Lessons from GW170817 / GRB170817A
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Outline of the Talk:

- The merger remnant: Black Hole or a massive NS?

- The afterglow emission:
  - Two main options for the early flux rise: $r$ vs. $\theta$ dependence
  - Breaking the degeneracy: lightcurves? Images, Polarization

- Conclusions
GW 170817: the type of remnant

- $M_{1,2} = \text{pre-merger NS mass}$ $M_{\text{gravitational}}$
- Post-merger total mass: $M_i = M_1 + M_2$
- Final mass $M_f \approx 0.93M_i$ due to:
  - GW & neutrino energy losses
  - Mass ejection during the merger
- A stable NS or SMNS $\implies P_0 \approx 1 \text{ ms}$
  $\implies E_{\text{rot}} \geq 10^{52.5} \text{ erg, } \tau_{\text{sd}} \approx 20B_{13}^{-2} \text{ days}$
  $\implies$ would contradict afterglow obs.
  (also what produces the GRB/afterglow?)

The argument can be reversed to constrain NS EoS & $M_{\text{max}} \lesssim 2.17M_\odot$
(Margalit & Metzger 2017; Rezzolla et al. 2018)

- A HMNS may explain $\Delta t \approx 1.74 \text{ s}$ by $t_{\text{HMNS}} \lesssim 0.5 \text{ s}$ & $t_{\text{bo}} \sim 1 \text{ s}$
  (Moharana & Piran 2017 find $t_{\text{bo}} \sim 0.5 \text{ s}$ for SGRBs)
- Direct BH formation $\implies$ shorter $t_{\text{bo}} \implies$ jet less likely to be choked
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GRB 170817A: afterglow observations

\( F_\nu \propto \nu^{-0.61} t^{0.78 \pm 0.05} \)

(Mooley et al. 2018)
GRB 170817A: afterglow observations

\[ F_v \propto \nu^{-0.61} t^{0.78 \pm 0.05} \]

A rise lasting > 100 days is very unusual!!!

(Mooley et al. 2018)
Analogy to rising $F_{\nu}$: X-ray Plateaus

- Possible solutions:
  - Evolution of shock microphysical parameters (JG, Konigl & Piran 2006)
  - Energy injection into ext. shock:
    1. long-lived relativistic wind
    2. slower ejecta catching up (Sari & Meszaros 00; Nousek+ 06; JG & Kumar 06)

- Viewing angle effects

Energy injection into the afterglow shock:

$1 \leq a \leq 2.5$ (ISM)

$a \geq 5$ (wind)

(E, JG & Kumar 2006)

Energy injection into radial:

$E(\gamma u) \propto u^{-2}$

(Vaughan et al. 2006)

Post jet break

“usual” decay $t^{-1.5}$

Flat part $t^{-0.1}$

Rapid decay $t^{-5}$

~10$^2$ s

~10$^4$ s

~10$^5$ s

Jet

$\theta_{\text{obs}}$

$\theta_0$

$\gamma \sim 50$

$\gamma \sim 10$

$\gamma \sim 3$

(Vaughan et al. 2006)

(JG, Ramirez-Ruiz & Perna 2005)
Off-Axis Afterglow Lightcurves

- The emission is initially strongly beamed away from our L.o.S
- $F_v$ rises as beaming cone widens
- When beaming cone reaches LoS, $F_v$ peaks & approaches on-axis $F_v$
- The rise is much more gradual for hydrodynamic simulations due to slower matter at the jet’s sides with non-radial velocities

![Graph showing Off-Axis Afterglow Lightcurves](image)

GRB170817 outflow structure: prompt, afterglow

- Cocoon model (Kasliwal+17; Mooley+18; Nakar & Piran 18): $r$ & $\theta$ profile
- Cocoon-driven shock breakout can naturally produce the $\gamma$-rays (Kasliwal+17; Gottlieb+17; Bromberg+18; Nakar & Piran 18; Nakar+18)

![Graph showing radio data and model fits for $S_\nu$ vs. time]

- Radio data (3 GHz)
- $\beta_{max}=0.8$, $E(\beta\gamma)=5 \times 10^{50} (\beta\gamma/0.4)^{-5}$, $n=0.03$ cm$^{-3}$, $\epsilon_B=0.003$
- $\gamma_{max}=3.5$, $E(\beta\gamma)=2 \times 10^{51} (\beta\gamma)^{-5}$, $n=8 \times 10^{-5}$ cm$^{-3}$, $\epsilon_B=0.01$
- Cocoon model from Gottlieb et al. 2017 (radial + angular profile)

(Mooley, Nakar, Hotokezaka, et al. 2018)
GRB170817 outflow structure: the afterglow

- **A structured jet explanation** (Lazzati+17; Margutti+18; Gill & JG 18;...):
  - Simulation of jet breaking out of the Newtonian ejecta near a NS-NS merger site: the cocoon energizes the jet’s sides/wings
  - Afterglow dominated by $\theta$ profile

(Lazzati et al. 2018)
Outflow structure: breaking the degeneracy (Gill & JG 18)

- The lightcurves leave a lot of degeneracy between models.
- The degeneracy may be lifted by calculating the afterglow images & polarization (e.g. Nakar & Piran 2018; Nakar et al. 2018).
- We considered 4 different models including both main types:
  - Sph+E_{inj}: Spherical with energy injection \( E(>u=\Gamma \beta) \propto u^{-6}, \ 1.5 < u < 4 \)
  - QSph+E_{inj}: Quasi-Spherical + energy injection \( E(>u) \propto u^{-5.5}, u_{\min,0} = 1.8, \ u_{\max,0} = 4, \ s = 5.5, \ \zeta = 0.1 \)

\[
\epsilon(\theta) = \frac{u_{0,\min}(\theta)}{u_{\min,0}} = \frac{u_{0,\max}(\theta)}{u_{\max,0}} \frac{\zeta + \cos^2 \theta}{\zeta + 1}
\]
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- We considered 4 different models including both main types:
  - **GJ**: Gaussian Jet (in $\epsilon = \frac{dE}{d\Omega}$, $\Gamma_0 - 1$) $\Gamma_c = 600$, $\theta_c = 4.7^\circ$
  - **PLJ**: Power-Law Jet; $\epsilon = \epsilon_c \Theta^{-a}$, $\Gamma_0 - 1 = (\Gamma_c - 1) \Theta^{-b}$, $\Theta = [1+(\theta/\theta_0)^2]^{1/2}$
    $\Gamma_c = 100$, $\theta_c = 5^\circ$, $a = 4.5$, $b = 2.5$
  - As there is a lot of freedom we fixed: $p = 2.16$, $\epsilon_B = n_0 = 10^{-3}$, $\theta_{\text{obs}} = 27^\circ$
The outflow structure: breaking the degeneracy

- Tentative fit to GRB170817A afterglow data (radio to X-ray)

![Graphs showing fit to different models with parameters and data points](image)
The outflow structure: breaking the degeneracy

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The outflow structure: breaking the degeneracy

- New data just came out establishing a peak at $t_p \sim 150$ days
- The jet models decay faster (slightly preferred by the latest data)
Afterglow Images: $Sph + E_{\text{inj}}$
Afterglow Images: \( QSph + E_{\text{inj}} \)
Afterglow Images: GJ, PLJ
Linear Polarization

- Assuming a shock-produce B-field with $b \equiv 2\langle B_\parallel^2 \rangle / \langle B_\perp^2 \rangle$

New: upper limit on linear pol. @ 2.8 GHz (Corsi + 2018)
Afterglow Images: flux centroid, size, shape

- The flux centroid motion: a potentially powerful diagnostic
- It may be hard to tell apart models based on the image size alone, but a much higher axis-ratio is expected for jet models

![Graphs showing flux centroid motion and size evolution over time.](image)
Afterglow Images: uniform jet simulations
(JG, De Colle & Remirez-Ruiz 2018)
Conclusions:

- First secure association of a sGRB with a NS-NS merger, but the sGRB is atypical (its afterglow, very low $E_{\gamma,iso}$)
- Merger Remnant: most likely BH or HMNS $\rightarrow$ BH
- Two main types of explanations for the rising afterglow flux energy distribution with proper velocity or with angle
- Possible diagnostics to distinguish between them
  - The post-peak flux decay slope
  - Flux centroid motion or image axis ratio (challenging with image size or polarization alone)