Gravitational Wave Observations

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On behalf of the
LIGO Scientific & Virgo Collaborations

DCC G1701806

Observing Black Holes: From the Lab to the Universe

Spoiler

We have observed gravitational waves

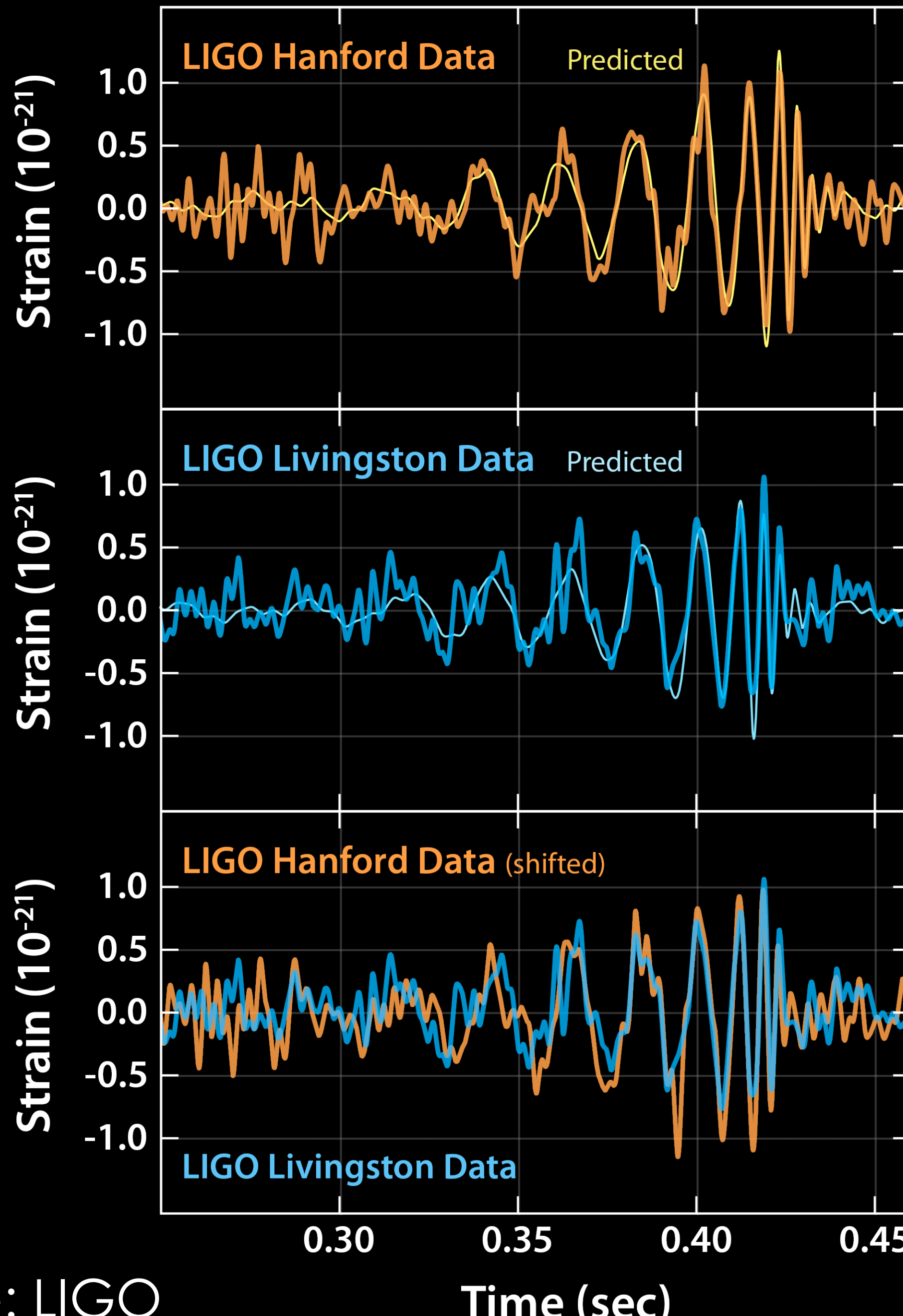
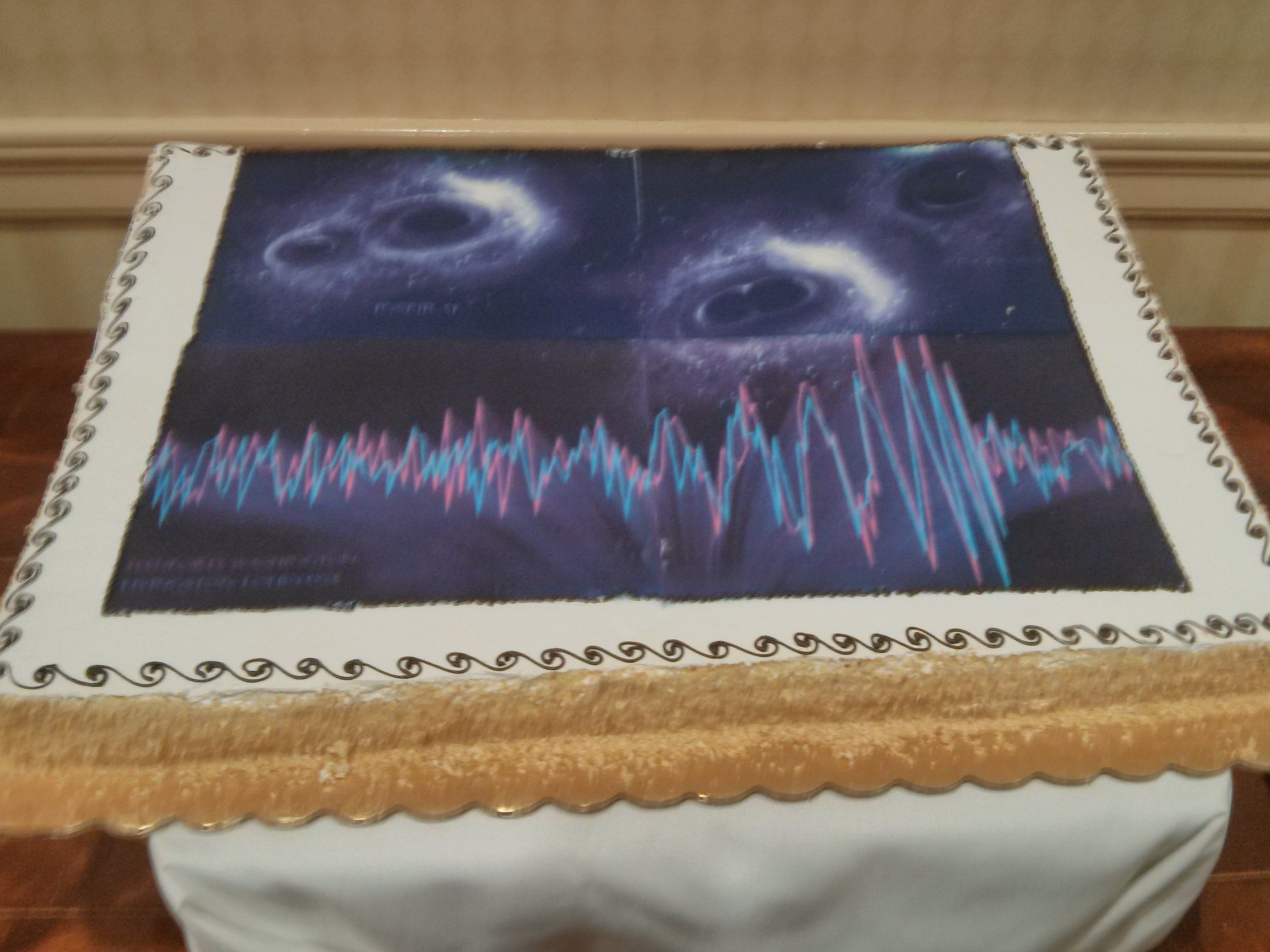


Image: LIGO



Gravitational wave observatories

Our measurements

The binary black hole family

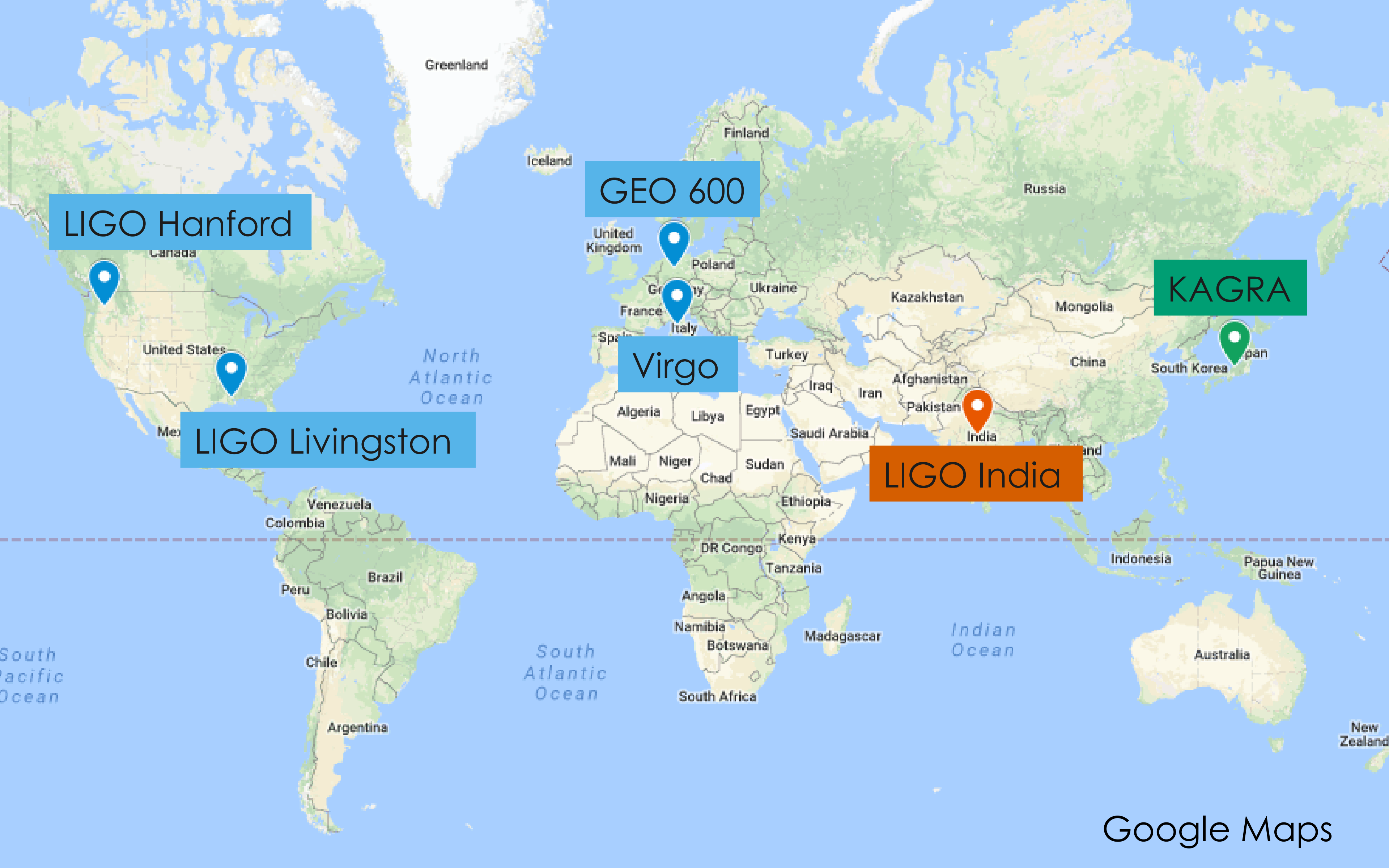
Gravitational wave observatories

Our measurements

The binary black hole family

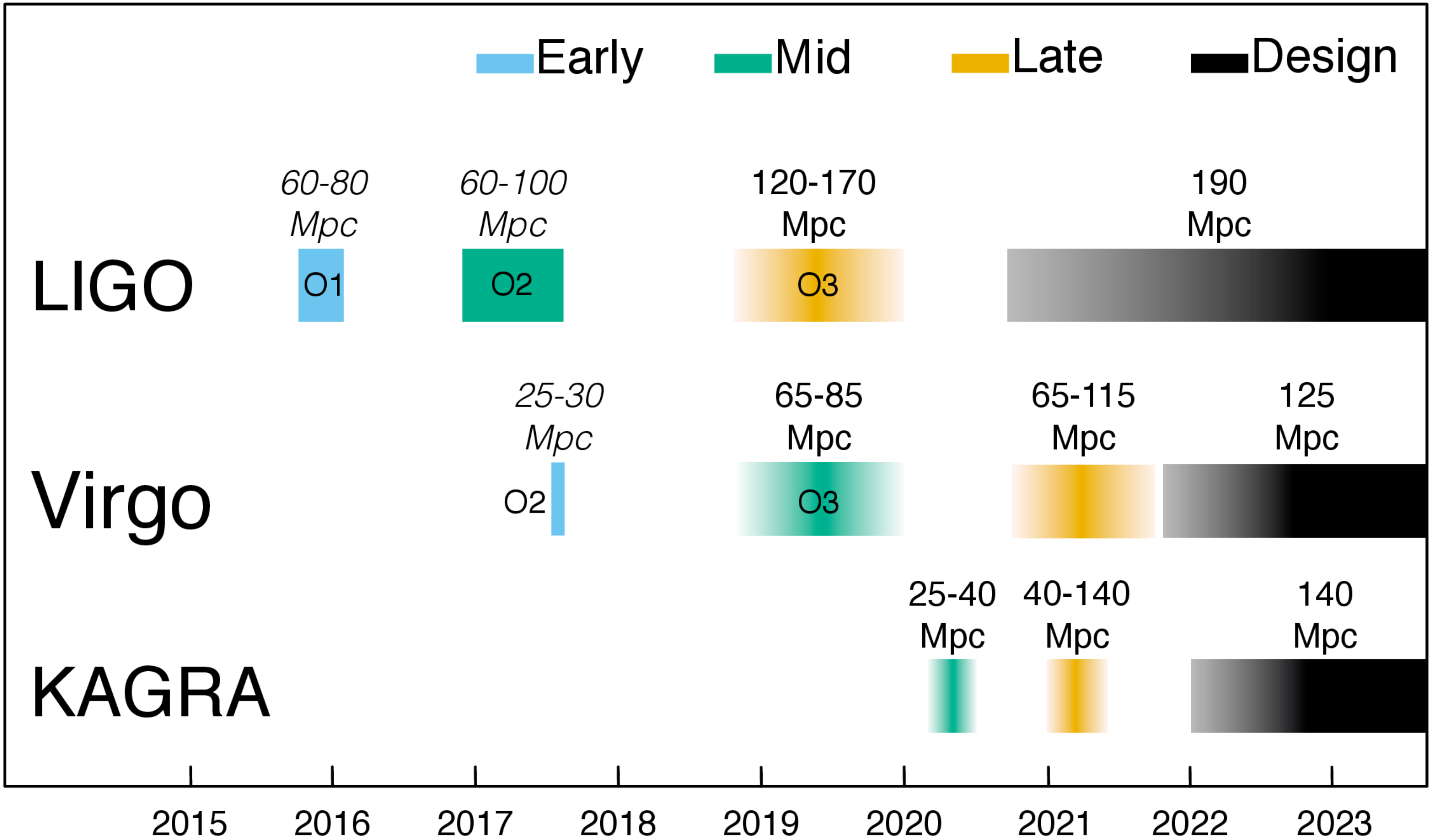

LIGO Livingston
4 km arms
Image: LIGO

Detector network



Google Maps

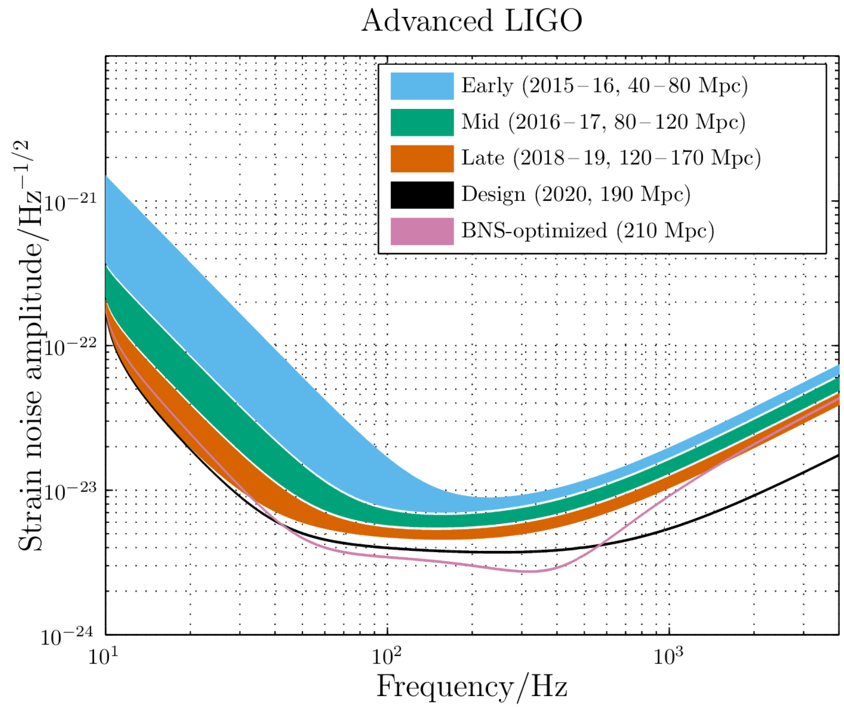
Observing timetable

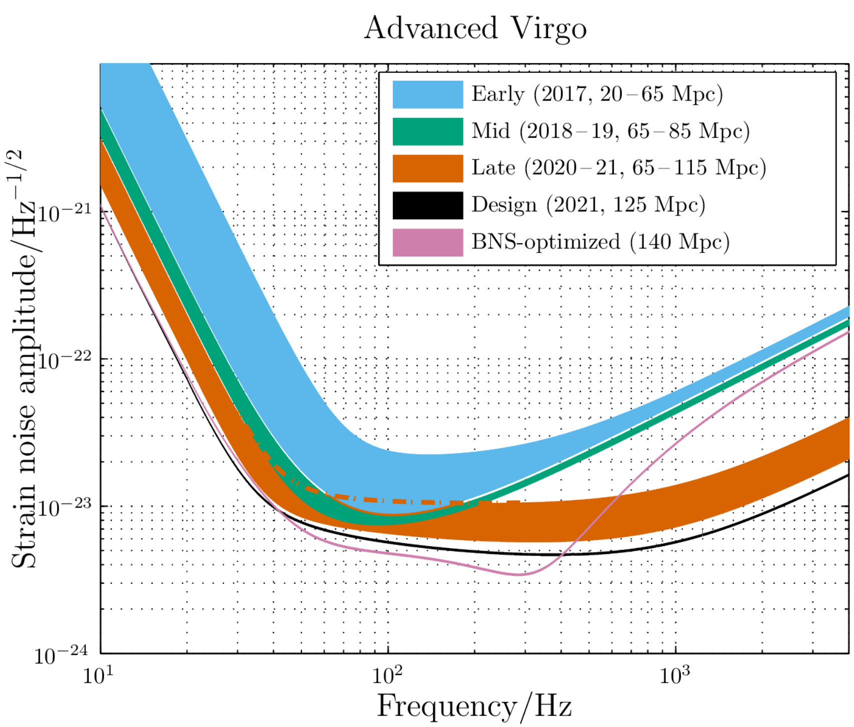


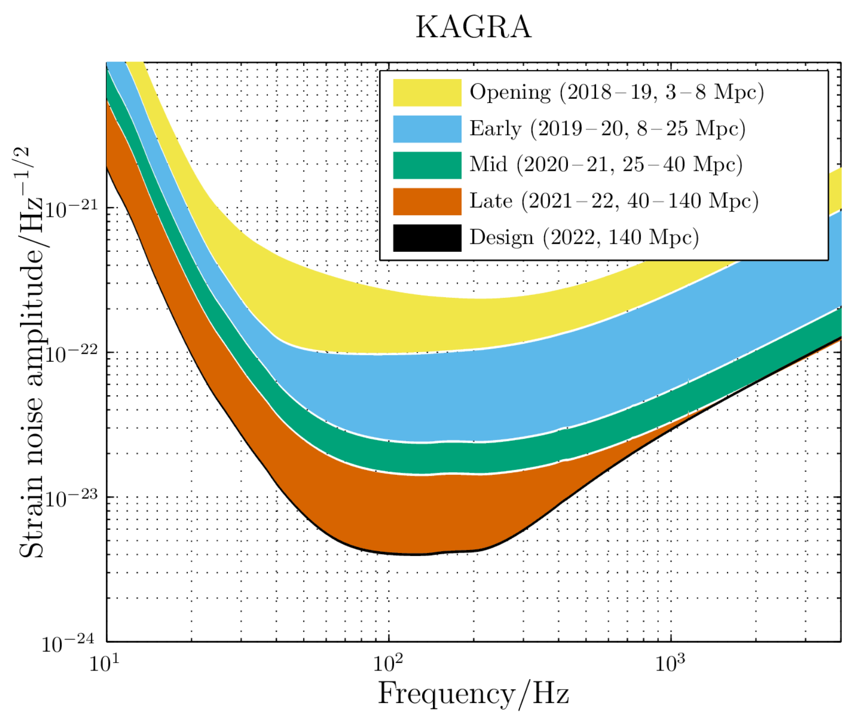
LVKC arXiv:1304.0670

Plausible detector sensitivities

LVKC arXiv:1304.0670







Gravitational wave observatories

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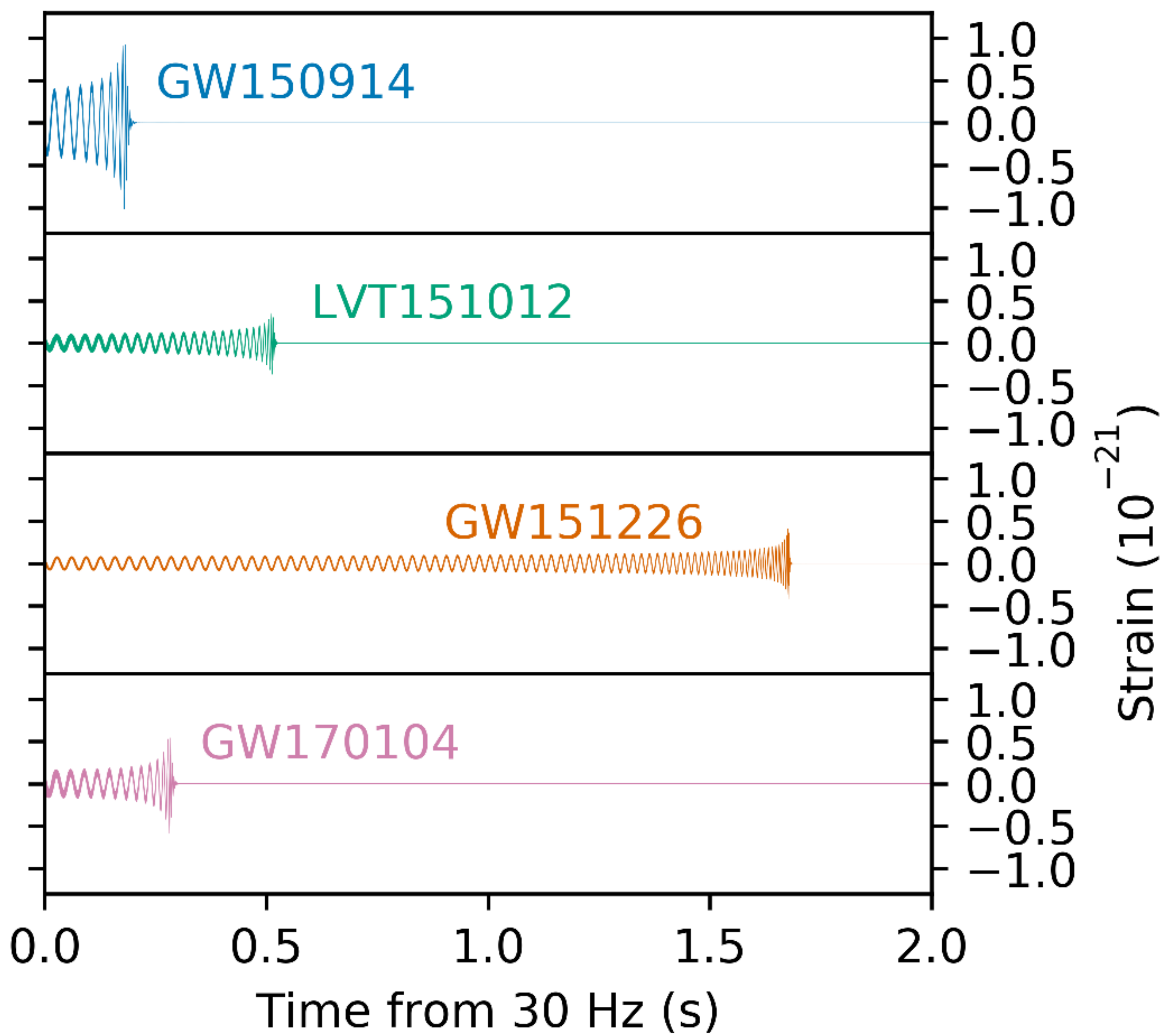
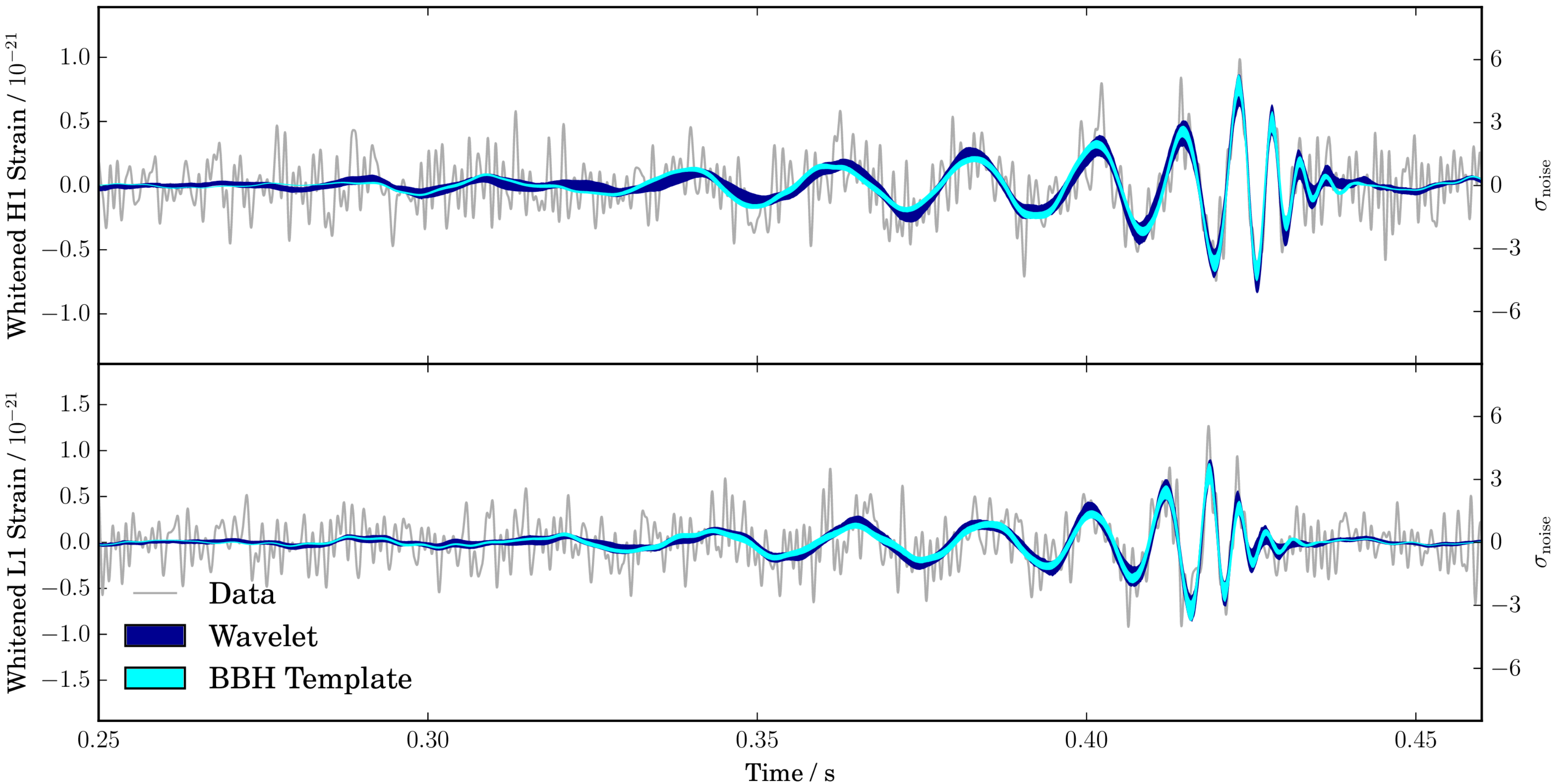
Binary black hole signals

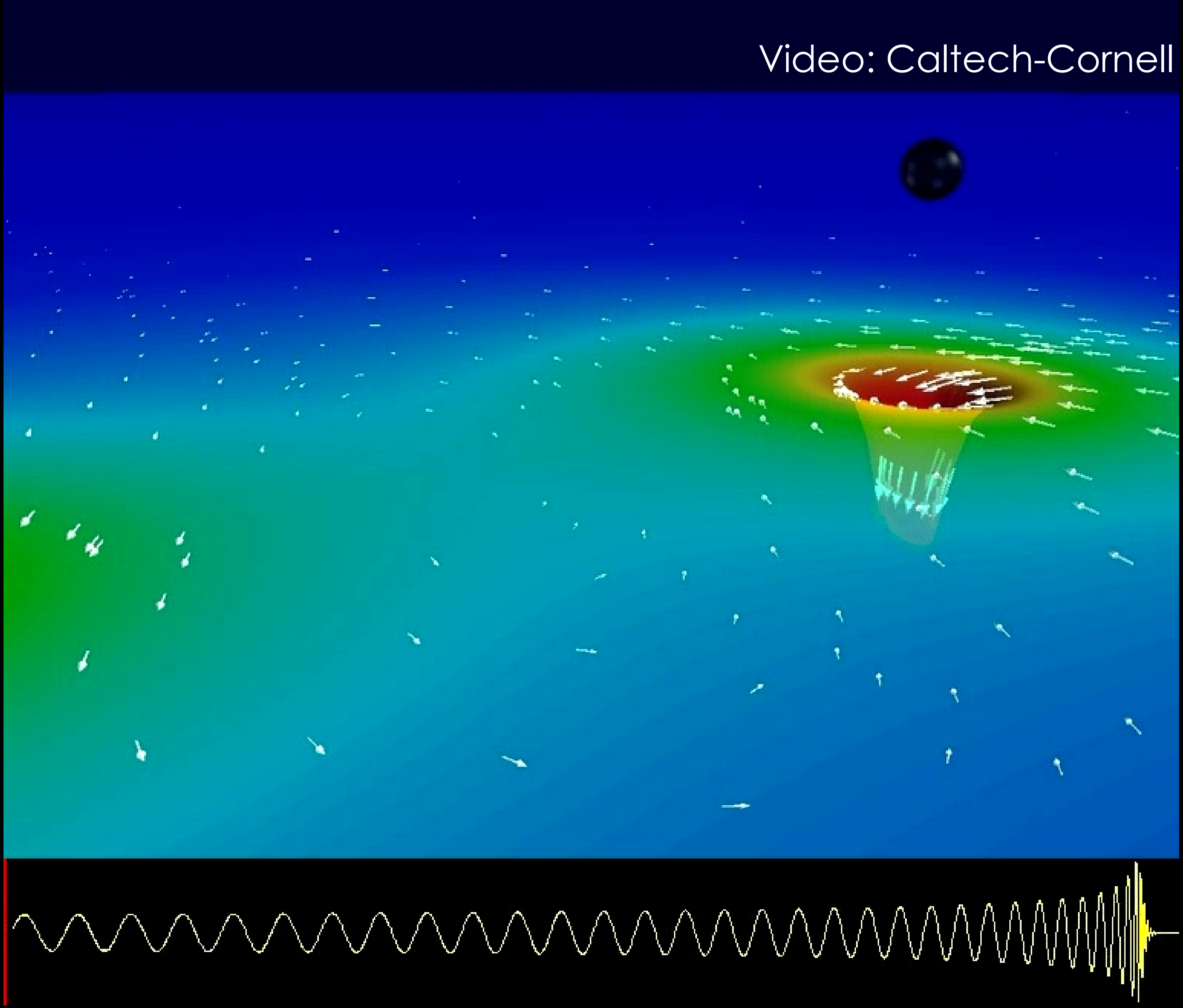


LVC
arXiv:1606.04856,
arXiv:1706.01812

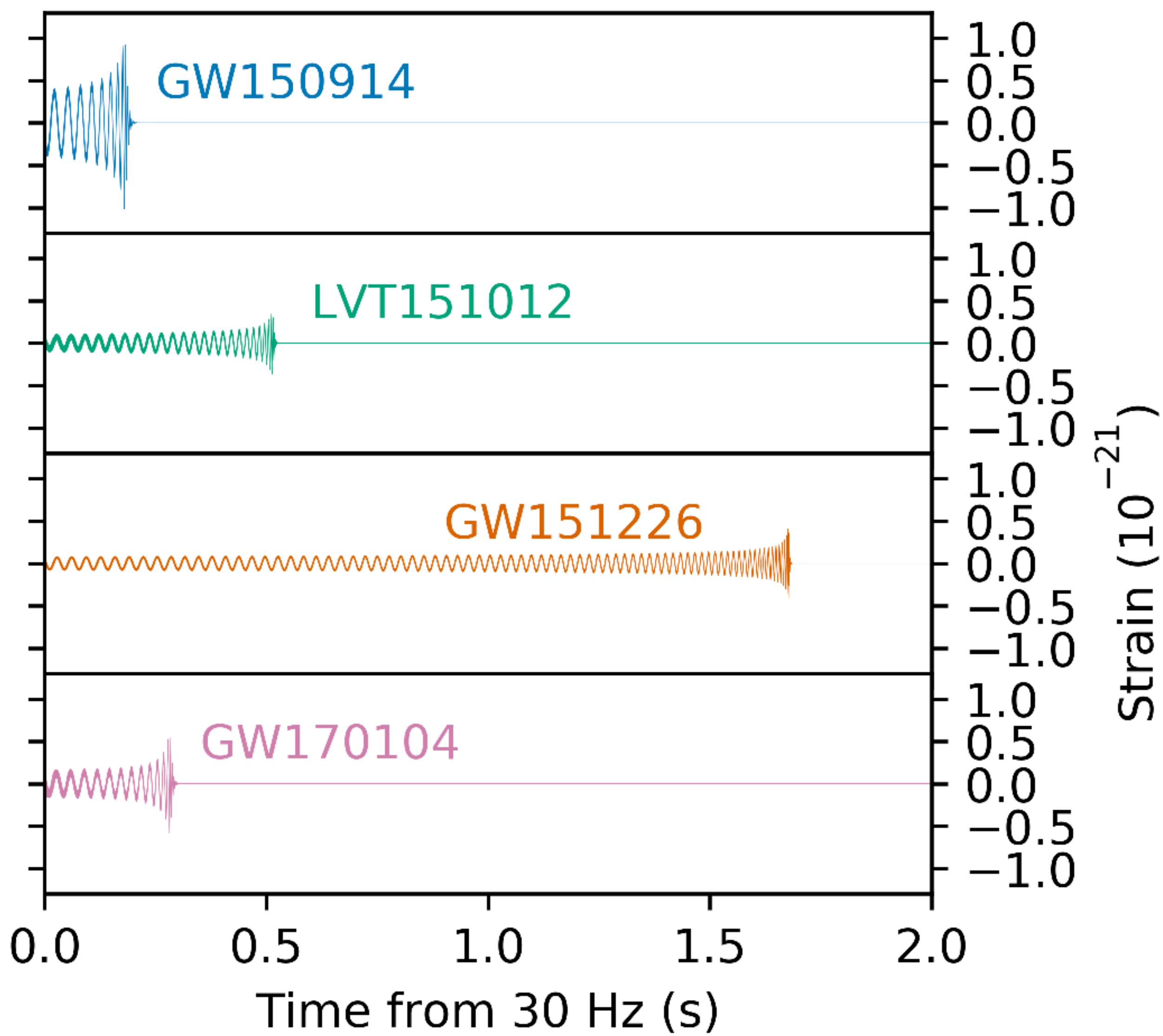
GW150914



LVC arXiv:1602.03840


Video: Caltech-Cornell

Binary black hole signals



LVC
arXiv:1606.04856,
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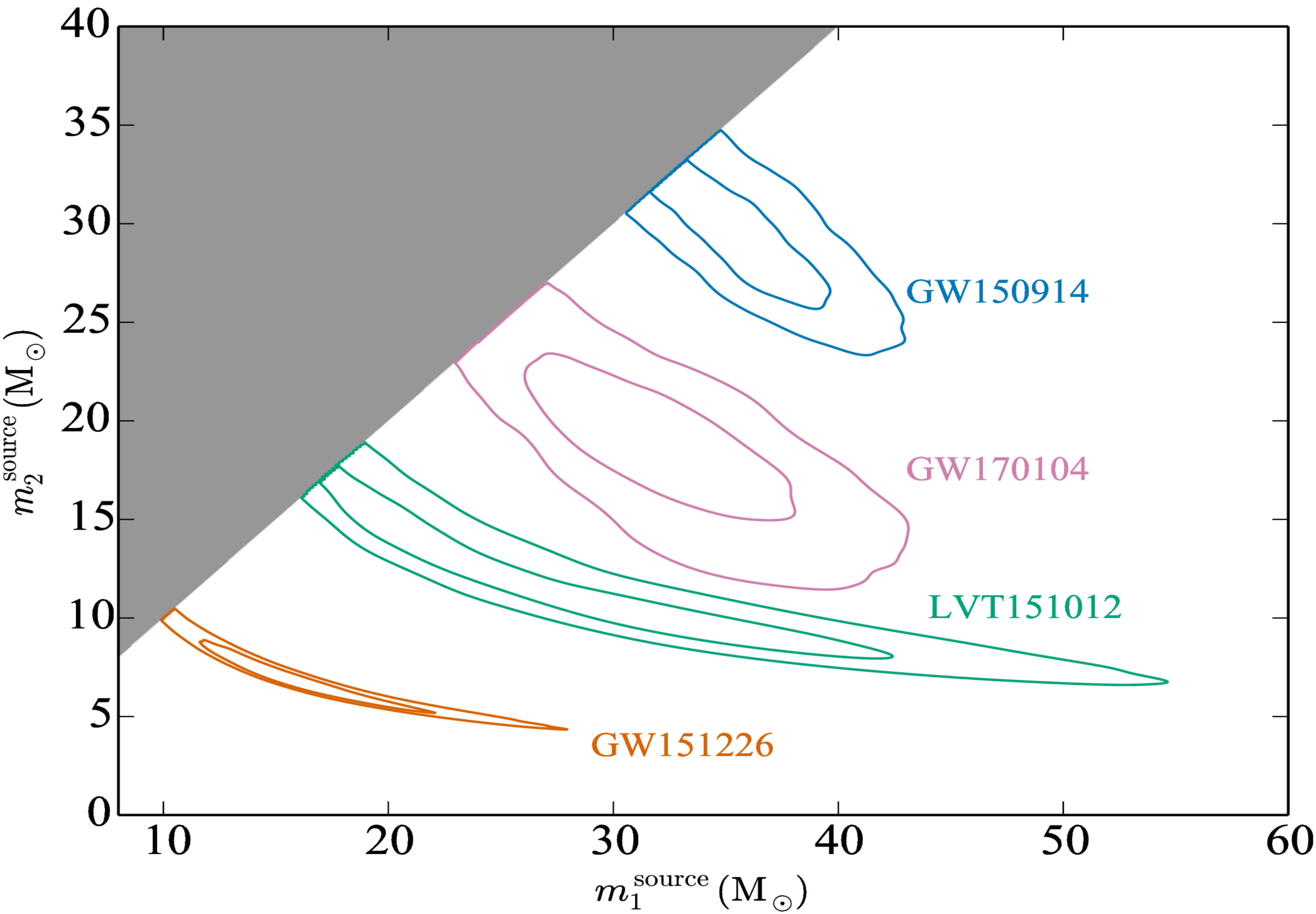
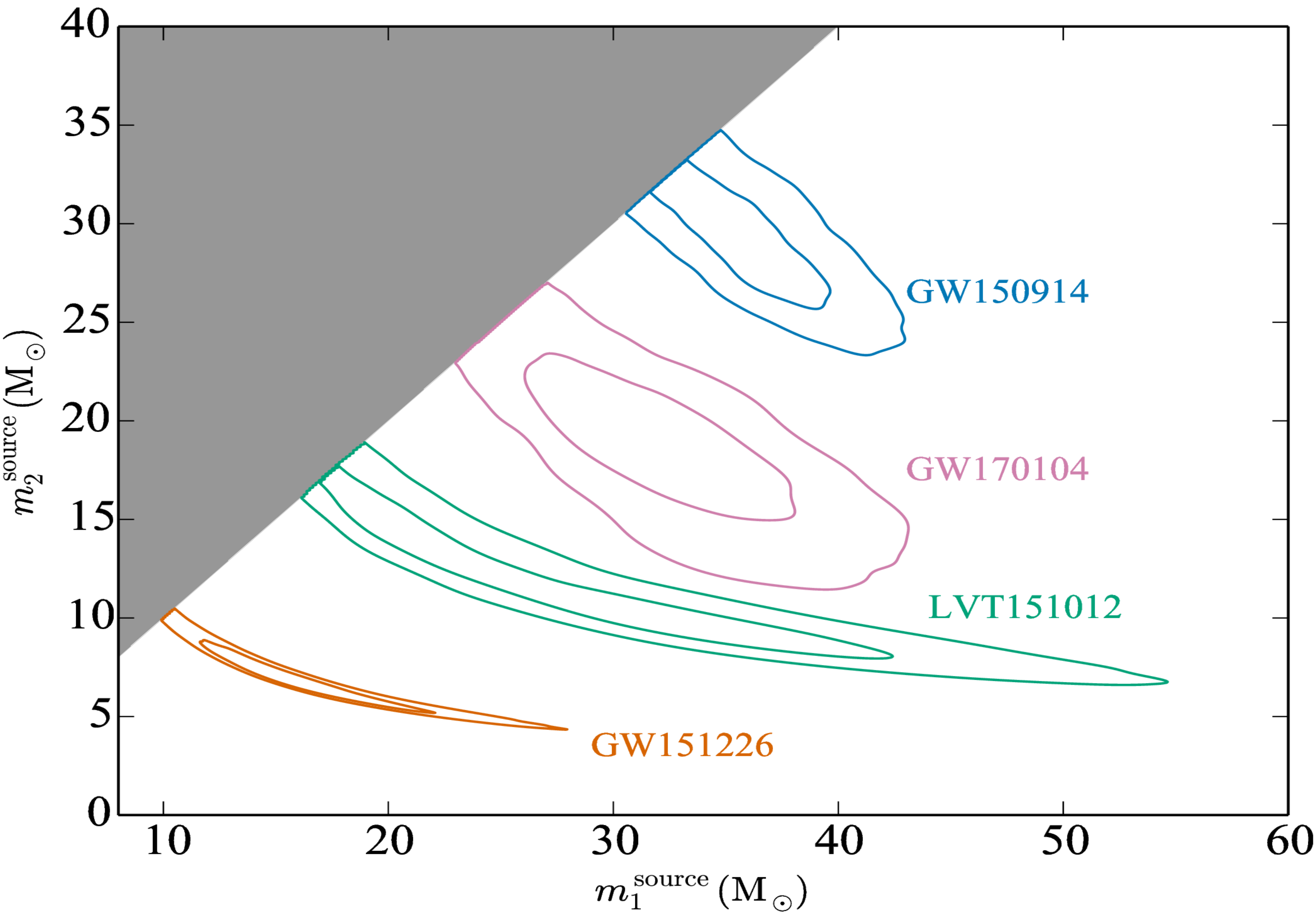


LVC arXiv:1706.01812

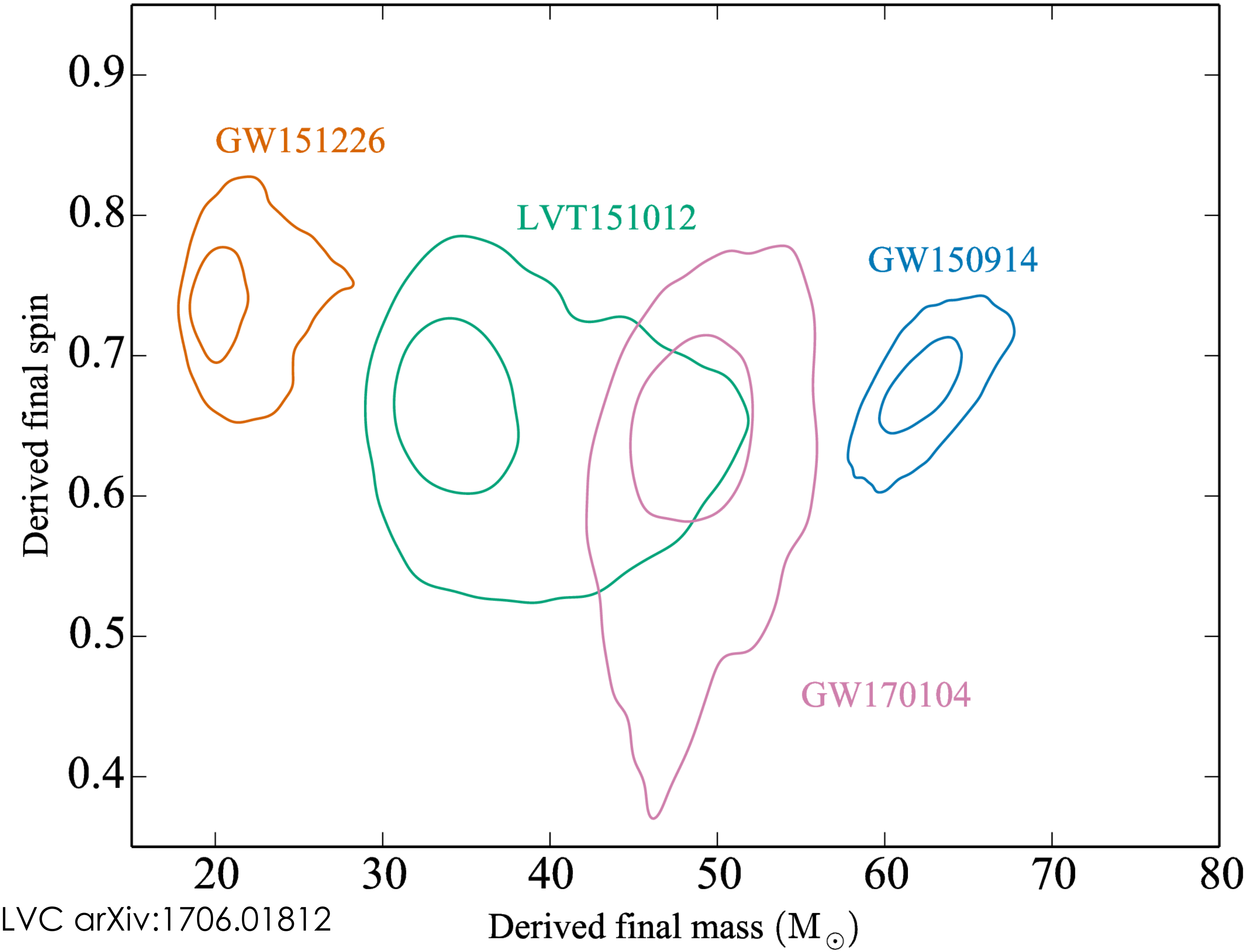
Chirp mass

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

Chirp mass gives leading-order amplitude and phase evolution (Sathyaprakash & Schutz arXiv:0903.0338)



LVC arXiv:1706.01812



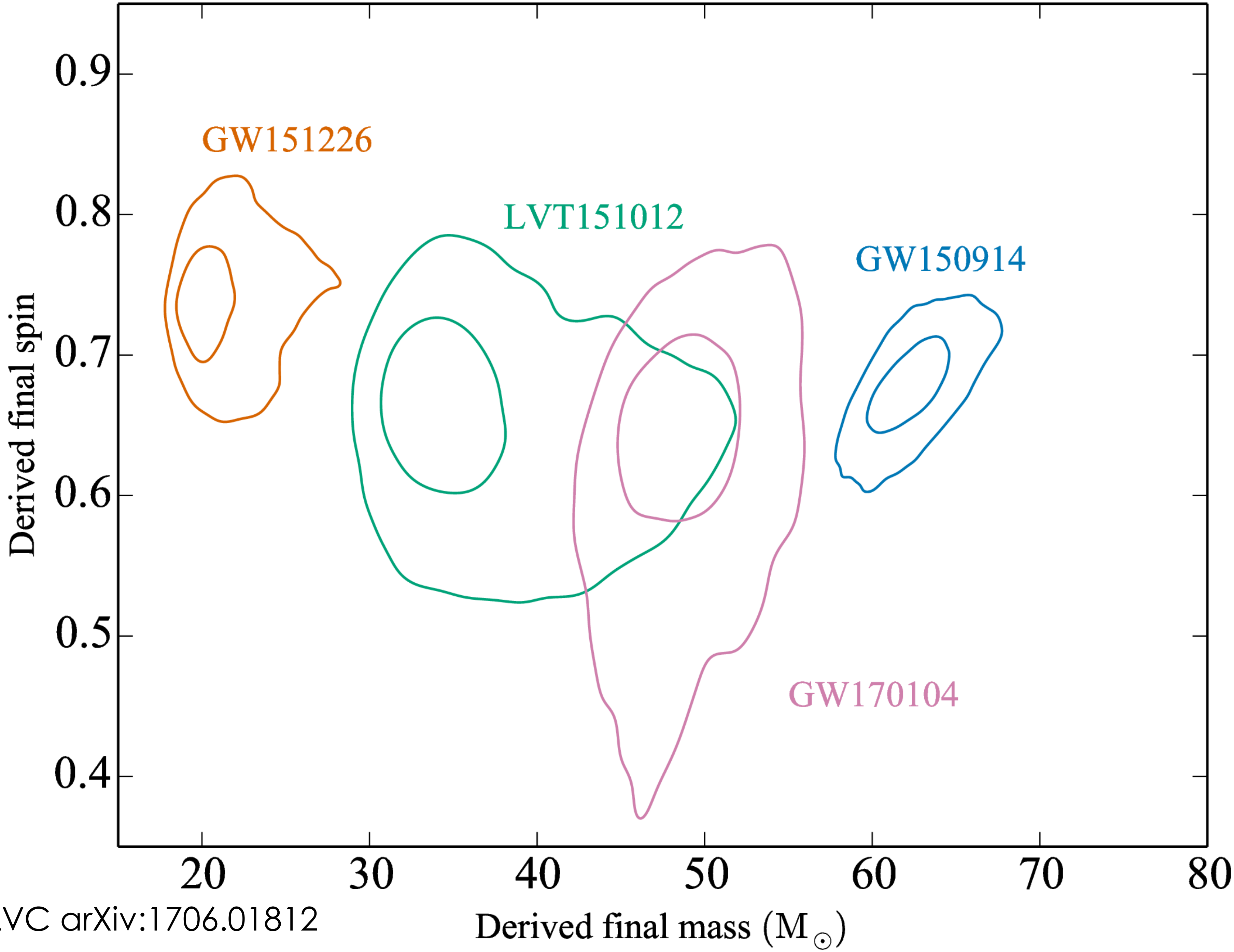
LVC arXiv:1706.01812

No hair theorem

Black holes have:

1. Mass
2. Spin
3. Electric charge

Image: Matt Groening



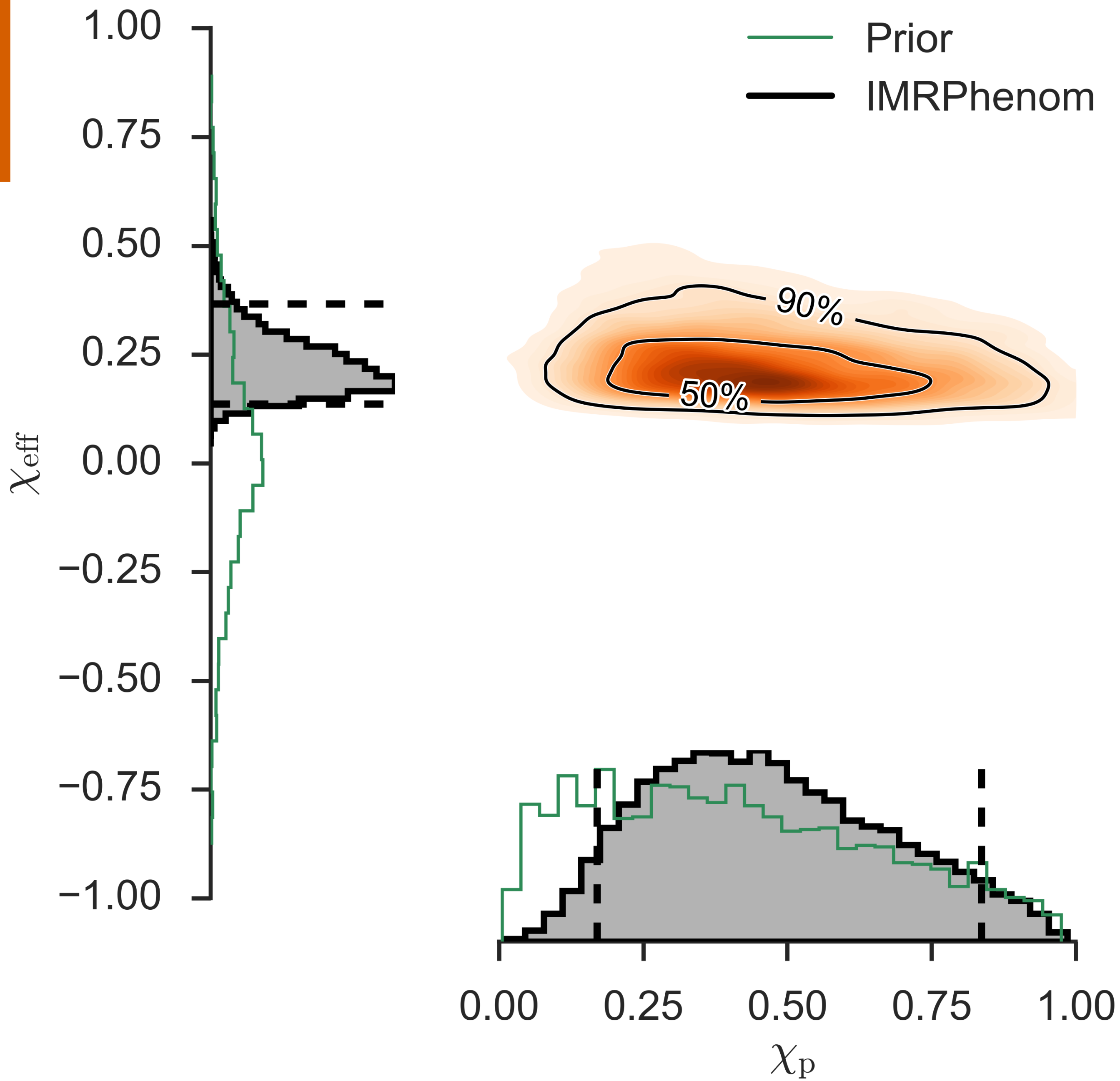
LVC arXiv:1706.01812

Effective inspiral spin

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

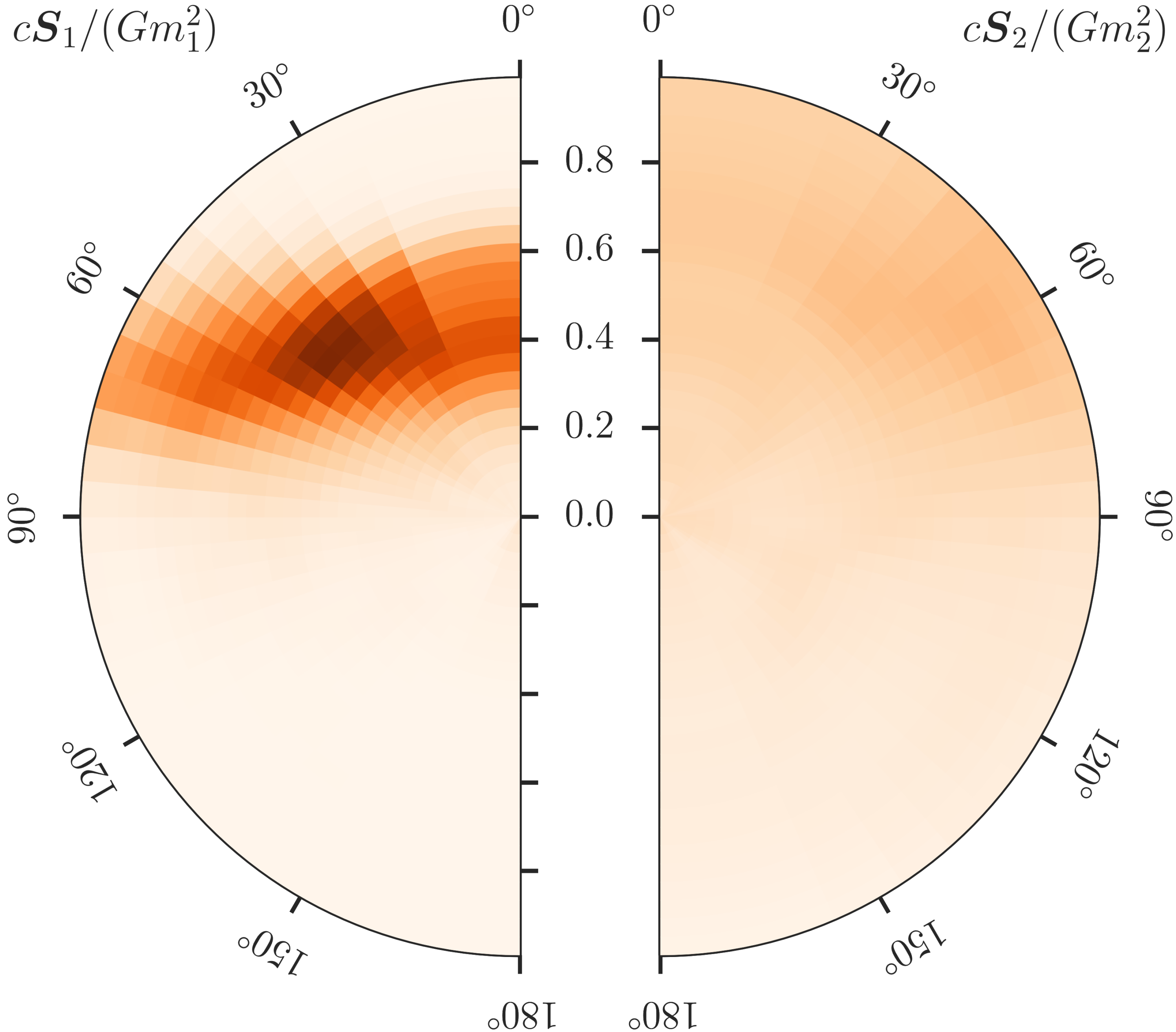
Most important combination of spins for evolution of inspiral (arXiv:0909.2867, 1005.3306)

Spin



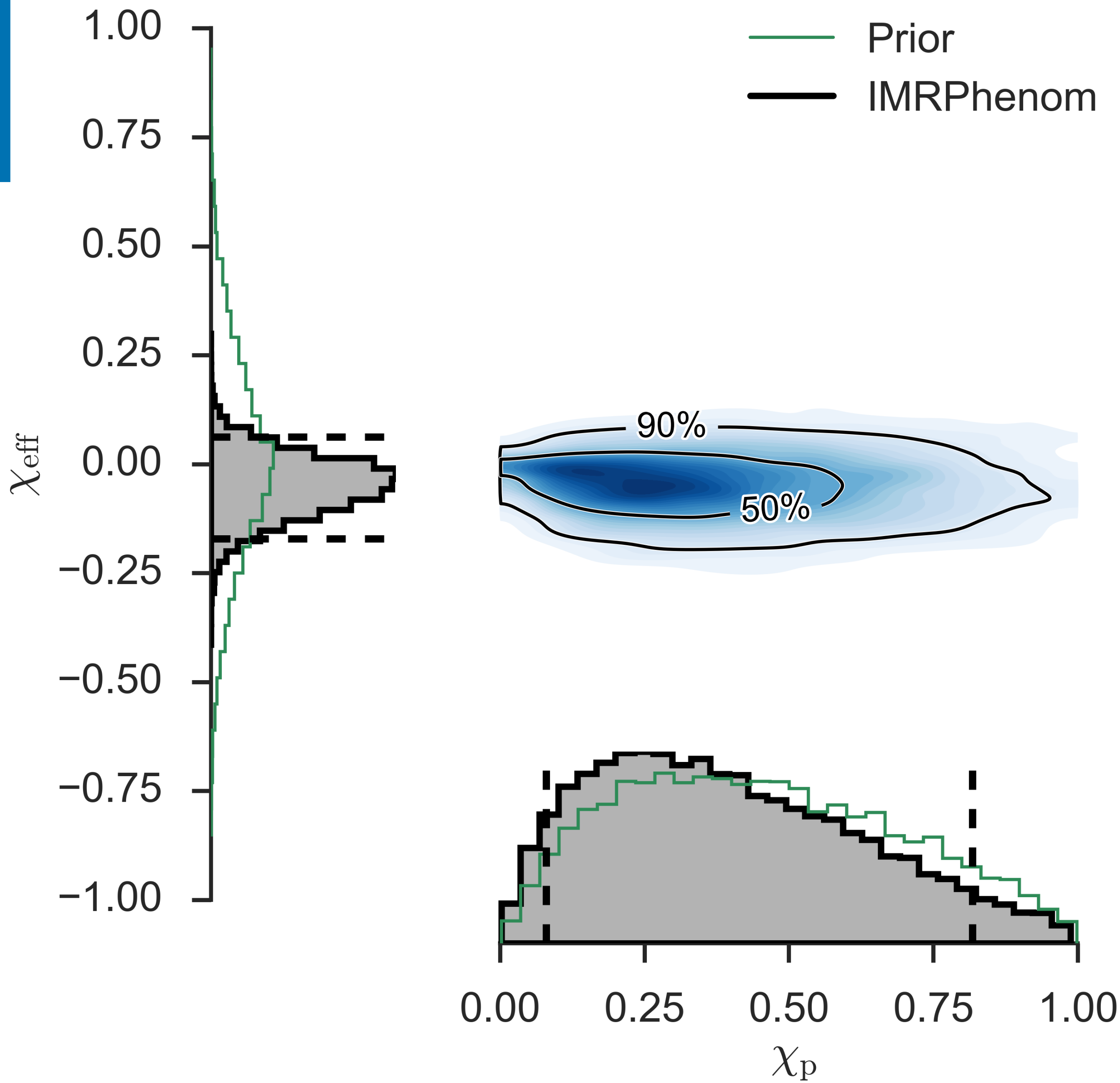
LVC
arXiv:1606.04856

Spin



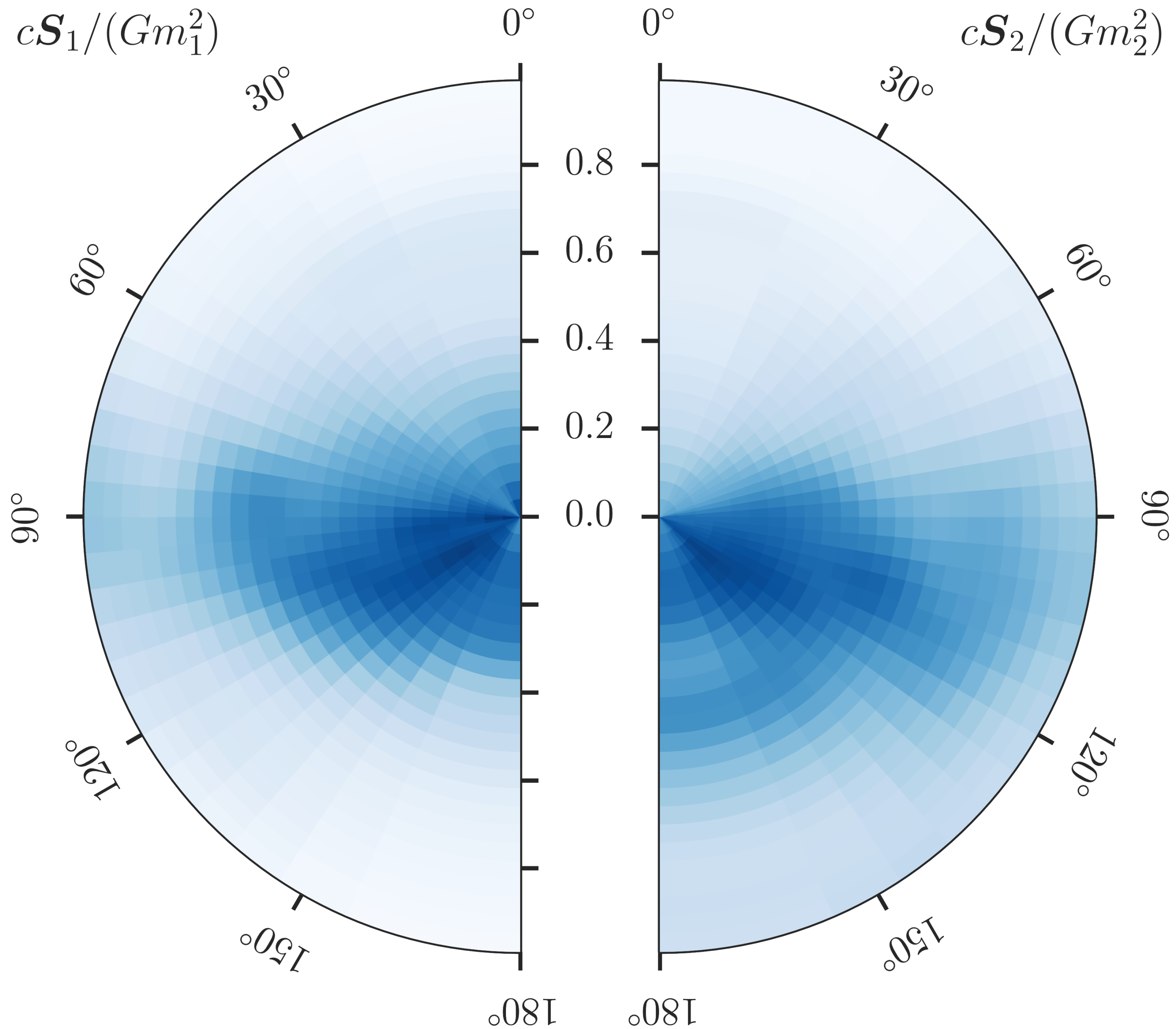
LVC
arXiv:1606.04855

Spin



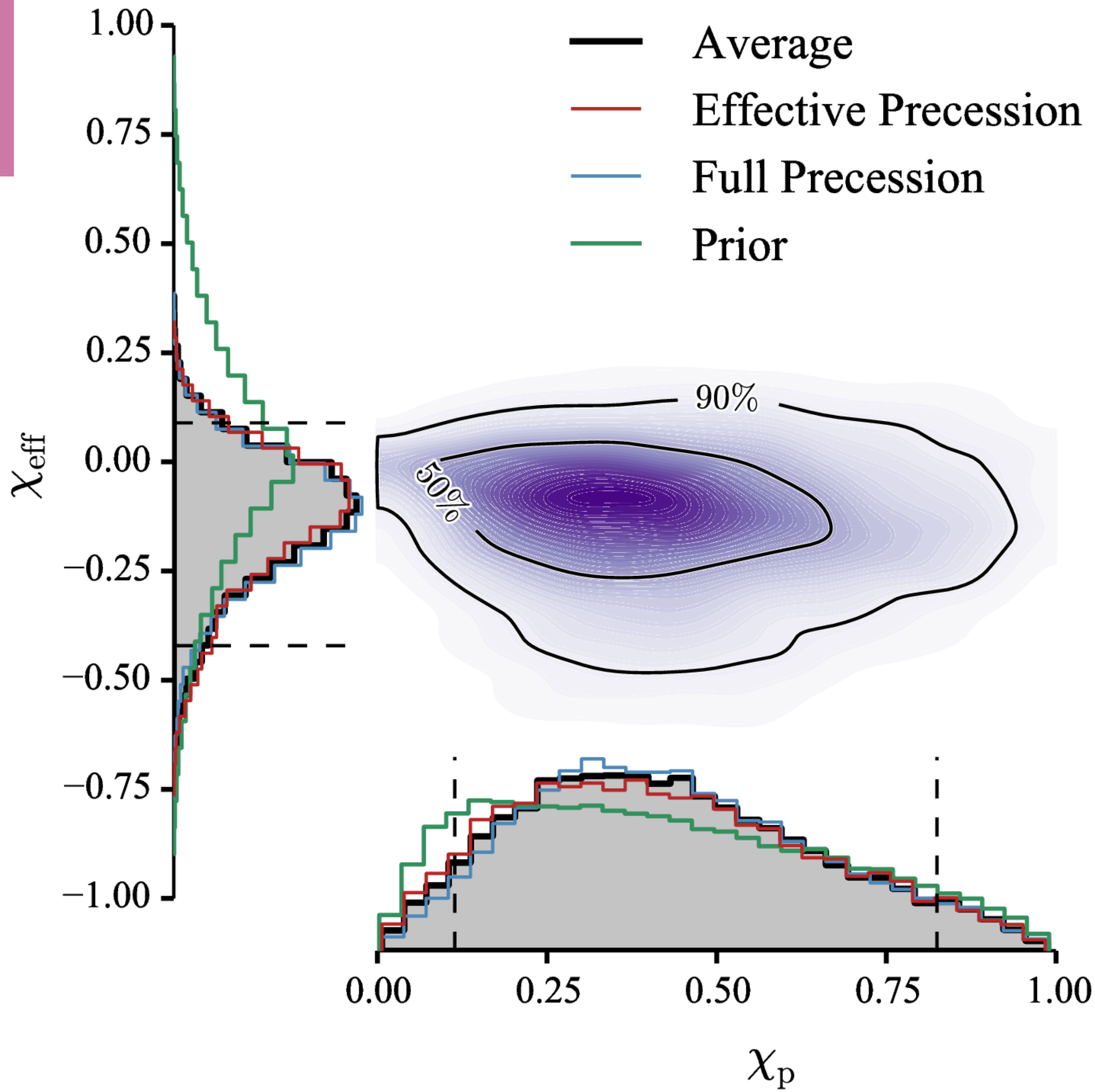
LVC
arXiv:1606.04856
arXiv:1602.03840

Spin



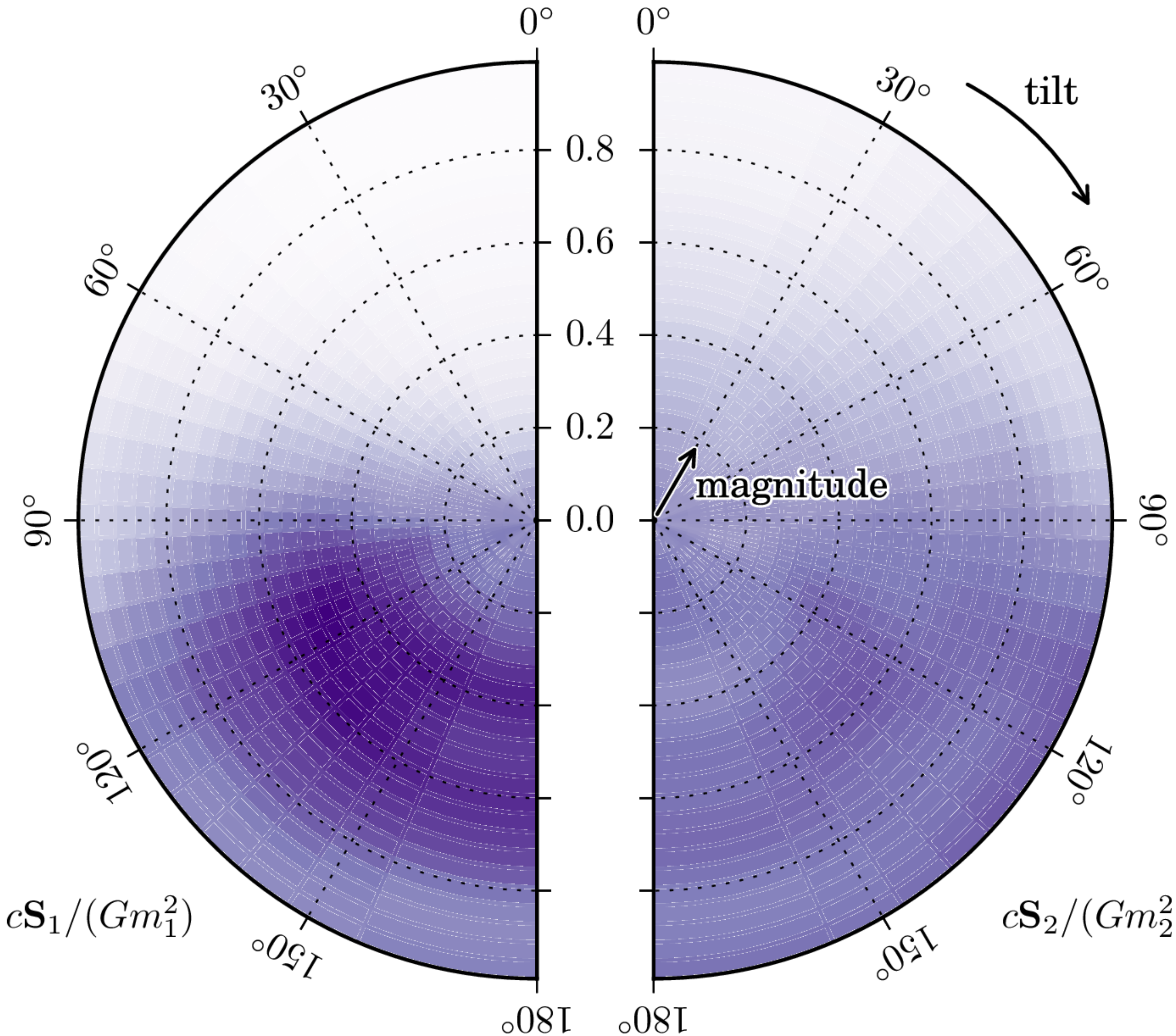
LVC
arXiv:1606.04856
arXiv:1602.03840

Spin



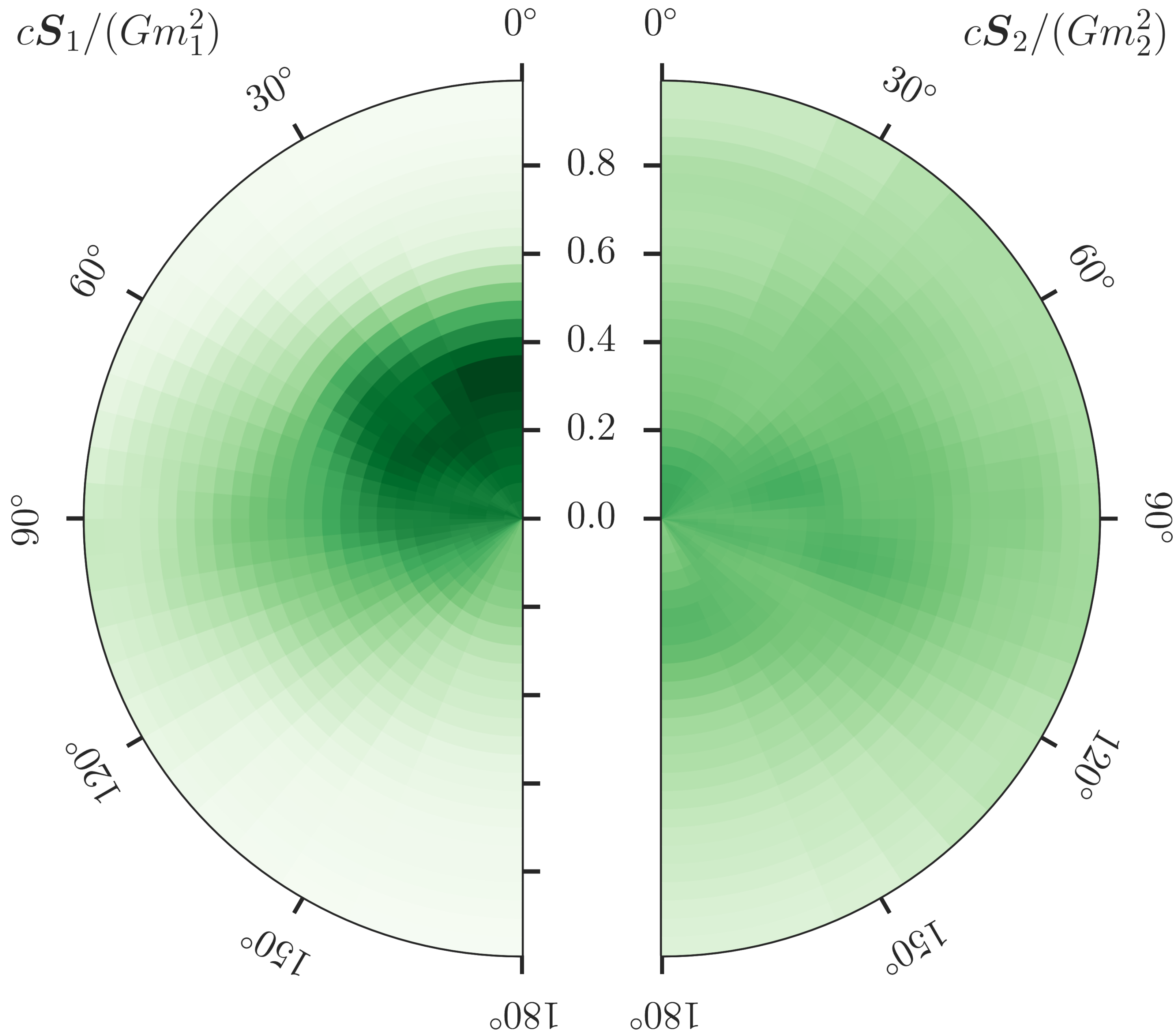
LVC
arXiv:1706:01812

Spin



LVC
arXiv:1706:01812

Spin



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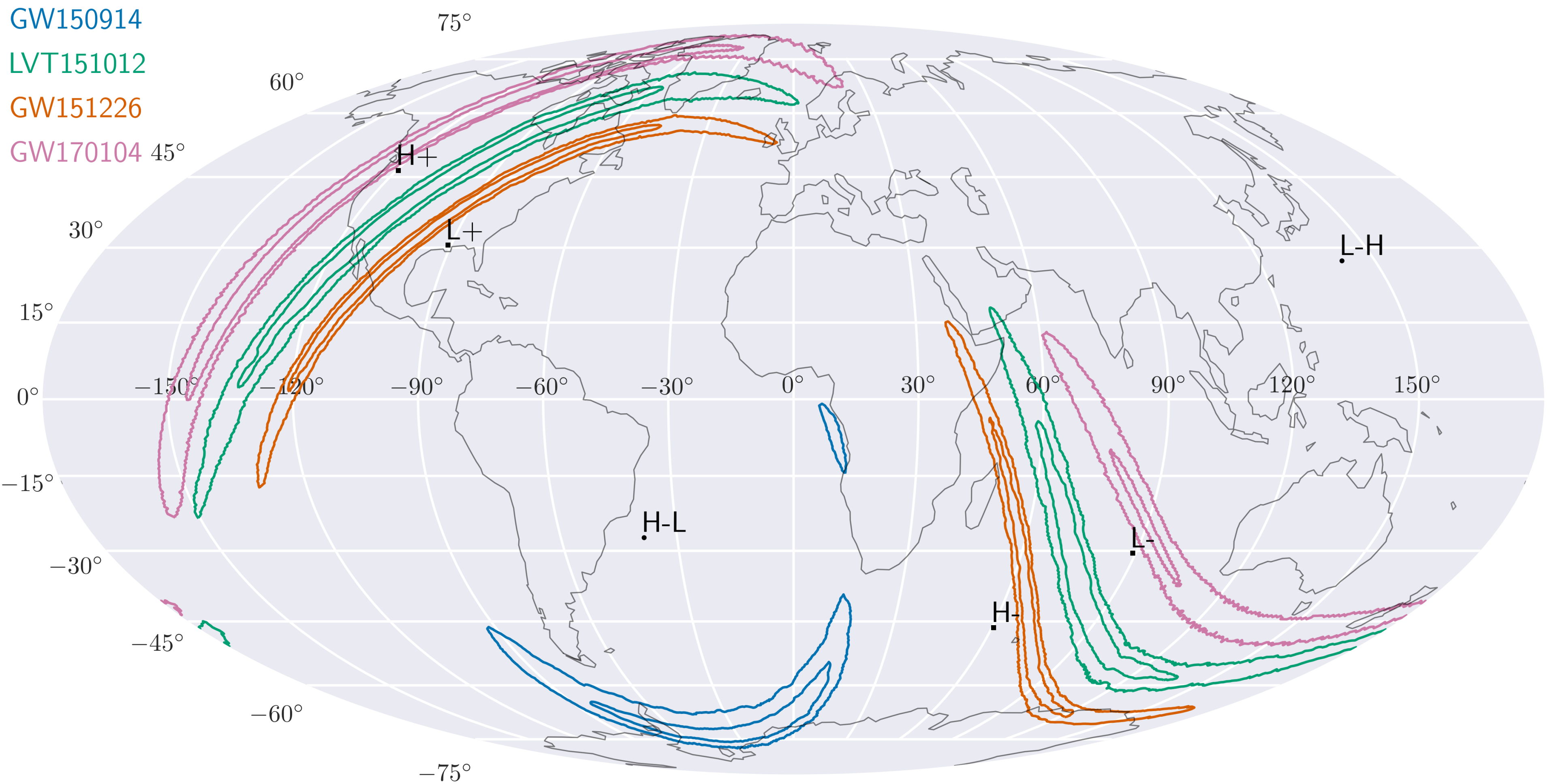

LVC
arXiv:1606.04856
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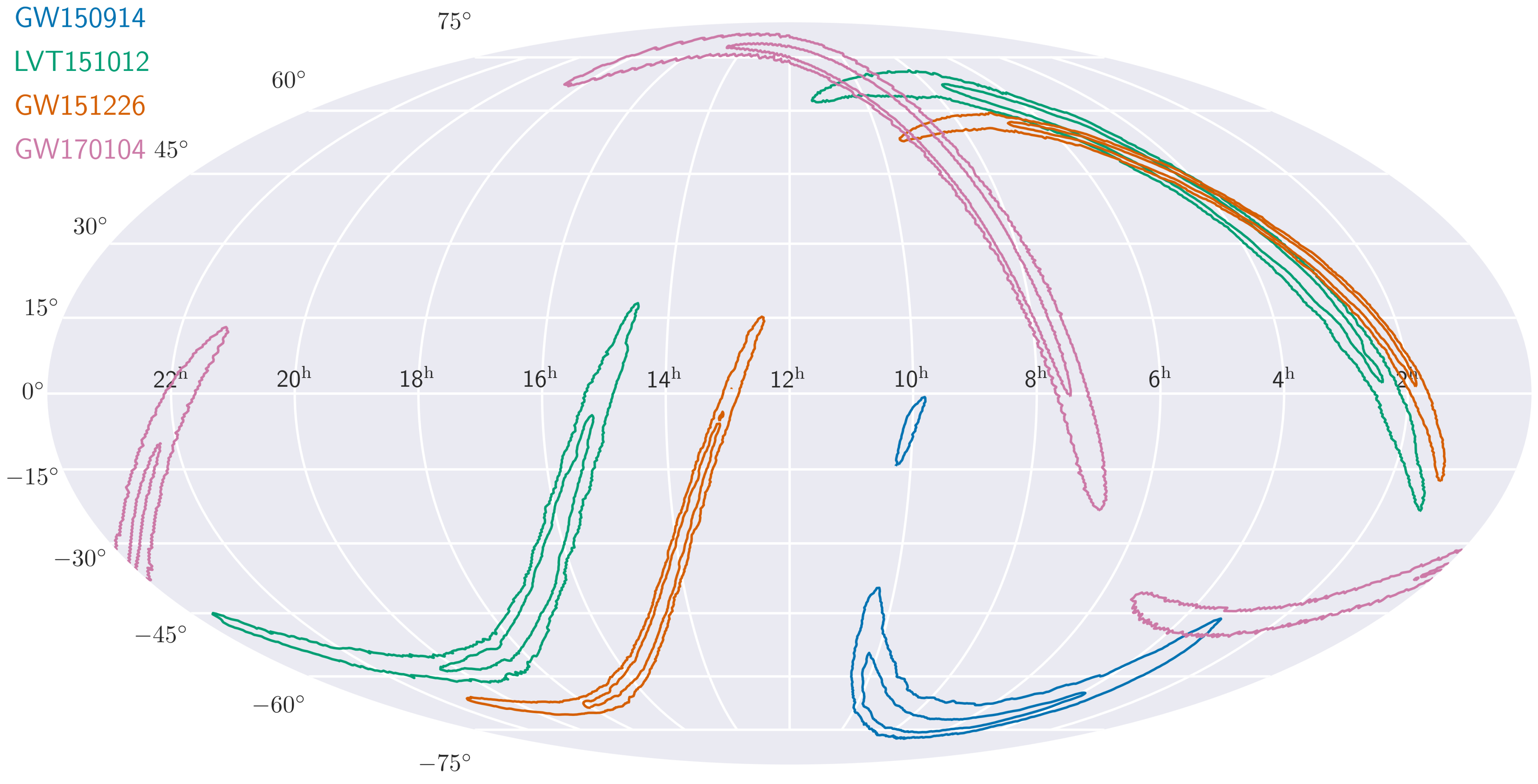

LVC
arXiv:1606.04856
arXiv:1706:01812

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/

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paper "Paramete
for Binary Neutro
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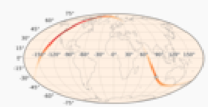
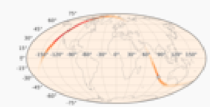
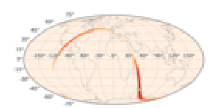
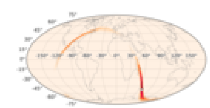
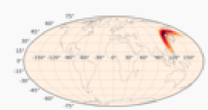
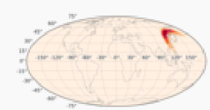
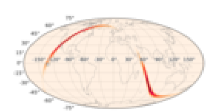
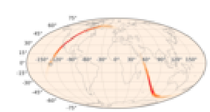
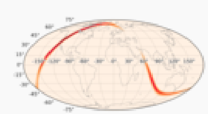
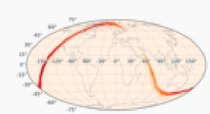
Data release | 2015, HL | 2016, HLV | new 2015, recoloured | Show/hide columns

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.

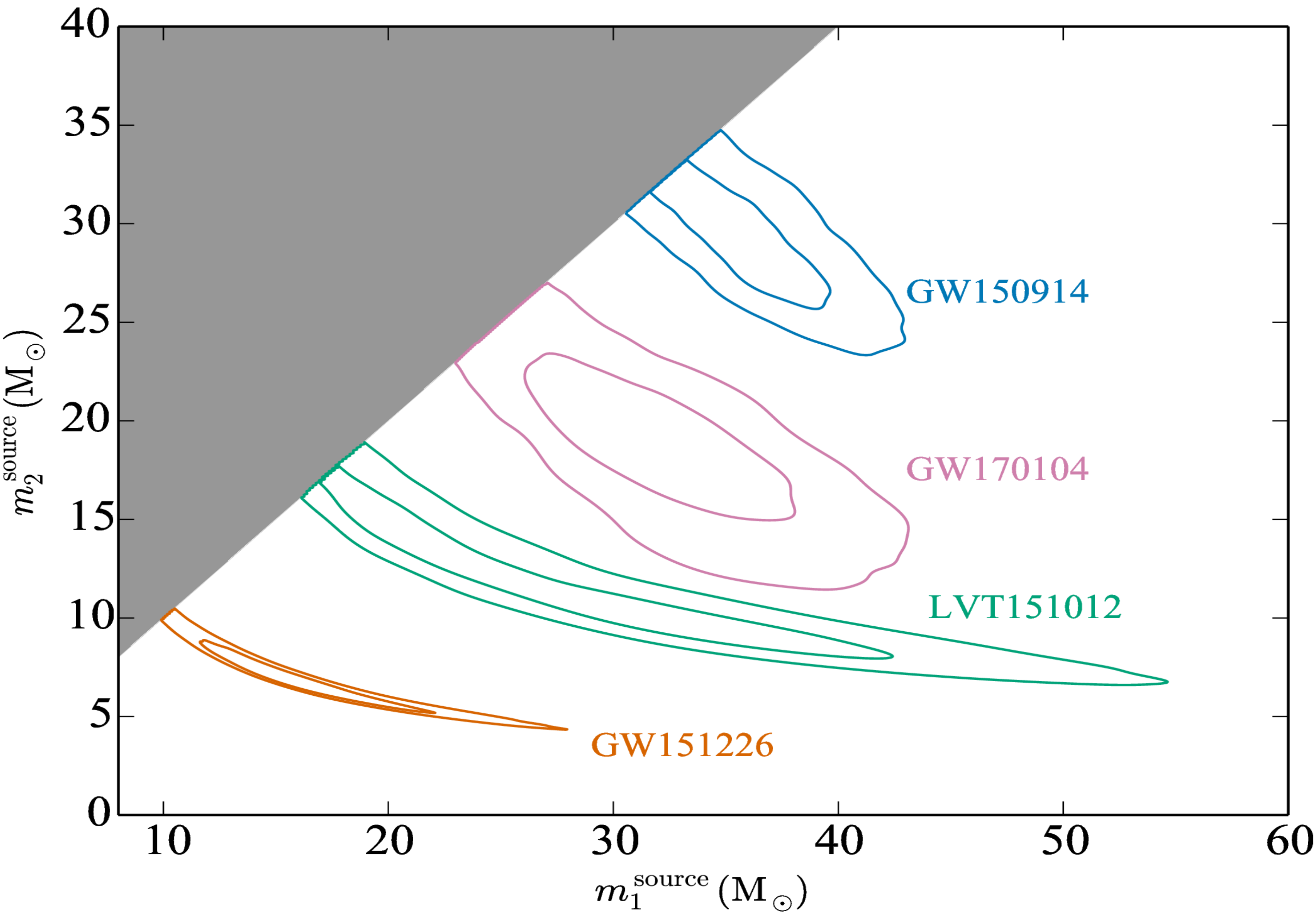
event ID	sim ID	network	SNR			BAYESTAR			LALINFERENCE_NEST			sky maps	
			net	H	L	50%	90%	searched	50%	90%	searched	BAYESTAR	LALINFERENCE_NEST
4532	899	HL	13.9	10.1	9.5	180	750	190	170	790	150		
4572	1243	HL	13.2	10.0	8.7	230	830	45	200	920	33		
4618	1768	HL	10.8	8.0	7.3	160	540	220	130	440	280		
4647	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		

Gravitational wave observatories

Our measurements

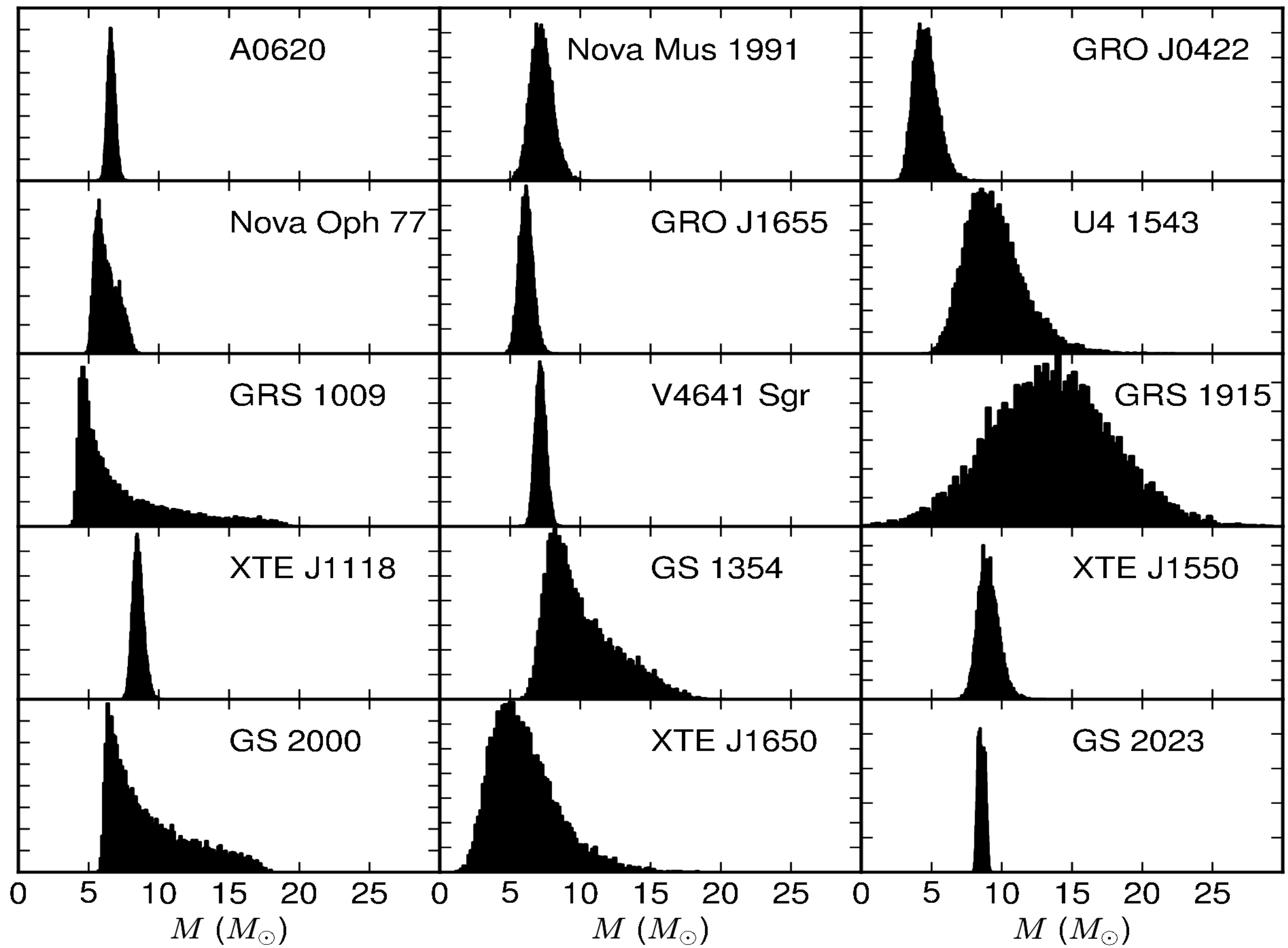
The binary black hole family

Credit: ButterflyLove1

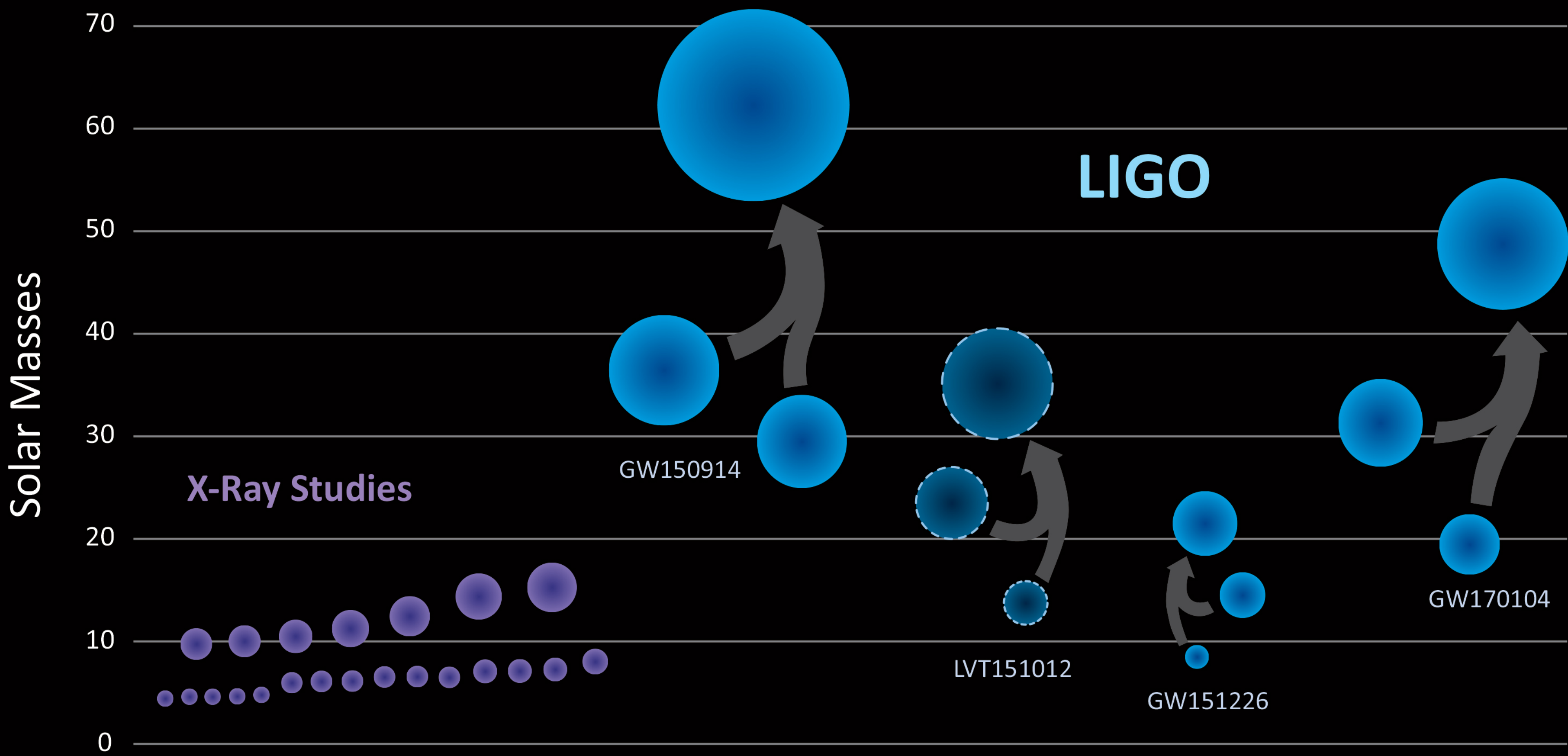


LVC arXiv:1706.01812

Farr *et al*. arXiv:1011.1459

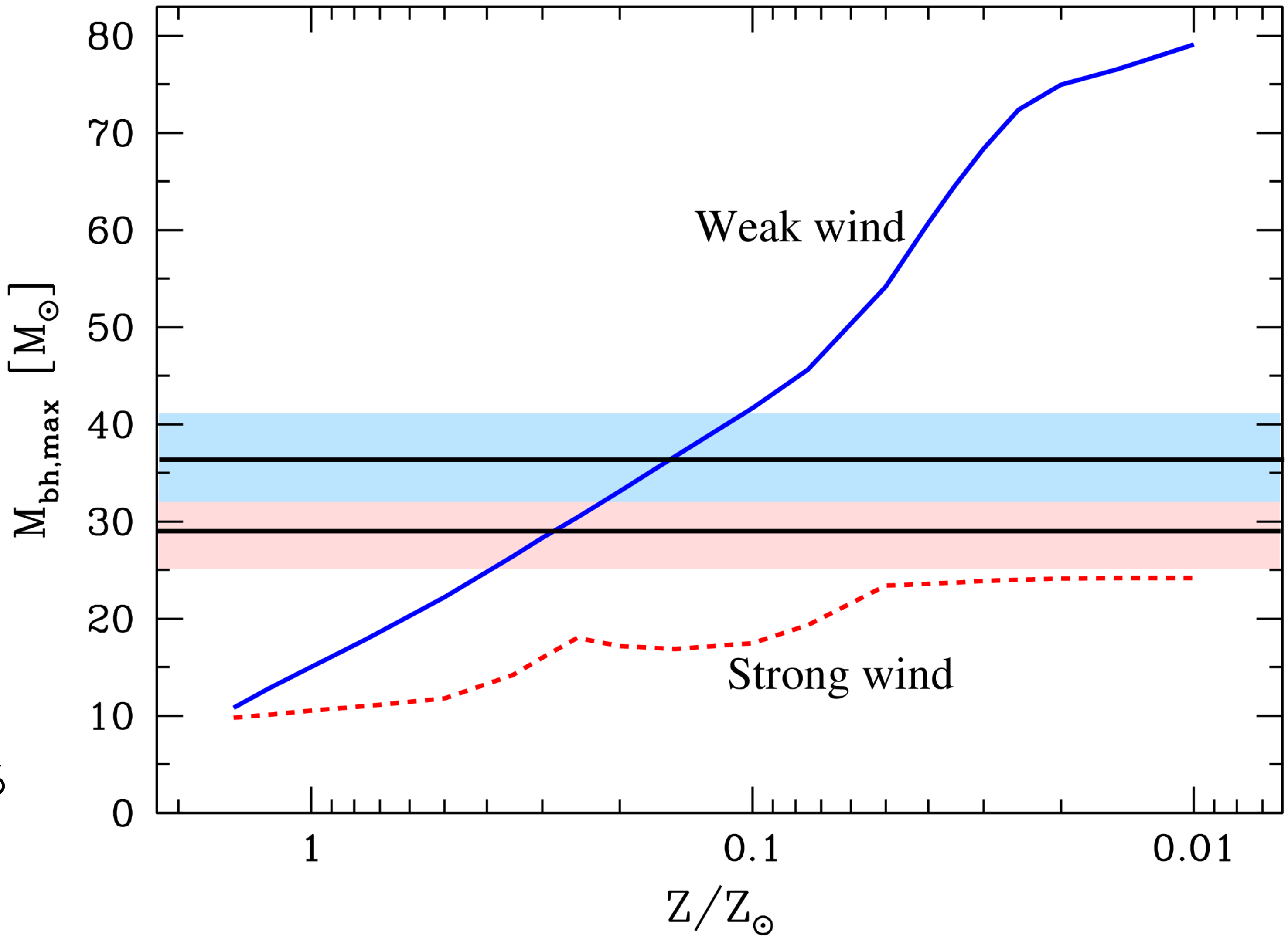


Black Holes of Known Mass



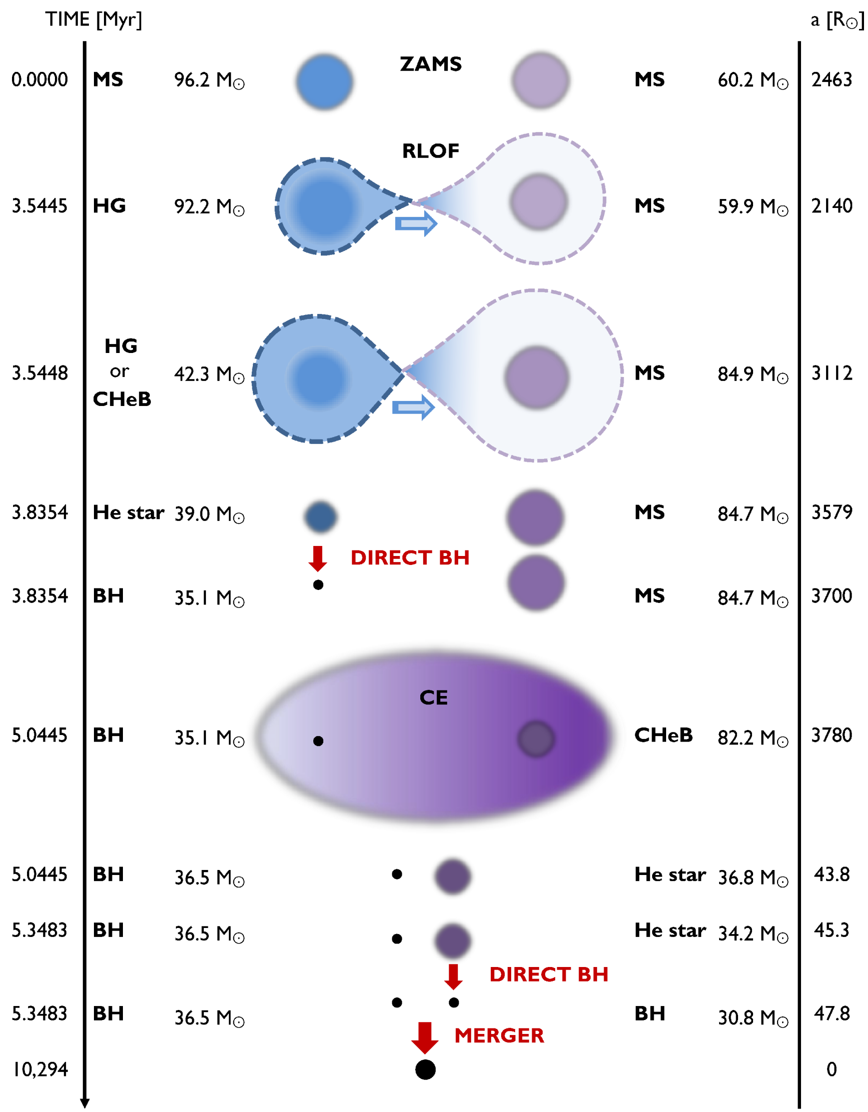
Credit: LVC

Metallicity



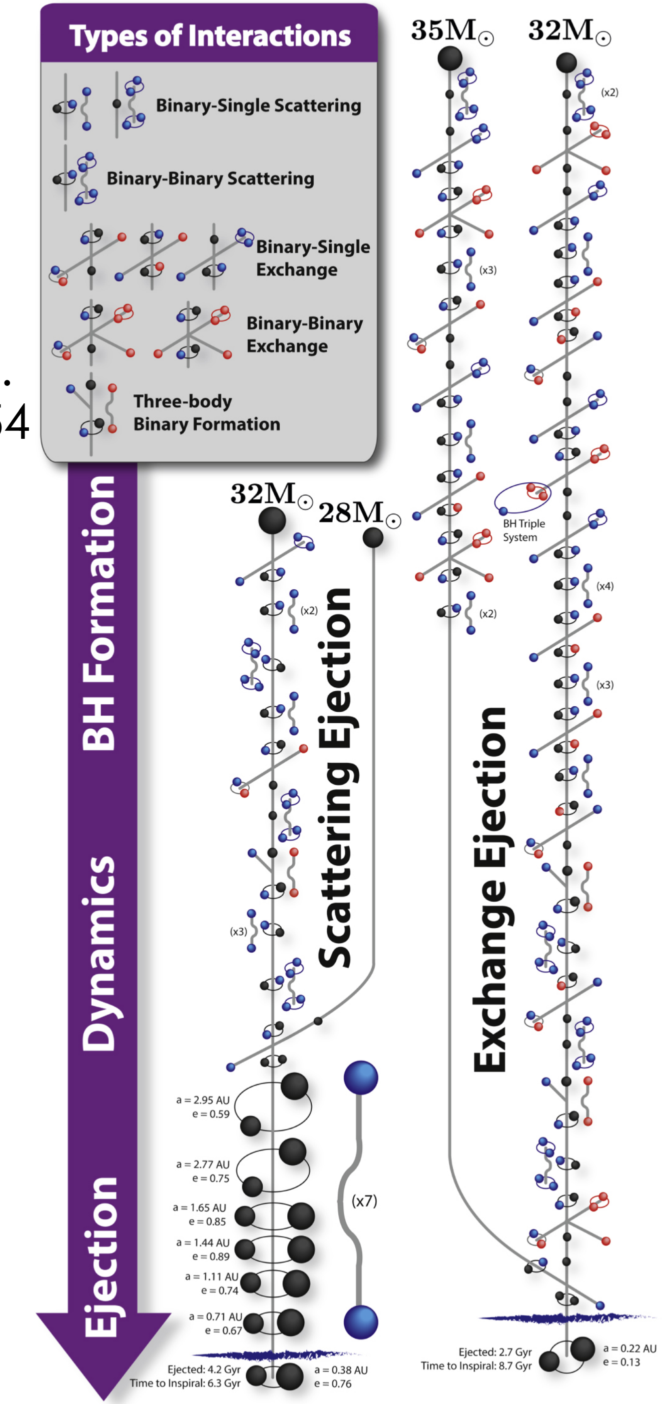
LVC
arXiv:1602.03846
Belczynski *et al.*
arXiv:0904.2784

Binary formation

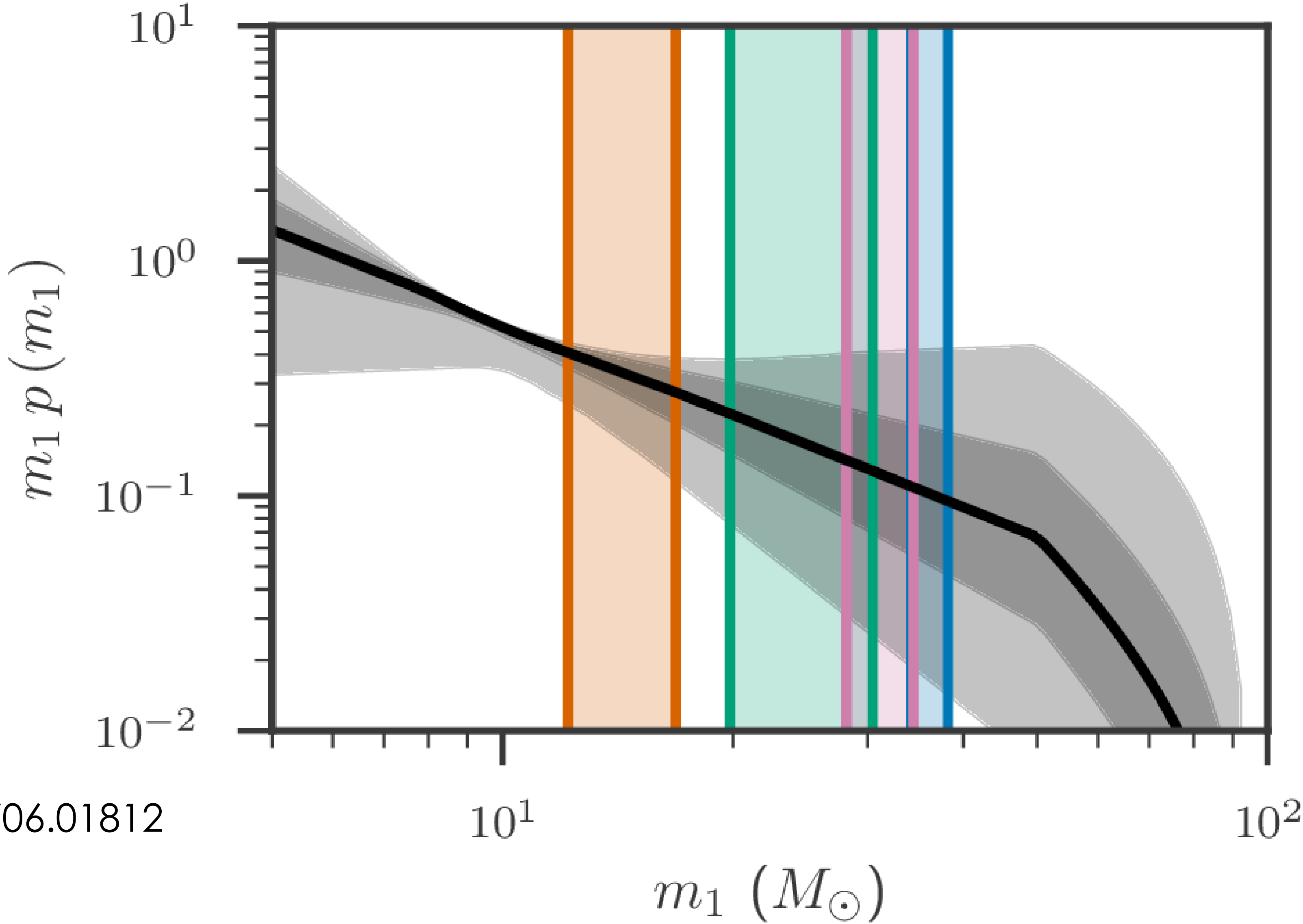


Rodriguez *et al.*
arXiv:1604.04254

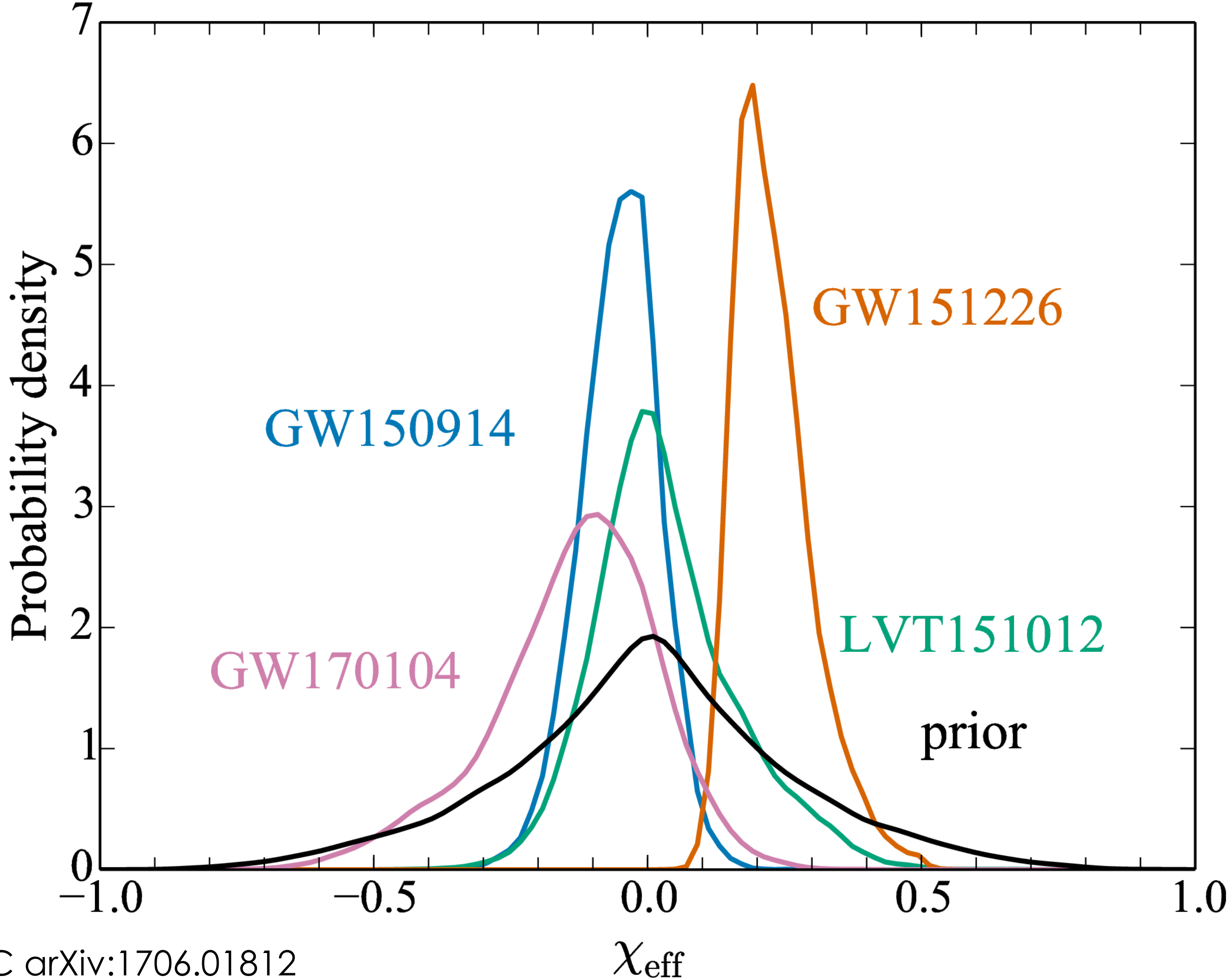
Belczynski *et al.*
arXiv:1602.04531



Mass distribution



LVC
arXiv:1706.01812



LVC arXiv:1706.01812

Hierarchical analysis

arXiv.org > astro-ph > arXiv:1706.01385

Astrophysics > High Energy Astrophysical Phe

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 $(2.9 \times 10^{-7}$ 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 docume

Subjects: **High Energy Astrophysical Phenom**

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 arXiv: 1703.06873

Talbot & Thrane arXiv:1704.08370

There is a growing network of ground-based gravitational wave observatories

We have observed a family of binary black holes

Masses and spins give hints to formation mechanisms, but need many detections

- Measured gravitational wave signal encodes information about the source
- Some parameters (like chirp mass) measured well, others (like in-plane spins) remain uncertain
- Observations give insight into black hole evolution
- Need a hierarchical analysis of a population of ~100 detections

LVKC arXiv:1304.0670
LVC arXiv:1602.03840 arXiv:1602.03846 arXiv:1606.04856 arXiv:1706.01812

Thank you

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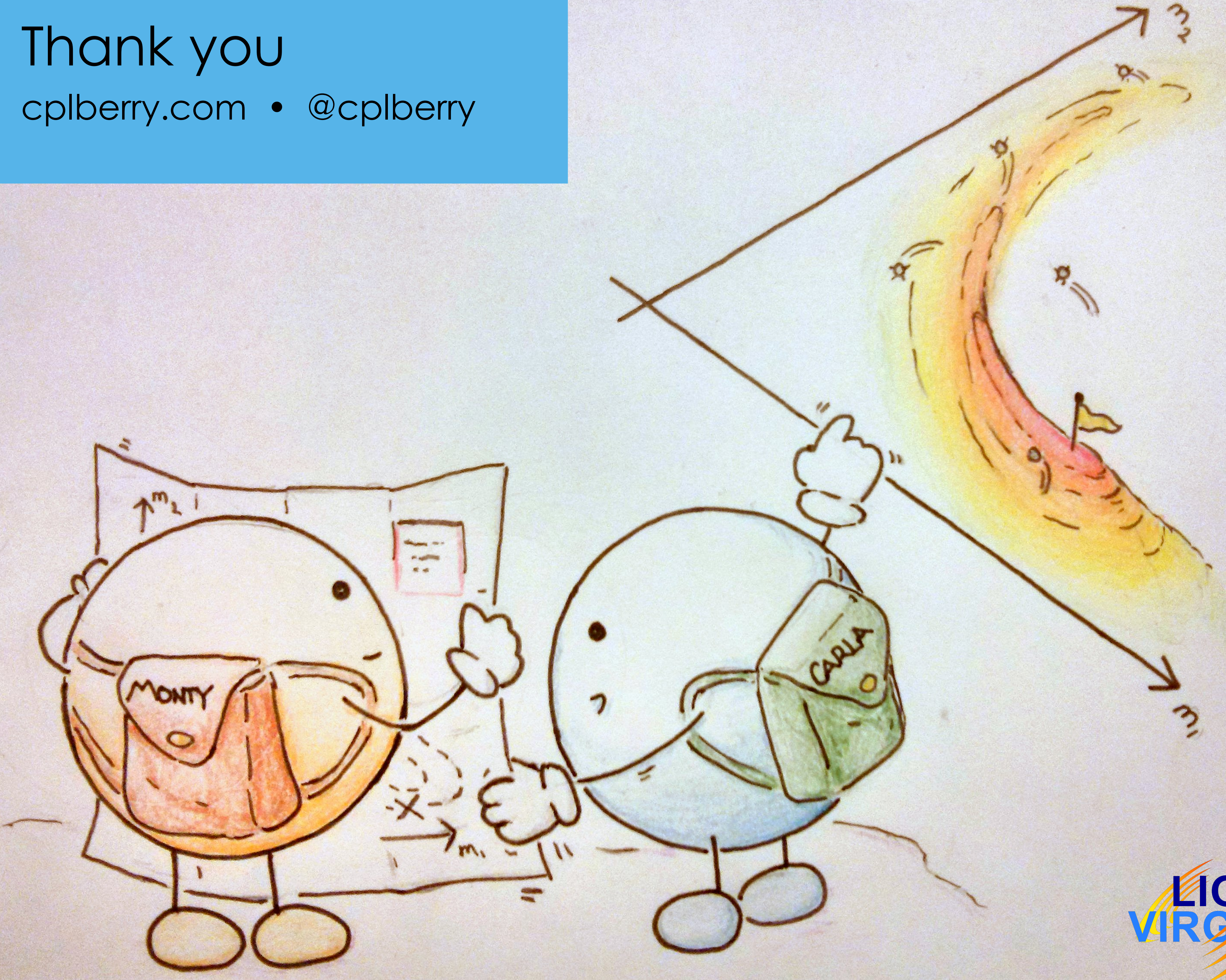
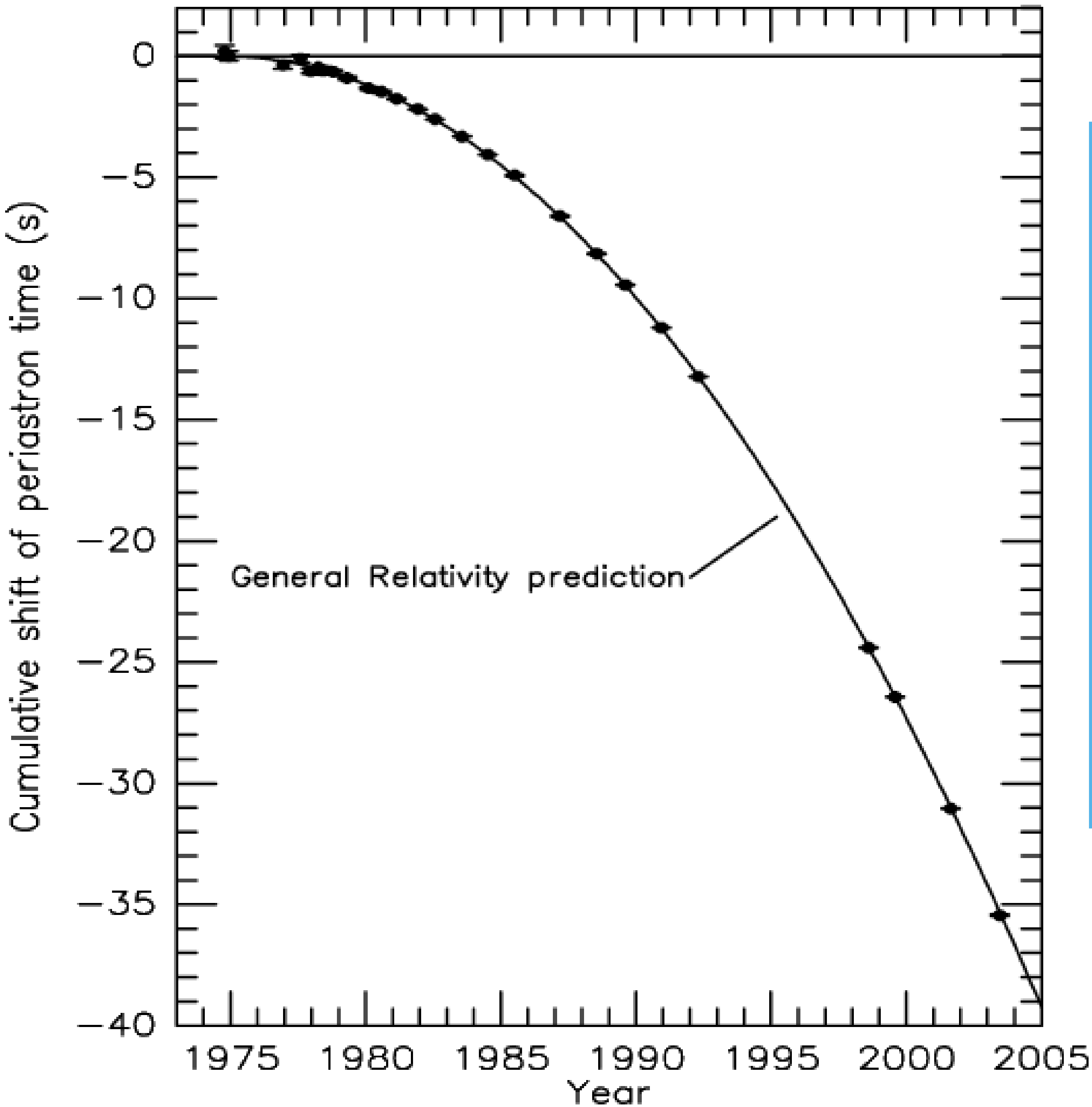


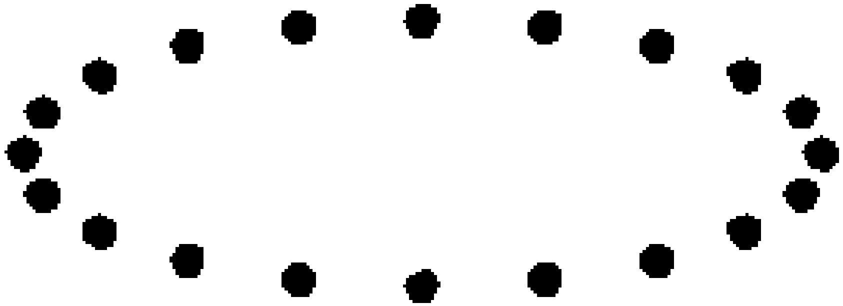
LIGO VIRGO

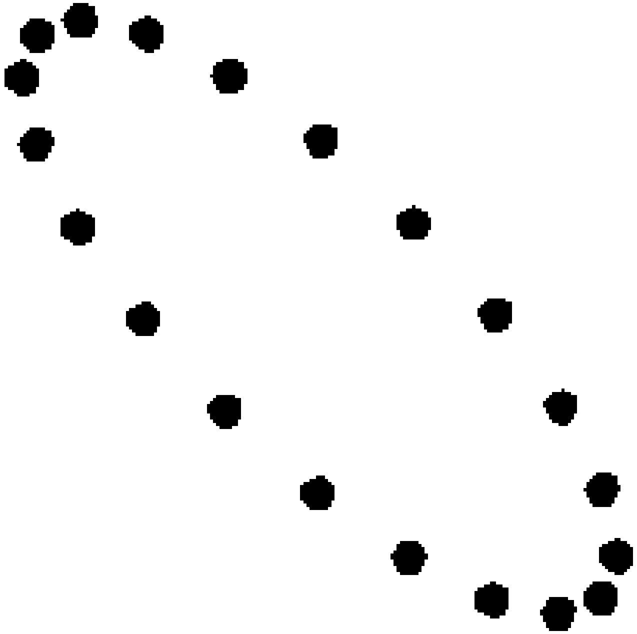


Indirect observations from pulsar binaries

Weisberg & Taylor
arXiv:astro-ph/0407149

Polarizations





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

Bayes' theorem

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

Bayes' theorem

Likelihood

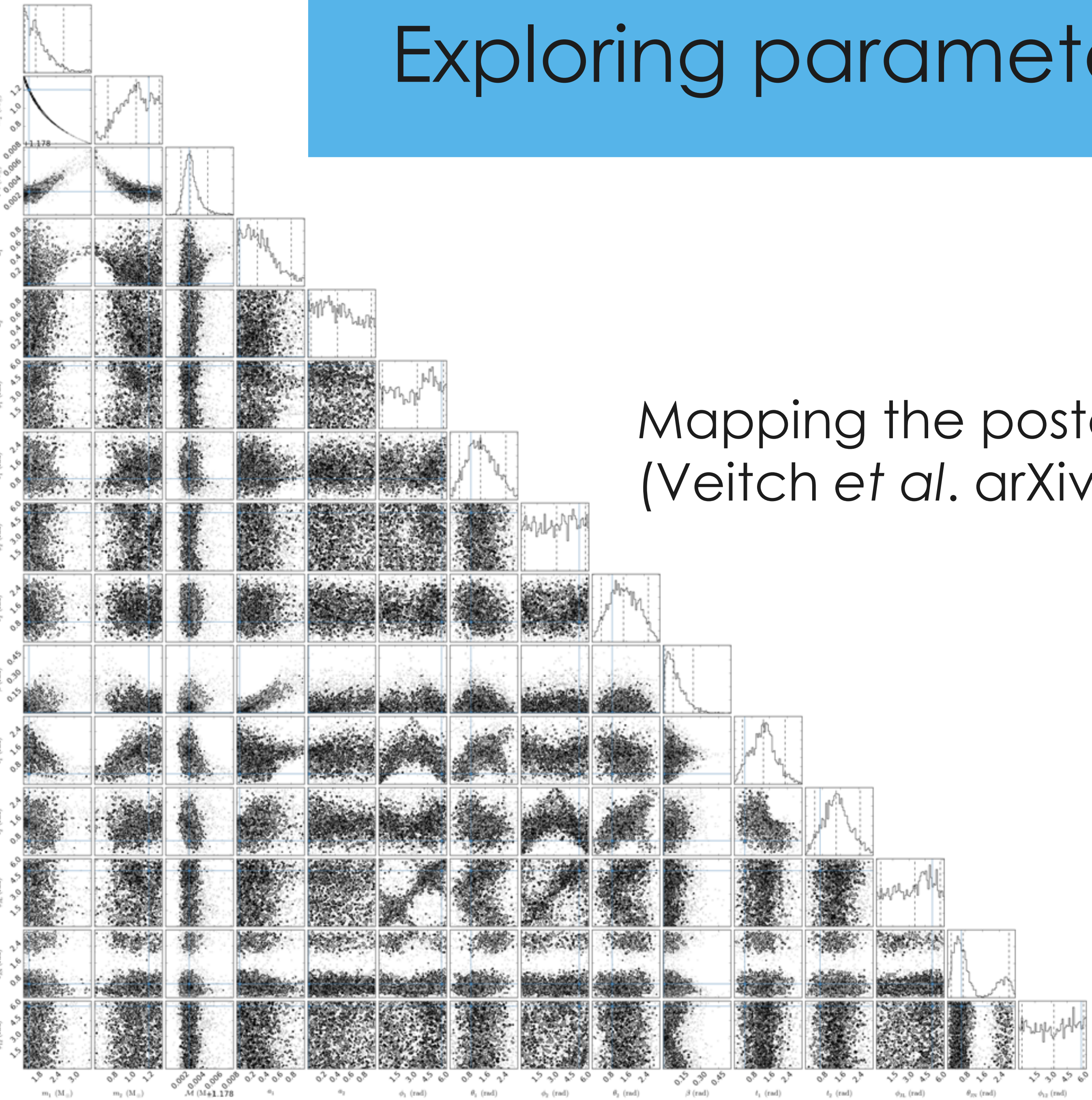
Prior

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

Posterior

Evidence

Exploring parameter space



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

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

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

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

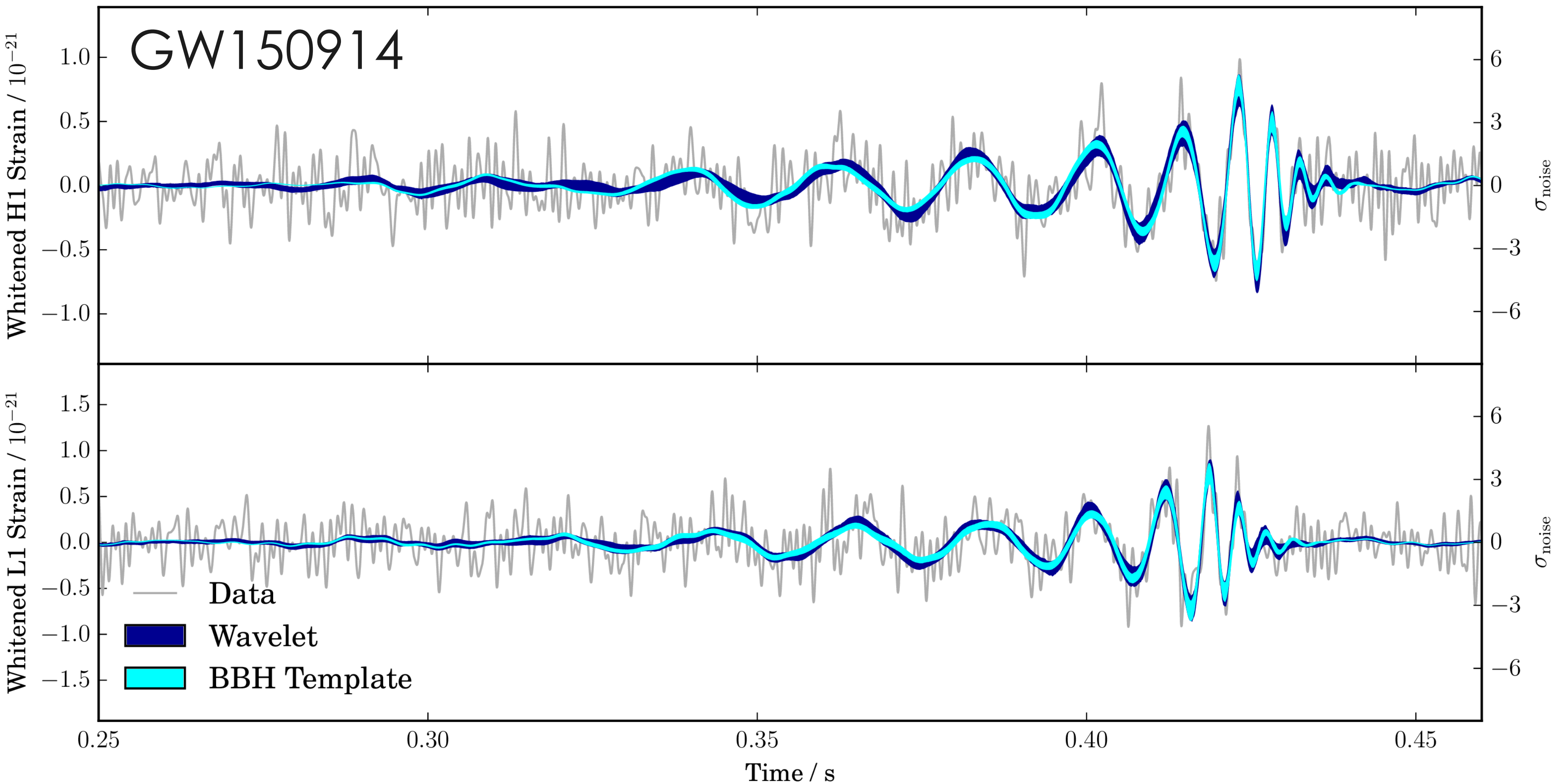
$$p(d|\theta) \propto \exp\left[-\frac{1}{2}\sum_k \langle h_k(\theta) - d_k | h_k(\theta) - d_k \rangle\right]$$

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

Waveform

LVC arXiv:1602.03840

Waveform



LVC arXiv:1602.03840

Bayes' theorem

Likelihood

Prior

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

Posterior

Evidence

Bayes' theorem

Likelihood

Prior

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

Posterior

Evidence

Bayes' theorem

Evidence

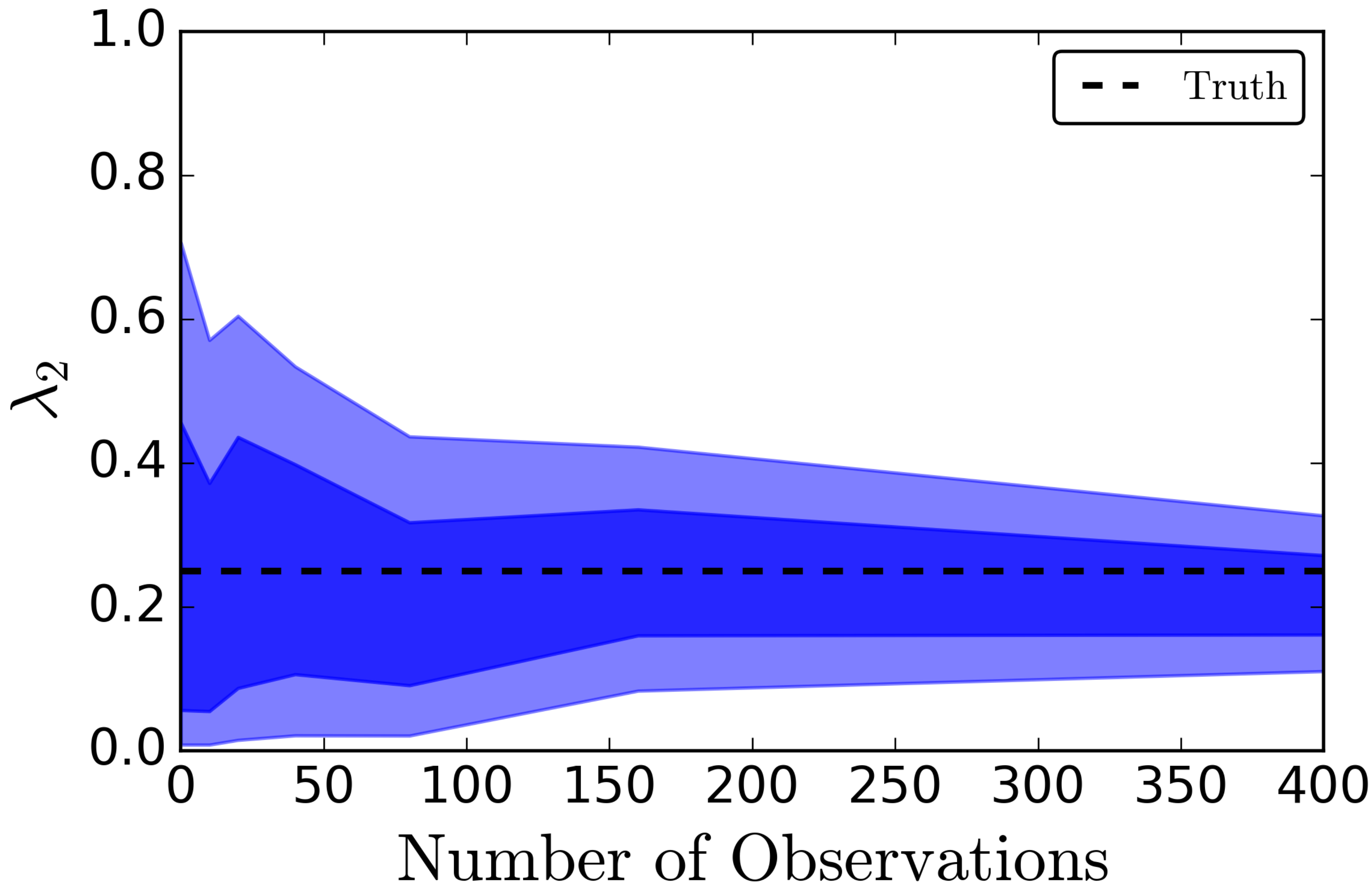
Model prior

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

Model posterior

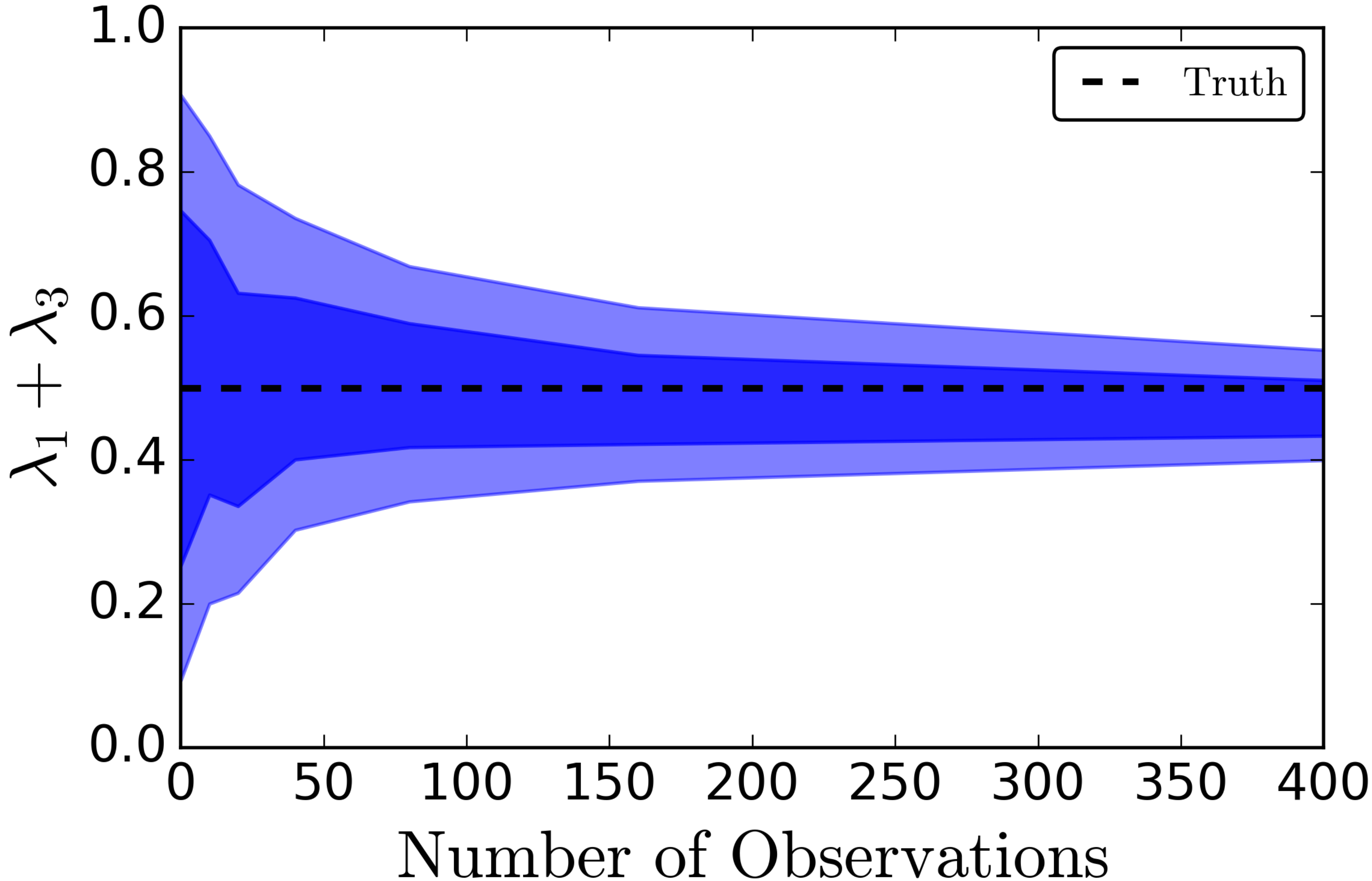
Model inference

Stevenson, CPLB & Mandel
arXiv:1703.06873



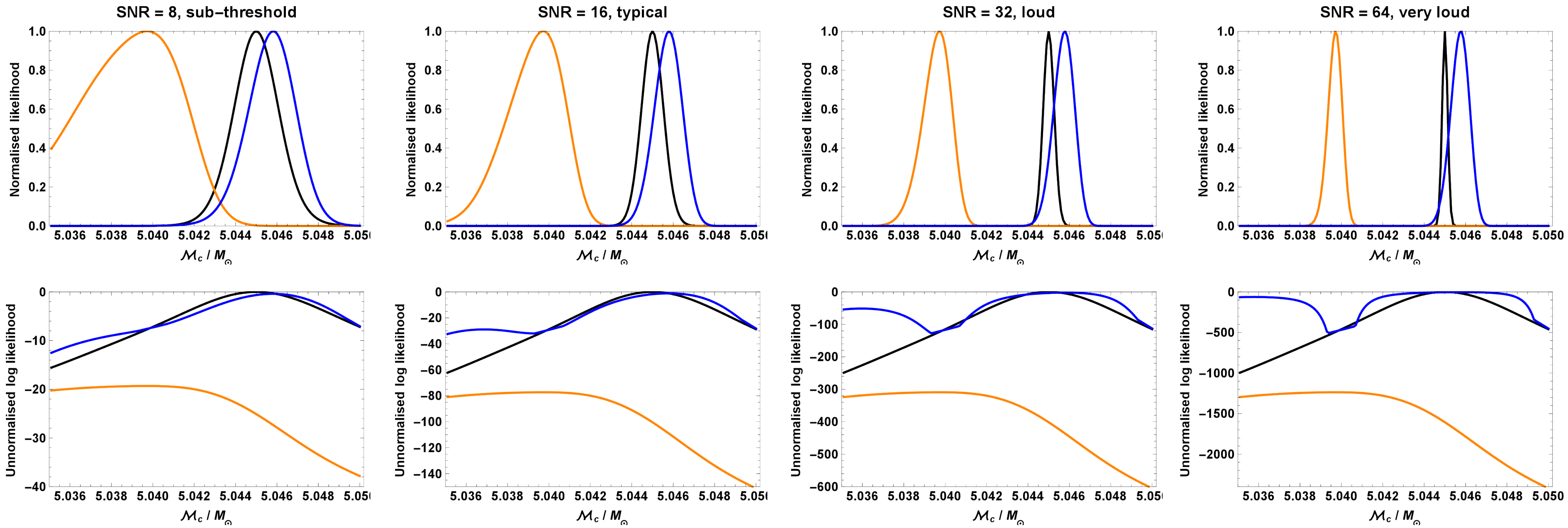
Model inference

Stevenson, CPLB & Mandel
arXiv:1703.06873



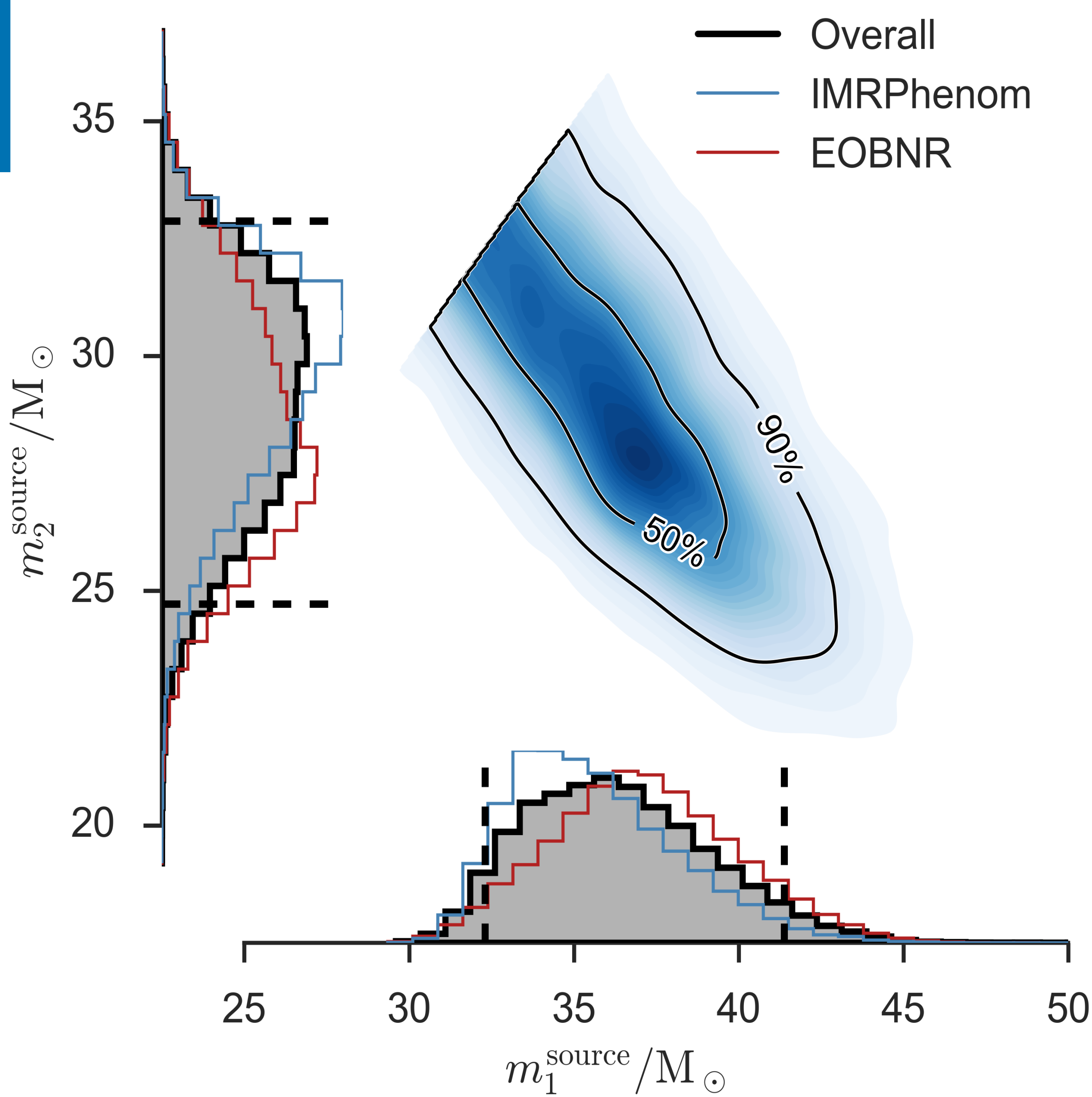
Waveform error

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



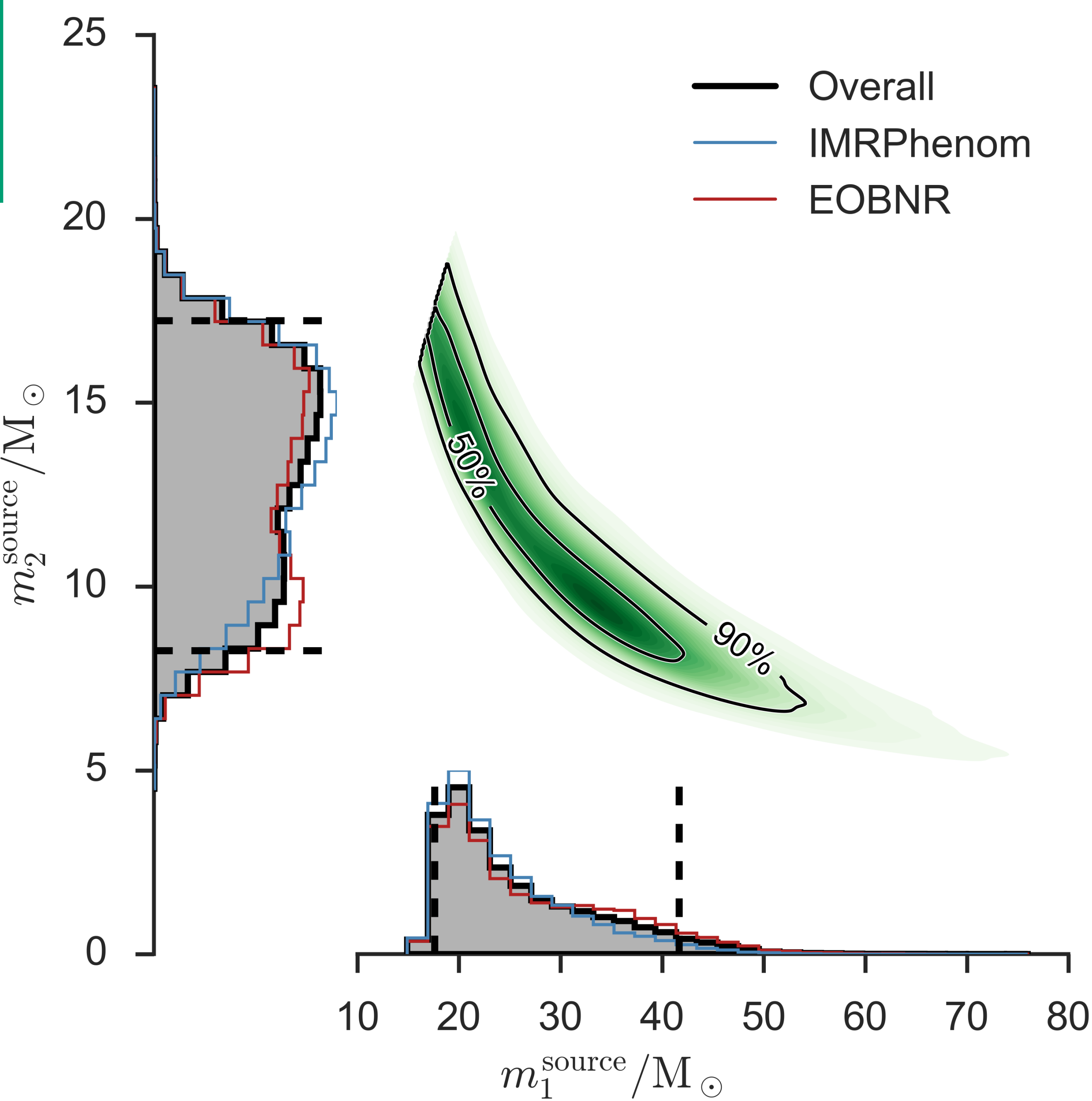
Moore *et al*. arXiv:1509.04066

Masses



LVC
arXiv:1606.04856
arXiv:1602.03840

Masses



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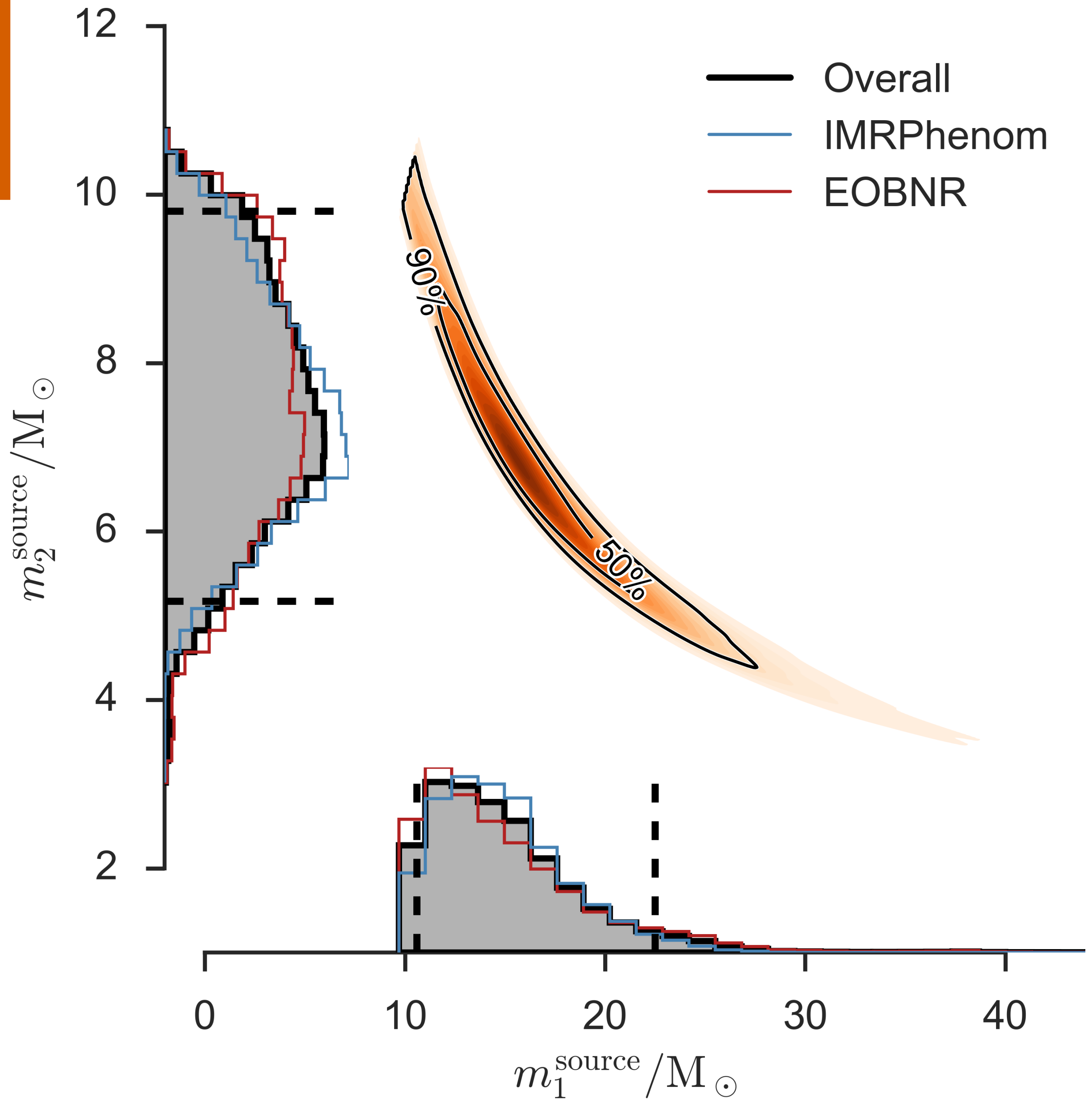
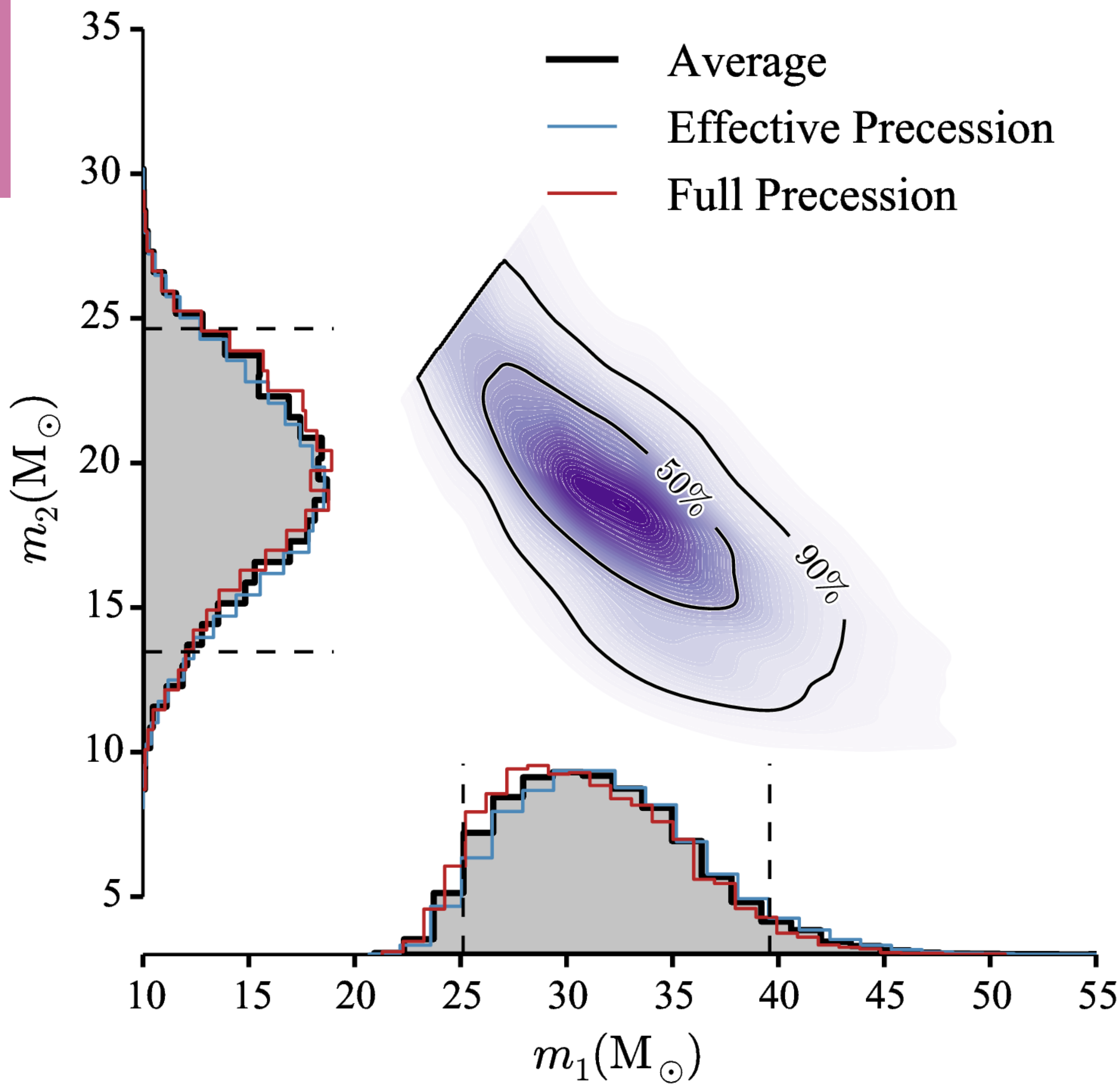
arXiv:1606.04856

Masses



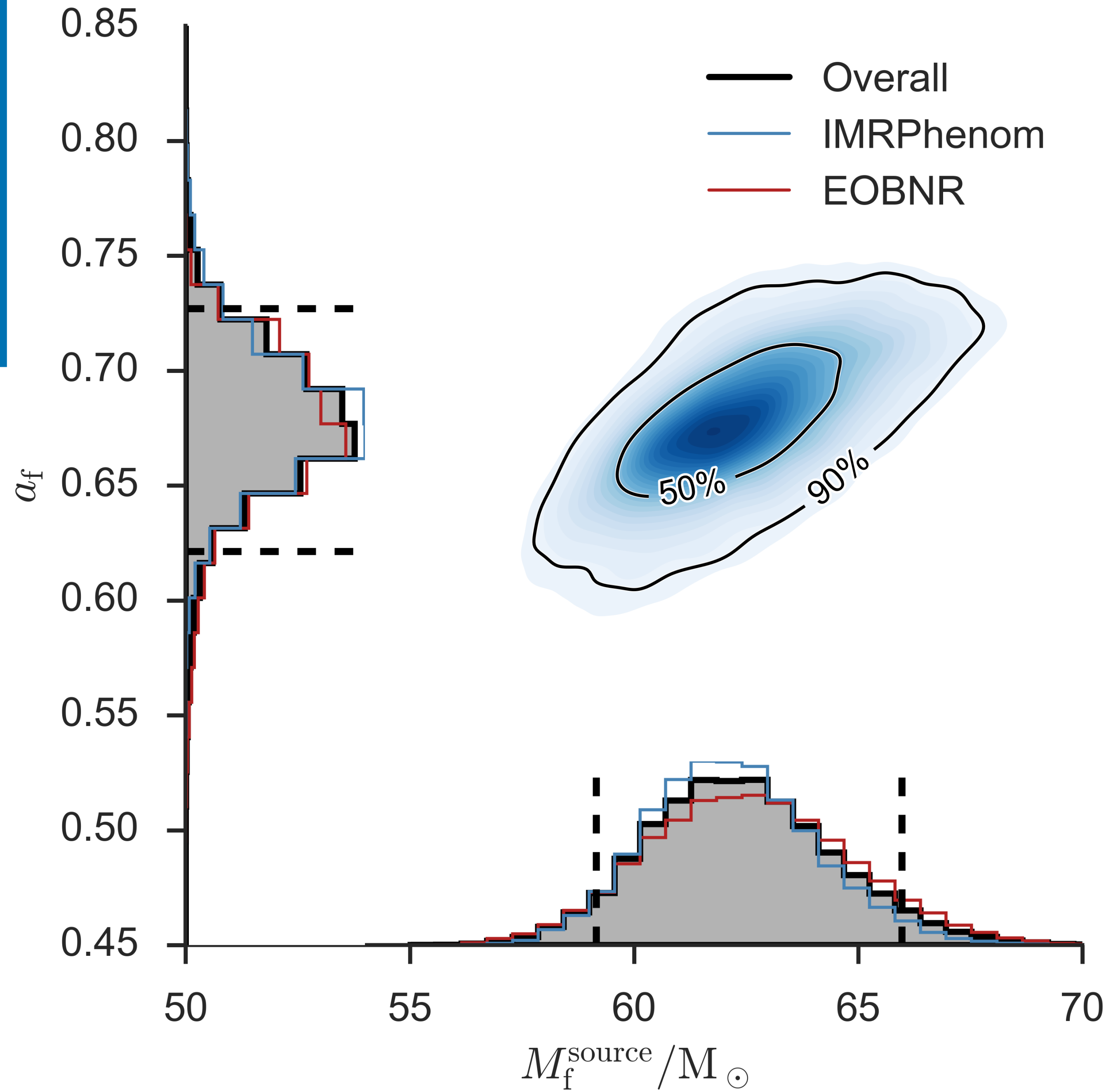
LVC
arXiv:1606.04855

Masses



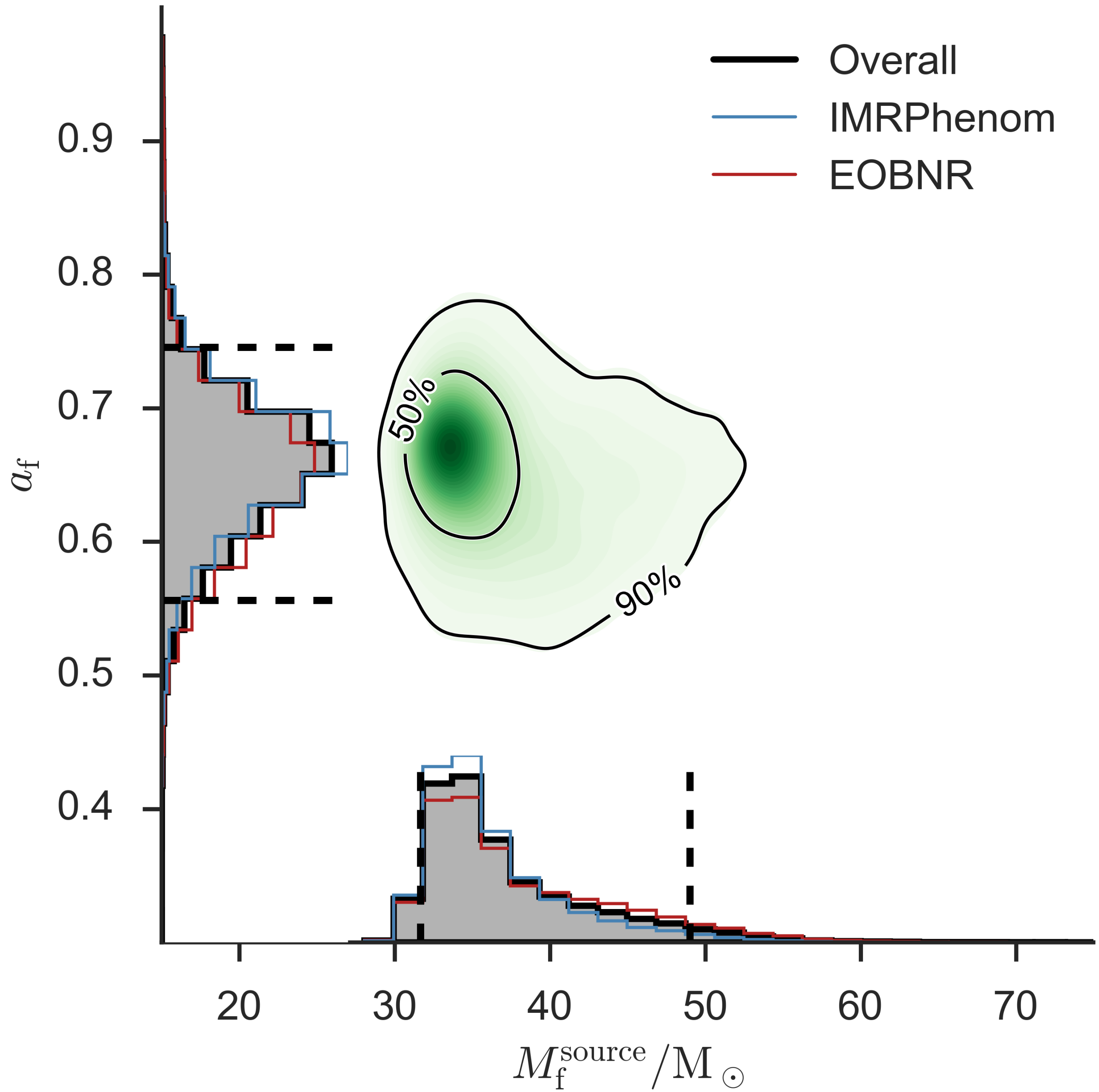
LVC
arXiv:1706.01812

Final mass & spin



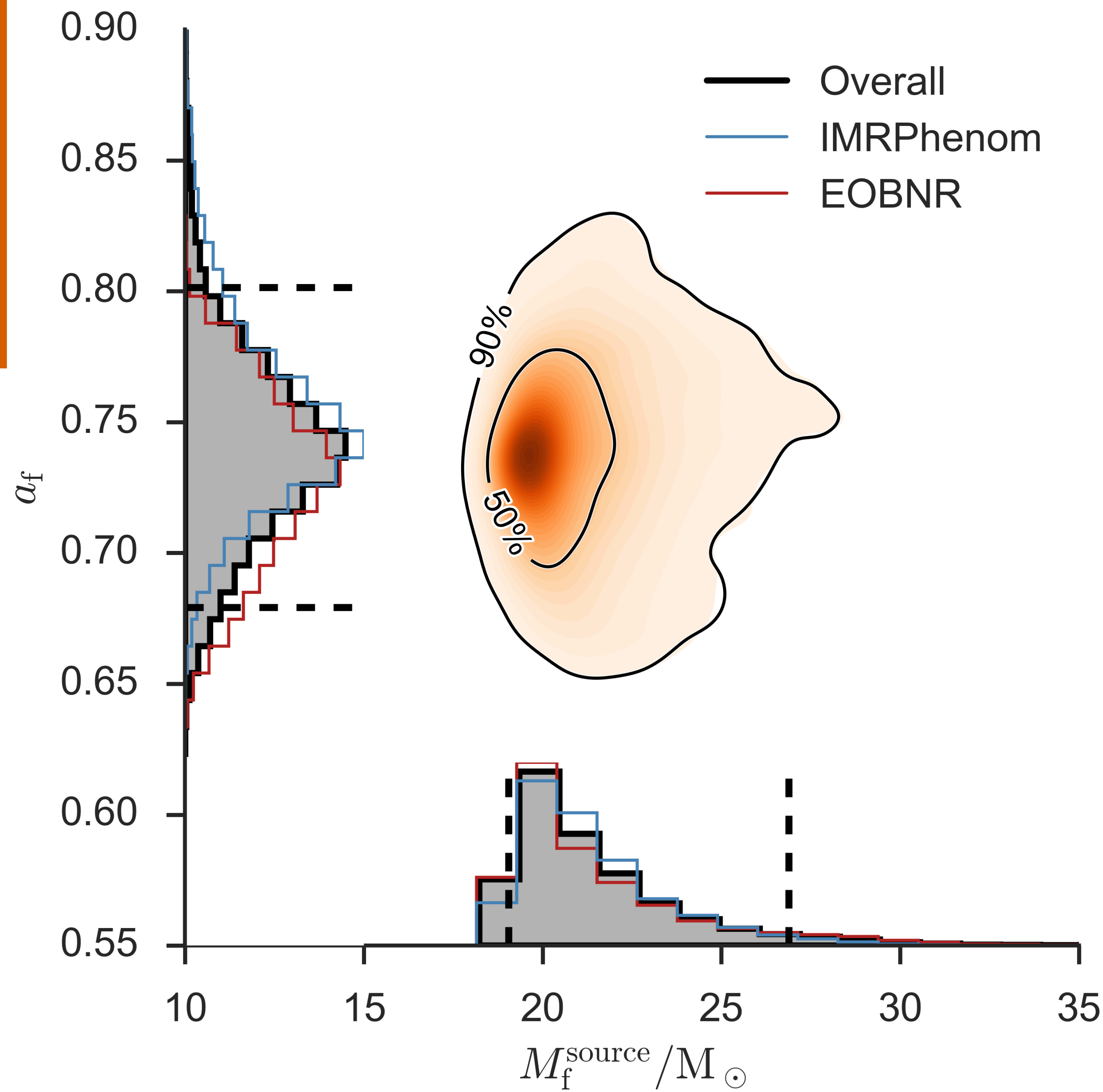
LVC
arXiv:1606.04856
arXiv:1602.03840

Final mass & spin



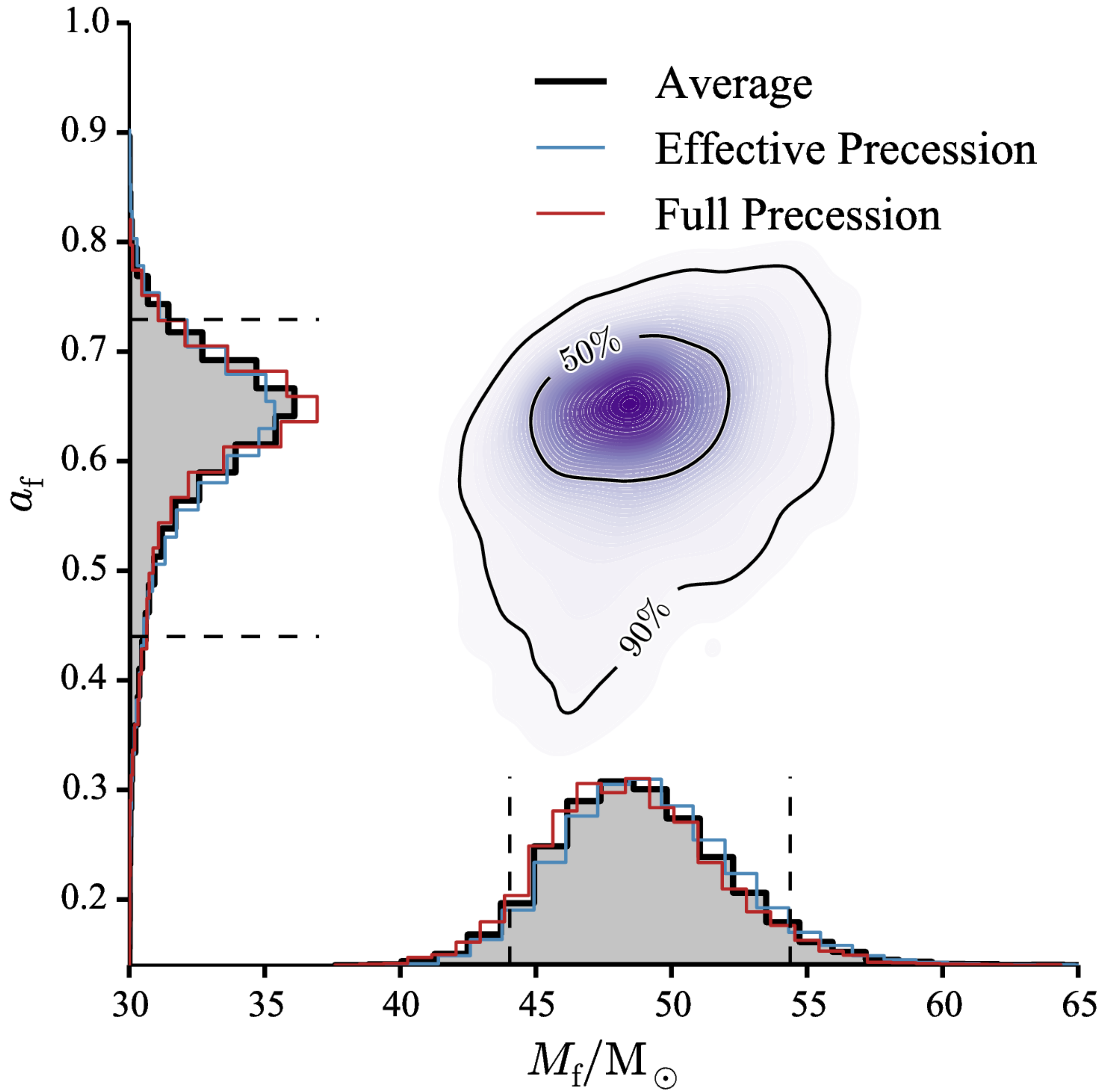
LVC
arXiv:1606.04856

Final mass & spin



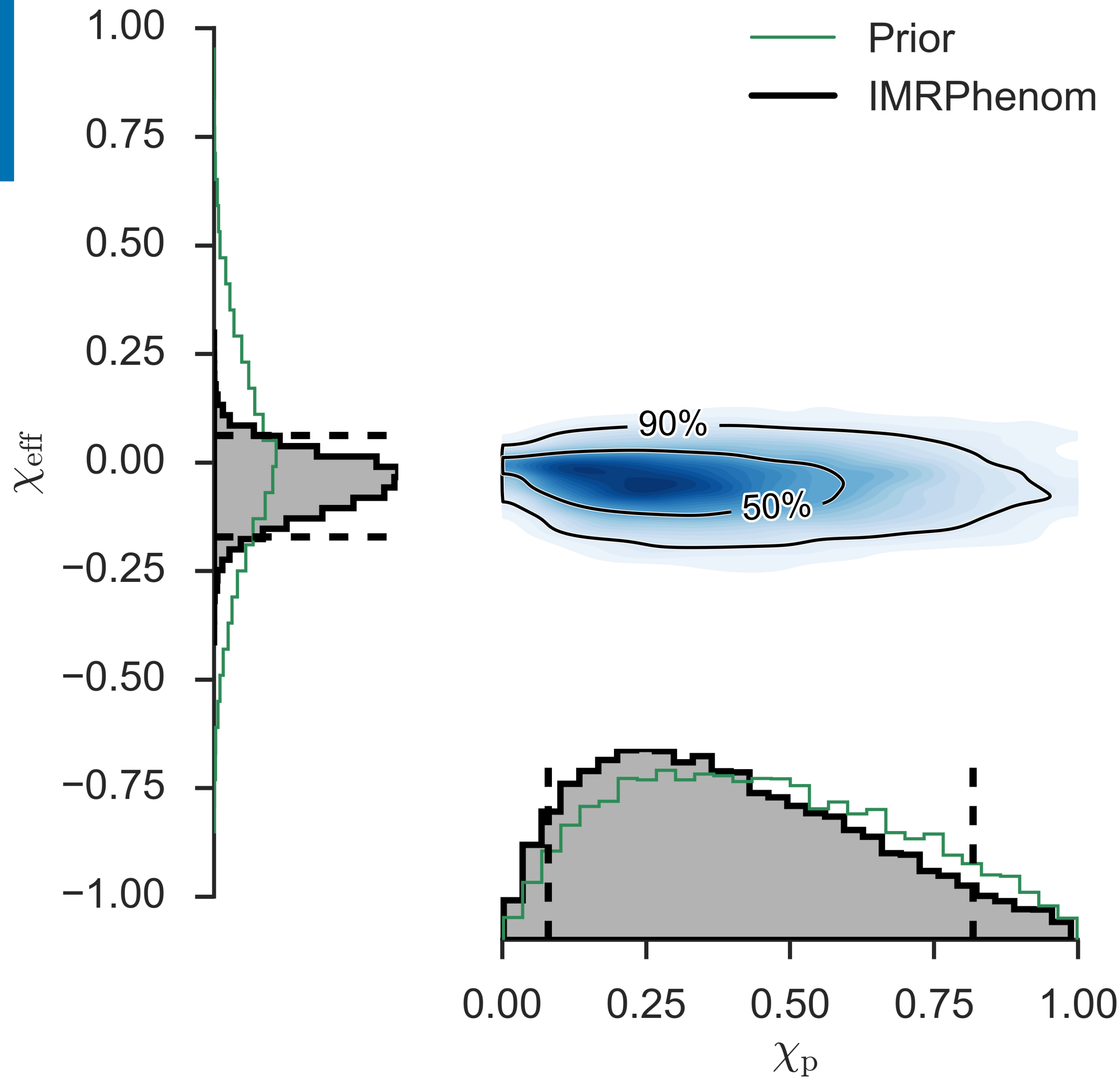
LVC
arXiv:1606.04856

Final mass & spin



LVC
arXiv:1706.01812

Spin



LVC
arXiv:1606.04856
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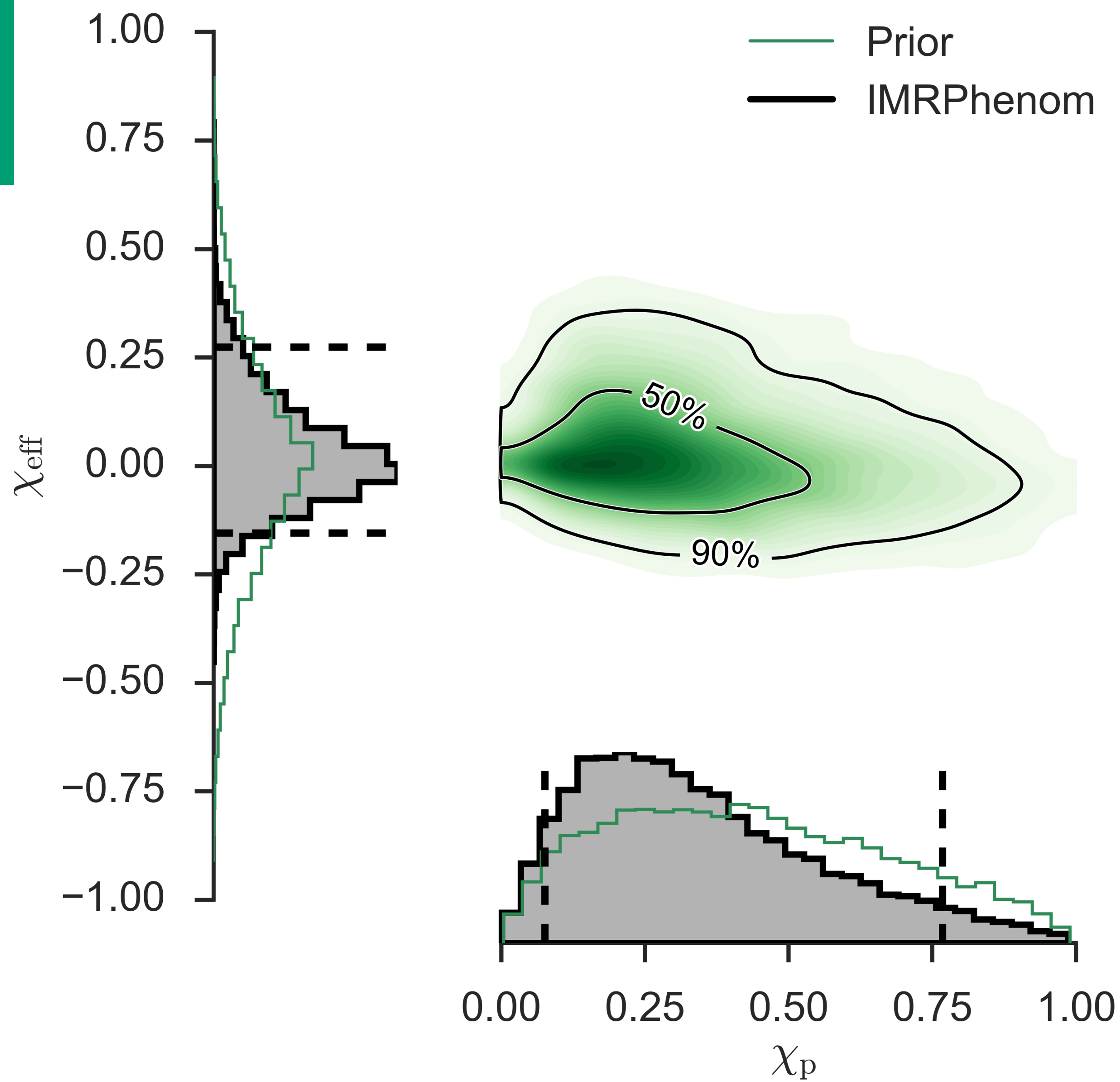
Spin



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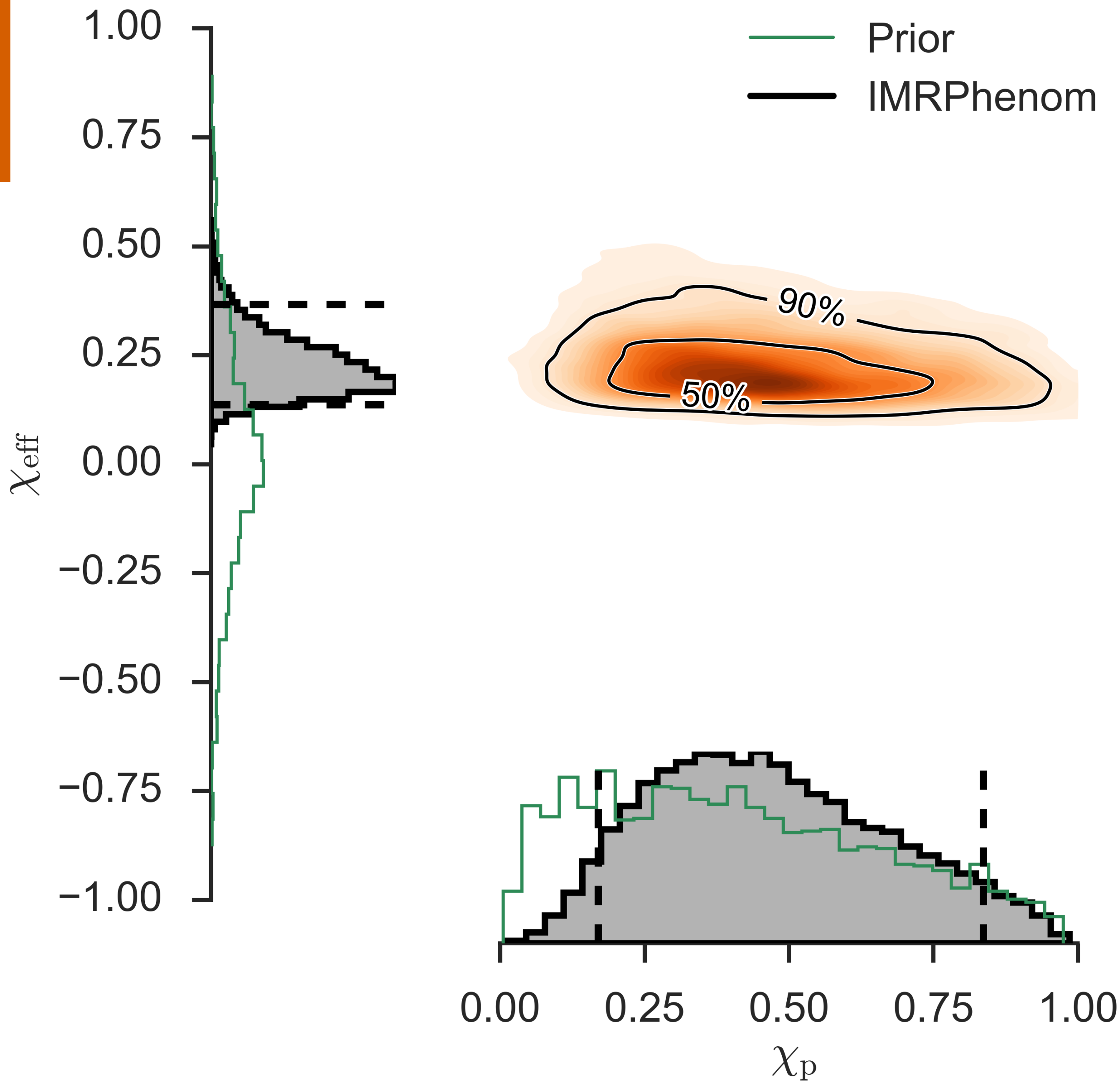
arXiv:1606.04856

Spin



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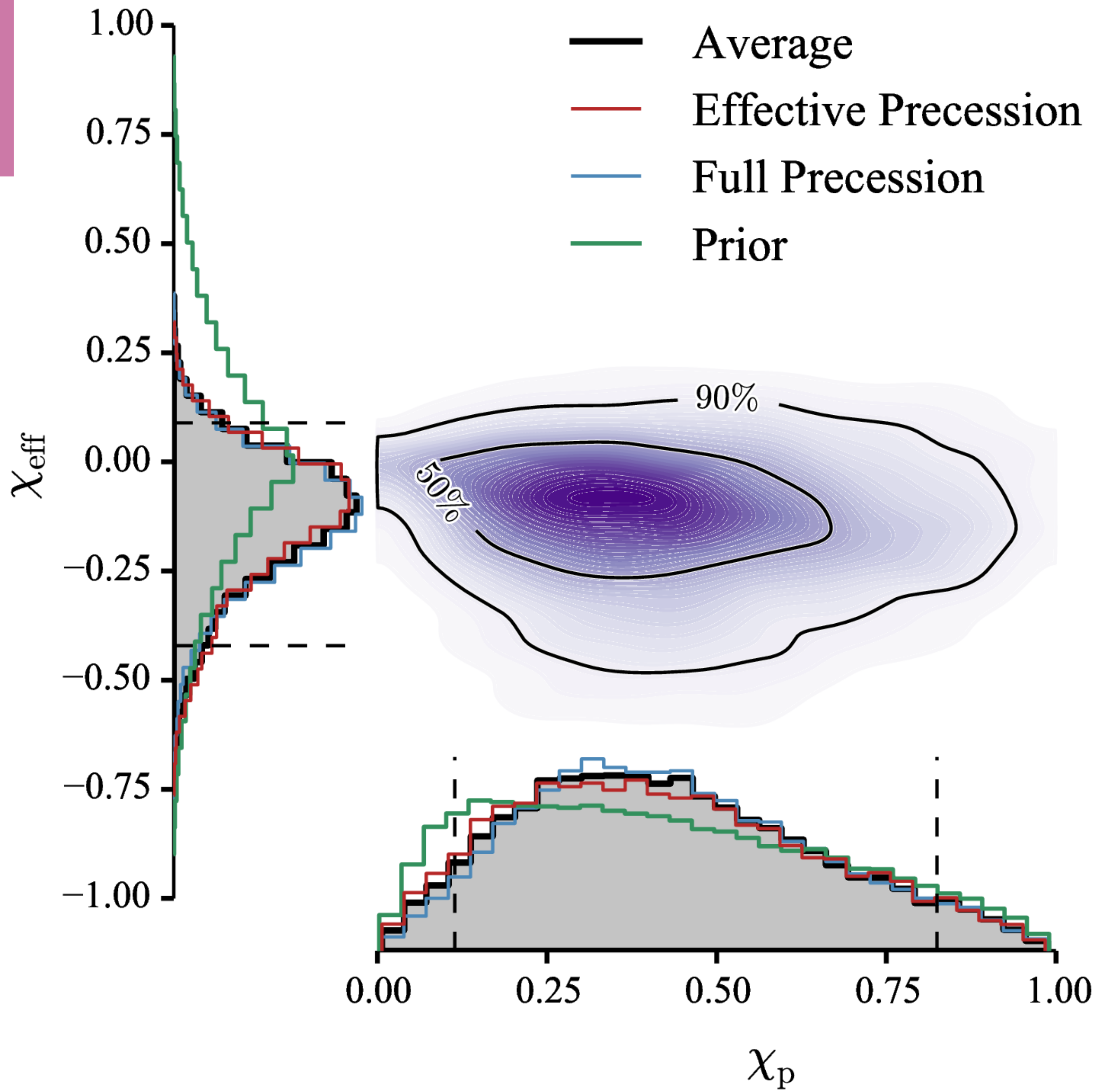
Spin



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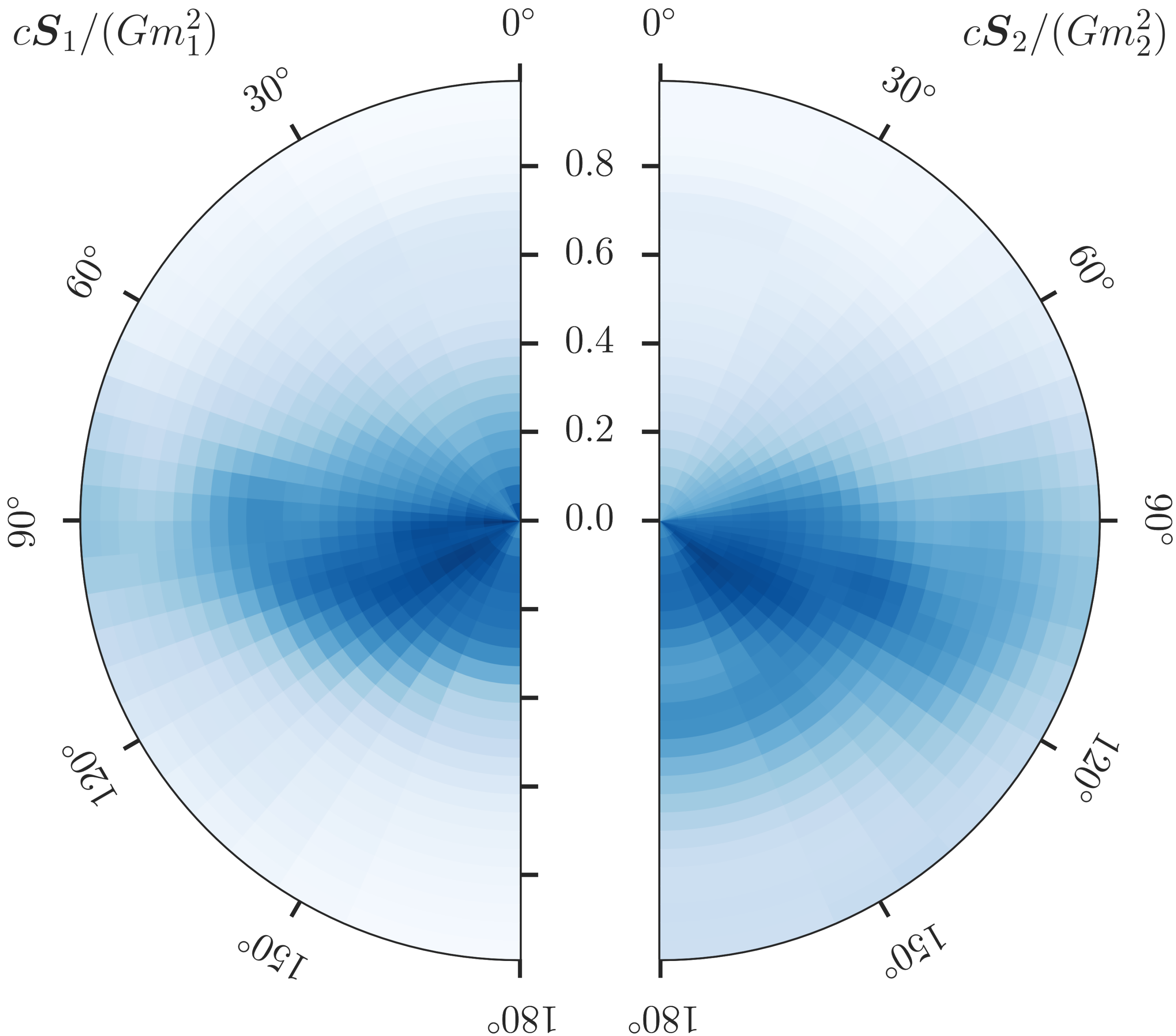
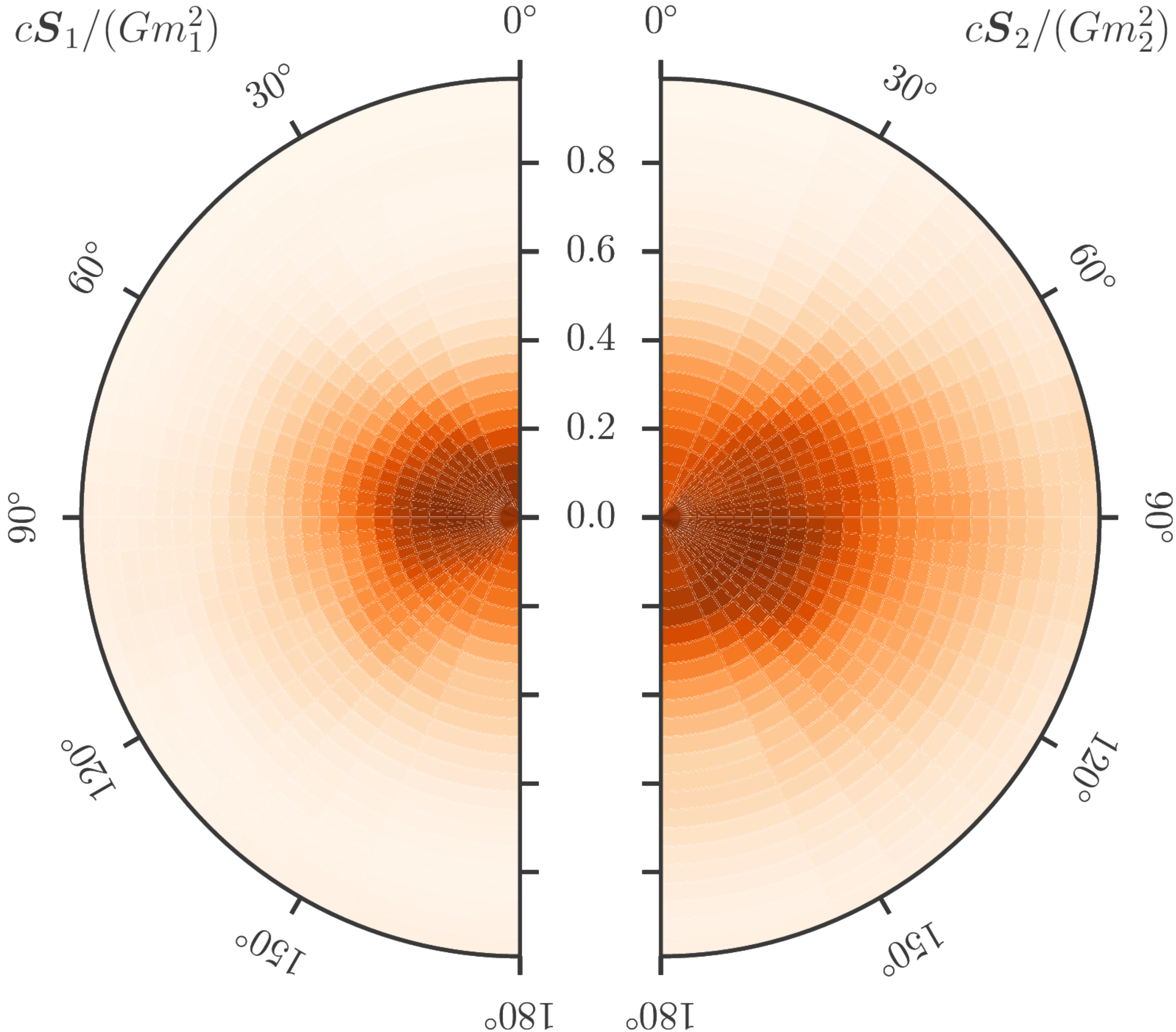
arXiv:1706.01812

Spin



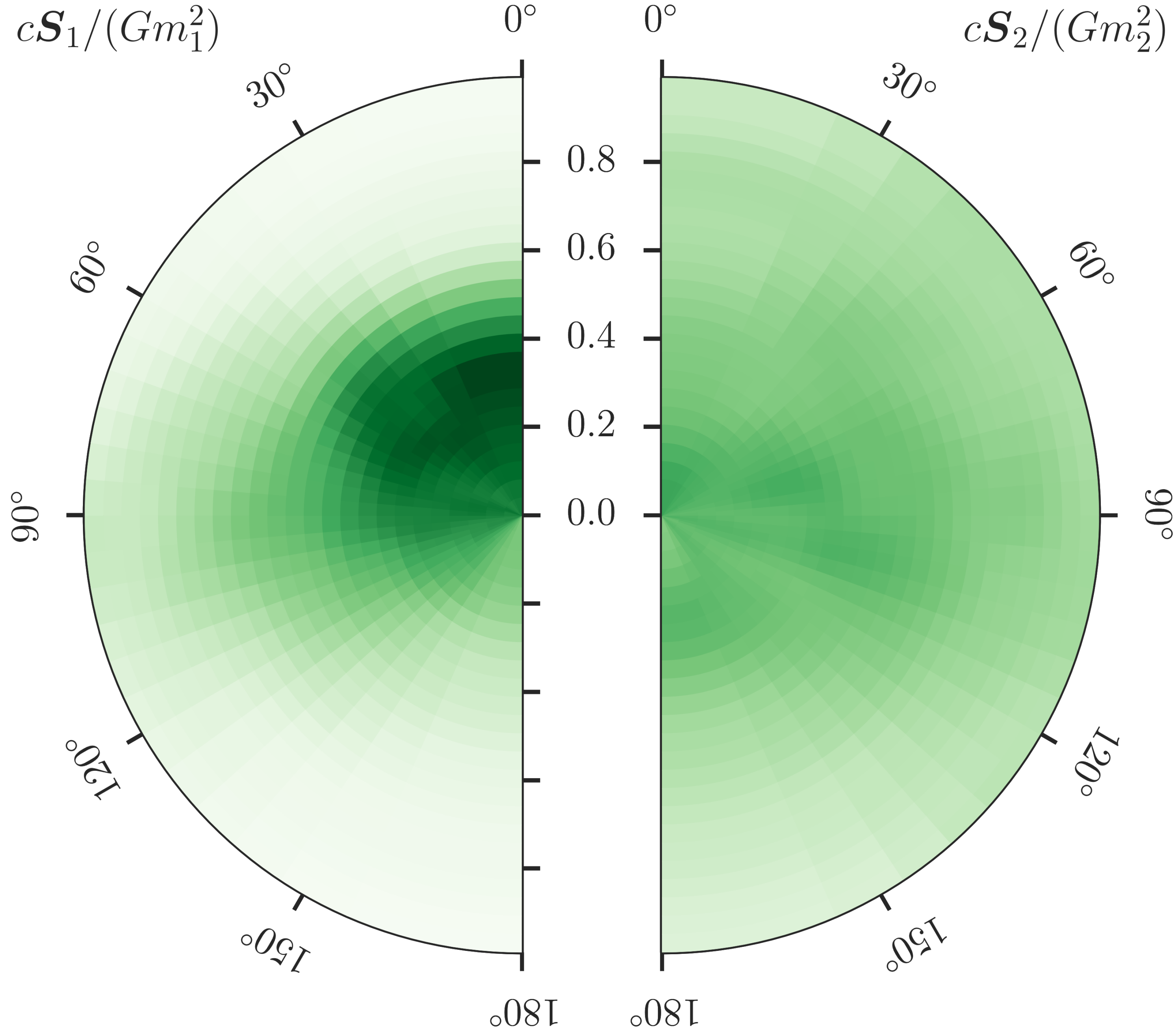
LVC
arXiv:1606.04856
arXiv:1602.03840

Spin



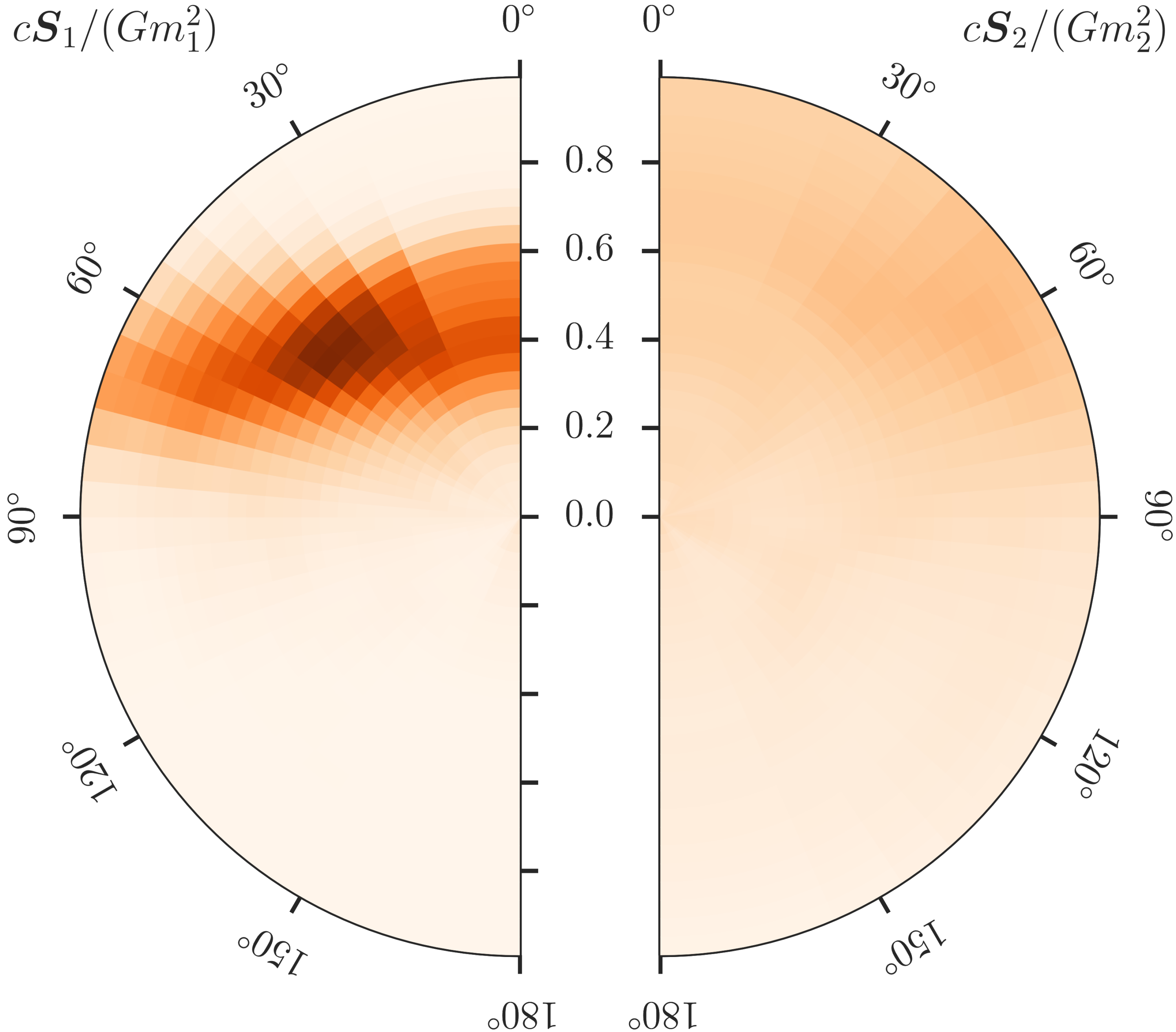
LVC
arXiv:1606.01210

Spin



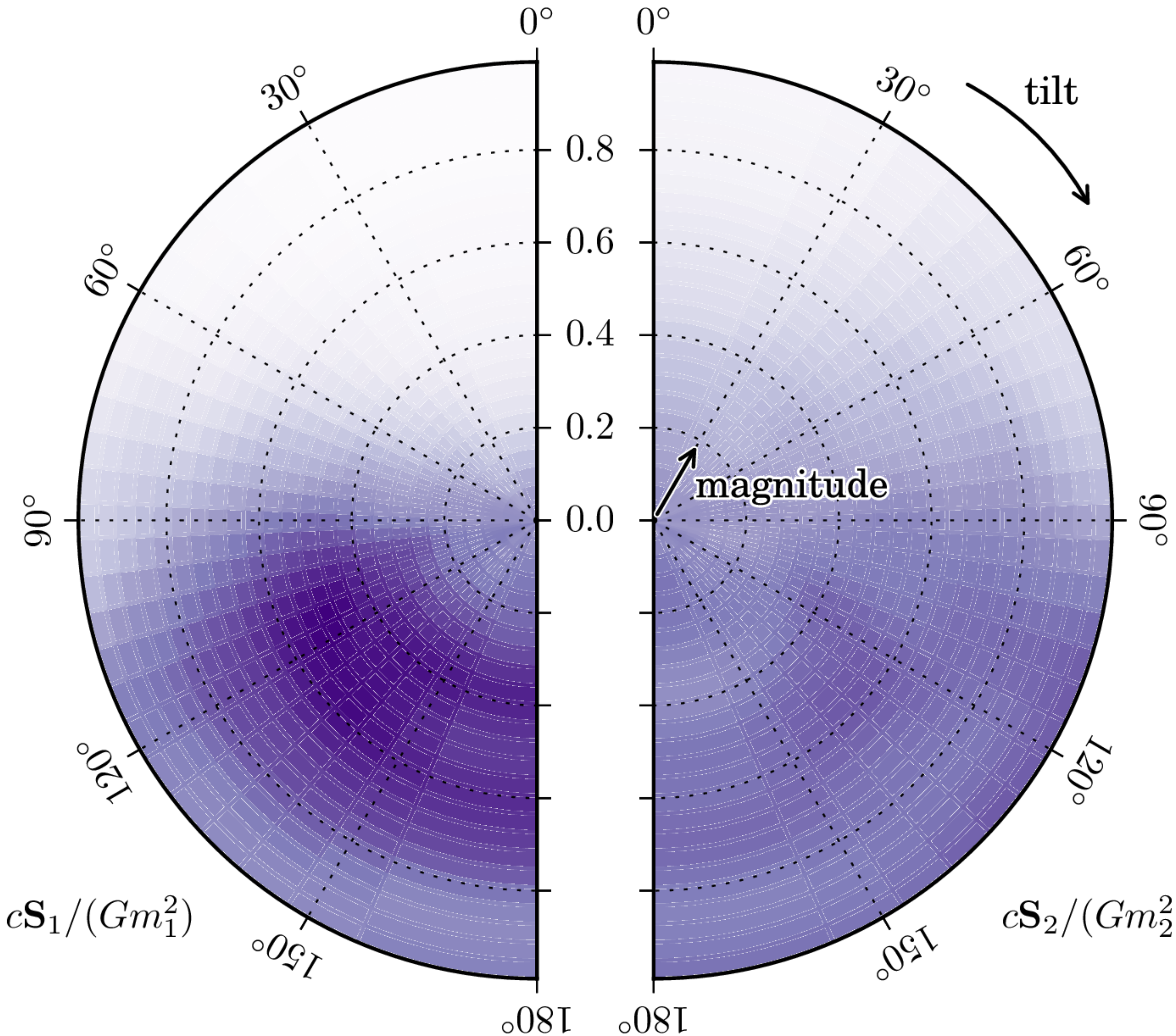
LVC
arXiv:1606.04856

Spin



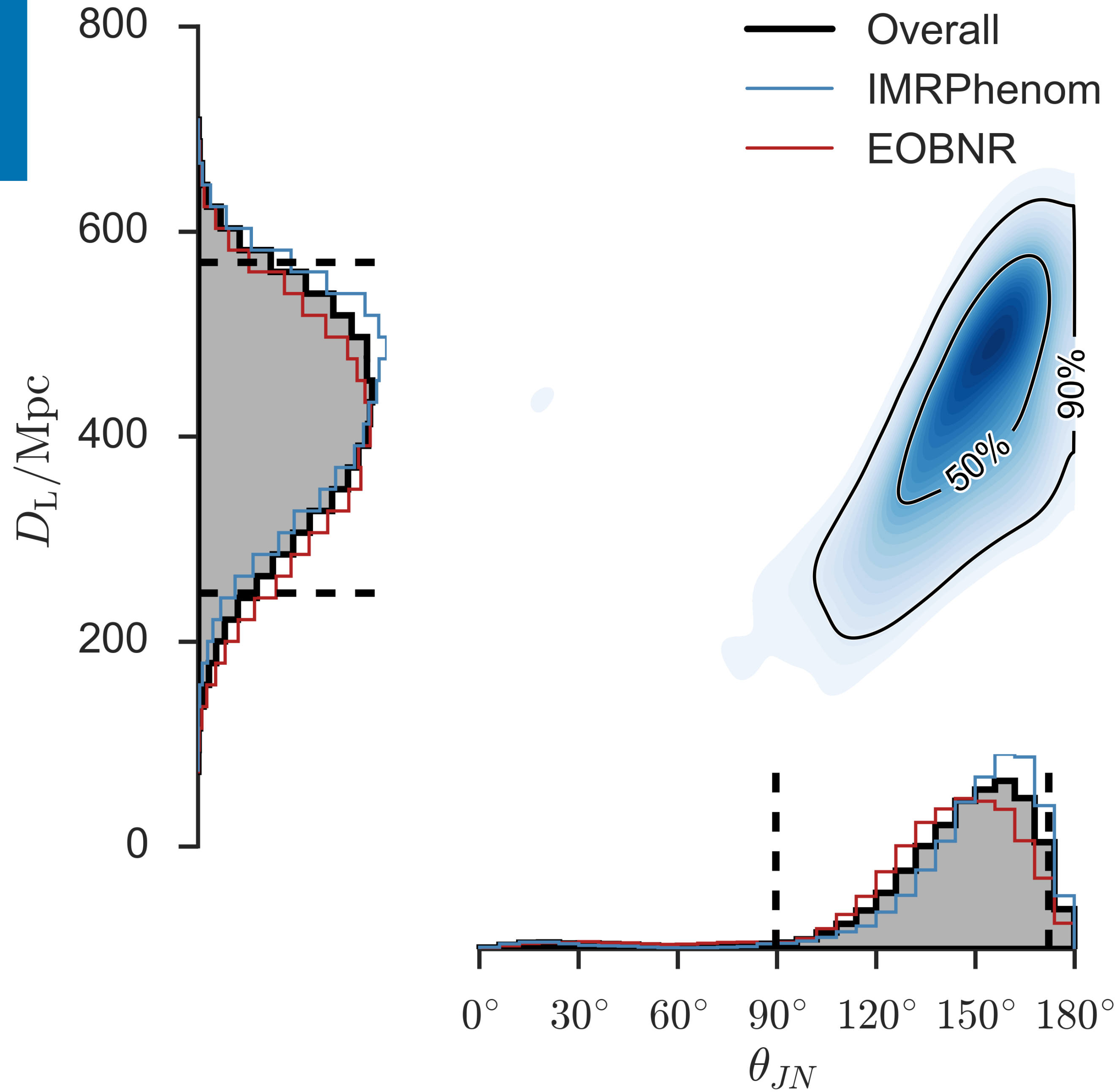
LVC
arXiv:1606.04855

Spin



LVC
arXiv:1706.01812

Distance



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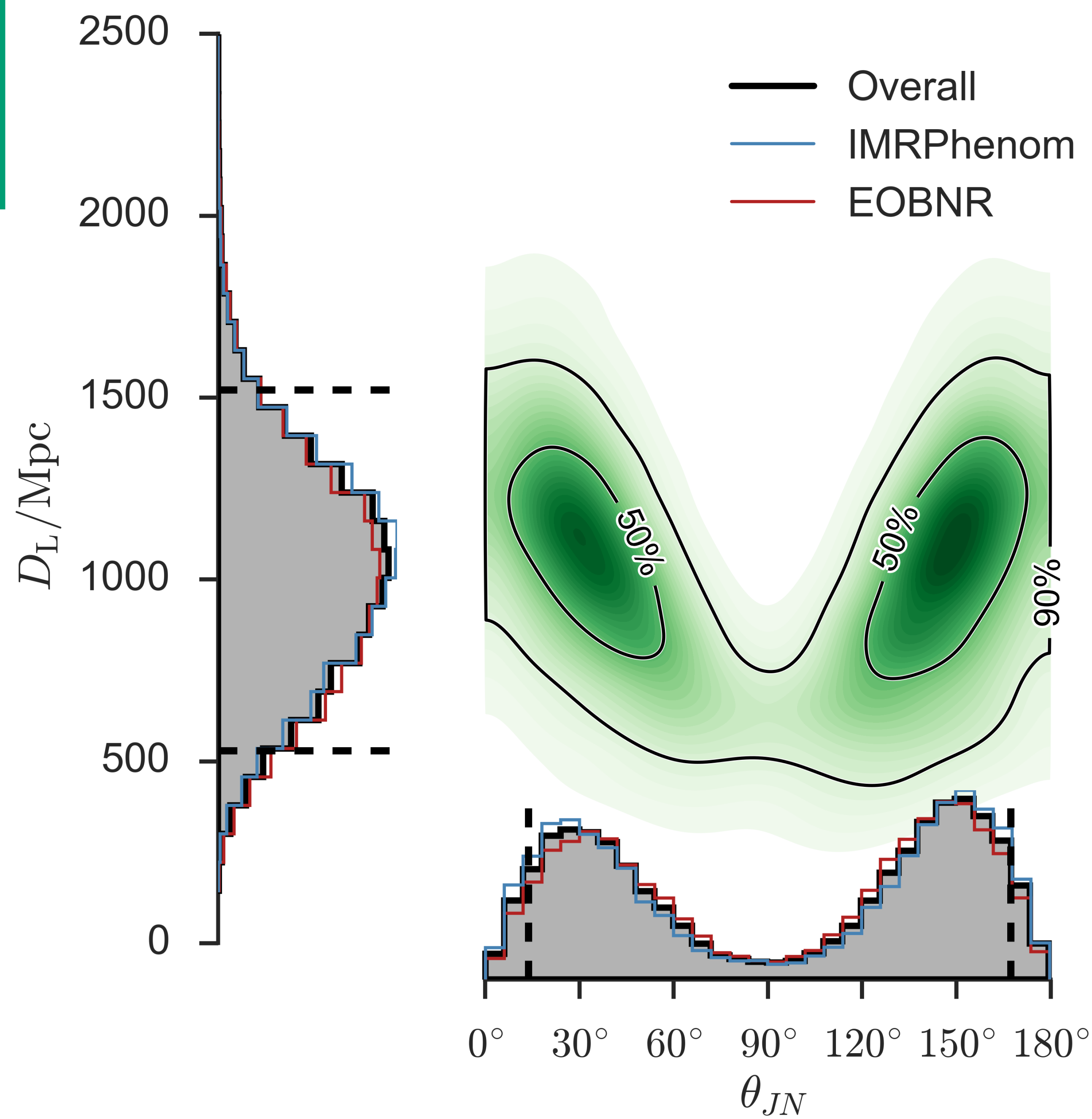

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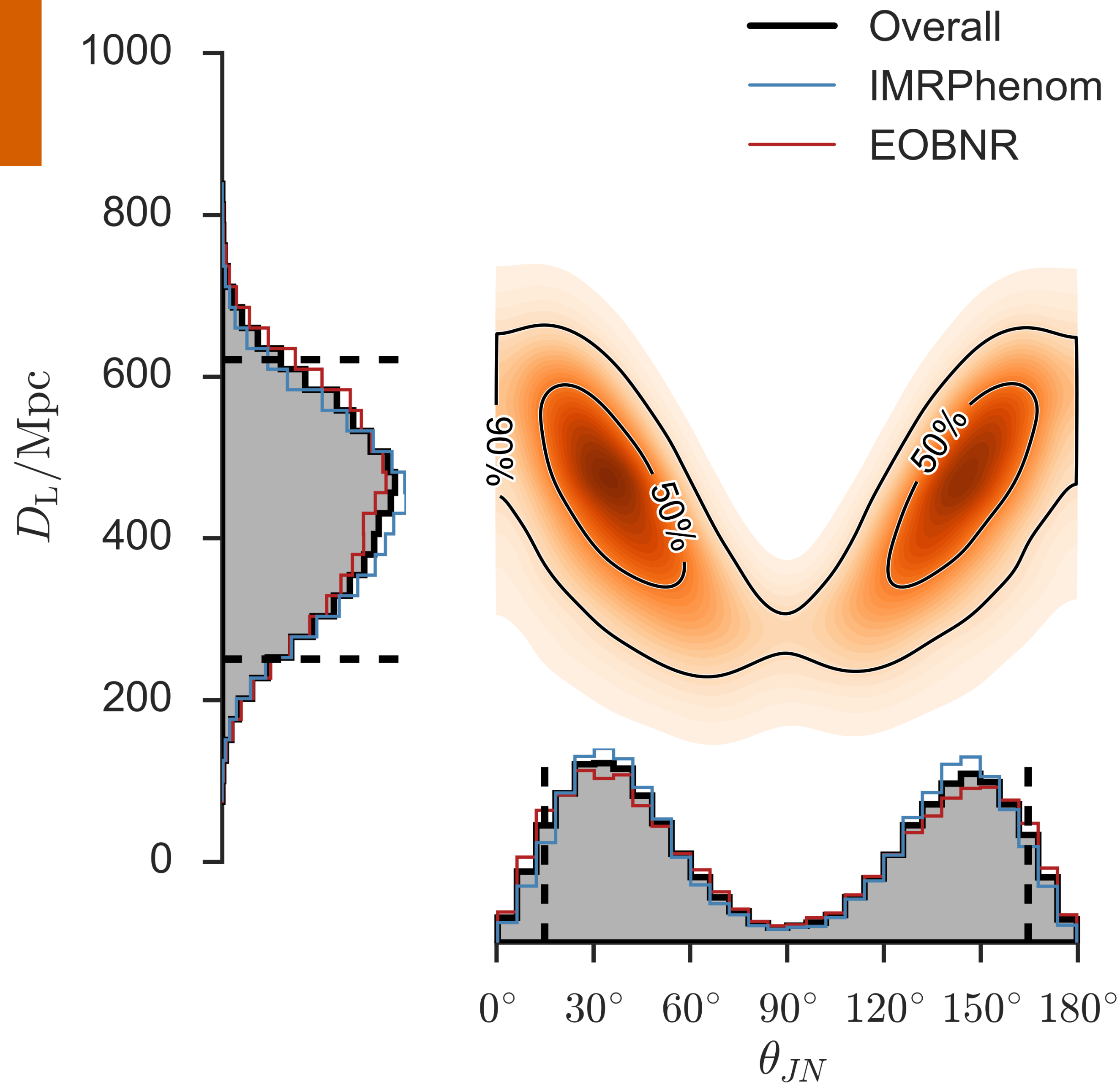
arXiv:1606.04856

Distance



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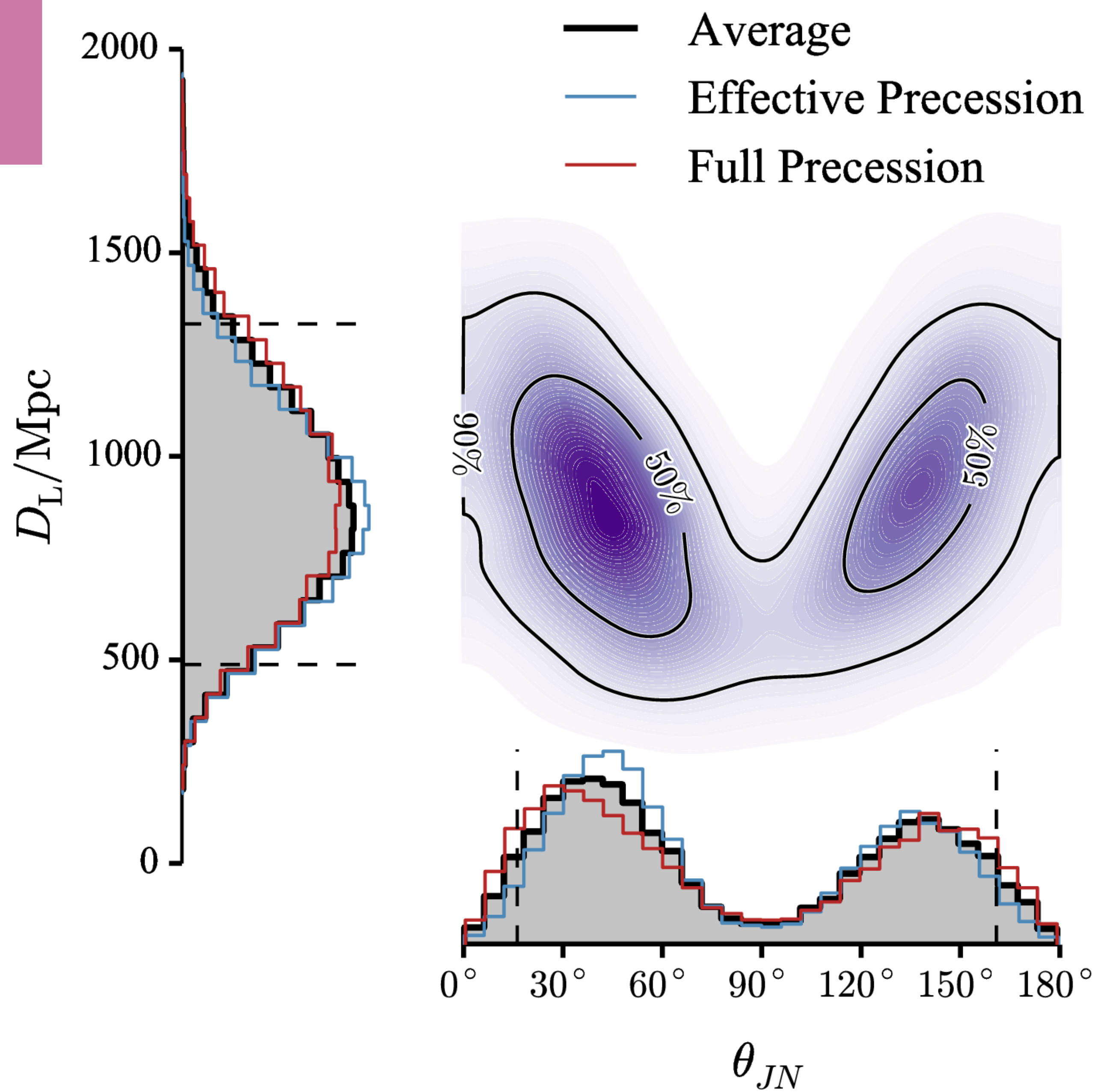
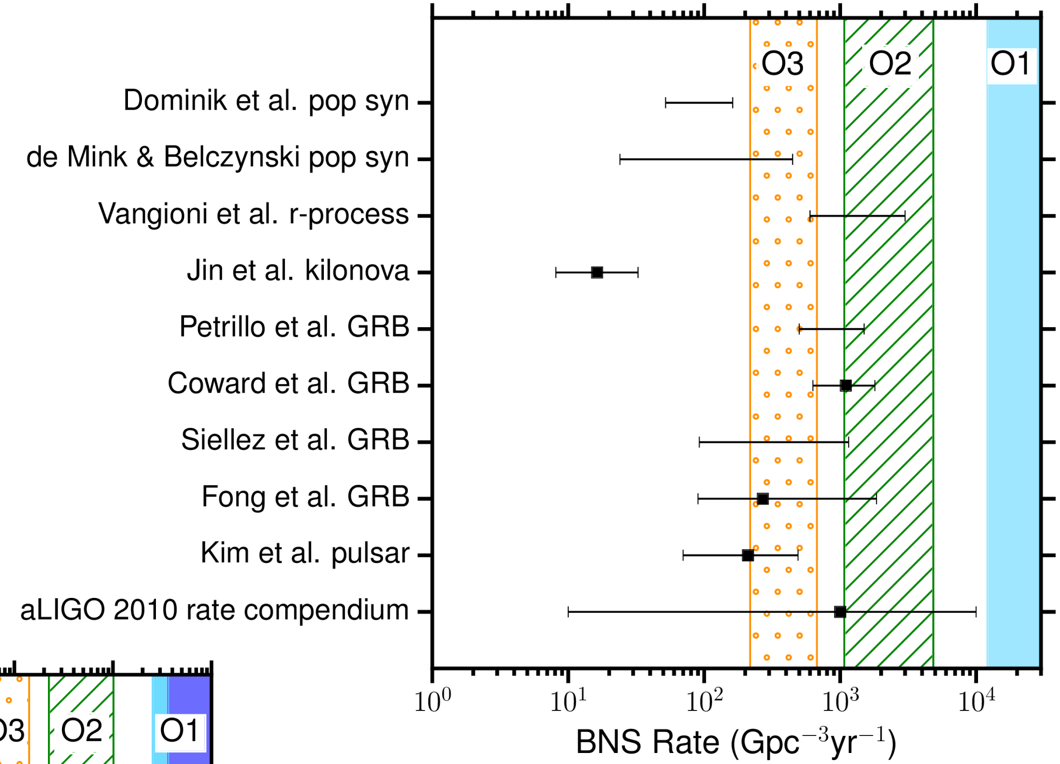
Distance

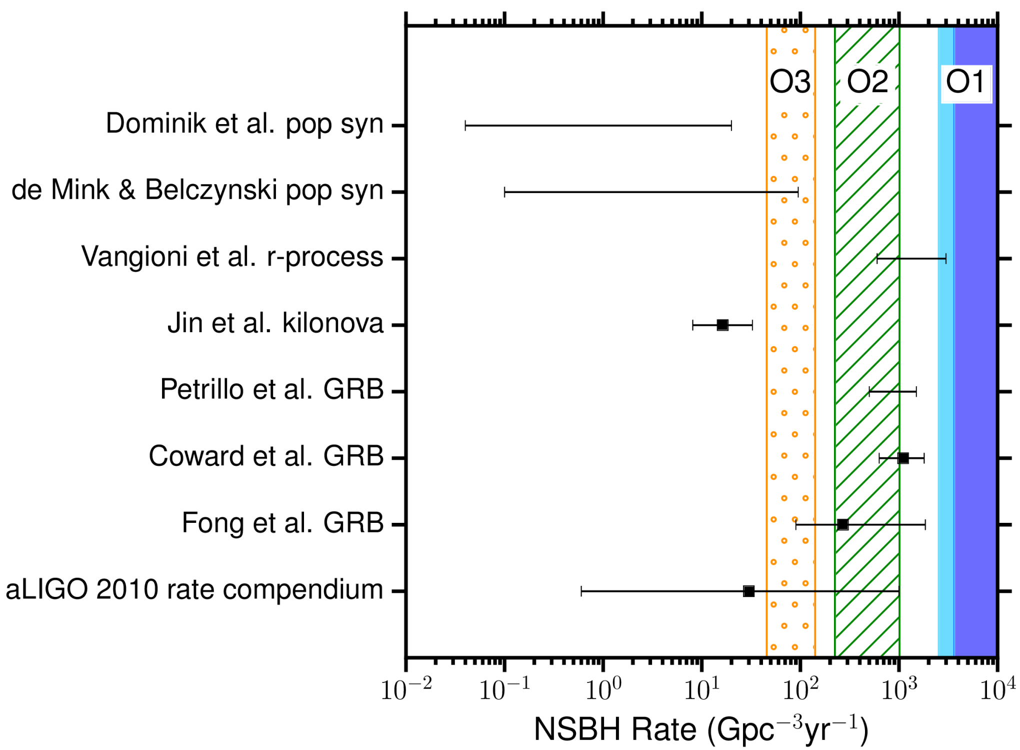


LVC
arXiv:1706.01812


LVT151012
I WANT TO
BELIEVE

Neutron stars





LVC
arXiv:1607.07456

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