GRB Jets from Compact Binary Mergers in the Era of Gravitational Wave Astronomy

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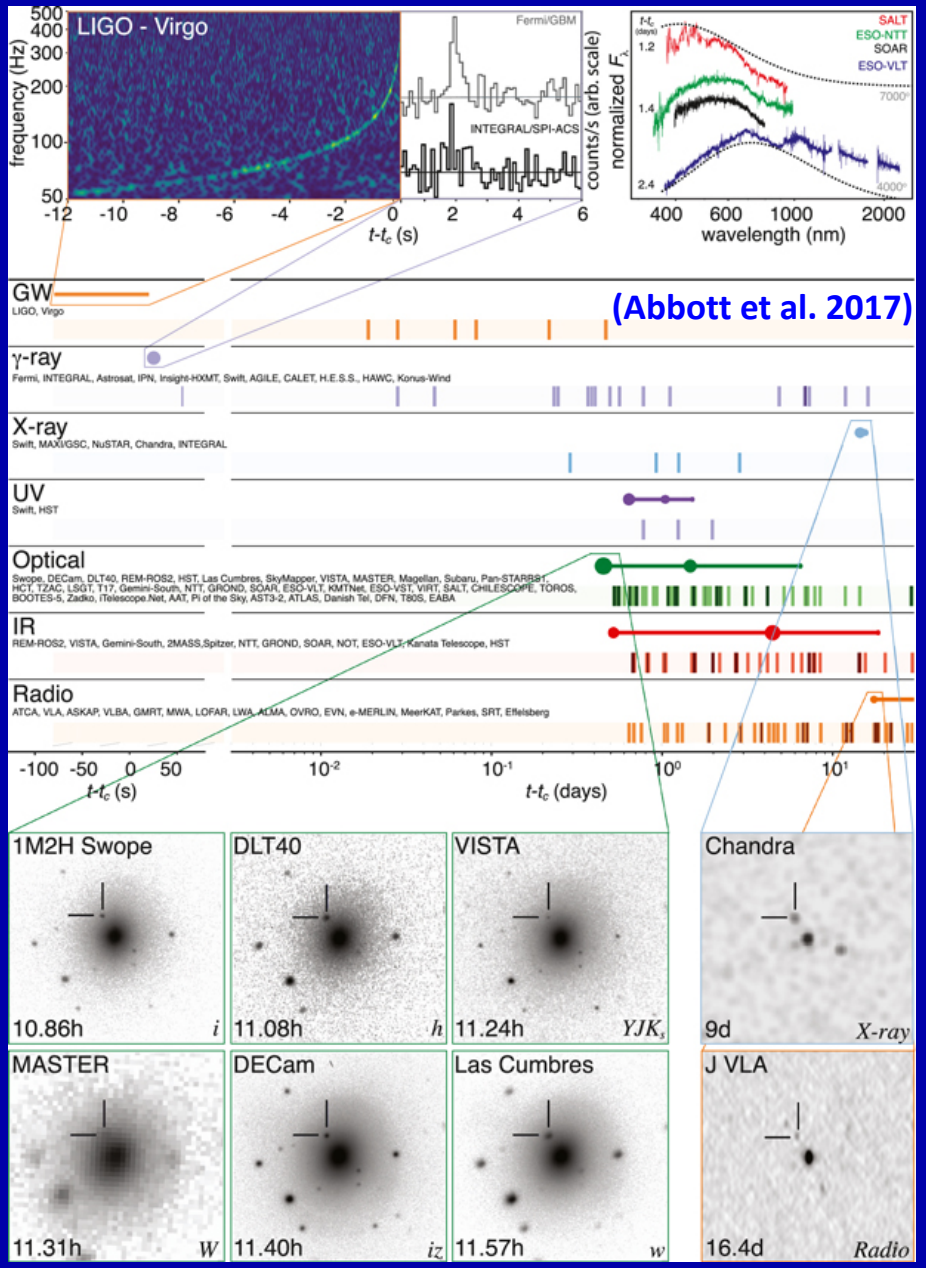
Astrophysics in the Next Decade: From the First Stars to Intelligent Life

In celebration of Avi Loeb's 60th birthday, 7.6.22, Martha's Vineyard, MA

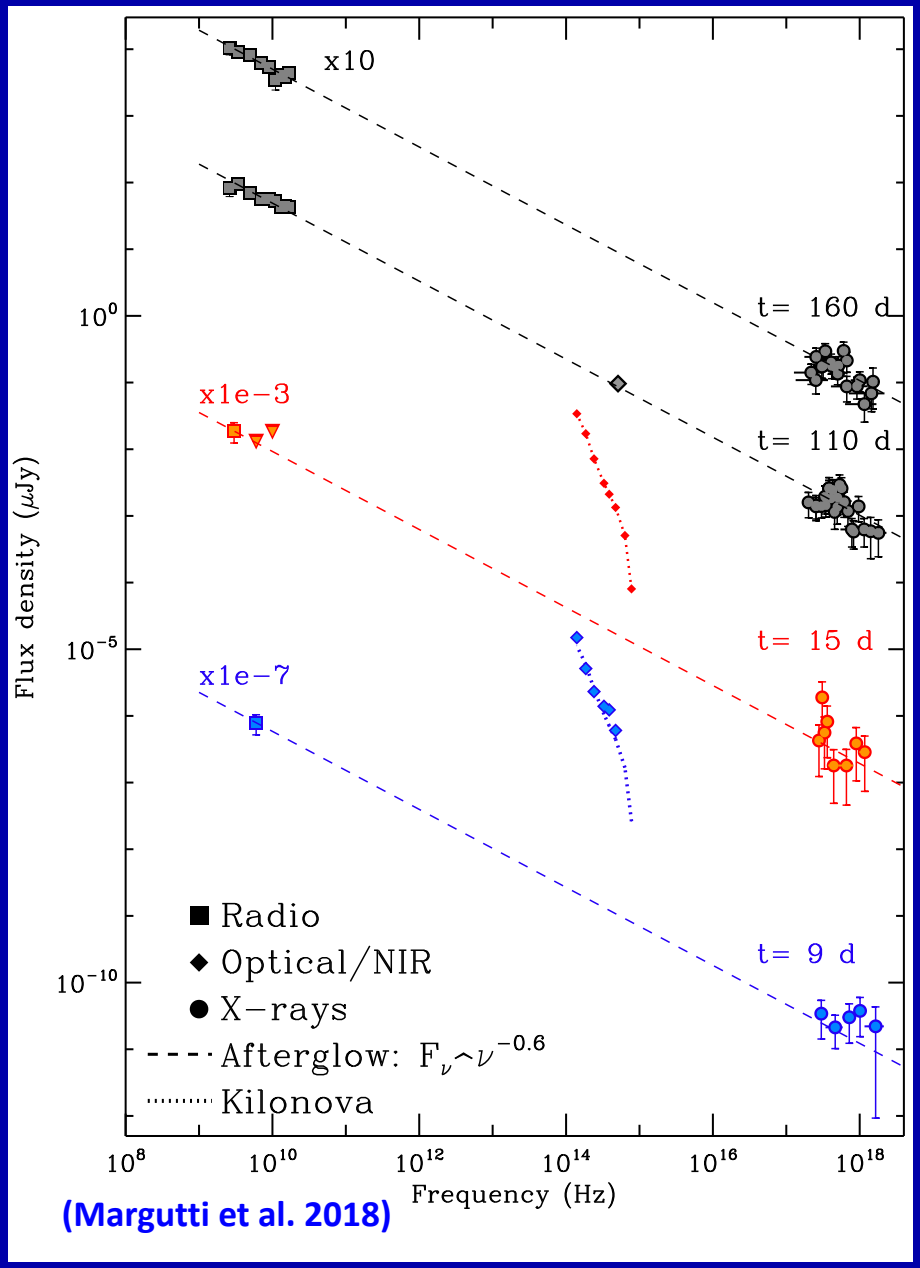
GW 170817 / GRB 170817A: D ≈ 40 Mpc

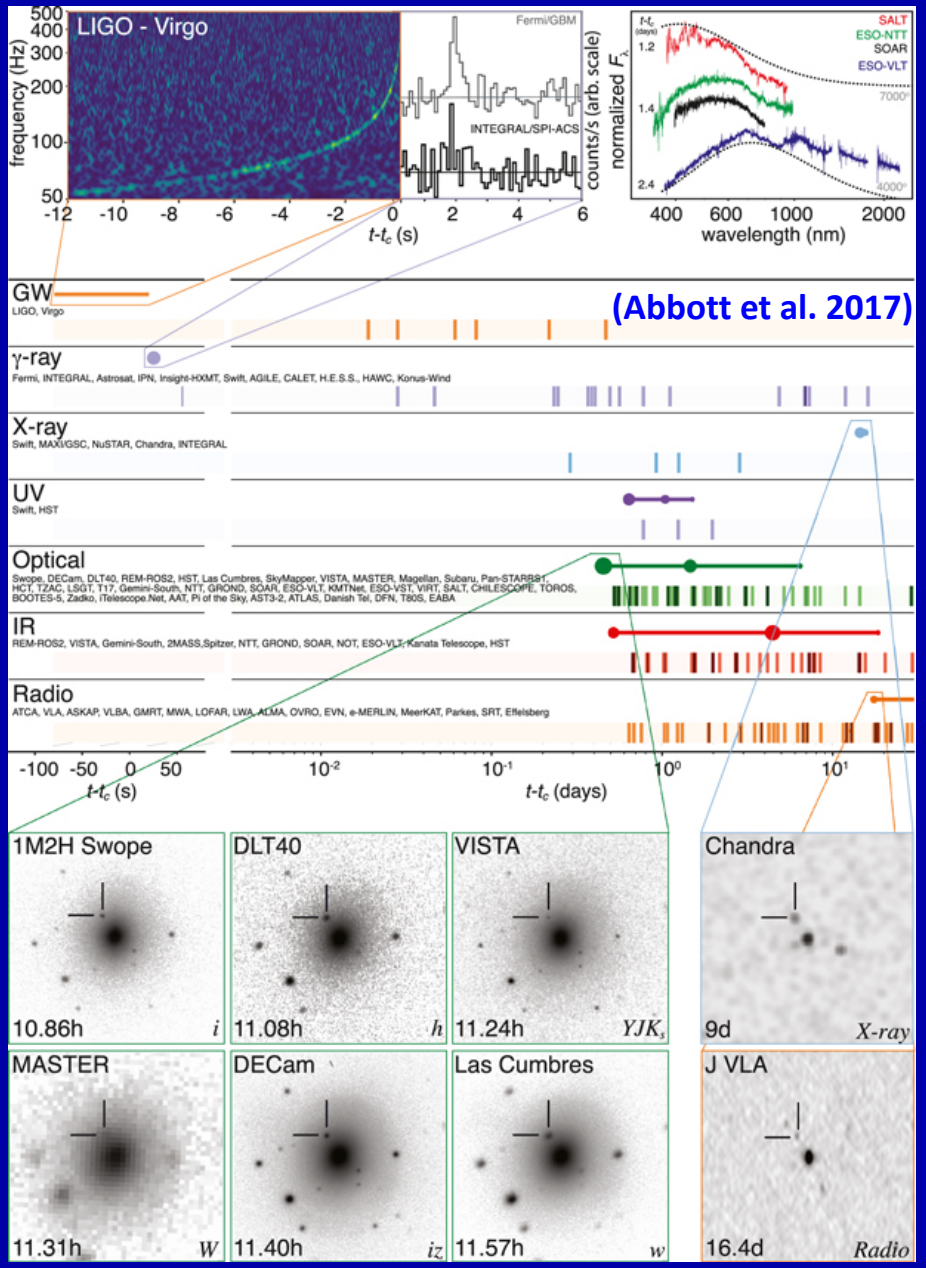
- **First GW detection** of a **NS-NS merger**
- **First electromagnetic counterpart** to a GW event
  - The **short GRB** 170817A (very under-luminous, 1.74 s γ-GW delay; ⇒ $|v_{GW}/c - 1| \lesssim 4 \cdot 10^{-16}$)
  - First clear-cut **kilonova**, in IR to UV, lasting a few weeks ⇒ NS-NS mergers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

(Eichler+ 1989; Narayan+ 1992)

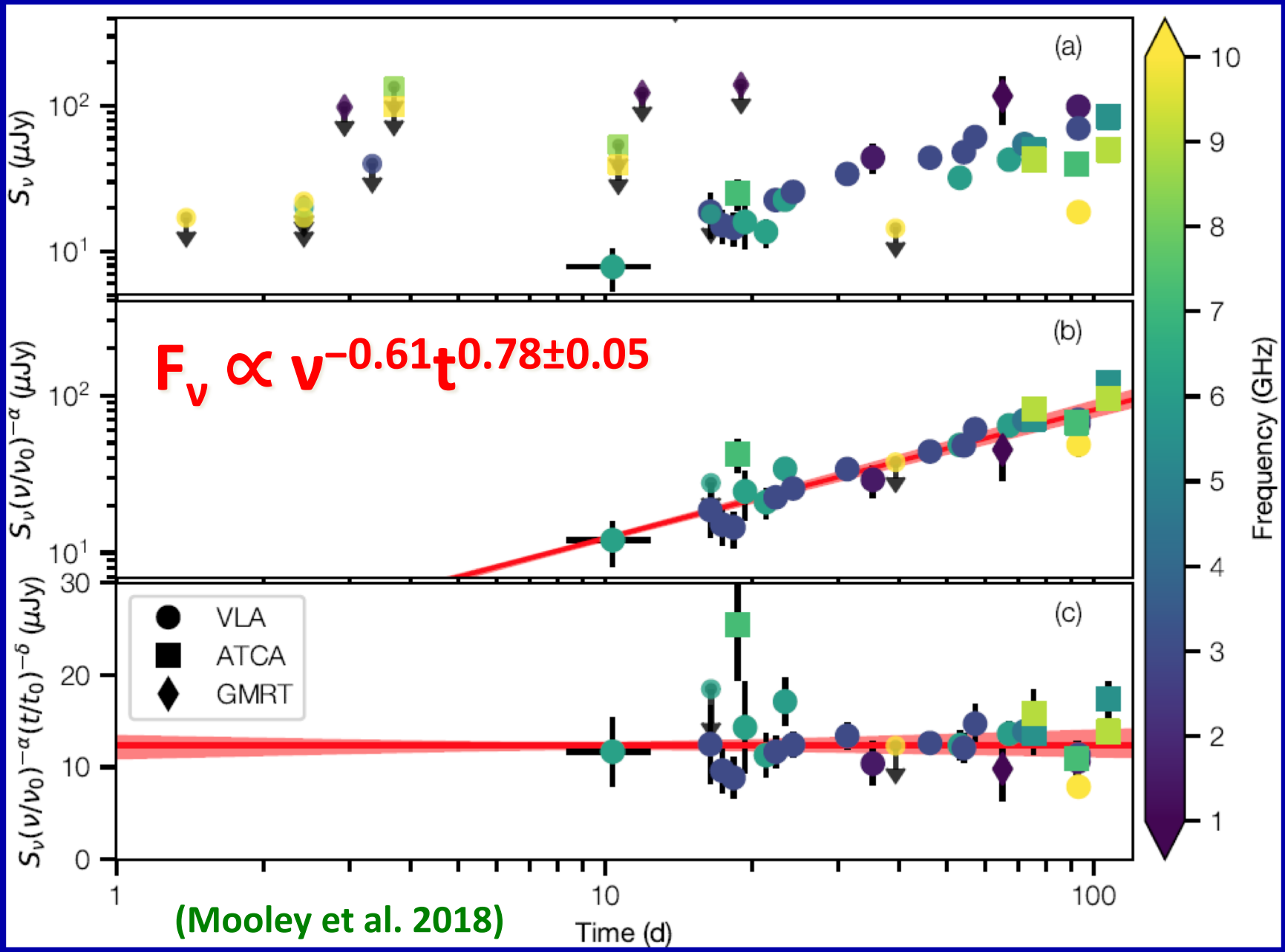


GW 170817 / GRB 170817A: D ≈ 40 Mpc



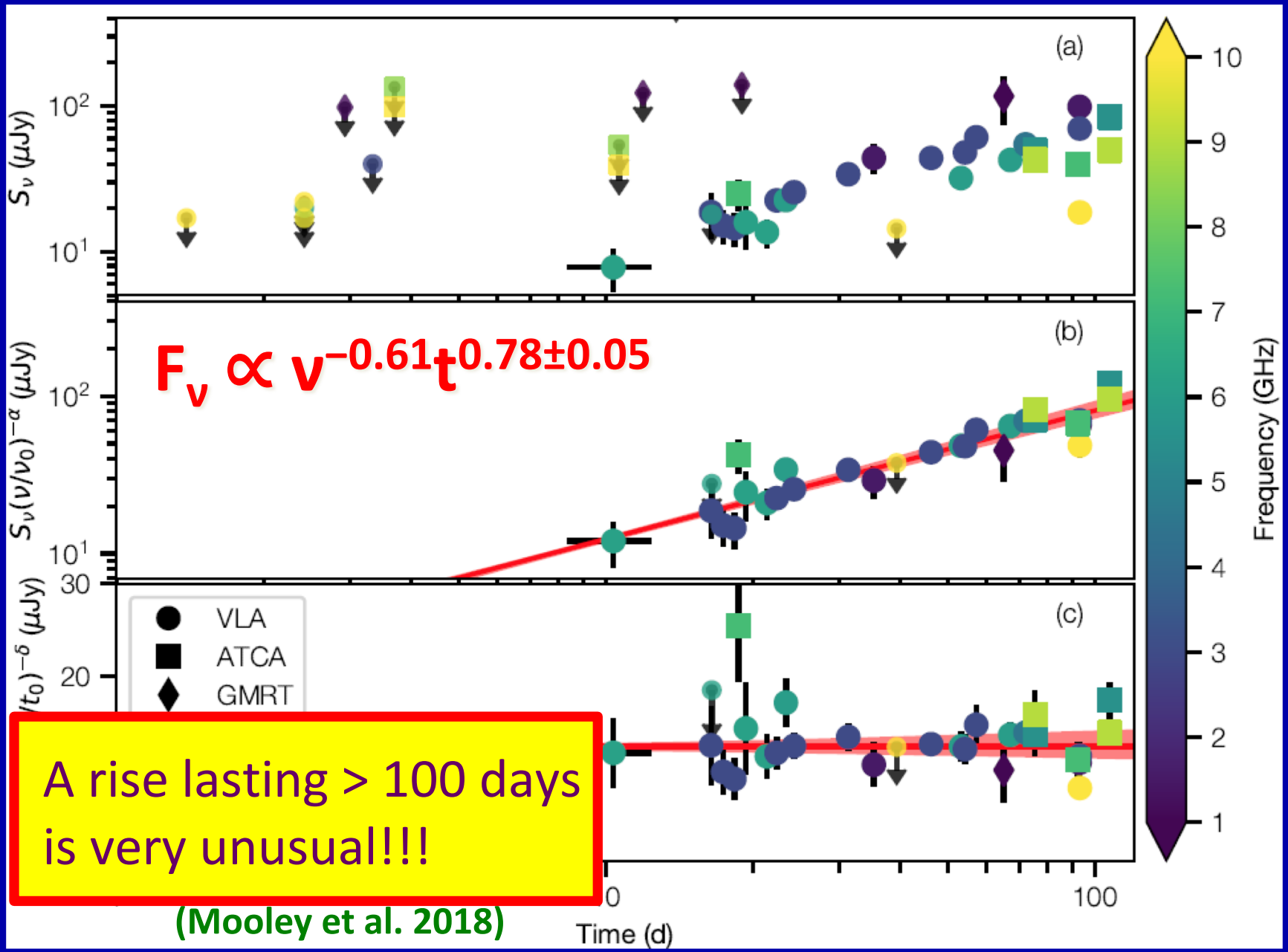


GRB 170817A: afterglow observations



(Mooley et al. 2018)

GRB 170817A: afterglow observations

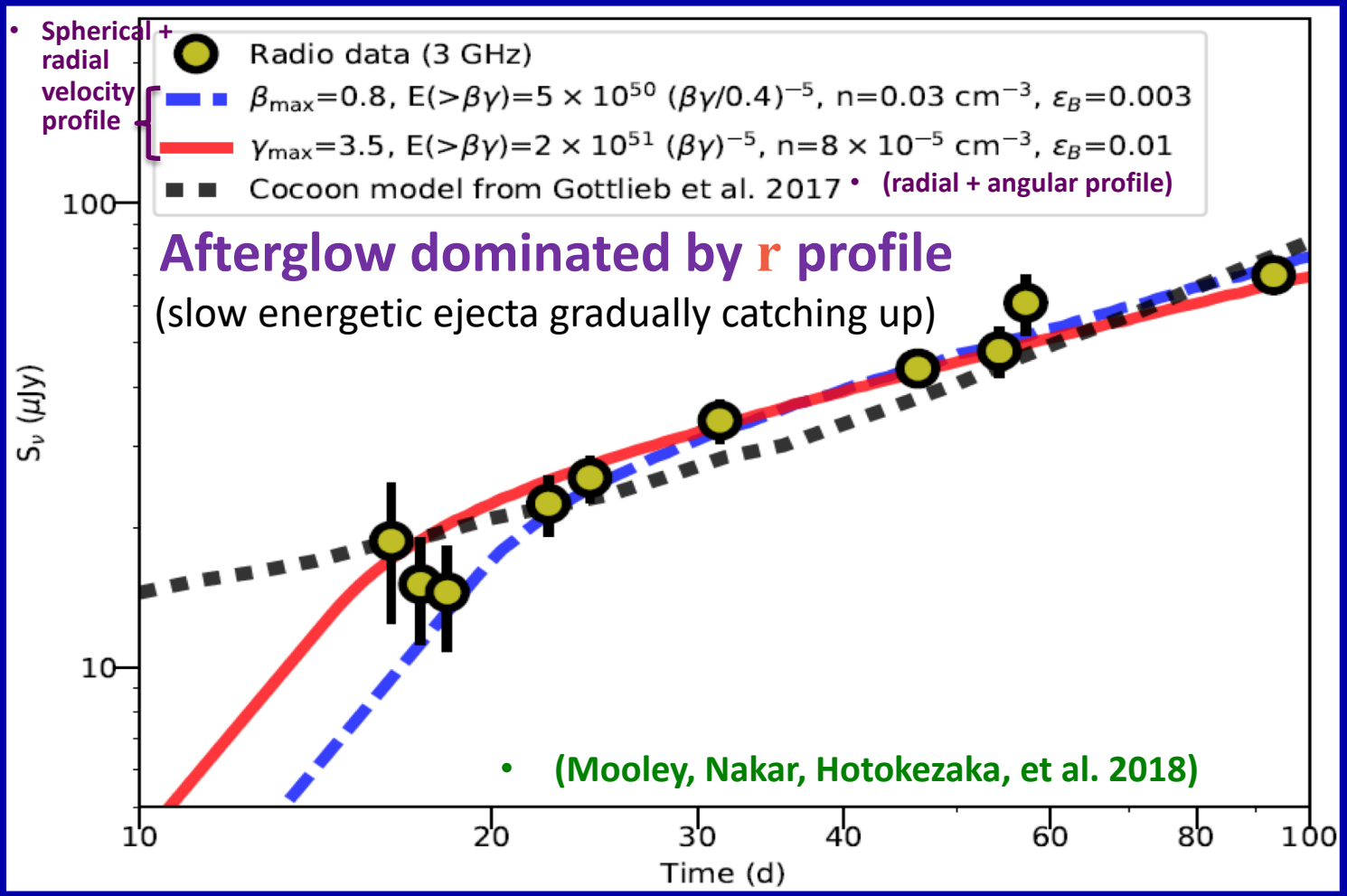


A rise lasting > 100 days is very unusual!!!

(Mooley et al. 2018)

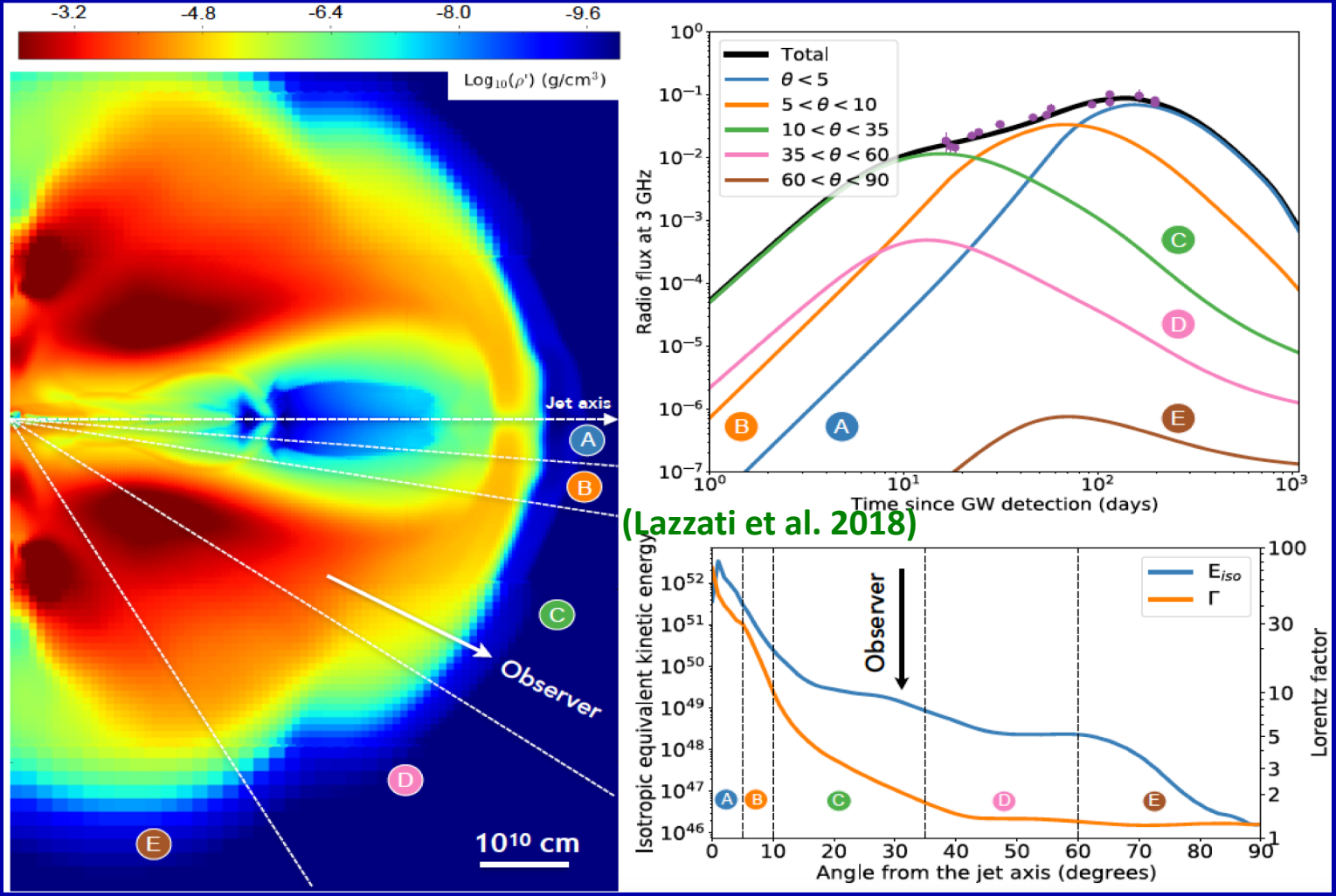
GRB170817 outflow structure: prompt, afterglow

- 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**



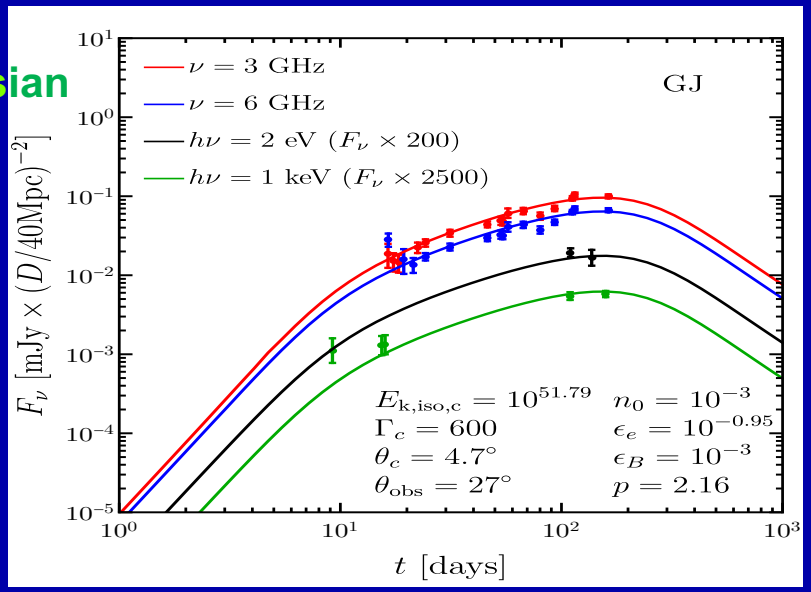
Outflow structure: breaking the degeneracy (Gill & JG 18)

- 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 $E(>u) \propto u^{-5.5}$, $1.8<u<4$
  - GJ: Gaussian Jet (in $\varepsilon = dE/d\Omega$, Γ_0-1) $\Gamma_c = 600$, $\theta_c = 4.7°$
  - PLJ: Power-Law Jet; $\varepsilon = \varepsilon_c \Theta^{-a}$, $\Gamma_0 - 1 = (\Gamma_c - 1)\Theta^{-b}$, $\Theta = [1+(\theta/\theta_c)^2]^{1/2}$
    $\Gamma_c = 100$, $\theta_c = 5°$, $a = 4.5$, $b = 2.5$

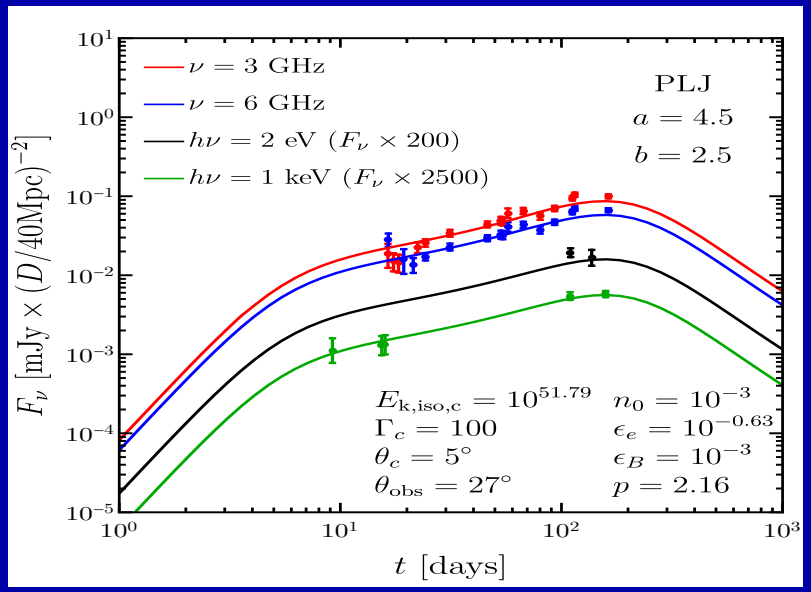
The outflow structure: breaking the degeneracy

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

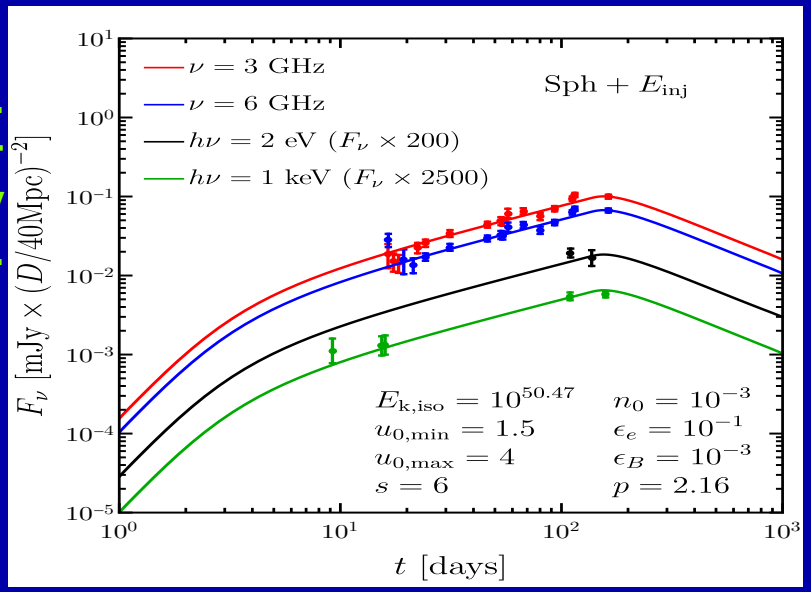
Gaussian Jet



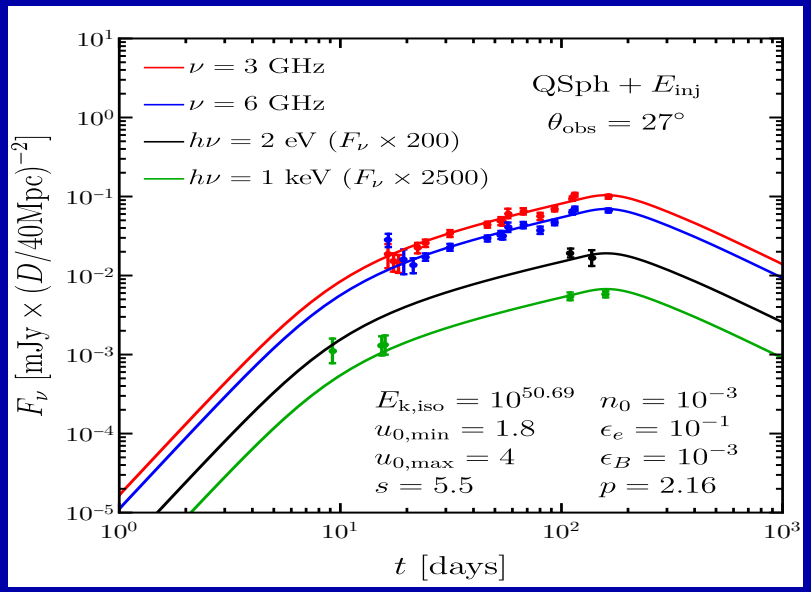
Power Law Jet



Spher. + Energy Inject.



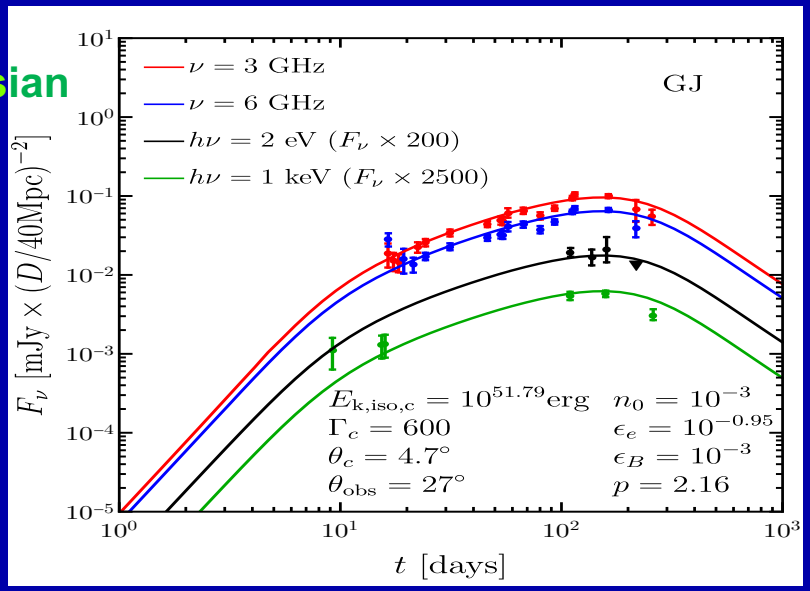
Quasi Spher. + Energy Inject.



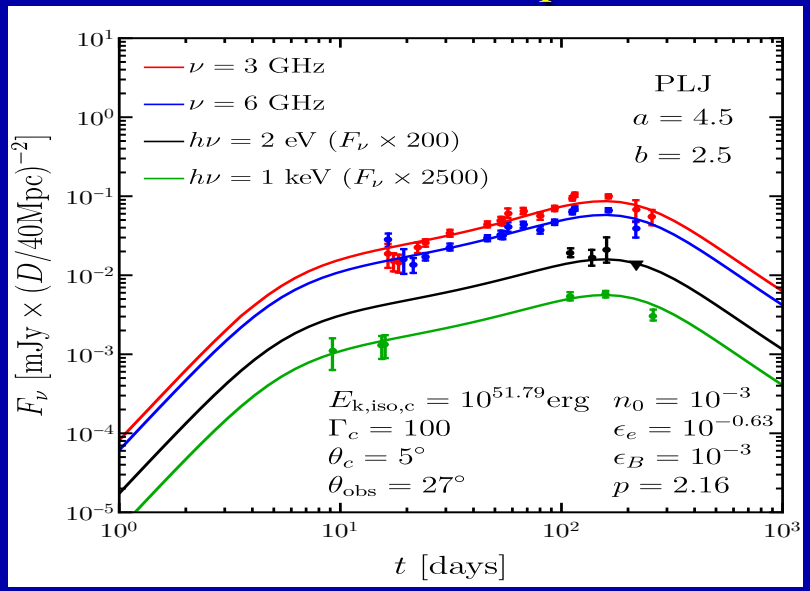
The outflow structure: breaking the degeneracy

- New data that came out established a peak at t_p ~150 days

Gaussian Jet



Power Law Jet



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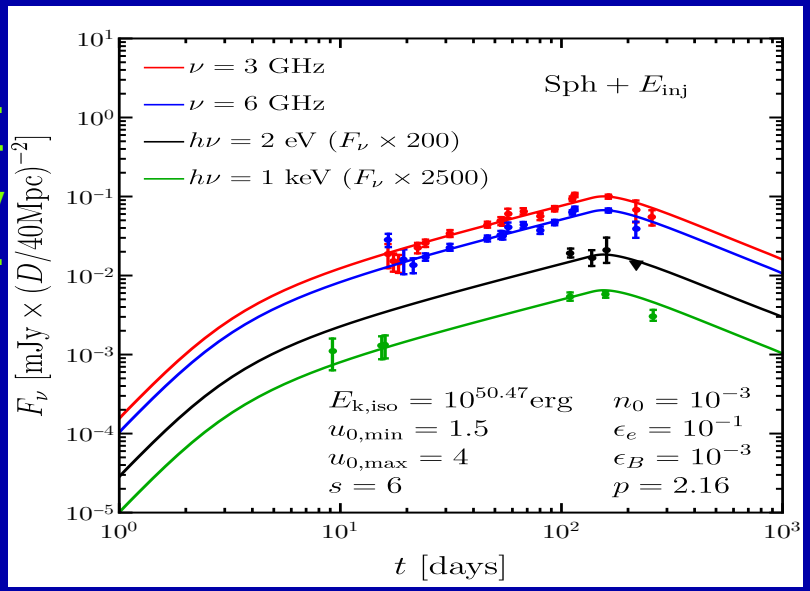

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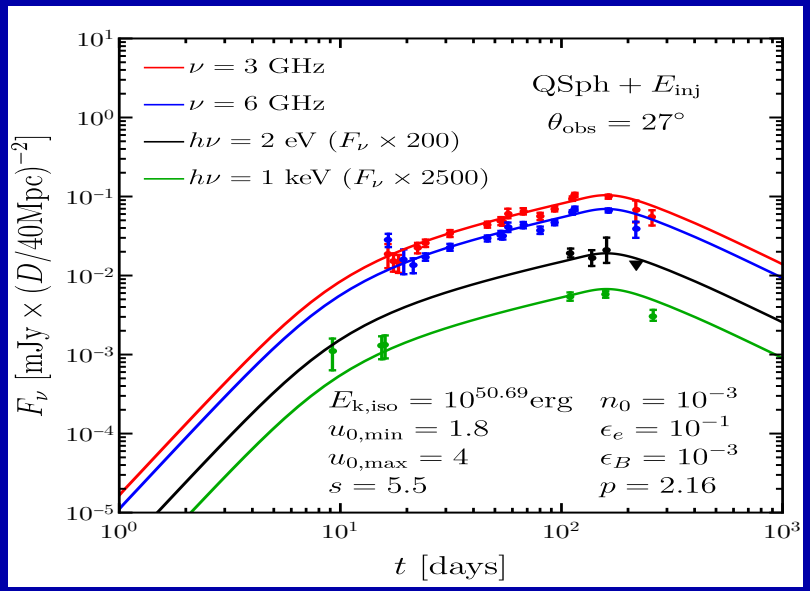
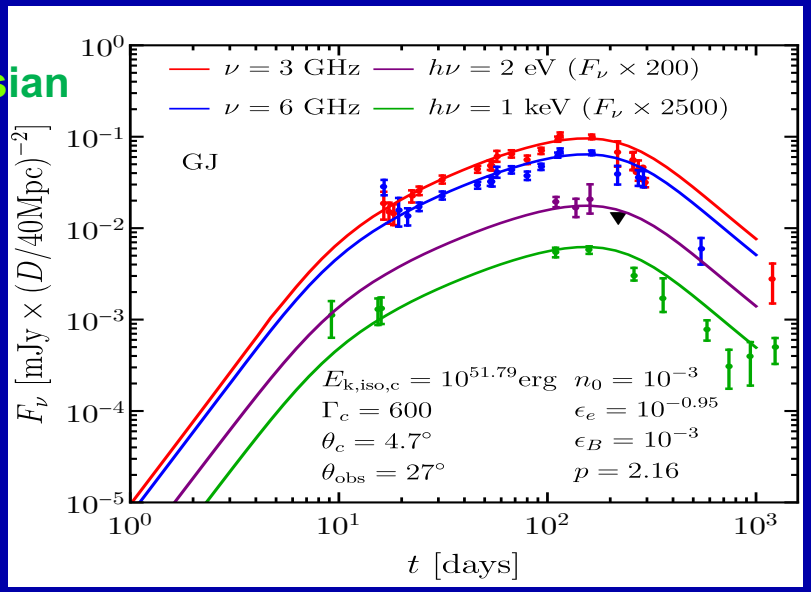


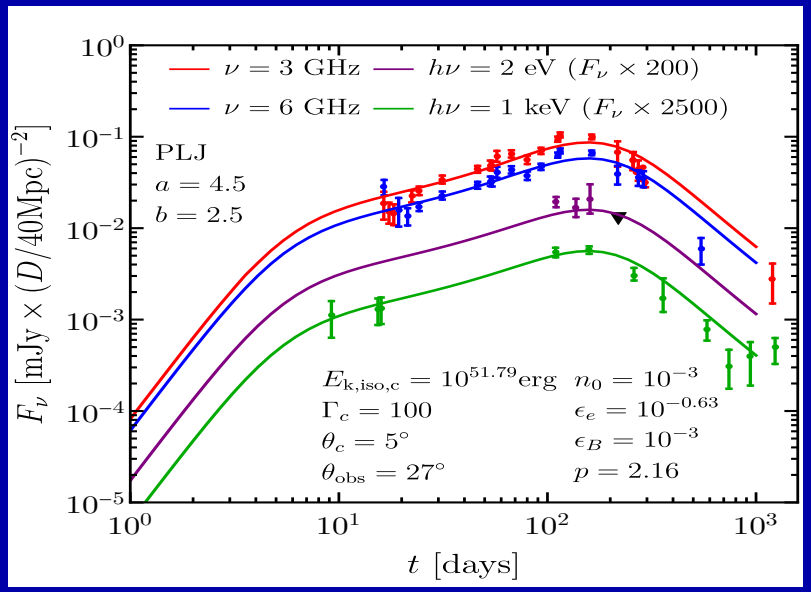
The outflow structure: breaking the degeneracy

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

Gaussian Jet



Power Law Jet



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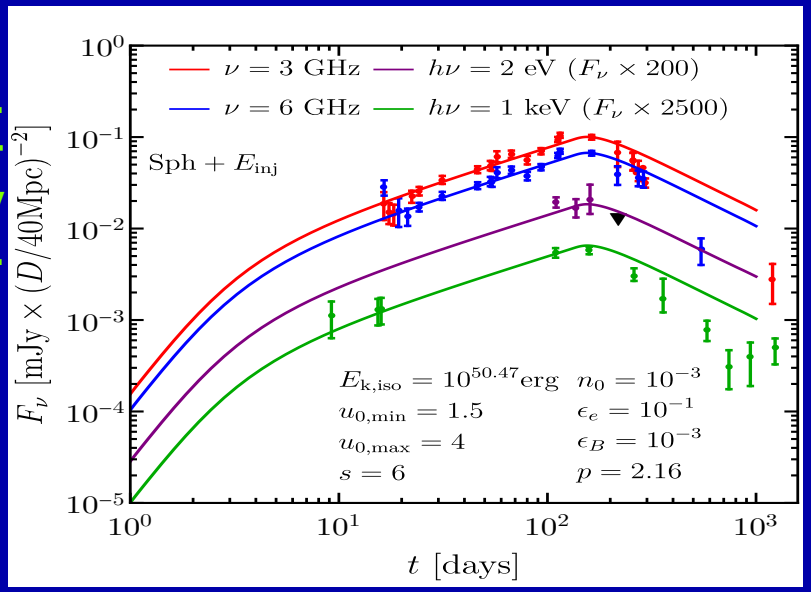

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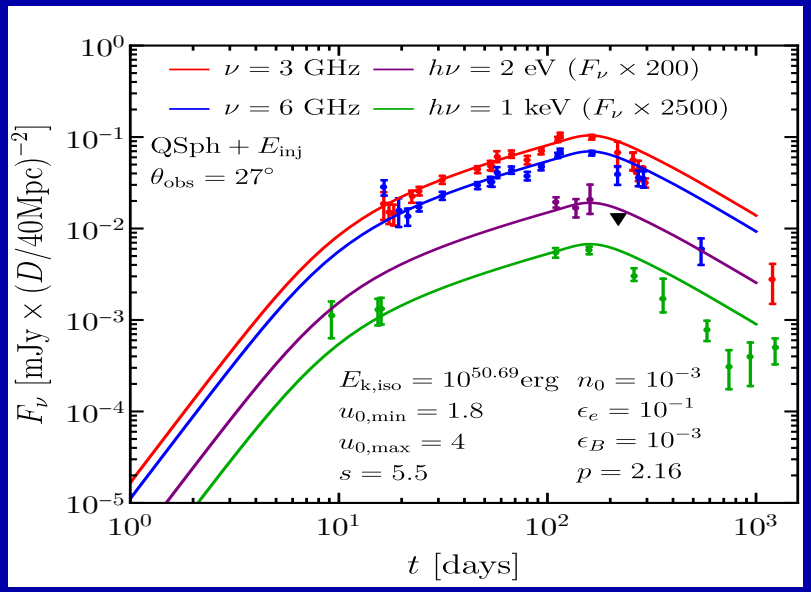
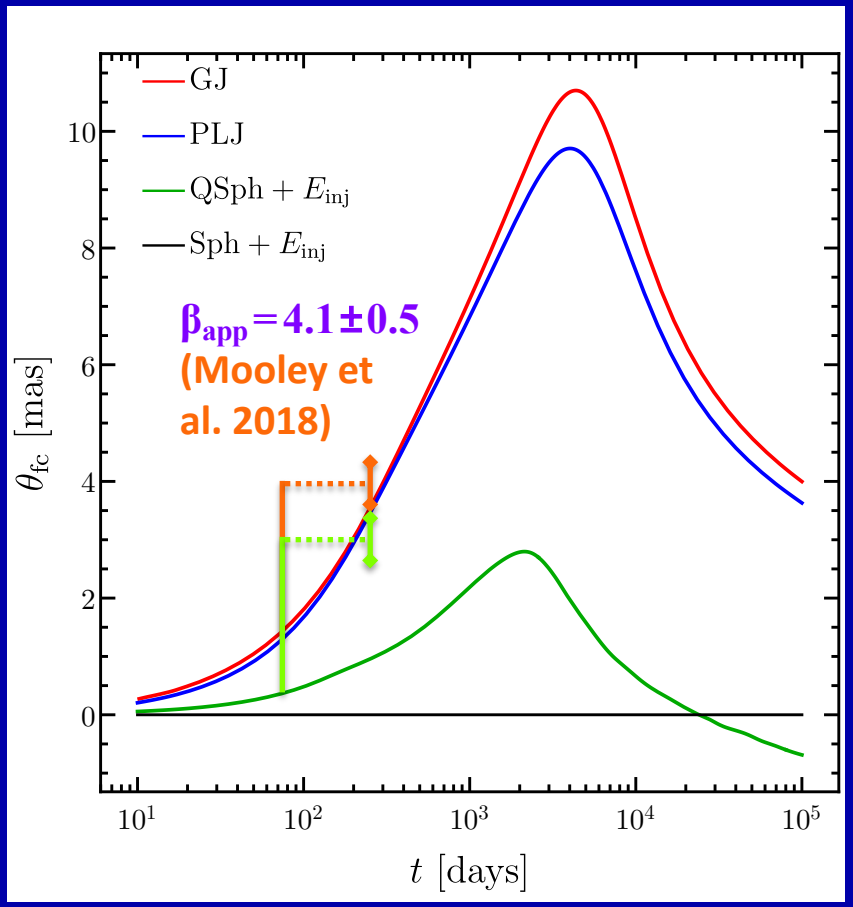
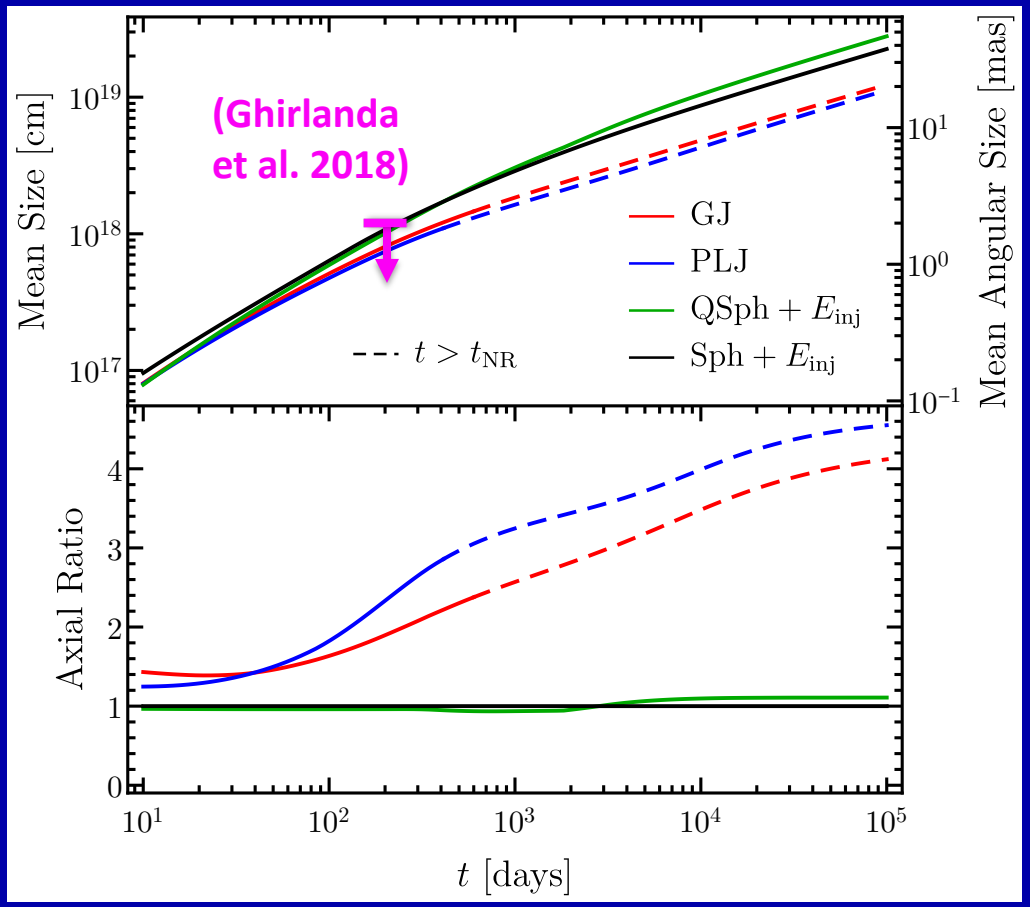


Afterglow Images: flux centroid, size, shape

- 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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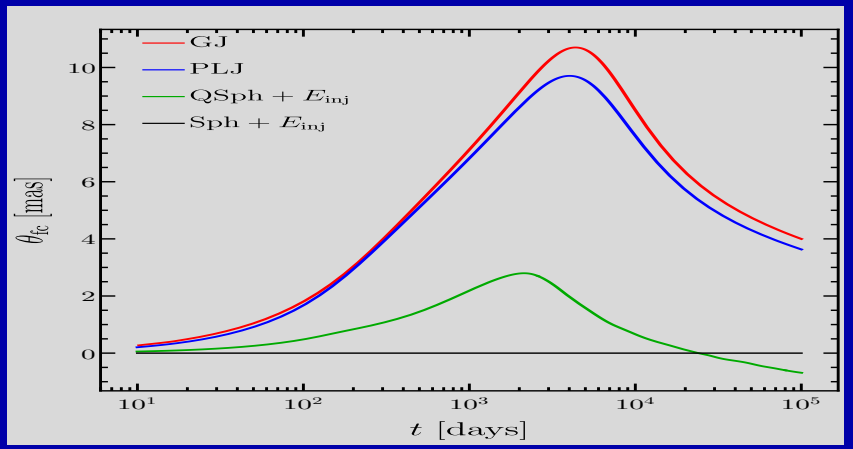

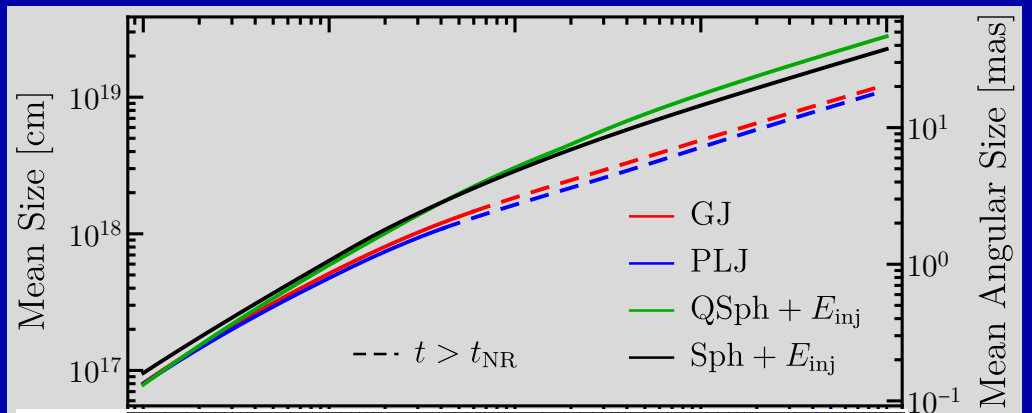

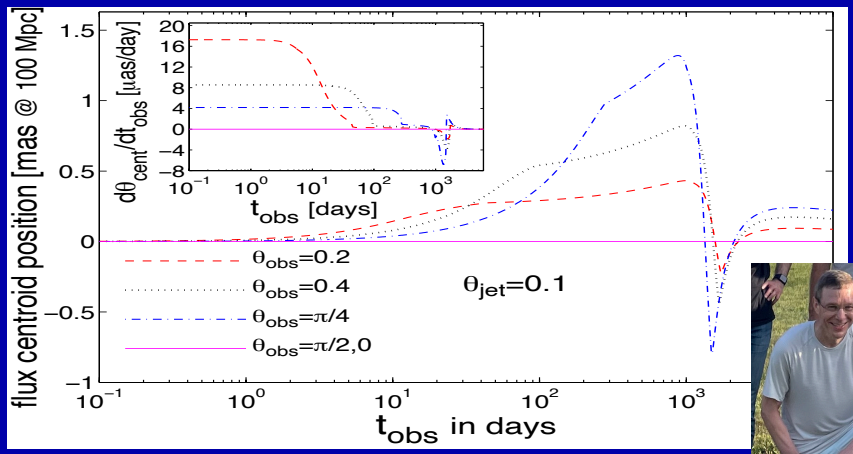

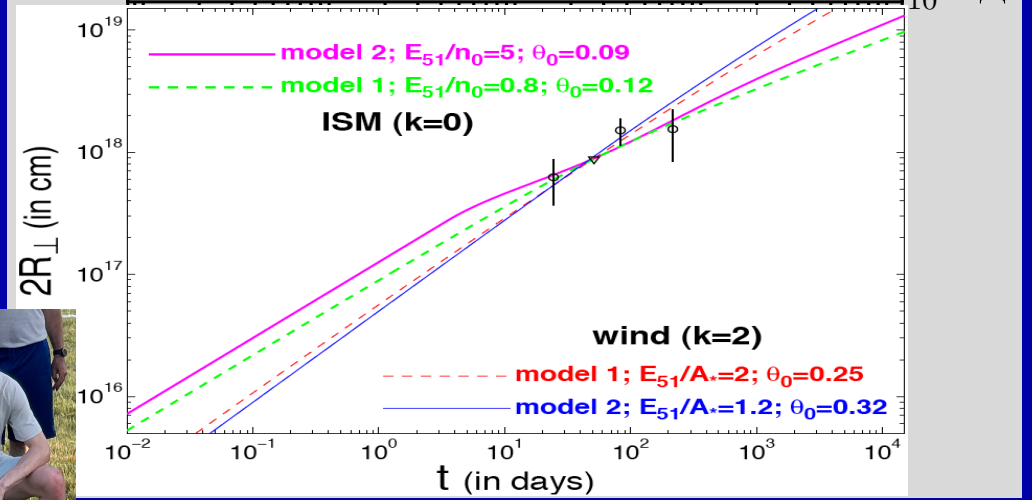

(JG & Loeb 2003)

(JG, Ramirez-Ruiz & Loeb 2005)

Afterglow Images: flux centroid, size, shape

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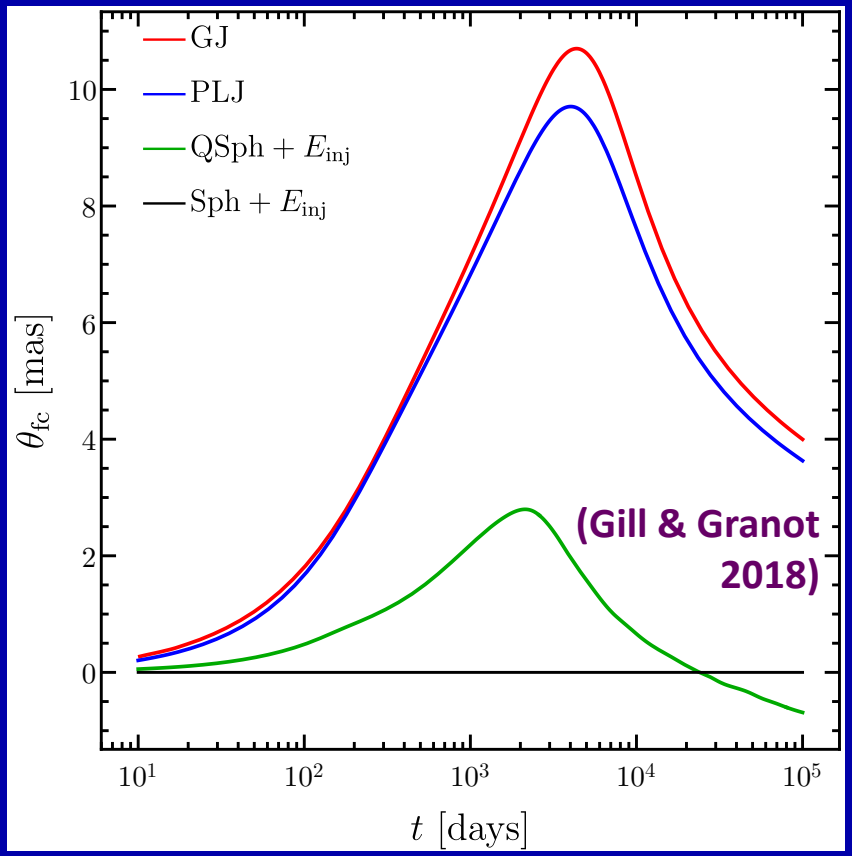
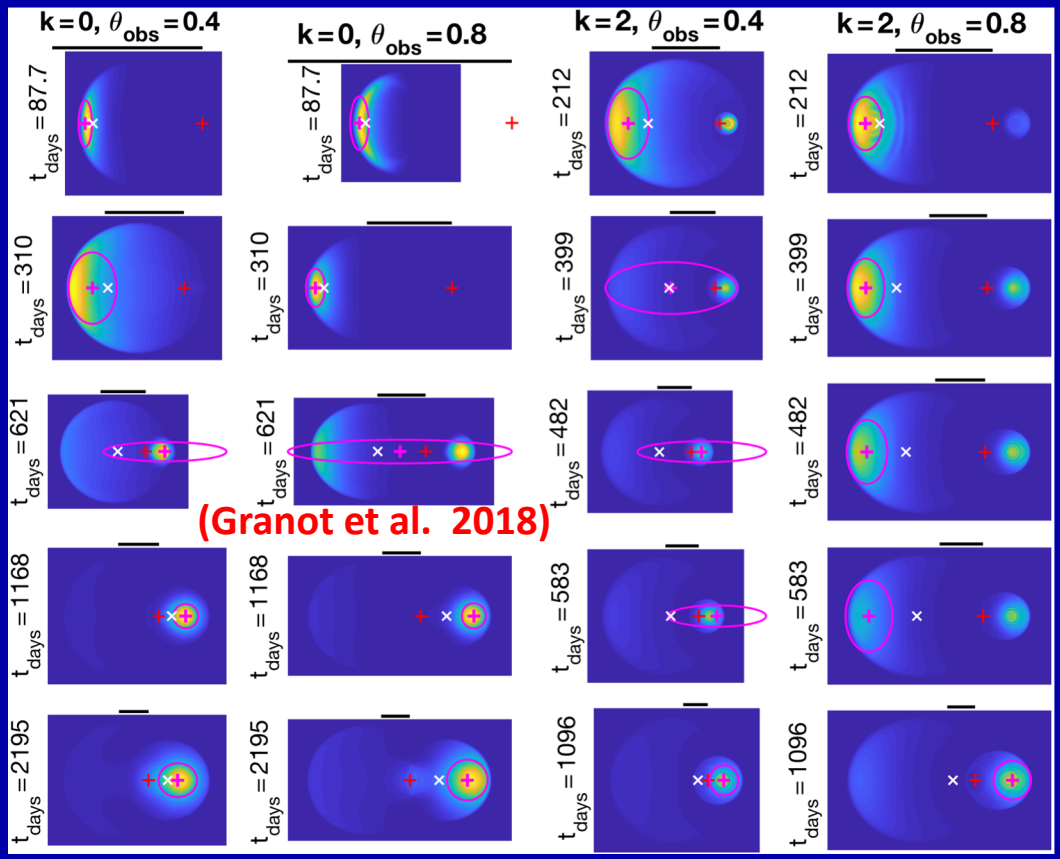
Radio flux centroid motion: semi-analytic



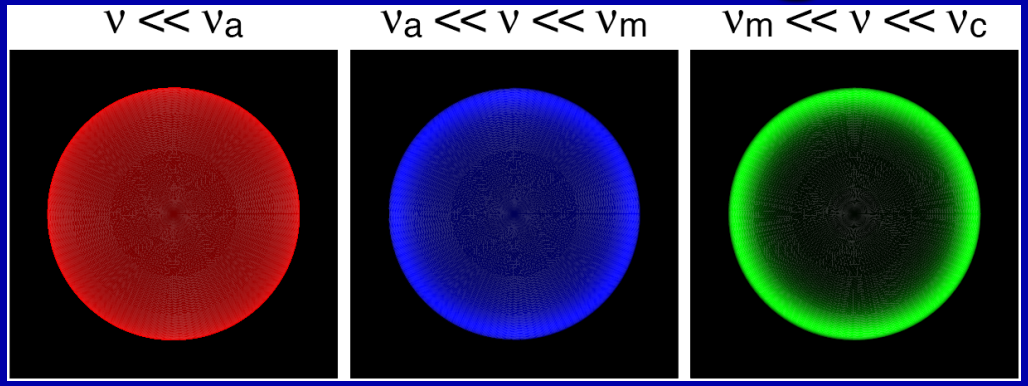
(Gill & JG 2018)

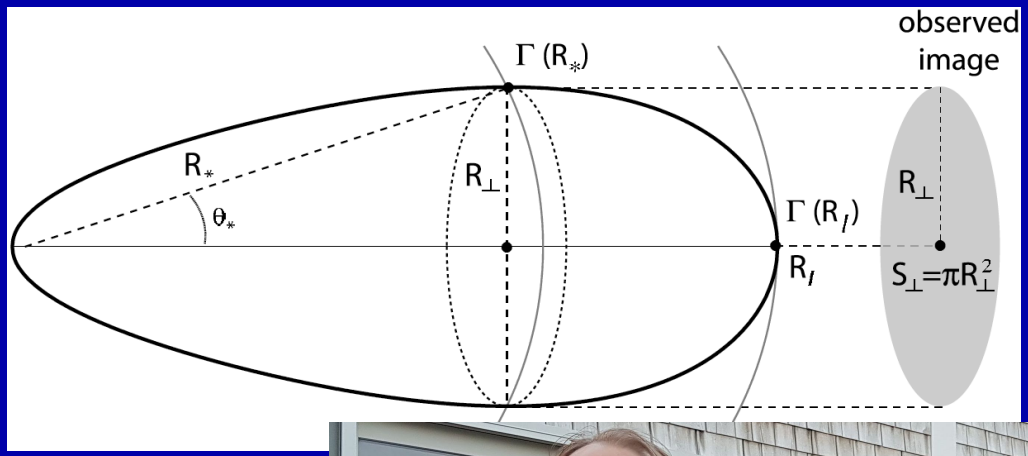
Agree with radio afterglow images from simulations



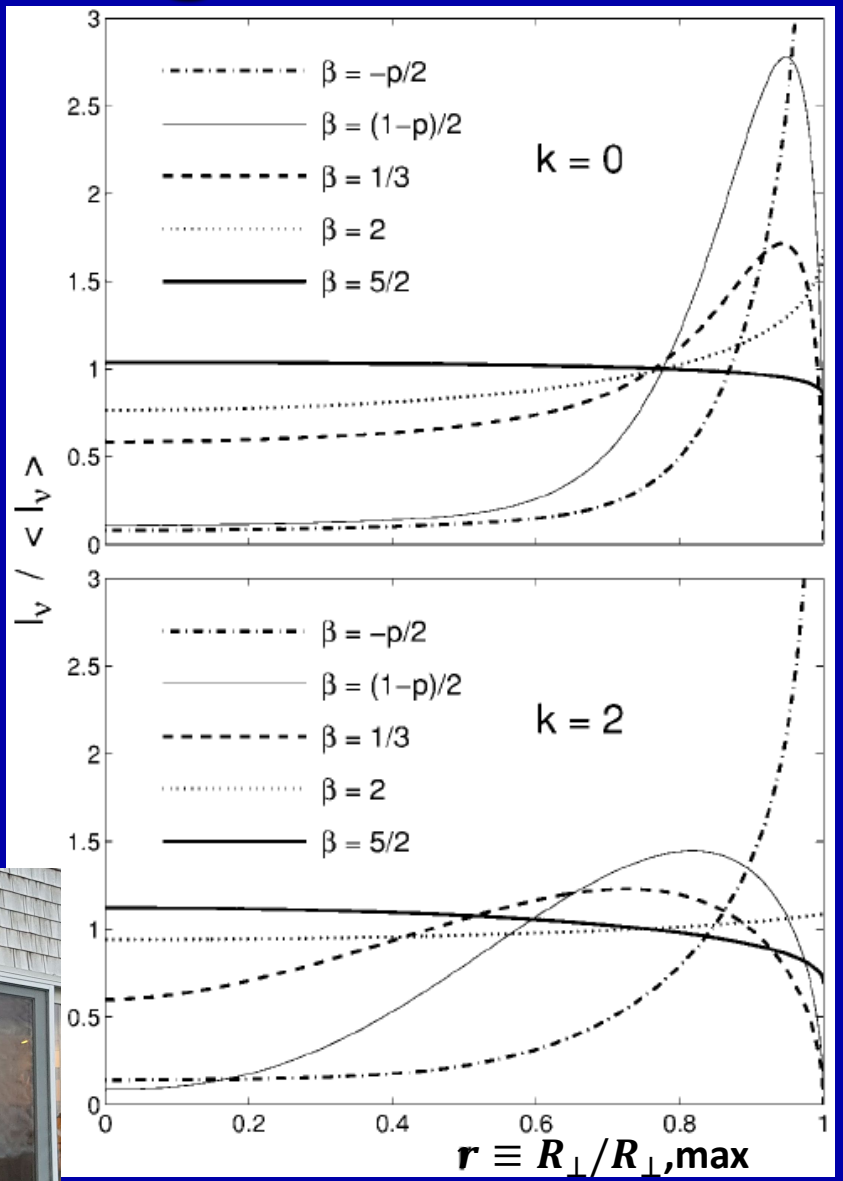
(JG, De Colle & Ramirez-Ruiz 2018)

Afterglow Images:



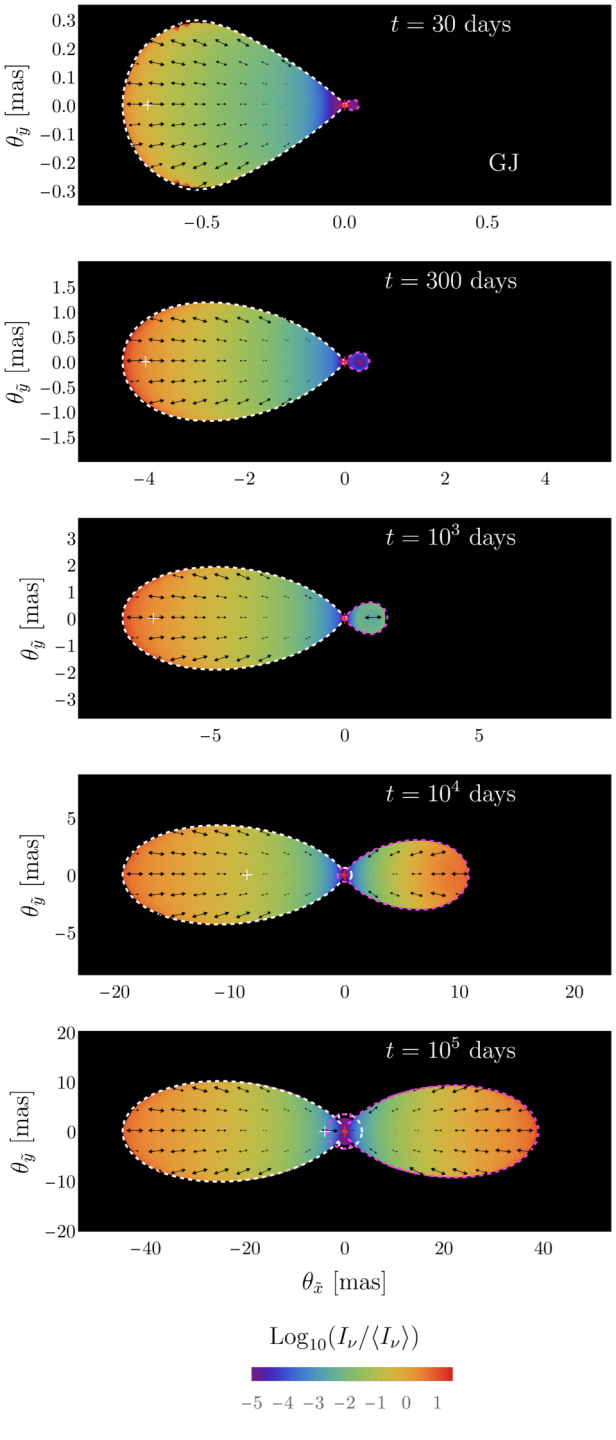


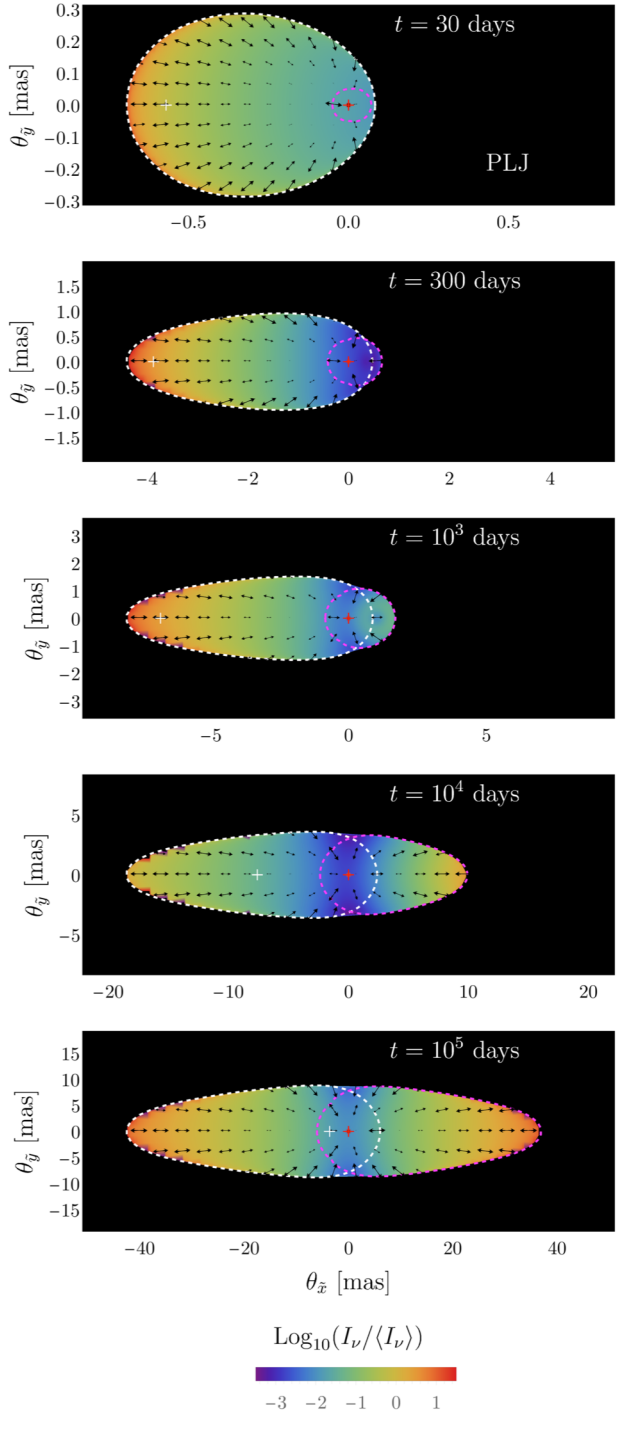
(JG, Ramirez-Ruiz & Loeb 2005)



(JG & Loeb 2001)

Afterglow Images + Polarization maps: GJ, PLJ



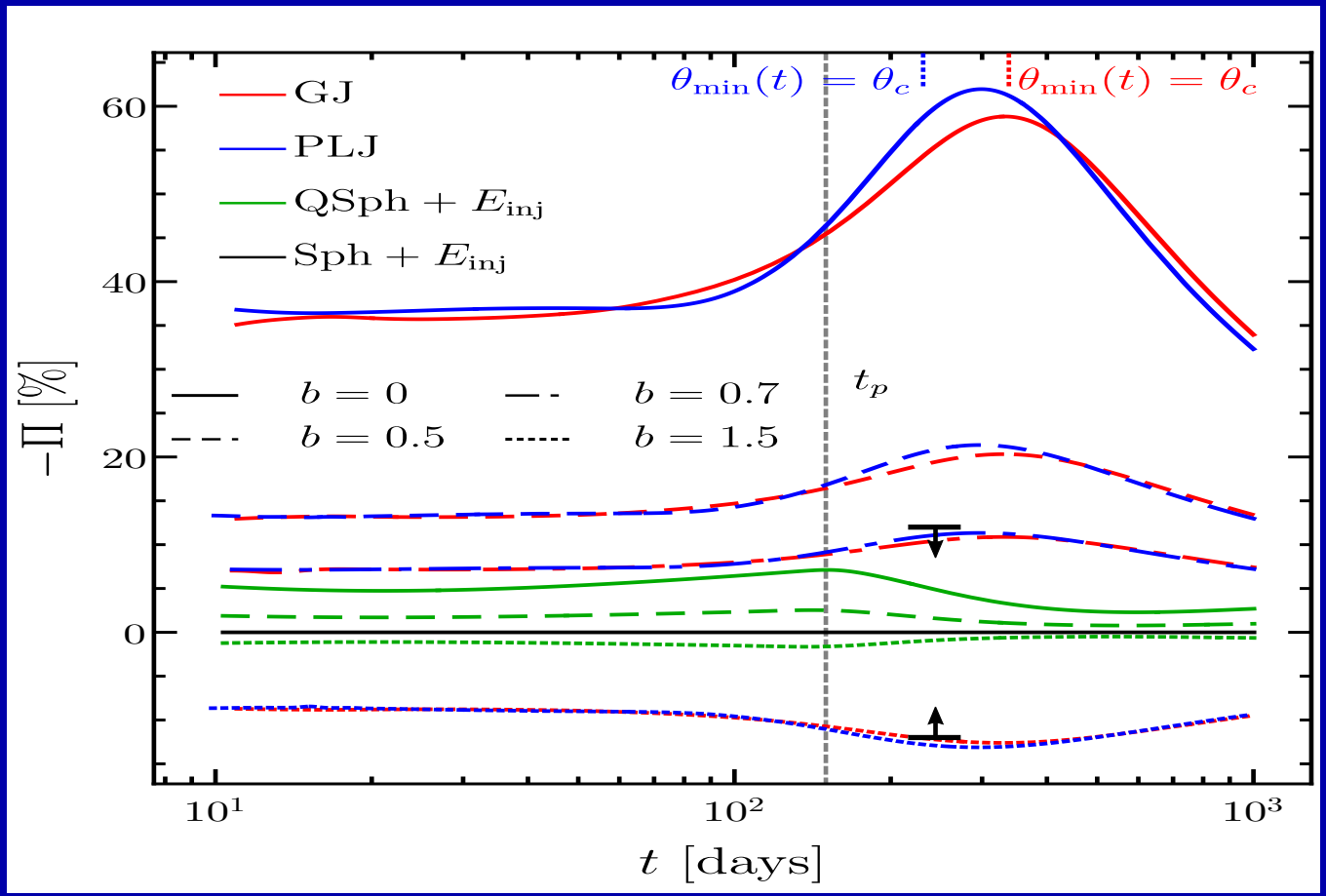


GW170817/GRB170817A Afterglow (Gill & JG 18)

- Assuming a shock-produce B-field with $b \equiv 2\langle B_{\parallel}^2 \rangle / \langle B_{\perp}^2 \rangle$
  - Weibel instability suggests $b \approx 0$ (Medvedev & Loeb 1999)

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, θ_{obs} & B-field structure



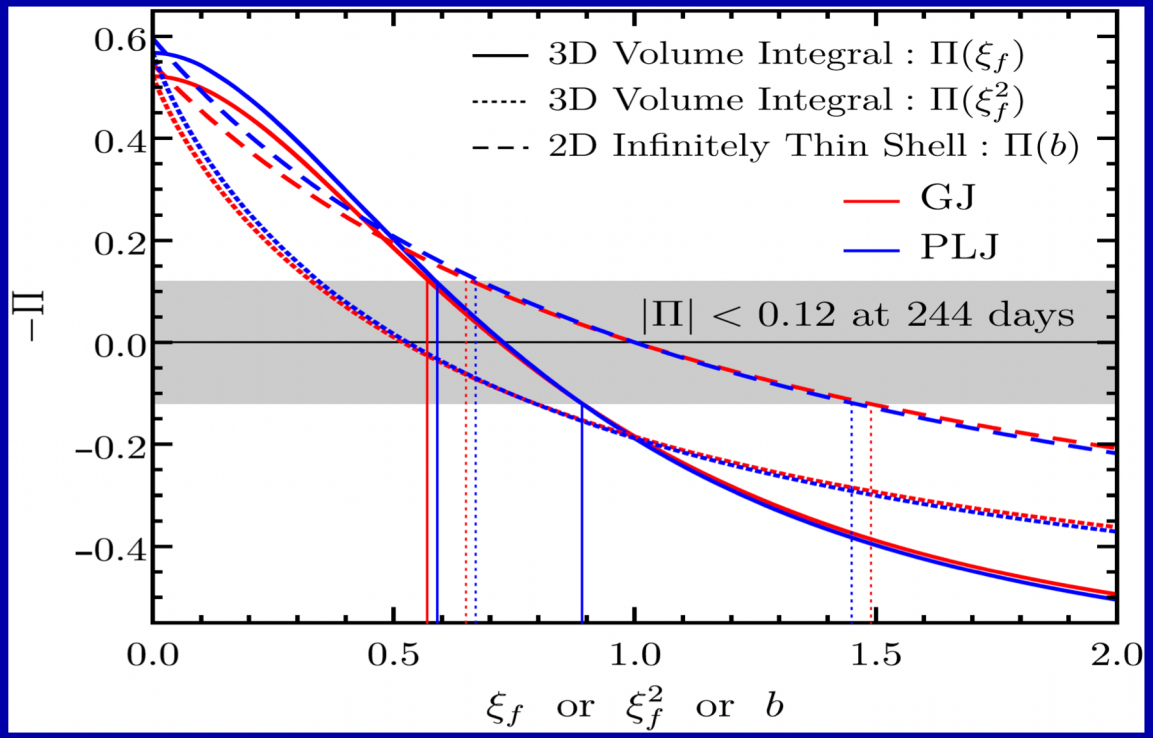
0.7 ≲ b ≲ 1.5 for jet models

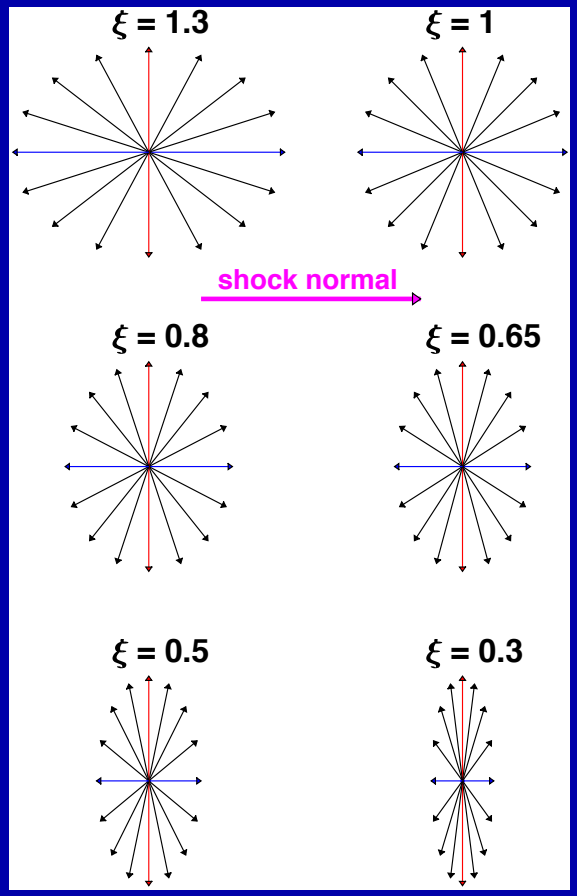
New: upper limit $P_{lin} < 12\%$ @ ν = 2.8 GHz, t = 244 days (Corsi + 2018)

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); $\xi = \xi_f \chi^{(7-2k)/(8-2k)}$





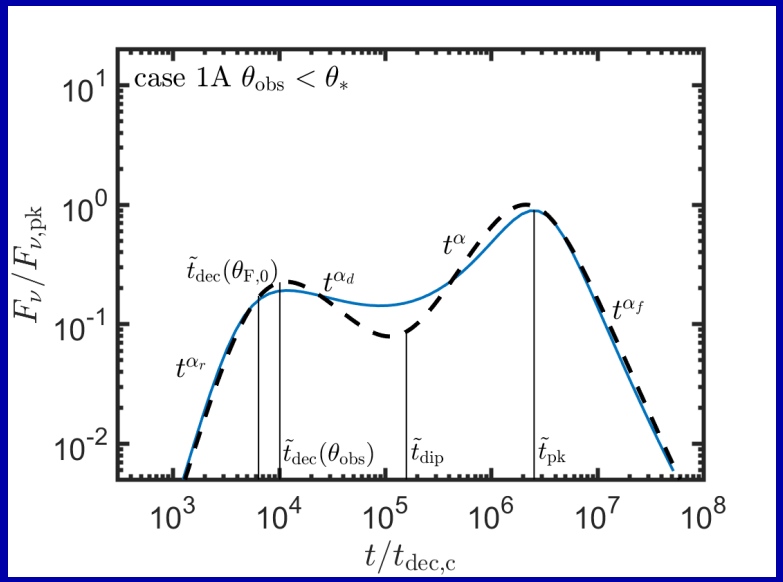
$0.57 \lesssim \xi_f \lesssim 0.89$

Predicted Off-Axis Lightcurves from Structured Jets

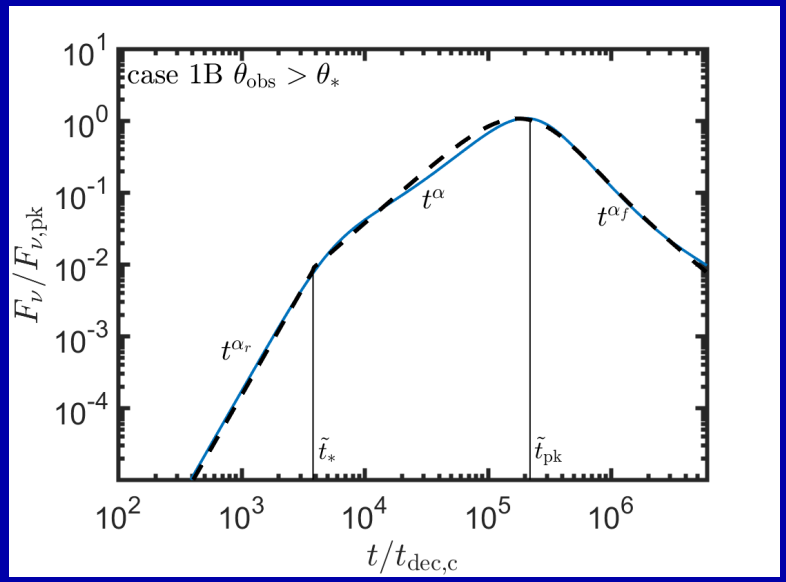
(Beniamini, JG & 2020; Beniamini, Gill & JG 2022)

- 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: $\theta_{obs} > \theta_*$



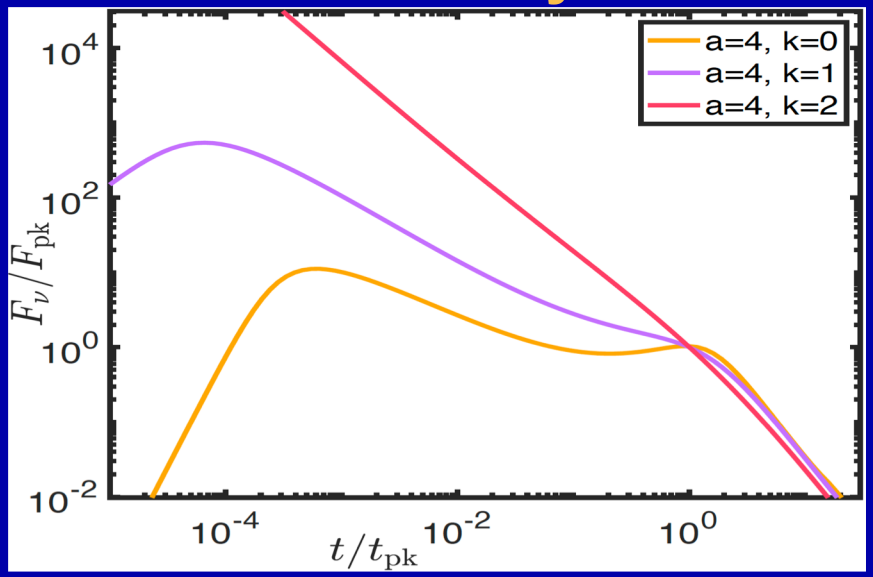
$\theta_* \Gamma_0(\theta_*) = 1$

Predicted Off-Axis Lightcurves from Structured Jets

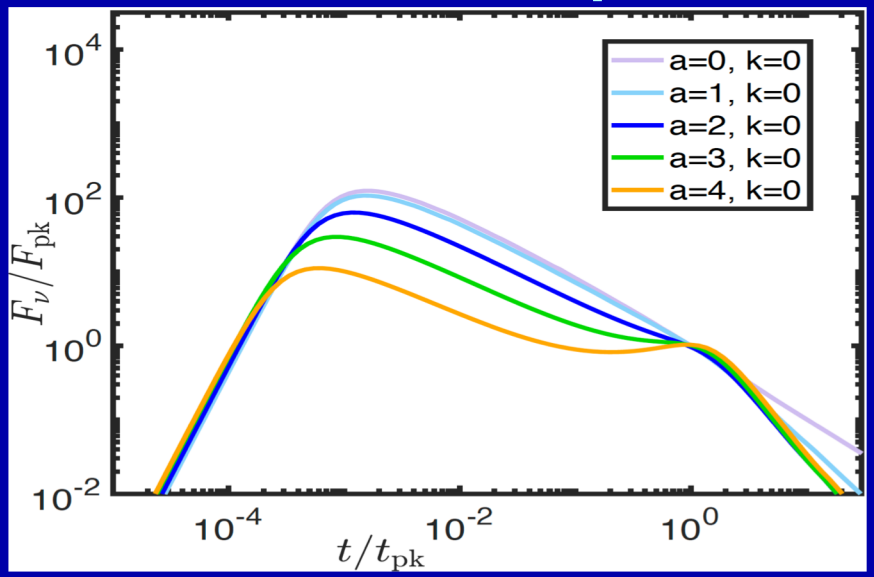
(Beniamini, JG & 2020; Beniamini, Gill & JG 2022)

- 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

External Density ∝ R^{-k} :



Shallow vs. Steep Jet:



Happy Birthday Avi!!!