**Fermi**

![Fermi Satellite Image](image1)

**GRB 170817A**

- **Gamma rays, 50 to 300 keV**
- **Counts per second**
- **Time from merger (seconds)**

**LIGO**

![LIGO Gravitational-Wave Detector](image2)

**GW170817**

- **Gravitational-wave strain**
- **Frequency (Hz)**
Gravitational Waves

WHAT ARE GRAVITATIONAL WAVES?
Gravitational distortion of space-time occurs when massive objects such as black holes collide and merge. The waves squeeze and stretch space as they pass, but the effect is sub-atomically small. (The effect of stretching due to passing gravitational waves is hugely magnified in the globes at right.)

Masses in the Stellar Graveyard
in Solar Masses

- LIGO-Virgo Black Holes
- X-ray Binary Black Holes
- Known Neutron Stars
- LIGO-Virgo Neutron Stars
Gamma-ray Bursts

Newly Formed Magnetar?

External Shocks
Jet collides with ambient medium (external shock wave)

Internal Shocks?
Colliding shells emit low-energy gamma rays (internal shock wave)

Prompt emission

Afterglow

Black hole engine

Low-energy gamma rays
Faster shell
Slower shell

High-energy gamma rays
X-rays
Visible light
Radio

6
Kilonovae

- Kilo?
  - 1000x less luminous than supernovae
  - 1000x more luminous than novae
- Production of heavy elements through rapid neutron capture (r-process) and their eventual decay
- Red kilonovae - lanthanide-rich dynamical ejecta via tidal forces
- Blue kilonovae - lanthanide-poor wind driven outflow or cooling of shock-heated ejecta
Short Gamma-ray Bursts as Neutron Star Mergers

- Live in low density, low star-formation environments
- Occur in all galaxy types
- Often seen slightly outside their hosts
- Associated with old stellar populations
- Less energetic than long GRBs
- Energy spectra peak at slightly higher energies

Gomboc et al. (2012)
Short Duration Gamma-ray Bursts as Gravitational Wave Counterparts

- Neutron Star + Neutron Star and Neutron Star + Black Hole mergers should produce Gamma-ray Bursts
  - detected if jet is pointed towards Earth (on axis)
- Merging compact objects produce GWs
  - we know this for sure from LIGO/Virgo
- If short GRBs are within LIGO detection range and pointed towards Earth, we should see gamma rays & GWs concurrently
The Discovery of
GW170817
GRB 170817A
SSS17a
AT 2017gfo
gbm alert

first on-board gbm localization

ligo report of coincident gw/grb

joint ligo/virgo sky map

+16 s

+27 s

+45 min

+5 hour

borrowed from dan kocevski (nasa/msfc)
GRB 170817A Spectral Components

- Typical short (~0.5 s) hard spike
  - $\alpha = -0.62 \pm 0.40$
  - $E_{\text{peak}} = 185 \pm 62 \text{ keV}$
- Longer (~1 s) soft thermal tail
  - $kT=10.3 \pm 1.5 \text{ keV}$

Goldstein et al. 2017
GRB 170817A Properties

Goldstein et al. 2017

Abbott et al. 2017
Reports of a blue optical transient near an elliptical S0 type galaxy NGC 4993 at ~40 Mpc (Abbott et al. 2017).

Coulter et al. (2017) first observed the region with the 1m Swope telescope at Las Campanas Observatory.

Swift observations reveal bright, but quickly fading, UV source with no evidence of X-ray emission (Evans et al. 2017).

NuStar observations show no X-ray emission (Evans et al. 2017).
Kilonova Evolution

Credit: ESO/E. Pian/S. Smartt & ePESSTO/N. Tanvir/VIN-ROUGE
https://www.eso.org/public/usa/videos/eso1733e/
Two kilonova components?

Or, emission from the cocoon?
Chandra observations reveal first evidence of delayed X-ray emission (Troja et al. 2017)

Radio counterpart reported by VLA (Mooley et al. 2017)

Hubble observations reveal a reddening source (Adams et al. 2017)

Chandra observations show no X-ray emission (Fong et al. 2017)

+2 days +5 days +9 days +16.4 days
HST and Chandra observations continue to show rising afterglow flux (Lyman et al. 2018, Ruan et al. 2018,Troja et al. 2018)

Hints of a plateau in x-rays (D’Avanzo et al. 2018) and radio (Resmi et al. 2018)

Evidence for a turn over in radio (Dobie et al. 2018)
On-Axis Weak sGRB

- We simply observed a top hat jet on the low end of the GRB luminosity function
- Pros:
  - Logical starting point
  - GW-EM delay is on the order of T90
- Cons:
  - Cannot explain the late-time X-ray and radio observations
  - Not clear how to produce delayed thermal emission
  - Would require very low ejecta mass to allow the low-energy jet to successfully breakout
- GW: $\theta_v \sim 29^\circ \pm 15^\circ\/10^\circ$ (LIGO - arXiv: 1805.11579v1)
  - Average sGRB is $\theta_{jet} \sim 16^\circ$ (Fong et al. 2015)
We observed outside the jet of a classical sGRB

Pros:
- Can naturally explain the lower energetics
- Thermal emission could be from the GRB photosphere or the cocoon

Cons:
- Observed $E_{pk}$ & $E_{iso}$ drop very quickly outside $\theta_{jet}$
  - $\theta_{v}$ would need to be just outside the jet edge
- The on-axis $E_{pk}$ would be on the high end of the observed GBM catalog distribution
- Expect bright afterglow in X-ray after $\sim$1 day
We observed the less energetic region of a structure jet where the Lorentz factor decreases with $\theta_v$.

Pros:
- Could produce arbitrary $E_{\text{peak}}$ and $E_{\text{iso}}$ values.
- GW-EM delay is on the order of T90.
- Thermal emission could be from the GRB photosphere or the cocoon.

Cons:
- Not entirely clear how such wings are generated or what their Lorentz profiles look like.
- On-axis Eiso would still need to be relatively low.

Predictions:
- Afterglow should peak and fade as the jet decelerates and we see the more energetic core region of the jet.
- VLBI imaging would reveal proper motion of the jet.
Hard emission from mildly-relativistic shock breakout and thermal emission from cocoon

Pros:
- Can naturally explain the lower energetics
- Could naturally explain both hard and thermal components

Cons:
- Cannot explain very high $E_{\text{peak}}$ values
- Difficult to explain fast variability
- Should overproduce look alike sGRBs

Predictions:
- Late time x-ray and radio should rise for months to years as the cocoon interacts with the ISM
- Quasi-spherical outflow should not produce any proper motion in VLBI imaging
Superluminal motion of the unresolved radio source and undeniable evidence of an off-axis jet (Mooley et al. 2018)

Further evidence for a turnover (Alexander et al. 2018)

Cocoon is ruled out at late times, but it could still explain prompt and early afterglow (Nynka et al. 2018, Mooley et al. 2018)
What can we learn from GW counterparts?

- GRB Physics
  - Jet Structure, Jet Composition, Energetics, Emission Mechanisms, Progenitors
- Origin of heavy elements in the Universe
  - r-process
- Fundamental Physics
  - Speed of Gravity = Speed of Light within $10^{-15}$
- Cosmology
  - Independent Measure of Hubble Constant
- Neutron Star Physics
  - Equation of State
Gravitational waves

- Masses in the range $1.17 - 1.6 \, M_{\odot}$ (consistent with neutron stars)
- Distance $40^{+8}_{-14} \, Mpc$ (close!)
- Viewing angle less than 28 deg (i.e. we are not viewing this side on)
- Rate of neutron star mergers (based on one detection!)

| Parameter                        | 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 $m_{\text{tot}}$      | $2.74^{+0.04}_{-0.01} \, M_{\odot}$  | $2.82^{+0.47}_{-0.09} \, M_{\odot}$  |
| Radiated energy $E_{\text{rad}}$ | $> 0.025M_{\odot}c^2$                | $> 0.025M_{\odot}c^2$                |
| Luminosity distance $D_L$        | $40^{+8}_{-14} \, \text{Mpc}$        | $40^{+8}_{-14} \, \text{Mpc}$        |
| Viewing angle $\theta$           | $\leq 55^\circ$                       | $\leq 56^\circ$                       |
| Using NGC 4993 location          | $\leq 28^\circ$                       | $\leq 28^\circ$                       |
| Combined dimensionless tidal deformability $\tilde{\Lambda}$ | $\leq 800$               | $\leq 700$               |
| Dimensionless tidal deformability $\Lambda(1.4M_{\odot})$ | $\leq 800$               | $\leq 1400$               |
Cosmology

- Hubble Constant - Expansion Rate of the Universe
- Measurements currently in conflict between
  - Cosmic Microwave Background
  - Type Ia Supernovae
- GW counterparts (independent distance measurements from GW and redshift) could help reconcile

$H_0 = 70^{+12}_{-8} \text{ km s}^{-1} \text{ Mpc}^{-1}$

Abbott et al., 2017, Nature

Burns et al. in-preparation
Gravitons and photons arrived \(\sim\)together

\[
\Delta v = v_{GW} - v_{EM}
\]

\[
\frac{\Delta v}{v_{EM}} \approx v_{EM} \frac{\Delta t}{D}
\]

\[-3 \times 10^{-15} \leq \frac{\Delta v}{v_{EM}} \leq +7 \times 10^{-16}\]

Assuming \(D = 26\) Mpc (the lower bound on the 90\% confidence interval for distance based on GW data alone, and bounding \(t\) between \([-10, +1.74]\) s, where the -10 s is a reasonably conservative assumption.
Fundamental Physics

Time delay between merger (GW signal) and GRB = 1.7 s

\[ \Delta t_{\text{total}} = (\Delta t_{\text{collapse}} + \Delta t_{\text{jet formation}} + \Delta t_{\text{breakout}} + \Delta t_f) \times (1+z) \]

Equation of State of Supranuclear matter

How jets form

Emission mechanism of GRBs

NS Merger Ejecta

Beyond GR, SM

Beyond GR

Beyond SR; Quantum Gravity

Fundamental Physics

Nuclear Physics

Astroparticle Physics

NS mergers involve the most extreme timescales, densities, and energetics in the universe.

Burns et al. in-preparation

Credit: Eric Burns (NASA/GSFC/USRA)
Neutron star mergers are messy
R-Process
Nucleosynthesis
# r-Process Nucleosynthesis

## Element Origins

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<thead>
<tr>
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Based on graphic created by Jennifer Johnson.
Challenging Gamma-ray Observations

A time resolved spectral analysis has shown evidence for very high $E_{\text{peak}}$ values

High $E_{\text{peak}}$ values become challenging for the cocoon shock breakout model to explain

We have found bursts that resemble GRB 170817 in BATSE, GBM, and Swift data

Very preliminary, but evidence for sub-structure in some of these cases
GRB 150101B

- The third closest SGRB with known redshift - GRB 150101B
- Very hard initial pulse with $E_{\text{peak}} = 1280 \pm 590$ keV followed by a soft thermal tail with $kT \sim 10$ keV
- Unlike GRB 170817, 150101B was not under luminous and can be modeled as an on-axis burst
- Suggests that the soft tail is common, but generally undetectable in more distant events
- Thermal tail can be explained as GRB photosphere, but degeneracy with the cocoon model still exists
Open Questions

• Where did the gamma-rays come from? How to reconcile other indicators of off-axis emission?
• Jet structure, implications for rates in future?
• Weak GRB – implications for luminosity function? Lots of nearby weak events?
• Do other short GRBs show short hard and long soft components?
• Do neutron star - black hole mergers also produce short GRBs?
• What’s the maximum mass of a neutron star?
• Is there a short lived hyper-massive neutron star?
• What is the minimum mass of a black hole?
• Can GW-GRBs reconcile Hubble Constant debate?

• Looking forward to more observations!
A Subset of Future GW Counterpart Missions/Concepts

- BurstCube (2021)
- ISS-TAO (2022)
- Nimble (~2024)
- TAP (2028+)
- AMEGO (2028+)