Lessons from the short GRB 170817A and off-axis emission from GRB jets

Ramandeep Gill
Open University of Israel
Ben-Gurion University of the Negev

Granot, Guetta, & Gill, 2017, ApJL, 850, 24
Granot, Gill, Guetta, De Colle, 2017, arXiv:1710.06421

Image:
NSF/LIGO/Sonoma State
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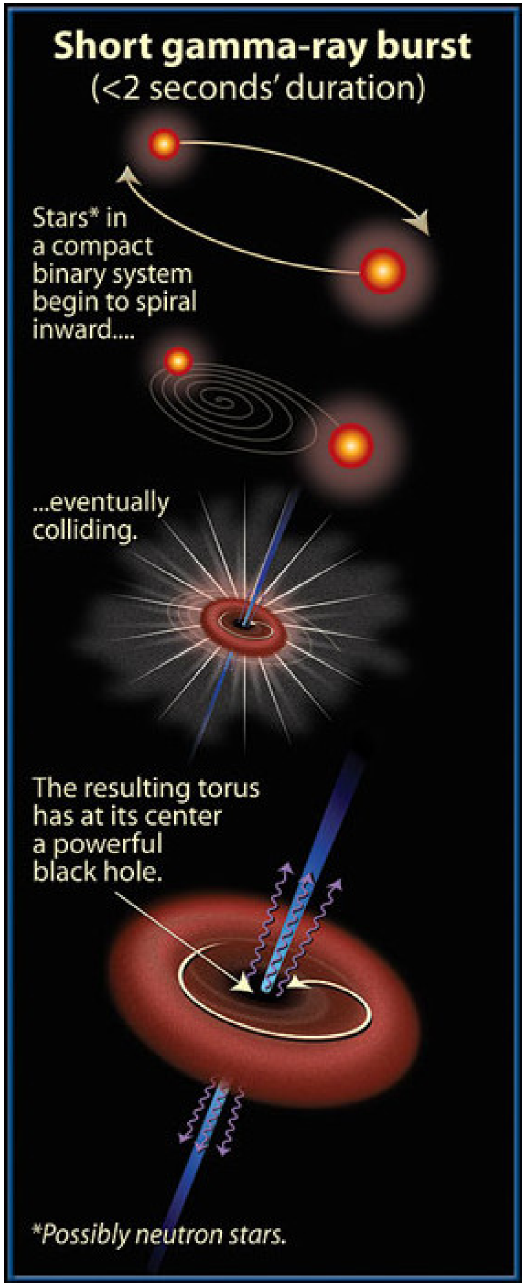
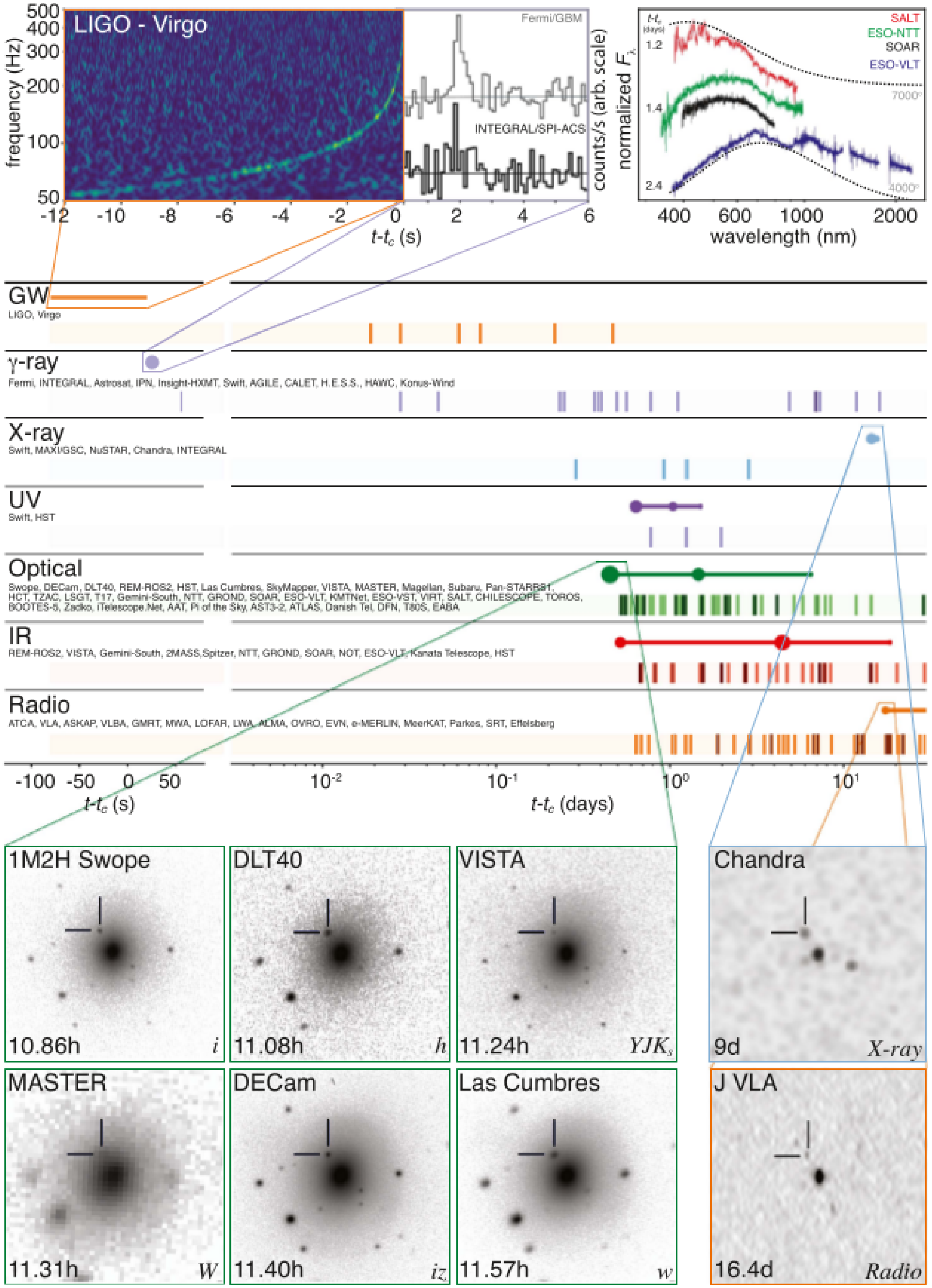
Playa Del Carmen, Mexico

Dec, 2017

Multi-Messenger (GW + EM) Observations



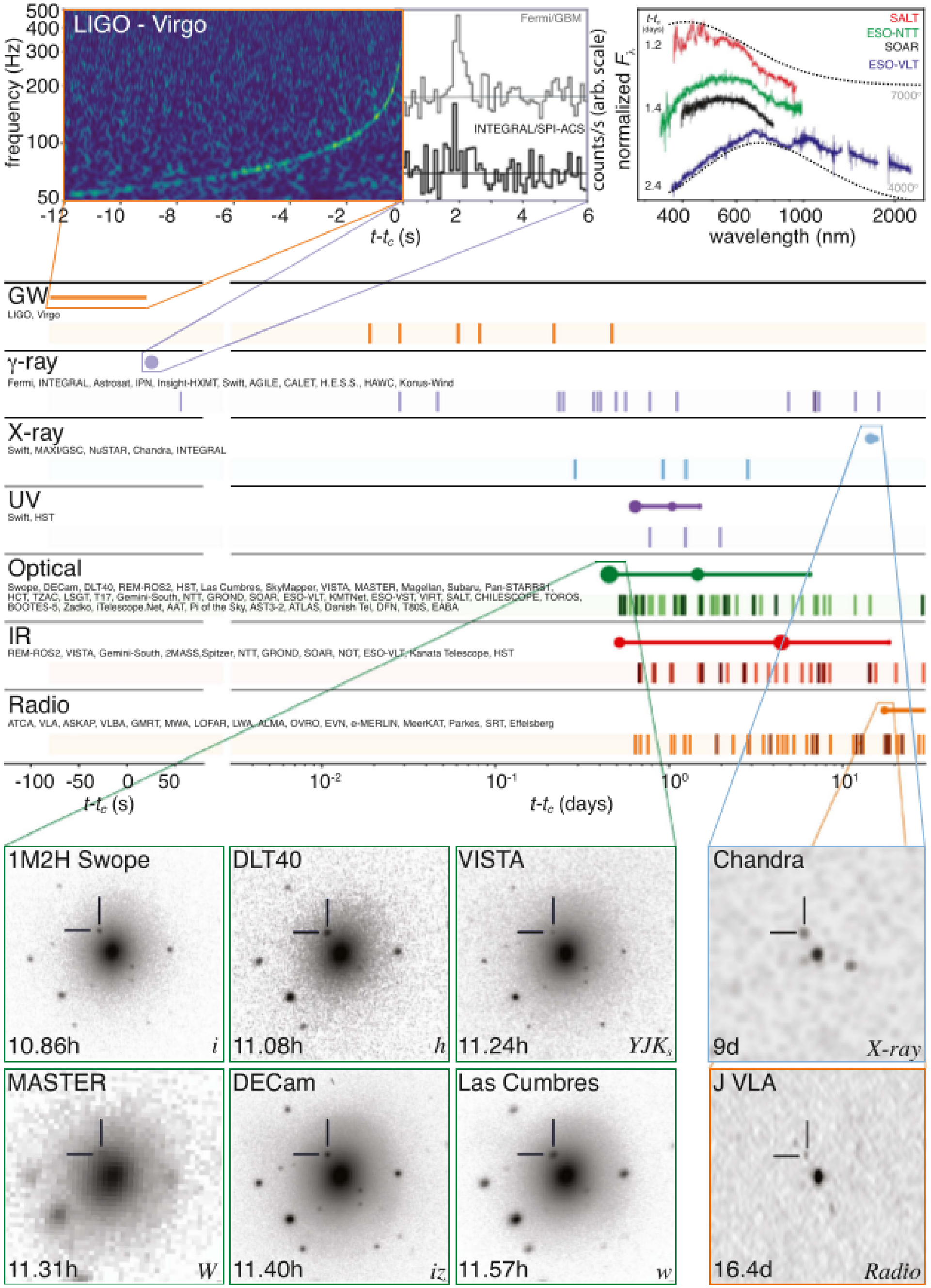


(Abbott+2017)

Multi-Messenger (GW + EM) Observations

Outline

- What can we learn from the prompt emission energetics and its onset delay w.r.t. the GW chirp signal?
- Can we say anything about the merger remnant?
- Is the interpretation for the prompt emission consistent with the afterglow data?



(Abbott+2017)

Prompt Emission

The delay between GW chirp signal and sGRB onset

- The temporal delay between the GW chirp signal and the onset of the sGRB was measured to be

$$\Delta t = 1.74 \pm 0.05\ \mathrm{s}$$

- The chance probability of the temporal + spacial coincidence is

$$5.0 \times 10^{-8}$$

- GW signal also gave a constraint on the viewing angle [w.r.t jet axis]:

$$\theta_{\rm obs} \lesssim 0.49 \approx 28^\circ$$

(LVC+Fermi+INTEGRAL 2017)

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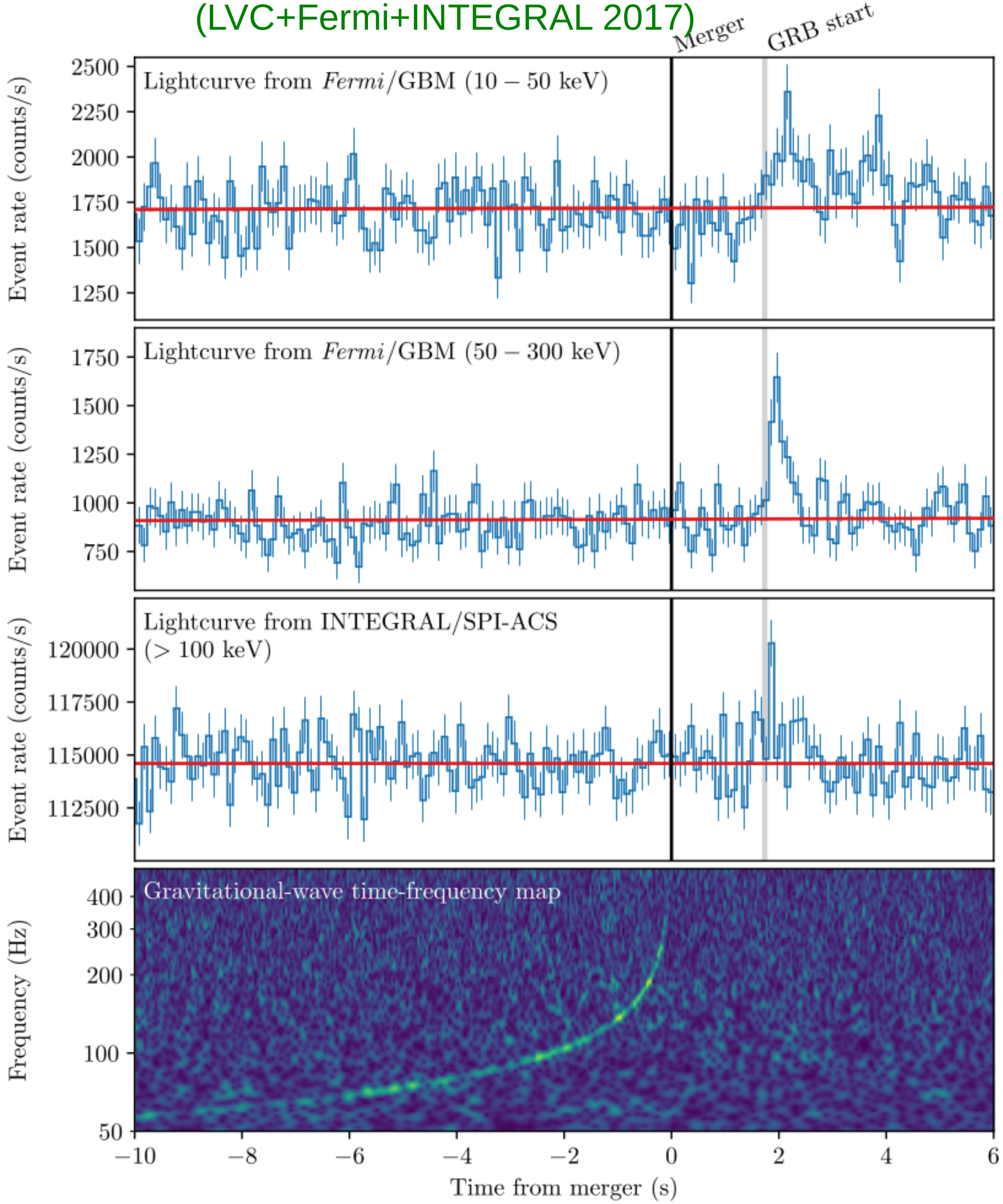
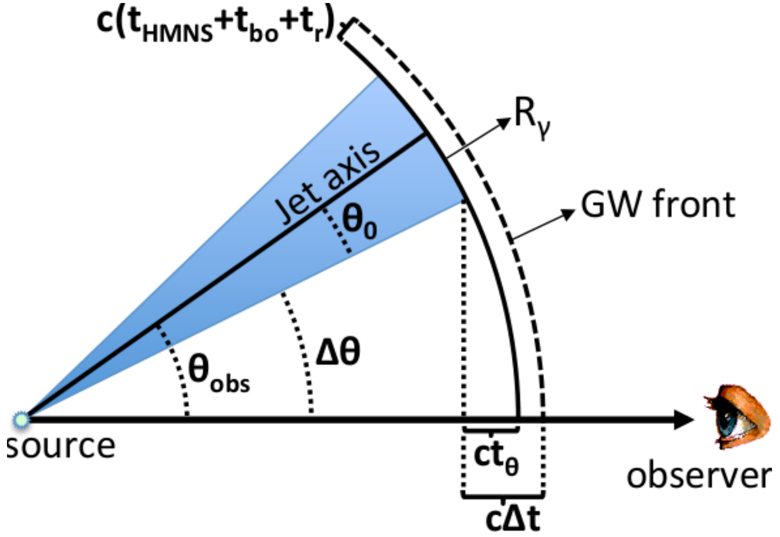


What can we learn from the delayed onset?



There could be at least 4 possible causes for the delay:

1) Delayed collapse to black hole due to the formation of a short lived hyper-massive neutron star (HMNS):

$$t_{\rm HMNS} \lesssim 1~{\rm s}$$

2) Time taken by the relativistic jet to bore a hole through the merger ejecta or neutrino driven wind: $t_{\rm bo} < 1~{\rm s}$

3) Radial time delay for an on-axis observer due to the jet traveling slightly slower than the GW, which yields:

$$t_r \lesssim \frac{R_\gamma}{2\Gamma^2 c} = 1.7 R_{13}\Gamma_{2.5}^{-2}~{\rm ms} – 1.7 R_{13}\Gamma_{1}^{-2}~{\rm s}$$

4) Extra light travel time for an off-axis observer:

$$t_\theta = \frac{R_\gamma}{c}[1-\cos(\Delta\theta)] \approx \frac{R_\gamma}{2c}\Delta\theta^2 = 1.67 R_{\gamma,13}\Delta\theta_{-1}^2~{\rm s}$$

Also see: Lazzati+17, Salafia+17, Alexander+17, Haggard+17, Ioka & Nakamura 17, Jin+17, Kathirgamaraju+17, Murguia-Berthier+17

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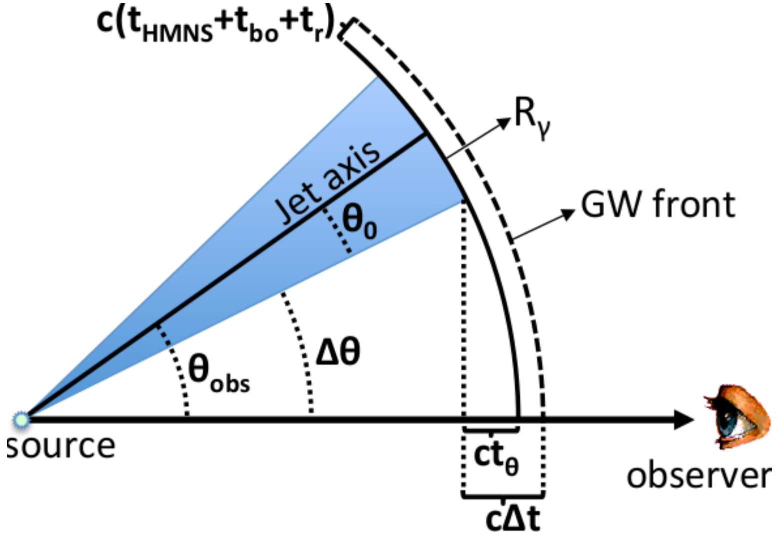
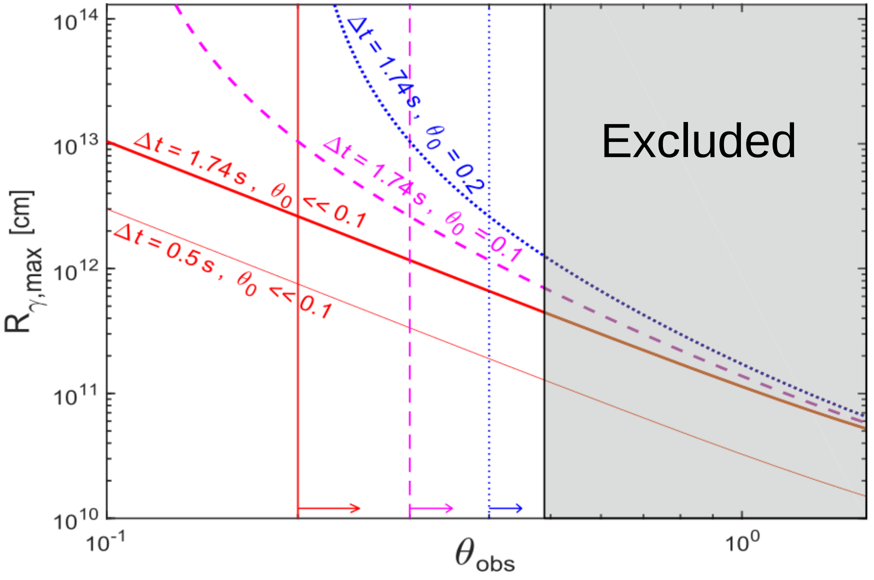


$$\Delta t \geq t_{\rm HMNS} + t_{\rm bo} + t_r + t_\theta > t_\theta$$

$$R_\gamma < \frac{2c\Delta t}{\Delta\theta^2} = 6\times 10^{12}\left(\frac{\Delta t}{1\ {\rm s}}\right)\Delta\theta_{-1}^{-2}\ {\rm cm}$$

(Granot, Guetta, & Gill 2017)



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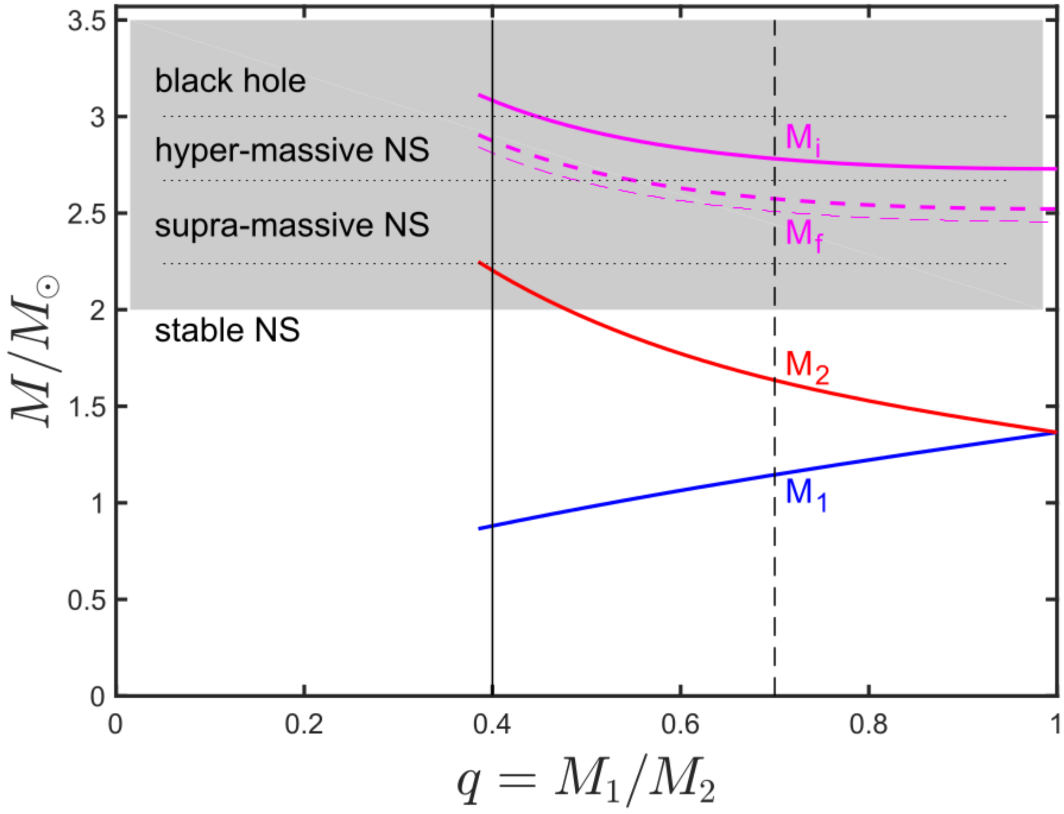
Nature of the remnant



(Granot, Guetta, & Gill 2017)

- Chirp mass from GW signal

$$\mathcal{M} \equiv (M_1 M_2)^{3/5} (M_1 + M_2)^{-1/5}$$

$$= 1.188^{+0.004}_{-0.002}\, M_\odot$$

(Abbott+17)

Nature of the remnant

- 4 possible merger outcomes:
  - Stable NS: Requires roughly equal binary masses and a stiff EOS.
  - Supra-massive NS: Supported by rigid-body rotation and collapses to BH on the spin-down time.

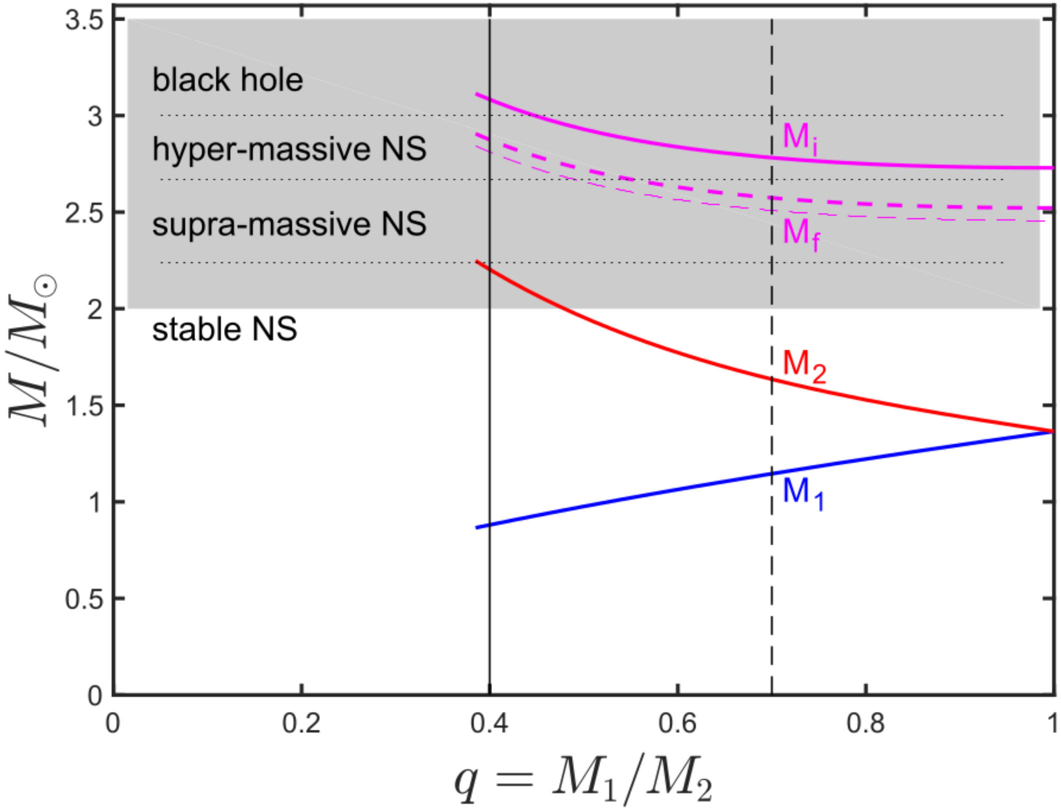
$$\tau_{\rm sd} = \frac{Ic^3}{2f\Omega_0^2 R_{\rm NS}^6 B_0^2} \gtrsim 3.4\times 10^4 \frac{P_{0,-3}^2}{fB_{14}^2}\ {\rm s}$$

$$E_{\rm rot} = \frac{1}{2} I\Omega_0^2 \sim 10^{52.5} - 10^{53}\ {\rm erg}$$

  - This energy is released as a relativistic MHD wind and should give a bright afterglow emission up to the spin-down time.
  - Hyper-massive NS: Supported by differential rotation until it collapses to a BH after a short time:

$$t_{\rm HMNS} \lesssim 1\ {\rm s}$$

(Granot, Guetta, & Gill 2017)



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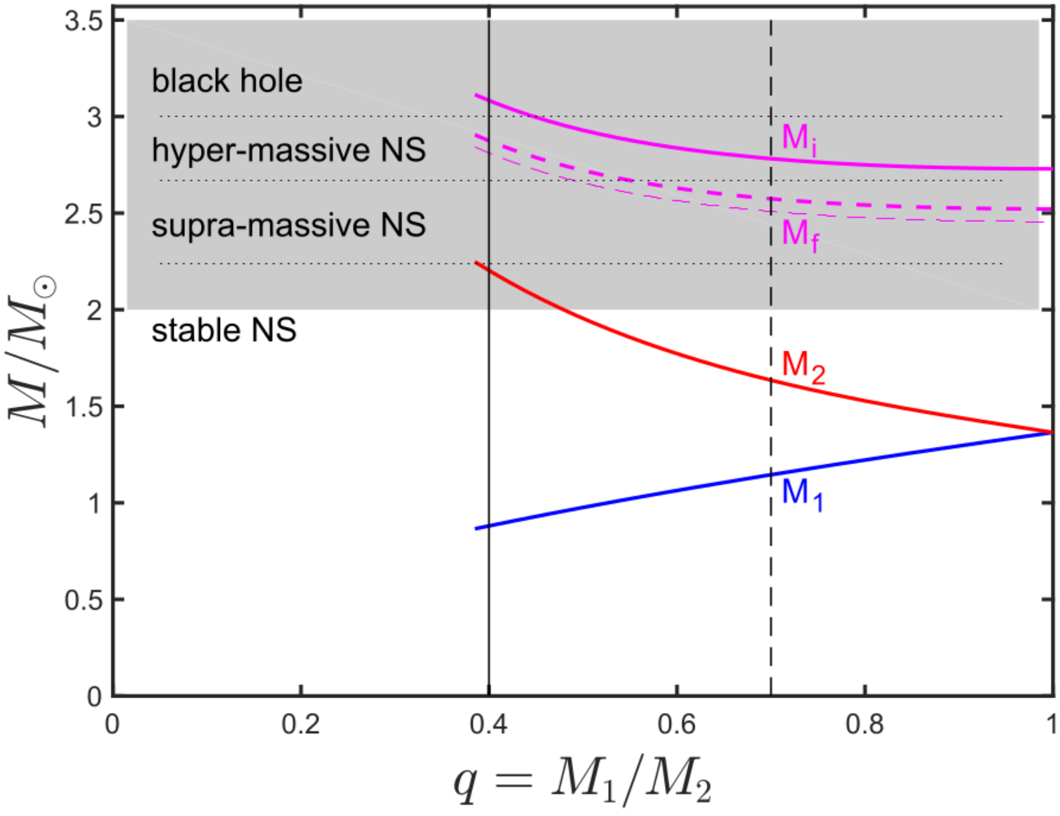
(Baumgarte+00, Margalit & Metzger '17)

(Granot, Guetta, & Gill 2017)



- **Direct formation of BH**: Requires a soft EOS.
  - Kilonova models predict $M_{\rm ej} \sim 0.05 M_\odot$

    (Drout+17, Evans+17, Kasen+17, Kasliwal+17, Kilpatrick+17, Pian+17, Smartt+17)
  - This favors low mass ratios: $q \lesssim 0.5 - 0.6$

(Rosswog+14, Sekiguchi+16, Ciolfi+17, Dietrich+17)

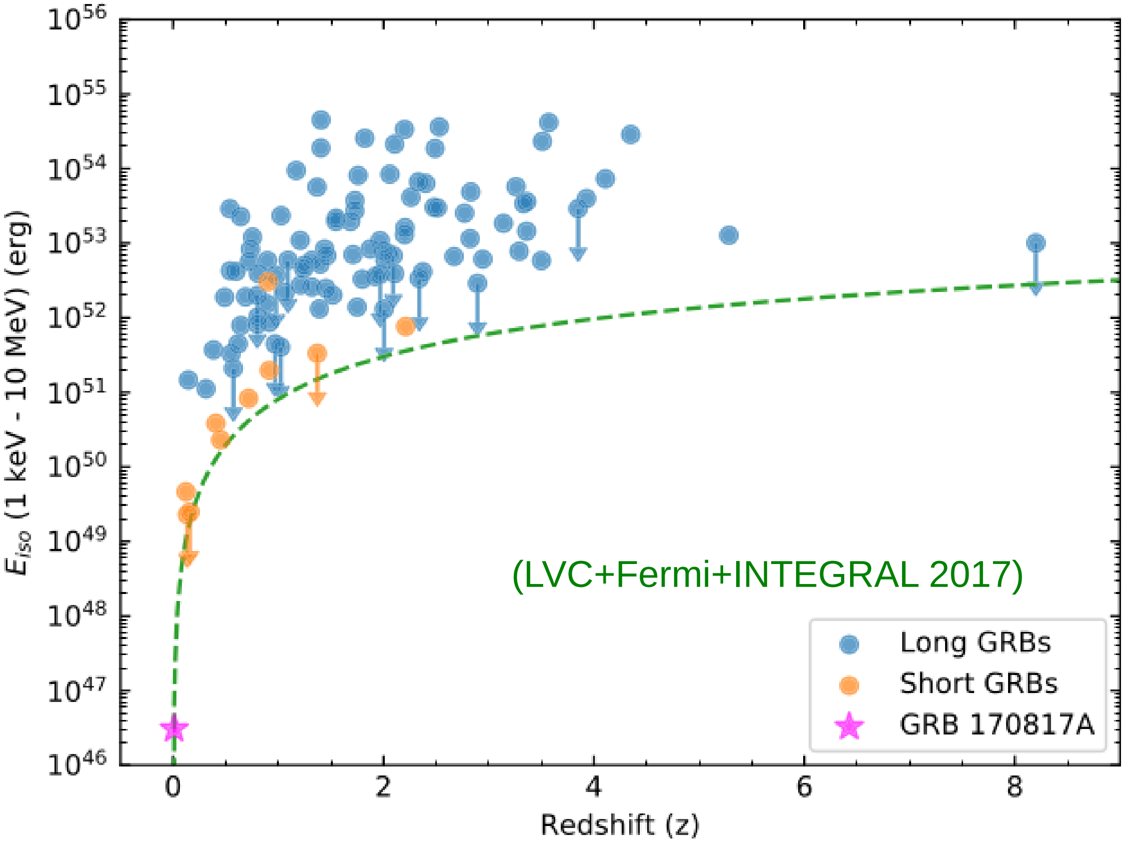
Constraints on jet geometry and $\theta_{\rm obs}$ from energetics

- Unusually lower isotropic-equivalent energy and typical photon energy (νF_ν - peak) for a SGRB

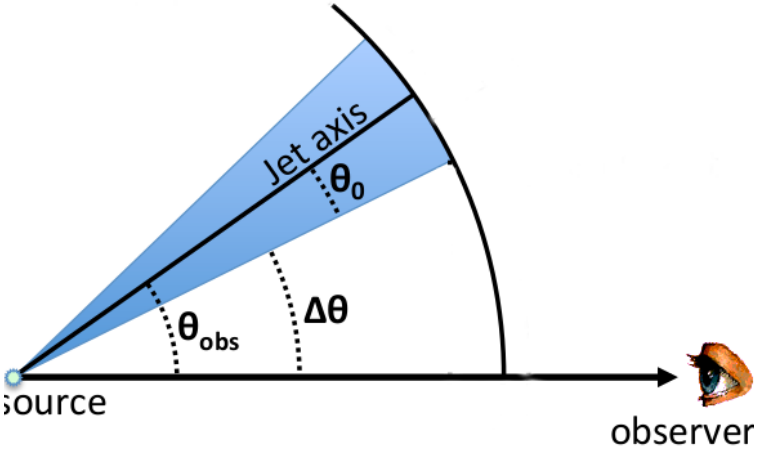
$$E_{\gamma,\rm iso} = (3.1 \pm 0.7) \times 10^{46}\ \rm erg \quad [1\ keV – 10\ MeV]$$

$$E_{\rm pk} = 185 \pm 62\ \rm keV$$

- This fact [along with afterglow observations] suggests an off-axis viewing angle.



Off-Axis Emission from Relativistic Jets



- Consider a relativistically expanding sharp-edged jet:

- $$E(\Delta\theta) = \delta_D E' \approx \frac{2\Gamma E'}{[1 + (\Gamma\Delta\theta)^2]}$$

$$\Rightarrow \frac{E(\Delta\theta)}{E(0)} \sim (\Gamma\Delta\theta)^{-2} \qquad \Gamma\Delta\theta \gg 1$$

- $$E_{\rm iso}(\Delta\theta) = 4\pi\delta_D^3 \frac{dE'}{d\Omega'} \propto (\Gamma\Delta\theta)^{-6}$$

  [This is true for a point source only]

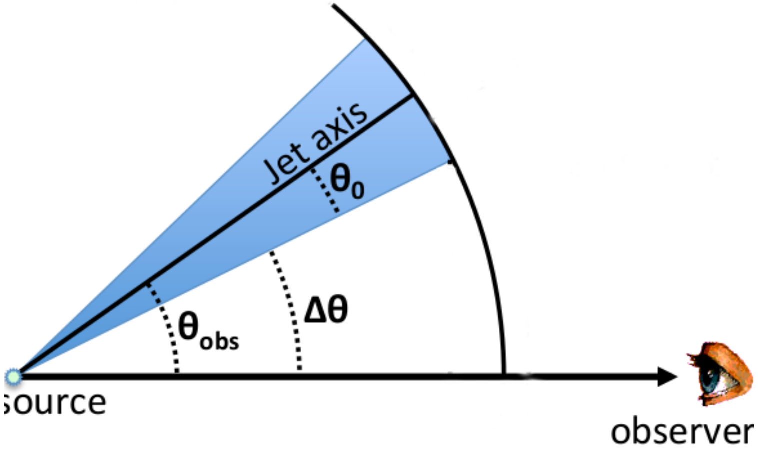
- For viewing angle only slightly larger than θ_0

$$\Rightarrow \frac{E_{\rm iso}(\Delta\theta)}{E_{\rm iso}(0)} \sim \frac{(\Gamma\Delta\theta)^2}{(\Gamma\theta_0)^2}(\Gamma\Delta\theta)^{-6} \propto (\Gamma\Delta\theta)^{-4}$$

$$= \left[\frac{E(\Delta\theta)}{E(0)}\right]^2 \qquad 0 < \frac{\Delta\theta}{\theta_0} < 1$$

Granot+02, 05; Eichler & Levinson ‘04; Ramirez-Ruiz+05; Granot & Ramirez-Ruiz ‘12

Off-Axis Emission from Relativistic Jets



- If SGRB 170817A was observed slightly outside of the sharp-edged jet:

$$\frac{E_{\rm iso,obs}}{E_{\rm iso}(0)} \sim 10^{-3}\left(\frac{\Gamma}{100}\right)^{-4}\left(\frac{\Delta\theta}{0.05}\right)^{-4}$$

$$\sim 10^{-4}\left(\frac{\Gamma}{100}\right)^{-4}\left(\frac{\Delta\theta}{0.1}\right)^{-4}$$

$$\boxed{\Rightarrow E_{\rm pk,obs} = E_{\rm pk,z} \sim 6 - 20\ {\rm MeV}}$$

In the initial hard spike the peak energy would be too hard for a SGRB!!

- Consider a relativistically expanding sharp-edged jet:
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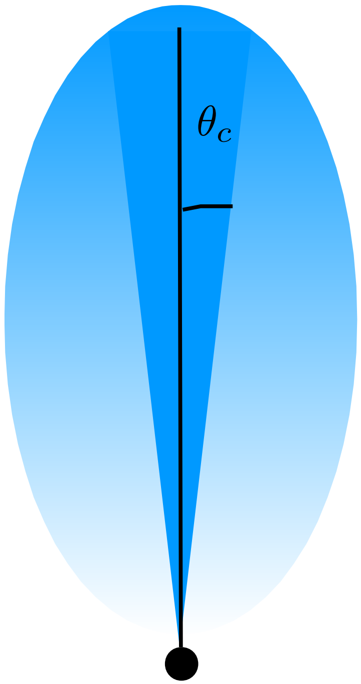
Structured Jets

- Structured jets may be modeled as e.g. having a uniform core and non-uniform wings outside of the initial jet aperture:

$$\frac{dE(\theta)}{d\Omega} = \begin{cases} E_c & 0 \leq \theta \leq \theta_c \\ E_c \left(\frac{\theta}{\theta_c}\right)^{-a} & \theta_c \leq \theta \leq \theta_j \end{cases}$$

$$\Gamma(\theta) = \begin{cases} \Gamma_c & 0 \leq \theta \leq \theta_c \\ \Gamma_c \left(\frac{\theta}{\theta_c}\right)^{-b} & \theta_c \leq \theta \leq \theta_j \end{cases}$$

(Rossi+02, Zhang & Meszaros ‘02)

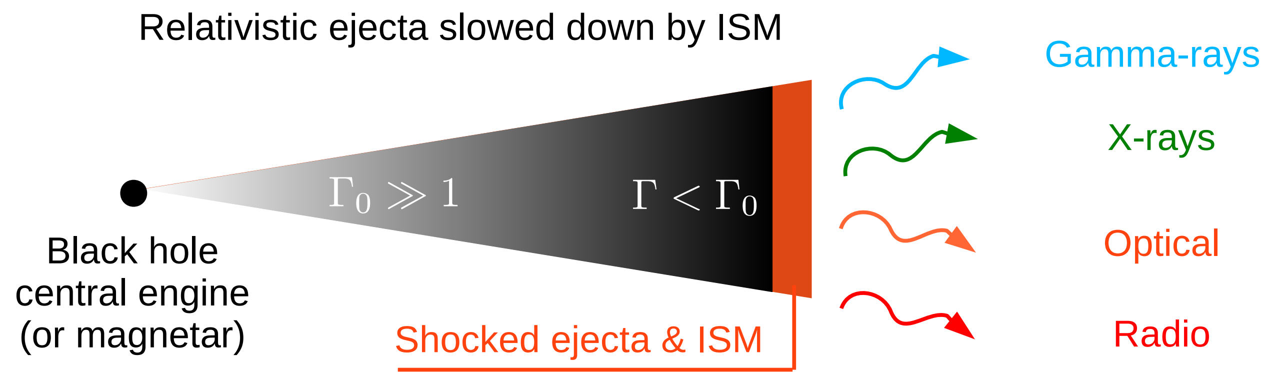


- It allows emission from material in the wings of the jet to be beamed into larger solid angles with $\theta_{\rm obs} > {\rm few} \times \theta_c$ which can be observed if the jet core is beamed away.

- The emission from the wings will also contribute to the early time sharply rising afterglow lightcurve (LC), which may lead to a shallow rise of the LC to the peak.

Afterglow Emission

Afterglow Theory



Relativistic ejecta slowed down by ISM

$\Gamma_0 \gg 1$

$\Gamma < \Gamma_0$

Black hole
central engine
(or magnetar)

Shocked ejecta & ISM

Gamma-rays

X-rays

Optical

Radio

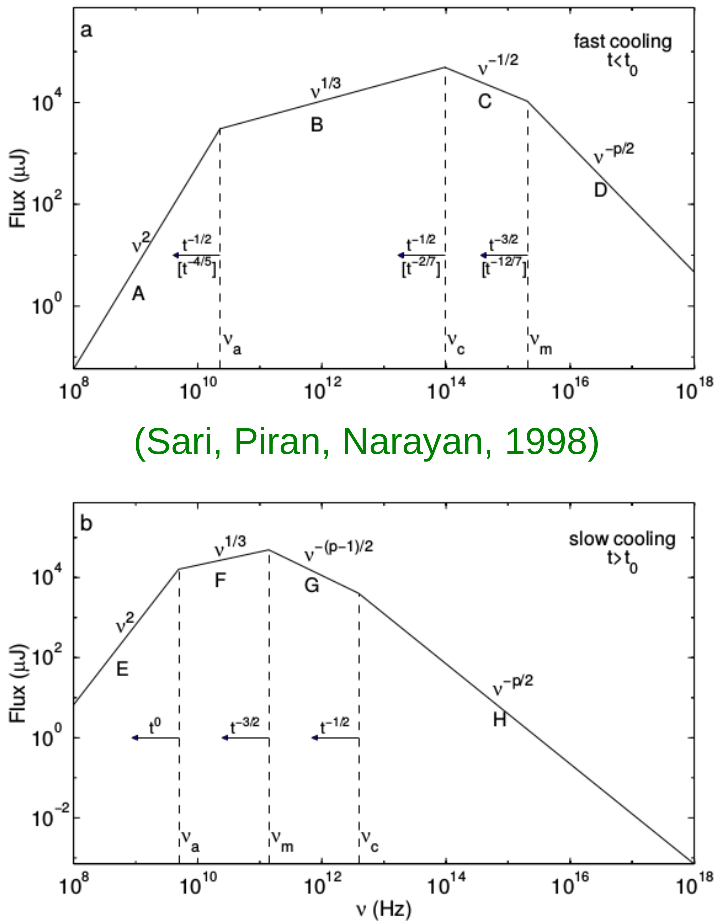
- The afterglow emission is produced when the ultra-relativistic ejecta is slowed down by the inertia of the swept up ISM.

- This gives rise to forward and reverse shocks that heat up both the swept up ISM and ejecta, respectively.

- The shock-heated relativistically hot electrons have a power-law distriubtion:

$$n_e(\gamma_e) \propto \gamma_e^{-p} \qquad \gamma_m \le \gamma_e \le \gamma_M$$

- They cool by emitting synchrotron radiation in the shock amplified magnetic field.



(Sari, Piran, Narayan, 1998)

Off-Axis Afterglow Lightcurves

Numerical Modeling

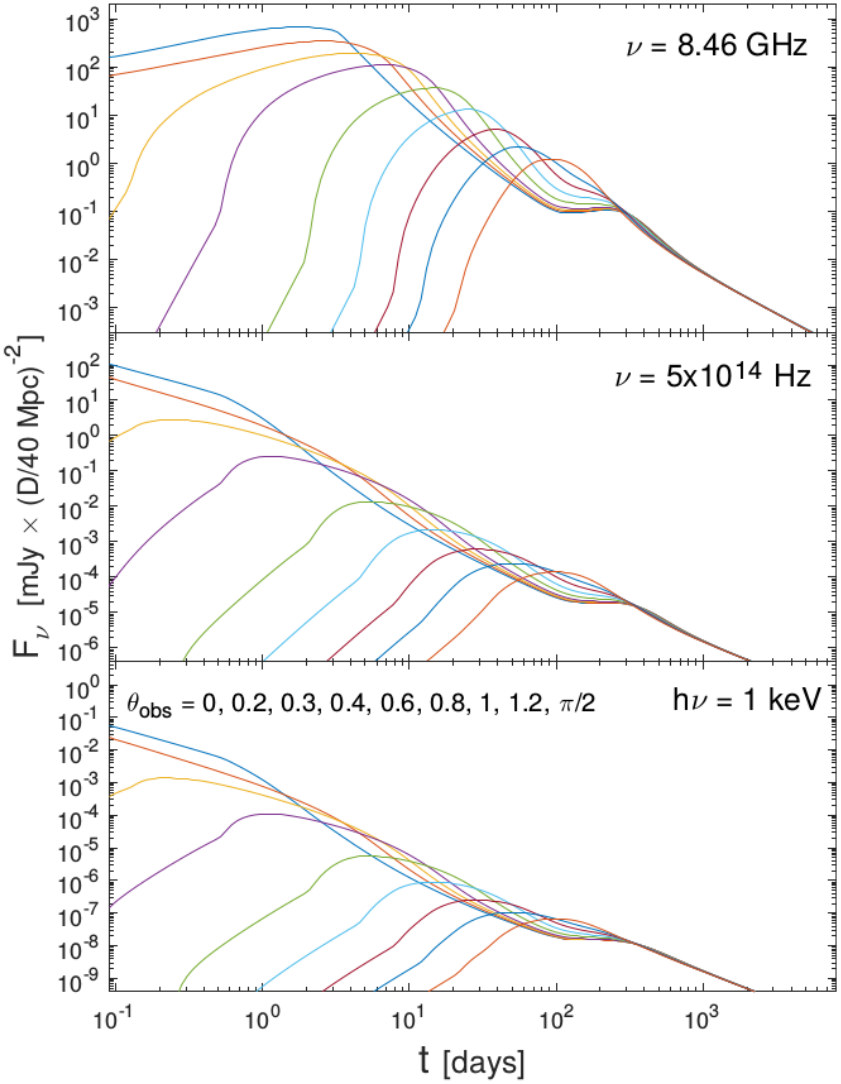
- We obtained realistic afterglow lightcurves from 2D relativistic MHD simulations:
  - Initial condition: Blandford-McKee self-similar conical wedge

$$E = 10^{49}\ \mathrm{erg} \qquad n = 1\ \mathrm{cm}^{-3} \qquad \theta_0 = 0.2$$

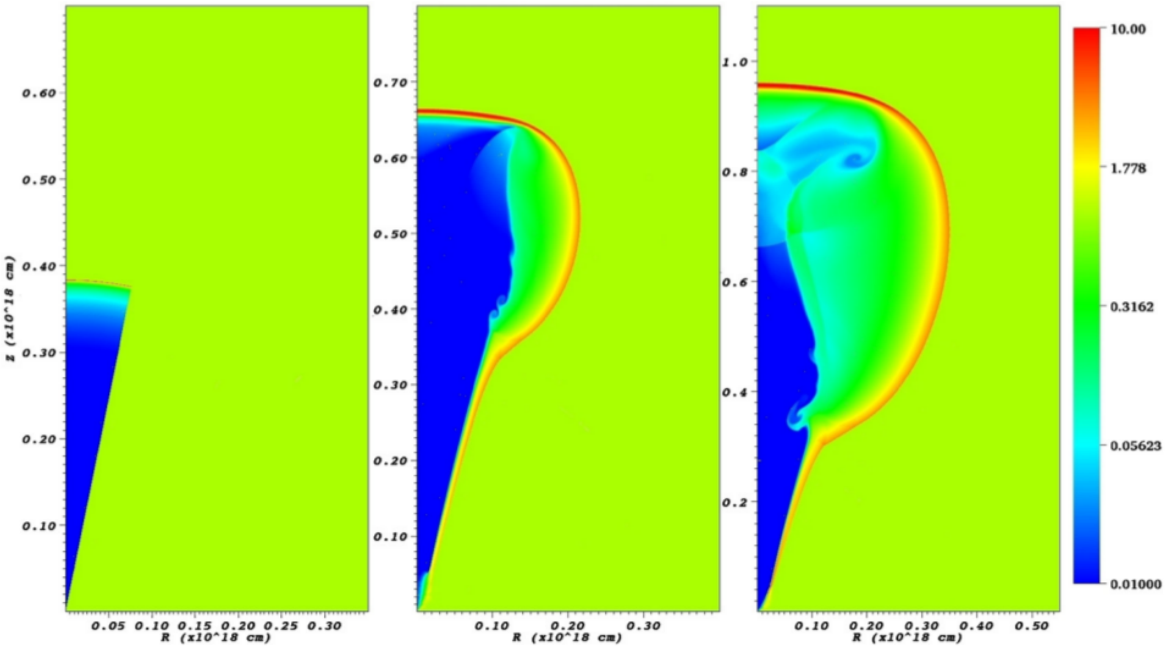
  - Lightcurves were obtained using shock microphysical parameters:

$$\epsilon_e = \epsilon_B = 0.1 \qquad p = 2.5$$

(Granot, Gill, Guetta, De Colle 2017)



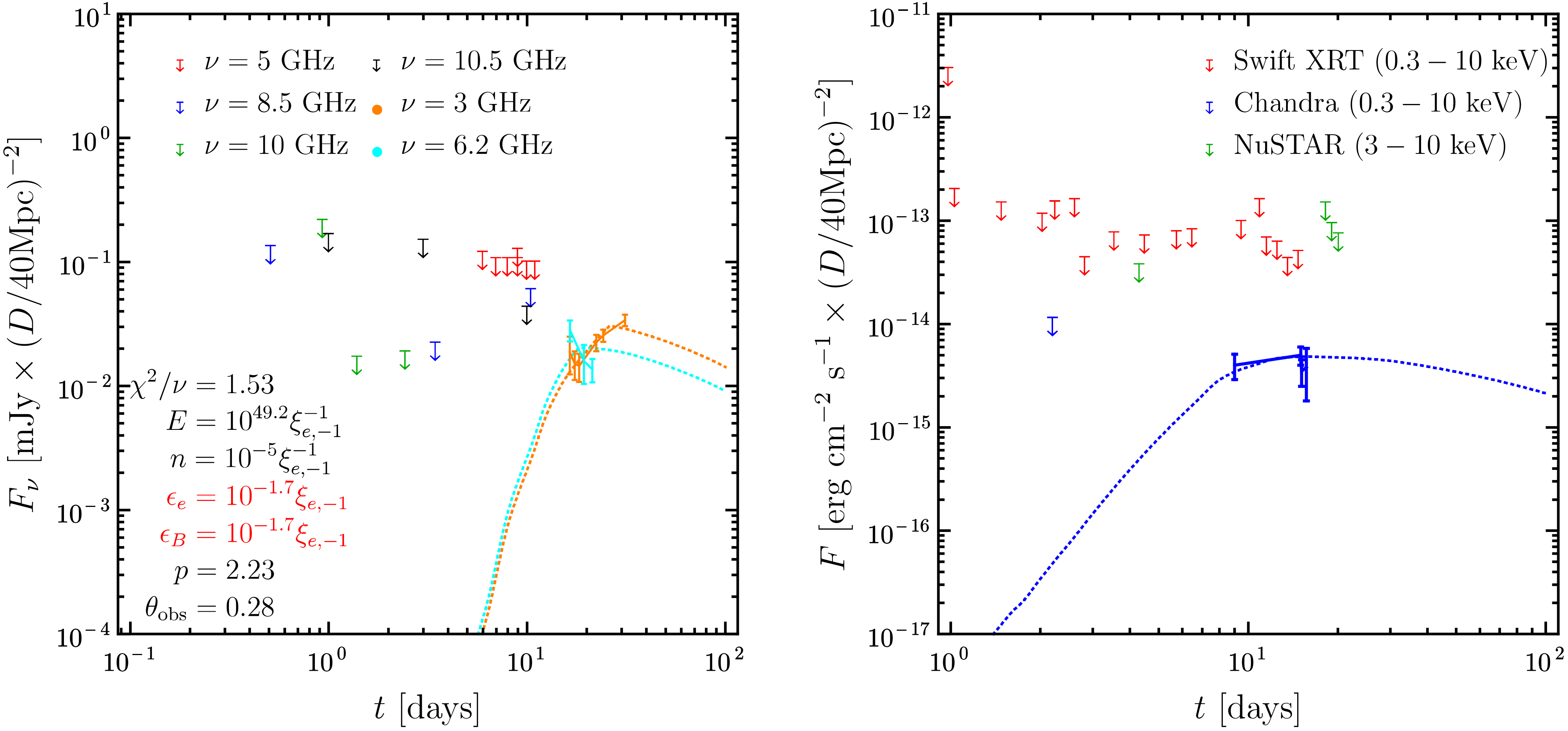
(De Colle+2012a,b)



Comparison with Observations

- We carried out least-squares fits of the numerical lightcurves to the initial X-ray and radio detections.
- Six parameters are needed for afterglow modeling: $E,\ n,\ \epsilon_e,\ \epsilon_B,\ p,\ \theta_{\rm obs}$
- We fix two (shown in red) and find the best-fit values for the other four.

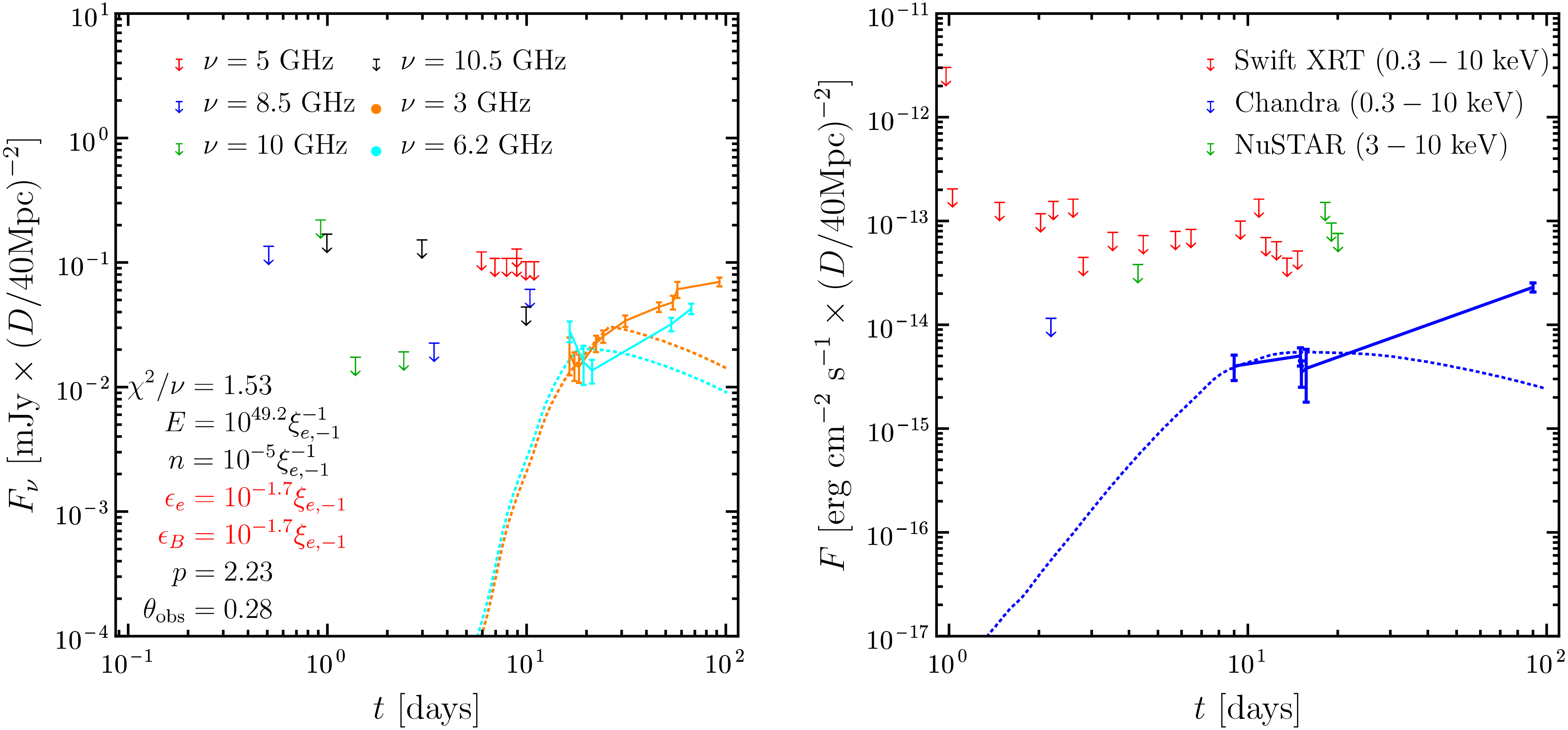
(Granot, Gill, Guetta, De Colle 2017)



Recent Late-Time X-ray and Radio Data

- Both X-ray and radio observations show late-time brightening – this makes off-axis emission from a homogeneous jet model very challenging.
- Mooley, Nakar, et al. 2017 have explained this rise due to emission from a mildly relativistic quasi-spherical cocoon.

(Granot, Gill, Guetta, De Colle 2017)



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- Mooley, Nakar, et al. 2017 have explained this rise due to emission from a mildly relativistic quasi-spherical cocoon.

- Lazzati et al. 2017 very recently have shown that off-axis emission from a structured jet can explain these observations.

  - The emission still does arise from a mildly relativistic cocoon around the core, but it doesn’t have to be a quasi-spherical cocoon.

- Are both of these explanations the one and the same?

- Further late-time radio observations and detailed modeling of structured jets can shed some more light on this issue.

Thanks!