Gamma-ray bursts after GW170817/GRB 170817A

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Gamma-ray Bursts 2
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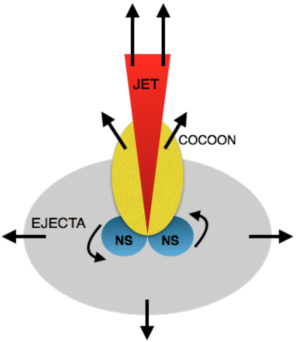
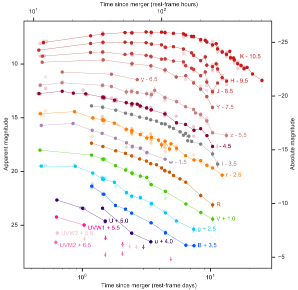
Jargon

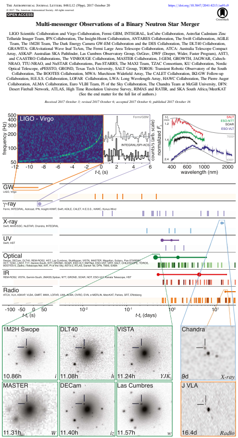
- *dynamical ejecta* - ejected moments before merger neutron rich material 0.01-0.1$M_\odot$
- *shock breakout* - shock passes through the dynamical ejecta - produces soft thermal spectrum
- *structured jet* - jet with lateral structure as a function of angle from axis
- *kilonova* - powered by radioactive decay of r-process elements in dyn. ej. ($\lesssim$ 10 day timescale)
- *r-process* - rapid neutron capture favorable conditions in dyn. ej. - high Z elements





Literature on 170817 - Many, many papers

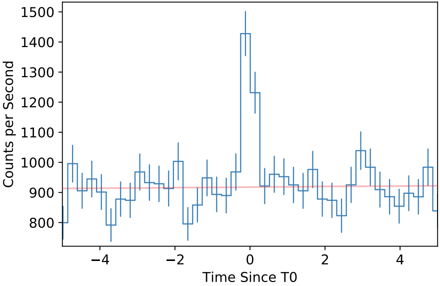
- Metzger (kilonova), Burns (gamma-ray, future prospects), Margutti (afterglow), Nakar (all EM)
- Discovery paper: Abbott et al., (LIGO-Virgo+)
- GW-GRB paper: Abbott et al., (LIGO, Fermi-GBM, INTEGRAL)
- GRB paper: Goldstein, Veres et al.
- Interesting: late follow up (Troja+, Ghirlanda+...)
- Cocoon, off-axis (Kasliwal et al. 2017)
- Collection of relevant papers: https://ui.adsabs.harvard.edu/public-libraries/56xnUi8oSS6prW-X_bfDOg



GRB 170817A - Basic information

"An ordinary GRB with extraordinary implications"

- GRBs brightest in 50-300 keV
- Triggered GBM: excess counts on 256 ms timescale
- Start: T_{GW}+1.7 s $\approx$ T_{GRB}-0.3 s
- Duration, T_{90}= 2.0$\pm$0.5 s
- "By eye" it's only 0.5 s long
- Main peak + soft component $\sim$ 1 to 2 s after trigger



50-300 keV lightcurve

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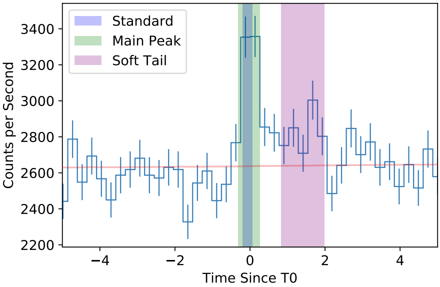
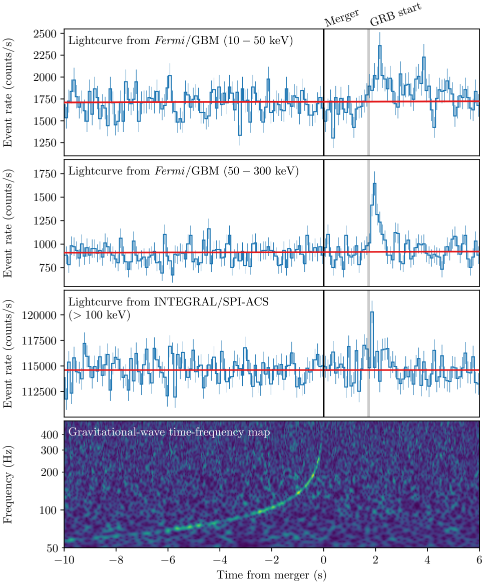


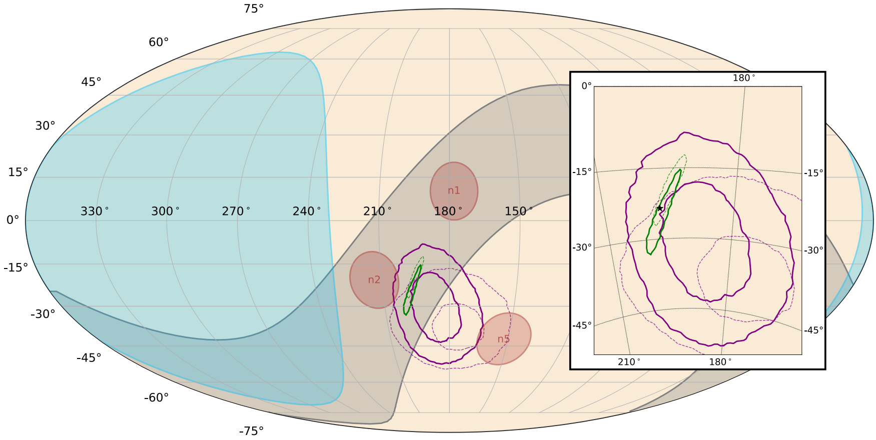
10-300 keV lightcurve

Joint discovery

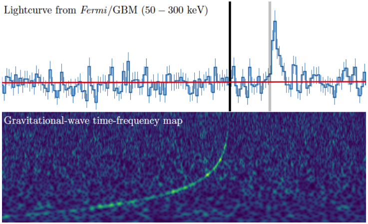


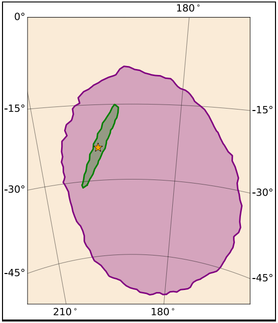
GRB 170817A - location - timeline

- $T_{GW} = T_{GRB}$ - 2.02 s
- T_{GW}+16 s: first **public** notice by flight software
- T_{GW}+27 s: on-board localization and classification
- T_{GW}+40 s: automatic on-ground localization
- T_{GW}+40 min: LIGO reports GW trigger coinc. w GRB
- T_{GW}+45 min: improved human-guided location
- Single IFO location consistent with GBM → good sign
- T_{GW}+67 min: report GRB properties
- T_{GW}+5 h: HLV map still consistent with GBM map (that was when we knew they are surely associated)



GRB 170817A - Significance of association



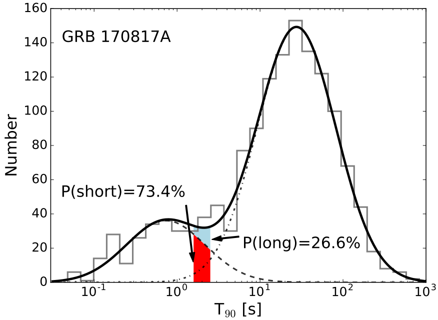


- $P_{\text{temporal}} = 5 \times 10^{-6}$
- $P_{\text{spatial}} = 10^{-2}$

$$P = 5 \times 10^{-8}\ (5.3\ \sigma)$$

GRB 170817A - Is this a short GRB?

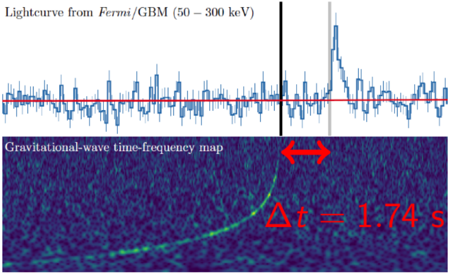
- Short - long divide (2 s ?)
- 3rd GBM GRB catalog
- $T_{90} = 2.0 \pm 0.5$ s $\rightarrow$conservative ($\sim$ 0.5 s + soft episode)
- 2 log-normals describe the duration distribution
- Answer:
  YES, short more likely ($\sim$ 3:1)



First direct evidence linking short GRBs to neutron star mergers

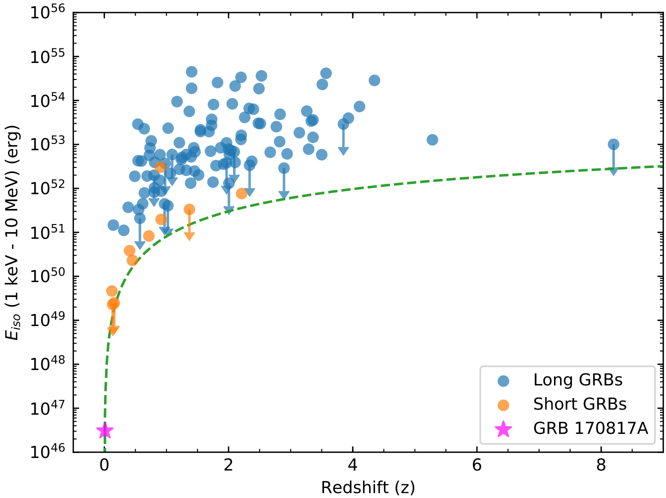
Speed of gravity

- 130 million light-years
- $\Delta t = 1.74 \pm 0.05$ s
- $\Delta v = v_g - v_{EM}$
- -10 s $\leq$ dt $\leq$ 1.7 s



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

GRB 170817A - Isotropic-equivalent energy



Low energy compared to GRBs with known distance

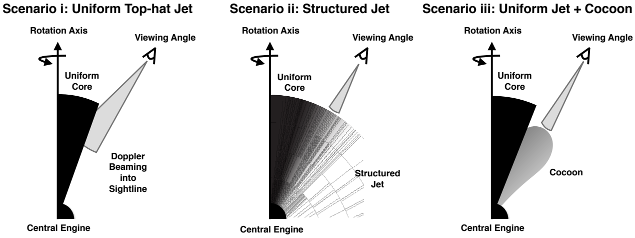
GRB 170817A - astrophysics - detectability

Observationally **ordinary** GRB. Redshift $\rightarrow$ subluminous by orders of magnitude.

- Off-axis top hat jet (?)
- Off-axis structured jet
- Cocoon shock breakout (?)
- $b = \delta_D(\theta = 0)/\delta_D(\theta_v - \theta_j)$
- $E_{\text{peak}}^{\text{ONaxis}}/E_{\text{peak}}^{\text{OFFaxis}} = T_{90}^{\text{OFF}}/T_{90}^{\text{ON}} \propto b$; $E_{\text{iso}} \propto b^{-2}$
- $E_{\text{peak}} = 6(b/30)$ MeV; $T_{90} = 7 \times 10^{-2}(b/30)^{-1}$ s; $E_{\text{iso}} \sim 5 \times 10^{49}(b/30)^2$ erg
- TOP hat jet doesn't work

- 30 % dimmer: still triggered
- 60 % dimmer: offline search

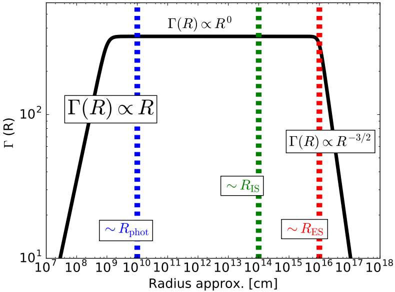
- O3: 1-50 BNS/year (0.1-1.4 joint)
- Design: 6-120 BNS/year (0.3-1.7 joint)



Prompt emission modeling when GRB is off-axis

Motivation: unusually subluminous GRB. Ingredients:

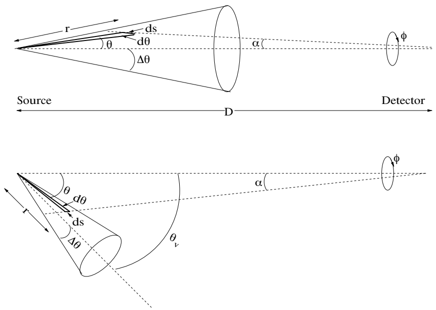
- Large energy ($E \sim 10^{52}$ erg) given to a small amount of matter ($M \sim 10^{-5} M_\odot$), in a small volume ($R_0 \sim \text{few} \times 2GM/c^2$)
- Matter starts expanding, accelerating - jet forms
- Reaches final/ coasting Lorentz factor, $\Gamma_0 \sim E/Mc^2 \sim 100$.
- Photosphere, internal shocks & external shocks
- Lorentz factor is a function of velocity - $\Gamma = 1/\sqrt{1-(v/c)^2}$



Prompt emission modeling when GRB is off-axis

Ingredients 2:

- Doppler factor $\delta_D = \frac{1}{\Gamma(1-\beta\cos\theta)}$
- Equal arrival time surface, EATS: Have to sum all the parts of the jet, for which the emitted radiation reaches us at some fixed $T_{\rm obs}$. Remember optically thin regime.
- $T_{\rm obs} = (1+z)\left(\frac{t-R\mu}{c}\right)$ $[\mu = \cos\theta]$
- Tip: Best to think of physical quantities in terms of spatial dim, time is less intuitive
- $F_\nu(T_{\rm obs}) = \frac{1+z}{D_L}\int_0^{2\pi} d\phi \int_{-1}^{1} d\mu \int_0^\infty R^2 dR \frac{j'_{\nu'}(\Omega'_d,\mathbf{r},t)}{\Gamma^2(1-\beta\cos\theta)^2}$



Prompt emission modeling when GRB is off-axis

Ingredients 3:

- Jet structure: need to specify $j_\nu(\theta)$ and $\Gamma(\theta)$. Usually assumed the same. Alternatively $dL_\nu/d\Omega$

- Top hat:

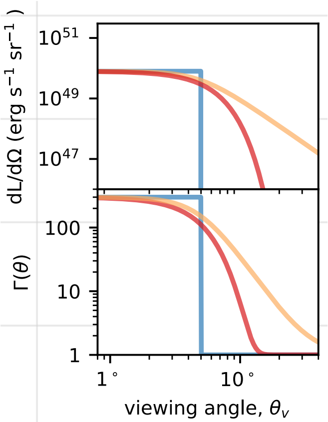
$$\Gamma(\theta) = 1 + (\Gamma_0 - 1) H(\theta - \theta_c) = \begin{cases} \Gamma_0 & \theta < \theta_c \\ 1 & \theta > \theta_c \end{cases}$$

- Gaussian:

$$\Gamma(\theta) = 1 + (\Gamma_0 - 1)\exp(-(\theta/\theta_c)^2)$$

- Power law:

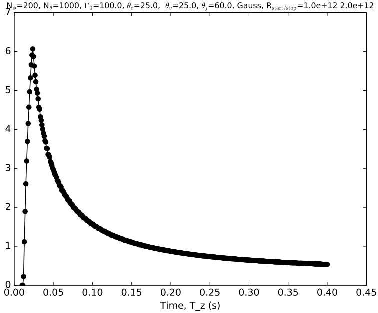
$$\Gamma(\theta) = \Gamma_0 \times \begin{cases} 1 & \theta < \theta_c \\ (\theta/\theta_c)^\alpha & \theta > \theta_c \end{cases}$$



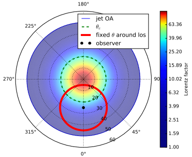
$H(x) = 0$ if $x < 1$, $H(x) = 1$ if $x > 0$ (Heaviside function)

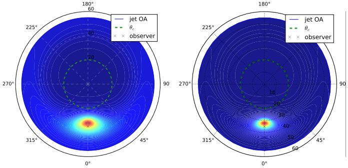
Prompt emission modeling when GRB is off-axis

Model: jet turned on/off between R_1 & R_2

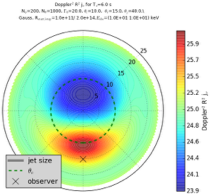


$$F_\nu(T_{\mathrm{obs}}) = \frac{1+z}{D_L}\int_0^{2\pi} d\phi \int_{-1}^{1} d\mu \int_0^{\infty} R^2 dR \, \frac{j'_{\nu'}(\Omega'_d,\mathbf{r},t)}{\Gamma^2(1-\beta\cos\theta)^2}$$





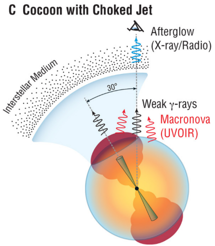
Doppler factor δ_D and δ_D^2.

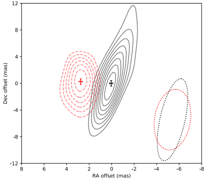


$\delta_D^2 R^2 j'_\nu$

Shock breakout model for GRB 170817A

- Motivation: unusually subluminous GRB.
- Idea borrowed from supernova shock breakout
- Closure relation $T_{90} = 1\ \mathrm{s}(E/10^{46}\ \mathrm{erg})^{1/2}(E_{\mathrm{peak}}/150\ \mathrm{keV})^{-\frac{9+\sqrt{3}}{4}}$
- Satisfied for GRB 170817A
- Unclear if this is the origin of $\gamma - rays$, doesn't work for afterglow
- VLBI image - proper motion - jet

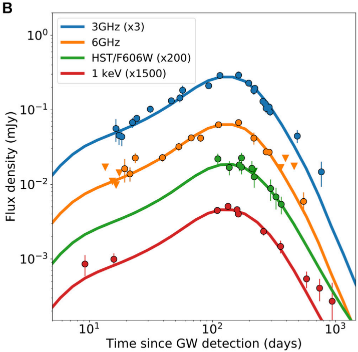


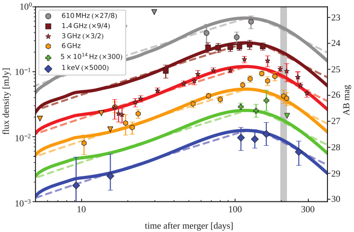


Afterglow

- Rising afterglow - signature of an off-axis geometry
- Unclear if Gaussian, Power law or simulation-based
- Best way to get physical parameters

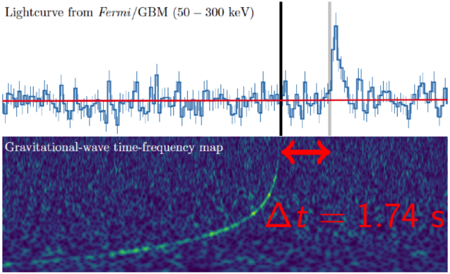
Parameter	Best fitting value	One sigma range
$\mathrm{Log}(E_c/\mathrm{erg})$	52.4	(51.7, 53.0)
s_1	5.5	(4.1, 6.8)
$\mathrm{Log}(\Gamma_c)$	2.4	(2.0, 2.9)
s_2	3.5	(1.8, 5.6)
θ_c/deg	3.4	(2.4, 4.4)
$\mathrm{Log}(\epsilon_B)$	-3.9	(-5.4, -2.2)
$\mathrm{Log}(n/\mathrm{cm}^{-3})$	-3.6	(-4.3, -2.9)
θ_v/deg	15	(14, 16.5)





Explaining the time delay in GW/GRB 170817a

- $\Delta T = 1.74 \pm 0.05$ s
- Merger to BH formation $\lesssim 0.1$ s
- BH formation to start of accretion .01 s
- Jet start to borrow through the dynamical ejecta $\lesssim 0.5$ s
- Jet breakout from dyn. ej. to place of gamma-ray emission (R)
- $T_{90} \sim \Delta T$, both on the order $R/2\Gamma^2 c$ suggests jet travel time dominant.



details: Zhang: *The delay time of gravitational wave – gamma-ray burst associations* Front. Phys. 14(6), 64402 (2019)

GW170817-GRB 170817A - scorecard

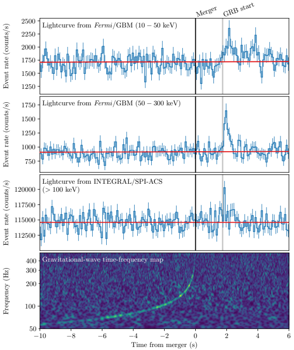
(errors omitted for clarity)

- $D_L = 40$ Mpc
- $E_{iso} = 3.1 \times 10^{46}$ erg
- $L_{iso} = 1.6 \times 10^{47}$ erg
- $E_{\rm peak} \sim 200$ keV
- $T_{90} = 2.0$ s
- $M_{tot} = 2.74 M_\odot$

- $E_{\rm kin} = 10^{49}$ erg
- $\theta_{\rm jet} \sim 5^\circ$
- $\theta_{\rm view} \sim 15 - 30^\circ$
- $n_{\rm ext} = 10^{-2}$ cm^{-3}
- $\Gamma = 140 - 250$

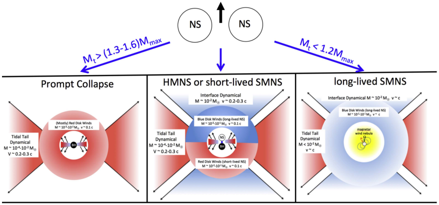
Conclusion

- GW170817 - GRB 170817A observed during Obsering run 2 (O2)
- No counterparts during O3
- Prompt emission origin: likely structured jet, not settled yet
- Afterglow - likely structured jet
- Lot of excitement, interpretation details still up in the air



What happened to the central engine after the merger?

- $M_{\rm tot} = 2.74 M_\odot$, remnant mass $M_{\rm remn} \sim 2.6 M_\odot$
- Interesting because constraints the central engine of GRBs.
- Black hole or neutron star (magnetar) ?
- When did it collapse to BH? uncertain, but no prompt collapse to BH - kilonova too bright (dynamical timescale $(R_s/GM)^{1/2} \sim 10^{-5} (M/2M_\odot)$ s)
- Up for debate. Limits for HMNS, SMNS depend on EoS, are close to possible remnant mass
- Likely scenario HMNS formed for 10 ms (ejecta OK for KN) collapsed to BH, powered jet



Margalit &Metzger (2017)