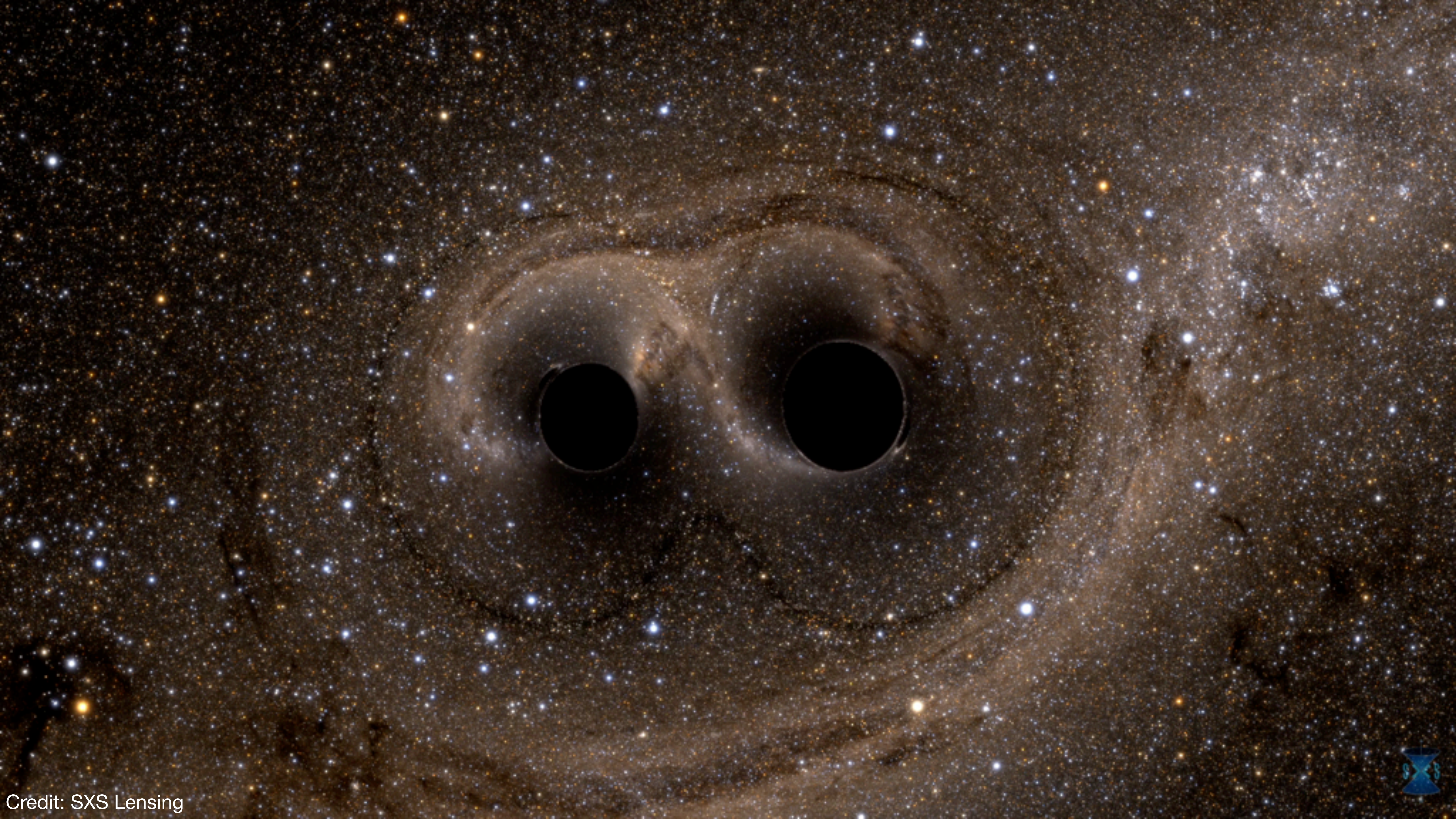


A new beginning for transient Gravitational-wave astrophysics

Vivien Raymond
Max Planck Institute for Gravitational Physics

LSC LIGO Scientific Collaboration

VIRGO

CaJAGWR, Caltech, November 8th, 2016

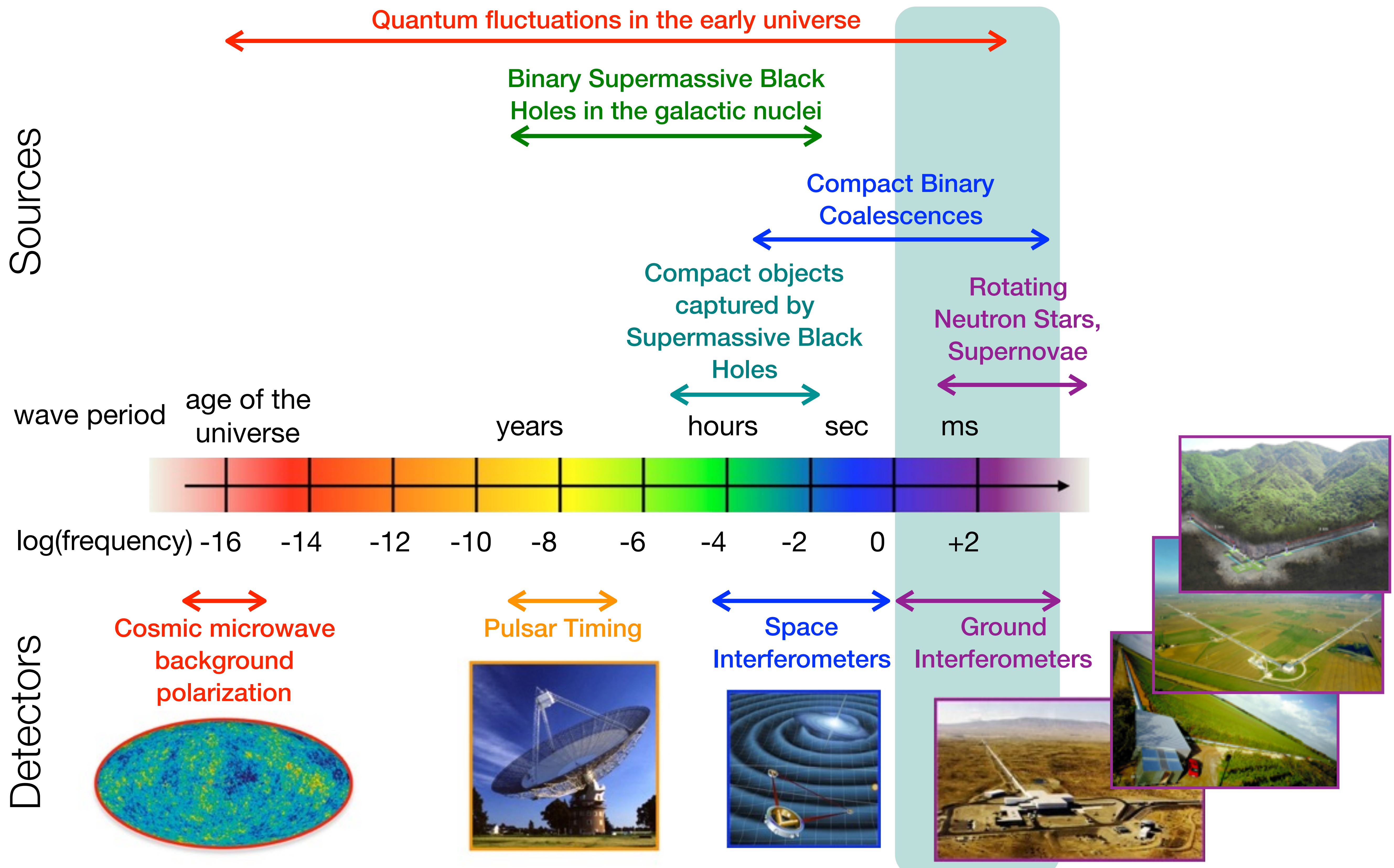
LIGO-G1600305

Gravitational-wave astrophysics

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

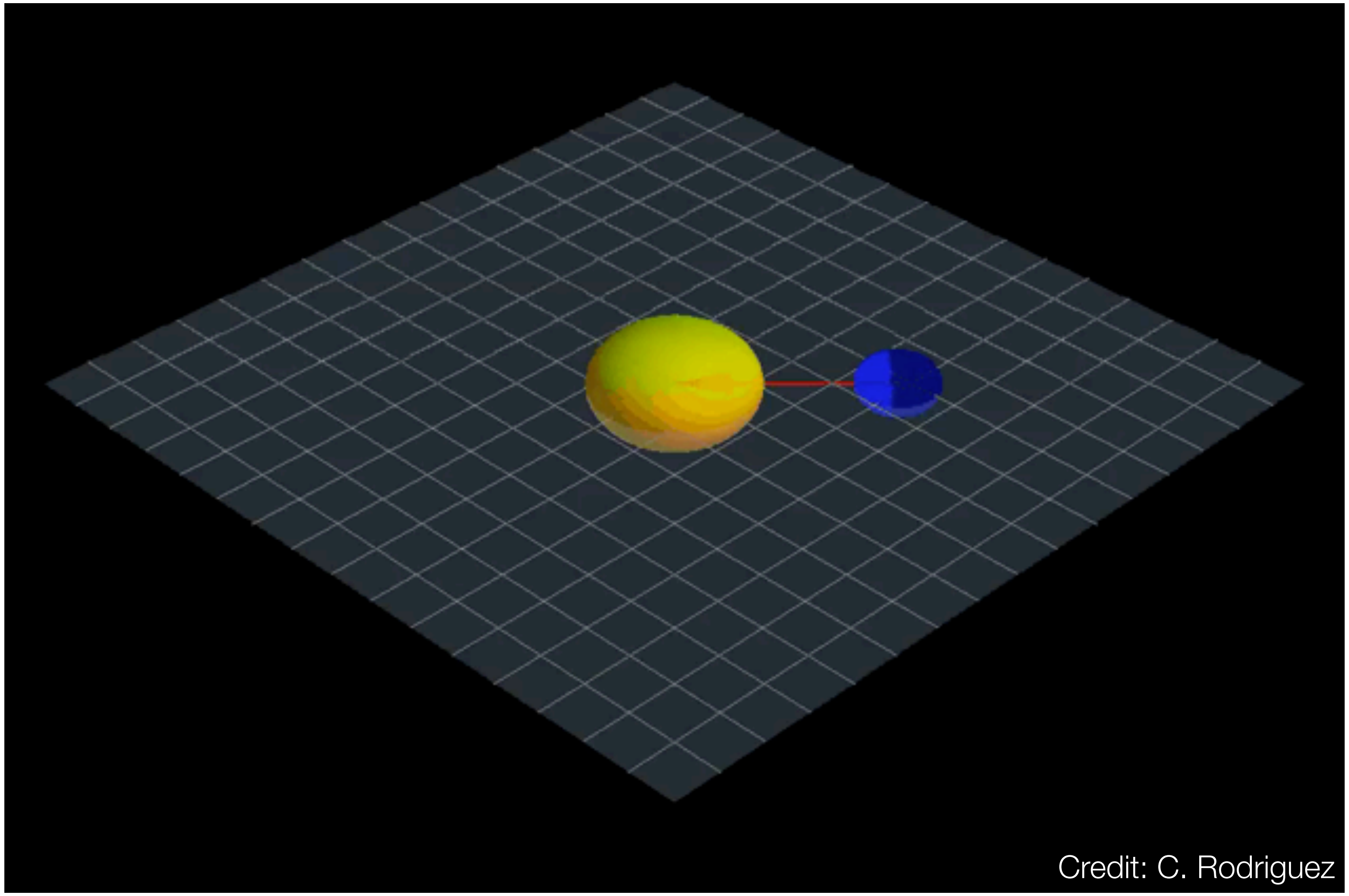
- Is **General Relativity** in the correct theory of **Gravity**?
- What happens when **matter** is compressed to **nuclear densities**?
- What are the properties of the population(s) of **compact objects**?
- Is the mechanism that generates **gamma-ray bursts** a **compact binary coalescence**?

The Gravitational Wave Spectrum



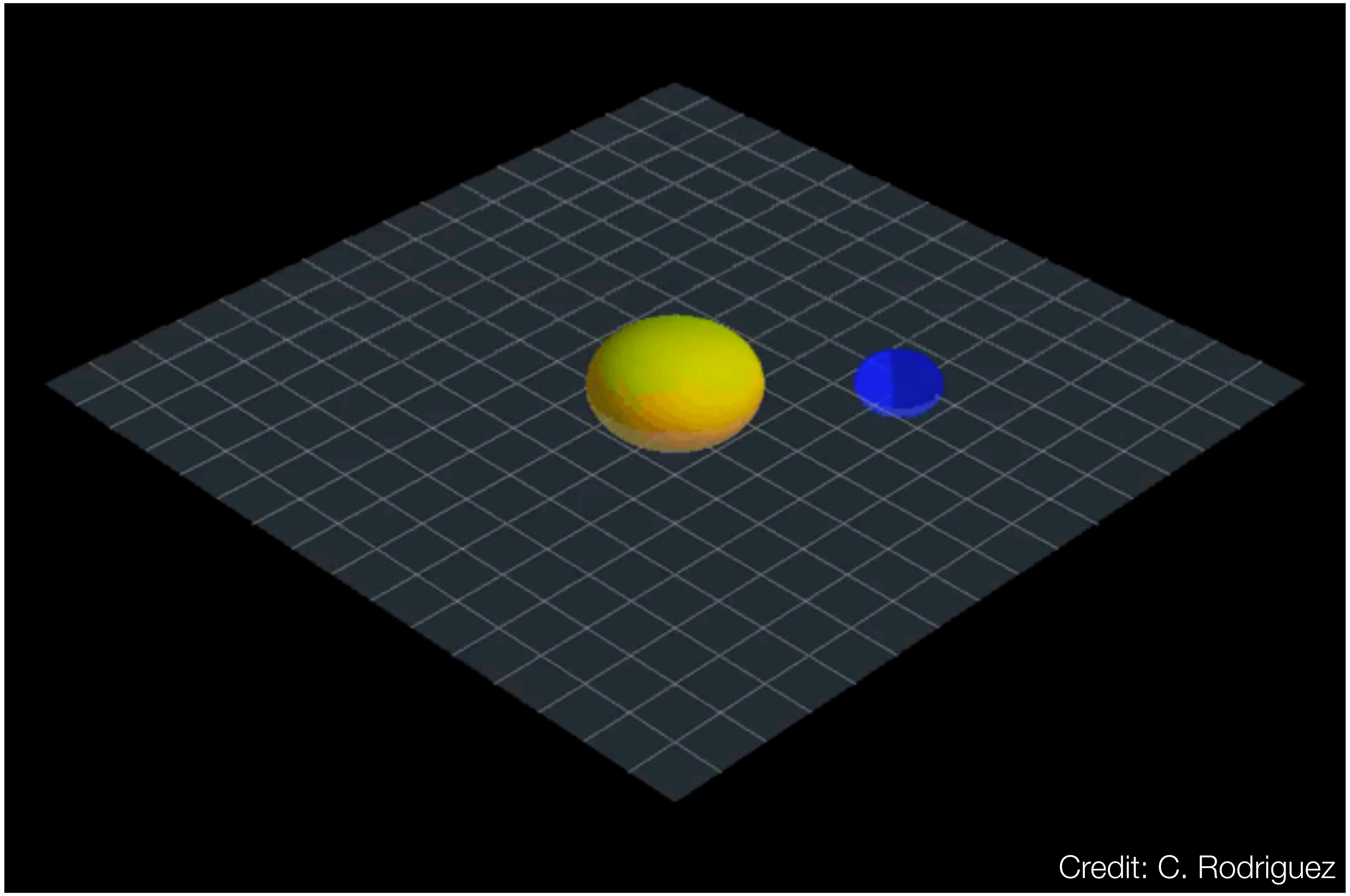
[Inspired from http://science.gsfc.nasa.gov/663/research/]

100 years ago:
General Relativity and Gravitational Waves



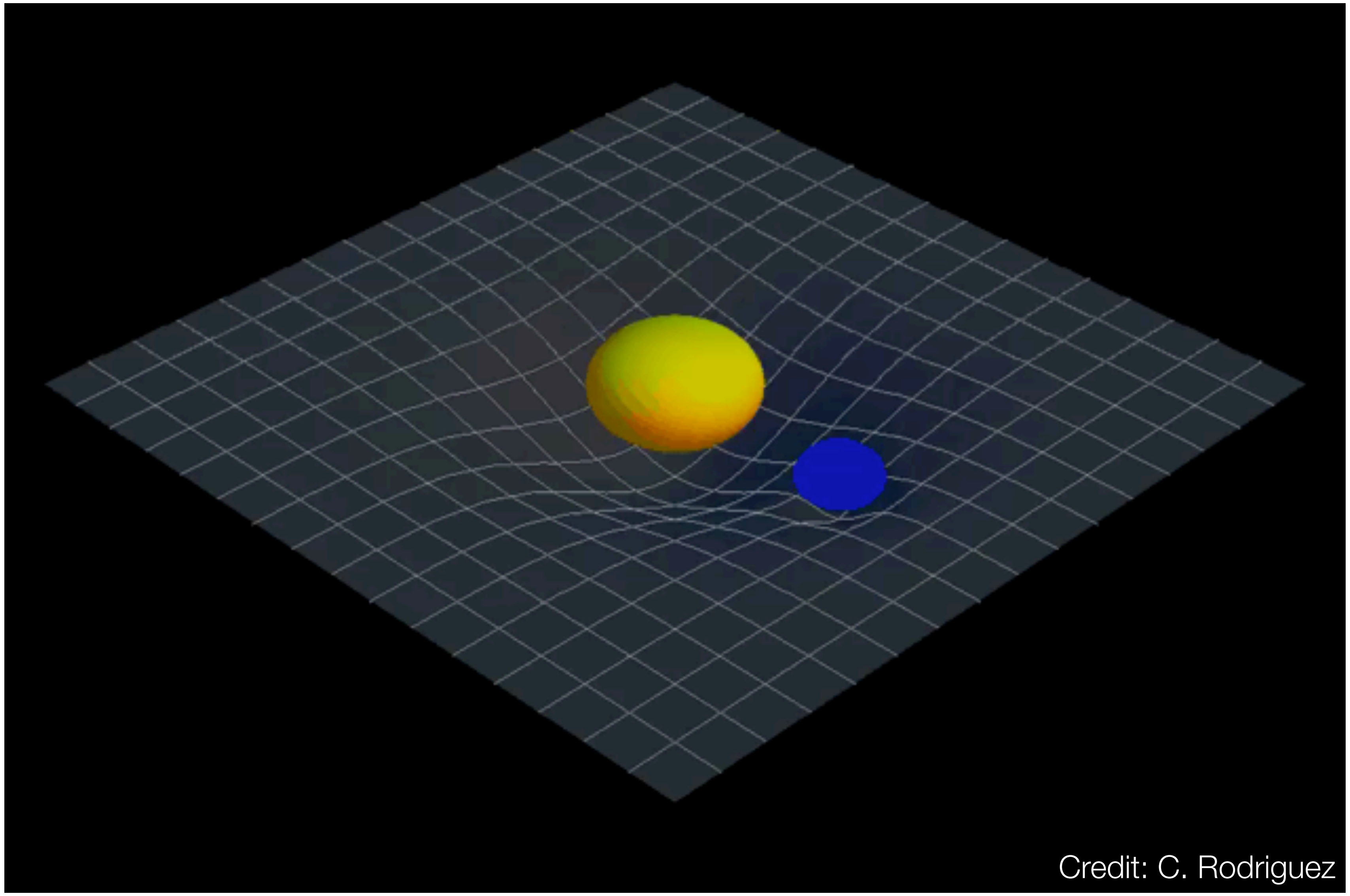
- **Before Einstein**: Newtonian gravity

100 years ago:
General Relativity and Gravitational Waves



- 1915: Einstein's **General Relativity,** gravitation due to **spacetime curvature**

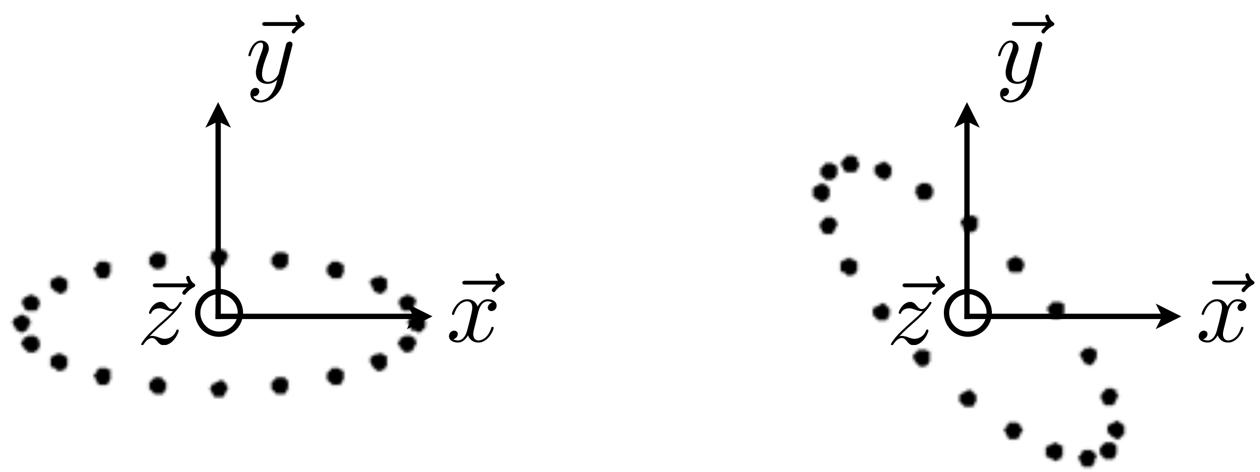
100 years ago:
General Relativity and Gravitational Waves



- 1916: **Albert Einstein** predicts the existence of **gravitational waves**

100 years ago:
General Relativity and Gravitational Waves

- The wave travels at the **speed of light**, is transverse, and has **two polarisations:**

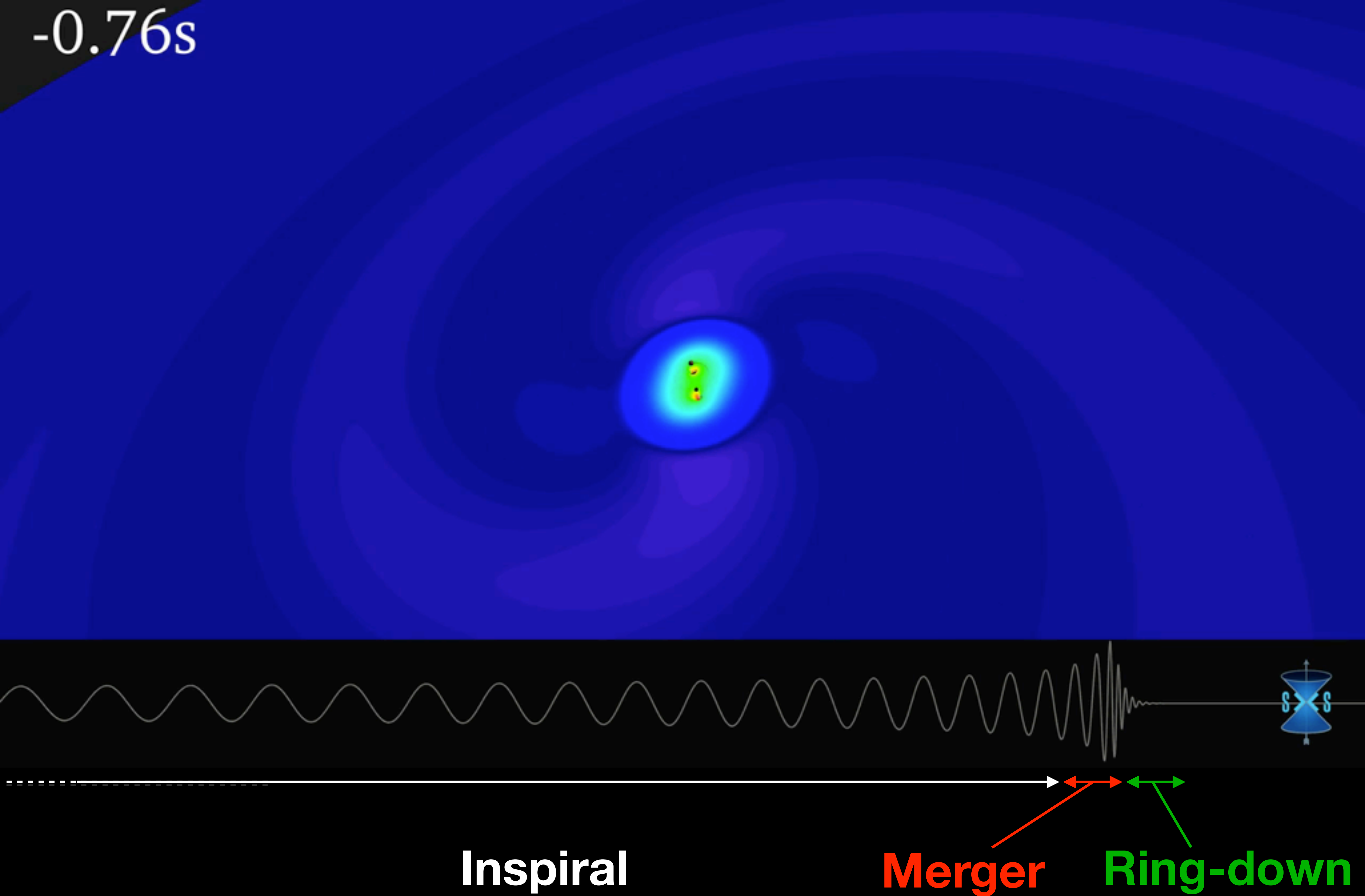


- **Weak** coupling with matter
  - **High-precision** length measurement: **Laser Interferometers**
  - **Dense** masses moving **fast**: **merging compact objects**

~30 years ago:
Laser Interferometer Gravitational-wave Observatory

- Two sites **10 light-milliseconds** apart
- Measurement of **space-time** deformations with $\Delta L/L$: $\sim 10^{-21}$!

LIGO Hanford and Livingston. Credit: LIGO

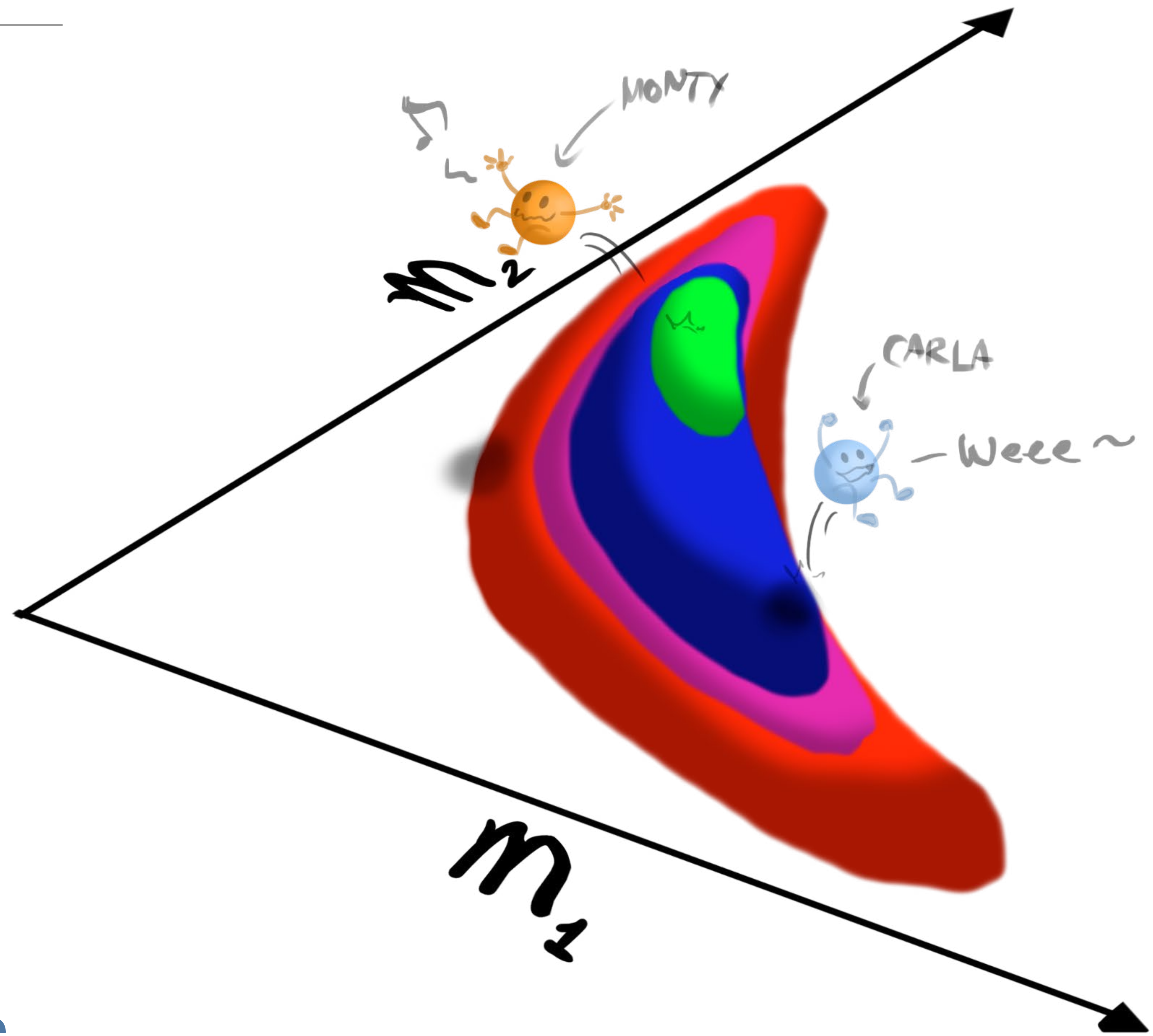


GW150914: September 14, 2015 at 09:50:45 UTC

Credit: SXS Collaboration/Canadian Institute for Theoretical Astrophysics/SciNet

Overview (or how can we study transient GWs?)

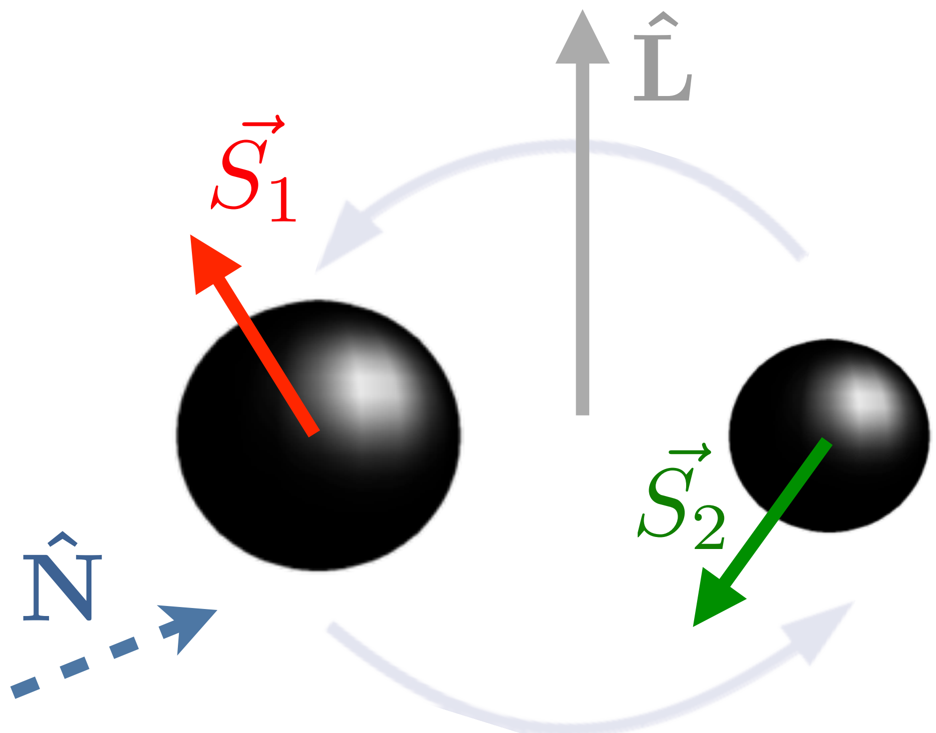
- Introduction
  - **Compact Binary Coalescence**
  - LIGO
- **Extracting astrophysics**
  - Waveform models
  - Parameter Estimation
- Beyond aLIGO first observing run:
  - **Astrophysics** with **multiple events**

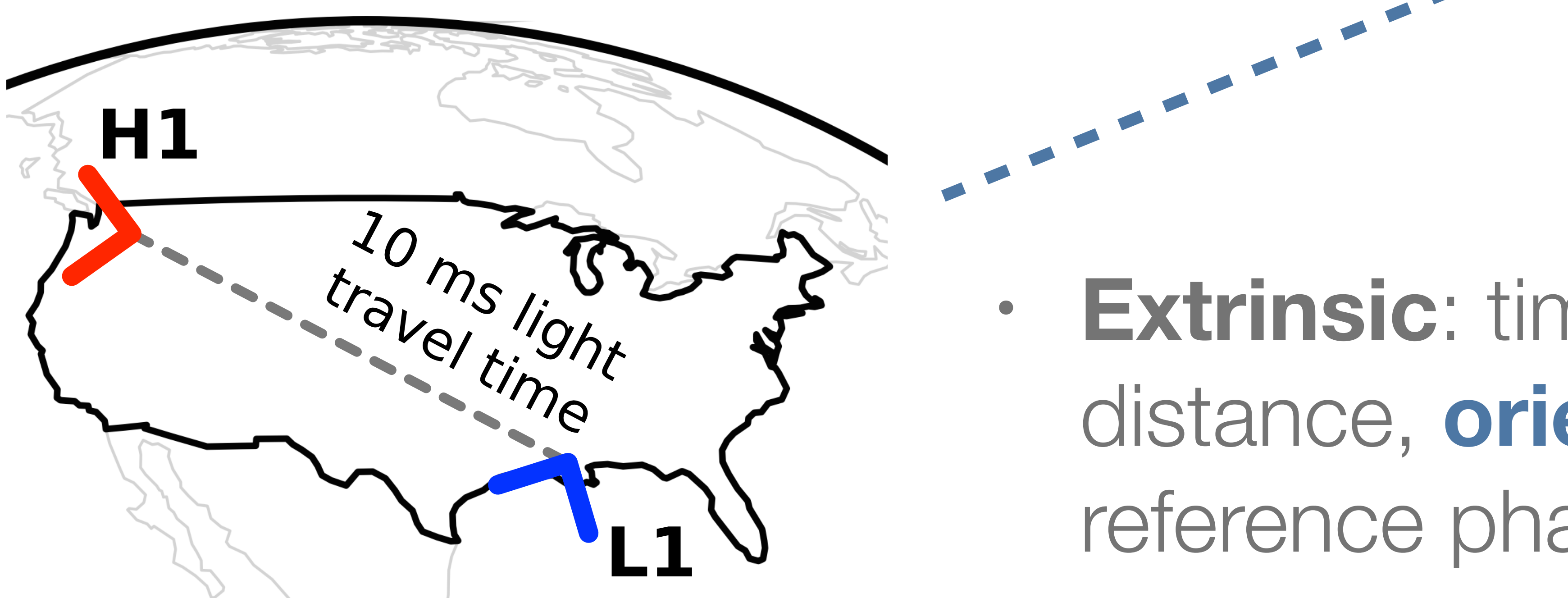


[LIGO Scientific Collaboration]

Compact Binary Coalescence

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



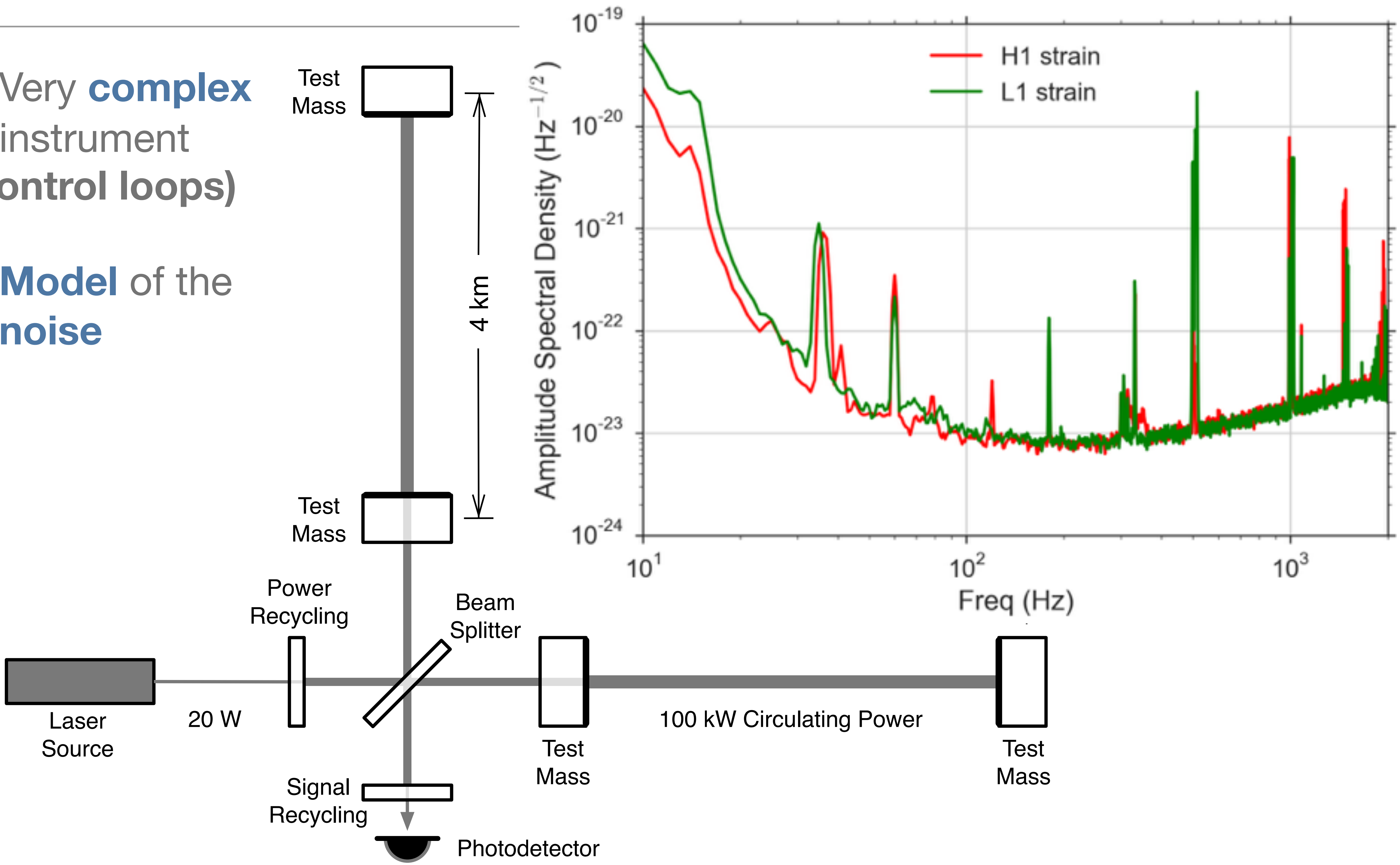


- **Extrinsic**: time, **sky-position**, distance, **orientation**, reference phase

Credit: LIGO

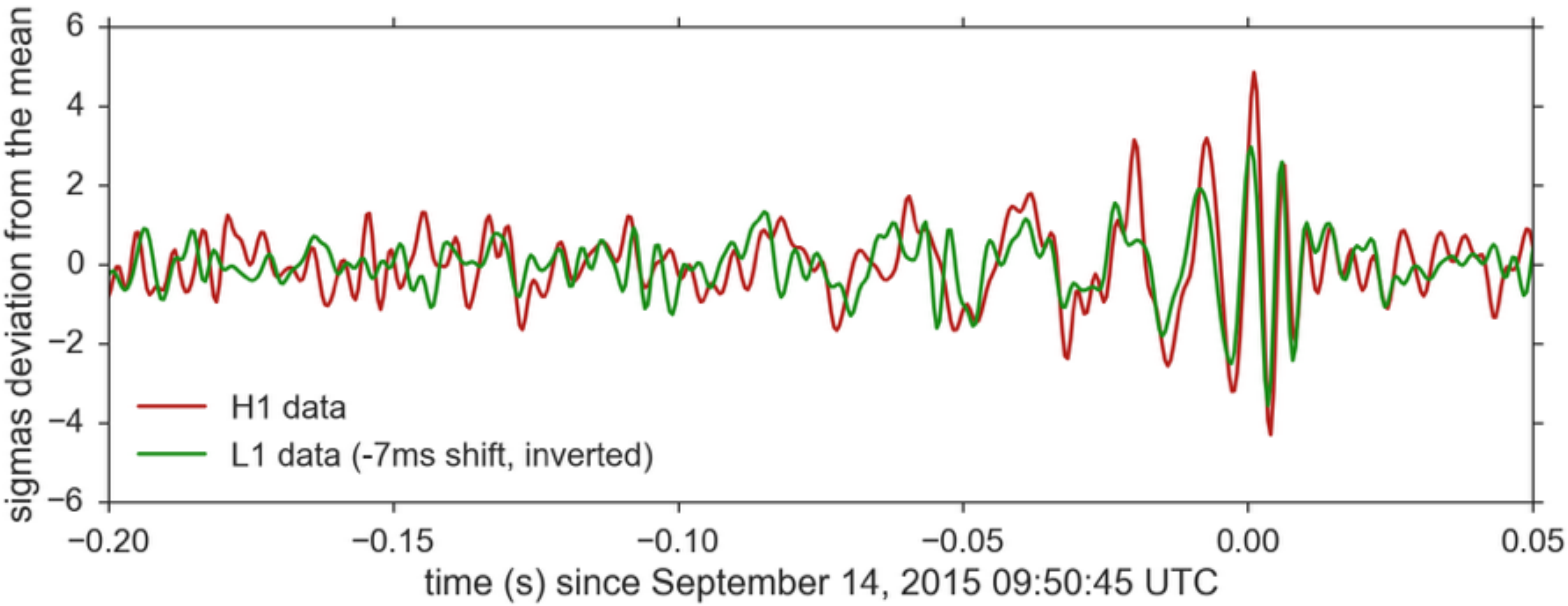
LIGO measurement technique

- Very **complex** instrument **(control loops)**
- **Model** of the **noise**



[LIGO-Virgo Collaboration, 2016]

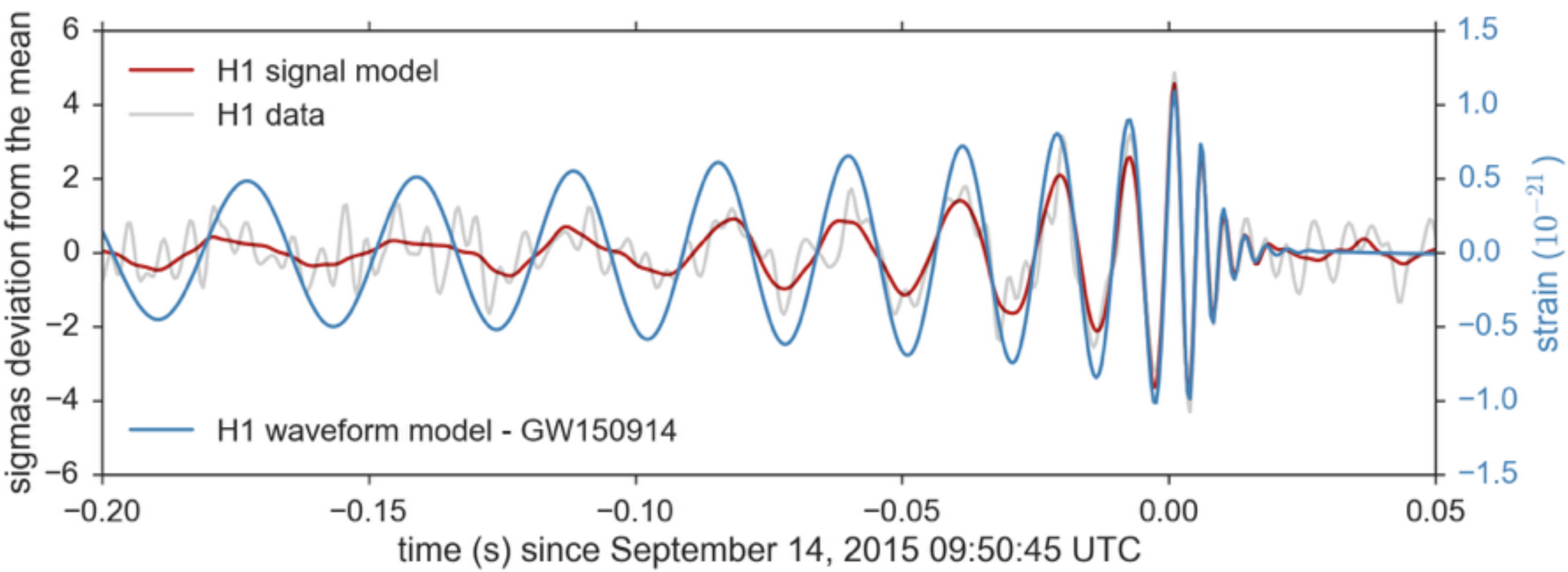
Parameter Inference: **GW150914** observation



- How do we extract the **scientific content**?

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])*



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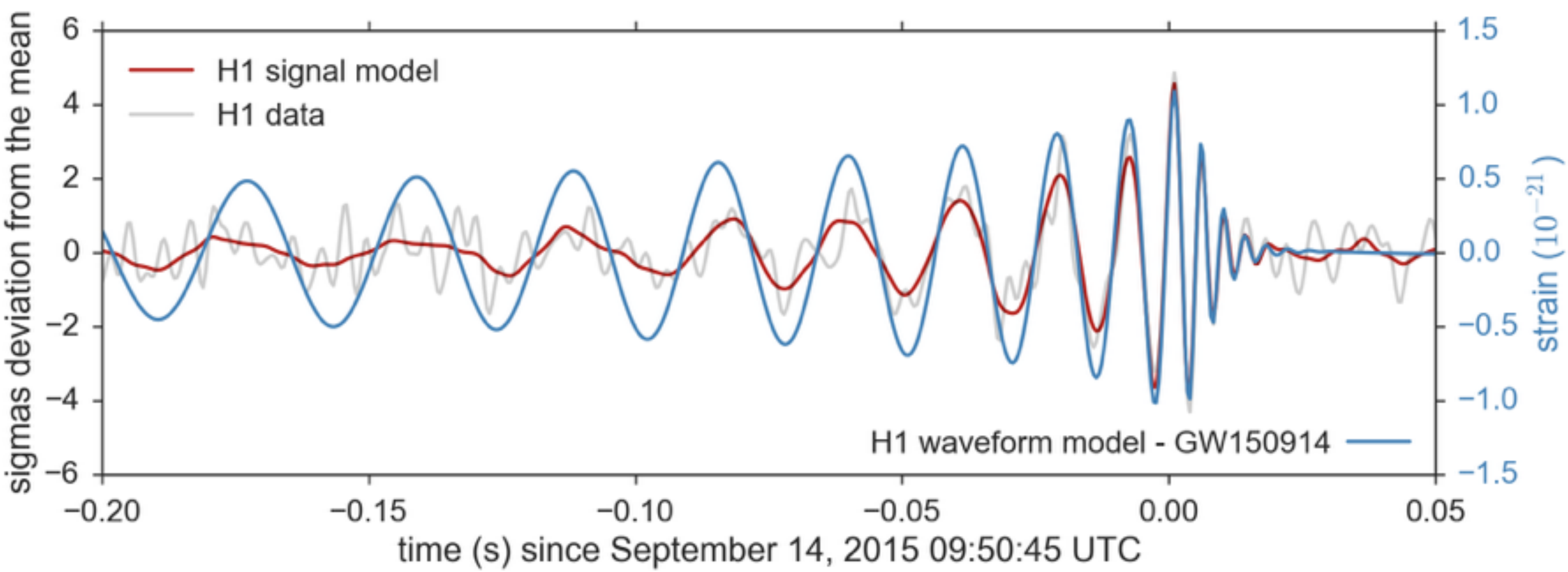
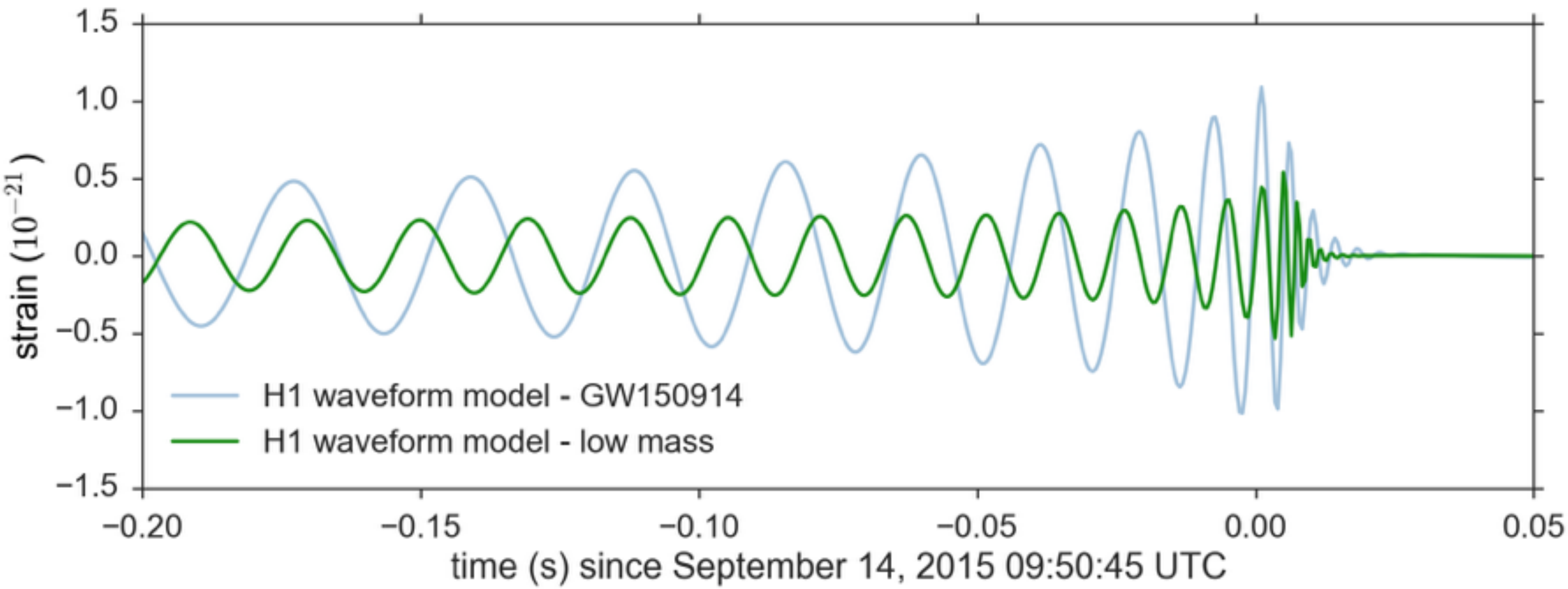


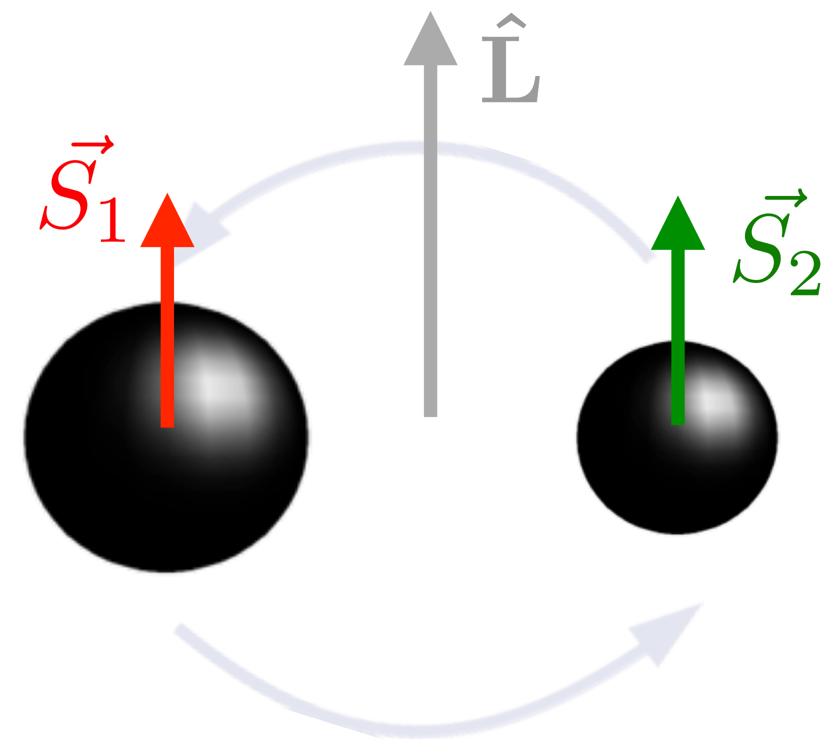
Masses from the inspiral and ringdown

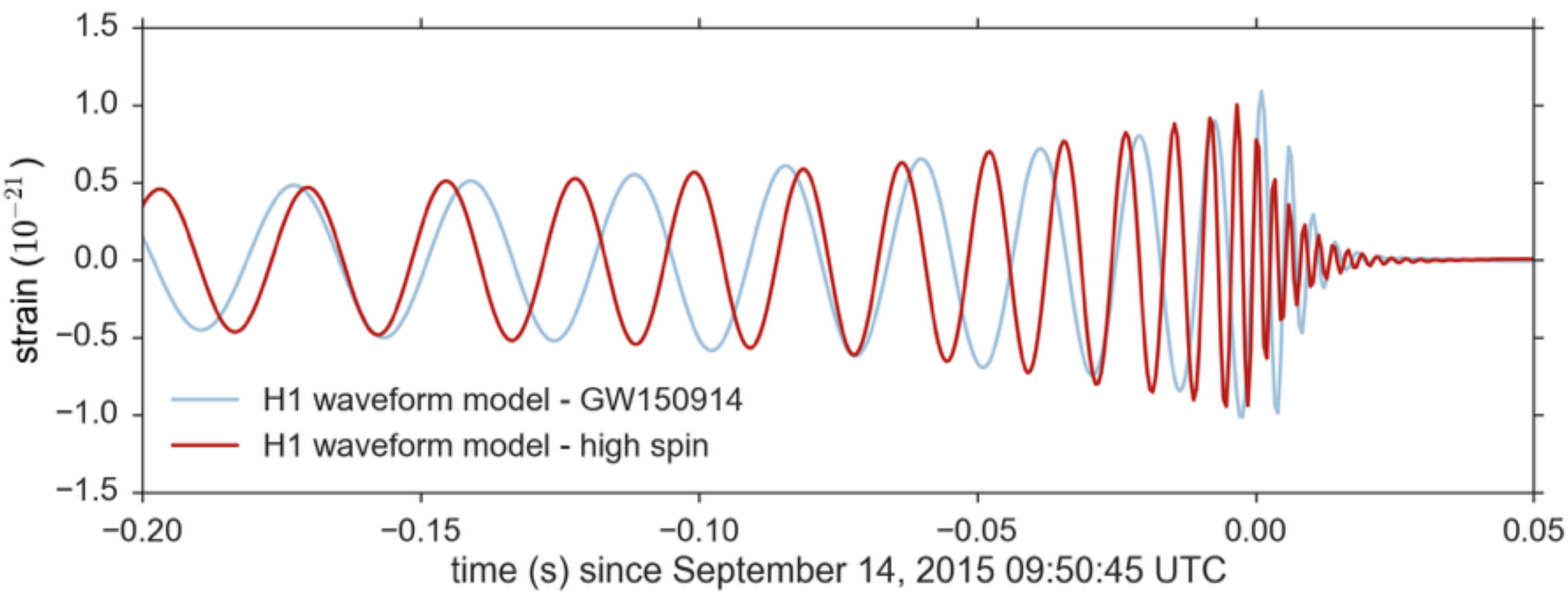
- Chirp mass: $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$
- Mass ratio: $q = \frac{m_1}{m_2}$
- Total mass: **ringdown**



Effects of spins

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





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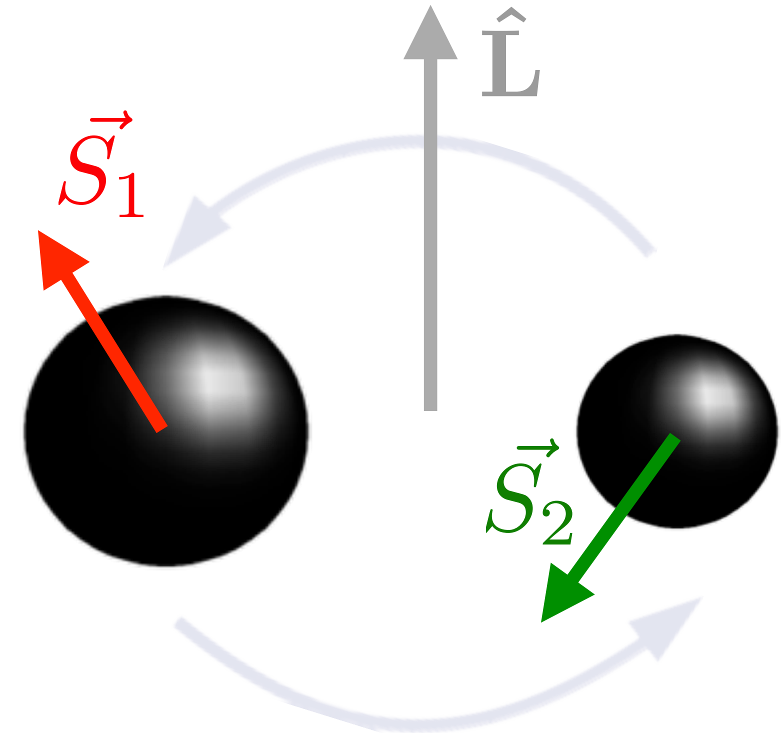

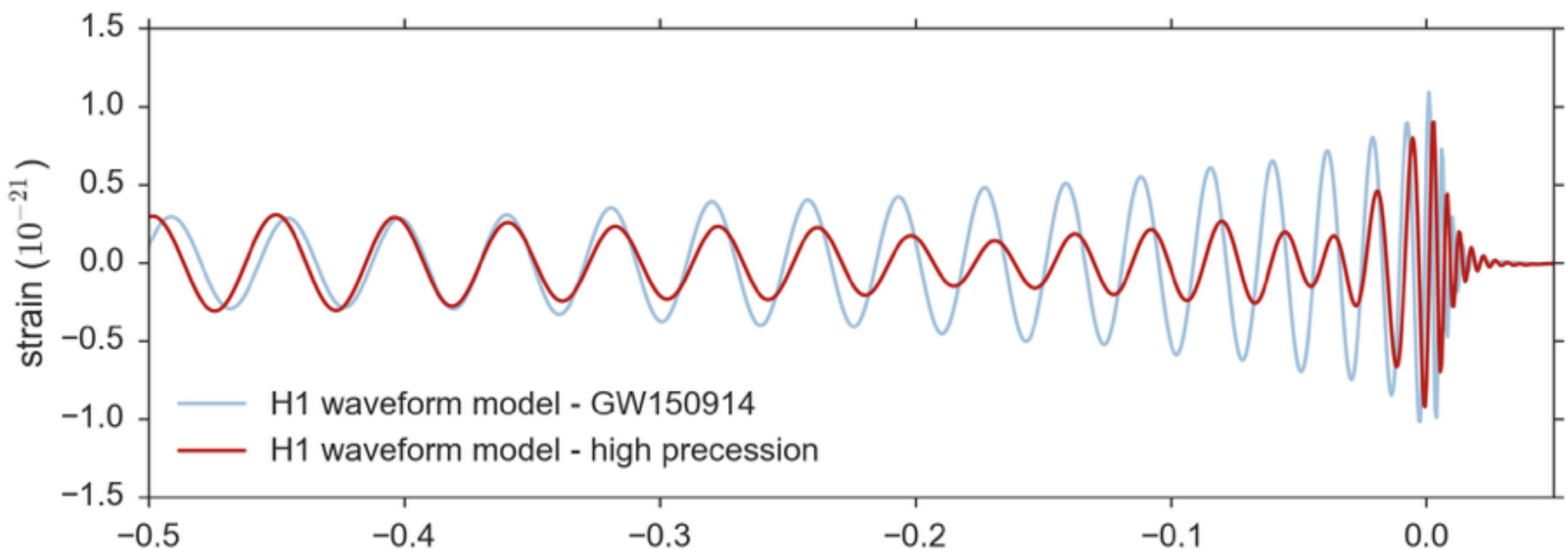

Parameter Estimation

- 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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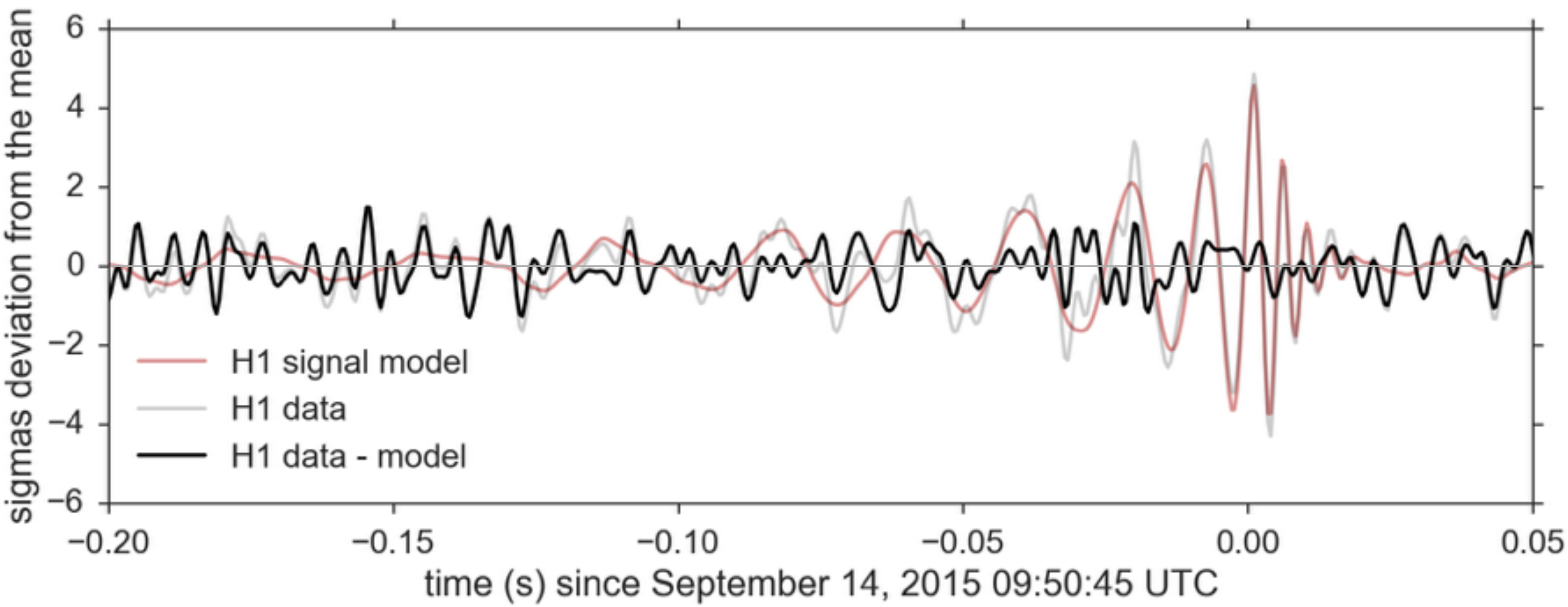
Likelihood



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

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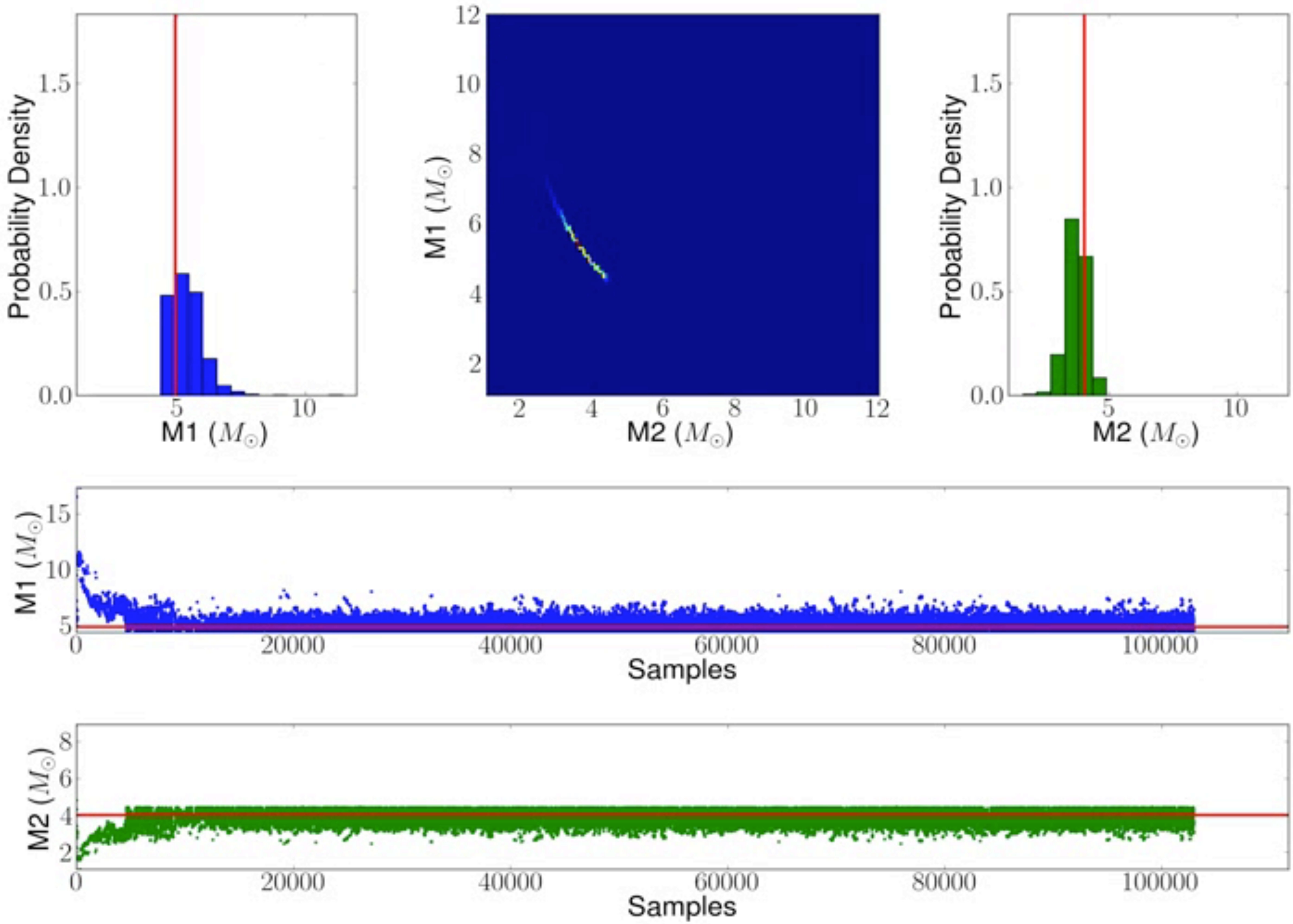
- Fit a **model** to the data (**noise** and **signal** models)
- Build a **likelihood** function
- Specify **prior** knowledge
- **Numerically** estimate the resulting **distribution** (efficient **sampling** algorithms) [Raymond, et al. 2010]

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

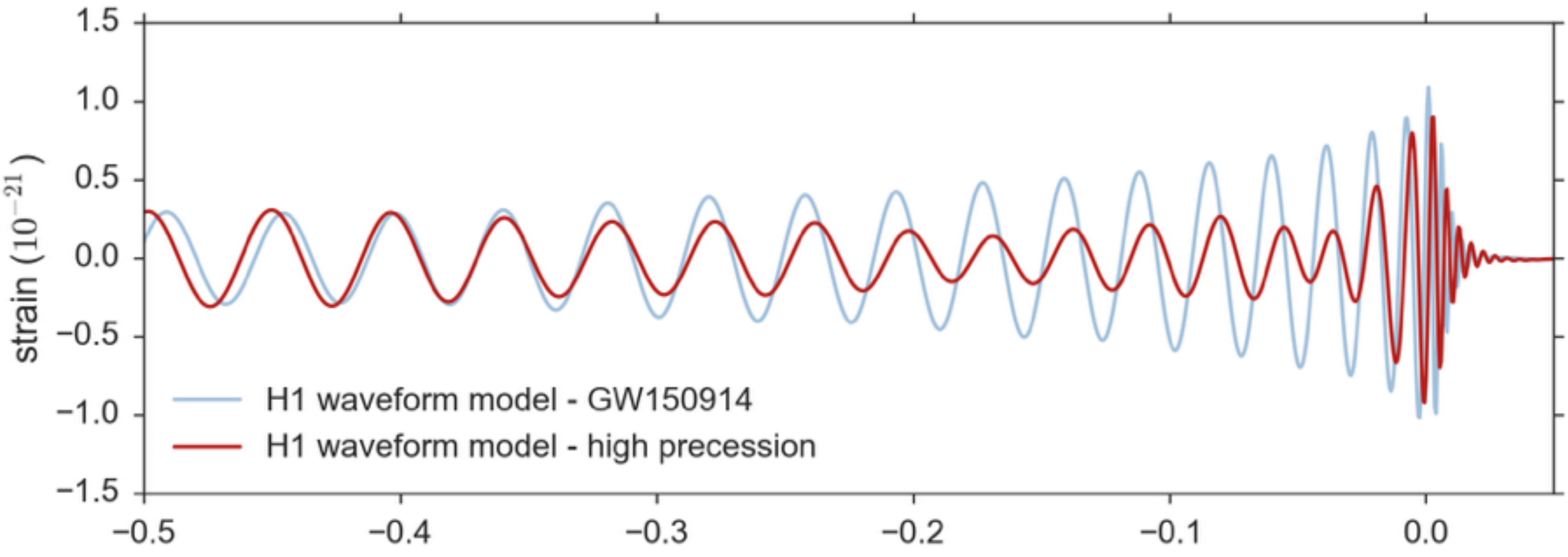

Probability Density
1.5
1.0
0.5
0.0
5
10
M1 ($M_\odot$)
12
10
8
6
4
2
M1 ($M_\odot$)
2
4
6
8
10
12
M2 ($M_\odot$)
Probability Density
1.5
1.0
0.5
0.0
5
10
M2 ($M_\odot$)
M1 ($M_\odot$)
15
10
5
0
20000
40000
60000
80000
100000
Samples
M2 ($M_\odot$)
8
6
4
2
0
20000
40000
60000
80000
100000
Samples

Markov-Chain Monte Carlo

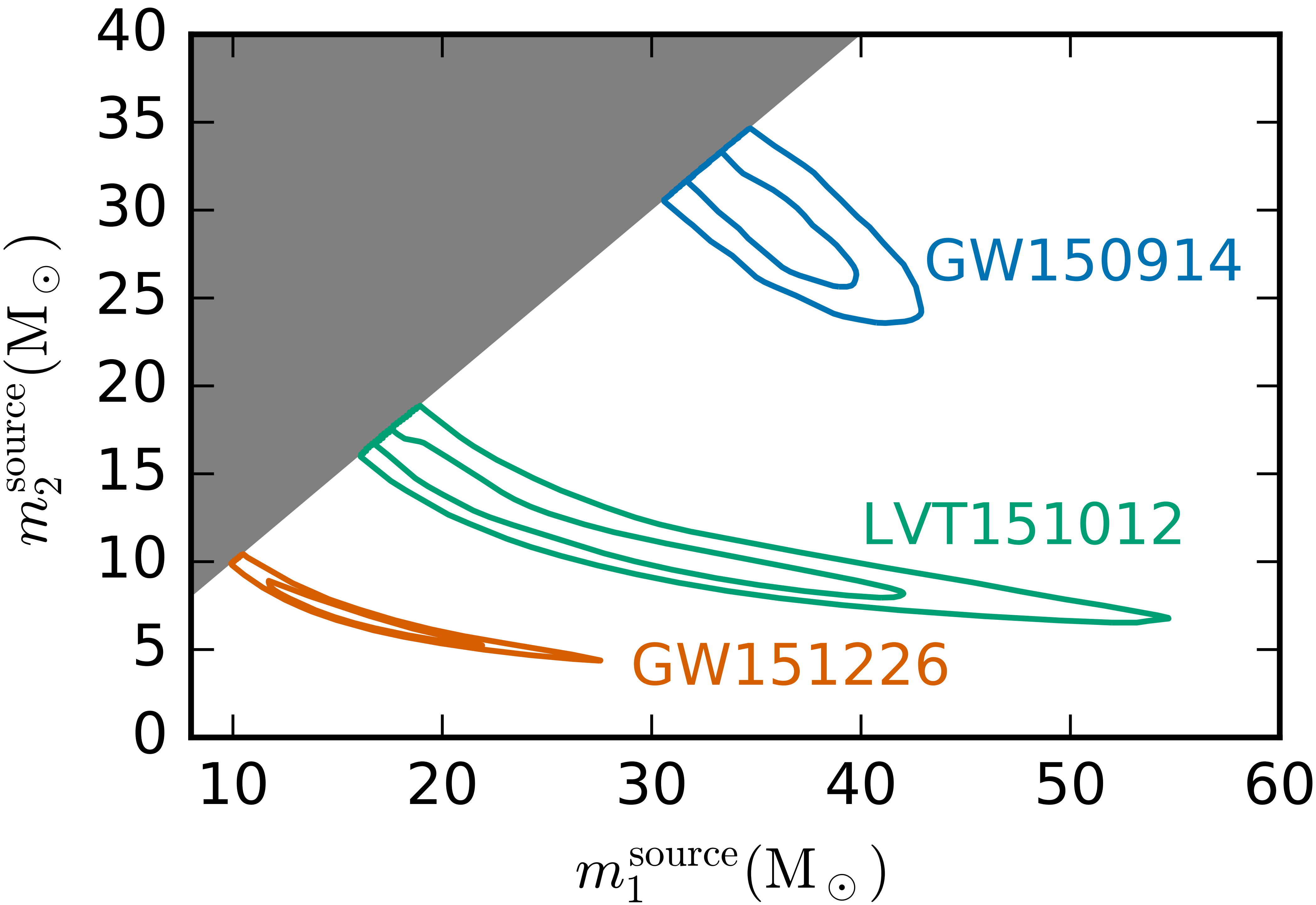
- **High dimensional** parameter space
- **Slow** waveform computation

Efficient sampling critical (especially with **precession**)

[*Raymond*, et al. 2010]



Gravitational-wave observations in the first observing run (O1)



[LIGO-Virgo Collaboration, 2016]

GW150914: masses

- 2 models as a proxy for systematic errors:
  - **Double-precessing-spin** model *(SEOBNRv3)*
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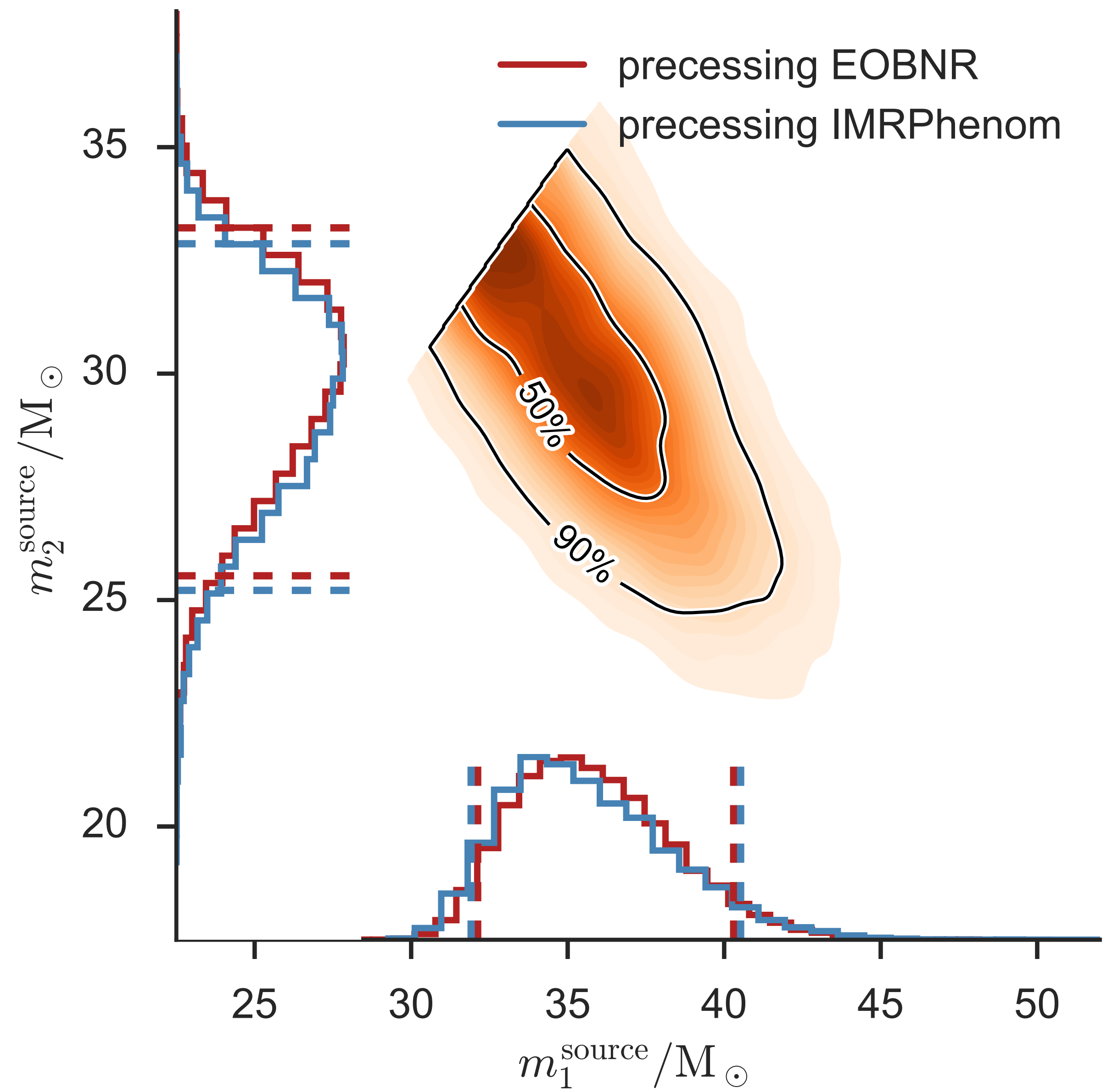
$$m_1 = 35.4^{+5.0}_{-3.4}\,\mathrm{M}_\odot$$

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



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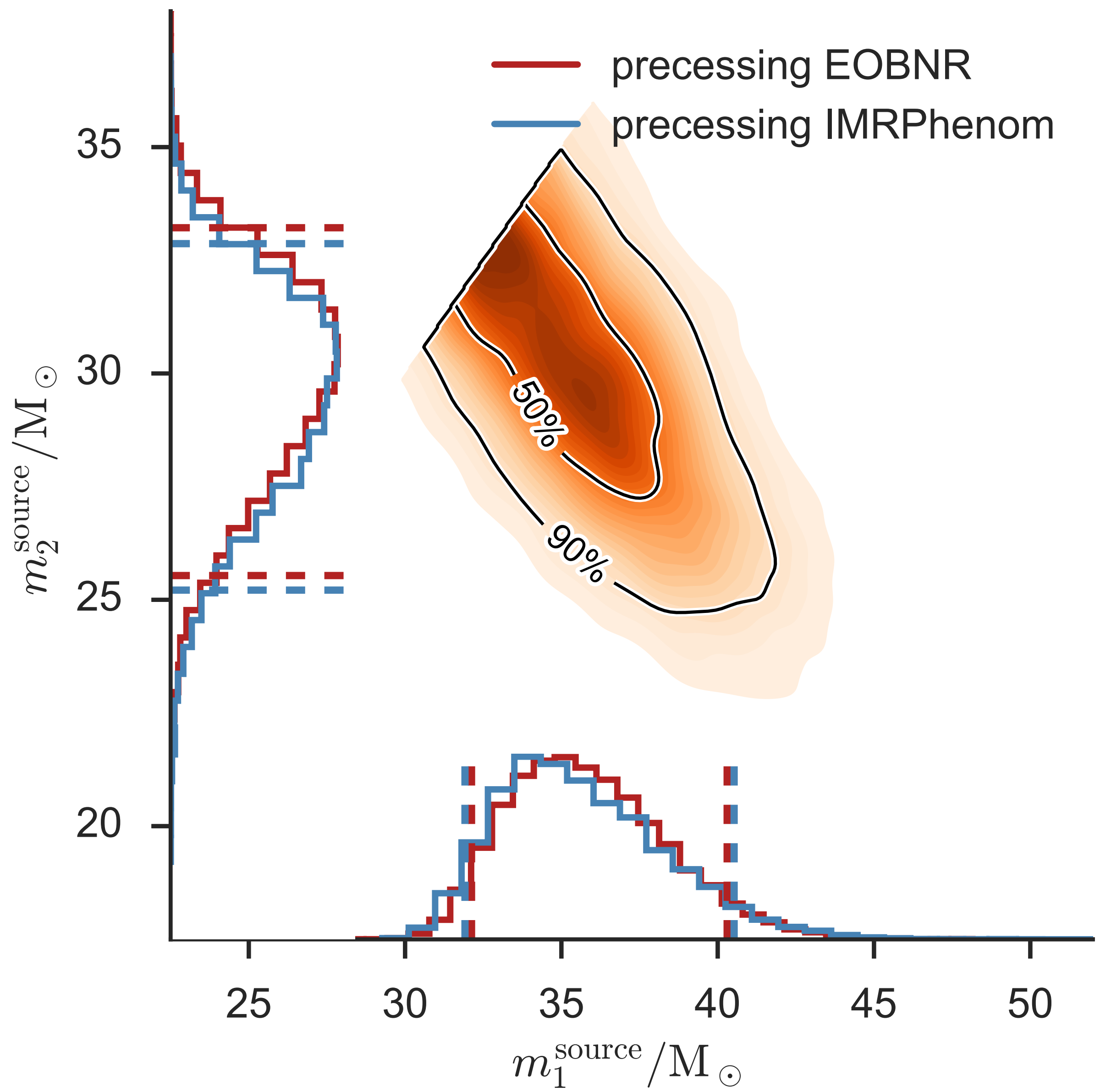

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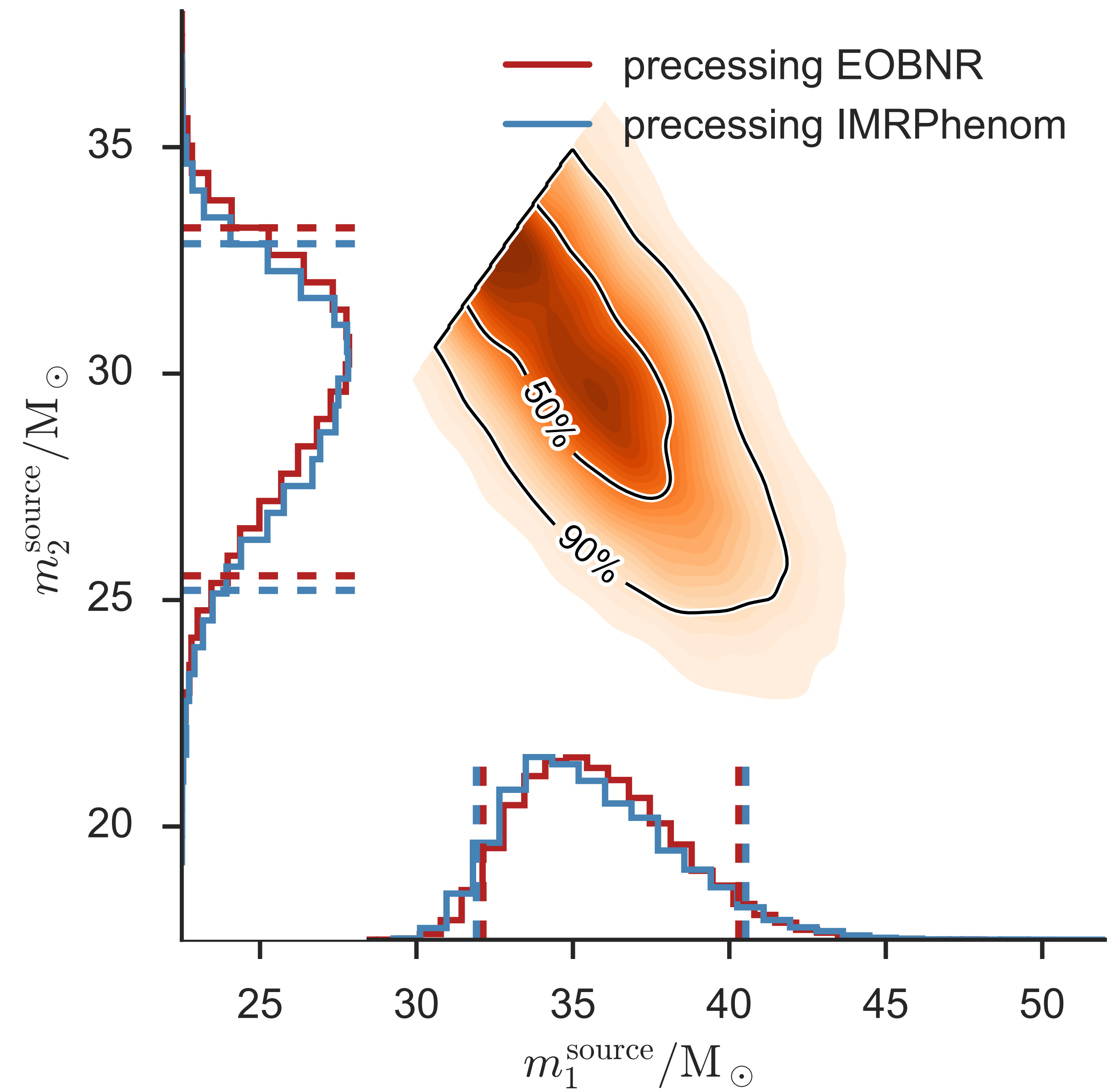
- Errors:

signal strength

model inaccuracies



[LIGO-Virgo Collaboration, 2016]

2.3 GW150914: remnant black hole

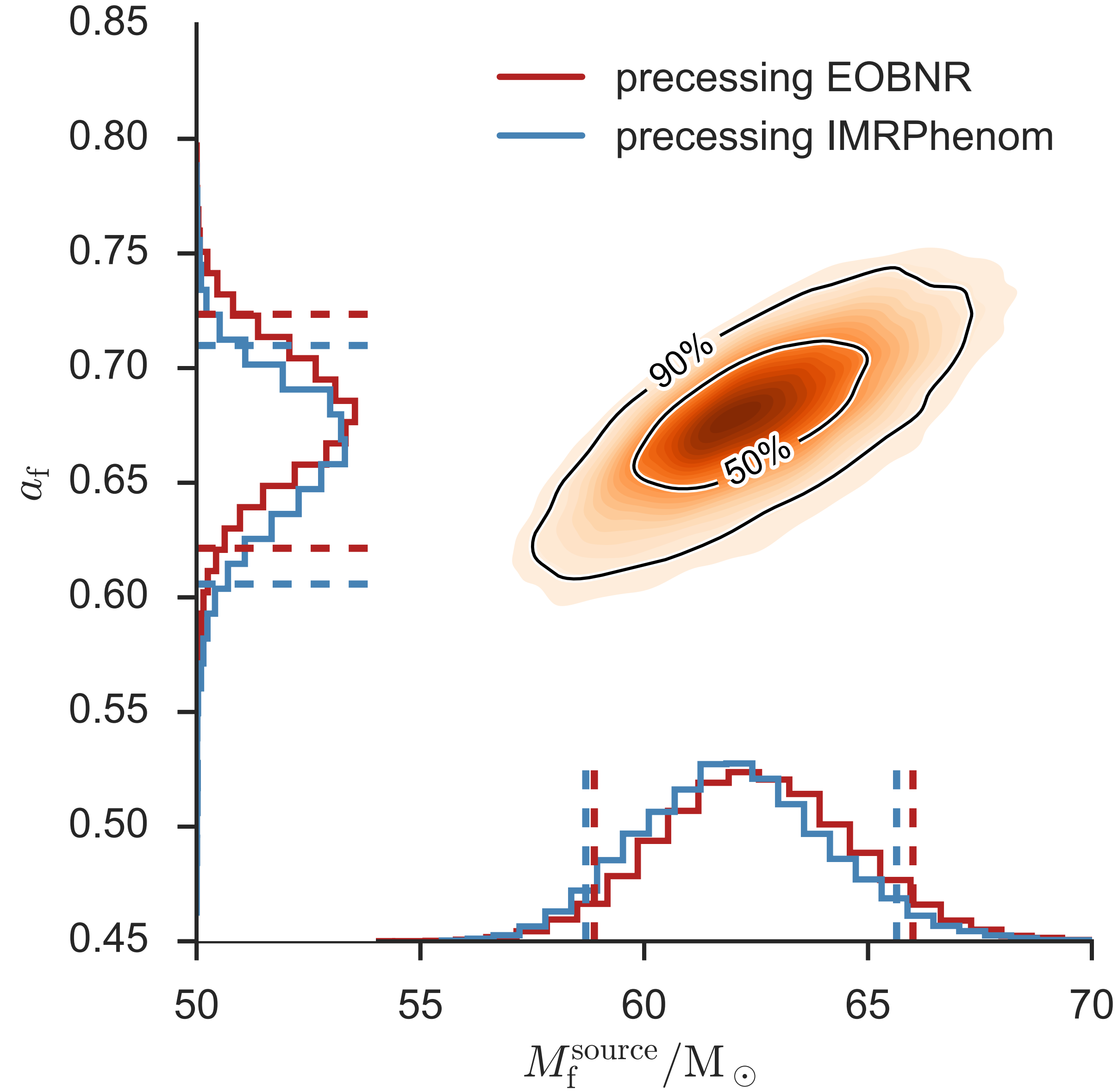
- Final values fitted from **Numerical Relativity** simulations
  - Final mass:

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

  - Final (dimensionless) spin:

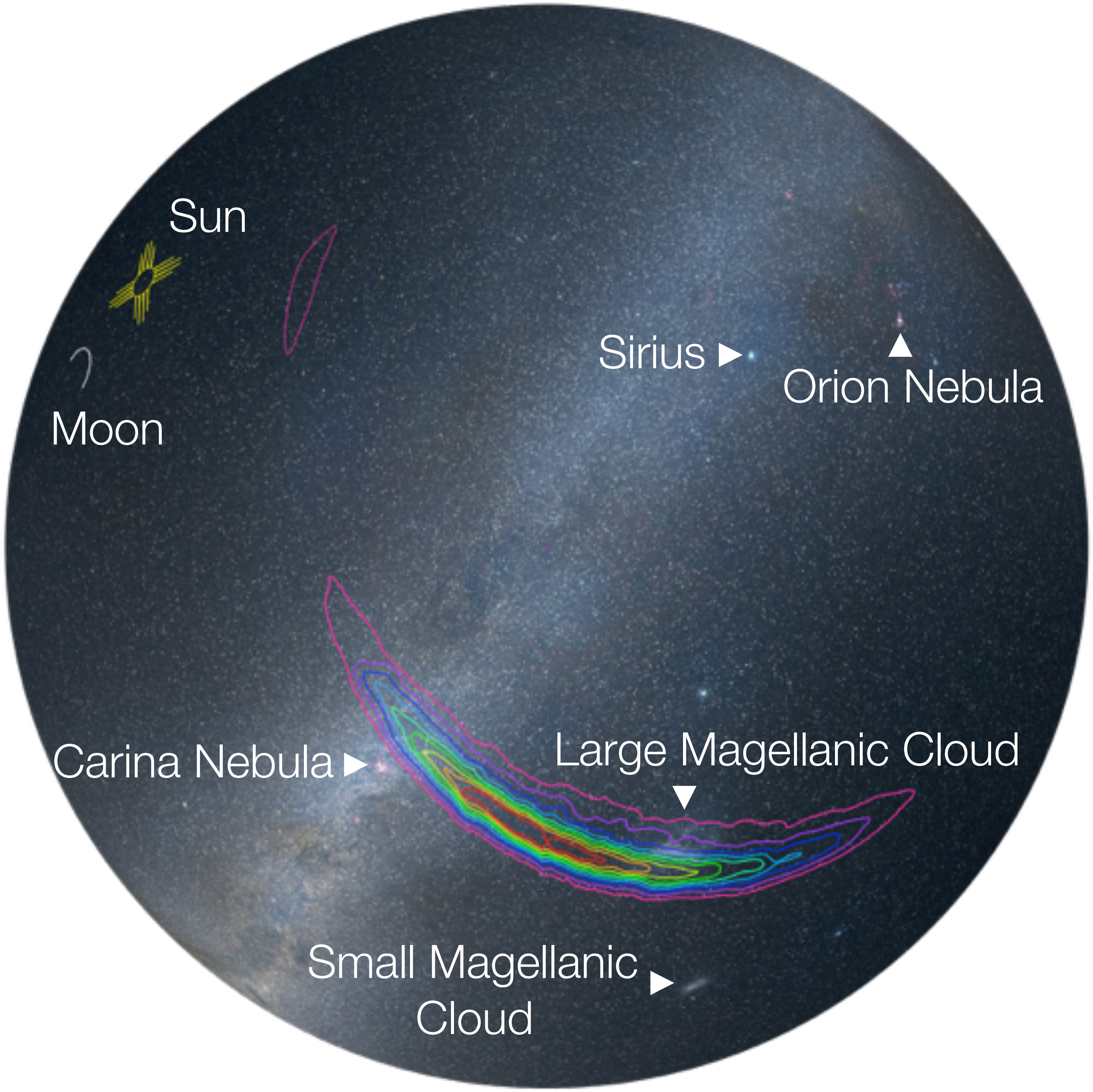
$$a_f = 0.68^{+0.05}_{-0.06}$$

  - ~**3 solar mass** radiated !



[LIGO-Virgo Collaboration, 2016]

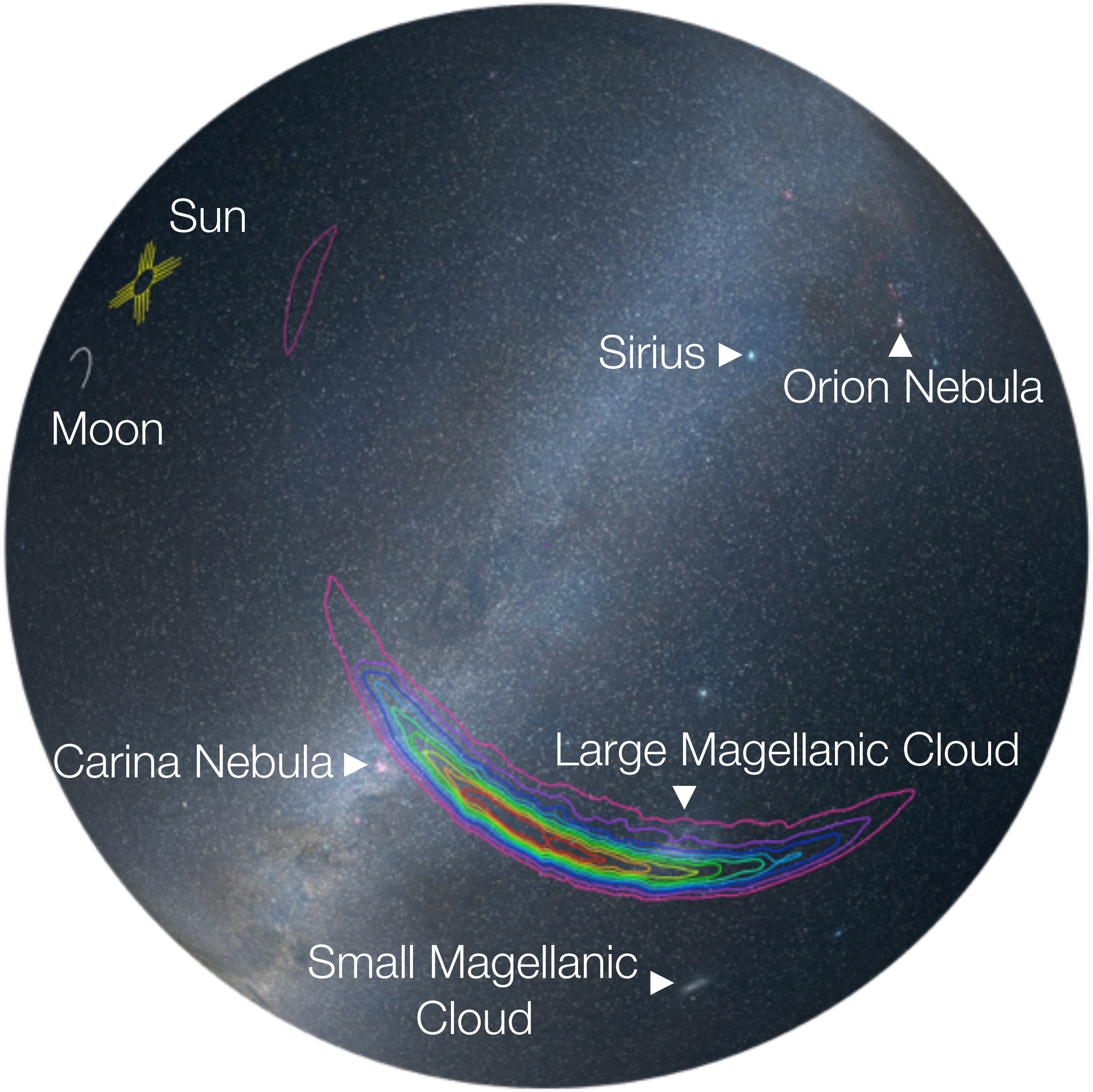
GW150914: location



[LIGO-Virgo Collaboration, 2016]

GW150914: location

- **CBC** LIGO sky maps
Electromagnetic counterpart
  - Bayestar **O(minutes)**
  - LALInference-lite **O(hours)**
    - Includes **spin effects**
    - Sub-threshold triggers in part of a **network**
  - Full LALInference **O(days-weeks)**
- **Sky localisation** degeneracies with only **2 detectors**
[*Raymond*, et al., 2009]



[LIGO-Virgo Collaboration, 2016]

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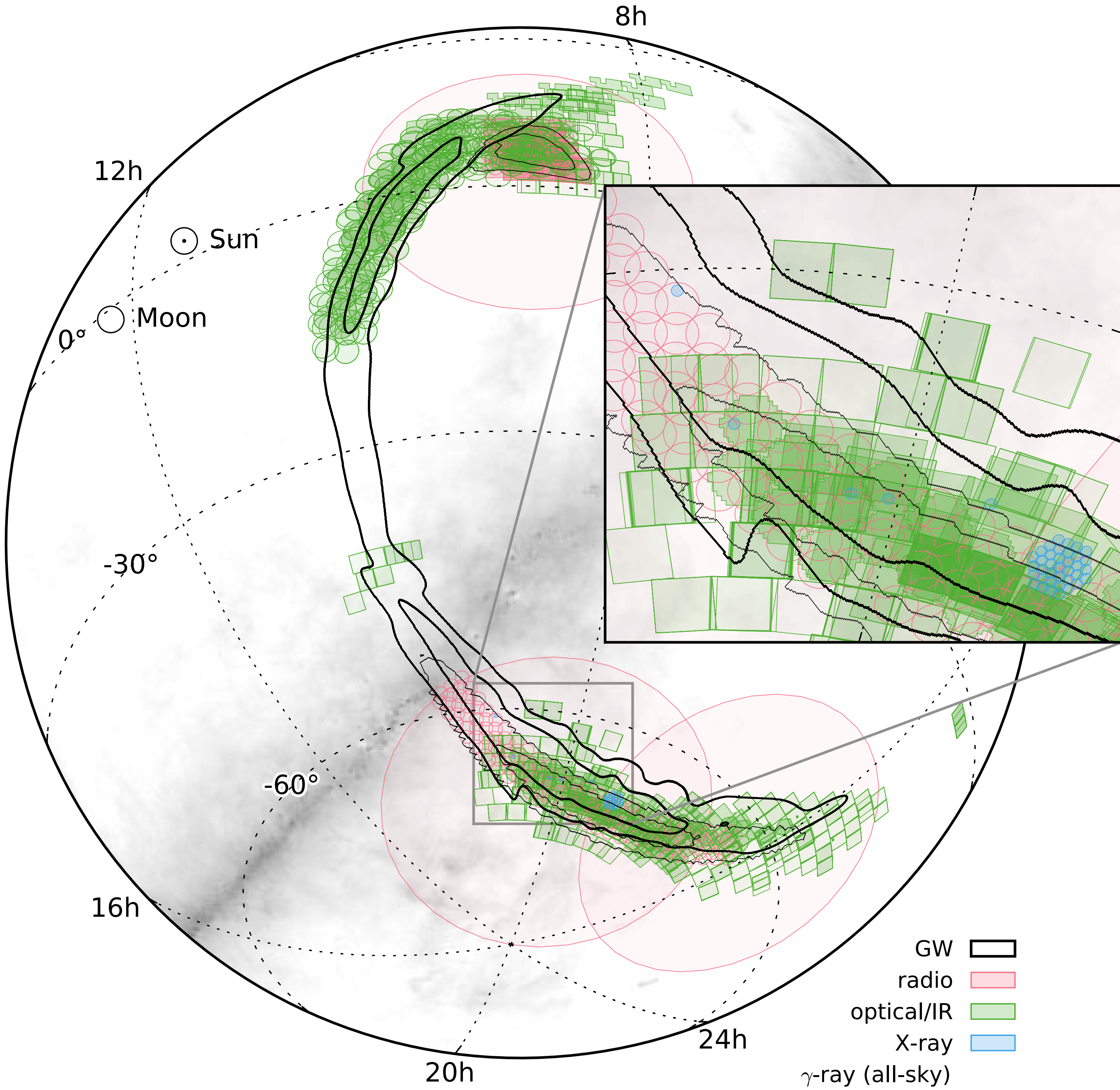
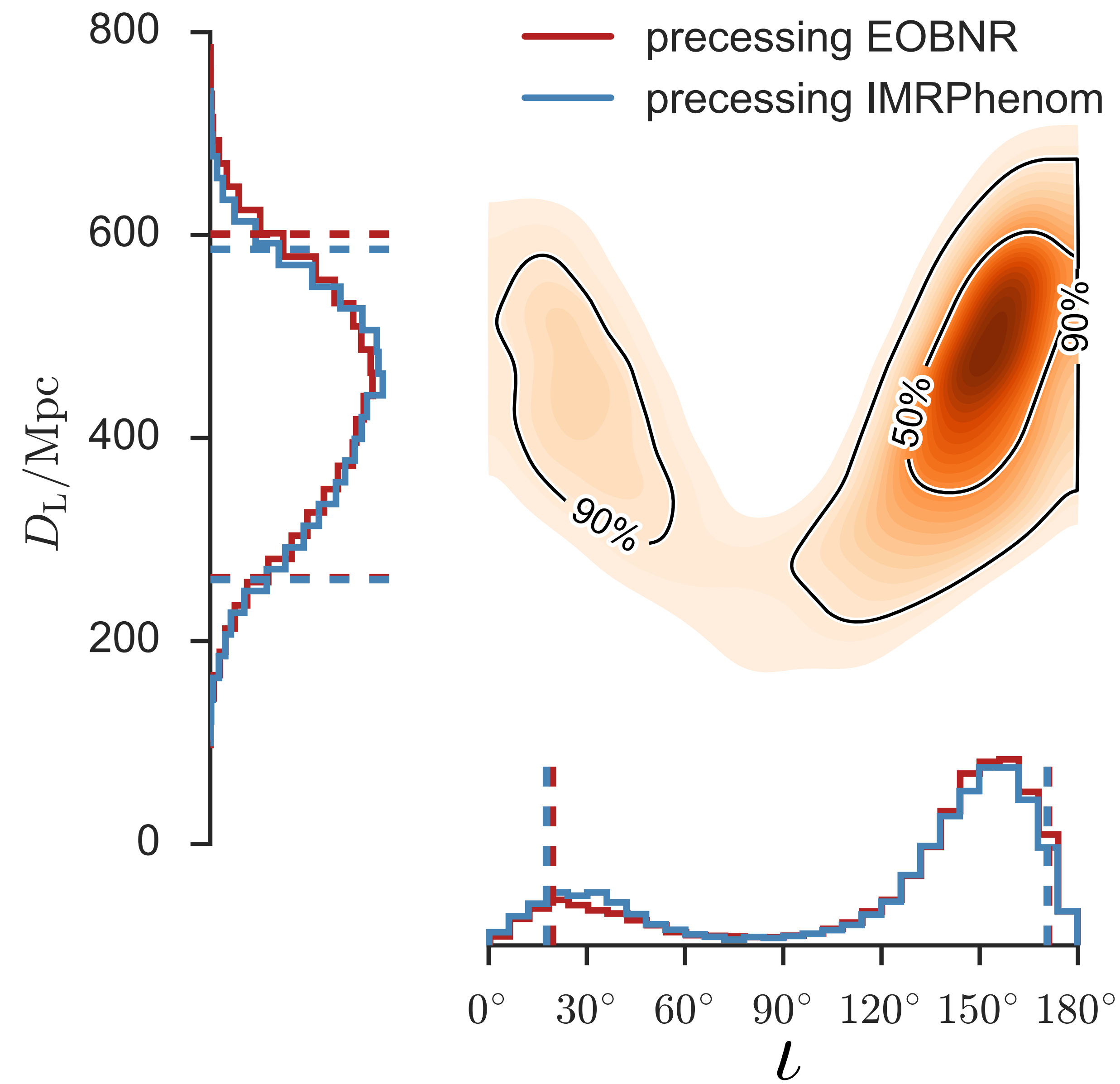


[LIGO-Virgo Collaboration, et al. 2016]

GW150914: distance - inclination



[LIGO-Virgo Collaboration, 2016]

GW150914: distance - inclination

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

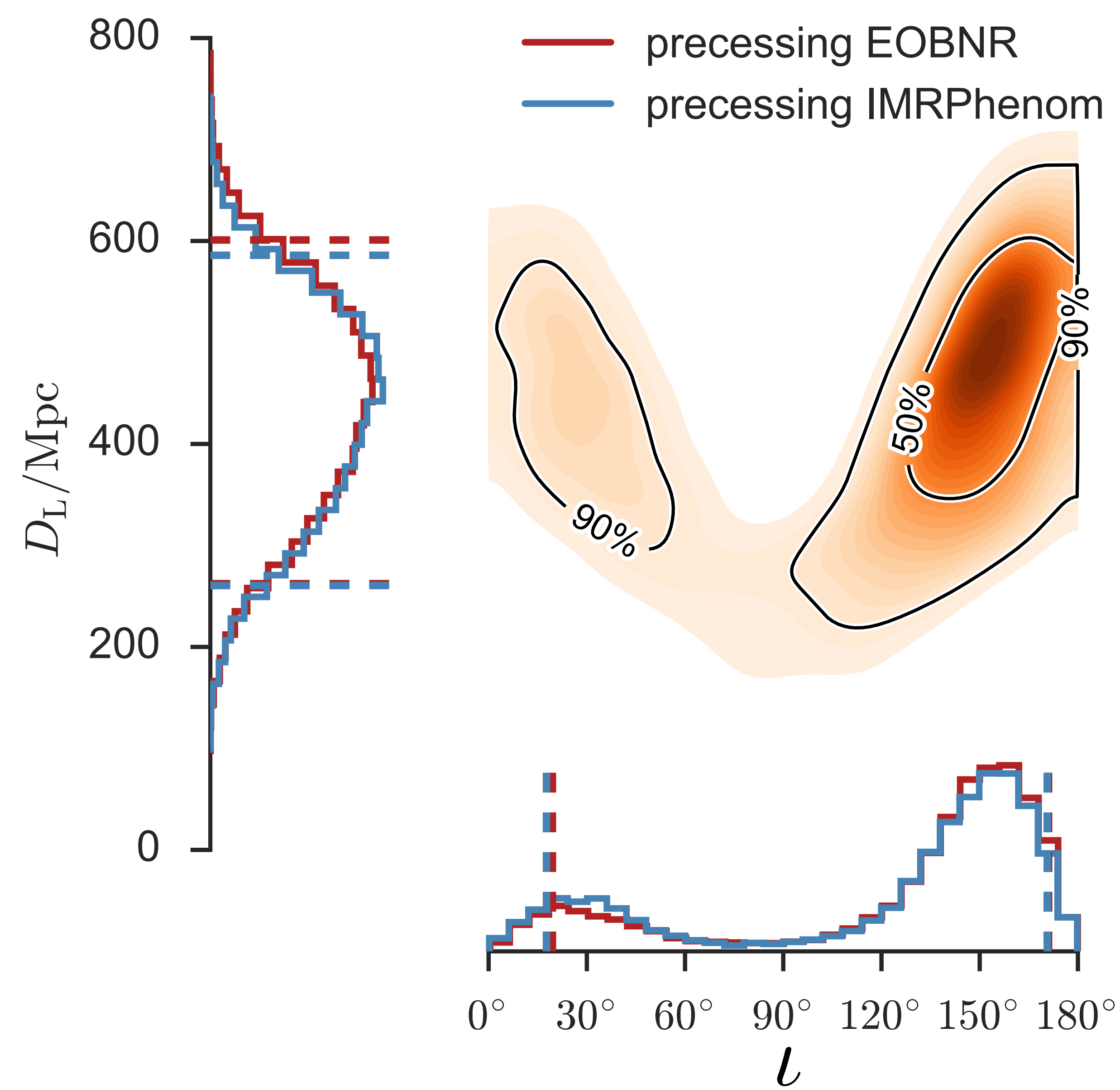
$$h = -\frac{1+\cos^2(\iota)}{2\,D_L} F_{j+}(\mathrm{R.A.}, \mathrm{dec}, \psi) H_+ + \frac{\cos\,\iota}{D_L} F_{j\times}(\mathrm{R.A.}, \mathrm{dec}, \psi) H_\times$$

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

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

- Sampling in `LALInference`

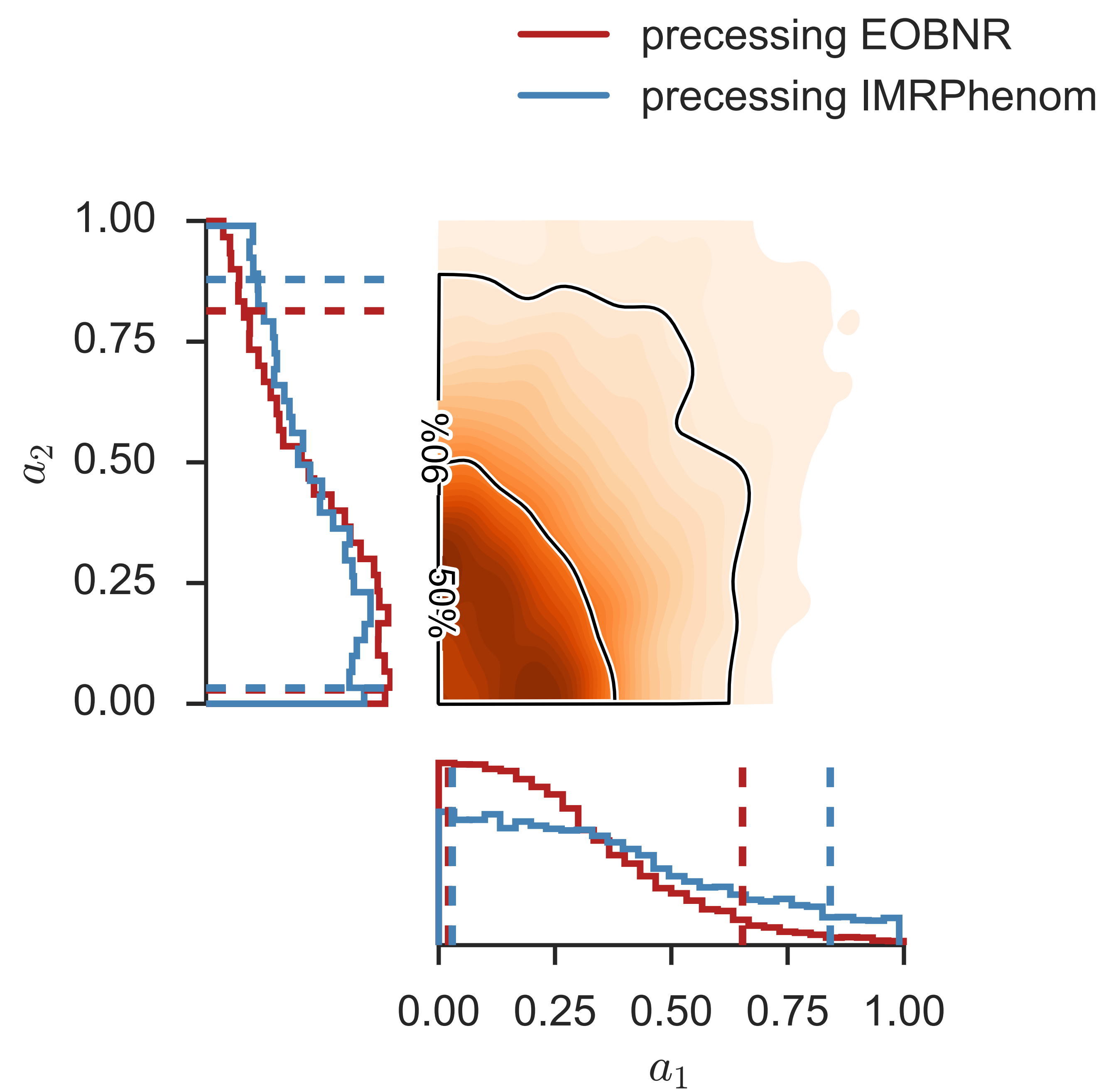
[*Raymond*, Farr, 2014]



[LIGO-Virgo Collaboration, 2016]

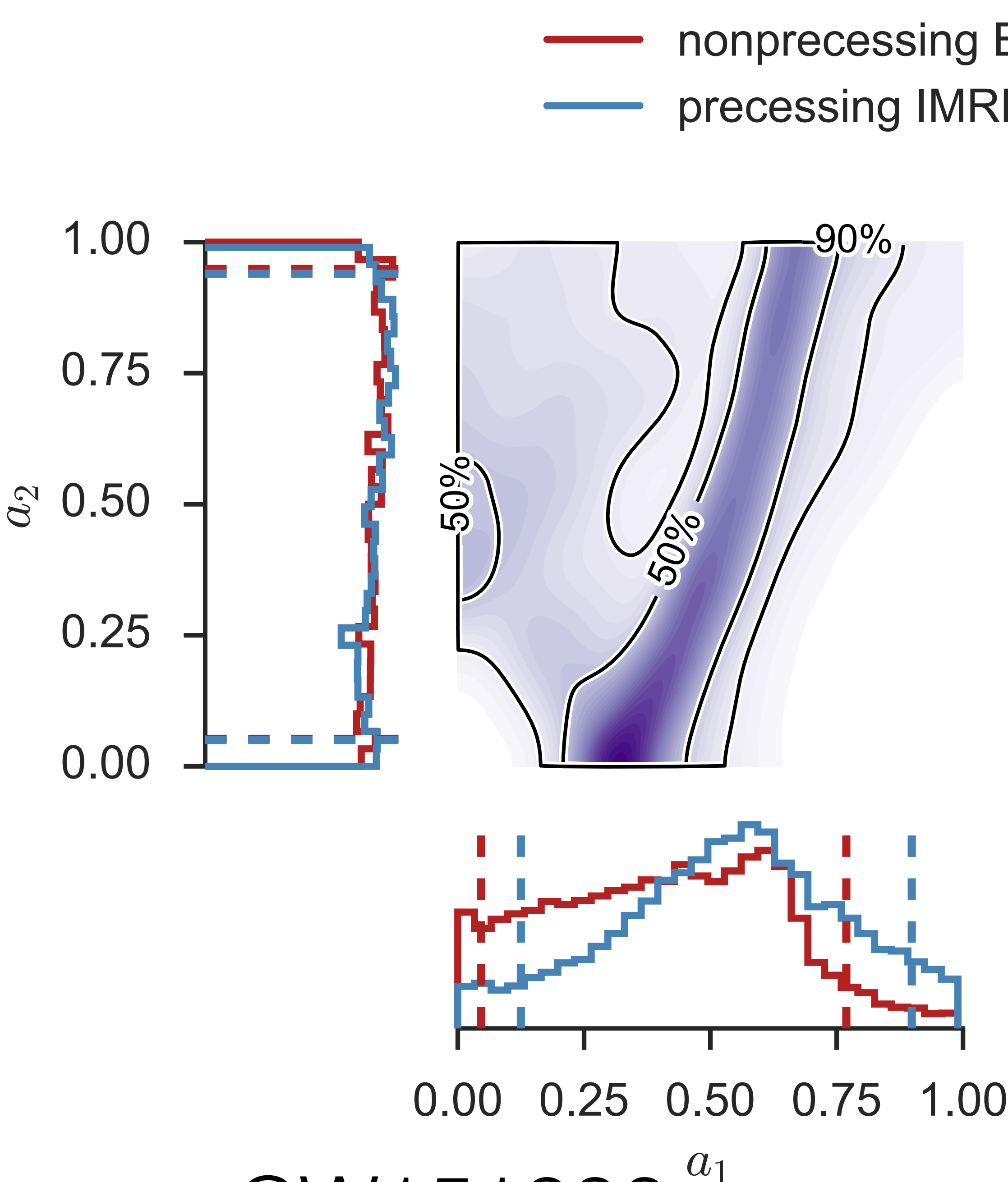
GW150914: spins

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

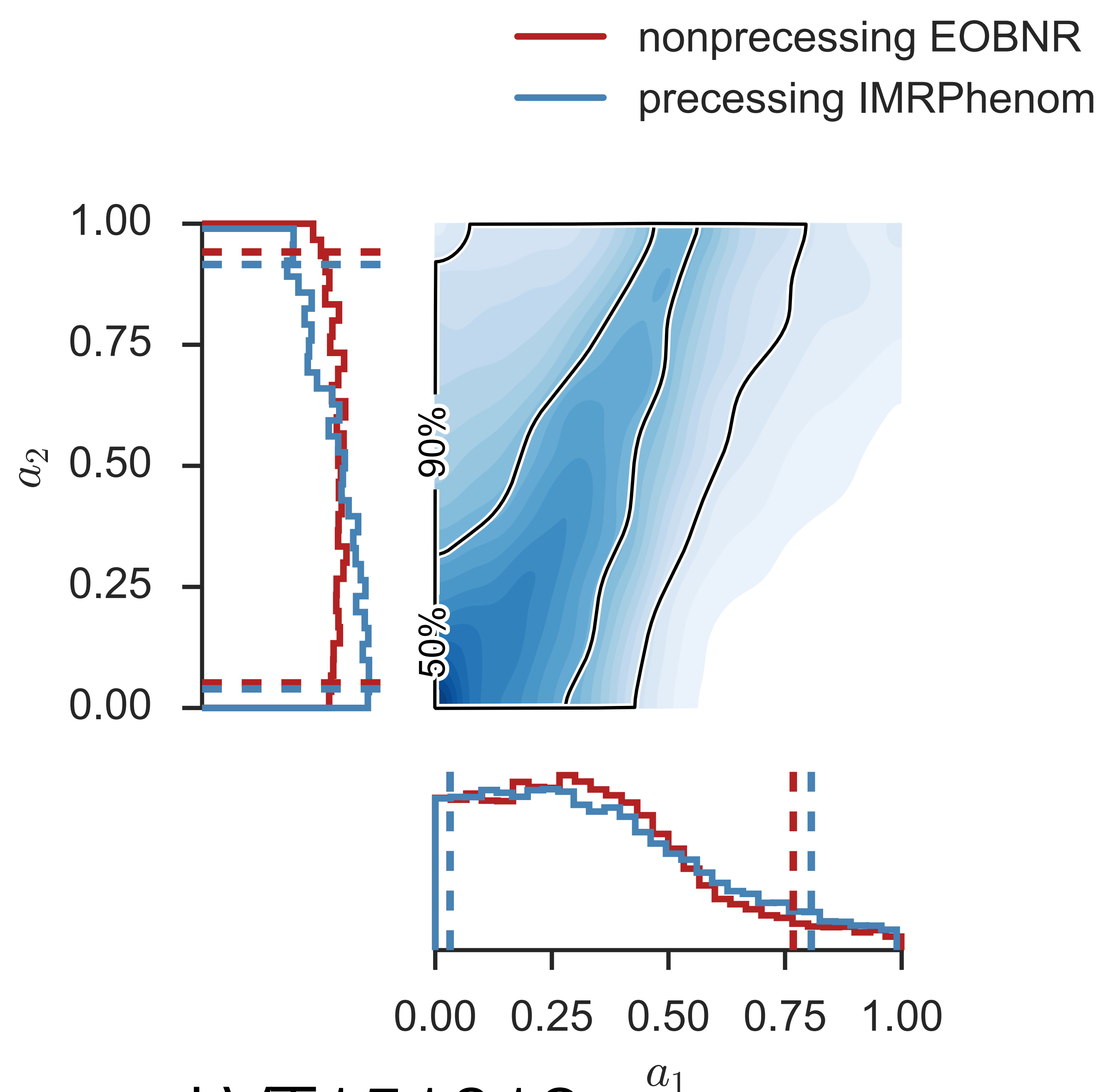


[LIGO-Virgo Collaboration, 2016]

Were the black-holes spinning?



GW151226



LVT151012

[LIGO-Virgo Collaboration, 2016]

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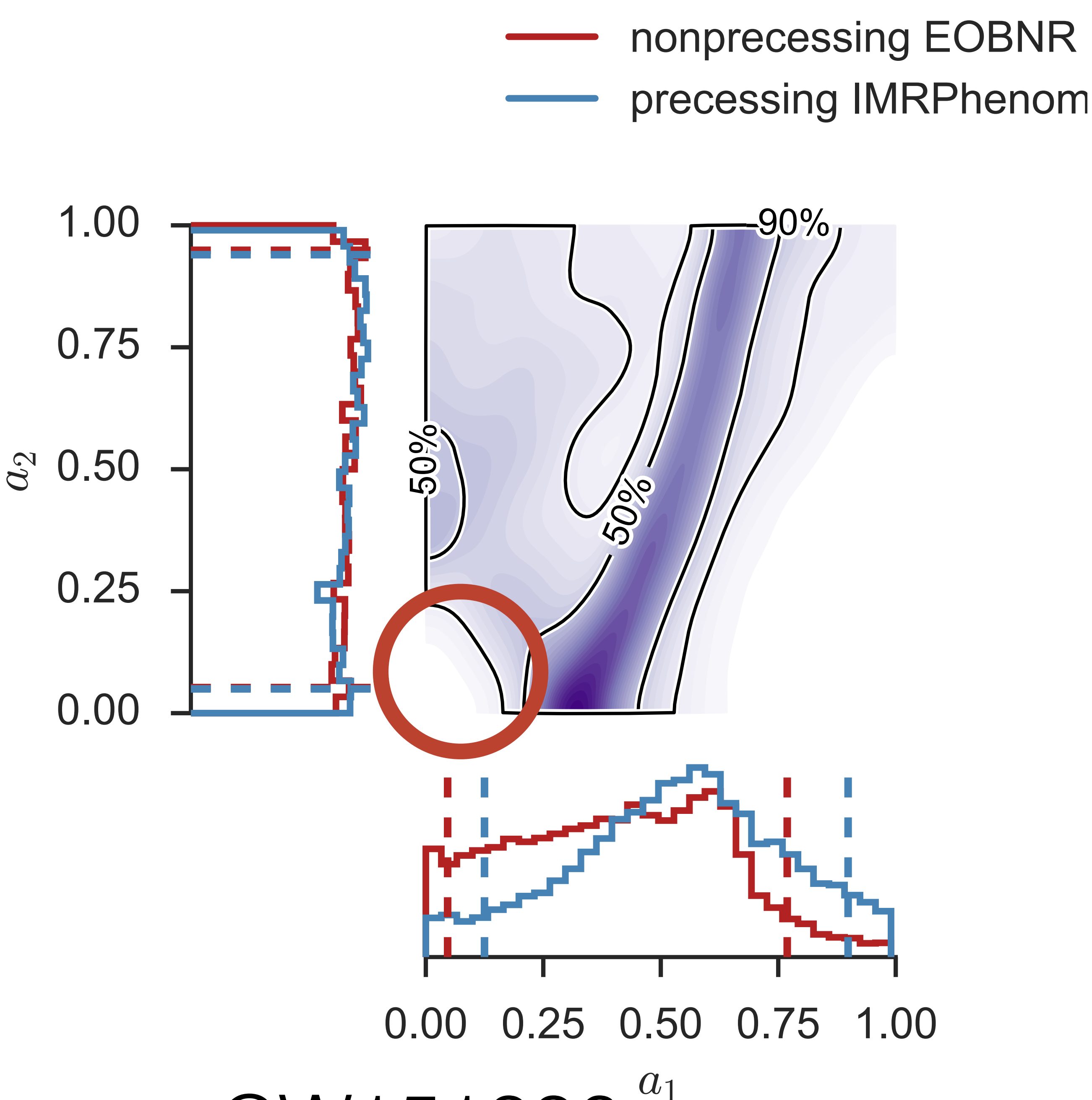
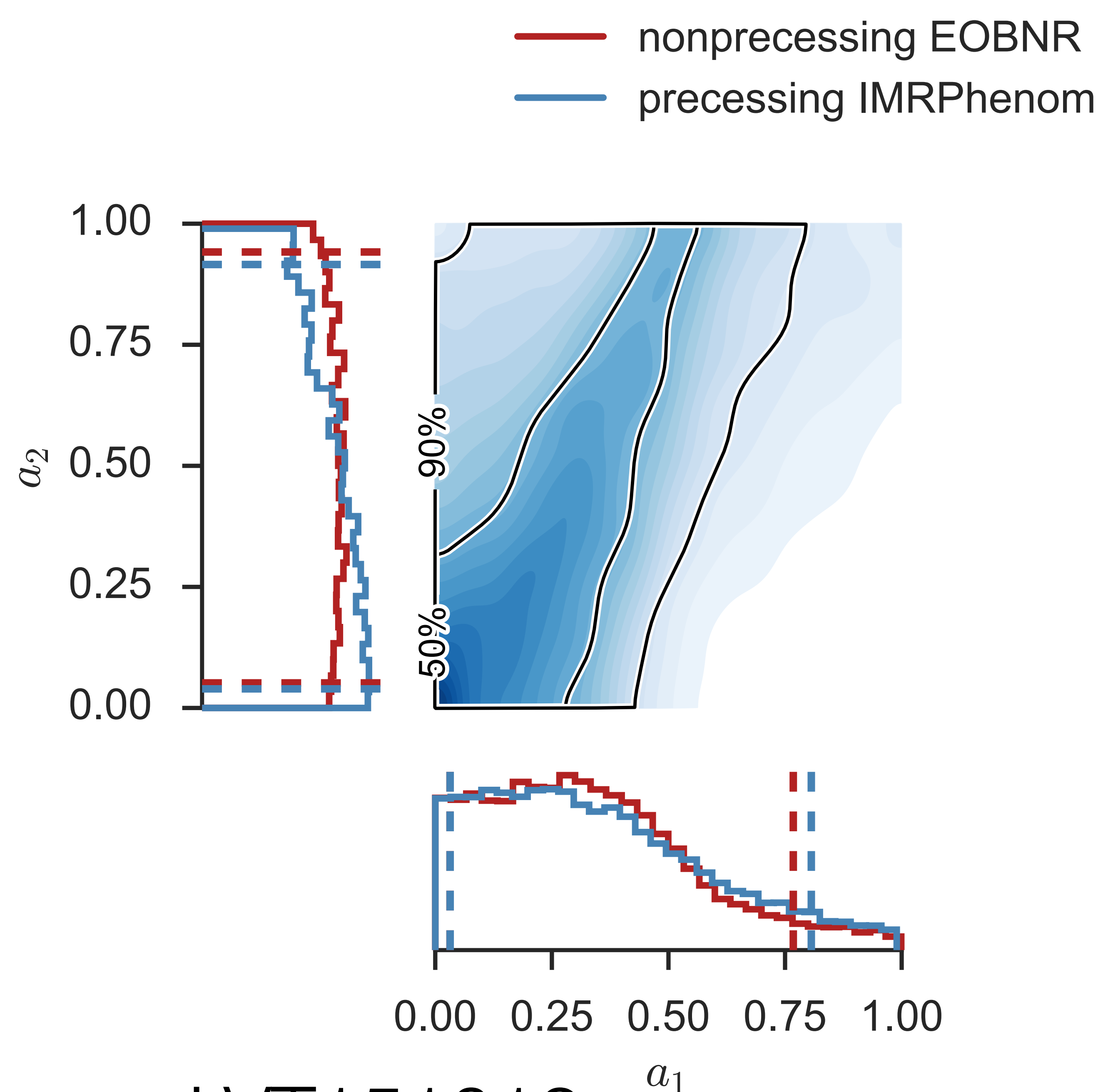


GW151226



LVT151012

[LIGO-Virgo Collaboration, 2016]

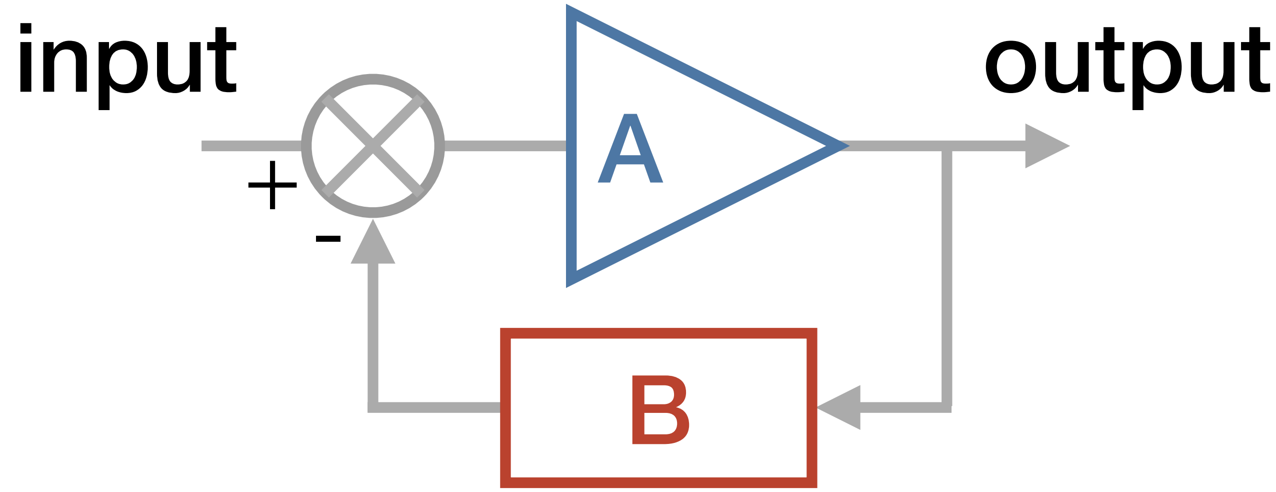
Some results of the first observing run (O1)

- Observational medium delivers **heavy** stellar mass black-holes
- 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

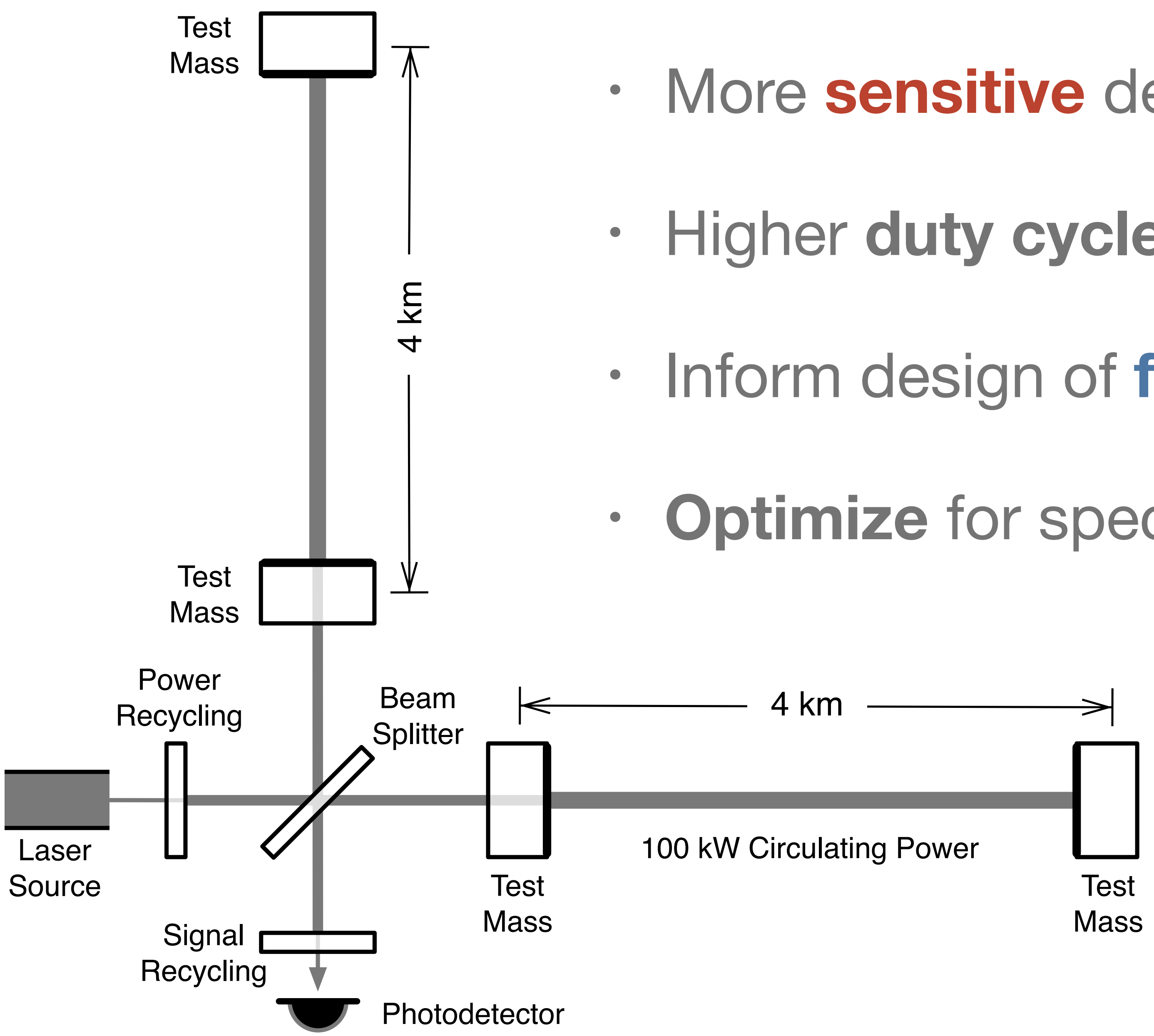
Ongoing work in Gravitational-wave astrophysics

- Joint analysis of **electromagnetic** and **gravitational-wave** data
  - Understanding of **extreme** astrophysical phenomena
  - Higher **probability of astronomical** origin, better **estimations**
- Testing **General Relativity** (with black-hole **ringdowns**)
- Waveform modelling:
  - **Reduced Order Modelling** [Canizares, Field, Gair, *Raymond*, et al., 2015]
  - **Calibration** of waveform **models** against **Numerical Relativity** [Bohé, Shao, Taracchini, Buonanno, Babak, Harry, Hinder, Ossokine, Pürrer, *Raymond*, et al., 2016]
- Towards **automated interferometers** control [Driggers, *Raymond*, et. al., 2014]
- **Combining** observations [*Raymond*, Price, 2015; *Raymond*, Price, Gendler, in prep]

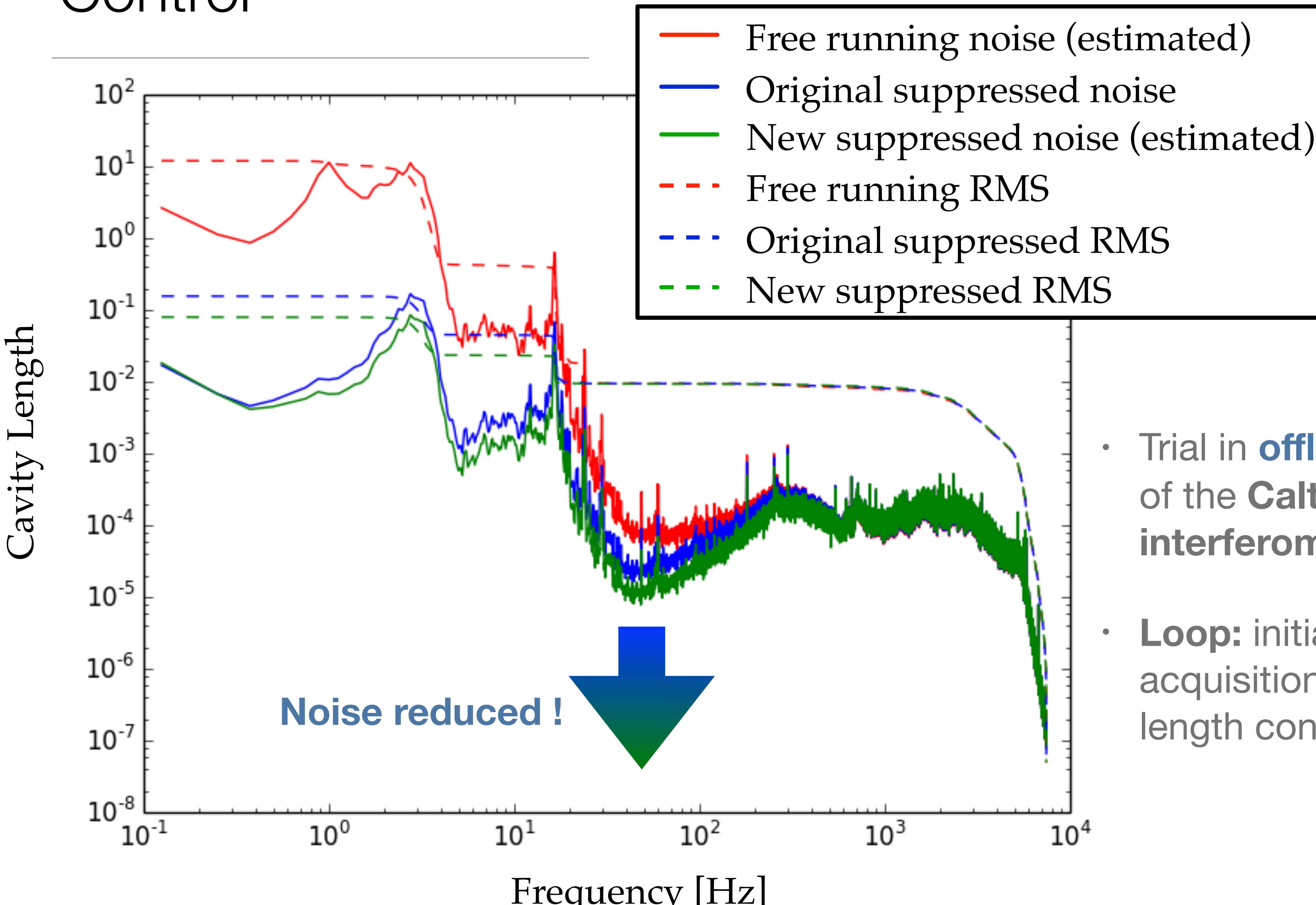
Towards Automated Control



- Improving **gravitational-wave observatories**:
  - More **sensitive** detector
  - Higher **duty cycle**
  - Inform design of **future instruments**
  - **Optimize** for specific **astrophysical sources**



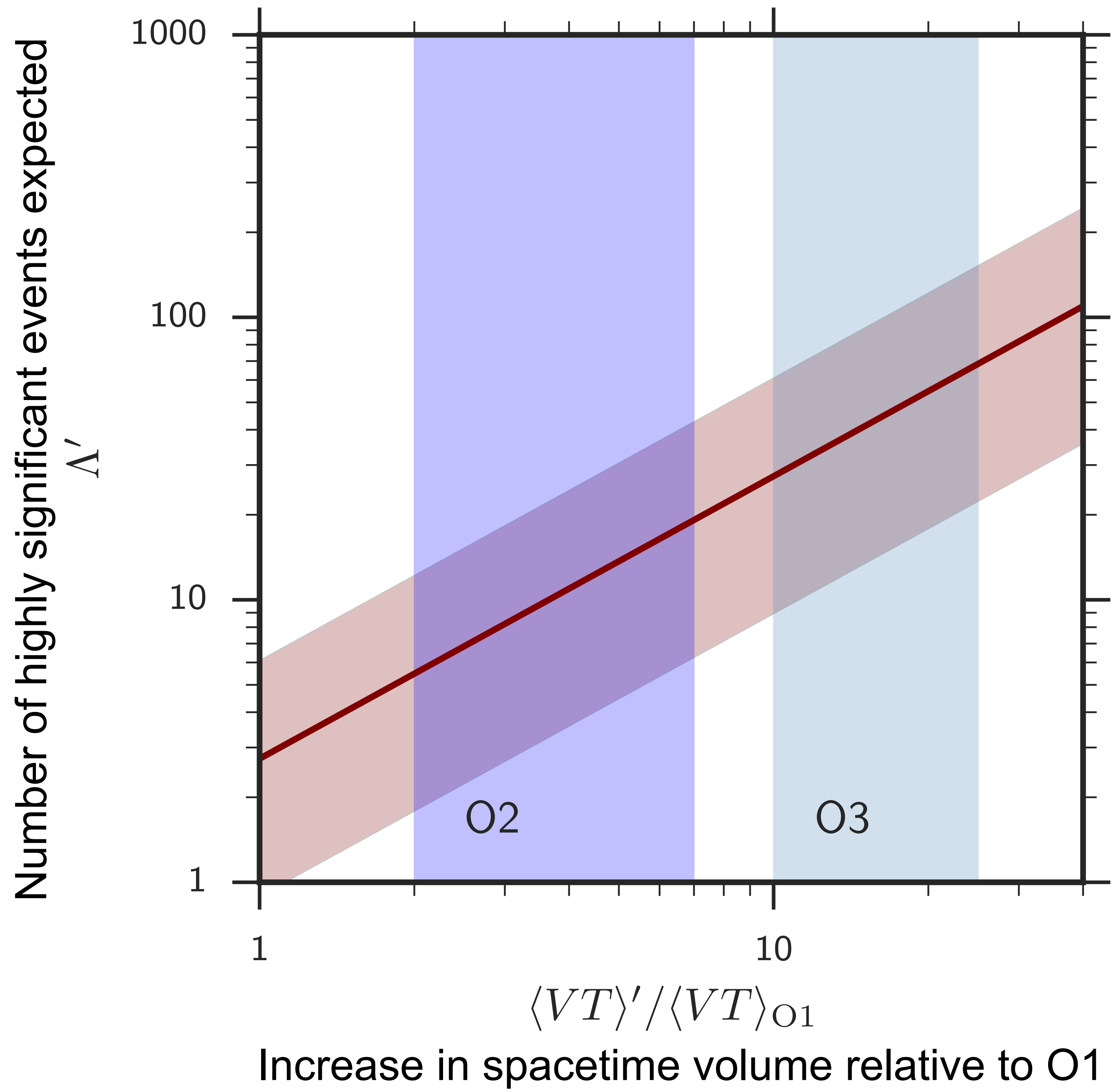
Towards Automated Control



- Trial in **offline data** of the **Caltech 40m interferometer**
- **Loop:** initial lock acquisition for length control

Beyond the first observing run (O1)

- **More** Binary Black Holes
  - Better **spin** constraints (magnitude AND orientation)
- **Neutron stars** in binaries
- New **tests** of **General Relativity**
- Neutron stars **equation of state**
- Population of **compact objects**



[LIGO-Virgo Collaboration, 2016]

Combining detections

- New **tests** of **General Relativity**
- Neutron stars **equation of state**
- **Mass gap**
- **Field** and **cluster** populations
- **Star formation** parameters
- ….

Monkey Head Nebula. Credit: NASA, ESA, Hubble Heritage Team STScI/AURA

For instance:

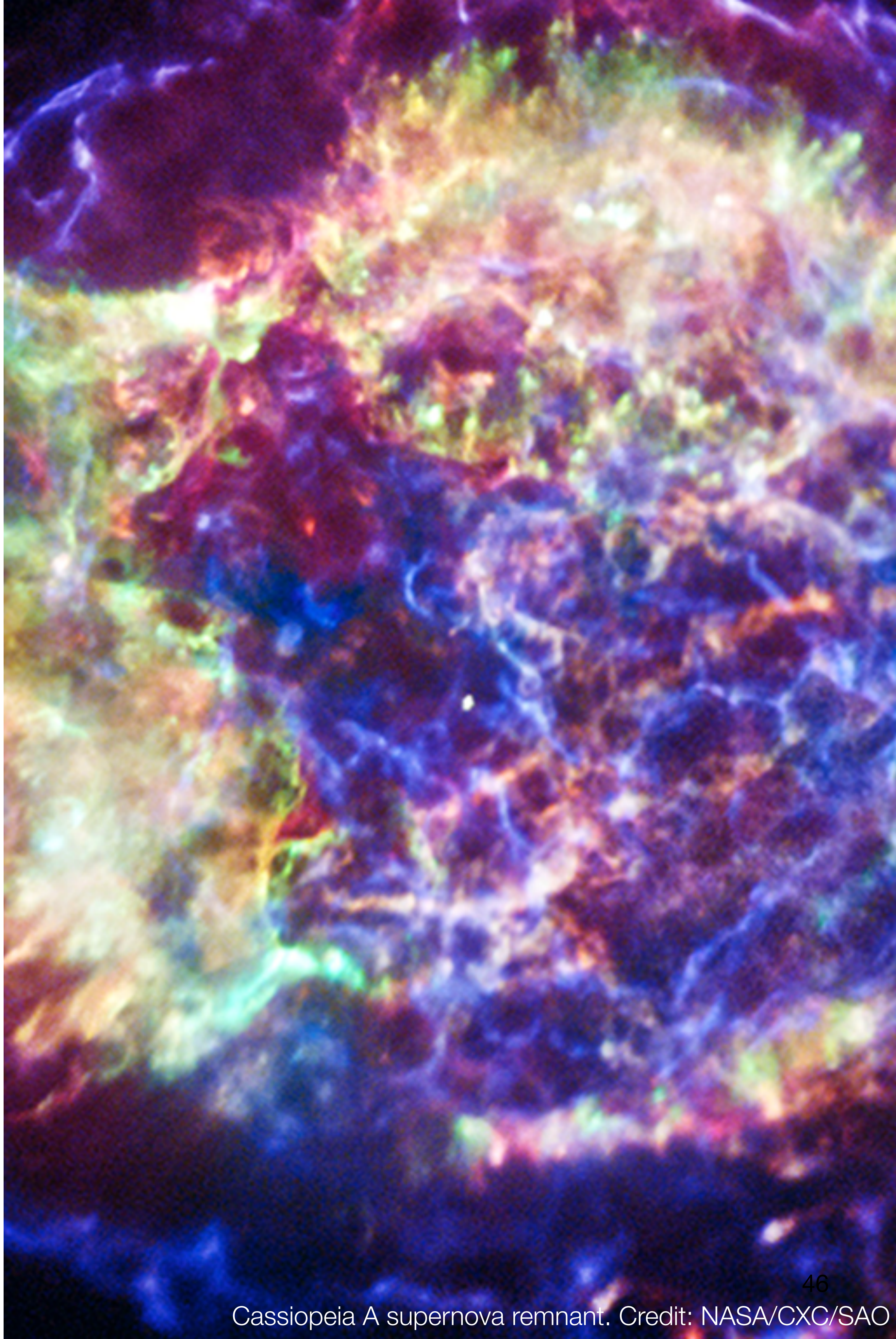
- Neutron-star mass distribution:
  - Iron-core collapse supernovae

$$\approx 1.35\,\mathrm{M}_\odot$$

  - Electron-capture supernovae

$$\approx 1.25\,\mathrm{M}_\odot$$

[Knigge, et al., 2011, Schwab, et al., 2010]



Cassiopeia A supernova remnant. Credit: NASA/CXC/SAO

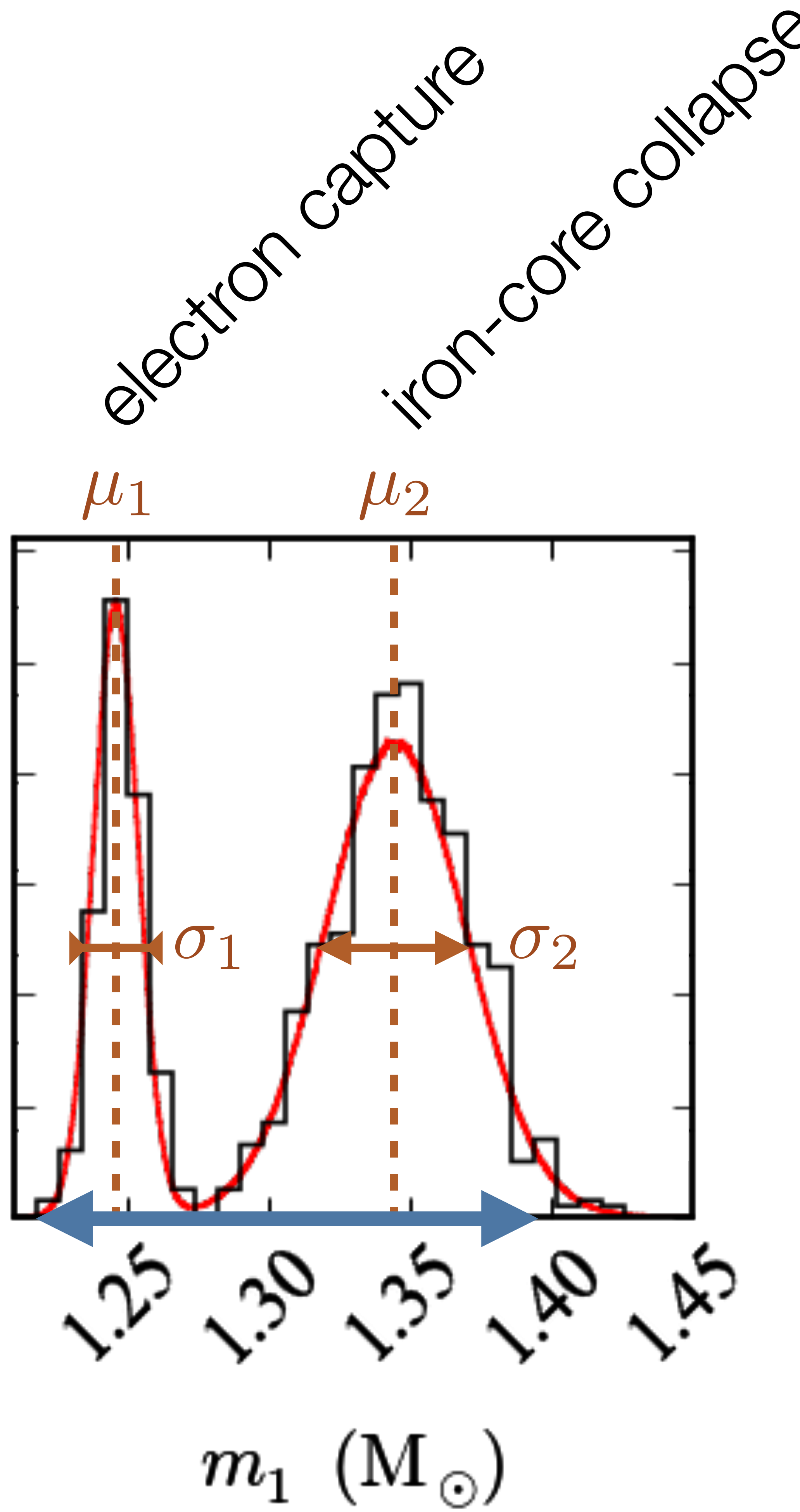
Parametrisation of a population

- Neutron-star mass distribution:

Parameters:

$$\mu_1 = 1.246$$
$$\sigma_1 = .008$$
$$\mu_2 = 1.345$$
$$\sigma_2 = 0.025$$
$$h_{12} = .293$$

Model inspired by [Schwab, et al., 2010]



Typical Neutron Star mass estimation from 1 observation
[Rodriguez, Farr, *Raymond*, et al., 2014]

Framework to combine observations

- There is a dense literature on how to use gravitational waves from compact binary coalescence to:
  - **distinguish** source populations [Stevenson, et al. 2015; Littenberg, et al. 2015, Mandel et al. 2015]
  - mitigate **detection** and **observation** bias [Gair, Moore, 2015; Messenger, Veitch, 2012]
  - **measure** source distribution **meta-parameters,** [Lackey, Wade 2014]

All of the above in a **common treatment** [*Raymond*, Price, 2015; *Raymond*, Price, Gendler, in prep]

- example with N~1000 (optimistic end of O3), we could **resolve** the distribution

Future outlook:

- What are the **properties** of gravitational waves? Is **General Relativity** still valid under **strong-gravity** conditions?
- How does **matter** behave under **extremes of density** and **pressure**?
- How **abundant** are stellar-mass **binary black holes**? And what are the **mass distributions** of coalescing compact objects?
- How are **compact binaries** that coalesce **formed**, what is their **accretion history** and what has been their effect on star formation rates?
- Is the mechanism that generates **gamma-ray bursts** a **compact binary coalescence**?
- Where and when do **massive black holes** form, and what role do they play in the **formation** and **evolution of galaxies**?
- And the **unexpected !**