# Binary neutron star mergers - insights from multi-messenger observations


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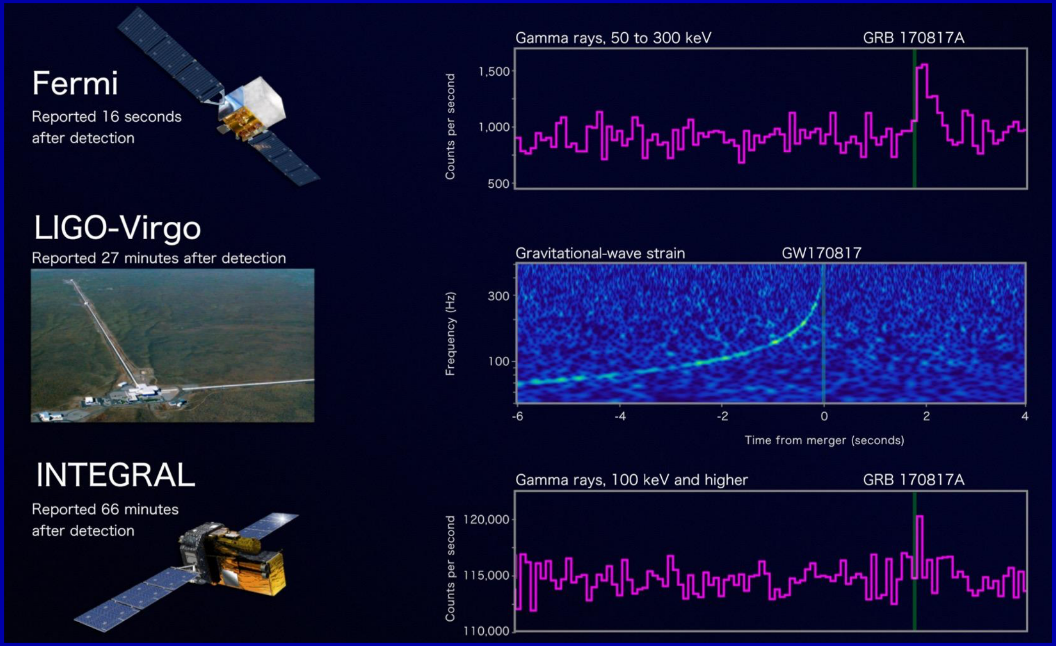
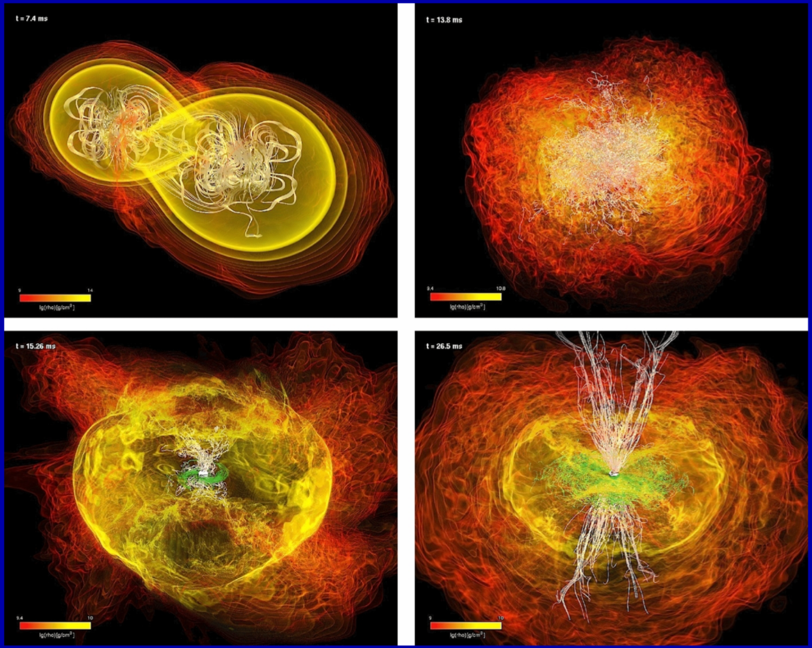


**Growing Black Holes: Accretion and Mergers, 18.5.22, Kathmandu**

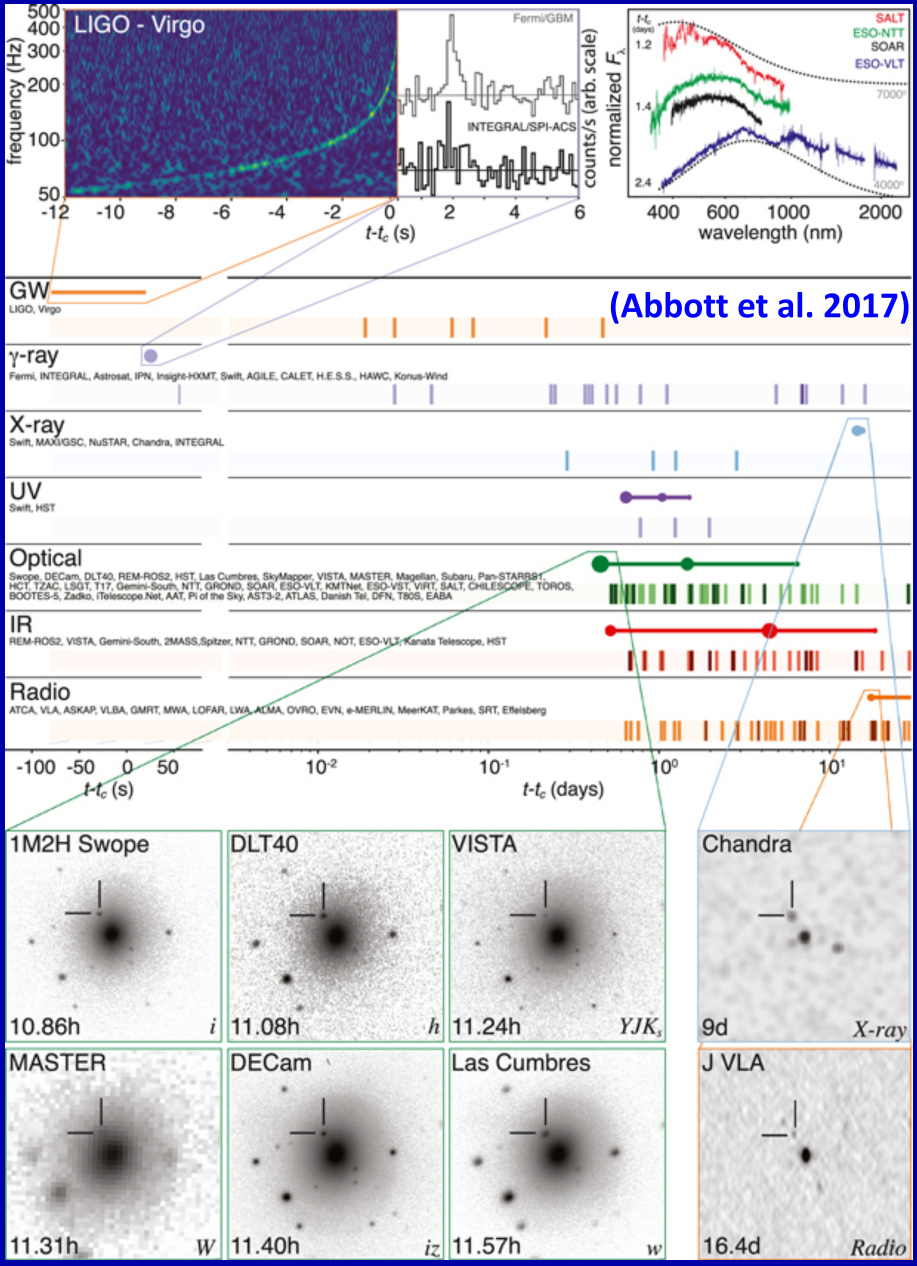
# Outline of the Talk:

- The **Extraordinary** event **GW170817/GRB170817A**
  - **GW speed** $\approx$ c, **r-process element production, nuclear EoS**
- **The merger remnant: Black Hole or a massive NS?**
- The **afterglow** emission:
  - **Early flux rise – two main options: r vs. θ structure of outflow**
  - **Breaking the degeneracy: lightcurves? Images, Polarization**
  - **Later observations ⇒ the θ structure dominates (off-axis jet)**
  - Radio polarization U.L. constrains the **shock-produced B-field**
- Predicted **off-axis lightcurves** from **structured jets**
- **Conclusions**

# GW 170817 / GRB 170817A: D ≈ 40 Mpc

- **First GW detection** of a **NS-NS merger**
- **First electromagnetic counterpart** to a GW event
  - The **short GRB** 170817A (very under-luminous, 1.74 s γ-GW delay; ⇒ $|v_{GW}/c - 1| \lesssim 4 \cdot 10^{-16}$ )
  - First clear-cut **kilonova**, in IR to UV, lasting a few weeks ⇒ NS-NS mergers may dominate the r-process nucleosynthesis
  - X-ray to radio **afterglow**
- **First direct association of a sGRB & NS-NS merger**

(Eichler+ 1989; Narayan+ 1992)



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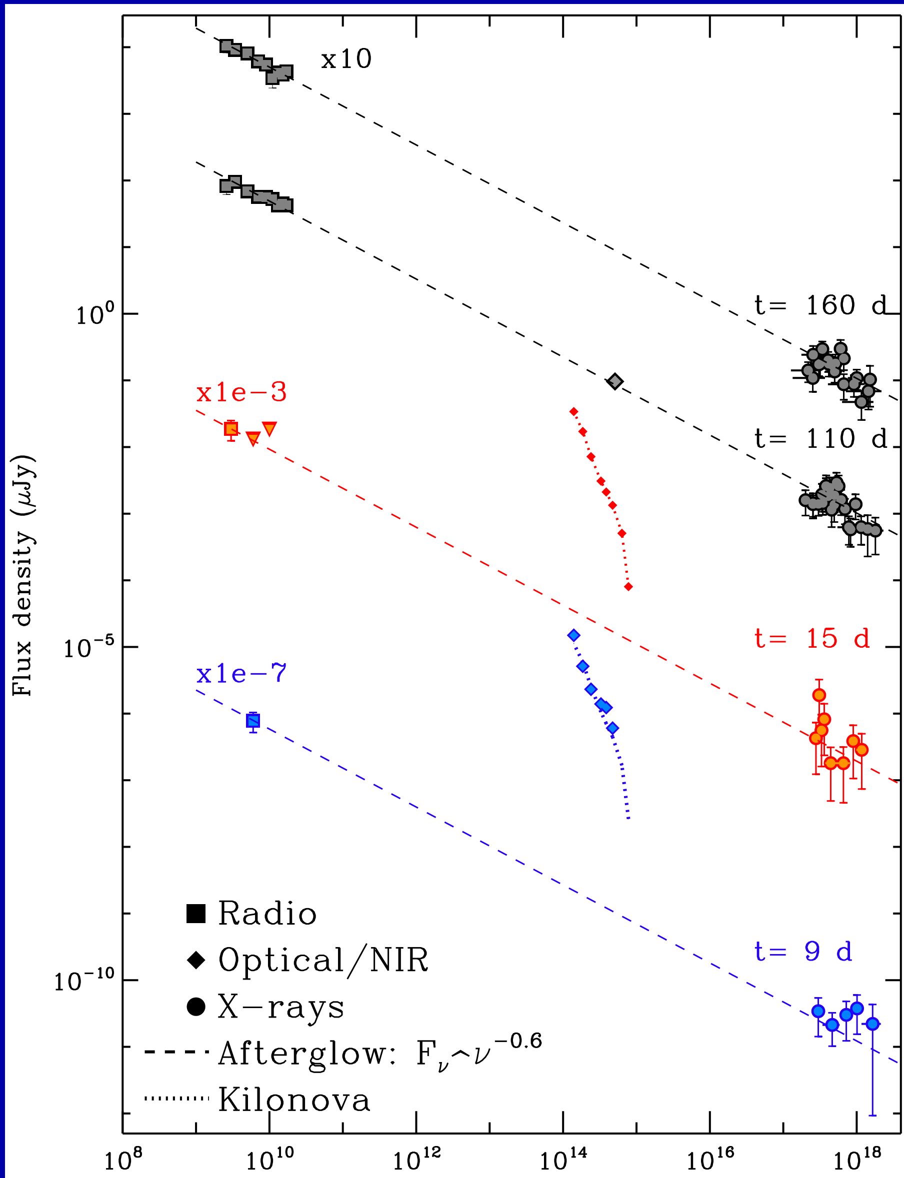
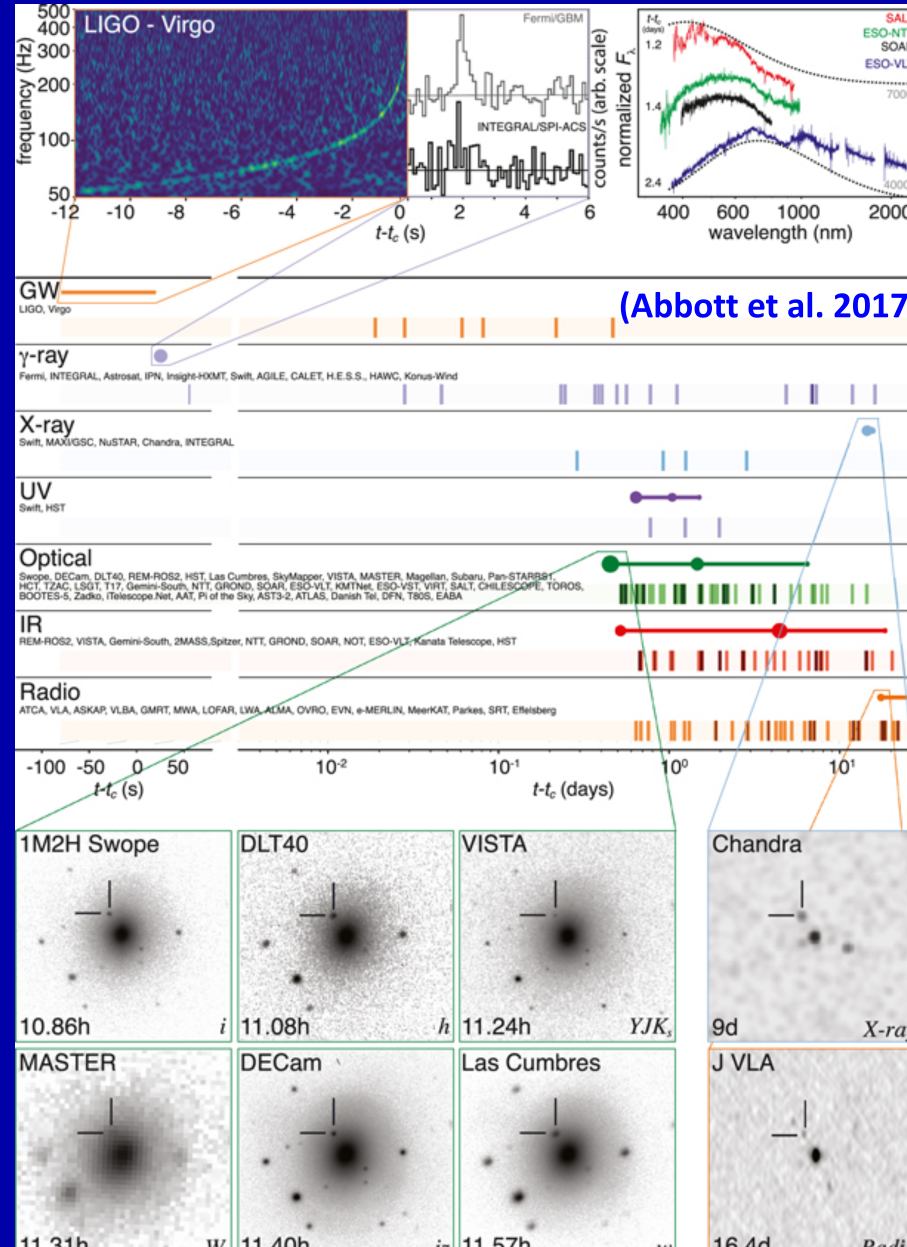


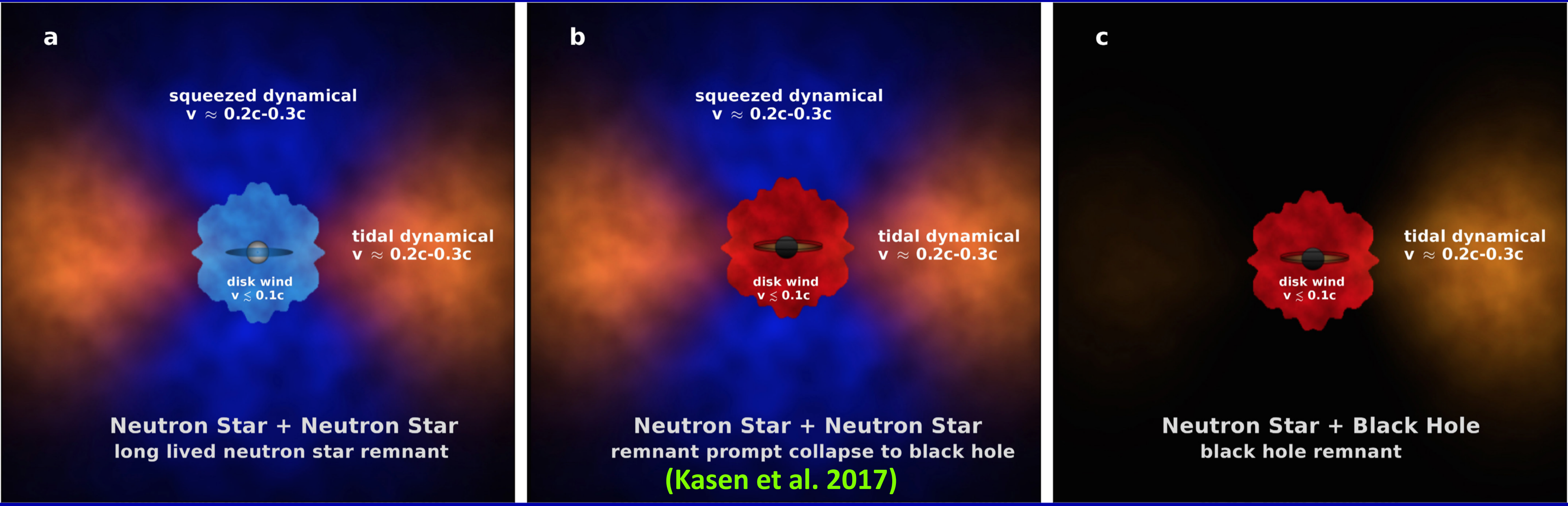

(Margutti et al. 2018)




(Abbott et al. 2017)

# GW 170817: the associated **kilonova**

- The observations require **two components:**
  - blue/fast, lanthanide-poor **$M_{ej}$ ~1–2% $M_{\odot}$, $v_{ej}$ ~0.2–0.3c**
  - red/slow, lanthanide-rich **$M_{ej}$ ~3–5% $M_{\odot}$, $v_{ej}$ ~0.05–0.2c**
- It produced a lot of heavy elements, showing that NS-NS mergers may dominate cosmic r-process nucleosynthesis



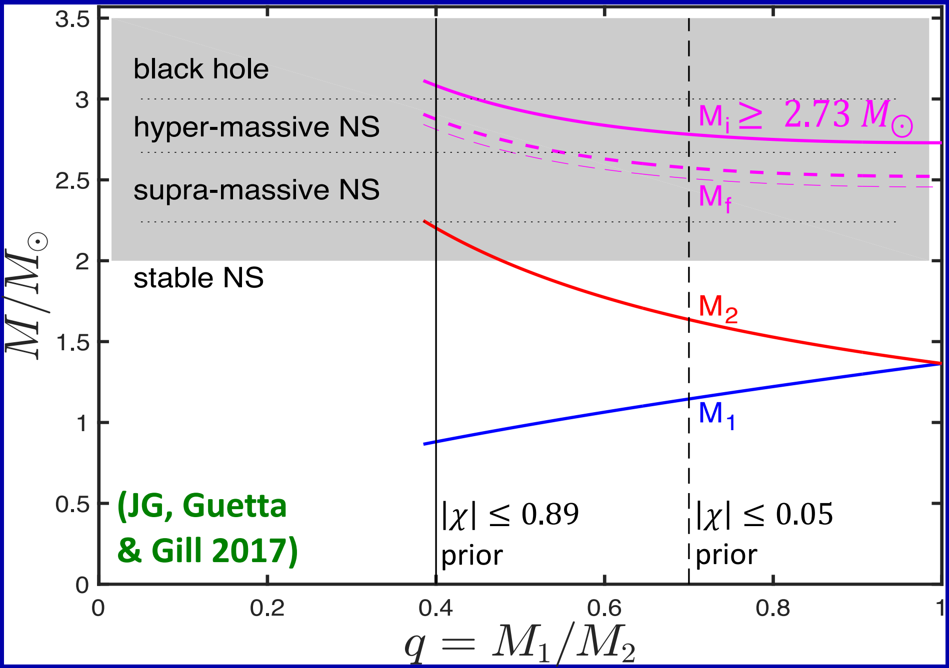
(Kasen et al. 2017)

# GW170817: the type of **remnant** (JG, Guetta & Gill 2017)

- $M_{1,2}$ = pre-merger NS $M_{\rm gravitational}$

post-merger total mass: $M_{\rm i} = M_1 + M_2$

- Final mass $M_{\rm f} \approx 0.93 M_{\rm i}$ due to:
  - GW & neutrino energy losses
  - Mass ejection during the merger




Chirp mass: $\mathcal{M} = \left(\frac{M_1^3 M_2^3}{M_1 + M_2}\right)^{1/5} = 1.188^{+0.004}_{-0.002}\, M_\odot$ **(Abbott+ 2017)**

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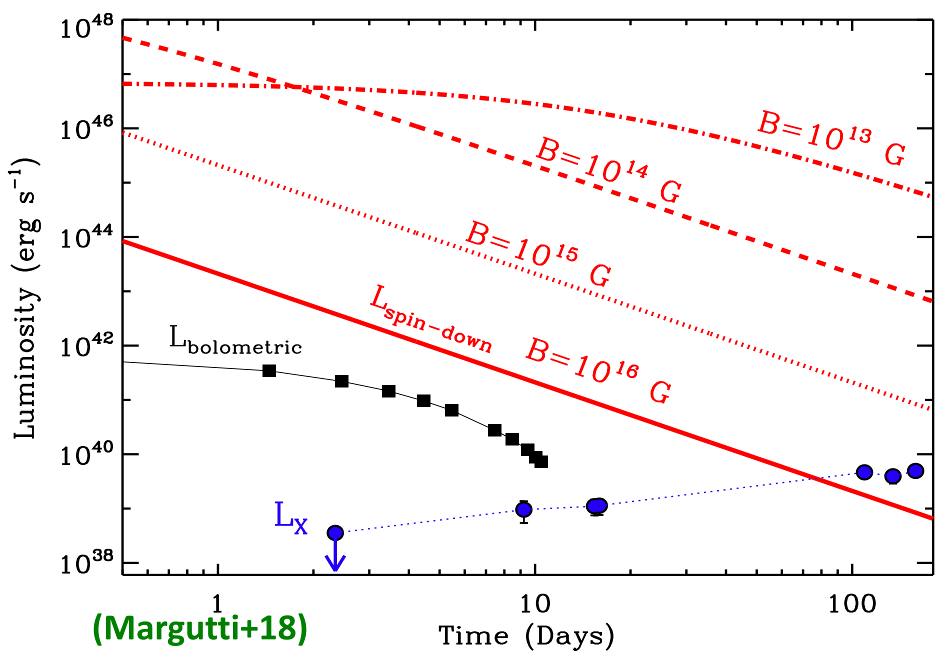
- A stable NS or SMNS $\Rightarrow P_0 \approx 1$ ms

$\Rightarrow E_{\rm rot} \gtrsim 10^{52.5}$ erg, $\tau_{\rm sd} \approx 20 B_{13}^{-2}$ days

$\Rightarrow$ would contradict afterglow obs.

(also what produces the GRB/afterglow?)

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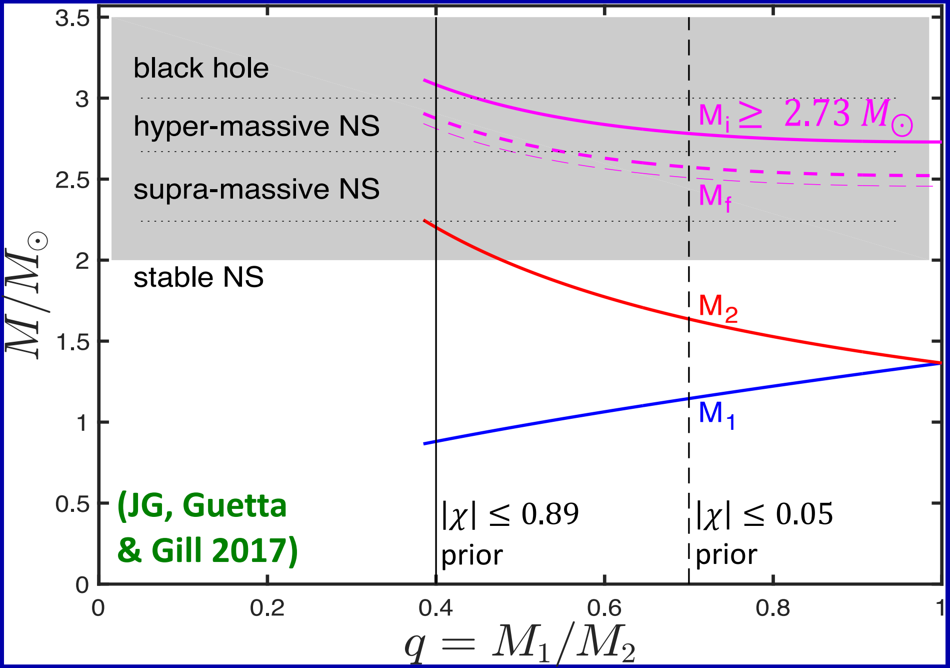


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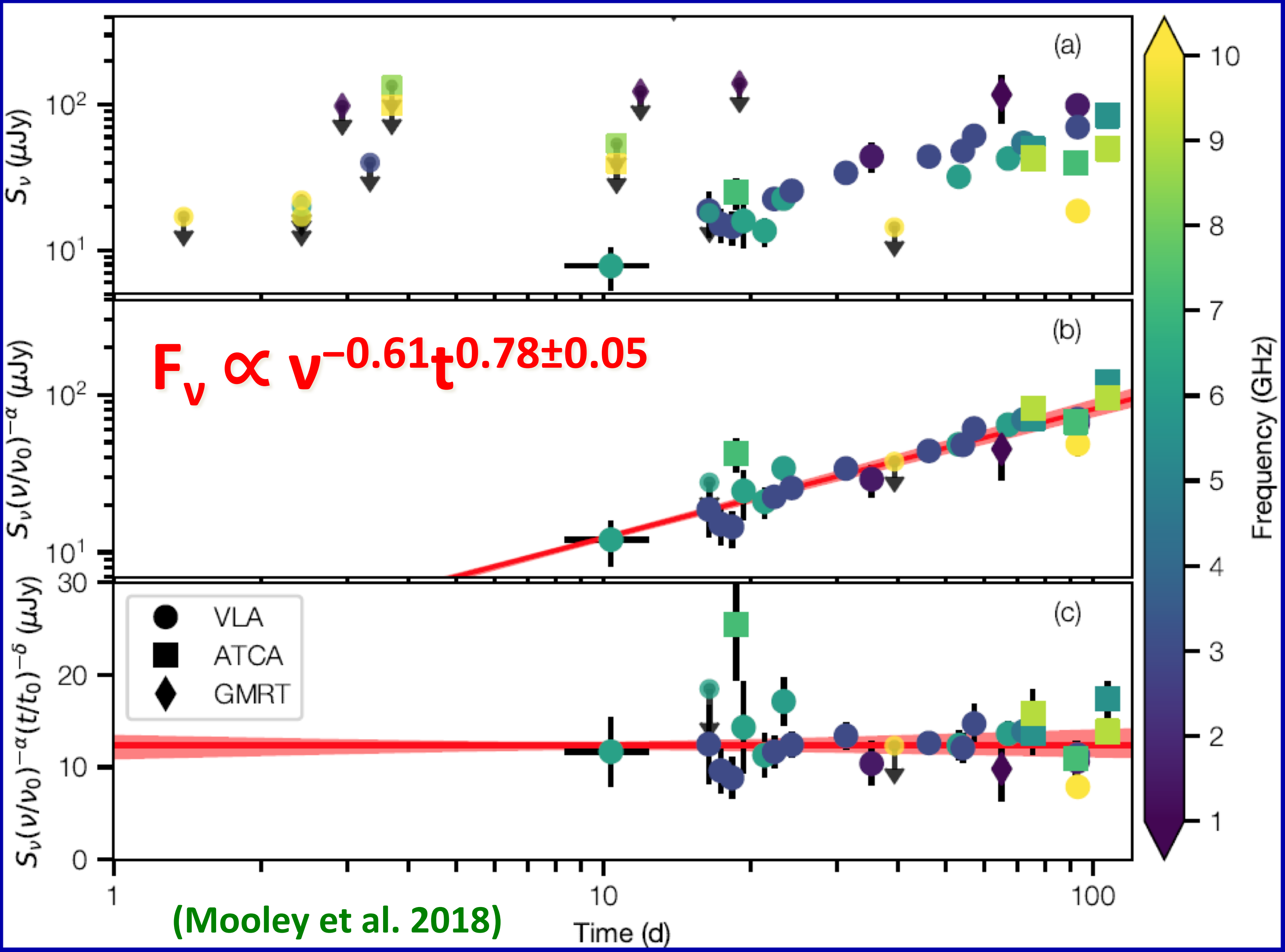
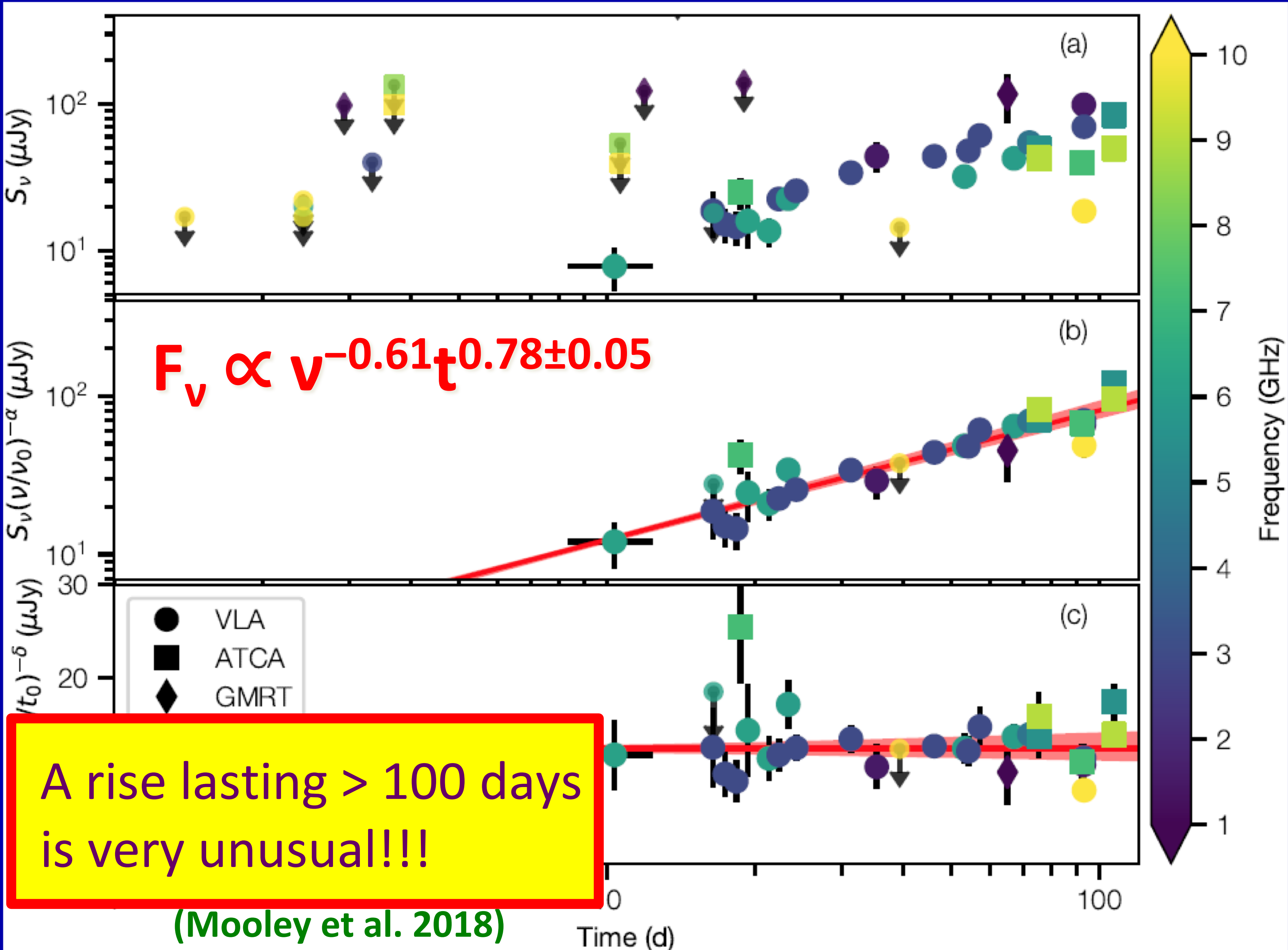
- The argument can be reversed to constrain NS EoS & $M_{\rm TOV} \lesssim 2.17 M_\odot$

(Margalit & Metzger 2017; Rezzolla et al. 2018)

# GRB 170817A: afterglow observations



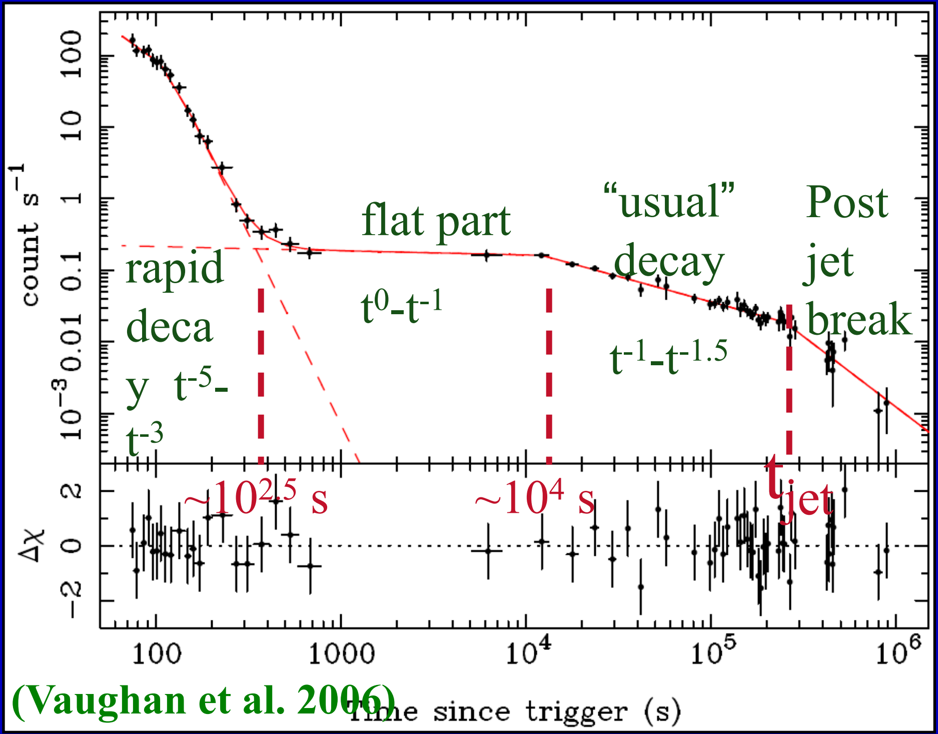
# GRB 170817A: afterglow observations



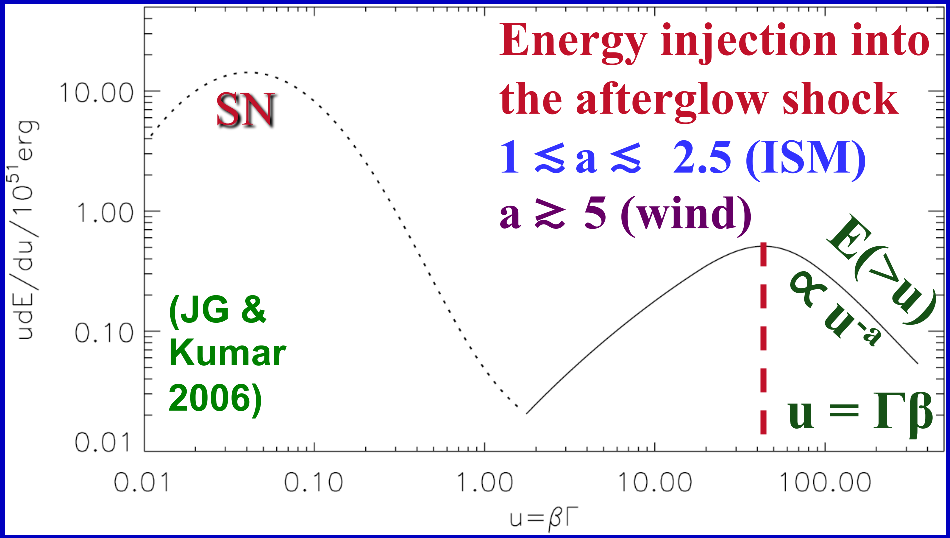

(Mooley et al. 2018)

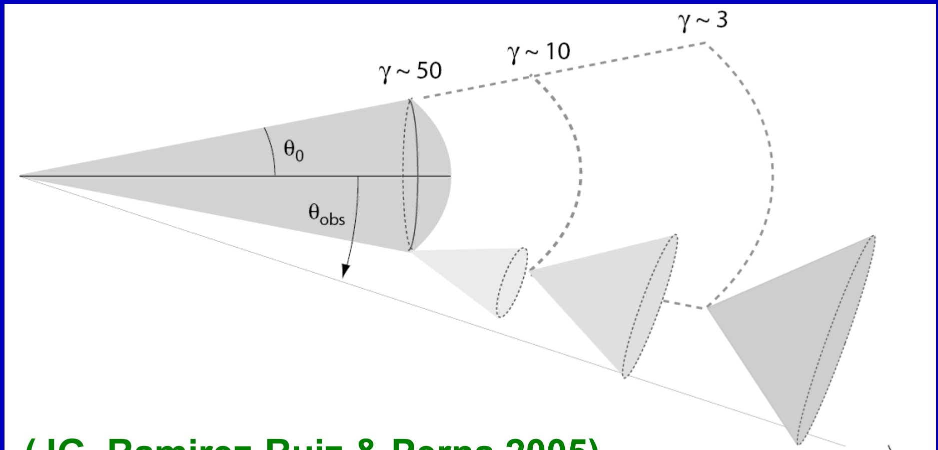
# Analogy to rising $F_\nu$: X-ray Plateaus

- 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)




(Vaughan et al. 2006)




(JG, Ramirez-Ruiz & Perna 2005)

- Viewing angle effects

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- Evolution of shock microphysical parameters (JG, Konigl & Piran 2006)
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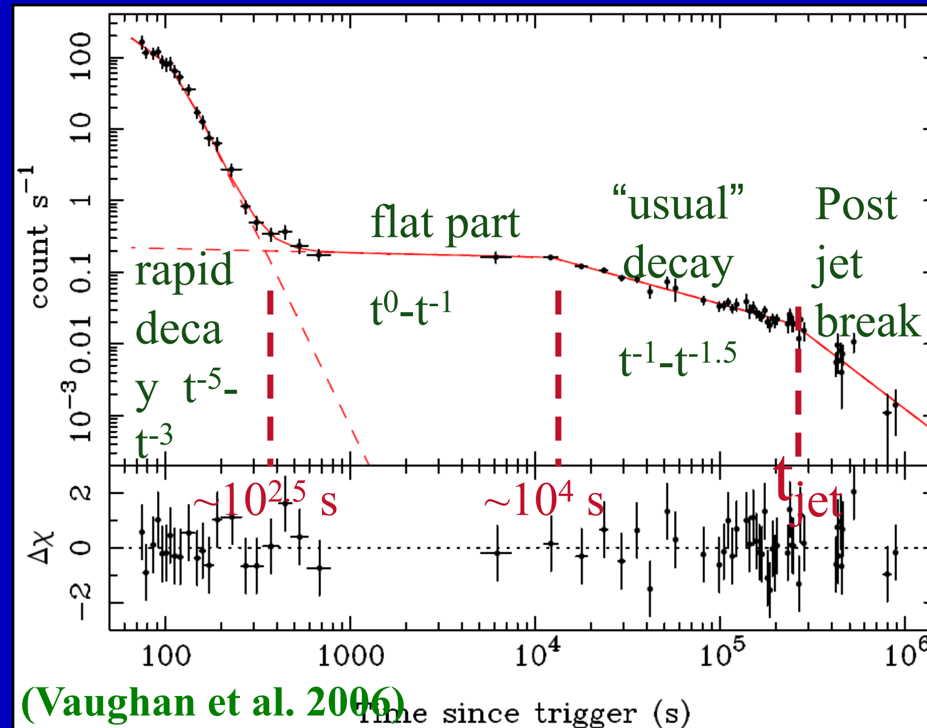
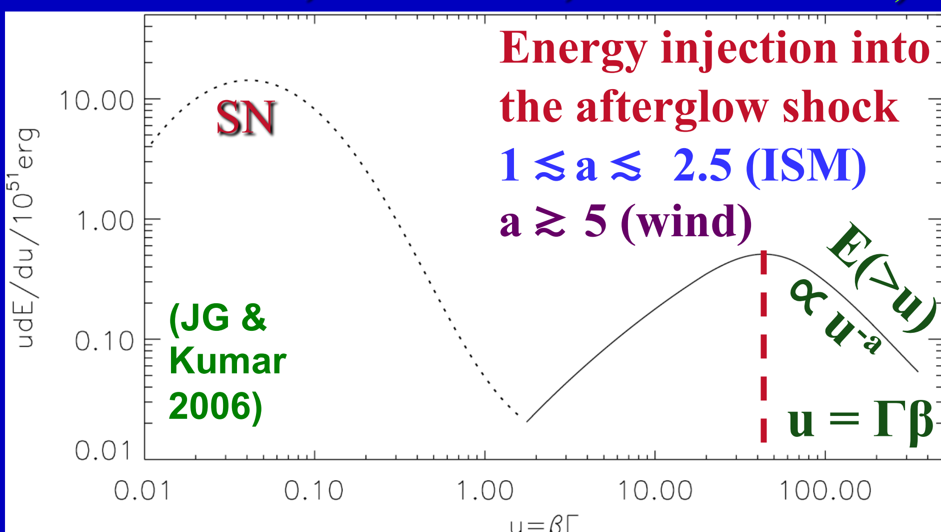
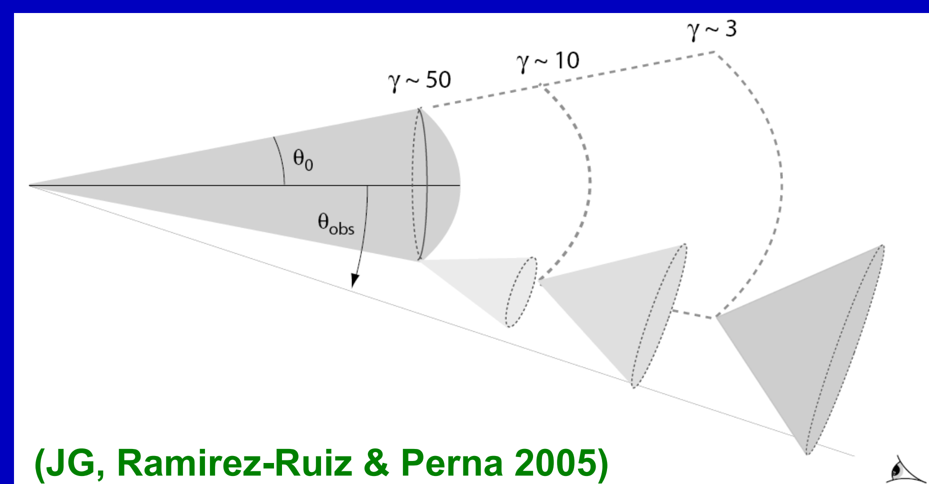



(Vaughan et al. 2006)




(JG & Kumar 2006)

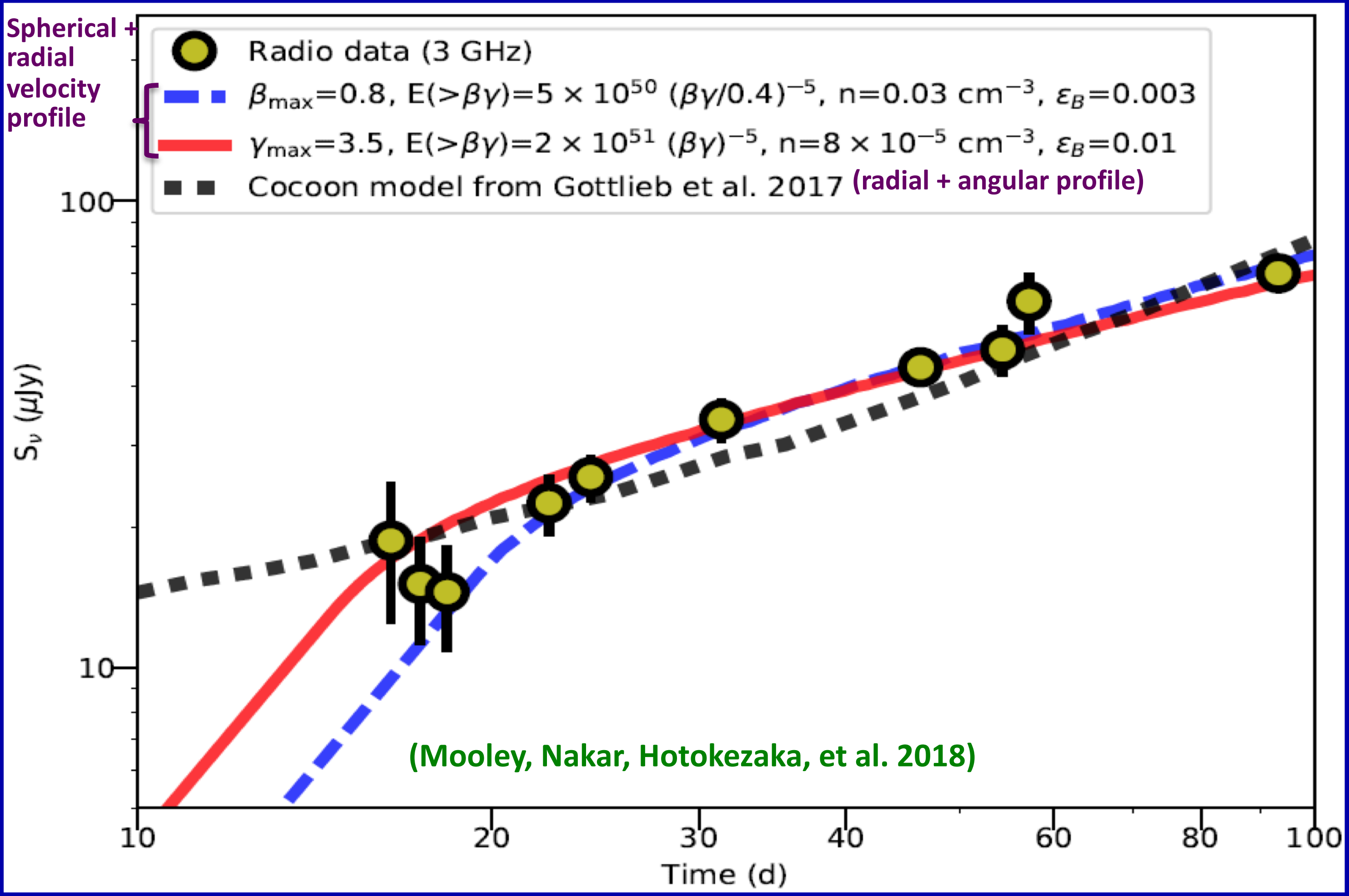



(JG, Ramirez-Ruiz & Perna 2005)

- Viewing angle effects **angular**

# GRB170817 outflow structure: prompt, afterglow

- Cocoon model (Kasliwal+17; Mooley+18; Nakar & Piran 18): **r** & **θ** profile
- Cocoon-driven shock breakout can naturally produce the γ-rays (Kasliwal+17; Gottlieb+17; Bromberg+18; Nakar & Piran 18; Nakar+18)

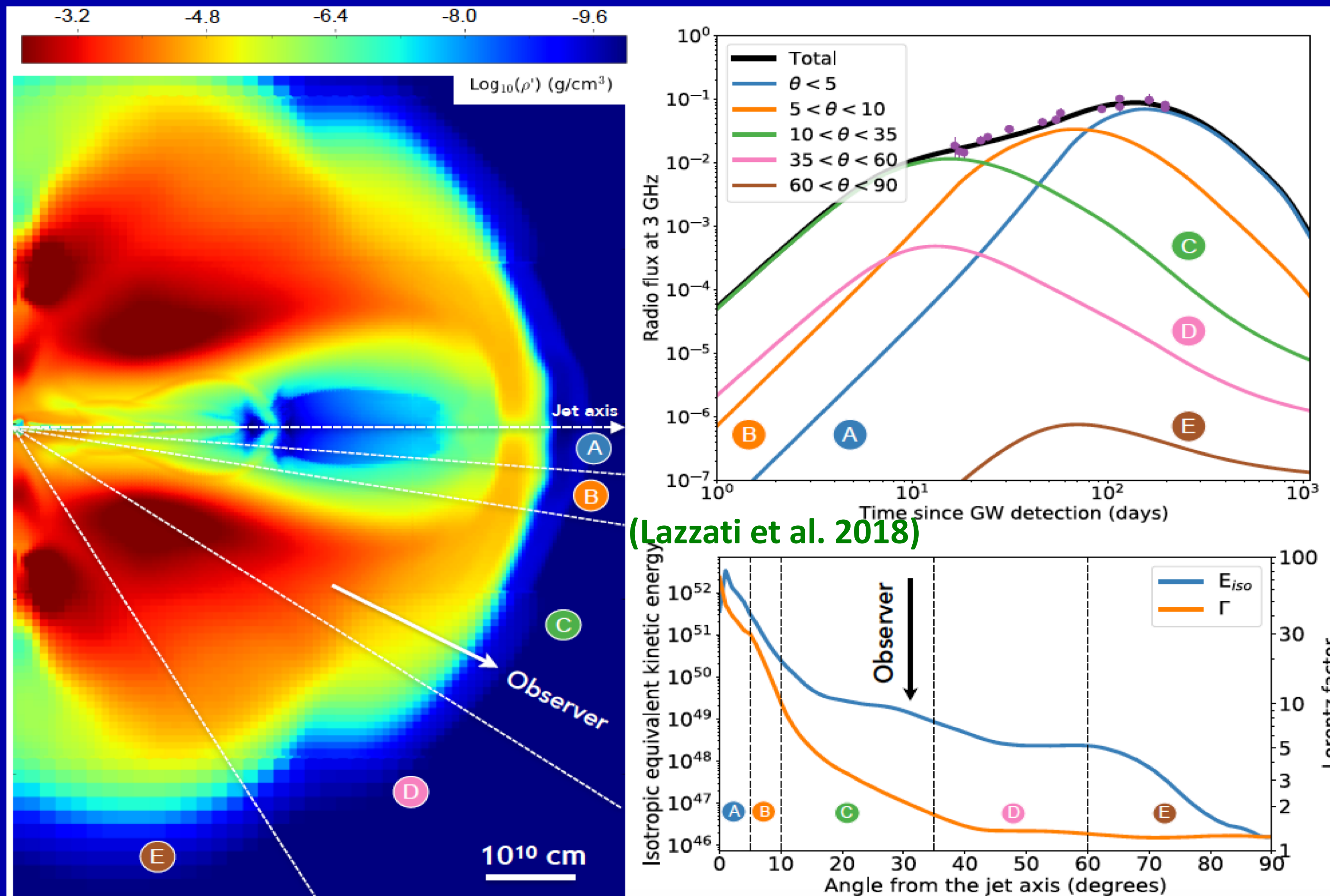


# GRB170817 outflow structure: the afterglow

- **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 θ profile**

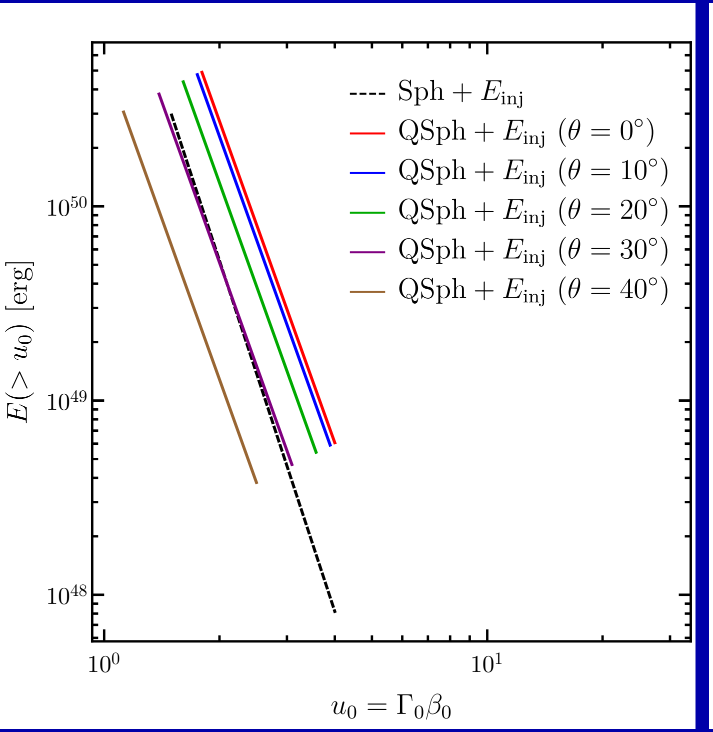


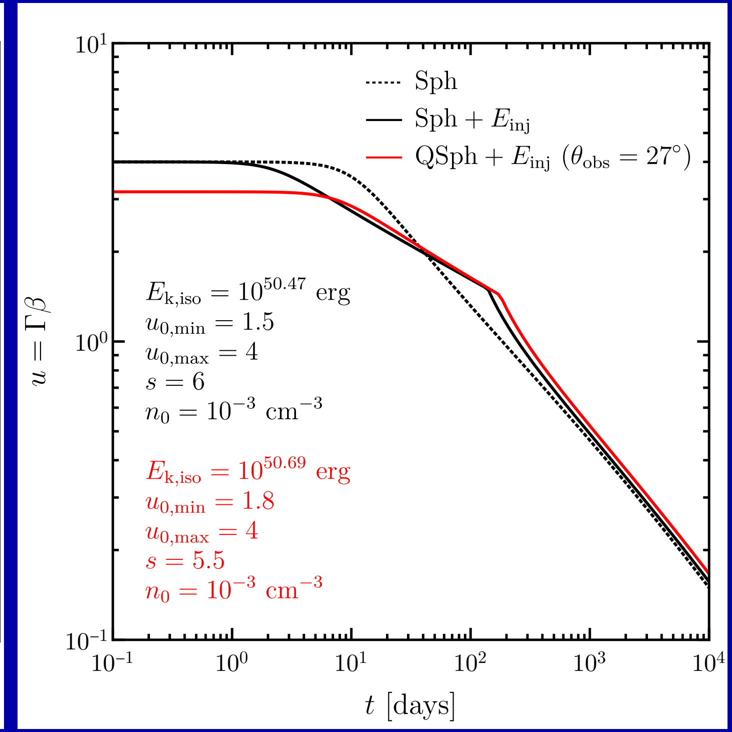

(Lazzati et al. 2018)

# Outflow structure: breaking the degeneracy (Gill & JG 18)

- The lightcurves leave a lot of degeneracy between models
- The degeneracy may be lifted by calculation 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 $E(>u)\propto u^{-s}$, $u_{min,0}=1.8$ $u_{max,0}=4$, $s=5.5$, $\zeta=0.1$

$$\frac{\epsilon(\theta)}{\epsilon_0}=\frac{u_{0,\min}(\theta)}{u_{\min,0}}=\frac{u_{0,\max}(\theta)}{u_{\max,0}}=\frac{\zeta+\cos^2\theta}{\zeta+1}$$



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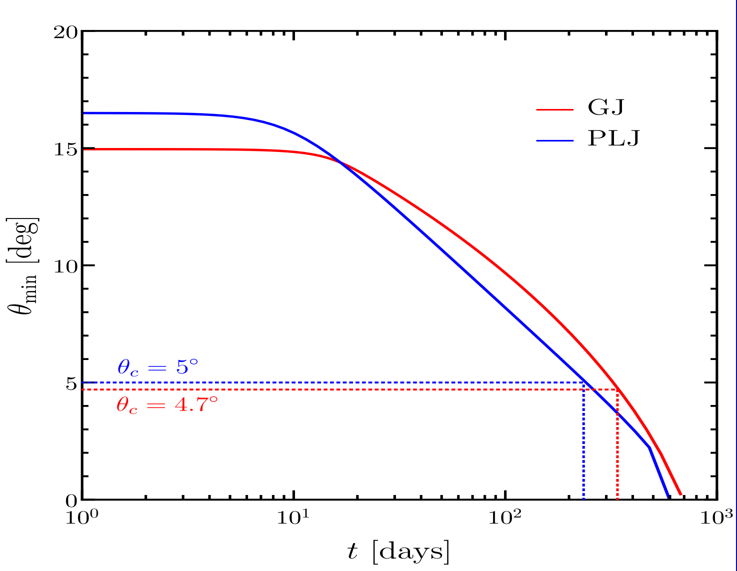
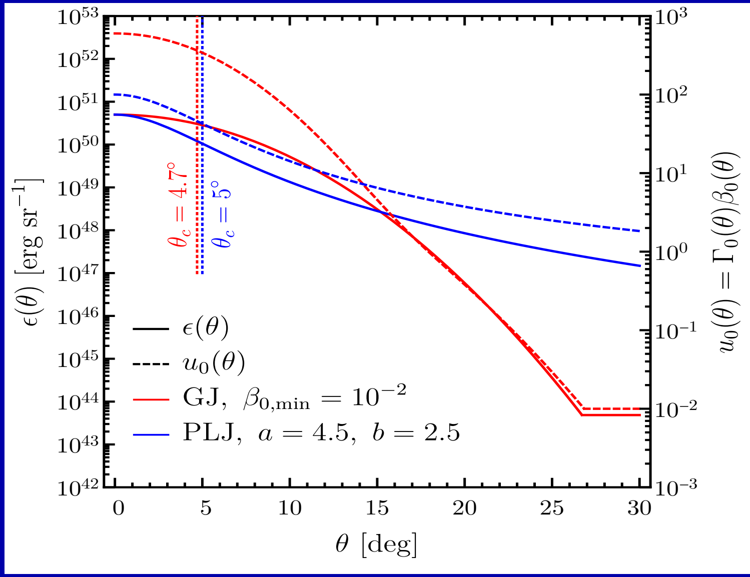
- We considered 4 different models including both main types
  - GJ: Gaussian Jet (in $\varepsilon = dE/d\Omega$, $\Gamma_0 - 1$) $\Gamma_c = 600$, $\theta_c = 4.7°$
  - PLJ: Power-Law Jet; $\varepsilon = \varepsilon_c \Theta^{-a}$, $\Gamma_0 - 1 = (\Gamma_c - 1)\Theta^{-b}$, $\Theta = [1+(\theta/\theta_c)^2]^{1/2}$ $\Gamma_c = 100$, $\theta_c = 5°$, $a = 4.5$, $b = 2.5$
- As there is a lot of freedom we fixed: $p = 2.16$, $\varepsilon_B = n_0 = 10^{-3}$, $\theta_{obs} = 27°$

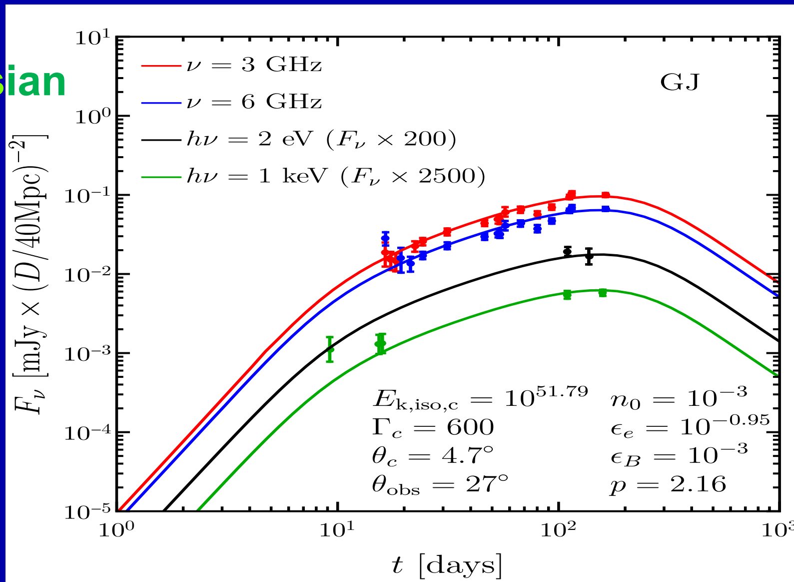


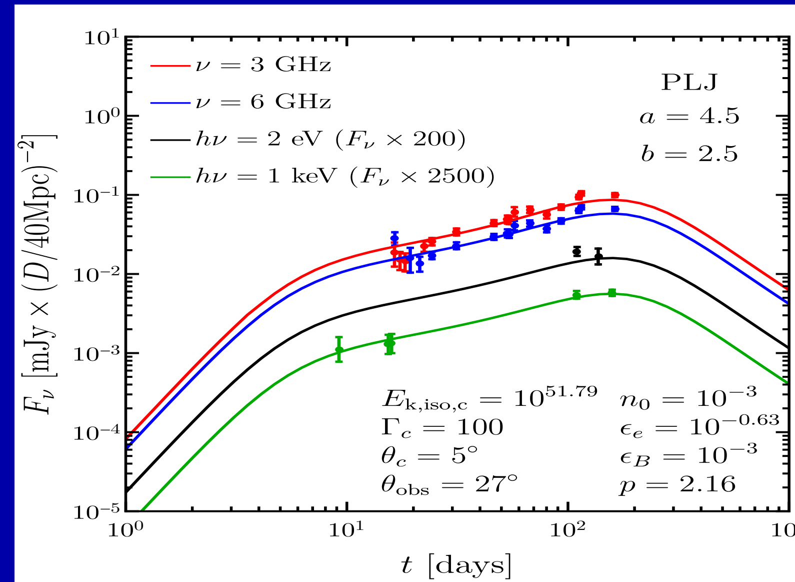



# The outflow structure: breaking the degeneracy

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

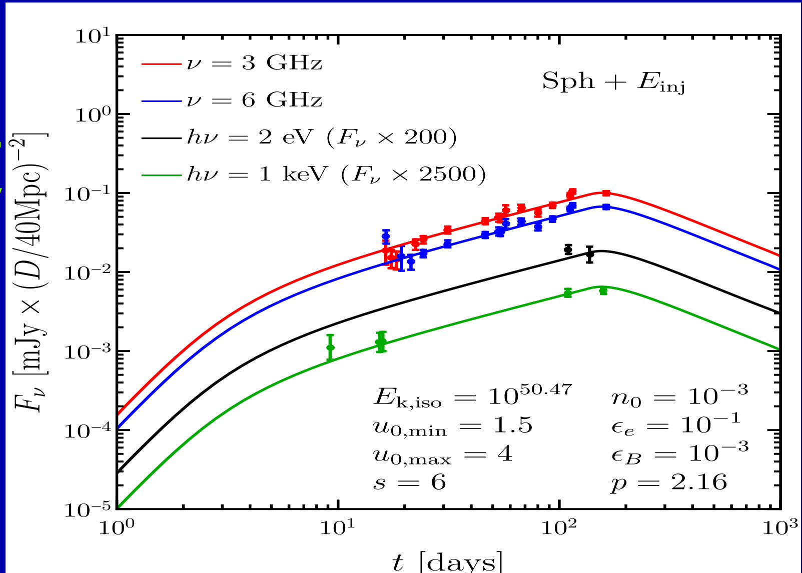
**Gaussian Jet**

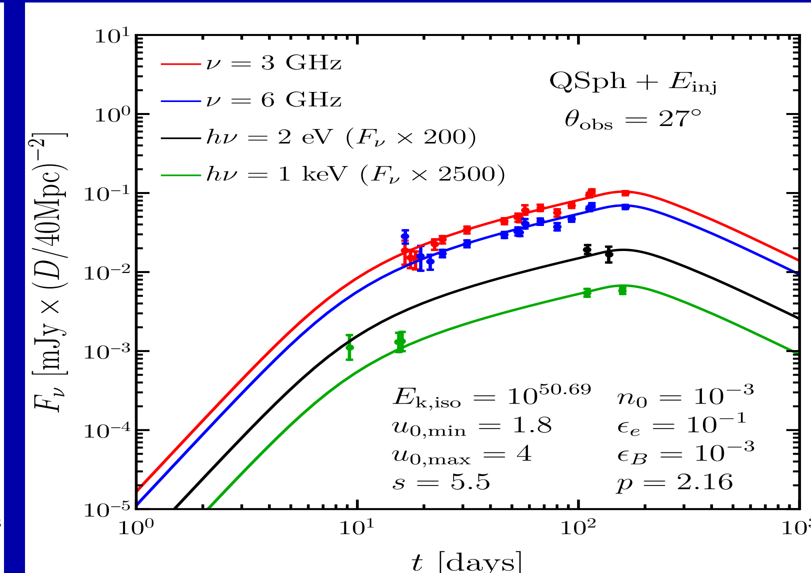



**Power Law Jet**

**Spher. + Energy Inject.**



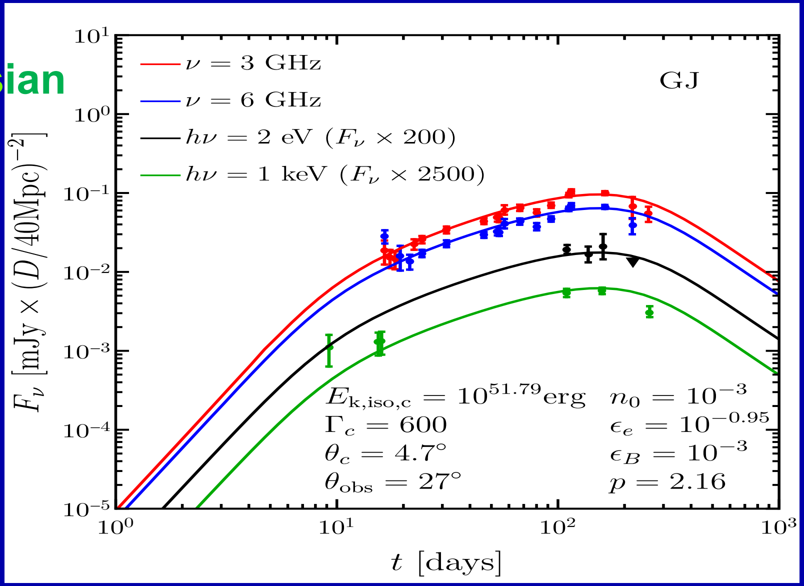



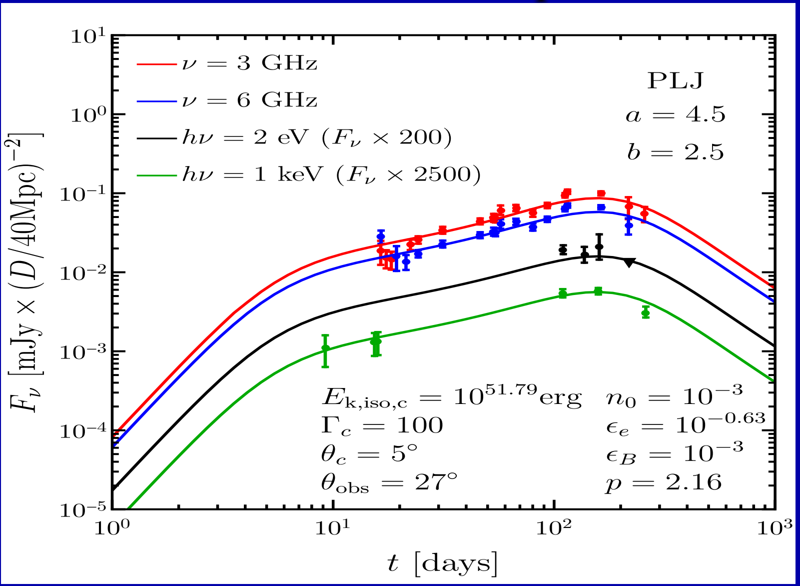

**Quasi Spher. + Energy Inject.**

# The outflow structure: breaking the degeneracy

- New data that came out established a peak at $t_p \sim 150$ days

**Gaussian Jet**

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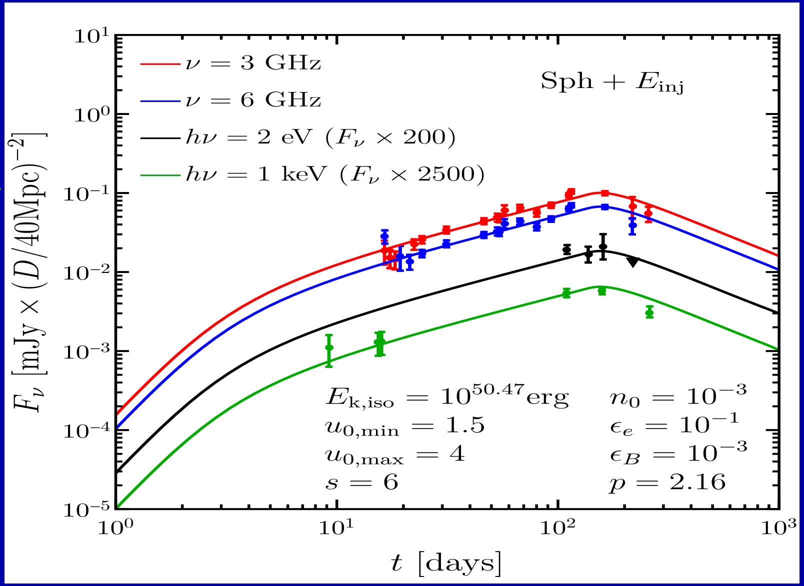
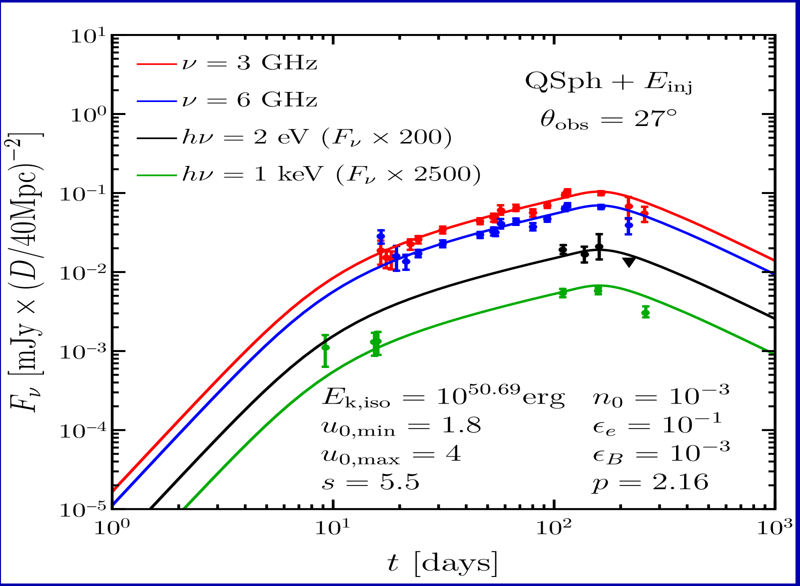


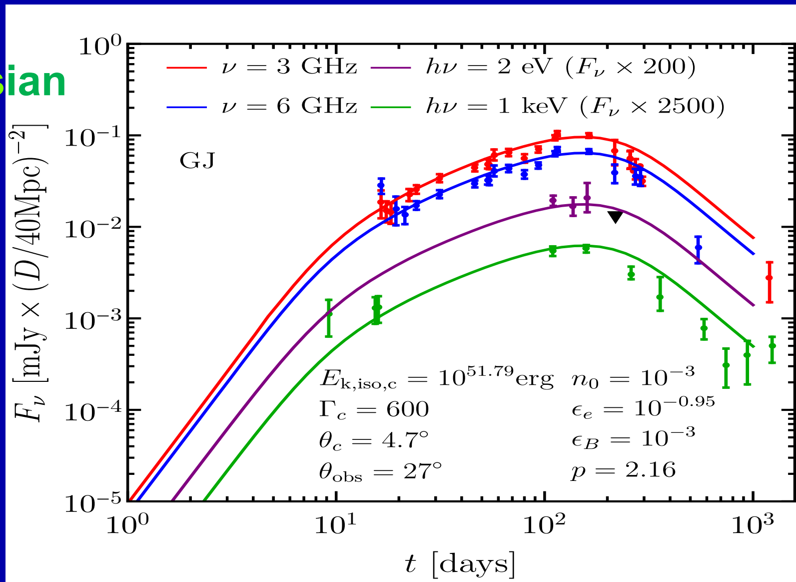




**Quasi Spher. + Energy Inject.**

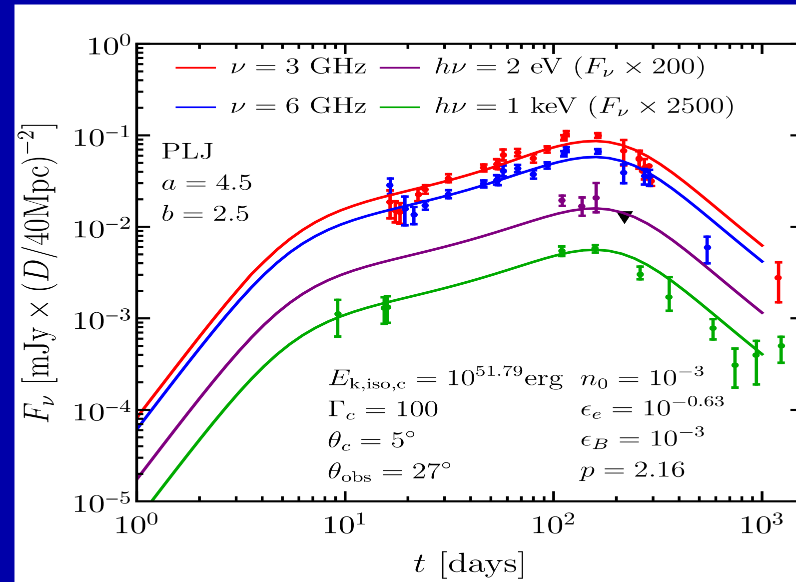
# The outflow structure: breaking the degeneracy

- The jet models decay faster (closer to post-peak data $\sim t^{-2.2}$)

Gaussian Jet




Power Law Jet

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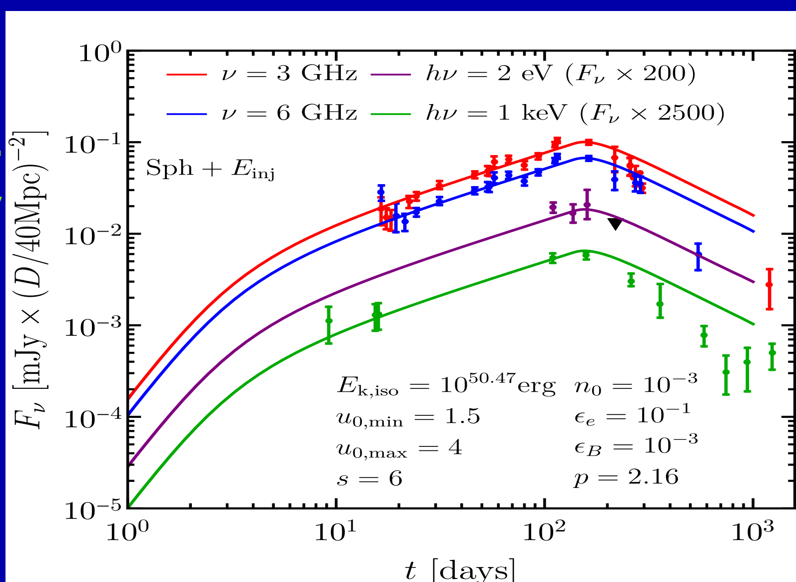


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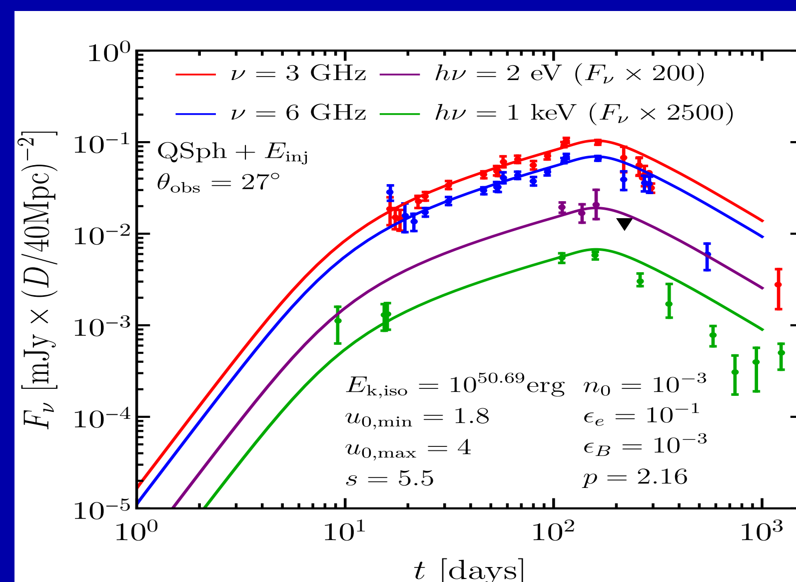
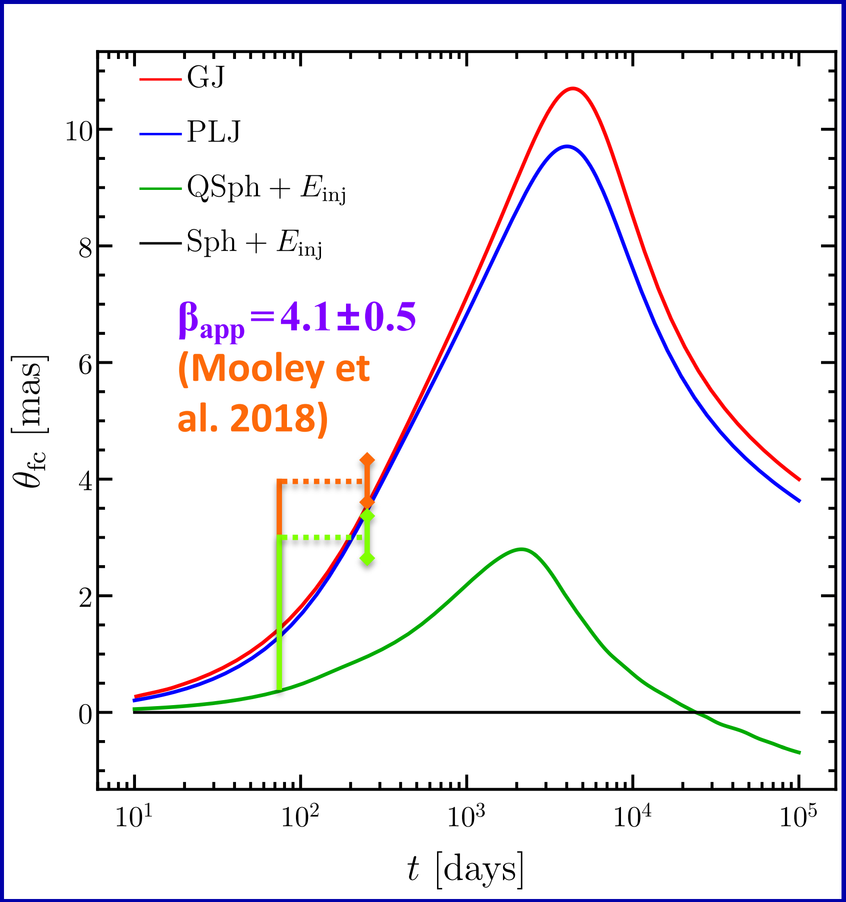
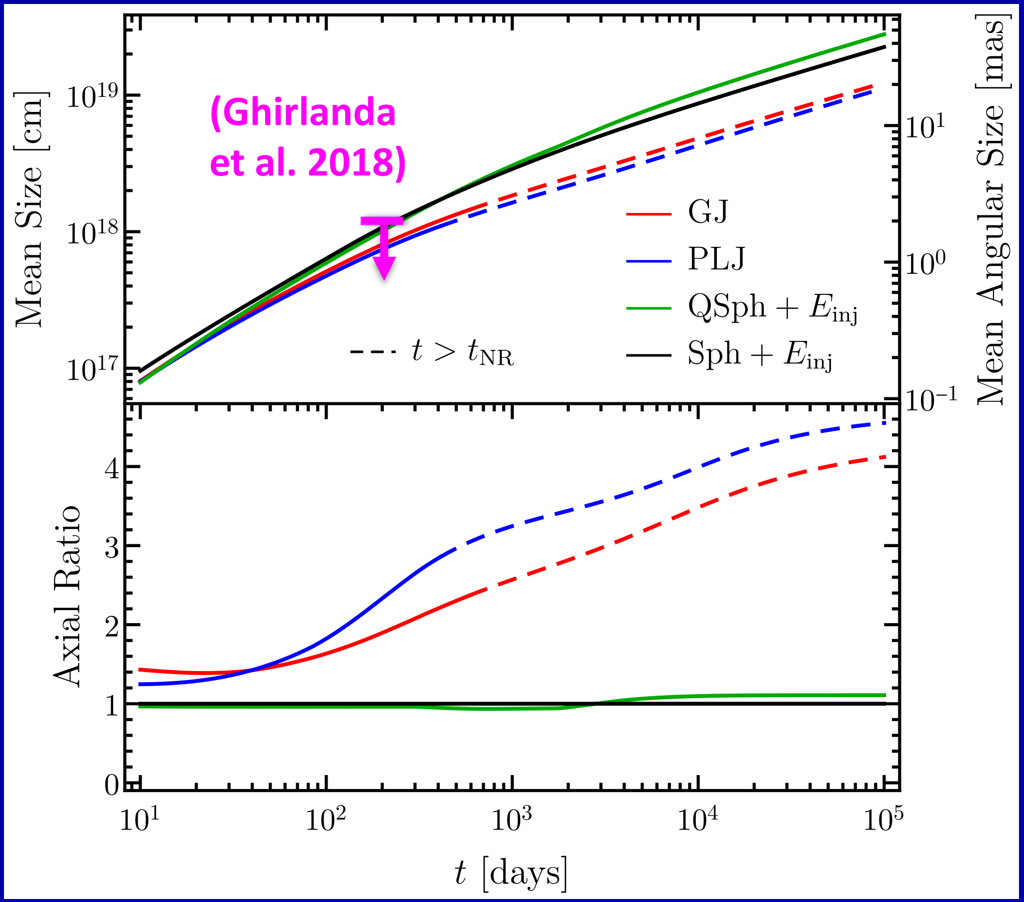


# Afterglow Images: flux centroid, size, shape

- 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



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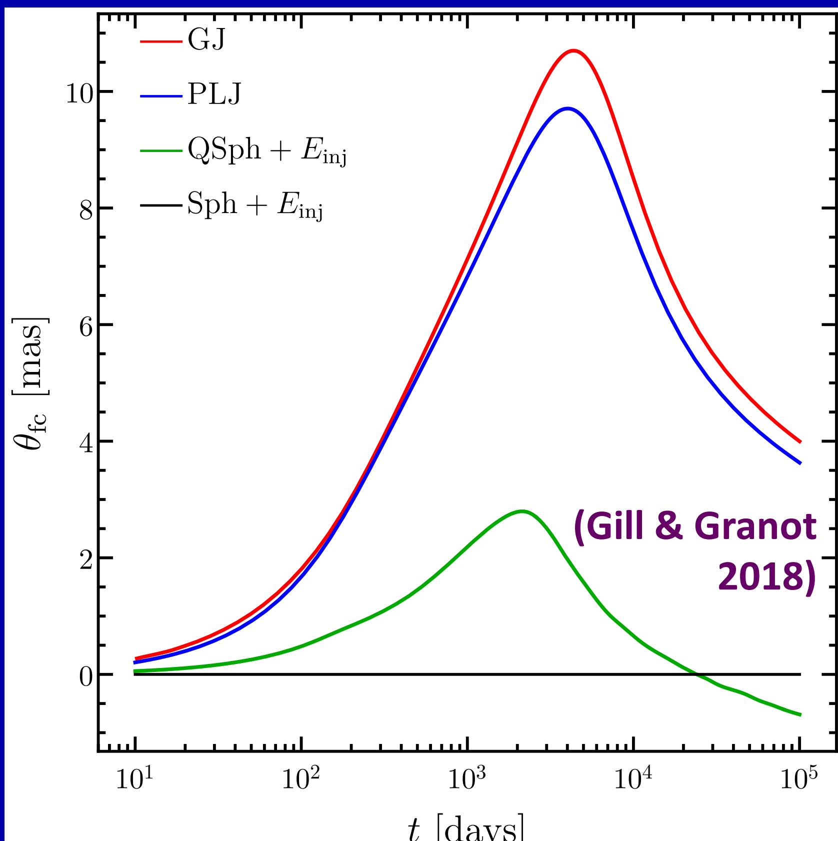
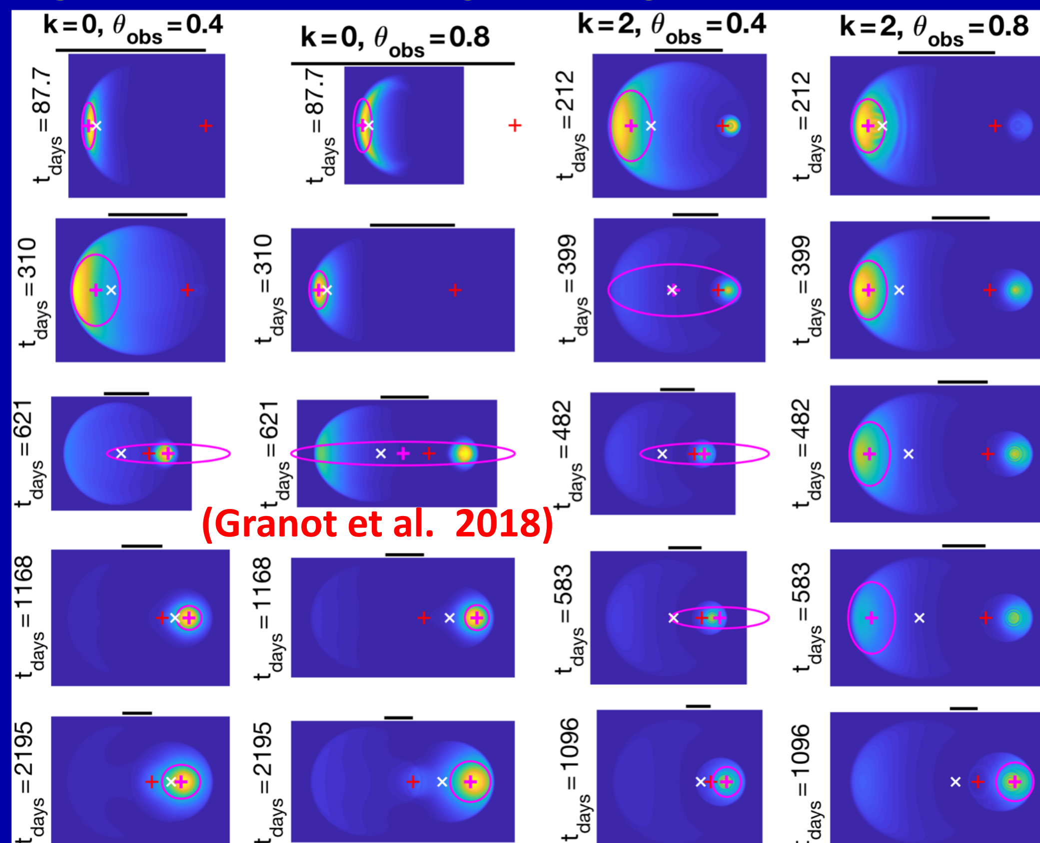
**Radio flux centroid motion: semi-analytic**

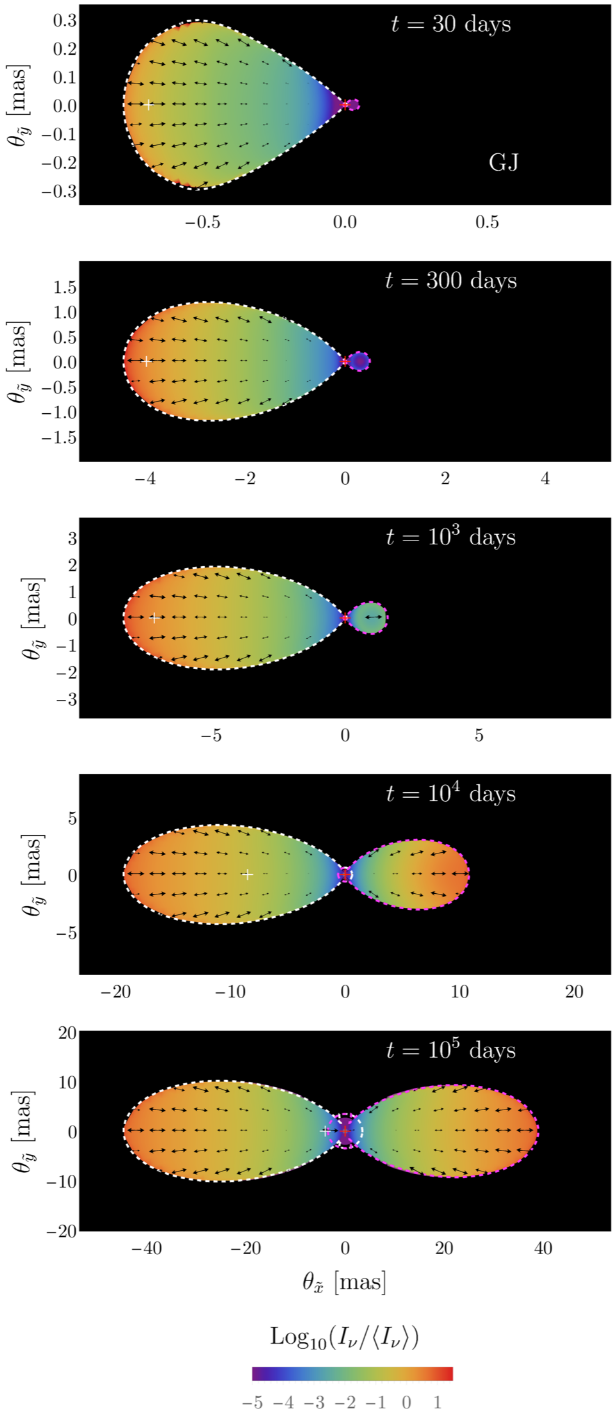



(Gill & JG 2018)

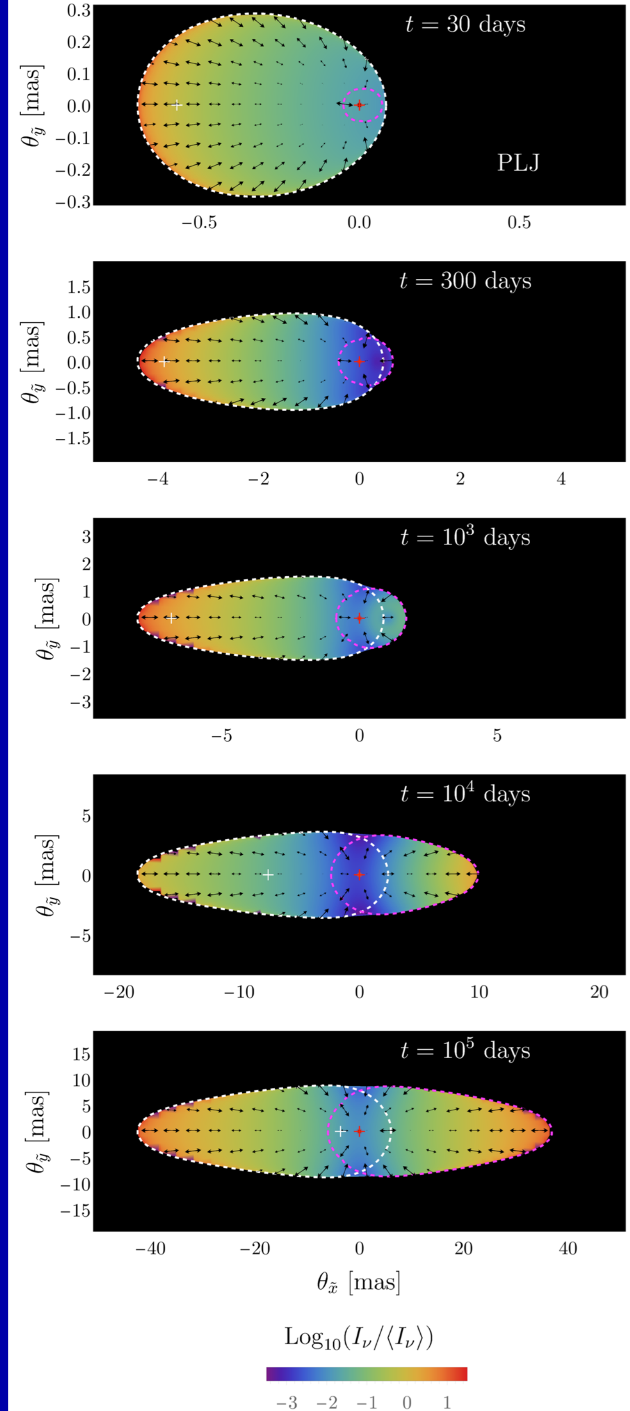
**Agree with radio afterglow images from simulations**




(JG, De Colle & Ramirez-Ruiz 2018)

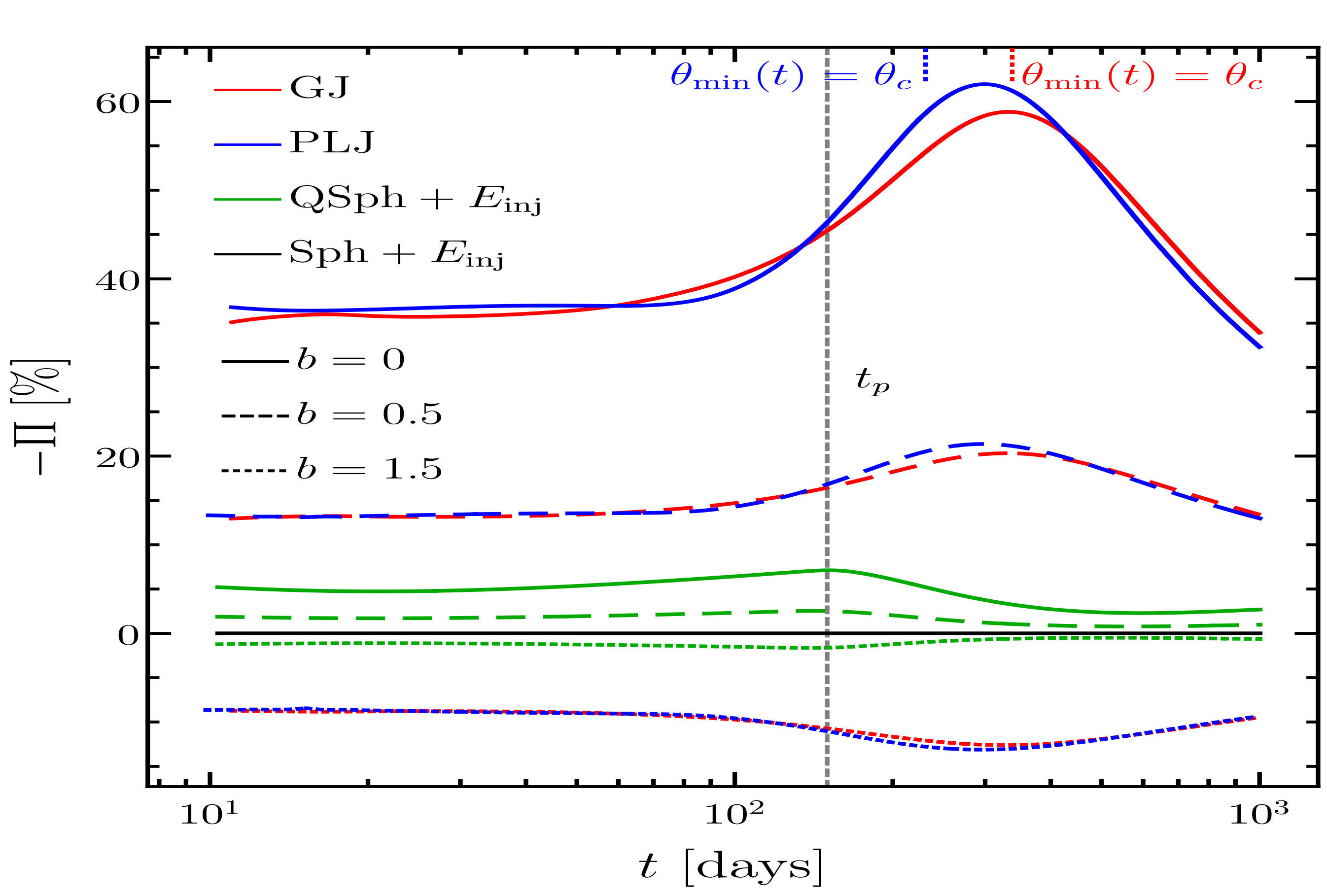



# Afterglow Images: GJ, PLJ



# GW170817/GRB170817A Afterglow (Gill & JG 18)

- Assuming a shock-produce B-field with $b \equiv 2\langle B_{\parallel}^2 \rangle / \langle B_{\perp}^2 \rangle$
- Data favor two core-dominated jet models with similar P(t)
- P(t) depends on the jet structure, $\theta_{obs}$ & B-field structure



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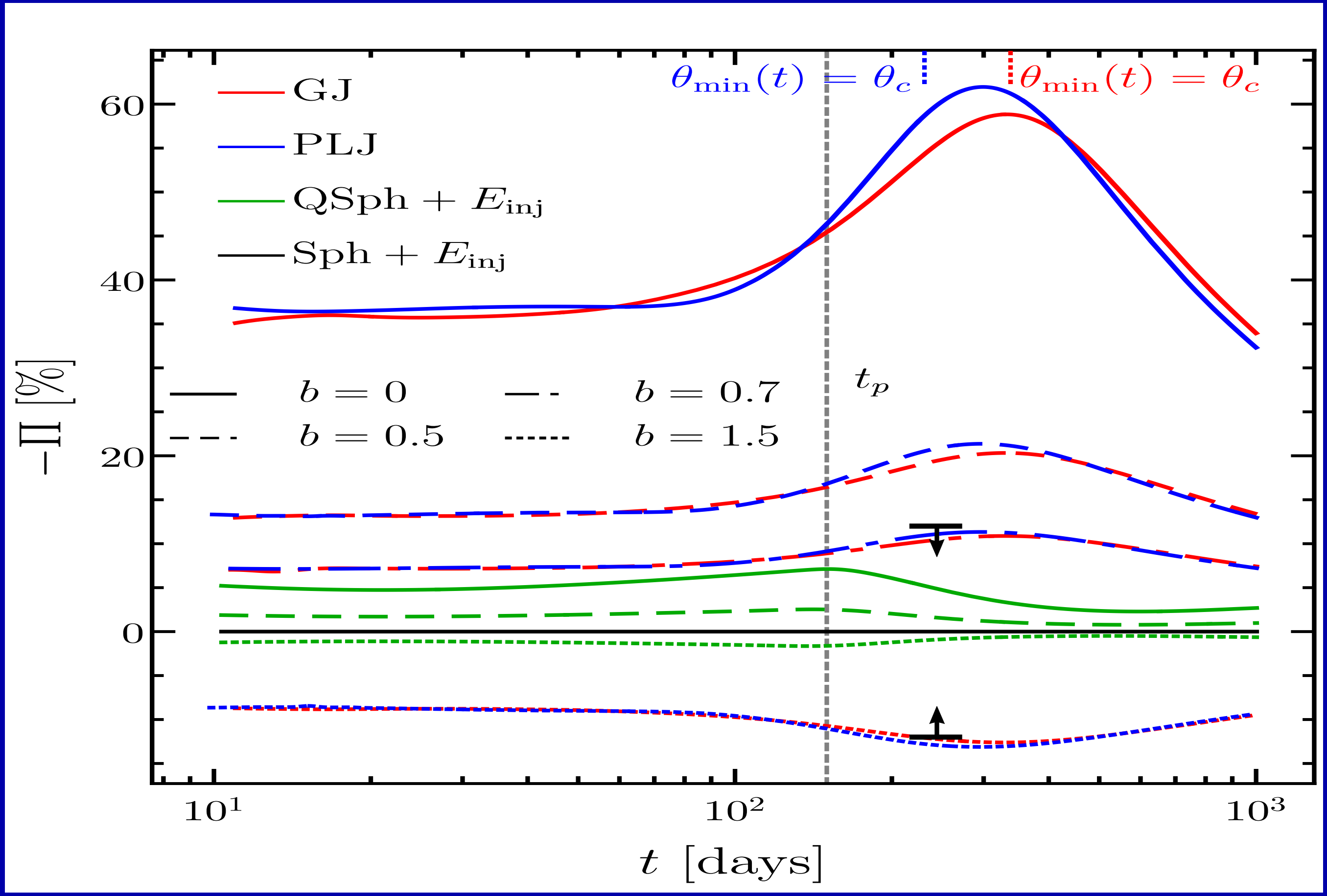


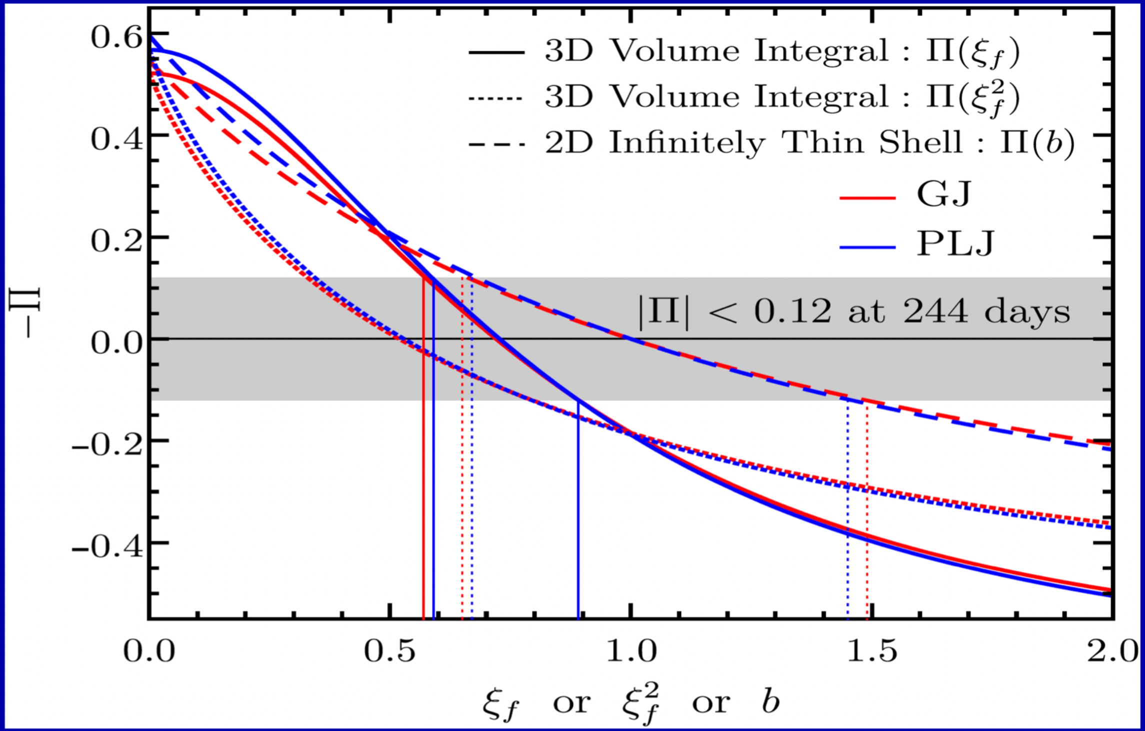

$0.7 \lesssim b \lesssim 1.5$ for jet models

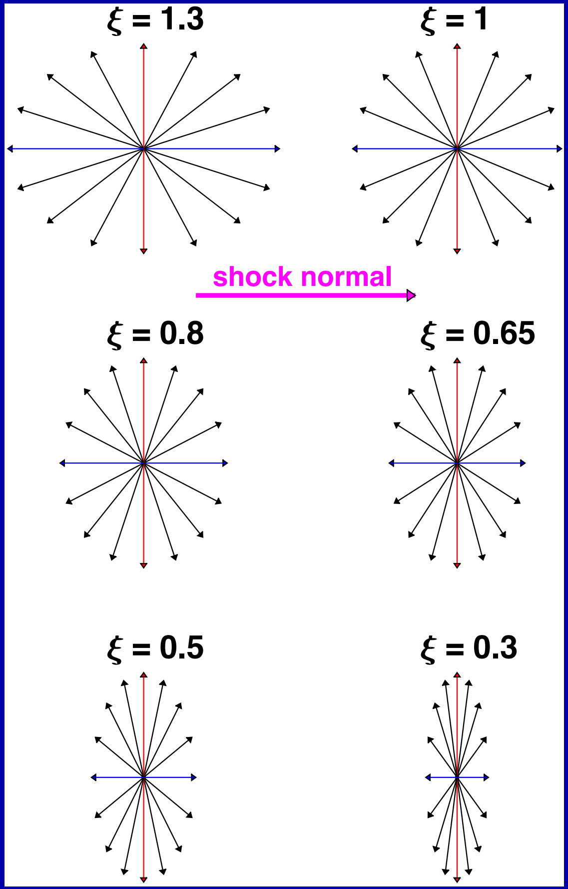
New: upper limit $P_{lin}$ < 12% @ ν = 2.8 GHz, t = 244 days (Corsi + 2018)

# GW170817/GRB170817A Afterglow (Gill & JG 19)

More realistic assumptions ⇒ B-field in collisionless shocks:

- 2D emitting shell → 3D emitting volume (local BM76 radial profile)
- B-field evolution by faster radial expansion: $L'_r / L'_{\theta,\varphi} \propto \chi^{(7-2k)/(8-2k)}$ B-field isotropic in 3D with $B'_r \to \xi B'_r$ (Sari 1999); $\xi = \xi_0 \chi^{(7-2k)/(8-2k)}$



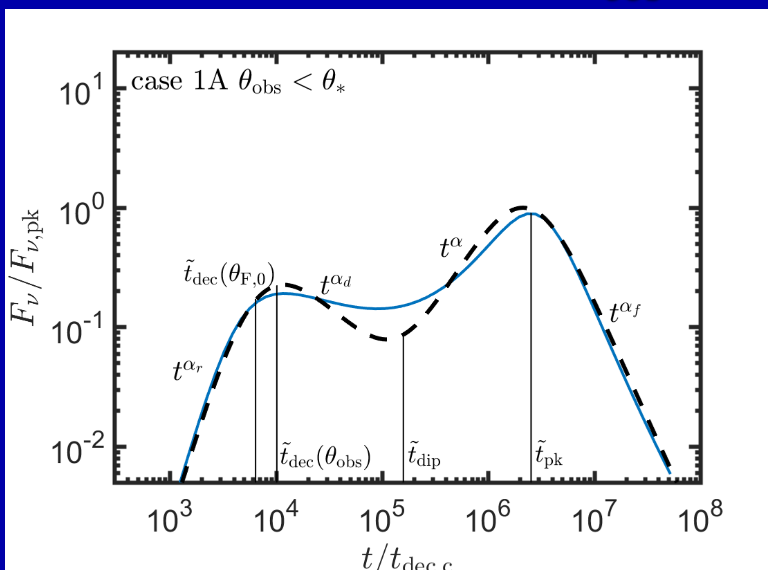

**$0.57 \lesssim \xi_f \lesssim 0.89$**

# Predicted Off-Axis Lightcurves from Structured Jets

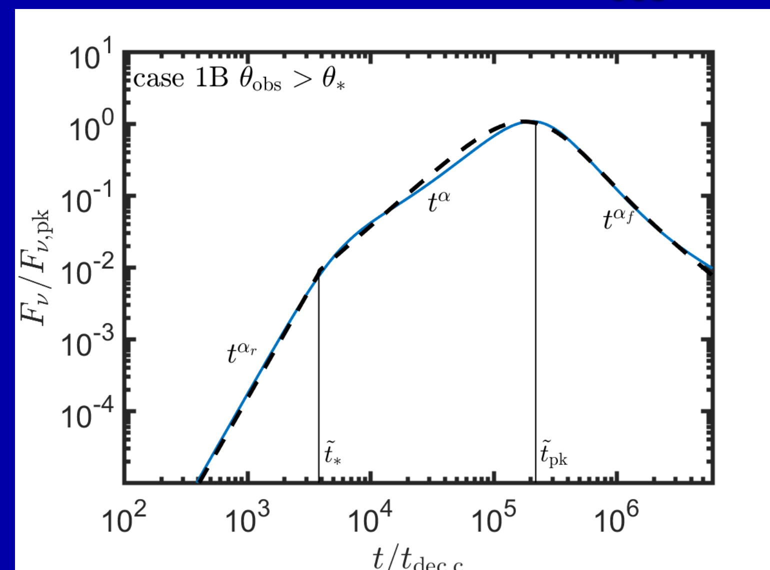
(Beniamini, JG & 2020; Beniamini, Gill & JG 2022)

- A general investigation of **Power-Law** (+Gaussian) **Jets**
- Provide detailed **analytic lightcurves**
- We find two main lightcurve types: double or single peaked

Double peaked LC: $\theta_{obs} < \theta_*$




Single peaked LC: $\theta_{obs} > \theta_*$




$$\theta_* \Gamma_0(\theta_*) = 1$$

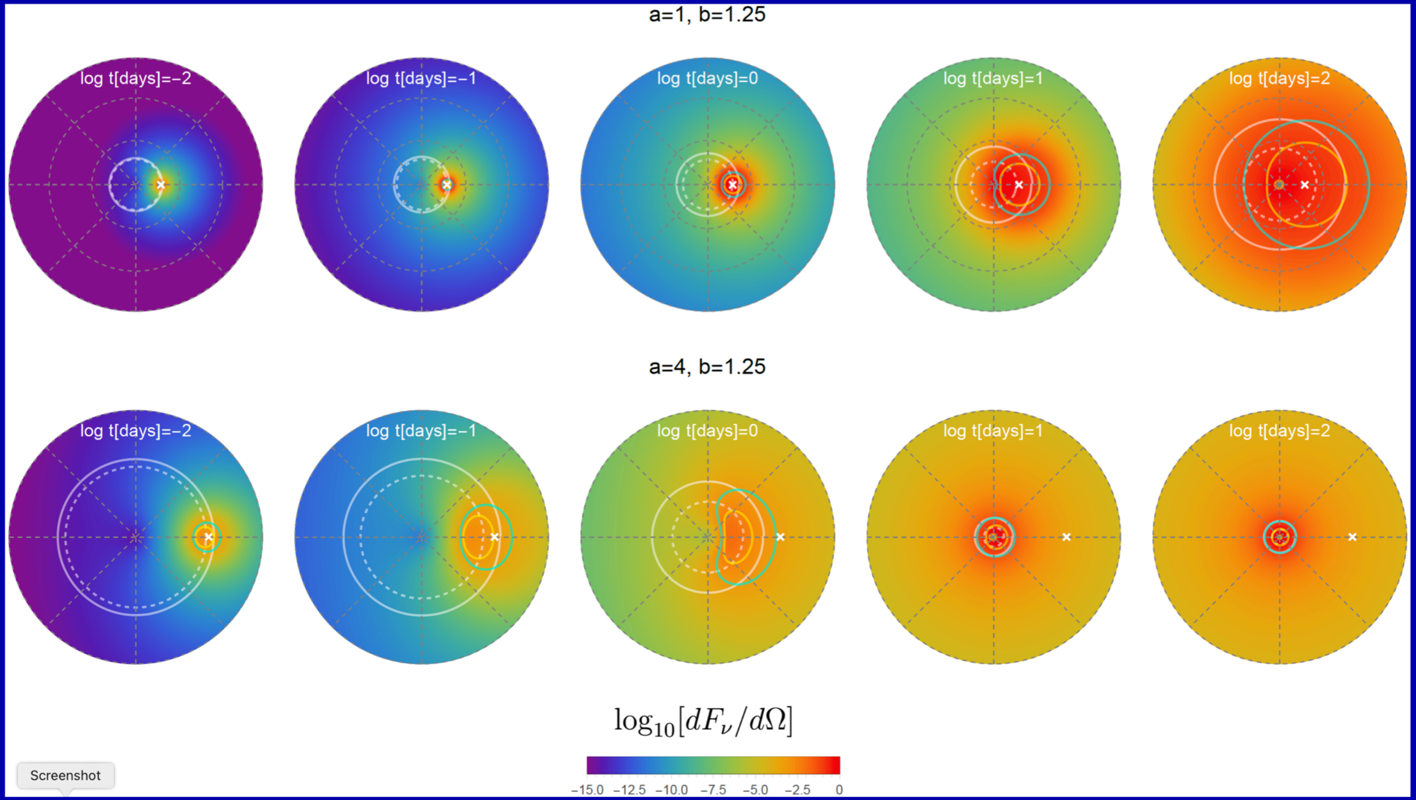
# Predicted Off-Axis Lightcurves from Structured Jets

(Beniamini, JG & 2020; Beniamini, Gill & JG 2022)

- Map the most relevant parameter space from simulations of long / short GRB jets breaking out of the star / merger ejecta
  - ⇒ Consider different external density profiles
- Consider both **shallow & steep jet** angular profiles

Shallow Jet:

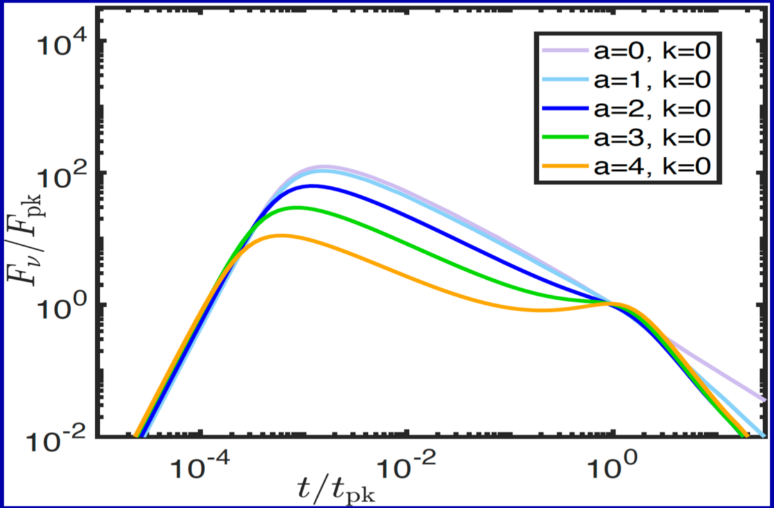
Steep Jet:



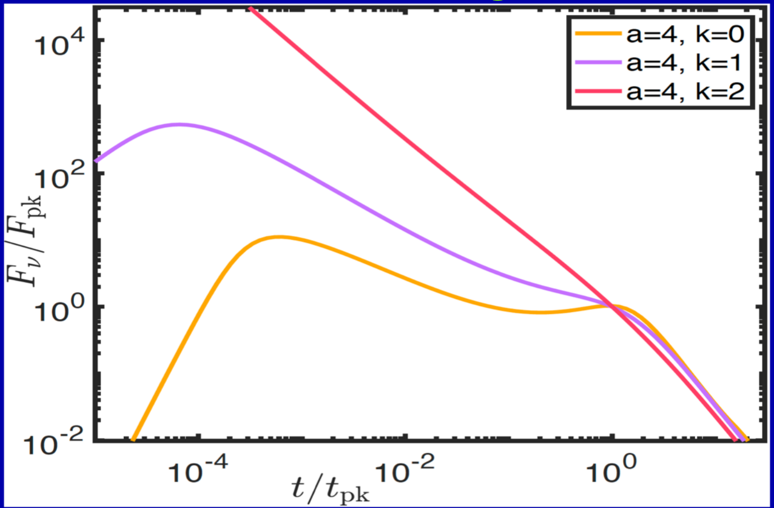
# Predicted Off-Axis Lightcurves from Structured Jets

(Beniamini, JG & 2020; Beniamini, Gill & JG 2022)

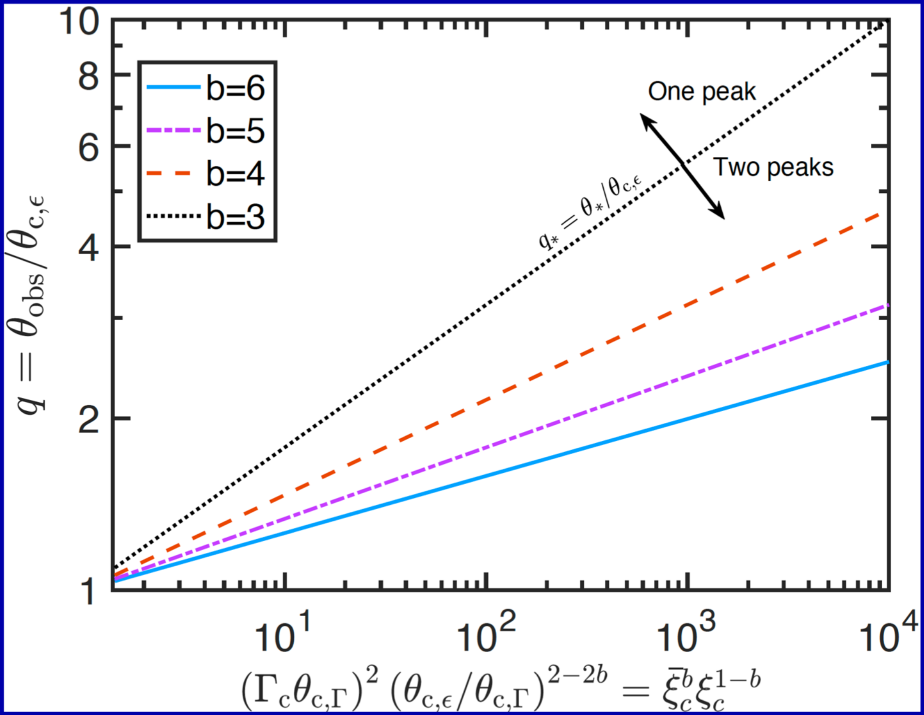
## Shallow vs. Steep Jet:




## External Density ∝ $R^{-k}$ :




## Single vs. Double Peaked LC:



# Conclusions on GW170817 / NS-NS mergers

- GW170817 is unique with a wide range of implications
- Merger Remnant: BH or HMNS → BH ⇒ $M_{TOV} \lesssim 2.17M_\odot$
- Two main types of explanations for the rising afterglow flux energy distribution with proper velocity (r) or with angle ($\theta$)
- 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)
- Later flux centroid motion observations: $\beta_{app} = 4.1 \pm 0.5$
- Polarization UL: shock-produced B-field $0.57 \lesssim \xi_0 \lesssim 0.89$
- Predicted **off-axis lightcurves** from **structured jets**