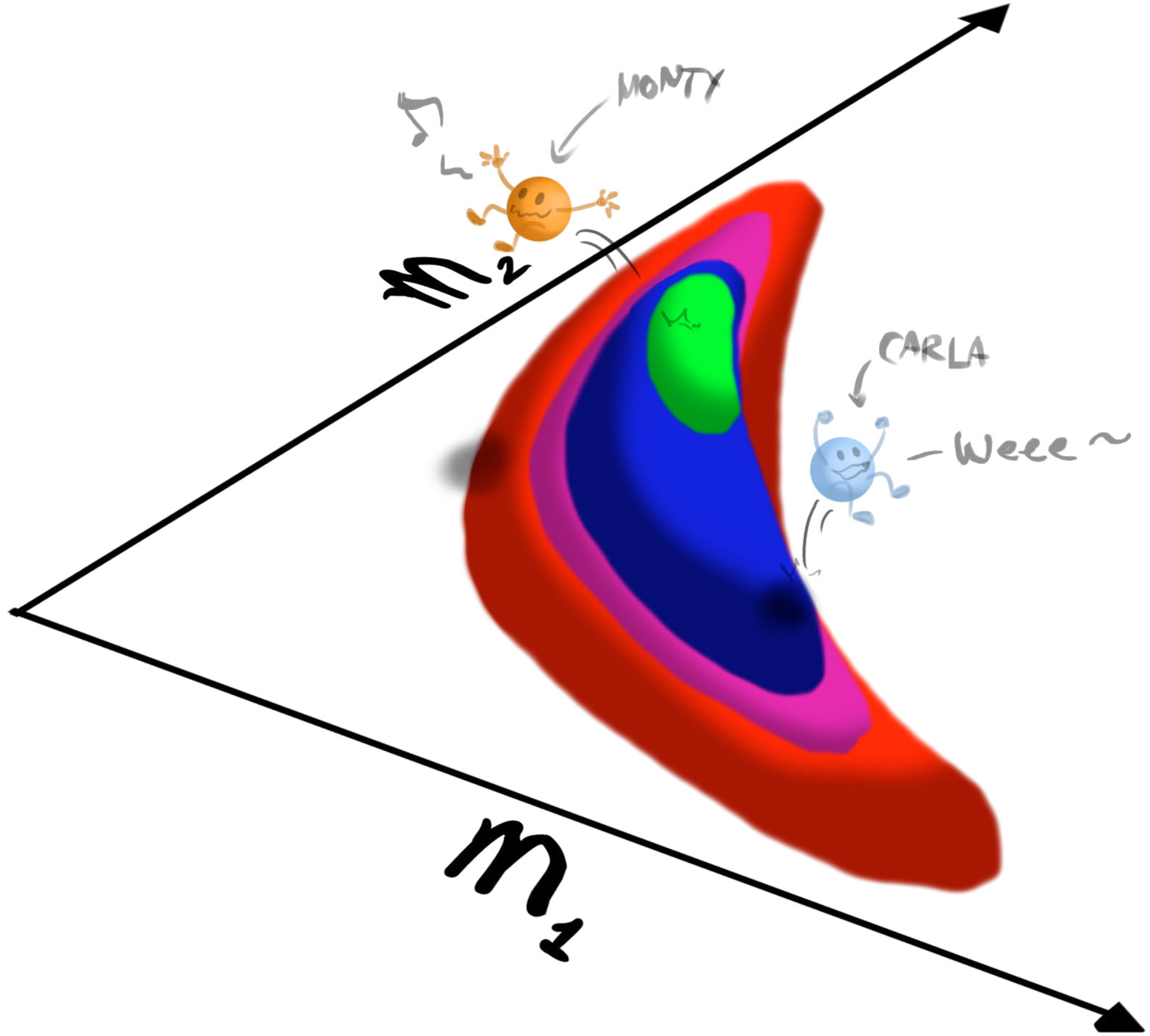


[LIGO Scientific Collaboration]

Parameter inference for compact binaries with the gravitational-wave observatory Advanced LIGO

Vivien Raymond
Max Planck Institute for Gravitational Physics

TeVPA, CERN, 15th September 2016

LIGO-G1601446

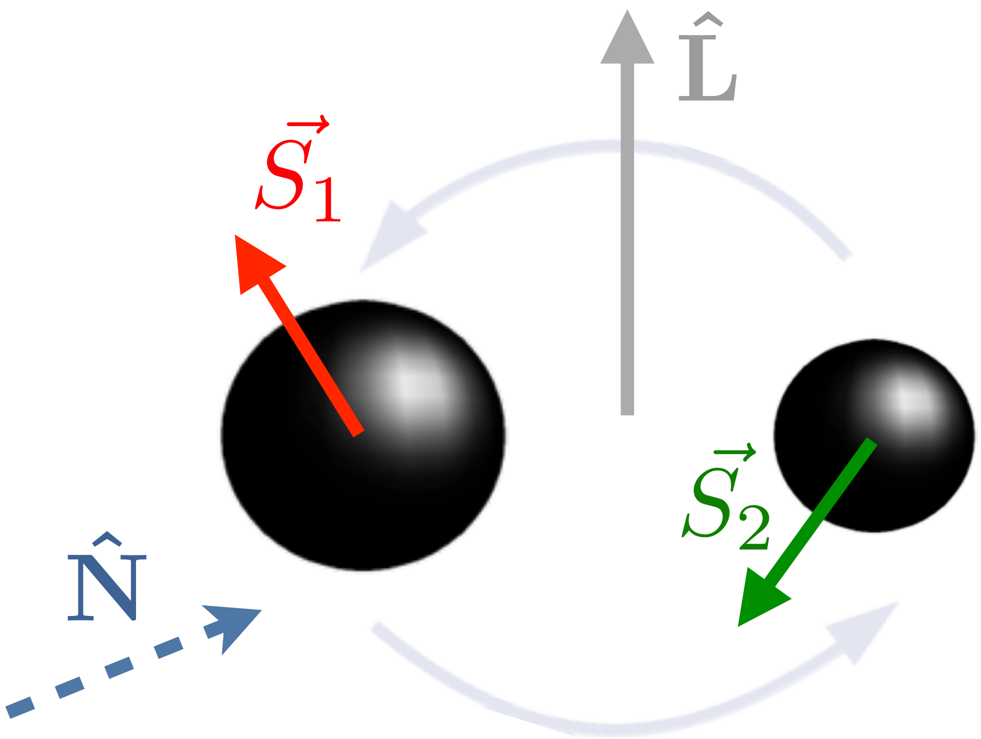
Gravitational-wave astrophysics

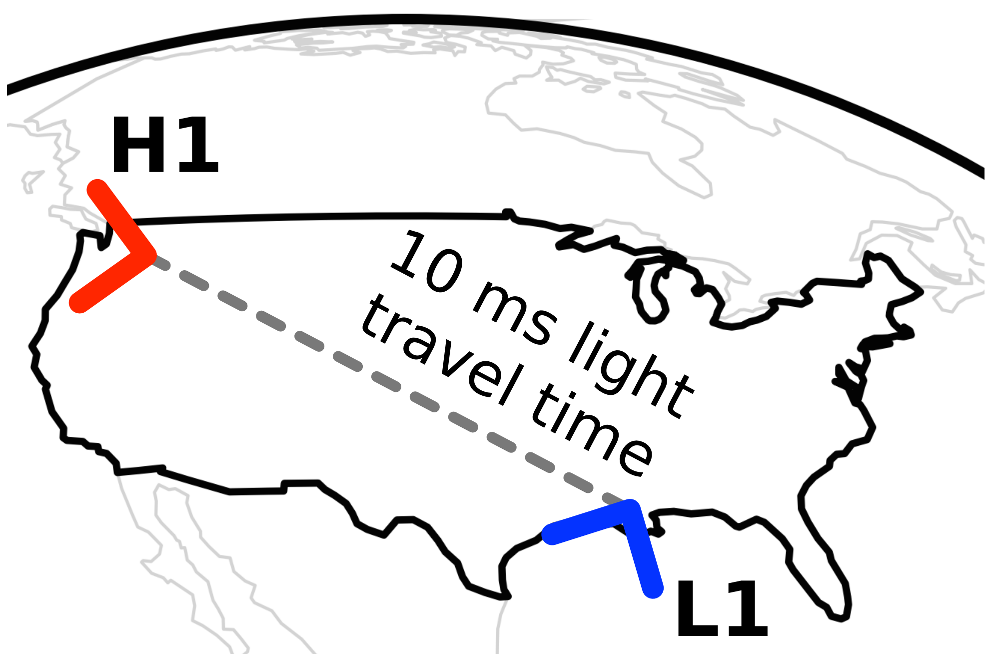
Fundamentally new way to learn about the **Universe:**

- Is **General Relativity** in the correct theory of **Gravity**?
- What happens when **matter** is compressed to **nuclear densities**?
- What are the properties of the population of **compact objects**? Especially the ones we **cannot see**?
- Is the mechanism that generates **gamma-ray bursts** a **compact binary coalescence**?

Compact Binary Coalescence

- **Intrinsic** parameters: primary and secondary **masses** and **spins** (and eccentricity)

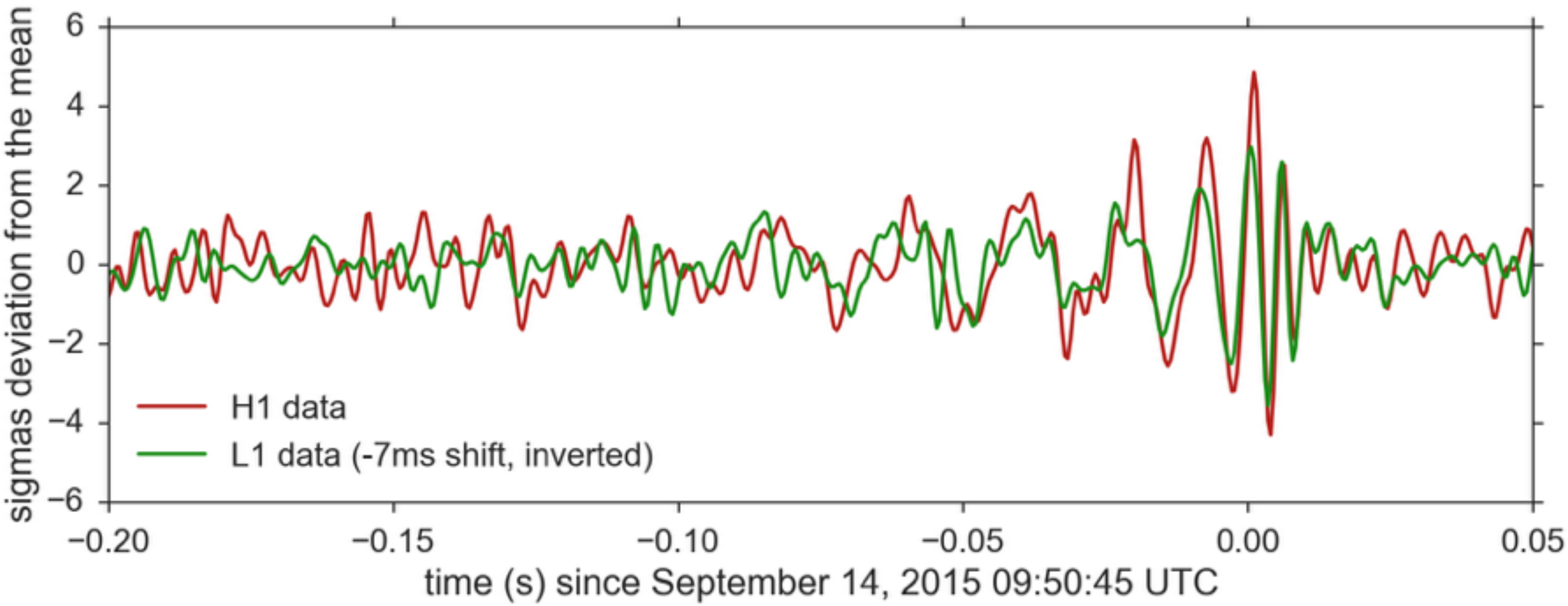




- **Extrinsic**: time, **sky-position**, distance, **orientation**, reference phase

Credit: LIGO

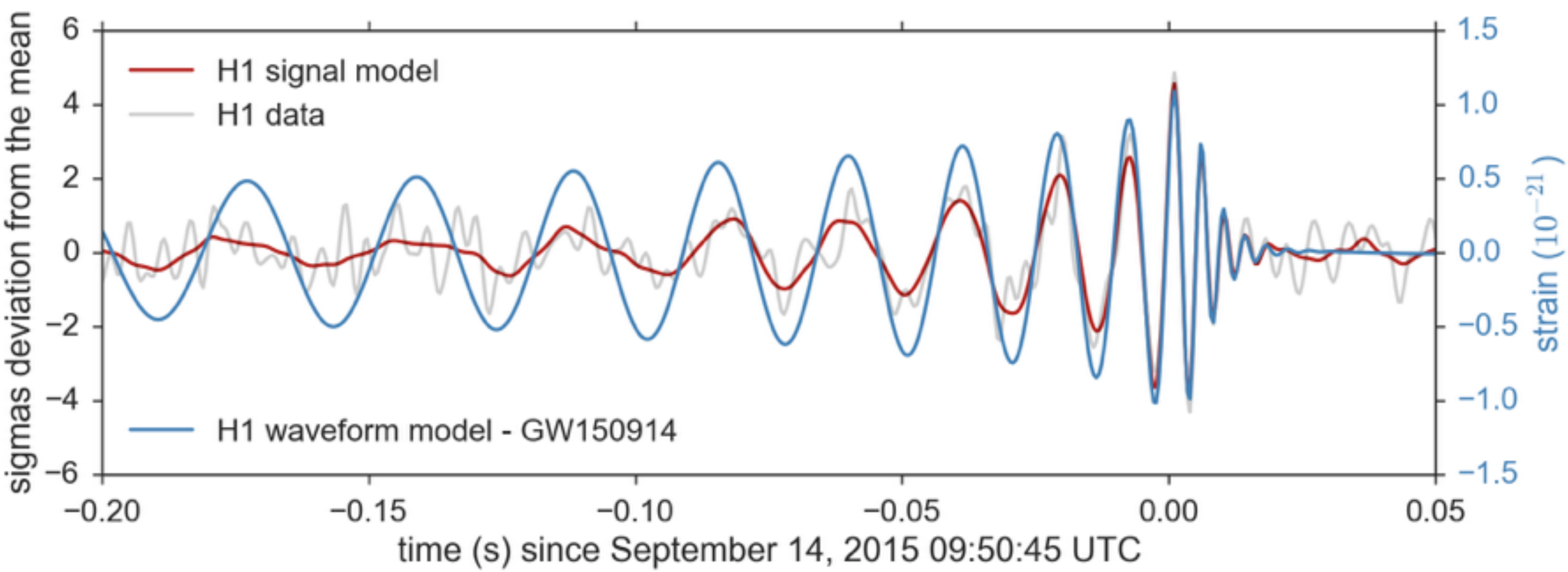
The GW150914 observation:



- How do we extract the **astrophysics**?

Gravitational waveform models

- 2 **models** of the **signal** as a proxy for systematic errors:
  - **Double-aligned-spin** model *(SEOBNRv2_ROM, [Taracchini, et al., 2014, Pürrer, 2014])*
  - **Single-precessing-spin** model *(IMRPhenomPv2, [Hannam et al. Phys. 2014])*



Gravitational waveform models

- 2 **models** of the **signal** as a proxy for systematic errors:
  - **Double-precessing-spin** model *(SEOBNRv3, [Pan et al., 2014, Babak et al., 2016])*
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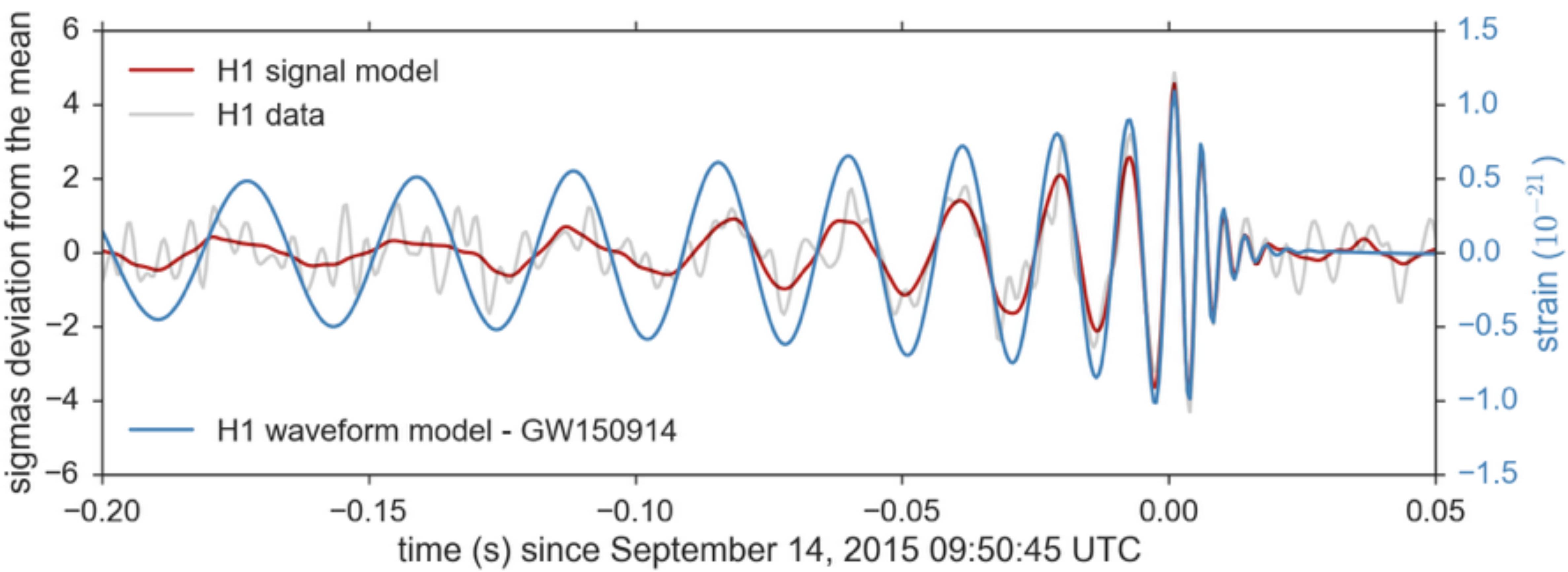
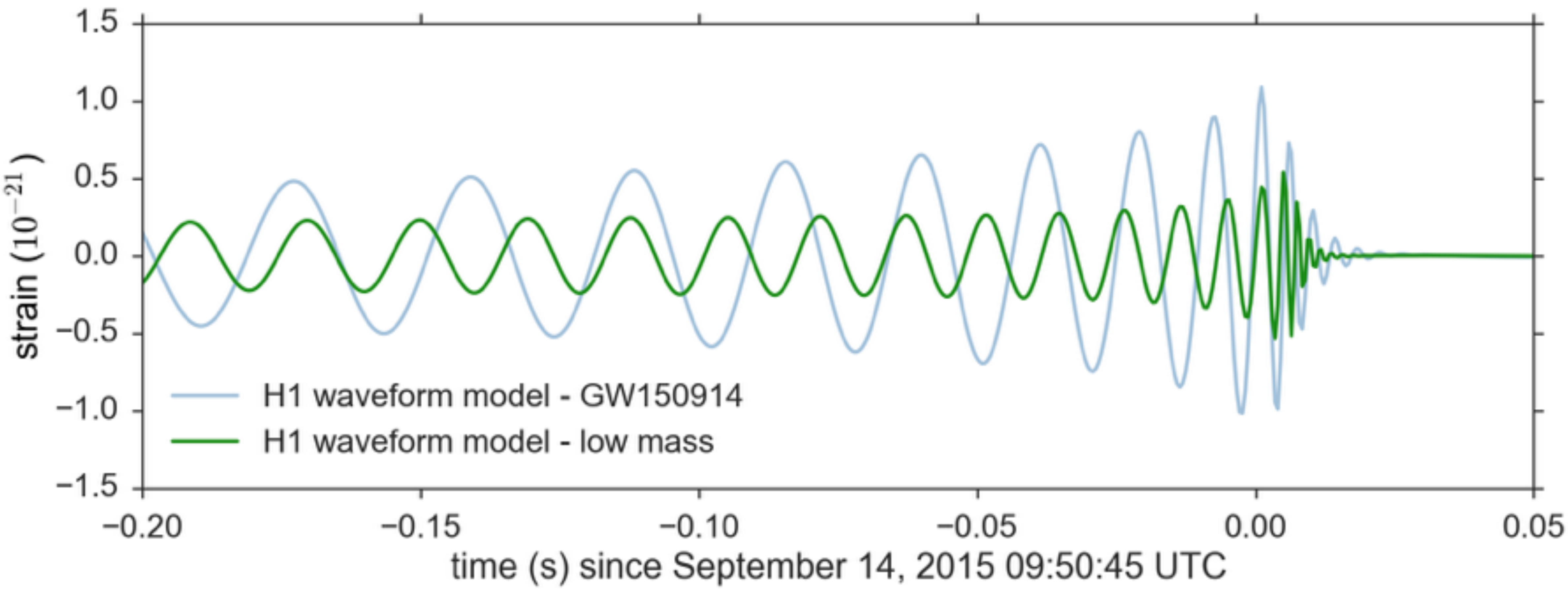


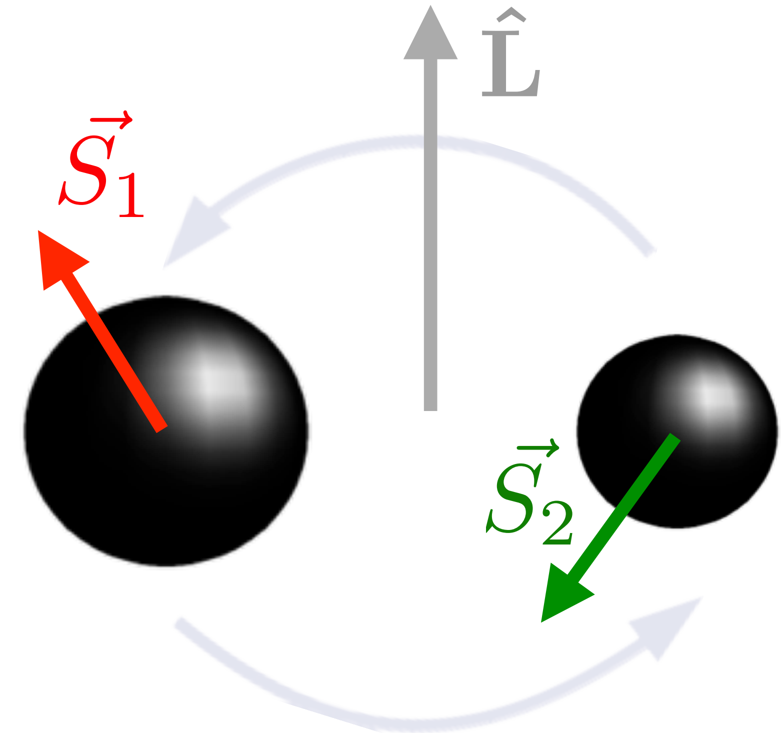
Masses from the inspiral and ringdown

- Chirp mass: $$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$
- Mass ratio: $$q = \frac{m_1}{m_2}$$
- Total mass: **ringdown**

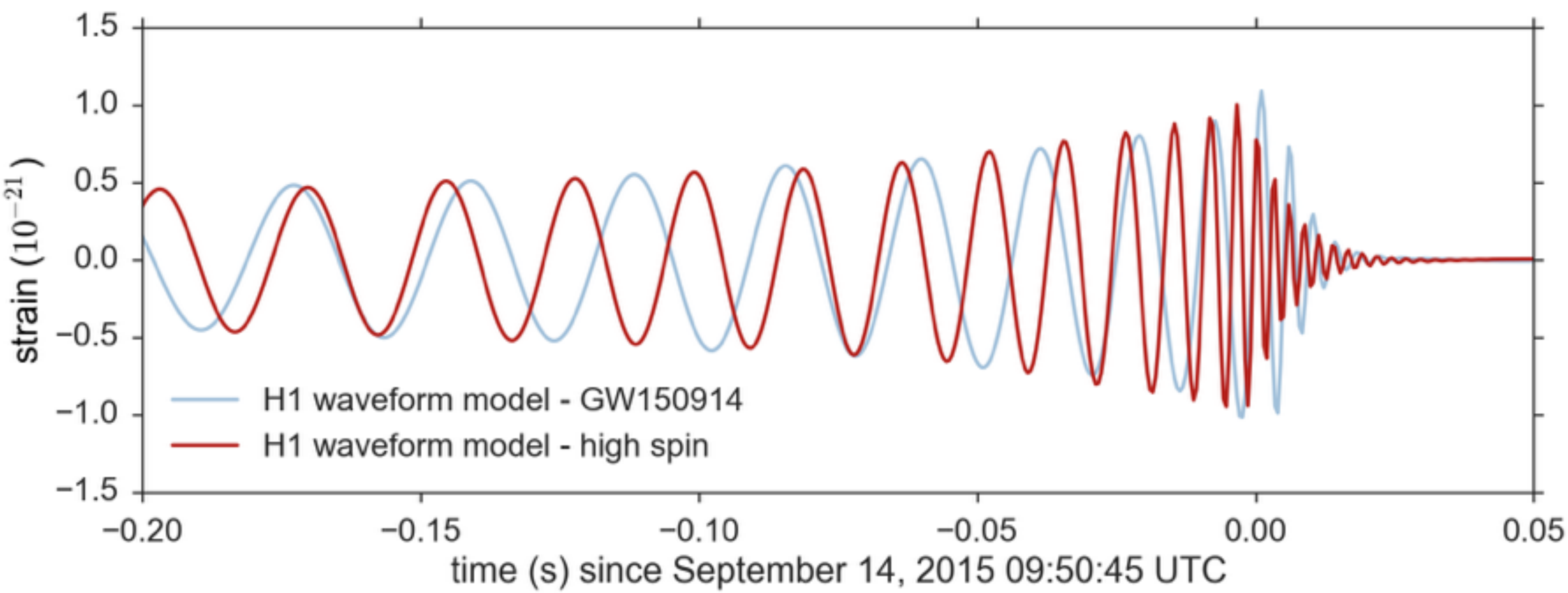
  (with total spin)



Effects of spins



- 2 spin vectors
  - **Magnitude: orbital hang-up**
  - Mis-alignment: precession and modulations



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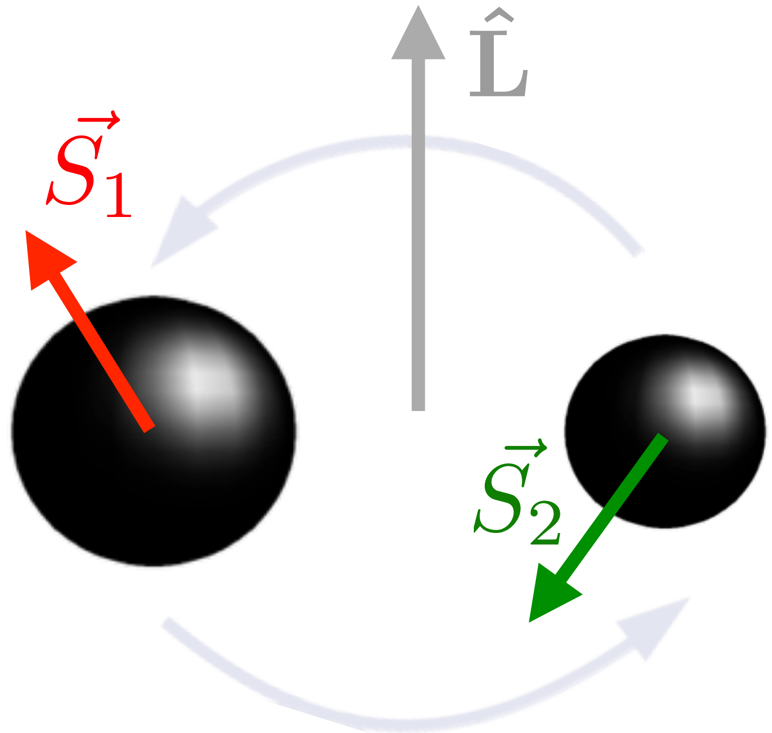

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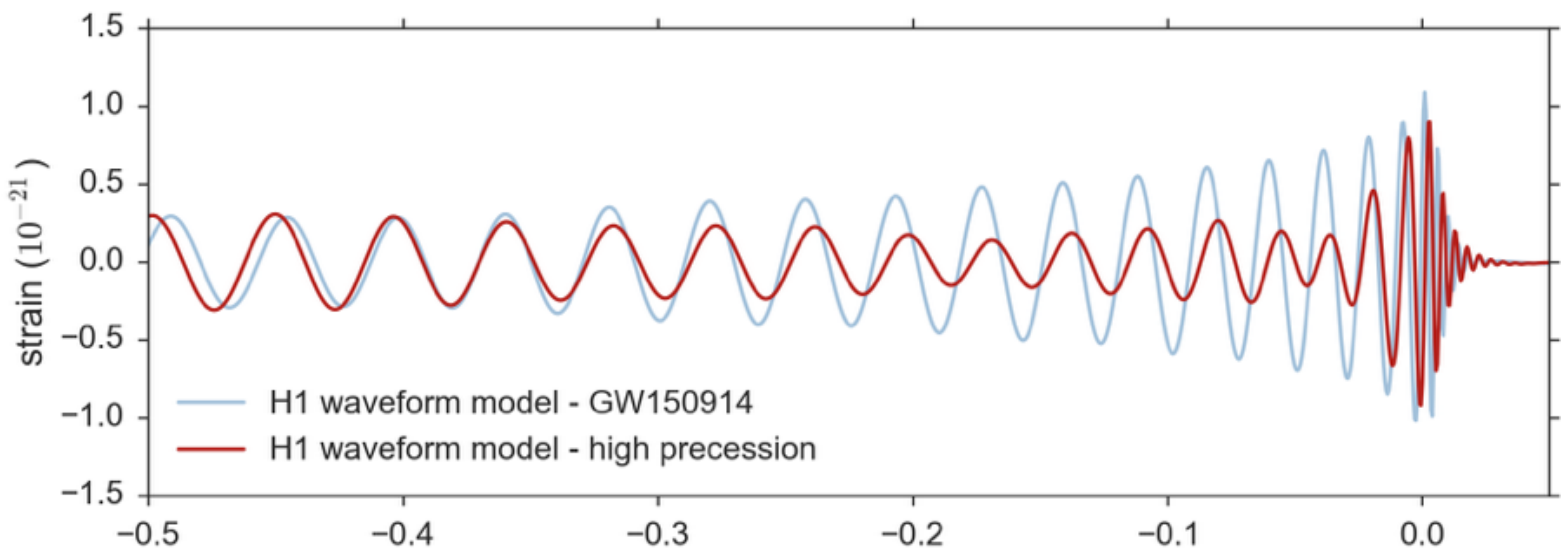

Parameter Estimation

- We want the **posterior** probability of parameters $\vec{\lambda}$, given the data $\vec{x}$. With **Bayes'** theorem:

$$p(\vec{\lambda}|\vec{x}, M) = \frac{p(\vec{\lambda}|M)\, p(\vec{x}|\vec{\lambda}, M)}{p(\vec{x}|M)}$$

- Fit a **model** to the data (**noise** and **signal** models)
- Build a **likelihood** function
- Specify **prior** knowledge
- **Numerically** estimate the resulting **distribution** (**sampling** algorithms)

`SPINSpiral`[van der Sluys, Raymond, et al. 2008], `LALInference` [Veitch, Raymond, et al., 2015]

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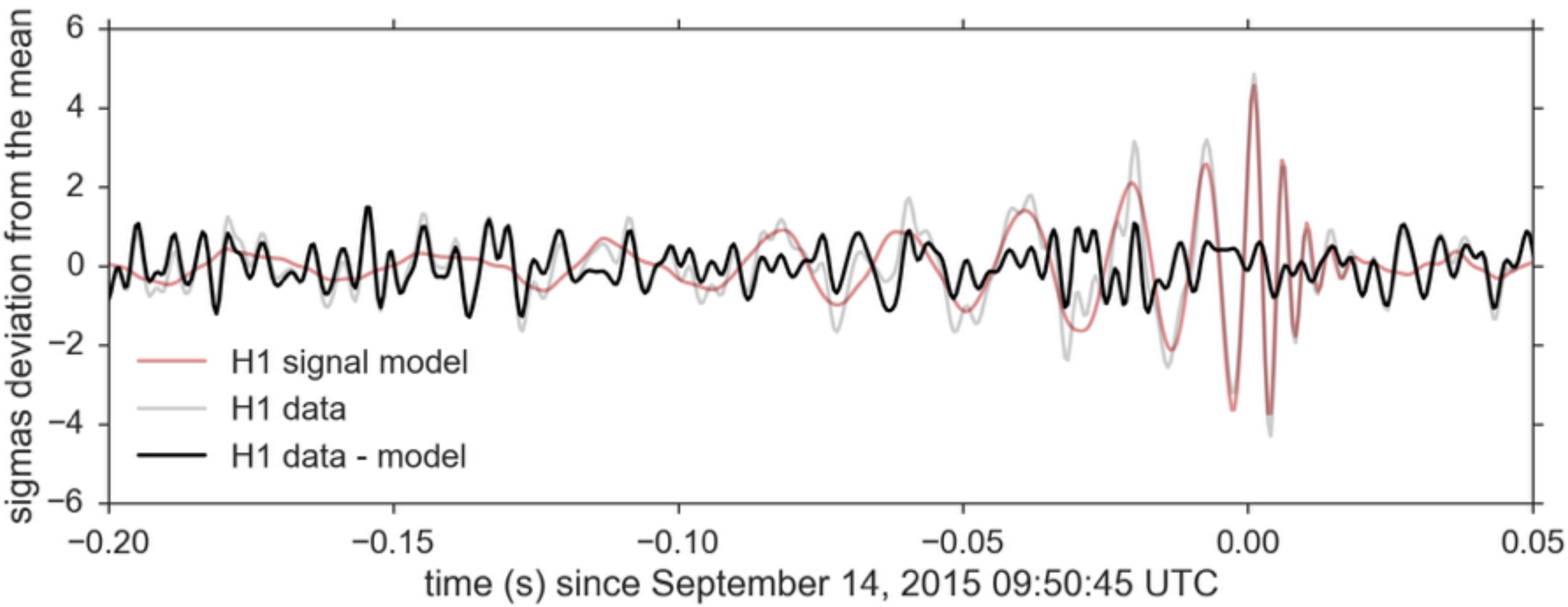
Likelihood



- How close is the **remainder** to the **mean**?
    - Assumptions: **gaussianity** and **stationarity**

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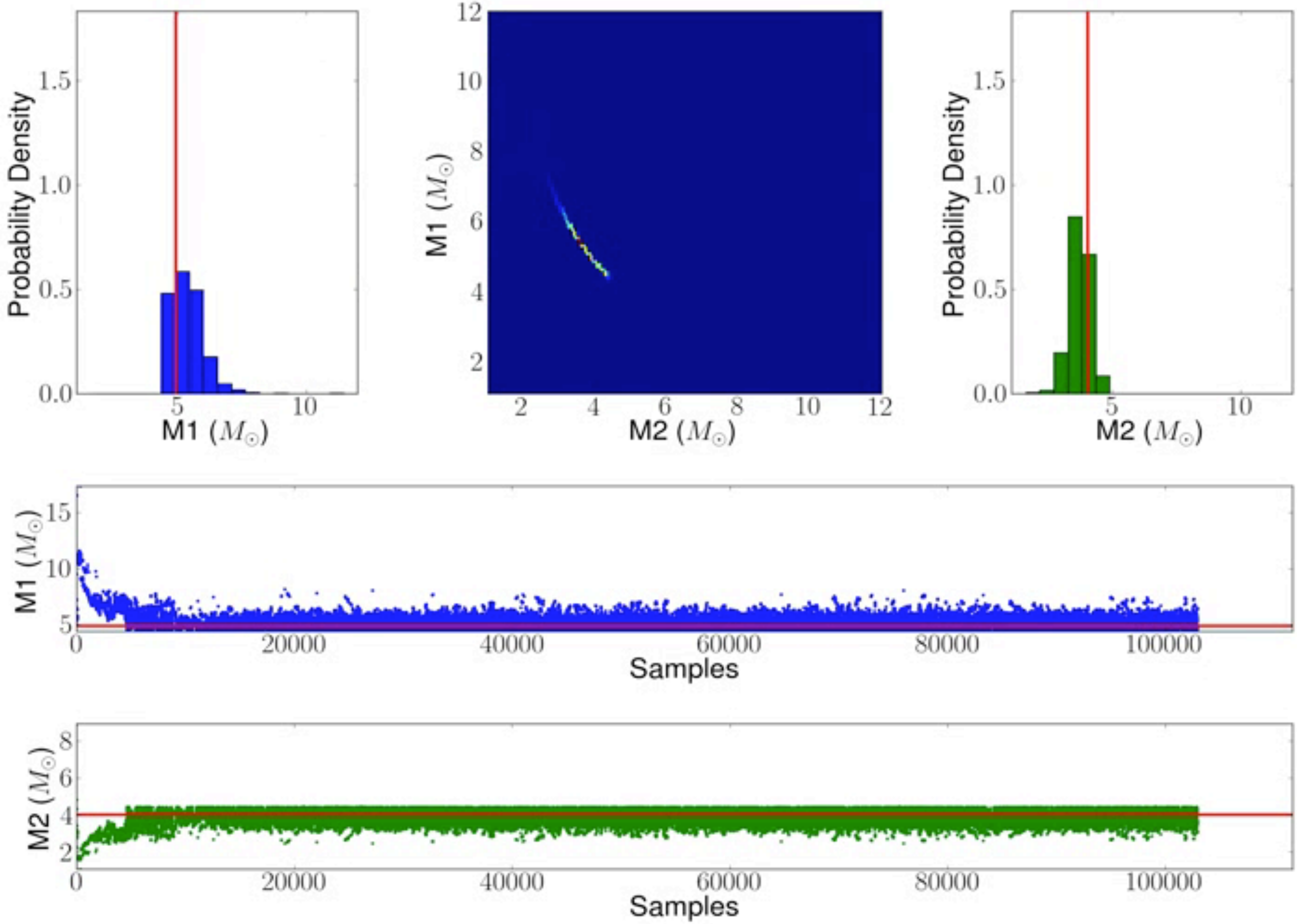
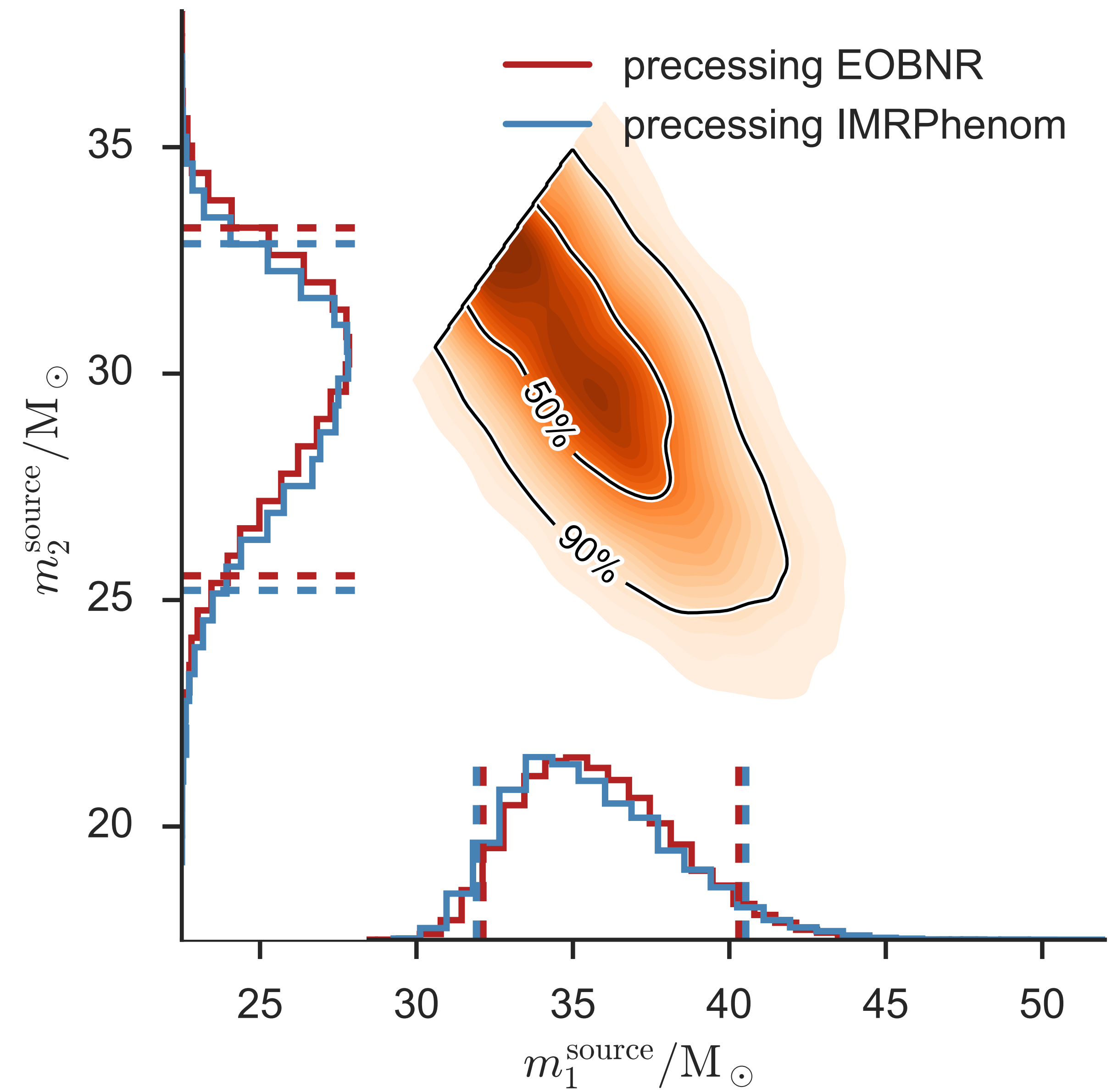

Probability Density
M1 ($M_\odot$)
M2 ($M_\odot$)
M1 ($M_\odot$)
Probability Density
M2 ($M_\odot$)
M1 ($M_\odot$)
Samples
M2 ($M_\odot$)
Samples

GW150914

- 2 models as a proxy for systematic errors:
  - **Double-precessing-spin** model *(SEOBNRv3)*
  - **Single-precessing-spin** model *(IMRPhenomP)*

$$m_1 = 35.4^{+5.0}_{-3.4}\,\mathrm{M}_\odot$$

$$m_2 = 28.9^{+3.3}_{-4.3}\,\mathrm{M}_\odot$$



[LIGO-Virgo Collaboration, 2016]

GW150914

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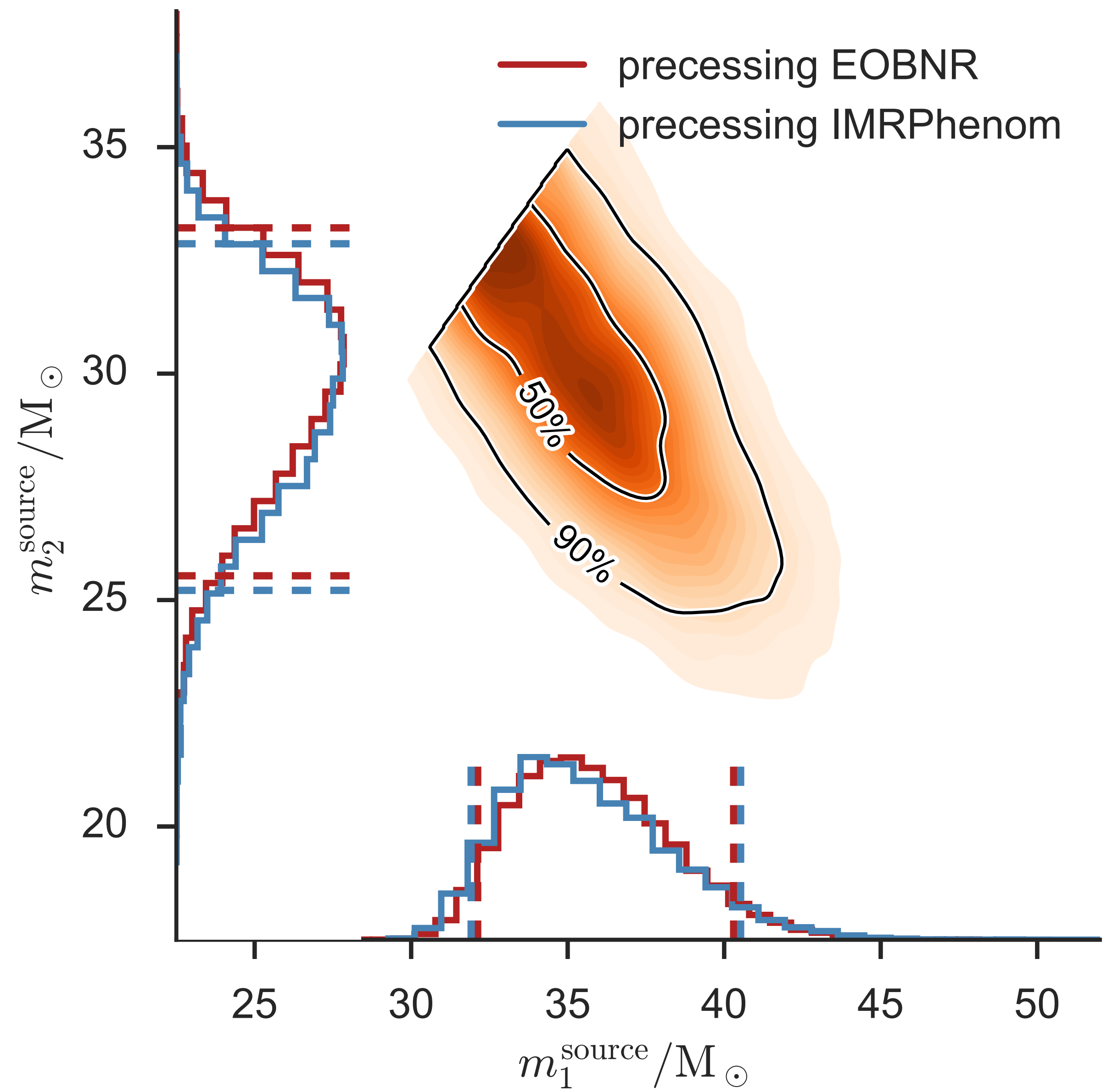

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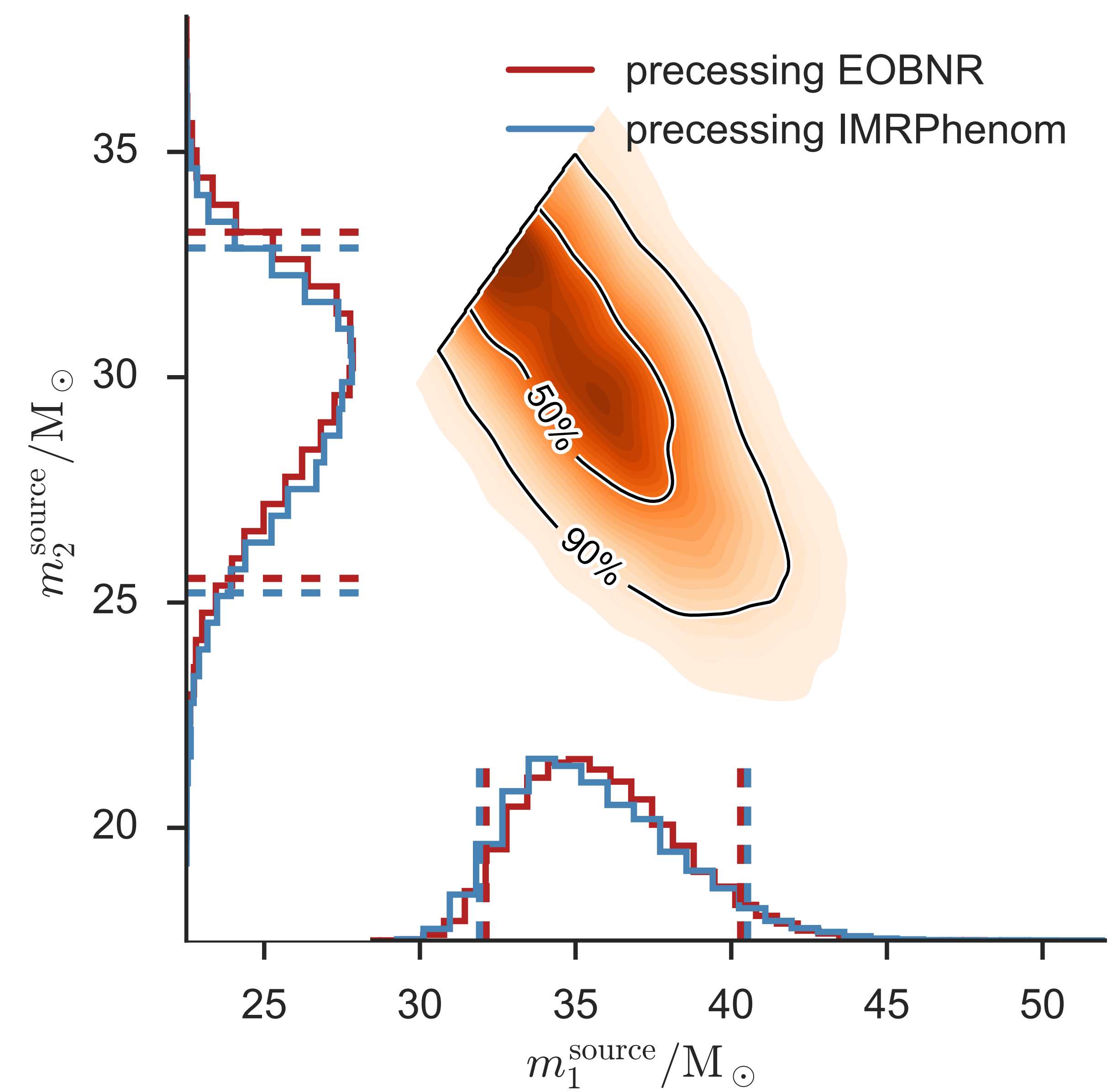
- Errors:

signal strength

model inaccuracies



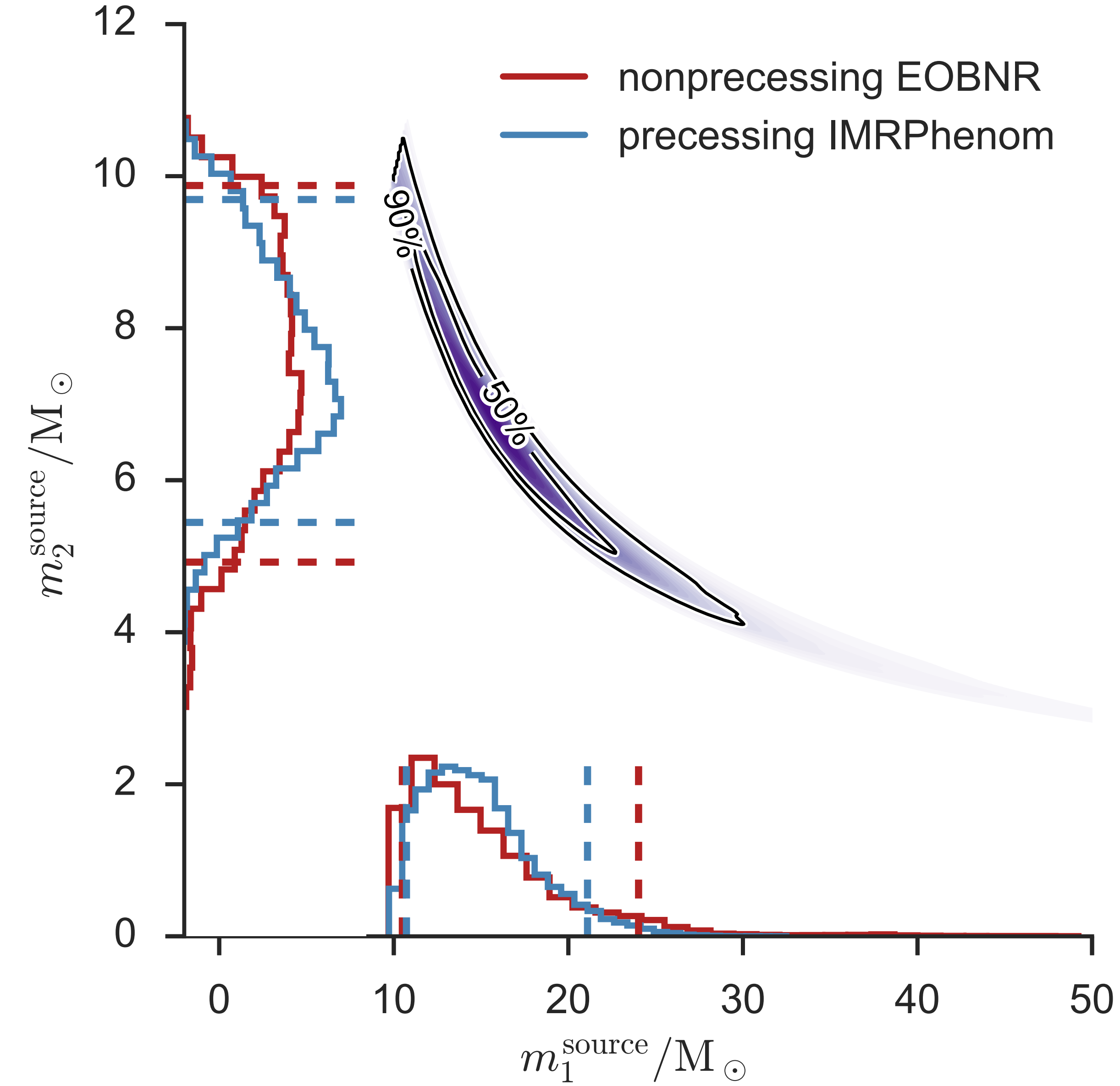
[LIGO-Virgo Collaboration, 2016]

GW151226

- 2 models as a proxy for systematic errors:
  - **Double-aligned-spin** model *(SEOBNRv2_ROM)*
  - **Single-precessing-spin** model *(IMRPhenomP)*

$$m_1 = 14.2^{+8.3}_{-3.7}\,\mathrm{M}_\odot$$

$$m_2 = 7.5^{+2.3}_{-2.3}\,\mathrm{M}_\odot$$



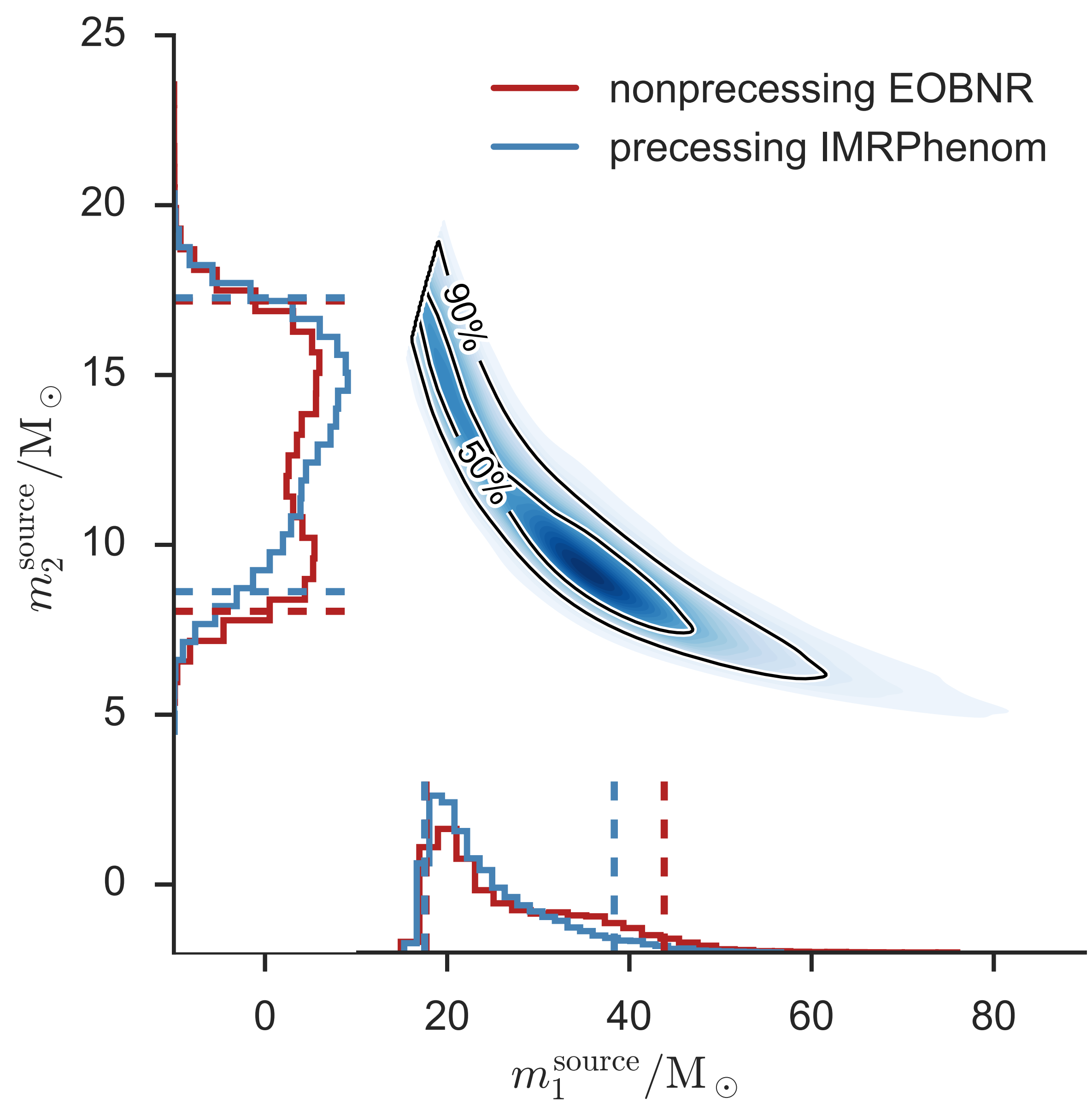
[LIGO-Virgo Collaboration, 2016]

LVT151012

- 2 models as a proxy for systematic errors:
  - **Double-aligned-spin** model *(SEOBNRv2_ROM)*
  - **Single-precessing-spin** model *(IMRPhenomP)*

$$m_1 = 23^{+18}_{-6}\,\mathrm{M}_\odot$$

$$m_2 = 13^{+4}_{-5}\,\mathrm{M}_\odot$$



[LIGO-Virgo Collaboration, 2016]

Remnant black hole

- Final values fitted from **Numerical Relativity** simulations

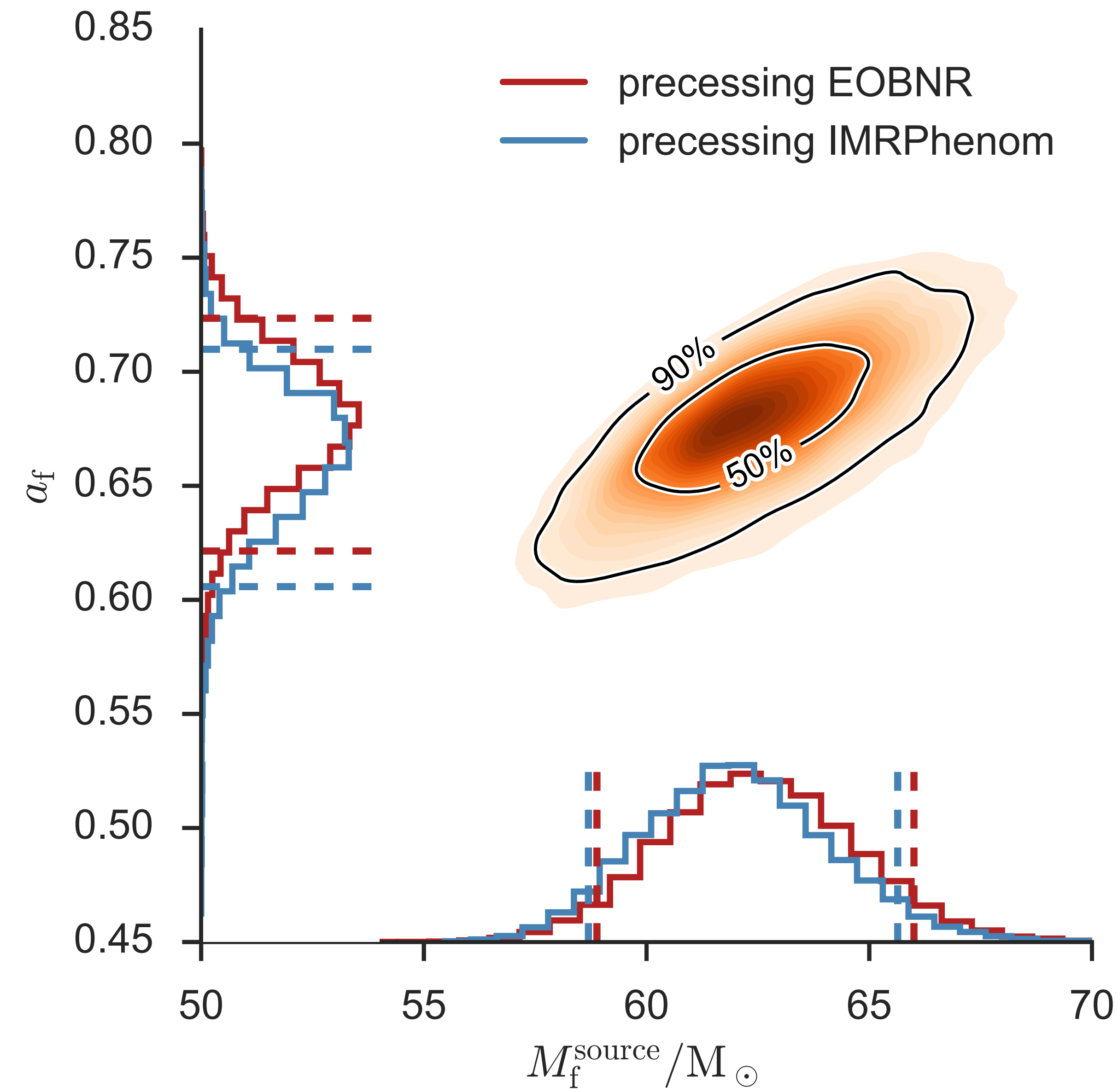
  - Final mass:

$$M_f = 62.2^{+3.7}_{-3.4}\,\mathrm{M}_{\odot}$$

  - Final (dimensionless) spin:

$$a_f = 0.68^{+0.05}_{-0.06}$$

  - ~**3 solar mass** radiated !



[LIGO-Virgo Collaboration, 2016]

Remnant black hole

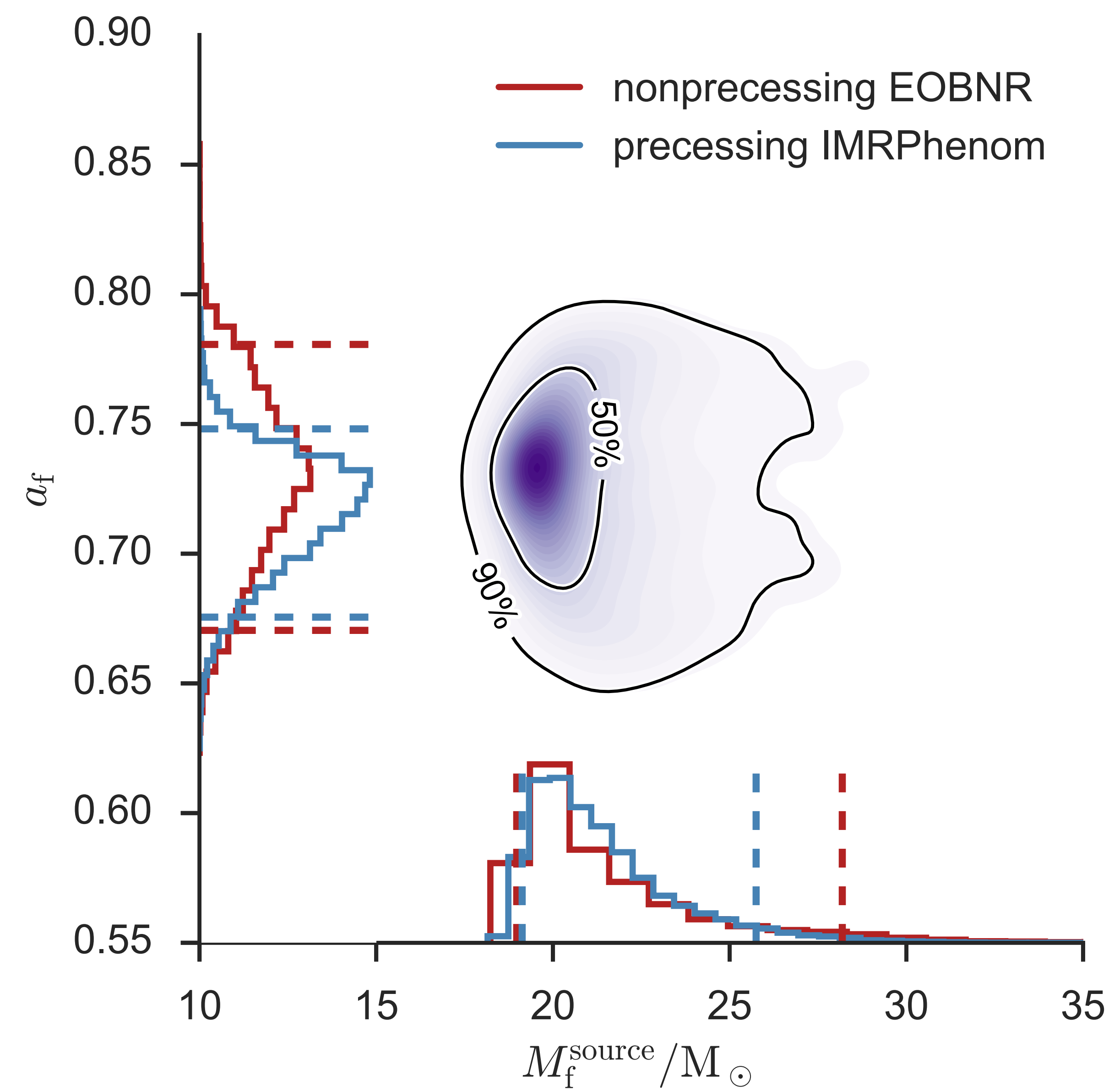
- Final values fitted from **Numerical Relativity** simulations
  - Final mass:

$$M_f = 20.8^{+6.1}_{-1.7}\,\mathrm{M}_\odot$$

  - Final (dimensionless) spin:

$$a_f = 0.74^{+0.06}_{-0.06}$$

  - **~1 solar mass** radiated



[LIGO-Virgo Collaboration, 2016]

Remnant black hole

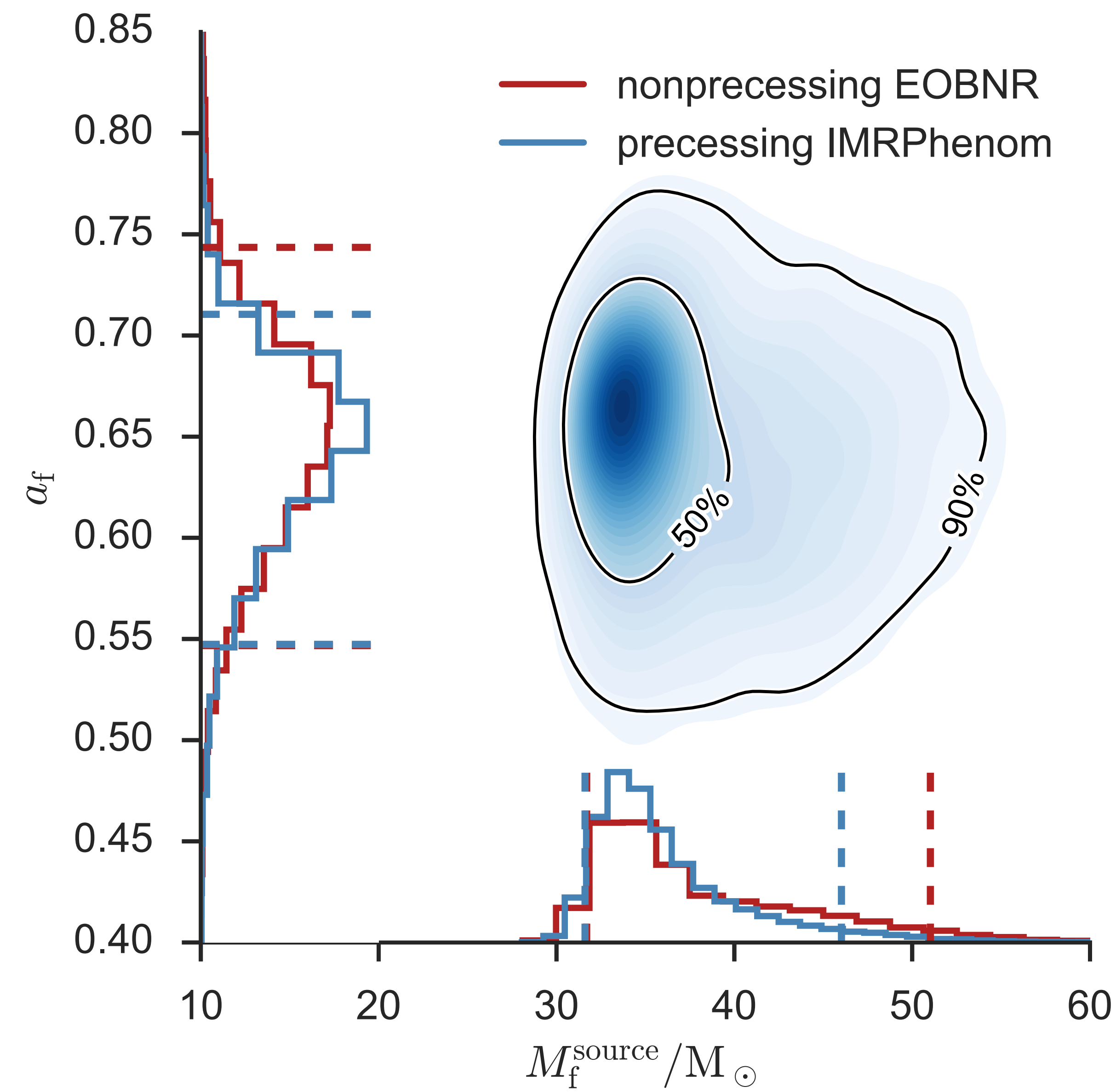
- Final values fitted from **Numerical Relativity** simulations
  - Final mass:

$$M_f = 35^{+14}_{-4}\,\mathrm{M}_\odot$$

  - Final (dimensionless) spin:

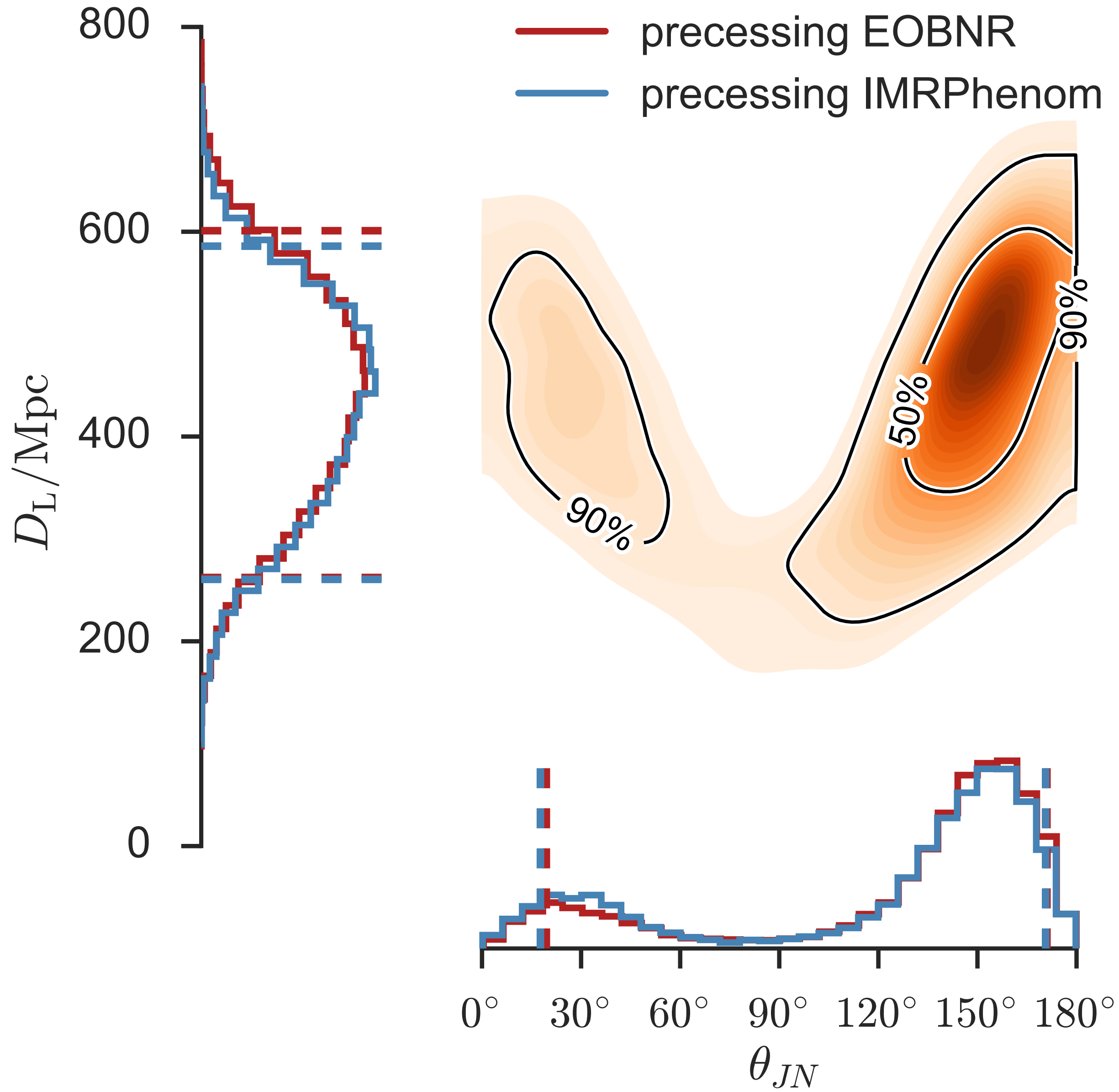
$$a_f = 0.66^{+0.1}_{-0.09}$$

  - **~1.5 solar mass** radiated !



[LIGO-Virgo Collaboration, 2016]

Distance - inclination



[LIGO-Virgo Collaboration, 2016]

Distance - inclination

- **Degeneracies** in **extrinsic** parameters, strain h:

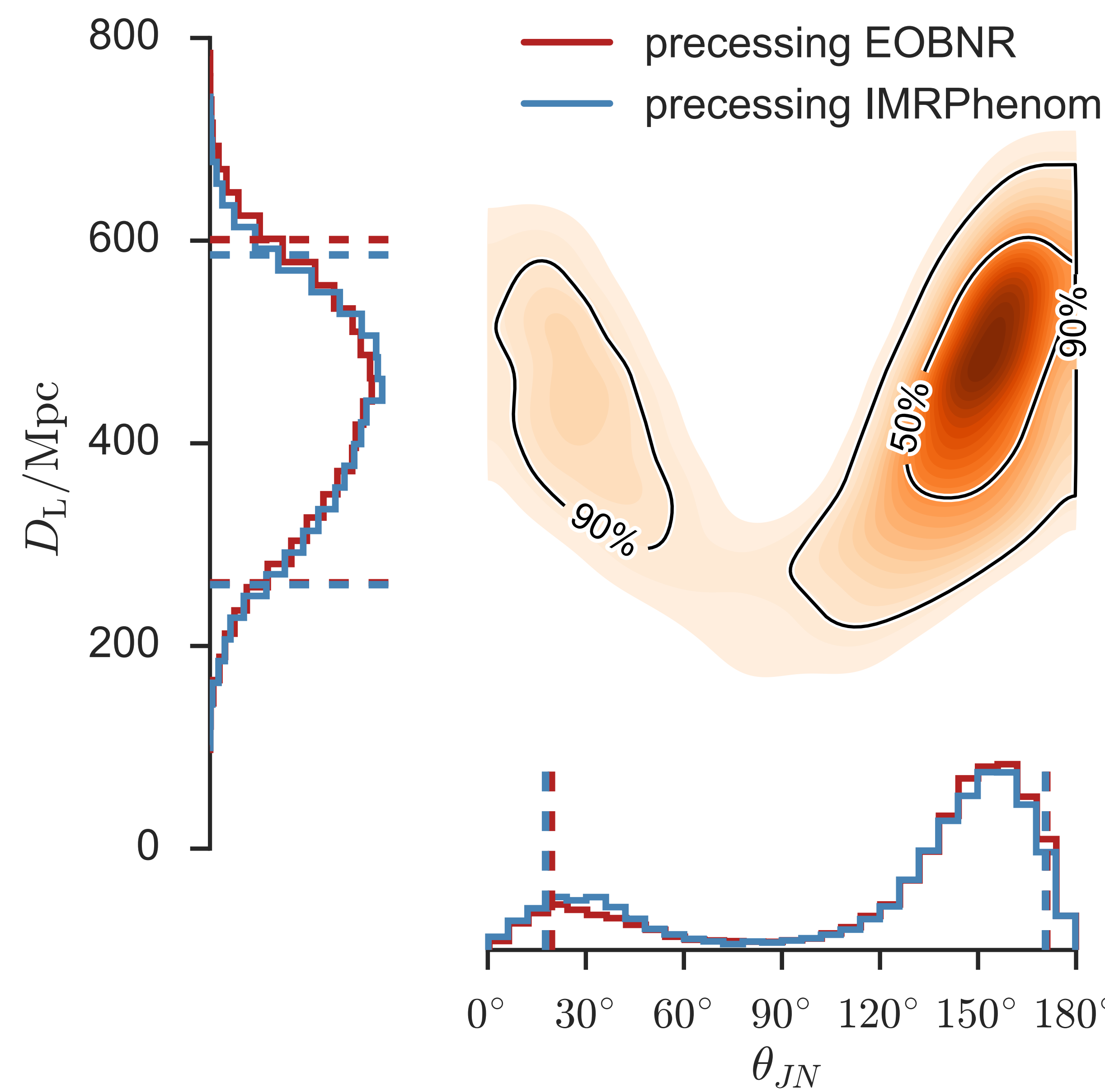
$$h = -\frac{1+\cos^2(\iota)}{2\,d} F_{j+}(\text{R.A.}, \text{dec}, \psi) H_+ + \frac{\cos\,\iota}{d} F_{j\times}(\text{R.A.}, \text{dec}, \psi) H_\times$$

3 angles for the orientation: $(\text{R.A.}, \text{dec}, \psi)$

Intrinsic waveform: $H_{+,\times}(m_1, m_2, \vec{S_1}, \vec{S_2})$

- Sampling in `LALInference`

[Raymond, Farr, 2014]



[LIGO-Virgo Collaboration, 2016]

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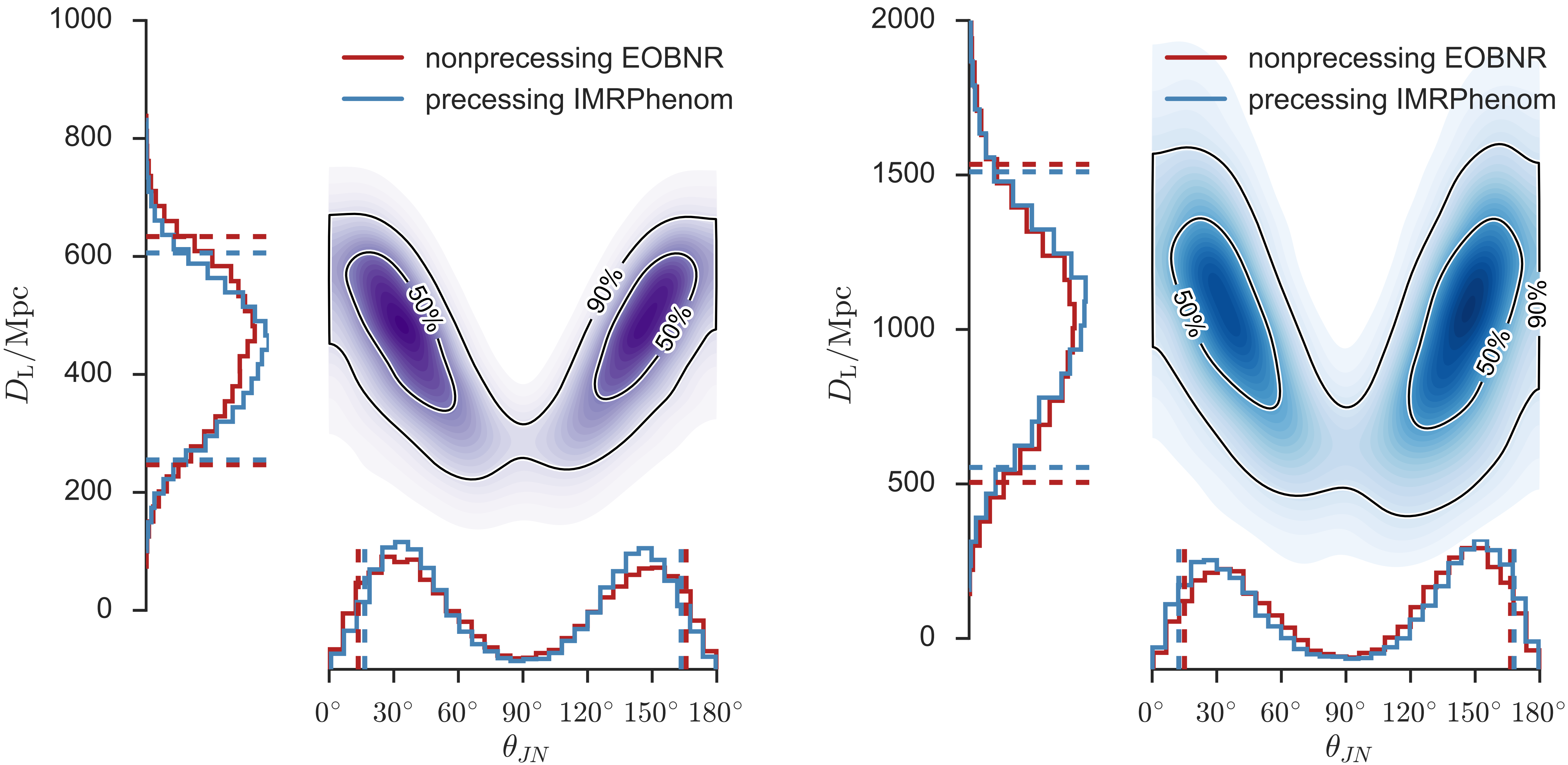


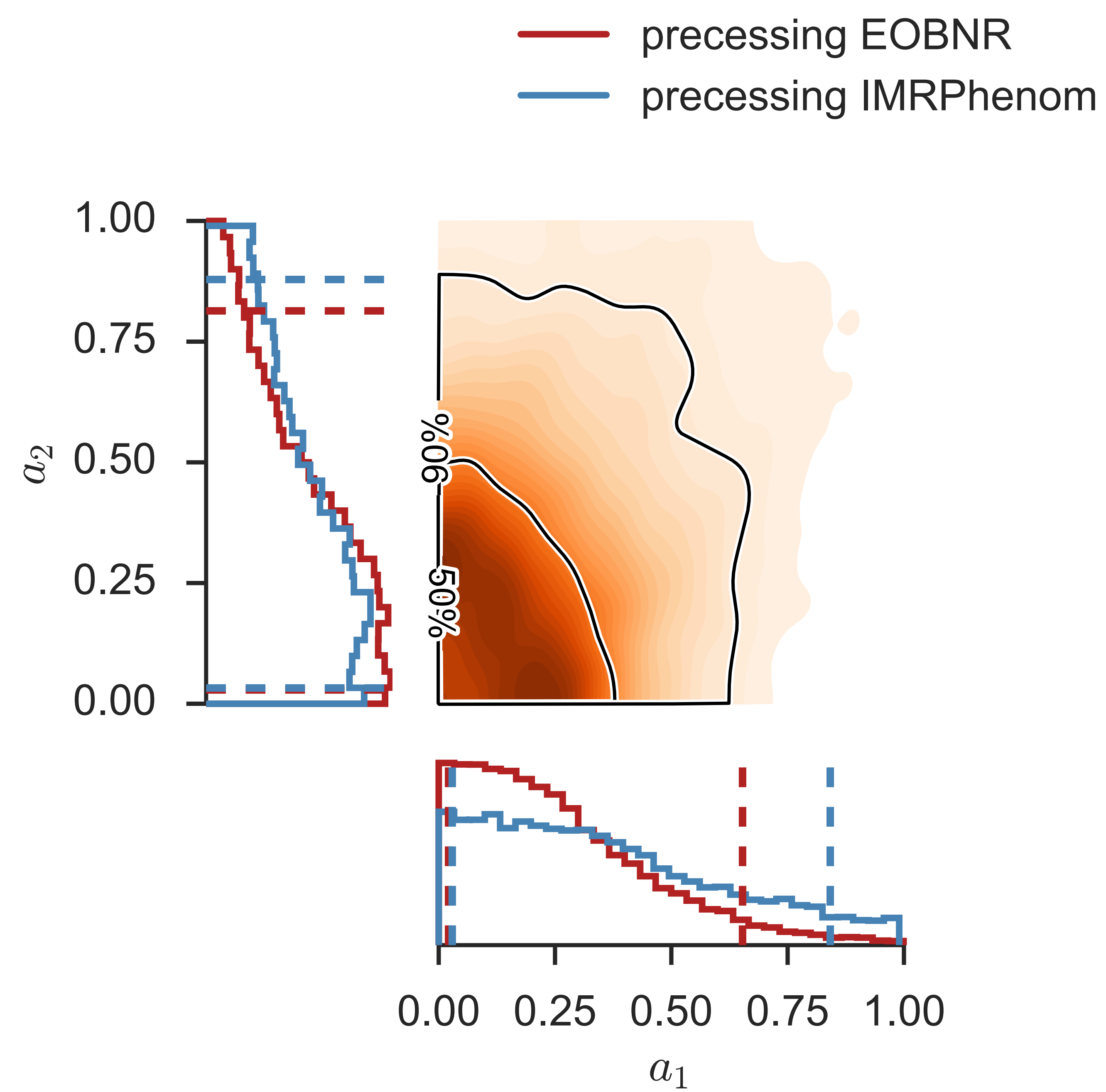
GW151226

LVT151012

[LIGO-Virgo Collaboration, 2016]

Were the black-holes spinning?

- Weak constrains on **spin magnitude**
  - Very weak constrains on **spin orientation**
- Due to Almost **equal-mass**, **face-off** binary
  [Raymond, 2012]
  [LIGO-Virgo Collaboration, 2013]



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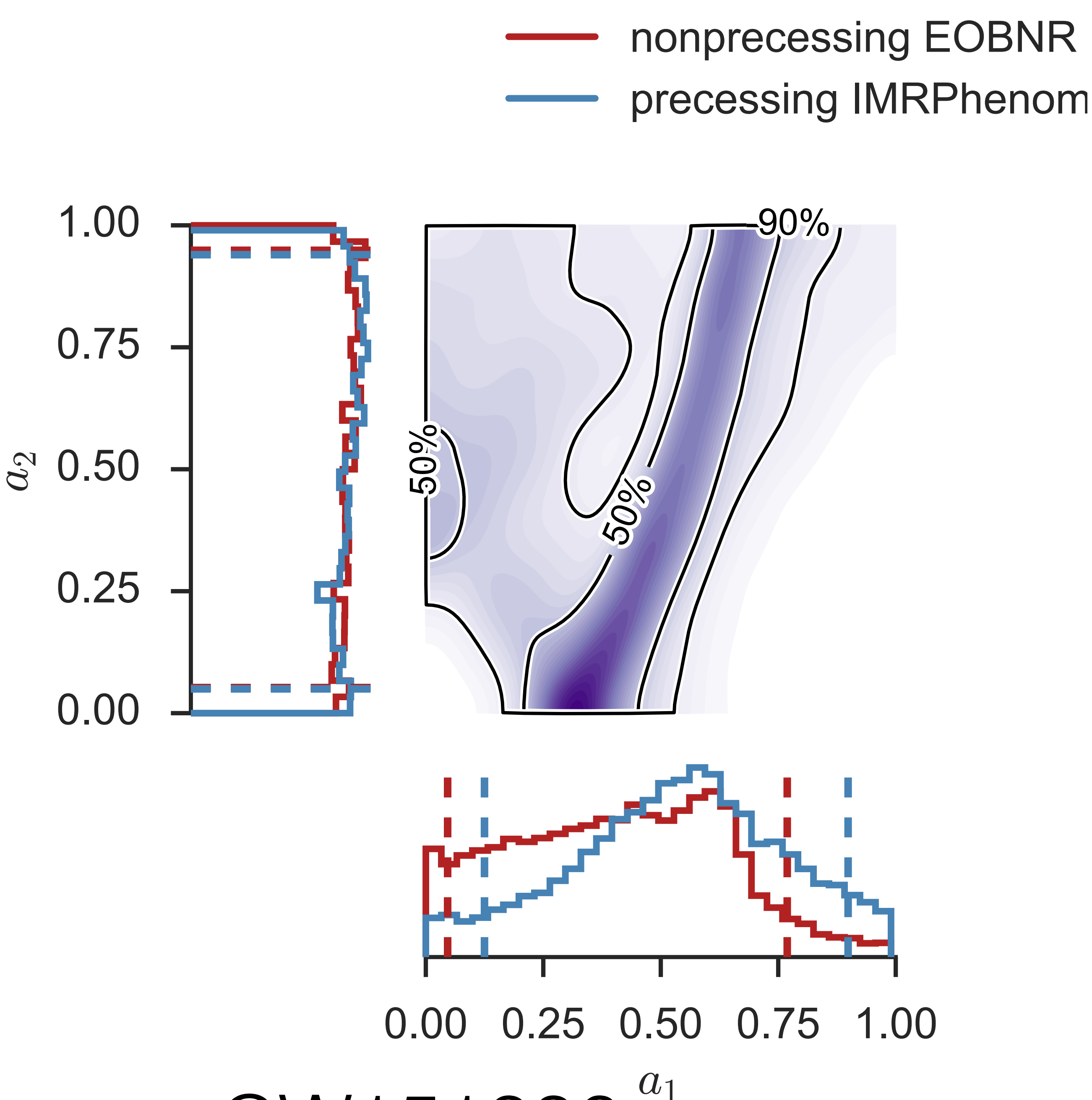
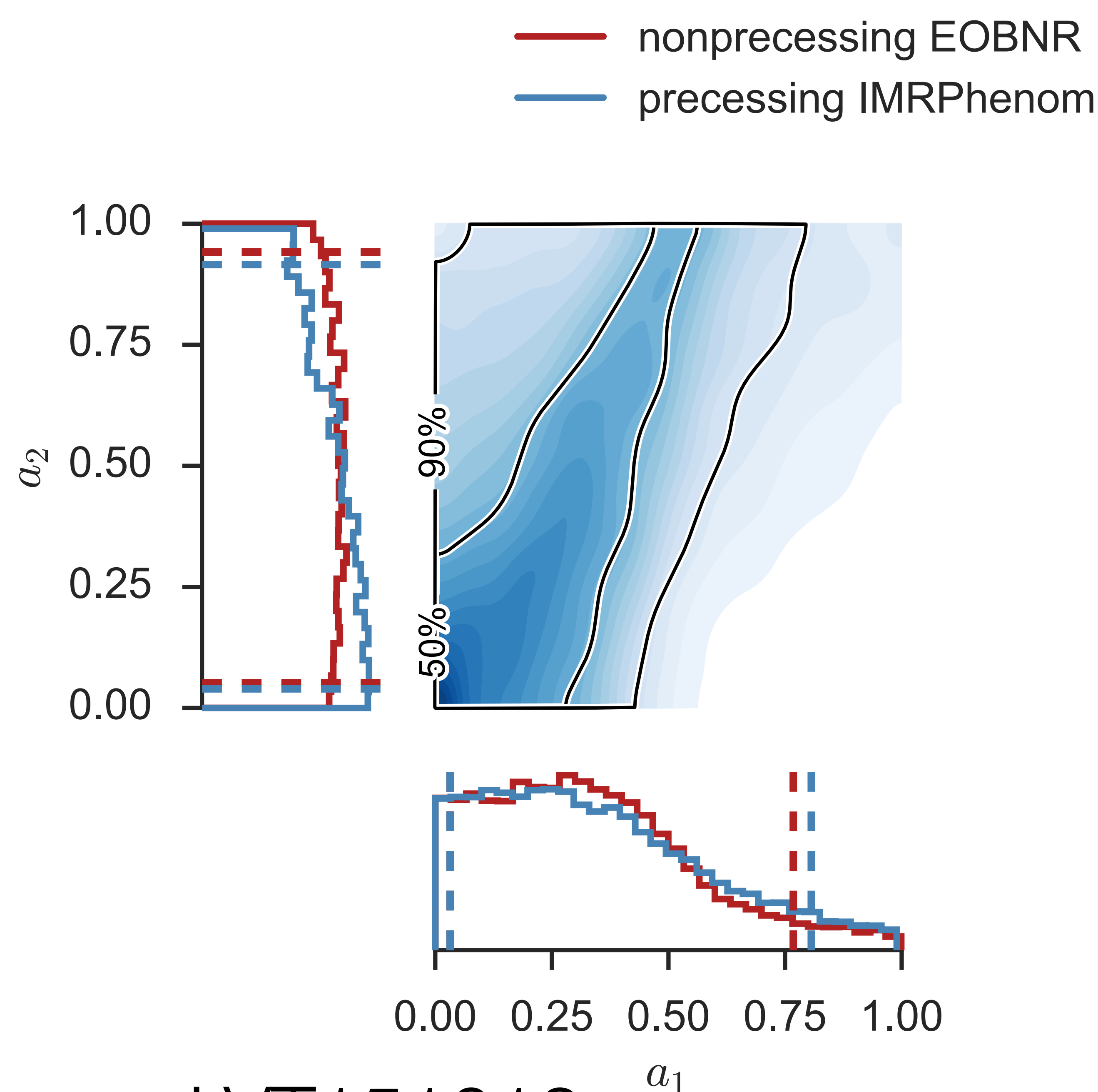


GW151226



LVT151012

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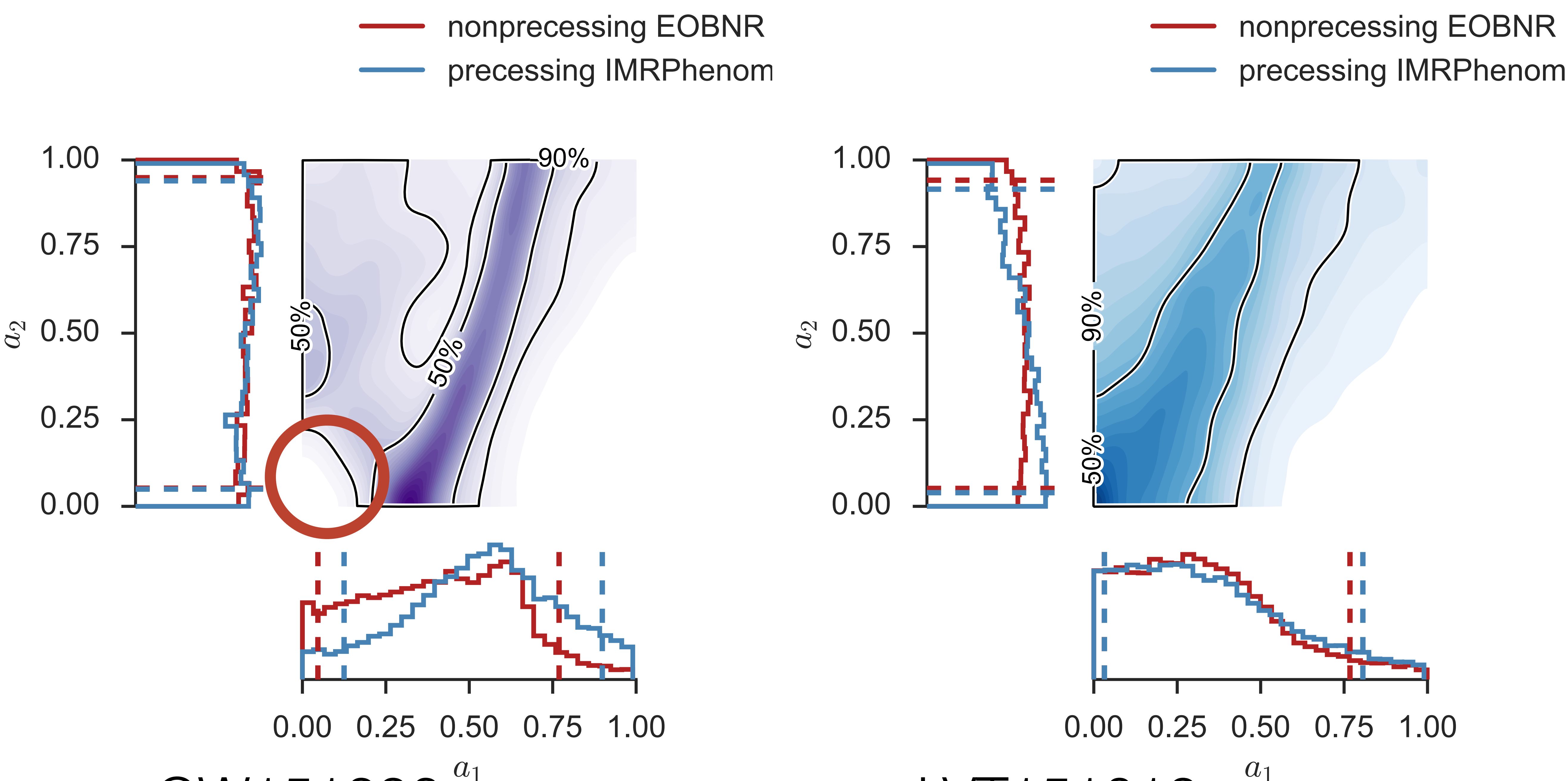

GW151226

LVT151012

[LIGO-Virgo Collaboration, 2016]

Observing run 1 to Observing run 2 and beyond

- Merging binary black holes exist in a **broad mass range**
- New access to **black holes spins** (GW151226 **at least one black-hole spinning**)
- Measured **masses** and **spins** consistent with both:
  - **Isolated binary evolution** (more aligned spins)
  - **Dynamical formation** (more misaligned spins)
- **Statistical** errors dominate waveform **systematical** errors