GRB Afterglow Polarization & GRB170817A

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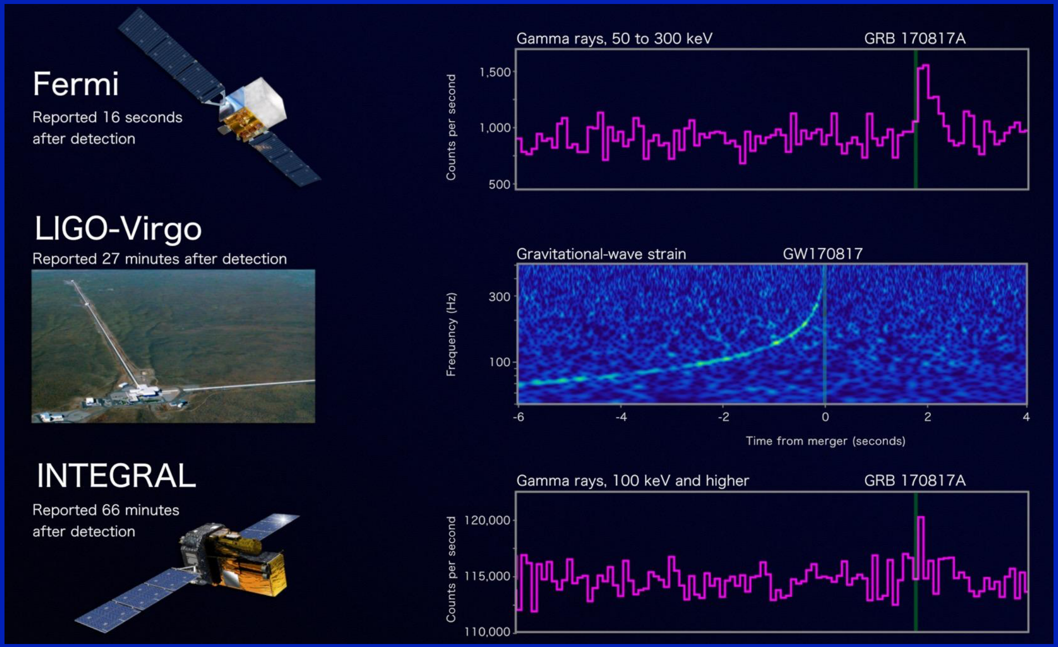
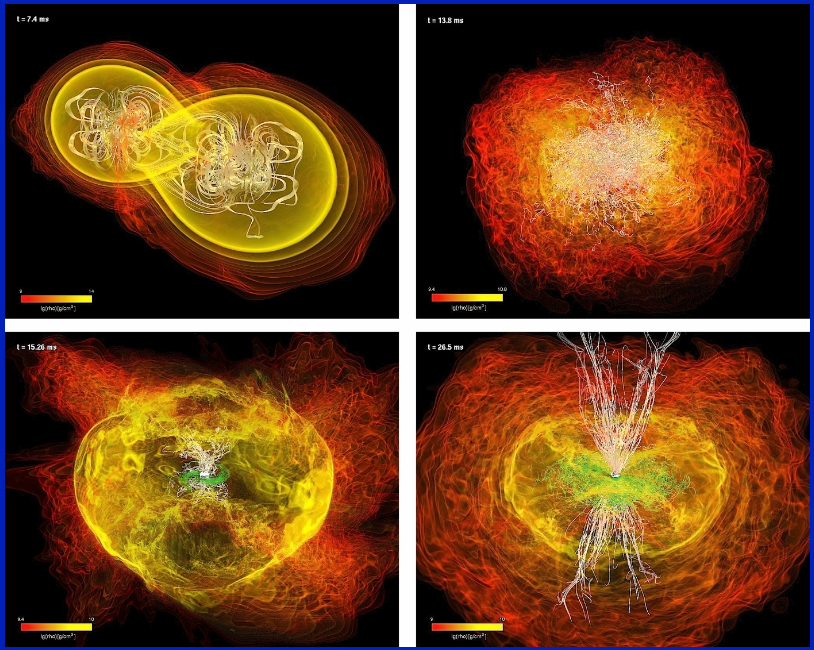




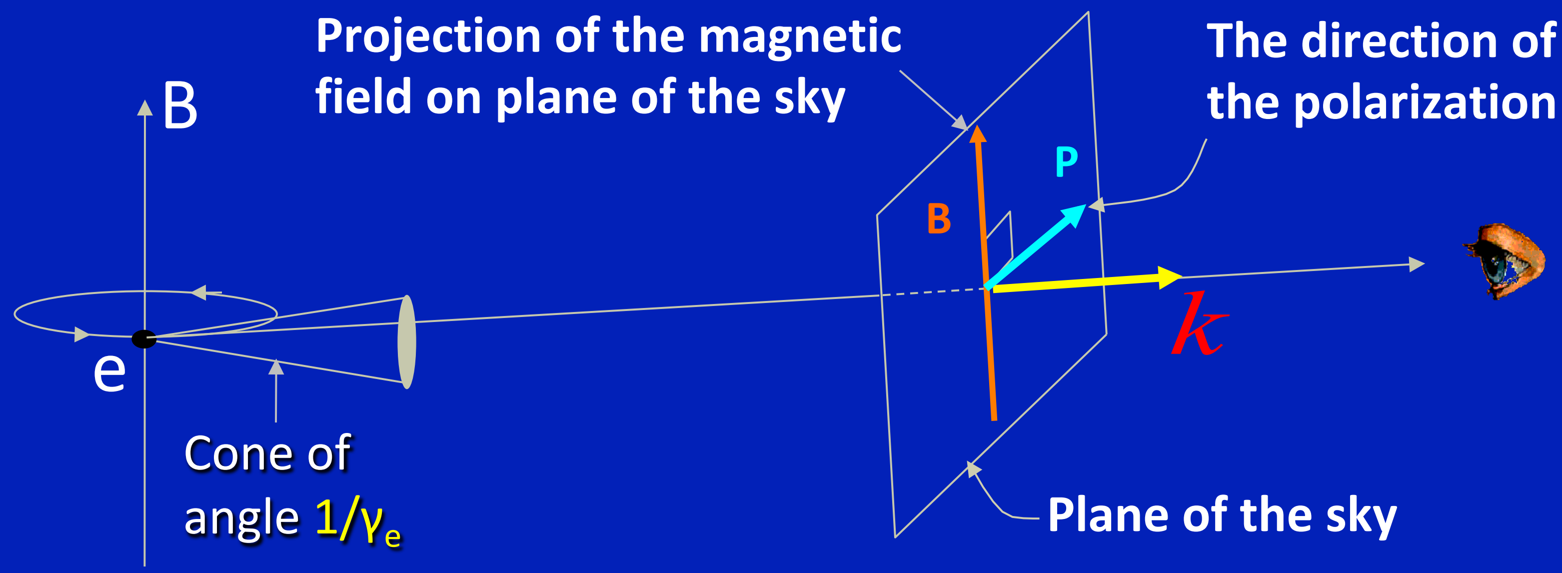
Shedding New Light on Gamma-Ray Bursts with Polarization Data

Geneva, 28 November 2018

Outline of the Talk:

- Polarization of synchrotron rad. from a relativistic source
- Afterglow: Jet structure & dynamics, B-field structure
  - **Top hat vs. structured jet**
  - **Shock-produced vs. ordered B-field**
- Reverse shock emission: optical flash & radio flare
- GRB170817A / GW170817 – the afterglow emission:
  - **Two main options for the early flux rise: r vs. θ dependence**
  - **Breaking the degeneracy: lightcurves? Images, Polarization**
  - **New observations imply: dominant θ dependence (off-axis jet)**
- **Conclusions**

Polarization of Synchrotron Emission

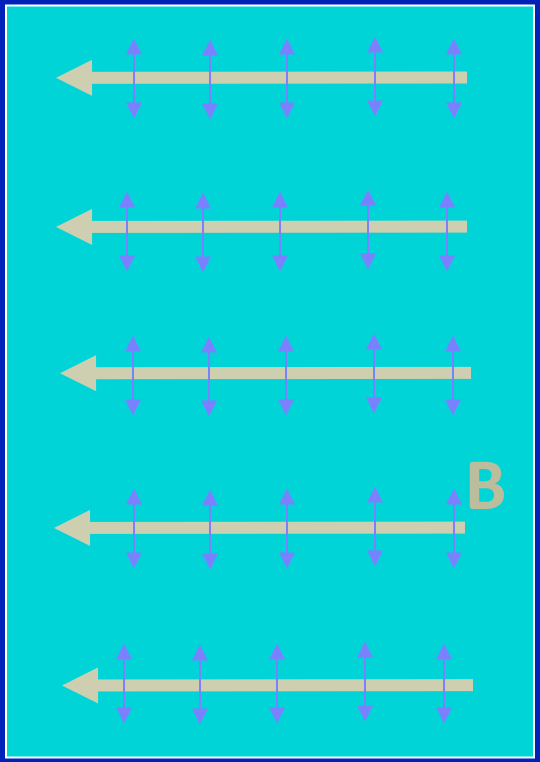


- **linear polarization** perpendicular to the projection of **B** on the plane of the sky (normal to the wave vector)
- The maximal polarization is for the local emission from an ordered **B**-field: $P_{max} = (\alpha+1)/(\alpha+5/3)$ where $F_\nu \propto \nu^{-\alpha}$, $-1/3 \leq \alpha \lesssim 1.5 \Rightarrow 50\% \leq P_{max} \lesssim 80\%$ (Rybicki & Lightman 1979; Granot 2003)

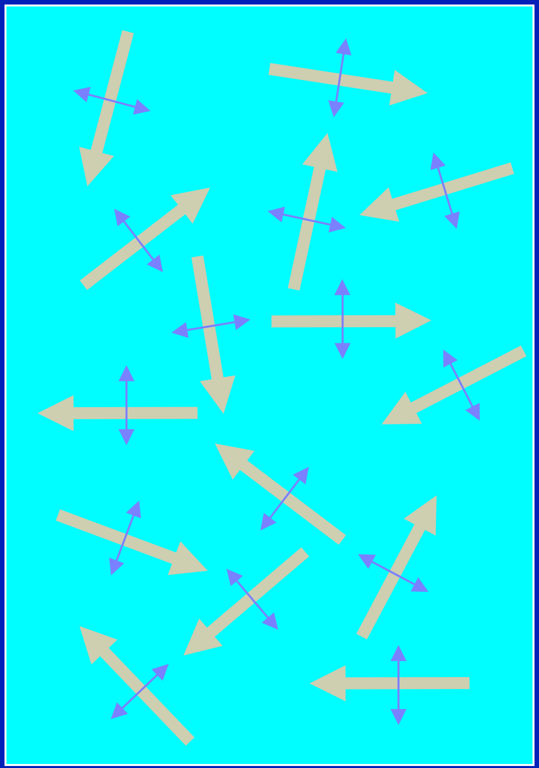
In the source rest frame:

- A uniform field produces $P = P_{max}$
- For a field random when projected on the plane of the sky: $P = 0$
- In particular, for a field isotropically tangled in 3D: $P = 0$

Uniform B

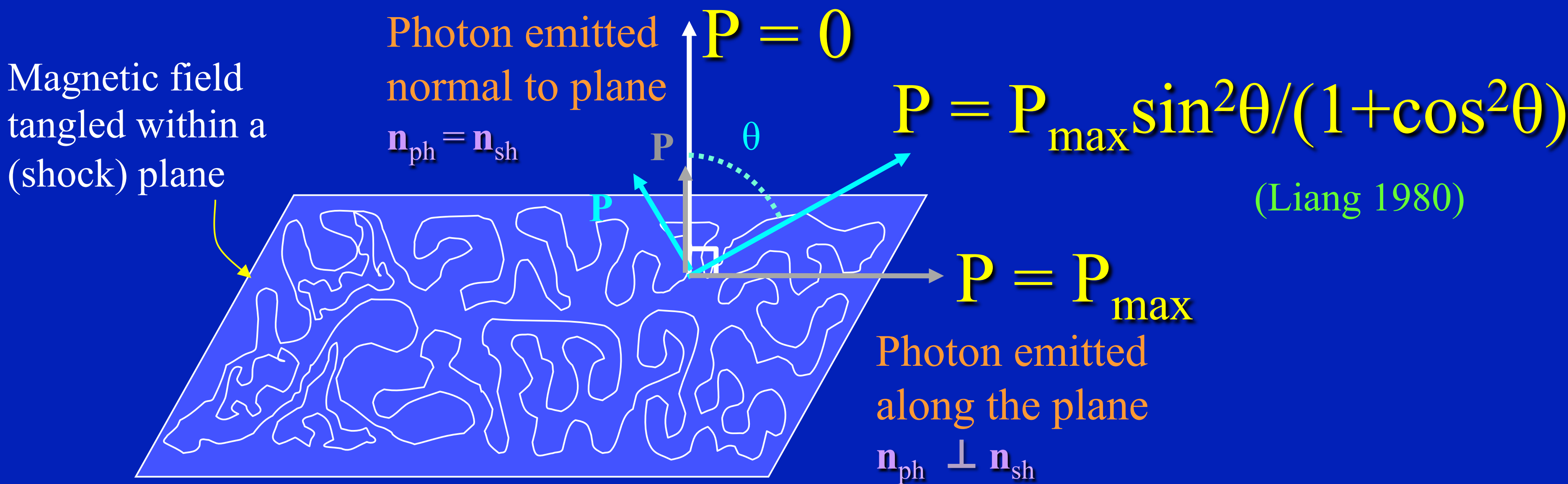


Random B



Shock Produced Magnetic Field:

- A magnetic field that is produced at a relativistic collisionless shock, due to the two-stream instability, is expected to be **tangled within the plane of the shock** (Medvedev & Loeb 1999)

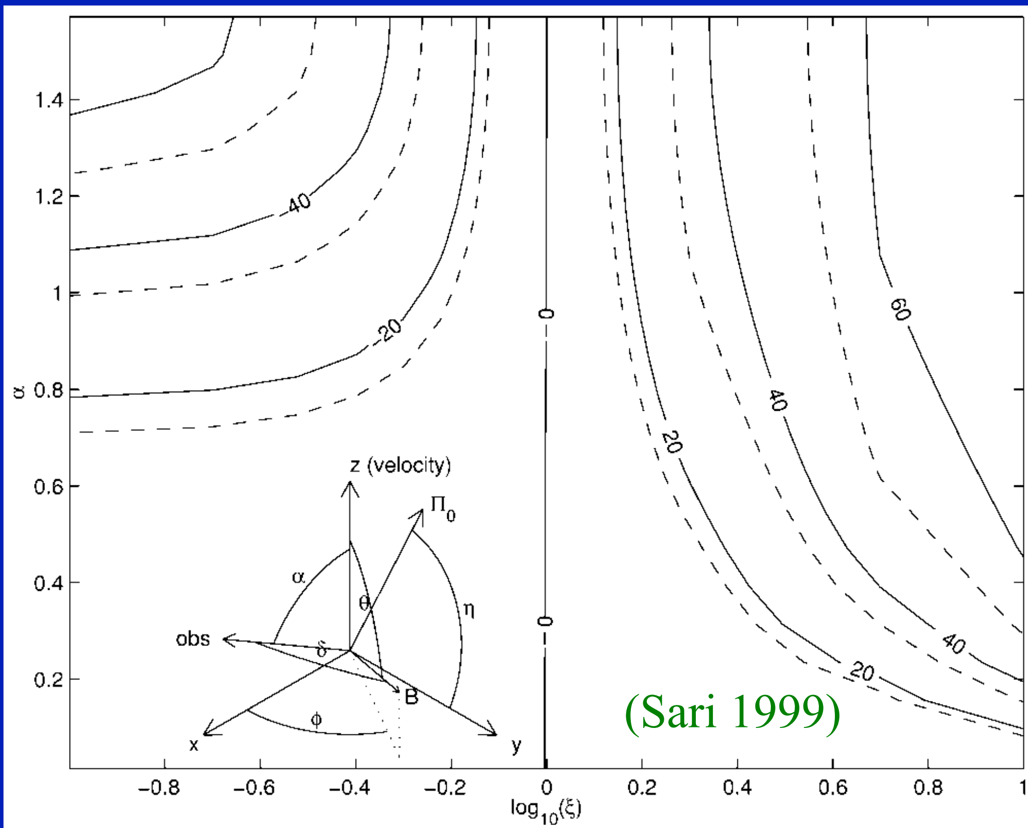


Pure shock-produced magnetic field:

- Symmetric w.r.t. the normal to the shock, $\mathbf{n}_{sh}$
- Produces no net polarization for a spherical outflow
- Breaking the circular symmetry of the observed image:
  - **jet** viewed from $\theta_{obs} > 0$ (Sari 99; Ghisellini & Lazzati 99)
  - Scintilations (relevant for radio) (Medvedev & Loeb 1999)
  - Microlensing (rare event) (Loeb & Perna 1998)
  - Clumps, patchy shell (LC variability) (JG & Königl 2003)
- The polarization light curves for a jet depend on:
  - The **jet structure**: uniform (Sari 99; Ghisellini & Lazzati 99) or smoothly varying with angle from its axis (Rossi et al. 03)
  - The **jet dynamics** (degree of lateral spreading, etc.)
  - The **magnetic field structure** in the emitting region

Effect of B-field degree of anisotropy:

- There are a wide variety of possible B-field configurations in the emitting region that affect the local polarization



the emission is proportional to some power of the magnetic field B^{ϵ}. The total polarization from a pointlike region is then

$$\Pi_p = \Pi_0 \frac{\int \cos 2\eta [B(\theta) \sin \delta]^{\epsilon} f(\theta) \sin \theta d\varphi d\theta}{\int [B(\theta) \sin \delta]^{\epsilon} f(\theta) \sin \theta d\varphi d\theta} . \quad (1)$$

For a power-law distribution of electrons, we have $\Pi_0 = (p+1)/(p+7/3)$ and $\epsilon = (p+1)/2$, where p is the electron power-law index, usually in the range of $p = 2$ to $p = 2.5$. Reasonable values are therefore $\Pi_0 \sim 70\%$ and $1.5 < \epsilon < 1.75$. Cooling may increase the effective p by 1/2.

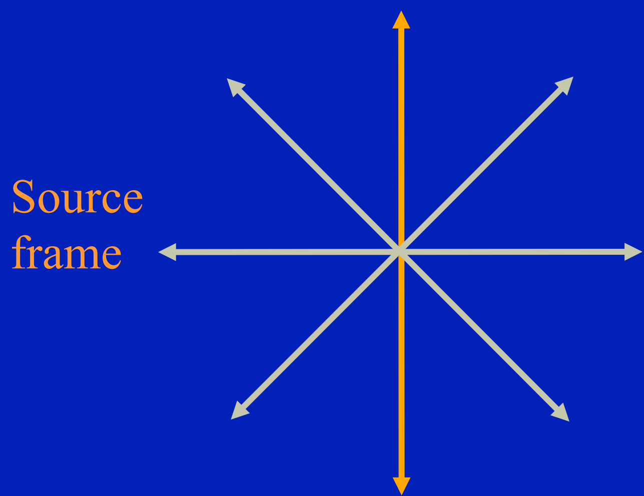
For frequency integrated polarization, the emission is proportional to the square of the magnetic field, $\epsilon = 2$, and the integration can be easily done. We obtain

$$\Pi_p = \Pi_0 \sin^2 \alpha \frac{\langle B_{\parallel}^2 \rangle - \langle B_{\perp}^2 \rangle /2}{\sin^2 \alpha \langle B_{\parallel}^2 \rangle + (1 + \cos^2 \alpha) \langle B_{\perp}^2 \rangle /2} . \quad (2)$$

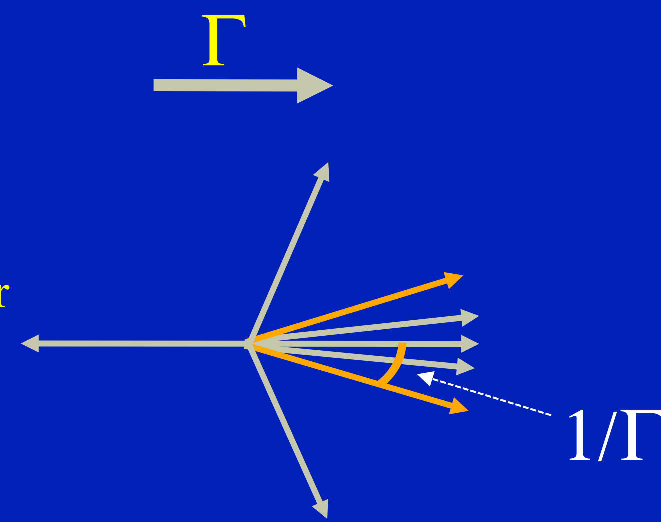
This is identical to the expression of Gruzinov (1999). As we remarked above, the relevant values of ϵ are probably below 2, and the integration is less simple. The results now depend on higher moments of $B(\theta)$ and $f(\theta)$, rather than simply through $\langle B_{\parallel}^2 \rangle$ and $\langle B_{\perp}^2 \rangle$. One realization of anisotropic magnetic field can be obtained from an isotropic magnetic field in which the component in the parallel direction was multiplied by some factor ξ. In the notation above this translates to

$$B(\theta) \propto (\xi^2 \sin^2 \theta + \cos^2 \theta)^{-1/2}, \quad f(\theta) \propto B^3(\theta). \quad (3)$$

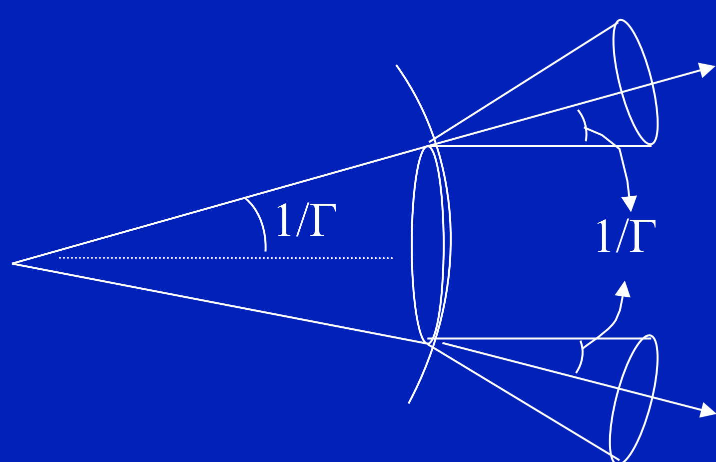
Relativistic source:



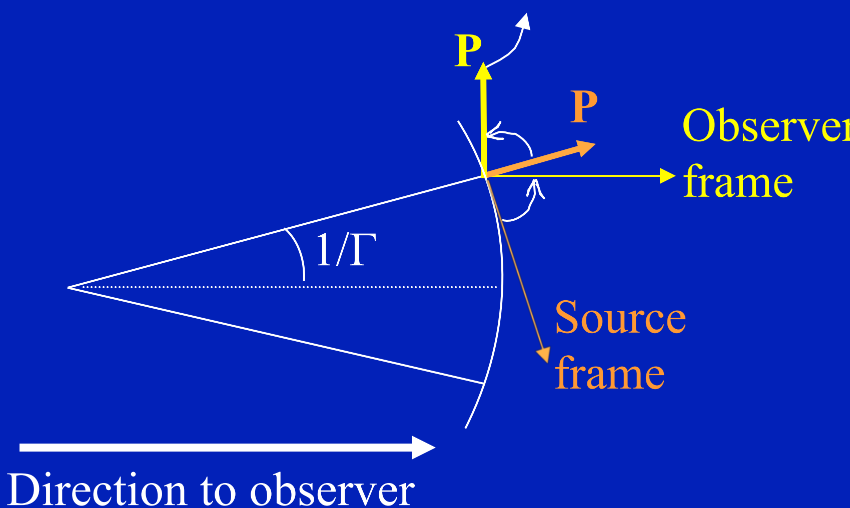
Aberration of light or
'relativistic beaming'



The observer sees mostly emission from within an angle of 1/Γ around the l.o.s.

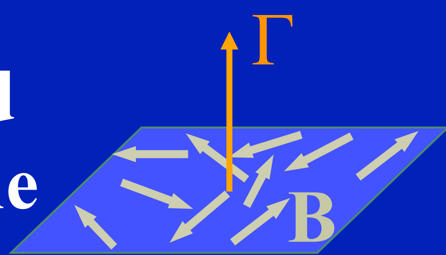


Direction of
Polarization

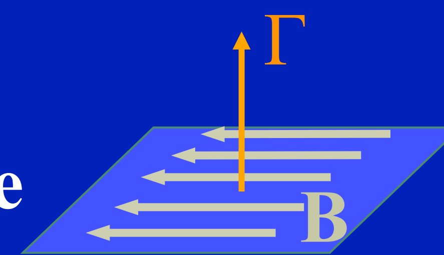


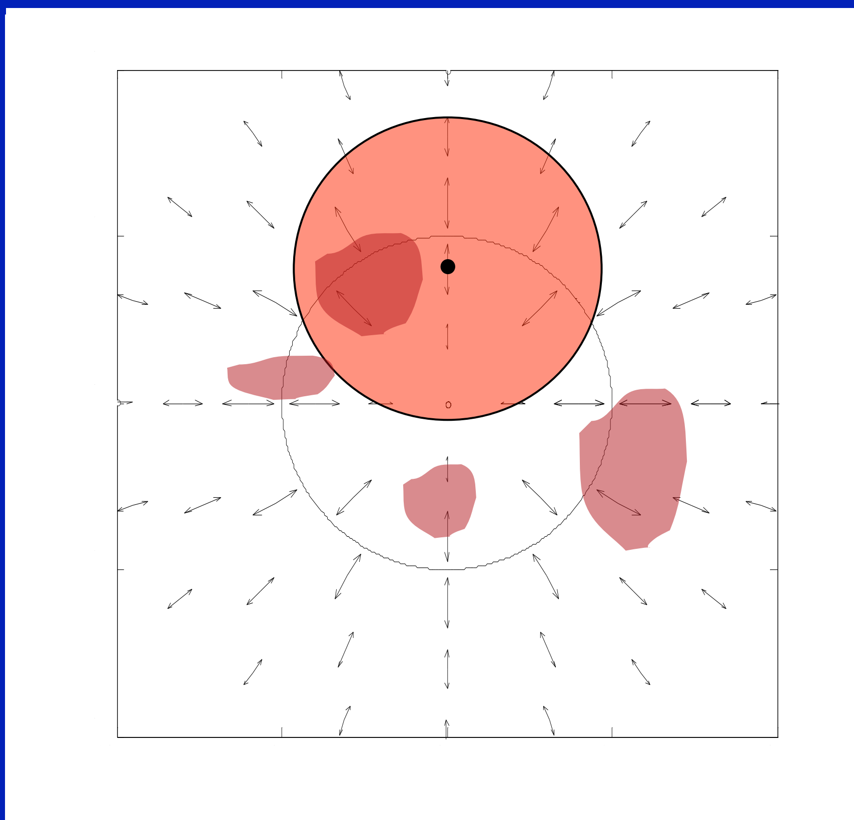
Polarization in the observer frame

Random field in shock plane

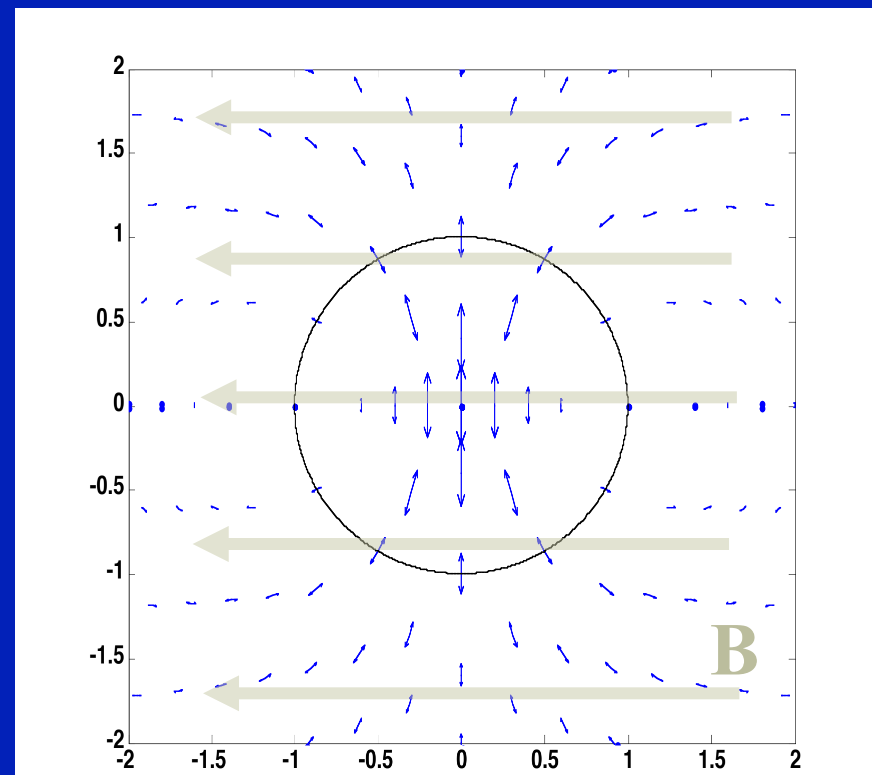


Ordered field in shock plane





Sari 99; Ghisellni & Lazzati 99

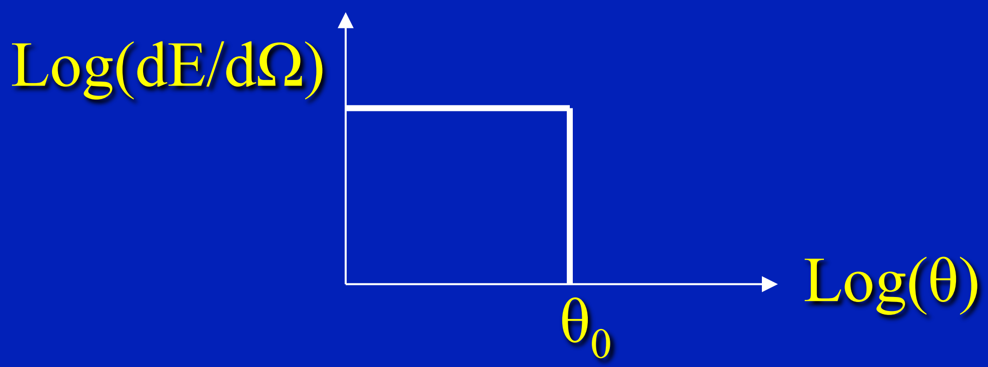


Granot & Königl 03

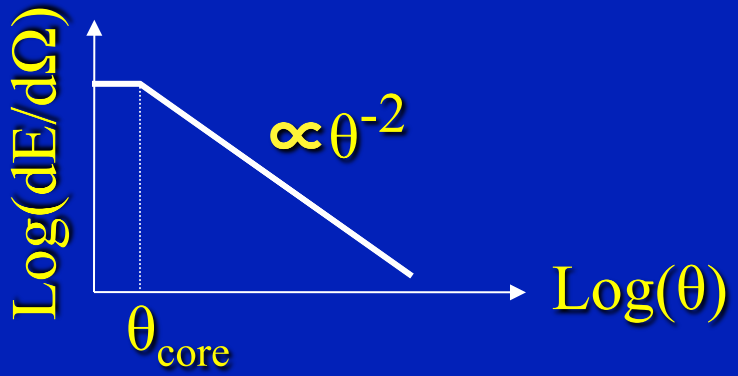
$P \sim P_{max}$

Two Competing Jet Structures:

Uniform (top hat) jet†:



Structured jet††:

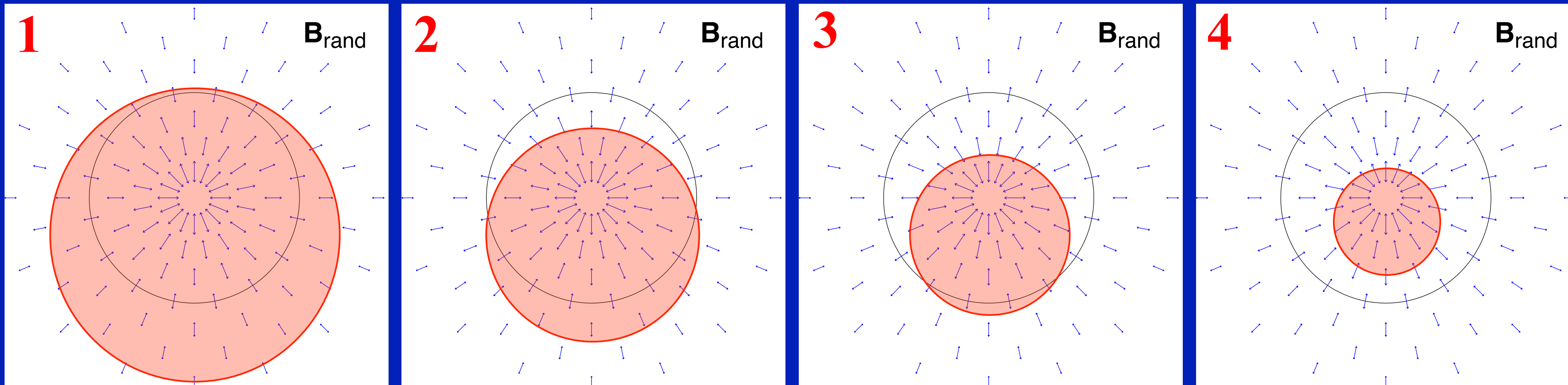


- A structured jet has a ~10 times larger energy than a uniform jet, and implies a ~10 times smaller GRB rate
- The jet structure constrains model for the central source
- There are small differences in the light curves of the two jet structures (Granot & Kumar 2003; Kumar & Granot 2003)
- Structured jet predicts dn/dzdθ (Nakar, Granot & Guetta 2004)

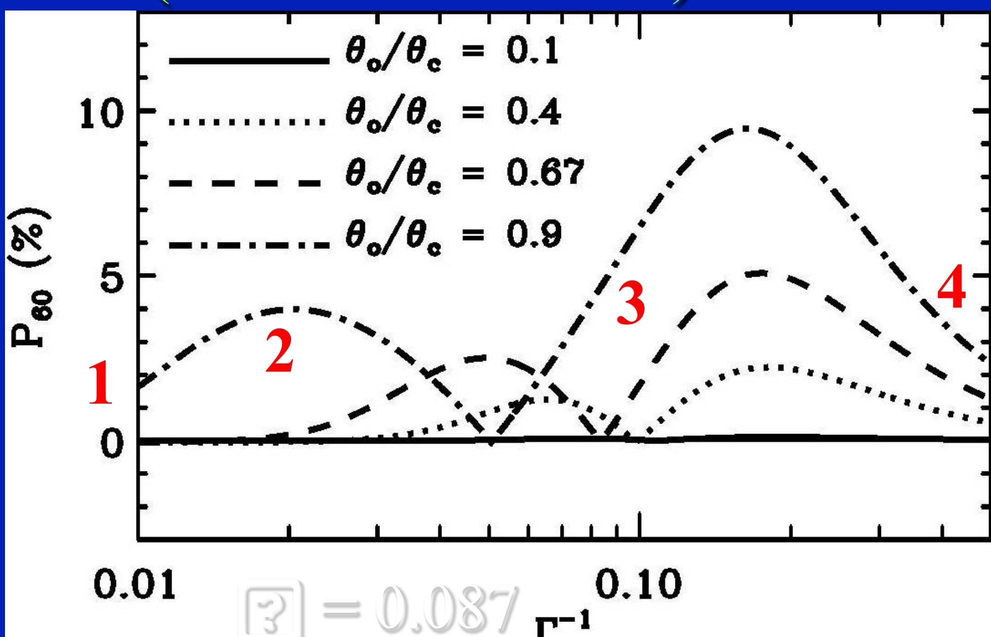
† Rhoads 97,99; Sari et al. 99, …

†† Postnov et al. 01; Rossi et al. 02; Zhang & Meszaros 02

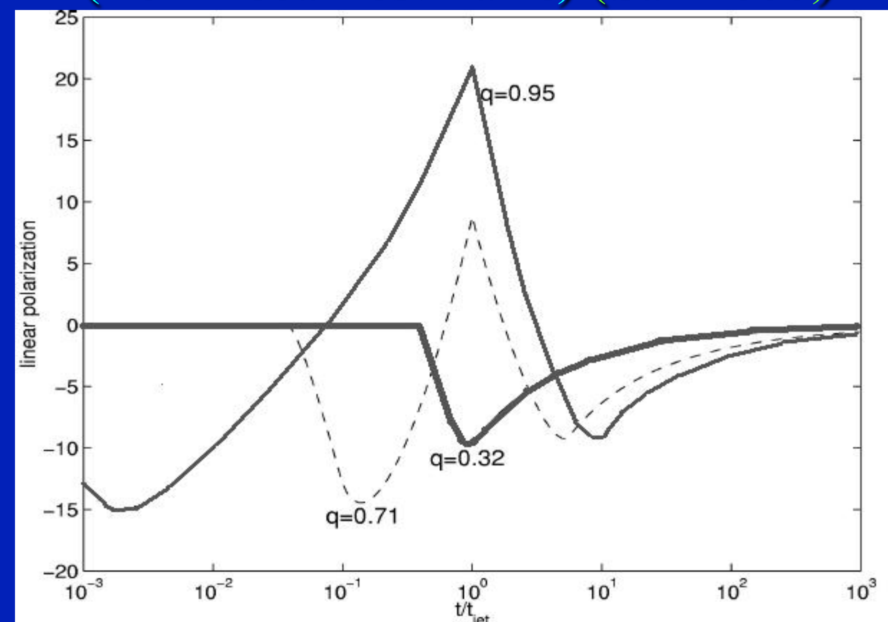
Polarization light curves: Uniform jet



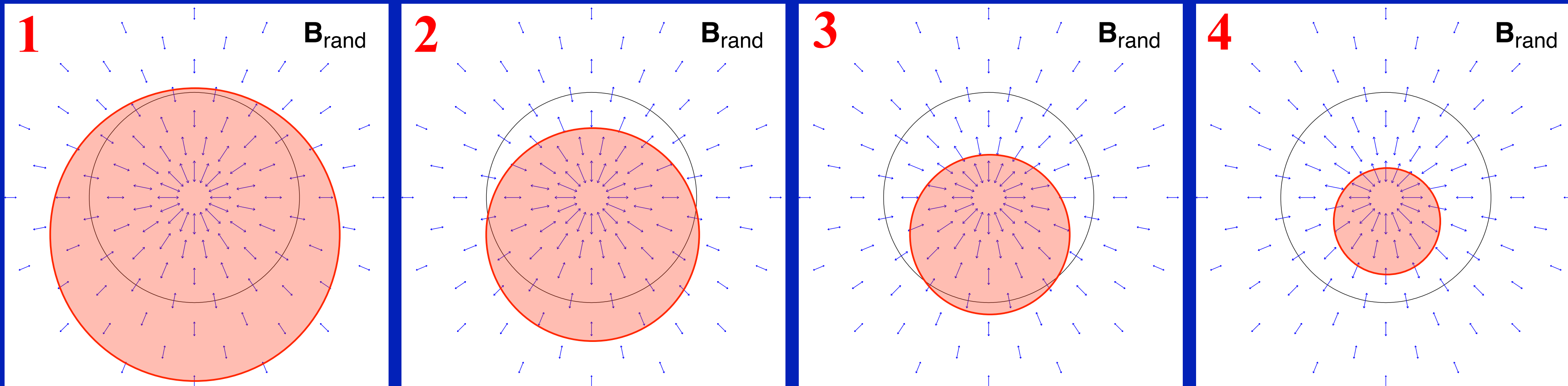
No sideways Expansion
(Ghisellini & Lazzati 99)



Very fast sideways Expansion
(~c in local rest frame) (Sari 1999)



Polarization light curves: Uniform jet



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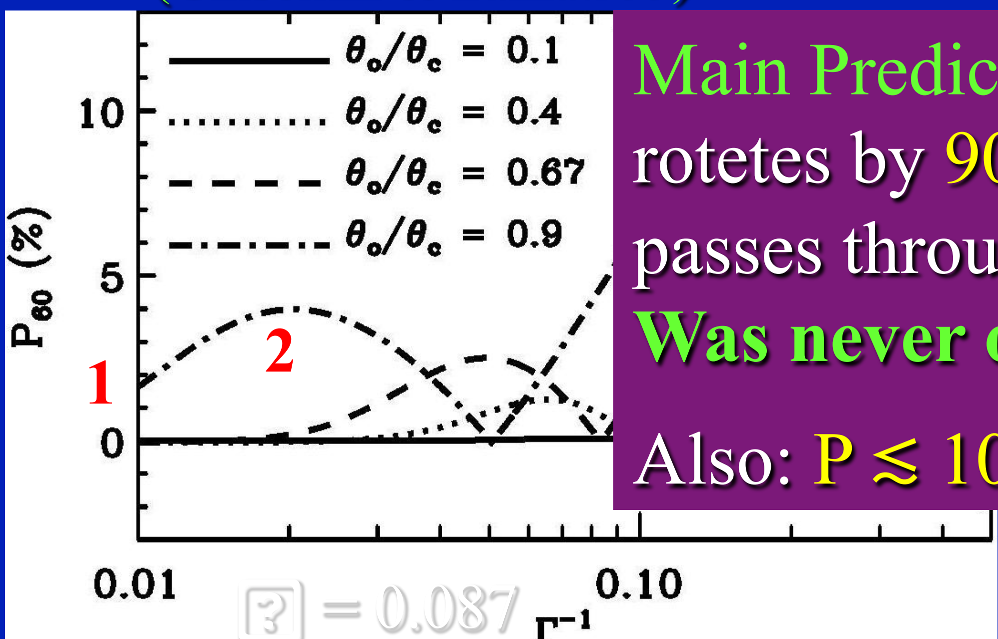
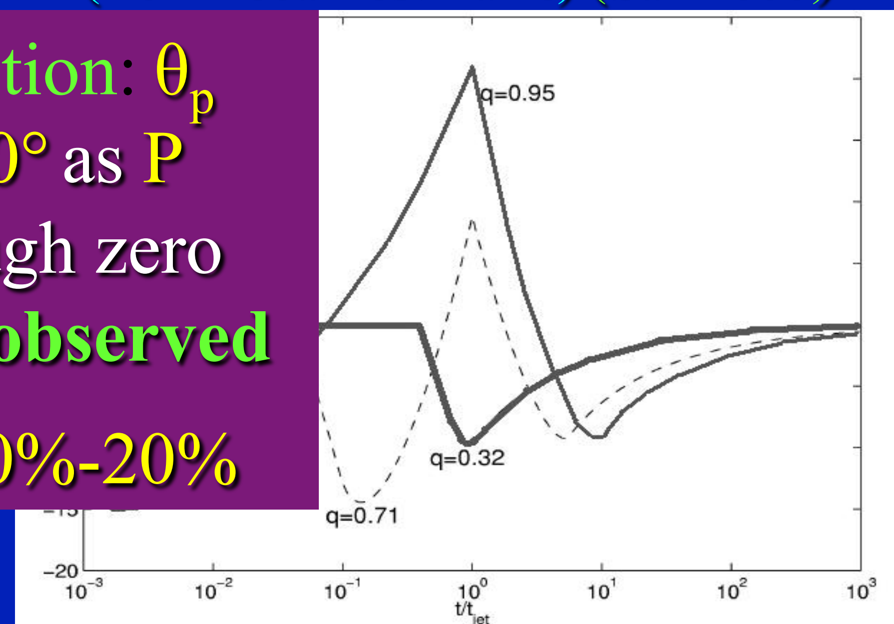




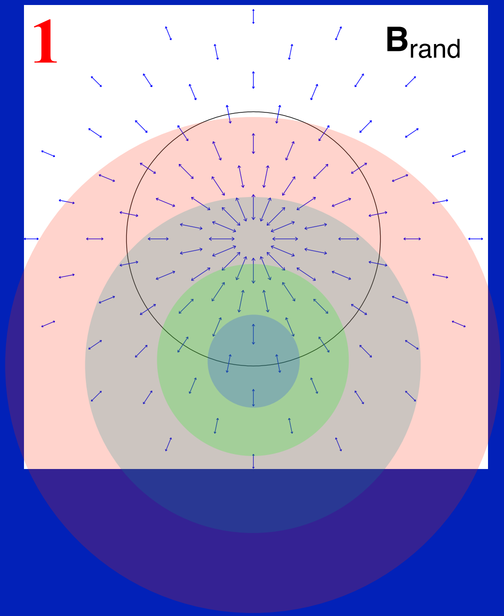
Main Prediction: θ_p rotetes by 90° as P passes through zero

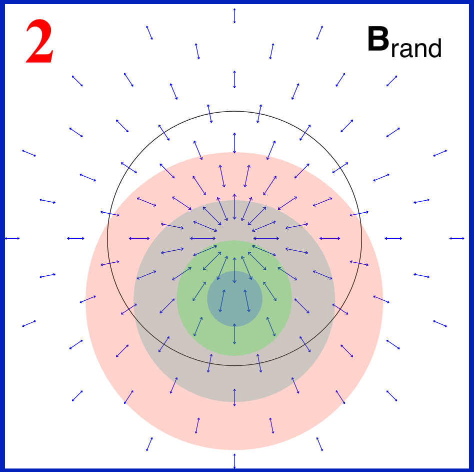
Was never observed

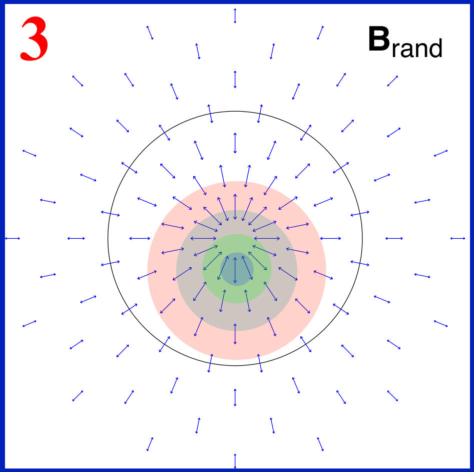
Also: P ≲ 10%-20%

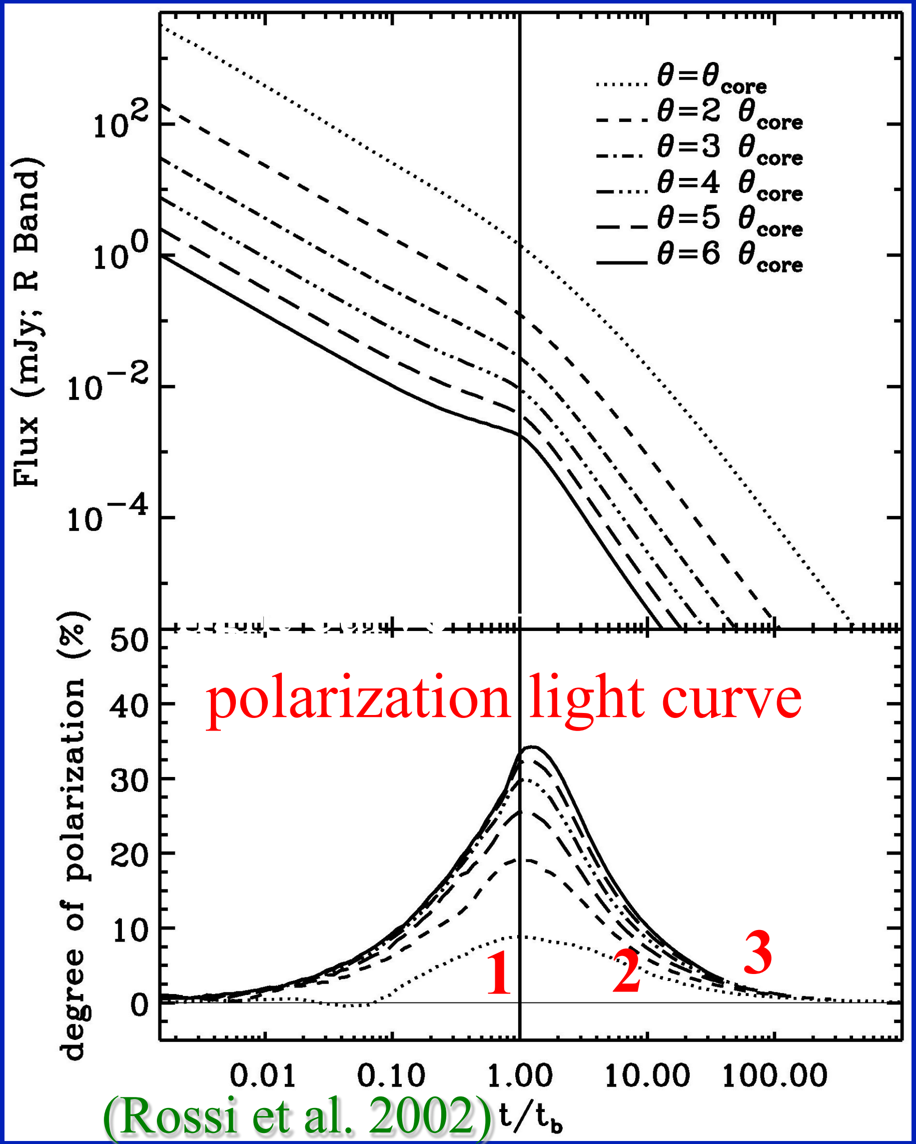
Polarization light curves: Structured jet

- P peaks at jet break time, θ_p = const, P ≲ 10%–30%





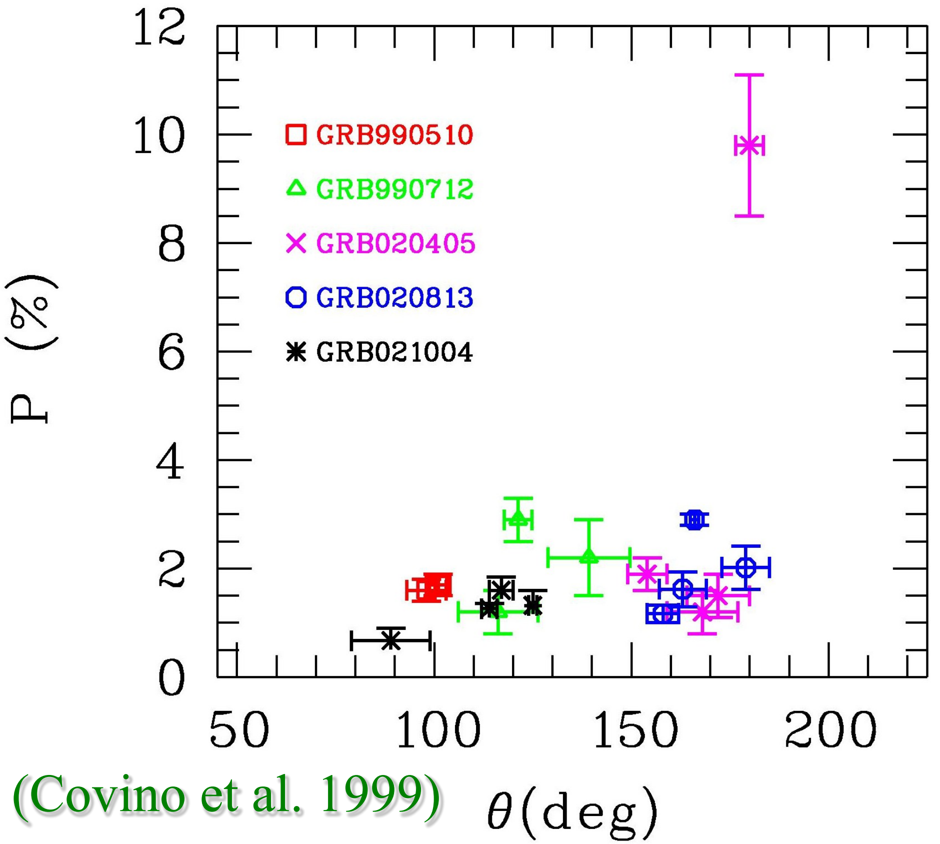




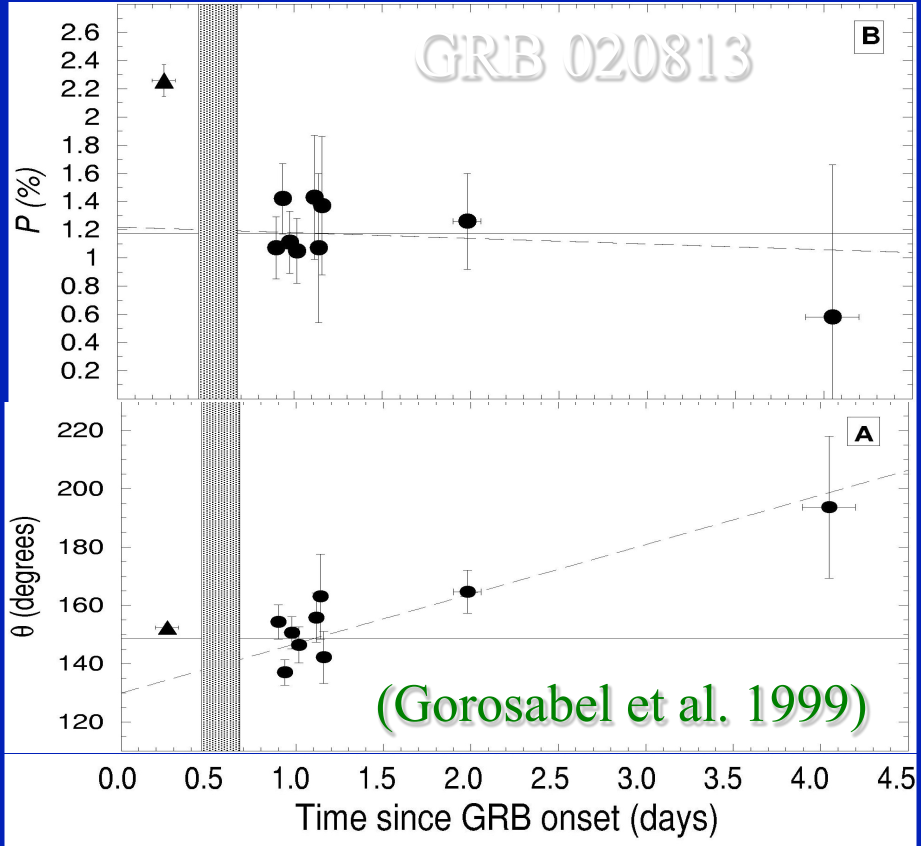
(Rossi et al. 2002)

Observations: Afterglow Polarization

- Linear polarization at the level of P ~ 1%-3% was detected in several optical afterglows
- In some cases P varied, but usually $\theta_p \approx$ const
- Different from predictions of uniform or structured jet



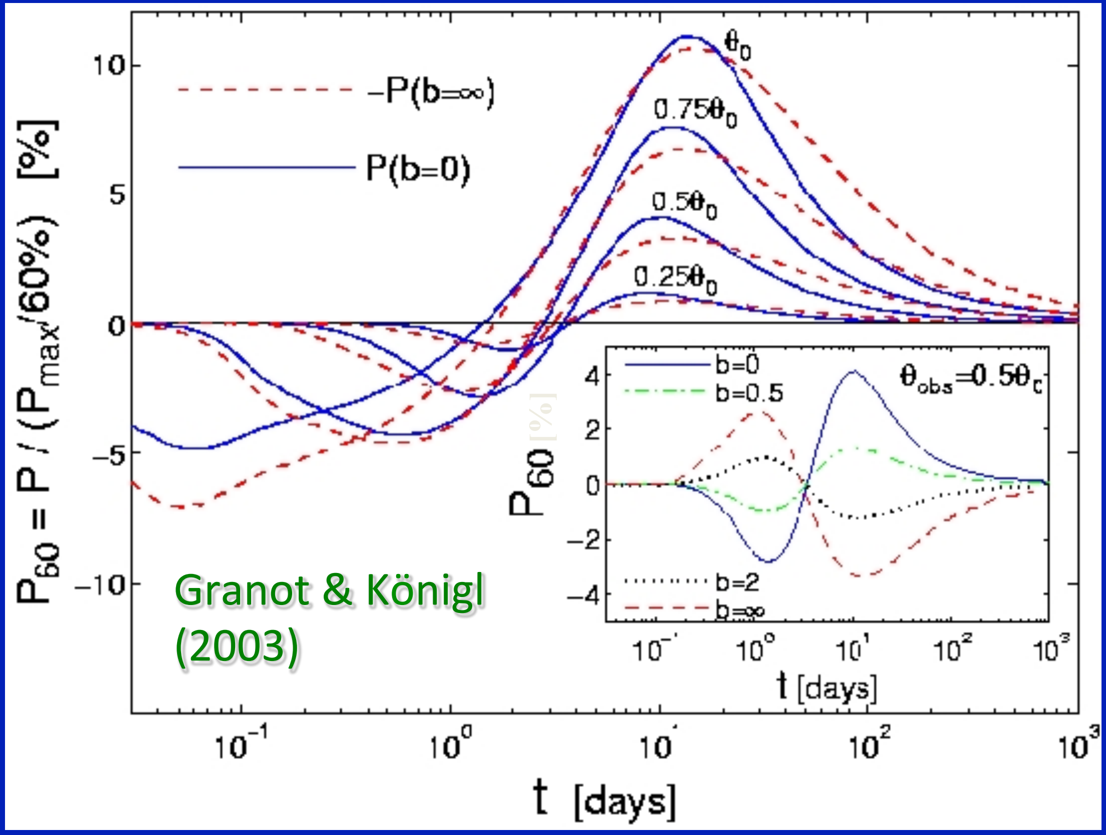
(Covino et al. 1999)



(Gorosabel et al. 1999)

Effect of Magnetic field structure:

- $b = 2\langle B_{||}^2\rangle / \langle B_{perp}^2\rangle$ parameterizes the asymmetry of B_{rnd}
- Sign(b-1) determines θ_p ($P > 0$ is along the direction from the line of sight to the jet axis & $P < 0$ is rotated by 90°)
- For $b \approx 1$ the polarization is very low (field is almost isotropic)
- $P \lesssim 3\%$ in afterglows observations $\Rightarrow 0.5 \lesssim b \lesssim 2$



$P = P_{max}/[1+2/(b-1)\sin^2\theta']$

$\theta_0 = 5^o$

$E_{jet} = 3\times10^{51}$ erg

$n = 1\ cm^{-3}$

$z = 1$

$p = 2.5$

$\varepsilon_e = 0.1$

$\varepsilon_B = 0.01$

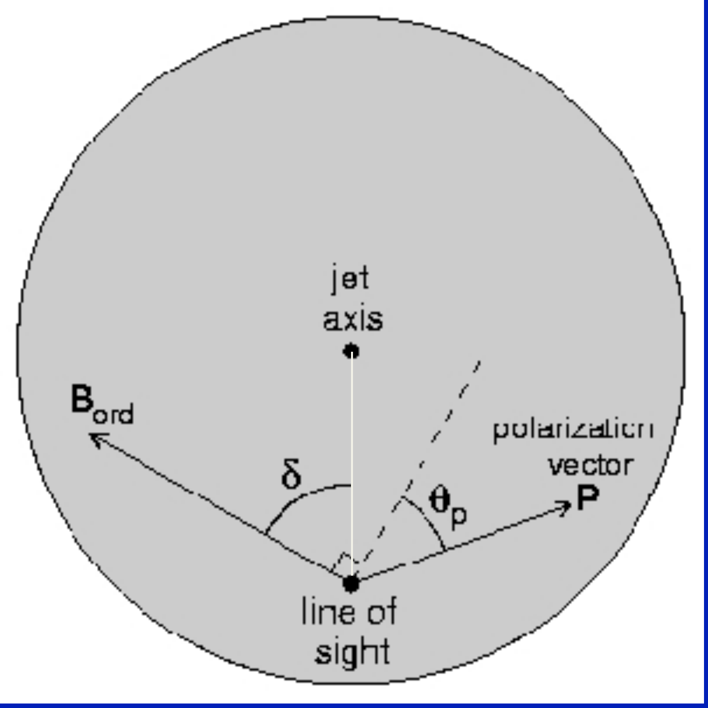
Adding an ordered B-field component

Motivation: amplification of ambient B-field

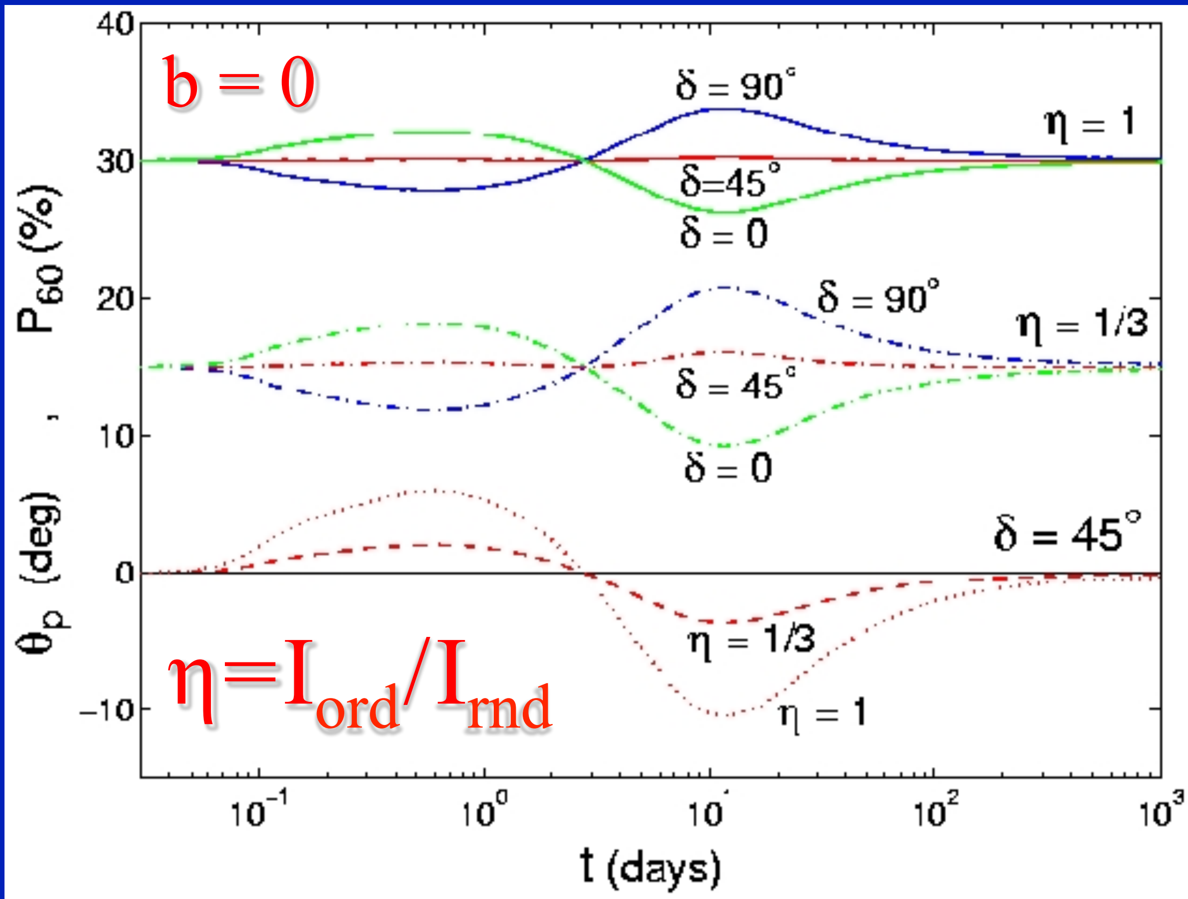
- At shock transition: $B_{||}$ remains unchanged, B_{perp} is amplified by the compression ratio (4Γ for $\Gamma \gg 1$) $\Rightarrow$ we expect $B_{perp} \gg B_{||}$ and for simplicity assume $B_{||} = 0$
- Afterglow observations $\Rightarrow$ $10^{-4} \lesssim \varepsilon_B \lesssim 0.1$, $P \lesssim 0.05P_{max}$ $\Rightarrow$ $10^{-5.5} \lesssim \varepsilon_{B,ord} \lesssim 10^{-2.5}$
- Values expected for the external medium:
  - Pulsar wind bubble (Königl & Granot 02): $\varepsilon_{B,ord} \sim 10^{-3}$ - 10^{-1}
  - Stellar wind of massive star progenitor: $\varepsilon_{B,ord} \sim 10^{-6}$ - 10^{-4}
  - Interstellar medium (ISM): $\varepsilon_{B,ord} \sim 10^{-10}$– 10^{-8}, however if the magnetic field is amplified in the shock preferentially in the direction of the initial field, then $\varepsilon_{B,ord}$ can be high enough

Combining B_{ord} & B_{rnd}:

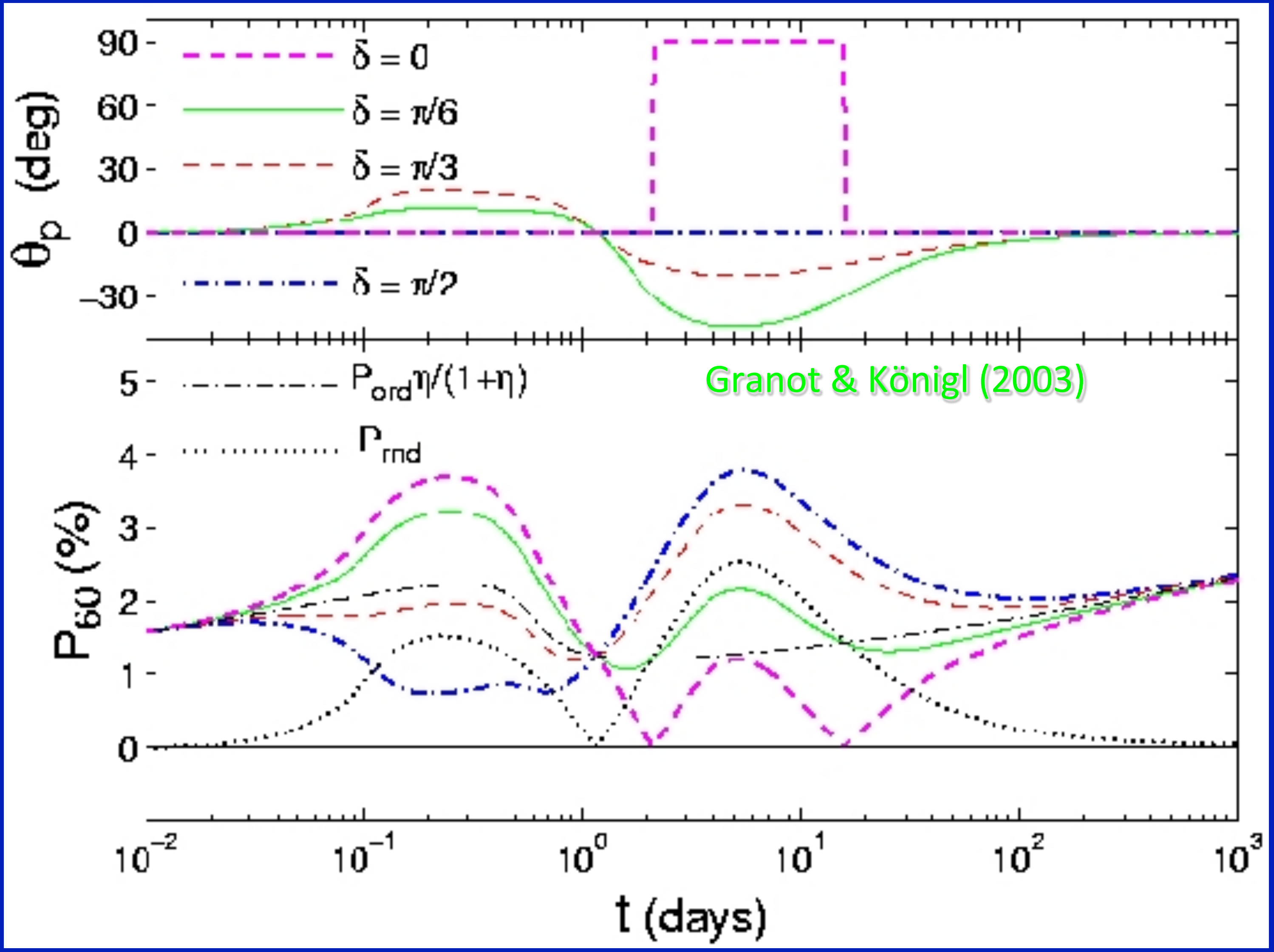
- $P_{ord} \sim P_{max} \sim 60\%$ & $\theta_p = 90°$ w.r.t. the direction of $\mathbf{B}_{ord}$
- In the afterglow we must have $I_{ord} \ll I_{rnd}$ so that $P \lesssim 3\%$ but we can still have $I_{ord}P_{ord} \gtrsim I_{rnd}P_{rnd}$
- $\Rightarrow$ B_{rnd} dominates I_{total} but B_{ord} dominates IP & P_{total}



Granot & Königl (2003)



- Adding evolution of I_{ord}/I_{rnd} with radius: can explain $\theta_p \approx$ const & variable P

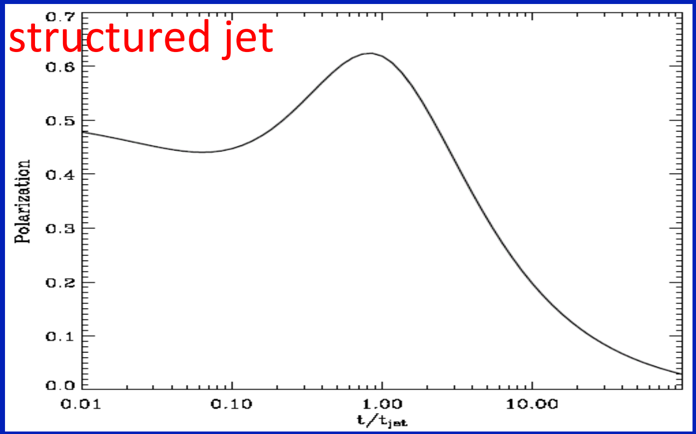


Predictions for an ordered B-field:

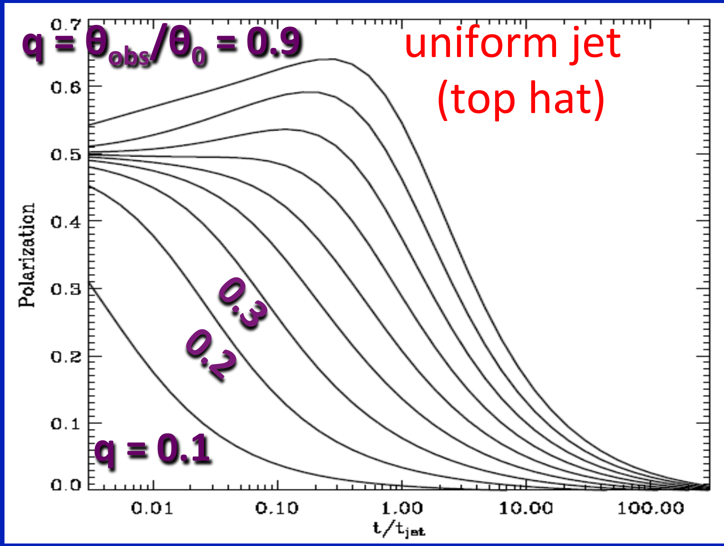
- $P(t \ll t_j) \sim P(t \sim t_j)$ while for jet+B_{rnd} **models:** $P(t \ll t_j) \ll P(t \sim t_j)$
- Emission from the original ejecta (**prompt GRB** & **reverse shock**) may have $P \sim P_{max}$ ($\lesssim 60\%$) due to an ordered B-field carried by the ejecta from the source
- If B_{ord} in the ejecta is ordered on angles $1/\Gamma_0 \lesssim \theta_B \lesssim 0.1$ then $P \sim P_{max} \times \min(1, \Gamma\theta_B)$ due to averaging over $N \sim (\Gamma\theta_B)^{-2}$ incoherent patches
- $\Rightarrow$ P can be smaller & θ_p different in the 'radio flare' ($\Gamma \sim 10$) compared to the 'optical flash' ($\Gamma \sim \Gamma_0 \sim 300$)

Reverse shock Pol.: B-field in ejecta

- The **existence** of a reverse shock $\Rightarrow E_{EM} \lesssim E_{kin}$ ($\sigma \lesssim 1$)
- In the '**optical flash**' the **pol.** should be **similar** to that in **γ-rays**, but much **easier to measure** & more **reliable**
- If B_{ord} in the ejecta is ordered on angles $1/\Gamma_0 \lesssim \theta_B < \theta_j$ then $P \approx P_{max} \times \min(1,\Gamma\theta_B)$ due to averaging over $N \sim (\Gamma\theta_B)^{-2}$ incoherent patches (Granot & Königl 03) $\Rightarrow$ smaller P & different θ_p in the '**radio flare**' ($\Gamma \sim 10$)
- Toroidal B-field in the ejecta:



(Lazzati et al. 2004)



B-field	Optical Flash	Radio Flare $(t \sim t_j)$
Shock Produced	$\theta_{obs} \lesssim \theta_j - 1/\Gamma$: $P \approx 0$ $\theta_{obs} \sim \theta_j + 1/\Gamma$: $P \lesssim 50\%$	pol. due to jet structure $\Rightarrow$ similar to afterglow
Uniform	$P \sim P_{max}$	$P \sim P_{max}$
Patches (θ_B)	$\theta_B \gtrsim 1/\Gamma_0$: $P \sim P_{max}$	$P \sim P_{max} \times \min(1, \Gamma\theta_B)$
Toroidal	$1/\Gamma_0 \lesssim \theta_{obs} \lesssim \theta_j$: $P \sim P_{max}$	structured jet: $P \sim P_{max}$ top hat: $P \sim P_{max}(\theta_{obs}/\theta_j)^2$

Upper Limits on Polarization of Radio Flare Emission (Granot & Taylor 2005)

GRB	t (days)	t_j (days)	Π_L (3 σ)	Π_C (3 σ)
990123	1.25	≈ 2	< 23%	< 32%
991216	1.49	~ 2	< 11%	< 17%
	2.68		< 9%	< 15%
	1.49, 2.68		< 7%	< 9%
020405	1.19	~ 1-2	< 11%	< 19%

- Probably almost no depolarization in the host galaxy
- Likely no significant depolarization in the source due to different amounts of Faraday rotation; hard to rule out

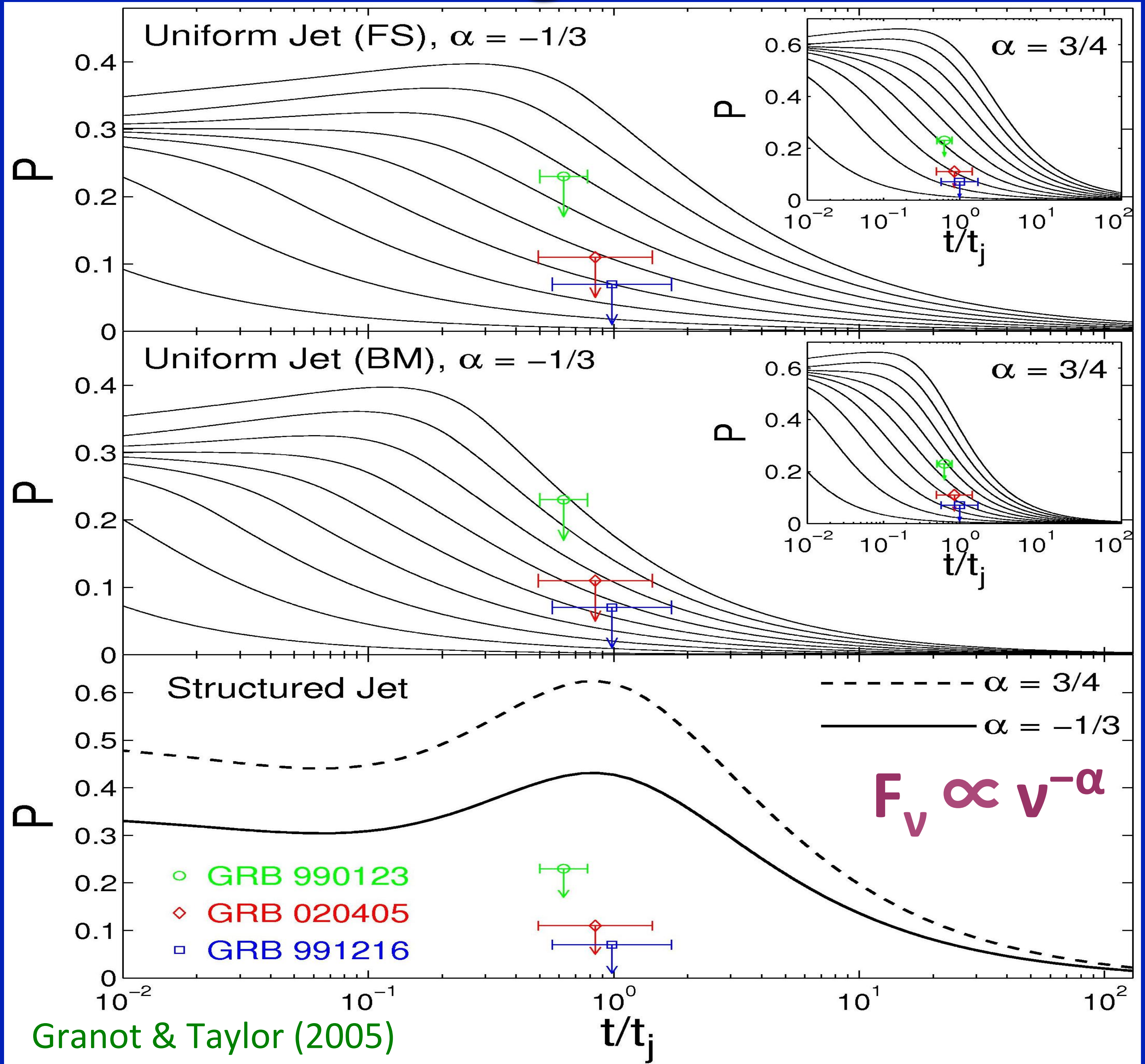
Toroidal Magnetic Field:

Dynamics of the Ejecta:

$\Gamma(t)$ follows that of the forward shock

$\Gamma(t)$ follows the Blandford & McKee self similar solution

$\Gamma(t)$ follows that of the forward shock

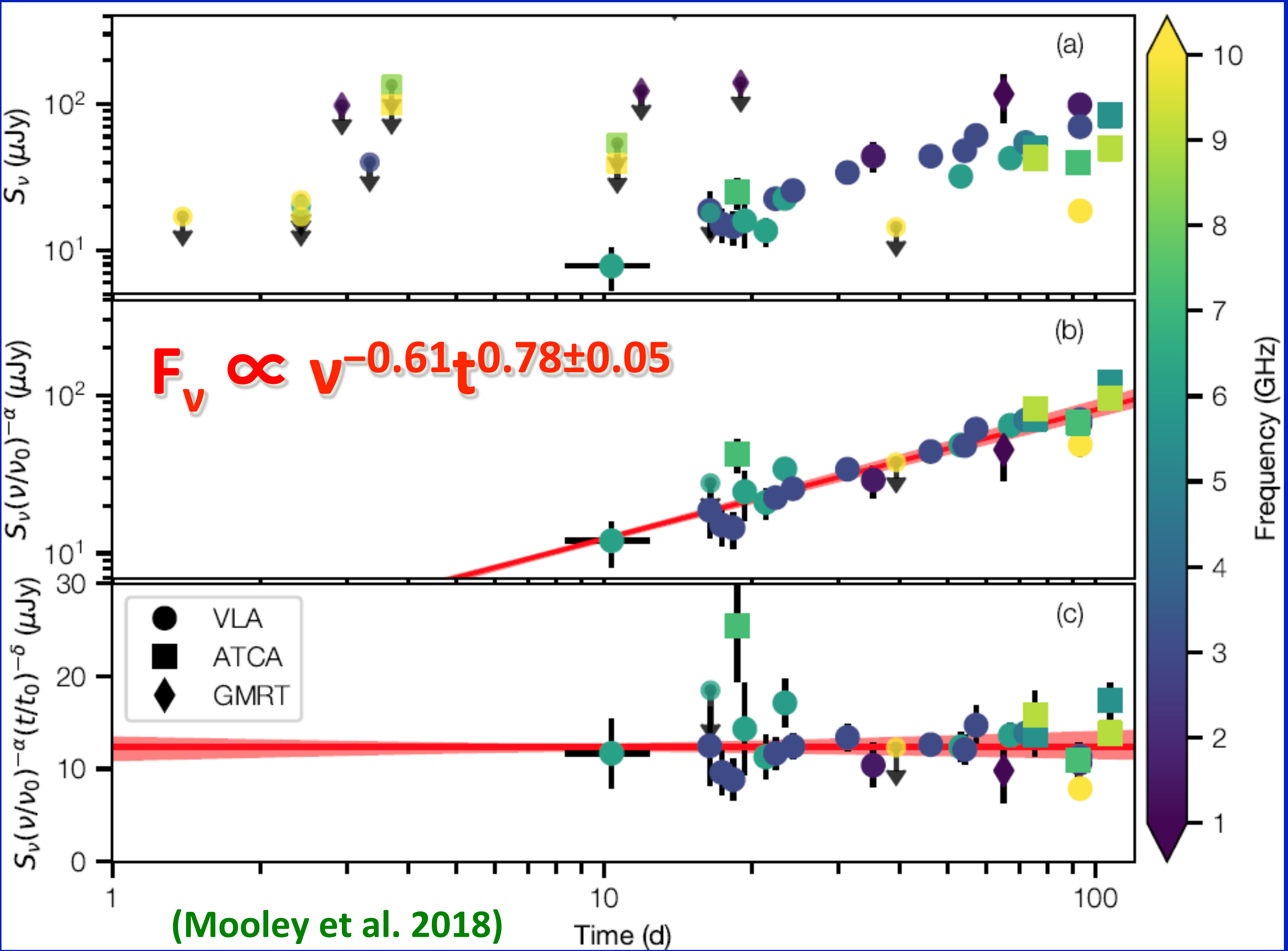


Granot & Taylor (2005)

Implications of the Upper limits on the Radio Flare Polarization

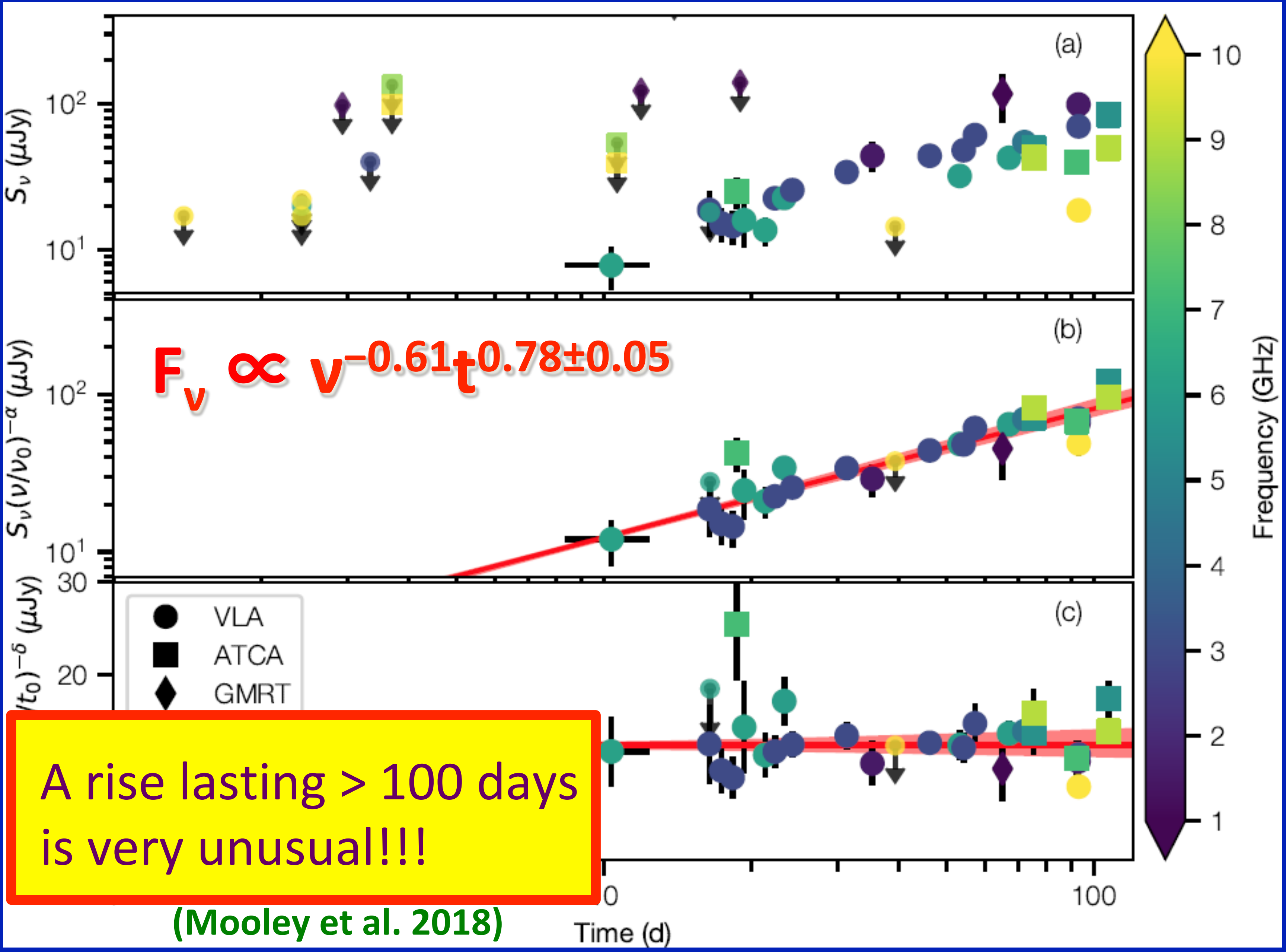
B-field structure	Theoretical prediction	Theory vs. Observation
Shock Produced	pol. due to jet structure $\Rightarrow$ similar to afterglow	✓
Uniform	$P \sim P_{max}$	X
Patches (θ_B)	$P \sim P_{max} \times \min(1, \Gamma\theta_B)$	$\theta_B \lesssim P_{lim}/\Gamma P_{max} \sim 10^{-2}$
Toroidal	structured jet: $P \sim P_{max}$ top hat: $P \sim P_{max}(\theta_{obs}/\theta_j)^2$	X $\theta_{obs}/\theta_j \lesssim 0.4 - 0.55$

GRB 170817A: afterglow observations



(Mooley et al. 2018)

GRB 170817A: afterglow observations



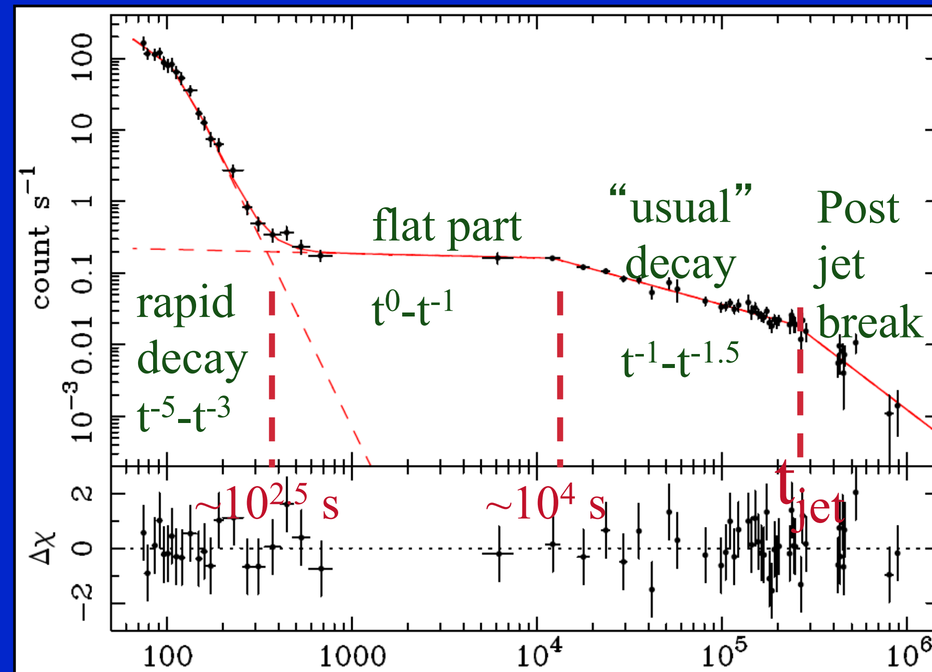
$F_\nu \propto \nu^{-0.61} t^{0.78\pm0.05}$

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

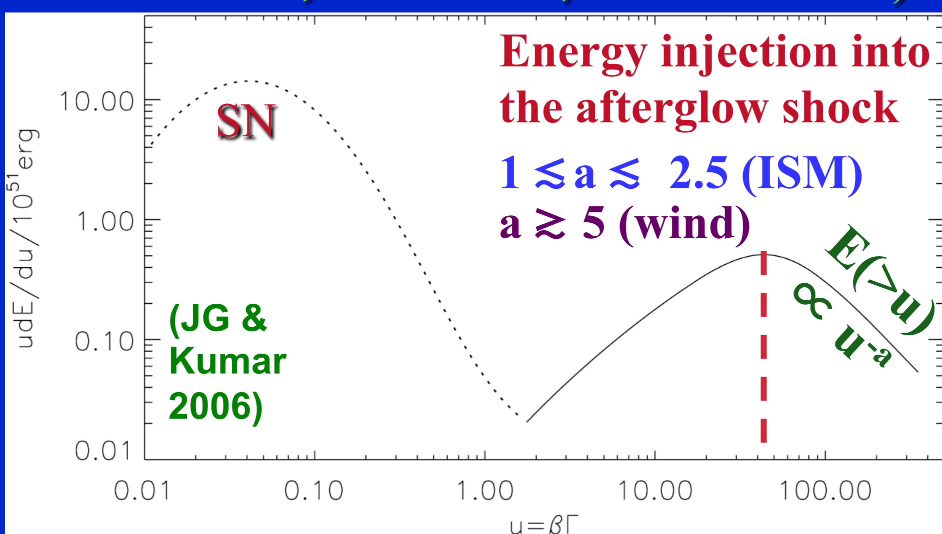
(Mooley et al. 2018)

Analogy to rising F_ν: X-ray Plateaus

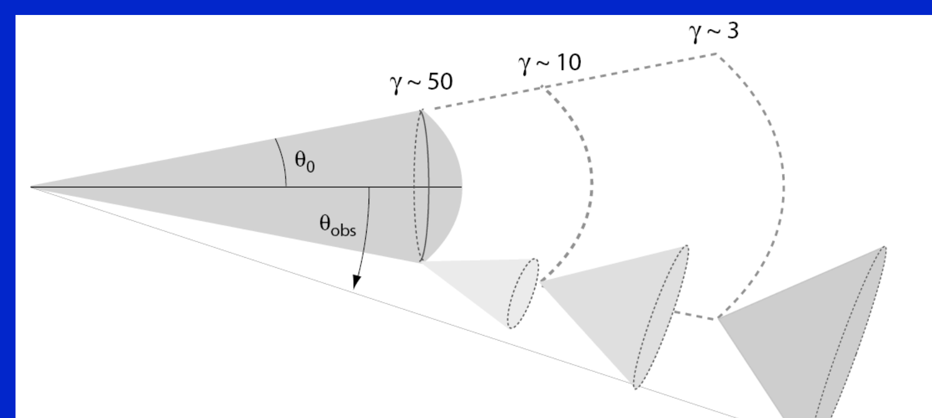
- Possible solutions:
- Evolution of shock microphysical parameters (JG, Konigl & Piran 2006)
- Energy injection into ext. shock:
  1. long-lived relativistic wind
  2. slower ejecta catching up (Sari & Meszaros 00; Nousek+ 06; JG & Kumar 06)
- Viewing angle effects



(Vaughan et al. 2006)



(JG & Kumar 2006)

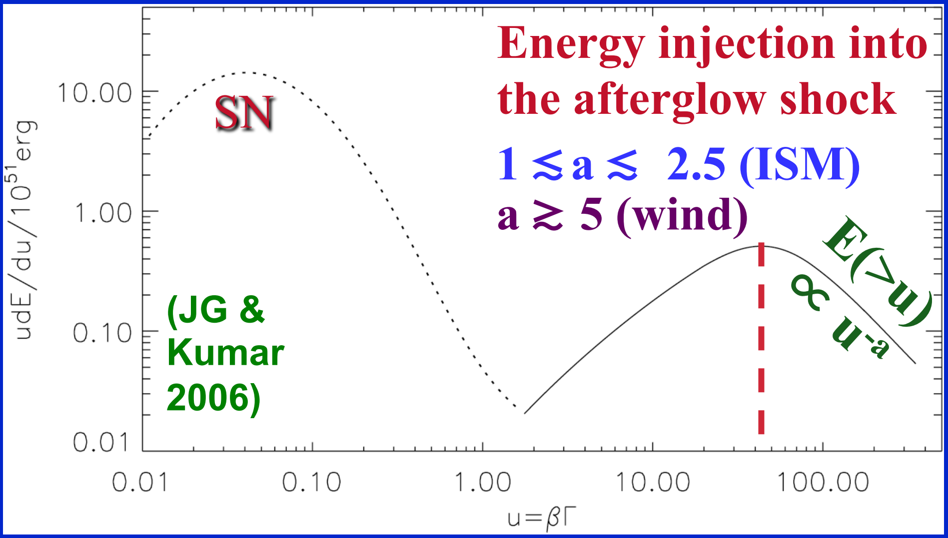


(JG, Ramirez-Ruiz & Perna 2005)

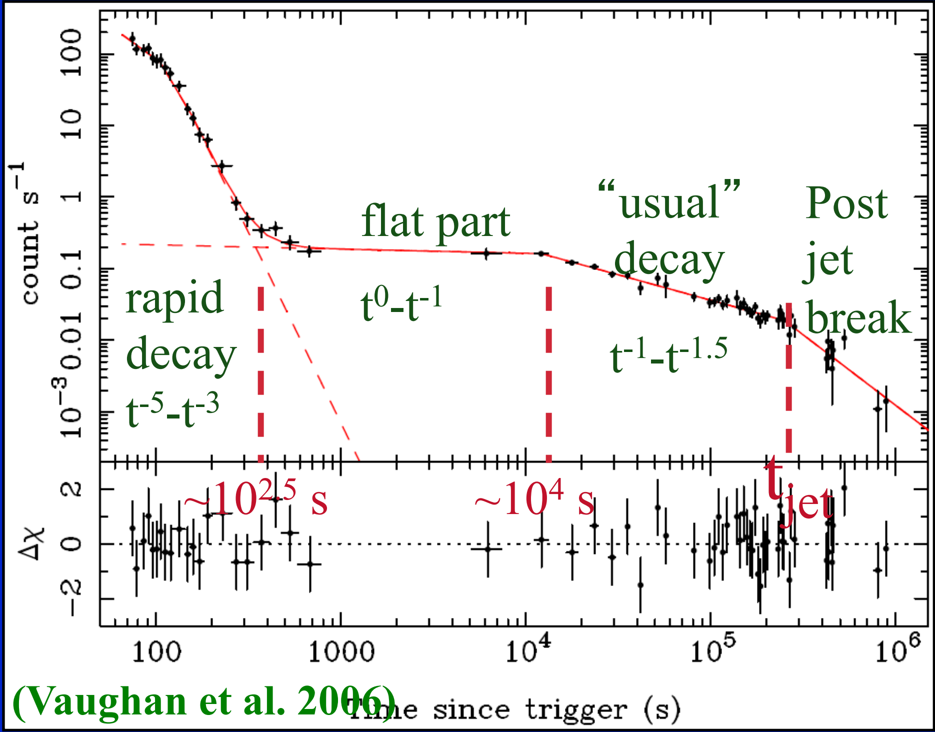
Analogy to rising F_ν: X-ray Plateaus

- Possible solutions:
- Evolution of shock microphysical parameters (JG, Konigl & Piran 2006)
- Energy injection into ext. shock:

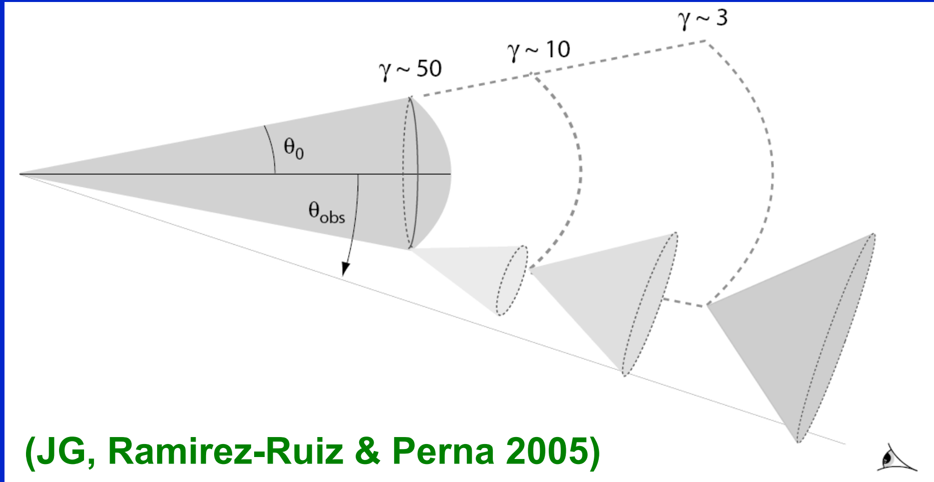
1. long-lived relativistic wind
2. slower ejecta catching up **radial** (Sari & Meszaros 00; Nousek+ 06; JG & Kumar 06)



- Viewing angle effects **angular**



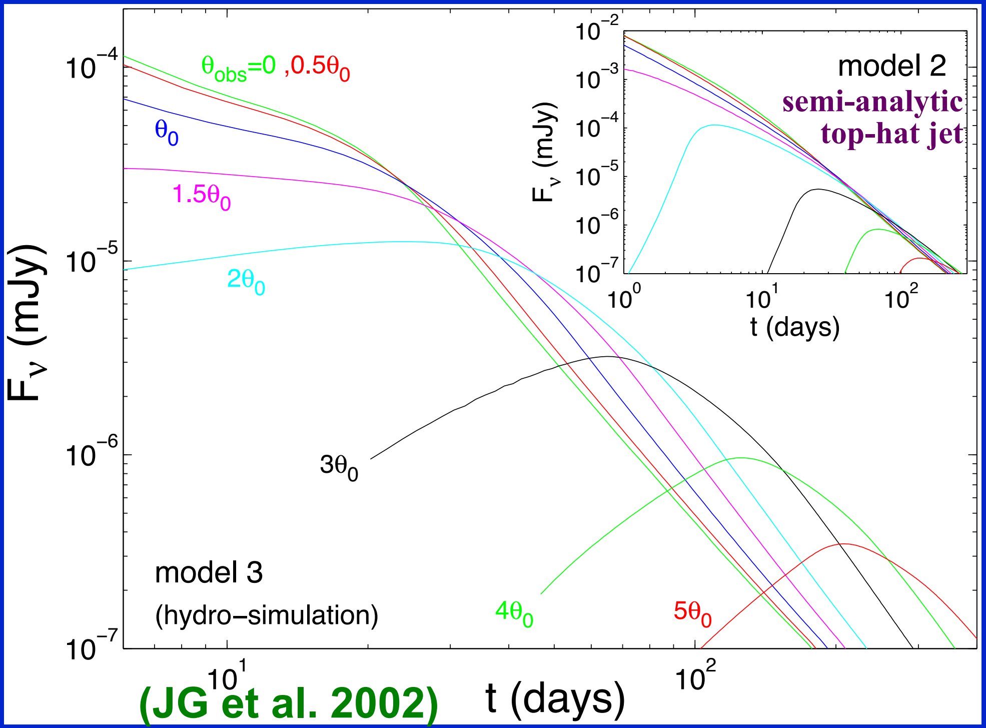
(Vaughan et al. 2006)



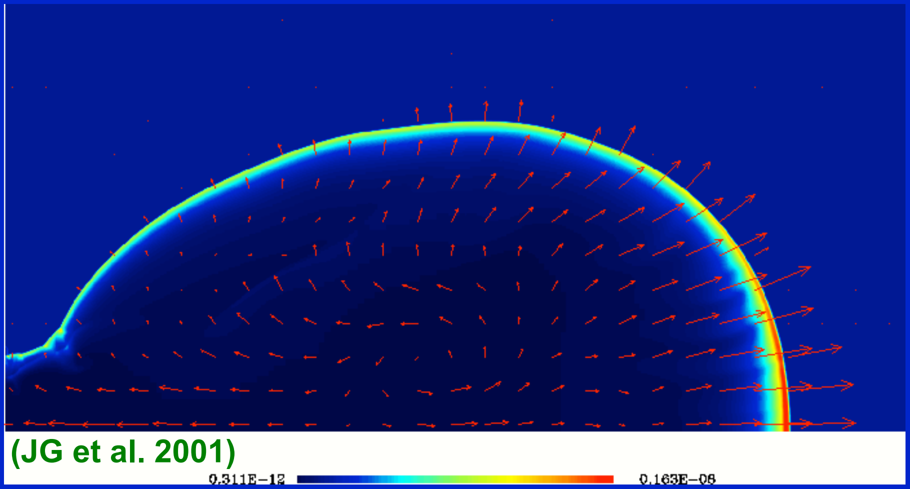
(JG, Ramirez-Ruiz & Perna 2005)

Off-Axis Afterglow Lightcurves

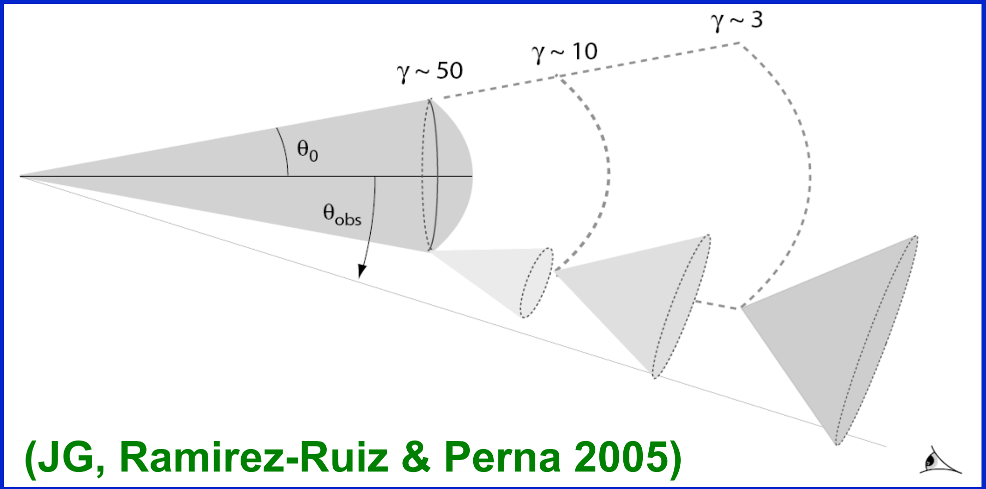
- The emission is initially strongly beamed away from our L.o.S
- F_ν rises as beaming cone widens
- When beaming cone reaches LoS F_ν peaks & approaches on-axis F_ν
- The rise is much more gradual for hydrodynamic simulations due to slower matter at the jet's sides with non-radial velocities



(JG et al. 2002)



(JG et al. 2001)

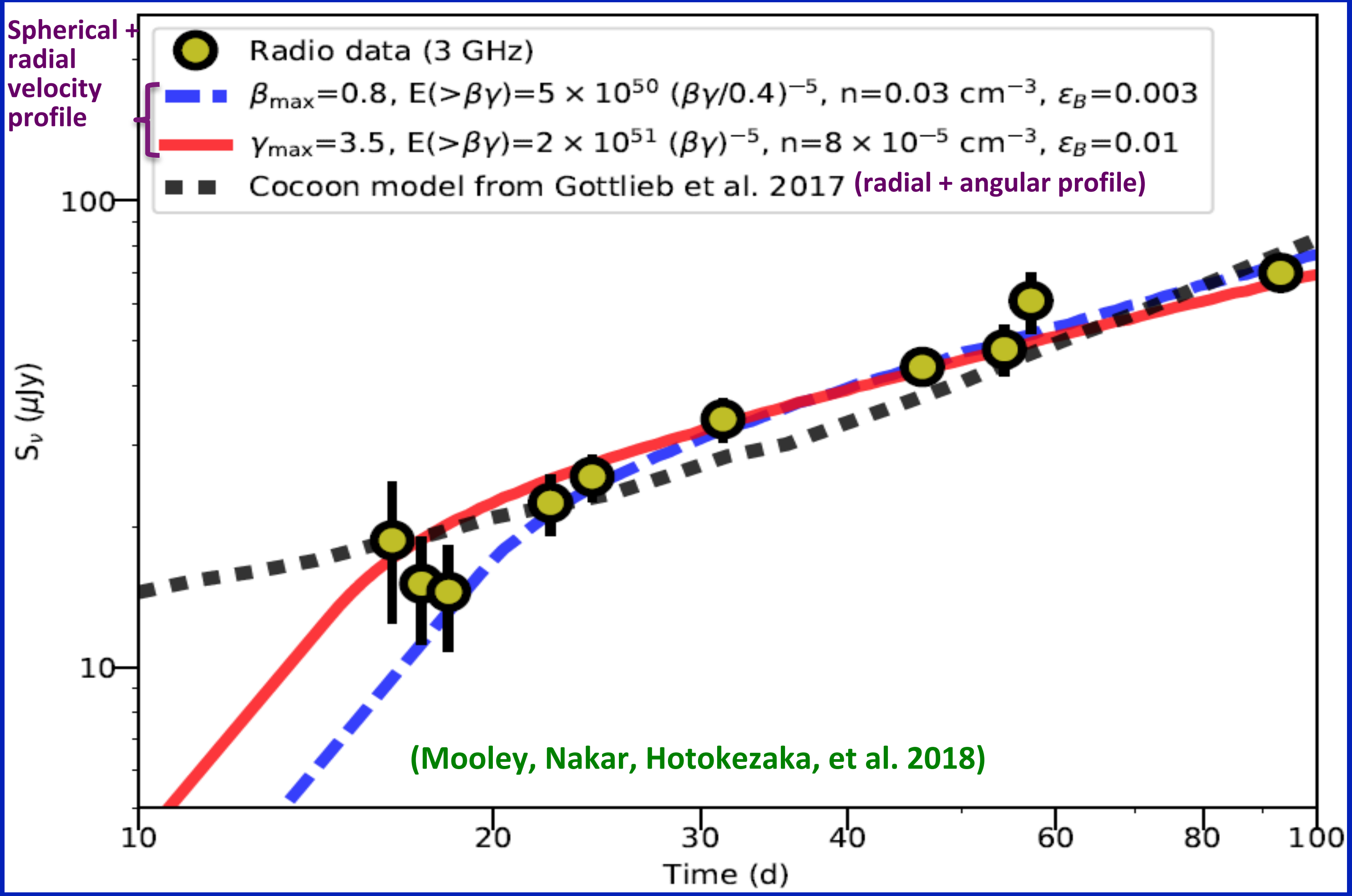


(JG, Ramirez-Ruiz & Perna 2005)

GRB170817 outflow structure: prompt, afterglow

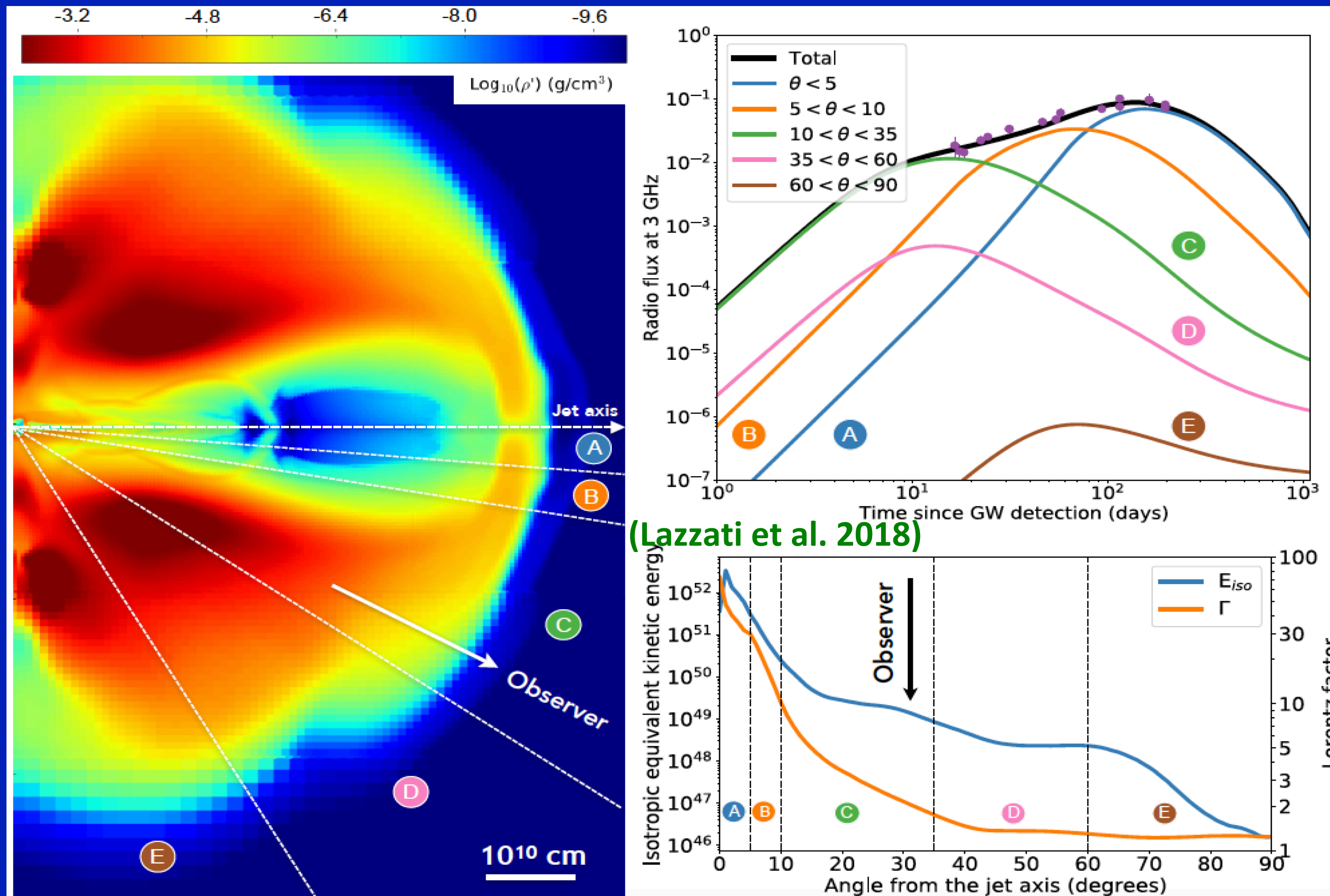
- Cocoon model (Kasliwal+17; Mooley+18; Nakar & Piran 18): **r** & **θ** profile

- 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

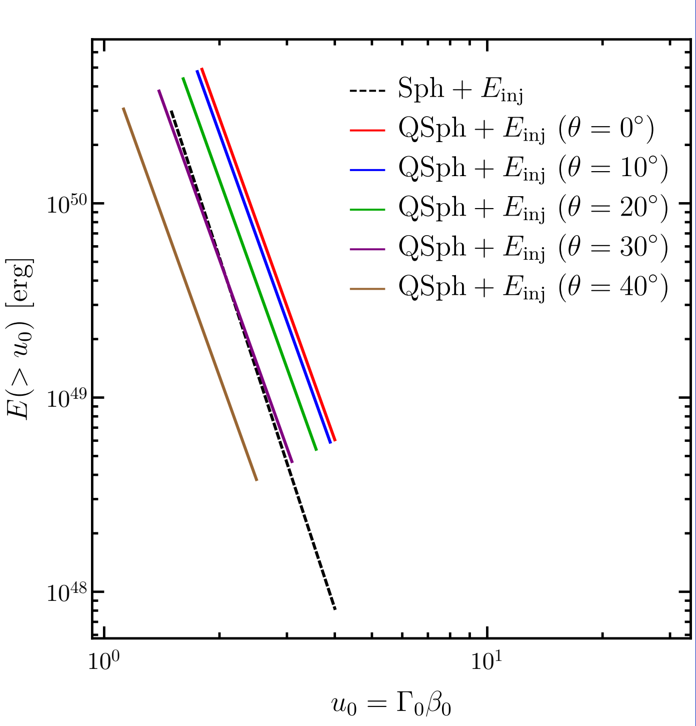


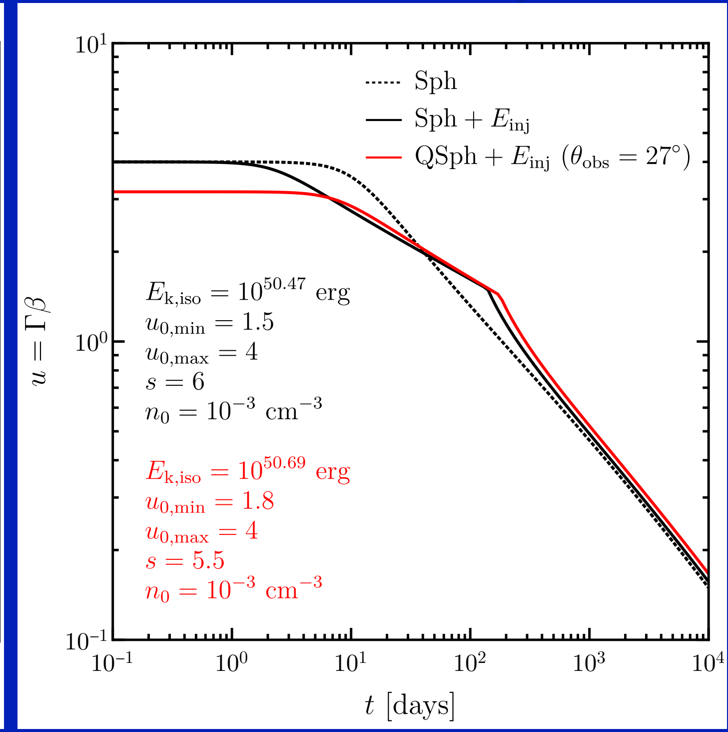
(Lazzati et al. 2018)

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

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





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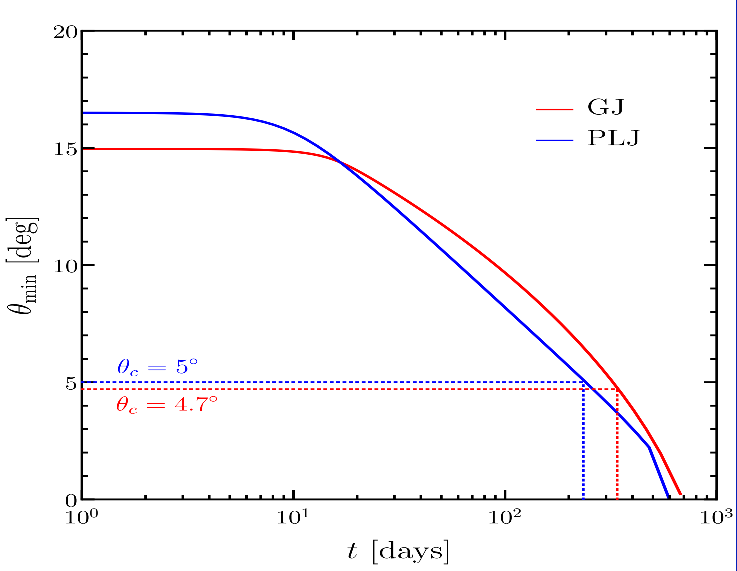
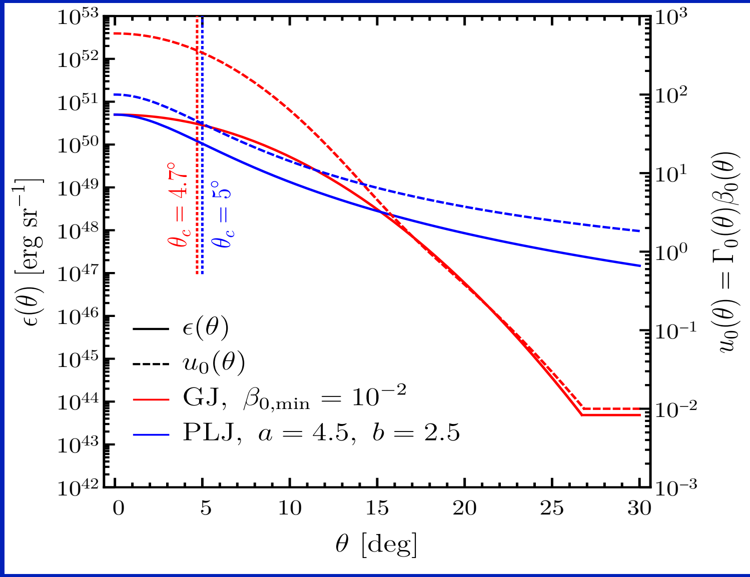
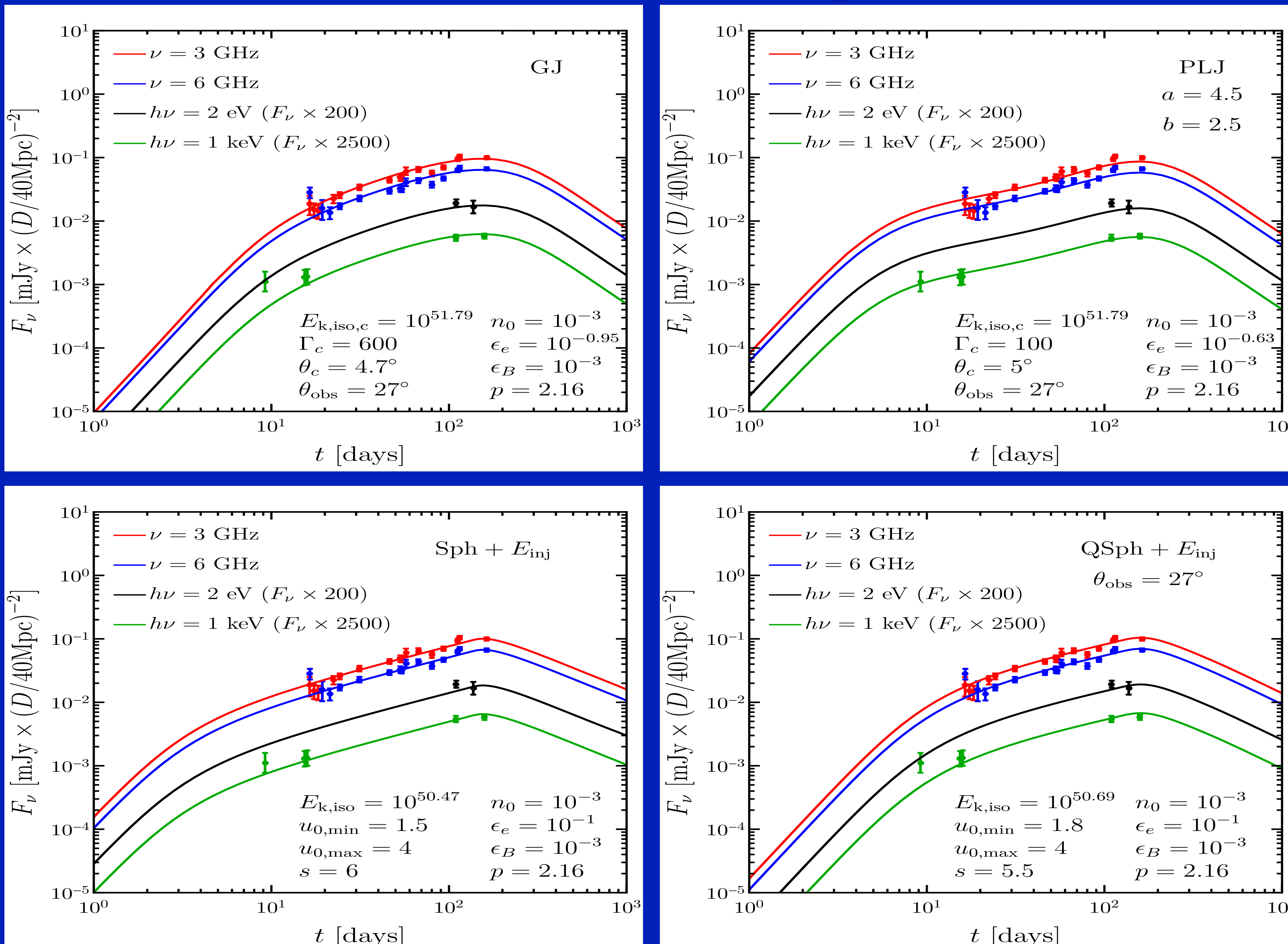
- We considered 4 different models including both main types
  - GJ: Gaussian Jet (in $\varepsilon = dE/d\Omega$, Γ_0-1) $\Gamma_c = 600$, $\theta_c = 4.7°$
  - PLJ: Power-Law Jet; $\varepsilon = \varepsilon_c\Theta^{-a}$, $\Gamma_0-1 = (\Gamma_c-1)\Theta^{-b}$, $\Theta = [1+(\theta/\theta_c)^2]^{1/2}$ $\Gamma_c = 100$, $\theta_c = 5°$, $a = 4.5$, $b = 2.5$
- 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)



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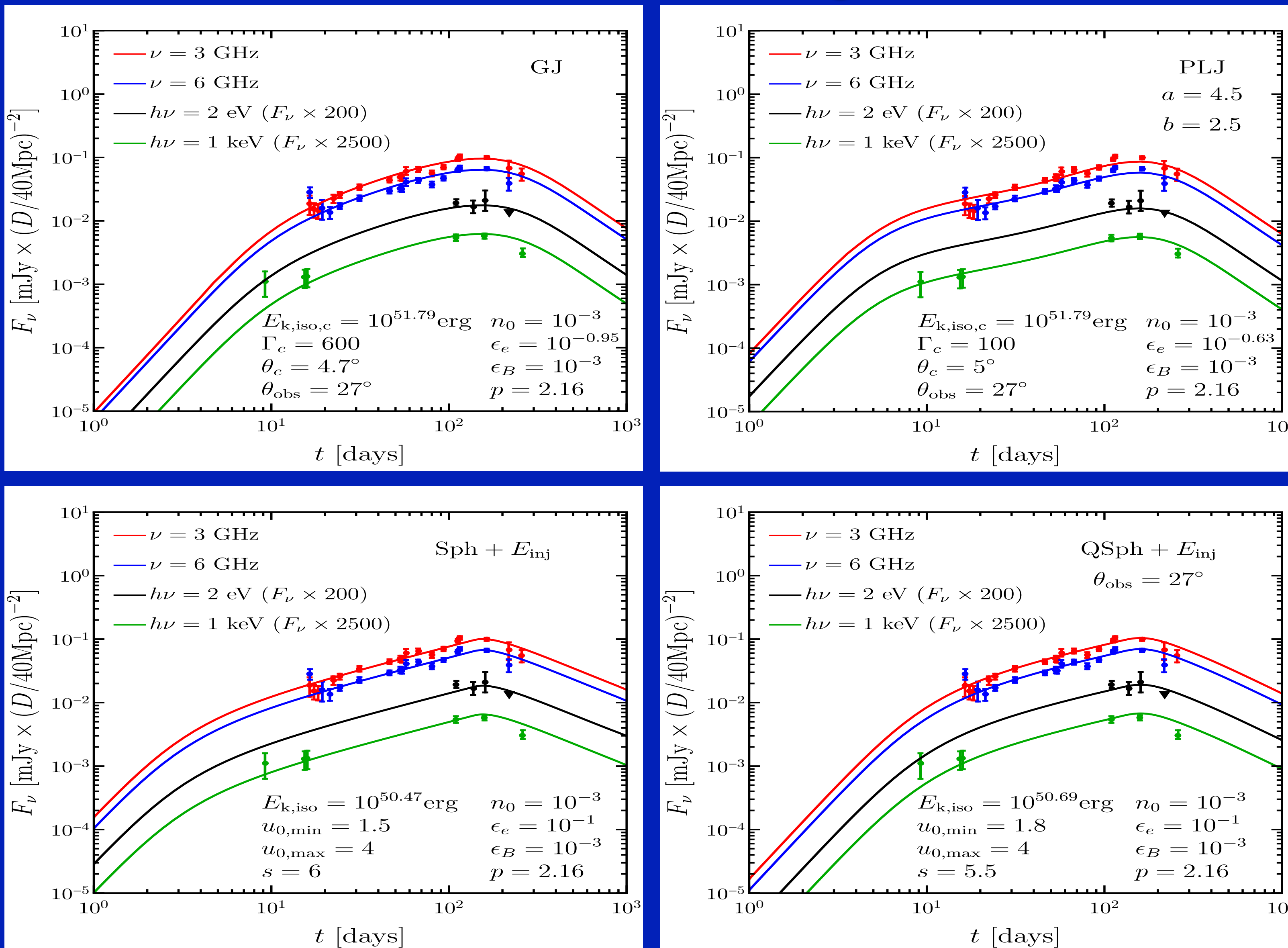
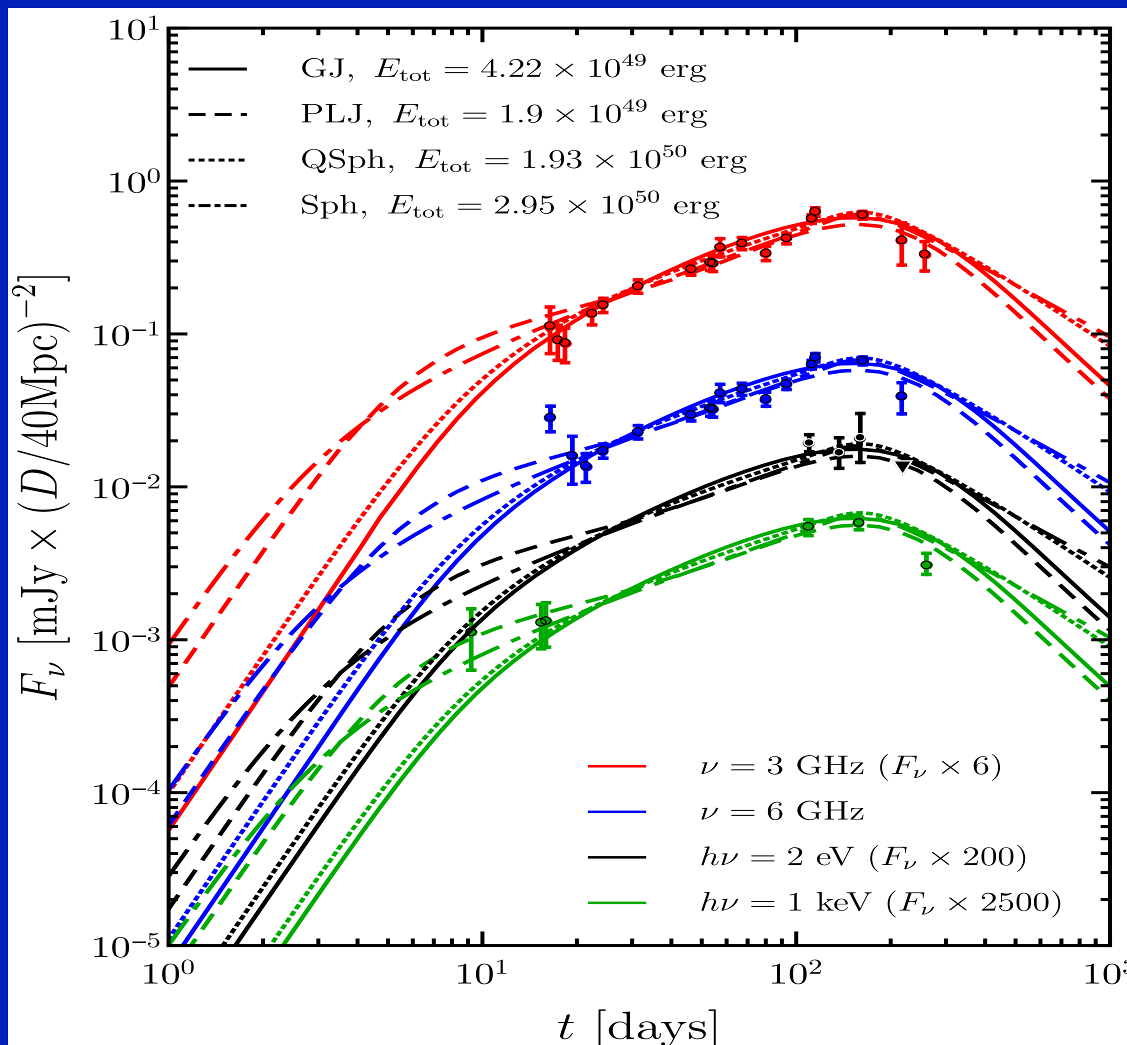


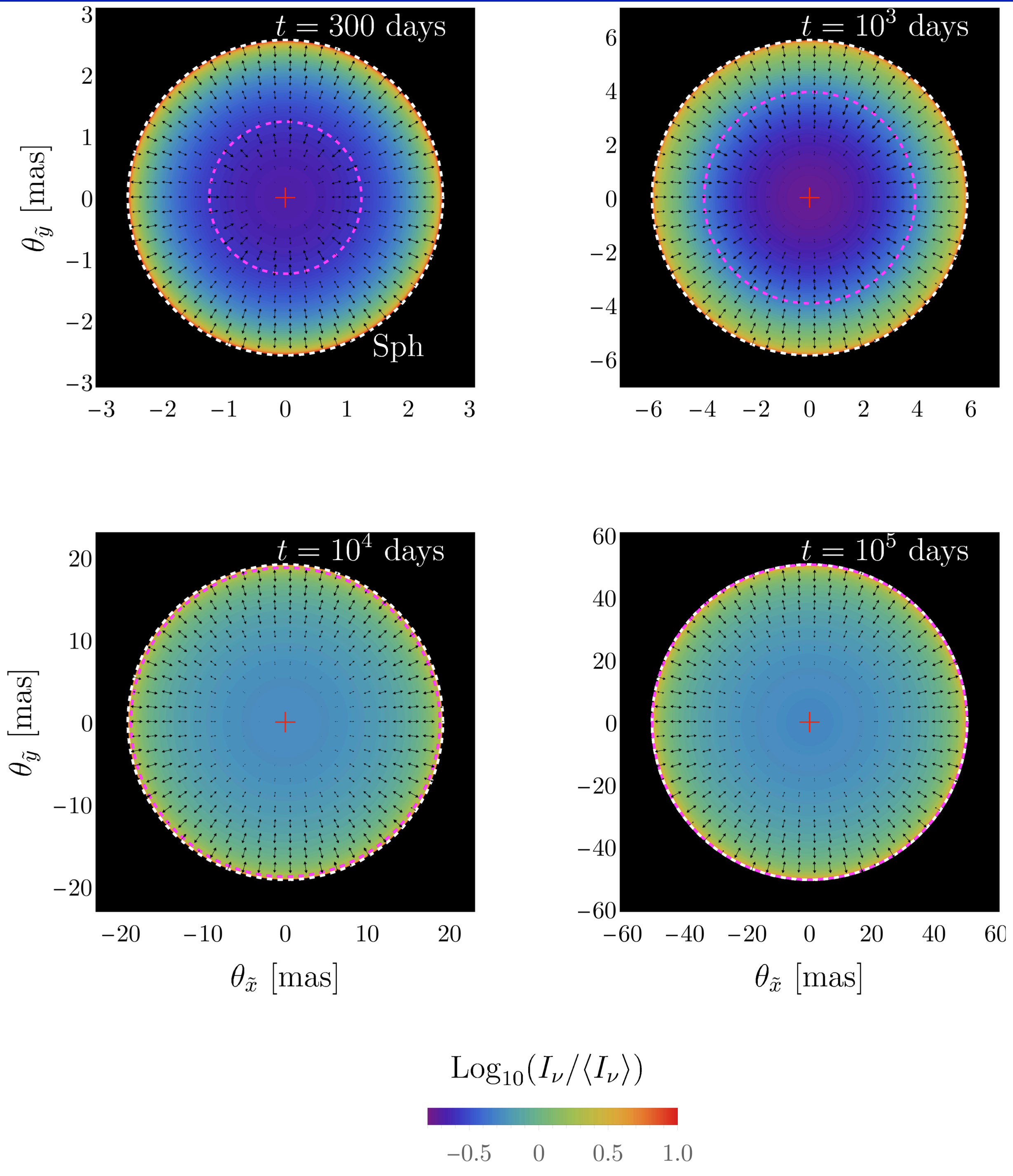
The outflow structure: breaking the degeneracy

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

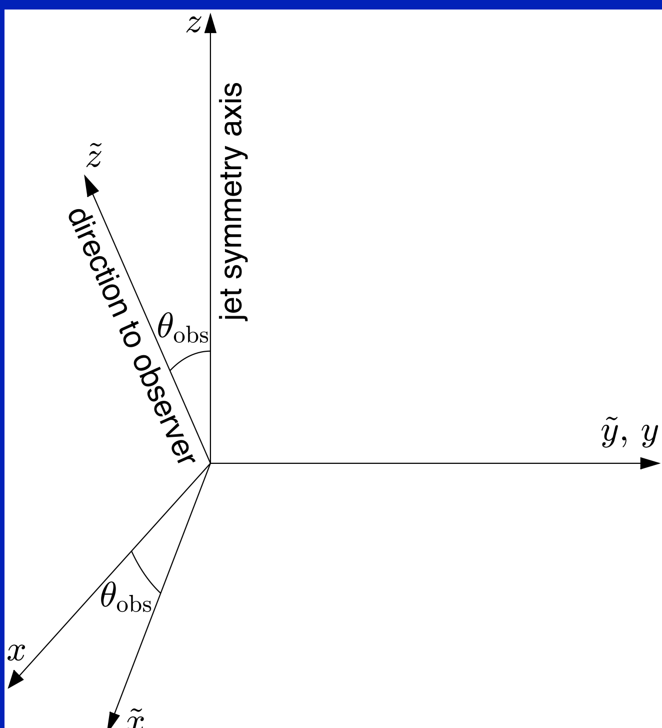


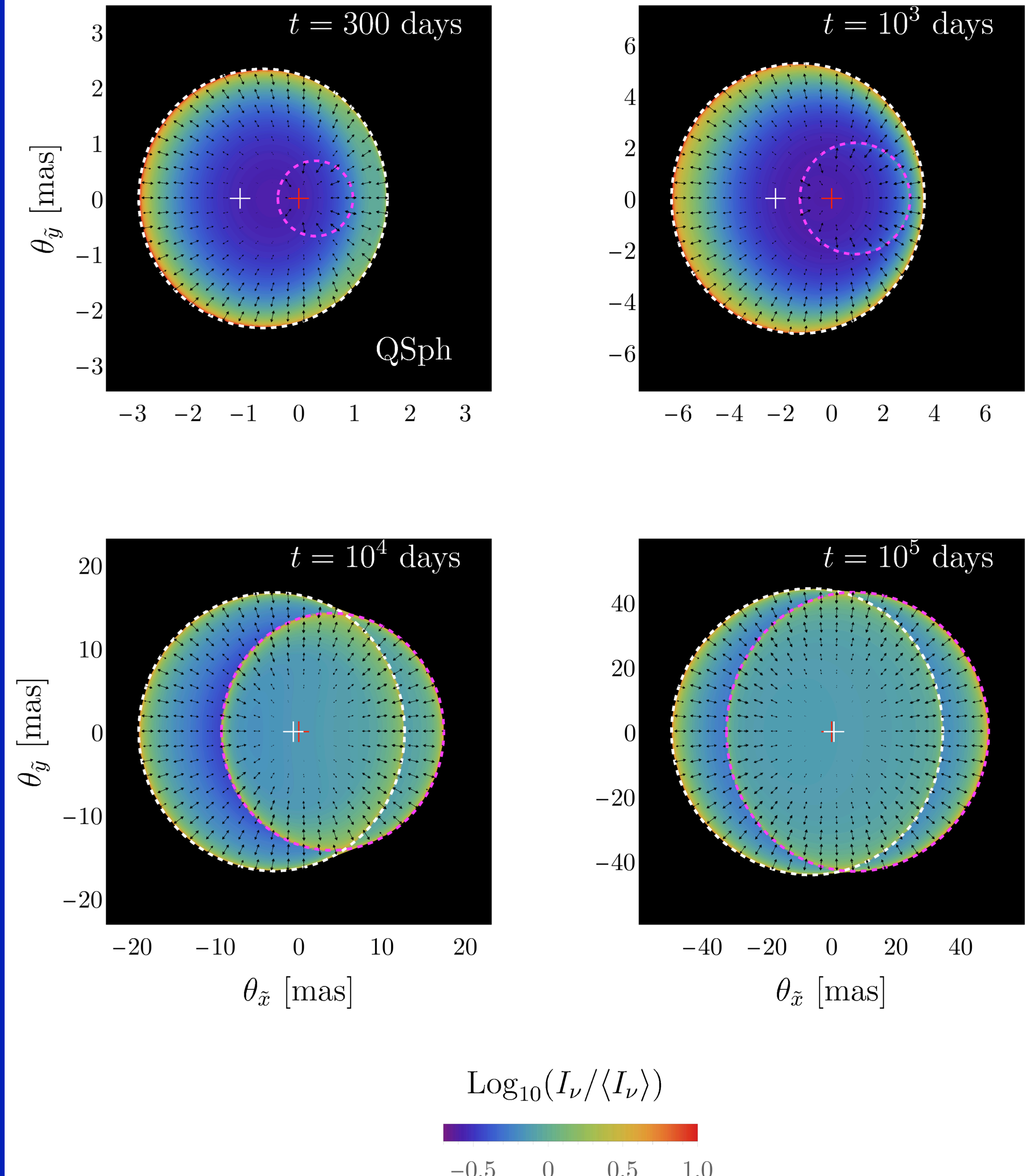
Decay: ~$t^{-2.2}$
(Mooley+18)

Afterglow Images: Sph + E_{inj}

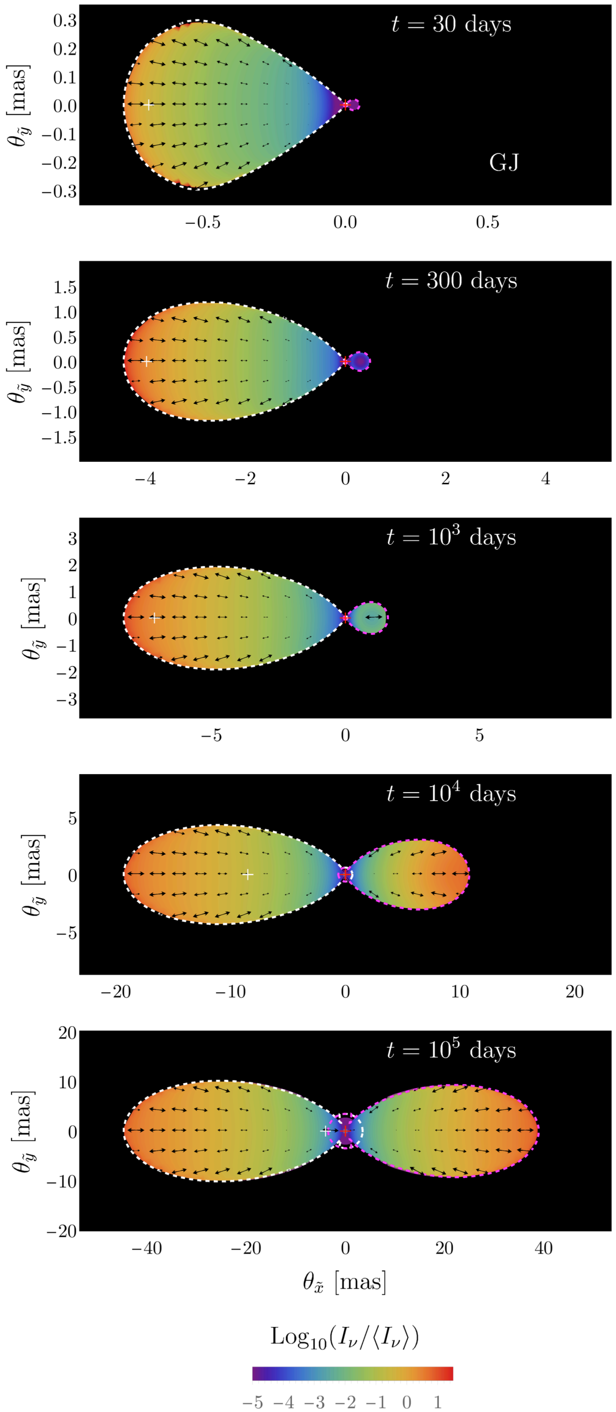


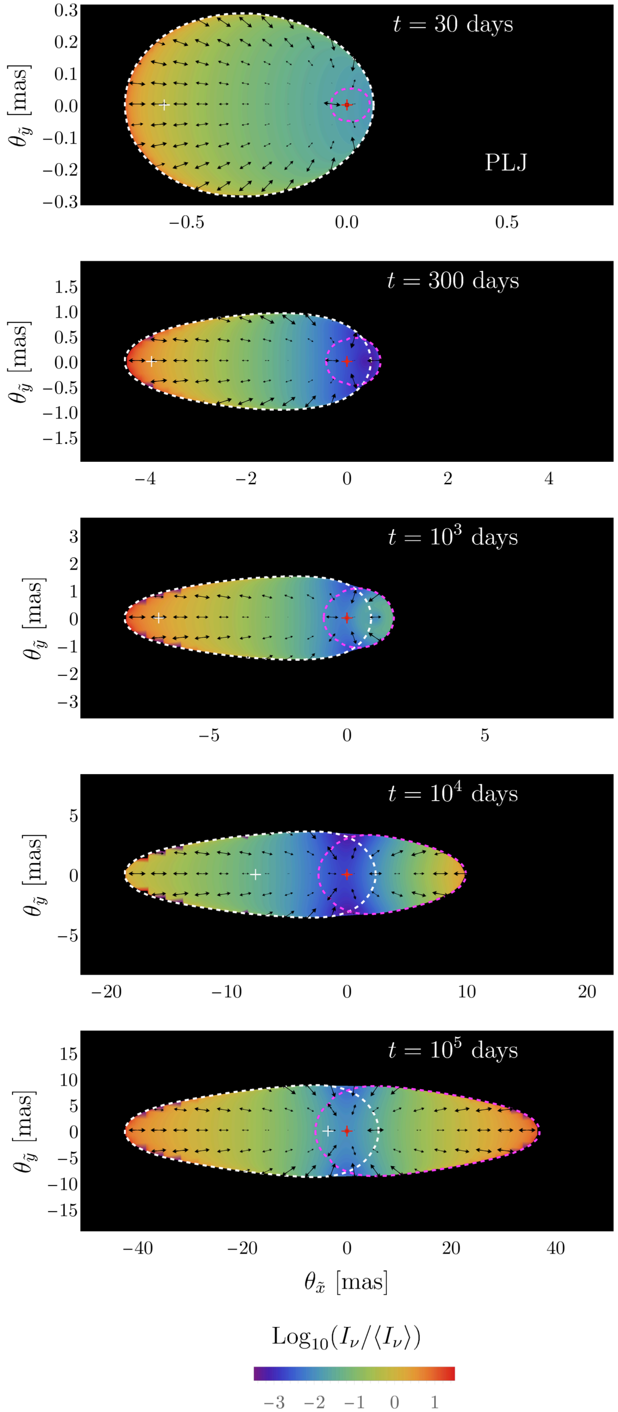
Afterglow Images: QSph + E_{inj}





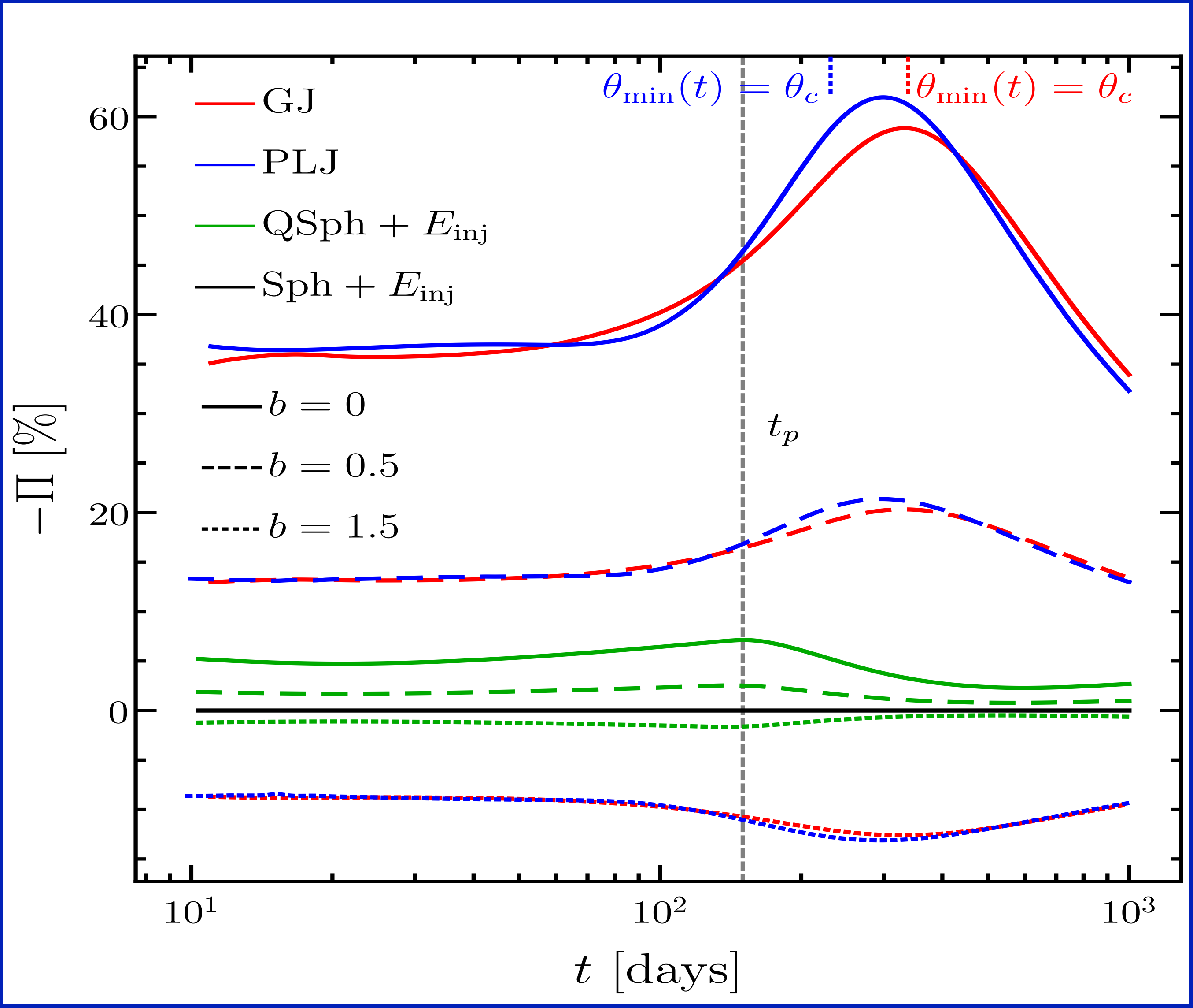
Afterglow Images: GJ, PLJ





Linear Polarization

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



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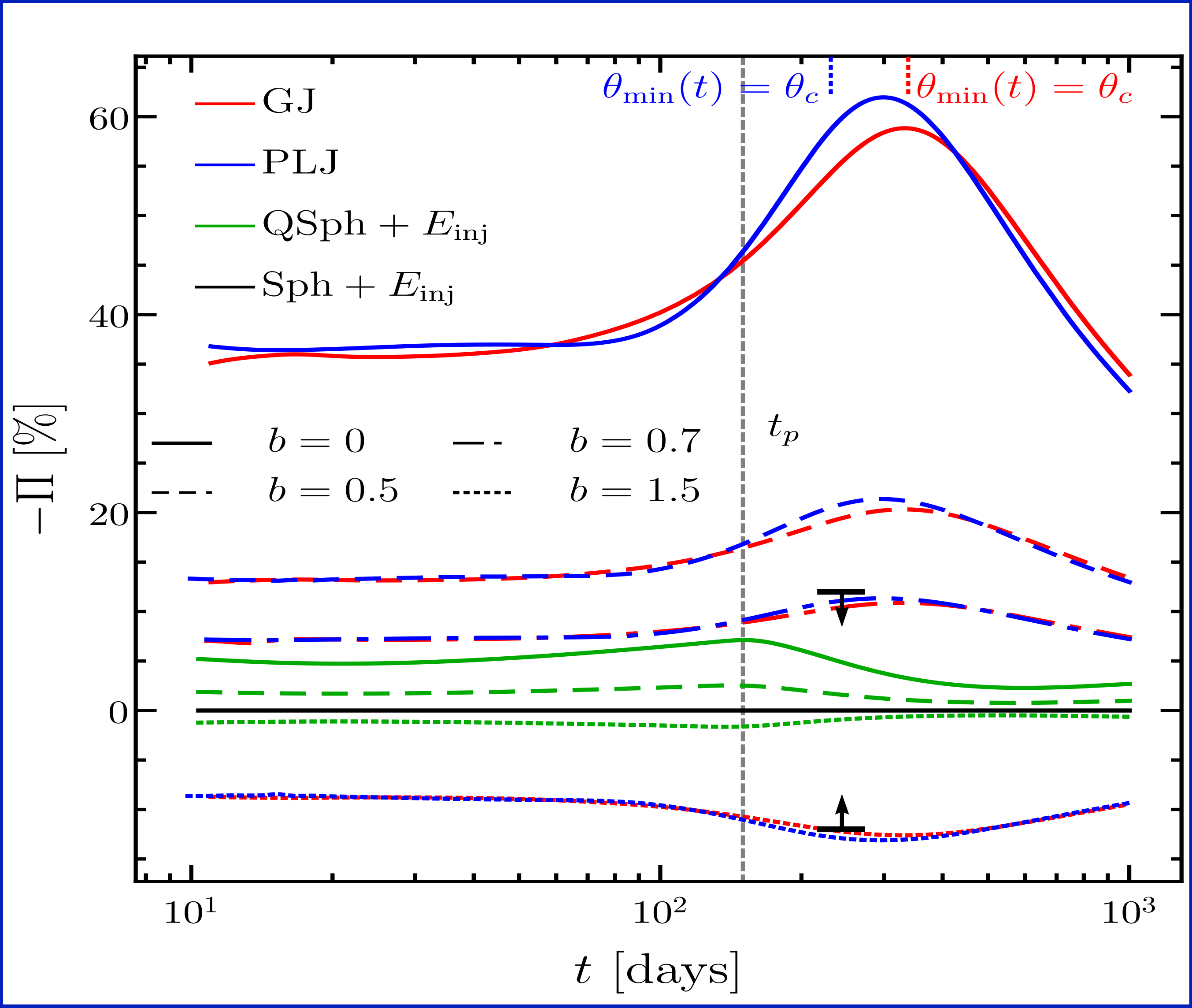
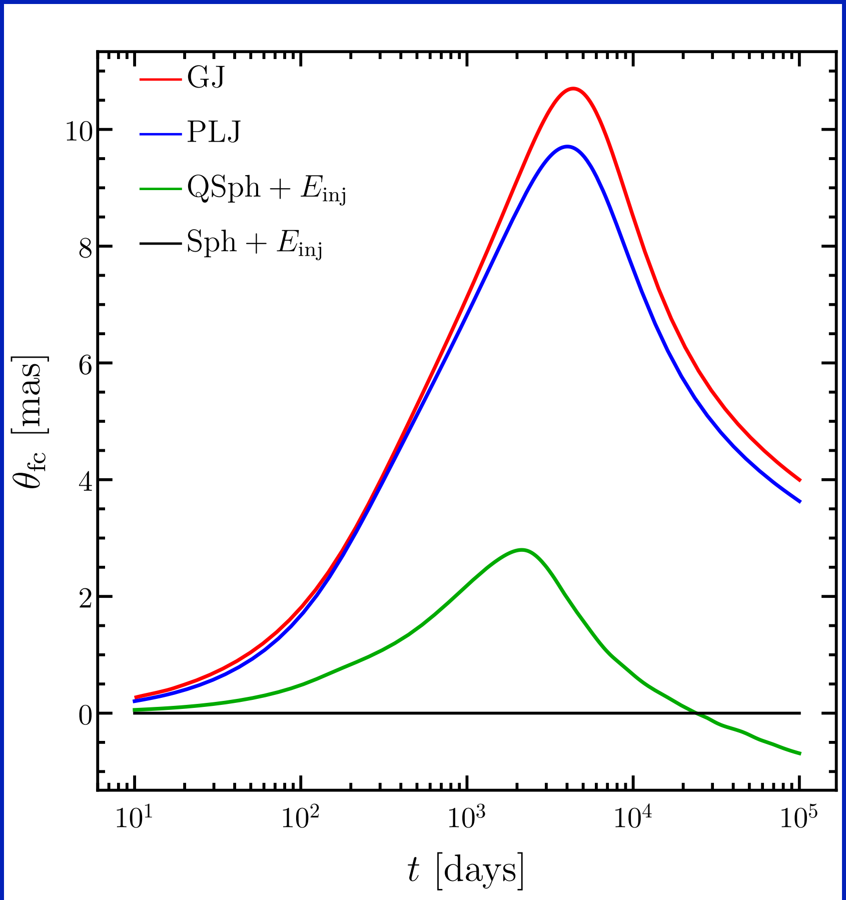


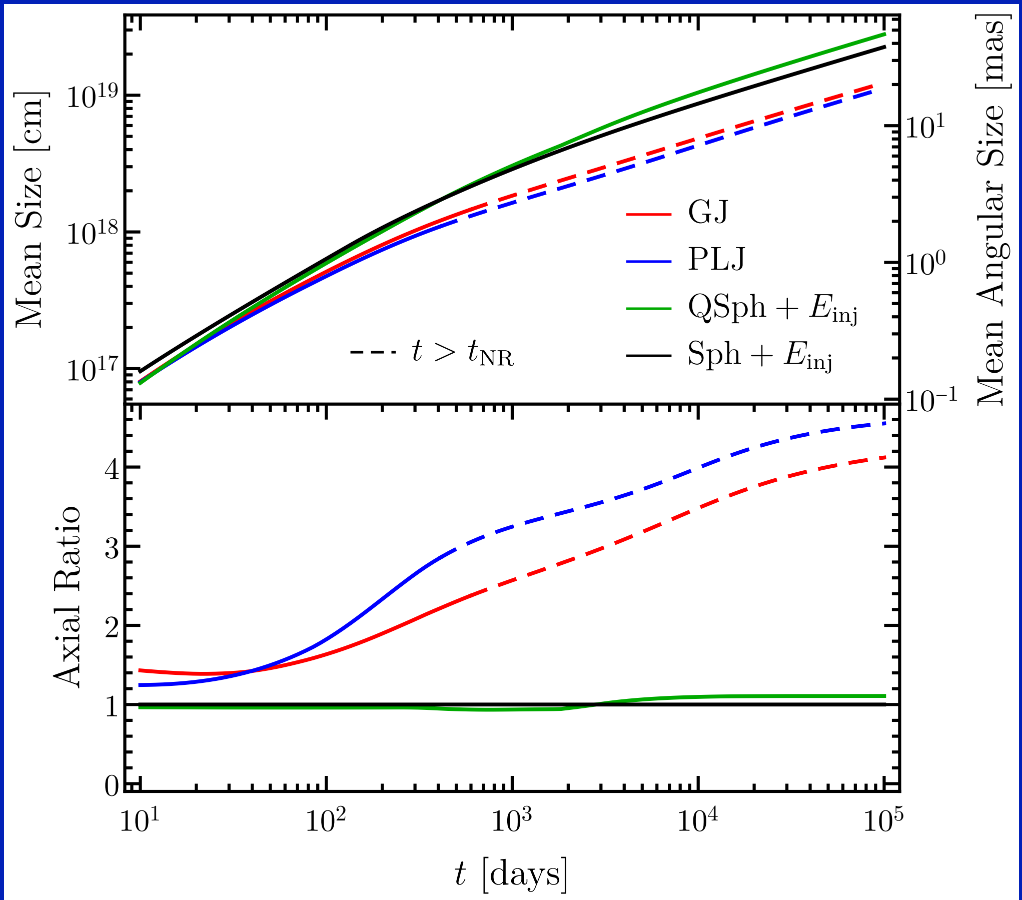
$0.7 \lesssim b \lesssim 1.5$ for jet models

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





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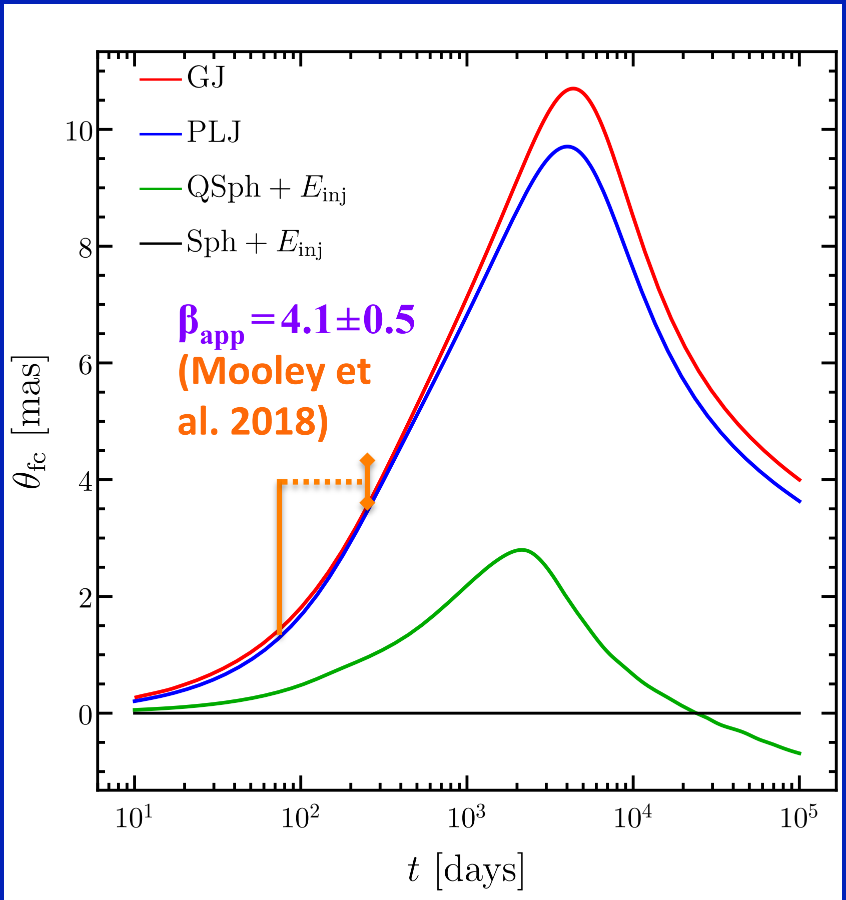

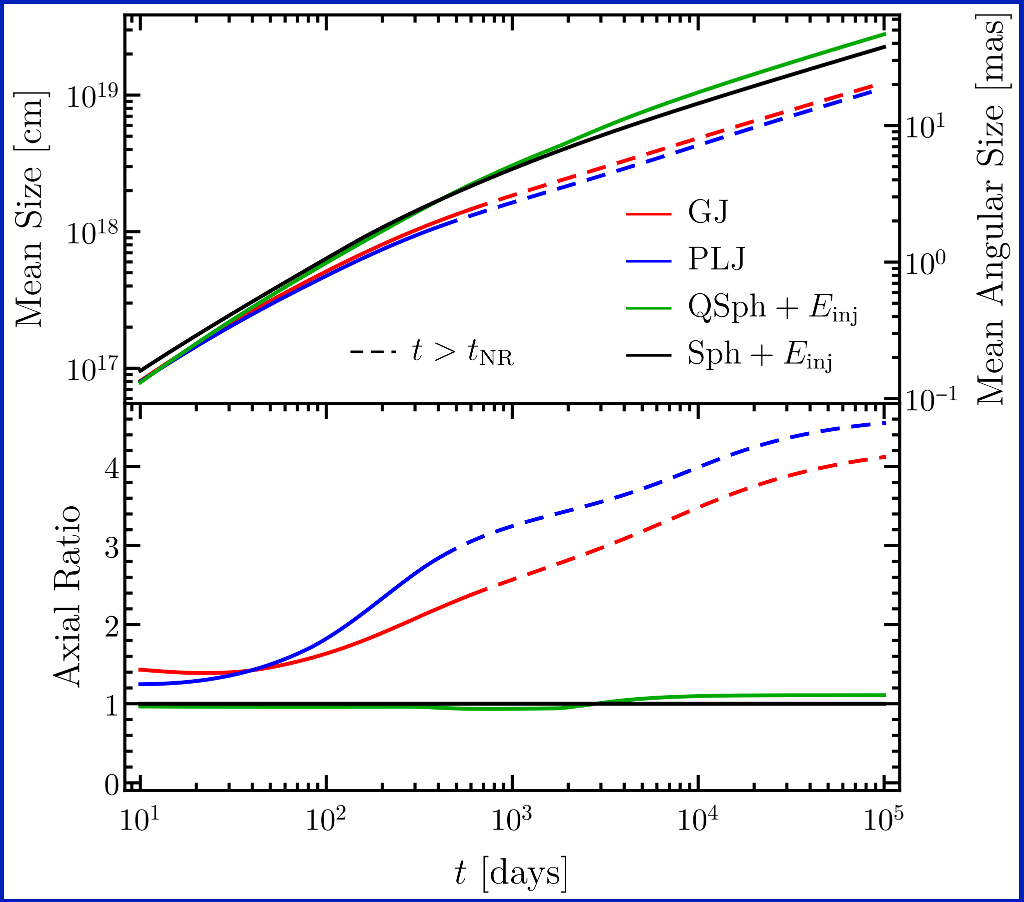

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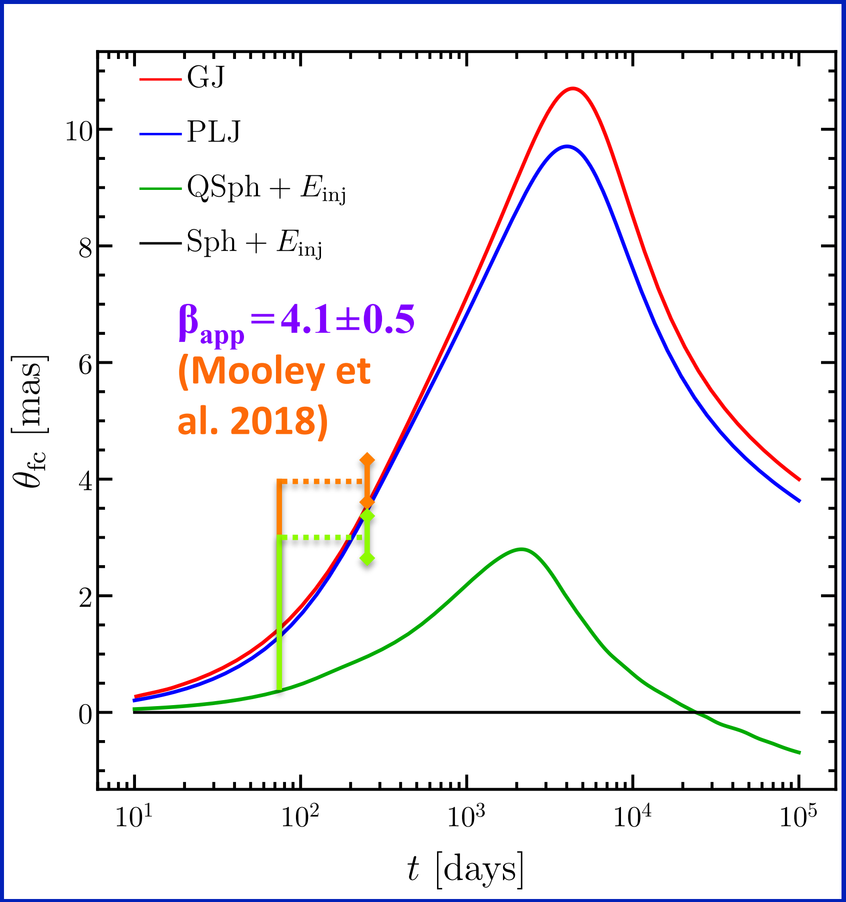

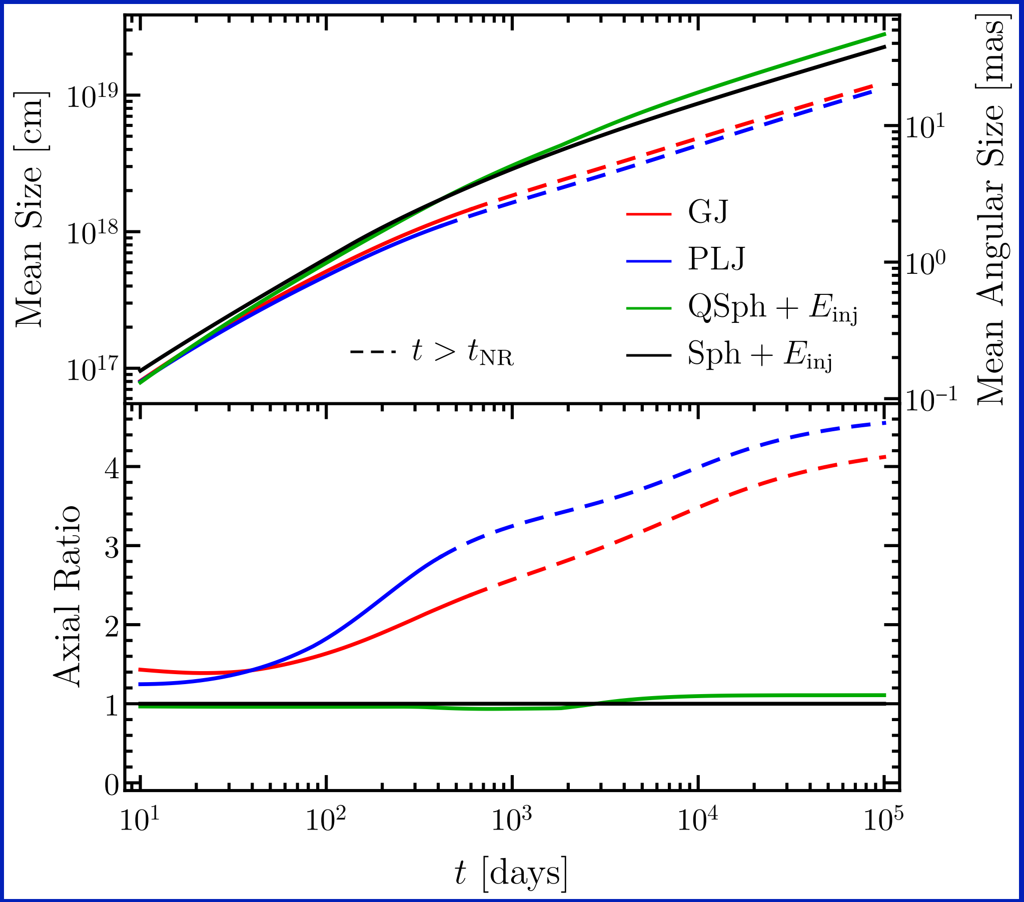

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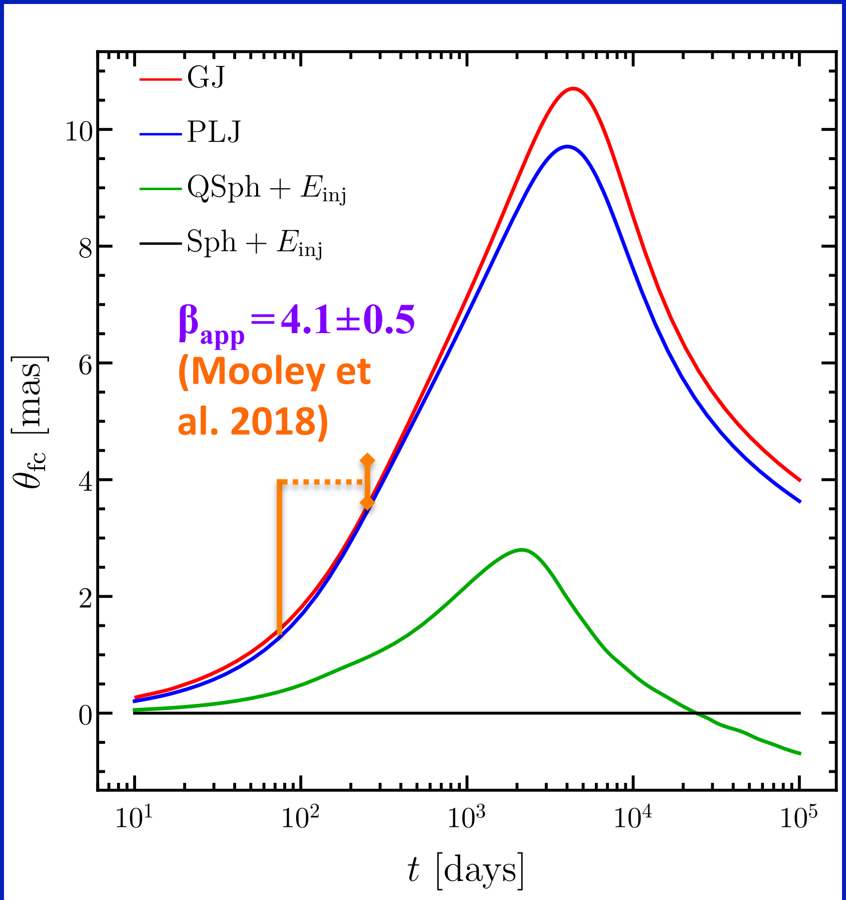
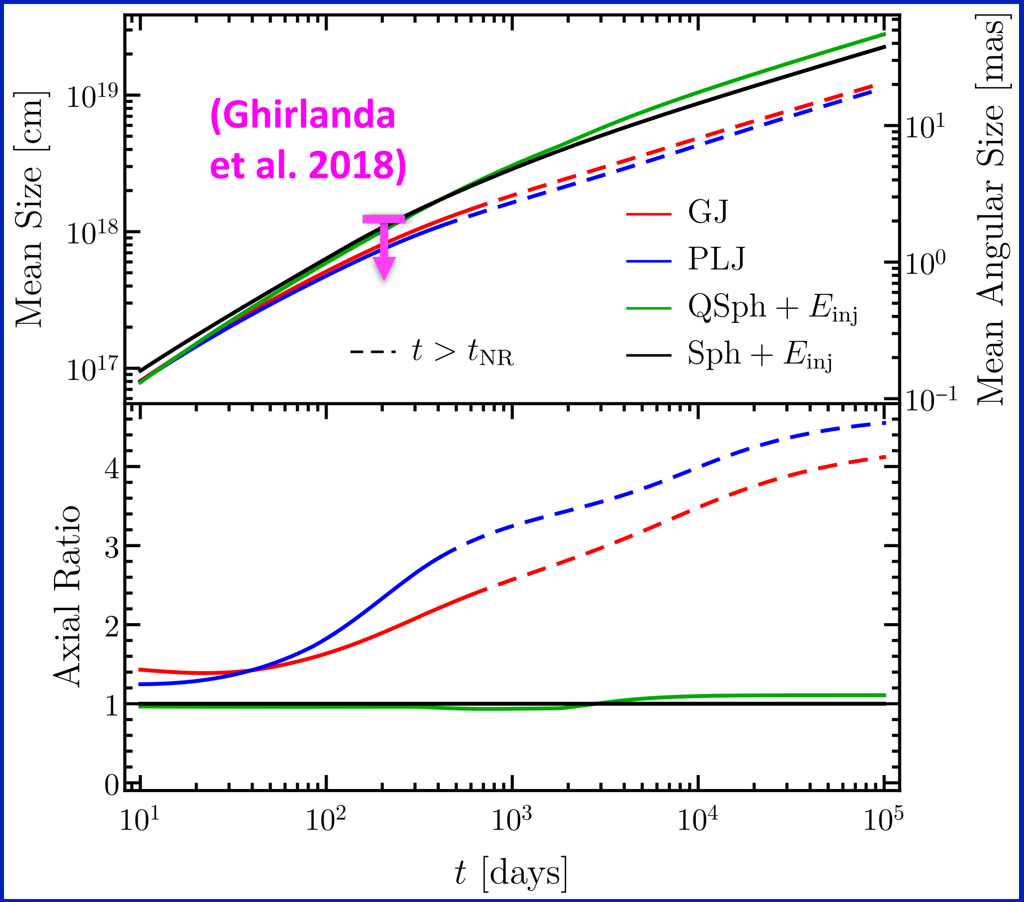
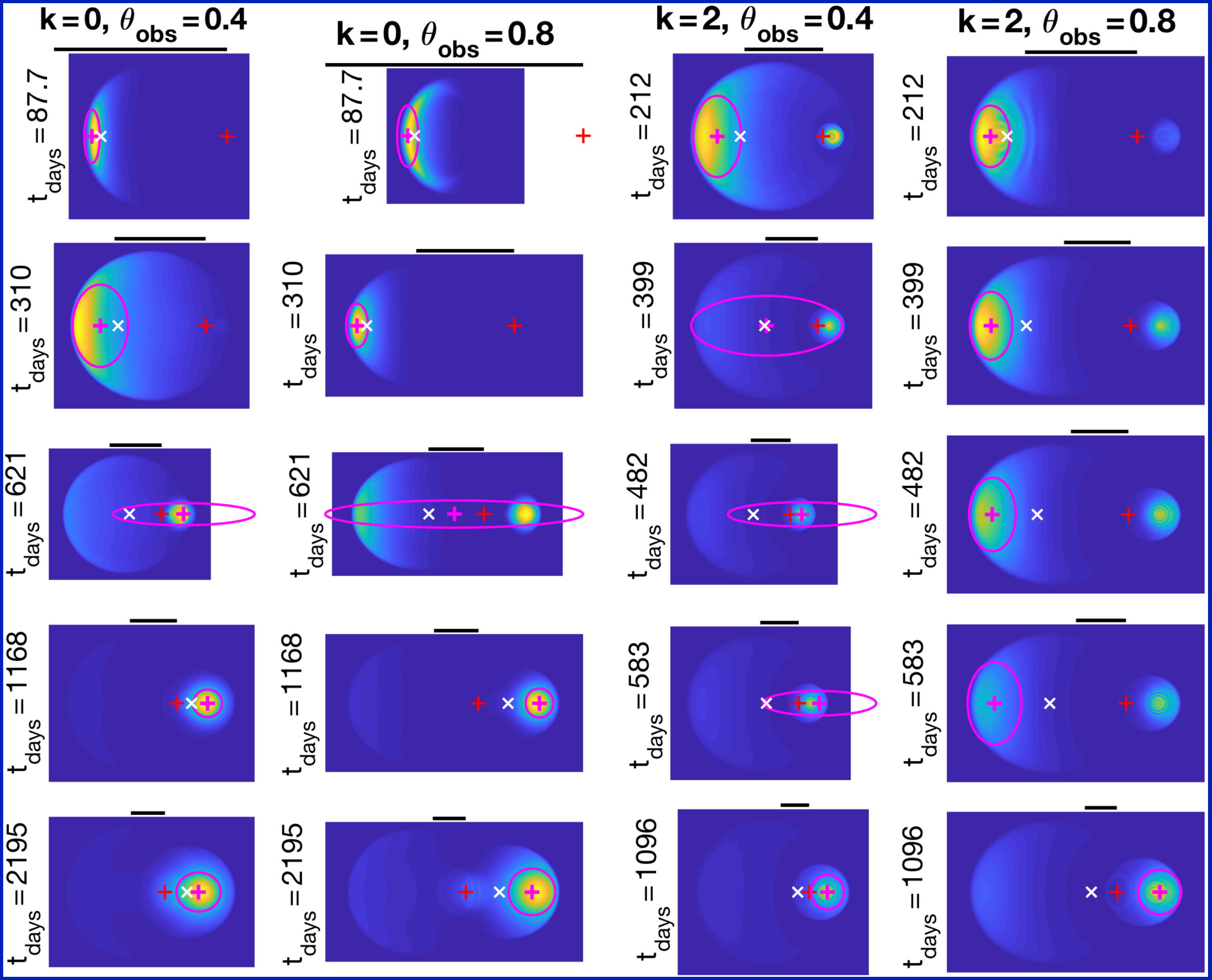




Afterglow Images: uniform jet simulations

(JG, De Colle & Remirez-Ruiz 2018)



Conclusions:

- **Afterglow polarization** probes jet structure & dynamics + the B-field structure behind relativistic collisionless shocks
- Reverse shock polarization probes B-field structure in ejecta
  - Optical flash ($\theta \sim 1/\Gamma_0 \lesssim 10^{-2}$), radio flare ($\theta \sim 1/\Gamma \sim 0.1$)
  - Reverse & forward (afterglow) shock emission may overlap
- More afterglow polarization **observations are needed**!!!
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- $\Rightarrow 0.7 \lesssim b \lesssim 1.5$ in the afterglow shock ($b = 2\langle B_{||}^2\rangle / \langle B_{perp}^2\rangle$)