GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

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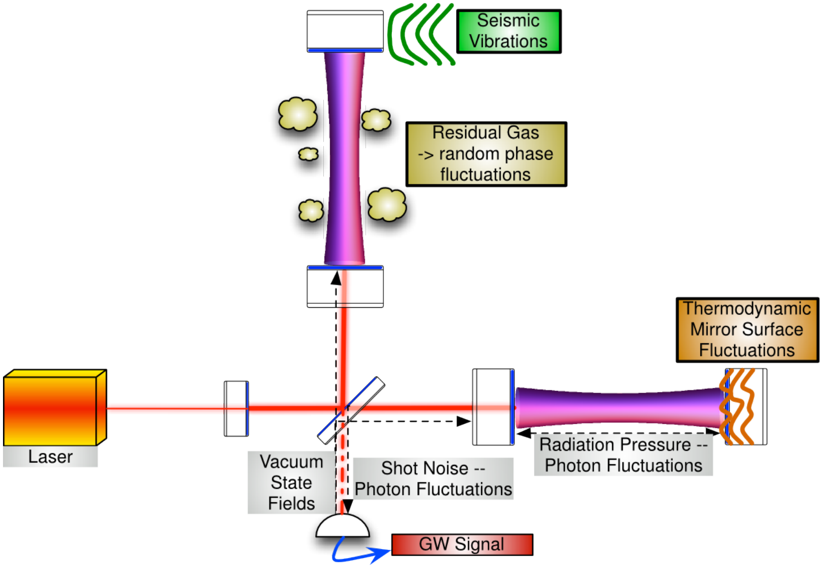
Presented at The University of Tokyo, December 19, 2017

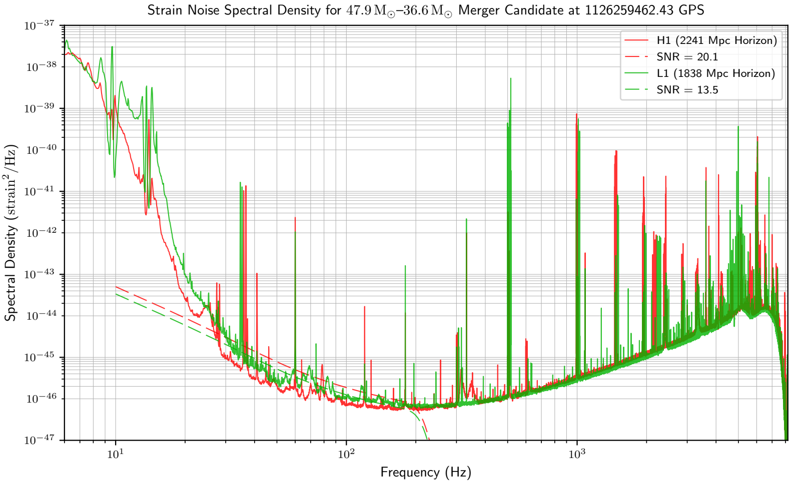
Technical Introduction

- Gravitational-wave antennas are like radio antennas.
- Observatory provides digitized record of projection of field strength onto detector.
- No (real) detector has infinite bandwidth: something sets a low-frequency cut-off and something sets a high-frequency cut-off.
- For ground-based detectors: seismic noise and shot noise (laser field quantization).
- Noise floor set by radiation-pressure (Brownian motion of mirror).
- Compact object merger signals are frequency-swept sinuoids;
- start at low frequency, move to high.

Technical Introduction



Technical Introduction



Technical Introduction

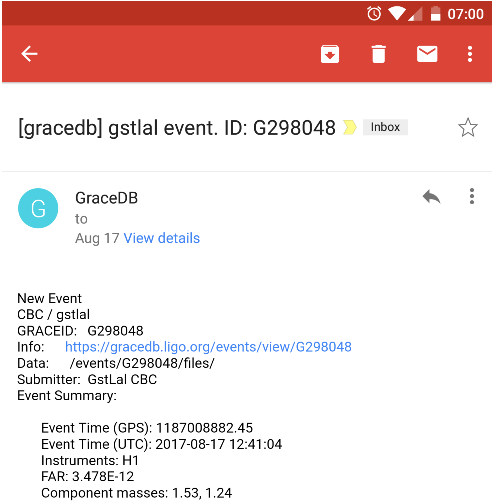
- Raw data must be transformed to gravitational strain — "calibration".
- Processed, to identify potential signals — using a "detection pipeline".
- Triggers a swarm of automated "follow-up" activities, including:
  - low-latency sky location and distance posterior PDF — computed by "Bayestar";
  - high-latency MCMC-based Bayesian posteriors on intrinsic and extrinsic parameters — "parameter estimation" / "PE".
- Bayestar's approximation: pipeline has measured the correct intrinsic (masses, etc.) and extrinsic (SNR, etc.) signal parameters.
- Allows sky location posterior PDF to be derived exclusively from pipeline's complex signal-to-noise ratio time series — no waveform generation required.

Detection System

- "gstlal" detection system uses consumer multimedia processing software called "gstreamer".
- $< 20\,\mathrm{s}$ of latency from phase centre to alert database.
- Latency dominated by data calibration and distribution: $\sim 14\,\mathrm{s}$

Detection

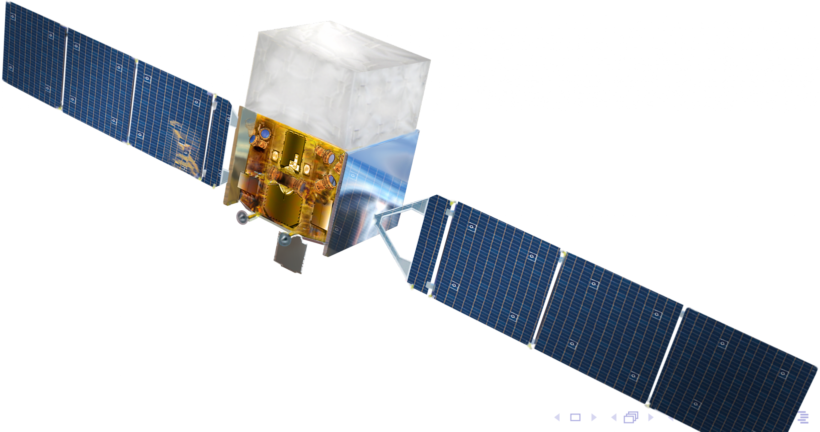
- On August 17, 2017, at about 21:50 JST I was just leaving a yakitori shop in Sendagaya.
- My phone's alarm was triggered.
- What I saw was this →
- A compact object merger,
- with masses of 1.5 and 1.2 × our sun,
- and a false-alarm rate (FAR) of about 1 in 10,000 years.



Detection

At the GraceDB web site (gravitational-wave candidate event database)

- A trigger from the Fermi gamma-ray burst monitor following the gravitational-wave candidate by 2 seconds.
- 2 seconds $\leftarrow$ GW-EM delay $=$ First Discovery! (actually several discoveries)



Detection

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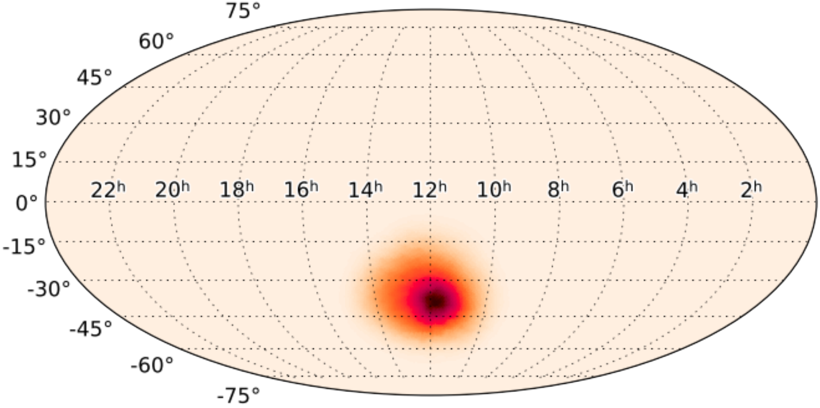

Detection

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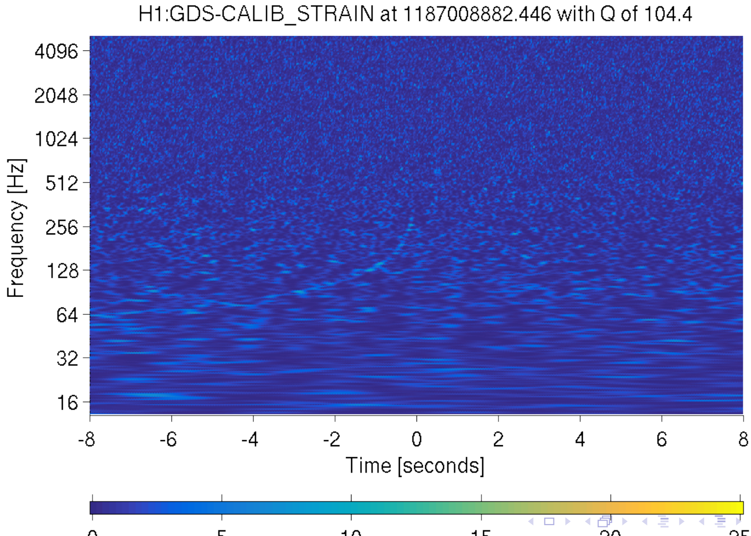

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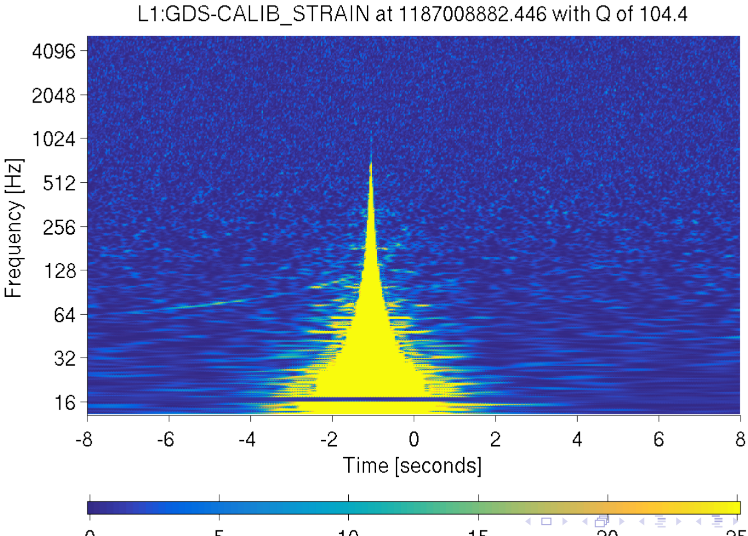

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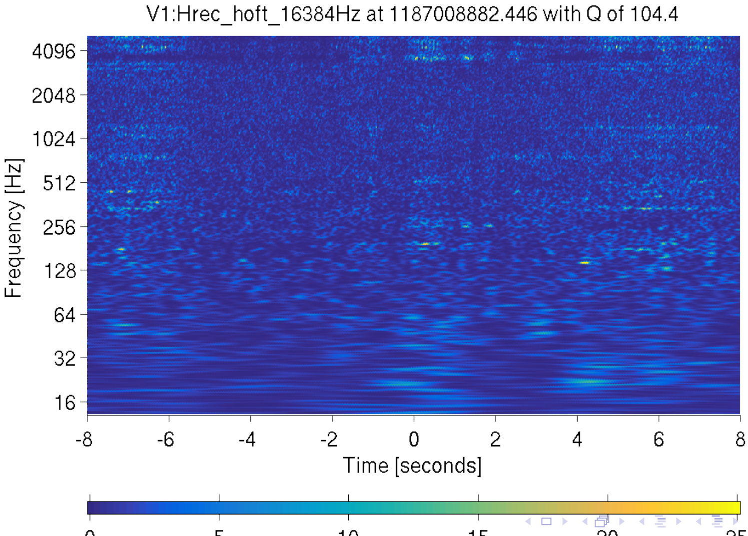

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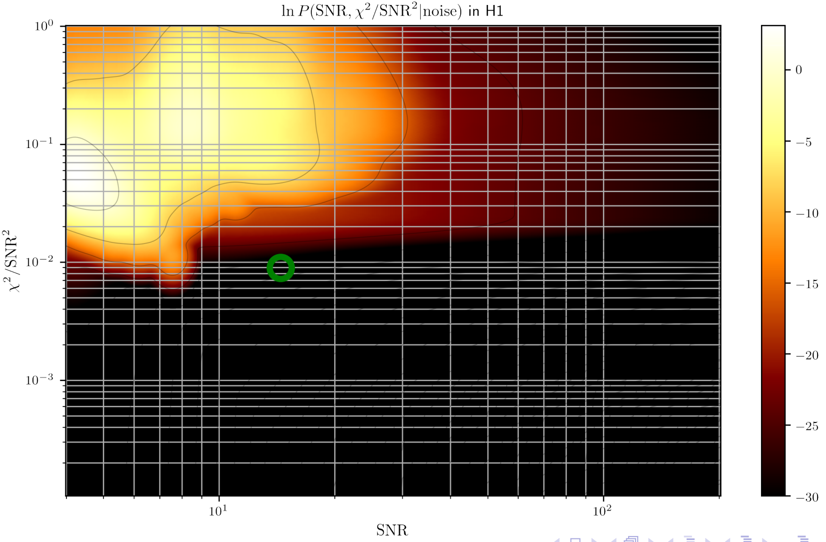

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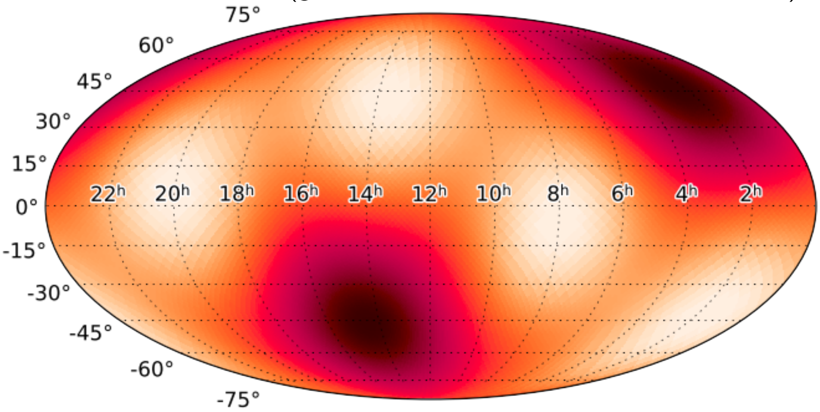

Detection

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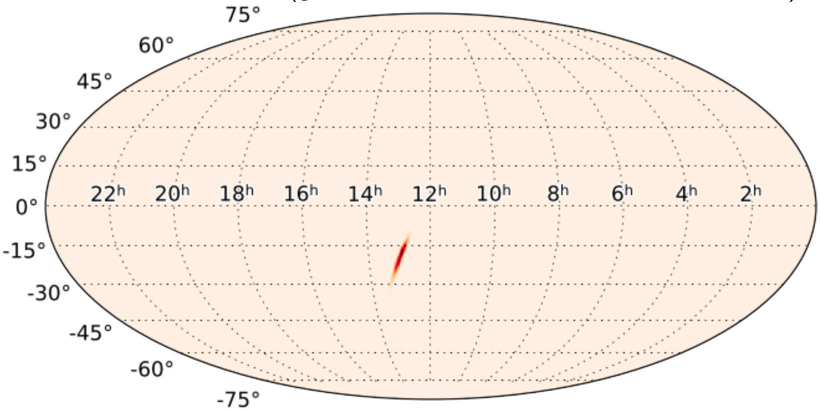

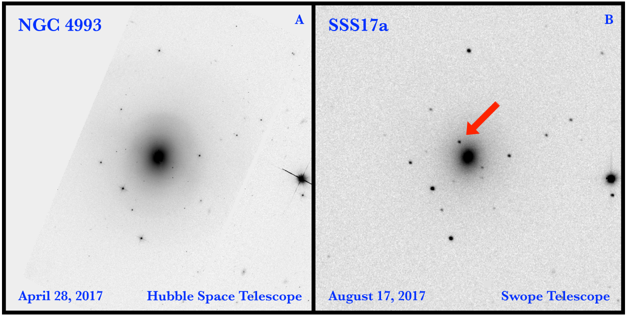

Figure 4 **$3' \times 3'$ images centered on NGC 4993 with North up and East left.** *Panel A*: *Hubble Space Telescope* F606W-band (broad V) image from 4 months before the GW trigger (*25, 35*). *Panel B*: Swope image of SSS17a. The i-band image was obtained on 2017 August 17 at 23:33 UT by the Swope telescope at Las Campanas Observatory. SSS17a is marked with the red arrow. No object is present in the *Hubble* image at the position of SSS17a (*25, 35*).

D. A. Coulter, *et al.*, "Swope Supernova Survey 2017a (SSS17a), the optical counterpart to a gravitational wave source" Science, October (2017). Photo taken August 18, 08:33 JST, reported 10:05:23 JST.

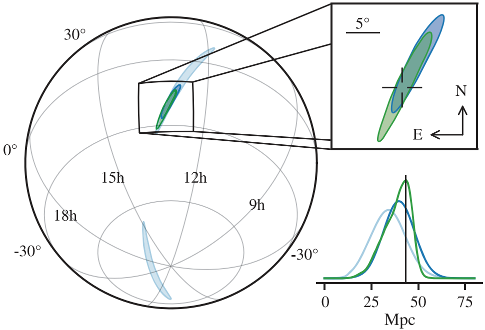

FIG. 3. Sky location reconstructed for GW170817 by a rapid localization algorithm from a Hanford-Livingston (190 deg^2, light blue contours) and Hanford-Livingston-Virgo (31 deg^2, dark blue contours) analysis. A higher latency Hanford-Livingston-Virgo analysis improved the localization (28 deg^2, green contours). In the top-right inset panel, the reticle marks the position of the apparent host galaxy NGC 4993. The bottom-right panel shows the *a posteriori* luminosity distance distribution from the three gravitational-wave localization analyses. The distance of NGC 4993, assuming the redshift from the NASA/IPAC Extragalactic Database [89] and standard cosmological parameters [90], is shown with a vertical line.

Detection System

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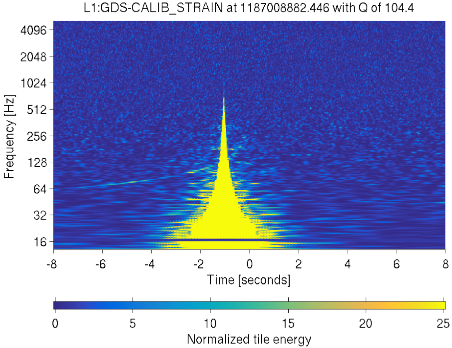
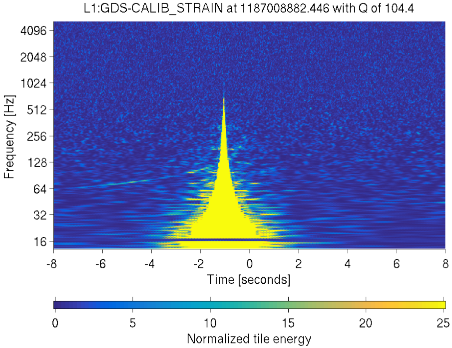
Glitch

- Blinded online detection system to signal in L1.
- Glitch blinding caused by known bug we had chosen to not fix.
- Did not expect to be so (un)lucky.



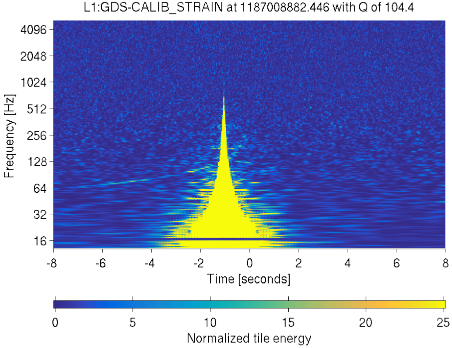
Glitch

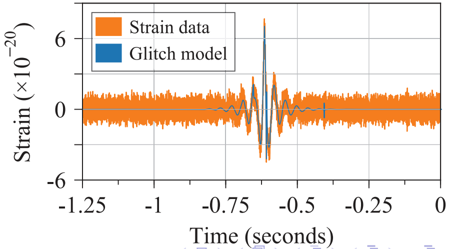
- Already had fix in the next version of the code (for O3), but not in the tagged version running online.
- False-alarm rate bound of $< 1/(10^6\,\mathrm{year})$ is obtained with the fix applied, to allow L1 signal to be identified.
- Extremely significant without any analysis changes: detection claim does not rely on *post facto* analysis changes.



Glitch

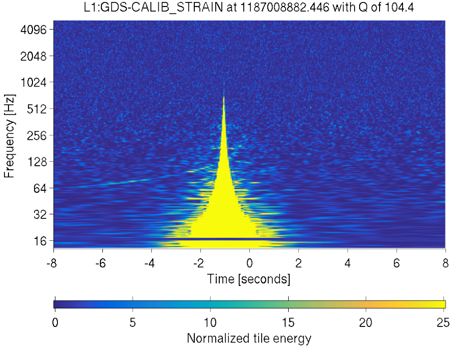
- Parameter estimation used a Bayesian glitch structure inference system to estimate the time structure and remove.
- Simulated signals added to data with other, similar, glitches,
- glitch subtraction found to introduce biases smaller than intrinsic parameter uncertainties.

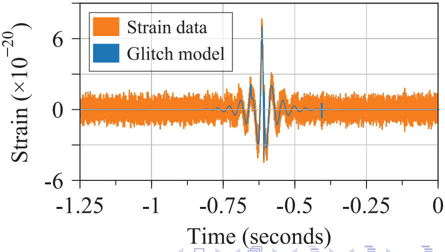




Glitch

- … For the parameters that have been published.
- Tests of GR still in progress, and glitch subtraction still being validated.

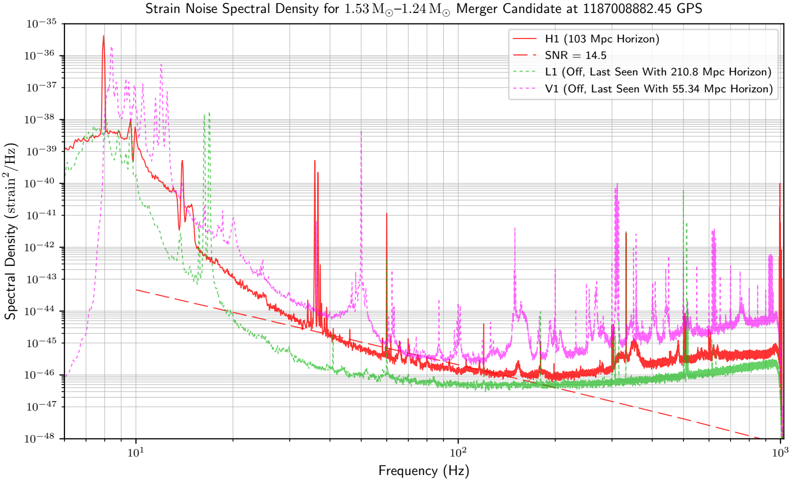




Gravitational Wave Signal

- Unlike electromagnetic sources, as GW sources compact object mergers have very few degrees of freedom.
- Waveform predictable from first-principles
- Allows many properties of the system to be inferred directly from the GW signal.
- The precise location, obtained from the optical counterpart, constrains the model: very important.
- Allows distance, orbit inclination, and tidal deformability of the component masses to be extracted

Gravitational Wave Signal



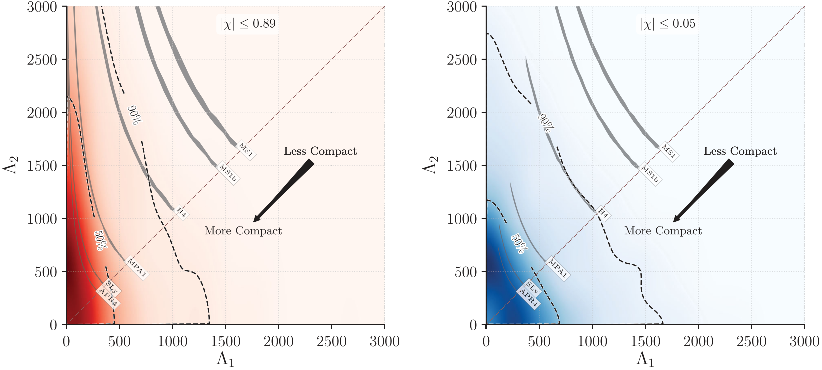
Details

TABLE I. Source properties for GW170817: we give ranges encompassing the 90% credible intervals for different assumptions of the waveform model to bound systematic uncertainty. The mass values are quoted in the frame of the source, accounting for uncertainty in the source redshift.

	Low-spin priors ($\lvert\chi\rvert \leq 0.05$)	High-spin priors ($\lvert\chi\rvert \leq 0.89$)
Primary mass m_1	1.36–$1.60\ M_\odot$	1.36–$2.26\ M_\odot$
Secondary mass m_2	1.17–$1.36\ M_\odot$	0.86–$1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_{L}	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

Details

- Distance: 85×10^6 light year–160×10^6 light year
- Primary mass: $1.36\ \mathrm{M}_\odot$–$2.26\ \mathrm{M}_\odot$
- Secondary mass: $0.86\ \mathrm{M}_\odot$–$1.36\ \mathrm{M}_\odot$
- Radius of a $1.4\ \mathrm{M}_\odot$ neutron star: $\leq 14\ \mathrm{km}$
- Spin of stars: ??? cannot tell.
- Merger rate: $1540^{+3200}_{-1230}\ \mathrm{Gpc}^{-3}\mathrm{a}^{-1}$
- Implies there should exist a detectable stochastic background of gravitational waves from distant neutron star collisions.

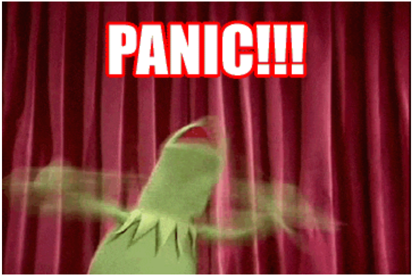


- Neutron star tidal deformability constraints. Left panel imposes no constraint on spins, right panel requires spins to be small.
- Bottom-left corner is the black-hole limit.

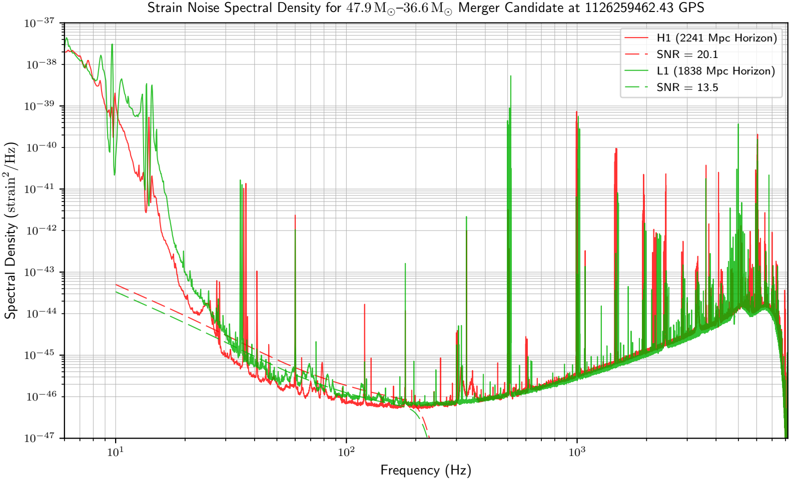
So ... let's regroup:

- GRBs are neutron star collisions.
- After travelling together for 130 million years, the GWs and the γ-rays arrived within 2 s of each other ...
- ... so gravity travels at the speed of light to 1 part in 10^{15}-ish.
- The delay from NS merger to γ-ray flash is 2 s.
- Light emission consistent with the signature of heavy element formation from the debris.
- $\rightarrow$ about 1/2 of the heavy elements in the universe are from NS collisions.

- Prospects for future observations have been changing rapidly.
- The "Observing Scenarios Document", arXiv:1304.0670v4.
- Last updated late this summer,
- accepted for publication, but still not in print.
- Discusses the possibility of a BNS observation as a future hypothetical possibility,
- Was osbolete before it was even posted to arXiv on Sept 8th.

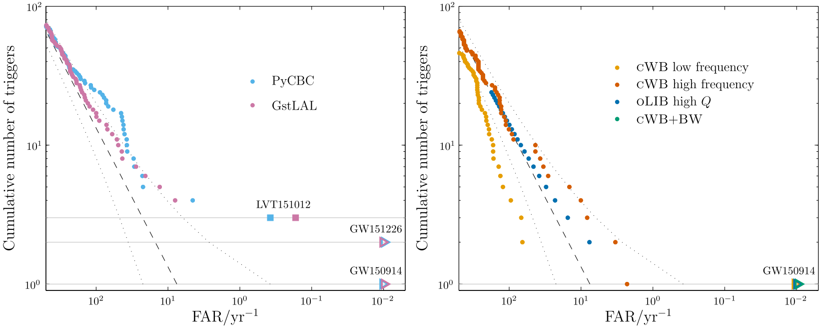


O1 Results

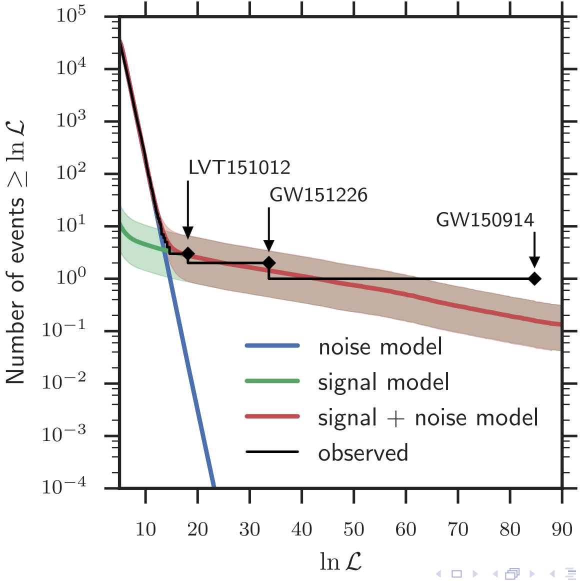


Strain Noise Spectral Density for $47.9\,M_\odot$–$36.6\,M_\odot$ Merger Candidate at 1126259462.43 GPS
H1 (2241 Mpc Horizon)
SNR = 20.1
L1 (1838 Mpc Horizon)
SNR = 13.5
Spectral Density $(\mathrm{strain}^2/\mathrm{Hz})$
Frequency (Hz)
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^1
10^2
10^3

O1 Results

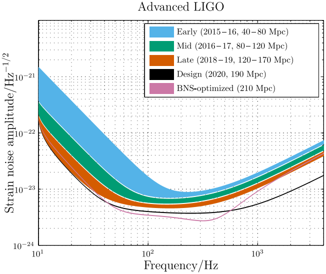

PyCBC
GstLAL
LVT151012
GW151226
GW150914
Cumulative number of triggers
FAR/yr^{-1}
cWB low frequency
cWB high frequency
oLIB high Q
cWB+BW
GW150914
Cumulative number of triggers
FAR/yr^{-1}

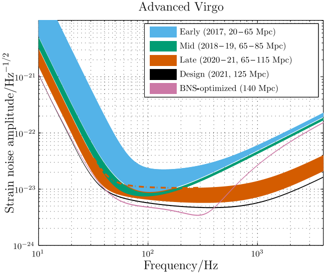
O1 Results

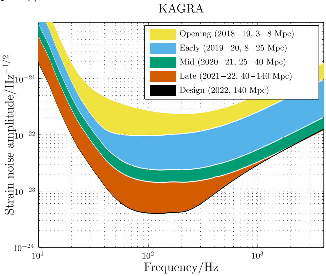


Number of events ≥ ln $\mathcal{L}$
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
LVT151012
GW151226
GW150914
noise model
signal model
signal + noise model
observed
10
20
30
40
50
60
70
80
90
ln $\mathcal{L}$

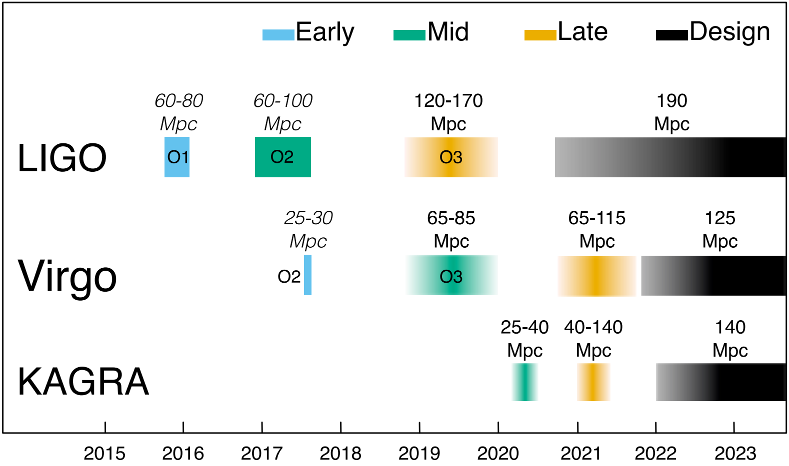
Future Science Runs

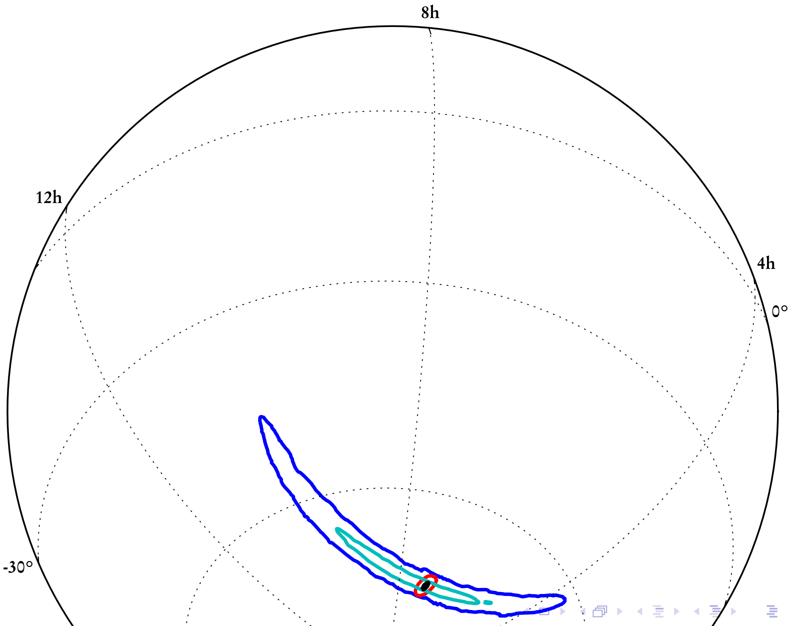


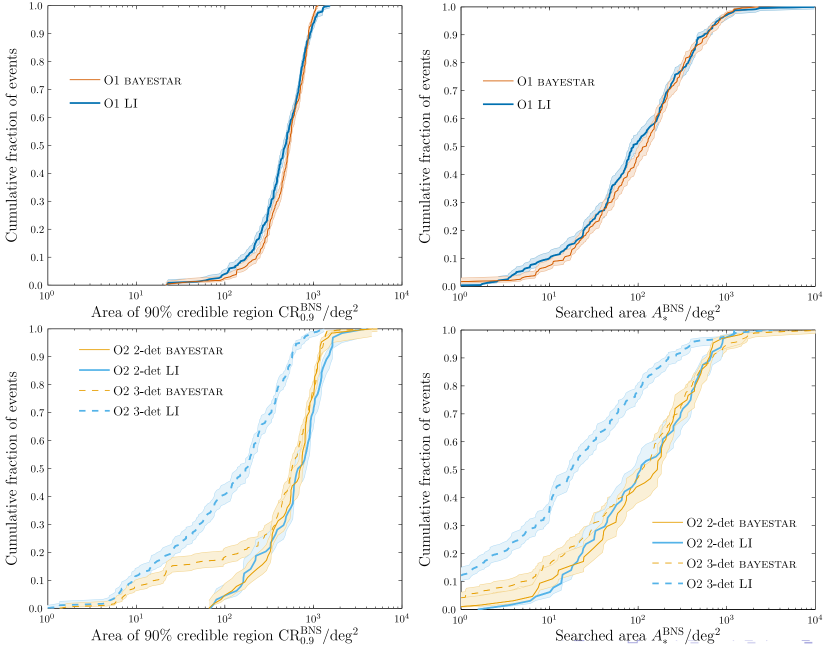




Future Science Runs

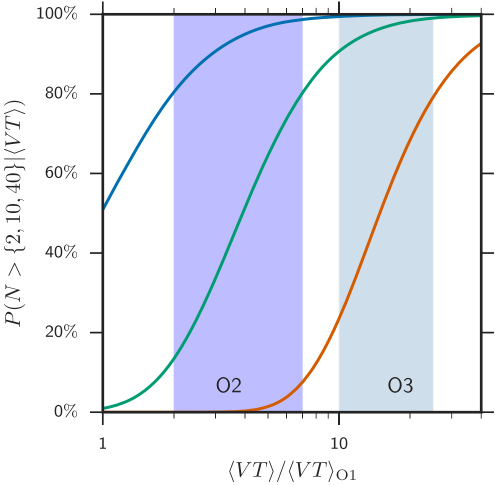



8h
12h
4h
0°
-30°


Cumulative fraction of events
O1 BAYESTAR
O1 LI
Area of 90% credible region $CR_{0.9}^{BNS}$/deg^2
Searched area A_*^{BNS}/deg^2
O2 2-det BAYESTAR
O2 2-det LI
O2 3-det BAYESTAR
O2 3-det LI
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
10^0
10^1
10^2
10^3
10^4

What Does Observing Scenarios Document Say?

BBH detection rate prediction.



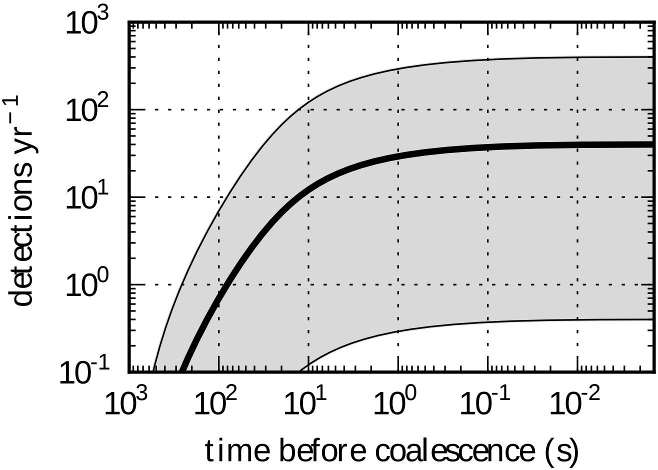
from arXiv:1606.04856 (not Observing scenarios, still best version of this plot)

What Does Observing Scenarios Document Say?

BNS detection rate prediction.

- Today, most up-to-date informatoin is in Phys. Rev. Lett., 119:161101 (2017) (report of GW170817 discovery)
- BNS merger rate $1500^{+3200}_{-1220}\,\mathrm{Gpc}^{-3}\mathrm{a}^{-1}$.
- $\approx$ what we have been calling the "plausible" rate estimate prior to the detection. $(1000\,\mathrm{Gpc}^{-3}\mathrm{a}^{-1})$
- Translates to 30 detections above SNR 8 in two detectors per year in late advanced detector era.

Early Warning



Pressing Questions: What we can do

- Is GW170817 the tip of the iceberg? Is there a previously undiscovered population of nearby GRBs?
- Was GW170817 in fact a “GRB”?
- NS-BH detections?
- Lots more 30+30 Msun black hole collisions: what is spin distribution, can we say if they are from stars or maybe primordial?
- Are there compact objects below 1 Msun?
- Are there compact objects between 3 Msun and 5 Msun?
- Stochastic GW flux from compact object mergers: how long ago did the mergers begin?

Pressing Questions: What we cannot do (yet)

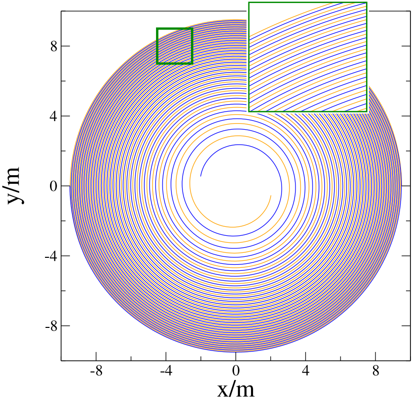
- Tests of GR: need predictions from alternative theories of gravity.
- E.g., evidence of extra dimensions in BH merger waveforms?

Pressing Questions: What we cannot do (yet)

- High performance waveform models: PE now computationally limited, e.g., could constrain tidal deformability better if PE's MCMC samplers could compute overlaps starting at 10 Hz instead of 24 Hz.
- GW170817's tidal deformability parameters could be better constrained with integrations starting at lower frequency.
- But PE runs would not complete in a practical amount of time.
- GW170817's $M_{\rm chirp} = (m_1 + m_2)\left(\frac{m_1 m_2}{(m_1+m_2)^2}\right)^{\frac{3}{5}}$ uncertainty dominated by waveform model systematics.
- (hidden by uncertainty in redshift)

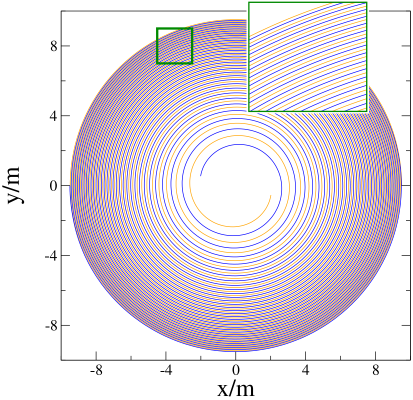
Pressing Questions: What we cannot do (yet)

- Correct waveform systematic errors: there is a gap between end of validity of post-Newtonian expansion and start of validity of NR simulations.
- Hybridization is intrinsically biased until that gap can be closed.



Pressing Questions: What we cannot do (yet)

- See, e.g, MacDonald, *et al.*, "Suitability of hybrid gravitational waveforms for unequal-mass binaries", arXiv:1210.3007.
- 33 orbit simulation, PN expansion up to $(v/c)^6$ already invalid at start.



Pressing Questions: What we cannot do (yet)

- They estimated that PN expansion up to $(v/c)^8$ would still not be good enough
- That expansion only became available earlier this year.