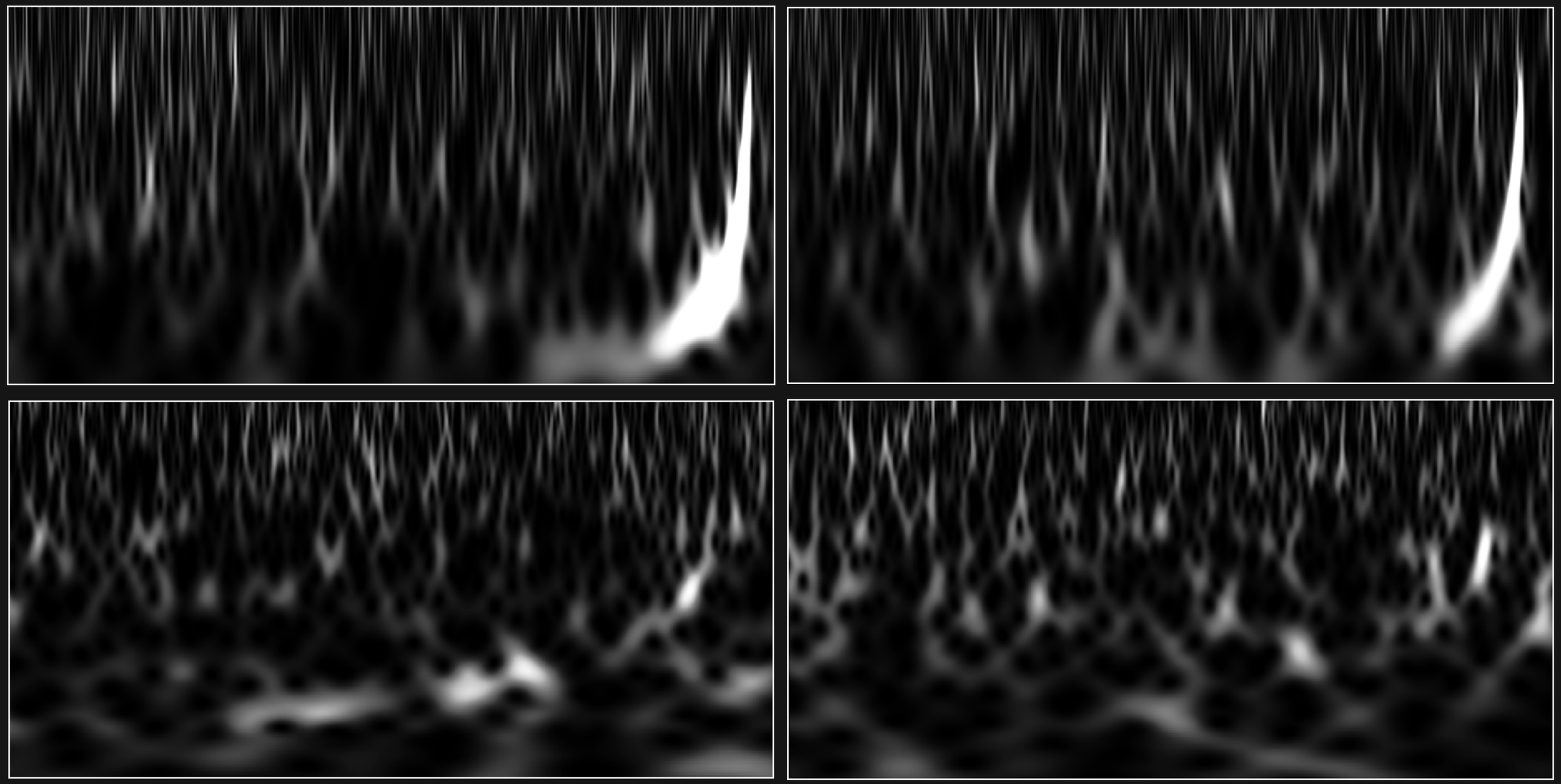
The First Four Months of Gravitational Wave Astronomy



Ben Farr

THE UNIVERSITY OF CHICAGO

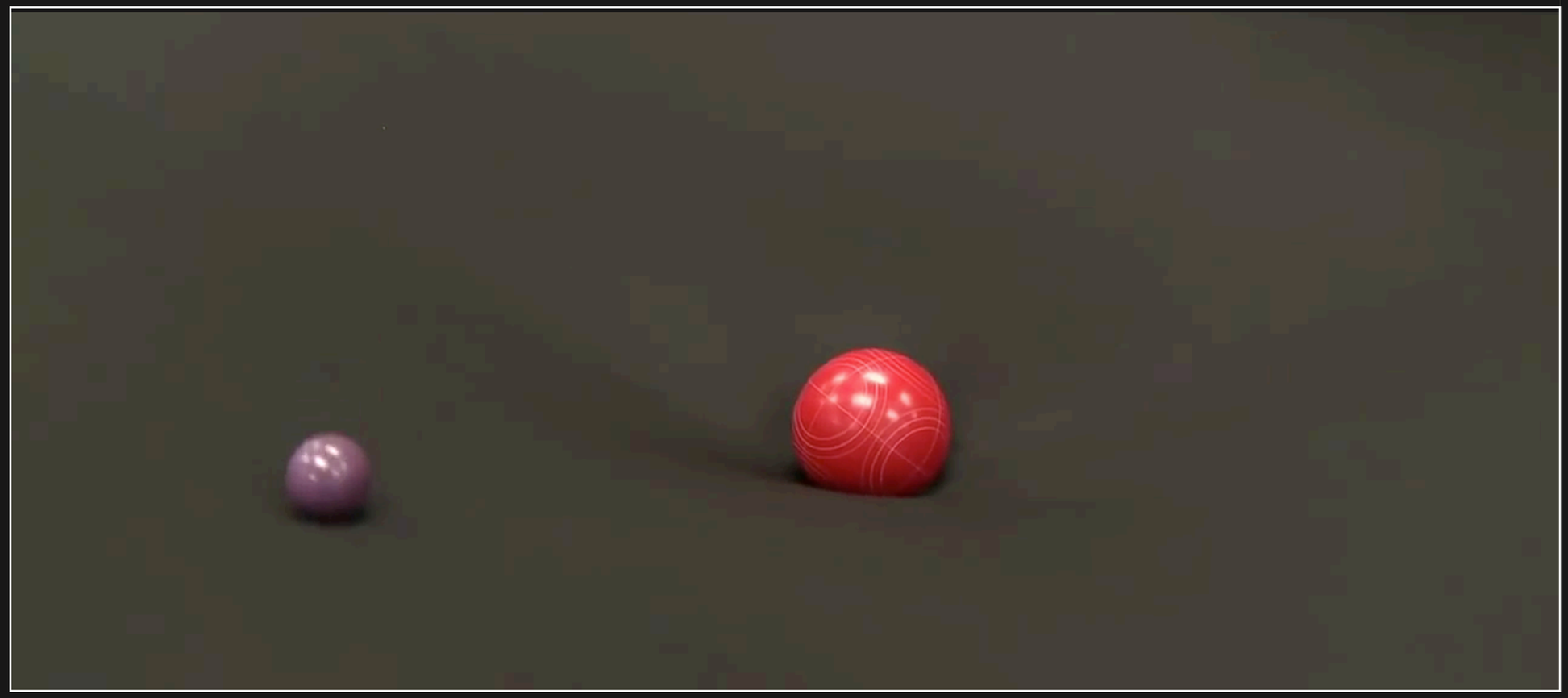
Outline

I. Gravitational wave primer

II. Compact binary detection and characterization methods

III. Results from LIGO's first observing run

General Relativity



"Spacetime tells matter how to move;
matter tells spacetime how to curve."

— John Wheeler

Gravitational Waves

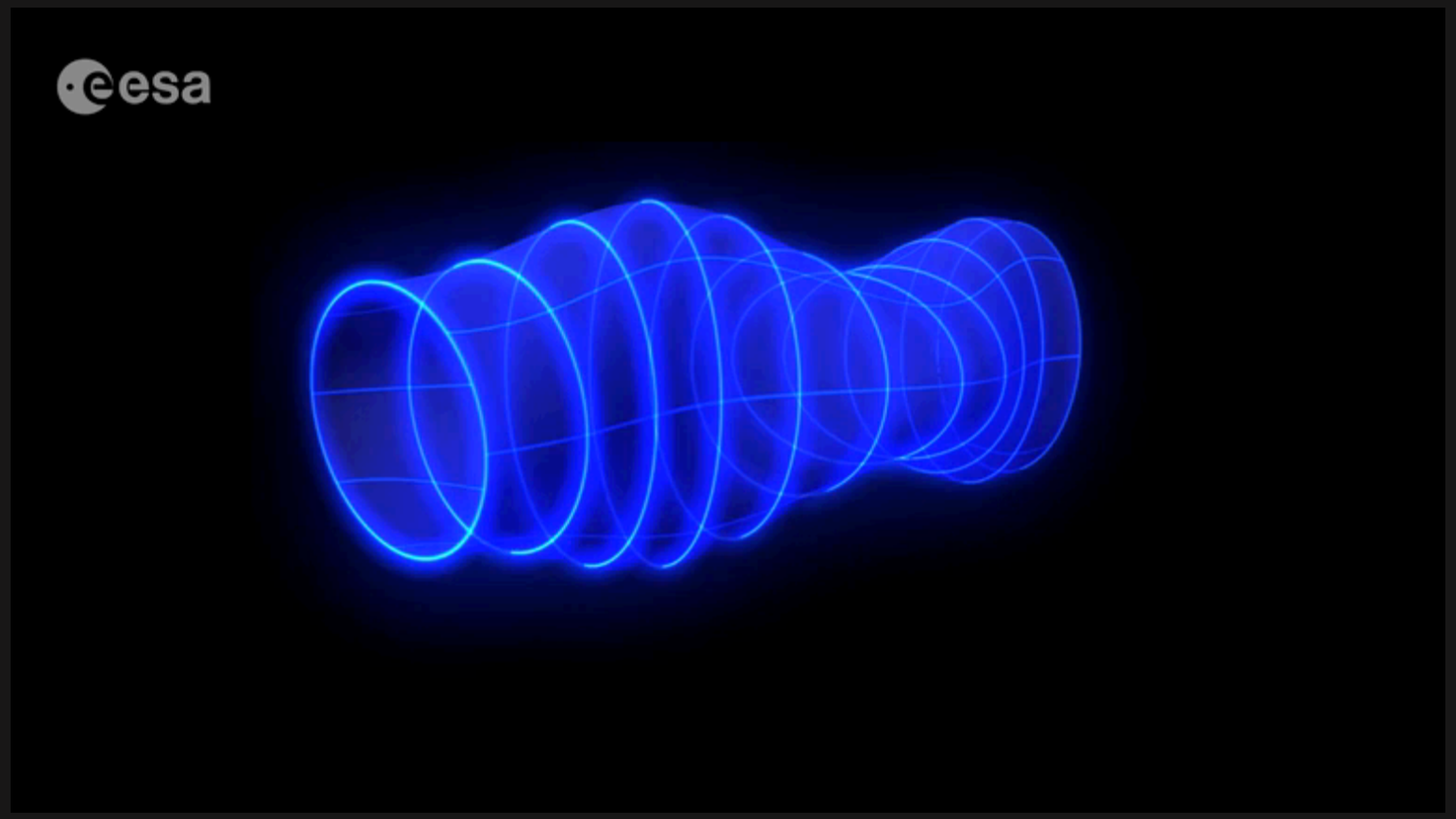
$$h_{\mu\nu} = \frac{2G}{rc^4}\ddot{I}_{\mu\nu}(\omega, t)$$

Strain on spacetime.

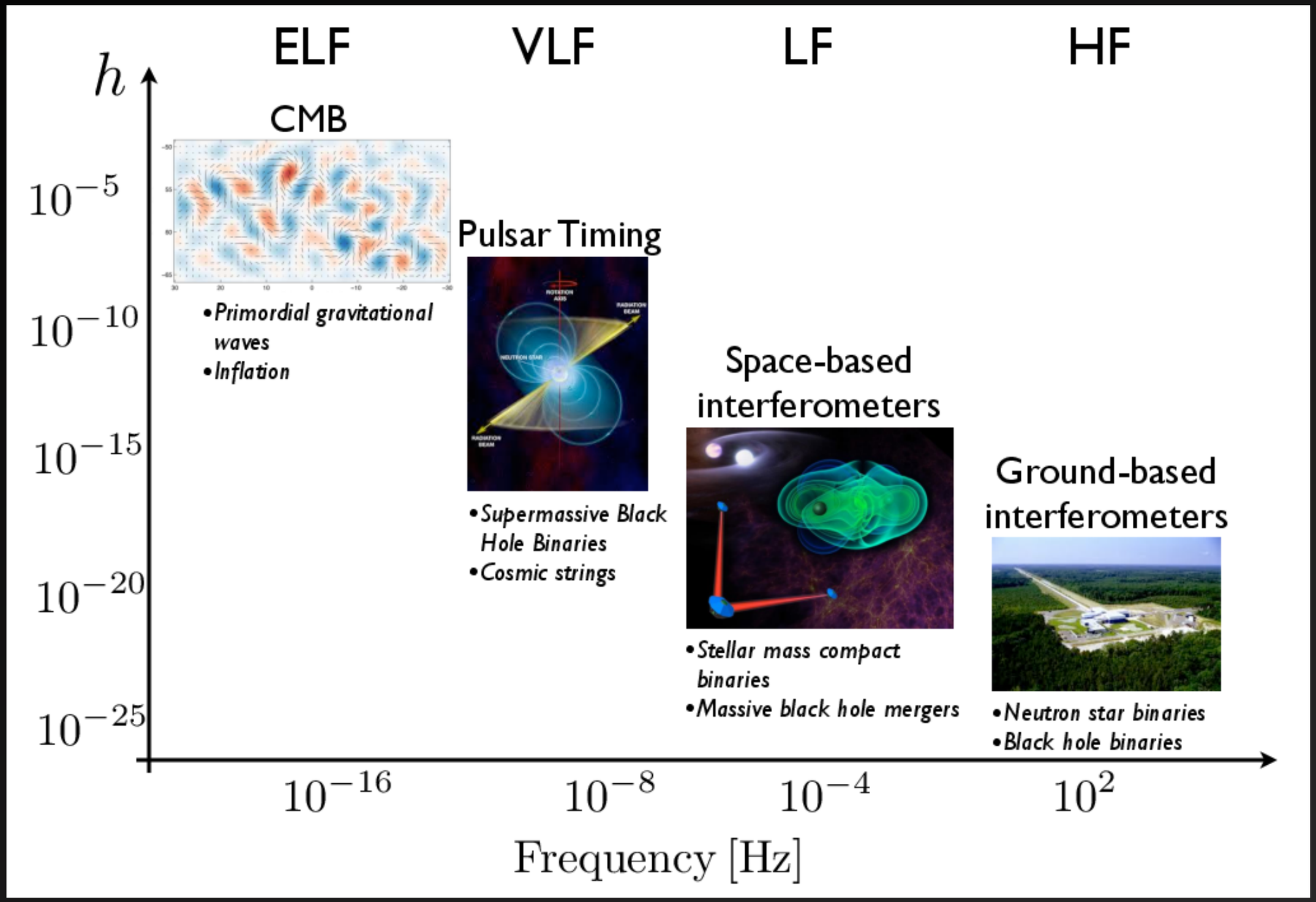
Generated by time-varying quadrupole moment.

Propagate at speed of light.

Unimpeded by matter.



The GW Spectrum

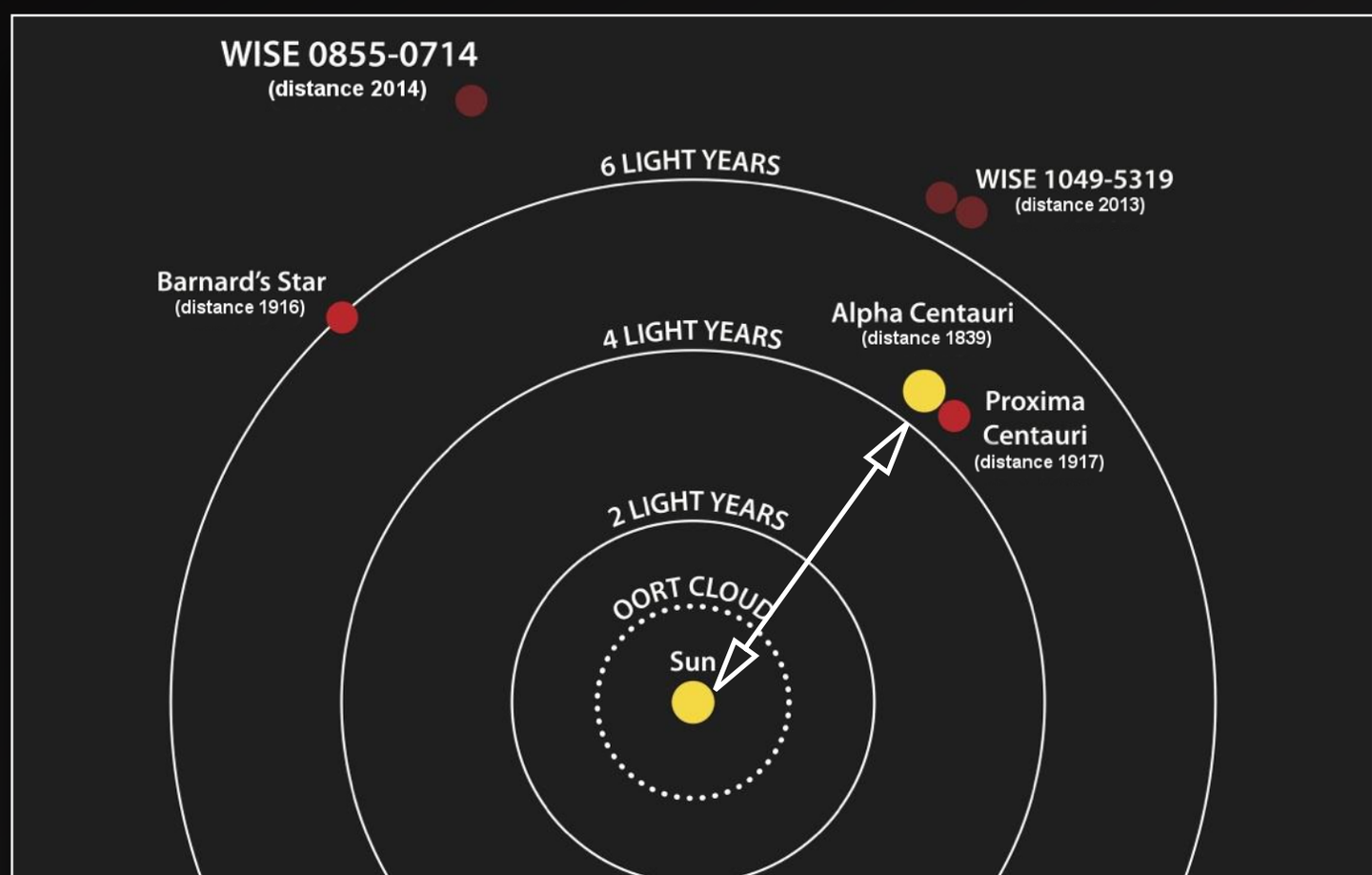


Credit: NANOGrav

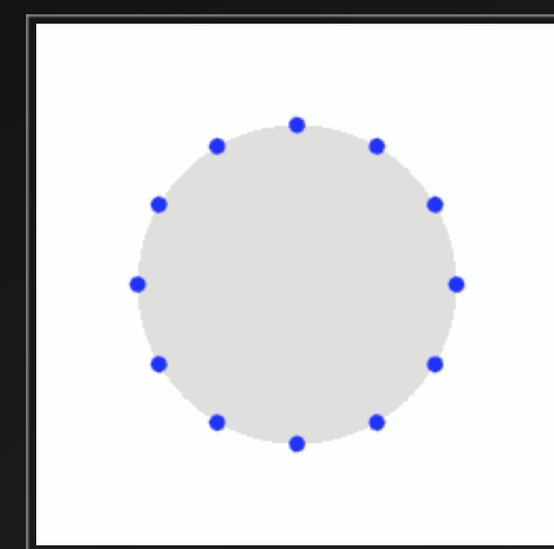
Detecting Gravitational Waves

Waves stretch and squeeze spacetime as they pass.

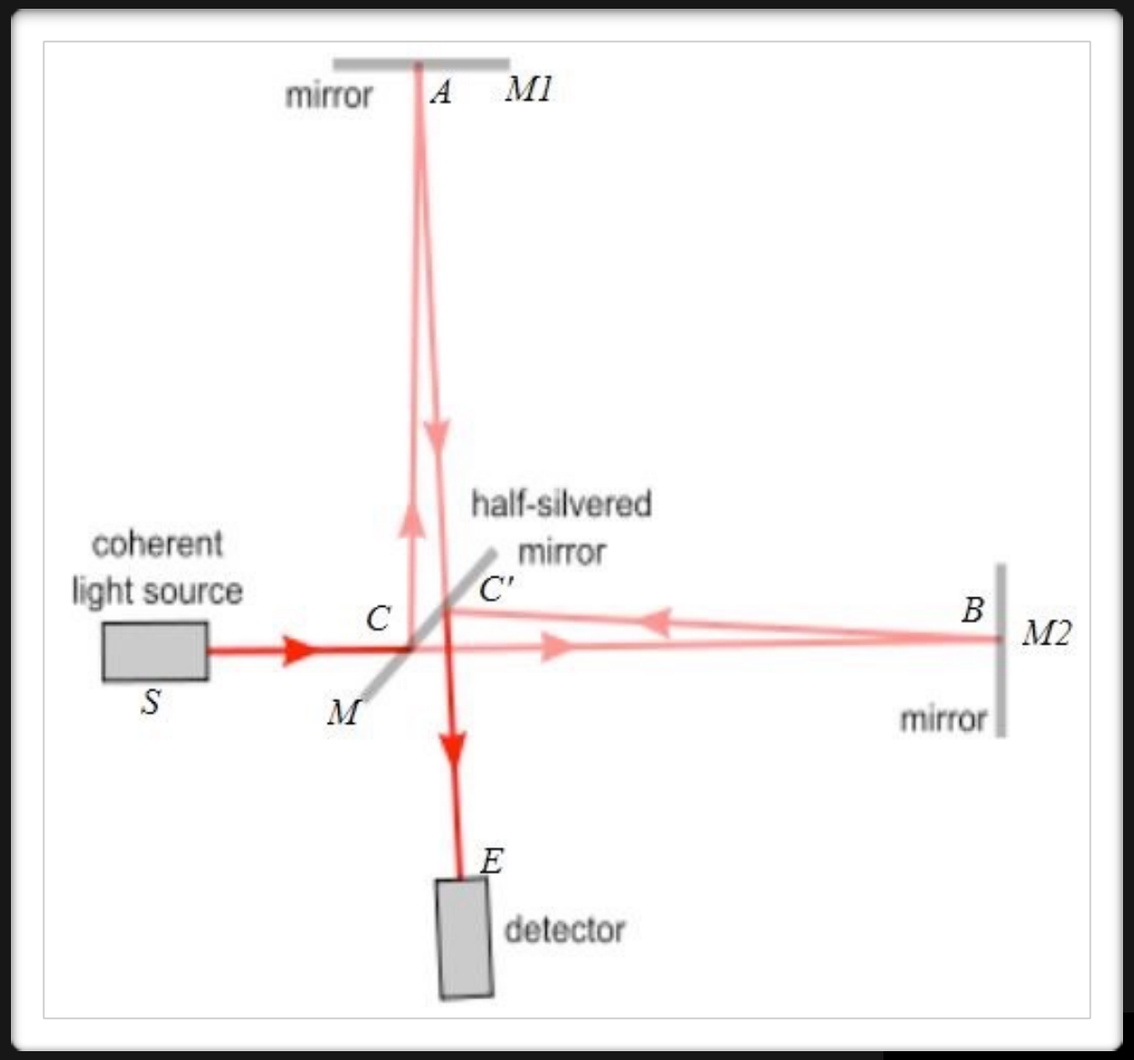
Typical strains ($\Delta l / l$) ~ 10^{-21}

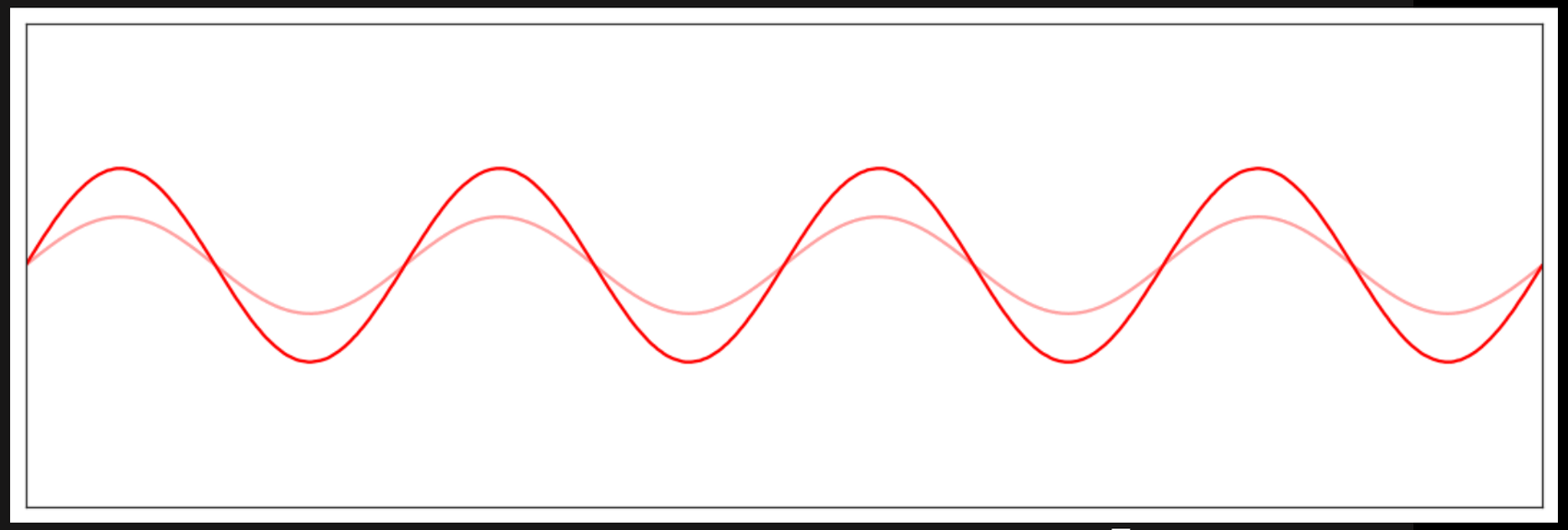


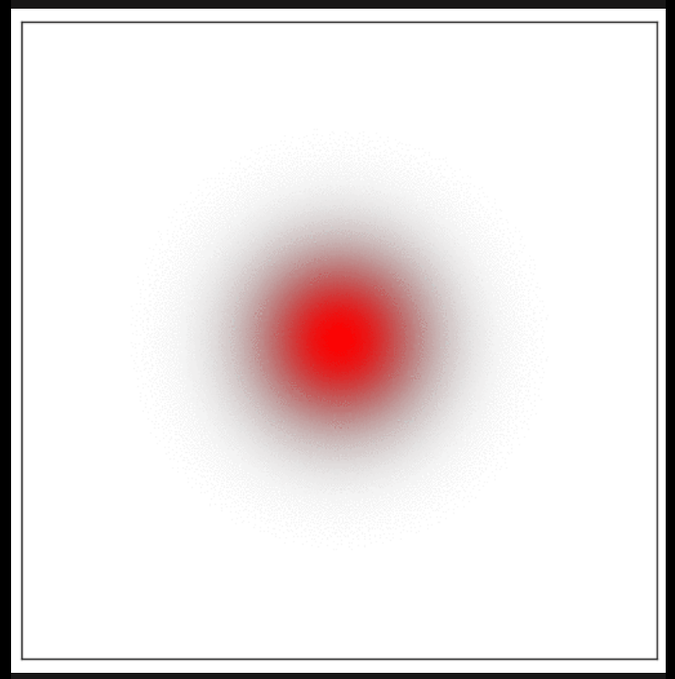
credit: wikipedia



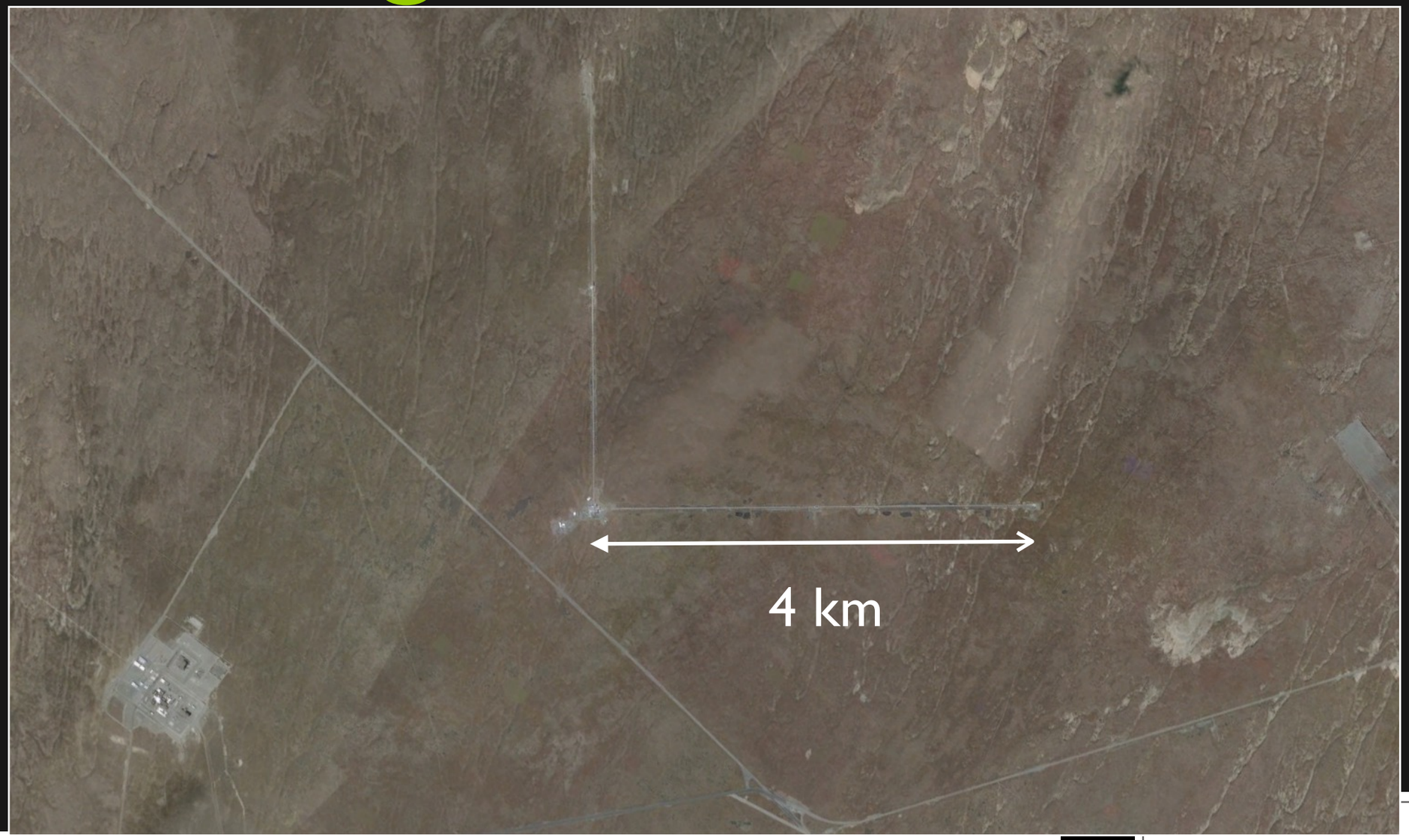
Detecting Gravitational Waves

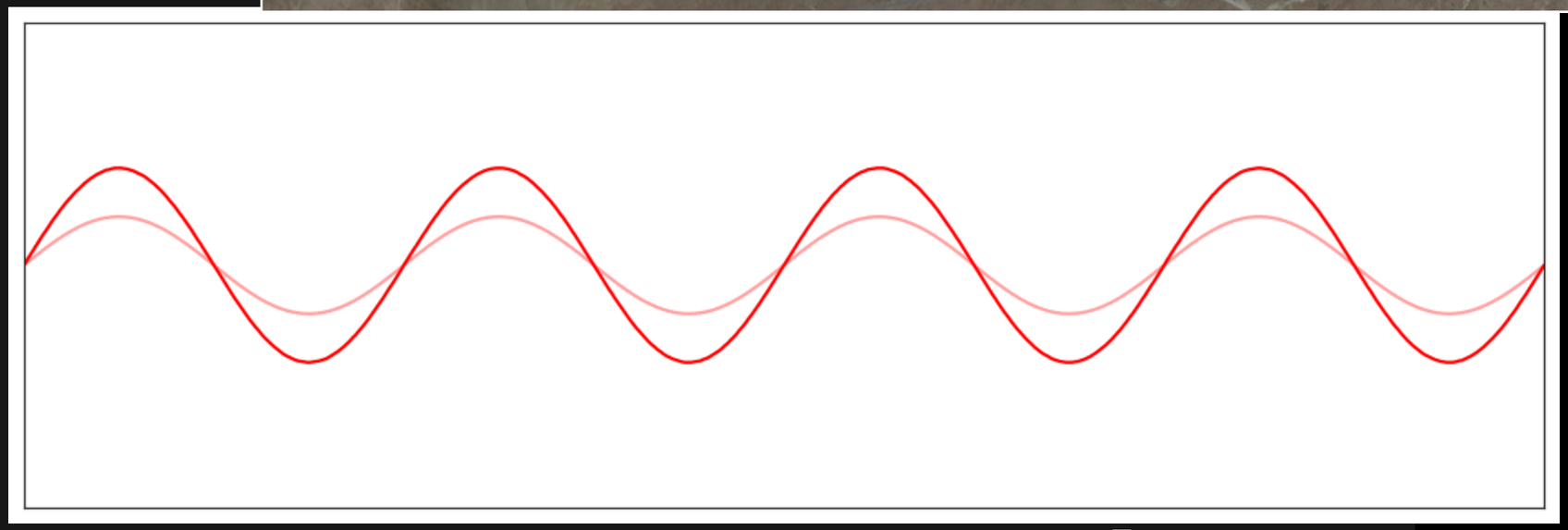


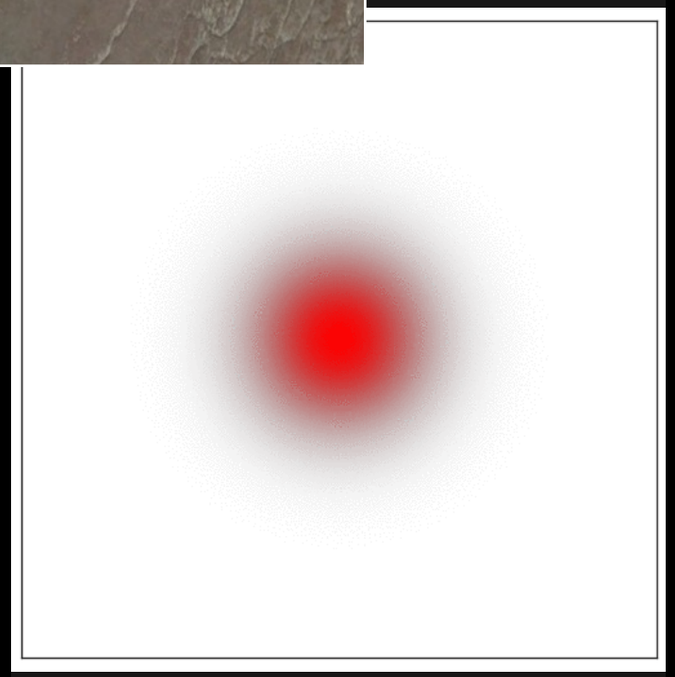




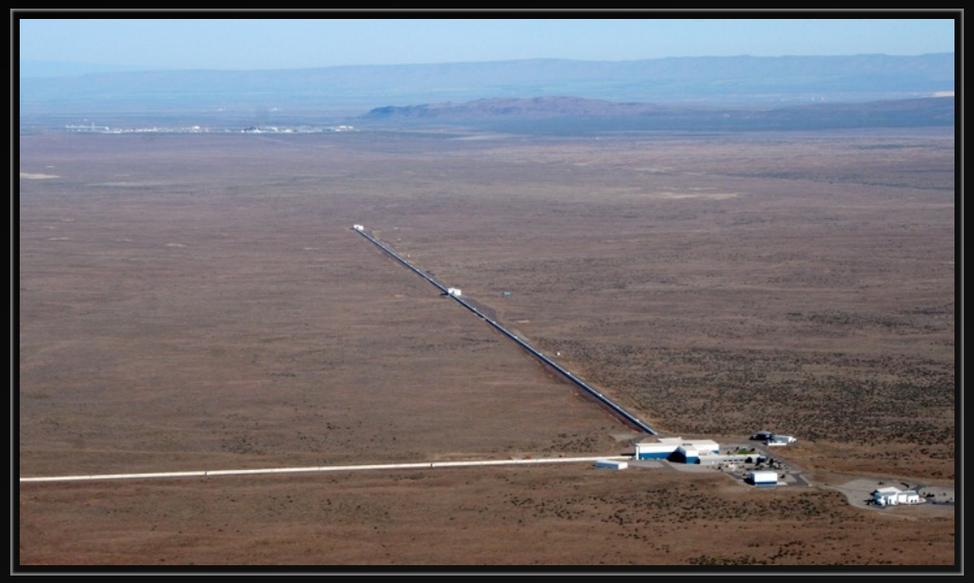
Detecting Gravitational Waves







LIGO-Virgo Network



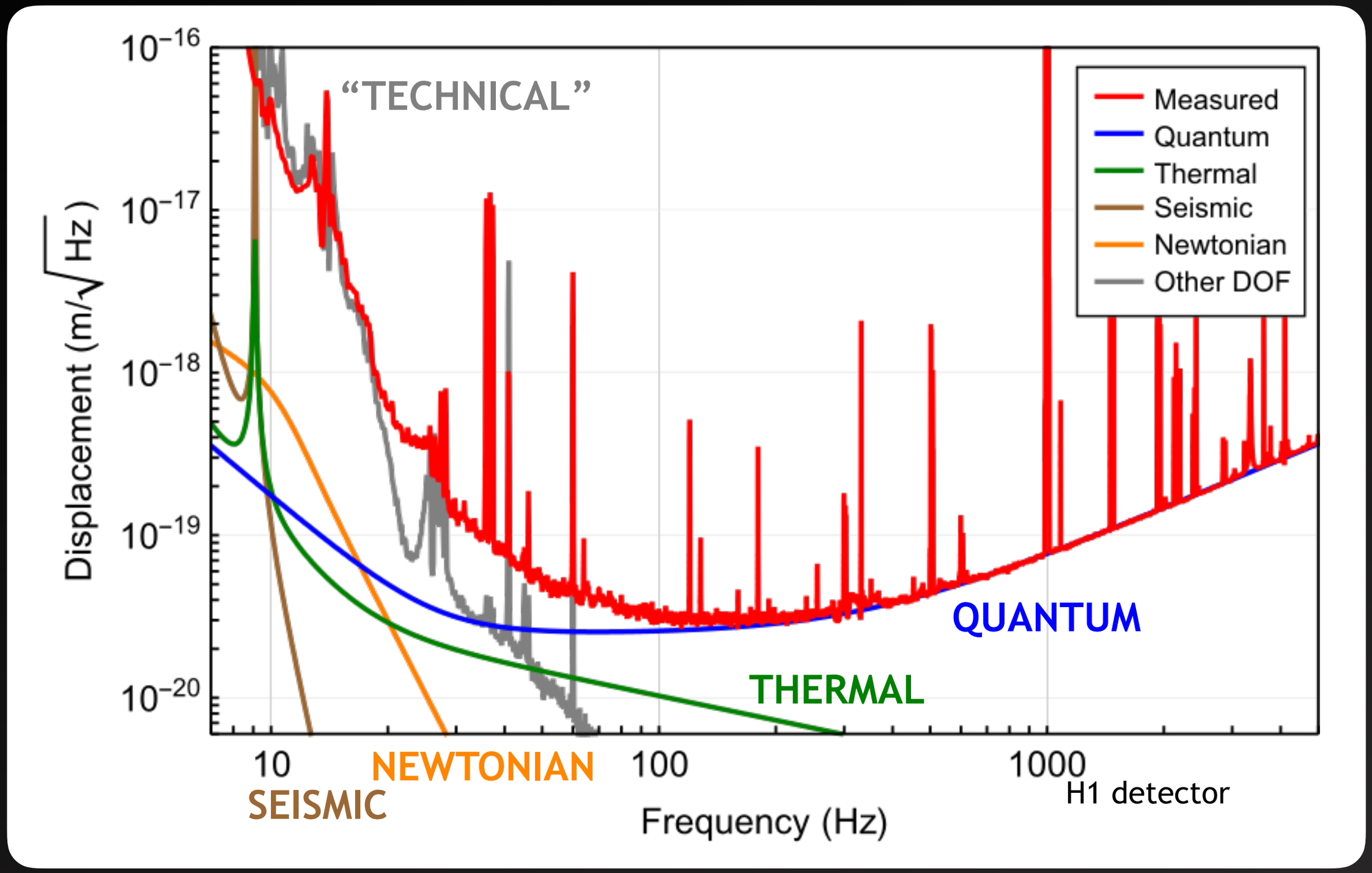
Hanford, WA

Livingston, LA

Pisa, Italy

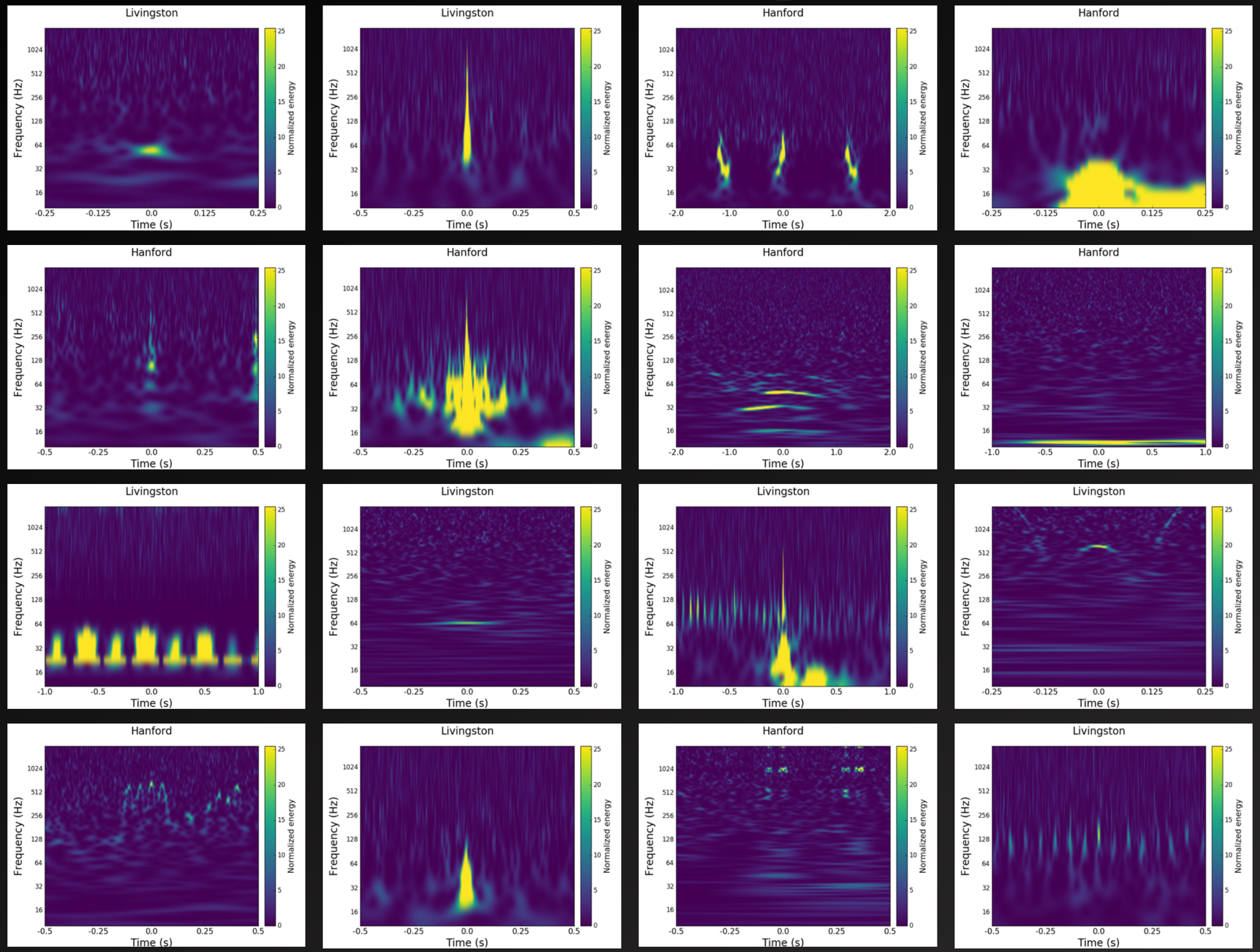
Noise

Abbott et al. (2016):
PRL **116**, 131103

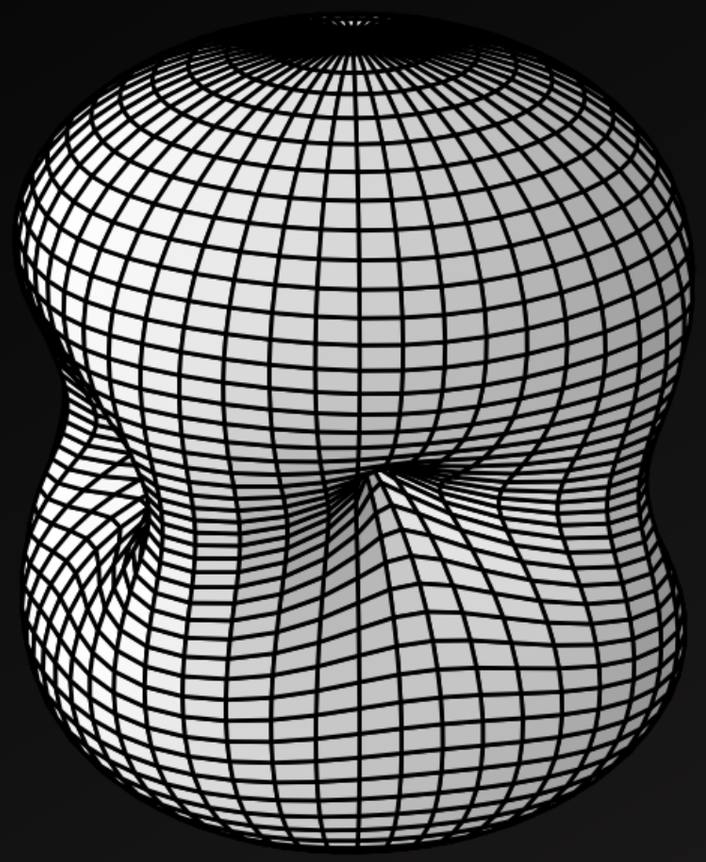


Gaussian and stationary on moderate time scales.

Nonstationary Noise



Antenna Beam Pattern



Omnidirectional Detectors

Most sensitive to sources above and below.

Single detectors have little directional accuracy.

LIGO Source Classes

I. Continuous wave

- Asymmetric neutron stars

II. Burst

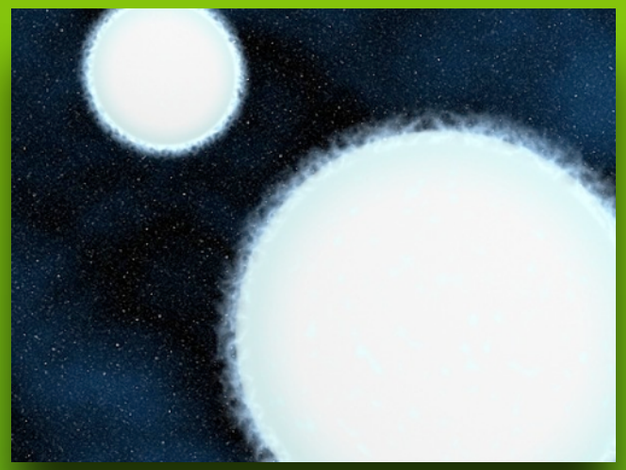
- Core collapse supernovae

III. Stochastic

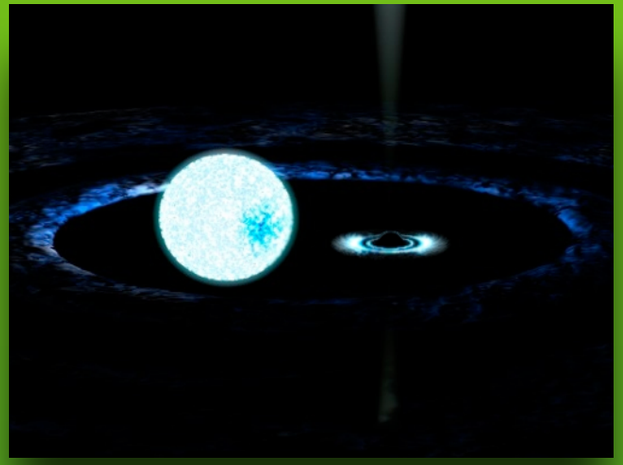
- Binary black hole background

IV. Compact binary mergers

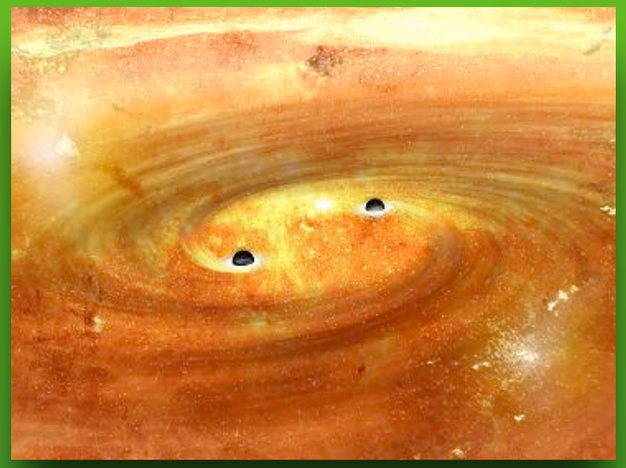
Compact Binaries



Binary Neutron Star

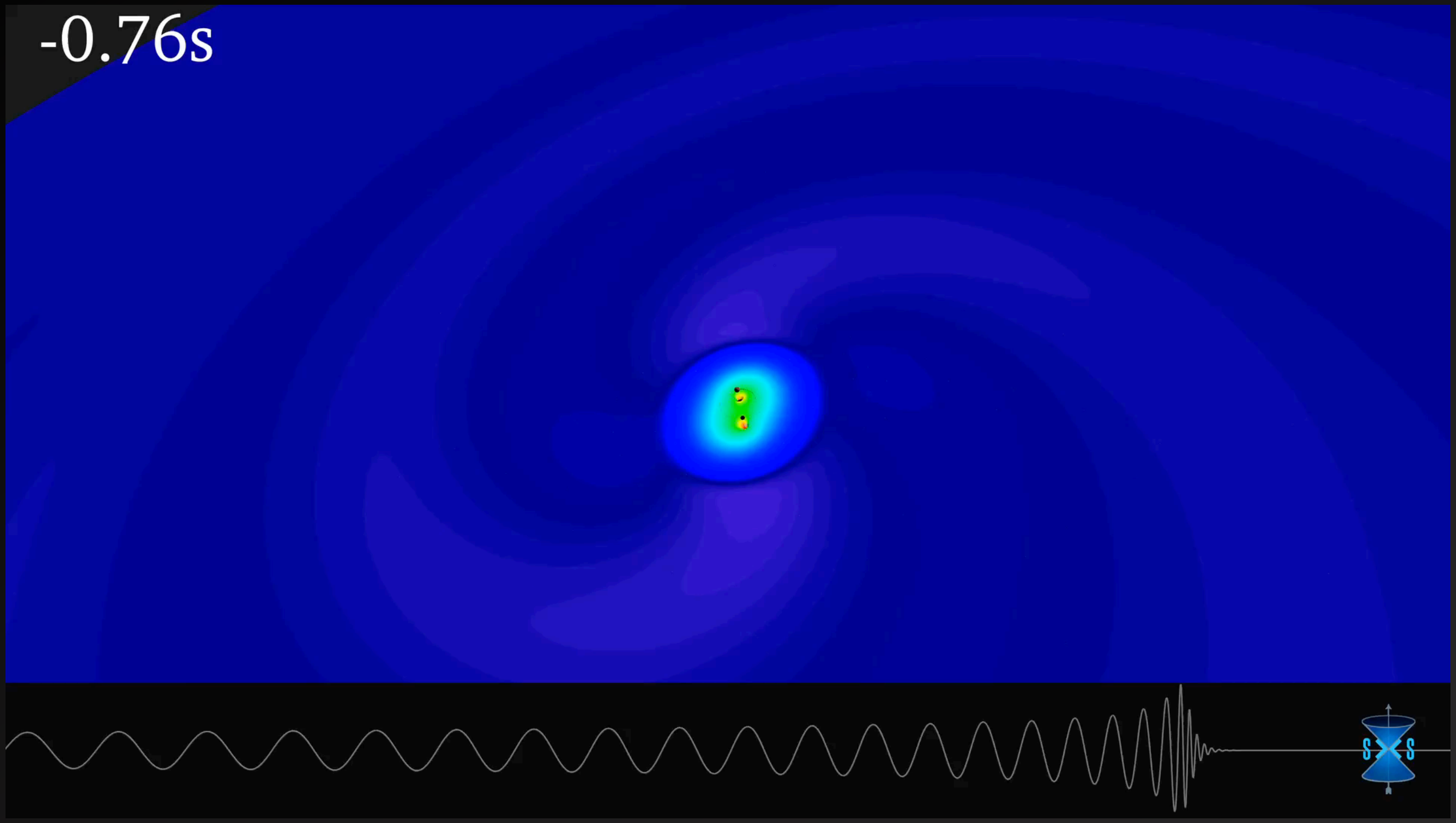


Black Hole-Neutron Star



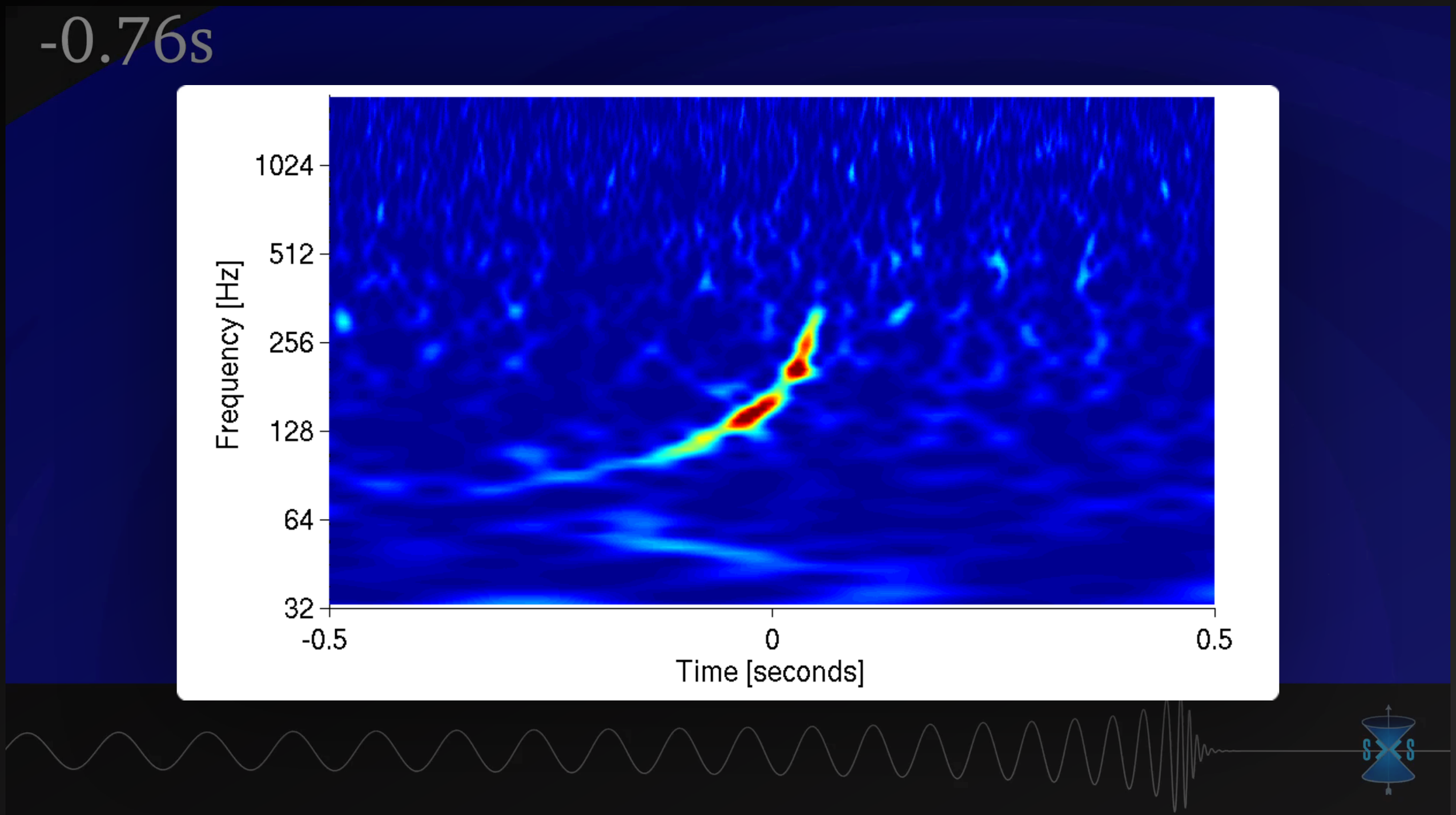
Binary Black Hole

Compact Binary Mergers



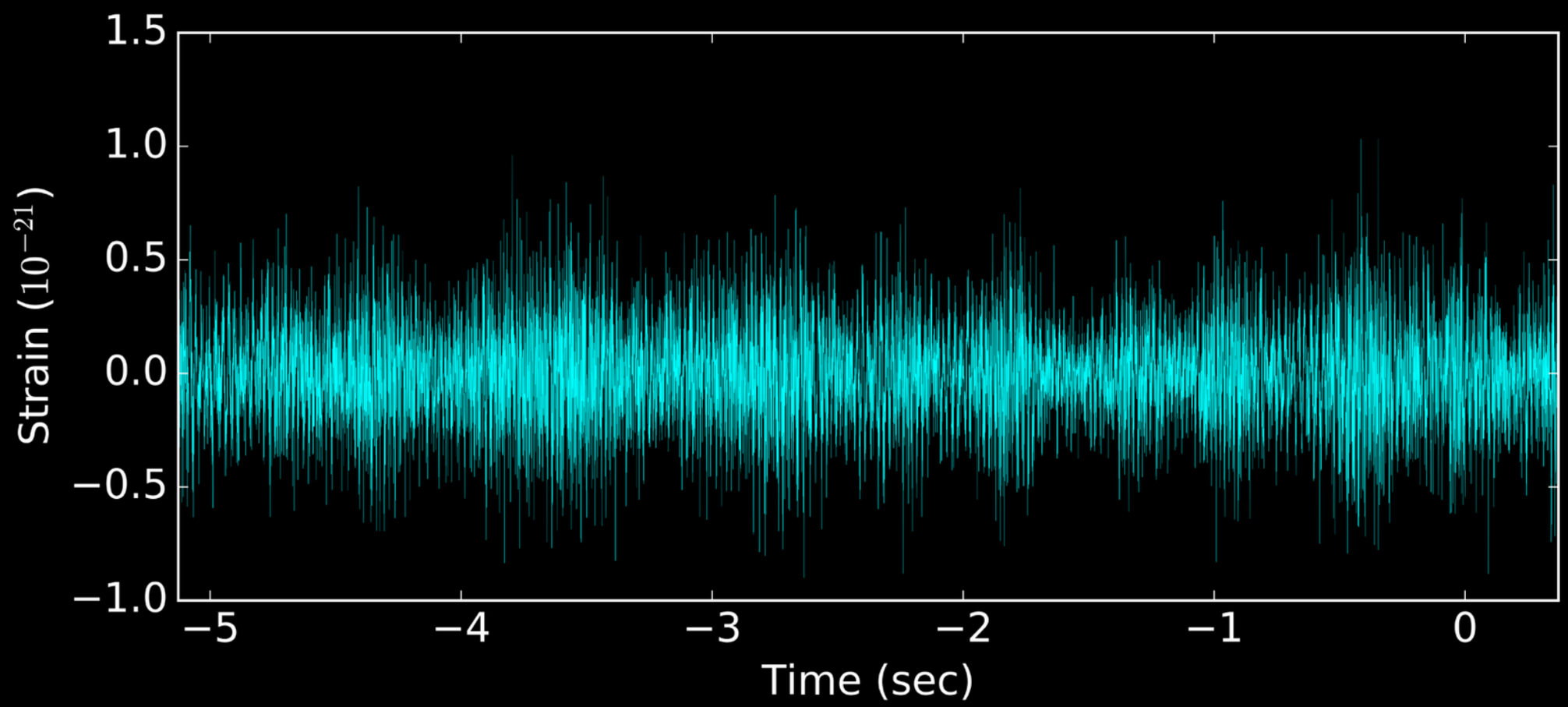
credit: Simulating eXtreme Spacetimes (SXS) Project

Compact Binary Mergers

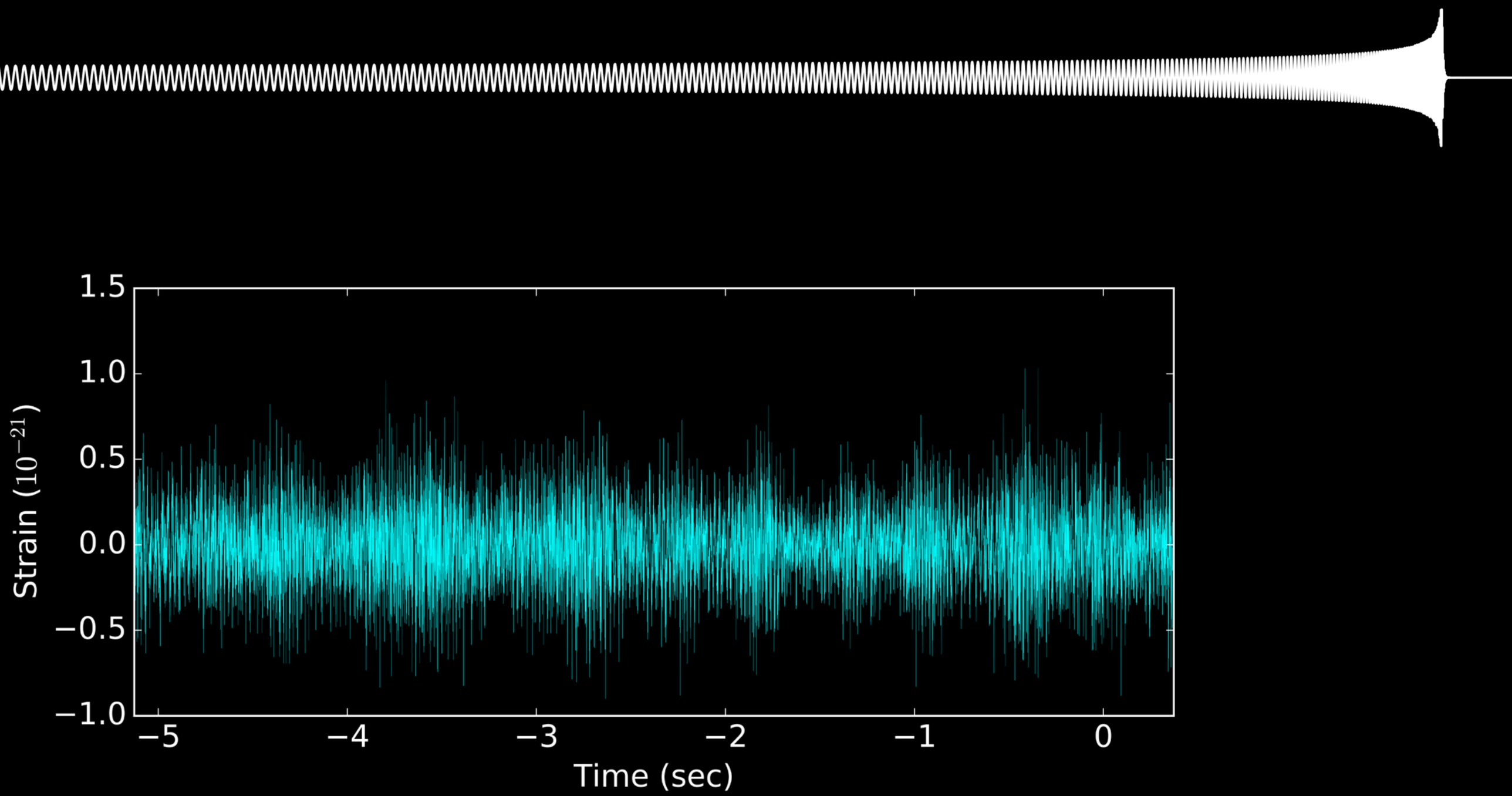


credit: Simulating eXtreme Spacetimes (SXS) Project

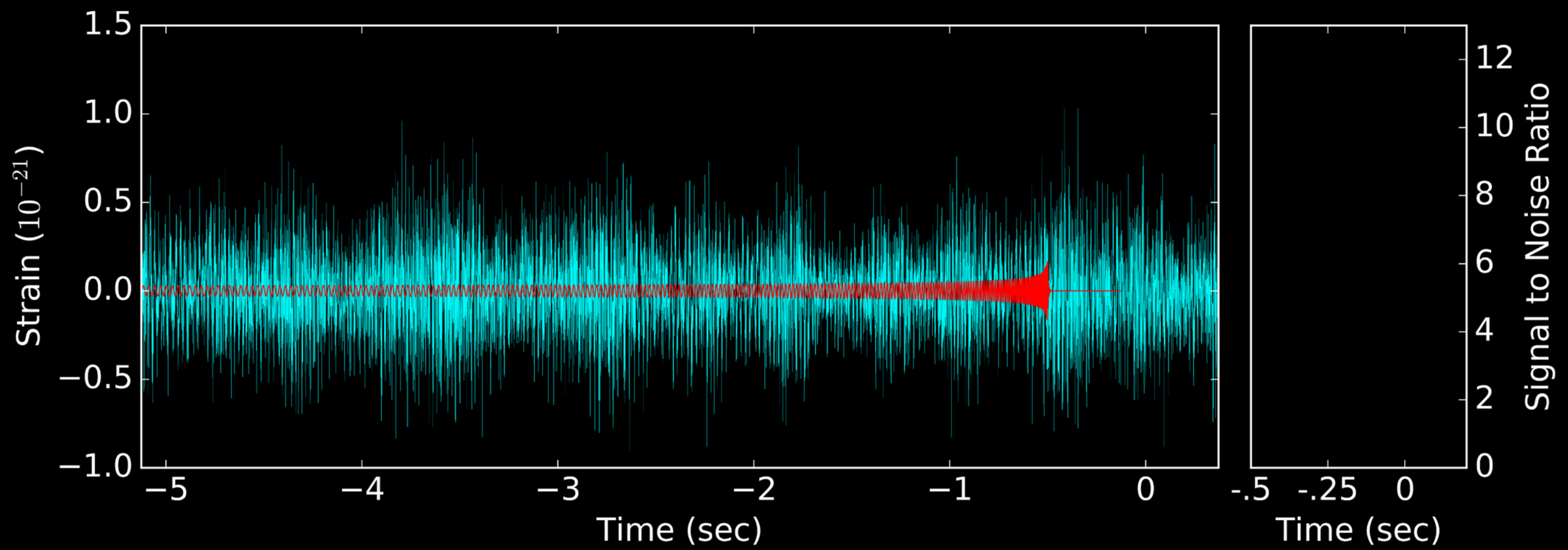
Matched Filtering



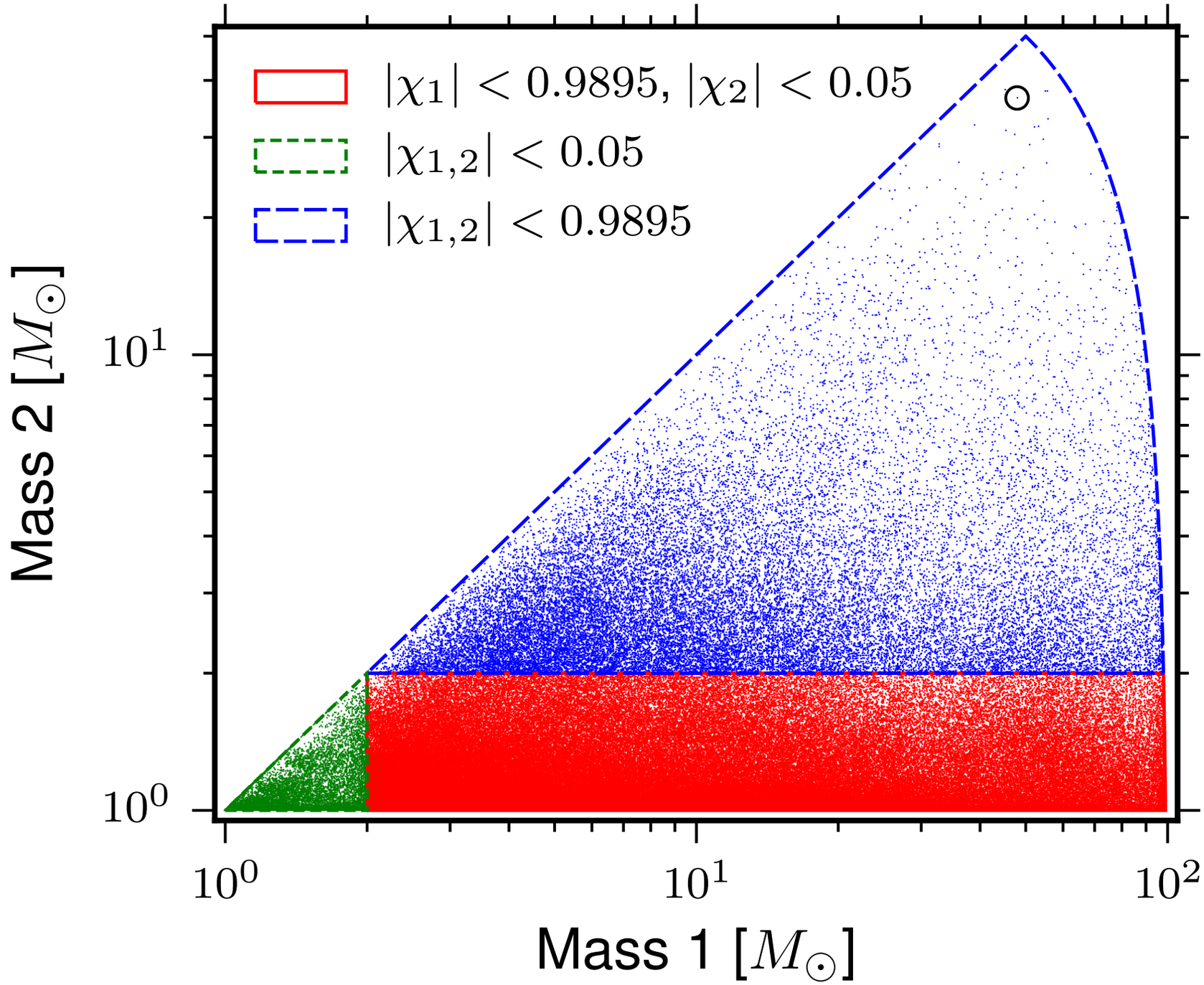
Matched Filtering



Matched Filtering

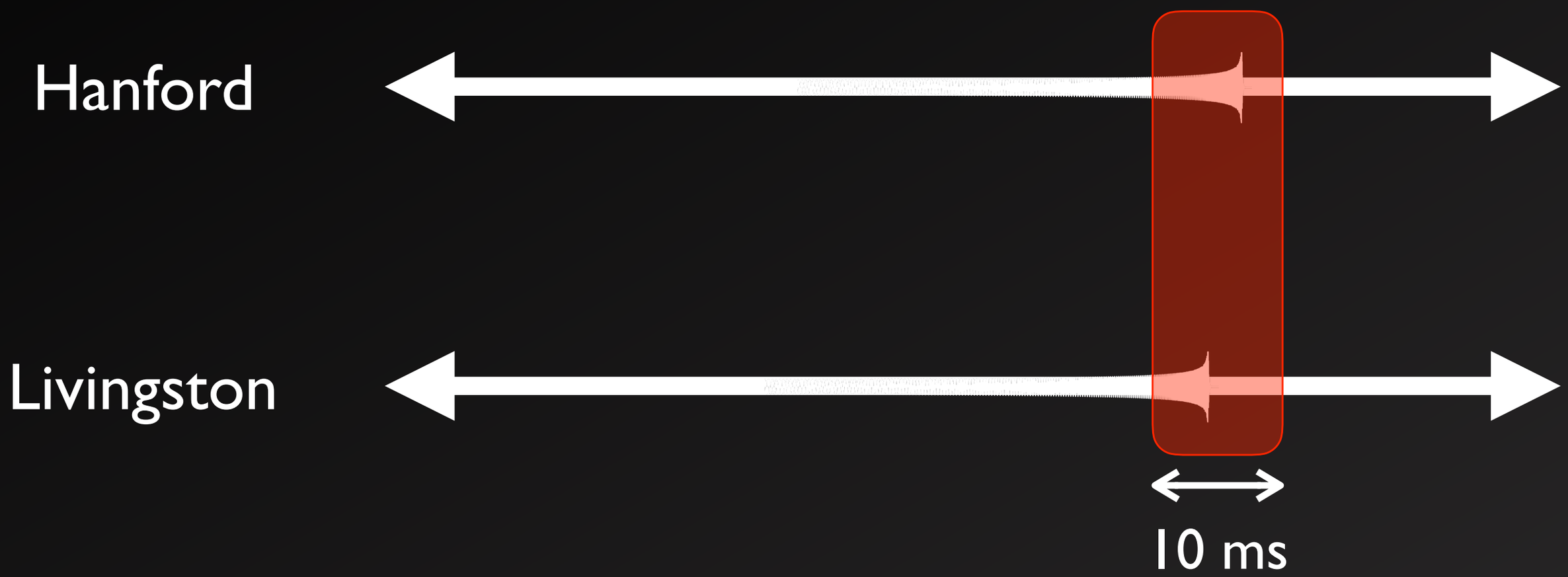


Compact Binary Search



Time Slides

Coincident gravitational wave



How often does noise look like this?

Time Slides

Instrumental Noise Events

Hanford

Livingston

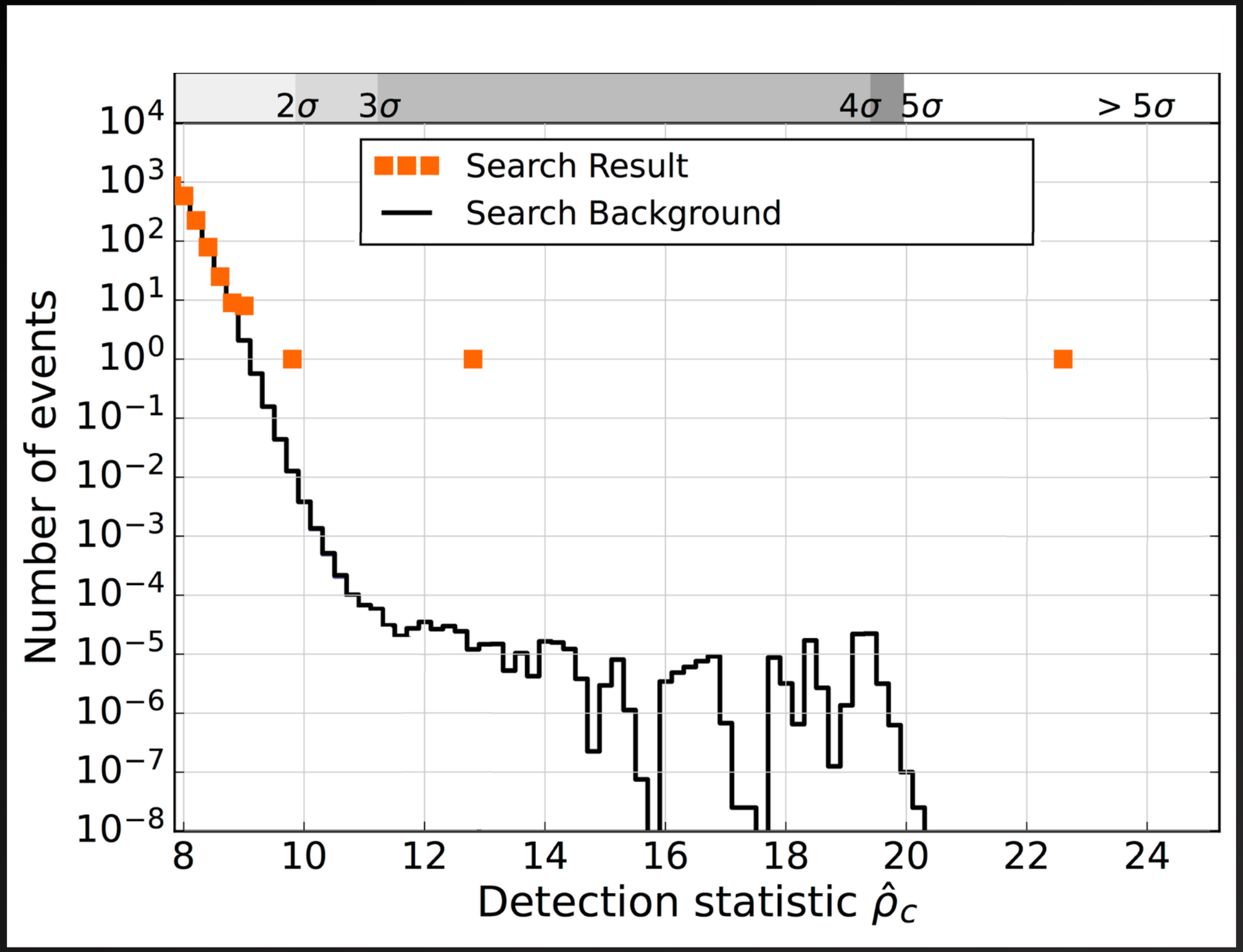
false alarms: 0

Time Slides

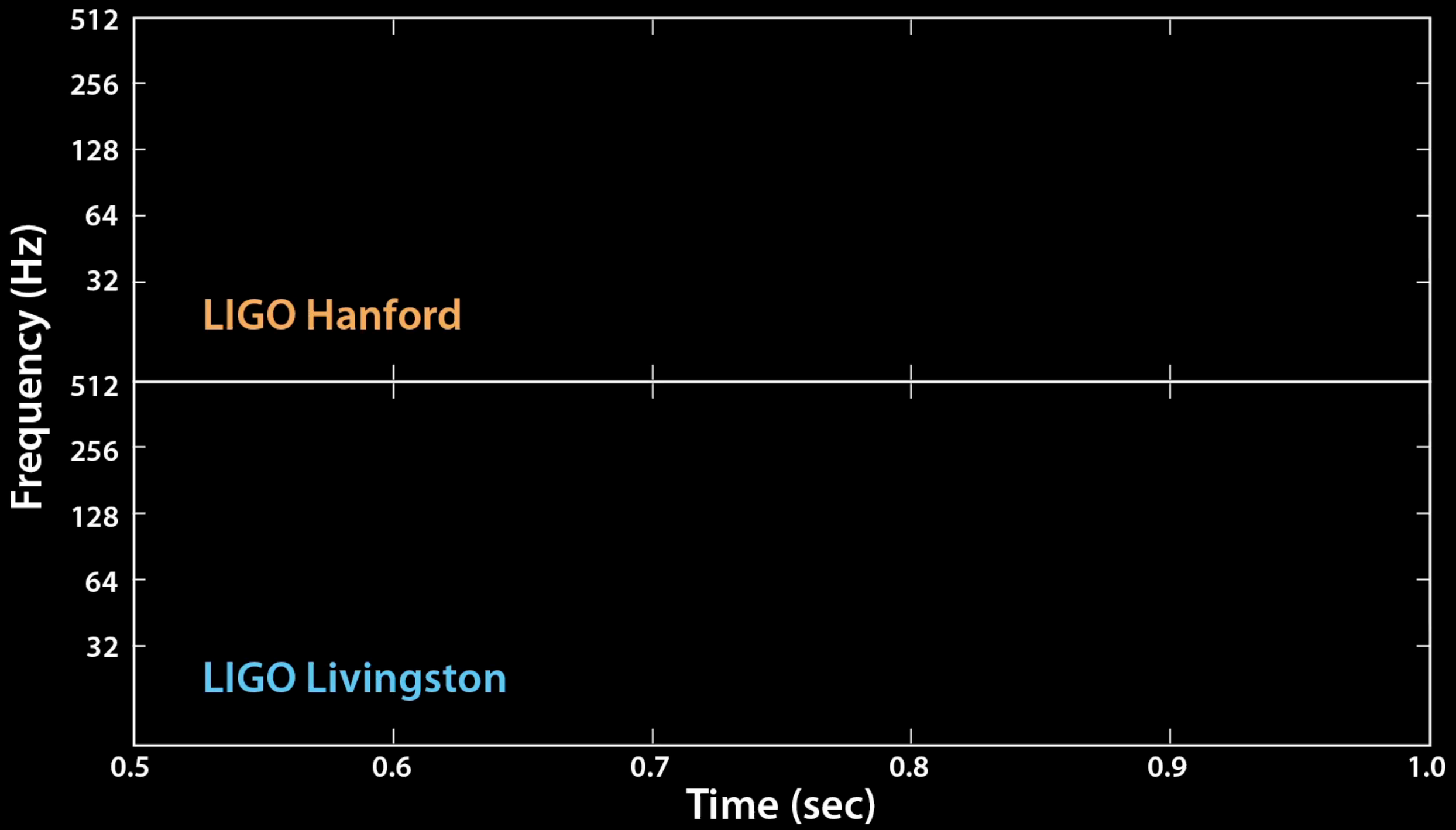
Instrumental Noise Events

false alarms: 4

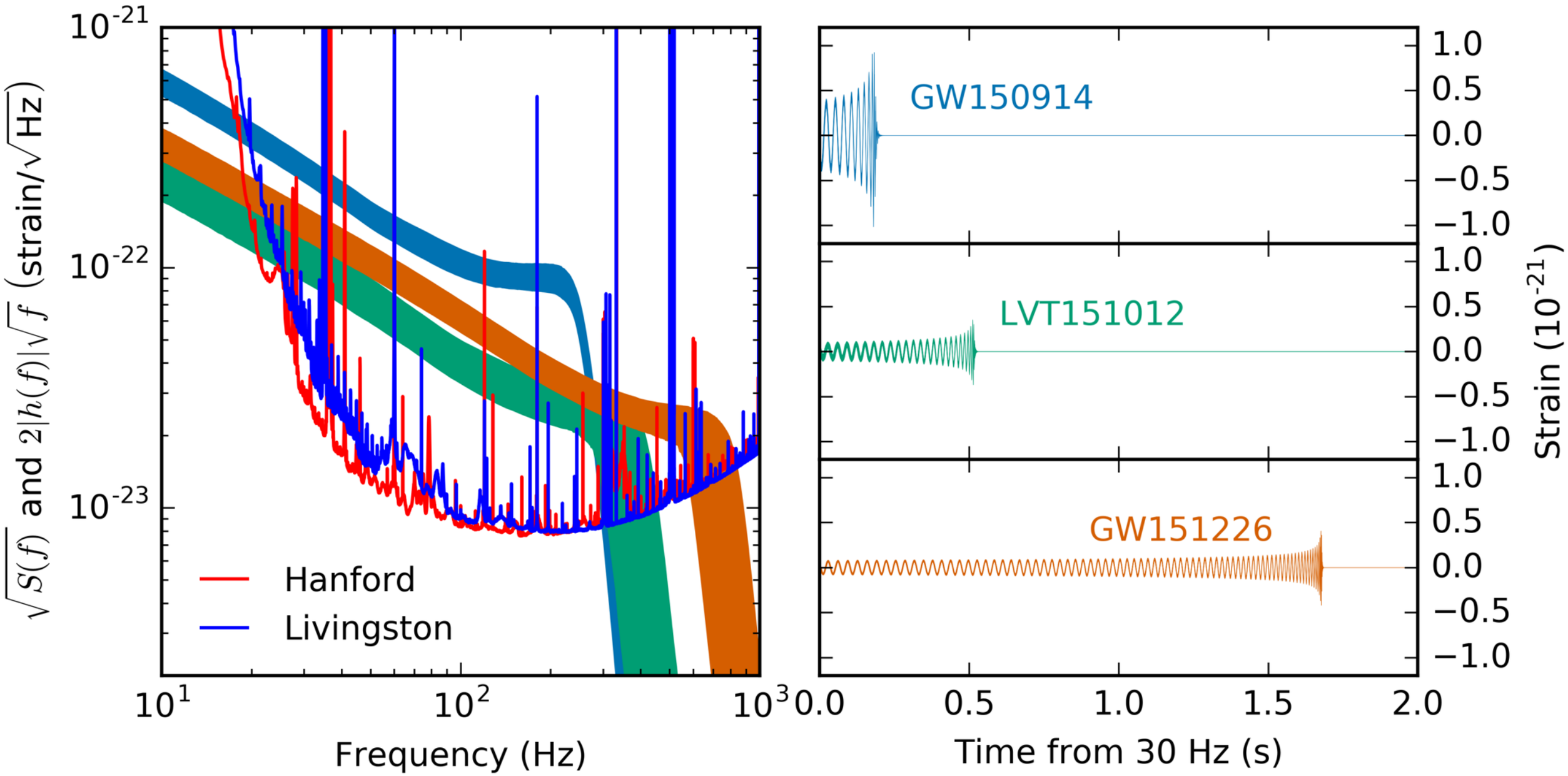
False Alarm Rate



September 14, 2015



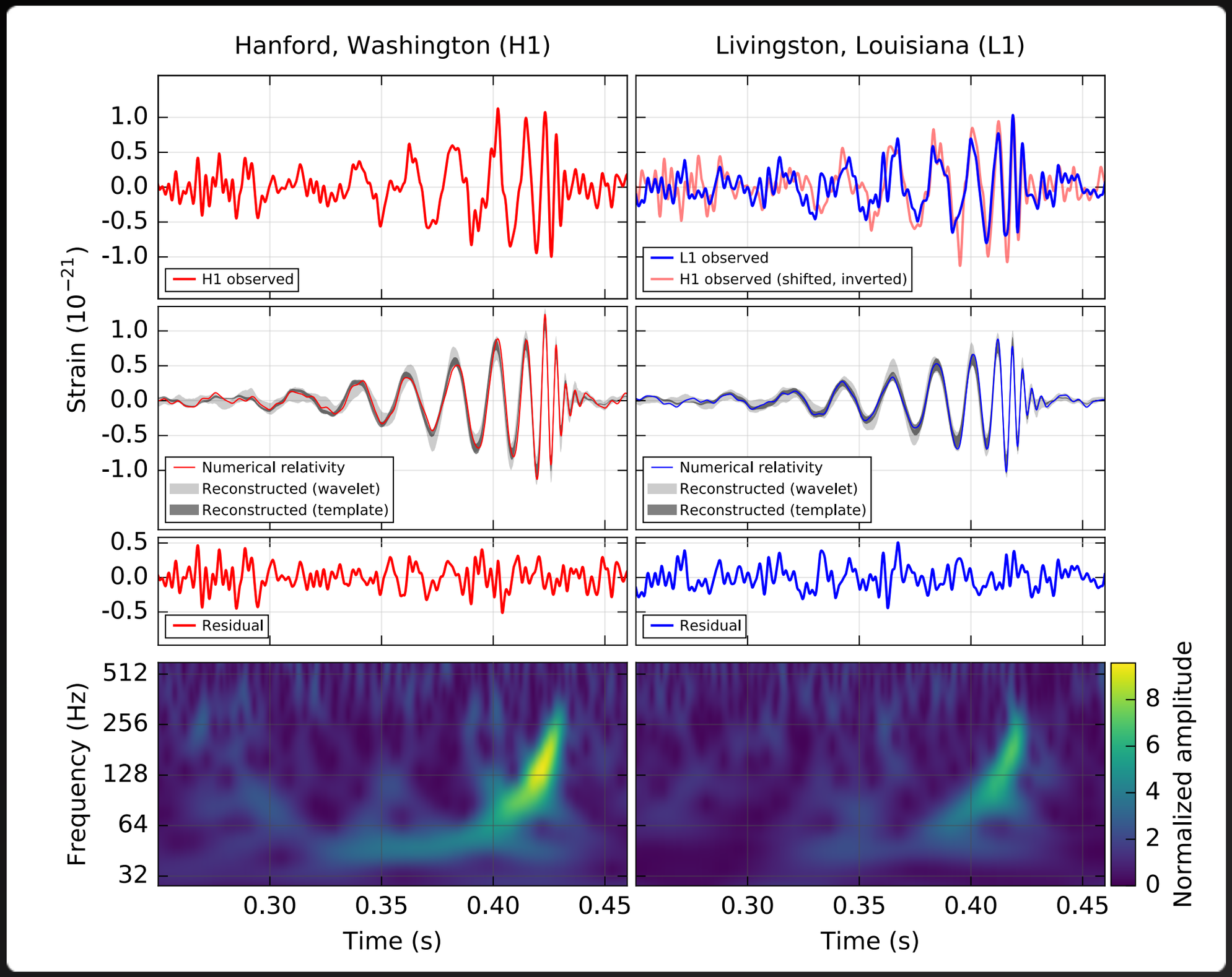
2.87 BBHs in O1



Abbott et al. (2016):
PRX 6, 041015

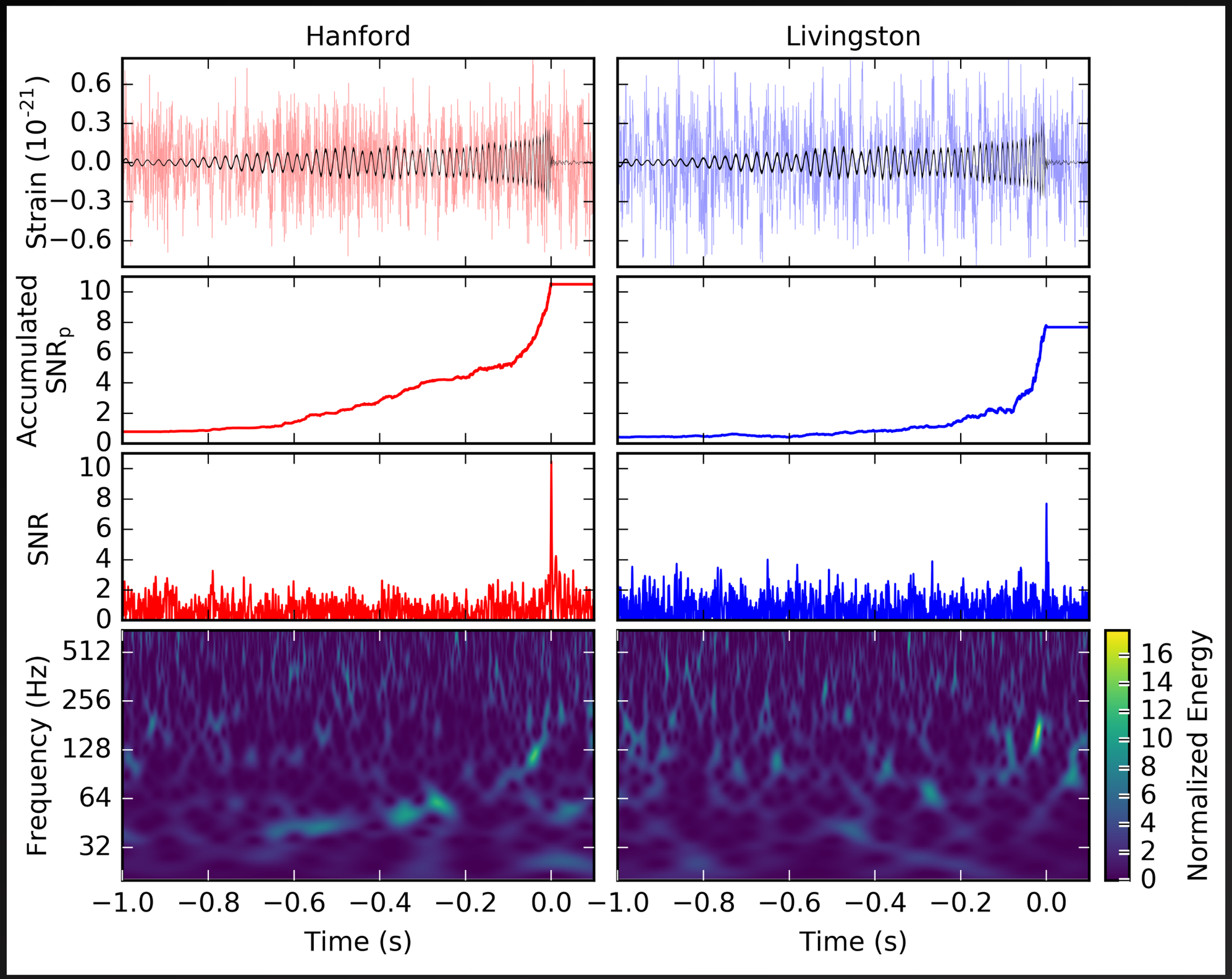
Abbott et al. (2016):
PRL **116**, 061102

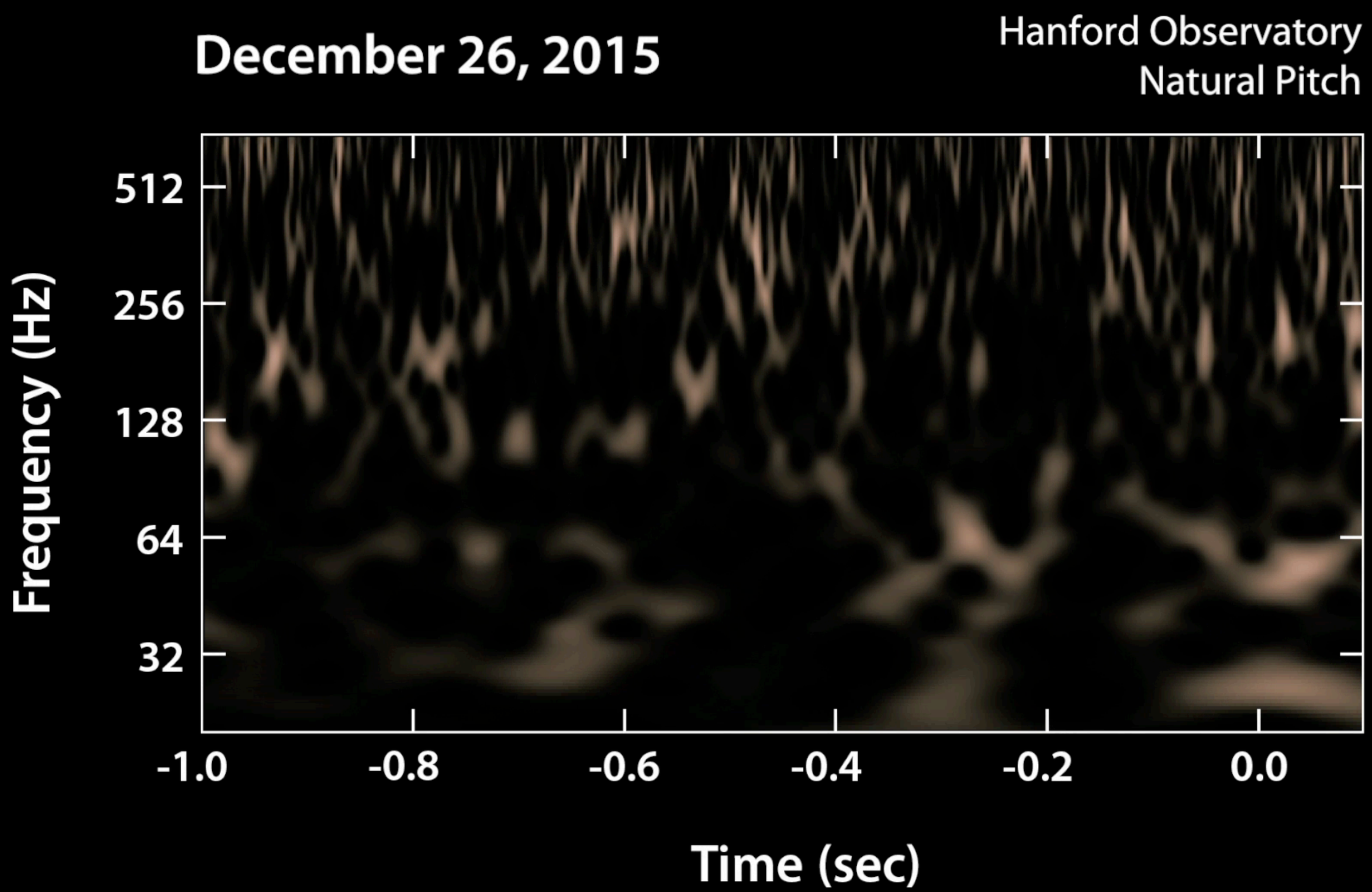
GW150914



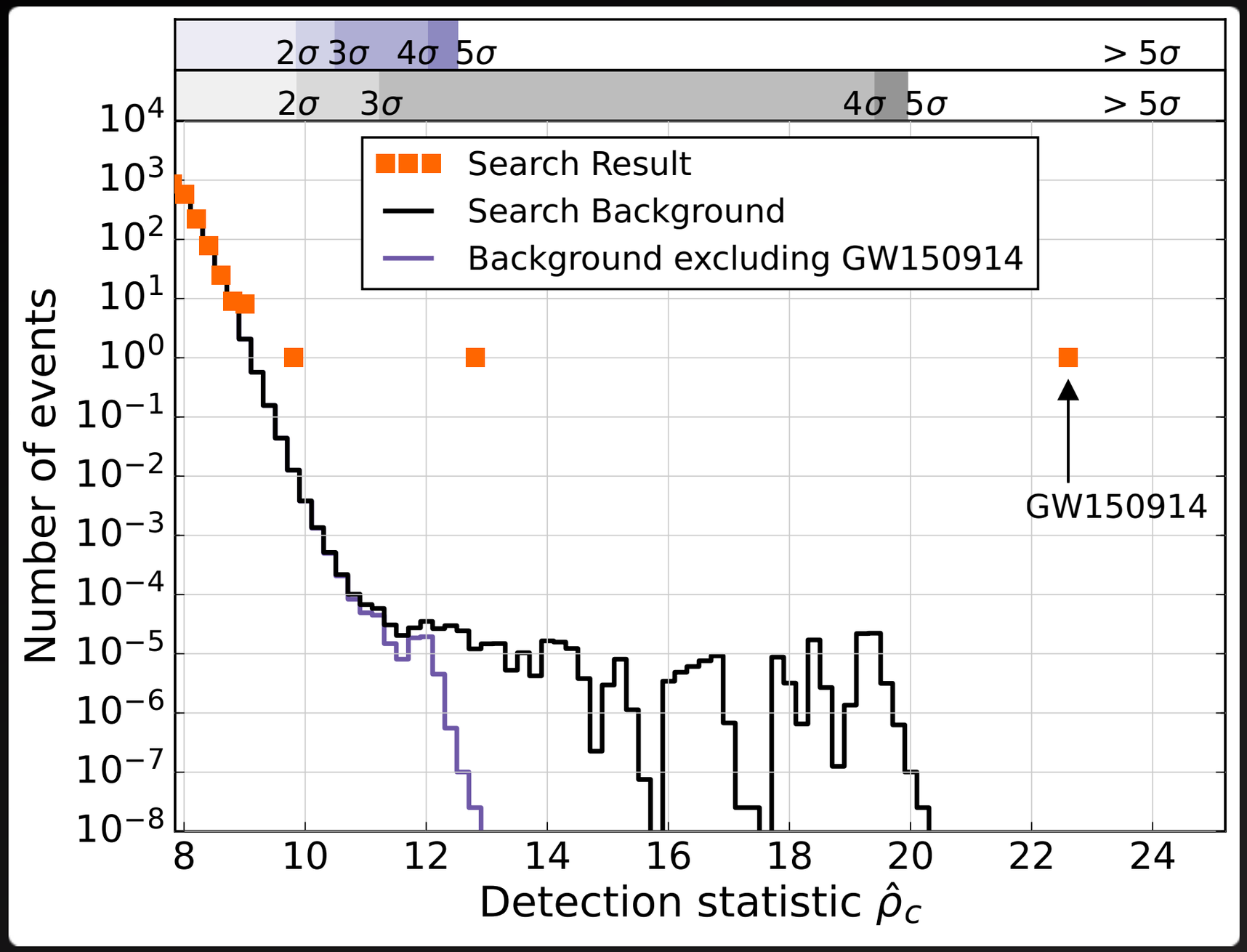
Abbott et al. (2016):
PRL **116**, 241103

GW151226



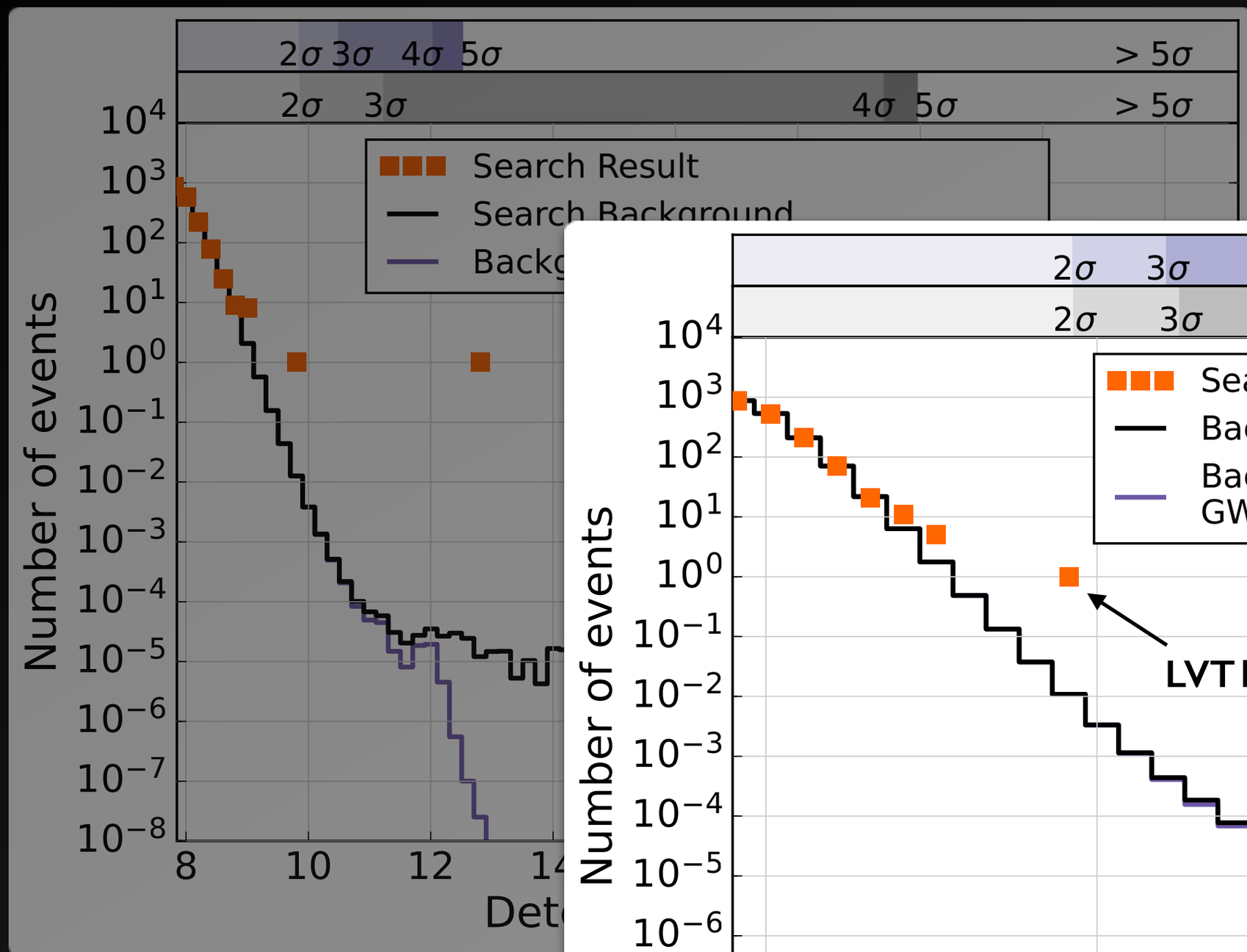

December 26, 2015
Hanford Observatory
Natural Pitch
Frequency (Hz)
512
256
128
64
32
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
Time (sec)

False Alarm Rate



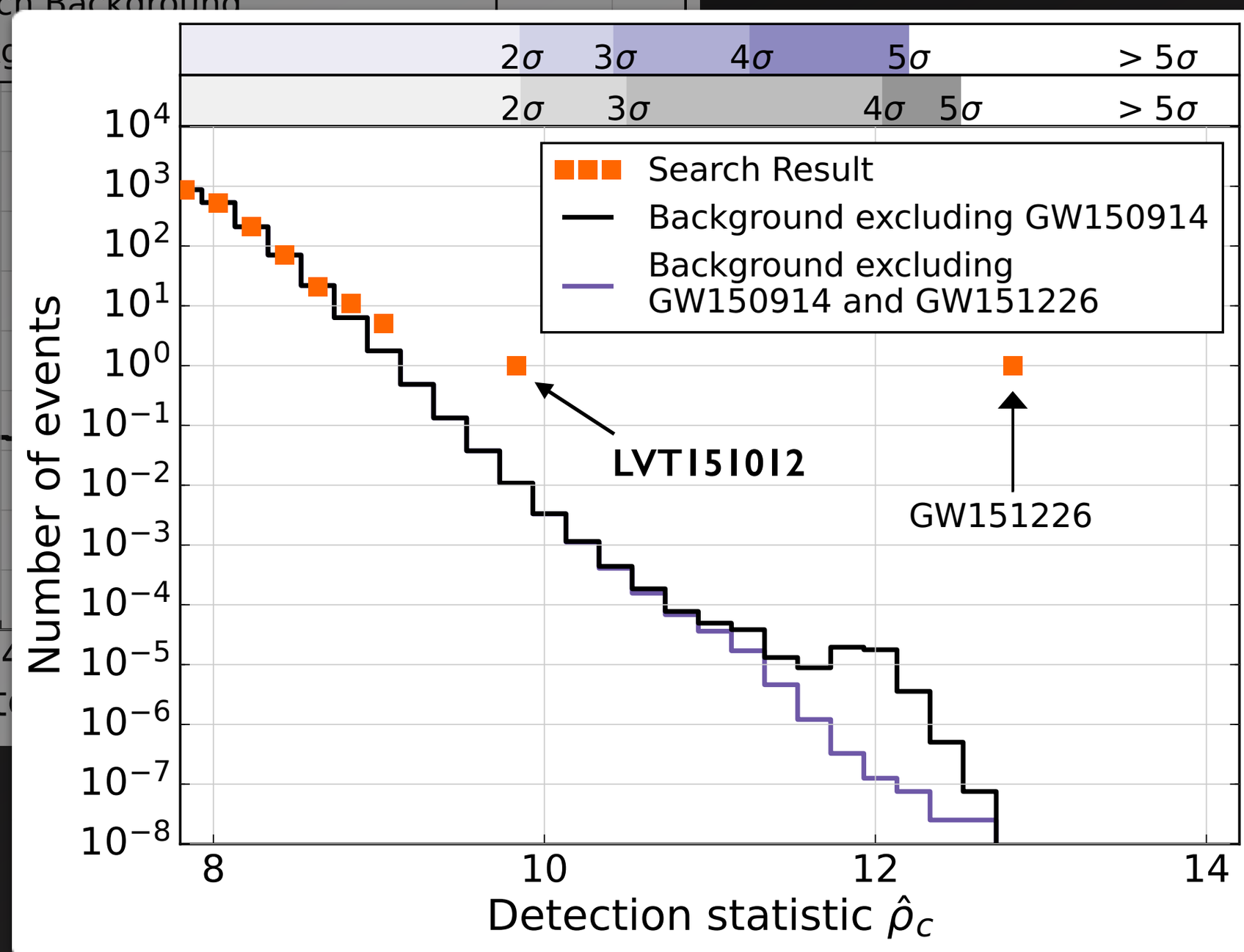
Abbott et al. (2016):
PRL **116**, 061102

False Alarm Rate

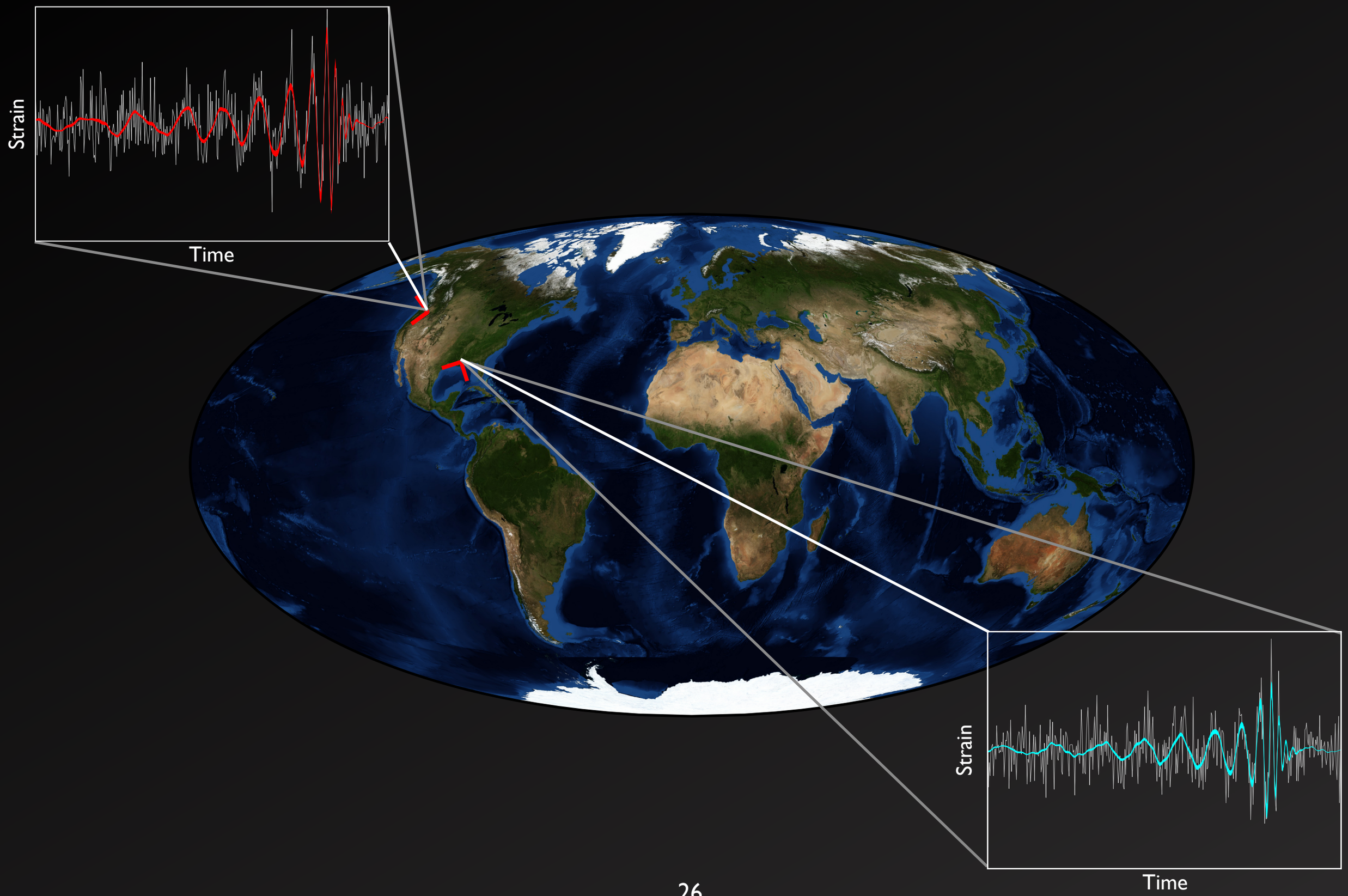


Abbott et al. (2016):
PRL **116**, 061102

Abbott et al. (2016):
PRL **116**, 241103



Parameter Estimation



Bayesian Inference

$$p(\vec{\theta}|d) \propto p(\vec{\theta})p(d|\vec{\theta})$$

Posterior

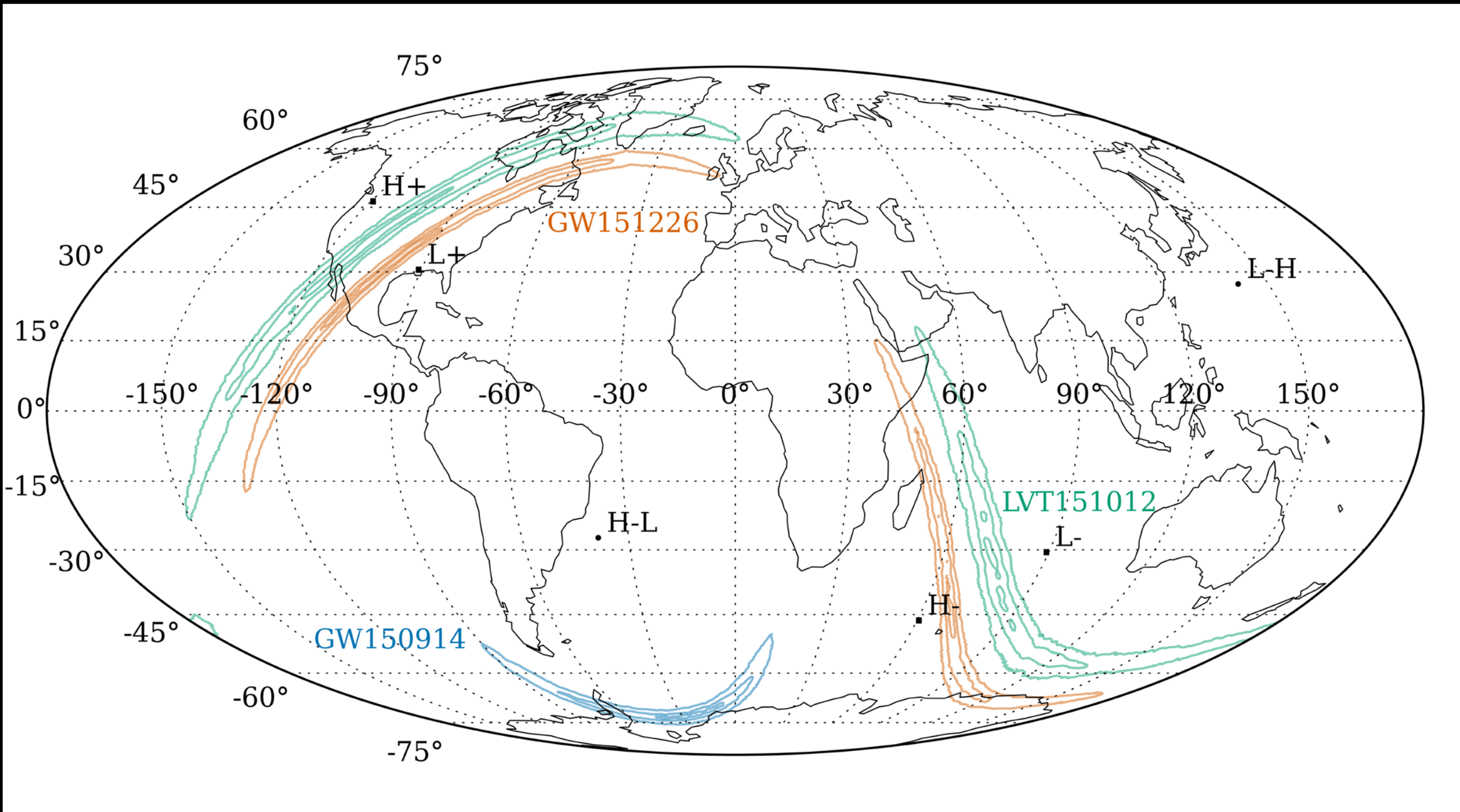
Prior

Likelihood

15 Model Parameters

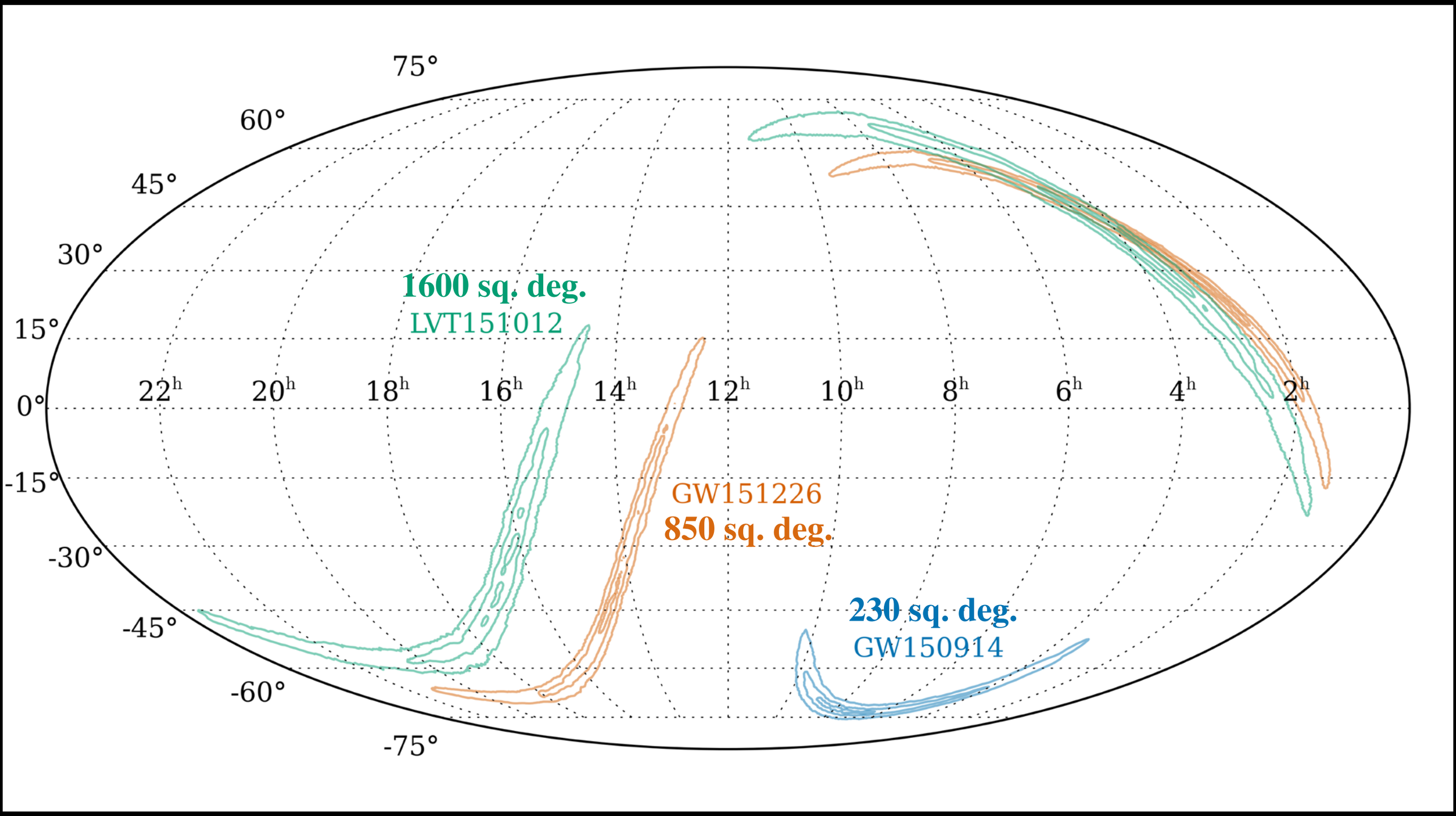
Intrinsic	Extrinsic
Masses (2) Spins (6)	Location (2) Distance (1) Inclination (1) Orientation (2) Merger Time (1)

Localization



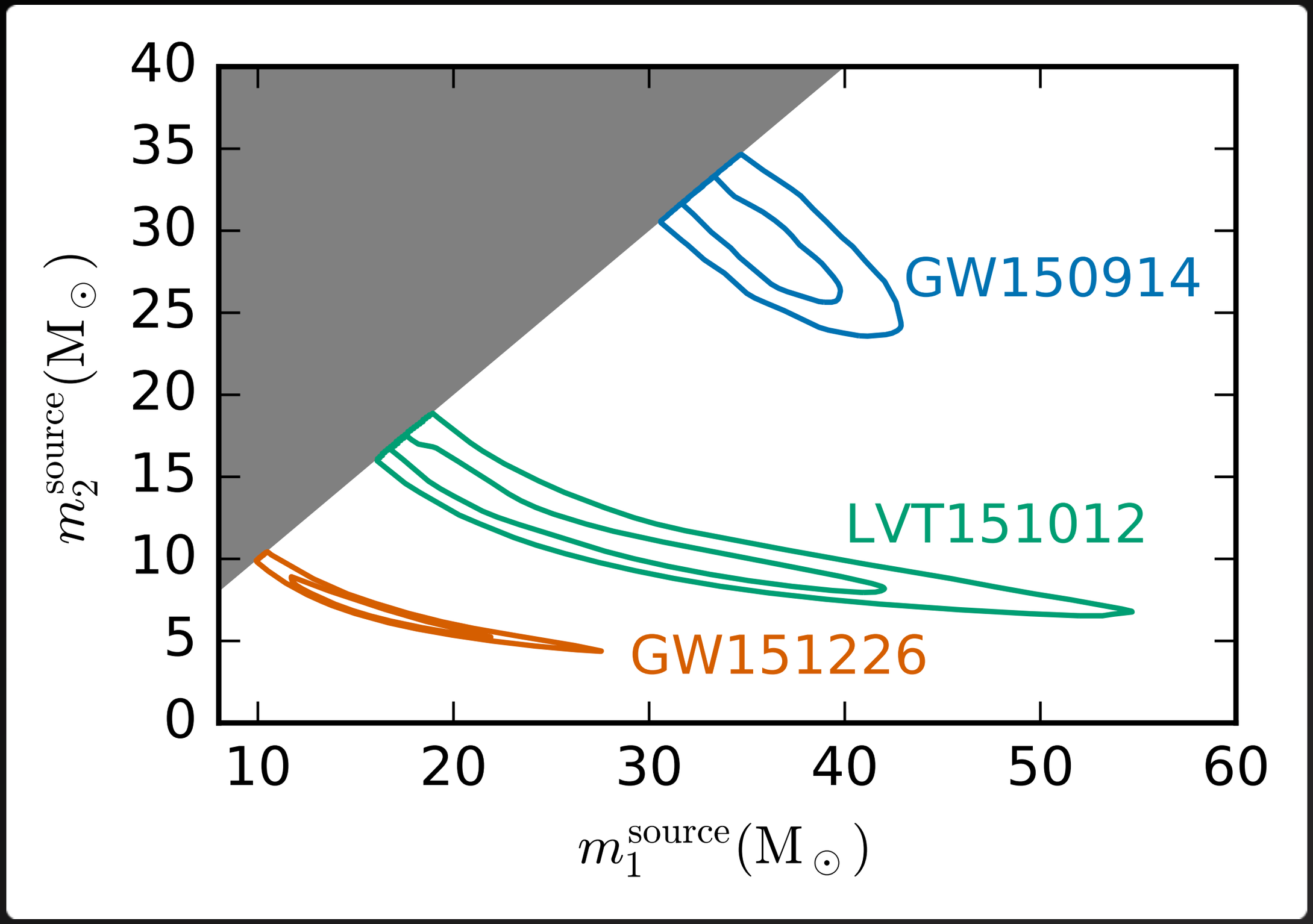
Abbott et al. (2016):
PRX **6**, 041015

Localization



Abbott et al. (2016):
PRX **6**, 041015

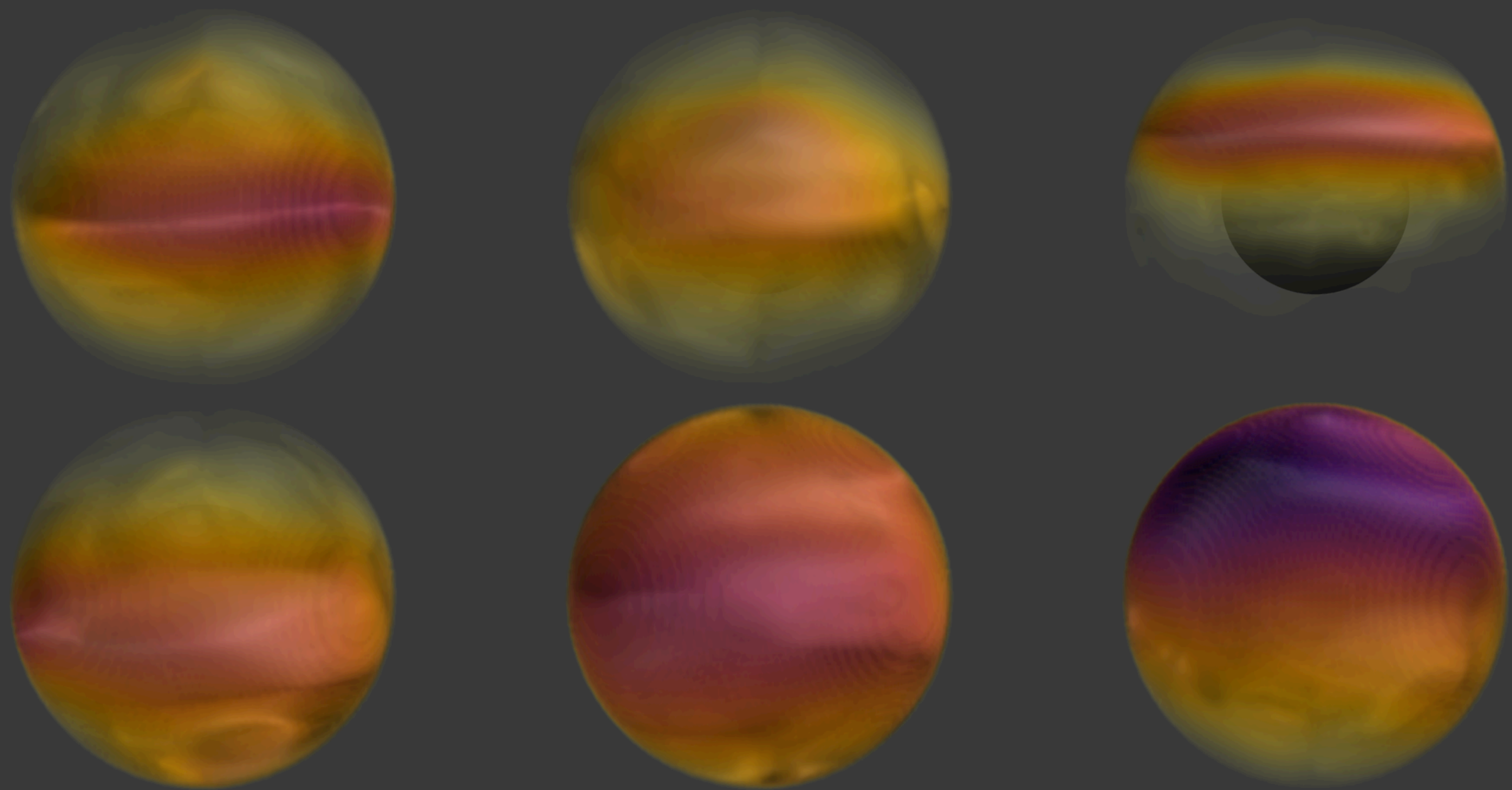
Black Hole Masses



Abbott et al. (2016):
PRX **6**, 041015

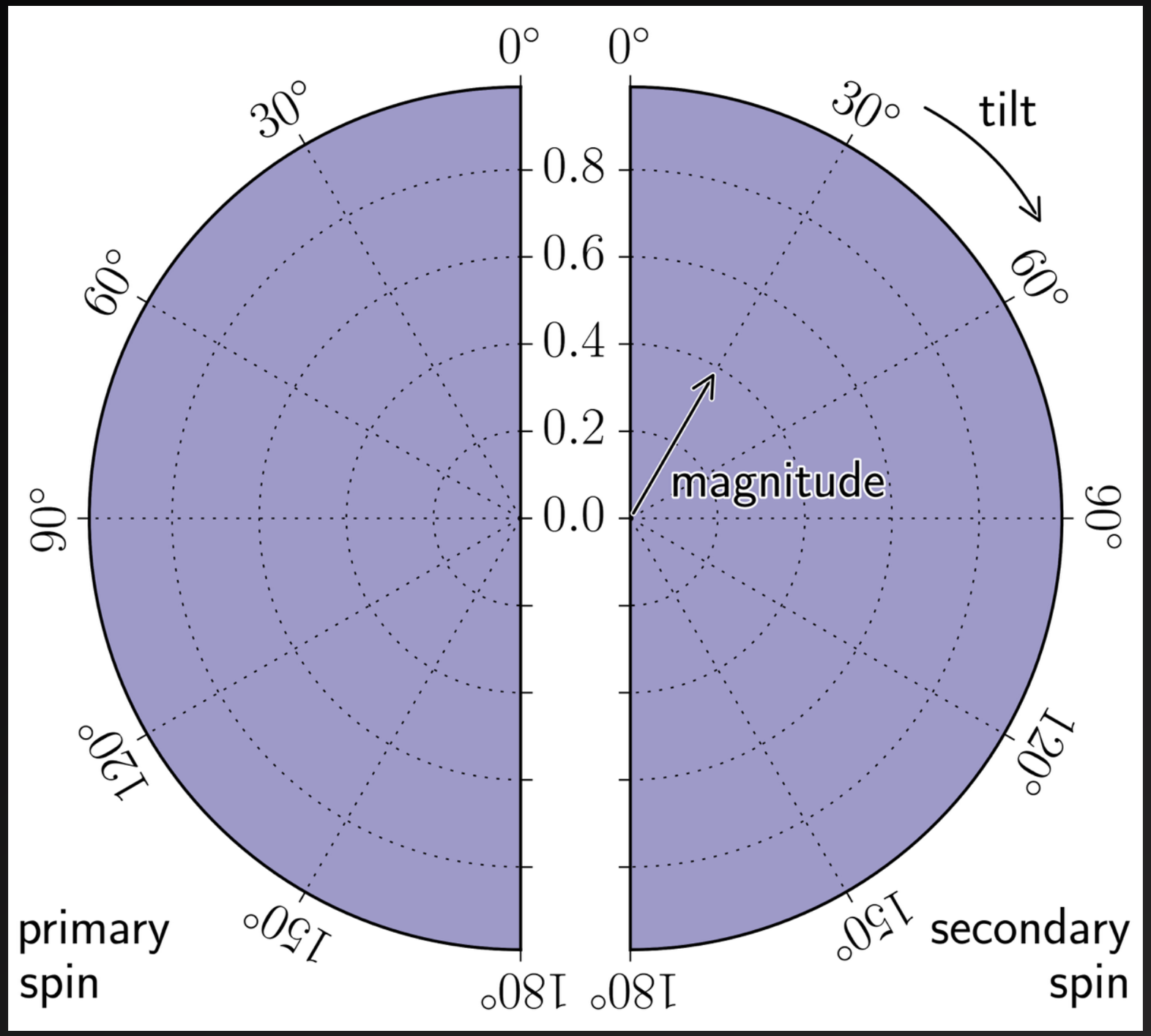
Black Hole Spins

GW150914 LVT151012 GW151226



Black Hole Spins

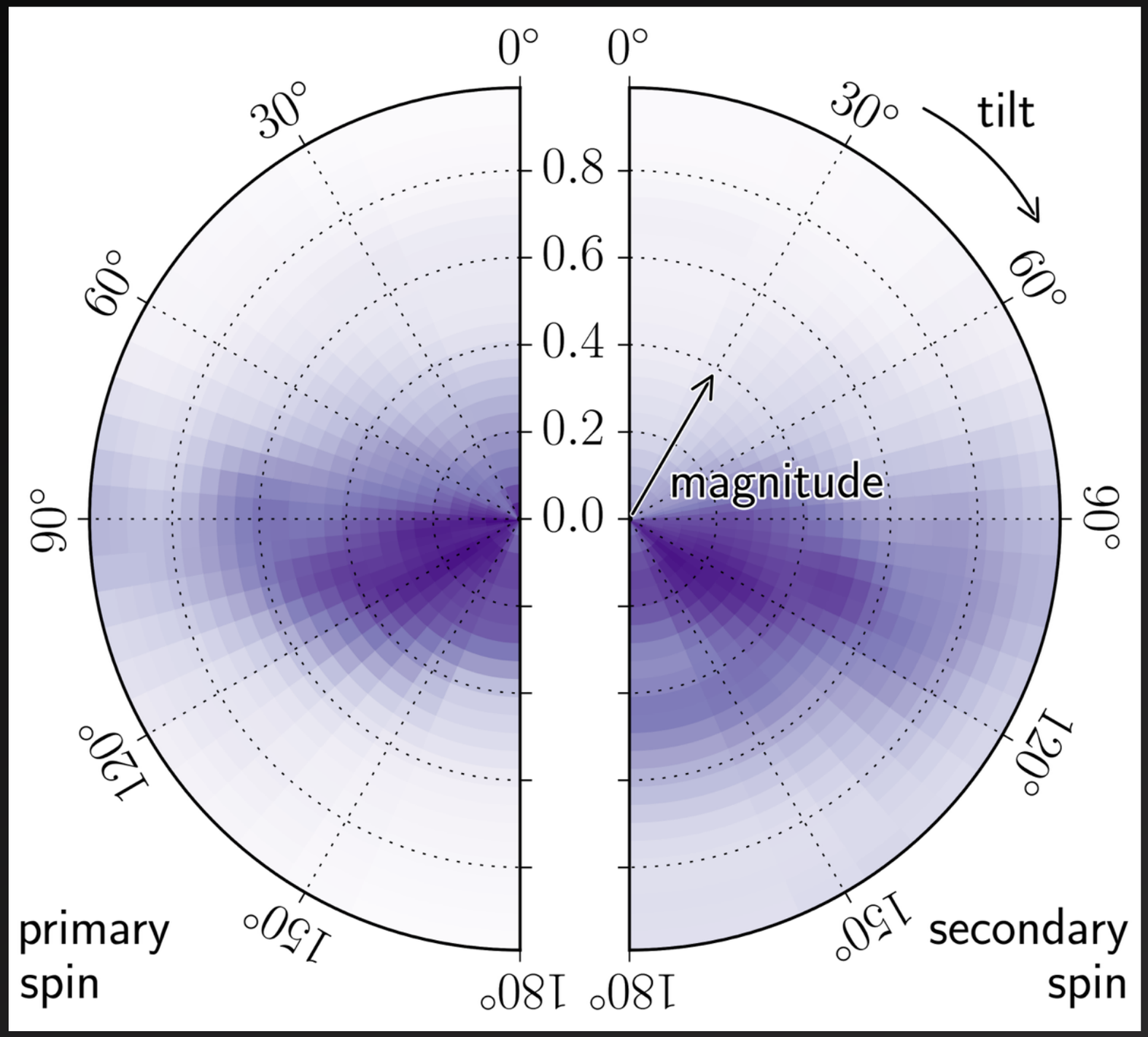
prior



Black Hole Spins

GW150914

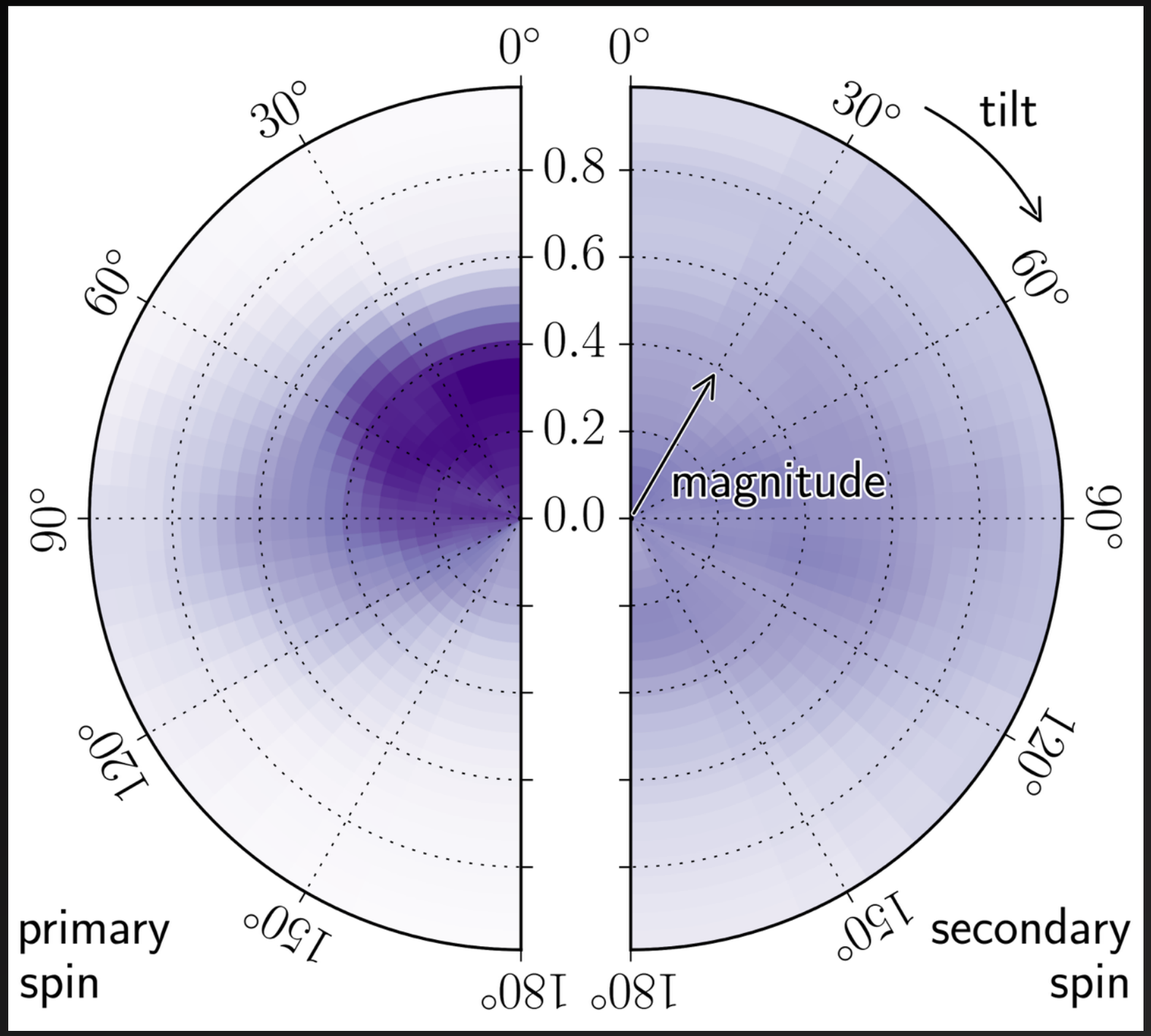
BH spin
not aligned and
extremal



Abbott et al. (2016):
PRL **116**, 241102

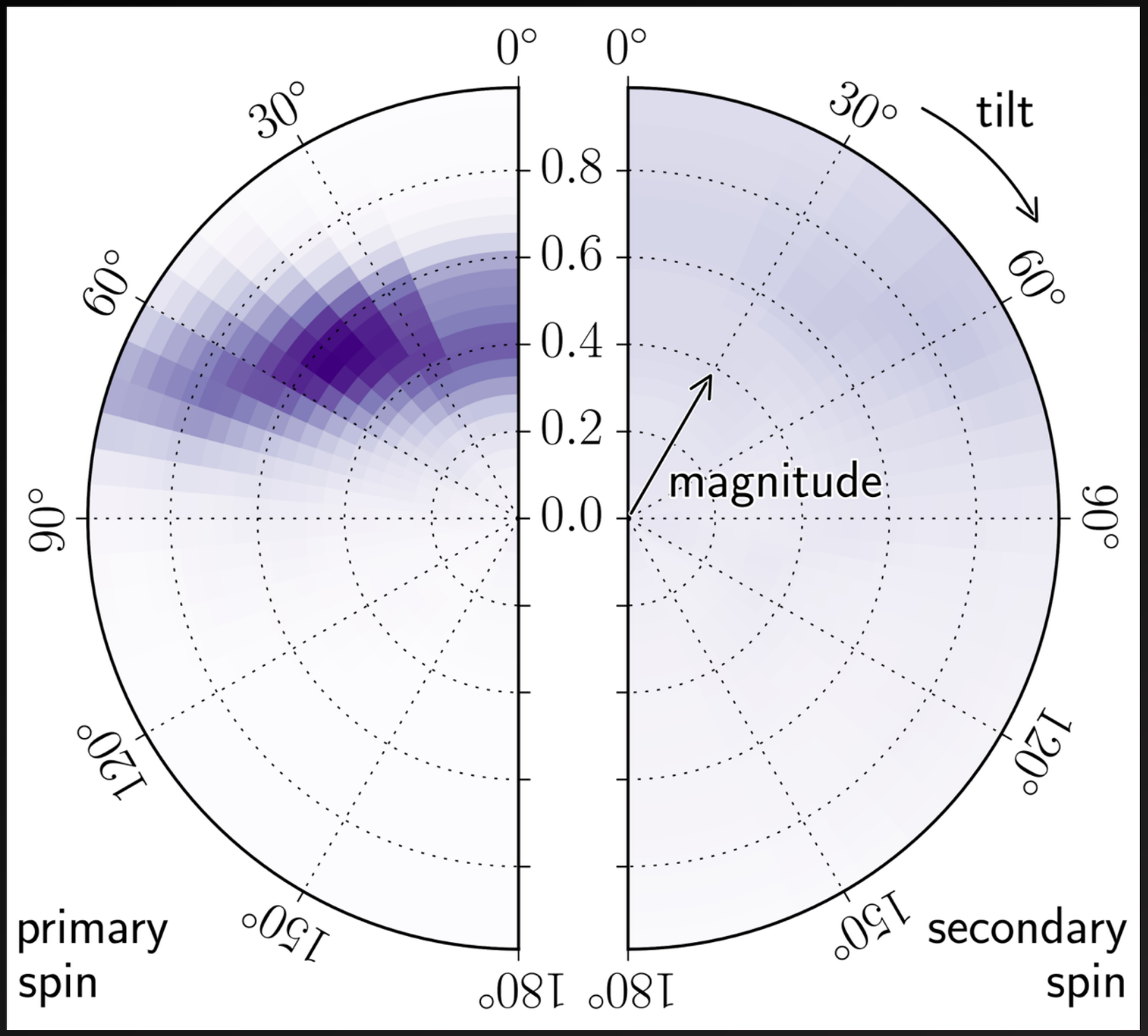
Black Hole Spins

LVT151012



Black Hole Spins

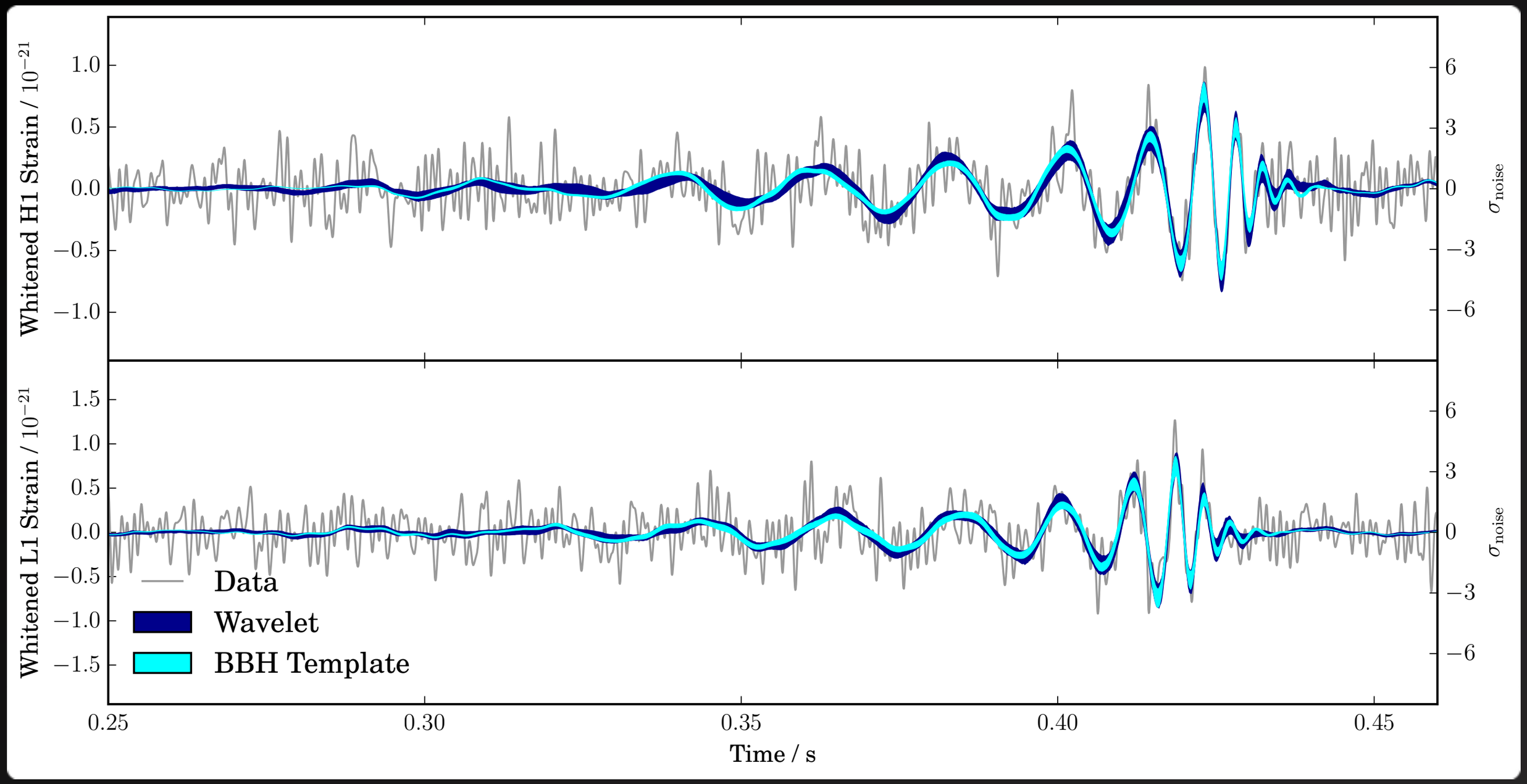
GW151226



At least one spinning BH

Abbott et al. (2016): PRL **116**, 241103

Signal Reconstructions

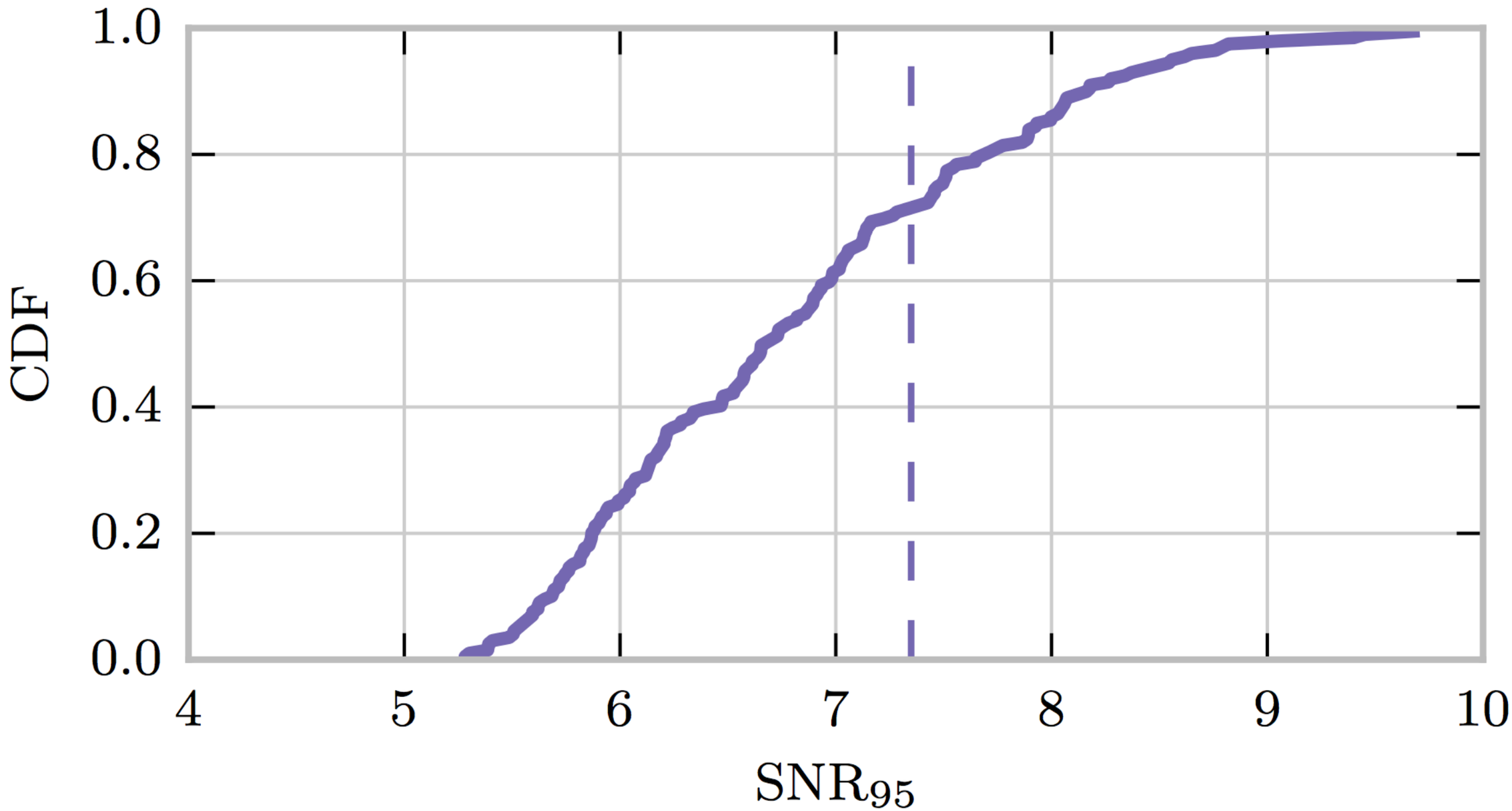


Abbott et al. (2016)
PRL **116**, 241102

Overlaps found to be 94 ± 1%.

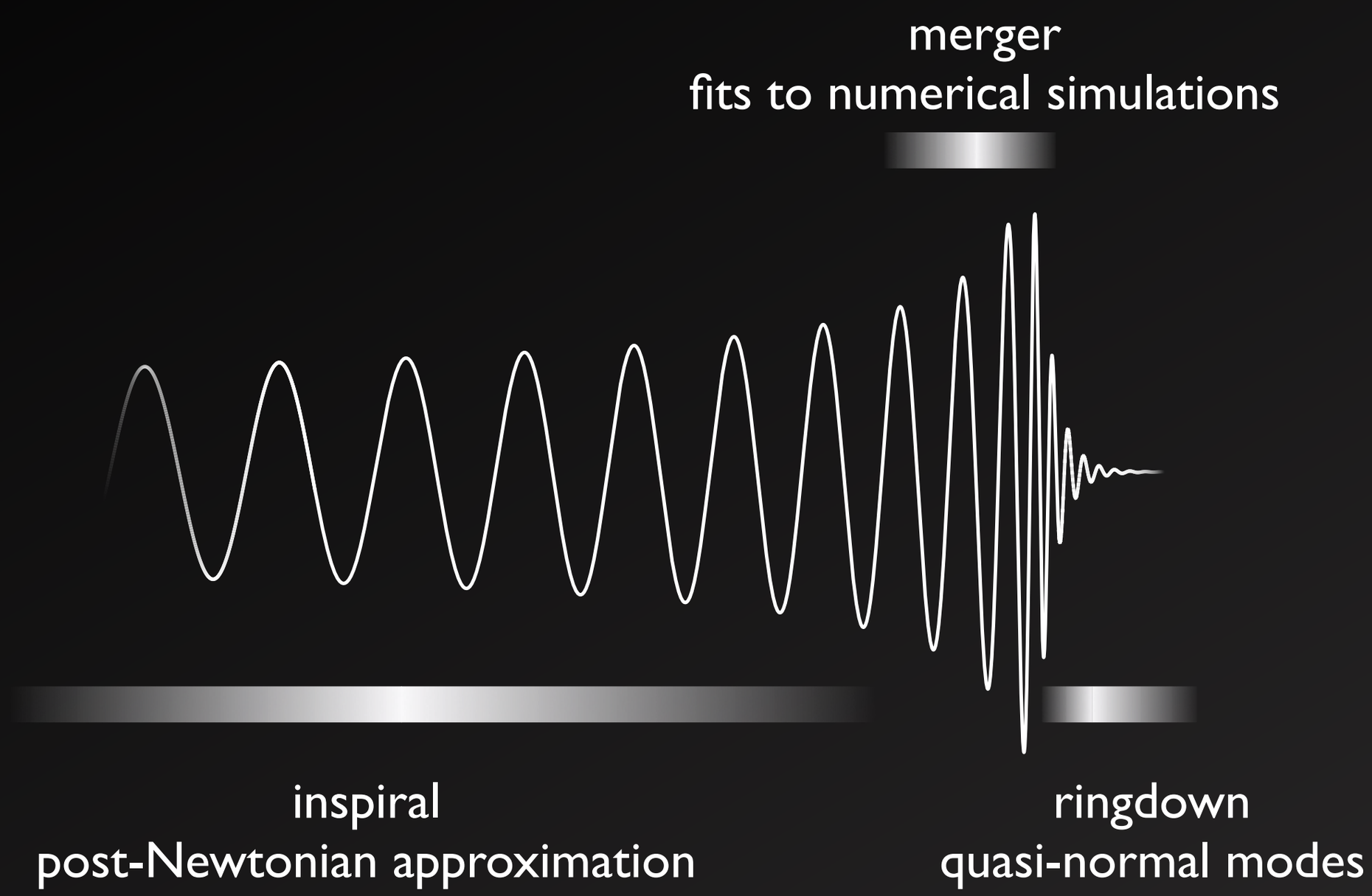
Consistent with a GW as described by general relativity.

Residual Test



Abbott et al. (2016)
PRL **116**, 221101

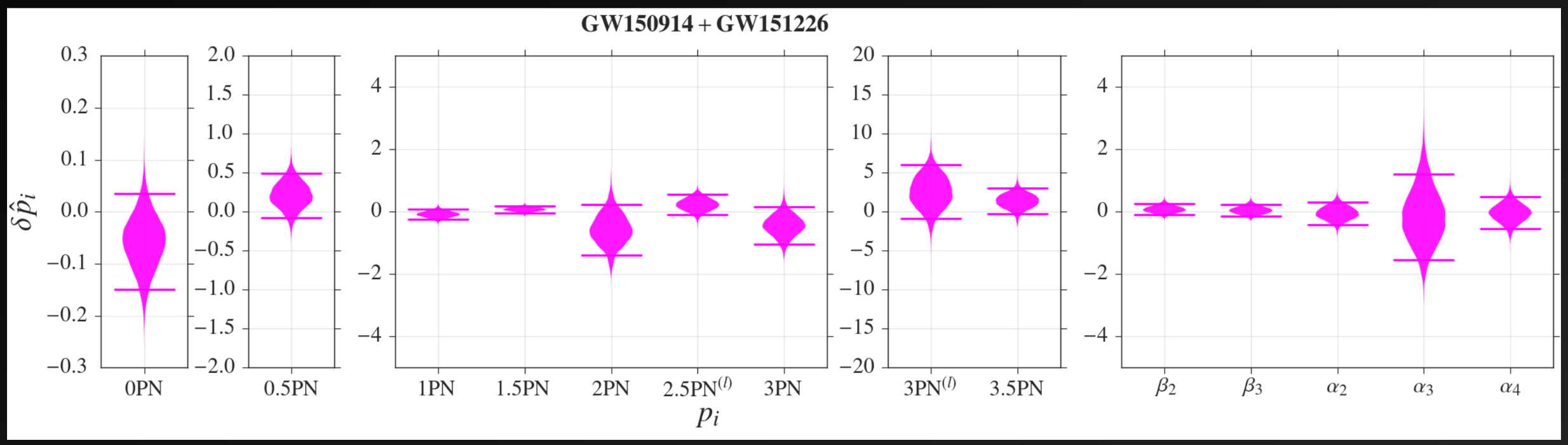
Constraining Deviations from GR



Constraining Deviations from GR

inspiral-merger corrections

Abbott et al. (2016)
PRL **116**, 221101



inspiral
corrections to post-Newtonian

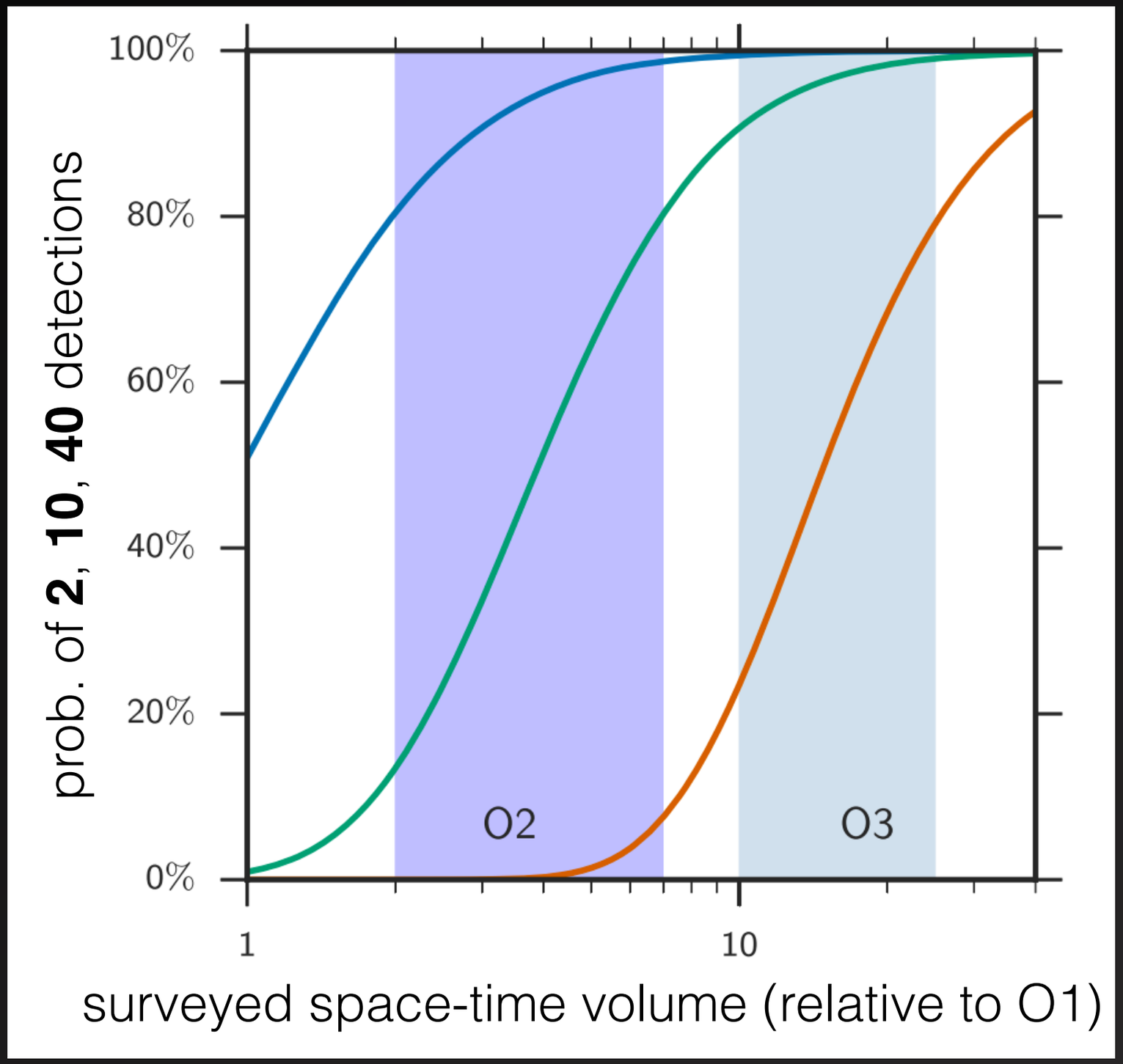
merger-ringdown
corrections

More to come…

~1 BBH/month detected in O1

BBH merger rate: ~9 - 240 Gpc^3yr^{-1}

Coming back online in November.



Abbott et al. (2016): PRL **116**, 241103

Summary

Confident detection of GWs from 2 binary black hole mergers.

- Binary black holes form and merge frequently.

Heavy ($\gtrsim$30 $M_\odot$) BHs exist.

- Likely formed in low metallicity environment, with weak winds.

Not all BHs have extremal spin.

Not all BHs have no spin.

Signals are consistent with GR.

Many more BBHs to come…

Questions?