AMALDI
RESEARCH CENTER

90 GW confirmed detections: what did we learn?

Irene Di Palma
University of Rome
La Sapienza and INFN
Irene.DiPalma@uniroma1.it

Schedule for the week

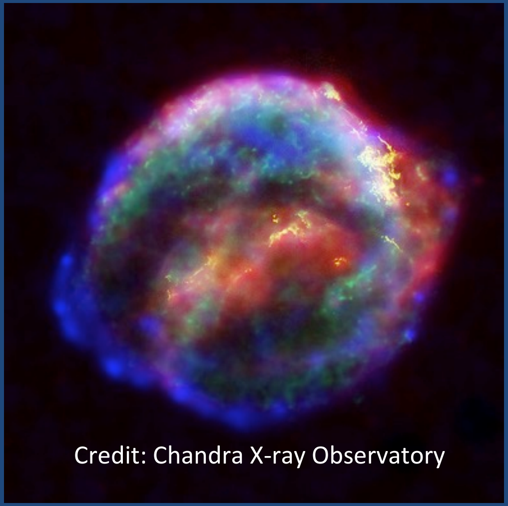
- ***Monday:*** Gravitational Waves: basic and data analysis
- ***Tuesday:*** Interferometric detectors of Gravitational Waves
- ***Wednesday:*** 90 Gravitational Wave detections: what did we learn?
- ***Thursday:*** Multimessenger probes
- ***Hands-on session:*** Gravitational Wave Open Science Center

The Astrophysical Gravitational-Wave Source Catalog

Credit: Bohn, Hébert, Throwe, SXS

Coalescing Binary Systems

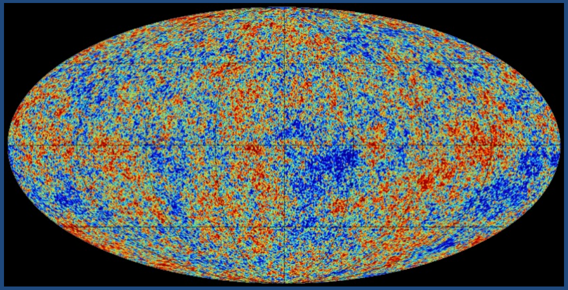
- Black hole – black hole
- Black hole – neutron star
- Neutron star – neutron star
- modeled waveform



Credit: Chandra X-ray Observatory

Transient ‘Burst’ Sources

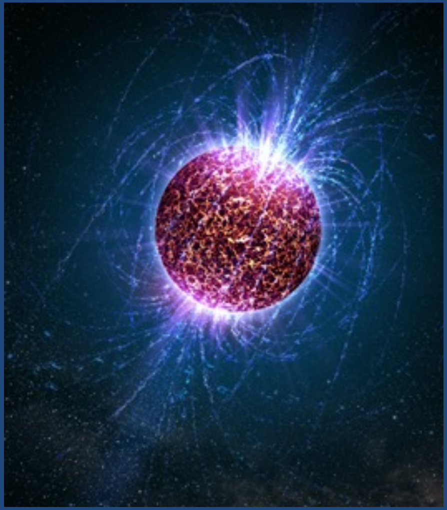
- asymmetric core collapse supernovae
- cosmic strings
- ???
- Unmodeled waveform



Credit: Planck Collaboration

Cosmic GW Background

- residue of the Big Bang
- probes back to < 10^{-15} s
- stochastic, incoherent background
- Difficult (impossible?) for LIGO-Virgo to detect



Credit: Casey Reed, Penn State

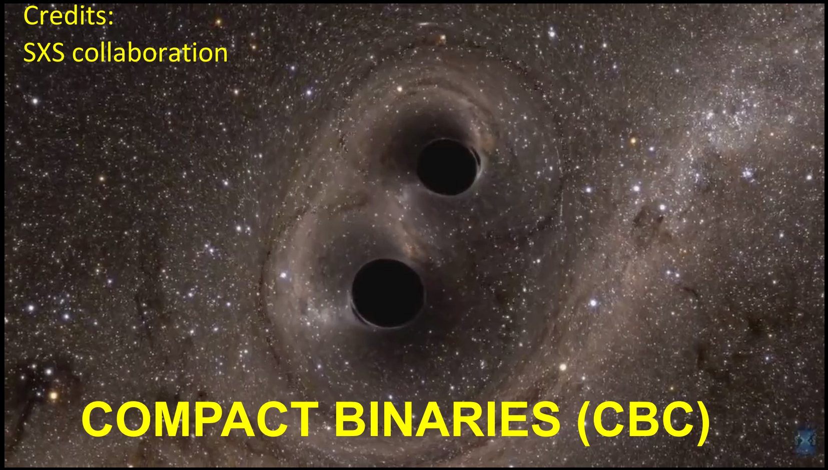
Continuous Sources

- Spinning neutron stars
- monotone waveform

Gravitational Wave Targets

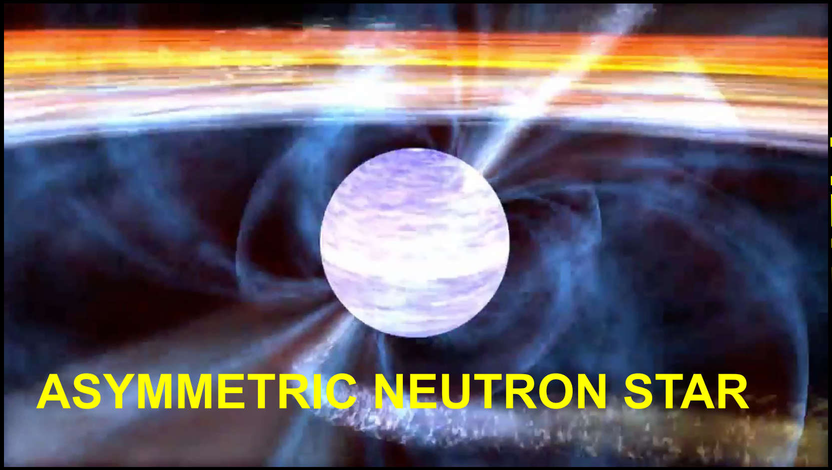
TRANSIENT

PERSISTENT



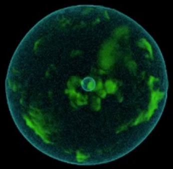
Credits:
SXS collaboration

COMPACT BINARIES (CBC)



ASYMMETRIC NEUTRON STAR

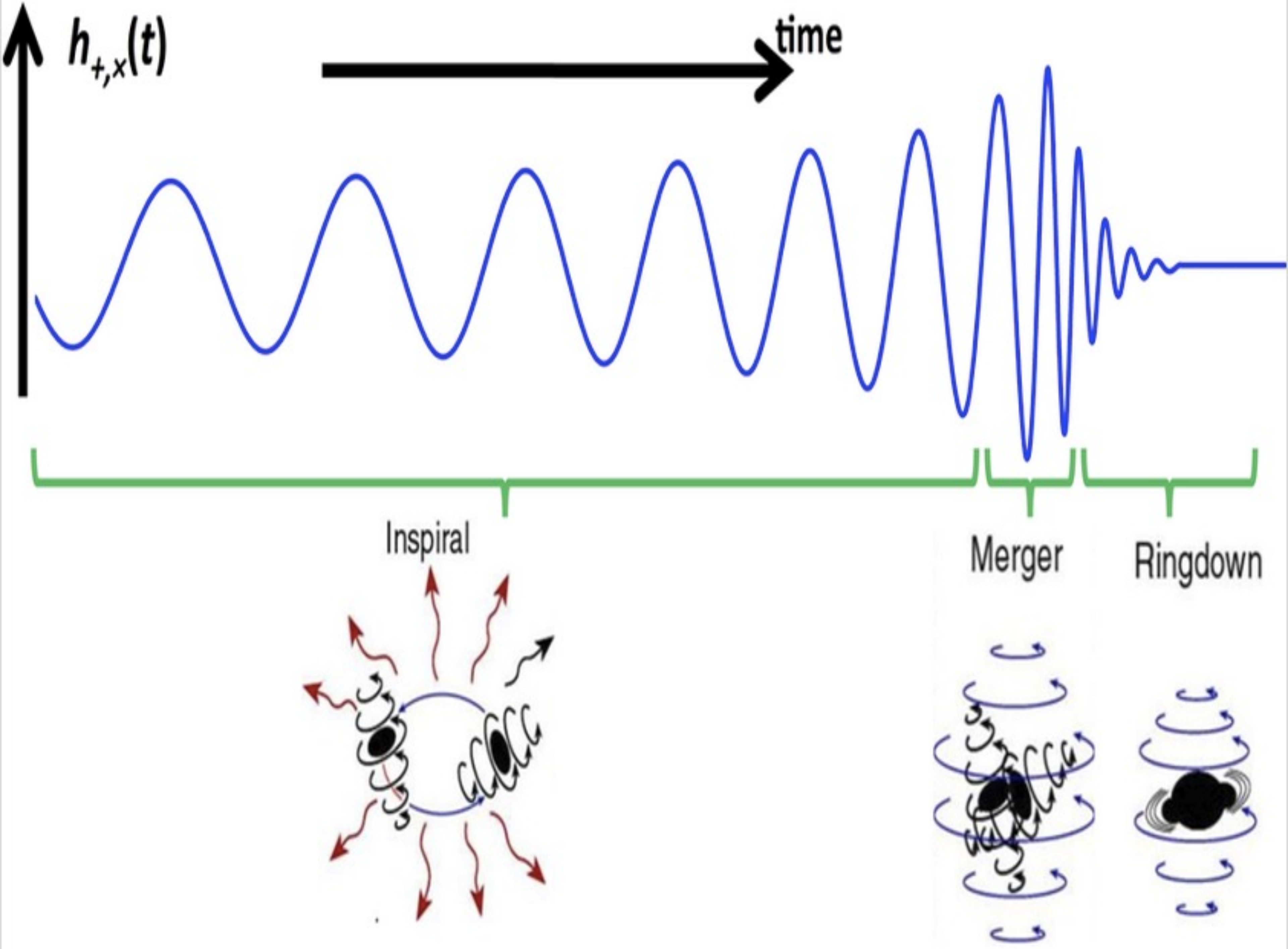
MATCHED FILTER



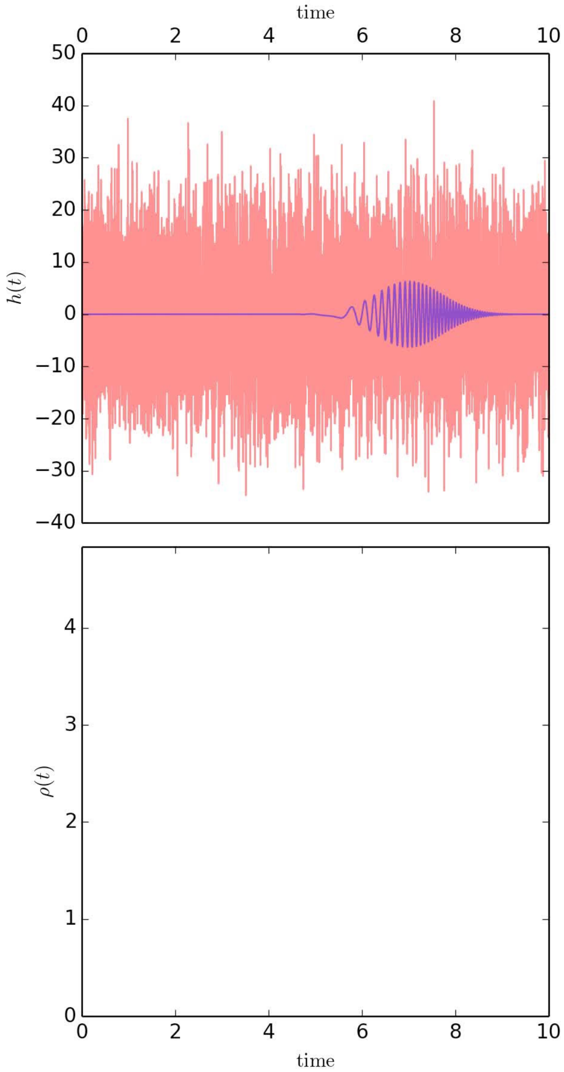
BURSTS: Core collapse Supernovae

STOCHASTIC BACKGROUND

UNMODELED


$h_{+,\times}(t)$
time
Inspiral
Merger
Ringdown

Assessing Statistical Significance: Modeled Search

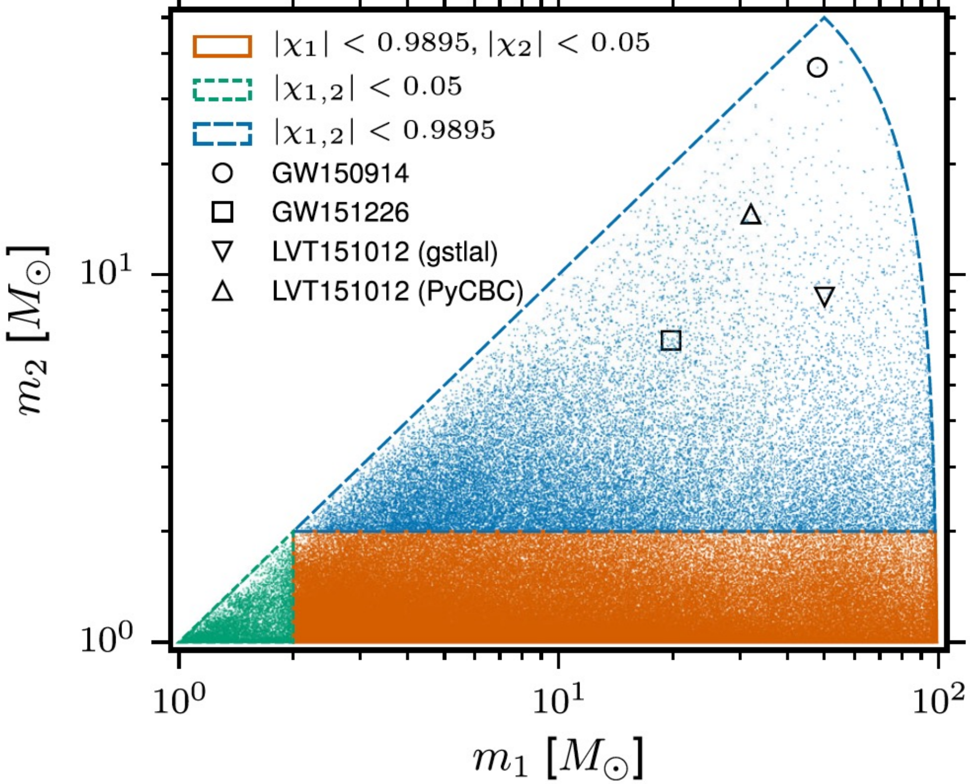


Simulation: Reed Essick, LIGO MIT

- Matched filter search: X-correlation of L1, H1 data streams

$$\boxed{\rho = \frac{\langle s|h\rangle}{\sqrt{\langle h|h\rangle}}} \qquad \langle a|b\rangle = 4\mathrm{Re}\int_{f_{\mathrm{low}}}^{f_{\mathrm{high}}} \frac{\tilde{a}(f)\tilde{b}(f)}{S_n(f)}\, df$$

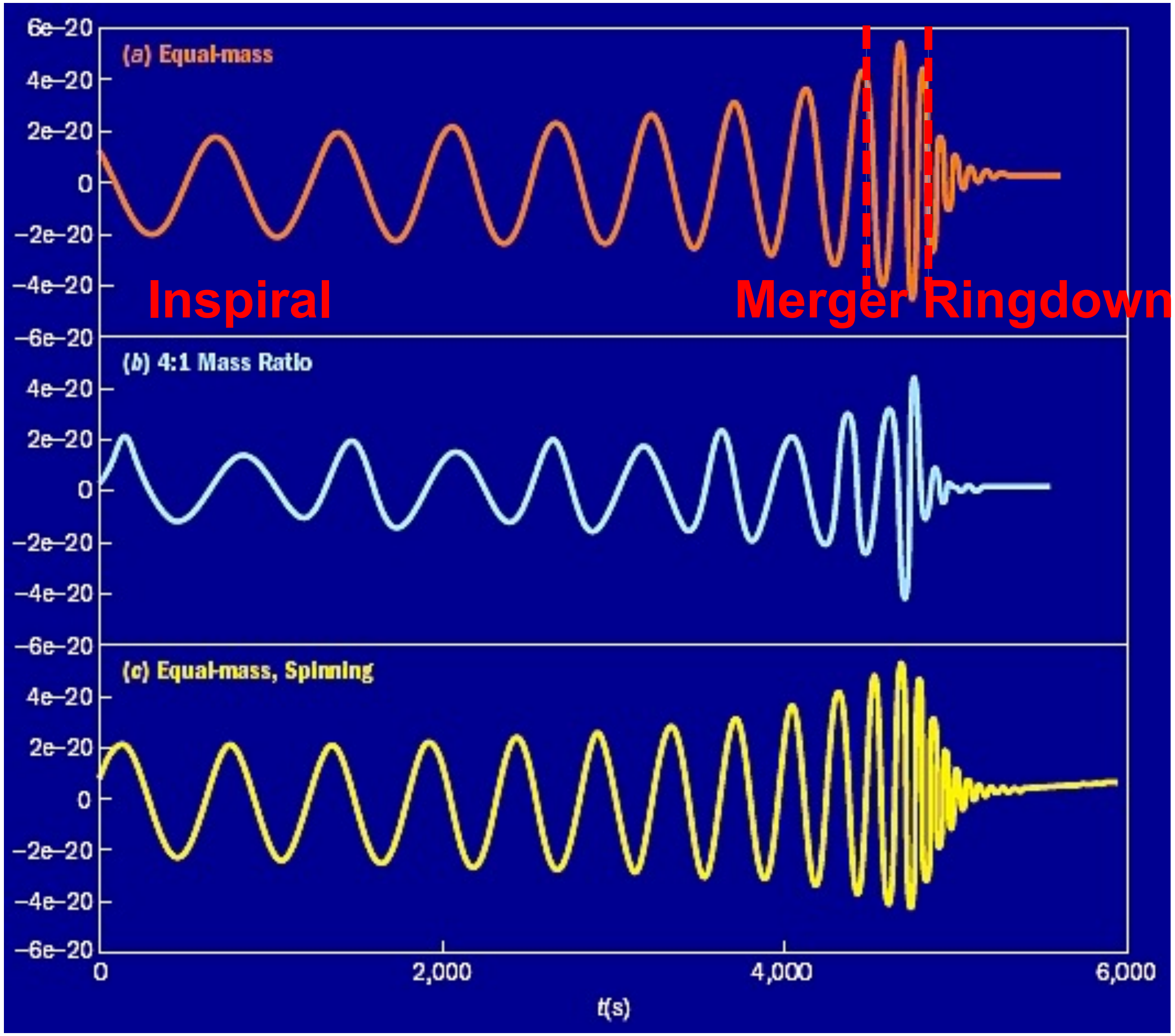
- Background computed from time-shifting coincident data in 100 ms steps
  - For GW150914, 51.5 days → $5\text{x}10^6$ years



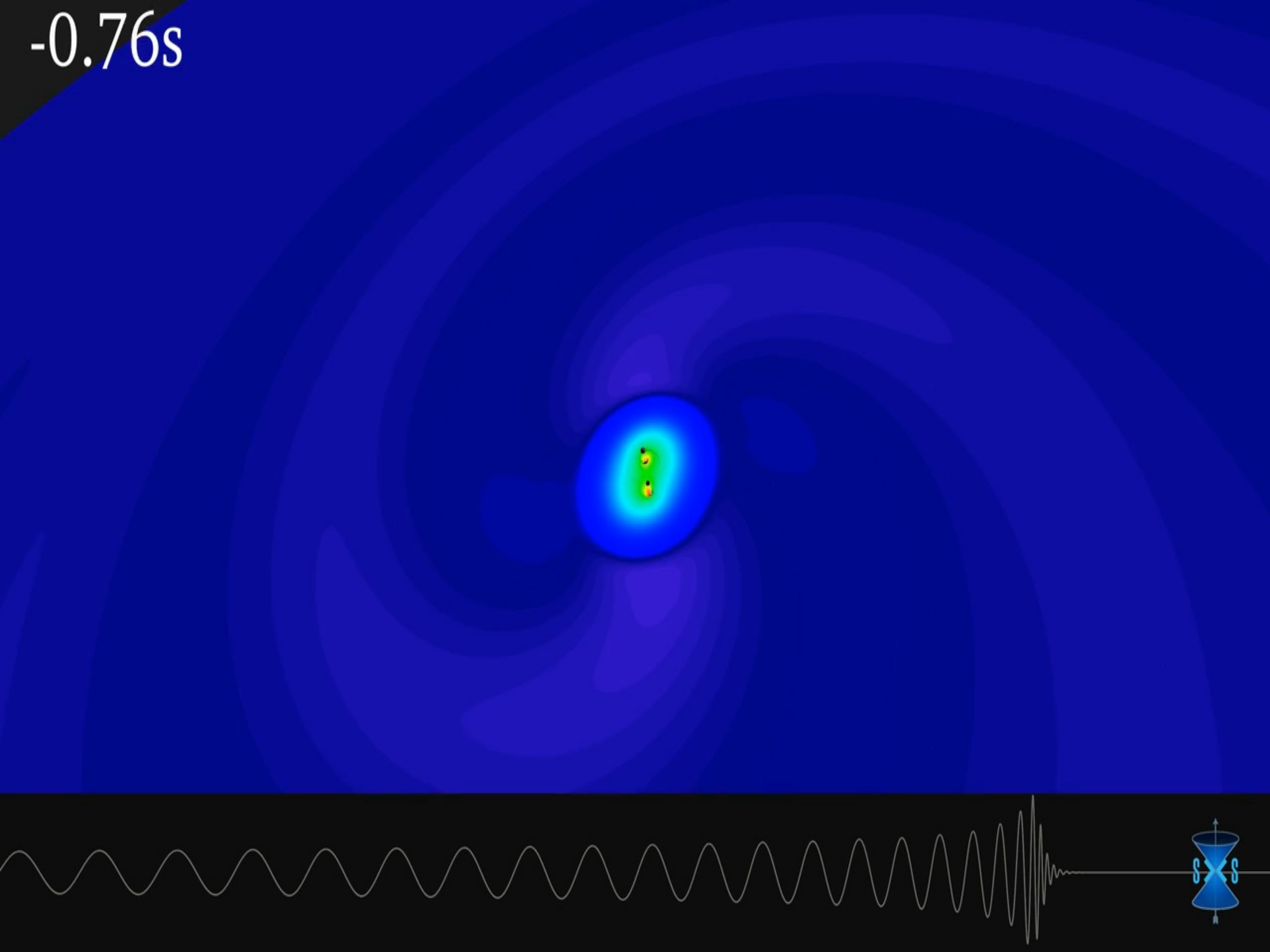
Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, “Binary Black Hole Mergers in the first Advanced LIGO Observing Run”, Phys. Rev. X 6, 041015 (2016).

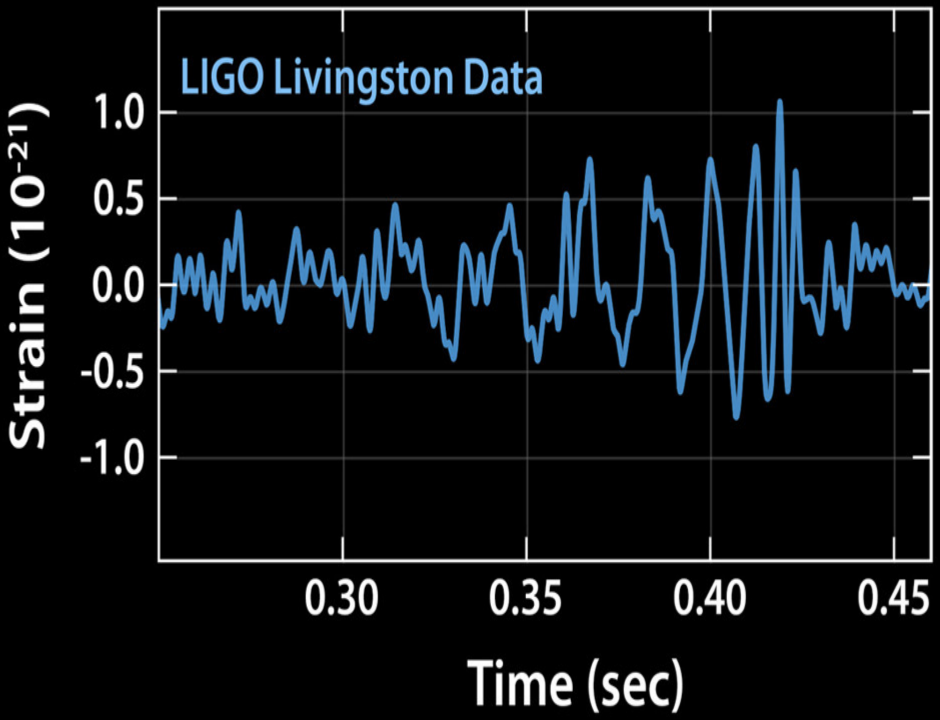
Extracting Astrophysical Parameters from GW Waveforms

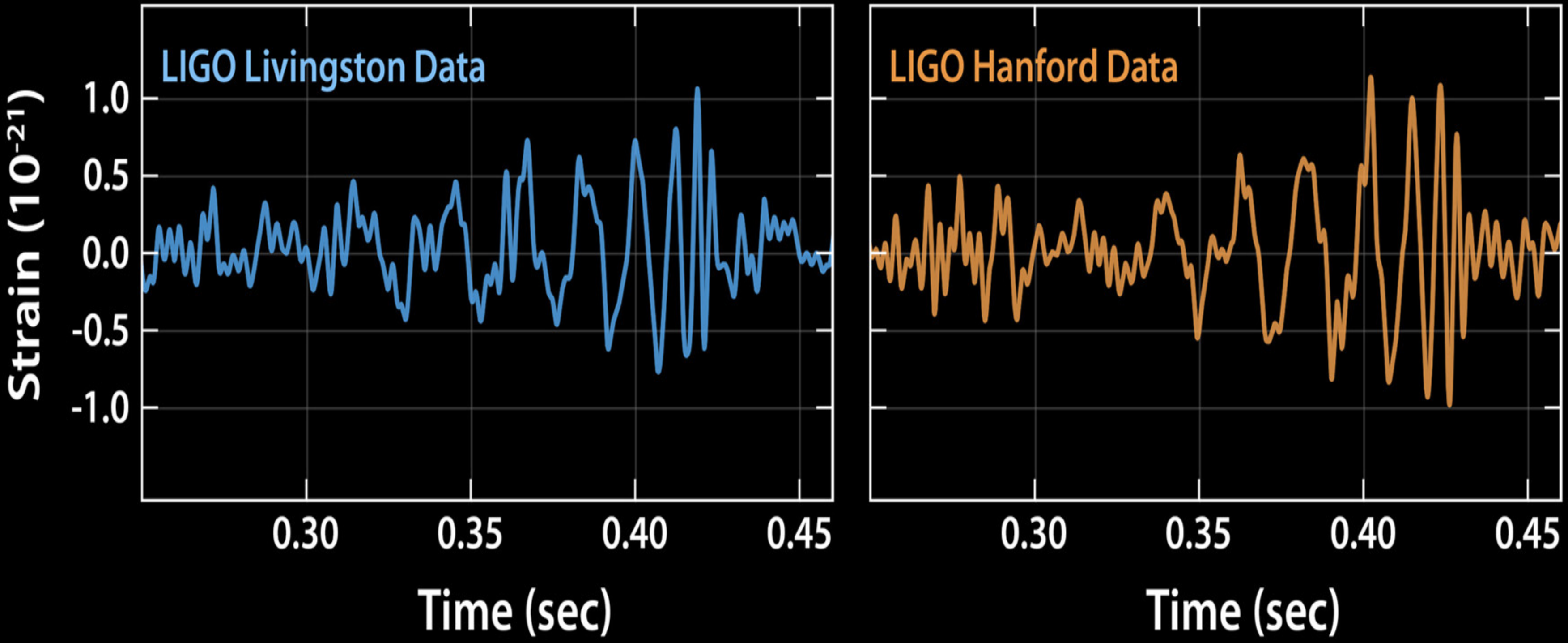
- Compact object parameters encoded in the waveforms:
  - Constituent masses, constituent spins, sky location, luminosity distance, orbital inclination, time of arrival
- Intrinsic degeneracies make parameter estimation difficult!
  - E.g., luminosity distance vs. inclination angle
- The SNR of the waveform matters
  - often buried in detector noise; lower SNR obscures parameter estimation

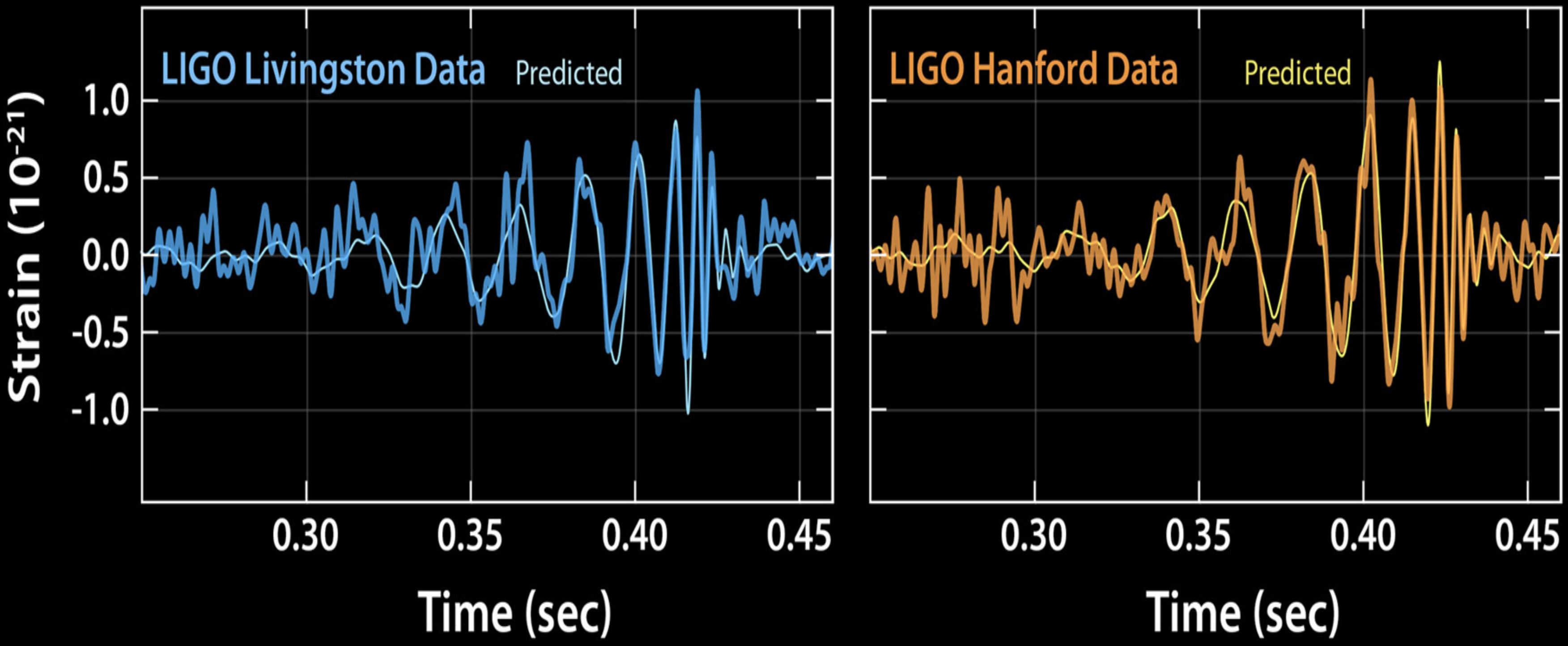


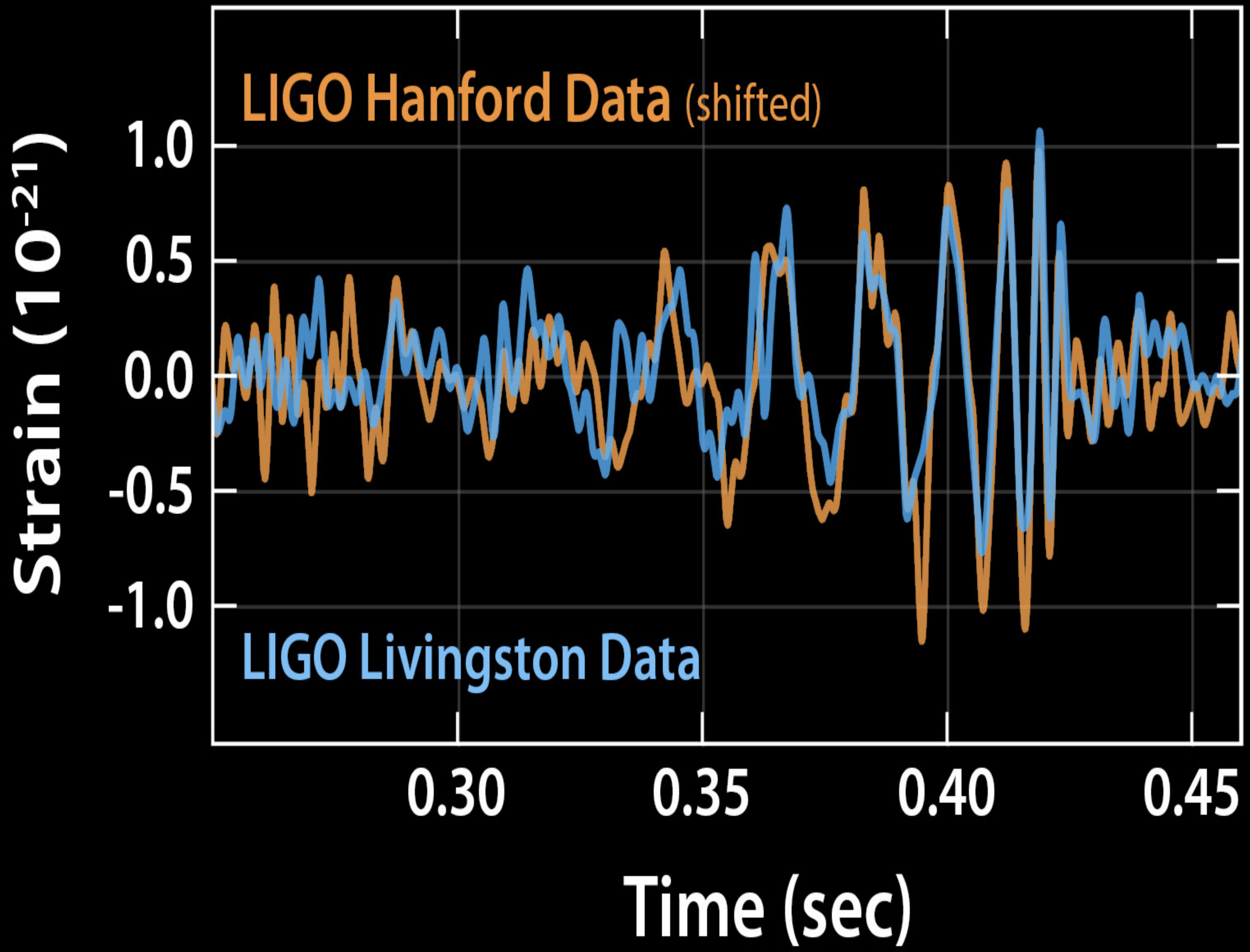
LIGO Scientific Collaboration and Virgo Collaboration, "Parameter estimation for compact binary coalescence signals with the first generation gravitational wave detector network" Phys. Rev. D 88(2013) 062001

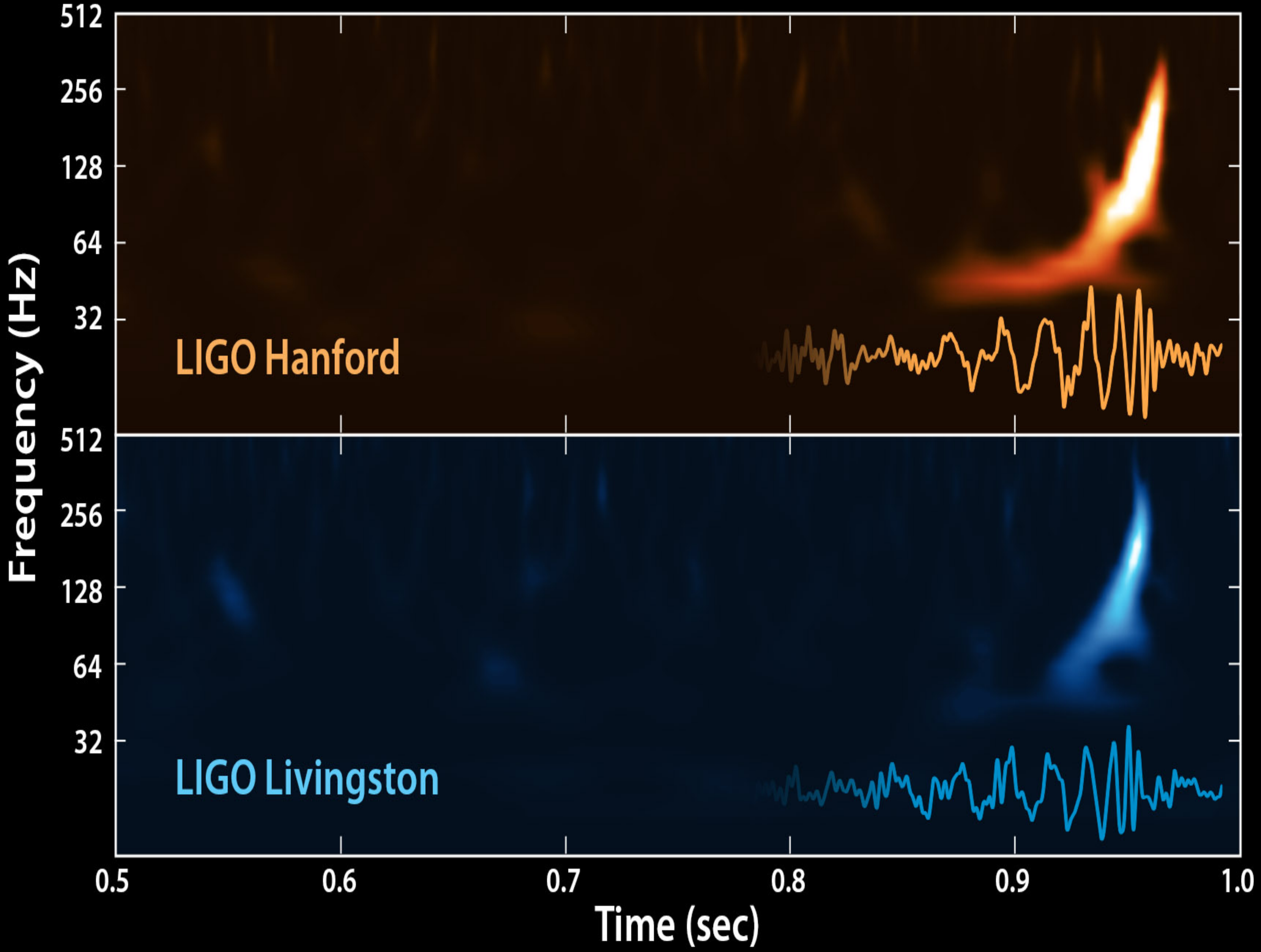

-0.76s

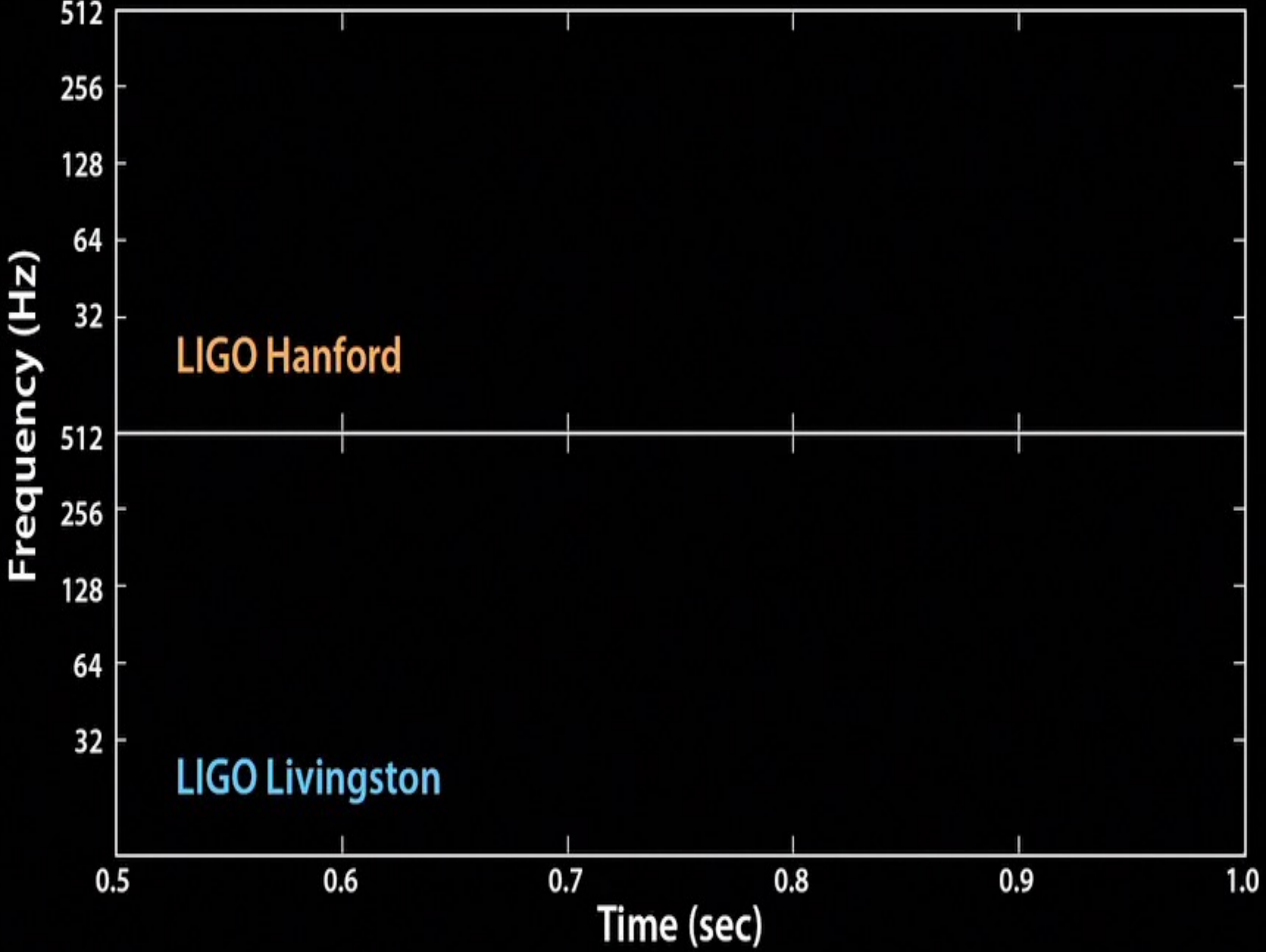

LIGO Livingston Data
Strain (10⁻²¹)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)

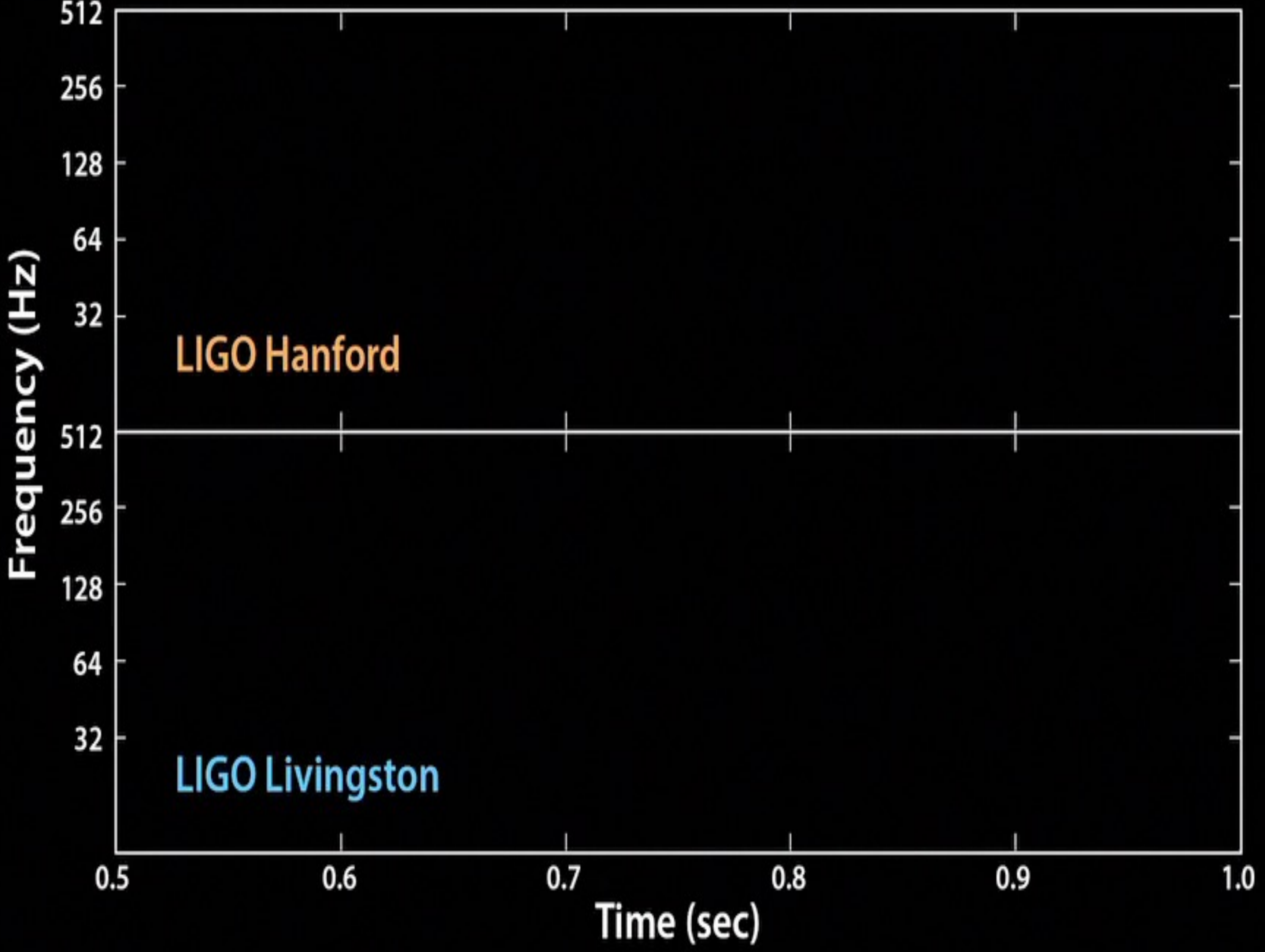

LIGO Livingston Data
LIGO Hanford Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
0.30
0.35
0.40
0.45
Time (sec)

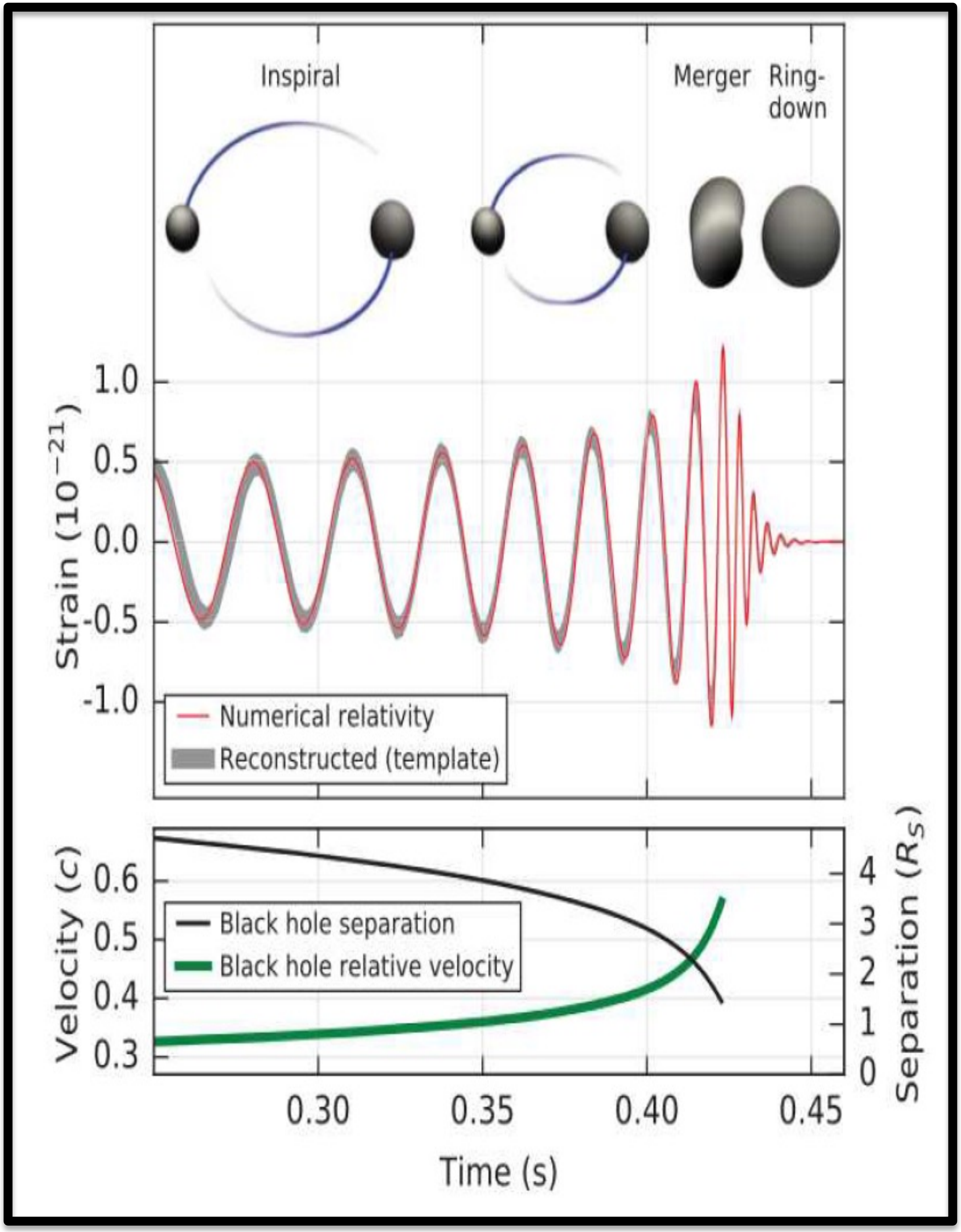

LIGO Livingston Data
Predicted
LIGO Hanford Data
Predicted
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
0.30
0.35
0.40
0.45
Time (sec)


LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)


512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)


512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)


512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)



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

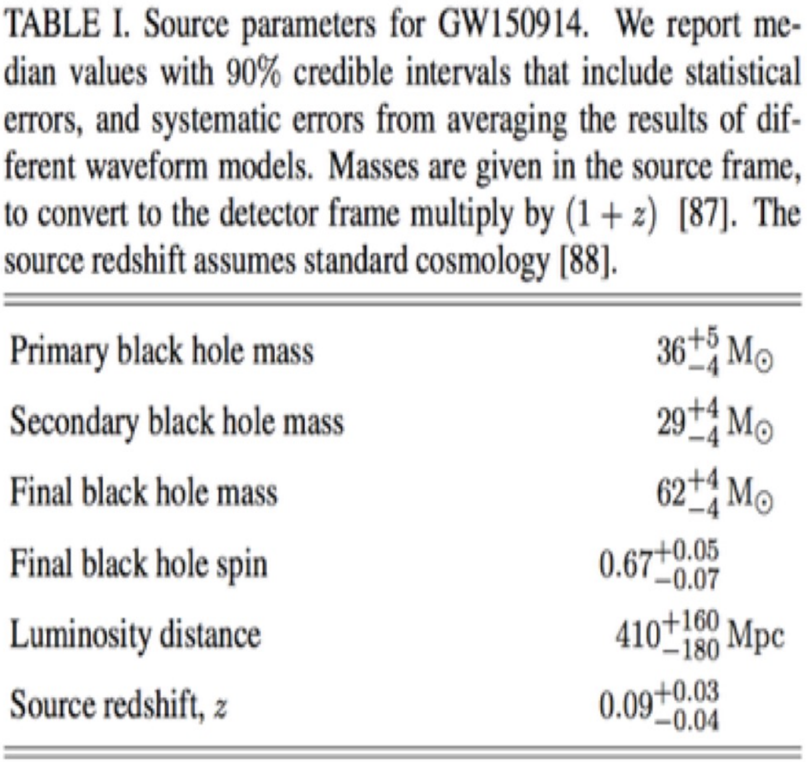


TABLE I. Source parameters for GW150914. We report median values with 90% credible intervals that include statistical errors, and systematic errors from averaging the results of different waveform models. Masses are given in the source frame, to convert to the detector frame multiply by $(1 + z)$ [87]. The source redshift assumes standard cosmology [88].

Primary black hole mass	$36^{+5}_{-4}\,M_\odot$
Secondary black hole mass	$29^{+4}_{-4}\,M_\odot$
Final black hole mass	$62^{+4}_{-4}\,M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift, z	$0.09^{+0.03}_{-0.04}$

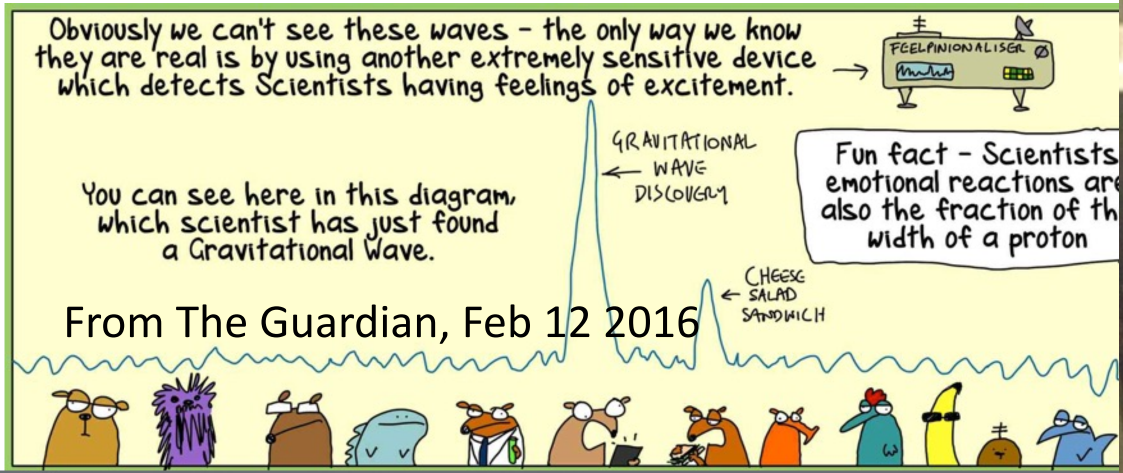
The Keplerian effective black hole separation in unit of Schwarzschild radii

$$R_S = 2GM/c^2$$

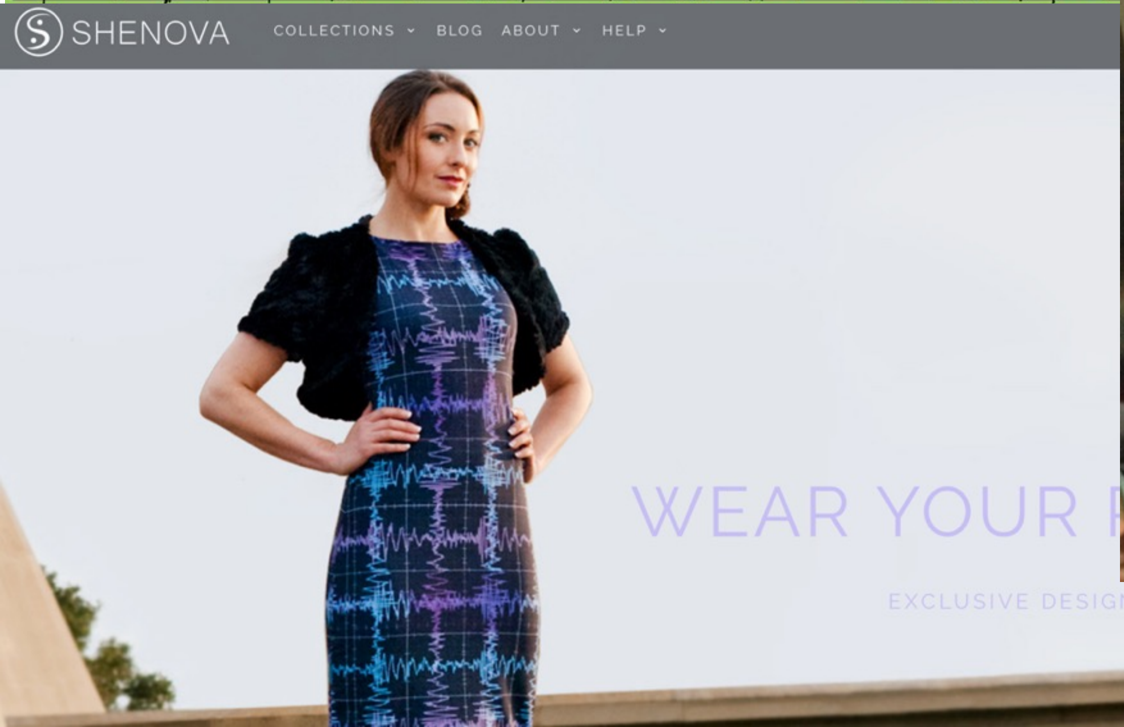
and the effective relative velocity given by the post-Newtonian parameter

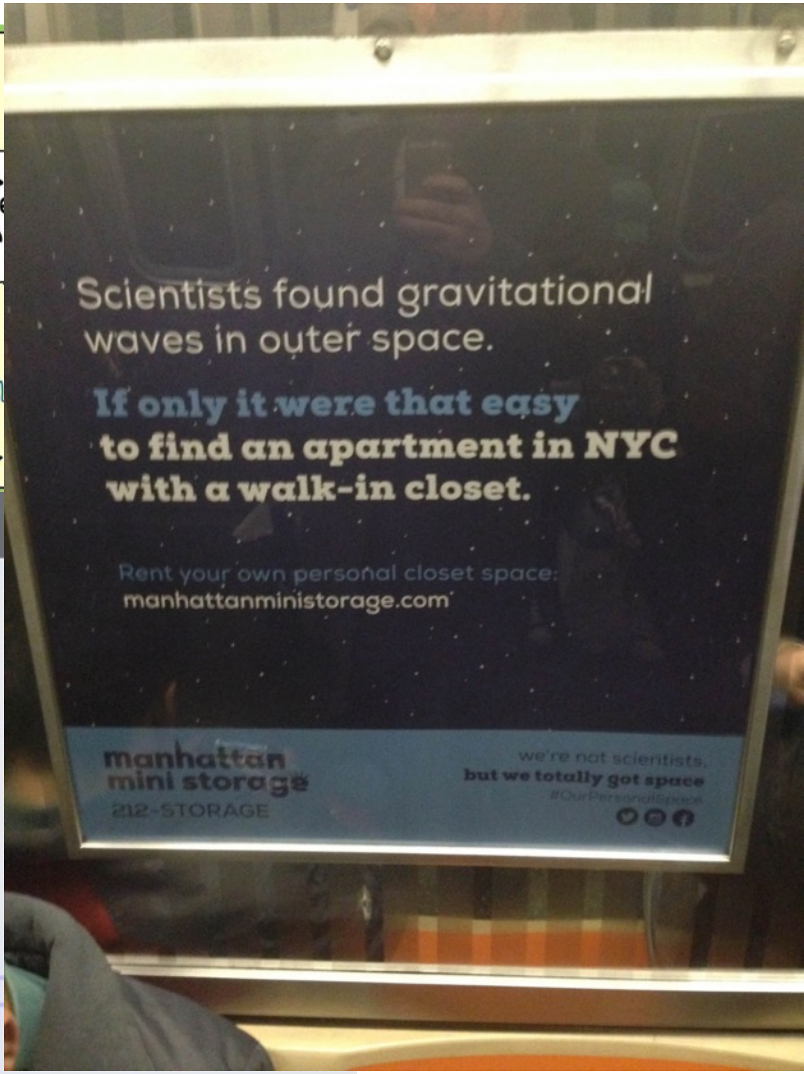
$$v/c = (GM\pi f/c^3)^{1/3}$$

Gravitational Waves in Pop Culture



From The Guardian, Feb 12 2016





Scientists found gravitational waves in outer space.

If only it were that easy to find an apartment in NYC with a walk-in closet.

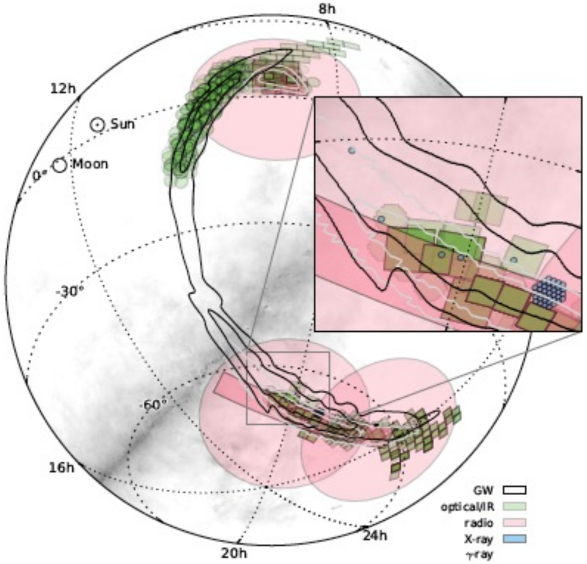
Rent your own personal closet space:
manhattanministorage.com

manhattan mini storage
212-STORAGE

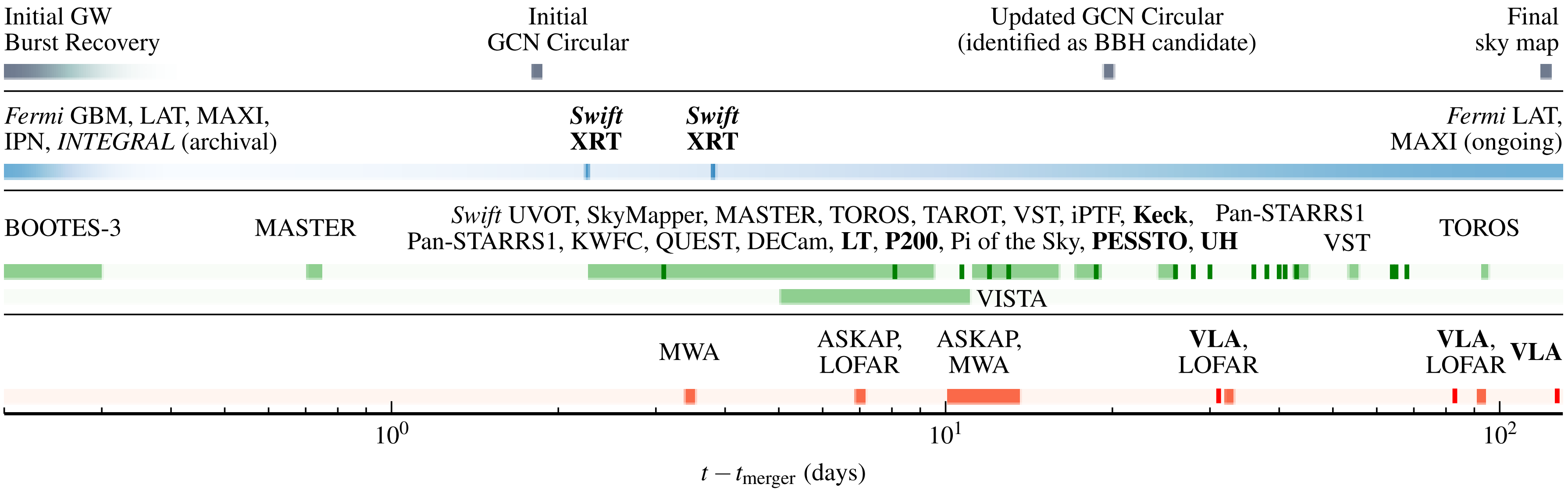
we're not scientists,
but we totally got space
#OurPersonalSpace

GW150914 EM Follow Up

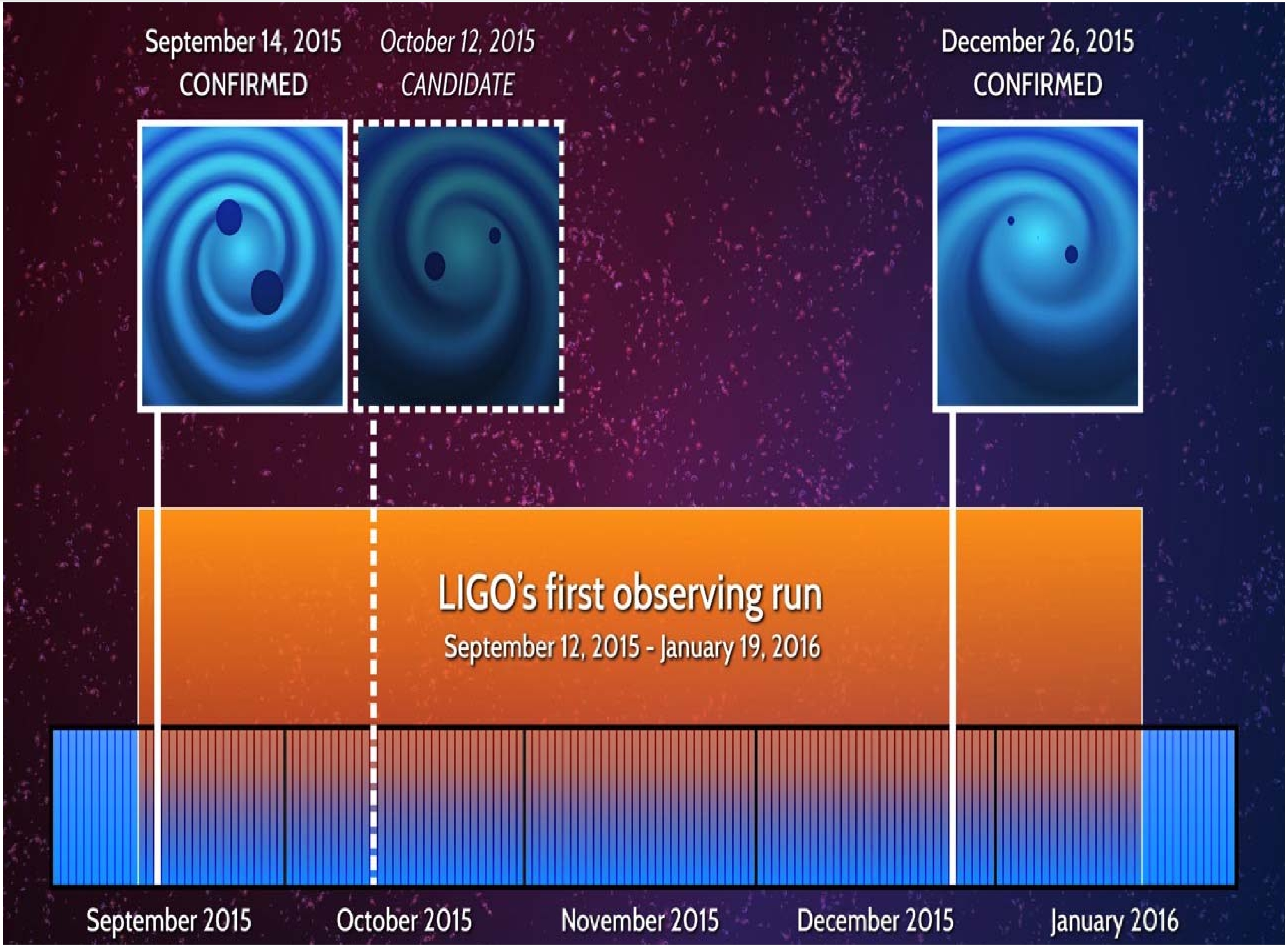
- Follow-up observations reported by 25 teams via private Gamma-ray Coordinates Network (GCN) Circulars



Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, “Localization and Broadband Follow-Up of the Gravitational-Wave Transient GW150914”, Ap. J. Lett, 826:L13, 2016.



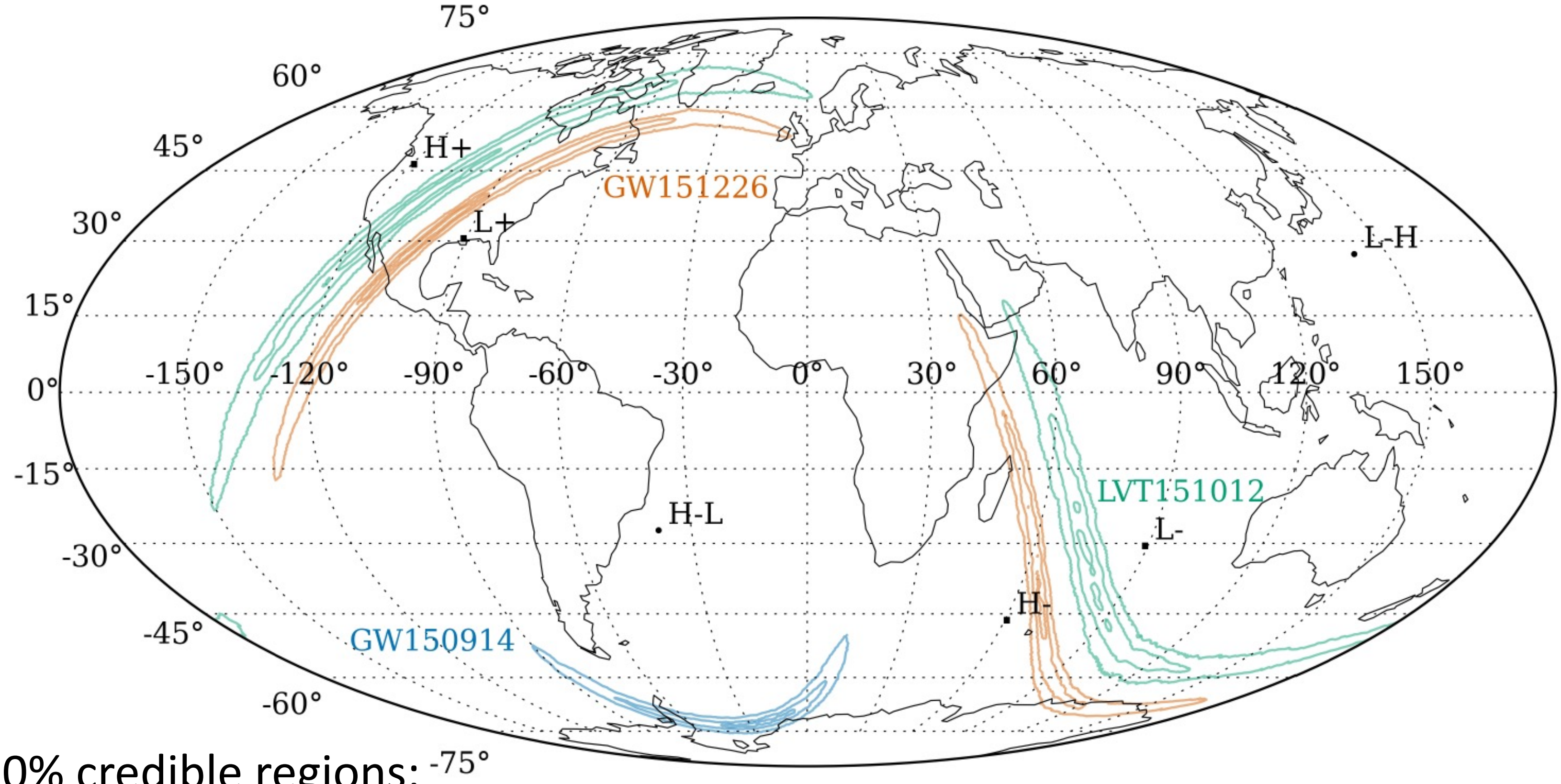
Events Observed during O1



Courtesy Caltech/MIT/LIGO Laboratory

Event Sky Location

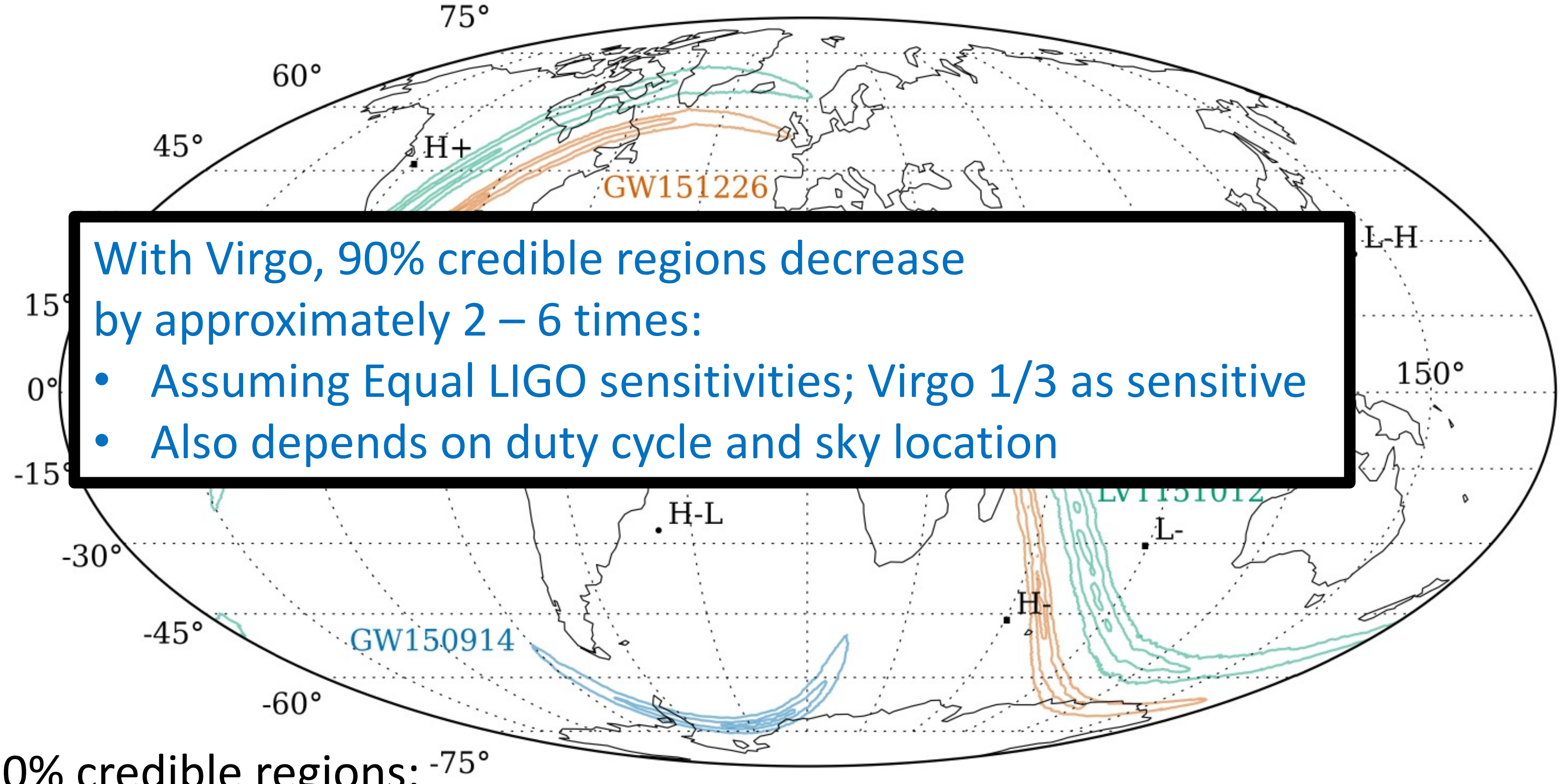
- With 2 detectors can only limit location to annulus on the sky
  - Preferential angles from interferometer antenna patterns



- 90% credible regions:
  - GW150914: 230 deg^2
  - GW151226: 850 deg^2
  - LVT151012: 1600 deg^2
  - (GW170104: 1200 deg^2)

Event Sky Location

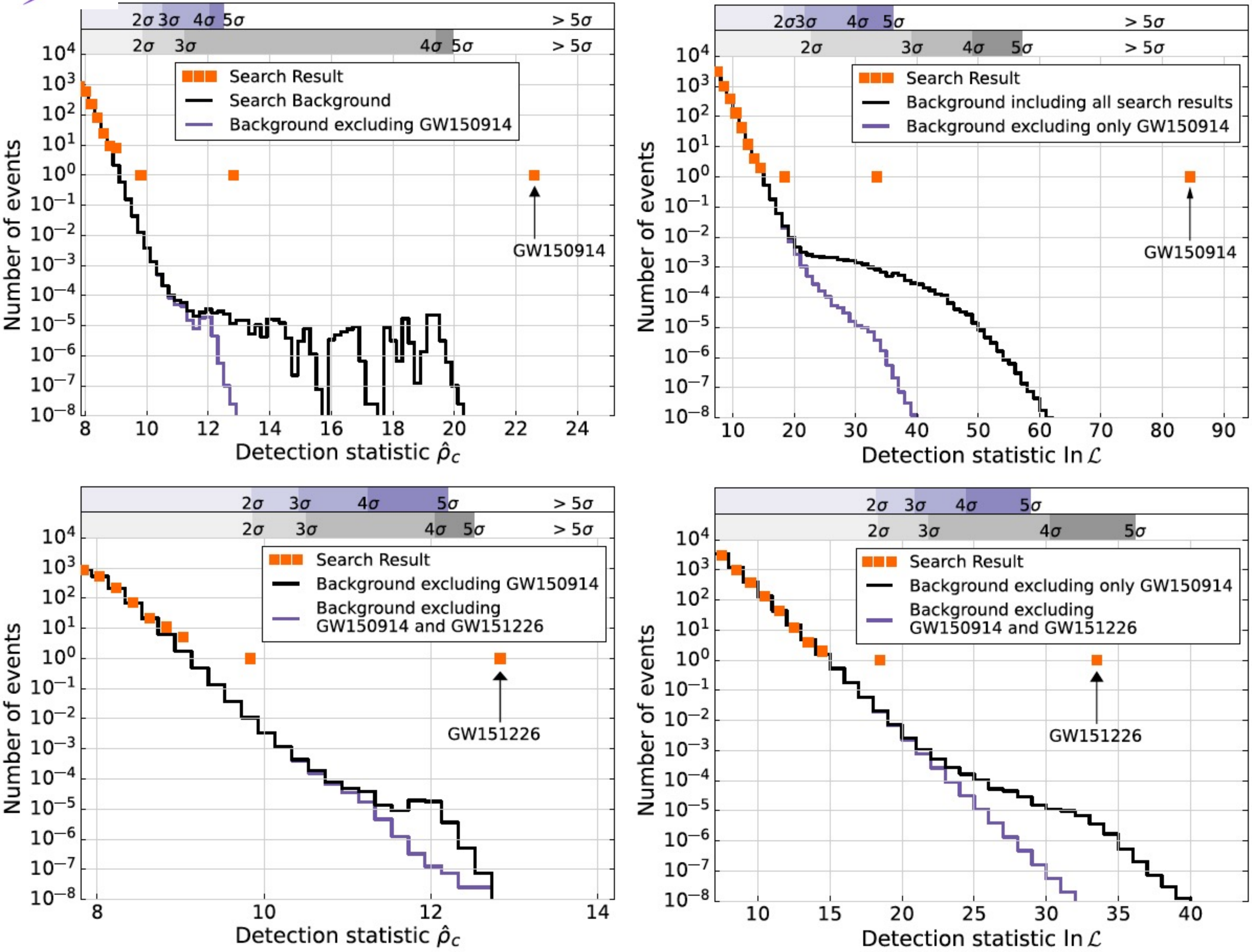
- With 2 detectors can only limit location to annulus on the sky
  - Preferential angles from interferometer antenna patterns



With Virgo, 90% credible regions decrease by approximately 2 – 6 times:
- Assuming Equal LIGO sensitivities; Virgo 1/3 as sensitive
- Also depends on duty cycle and sky location

- 90% credible regions:
  - GW150914: 230 deg^2
  - GW151226: 850 deg^2
  - LVT151012: 1600 deg^2
  - (GW170104: 1200 deg^2)

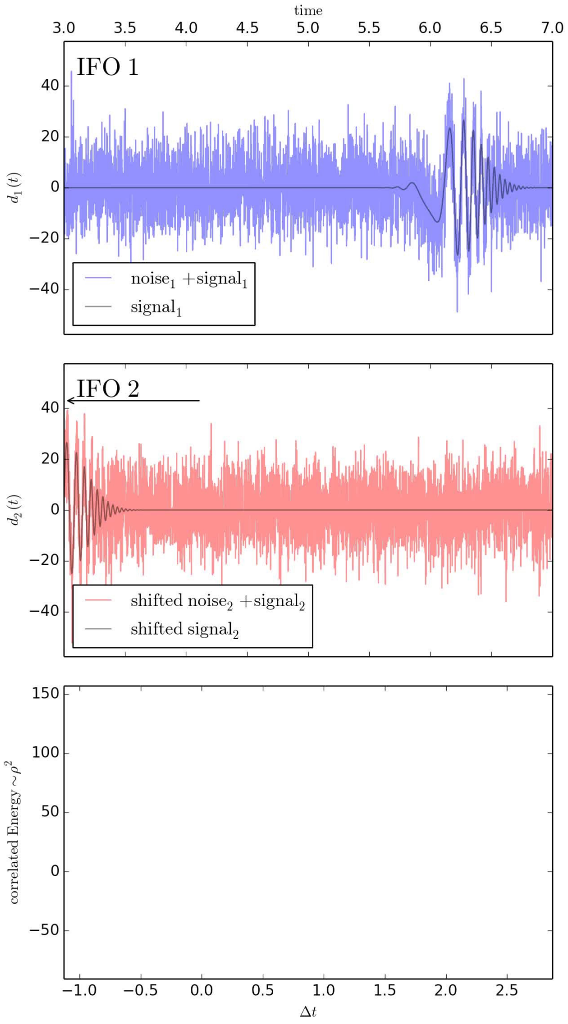
Assessing Statistical Significance: Modeled Search



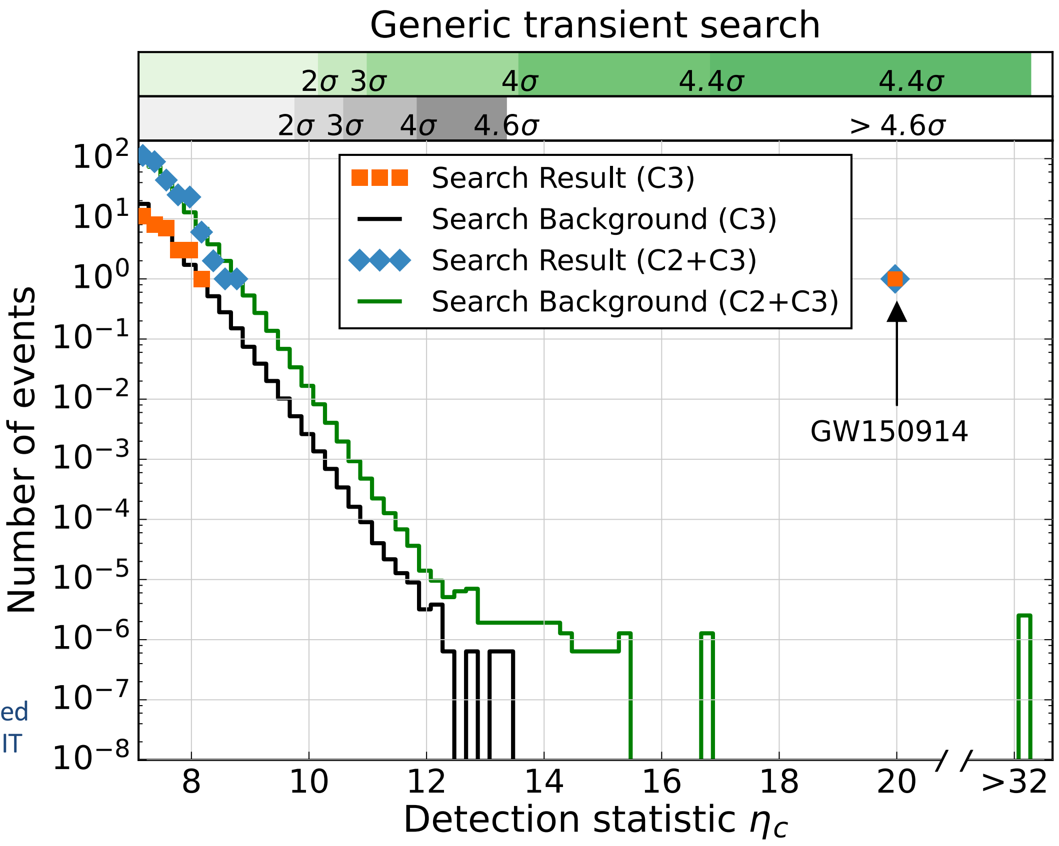
Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, "Binary Black Hole Mergers in the first Advanced LIGO Observing Run", Phys. Rev. X 6, 041015 (2016).

Assessing Statistical Significance: Unmodeled Search

- Pipelines look for excess power in time-frequency domain
  - e.g. wavelet basis
  - More sensitive to generic sources, but also to noise transients in the interferometers



Simulation: Reed Essick, LIGO MIT



Extracting Astrophysical Parameters from Waveforms

- **Total Mass:** $M = m_1 + m_2$
- **Mass ratio:** $q = \frac{m_2}{m_1} \le 1$
- **Chirp Mass:** $\mathscr{M} = \frac{(m_1 m_2)^{3/5}}{M^{1/5}}$

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

- **Black Hole Spins:**

$$a_{1,2} = \frac{c}{Gm_{1,2}^2}|S_{1,2}|$$

- **Spin component aligned with orbital angular momentum:**

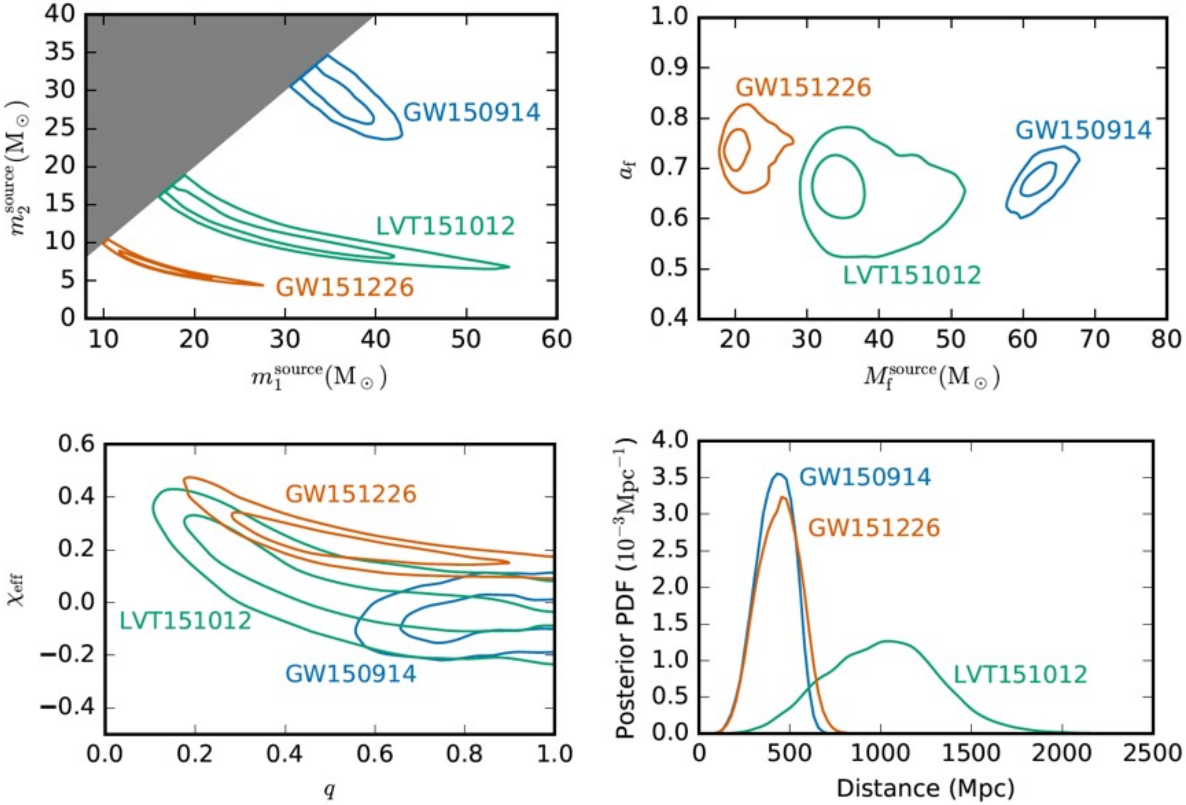
$$\chi_{1,2} = \frac{c}{Gm_{1,2}^2} S_{1,2}\cdot\hat{L}$$

- **Effective spin parameter:**

$$\chi_{\text{eff}} = \frac{m_1\chi_1 + m_2\chi_2}{M}$$

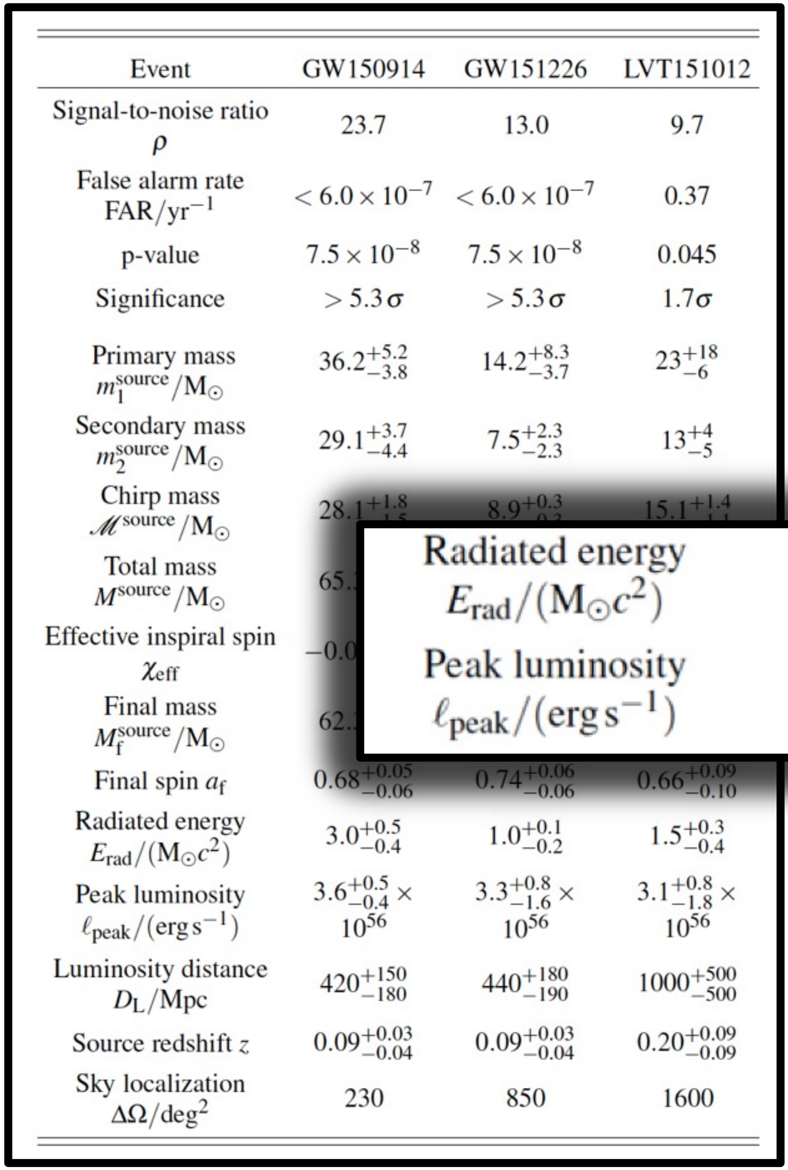
- **Luminosity Distance D_L**

- Bayesian computation of posterior PDFs
  - Markov chain Monte Carlo
  - Nested Sampling

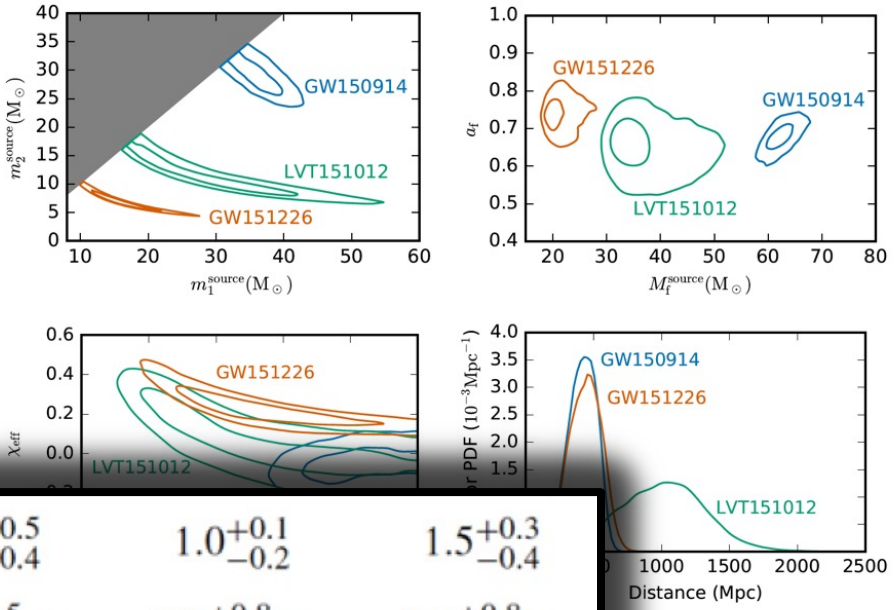


Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, "Binary Black Hole Mergers in the first Advanced LIGO Observing Run", Phys. Rev. X 6, 041015 (2016).

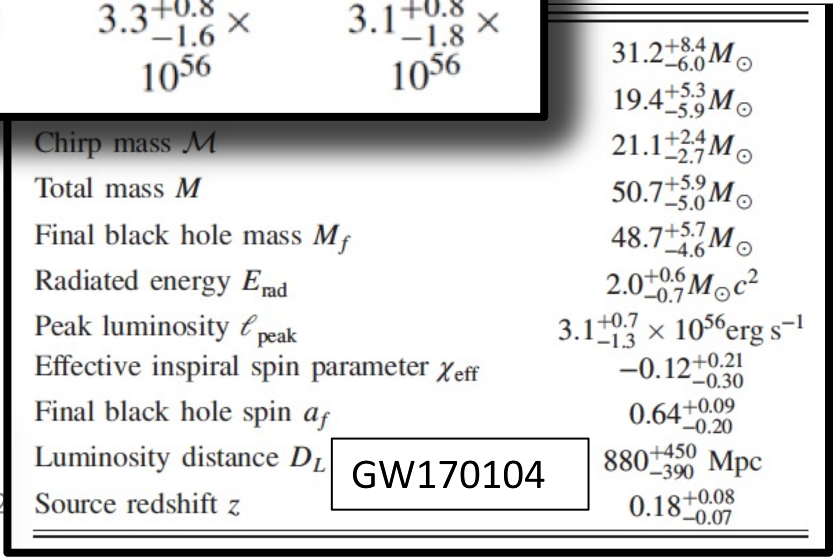
Astrophysical Parameters of the Detected BBH Mergers



Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate $\mathrm{FAR}/\mathrm{yr}^{-1}$	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\,\sigma$	$> 5.3\,\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathcal{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}$	$8.9^{+0.3}$	$15.1^{+1.4}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	65.		
Effective inspiral spin χ_{eff}	−0.0		
Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	62.		
Final spin a_{f}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600



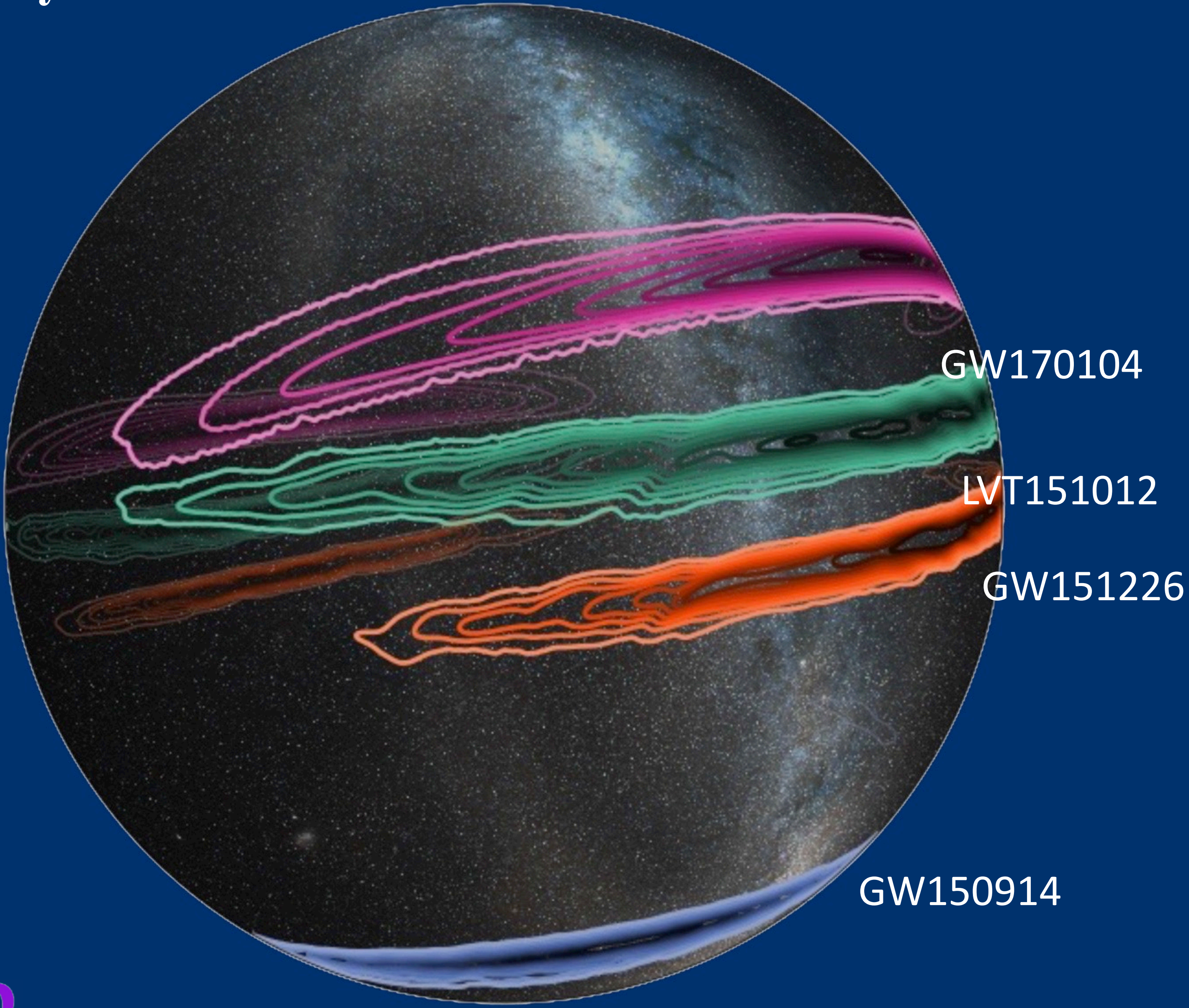
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$



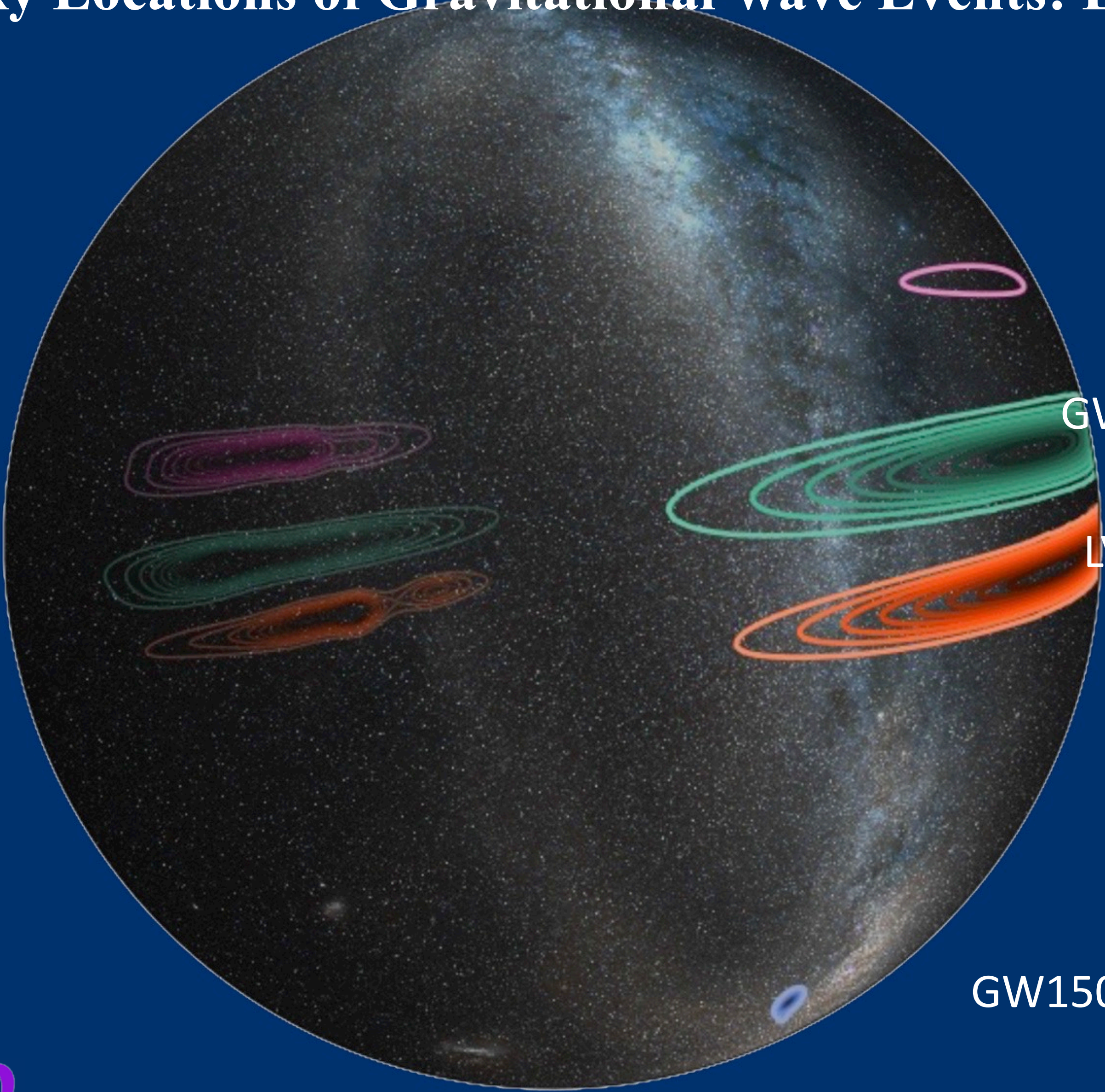
	$31.2^{+8.4}_{-6.0} M_\odot$
	$19.4^{+5.3}_{-5.9} M_\odot$
Chirp mass $\mathcal{M}$	$21.1^{+2.4}_{-2.7} M_\odot$
Total mass M	$50.7^{+5.9}_{-5.0} M_\odot$
Final black hole mass M_f	$48.7^{+5.7}_{-4.6} M_\odot$
Radiated energy E_{rad}	$2.0^{+0.6}_{-0.7} M_\odot c^2$
Peak luminosity ℓ_{peak}	$3.1^{+0.7}_{-1.3} \times 10^{56} \mathrm{erg\ s^{-1}}$
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} Mpc
Source redshift z	$0.18^{+0.08}_{-0.07}$

GW170104

Sky Locations of Gravitational-wave Events: LIGO Only



Sky Locations of Gravitational-wave Events: LIGO + Virgo



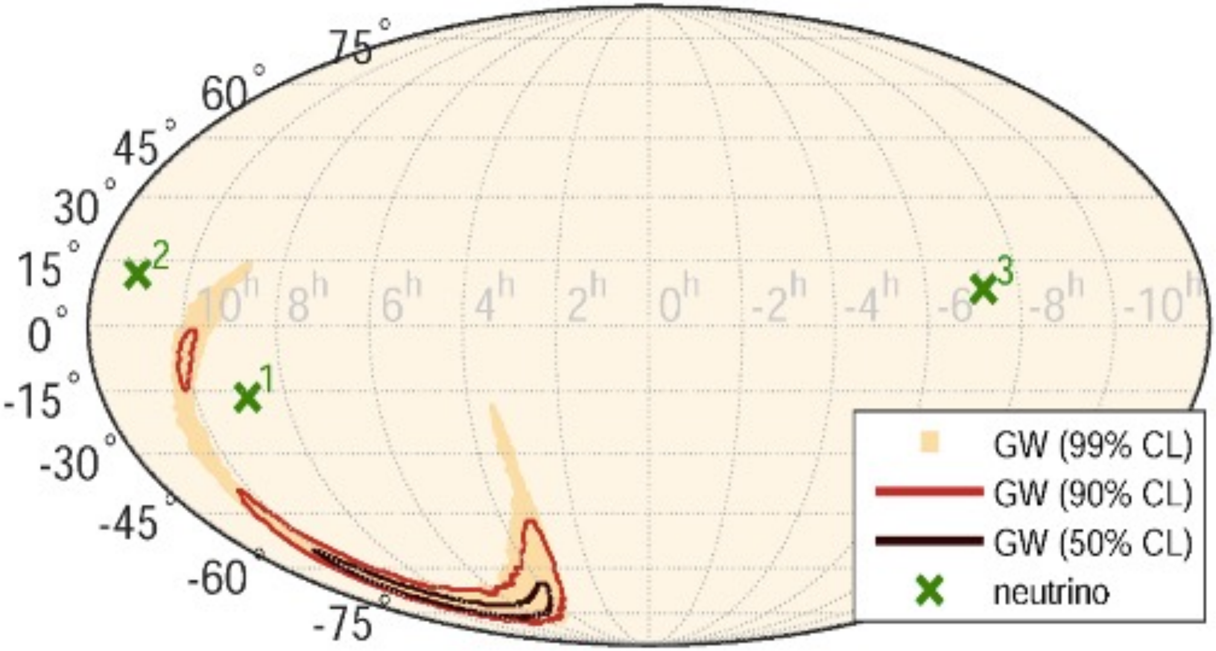
GW170104+V

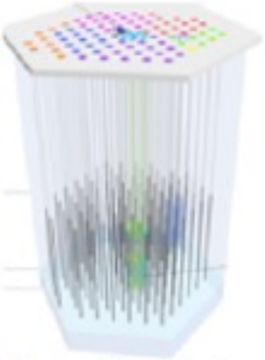
LVT151012+V

GW151226+V

GW150914+V

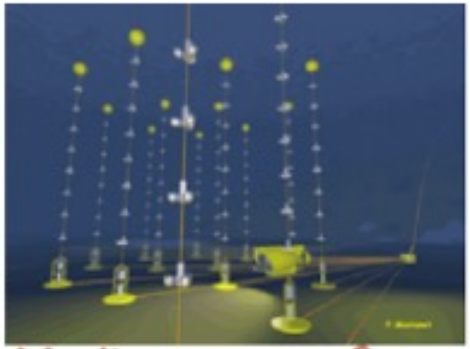
Previous search: GW150914





← IceCube

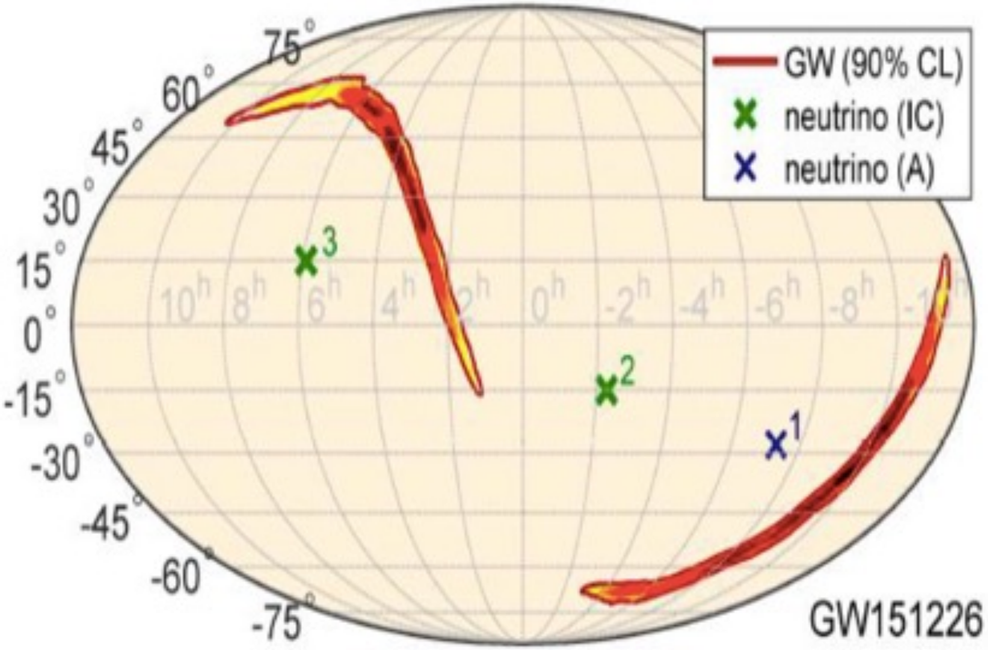
South Pole

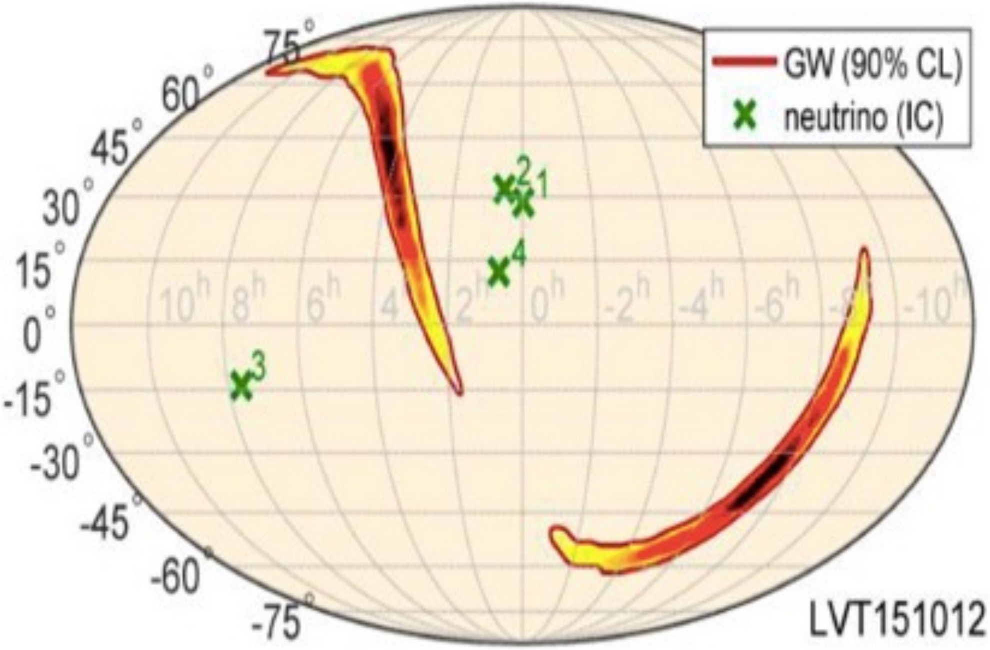


ANTARES →

Mediterranean Sea

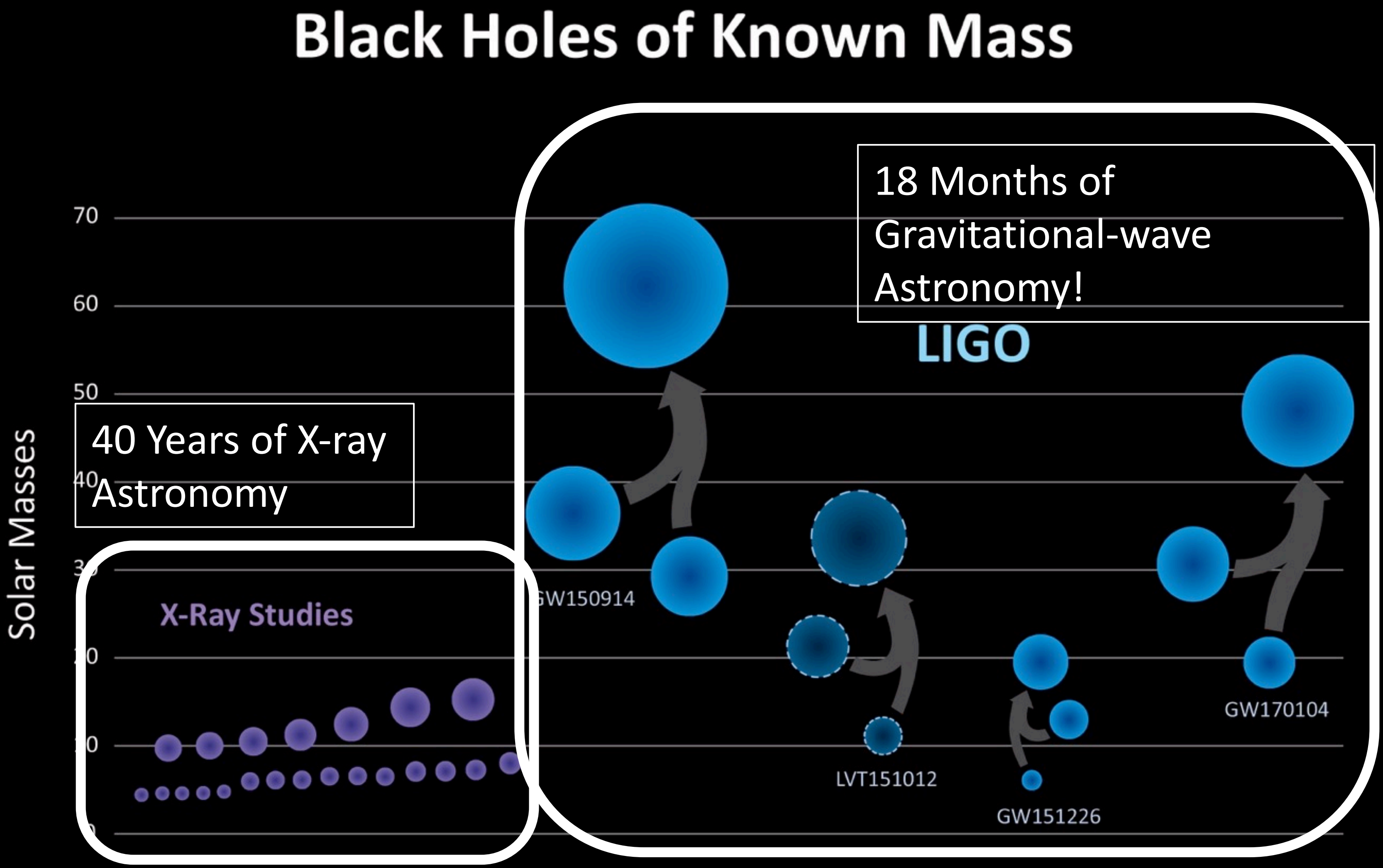
GW151226
&
LVT151012





Event	#	Detector	ΔT [s]	RA [h]	Dec [°]	$\sigma_\mu^{\rm rec}$ [°]	$E_\mu^{\rm rec}$ [TeV]
GW151226	1	ANTARES	−387.3	16.7	−28.0	0.7	9
GW151226	2	IceCube	−290.9	21.7	−15.1	0.1	158
GW151226	3	IceCube	−22.5	5.9	14.9	0.7	6.3
LVT151012	1	IceCube	−423.3	24.0	28.7	3.5	0.38
LVT151012	2	IceCube	−410.0	0.5	32.0	1.1	0.45
LVT151012	3	IceCube	−89.8	7.7	−14.0	0.6	13.7
LVT151012	4	IceCube	147.0	0.6	12.3	0.3	0.35

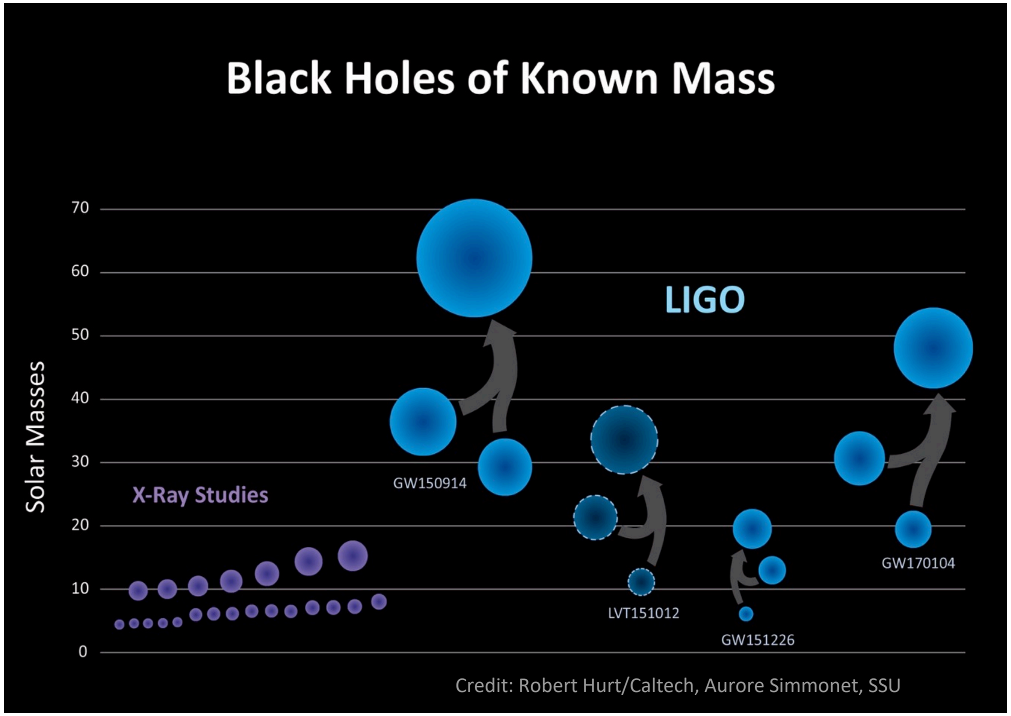
The Black Hole Mass Menagerie



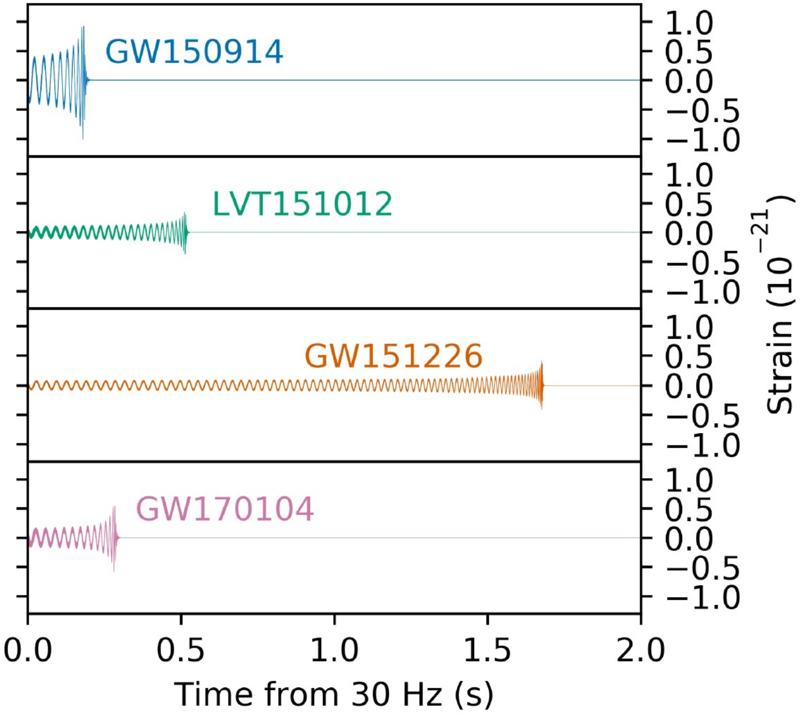
18 Months of Gravitational-wave Astronomy!

40 Years of X-ray Astronomy

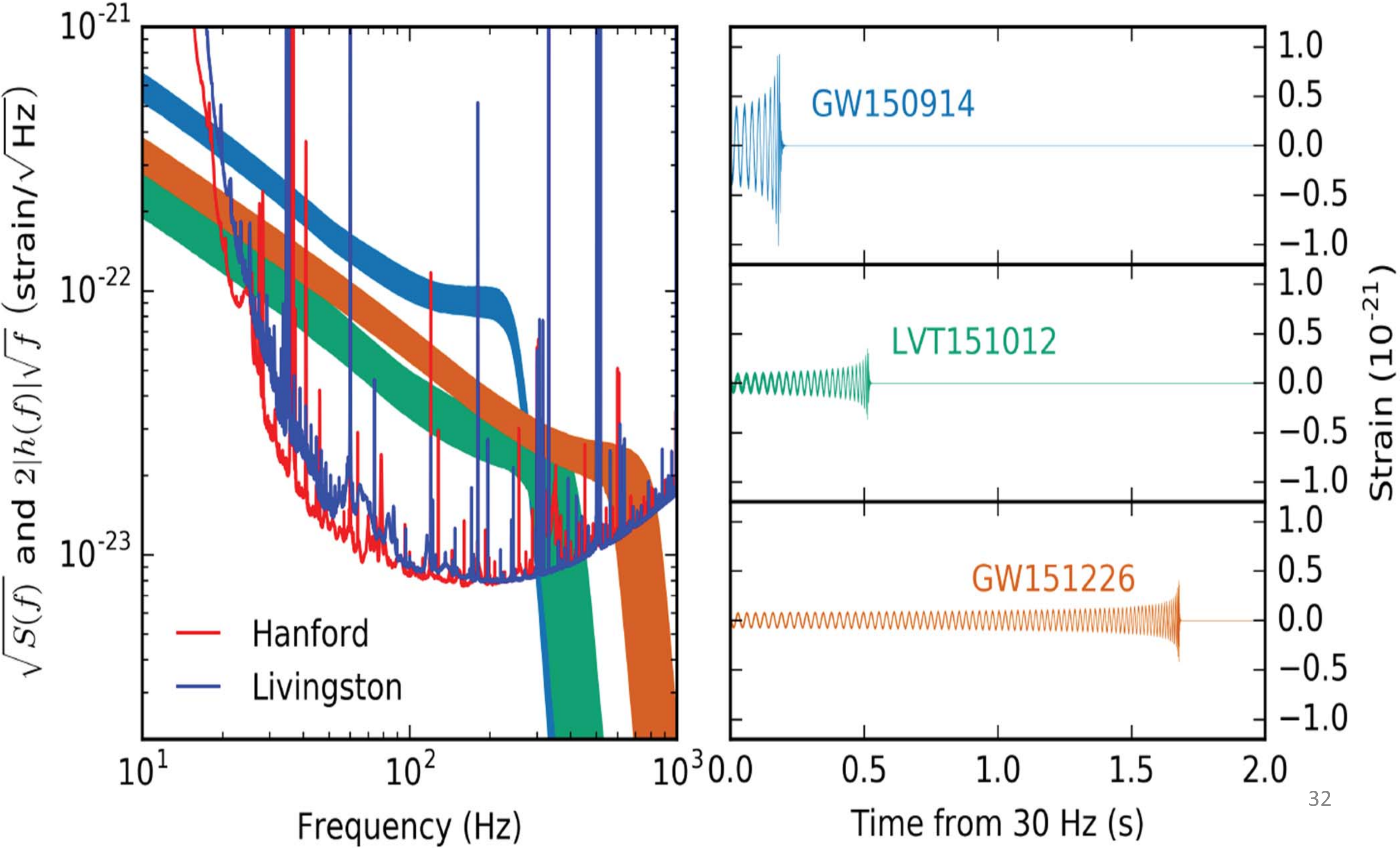
Black Holes Detected By LIGO


Black Holes of Known Mass

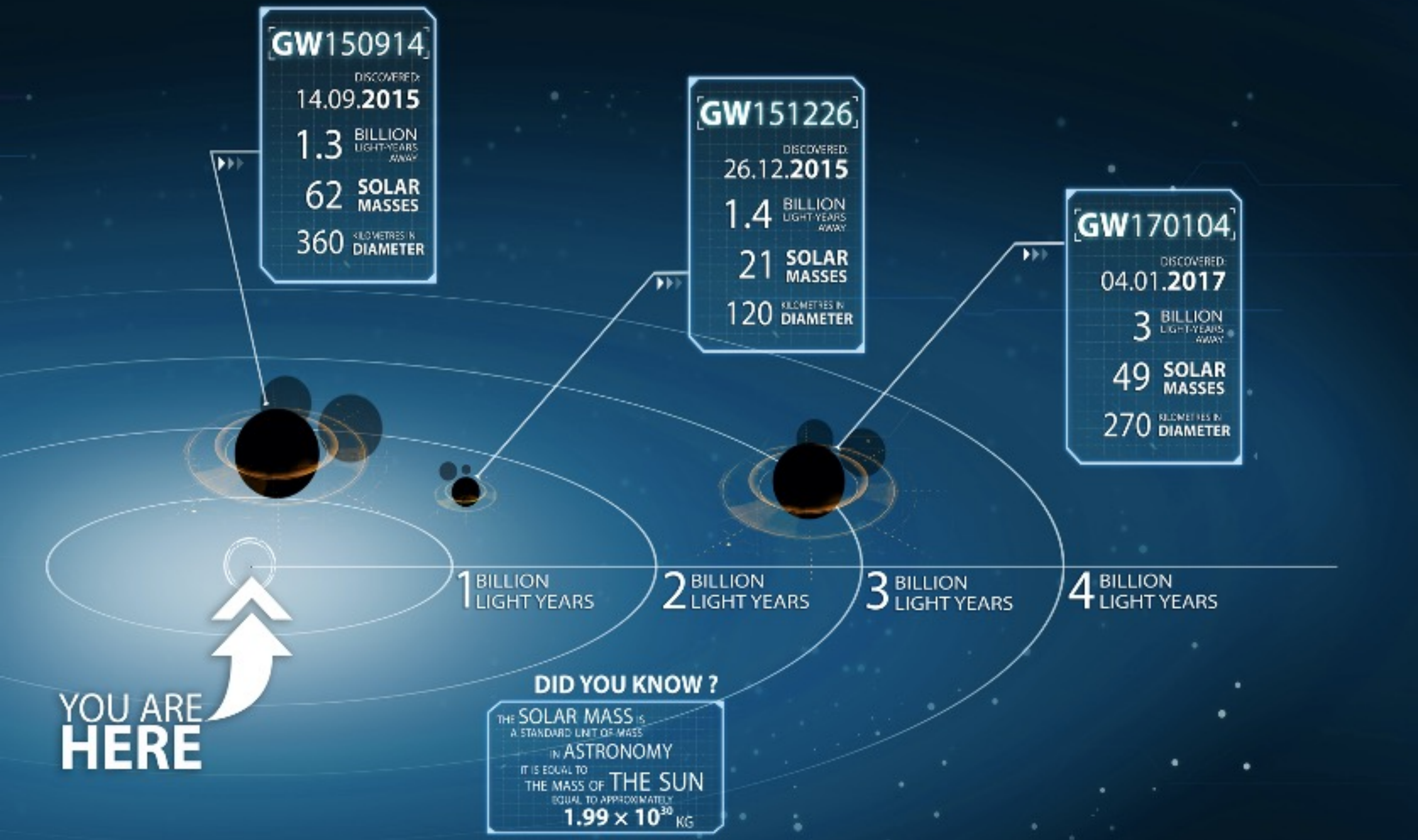
Credit: Robert Hurt/Caltech, Aurore Simmonet, SSU



Frequency dependence of 3 events in O1 compared to the LIGO sensitivity



LIGO'S **GRAVITATIONAL-WAVE** DETECTIONS



GW150914

DISCOVERED:
14.09.**2015**
1.3 BILLION LIGHT-YEARS AWAY
62 **SOLAR MASSES**
360 KILOMETRES IN **DIAMETER**

GW151226

DISCOVERED:
26.12.**2015**
1.4 BILLION LIGHT-YEARS AWAY
21 **SOLAR MASSES**
120 KILOMETRES IN **DIAMETER**

GW170104

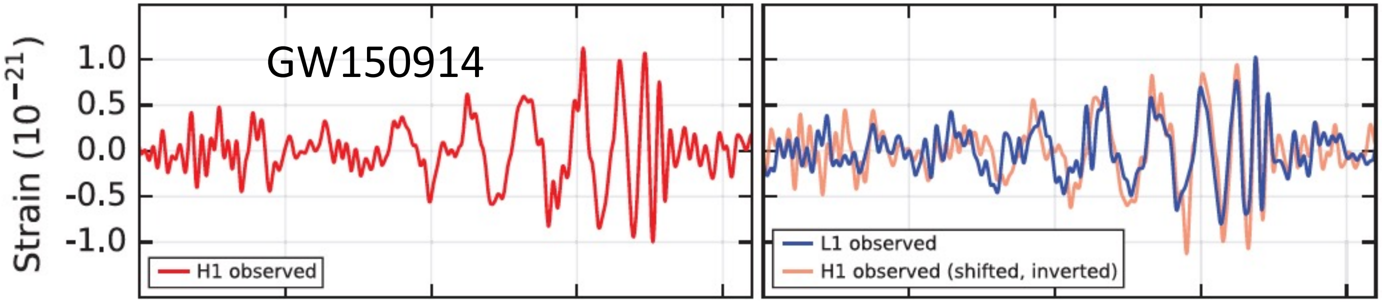
DISCOVERED:
04.01.**2017**
3 BILLION LIGHT-YEARS AWAY
49 **SOLAR MASSES**
270 KILOMETRES IN **DIAMETER**

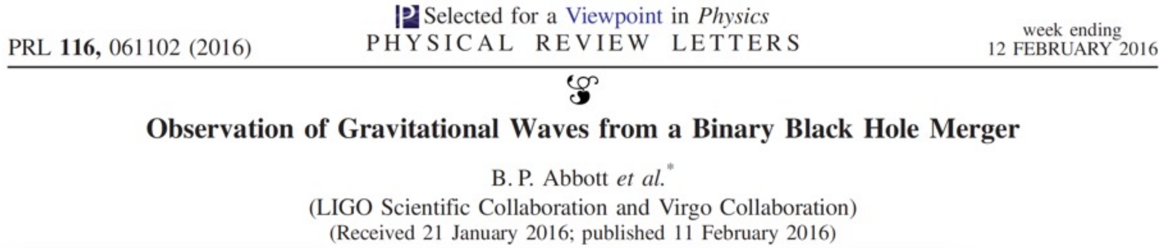
DID YOU KNOW ?

THE SOLAR MASS IS A STANDARD UNIT OF MASS IN ASTRONOMY
IT IS EQUAL TO THE MASS OF THE SUN
EQUAL TO APPROXIMATELY **1.99×10^{30}** KG

Data credit: LIGO Scientific Collaboration/OzGrav ARC Centre of Excellence

Black Holes Detected By LIGO

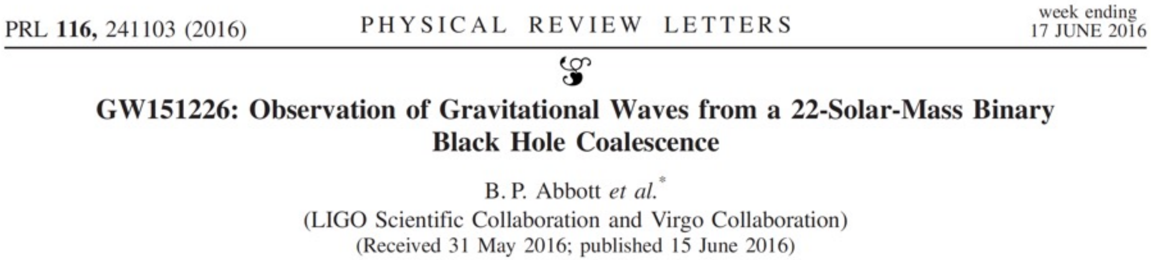



Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

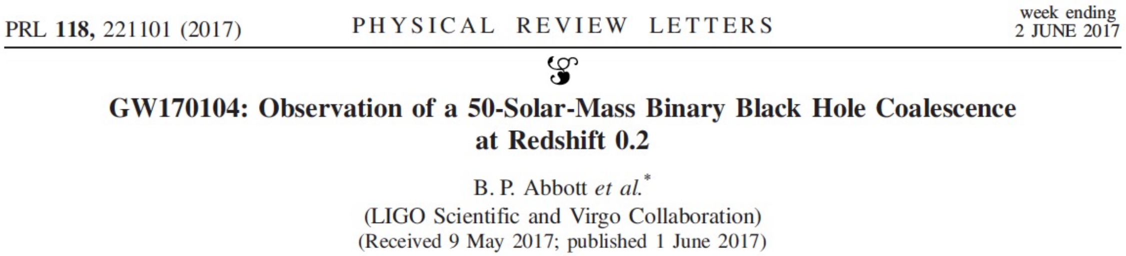
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)


PRL **116,** 241103 (2016) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2016

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

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 31 May 2016; published 15 June 2016)


PRL **118,** 221101 (2017) PHYSICAL REVIEW LETTERS week ending 2 JUNE 2017

GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2

B. P. Abbott *et al.*[*]
(LIGO Scientific and Virgo Collaboration)
(Received 9 May 2017; published 1 June 2017)


PHYSICAL
REVIEW
LETTERS™

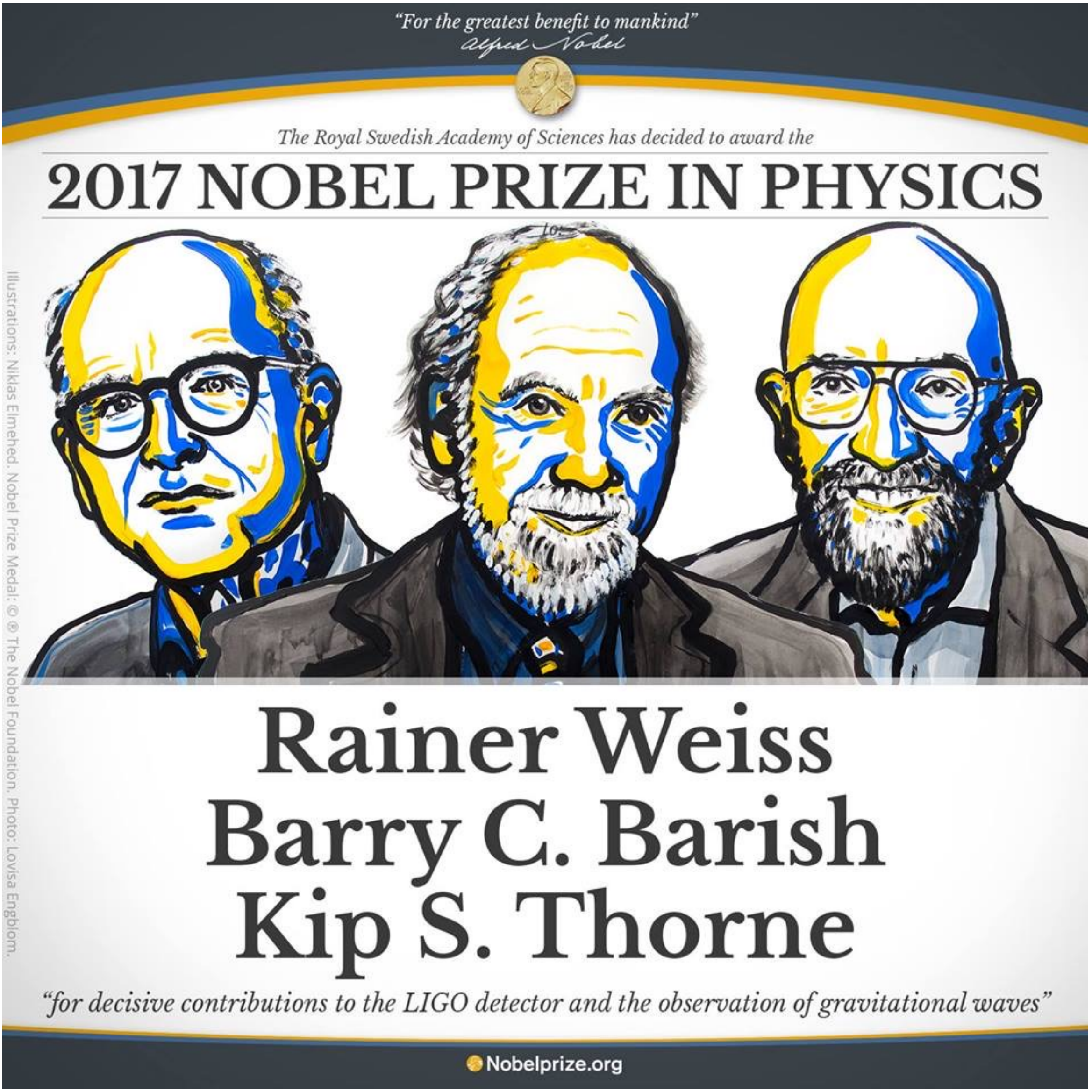
Member Subscription Copy
Library or Other Institutional Use Prohibited Until 2017

Articles published week ending 12 FEBRUARY 2016

Published by
American Physical Society™

APS physics

Volume 116, Number 6



"For the greatest benefit to mankind"
Alfred Nobel

The Royal Swedish Academy of Sciences has decided to award the

2017 NOBEL PRIZE IN PHYSICS

to

Rainer Weiss
Barry C. Barish
Kip S. Thorne

"for decisive contributions to the LIGO detector and the observation of gravitational waves"

Nobelprize.org

Illustrations: Niklas Elmehed. Nobel Prize Medal: © ® The Nobel Foundation. Photo: Lovisa Engblom.

LIGO
@LIGO

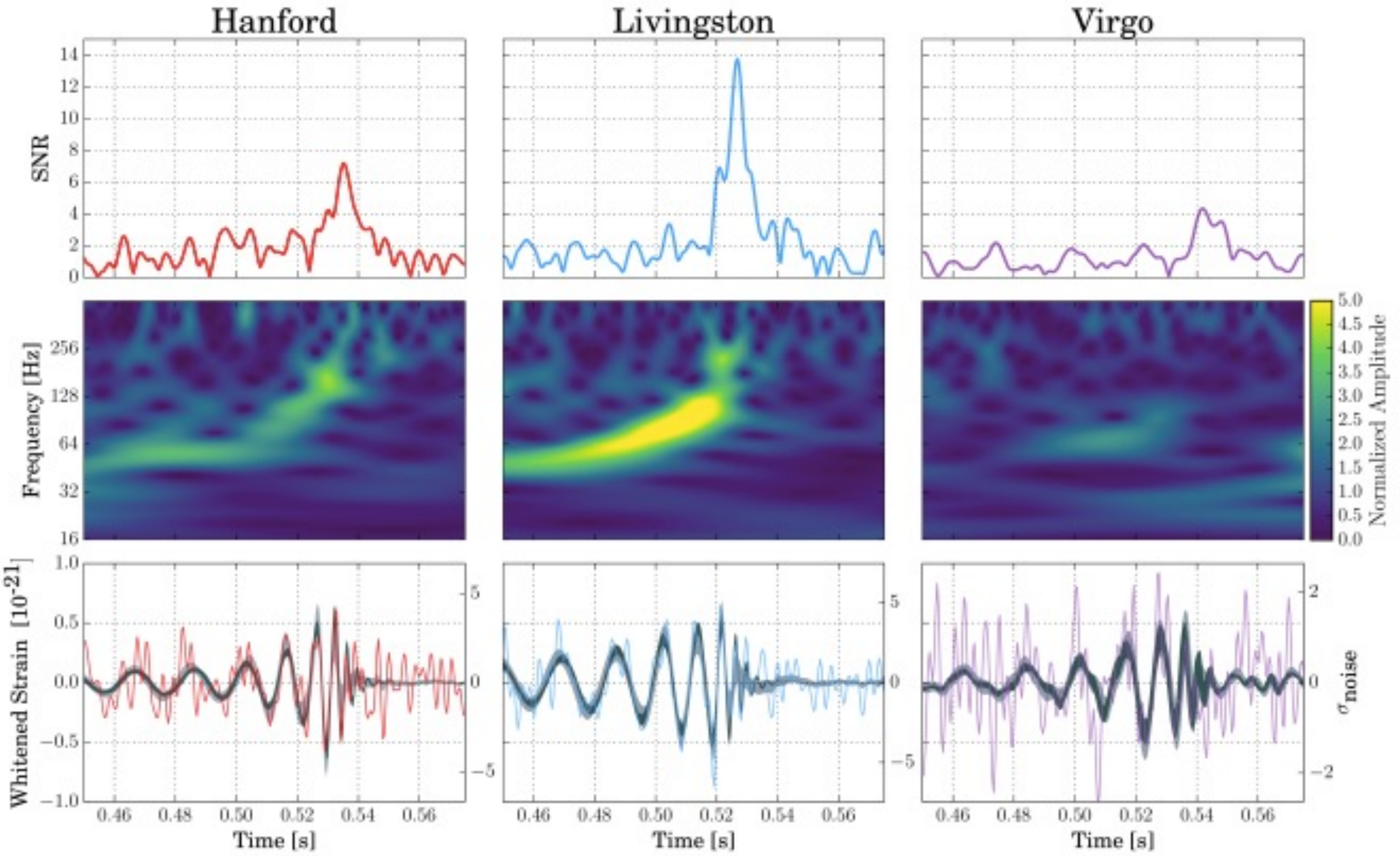
The 2017 winners of the @NobelPrize in Physics: @LIGO pioneers Rai Weiss, Kip Thorne and Barry Barish. Watch their lectures online at youtube.com/watch?v=scVyxV...

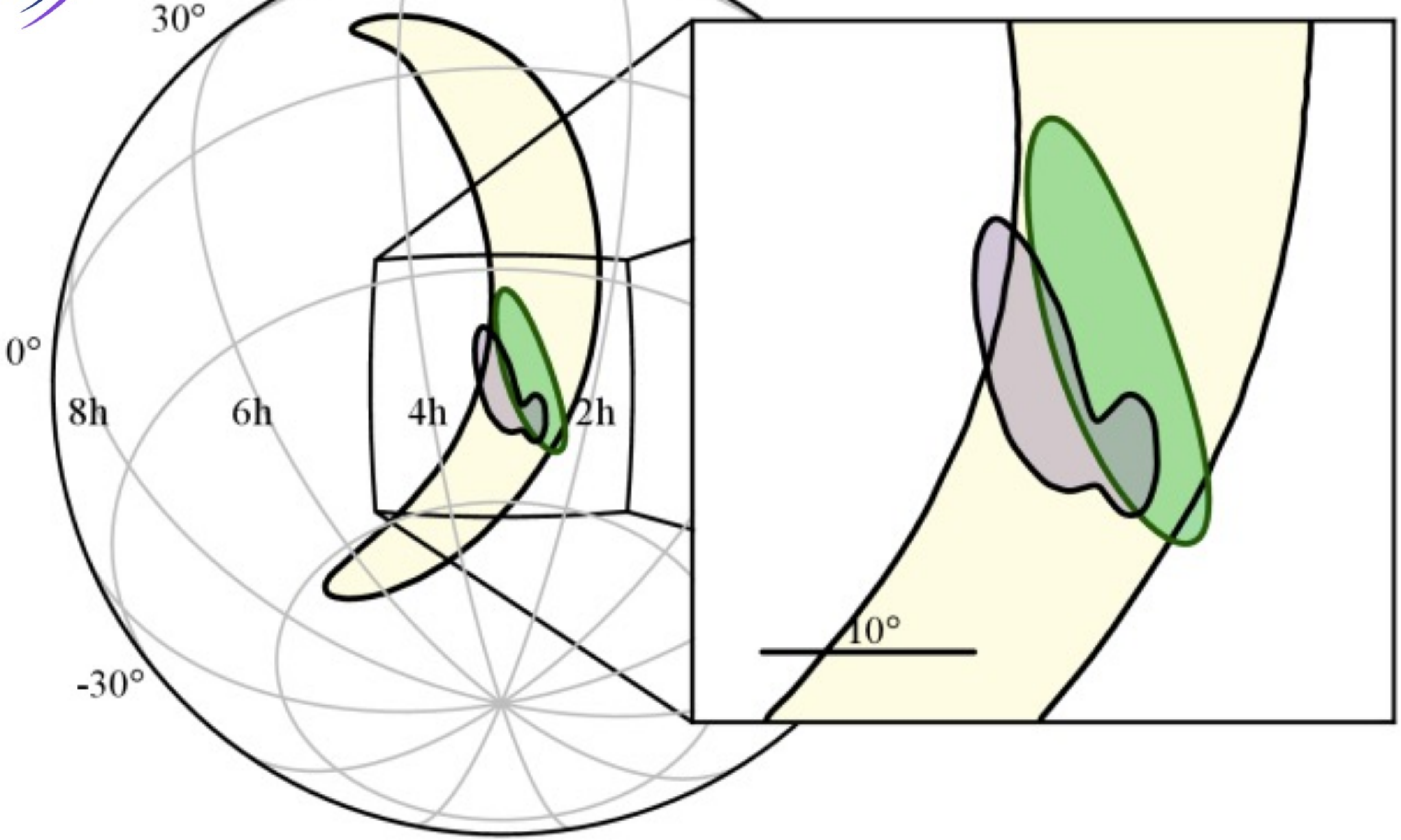
12:26 PM - 8 Dec 2017

92 Retweets 208 Likes

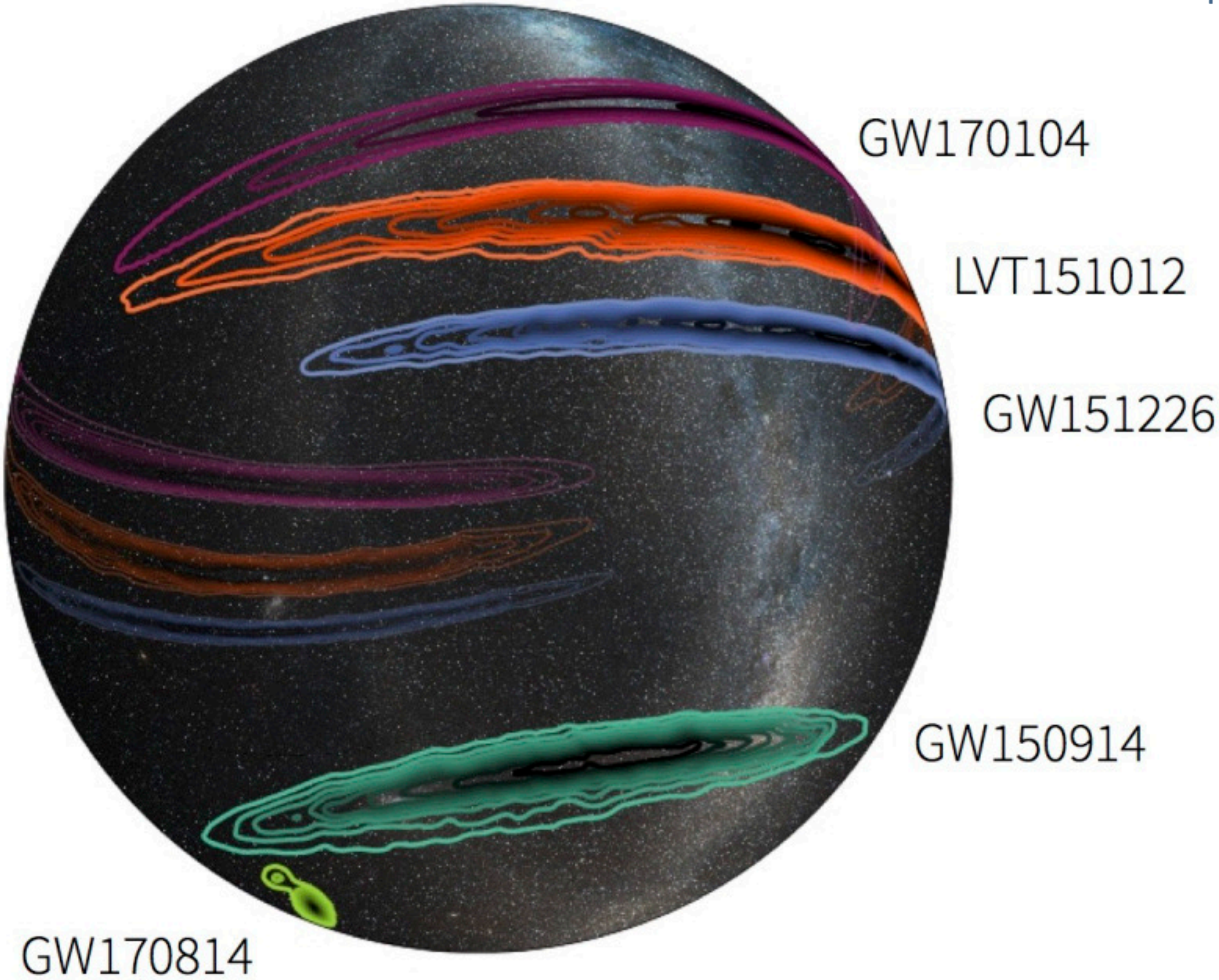
4 92 208

GW170814: First three-detector signal





If we only had the two LIGO detectors, we'd have an uncertainty on the source's sky position of over 1000 square degrees (yellow), but adding in Virgo, we get this down to 60 square degrees (green). The purple map is the final localization from our full parameter estimation analysis. That's still pretty large by astronomical standards (the full Moon is about a quarter of a square degree), but a fantastic improvement!

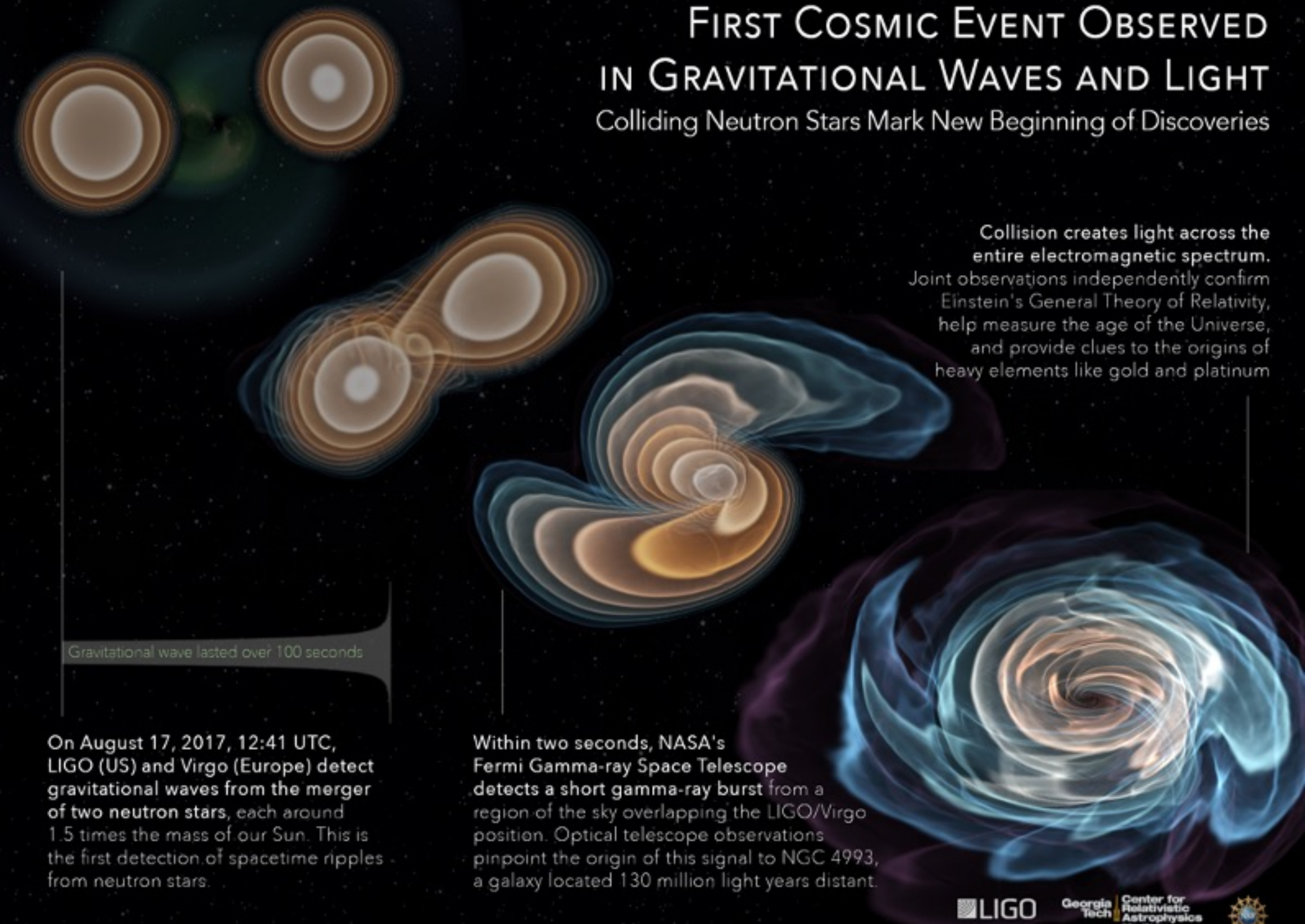

GW170104
LVT151012
GW151226
GW150914
GW170814

GW170817: observation of a binary neutron star merger

GW170817:
observation of a binary neutron star merger

FIRST COSMIC EVENT OBSERVED IN GRAVITATIONAL WAVES AND LIGHT

Colliding Neutron Stars Mark New Beginning of Discoveries



Collision creates light across the entire electromagnetic spectrum. Joint observations independently confirm Einstein's General Theory of Relativity, help measure the age of the Universe, and provide clues to the origins of heavy elements like gold and platinum

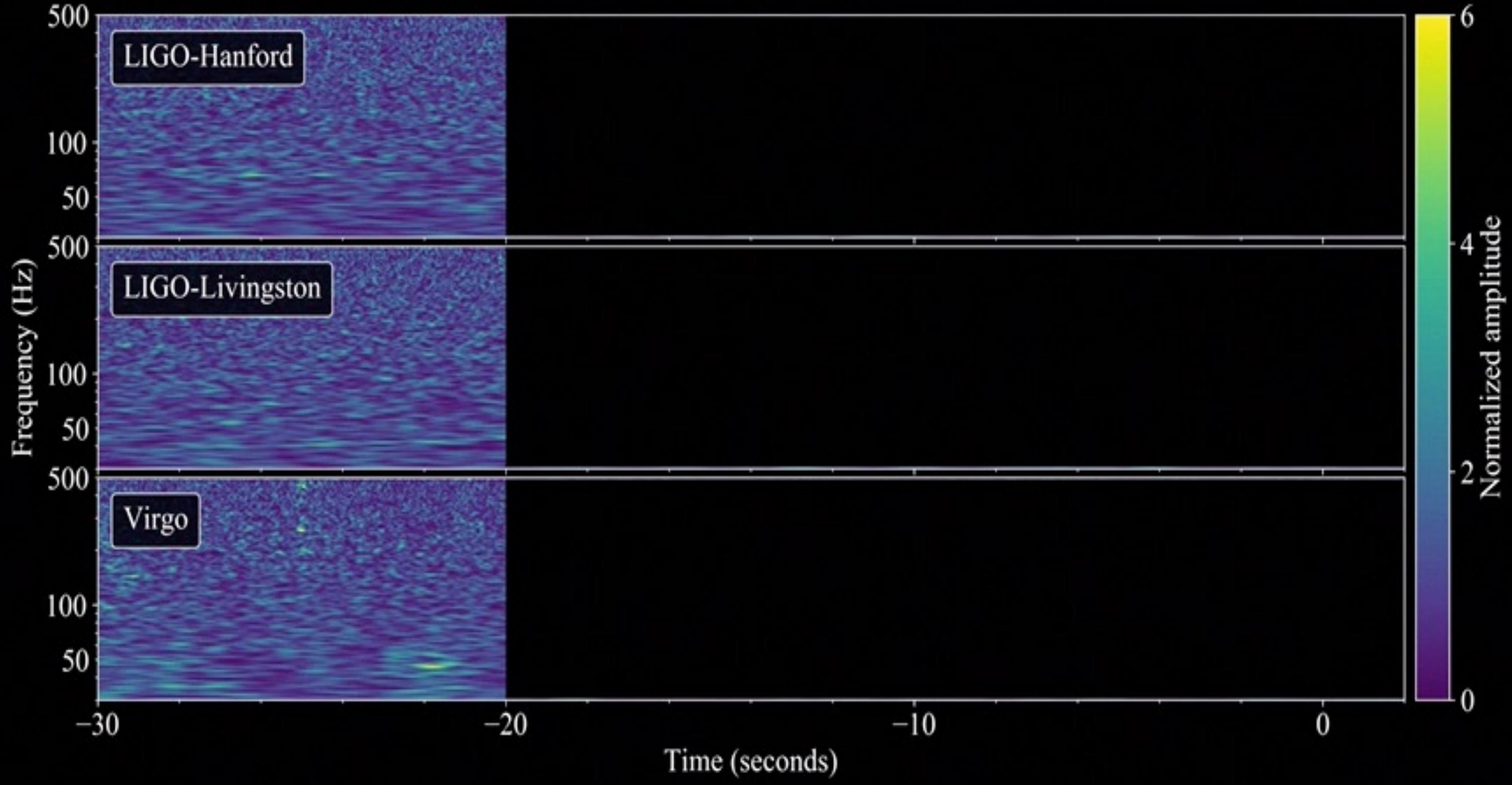
On August 17, 2017, 12:41 UTC, LIGO (US) and Virgo (Europe) detect gravitational waves from the merger of two neutron stars, each around 1.5 times the mass of our Sun. This is the first detection of spacetime ripples from neutron stars.

Within two seconds, NASA's Fermi Gamma-ray Space Telescope detects a short gamma-ray burst from a region of the sky overlapping the LIGO/Virgo position. Optical telescope observations pinpoint the origin of this signal to NGC 4993, a galaxy located 130 million light years distant.

LIGO

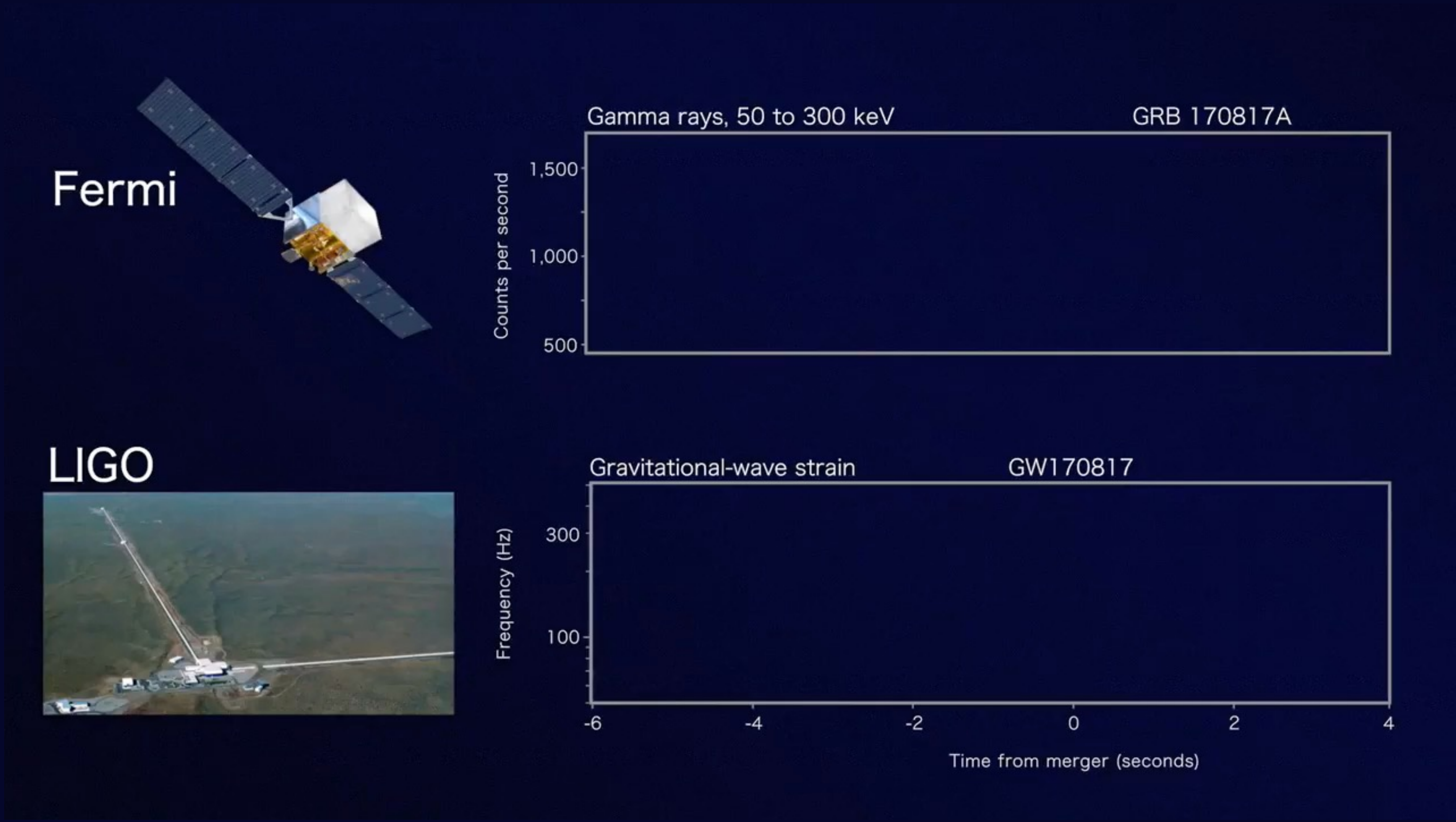
Georgia Tech | Center for Relativistic Astrophysics

GW170817



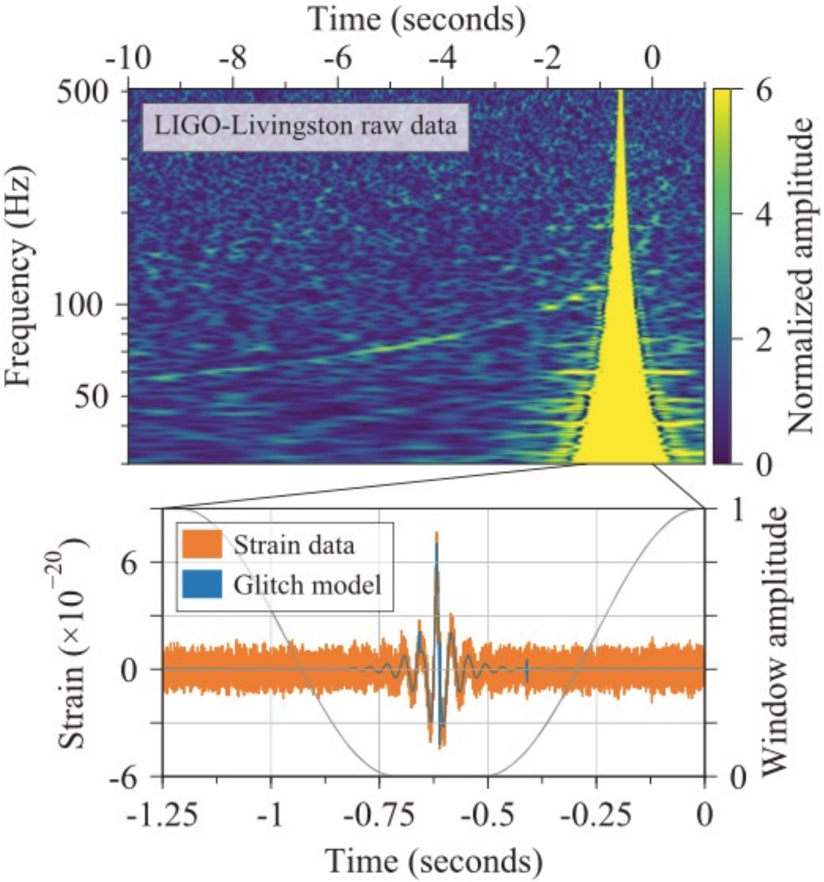
https://doi.org/10.1103/PhysRevLett.119.161101

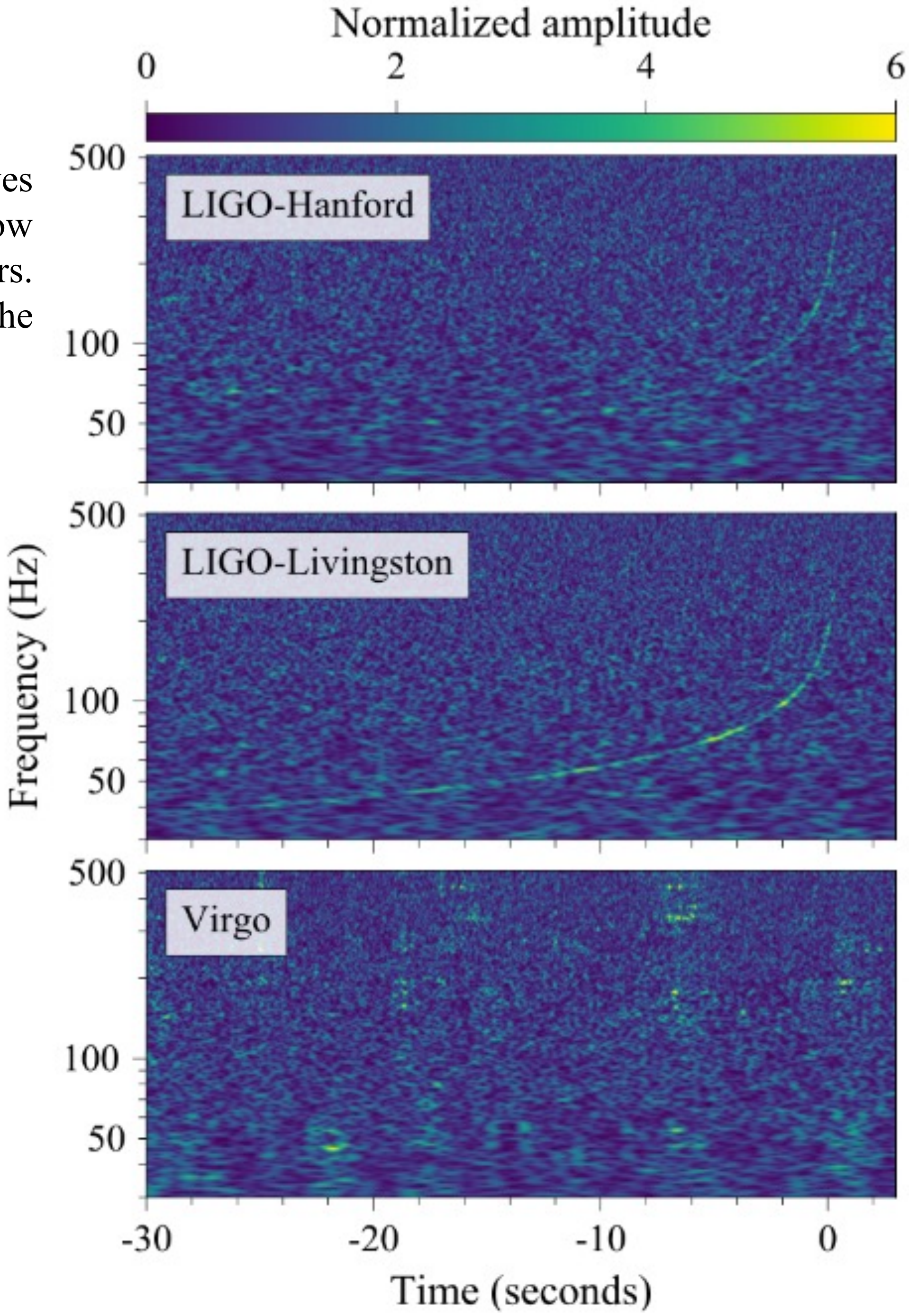
Fermi detected a short gamma ray burst in coincidence with GW170817

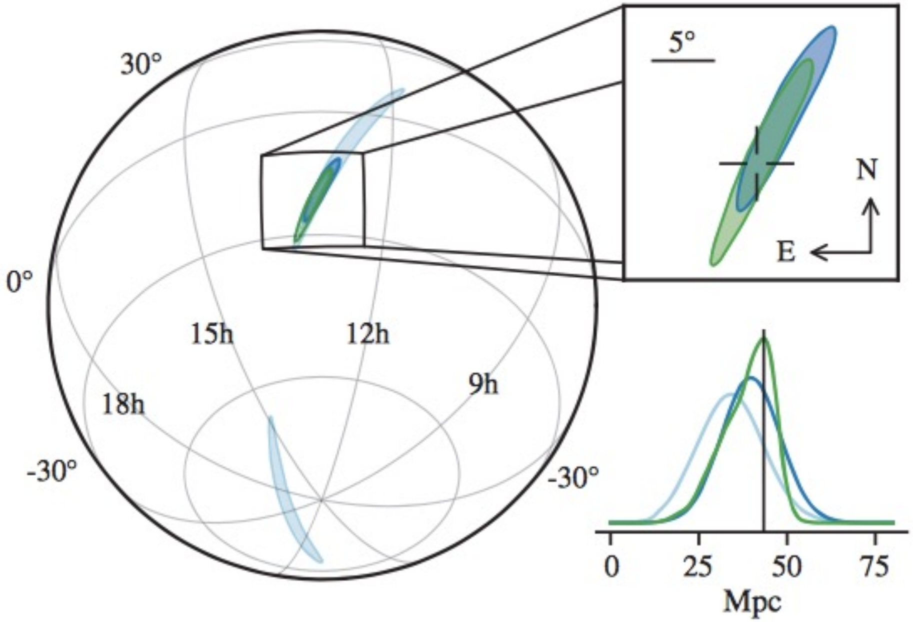


Credit: NASA GSFC & Caltech/MIT/LIGO Lab

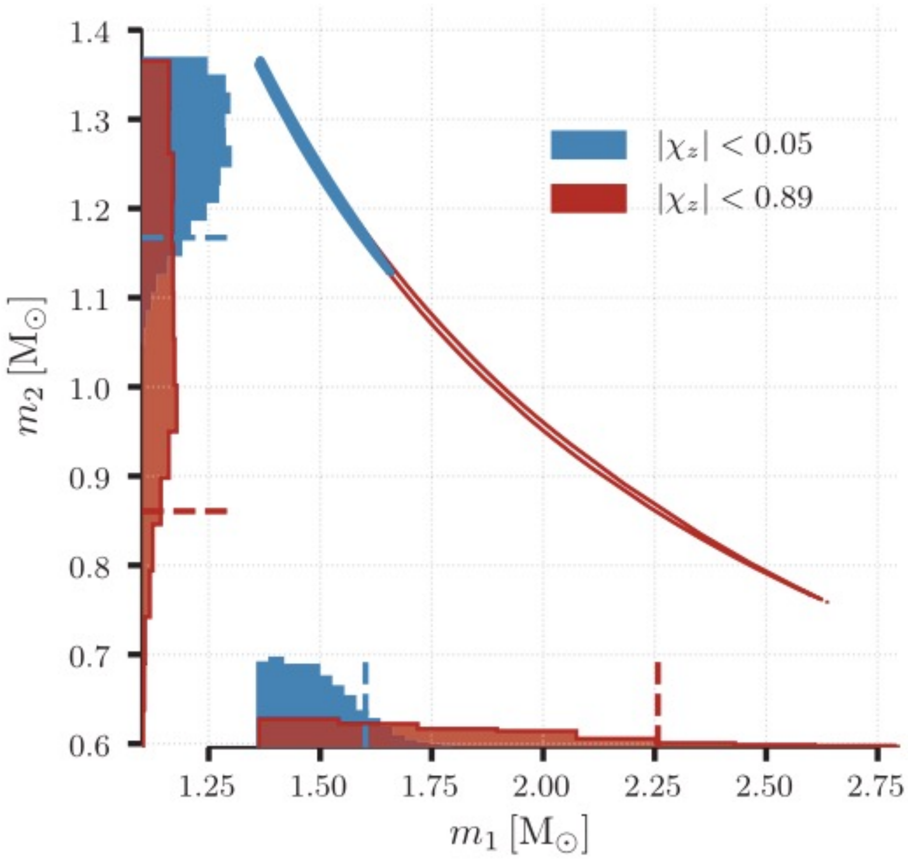
Shown here is a spectrogram of the gravitational waves as seen in the LIGO-Livingston detector. Here we show the spectrograms from all three LIGO-Virgo detectors. You can see the characteristic "chirp", when the frequency increases, of a binary merger.





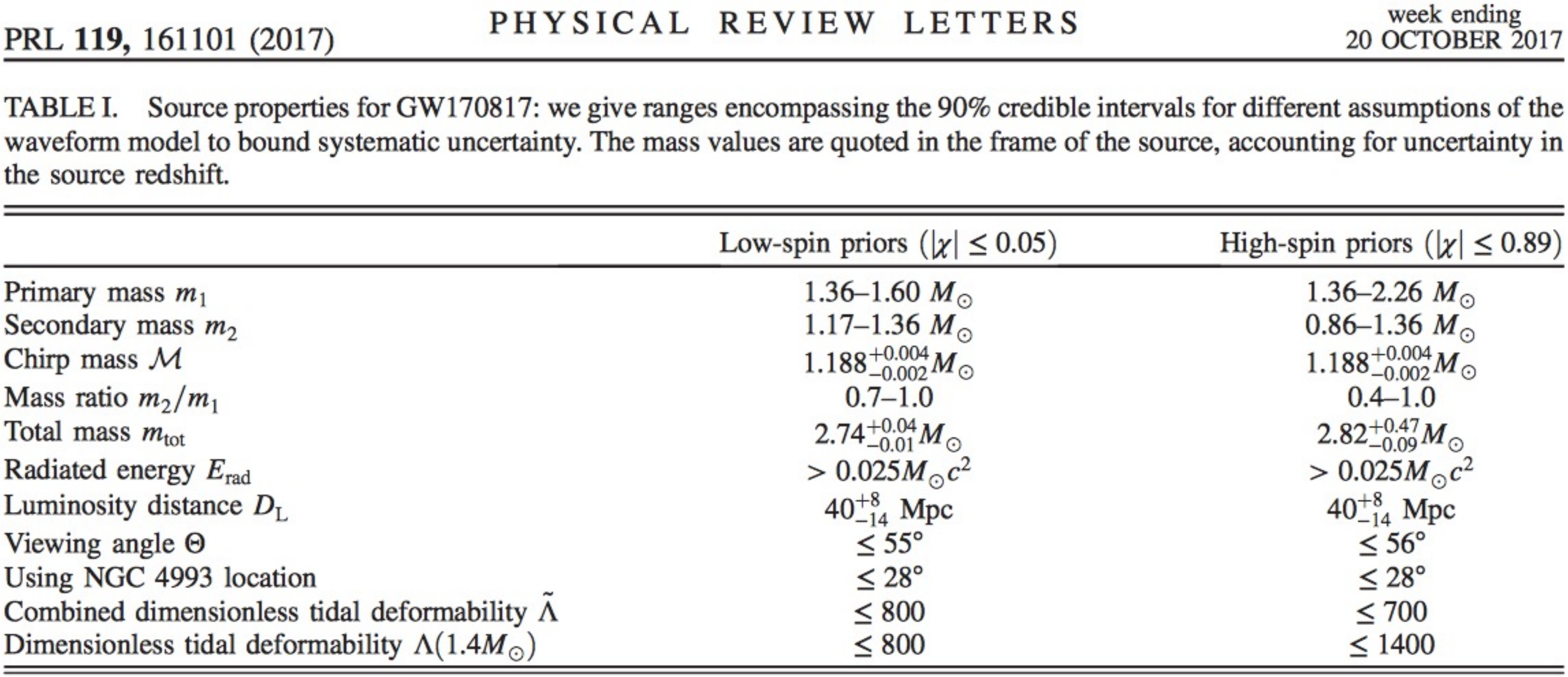


Sky location reconstructed for GW170817 by a rapid localization algorithm from a Hanford-Livingston (190 deg^2, light blue contours) and Hanford-Livingston-Virgo (31 deg^2, dark blue contours) analysis. A higher latency Hanford-Livingston-Virgo analysis improved the localization (**28 deg^2**, green contours). In the top-right inset panel, the reticle marks the position of the apparent host galaxy NGC 4993.



Two dimentional posterior distribution for the component masses m_1 and m_2 in the rest frame of the source for the low-spin scenario ($|\chi| < 0.05$, blue) and the high-spin scenario ($|\chi| < 0.89$, red). The colored contours enclose 90% of the probability from the joint posterior probability density function for m_1 and m_2.

GW170817:
observation of a binary neutron star merger

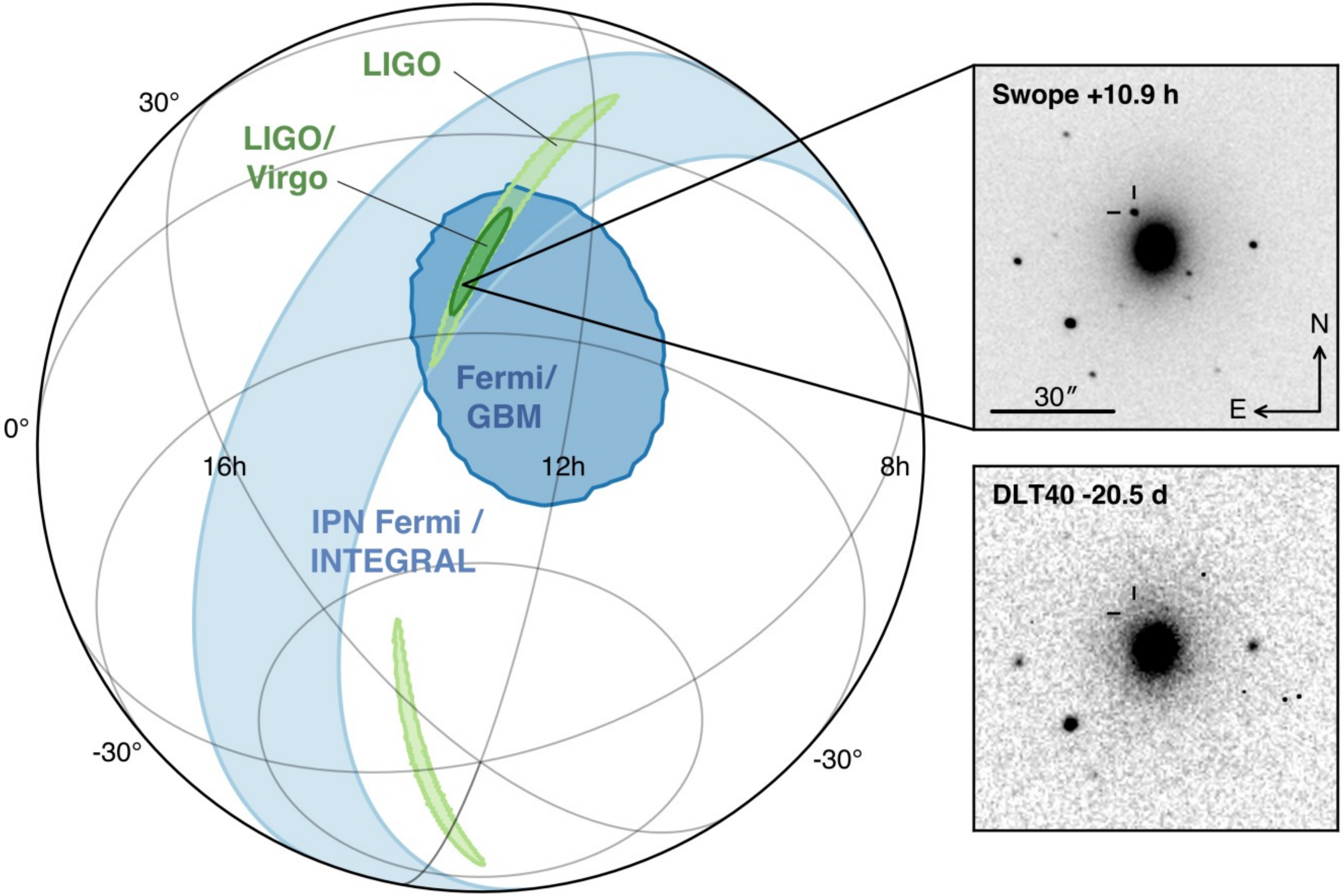


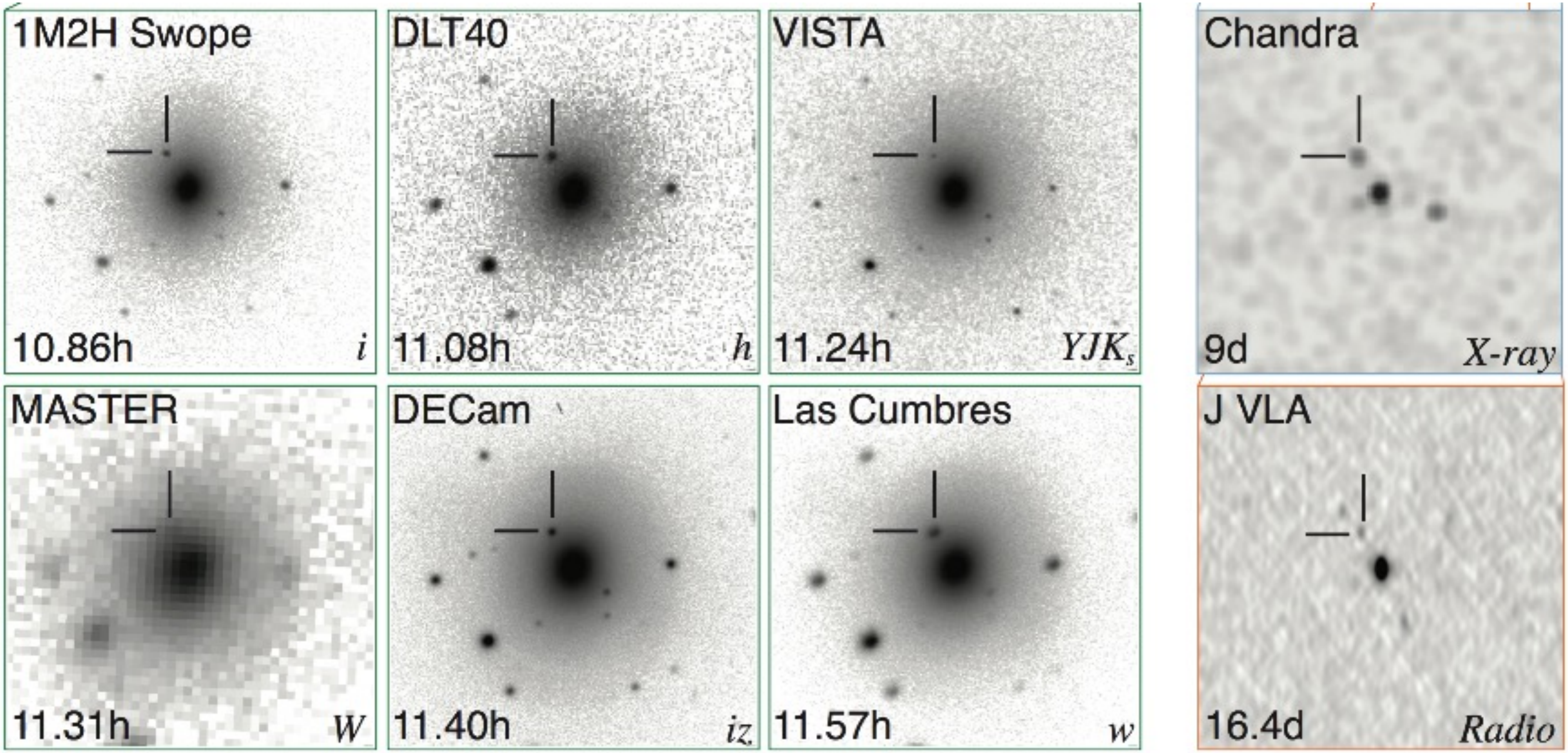
PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

TABLE I. Source properties for GW170817: we give ranges encompassing the 90% credible intervals for different assumptions of the waveform model to bound systematic uncertainty. The mass values are quoted in the frame of the source, accounting for uncertainty in the source redshift.

	Low-spin priors ($\|\chi\| \leq 0.05$)	High-spin priors ($\|\chi\| \leq 0.89$)
Primary mass m_1	1.36–$1.60\ M_\odot$	1.36–$2.26\ M_\odot$
Secondary mass m_2	1.17–$1.36\ M_\odot$	0.86–$1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_{L}	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

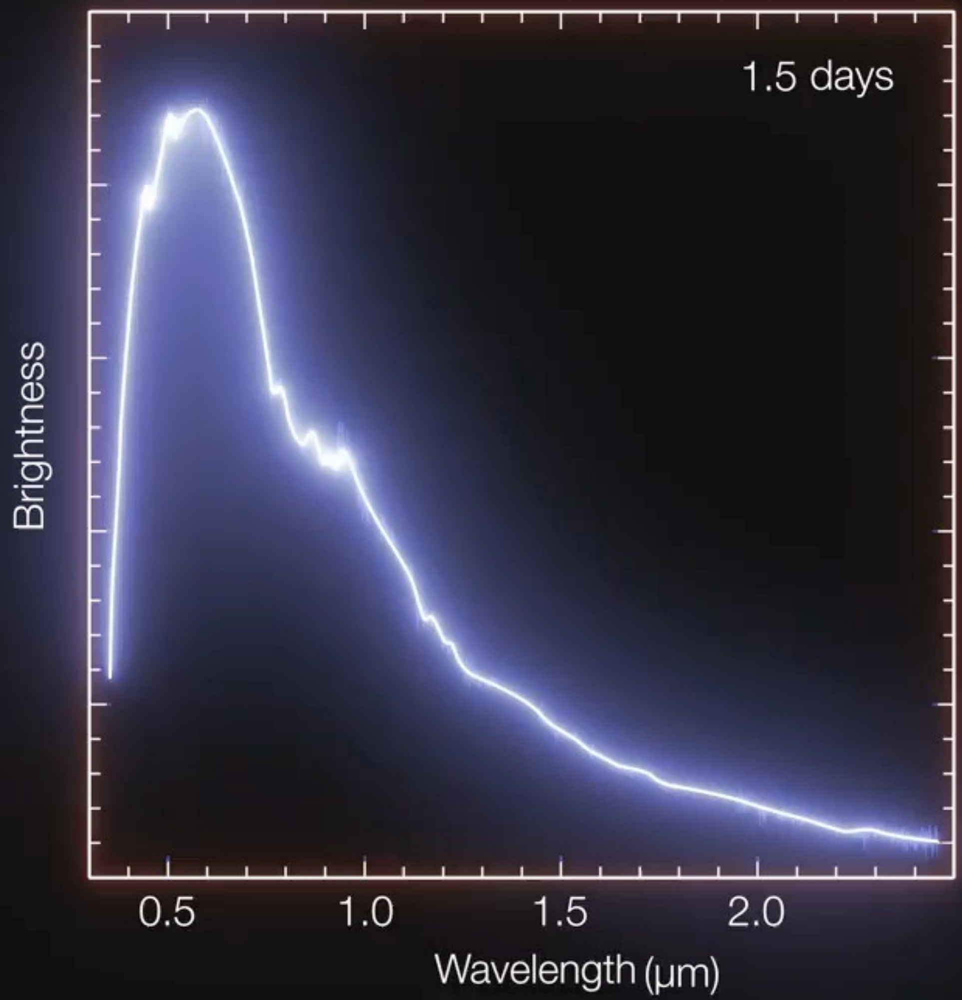
LIGO
VIRGO
KAGRA





Shown here are 8 images of the aftermath of the BNS merger (designated SSS17a/AT2017gfo). On the left are six optical images taken between 10 and 12 hours after the merger by different telescopes. On the right are images constructed from x-ray and radio observations. The x-ray image was taken 9 days after the merger by NASA's Chandra X-ray Observatory. 16 days after the merger NRAO's Jansky Very Large Array (VLA) captured the radio image. In all 8 images the galaxy NGC 4993 is seen in the middle and SSS17a/AT2017gfo is marked by two lines.

Brightness of the kilonova



For the first time, it was observed an ultraviolet, optical, and infrared transient (known as a kilonova), due to the radioactive decay of heavy elements formed by neutron capture.

This observation firmly connects kilonovae with the BNS merger, providing evidence supporting the idea that kilonovae result from the radioactive decay of the heavy elements formed by neutron capture duringa BNS merger.

Credits: European Southern Observatory (ESO)

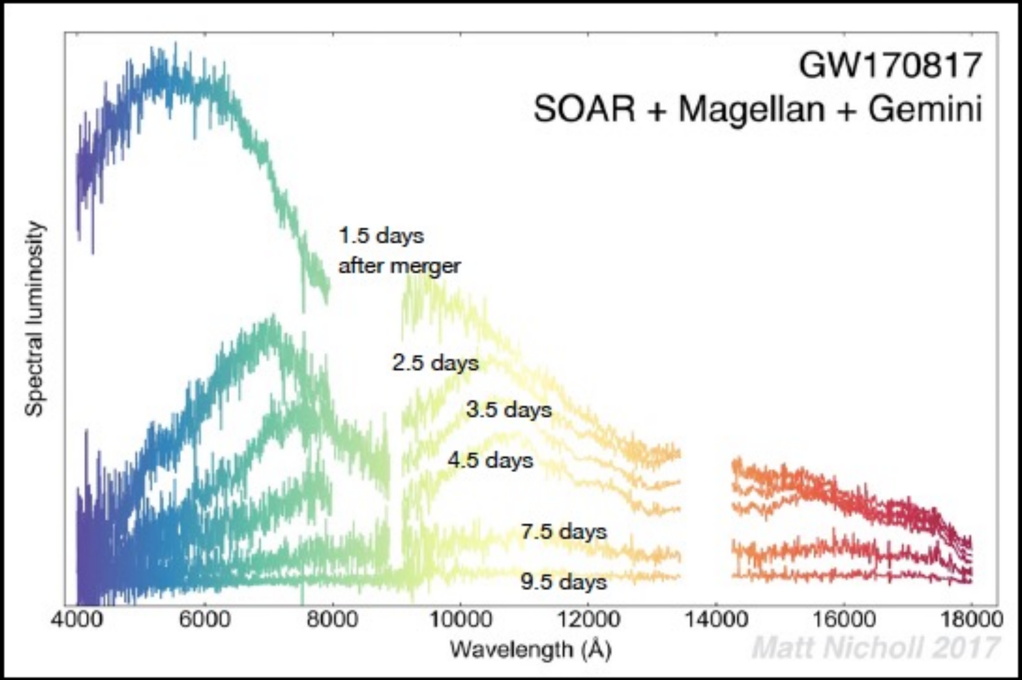
Kilonova

SSS17a

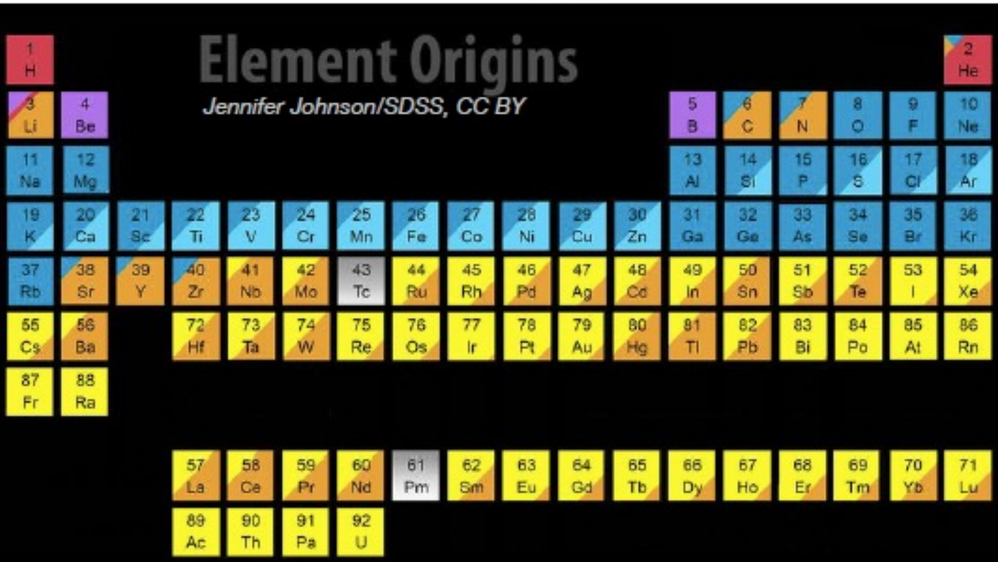
August 17, 2017

August 21, 2017

Swope & Magellan Telescopes



Matt Nicholl 2017



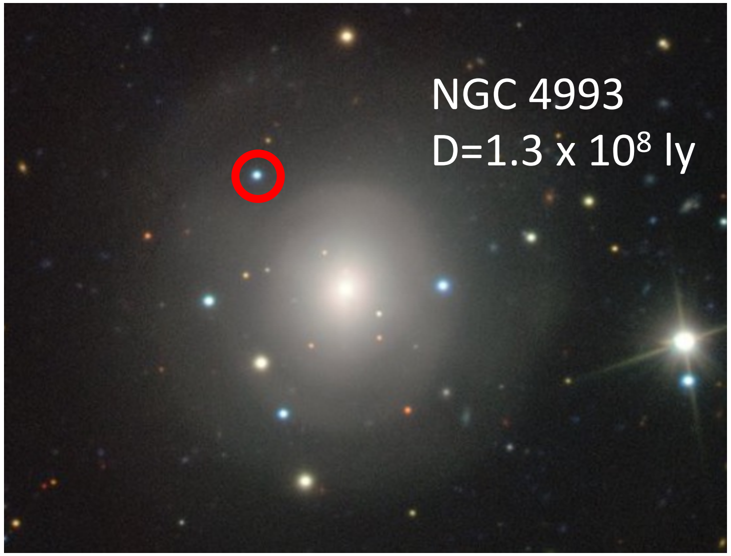
Element Origins

Jennifer Johnson/SDSS, CC BY

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			89 Ac	90 Th	91 Pa	92 U											

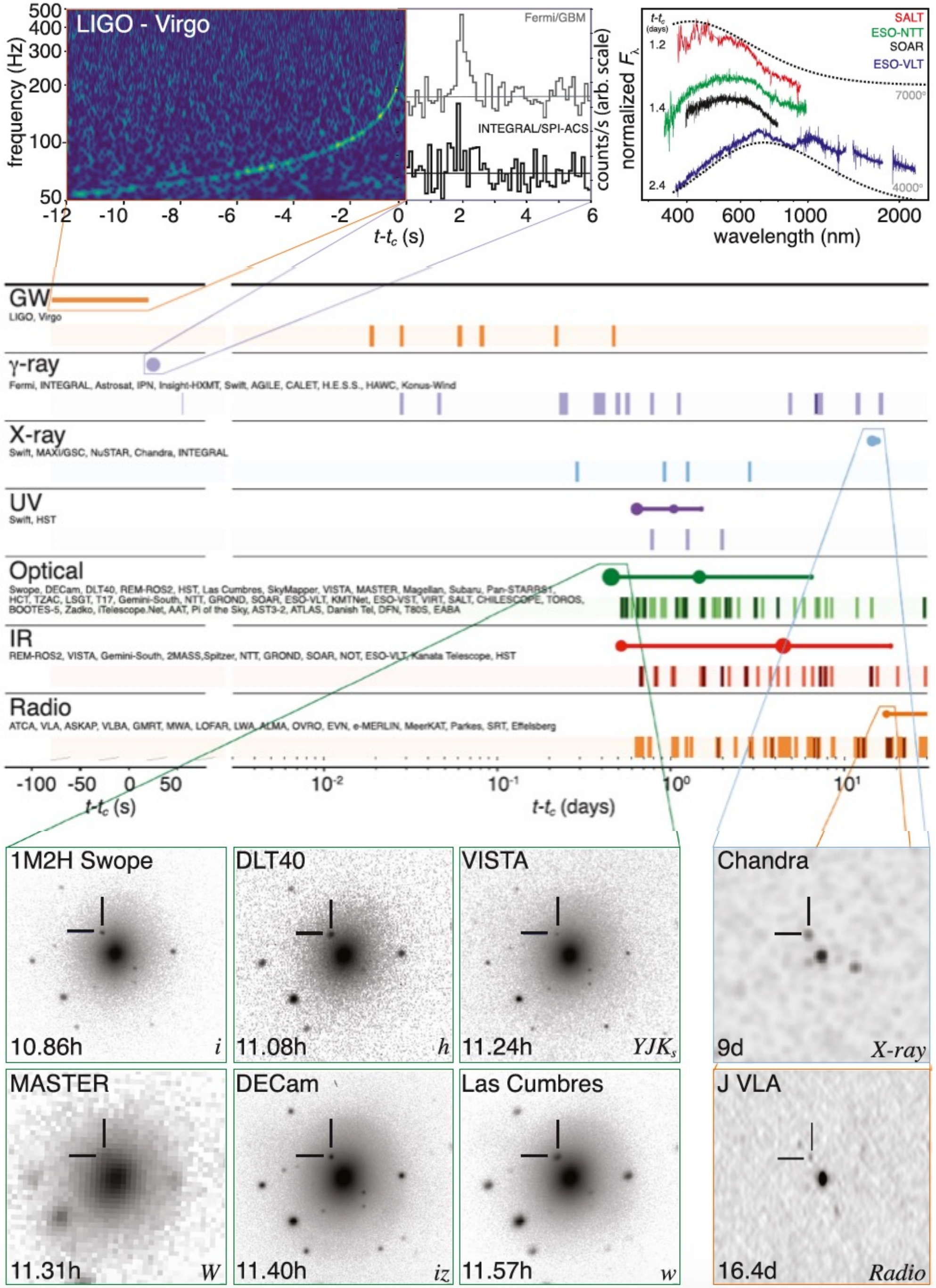
Merging Neutron Stars
Dying Low Mass Stars
Exploding Massive Stars
Exploding White Dwarfs
Big Bang
Cosmic Ray Fission

Observations Across the Electromagnetic Spectrum

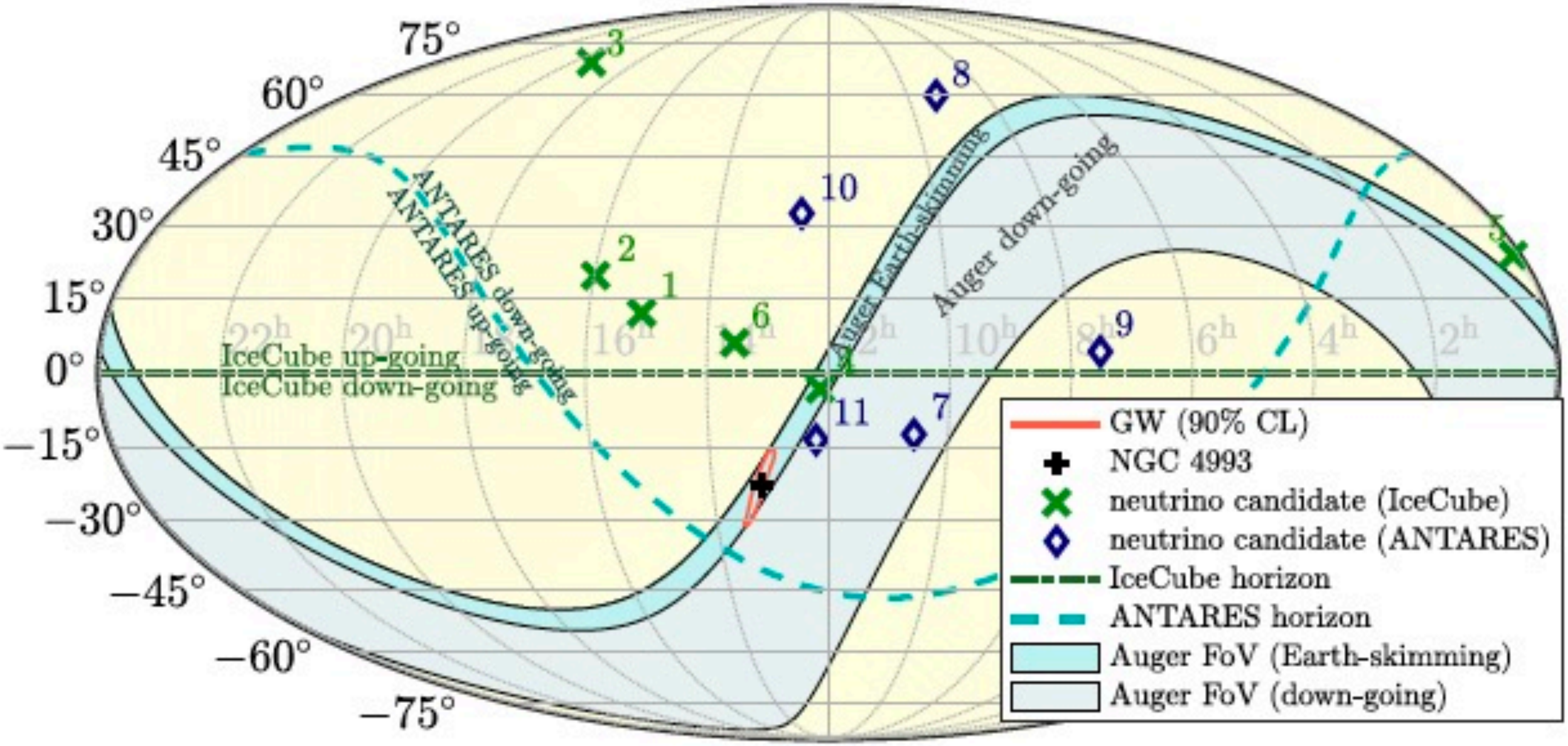


Credit: European Southern Observatory
Very Large Telescope

Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, “Multi-messenger Observations of a Binary Neutron Star Merger” Astrophys. J. Lett., 848:L12, (2017)



Search for neutrinos in coincidence with the BNS merger



Astrophys.J. 870 (2019) no.2, 134

Are Gravitons Massless?

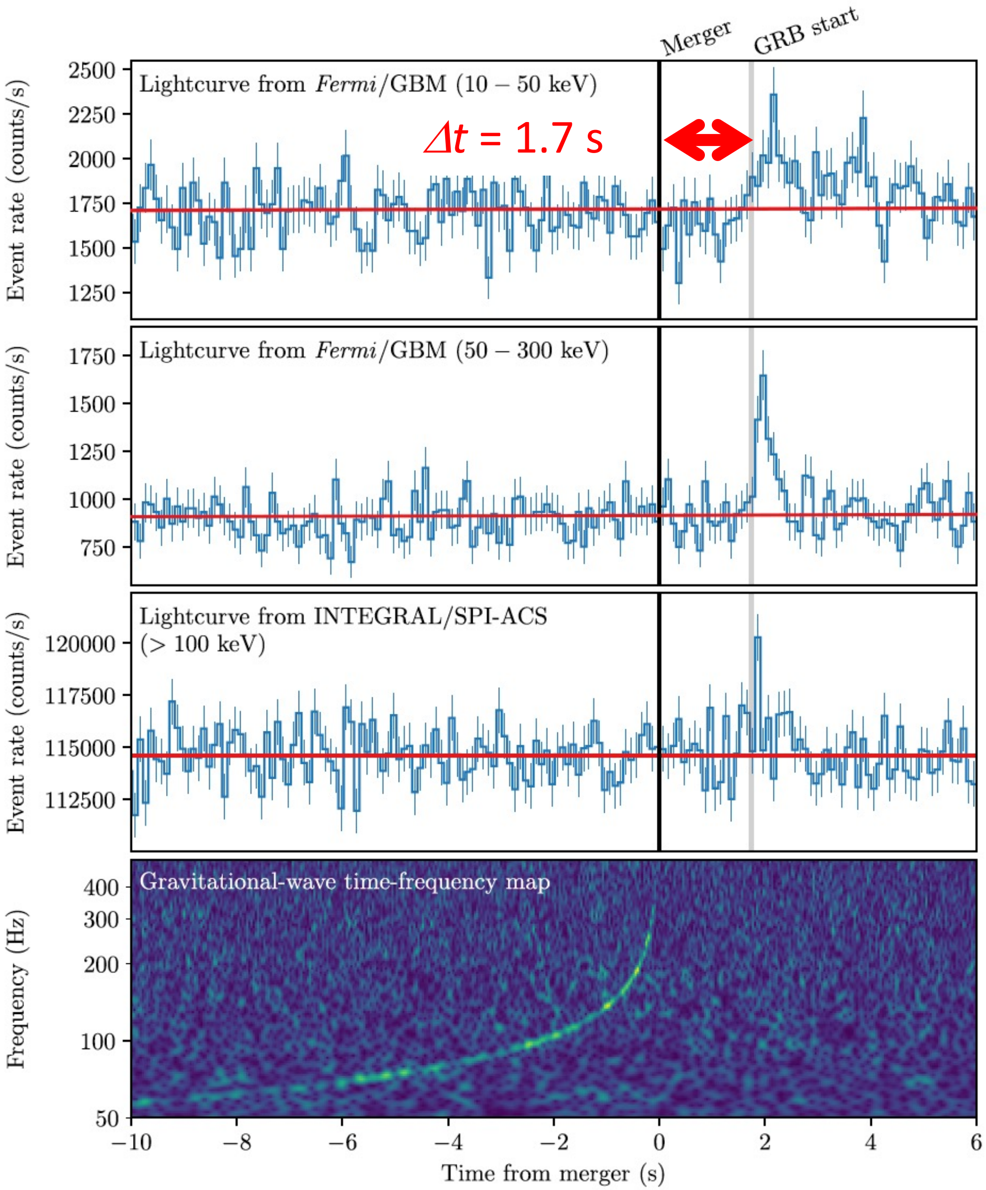
- GW170817 provides a stringent test of the speed of gravitational waves

$$\frac{v_{GW} - c}{c} \approx \frac{c\Delta t}{D}$$

- Δt =1.74 +/- 0.05 s
- $D \approx$ 26 Mpc
  - Conservative limit – use 90% confidence level lower limit on GW source from parameter estimation

$$\boxed{-3 \times 10^{-15} \leq \frac{v_{GW} - c}{c} \leq +7 \times 10^{-16}}$$

- GW170814 also puts limits on violations of Lorentz Invariance and Equivalence Principle

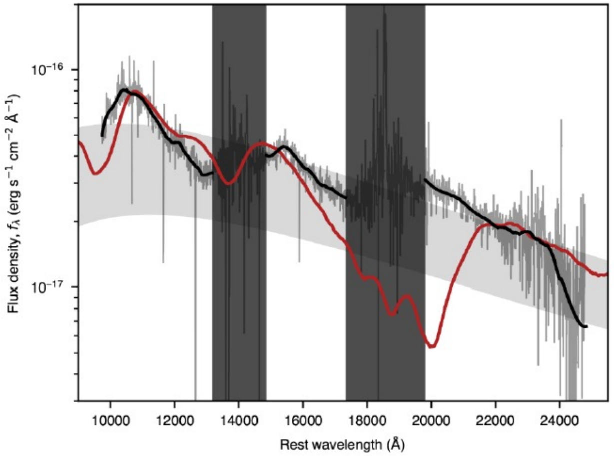


LIGO Scientific Collaboration and Virgo Collaboration, Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A" Astrophys. J. Lett., 848:L13, (2017)

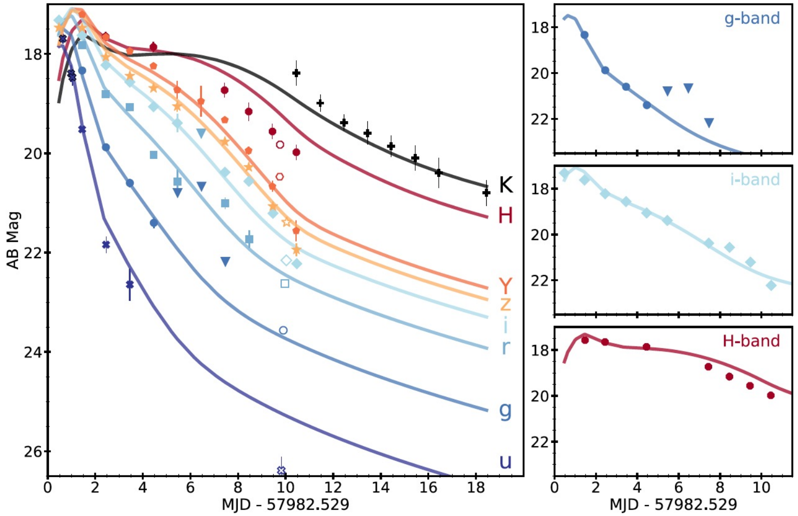
Binary Neutron Star Mergers Produce Kilonovae

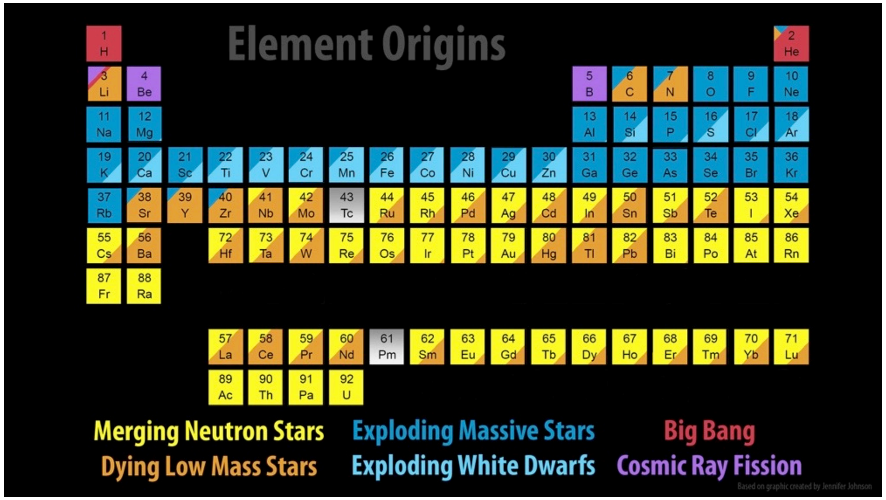
- Electromagnetic follow-up of GW170817 provides strong evidence for kilonova model
  - kilonova - isotropic thermal emission produced by radioactive decay of rapid neutron capture (‘r-process’) elements synthesized in the merger ejecta
- Spectra taken over 2 week period across all electromagnetic bands consistent with kilonova models
  - “Blue” early emission dominated by Fe-group and light r-process formation; later “red” emission dominated by heavy element (lanthanide) formation
- Recent radio data prefers ‘cocoon’ model to classical short-hard GRB production!

Kasliwal et al. 2017,
Science, DOI: https://doi.org/10.1126/science.aap9455



Cowperthwaite, et al. 2017,
Ap. J. Lett. DOI: https://doi.org/10.3847/2041-8213/aa8fc7



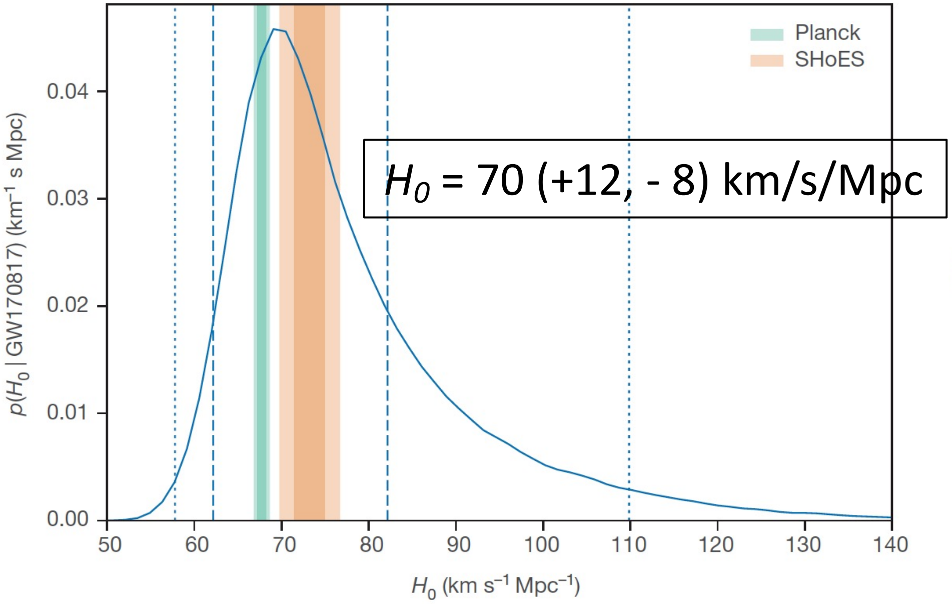


A gravitational-wave standard siren measurement of the Hubble constant

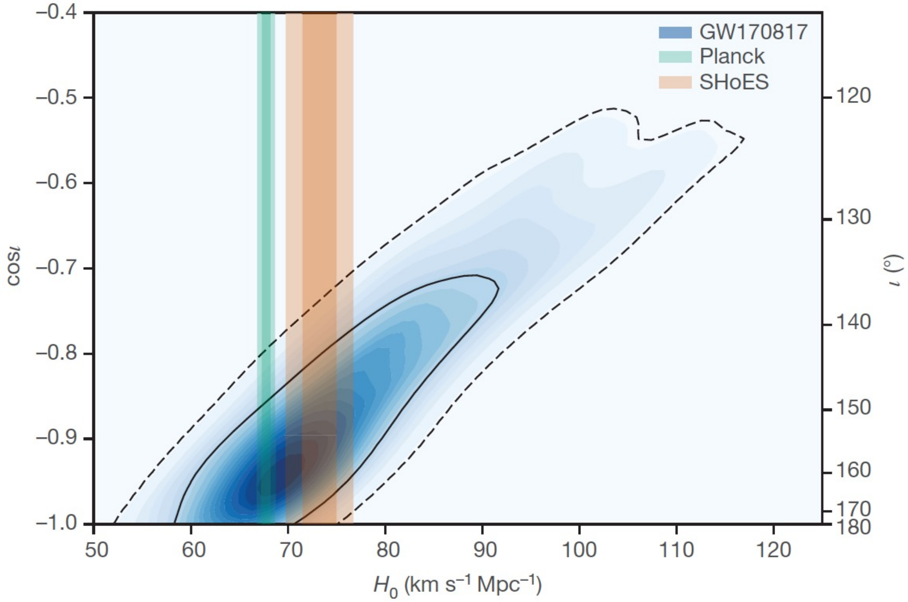
- Gravitational waves are ‘standard sirens’, providing absolute measure of luminosity distance d_L
- can be used to determine H_0 directly if red shift is known:

$$c\,z = H_0\,d_L$$

- … without the need for a cosmic distance ladder!



H_0 = 70 (+12, - 8) km/s/Mpc



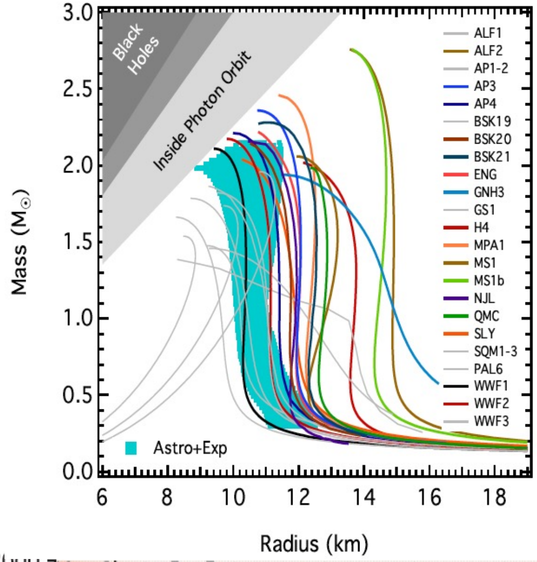
Abbott, et al., LIGO-Virgo Collaboration, 1M2H, DeCAM GW-EM & DES, DLT40, Las Cumbres Observatory, VINRO UGE, MASTER Collaborations, A gravitational-wave standard siren measurement of the Hubble constant”, *Nature* 551, 85–88 (2017).

Constraining the Neutron Star Equation of State with GW170817

- Gravitational waveforms contain information about NS tidal deformations → allows us to constrain NS equations of state (EOS)
- Tidal deformability parameter:

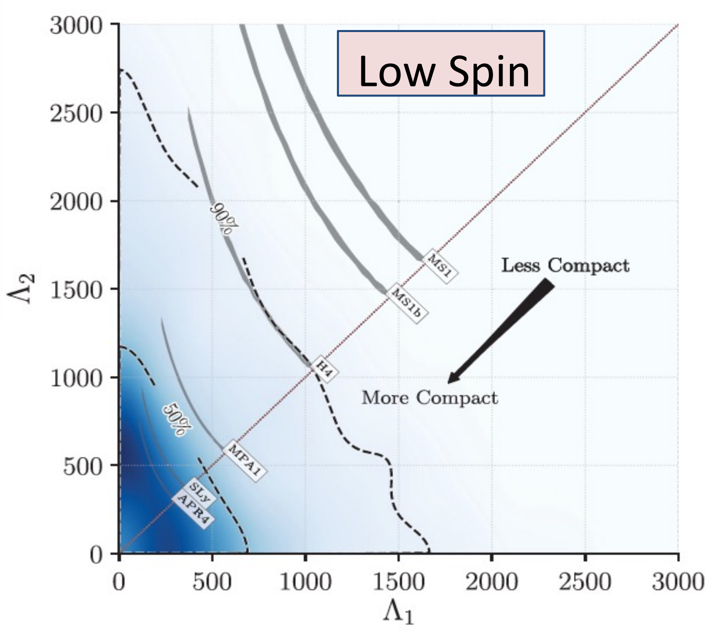
$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{M} \right)^5$$

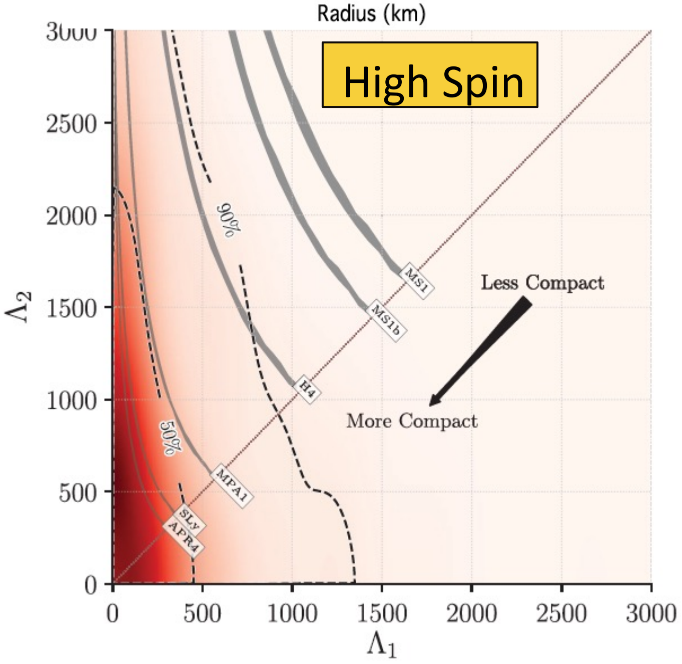
- GW170817 data consistent with softer EOS → more compact NS



Ozel and Friere (2016)

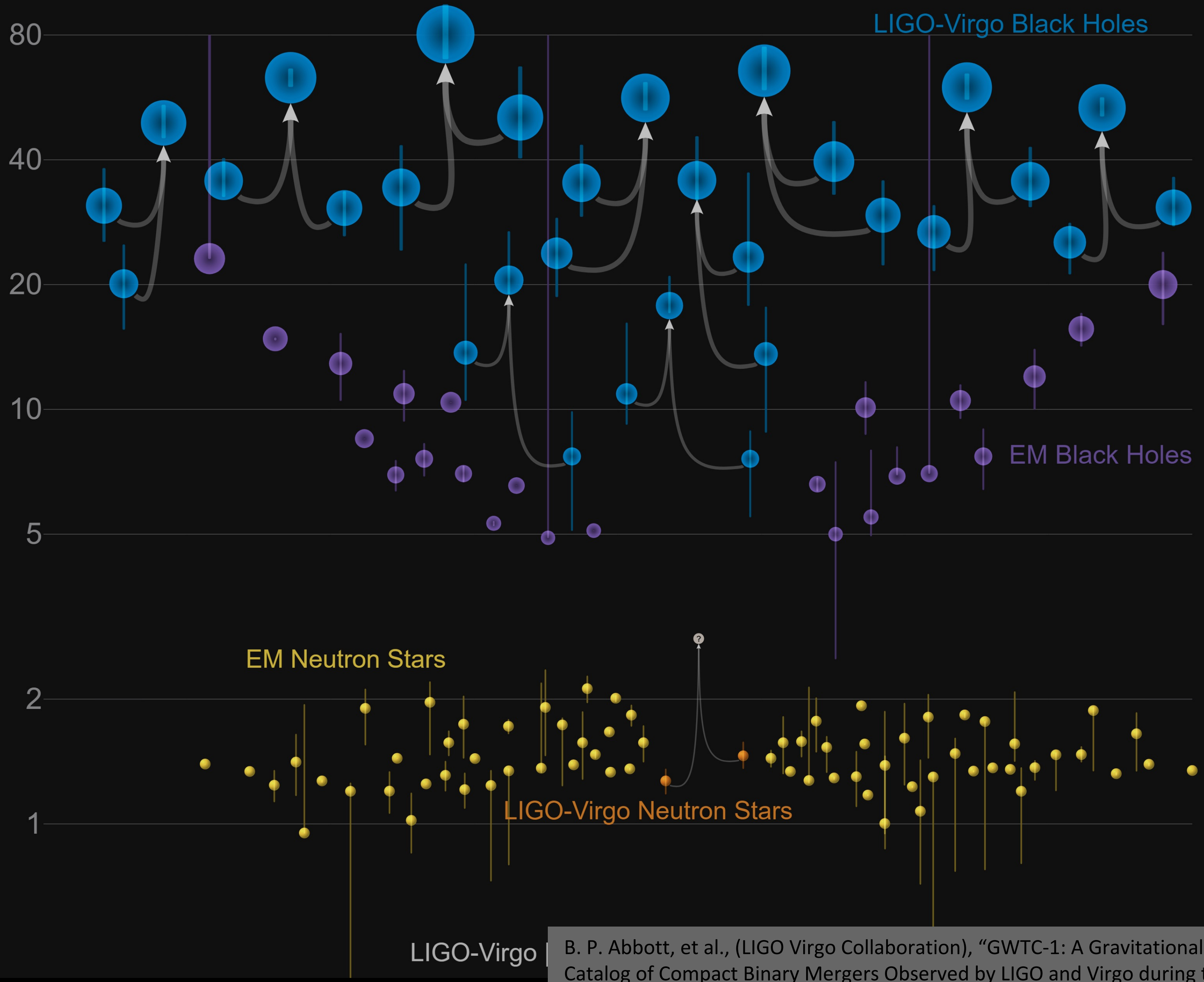
Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral" Phys. Rev. Lett. 161101 (2017)





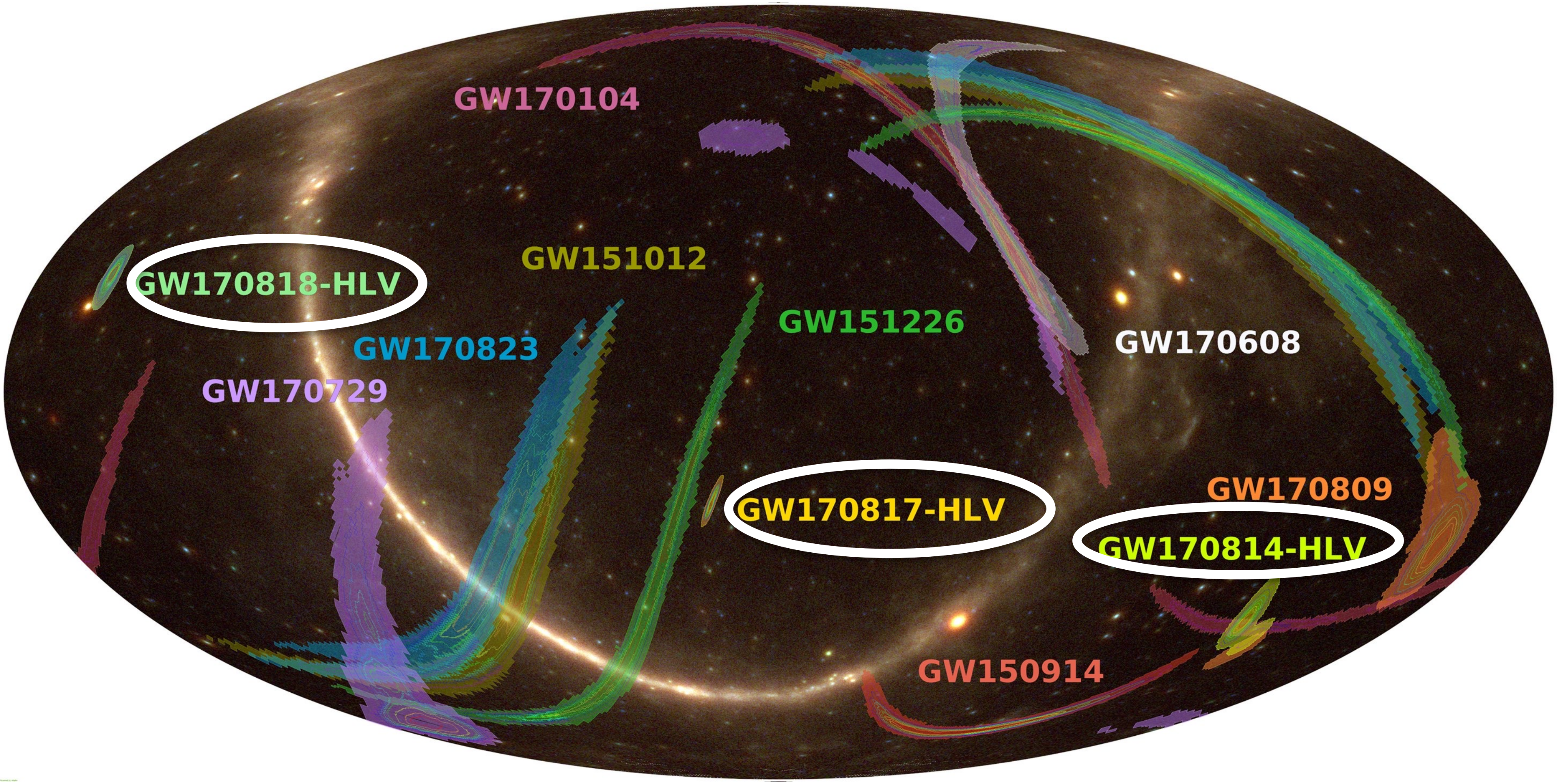
Masses in the Stellar Graveyard

in Solar Masses



B. P. Abbott, et al., (LIGO Virgo Collaboration), “GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs” , https://arxiv.org/abs/1811.12907

Skymaps of LIGO-Virgo’s Detections



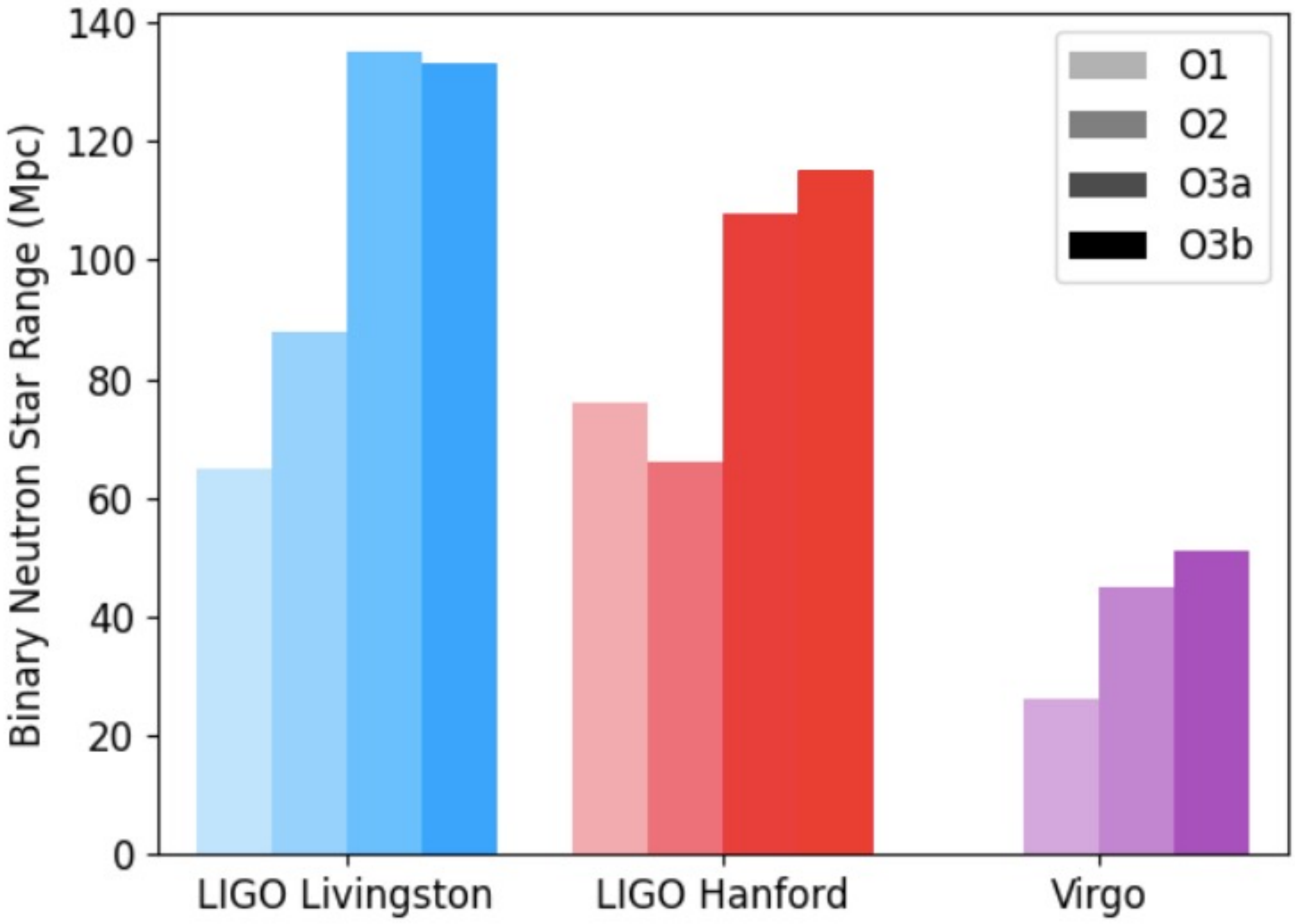
Abbott, et al, (LIGO Virgo Collaboration "Low-Latency Gravitational Wave Alerts for Multi-Messenger Astronomy During the Second Advanced LIGO and Virgo Observing Run", https://arxiv.org/abs/1901.03310

Gravitational Wave Transients Catalog

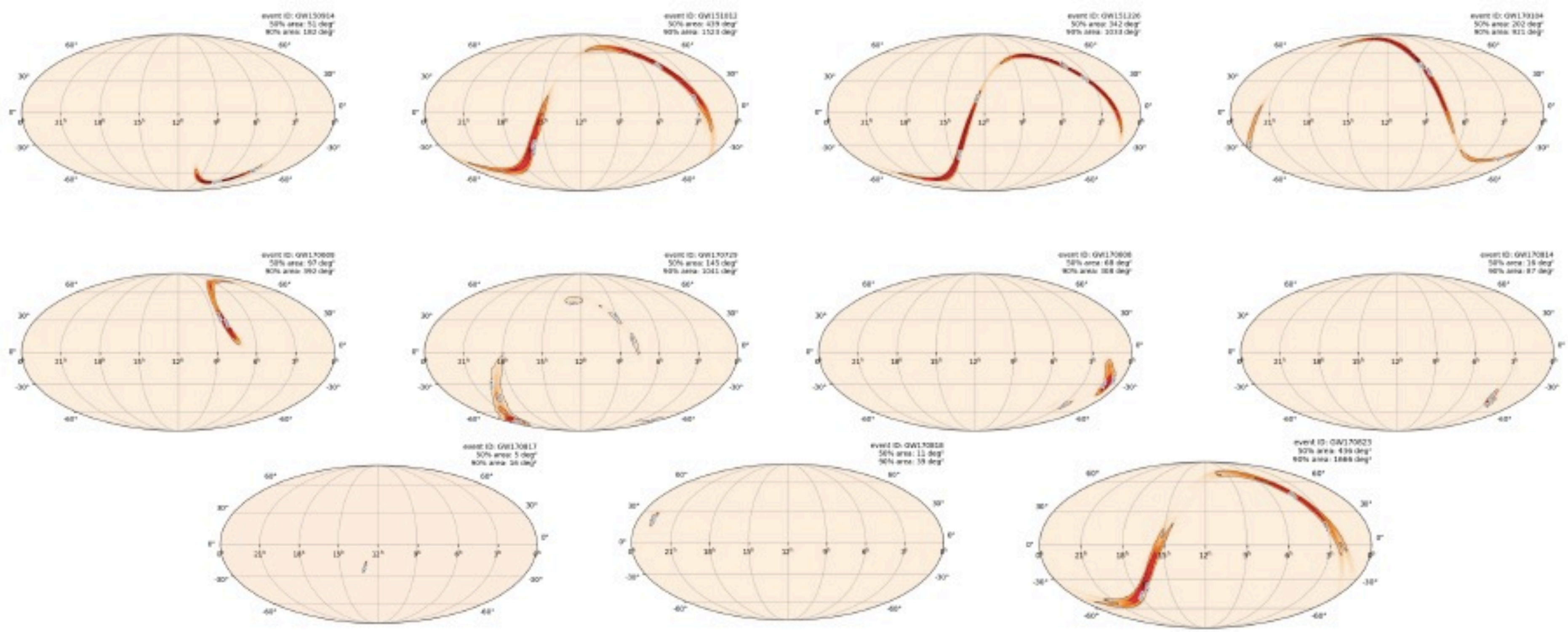
- GWTC-1: 11 confirmed events (10 BBHs, 1BNS), O1+O2
- GWTC-2: 39 confirmed events, O3a
- GWTC-2.1: 8 new events in O3a and reclassified 3 candidates in GWTC-2-> 55 total events
- GWTC-3: 35 events in O3b

- O1 from 12th September 2015 to 19th January 2016
- O2 from 30th November 2016 to 25th August 2017
- O3a from April 1st to October 1st,2019
- O3b from November 2019 to March 2020

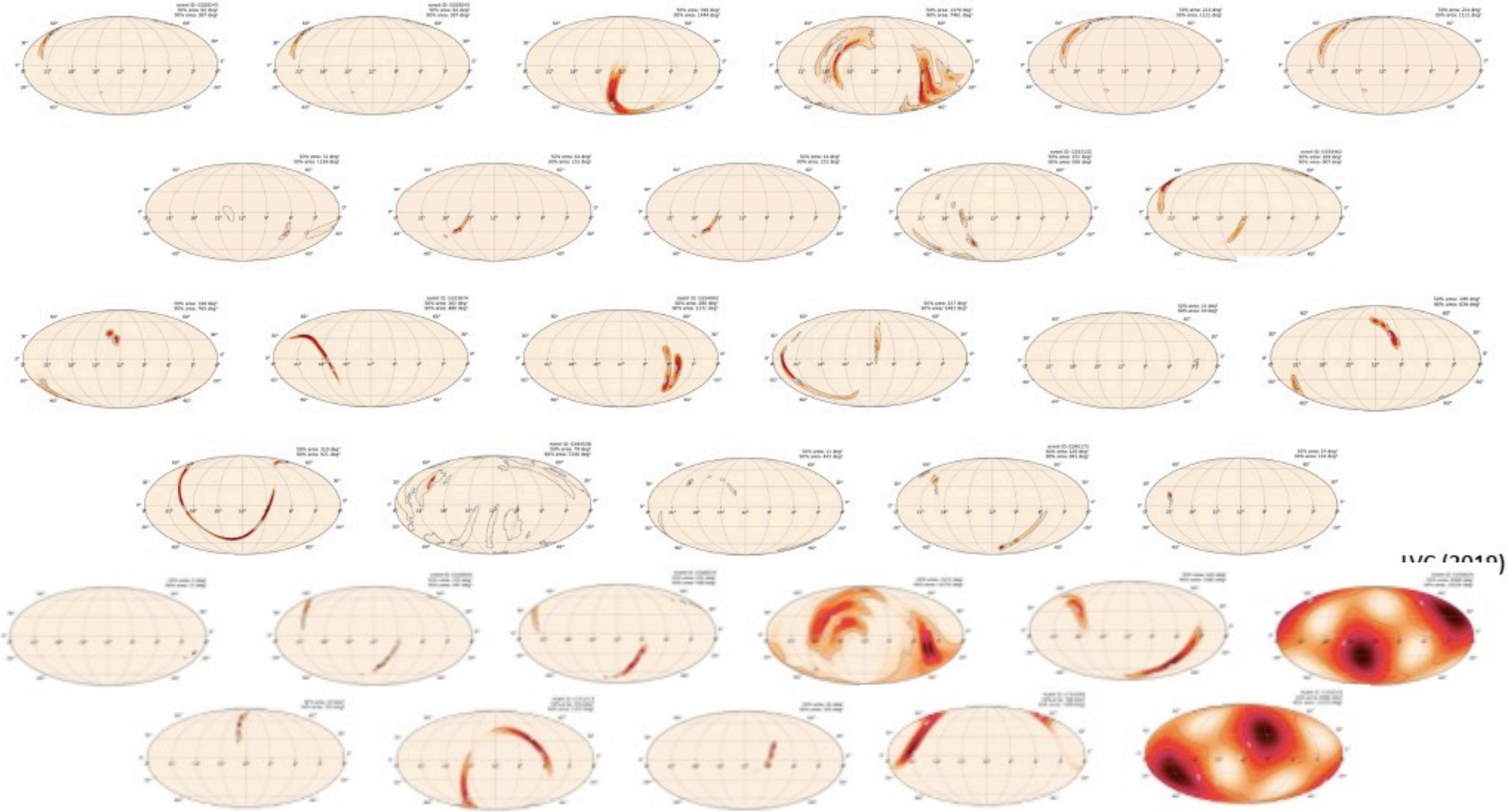
Detector Sensitivity



LVC observations after O1-O2: 11 detections (10 BBH + 1BNS)

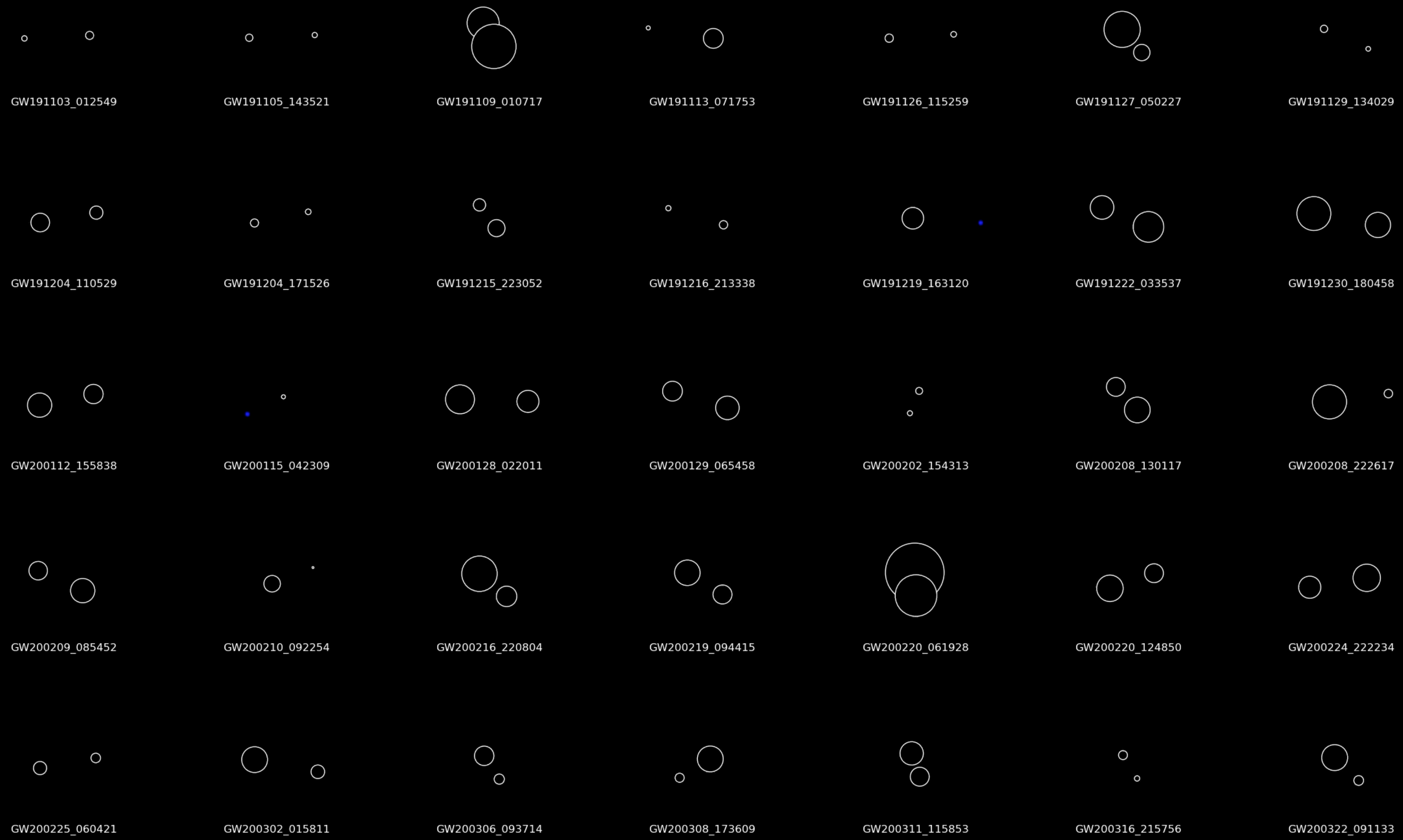


LVC candidates (so far) in O3 – since April 2019 – 33 Candidates



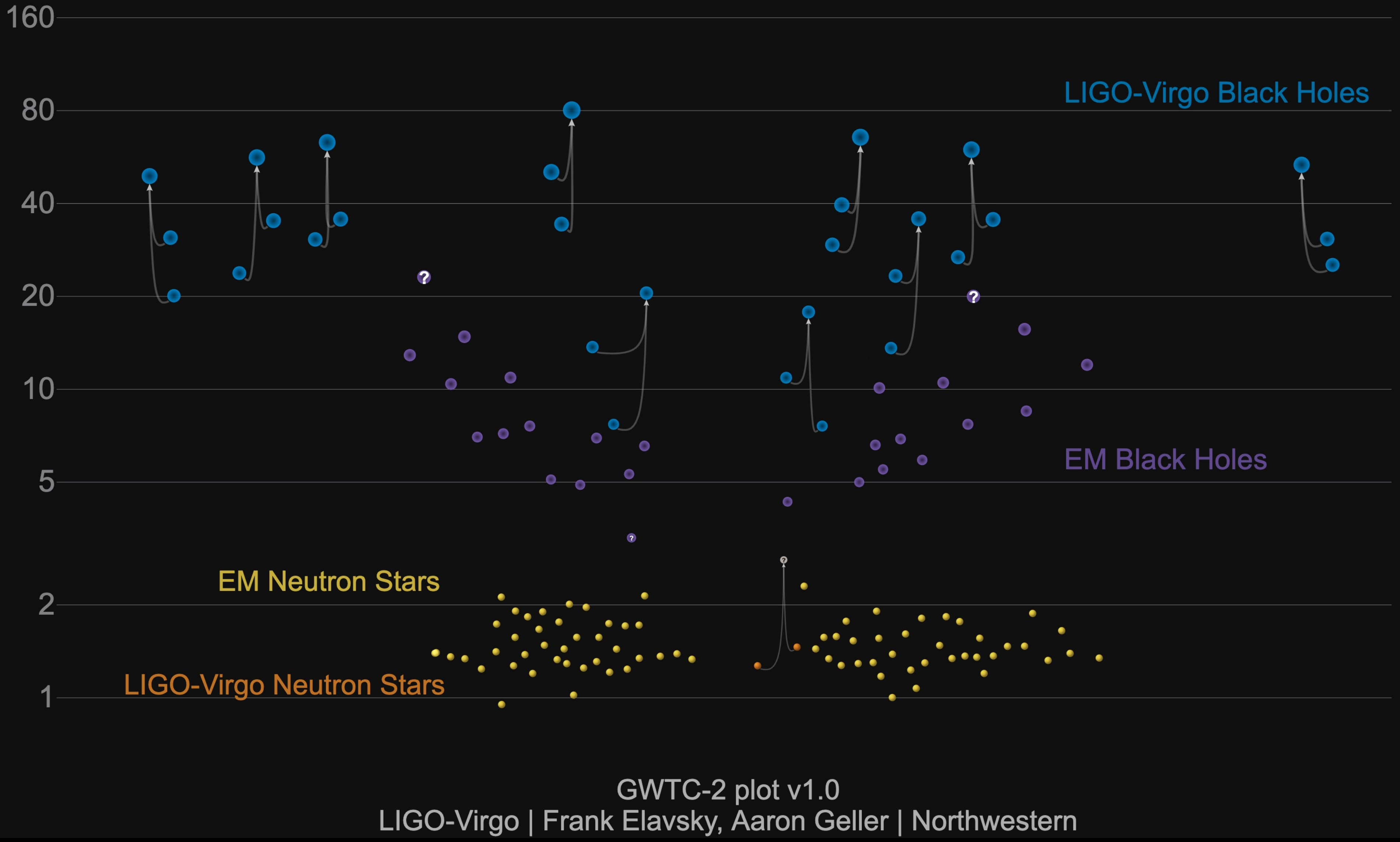
LVC (2019)

https://gracedb.ligo.org/superevents/public/O3/

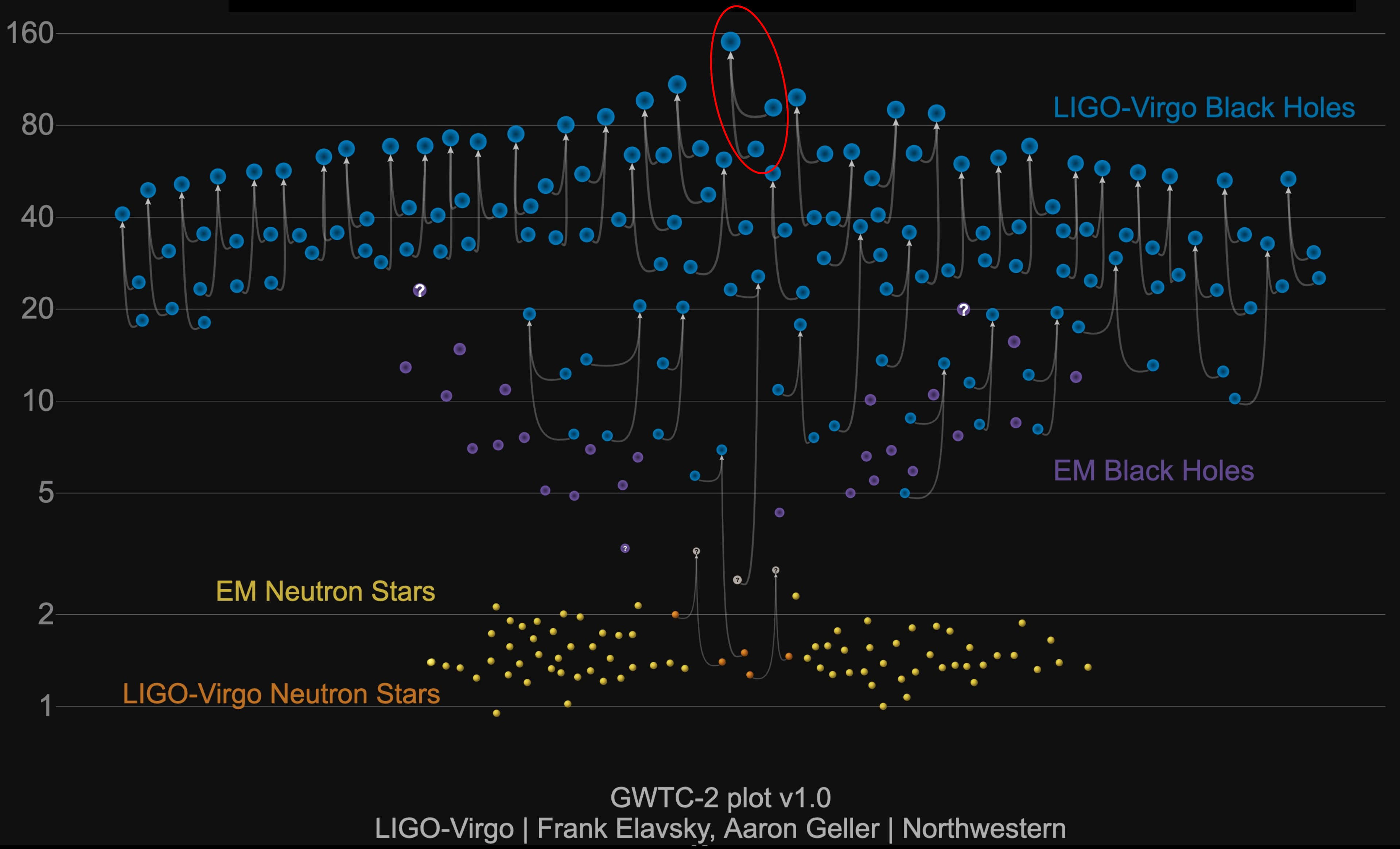


Zoheyr Doctor / CIERA / LIGO-Virgo Collaboration

Detected Events in the First Two LIGO-Virgo Observing Runs



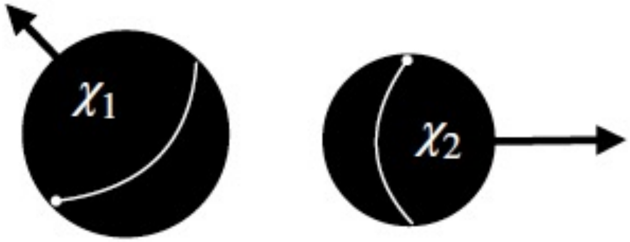
Detected Events in the First Two LIGO-Virgo Observing Runs and the O3a Run



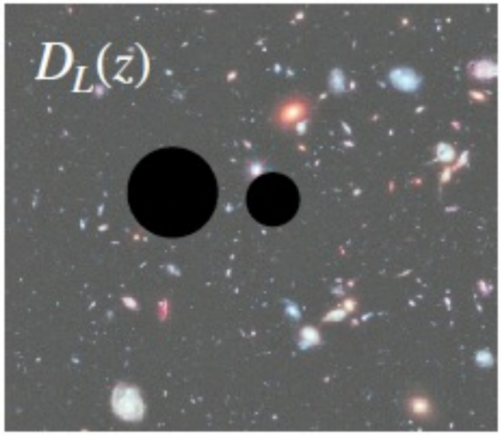
Gravitational waves encode source properties, like …

How *big* is each black hole or neutron star?

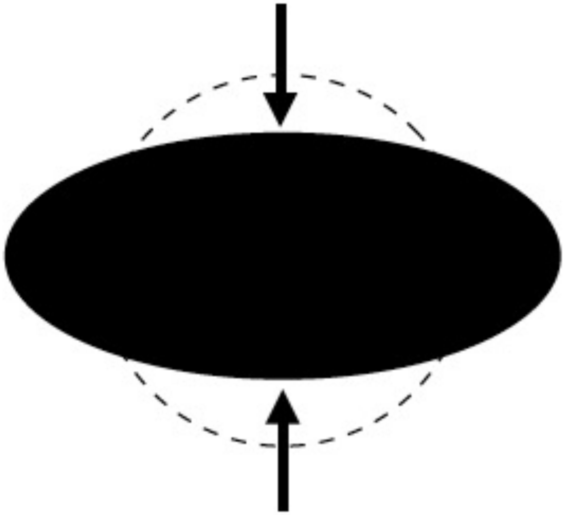
How fast are they *spinning*?



Where and *when* did they merge?



How squishy are neutron stars?



GRAVITATIONAL WAVE **MERGER** DETECTIONS

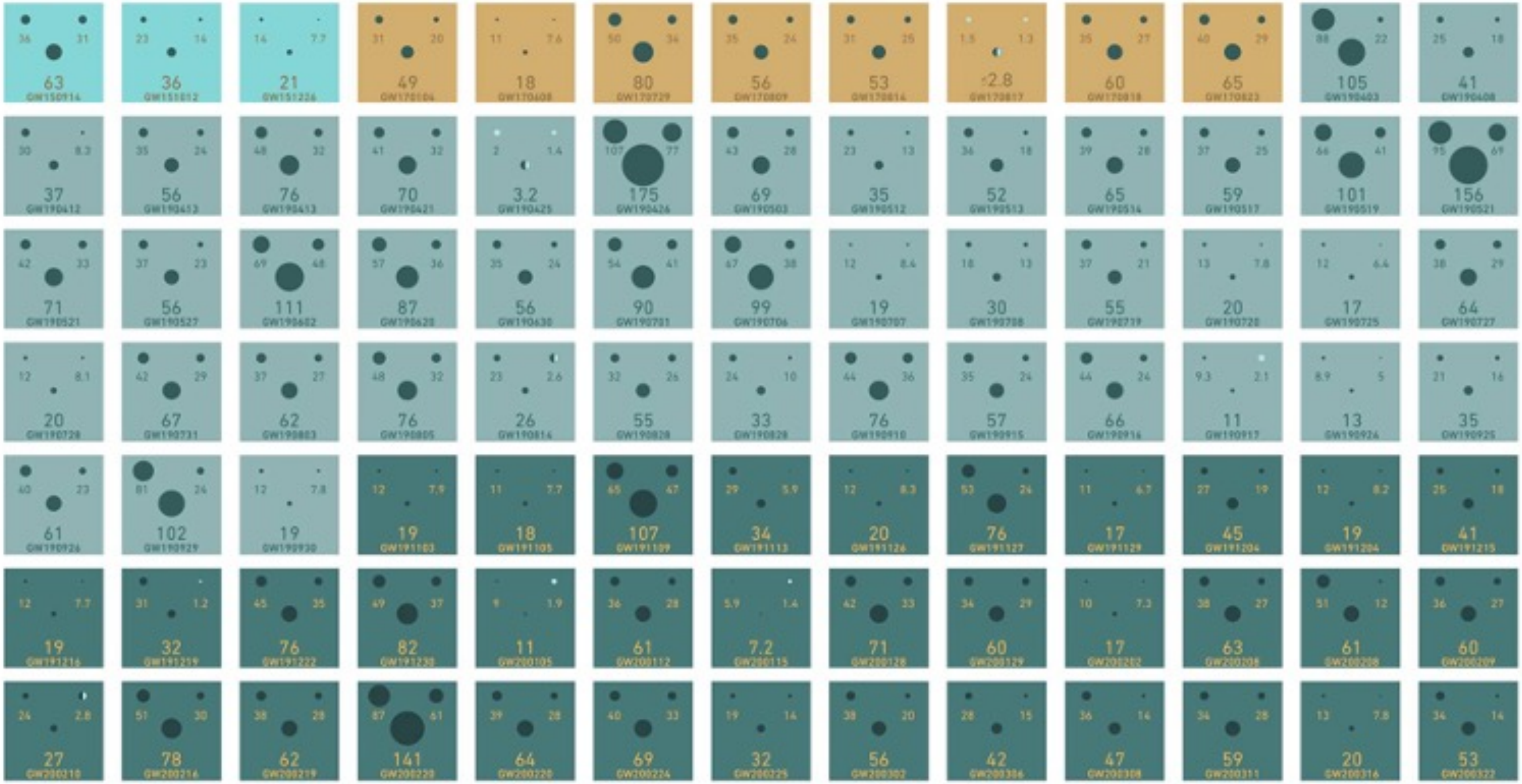
SINCE 2015

SERVING
IN

01 2015-2016

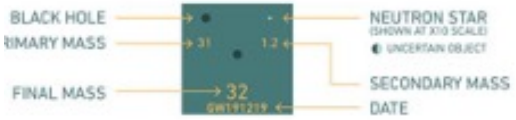
02 2016-2017

03a+b 2019-2020



36 31 63 GW150914	23 14 36 GW151012	14 7.7 21 GW151226	31 20 49 GW170104	11 7.6 18 GW170608	50 34 80 GW170729	35 24 56 GW170809	31 25 53 GW170814	1.5 1.3 ≤2.8 GW170817	35 27 60 GW170818	40 29 65 GW170823	88 22 105 GW190403	25 18 41 GW190408
30 8.3 37 GW190412	35 24 56 GW190413	48 32 76 GW190413	41 32 70 GW190421	2 1.4 3.2 GW190425	107 77 175 GW190426	43 28 69 GW190503	23 13 35 GW190512	36 18 52 GW190513	39 28 65 GW190514	37 25 59 GW190517	66 41 101 GW190519	95 69 156 GW190521
42 33 71 GW190521	37 23 56 GW190527	69 48 111 GW190602	57 36 87 GW190620	35 24 56 GW190630	54 41 90 GW190701	67 38 99 GW190706	12 8.4 19 GW190707	18 13 30 GW190708	37 21 55 GW190719	13 7.8 20 GW190720	12 6.4 17 GW190725	38 29 64 GW190727
12 8.1 20 GW190728	42 29 67 GW190731	37 27 62 GW190803	48 32 76 GW190805	23 2.6 26 GW190814	32 26 55 GW190828	24 10 33 GW190828	44 36 76 GW190910	35 24 57 GW190915	44 24 66 GW190916	9.3 2.1 11 GW190917	8.9 5 13 GW190924	21 16 35 GW190925
40 23 61 GW190926	81 24 102 GW190929	12 7.8 19 GW190930	12 7.9 19 GW191103	11 7.7 18 GW191105	65 47 107 GW191109	29 5.9 34 GW191113	12 8.3 20 GW191126	53 24 76 GW191127	11 6.7 17 GW191129	27 19 45 GW191204	12 8.2 19 GW191204	25 18 41 GW191215
12 7.7 19 GW191216	31 1.2 32 GW191219	45 35 76 GW191222	49 37 82 GW191230	9 1.9 11 GW200105	36 28 61 GW200112	5.9 1.4 7.2 GW200115	42 33 71 GW200128	34 29 60 GW200129	10 7.3 17 GW200202	38 27 63 GW200208	51 12 61 GW200208	36 27 60 GW200209
24 2.8 27 GW200210	51 30 78 GW200216	38 28 62 GW200219	87 61 141 GW200220	39 28 64 GW200220	40 33 69 GW200224	19 14 32 GW200225	38 20 56 GW200302	28 15 42 GW200306	36 14 47 GW200308	34 28 59 GW200311	13 7.8 20 GW200316	34 14 53 GW200322

Y



UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^{30}kg

Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

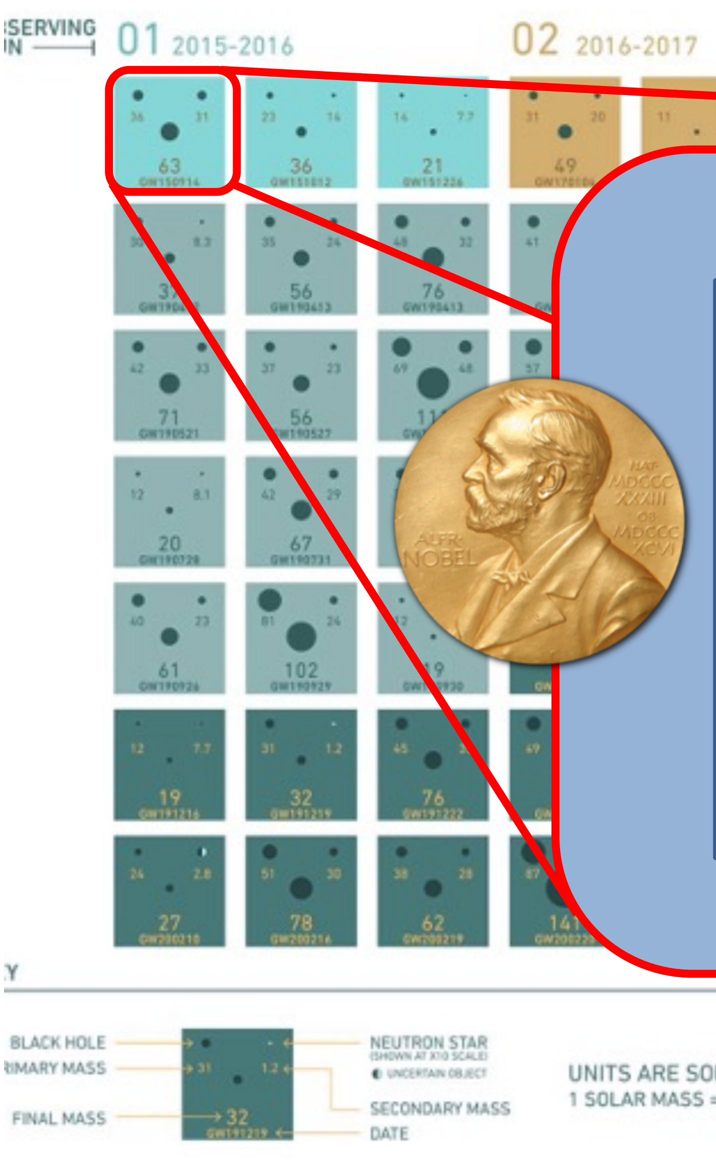
The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.

OzGrav
ARC Centre of Excellence for Gravitational Wave Discovery

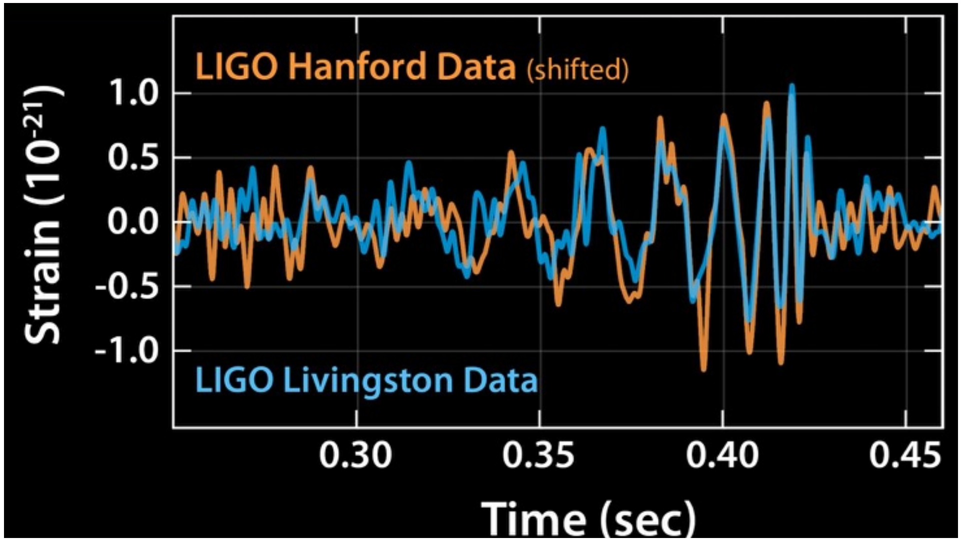
LIGO
VIRGO
KAGRA

GRAVITATIONAL WAVE **MERGER** DETECTIONS

→ SINCE 2015



GW150914: First Detection



Abbott et al, "**Observation of Gravitational Waves from a Binary Black Hole Merger**", 2016

UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^{30}kg

Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.

OzGrav

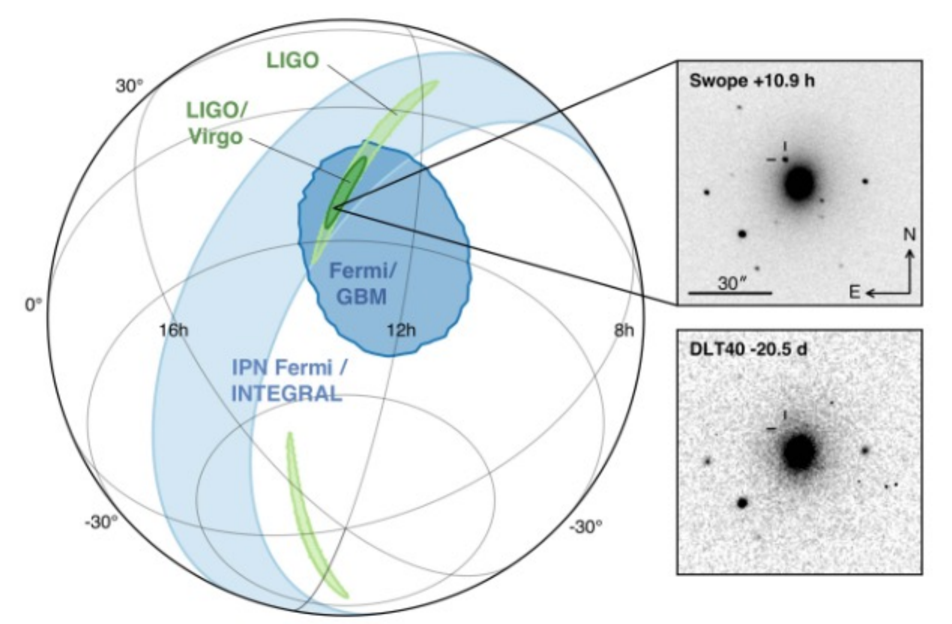
LIGO VIRGO KAGRA

Slide: S. Fairhurst

GRAVITATIONAL WAVE **MERGER** DETECTIONS

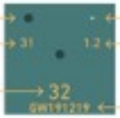
SINCE 2015

GW170817: Neutron Stars and Multi-messenger Observation



From Abbott et al, “**Multi-Messenger Observations of a Binary Neutron Star Merger** ”, 2017

O3a+b 2019-2020



BLACK HOLE

PRIMARY MASS

FINAL MASS

NEUTRON STAR
(SHOWN AT X10 SCALE)

UNCERTAIN OBJECT

SECONDARY MASS

DATE

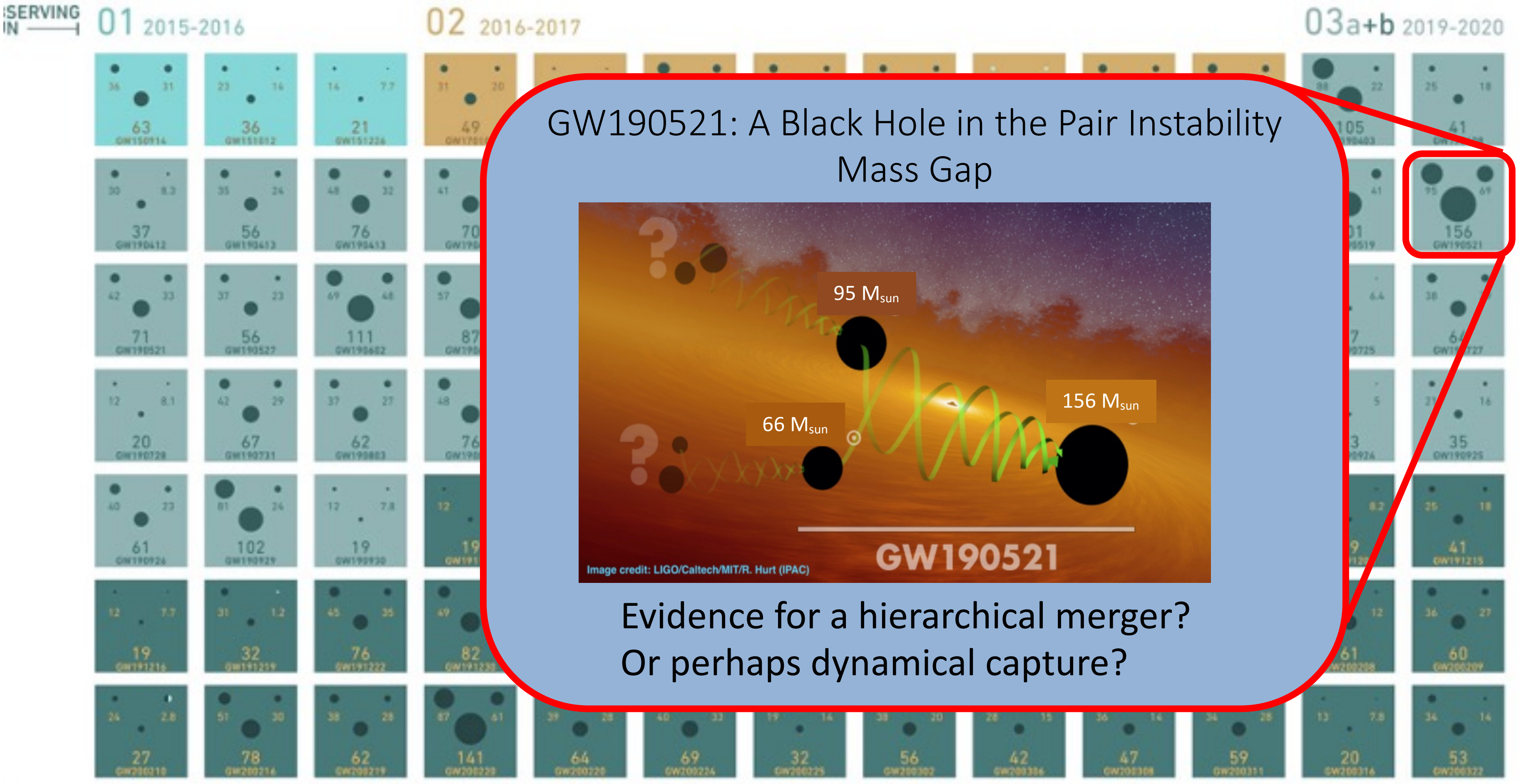
UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^{30}kg

Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.

GRAVITATIONAL WAVE **MERGER** DETECTIONS

SINCE 2015



GW190521: A Black Hole in the Pair Instability Mass Gap

Image credit: LIGO/Caltech/MIT/R. Hurt (IPAC)

Evidence for a hierarchical merger?
Or perhaps dynamical capture?

Y

BLACK HOLE
RIMARY MASS
FINAL MASS
NEUTRON STAR (SHOWN AT X10 SCALE)
◐ UNCERTAIN OBJECT
SECONDARY MASS
DATE

UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^{30}kg

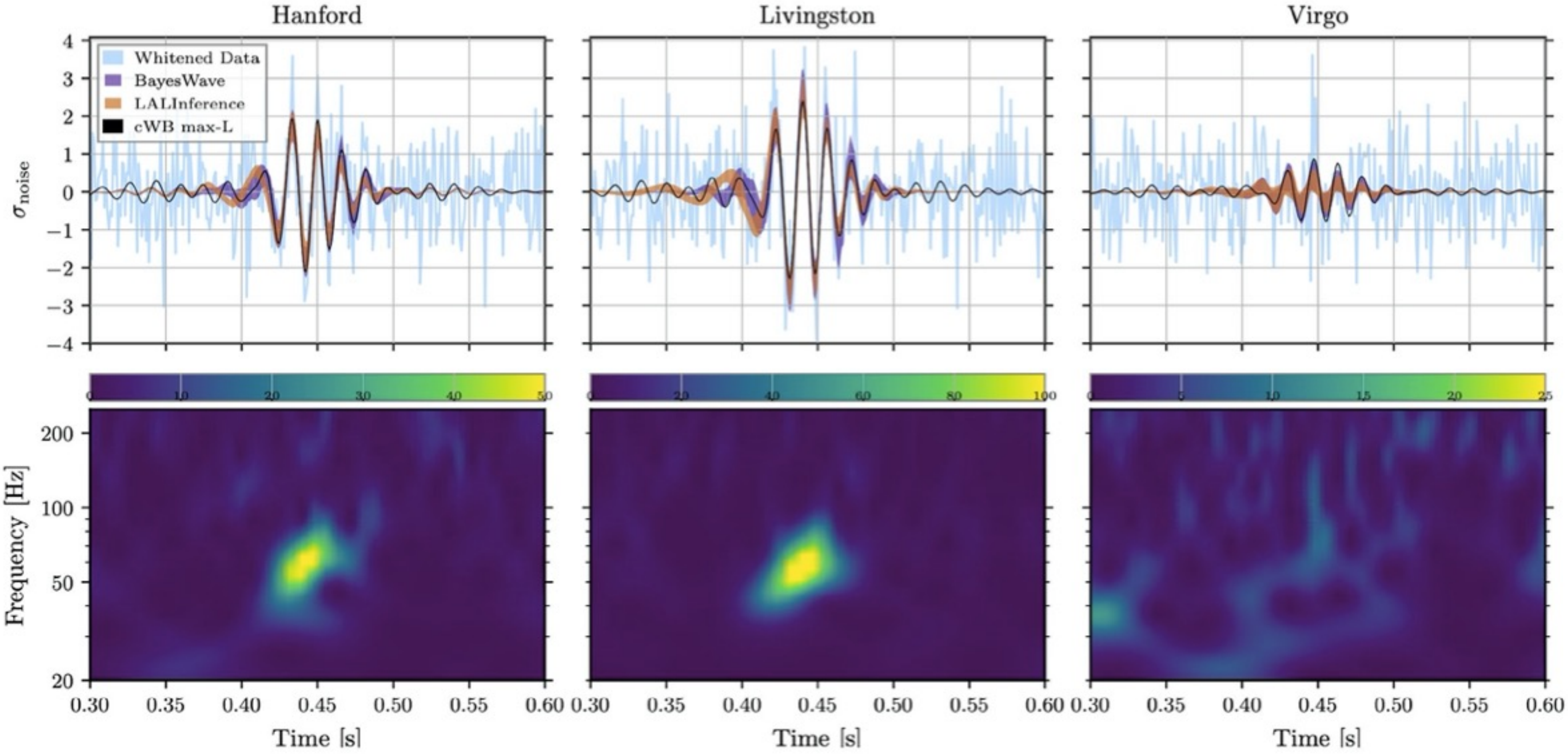
Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.

Slide: S. Fairhurst

The Most Massive & Distant Black Hole Merger Yet: GW190521

(May 21, 2019)



The signal wa shorter in duration (0.1 s), and peaked at lower frequency than any other binary black hole merger observed to date.

The time interval that the signal spends in the sensityvity band is inversely propotional to the total mass of the binary system.

The frequency of the merger is also inversely proportional to the binary's total mass.

GW190521 parameters

- Most massive observation to date
- Most distant
- Pair-instability supernova mass gap, 65-120 $M_\odot$
- Intermediate Mass Black Hole
- Important astrophysical implications
- Orbital precession

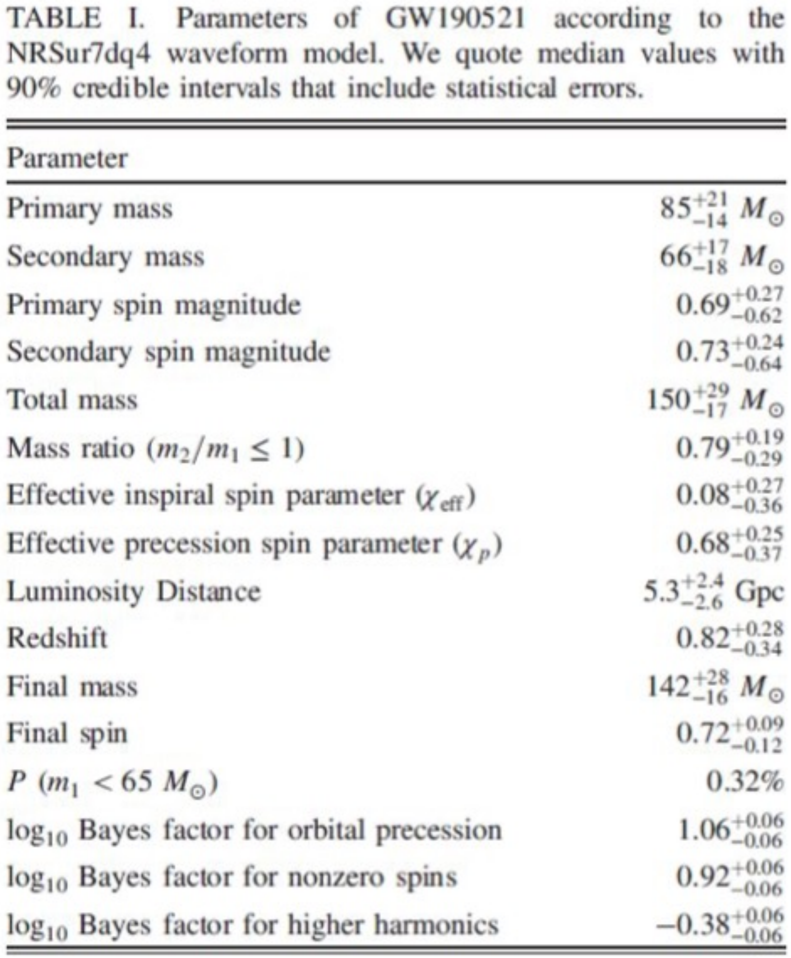
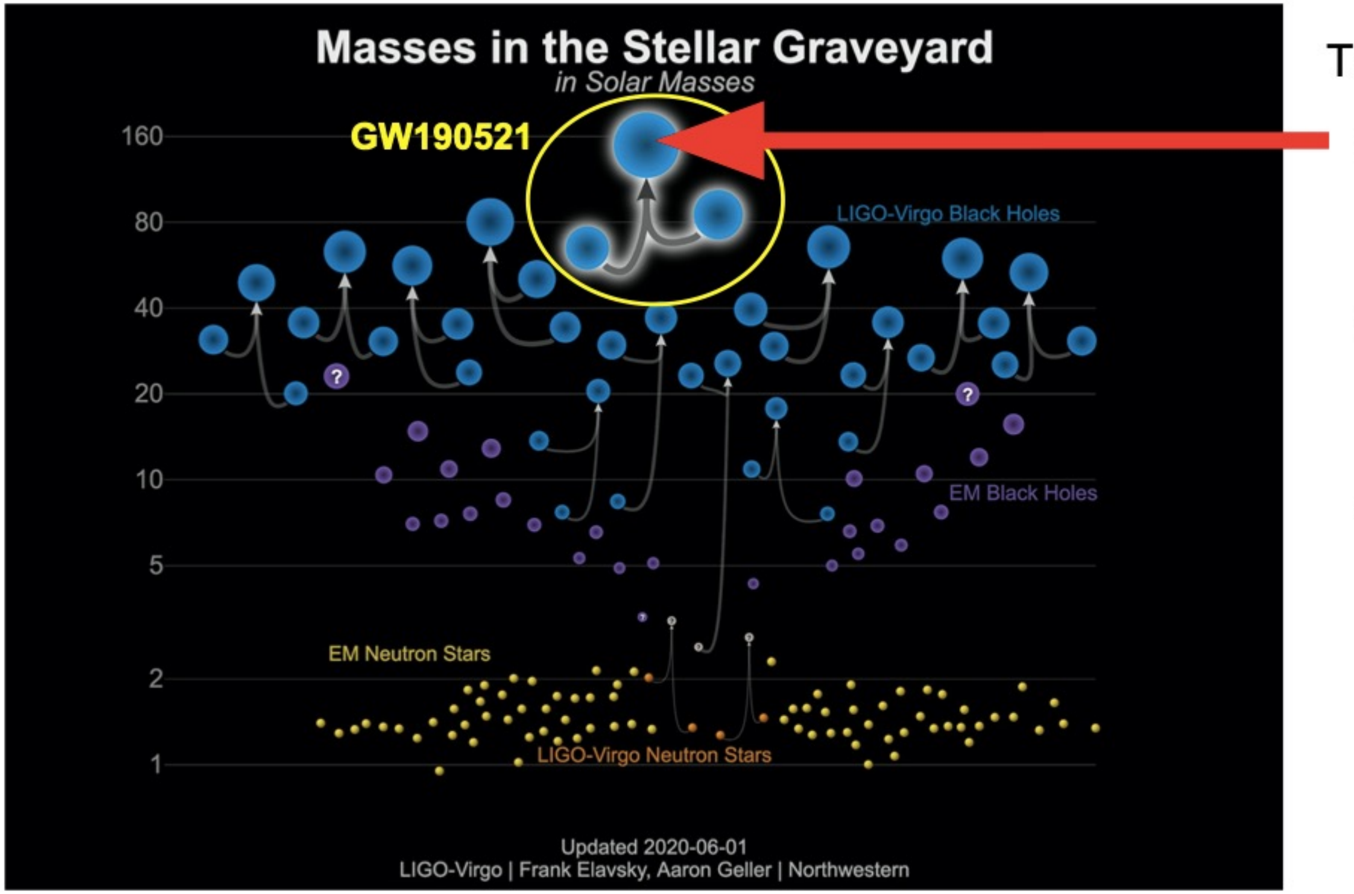


TABLE I. Parameters of GW190521 according to the NRSur7dq4 waveform model. We quote median values with 90% credible intervals that include statistical errors.

Parameter	
Primary mass	$85^{+21}_{-14}\ M_\odot$
Secondary mass	$66^{+17}_{-18}\ M_\odot$
Primary spin magnitude	$0.69^{+0.27}_{-0.62}$
Secondary spin magnitude	$0.73^{+0.24}_{-0.64}$
Total mass	$150^{+29}_{-17}\ M_\odot$
Mass ratio ($m_2/m_1 \leq 1$)	$0.79^{+0.19}_{-0.29}$
Effective inspiral spin parameter ($\chi_{\rm eff}$)	$0.08^{+0.27}_{-0.36}$
Effective precession spin parameter (χ_p)	$0.68^{+0.25}_{-0.37}$
Luminosity Distance	$5.3^{+2.4}_{-2.6}$ Gpc
Redshift	$0.82^{+0.28}_{-0.34}$
Final mass	$142^{+28}_{-16}\ M_\odot$
Final spin	$0.72^{+0.09}_{-0.12}$
$P\ (m_1 < 65\ M_\odot)$	0.32%
$\log_{10}$ Bayes factor for orbital precession	$1.06^{+0.06}_{-0.06}$
$\log_{10}$ Bayes factor for nonzero spins	$0.92^{+0.06}_{-0.06}$
$\log_{10}$ Bayes factor for higher harmonics	$-0.38^{+0.06}_{-0.06}$

The most massive black hole ever observed with gravitational waves

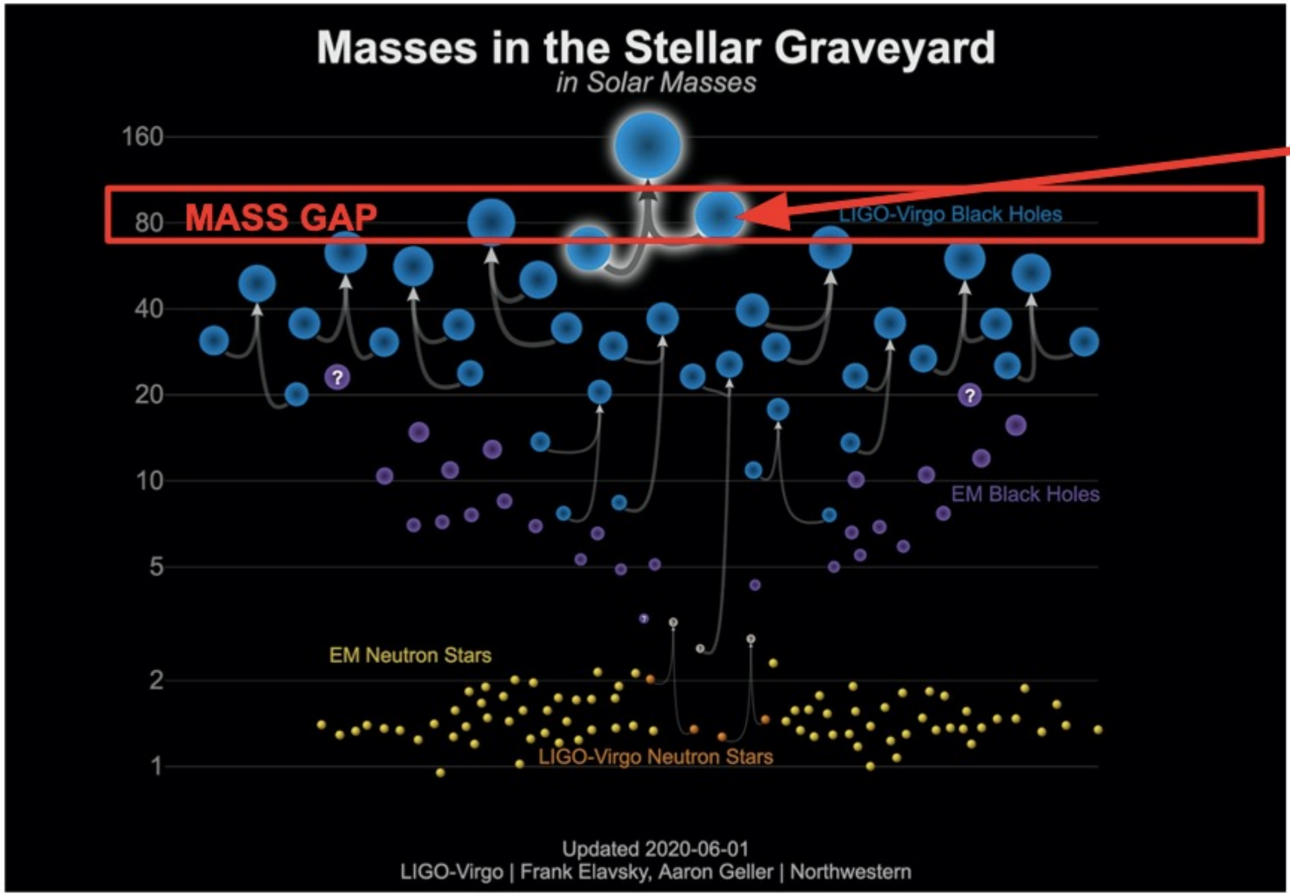


Updated 2020-06-01
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

The final black hole is

- the most massive black hole ever observed with gravitational waves
- the first evidence of a black hole in the 100 - 1000 solar mass range
- an intermediate-mass black hole: the missing link between stellar-mass and supermassive black holes

The first black hole in the pair-instability mass gap

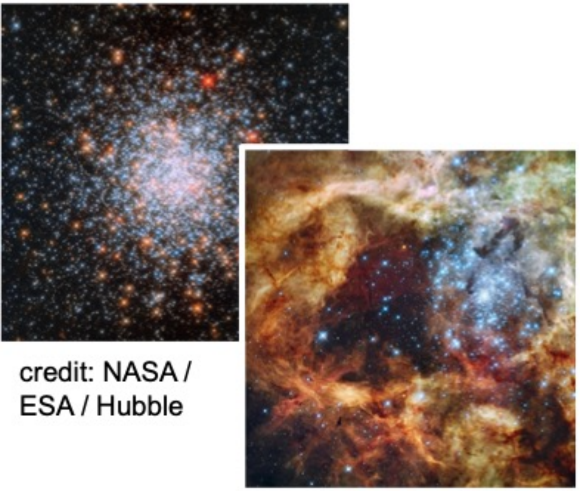


- One of the two merging black holes has mass 85 solar masses: it cannot form from stellar collapse
- Very massive stars (He core ~ 30 - 135 solar masses) undergo (PULSATIONAL) PAIR INSTABILITY
- Expected gap in the black hole mass spectrum between ~ 65 and ~120 solar masses

GW190521 crashes the party because the mass of larger black hole that merged (the ‘primary’ black hole) sits squarely in the interval where stellar collapse is not expected to directly produce black holes – and, moreover, it produced a post-merger remnant black hole that can be classified as an intermediate mass black hole.

Challenge for the models of black hole formation

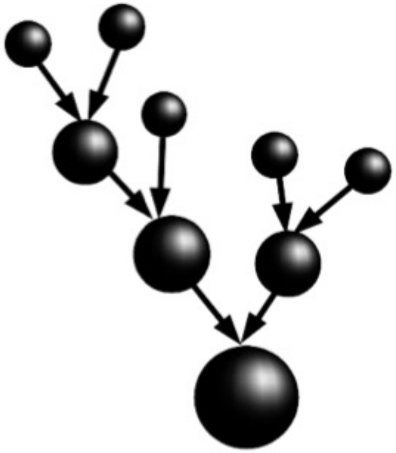
In dense star clusters and galactic nuclei, black holes can have close encounters with other black holes



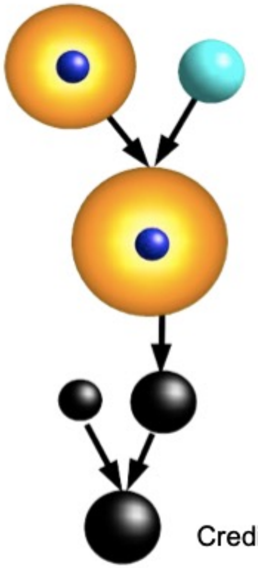
credit: NASA / ESA / Hubble

credit: NASA, ESA, F. Paresce, R. O'Connell

Hierarchical mergers

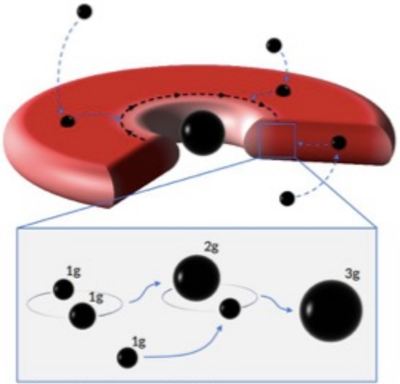


Stellar mergers



Credit: Ugo N. Di Carlo

AGN disks



Credit: Imre Bartos

...or even more exotic scenarios

This multiple merger scenario requires that black holes form in special environments where there are enough other black holes nearby for multiple merger events to occur. Astronomers have proposed dense clusters of stars or the disks of active galactic nuclei as possible examples of such special environments.

The Most Massive & Distant Black Hole Merger Yet: GW190521

(May 21, 2019)

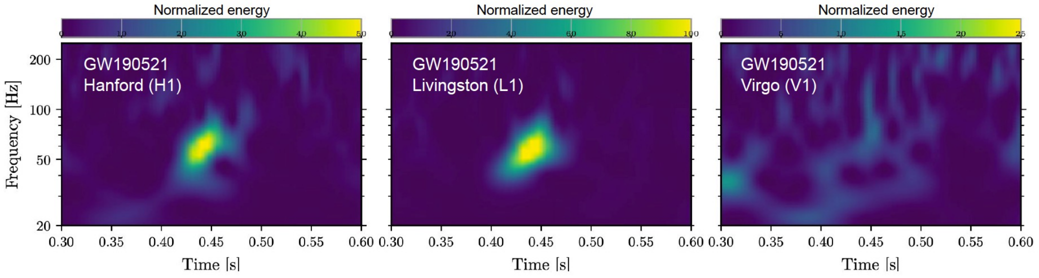
The furthest GW event ever recorded: ~ 7 Glyr distant

At least one of the progenitor black holes (85 M_{sun}) lies in the pair instability supernova gap

Strong evident for spin precession; both progenitor black holes were spinning

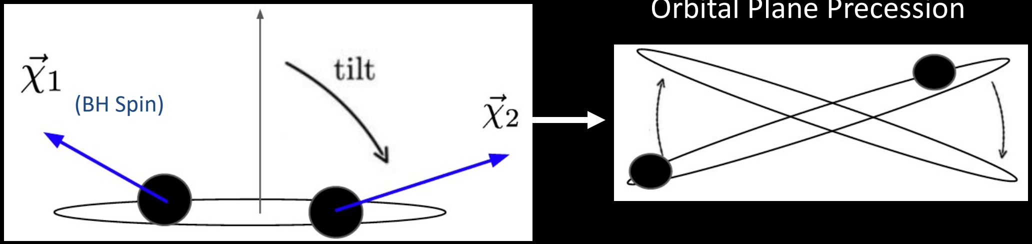
Evidence that GW190521 might be a 2nd generation merger!!

The final black hole mass is 145 M_{sun} is the first ever observation of an intermediate mass black hole



Orbital Angular Momentum

Orbital Plane Precession



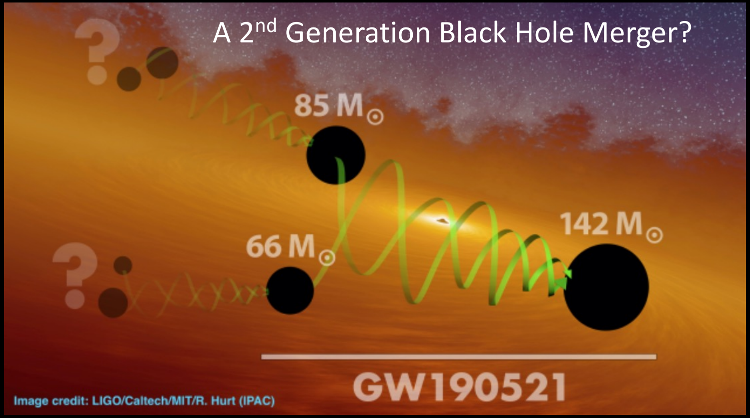


Image credit: LIGO/Caltech/MIT/R. Hurt (IPAC)

Abbott, et al., "GW190521: A Binary Black Hole Merger with a Total Mass of 150 M_{sun}, Phys. Rev. Lett. 125, 101102 (2020).

Abbott, et al., "Properties and Astrophysical Implications of the 150 M_{sun} Binary Black Hole Merger GW190521, Ap. J. Lett. 900, L13 (2020).

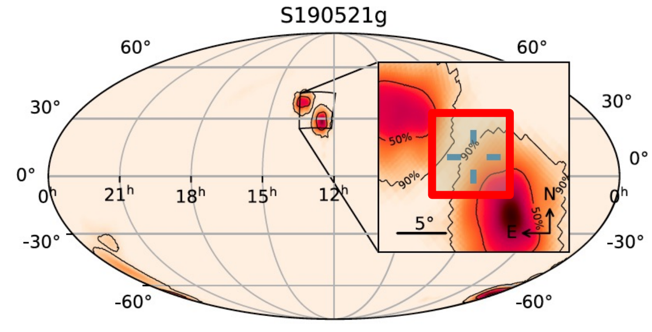
A Possible Electromagnetic Counterpart to GW190521

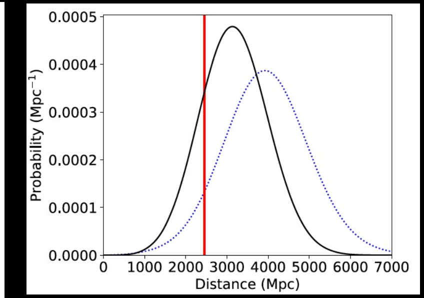
Zwicky Transient Facility surveyed 48% of the LIGO-Virgo 90% error box for GW190521

An electromagnetic flare in the visible was found within the initial 90% LIGO-Virgo contour beginning ~ 25 days after GW190521, lasting for ~ 100 days

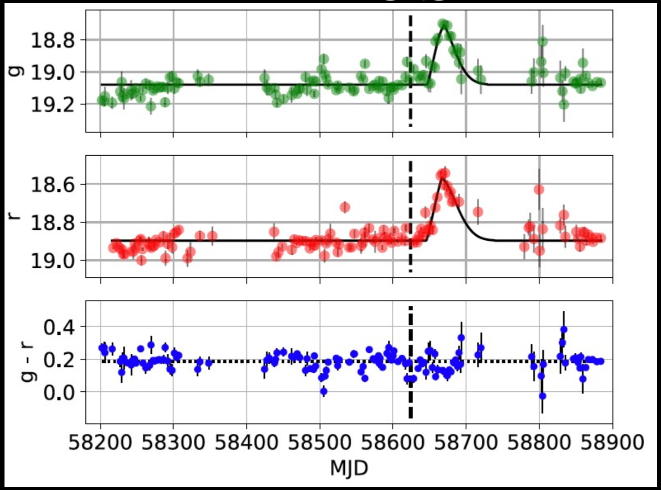
- Consistent with LIGO-Virgo initial distance estimates
- But less consistent with updated maps

The EM flare is consistent with emission from gas in the accretion disk an active galactic nucleus (AGN) excited by the 'kicked' black hole passing through the AGN disk



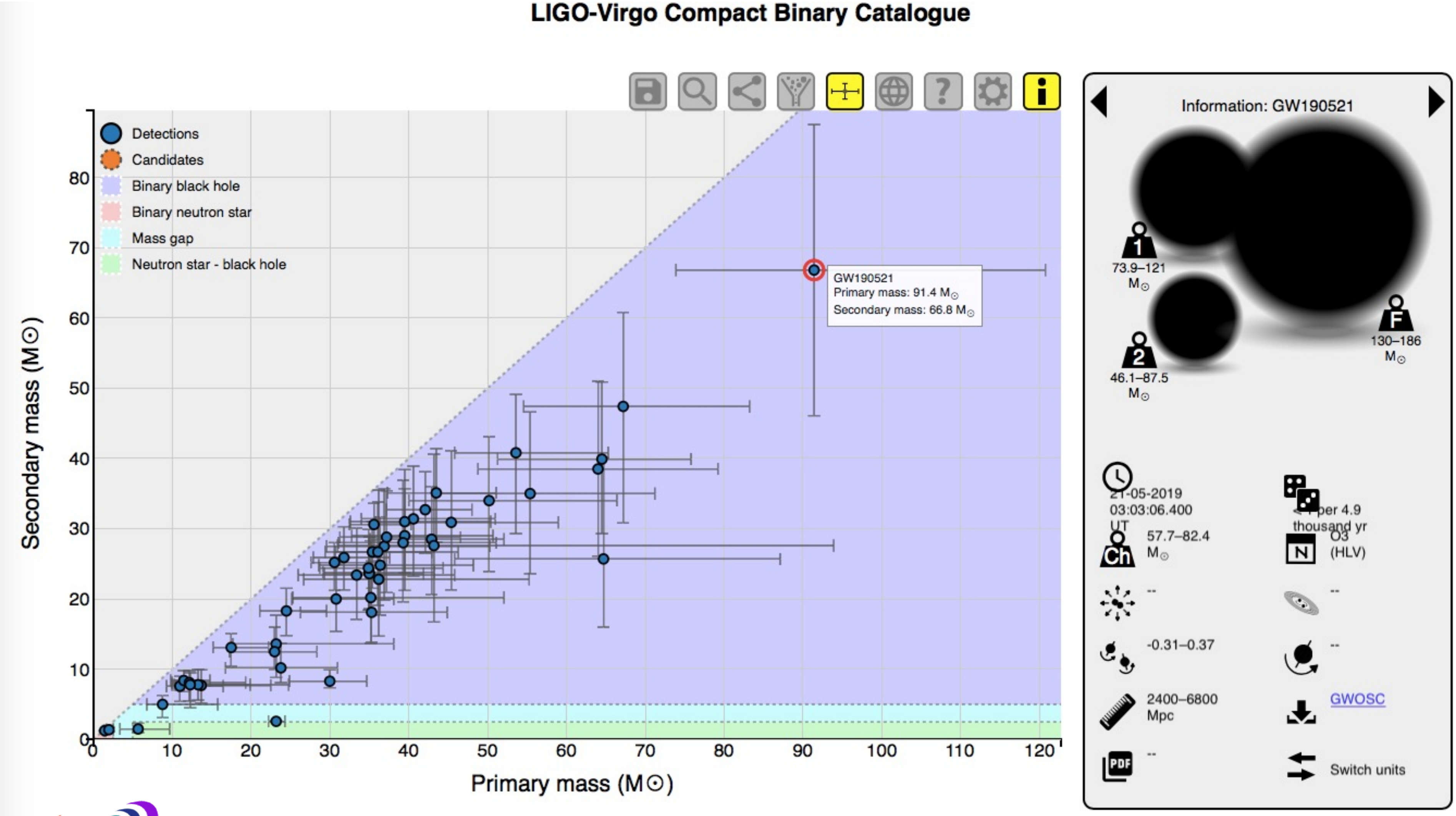


EM Flare from S190521g (g-band, r-band)



Graham, et al., "Candidate Electromagnetic Counterpart to the Binary Black Hole Merger Gravitational-Wave Event S190521g*, Phys. Rev. Lett. 124, 251102 (2020).

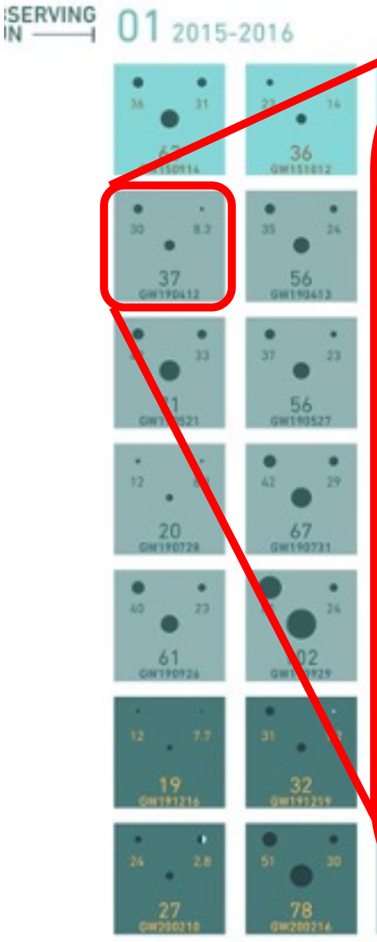
Interactive Catalogue of Binary Black Holes



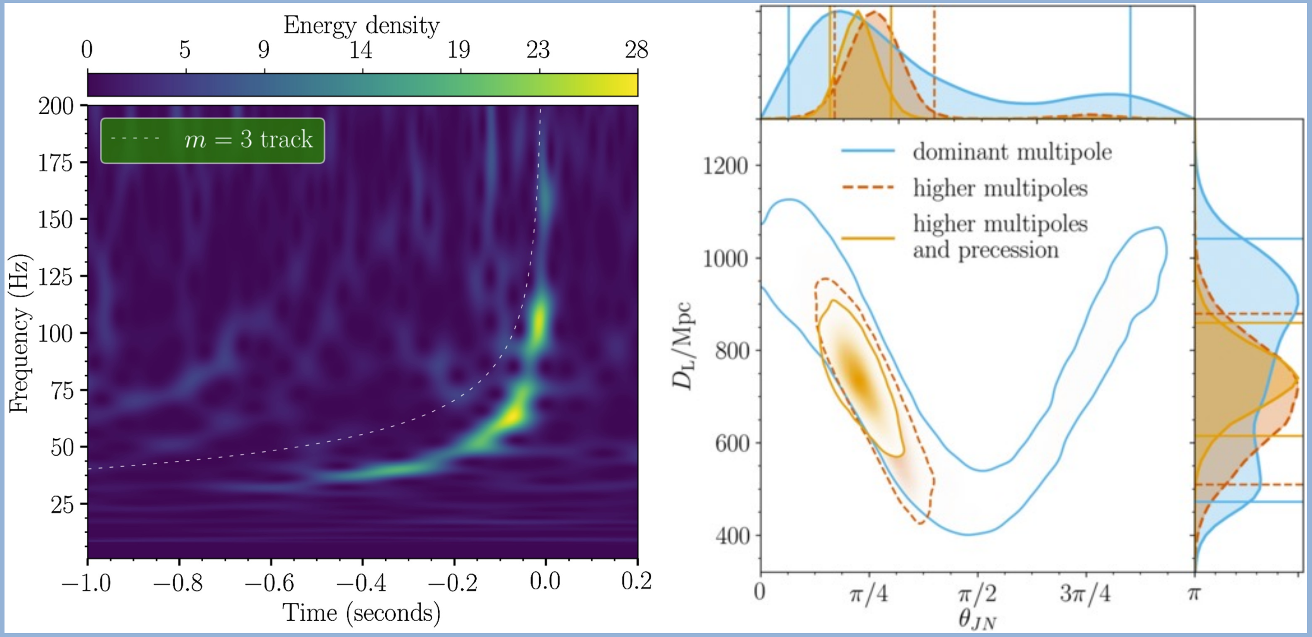
https://catalog.cardiffgravity.org

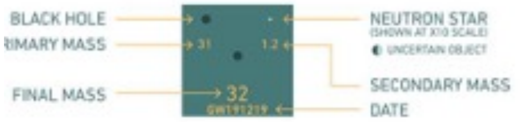
GRAVITATIONAL WAVE **MERGER** DETECTIONS

→ SINCE 2015



GW190412: Unequal mass binary





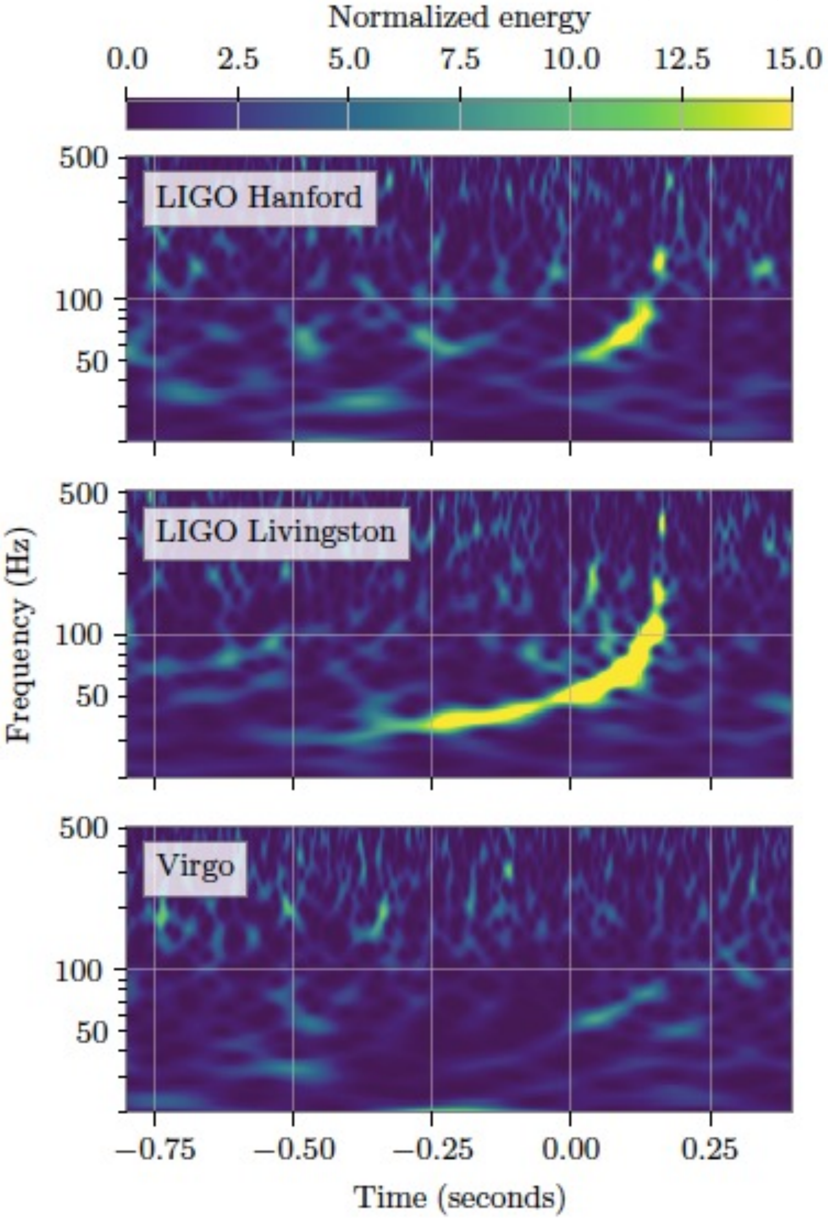
UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^{30}kg

Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.

Slide: S. Fairhurst

GW190412: the first unequal-mass black hole merger



- One black hole in the system is more than 3 times heavier than the other: 30 $M_\odot$+ 8 $M_\odot$.
- This asymmetry in masses modifies the gravitational-wave signal in such a way that we can better measure other parameters, such as the distance and inclination of the system, the spin of the heavier black hole, and the amount that the system is precessing.
- Due to the unequal masses of GW190412 we can for the first time put strong constraints on the spin of the larger black hole, which we find to be spinning at about 40% of the maximal spin allowed by general relativity.

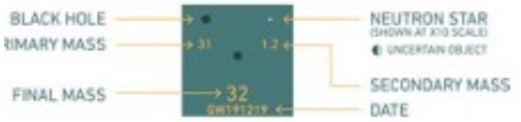
GRAVITATIONAL WAVE **MERGER** DETECTIONS

→ SINCE 2015

GW190814: the coalescence of a stellar mass black hole and a mystery compact object

Black hole (23 $M_\odot$) + 'Mass Gap' (~3 $M_\odot$) (?)

800 million light-years away

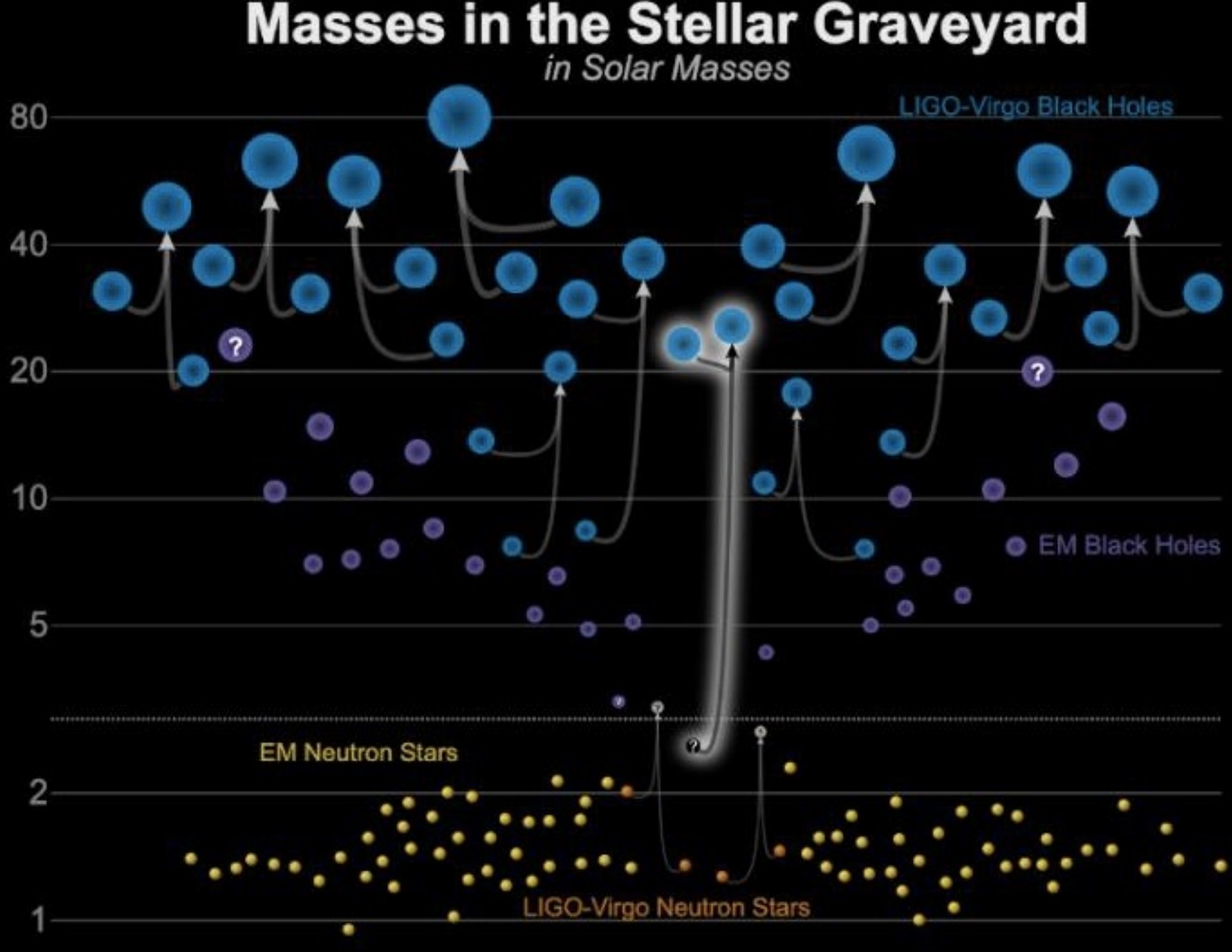


UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^{30}kg

Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.

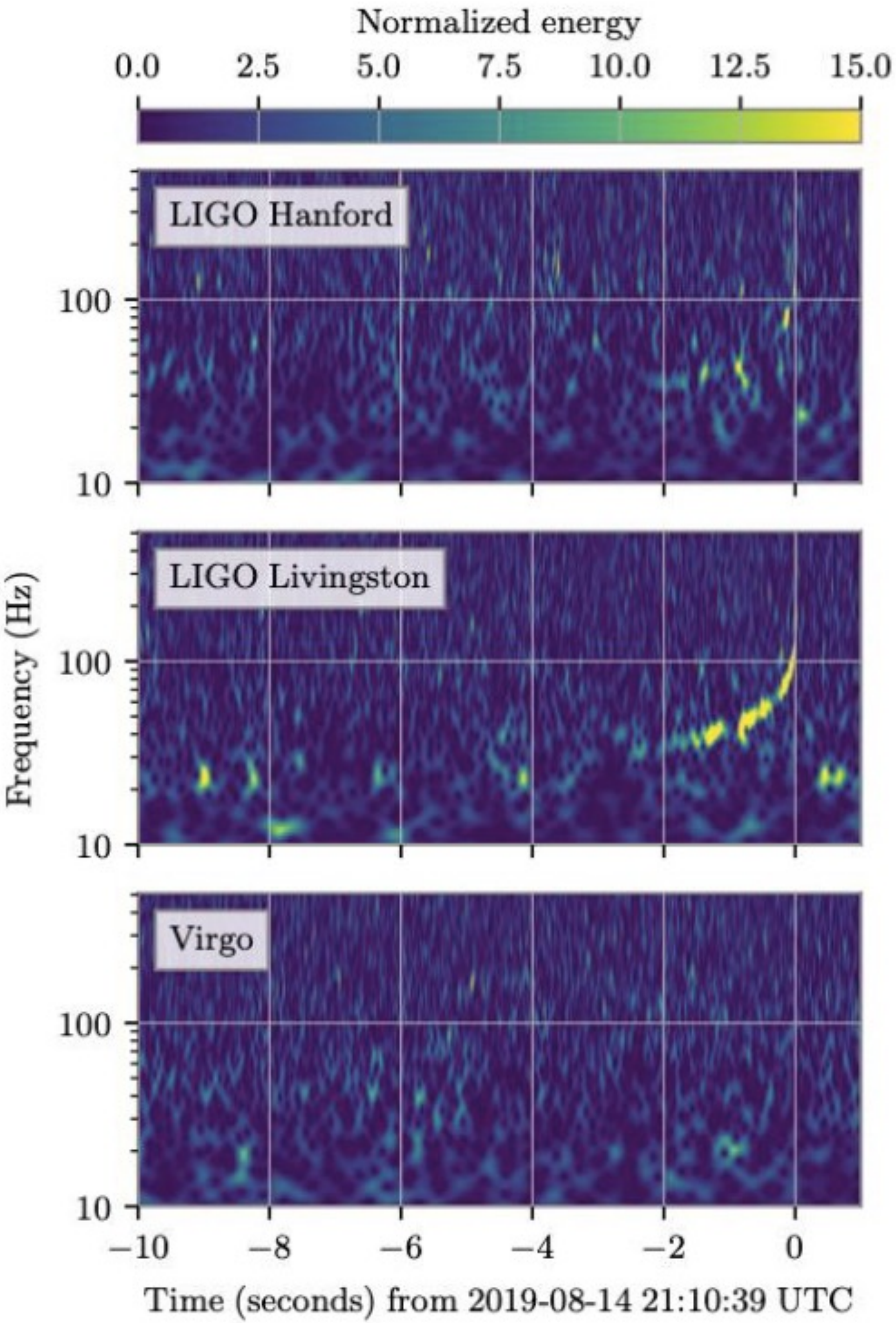
GW190814



Updated 2020-05-16
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

GW190814

- Exactly two years after the first triple coincidence event, the extremely loud event GW190814 was produced by the merger of a black hole and an undetermined object.
- The most asymmetric system observed (the heavier compact object is about nine times more massive than its companion), 23 $M_\odot$ + ~3 $M_\odot$.
- The second mass is either the lightest black hole or the heaviest neutron star ever discovered in a system of two compact objects.



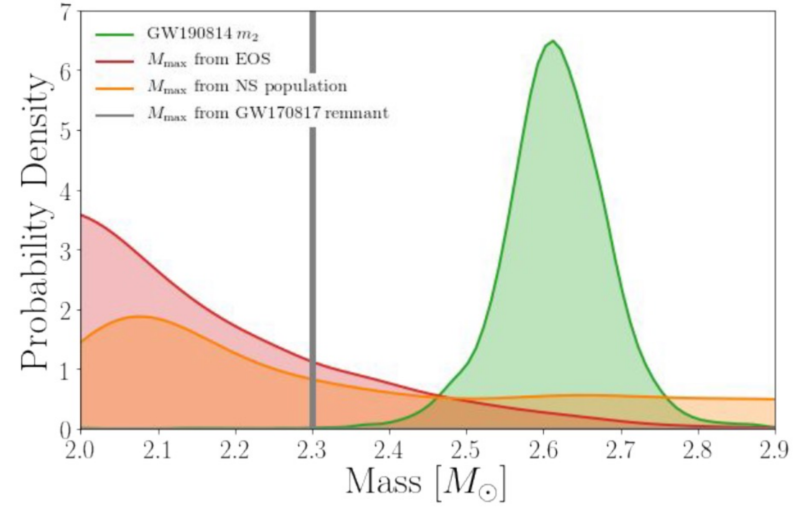
Mystery Merger: GW190814

(Aug 14, 2018)

The secondary mass of 2.6 M_{sun} lies in a '*mass gap*';

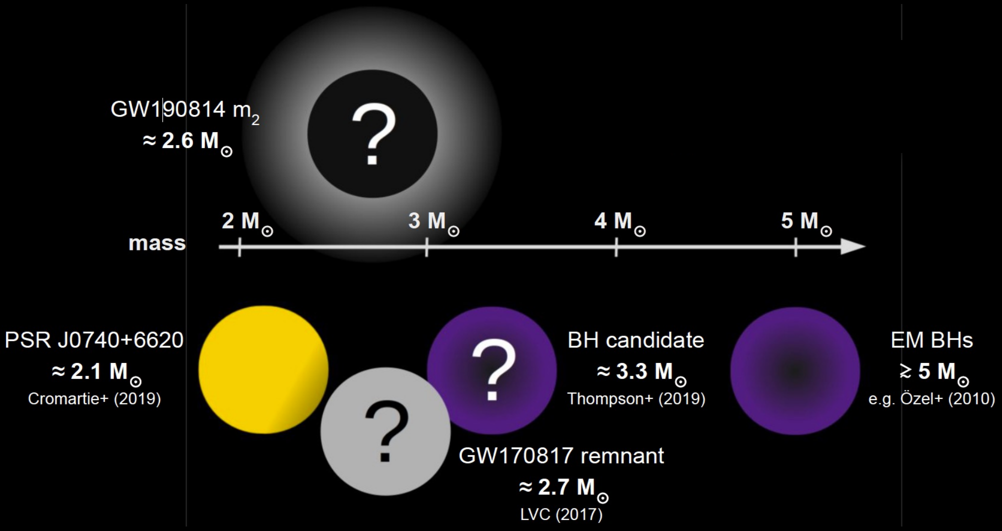
It's greater than estimates of the maximum possible NS mass and less than masses of the lightest black holes ever observed

- Mass of this object comparable to the final merger product in GW170817, which was more likely a black hole.



How did this system form? This detection challenges existing binary formation scenarios

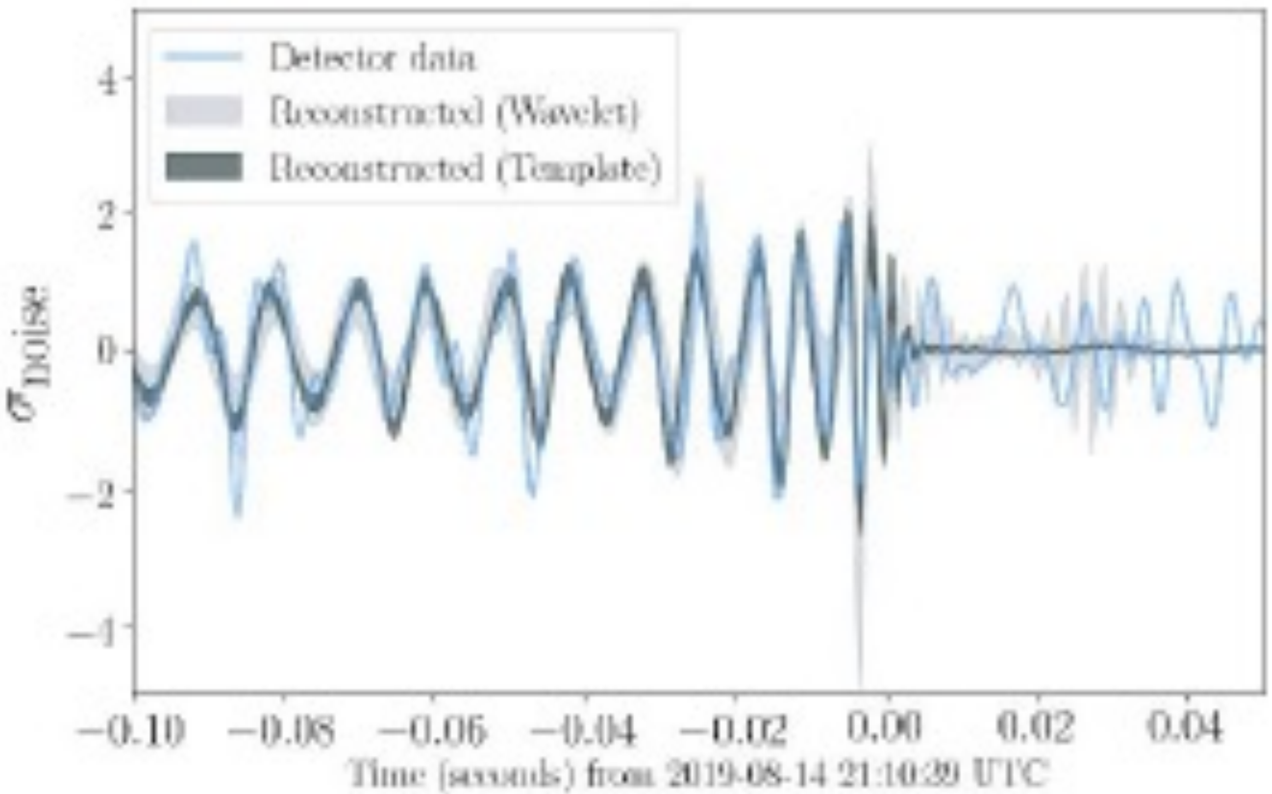
- young dense star clusters and disks around active galactic nuclei are slightly favored, but many other possibilities



Many follow up observations by electromagnetic observatories, but no confirmed counterpart found

Abbott, et al., "GW190814: Gravitational Waves from the Coalescence of a 23 M_{sun} Black Hole with a 2.6 M_{sun} Compact Object, Ap. J. Lett. 896, L44 (2020)

GW190814

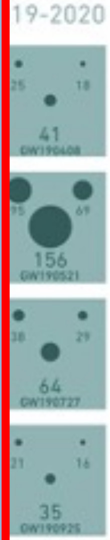


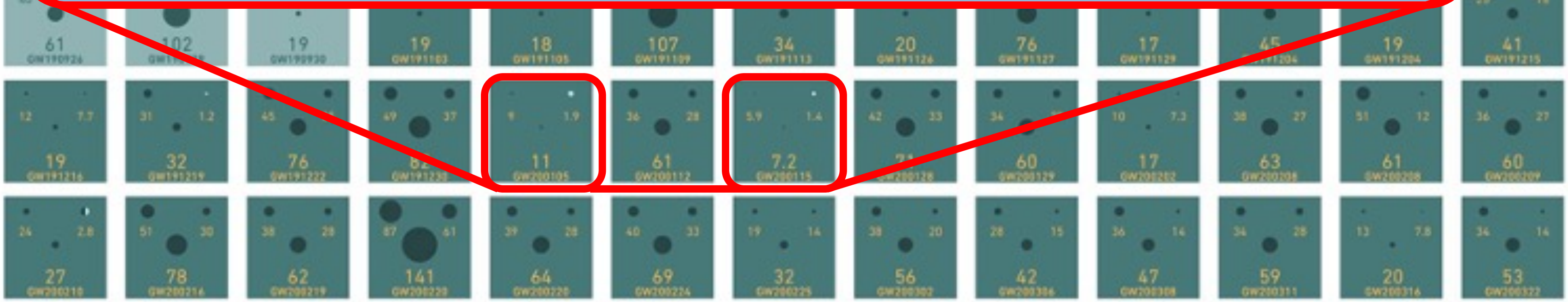
- For a system as massive and asymmetric as GW190814, the tidal imprint is too small to measure. In this case, our attempt to measure tides does not tell us whether GW190814 was caused by the merger of a black hole and a neutron star, as opposed to two black holes.
- Theoretical models for neutron-star matter, as well as observations of the population of neutron stars with electromagnetic astronomy, allow us to estimate the maximum mass that a neutron star can attain. These predictions suggest that the lighter compact object is probably too heavy to be a neutron star, and is therefore more likely to be a black hole.
- We can’t rule out the possibility that GW190814 contains an especially heavy neutron star.

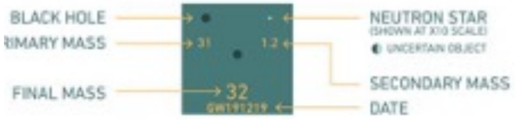
GRAVITATIONAL WAVE **MERGER** DETECTIONS
→ SINCE 2015

GW200105 and GW200115: Observation of Neutron Star Black Hole Mergers

First unambiguous observations of NS-BH system







UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^{30}kg

Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

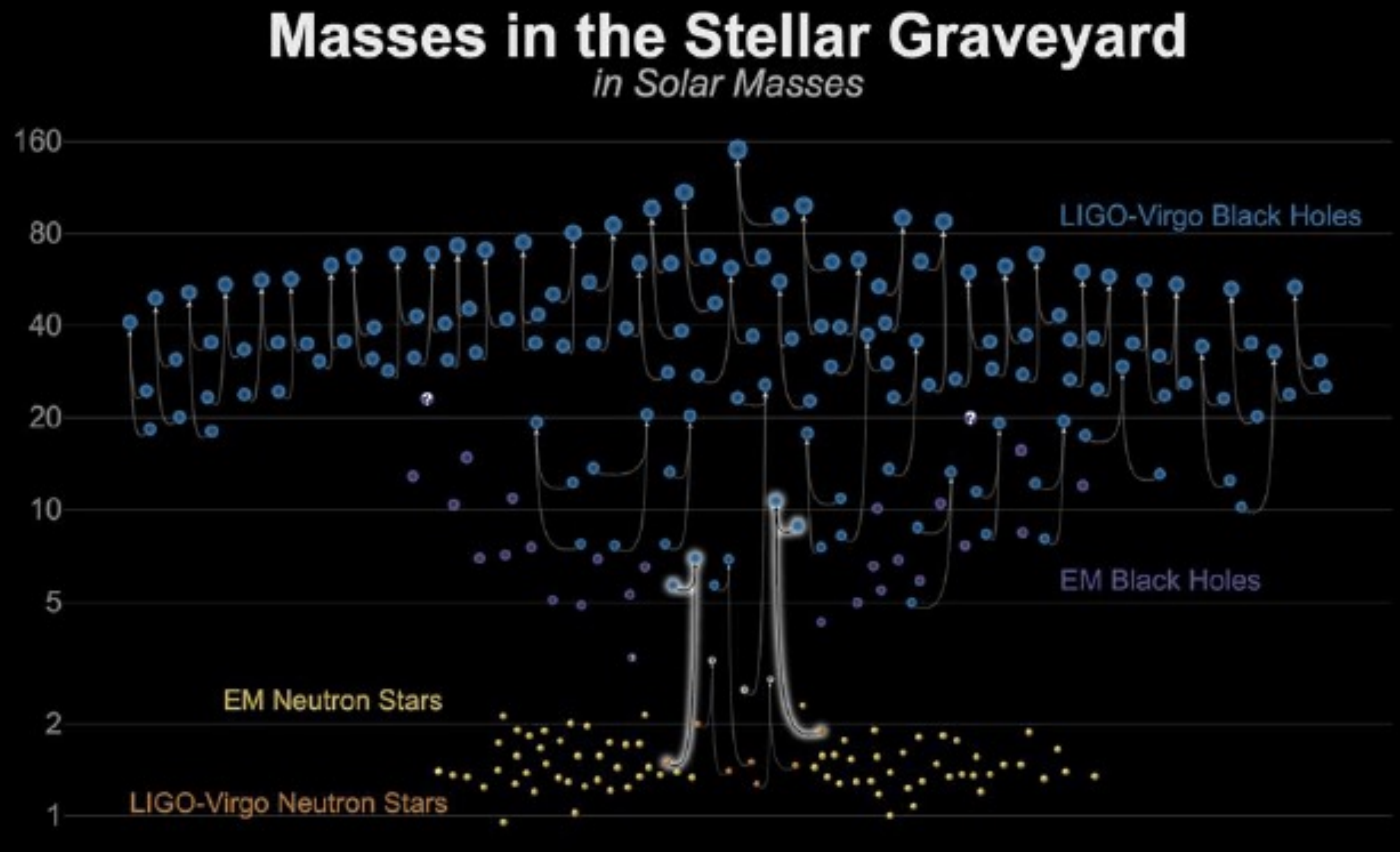
The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.

OzGrav

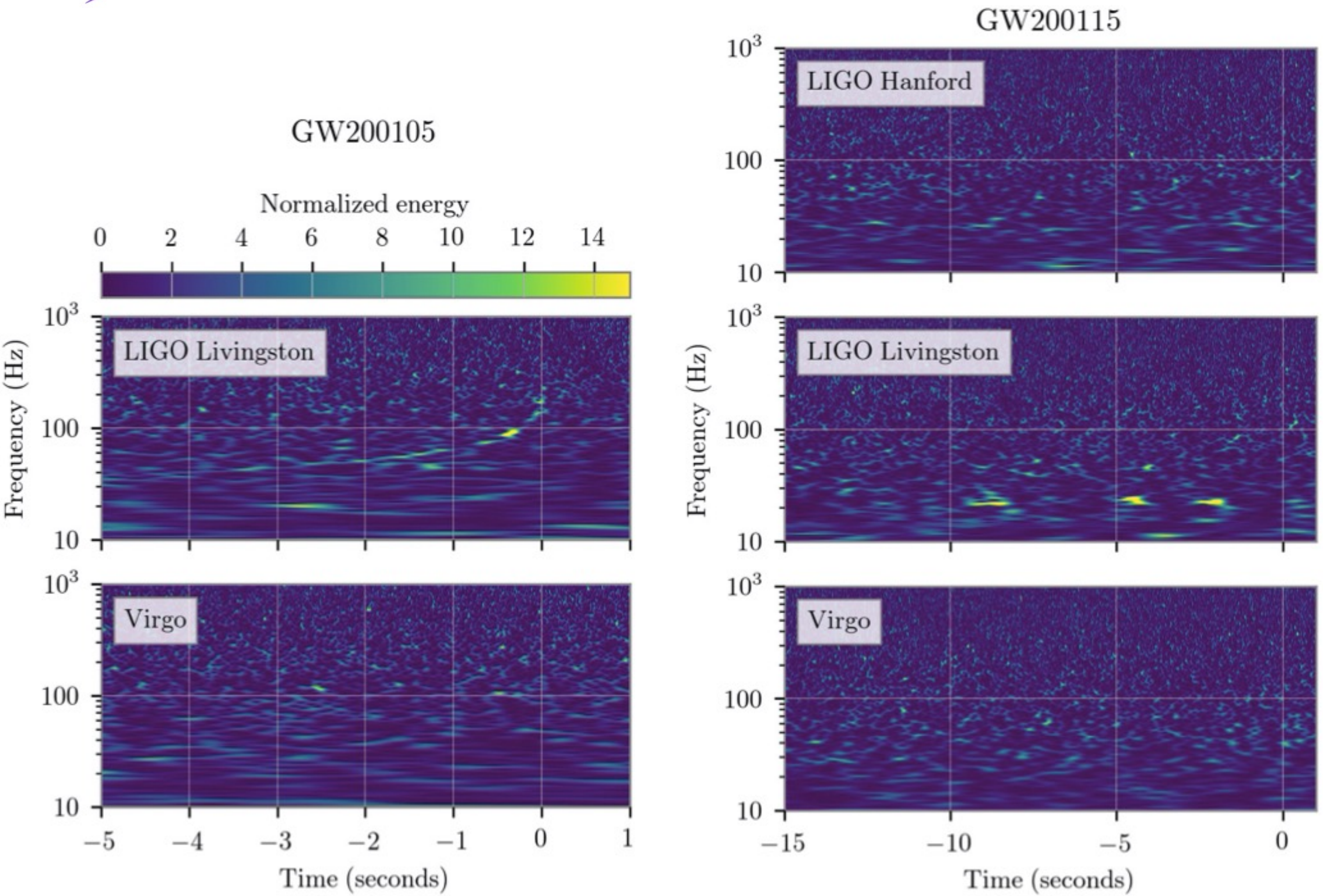
LIGO VIRGO KAGRA

Slide: S. Fairhurst

Neutron star – Black hole Binaries: GW200105 and GW200115

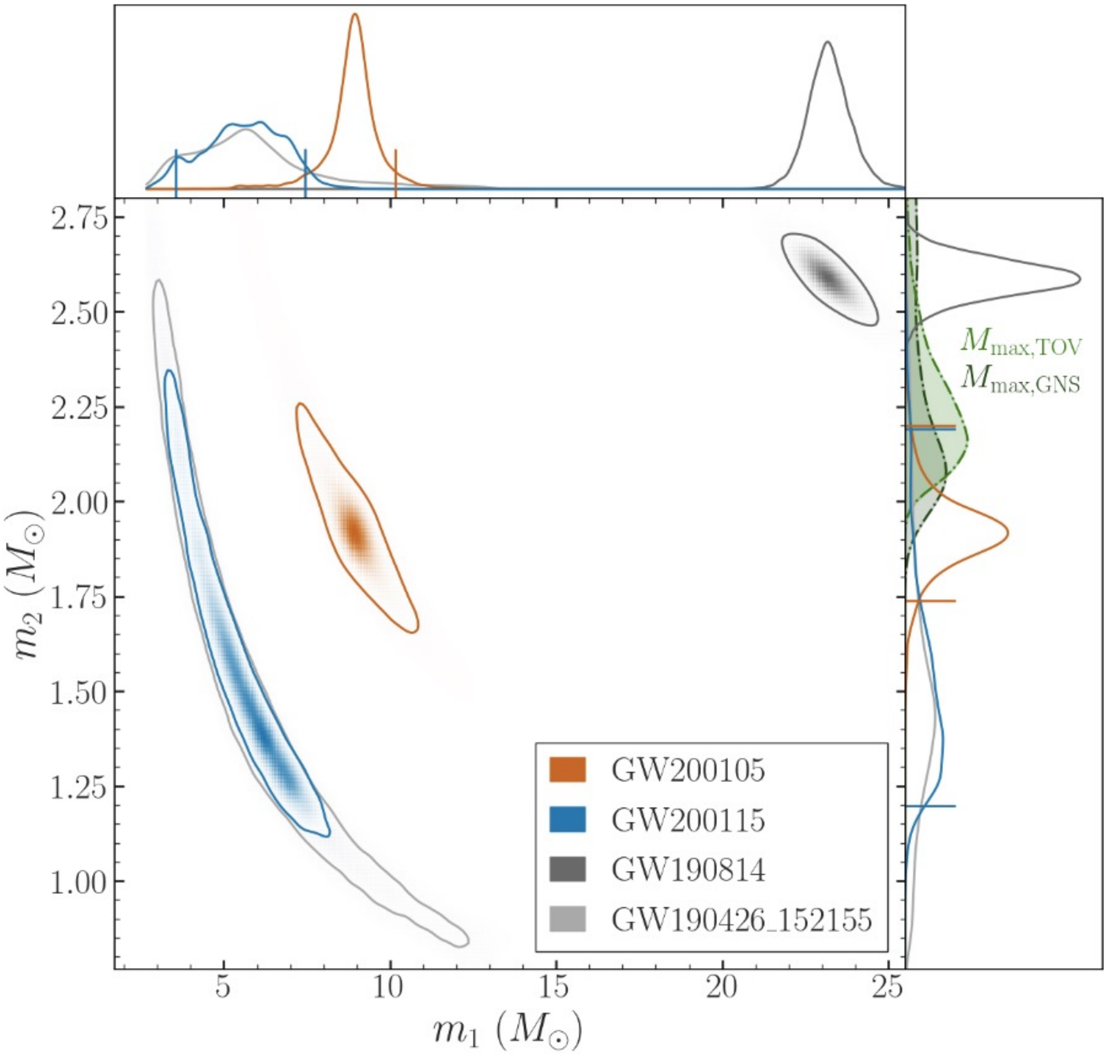


Neutron star – Black hole Binaries



Neutron star – Black hole Binaries

- GW200105: 8.9 $M_{\odot}$ + 1.9 $M_{\odot}$, their merger happened 800 million years ago.
- GW200115: 5.7 $M_{\odot}$ + 1.5 $M_{\odot}$, their merger happened nearly 1 billion years ago.



Neutron star – Black hole Binaries: how did they form?

- **Isolated binary evolution**: two stars orbiting each other explode in supernova explosion leaving behind a black hole and a neutron star.
- The spin directions of the BH tend to align with the binary orbit, we expect the neutron star to orbit in the equatorial plane of the black hole.

- **Dinamical interaction**: the neutron star and the black hole formed separately in unrelated supernova explosions and afterwards find each other.
- No prefer direction of the spin, and so the neutron star orbit could have any orientation relative to the black hole’s equatorial plane.

GW200105 and GW200115

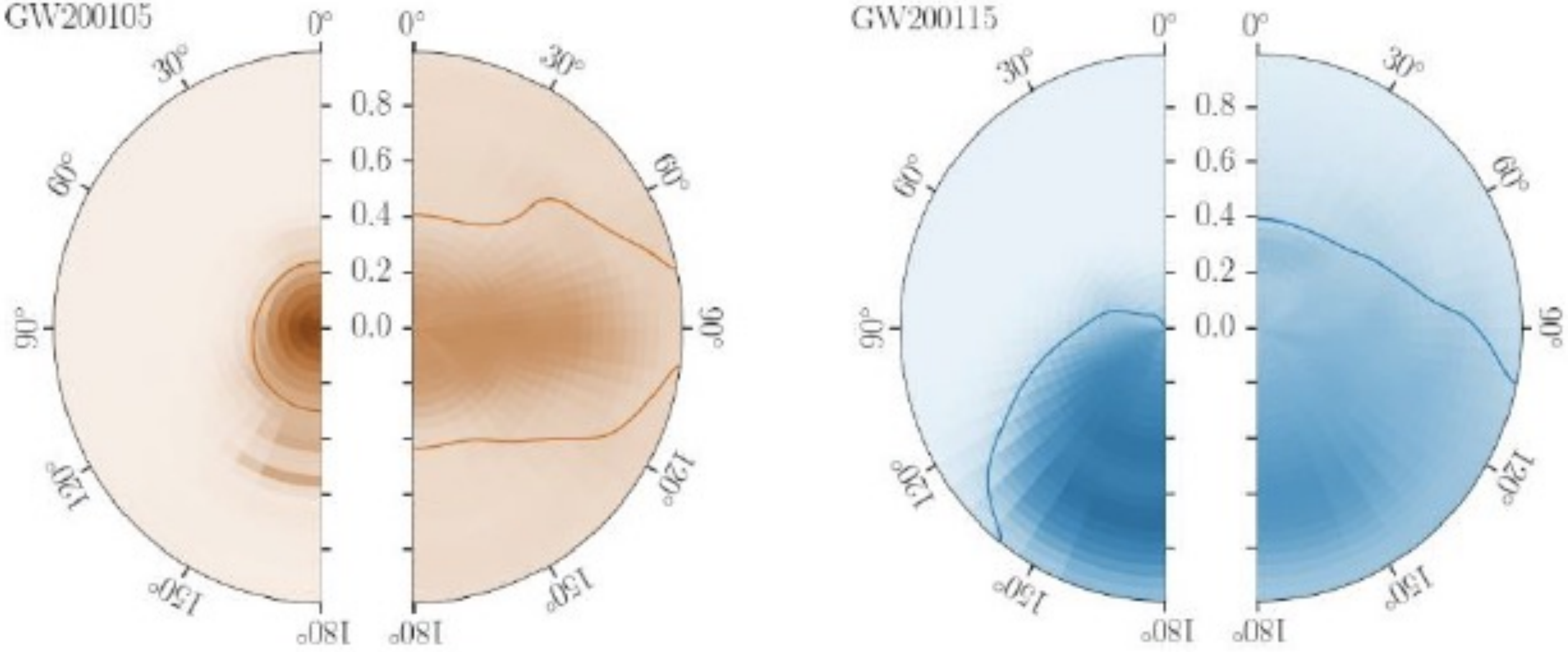
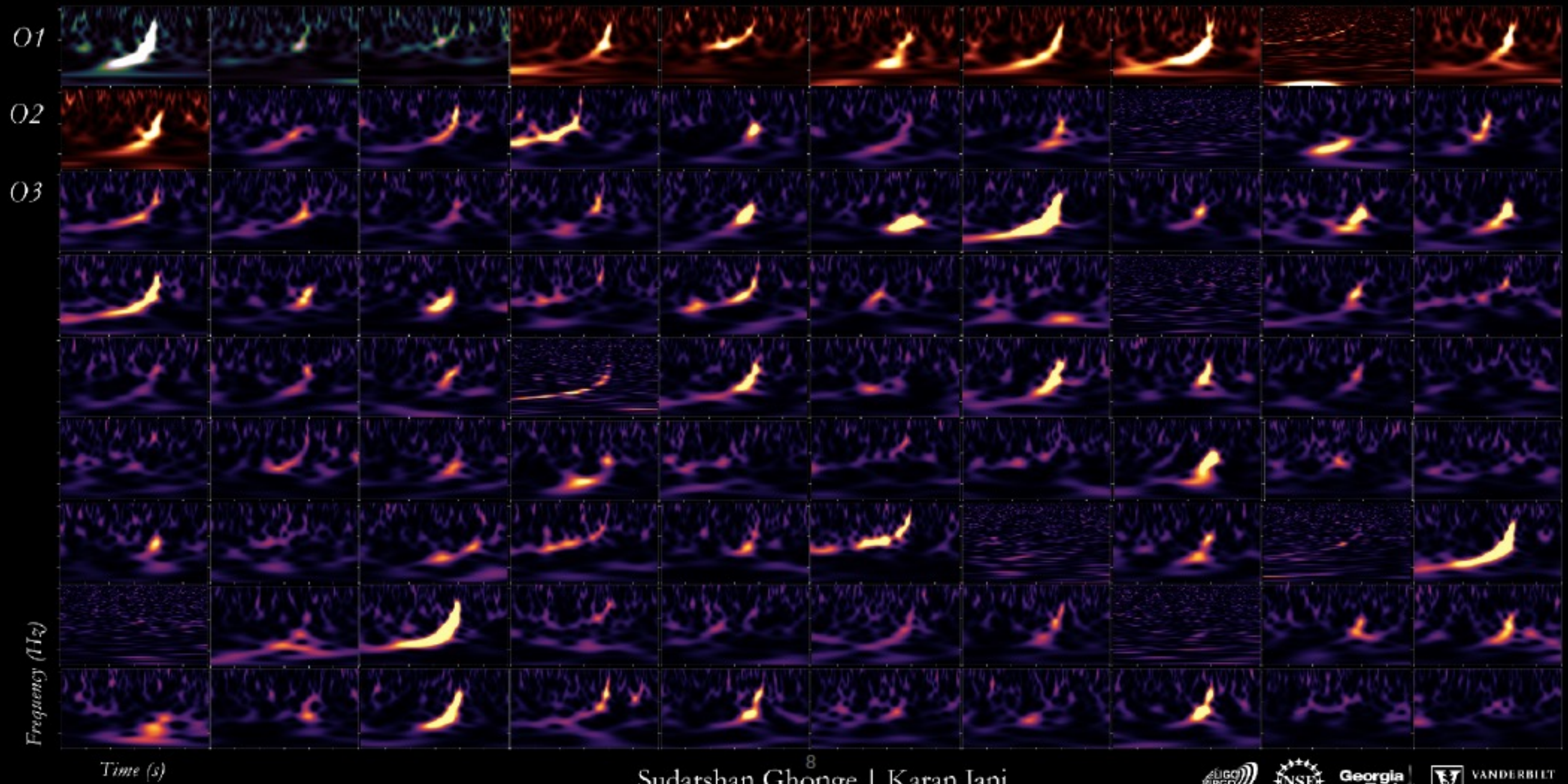


Figure 3: The inferred spin magnitude and direction of the black holes (left half-disks) and neutron stars (right half-disks) of GW200105 and GW200115. The radius of the disk indicates the spin magnitude, and range between 0 (no spin) to 1 (maximum rotation rate of black holes). The spin direction is shown as an angle, which ranges from 0º (objects spin in the same direction as the orbit of the binary) to 180º (objects spin in the opposite direction of the orbit of the binary). Shading indicates probable values of spin magnitude and direction. The left-most hemisphere has shading that peaks near the centre, indicating that GW200105's black hole has a spin that is likely small. The second to right hemisphere's shading extends downward, indicating that GW200115's black hole may be spinning in a direction opposite to the orbital motion.

Gravitational-Wave Transient Catalog

Detections from 2015-2020 of compact binaries with black holes & neutron stars

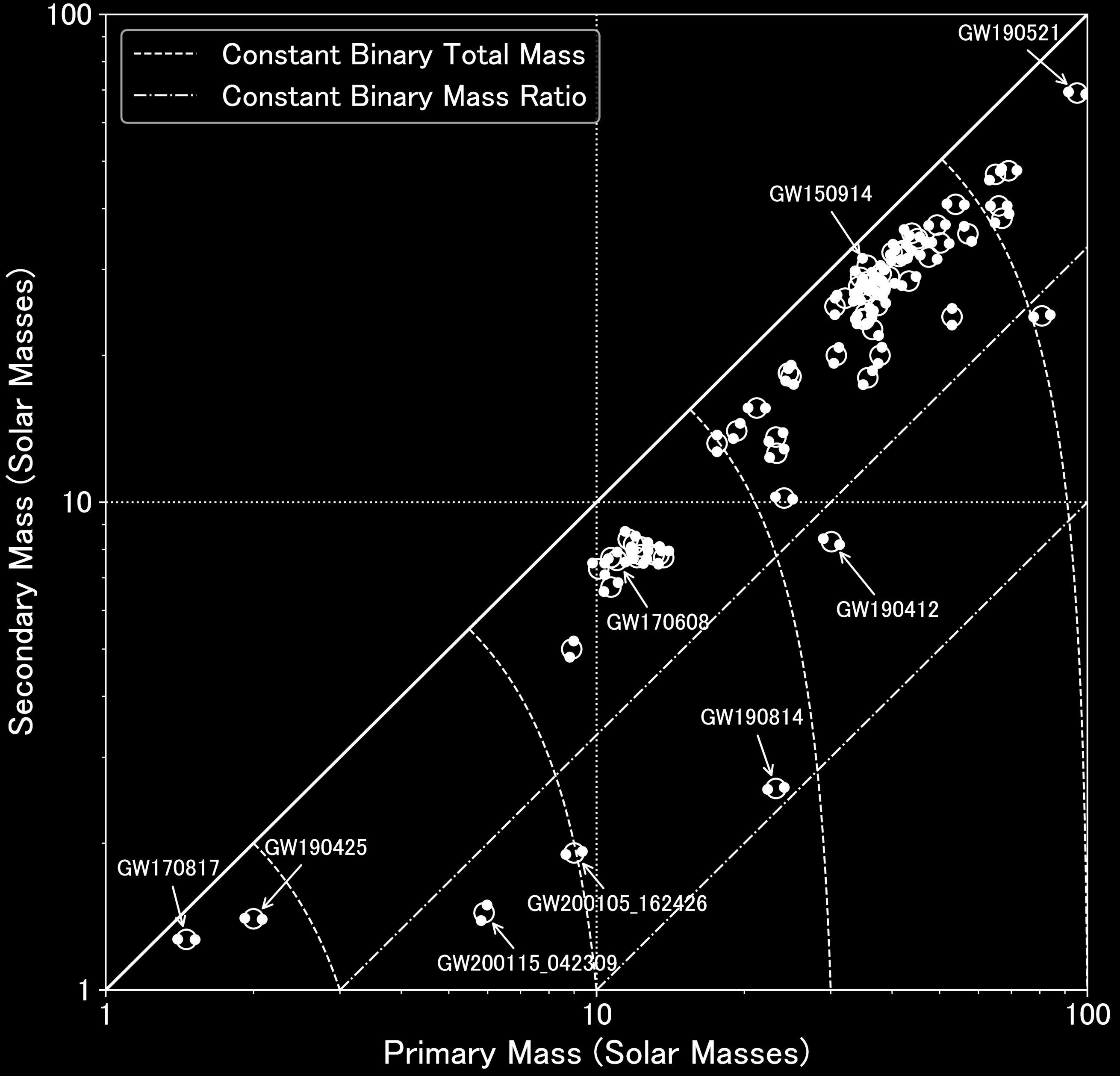


Sudarshan Ghonge | Karan Jani

LIGO VIRGO KAGRA NSF Georgia Tech VANDERBILT UNIVERSITY

The population properties

We use a set of 74 compact binary mergers identified in LIGO-Virgo data up to the end of the third observing run including 70 binary black hole (BBH) events, two binary neutron stars (BNS), and two neutron-star black hole (NSBH) mergers.



The population properties of black holes and neutron stars

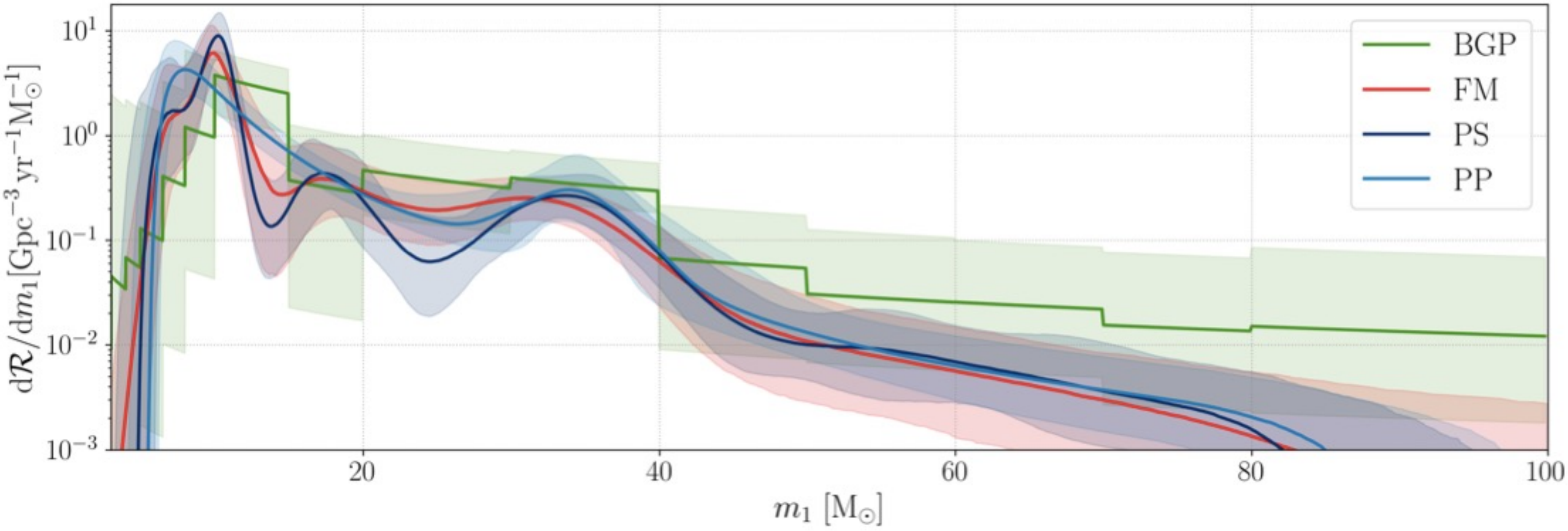
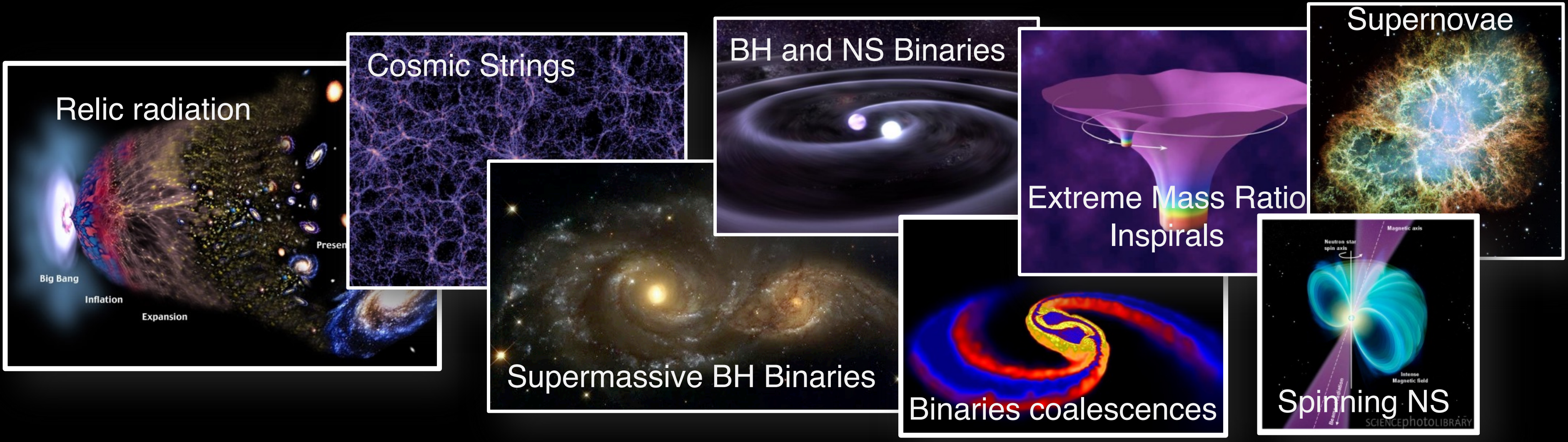


FIG. 11. The differential merger rate for the primary mass predicted using three non-parametric models compared to the fiducial PP model. Solid curves are the medians and the colored bands are the 90% credible intervals.

- We can identify two new bumps in the distribution of the more massive black hole in each binary (also called the primary) at around 10 and 18 $M_\odot$, in addition to the previously-identified peak at about 35 $M_\odot$.
- While isolated binary evolution models can explain the clustering of sources in the 8-10 $M_\odot$ range, the origins of the additional peaks are not yet understood. Similarly to the lower mass gap, we are unable to confidently identify the presence of an upper mass gap for binary black holes.

The Gravitational Wave Spectrum



Relic radiation

Cosmic Strings

Supermassive BH Binaries

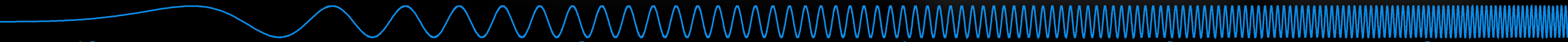
BH and NS Binaries

Extreme Mass Ratio Inspirals

Binaries coalescences

Supernovae

Spinning NS



10^{-16} Hz

10^{-9} Hz

10^{-4} Hz

10^{0} Hz

10^{3} Hz

Pulsar timing

Space detectors

Ground interferometers

Bibliography

- B.P. Abbott et al, Phys.Rev.Lett. 116 (2016) no.24, 241102
- B.P. Abbott et al, Astrophys.J. 818 no.2, L22, 2016.
- B.P. Abbott et al, Phys.Rev.Lett. 116 no.22, 221101, 2016.
- B.P. Abbott et al, Phys. Rev. D 93, 122010, 2016.
- B.P. Abbott et al, The Astrophysical Journal Letters, Volume 826, Number 1 2016.
- B.P. Abbott et al, Phys.Rev.Lett. 116 (2016) no.24, 241103.
- B.P. Abbott et al, Phys.Rev. X6 (2016) no.4, 041015.
- B.P. Abbott et al, Astrophys.J. 832 (2016) no.2, L21.
- B.P. Abbott et al, Astrophys.J. 841 (2017) no.2, 89.
- A.Albert et al, Phys.Rev. D96 (2017) no.2, 022005.
- B.P. Abbott et al, Phys.Rev.Lett. 118 (2017) no.22, 221101.
- B.P. Abbott et al, Phys.Rev.Lett. 119 (2017) no.14, 141101.
- B.P. Abbott et al, Phys.Rev.Lett. 119 (2017) no.16, 161101.
- B.P. Abbott et al, Astrophys.J. 848 (2017) no.2, L12.

Bibliography

- B.P. Abbott et al, Astrophys.J. 848 (2017) no.2, L13.
- A.Albert et al, Phys.Rev. D96 (2017) no.2, 022005.
- B.P. Abbott et al, Nature 551 (2017) no.7678, 85-88.
- B.P. Abbott et al, Astrophys.J. 850 (2017) no.2, L39.
- A.Albert et al, Astrophys.J. 850 (2017) no.2, L35.
- B.P. Abbott et al, Astrophys.J. 851 (2017) no.2, L35.
- B.P. Abbott et al, Astrophys.J. 851 (2017) no.1, L16
- B.P. Abbott et al, Phys.Rev.Lett. 121 (2018) no.16, 161101
- B.P. Abbott et al, Phys.Rev. X9 (2019) no.1, 011001.
- B.P. Abbott et al, Astrophys.J. 871 (2019) no.1, 90.
- B.P. Abbott et al, Phys.Rev. X9 (2019) no.3, 031040.
- B.P. Abbott et al, Astrophys.J. 882 (2019) no.2, L24.
- B.P. Abbott et al, Physical Review D, 2020, 102(4), 043015.
- B.P. Abbott et al, Physical review letters, 2020, 125(10).
- R. Abbott et al, Astrophys.J.Lett. 913 (2021) 1, L7.
- R. Abbott et al, Phys.Rev.X 11 (2021) 021053.
- R. Abbott et al, Astrophys.J.Lett. 915 (2021) 1, L5.
- R. Abbott et al, Astrophys.J.Lett. 941 (2022) 2, L30