



UNIVERSITY OF
BIRMINGHAM



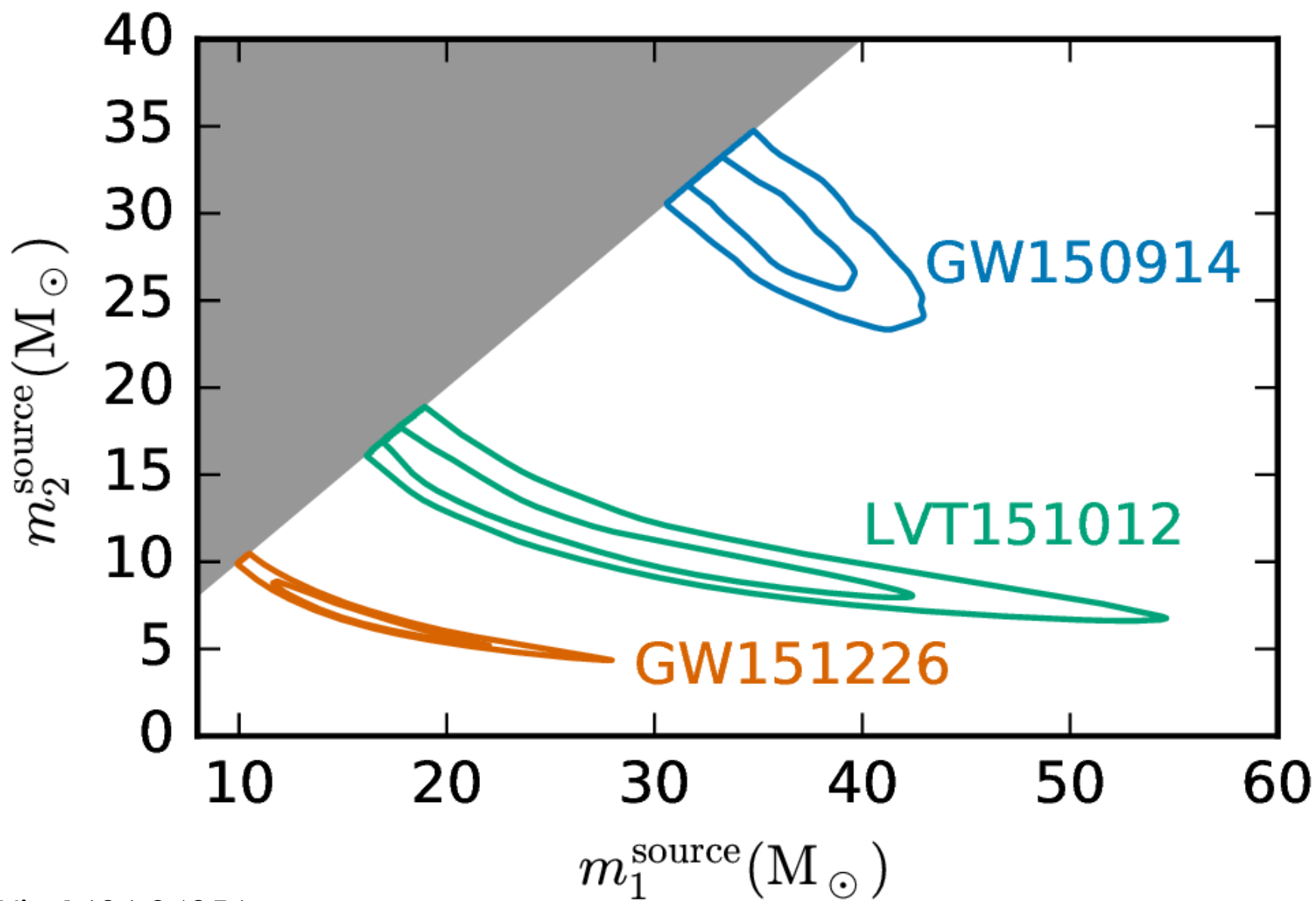
Black hole observations from Advanced LIGO

Christopher Berry

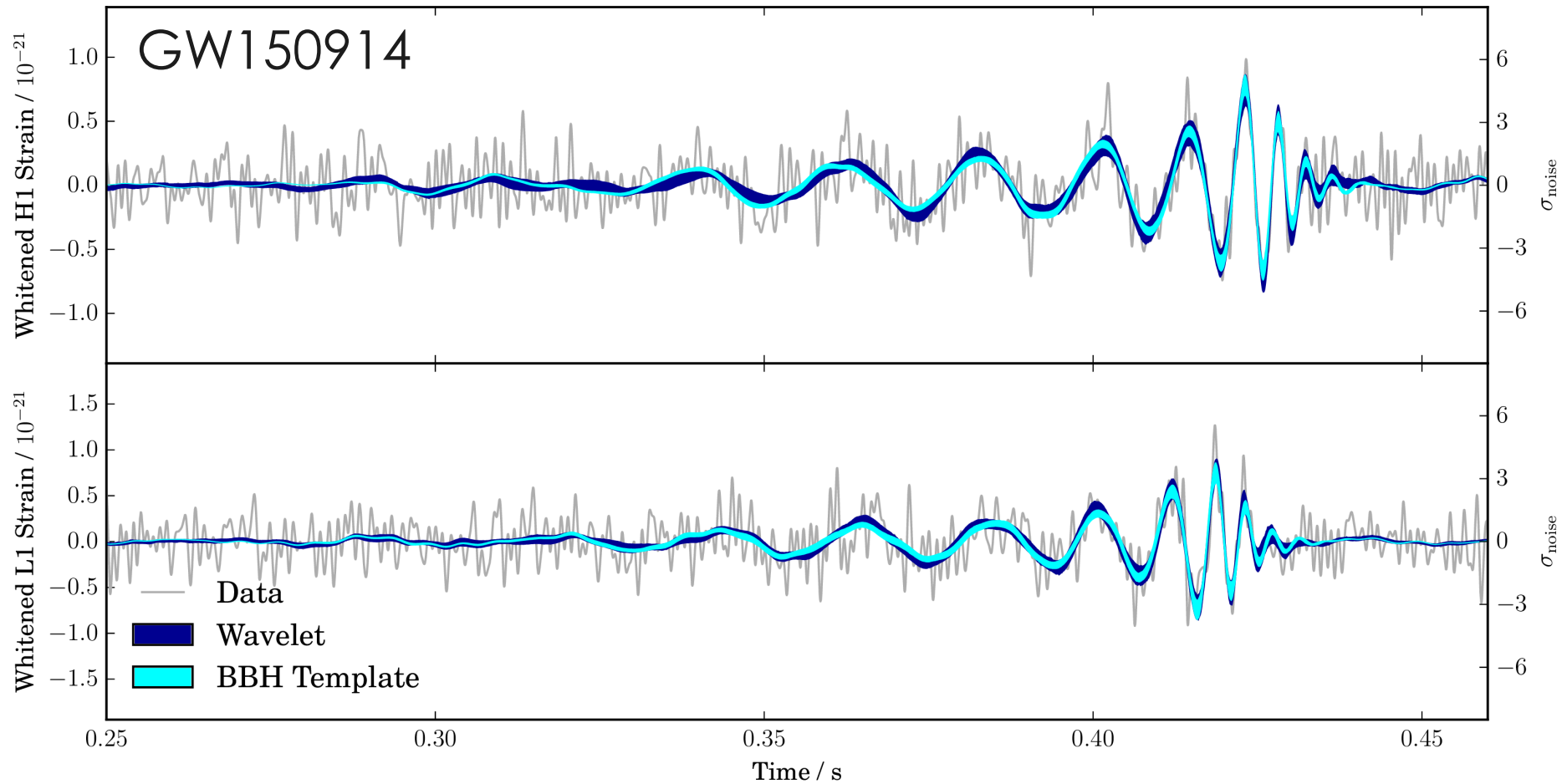
University of Birmingham
cplb@star.sr.bham.ac.uk
@cplberry

On behalf of the
LIGO Scientific & Virgo Collaborations
DCC G1600868

27 June 2016, NAM2016

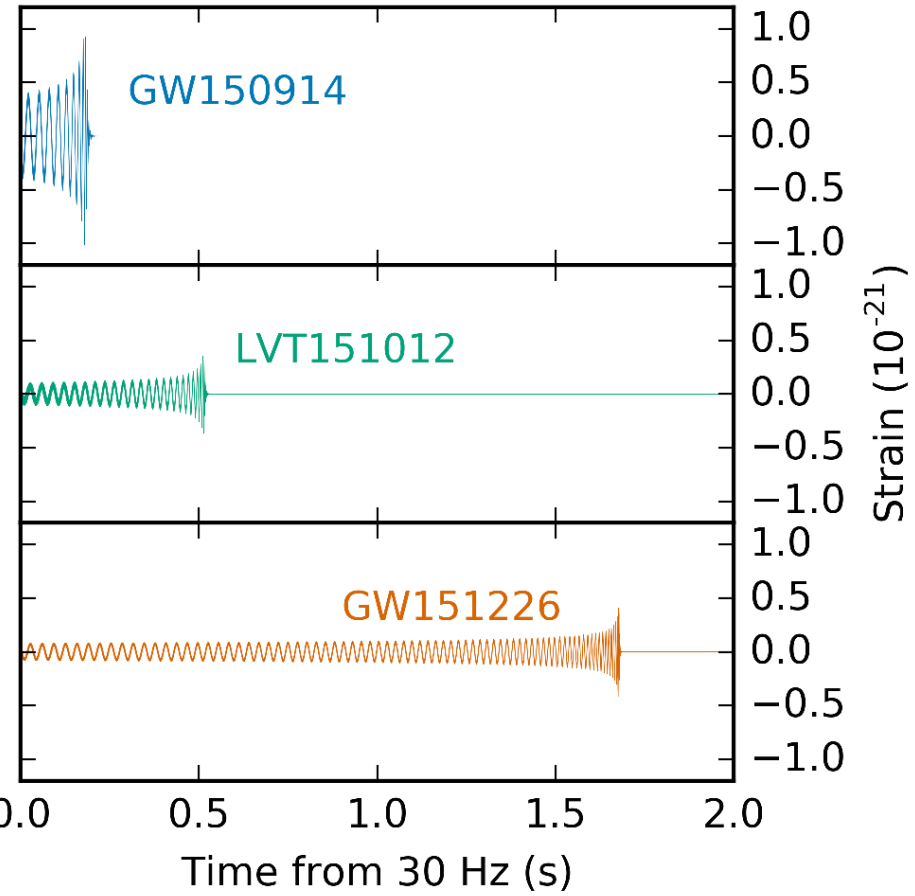
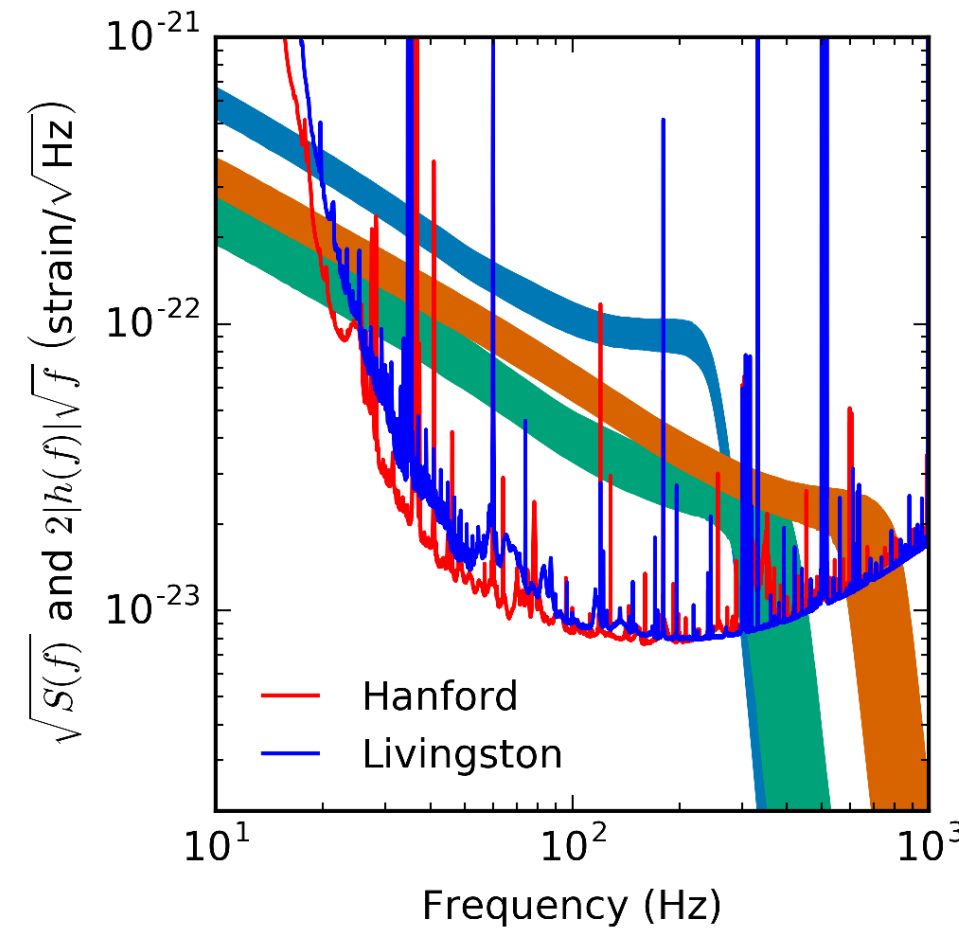


Waveform

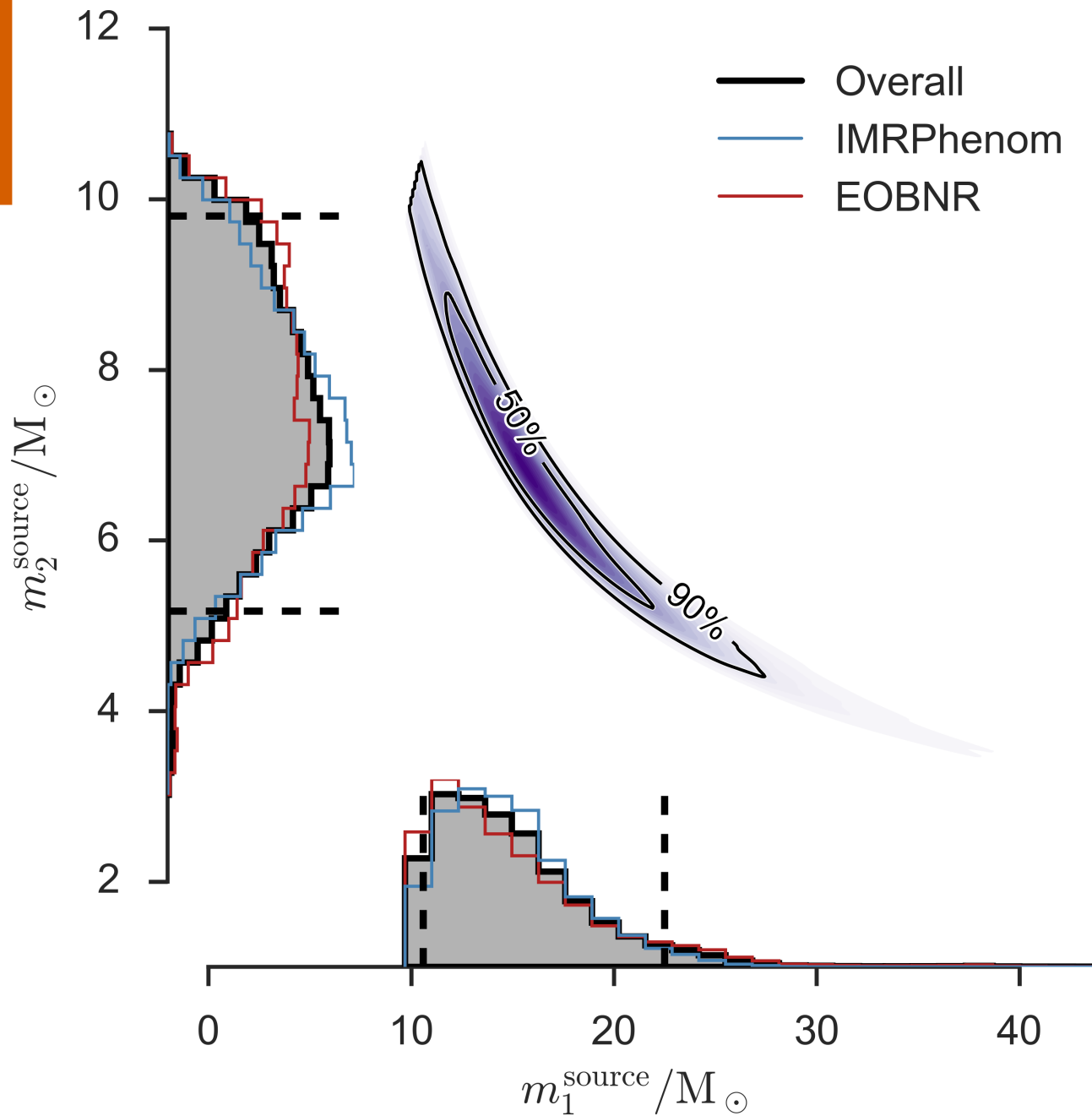


arXiv:1602.03840

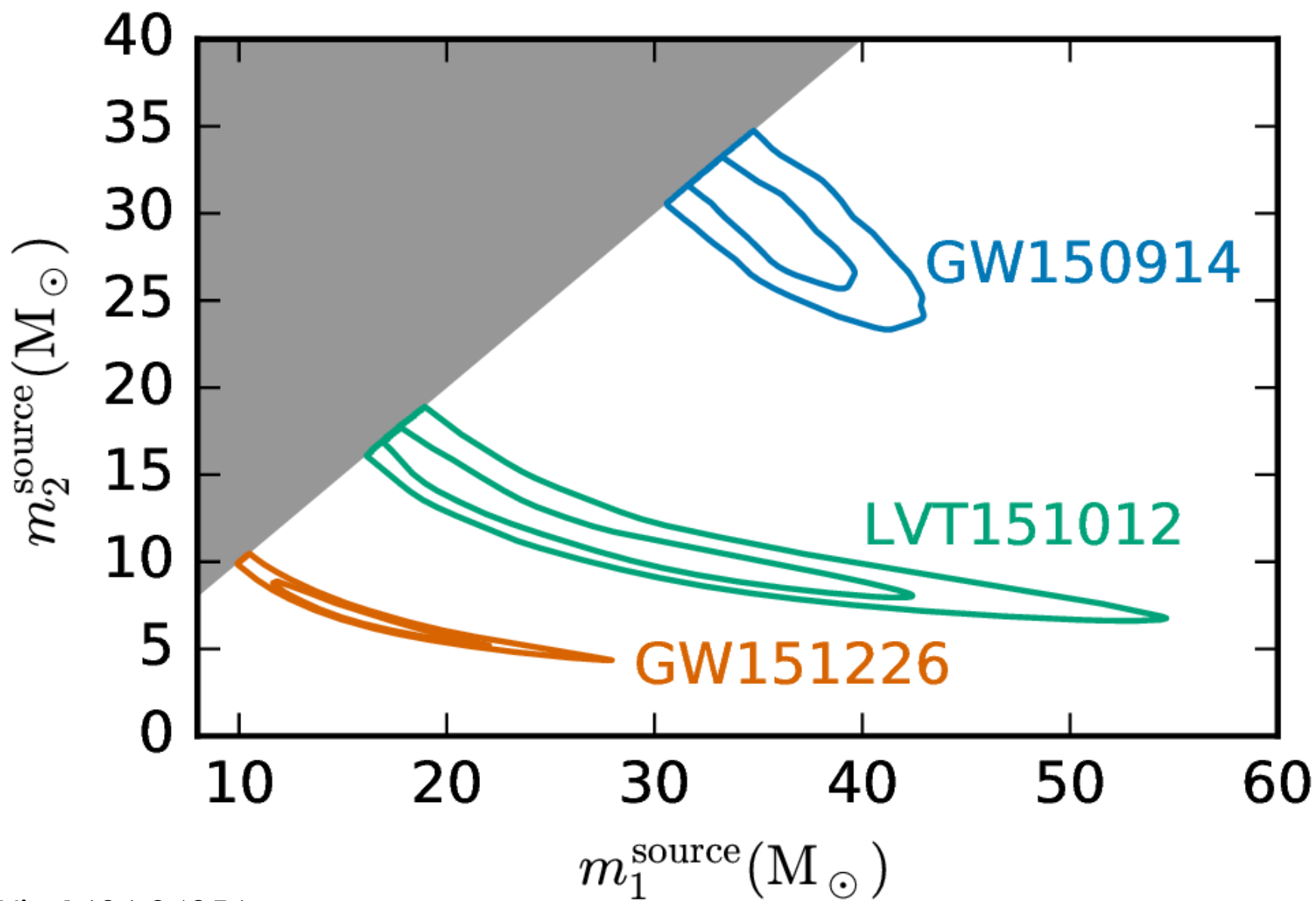
Waveforms



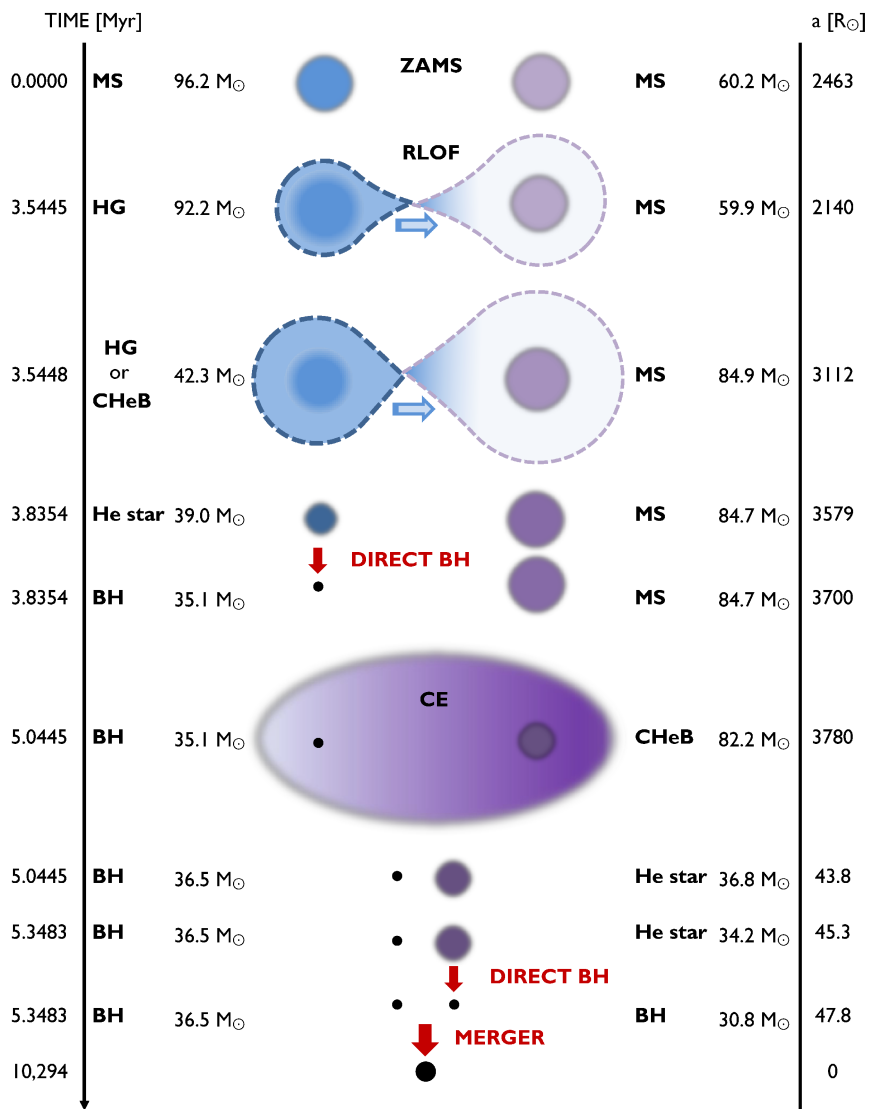
Masses



arXiv:1606.04855

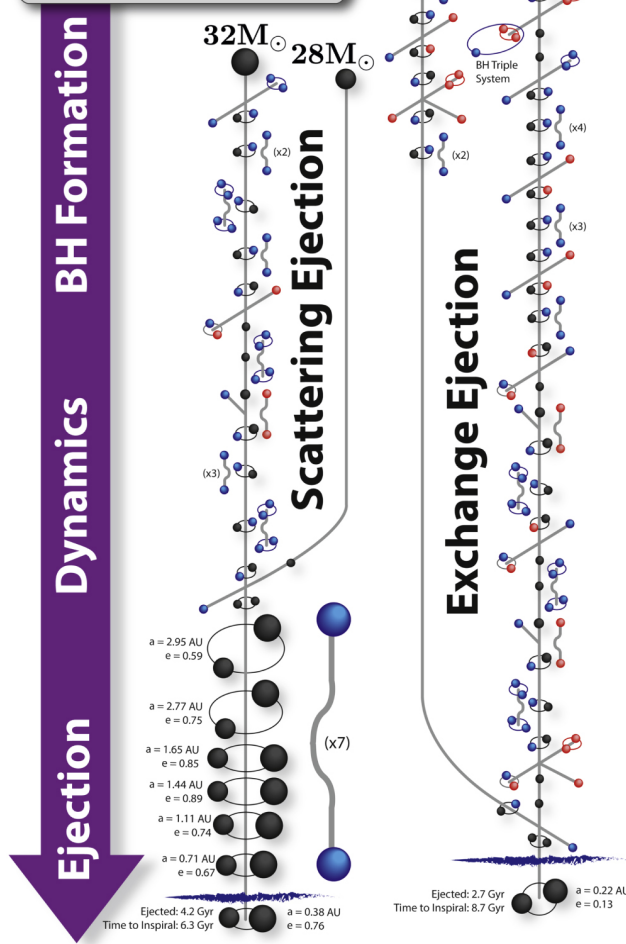
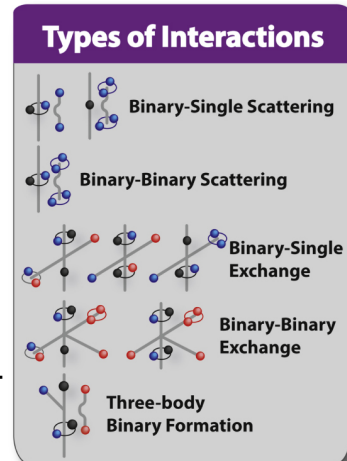


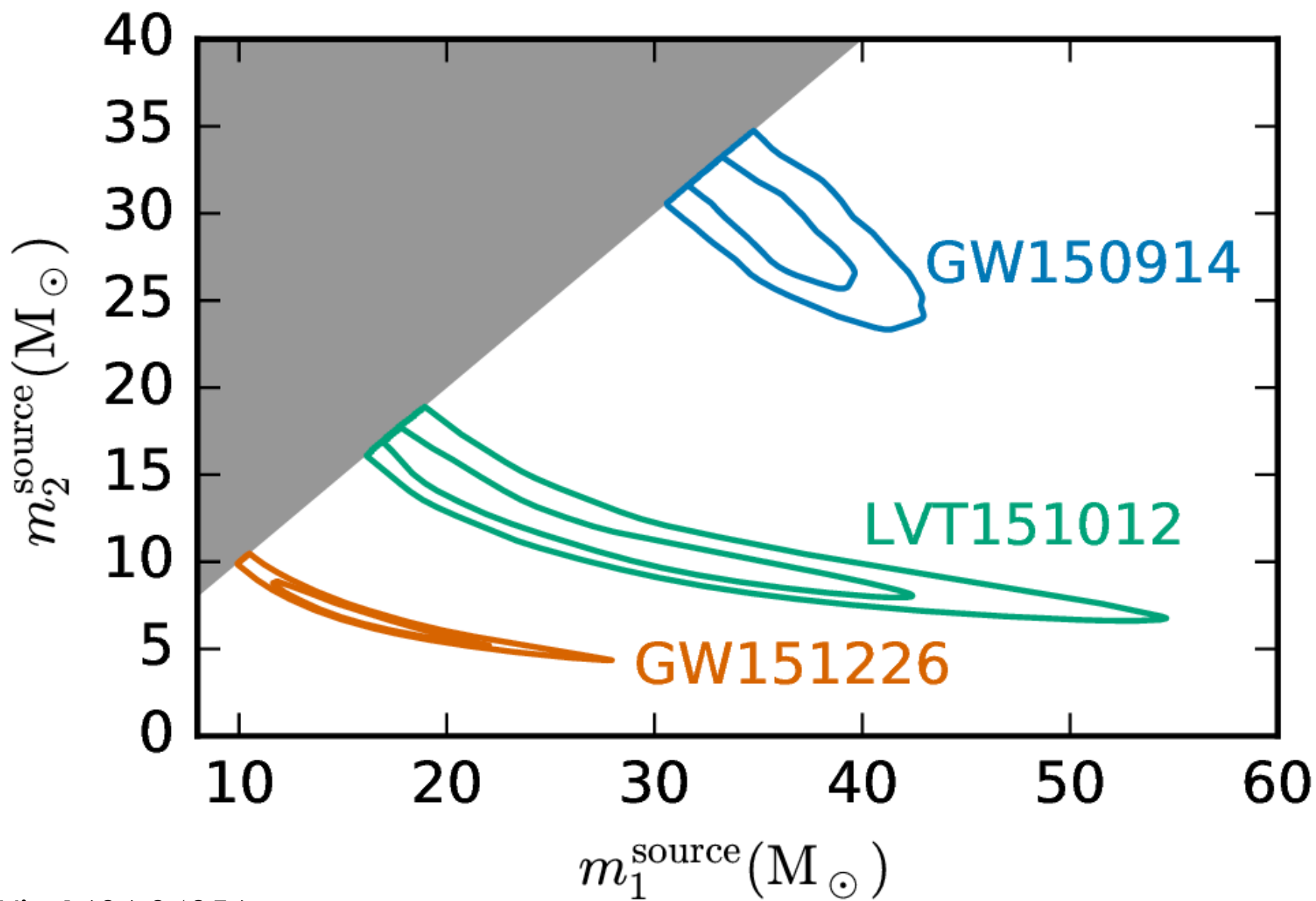
Binary formation

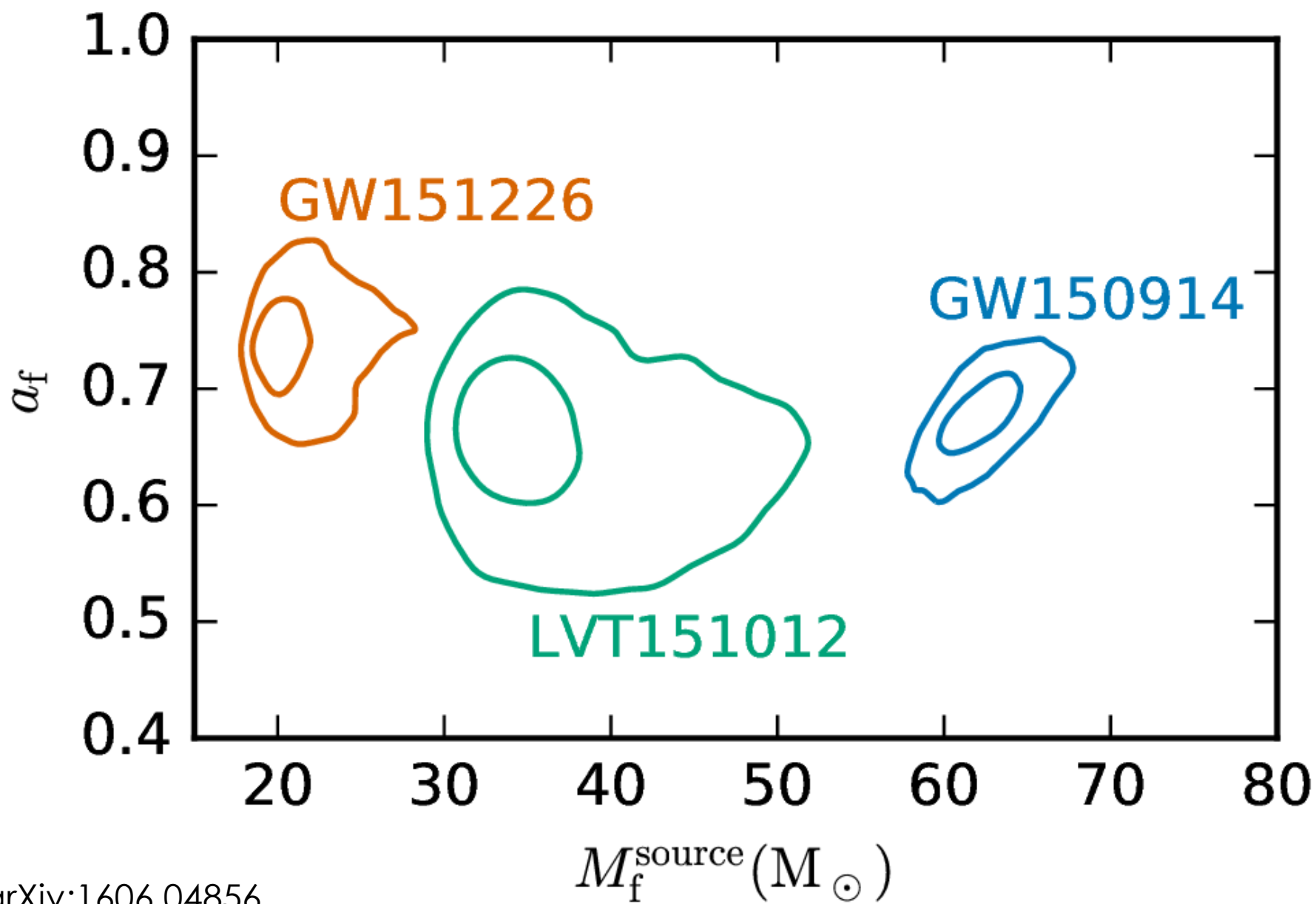


arXiv:1604.04254

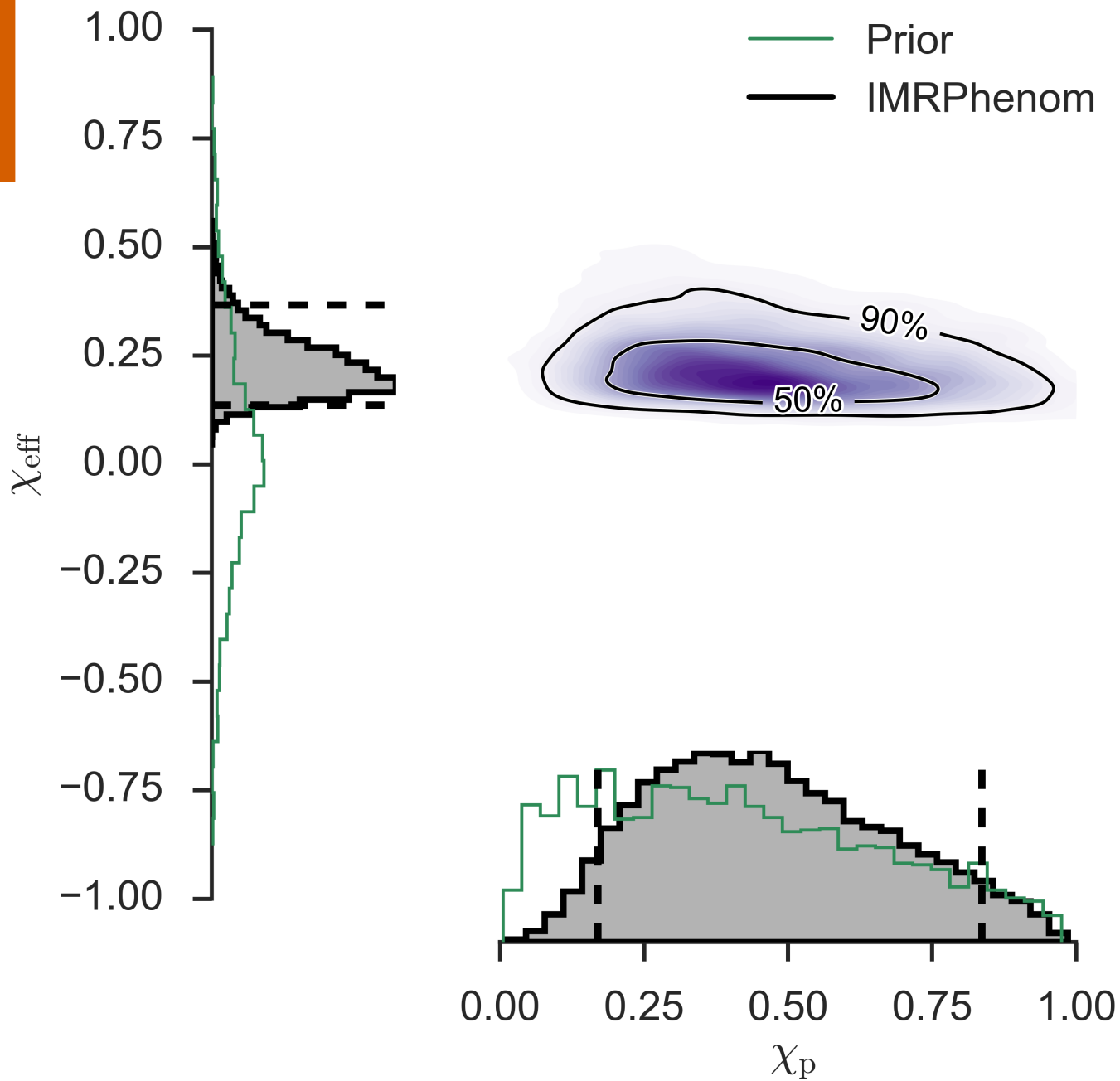
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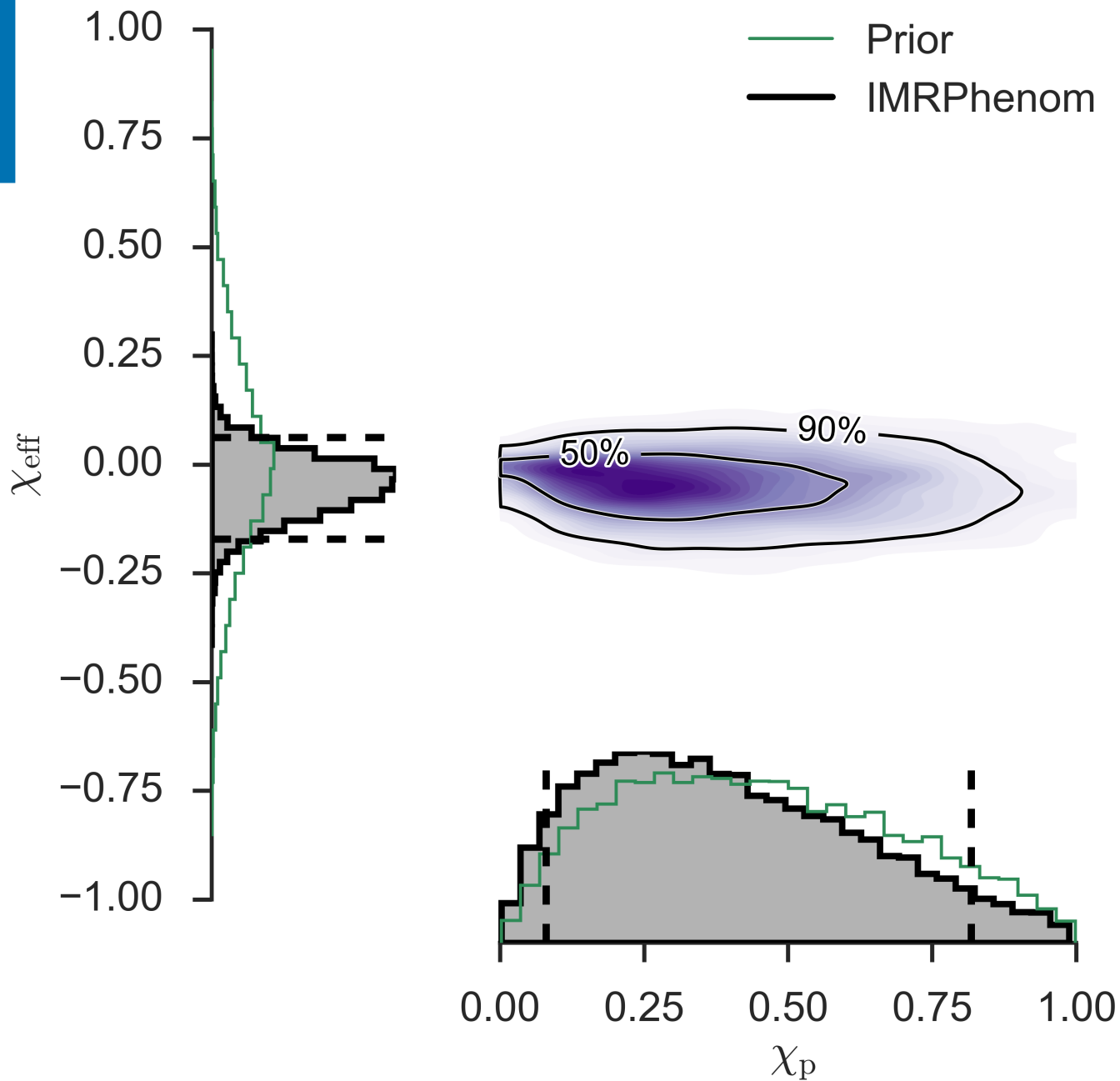




Spin

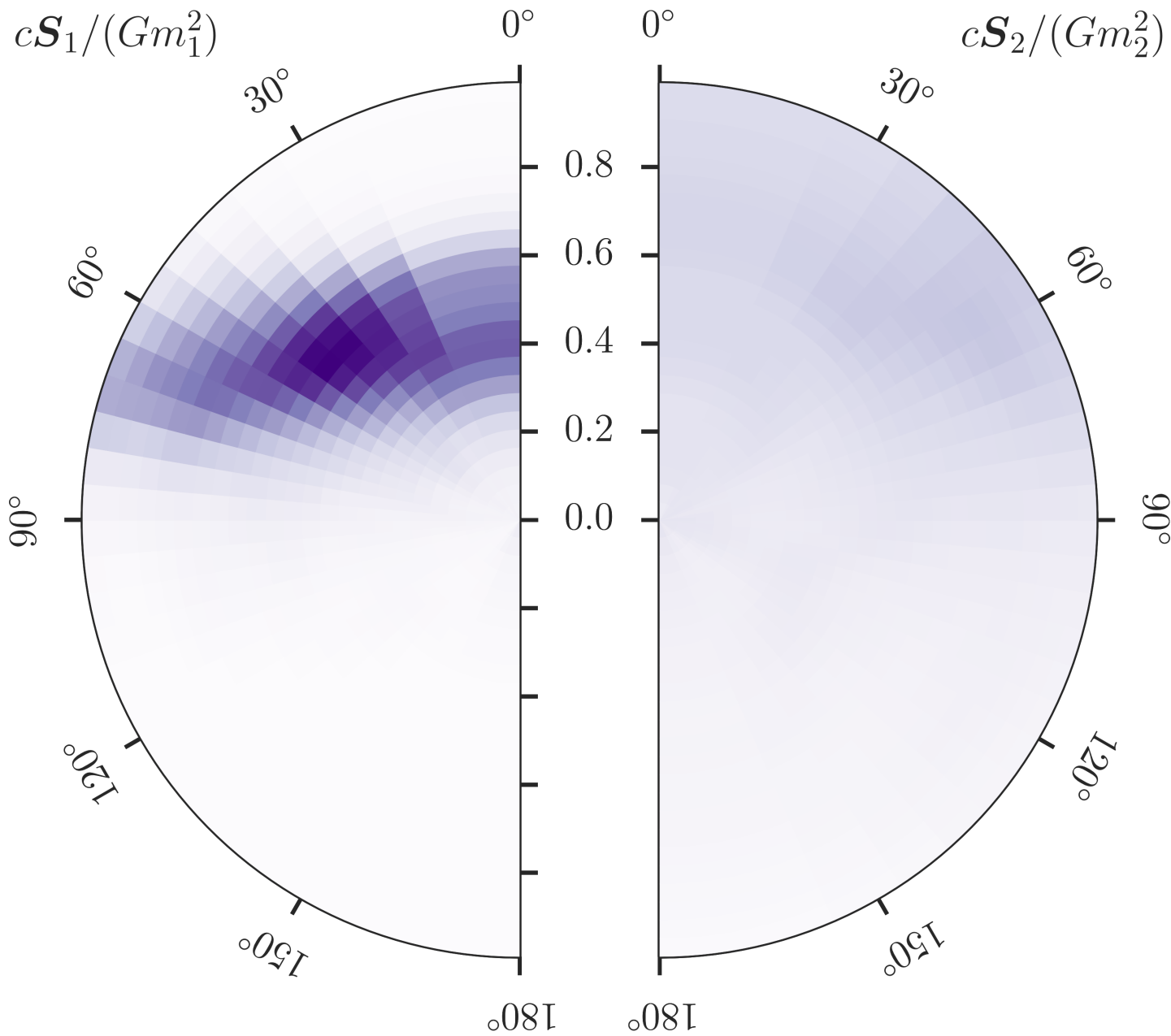


Spin

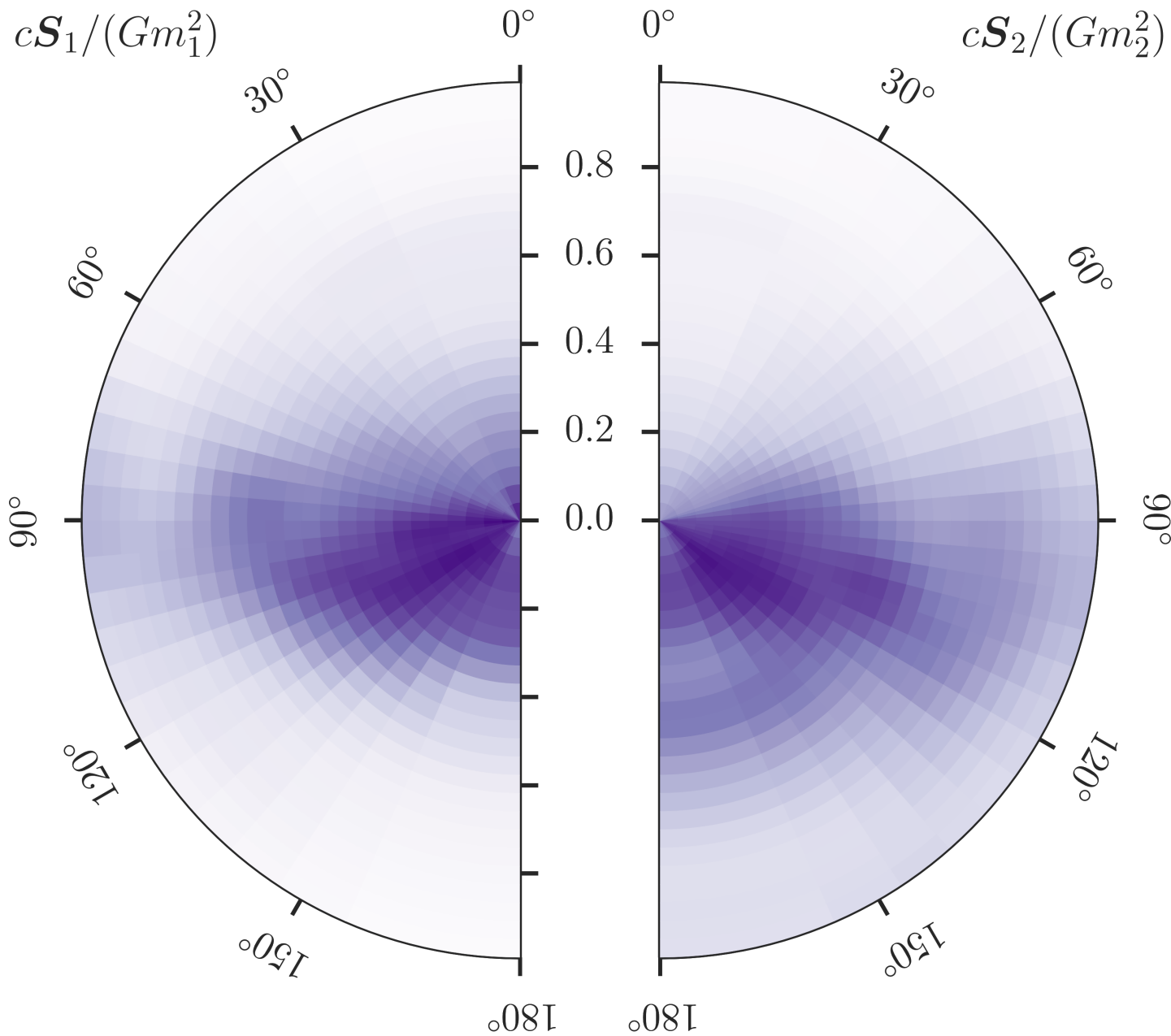


arXiv:1606.04856
arXiv:1602.03840

Spin

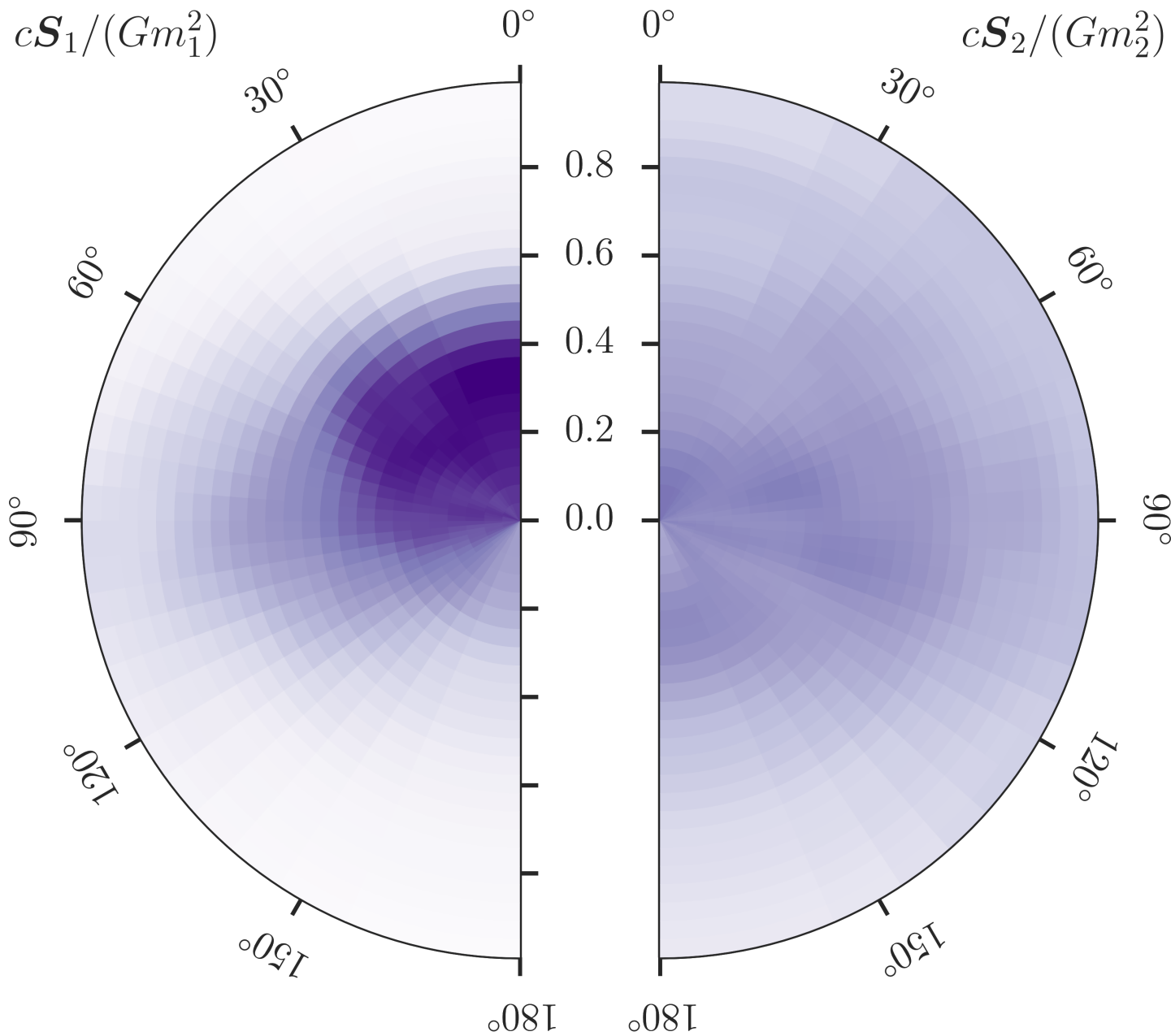


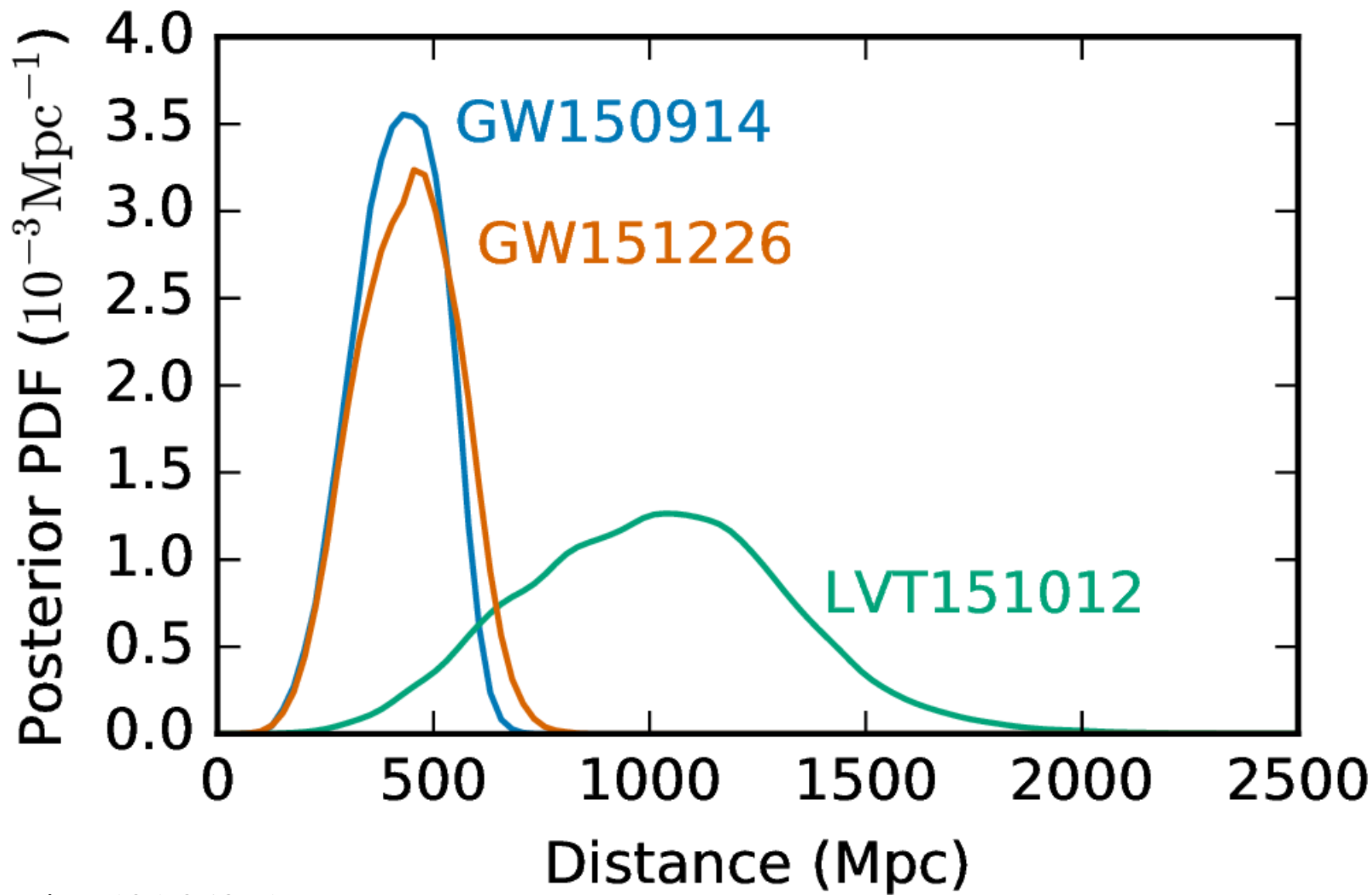
Spin



arXiv:1606.04856
arXiv:1602.03840

Spin

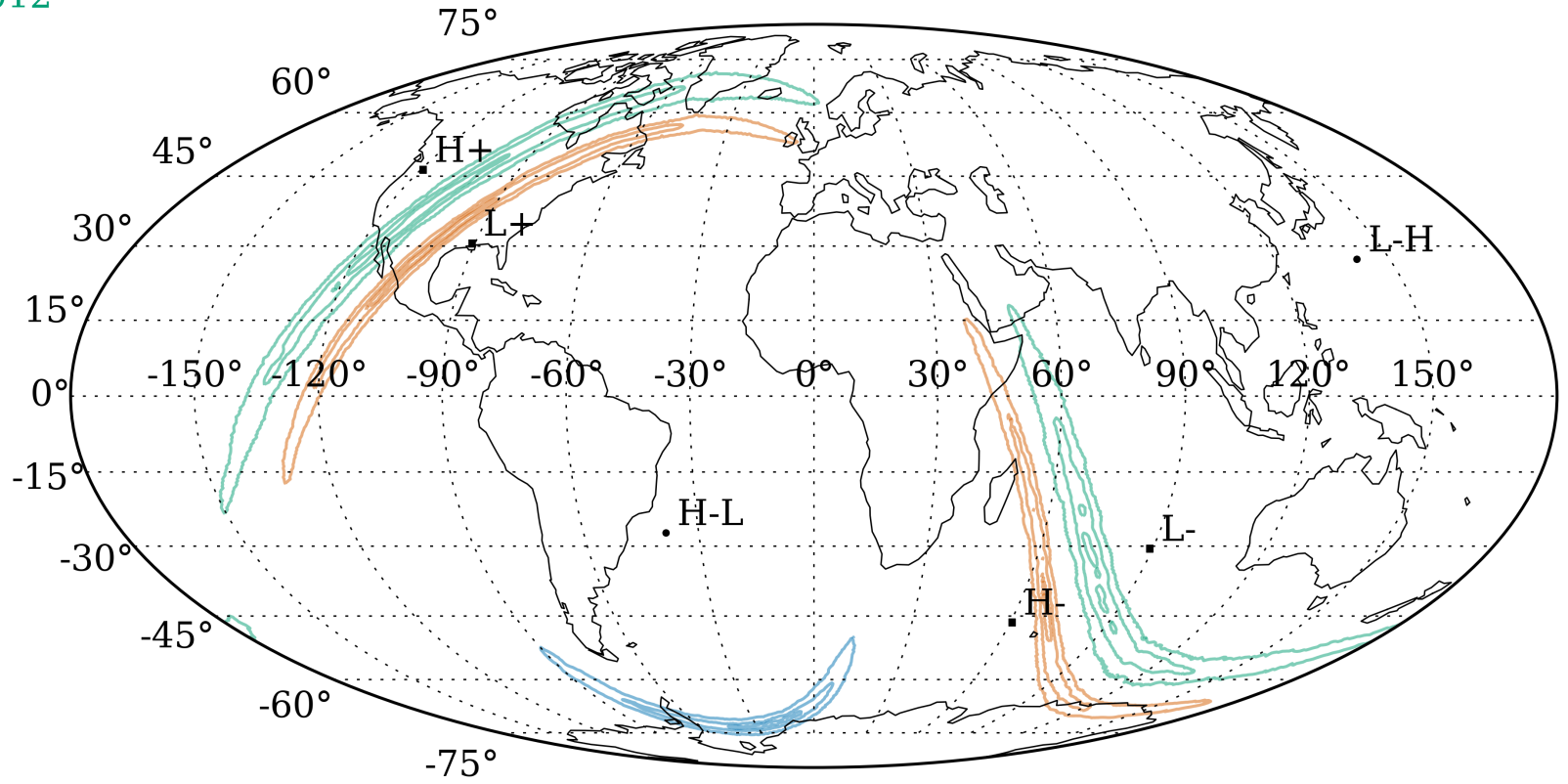




GW150914

GW151226

LVT151012

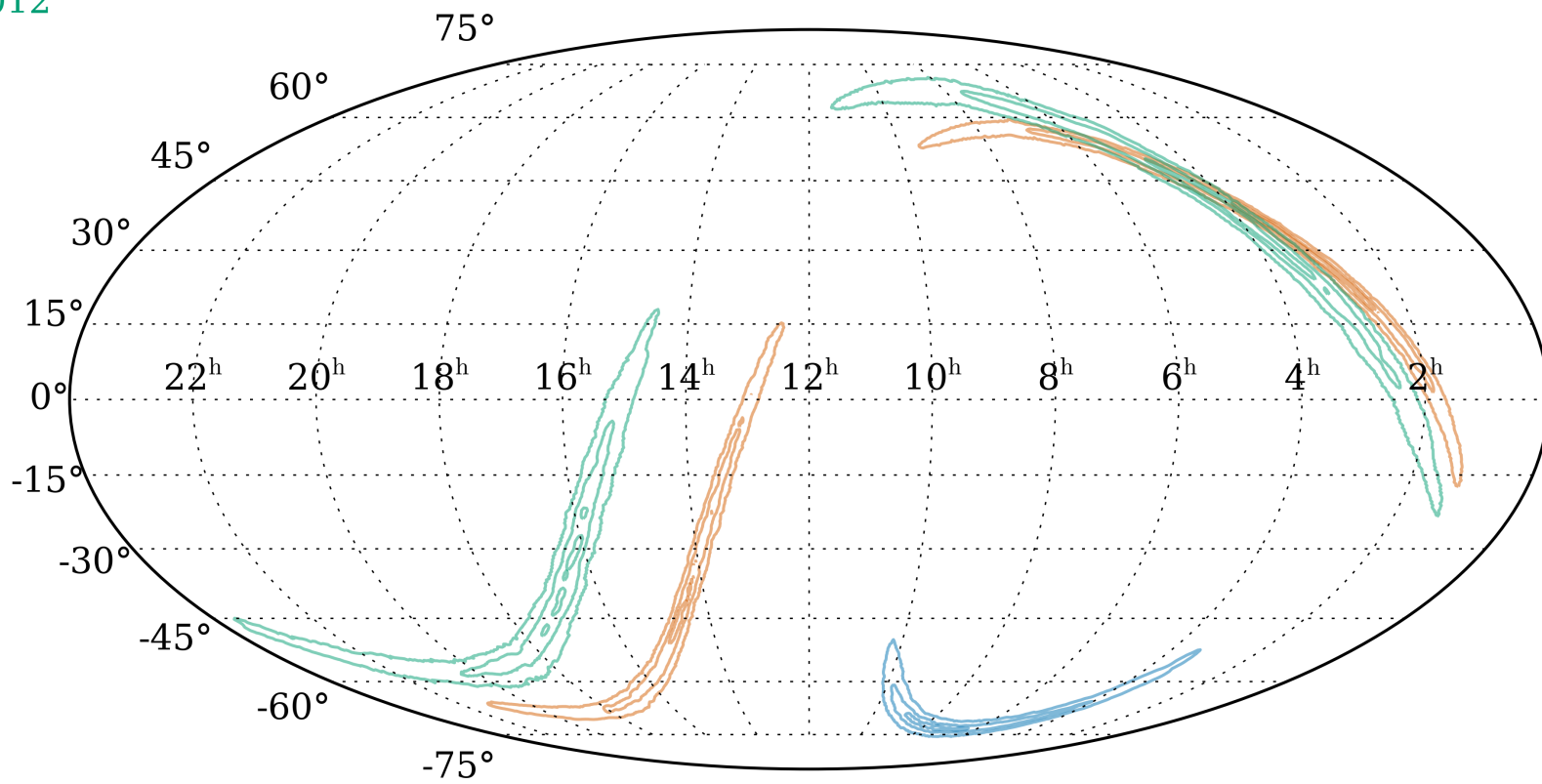


arXiv:1606.04856

GW150914

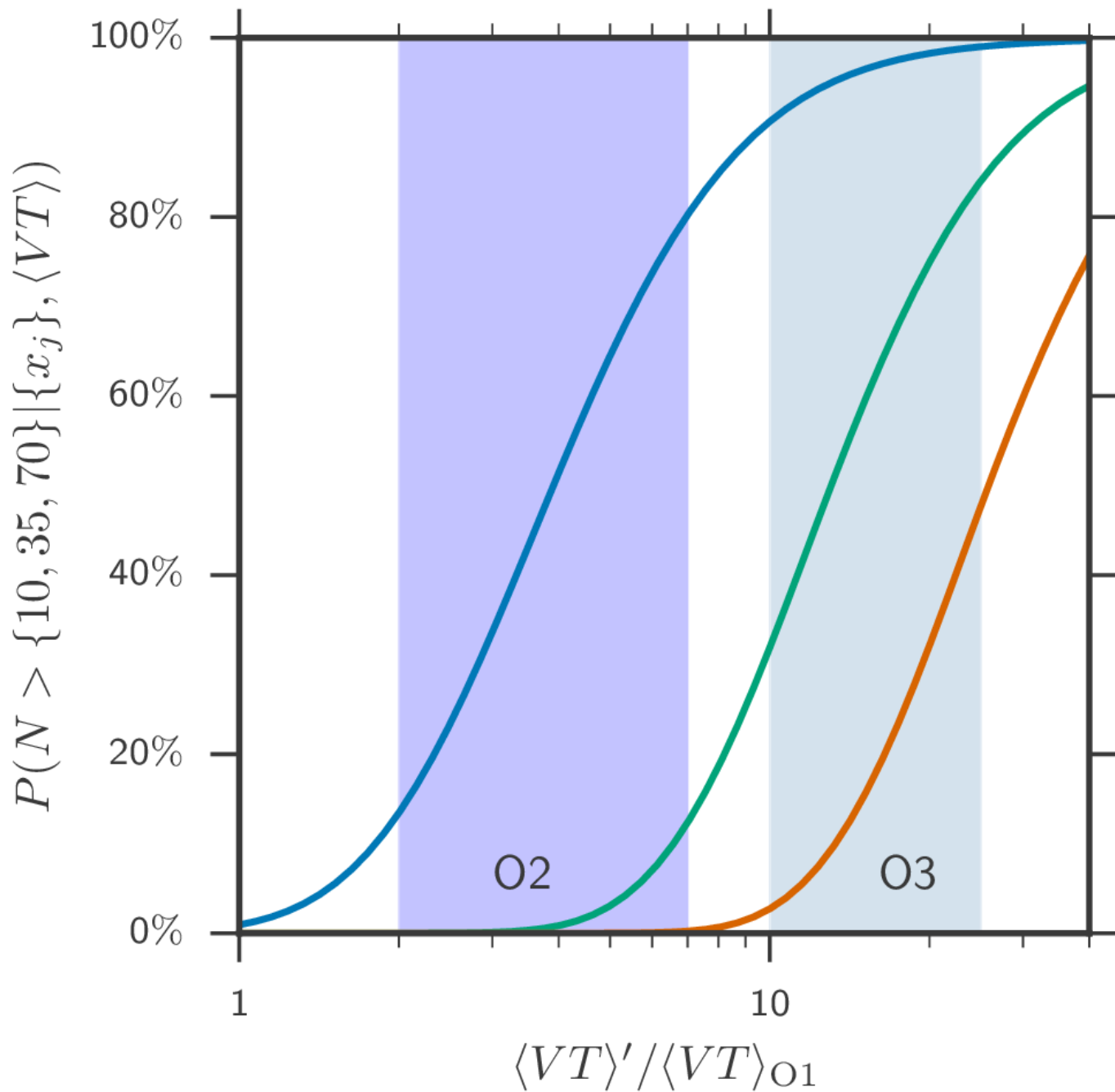
GW151226

LVT151012



arXiv:1606.04856

Rates



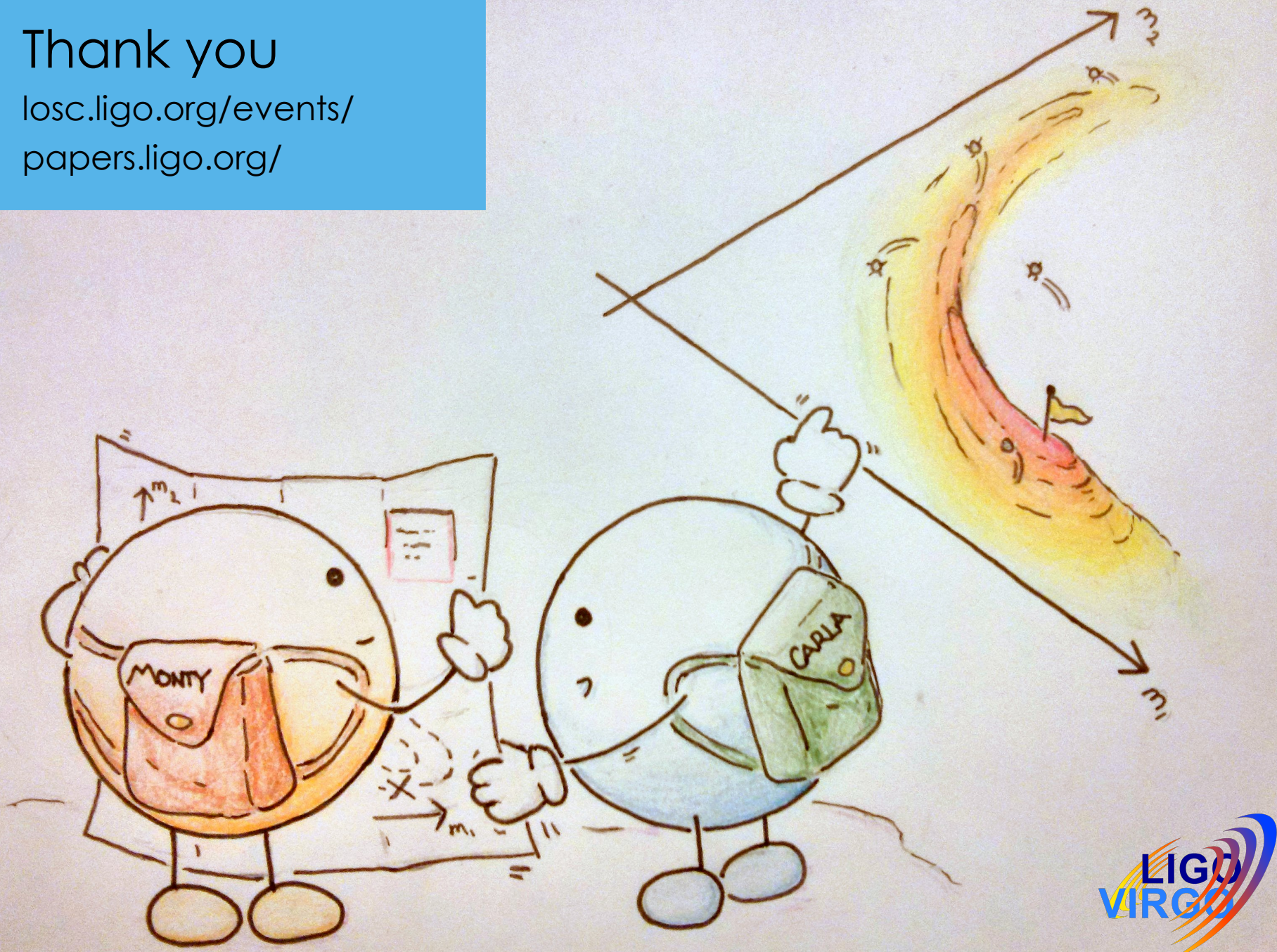
arXiv:1606.04856
arXiv:1602.03842

- Binary black holes exist and merge
- There is a population of heavy black holes
- Spin uncertain but moderate values preferred
- Two-detector sky localization is broad
- There will be more detections

[arXiv:1602.03840](https://arxiv.org/abs/1602.03840) [arXiv:1602.03846](https://arxiv.org/abs/1602.03846) [arXiv:1606.04856](https://arxiv.org/abs/1606.04856)

Thank you

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



Bayes' theorem

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

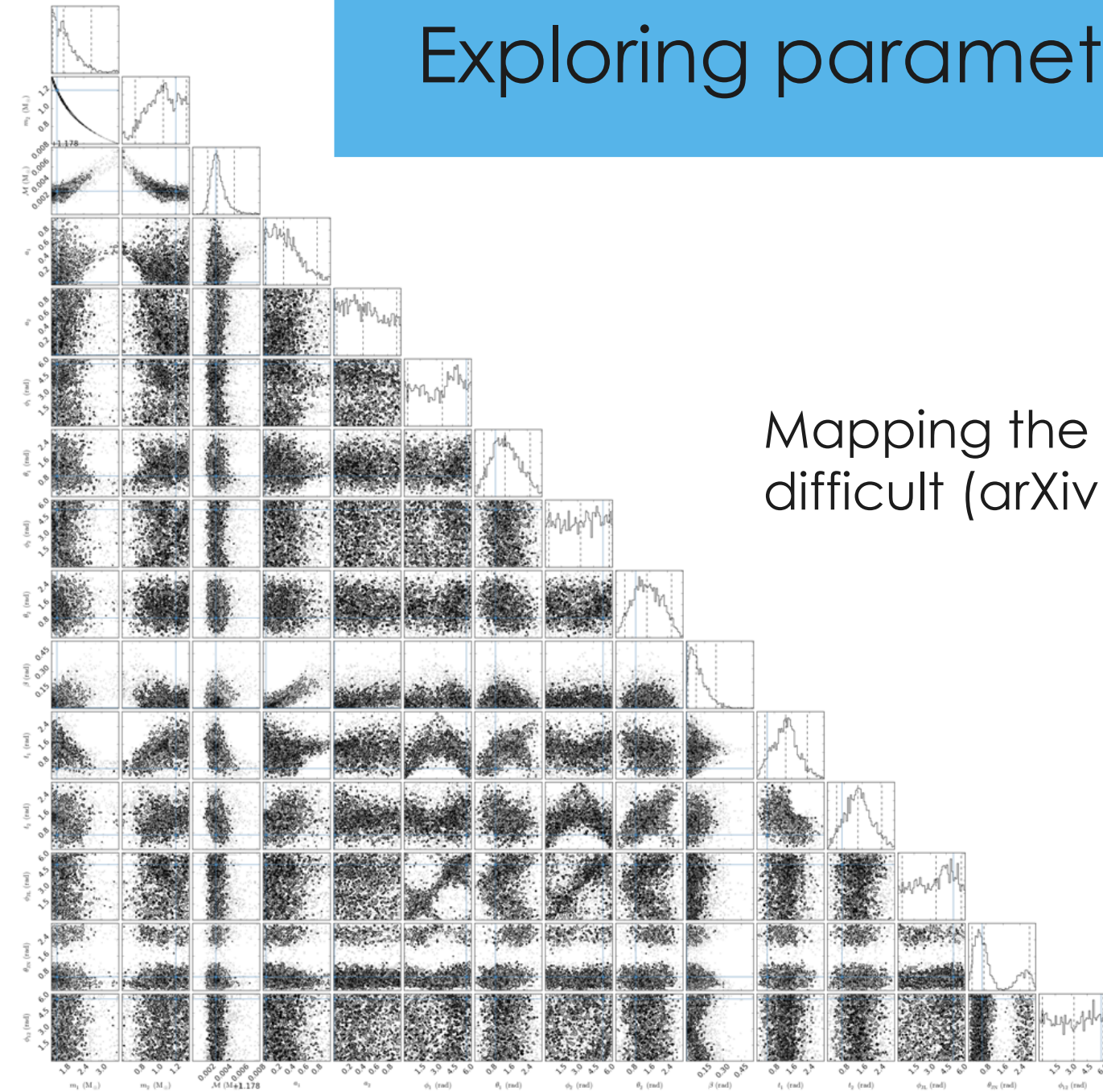
Bayes' theorem

The diagram illustrates Bayes' theorem with the following components:

- Posterior:** $p(\theta|d)$ (blue box)
- Likelihood:** $p(d|\theta)$ (pink box)
- Prior:** $p(\theta)$ (orange box)
- Evidence:** $p(d)$ (green box)

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

Exploring parameter space



Mapping the posterior is difficult (arXiv:1409.7215)

Likelihood

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

Likelihood

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

Likelihood

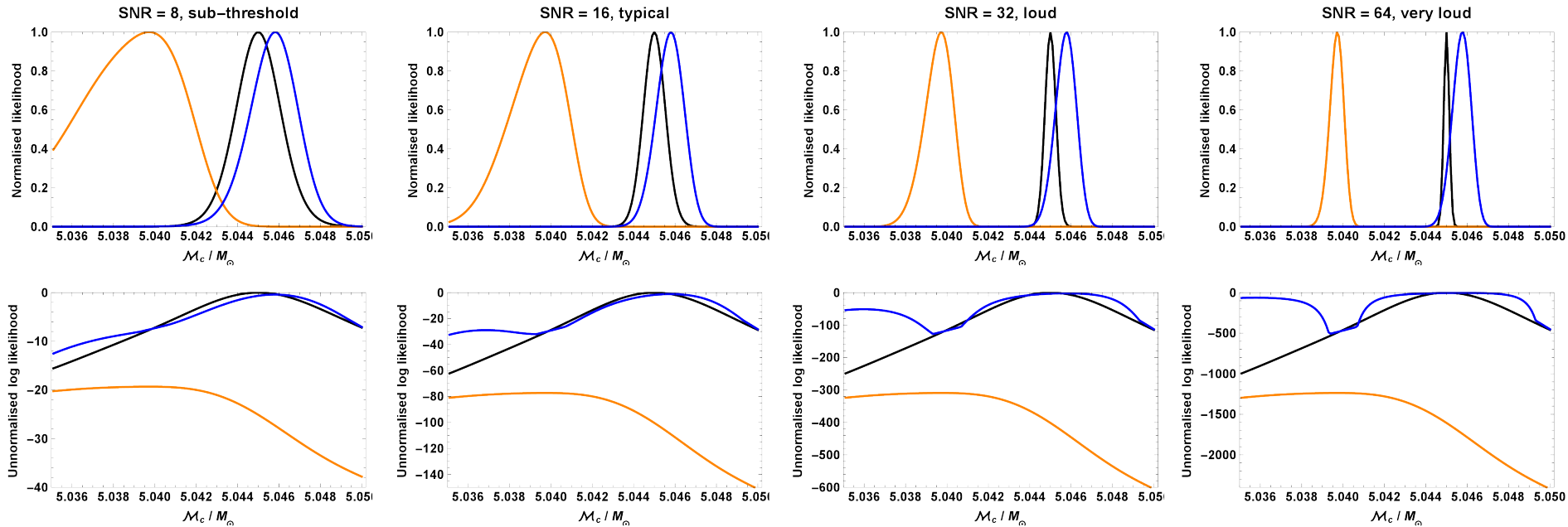
$$p(d|\theta) \propto \exp \left[-\frac{1}{2} \sum_k \langle h_k(\theta) - d_k | h_k(\theta) - d_k \rangle \right]$$

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

Waveform

Waveform error

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



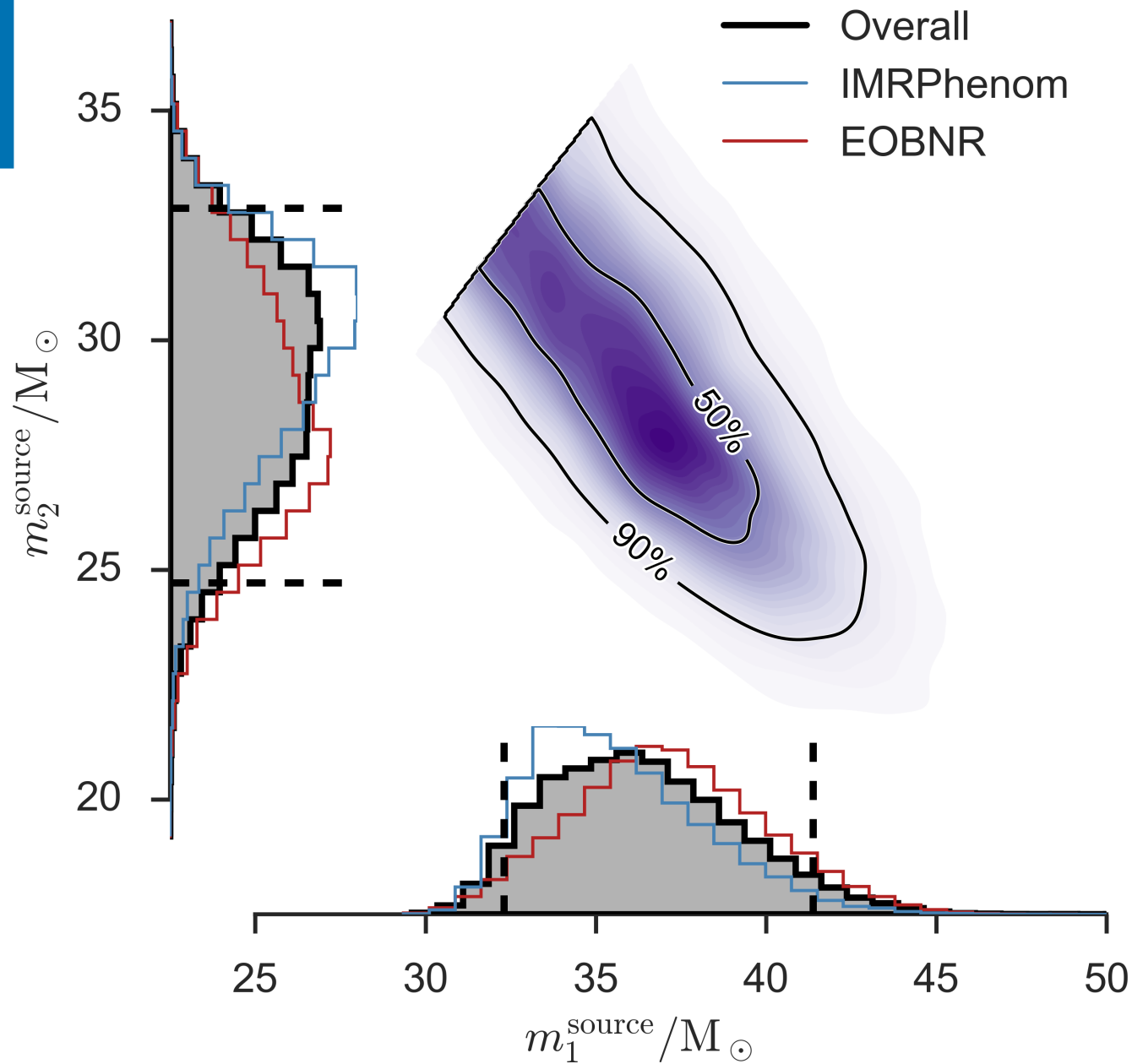
arXiv:1509.04066

Chirp mass

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

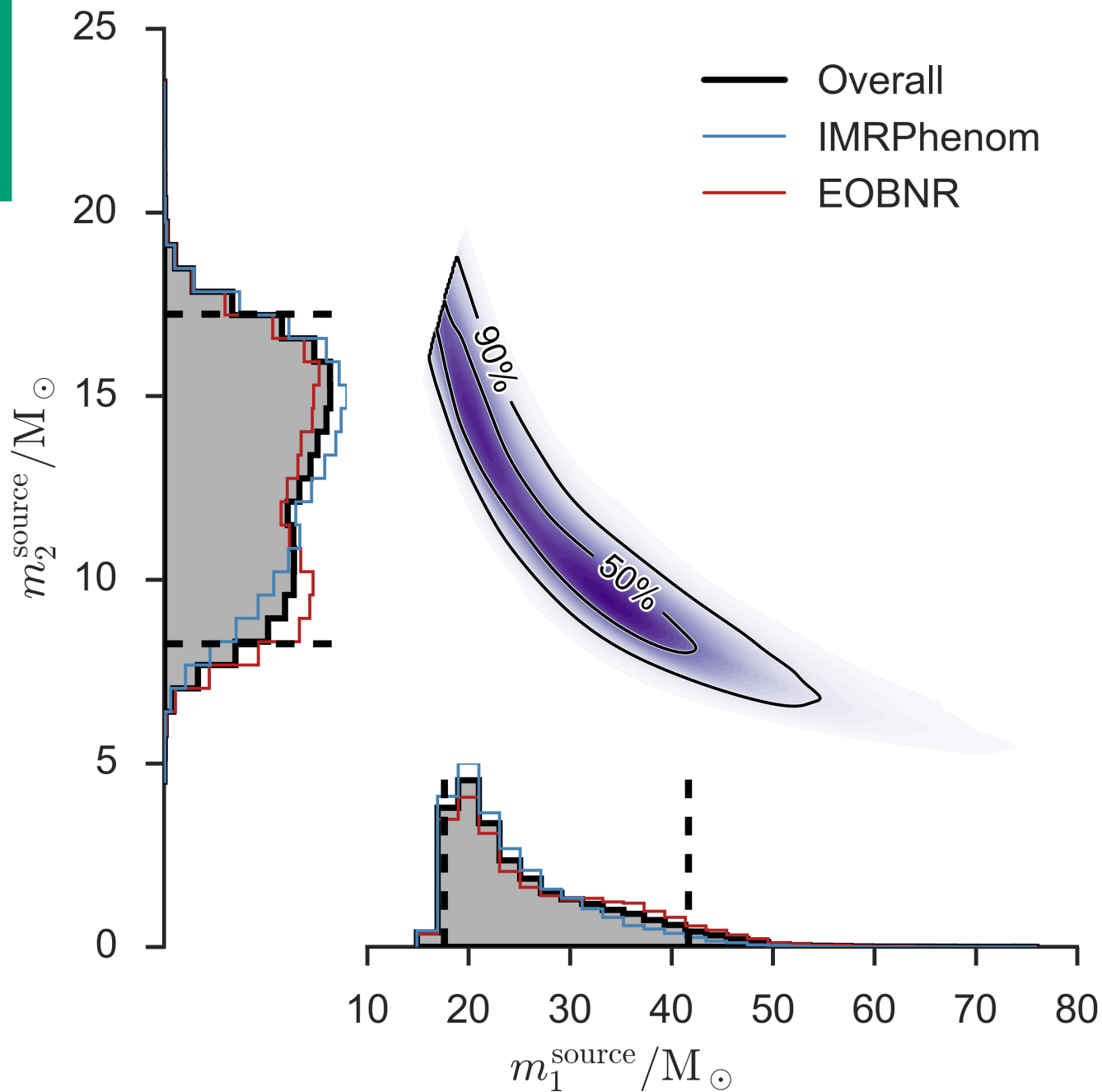
Chirp mass gives leading-order amplitude and phase evolution (arXiv:0903.0338)

Masses

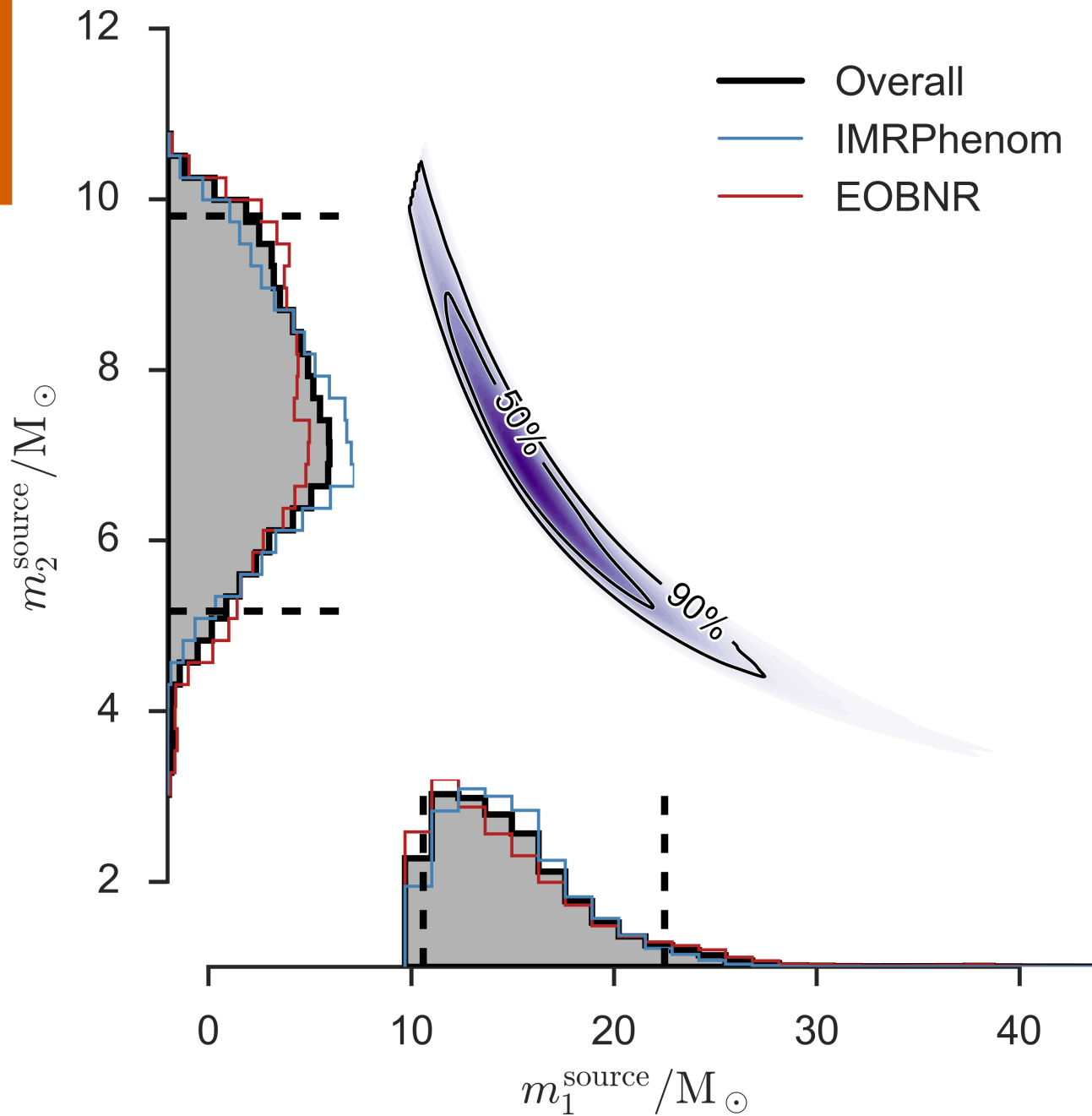


arXiv:1606.04856
arXiv:1602.03840

Masses

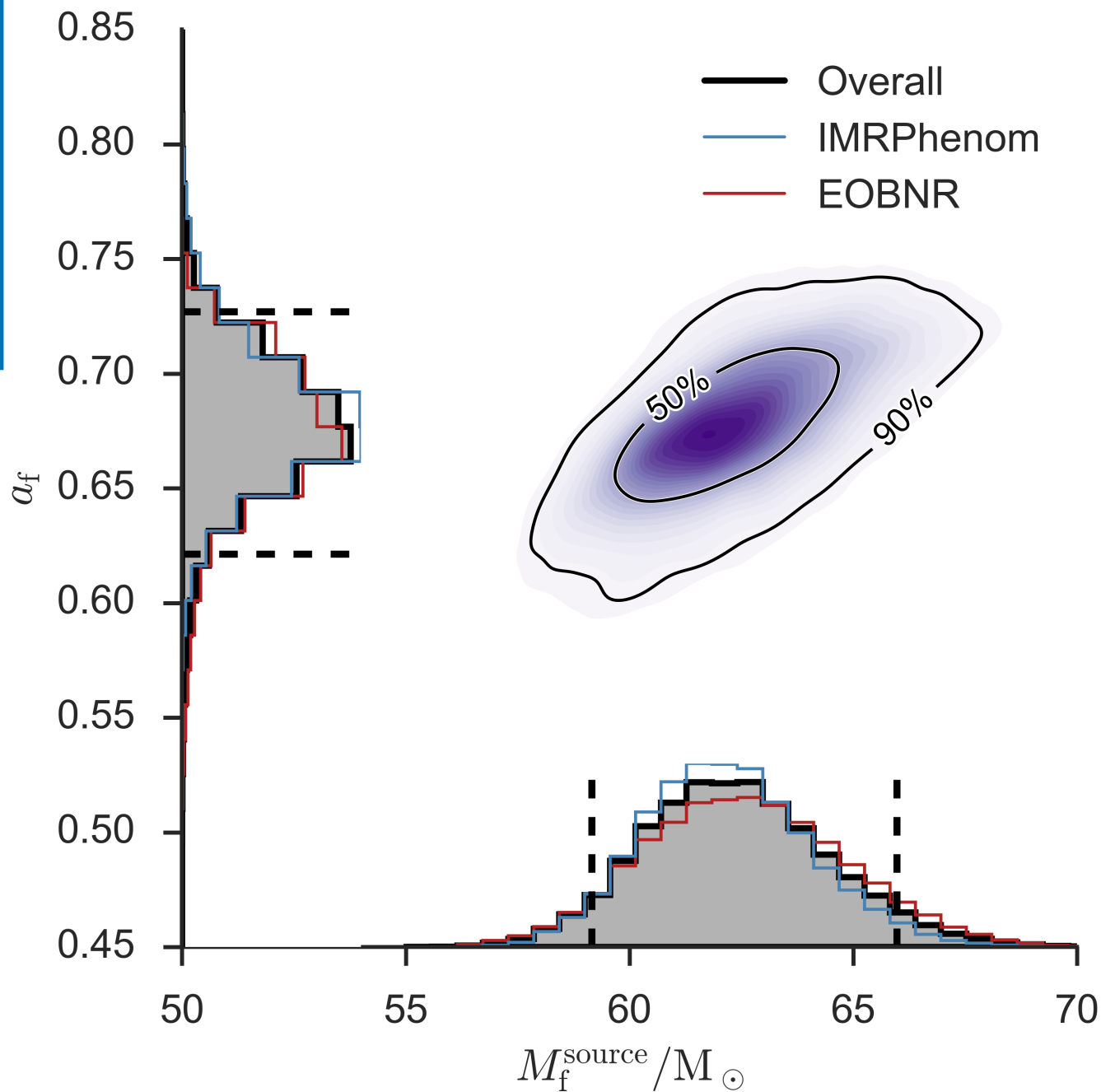


Masses



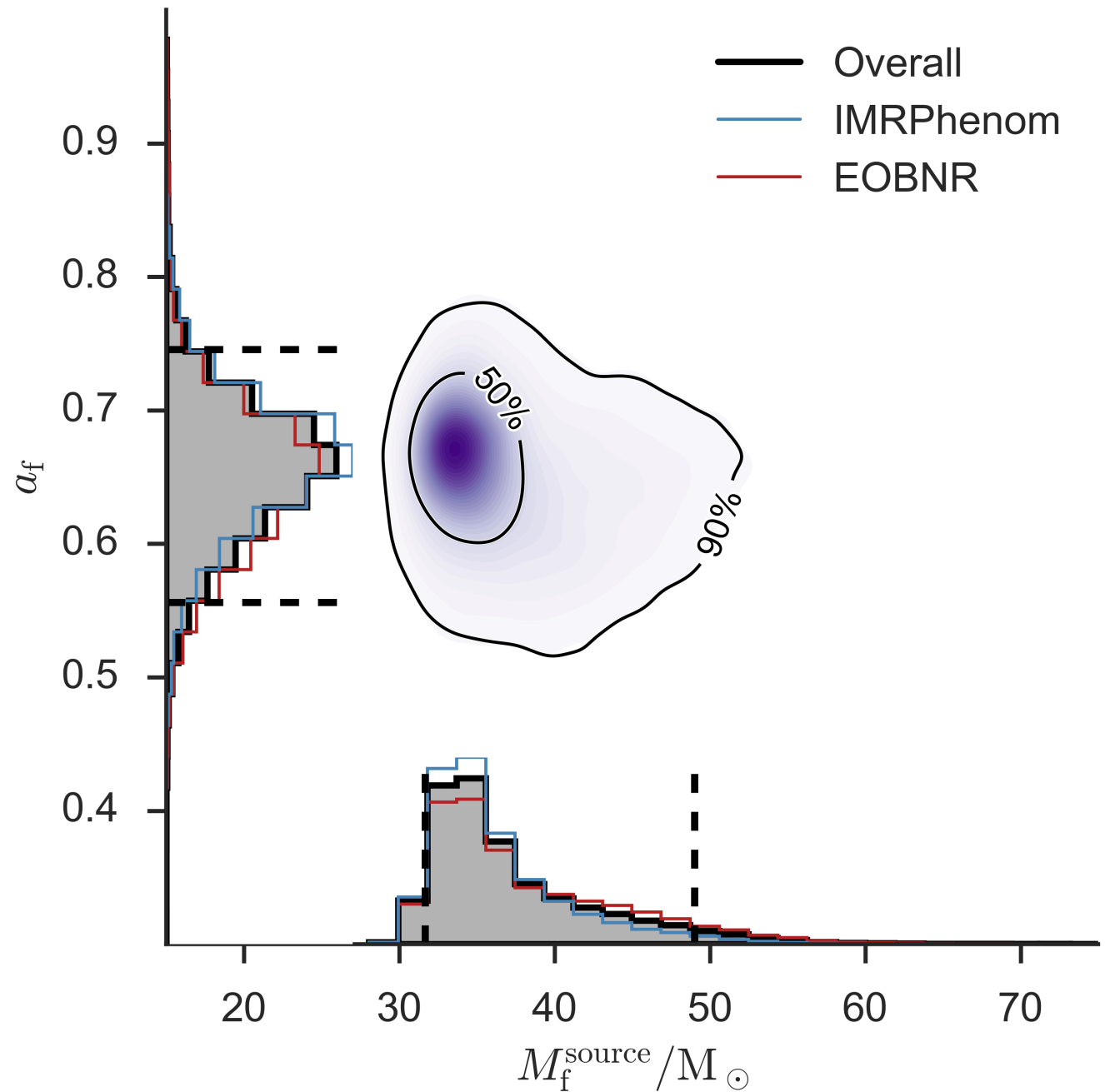
arXiv:1606.04855

Final mass & spin

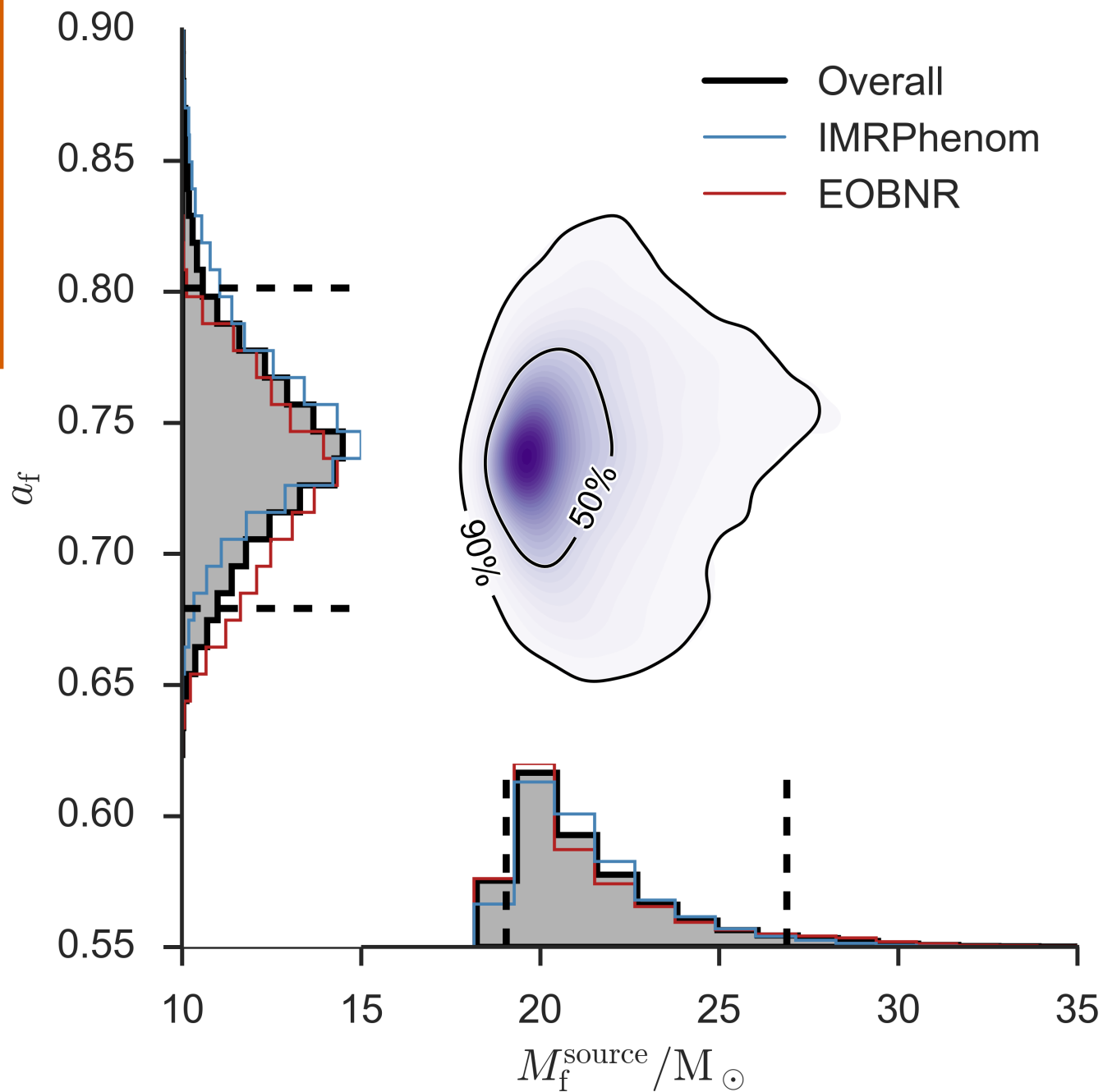


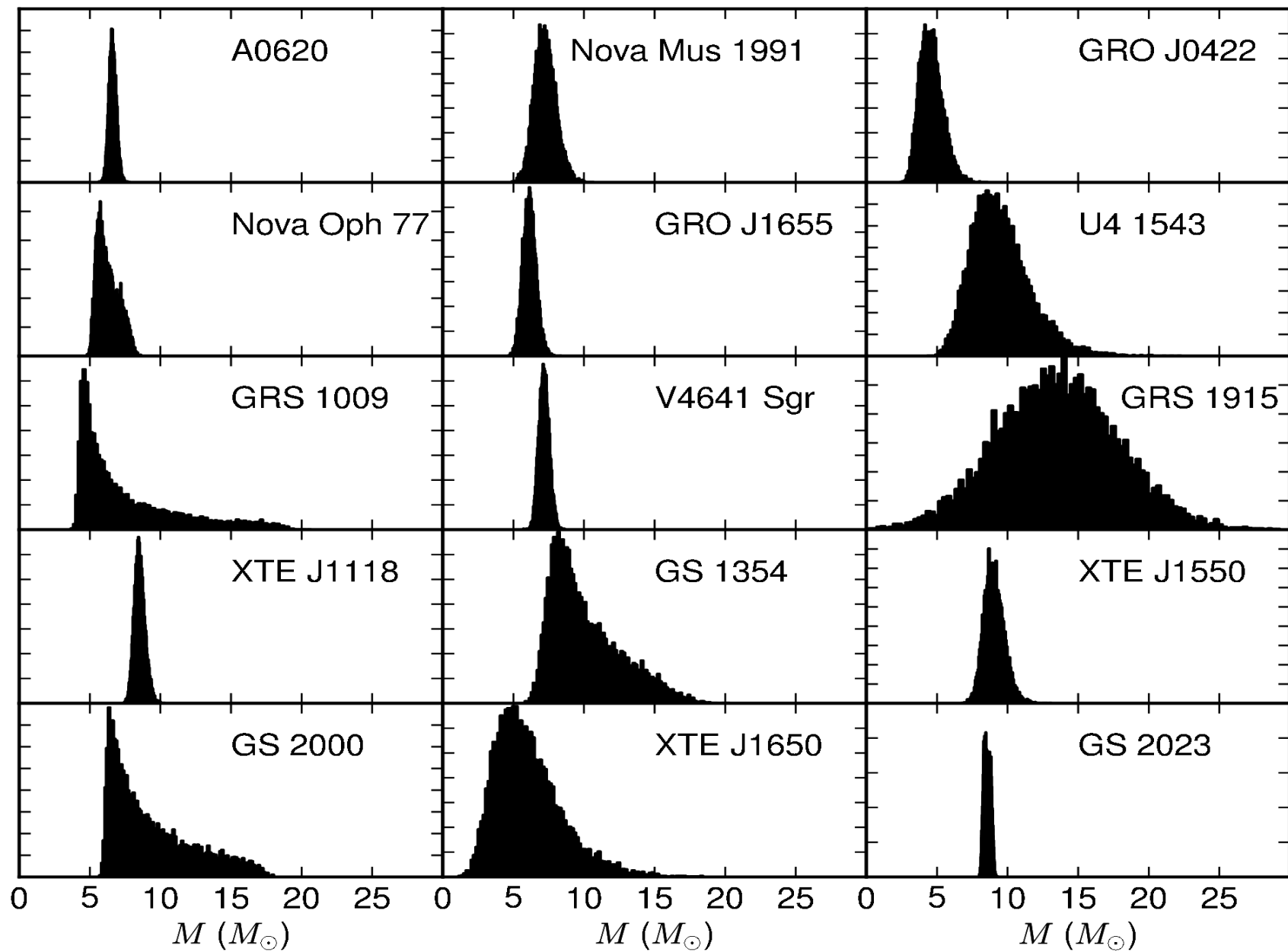
arXiv:1606.04856
arXiv:1602.03840

Final mass & spin

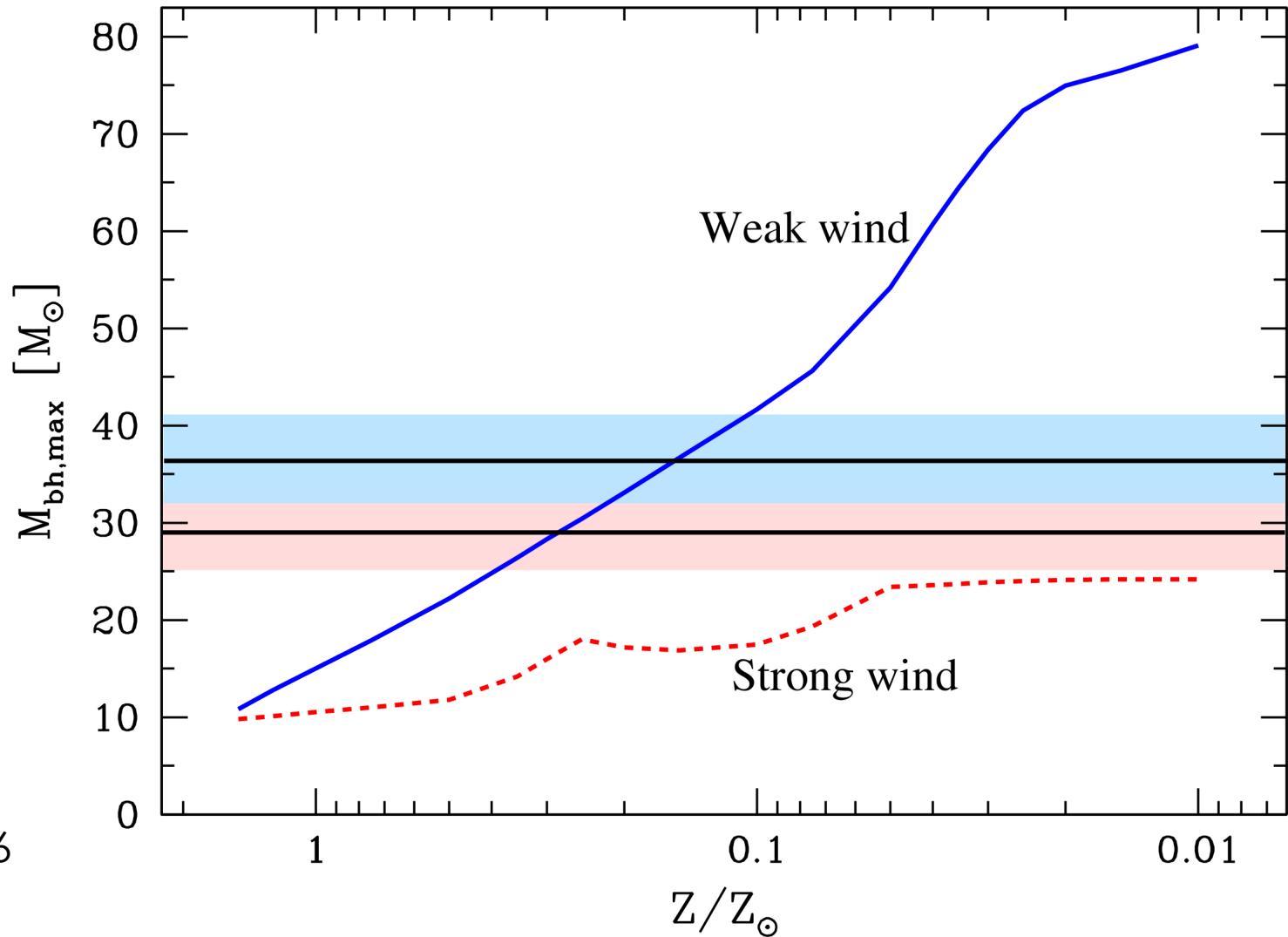


Final mass & spin

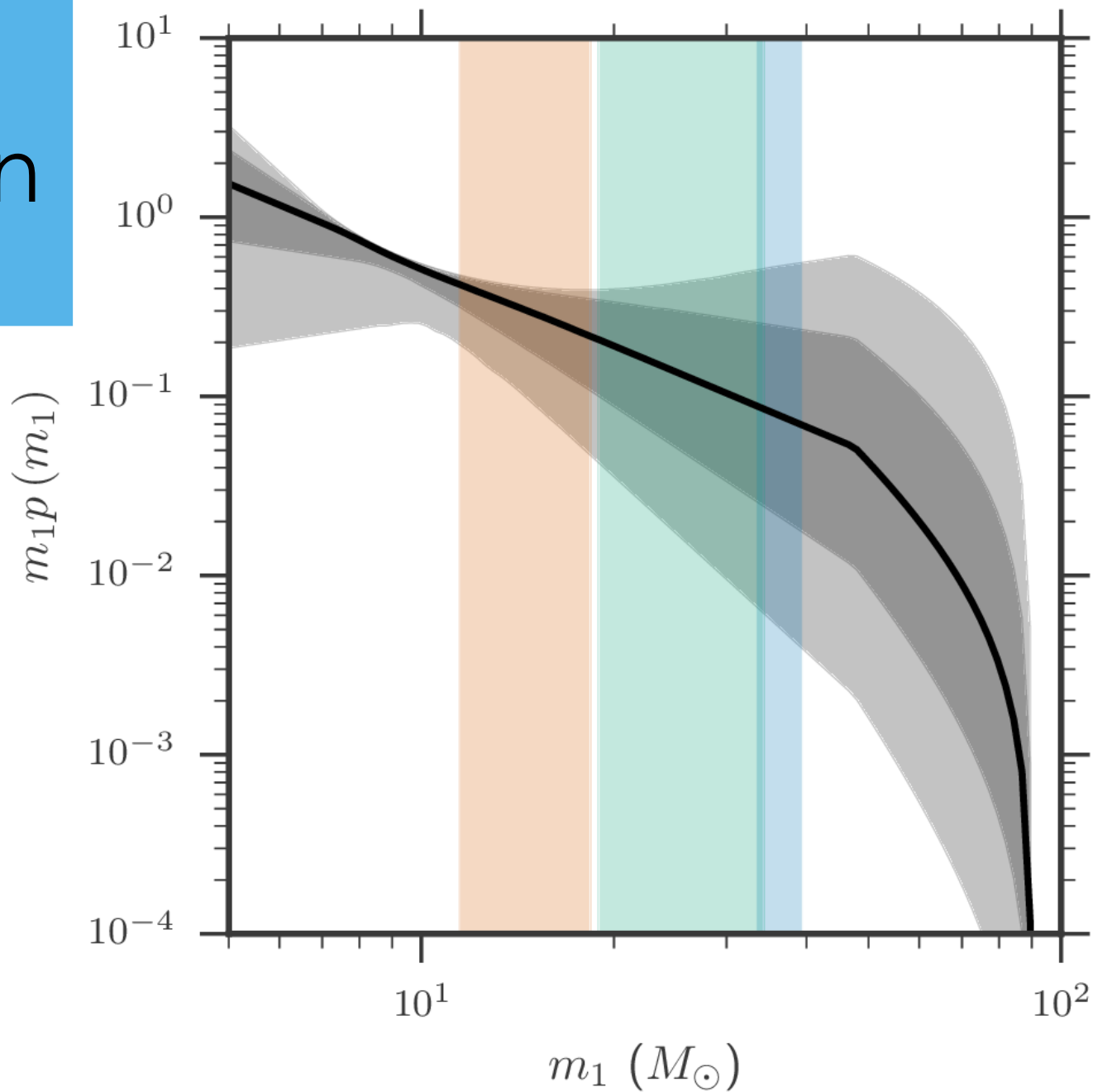




Metallicity

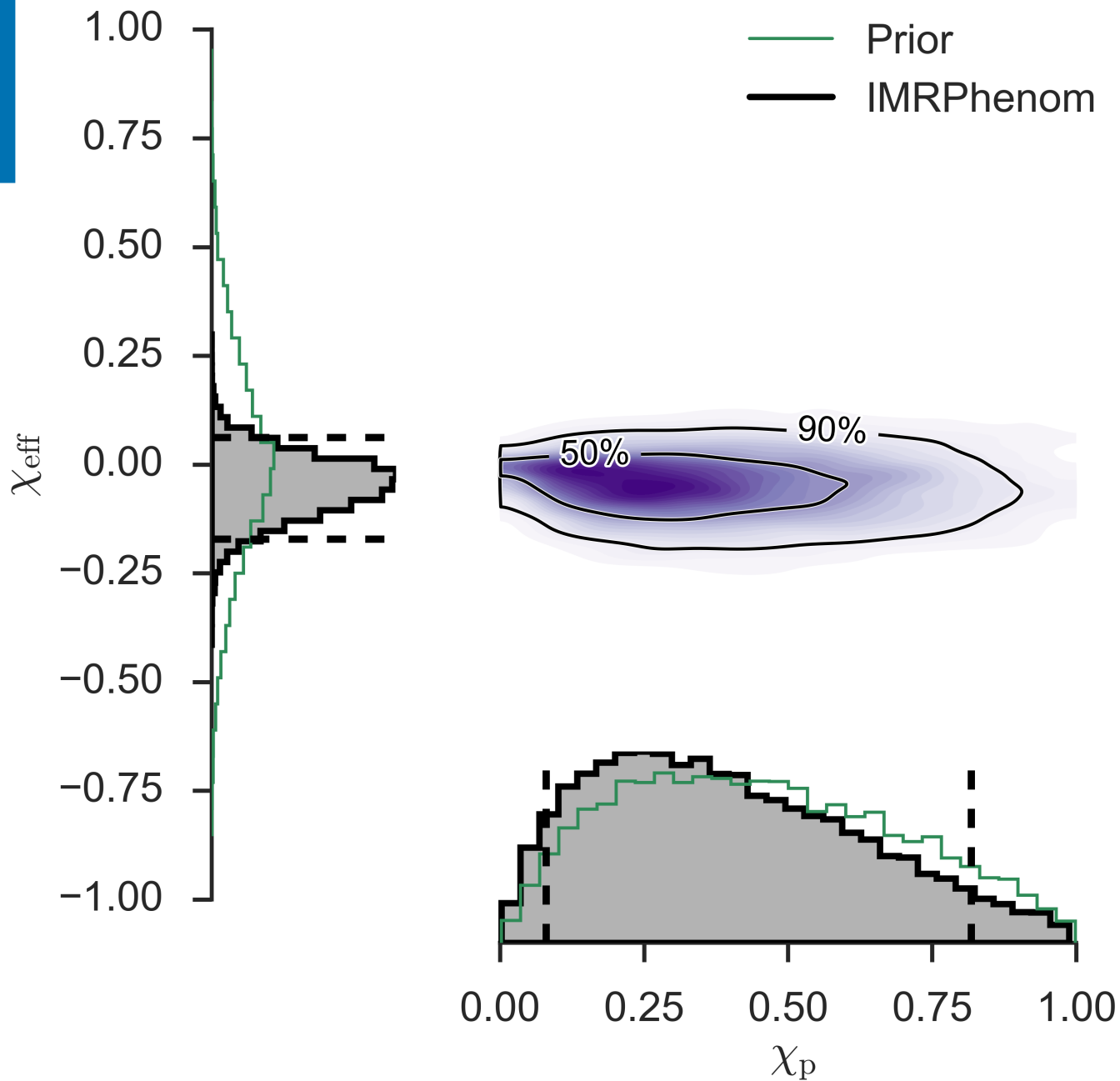


Mass distribution



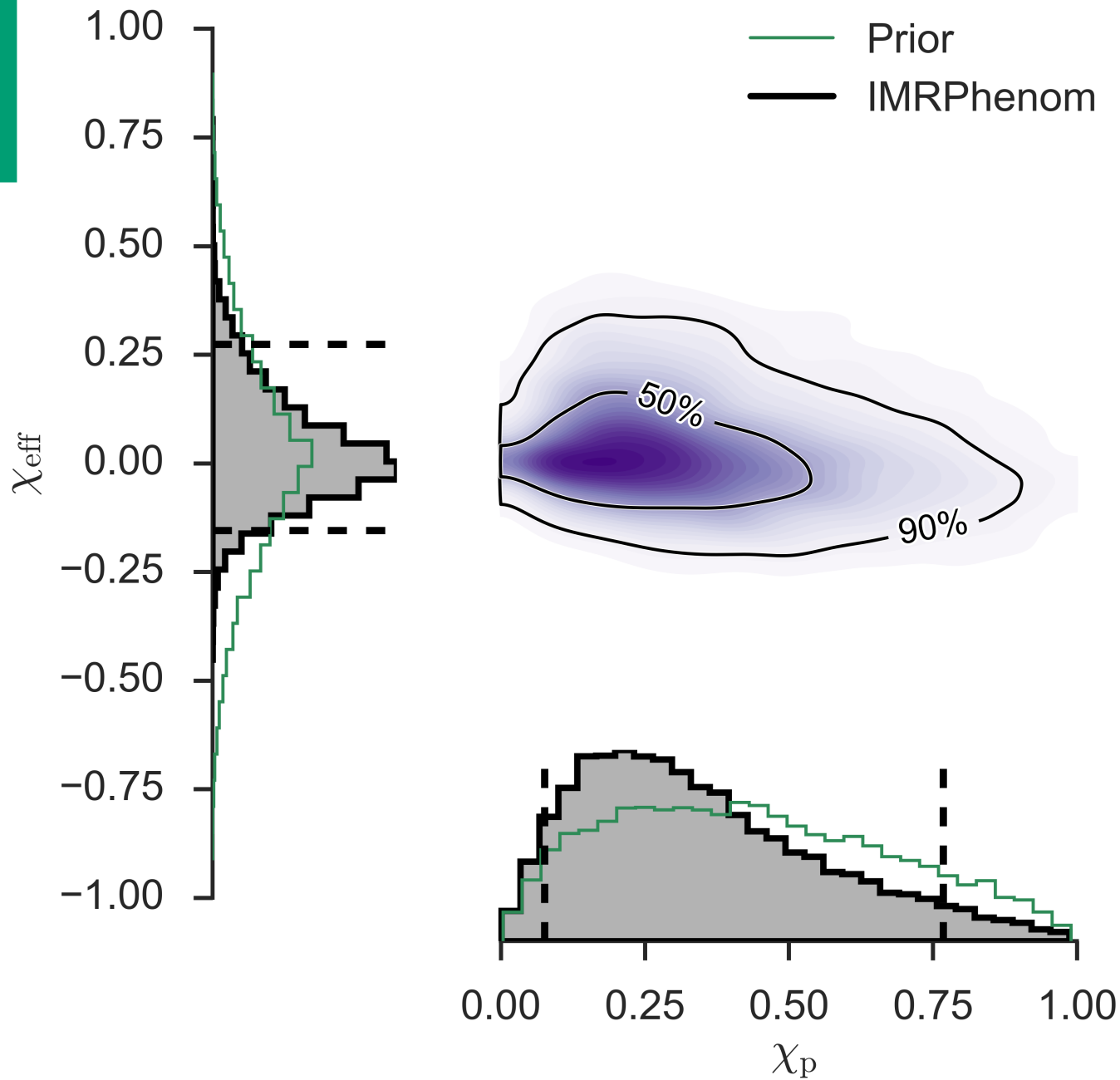
arXiv:1606.04856

Spin

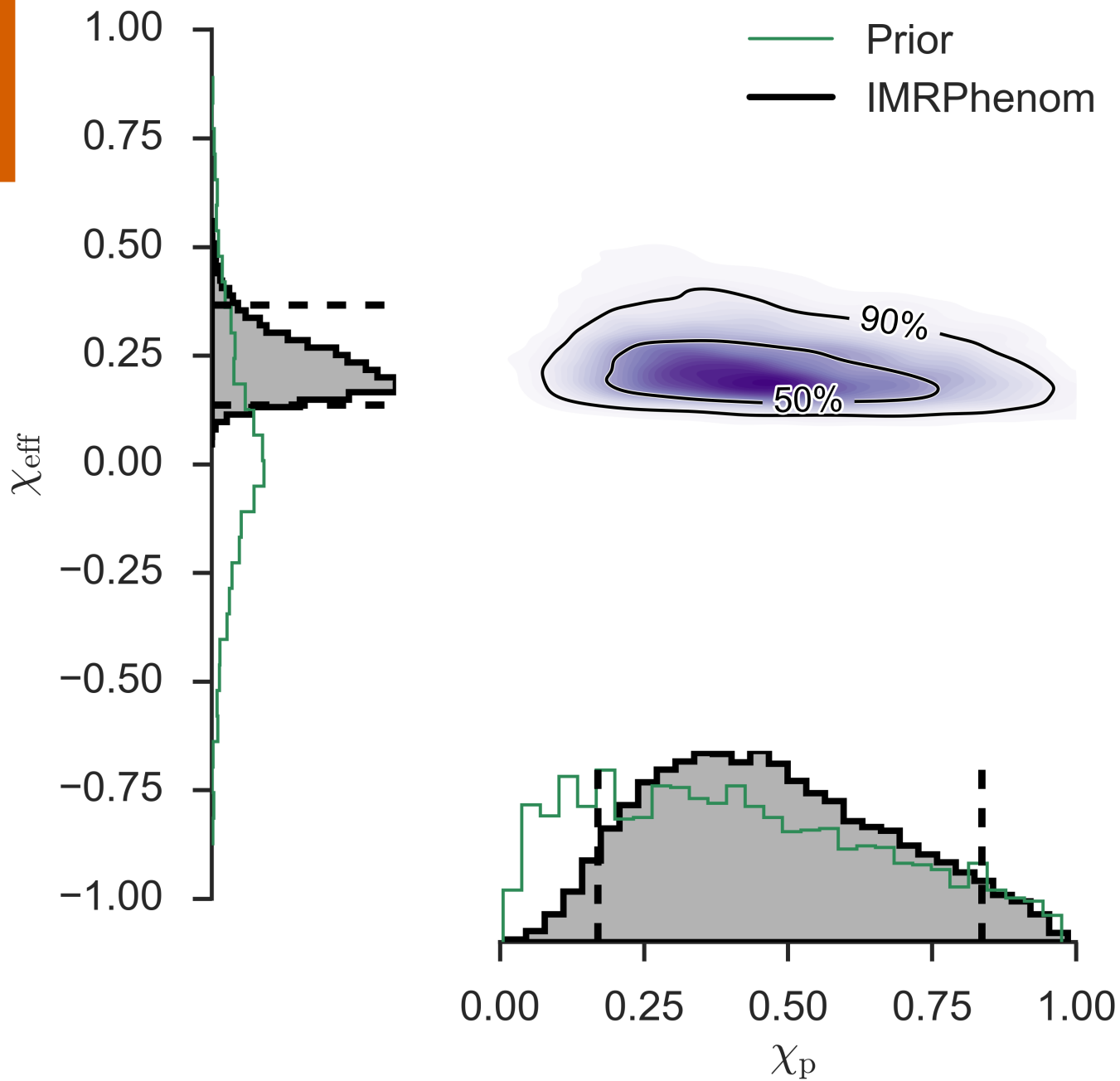


arXiv:1606.04856
arXiv:1602.03840

Spin



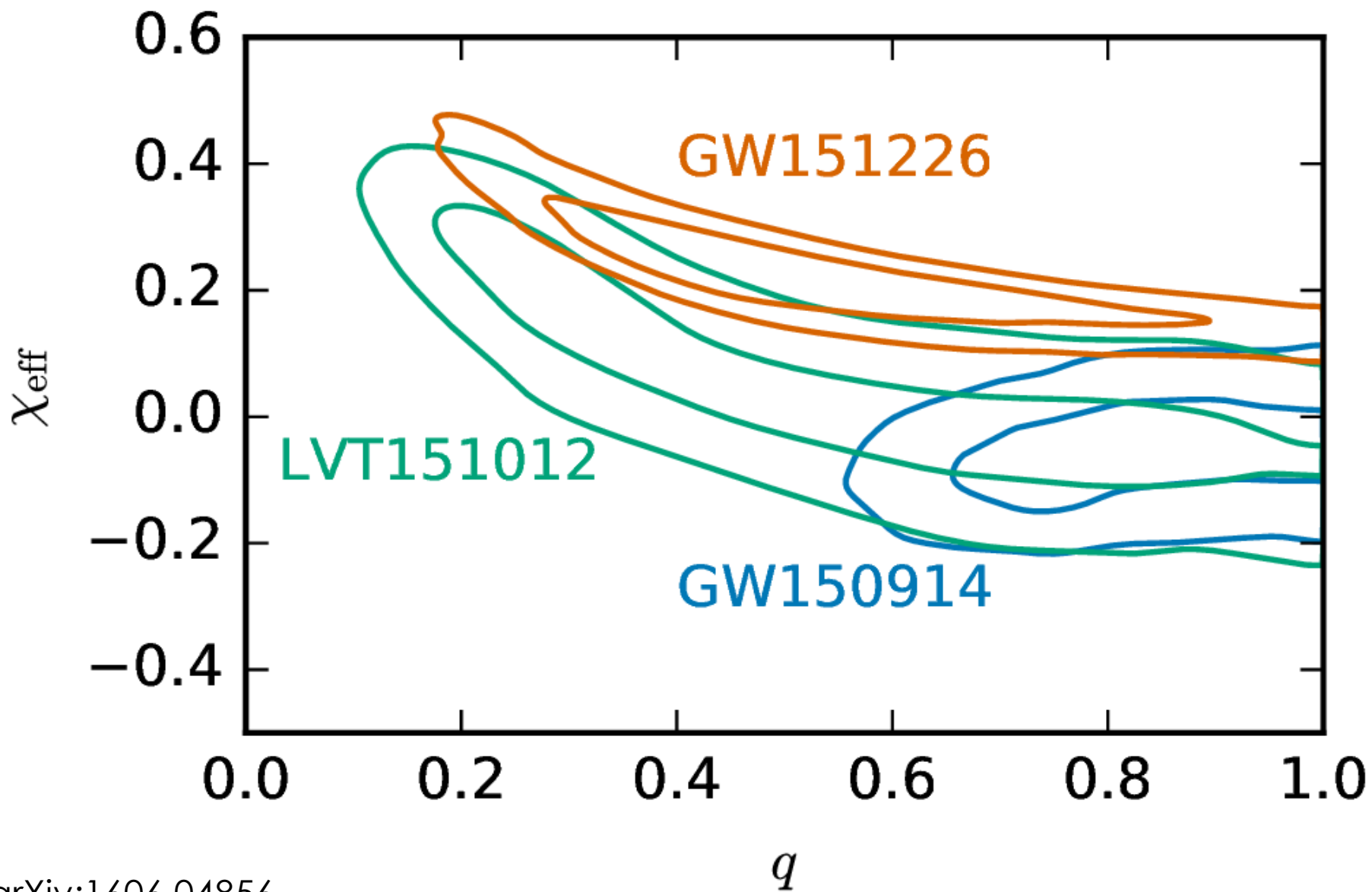
Spin



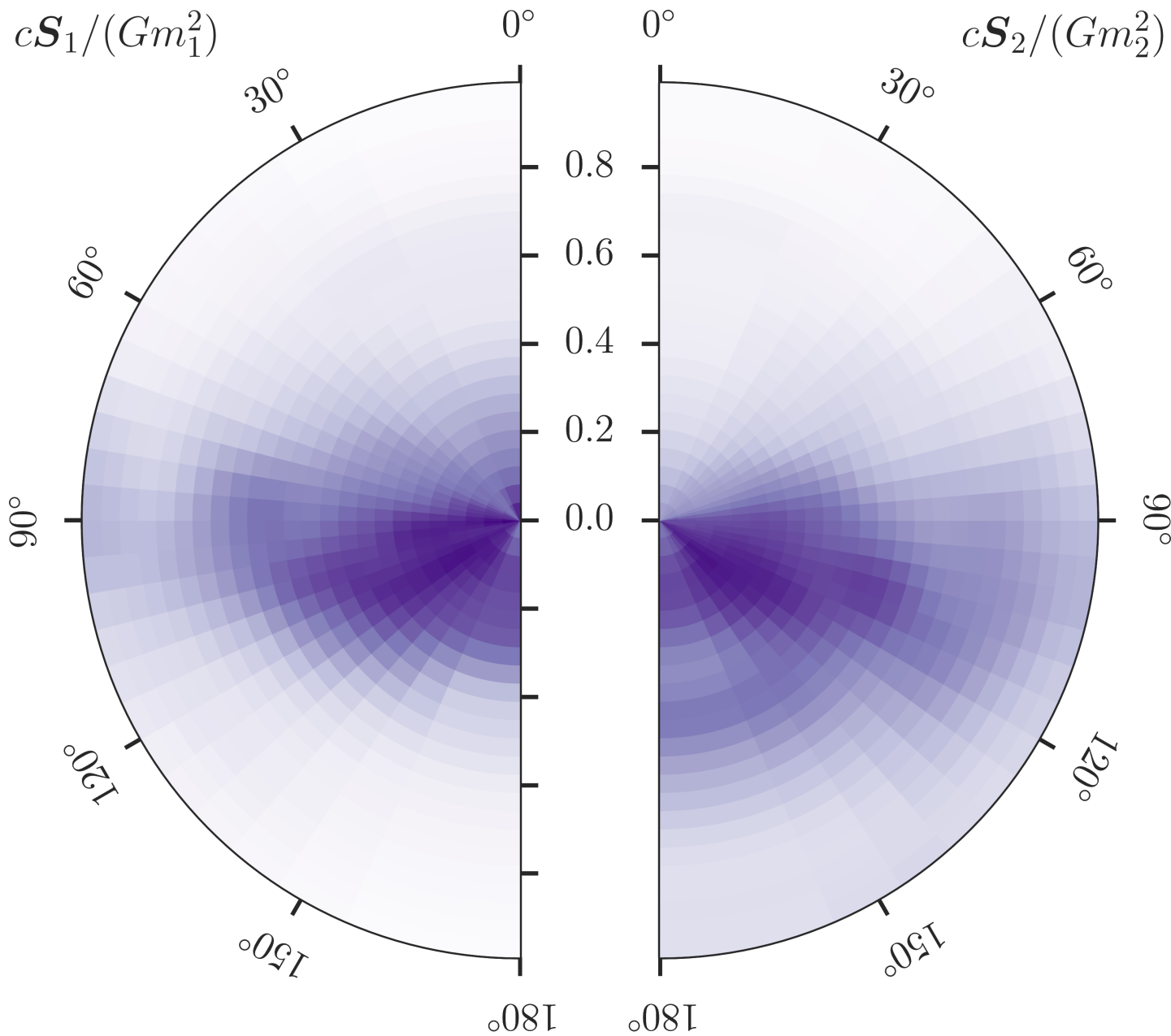
Effective inspiral spin

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

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



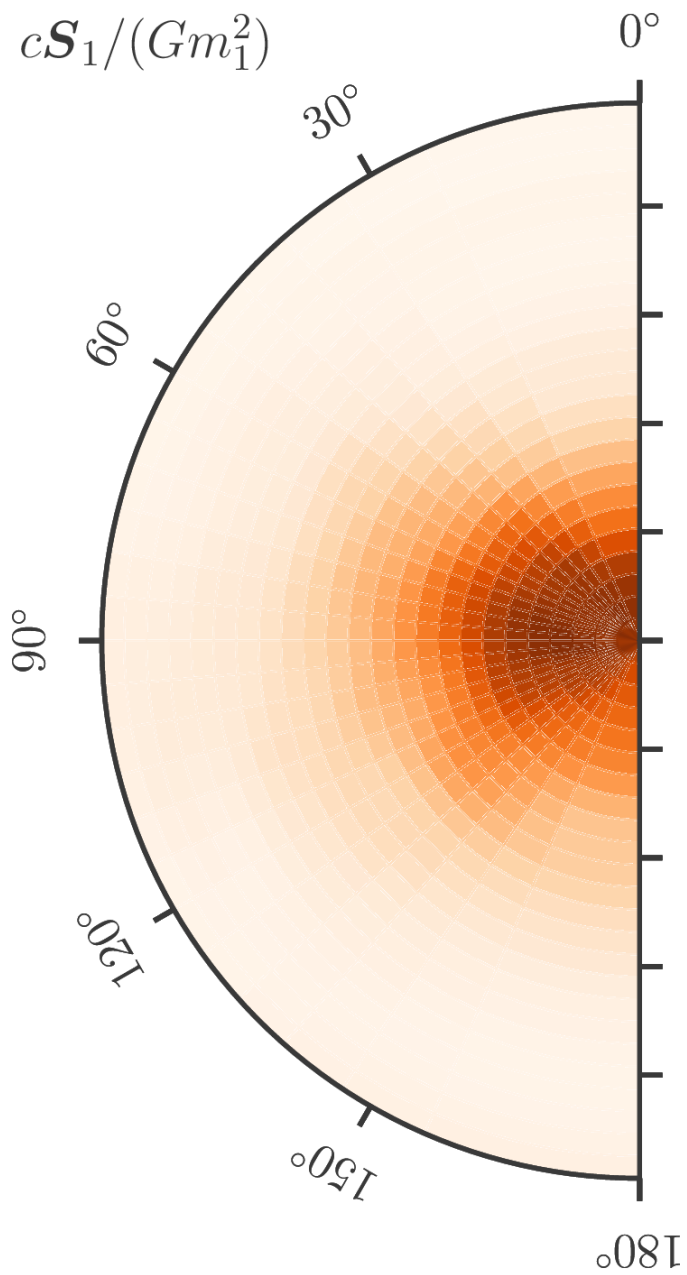
Spin



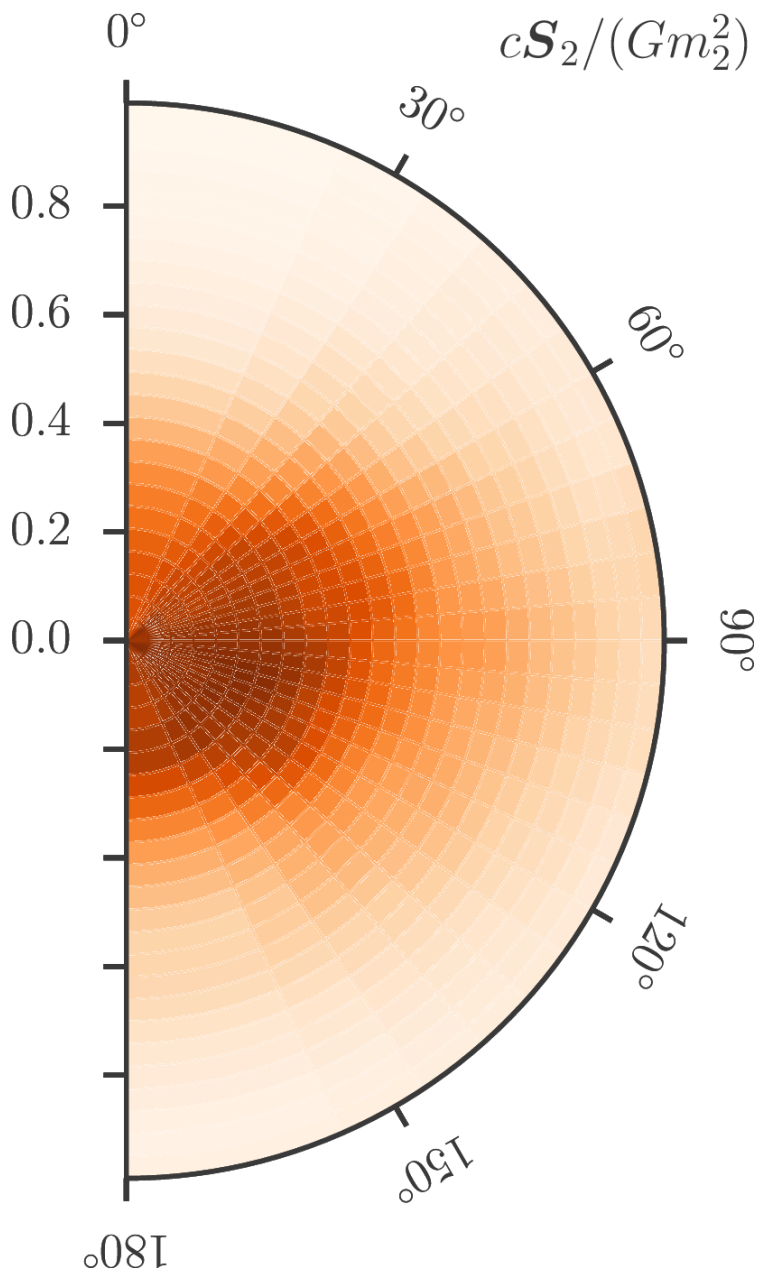
arXiv:1606.04856
arXiv:1602.03840

Spin

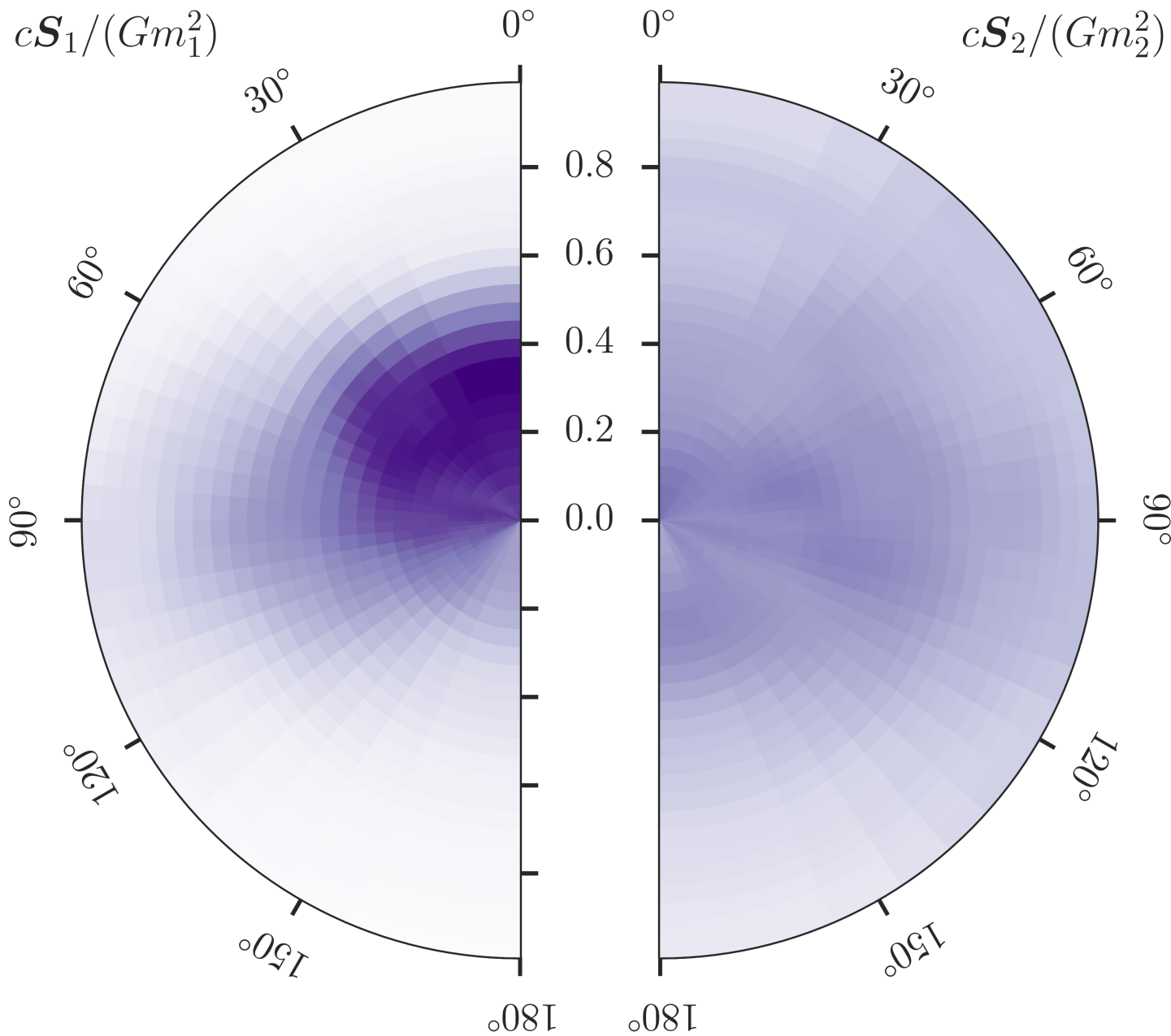
$c\mathcal{S}_1/(Gm_1^2)$



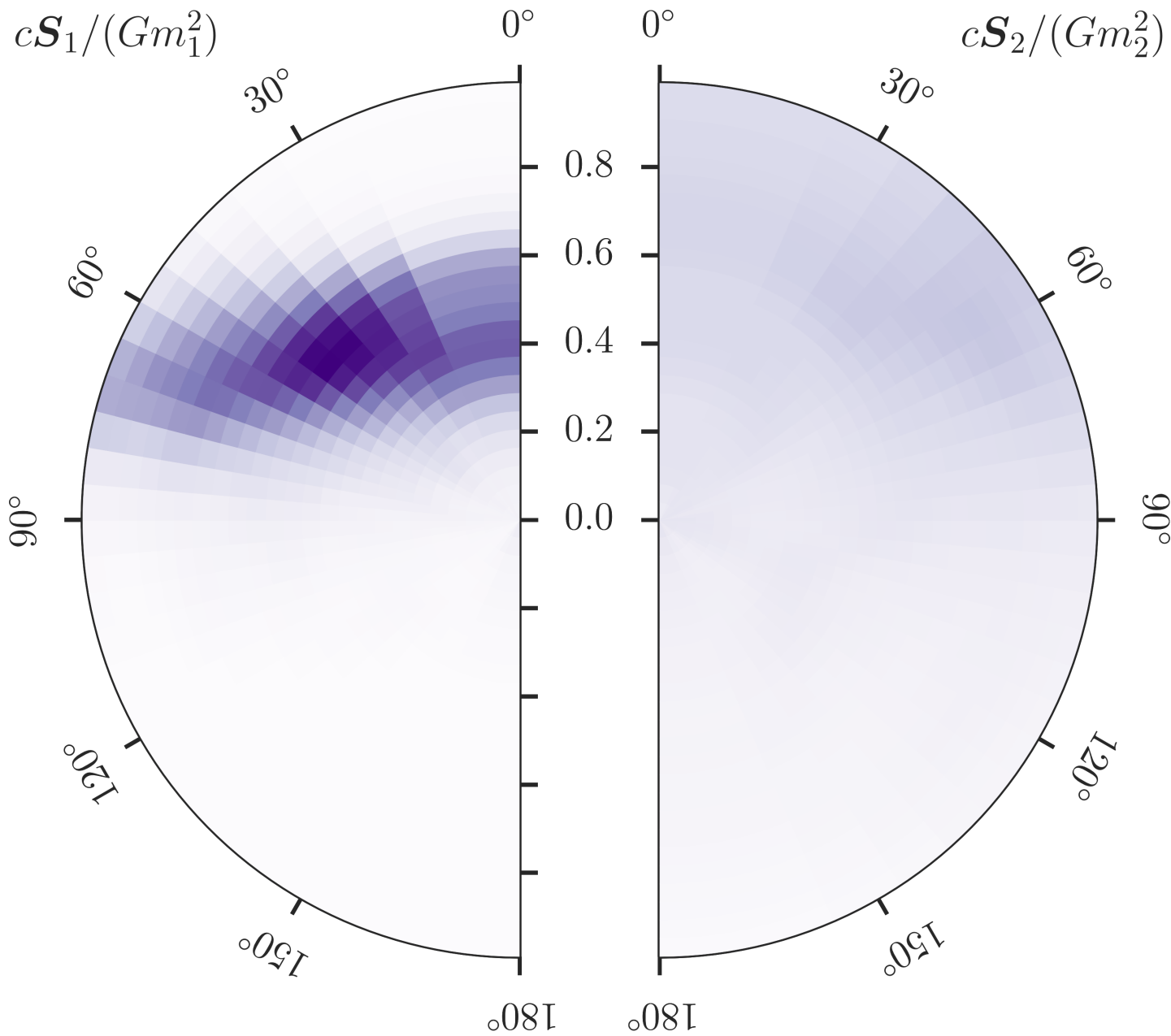
$c\mathcal{S}_2/(Gm_2^2)$



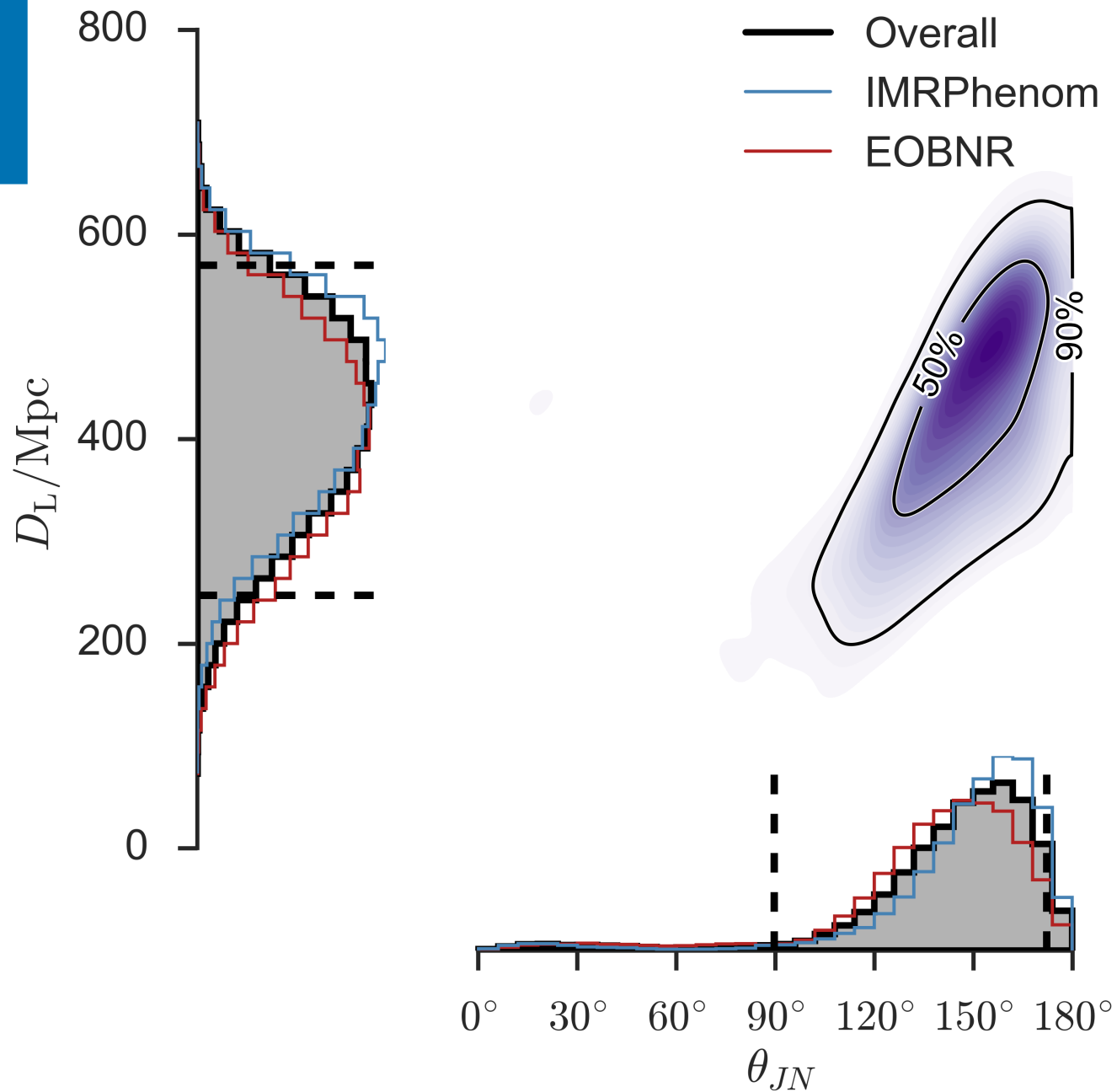
Spin



Spin

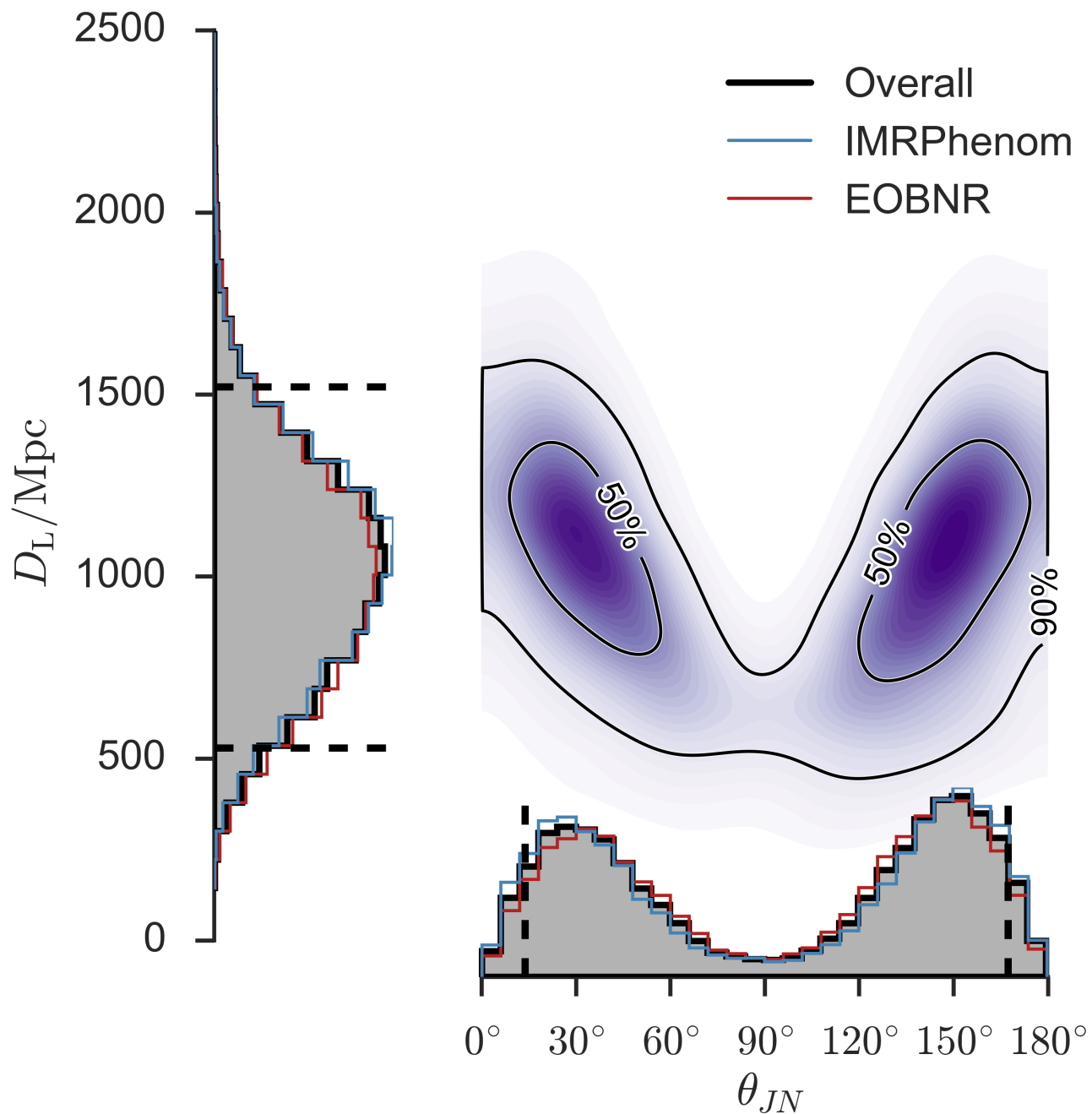


Distance

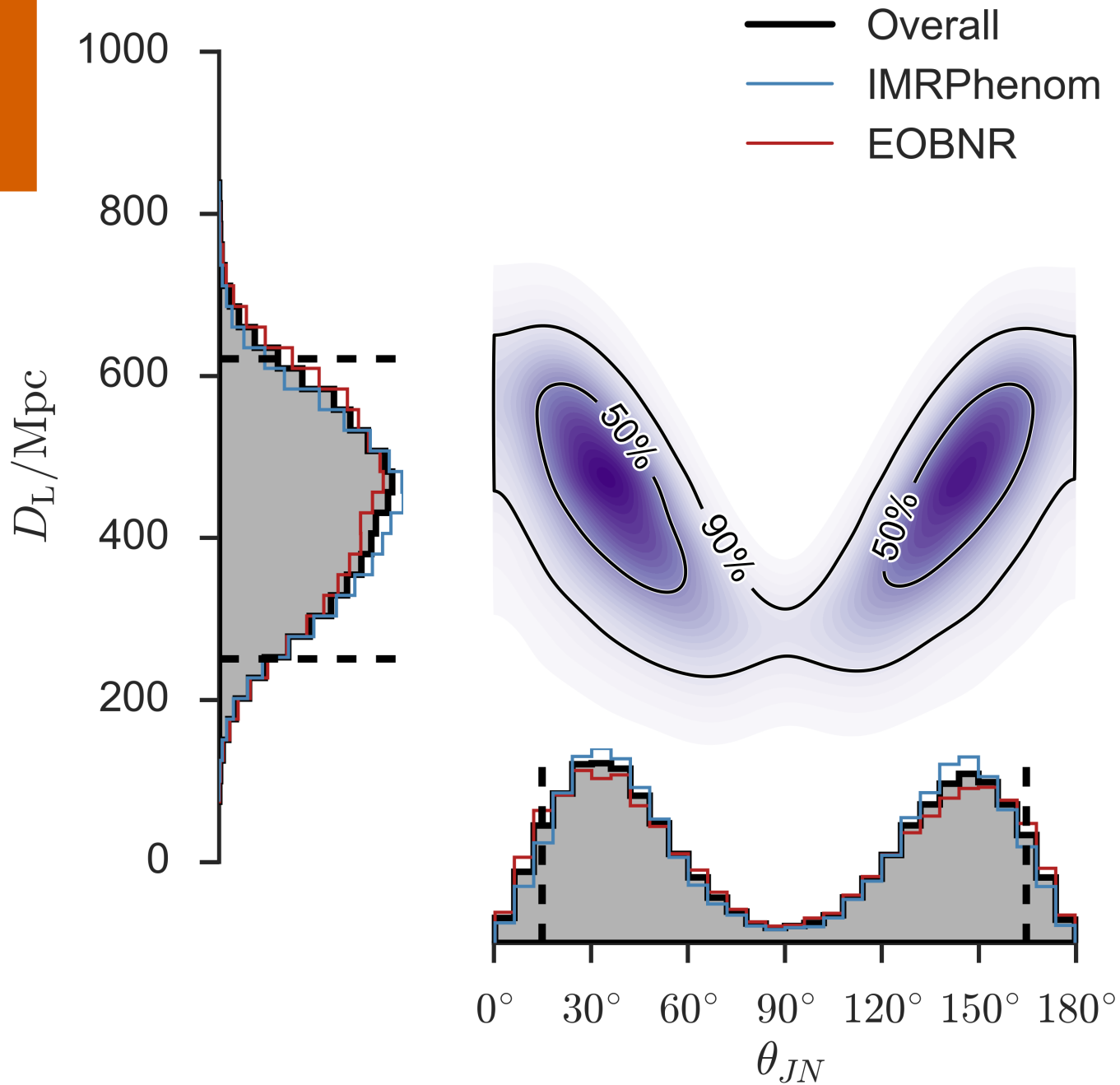


arXiv:1606.04856
arXiv:1602.03840


Distance




Distance







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

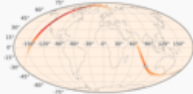
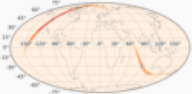
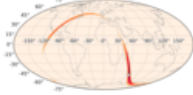
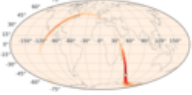


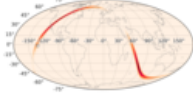
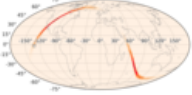
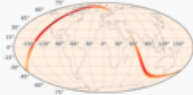
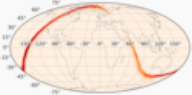
 [Singer et al. 2014](#)
arXiv:1404.5623

 [Berry et al. 2015](#)
arXiv:1411.6934

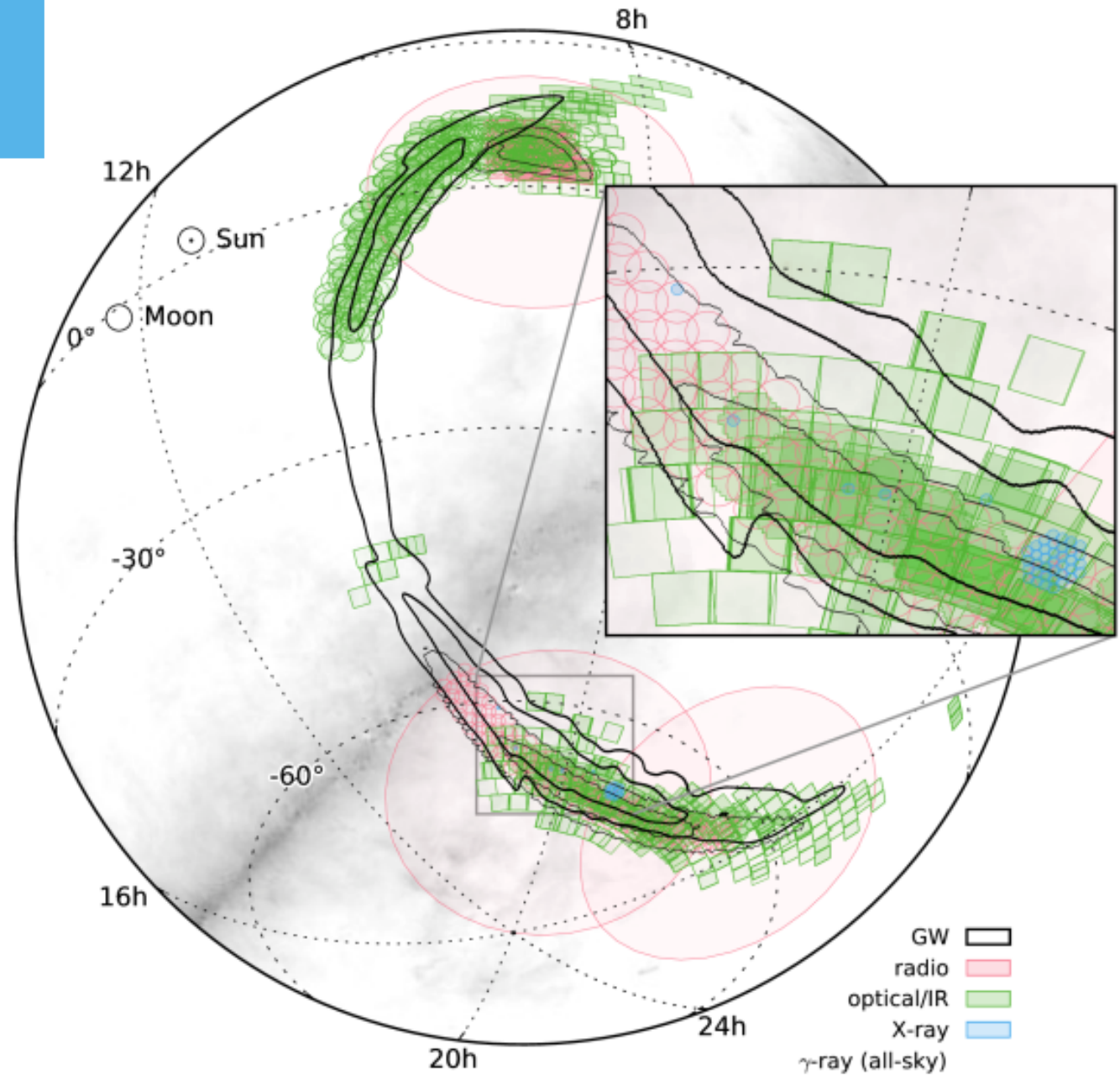
www.ligo.org/scientists/first2years/
asd.gsfc.nasa.gov/Leo.Singer/going-the-distance/

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.

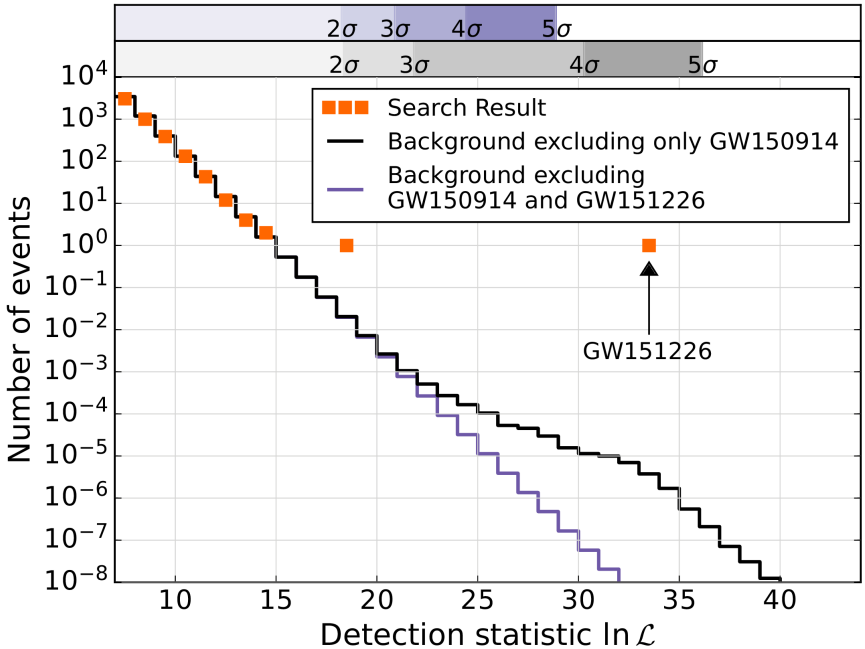
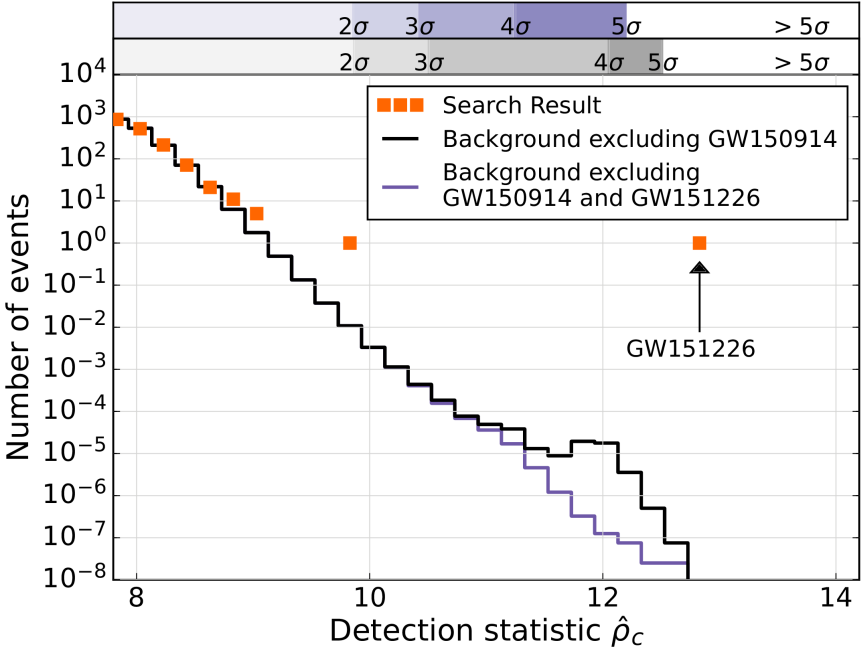
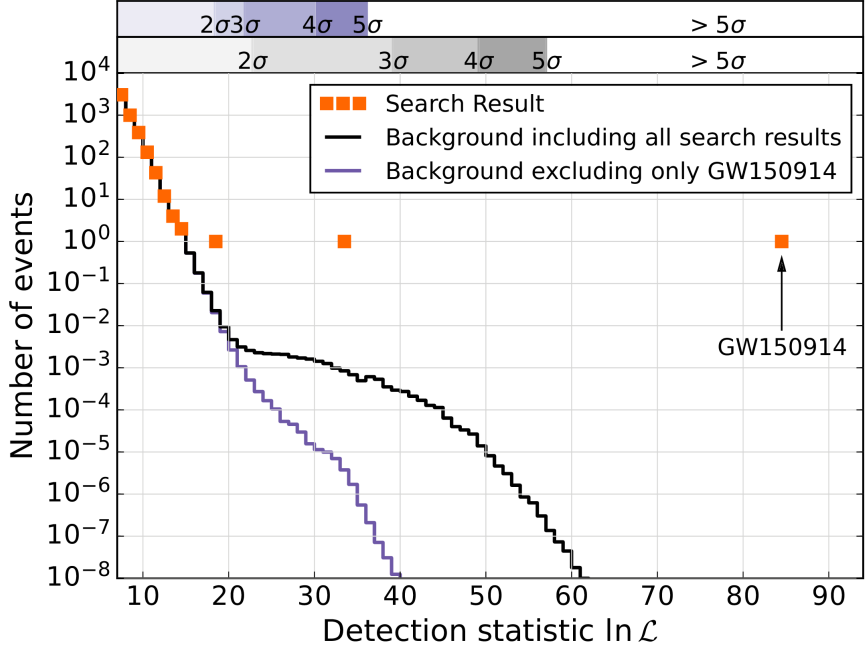
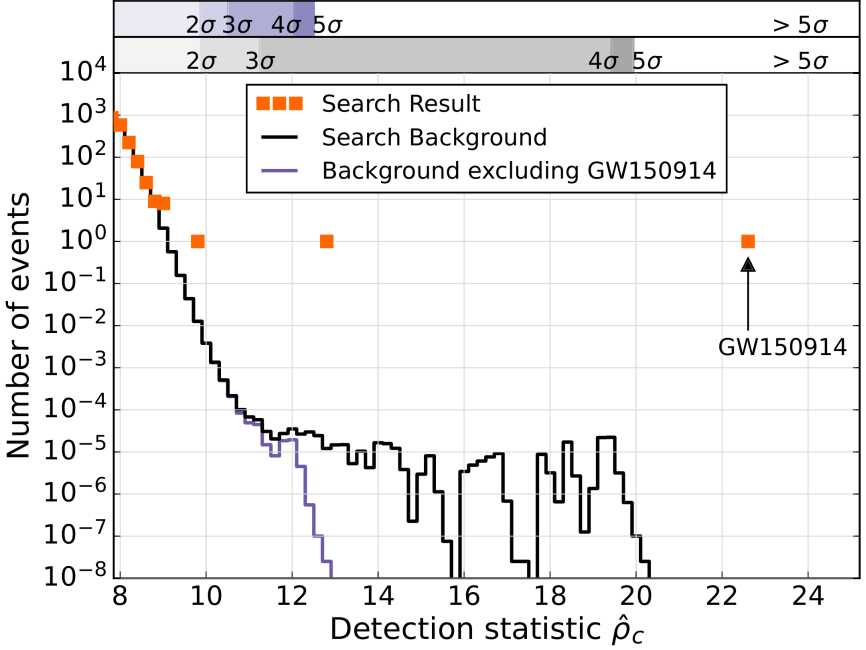
This web page provides additional online information related to the paper "Two Years of Electromagnetic Follow-Up with Advanced LIGO and Virgo" and the paper "Parameter Estimation for Binary Neutron Star Coalescences with Advanced LIGO and Virgo".

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		

Follow-up



arXiv:1602.08492
arXiv:1604.07864

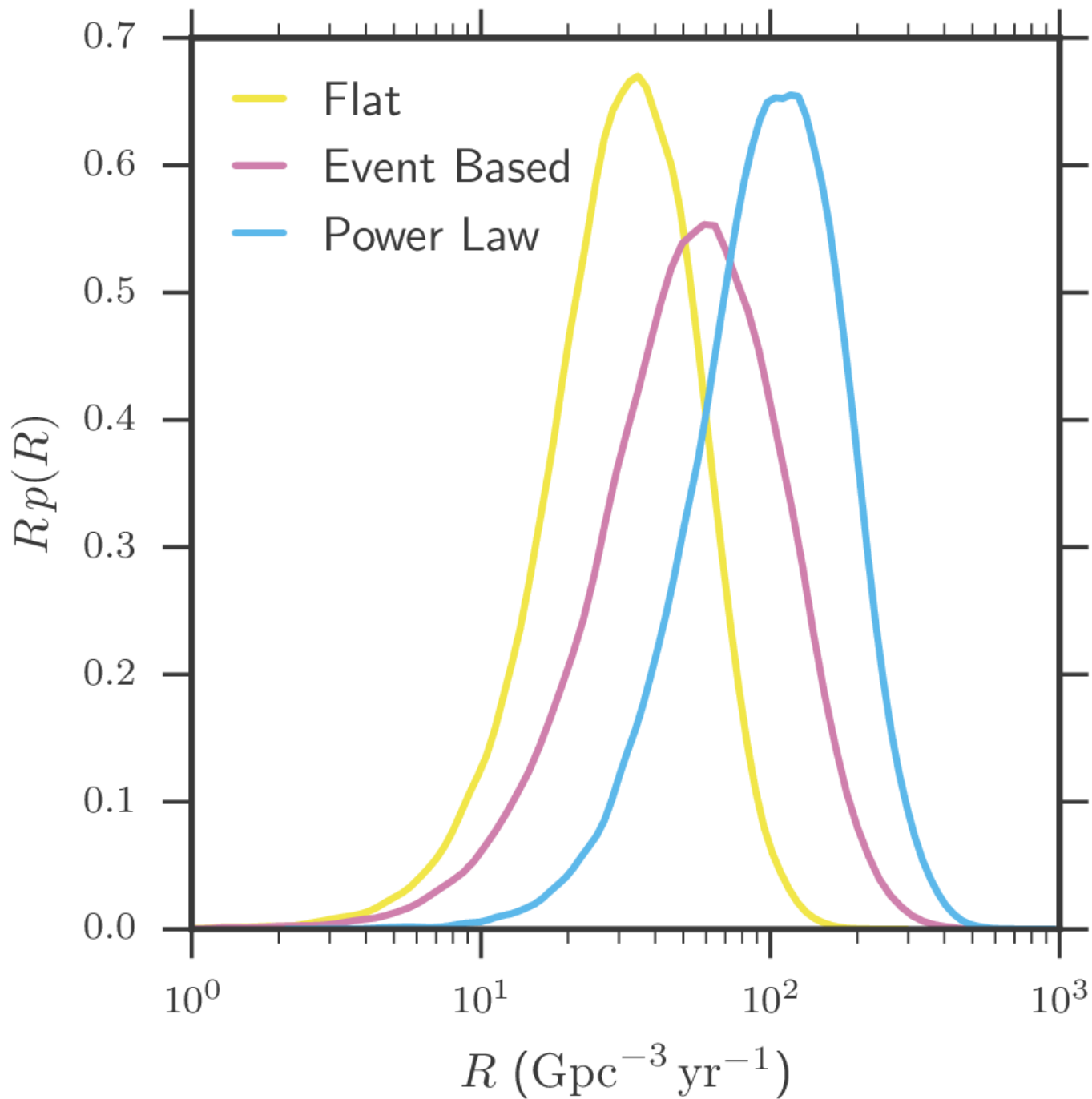




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**I WANT TO
BELIEVE**

Rates



arXiv:1606.04856
arXiv:1602.03842

