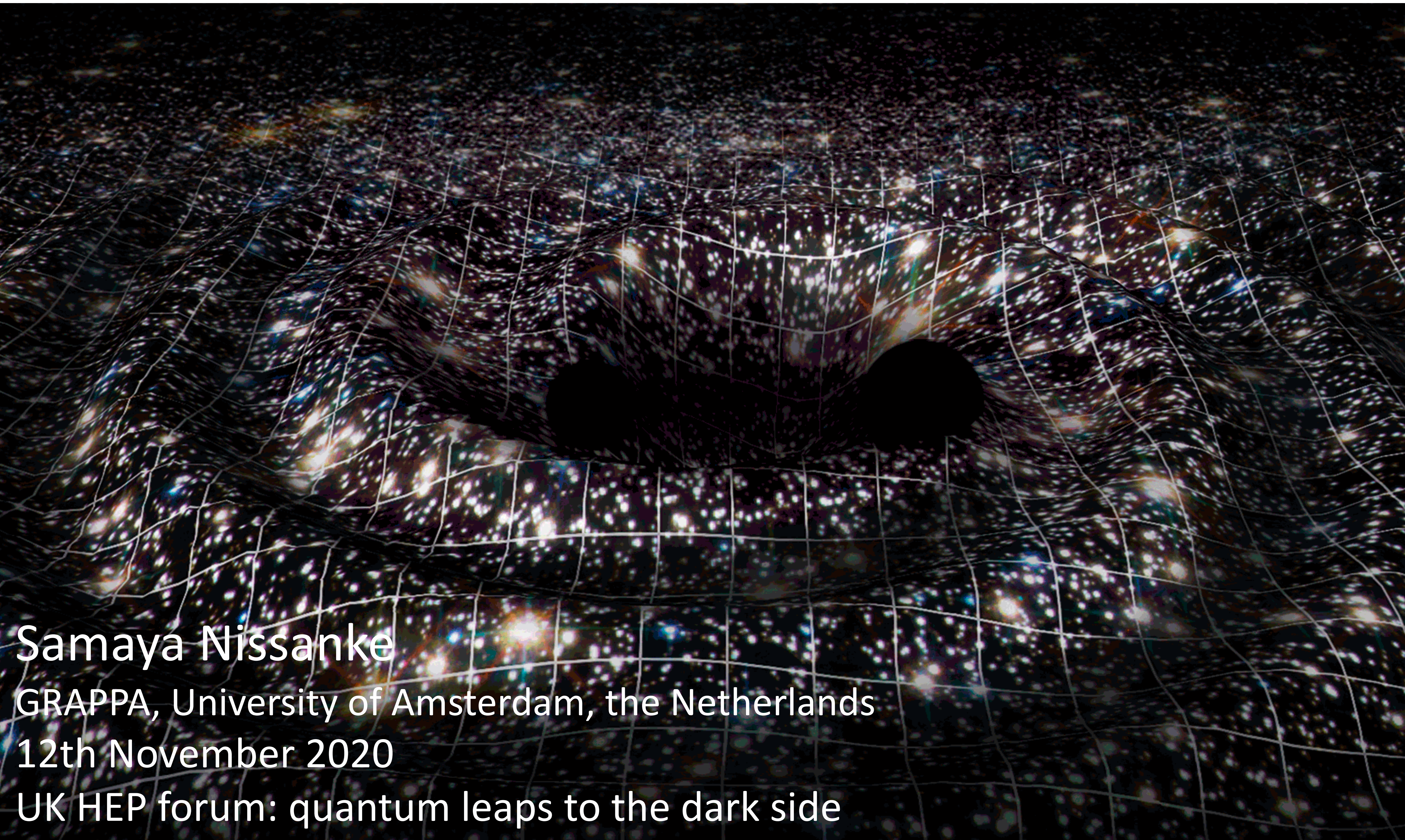
New perspectives onto the Universe in the era of multi-messenger astronomy (MMA)

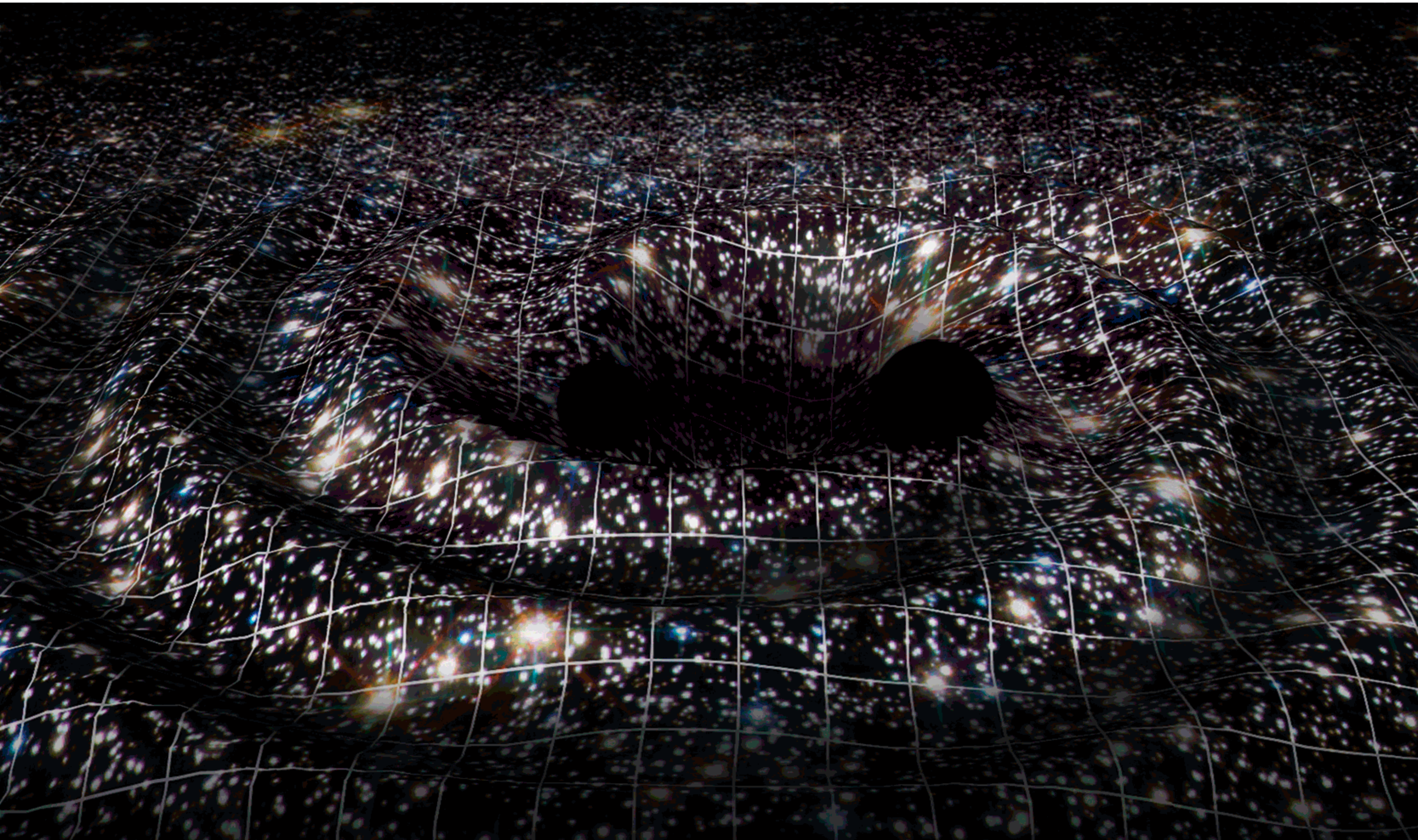


Samaya Nissanke
GRAPPA, University of Amsterdam, the Netherlands

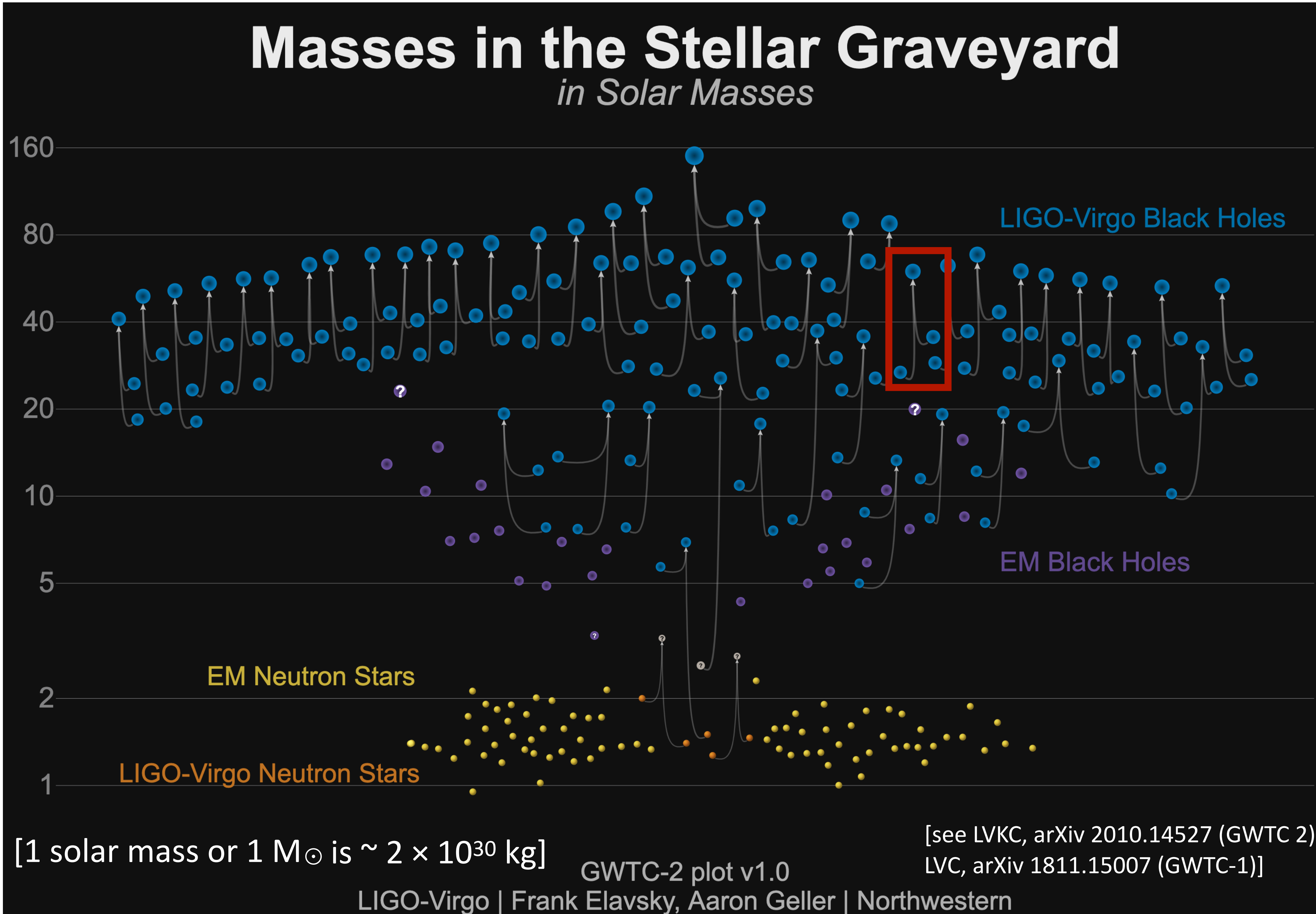
12th November 2020

UK HEP forum: quantum leaps to the dark side

New perspectives onto the Universe in the era of multi-messenger astronomy (MMA)

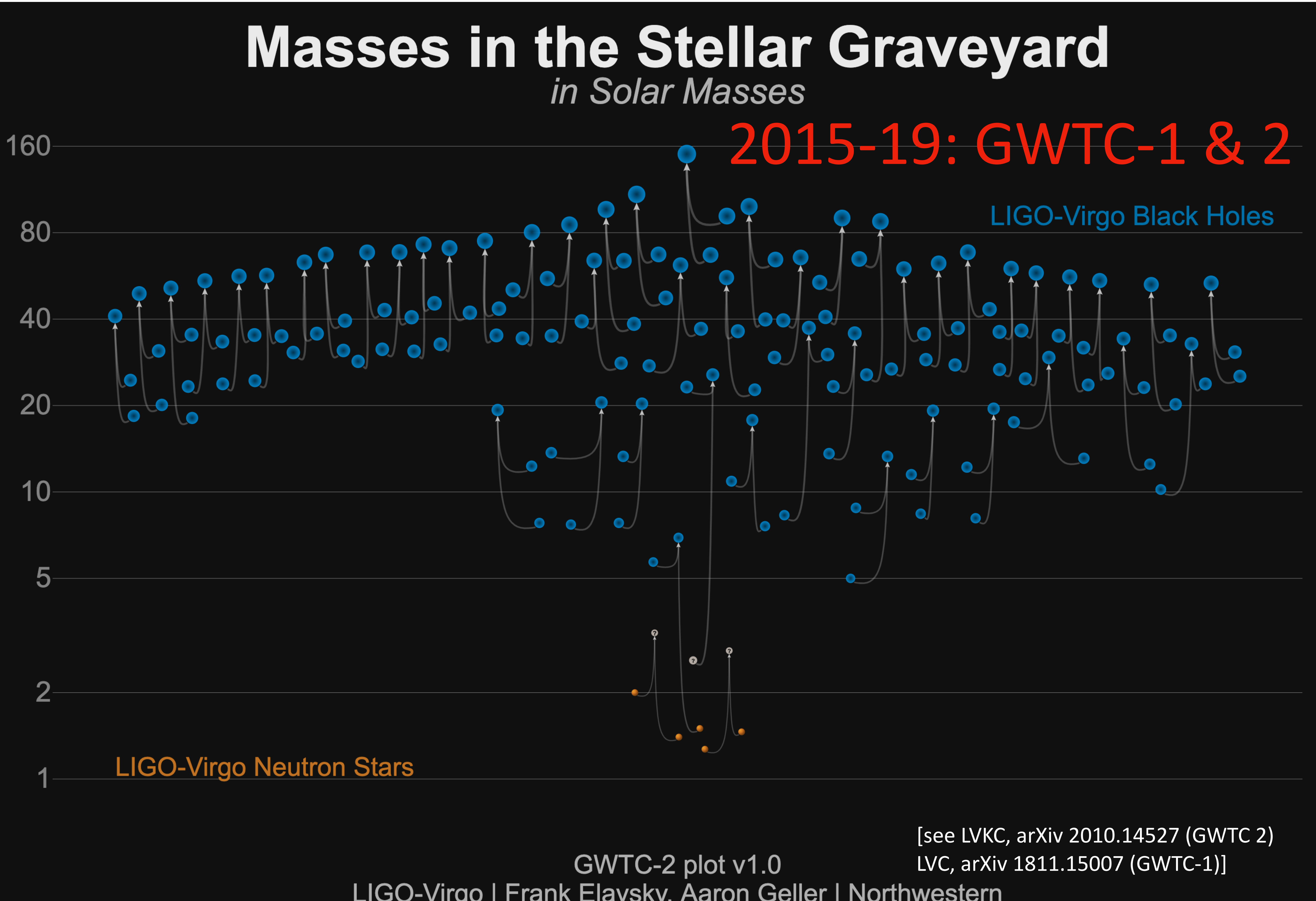


A revolution in the past five years: gravitational waves (GW), black holes and neutron stars

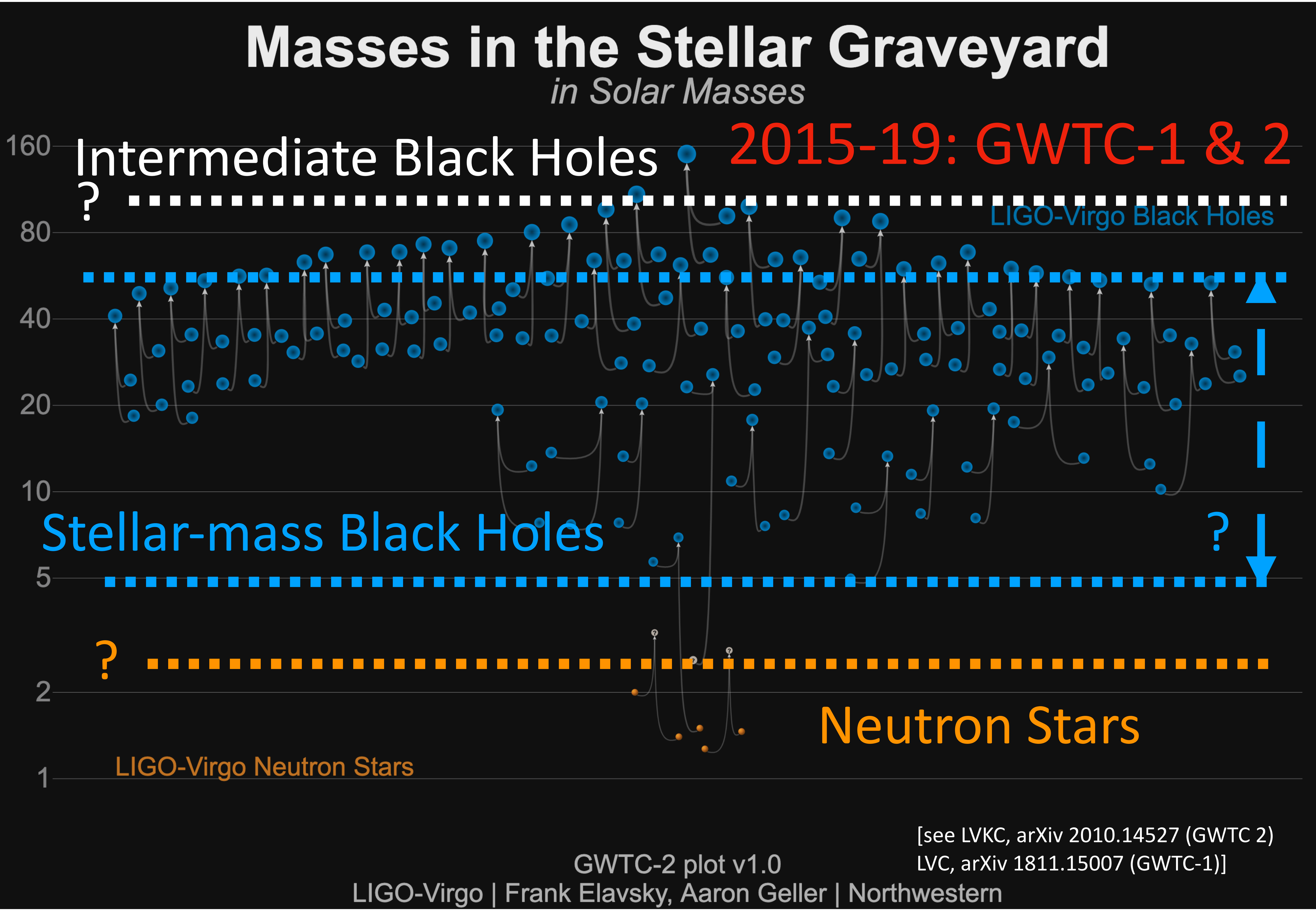


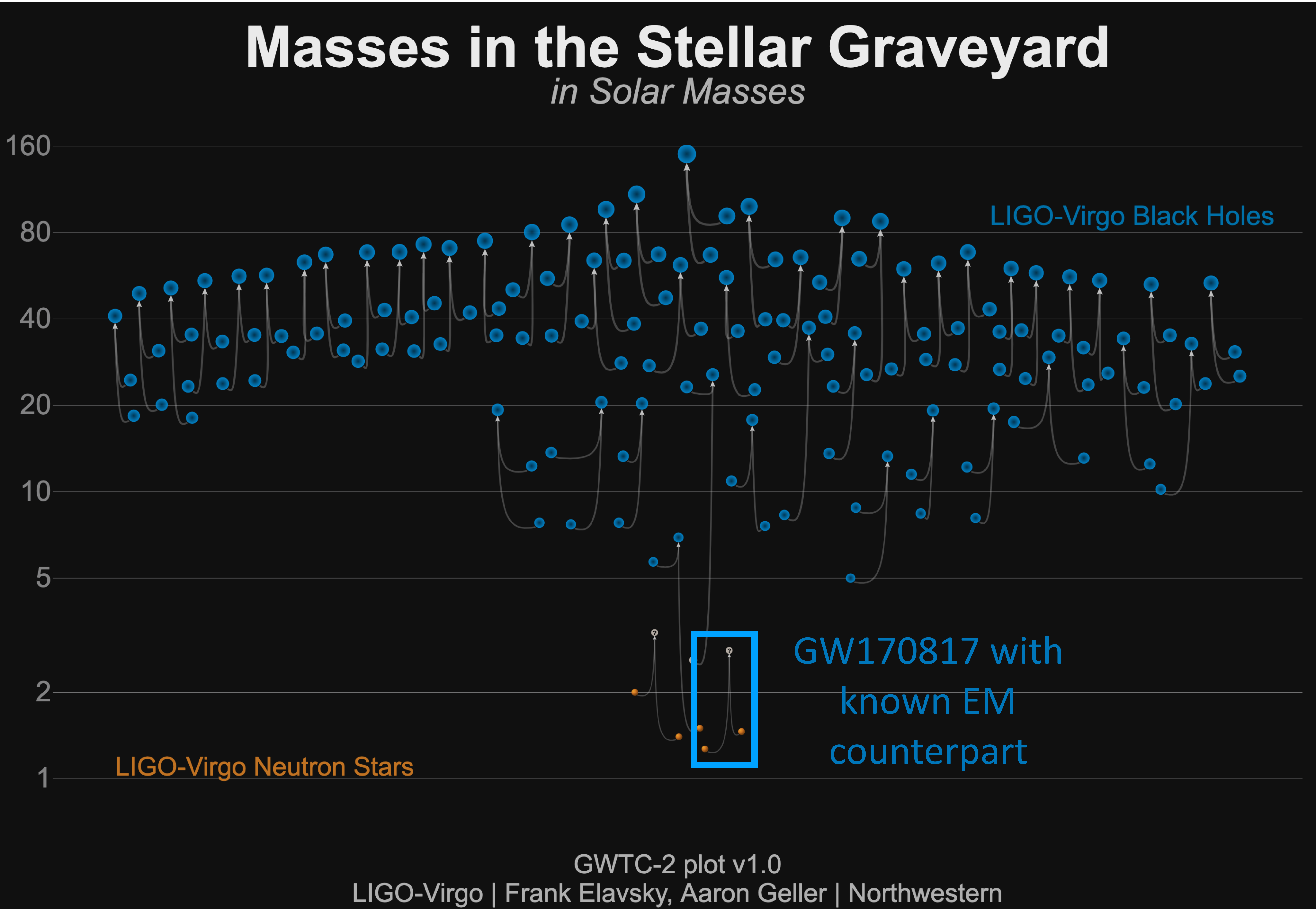
[1 solar mass or 1 M⊙ is ~ 2 × 10^{30} kg]

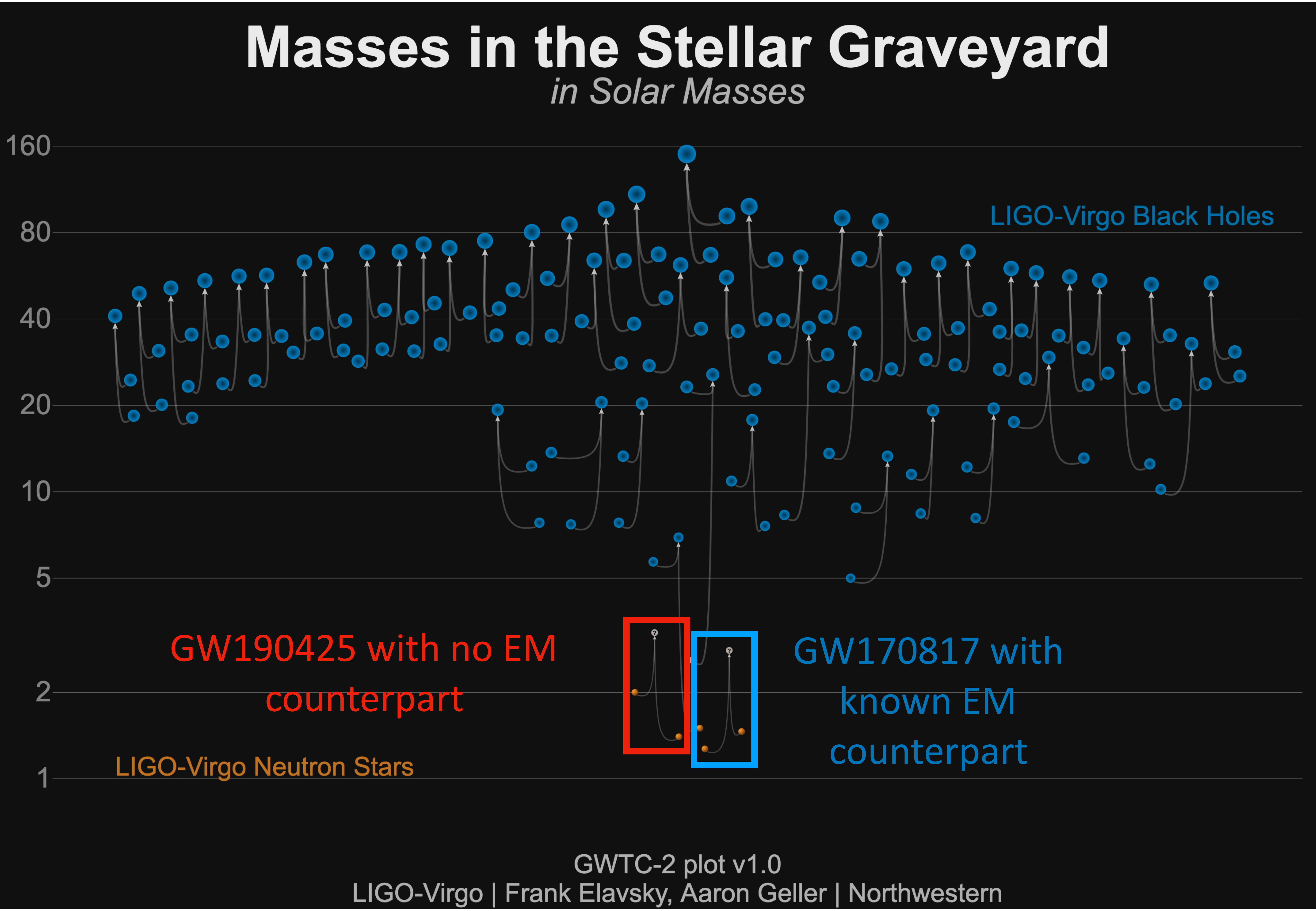
[see LVKC, arXiv 2010.14527 (GWTC 2)
LVC, arXiv 1811.15007 (GWTC-1)]

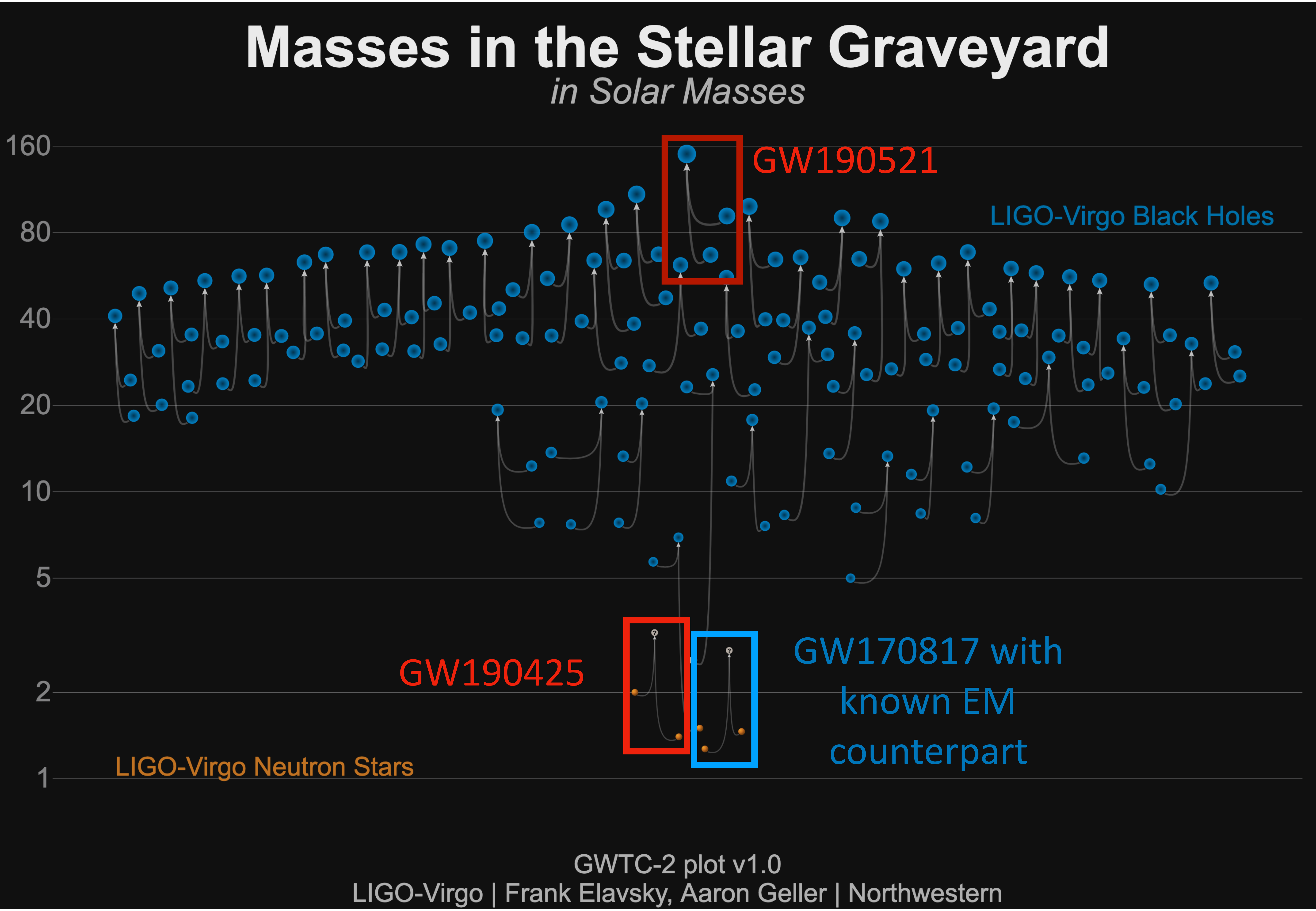


[see also Venumadhav, Zackay, Dai, …2019; Nitz, + 2019, 2020]

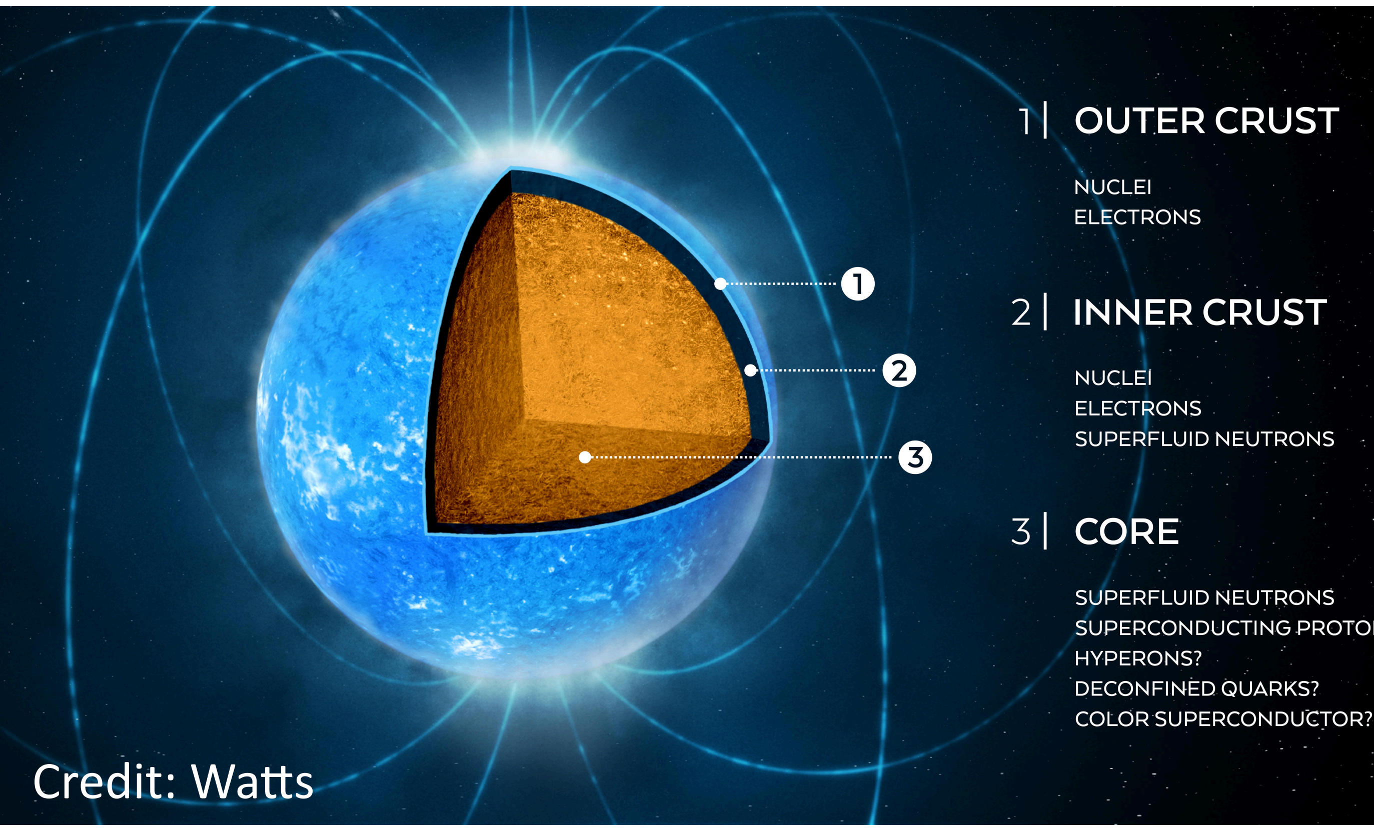

Masses in the Stellar Graveyard
in Solar Masses
2015-19: GWTC-1 & 2
Intermediate Black Holes
?
LIGO-Virgo Black Holes
160
80
40
20
10
5
2
1
Stellar-mass Black Holes
?
Neutron Stars
?
LIGO-Virgo Neutron Stars
[see LVKC, arXiv 2010.14527 (GWTC 2)
LVC, arXiv 1811.15007 (GWTC-1)]
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

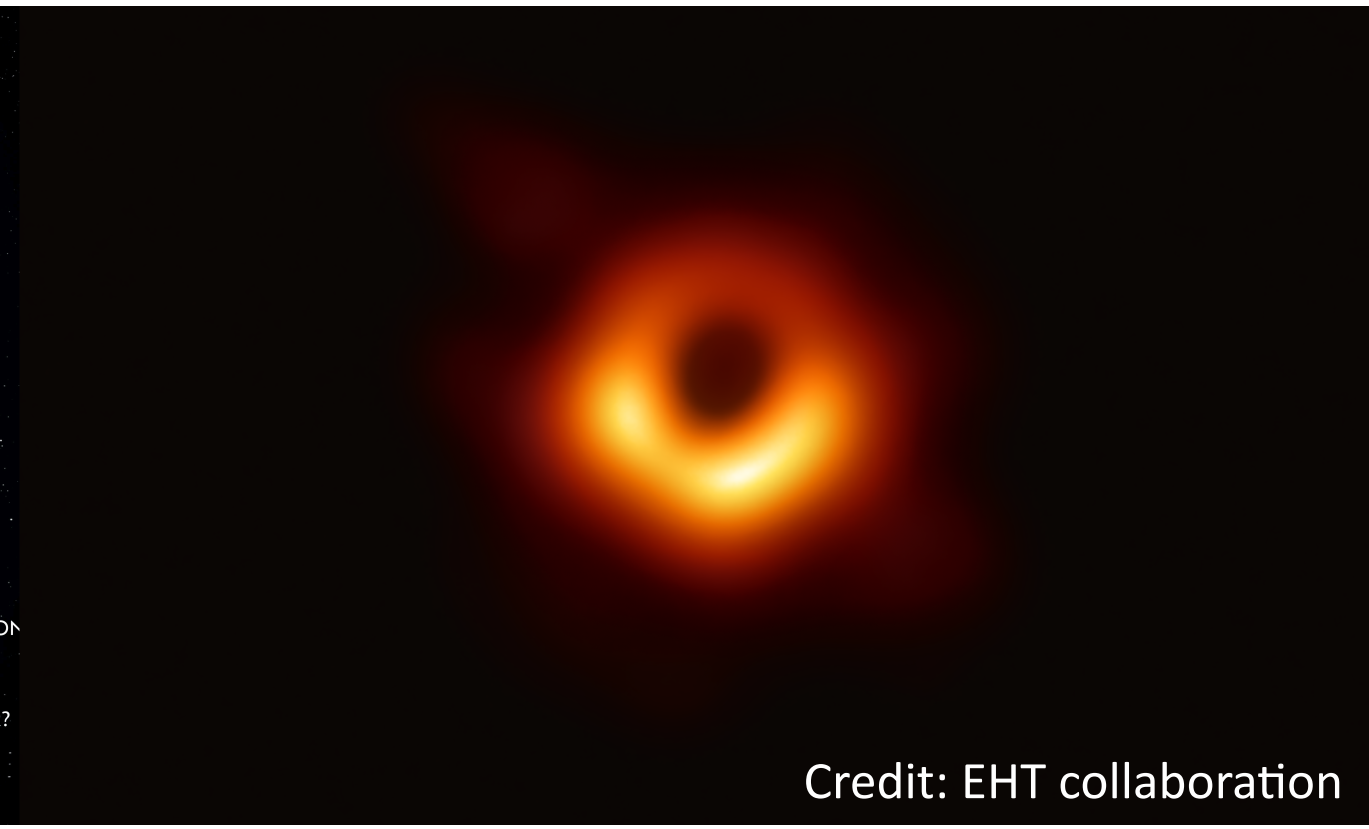

Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
LIGO-Virgo Neutron Stars
GW170817 with known EM counterpart
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
LIGO-Virgo Neutron Stars
GW190425 with no EM counterpart
GW170817 with known EM counterpart
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
GW190521
LIGO-Virgo Black Holes
GW190425
GW170817 with
known EM
counterpart
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Extreme Matter, Extreme Spacetime Curvature!





Neutron Stars (NSs) > 1.2 - 2.7 $M_\odot$ (?),
~10-15 km radii,
Large magnetic fields,
Extreme matter and exotic equations of state

Black Holes (BHs): < 10^{10} $M_\odot$,
No hair: mass and spin,
Mathematical singularities.

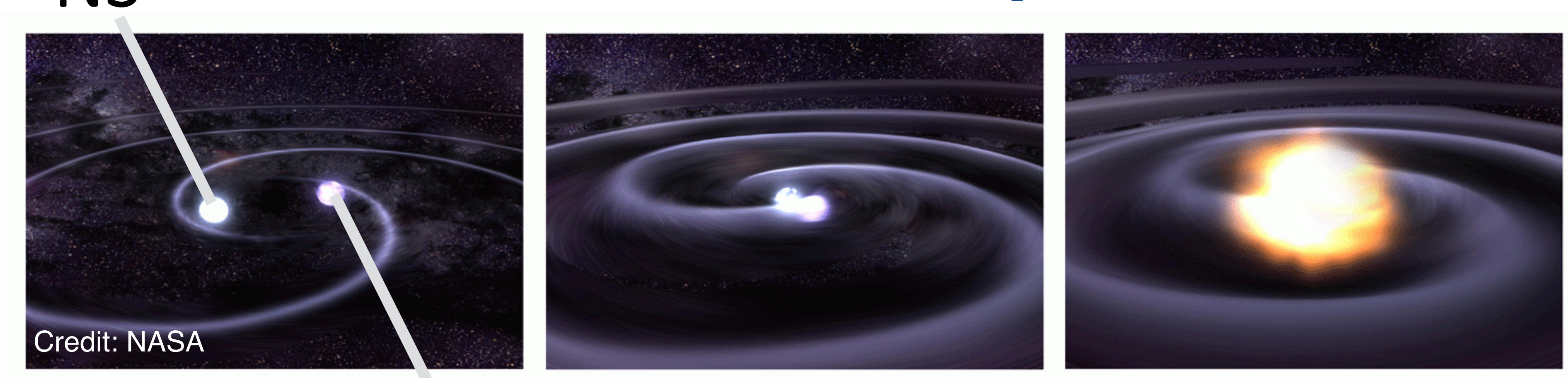
The game changer: First NS Binary Merger detected in GWs & Electromagnetic (EM) radiation!

GW signal ~ 1 minute

EM

minus few seconds to years

NS

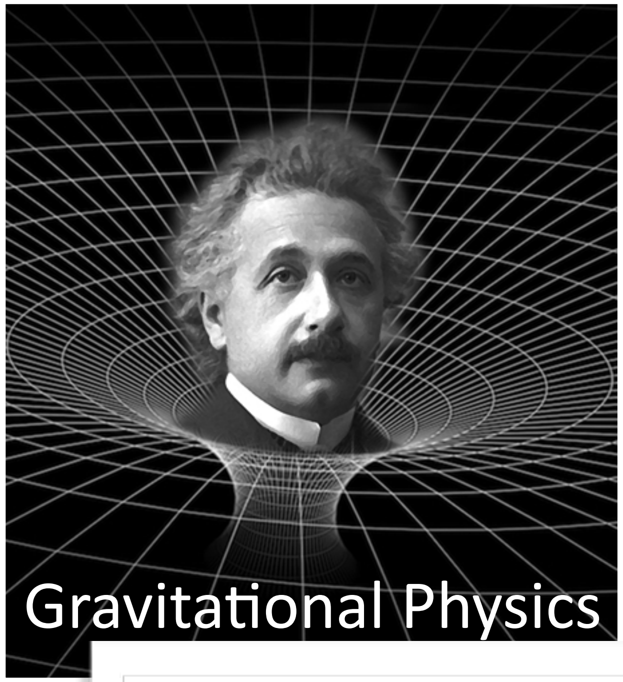


Merger Outcome ???

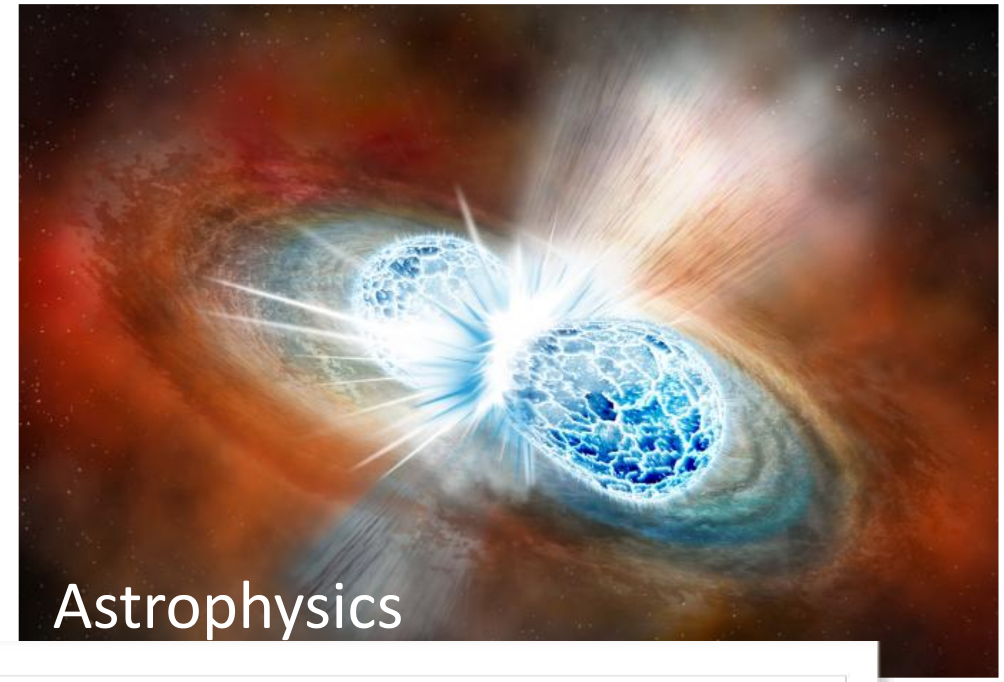
NS/BH

GW energy released > 0.025 $M_\odot c^2$

EM counterpart:
delayed matter outflows,
$10^{-6} M_\odot$ (jet)/ < 0.05 $M_\odot$ (isotropic)



GW170817: The source of many discoveries



First Binary Neutron Star detected in Gravitational Waves

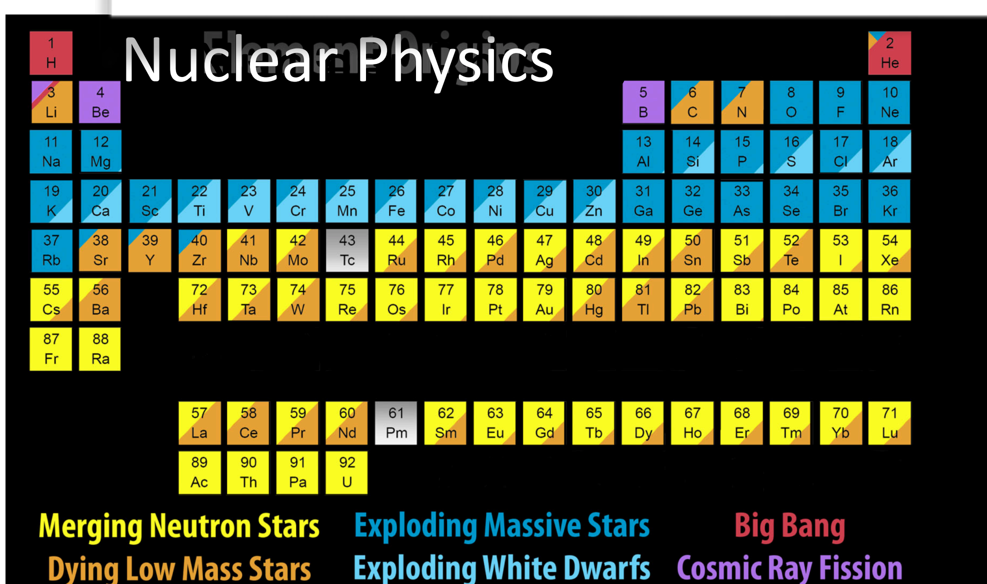
First Electromagnetic Counterpart of a GW merger in every waveband!

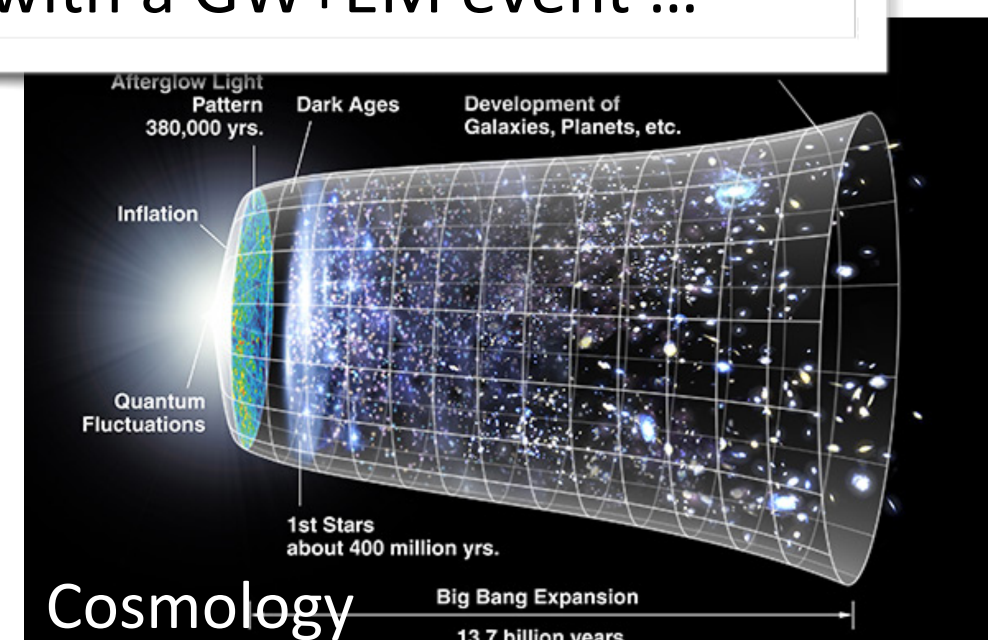
First Gravitational Wave Standard Siren Hubble Constant Constraint

First Short Gamma Ray Burst - Binary Neutron Star Merger Association

First kilonova discovery and astrophysical sites of r-process heavy elements

First tests of the speed of light and gravity with a GW+EM event …



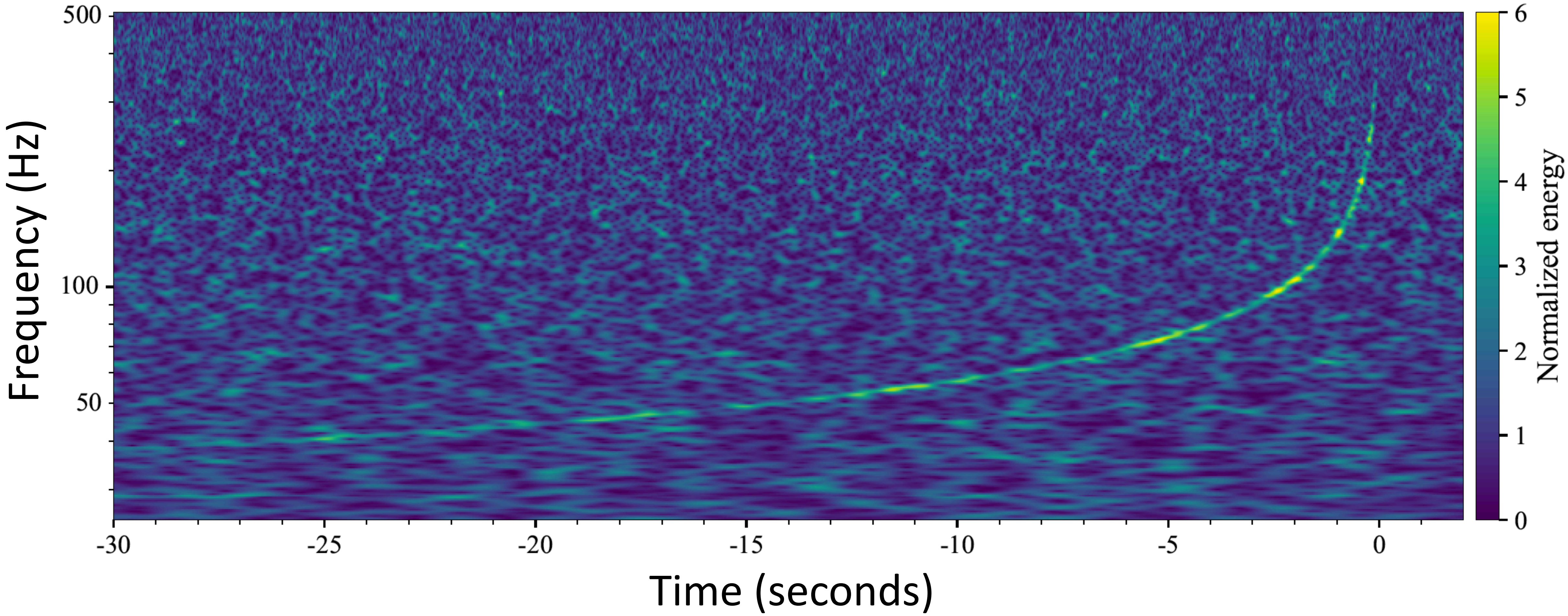


Part I:
What are GWs?

First Measurement of GWs from a Binary Neutron Star Merger

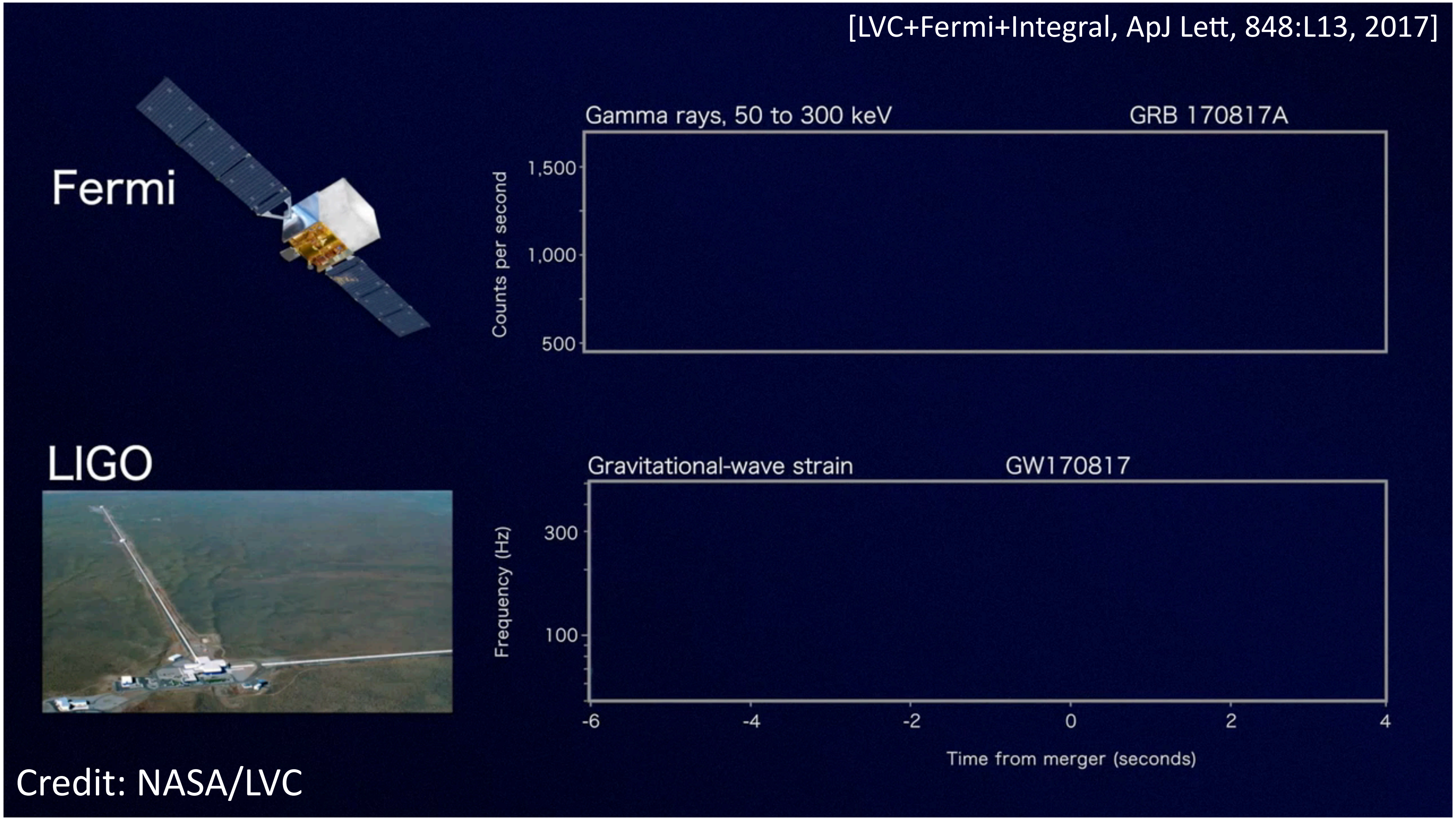
August 17th 2017 at 12:41:04 UTC

[LVC,PRL, 119, 161101 (2017)]



Loudest (SNR ~ 32.2) and longest (~ 100 s) signal so far:
False alarm rate < 1 in 80 000 years

The first two seconds post-merger

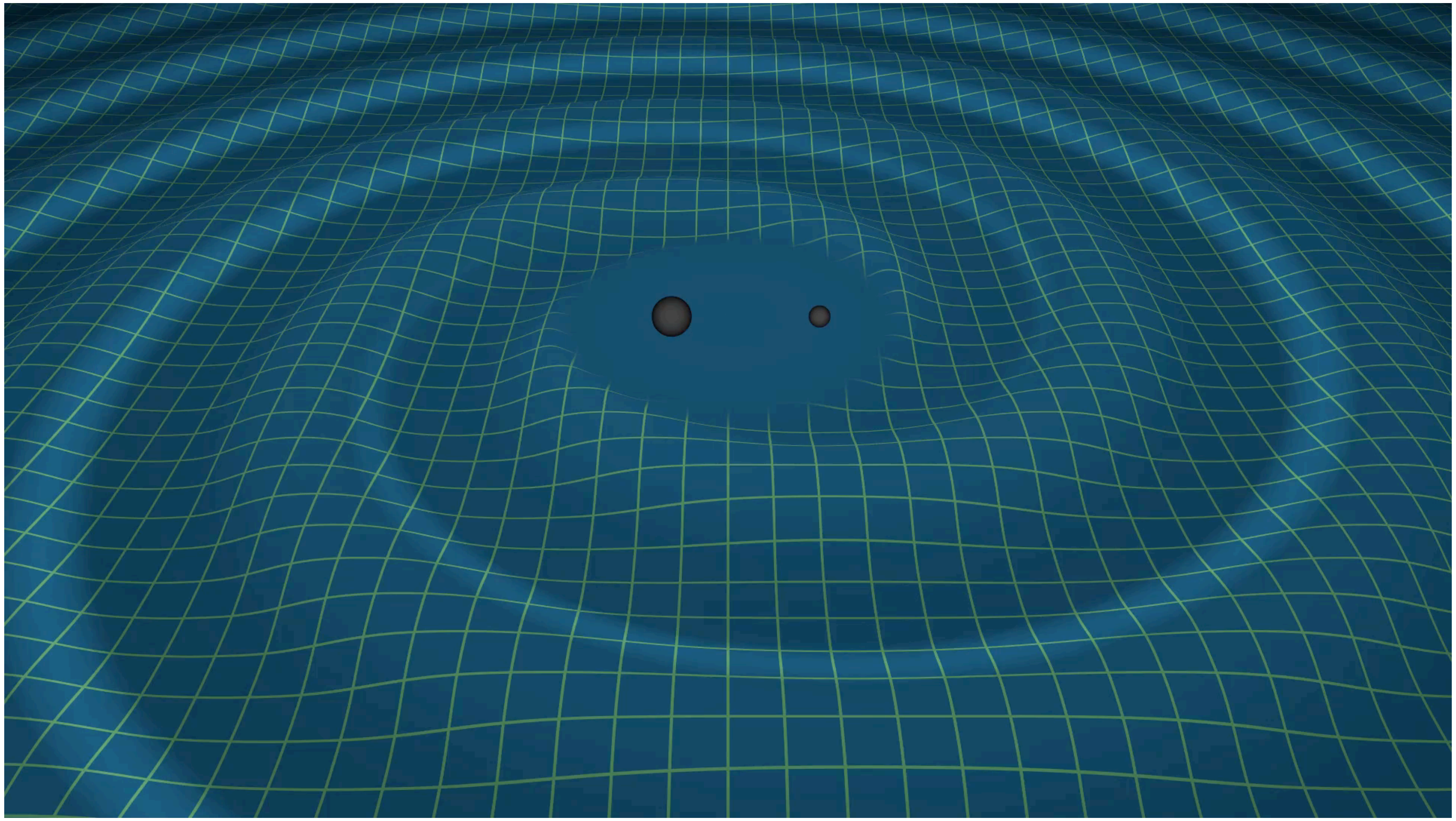


Test of speed of gravity and light and equivalence principle

$$-3 \times 10^{-15} \leq \frac{v_{gw}}{v_{em}} - 1 \leq 7 \times 10^{-16}$$

GWs are perturbations in spacetime curvature

Accelerating quadrupole matter sources

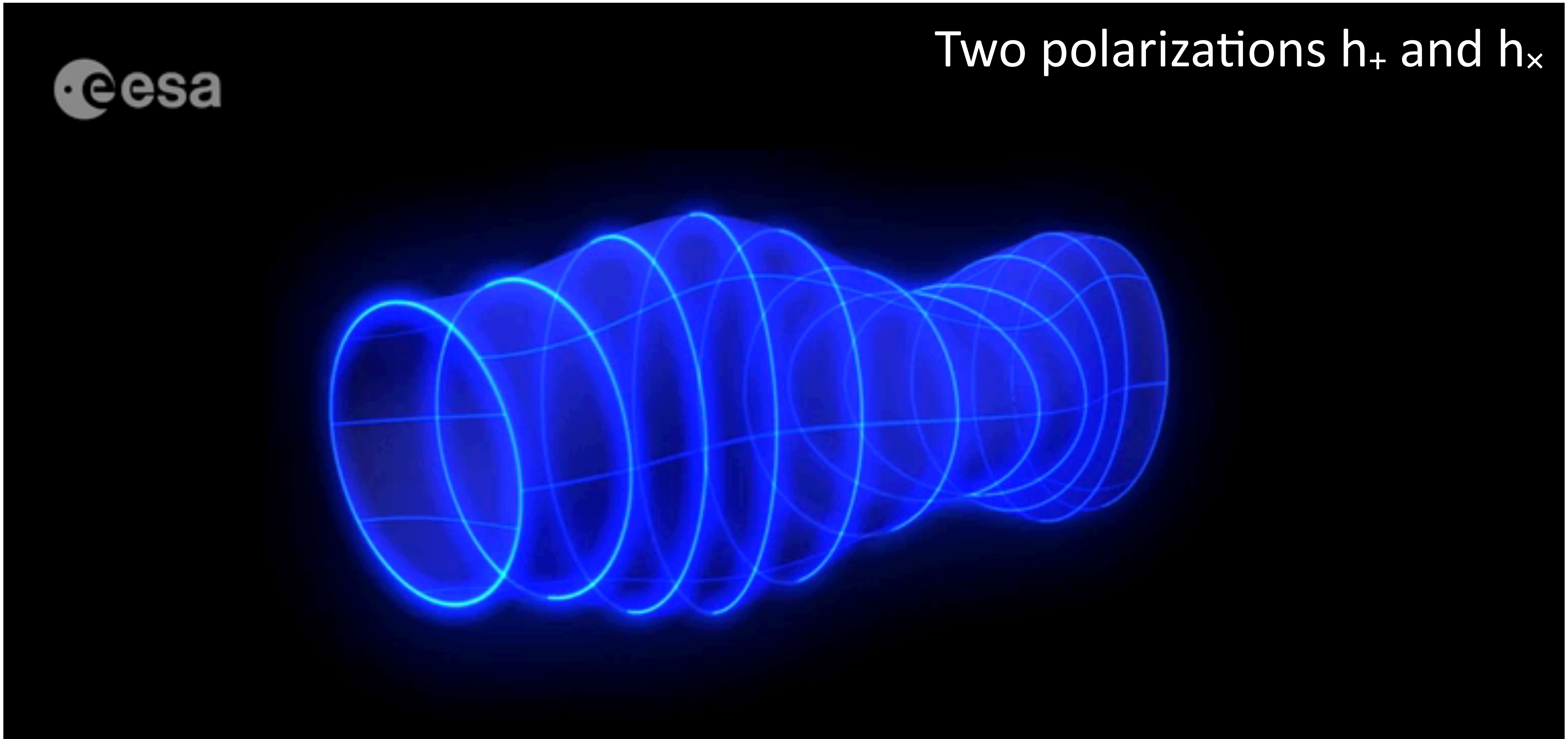


Measurable GW strain h (t) ~ 1/distance

Newtonian Quadrupole formula (1916): $\mathcal{L} = \frac{G}{5c^5}\left\langle \frac{d^3 I_{ij}}{dt^3}\frac{d^3 I_{ij}}{dt^3}\right\rangle + \mathcal{O}\left(\frac{1}{c^7}\right)$

GWs act as transverse tidal fields on matter

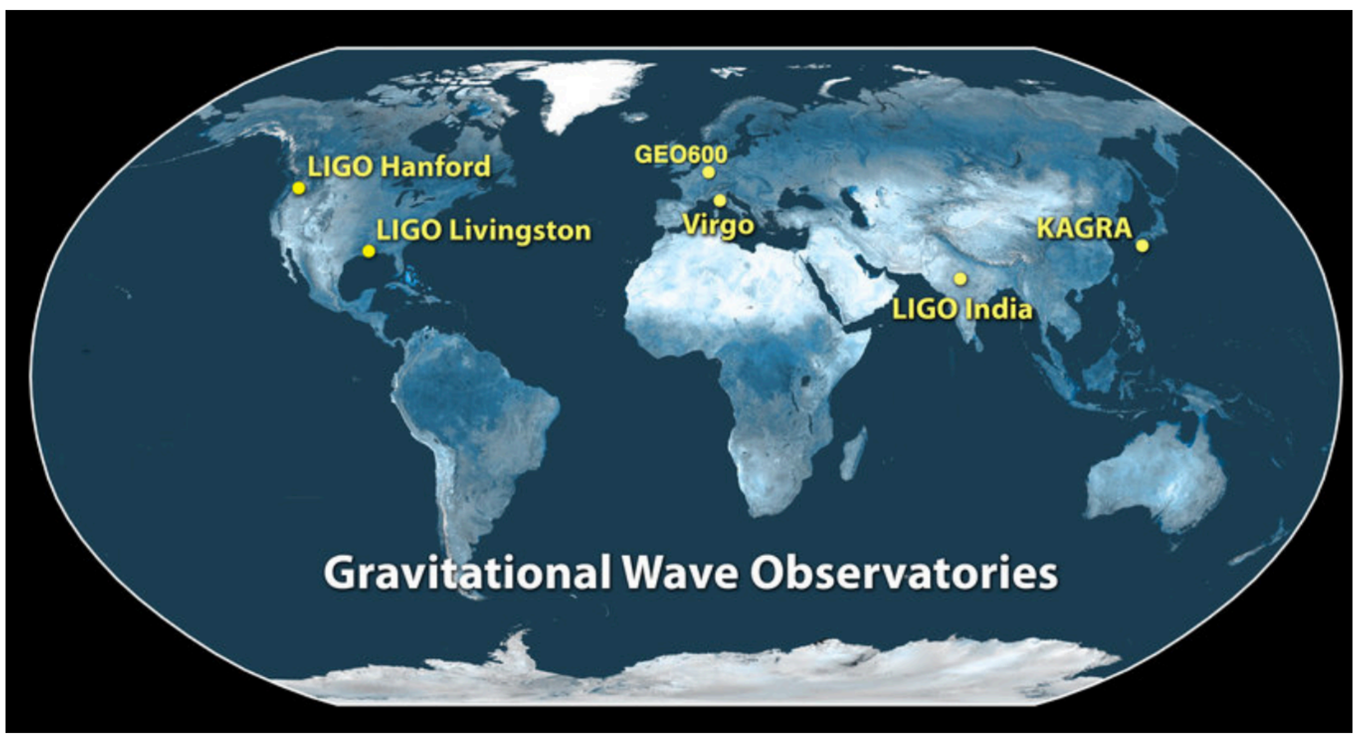
Two polarizations h_+ and $h_\times$



Coherent, weakly interacting,
bulk dynamic properties of matter

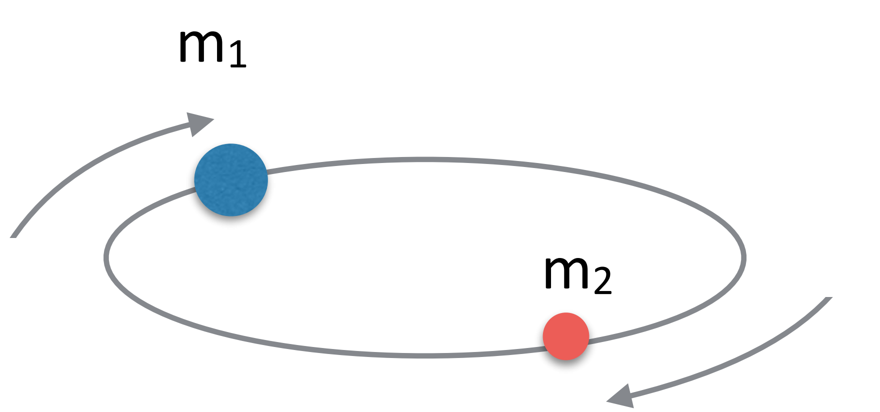
kHz GW detectors measure tidal stretching and squeezing of spacetime

$$h \sim \frac{\Delta L}{L} \sim 10^{-21}$$

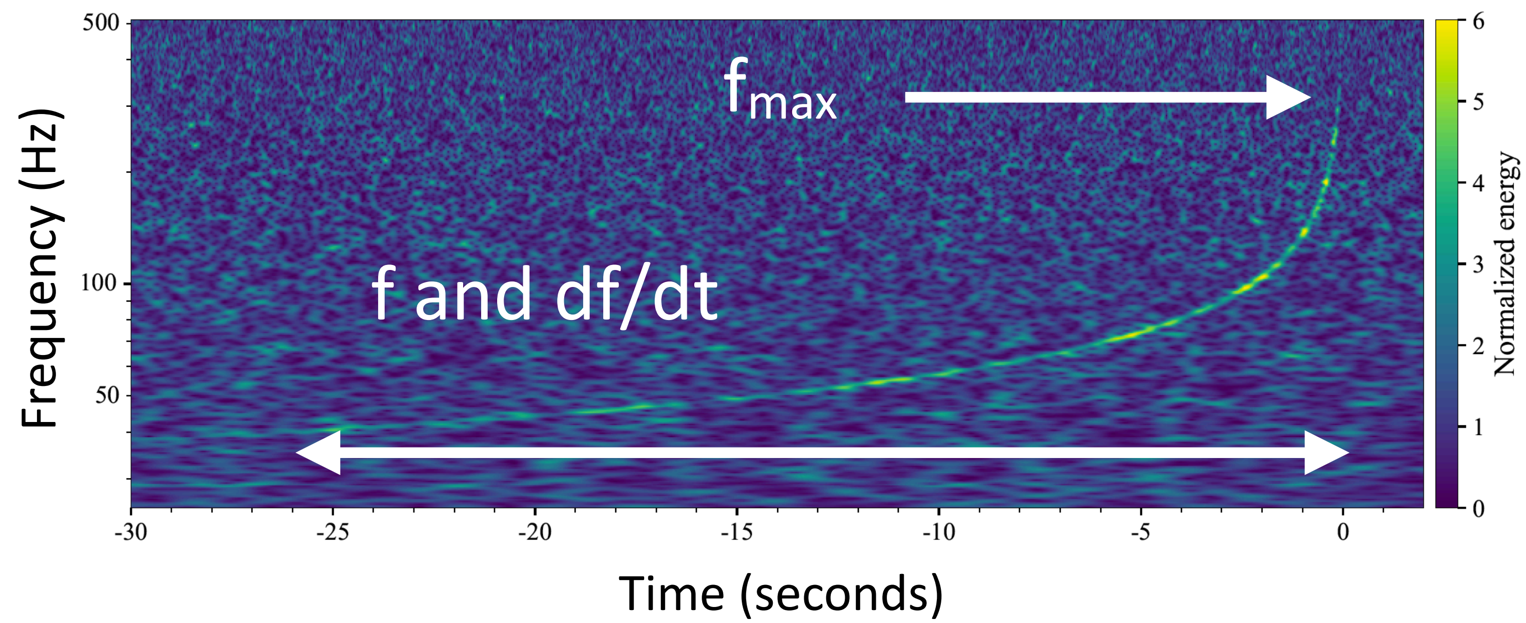


19 - 2048 Hz

Simplest "Newtonian" model explains frequency chirp



$$\left(\frac{dE}{dt}\right)_{\rm rad} + \left(\frac{dE}{dt}\right)_{\rm orb} = 0$$



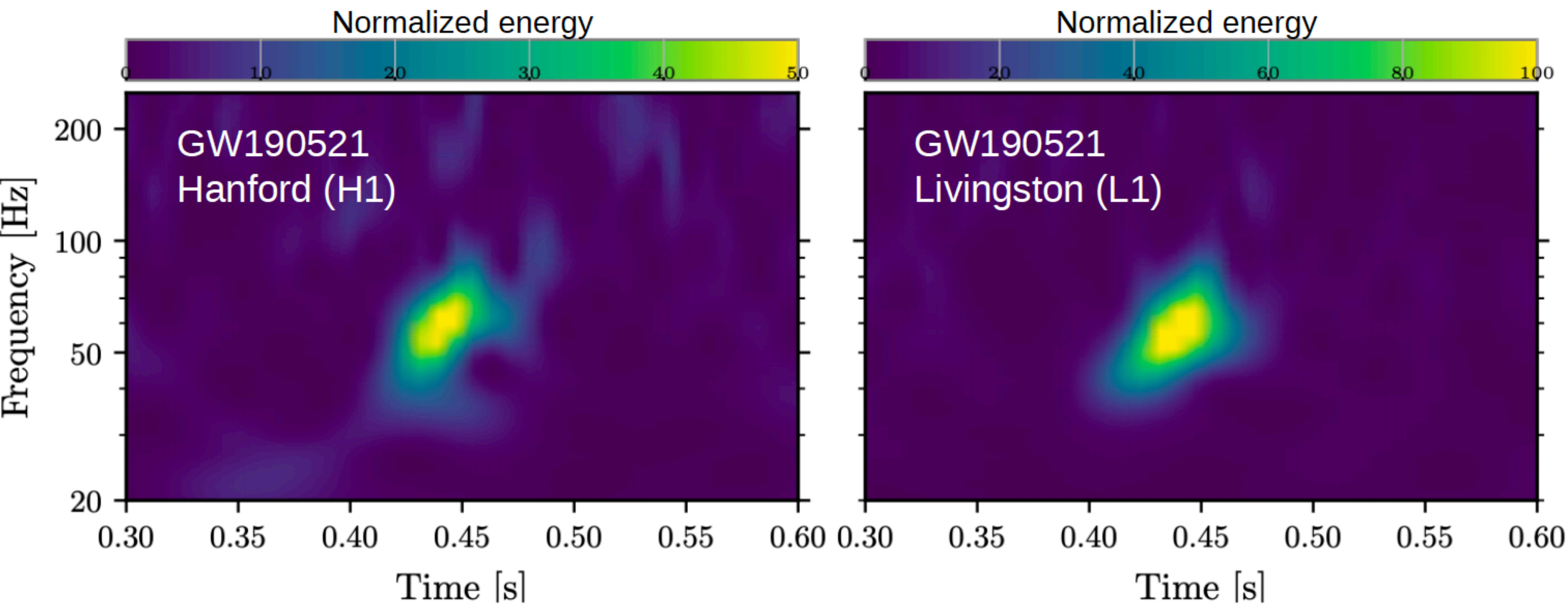
[LVC, PRL 119, 161101 (2017)]

⇒ Frequency chirp: $$\frac{df}{dt} = \frac{96\,\pi}{5}\left(\frac{\pi\, G\mathcal{M}}{c^3}\right)^{5/3} f^{11/3}$$

Chirp mass: $$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

Most Massive Black Hole Merger seen in GWs

GW190521: May 21st 2019 at 03:02:29 UTC

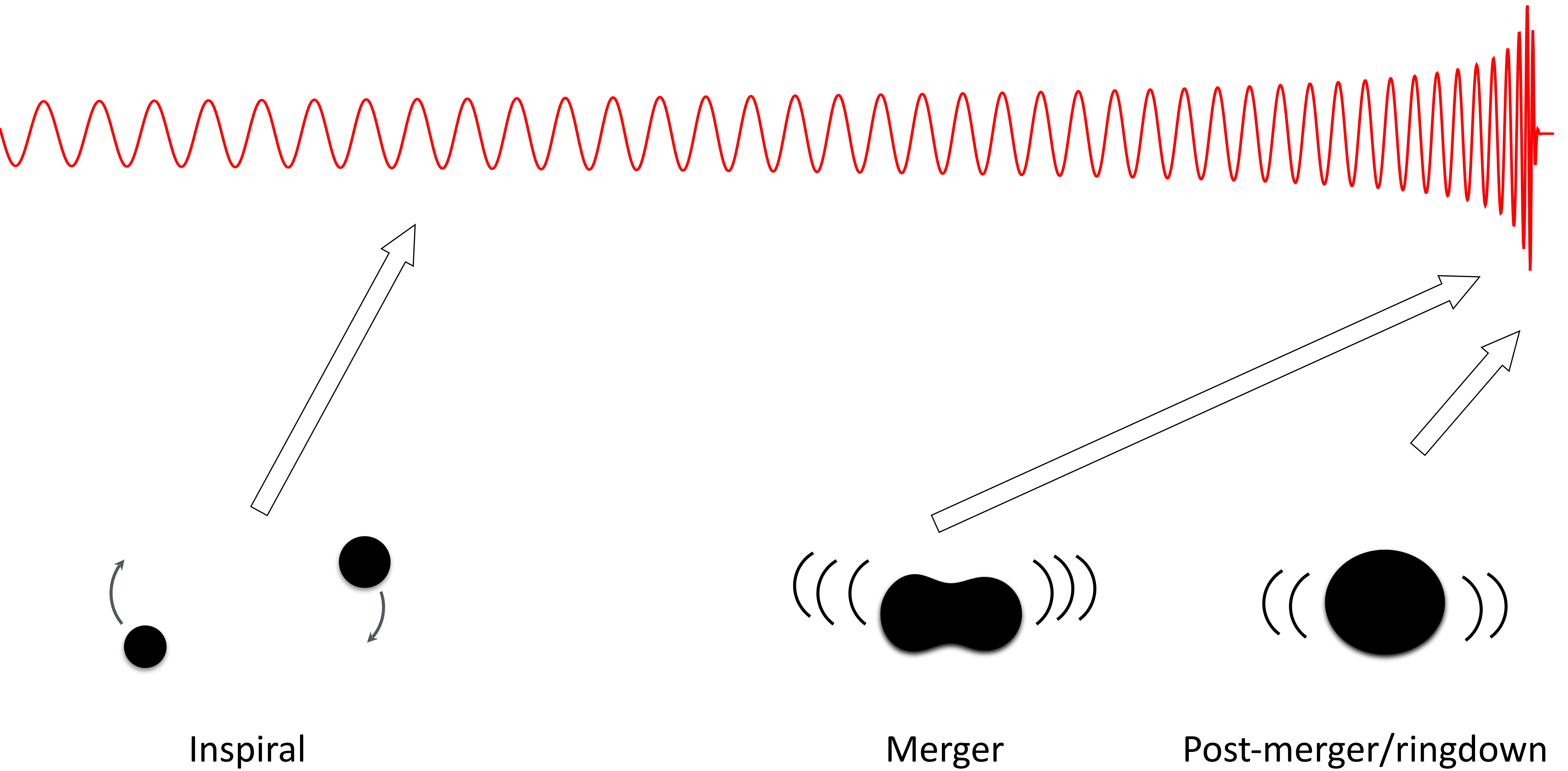


Shortest (~ 0.1 s) signal so far,
False alarm rate < 1 in 5 000 years (Signal-to-noise: 14.7),
Rare Event: 1 every 8 years in Gpc^3

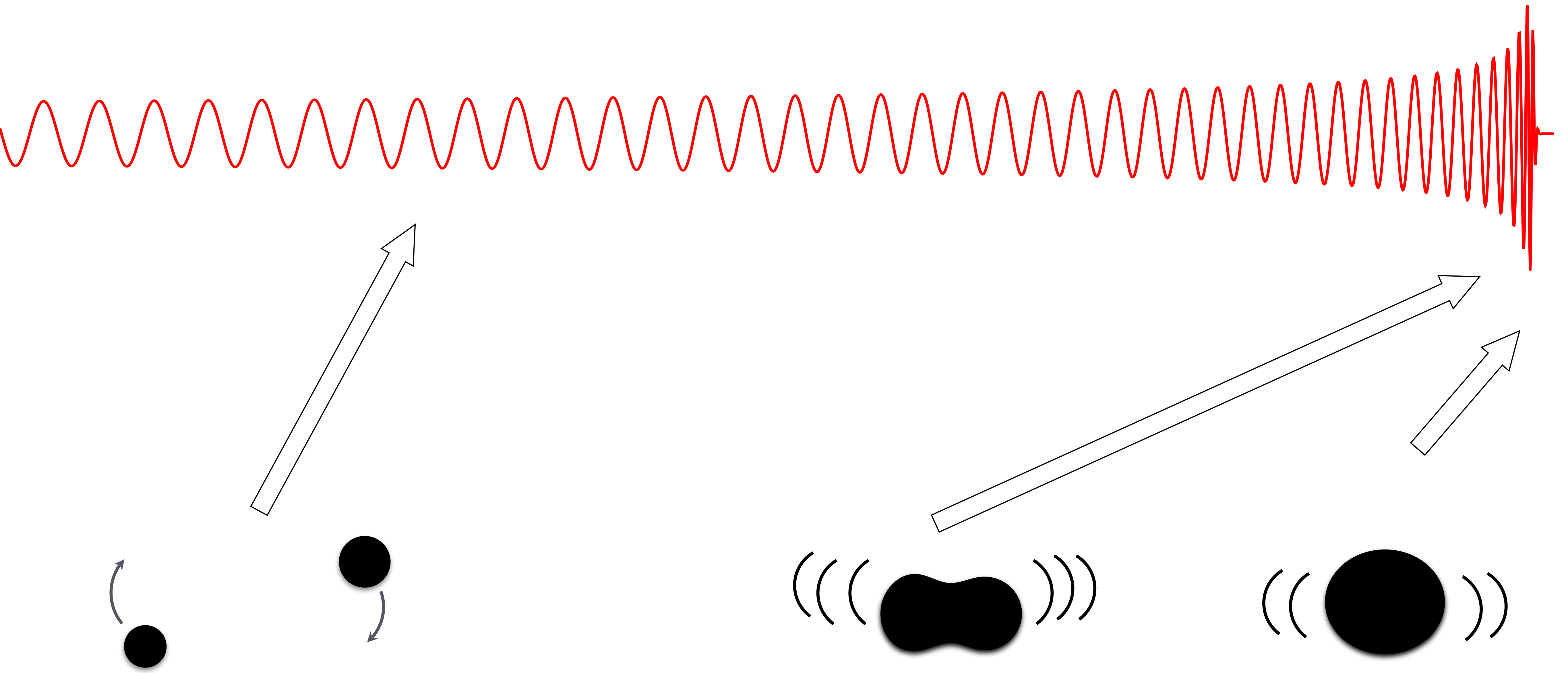
Part II:

Retrieving information about BHs and NSs from GW

The GW waveform encodes source parameters



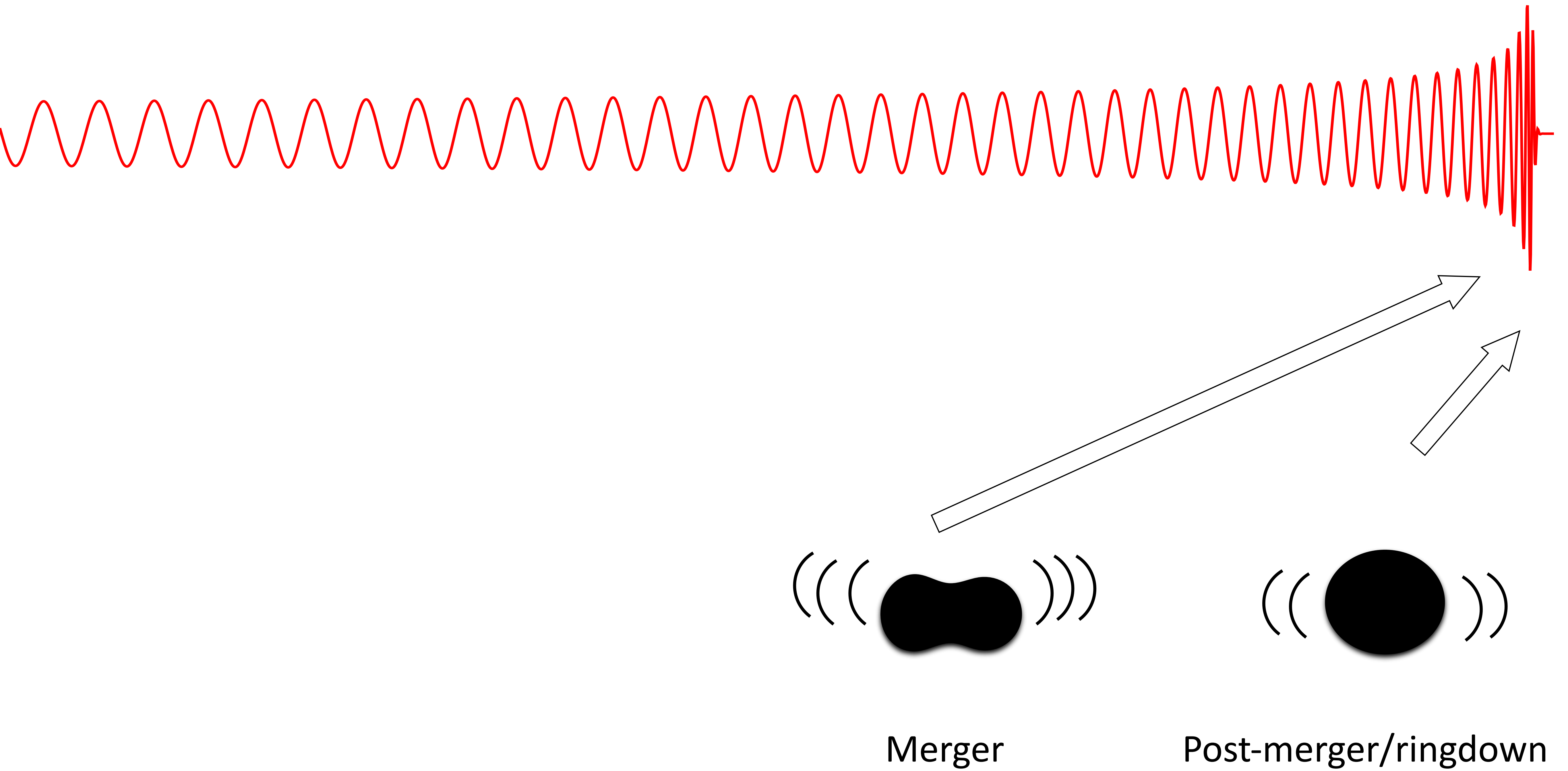
The GW waveform encodes source parameters



Inspiral Merger Post-merger/ringdown

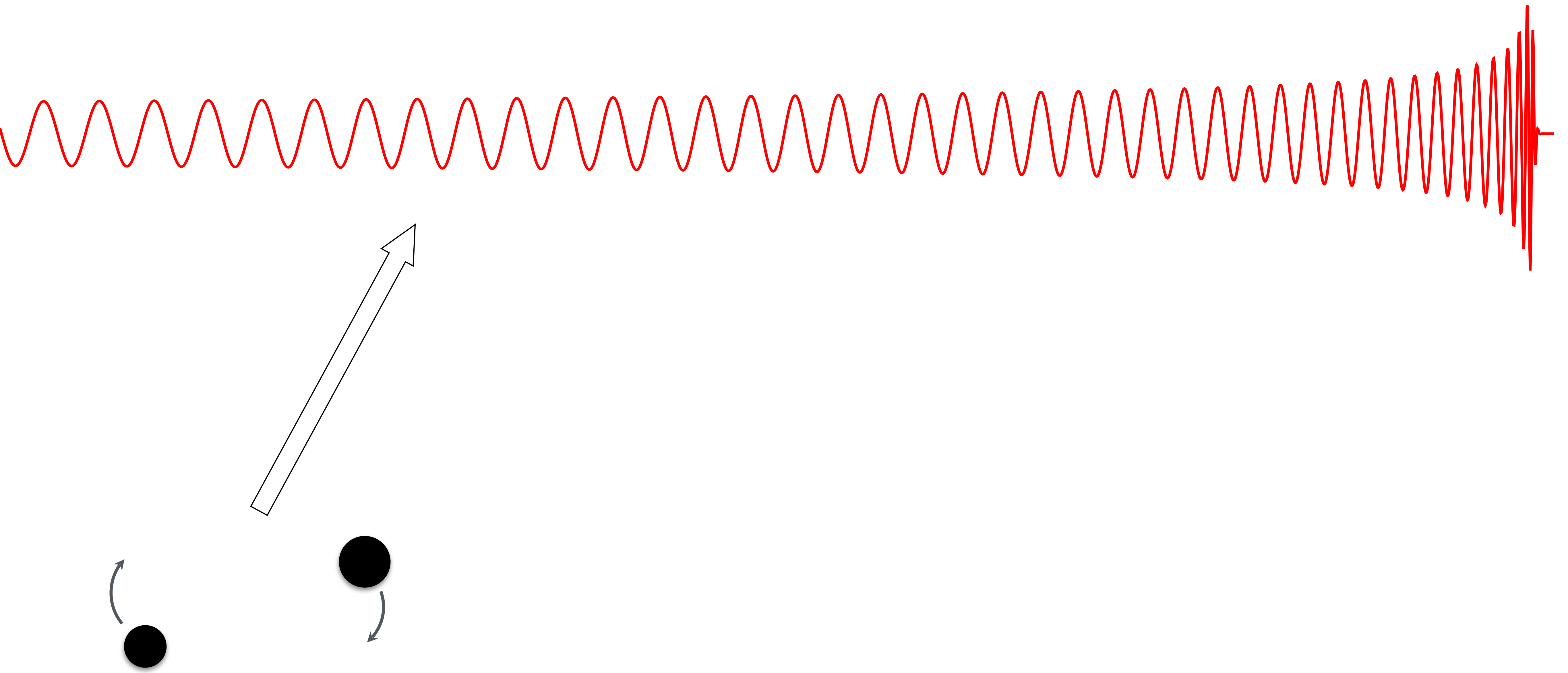
$$\frac{df}{dt} = \frac{96\,\pi}{5}\left(\frac{\pi\, G\mathcal{M}}{c^3}\right)^{5/3} f^{11/3}$$

The GW waveform encodes source parameters



~ 10 cycles of merger for ~ 10 $M_\odot$ BHs: seconds

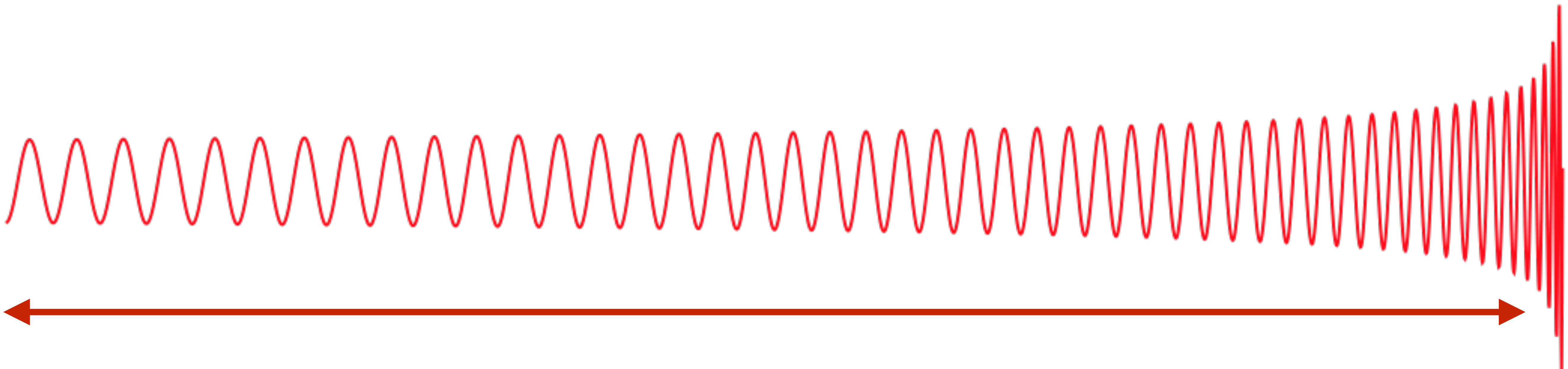
The GW waveform encodes source parameters



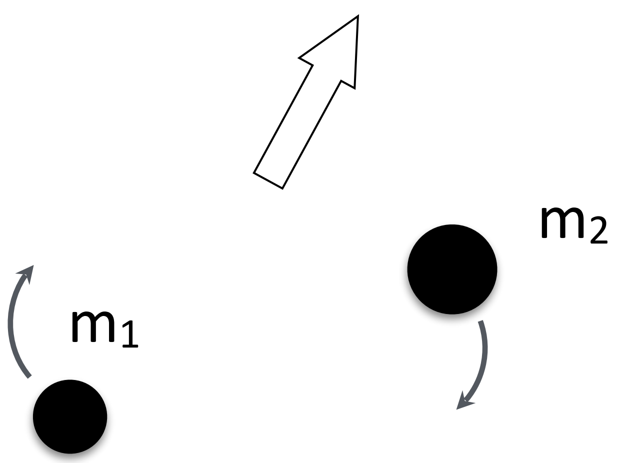
Inspiral

~10^3 cycles of the inspiral for few $M_\odot$ with LIGO/Virgo: minutes

The GW waveform encodes source parameters

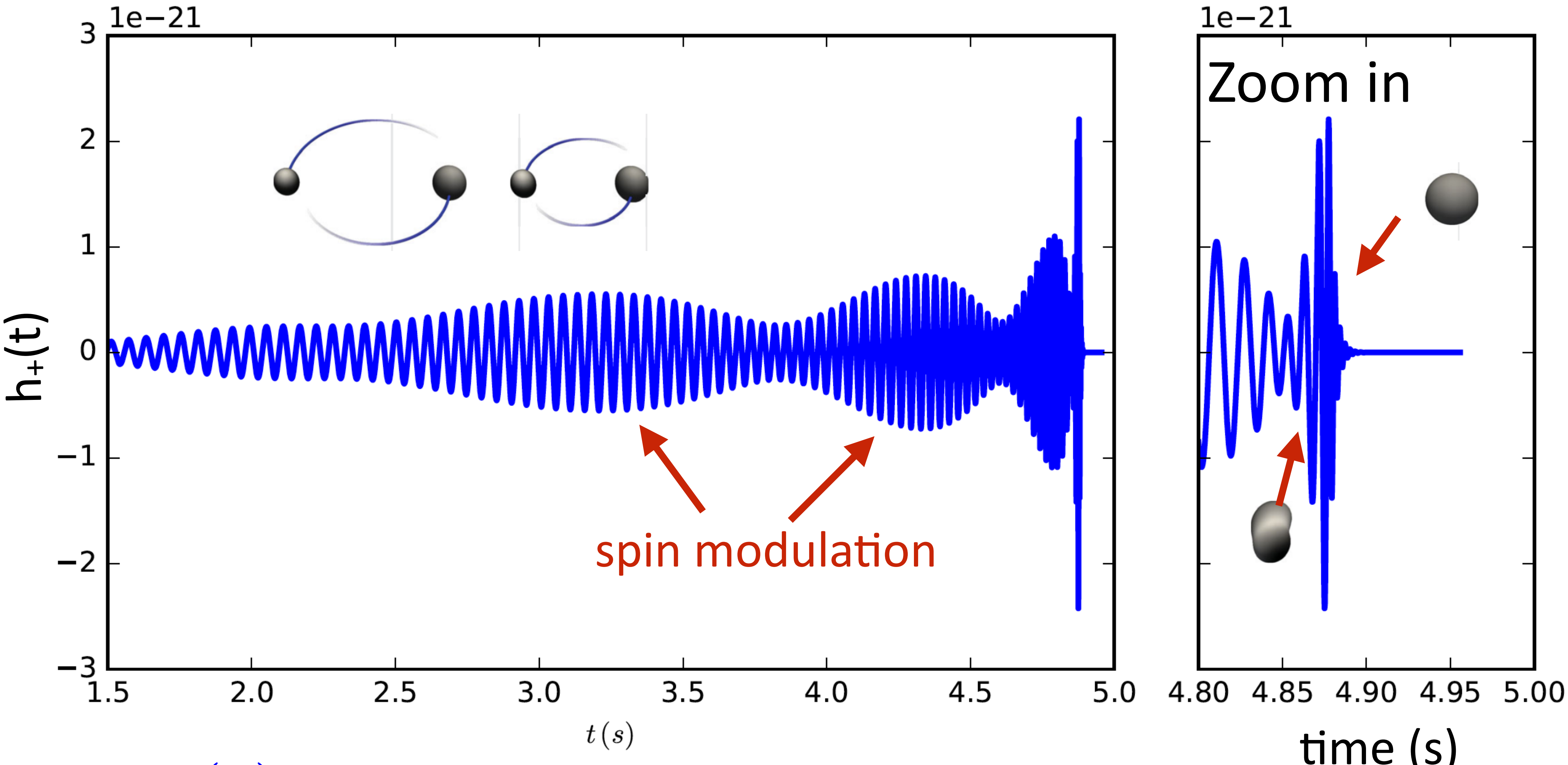


post-Newtonian (PN) Inspiral — driven by the chirp mass



$$1\mathrm{PN} \sim \frac{v^2}{c^2} \sim \frac{Gm}{rc^2} << 1$$

The GW waveform encodes source parameters



$$\Phi_{\rm GW}(t)$$

⇒ chirp mass, reduced mass (1PN), spin-orbit (1.5PN), spin-spin (2PN)…

tidal deformability (5PN)

The GW chirp gives the progenitor masses and spins

$$a_1^i = -\frac{Gm_2 n_{12}^i}{r_{12}^2}$$

$$+\frac{1}{c^2}\left\{ \left[\frac{5G^2m_1m_2}{r_{12}^3} + \frac{4G^2m_2^2}{r_{12}^3} + \frac{Gm_2}{r_{12}^2}\left(\frac{3}{2}(n_{12}v_2)^2 - v_1^2 + 4(v_1v_2) - 2v_2^2\right)\right] n_{12}^i \right.$$

$$\left. + \frac{Gm_2}{r_{12}^2}\left(4(n_{12}v_1) - 3(n_{12}v_2)\right) v_{12}^i \right\}$$

$$+\frac{1}{c^4}\left\{ \left[-\frac{57G^3m_1^2m_2}{4r_{12}^4} - \frac{69G^3m_1m_2^2}{2r_{12}^4} - \frac{9G^3m_2^3}{r_{12}^4} \right.\right.$$

$$+\frac{Gm_2}{r_{12}^2}\left(-\frac{15}{8}(n_{12}v_2)^4 + \frac{3}{2}(n_{12}v_2)^2v_1^2 - 6(n_{12}v_2)^2(v_1v_2) - 2(v_1v_2)^2 + \frac{9}{2}(n_{12}\right.$$

$$\left. +4(v_1v_2)v_2^2 - 2v_2^4\right)$$

$$+\frac{G^2m_1m_2}{r_{12}^3}\left(\frac{39}{2}(n_{12}v_1)^2 - 39(n_{12}v_1)(n_{12}v_2) + \frac{17}{2}(n_{12}v_2)^2 - \frac{15}{4}v_1^2 - \frac{5}{2}(v_1v_2) + \right.$$ [illegible]

$$\left. +\frac{G^2m_2^2}{r_{12}^3}\left(2(n_{12}v_1)^2 - 4(n_{12}v_1)(n_{12}v_2) - 6(n_{12}v_2)^2 - 8(v_1v_2) + 4v_2^2\right)\right] n_{12}^i$$

$$+\left[\frac{G^2m_2^2}{r_{12}^3}\left(-2(n_{12}v_1) - 2(n_{12}v_2)\right) + \frac{G^2m_1m_2}{r_{12}^3}\left(-\frac{63}{4}(n_{12}v_1) + \frac{55}{4}(n_{12}v_2)\right)\right.$$

$$+\frac{Gm_2}{r_{12}^2}\left(-6(n_{12}v_1)(n_{12}v_2)^2 + \frac{9}{2}(n_{12}v_2)^3 + (n_{12}v_2)v_1^2 - 4(n_{12}v_1)(v_1v_2)\right.$$

$$\left.\left.\left. + 4(n_{12}v_2)(v_1v_2) + 4(n_{12}v_1)v_2^2 - 5(n_{12}v_2)v_2^2\right)\right] v_{12}^i \right\}$$

$$+\frac{1}{c^5}\left\{ \left[\frac{208G^3m_1m_2^2}{15r_{12}^4}(n_{12}v_{12}) - \frac{24G^3m_1^2m_2}{5r_{12}^4}(n_{12}v_{12}) + \frac{12G^2m_1m_2}{5r_{12}^3}(n_{12}v_{12})v_{12}^2\right] n_{12}^i \right.$$

$$\left. + \left[\frac{8G^3m_1^2m_2}{5r_{12}^4} - \frac{32G^3m_1m_2^2}{5r_{12}^4} - \frac{4G^2m_1m_2}{5r_{12}^3}v_{12}^2\right] v_{12}^i \right\}$$

$$+\frac{1}{c^6}\left\{ \left[\frac{Gm_2}{r_{12}^2}\left(\frac{35}{16}(n_{12}v_2)^6 - \frac{15}{8}(n_{12}v_2)^4v_1^2 + \frac{15}{2}(n_{12}v_2)^4(v_1v_2) + 3(n_{12}v_2)^2(v_1v_2)^2\right.\right.\right.$$

$$-\frac{15}{2}(n_{12}v_2)^4v_2^2 + \frac{3}{2}(n_{12}v_2)^2v_1^2v_2^2 - 12(n_{12}v_2)^2(v_1v_2)v_2^2 - 2(v_1v_2)^2v_2^2$$

$$\left. +\frac{15}{2}(n_{12}v_2)^2v_2^4 + 4(v_1v_2)v_2^4 - 2v_2^6\right)$$

$$+\frac{G^2m_1m_2}{r_{12}^3}\left(-\frac{171}{8}(n_{12}v_1)^4 + \frac{171}{2}(n_{12}v_1)^3(n_{12}v_2) - \frac{723}{4}(n_{12}v_1)^2(n_{12}v_2)^2\right.$$

$$+\frac{383}{2}(n_{12}v_1)(n_{12}v_2)^3 - \frac{455}{8}(n_{12}v_2)^4 + \frac{229}{4}(n_{12}v_1)^2v_1^2$$

$$-\frac{205}{2}(n_{12}v_1)(n_{12}v_2)v_1^2 + \frac{191}{4}(n_{12}v_2)^2v_1^2 - \frac{91}{8}v_1^4 - \frac{229}{2}(n_{12}v_1)^2 v_1$$

$$+244(n_{12}v_1)(n_{12}v_2)(v_1v_2) - \frac{225}{2}(n_{12}v_2)^2(v_1v_2) + \frac{91}{2}v_1^2(v_1v_2)$$

$$-\frac{177}{4}(v_1v_2)^2 + \frac{229}{4}(n_{12}v_1)^2v_2^2 - \frac{283}{2}(n_{12}v_1)(n_{12}v_2)v_2^2$$

$$\left. +\frac{259}{4}(n_{12}v_2)^2v_2^2 - \frac{91}{4}v_1^2v_2^2 + 43(v_1v_2)v_2^2 - \frac{81}{8}v_2^4\right)$$

$$+\frac{G^2m_2^2}{r_{12}^3}\left(-6(n_{12}v_1)^2(n_{12}v_2)^2 + 12(n_{12}v_1)(n_{12}v_2)^3 + 6(n_{12}v_2)^4\right.$$

$$+4(n_{12}v_1)(n_{12}v_2)(v_1v_2) + 12(n_{12}v_2)^2(v_1v_2) + 4(v_1v_2)^2$$

$$\left. -4(n_{12}v_1)(n_{12}v_2)v_2^2 - 12(n_{12}v_2)^2v_2^2 - 8(v_1v_2)v_2^2 + 4v_2^4\right)$$

$$+\frac{G^3m_2^3}{r_{12}^4}\left(-(n_{12}v_1)^2 + 2(n_{12}v_1)(n_{12}v_2) + \frac{43}{2}(n_{12}v_2)^2 + 18(v_1v_2) - 9v_2^2\right)$$

$$+\frac{G^3m_1m_2^2}{r_{12}^4}\left(\frac{415}{8}(n_{12}v_1)^2 - \frac{375}{4}(n_{12}v_1)(n_{12}v_2) + \frac{1113}{8}(n_{12}v_2)^2 - \frac{615}{64}(n_{12}v_{12})^2\pi^2\right.$$

$$\left. +18v_1^2 + \frac{123}{64}\pi^2v_{12}^2 + 33(v_1v_2) - \frac{33}{2}v_2^2\right)$$

$$+\frac{G^3m_1^2m_2}{r_{12}^4}\left(-\frac{45887}{168}(n_{12}v_1)^2 + \frac{24025}{42}(n_{12}v_1)(n_{12}v_2) - \frac{10469}{42}(n_{12}v_2)^2 + \frac{48197}{840}v_1^2\right.$$

$$\left. -\frac{36227}{420}(v_1v_2) + \frac{36227}{840}v_2^2 + 110(n_{12}v_{12})^2\ln\left(\frac{r_{12}}{r'_1}\right) - 22v_{12}^2\ln\left(\frac{r_{12}}{r'_1}\right)\right)$$

$$+\frac{16G^4m_2^4}{r_{12}^5} + \frac{G^4m_1^2m_2^2}{r_{12}^5}\left(175 - \frac{41}{16}\pi^2\right) + \frac{G^4m_1^3m_2}{r_{12}^5}\left(-\frac{3187}{1260} + \frac{44}{3}\ln\left(\frac{r_{12}}{r'_1}\right)\right)$$

$$\left. +\frac{G^4m_1m_2^3}{r_{12}^5}\left(\frac{110741}{630} - \frac{41}{16}\pi^2 - \frac{44}{3}\ln\left(\frac{r_{12}}{r'_2}\right)\right)\right] n_{12}^i$$

$$+\left[\frac{Gm_2}{r_{12}^2}\left(\frac{15}{2}(n_{12}v_1)(n_{12}v_2)^4 - \frac{45}{8}(n_{12}v_2)^5 - \frac{3}{2}(n_{12}v_2)^3v_1^2 + 6(n_{12}v_1)(n_{12}v_2)^2(v_1v_2)\right.\right.$$

$$-6(n_{12}v_2)^3(v_1v_2) - 2(n_{12}v_2)(v_1v_2)^2 - 12(n_{12}v_1)(n_{12}v_2)^2v_2^2 + 12(n_{12}v_2)^3v_2^2$$

$$+(n_{12}v_2)v_1^2v_2^2 - 4(n_{12}v_1)(v_1v_2)v_2^2 + 8(n_{12}v_2)(v_1v_2)v_2^2 + 4(n_{12}v_1)v_2^4$$

$$\left. -7(n_{12}v_2)v_2^4\right)$$

$$+\frac{G^2m_2^2}{r_{12}^3}\left(-2(n_{12}v_1)^2(n_{12}v_2) + 8(n_{12}v_1)(n_{12}v_2)^2 + 2(n_{12}v_2)^3 + 2(n_{12}v_1)(v_1v_2)\right.$$

$$\left. +4(n_{12}v_2)(v_1v_2) - 2(n_{12}v_1)v_2^2 - 4(n_{12}v_2)v_2^2\right)$$

$$+\frac{G^2m_1m_2}{r_{12}^3}\left(-\frac{243}{4}(n_{12}v_1)^3 + \frac{565}{4}(n_{12}v_1)^2(n_{12}v_2) - \frac{269}{4}(n_{12}v_1)(n_{12}v_2)^2\right.$$

$$-\frac{95}{12}(n_{12}v_2)^3 + \frac{207}{8}(n_{12}v_1)v_1^2 - \frac{137}{8}(n_{12}v_2)v_1^2 - 36(n_{12}v_1)(v_1v_2)$$

$$\left. +\frac{27}{4}(n_{12}v_2)(v_1v_2) + \frac{81}{8}(n_{12}v_1)v_2^2 + \frac{83}{8}(n_{12}v_2)v_2^2\right)$$

$$+\frac{G^3m_2^3}{r_{12}^4}\left(4(n_{12}v_1) + 5(n_{12}v_2)\right)$$

$$+\frac{G^3m_1m_2^2}{r_{12}^4}\left(-\frac{307}{8}(n_{12}v_1) + \frac{479}{8}(n_{12}v_2) + \frac{123}{32}(n_{12}v_{12})\pi^2\right)$$

$$\left.\left. +\frac{G^3m_1^2m_2}{r_{12}^4}\left(\frac{31397}{420}(n_{12}v_1) - \frac{36227}{420}(n_{12}v_2) - 44(n_{12}v_{12})\ln\left(\frac{r_{12}}{r'_1}\right)\right)\right] v_{12}^i \right\}$$

$$+\frac{1}{c^7}\left\{ \left[\frac{G^4m_1^3m_2}{r_{12}^5}\left(\frac{3992}{105}(n_{12}v_1) - \frac{4328}{105}(n_{12}v_2)\right)\right.\right.$$

$$+\frac{G^4m_1^2m_2^2}{r_{12}^6}\left(-\frac{13576}{105}(n_{12}v_1) + \frac{2872}{21}(n_{12}v_2)\right) - \frac{3172}{21}\frac{G^4m_1m_2^3}{r_{12}^6}(n_{12}v_{12})$$

$$+\frac{G^3m_1^2m_2}{r_{12}^4}\left(48(n_{12}v_1)^3 - \frac{696}{5}(n_{12}v_1)^2(n_{12}v_2) + \frac{744}{5}(n_{12}v_1)(n_{12}v_2)^2 - \frac{288}{5}(n_{12}v_2)^3\right.$$

$$-\frac{4888}{105}(n_{12}v_1)v_1^2 + \frac{5056}{105}(n_{12}v_2)v_1^2 + \frac{2056}{21}(n_{12}v_1)(v_1v_2)$$

$$\left. -\frac{2224}{21}(n_{12}v_2)(v_1v_2) - \frac{1028}{21}(n_{12}v_1)v_2^2 + \frac{5812}{105}(n_{12}v_2)v_2^2\right)$$

$$+\frac{G^3m_1m_2^2}{r_{12}^4}\left(-\frac{582}{5}(n_{12}v_1)^3 + \frac{1746}{5}(n_{12}v_1)^2(n_{12}v_2) - \frac{1954}{5}(n_{12}v_1)(n_{12}v_2)^2\right.$$

$$+158(n_{12}v_2)^3 + \frac{3568}{105}(n_{12}v_{12})v_1^2 - \frac{2864}{35}(n_{12}v_1)(v_1v_2)$$

$$\left. +\frac{10048}{105}(n_{12}v_2)(v_1v_2) + \frac{1432}{35}(n_{12}v_1)v_2^2 - \frac{5752}{105}(n_{12}v_2)v_2^2\right)$$

$$+\frac{G^2m_1m_2}{r_{12}^3}\left(-56(n_{12}v_{12})^5 + 60(n_{12}v_1)^3v_{12}^2 - 180(n_{12}v_1)^2(n_{12}v_2)v_{12}^2\right.$$

$$+174(n_{12}v_1)(n_{12}v_2)^2v_{12}^2 - 54(n_{12}v_2)^3v_{12}^2 - \frac{246}{35}(n_{12}v_{12})v_1^4$$

$$+\frac{1068}{35}(n_{12}v_1)v_1^2(v_1v_2) - \frac{984}{35}(n_{12}v_2)v_1^2(v_1v_2) - \frac{1068}{35}(n_{12}v_1)(v_1v_2)^2$$

$$+\frac{180}{7}(n_{12}v_2)(v_1v_2)^2 - \frac{534}{35}(n_{12}v_1)v_1^2v_2^2 + \frac{90}{7}(n_{12}v_2)v_1^2v_2^2$$

$$+\frac{984}{35}(n_{12}v_1)(v_1v_2)v_2^2 - \frac{732}{35}(n_{12}v_2)(v_1v_2)v_2^2 - \frac{204}{35}(n_{12}v_1)v_2^4$$

$$\left.\left. +\frac{24}{7}(n_{12}v_2)v_2^4\right)\right] n_{12}^i$$

$$+\left[-\frac{184}{21}\frac{G^4m_1^3m_2}{r_{12}^5} + \frac{6224}{105}\frac{G^4m_1^2m_2^2}{r_{12}^6} + \frac{6388}{105}\frac{G^4m_1m_2^3}{r_{12}^6}\right.$$

$$+\frac{G^3m_1^2m_2}{r_{12}^4}\left(\frac{52}{15}(n_{12}v_1)^2 - \frac{56}{15}(n_{12}v_1)(n_{12}v_2) - \frac{44}{15}(n_{12}v_2)^2 - \frac{132}{35}v_1^2 + \frac{152}{35}(v_1v_2)\right.$$

$$\left. -\frac{48}{35}v_2^2\right)$$

$$+\frac{G^3m_1m_2^2}{r_{12}^4}\left(\frac{454}{15}(n_{12}v_1)^2 - \frac{372}{5}(n_{12}v_1)(n_{12}v_2) + \frac{854}{15}(n_{12}v_2)^2 - \frac{152}{21}v_1^2\right.$$

$$\left. +\frac{2864}{105}(v_1v_2) - \frac{1768}{105}v_2^2\right)$$

$$+\frac{G^2m_1m_2}{r_{12}^3}\left(60(n_{12}v_{12})^4 - \frac{348}{5}(n_{12}v_1)^2v_{12}^2 + \frac{684}{5}(n_{12}v_1)(n_{12}v_2)v_{12}^2\right.$$

$$-66(n_{12}v_2)^2v_{12}^2 + \frac{334}{35}v_1^4 - \frac{1336}{35}v_1^2(v_1v_2) + \frac{1308}{35}(v_1v_2)^2 + \frac{654}{35}v_1^2v_2^2$$

$$\left.\left.\left. -\frac{1252}{35}(v_1v_2)v_2^2 + \frac{292}{35}v_2^4\right)\right] v_{12}^i \right\}$$

$$+\mathcal{O}\left(\frac{1}{c^8}\right).$$

[Nissanke et al. 2004]

3.5PN

Extract source information from GWs

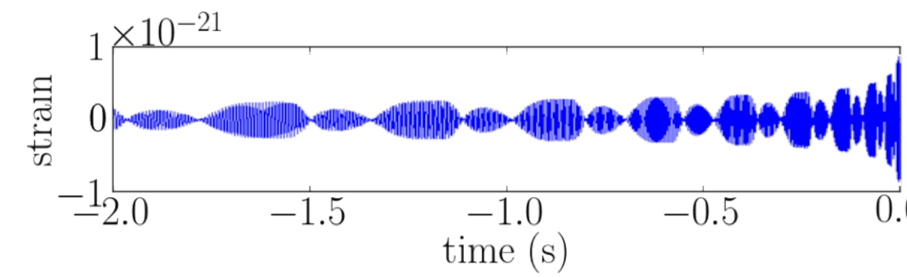
$$h_+(t) = \frac{A[\mathcal{M}\, f(t)]}{D}(1+\cos^2\iota)\cos\Phi_{\rm GW}(t)$$

frequency ($f(t)$), distance (D), inclination angle (ι), GW Phase ($\Phi_{\rm GW}(t)$)

h(t): 9-16 parameters

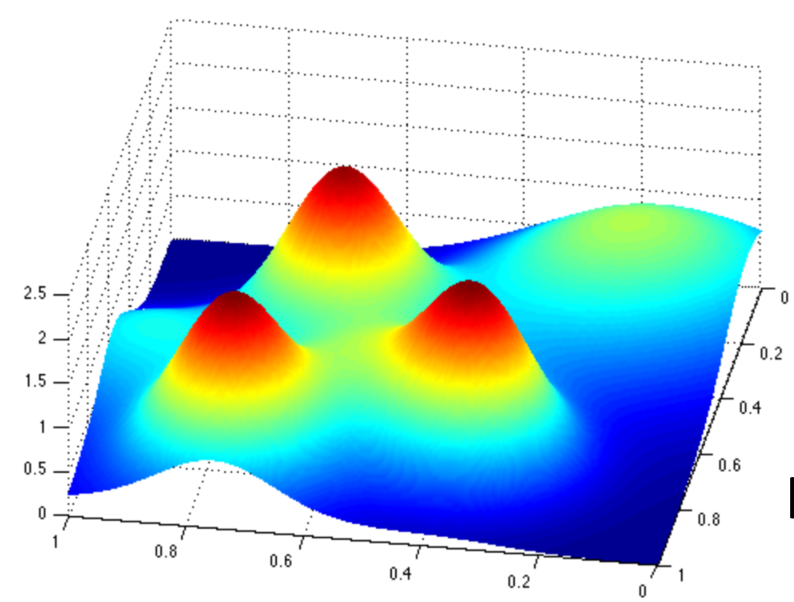
+ Redshifted Masses
+ Spins
+ Tidal deformability
+ Geometric properties:
  - Inclination angle
  - Source Position
  - Luminosity distance

Model h(t)



Detector output

Explicitly map out: $p(\boldsymbol{\theta}|s) \propto p(\boldsymbol{\theta})\mathcal{L}_{\rm total}(s|\boldsymbol{\theta})$



Likelihood

parameter 1

parameter 2

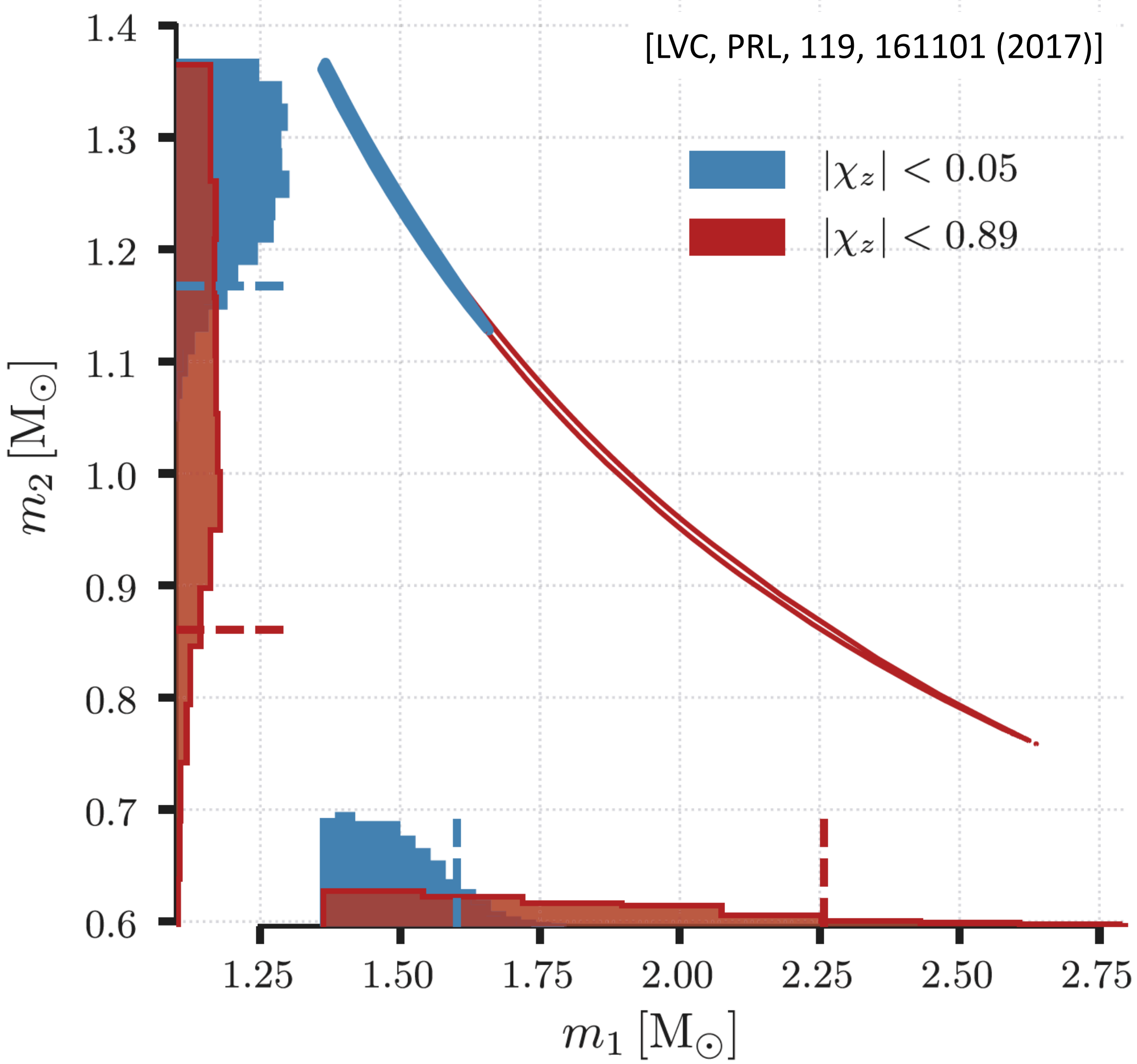
using Bayesian Markov Chain Monte Carlo and Nested Sampling Techniques

[see LVC, arXiv: 1602.03840, PRL 116, 241102, 2016]
[see Nissanke et al. 2010, 11, 13a, 13b]

Part III:
GW source parameter inference

Progenitor masses and spins retrieval

GW170817



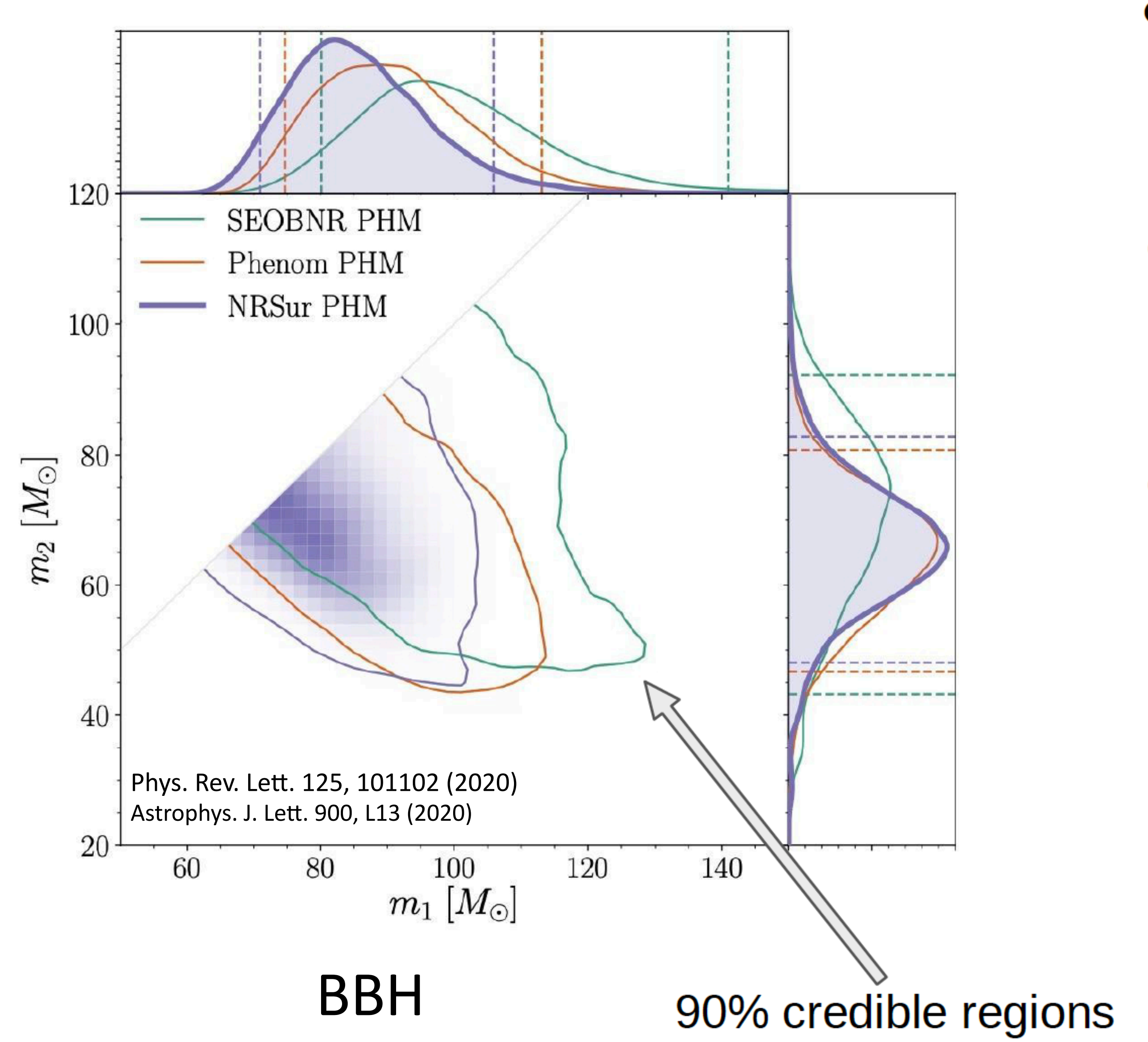
BNS or NS-BH ?

Masses: 1.00 - 1.89 M⊙ (high spins)

1.16 - 1.60 M⊙ (low spins)

Total Mass: $2.73^{+0.04}_{-0.01}$ M⊙

GW190521



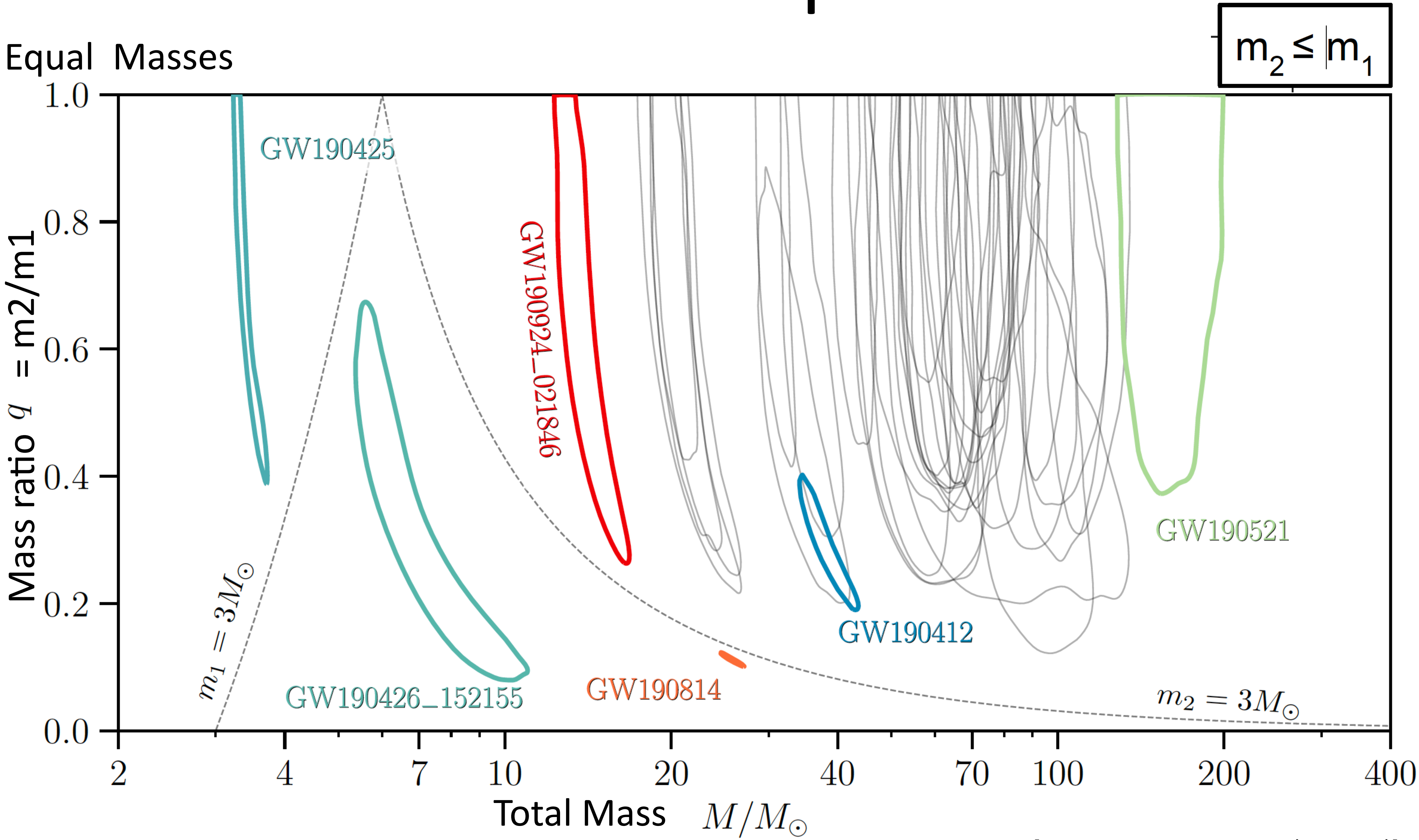
BBH

BH mass 1: 85^{+21}_{-14} M⊙

BH mass 2: 66^{+17}_{-19} M⊙

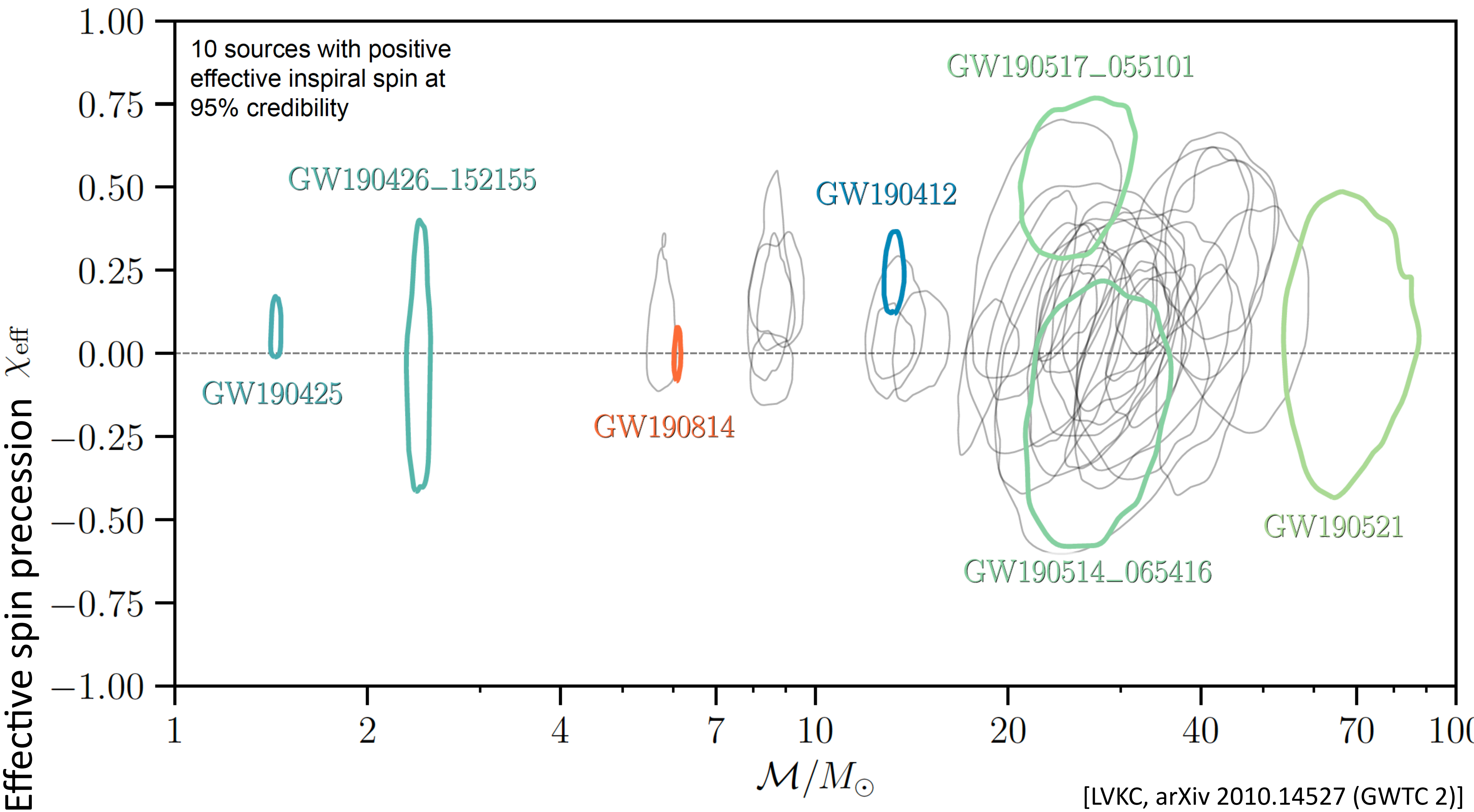
Total Mass: 150^{+29}_{-17} M⊙

GWTC-2 indicates broad mass distribution also with non-equal masses



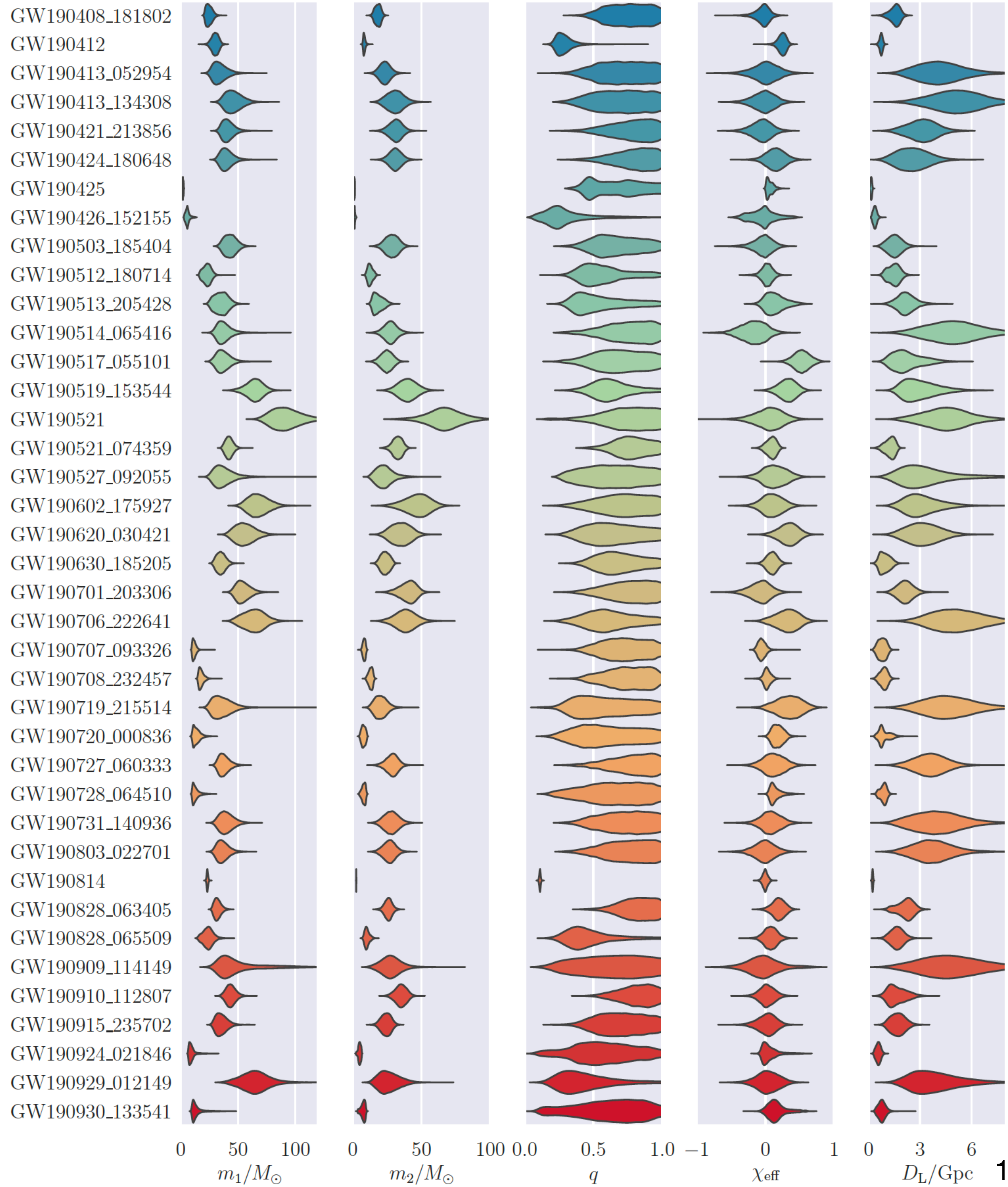
[LVKC, arXiv 2010.14527 (GWTC 2)]

GWTC-2 indicates spin induced precession of orbital plane



[LVKC, arXiv 2010.14527 (GWTC 2)]

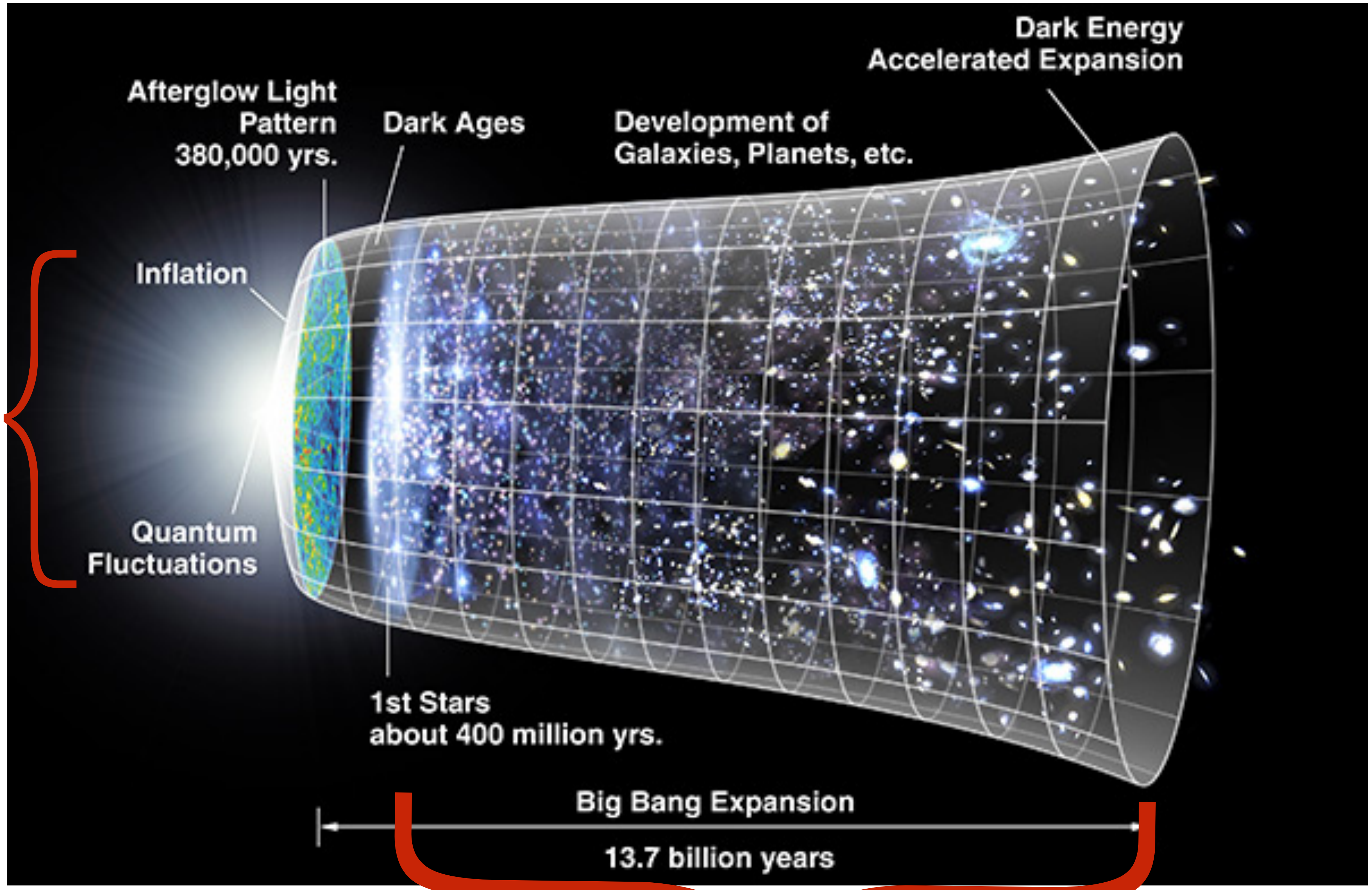
Compact Object Portrait Gallery



[LVKC, arXiv 2010.14527 (GWTC 2)]

Challenge: how, when and where do BBHs form?

Primordial BHs from density fluctuations in early Universe



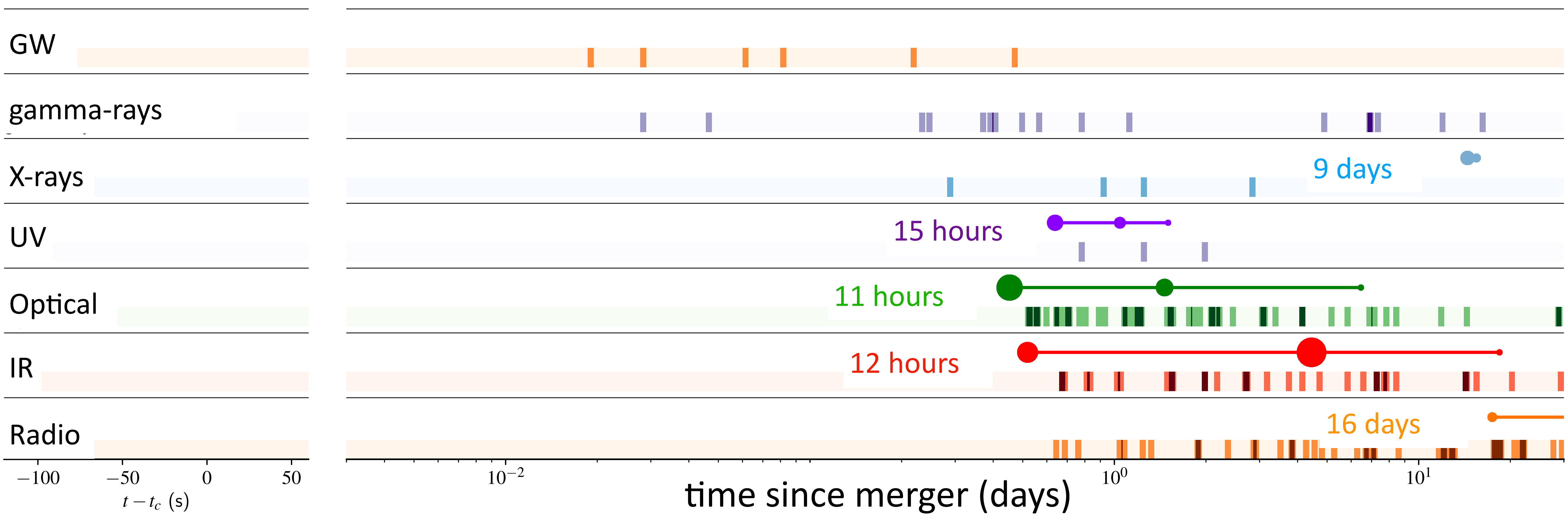
Pop III: first massive stars (1% of stars in Universe)
Pop II/I: classic field binary evolution (90%)
Pop II/I: rapid rotation
Pop II/I: dynamical formation in globular clusters, stellar clusters
Exotic

[see LVKC; arXiv: 2010.14533]

Part III:
The Multi-messenger discovery and cosmology of GW170817

The first month(s) of multi-messenger observations of GW170817

adapted from LIGO, Virgo, EM partners + ApJ 848 L12 (2017) with Nissanke



Global ground and space-based effort:

70+ teams, 100+ instruments, over 3500 co-authors

A Tale of Two+ Matter Outflows ⇒ EM counterparts

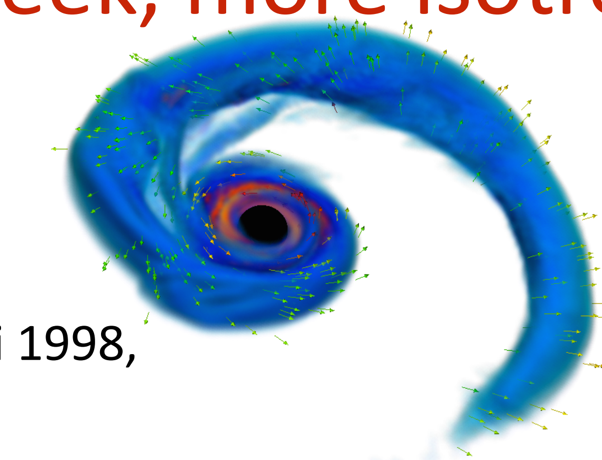
1. Tidal Tails + Disk Winds + Core-bounce Heating ⇒ Kilonova: Ultraviolet Optical IR (days-week, more isotropic)

$M_{ej} \approx 0.01\text{-}0.05\ M_\odot$

$E \approx 10^{50}$ ergs

$v \approx 0.1\text{-}0.3c$

[Lattimer and Schramm 1974, Li and Paczynski 1998, Rosswog 1999, Kulkarni 2005, Metzger +.. 2010, Kasen + 2013 ...]



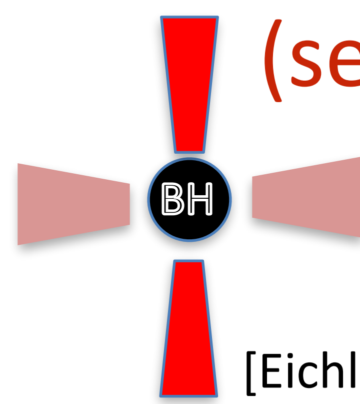
[Foucart et el. 2014]

2. Ultra-relativistic Jet ⇒ Short Gamma Ray Burst + afterglow (seconds - months, collimated)

$M_{ej} \approx 10^{-6}\ M_\odot$

$E \approx 10^{49}\text{-}10^{50}$ ergs

$v \approx 0.99c - 0.99995c$



[Eichler+ 1989, Paczynski 1989,...]

Outflows' expand, cool and are heated by shocks or radioactivity.

(cf. Supernova: 10^{51} ergs; L_{sun}: 4×10^{26} W or 4×10^{33} erg/s)

Extract source & environment from EM

$F_\lambda(t)$: 15 parameters

- Energetics and beaming
- R-process nucleosynthesis
- Mass ejecta and velocity
- Environment
- Redshift, Accurate Position (1")
- Stellar populations
- Magnetic field strength
- Previous binary evolution & mass loss

New field: break degeneracies to measure properties of BHs and NSs

h(t): 9-16 parameters

- Redshifted Masses (several to tens %)
- Spins (tens of %)
- NS radii (tens of %)
- Geometric properties: (tens of %)
  - Inclination angle
  - Source Position
  - Luminosity distance

$F_\lambda(t)$: 15 parameters

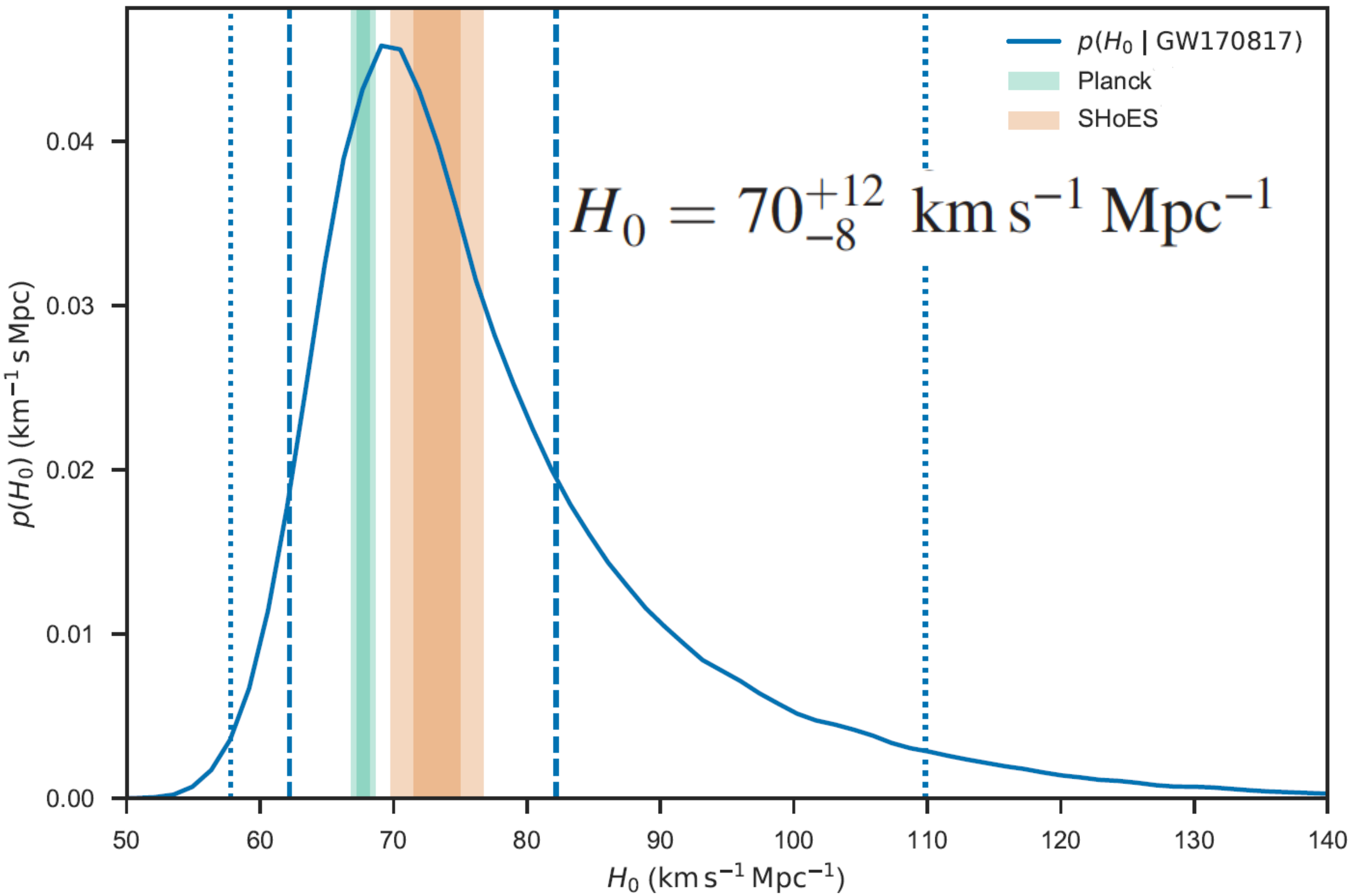
- Energetics and beaming
- R-process nucleosynthesis
- Mass ejecta and velocity
- Environment
- Redshift, Accurate Position (1")
- Stellar populations
- Magnetic field strength
- Previous binary evolution & mass loss

→ Strong signal binary: Characterisation

Population: Demographics, ecology and census

GW+EM: Standard siren measurement of Hubble constant

[LVC +6 OIR, Nature, 551, 2017]

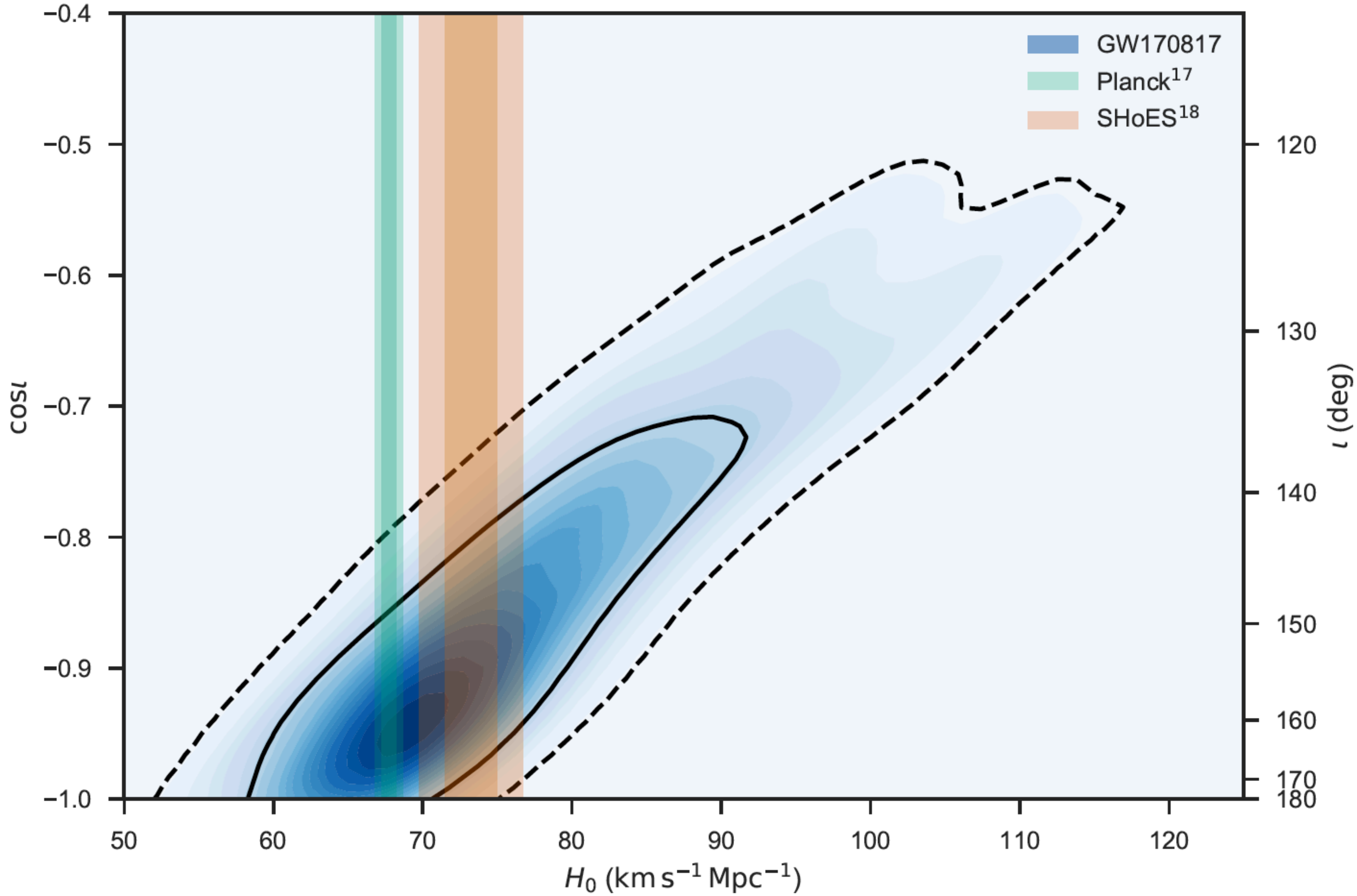


Peculiar velocity error of 150 km/s; Hubble flow velocity of 3017 +/- 166 km s^{-1}

[Schutz 1986, Dalal + 2006, see formalism used in SN + 2010, 13, …]

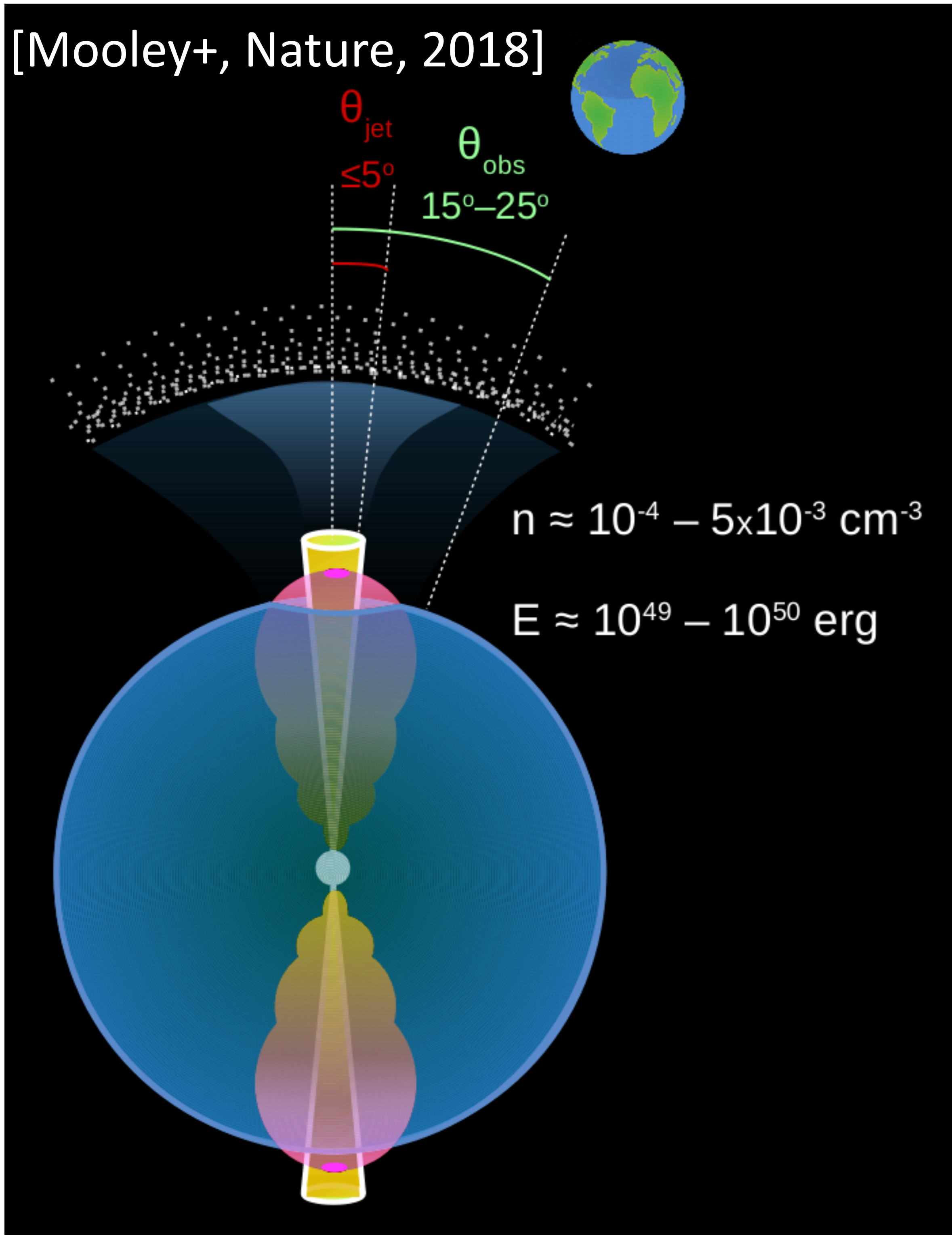
GW challenge: Inclination angle and distance degeneracy

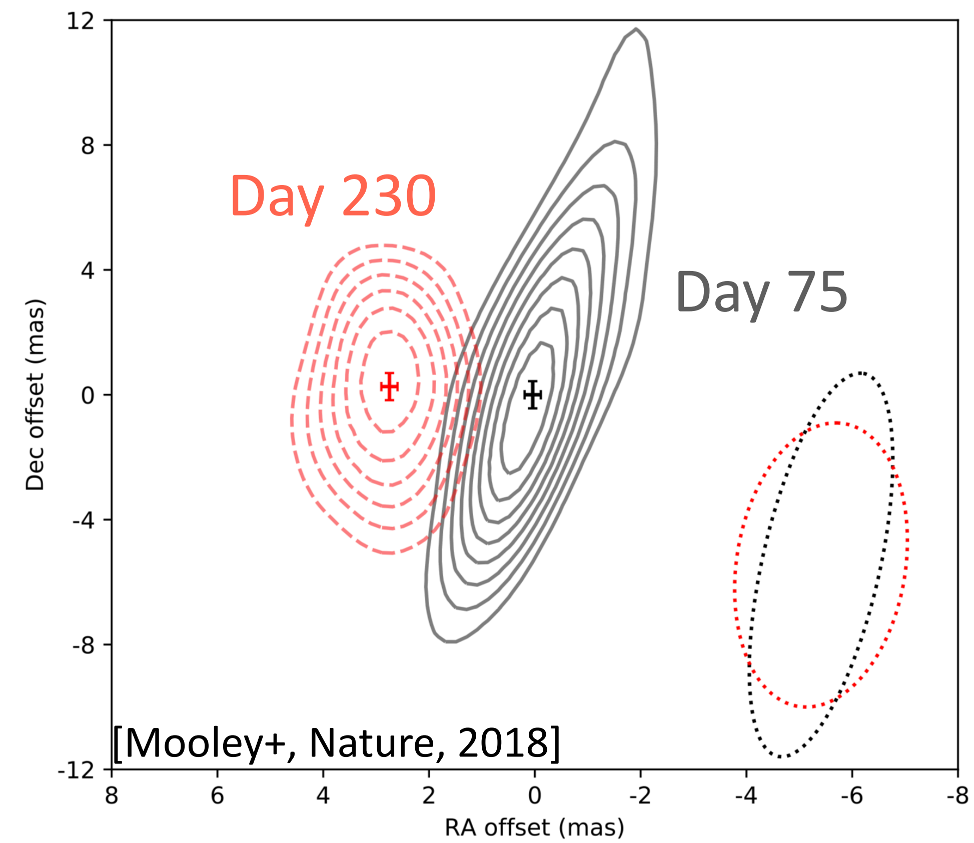
[LVC +6 OIR, Nature, 551, 2017]



[see SN+10, Guidorzi+ 2017, Finstead +18, Mandel 18]

EM SGRB VLBI ⇒ superluminal jet with structure



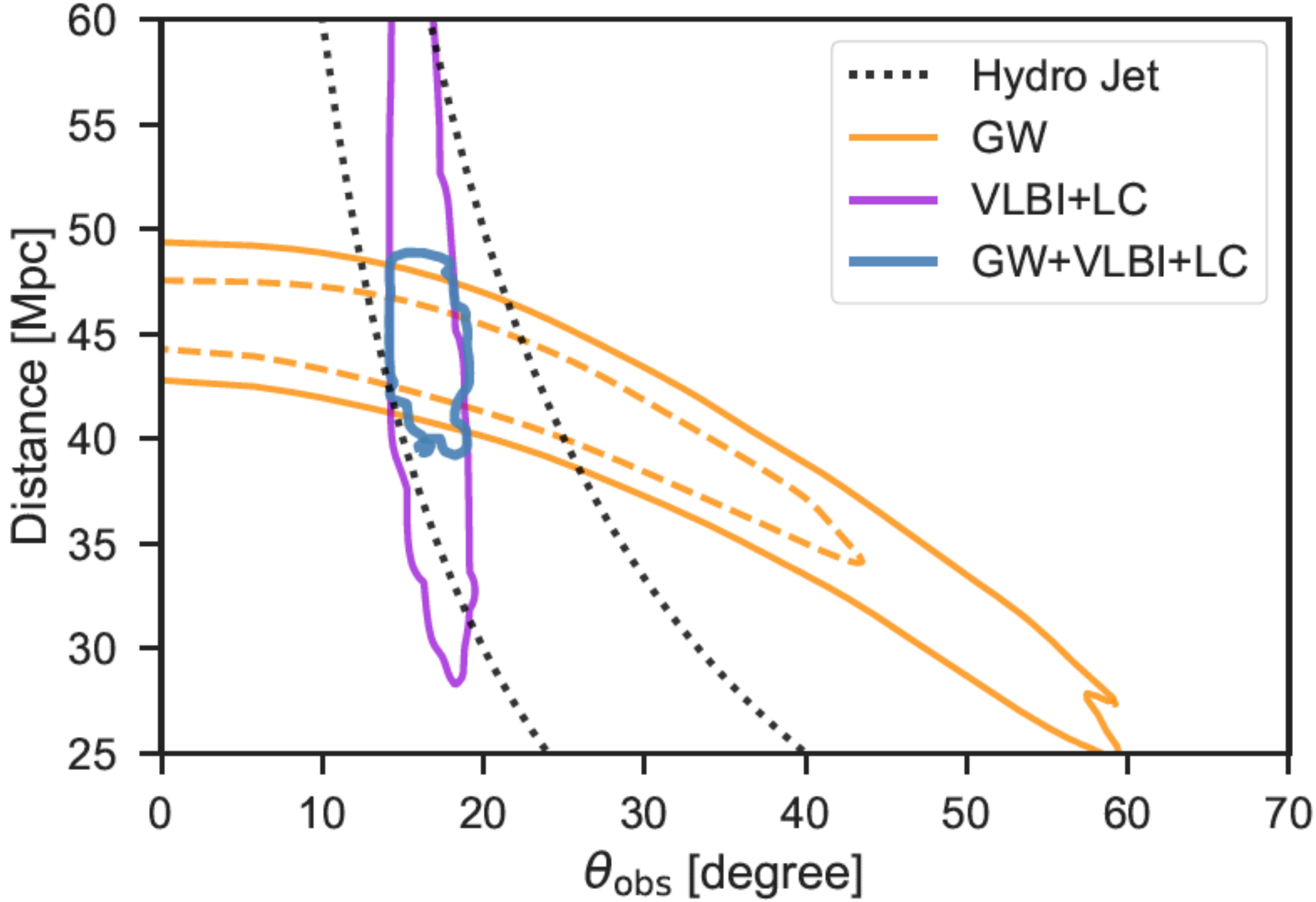


[see also Lazzati 2017,18, Ghirlanda + 2019, Troja+ 2018]

Proper motion of 2.7 mas, β_{app} ~4.7

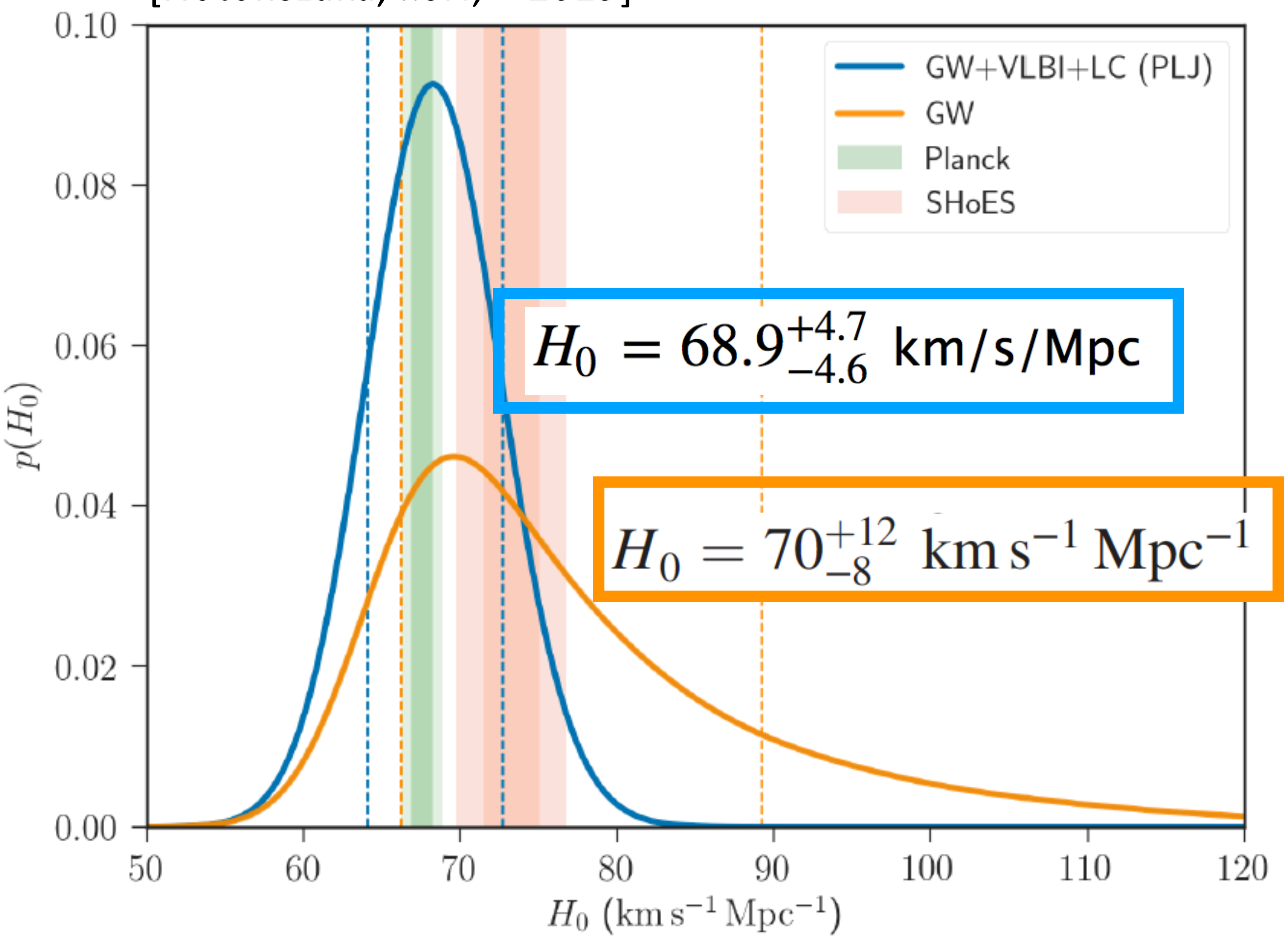
GW+ radio: Hubble measurement improves by a factor of 2

[Hotokezaka, ..SN, + 2019, Nature Astro.]



GW+radio: Hubble measurement improves by a factor of 2

[Hotokezaka, ..SN, + 2019]

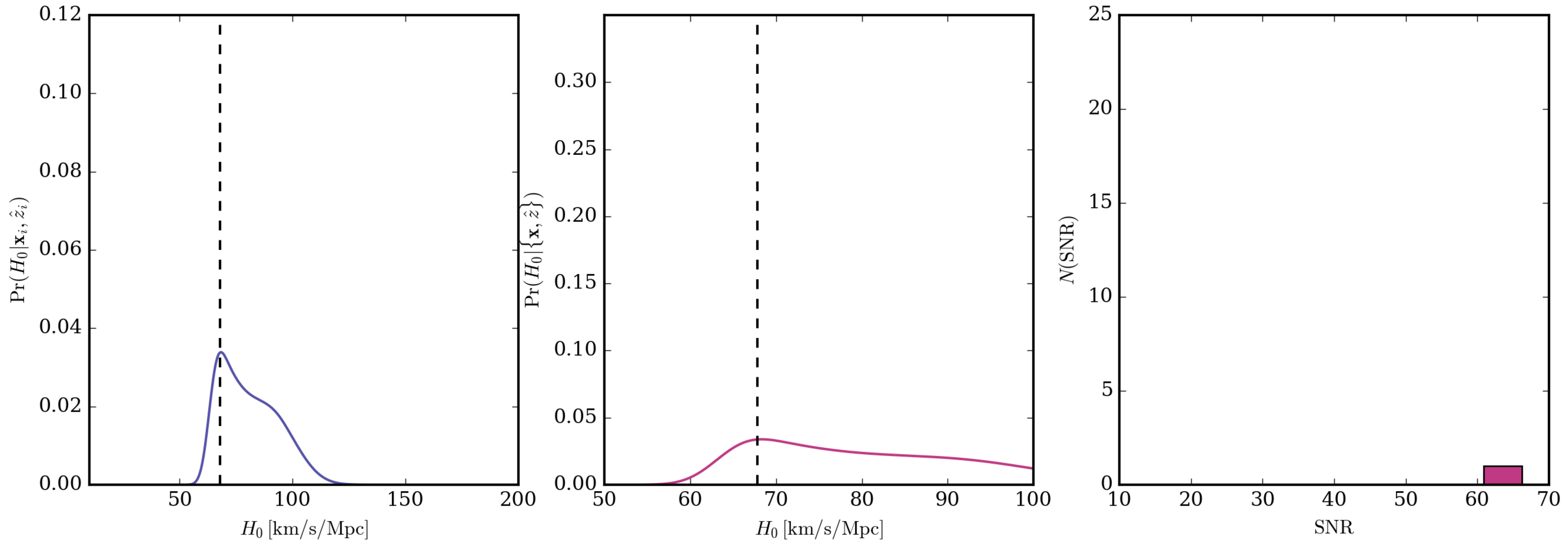


[for improvement of peculiar velocity inference; Mukherjee, .. SN+ 2019, Davies + 2019, Nicolaou, +2019]

Caveat: astrophysical modelling of jet

GW+EM: importance of populations to potentially resolve "Hubble trouble"

[Feeney, Peiris, Williamson, SN,..+,PRL, 2019; Mortlock, … SN, 2019]



[see also Chen+ 2018, …]

50 binaries (~8-10 years) to reach a precision of 1.8 % (1/√N); high SNR binaries dominate joint PDF; important caveat is assumption of EM

Part IV:
Perspectives

GW170817: follow-up was easy — very close by and bright,

small GW volume

BBH merger rate: $23.9^{+14.9}_{-8.6}$ Gpc^3 yr^{-1}
NS-NS merger rate: 320^{+490}_{-240} Gpc^3 yr^{-1}
NS-BH merger rate: < 610 Gpc^3 yr^{-1}

[LVC, arXiv: 1811.15007
arXiv: 1901.03310, 2019; arXiv: 2010.14533]

1. GW+EM: Expect a diversity of EM counterparts

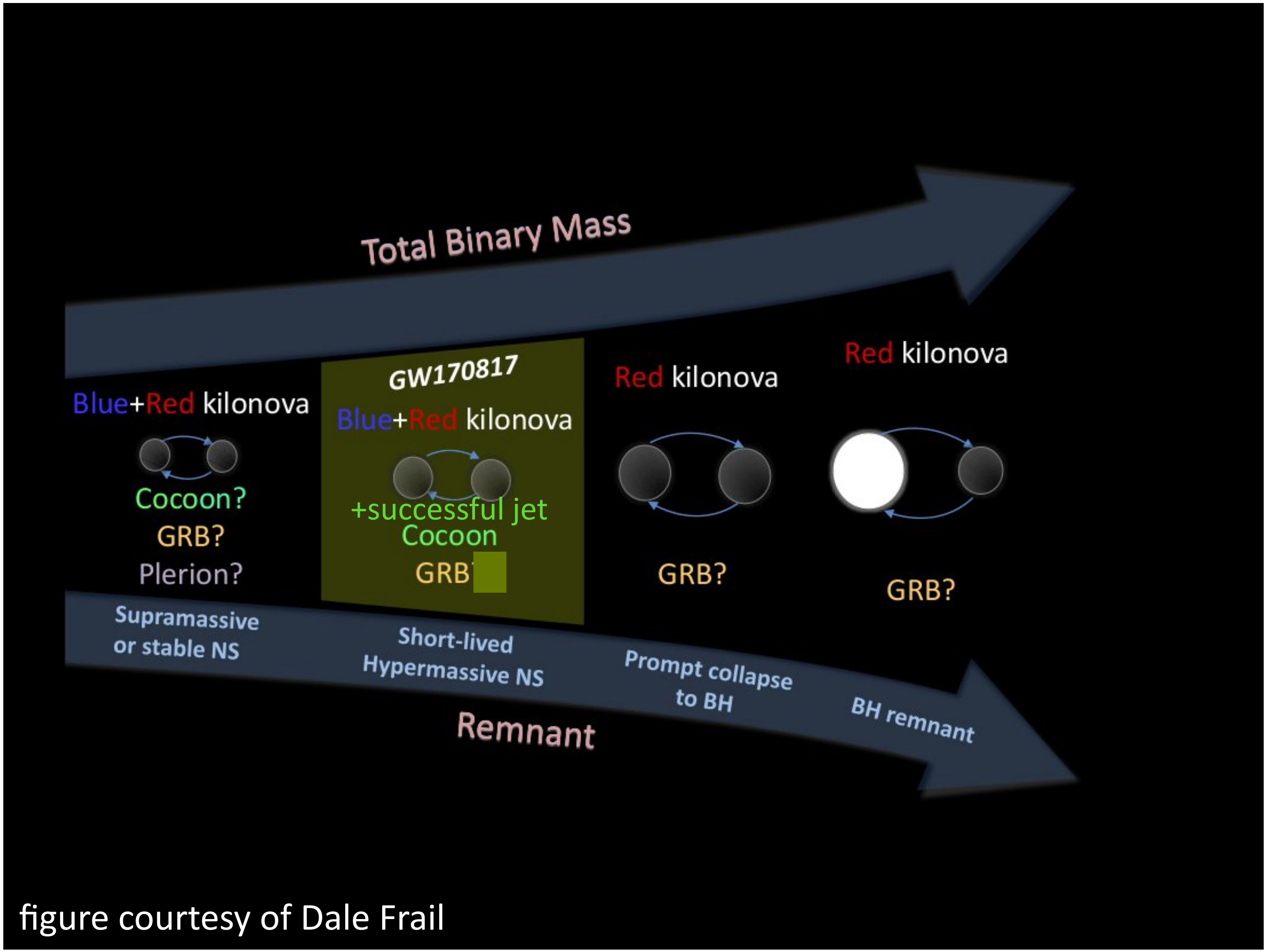
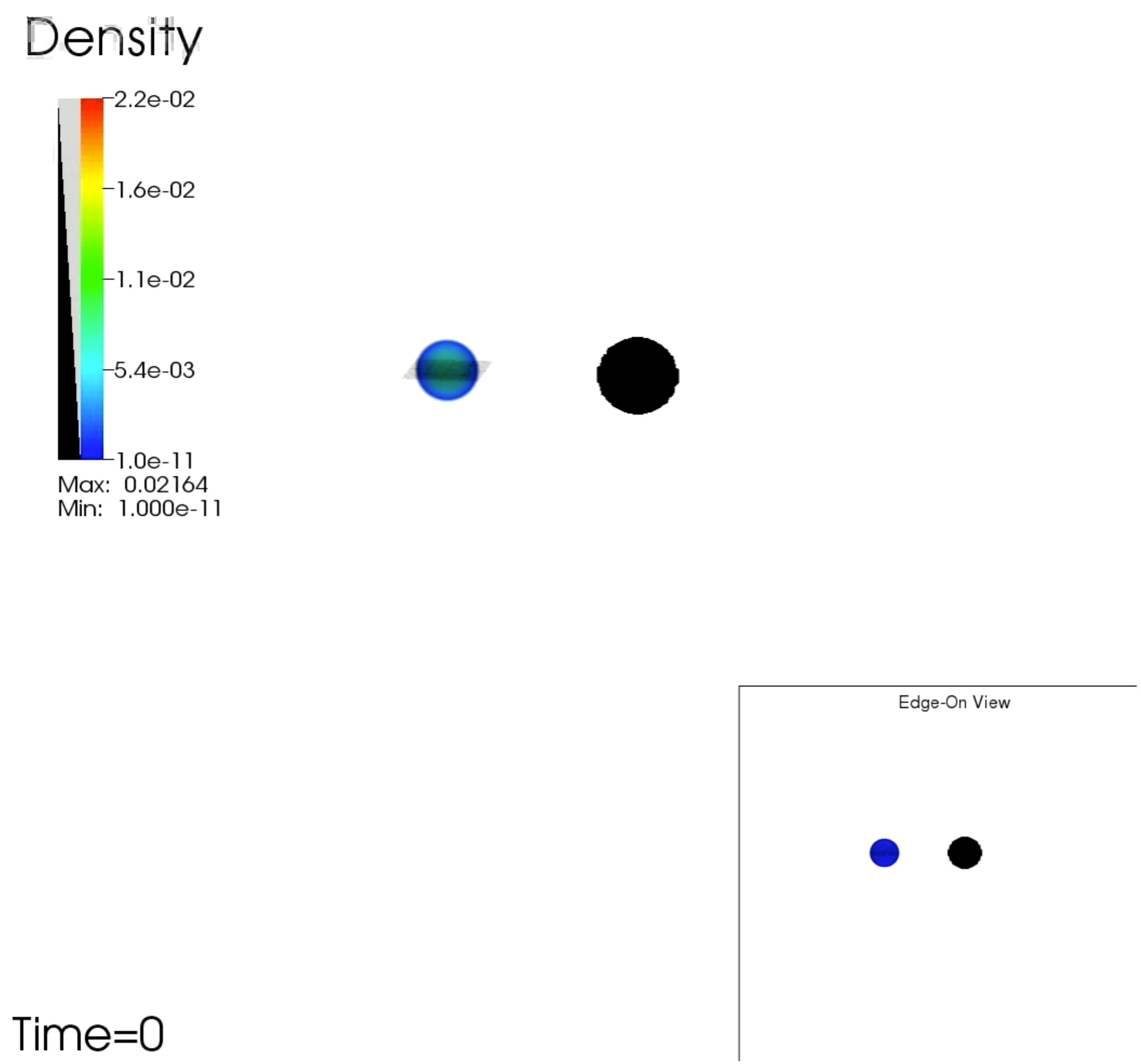


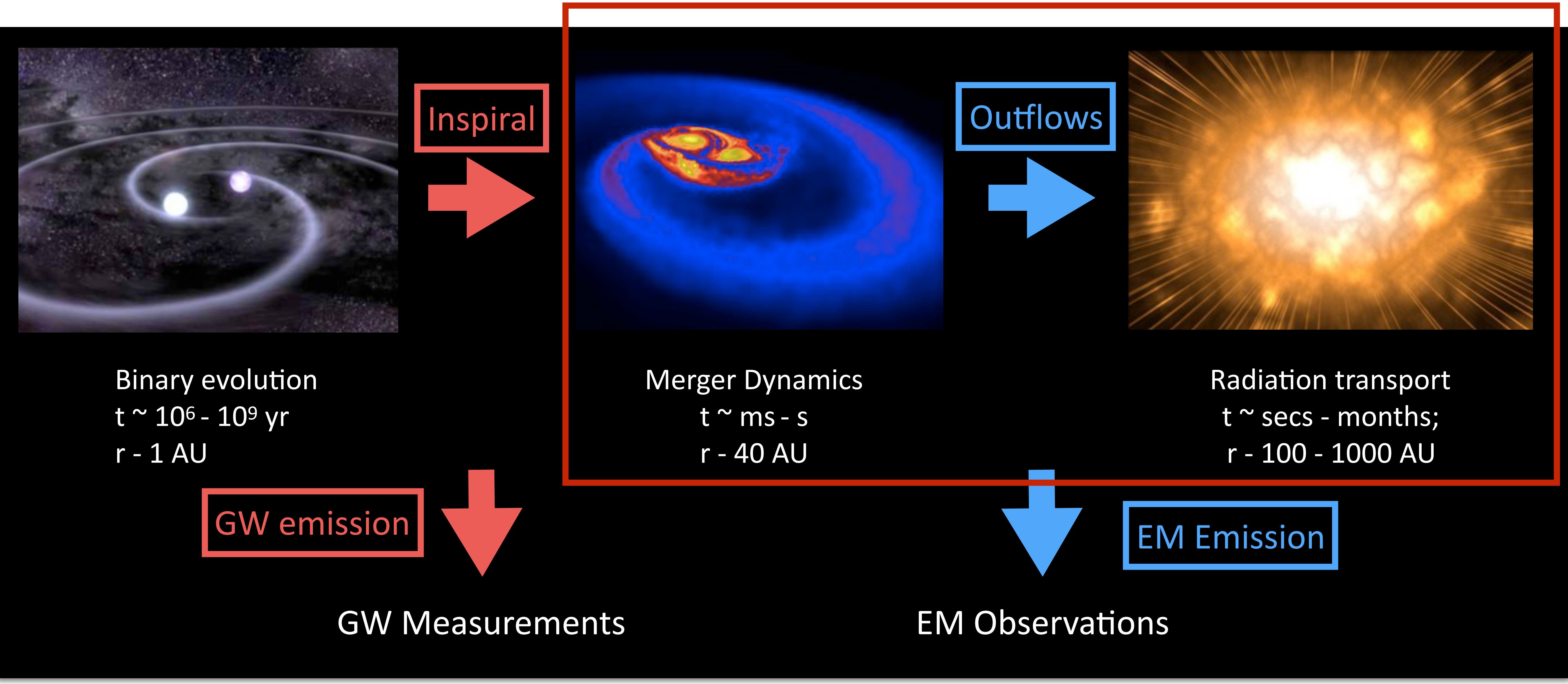
figure courtesy of Dale Frail

2) GW+EM: New discovery space — NS-BH mergers!

Movie courtesy of Francois Foucart

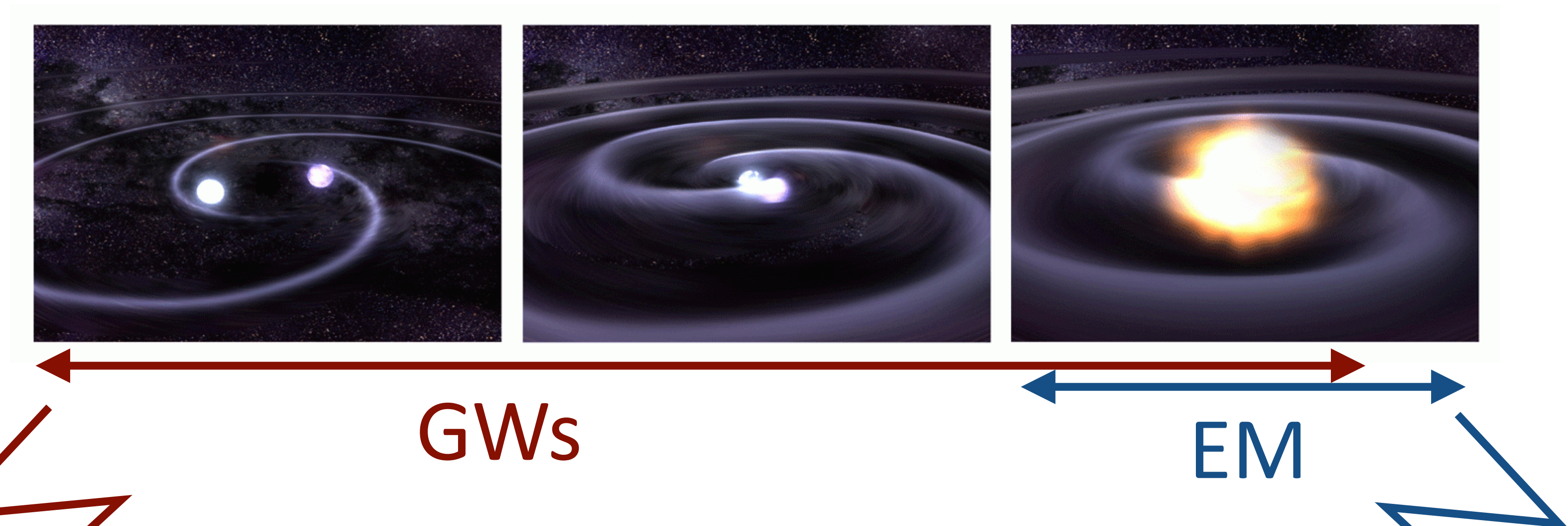


3. GW+EM challenge remains to build a coherent model: a key step to joint characterization



Outflows carry energy from small (10^6 cm) to large distances (10^{14}-10^{16} cm) for radiation to escape.

4. GW+EM challenge: from individual objects to statistics

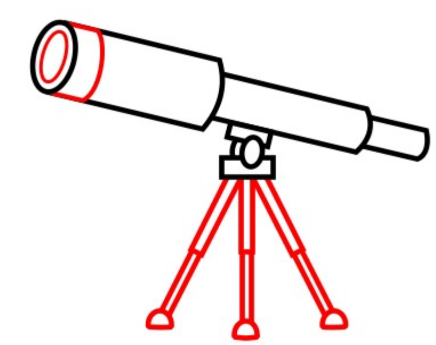


<u>2019-2023 (LIGO+Virgo+…):</u>

NS-NS: 0 to 42 year^{-1}

NS-BH: 0 to 96 per year^{-1}

BH-BH: tens to hundred year^{-1}



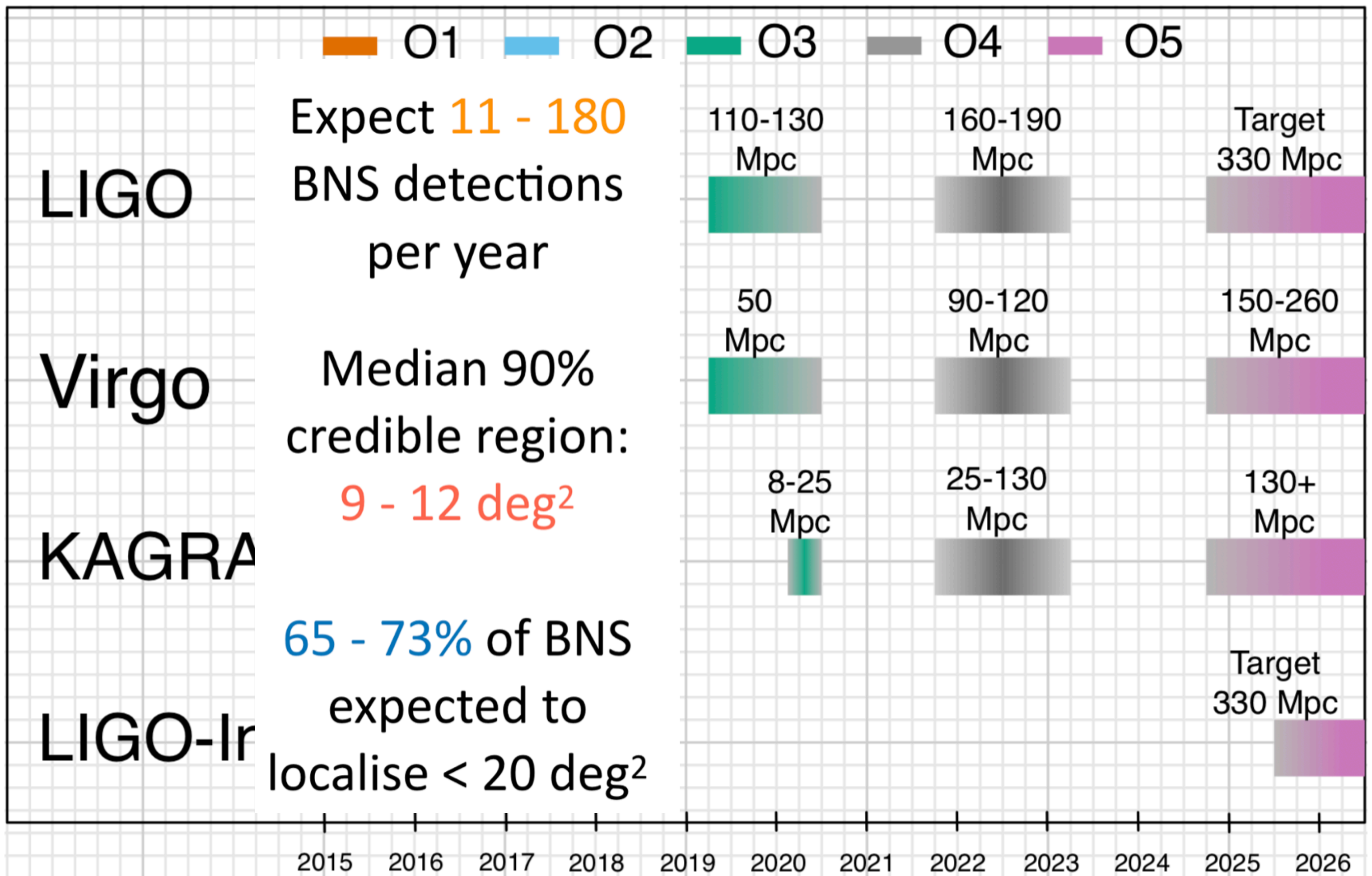
<u>2019-2023:</u>

Wide-field optical and radio telescopes (ZTF, BlackGEM,LOFAR, Apertif, SKA, LSST, ELT ..)

[LVC, Living Reviews in Relativity 19, 1, 2018 and PRX 6, 041015, 2016; LVC+Fermi+Integral, ApJ Lett, 848:L13, 2017]

Mid 2020s: small GW areas, depth and rate

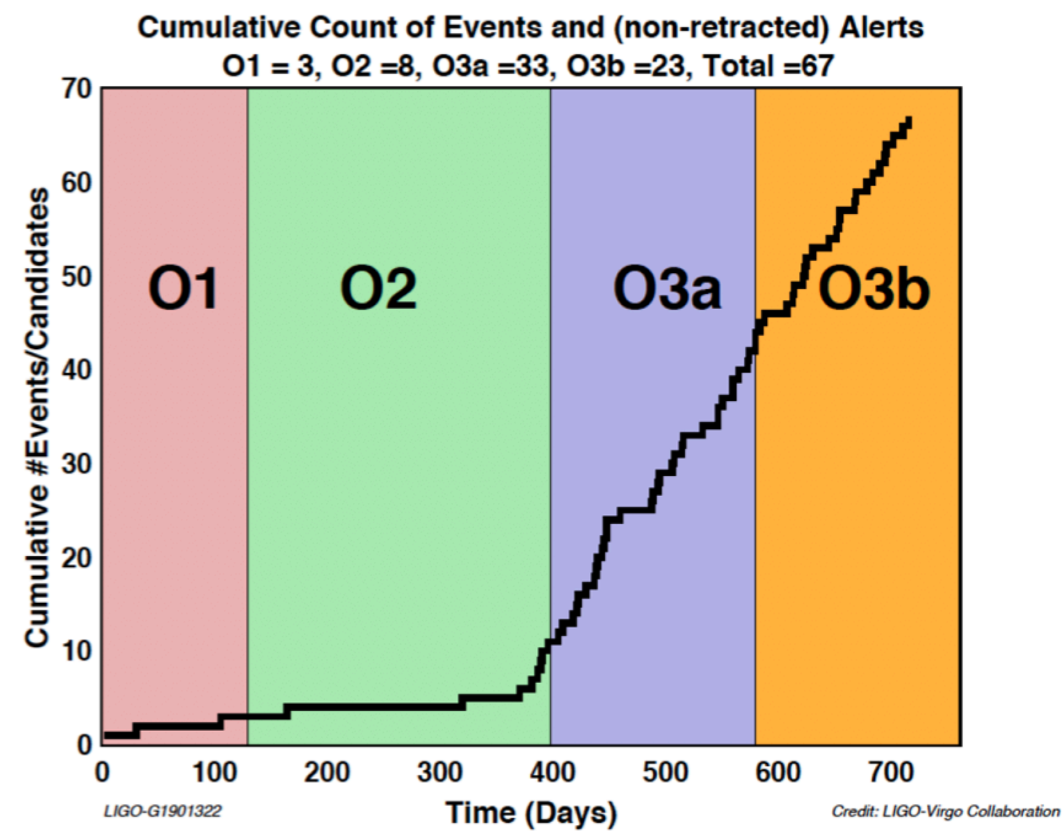
[B. P. Abbott et al., Living Rev Relativ, 2019, 1304.0670]



Expect 11 - 180 BNS detections per year

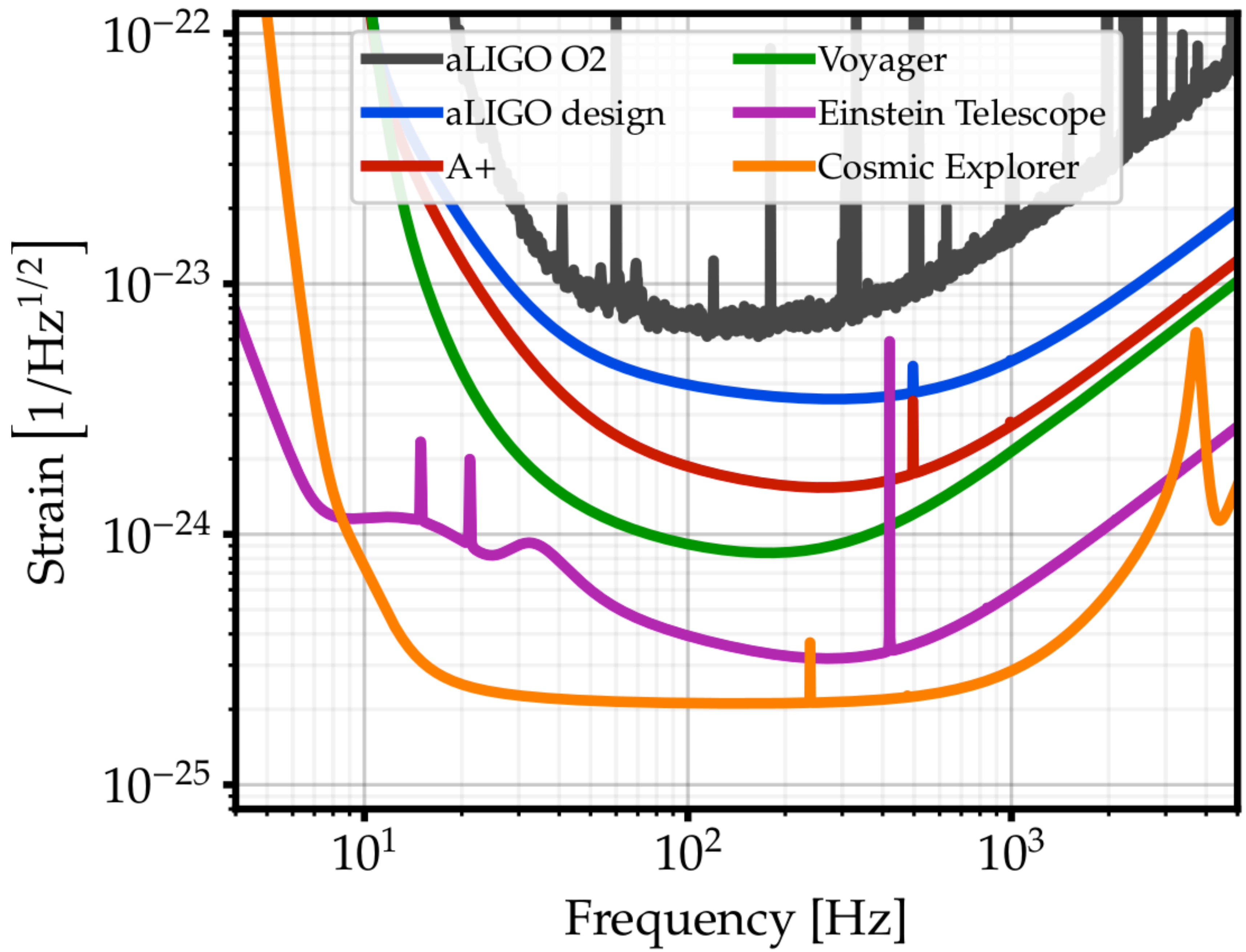
Median 90% credible region: 9 - 12 deg²

65 - 73% of BNS expected to localise < 20 deg²



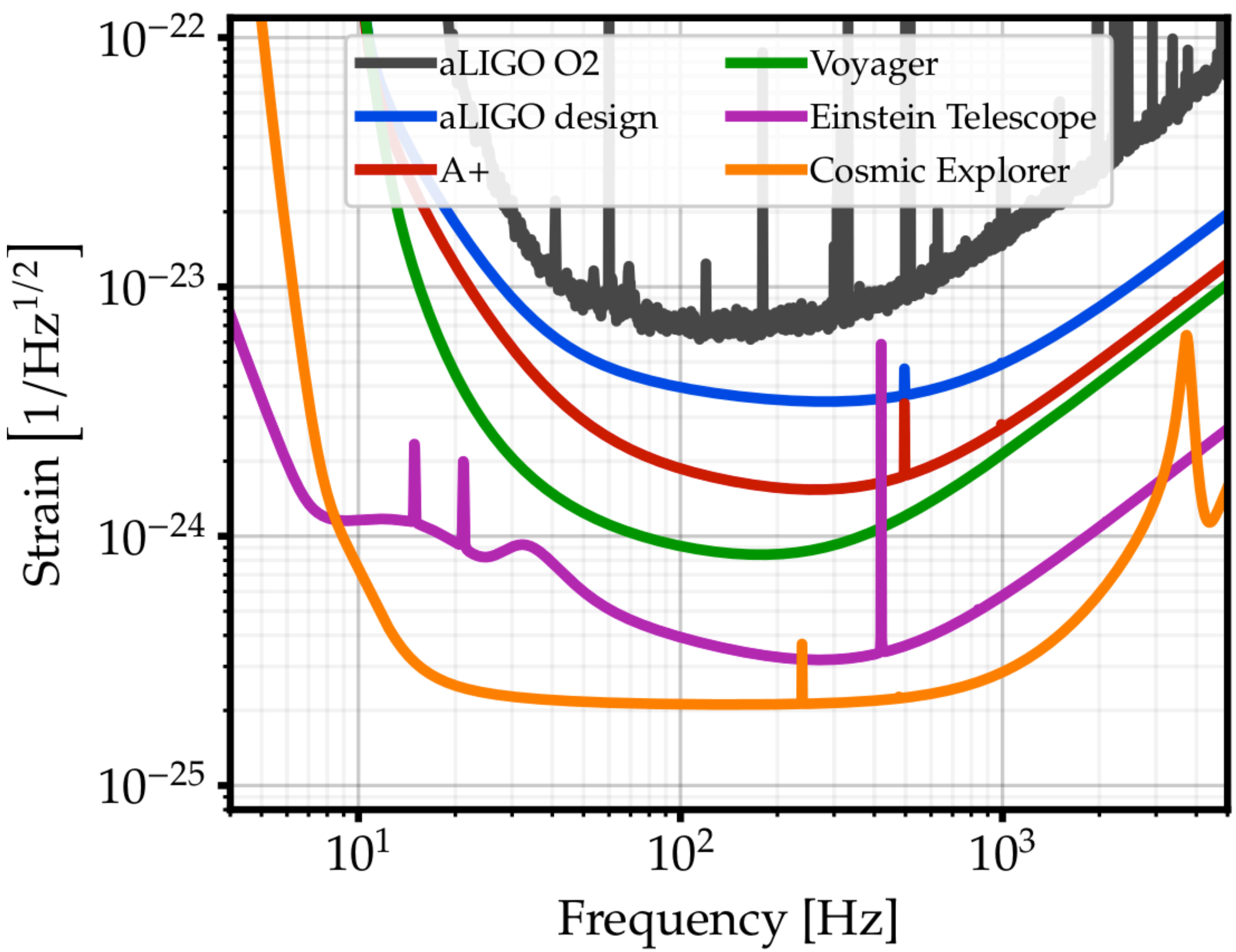
https://dcc.ligo.org/LIGO-G1901322/public

Mid 2020s - 2030s: aLIGO+, Cosmic Explorer



Factor of 2/10 in sensitivity; x 8/1000 in rates

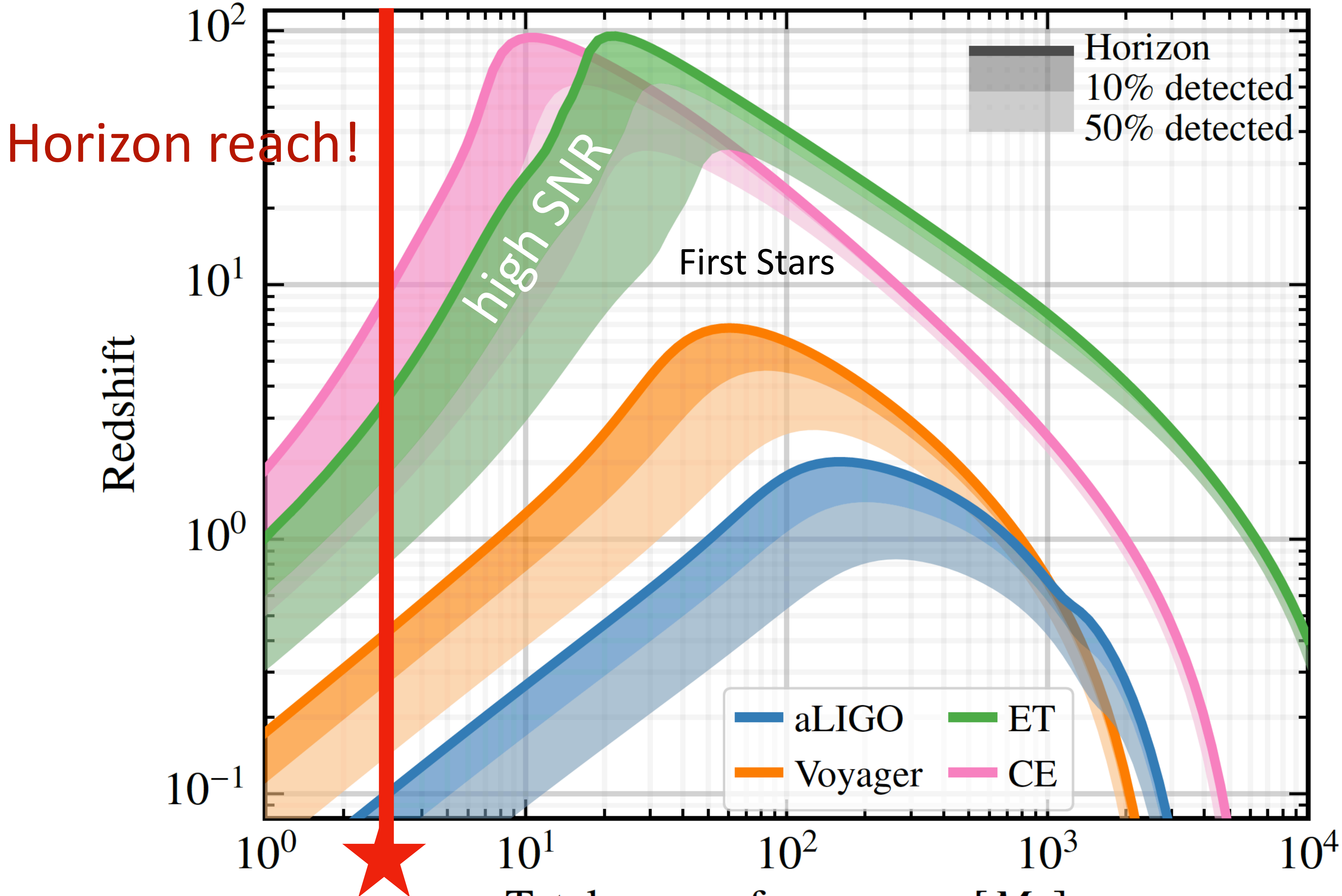
Mid 2020s - 2030s: aLIGO+, Cosmic Explorer



Sensitivity and frequency band increase

2030s: Einstein Telescope and Cosmic Explorer have cosmological reach

MMA co-chairs: Bailes, Kasliwal, Nissanke

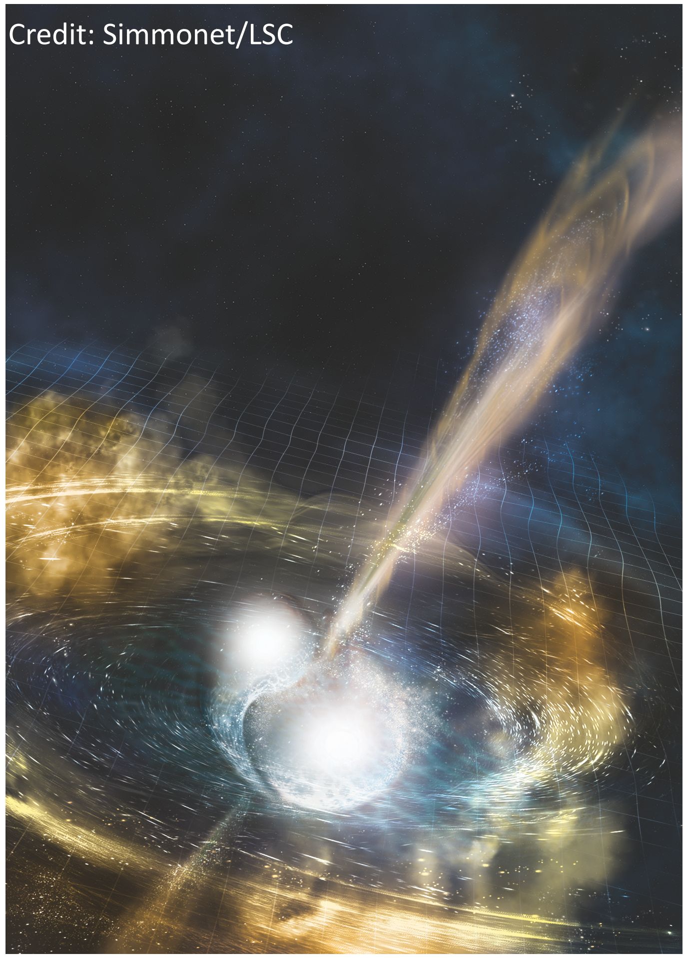


GW170817: z ~ 10^{-2}

Evan Hall, MIT

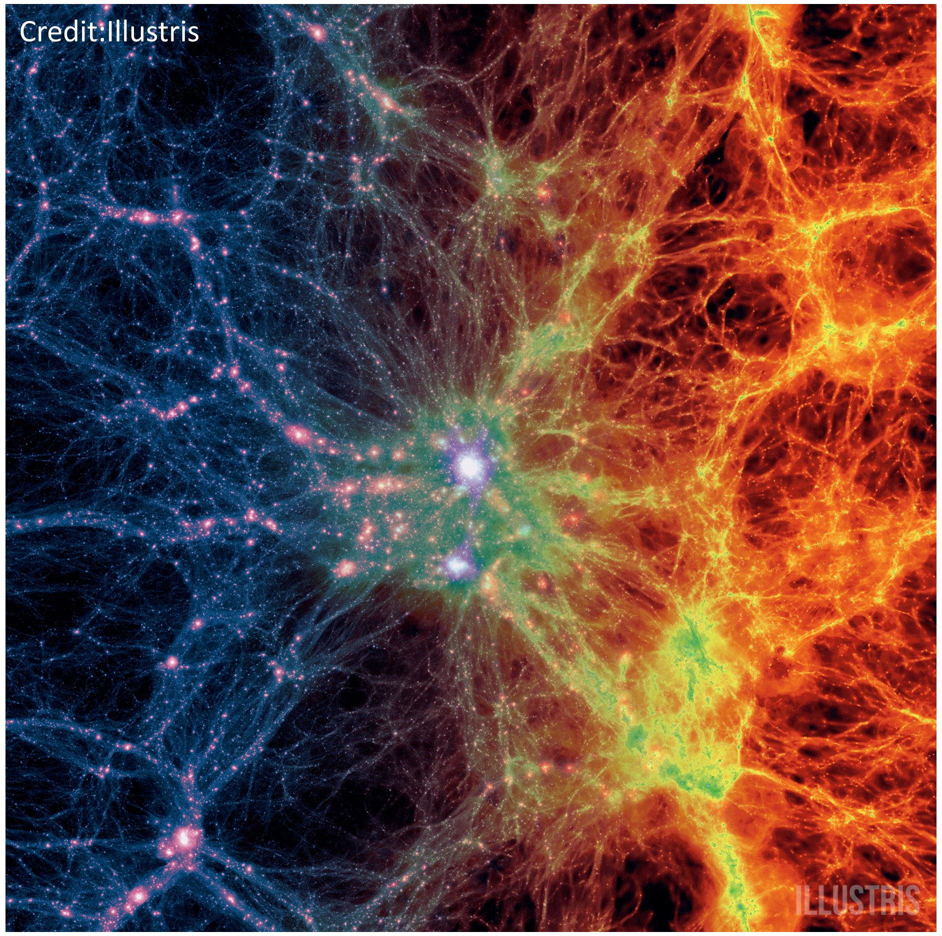
MMO in 2030s is not just EM follow up!

EM follow up of single sources

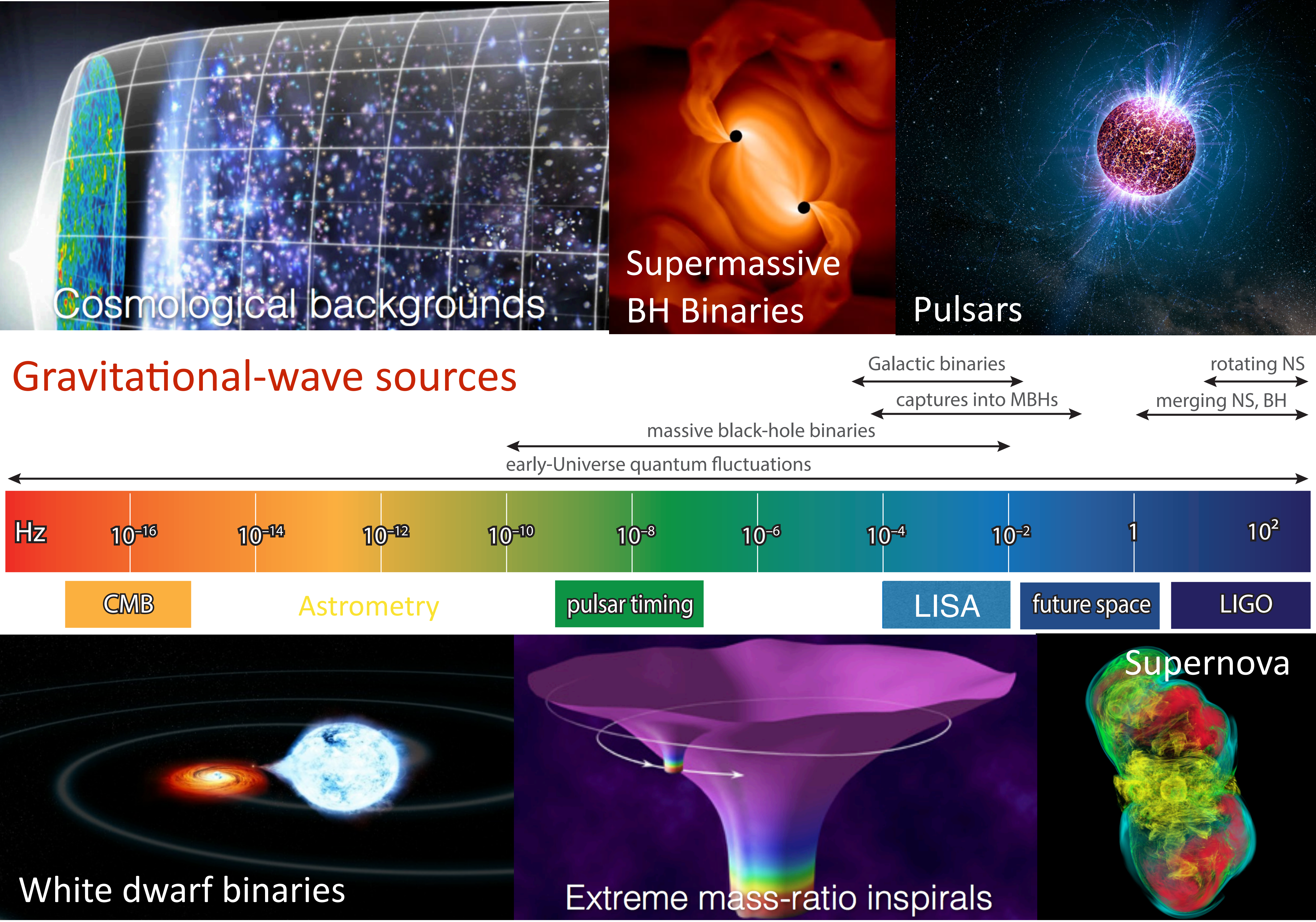


Cherry Pick Loud events - golden for GW+EM

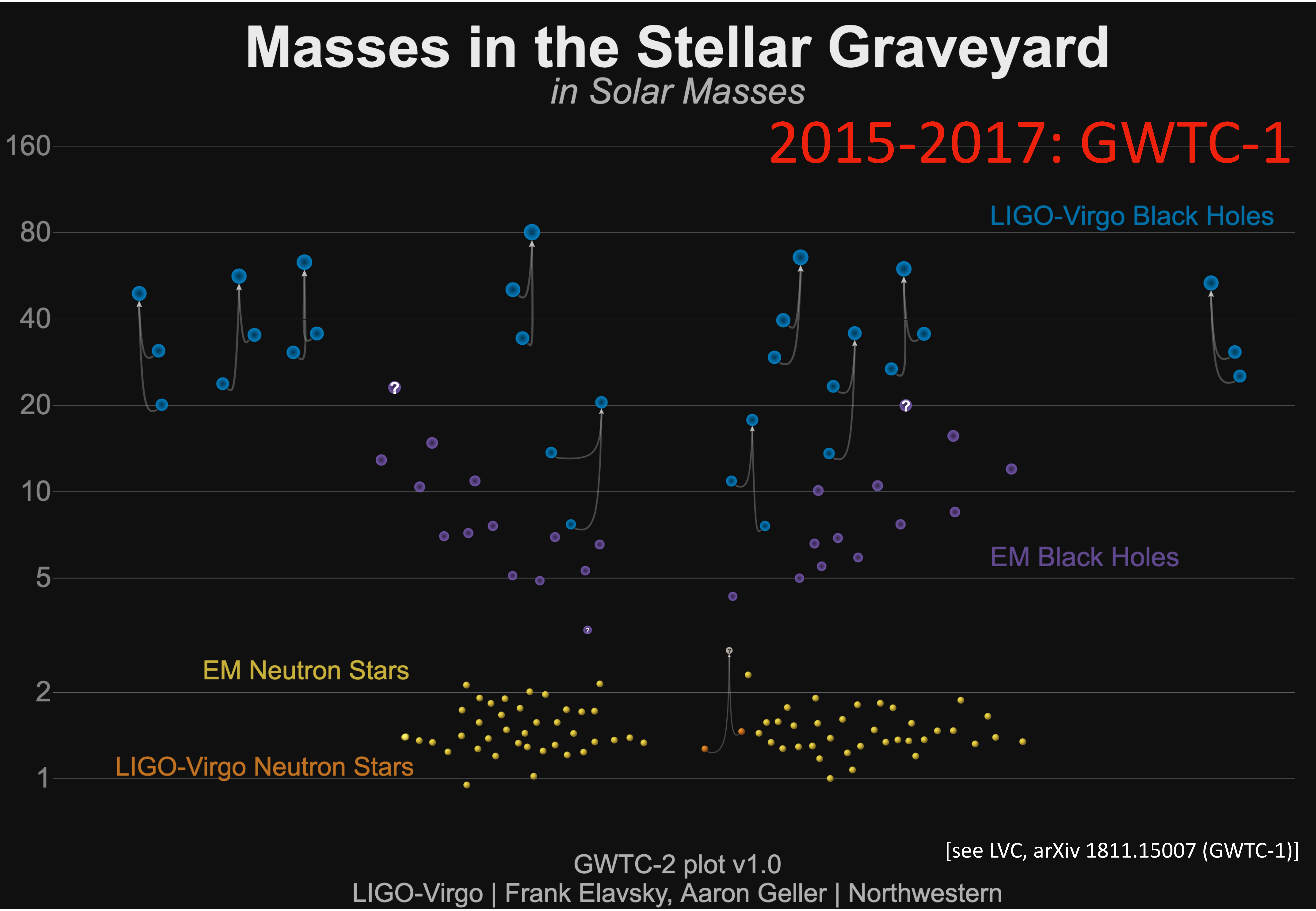
Cross correlating GW and EM source catalogs



Large Scale Structure; Extragalactic Astronomy



First-order phase transitions, superstring kink & cusps, inflationary signature, new sources!



Masses in the Stellar Graveyard
in Solar Masses
2015-2017: GWTC-1
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
[see LVC, arXiv 1811.15007 (GWTC-1)]
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern