GW170817 – GRB 170817A – AT2017gfo: a multi-messenger binary neutron star merger

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An incredible initial campaign (summary paper: 3500 authors, 574 citations in 14 months)

+ observations up to ~300 days after the event
Outline of this talk

• Some notions on gamma-ray bursts

Three electromagnetic components

• The initial burst of gamma-rays
• The kilonova (UV to IR)
• The afterglow (X-rays to radio)
Gamma-ray bursts
Gamma-ray bursts

- Flashes of gamma-rays outshining any other source in the sky.
- First discovered in 1967 with military satellites.
- Observed almost daily, they are a very active field of research until today.
• Rare events but so powerful to be seen up to redshift 9.

Gehrels et al (2009 review)
Model of GRBs

FORMATION OF A GAMMA-RAY BURST could begin either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk system, in turn, pumps out a jet of material at close to the speed of light. Shock waves within this material give off radiation.

- jet aperture \( \sim 10^\circ \)

- Relativistic jet \( \Gamma \sim 100-1000 \)

- \( \rightarrow \) Strong beaming of radiation

- \( \rightarrow \) we see a small fraction of events

Duration

<2s

>2s
A prompt gamma-ray emission

An X-ray afterglow with power-law decline and possible structures.

Afterglows similar also in optical and radio, but less common.
Results from the gravitational signal
GW170817: NS+NS merger

- Identified by matched filtering
- A long signal of \( \sim 100 \) s gives a precise chirp mass
- The loudest signal in GW ever detected

| 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 \( E_{\text{rad}} \)| \(> 0.025 \, M_\odot \, c^2\)        | \(> 0.025 \, M_\odot \, c^2\)        |
| Luminosity distance \( D_L \)| \(40^{+8}_{-14} \, \text{Mpc}\)       | \(40^{+8}_{-14} \, \text{Mpc}\)       |
| Viewing angle \( \Theta \)    | \(\leq 55^\circ\)                     | \(\leq 56^\circ\)                     |
| using counterpart location     | \(\leq 31^\circ\)                     | \(\leq 31^\circ\)                     |
| Combined dimensionless tidal deformability \( \tilde{\Lambda} \) | \(\leq 800\)                         | \(\leq 700\)                         |
| Dimensionless tidal deformability \( \Lambda(1.4 M_\odot) \) | \(\leq 800\)                         | \(\leq 1400\)                        |
- No merging signal due to limited band width
- Loose limits on equation of state
GRB170817A
The Gamma-ray burst
(1.7 s after the GW)
Binary Neutron Star merger, discovered by Fermi/GBM and LIGO, independently observed by INTEGRAL/SPI-ACS, in good agreement with Fermi/GBM. Despite an unfavorable soft GRB spectrum and moderately favorable orientation, INTEGRAL achieved a confident detection.
Fundamental consequences

At least some **short GRBs are associated to BNS mergers**

The 2 s delay comparing to 130 Mly distance implies that **speed of gravity** can be constrained to unprecedented precision:

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

Such a consistency between GW speed and speed of light, implies stringent **limits on Lorentz Invariance Violation**
A very faint GRB

Distance of 120 Mly is much less than ever measured for any GRB (short or long).

This implies low luminosity, which is much less than that measured for other sGRB with known distances (Gamma-ray to GW ratio of $<10^{-6}$). Why?
AT2017gfo: the kilonova (observed from 11 hour to weeks after the GW)
Kilonova

- Sub-relativistic outflows emitted from tidal interaction, collision and subsequent accretion disc.
- They produce heavy elements like Gold, Platinum, Uranium, Thorium (which cannot be forged with the observed abundances in Supernovae)
Kilonovae (predictions)

- faster lanthanide-poor ejecta from polar regions
- slower lanthanide-rich outflow from the equatorial belt
- Evolution of spectra from UV to IR over the first days

Fernandez & Metzger (2016)
• Twelve hours after the joint GRB-GW detection, an optical/UV counterpart has been detected in NGC 4993, at distance (40 Mpc) and redshift (0.0097) perfectly consistent with the GW: a kilonova!
Spectral evolution

• General continuum consistent with black body with temperature decreasing from \( \sim 7000 \) to \( \sim 3000 \) K
• 0.2 Msol mass of ejecta
  Broad features can be interpreted as blends of heavy element lines.

Pian et al. 2017
• Not observed a normal GRB
• Not seen the early afterglow
• Radio signal from interactions of kilonova with ISM ?

Fernandez & Metzger (2016)
The X-ray and radio afterglow
• X-ray and Radio observations detected a source after 9 and 16 days and they can be joined in a synchrotron emission model.
• Late appearance can be due to slowing down of jet (reduced Doppler beaming), but also to a structured emission pattern.
Off-axis event

- As revealed by LIGO/Virgo data, the merger was observed at 20-60 deg off-axis, proving that a considerable amount of EM energy is emitted far from the axis of the system.
- Has the jet broken through or has it formed a hot cocoon?

Mooley et al. (2018)
A panchromatic light curve

From X-rays to radio, the same light curve up to 300 days after the event: synchrotron emission.

Two models consistent with the data

Ghirlanda et al. (2018)
Very Long Baseline Interferometry (radio)

Able to reach milliarcsecond resolution.
A displacement of 2.4+/-0.4 marcsec confirms jet model and rules out cocoon. Combining image and light curve allows parameter estimation.
Inconsistent with a choked jet

Comparison of image with simulations favors strongly a successful jet rather than a choked jet in a cocoon.

Ghirlanda et al. (2018)
It must be a very narrow jet (<5 deg) viewed at about 20 degrees off-axis. Transition happens in less than 25 days.

Mooley et al. (2018)
Rate of observable binary neutron star mergers

- At least 10% of events have a successful jet
- Depending on how the jet fades and is opened, we might observe more or less events in the future.

Ghirlanda et al. (2018)
Conclusions

- Gravitational waves and EM follow-up observations gave the definitive confirmation that binary neutron star mergers produce short gamma-ray bursts, kilonovae, and GRB afterglows.
- The GW170817 event was seen off-axis and is possibly even more energetic than the average.
- It produced a very narrow jet, which came completely into sight only 175 days after the merging. Structured cocoon was dominating beforehand.
- This event allows us to measure for the first time properties of the short GRB with high precision.
- Predictions on event rate are still very uncertain, but at least one other good candidate has been identified among the population of faint GRBs in 2015 at z=0.131 (Troja et al., 2018), beyond the reach of LIGO.
- More events are likely to be observed with the new runs of LIGO and Virgo starting in March 2019!
GW + Gamma-rays