Discoveries from Advanced LIGO

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On behalf of the
LIGO Scientific & Virgo Collaborations
DCC G1601624
30 August 2016, GRAMPA

We can detect gravitational waves

Binary black holes exist

Binary black holes merge

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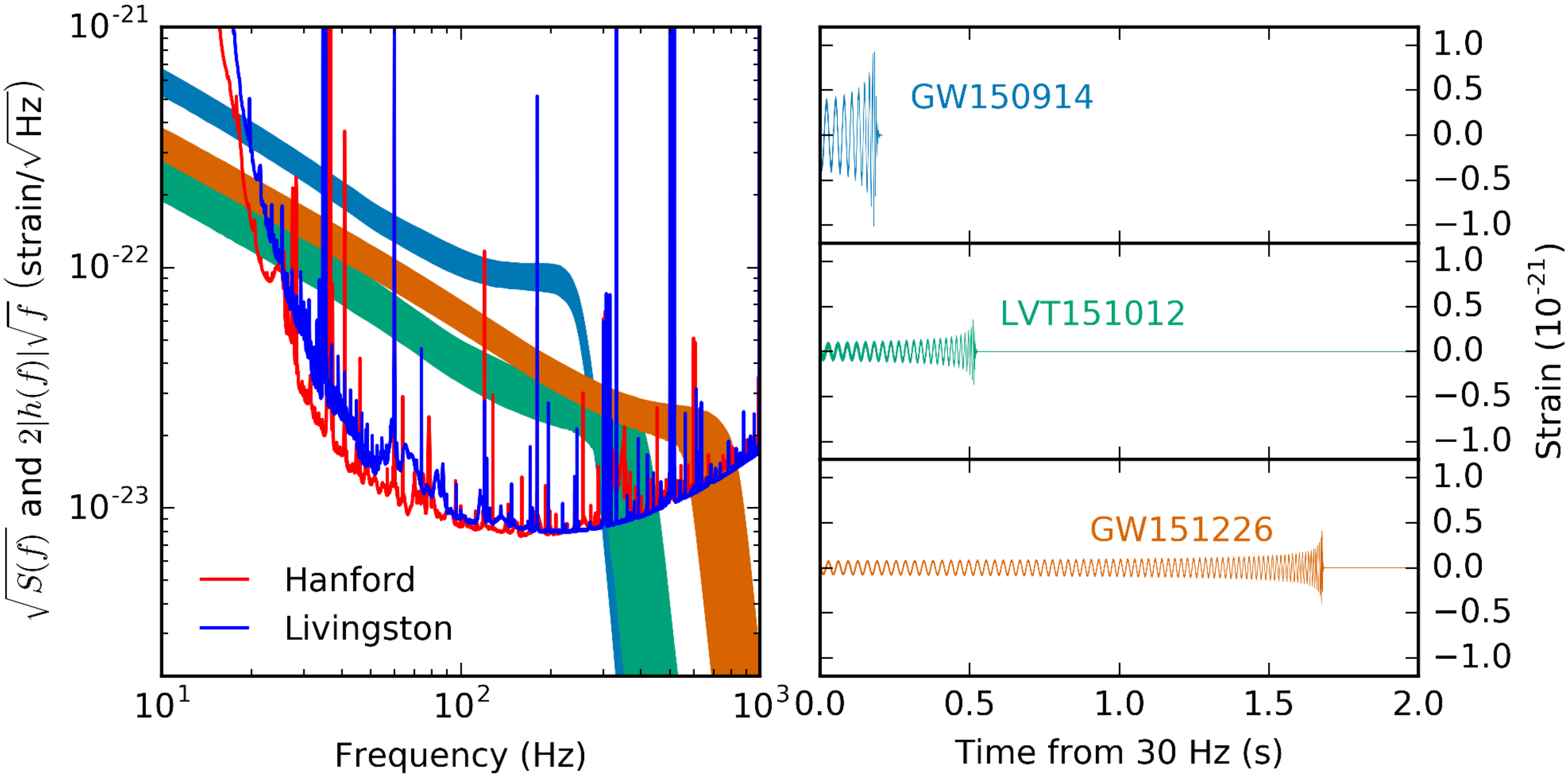
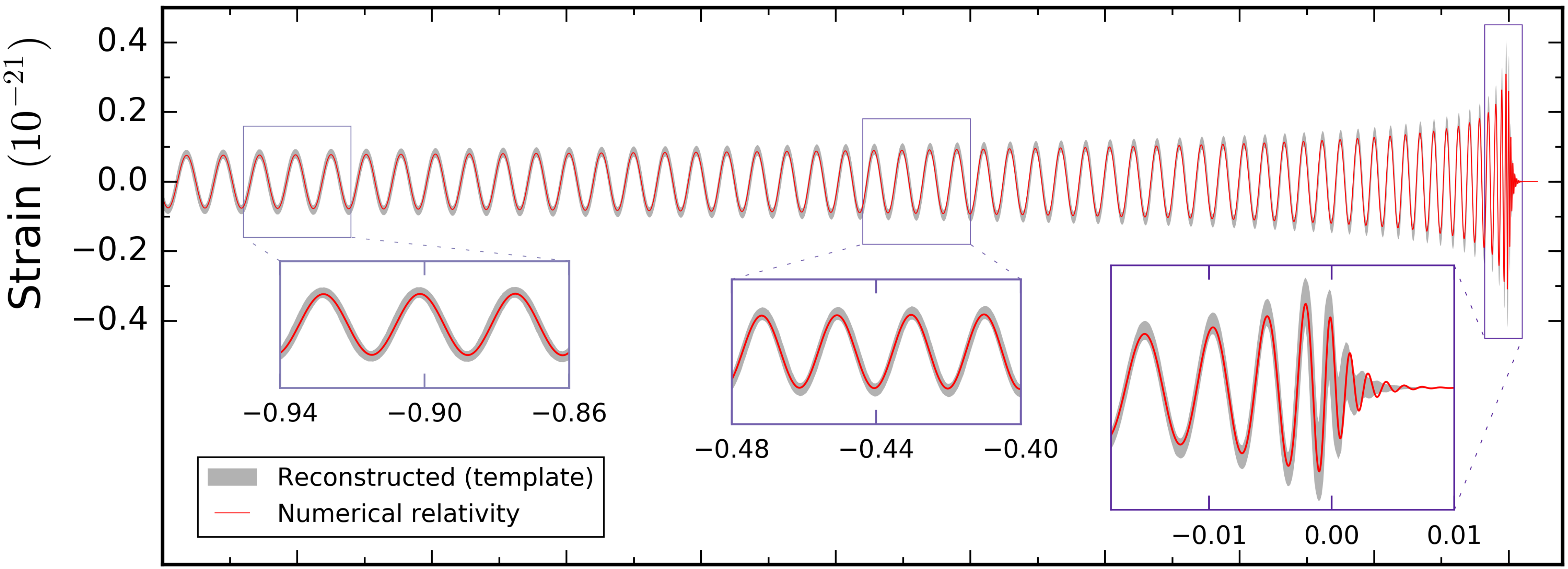
Detection



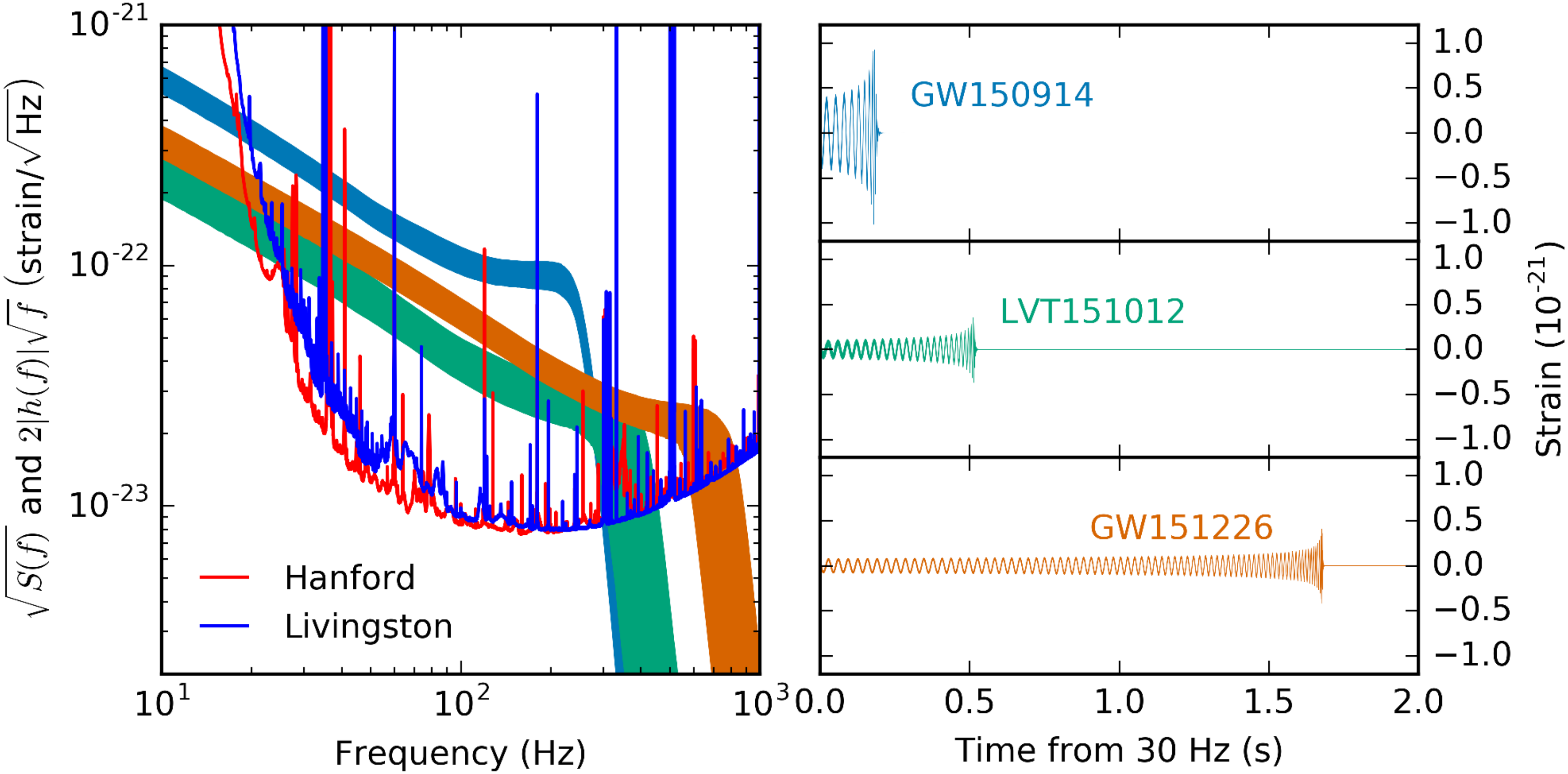
LVC arXiv:1606.04856

Waveforms



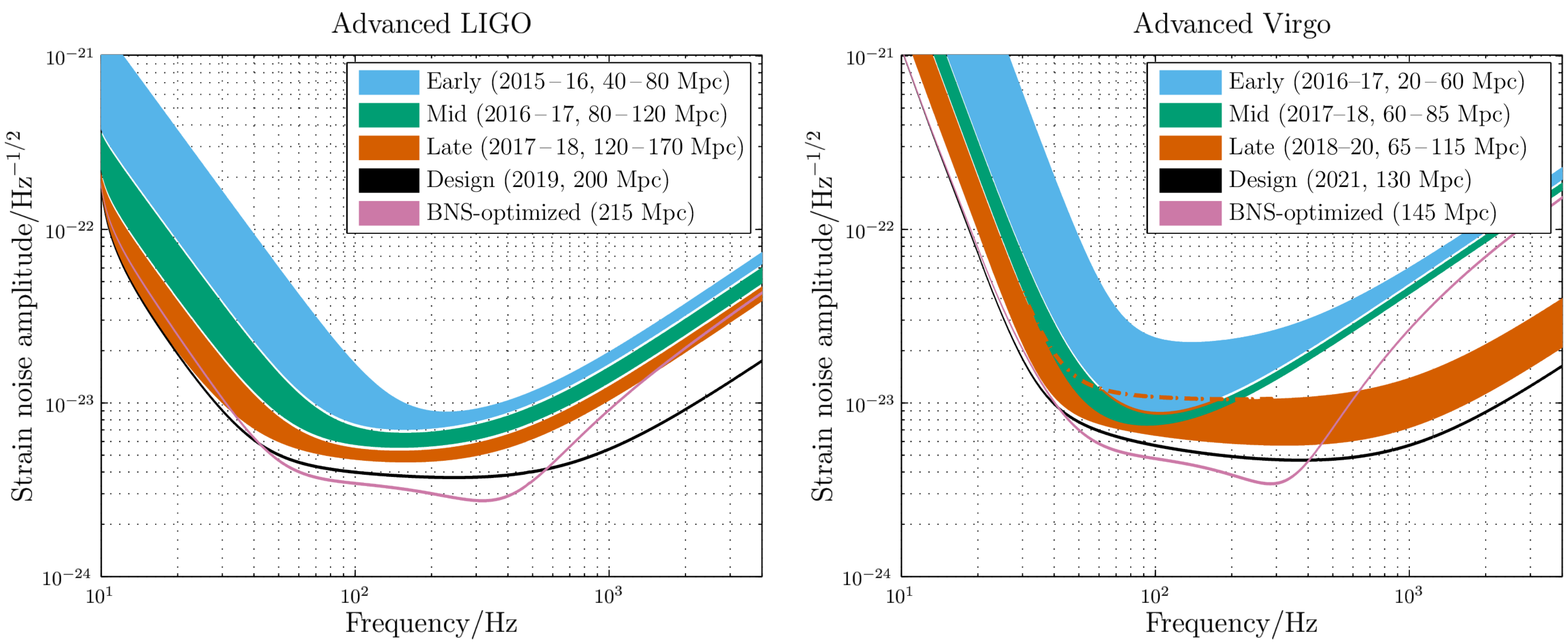
LVC arXiv:1606.04855

Detection



LVC arXiv:1606.04856

Future observing runs



LVC arXiv:1303.0670

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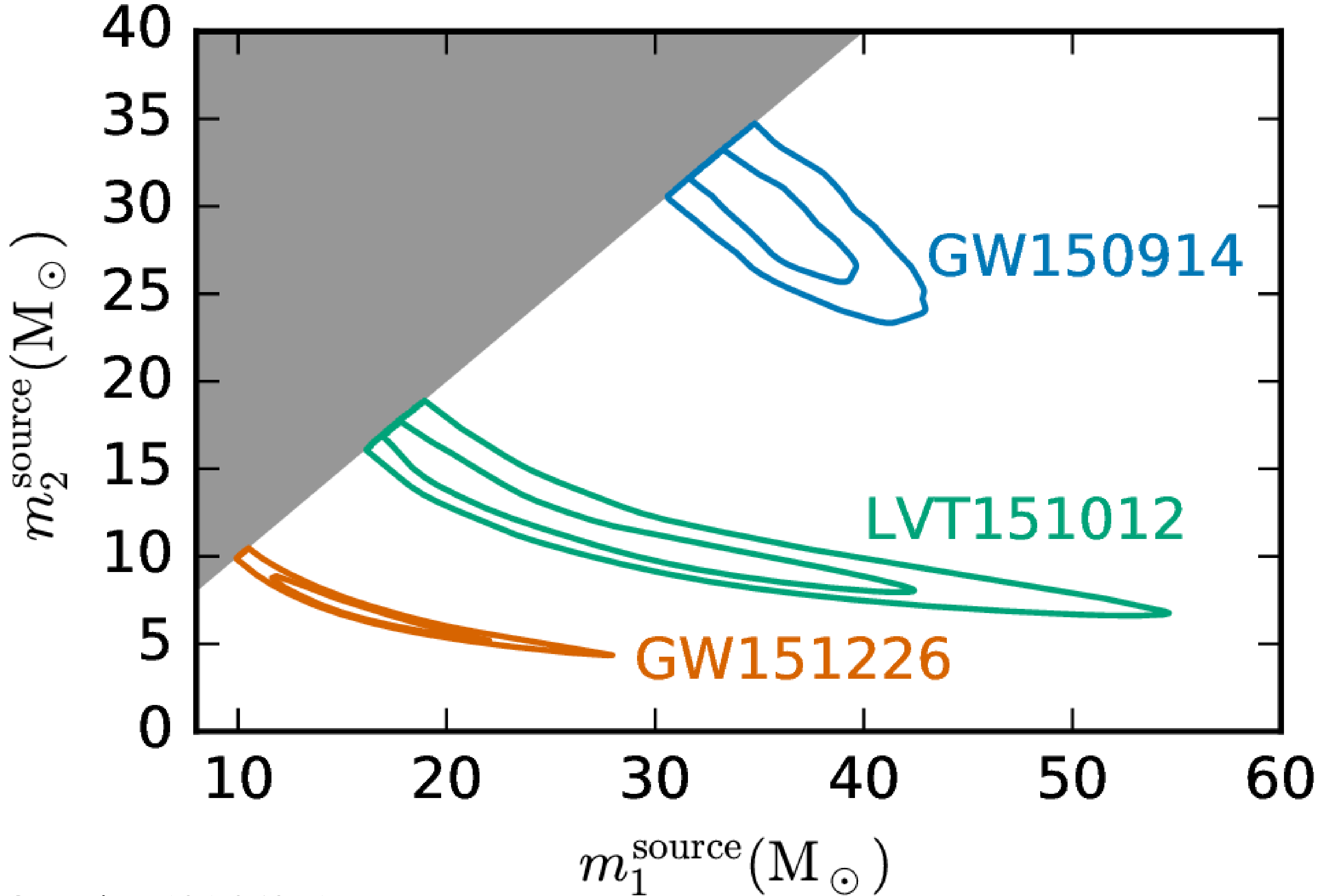


LVC arXiv:1606.04856

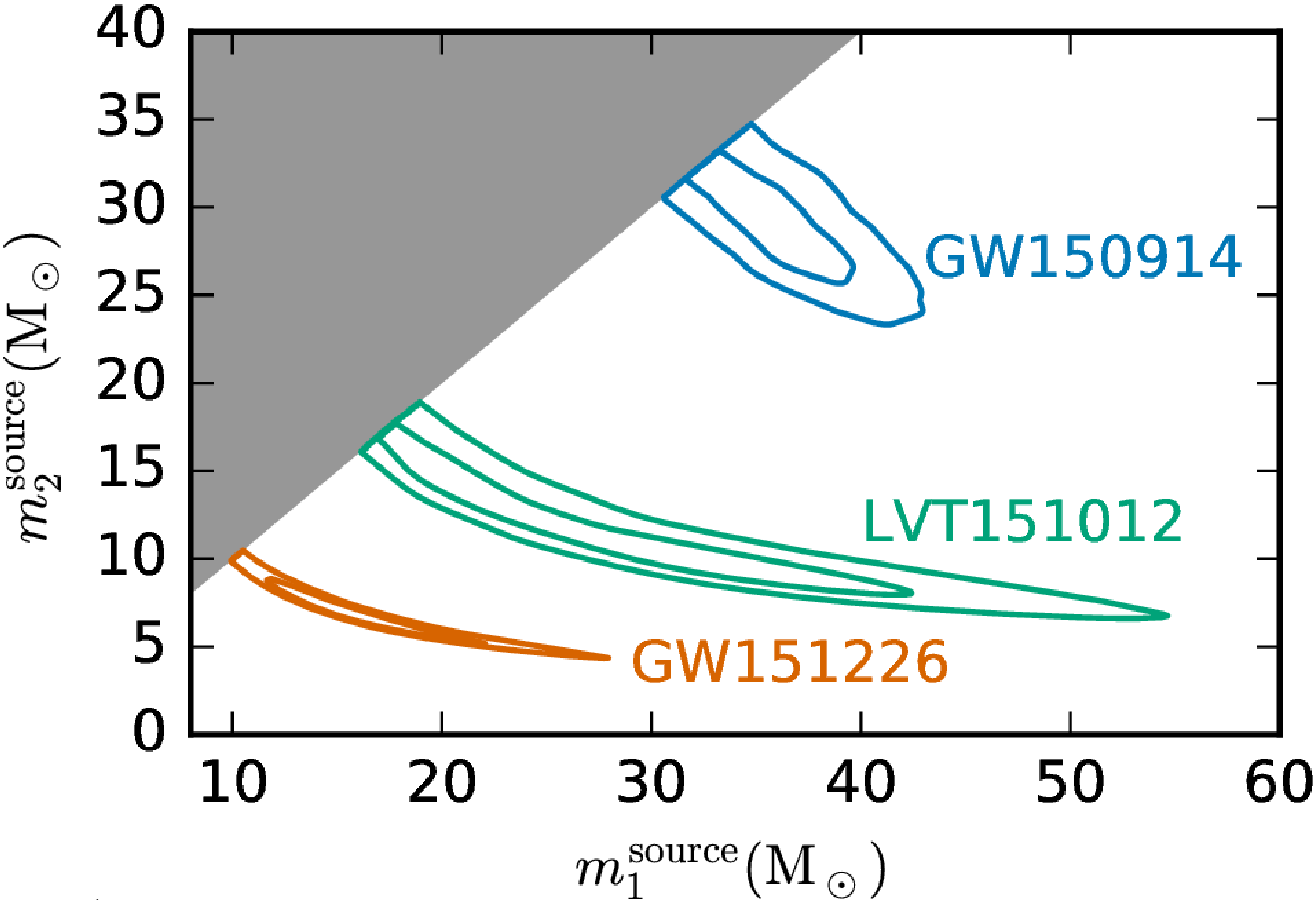
Credit: ButterflyLove1

Upper limits on the rates of binary neutron star and neutron-star--black-hole mergers from Advanced LIGO's first observing run

The LIGO Scientific Collaboration, the Virgo Collaboration: B. P. Abbott, R. Abbott, T. D. Abbott, M. R. Abernathy, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, V. B. Adya, C. Affeldt, M. Agathos, K. Agatsuma, N. Aggarwal, O. D. Aguiar, L. Aiello, A. Ain, P. Ajith, B. Allen, A. Allocca, P. A. Altin, S. B. Anderson, W. G. Anderson, K. Arai, M. C. Araya, C. C. Arceneaux, J. S. Areeda, N. Arnaud, K. G. Arun, S. Ascenzi, G. Ashton, M. Ast, S. M. Aston, P. Astone, P. Aufmuth, C. Aulbert, S. Babak, P. Bacon, M. K. M. Bader, P. T. Baker, F. Baldaccini, G. Ballardin, S. W. Ballmer, J. C. Barayoga, S. E. Barclay, B. C. Barish, D. Barker, F. Barone, B. Barr, L. Barsotti, M. Barsuglia, D. Barta, J. Bartlett, I. Bartos, R. Bassiri, A. Basti, J. C. Batch, C. Baune, V. Bavigadda, et al. (899 additional authors not shown)

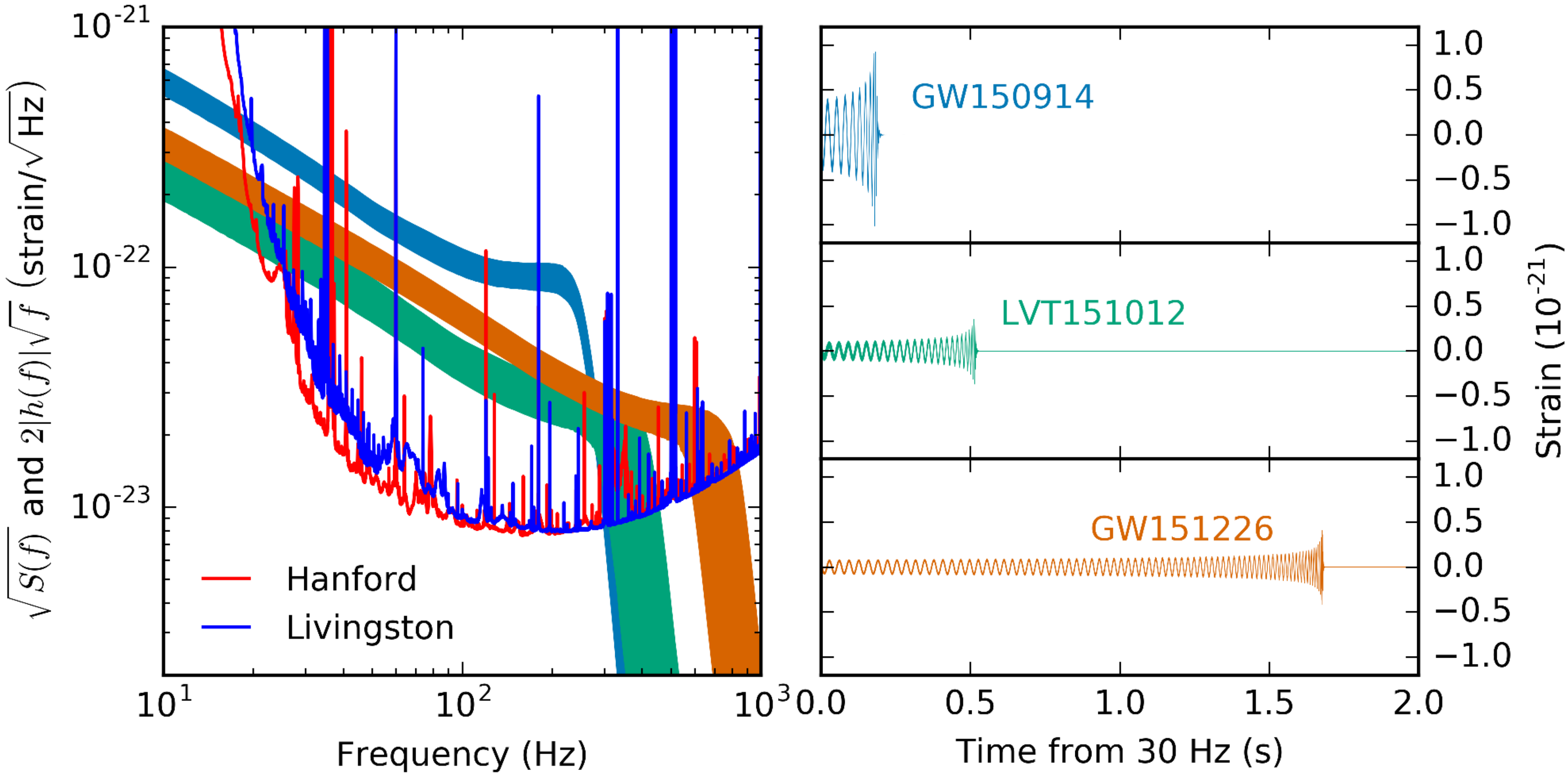
(Submitted on 25 Jul 2016)

We report here the non-detection of gravitational waves from the merger of binary neutron star systems and neutron-star--black-hole systems during the first observing run of Advanced LIGO. In particular we searched for gravitational wave signals from binary neutron star systems with component masses $\in [1,3]M_\odot$ and component dimensionless spins < 0.05. We also searched for neutron-star--black-hole systems with the same neutron star parameters, black hole mass $\in [2,99]M_\odot$ and no restriction on the black hole spin magnitude. We assess the sensitivity of the two LIGO detectors to these systems, and find that they could have detected the merger of binary neutron star systems with component mass distributions of $1.35 \pm 0.13M_\odot$ at a volume-weighted average distance of $\sim$ 70Mpc, and for neutron-star--black-hole systems with neutron star masses of $1.4M_\odot$ and black hole masses of at least $5M_\odot$, a volume-weighted average distance of at least $\sim$ 110Mpc. From this we constrain with 90% confidence the merger rate to be less than 12,600 Gpc^{-3} yr^{-1} for binary-neutron star systems and less than 3,600 Gpc^{-3} yr^{-1} for neutron-star--black-hole systems. We find that if no detection of neutron-star binary mergers is made in the next two Advanced LIGO and Advanced Virgo observing runs we would place significant constraints on the merger rates. Finally, assuming a rate of 10^{+20}_{-7}Gpc^{-3} yr^{-1} short gamma ray bursts beamed towards the Earth and assuming that all short gamma-ray bursts have binary-neutron-star (neutron-star--black-hole) progenitors we can use our 90% confidence rate upper limits to constrain the beaming angle of the gamma-ray burst to be greater than $2.3^{+1.7^\circ}_{-1.1}$ $(4.3^{+3.1^\circ}_{-1.9})$.



LVC arXiv:1606.04856

Waveforms



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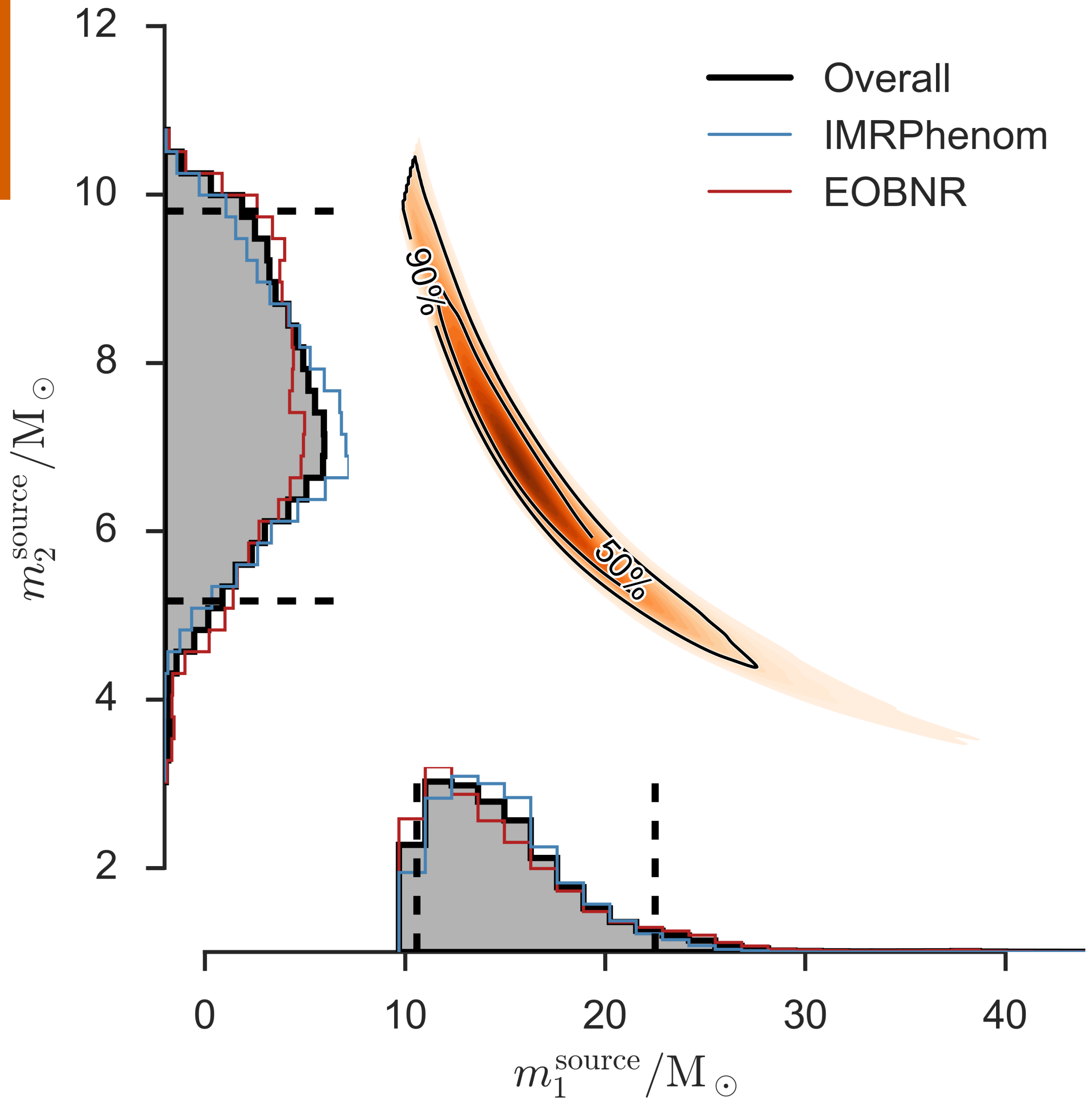
Masses



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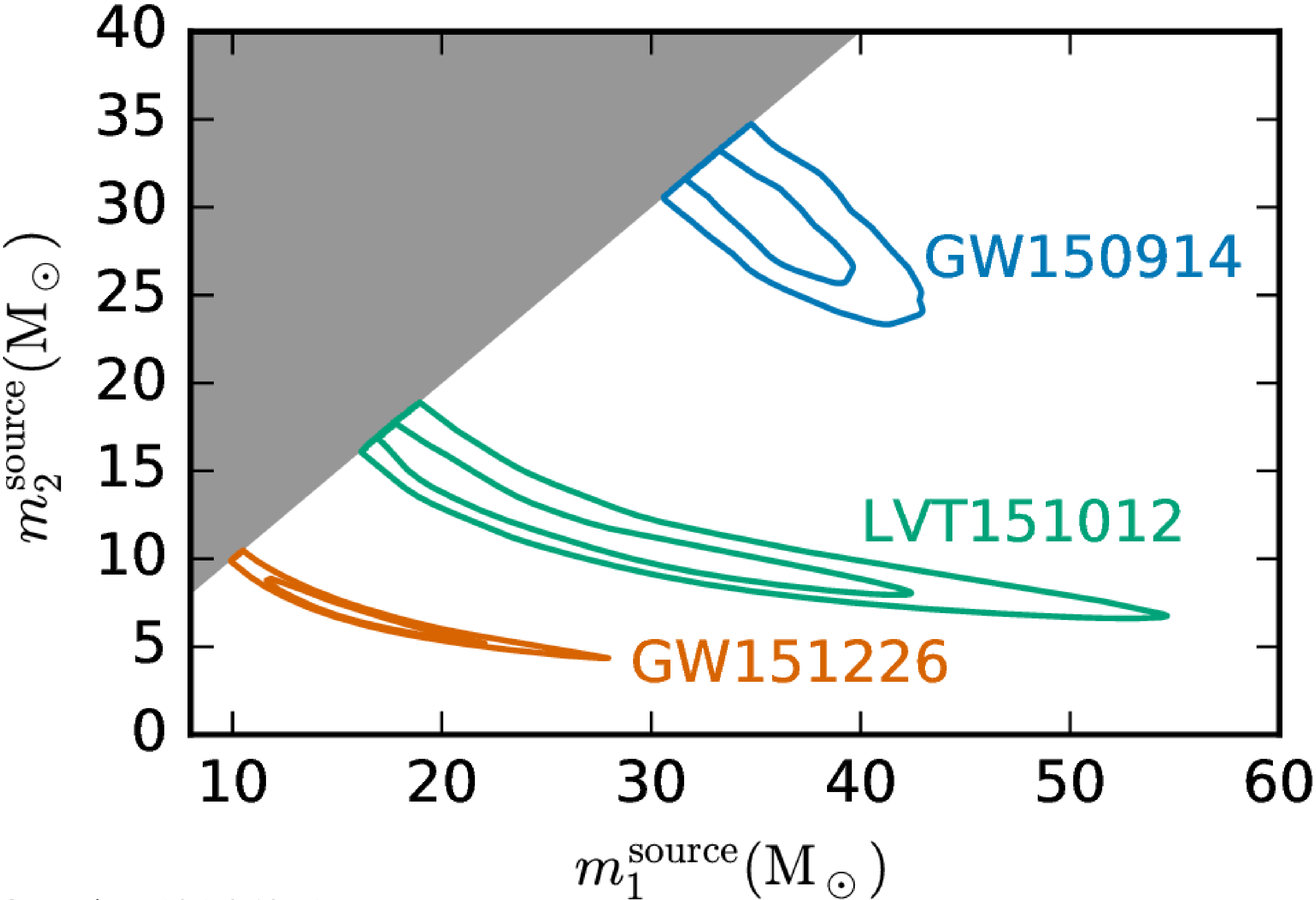

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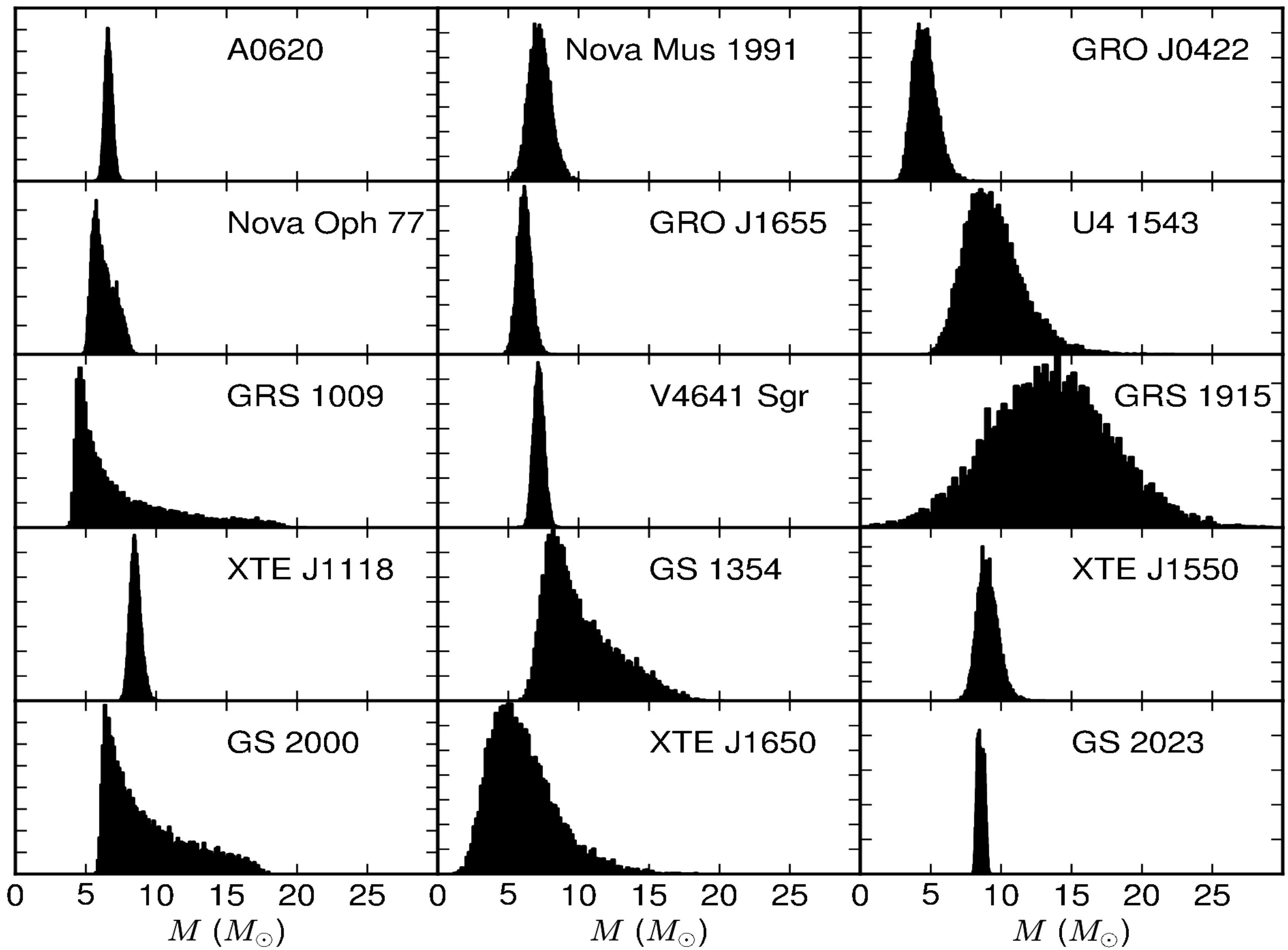
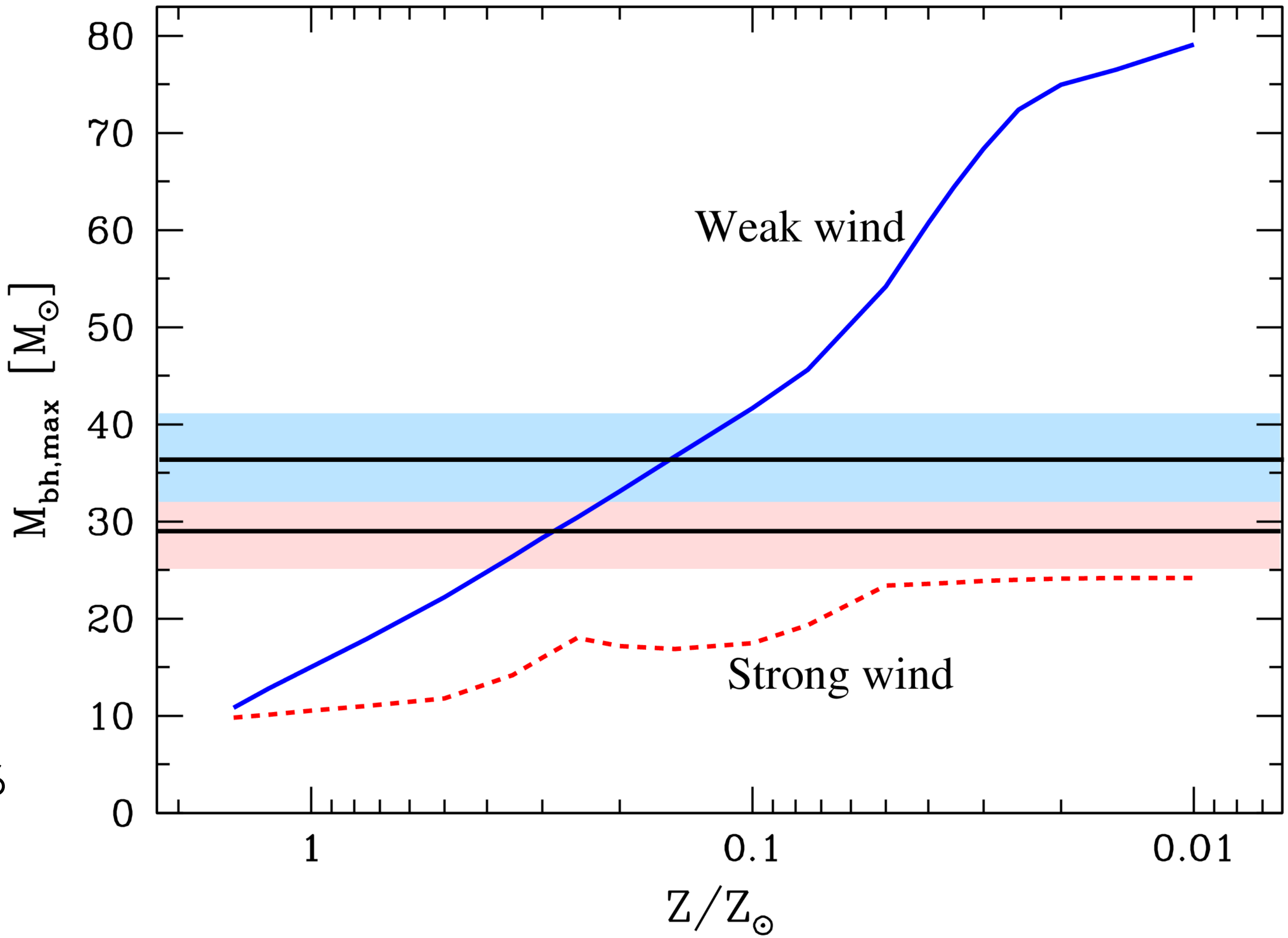
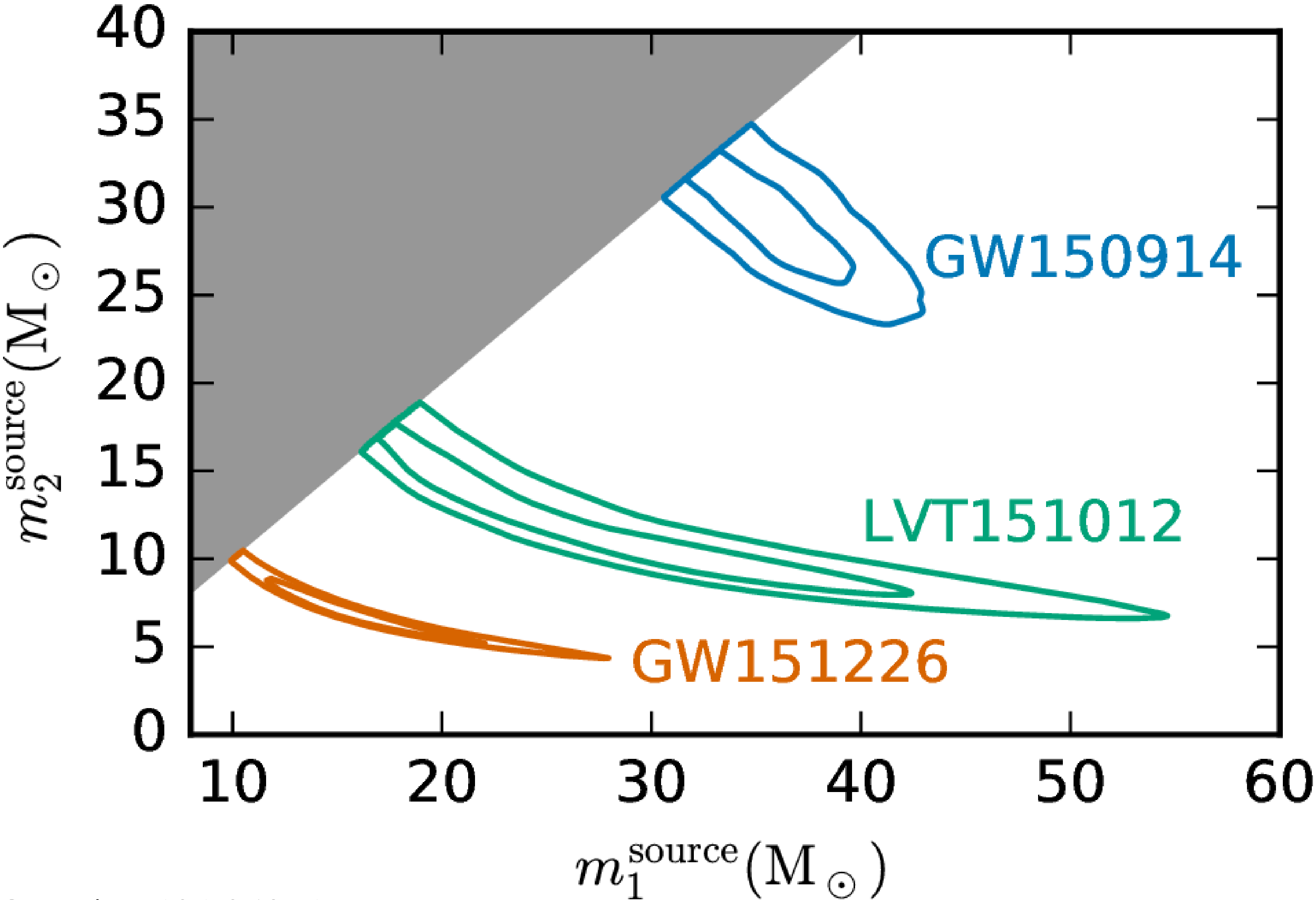
Farr *et al*. arXiv:1011.1459



Metallicity



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



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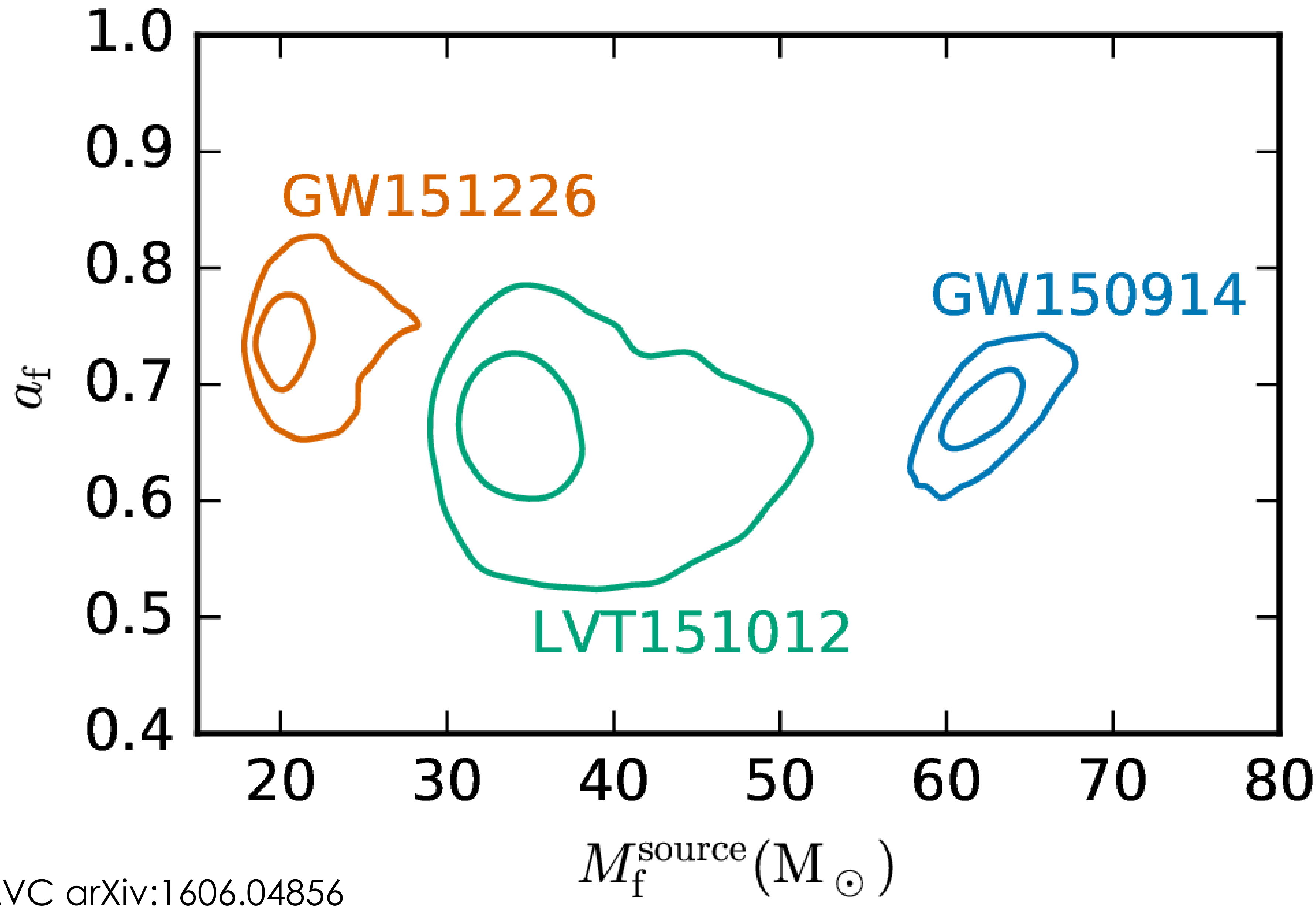

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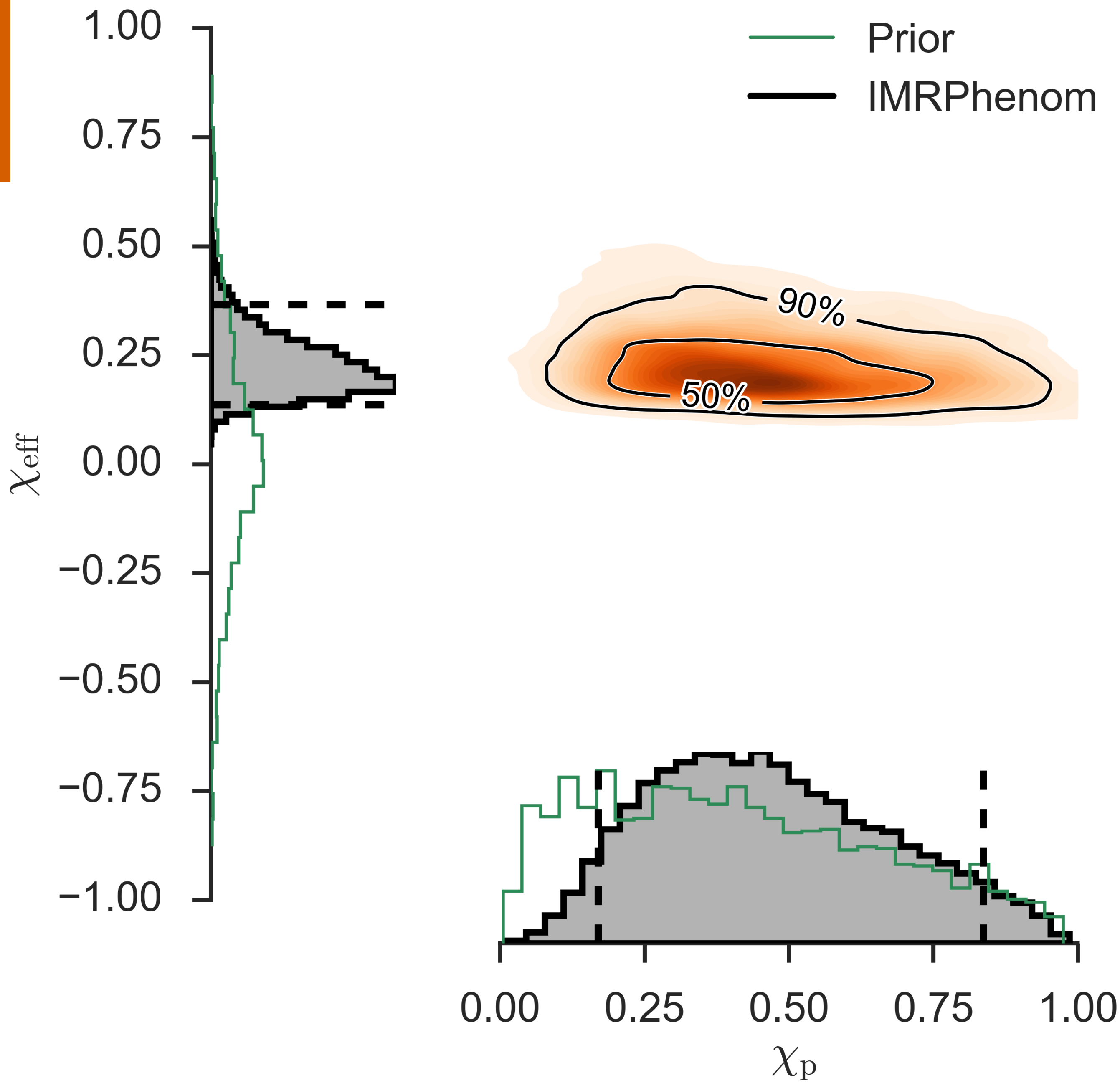
Spin



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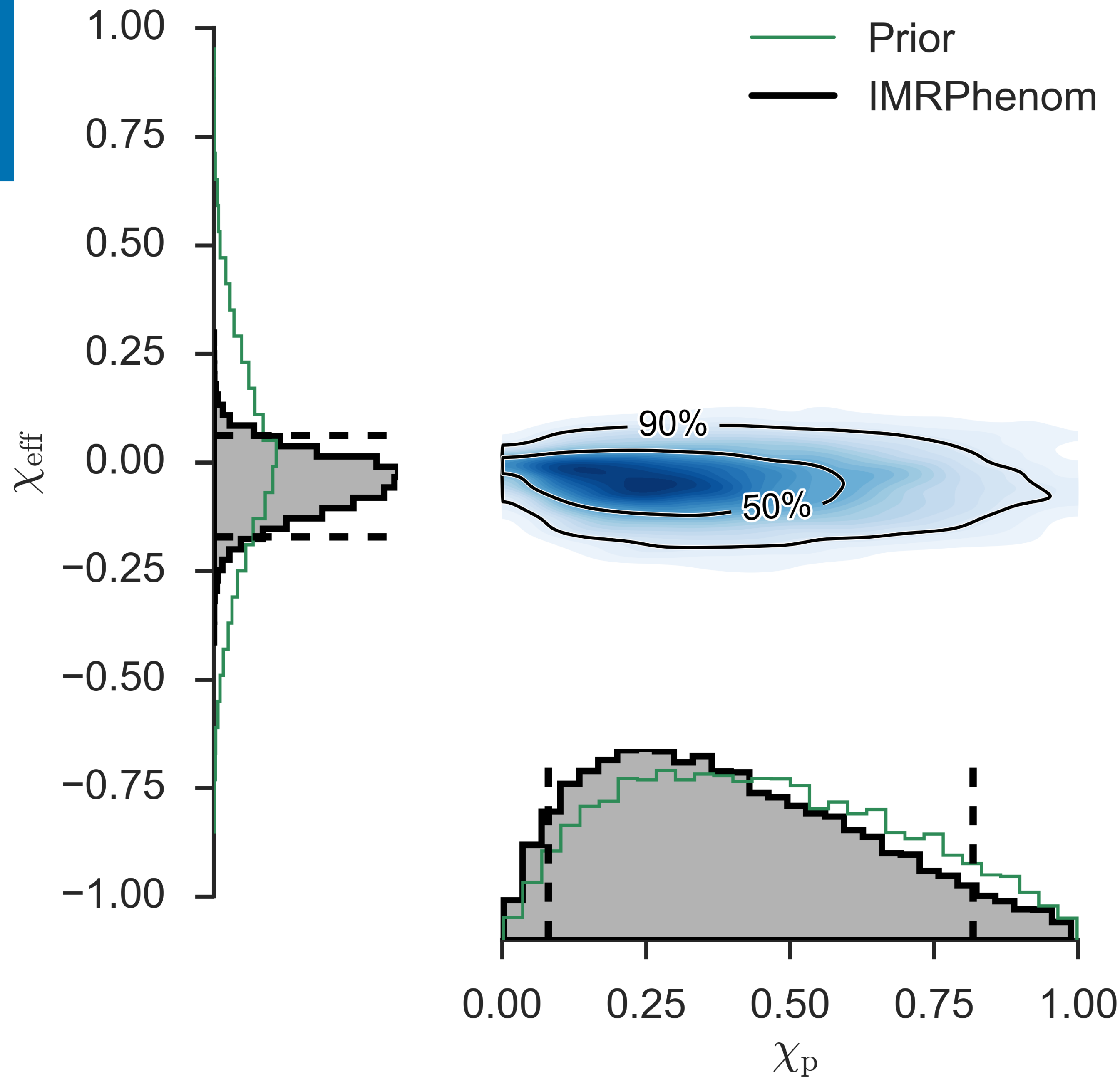
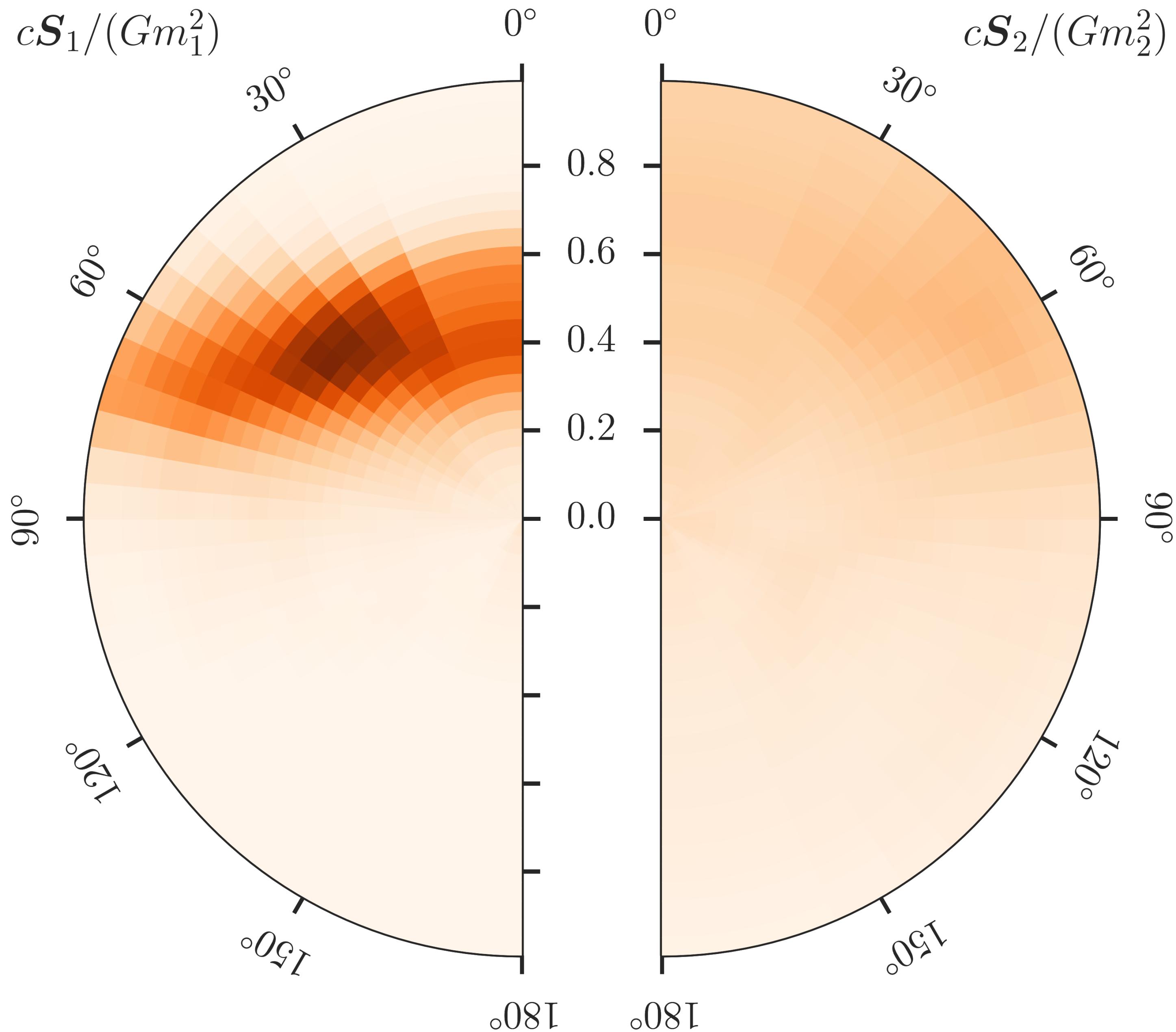


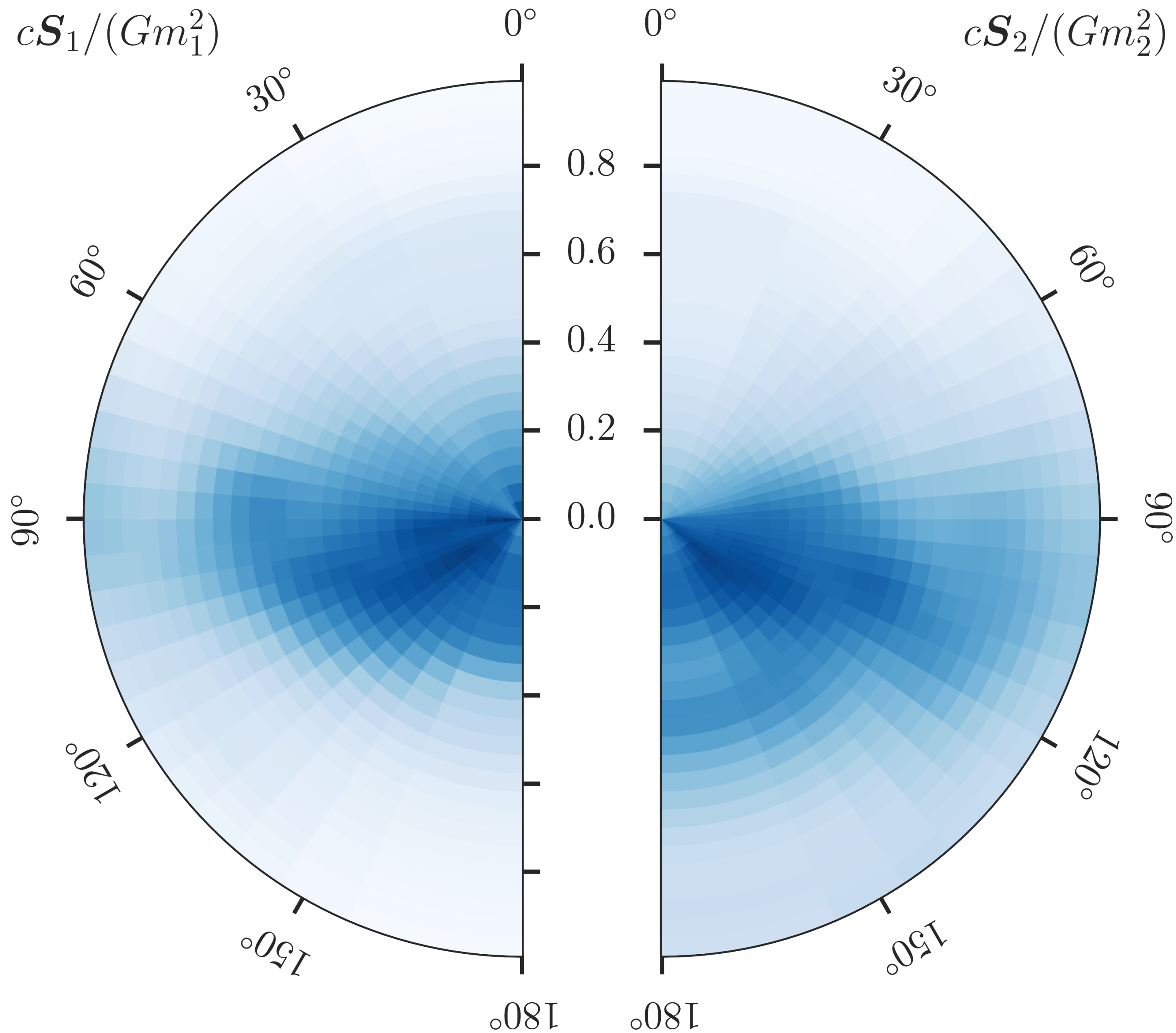
LVC
arXiv:1606.04856
arXiv:1602.03840

Spin



LVC
arXiv:1606.04855

Spin



LVC
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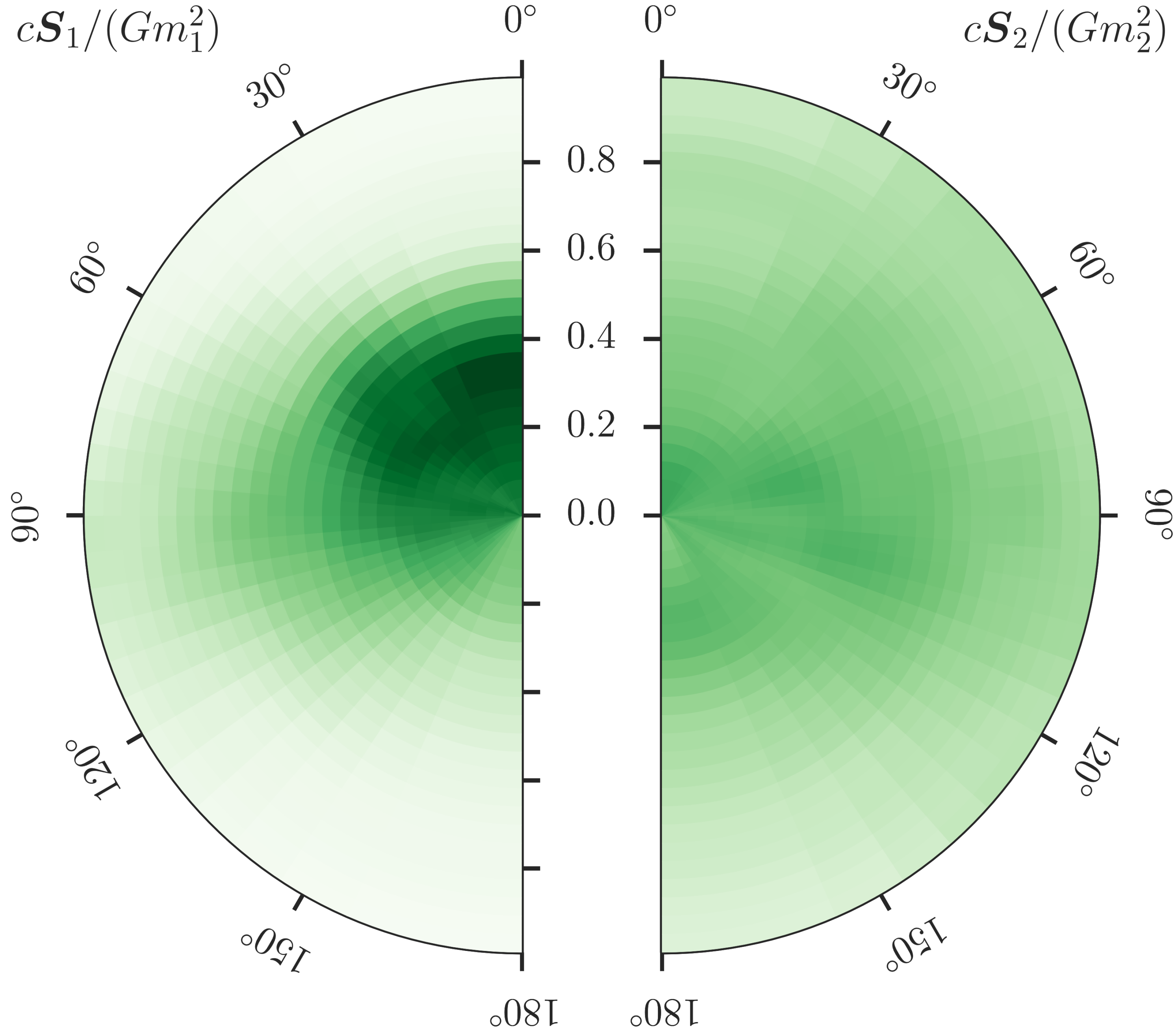
Spin



LVC
arXiv:1606.04856

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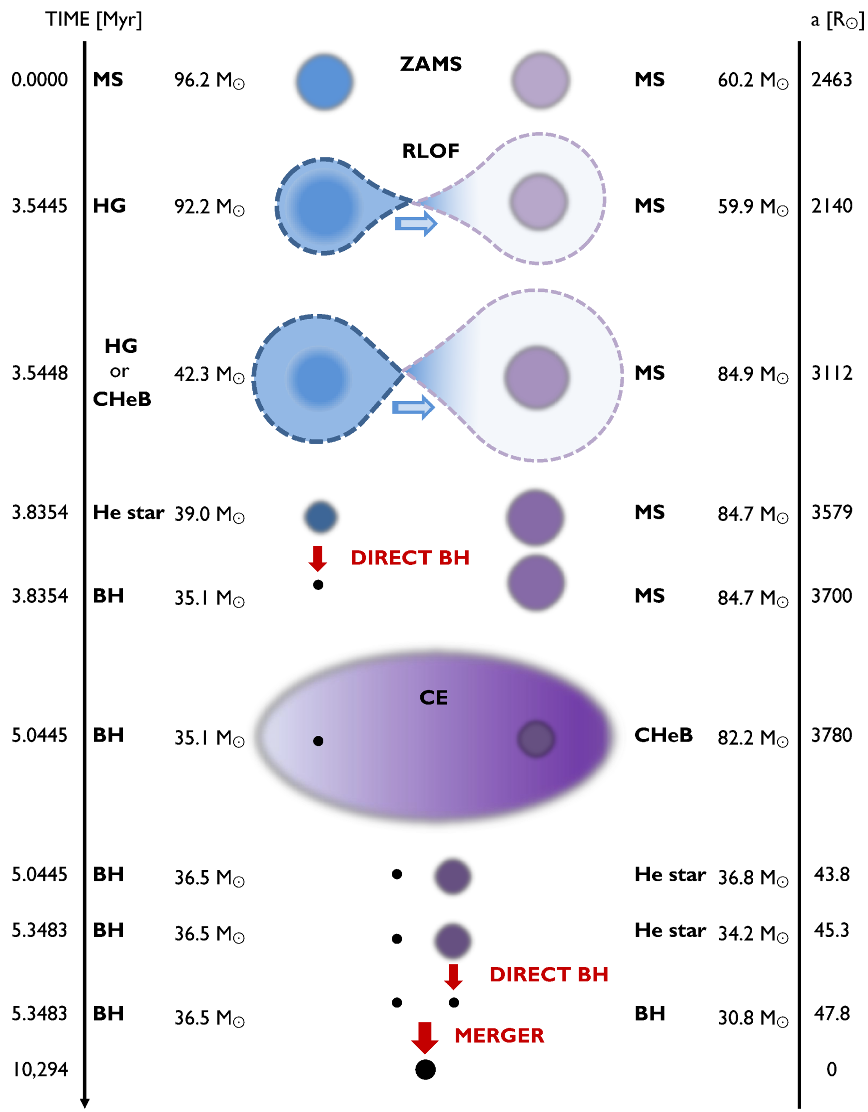
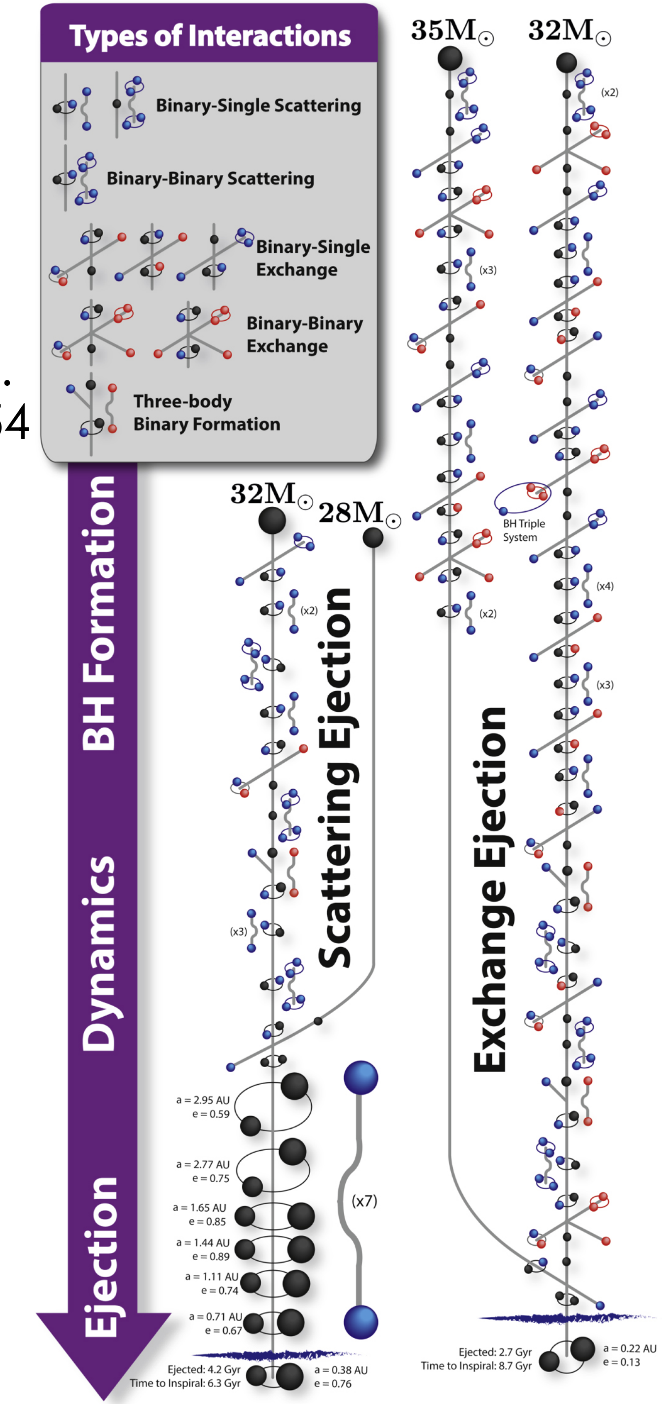
Binary formation



Rodriguez *et al.*
arXiv:1604.04254



Belczynski *et al.*
arXiv:1602.04531

Binary formation

Lipunov *et al.* arXiv:astro-ph/9702060
Lipunov *et al.* arXiv:1605.01604

Dominik *et al.* arXiv:1202.4901
Belczynski et al. arXiv:1403.0677
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Eldridge & Stanway arXiv:1602.03790

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Inayoshi *et al.* arXiv: 1603.06921

Mandel & de Mink arXiv:1601.00007
de Mink & Mandel arXiv:1603.02291

Marchant *et al.* arXiv:1601.03718

O'Leary *et al.* arXiv:astro-ph/0508224
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Morscher *et al.* arXiv:1409.0866
Rodriduez *et al.* arXiv:1505.00792
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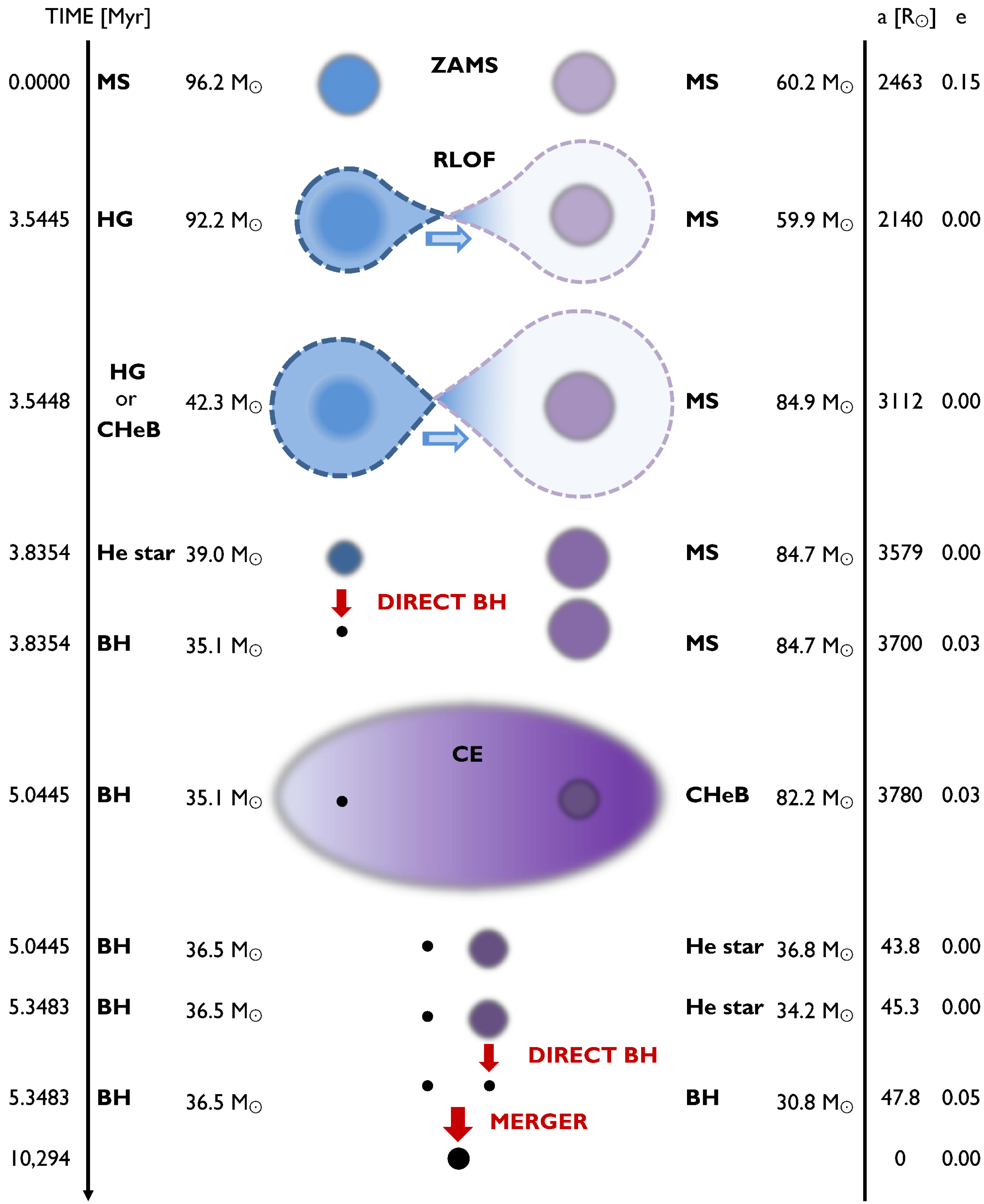

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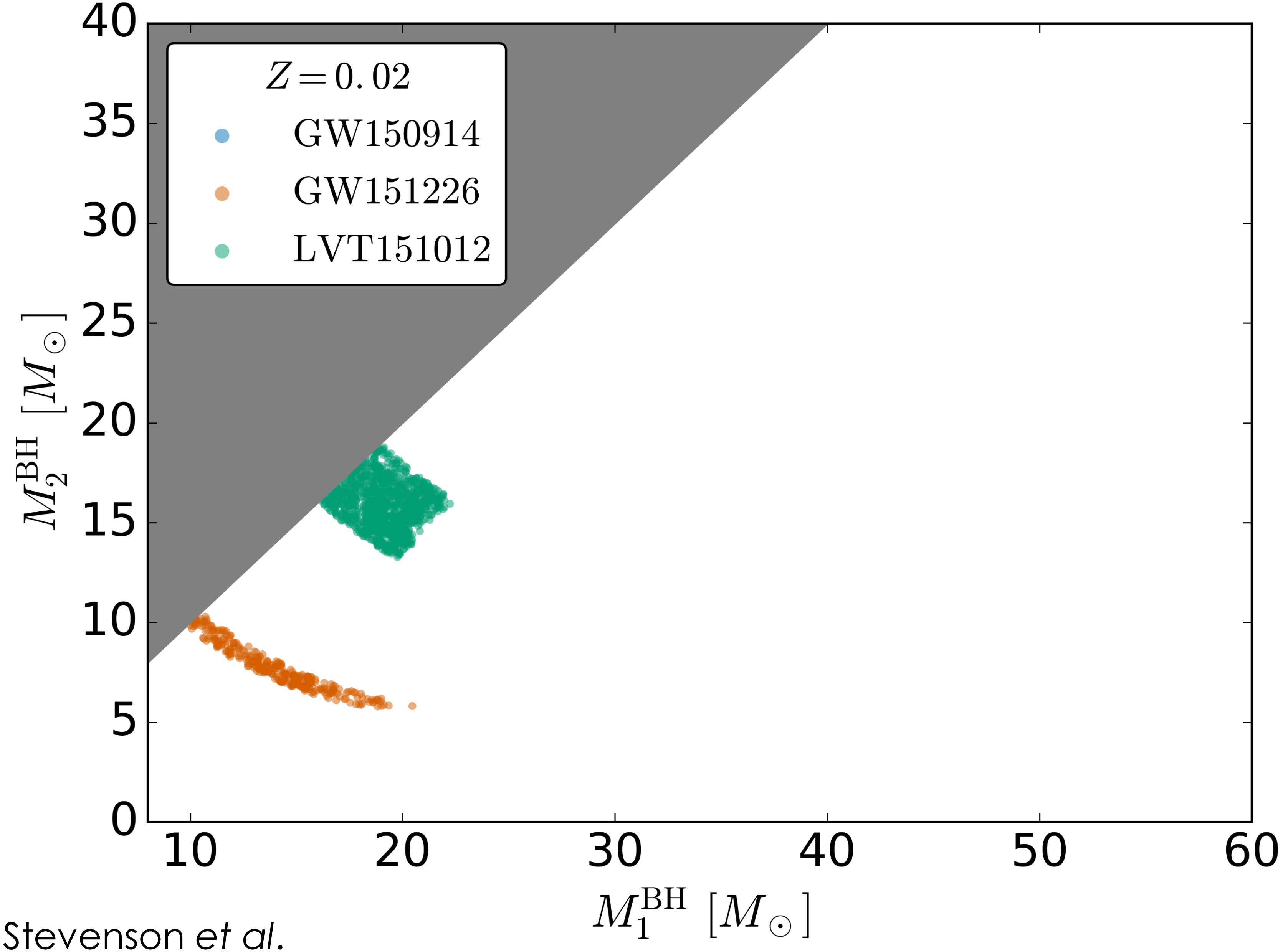
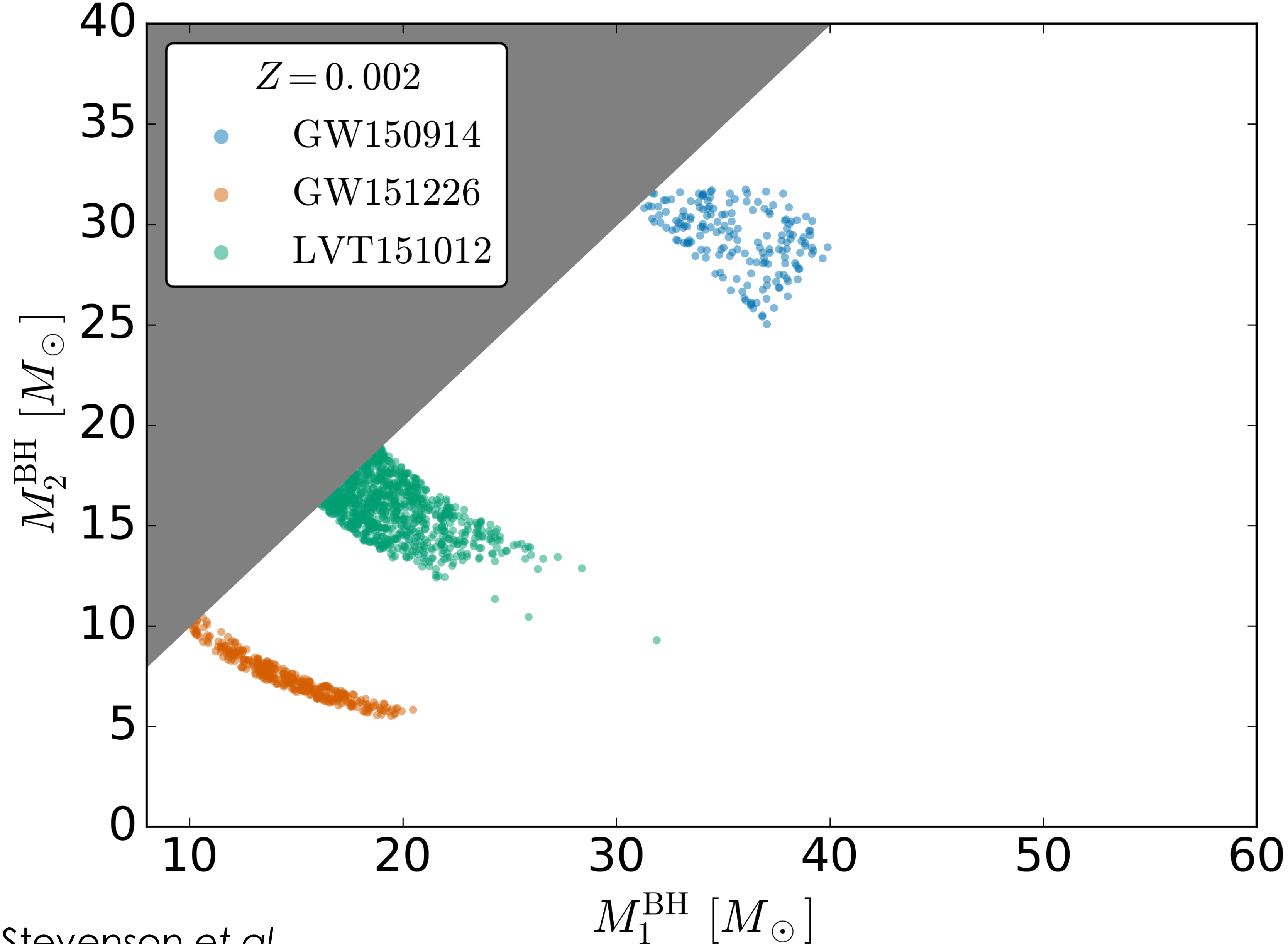


Stevenson *et al.*



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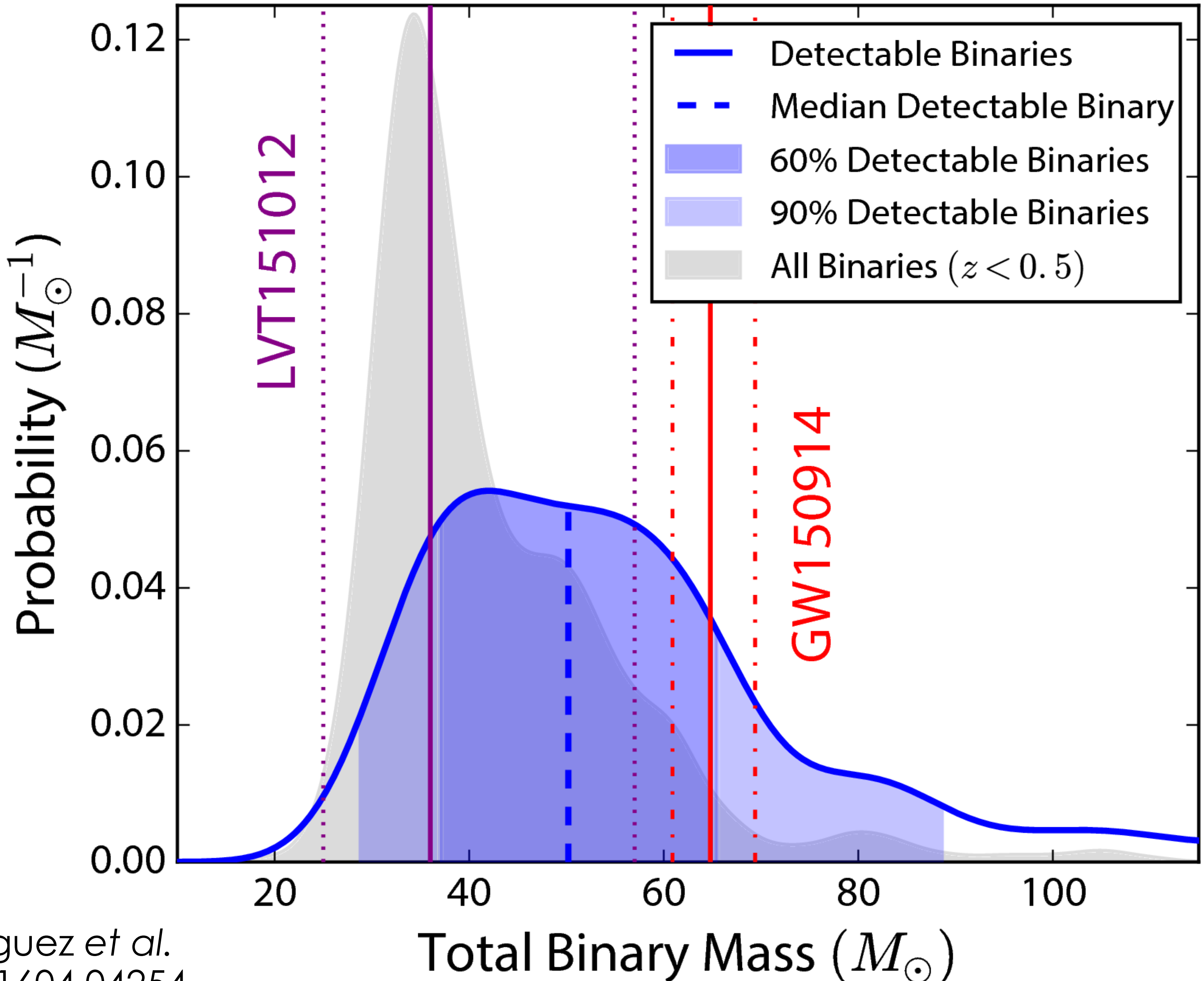
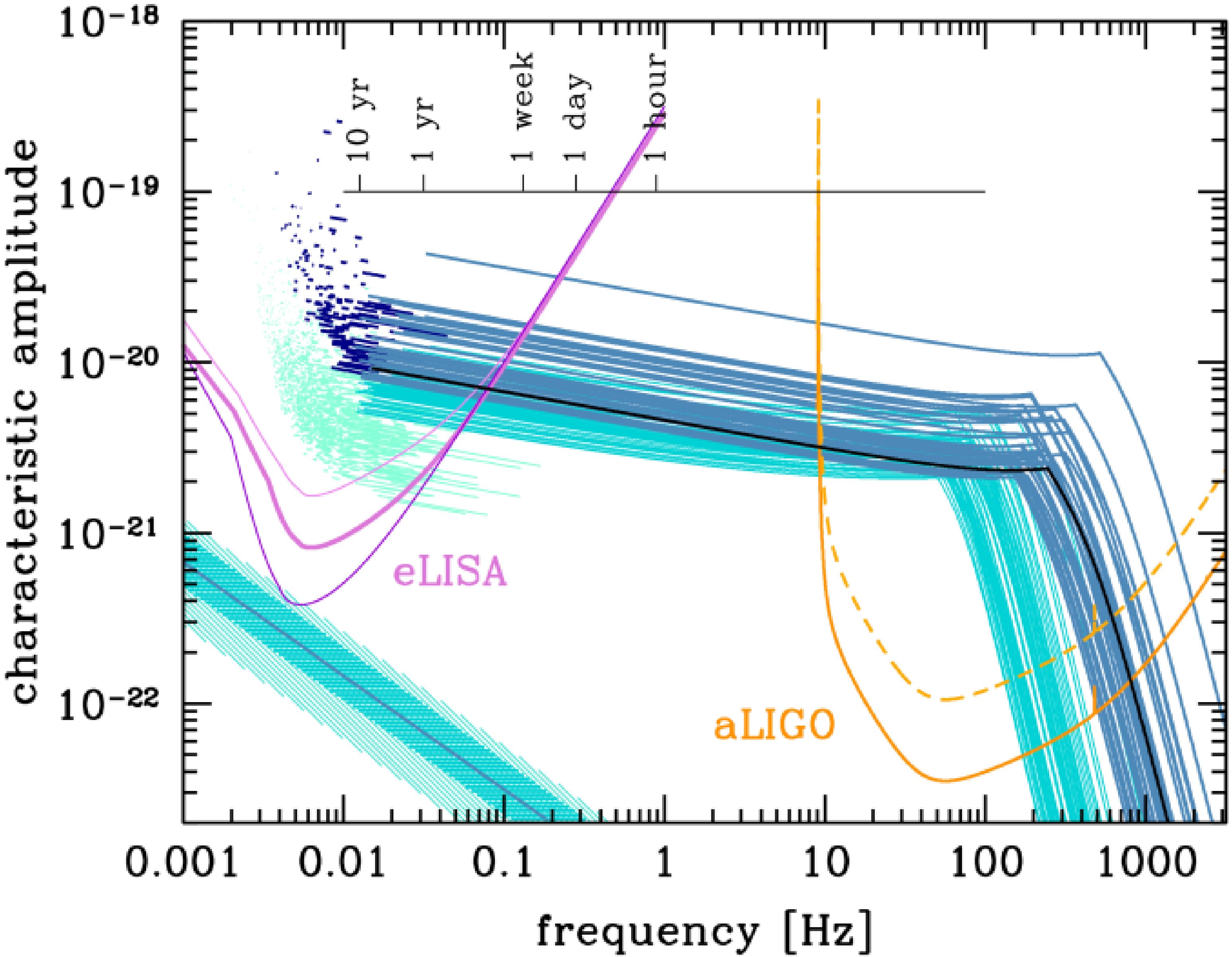


Rodriguez *et al.*
arXiv:1604.04254

Sesana arXiv:1602.06951



Nishizawa *et al*. arXiv:1606.09295 Breivik *et al*. arXiv:1606.09558

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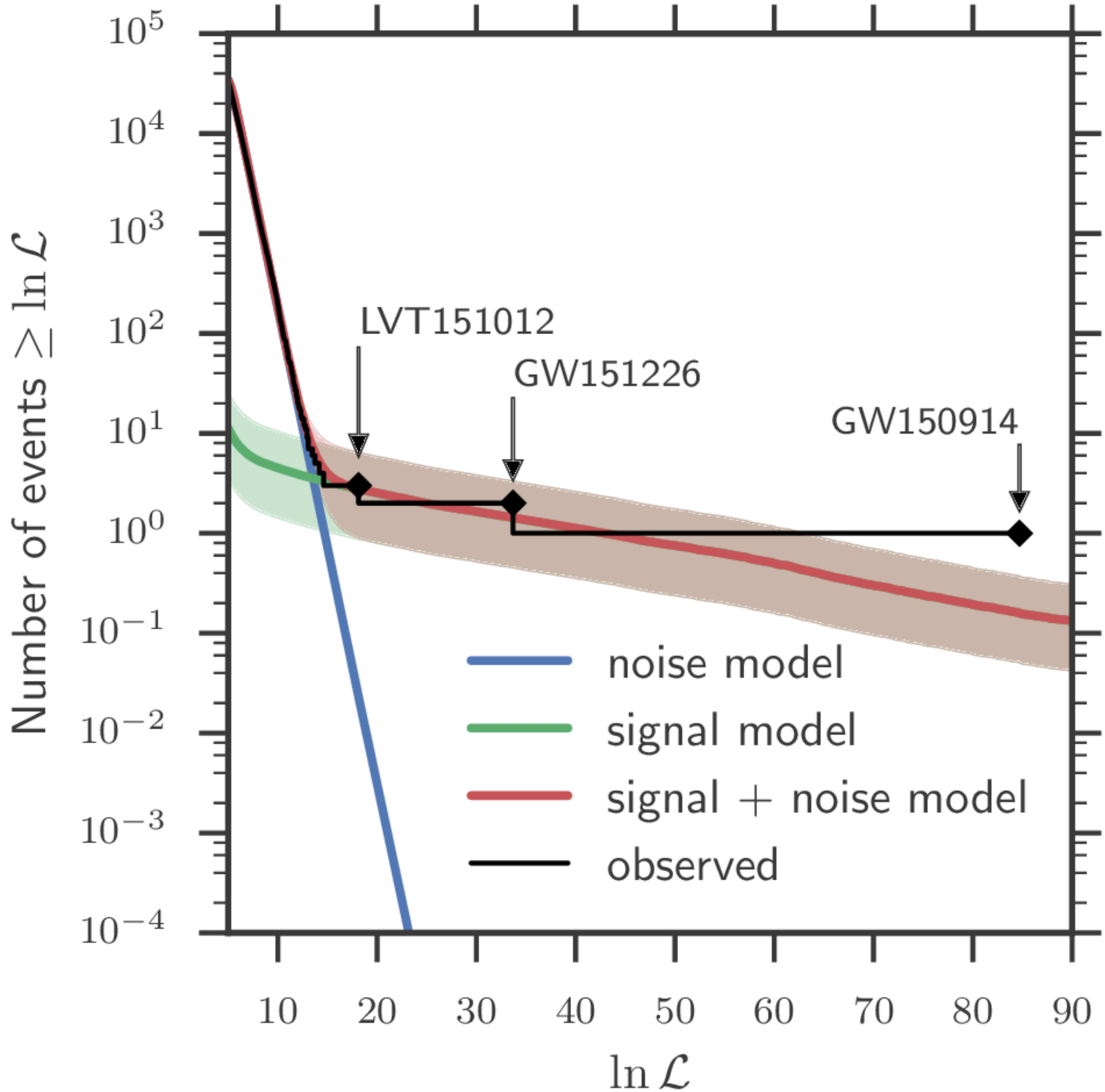
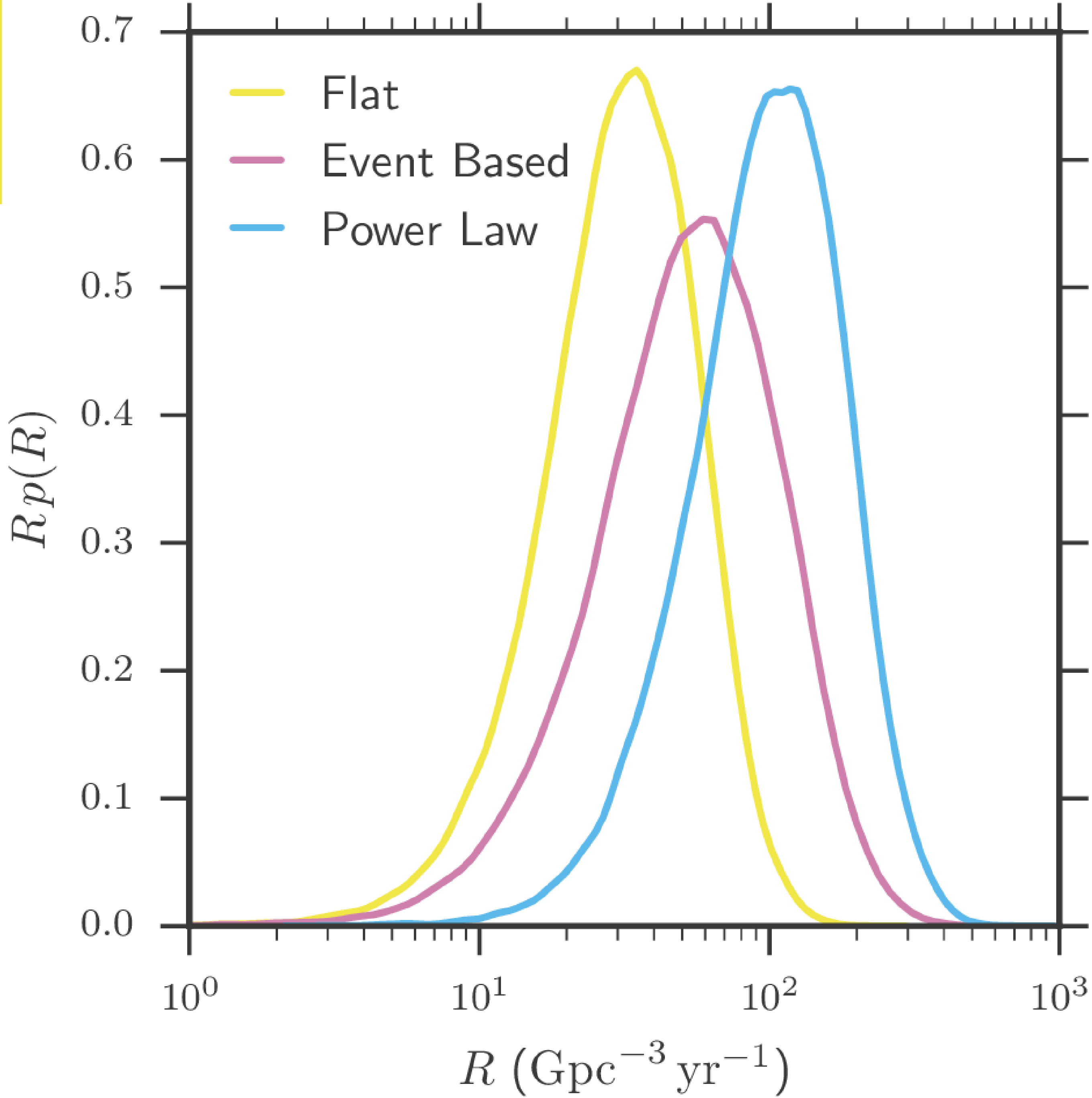
Counts



LVC
arXiv:1606.04856
arXiv:1602.03842

Rates



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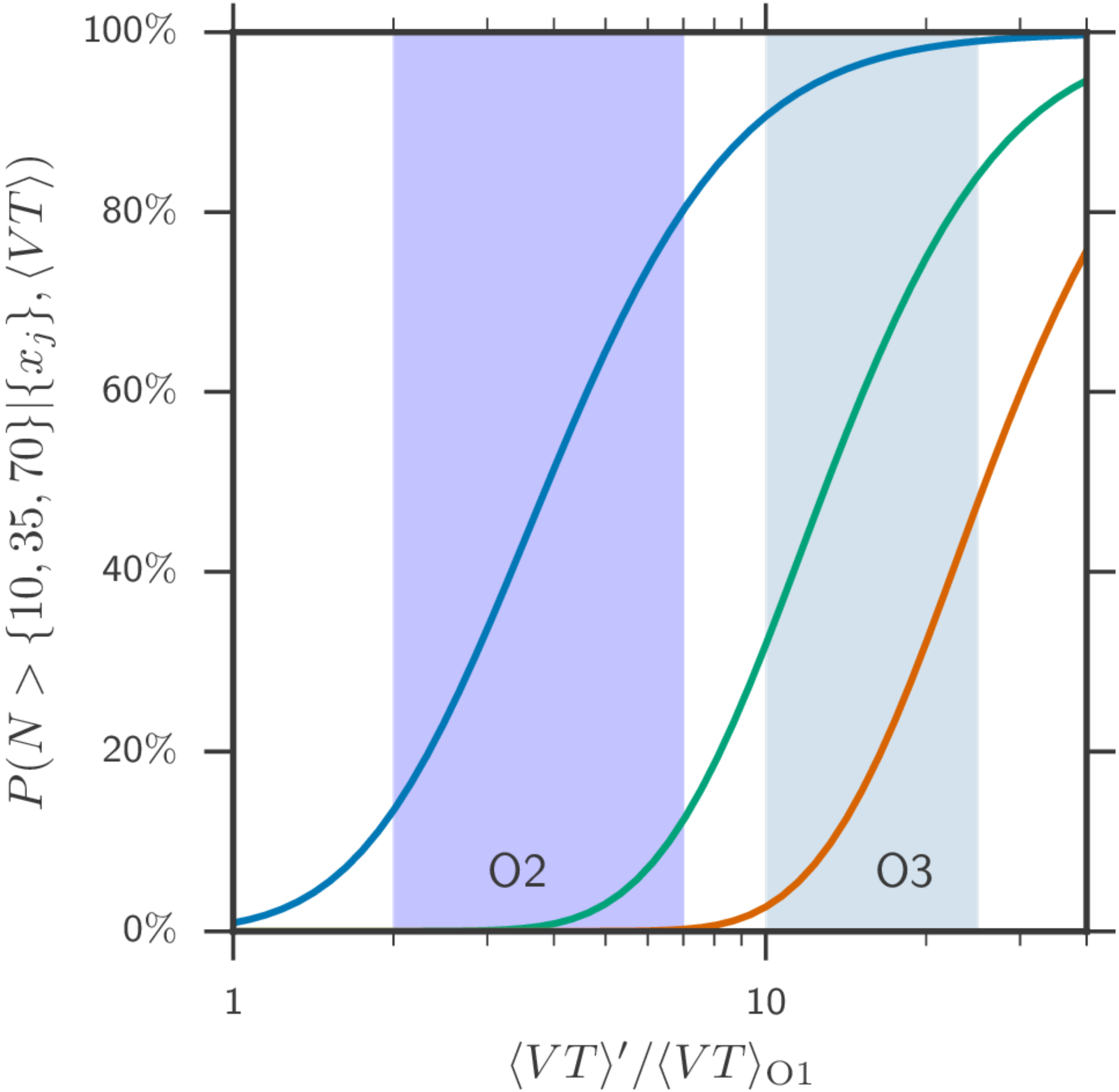
Events



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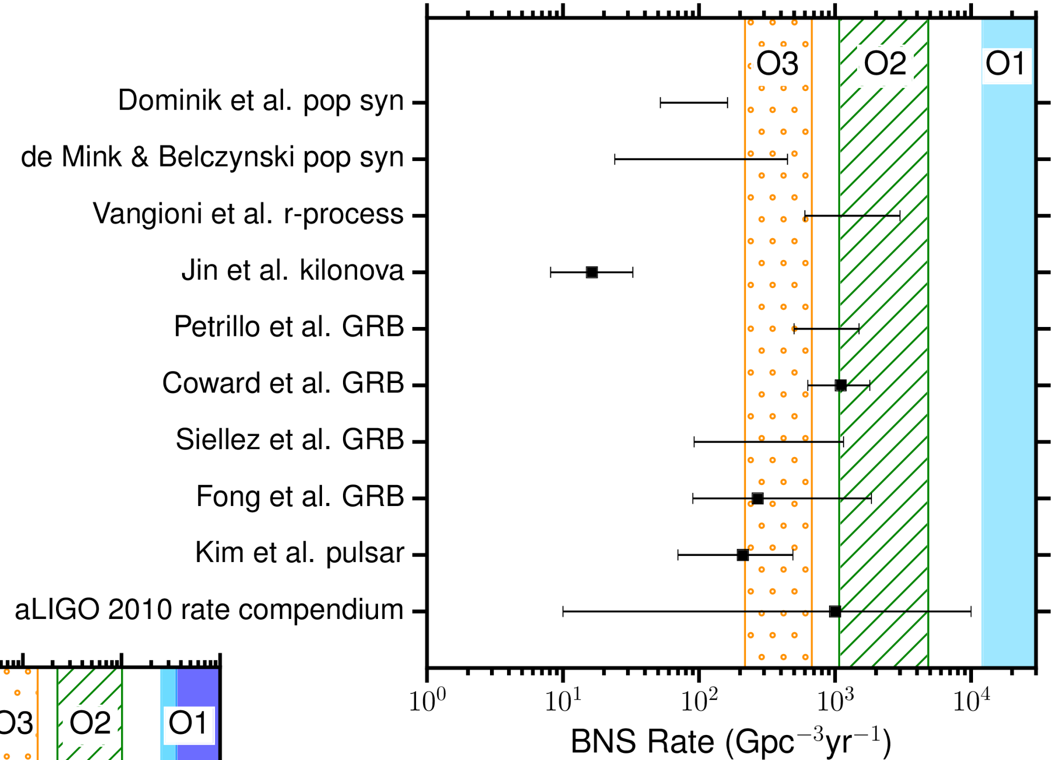
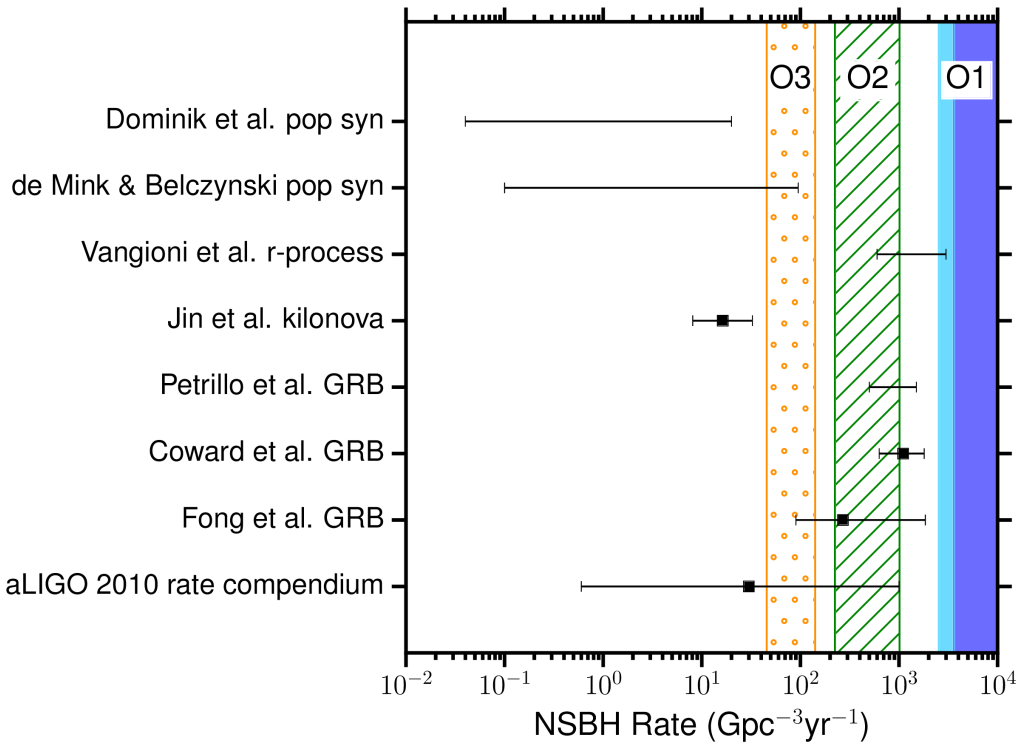
Limits





LVC
arXiv:1607.07456

- Gravitational-wave detection is possible
- There is a family of heavy binary black holes
- Spin uncertain but moderate values preferred
- Formation channel is currently uncertain
- There will be more detections

LVC arXiv:1602.03840 arXiv:1602.03846 arXiv:1606.04856

Thank you

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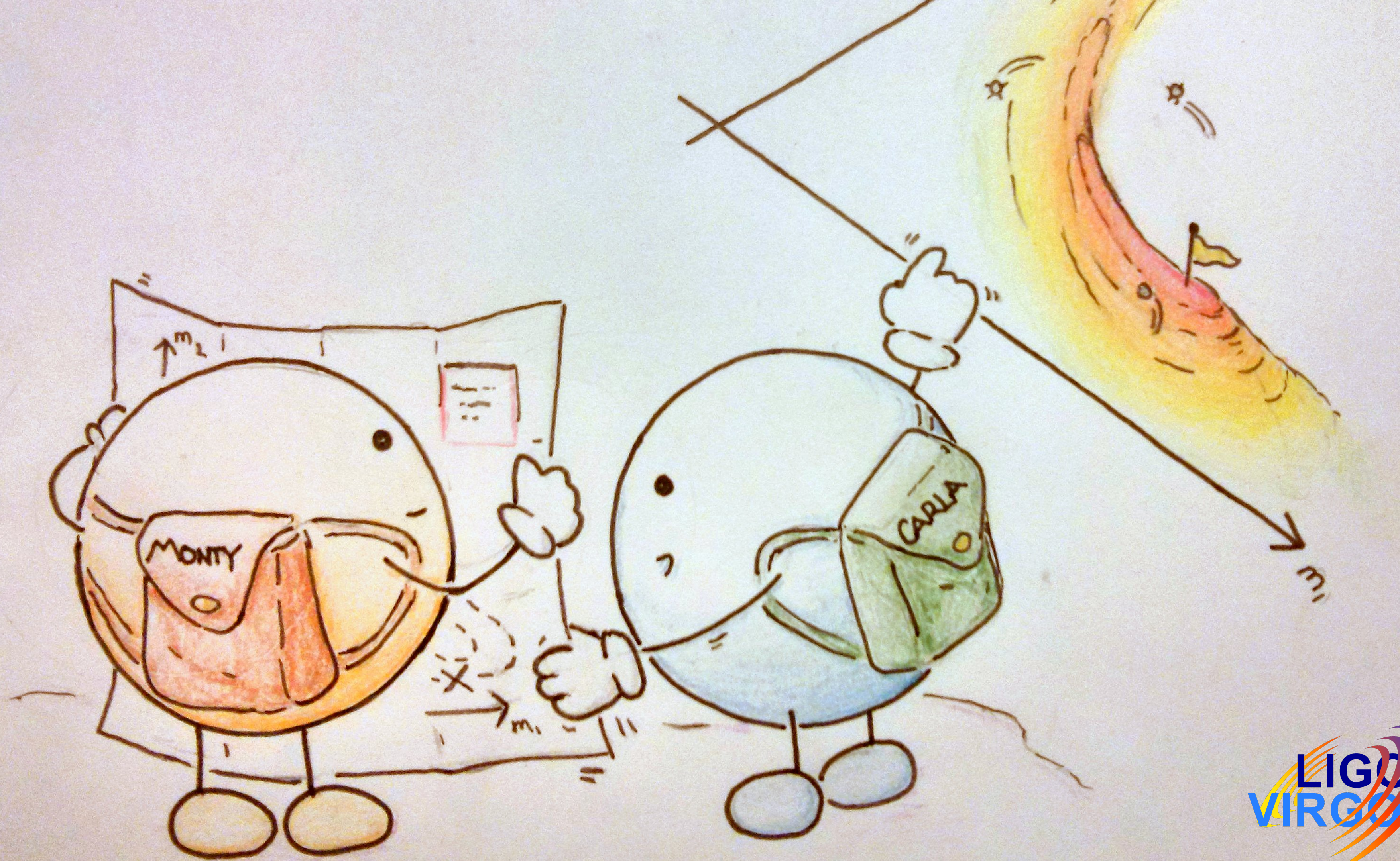


Bayes' theorem

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

Bayes' theorem

Likelihood

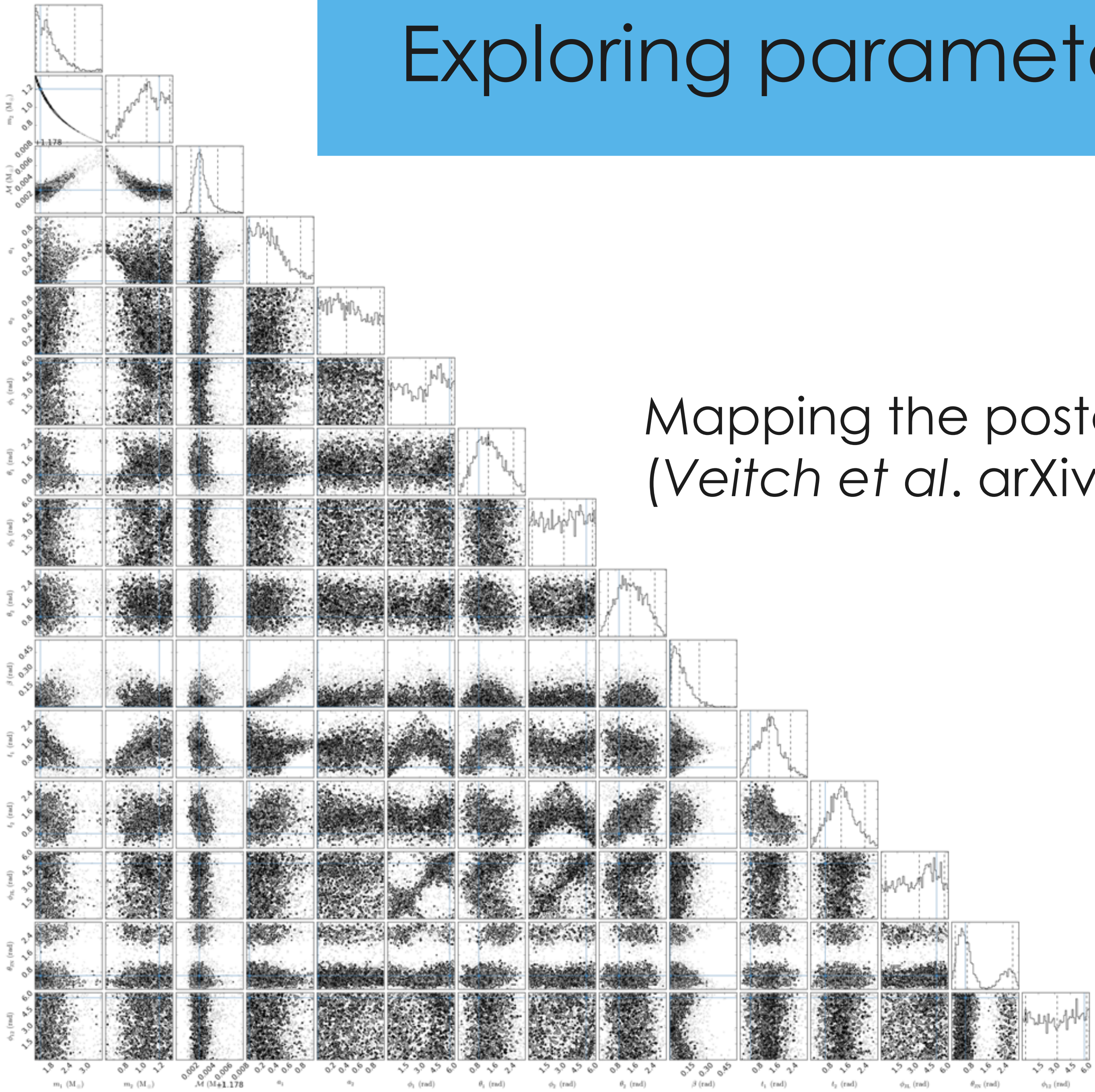
Prior

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

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

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

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

LVC arXiv:1602.03840

Likelihood

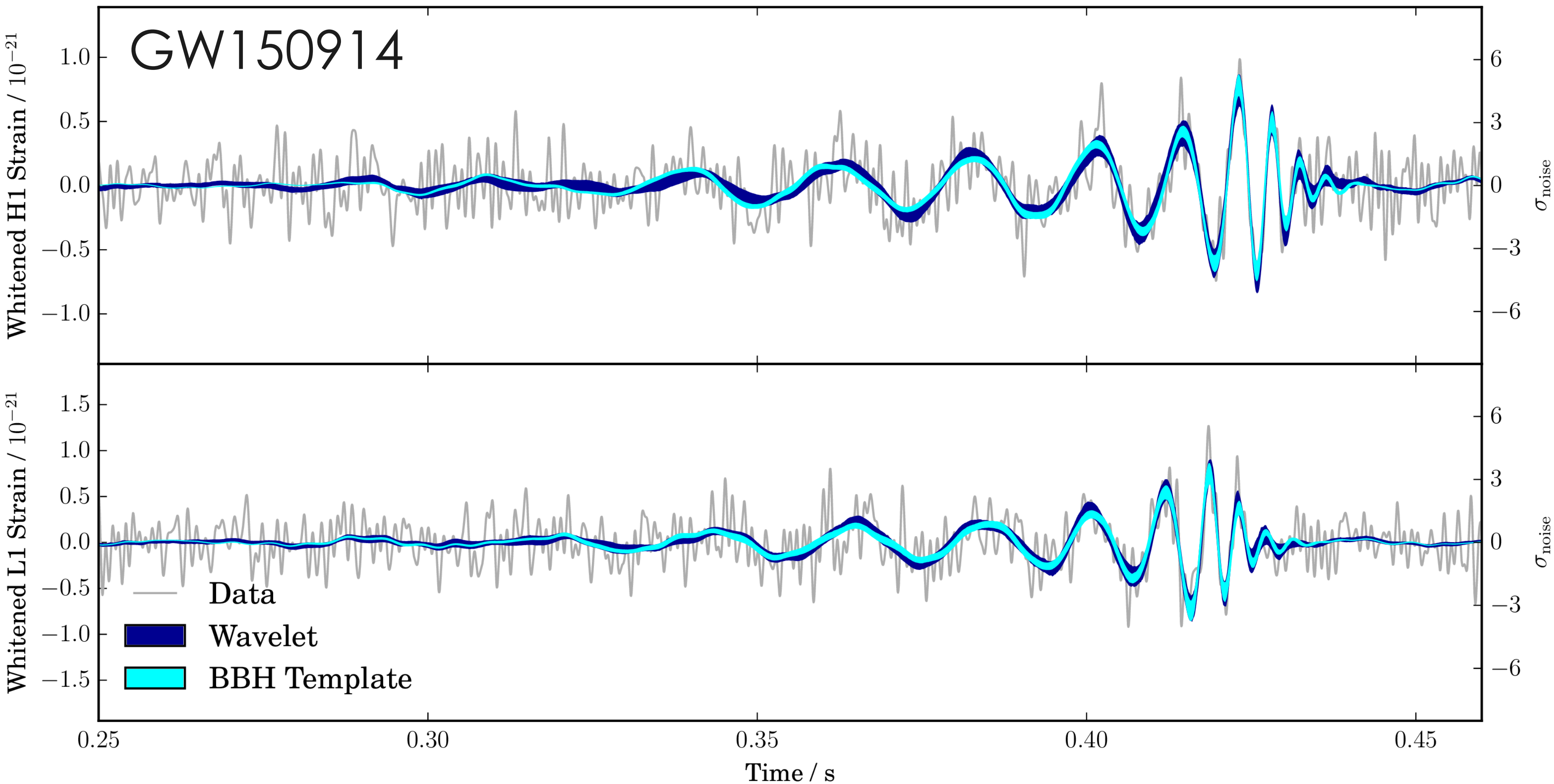
$$p(d|\theta) \propto \exp\left[-\frac{1}{2}\sum_k \langle h_k(\theta) - d_k | h_k(\theta) - d_k \rangle\right]$$

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

Waveform

LVC arXiv:1602.03840

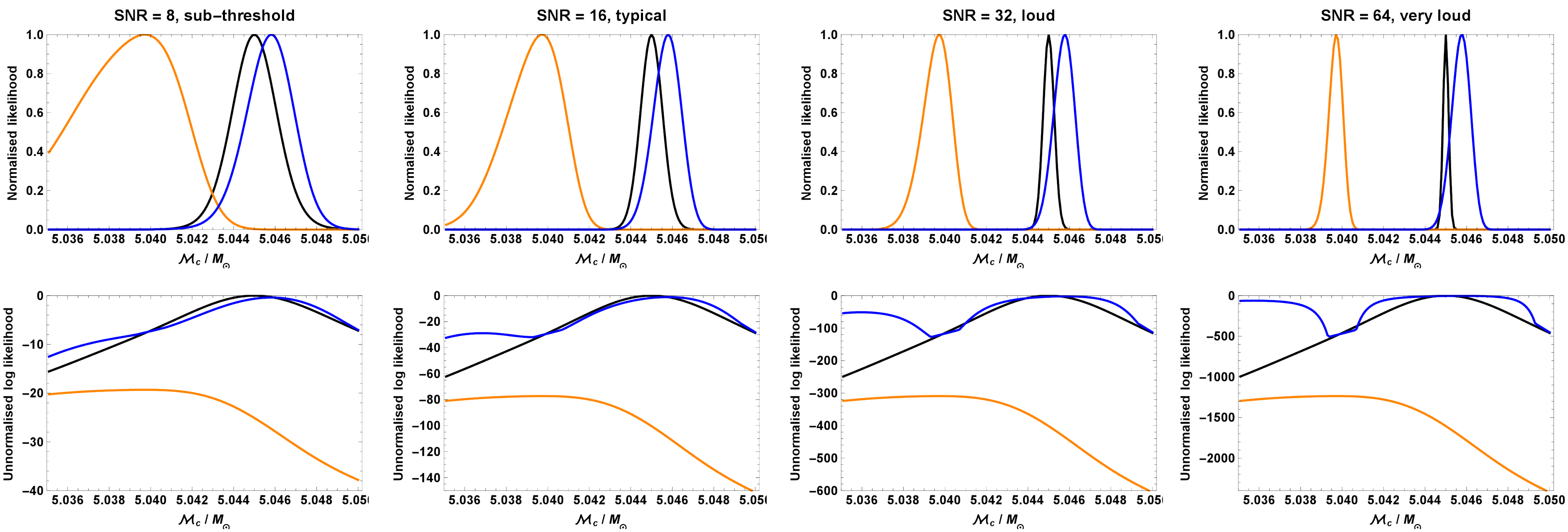
Waveform



LVC arXiv:1602.03840

Waveform error

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



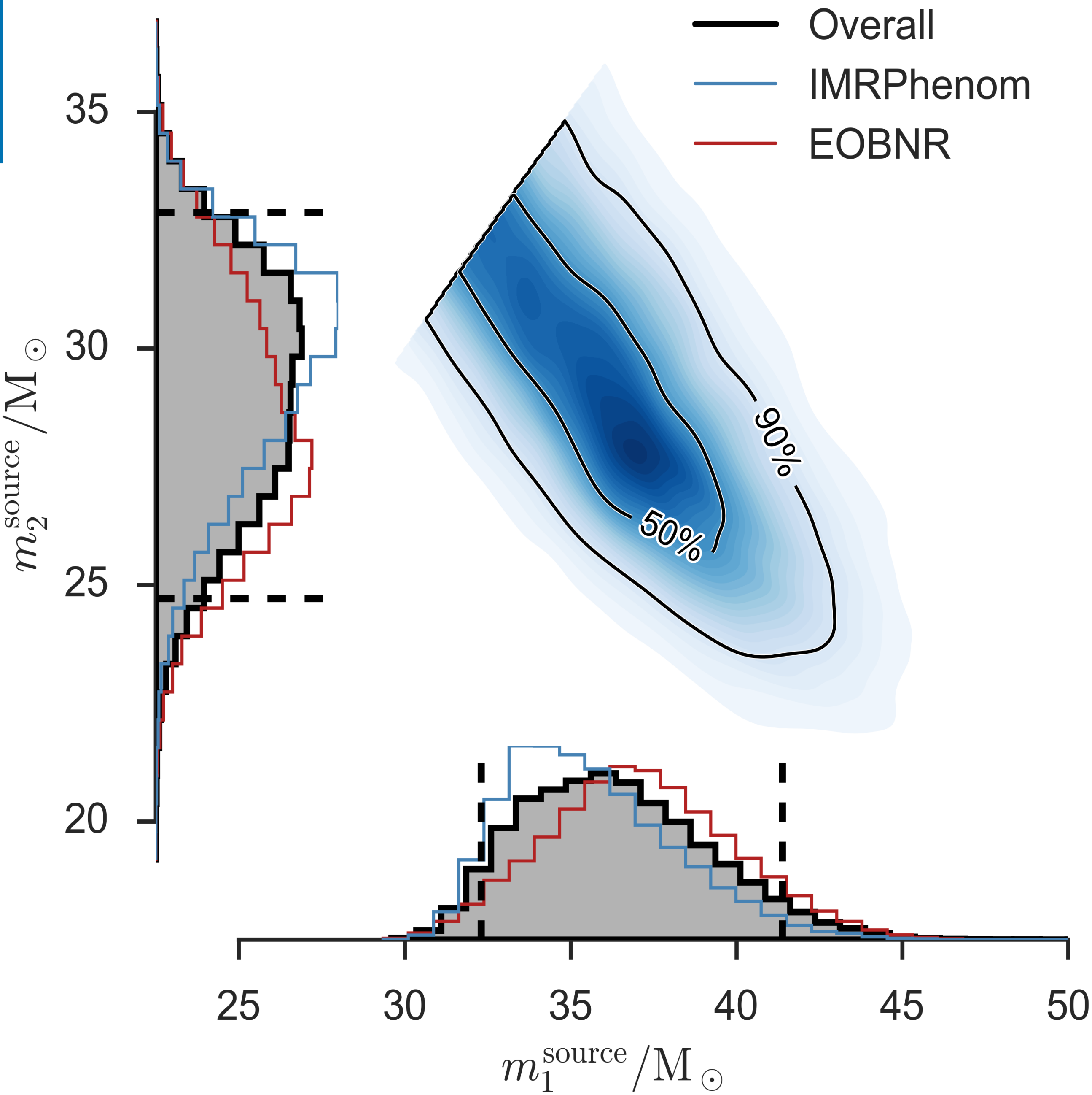
Moore *et al*. arXiv:1509.04066

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)

Masses



LVC
arXiv:1606.04856
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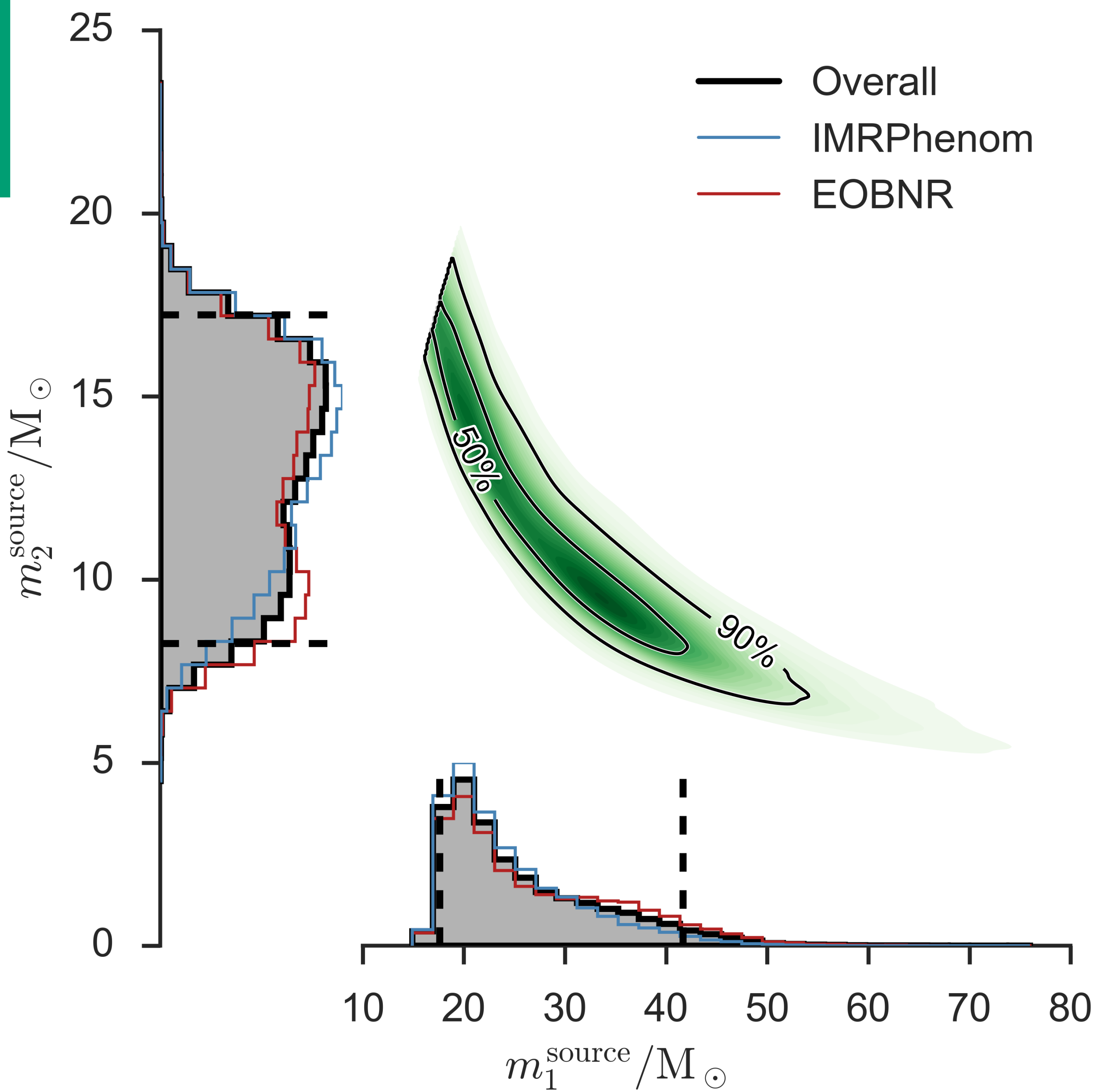
Masses



LVC
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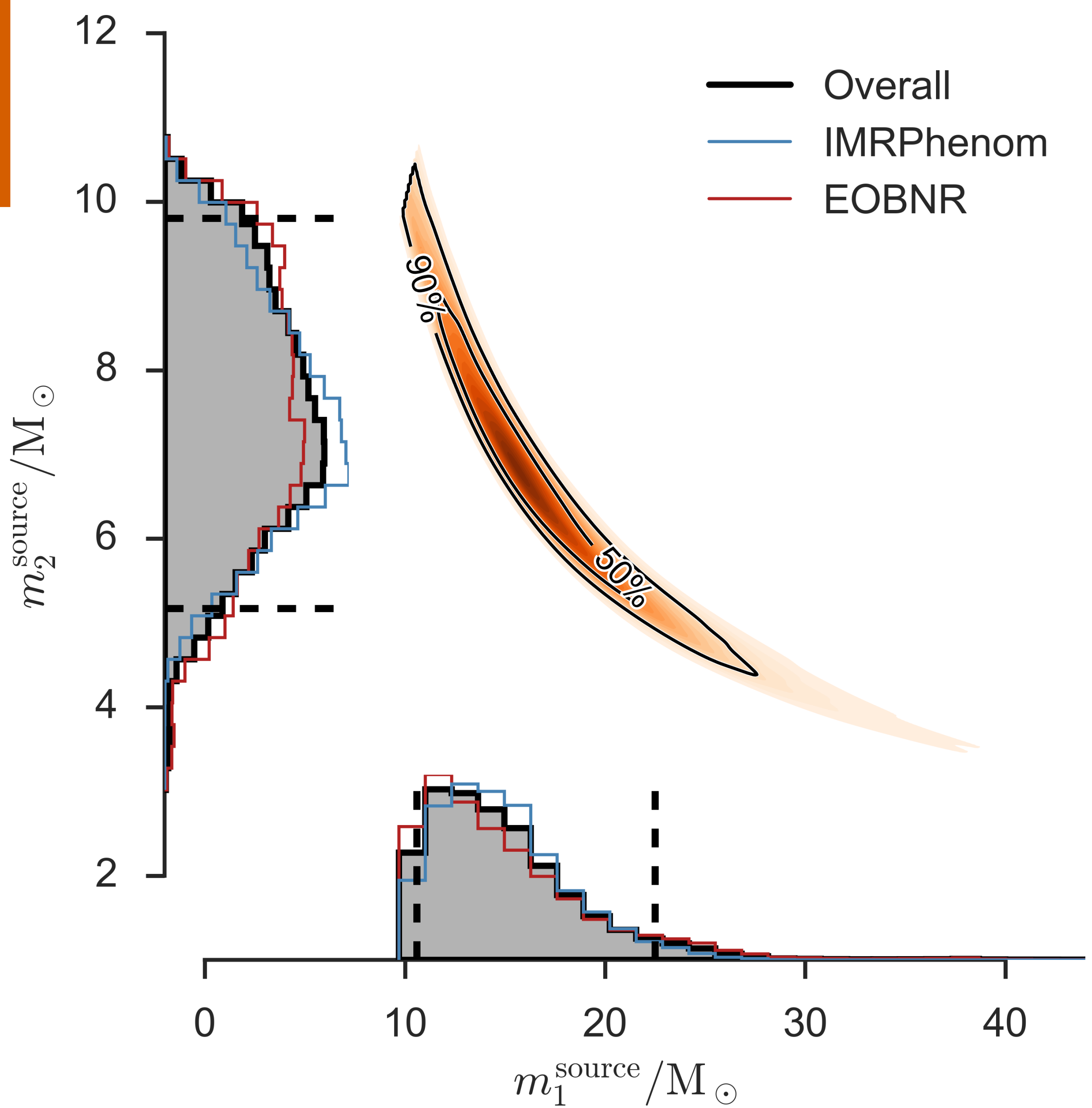
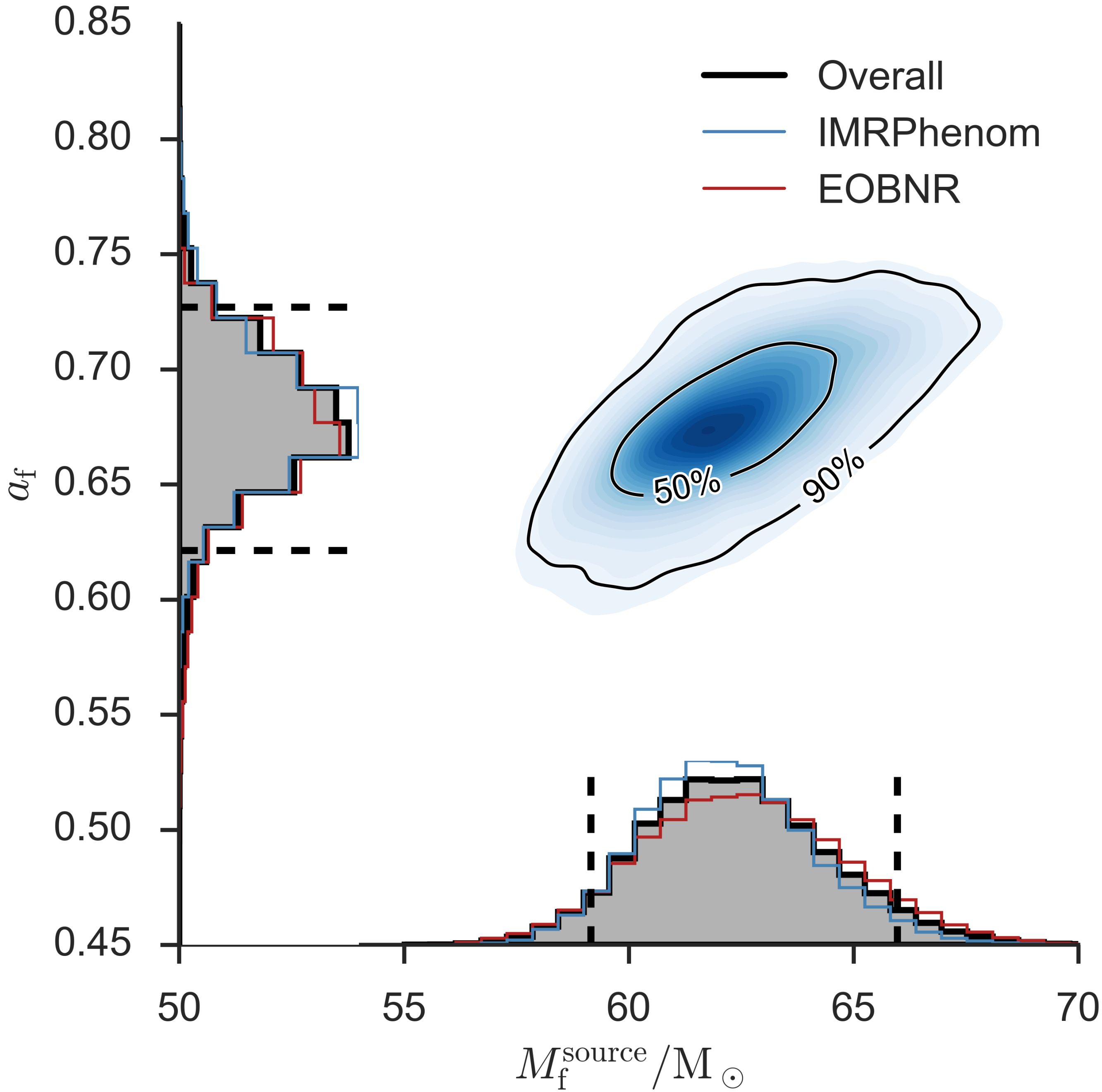
Masses



LVC
arXiv:1606.04855

Final mass & spin



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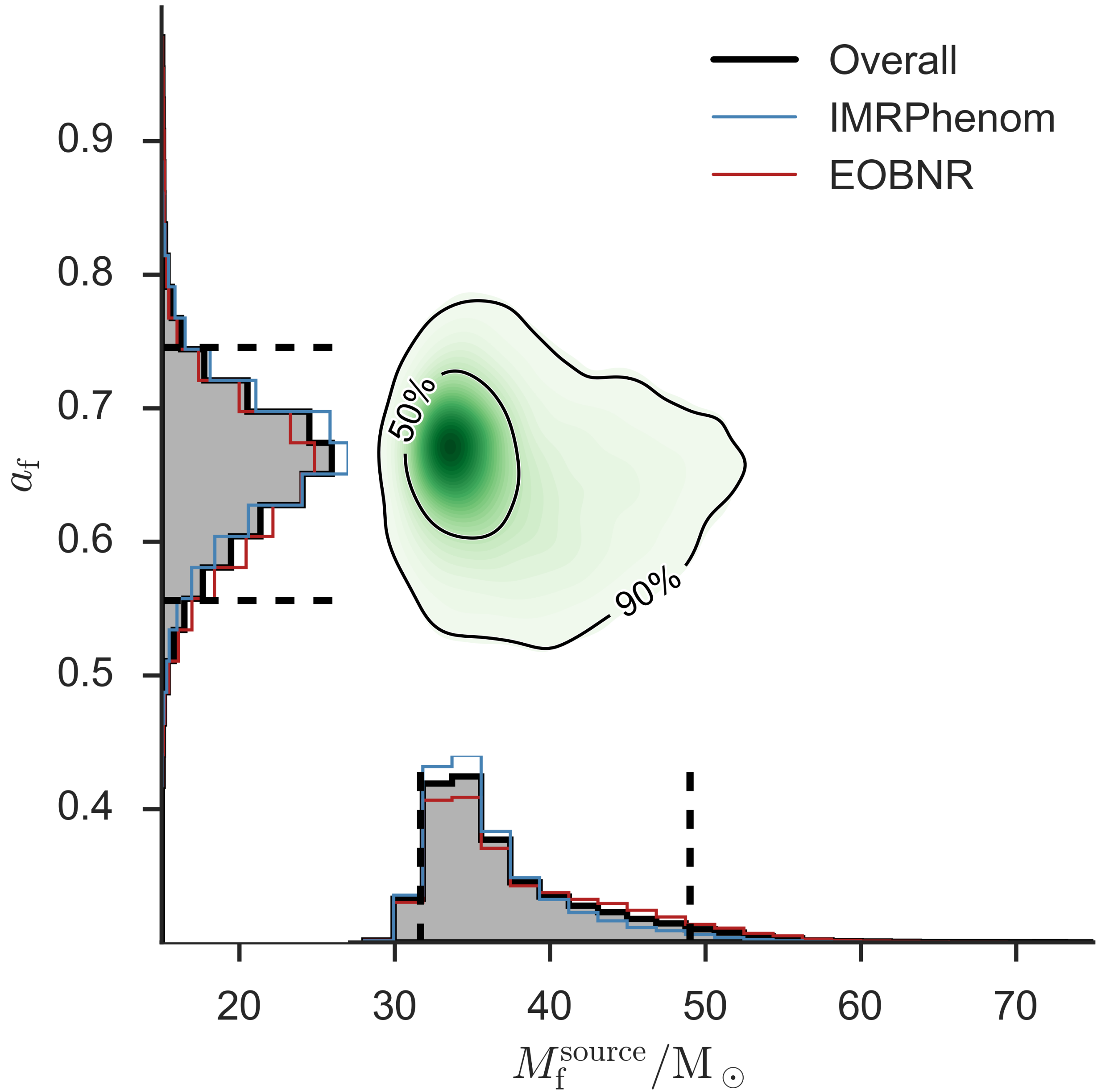

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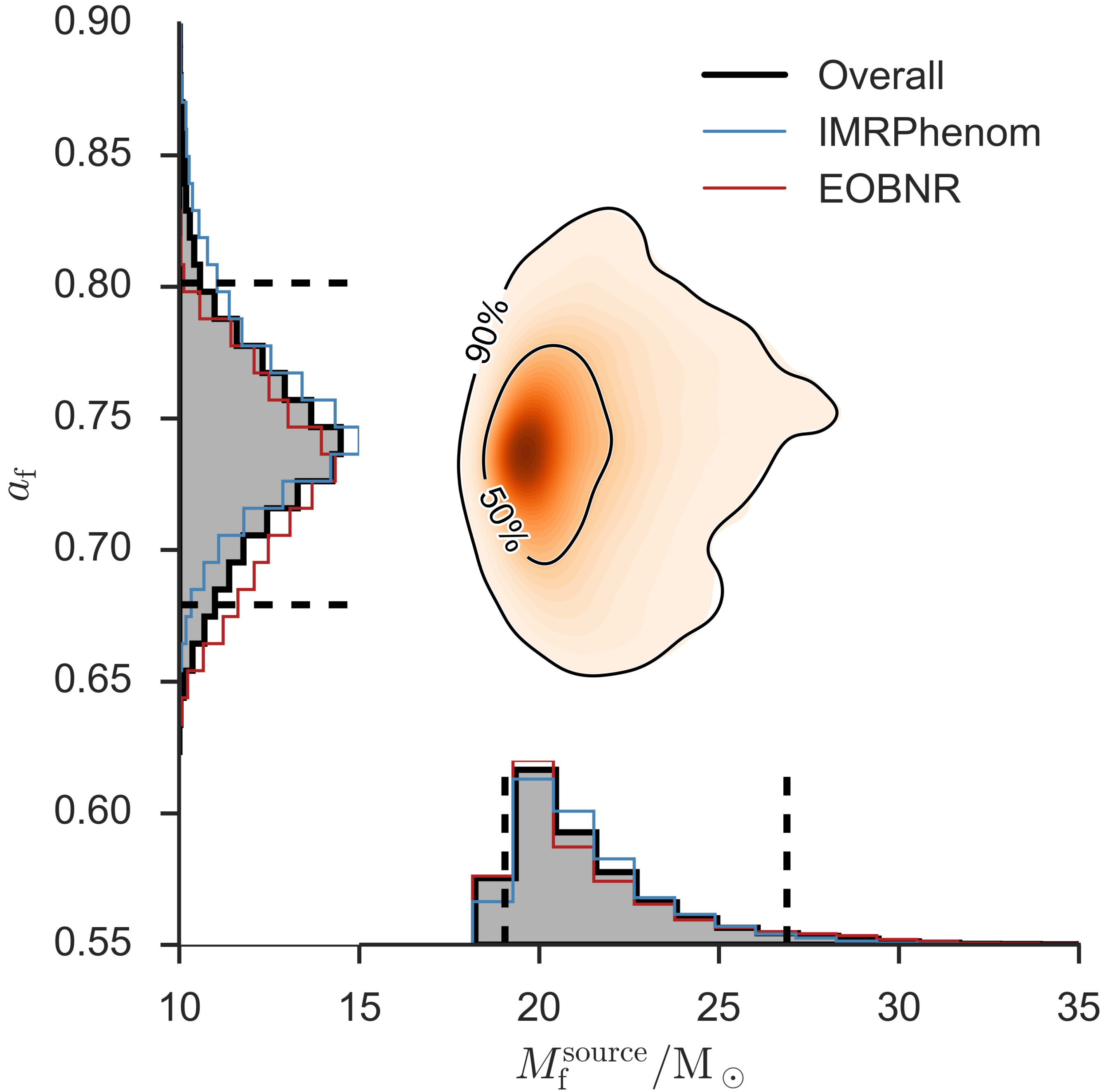

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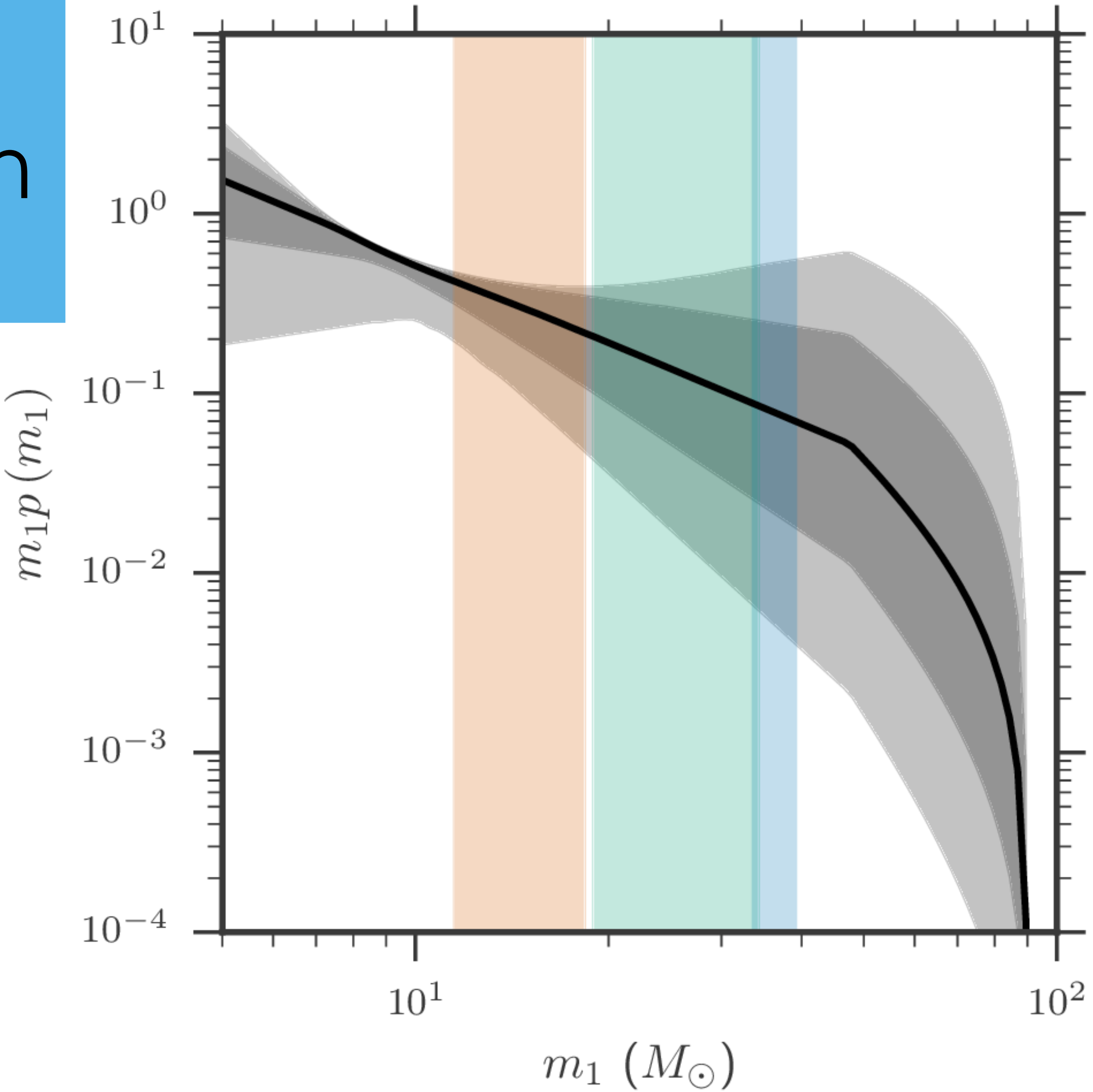
Mass distribution



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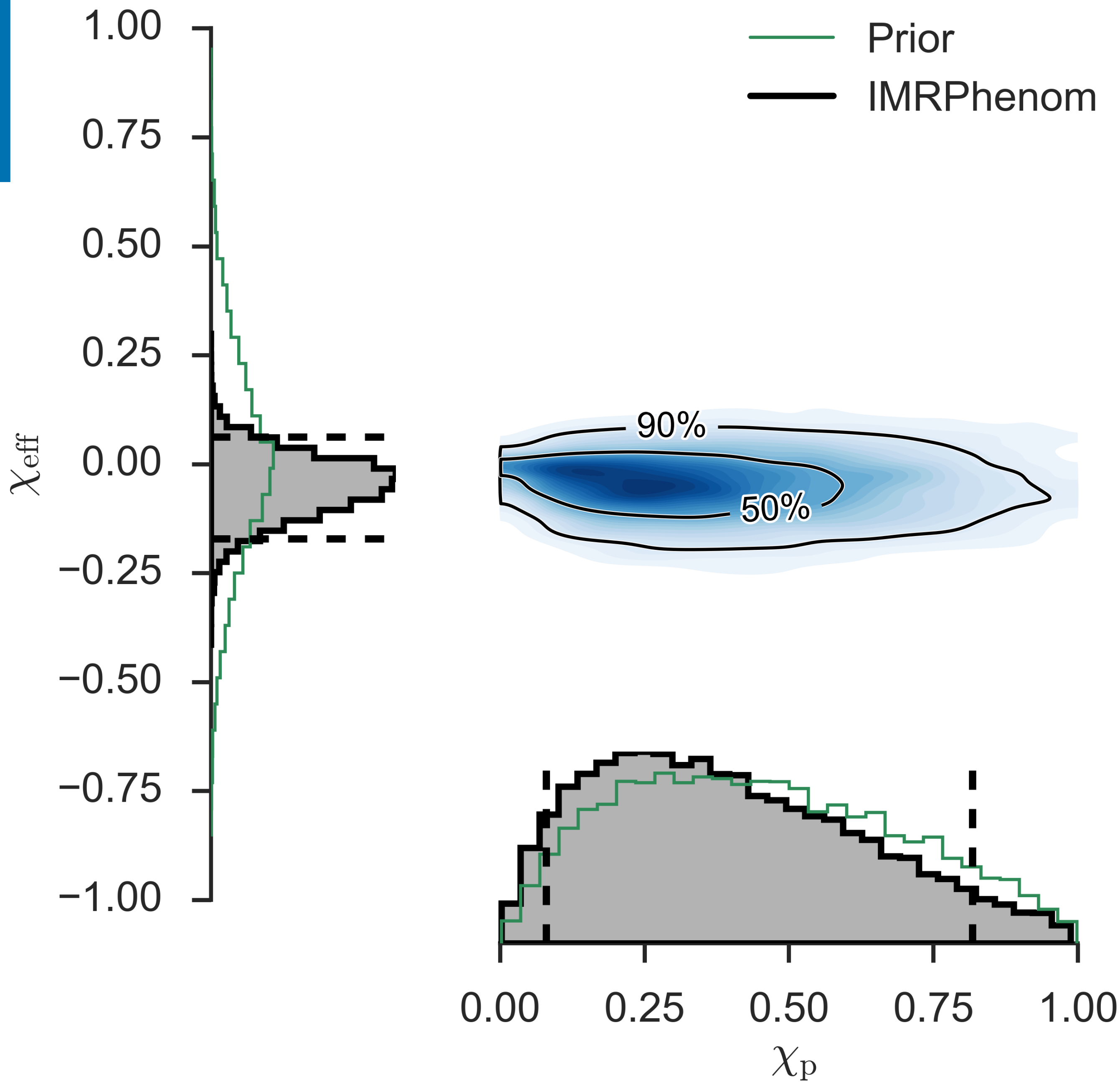
Spin



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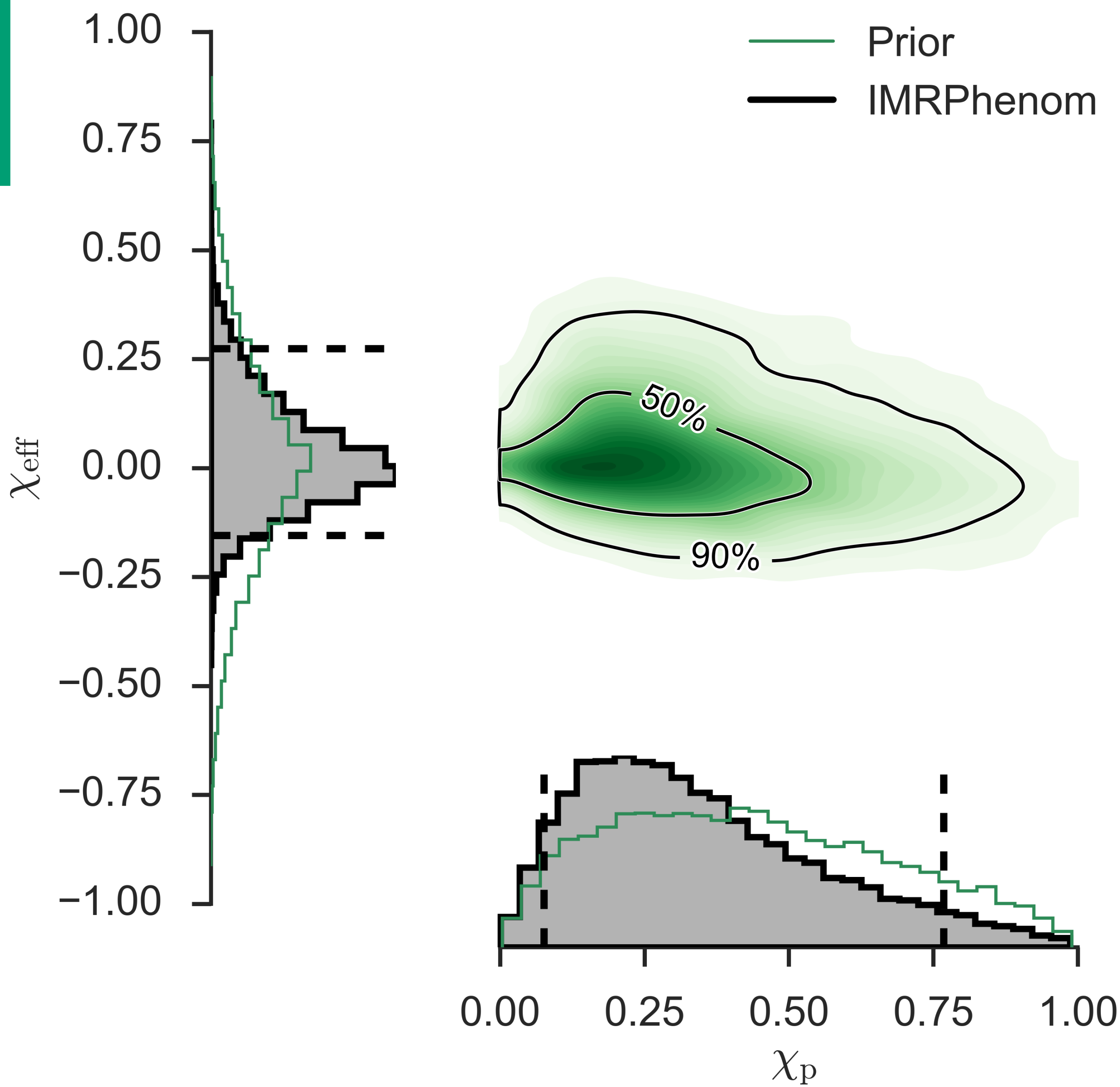

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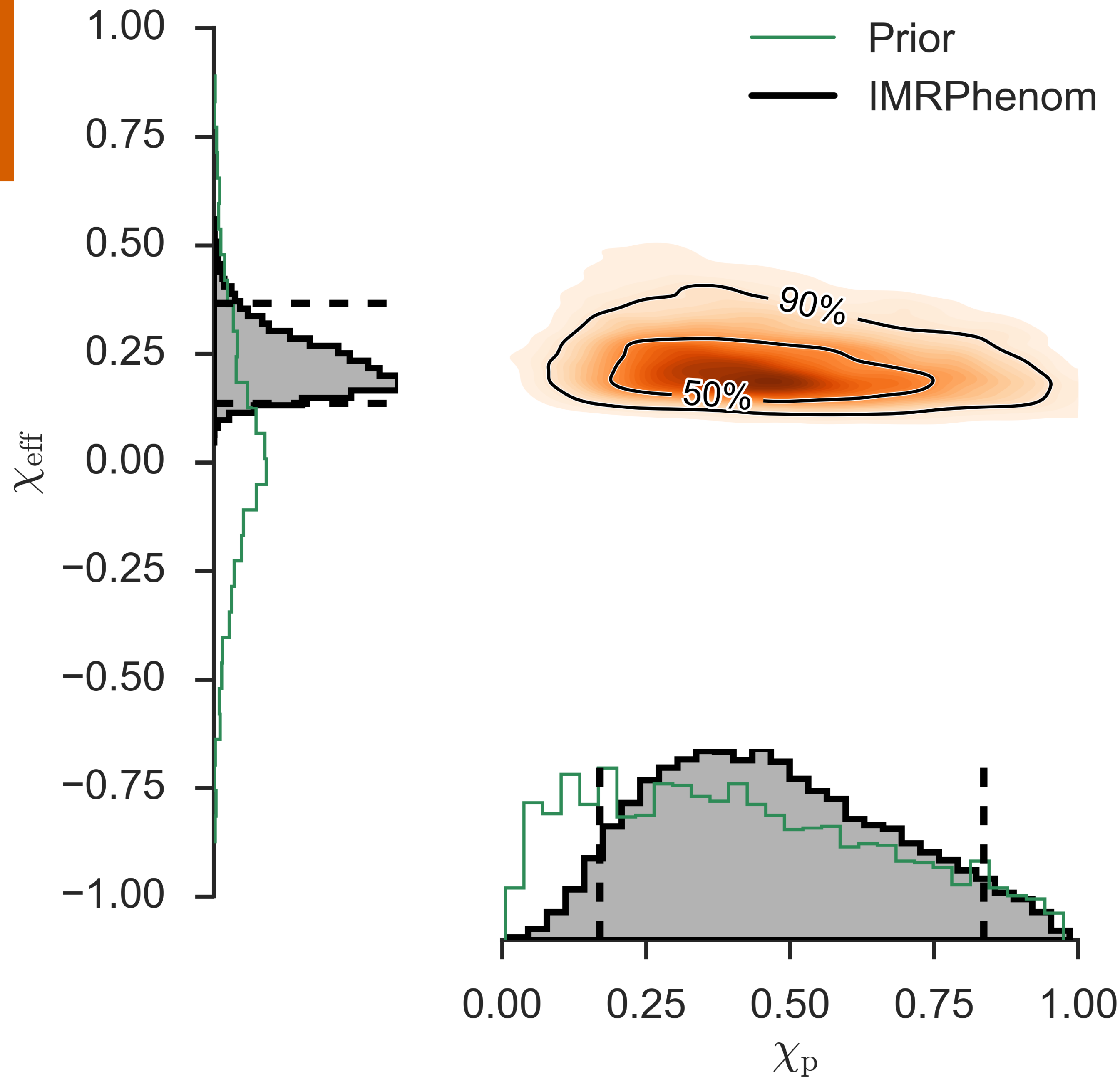

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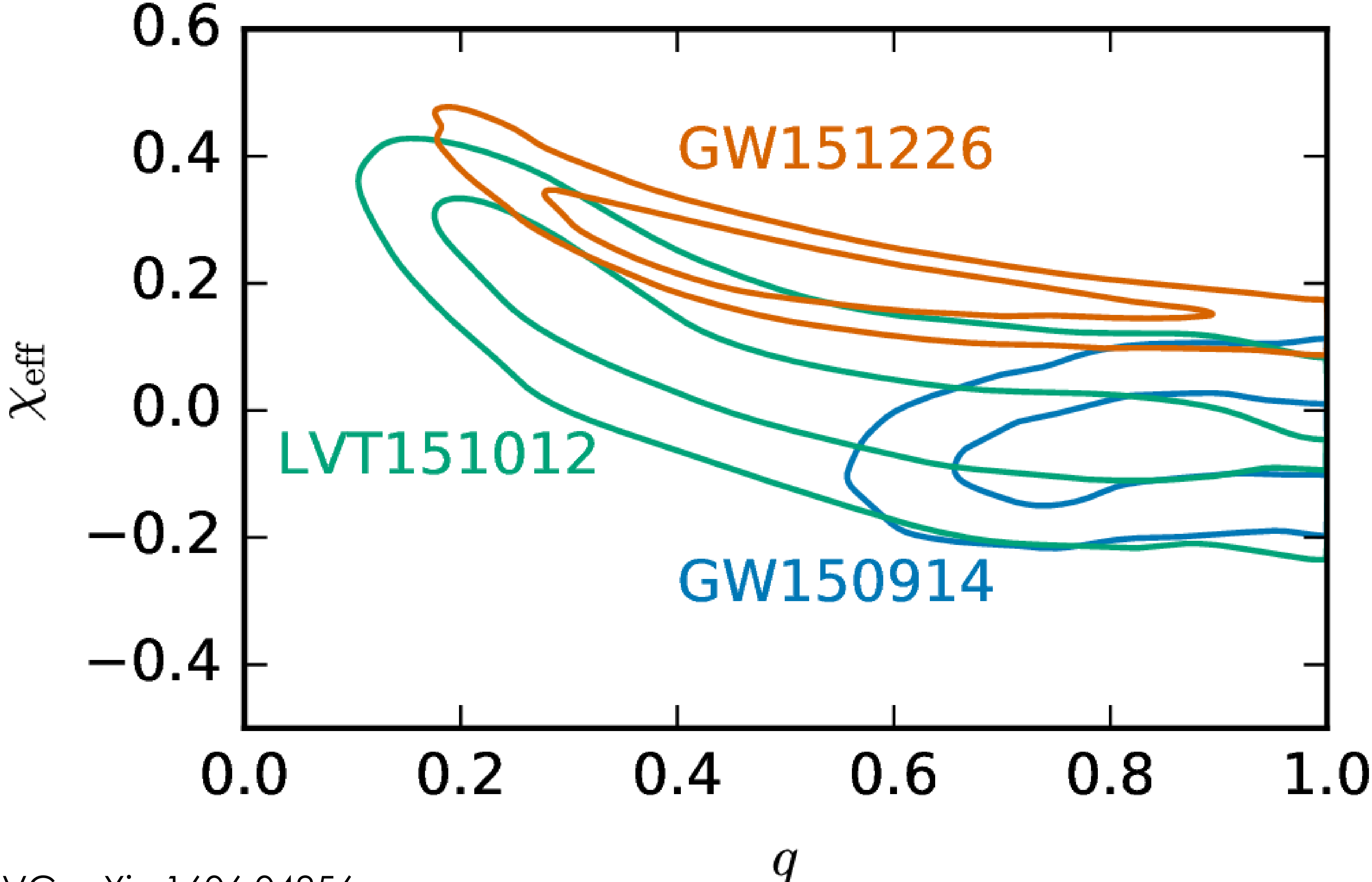
Effective inspiral spin

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

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



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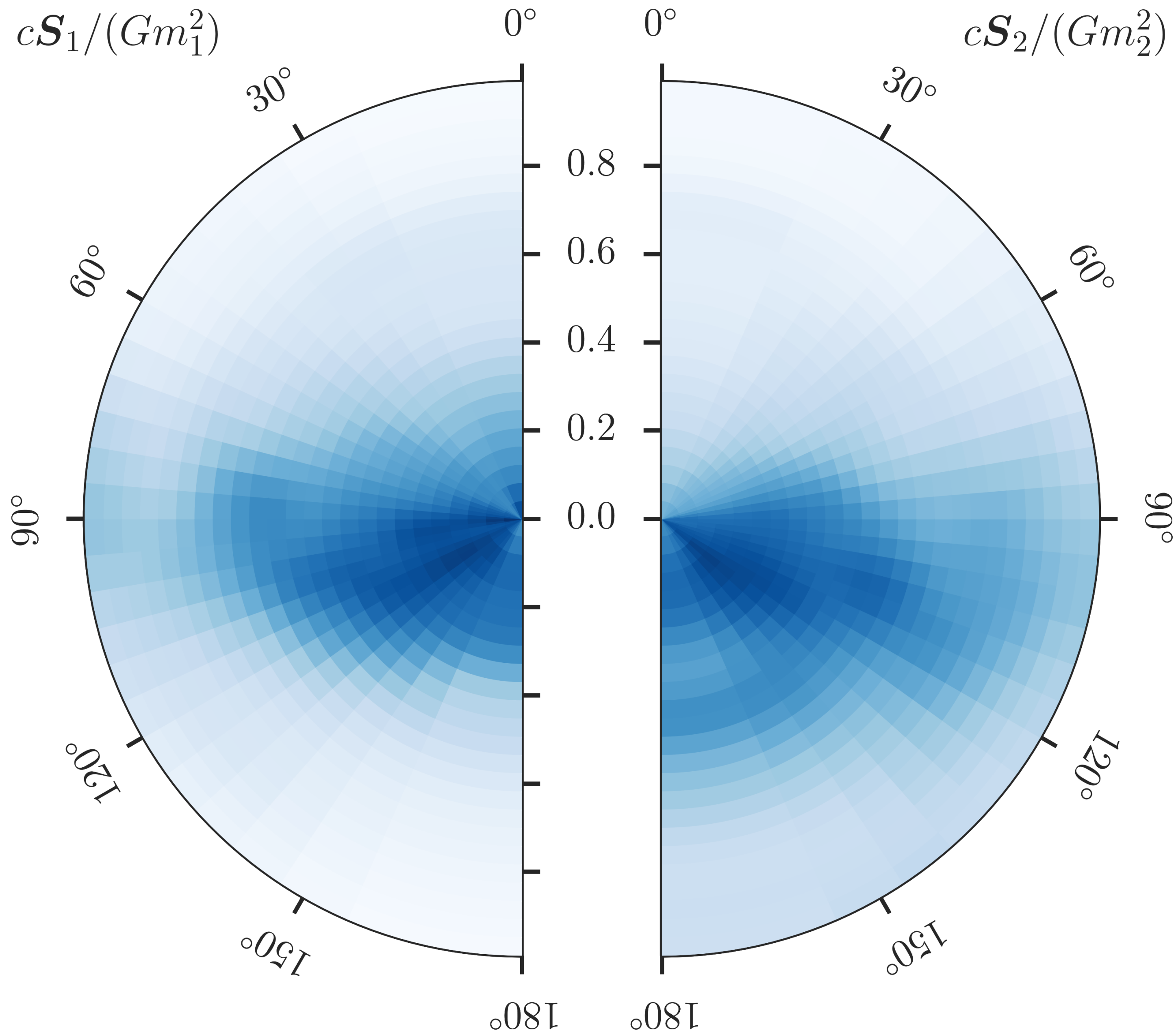
Spin



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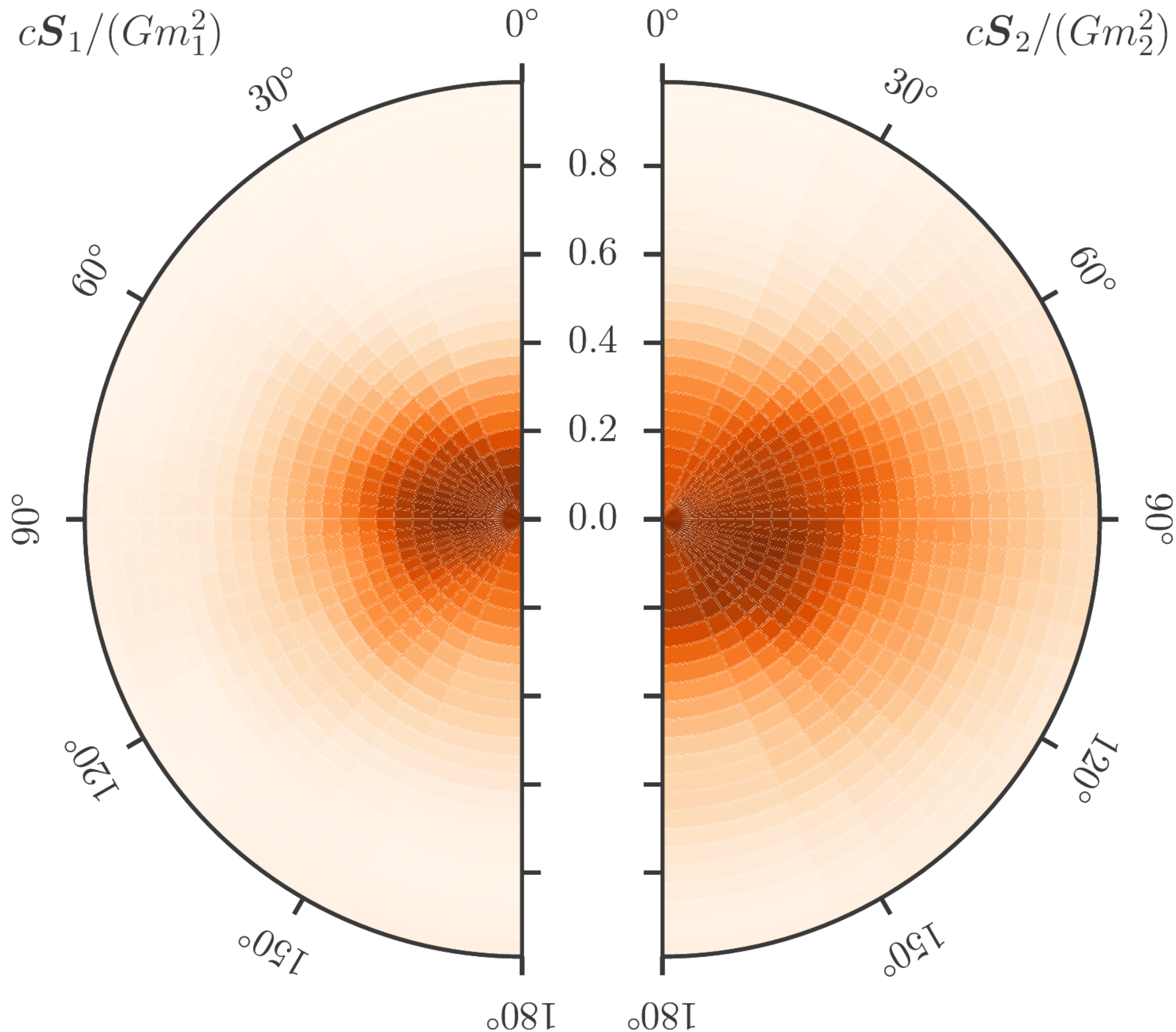
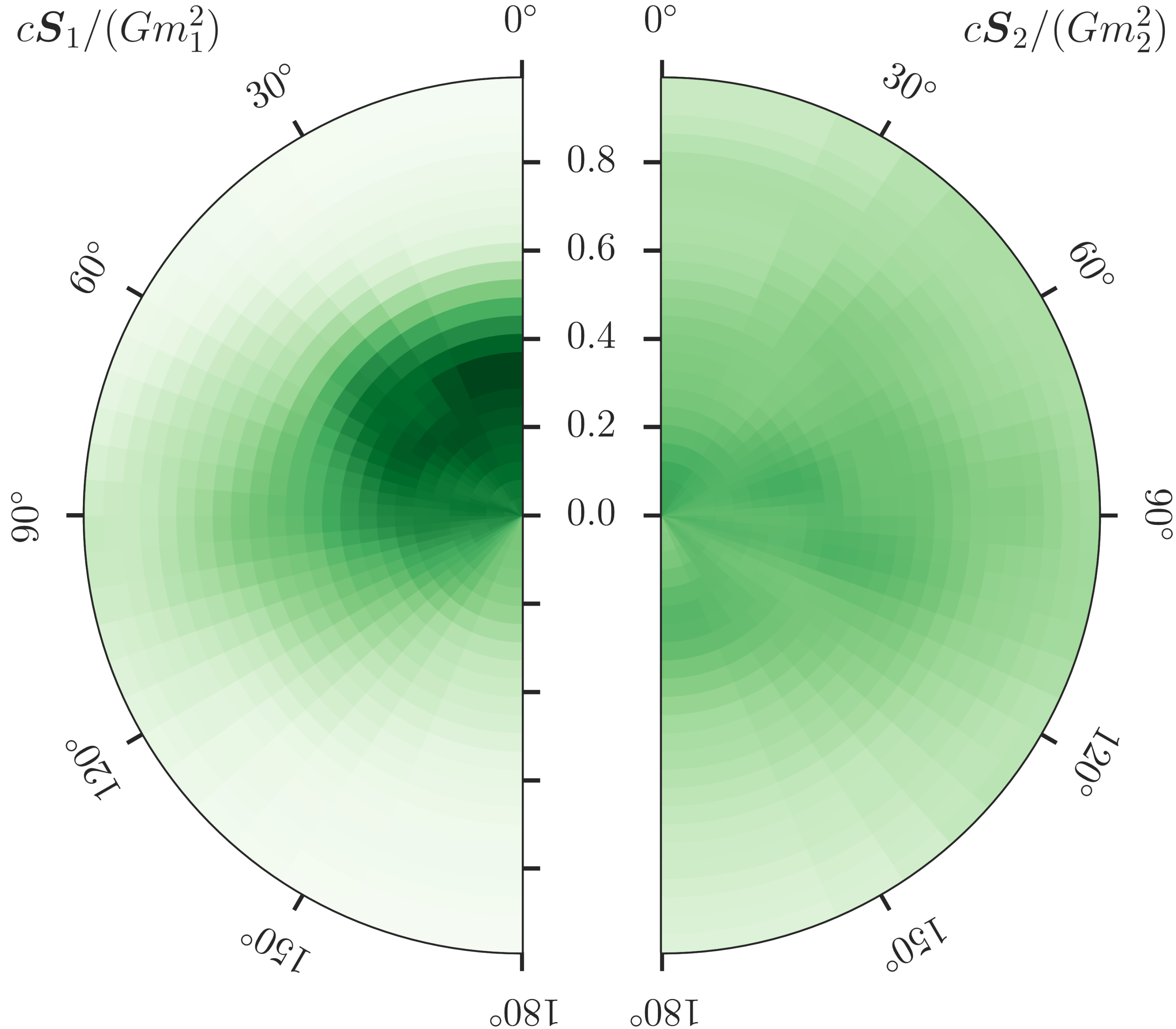


LVC
arXiv:1606.01210

Spin



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arXiv:1606.04856

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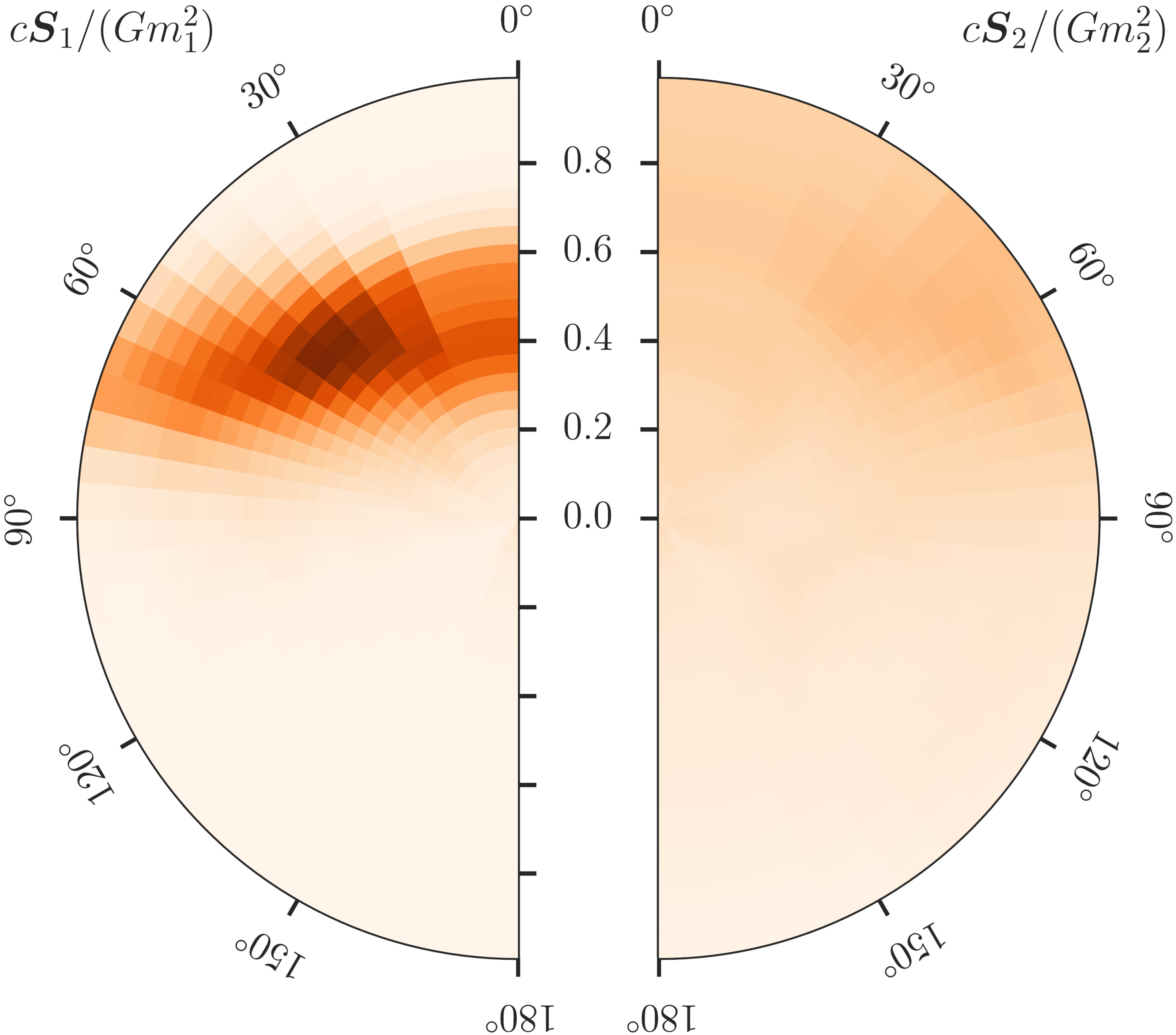

LVC
arXiv:1606.04855

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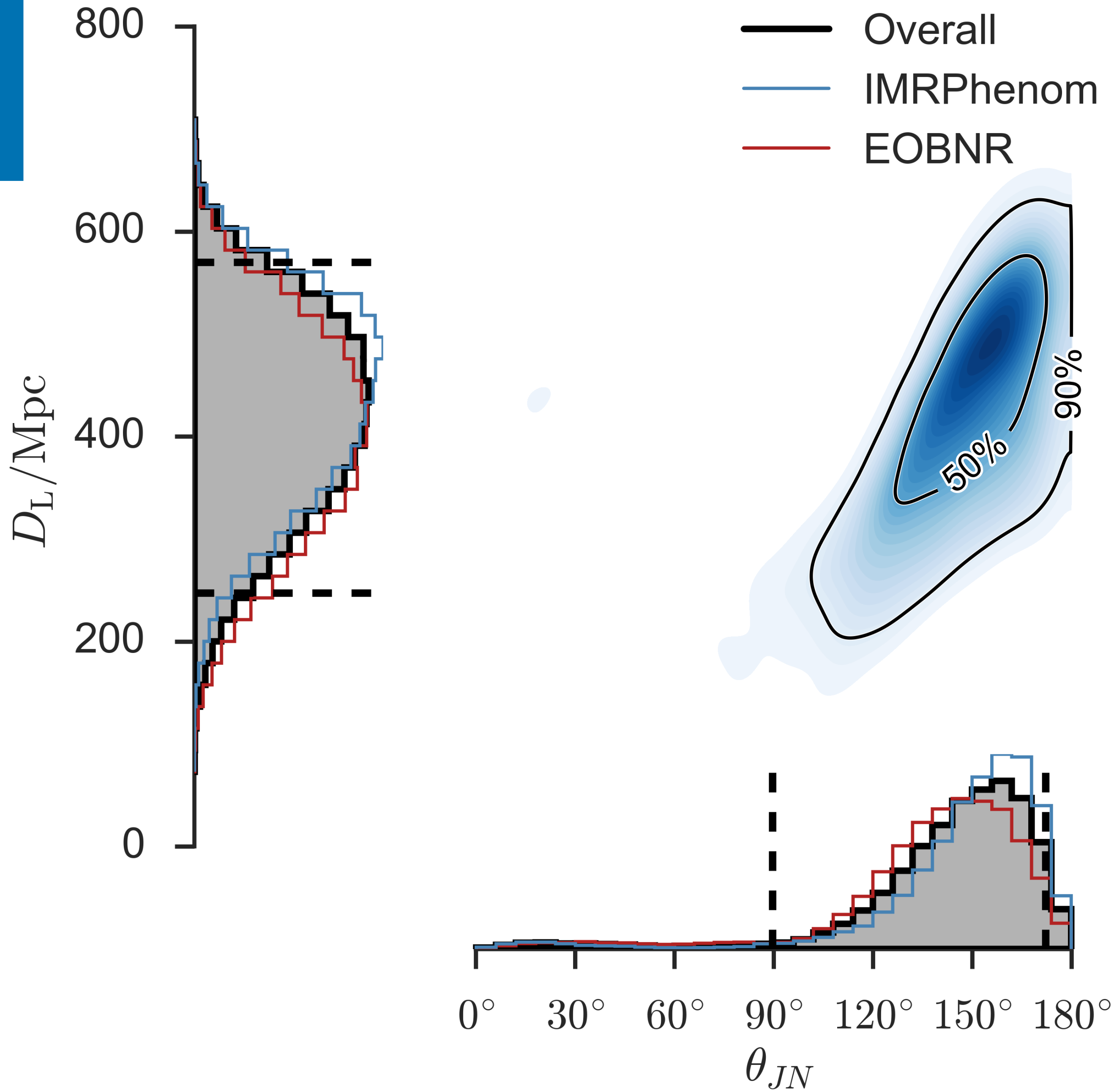

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arXiv:1606.04856
arXiv:1602.03840

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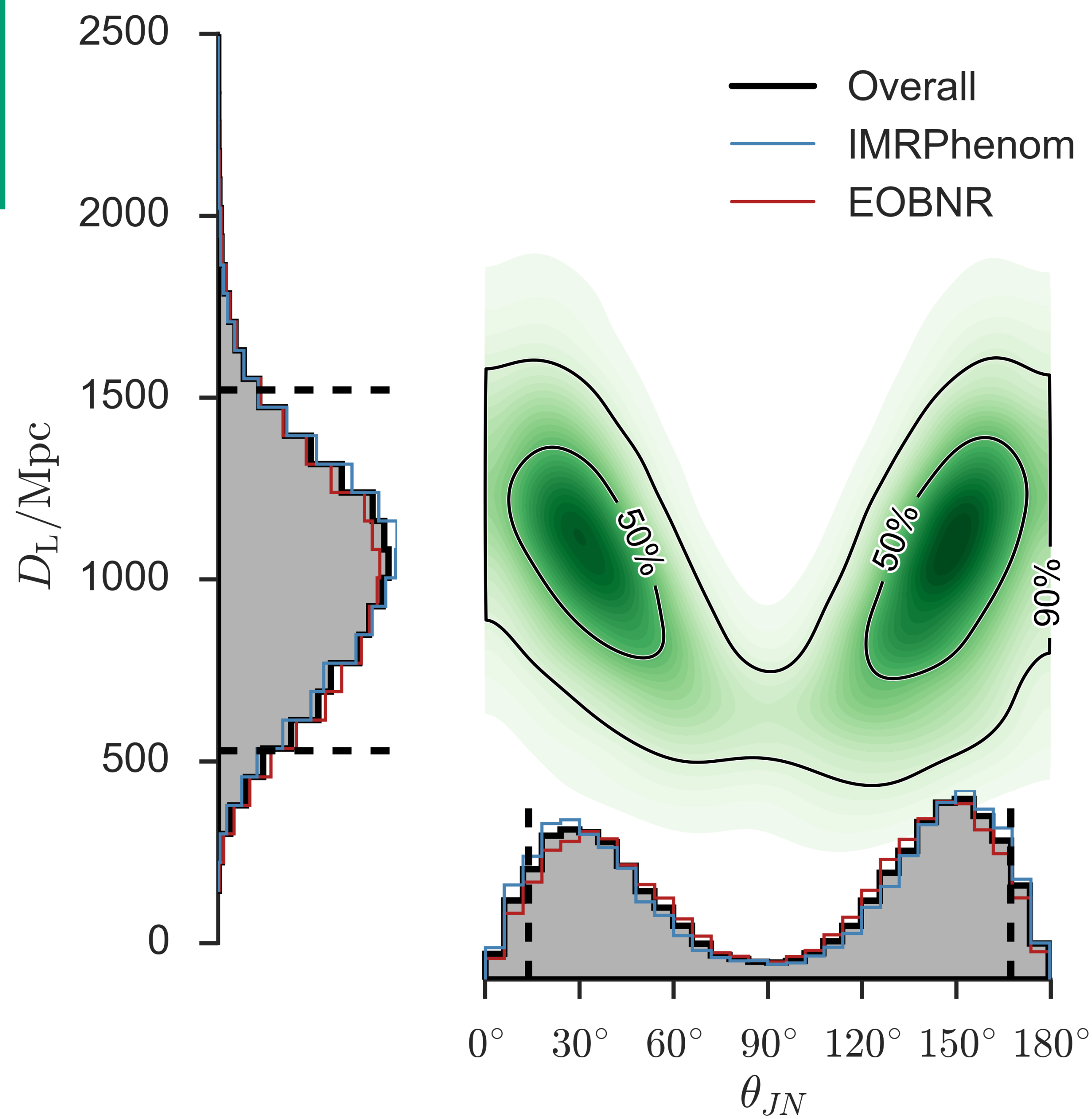

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arXiv:1606.04856

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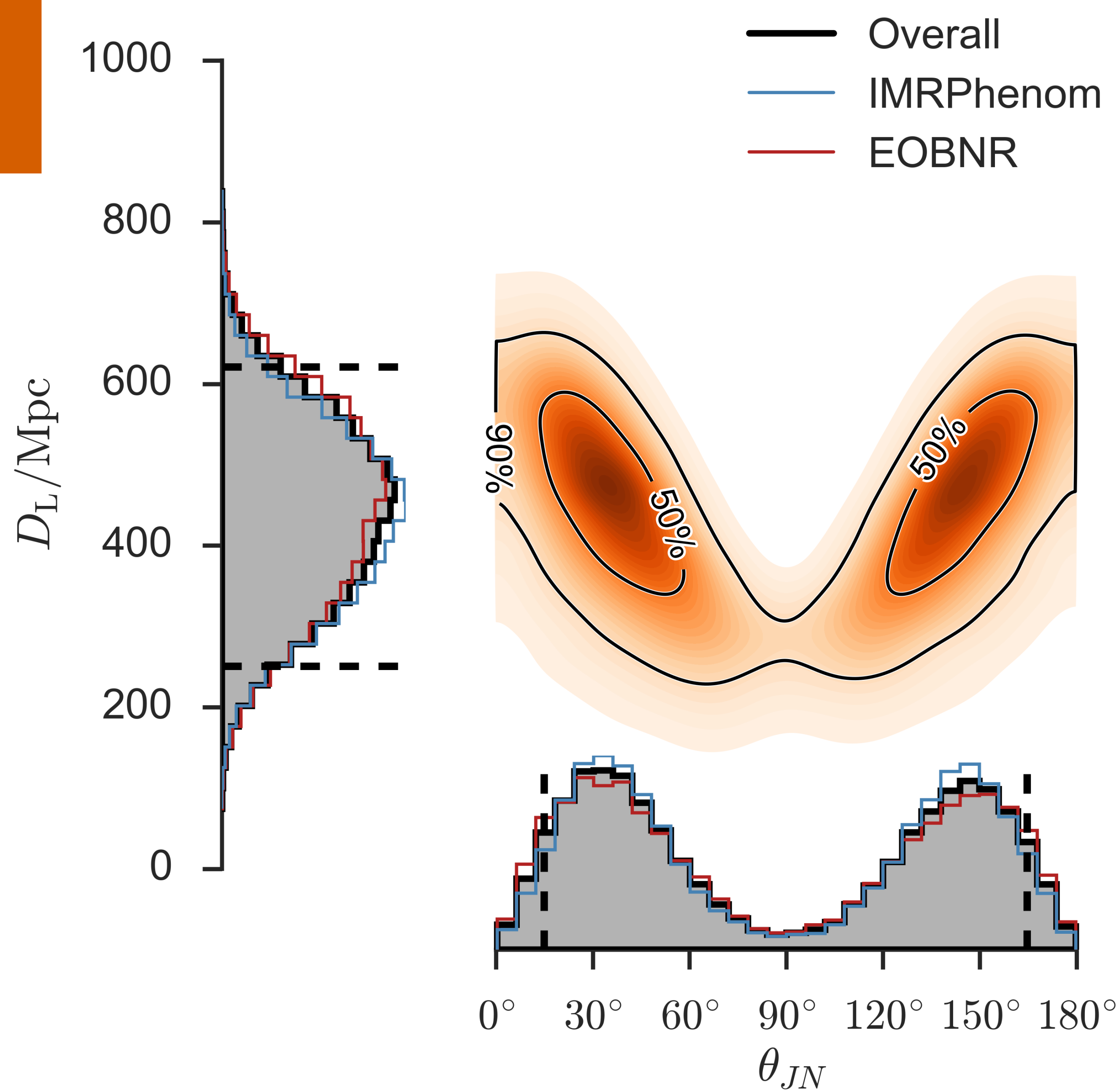

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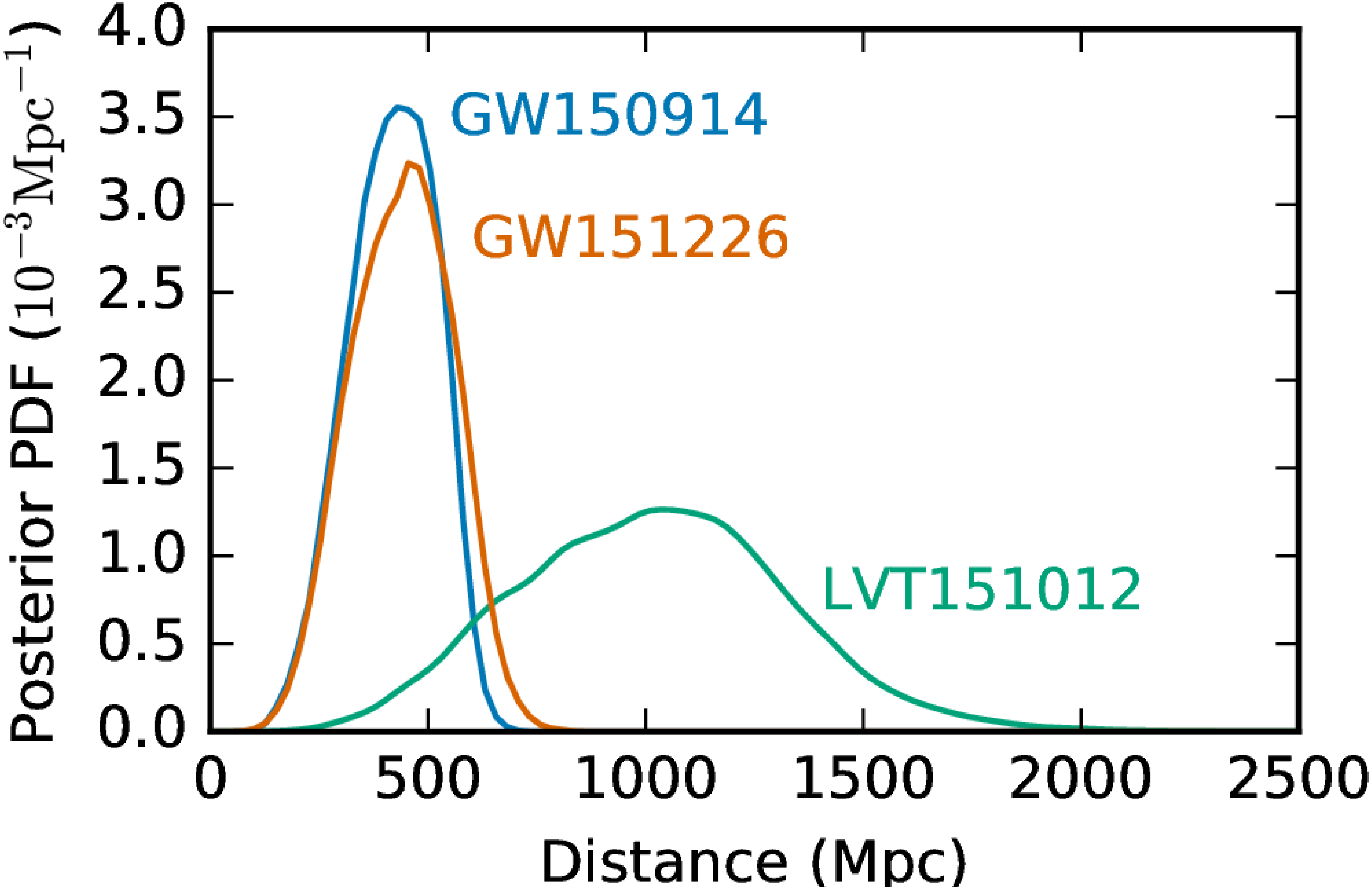

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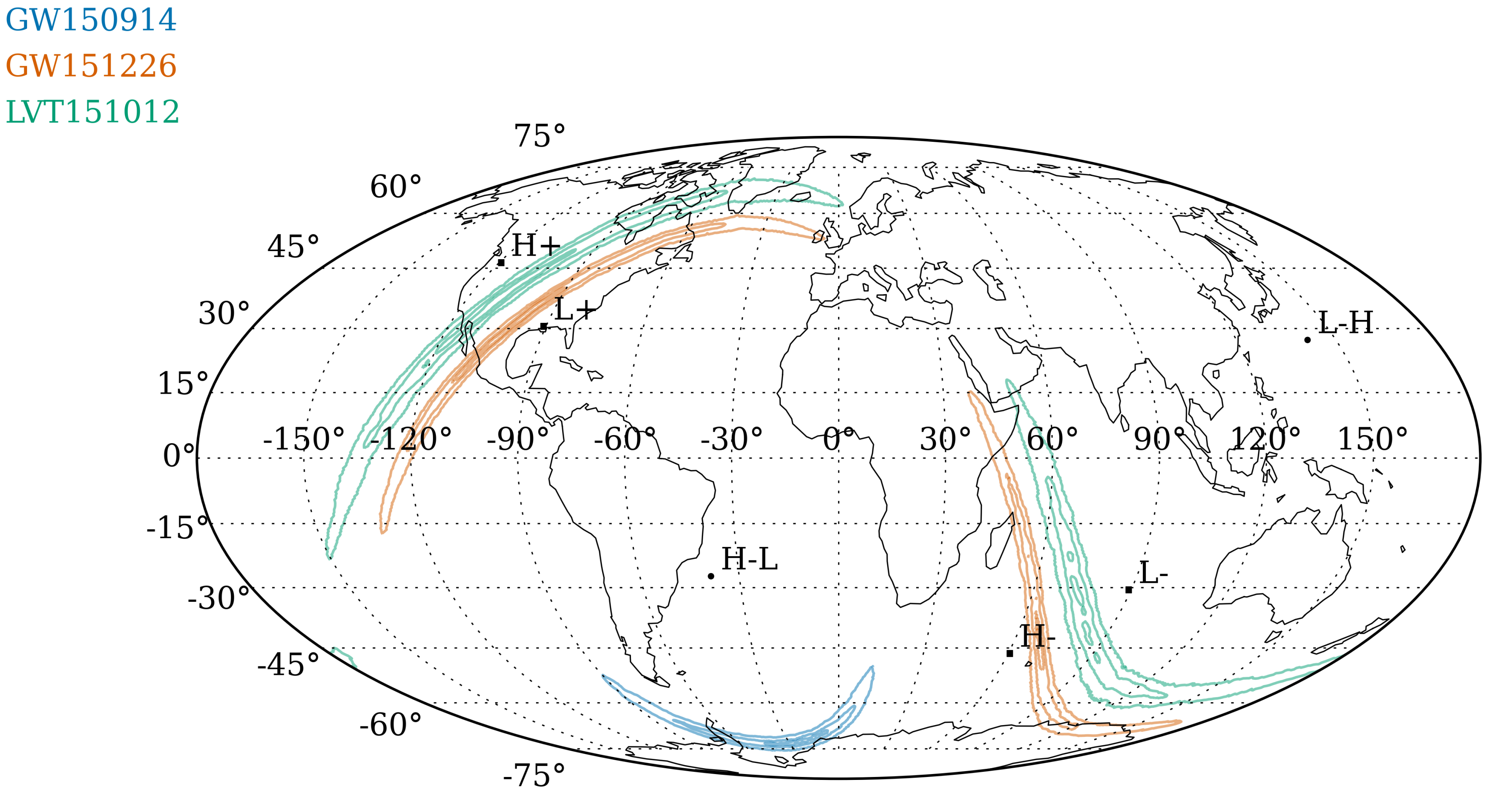

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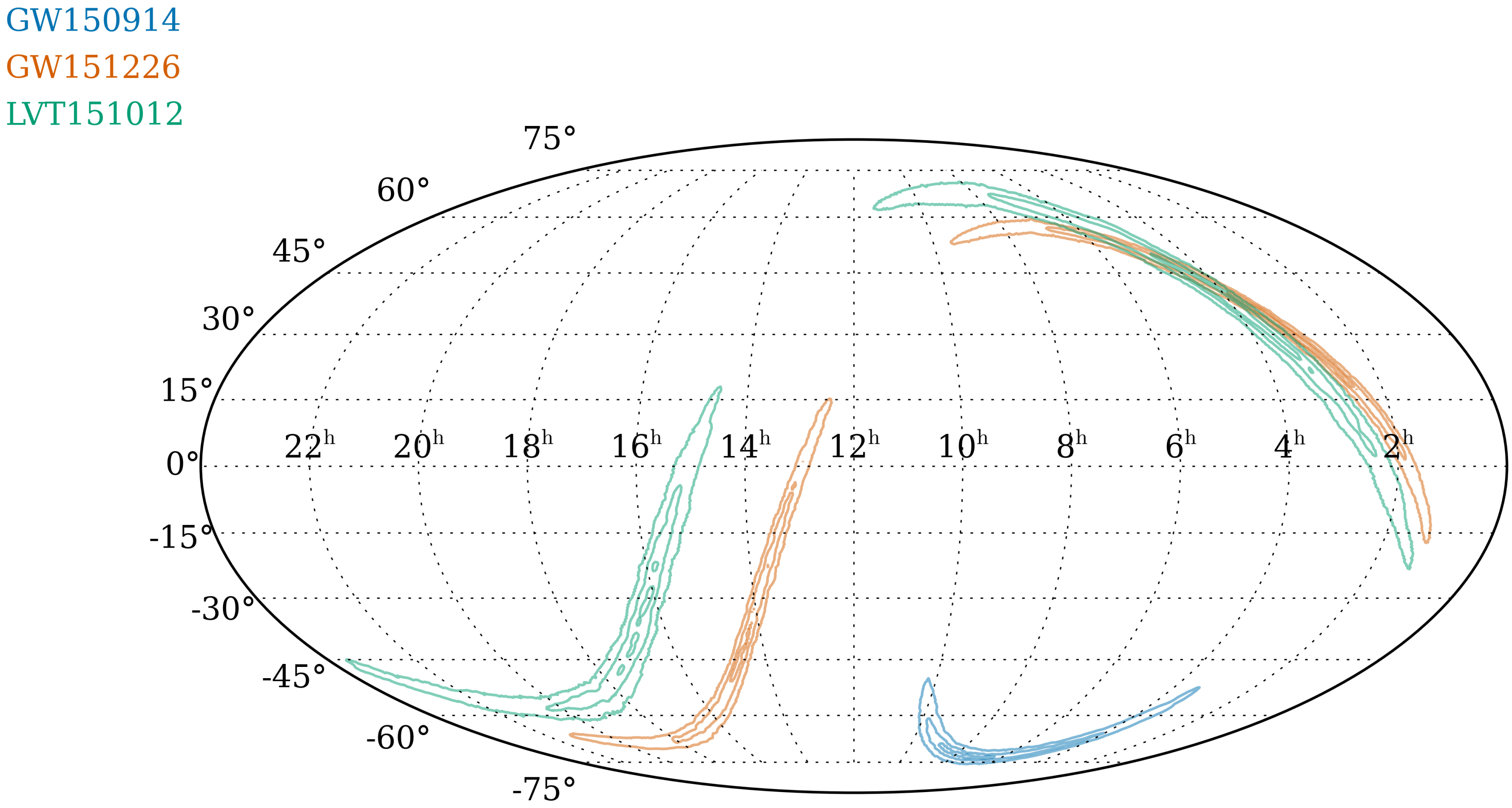
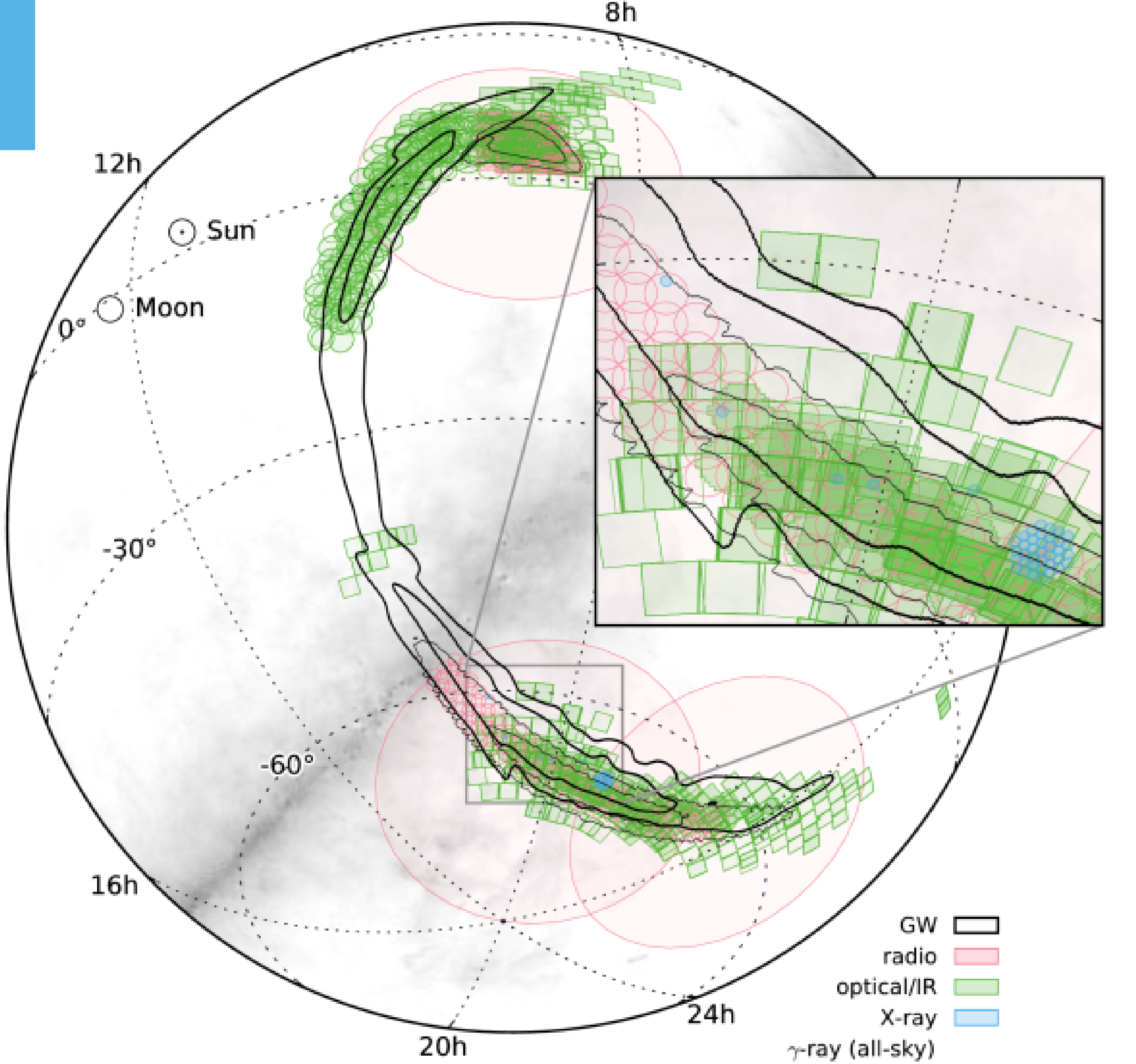


LVC arXiv:1606.04856

Follow-up



LVC
arXiv:1602.08492
arXiv:1604.07864

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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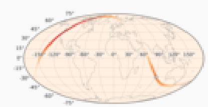
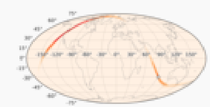
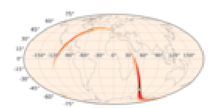
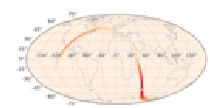
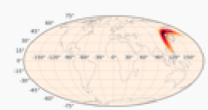
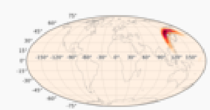
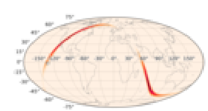
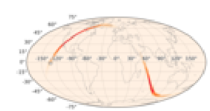
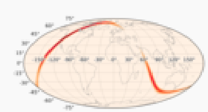
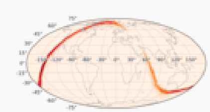
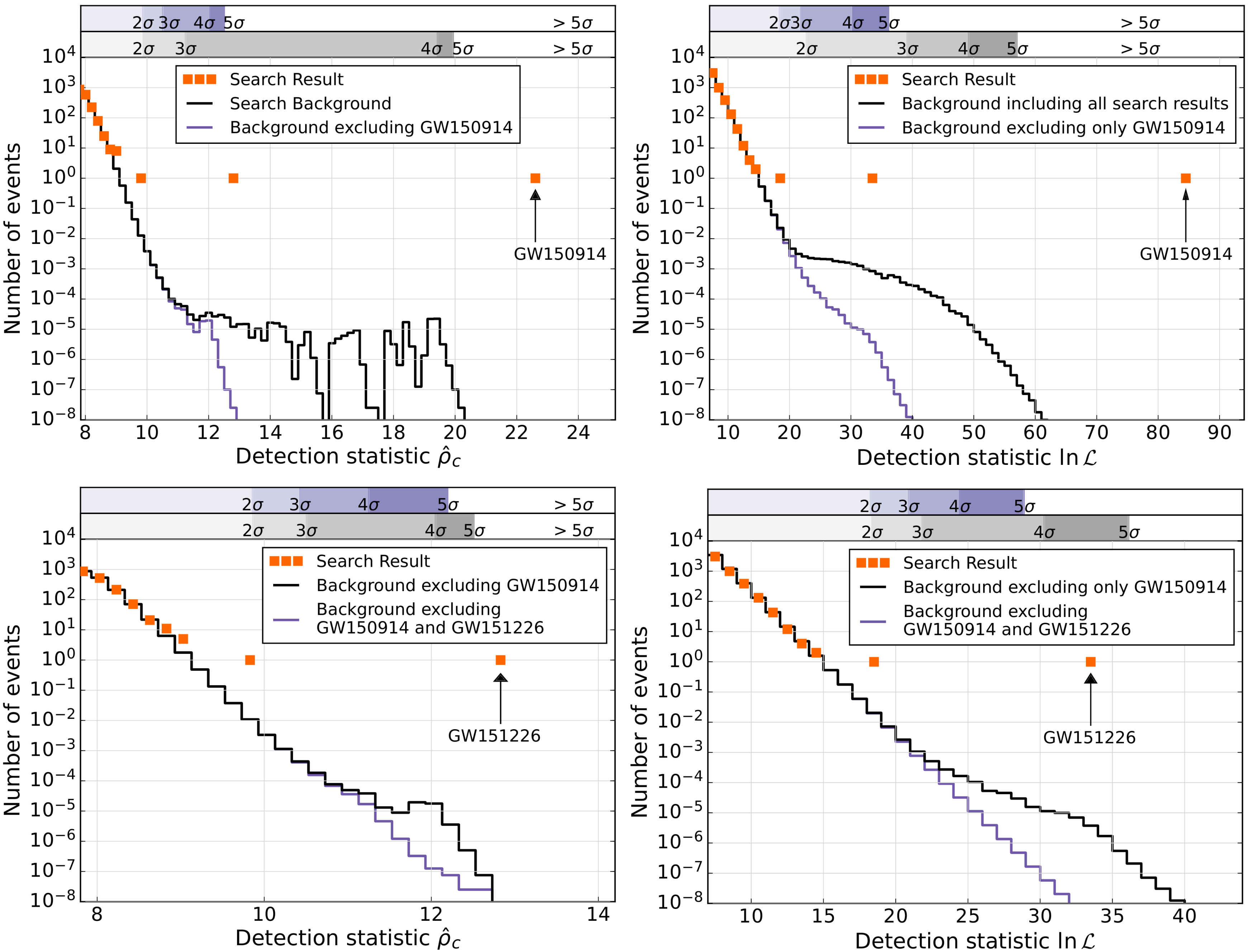
additional online r
related to the pap
Two Years of Ele
Follow-Up with Ac
and Virgo" and th
paper "Parameter
for Binary Neutron
Coalescences wit

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		

LVC arXiv:1606.04856 arXiv:1607.07456

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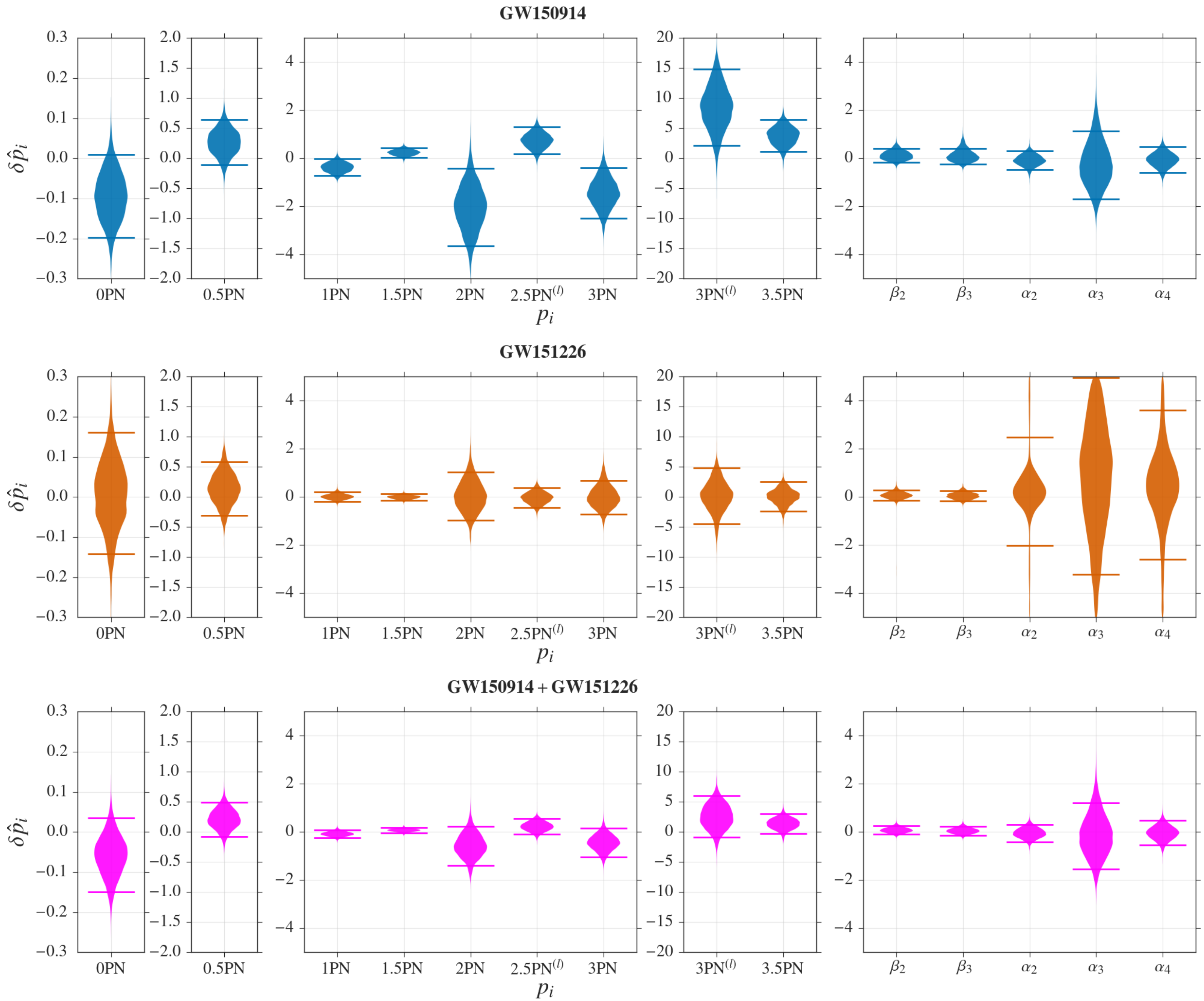
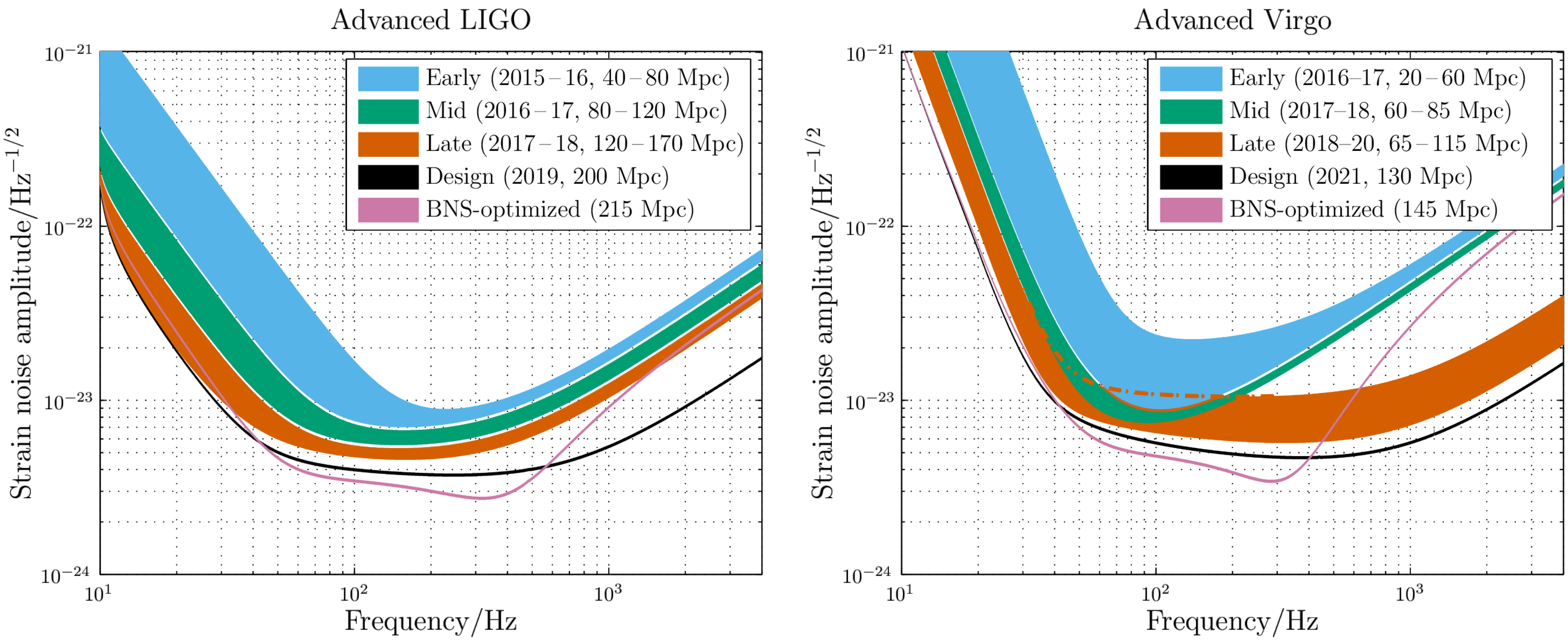
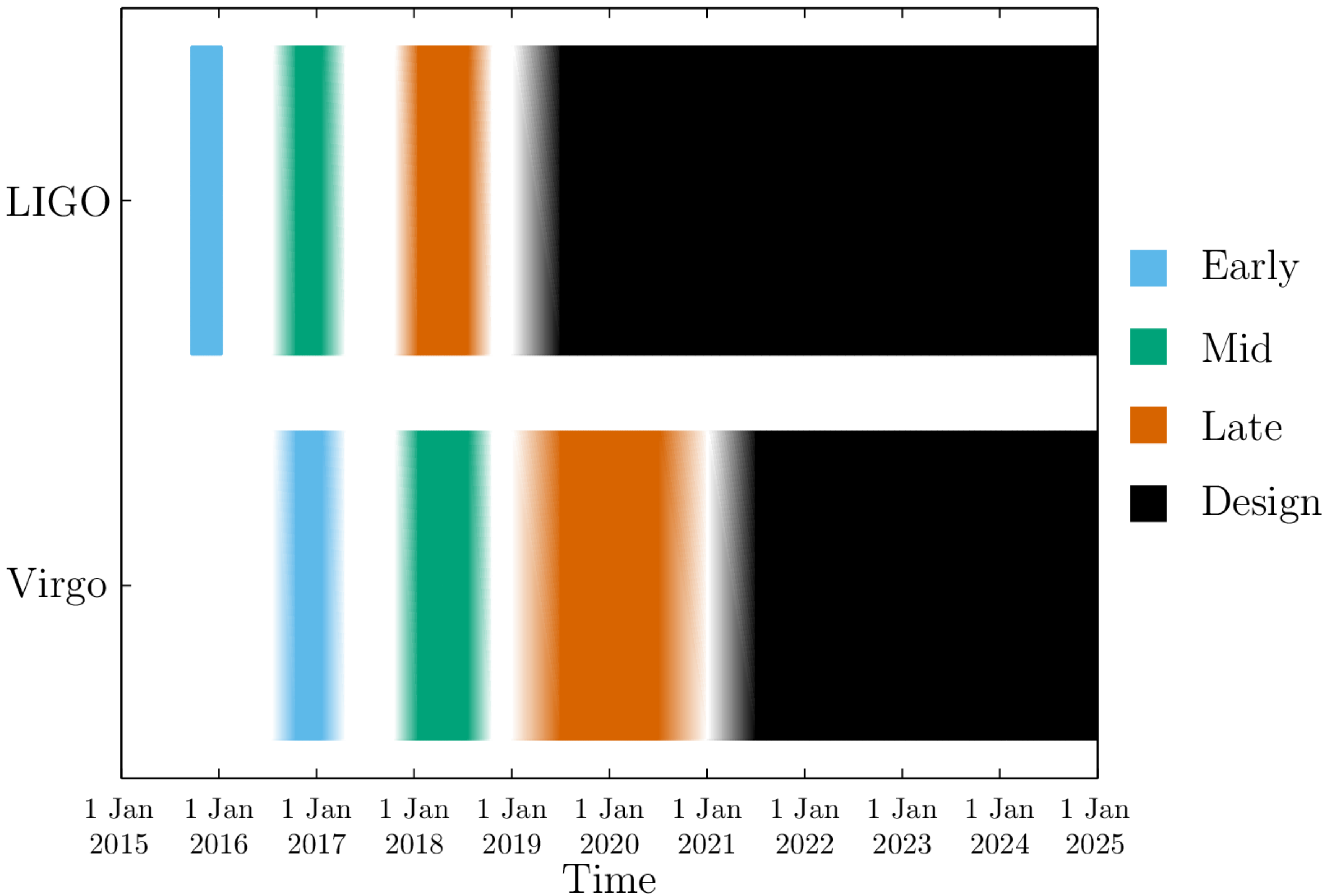
LVC arXiv:1606.04856 arXiv:1602.03841



Future observing runs



LVC arXiv:1303.0670



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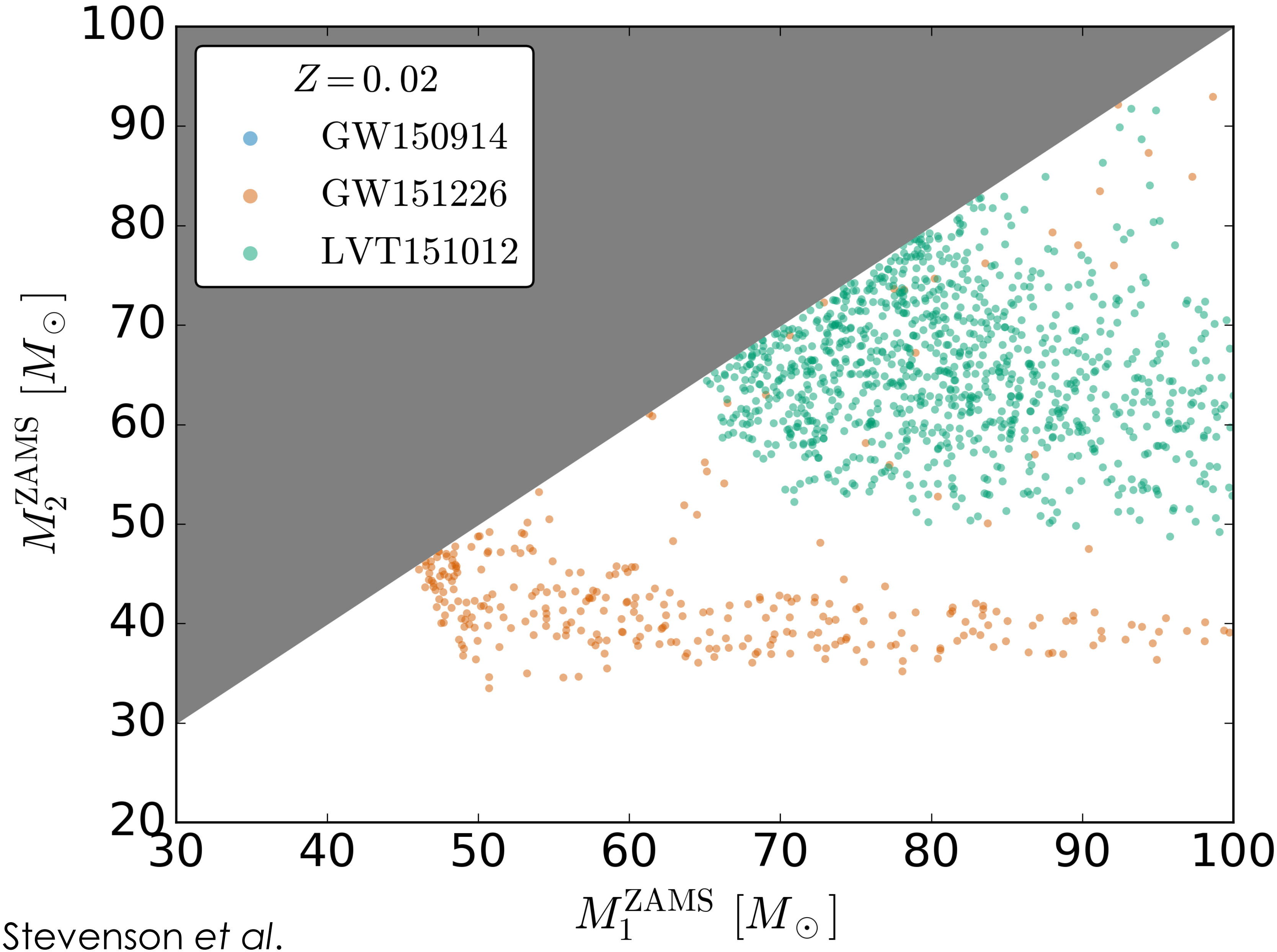
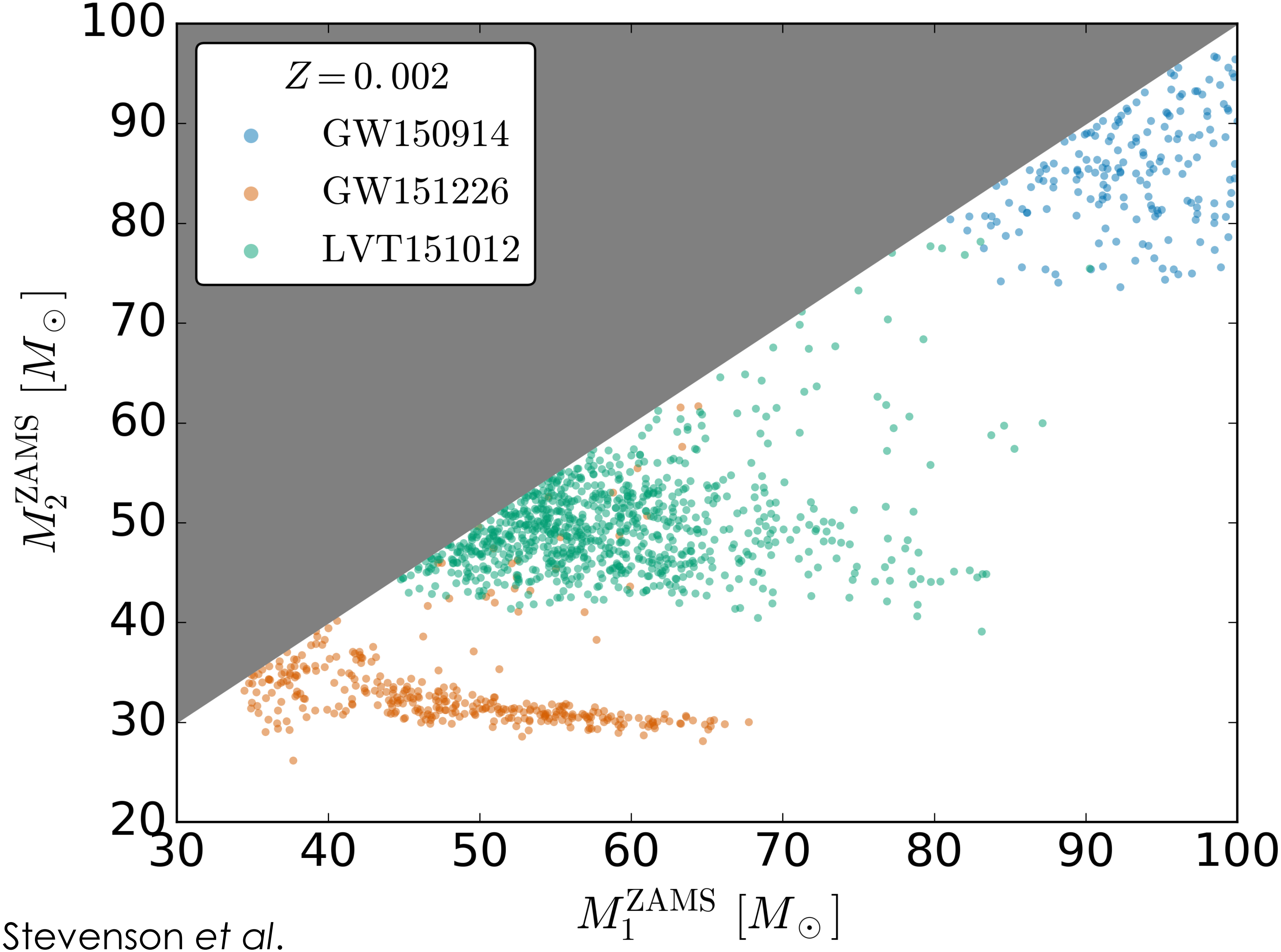


Stevenson *et al.*



Stevenson et al.

losc.ligo.org/events/
papers.ligo.org/