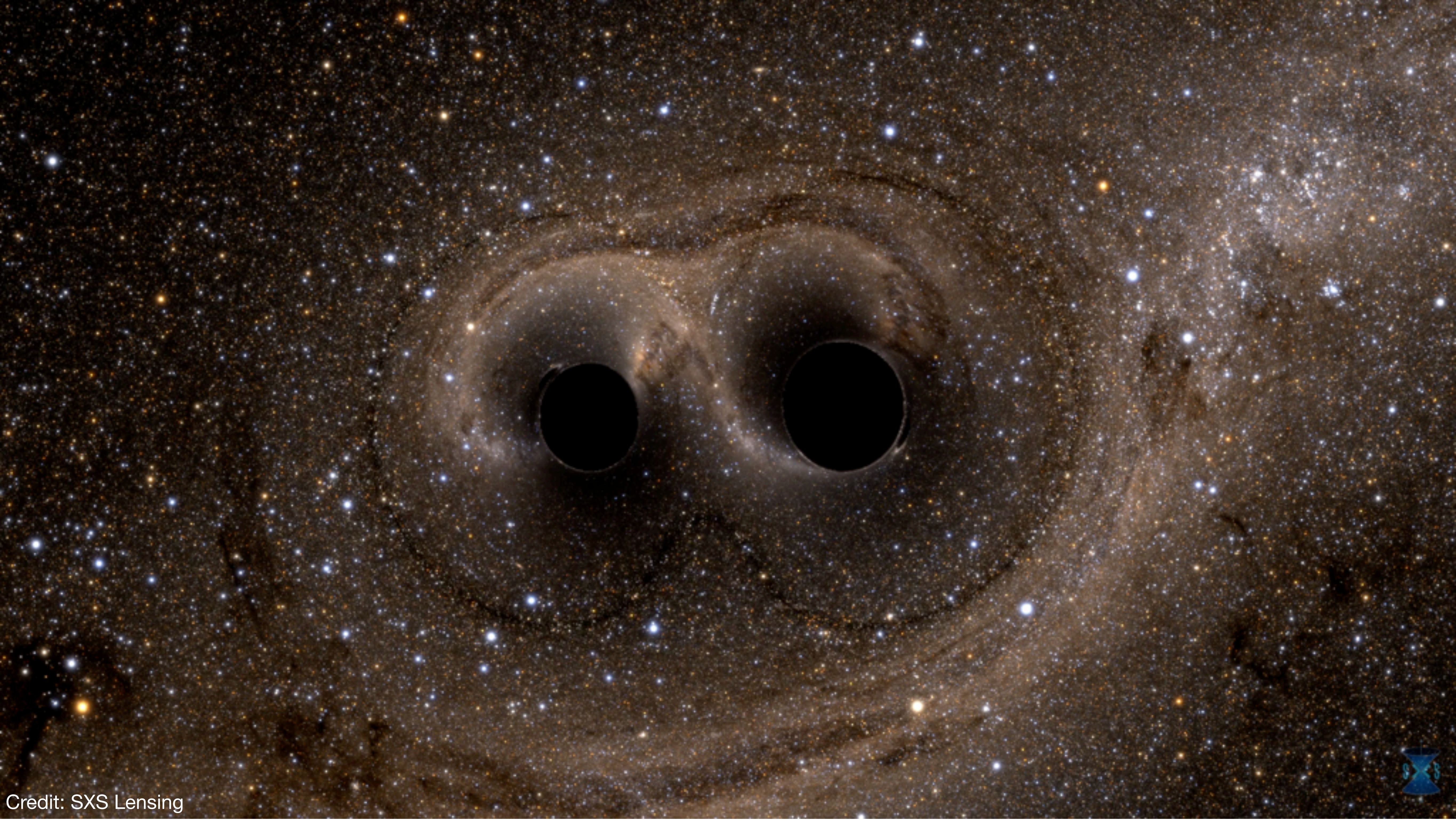

Credit: SXS Lensing

Gravitational-wave astrophysics

Vivien Raymond
Max Planck Institute for Gravitational Physics

LSC LIGO Scientific Collaboration

VIRGO

2nd International Interdisciplinary Workshop on Time Series Analysis, University Paris Descartes

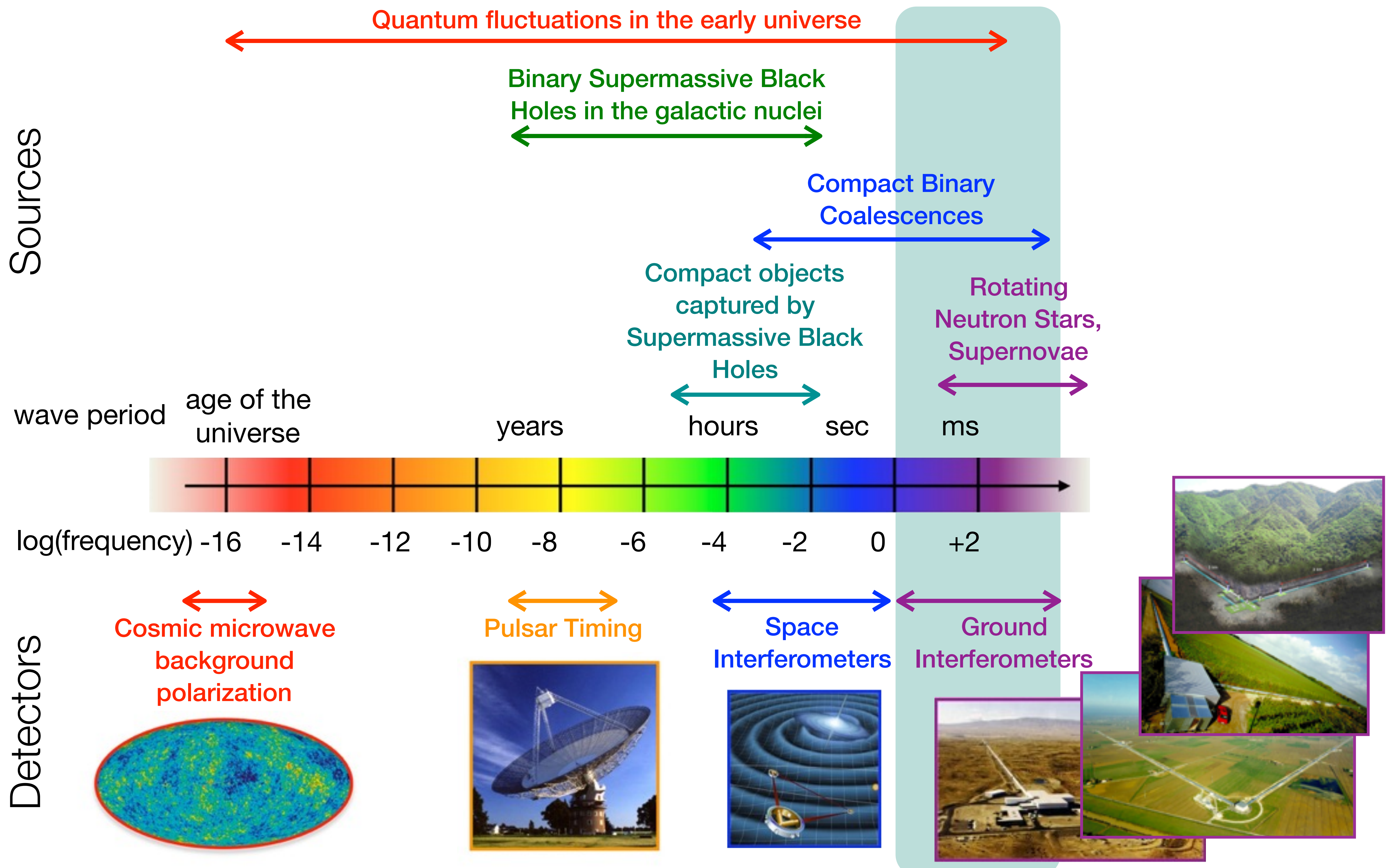
LIGO-G1602408

Gravitational-wave astrophysics

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

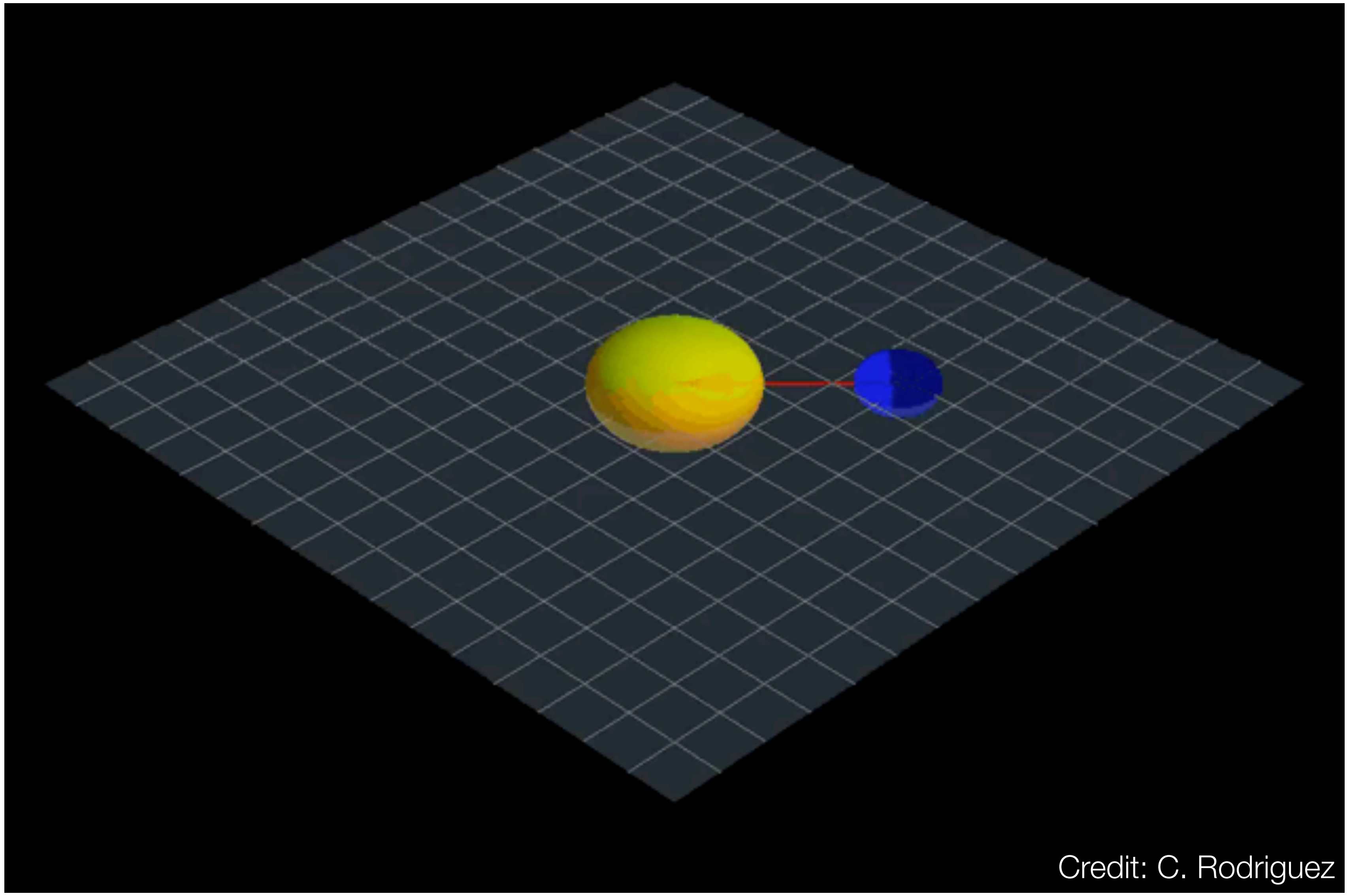
- Is **General Relativity** in the correct theory of **Gravity**?
- What happens when **matter** is compressed to **nuclear densities**?
- What are the properties of the population(s) of **compact objects**?
- Is the mechanism that generates **gamma-ray bursts** a **compact binary coalescence**?

The Gravitational Wave Spectrum



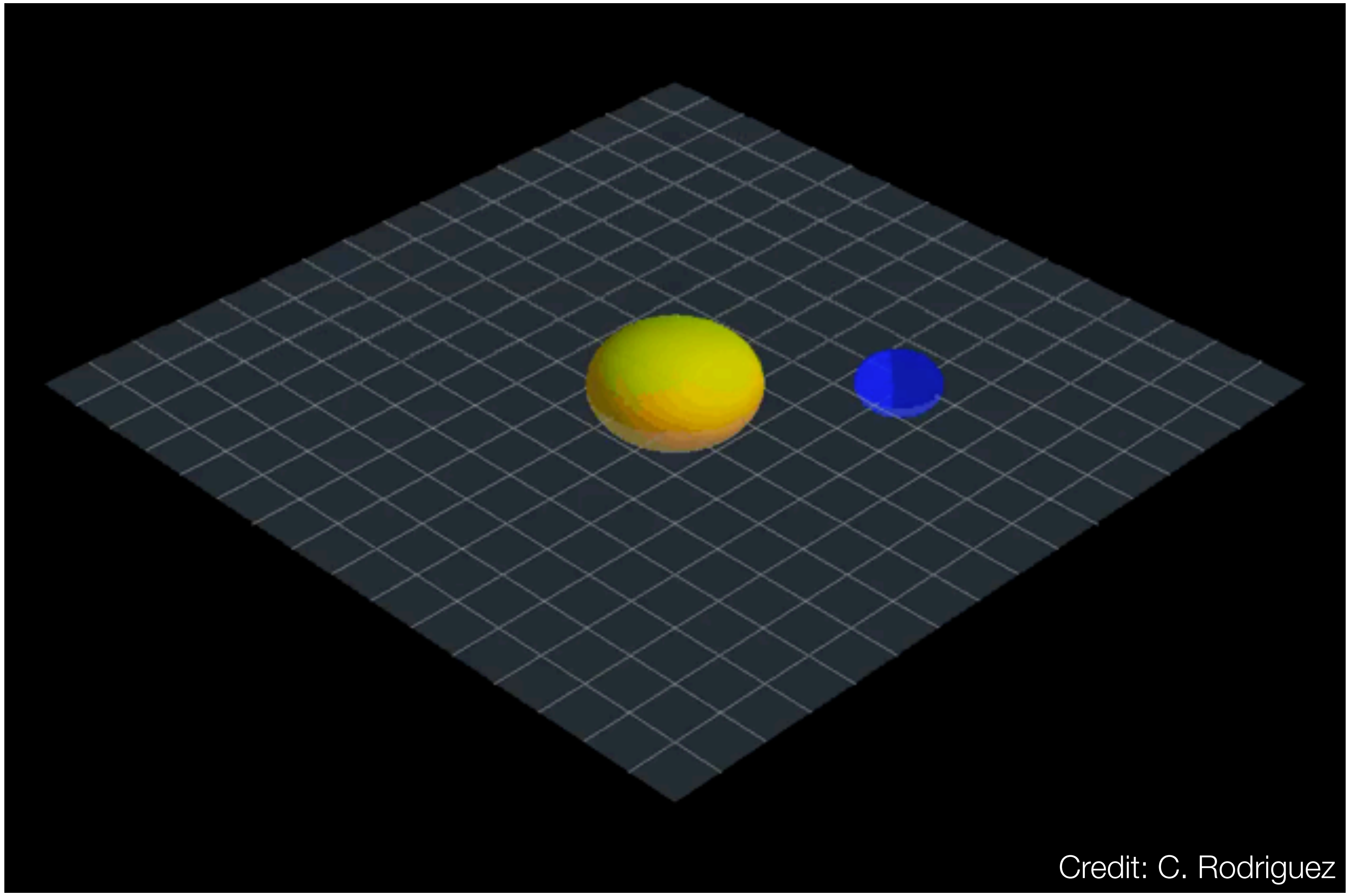
[Inspired from http://science.gsfc.nasa.gov/663/research/]

100 years ago:
General Relativity and Gravitational Waves



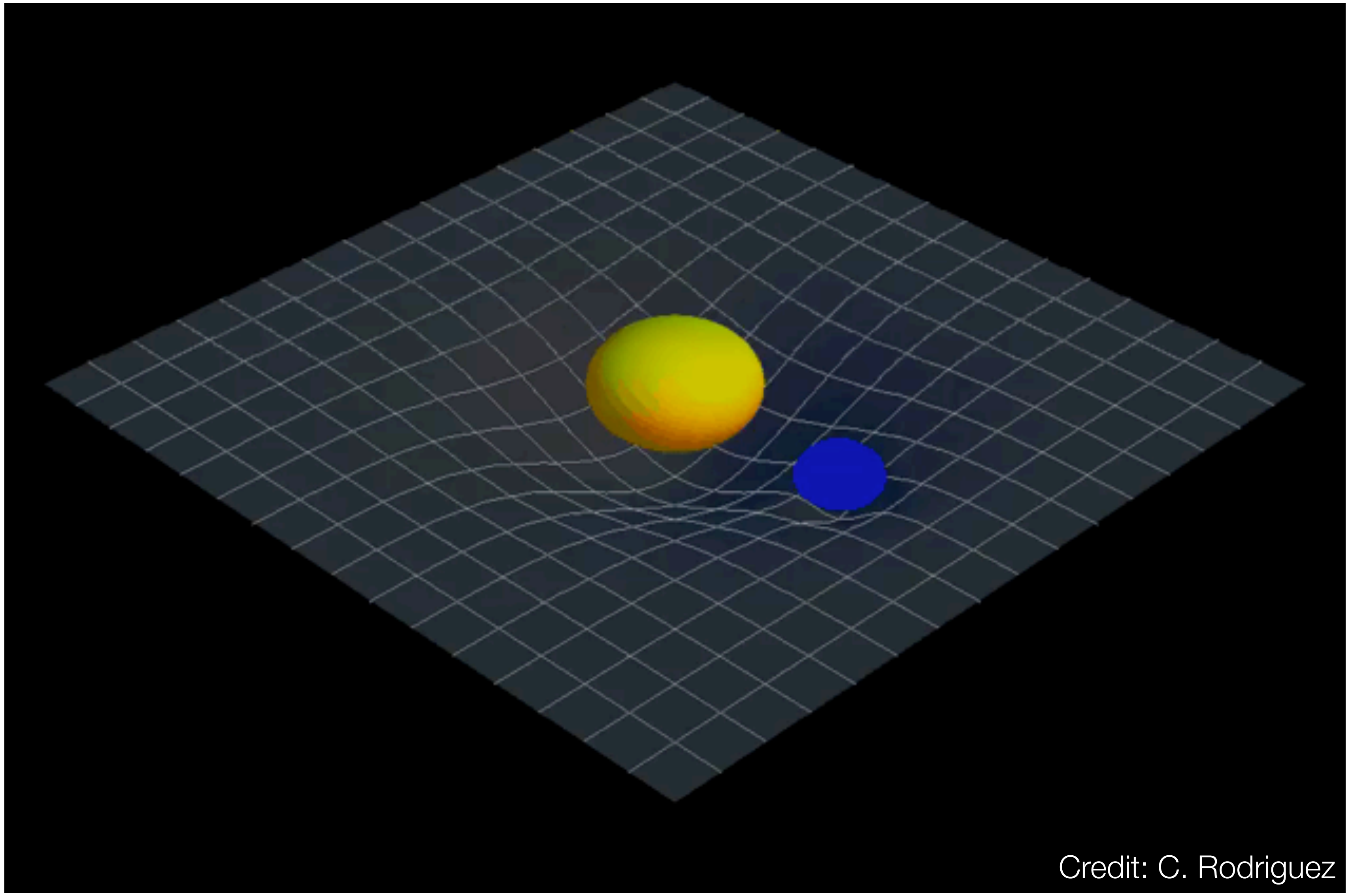
- **Before Einstein**: Newtonian gravity

100 years ago:
General Relativity and Gravitational Waves



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

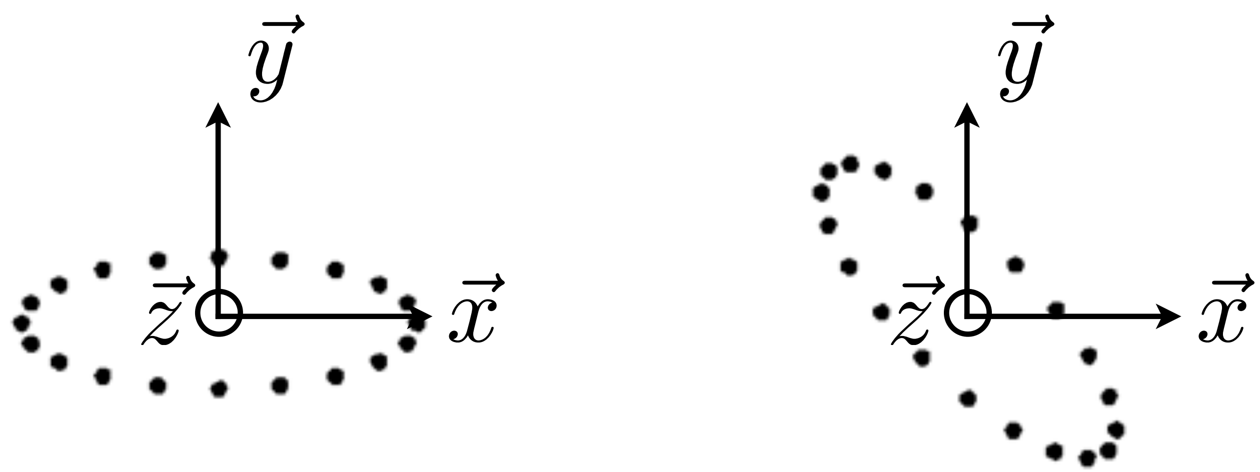
100 years ago:
General Relativity and Gravitational Waves



- 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**

Gravitational-wave effect

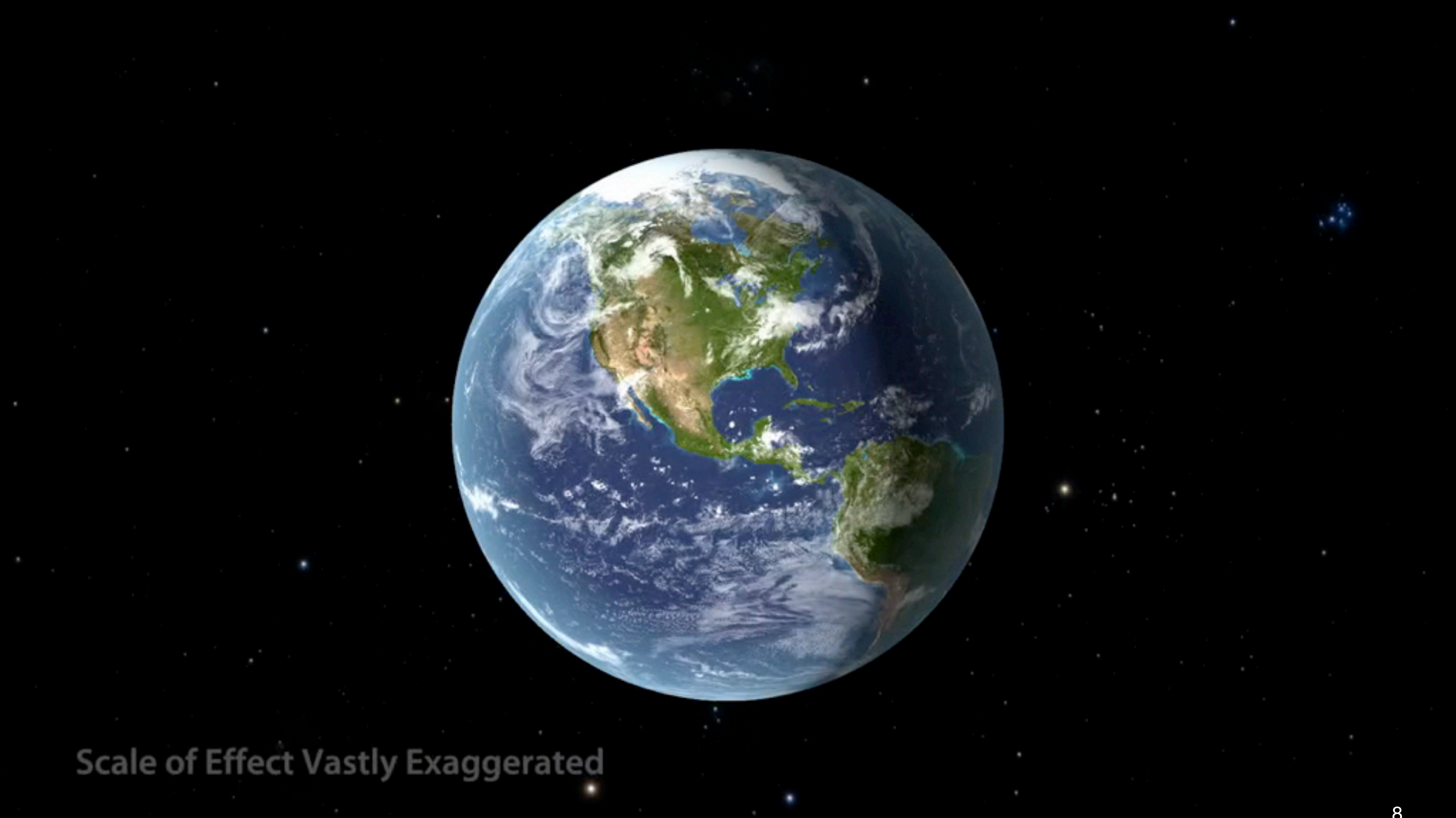


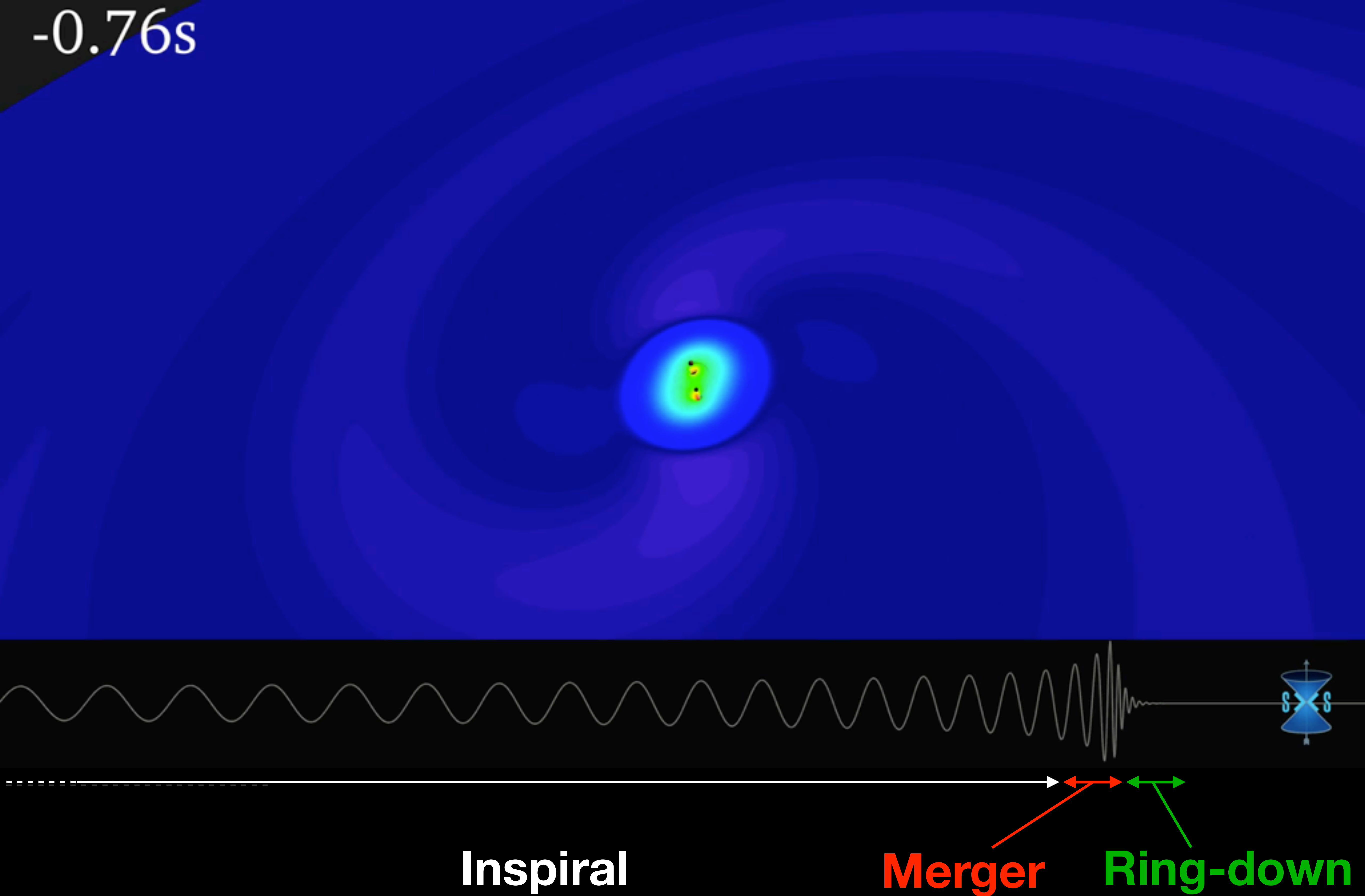
Image credit: LIGO/Virgo

~30 years ago: gravitational-wave observatories

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

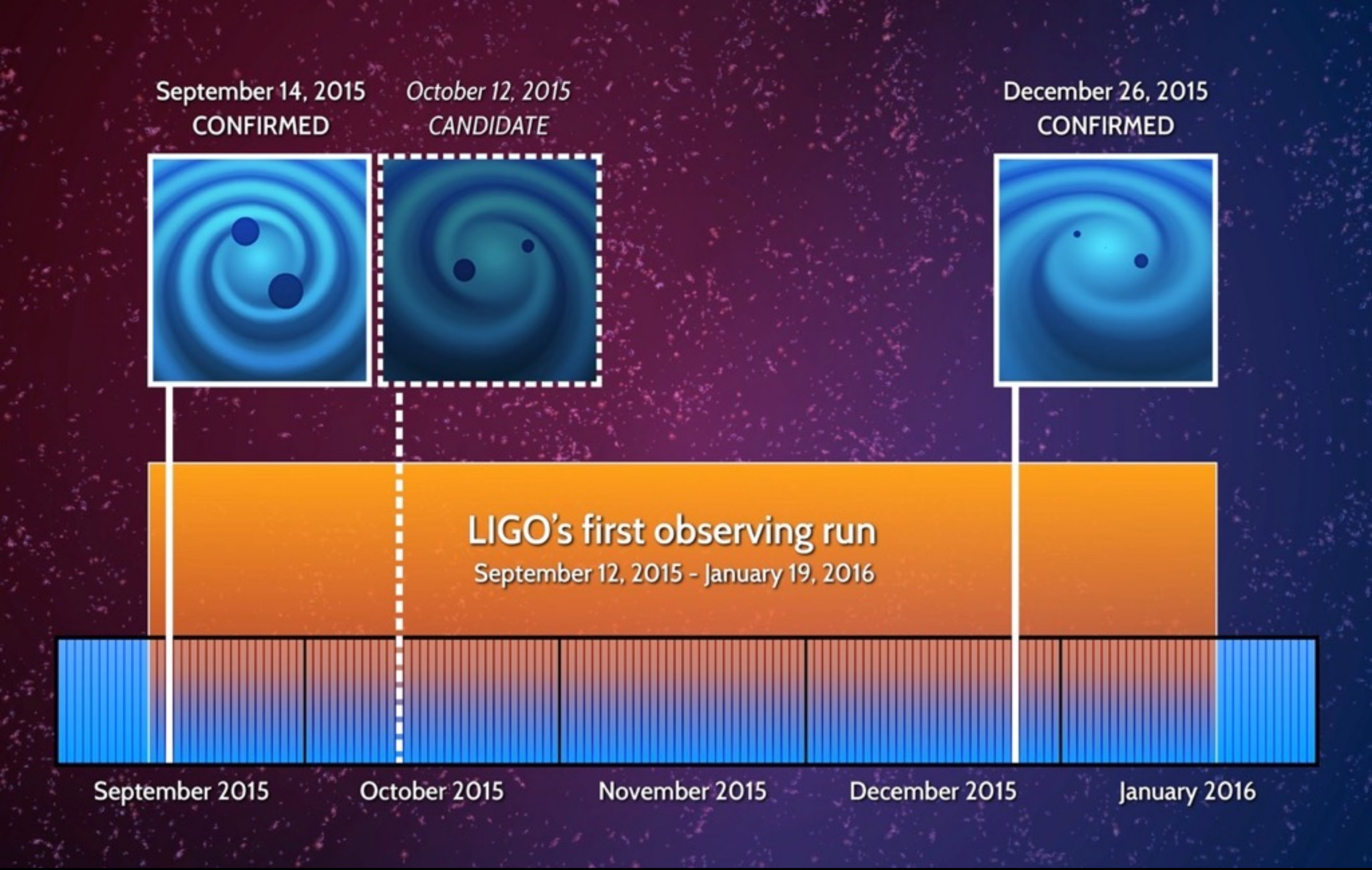
Virgo observatory. Credit: Virgo

LIGO Hanford and Livingston. Credit: LIGO



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

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



GW150914

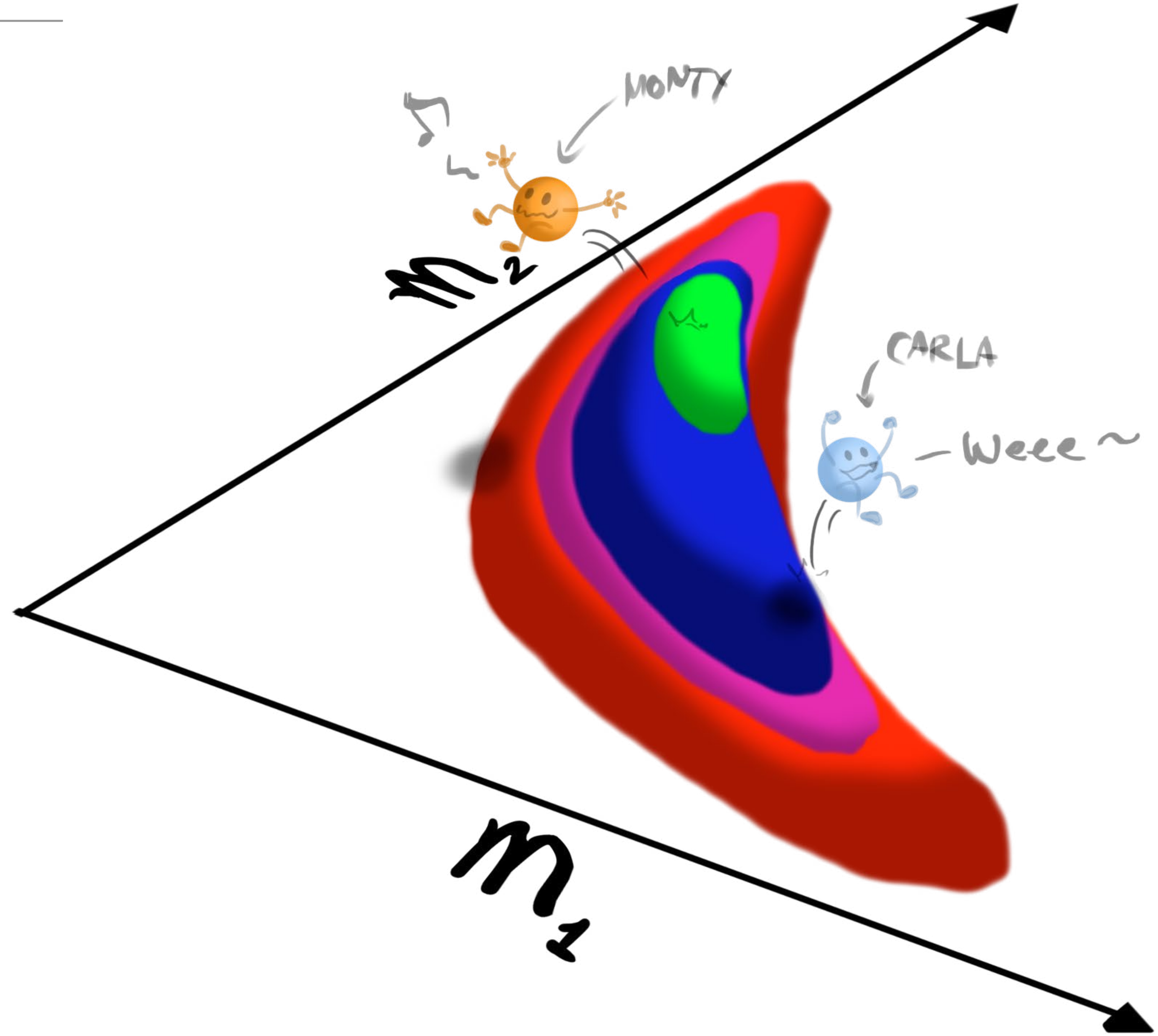
GW151226

LVT151012

Image credit: LIGO/Virgo

Overview

- Introduction
  - Observatories
  - **Sources**
- **Gravitational-wave astronomy**
  - Detection
  - **Parameter Estimation**
- **Gravitational-wave astrophysics** after the first detections



[LIGO Scientific Collaboration]

Observatories

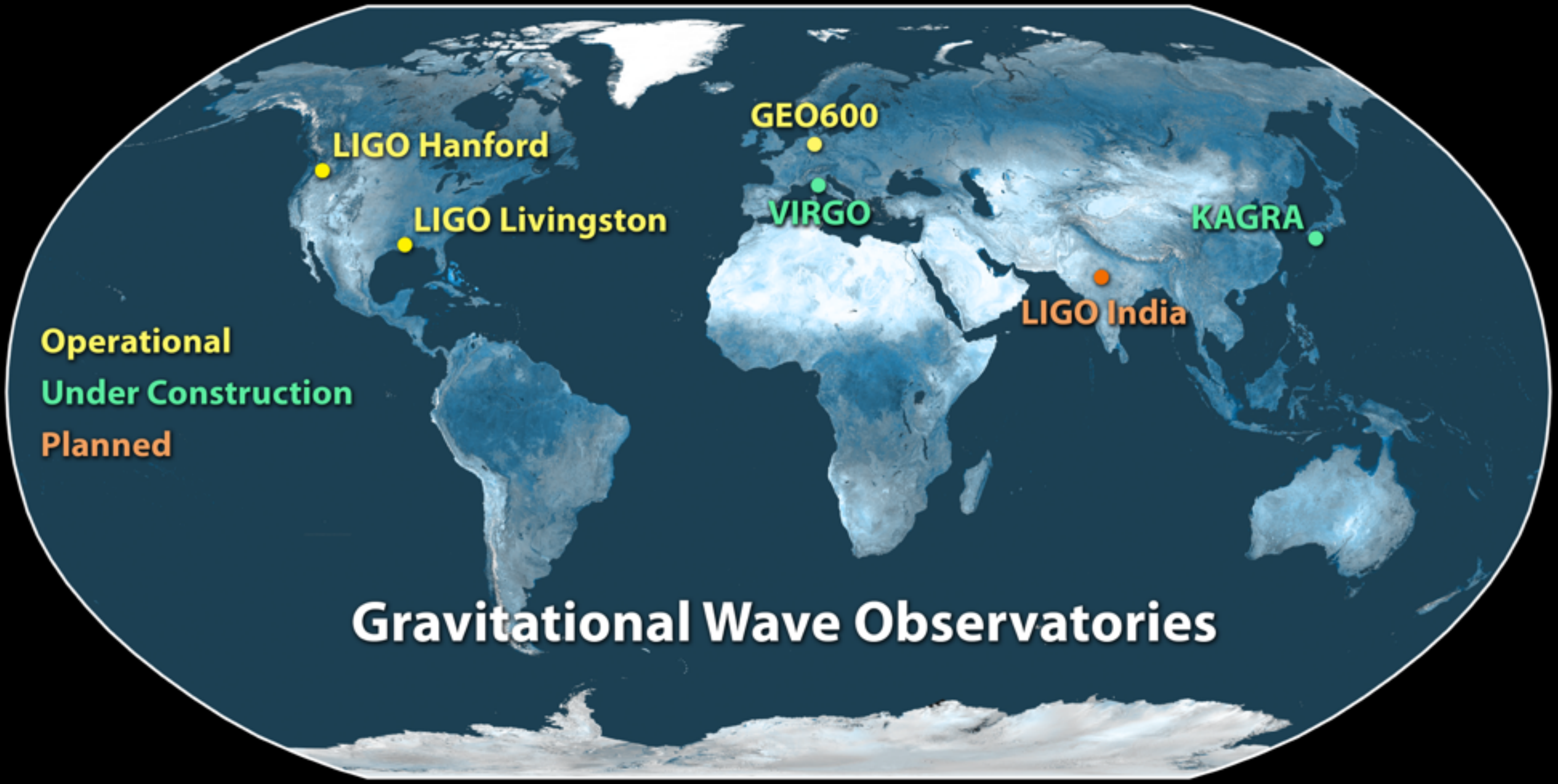
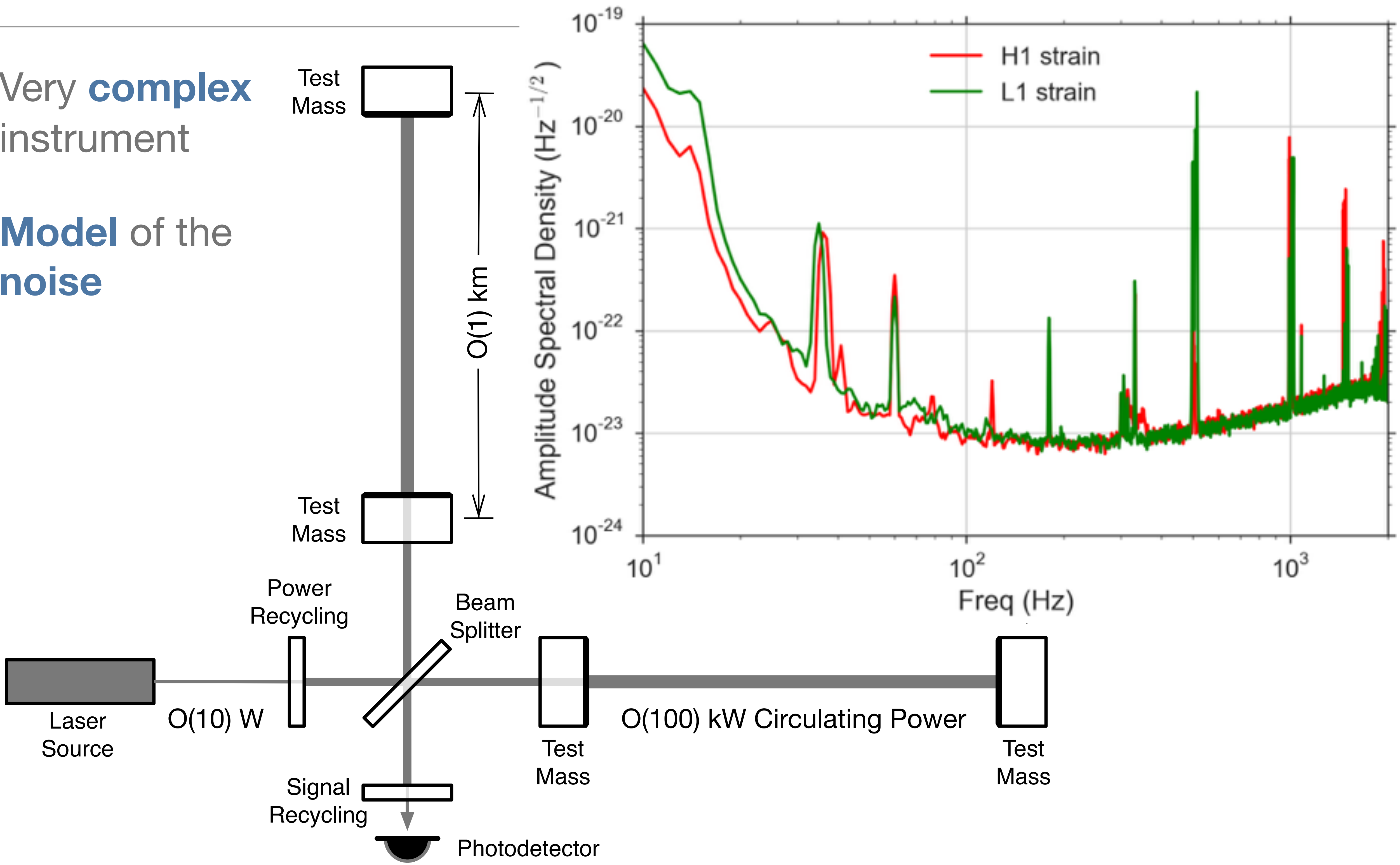


Image credit: LIGO/Virgo

Observatories

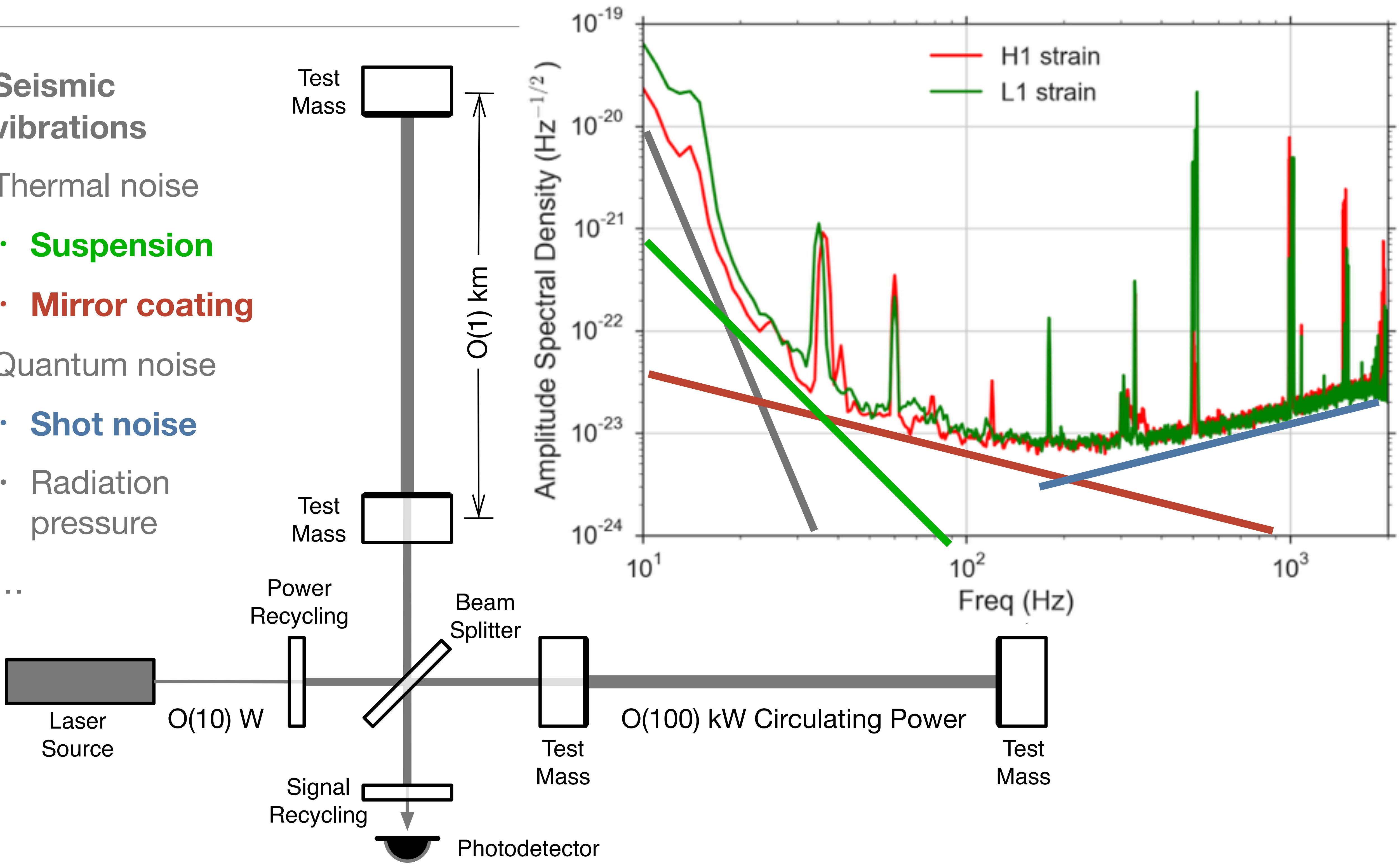
- Very **complex** instrument
- **Model** of the **noise**



[LIGO-Virgo Collaboration, 2016]

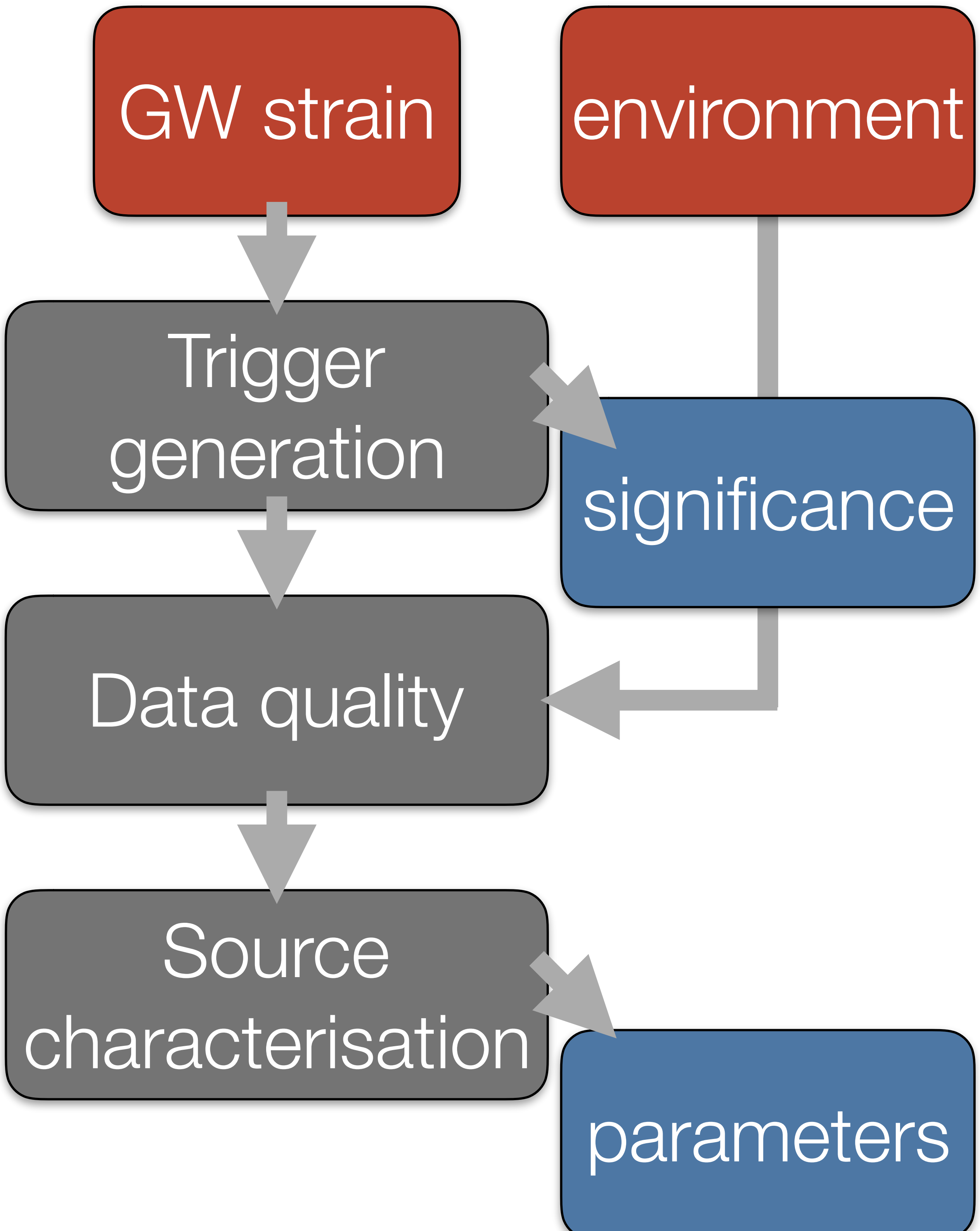
Noise sources

- **Seismic vibrations**
- Thermal noise
    - **Suspension**
    - **Mirror coating**
- Quantum noise
    - **Shot noise**
    - Radiation pressure
- …



[LIGO-Virgo Collaboration, 2016]

GW pipeline



Virgo observatory. Credit: Virgo

Gravitational-wave sources

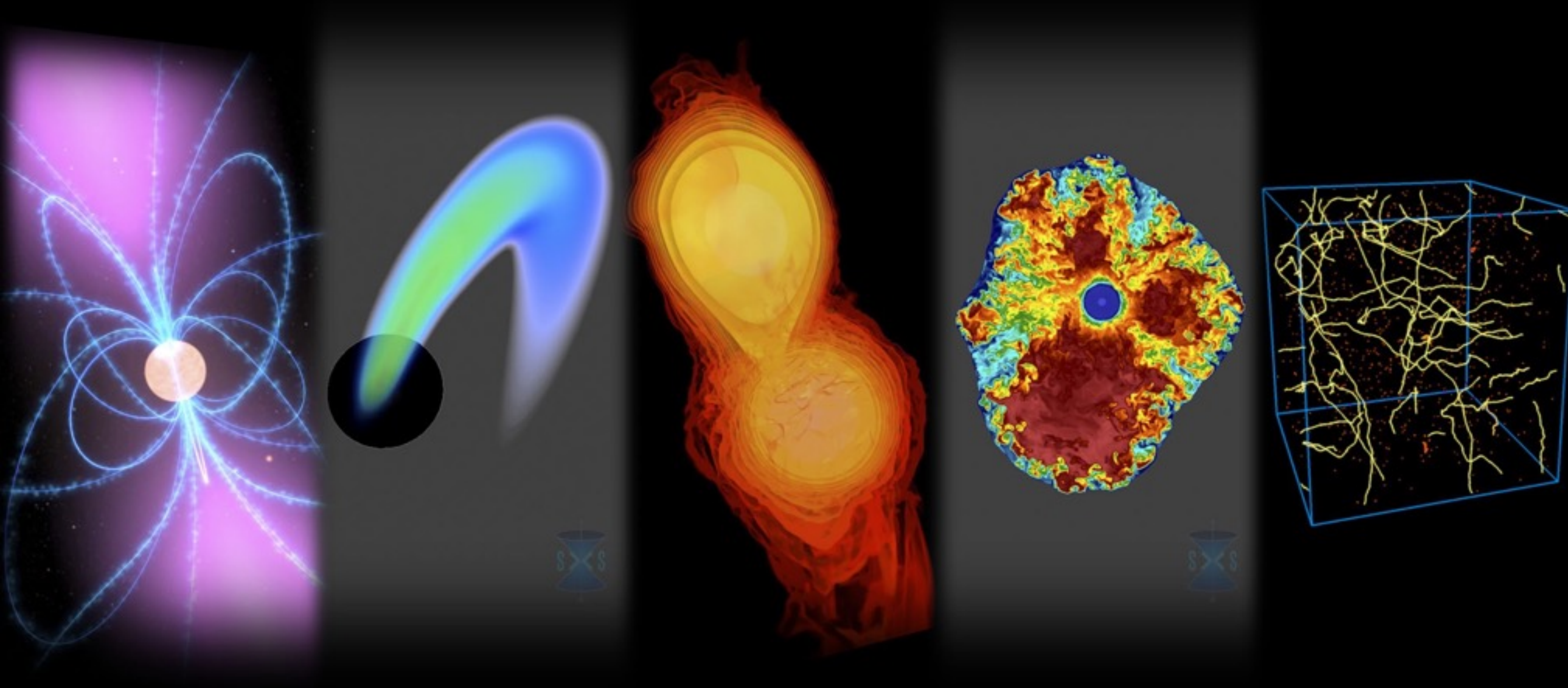


Image credit: LIGO/Virgo

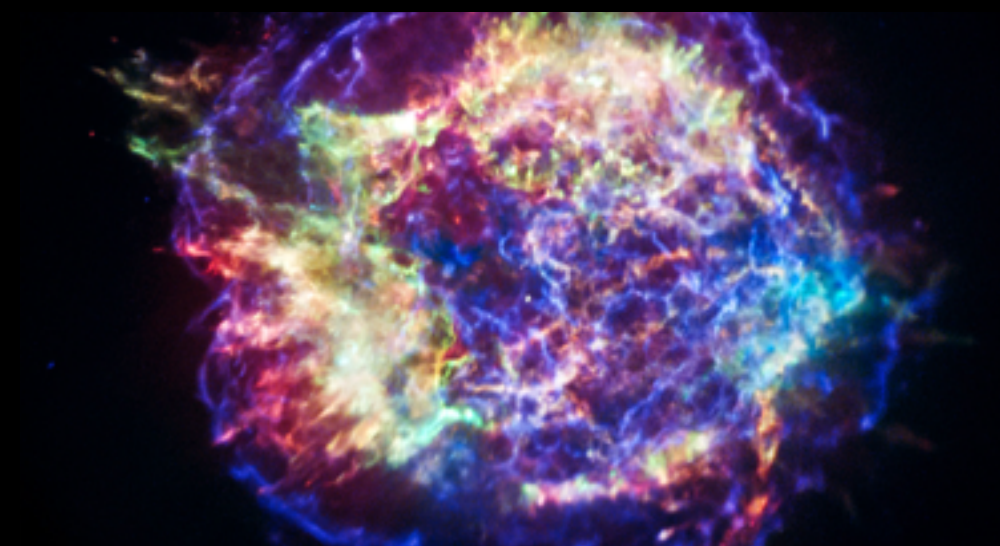
Gravitational-wave sources

Modelled | Unmodelled

Transient

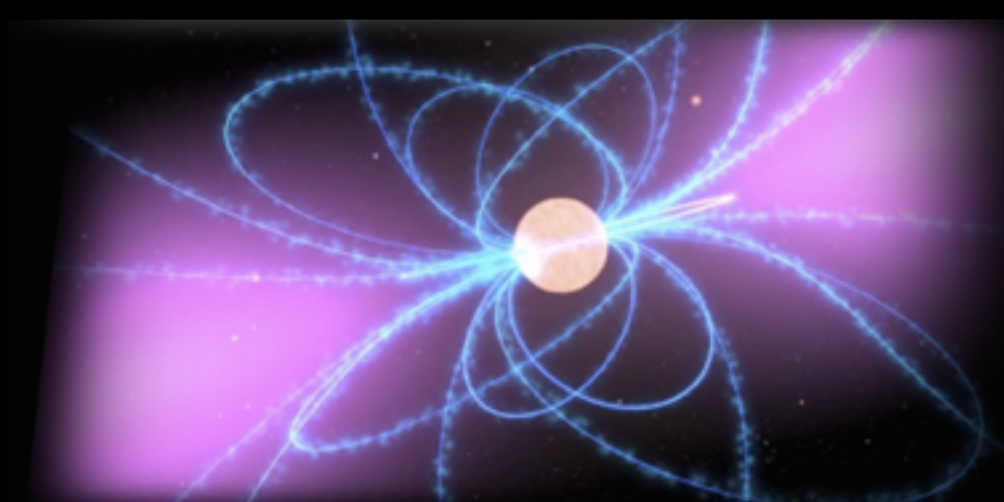
Compact Binary Coalescence

Burst



Continuous

Continuous waves



Stochastic

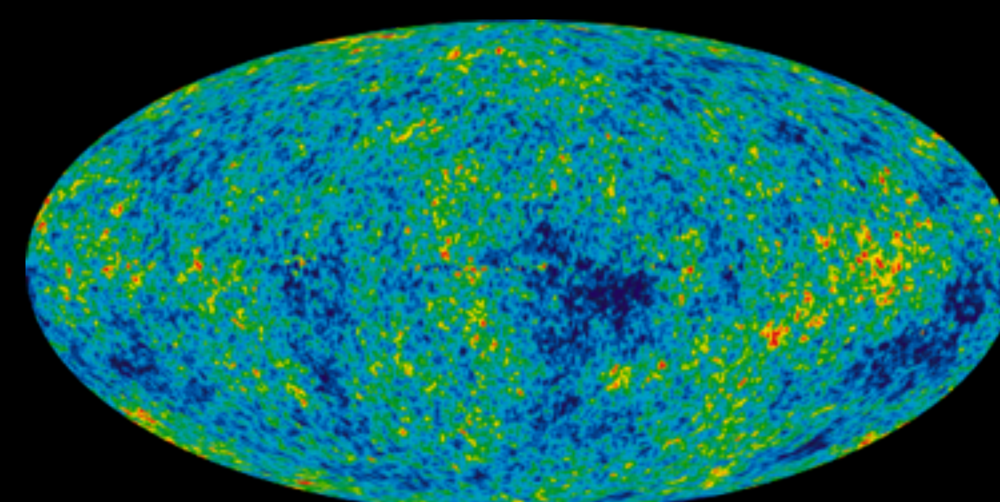
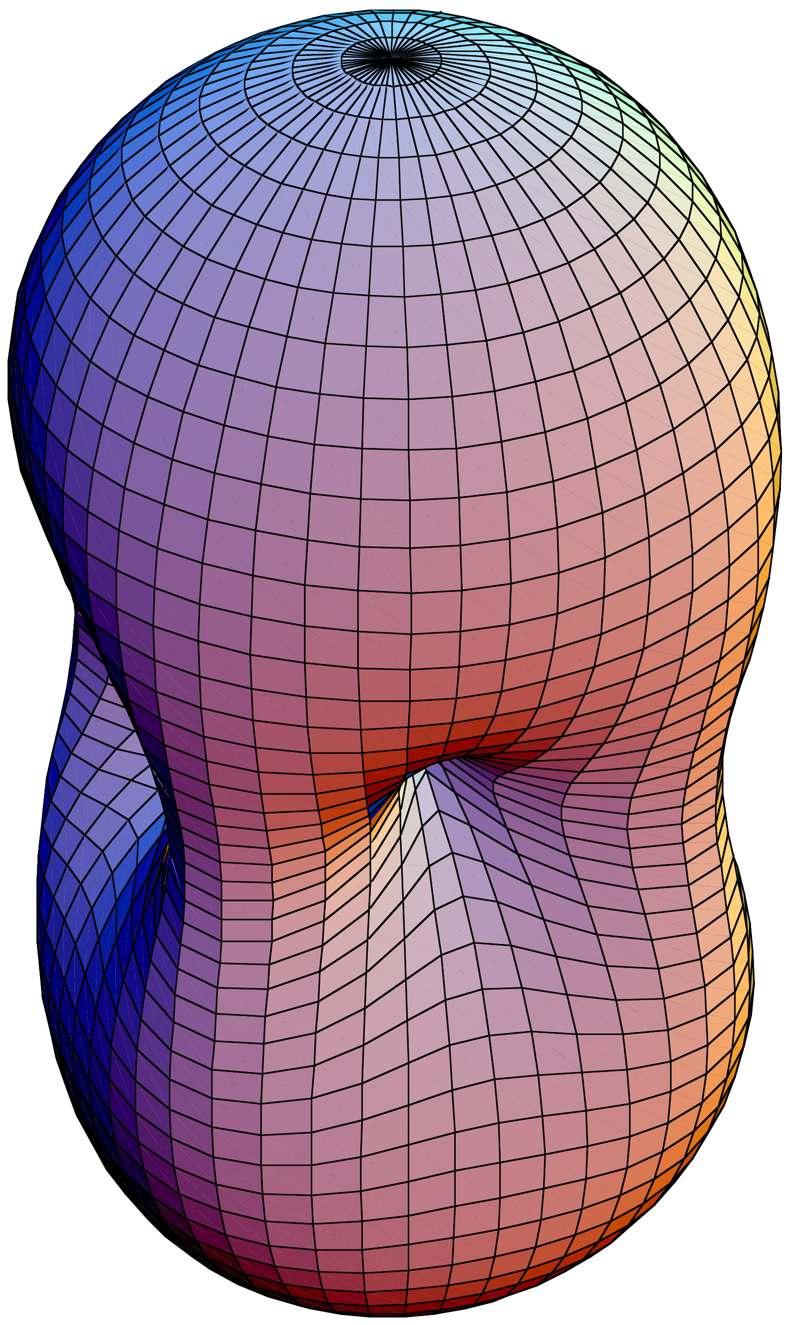


Image credit: SXS, NASA/CXC/SAO, LIGO/Virgo, NASA/WMAP Science Team

Unmodelled approaches

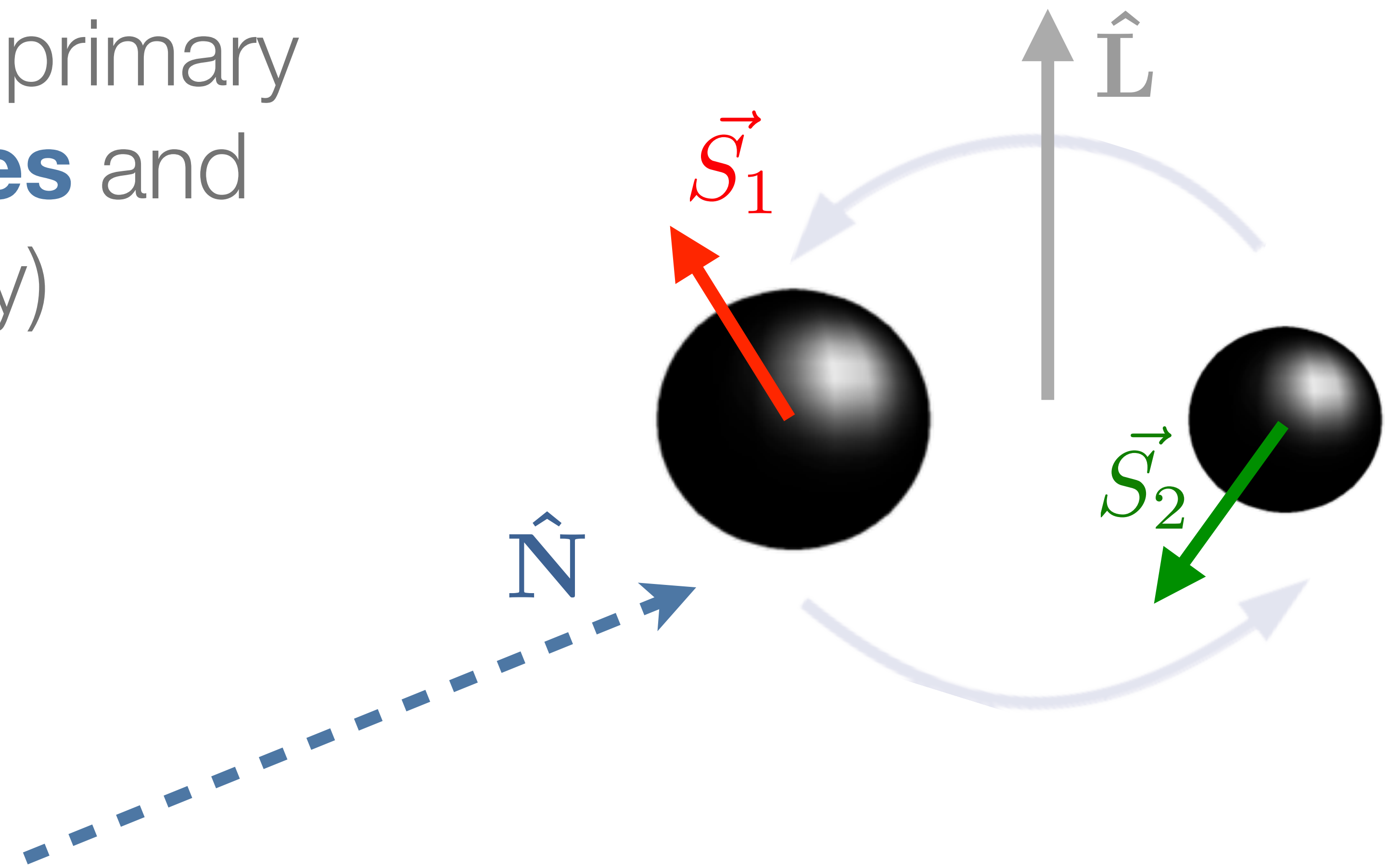
- Find periods of **excess power**
- **Coherence** between detectors
    - Detector response (depends on **sky-position** and **polarization**)
    - Light travel time between detectors

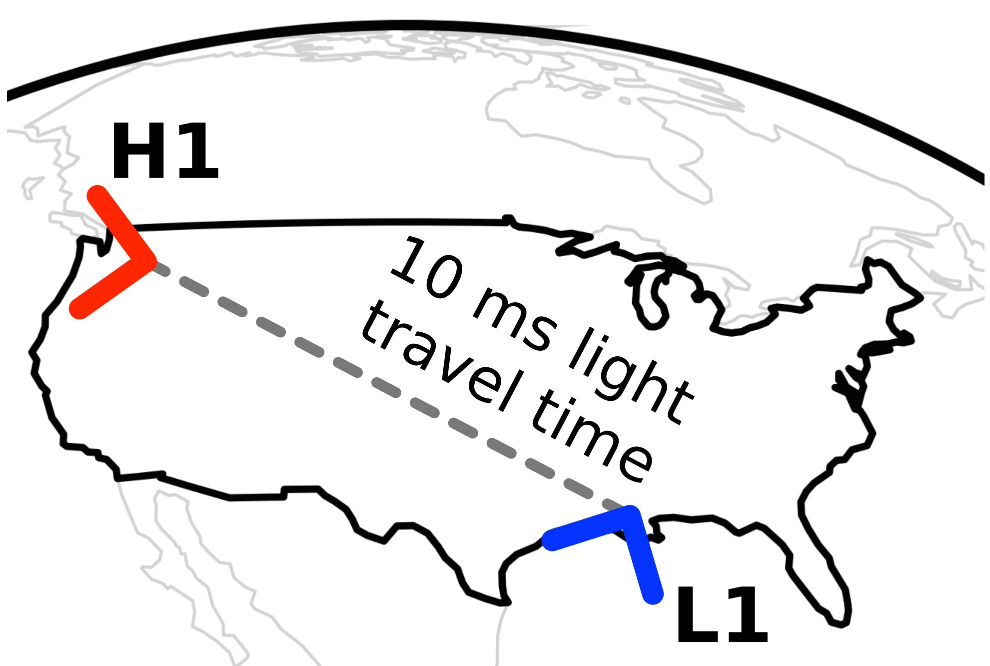


Detector antenna pattern

Compact Binary Coalescence

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

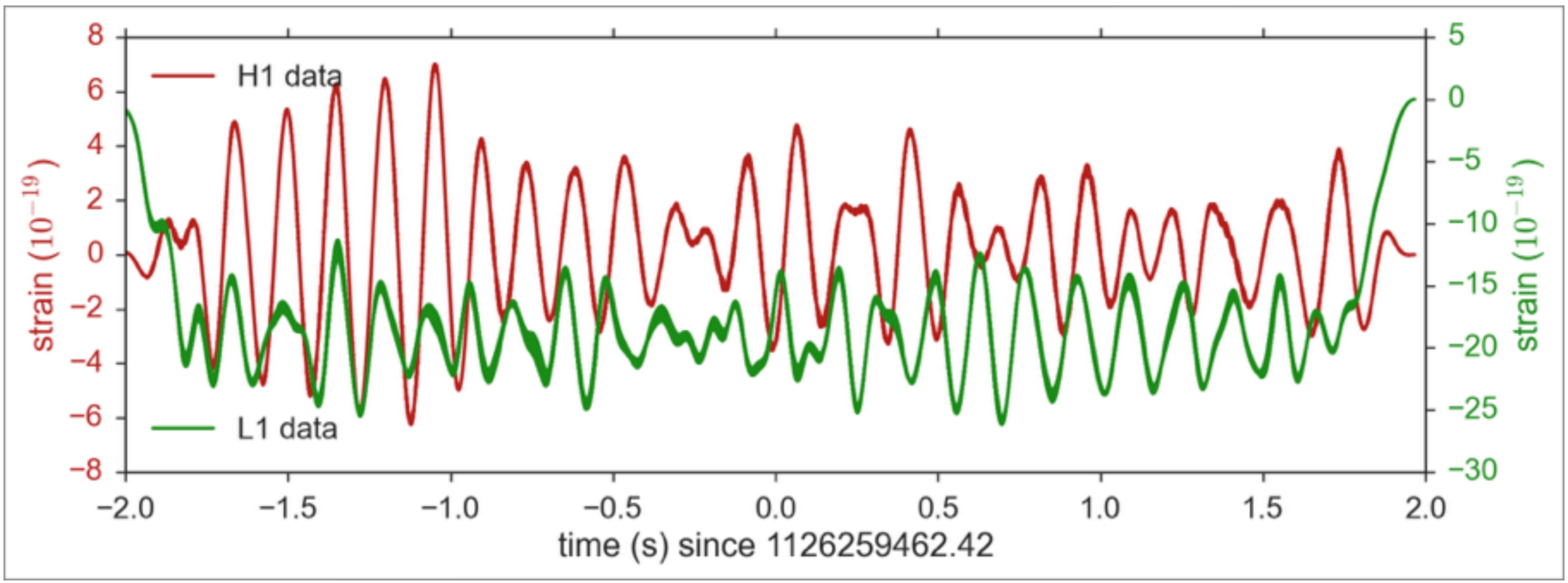




- **Extrinsic**: time, **sky-position**, distance, **orientation**, reference phase

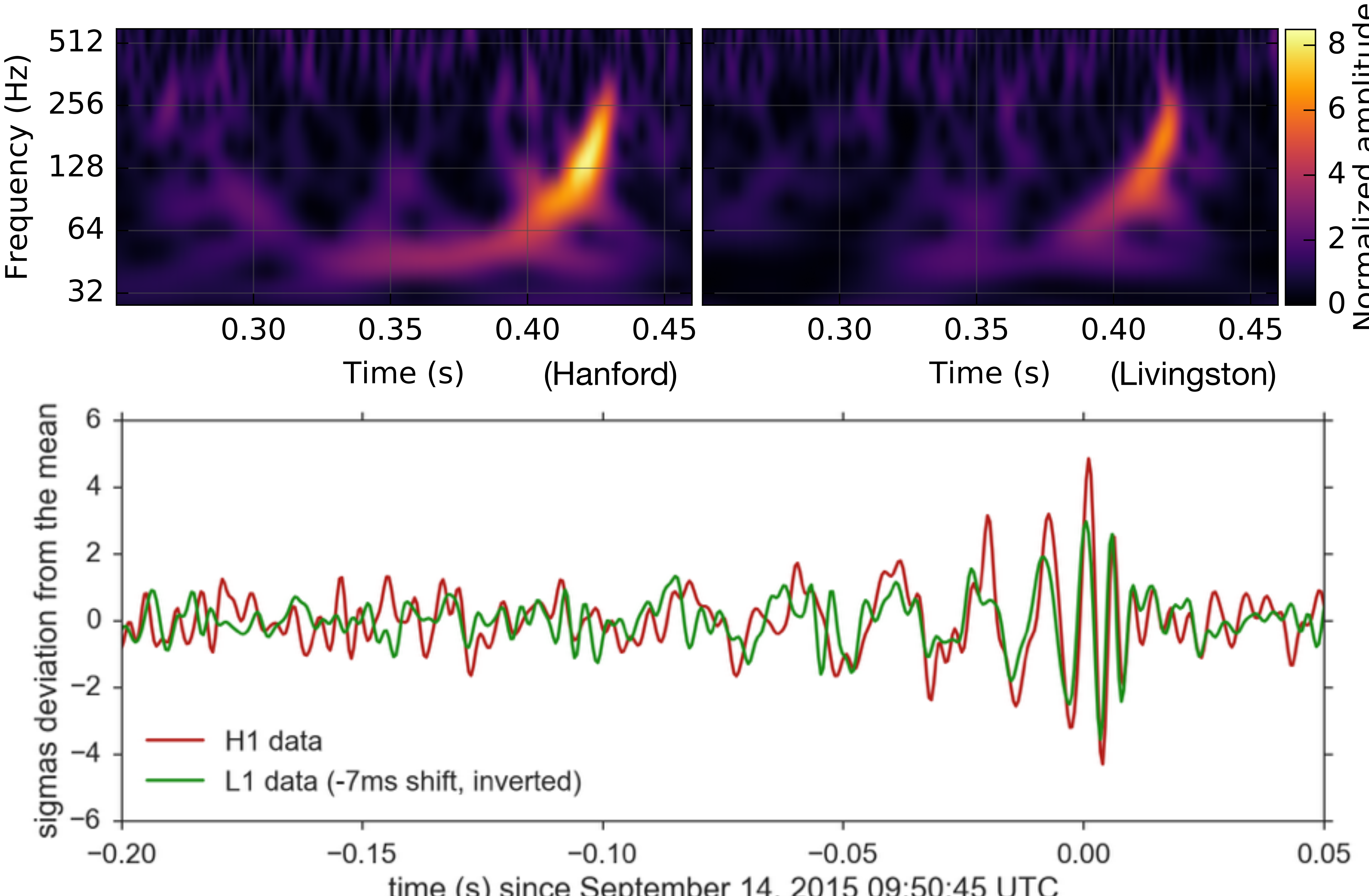
GW150914 strain data

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



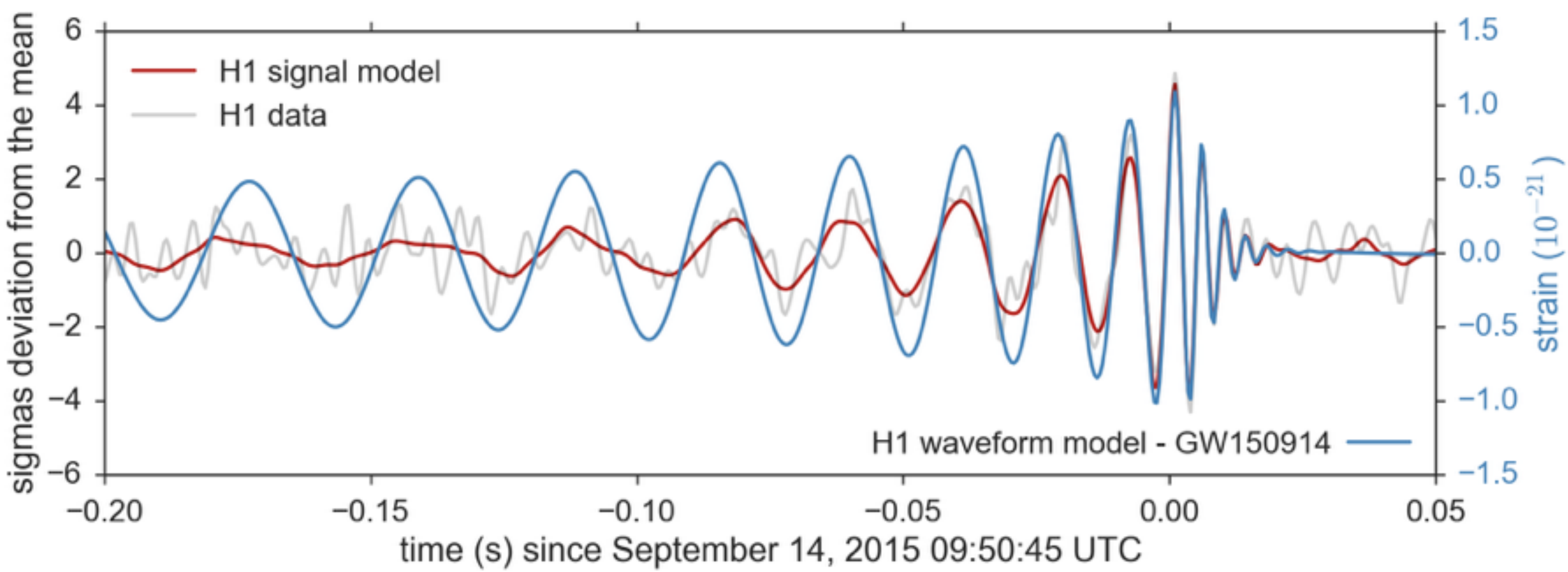
[adapted from the LIGO Open Science Center]

GW150914 observation



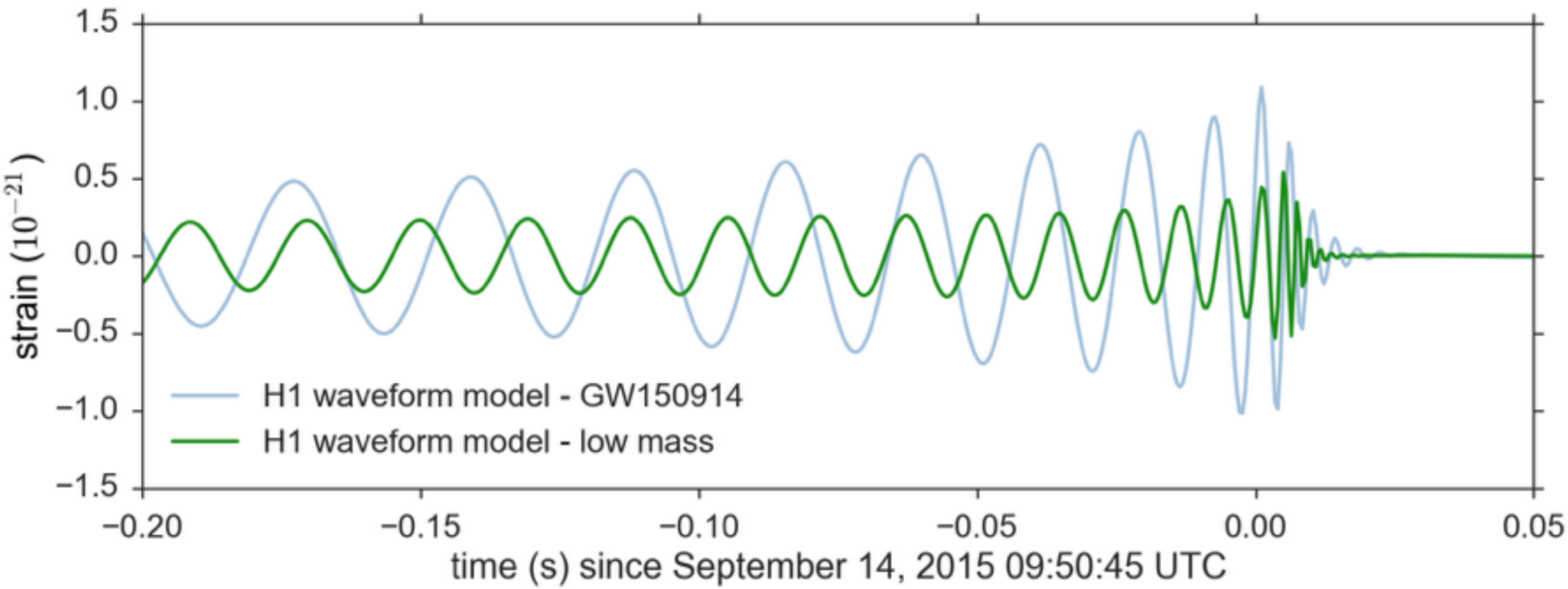
Gravitational waveform models

- **Modelled** versus **Unmodelled** approach

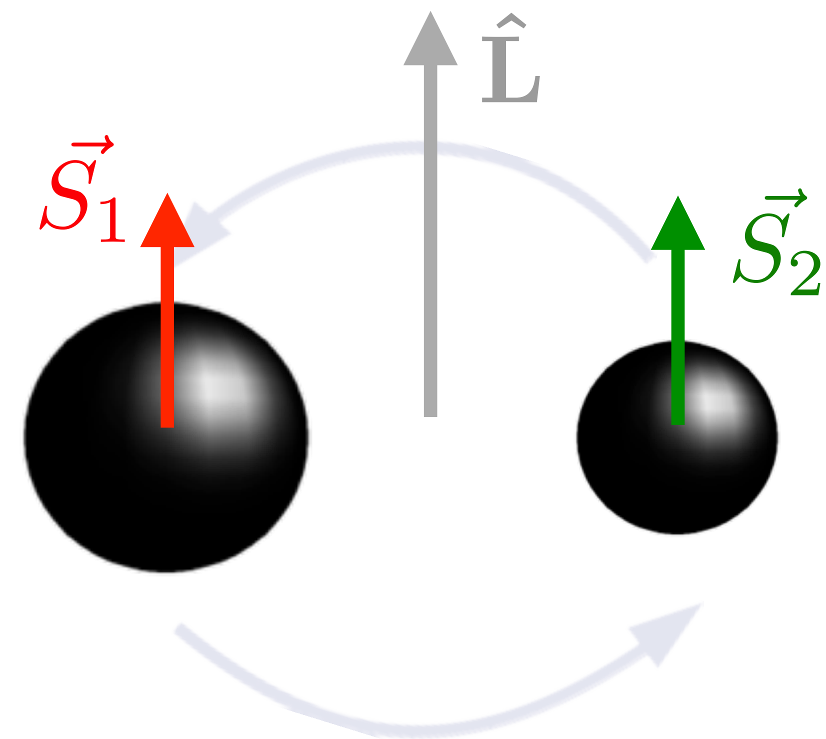


Masses from the inspiral and ringdown

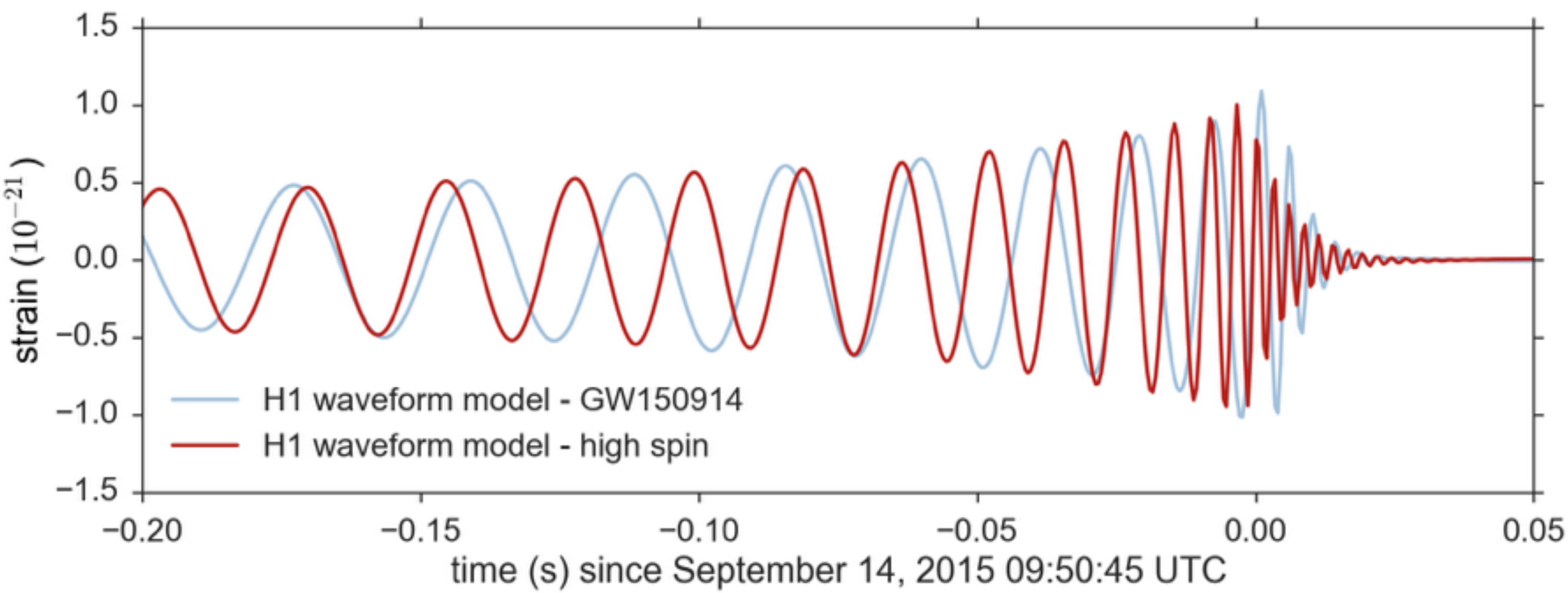
- Chirp mass: $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$
- Mass ratio: $q = \frac{m_1}{m_2}$
- Total mass: **ringdown**



Effects of spins



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



Effects of spins

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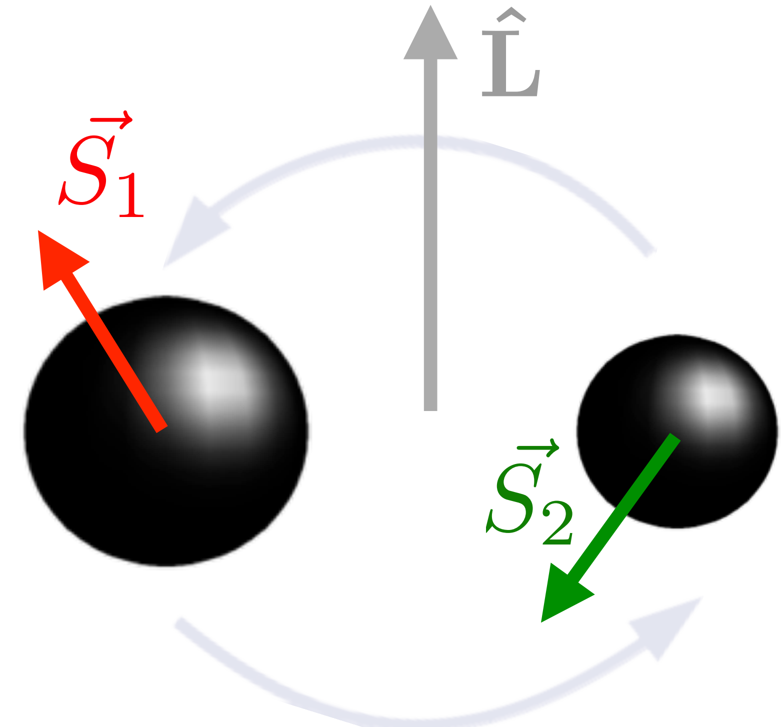
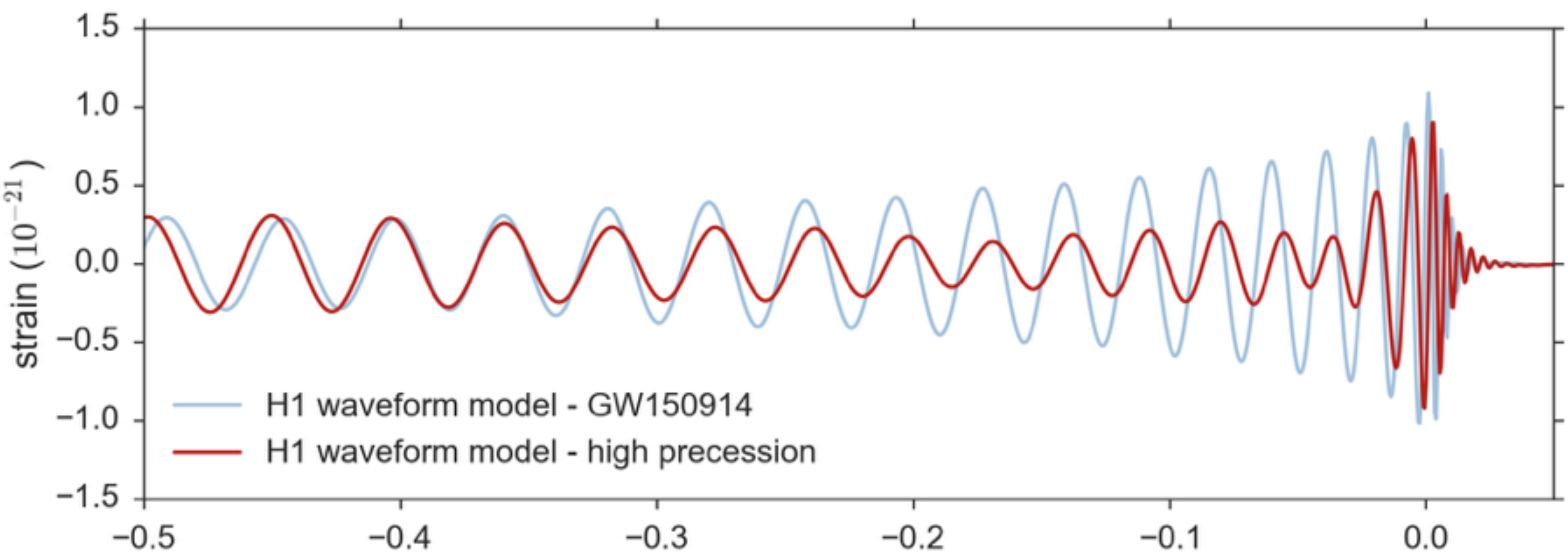
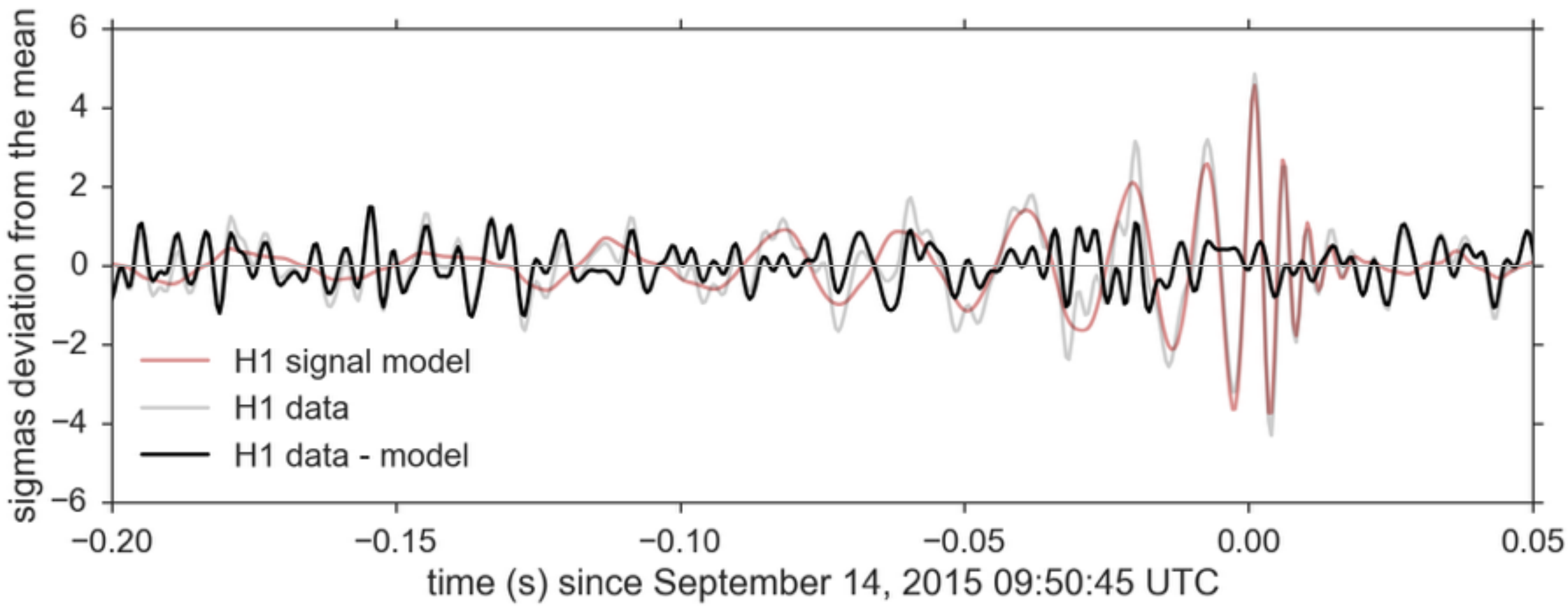




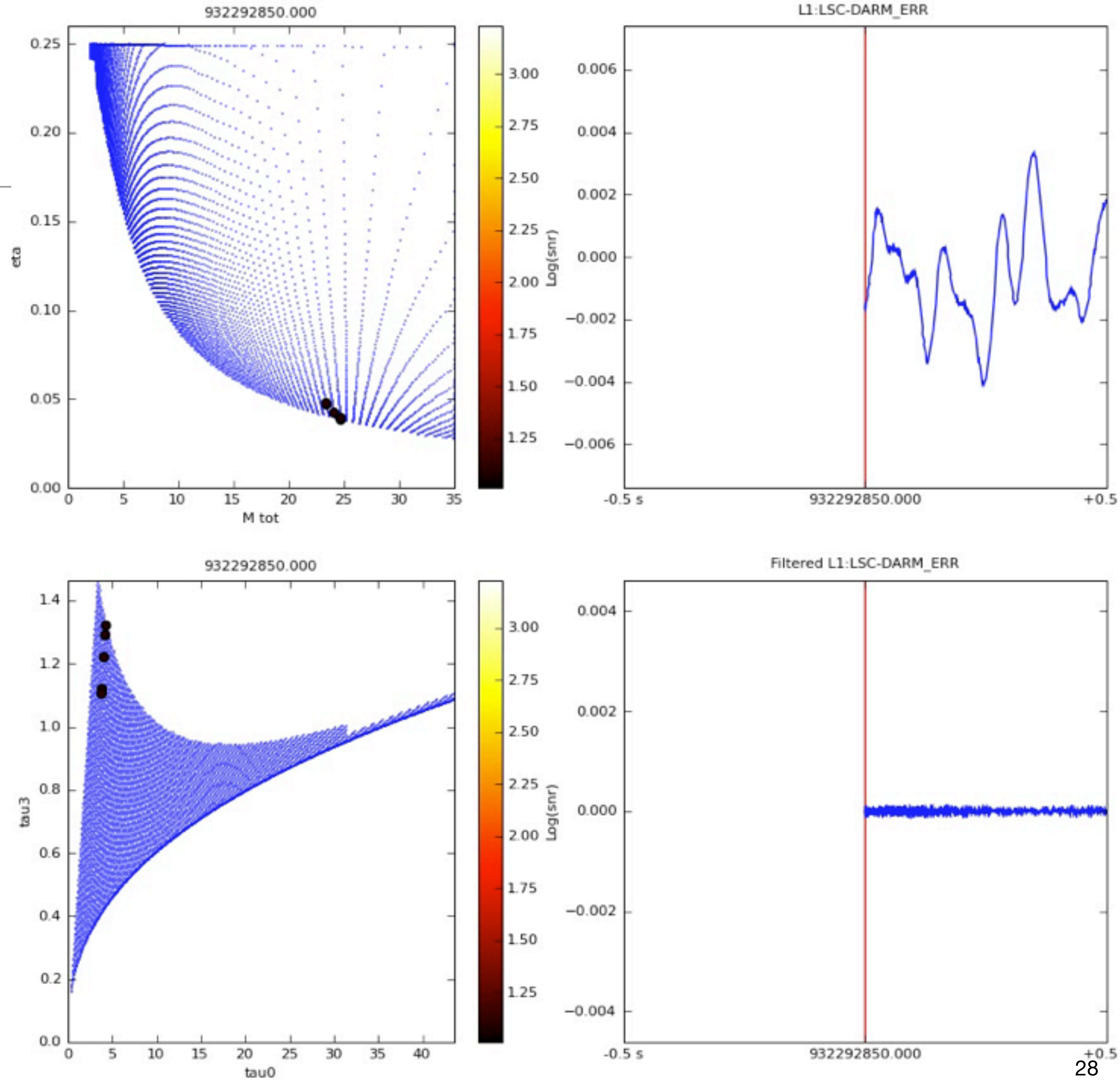
To find the signal: Likelihood



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

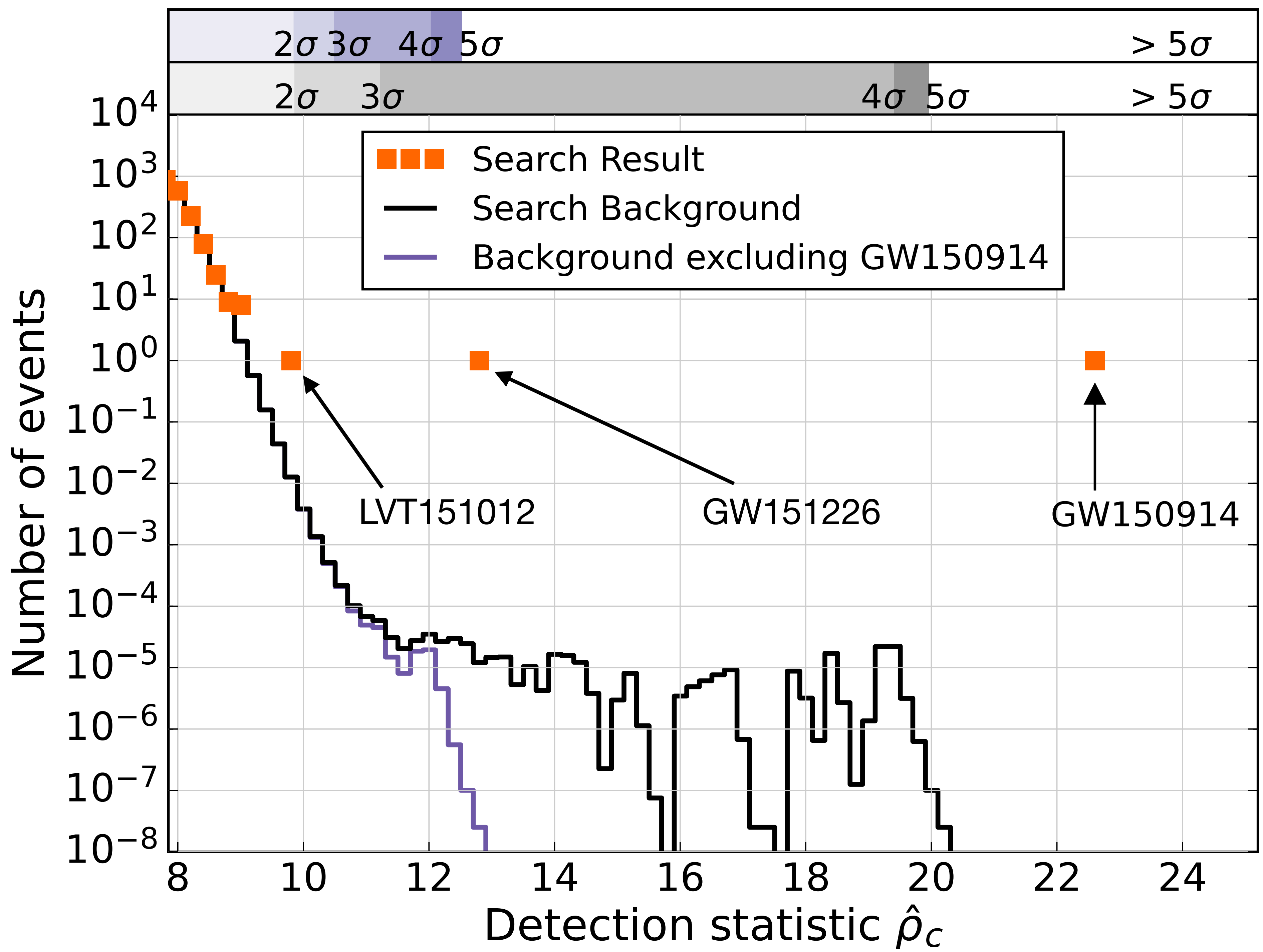
Templates

- Banks of waveform **templates**
- Matched filter (convolution)



[LIGO-Virgo Collaboration, 2009]

Background and time slides



[LIGO-Virgo Collaboration, 2016]

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)

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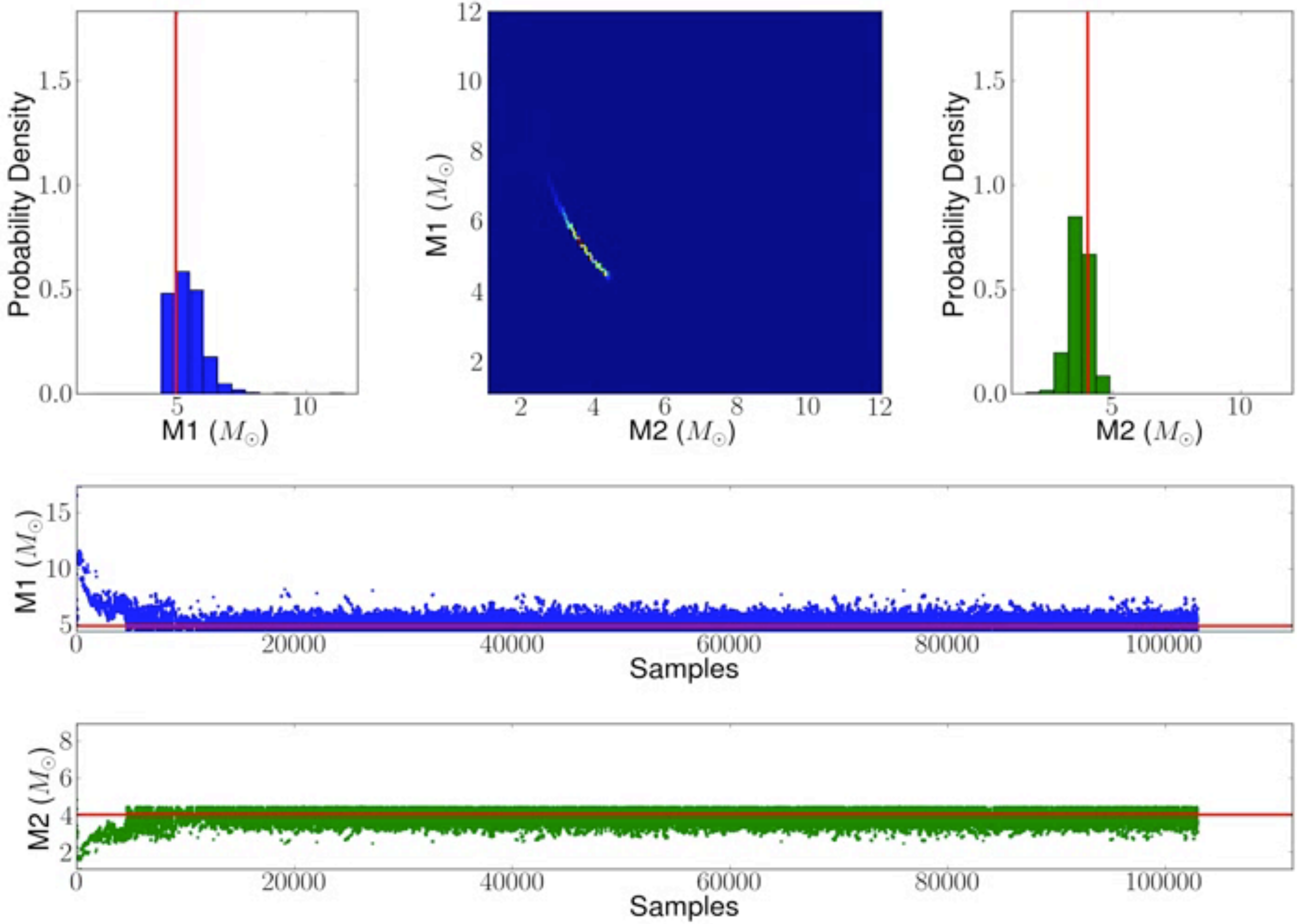
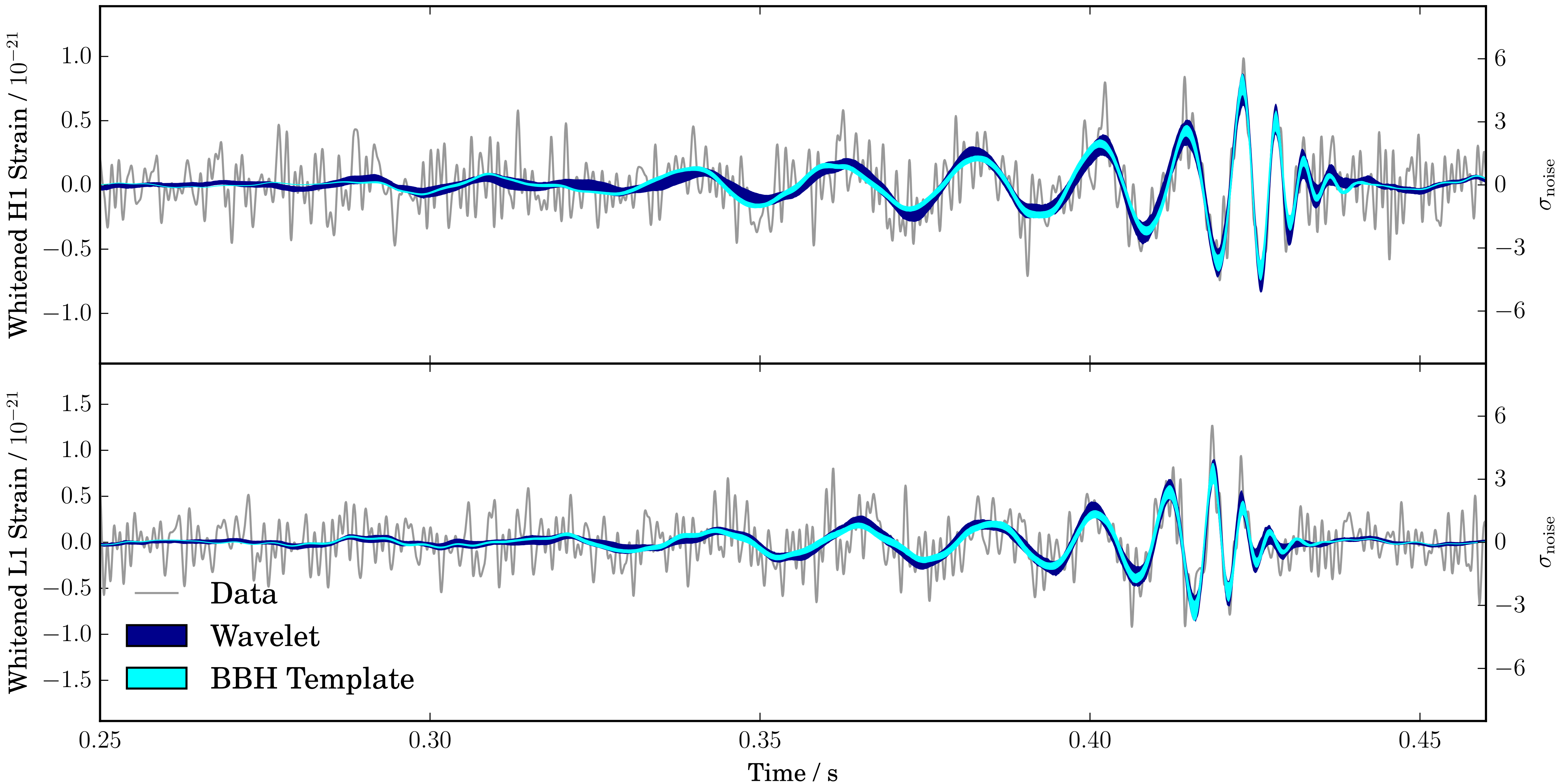


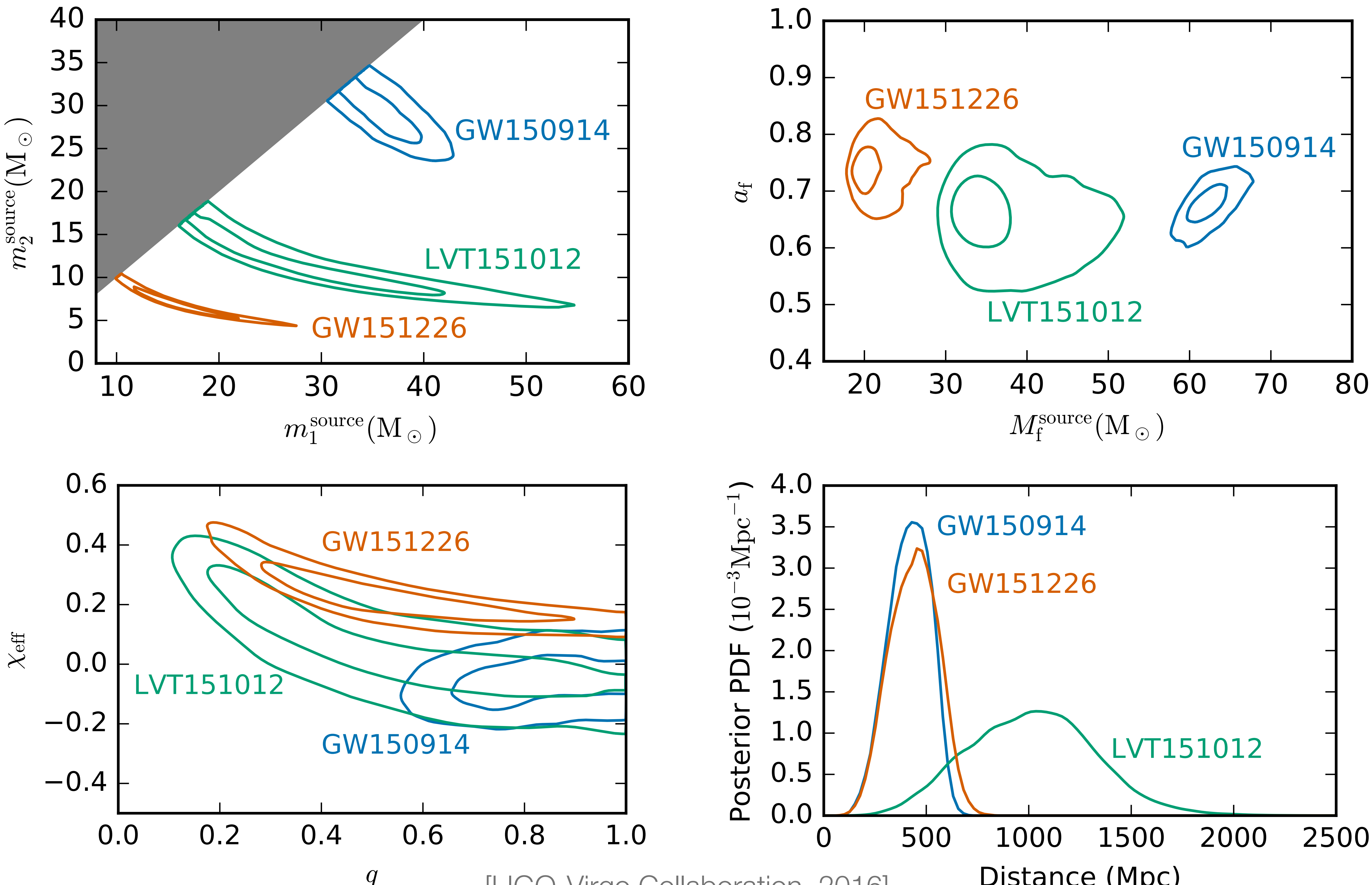
Probability Density
M1 ($M_\odot$)
M1 ($M_\odot$)
M2 ($M_\odot$)
Probability Density
M2 ($M_\odot$)
M1 ($M_\odot$)
Samples
M2 ($M_\odot$)
Samples

Modelled and unmodelled analyses



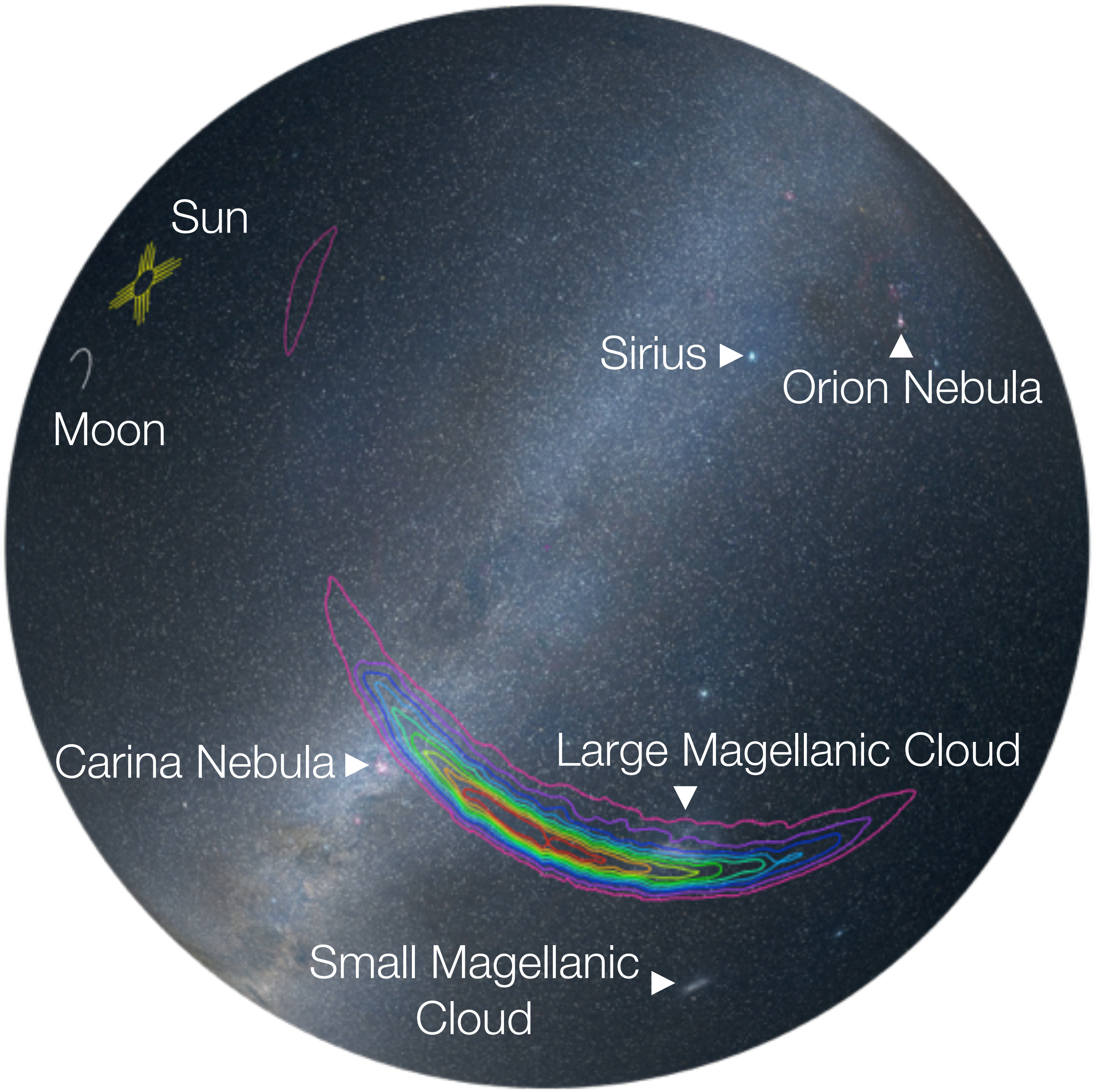
[LIGO-Virgo Collaboration, 2016]

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



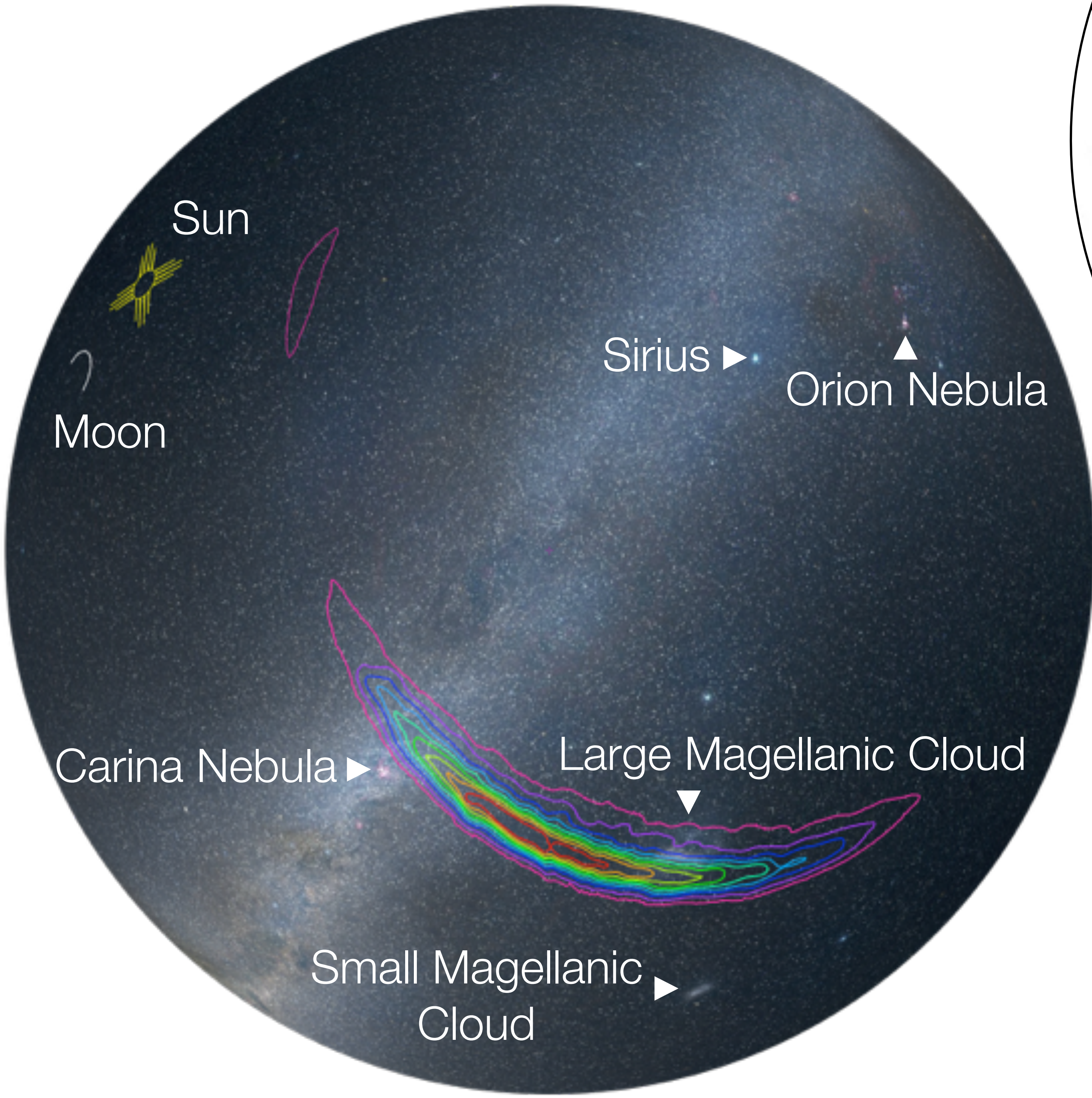
[LIGO-Virgo Collaboration, 2016]

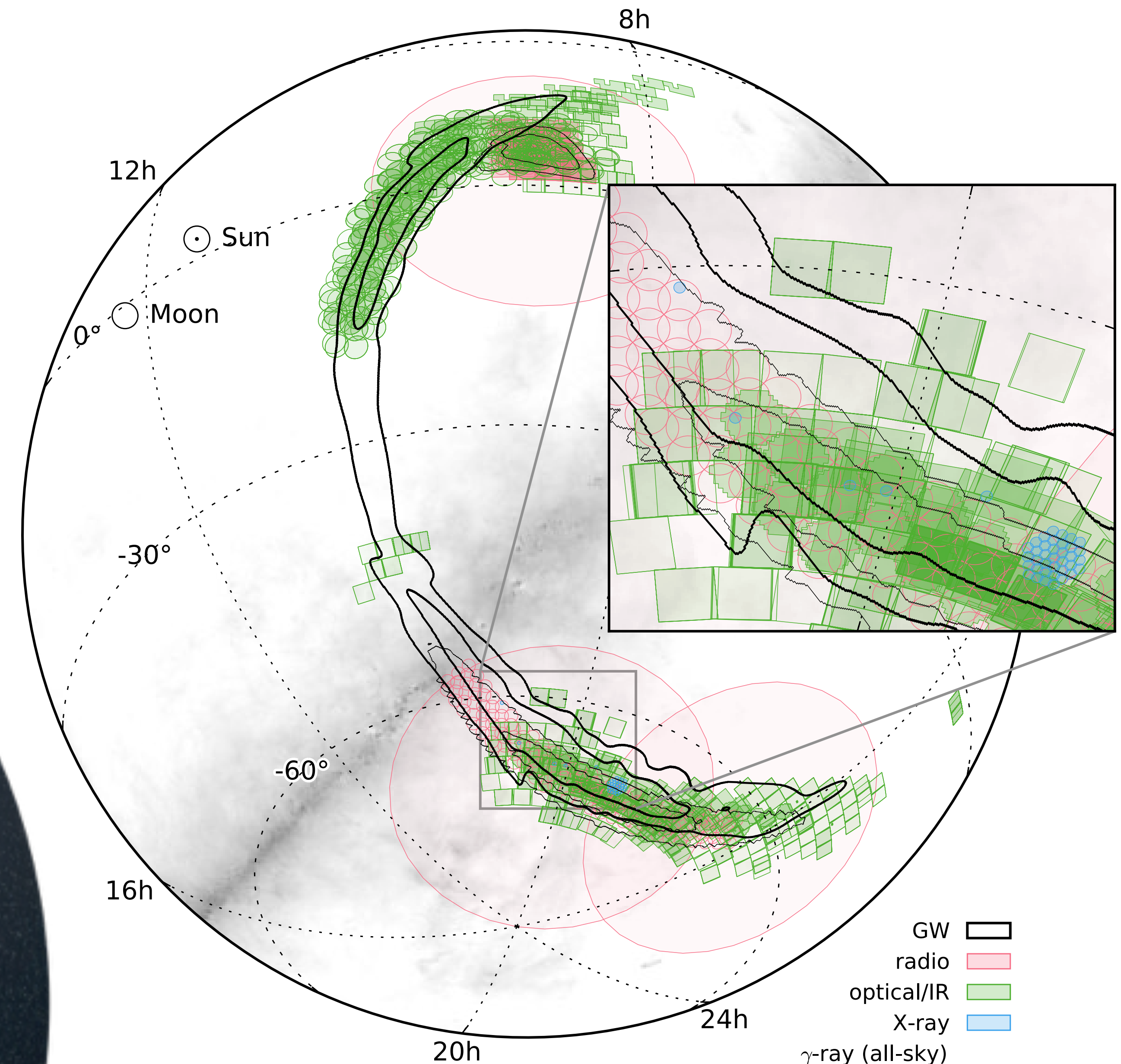
GW150914: location



[LIGO-Virgo Collaboration, 2016]

GW150914: location





[LIGO-Virgo Collaboration, 2016]

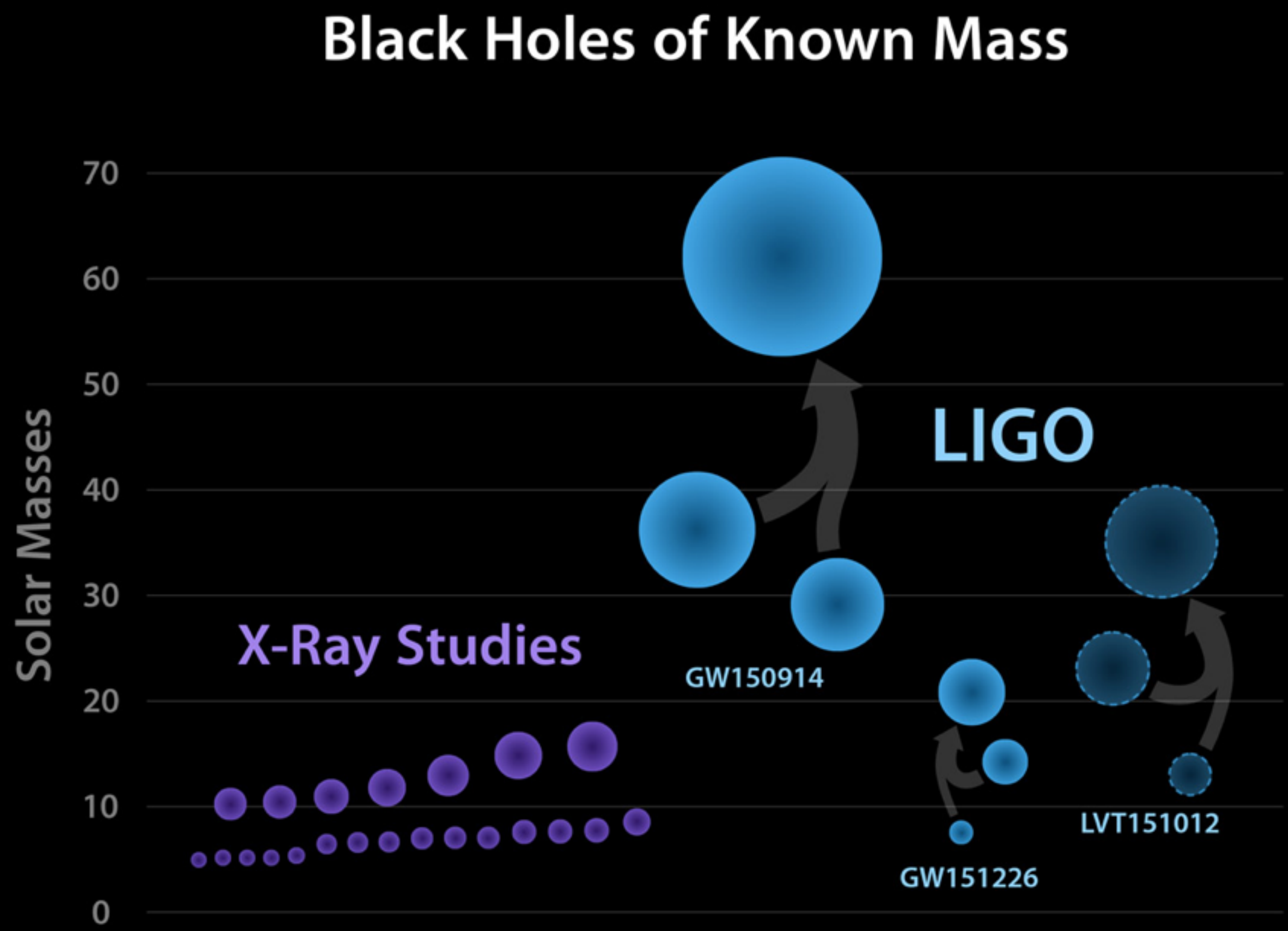


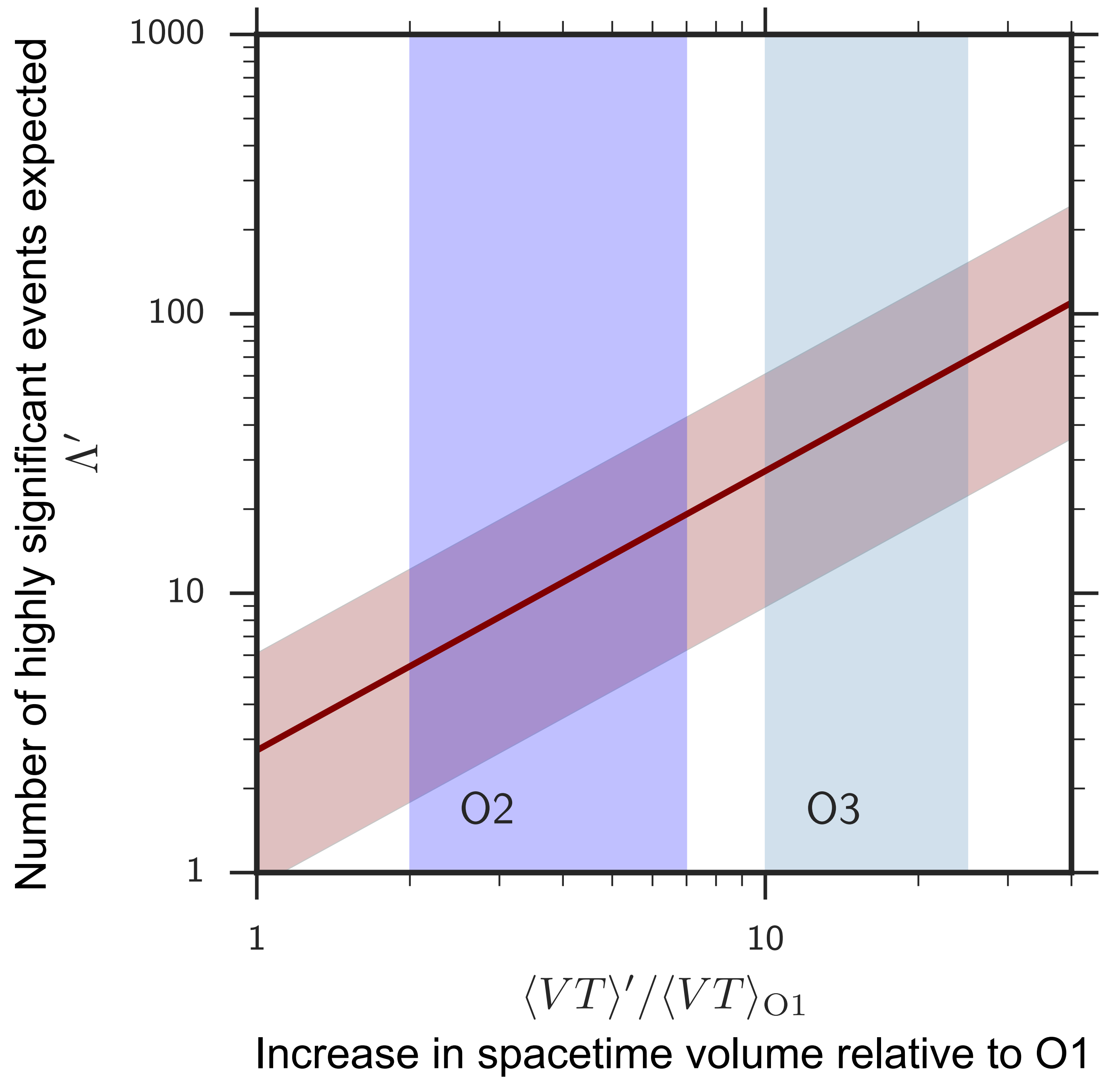
Image credit: LIGO/Virgo

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

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**

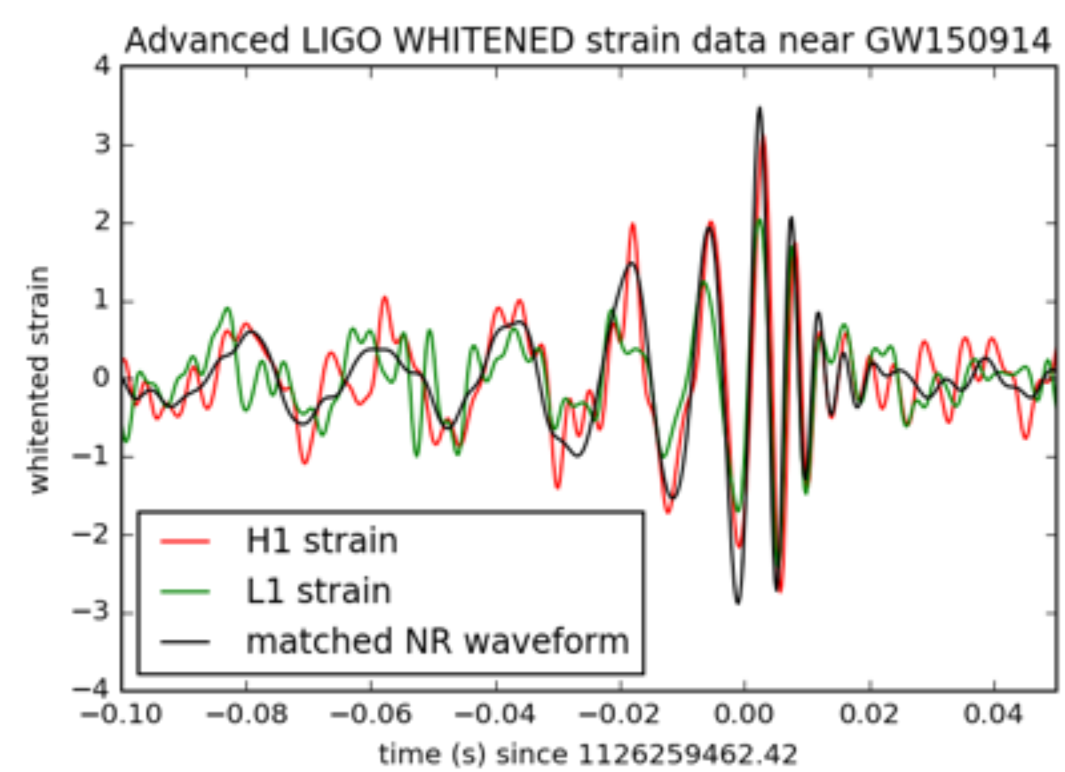


[LIGO-Virgo Collaboration, 2016]

Hands on session for GW data analysis

LIGO Open Science Center: https://losc.ligo.org/

- https://losc.ligo.org/s/events/GW150914/GW150914_tutorial.html
  - **python packages**: numpy, scipy, matplotlib, h5py
  - **download** the data



SIGNAL PROCESSING WITH GW150914 OPEN DATA

Welcome! This ipython notebook (or associated python script GW150914_tutorial.py) will go through some typical signal processing tasks on strain time-series data associated with the LIGO GW150914 data release from the LIGO Open Science Center (LOSC):

- https://losc.ligo.org/events/GW150914/ (https://losc.ligo.org/events/GW150914/)
- View the tutorial as a web page - https://losc.ligo.org/s/events/GW150914/GW150914_tutorial.html (https://losc.ligo.org/s/events/GW150914/GW150914_tutorial.html)
- Download the tutorial as a python script - https://losc.ligo.org/s/events/GW150914/GW150914_tutorial.py (https://losc.ligo.org/s/events/GW150914/GW150914_tutorial.py)
- Download the tutorial as iPython Notebook - https://losc.ligo.org/s/events/GW150914/GW150914_tutorial.ipynb (https://losc.ligo.org/s/events/GW150914/GW150914_tutorial.ipynb)