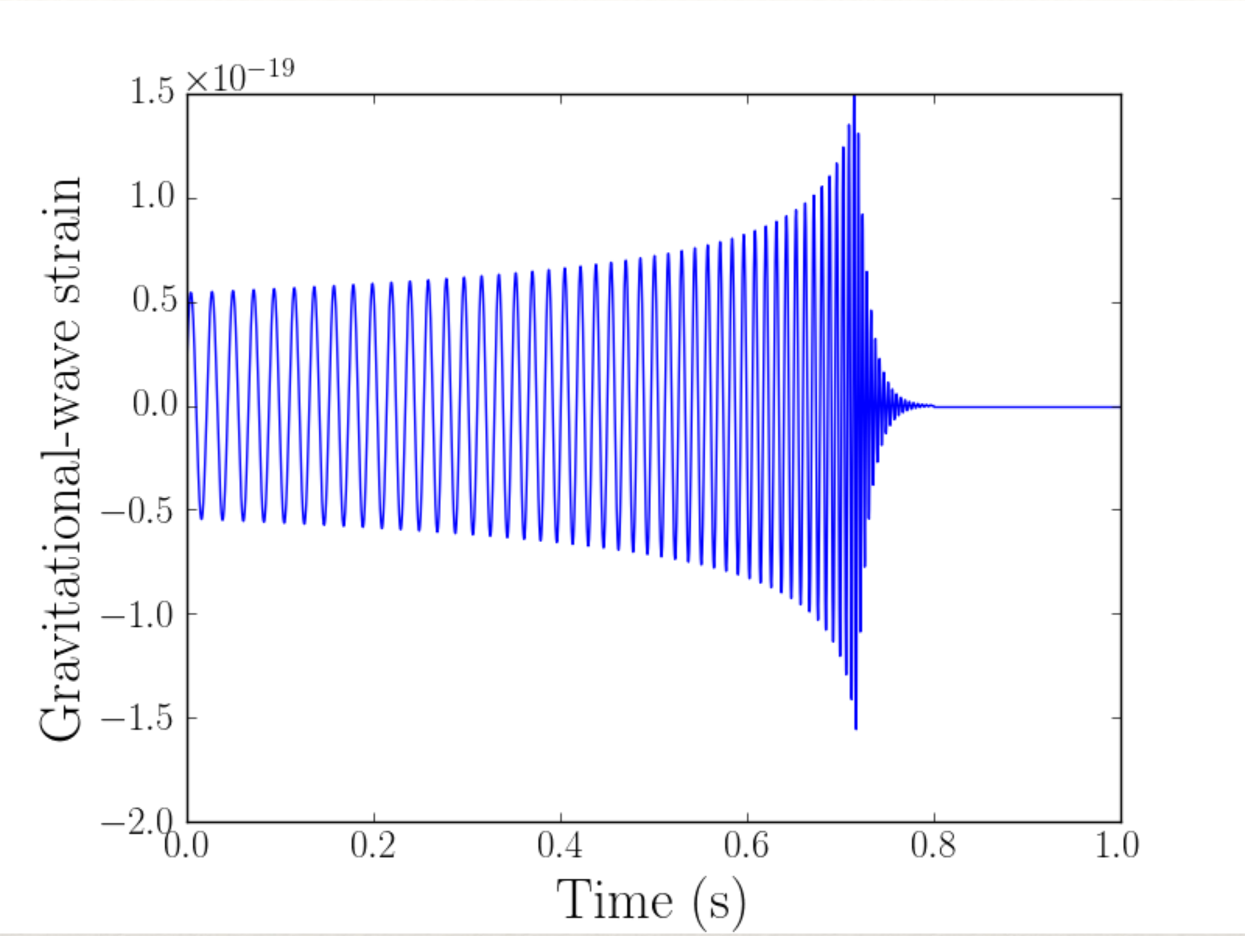
Gravitational wave observations so far (part 1)

Ian Harry

Outline

- A brief overview to gravitational-wave data analysis
- What have we learned from a single binary neutron star observation?
- What do the public alerts mean?
- What have we learned from binary black hole observations in O1/O2 (BEN)
- Summary of public alerts in O3 to date (BEN)

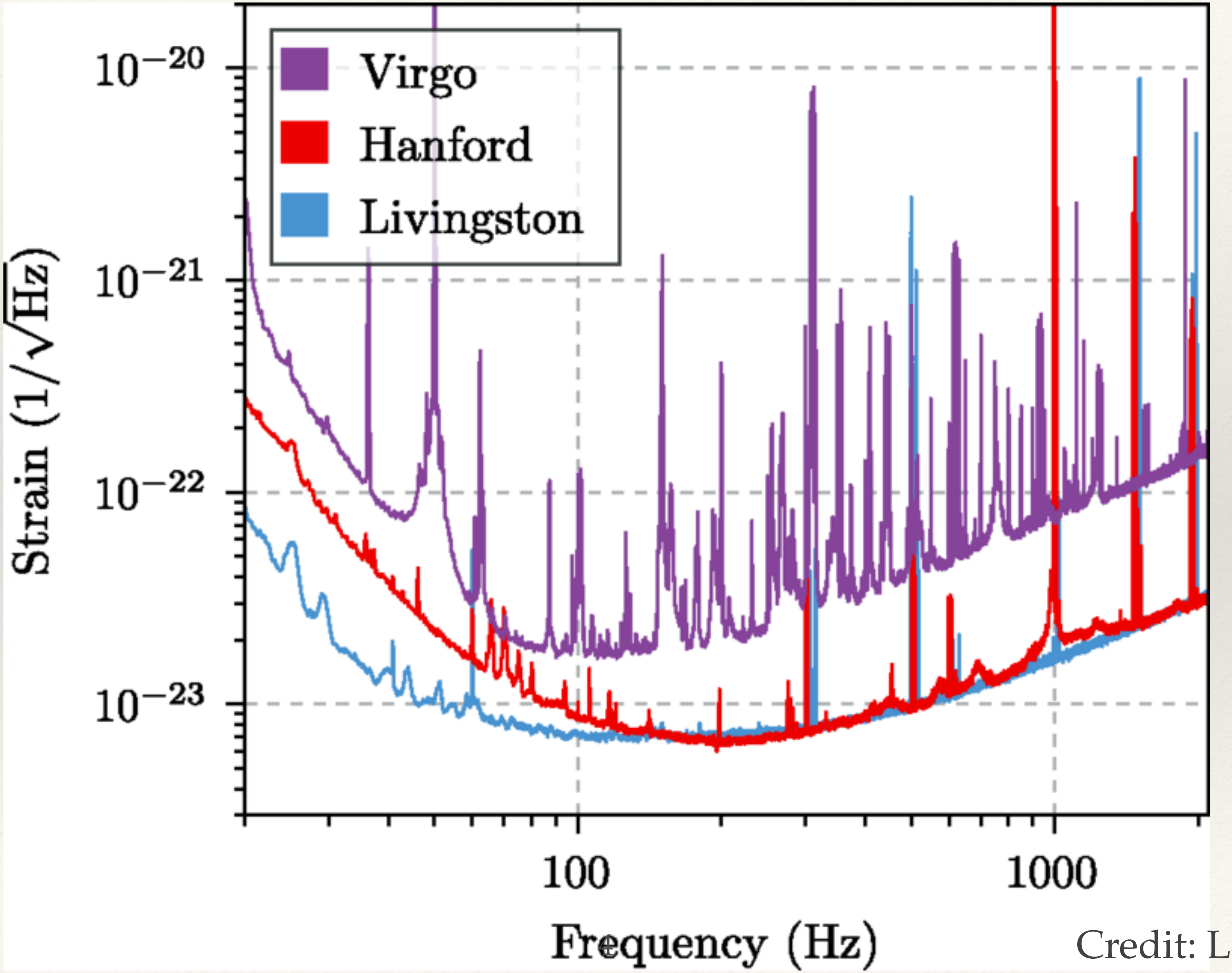
Do we know what we're looking for?



Yes (with some uncertainty)

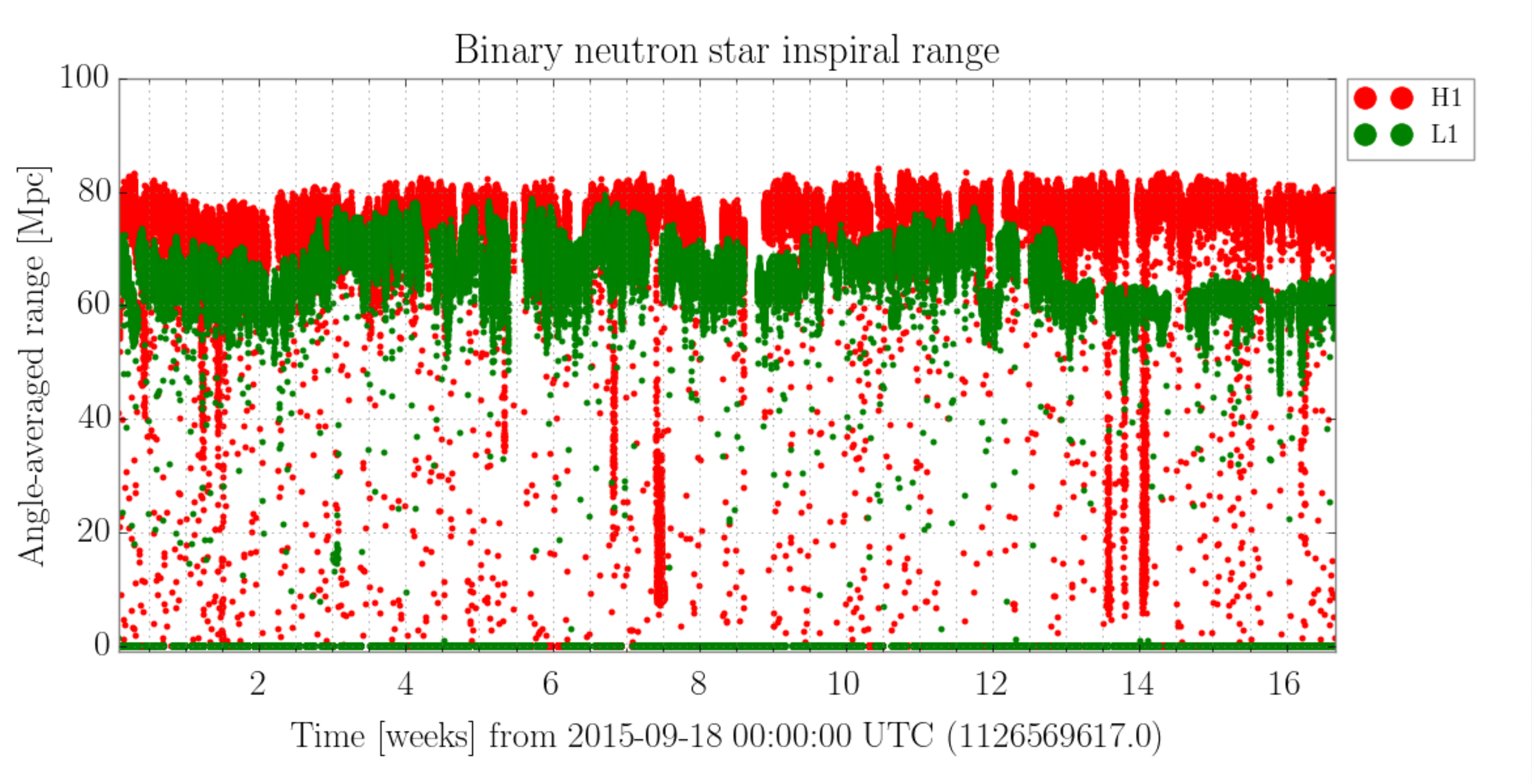
Buonanno and Damour Phys.Rev. D59 (1999) 084006
Buonanno et al., Phys.Rev. D80 (2009) 084043
Pretorius, Phys.Rev.Lett. 95 (2005) 121101
Campanelli et al., Phys.Rev.Lett. 96 (2006) 111101

LIGO/Virgo noise: Complex noise curve



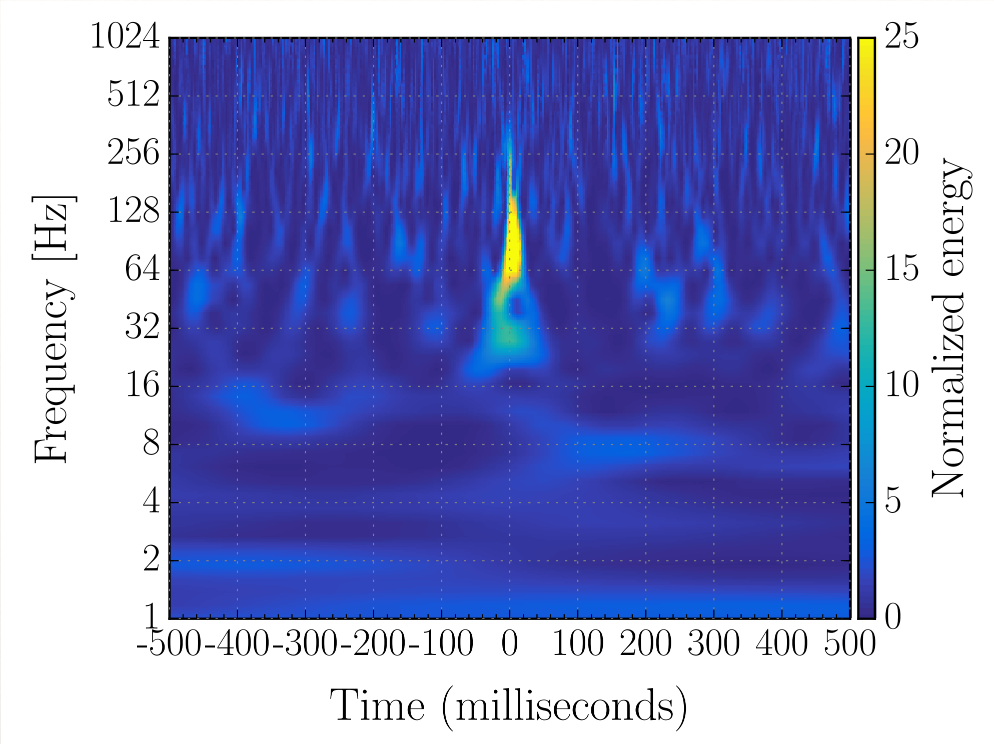
Credit: LIGO/Virgo

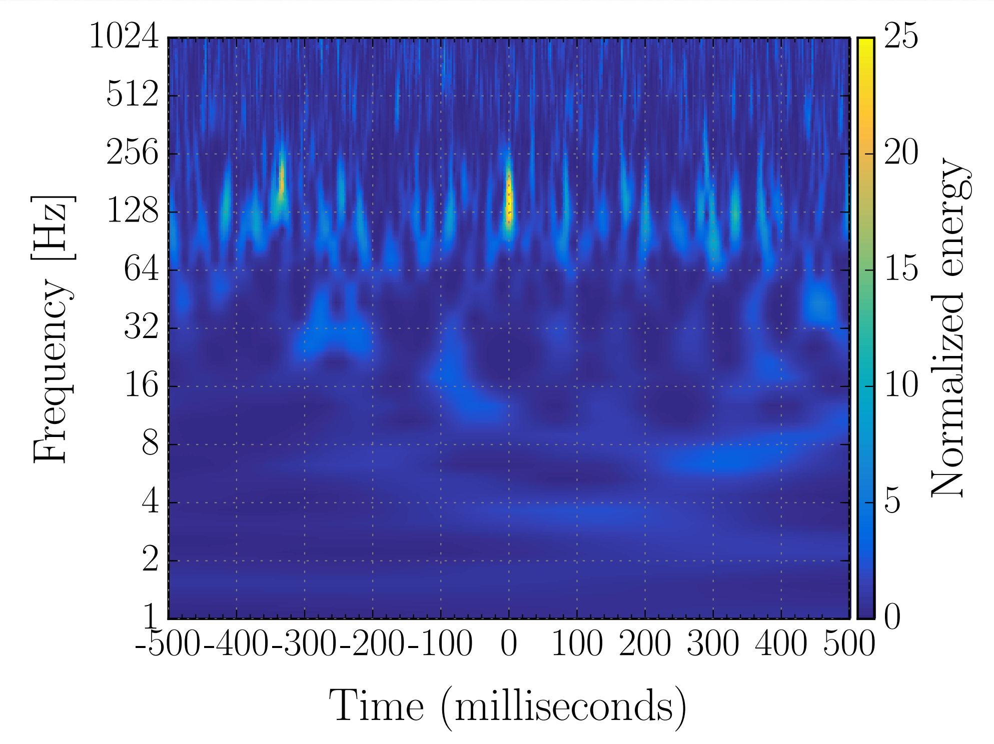
LIGO/Virgo noise: Non-stationary

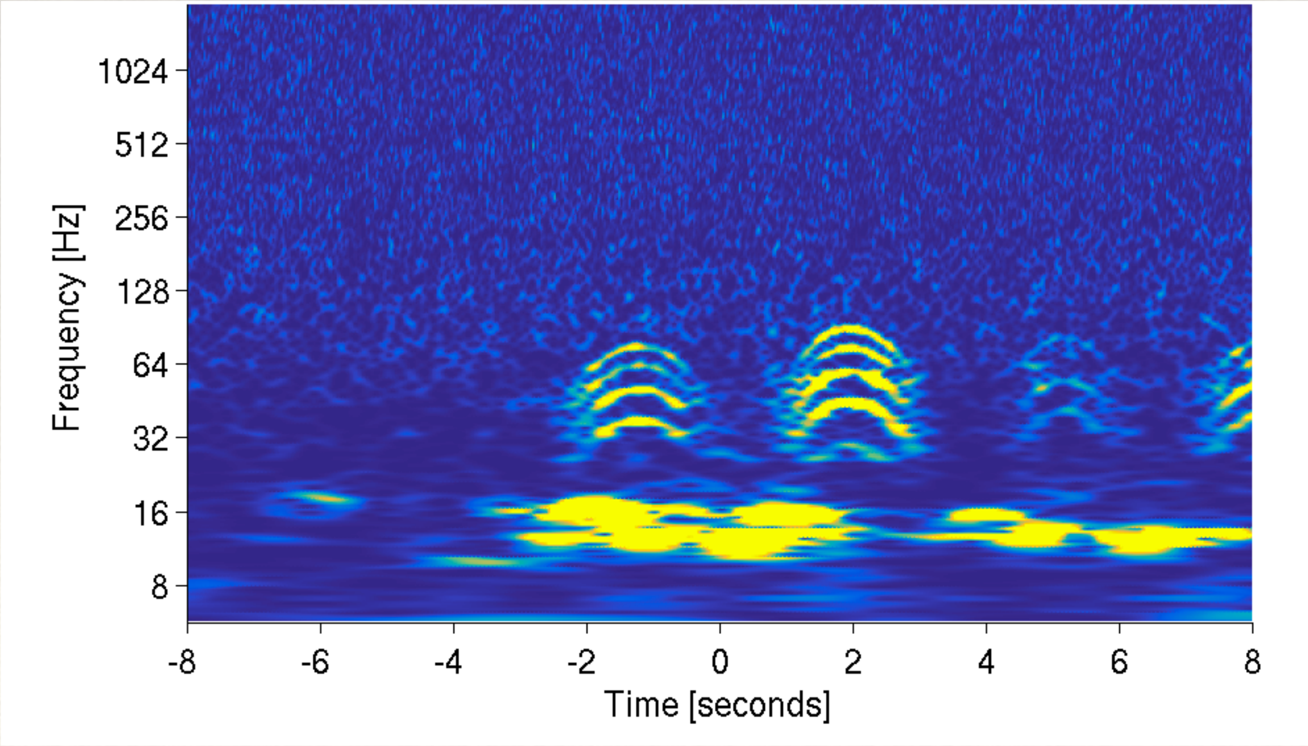


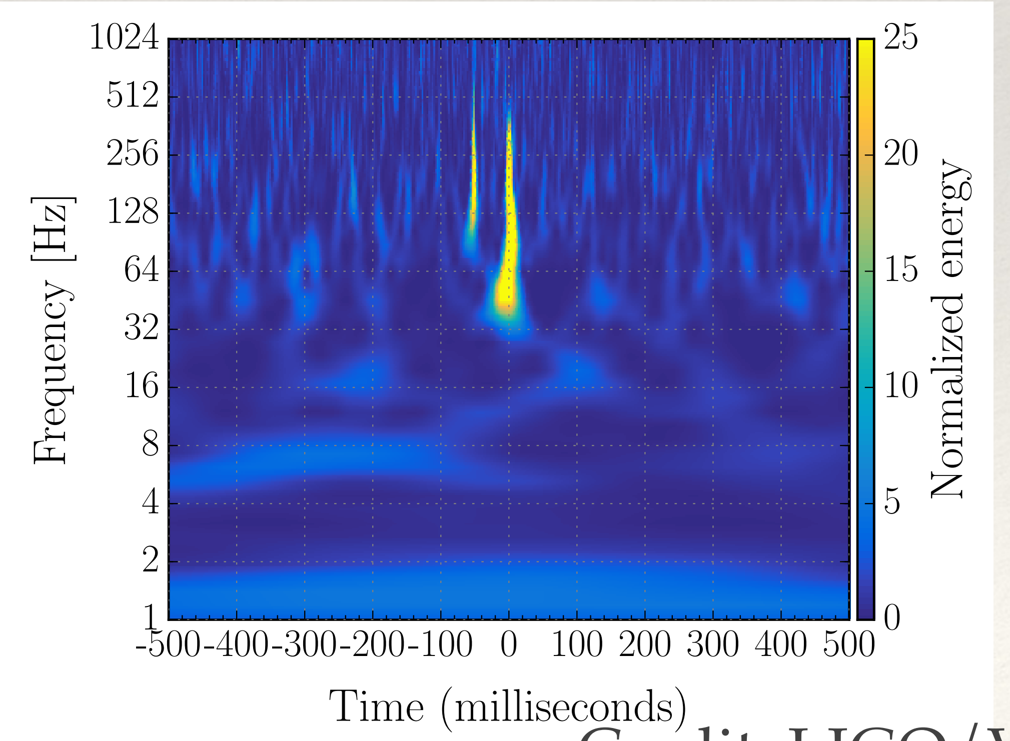
Credit: LIGO/Virgo

LIGO/Virgo noise: Non-Gaussian







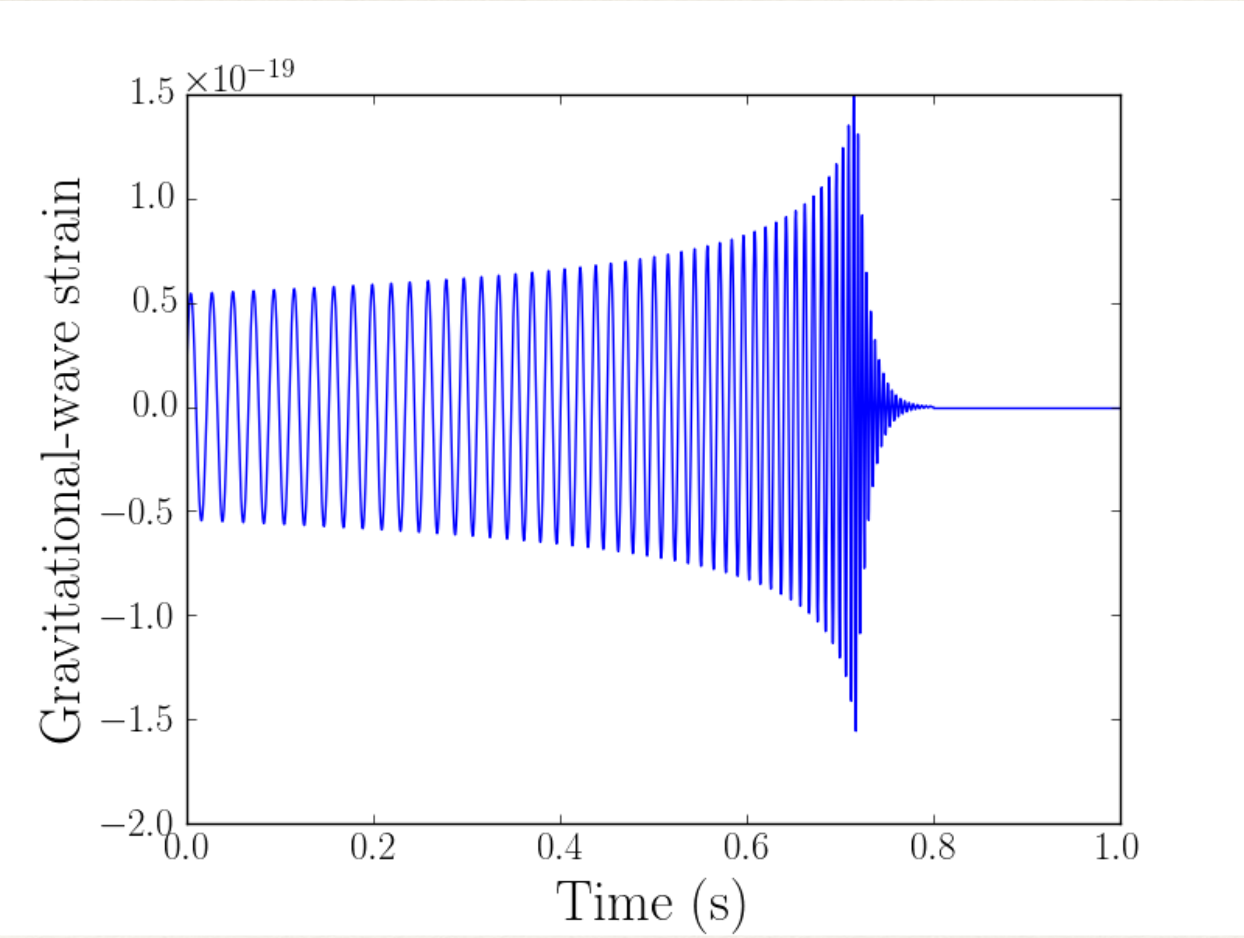


Credit: LIGO/Virgo

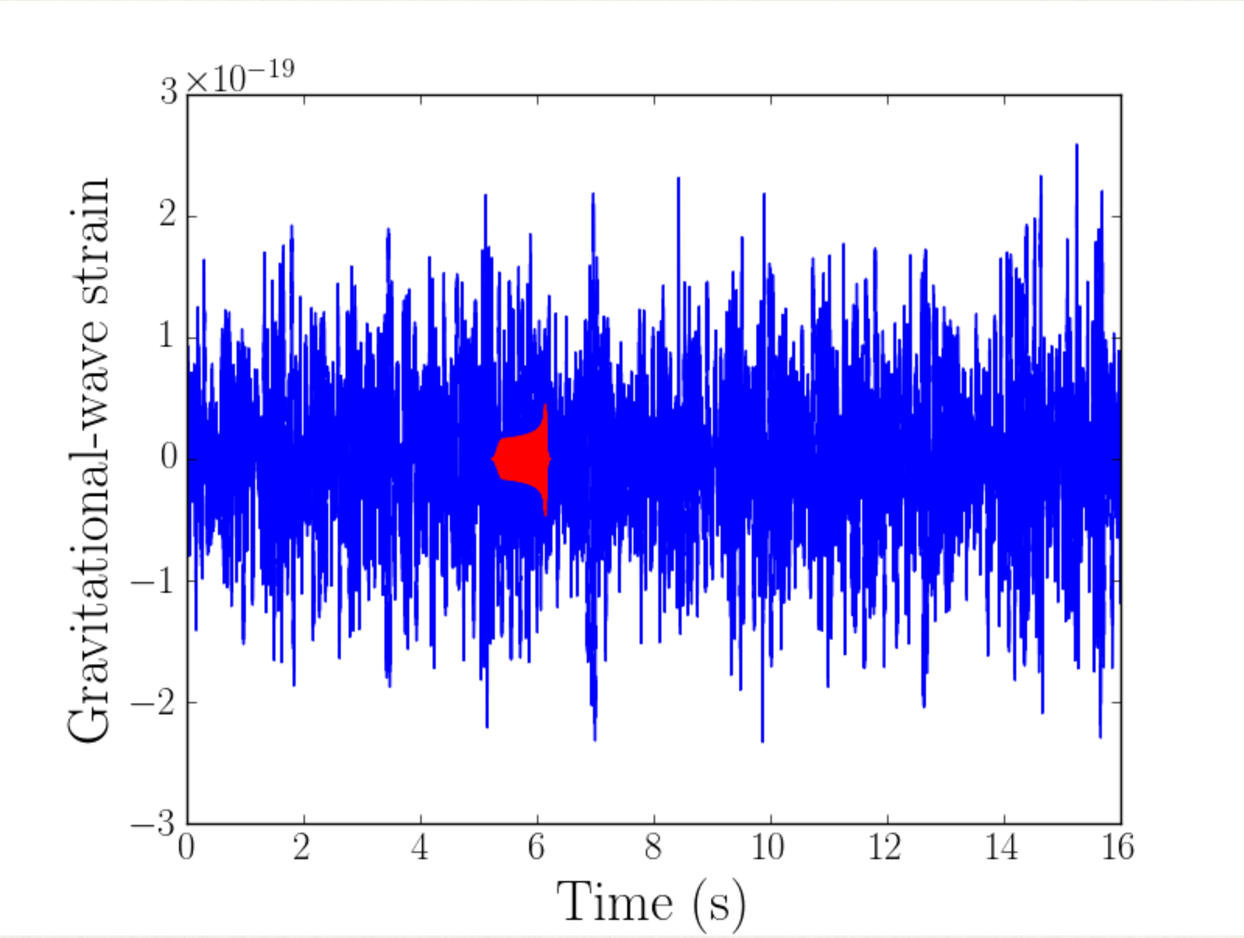
Searching for colliding black holes: How do we actually search for them?

Detection problem

We know what we're looking for

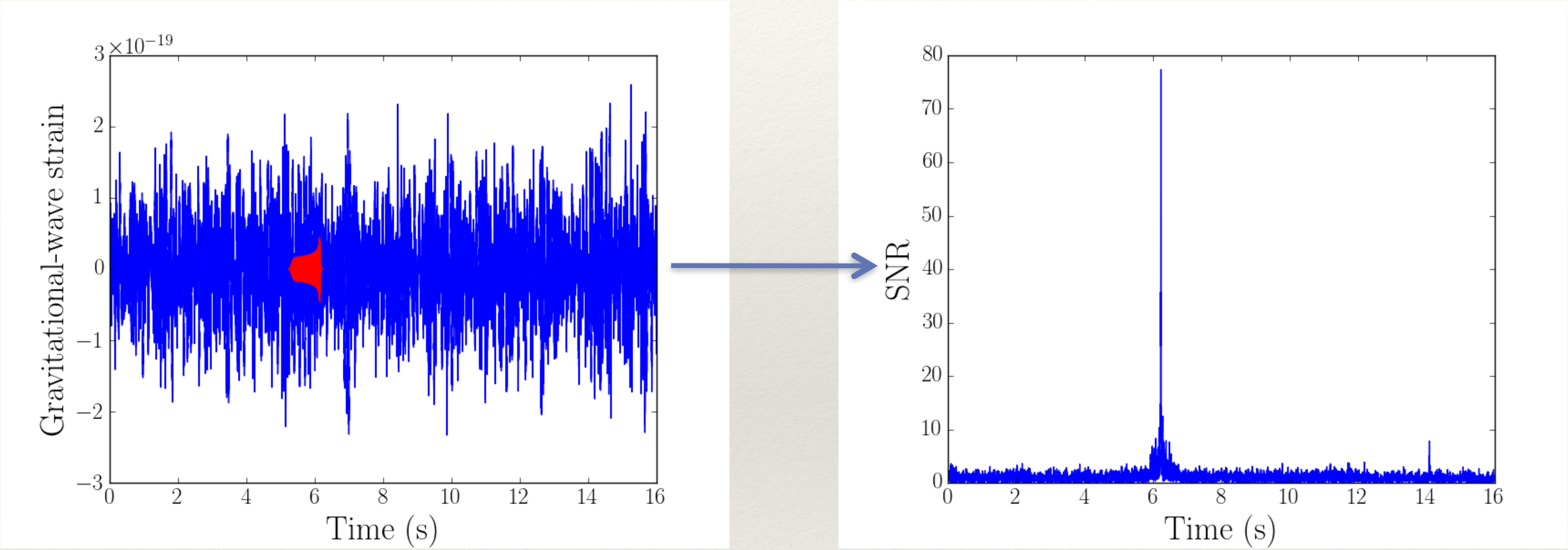


But signals will be buried in the detector noise



Plots and data courtesy of the GW open-science center: https://www.gw-openscience.org

Matched filtering



$$s(t)$$

$$(s|h) = 4\Re \int_0^\infty \frac{\tilde{s}(f)\tilde{h}^\star(f)}{S_h(f)} df$$

Plots and data courtesy of the GW open-science center: http://www.gw-openscience.org

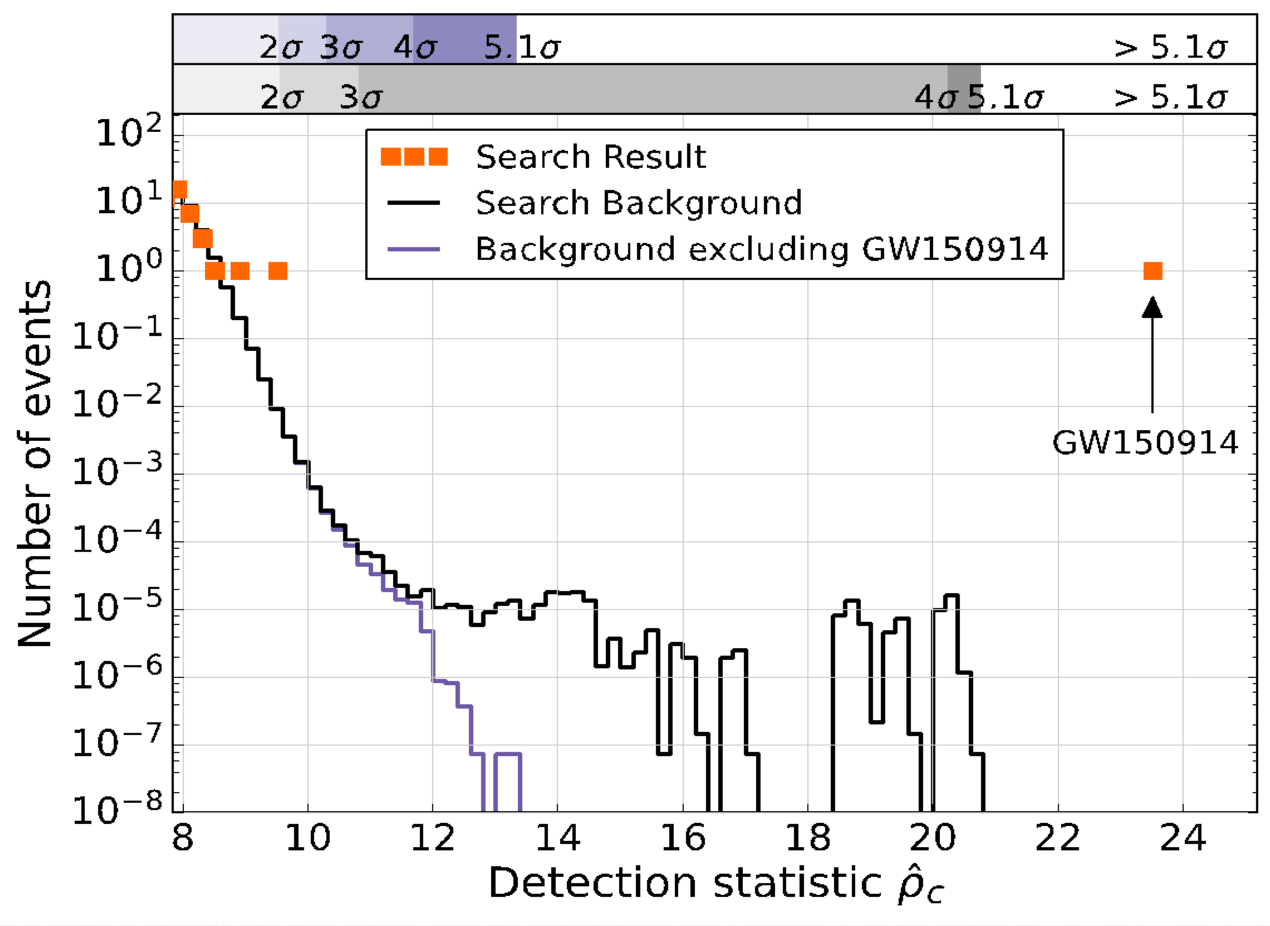
Problems

- Compact binary mergers are described by at least 15 parameters -> NEED TO COVER A LARGE PARAMETER SPACE
- Matched-filtering is optimal statistic for Gaussian noise -> NEED TO BE ABLE TO DISTINGUISH, OR REMOVE, INSTRUMENTAL ARTEFACTS
- Significance must be evaluated empirically from the data

How to deal with this?
Split data analysis into two parts

Part 1: Identification of observations

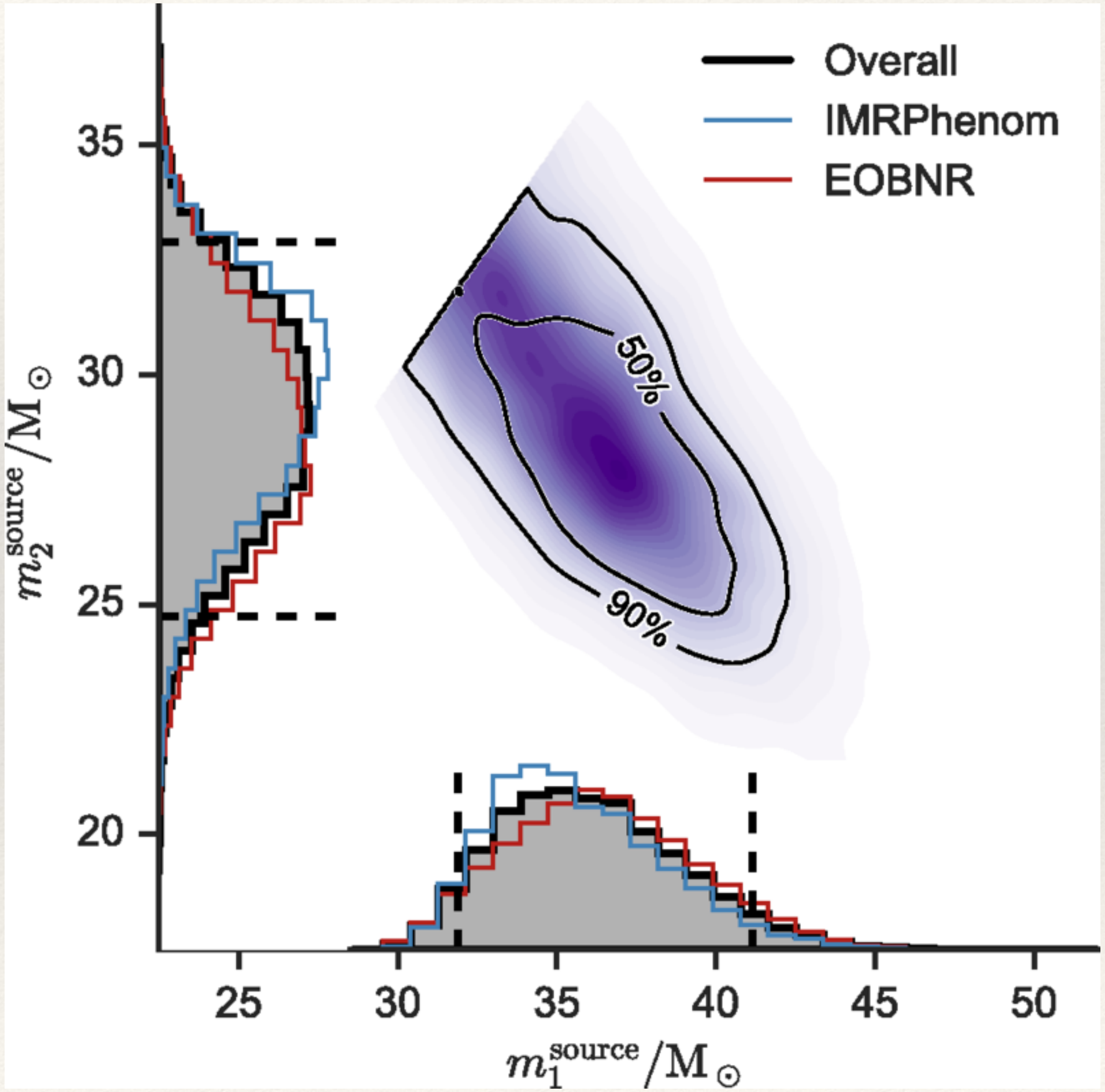
- Signal assumptions reduce dimensionality
- Empirically tuned tests distinguish instrument artefacts from signals
- Background measured from the data itself



Phys. Rev. Lett. 116, 061102

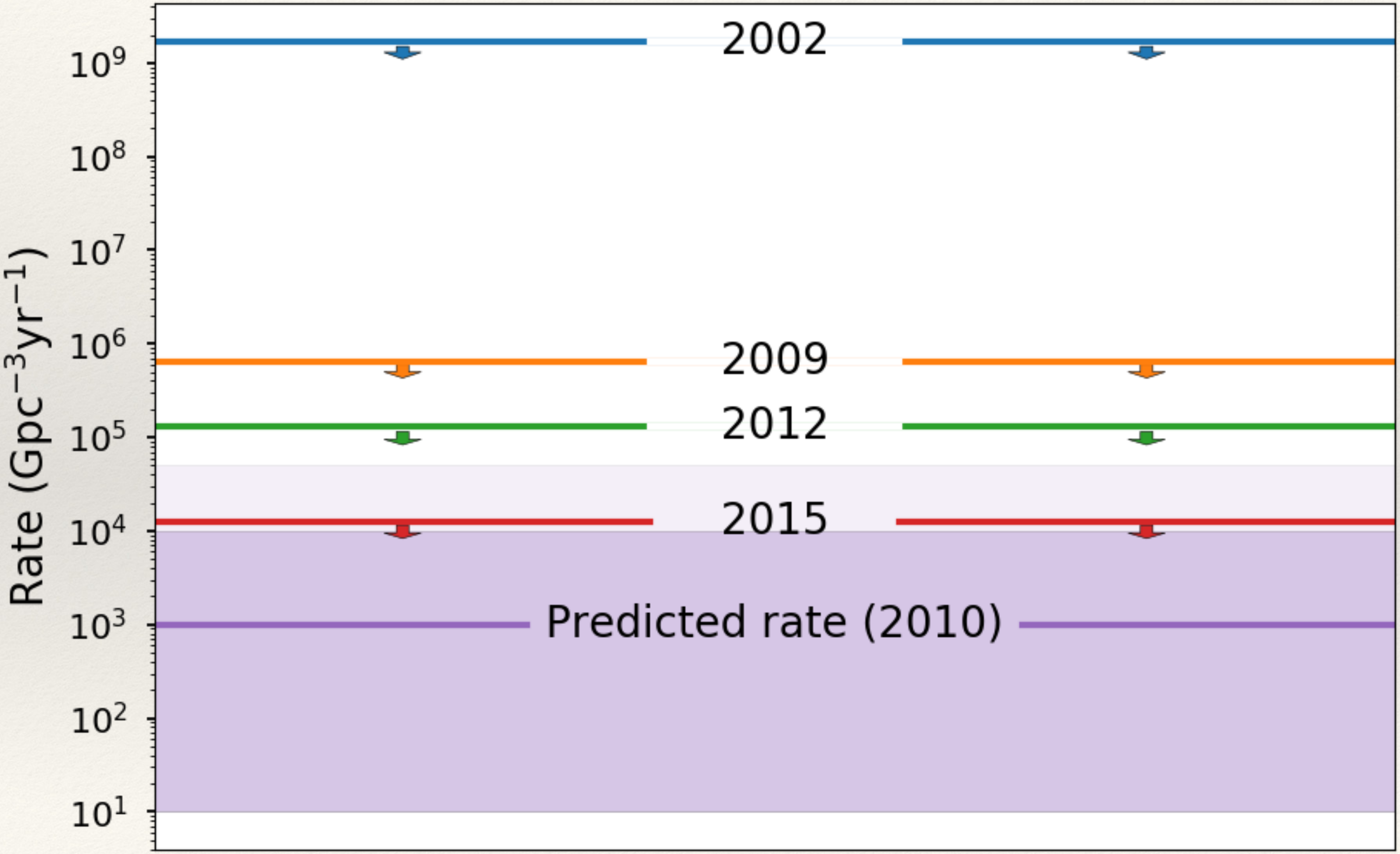
Part 2: Characterizing observations

- Bayesian analysis method to constrain physical parameters
- Requires a prior
- Use full signal space
- Include known uncertainties, where possible
- Attempt to identify and remove artefacts.



Phys. Rev. Lett. 116, 241102

Evolution of BNS upper limits

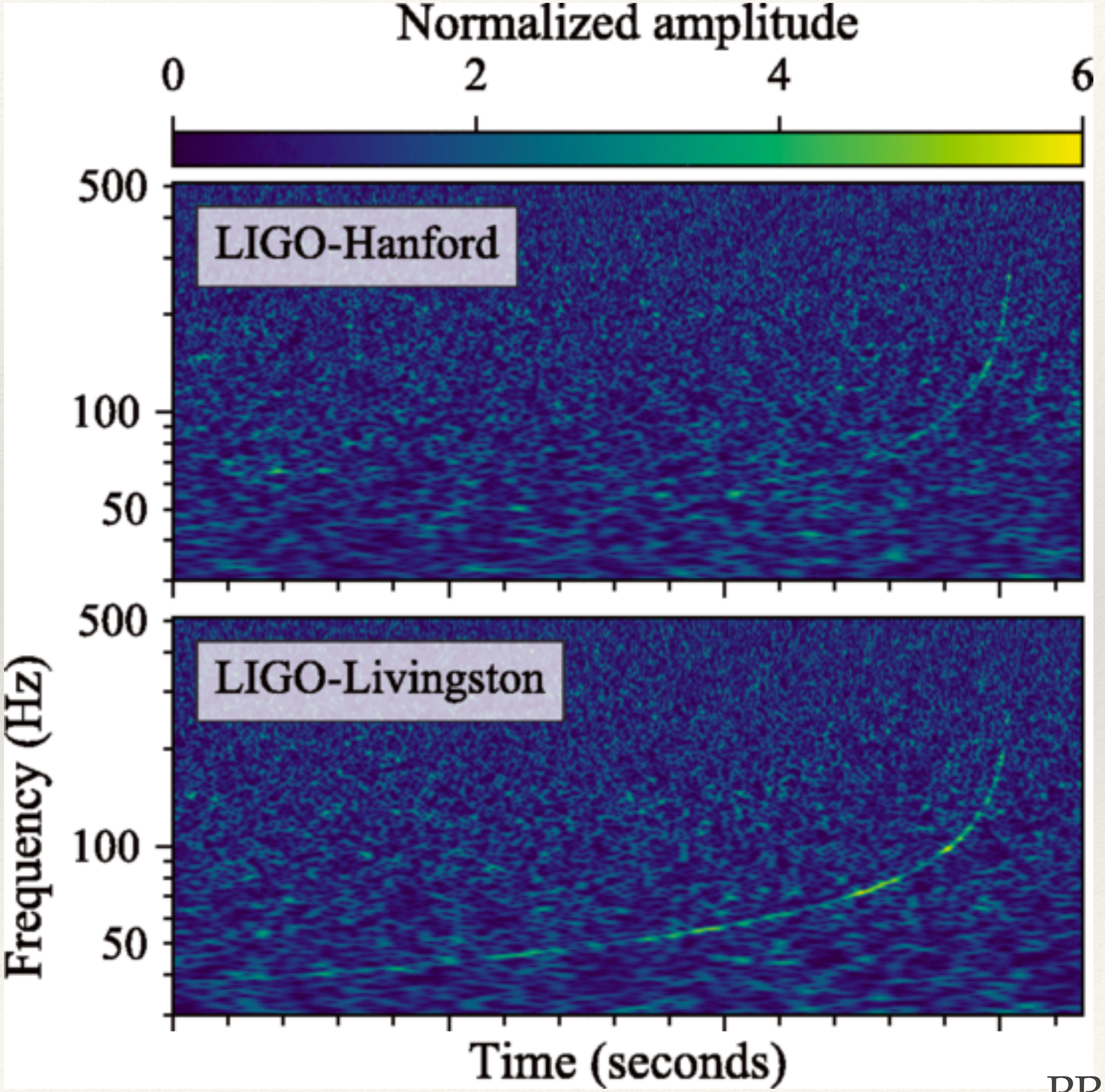


LVC publications 2002 - 2017

Evolution of sensitivity

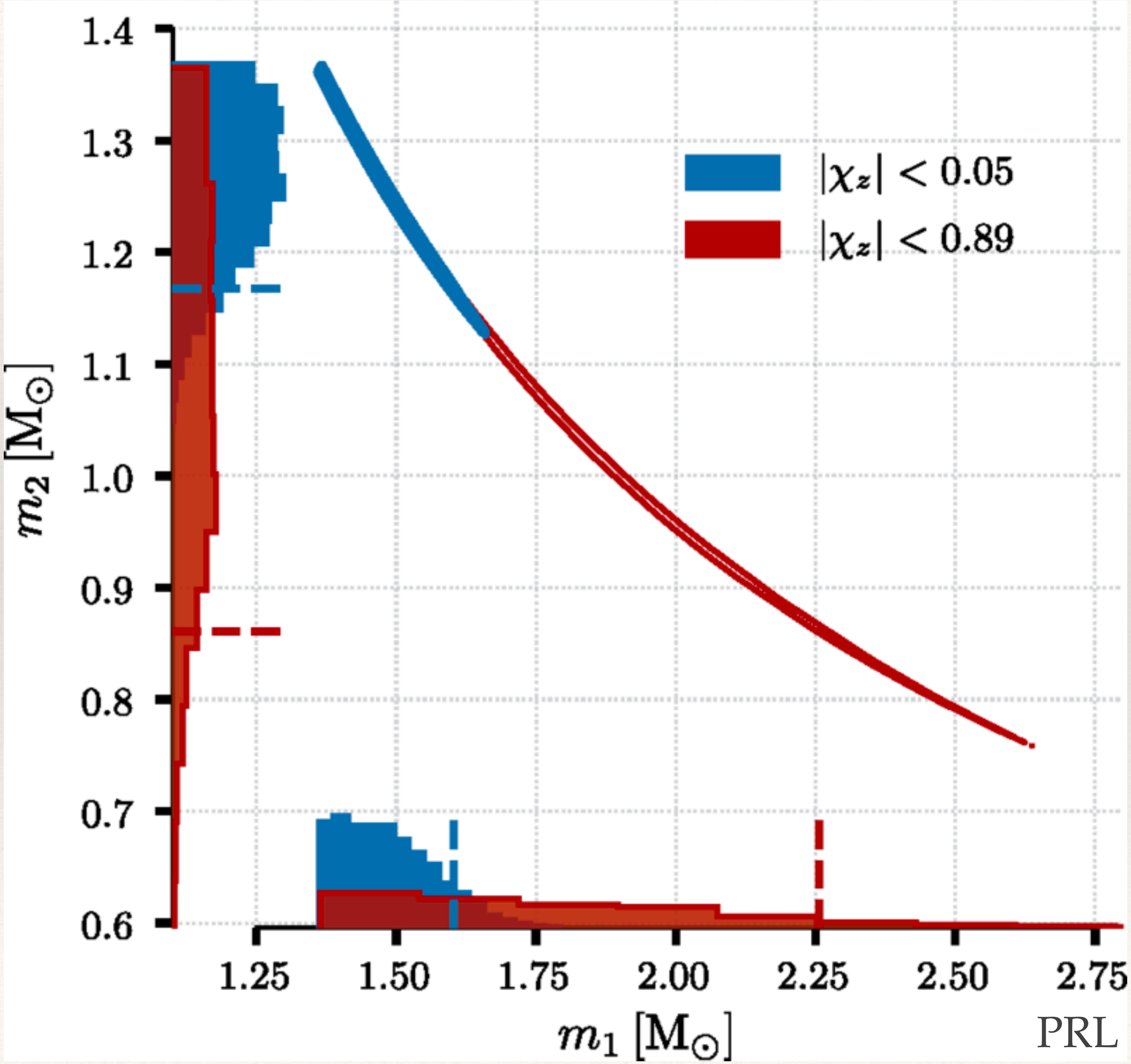
LVC publications 2002 - 2017

What have we learned so far from GW170817 (a GW perspective)



PRL 119, 161101 (2017)

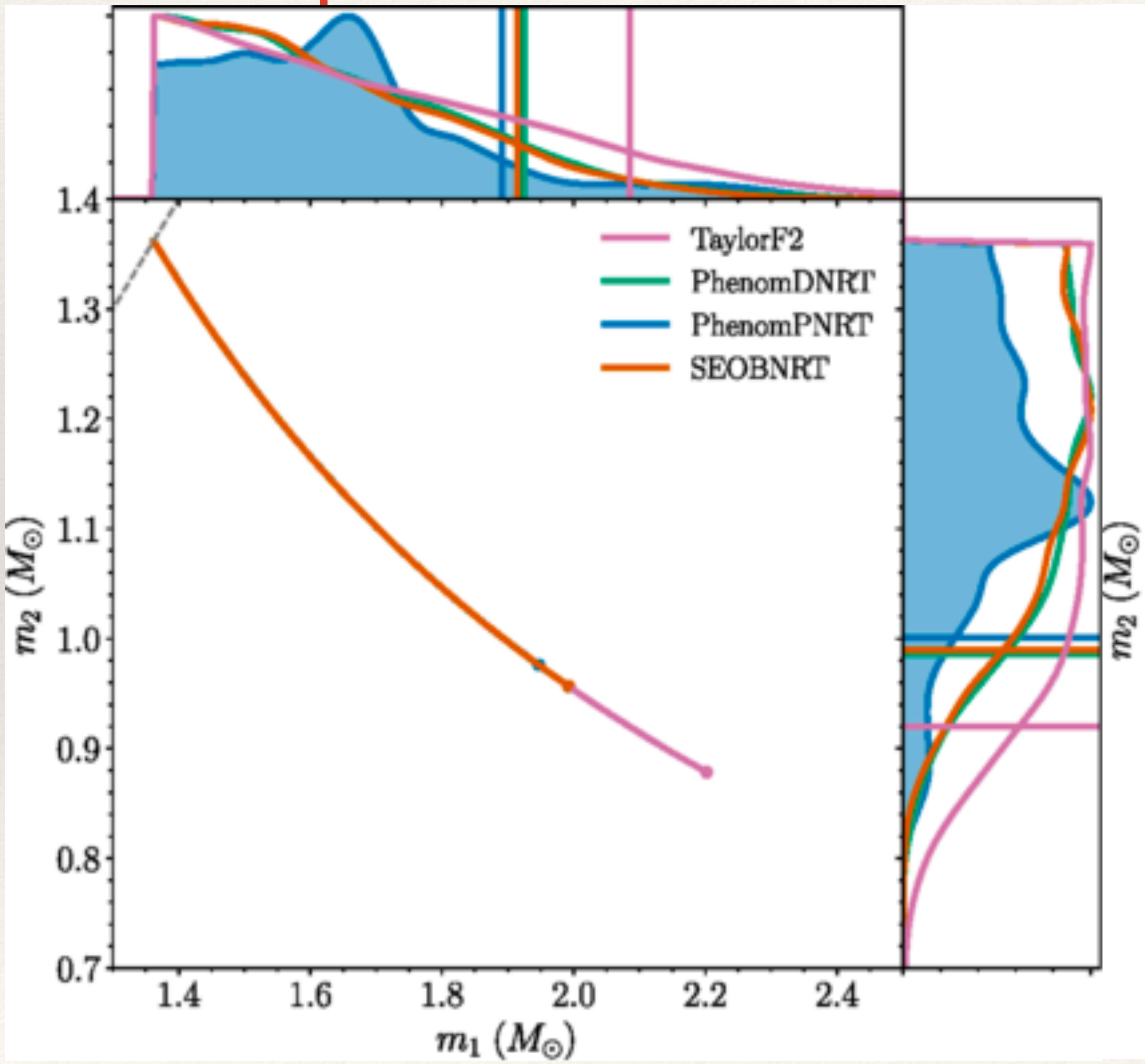
Mass determination



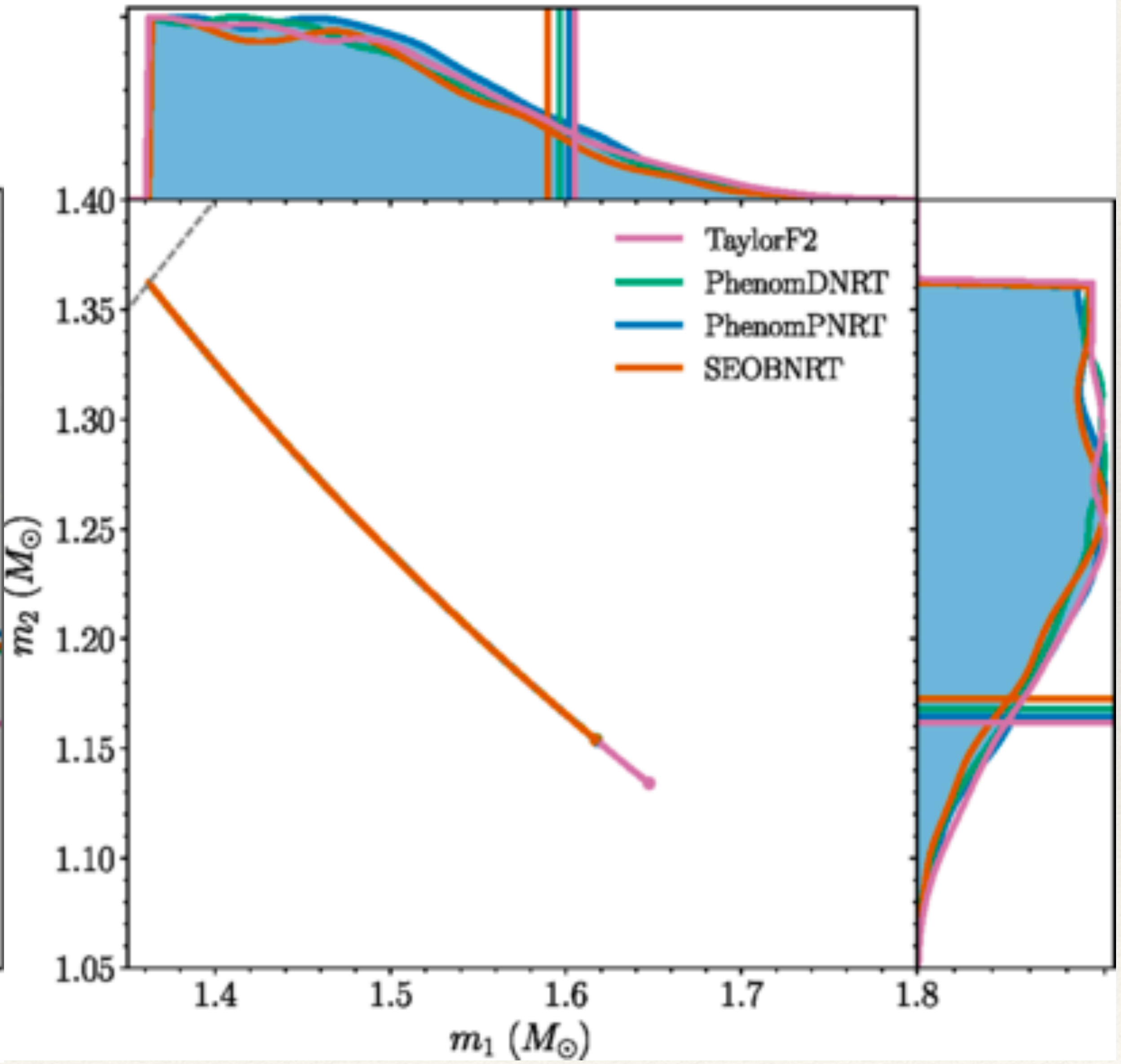
PRL 119, 161101 (2017)

Mass determination

Large neutron star spins allowed

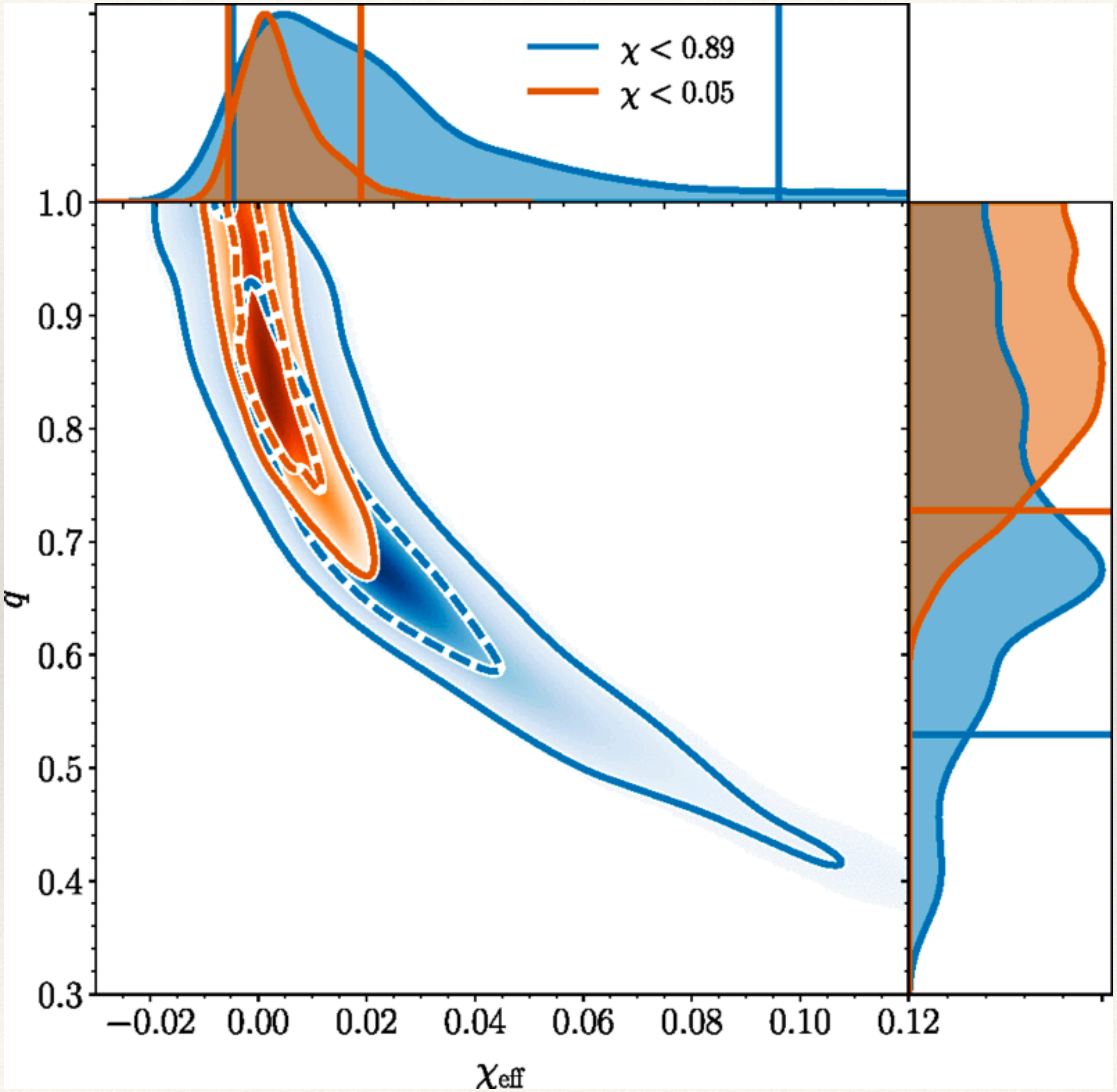


Large neutron star spins not allowed



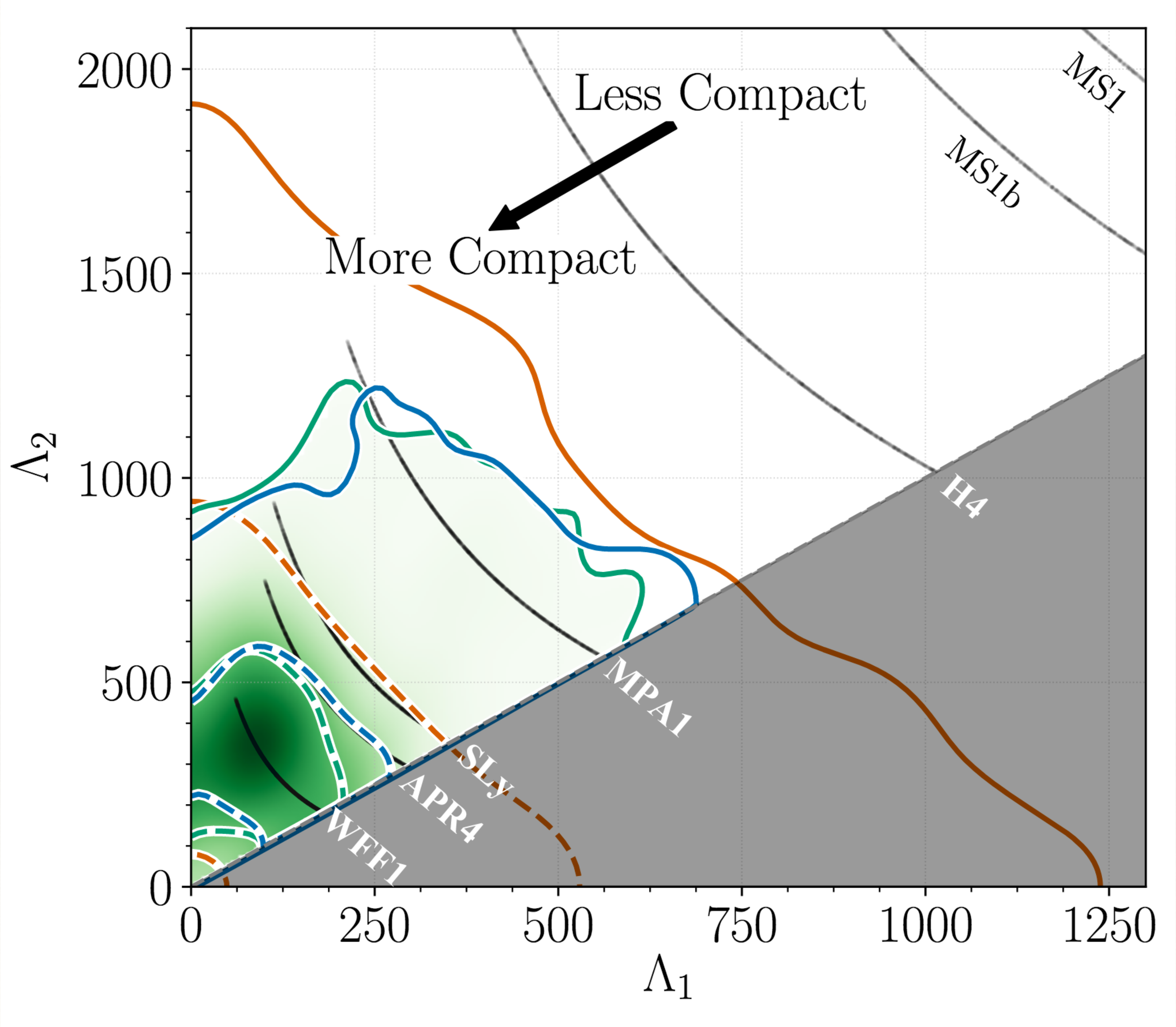
PRX 9, 011001 (2019)

Spin determination



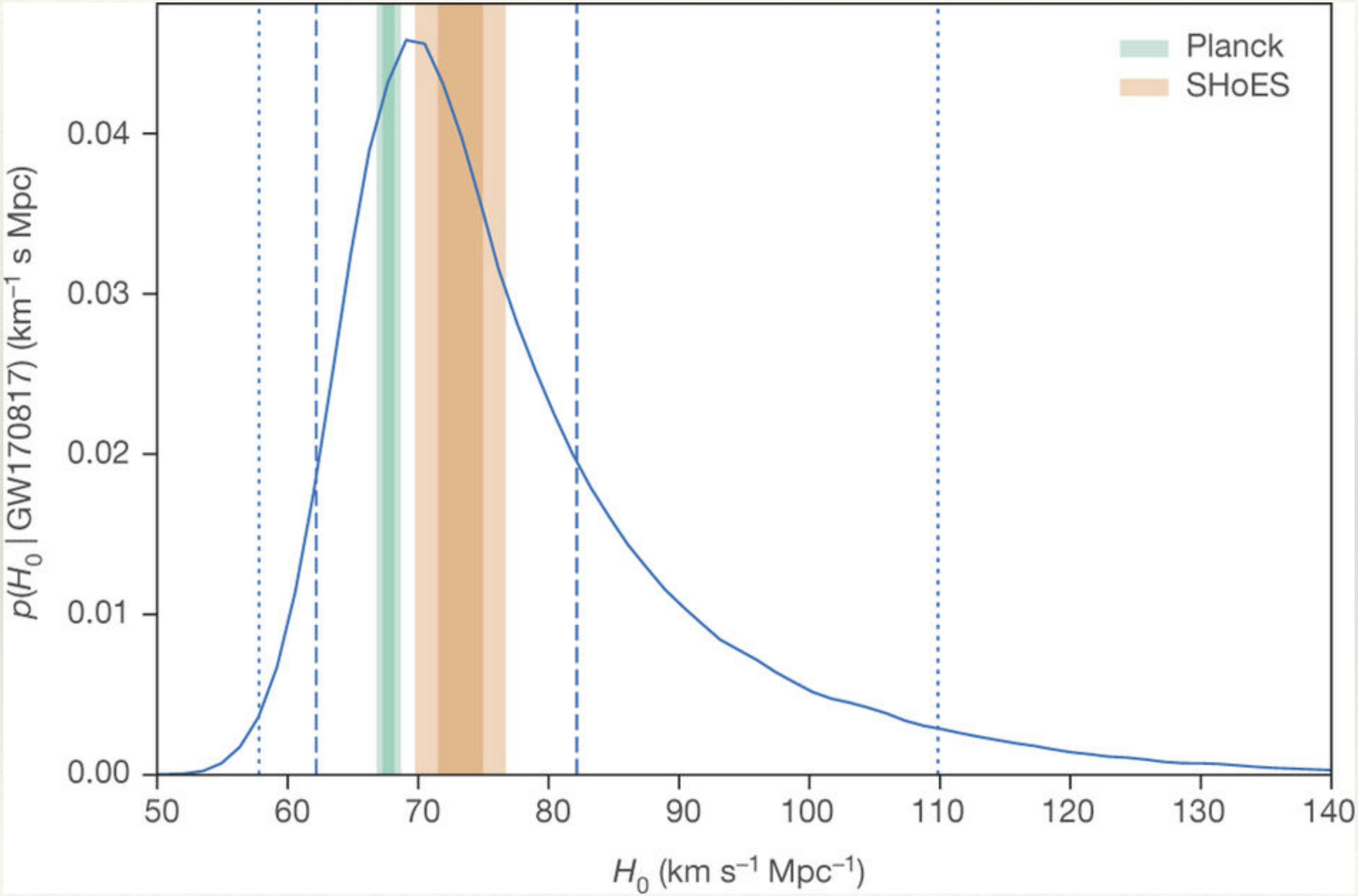
PRX 9, 011001 (2019)

Neutron star internal physics



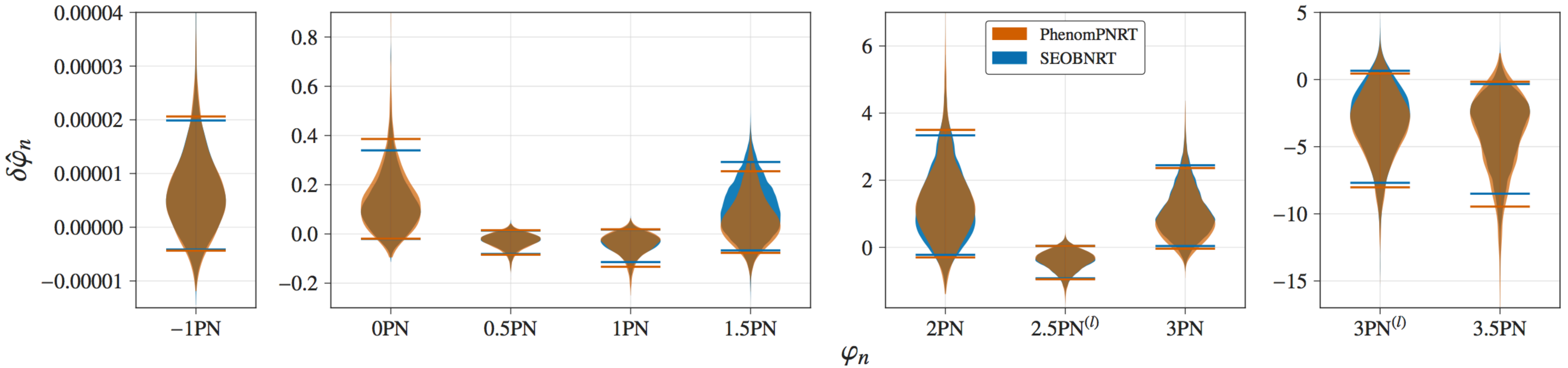
PRL 121, 161101 (2018)

GW170817 - Measuring Hubble's constant



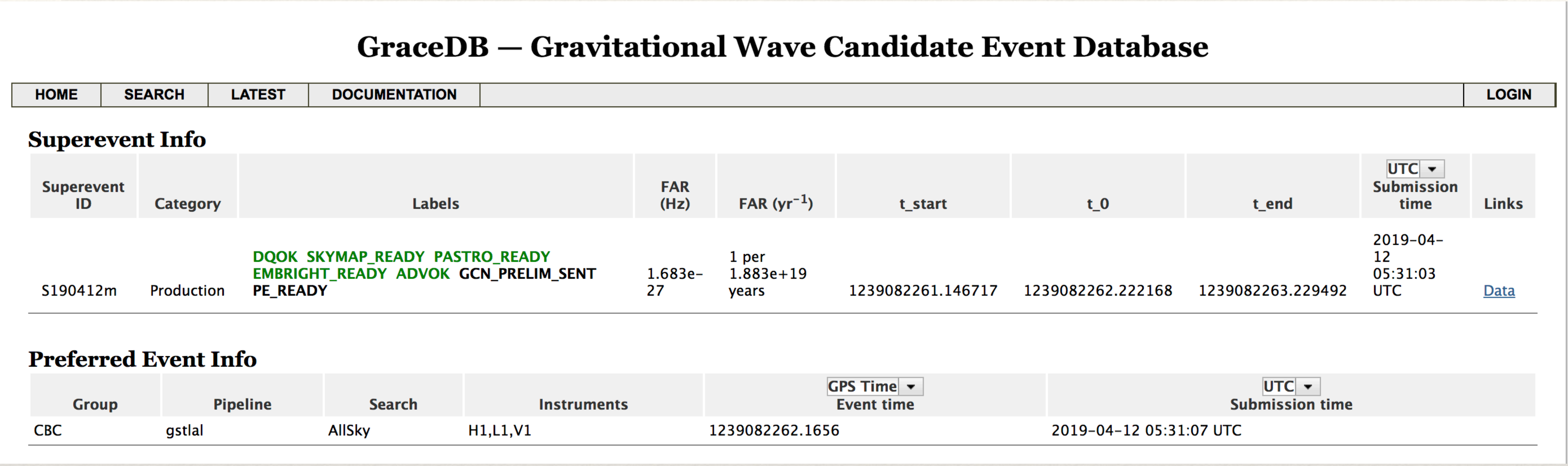
Nature 551, 85 (2017)

GW170817: Testing general relativity



arXiv:1811.12907

Open alerts: What does it all mean?



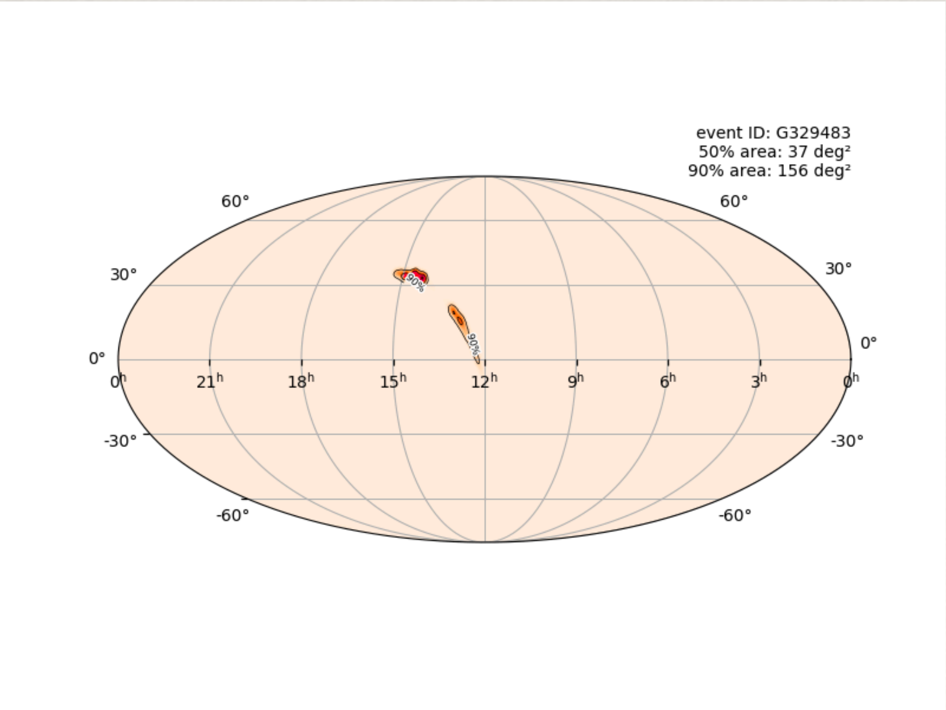
GraceDB — Gravitational Wave Candidate Event Database

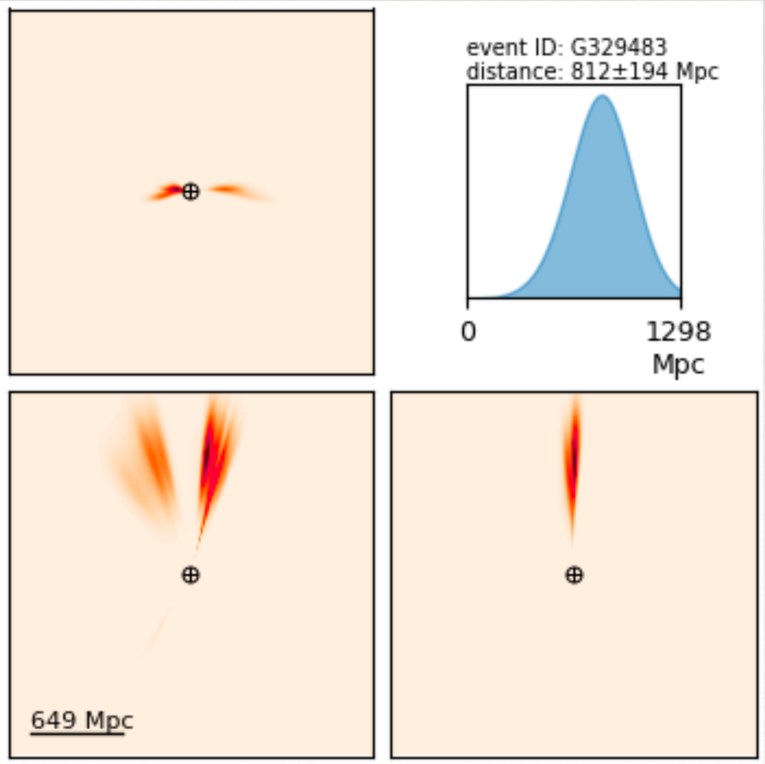
Superevent Info

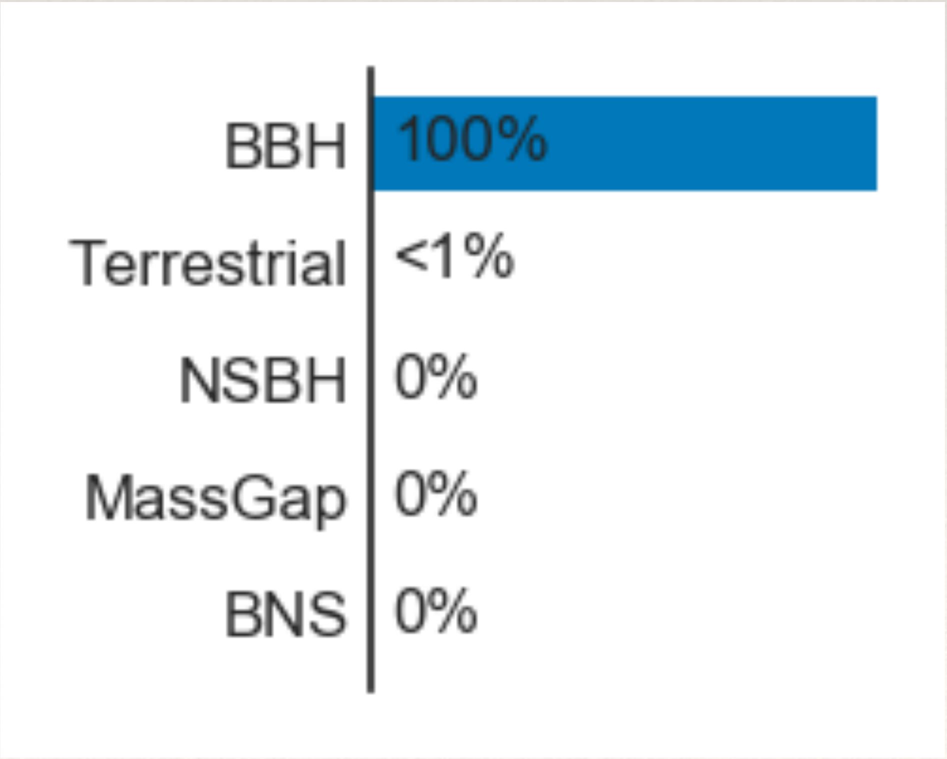
Superevent ID	Category	Labels	FAR (Hz)	FAR (yr^{-1})	t_start	t_0	t_end	UTC ▾ Submission time	Links
S190412m	Production	DQOK SKYMAP_READY PASTRO_READY EMBRIGHT_READY ADVOK GCN_PRELIM_SENT PE_READY	1.683e-27	1 per 1.883e+19 years	1239082261.146717	1239082262.222168	1239082263.229492	2019-04-12 05:31:03 UTC	Data

Preferred Event Info

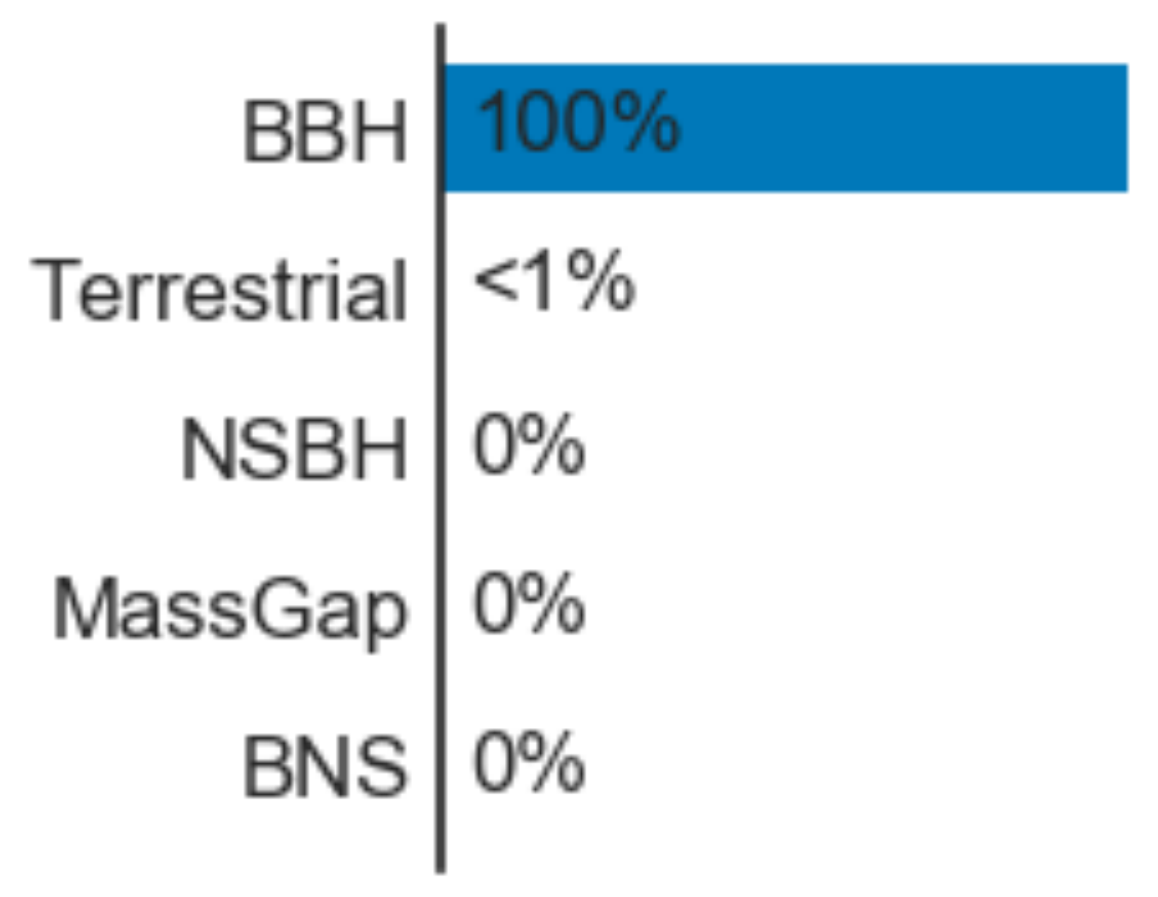
Group	Pipeline	Search	Instruments	GPS Time ▾ Event time	UTC ▾ Submission time
CBC	gstlal	AllSky	H1,L1,V1	1239082262.1656	2019-04-12 05:31:07 UTC

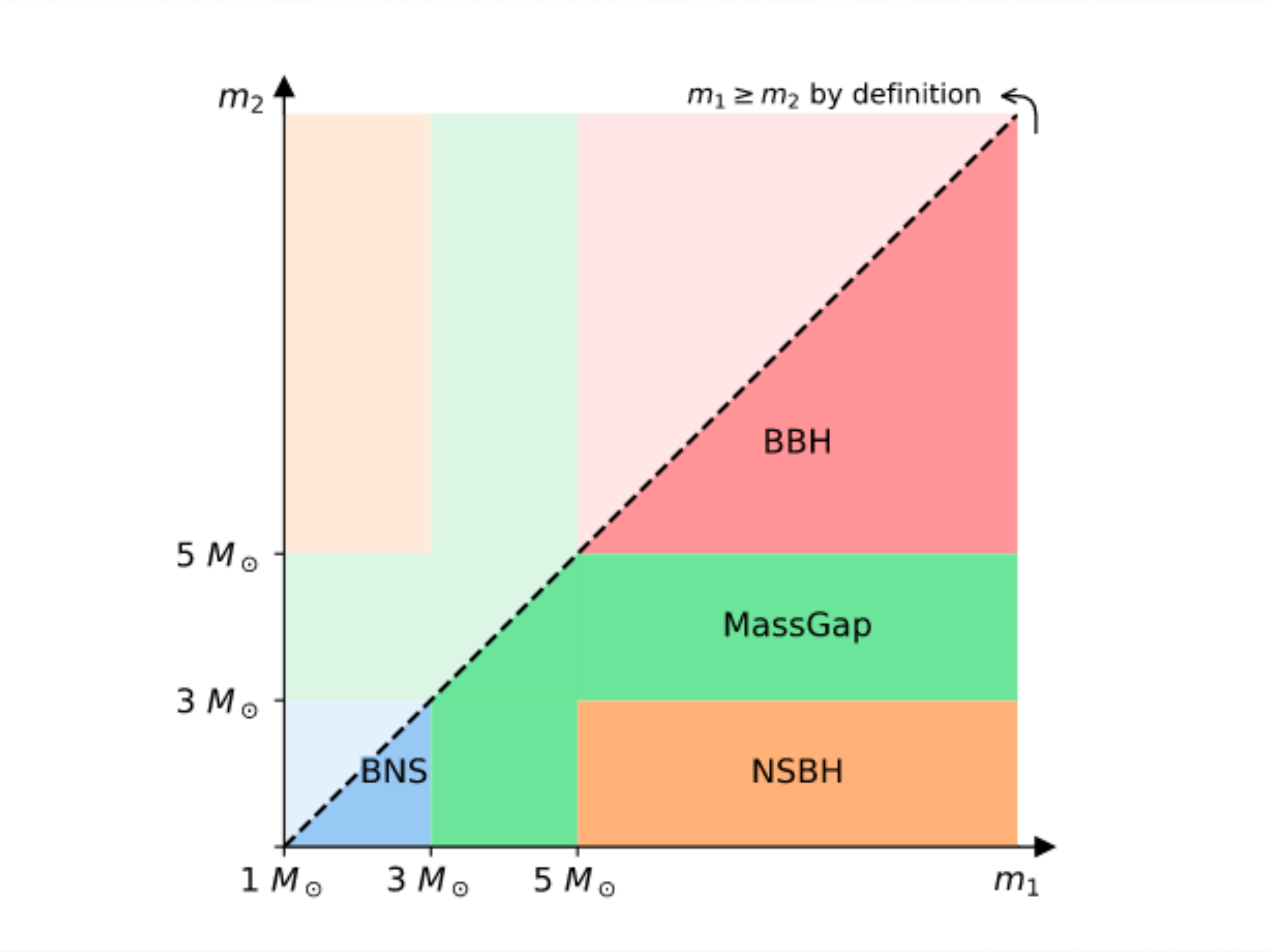






Open alerts: What does it all mean?





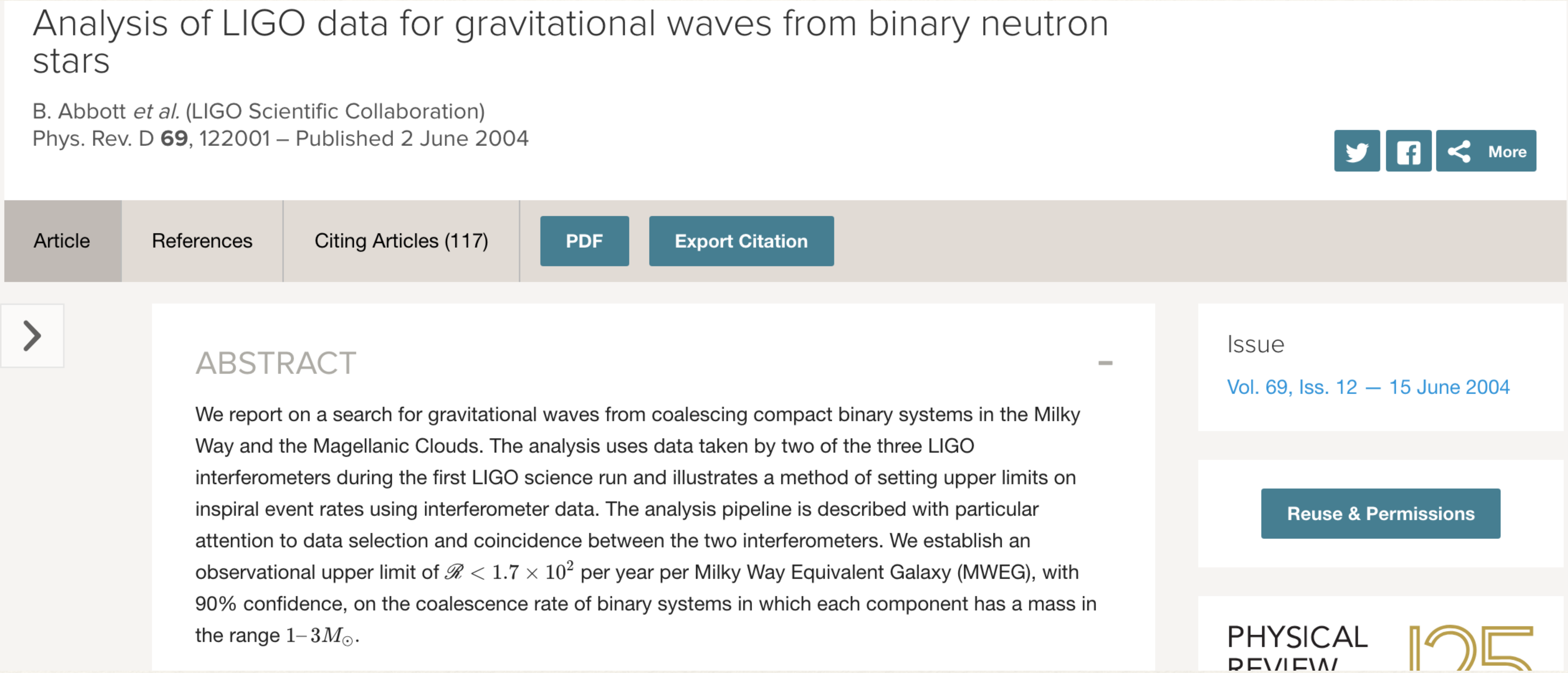
LIGO/Virgo Public Alerts User Guide
Kapadia et al. arXiv:1903.06881

See the user guide also

https://emfollow.docs.ligo.org/userguide/

THANKS

Gravitational-wave astronomy in 2002



Analysis of LIGO data for gravitational waves from binary neutron stars

B. Abbott *et al.* (LIGO Scientific Collaboration)
Phys. Rev. D **69**, 122001 – Published 2 June 2004

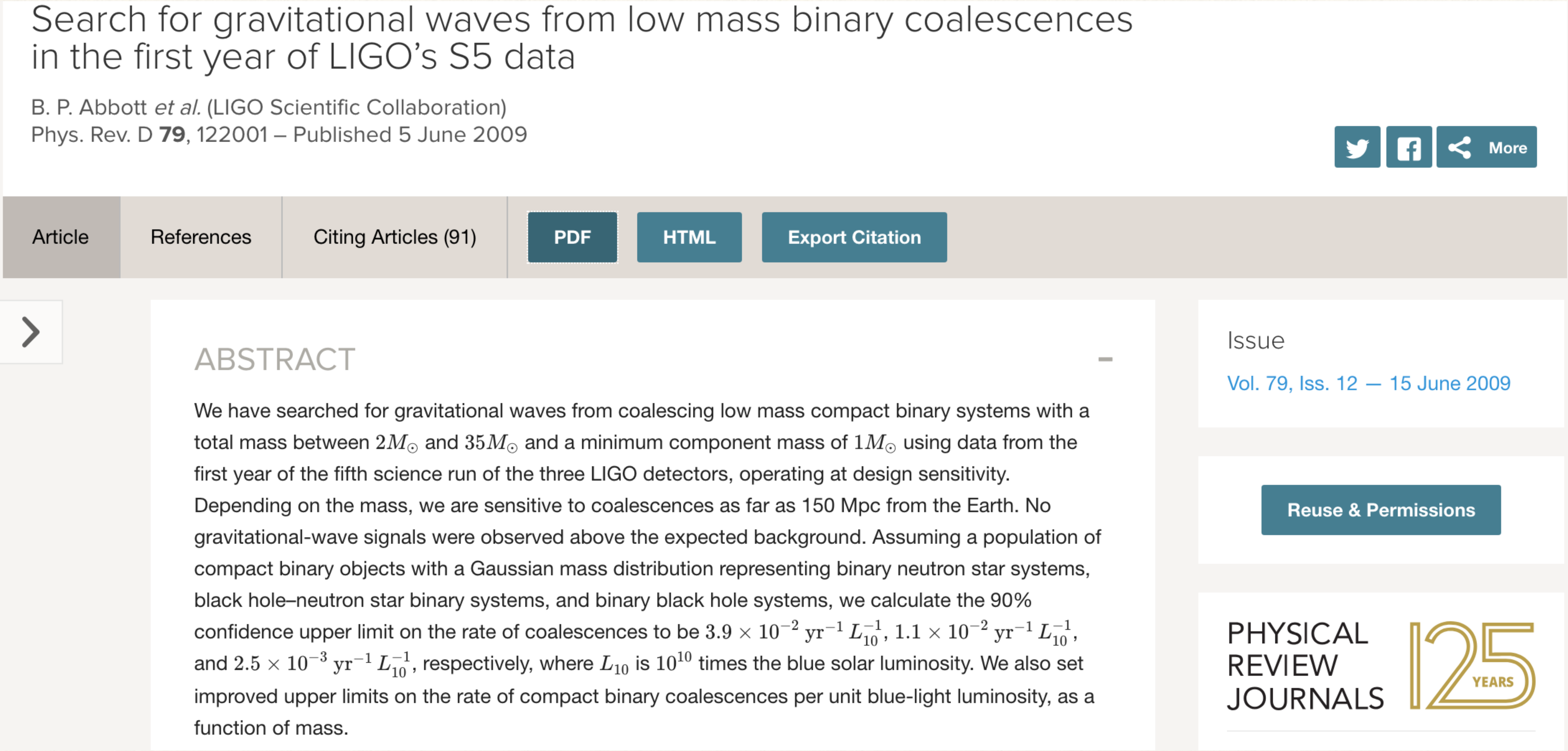
ABSTRACT

We report on a search for gravitational waves from coalescing compact binary systems in the Milky Way and the Magellanic Clouds. The analysis uses data taken by two of the three LIGO interferometers during the first LIGO science run and illustrates a method of setting upper limits on inspiral event rates using interferometer data. The analysis pipeline is described with particular attention to data selection and coincidence between the two interferometers. We establish an observational upper limit of $\mathscr{R} < 1.7 \times 10^2$ per year per Milky Way Equivalent Galaxy (MWEG), with 90% confidence, on the coalescence rate of binary systems in which each component has a mass in the range $1–3 M_\odot$.

BNS UPPER LIMIT: 170 per year per Milky Way equivalent galaxy

~ 1.7 x 10^9 per Gpc^3 per yr

Gravitational-wave astronomy in 2009



Search for gravitational waves from low mass binary coalescences in the first year of LIGO’s S5 data

B. P. Abbott *et al.* (LIGO Scientific Collaboration)
Phys. Rev. D **79**, 122001 – Published 5 June 2009

Issue
Vol. 79, Iss. 12 — 15 June 2009

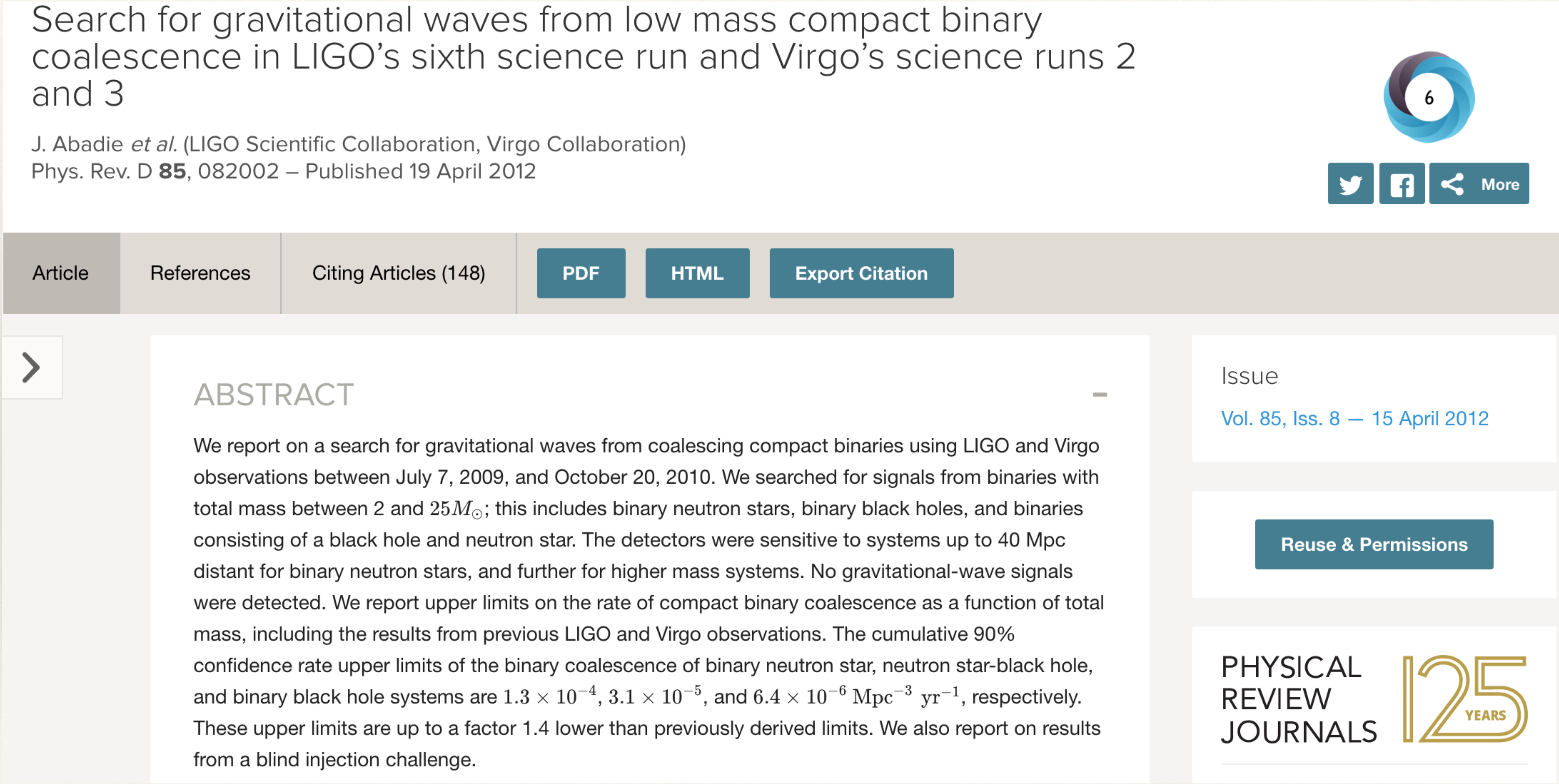
ABSTRACT

We have searched for gravitational waves from coalescing low mass compact binary systems with a total mass between $2M_\odot$ and $35M_\odot$ and a minimum component mass of $1M_\odot$ using data from the first year of the fifth science run of the three LIGO detectors, operating at design sensitivity. Depending on the mass, we are sensitive to coalescences as far as 150 Mpc from the Earth. No gravitational-wave signals were observed above the expected background. Assuming a population of compact binary objects with a Gaussian mass distribution representing binary neutron star systems, black hole–neutron star binary systems, and binary black hole systems, we calculate the 90% confidence upper limit on the rate of coalescences to be $3.9 \times 10^{-2}\ \mathrm{yr}^{-1} L_{10}^{-1}$, $1.1 \times 10^{-2}\ \mathrm{yr}^{-1} L_{10}^{-1}$, and $2.5 \times 10^{-3}\ \mathrm{yr}^{-1} L_{10}^{-1}$, respectively, where L_{10} is 10^{10} times the blue solar luminosity. We also set improved upper limits on the rate of compact binary coalescences per unit blue-light luminosity, as a function of mass.

BNS UPPER LIMIT: 0.039 per year per 10 trillion solar-like stars

~ 650,000 per Gpc^3 per yr

Gravitational-wave astronomy in 2012



Search for gravitational waves from low mass compact binary coalescence in LIGO's sixth science run and Virgo's science runs 2 and 3

J. Abadie *et al.* (LIGO Scientific Collaboration, Virgo Collaboration)
Phys. Rev. D **85**, 082002 – Published 19 April 2012

ABSTRACT

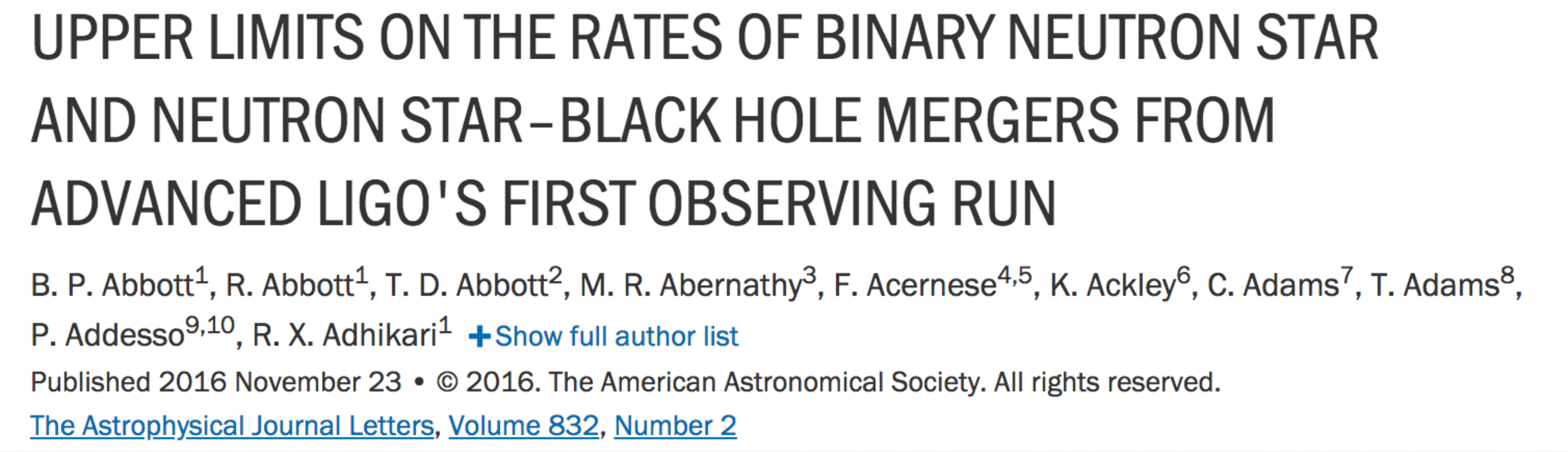
We report on a search for gravitational waves from coalescing compact binaries using LIGO and Virgo observations between July 7, 2009, and October 20, 2010. We searched for signals from binaries with total mass between 2 and $25 M_\odot$; this includes binary neutron stars, binary black holes, and binaries consisting of a black hole and neutron star. The detectors were sensitive to systems up to 40 Mpc distant for binary neutron stars, and further for higher mass systems. No gravitational-wave signals were detected. We report upper limits on the rate of compact binary coalescence as a function of total mass, including the results from previous LIGO and Virgo observations. The cumulative 90% confidence rate upper limits of the binary coalescence of binary neutron star, neutron star-black hole, and binary black hole systems are 1.3×10^{-4}, 3.1×10^{-5}, and $6.4 \times 10^{-6}\ \mathrm{Mpc}^{-3}\ \mathrm{yr}^{-1}$, respectively. These upper limits are up to a factor 1.4 lower than previously derived limits. We also report on results from a blind injection challenge.

Issue
Vol. 85, Iss. 8 — 15 April 2012

BNS UPPER LIMIT: 1.3 x 10^{-4} per Mpc^3 per year

~ 130,000 per Gpc^3 per yr

Gravitational-wave astronomy in 2015



UPPER LIMITS ON THE RATES OF BINARY NEUTRON STAR AND NEUTRON STAR–BLACK HOLE MERGERS FROM ADVANCED LIGO'S FIRST OBSERVING RUN

B. P. Abbott[1], R. Abbott[1], T. D. Abbott[2], M. R. Abernathy[3], F. Acernese[4,5], K. Ackley[6], C. Adams[7], T. Adams[8], P. Addesso[9,10], R. X. Adhikari[1] +Show full author list

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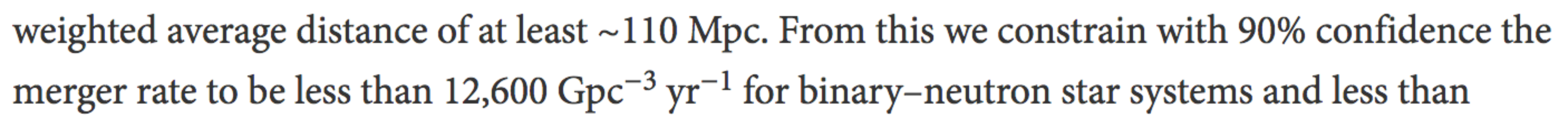
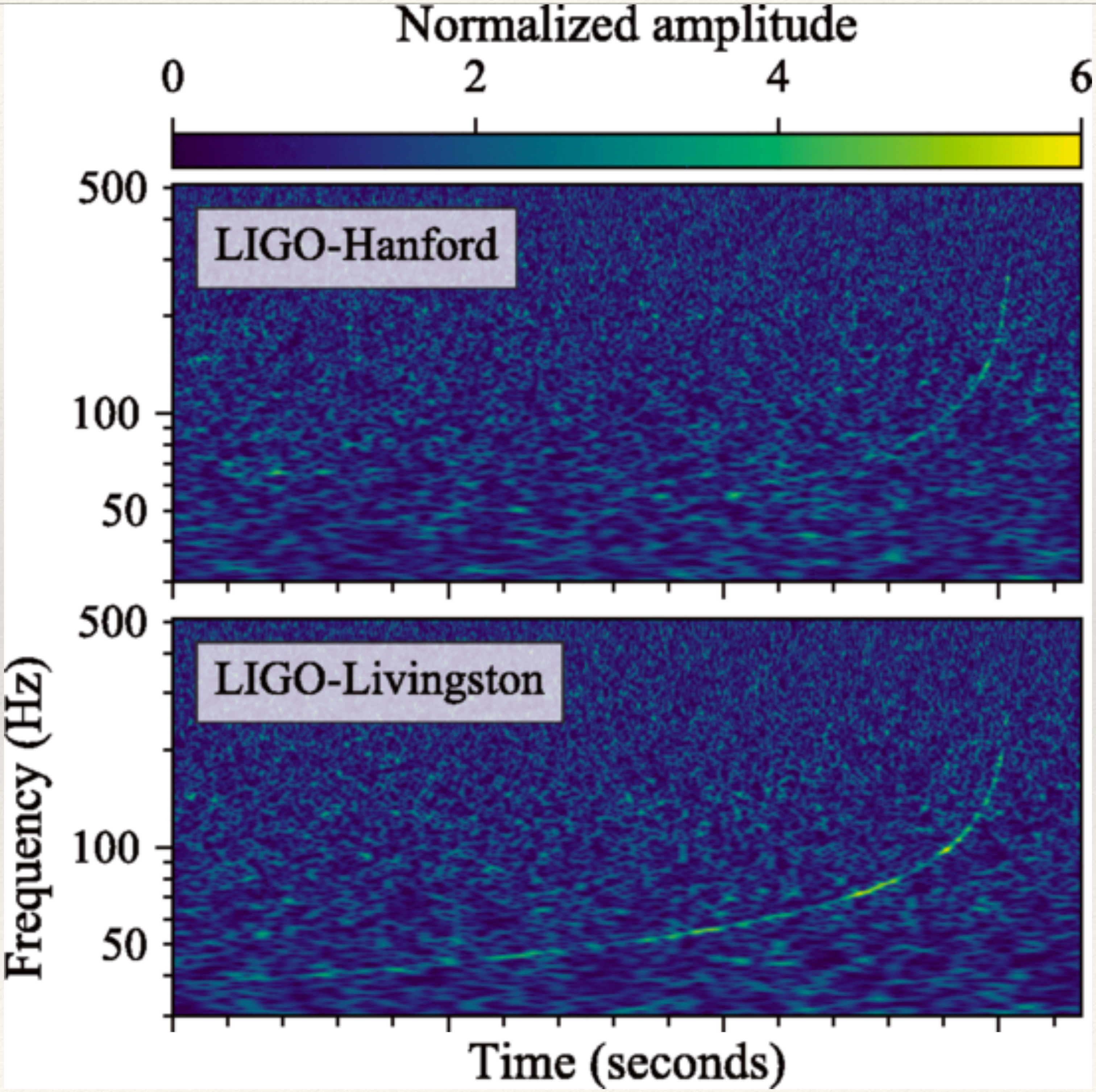
The Astrophysical Journal Letters, Volume 832, Number 2



weighted average distance of at least ~110 Mpc. From this we constrain with 90% confidence the merger rate to be less than 12,600 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ for binary–neutron star systems and less than

BNS UPPER LIMIT: **12,600 per Gpc^3 per yr**

Gravitational-wave astronomy now



Searching for colliding compact objects: What do we know about the signal?

Searching for colliding black holes: What do we know about the noise?

Do we know what we're looking for?

Approximate analytical solutions

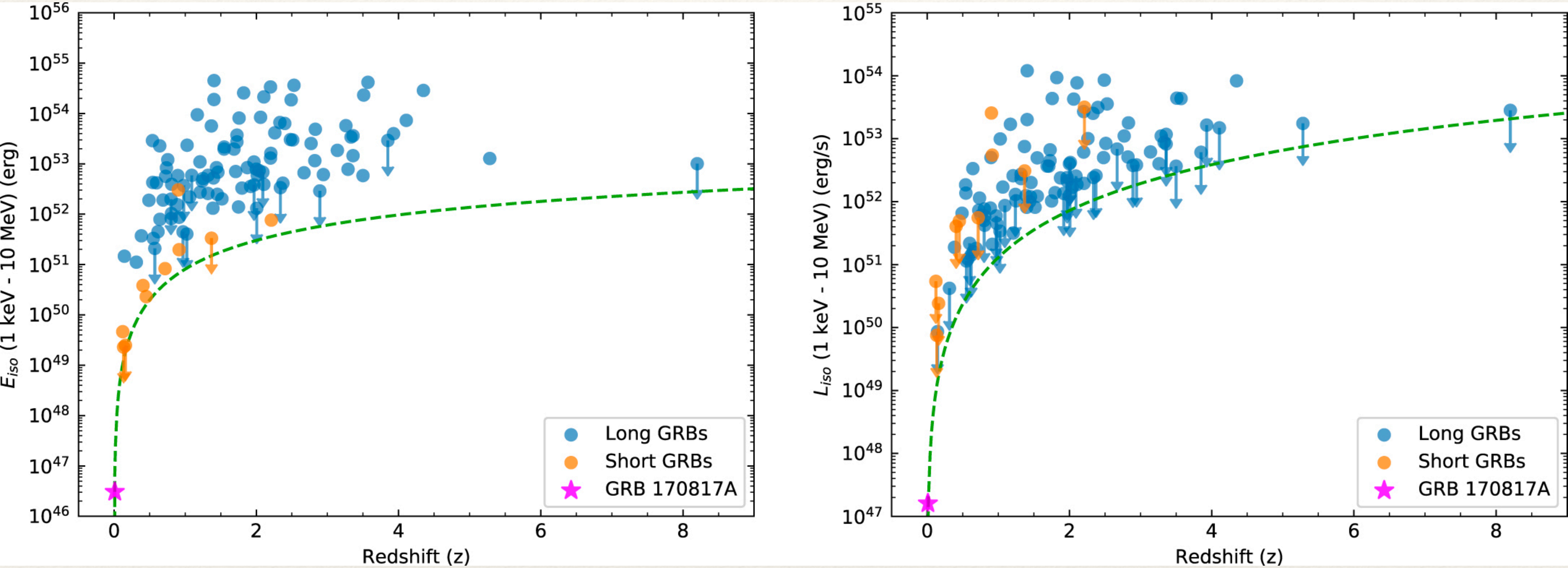
- Perturbative approaches can be used.
- Effective-one-body approach is one example of this
- Loses accuracy as the two black holes come close to merger

Buonanno and Damour Phys.Rev. D59 (1999) 084006
Buonanno et al., Phys.Rev. D80 (2009) 084043
Pretorius, Phys.Rev.Lett. 95 (2005) 121101
Campanelli et al., Phys.Rev.Lett. 96 (2006) 111101

Numerical solutions

- Einstein's equations can be solved directly using numerical evolution methods
- Very computationally expensive — cannot be used to model many orbits
- Can model the collision
- Some inaccuracy from numerical approach

GRB170817A: An outlier



Astrophys. J. Lett. 848, L13 (2017)

PLOTS FROM NEW MODEL COMPARISON PAPER

- ONLY TO BE INCLUDED IF THIS PAPER APPEARS ON THE ARXIV BEFORE THE TALK