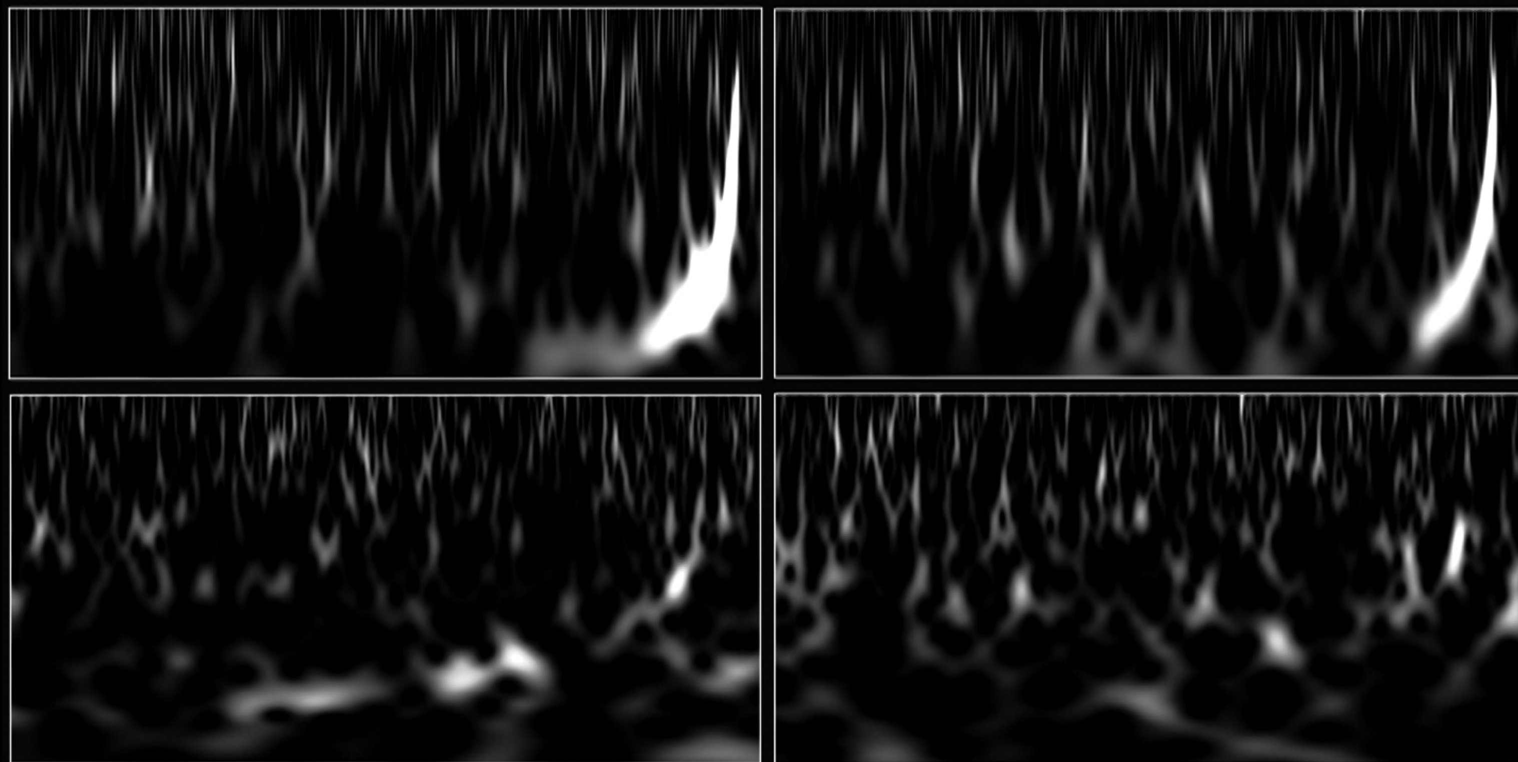
Title: Compact Binaries in the Era of Gravitational Wave Astronomy

Date: Mar 13, 2017 11:00 AM

URL: http://pirsa.org/17030016

Abstract: <p class="m-4660874918454726287inbox-inbox-p1">With two confident binary black hole mergers already detected in their first observing run, the advanced LIGO detectors are expected to detect hundreds more in coming years. We are poised to learn more about compact binary <span style="font-size:
10.0pt;color:#212121">(e.g., BNS, NSBH, BBH) formation than ever before, but doing so will demand both detailed characterization of individual events, and inference of the properties of the underlying population as a whole. I will present the methods behind the detection and characterization of LIGO's binary black hole mergers, what they have taught us about compact binaries thus far, and what they will potentially teach us about compact binary formation in the future.<o:p></o:p></p>

Compact Binaries in the Era of Gravitational Wave Astronomy



Ben Farr

Perimeter Institute

Science Questions

How are compact binaries formed?

What environments are they formed in?

Is general relativity valid in the strong-field regime?

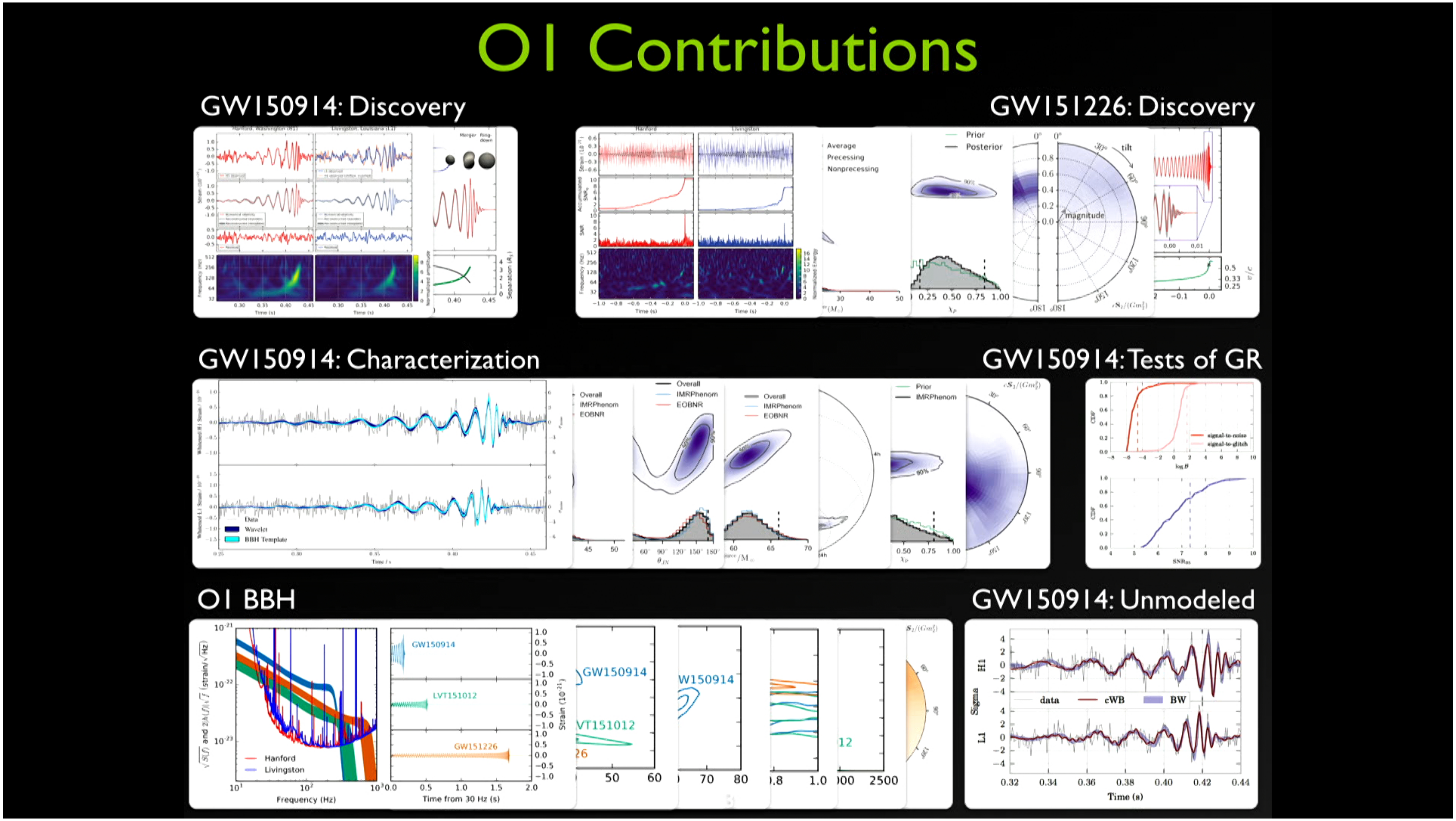
Outline

I. Gravitational wave primer

II. Compact binary detection and characterization methods

III. Constraining binary formation channels

IV. Constraining deviations from general relativity


O1 Contributions
GW150914: Discovery
GW151226: Discovery
GW150914: Characterization
GW150914: Tests of GR
O1 BBH
GW150914: Unmodeled
Hanford
Livingston
Frequency (Hz)
GW150914
LVT151012
GW151226
Time from 30 Hz (s)
data
cWB
BW
Time (s)

Gravitational Waves

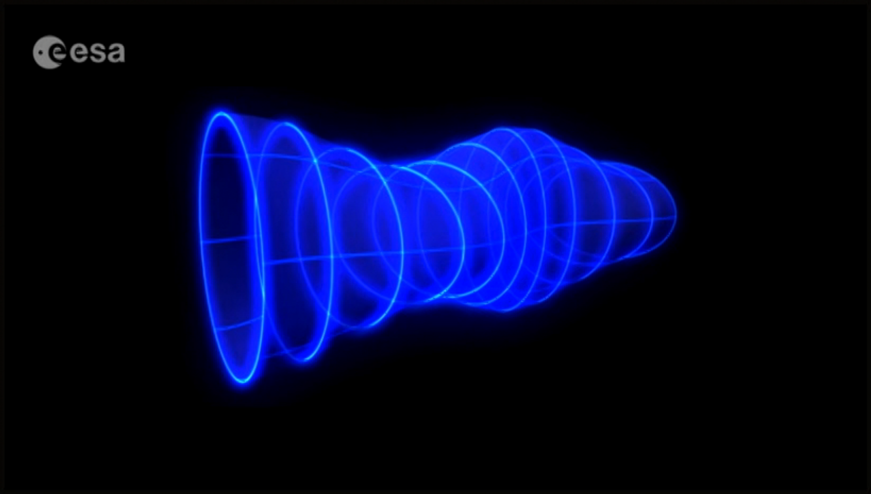
$$h_{\mu\nu} = \frac{2G}{rc^4}\ddot{I}_{\mu\nu}(\omega, t)$$

Strain on spacetime.

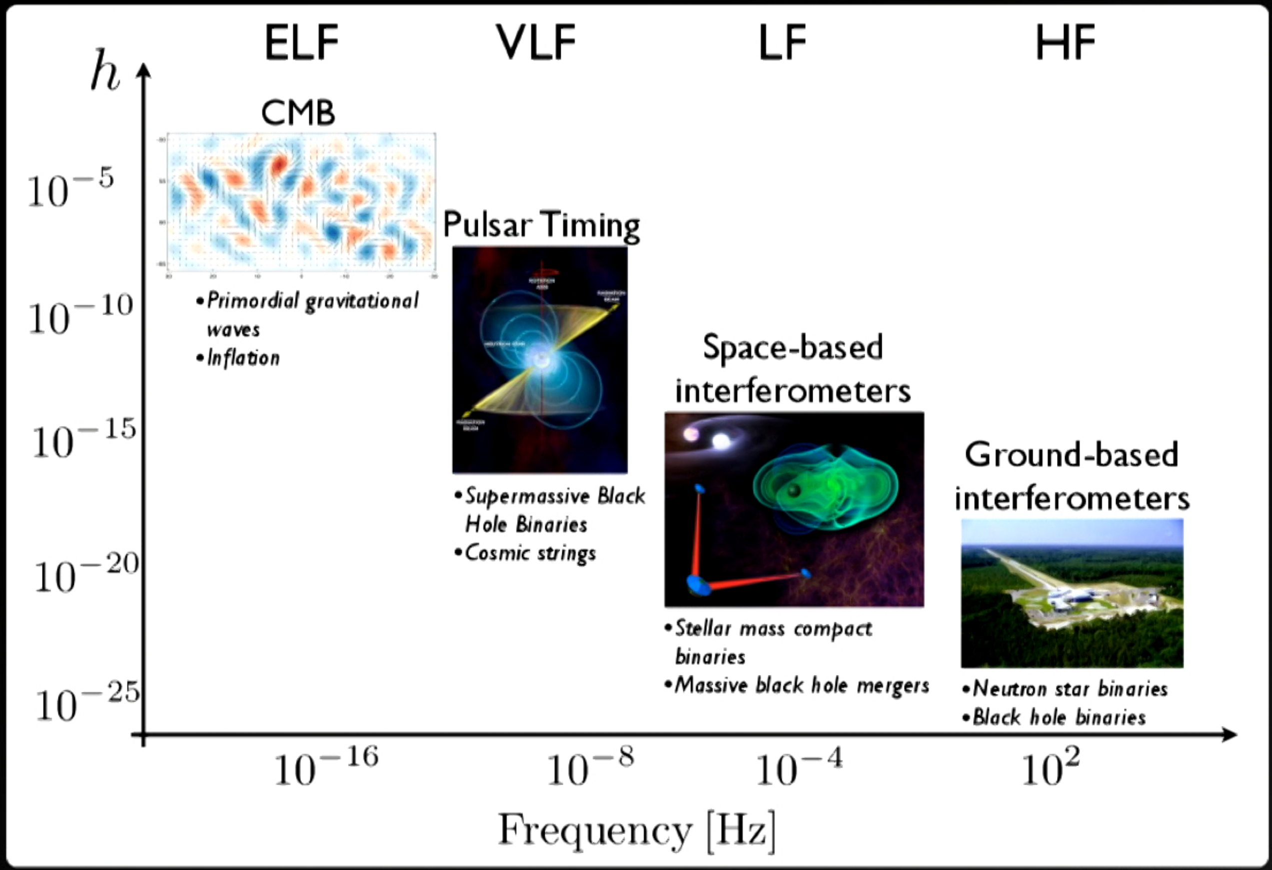
Generated by time-varying quadrupole moment.

Propagate at speed of light.

Unimpeded by matter.



The GW Spectrum



Credit: NANOGrav

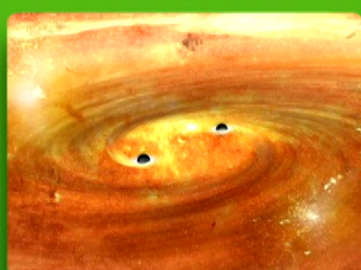
6

Compact Binaries

Binary Neutron Star

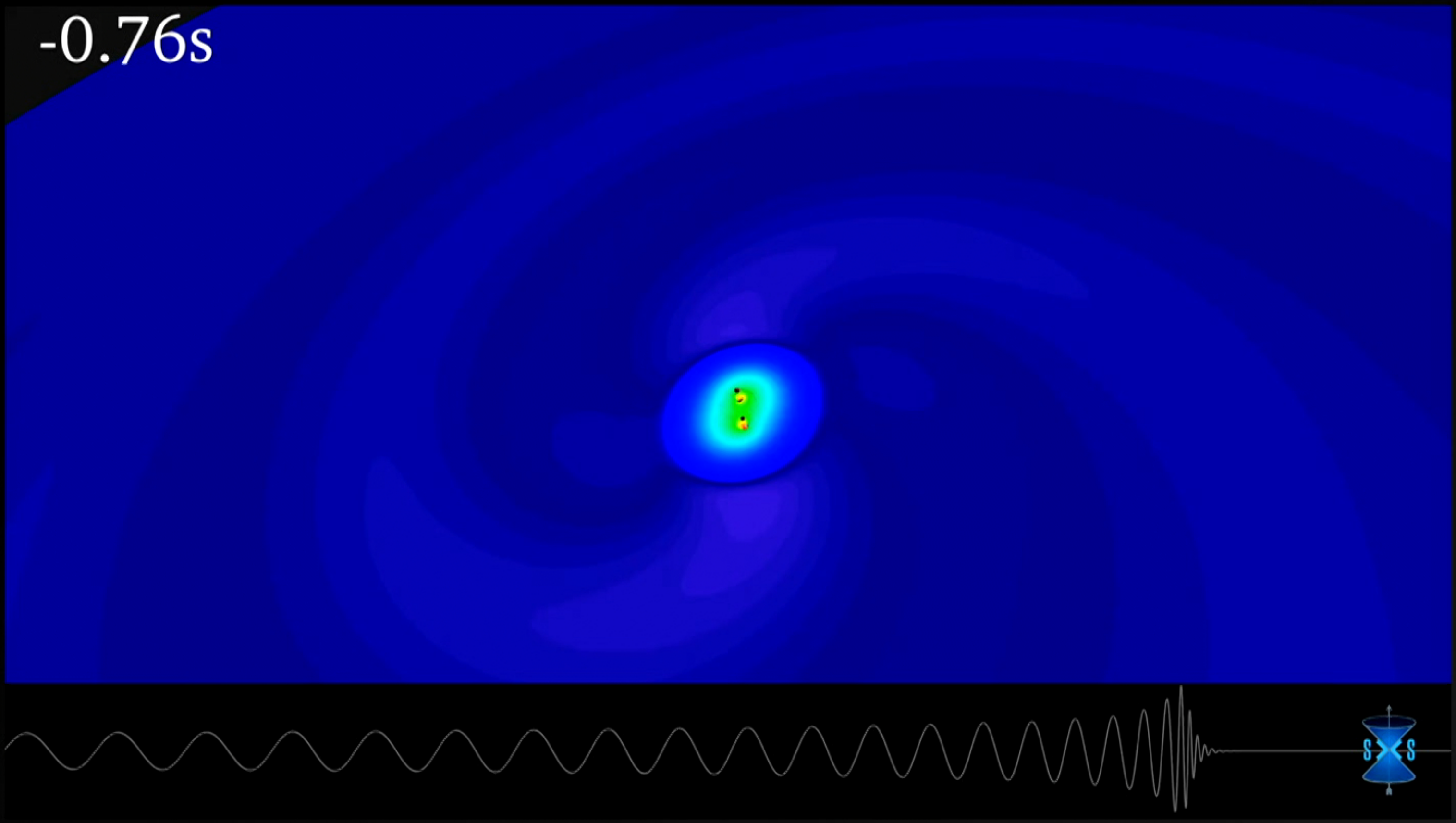
Black Hole-Neutron Star

Binary Black Hole



7

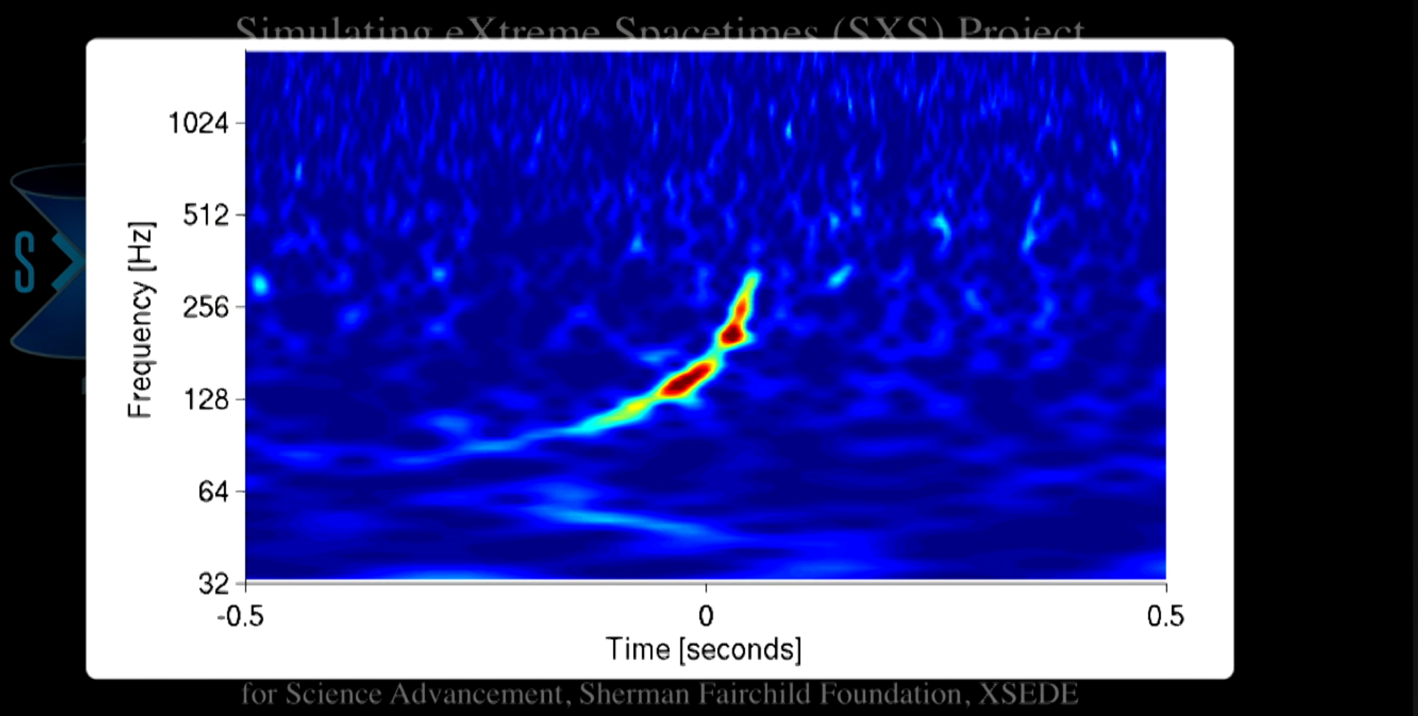
Compact Binary Mergers



credit: Simulating eXtreme Spacetimes (SXS) Project

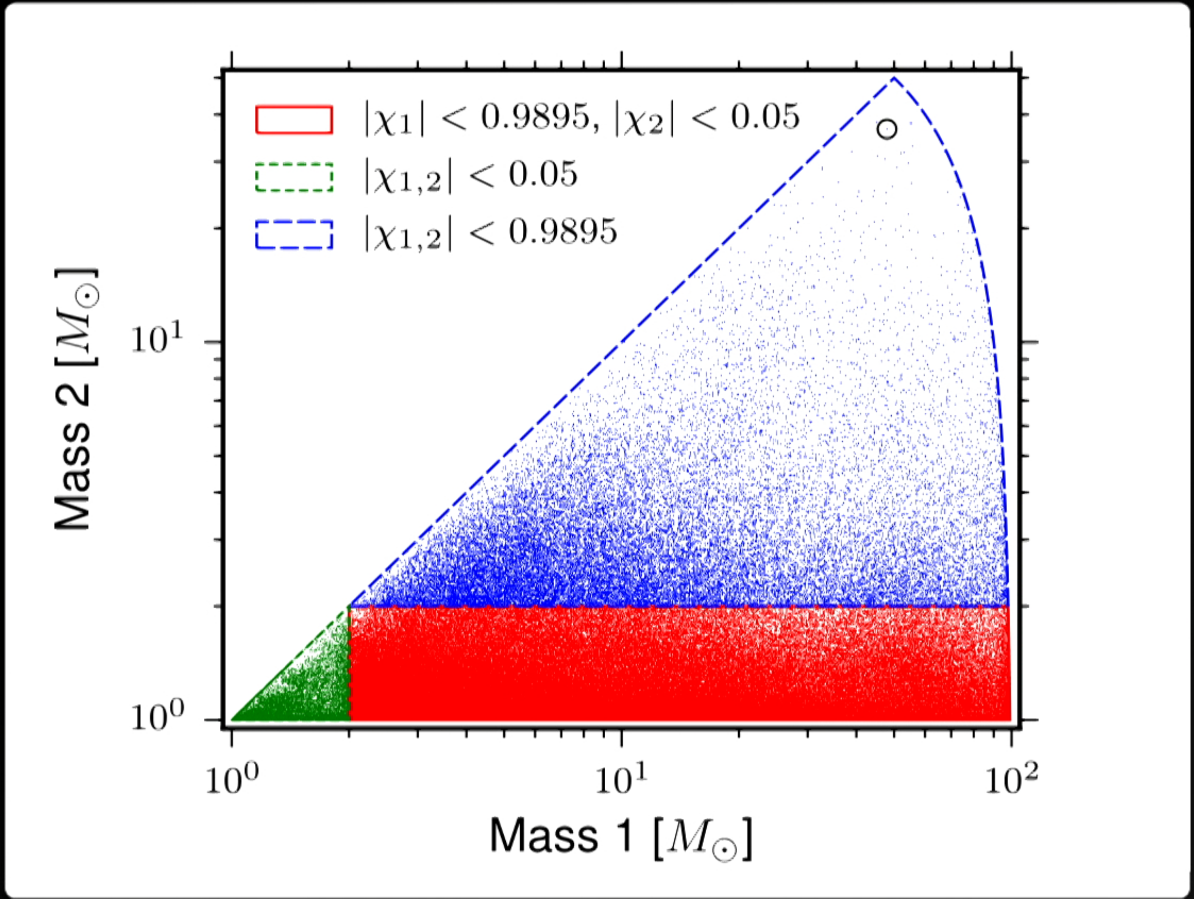
8

Compact Binary Mergers



credit: Simulating eXtreme Spacetimes (SXS) Project

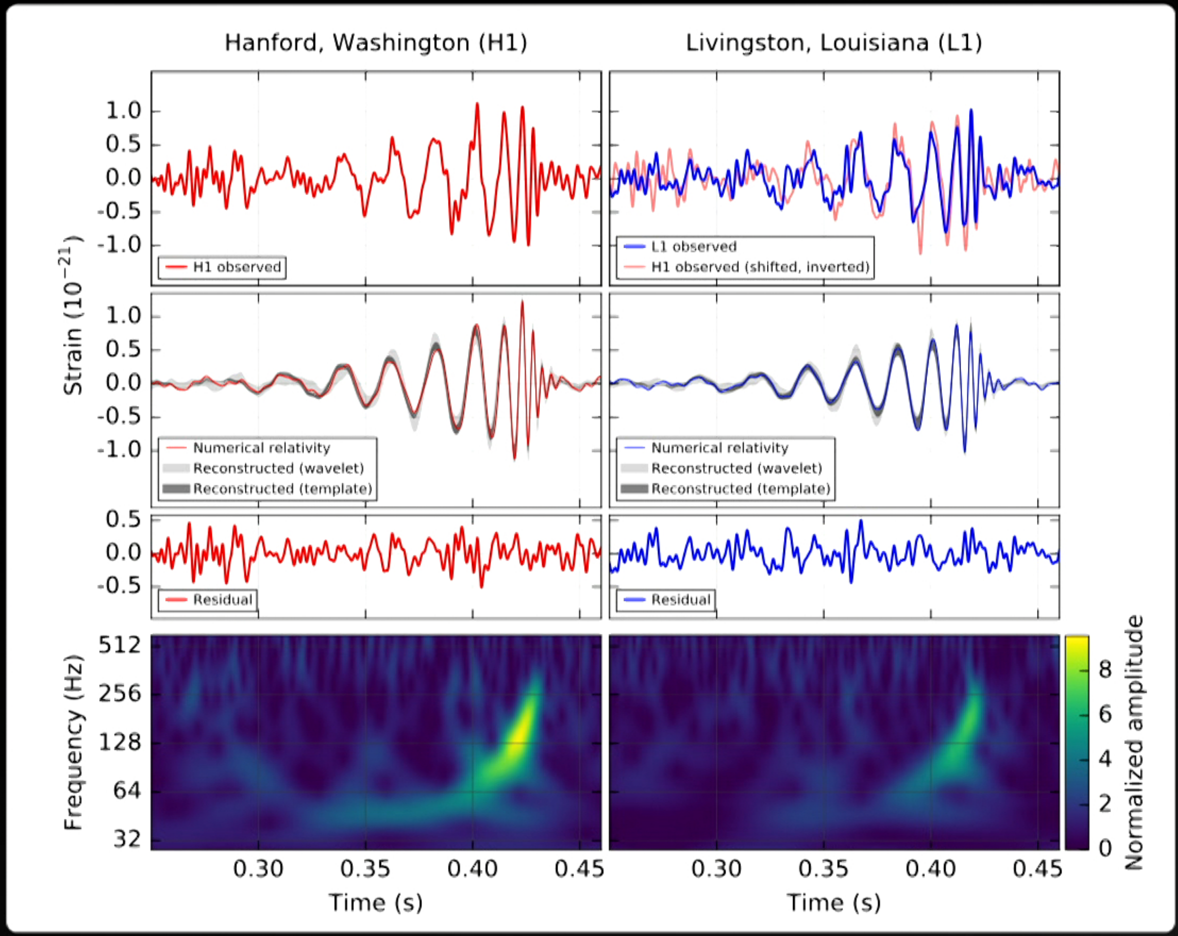
Compact Binary Search



9

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

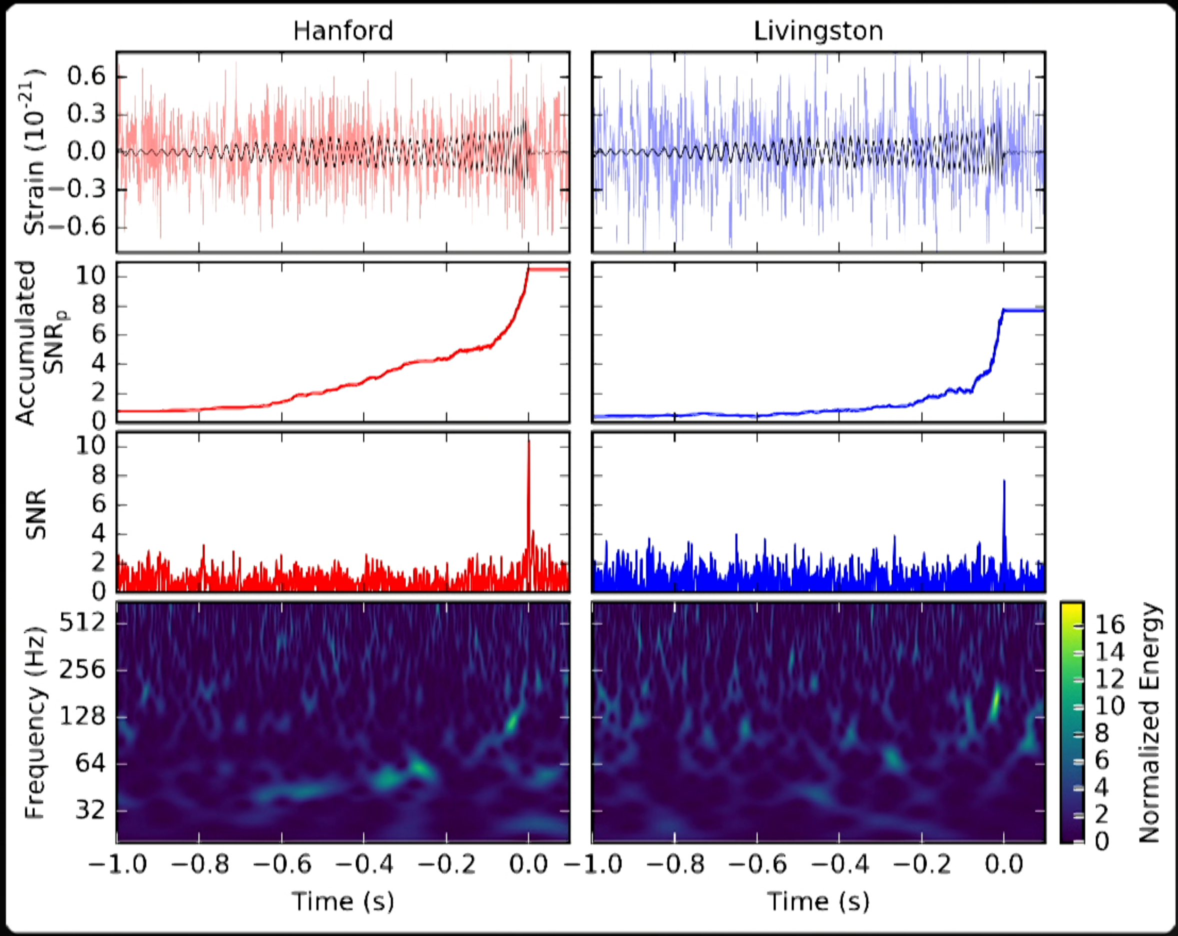
GW150914



10

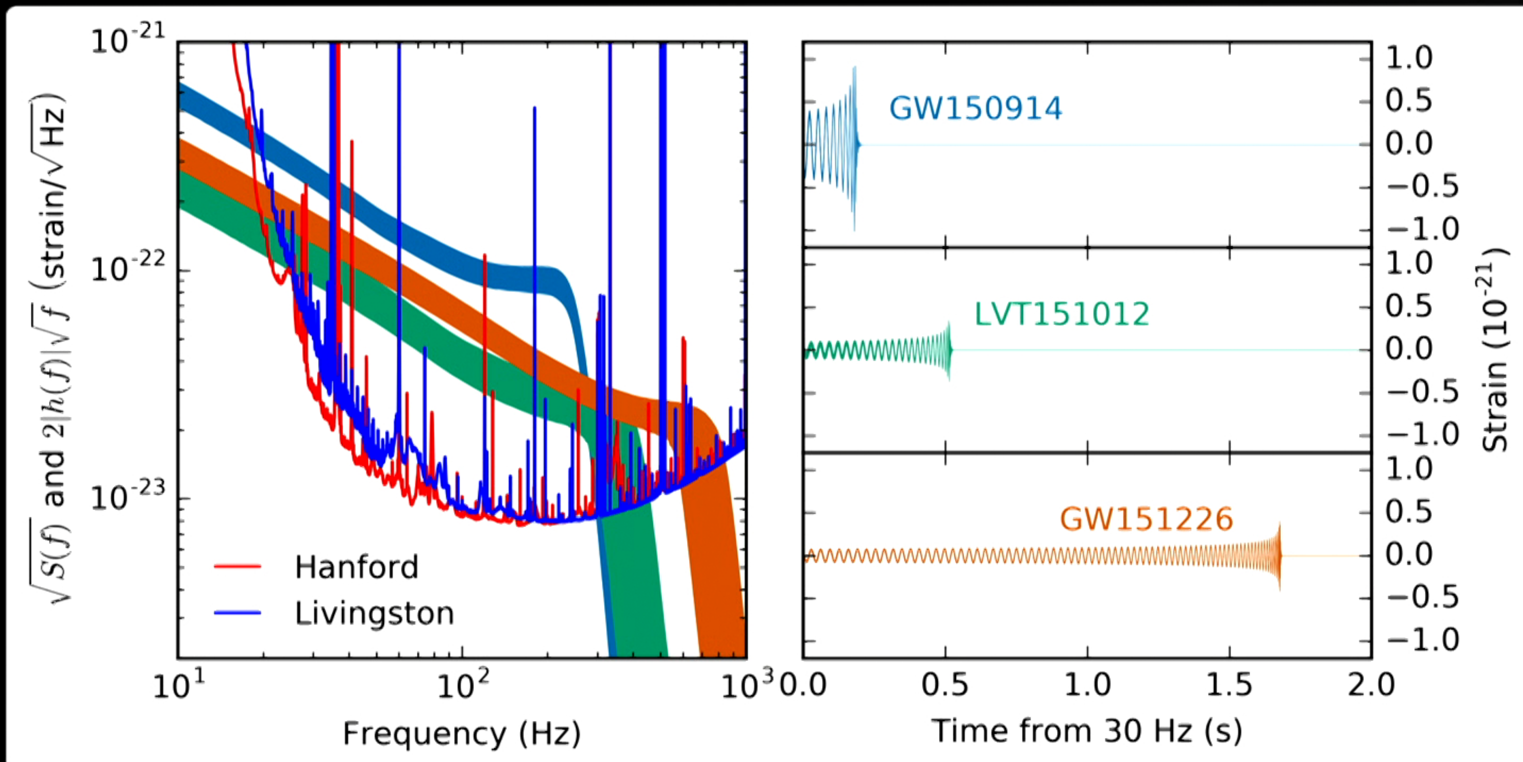
Abbott et al. (2016):
PRL 116, 241103

GW151226



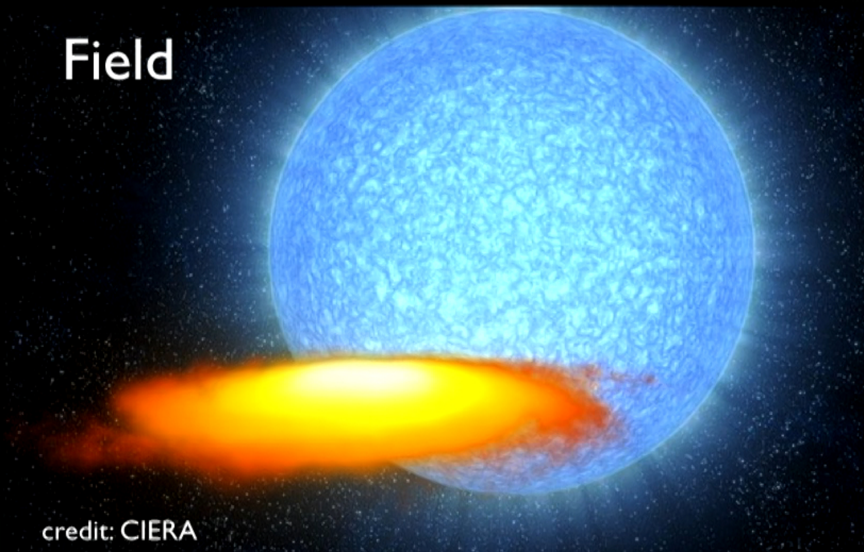
11

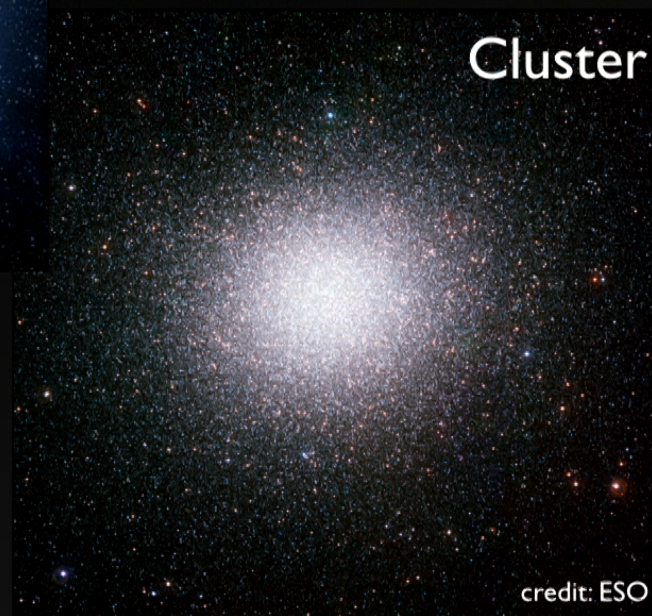
2.87 BBHs in O1



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

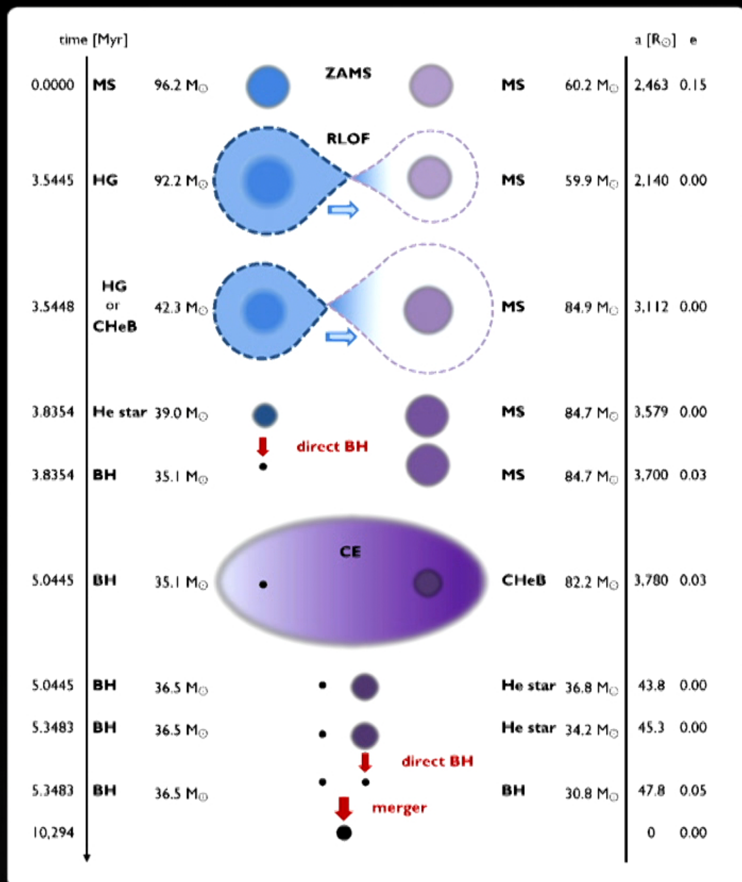
Where did they come from?



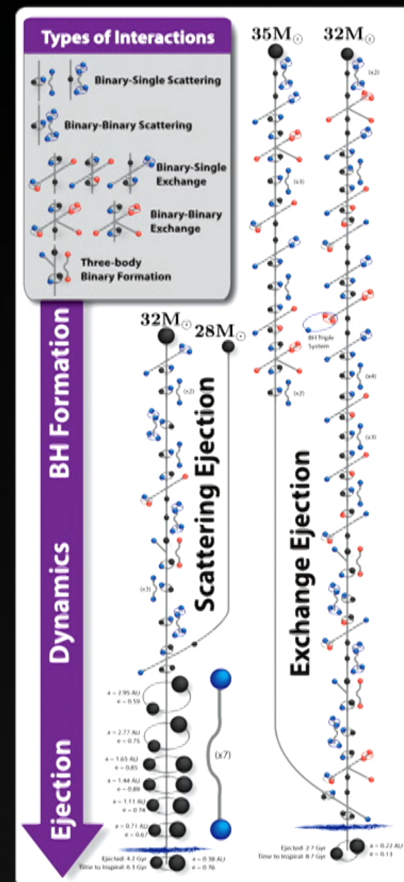


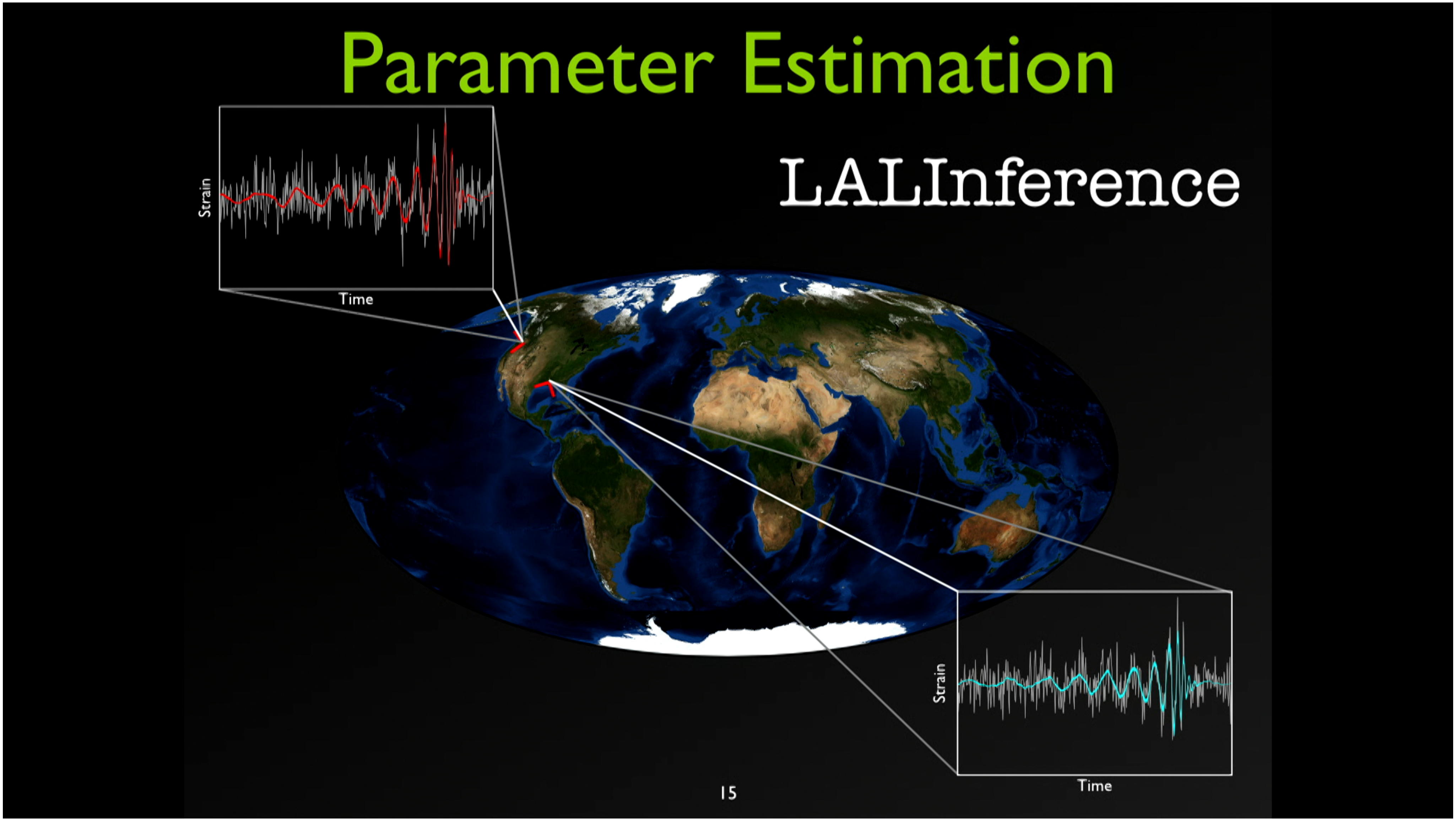
Compact Binary Formation Channels

Field



Cluster




Parameter Estimation
LALInference
Strain
Time
Strain
Time
15

Bayesian Inference

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

Posterior

Prior

Likelihood

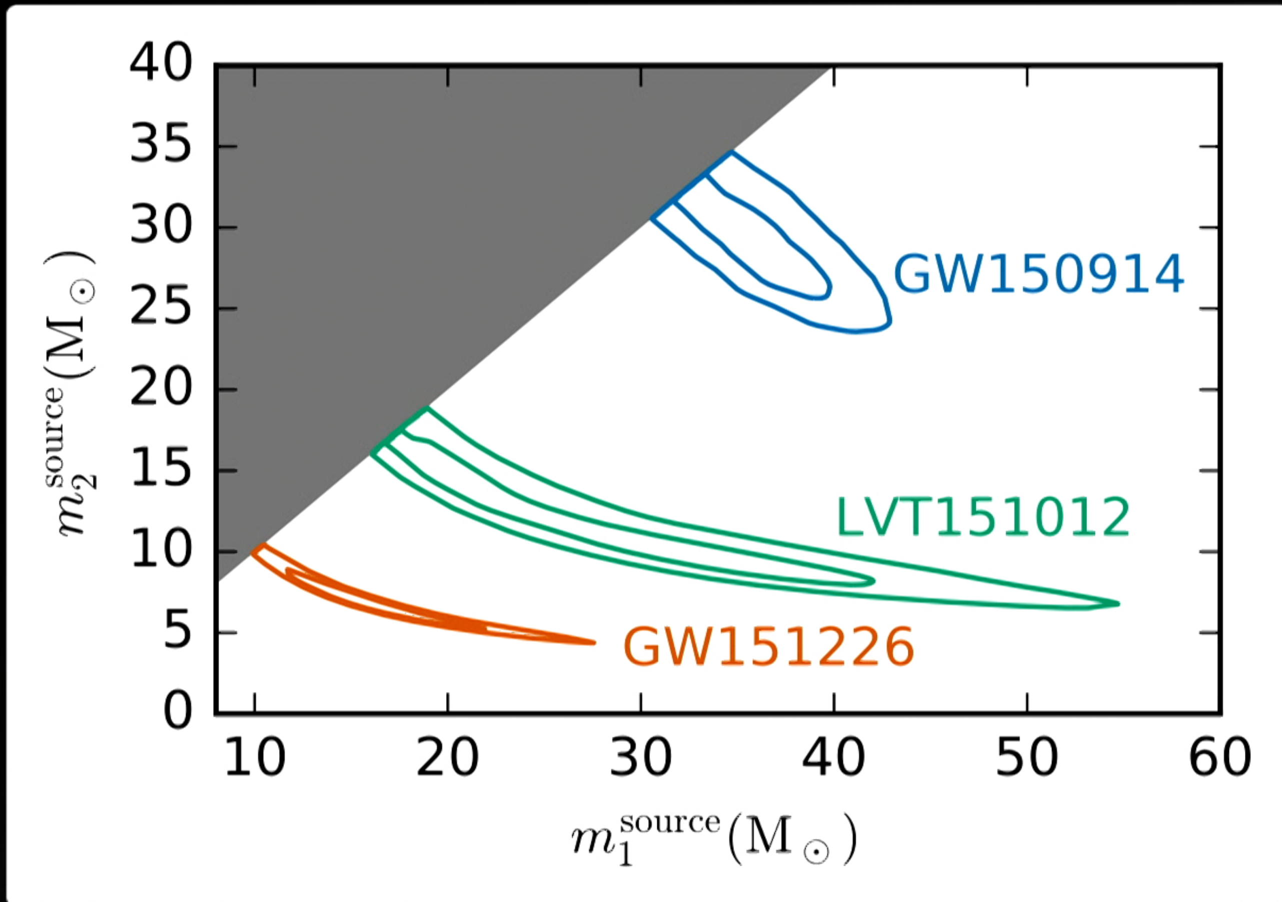
16

15 Model Parameters

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

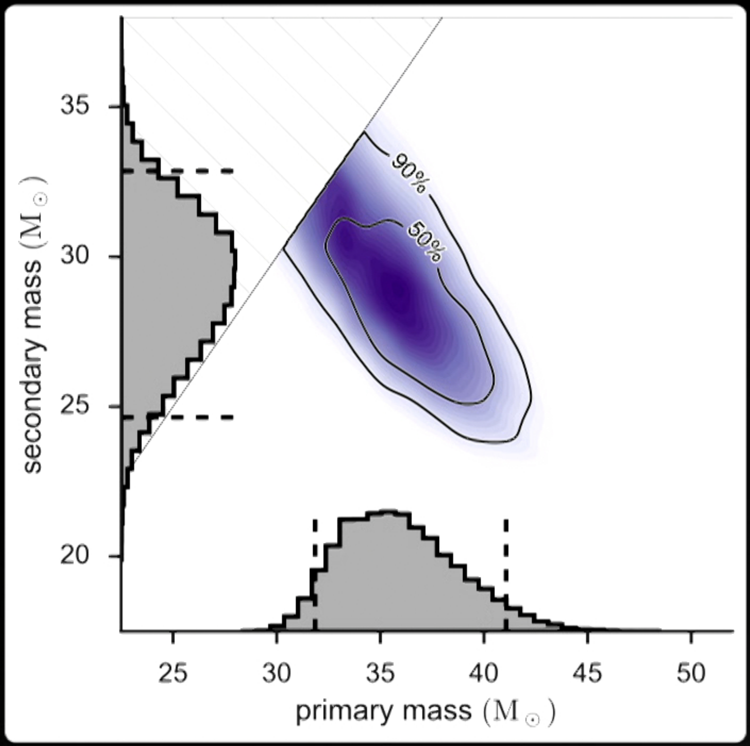
17

Black Hole Masses

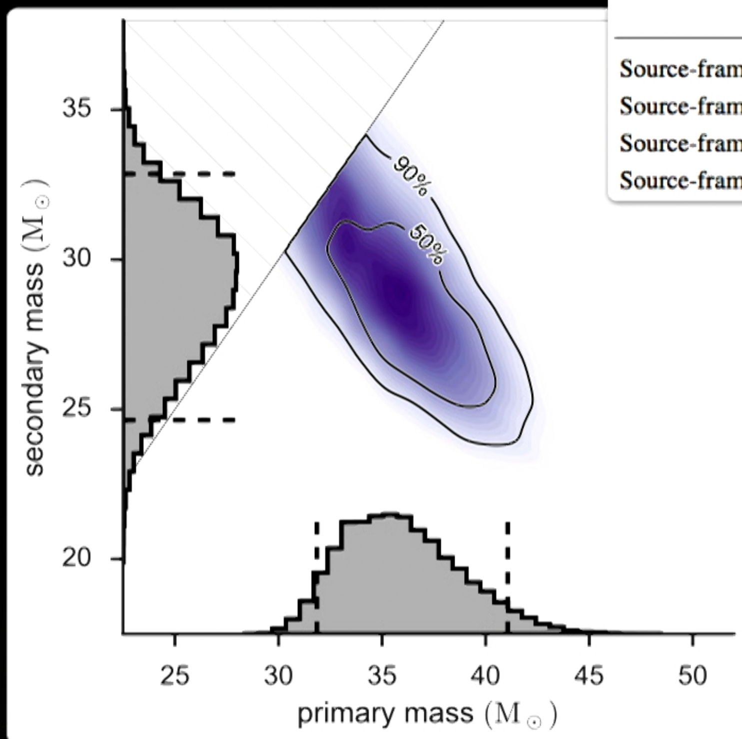


Abbott et al. (2016):
PRX 6, 041015

GW150914 Component Masses



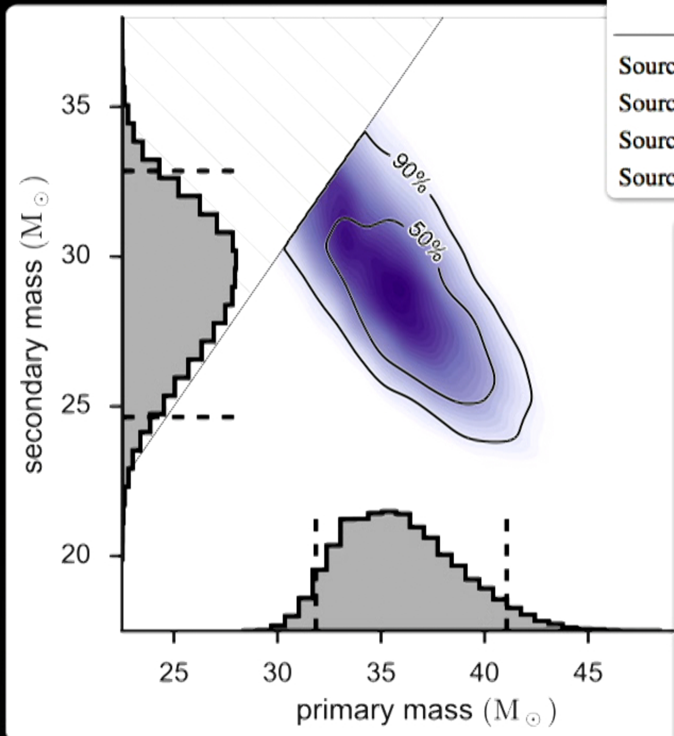
GW150914 Component Masses

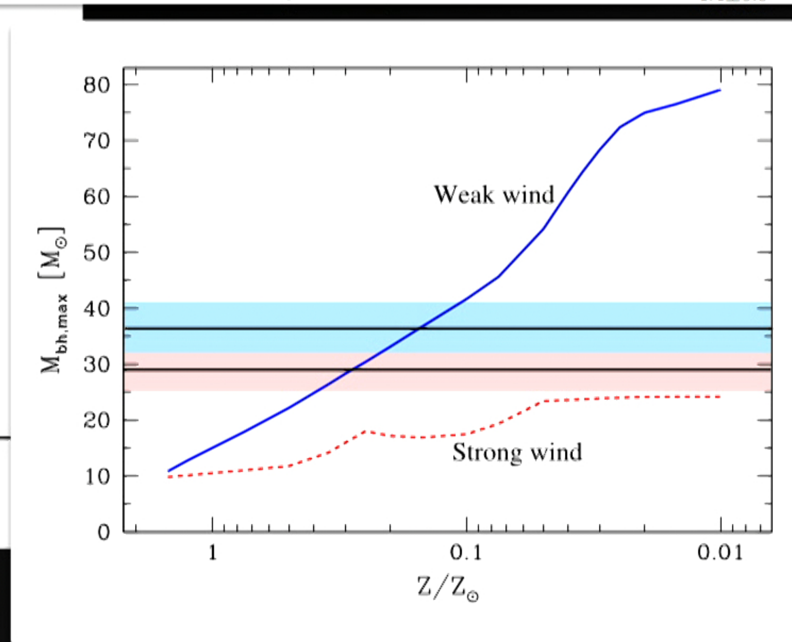


	Overall
Source-frame total mass $M^{\rm source}/{\rm M}_\odot$	$64.8^{+4.6\pm1.0}_{-3.9\pm0.5}$
Source-frame chirp mass $\mathcal{M}^{\rm source}/{\rm M}_\odot$	$27.9^{+2.1\pm0.4}_{-1.7\pm0.2}$
Source-frame primary mass $m_1^{\rm source}/{\rm M}_\odot$	$35.7^{+5.4\pm1.1}_{-3.8\pm0.0}$
Source-frame secondary mass $m_2^{\rm source}/{\rm M}_\odot$	$29.1^{+3.8\pm0.2}_{-4.4\pm0.5}$

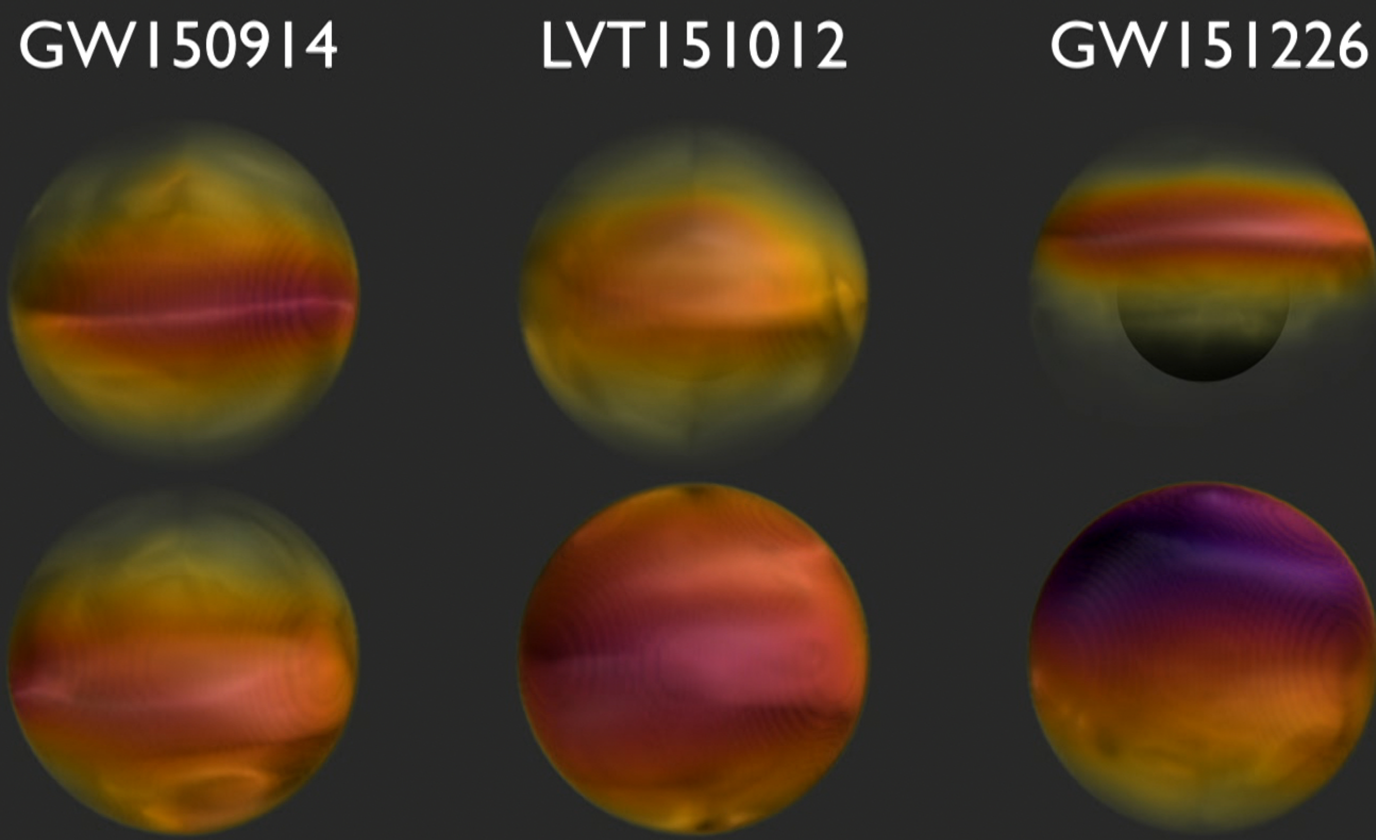
GW150914 Component Masses

	Overall
Source-frame total mass $M^{\rm source}/{\rm M}_\odot$	$64.8^{+4.6\pm1.0}_{-3.9\pm0.5}$
Source-frame chirp mass $\mathcal{M}^{\rm source}/{\rm M}_\odot$	$27.9^{+2.1\pm0.4}_{-1.7\pm0.2}$
Source-frame primary mass $m_1^{\rm source}/{\rm M}_\odot$	$35.7^{+5.4\pm1.1}_{-3.8\pm0.0}$
Source-frame secondary mass $m_2^{\rm source}/{\rm M}_\odot$	$29.1^{+3.8\pm0.2}_{-4.4\pm0.5}$





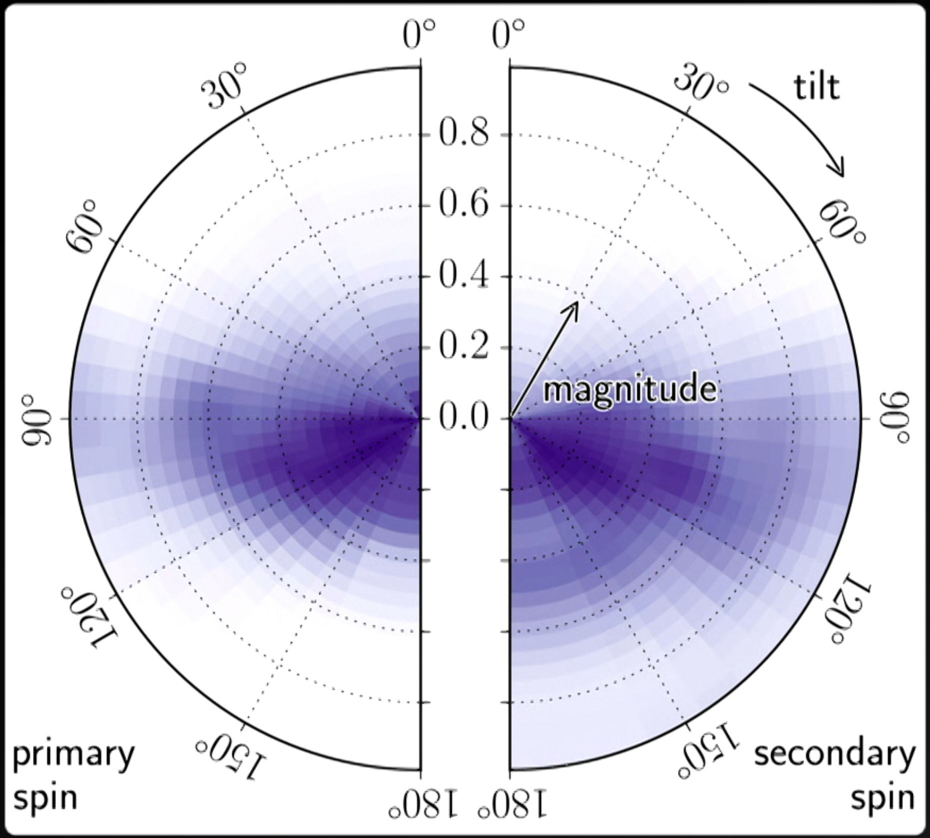
Black Hole Spins



20

Black Hole Spins

GW150914



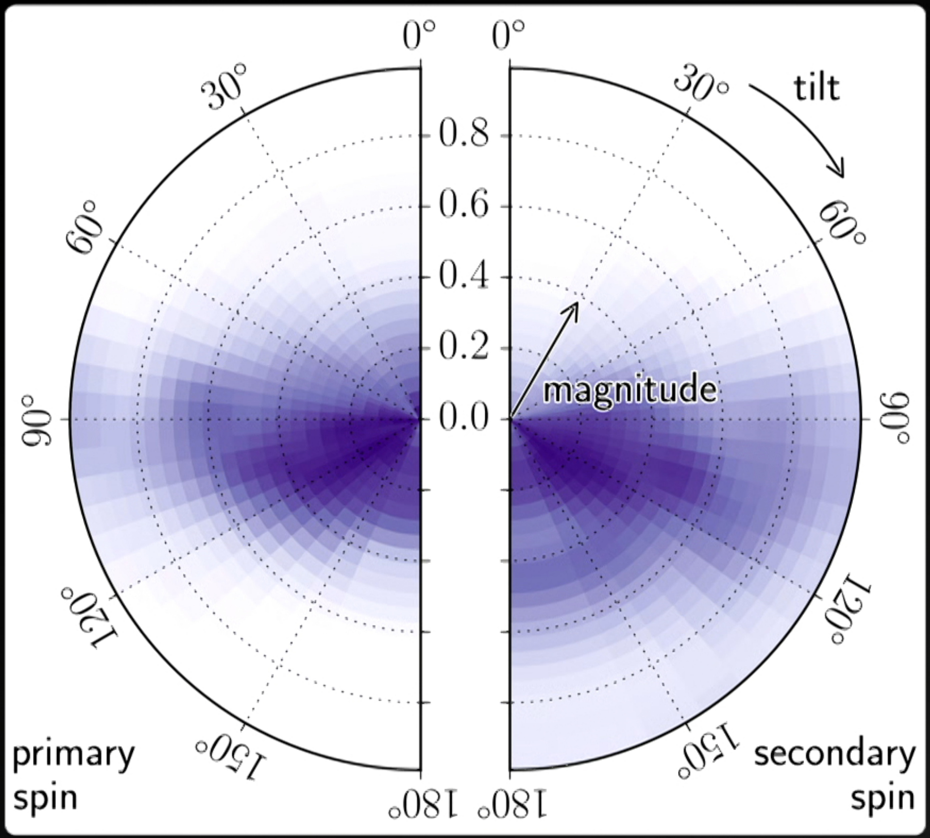
Abbott et al. (2016): PRL 116, 241102

21

Black Hole Spins

GW150914

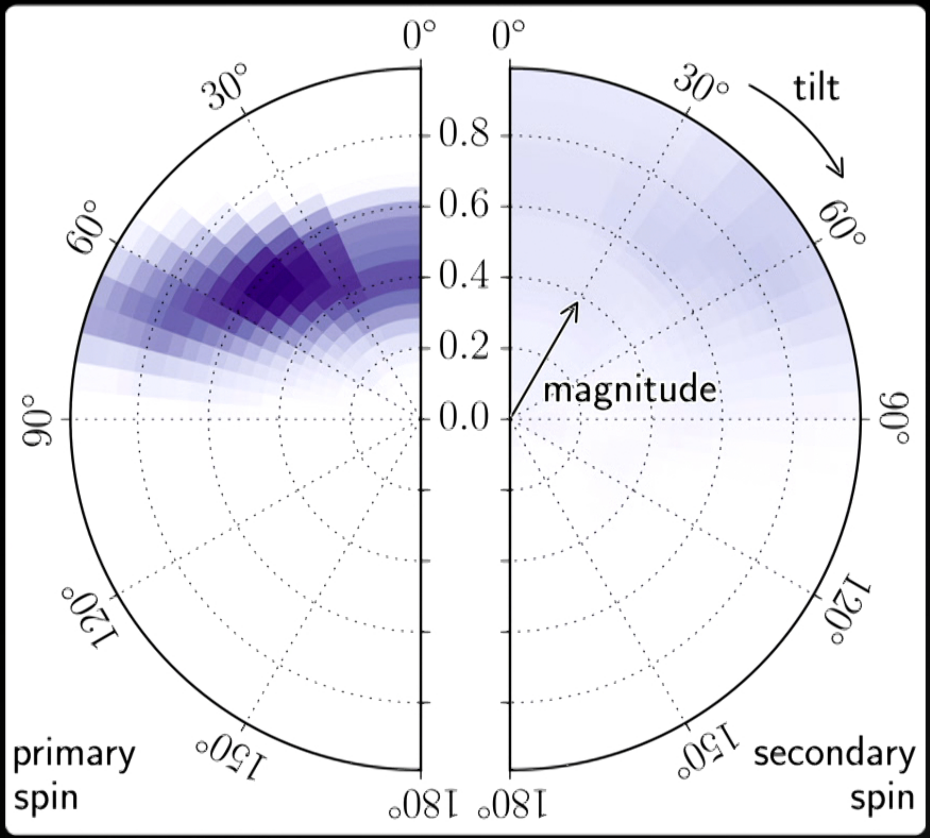
BH spin
not aligned and
extremal



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

Black Hole Spins

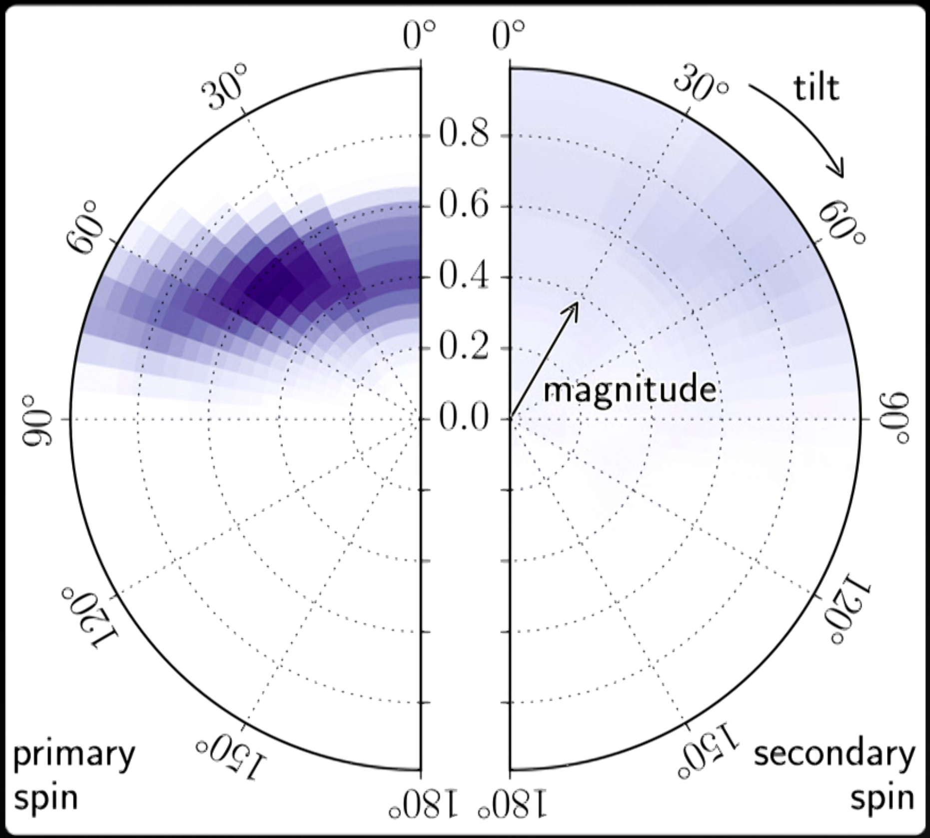
GW151226



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

Black Hole Spins

GW151226



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

At least one spinning BH

Lessons from O1

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…

Next Step: Population Inference

Goal: Use multiple detections to infer population characteristics

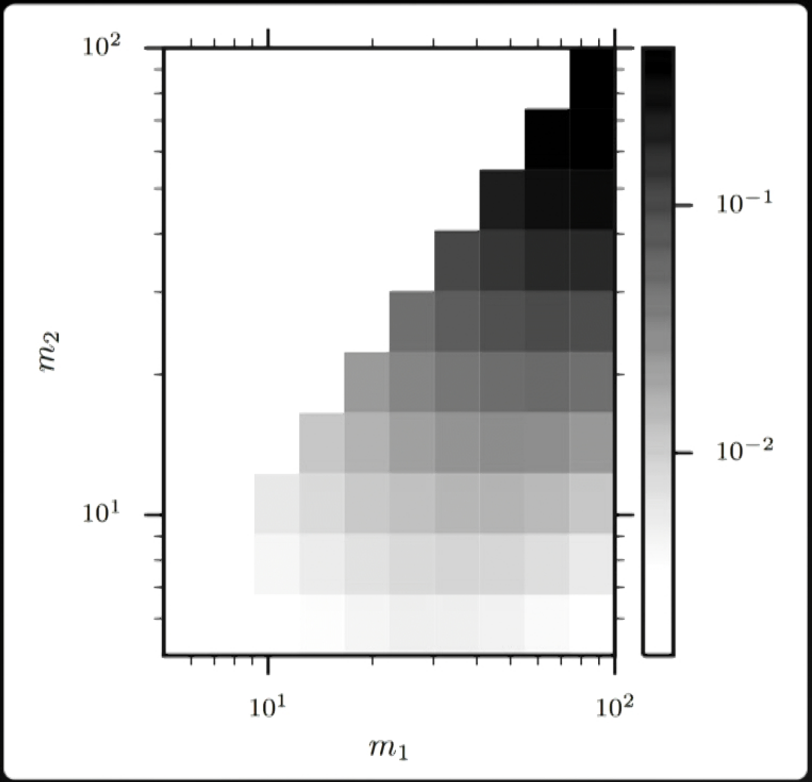
Challenges:

- We never precisely characterize sources
- Detections may sparsely cover parameters space

Population Inference

Parameterized Model:

$$\Gamma_{\boldsymbol{\alpha}}(\boldsymbol{\theta}) \begin{cases} \exp(\alpha_1) & \boldsymbol{\theta} \in \Delta_1 \\ \exp(\alpha_2) & \boldsymbol{\theta} \in \Delta_2 \\ \dots & \\ \exp(\alpha_K) & \boldsymbol{\theta} \in \Delta_K \\ 0 & \text{otherwise} \end{cases}$$



Gaussian Process Prior

Gaussian process to regularize the histogram

$$p(\boldsymbol{\alpha}) = p(\boldsymbol{\alpha}|\mu, \lambda)$$
$$= \mathcal{N}[\boldsymbol{\alpha}; \boldsymbol{\mu}, K(\{\Delta_j\}, \boldsymbol{\lambda})]$$

$\boldsymbol{\mu}, \boldsymbol{\lambda}$: hyperparameters for the mean and length scales of the GP,

Hierarchical Bayesian Inference

Population posterior density:

$$p(\vec{\alpha}|\{d_i\}) \propto p(\vec{\alpha}) \int p(\{d_i\}|\{\theta_i\}) p(\{\theta_i\}|\vec{\alpha}) d\{\theta_i\}$$

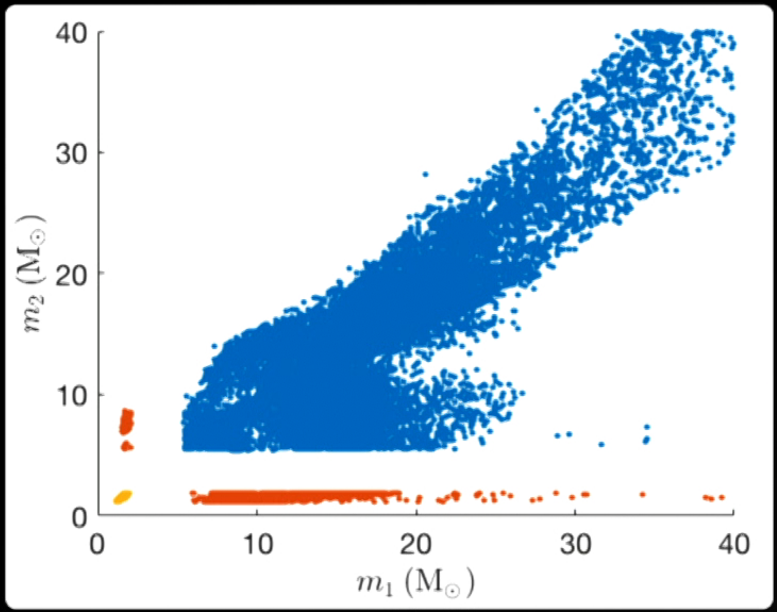
Gaussian process prior

Single-event likelihood

Single-event (population-based) prior

$$p(\{\boldsymbol{\theta}_i\}|\boldsymbol{\alpha}) = \exp\left(-\int \hat{\Gamma}_{\boldsymbol{\alpha}}(\boldsymbol{\theta}) d\boldsymbol{\theta}\right) \prod_i \hat{\Gamma}_{\boldsymbol{\alpha}}(\boldsymbol{\theta}_i)$$

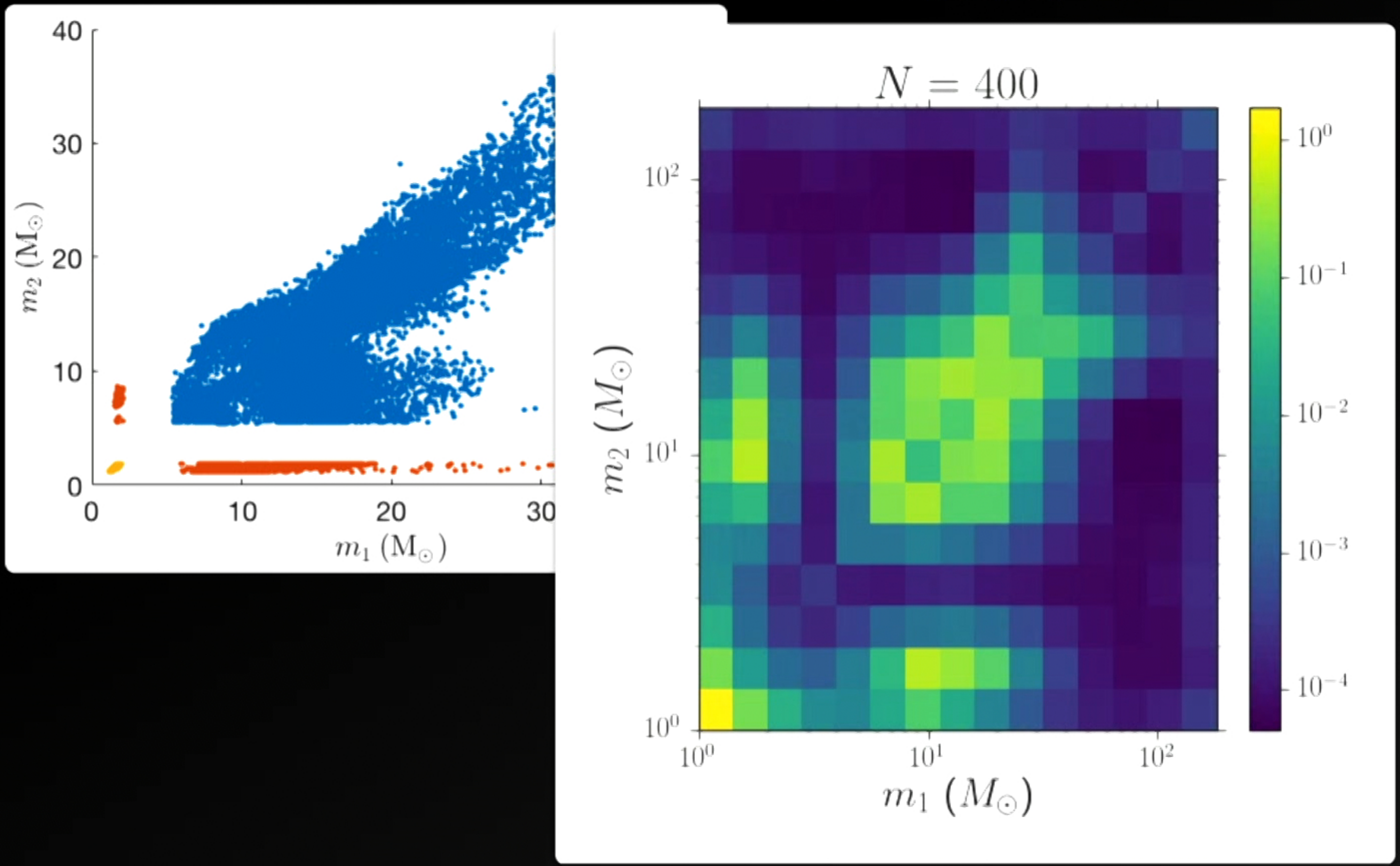
Mass Distribution



Mandel, Farr, Colonna et al. (2016)

27

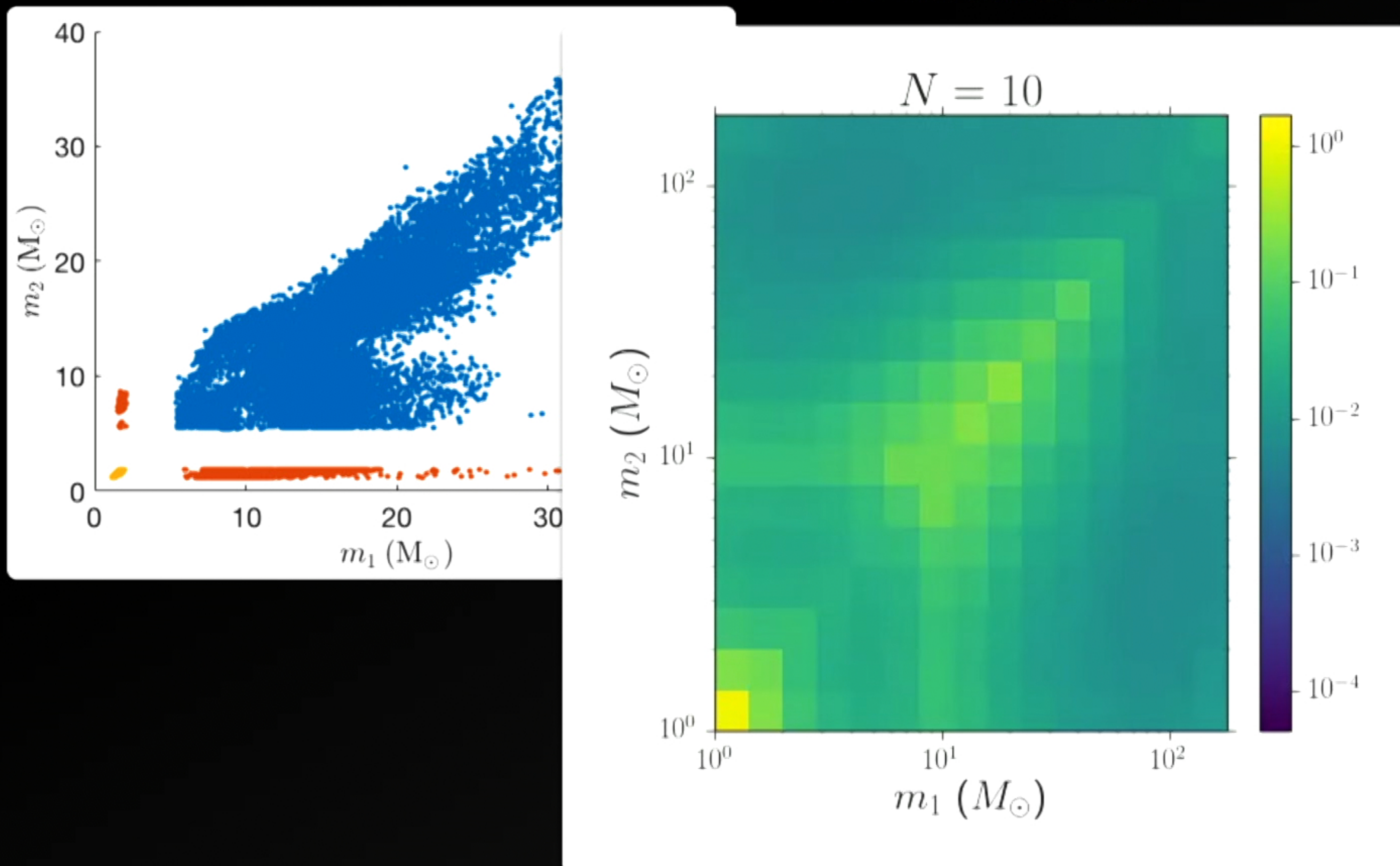
Mass Distribution



Mandel, Farr, Colonna et al. (2016)

27

Mass Distribution



Mandel, Farr, Colonna et al. (2016)

Mass Distribution

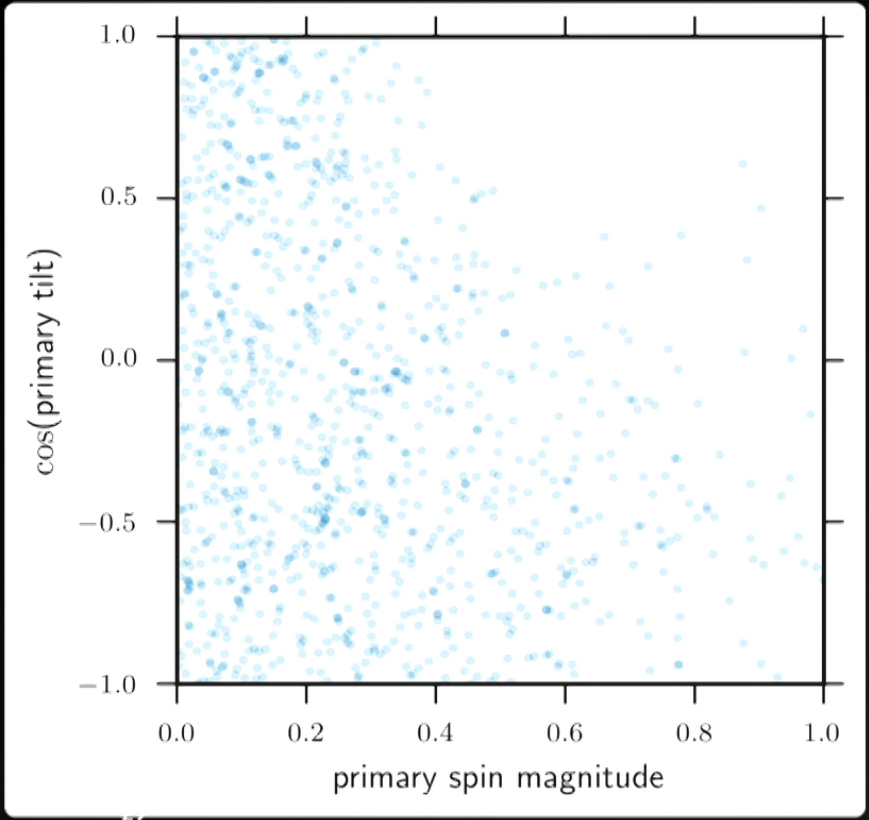
Strong features become present after ~10s of detections

If mass gap exists, the data may support it after ~80 events.

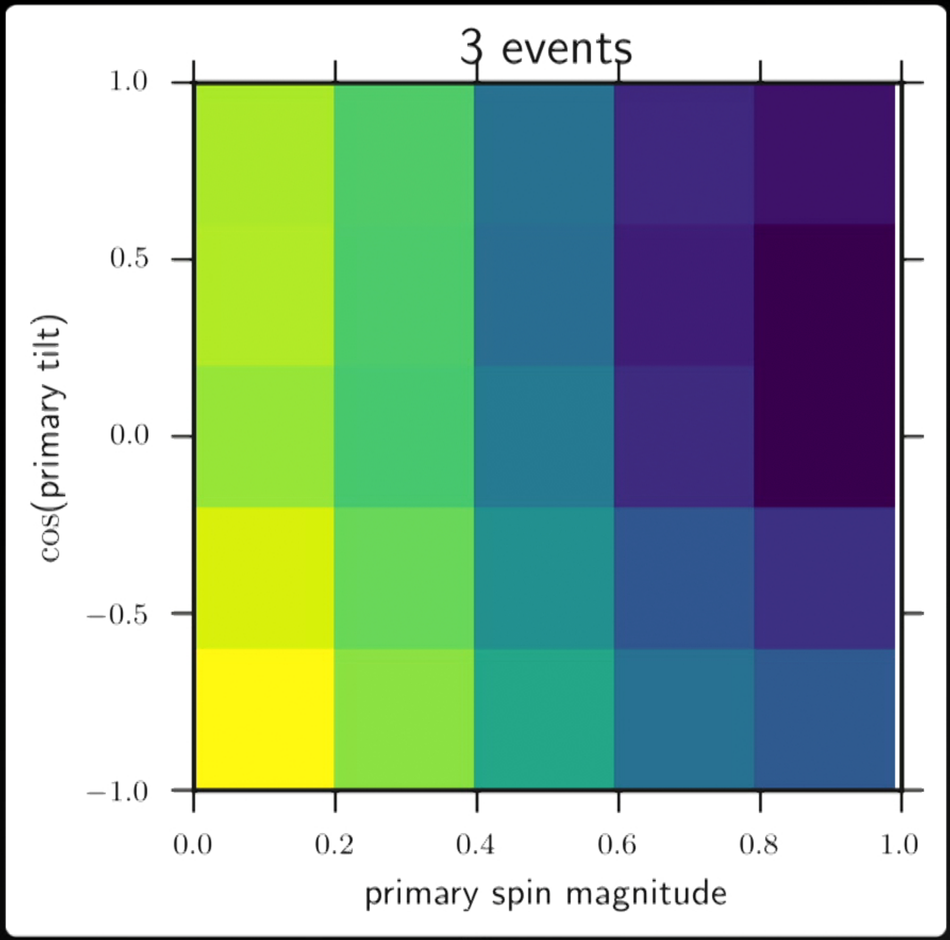
Spin Distribution

Simulated distribution:
primary spin < 0.5
primary tilt < 45°

Individual Event Posteriors:

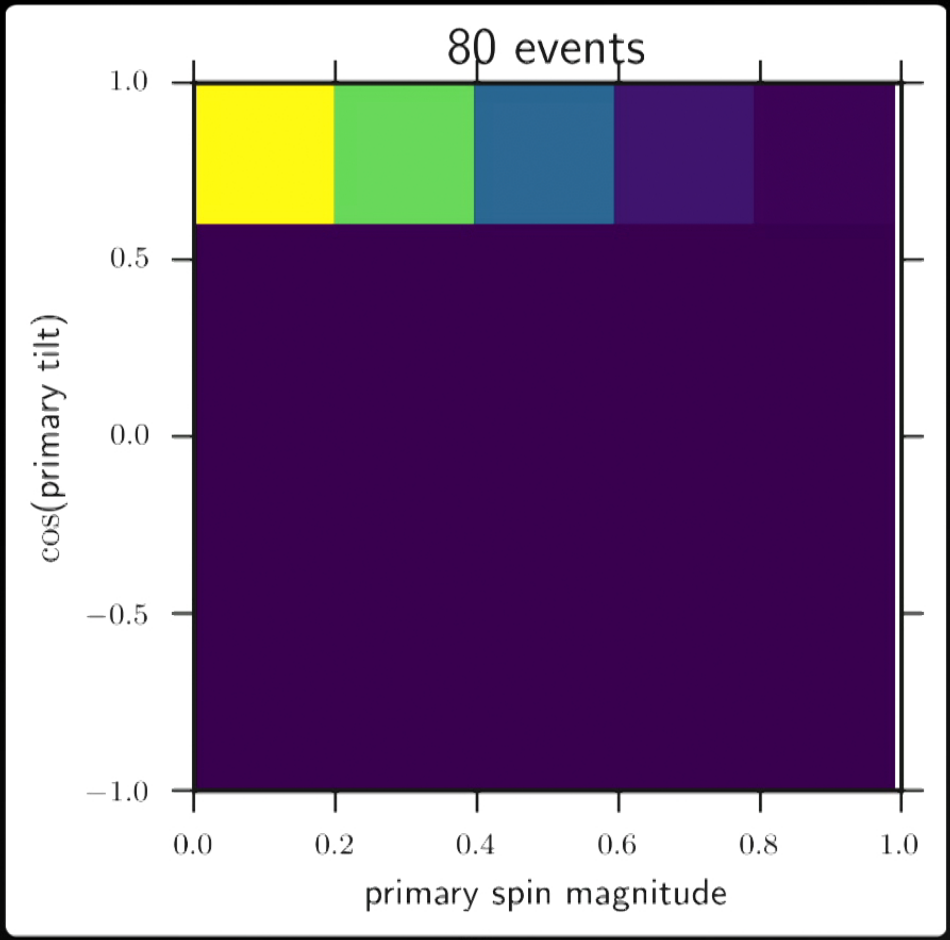


Spin Distribution



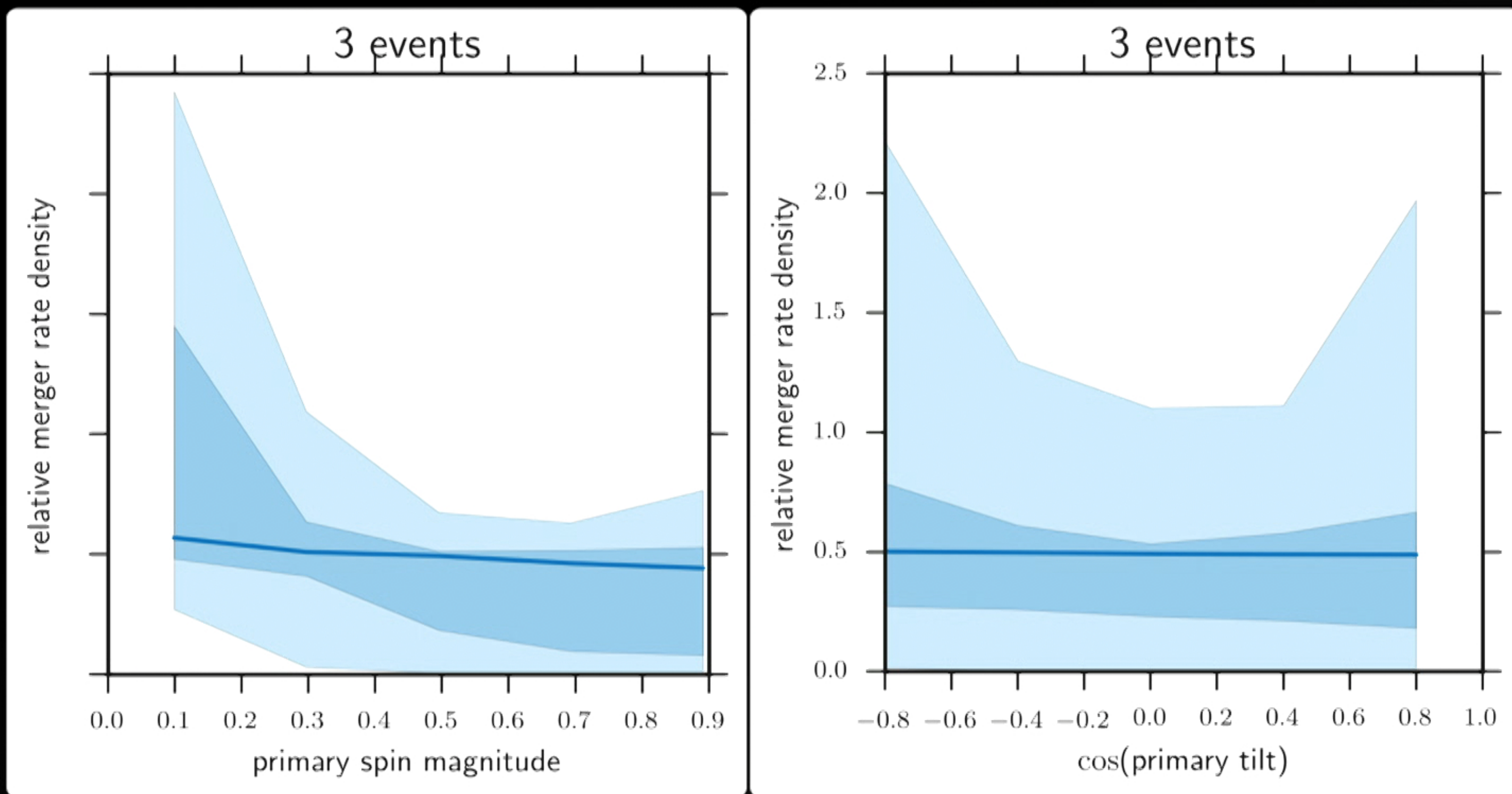
30

Spin Distribution



30

Spin Distribution



31

Spin Distribution

Support for non-uniform distribution of spin magnitudes after ~10 events.

Rule out isotropic spin distribution after ~20 events.

Prospects for Population Constraints

Interesting population characteristics may be found after only ~10 events.

After 10's of events, strong features in the population begin to be constrained.

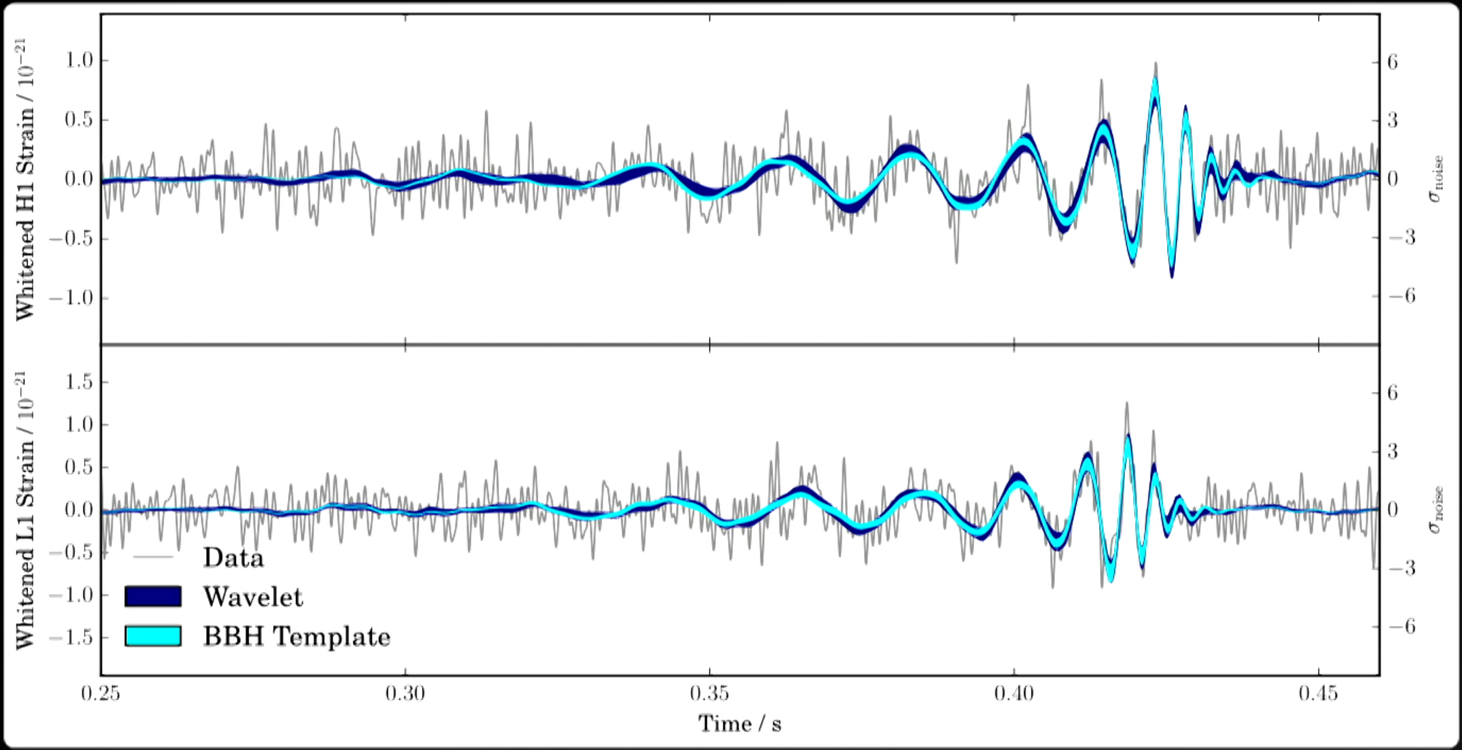
Possibly by the end of O2, likely by the end of O3, things should get interesting.

33

Tests of General Relativity

We can only test GR to the precision of our models.

Signal Reconstructions

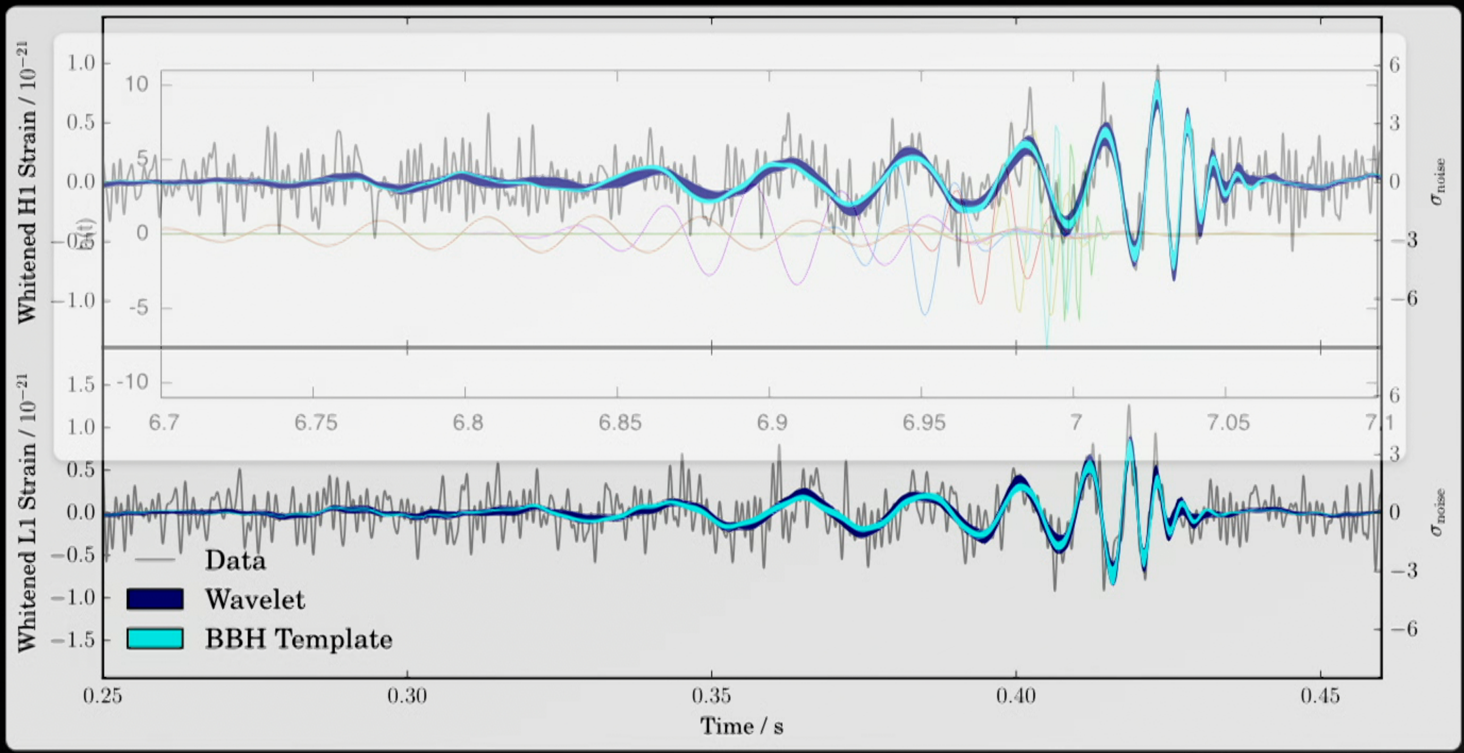


Abbott et al. (2016)
PRL 116, 241102

Overlaps found to be 94 ± 1%.

Consistent with a GW as described by general relativity.

Signal Reconstructions

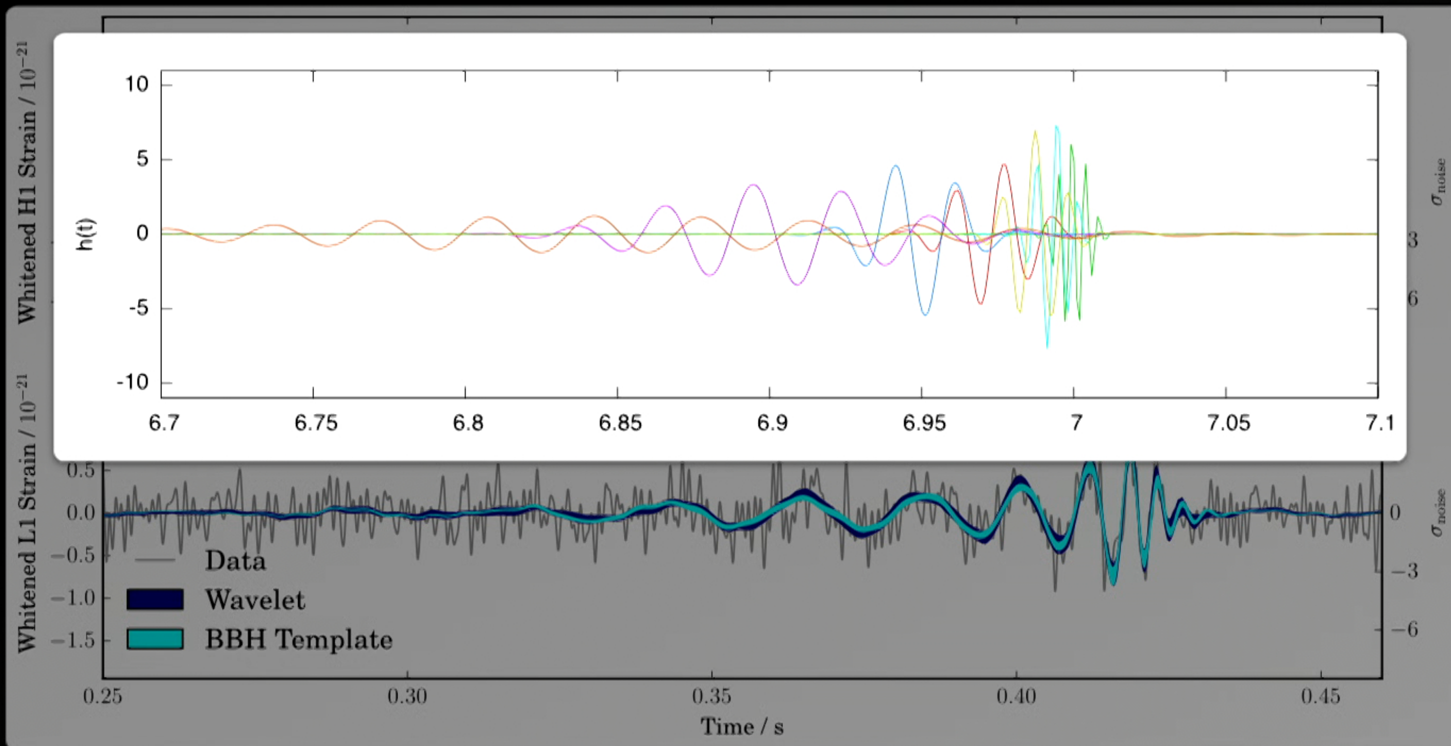


Abbott et al. (2016)
PRL 116, 241102

Overlaps found to be 94 ± 1%.

Consistent with a GW as described by general relativity.

Signal Reconstructions

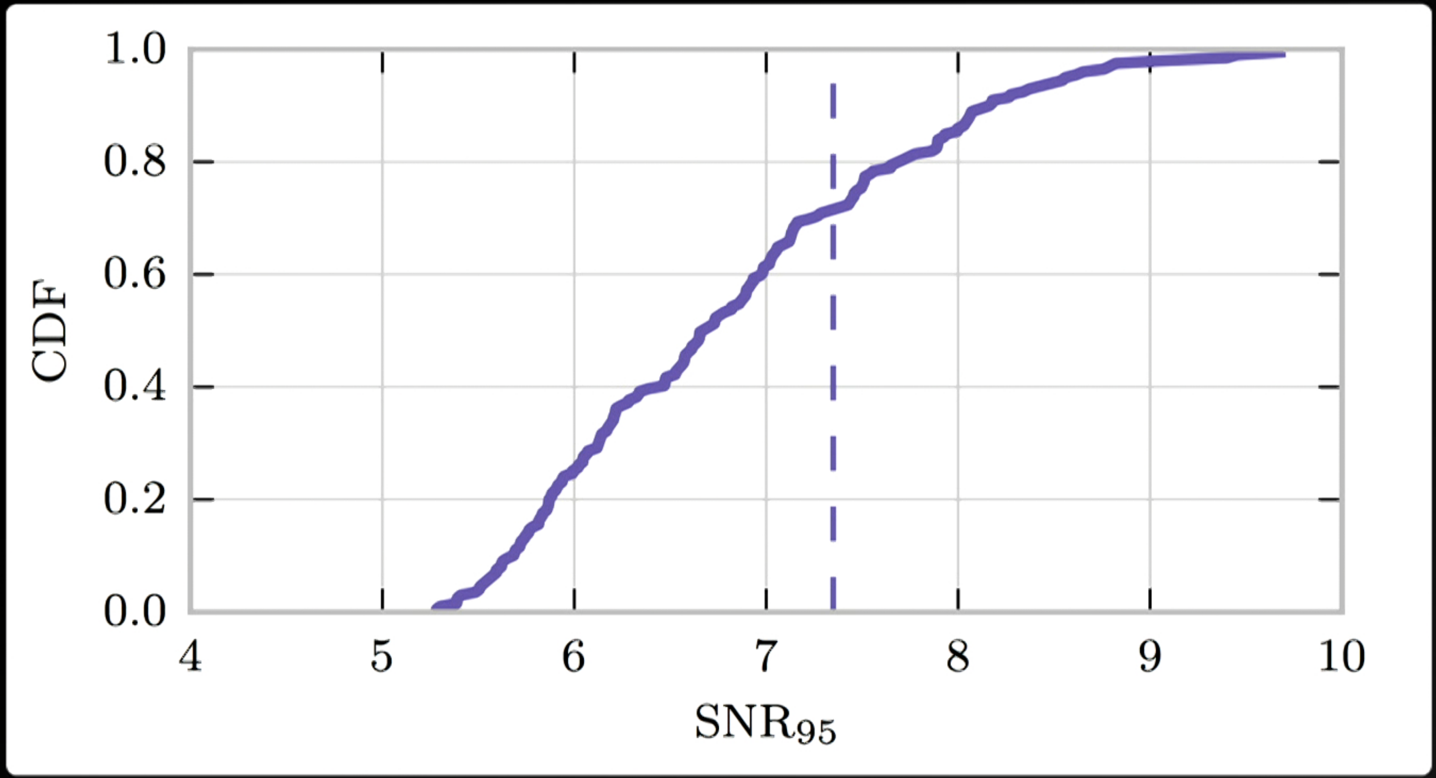


Abbott et al. (2016)
PRL 116, 241102

Overlaps found to be 94 ± 1%.

Consistent with a GW as described by general relativity.

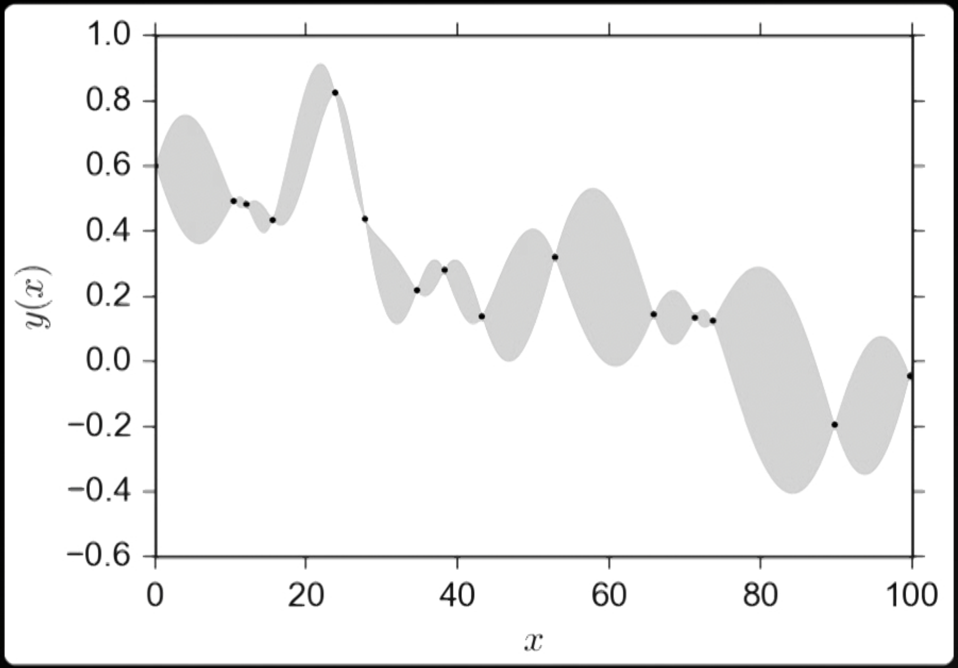
Residual Test



Abbott et al. (2016)
PRL 116, 221101

PE using Numerical Relativity

Gaussian Process Emulation



$$f(x) = \mathcal{GP}(m(x), k(x, x'))$$

The Future

Need fundamental parameter estimation for the 100's of BBHs, and other sources, expected in the coming years.

Population constraints could be interesting after ~10 detections; need techniques and expertise to extract astrophysical information.

Direct use of numerical results in data analyses can enable new science: more robust PE, tests of GR, NS equation-of-state constraints.

18