Gravitational Waves From Neutron Star Collisions

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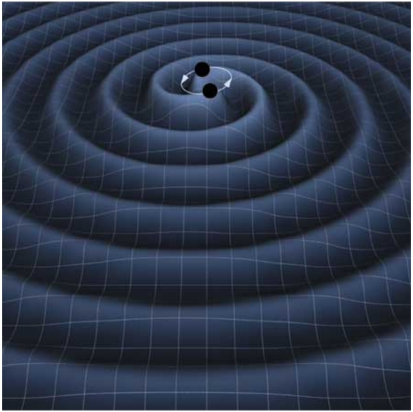
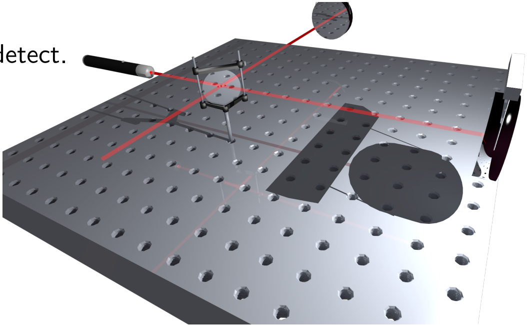
Gravitational Waves

- In electrodynamics, movement of charges and currents can lead to radiation of waves.
- In general relativity (gravity), similar phenomenon: movement of charges (mass) and currents (momentum) can lead to radiation of waves.
- The waves transport energy away from the system.
- Canonical example: spiral pattern of waves radiated by orbiting masses.
- Lycra and drill...



Gravitational-Wave Astronomy

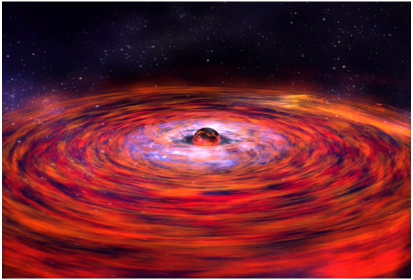
- Gravitational waves are produced by different physical processes than those that produce EM waves: carry different information about their sources.
- Weak coupling of gravity to matter: nearly everything is transparent to GWs.
- Promise to reveal things about nature that are inaccessible by other means.
- But are hard to detect.

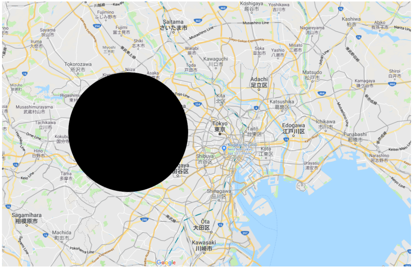


Real Detectors

LIGO Livingston Observatory. Each arm is 4 km long. An O(1) MW laser field resonates in the arm cavities.

Neutron Stars



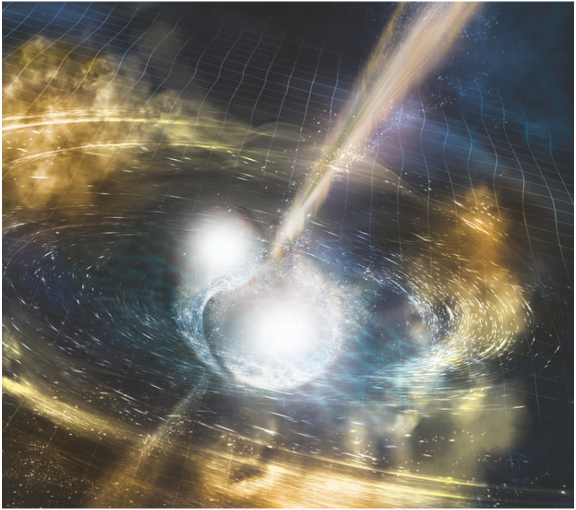


- Collapsed core of massive star.
- ≈1.5x mass of our Sun.

- About 20 km in diameter.

Simulation of GW170817 by BAM collaboration...

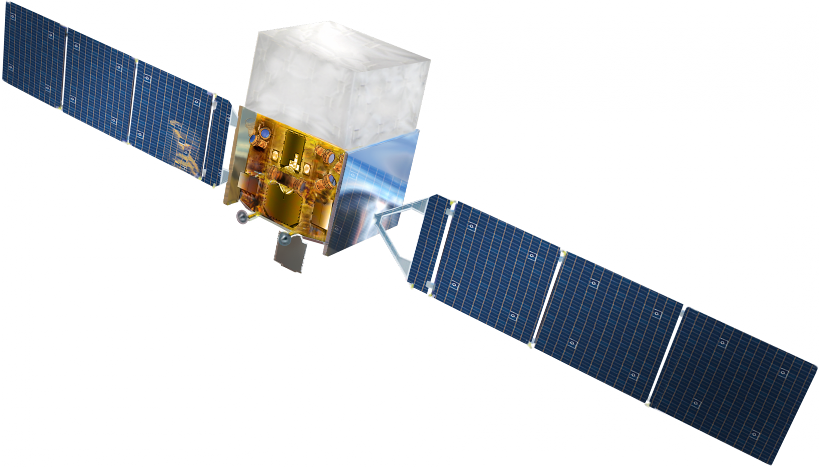
GW170817 Discovery Story



Depiction of GW170817. Aurore Simonnet.

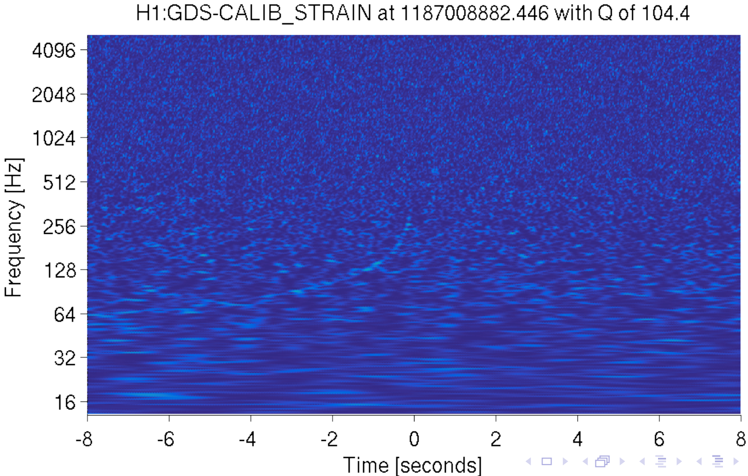
First Report

- A blip of γ rays reported by the Fermi GBM. GBM trigger 170817.529 524666471.



Detection

- Followed by a report of a gravitational-wave signal preceding the γ rays by about 2 s.
- Consistent with a neutron star collision.



Optical Counterpart

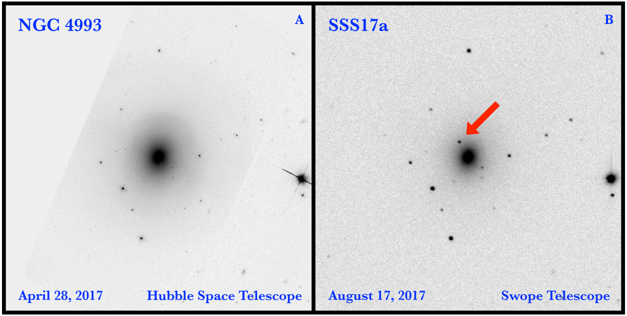
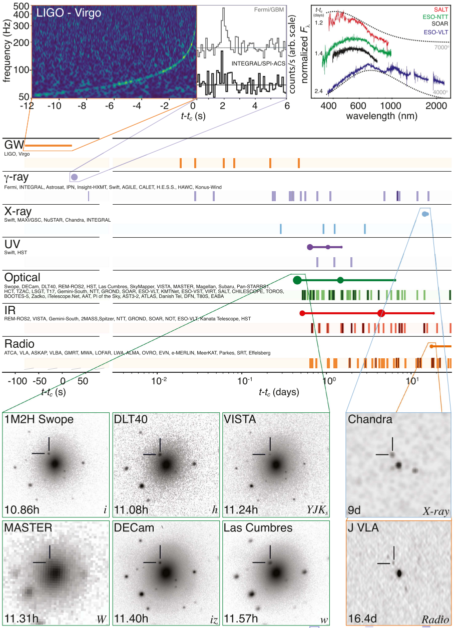


Figure 4 **3′ × 3′ images centered on NGC 4993 with North up and East left.** *Panel A*: *Hubble Space Telescope* F606W-band (broad V) image from 4 months before the GW trigger (*25, 35*). *Panel B*: Swope image of SSS17a. The i-band image was obtained on 2017 August 17 at 23:33 UT by the Swope telescope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

Vast Follow-up Campaign

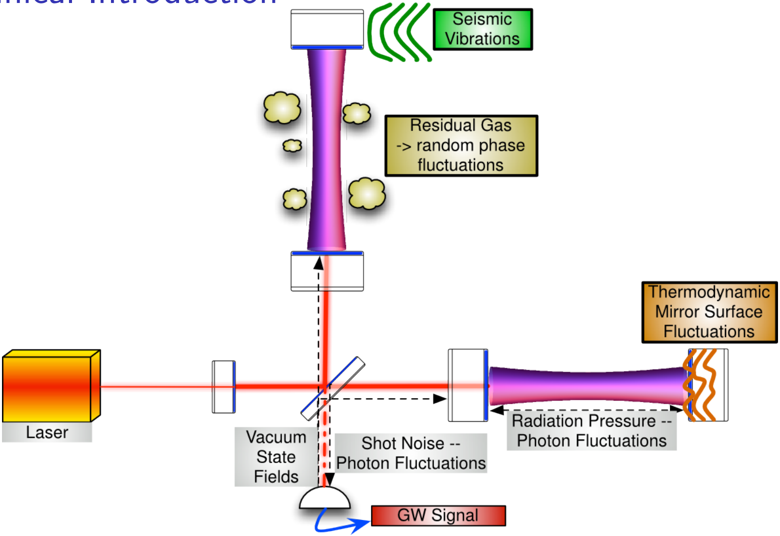


From Astrophys. J. Lett., 848:L12, 2017, arXiv:1710.05883

Behind The Scenes: Technical Introduction

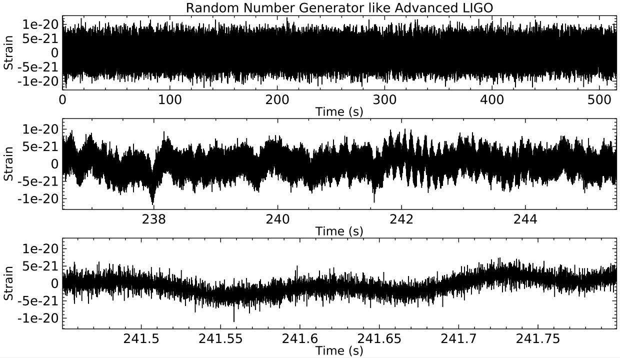
- Gravitational-wave antennas are like radio antennas.
- Observatory provides digitized record of projection of field strength onto detector.
- No (real) detector has infinite bandwidth: something sets a low-frequency cut-off and something sets a high-frequency cut-off.
- For ground-based detectors: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

Technical Introduction



Credit: Rana Adhikari.

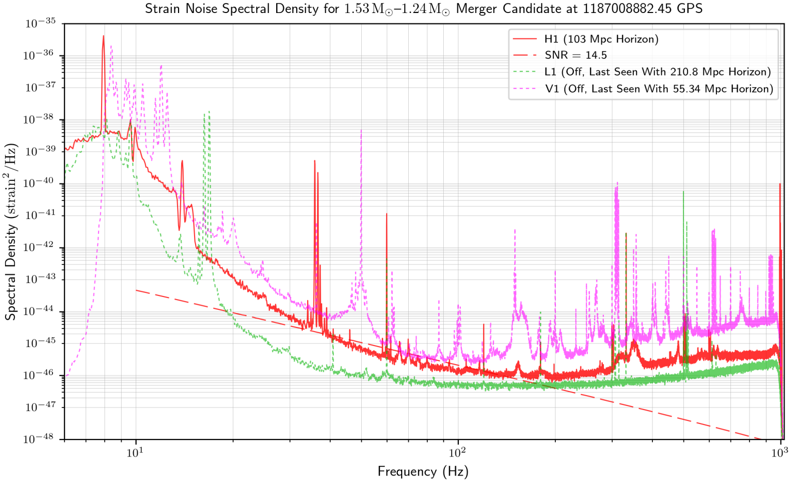
Technical Introduction



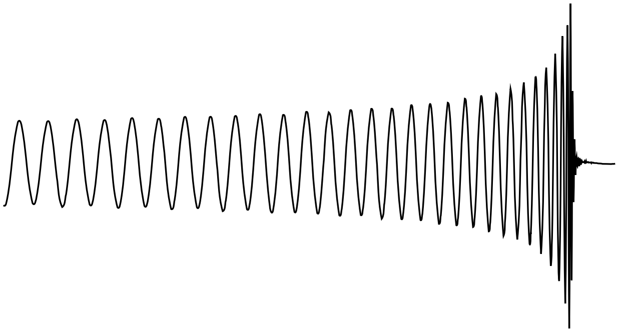
- We have audio frequency time series data from O(few) antennas.
- Noise is mostly stationary, coloured, Gaussian noise,
- but also contains non-stationary "glitch" components.

Movie of noise spectrum...

Technical Introduction



Technical Introduction



- We are looking for signals like the above in the data.

Sound of neutron star collision...
Sound of GW170817...
Graphical depiction of matched filtering by Alex Nitz...

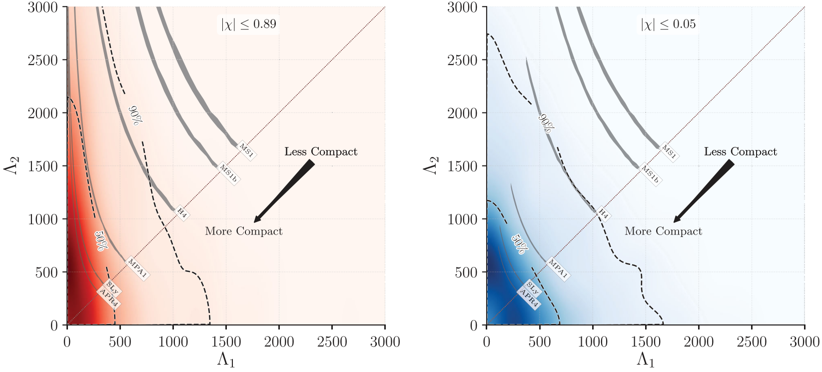
Details

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 ($|\chi| \leq 0.05$)	High-spin priors ($|\chi| \leq 0.89$)
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 $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	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.

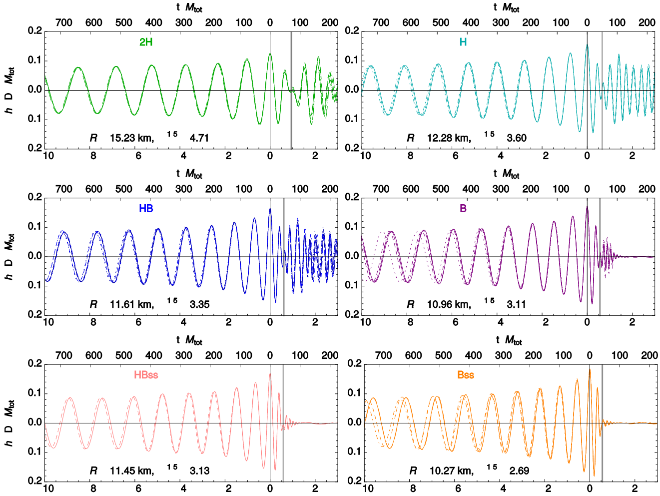
Gravitational Waves from Neutron Star Collisions

Gravitational Waves from Neutron Star Collisions

1. searching for more: improvements to antennas
2. searching for more: improvements to analysis system
3. searching for more: early warning (GW170817 had SNR 6 in L1 25 s before merger, SNR 3.3 in L1 55 s before merger)
4. other fallout: know BAYESTAR map is correct, makes R&D much easier knowing there is a correct answer to compare to
5. tests of GR (speed of gravity, basically done)
6. tests of GR (e.g., mass/radius relationship)
7. tests of equation of state (mass/radius relationship, post-merger signals)

Gravitational Waves from Neutron Star Collisions

From Read *et al.*, Phys. Rev., D88:044042, 2013, arXiv:1306:4065.

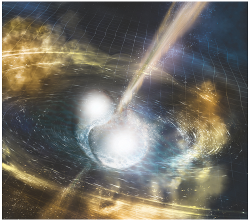


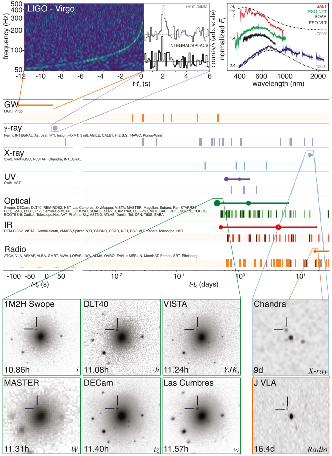
Things to Watch For

1. Calibrate GW detector networks with NS collision waveforms. *e.g.*, Essick and Holz, arXiv:1902.08076. 20% relative amplitude (compare to standard measurements, which yield O(few) % accuracy)
2. GW170817's SNR is so high it exceeds our ability to say what, exactly, GR's prediction is for that waveform. Hidden by uncertainty in red-shift (Hubble parameter and binary's motion w.r.t. NGC 4993). For red-shift see Levan, *et al.*, Astrophys. J. Lett., 848:L28 (2017).

Summary

- Despite
  - Data distribution failure.
  - Suspension saturation glitch.
  - Improper alert procedures.
  - Most high-energy telescopes being blind or nearly blind.
  - Everybody believing it to be impossible.
- We still did it.





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