An introduction to gravitational waves and LIGO

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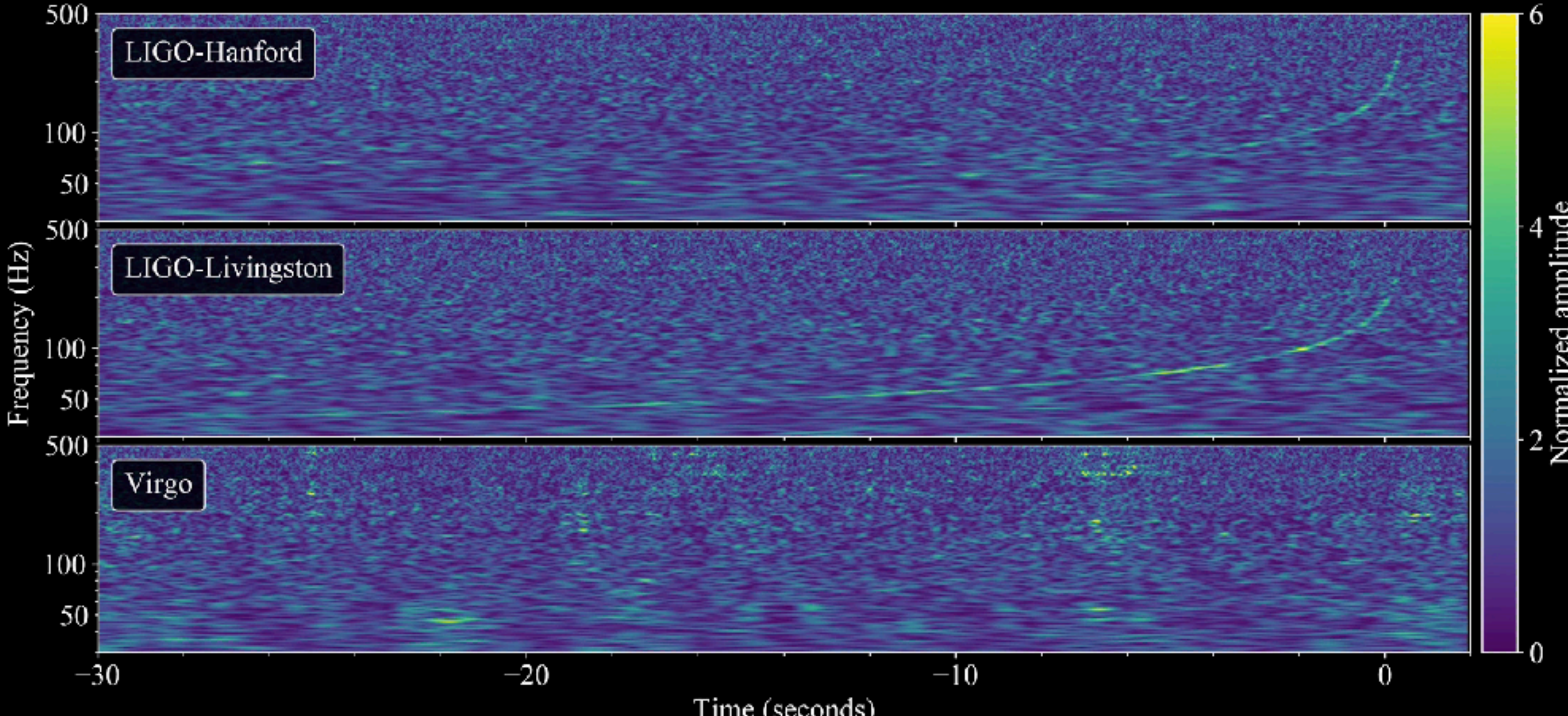
Neutron star merger summer school (FRIB)
May 16, 2018



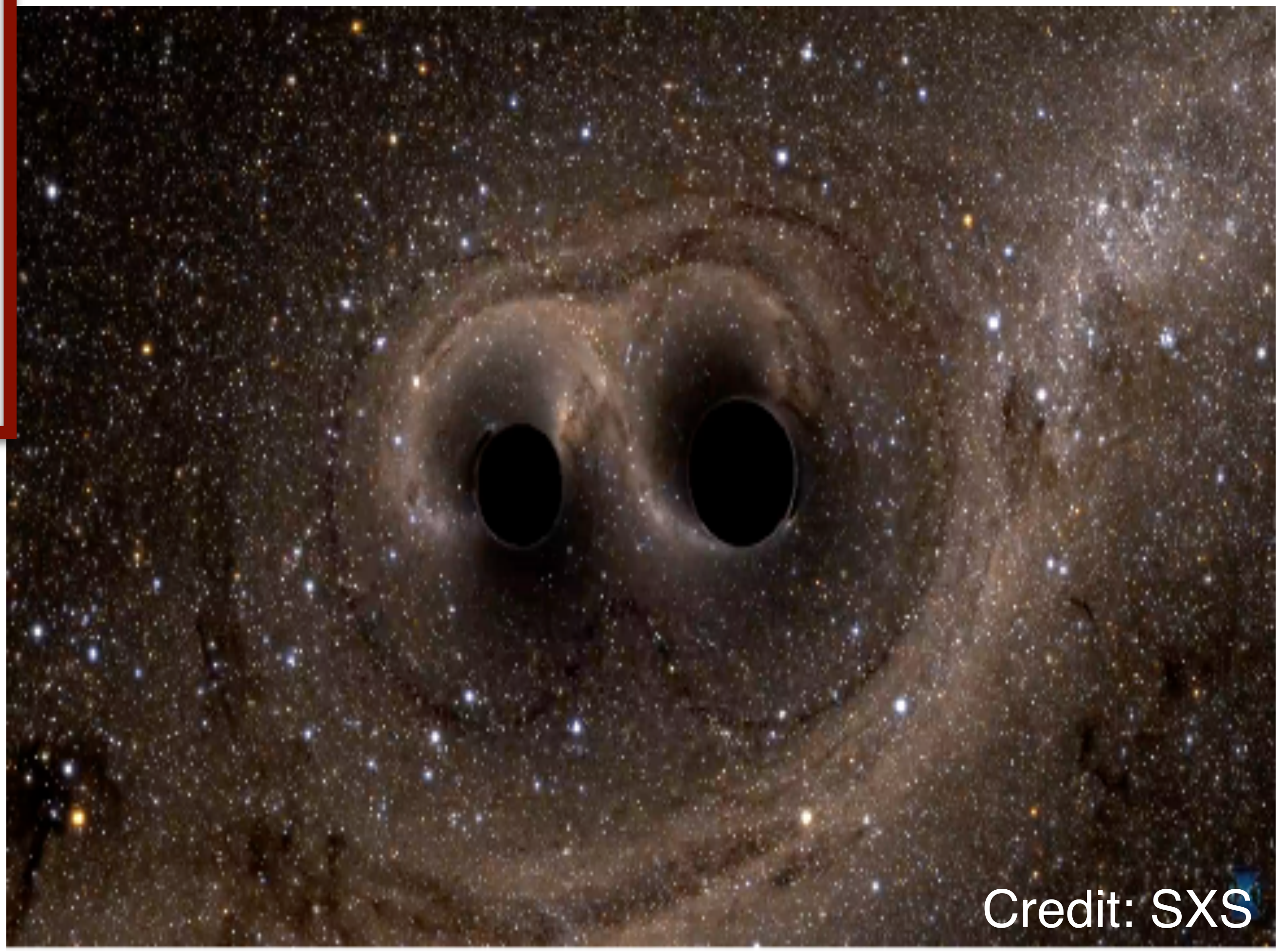
Credit: LIGO/Virgo/Lovelace, Brown, Macleod, McIver, Nitz

Gravitational waves

Definition: Wave-like perturbation of the gravitational field $\Box h_{\mu\nu} = T_{\mu\nu}$

Generation: Accelerating masses (changing quadrupole and higher multipole moments)

$$h_{ij} \sim \frac{1}{R}\frac{d^2 Q_{ij}}{dt^2}$$



Amplitude: Small

$$h \sim \frac{G}{c^4}\frac{mu^2}{R} \sim 10^{-22}$$

Luminosity: Large

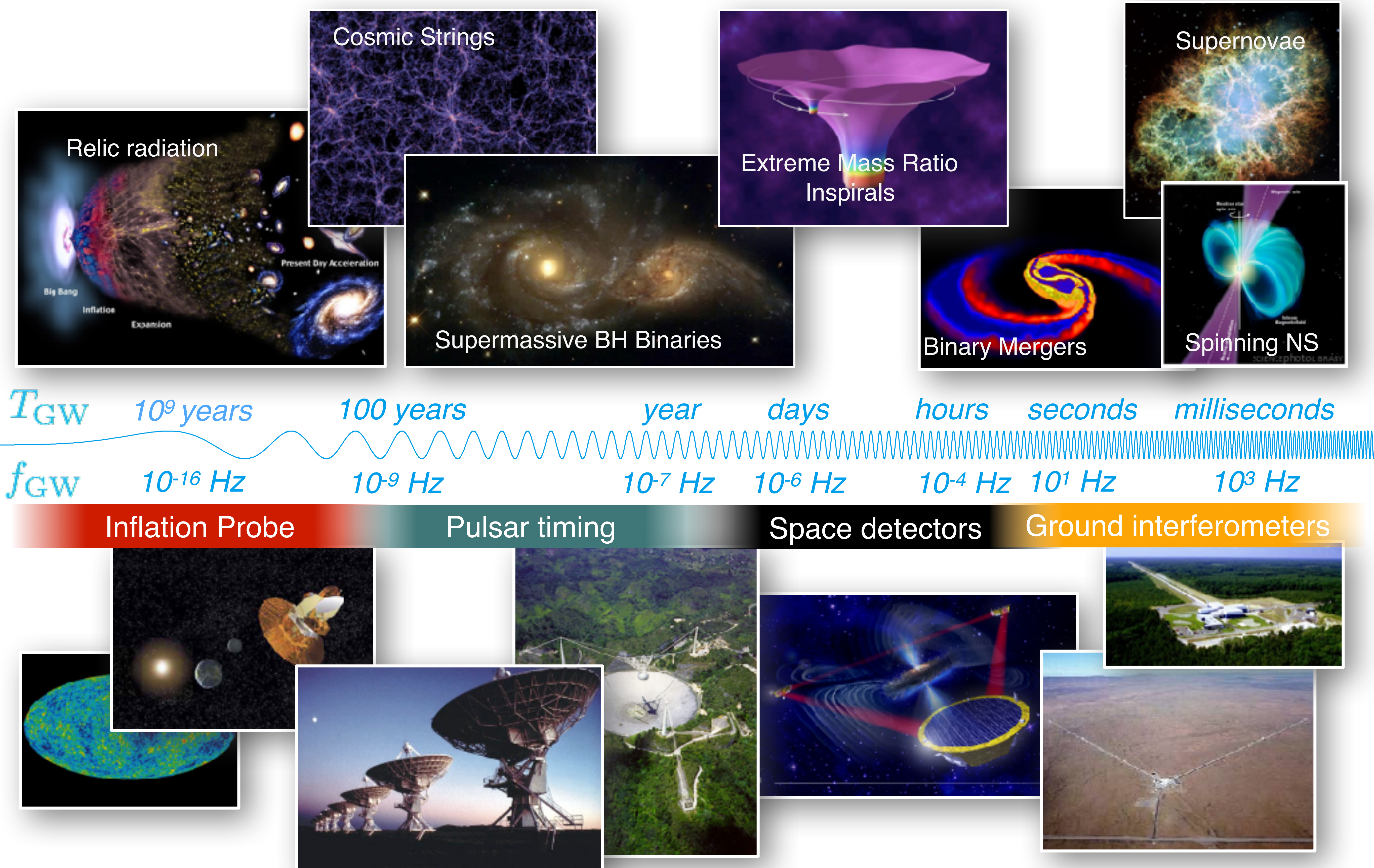
$$L \sim \frac{c^5}{G}\frac{u^{10}}{c^{10}}$$

Propagation: Light speed, weakly interacting

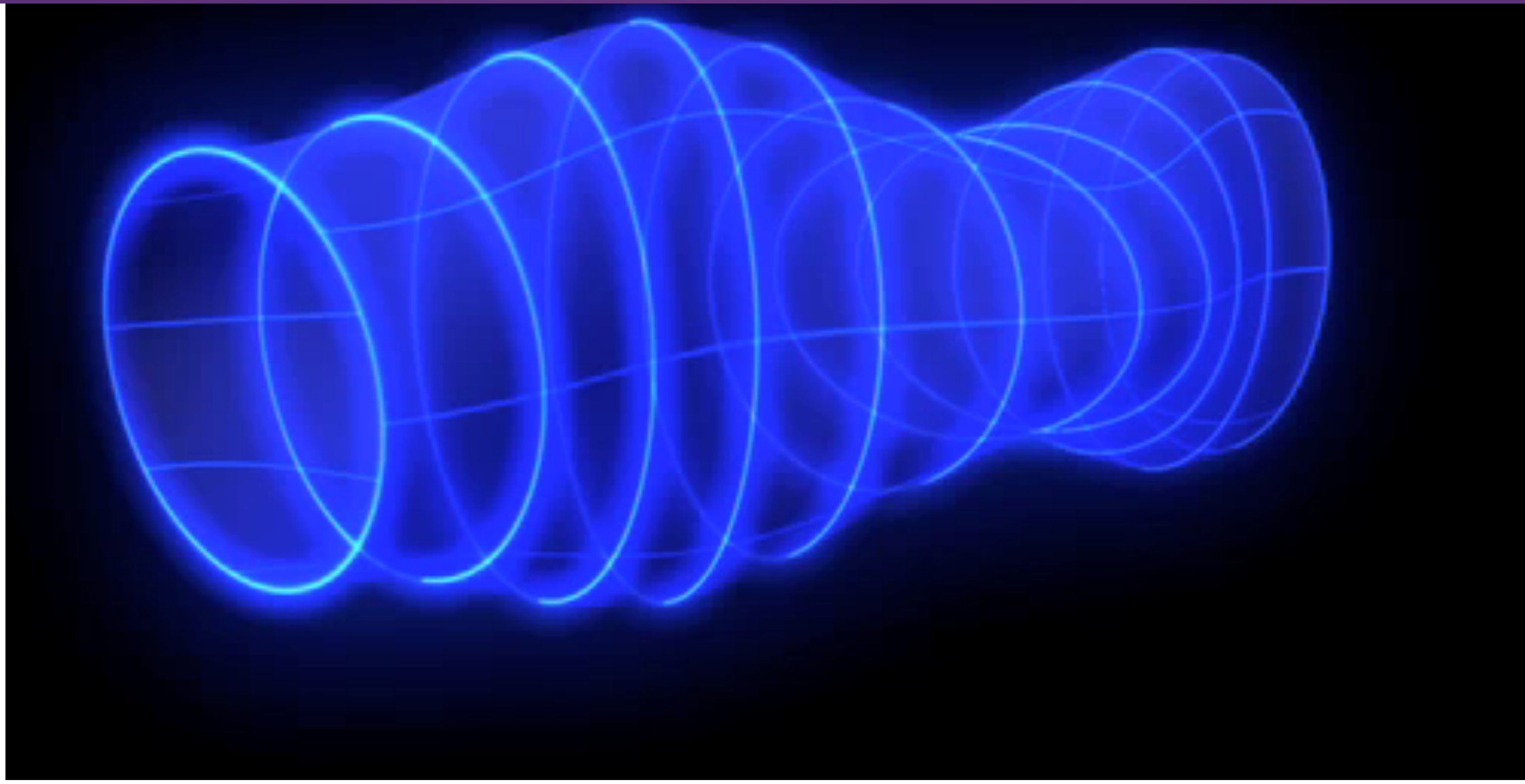
Spectrum: Kepler 3rd Law: $f \sim \sqrt{\frac{m}{r_{12}^3}} \sim \frac{1}{m}\,,\quad E_{rad} \sim \%m$

Example: for GW150914, $E_{\mathrm{GW}} \sim 3M_\odot$

The Gravitational Wave Spectrum



Three detectors (for now)

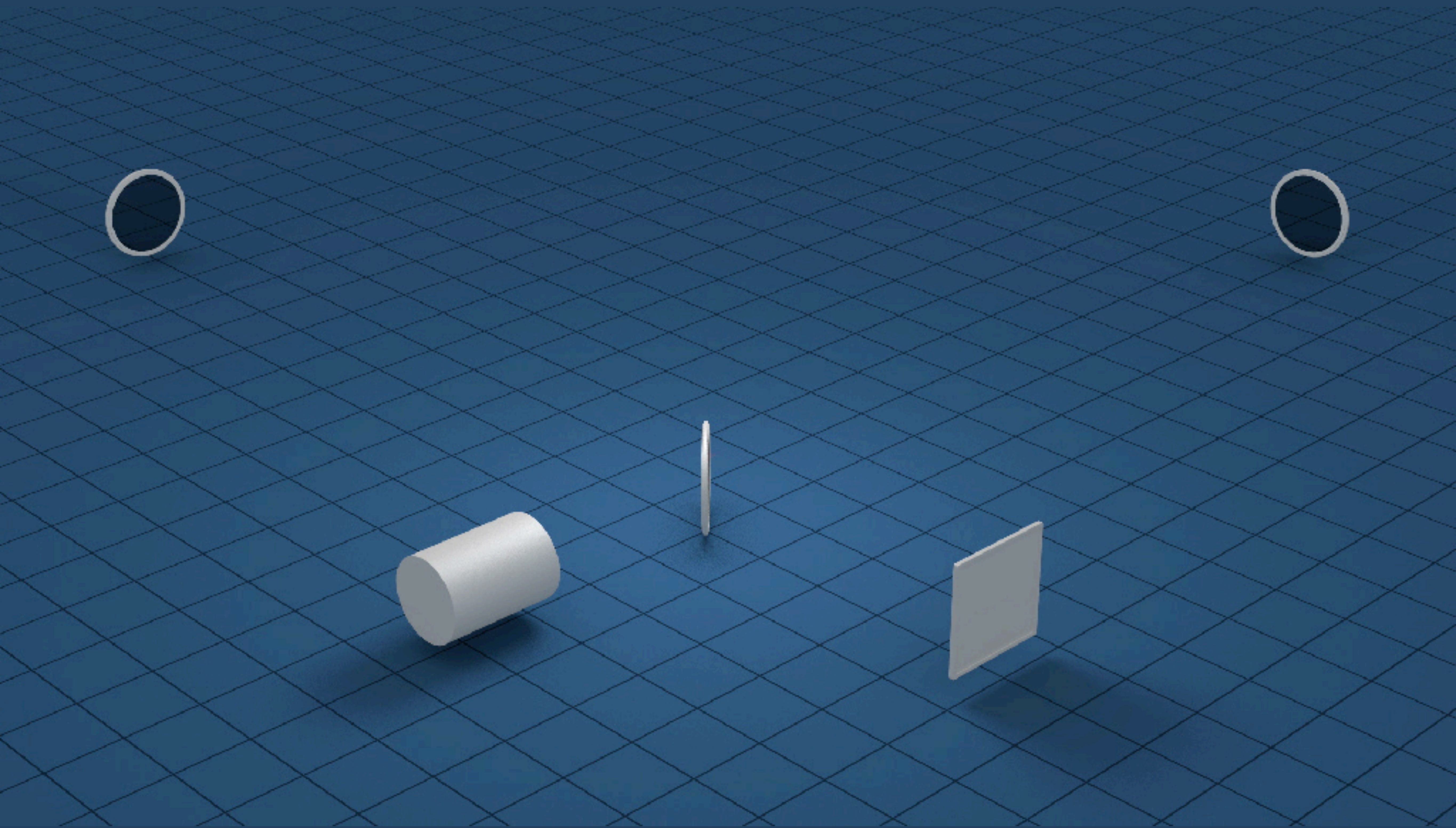


LIGO Hanford

LIGO Livingston

Virgo

LIGO (and similar interferometers)



Credit: LIGO/T. Pyle

Questions

- General relativity is a highly non-linear theory. Can you think of a non-linear effect?

- Why do changing monopole or dipole moments not radiate?

Gravitational waves and deformability of neutron stars

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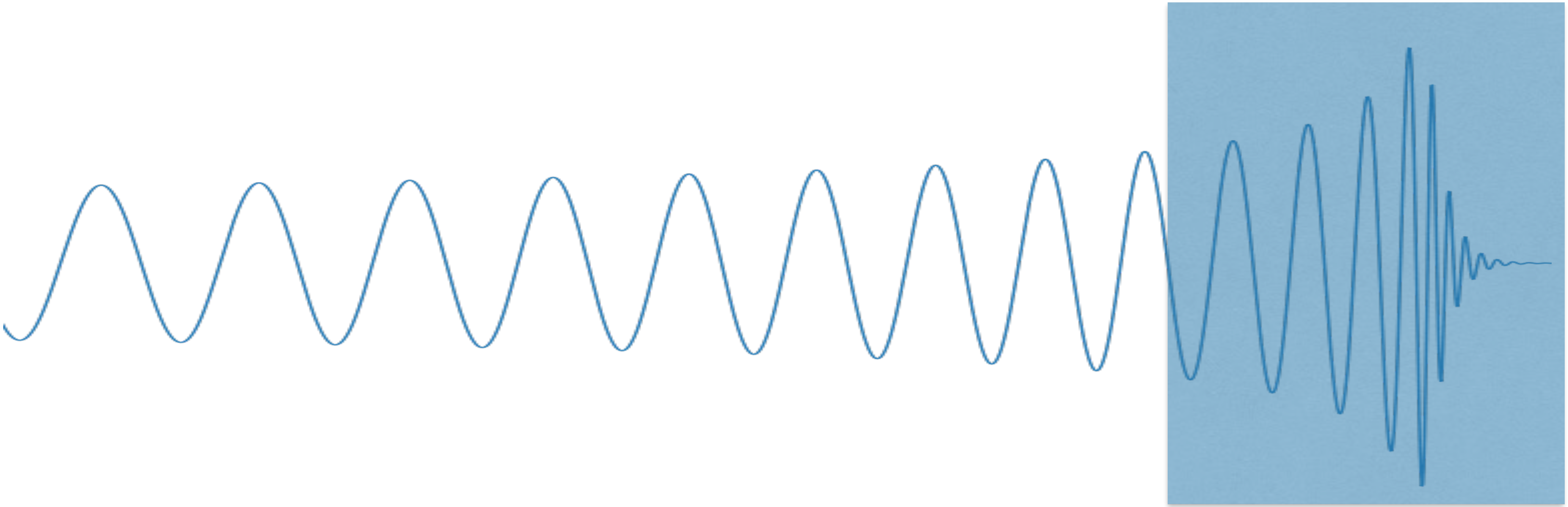
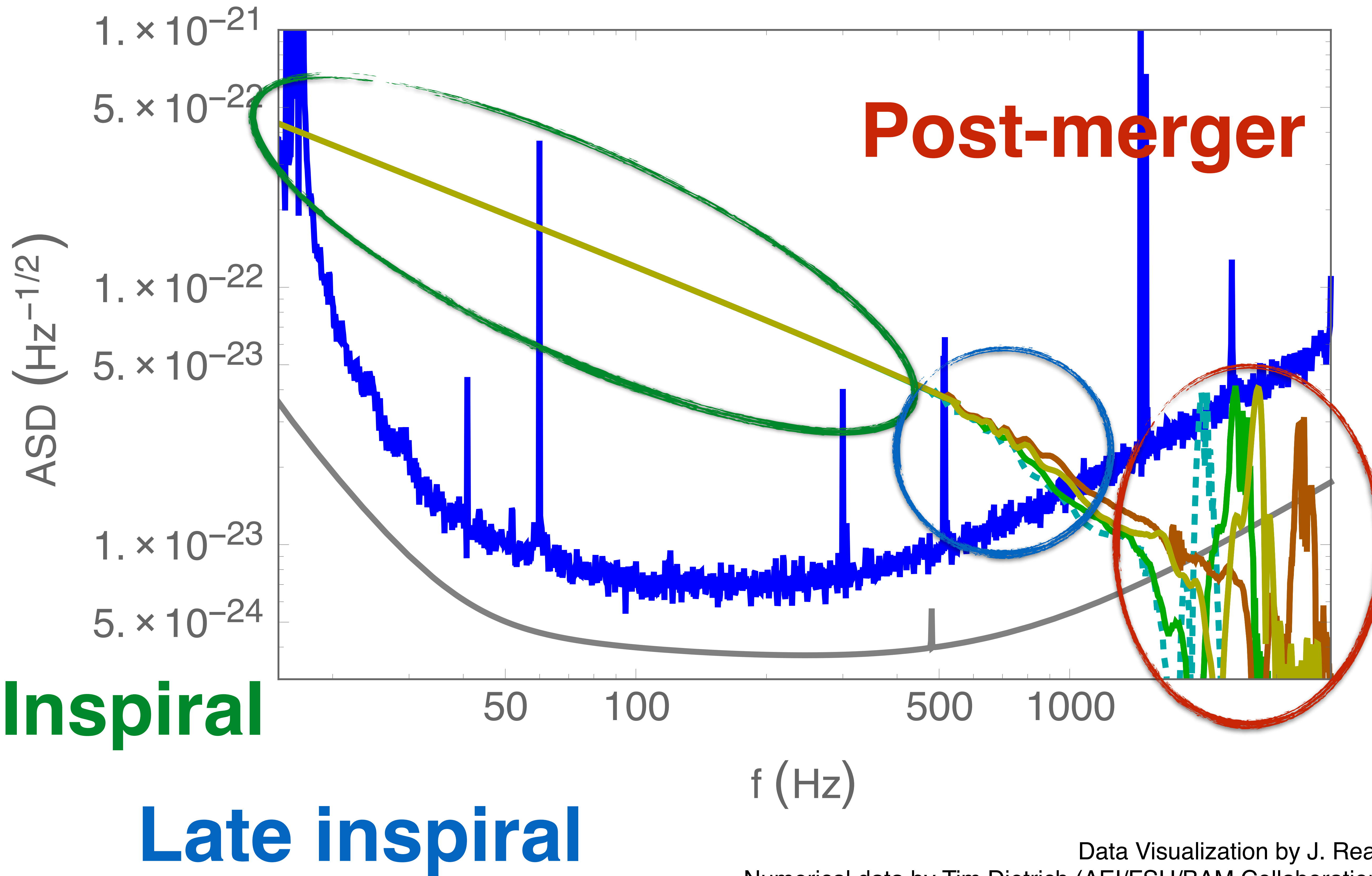
May 18, 2018

Gravitational waves



NS/NS:	(10 mins, 10,000 cycles)
BH/NS:	[(3-7) mins, (1,000-5,000) cycles]
BH/BH:	[secs, (10-700) cycles]

Anatomy of a BNS coalescence



Data Visualization by J. Read
Numerical data by Tim Dietrich (AEI/FSU/BAM Collaboration)
Phys. Rev. D95(12):124006 and Phys. Rev. D95(2):024029

Waveform phase

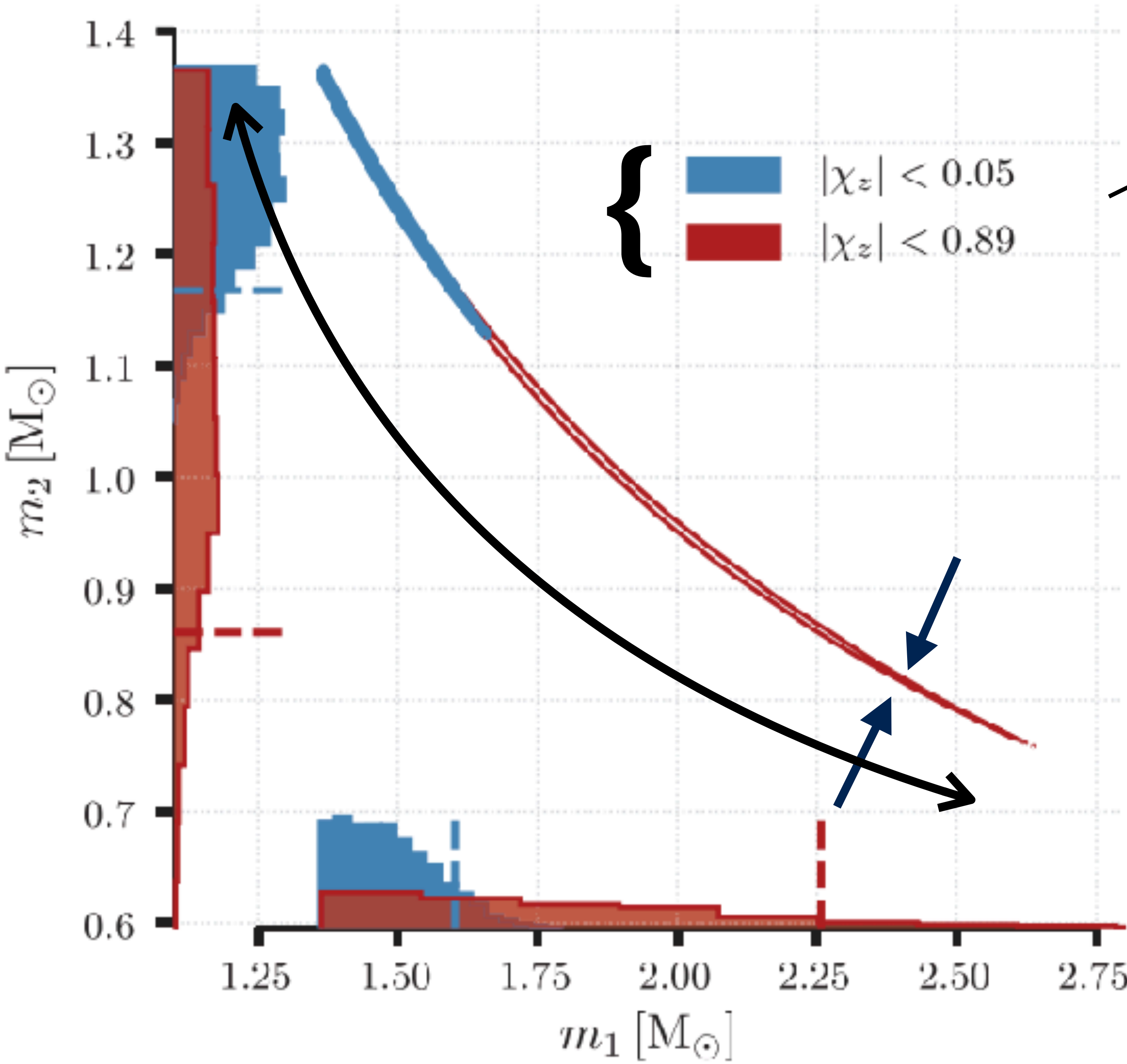
measure less well

mass and spin enter together

$$\Psi(u) \sim a_0(\mathcal{M})u^{-5}\left[1 + a_2(\eta)u^2 + a_3(\eta, \vec{S}_i)u^3 \right.$$
$$\left. + \qquad \cdots \right]$$

measure VERY well

GW170817 masses



$$\chi \sim 0.4 \frac{1\text{ms}}{T}$$

The chirp mass is measured very well

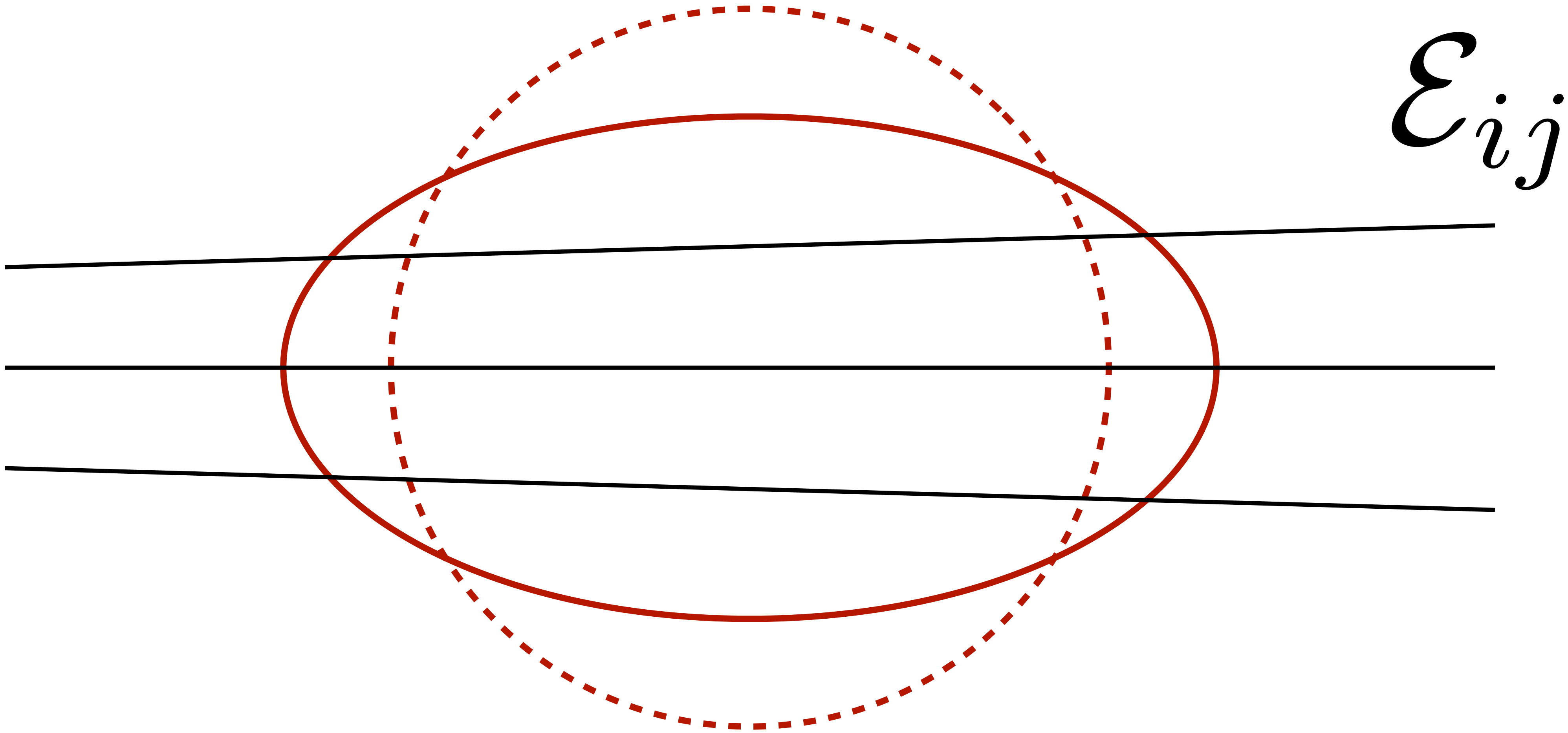
The mass ratio is measured less well

The mass ratio is correlated with the spin

LVC PRL 119, 161101 (2017)

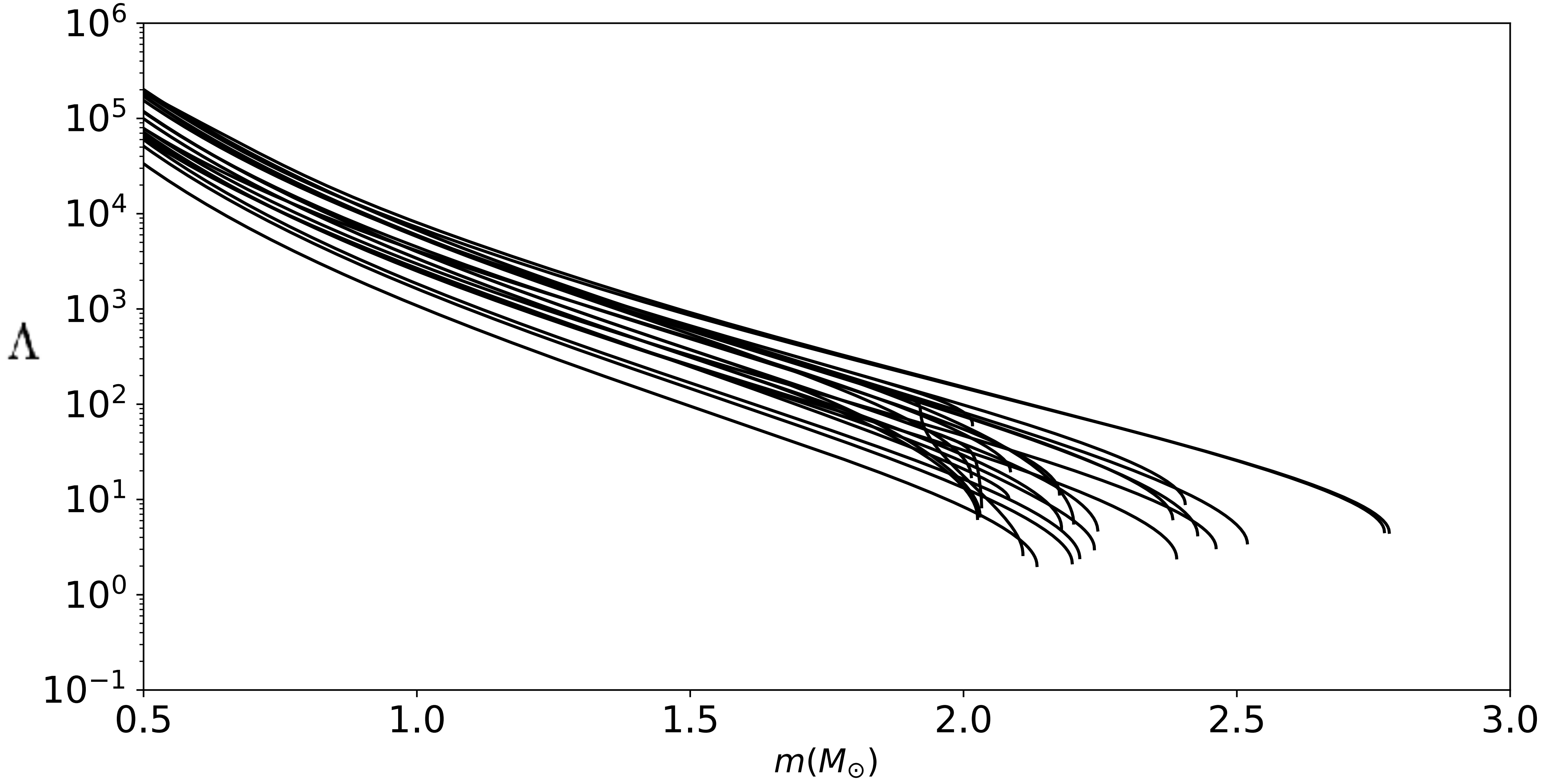
Late inspiral

Neutron stars are extended bodies with structure



$$Q_{ij} = -\Lambda \mathcal{E}_{ij}$$

Tidal Deformability



Waveform phase

measure
less well

mass and spin
enter together

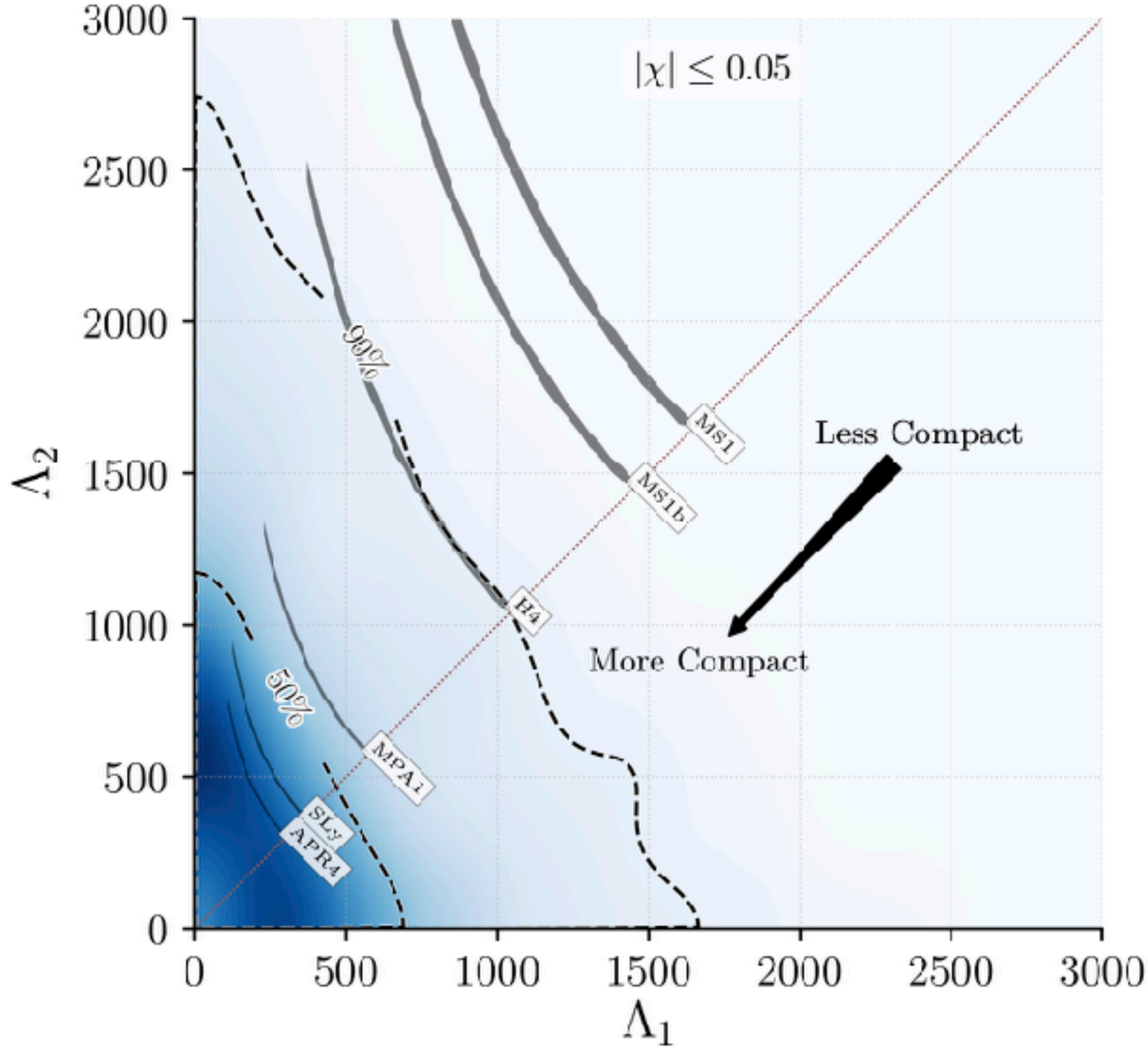
$$\Psi(u) \sim a_0(\mathcal{M})u^{-5}\Big[1 + a_2(\eta)u^2 + a_3(\eta, \vec{S}_i)u^3$$

$$+a_4(\eta, S_i^2, Q_i)u^4 + \ldots + a_{10}(\Lambda)u^{10} + \ldots\Big]$$

measure
VERY well

information
about the EoS

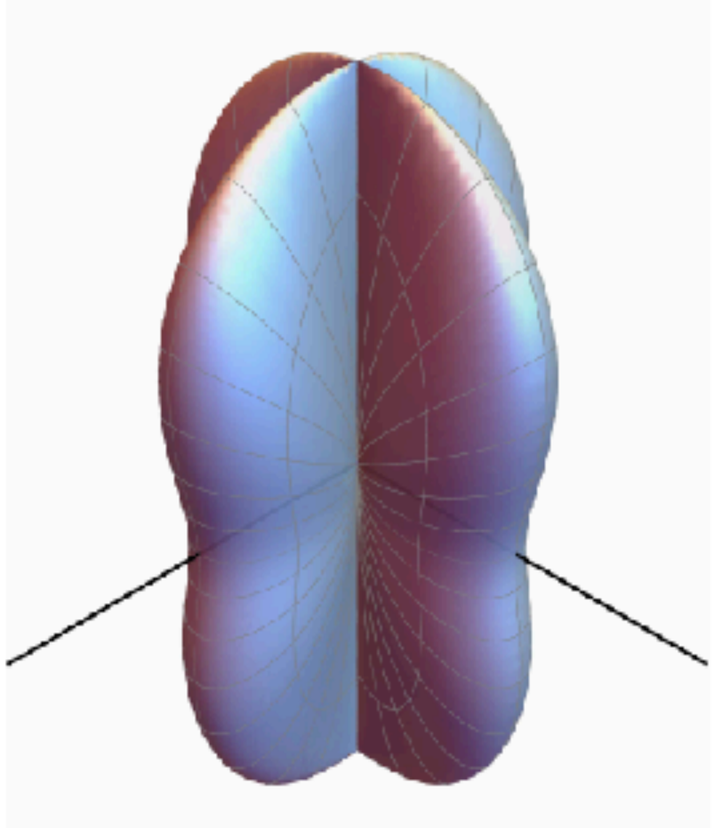
GW170817 deformability



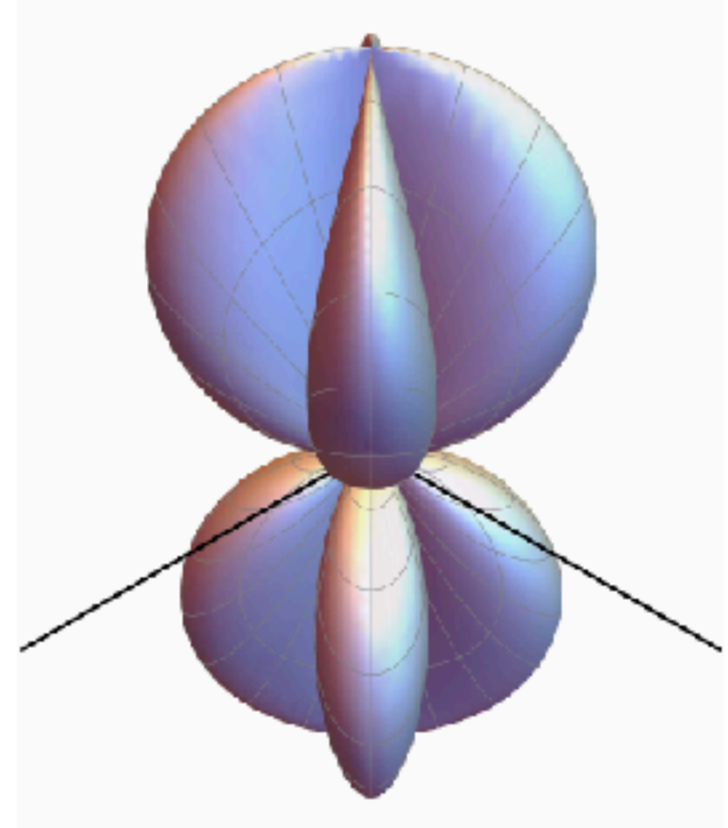
The tidal deformation accelerates the inspiral (additional energy sinks)

LVC PRL 119, 161101 (2017)

Sky response

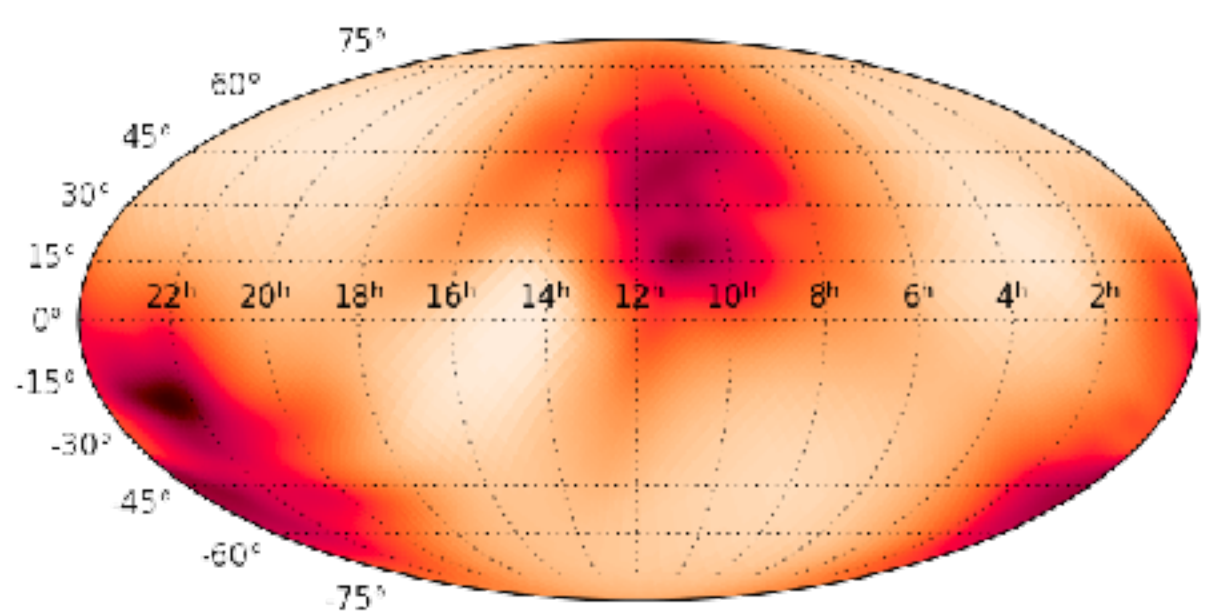


(a) Plus (+)

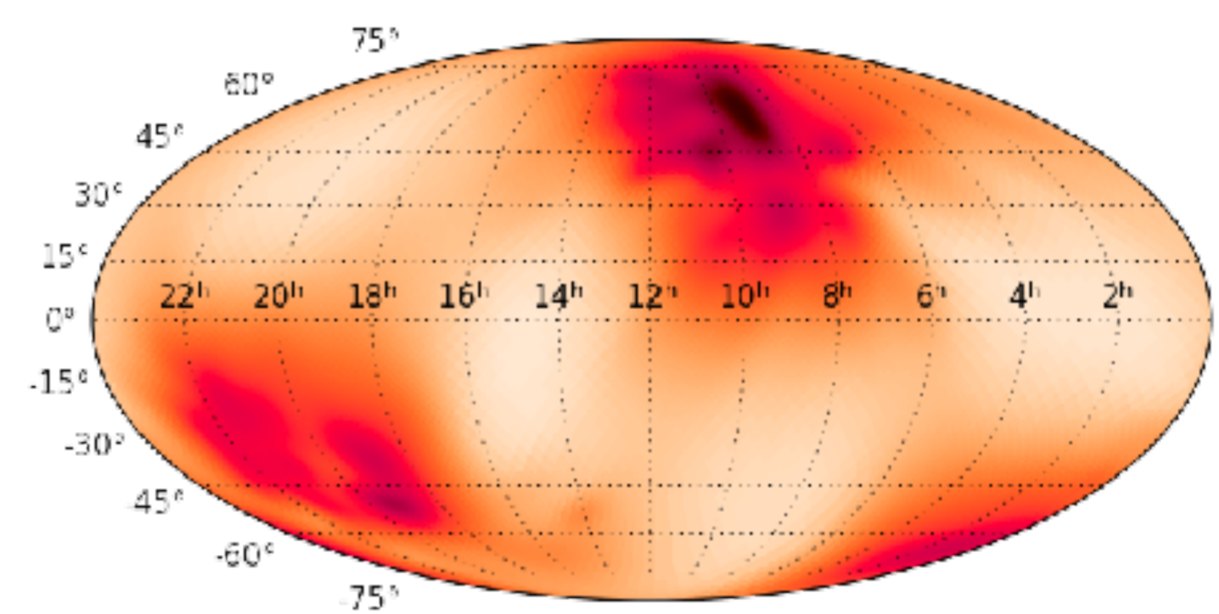


(b) Cross (×)

Livingston

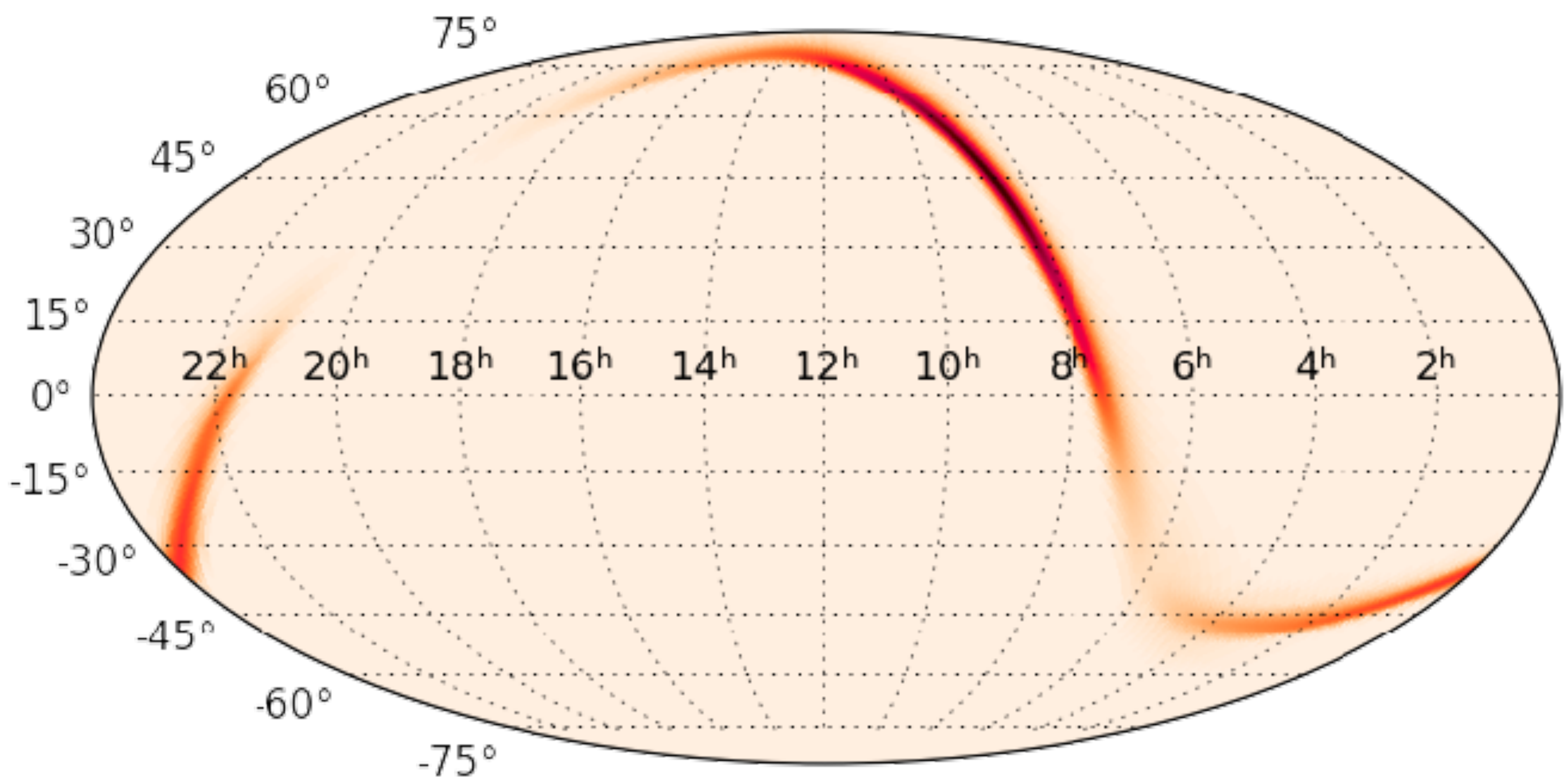


Hanford



Triangulation

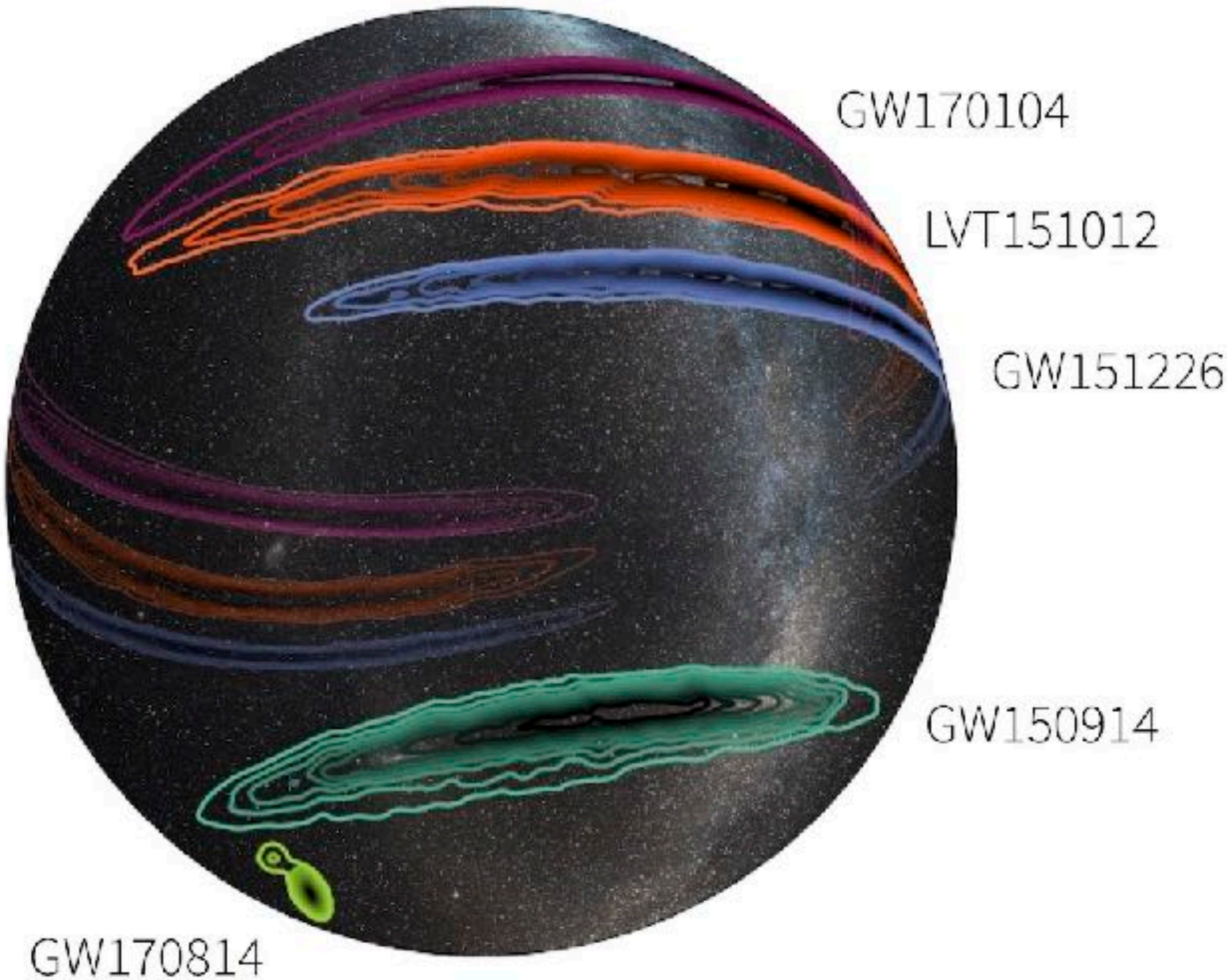
Why is it not a full ring?



Where should we put the next detector to optimize localization?

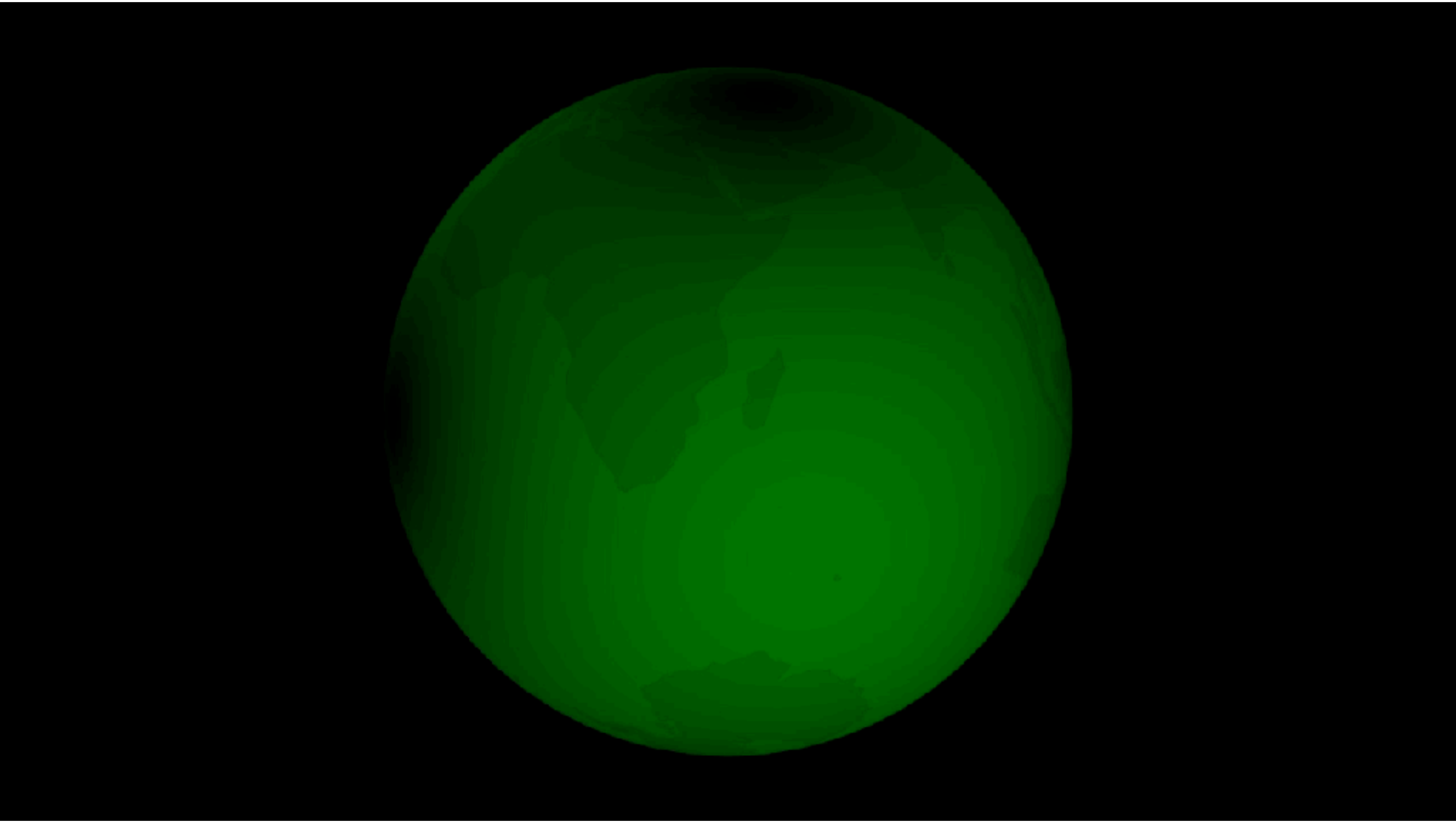
More detectors

Which event was seen by more detectors than the others?



Credit: LIGO/Virgo/Singer

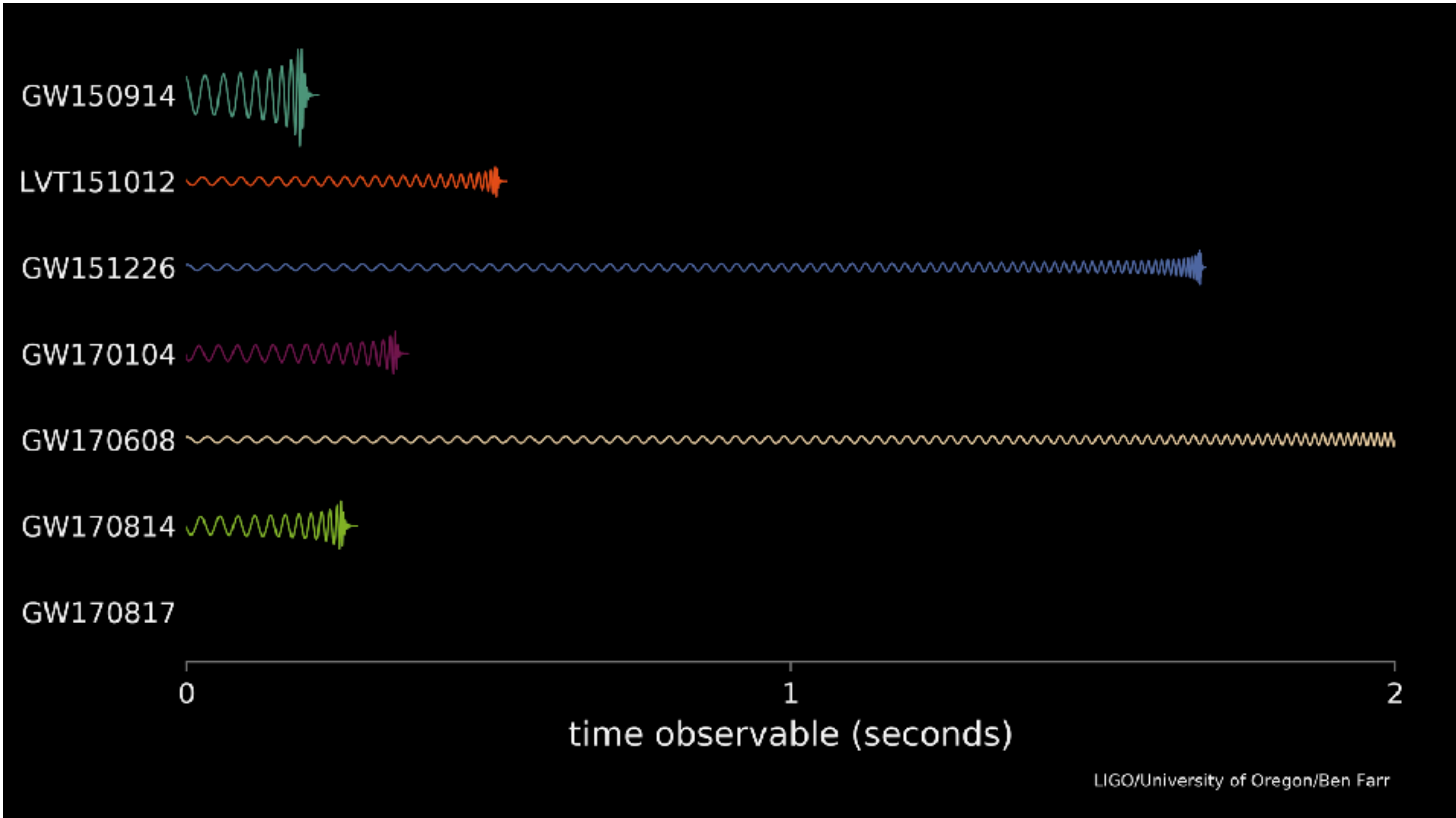
Sky response



Credit: LIGO/Virgo/Singer

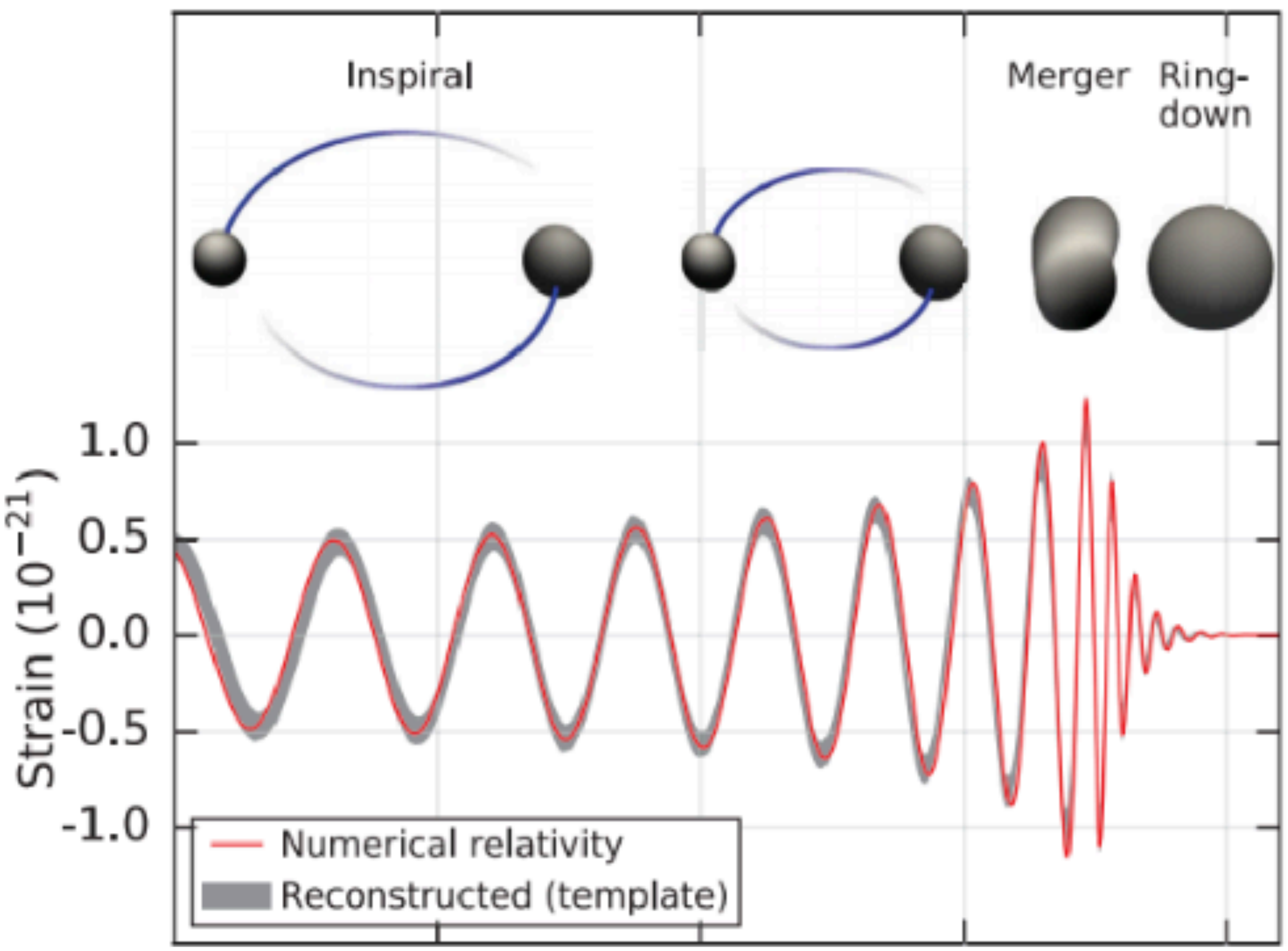
Telling NSs and BHs apart

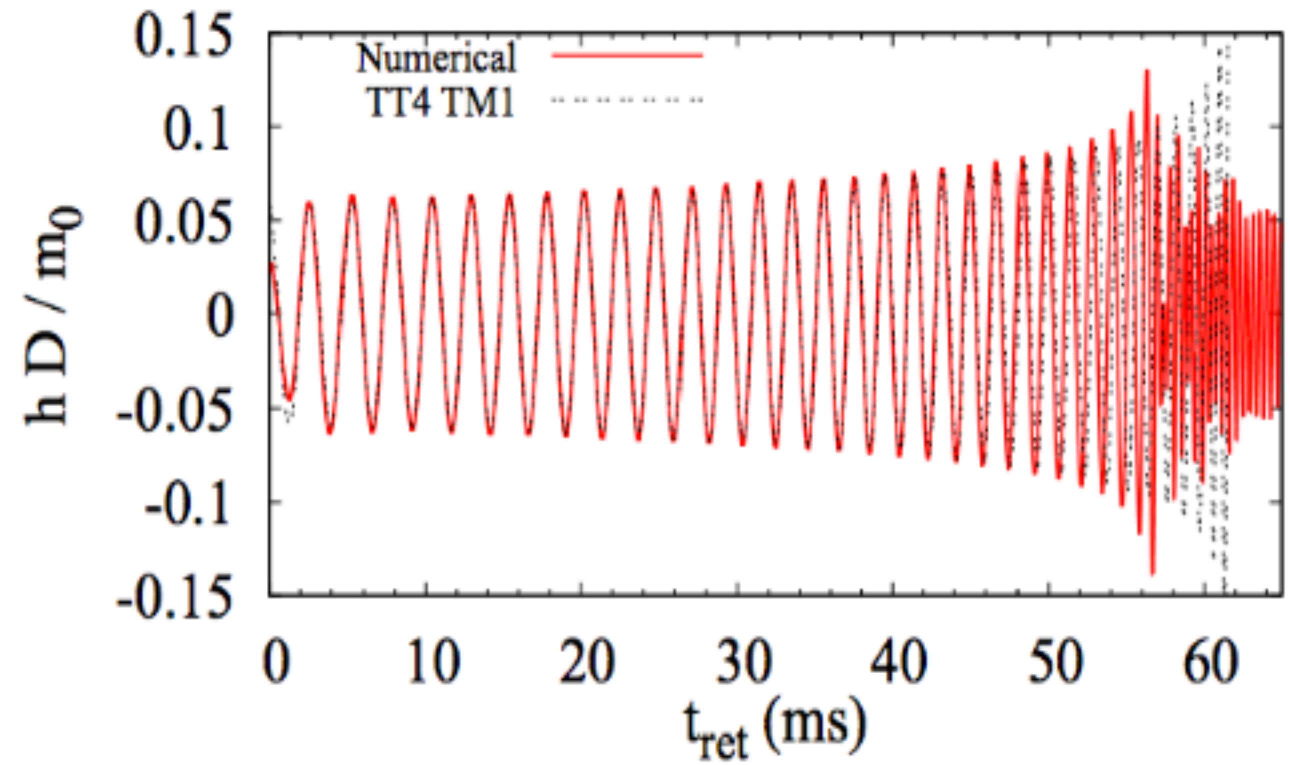
1. Mass/duration



Telling NSs and BHs apart

2. Tidal effects

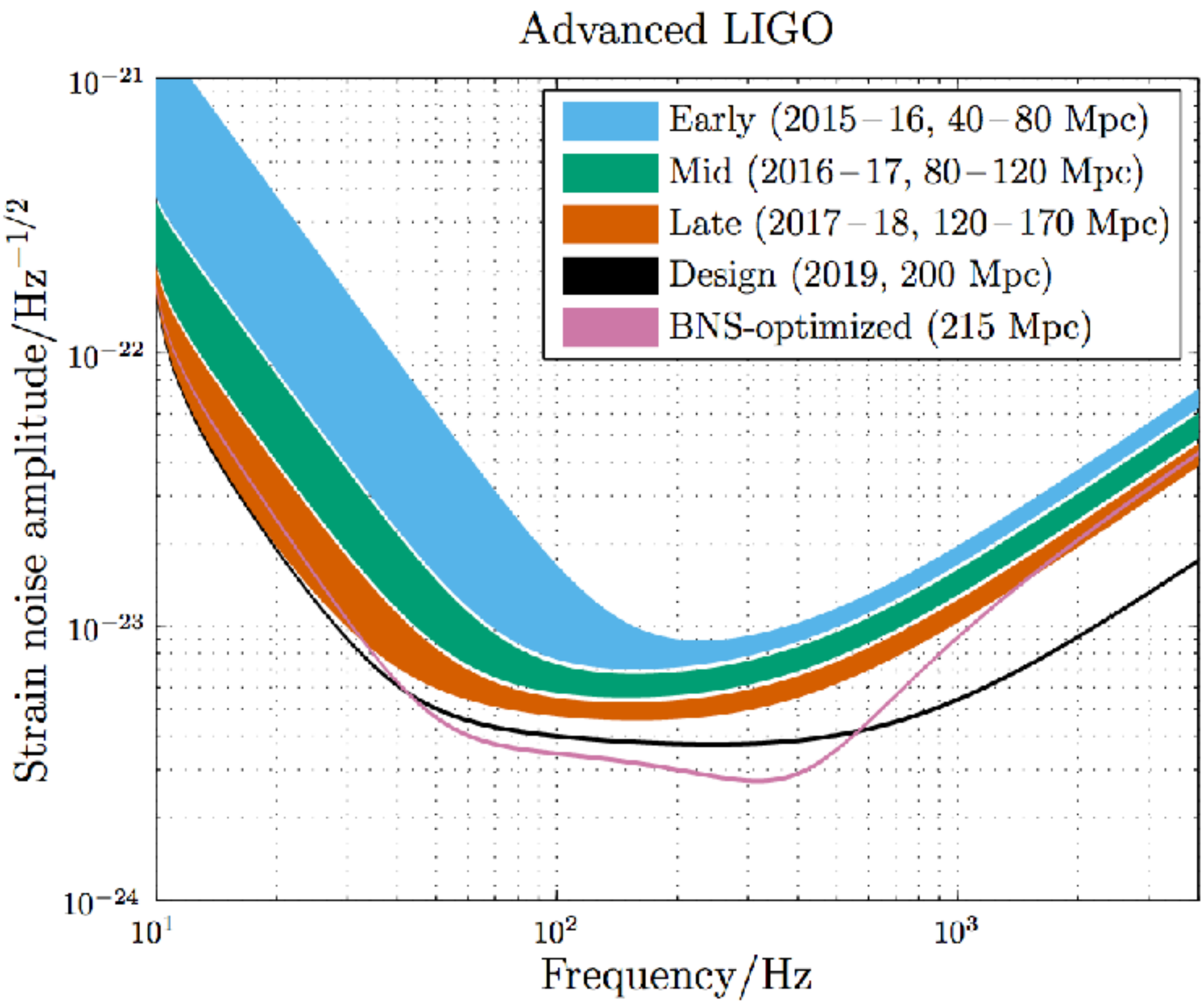




LVC PRL 116, 061102 (2016)

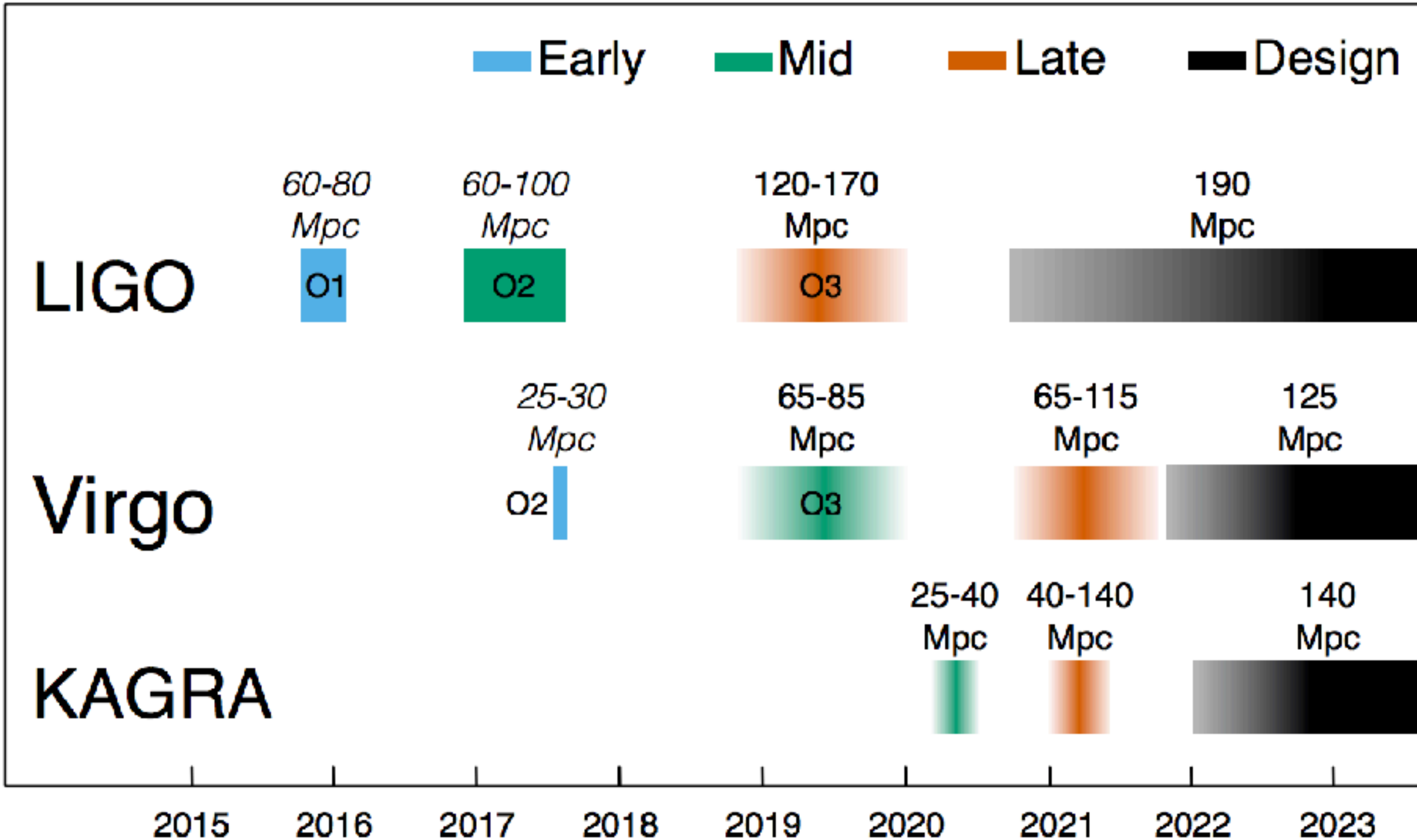
Hotokezaka+ (arxiv:1105.4370)

Looking ahead



LVC LRR 19 (2016) 1

Looking ahead



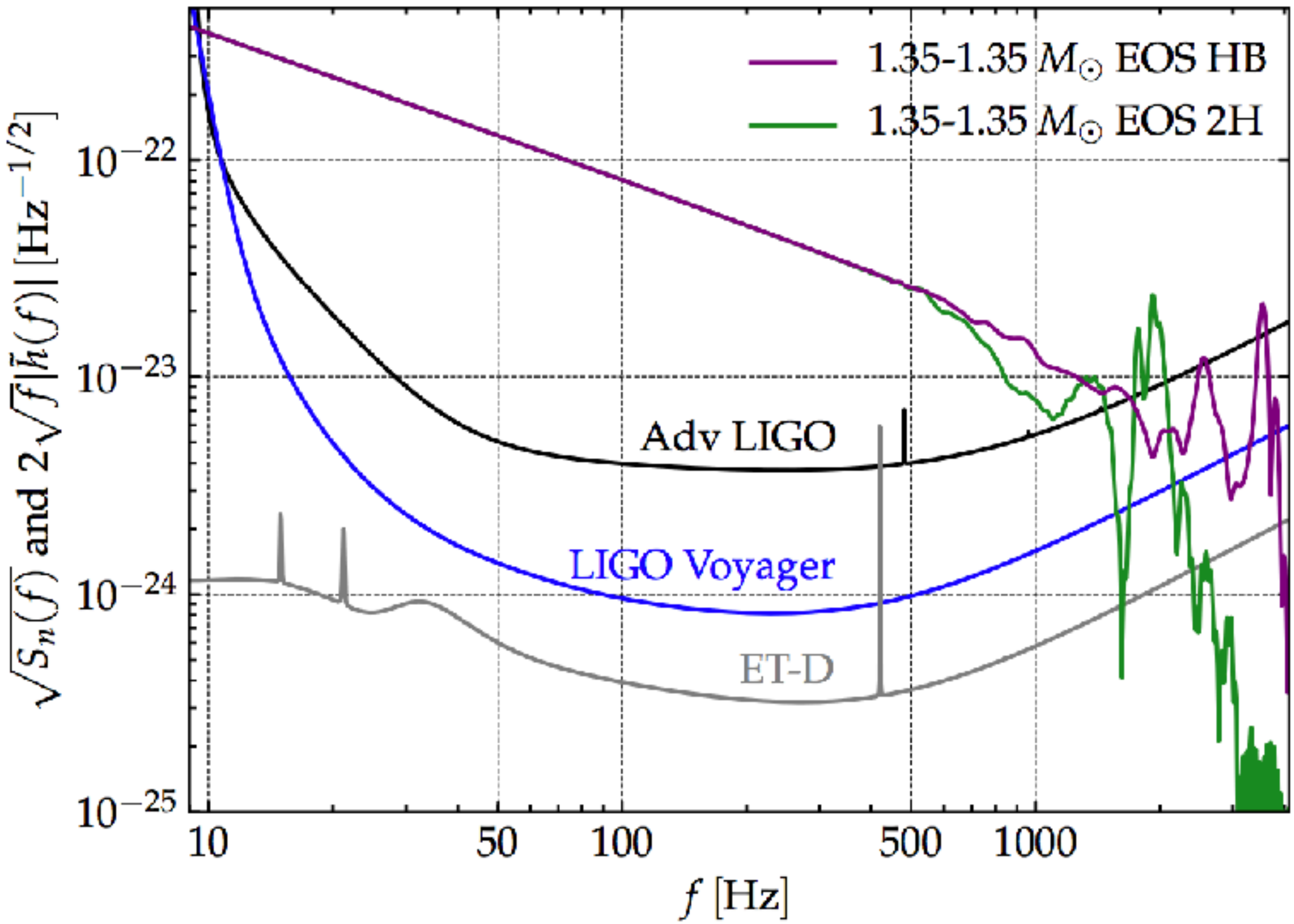
LVC LRR 19 (2016) 1

Looking ahead

Epoch			2015 – 2016	2016 – 2017	2018 – 2019	2020+	2024+
Planned run duration			4 months	9 months	12 months	(per year)	(per year)
Expected BNS range/Mpc		LIGO	40 – 80	80 – 120	120 – 170	190	190
		Virgo	—	20 – 65	65 – 85	65 – 115	125
		KAGRA	—	—	—	—	140
Achieved BNS range/Mpc		LIGO	60 – 80	60 – 100	—	—	—
		Virgo	—	25 – 30	—	—	—
		KAGRA	—	—	—	—	—
Estimated BNS detections			0.05 – 1	0.2 – 4.5	1 – 50	4 – 80	11 – 180
Actual BNS detections			0	1	—	—	—
90% CR	% within	5 deg^2	< 1	1 – 5	1 – 4	3 – 7	23 – 30
		20 deg^2	< 1	7 – 14	12 – 21	14 – 22	65 – 73
	Median/deg^2		460 – 530	230 – 320	120 – 180	110 – 180	9 – 12
Searched area	% within	5 deg^2	4 – 6	15 – 21	20 – 26	23 – 29	62 – 67
		20 deg^2	14 – 17	33 – 41	42 – 50	44 – 52	87 – 90

LVC LRR 19 (2016) 1

Even further ahead



Adhikari+ (in preparation), LSC