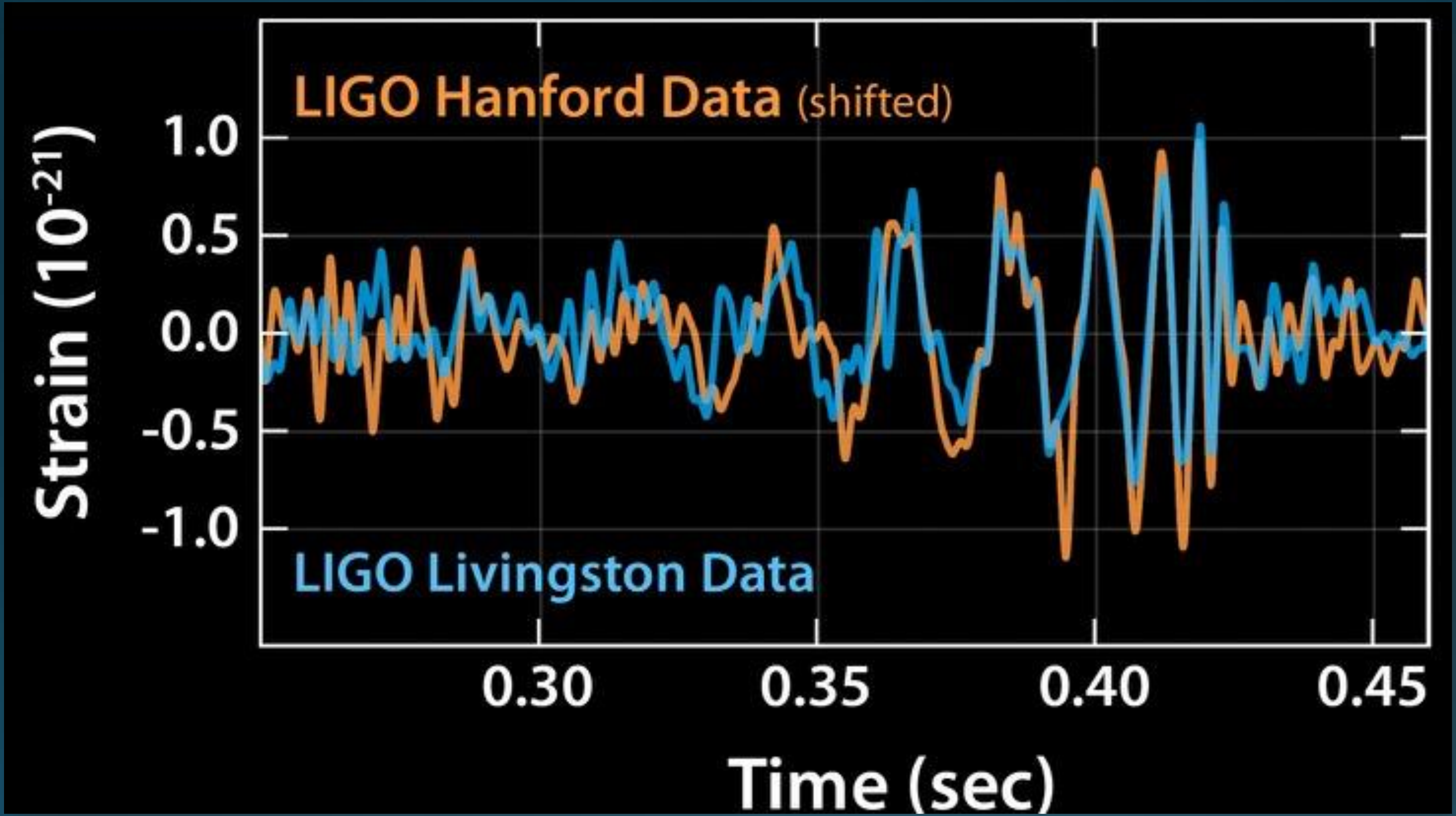
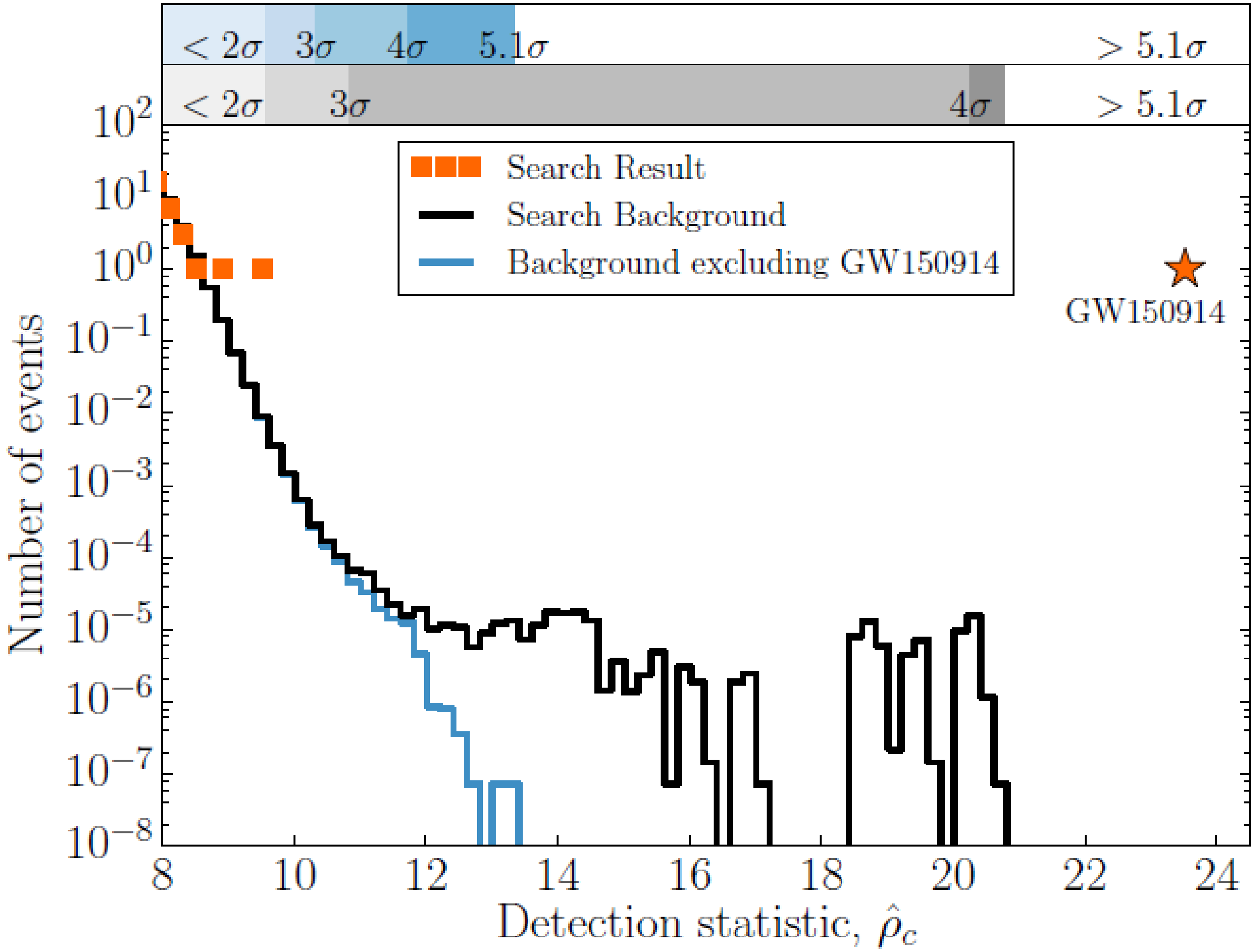
Lessons from two decades of looking at gravitational wave data

Stephen Fairhurst

The First Detection – GW150914



The real detection plot



From Abbott et al, arXiv: 1602.03837

Search Results

VOLUME 83, NUMBER 8 PHYSICAL REVIEW LETTERS 23 AUGUST 1999

Observational Limit on Gravitational Waves from Binary Neutron Stars in the Galaxy

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(Received 31 March 1999)

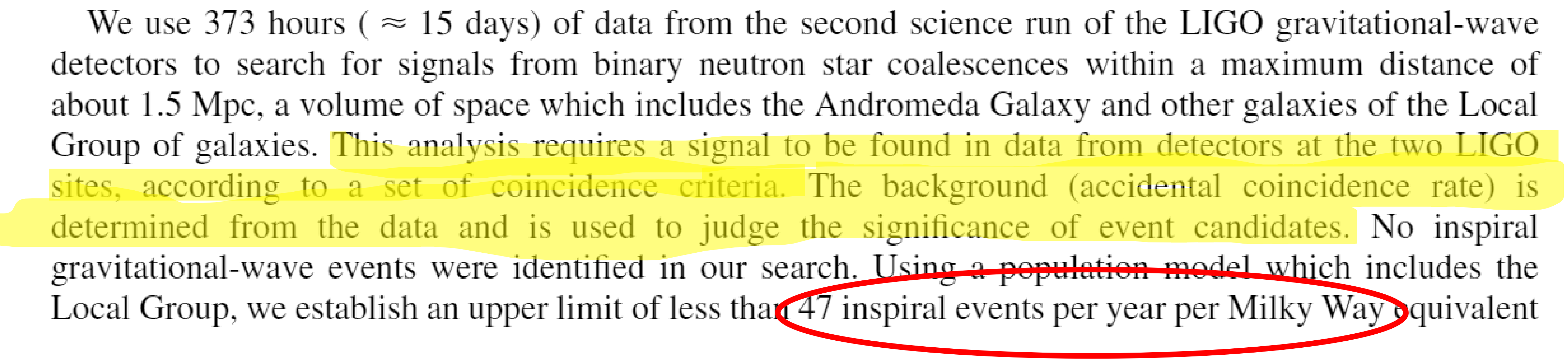
Using optimal matched filtering, we search 25 hours of data from the LIGO 40-m prototype laser interferometric gravitational-wave detector for gravitational-wave chirps emitted by coalescing binary systems within our Galaxy. This is the first test of this filtering technique on real interferometric data. An upper limit on the rate R of neutron star binary inspirals in our Galaxy is obtained: with 90% confidence, $R < 0.5\ \mathrm{h}^{-1}$. Similar experiments with LIGO interferometers will provide constraints on the population of tight binary neutron star systems in the Universe.

PACS numbers: 95.85.Sz, 04.80.Nn, 07.05.Kf, 97.80.–d

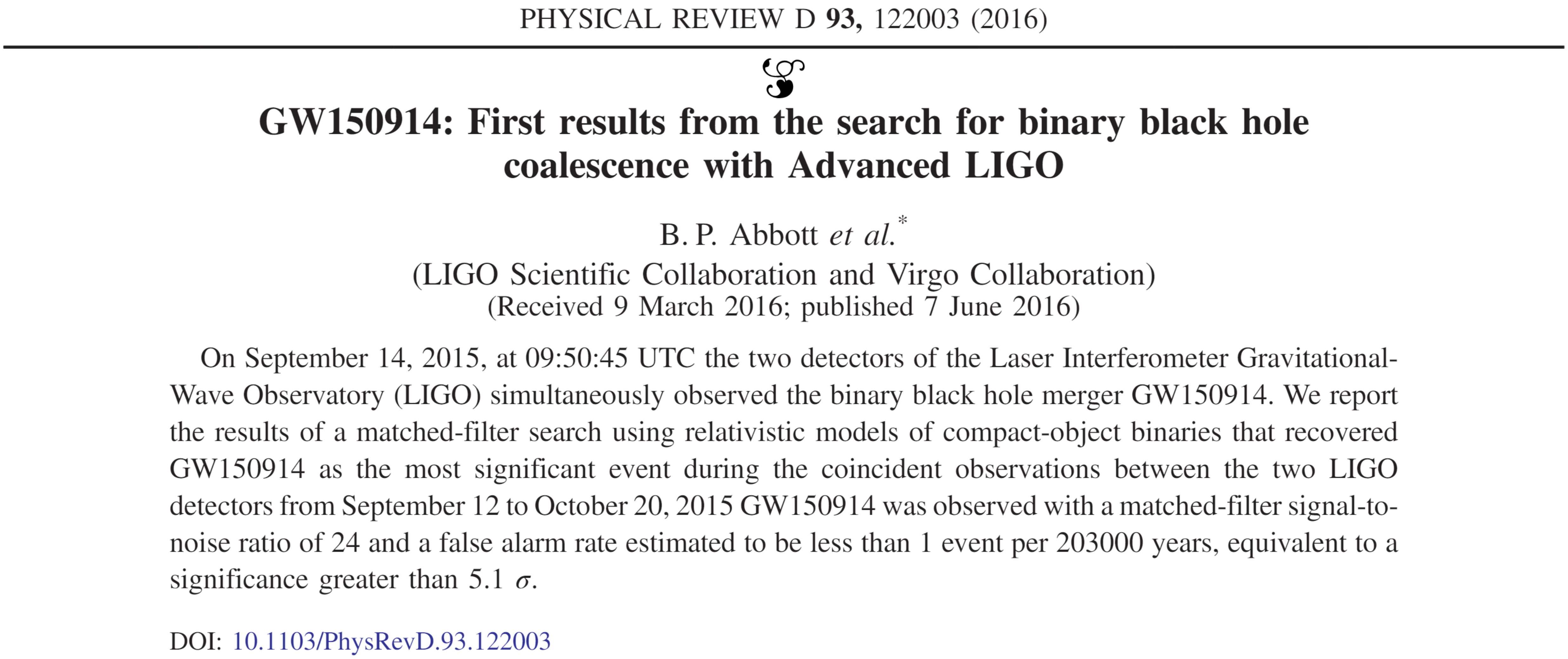
PHYSICAL REVIEW D **72,** 082001 (2005)

Search for gravitational waves from galactic and extra-galactic binary neutron stars

B. Abbott,[12] R. Abbott,[15] R. Adhikari,[13] A. Ageev,[20,27] B. Allen,[39] R. Amin,[34] S. B. Anderson,[12] W. G. Anderson,[29] M. Araya,[12] H. Armandula,[12] M. Ashley,[28] F. Asiri,[12,a] P. Aufmuth,[31] C. Aulbert,[1] S. Babak,[7] R. Balasubramanian,[7] S. Ballmer,[13] B. C. Barish,[12] C. Barker,[14] D. Barker,[14] M. Barnes,[12,b] B. Barr,[35] M. A. Barton,[12] K. Bayer,[13] R. Beausoleil,[26,c] K. Belczynski,[23] R. Bennett,[35,d] S. J. Berukoff,[1,e] J. Betzwieser,[13] B. Bhawal,[12] I. A. Bilenko,[20] C. Billingsley,[12] E. Black,[12] K. Blackburn,[12] L. Blackburn,[13] R. Bland,[14] B. Bochner,[13,f] L. Bogue,[12] R. Bork,[12]



We use 373 hours (≈ 15 days) of data from the second science run of the LIGO gravitational-wave detectors to search for signals from binary neutron star coalescences within a maximum distance of about 1.5 Mpc, a volume of space which includes the Andromeda Galaxy and other galaxies of the Local Group of galaxies. This analysis requires a signal to be found in data from detectors at the two LIGO sites, according to a set of coincidence criteria. The background (accidental coincidence rate) is determined from the data and is used to judge the significance of event candidates. No inspiral gravitational-wave events were identified in our search. Using a population model which includes the Local Group, we establish an upper limit of less than 47 inspiral events per year per Milky Way equivalent



PHYSICAL REVIEW D **93,** 122003 (2016)

GW150914: First results from the search for binary black hole coalescence with Advanced LIGO

B. P. Abbott *et al.*[*]

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 9 March 2016; published 7 June 2016)

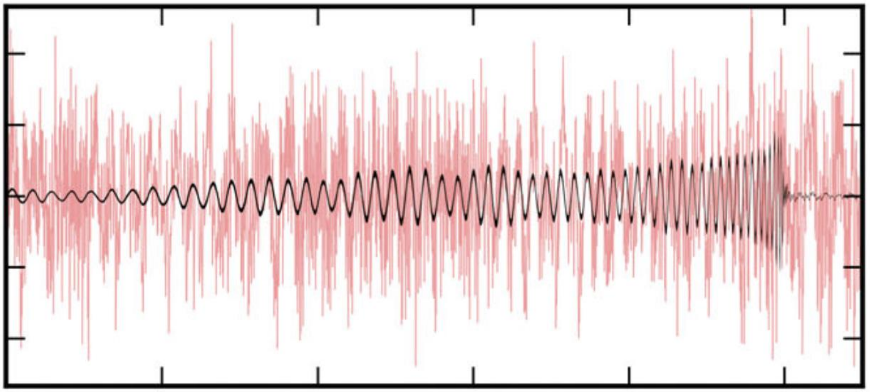
On September 14, 2015, at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) simultaneously observed the binary black hole merger GW150914. We report the results of a matched-filter search using relativistic models of compact-object binaries that recovered GW150914 as the most significant event during the coincident observations between the two LIGO detectors from September 12 to October 20, 2015 GW150914 was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203000 years, equivalent to a significance greater than 5.1 σ.

DOI: 10.1103/PhysRevD.93.122003

Search Details

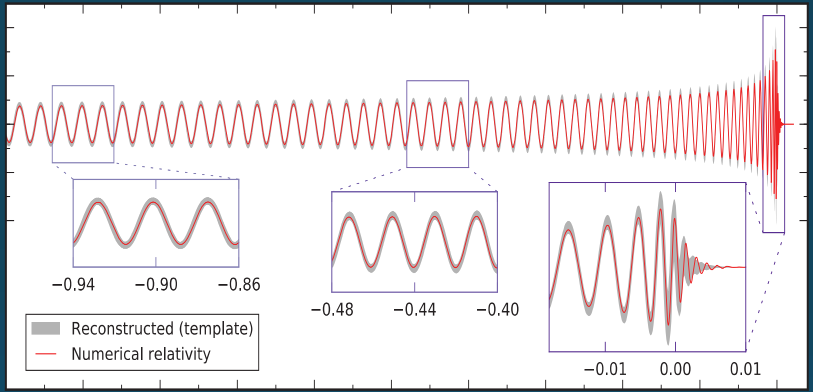
Identifying the signal: Matched filtering

Data



X

Waveform



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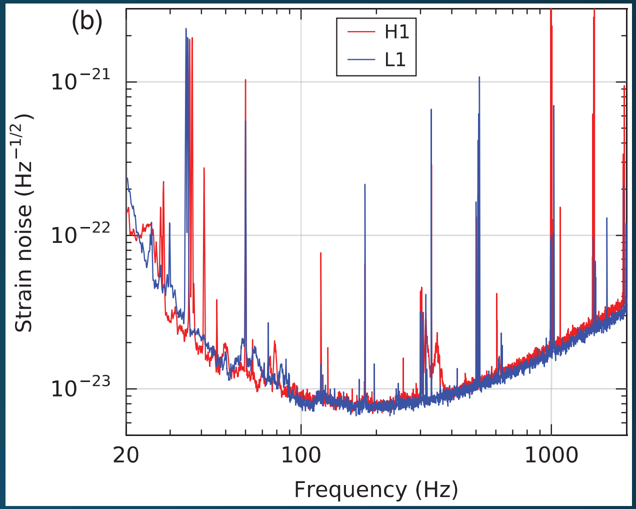
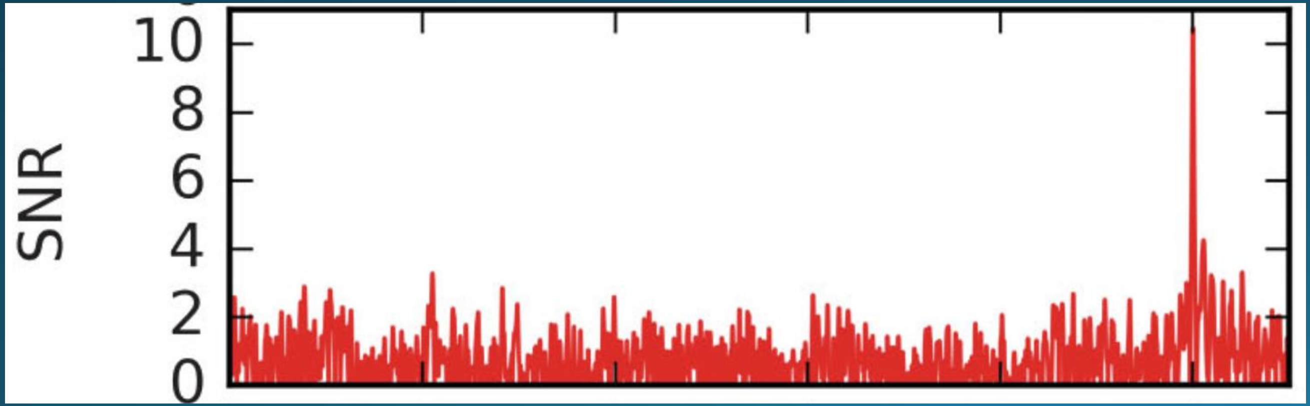
Sensitivity



Signal to Noise Ratio

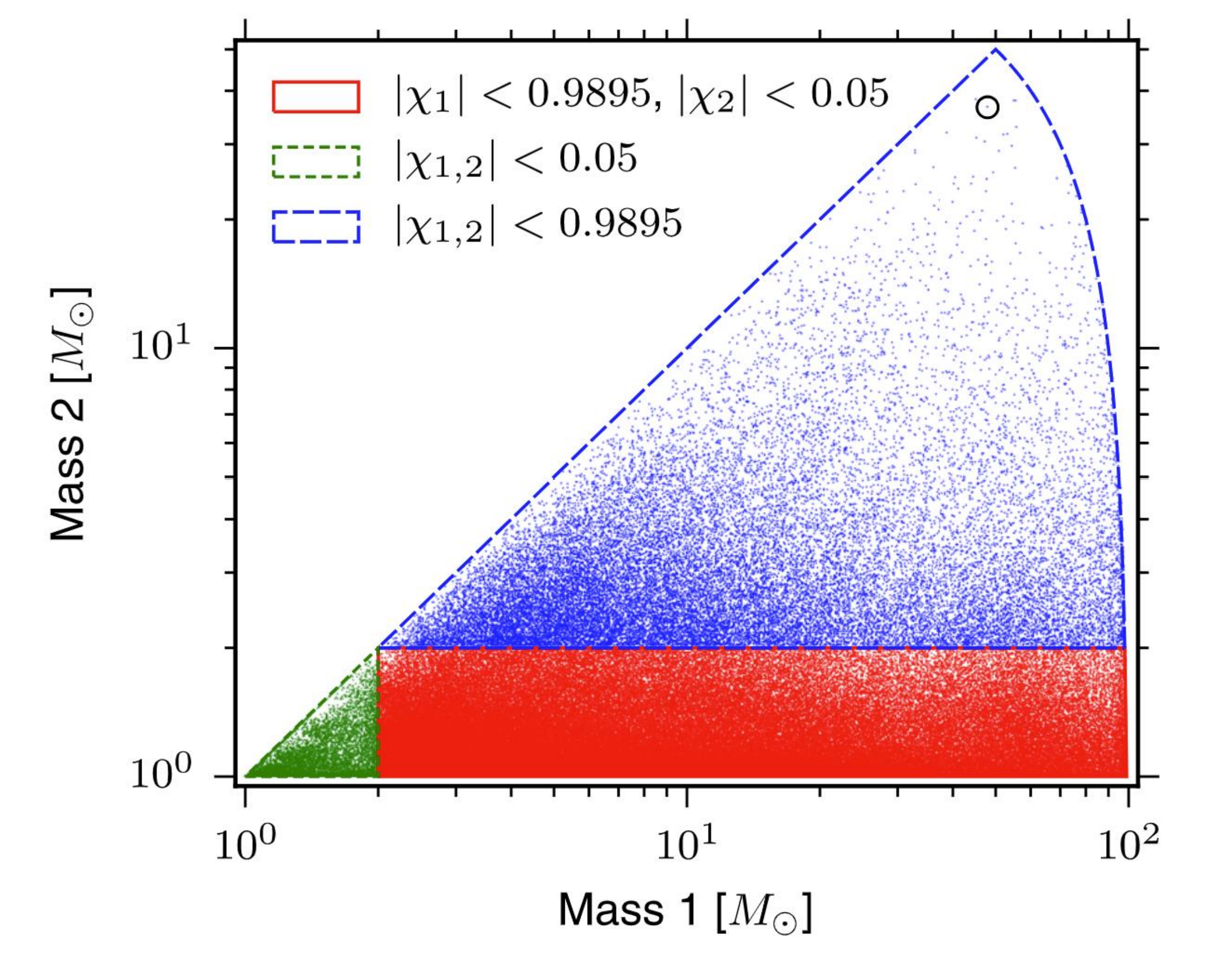
=



Coalescence Time

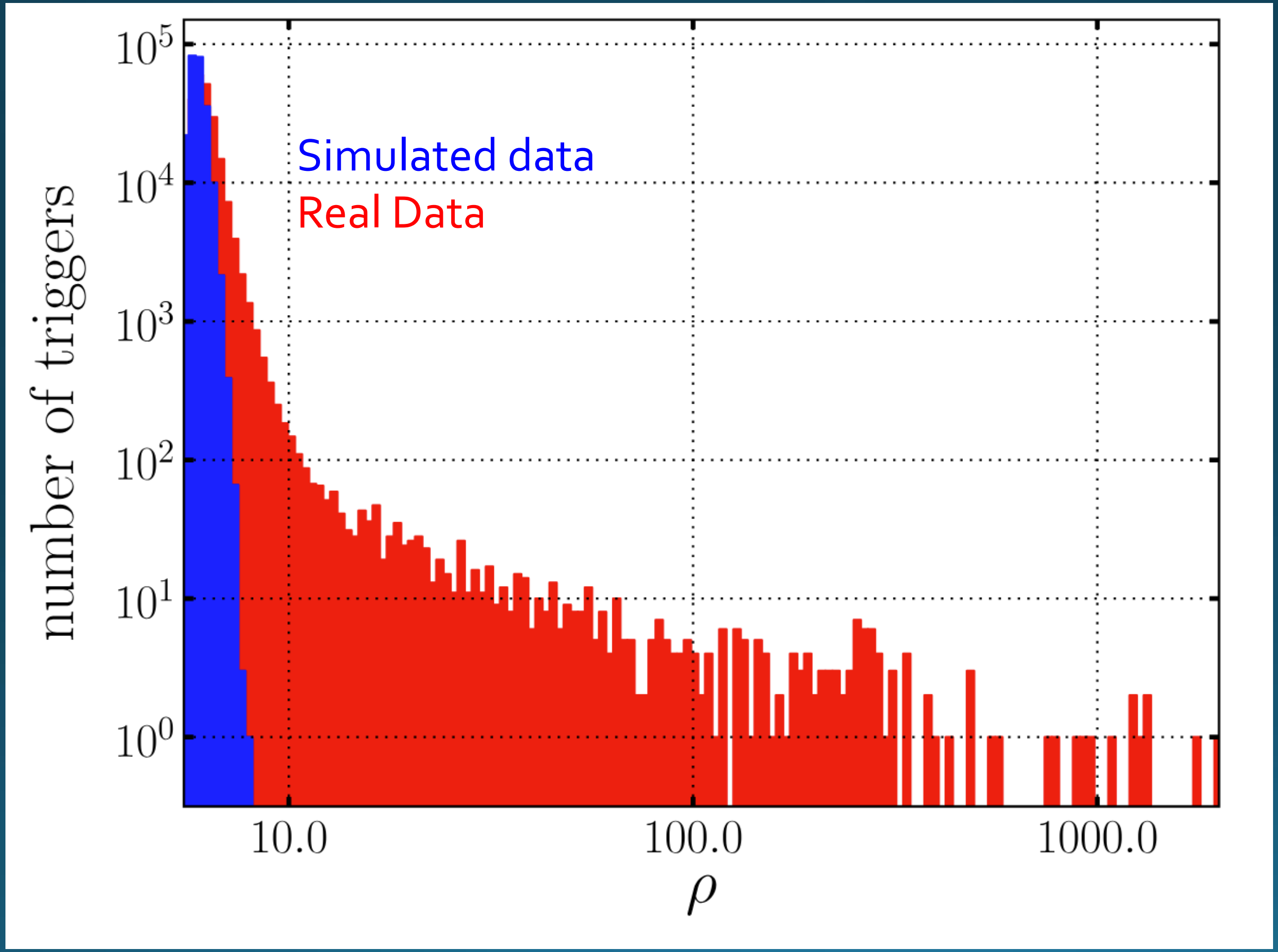
Figures from Abbott et al, “GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence”, 2016

Template Bank



From Abbott et al, arXiv: 1602.03839

Matched filtering results

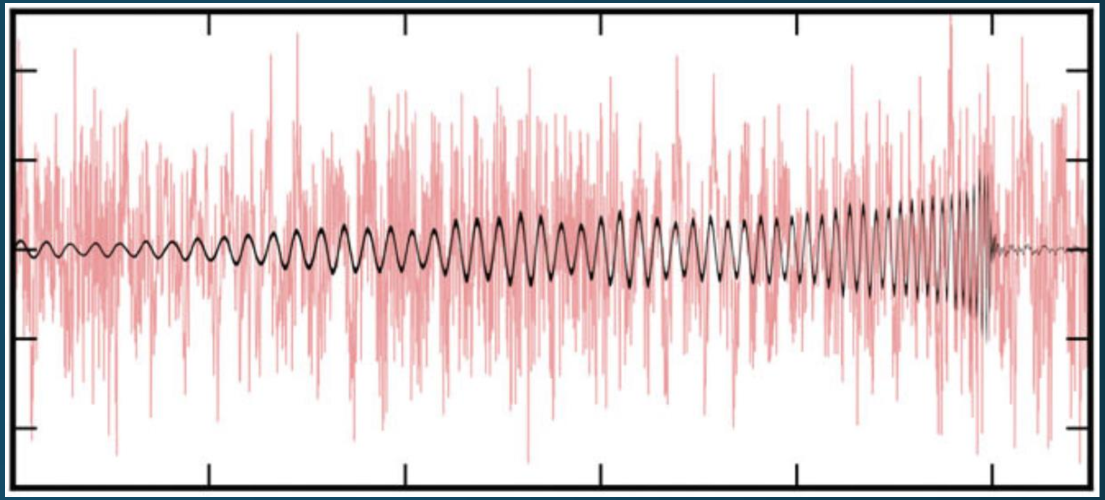


From Babak et al, arXiv: 1208.3491

Signal Consistency tests

- A loud glitch will produce a high SNR, even if it doesn’t match the signal
- Split the signal into N parts, with equal power in each, and calculate SNR for each part
- χ^2 test to verify that SNR correctly distributed

Introduced in B. Allen, arXiv: gr-qc/0405045



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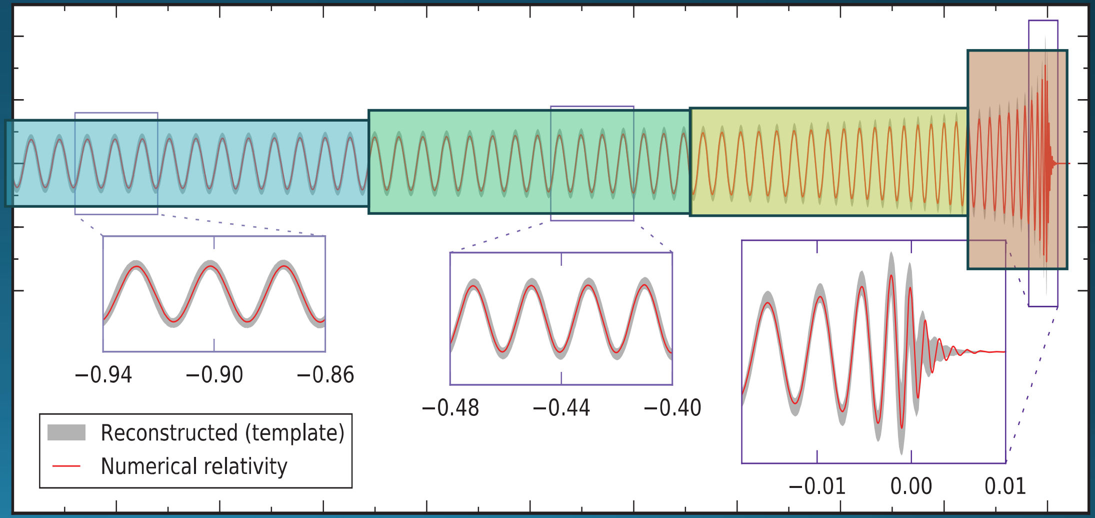
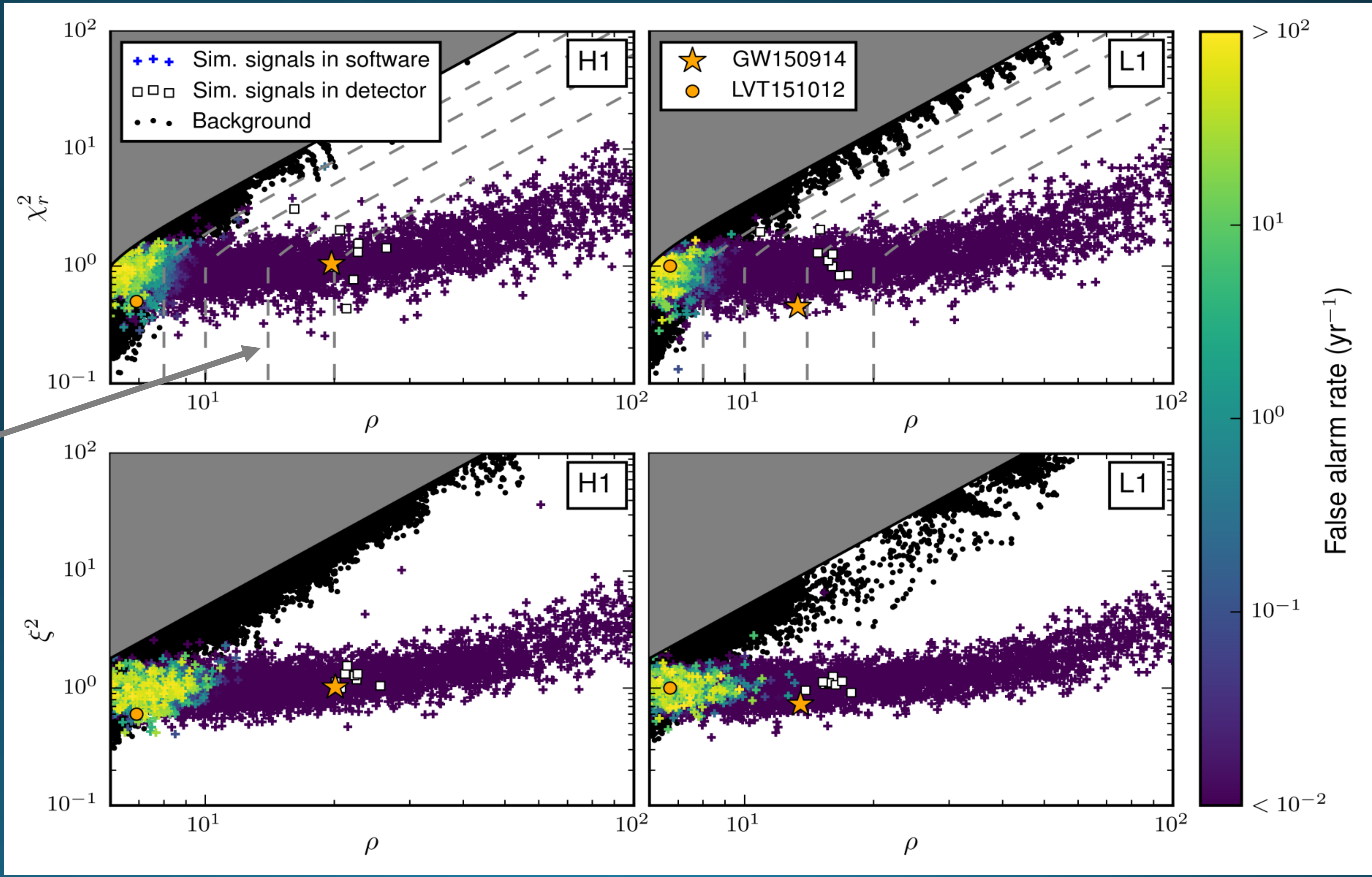


Event Ranking

- Triggers in each detector are ranked based on a “re-weighted” SNR

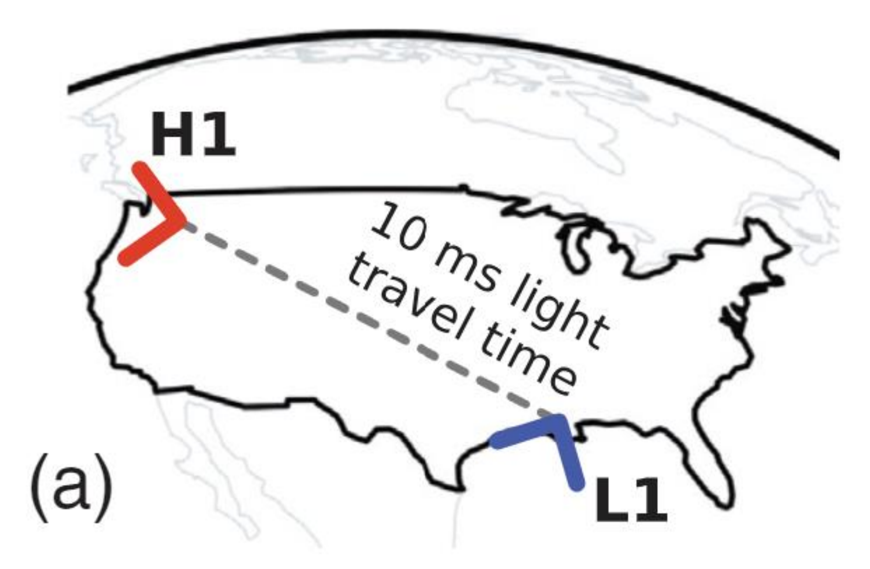
Lines of constant re-weighted SNR

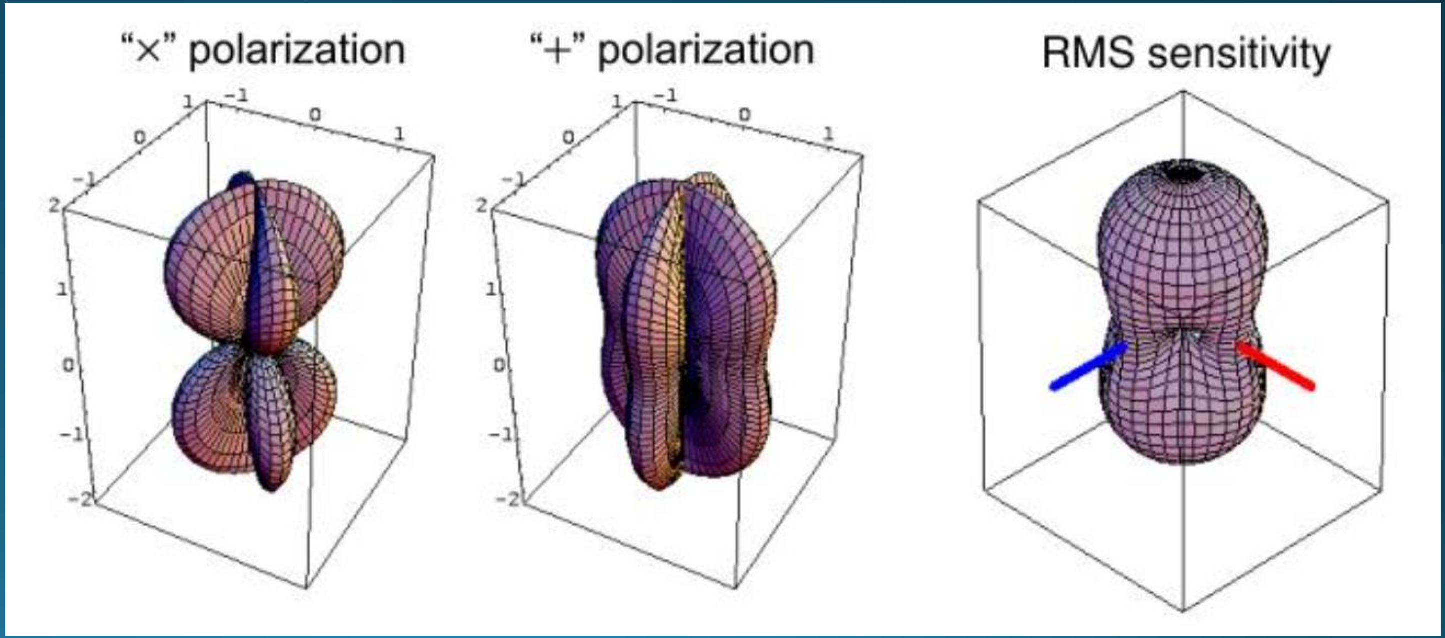


From Abbott et al, arXiv: 1602.03839

Coincidence

- Require a signal in all detectors consistent with an astrophysical source
- Consistent time of arrival and amplitude/phase of signal in all detectors





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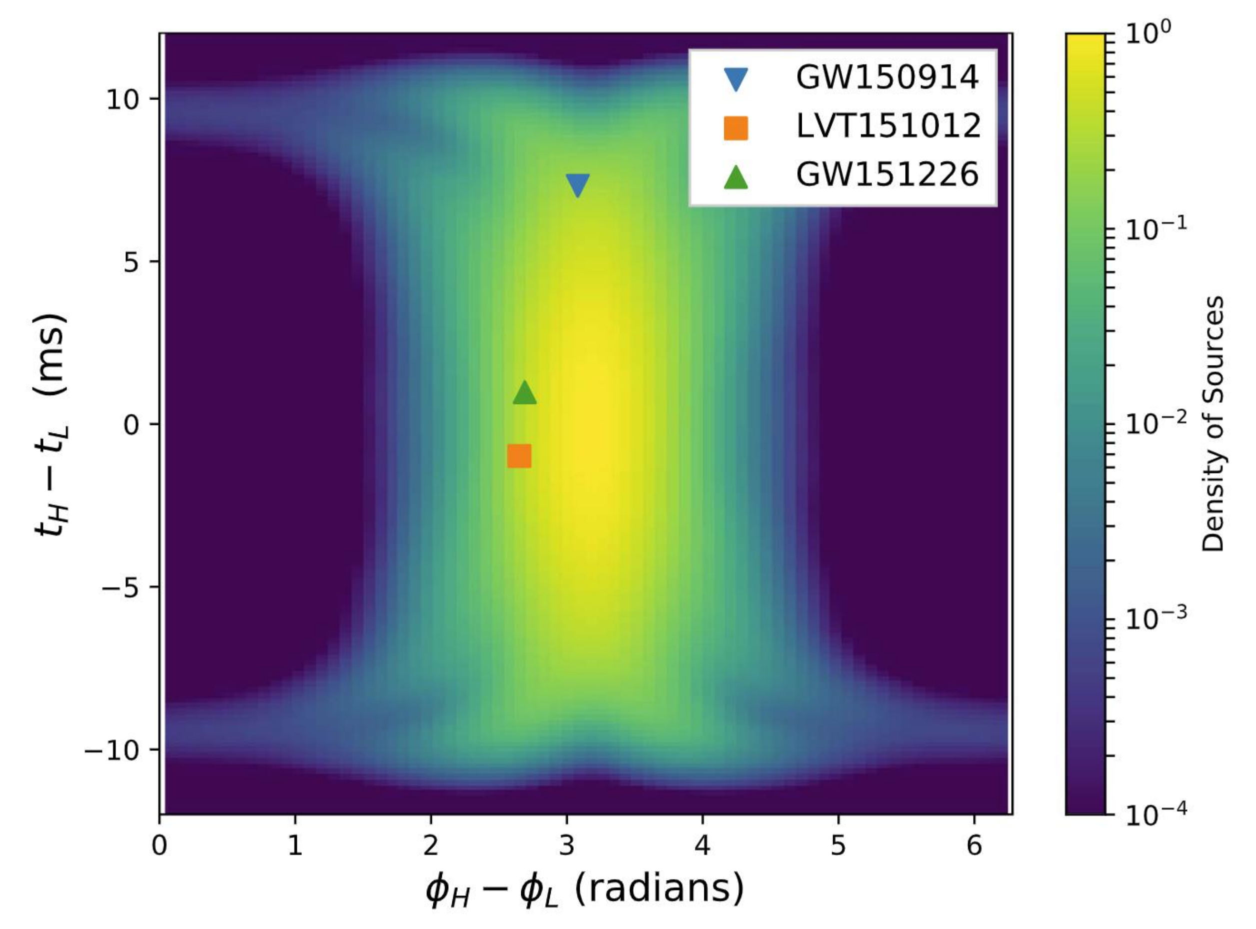
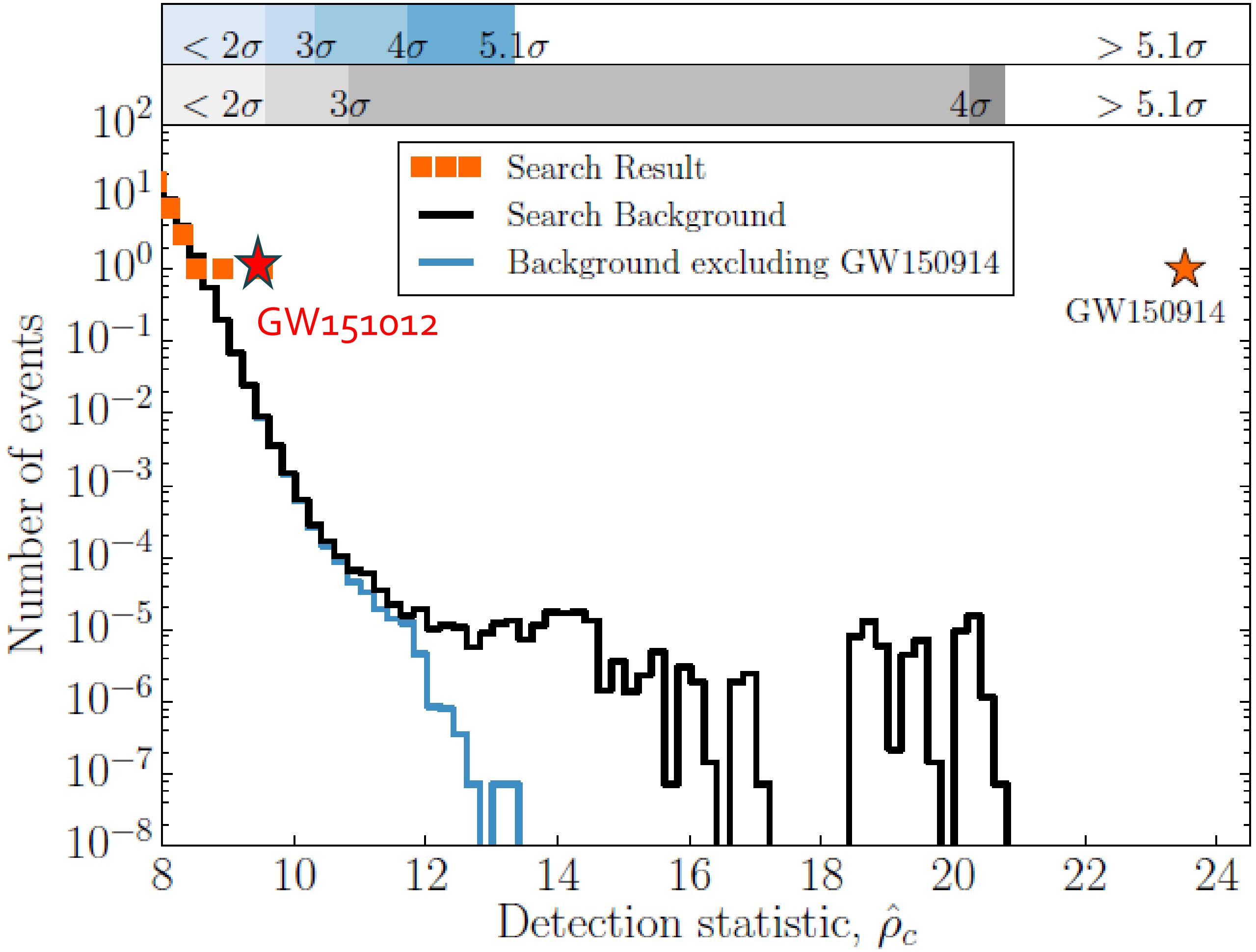


From Nitz et al, arXiv: 1705.01513

Binary Coalescence Search for GW150914

- Search from 1 to 99 solar masses; total mass , 100 solar masses and dimensionless spin < 0.99
- 250,000 waveforms are used to cover the parameter space
- Calculate matched filter SNR as function of time $\rho(t)$ and identify maxima and calculate χ^2 to test consistency with matched template
- Apply detector coincidence within 15 msec.
- Calculate quadrature sum ρ_c of the signal to noise of each detector
- Background: Time shift and recalculate 10^7 times equivalent to 608,000 years.
- Significance: GW150914 has $\rho_c = 23.6$ corresponding to false alarm rate less than 1 per 203,000 years or significance > 5.1 σ

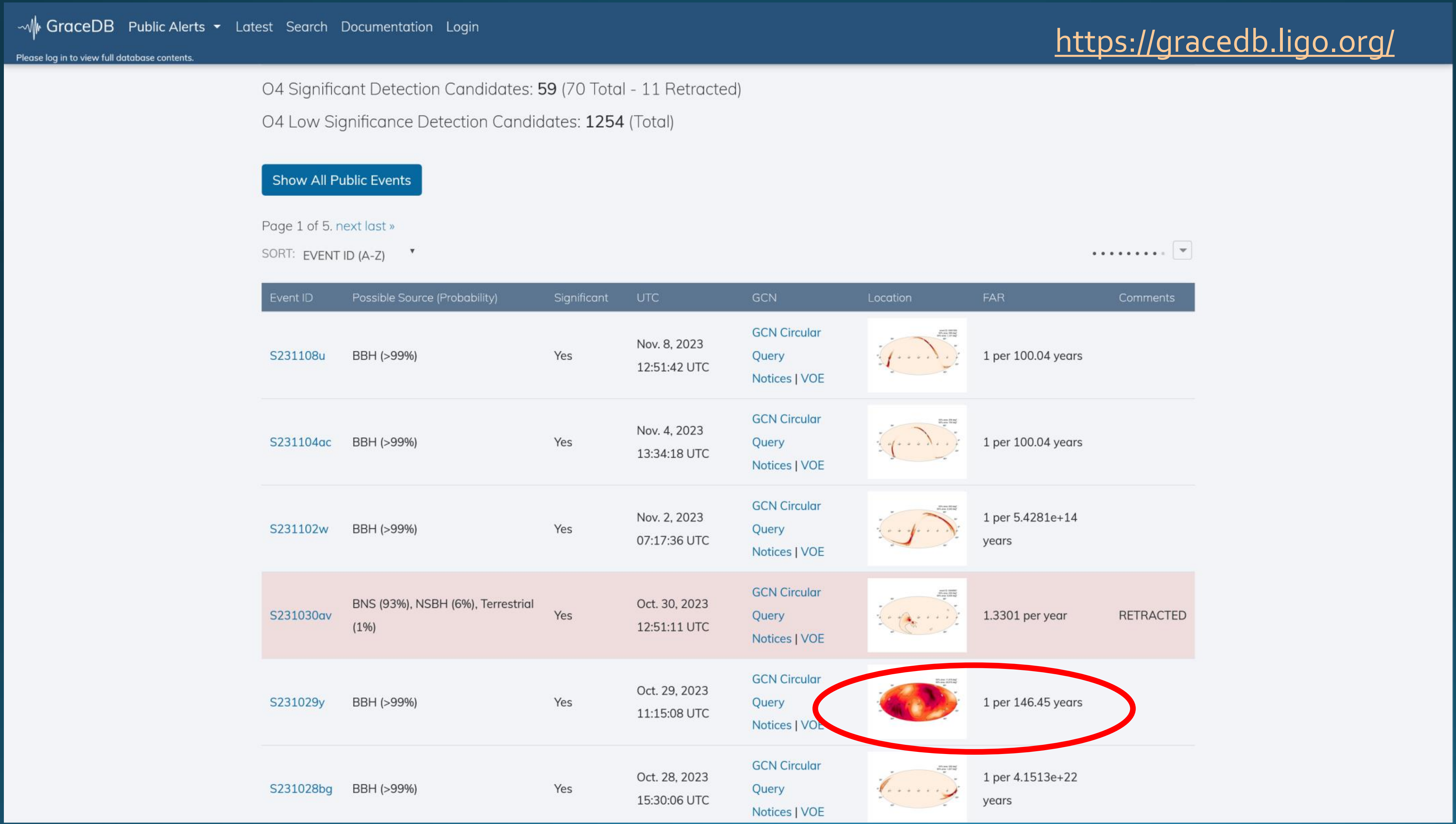
The real detection plot



From Abbott et al, arXiv: 1602.03837

Other Issues

Single Detector Events



https://gracedb.ligo.org/

Please log in to view full database contents.

O4 Significant Detection Candidates: **59** (70 Total - 11 Retracted)

O4 Low Significance Detection Candidates: **1254** (Total)

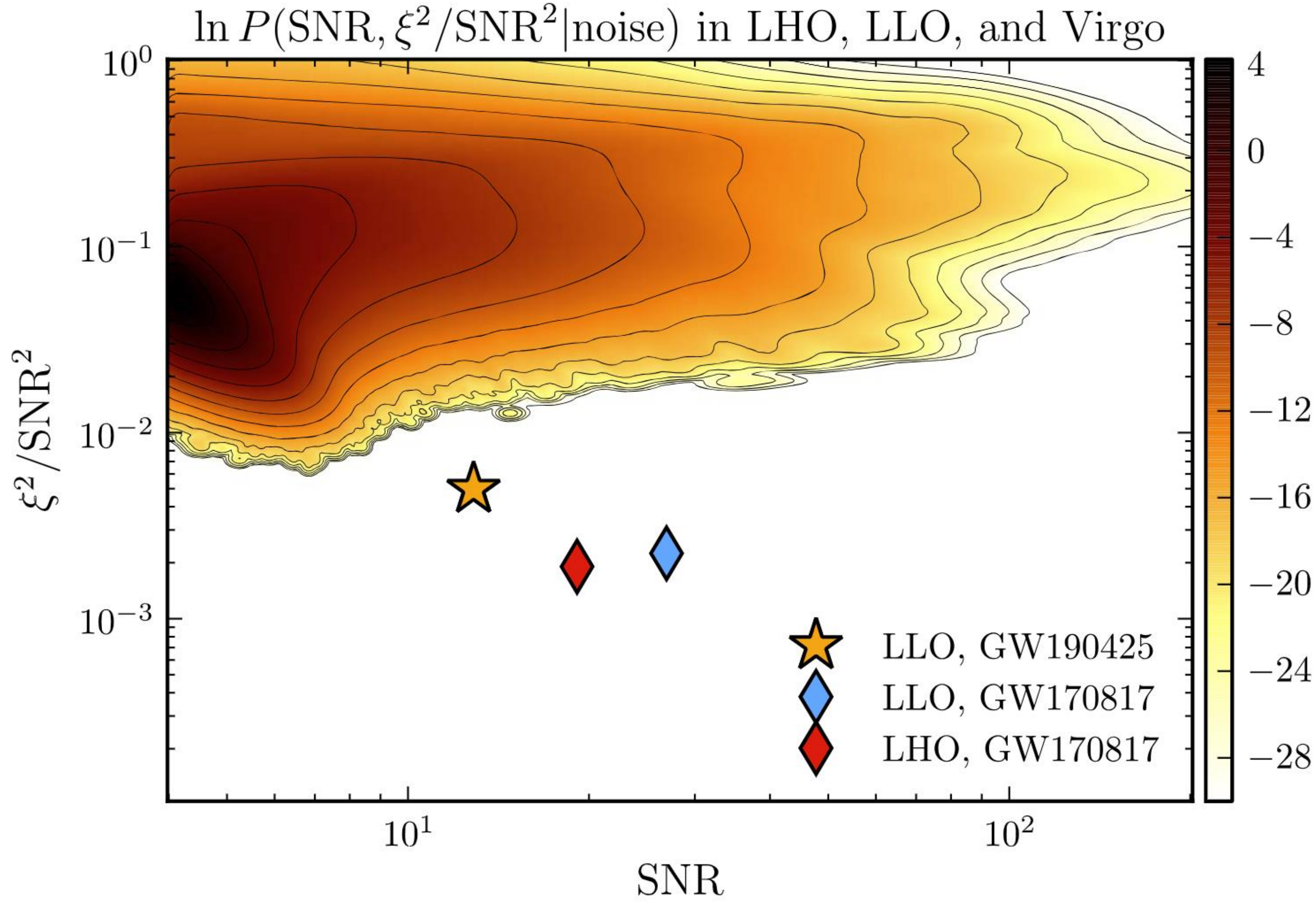
Page 1 of 5. next last »

SORT: EVENT ID (A-Z)

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S231108u	BBH (>99%)	Yes	Nov. 8, 2023 12:51:42 UTC	GCN Circular Query Notices | VOE		1 per 100.04 years	
S231104ac	BBH (>99%)	Yes	Nov. 4, 2023 13:34:18 UTC	GCN Circular Query Notices | VOE		1 per 100.04 years	
S231102w	BBH (>99%)	Yes	Nov. 2, 2023 07:17:36 UTC	GCN Circular Query Notices | VOE		1 per 5.4281e+14 years	
S231030av	BNS (93%), NSBH (6%), Terrestrial (1%)	Yes	Oct. 30, 2023 12:51:11 UTC	GCN Circular Query Notices | VOE		1.3301 per year	RETRACTED
S231029y	BBH (>99%)	Yes	Oct. 29, 2023 11:15:08 UTC	GCN Circular Query Notices | VOE		1 per 146.45 years	
S231028bg	BBH (>99%)	Yes	Oct. 28, 2023 15:30:06 UTC	GCN Circular Query Notices | VOE		1 per 4.1513e+22 years	

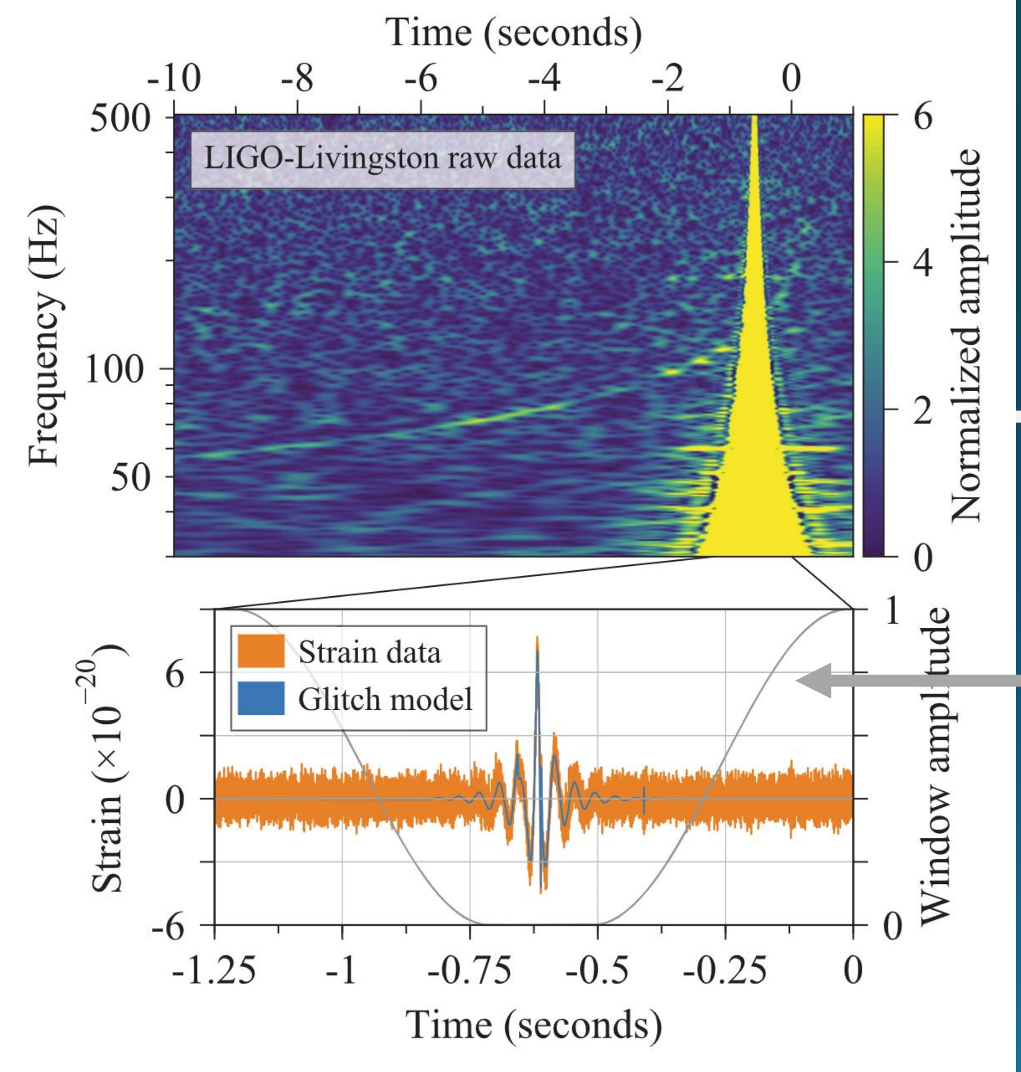
Single Detector Events

- Difficult to evaluate significance
    - Strictly, limited to 1/T, where T is observing time
- Second observed BNS, GW190425, was seen in 1-detector



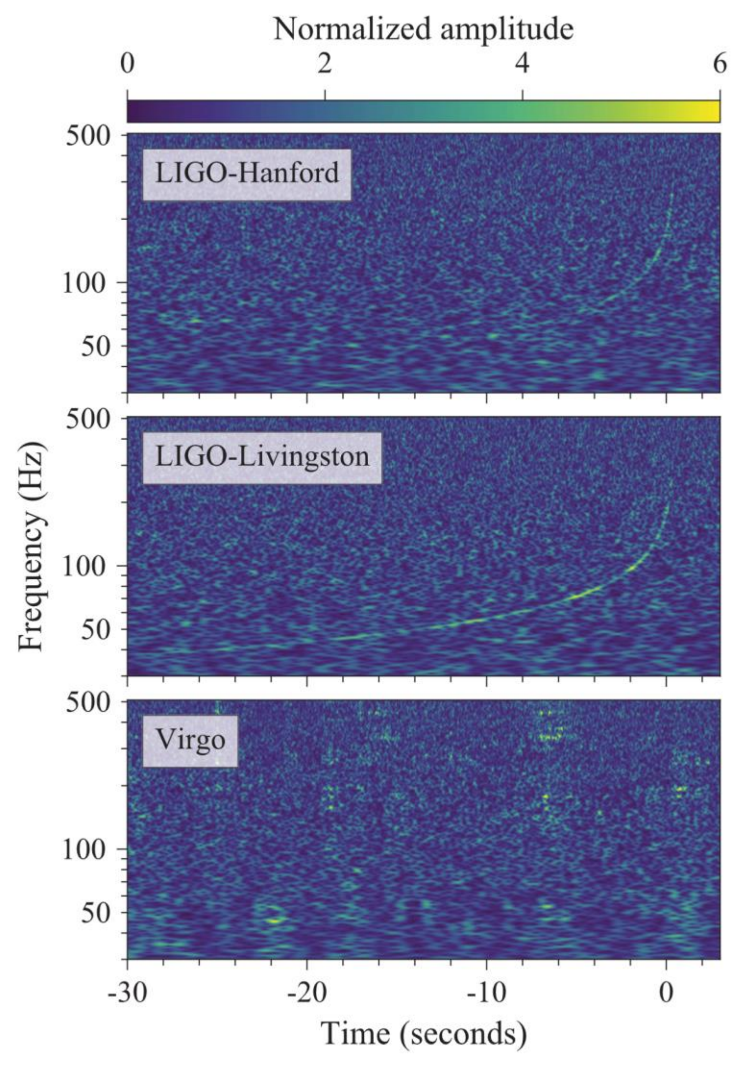
From Abbott et al, arXiv: 2001.01761

Glitches mid-signal: GW170817



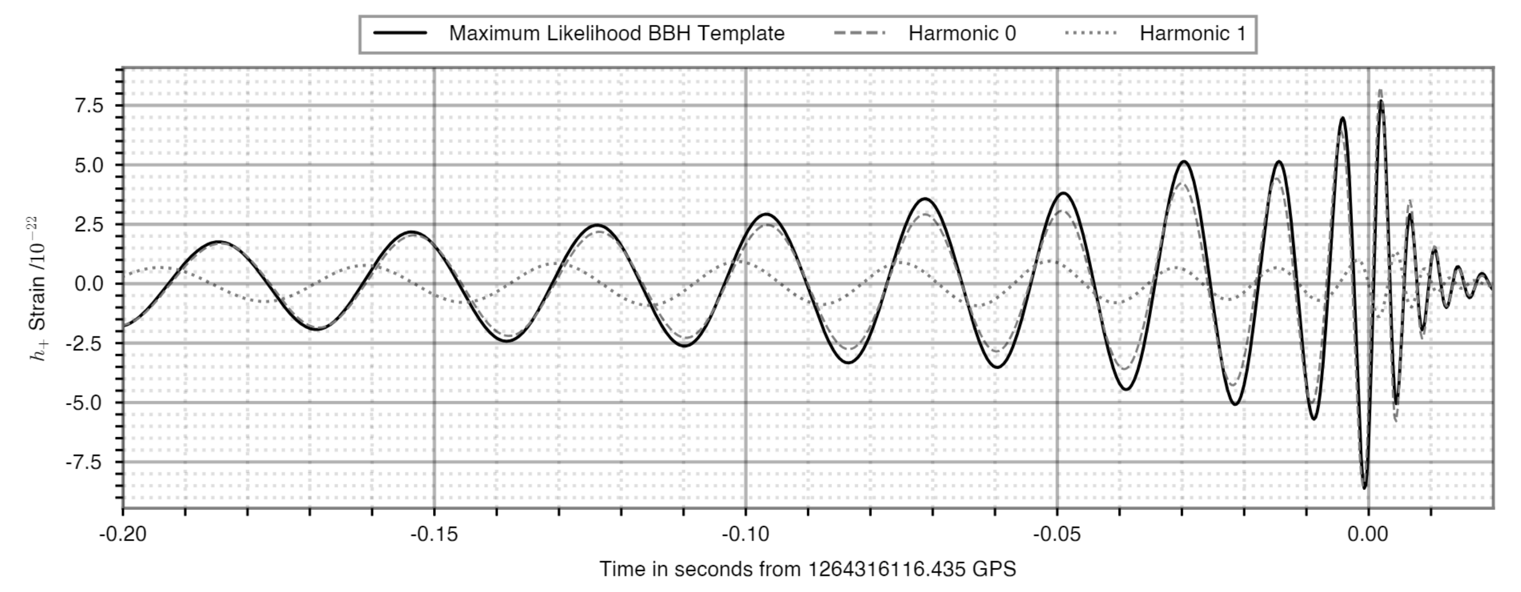
Glitch removal

Data “gating”:
- Zero out data around glitch
- Allows identification of signal using matched filter



Non-stationarity during signal: GW200129

- First signal with observable precession
  (see Hannam et al, arXiv: 2112.11300)
- Presence of non-stationarity complicates identification of precession contribution to waveform
  (see Payne et al, arXiv: 2206.11932, Macas et al, in preparation)

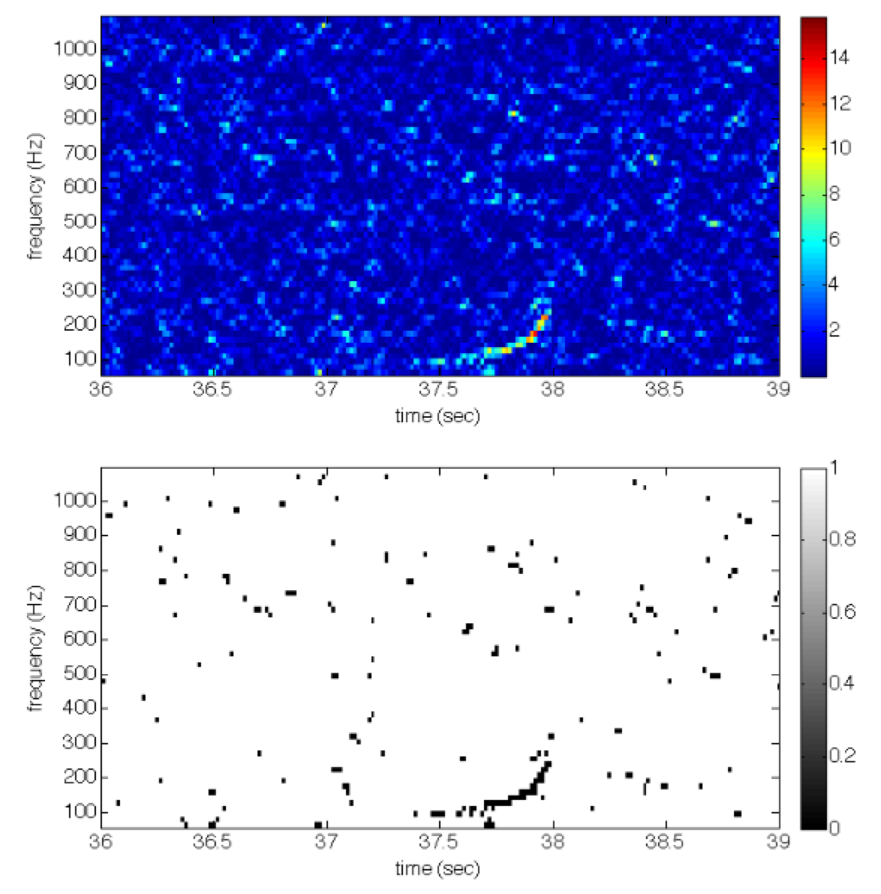


From Hannam et al, arXiv: 2112.11300

Unmodelled searches

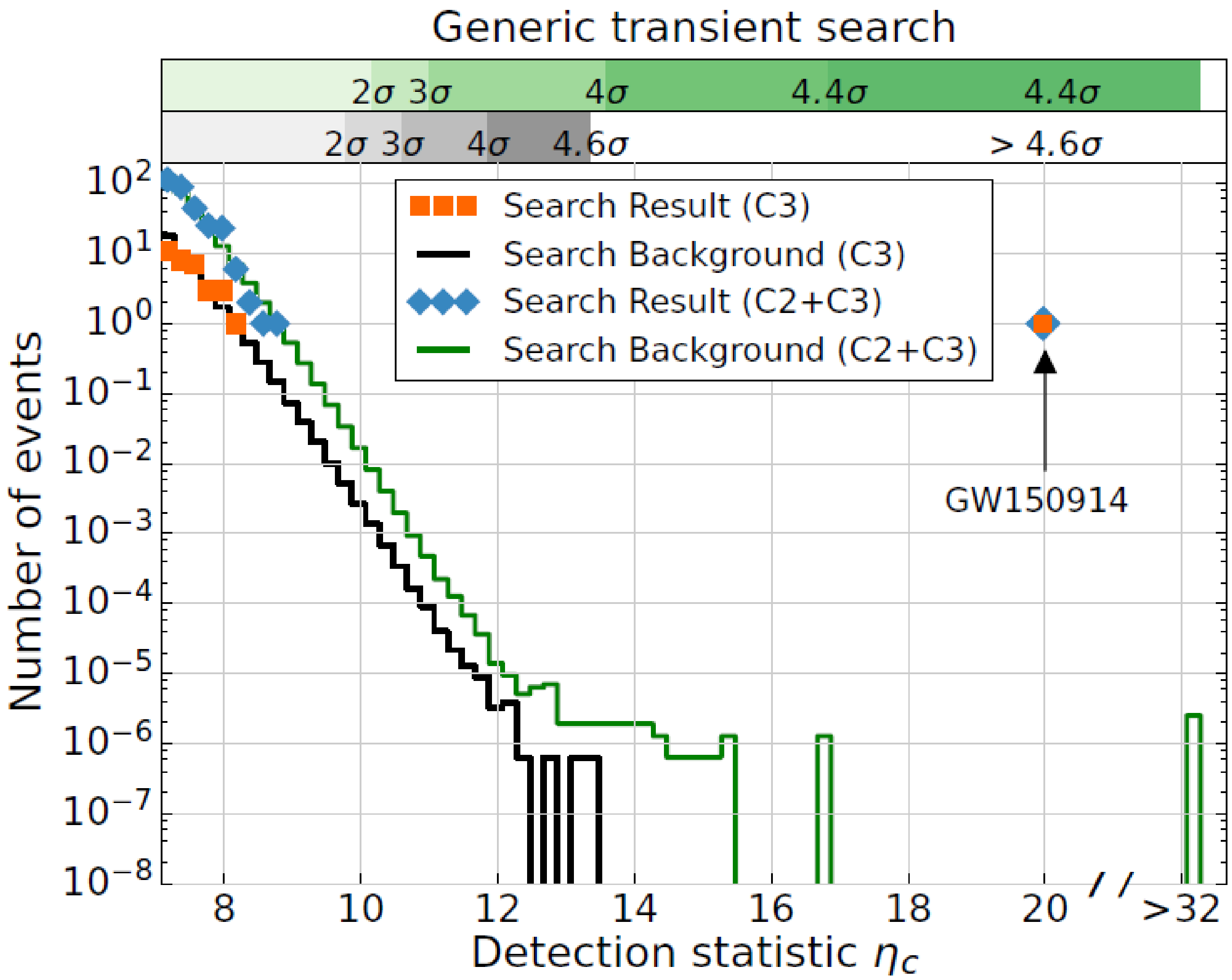
- No specific waveform model: Identifies coincident excess power in time-frequency representations from all detectors (f < 1 kHz and t < few seconds)
- Require consistency with two gravitational-wave polarizations
- Reconstruct waveform in both detectors using multi-detector maximum likelihood method

See Klimenko et al, arXiv: [0802.3232]()



From Sutton et al, arXiv: [0908.3665]()

Unmodelled search detection plot



From Abbott et al, arXiv: 1602.03837

Summary

- Analysis of GW data began long before detections
- Major effort required to minimize impact of non-stationary noise
  - Coincidence between detectors is probably the most important
  - “Signal consistency tests” and re-weighting of events
  - Use astrophysical expectations
- Knowing what you’re looking for helps, but it’s not essential