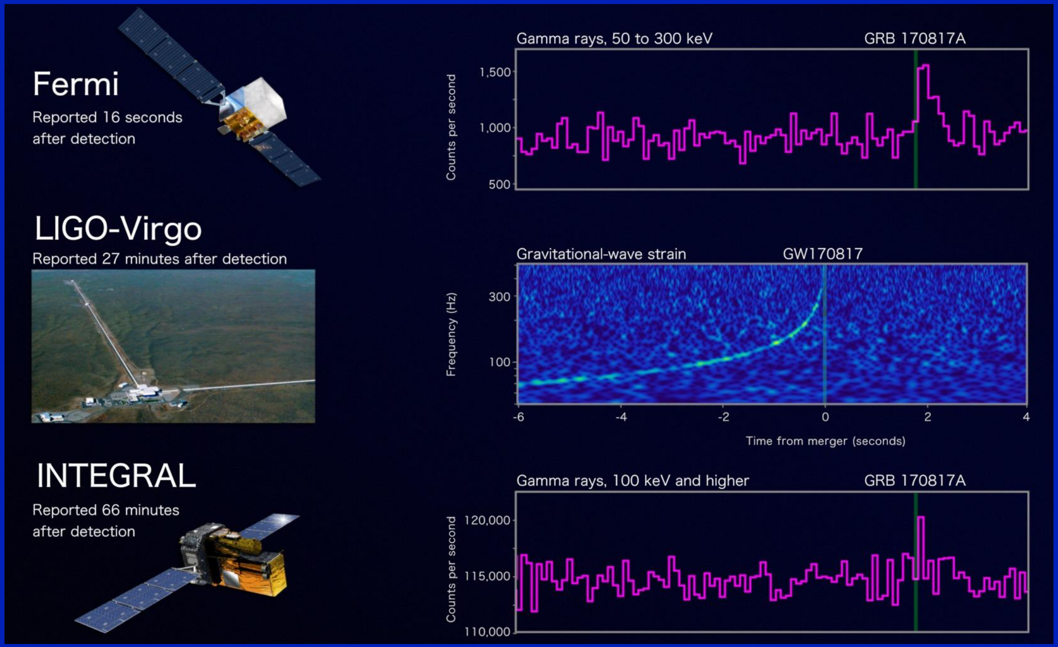
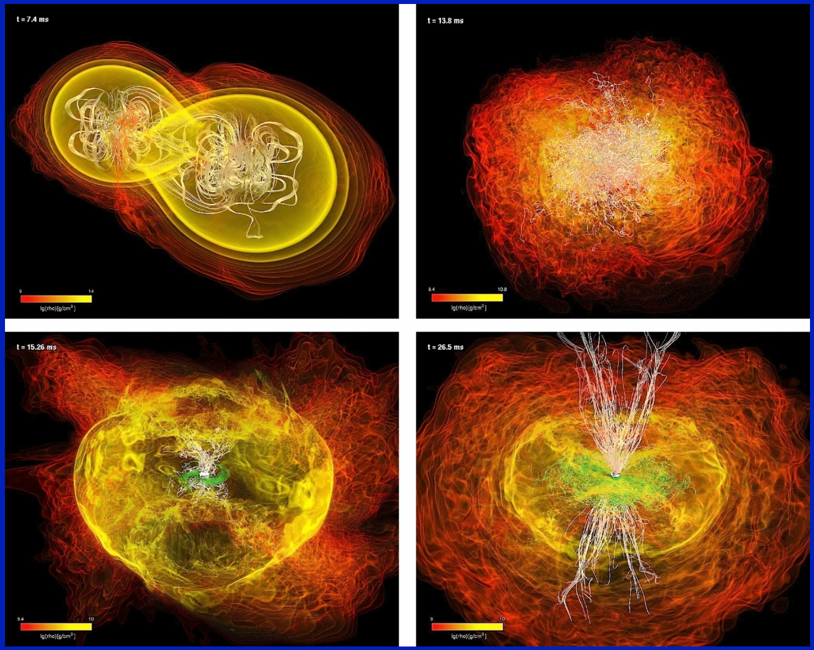
Lessons from GW170817 / GRB170817A

Jonathan Granot

Open University of Israel & George Washington University

Collaborators: R. Gill, F. De Colle, D. Guetta, E. Ramirez-Ruiz, T. Piran





3rd PANDA Symposium on Time Domain Astronomy & 1st results from Insight-HXMT; Chengdu, China, June 19, 2018

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. θ dependence**
  - **Breaking the degeneracy: lightcurves? Images, Polarization**
- **Conclusions**

GW 170817: the type of remnant

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

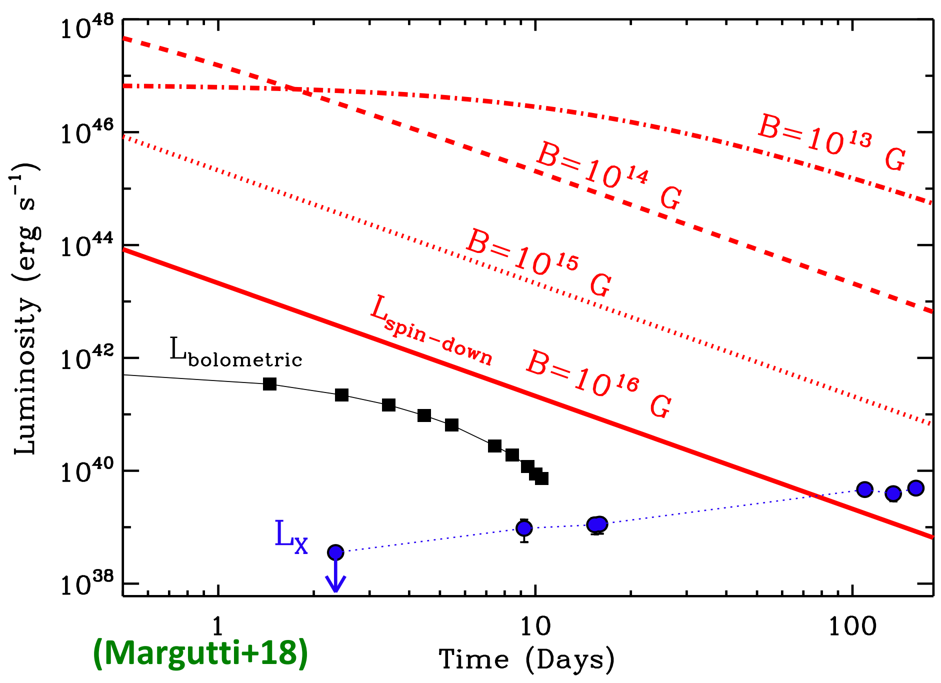
post-merger total mass: $M_i = M_1 + M_2$

- Final mass $M_f \approx 0.93 M_i$ due to:
  - GW & neutrino energy losses
  - Mass ejection during the merger
- A stable NS or SMNS $\Rightarrow P_0 \approx 1$ ms

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

$\Rightarrow$ would contradict afterglow obs.

(also what produces the GRB/afterglow?)



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)

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

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

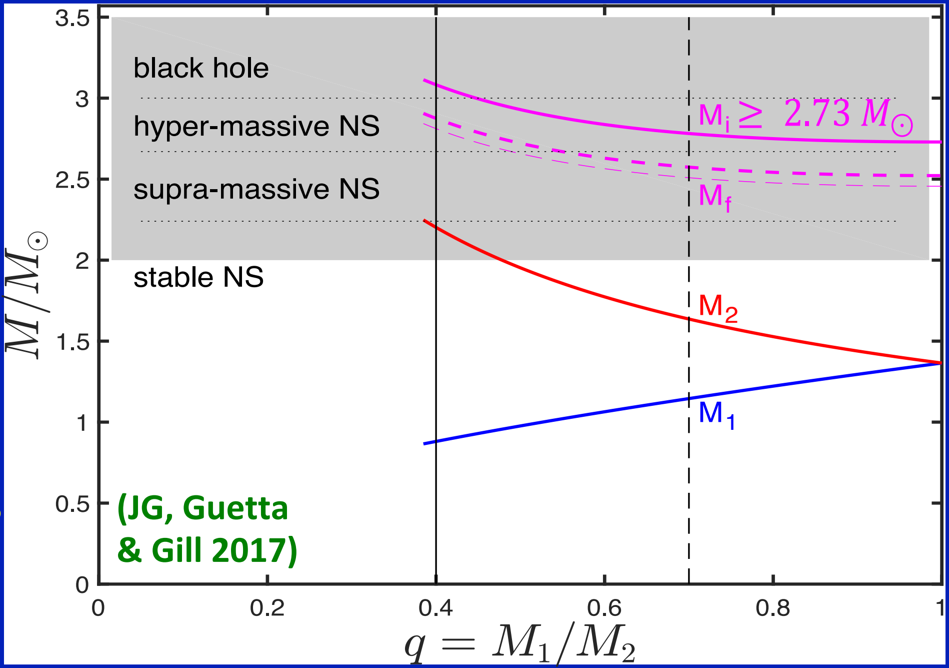
- A HMNS may explain $\Delta t \approx 1.74$ s by $t_{HMNS} \lesssim 0.5$ s & $t_{bo} \sim 1$ s

(Moharana & Piran 2017 find $t_{bo} \sim 0.5$ s for SGRBs)

- direct BH formation $\Rightarrow$ shorter $t_{bo} \Rightarrow$ jet less likely to be chocked

GW 170817: the type of **remnant**

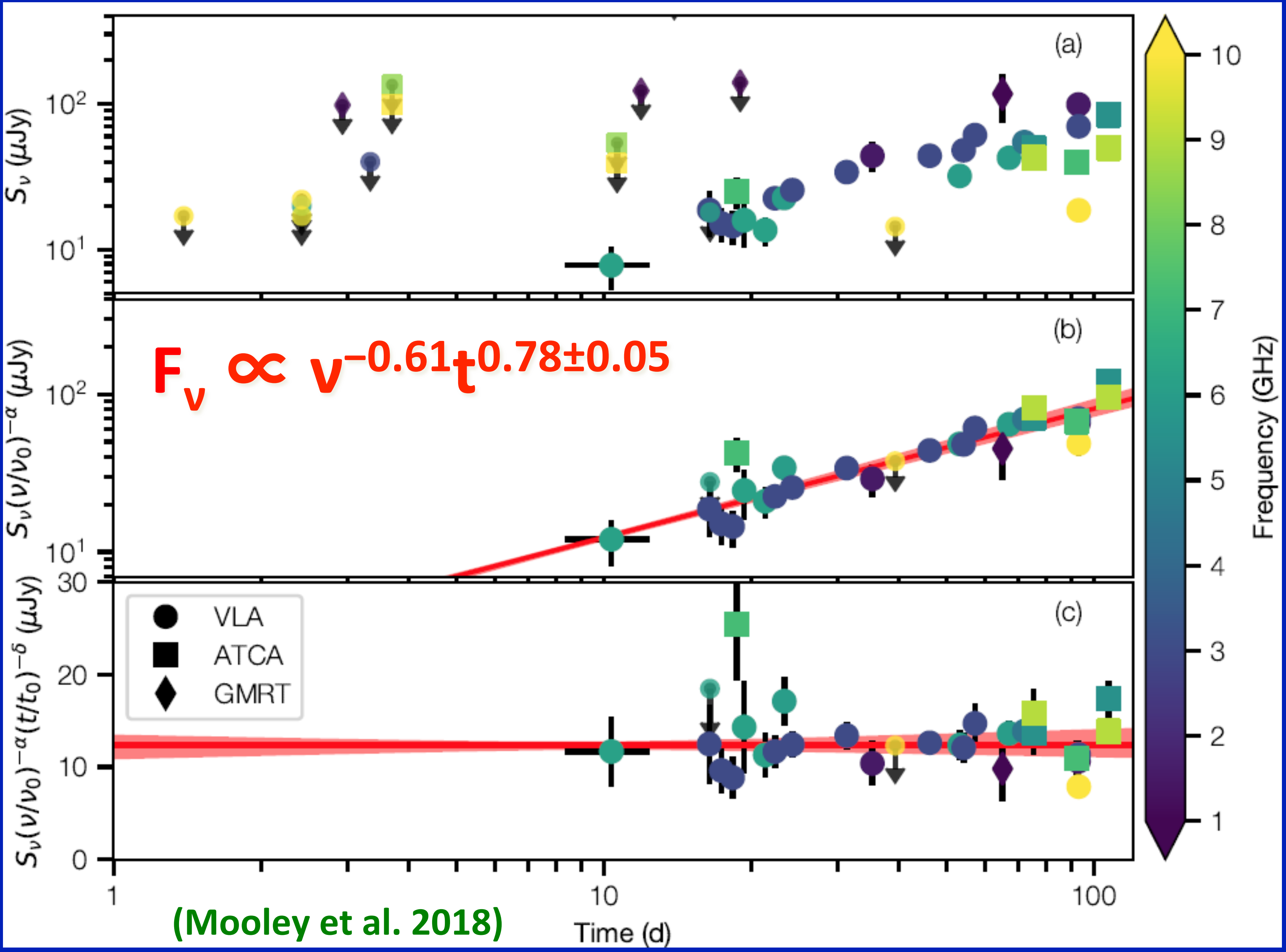
- $M_{1,2}$ = pre-merger NS $M_{\rm gravitational}$
post-merger total mass: $M_i = M_1 + M_2$
- Final mass $M_f \approx 0.93 M_i$ due to:
  - GW & neutrino energy losses
  - Mass ejection during the merger
- A stable NS or SMNS $\Rightarrow P_0 \approx 1\,$ms
$\Rightarrow E_{\rm rot} \gtrsim 10^{52.5}$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



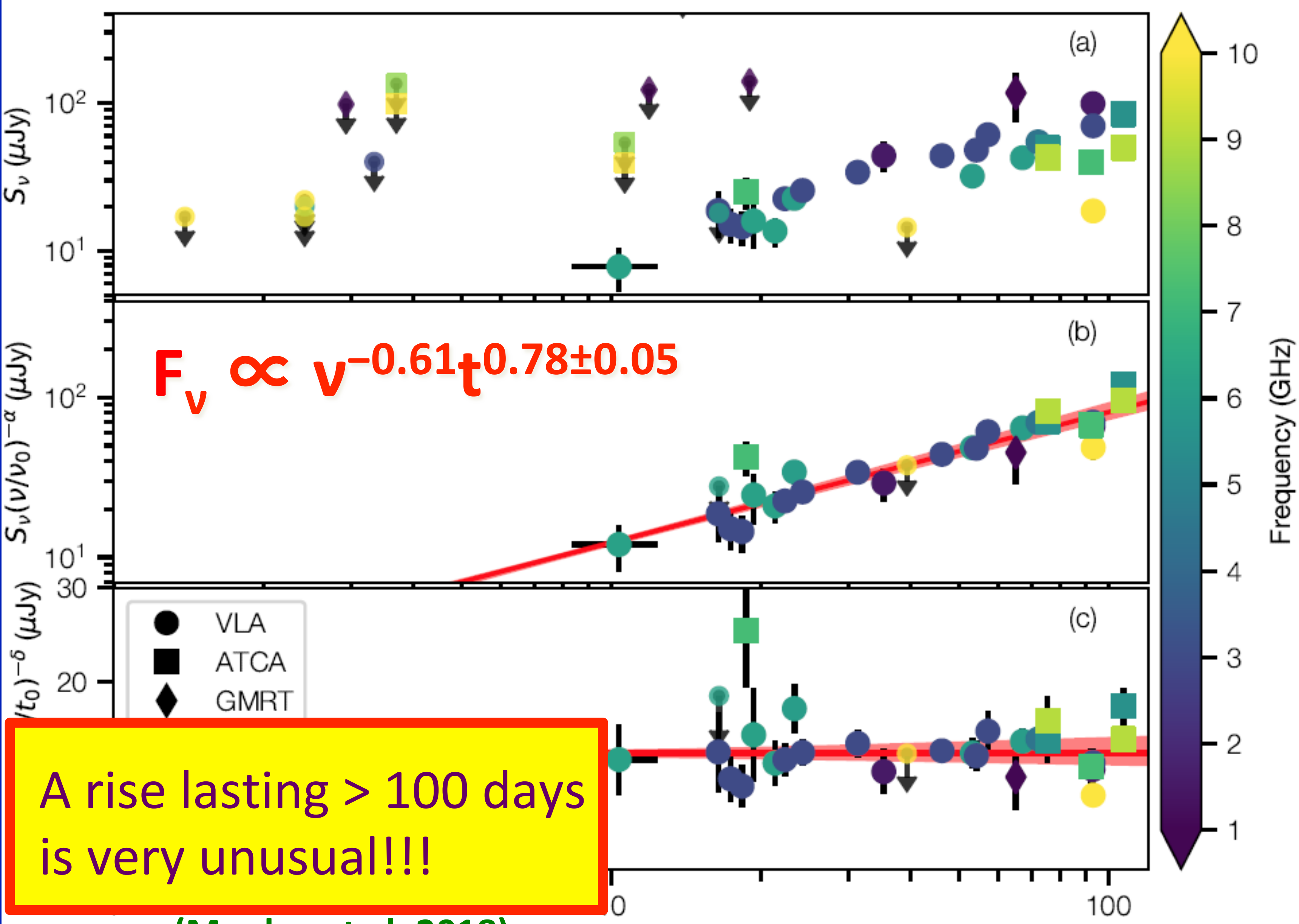
Chirp mass: $\mathcal{M} = \left(\frac{M_1^3 M_2^3}{M_1 + M_2}\right)^{1/5} = 1.188^{+0.004}_{-0.002}\, M_\odot$ (Abbott+ 2017)

- The argument can be reversed to constrain NS EoS & $M_{\max} \lesssim 2.17 M_\odot$
(Margalit & Metzger 2017; Rezzolla et al. 2018)
- A HMNS may explain $\Delta t \approx 1.74$ s by $t_{\rm HMNS} \lesssim 0.5$ s & $t_{\rm bo} \sim 1$ s
(Moharana & Piran 2017 find $t_{\rm bo} \sim 0.5$ s for SGRBs)
- direct BH formation $\Rightarrow$ shorter $t_{\rm bo} \Rightarrow$ jet less likely to be chocked

GRB 170817A: afterglow observations



GRB 170817A: afterglow observations

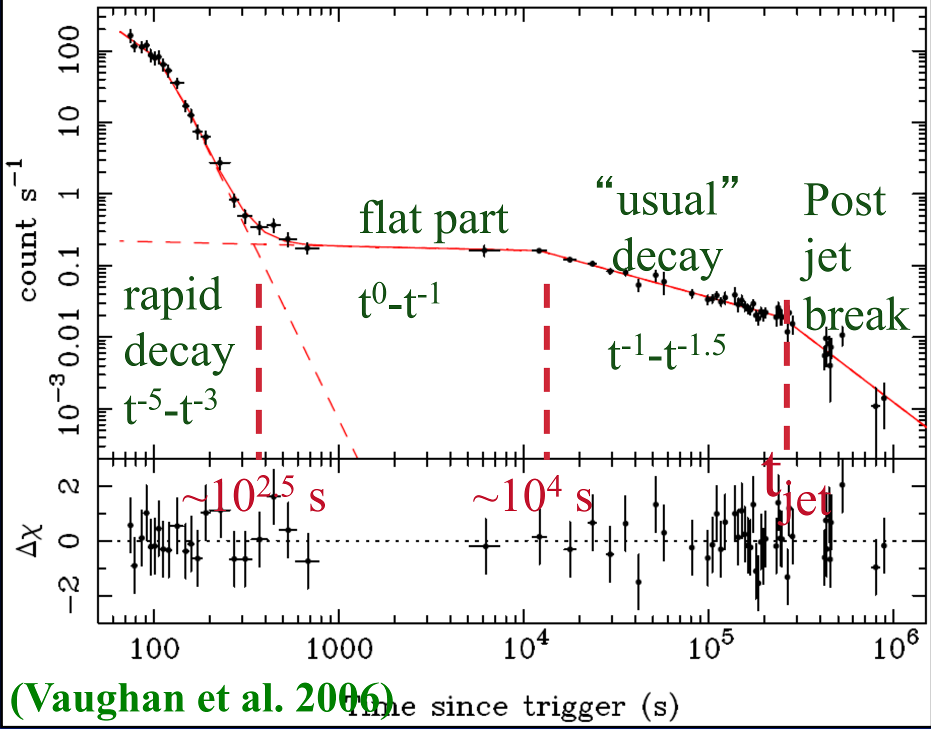


(Mooley et al. 2018)

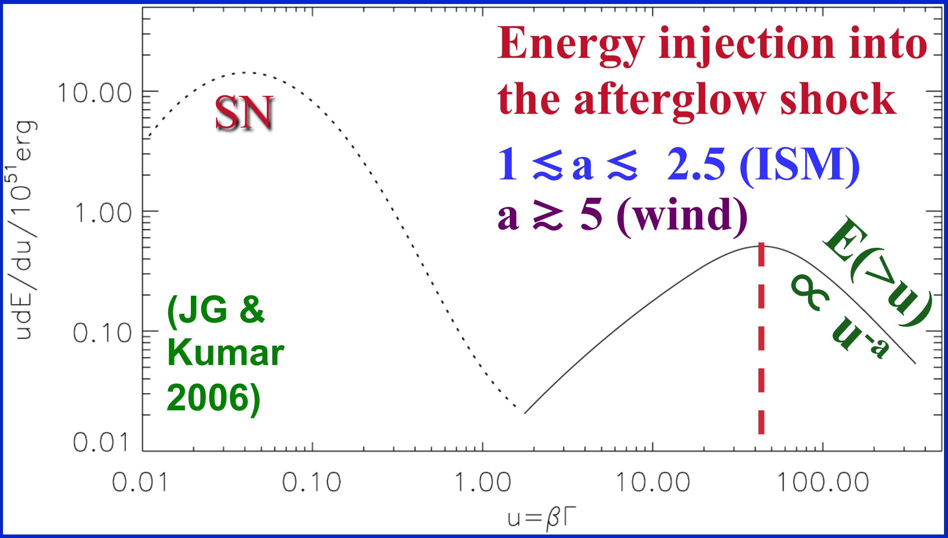
Analogy to rising F_ν: X-ray Plateaus

- 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 **radial** (Sari & Meszaros 00; Nousek+ 06; JG & Kumar 06)

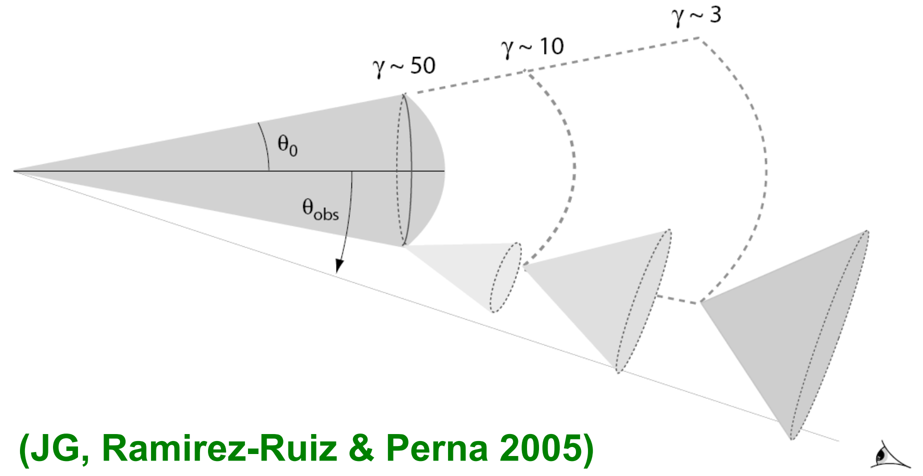


(Vaughan et al. 2006)



(JG & Kumar 2006)

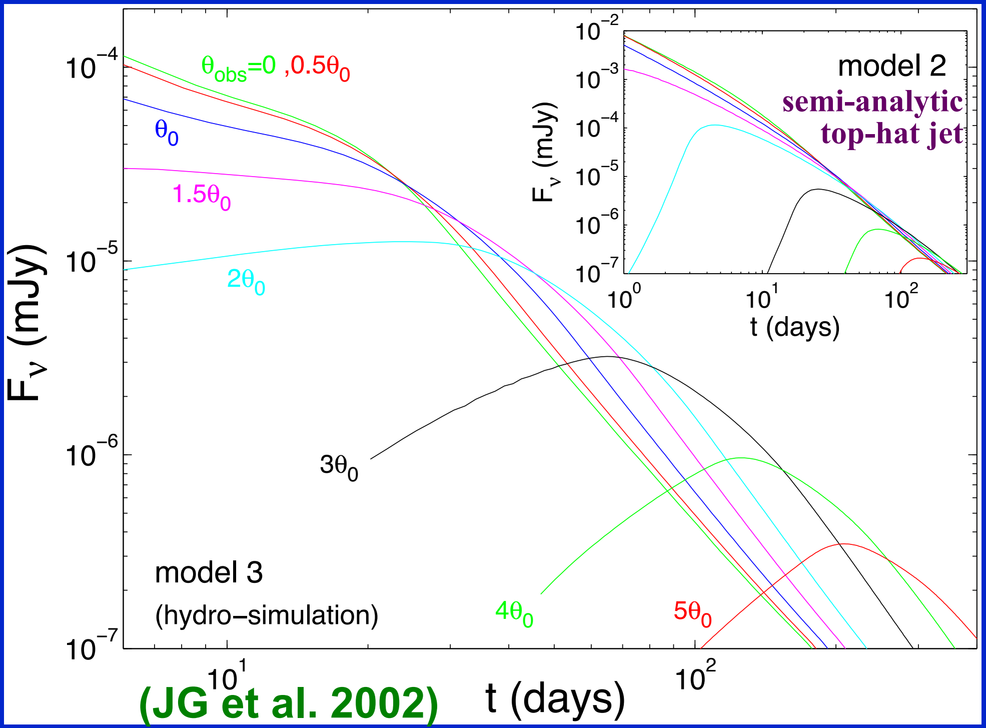
- Viewing angle effects **angular**



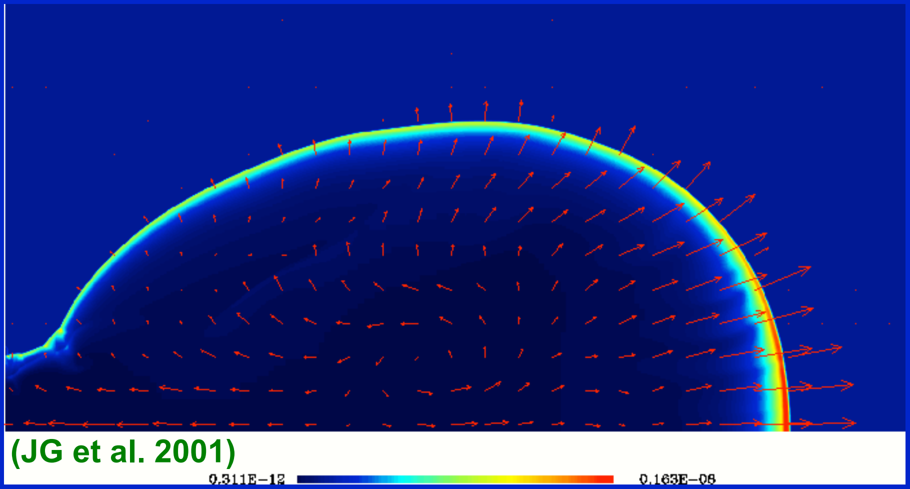
(JG, Ramirez-Ruiz & Perna 2005)

Off-Axis Afterglow Lightcurves

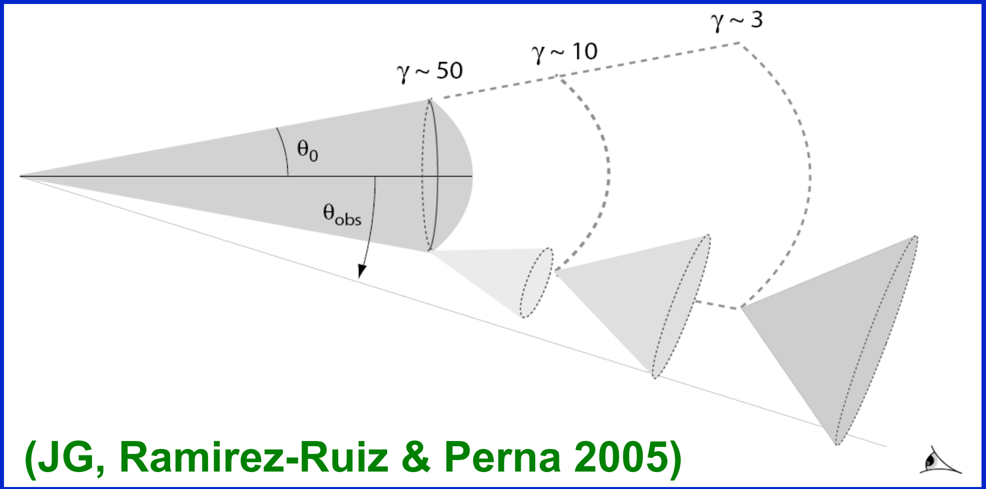
- The emission is initially strongly beamed away from our L.o.S
- F_ν rises as beaming cone widens
- When beaming cone reaches LoS F_ν peaks & approaches on-axis F_ν
- The rise is much more gradual for hydrodynamic simulations due to slower matter at the jet's sides with non-radial velocities



(JG et al. 2002)



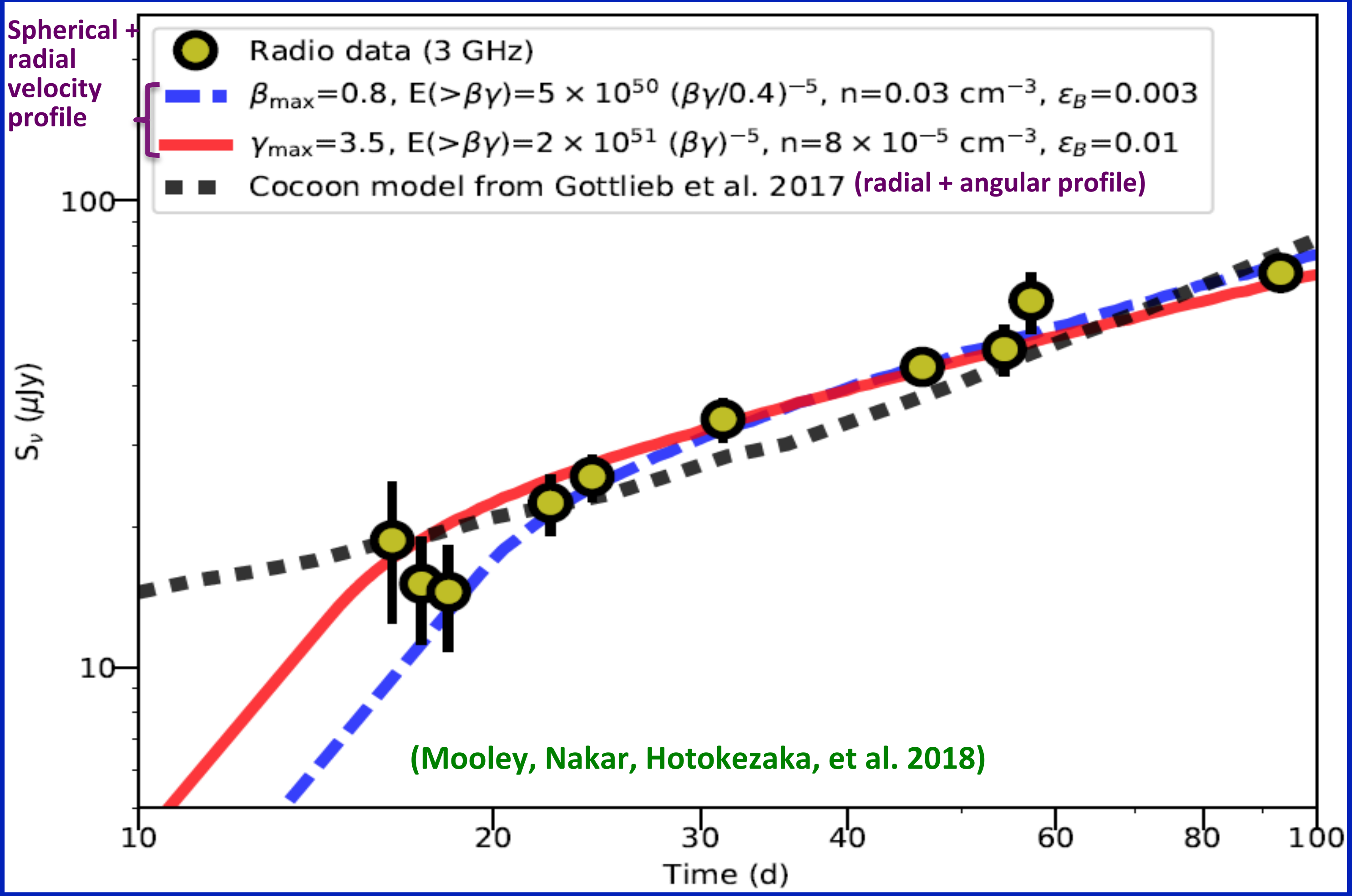
(JG et al. 2001)



(JG, Ramirez-Ruiz & Perna 2005)

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)

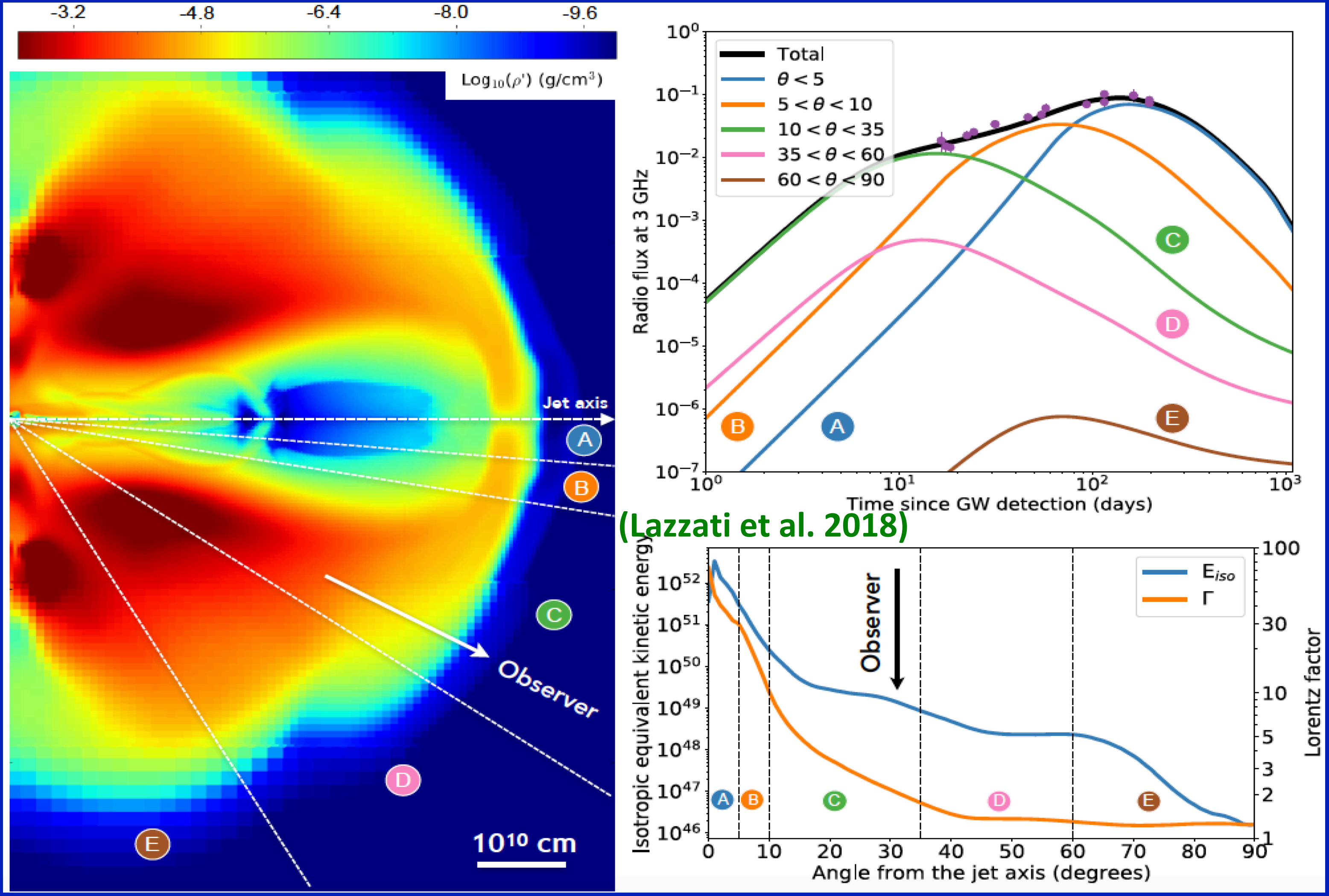


GRB170817 outflow structure: the afterglow

- 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

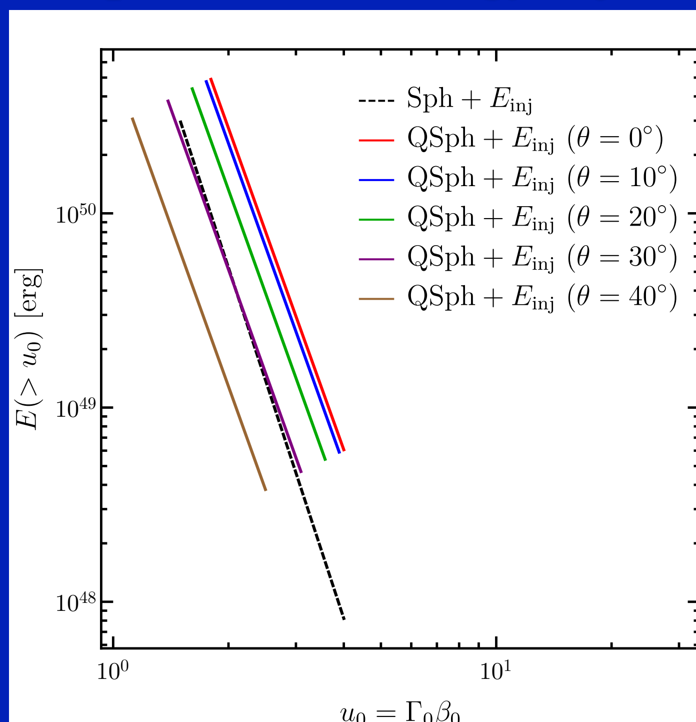


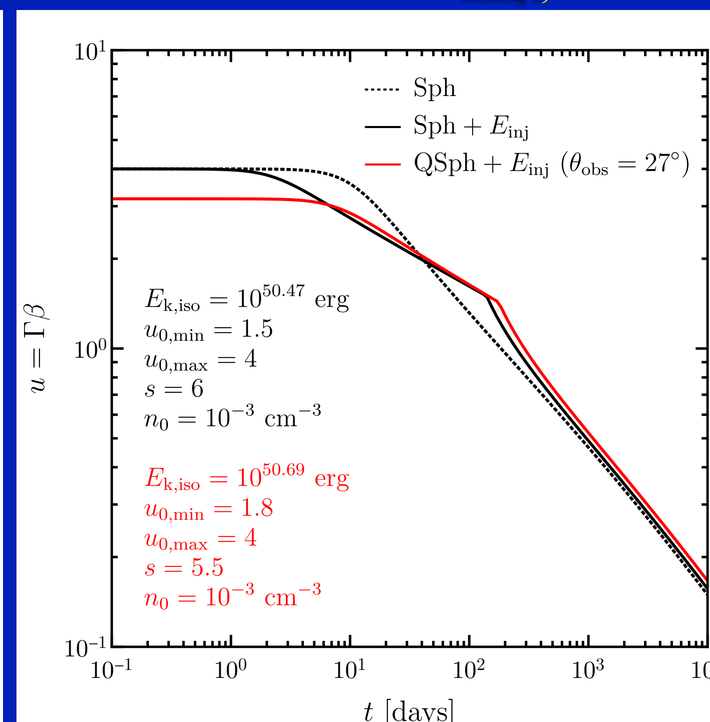
(Lazzati et al. 2018)

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 $E(>u) \propto u^{-s}$, $u_{min,0}=1.8$ $u_{max,0} = 4$, $s = 5.5$, $\zeta = 0.1$

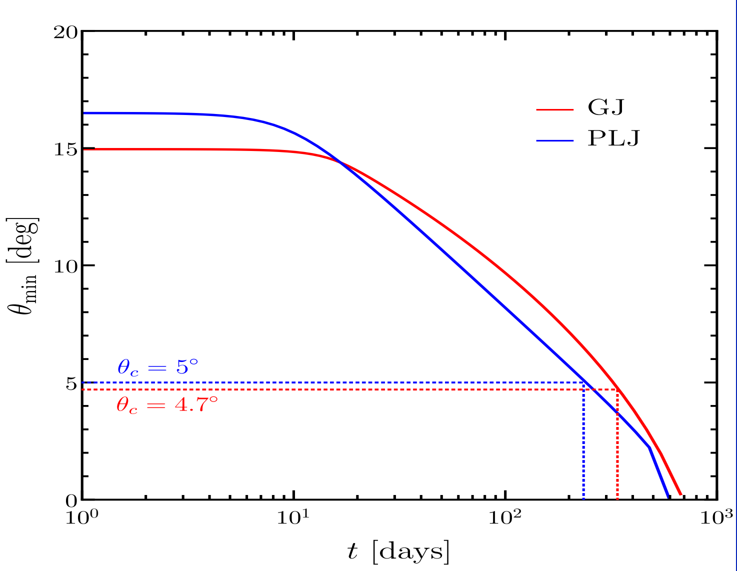
$$\frac{\epsilon(\theta)}{\epsilon_0} = \frac{u_{0,\min}(\theta)}{u_{\min,0}} = \frac{u_{0,\max}(\theta)}{u_{\max,0}} = \frac{\zeta + \cos^2\theta}{\zeta + 1}$$

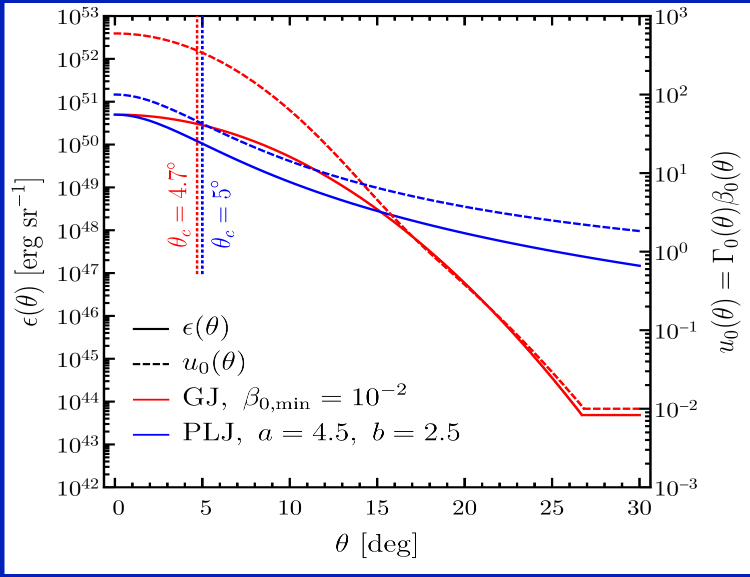




Outflow structure: breaking the degeneracy (Gill & JG 18)

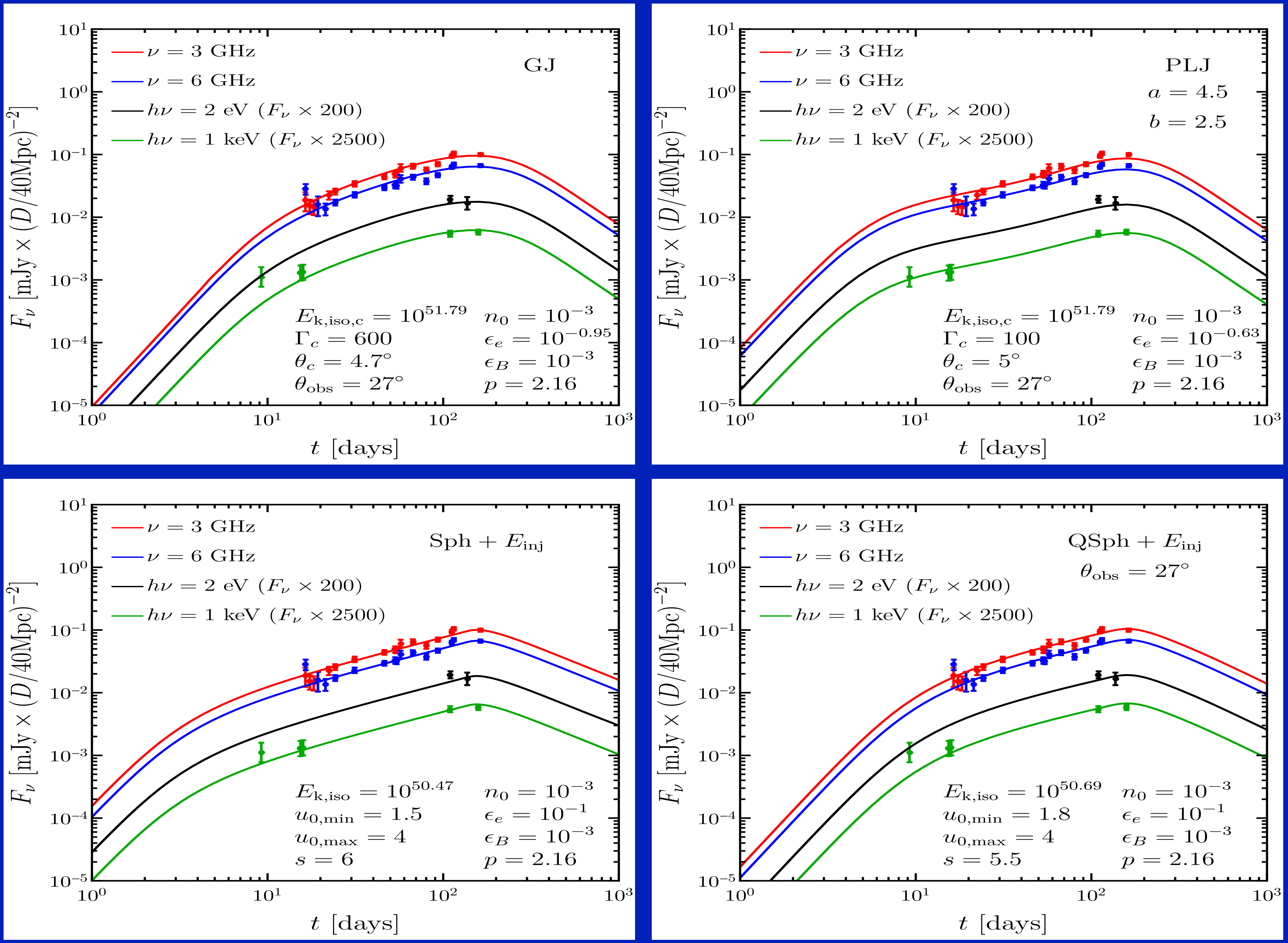
- The lightcurves leave a lot of degeneracy between models
- The degeneracy may be lifted by calculation the afterglow images & polarization (e.g. Nakar & Piran 2018; Nakar et al. 2018)
- We considered 4 different models including both main types
  - GJ: Gaussian Jet (in $\varepsilon = dE/d\Omega$, Γ_0-1) $\Gamma_c = 600$, $\theta_c = 4.7°$
  - PLJ: Power-Law Jet; $\varepsilon = \varepsilon_c\Theta^{-a}$, $\Gamma_0-1 = (\Gamma_c-1)\Theta^{-b}$, $\Theta = [1+(\theta/\theta_0)^2]^{1/2}$ $\Gamma_c = 100$, $\theta_c = 5°$, $a = 4.5$, $b = 2.5$
- As there is a lot of freedom we fixed: $p = 2.16$, $\varepsilon_B = n_0 = 10^{-3}$, $\theta_{obs} = 27°$





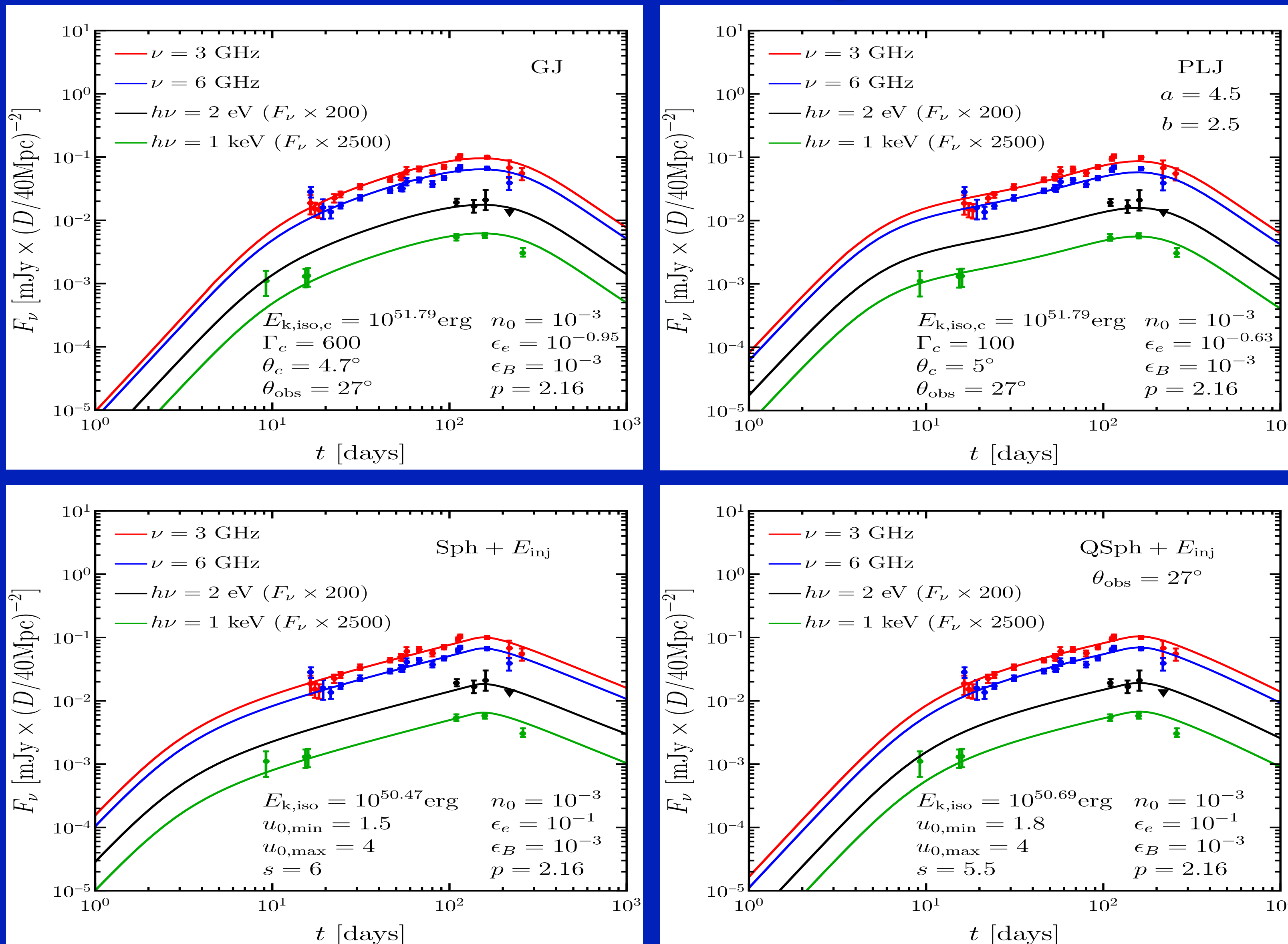
The outflow structure: breaking the degeneracy

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



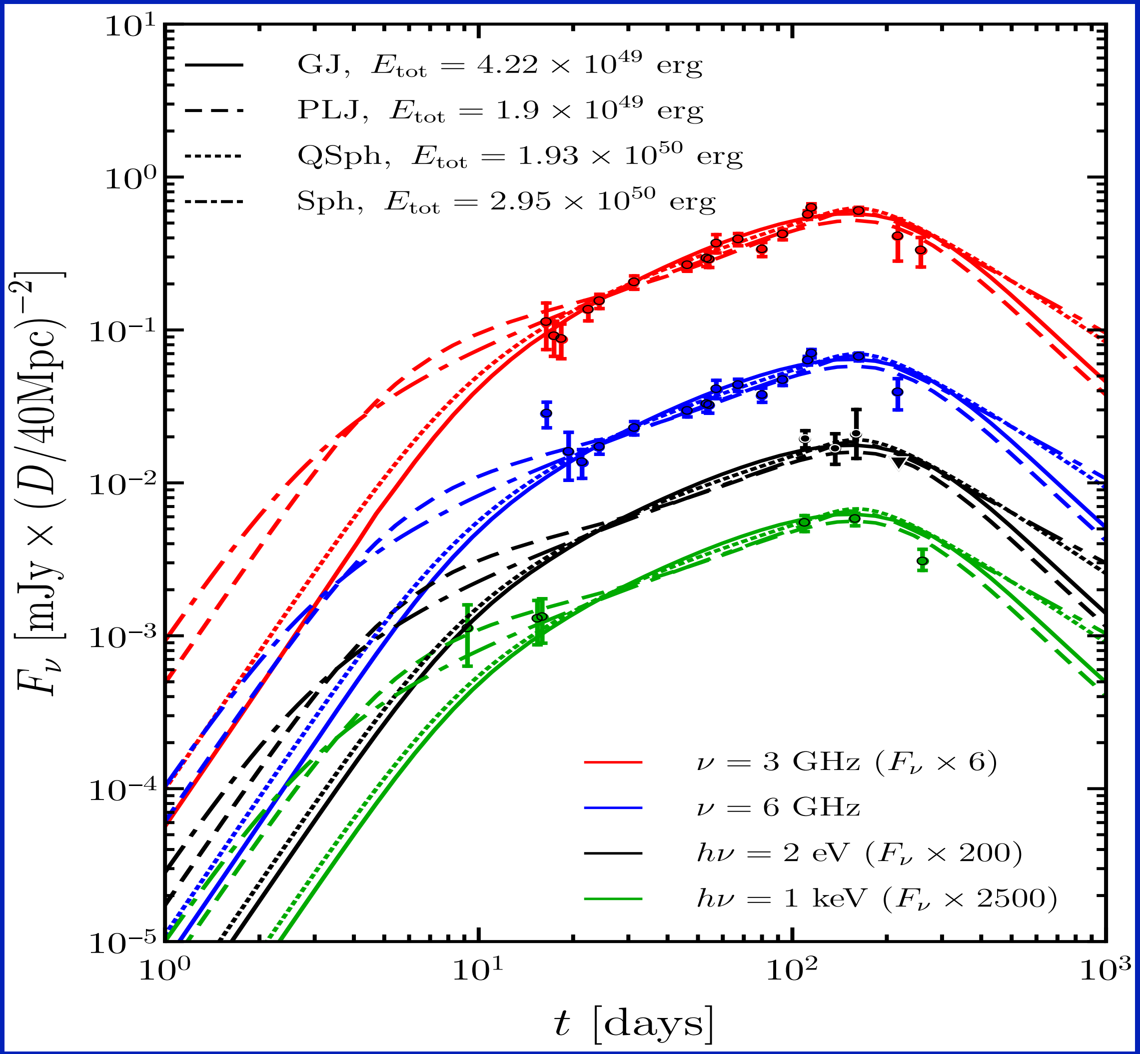
The outflow structure: breaking the degeneracy

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

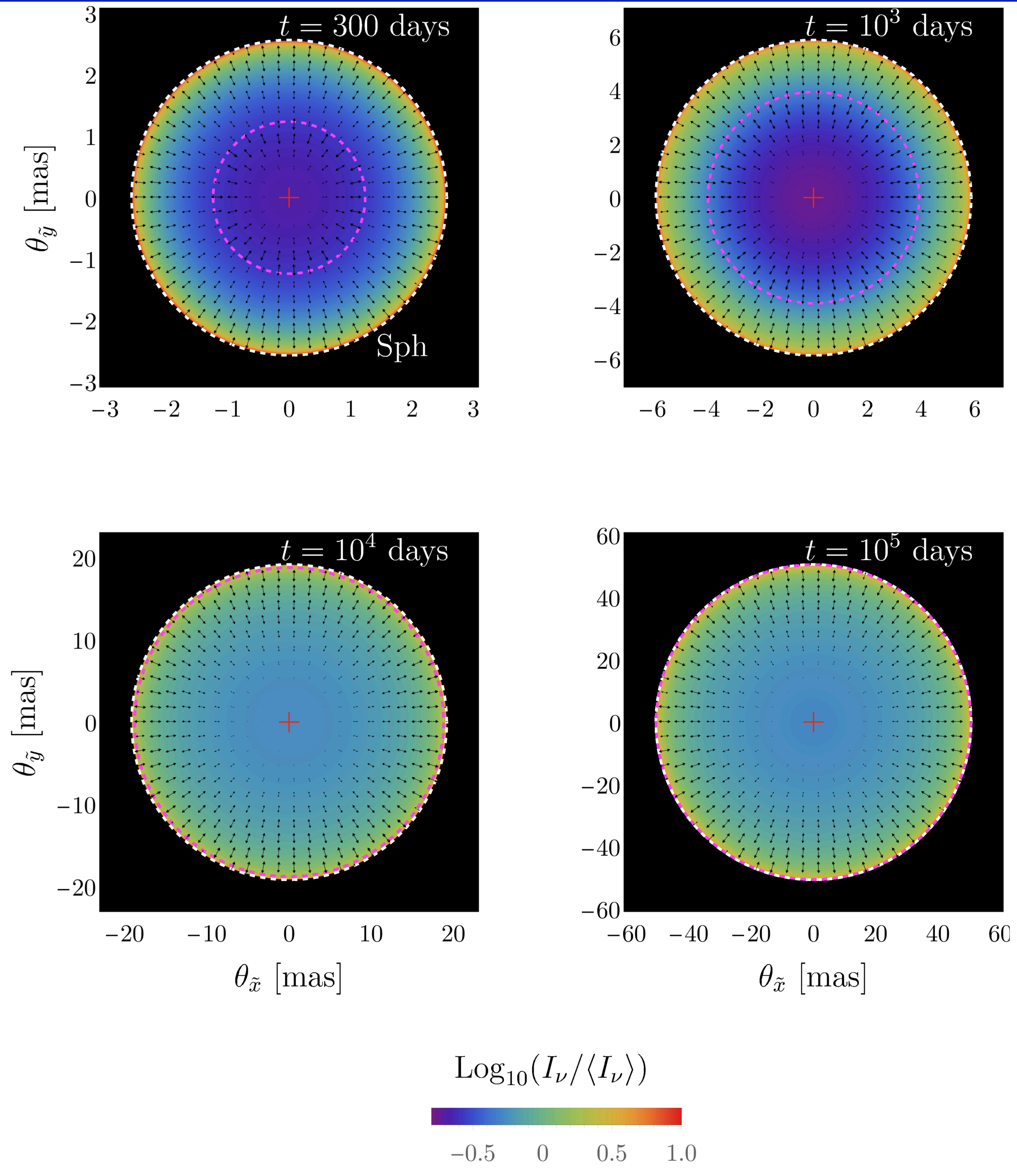


The outflow structure: breaking the degeneracy

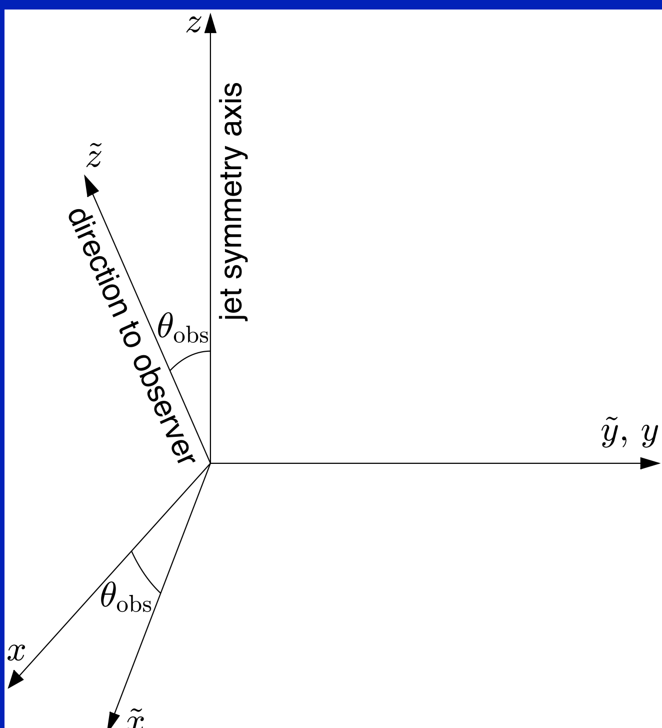
- New data just came out establishing a peak at t_p ~150 days
- The jet models decay faster (slightly preferred by the latest data)

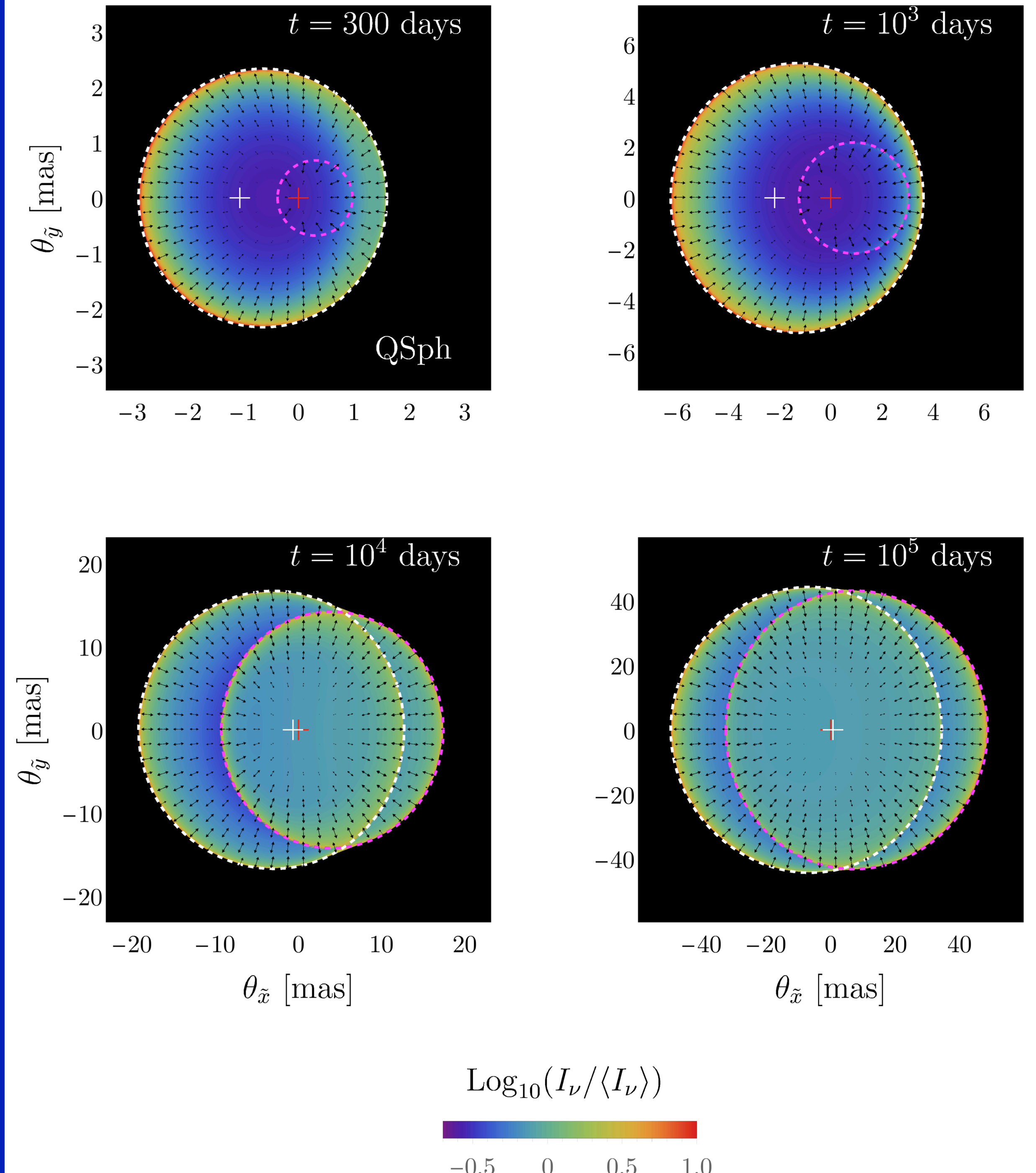


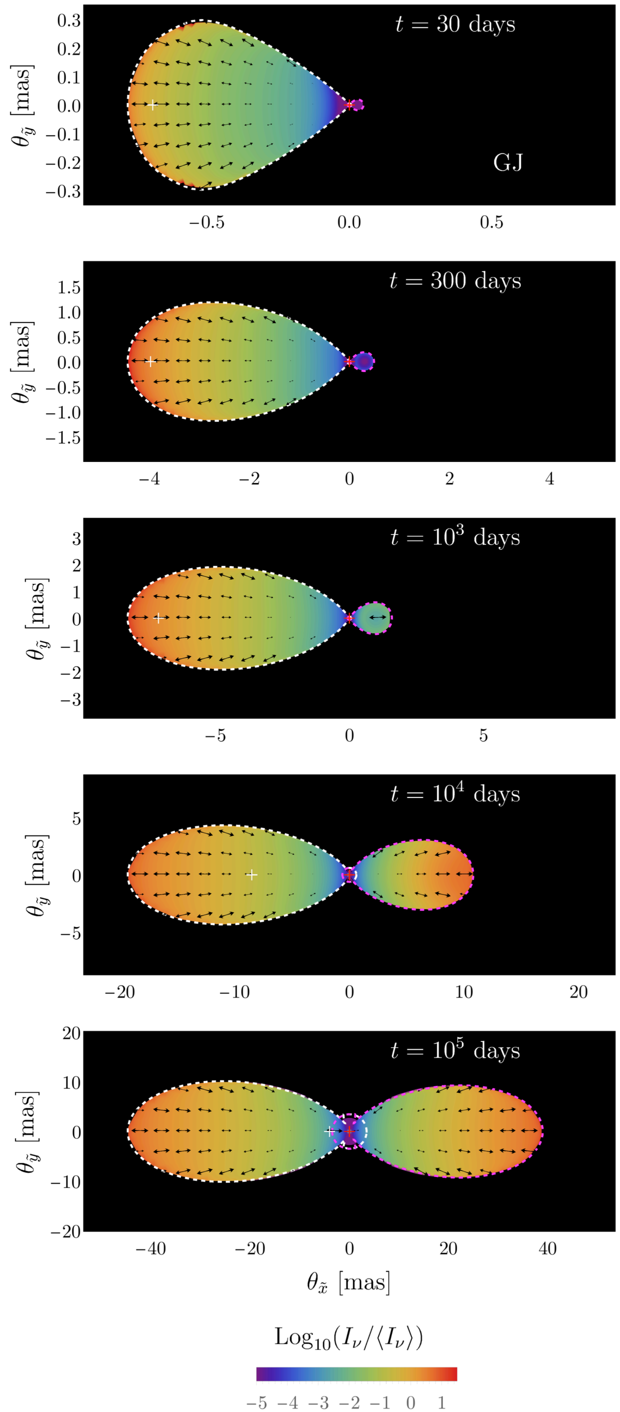
Afterglow Images: Sph + E_{inj}



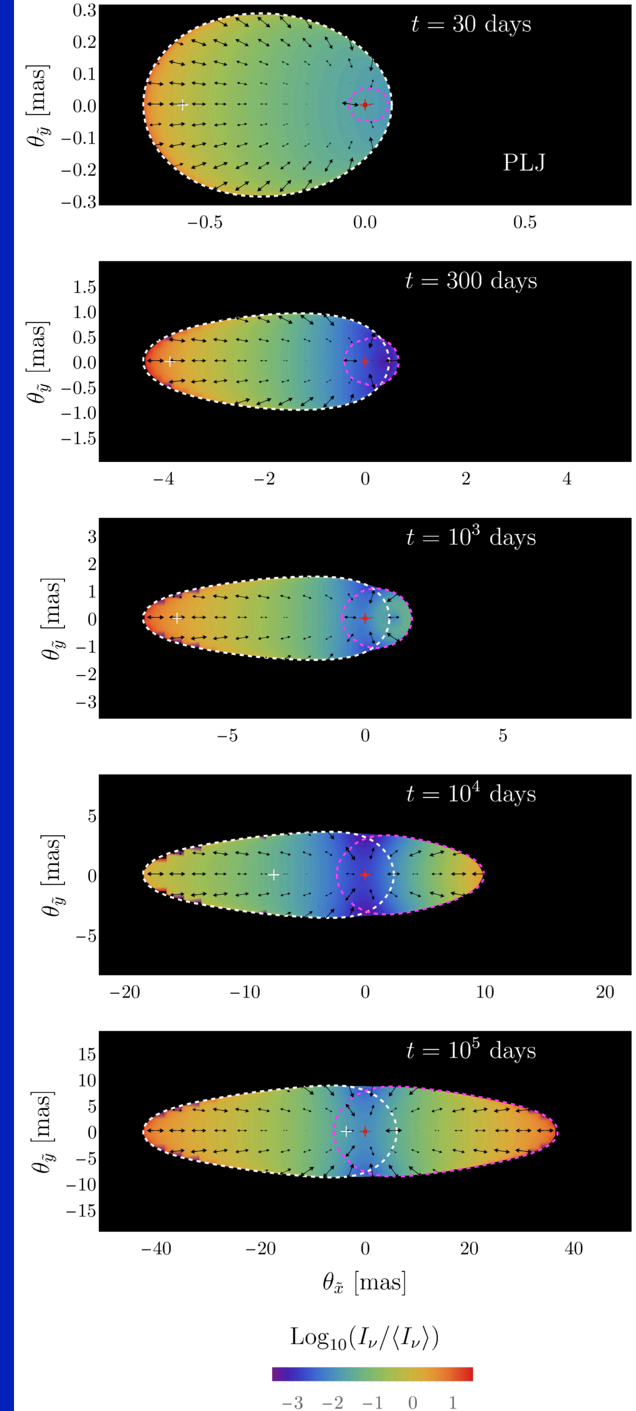
Afterglow Images: QSph + E_{inj}





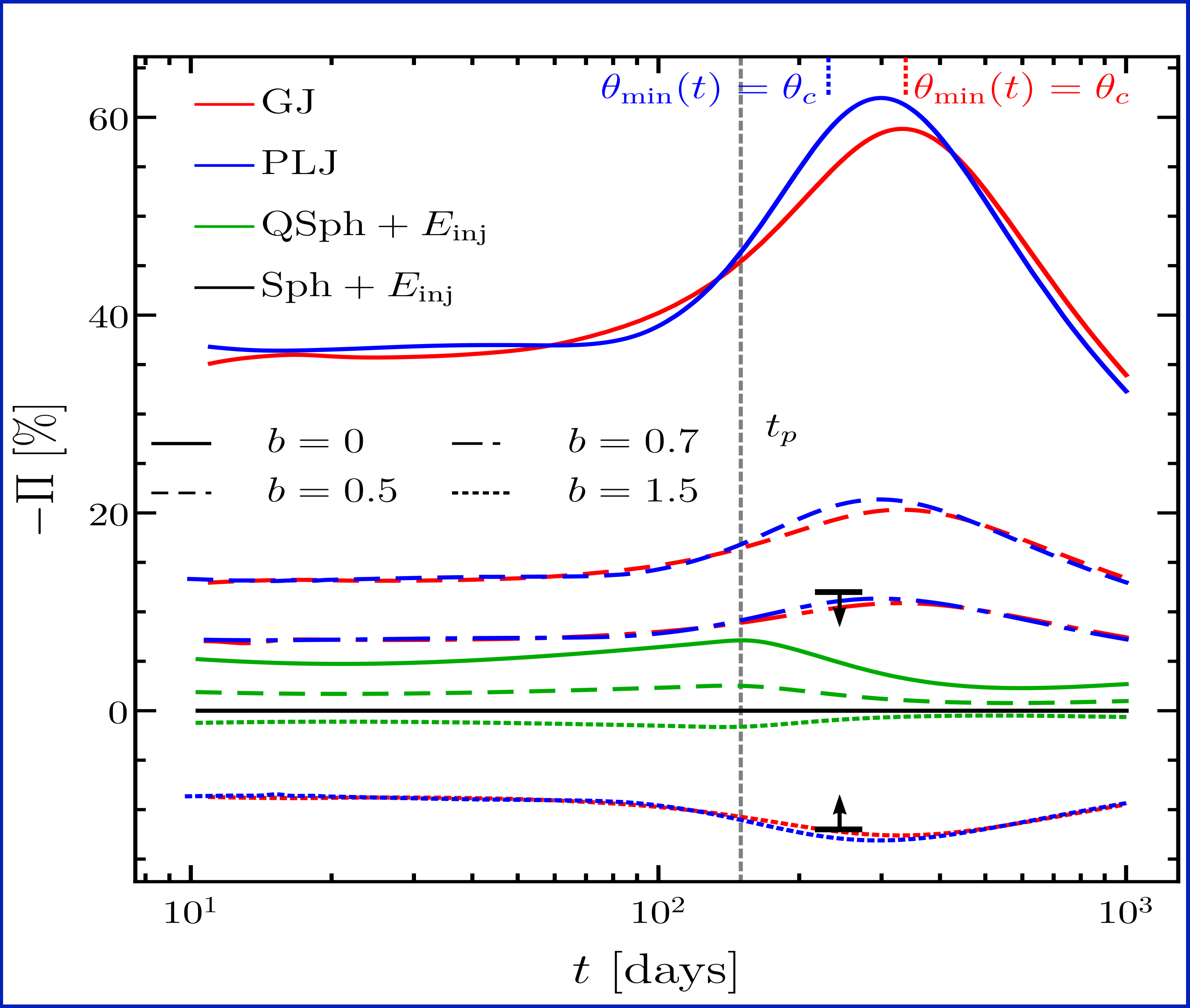


Afterglow Images: GJ, PLJ



Linear Polarization

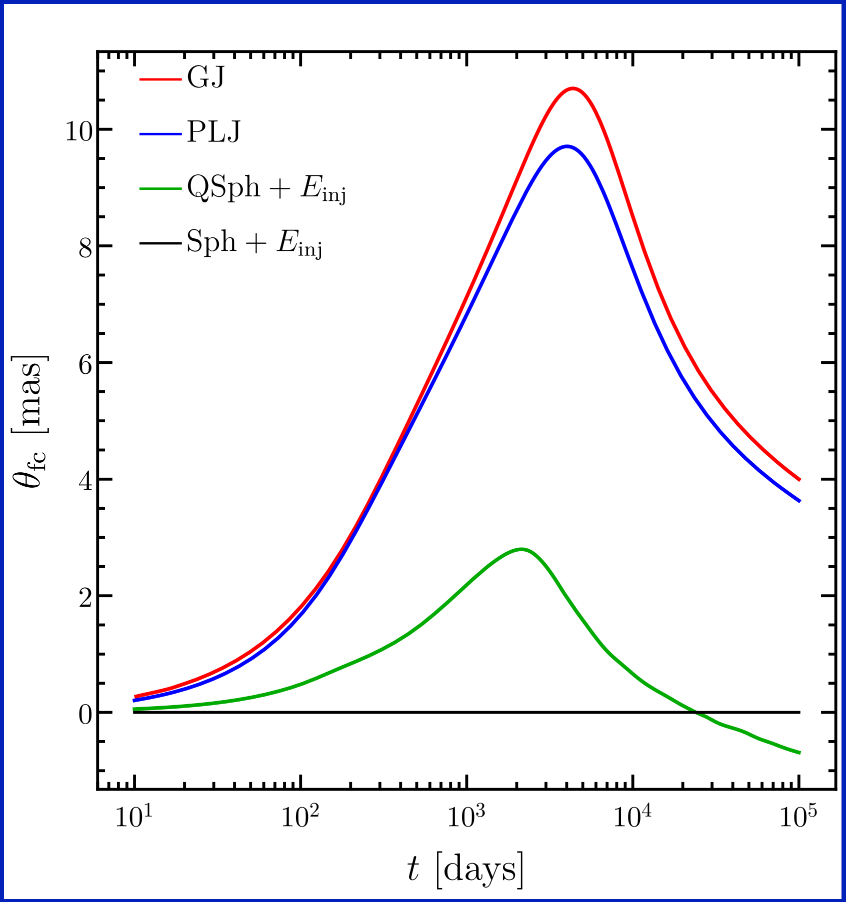
- Assuming a shock-produce B-field with $b \equiv 2\langle B_{\parallel}^2 \rangle / \langle B_{\perp}^2 \rangle$

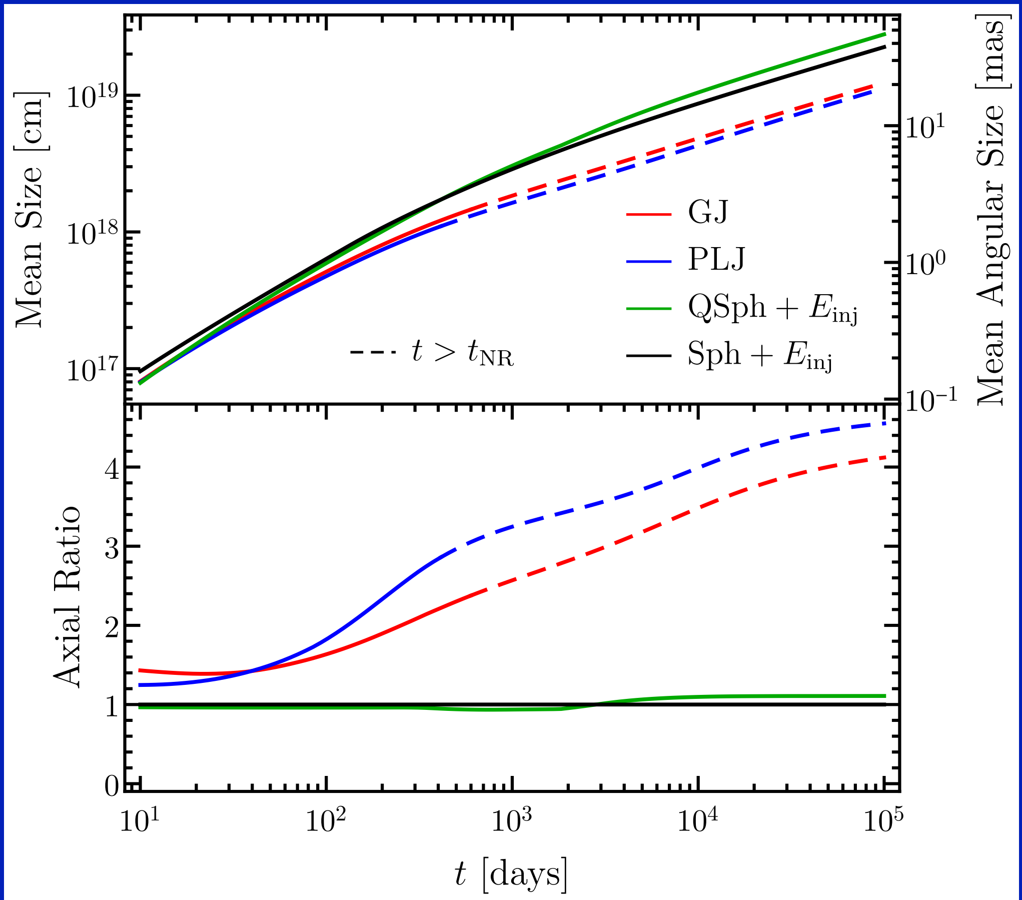


New: upper limit on linear pol. @ 2.8 GHz (Corsi + 2018)

Afterglow Images: flux centroid, size, shape

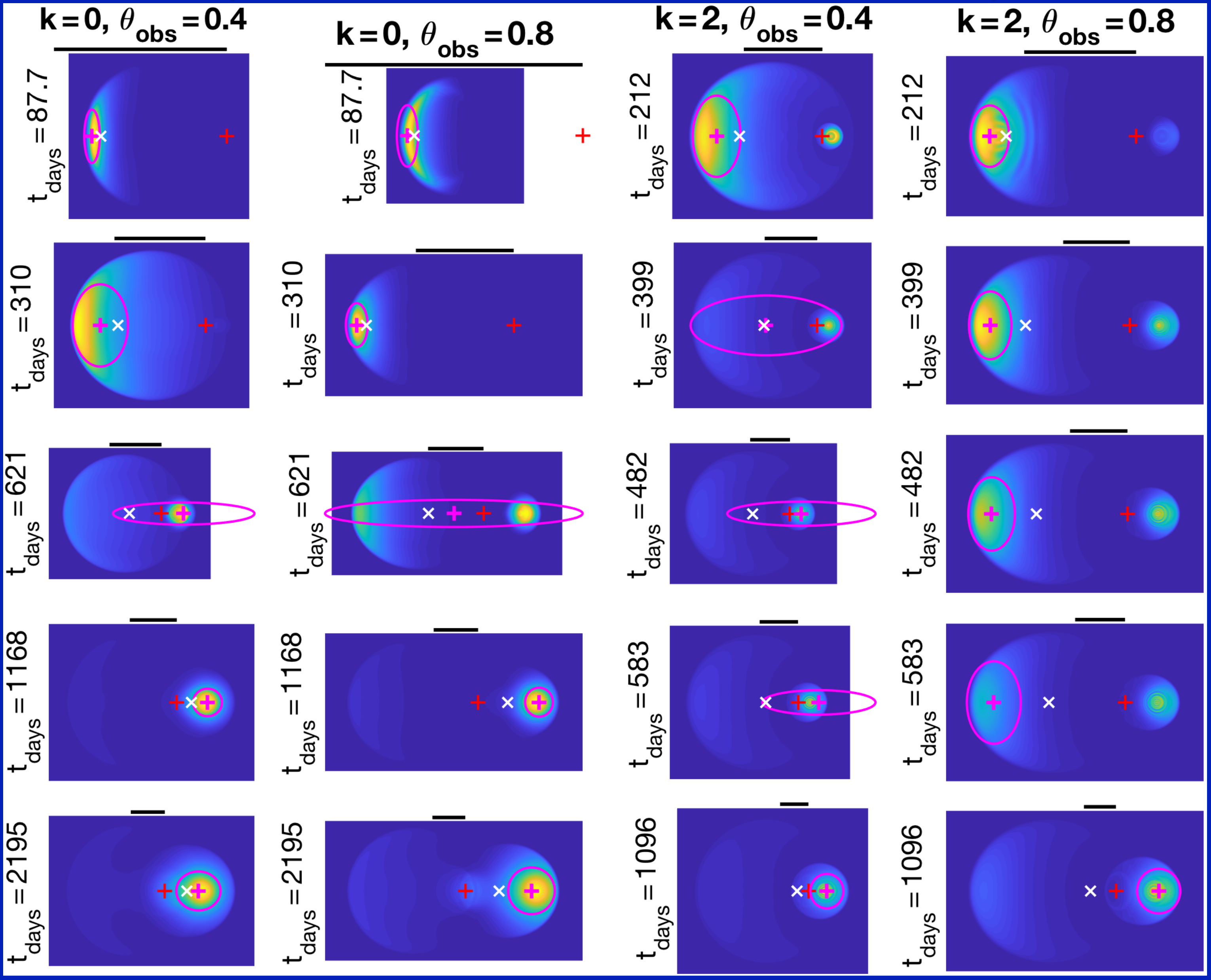
- The flux centroid motion: a potentially powerful diagnostic
- It may be hard to tell apart models based on the image size alone, but a much higher axis-ratio is expected for jet models





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 → 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)