Binary black hole spins

Christopher Berry
University of Birmingham
@cplberry

On behalf of the
LIGO Scientific & Virgo Collaborations

In collaboration with Simon Stevenson & Ilya Mandel

DCC G1700741

GWPAW 2017

We have gravitational-wave observations of binary black holes

Gravitational-waves provide some constraints on black hole spins

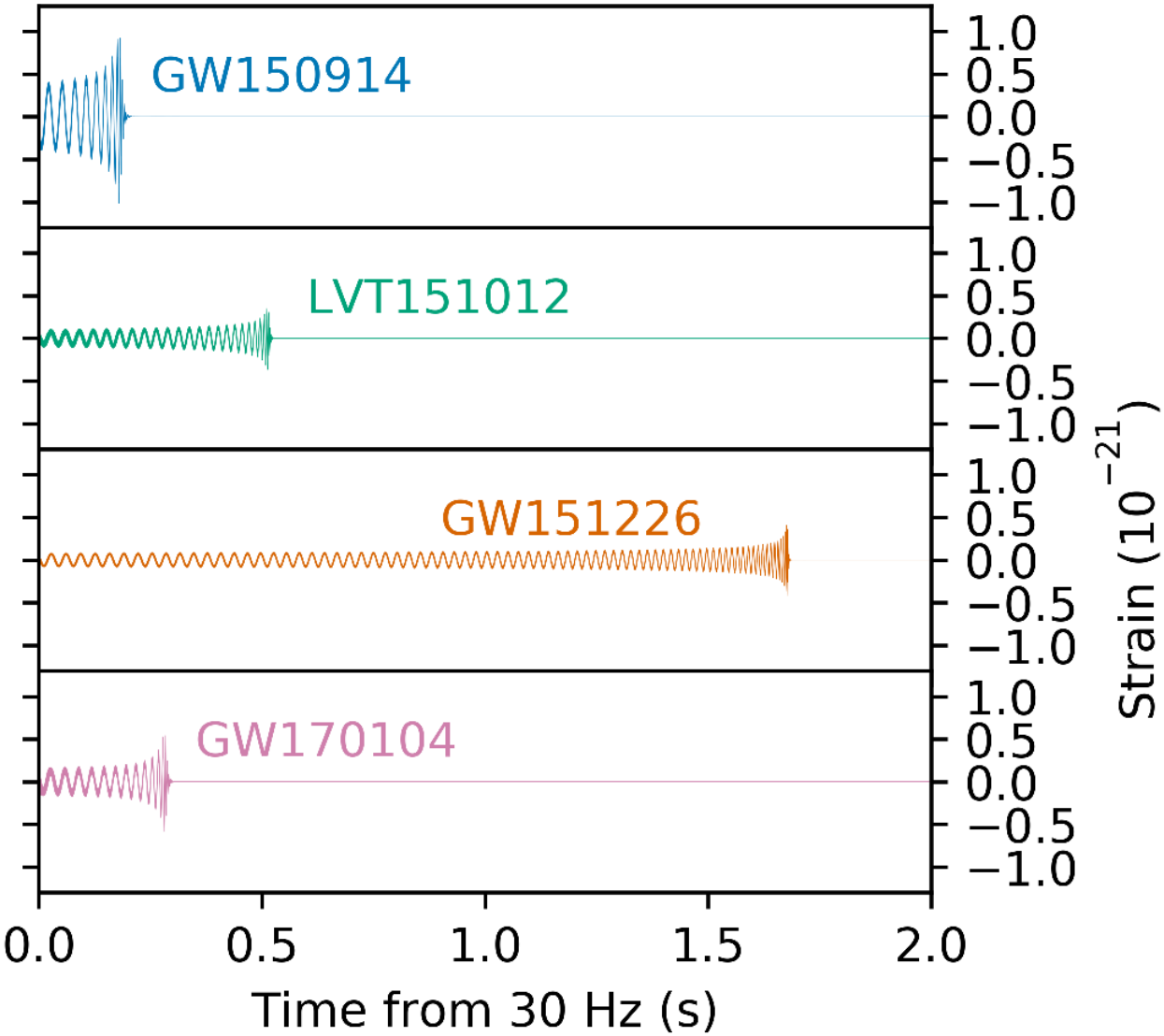
Spins could provide insight into formation and evolution

We have gravitational-wave observations of binary black holes

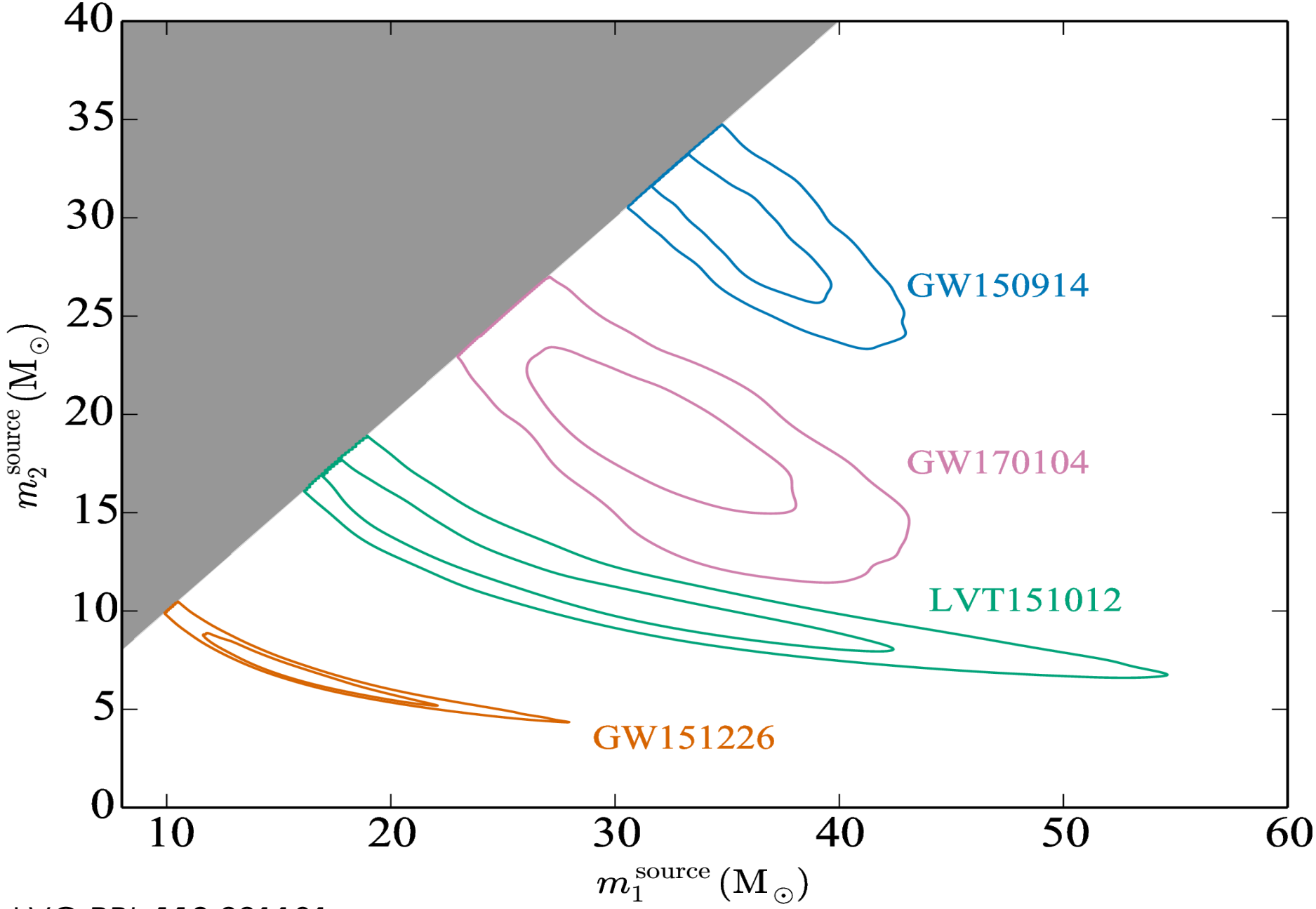
Gravitational-waves provide some constraints on black hole spins

Spins could provide insight into formation and evolution

Binary black hole signals



LVC
arXiv:1606.04856
PRL **118**:221101



LVC *PRL* **118**:221101

Credit: ButterflyLove1

We have gravitational-wave observations of binary black holes

Gravitational-waves provide some constraints on black hole spins

Spins could provide insight into formation and evolution

No hair theorem

Black holes have:

1. Mass
2. Spin
3. Electric charge

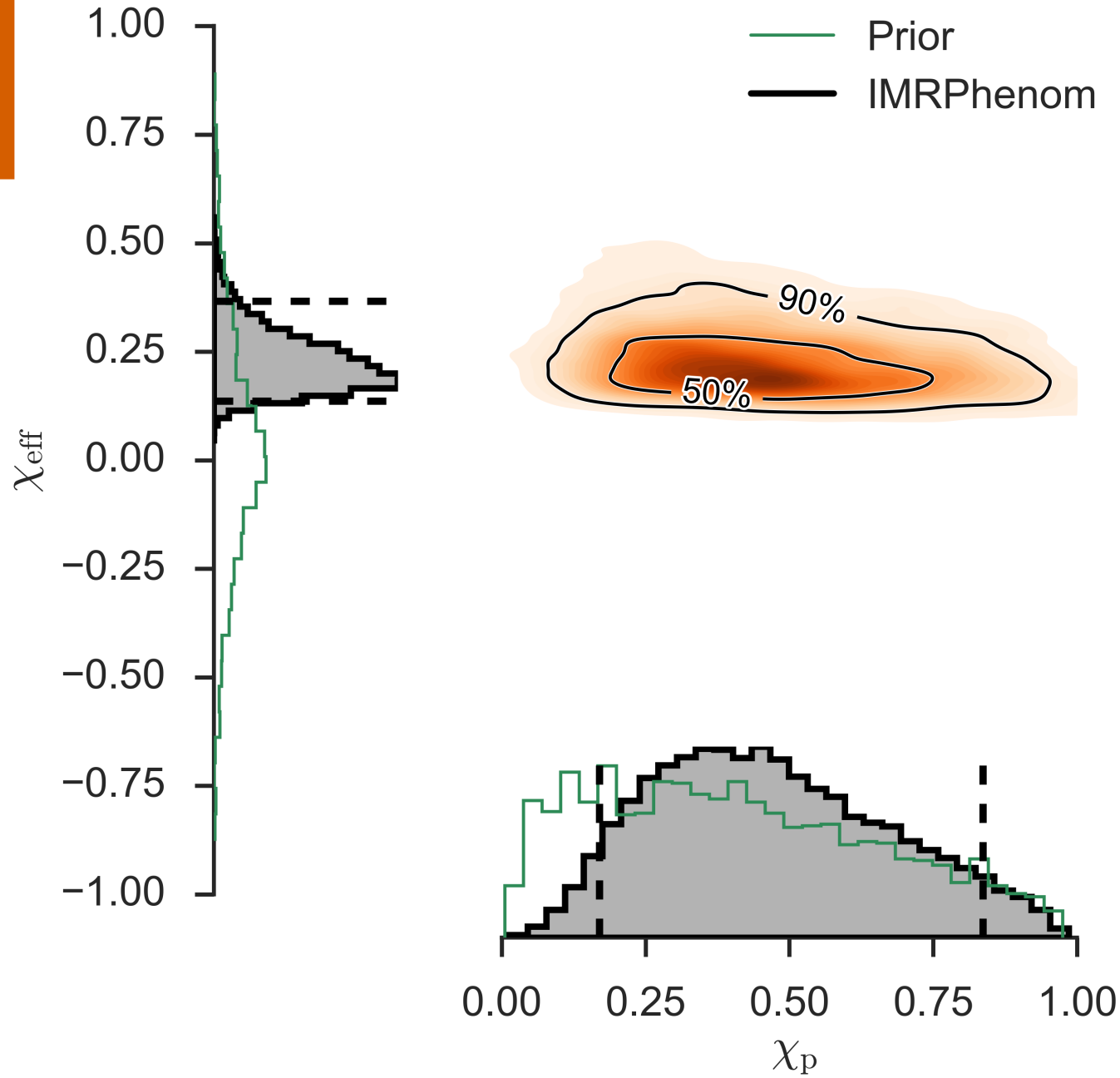
Image: Matt Groening

Effective inspiral spin

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

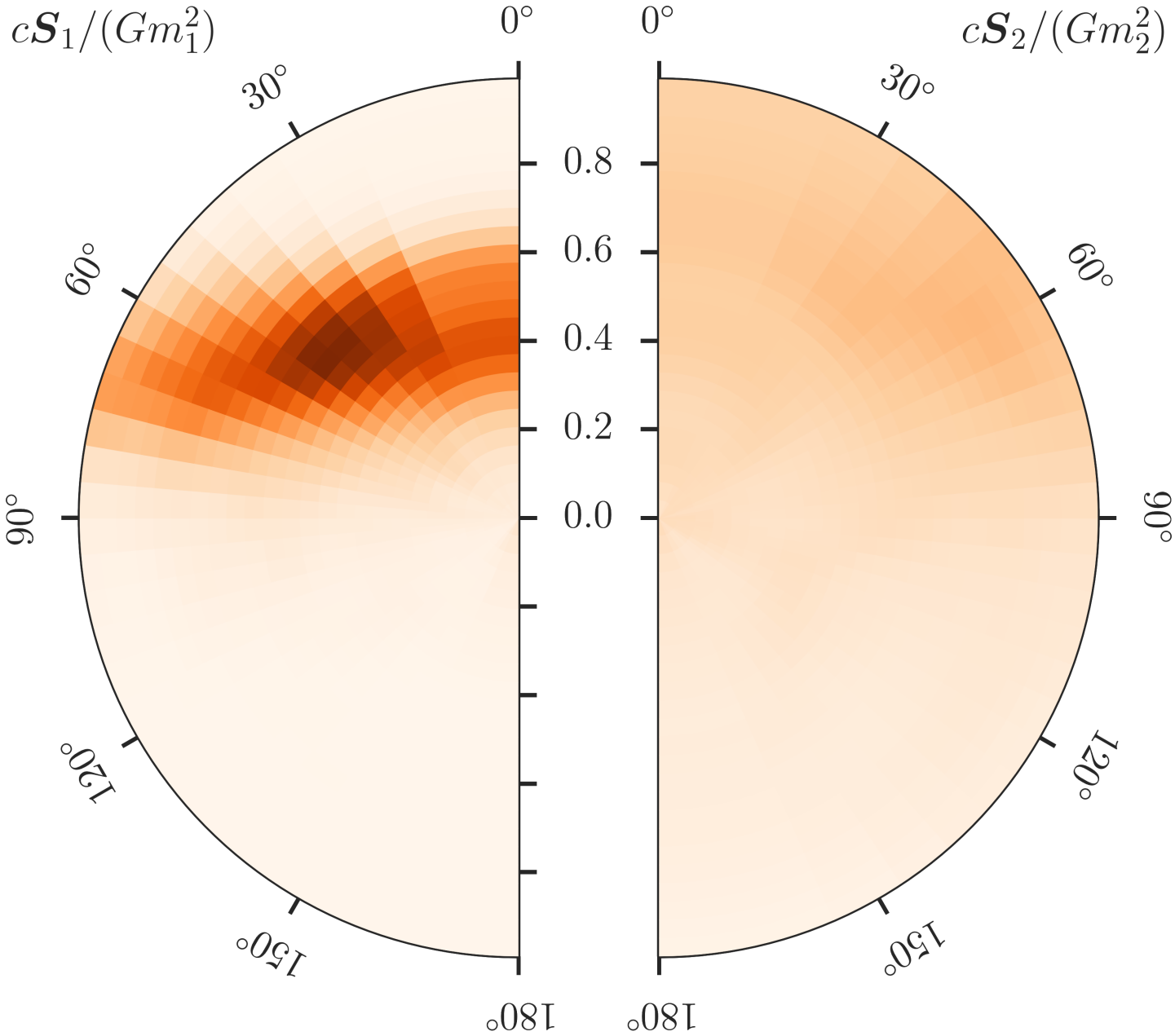
Most important combination of spins for evolution of inspiral (arXiv:0909.2867, 1005.3306)

Spin



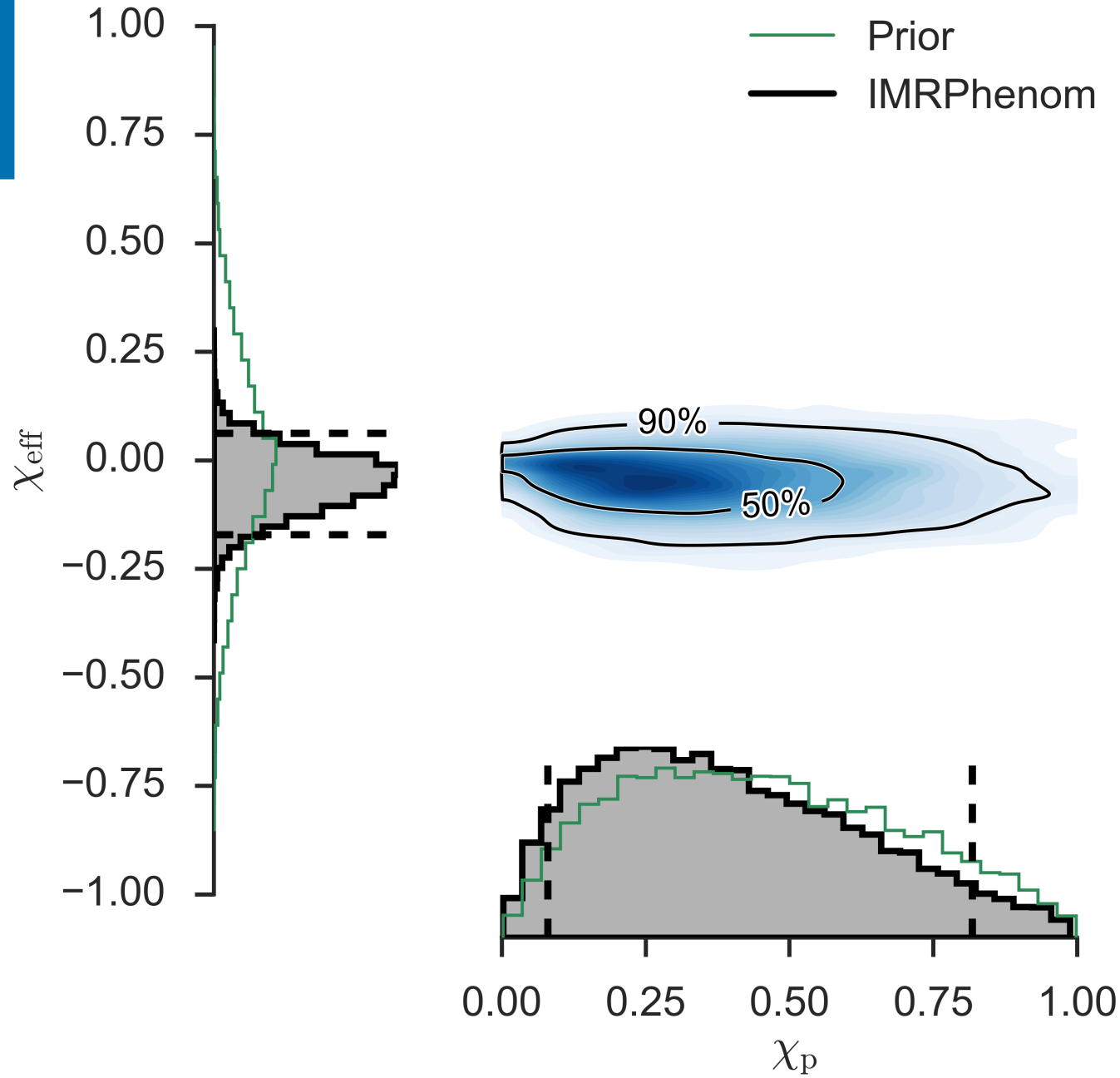
LVC
arXiv:1606.04856

Spin



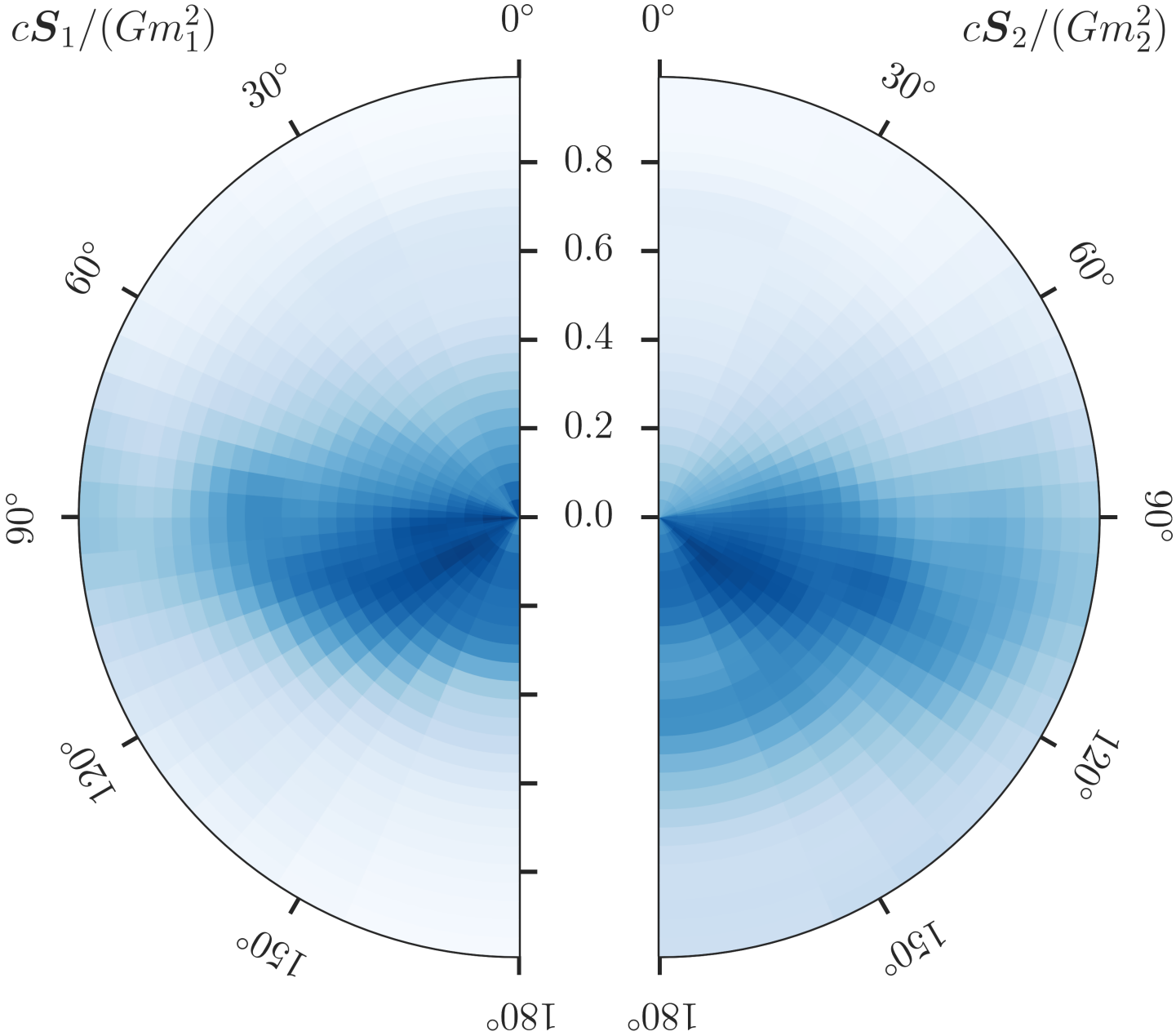
LVC
arXiv:1606.04855

Spin



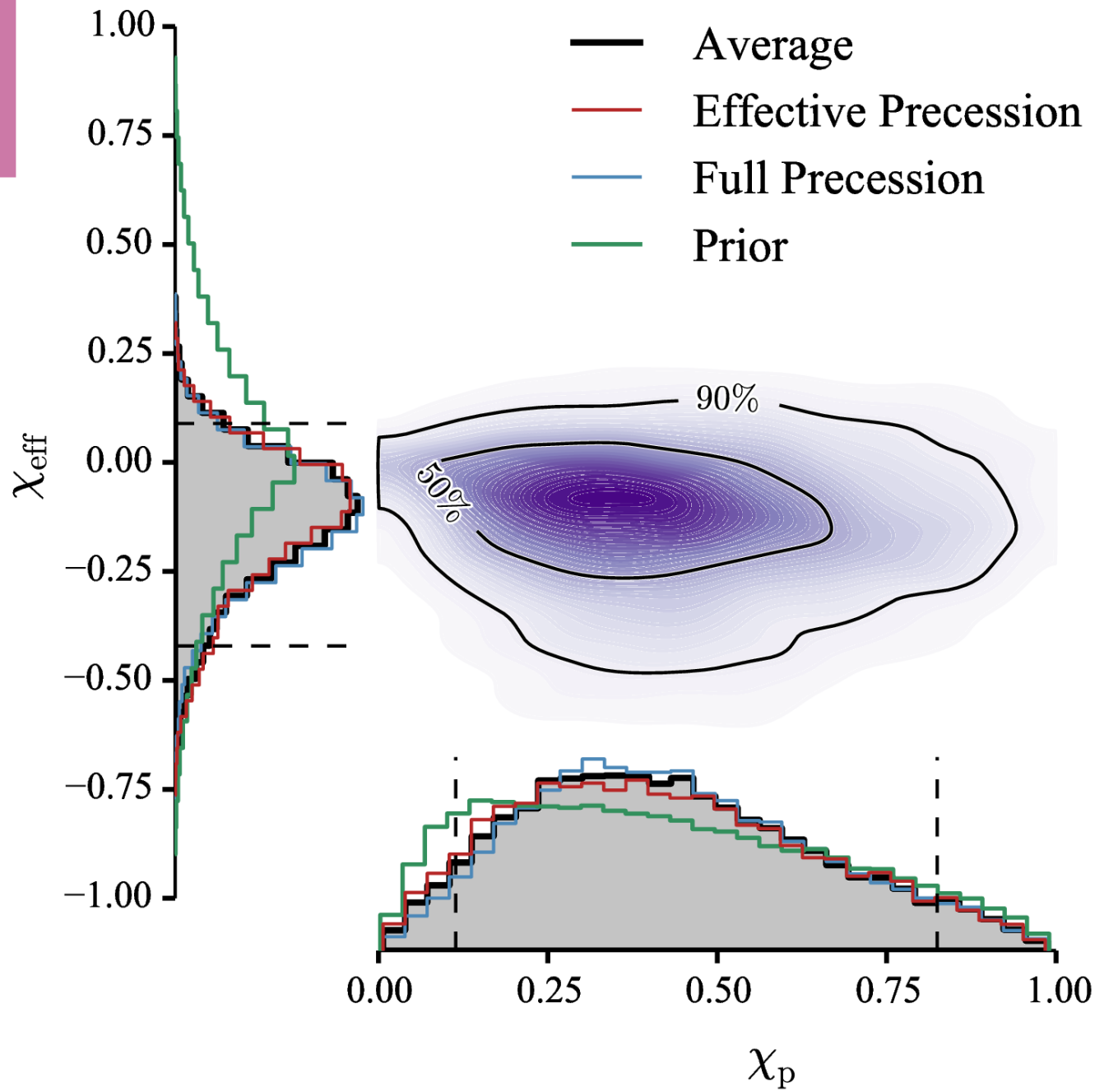
LVC
arXiv:1606.04856
arXiv:1602.03840

Spin



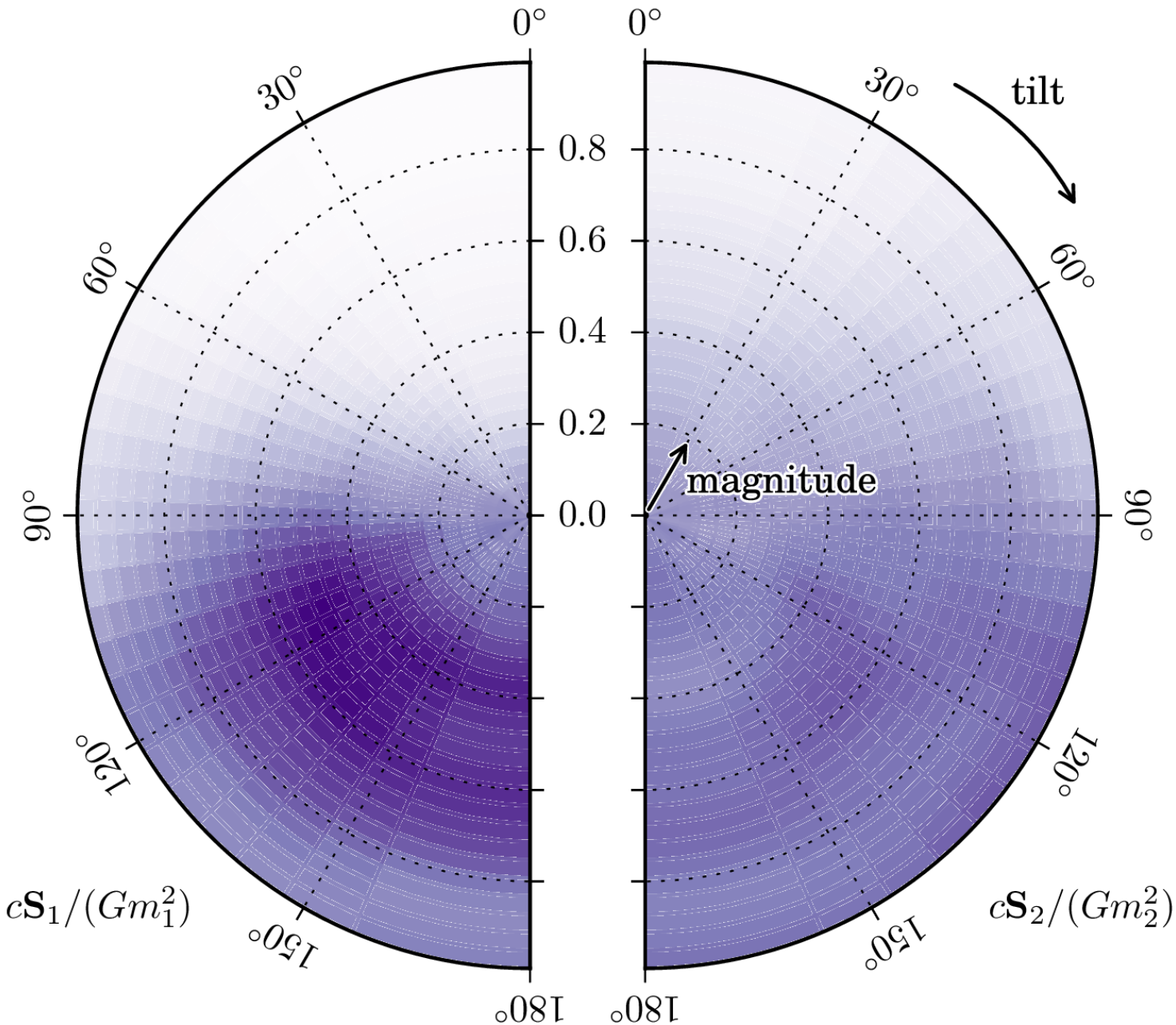
LVC
arXiv:1606.04856
arXiv:1602.03840

Spin



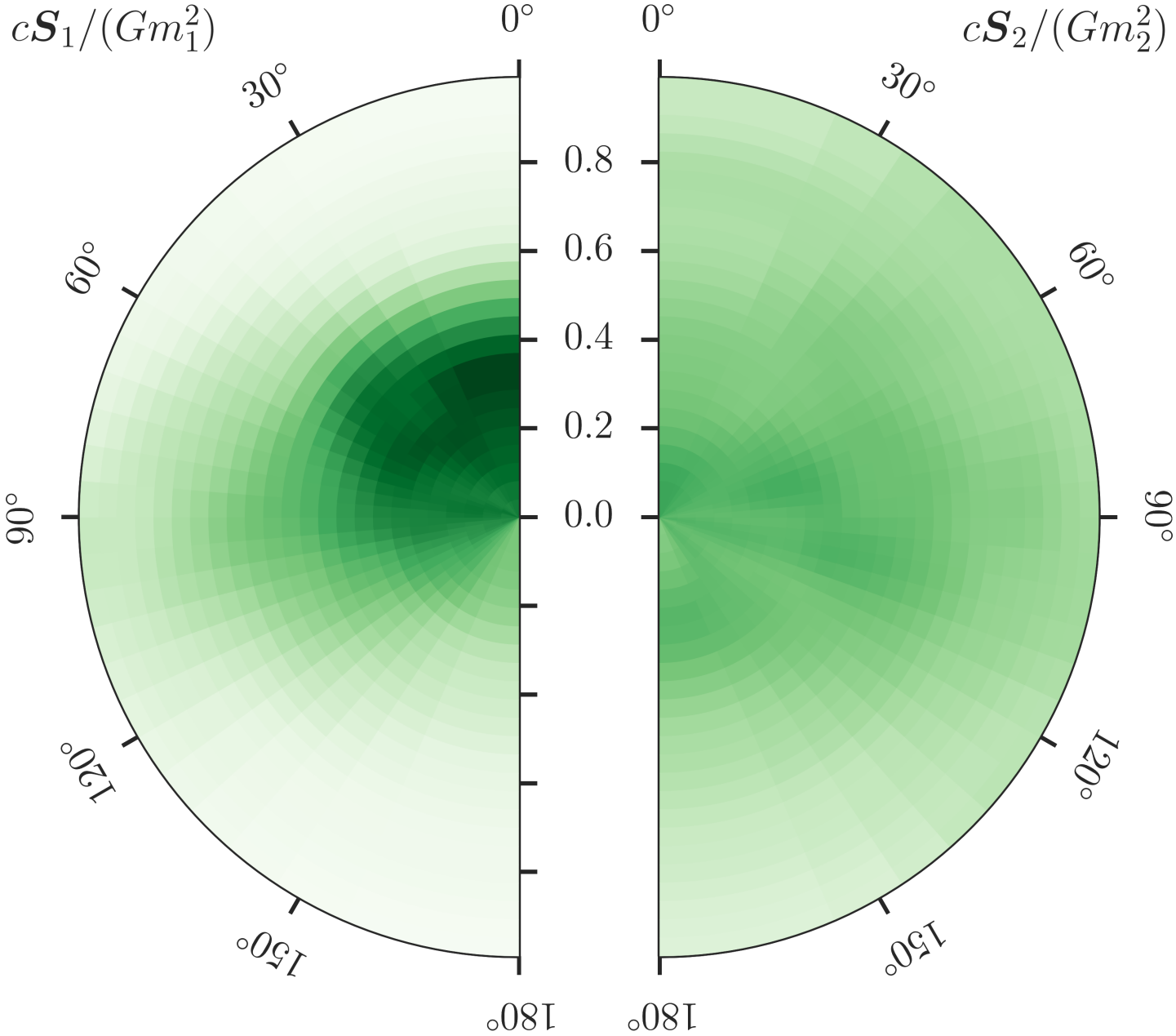
LVC
PRL **118**:221101

Spin

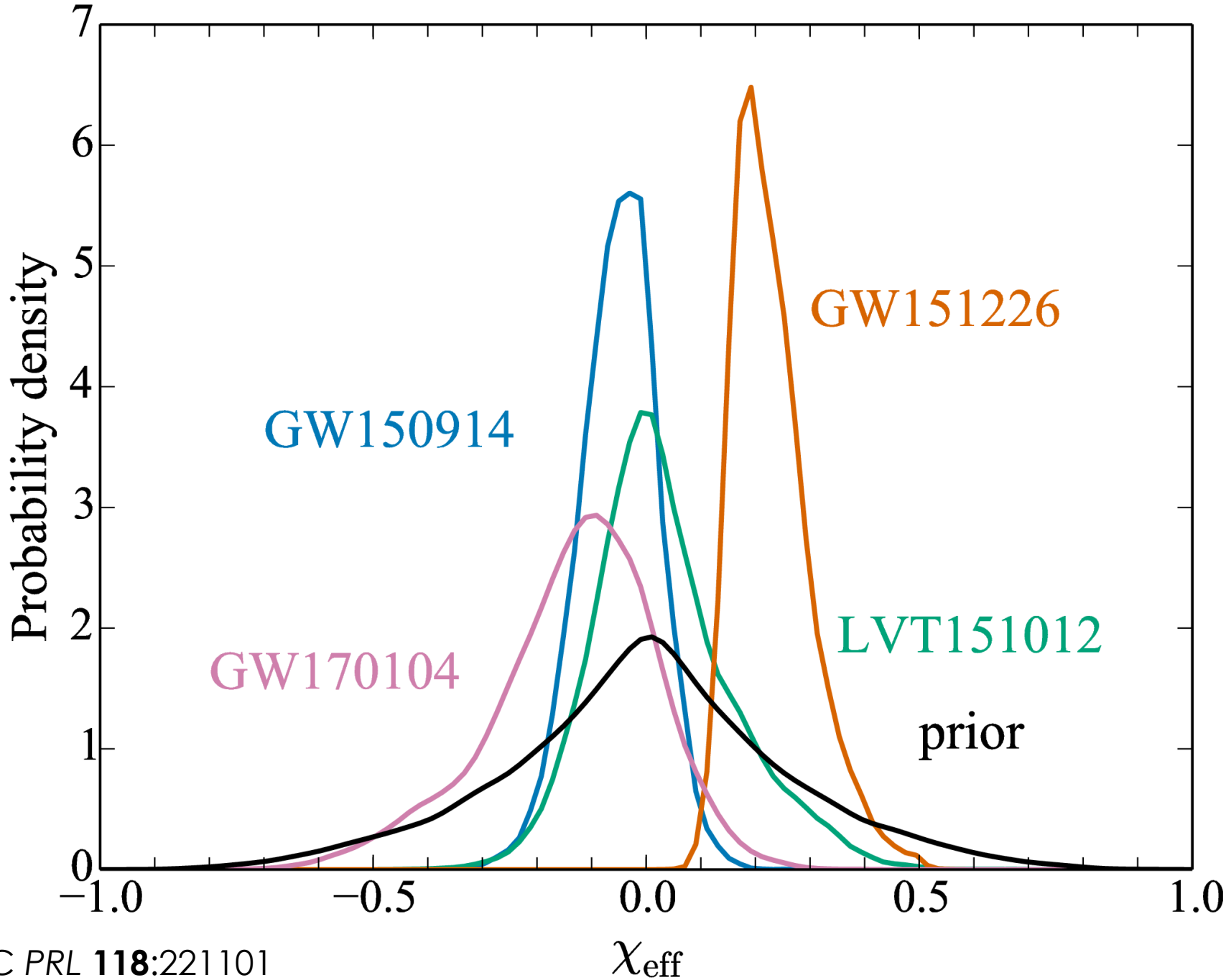


LVC
PRL **118**:221101

Spin



LVC
arXiv:1606.04856



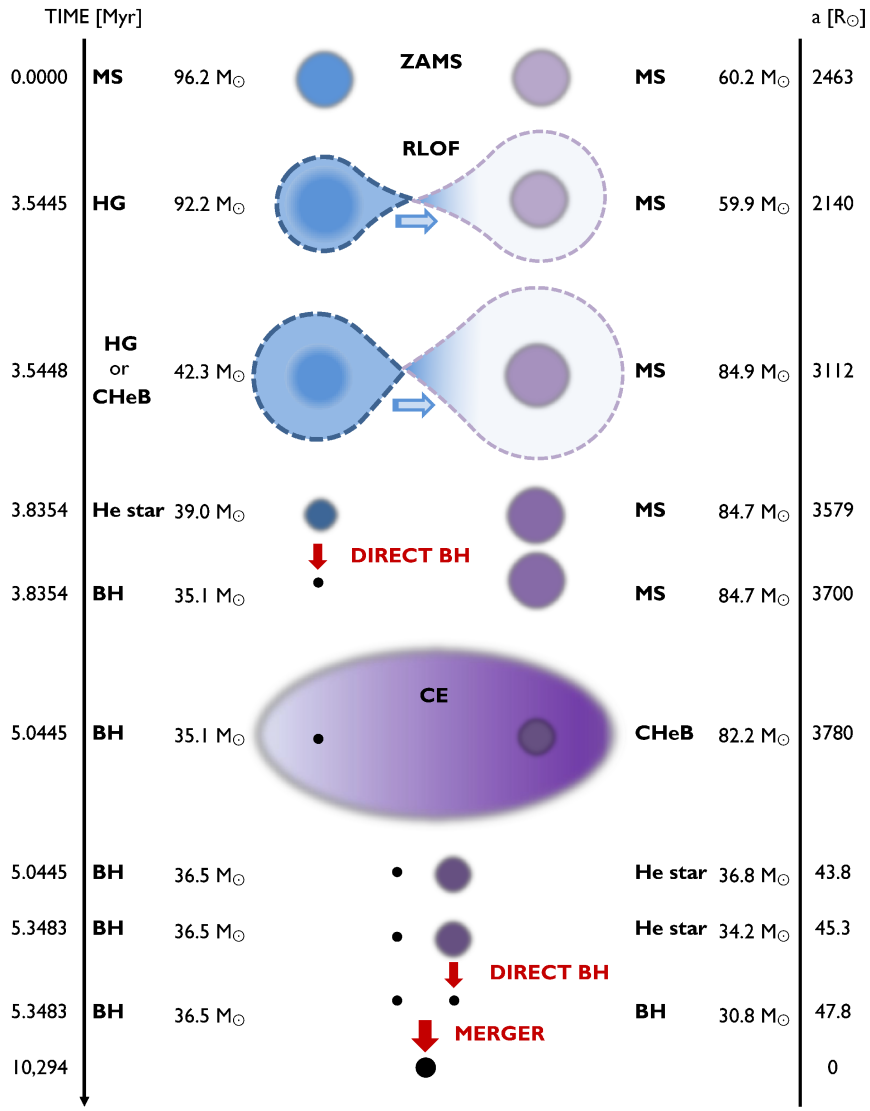
LVC *PRL* **118**:221101

We have gravitational-wave observations of binary black holes

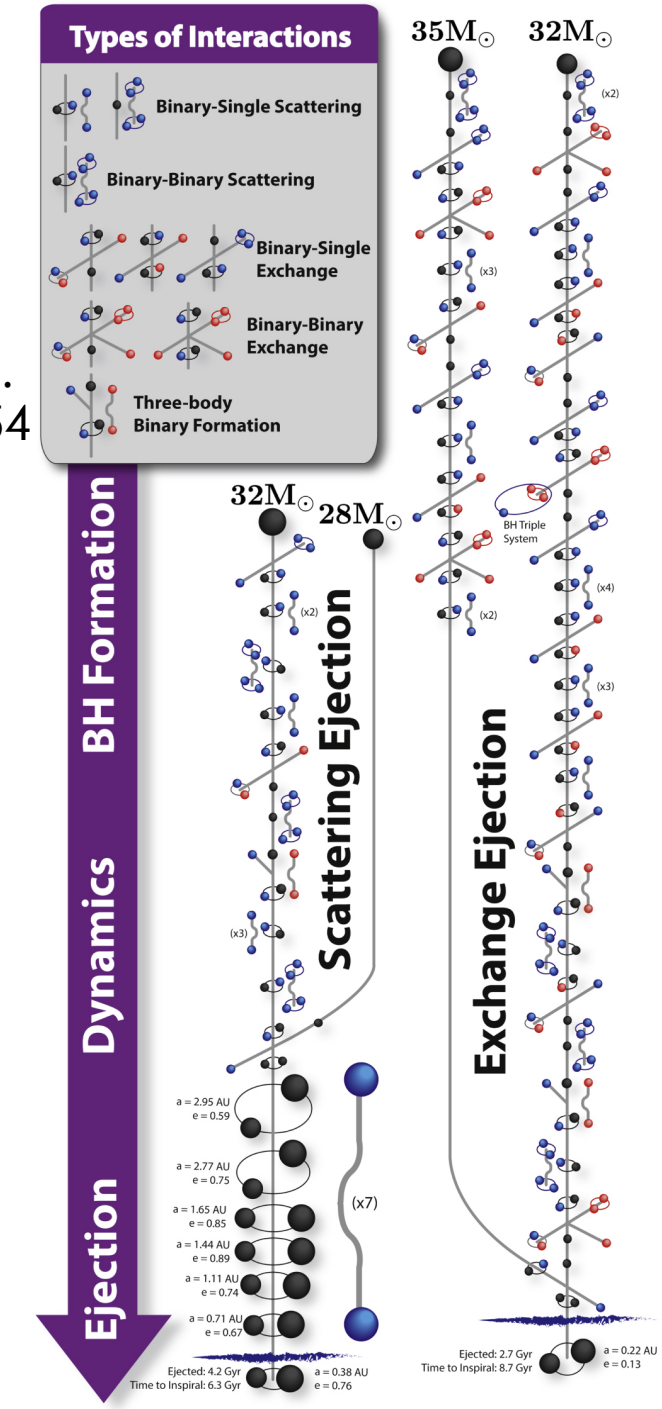
Gravitational-waves provide some constraints on black hole spins

Spins could provide insight into formation and evolution

Binary formation



Rodriguez *et al.*
arXiv:1604.04254



Belczynski *et al.*
arXiv:1602.04531

Hierarchical analysis

arXiv.org > astro-ph > arXiv:1703.06873

Astrophysics > High Energy Astrophysical Phenomena

Hierarchical analysis of gravitational-wave measurements of binary black hole spin-orbit misalignments

Simon Stevenson, Christopher P. L. Berry, Ilya Mandel

(Submitted on 20 Mar 2017)

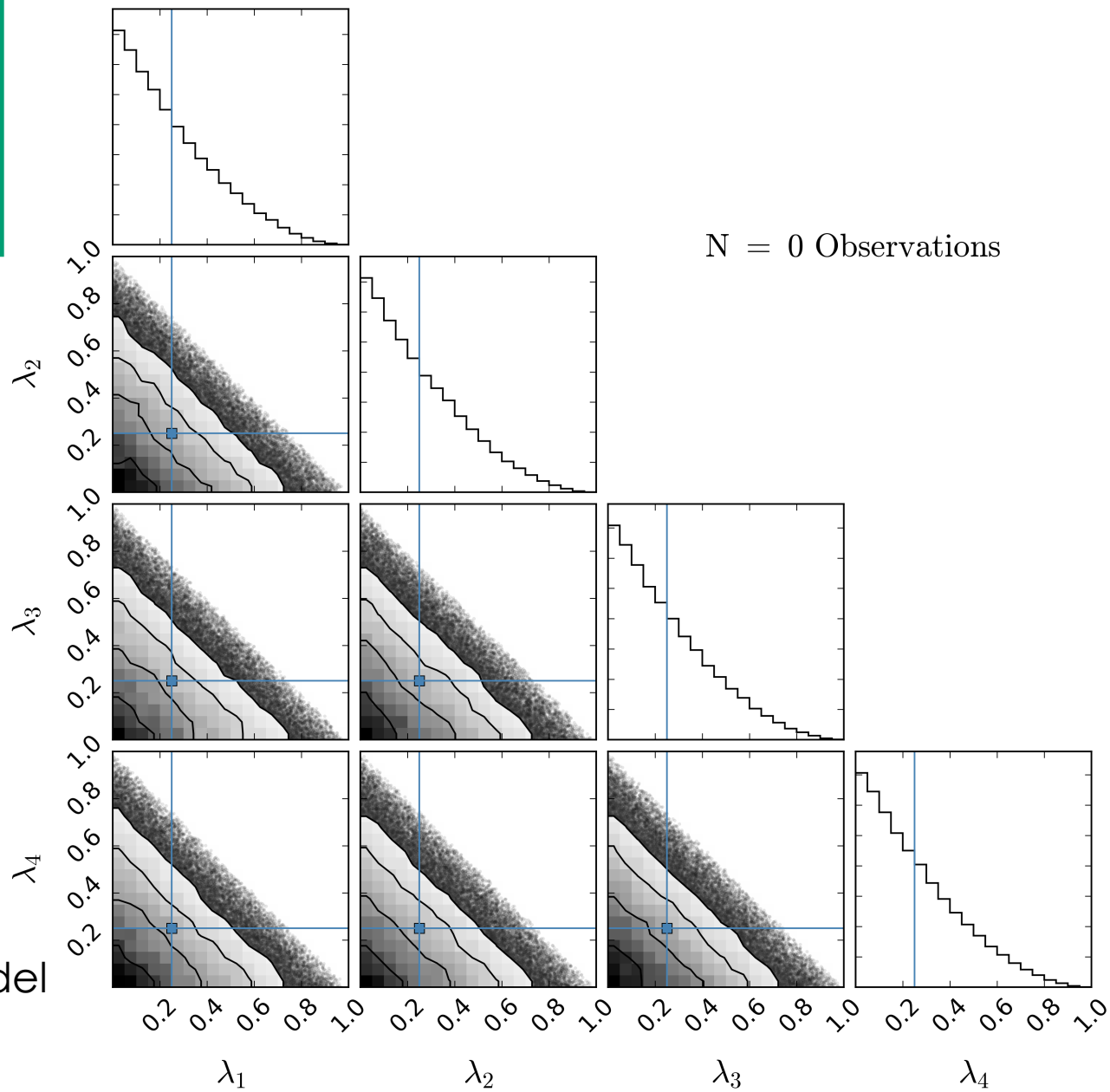
Black hole binaries may form both through isolated binary evolution and through dynamical interactions in dense stellar environments. During the formation and evolution of isolated binaries, several processes can alter the orientation of the black hole spin vectors with
ge through the emission of gravitational radiation
ational waves from these systems directly encode
nstrained. Identifying sub-populations of spinning
ially shedding light on the ratio of dynamically

odelled under a range of assumptions. We then
f these populations. We show that with tens of
scing binary black holes based on their spin
alescing binary black holes with isotropic spin
directions (corresponding to dynamical formation) with a fractional uncertainty of $\sim 40\%$. Meanwhile, only ~ 5 observations are sufficient to distinguish between extreme models---all binary black holes either having exactly aligned spins or isotropic spin directions---if all black holes are rapidly spinning ($\chi \sim 0.7$).

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

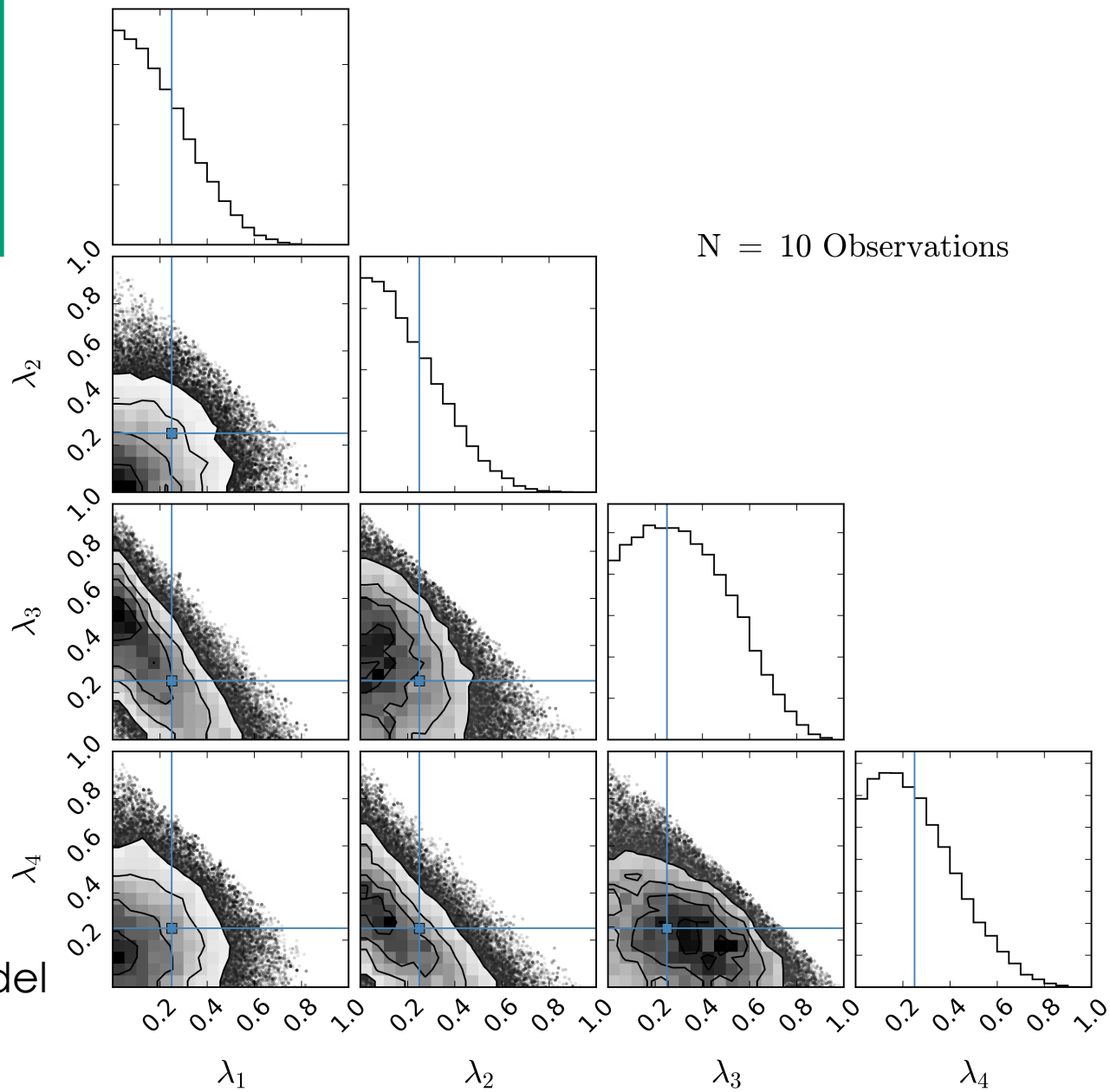
Comments: 11 pages, 8 figures. Submittied to MNRAS
Subjects: **High Energy Astrophysical Phenomena (astro-ph.HE)**
Cite as: **arXiv:1703.06873 [astro-ph.HE]**
(or **arXiv:1703.06873v1 [astro-ph.HE]** for this version)

Model inference



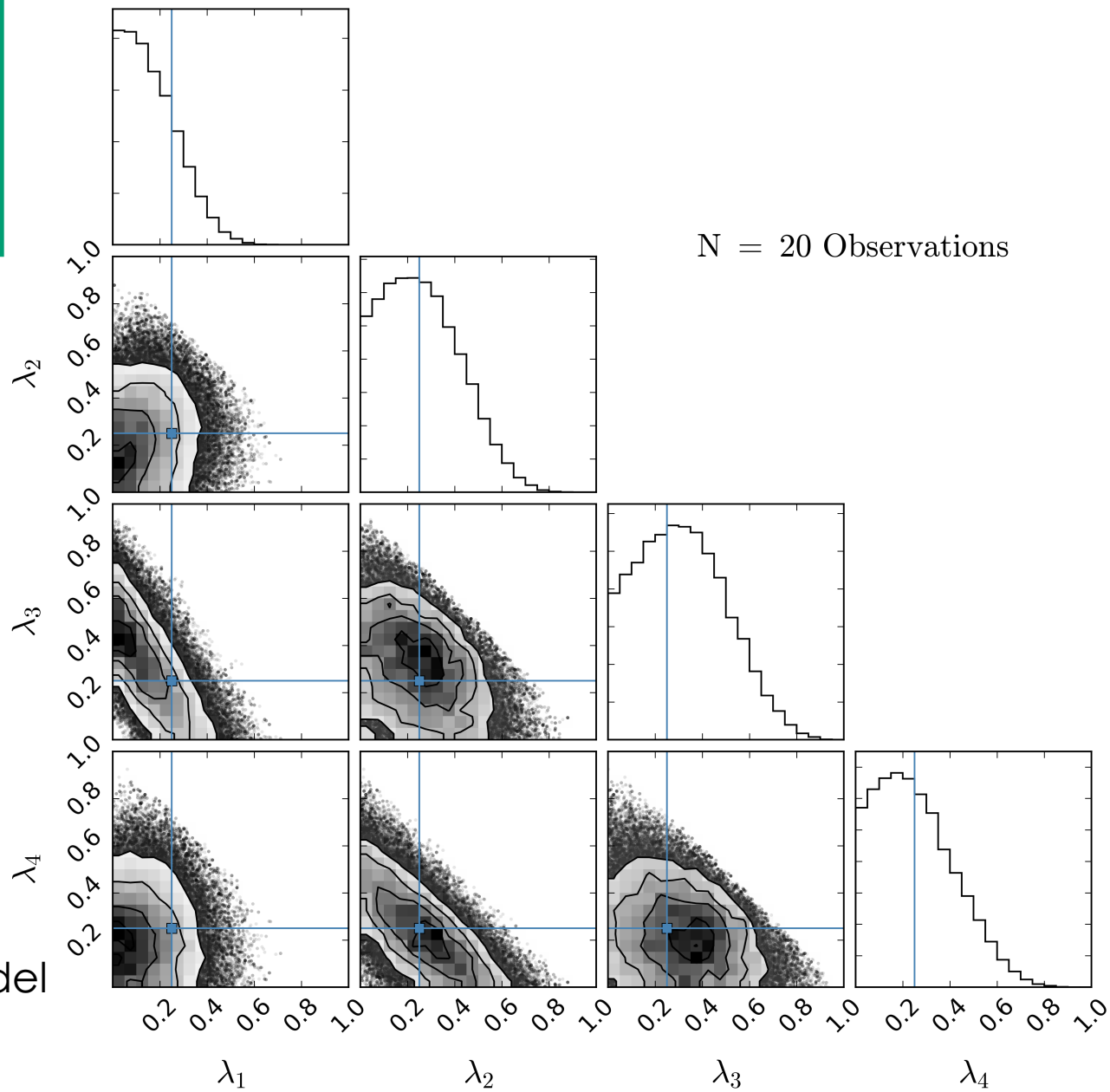
Stevenson, CPLB & Mandel
arXiv:1703.06873

Model inference



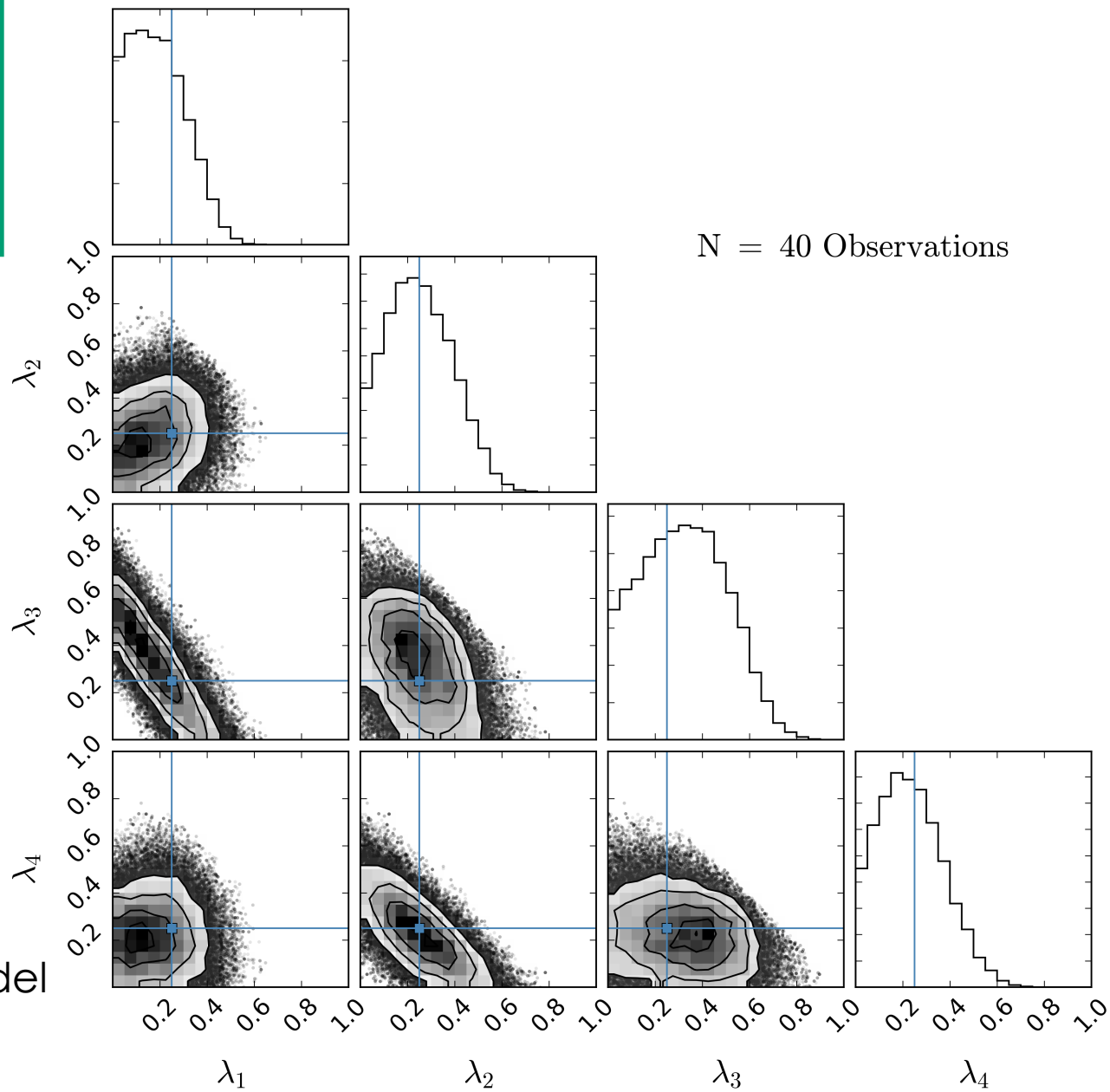
Stevenson, CPLB & Mandel
arXiv:1703.06873

Model inference



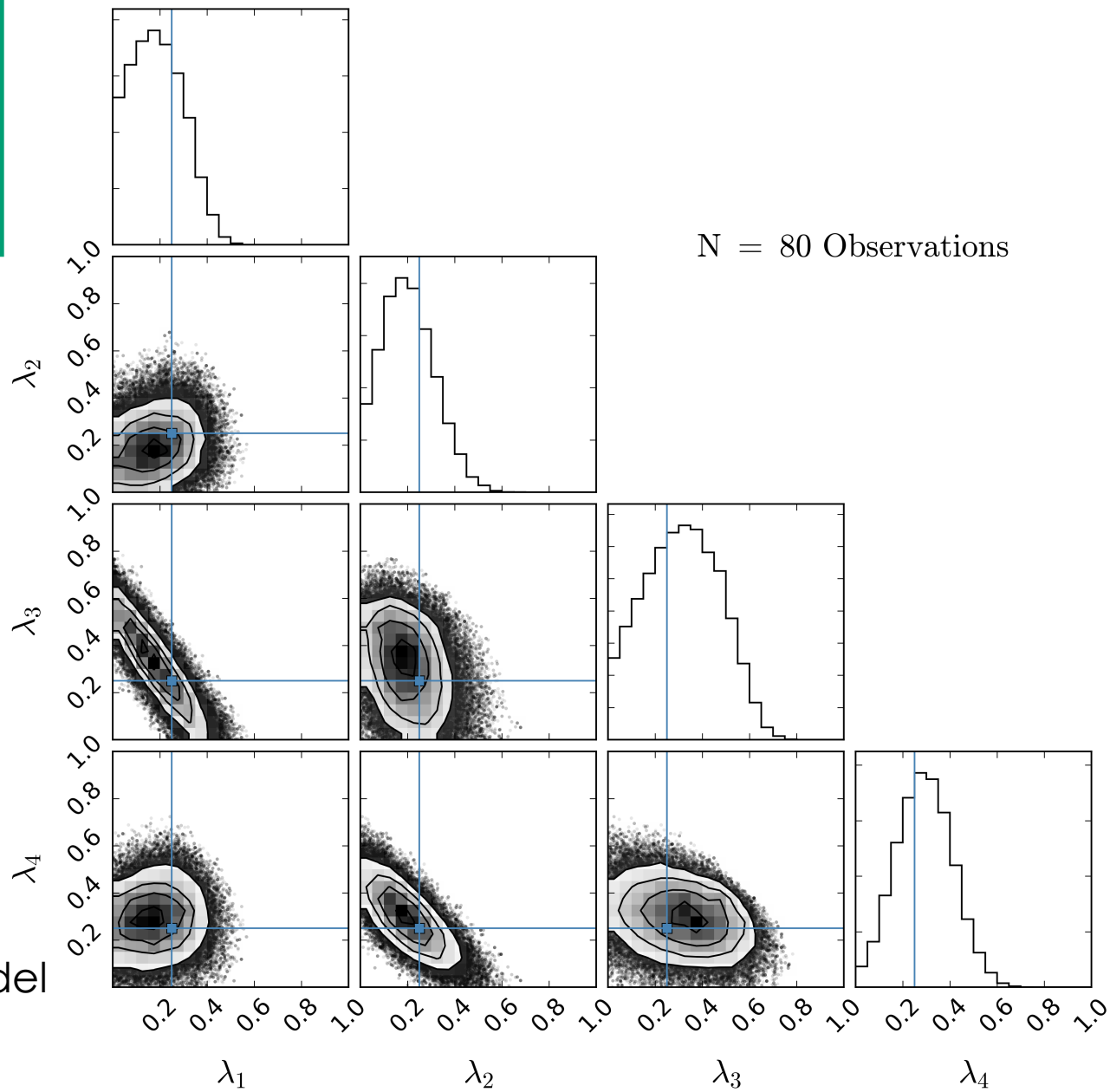
Stevenson, CPLB & Mandel
arXiv:1703.06873

Model inference



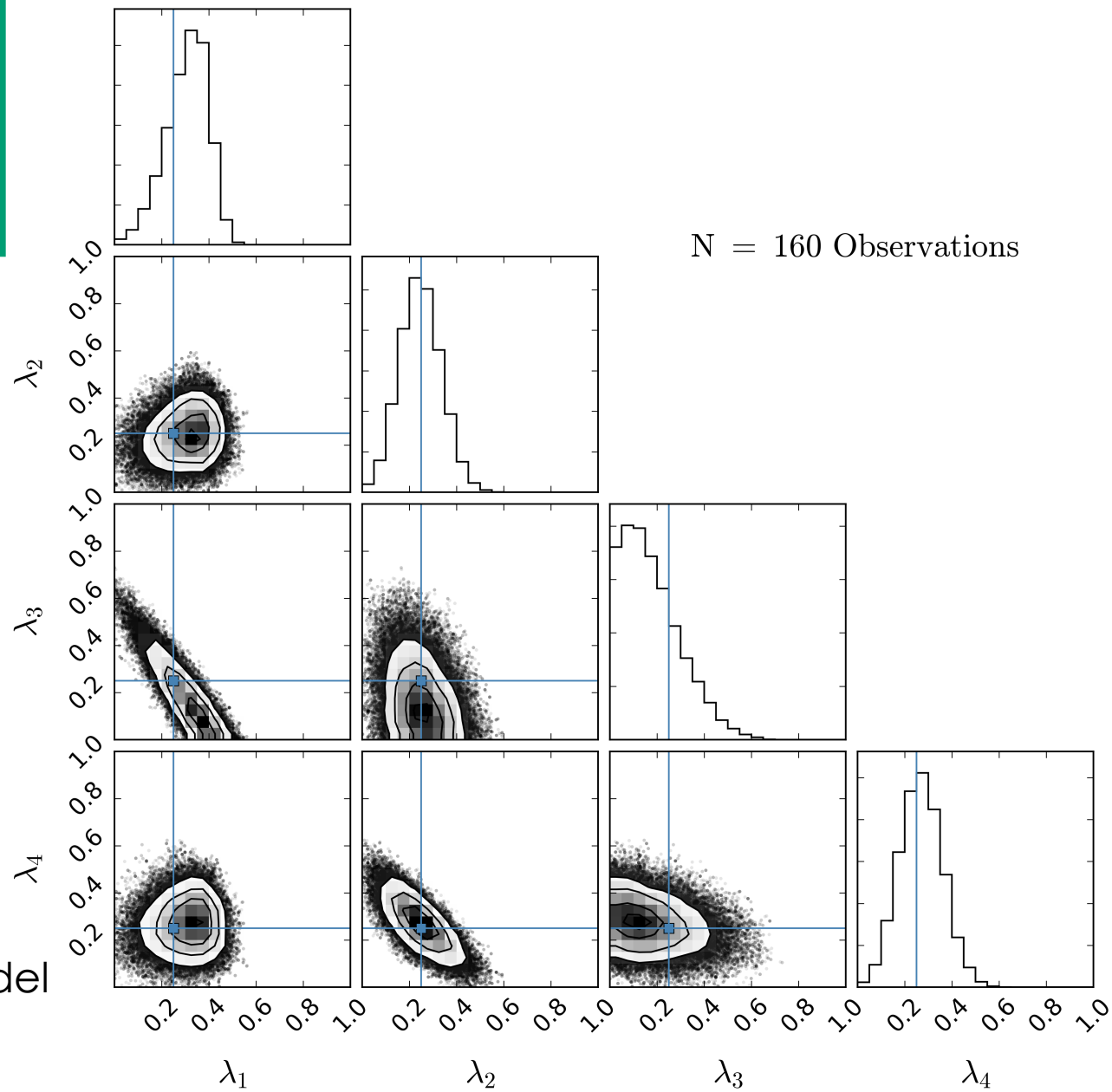
Stevenson, CPLB & Mandel
arXiv:1703.06873

Model inference



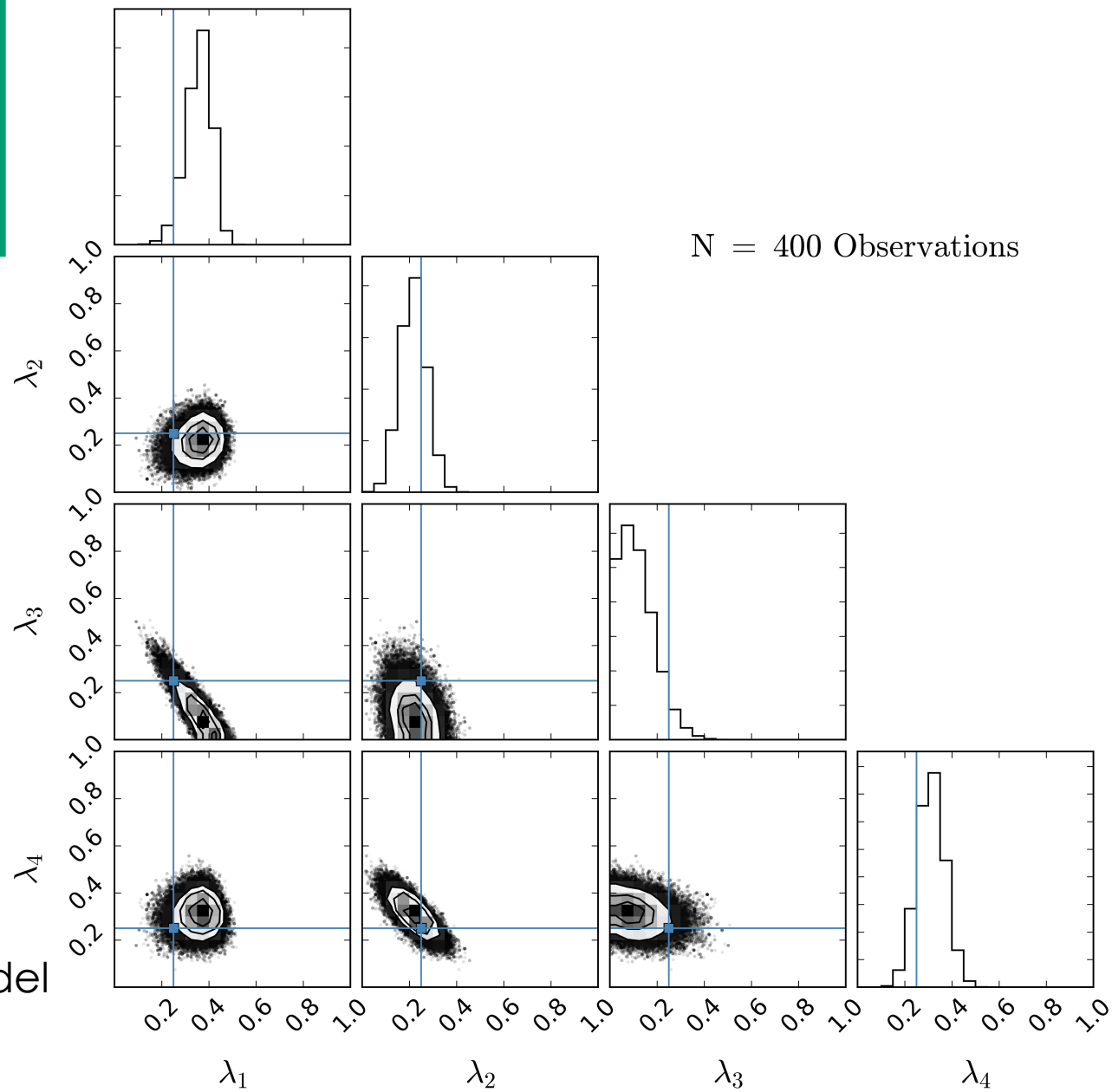
Stevenson, CPLB & Mandel
arXiv:1703.06873

Model inference



Stevenson, CPLB & Mandel
arXiv:1703.06873

Model inference



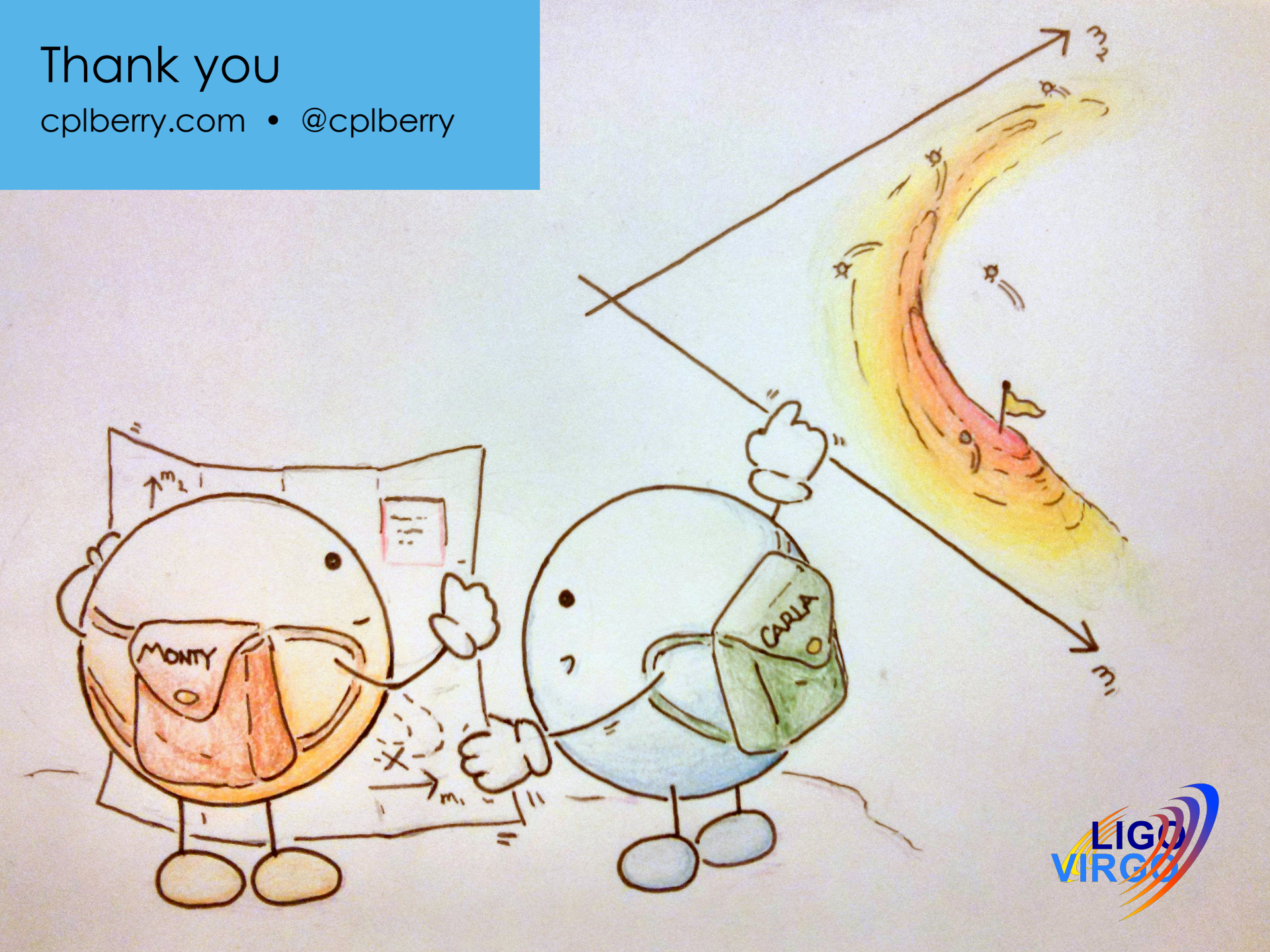
Stevenson, CPLB & Mandel
arXiv:1703.06873

- We observe binary black holes with gravitational waves
- Spins are difficult to measure but informative
- Need a hierarchical analysis of the population
- Different spins distinguishable after a few detections
- Hard to resolve similar spin populations

LVC arXiv:1602.03840 arXiv:1602.03846 arXiv:1606.04856 *PRL* **118**:221101
Stevenson, CPLB & Mandel arXiv:1703.06873

Thank you

cplberry.com • @cplberry



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

Bayes' theorem

$$\underbrace{\boxed{p(\theta|d,\lambda)}}_{\text{Posterior}} = \frac{\overbrace{\boxed{p(d|\theta,\lambda)}}^{\text{Likelihood}}\ \overbrace{\boxed{p(\theta|\lambda)}}^{\text{Prior}}}{\underbrace{\boxed{p(d|\lambda)}}_{\text{Evidence}}}$$

Bayes' theorem

Evidence

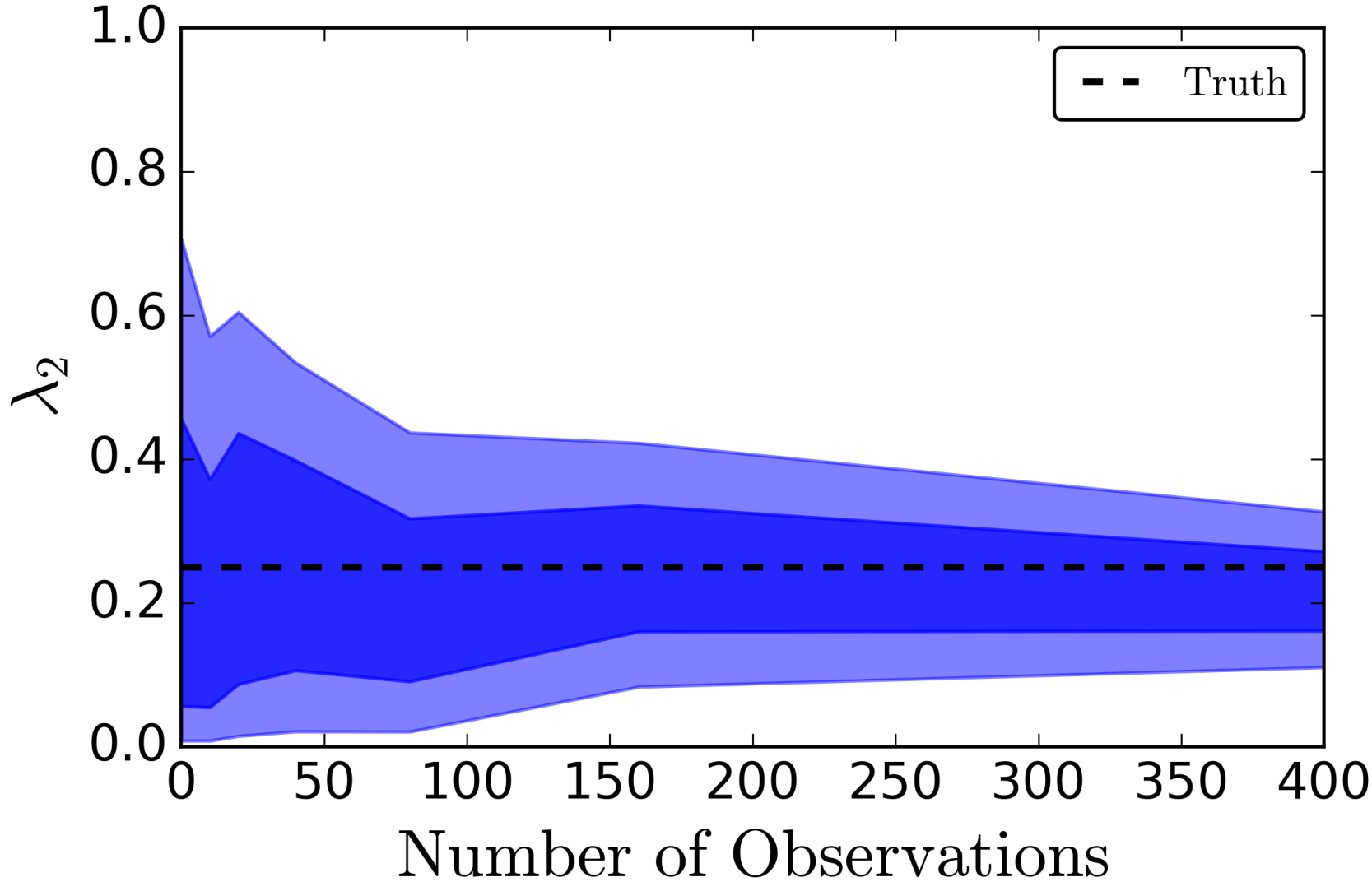
Model prior

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

Model posterior

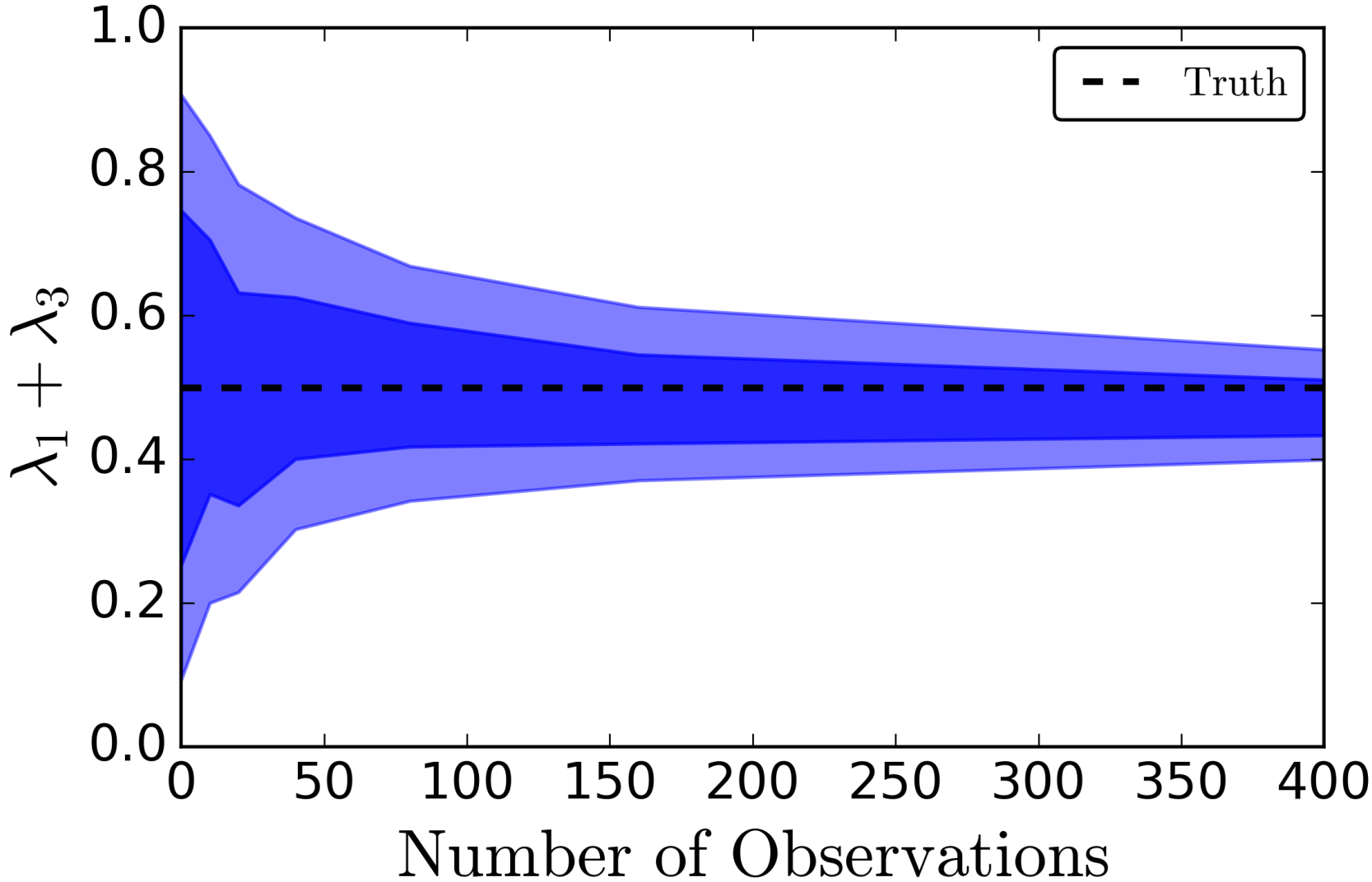
Model inference

Stevenson, CPLB & Mandel
arXiv:1703.06873

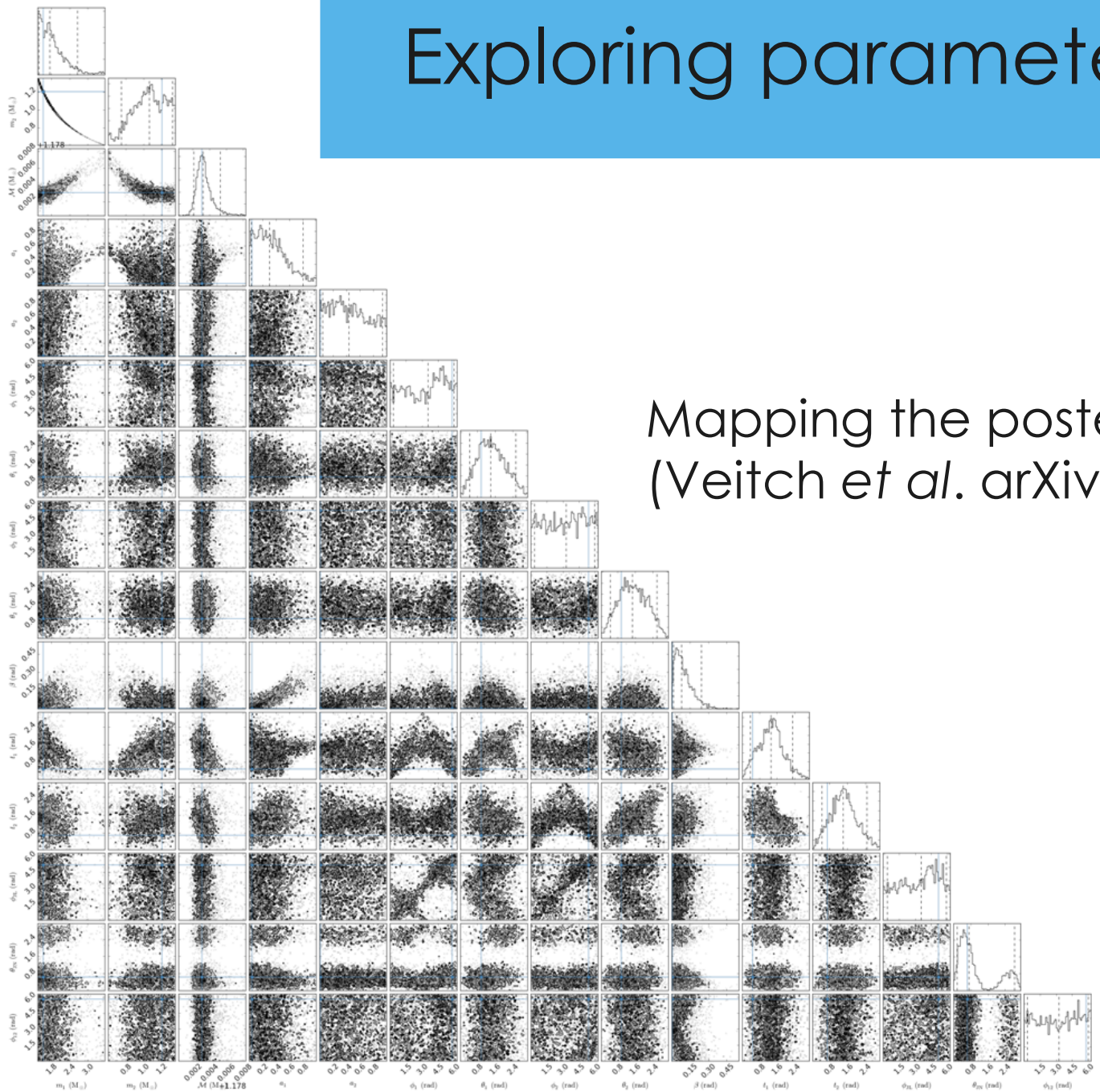


Model inference

Stevenson, CPLB & Mandel
arXiv:1703.06873



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

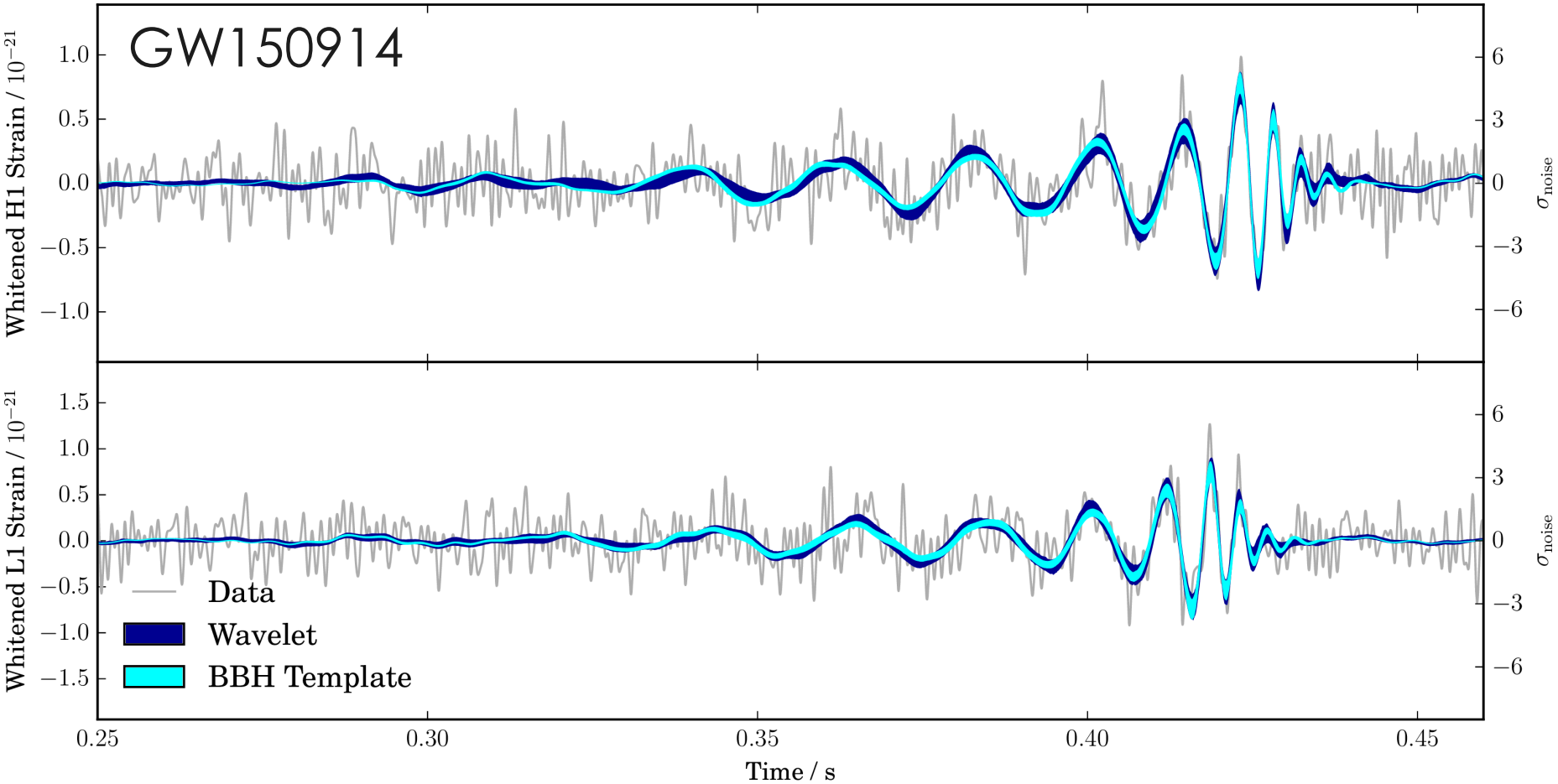
$$p(d|\theta) \propto \exp\left[-\frac{1}{2}\sum_k \langle h_k(\theta) - d_k | h_k(\theta) - d_k \rangle\right]$$

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

Waveform

LVC arXiv:1602.03840

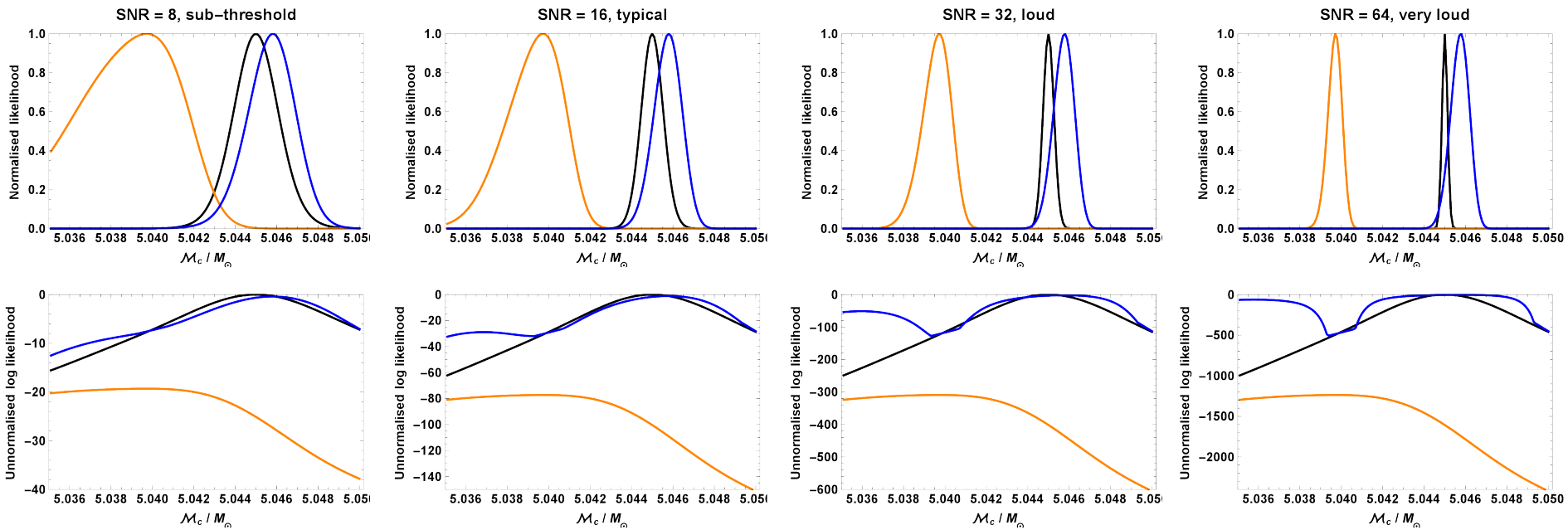
Waveform



LVC arXiv:1602.03840

Waveform error

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



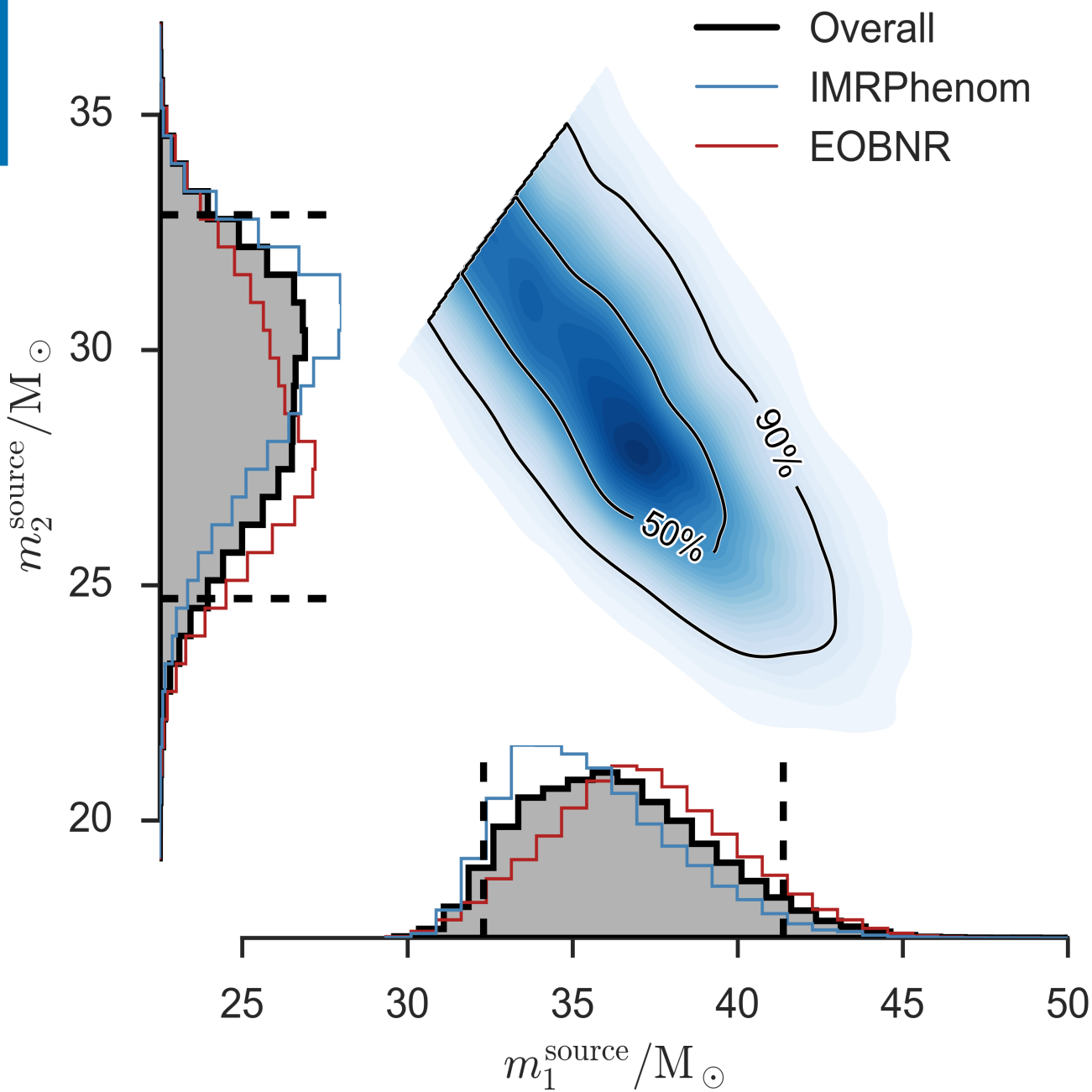
Moore *et al*. arXiv:1509.04066

Chirp mass

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

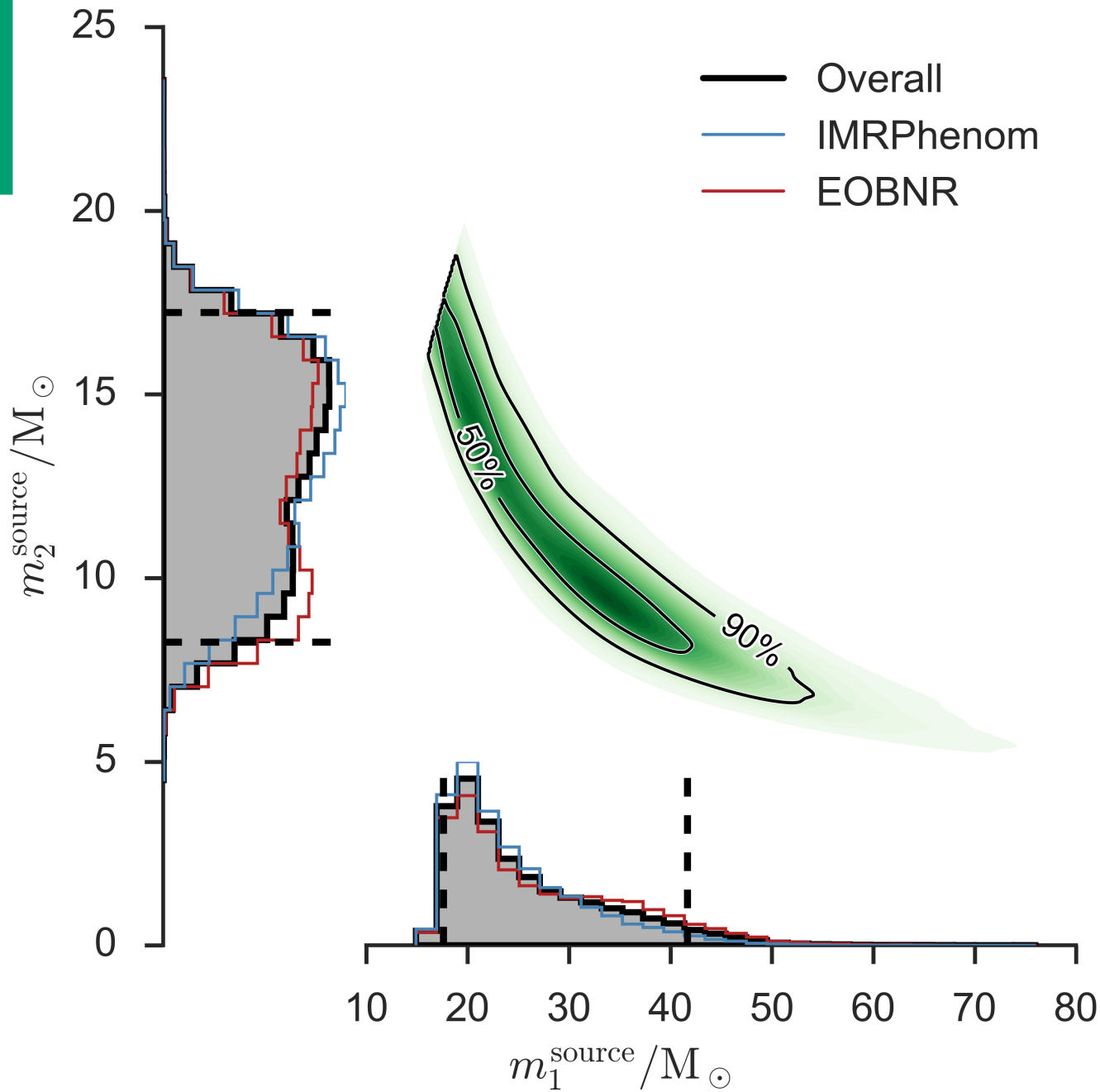
Chirp mass gives leading-order amplitude and phase evolution (Sathyaprakash & Schutz arXiv:0903.0338)

Masses



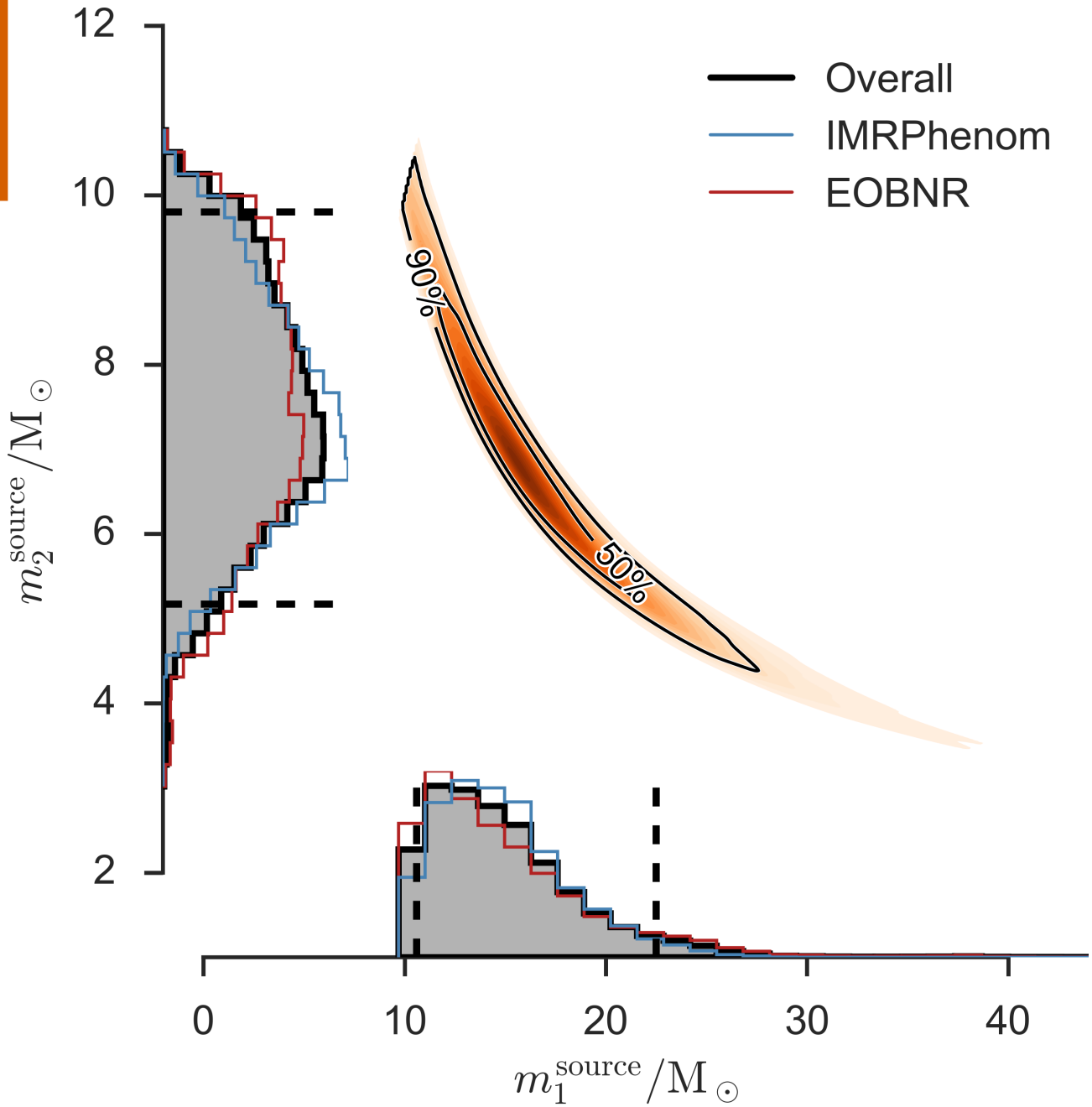
LVC
arXiv:1606.04856
arXiv:1602.03840

Masses



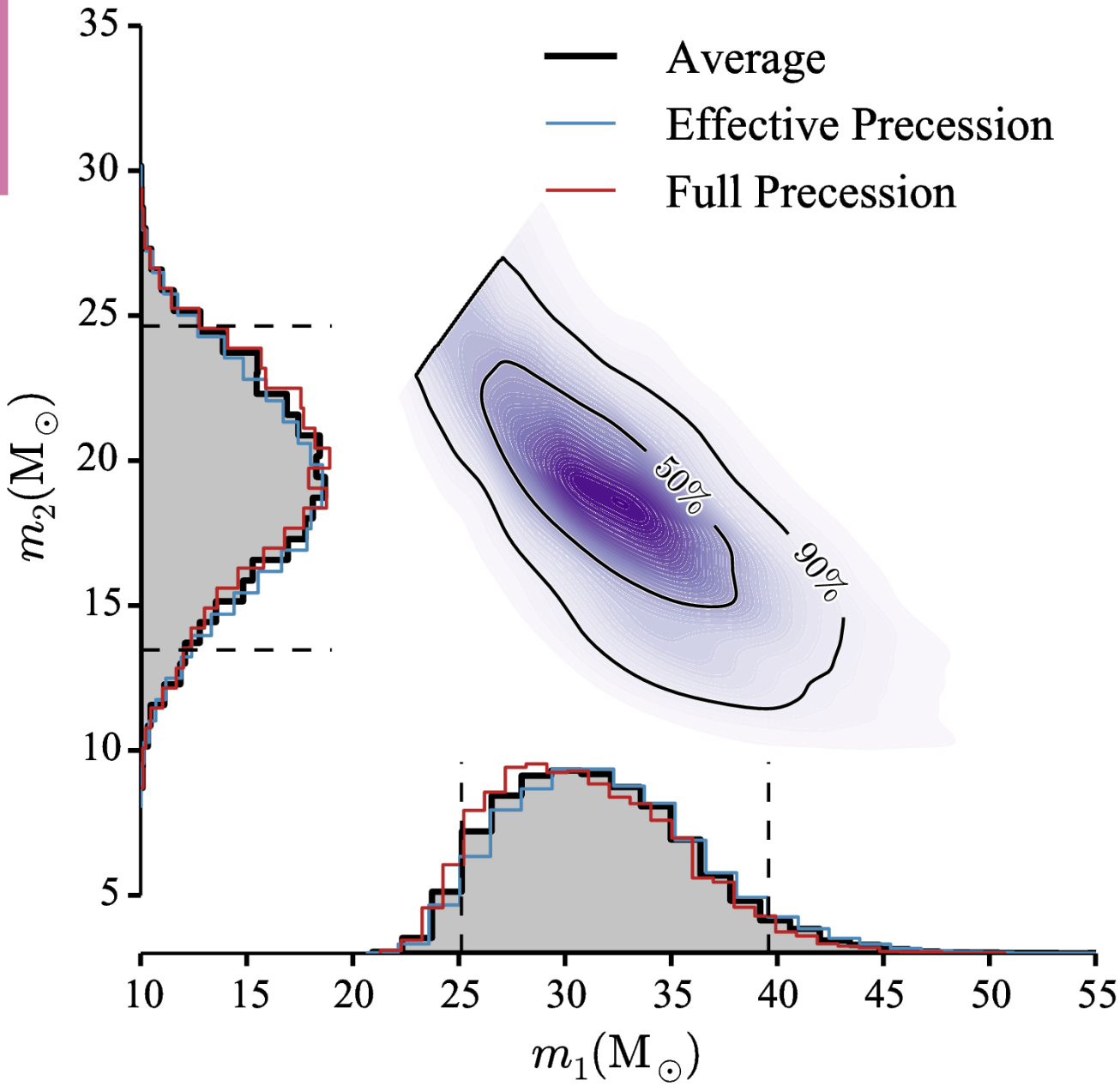
LVC
arXiv:1606.04856

Masses



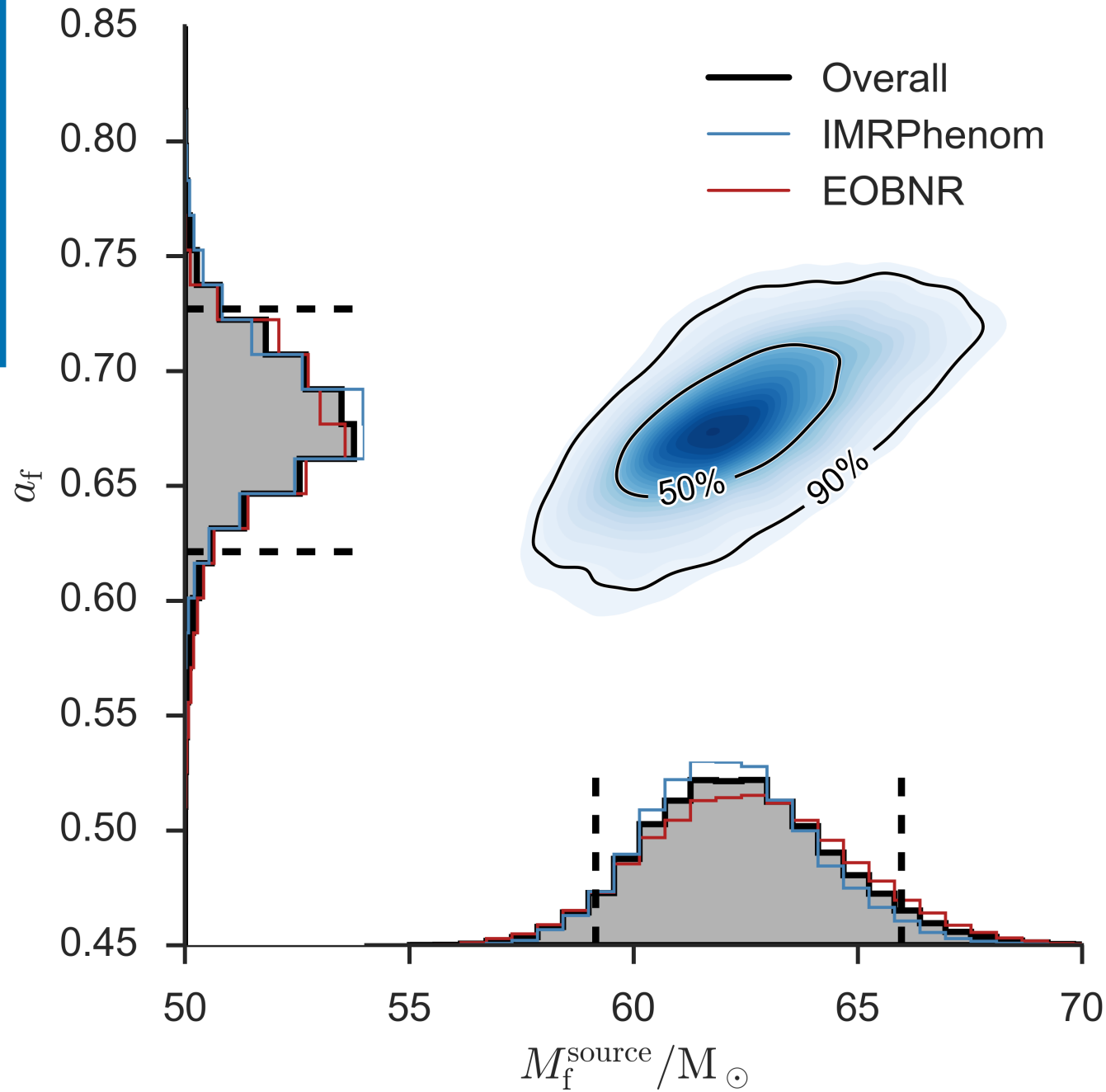
LVC
arXiv:1606.04855

Masses



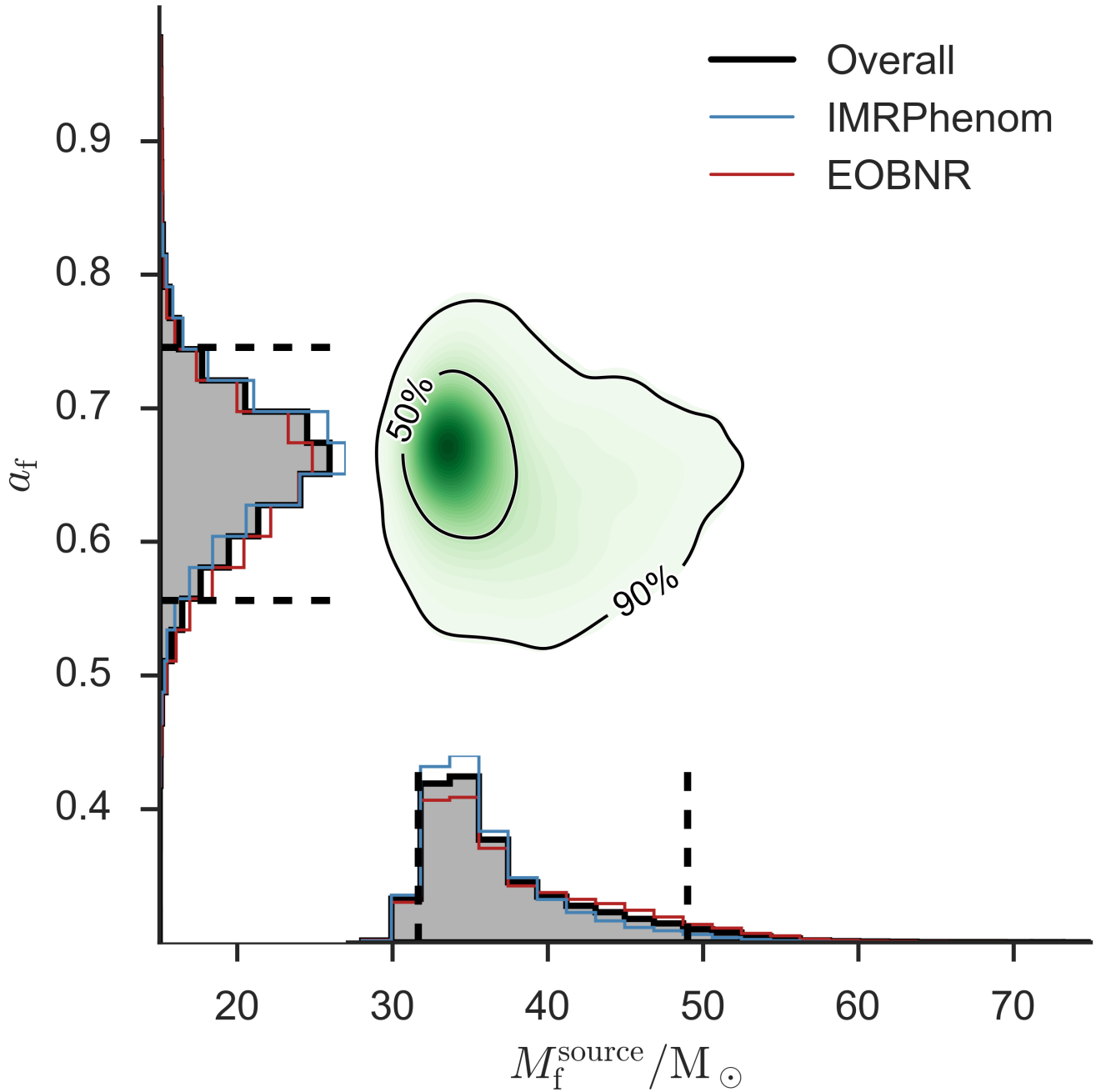
LVC
PRL **118**:221101

Final mass & spin



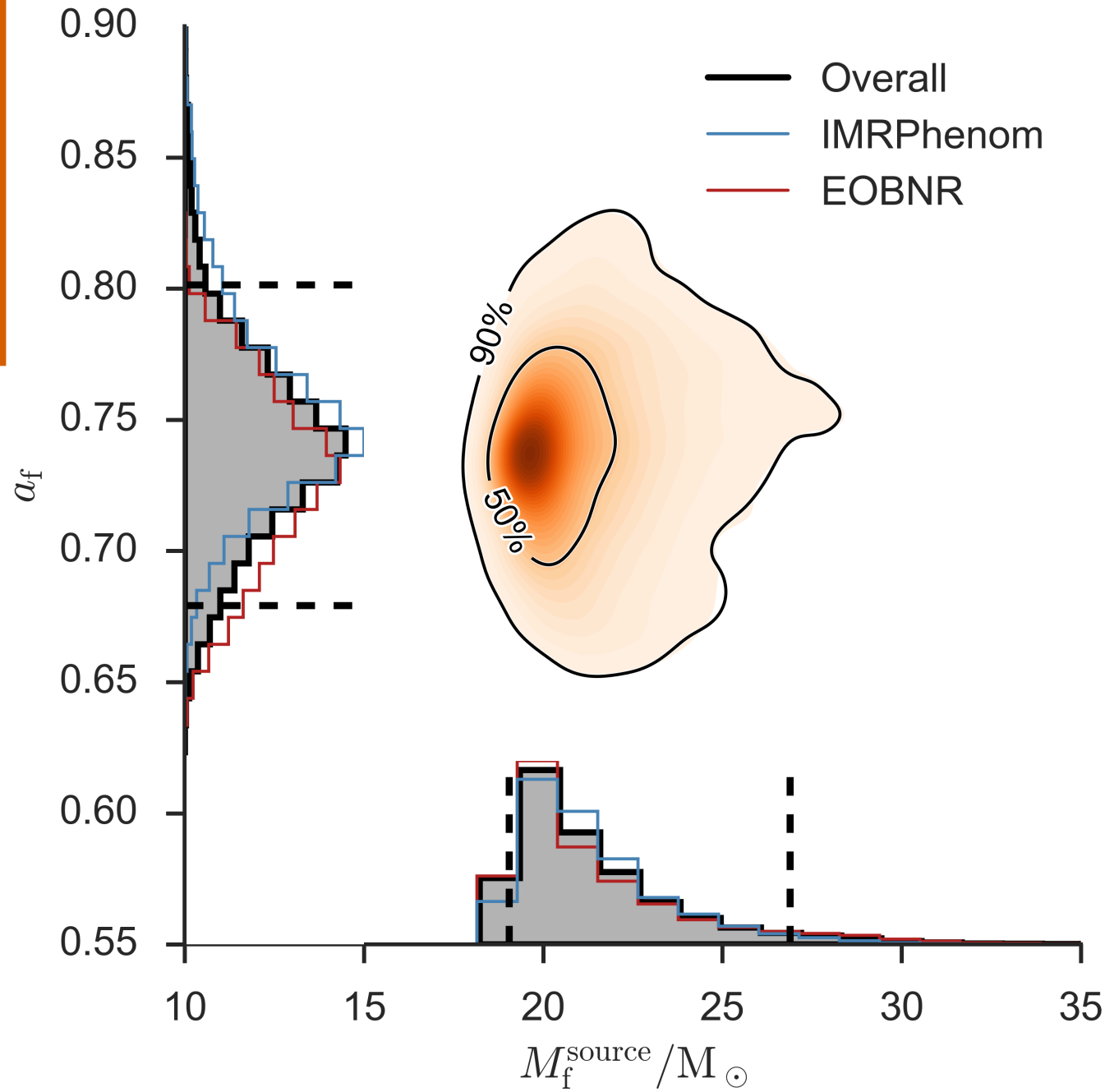
LVC
arXiv:1606.04856
arXiv:1602.03840

Final mass & spin



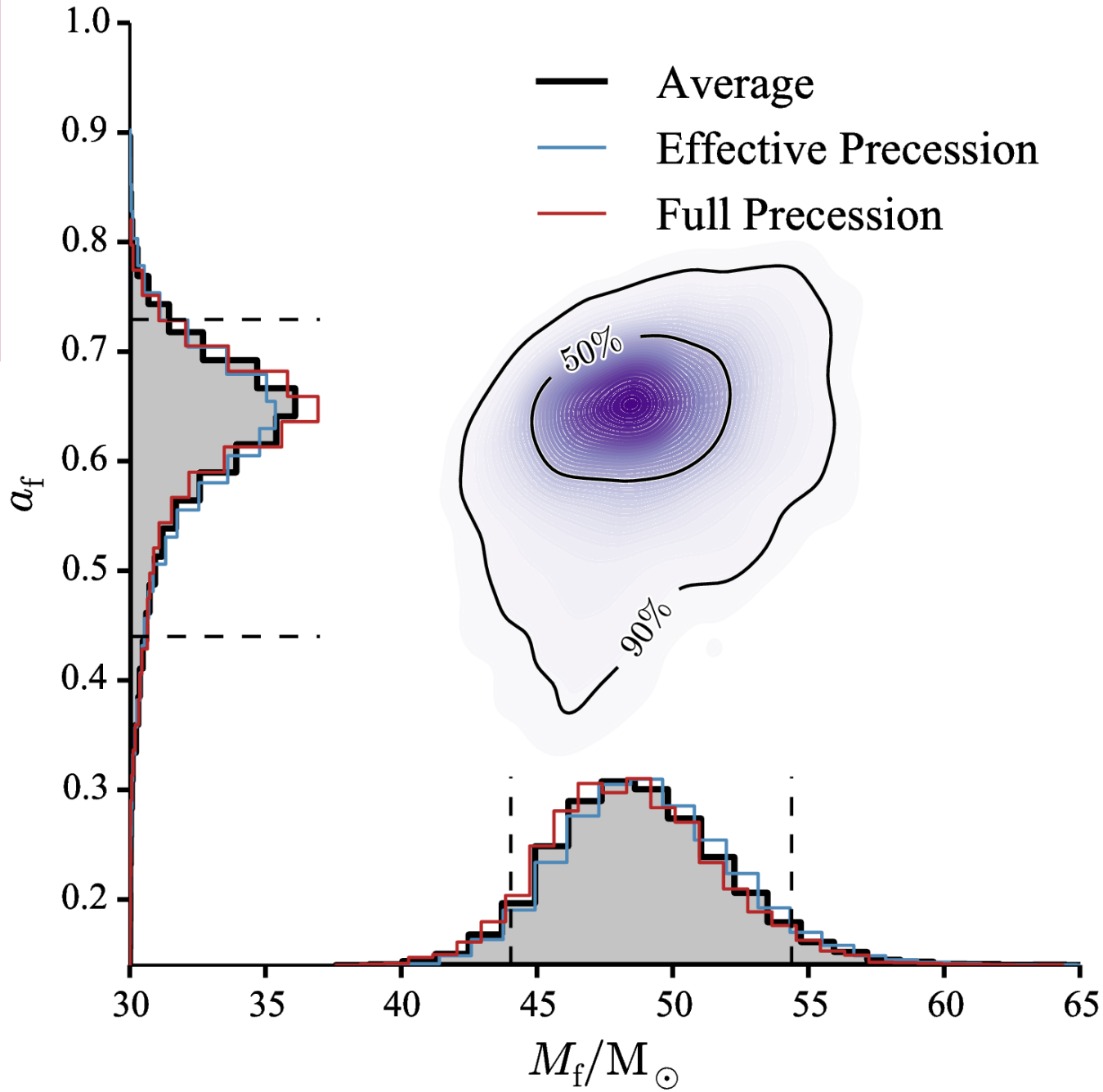
LVC
arXiv:1606.04856

Final mass & spin



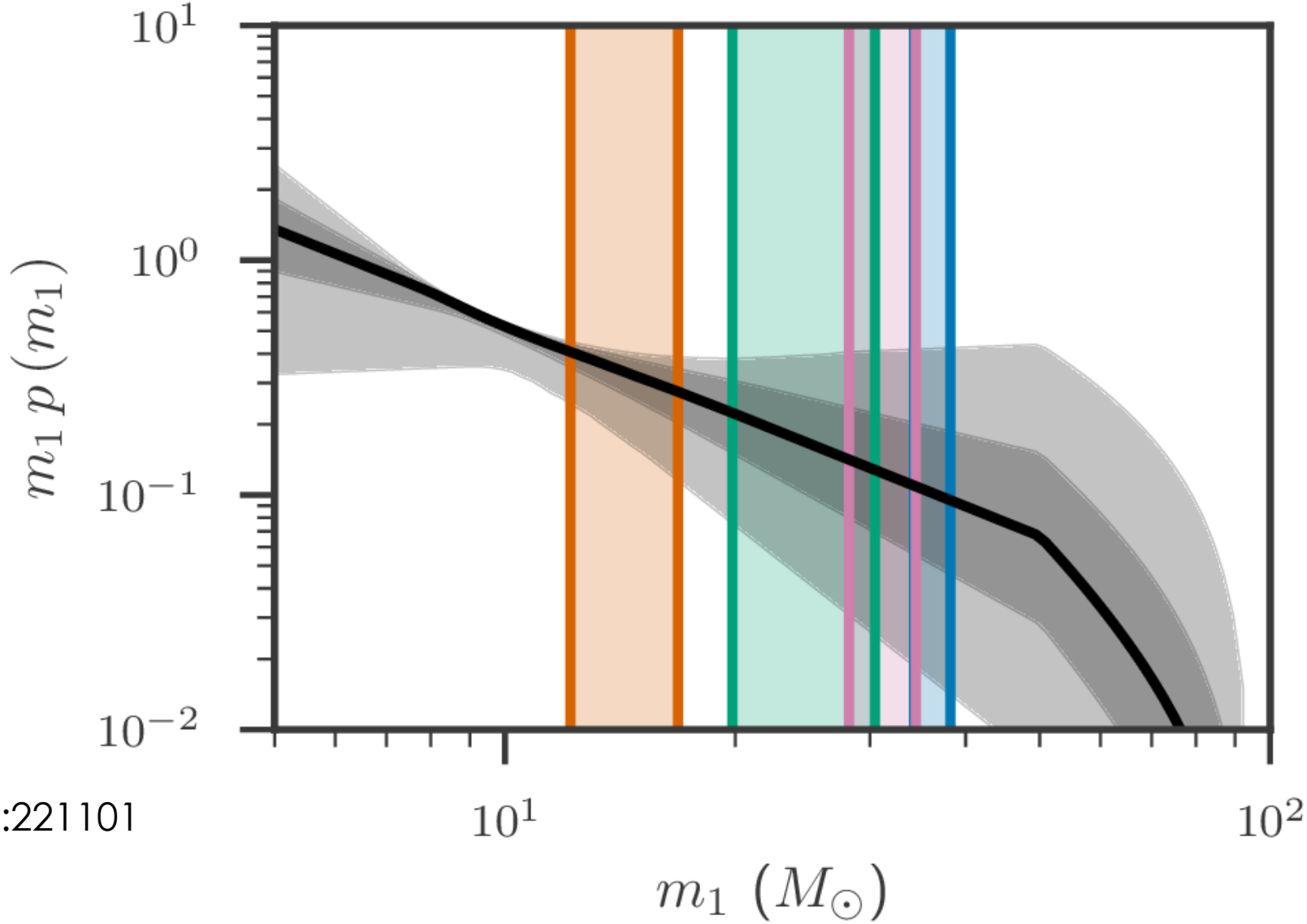
LVC
arXiv:1606.04856

Final mass & spin



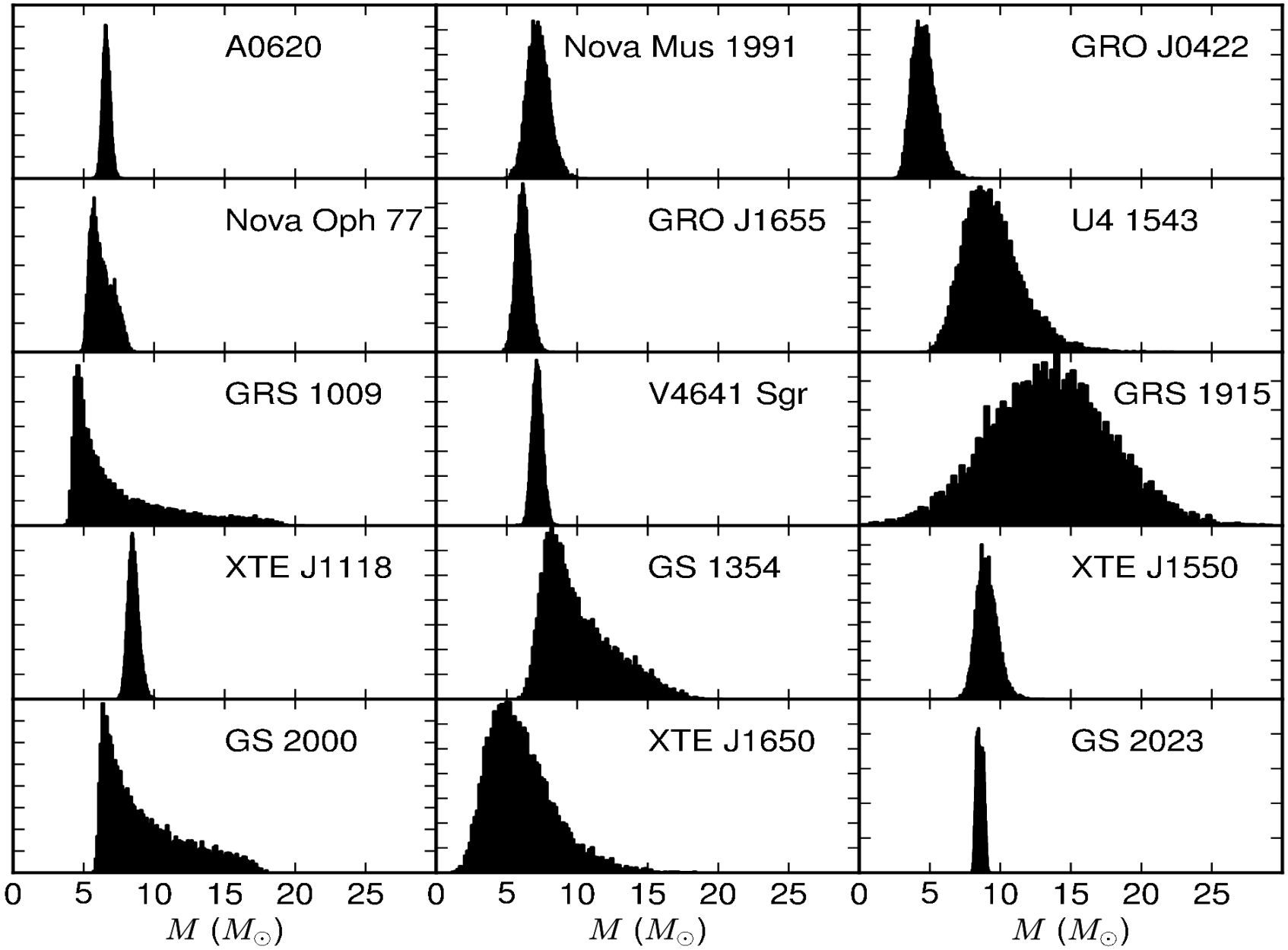
LVC
PRL **118**:221101

Mass distribution

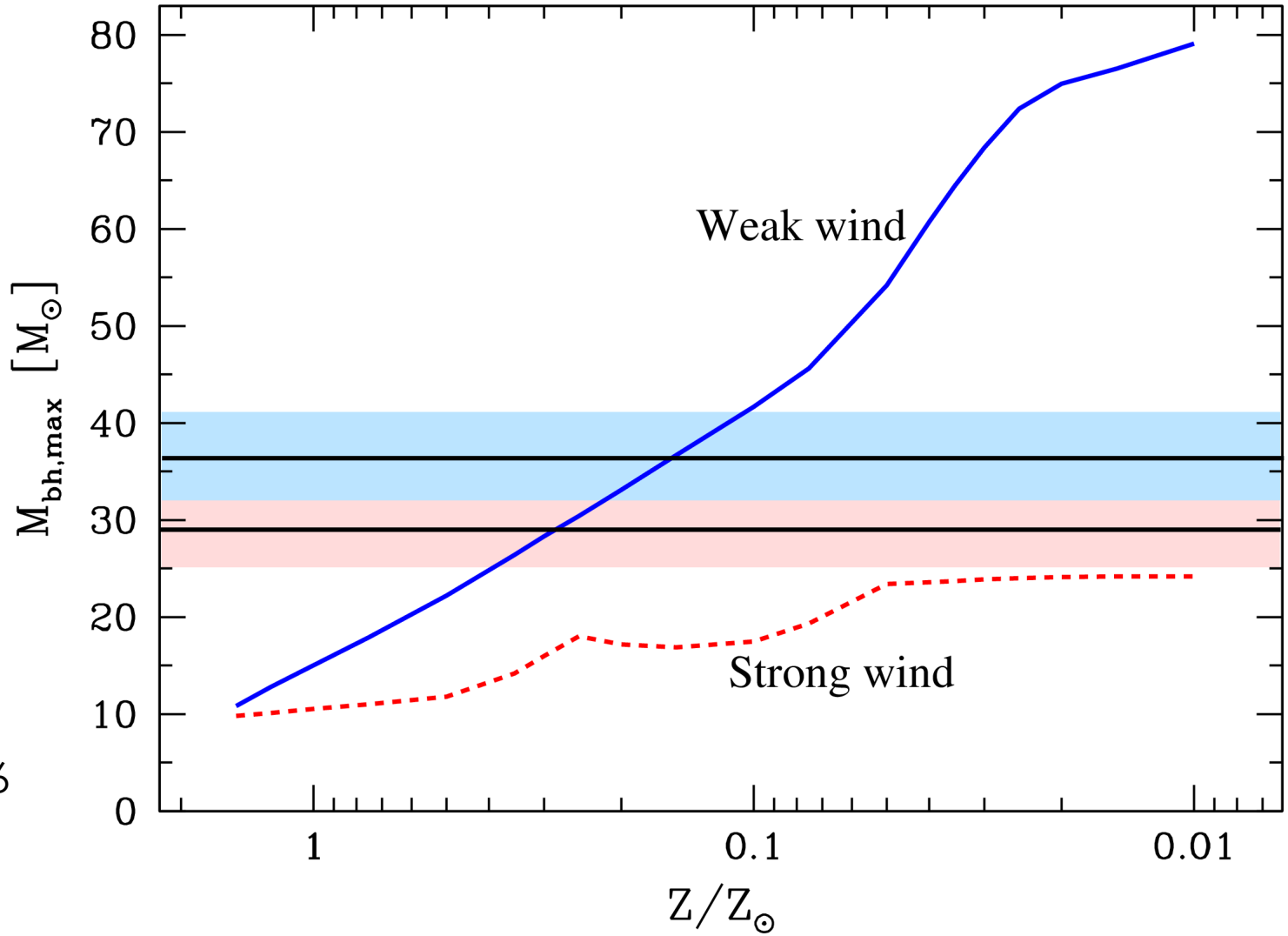


LVC
PRL **118**:221101

Farr *et al*. arXiv:1011.1459

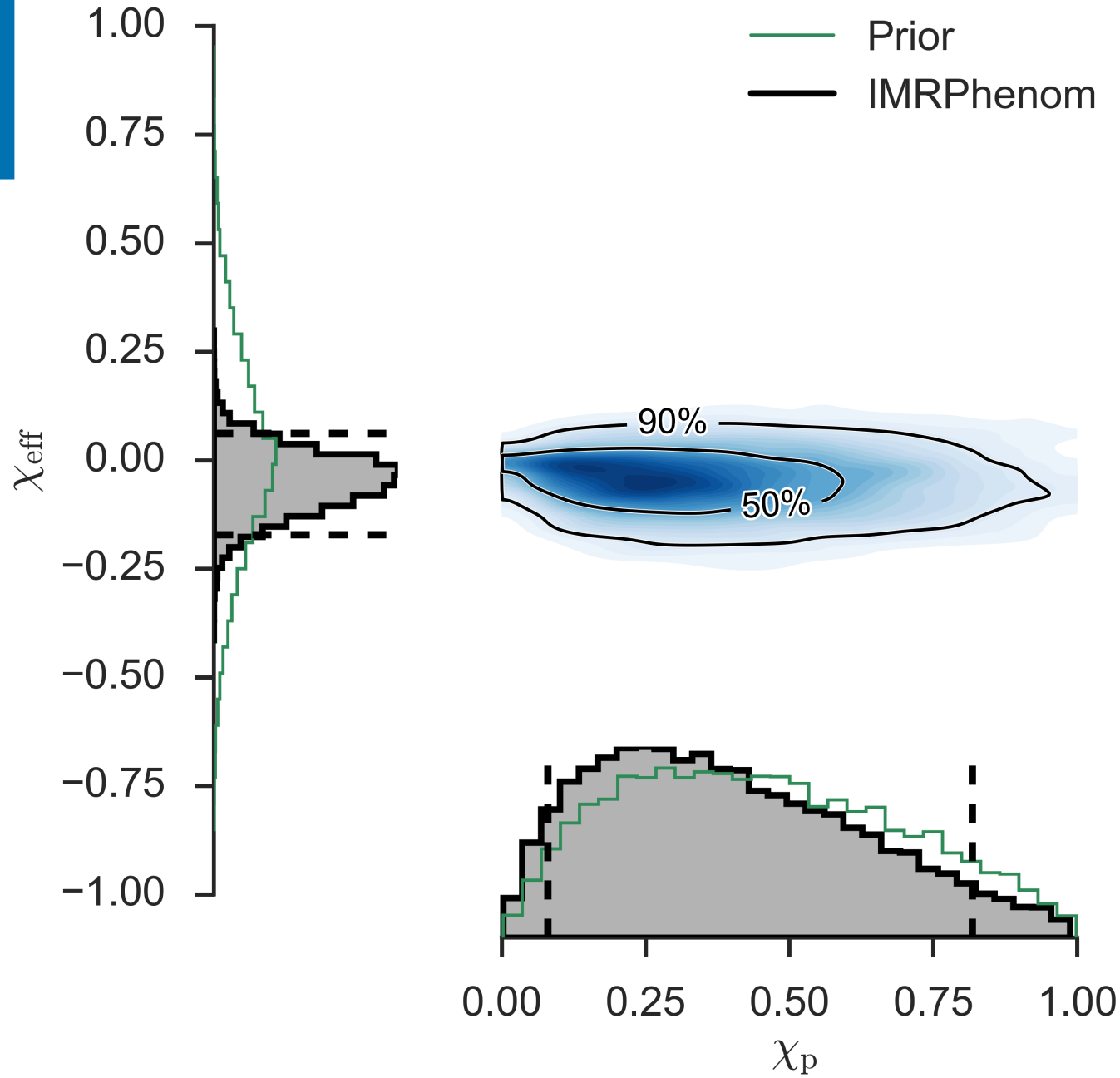


Metallicity



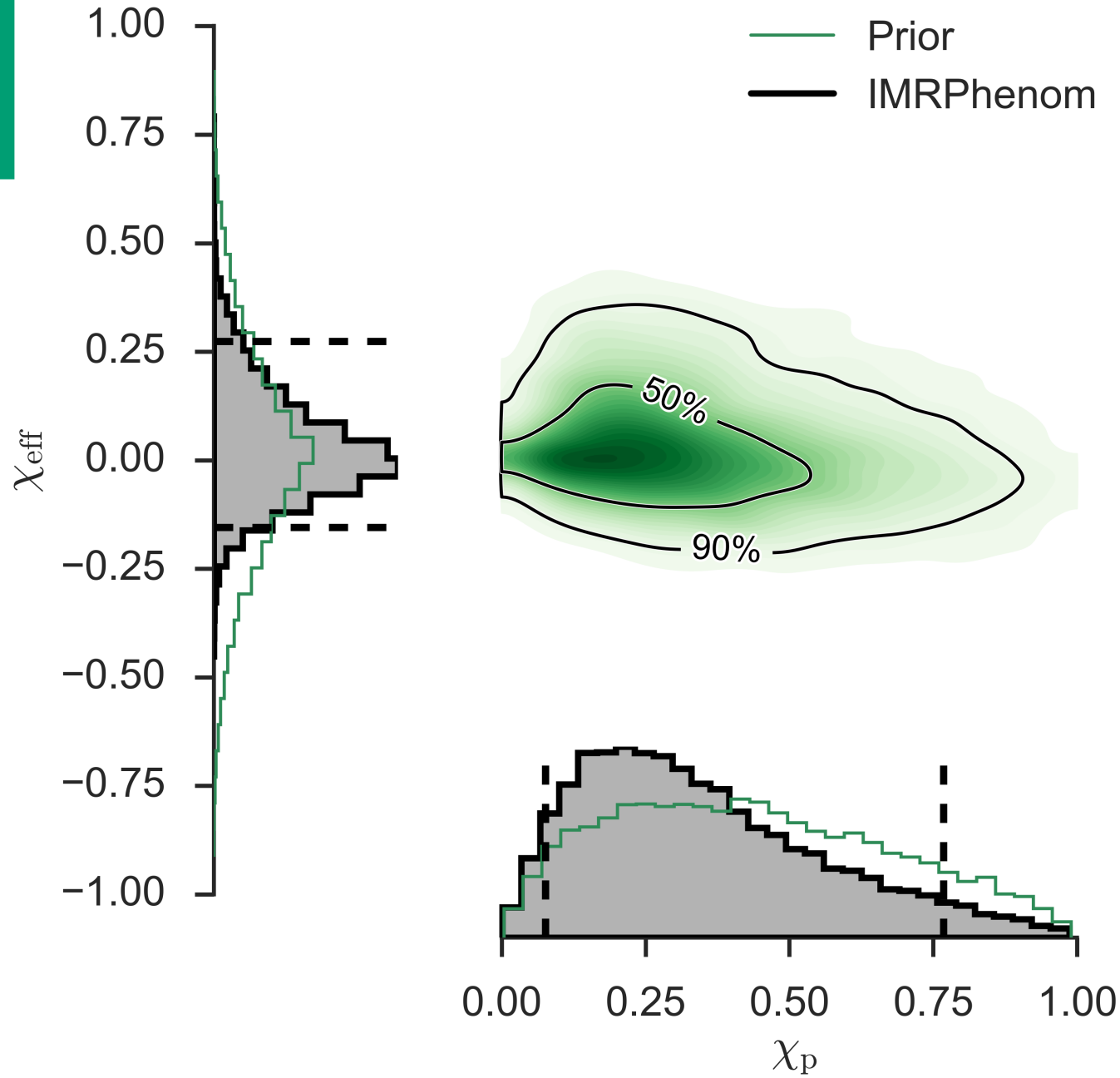
LVC
arXiv:1602.03846
Belczynski *et al.*
arXiv:0904.2784

Spin



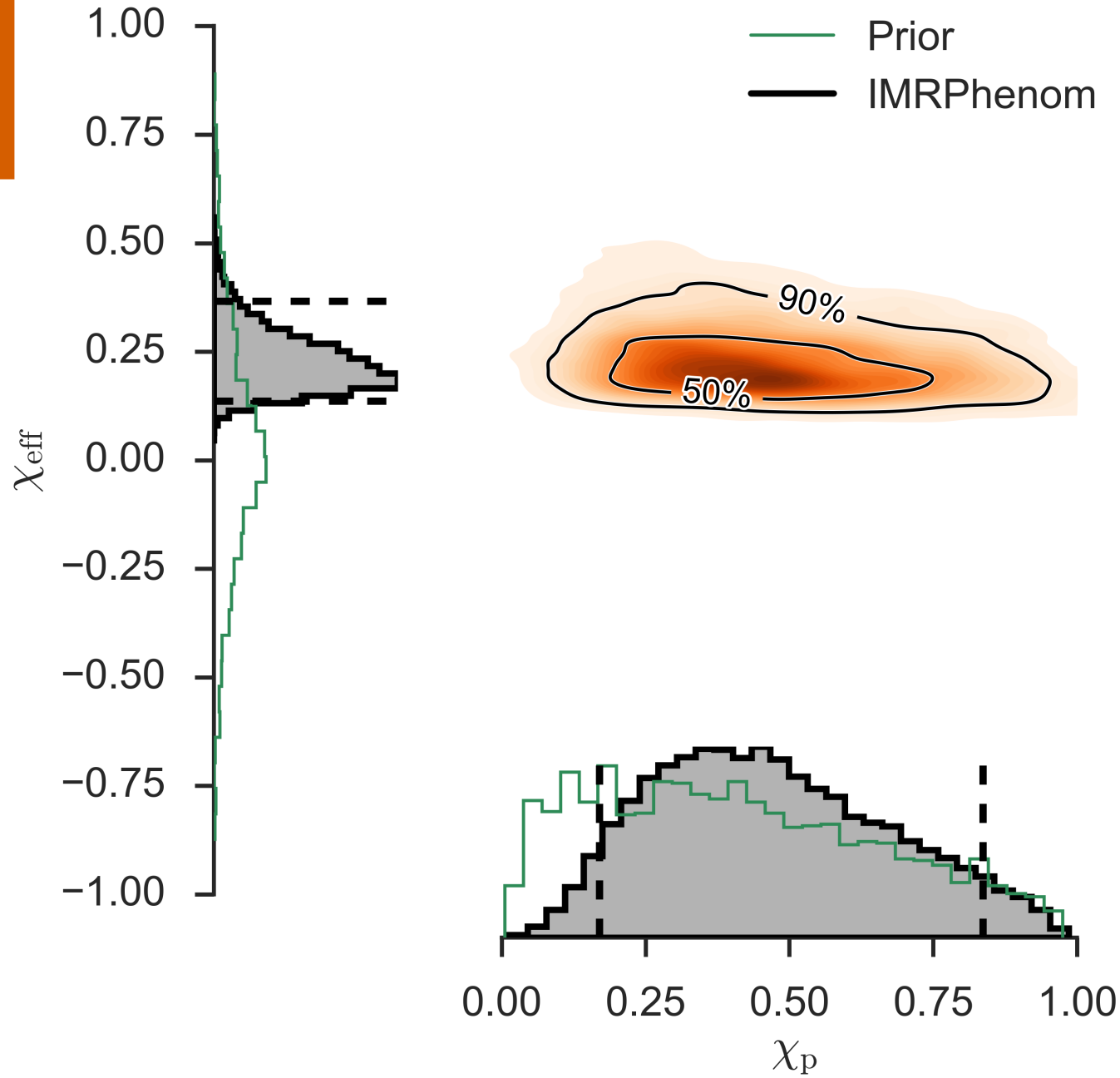
LVC
arXiv:1606.04856
arXiv:1602.03840

Spin



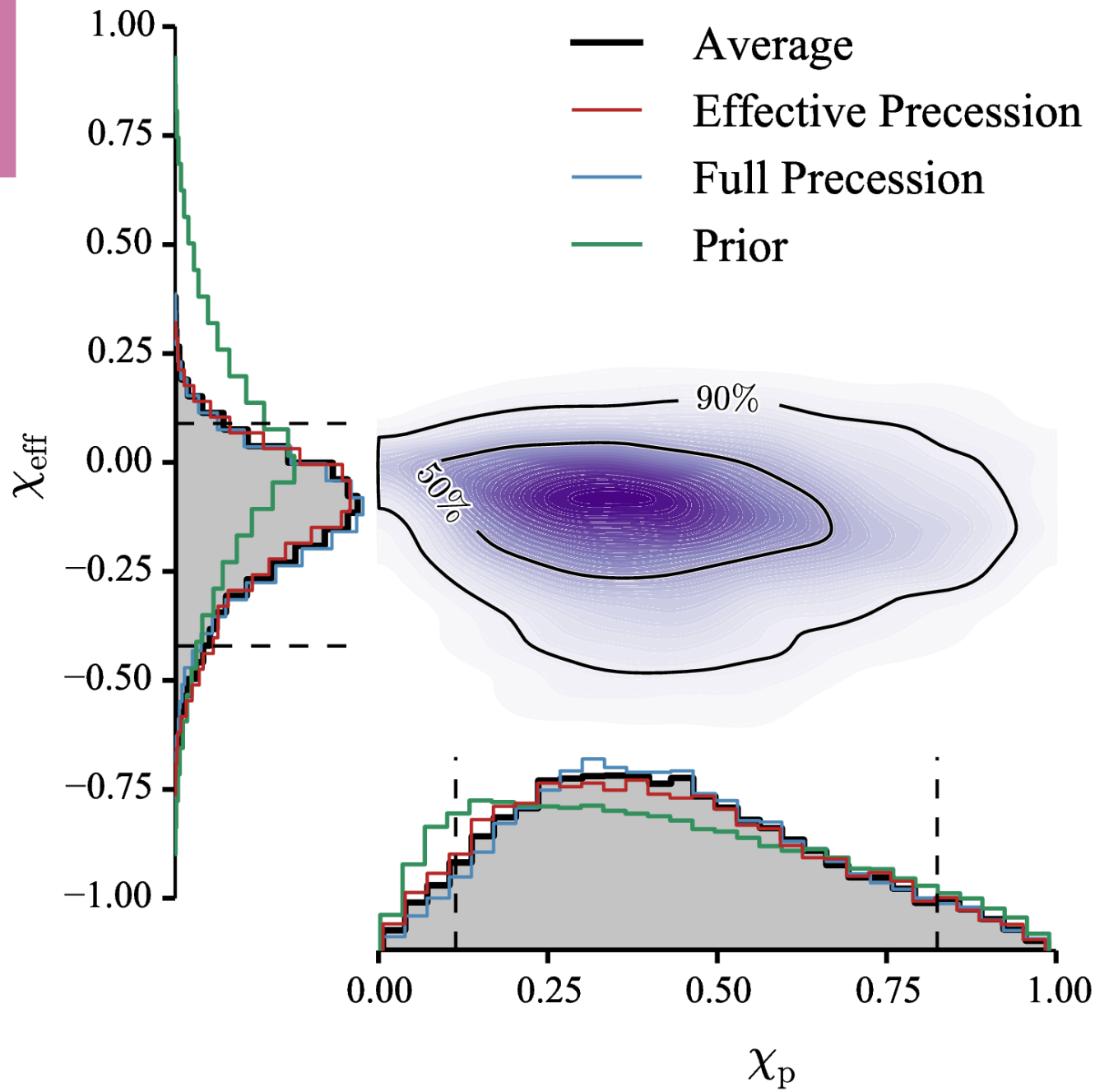
LVC
arXiv:1606.04856

Spin



LVC
arXiv:1606.04856

Spin



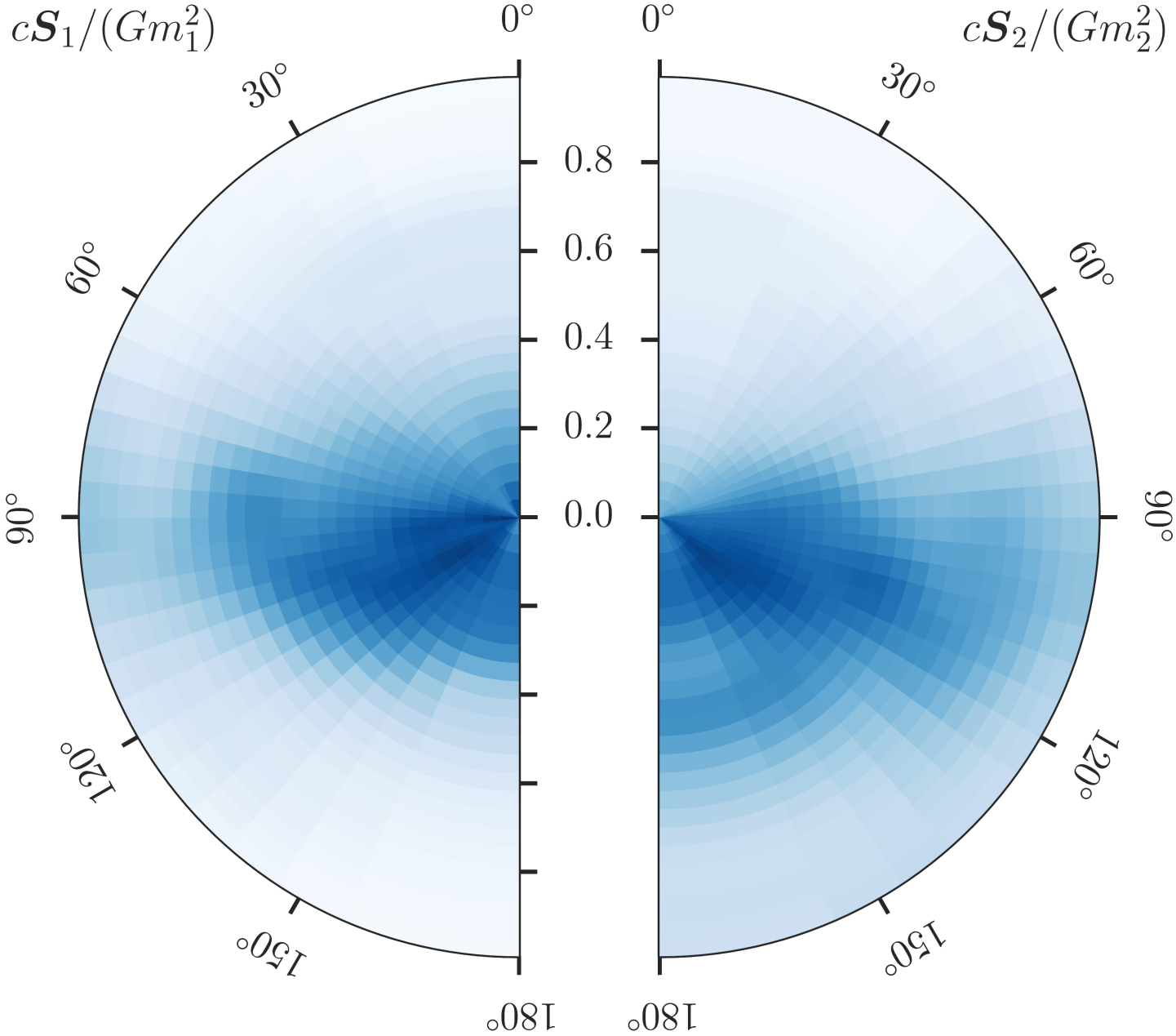
LVC
PRL **118**:221101

Effective inspiral spin

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

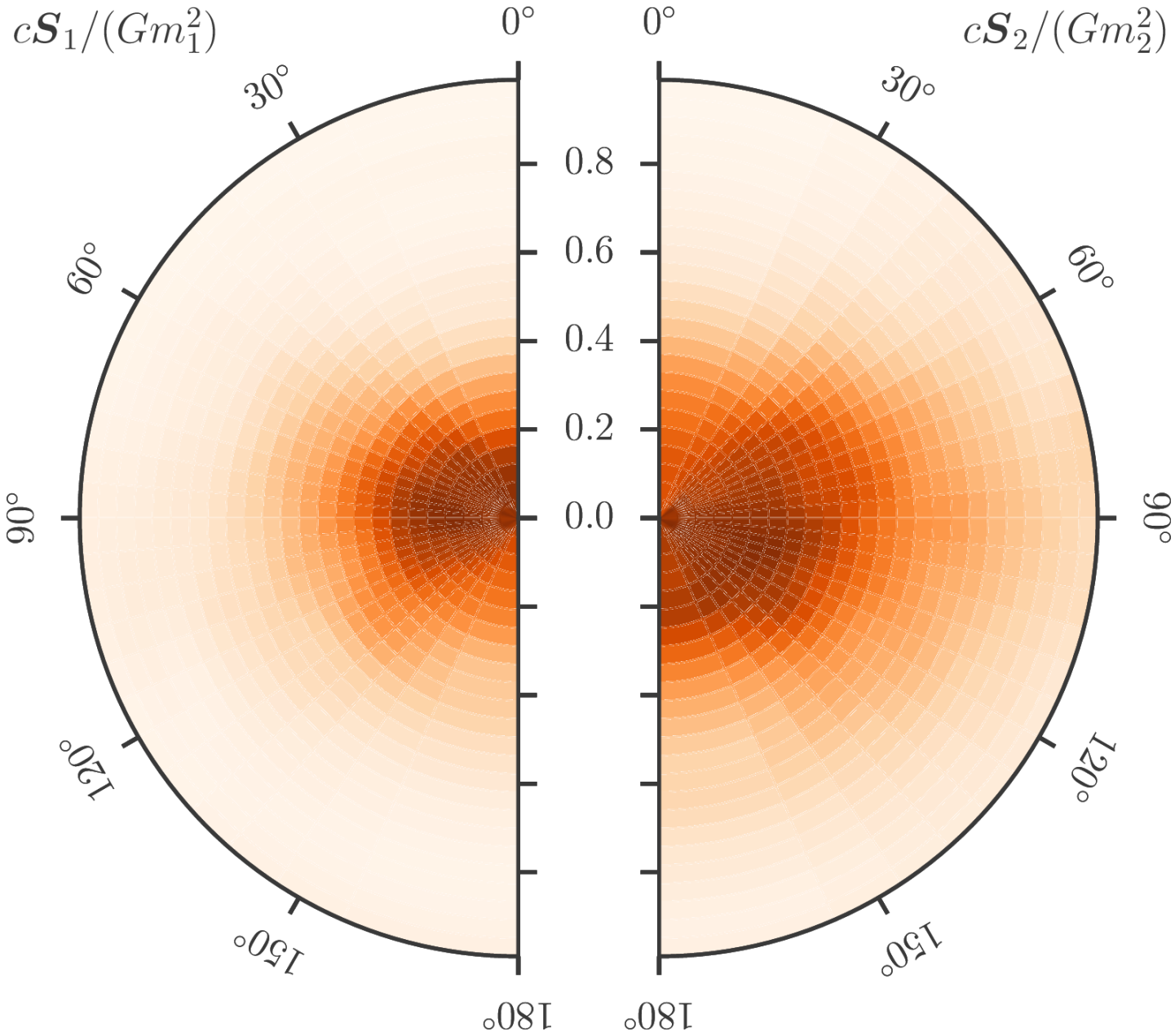
Most important combination of spins for evolution of inspiral (arXiv:0909.2867, 1005.3306)

Spin



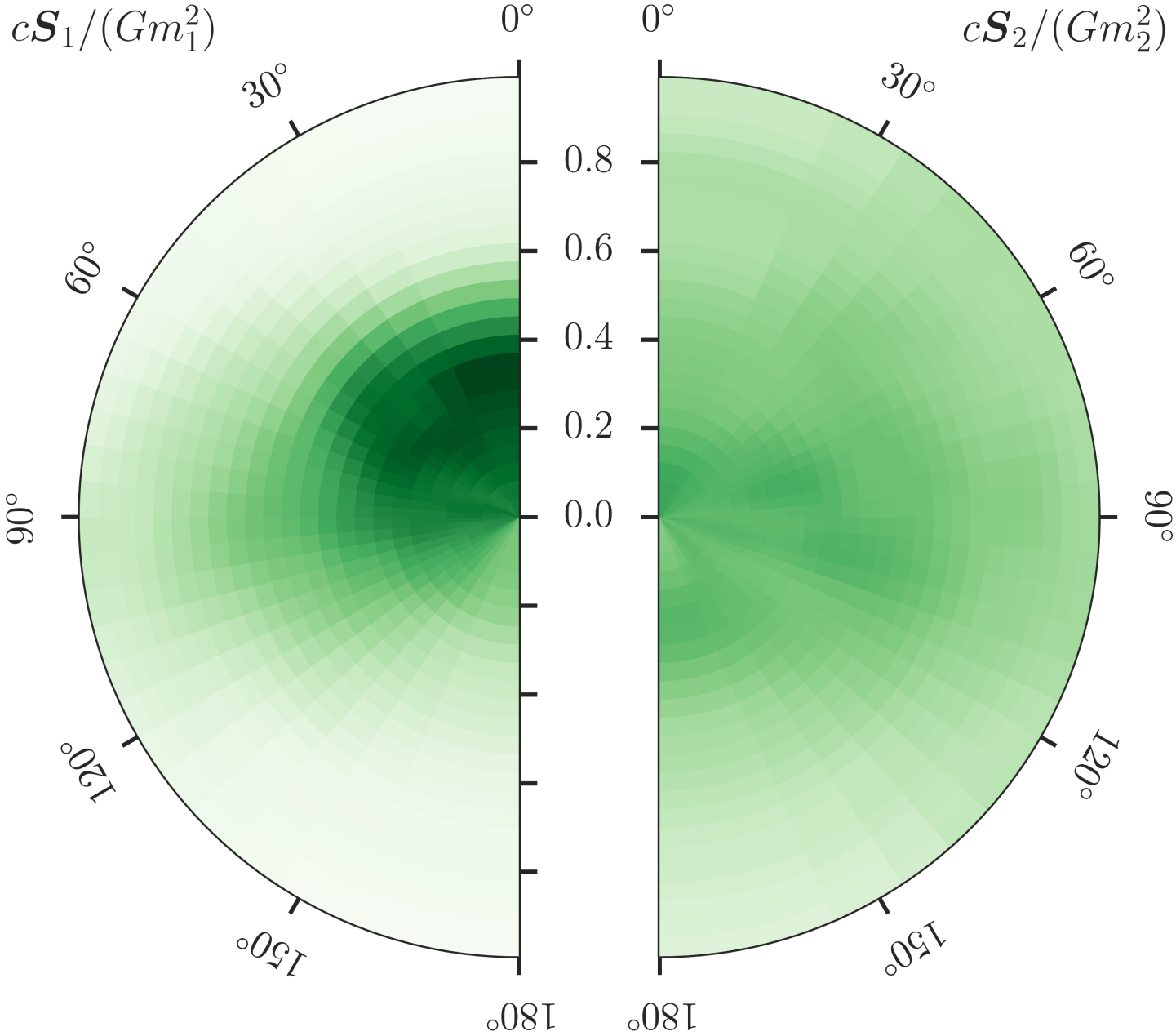
LVC
arXiv:1606.04856
arXiv:1602.03840

Spin



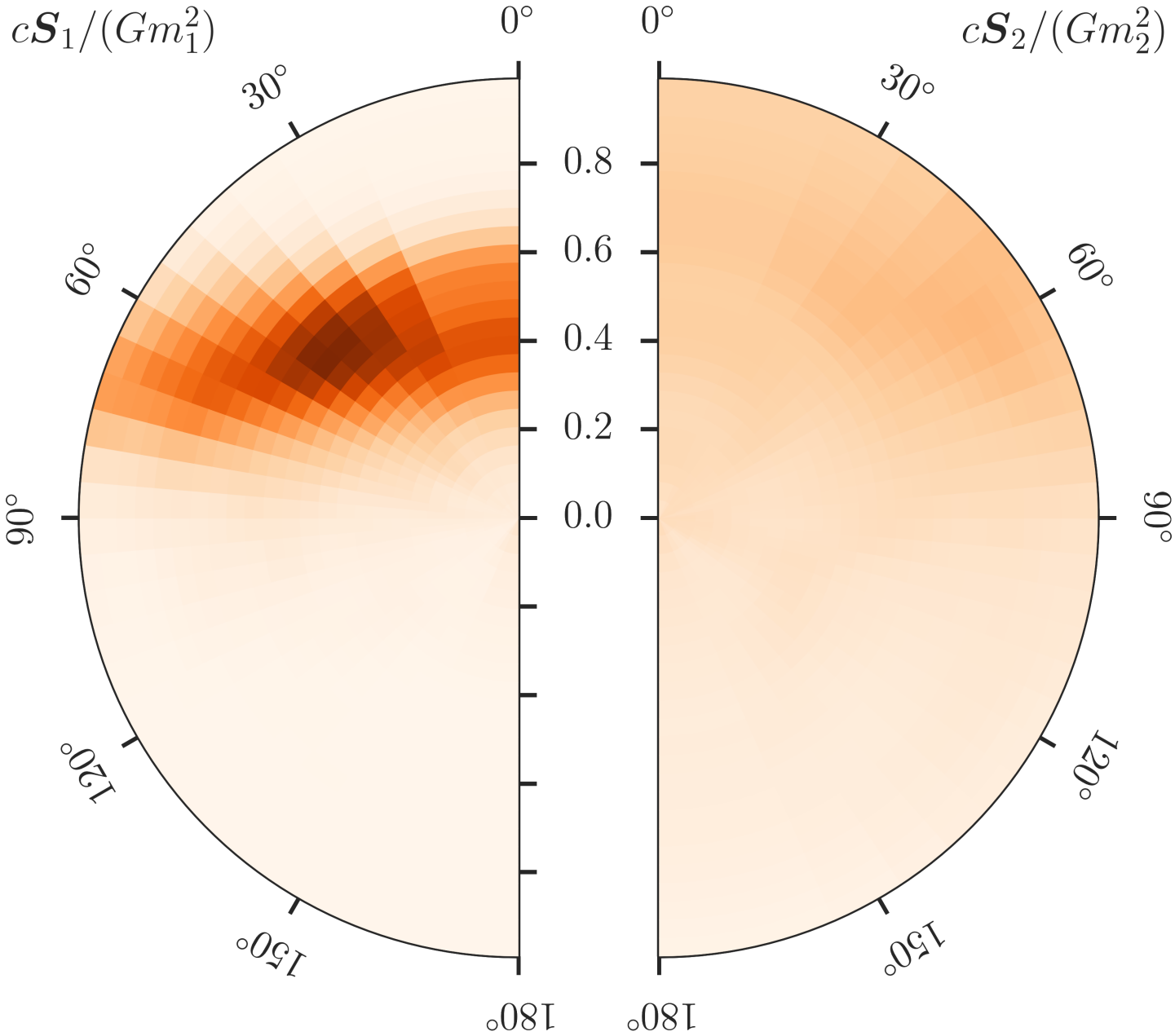
LVC
arXiv:1606.01210

Spin



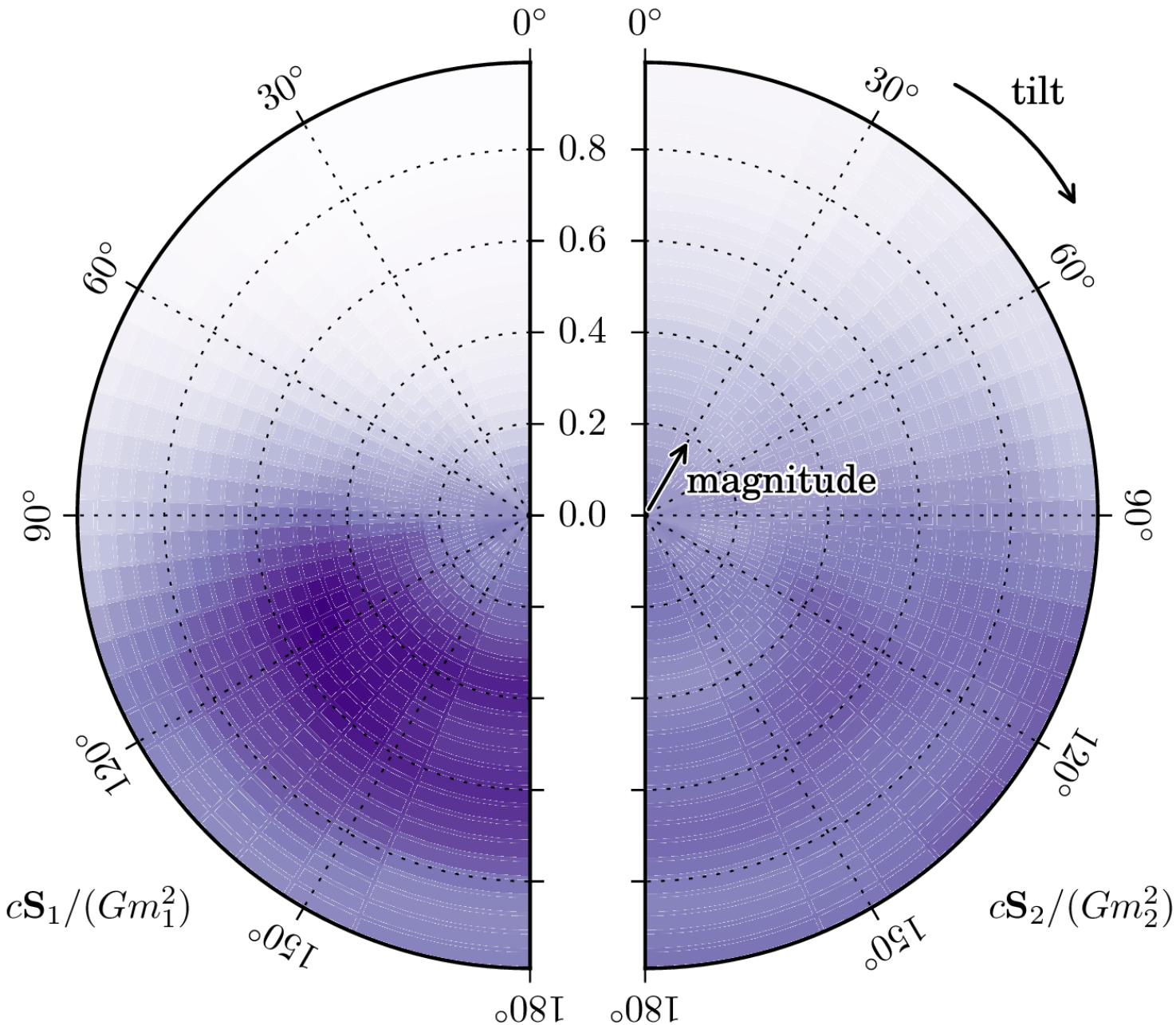
LVC
arXiv:1606.04856

Spin



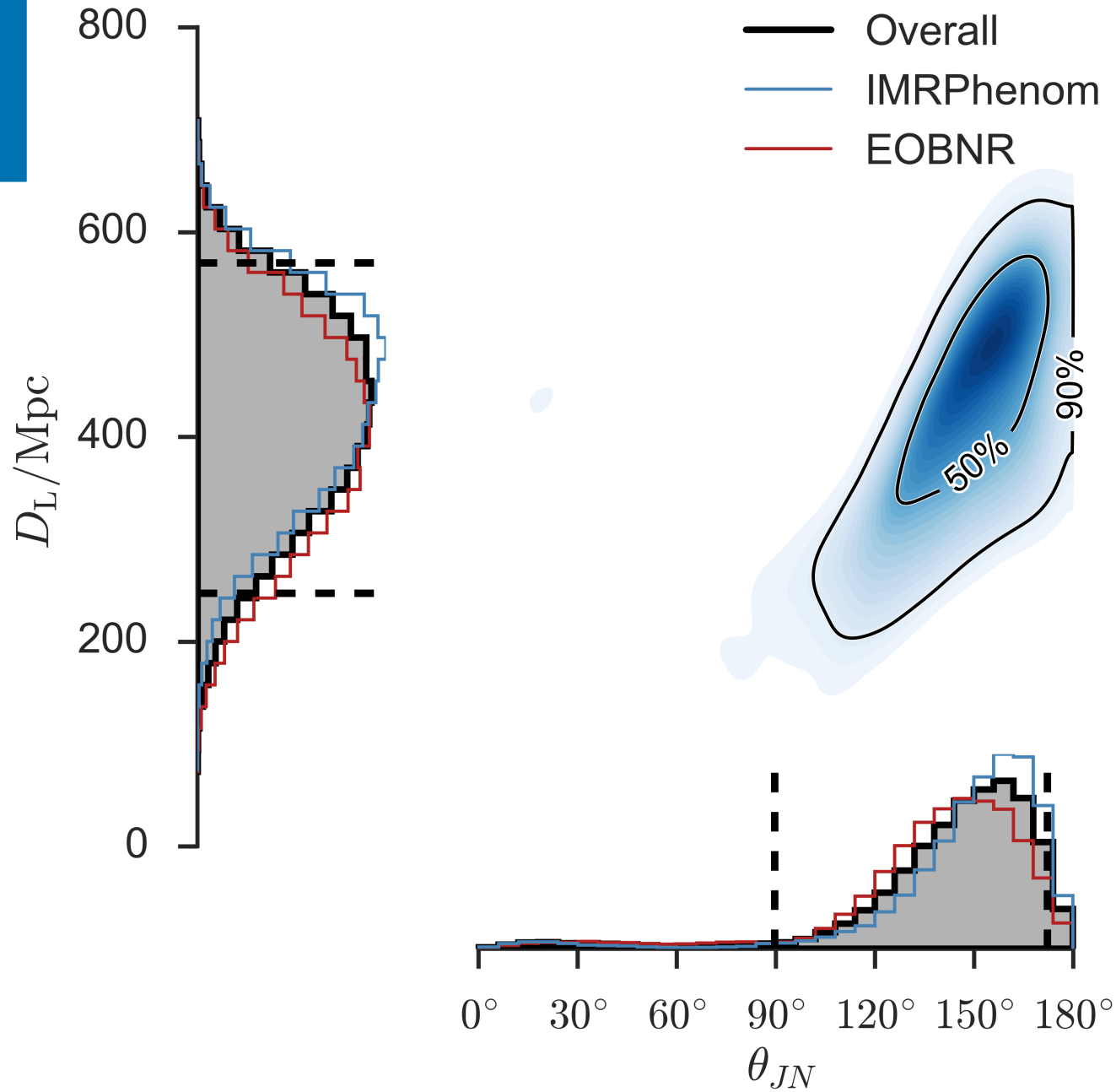
LVC
arXiv:1606.04855

Spin



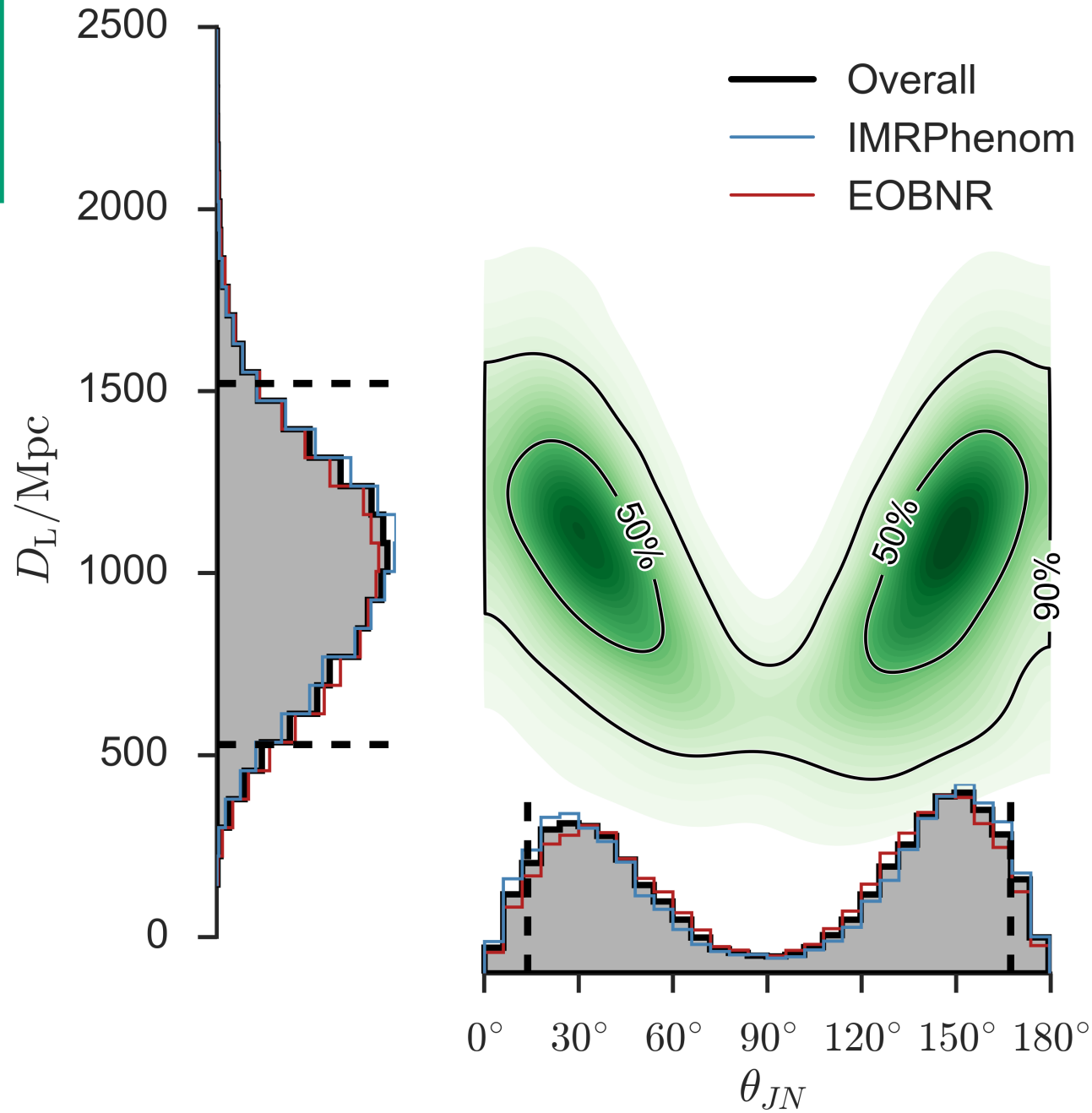
LVC
PRL **118**:221101

Distance



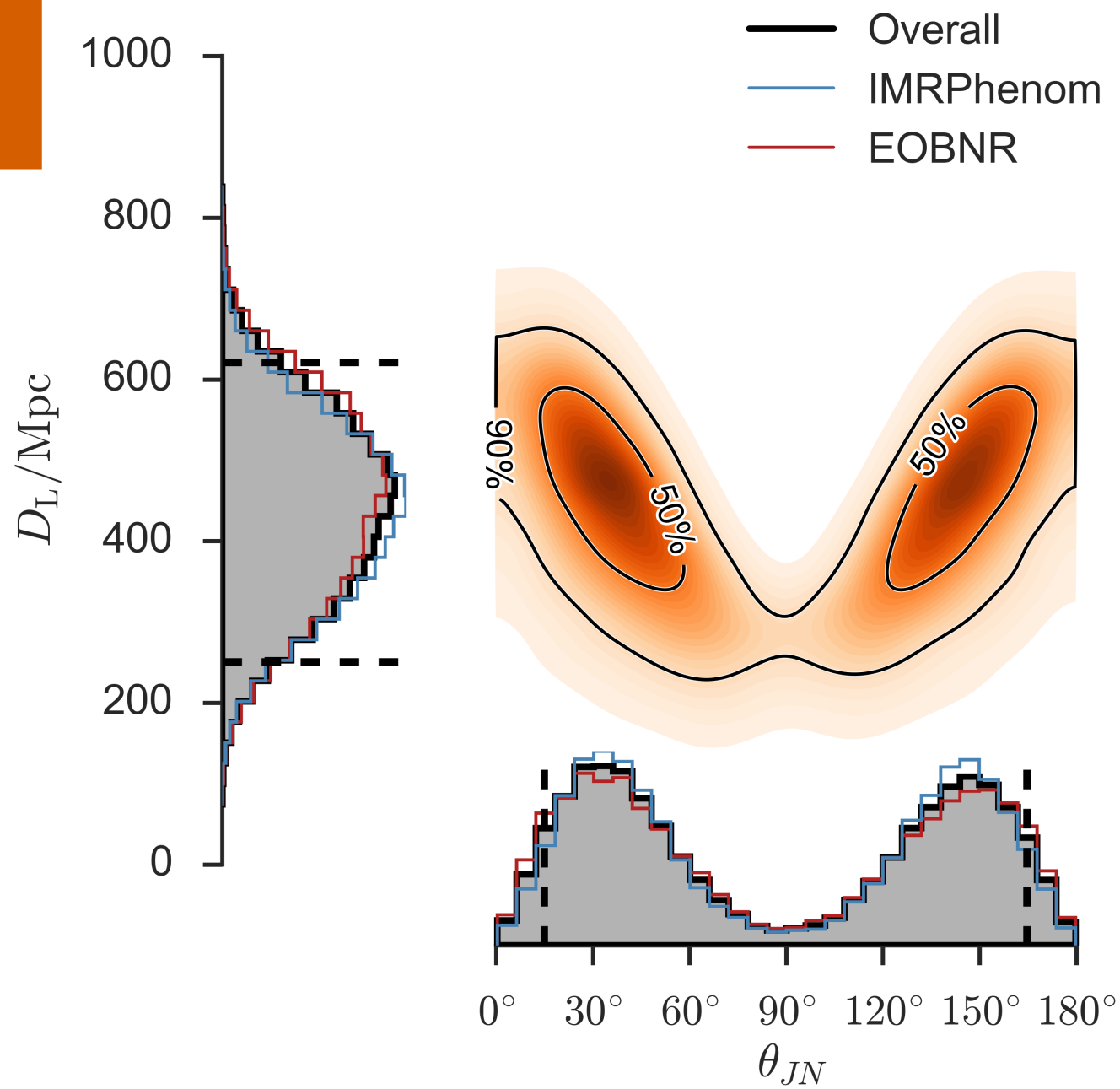
LVC
arXiv:1606.04856
arXiv:1602.03840

Distance



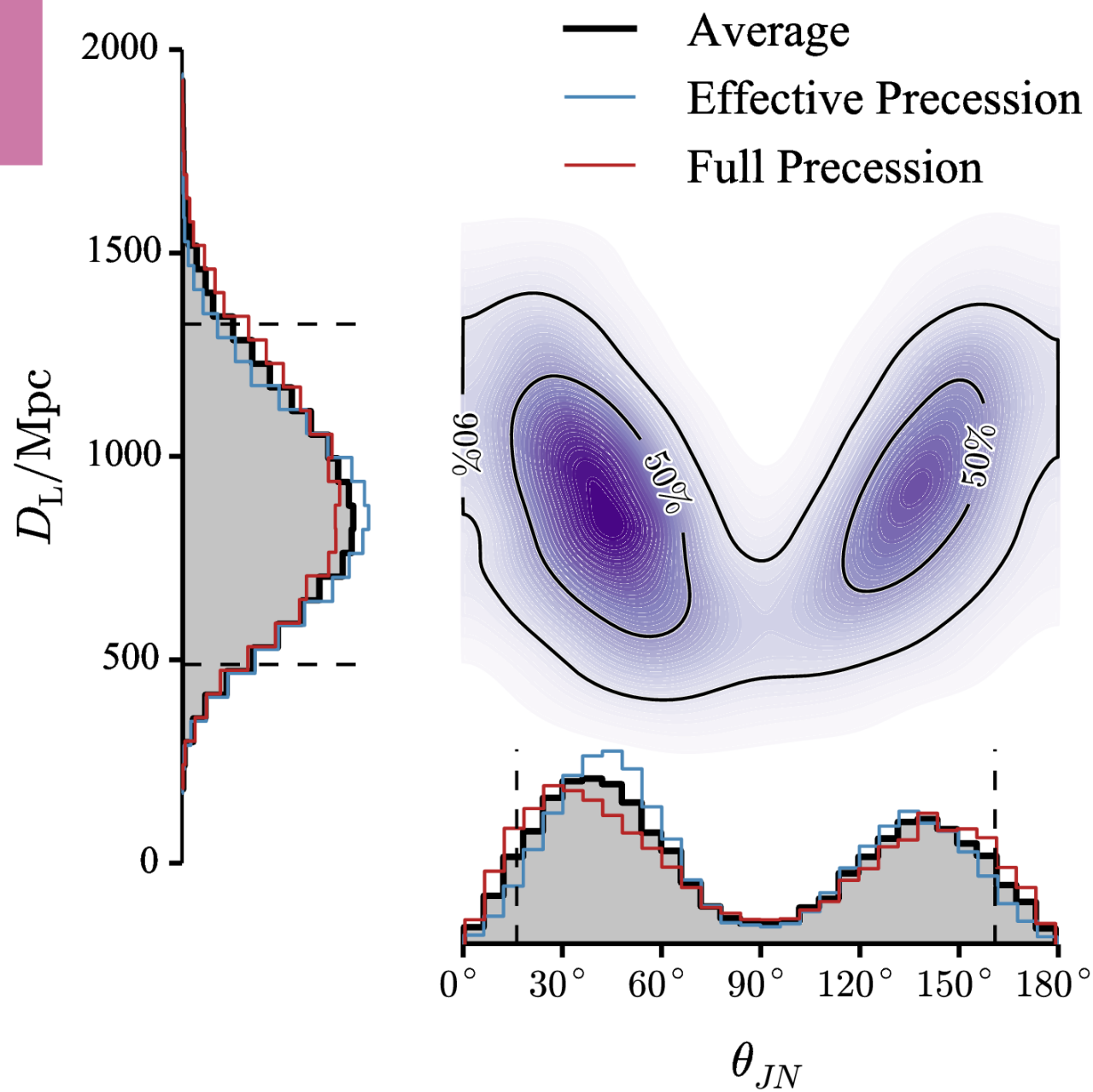
LVC
arXiv:1606.04856

Distance



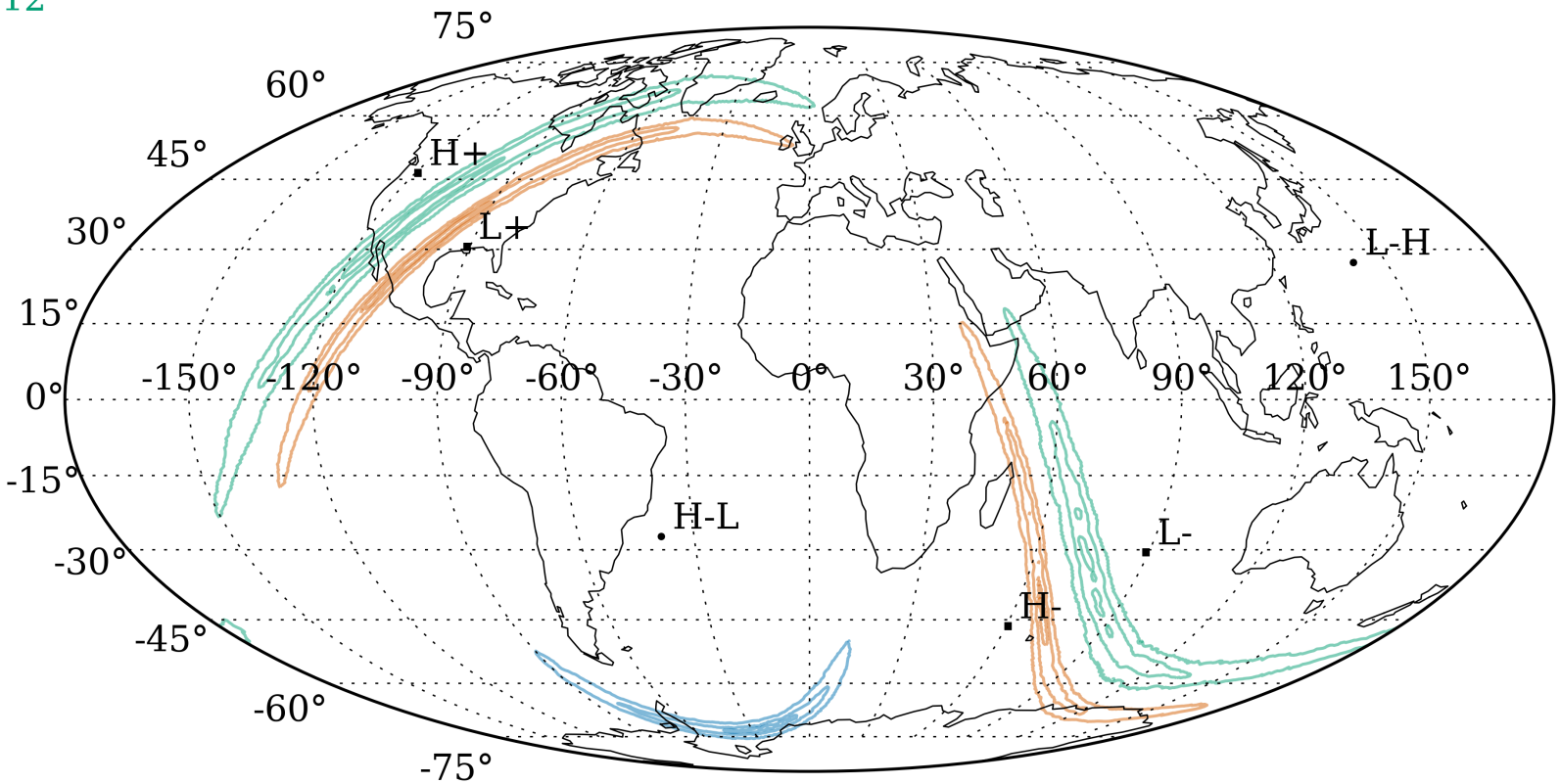
LVC
arXiv:1606.04856

Distance

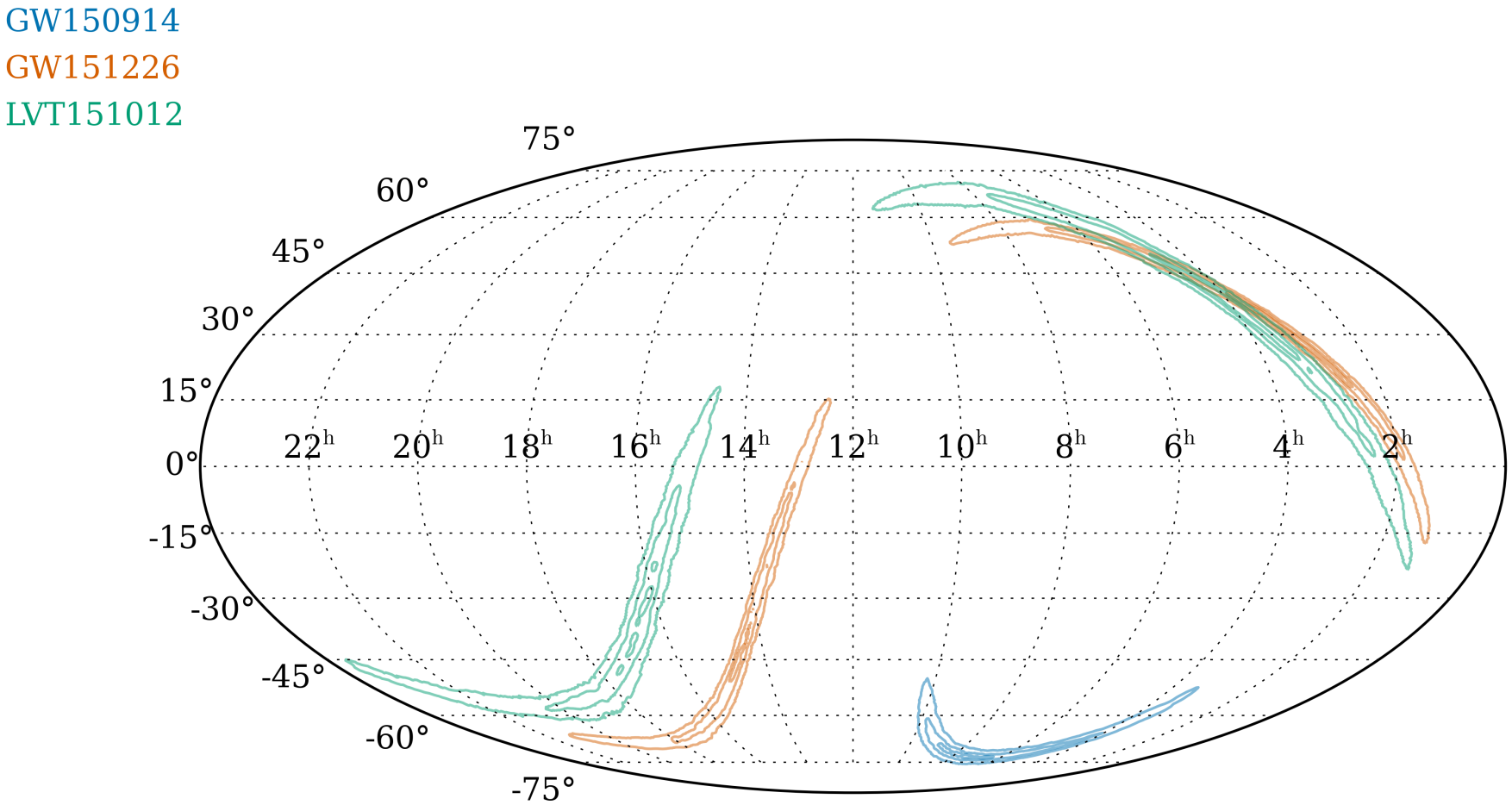


LVC
PRL **118**:221101

GW150914
GW151226
LVT151012



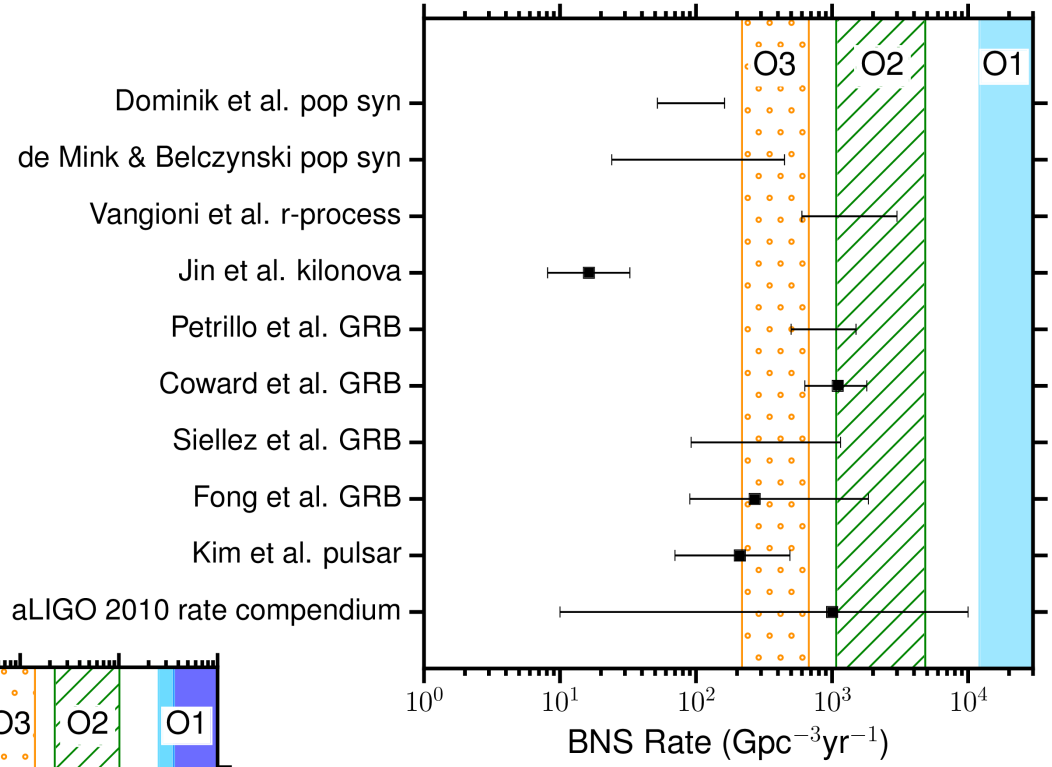
LVC arXiv:1606.04856

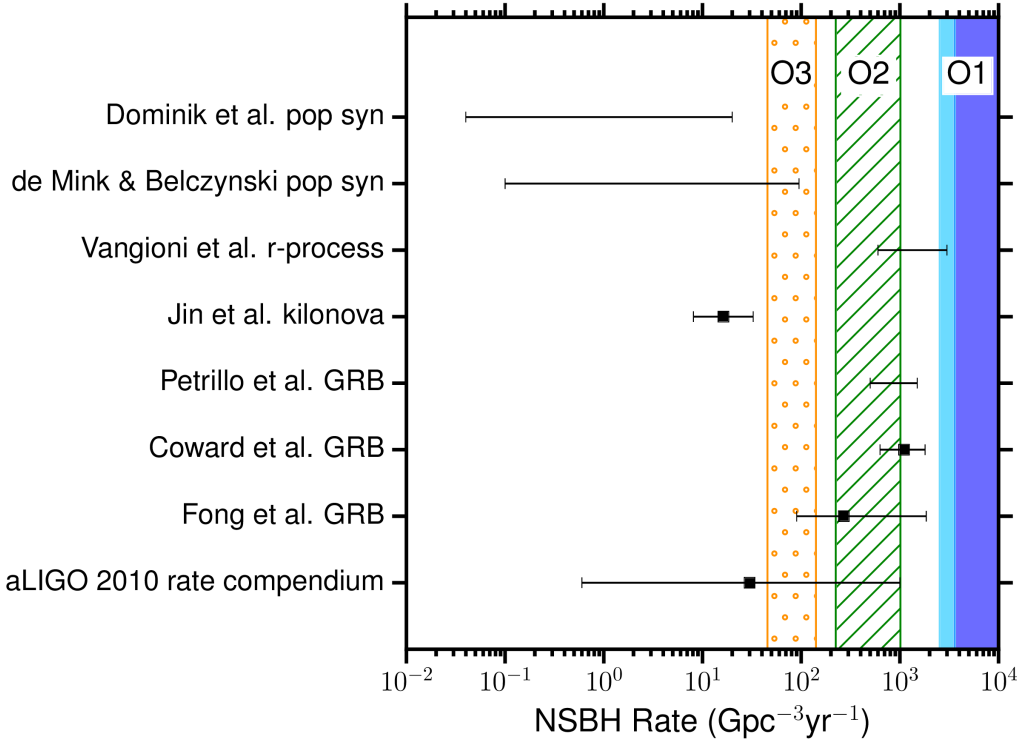


LVC arXiv:1606.04856


LVT151012
I WANT TO
BELIEVE

Limits





LVC
arXiv:1607.07456

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