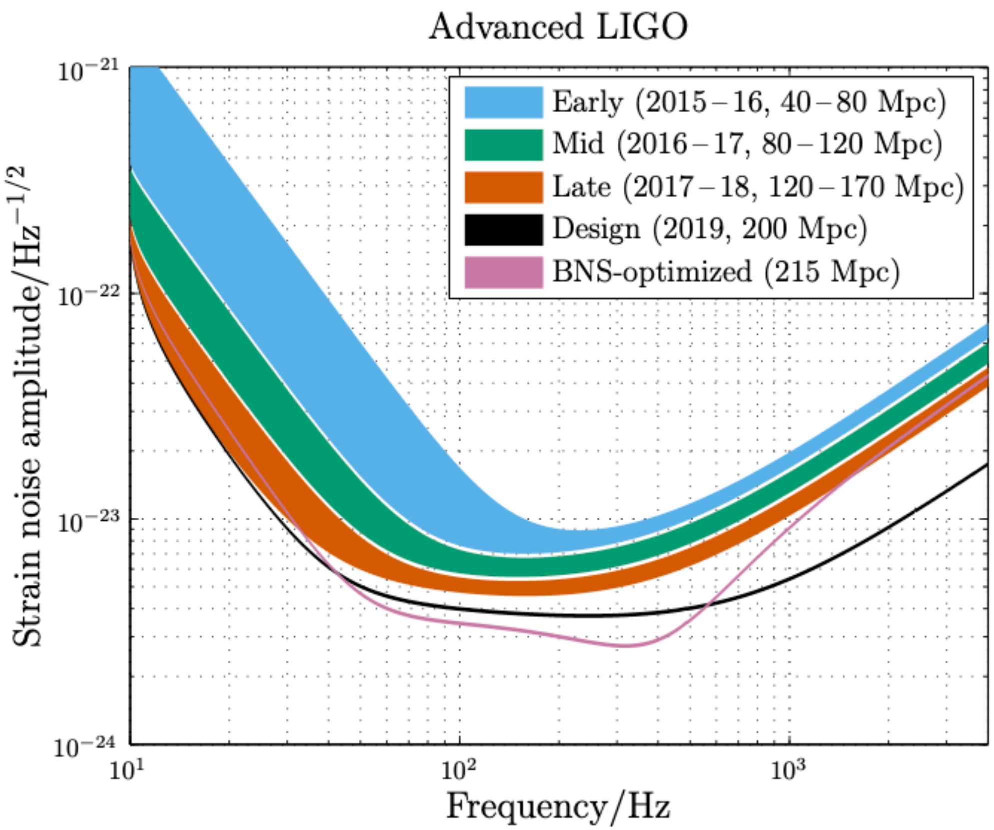
LIGO-Virgo Collaboration, arXiv:1602.03844 (2016)

The rest of the 1st observing run (O1)

GW151012 (formerly LVT151012), and GW151226

The O1 run (Sep 2015 - Jan 2016)

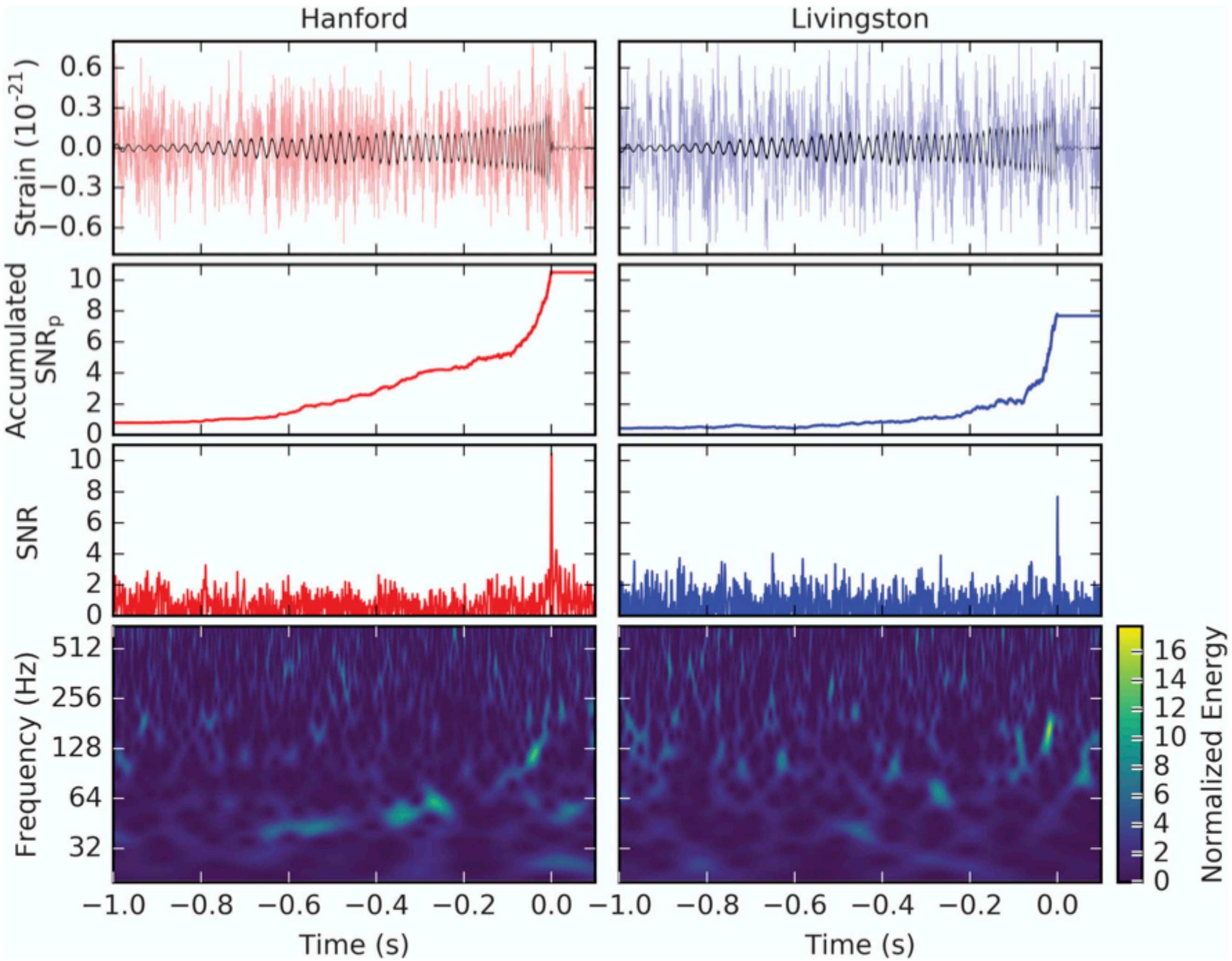
- Initial LIGO and Virgo successfully completed their operations with the S6/VSR2,3 runs in 2011.
- Advanced LIGO began operation in September 2015 with the first “Observing” run O1 spanning 12th Sep - 19th Jan.
- This accumulated 51.5 days of coincident data.



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

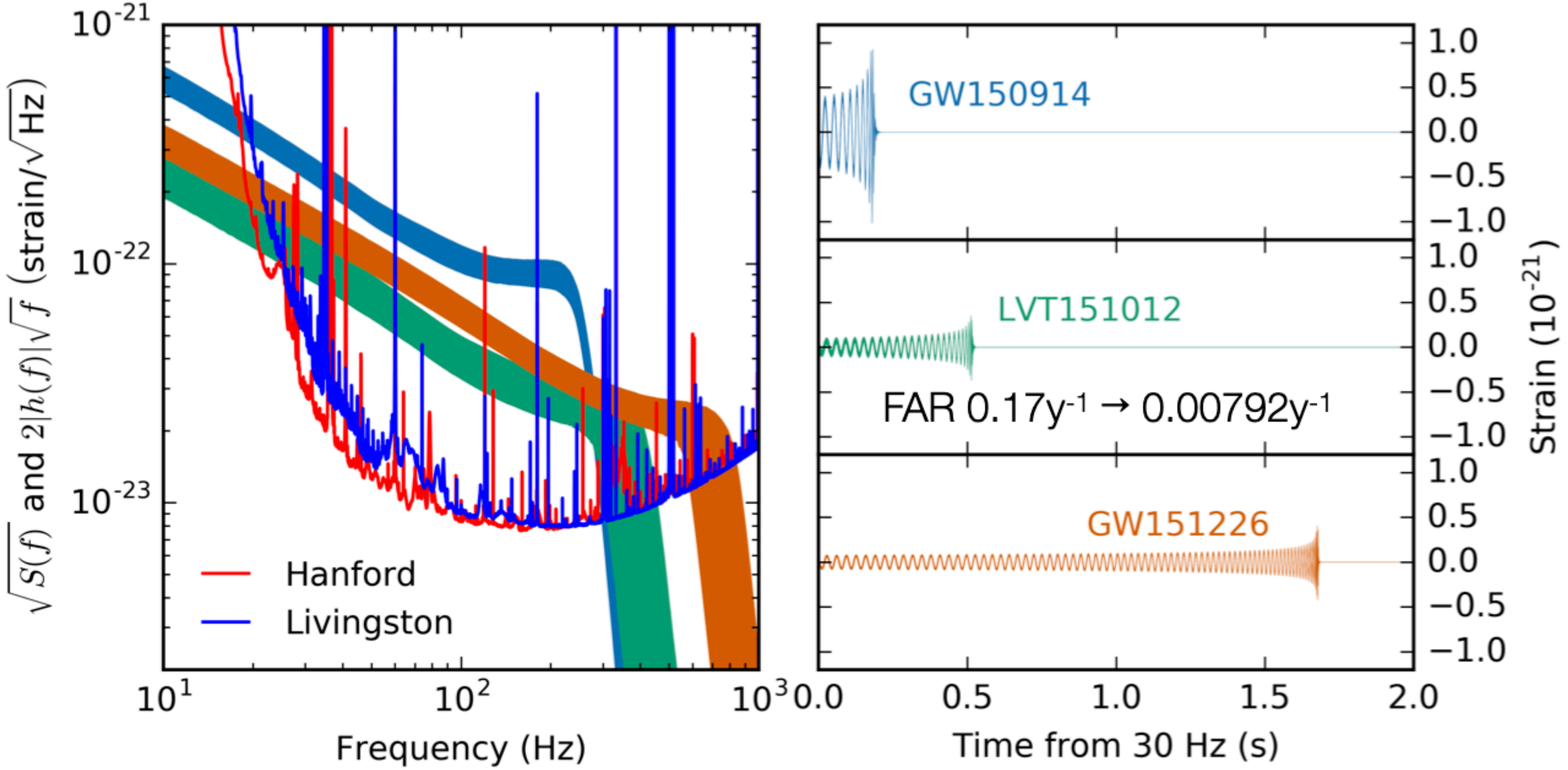
GW151226 (Boxing Day event)

3rd



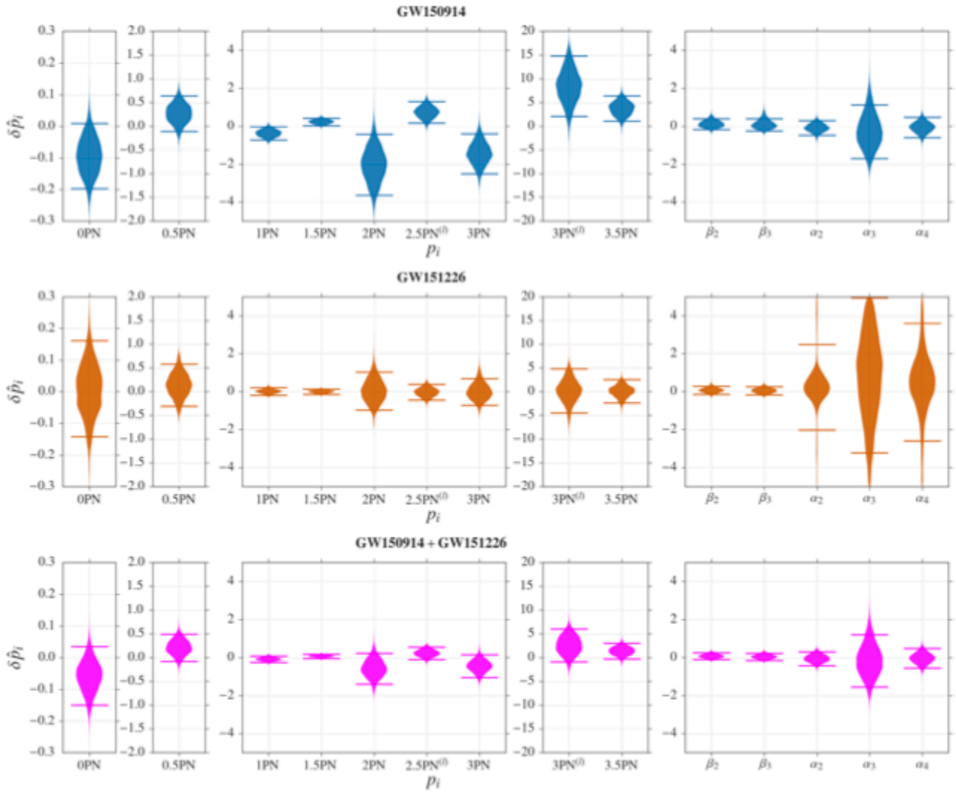
LIGO-Virgo Collaboration, PRL **116**, 241103 (2016)

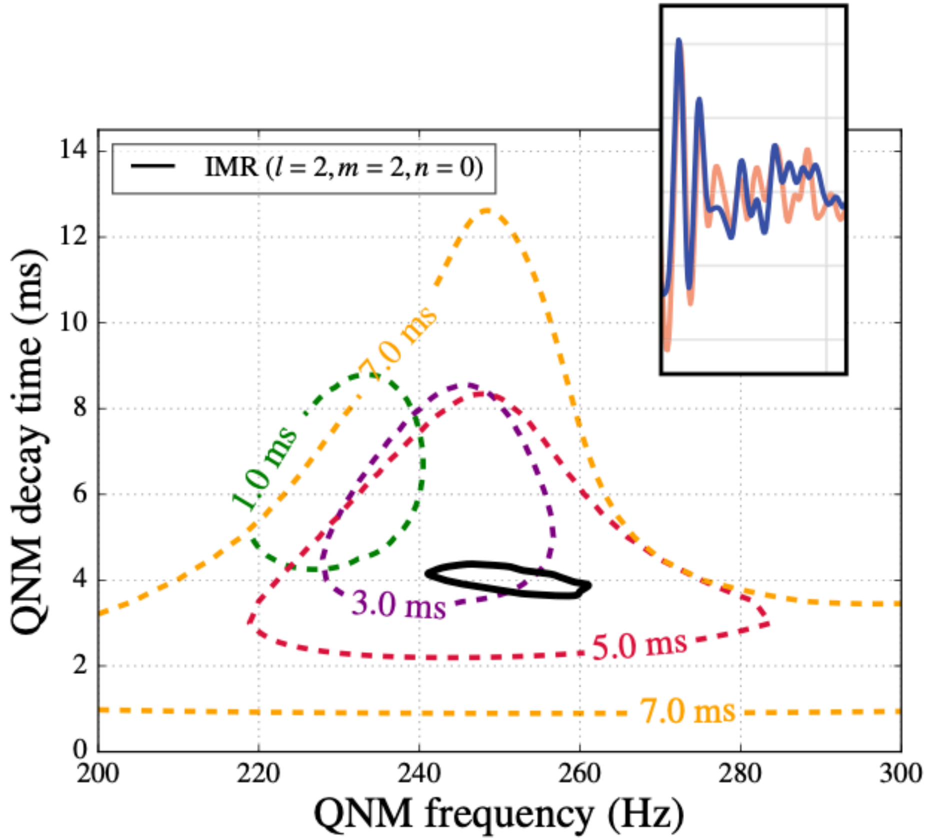
O1 Waveform comparison



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

Is general relativity right?

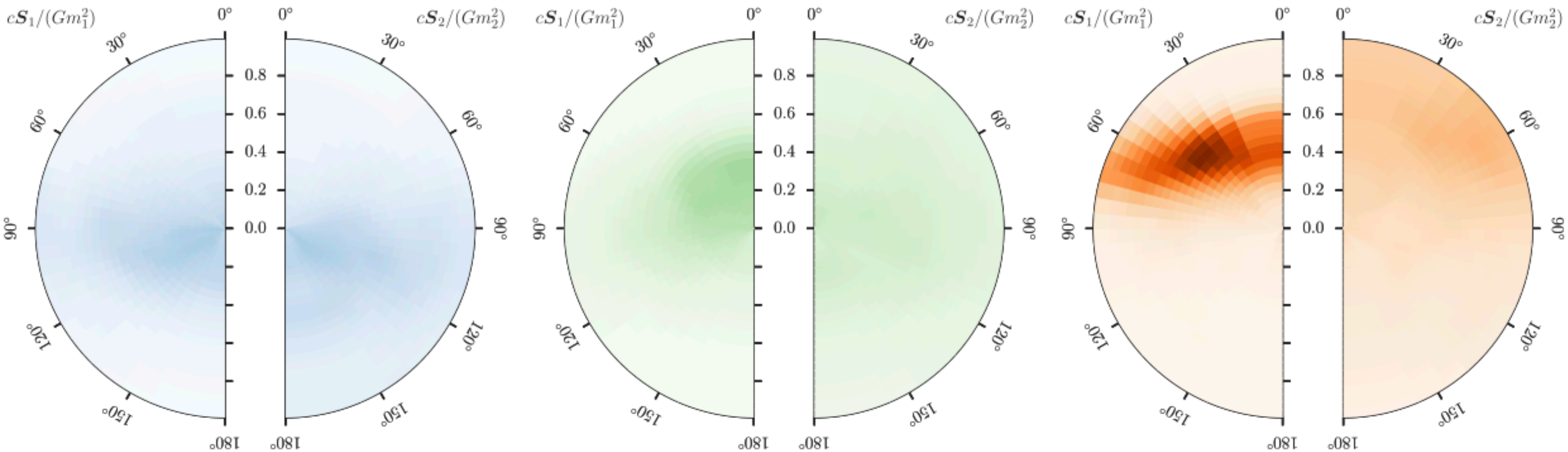




LIGO-Virgo Collaboration, PRX **6**, 041015 (2016)

O1 Spins

GW150914 GW151012 GW151226



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

The 2nd observing run (O2)

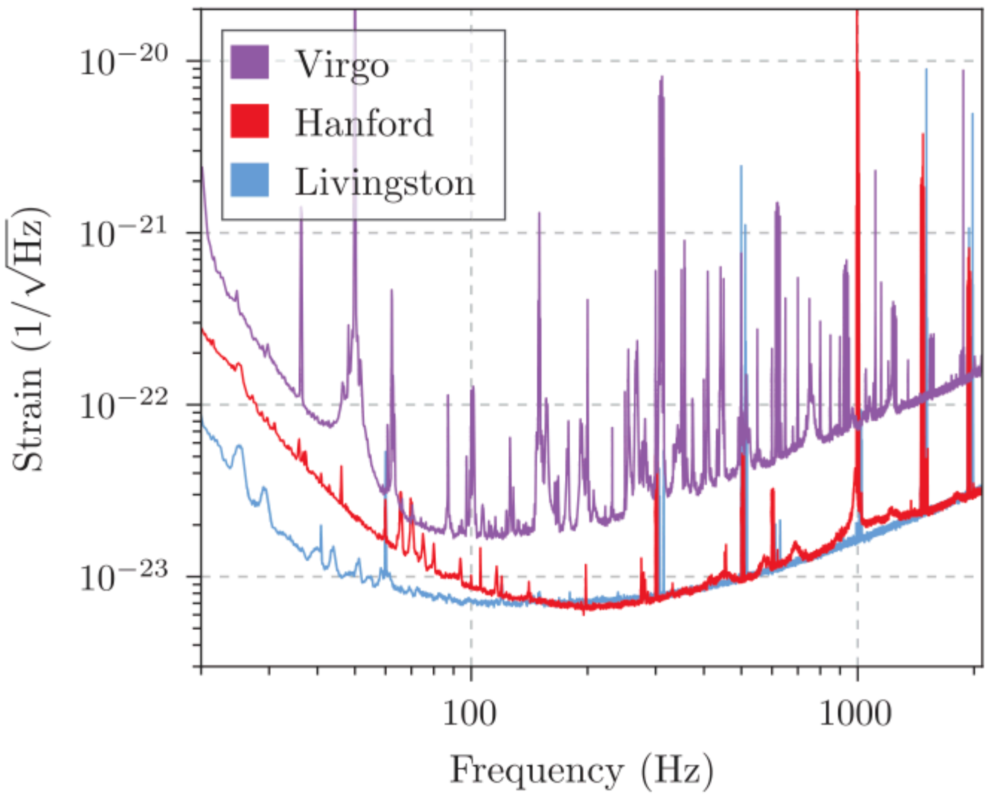
[ONLINE] GW170104, GW170608, GW170814, (the BNS GW170817),

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

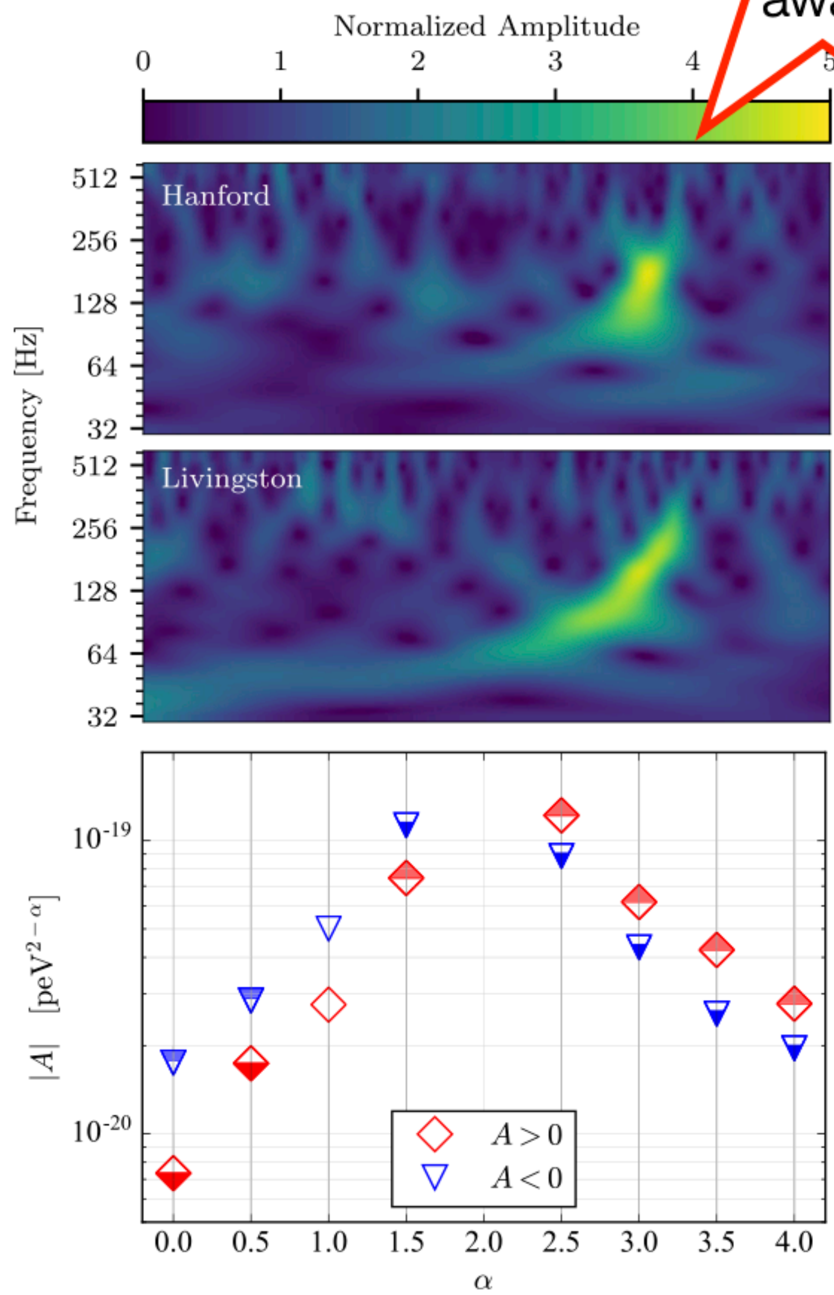
Far away

- 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

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

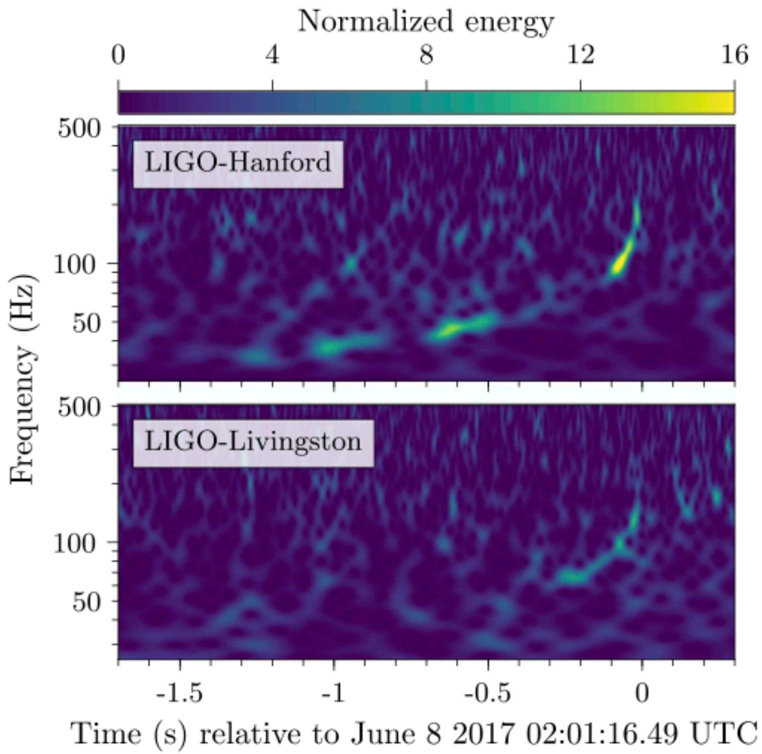


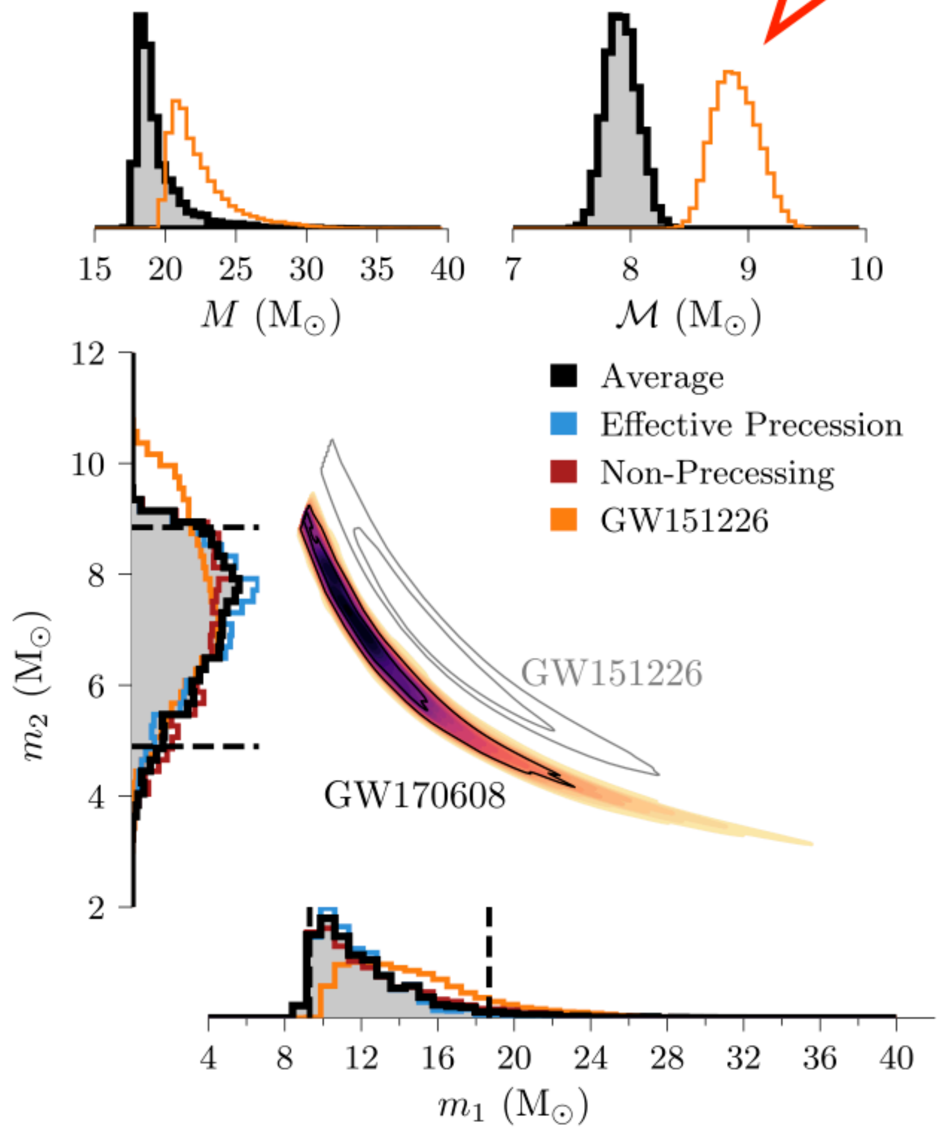
LIGO-Virgo Collaboration, PRL **118**, 221101 (2017)

GW170608

light

- 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.

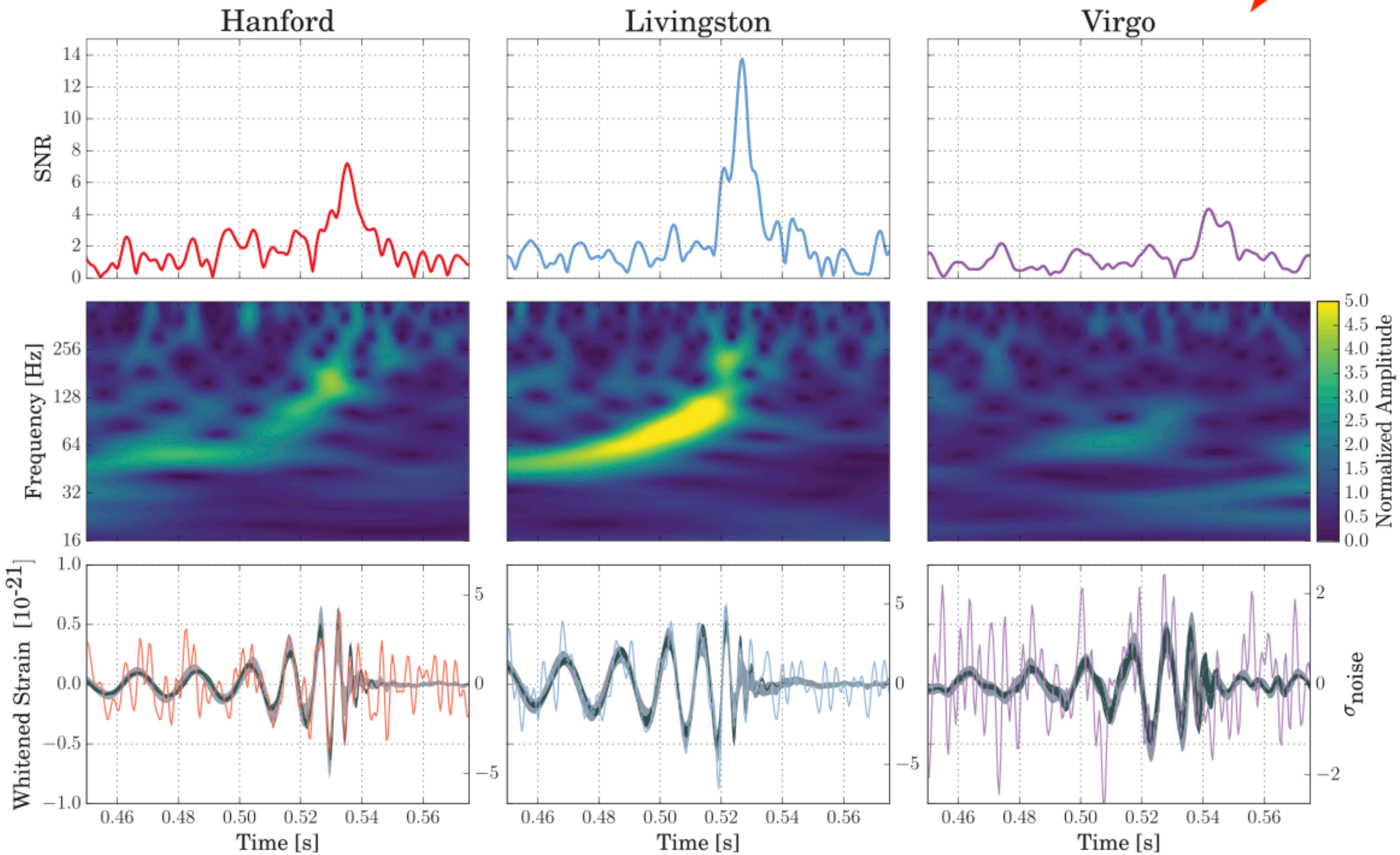




LIGO-Virgo Collaboration, ApJ Lett., 851, L35, (2017)

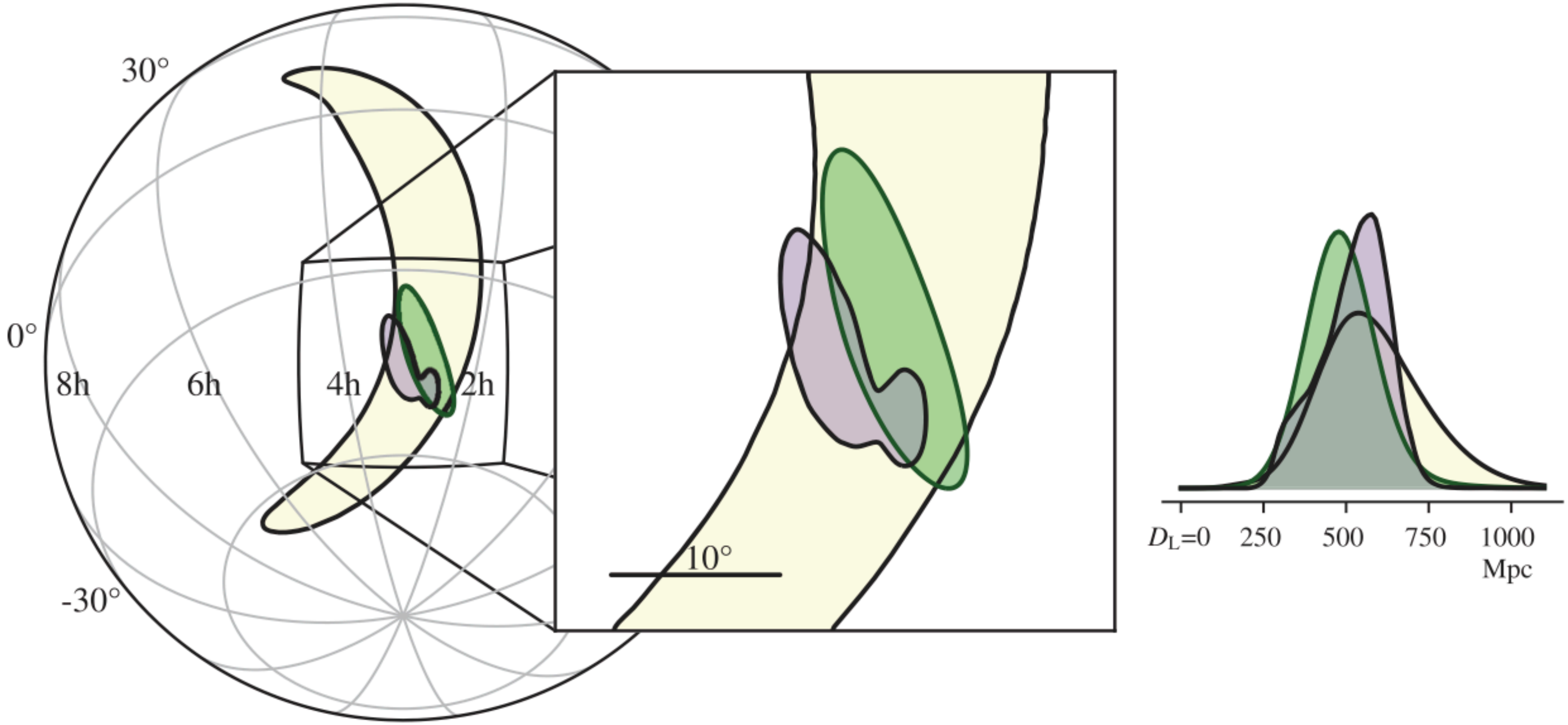
GW170814

LIGO & Virgo



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

GW170814

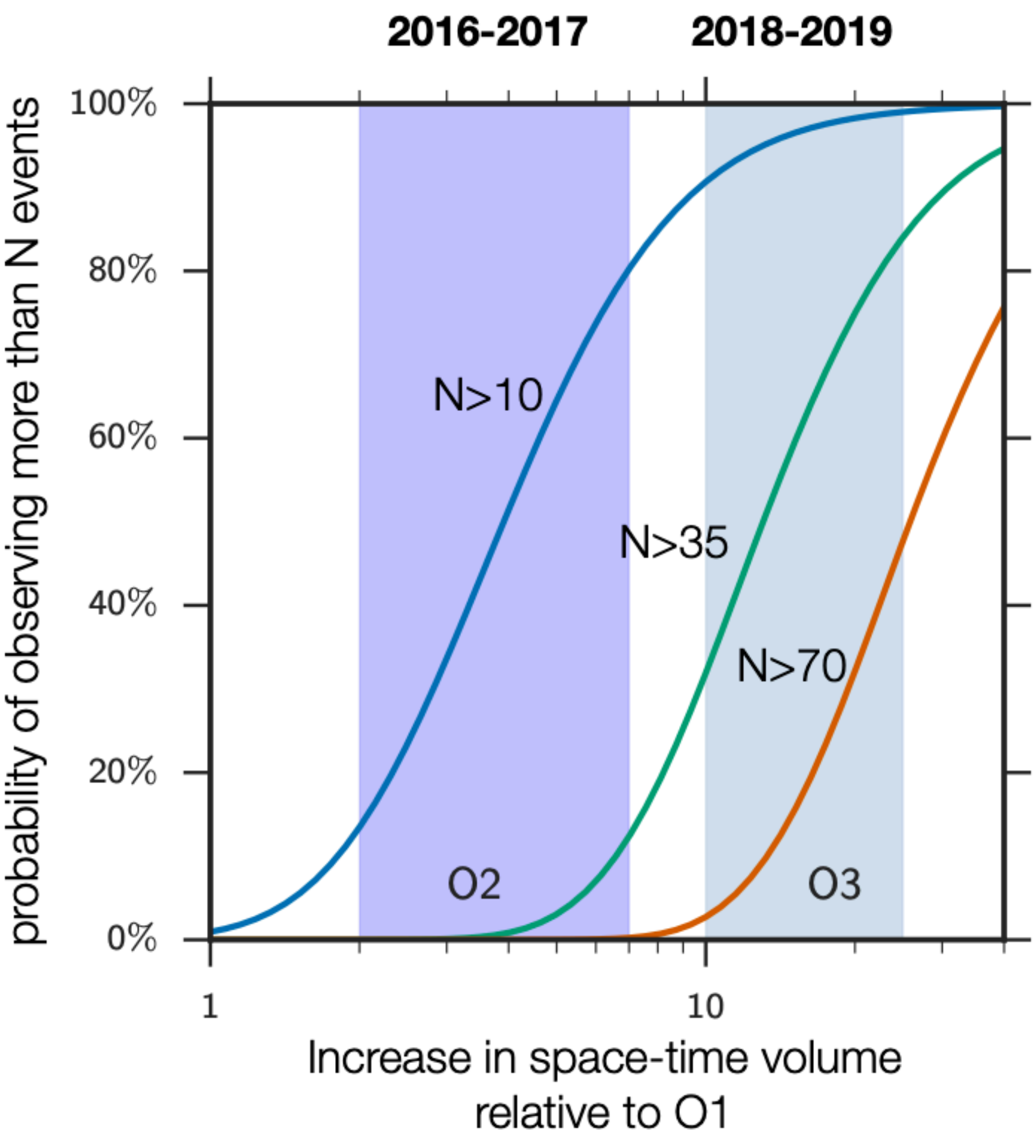


- This event had component masses of 31 and 19 $M_{\odot}$.
- This event was at redshift 0.2 and had SNR 13.

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

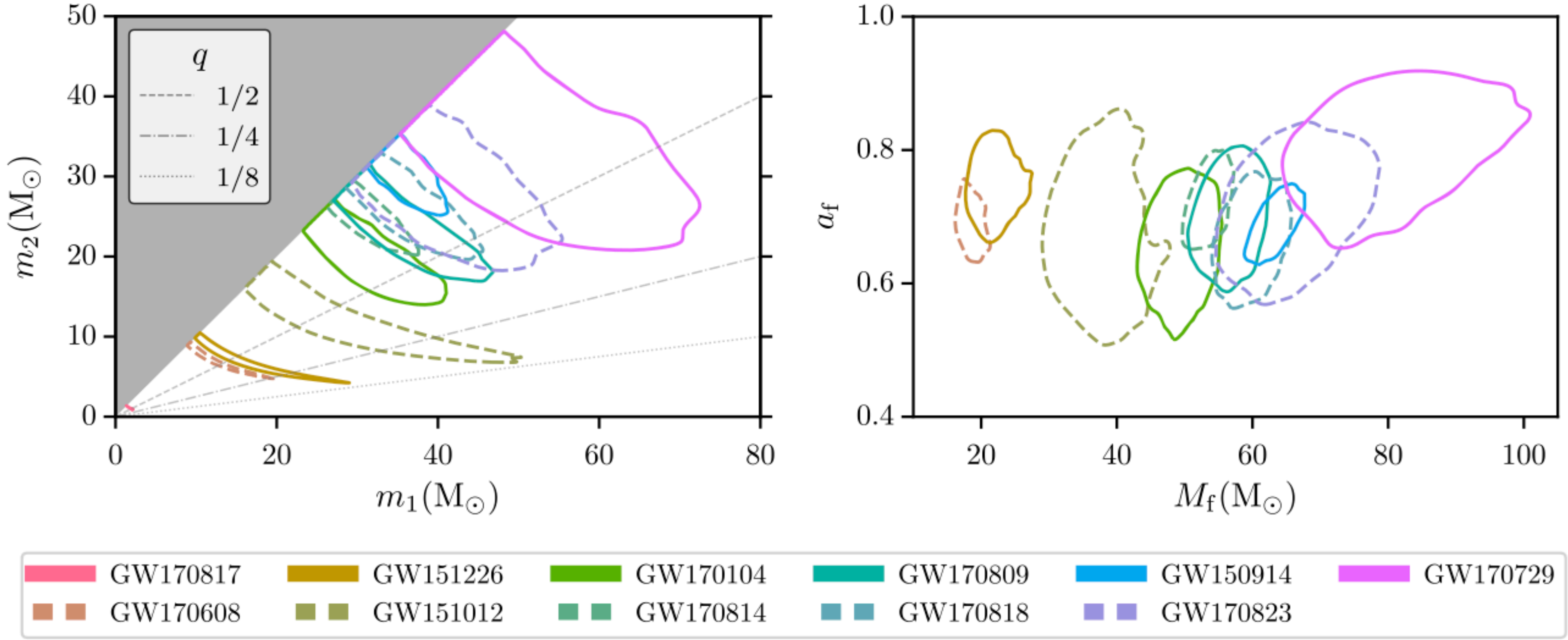
Characteristics of the ensemble

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



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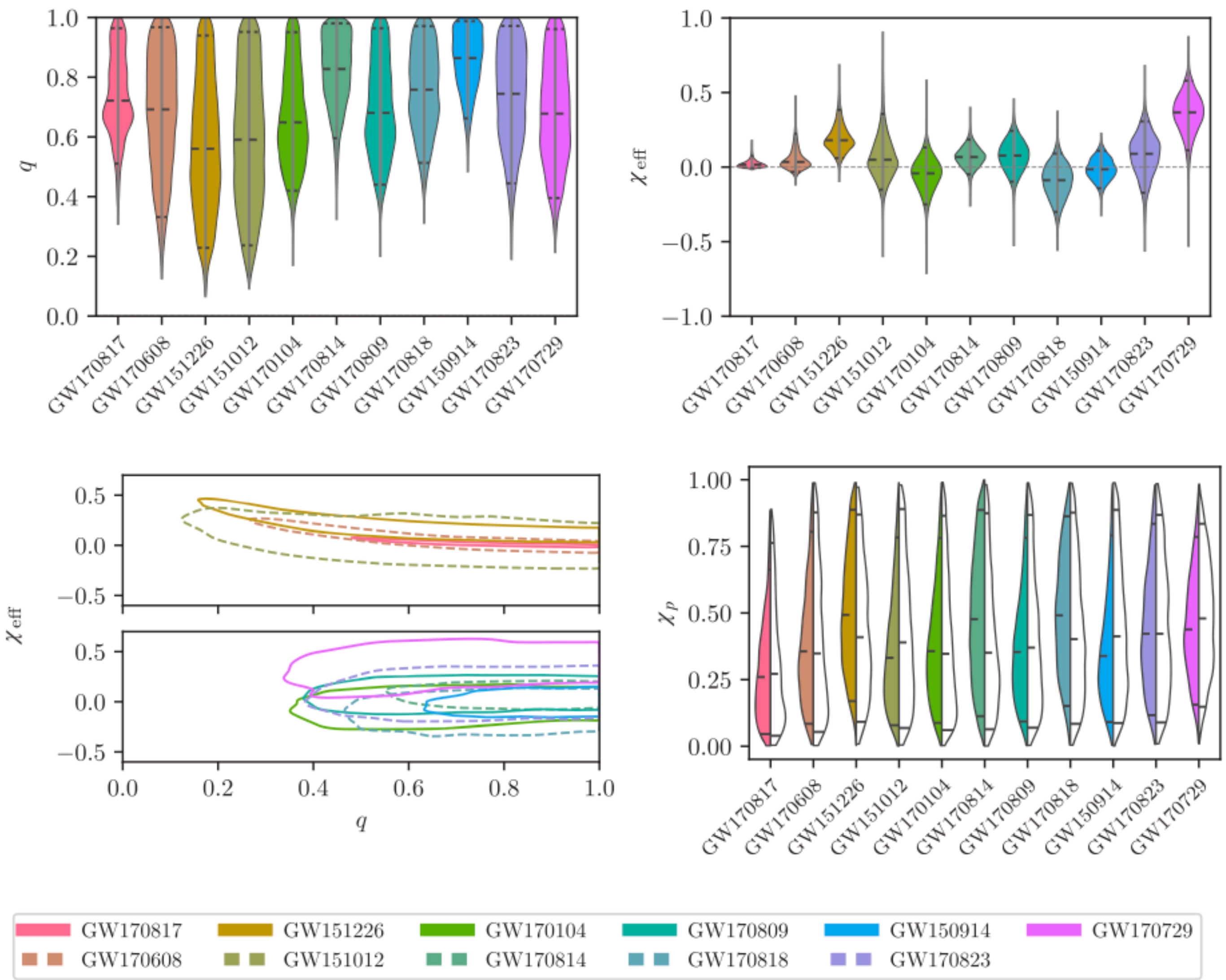
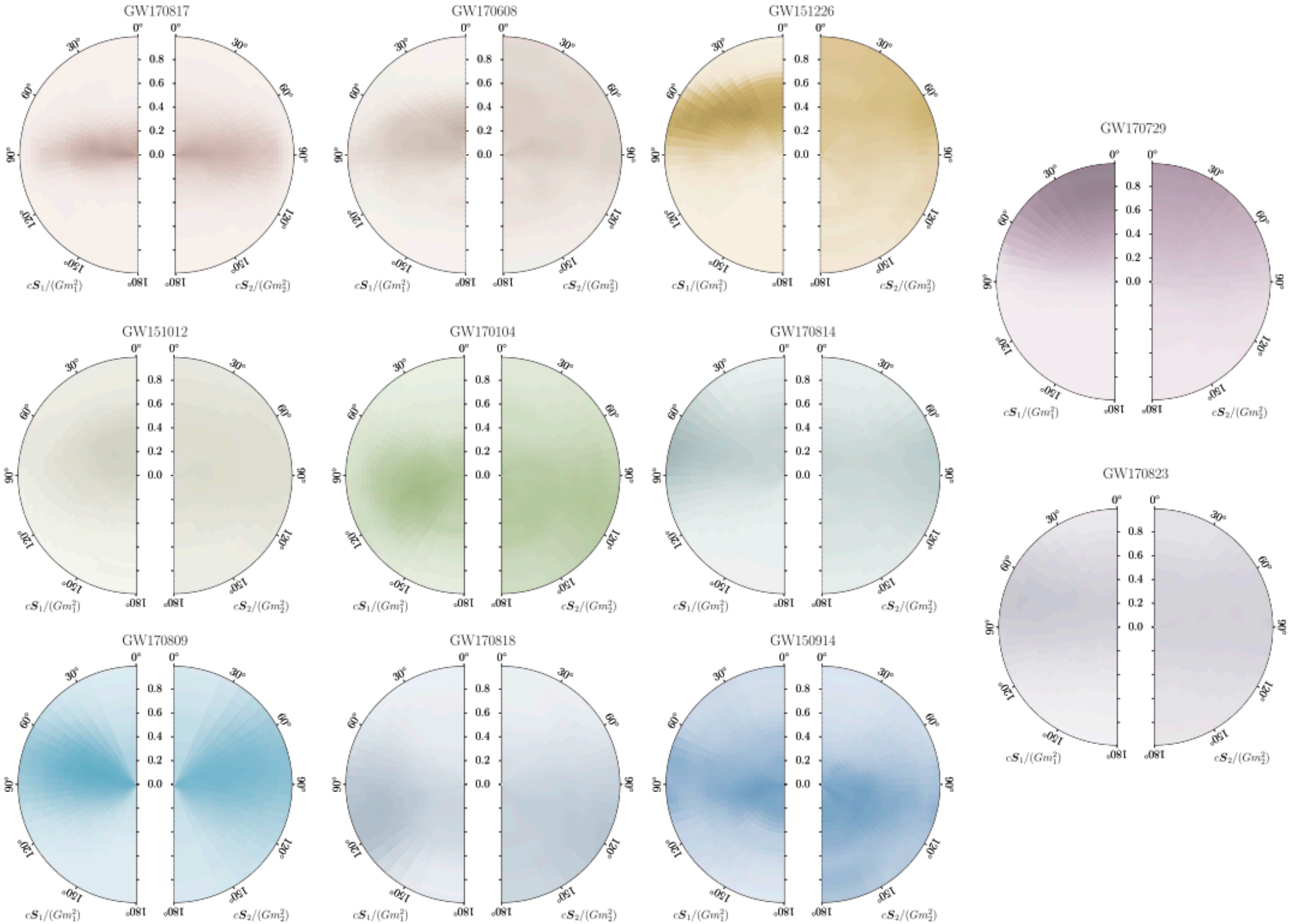
Masses and spins



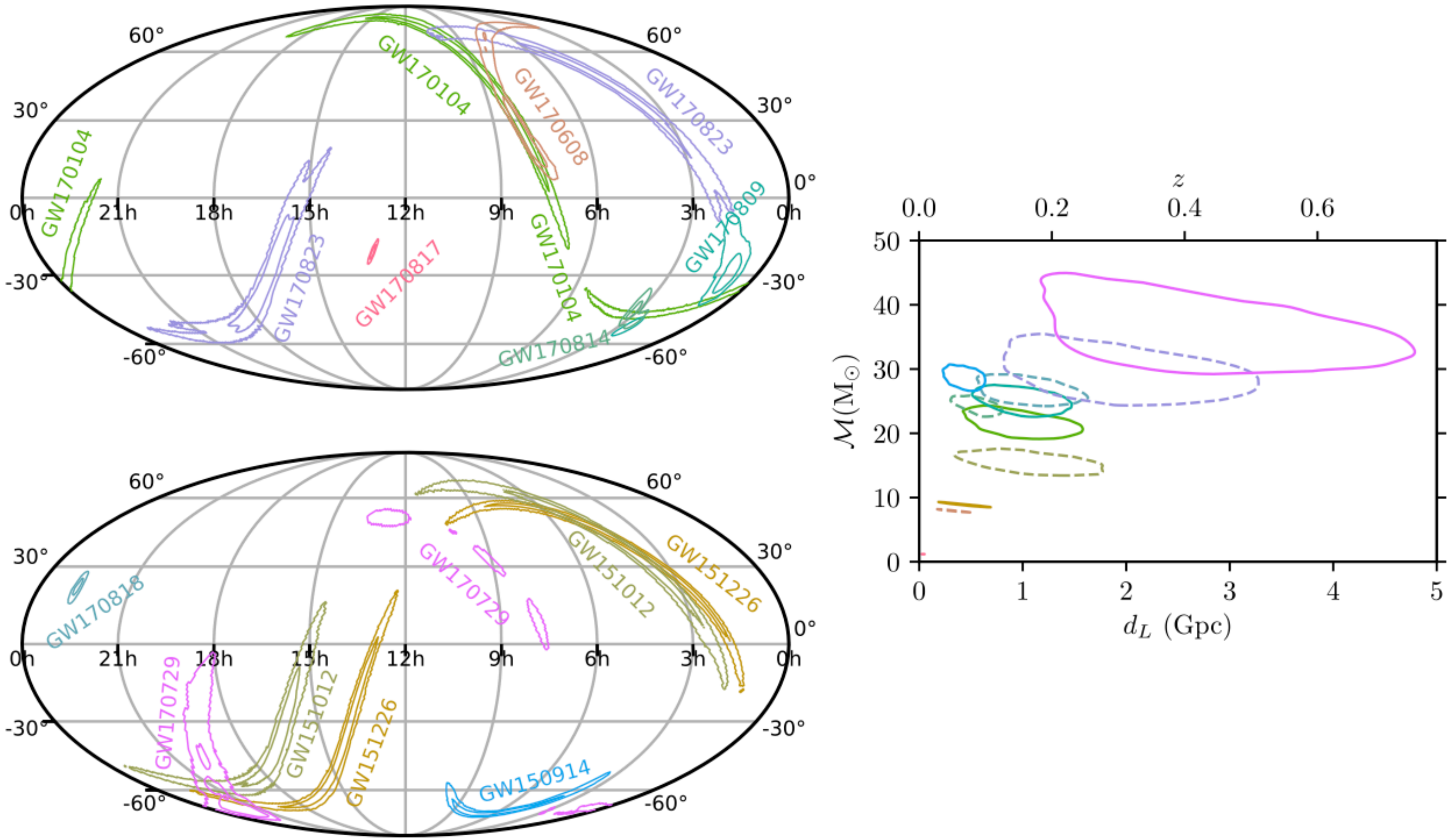
LIGO-Virgo Collaboration, PRX **9**, 031040 (2019)

Spins



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

Sky localisation



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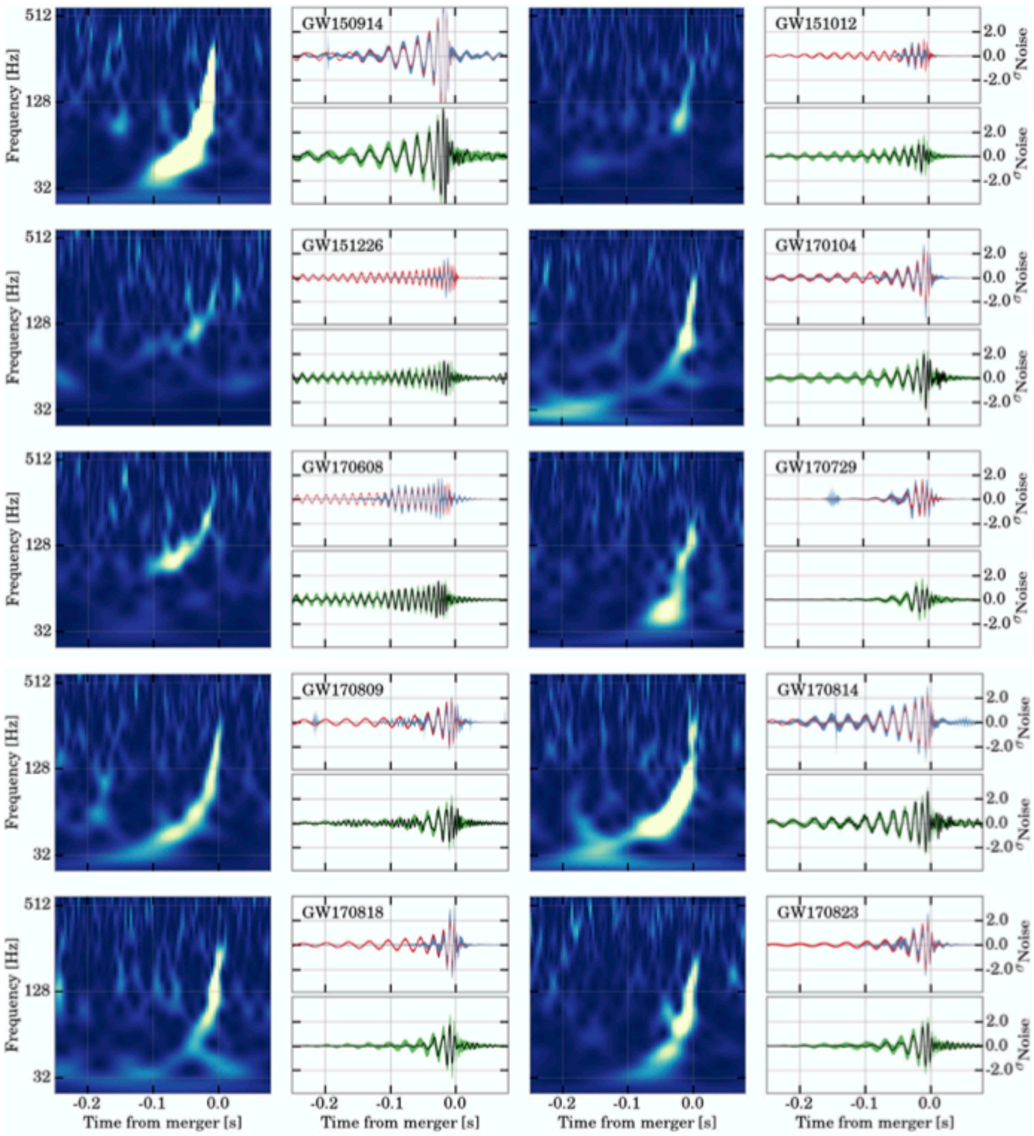
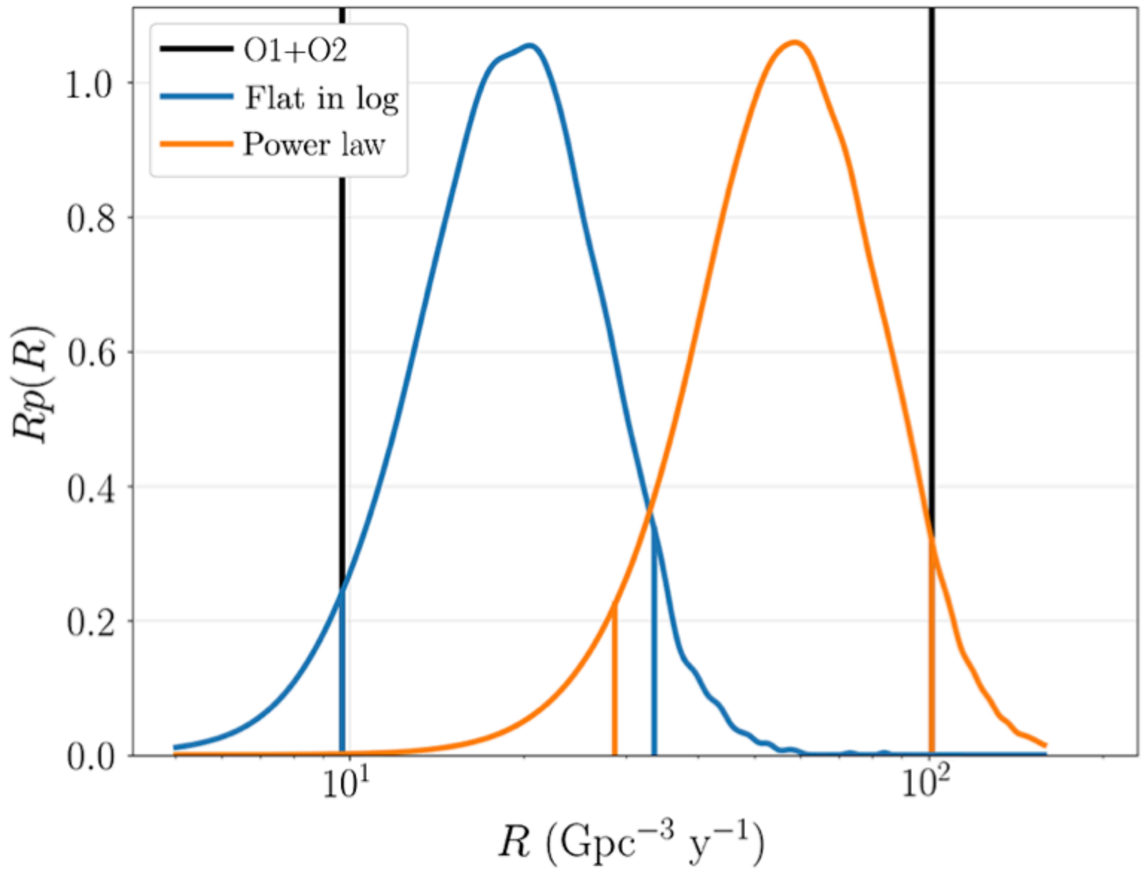
Waveforms



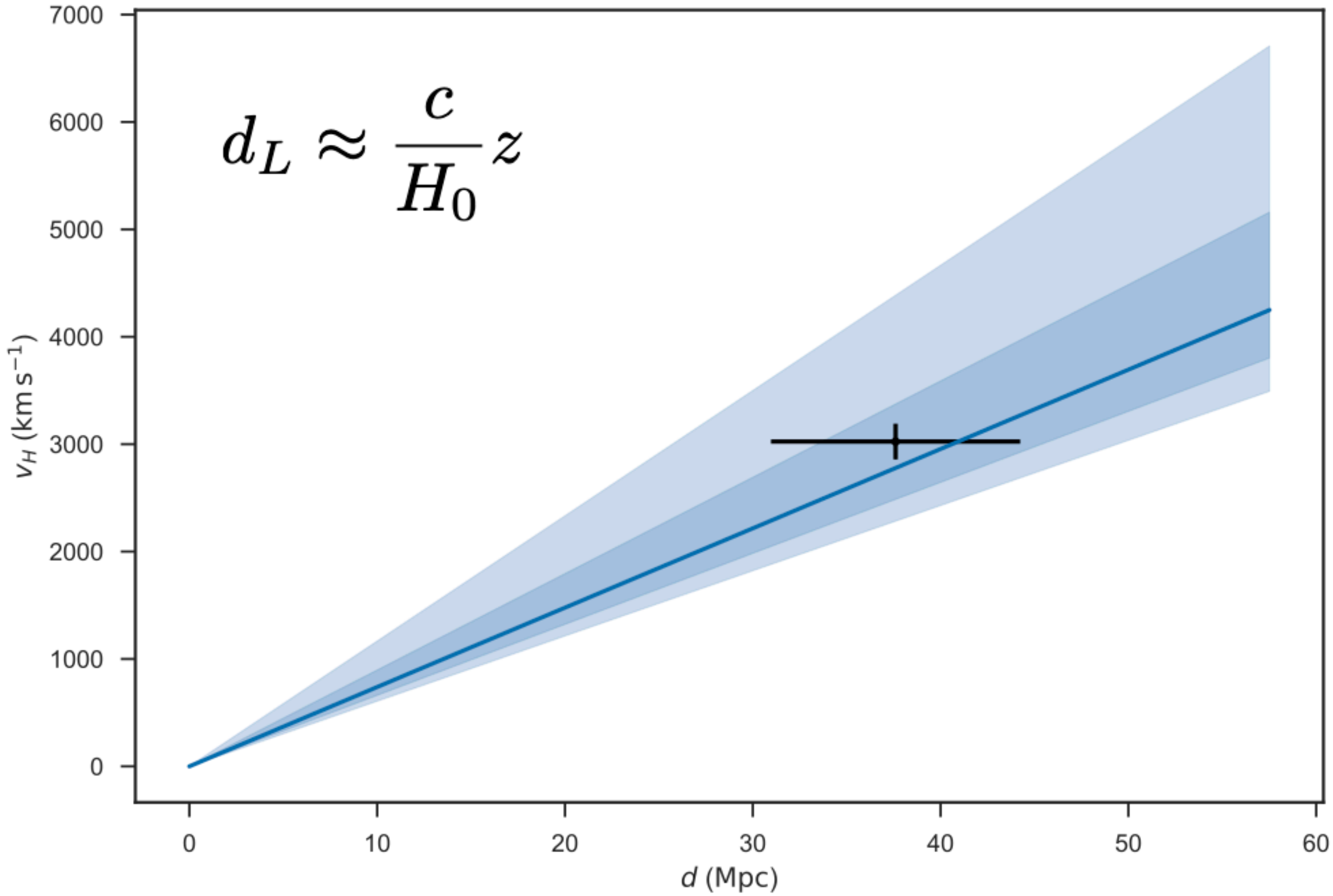
LIGO-Virgo Collaboration, PRX **9**, 031040 (2019)

Astrophysical Event Rate



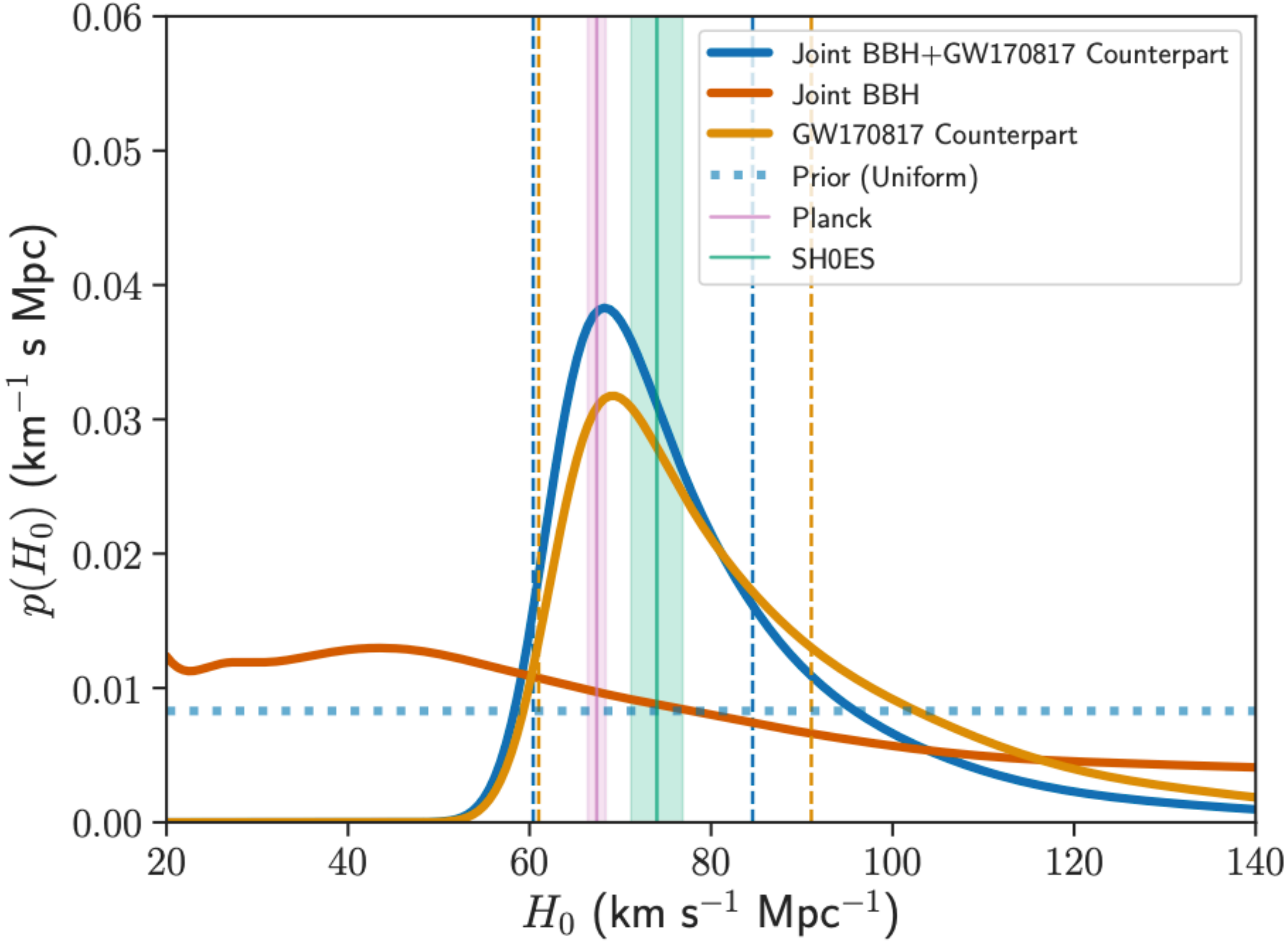
LIGO-Virgo Collaboration, PRX **9**, 031040 (2019)

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

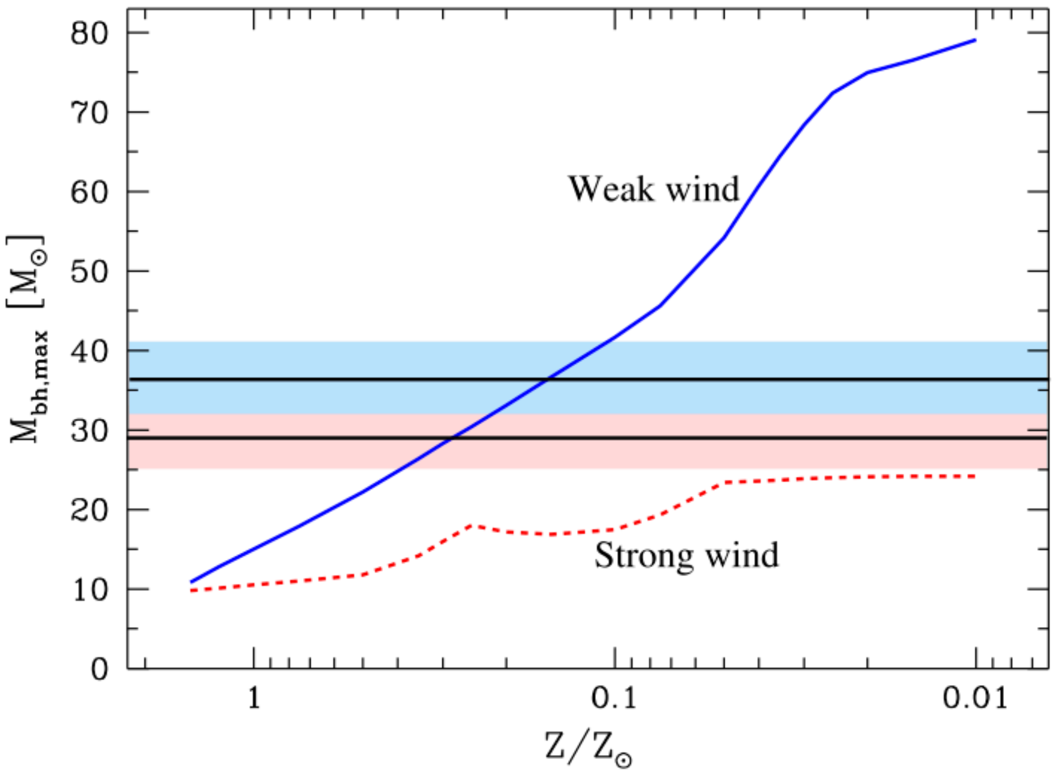
$$L \sim L_{\text{Planck}} = c^5/G.$$

- 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 $L \sim \frac{c^3 d_L^2}{4G} |\dot{h}|^2 \sim \frac{c^5}{4G} \left(\frac{\omega_{\text{GW}} d_L h|_{\text{max}}}{c} \right)^2$

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 $\chi = \dfrac{c}{G}\dfrac{S}{m^2}$
- 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

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

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

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

- 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

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

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

LIGO-Virgo Collaboration, arXiv:1608.01940 (2016)

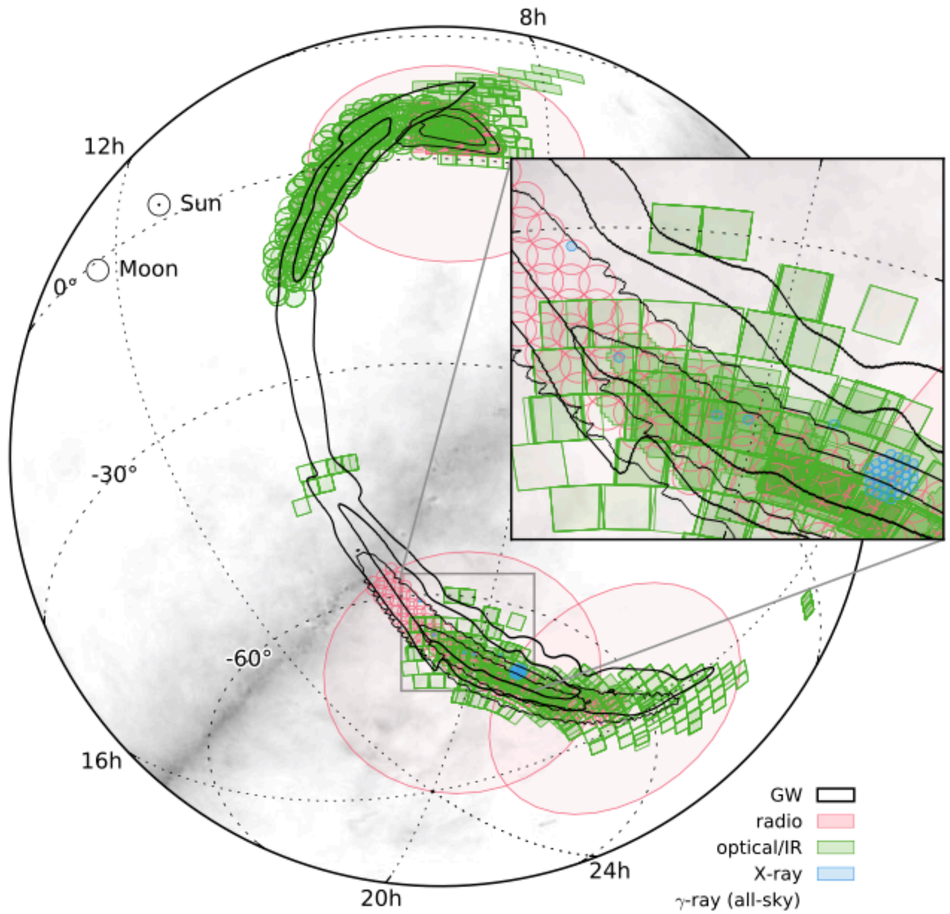
Formation channels

- 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?

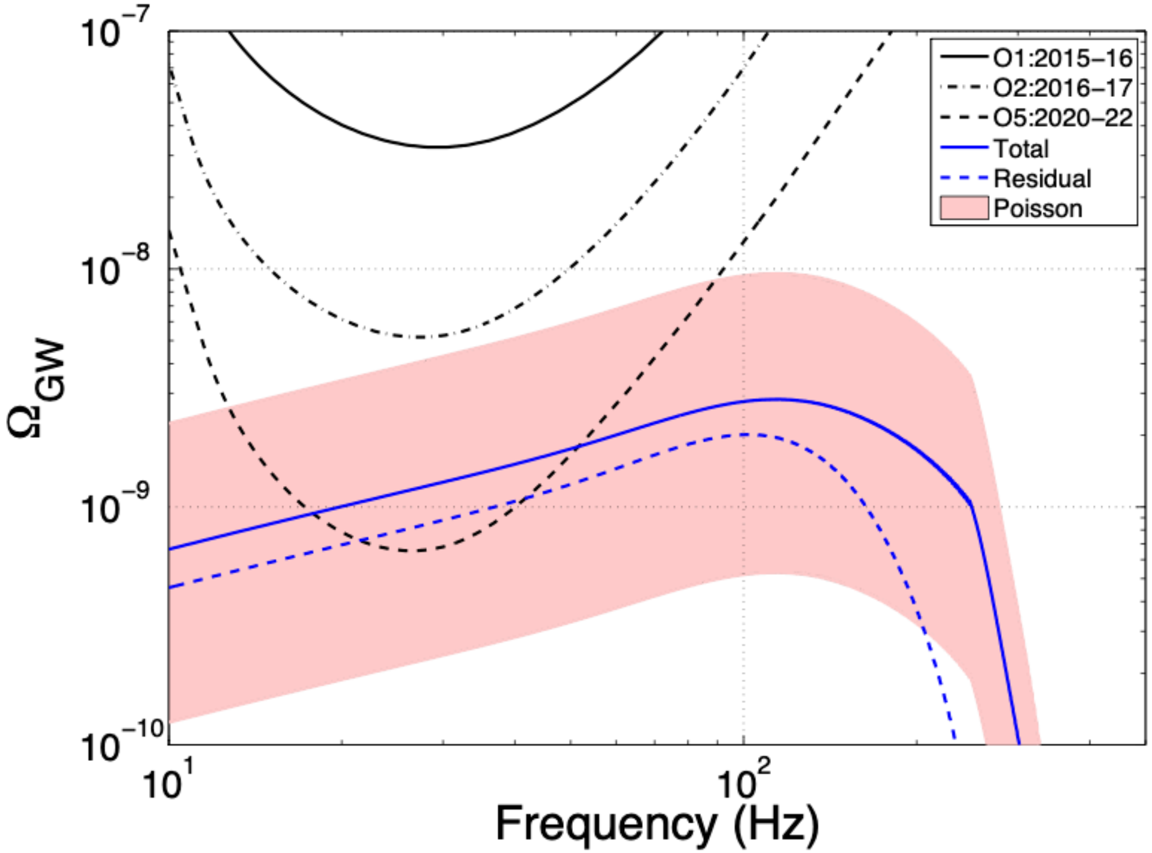
- The event time and location was shared with 63 teams of observers covering radio, optical, near-infrared, X-ray, and gamma-ray wavelengths with ground- and space-based facilities (**multi-messenger astronomy**).
- As this event turned out to be a binary black hole merger, there is little expectation 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.

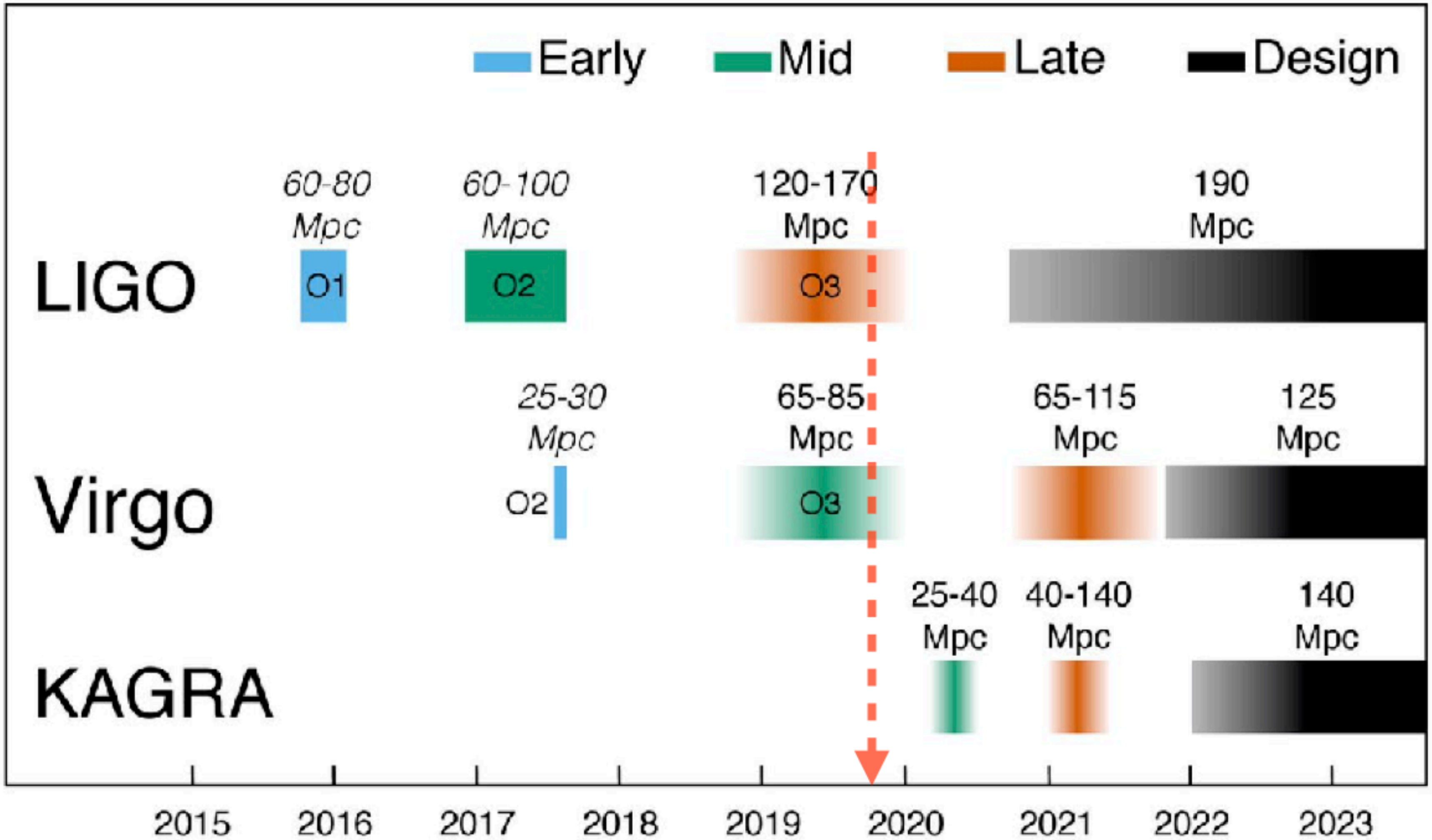
3. Show that ~$3M_\odot$ of energy were emitted during the merger of GW150914.

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

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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)	UTC Created
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
S191105e	PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1256999738.931152	1256999739.933105	1256999740.933105	2.283e-08	2019-11-05 14:35:45 UTC
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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S190928c	ADVNO EM_Selected SKYMAP_READY DQOK GCN_PRELIM_SENT	1253671923.328316	1253671923.364500	1253671923.400684	6.729e-09	2019-09-28 02:14:18 UTC
S190924h	PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253326743.785645	1253326744.846654	1253326745.876674	8.928e-19	2019-09-24 02:19:25 UTC
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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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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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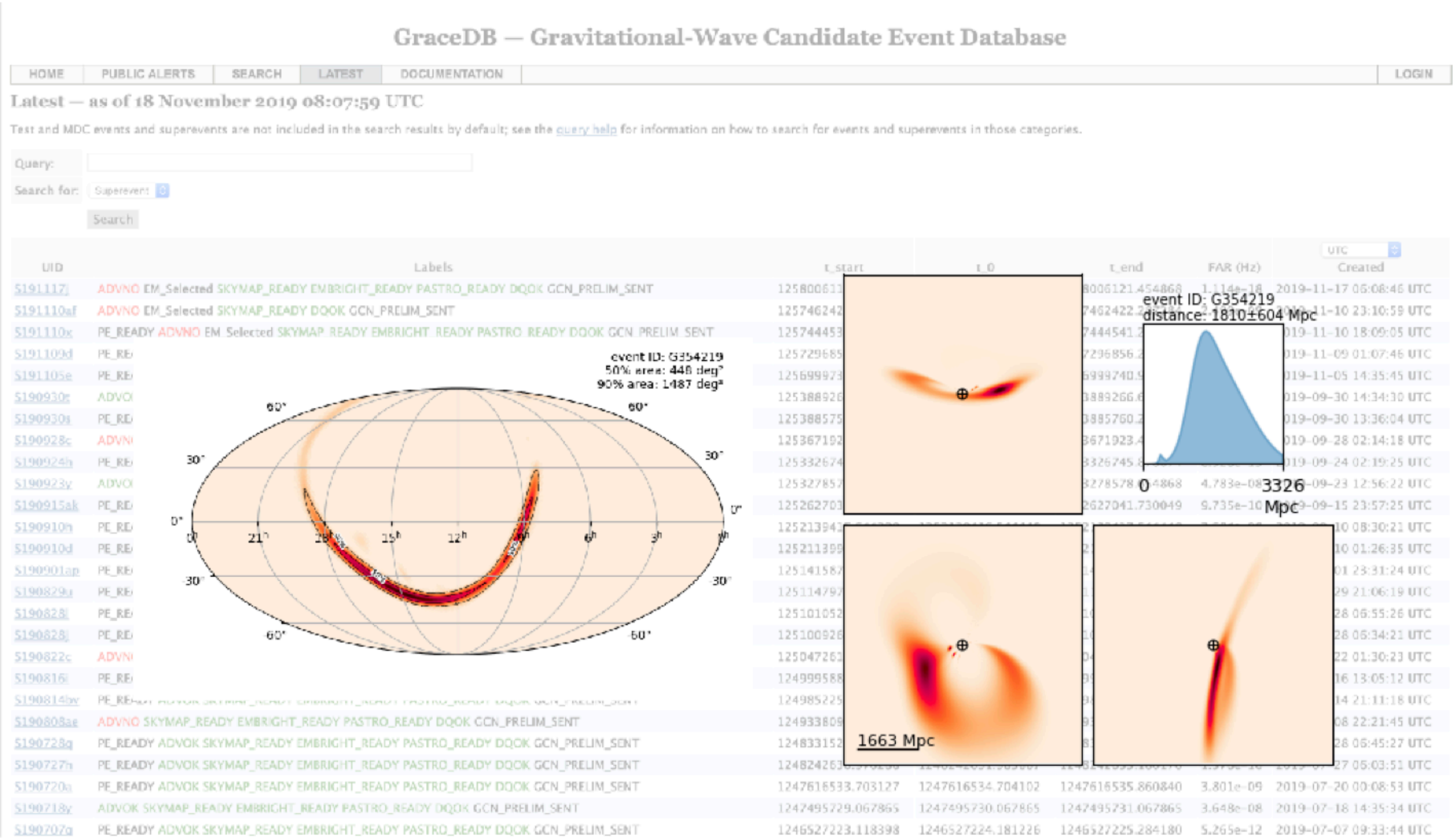
S190728q	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1248331527.497344	1248331528.546797	1248331529.706055	2.527e-23	2019-07-28 06:45:27 UTC
S190727h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1248242630.976288	1248242631.985887	1248242633.180176	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

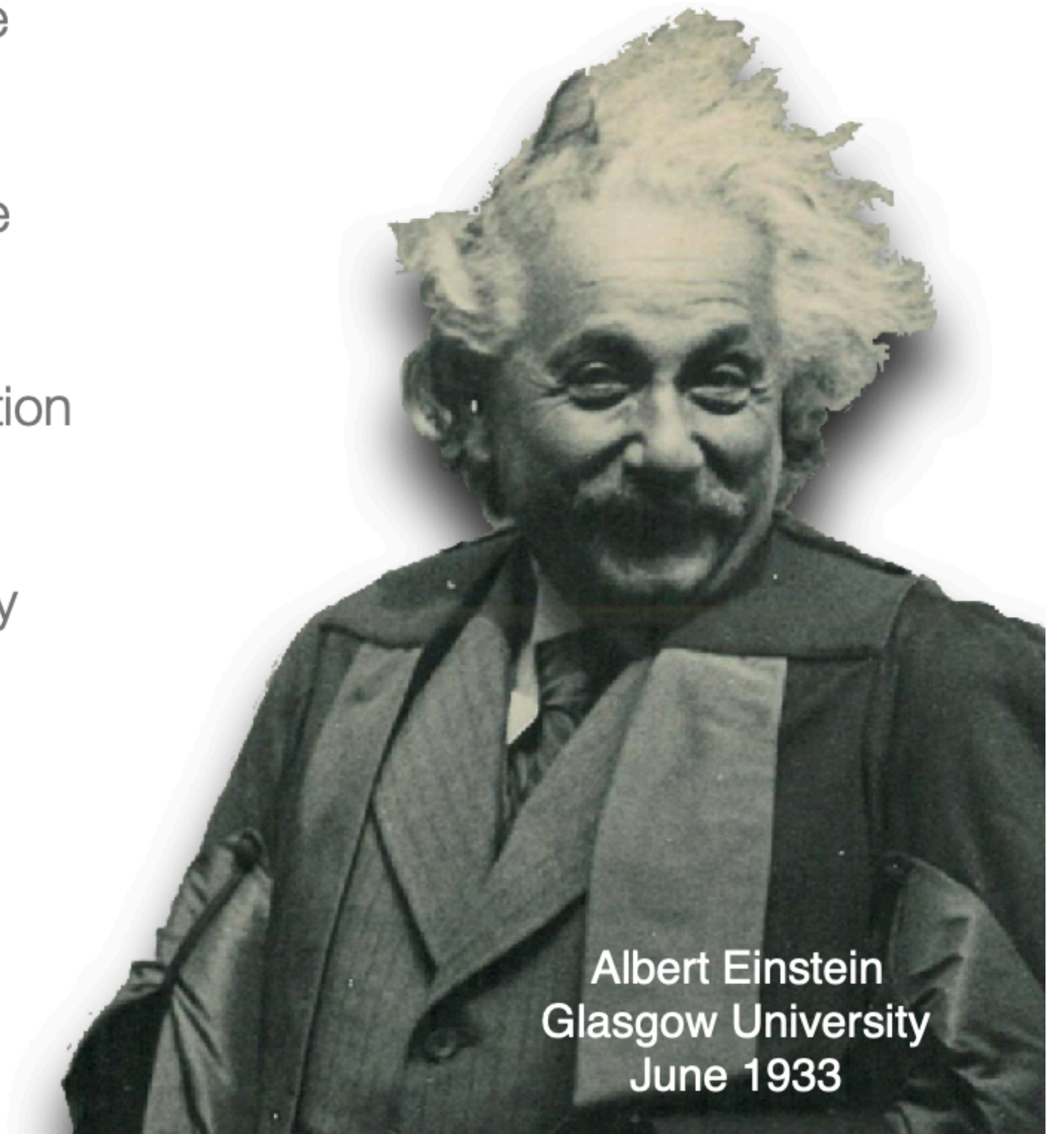
GraceDB [https://gracedb.ligo.org]



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