UNIVERSITY OF BIRMINGHAM

Gravitational-wave astronomy & black hole astrophysics

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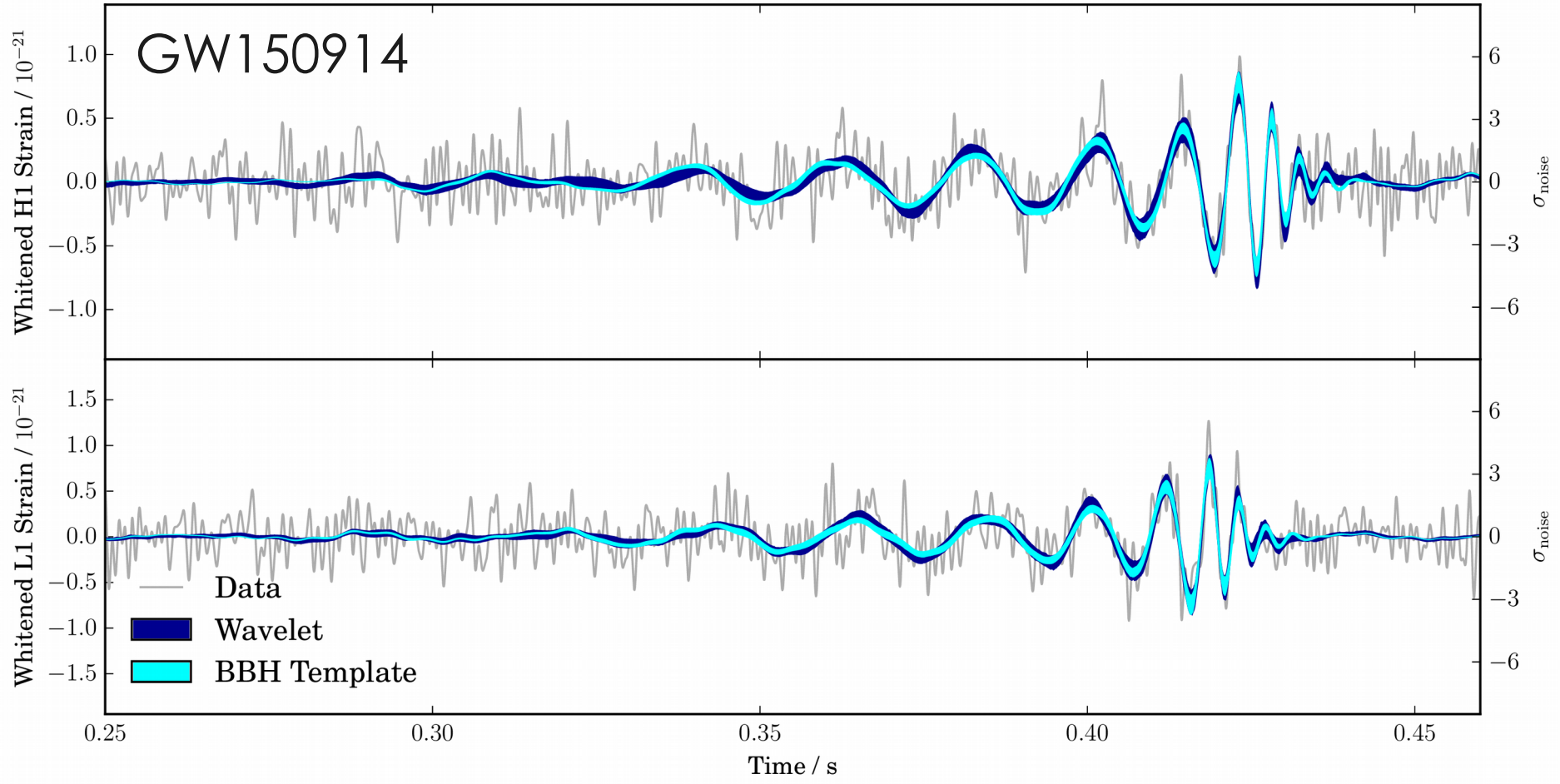
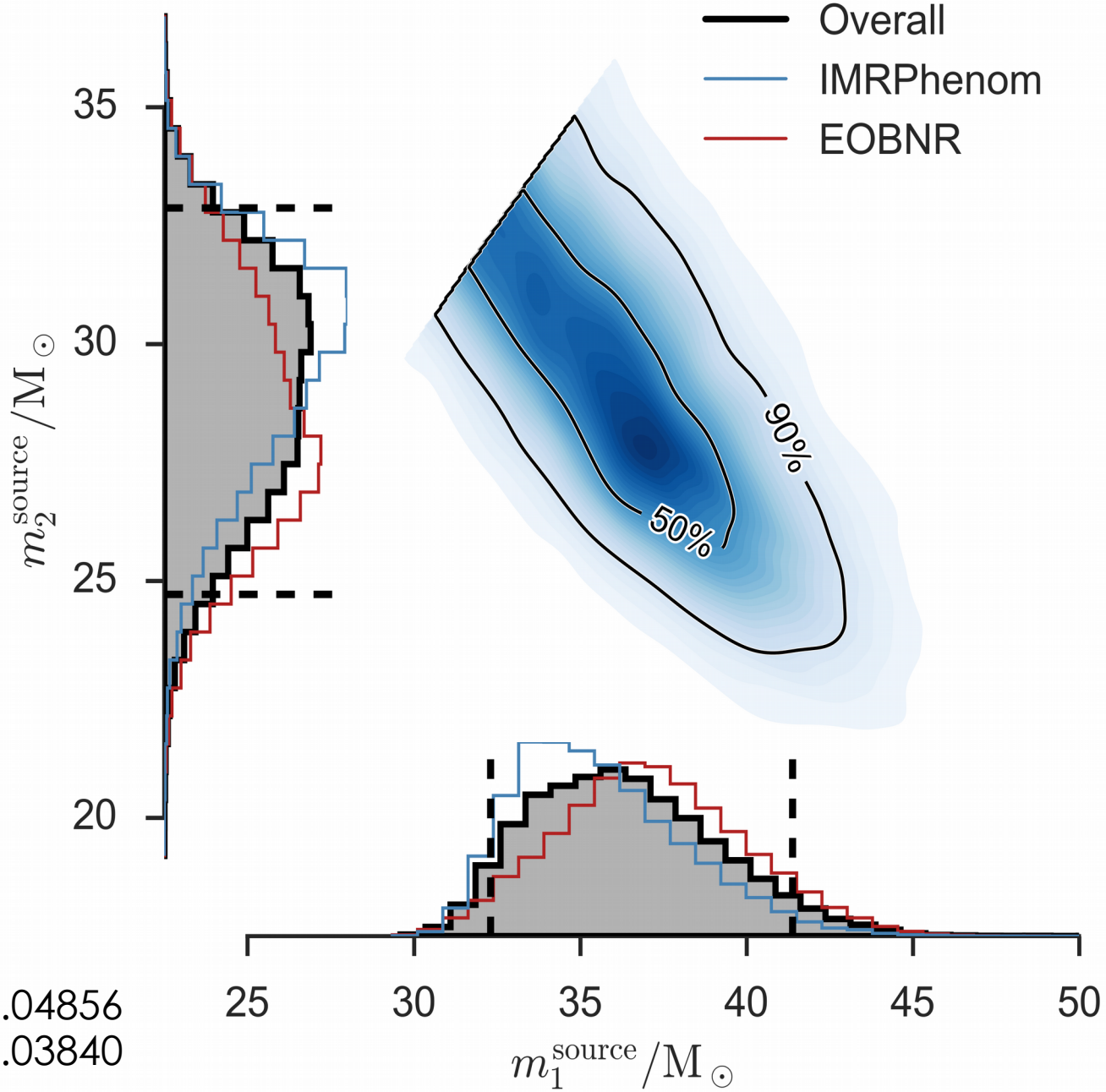
On behalf of the
LIGO Scientific & Virgo Collaborations

DCC G1800621
IOP APP & HEPP 2018



LVC arXiv:1602.03840



LVC
arXiv:1606.04856
arXiv:1602.03840

How to infer source properties

Our measurements so far

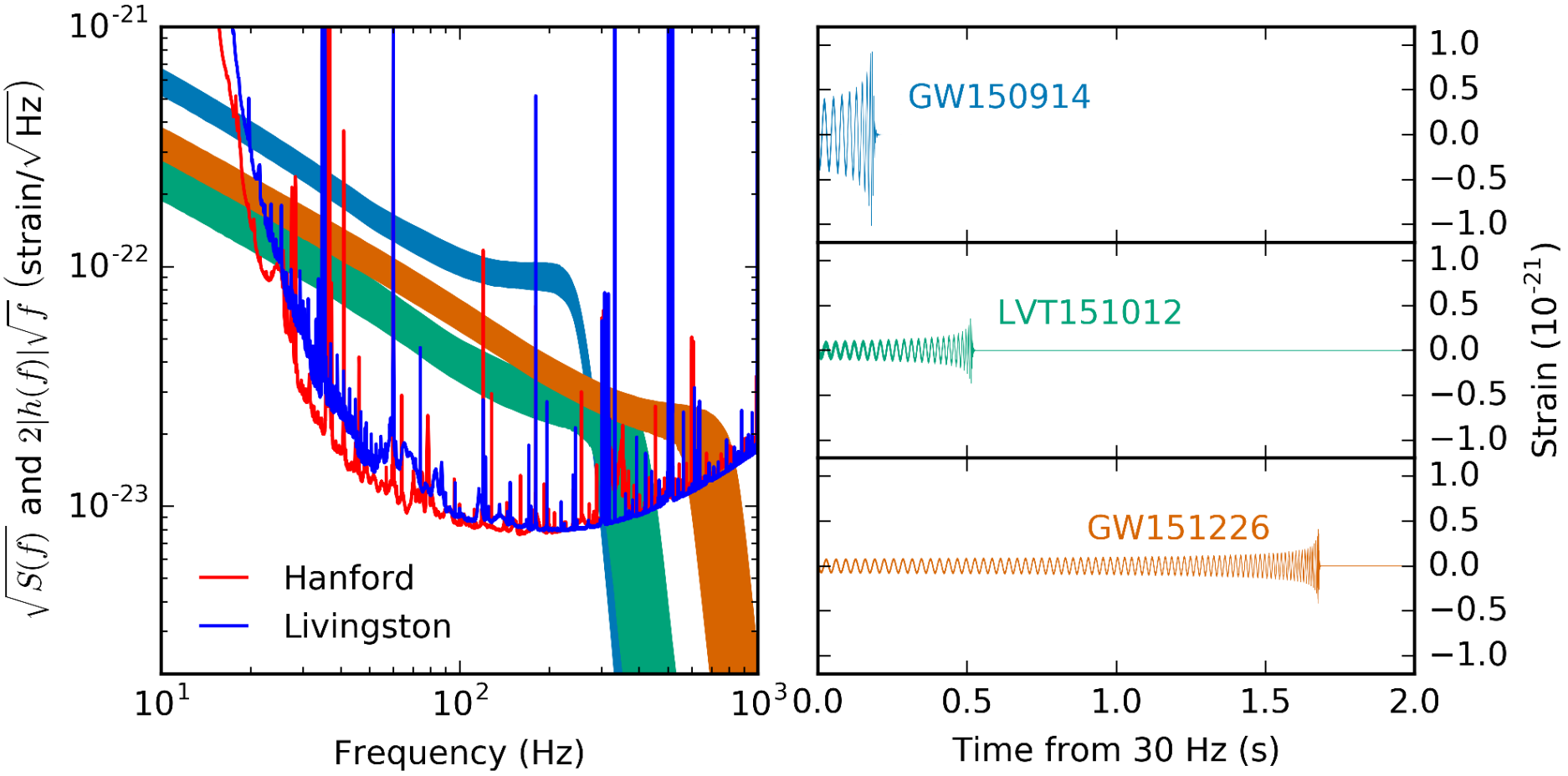
How we can use gravitational-wave observations

How to infer source properties

Our measurements so far

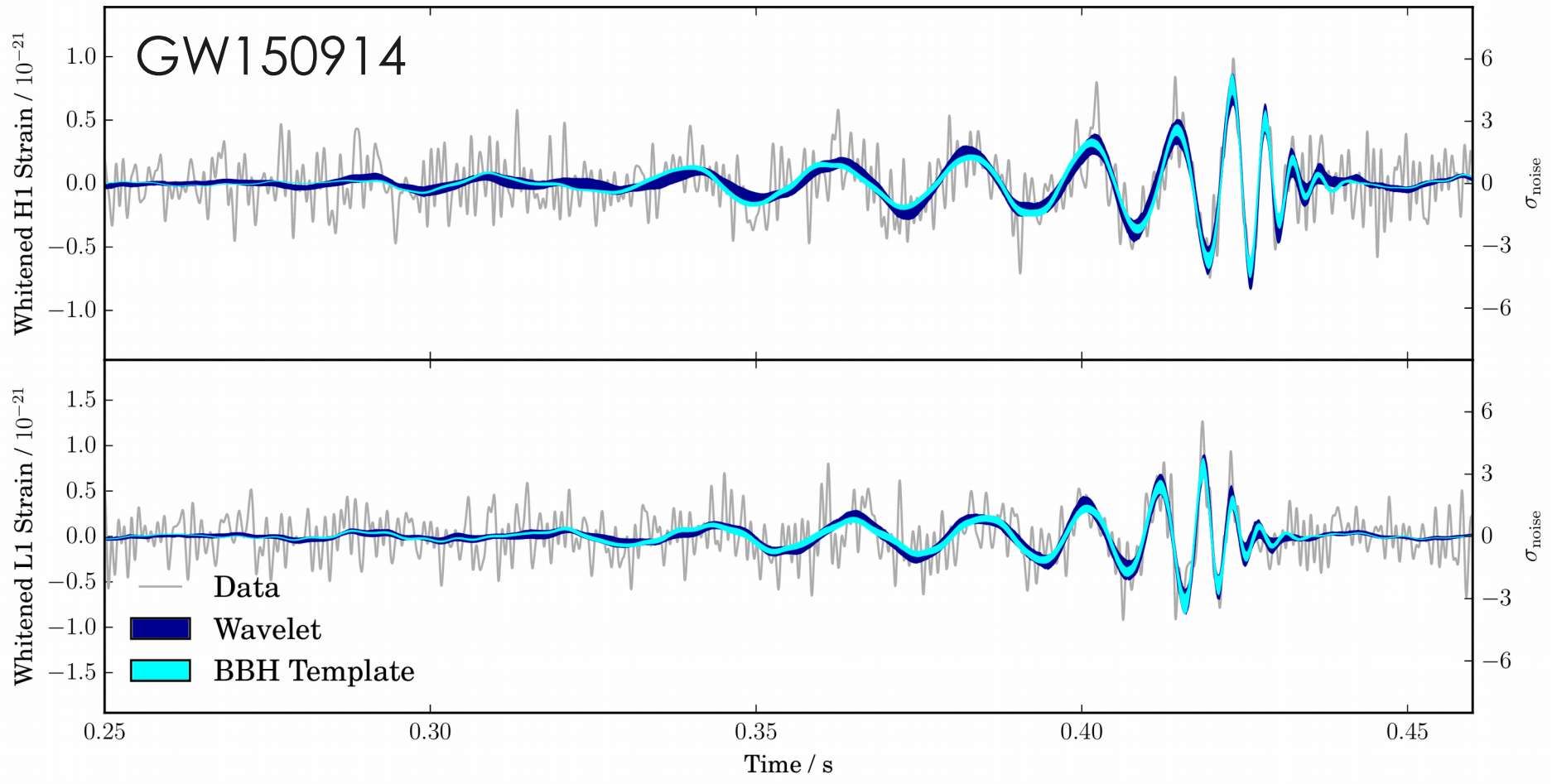
How we can use gravitational-wave observations

Measurement



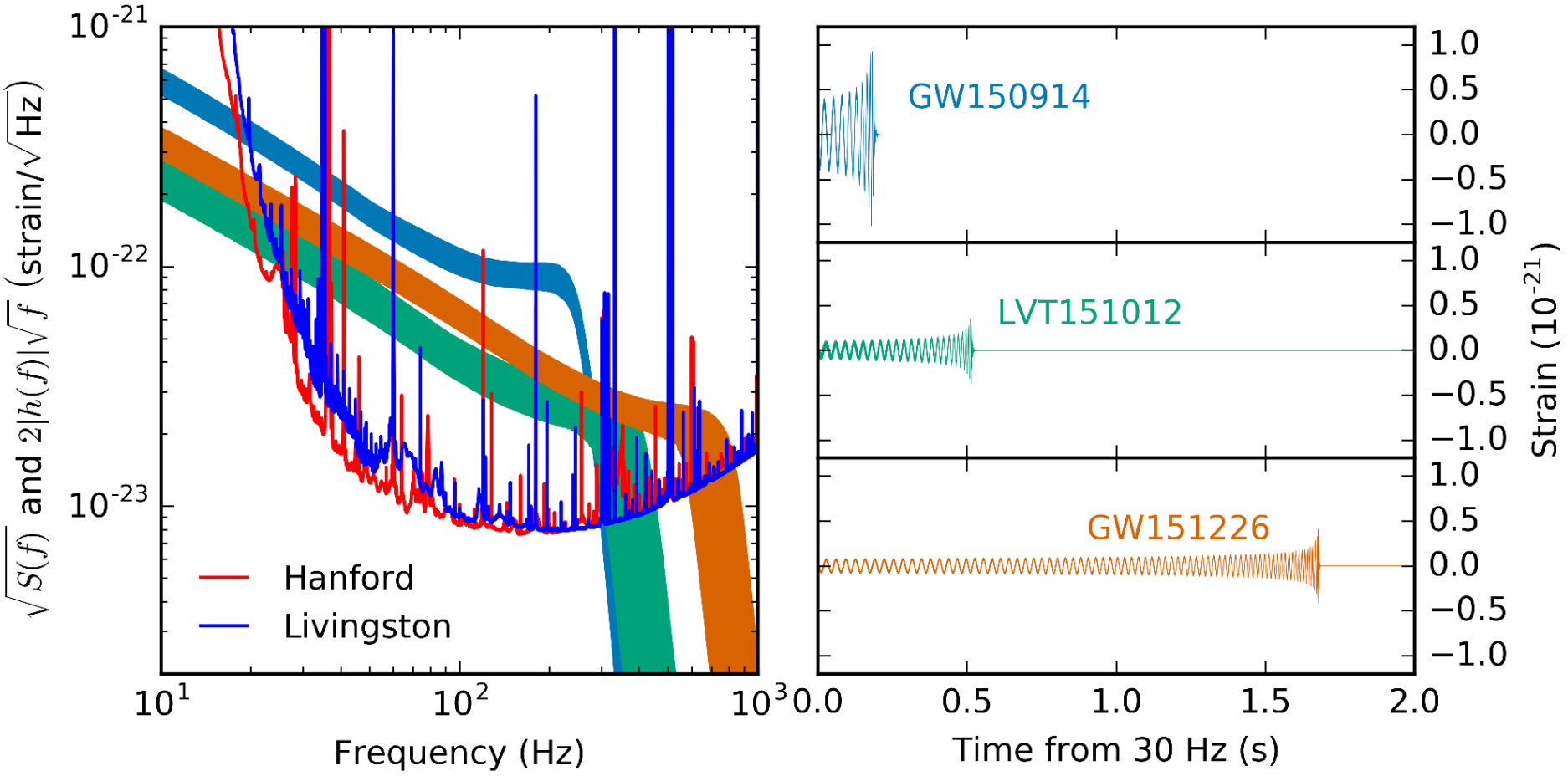
LVC arXiv:1606.04856

Waveform



LVC arXiv:1602.03840

Measurement



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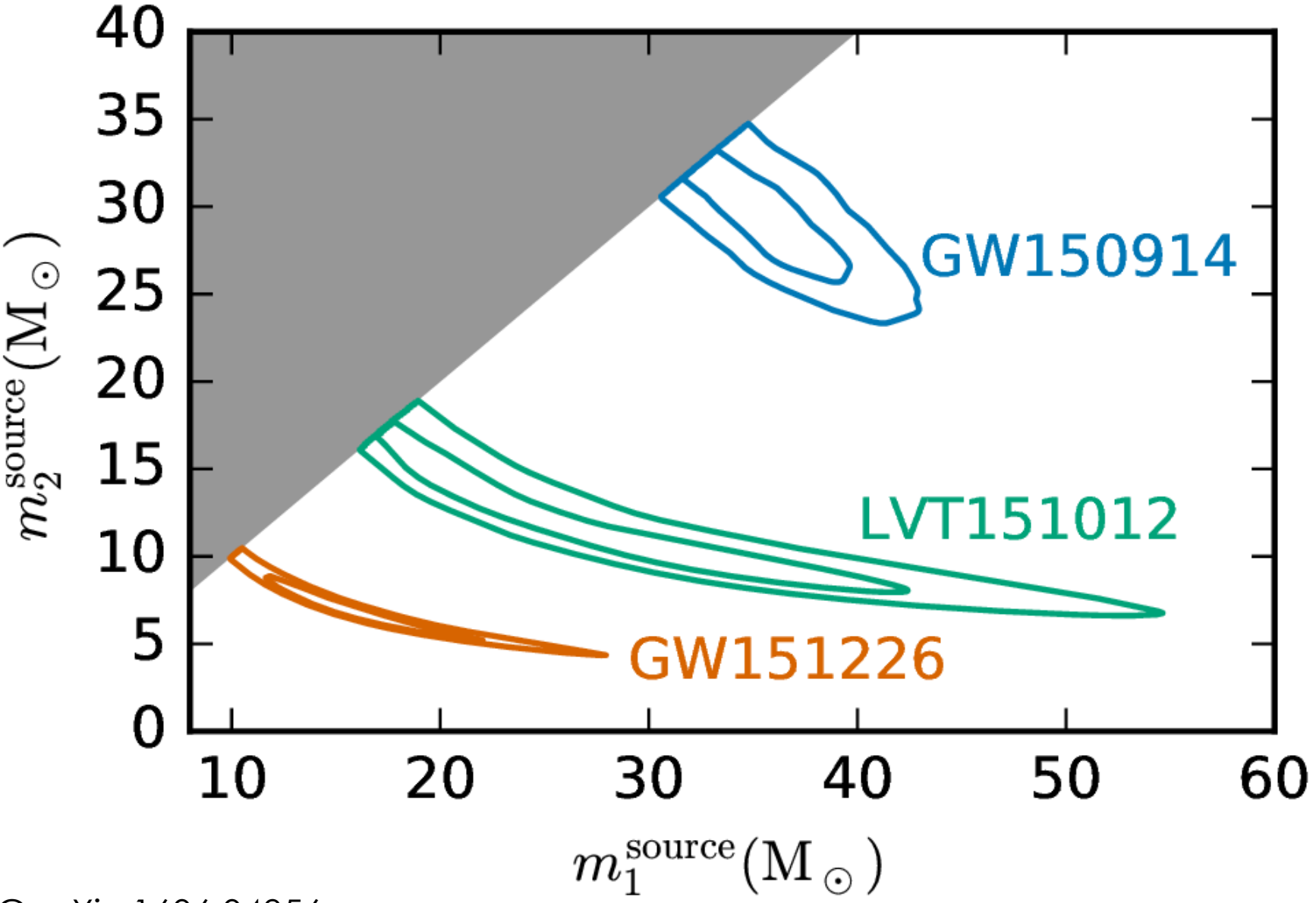

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How to infer source properties

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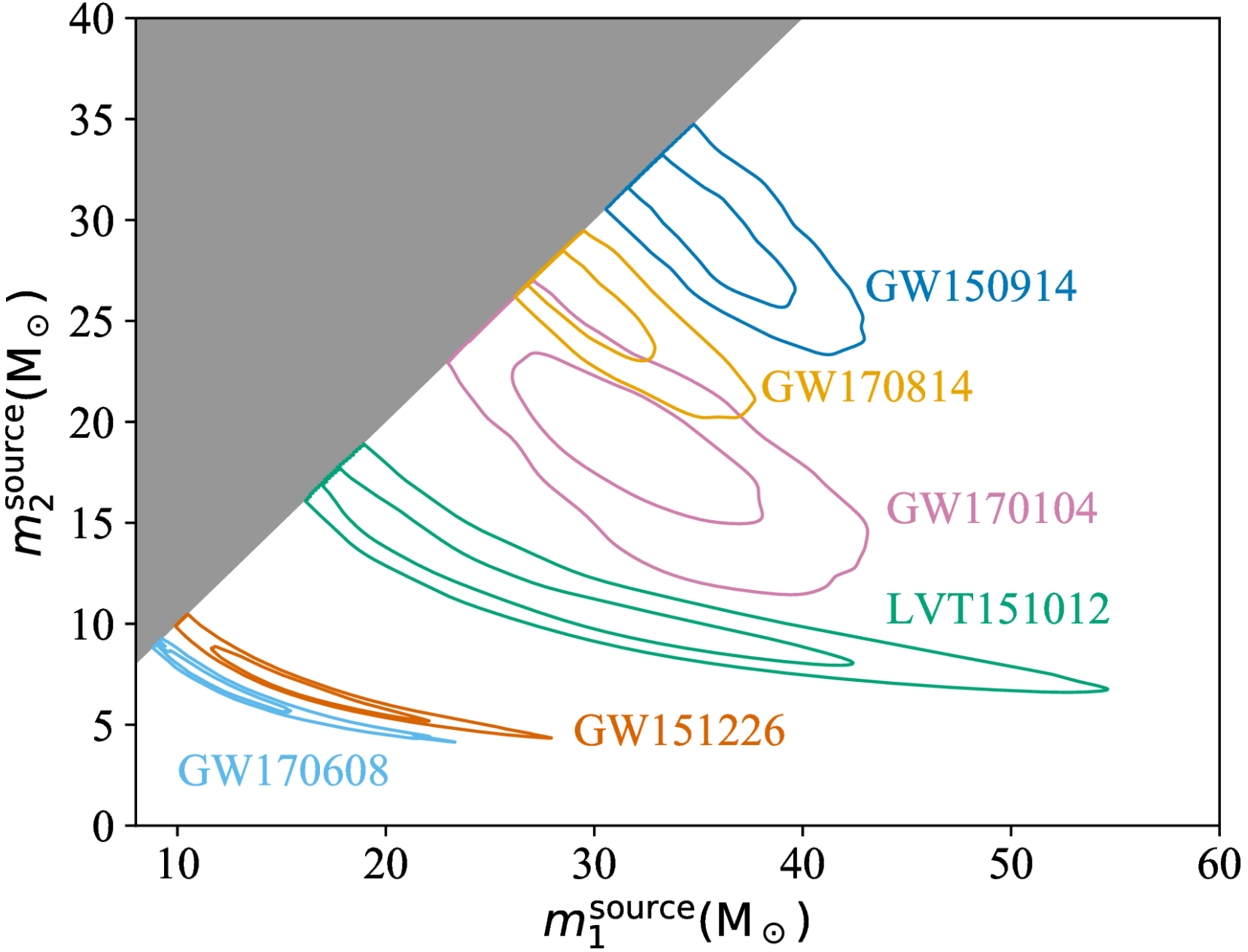
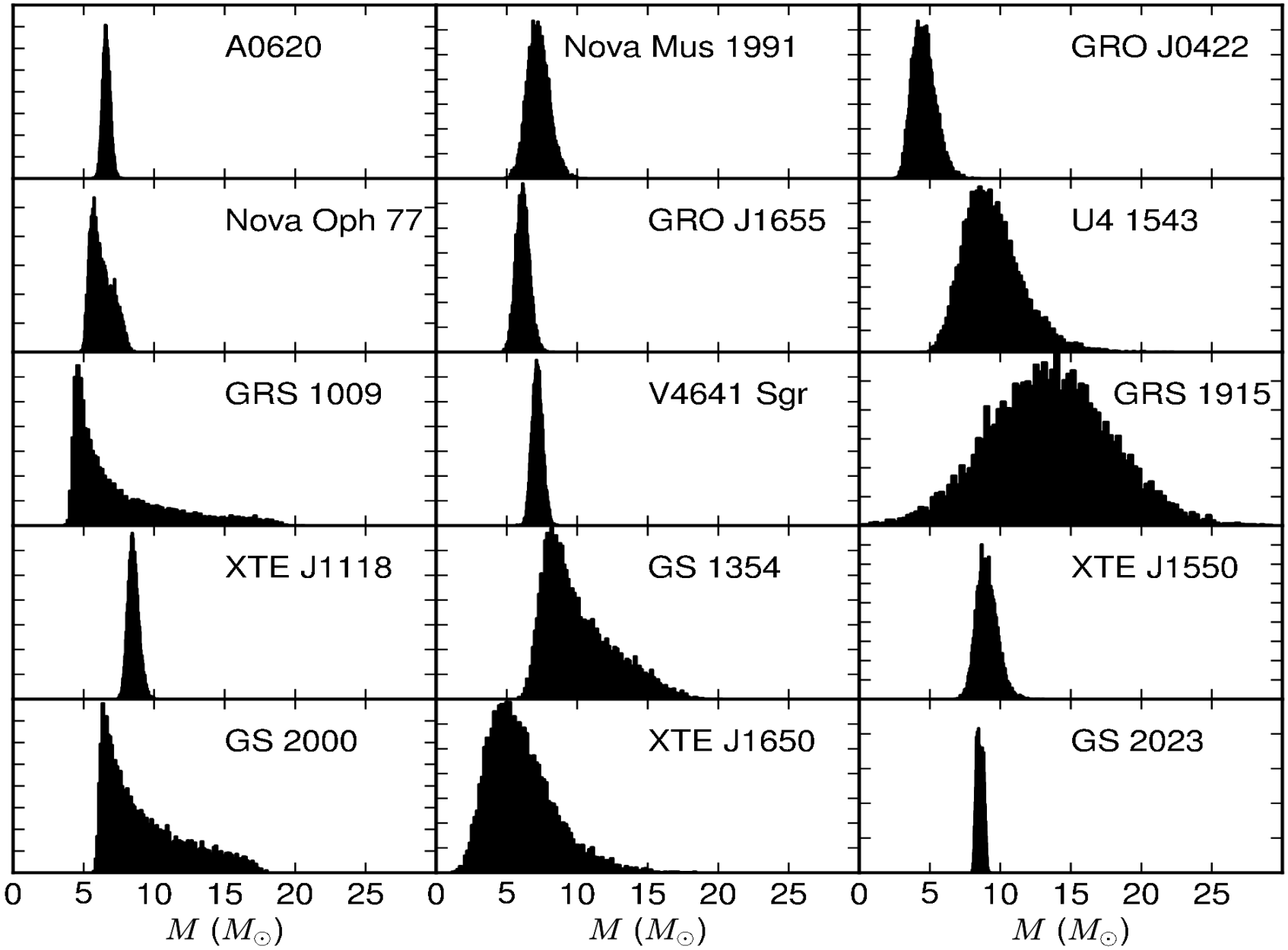
How we can use gravitational-wave observations

Credit: ButterflyLove1

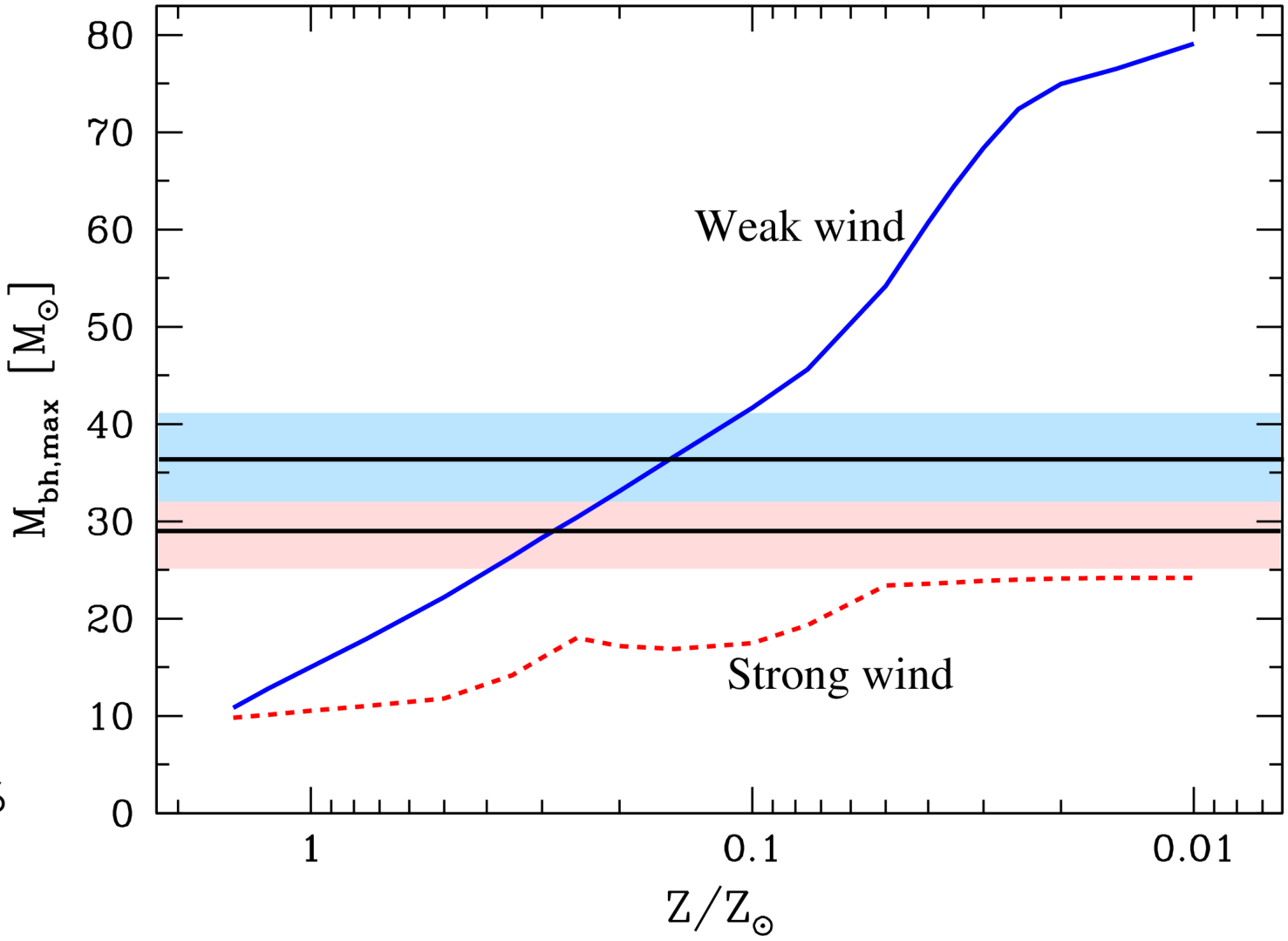


LVC arXiv:1606.04856 arXiv:1706.01812 arXiv:1709.09660 arXiv:1711.05578

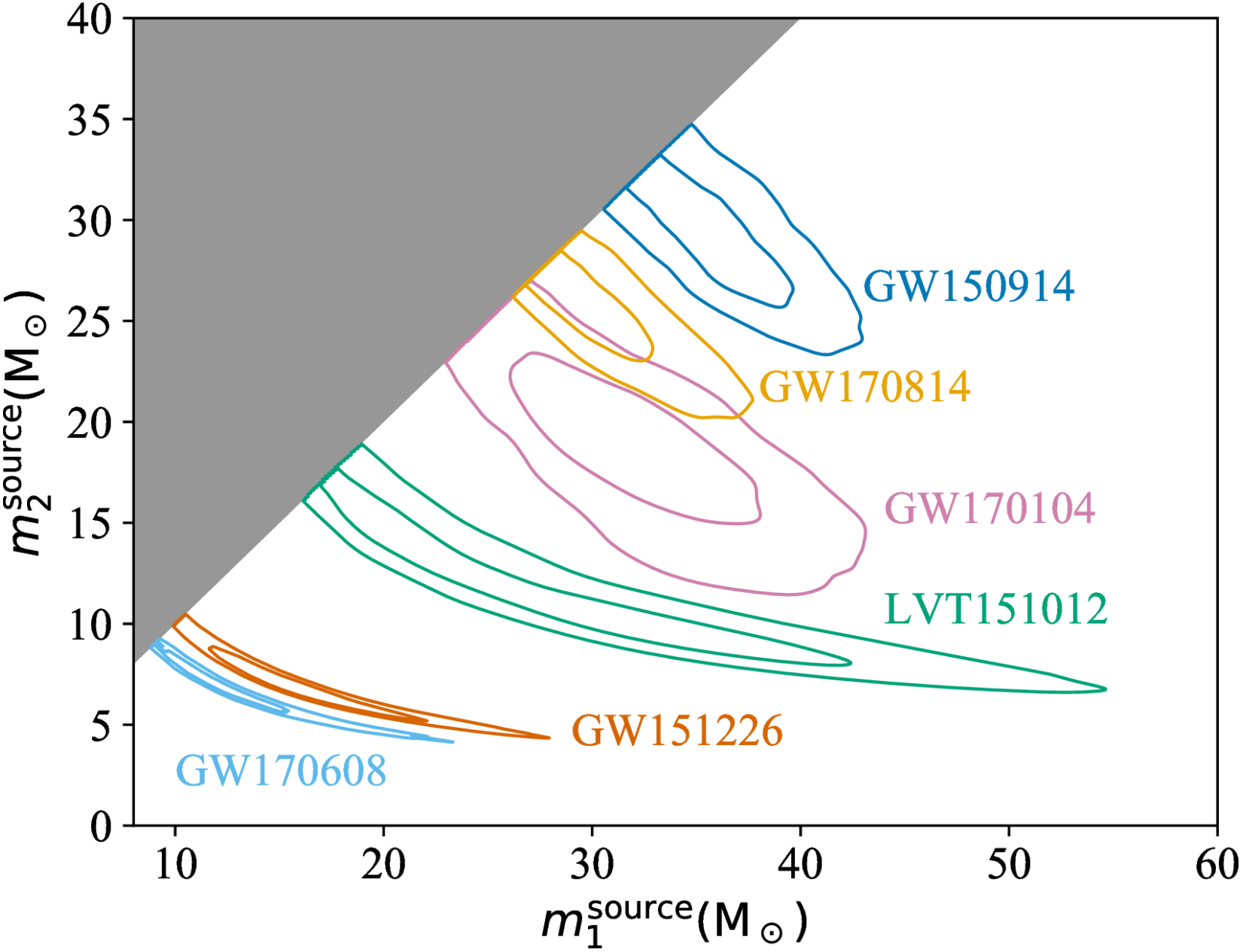
Farr *et al*. arXiv:1011.1459



Metallicity



LVC
arXiv:1602.03846
Belczynski *et al.*
arXiv:0904.2784



LVC arXiv:1606.04856 arXiv:1706.01812 arXiv:1709.09660 arXiv:1711.05578

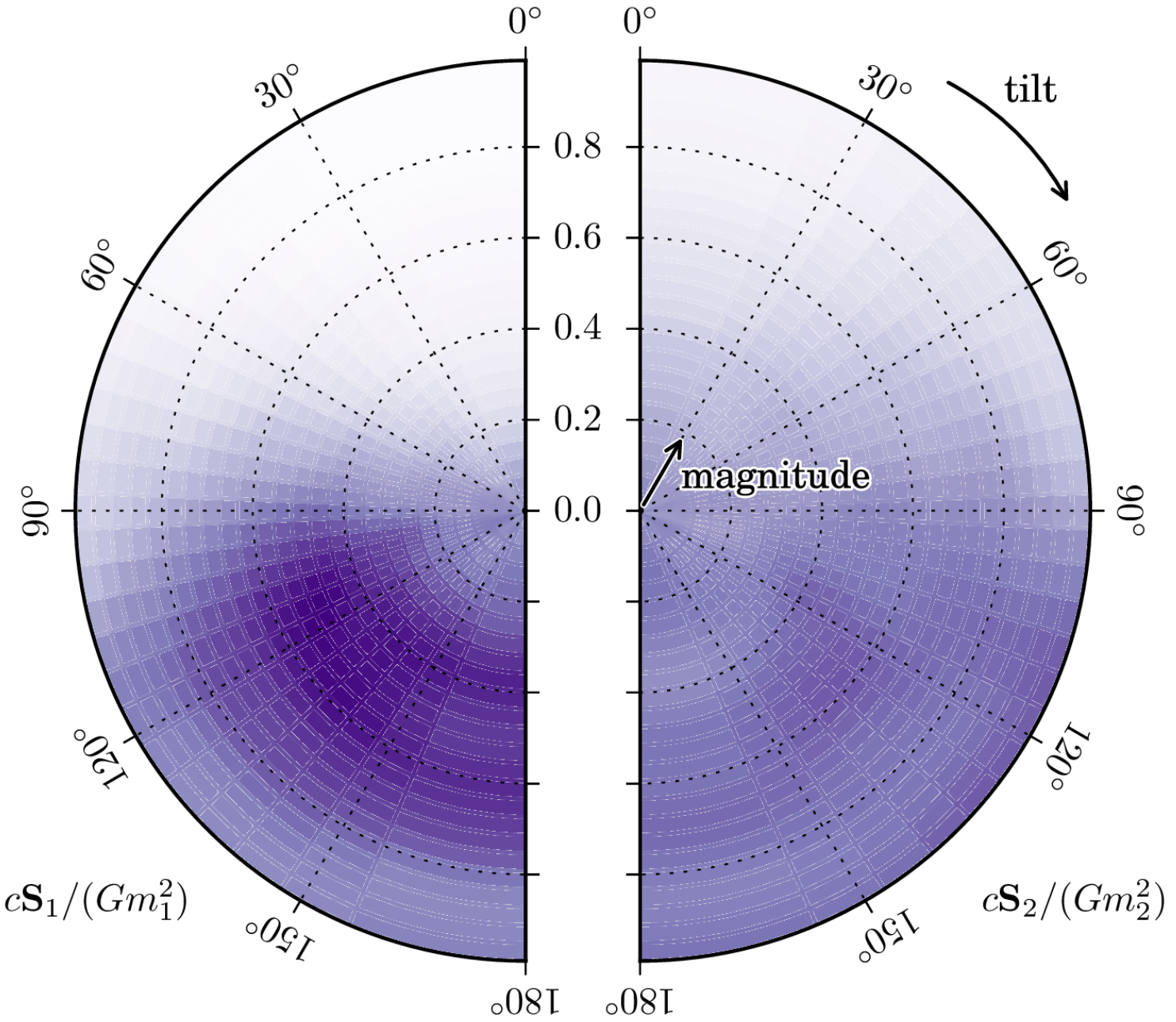
No hair theorem

Black holes have:

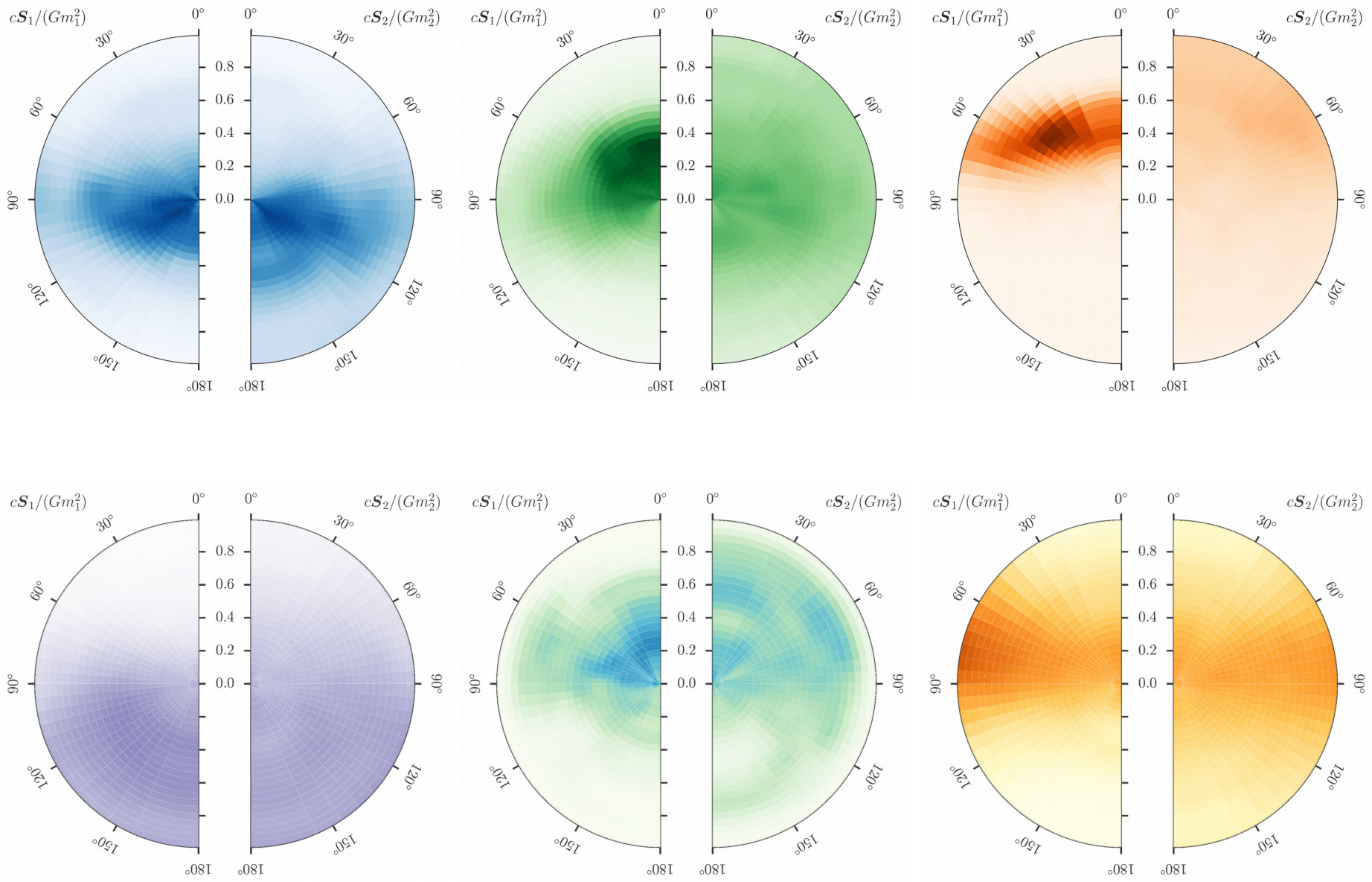
1. Mass
2. Spin
3. Electric charge

Credit: Matt Groening

Spin



LVC
arXiv:1706.01812



LVC arXiv:1606.04856 arXiv:1706.01812 arXiv:1709.09660 arXiv:1711.05578

How to infer source properties

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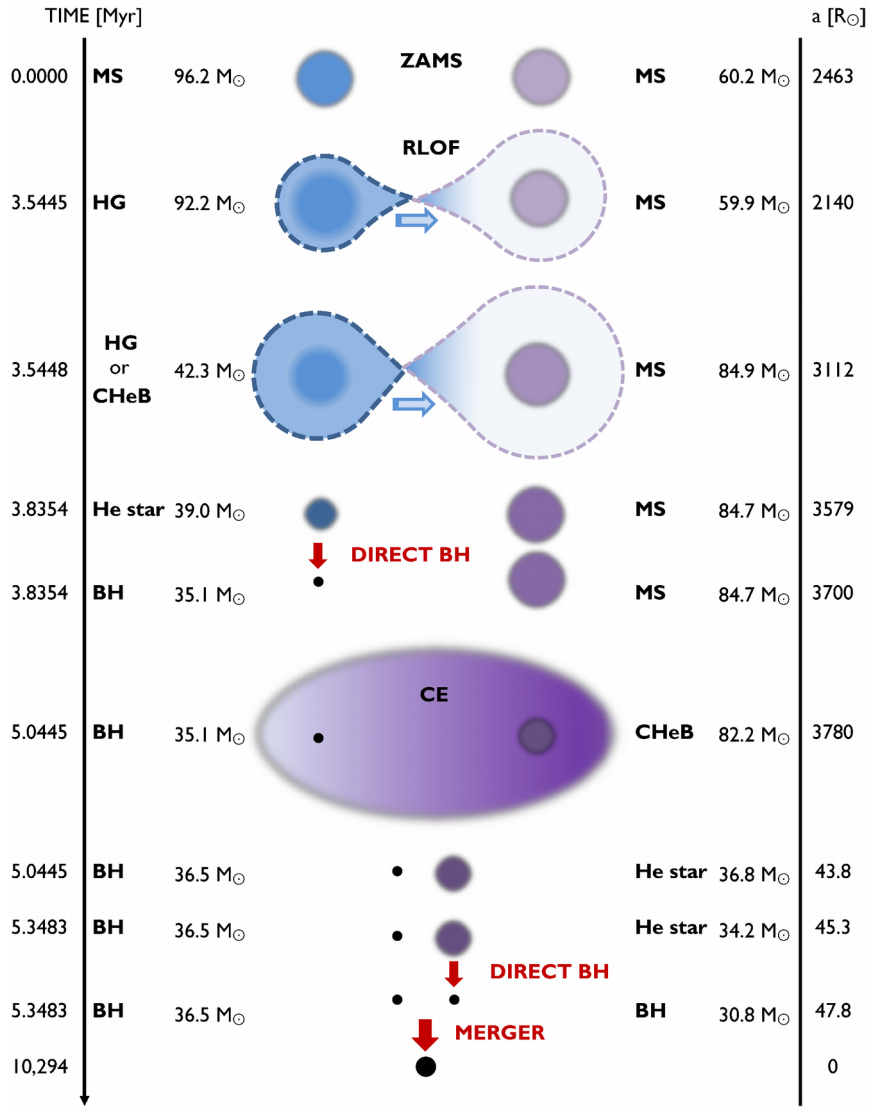
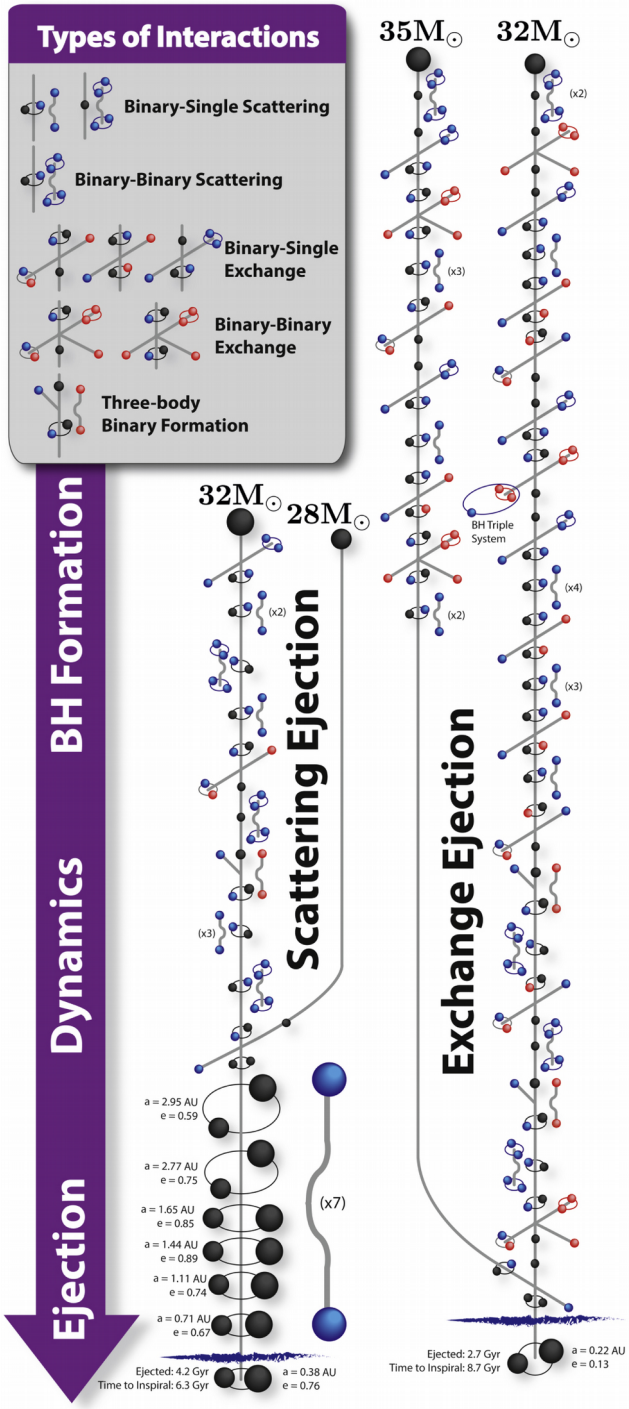
How we can use gravitational-wave observations

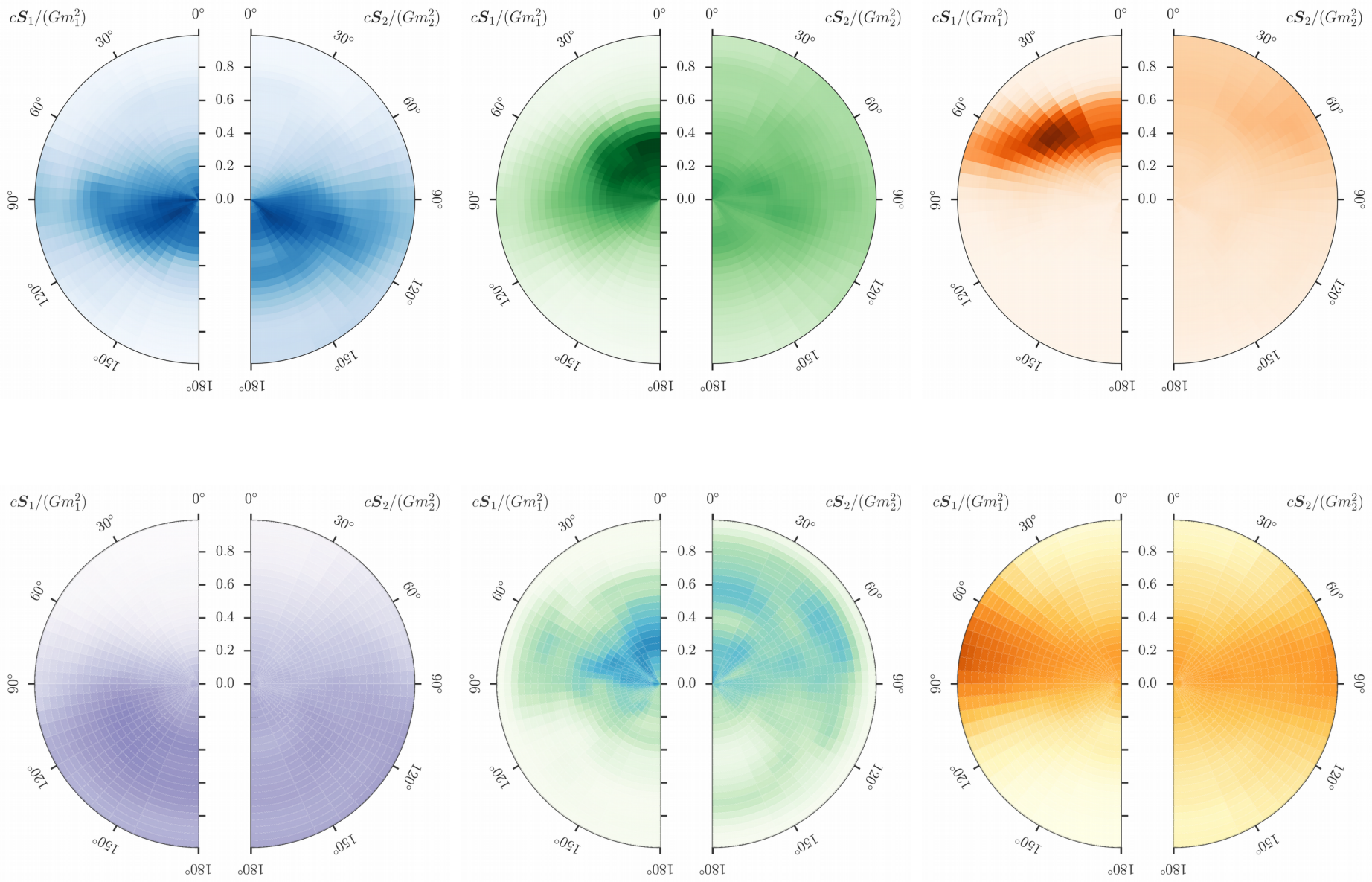
Binary formation



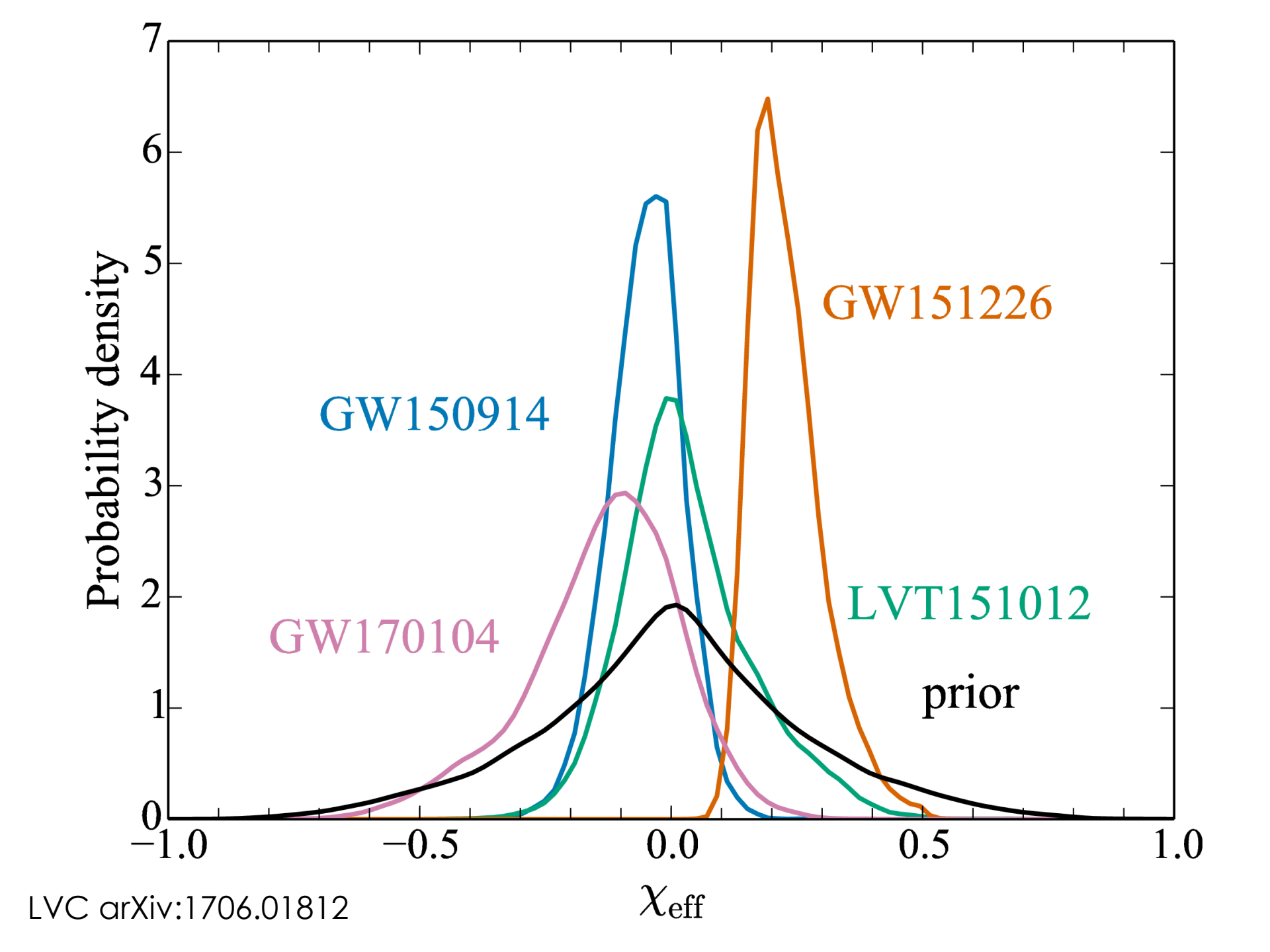
Rodriguez *et al.*
arXiv:1604.04254



Belczynski *et al.*
arXiv:1602.04531



LVC arXiv:1606.04856 arXiv:1706.01812 arXiv:1709.09660 arXiv:1711.05578



LVC arXiv:1706.01812

Hierarchical analysis

Distinguishing Spin-Aligned and Isotropic Black Hole Populations With Gravitational Waves

Will M. Farr, Simon Stevenson, M. Coleman Miller, Ilya Mandel, Ben Farr, Alberto Vecchio

(Submitted on 5 Jun 2017 (v1), last revised 6 Jun 2017 (this version, v2))

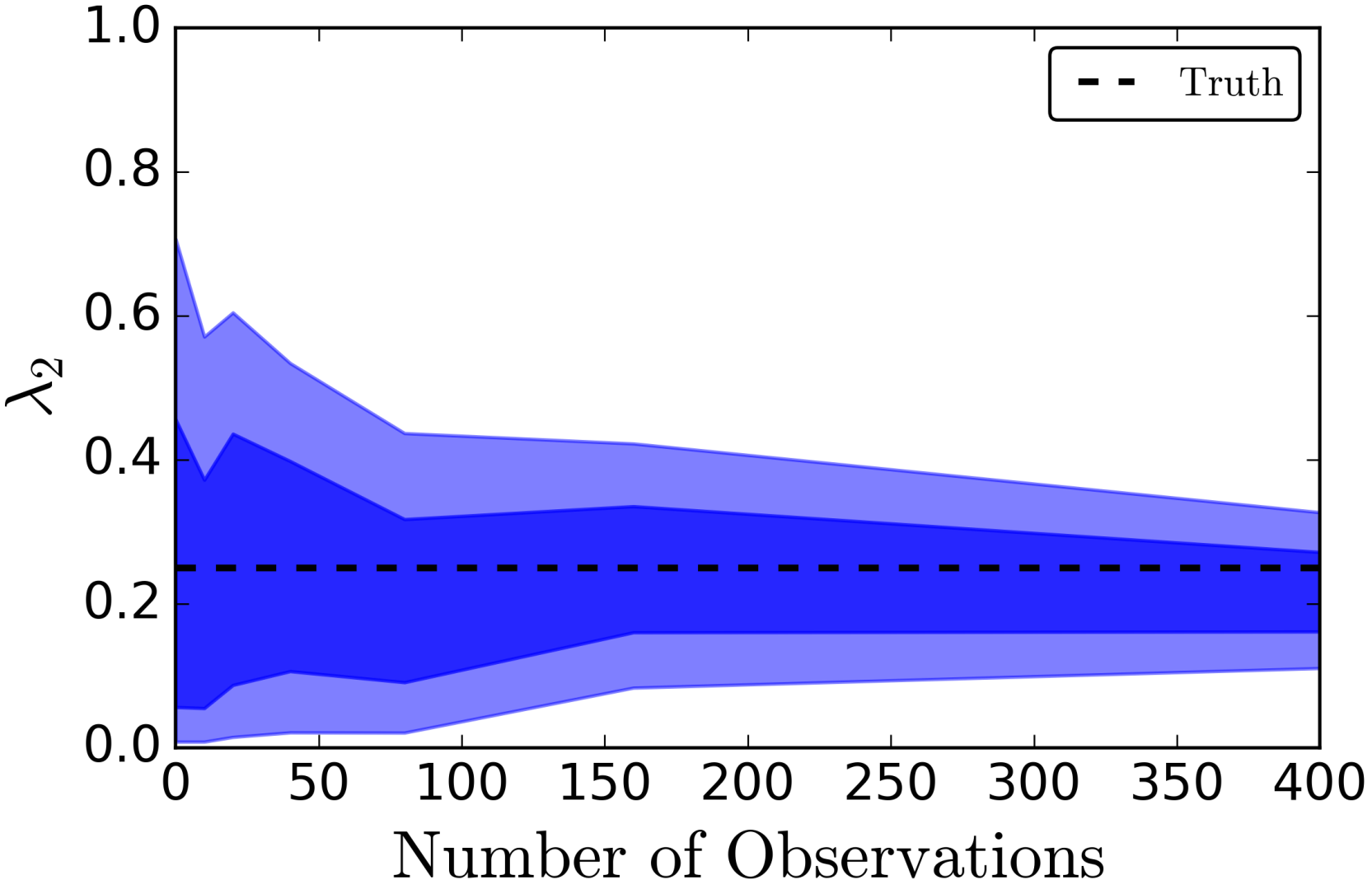
The first direct detections of gravitational waves from merging binary black holes open a unique window into the binary black hole formation environment. One promising environmental signature is the angular distribution of the black hole spins; systems formed through dynamical interactions among already-compact objects are expected to have isotropic spin orientations whereas binaries formed from pairs of stars born together are more likely to have spins preferentially aligned with the binary orbital angular momentum. We consider existing gravitational wave measurements of the binary effective spin, the best-measured combination of spin parameters, in the four likely binary black hole detections GW150914, LVT151012, GW151226, and GW170104. If binary black hole spin magnitudes extend to high values we show that the data exhibit a 2.4σ (0.015 odds ratio) preference for an isotropic angular distribution over an aligned one. By considering the effect of 10 additional detections, we show that such an augmented data set would enable in most cases a preference stronger than 5σ (2.9×10^{-7} odds ratio). The existing preference for either an isotropic spin distribution or low spin magnitudes for the observed systems will be confirmed (or overturned) confidently in the near future.

Comments: 32 pages, 9 figures, code and docum
Subjects: **High Energy Astrophysical Phenon**
Report number: LIGO-P1700067
Cite as: **arXiv:1706.01385 [astro-ph.HE]**
(or **arXiv:1706.01385v2 [astro-ph.HE**

Vitale *et al*. arXiv: 1503.04307
Gerosa & Berti arXiv: 1703.06223
Fishbach, Holz & Farr arXiv:1703.06869
Stevenson, **CPLB** & Mandel: 1703.06873
Talbot & Thrane arXiv:1704.08370

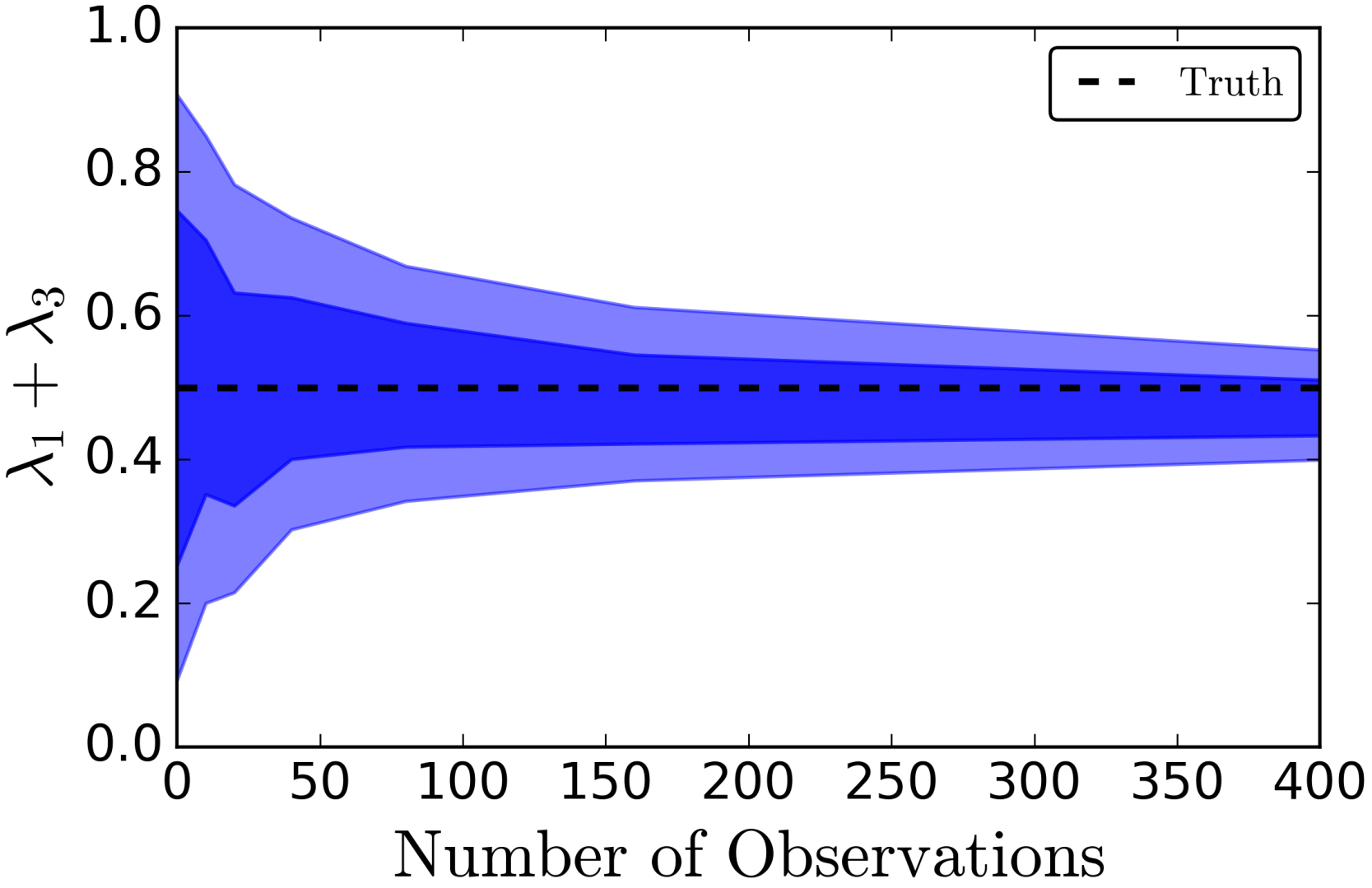
Model inference

Stevenson, CPLB & Mandel
arXiv:1703.06873

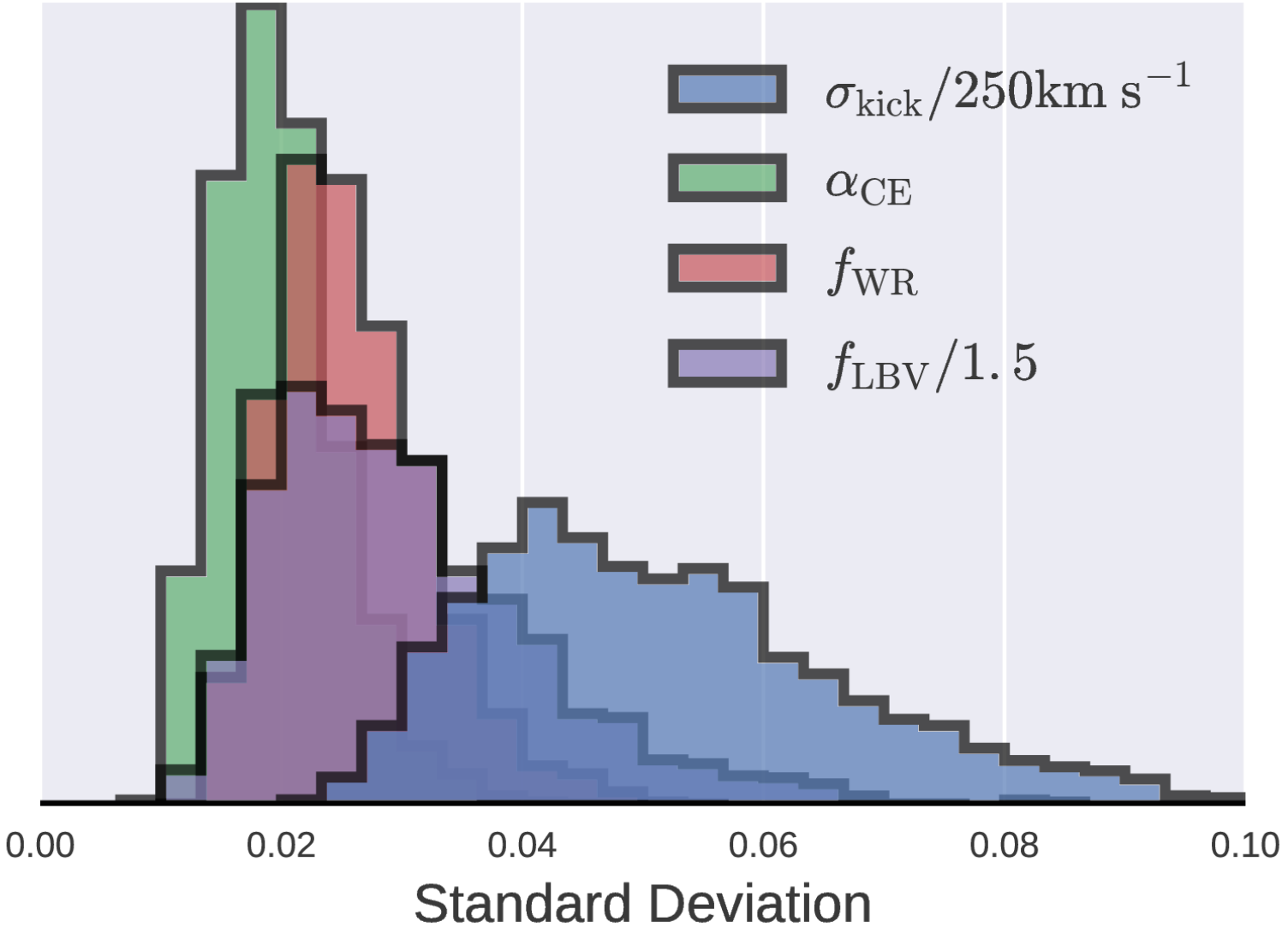


Model inference

Stevenson, CPLB & Mandel
arXiv:1703.06873

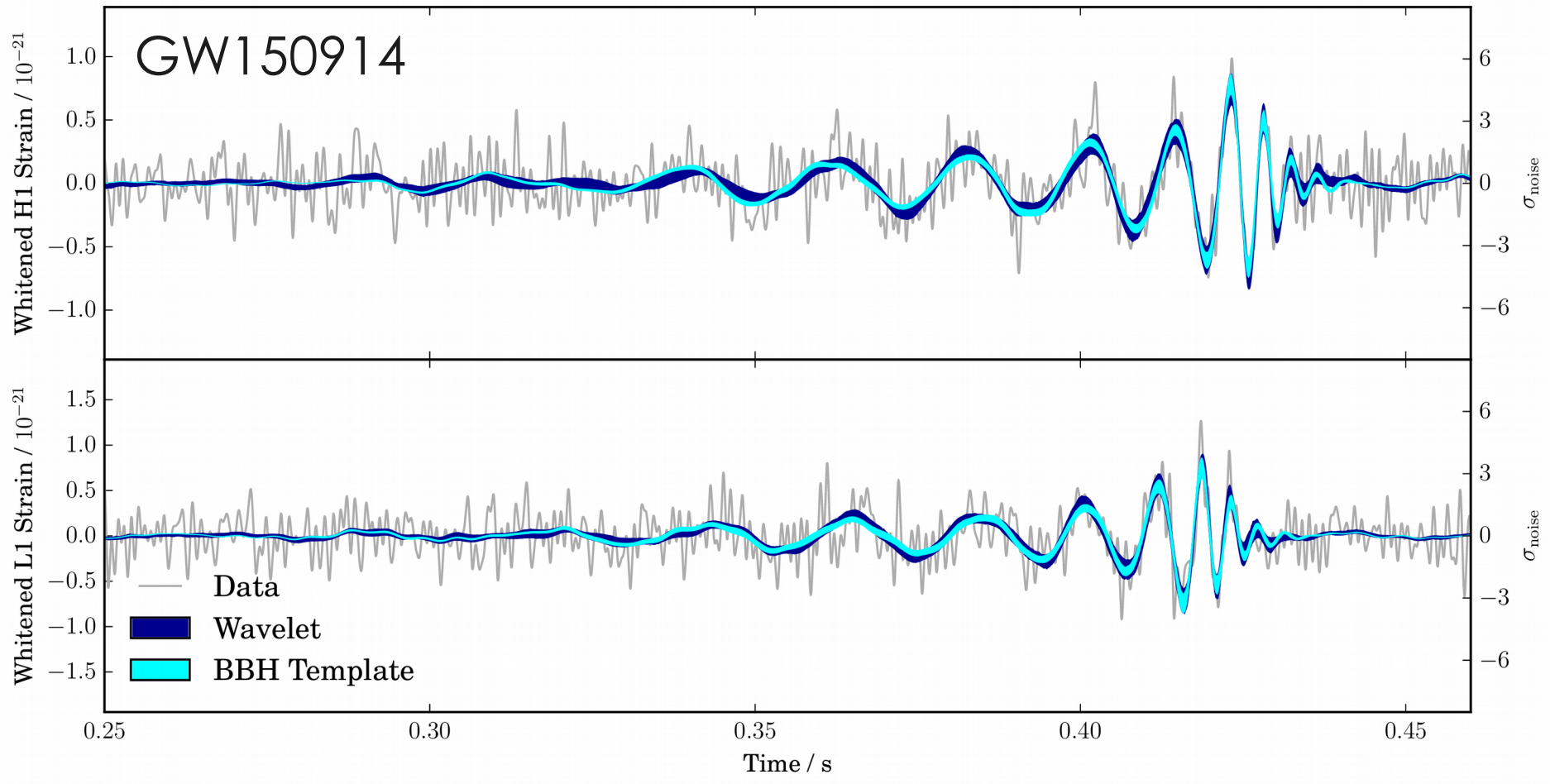


Binary evolution



Barrett *et al.* arXiv:1711.06287

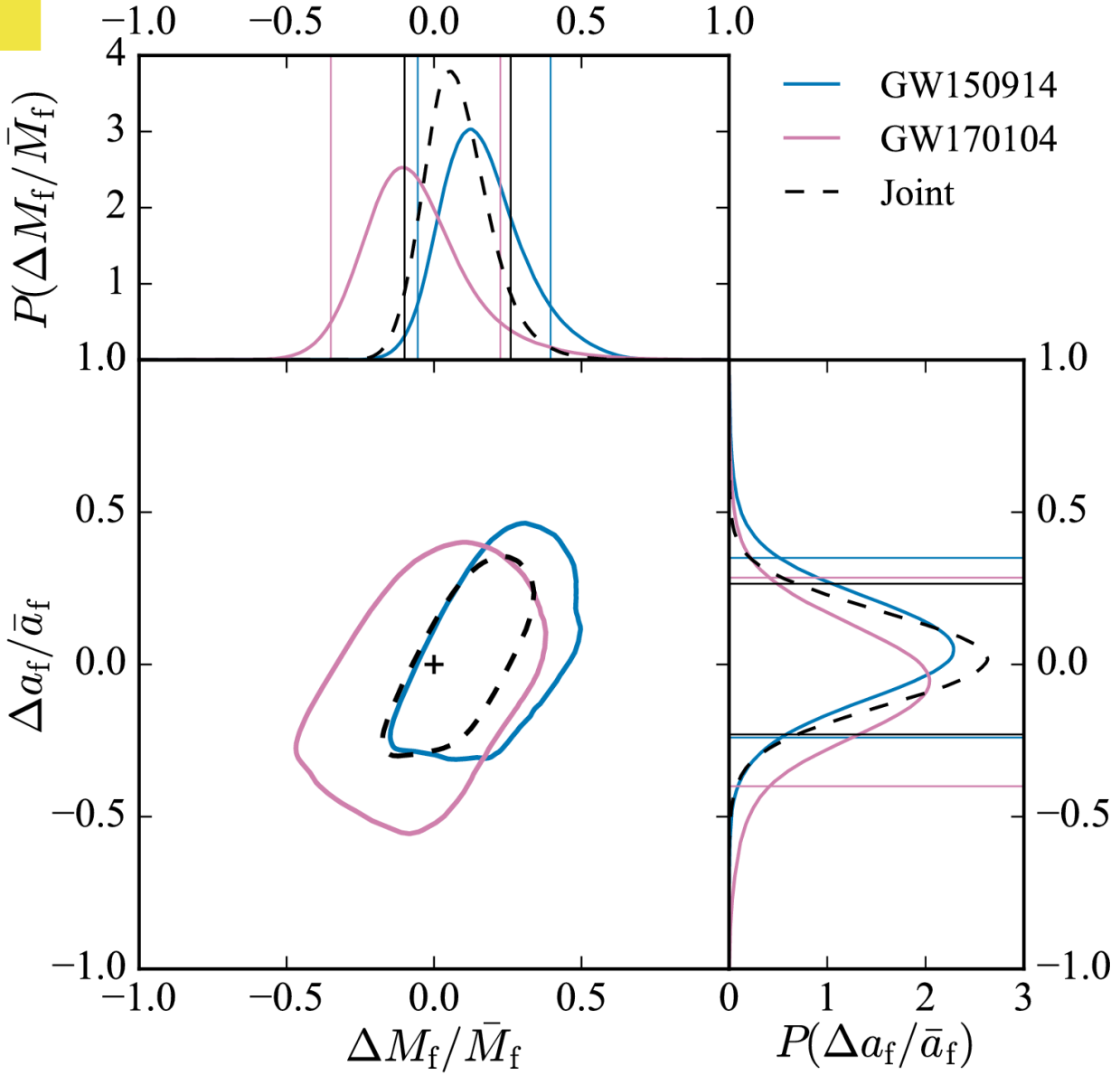
Waveform



LVC arXiv:1602.03840

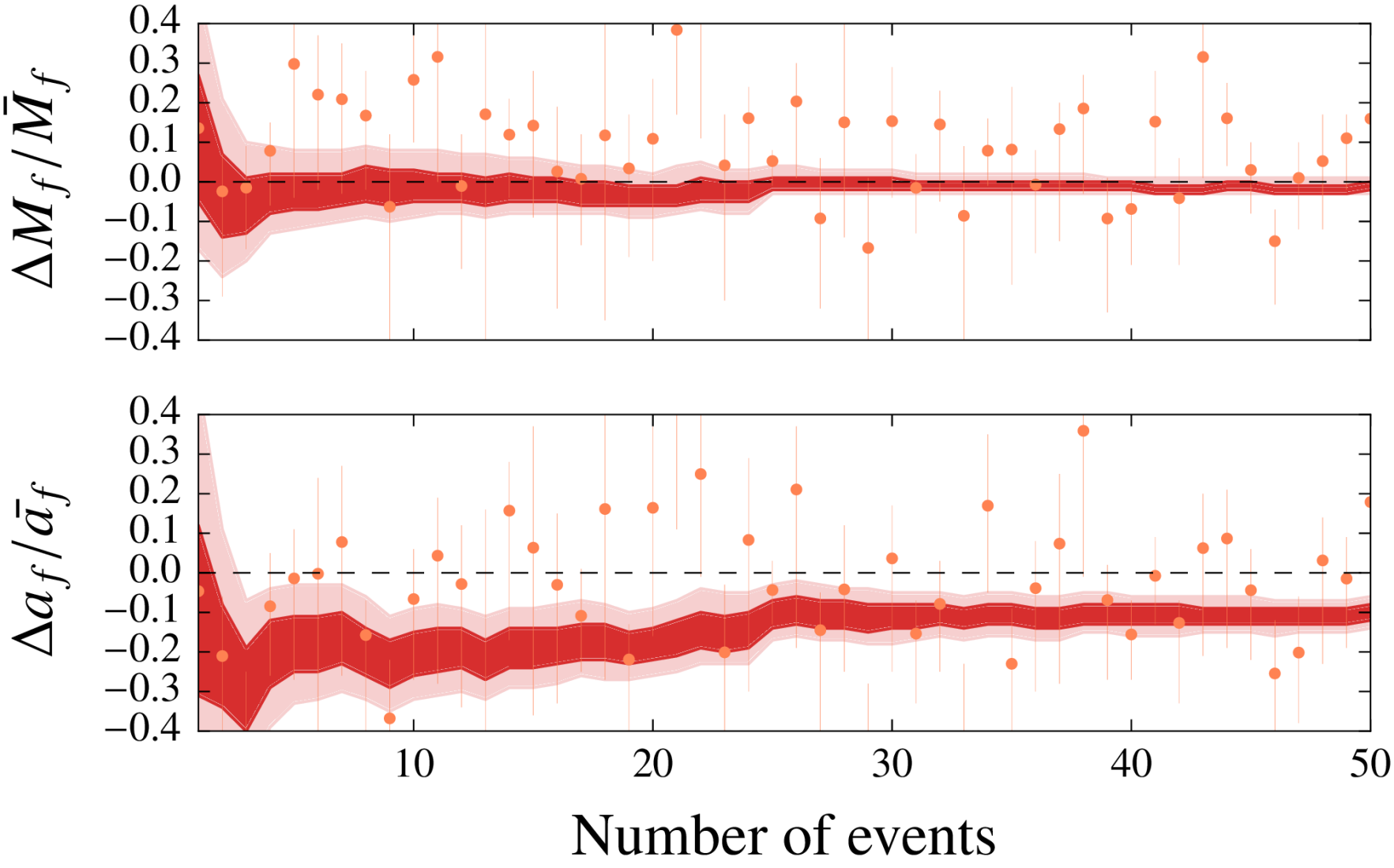
Testing GR

LVC arXiv:1602.03841
arXiv:1706.01812



Testing GR

Ghosh *et al*. arXiv:1704.06784



Gravitational waves provide a new tool for astronomy

We are learning about the population of binary black holes

Combining measurements lets us test binary physics and general relativity

- Infer source properties by comparing waveform templates to data
- Some parameter (like chirp mass) measured well, others (like in-plane spins) remain uncertain
- Parameters (masses, spins, redshifts) could give insight into evolution
- Need a hierarchical analysis of a population of ~100–1000 detections

arXiv:1602.03837 arXiv:1602.03839 arXiv:1606.04855 **arXiv:1706.01812**

arXiv:1711.05578 arXiv:1709.09660 *arXiv:1710.05832*

Image: NSF/LIGO/Sonoma State University/A. Simonnet

Thank you

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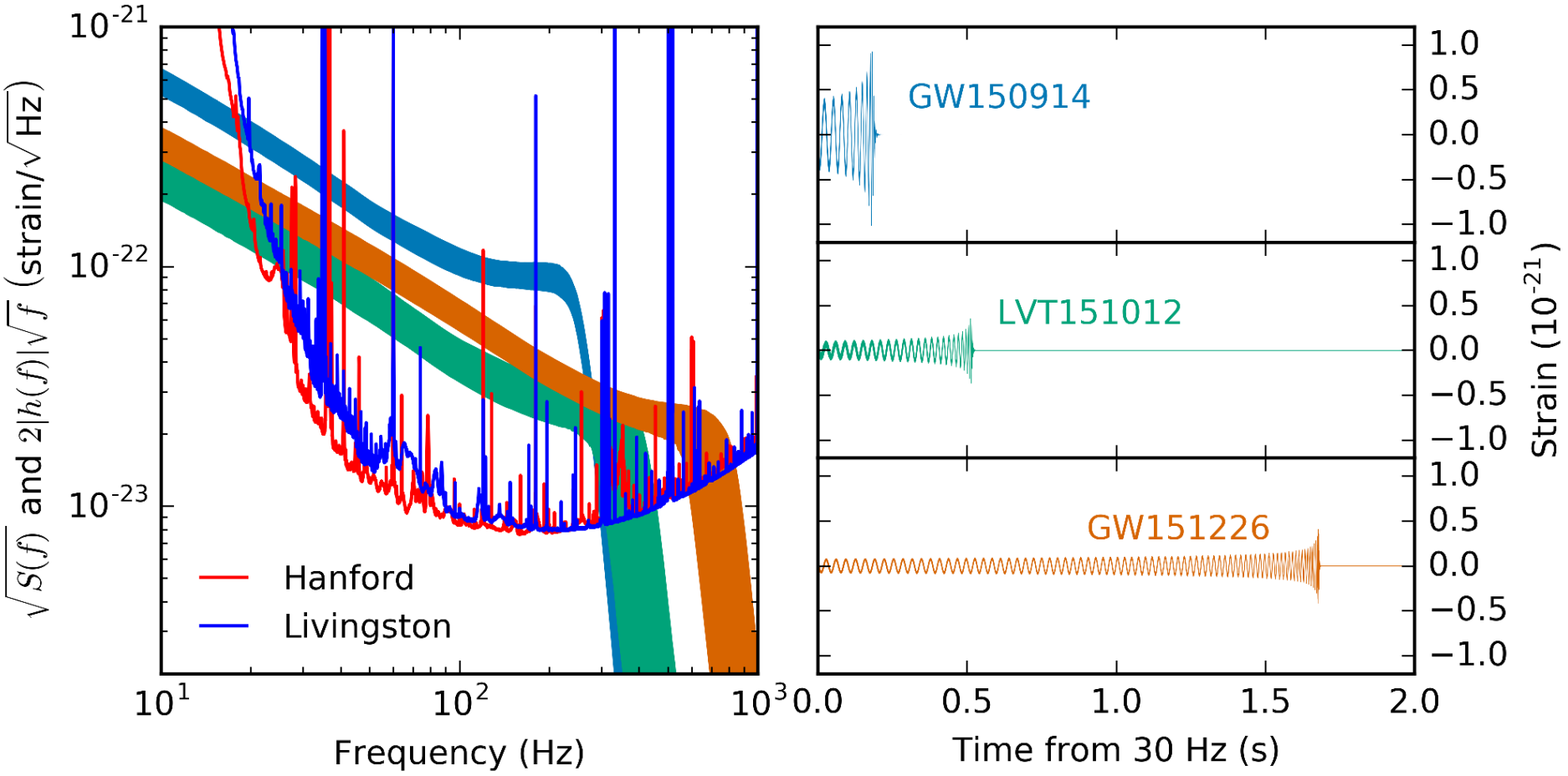
Detector network

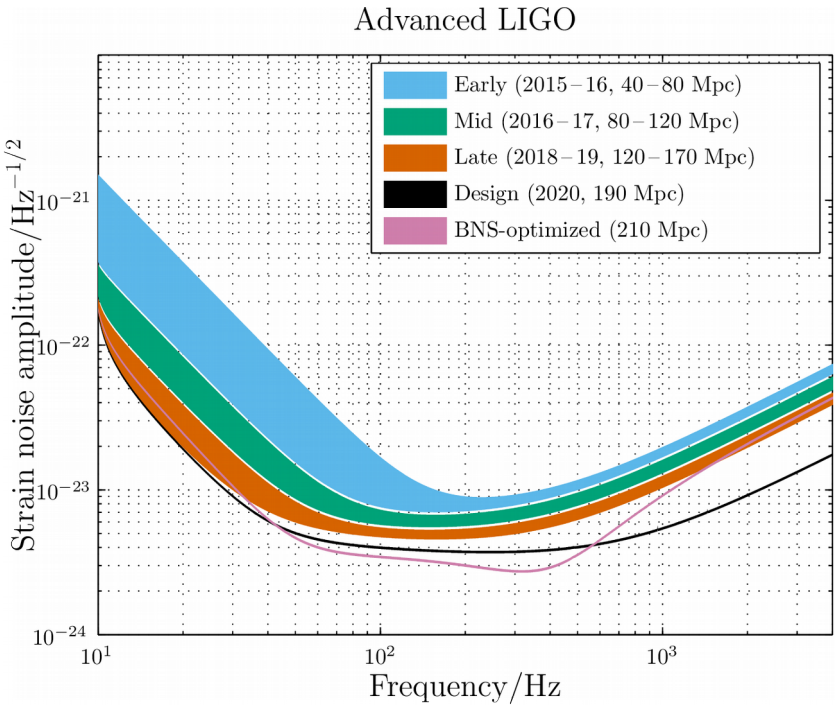
Detection

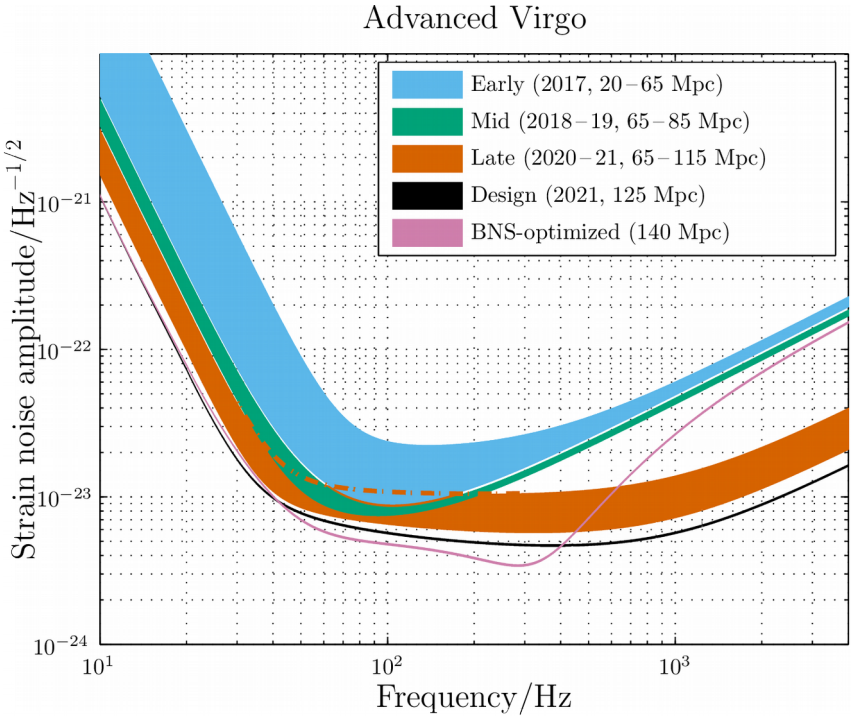


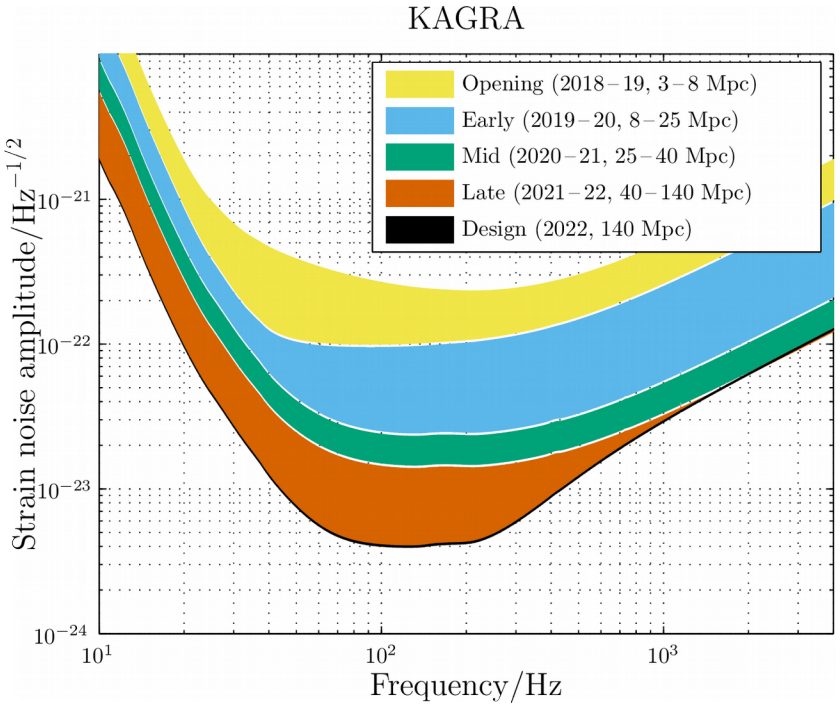
LVC arXiv:1606.04856

Plausible detector sensitivities

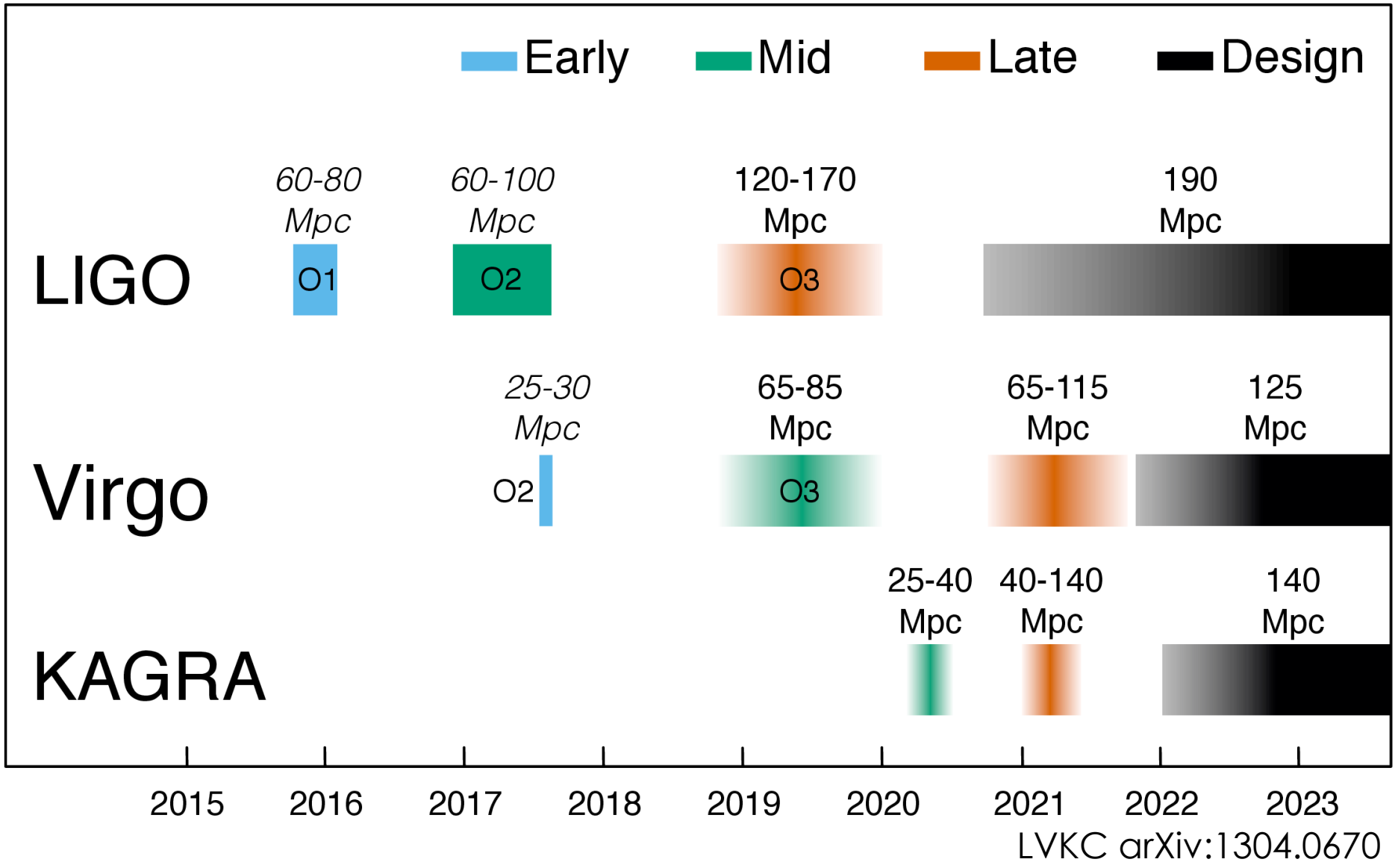
LVKC arXiv:1304.0670







Observing timetable



LVKC arXiv:1304.0670

Ranges

Table 1 Plausible target detector sensitivities. The different phases match those in Figure 1. We quote the range, the average distance to which a signal could be detected, for a $1.4M_{\odot}$+$1.4M_{\odot}$ binary neutron star (BNS) system and a $30M_{\odot}$+$30M_{\odot}$ binary black hole (BBH) system.

	LIGO		Virgo		KAGRA	
	BNS range/Mpc	BBH range/Mpc	BNS range/Mpc	BBH range/Mpc	BNS range/Mpc	BBH range/Mpc
Early	40 – 80	415 – 775	20 – 65	220 – 615	8 – 25	80 – 250
Mid	80 – 120	775 – 1110	65 – 85	615 – 790	25 – 40	250 – 405
Late	120 – 170	1110 – 1490	65 – 115	610 – 1030	40 – 140	405 – 1270
Design	190	1640	125	1130	140	1270

LVC arXiv:1304.0670

Observing scenarios

Epoch			2015–2016	2016–2017	2018–2019	2020+	2024+
Planned run duration			4 months	9 months	12 months	(per year)	(per year)
Expected burst range/Mpc		LIGO	40–60	60–75	75–90	105	105
		Virgo	—	20–40	40–50	40–70	80
		KAGRA	—	—	—	—	100
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

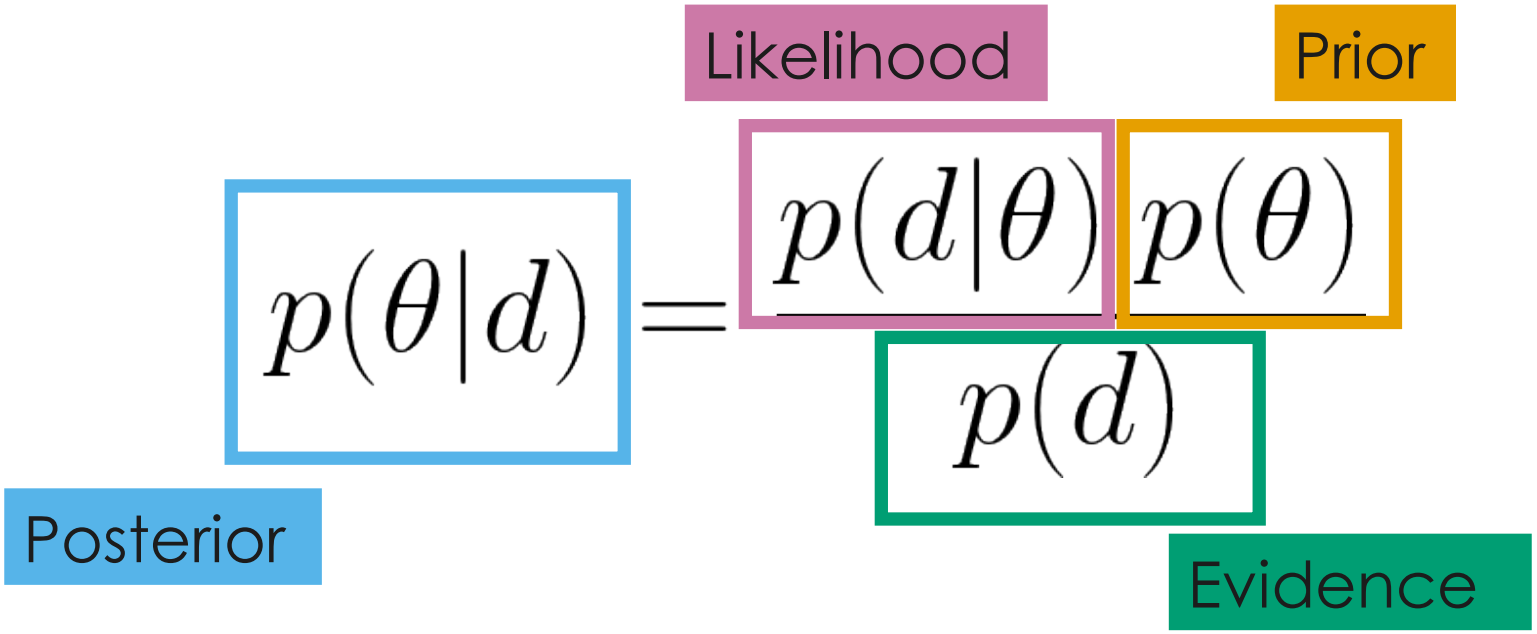
LVC arXiv:1304.0670


LVT151012
I WANT TO
BELIEVE

Bayes' theorem

$$p(\theta|d) = \frac{p(d|\theta)\, p(\theta)}{p(d)}$$

Bayes' theorem



Likelihood

$$p(d|\theta) \propto \exp\left[-\frac{1}{2}\sum_k \langle h_k(\theta) - d_k | h_k(\theta) - d_k\rangle\right]$$

LVC arXiv:1602.03840

Likelihood

Noise-weighting

$$p(d|\theta) \propto \exp\left[-\frac{1}{2}\sum_k \langle h_k(\theta) - d_k | h_k(\theta) - d_k \rangle\right]$$

LVC arXiv:1602.03840

Likelihood

Noise-weighting

$$p(d|\theta) \propto \exp\left[-\frac{1}{2}\sum_k \langle h_k(\theta) - d_k | h_k(\theta) - d_k\rangle\right]$$

$$h_k(\theta) \rightarrow h_k(\theta)\left[1 + \delta A_k\right]\exp\left[i\delta\phi_k\right]$$

LVC arXiv:1602.03840

Likelihood

Noise-weighting

$$p(d|\theta) \propto \exp\left[-\frac{1}{2}\sum_k \langle h_k(\theta) - d_k | h_k(\theta) - d_k\rangle\right]$$

Calibration

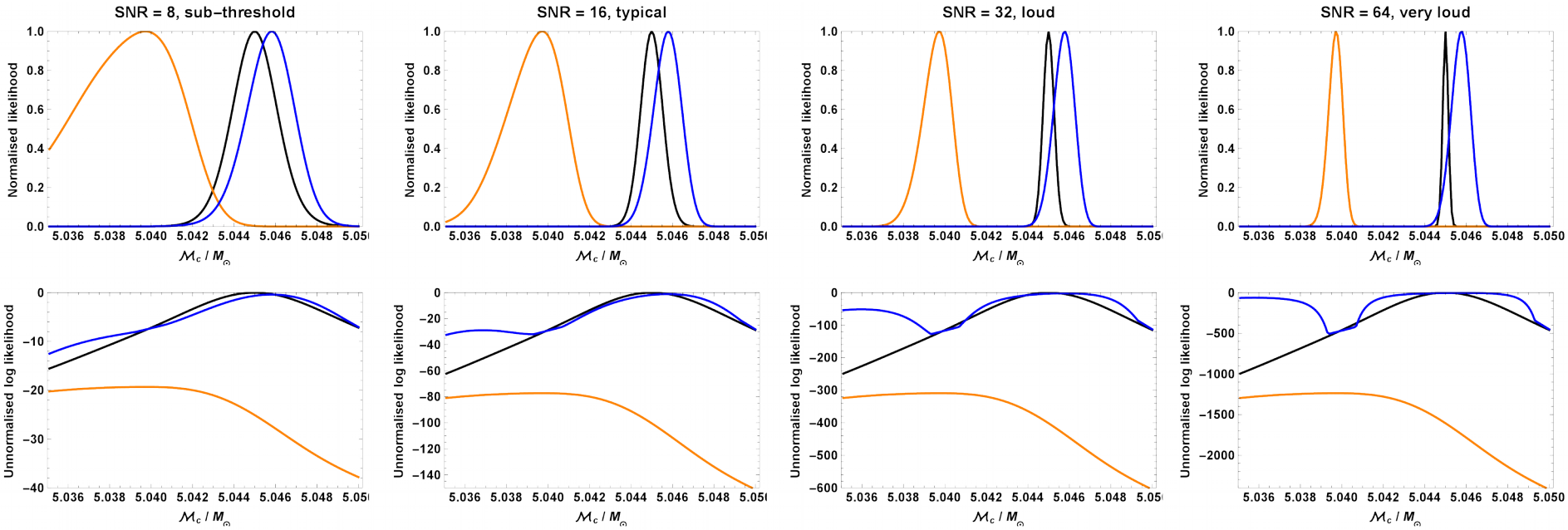
$$h_k(\theta) \rightarrow h_k(\theta)\,[1+\delta A_k]\exp\left[i\delta\phi_k\right]$$

Waveform

LVC arXiv:1602.03840

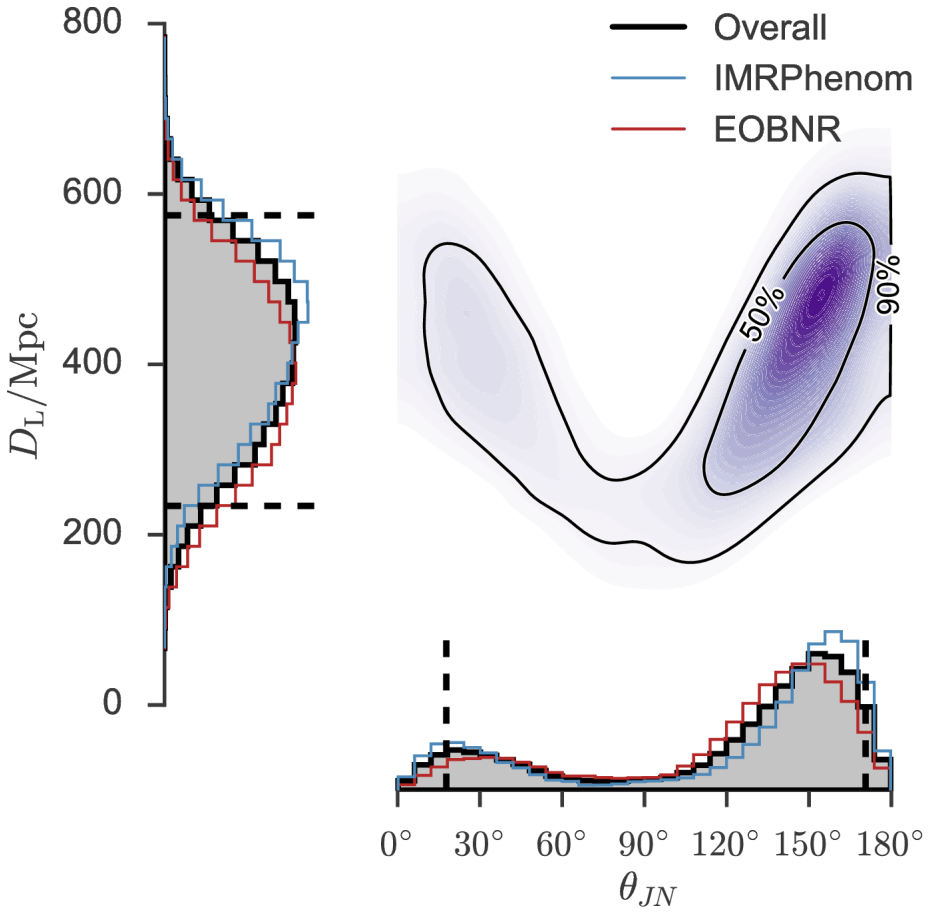
Waveform error

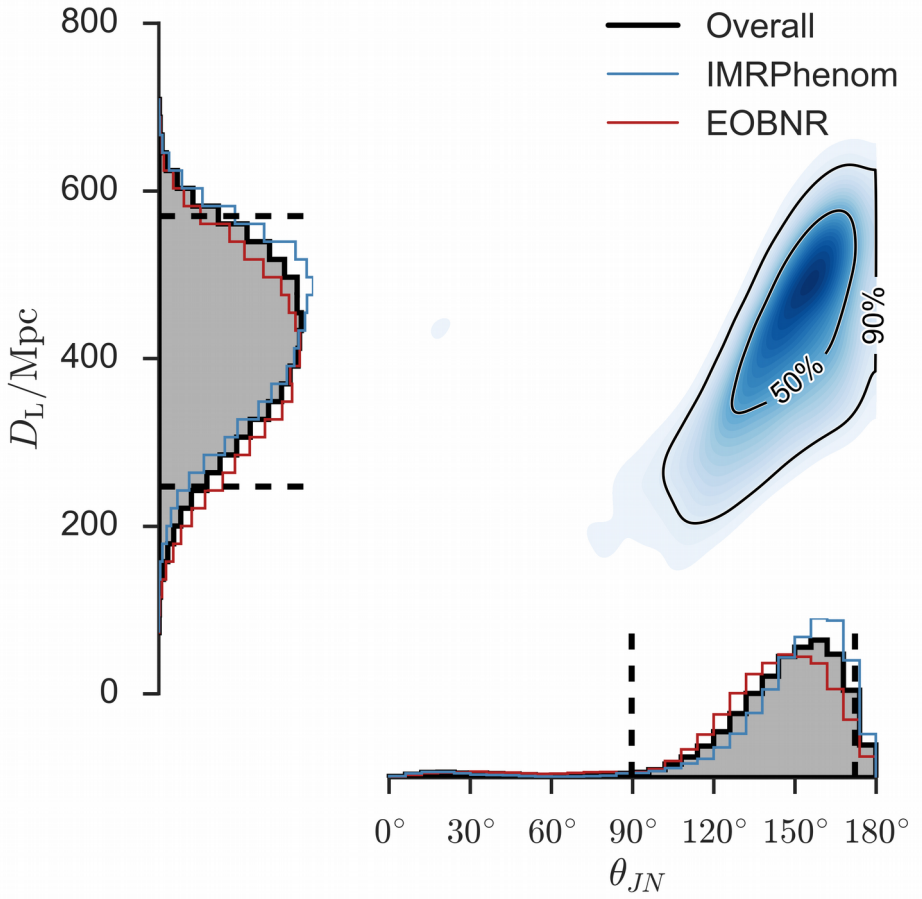
Waveforms introduce theoretical error (arXiv:0707.2982).
Mitigated using Gaussian processes (arXiv:1509.04066).



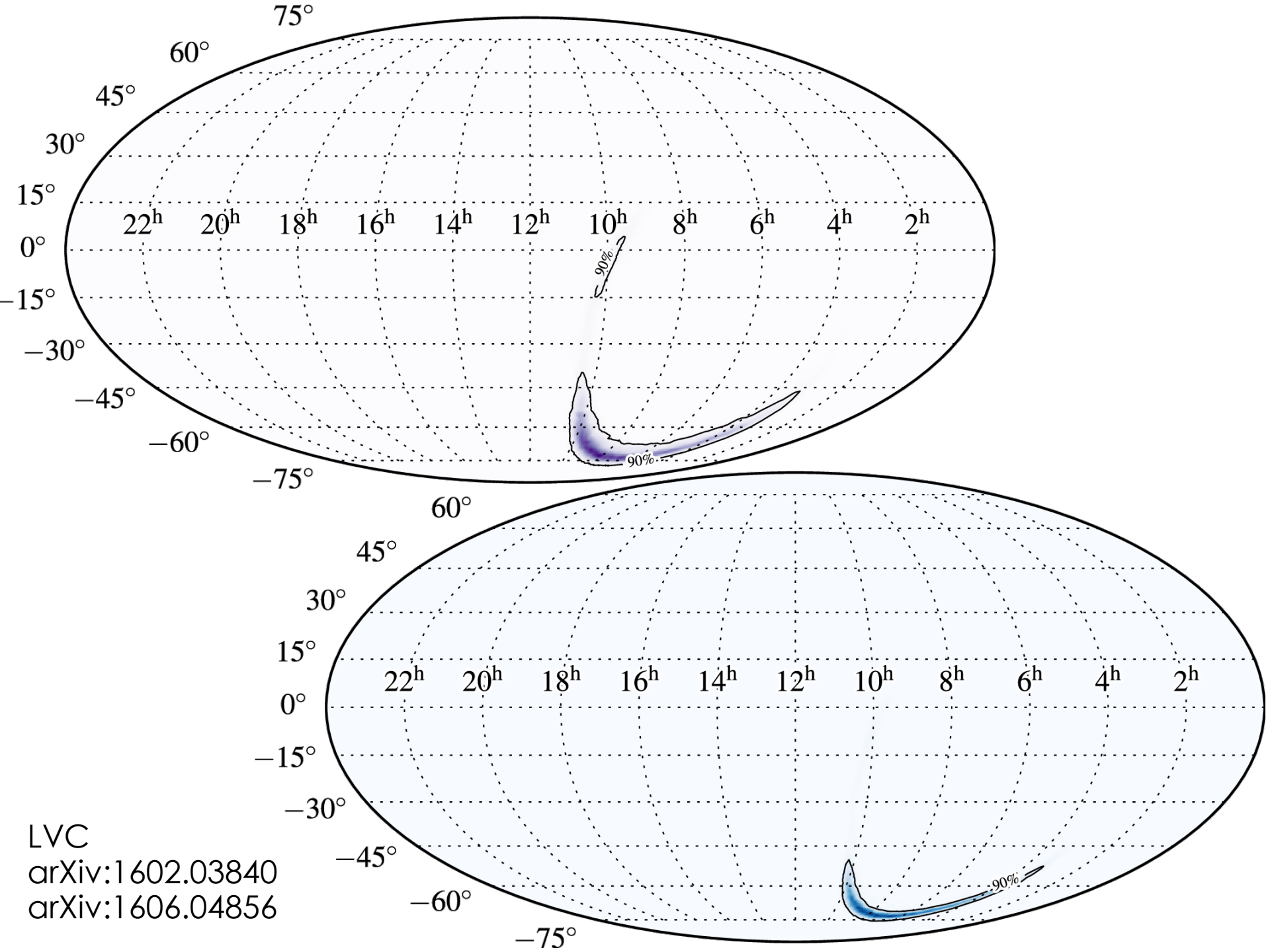
Moore *et al*. arXiv:1509.04066

Inclination





LVC
arXiv:1602.03840
arXiv:1606.04856



LVC
arXiv:1602.03840
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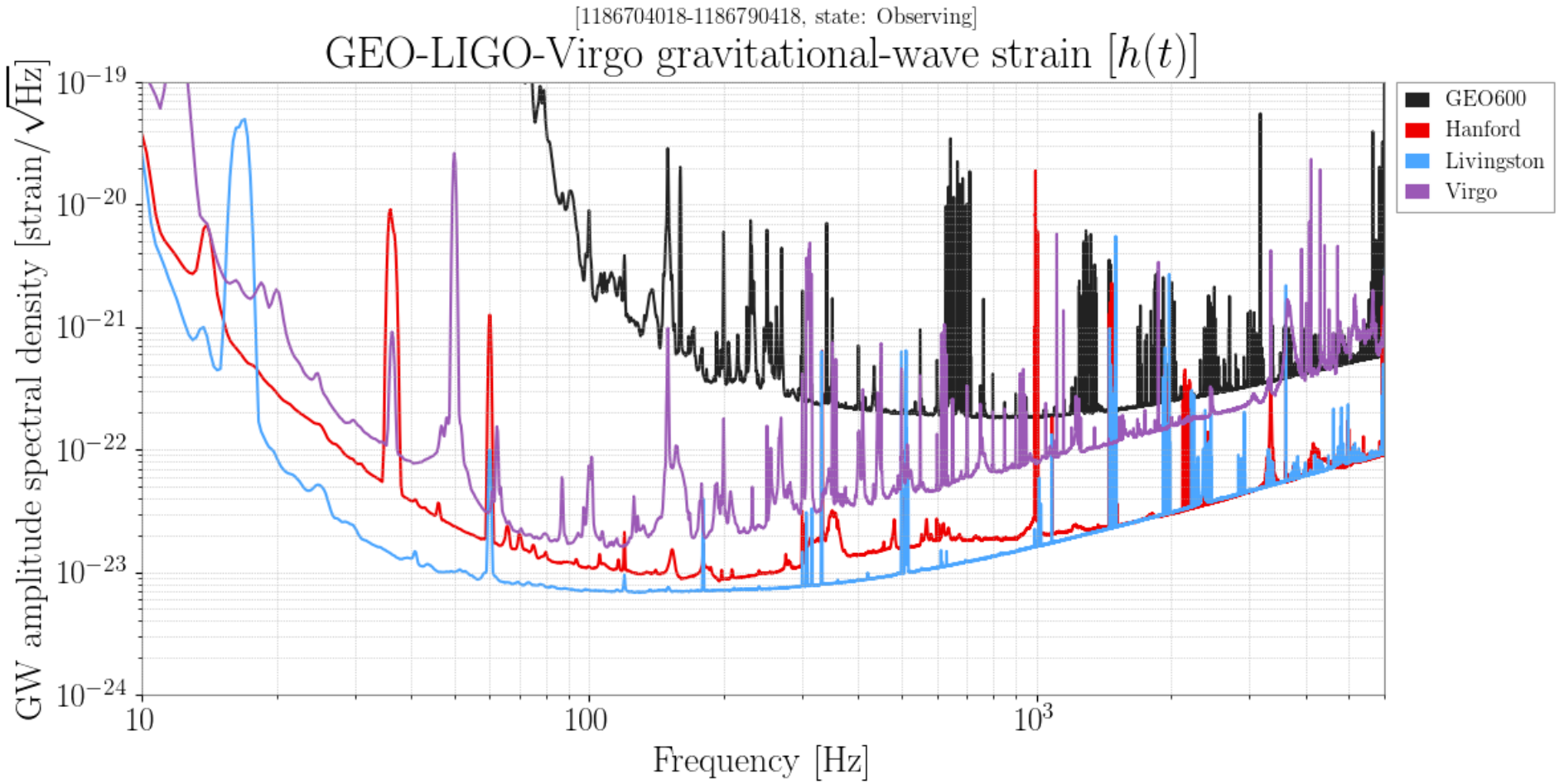
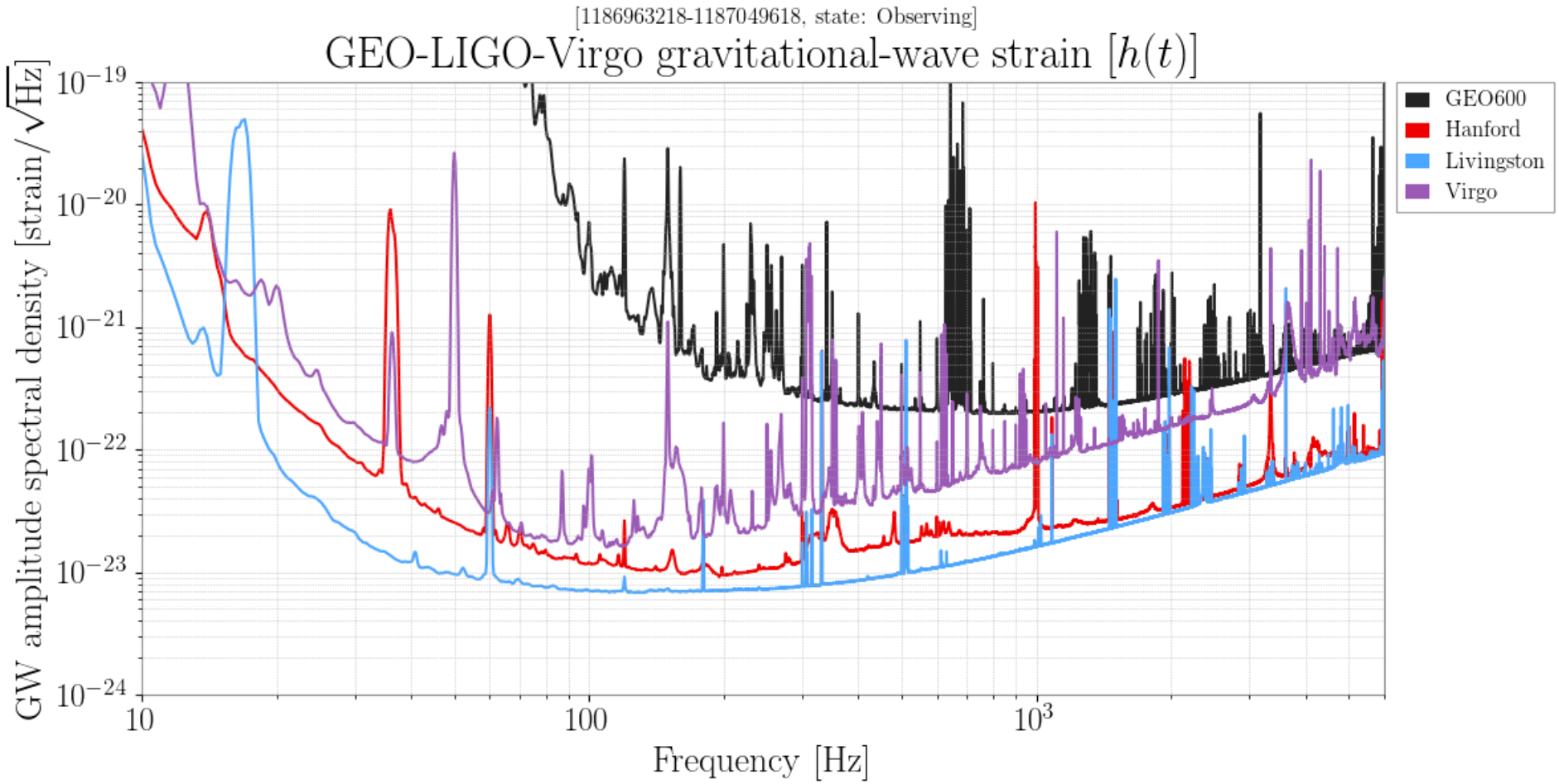
Stationarity



losc.ligo.org/detector_status/day/20170814/

Stationarity



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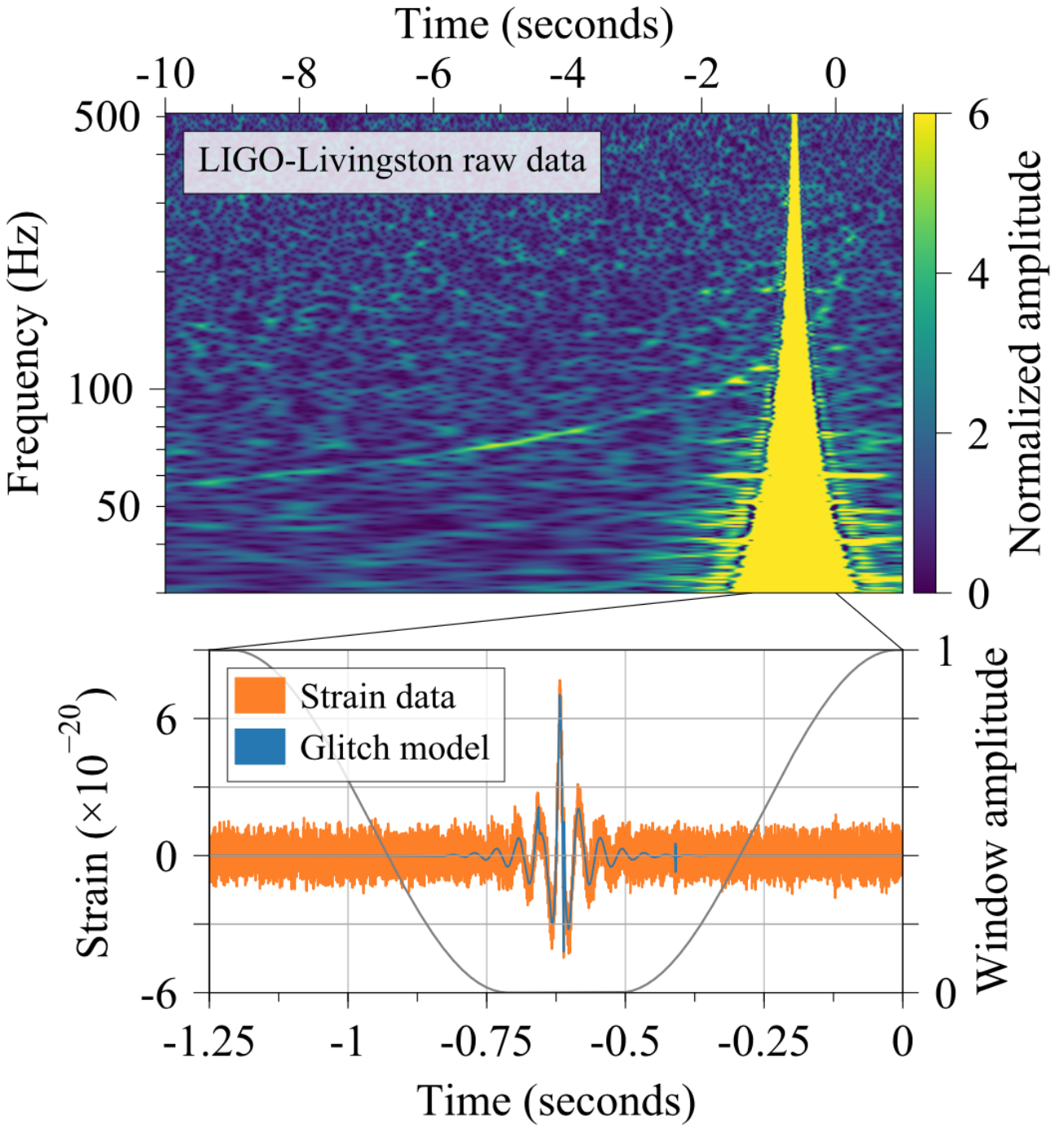
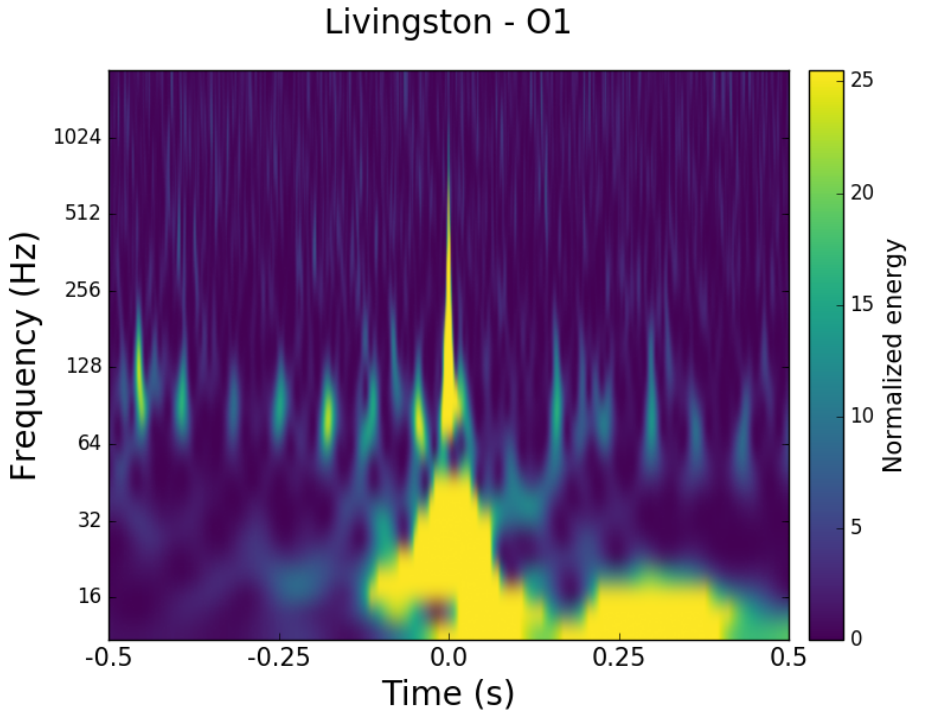
Glitch

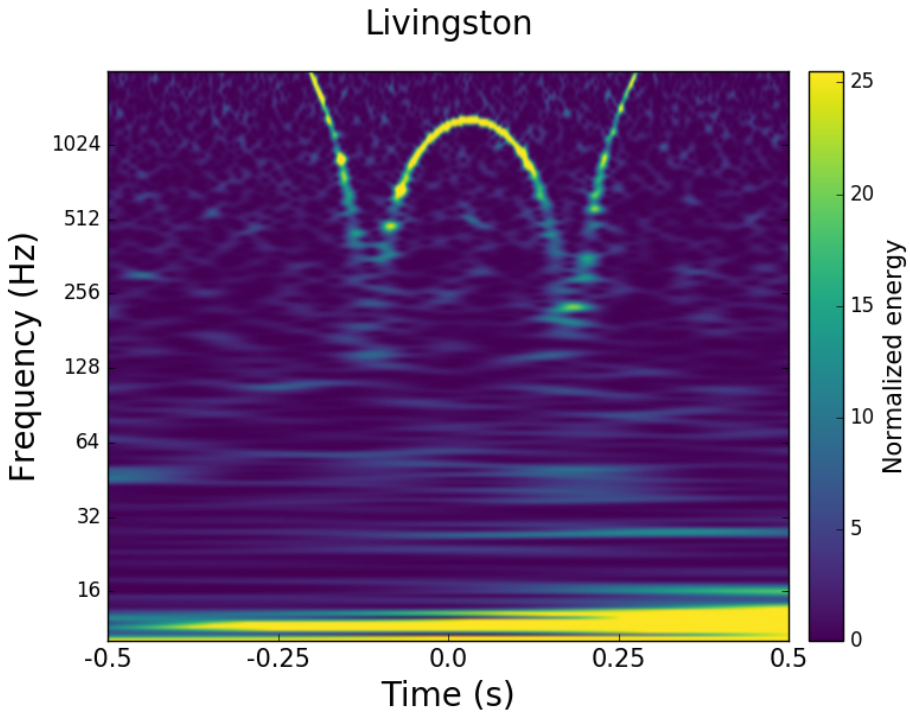


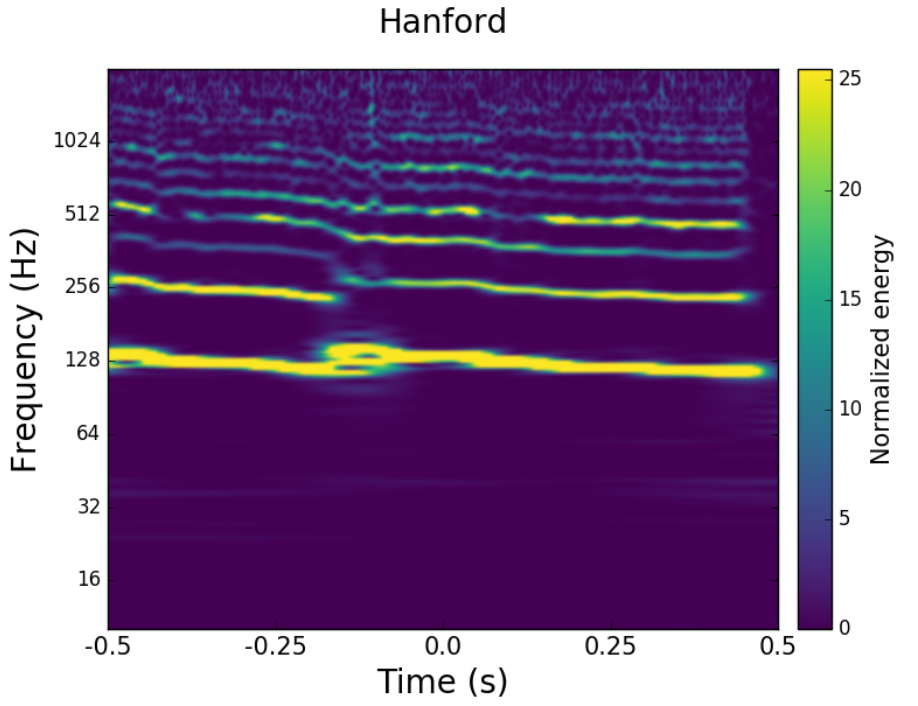
LVC arXiv:1710.05832

Glitch zoo

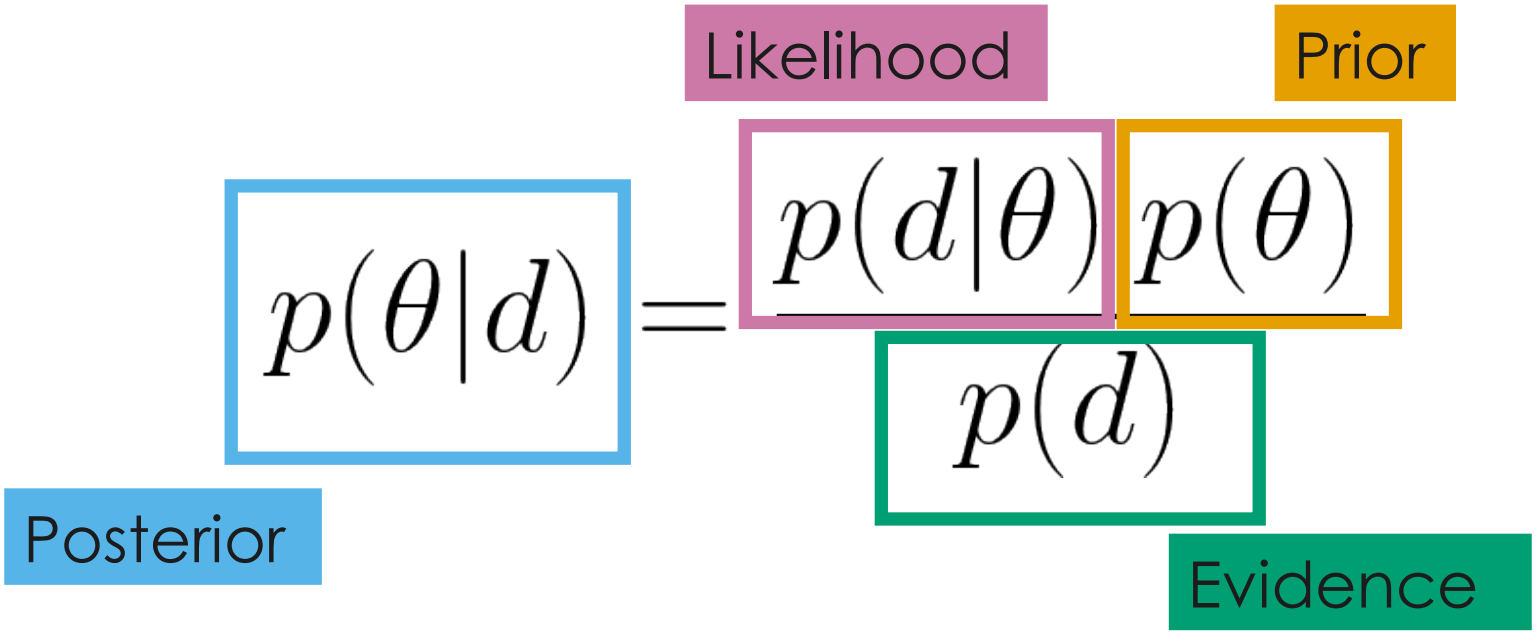
gravityspy.org
Zevin *et al*. arXiv:1611.04596
LVC arXiv:1602.03844



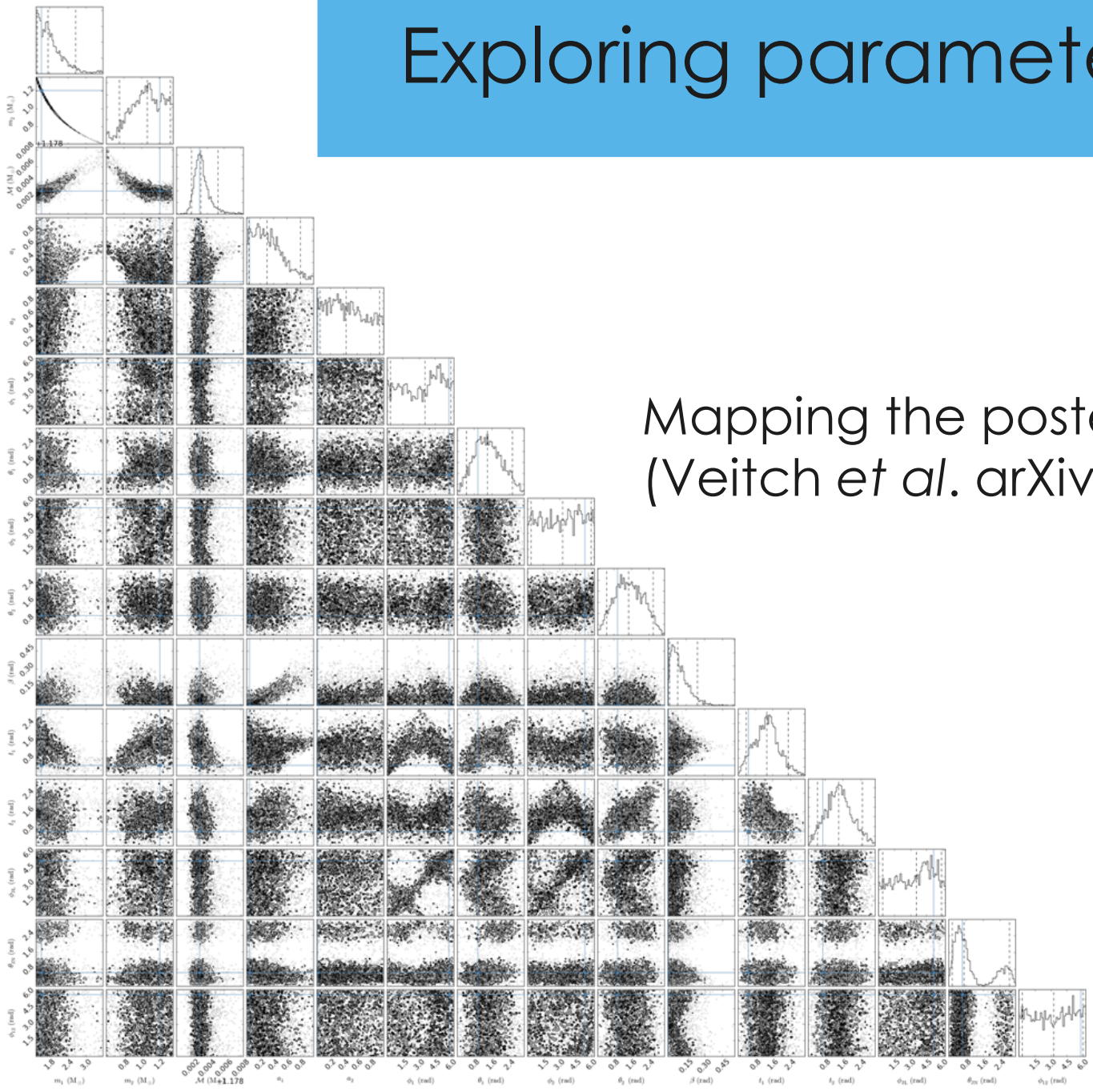




Bayes' theorem

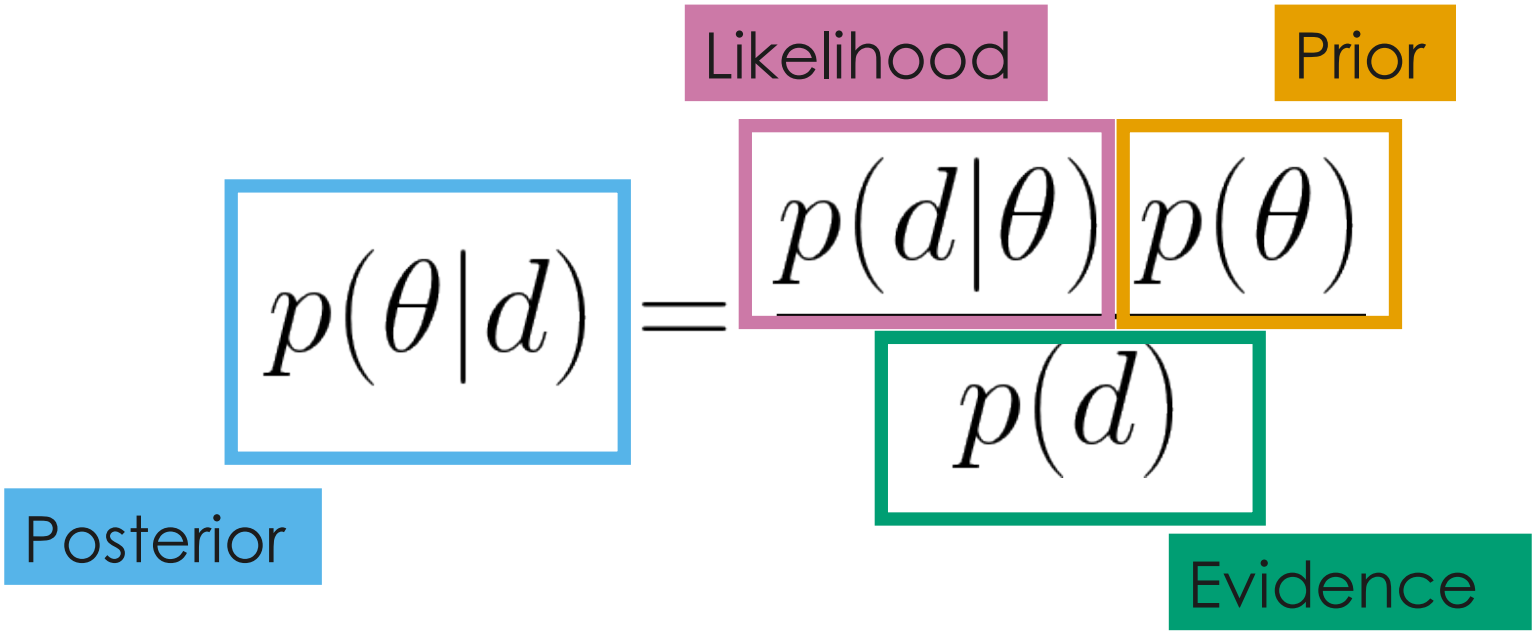


Exploring parameter space

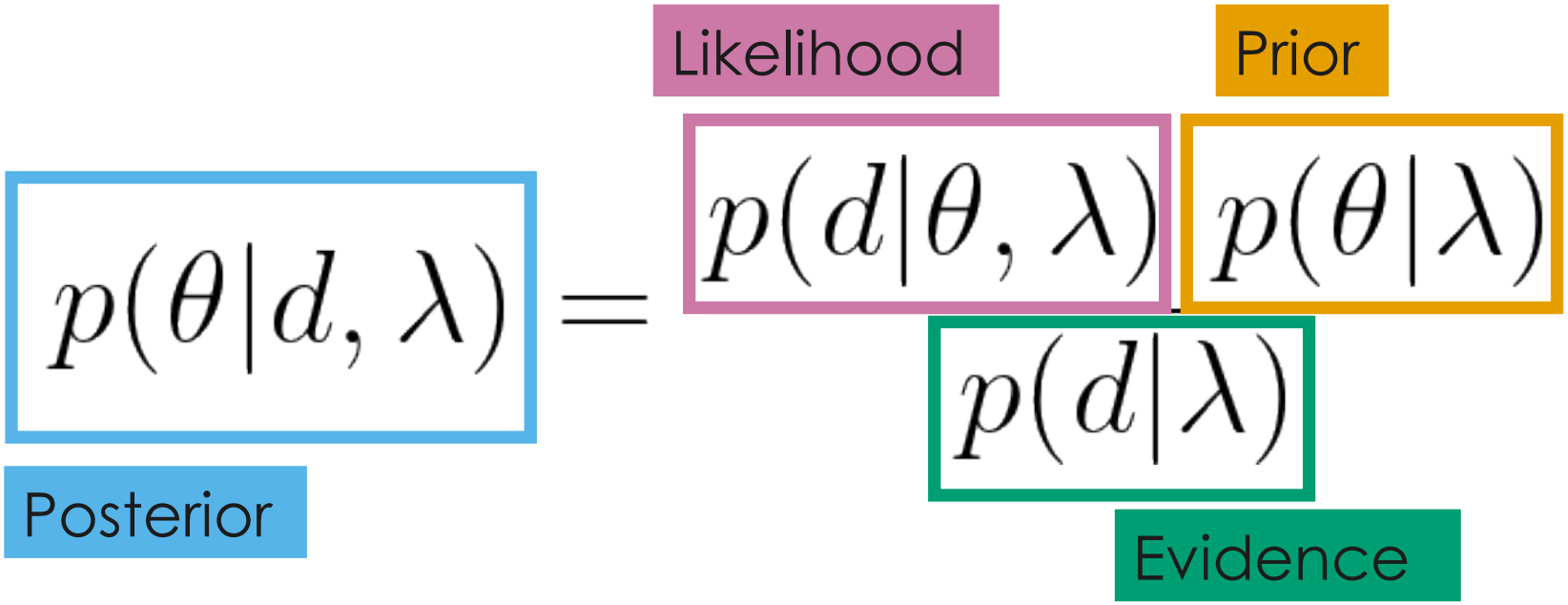


Mapping the posterior is difficult (Veitch *et al*. arXiv:1409.7215)

Bayes' theorem



Bayes' theorem



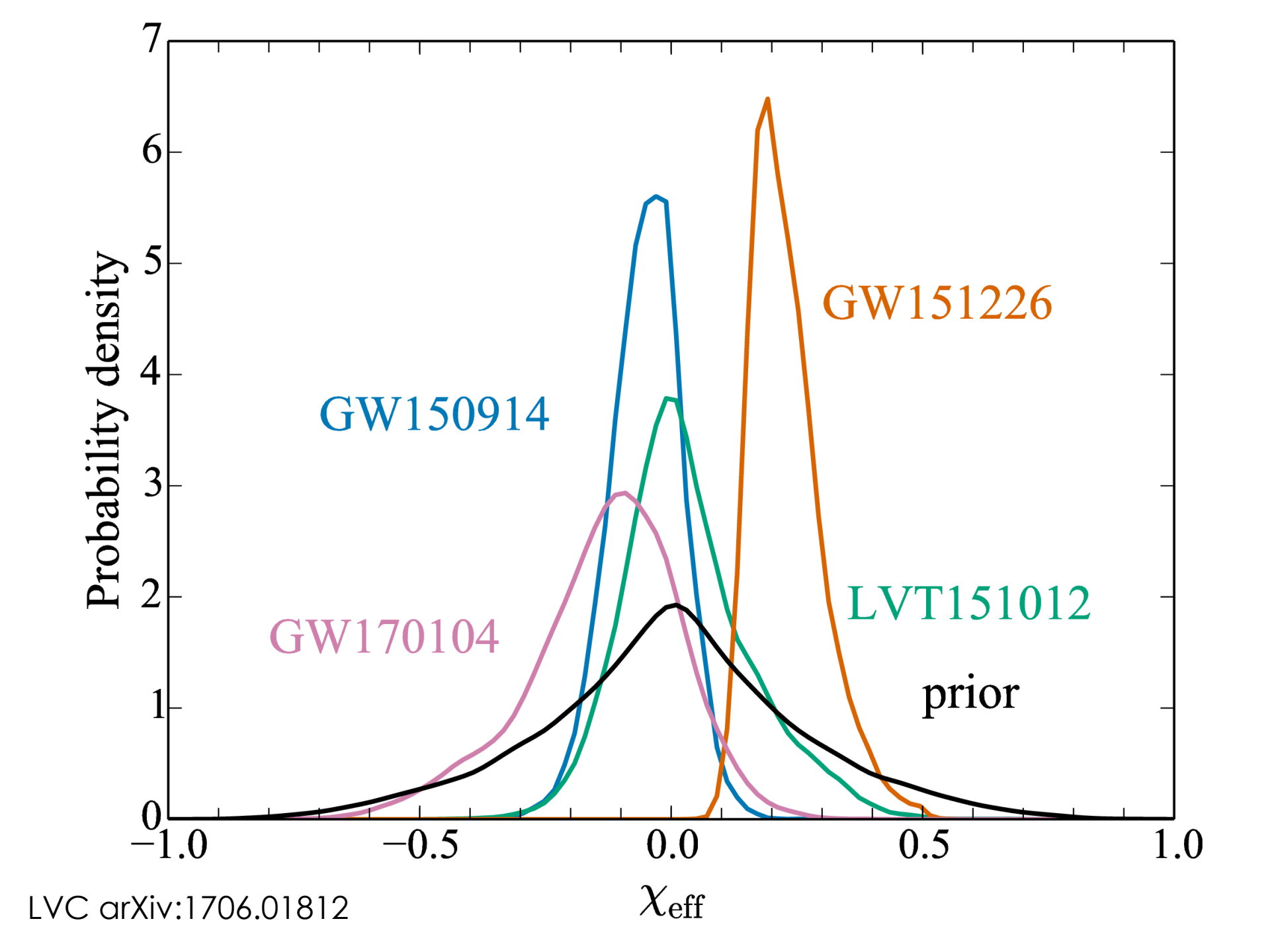
Bayes' theorem

Evidence

Model prior

$$p(\lambda|\{d\}) = \frac{p(\{d\}|\lambda)\,p(\lambda)}{p(\{d\})}$$

Model posterior



LVC arXiv:1706.01812

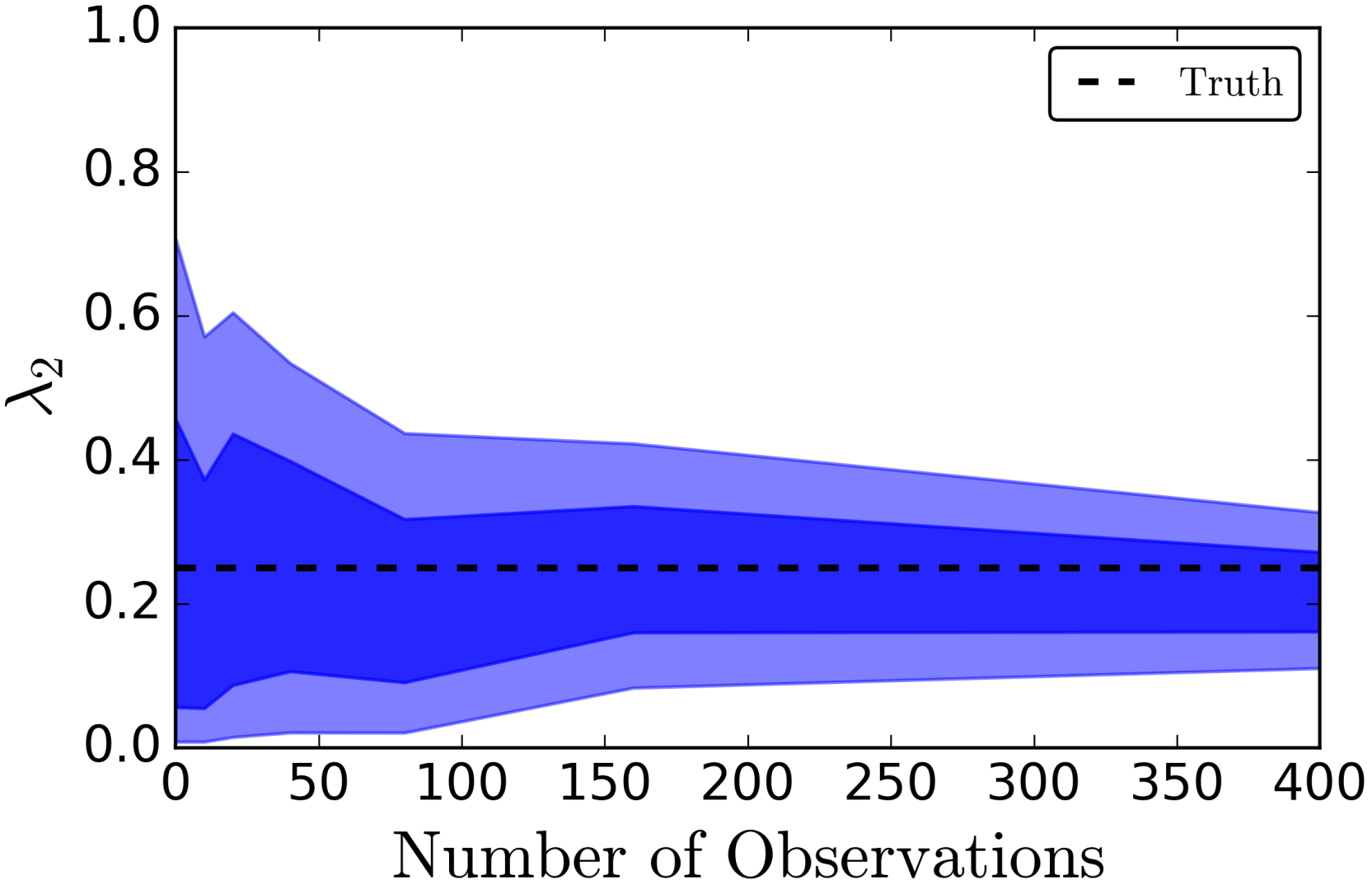
Effective inspiral spin

$$\chi_{\rm eff} = \frac{c}{GM}\left(\frac{\boldsymbol{S}_1}{m_1} + \frac{\boldsymbol{S}_2}{m_2}\right) \cdot \hat{\boldsymbol{L}}$$

Most important combination of spins for evolution of inspiral (Ajith *et al*. arXiv:0909.2867, Santamaría *et* al. arXiv:1005.3306)

Model inference

Stevenson, CPLB & Mandel
arXiv:1703.06873



Model inference

Stevenson, CPLB & Mandel
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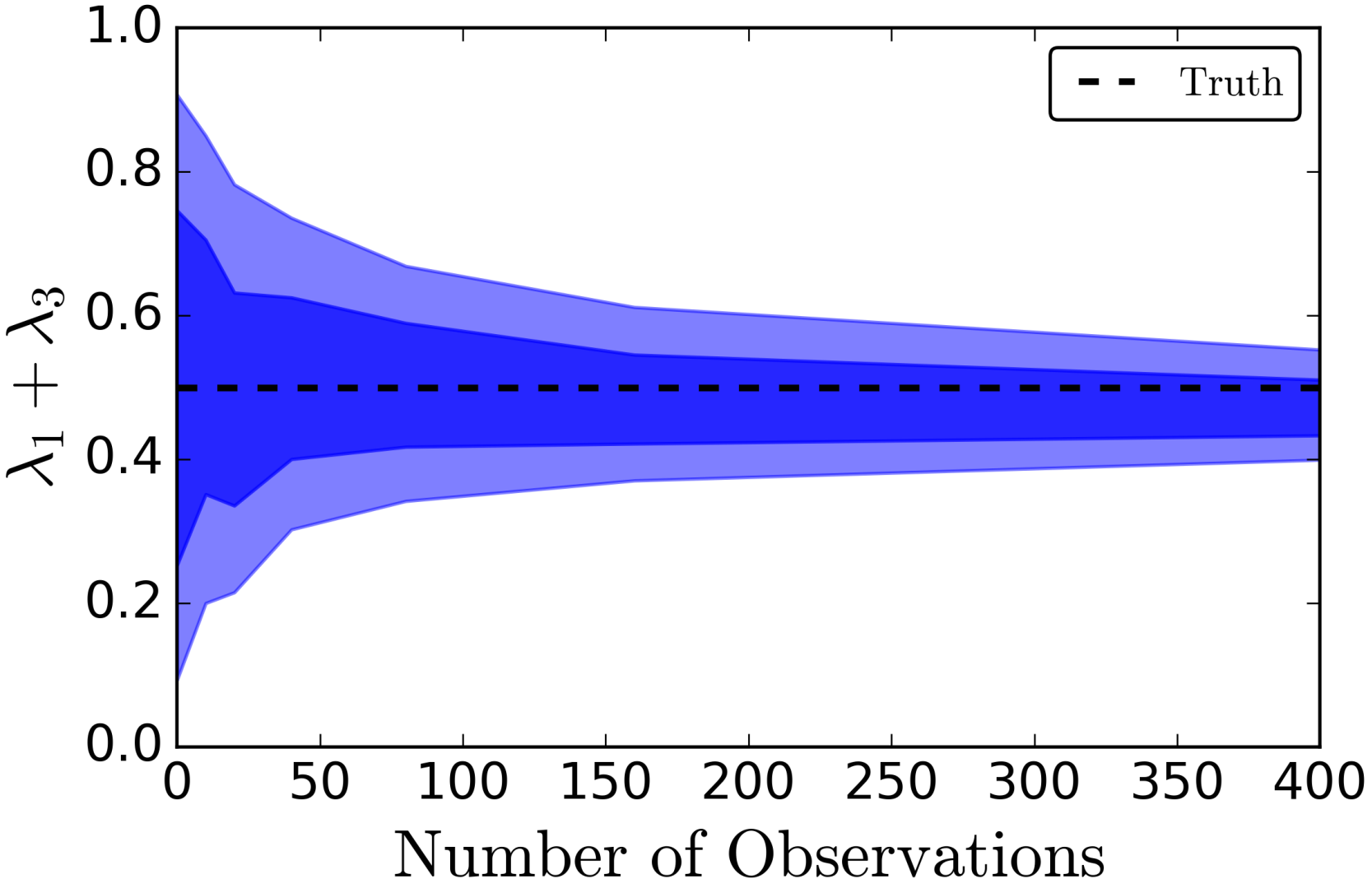
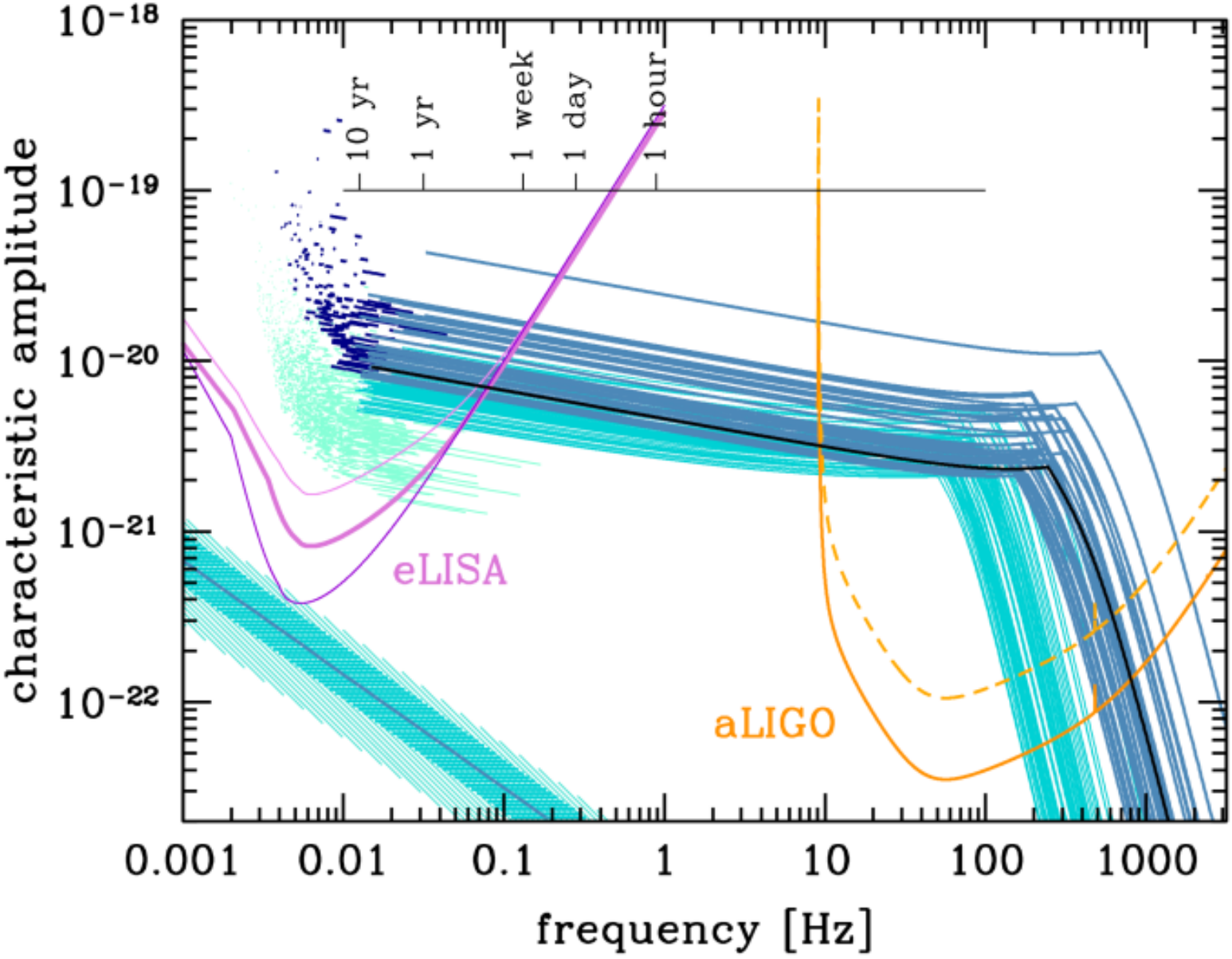


Chirp mass

$$\mathcal{M}_{\rm c} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

Chirp mass gives leading-order amplitude and phase evolution (Blanchet *et al*. arXiv:gr-qc/9501027 Poisson & Will arXiv:gr-qc/9502040)

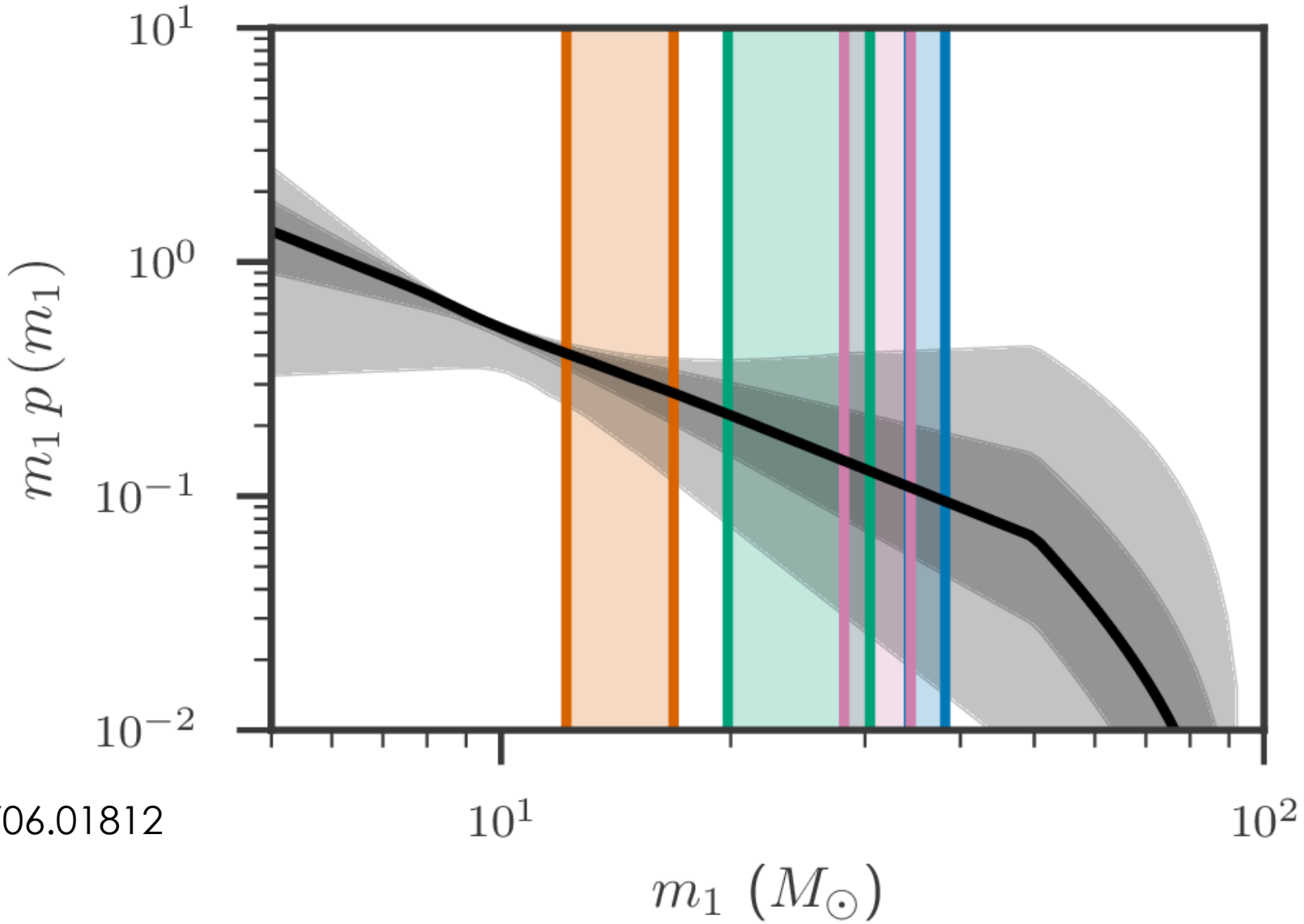
Sesana arXiv:1602.06951



Nishizawa *et al*. arXiv:1606.09295

Breivik *et al*. arXiv:1606.09558

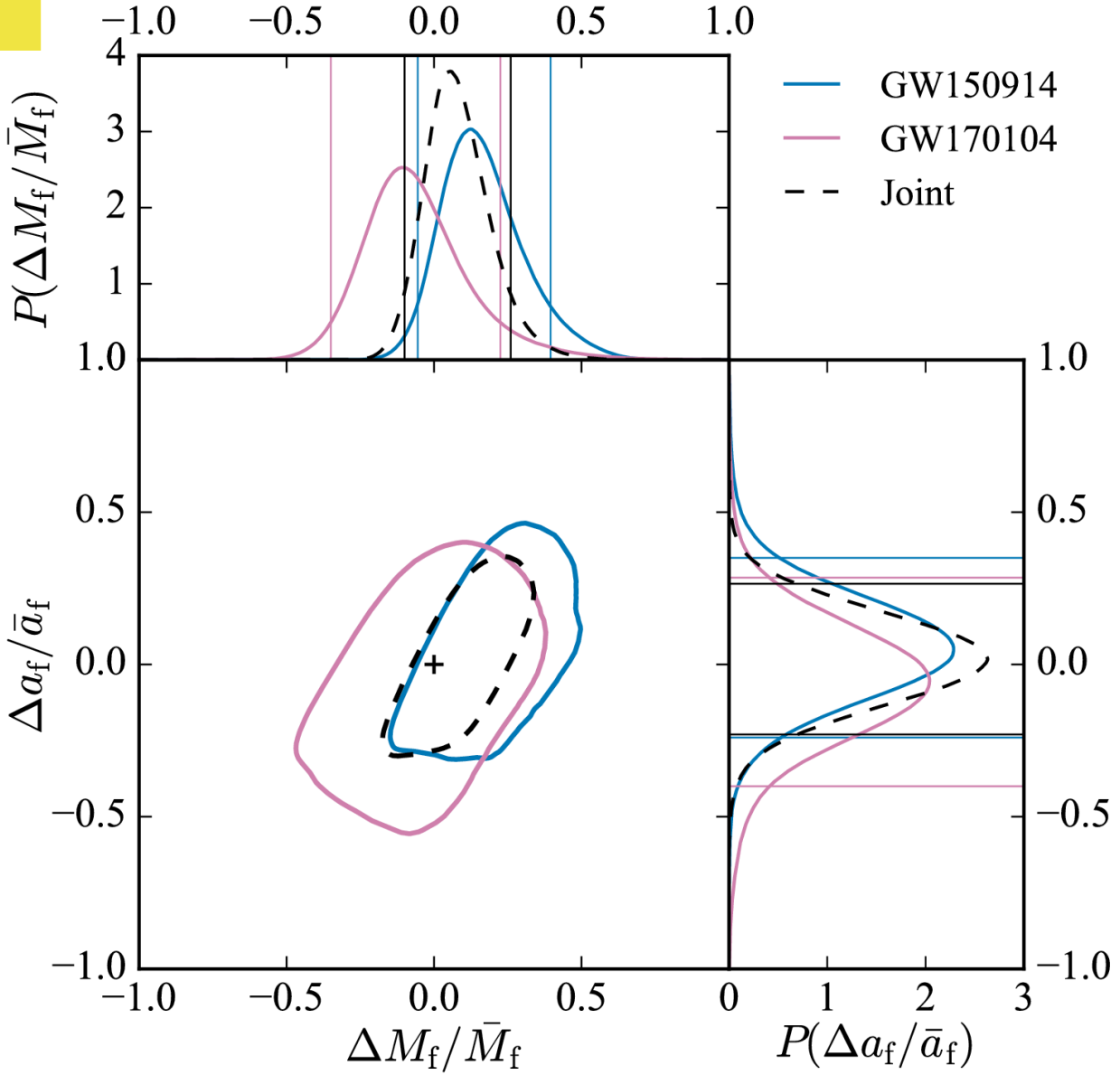
Mass distribution



LVC
arXiv:1706.01812

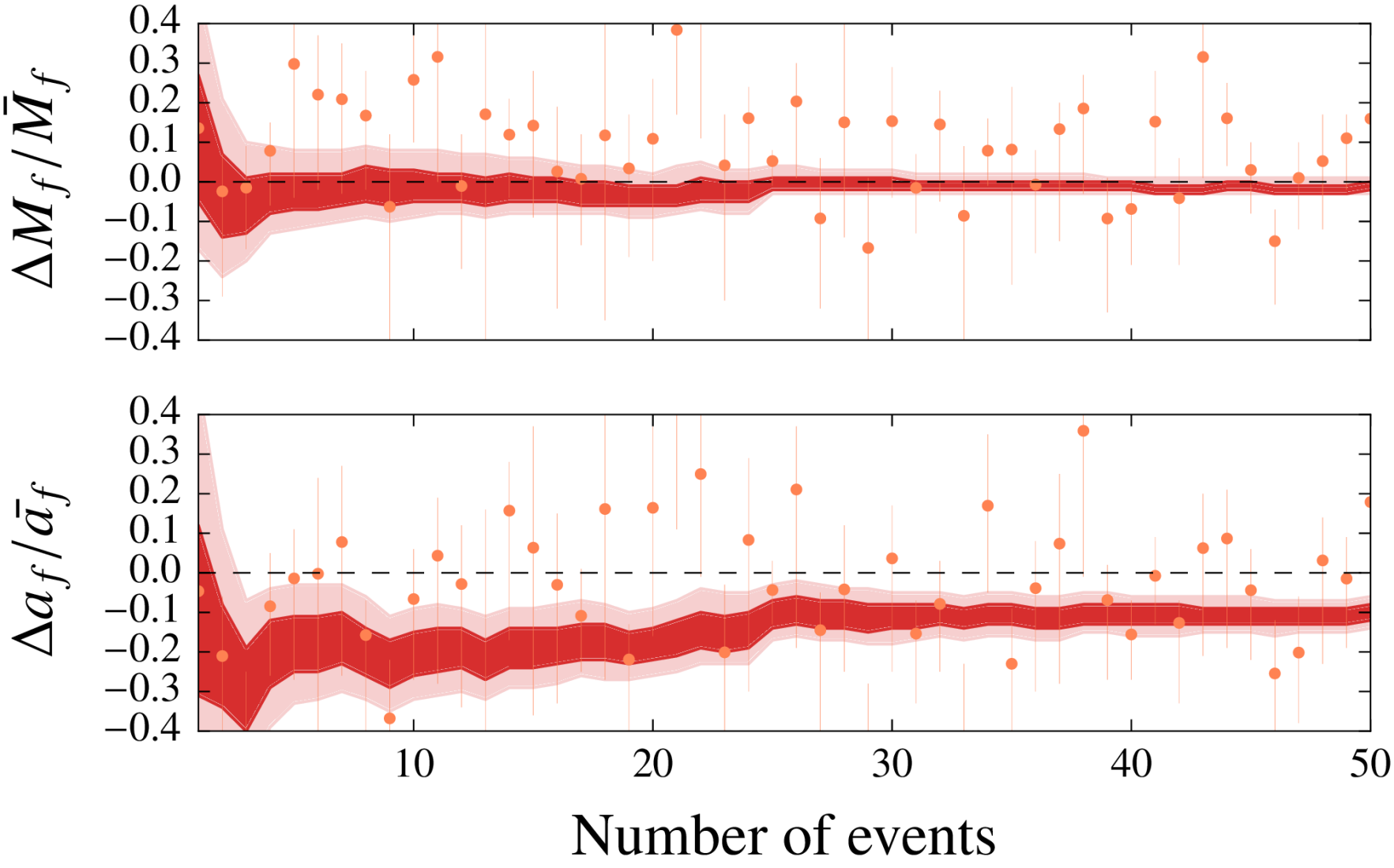
Testing GR

LVC arXiv:1602.03841
arXiv:1706.01812



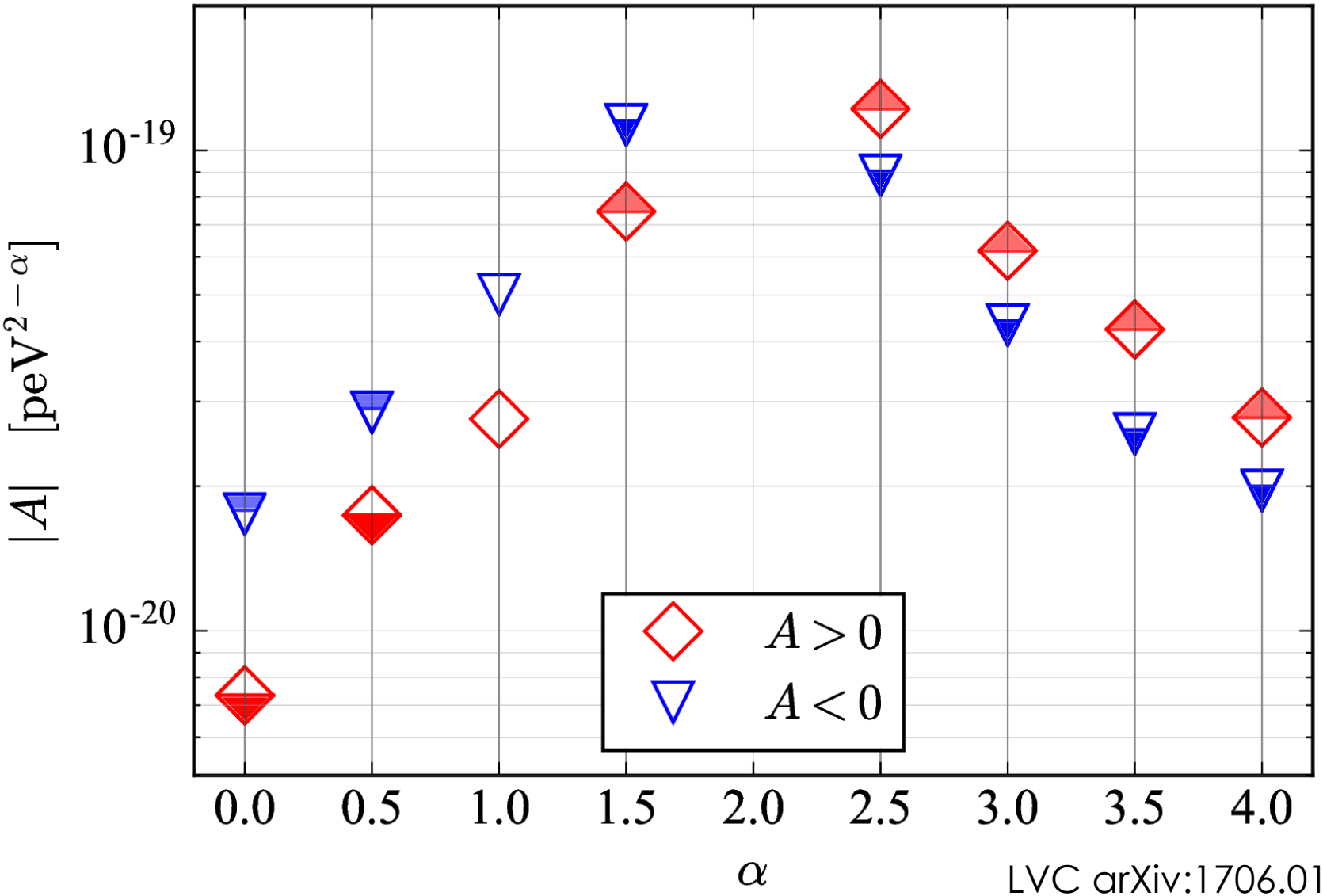
Testing GR

Ghosh *et al*. arXiv:1704.06784



Dispersion

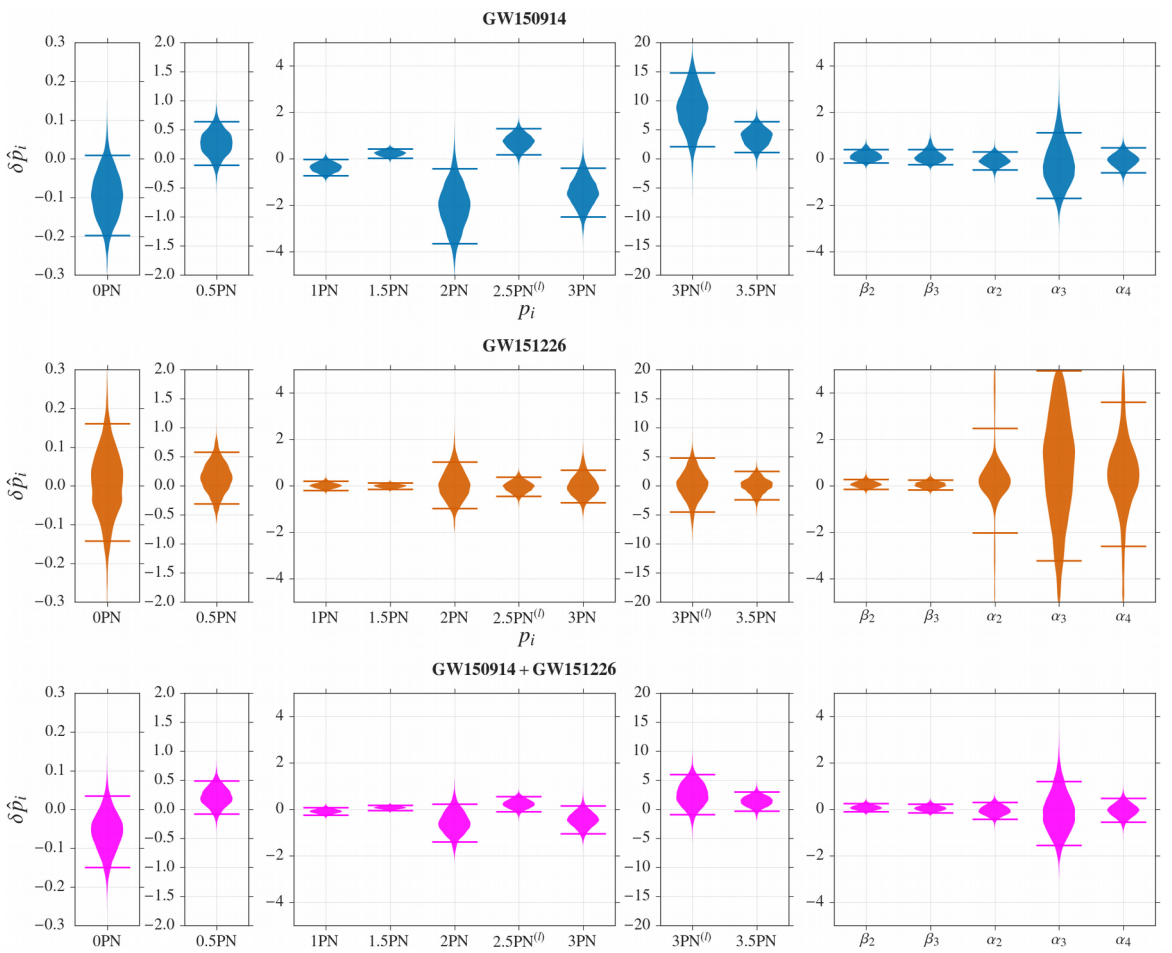
$$E^2 = p^2c^2 + Ap^\alpha c^\alpha$$

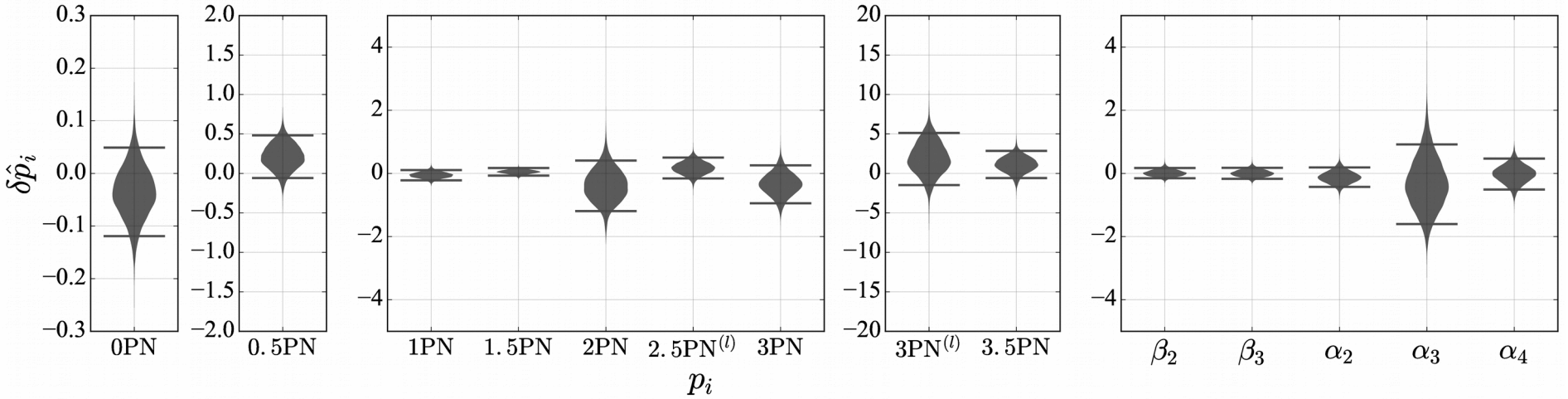


LVC arXiv:1706.01812

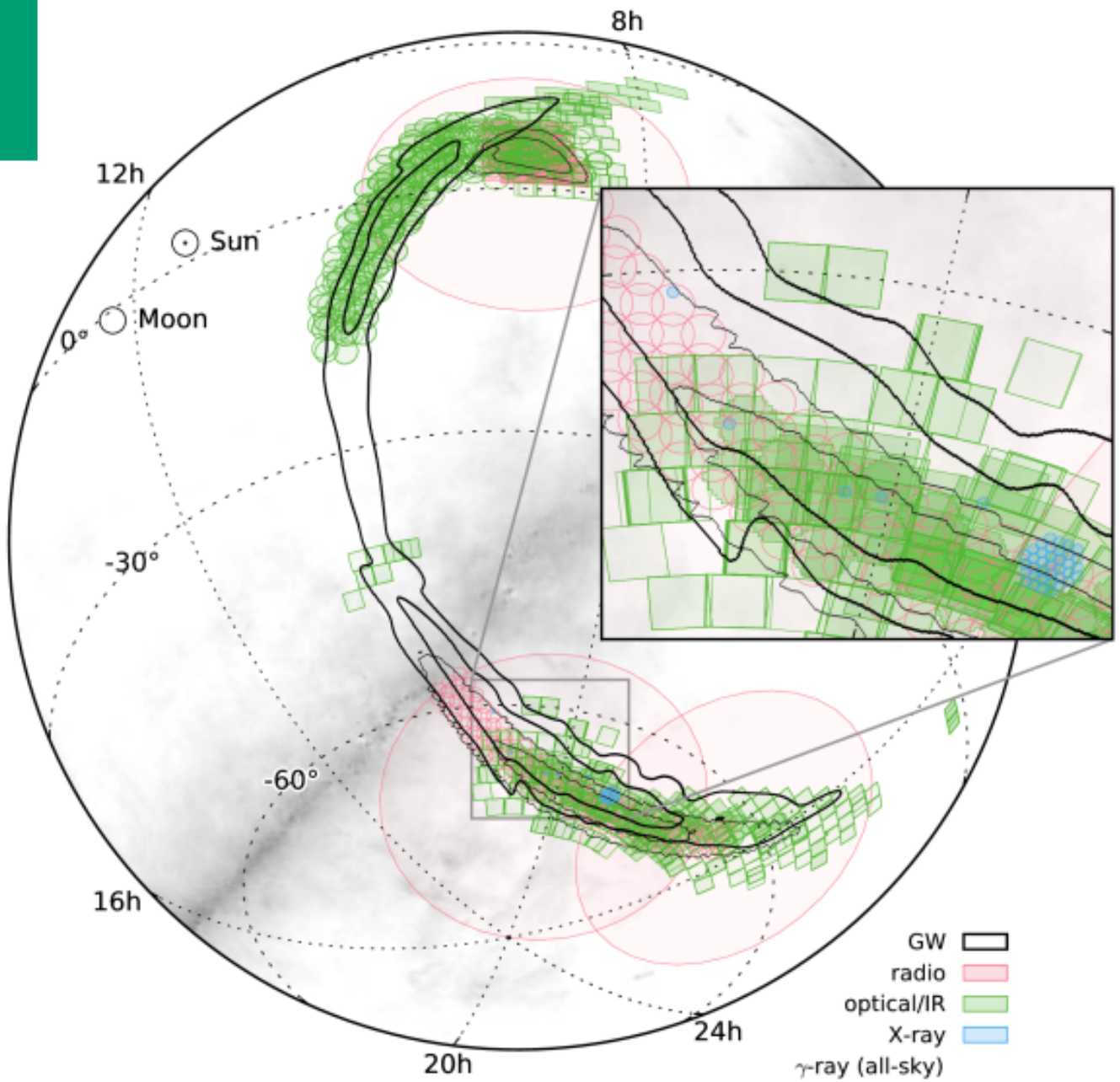
Testing GR

LVC arXiv:1606.04856
arXiv:1706.01812

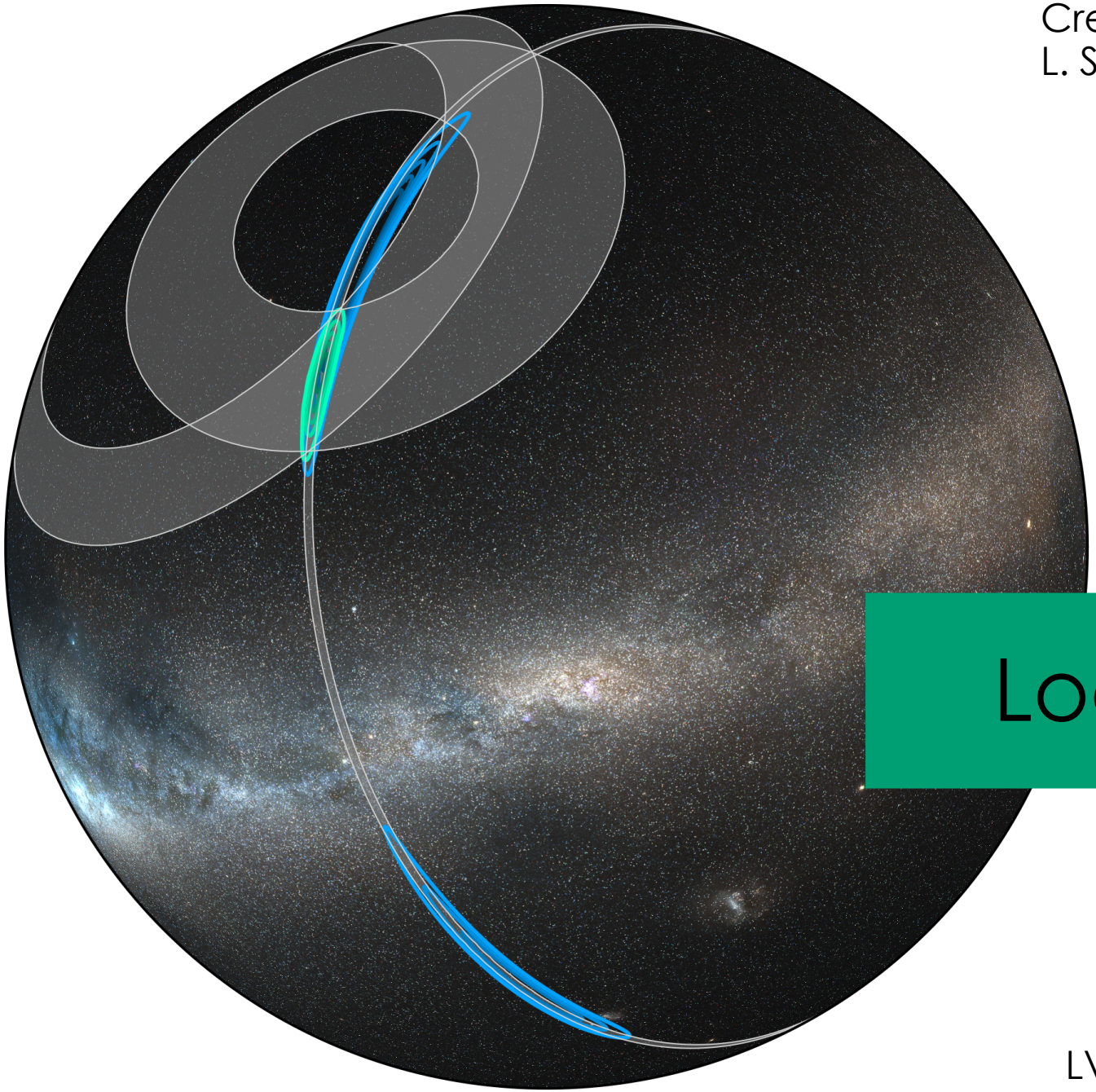




Follow-up



LVC
arXiv:1602.08492
arXiv:1604.07864



Credit: LVC/NASA/
L. Singer/A. Mellinger

Location

LVC arXiv:1710.05832

Data release 2015, HL 2016, HLV new 2015, recoloured Show/hide columns

The First Two Years of Electromagnetic Follow-Up with Advanced LIGO and Virgo

Singer et al. 2014 arXiv:1404.5623

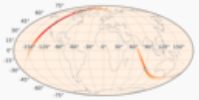
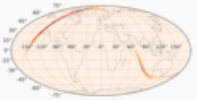
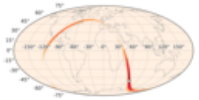
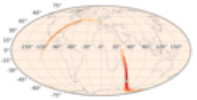
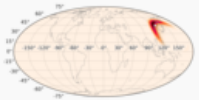
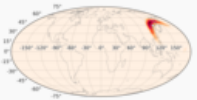
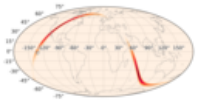
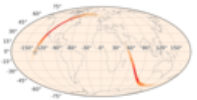
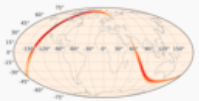
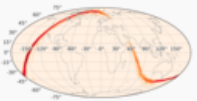
Berry et al. 2015 arXiv:1411.6934

www.ligo.org/scientists/first2years/
asd.gsfc.nasa.gov/Leo.Singer/going-the-distance/

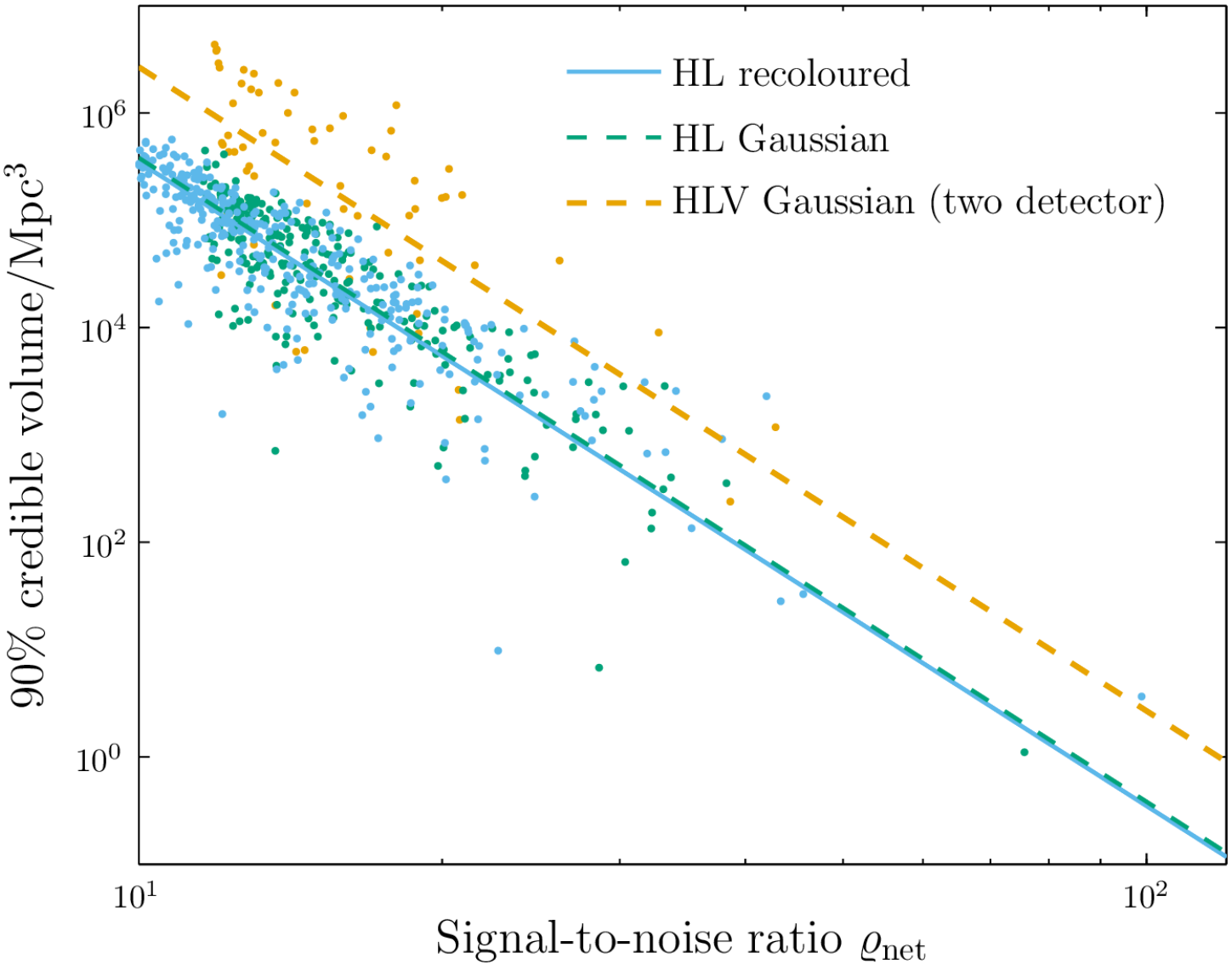
Data release 2015, HL 2016, HLV new 2015, recoloured Show/hide columns

This web page pr
additional online r
related to the pap
Two Years of Ele
Follow-Up with Ad
and Virgo" and th
paper "Parameter
for Binary Neutro
Coalescences wit

Catalog of simulated events and sky maps for two-detector, HL, 2015 configuration. This is the same configuration as the 2015 tab, except that the simulated detector noise is data from initial LIGO's sixth science run, recoloured (filtered) to have the same PSD as the early Advanced LIGO configuration. See also ASCII tables of simulated signals, detections, and parameter-estimation accuracies in Machine Readable Table format.

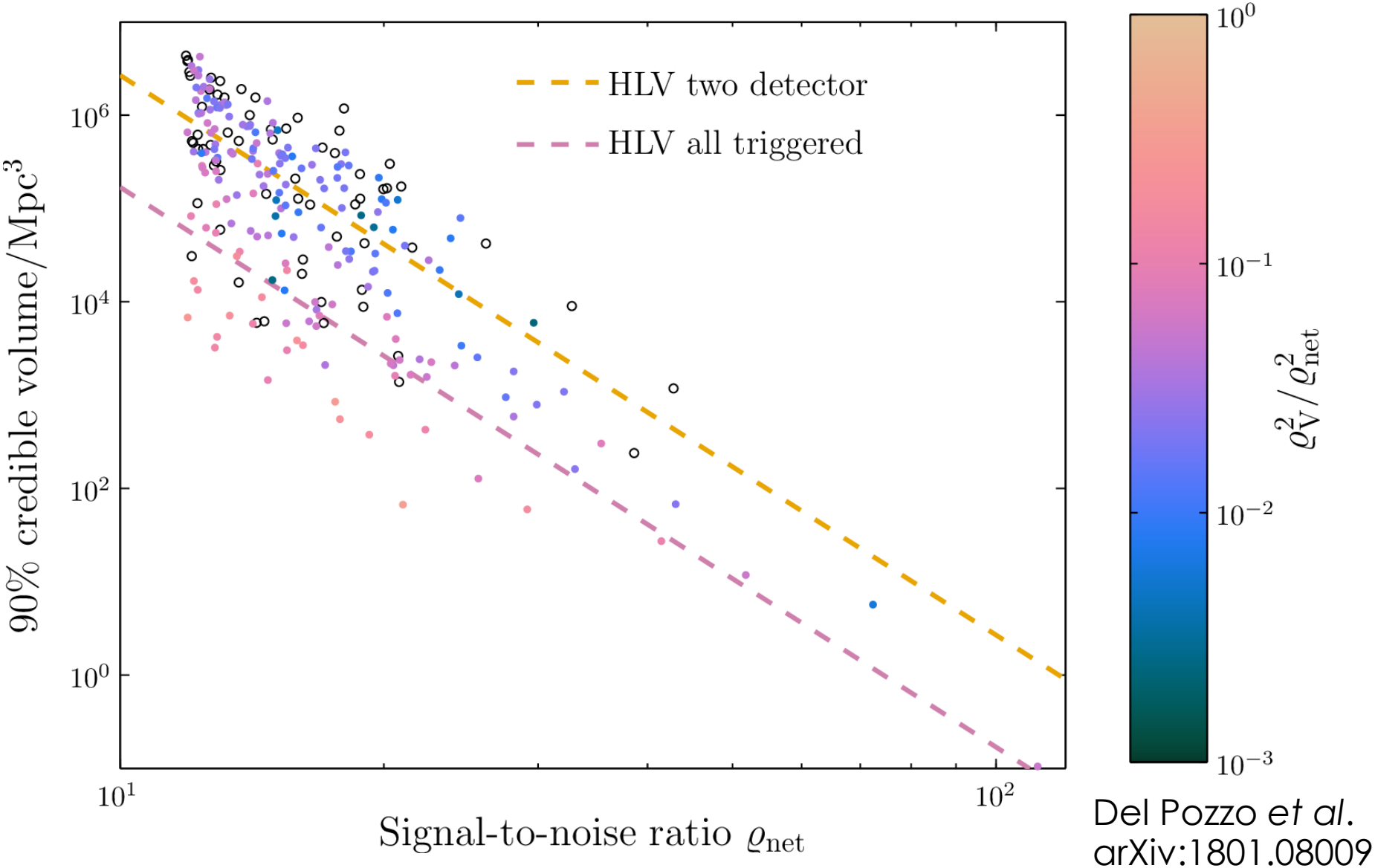
event ID	sim ID	network	SNR			BAYESTAR			LALINFERENCE_NEST			sky maps	
			net	H	L	50%	90%	searched	50%	90%	searched	BAYESTAR	LALINFERENCE_NEST
4532	899	HL	13.9	10.1	9.5	180	750	190	170	790	150		
4572	1243	HL	13.2	10.0	8.7	230	830	45	200	920	33		
4618	1768	HL	10.8	8.0	7.3	160	540	220	130	440	280		
4647	1964	HL	12.4	8.6	9.0	260	890	1200	190	780	780		
4711	2704	HL	10.7	8.0	7.1	370	1200	300	450	1600	520		

3-dimensional localization

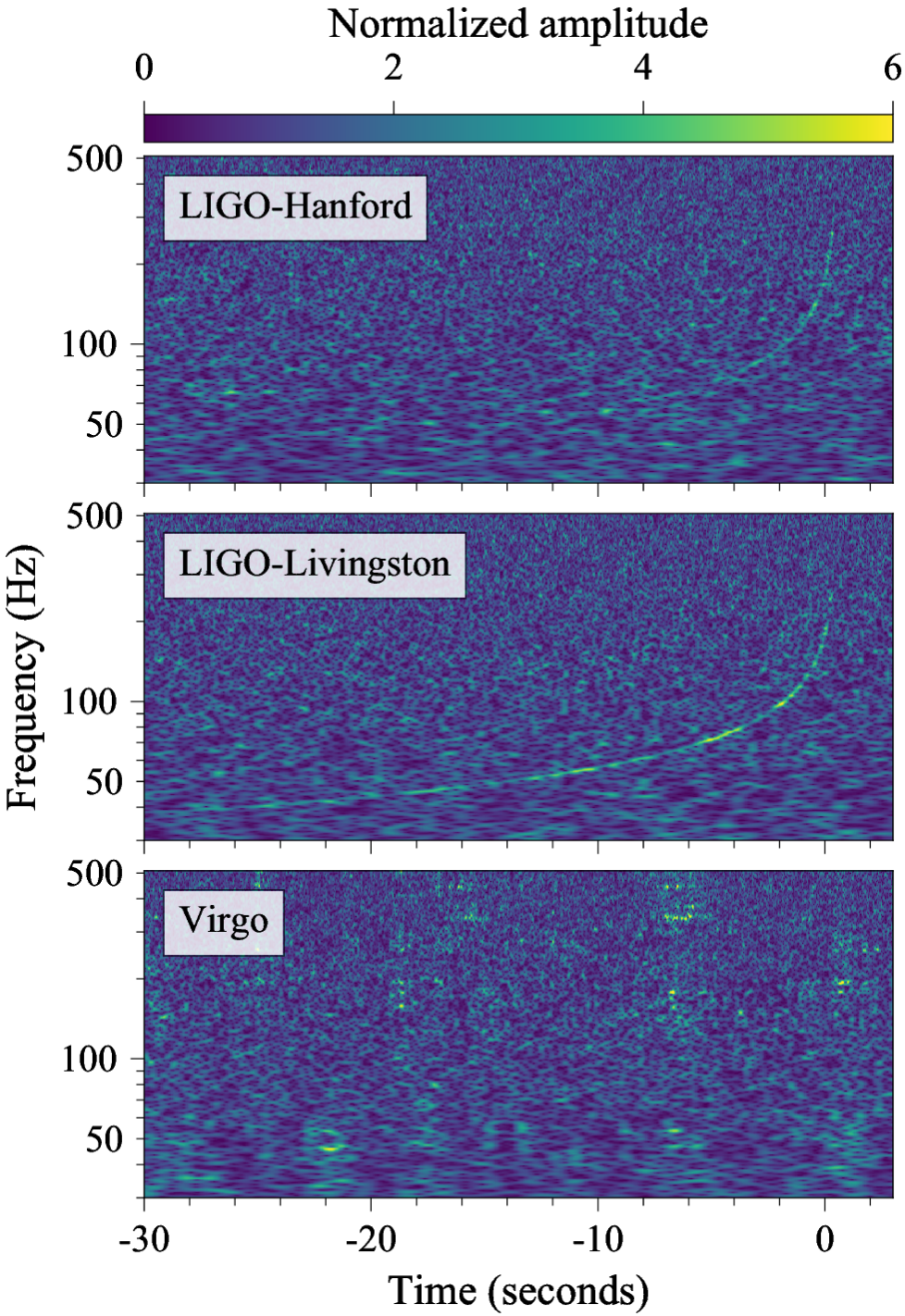


Del Pozzo *et al.*
arXiv:1801.08009

3-dimensional localization



Del Pozzo *et al.*
arXiv:1801.08009

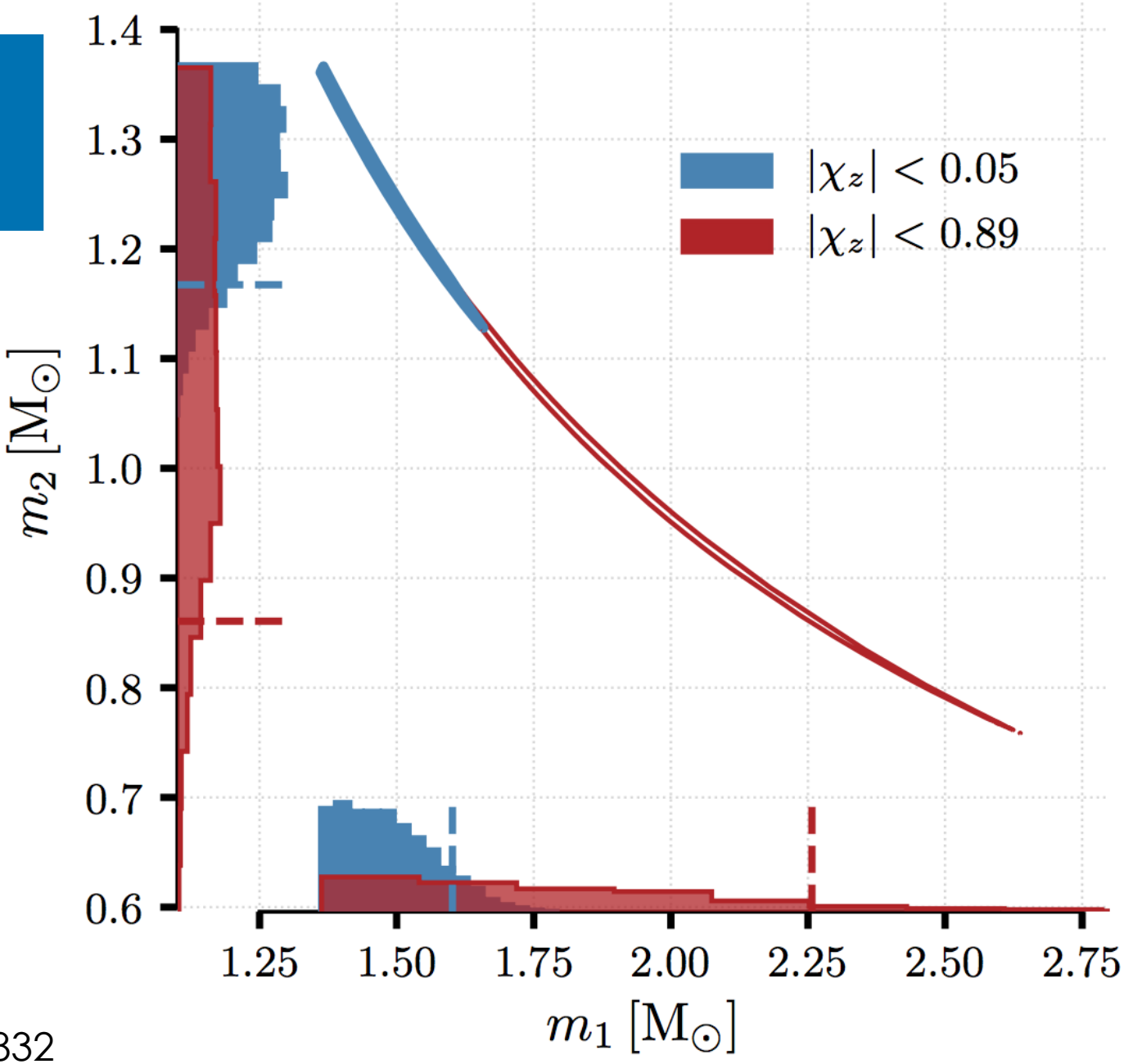


GW170817

13:41:04 BST 17 August 2017

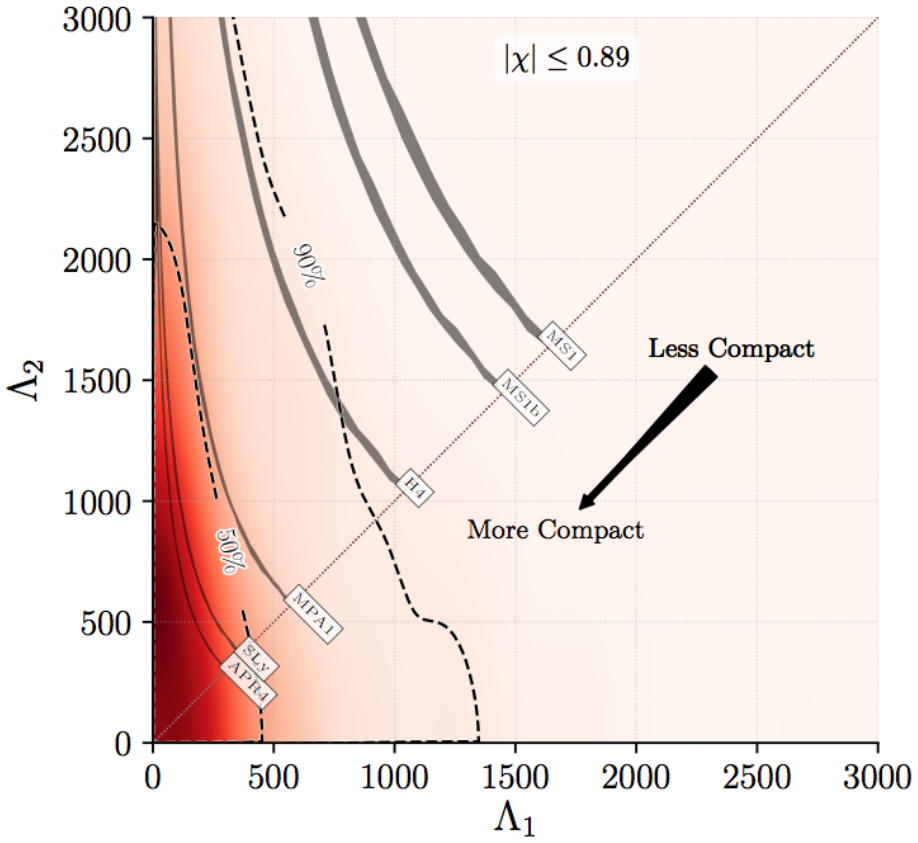
LVC arXiv:1710.05832

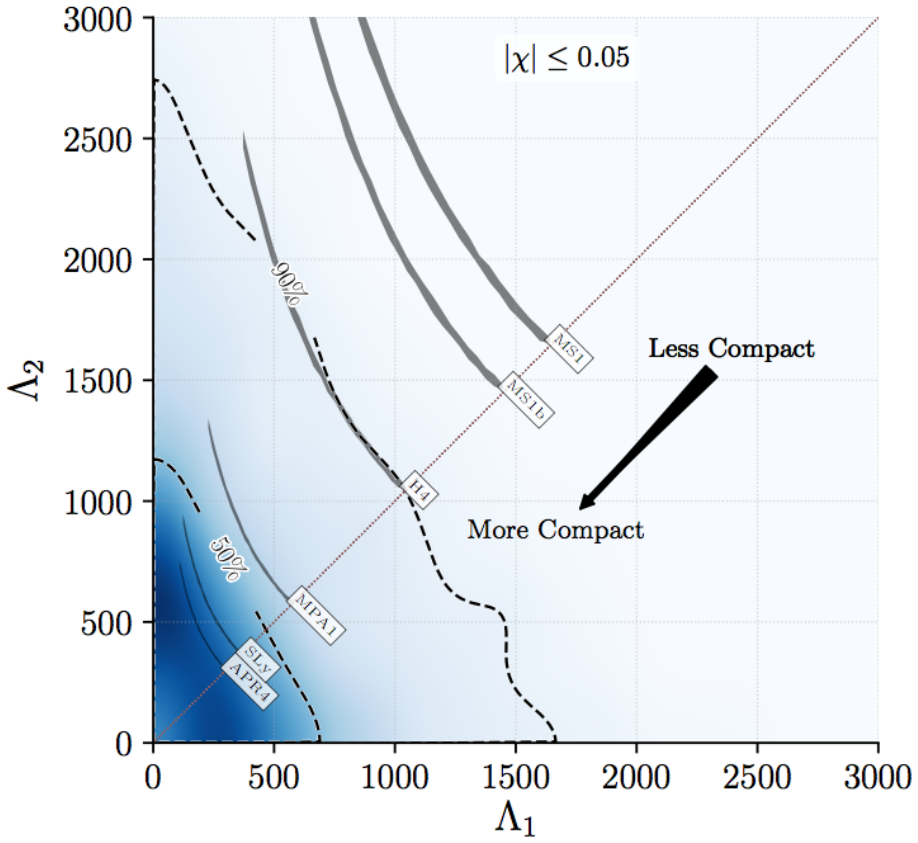
Masses



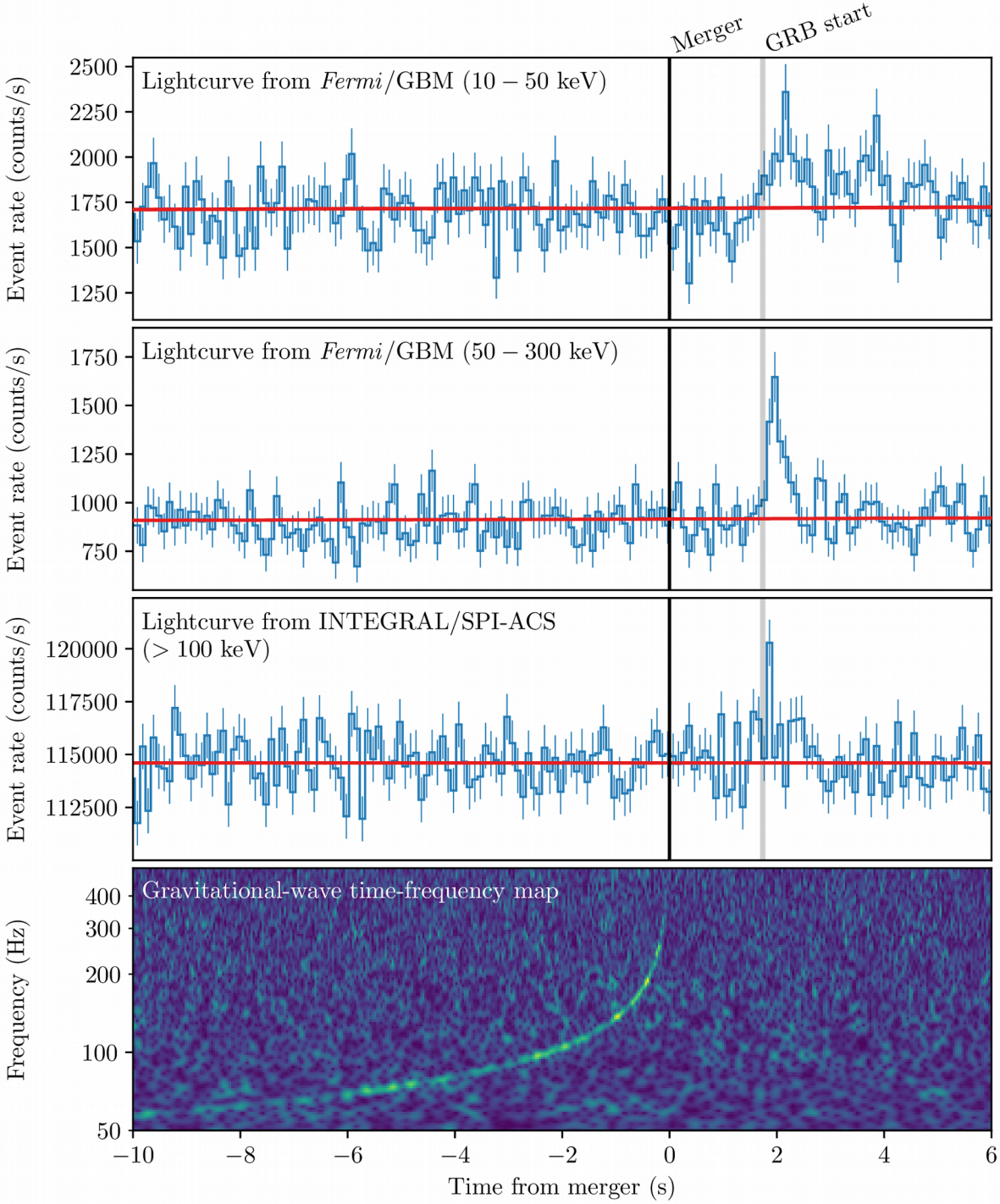
LVC arXiv:1710.05832

Tidal distortion





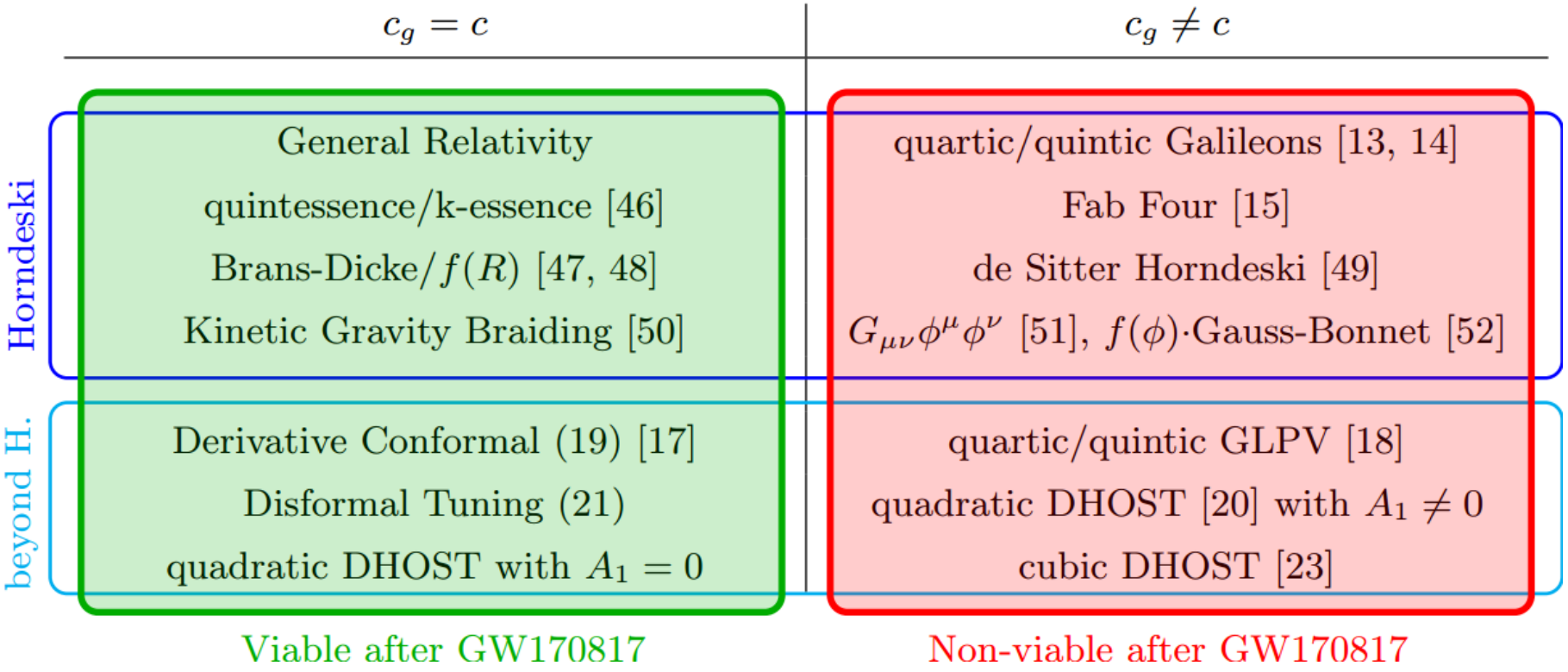
LVC arXiv:1710.05832



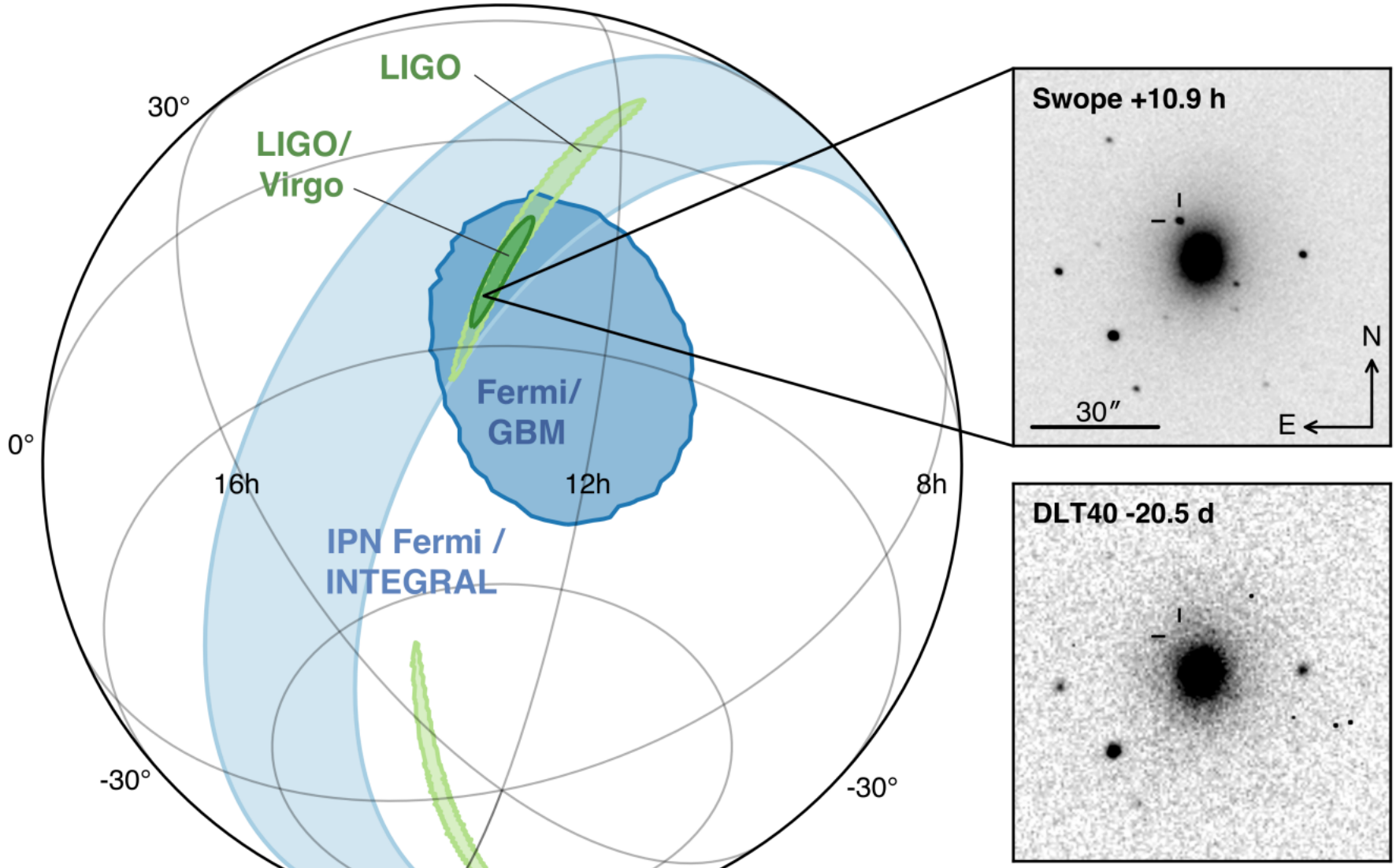
Gamma-rays

LVC, Fermi & INTEGRAL
arXiv:1710.05834

Gravity vs light

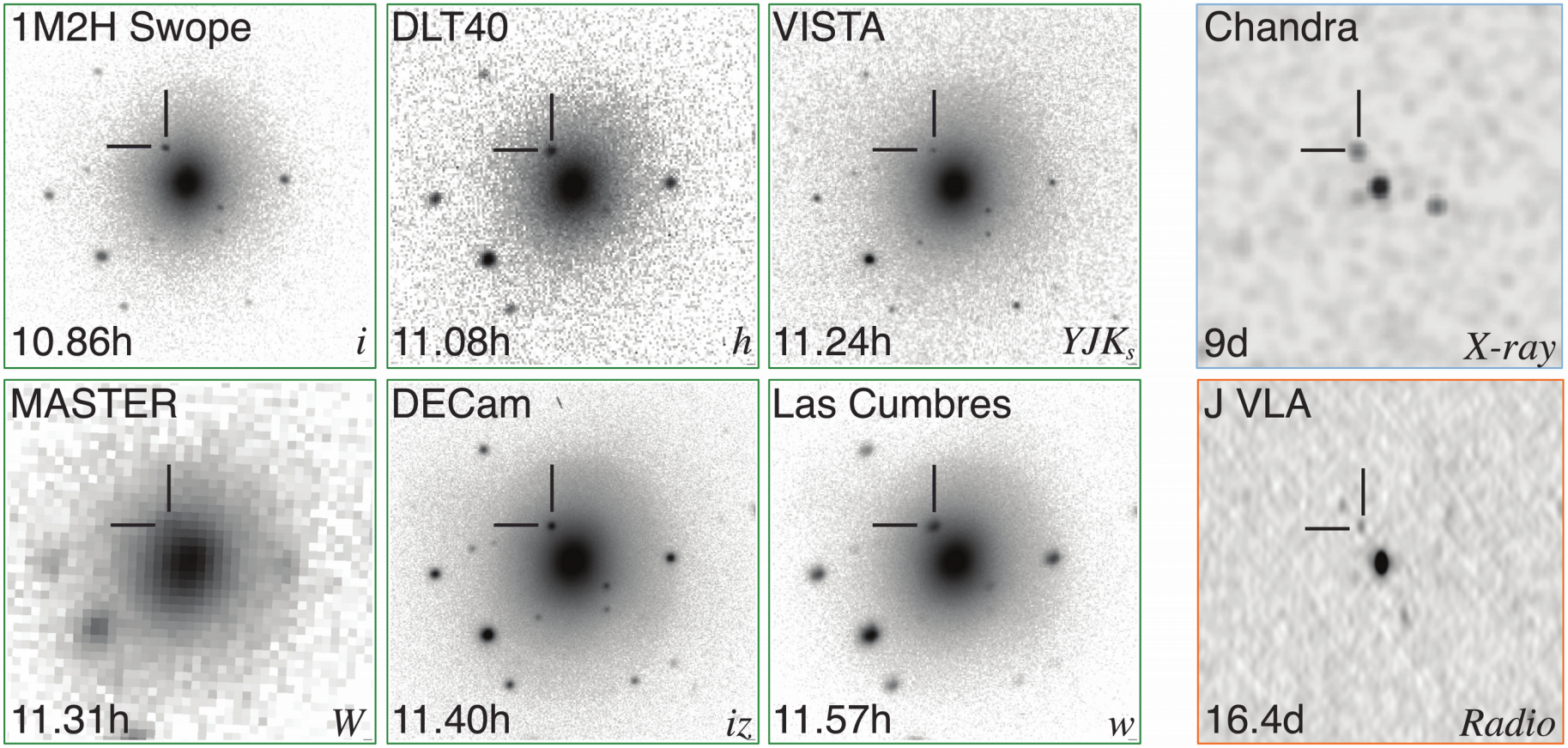


Ezquiaga & Zumalacárregui arXiv:1710.05901



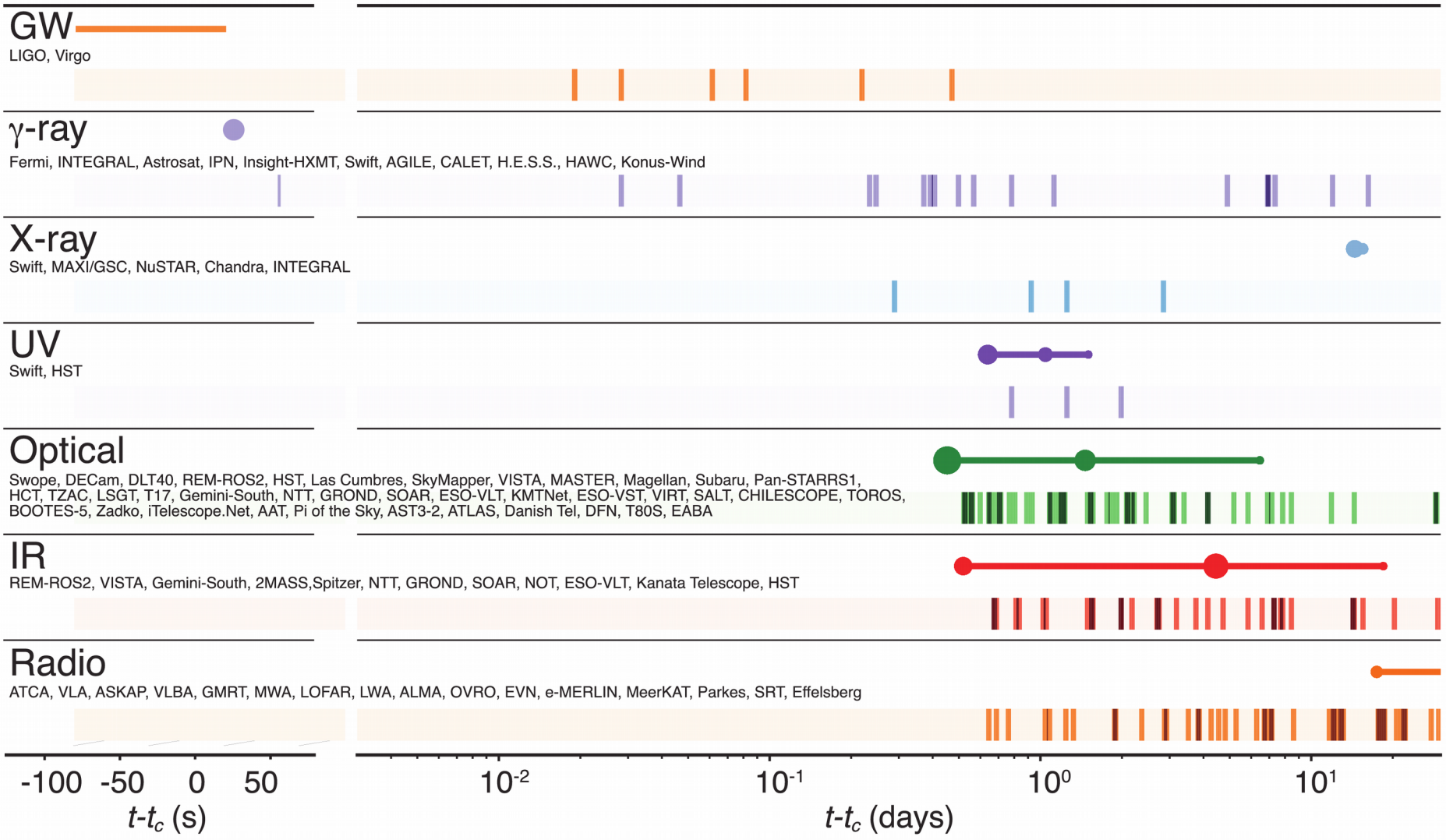
LVC+ arXiv:1710.05833

Spectrum of observations



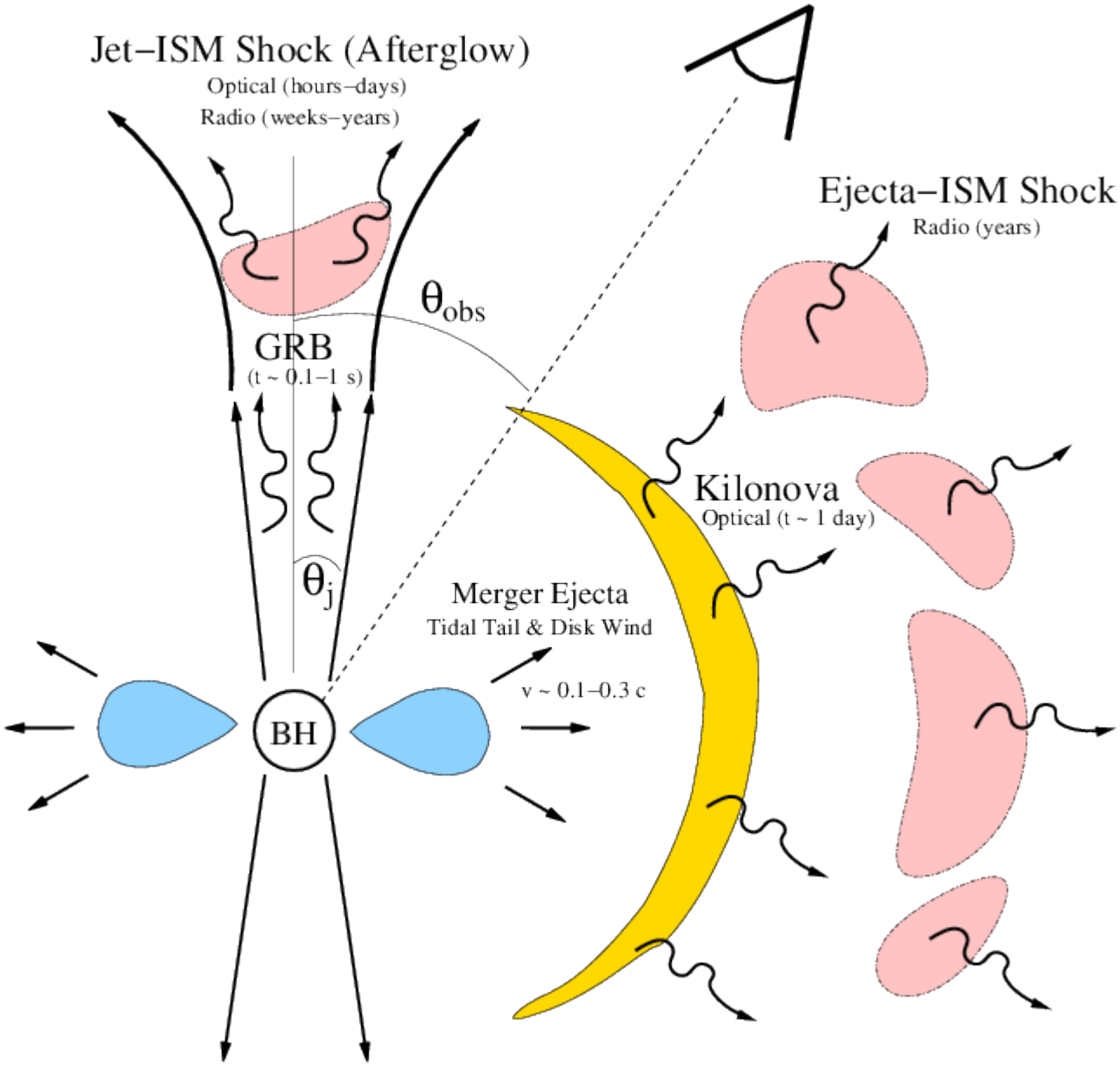
LVC+ arXiv:1710.05833

Spectrum of observations



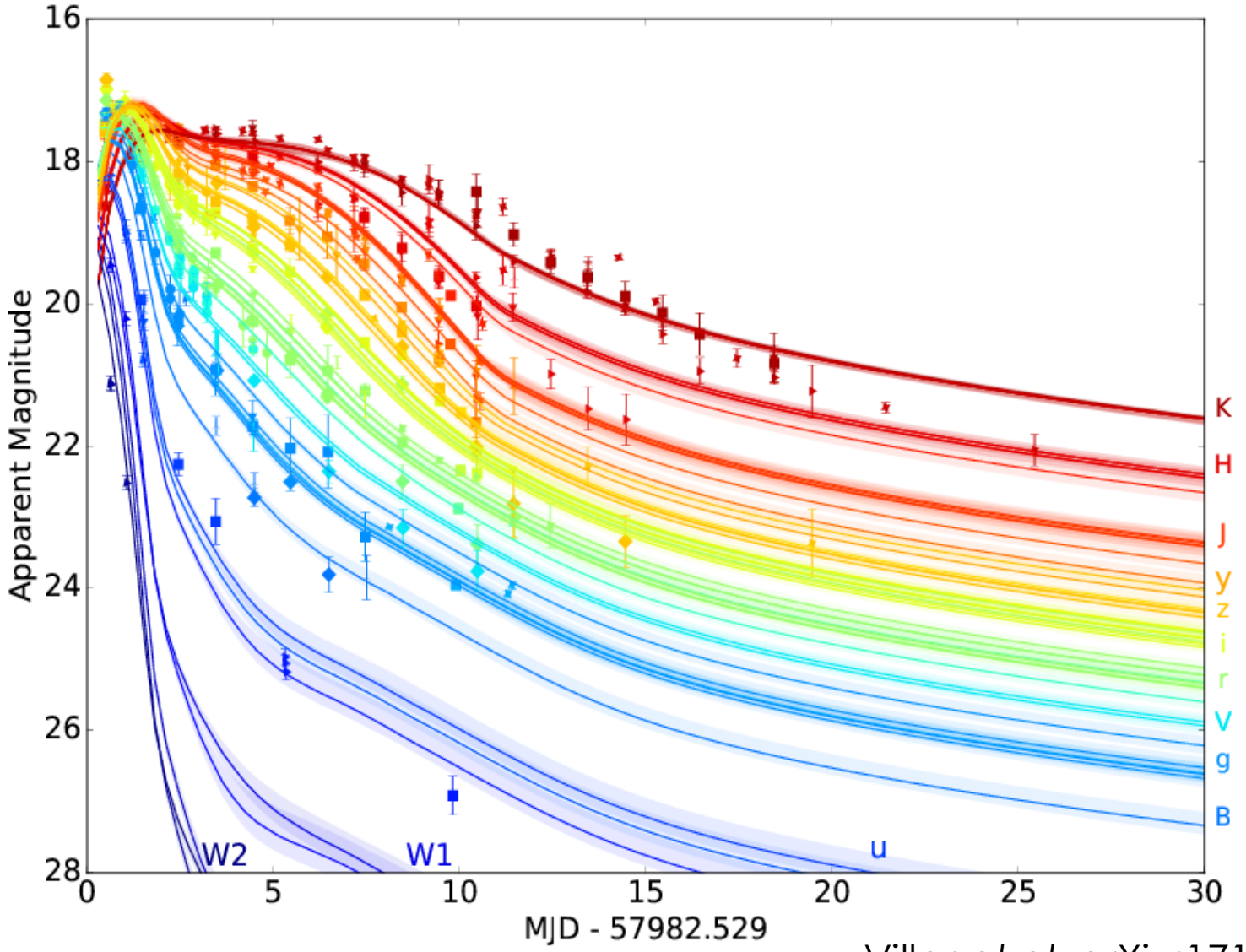
LVC+ arXiv:1710.05833

Light



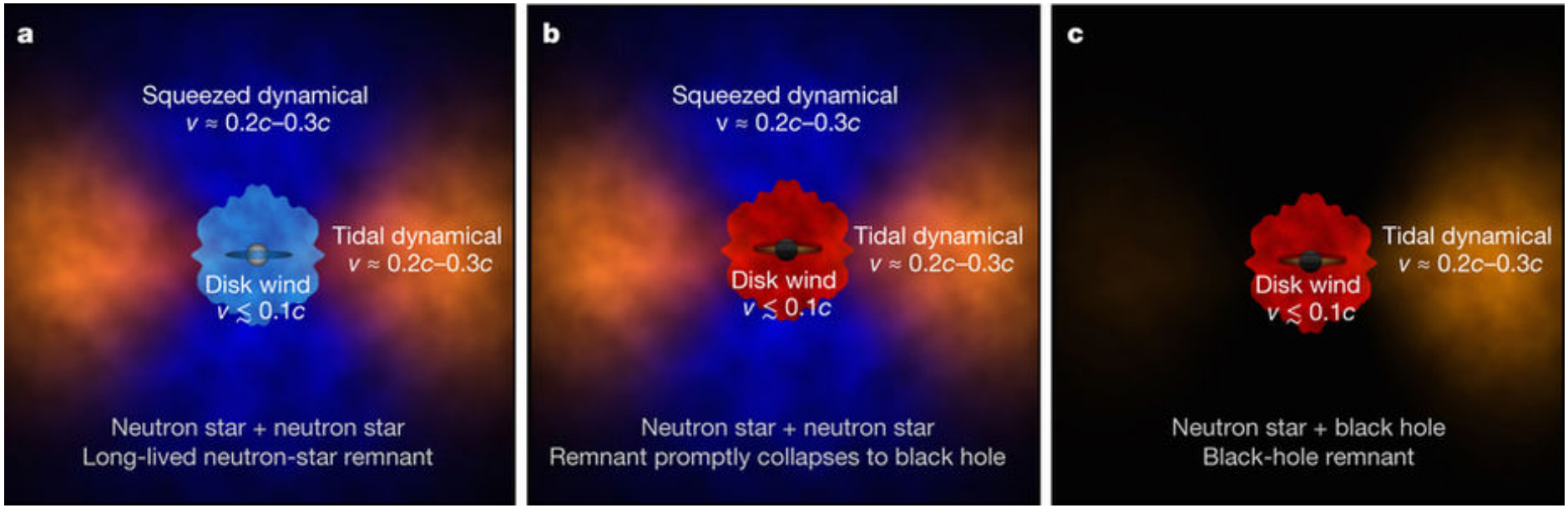
Metzger & Berger
arXiv:1108.6056

Spectrum of observations



Villar *et al*. arXiv:1710.11576

Kilonova

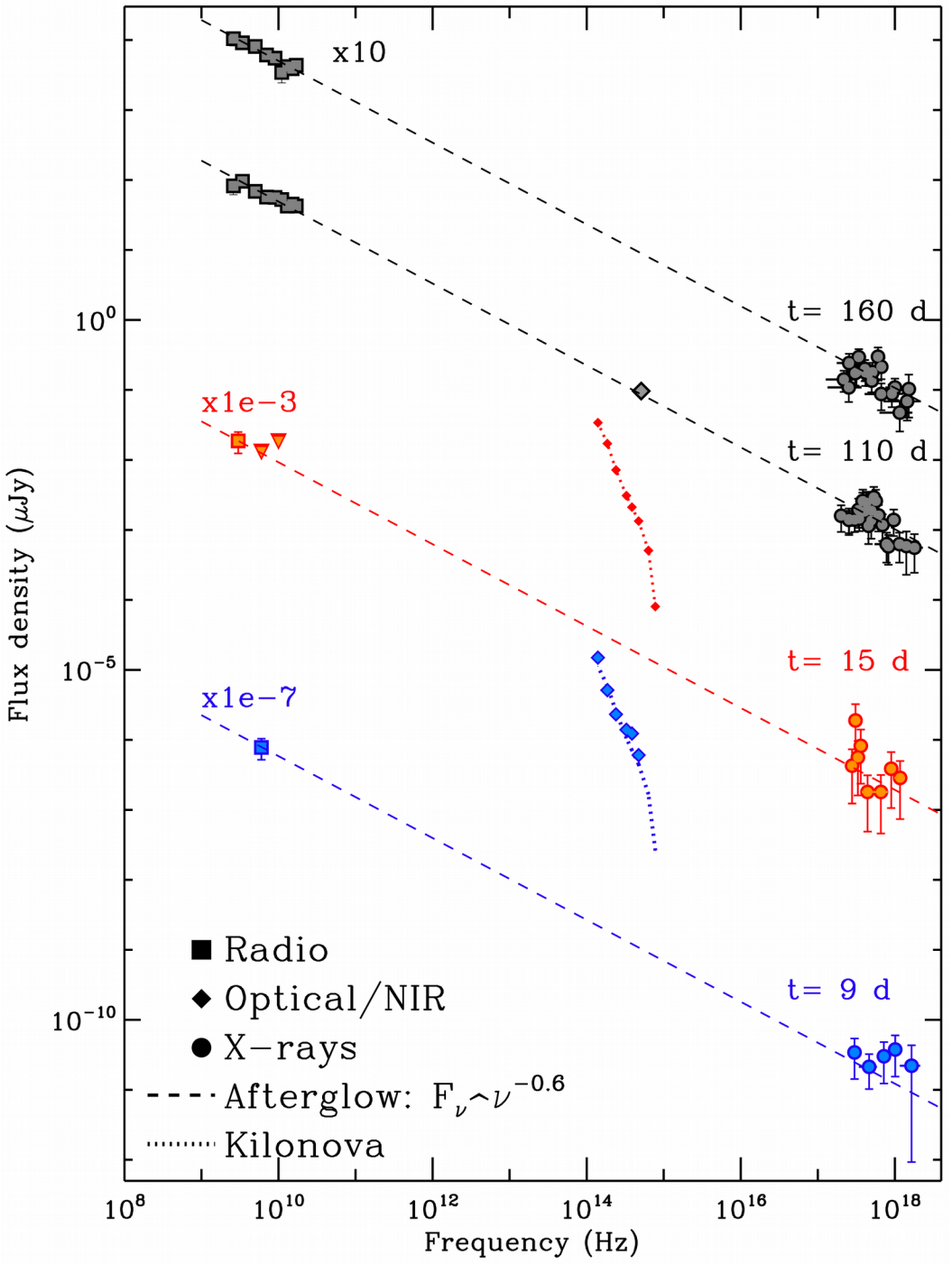


Kasen *et al*. arXiv:1710.05463

Heavy elements

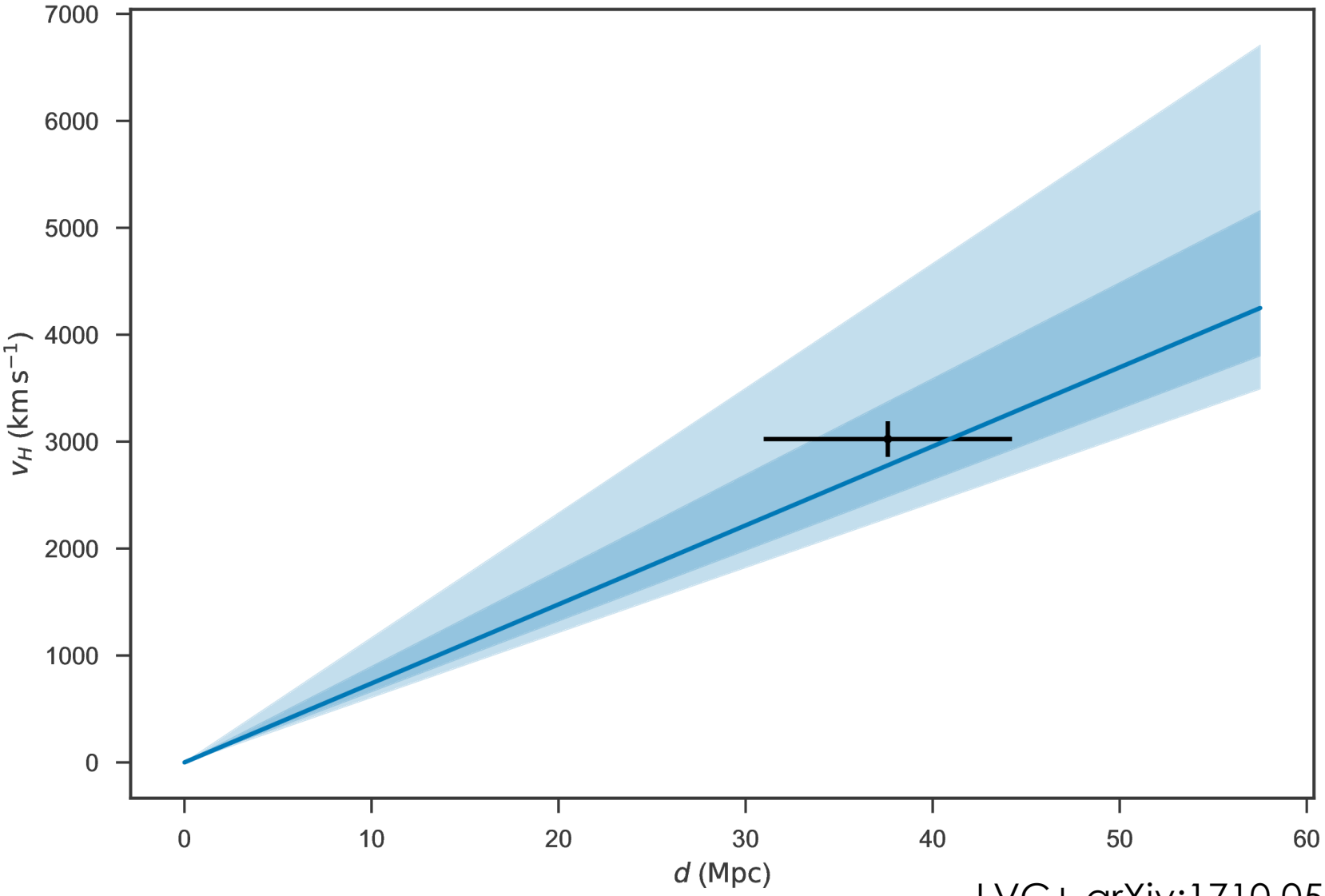
Credit: AP/F. Vergara

Afterglow



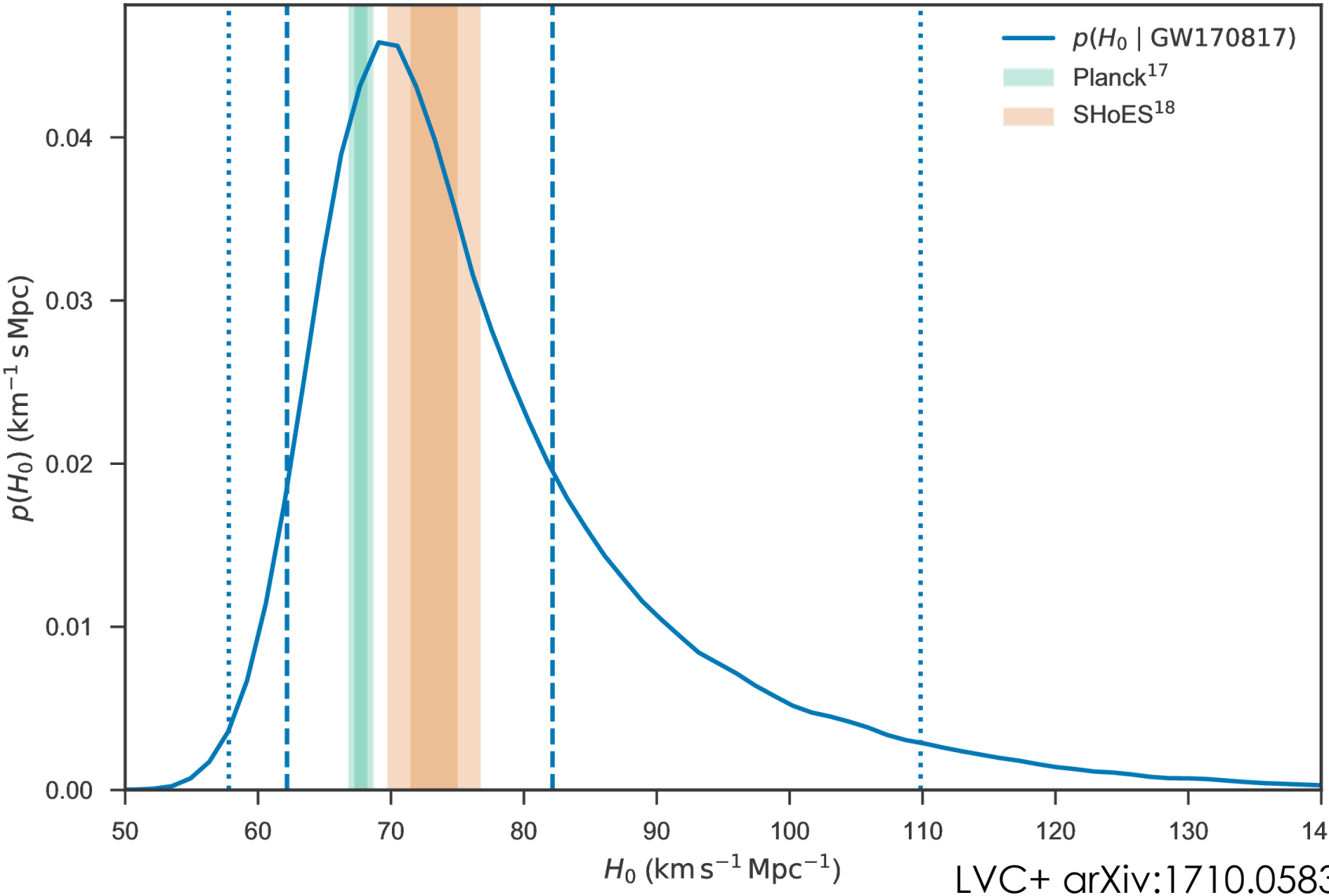
Margutti *et al*. arXiv:1801.03531

Expansion of the Universe



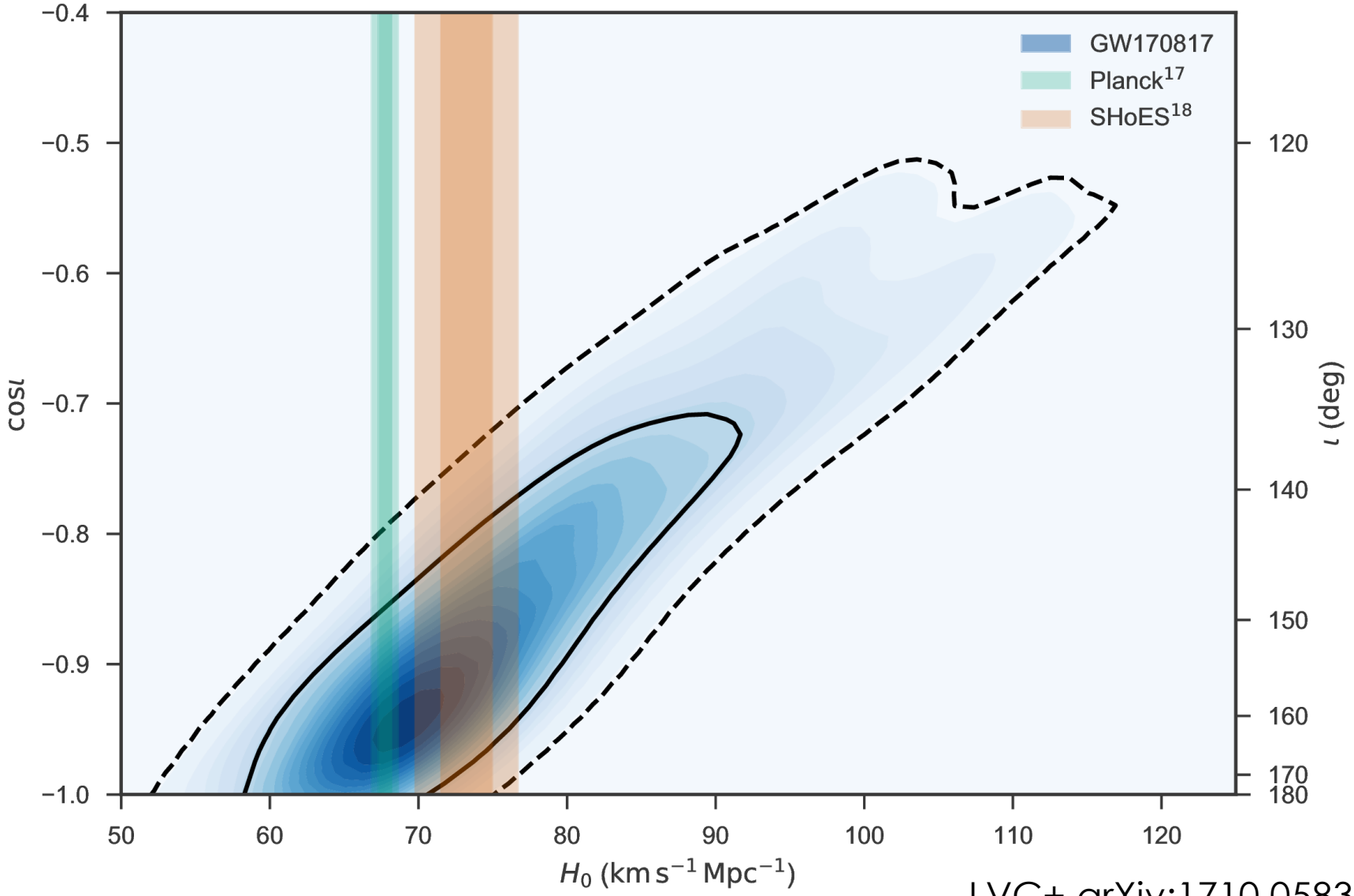
LVC+ arXiv:1710.05835

Hubble constant



LVC+ arXiv:1710.05835

Inclination



LVC+ arXiv:1710.05835

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papers.ligo.org/