Back story of GW170817 and Electromagnetic Follow-up Observations

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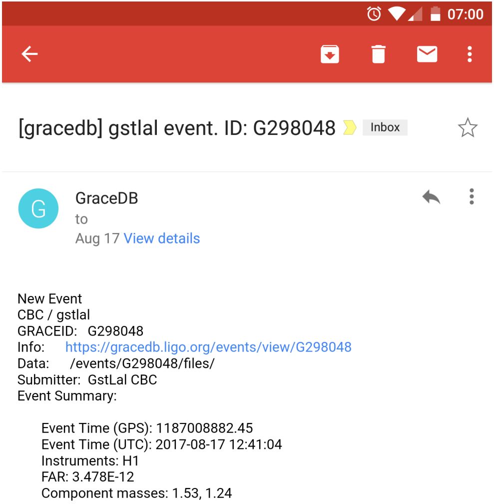
Detection

- 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.



07:00

[gracedb] gstlal event. ID: G298048 Inbox

GraceDB
to
Aug 17 View details

New Event
CBC / gstlal
GRACEID: G298048
Info: https://gracedb.ligo.org/events/view/G298048
Data: /events/G298048/files/
Submitter: GstLal CBC
Event Summary:

Event Time (GPS): 1187008882.45
Event Time (UTC): 2017-08-17 12:41:04
Instruments: H1
FAR: 3.478E-12
Component masses: 1.53, 1.24

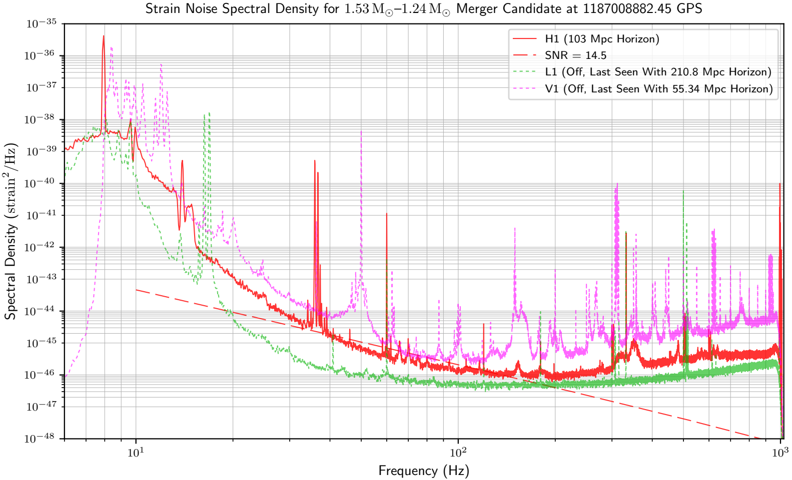
Detection

- Wonderful news, but ...
- Event time was 12:41 UTC, phone alarm occurred at 12:50 UTC.
- Normal latency should be 20 seconds ... what happened?
- Found only in LIGO Hanford detector.
- LIGO Livingston and Virgo detectors were operating ... what happened?
- Six low-latency analyses were operating during O2, only one found the signal ... what happened?

Technical Introduction

- Gravitational-wave antennas provide 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, radiation pressure, and shot noise (laser field quantization).
- Compact object merger signals are frequency-swept sinusoids;
- start at low frequency, move to high.

Technical Introduction

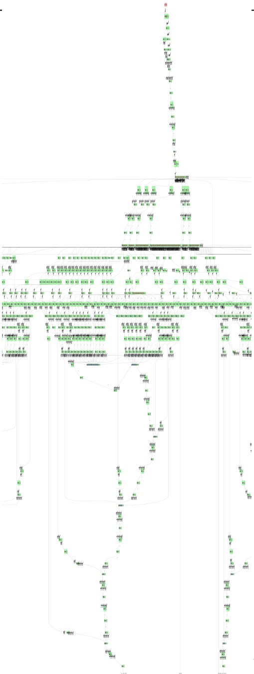


Technical Introduction

- 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.

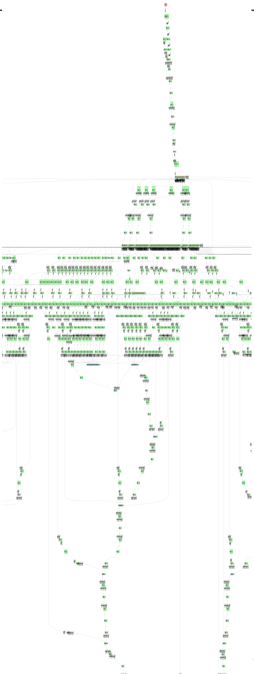
Detection System

- "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: $\sim 14\,\mathrm{s}$

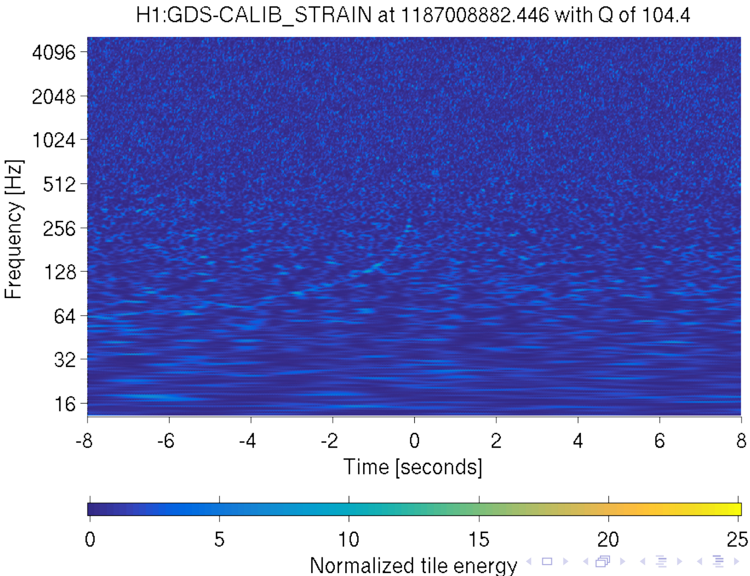


Detection System

- System is not informed of data distribution failures.
- Relies on timeouts.
- Adds extra latency.
- Virgo data was not arriving:
  - 5 min delay.



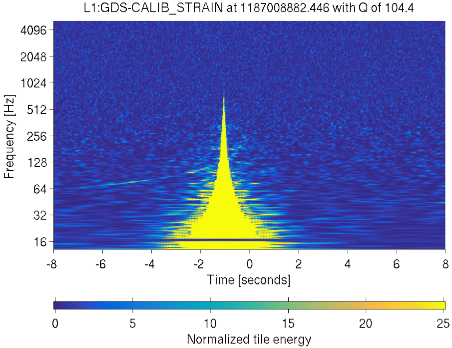
Glitch



H1:GDS-CALIB_STRAIN at 1187008882.446 with Q of 104.4
Frequency [Hz]
4096
2048
1024
512
256
128
64
32
16
-8
-6
-4
-2
0
2
4
6
8
Time [seconds]
0
5
10
15
20
25
Normalized tile energy

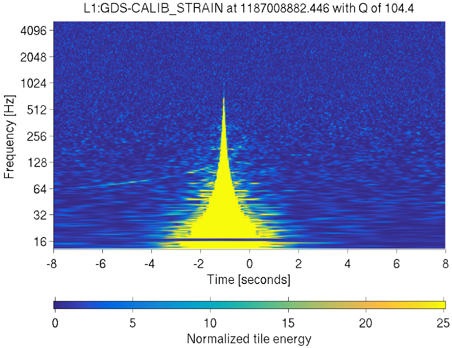
Glitch

- 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

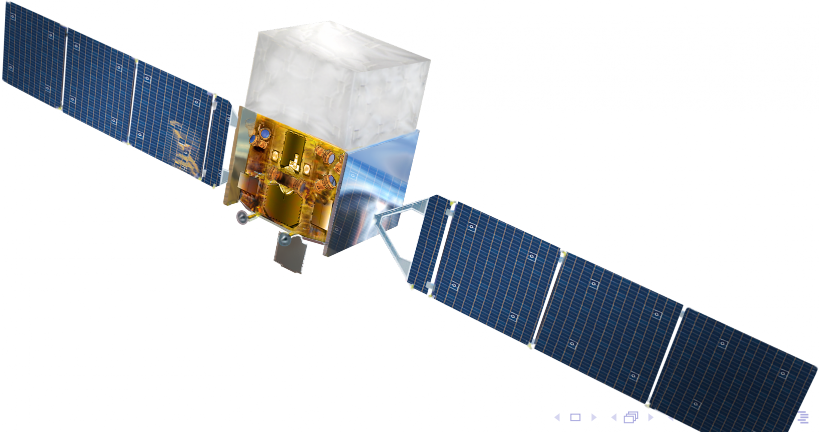
- Already had fix in the next version of the code (for O3), but not in the tagged version running online.
- False-alarm rate bound of $< 1/(10^6\ \mathrm{year})$ is obtained with the fix applied, to allow L1 signal to be identified.
- Extremely significant without any analysis changes: detection claim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



Electromagnetic Counterpart

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 ← GW-EM delay = First Discovery! (actually several discoveries)



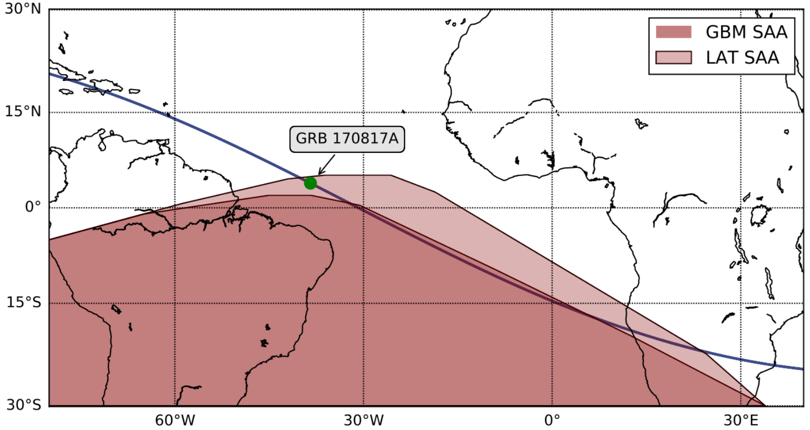
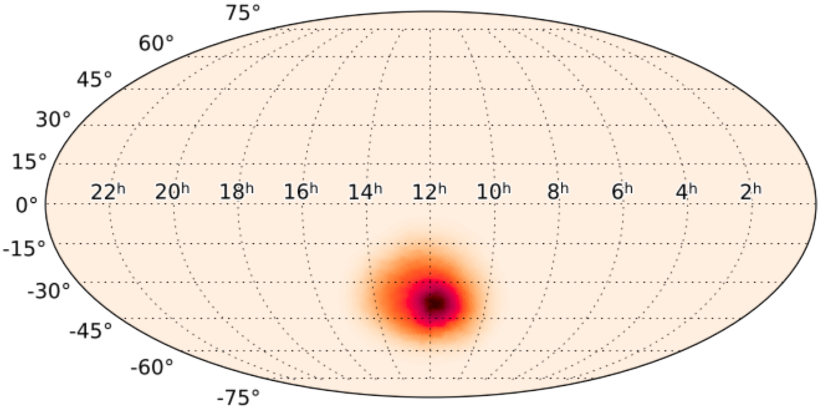


Figure 1. The position of *Fermi* at the trigger time of GRB 170817A (green dot) and its orbital path from West to East. The dark and light red regions define the boundaries of the SAA for the GBM and LAT instruments respectively. Both instruments do not collect data inside their respective SAA boundaries due to an elevated charged particle background.

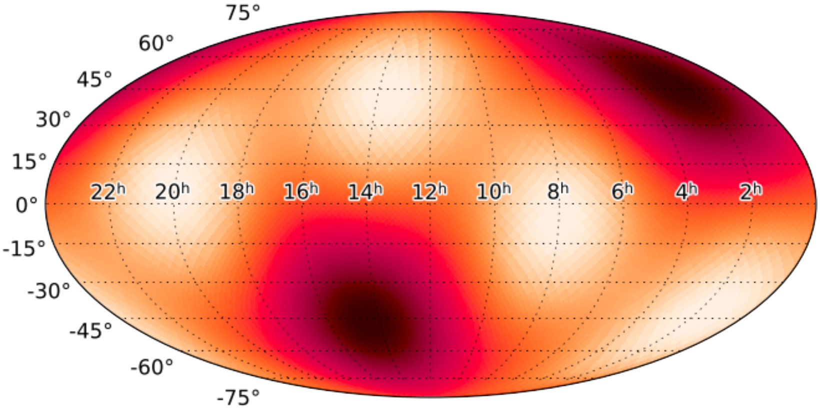
From The Fermi-LAT Collaboration, "Fermi-LAT Observations of the LIGO/Virgo Event GW170817", arXiv:1710.0540.

Electromagnetic Counterpart



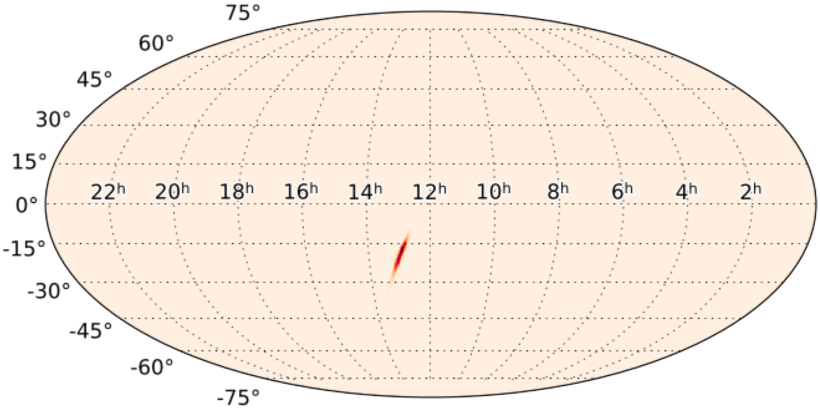
Fermi GBM posterior.

Electromagnetic Counterpart



LIGO Hanford posterior.

Electromagnetic Counterpart



LIGO Hanford, LIGO Livingston, Virgo posterior.

Electromagnetic Counterpart

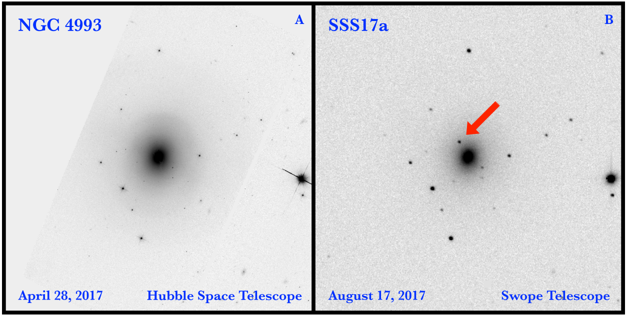


Figure 4 **$3' \times 3'$ images centered on NGC 4993 with North up and East left.** *Panel A*: *Hubble Space Telescope* F606W-band (broad V) image from 4 months before the GW trigger (*25, 35*). *Panel B*: Swope image of SSS17a. The i-band image was obtained on 2017 August 17 at 23:33 UT by the Swope 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.

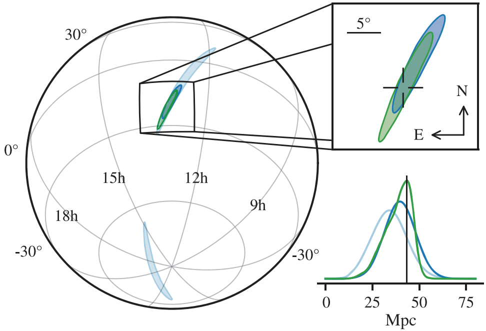


FIG. 3. Sky location reconstructed for GW170817 by a rapid localization algorithm from a Hanford-Livingston (190 deg^2, light blue contours) and Hanford-Livingston-Virgo (31 deg^2, dark blue contours) analysis. A higher latency Hanford-Livingston-Virgo analysis improved the localization (28 deg^2, green 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.

- What about other 5 detection systems?
- Probably missed signal because of some combination of the glitch and the data distribution failure.
- The gstlal system has been under development since 2007.
- Participated in “engineering runs” for many years prior to data taking.
- Much effort has been put into stability, robustness: not required for scientific correctness.
- Discovery of GW170817 relied critically on analysis tools being not simply correct, but robust and stable.
- In English we say “perfection is the enemy of good”.
- Don’t be afraid of putting in extra effort.