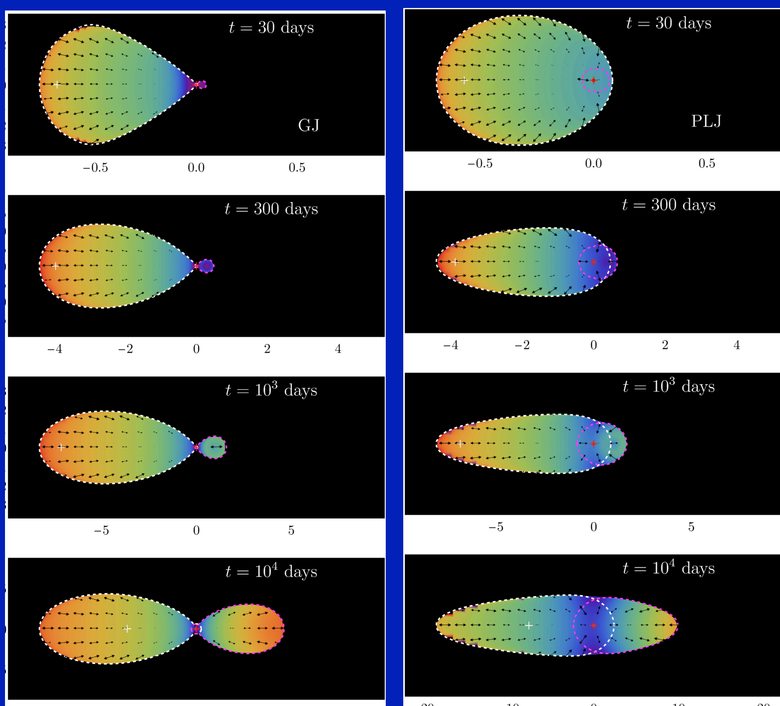
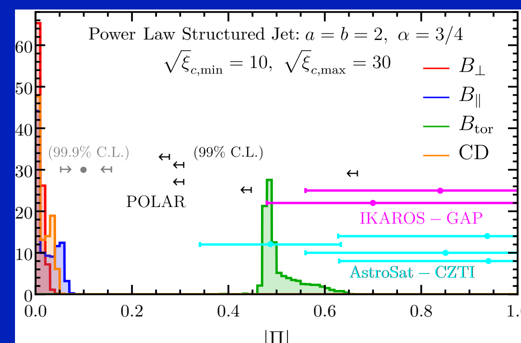
Polarization in Gamma-Ray Bursts

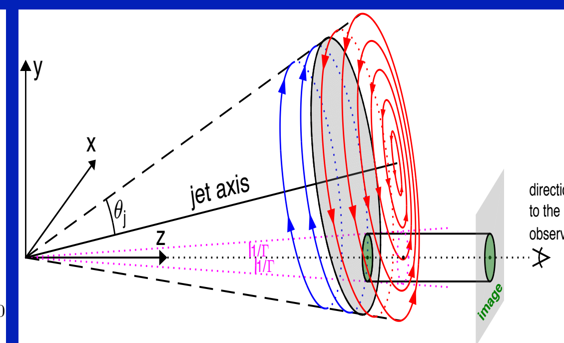
Jonathan Granot

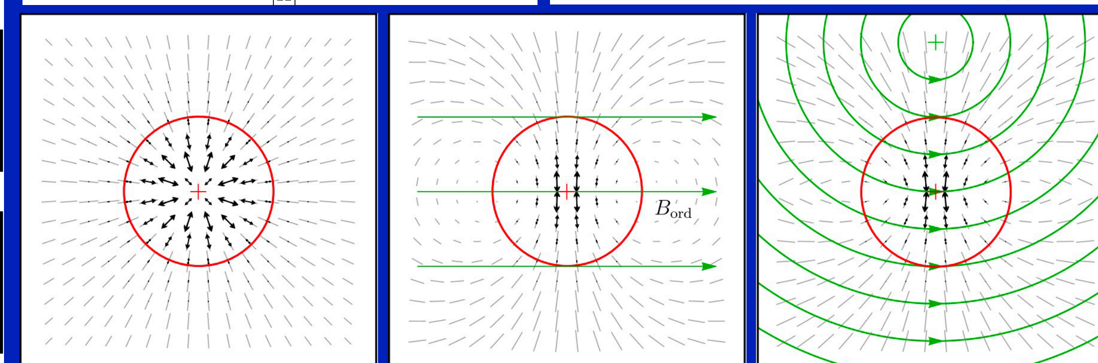
Open University of Israel & George Washington University

Collaborators: R. Gill, A. Königl, F. De Colle, E. Ramirez-Ruiz, T. Piran







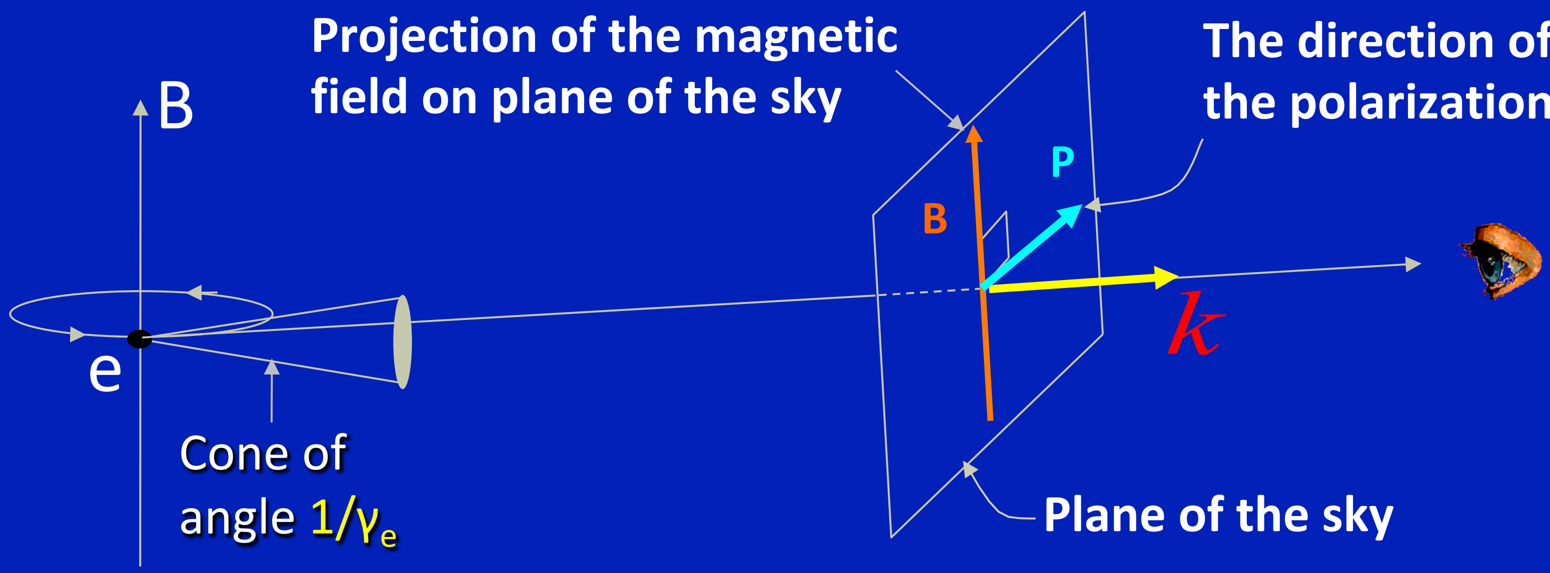


Workshop to bring together experts on High Energy Astrophysics from Japan & Israel; RIKEN, Kobe, Hyogo, Japan; 22 July 2019

Outline of the Talk:

- Polarization of synchrotron rad. from a relativistic source
- Afterglow: Jet structure & dynamics, B-field structure (ES)
  - **Top hat vs. structured jet**
  - **Shock-produced vs. ordered B-field, or combining the two**
  - **Shock-produced B-field's degree of anisotropy**
- Reverse shock: optical flash & **radio flare** (ejecta B-field)
- Prompt GRB: emission mechanism, Jet structure, ejecta B
  - **High P: Syn. + ordered B vs. sharp jet + special viewing angle**
  - **Different emission mechanisms**
  - **What can be learned from single GRBs or a large sample**
- **Conclusions**

Polarization of Synchrotron Emission

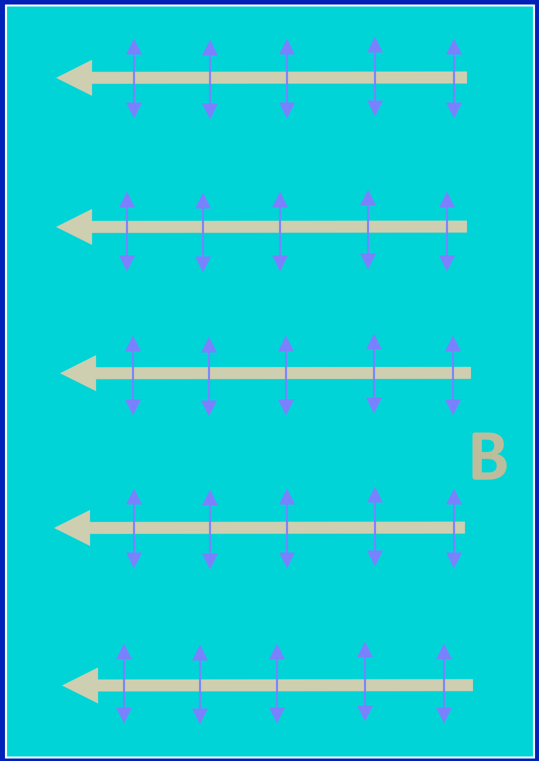


- **linear polarization** is perpendicular to the projection of **B** on the plane of the sky (normal to the wave vector)
- The maximal polarization is for the local emission from an ordered **B**-field: $P_{max} = (\alpha+1)/(\alpha+5/3)$ where $F_\nu \propto \nu^{-\alpha}$, $-1/3 \leq \alpha \lesssim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

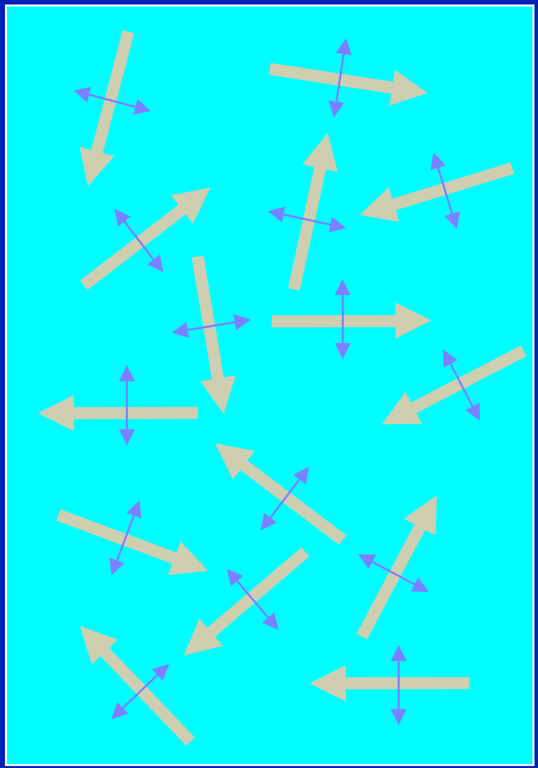
In the source rest frame:

- 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

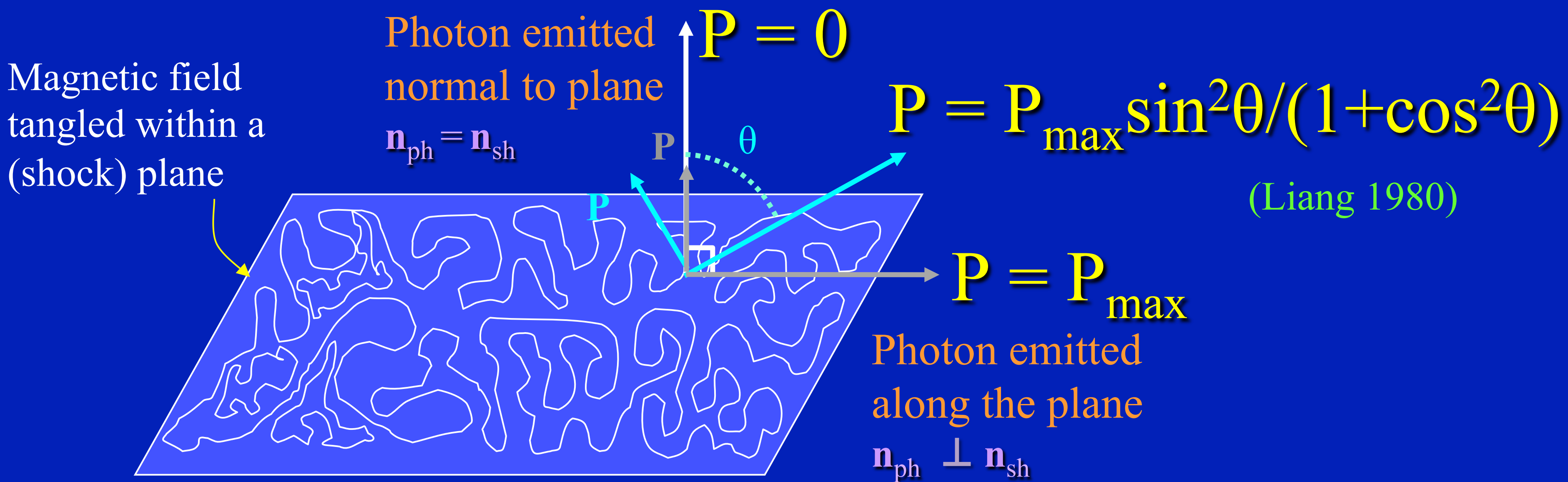


Random B



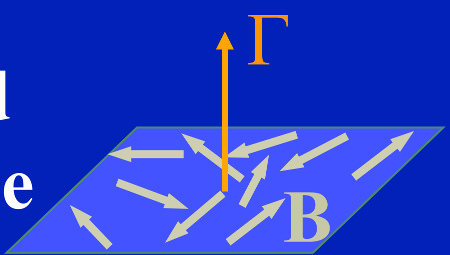
Shock Produced Magnetic Field:

- 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)

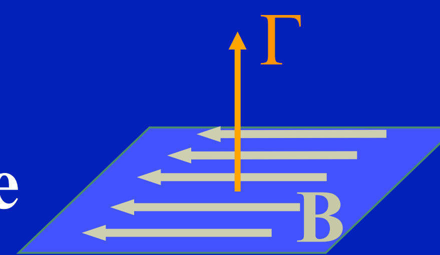


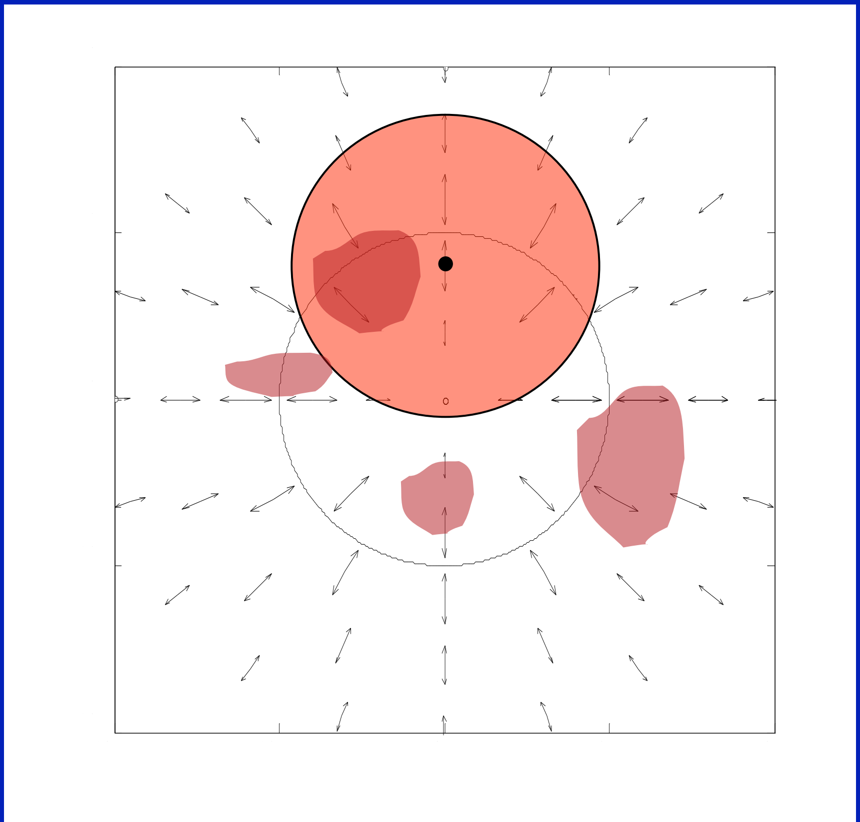
Relativistic Source:

Random field in shock plane

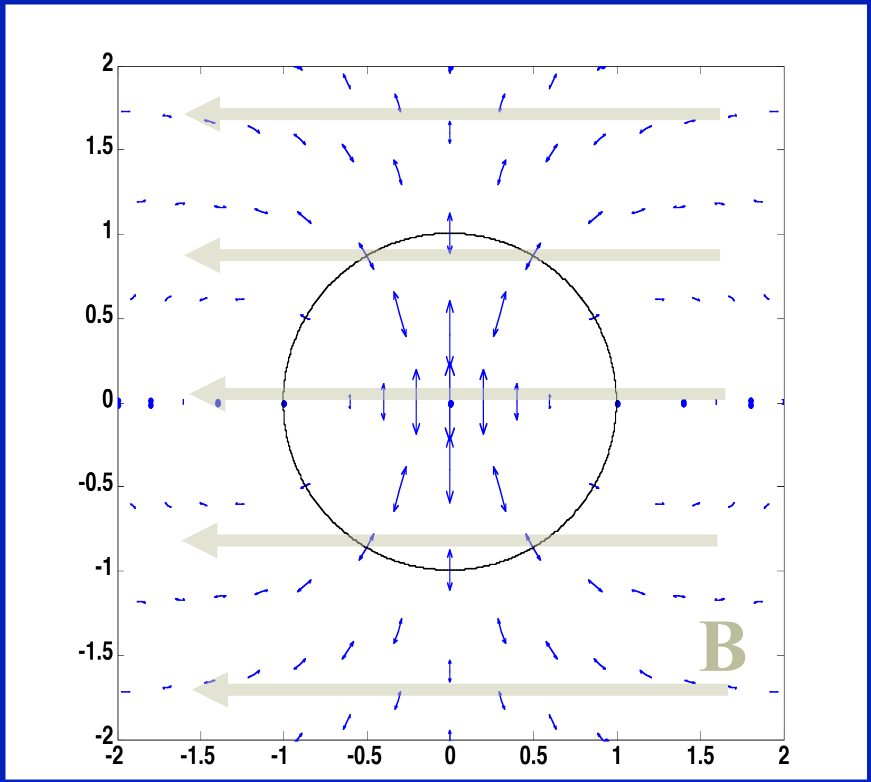


Ordered field in shock plane





Sari 99; Ghisellni & Lazzati 99



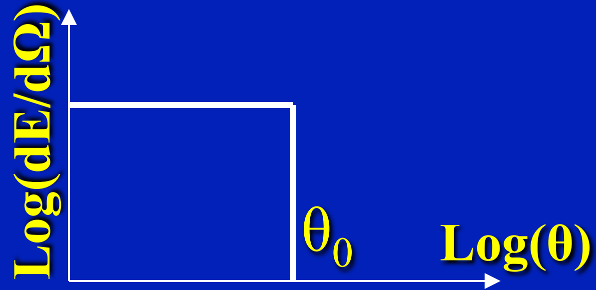
Granot & Königl 03

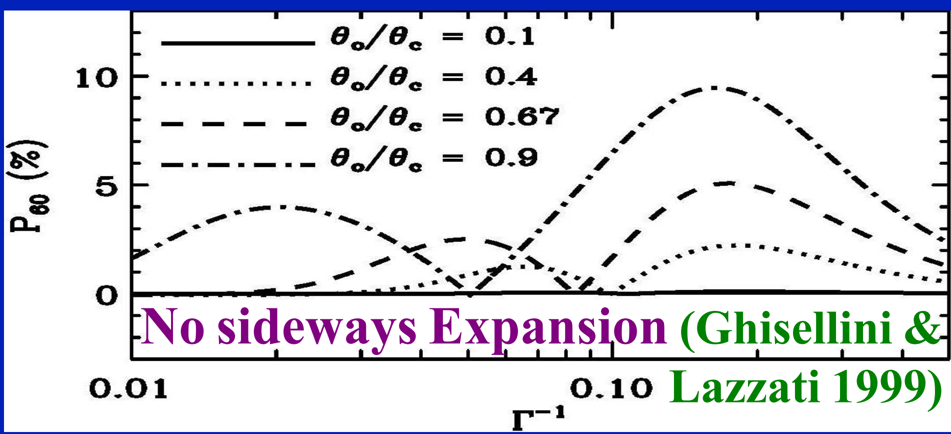
$$P \sim P_{max}$$

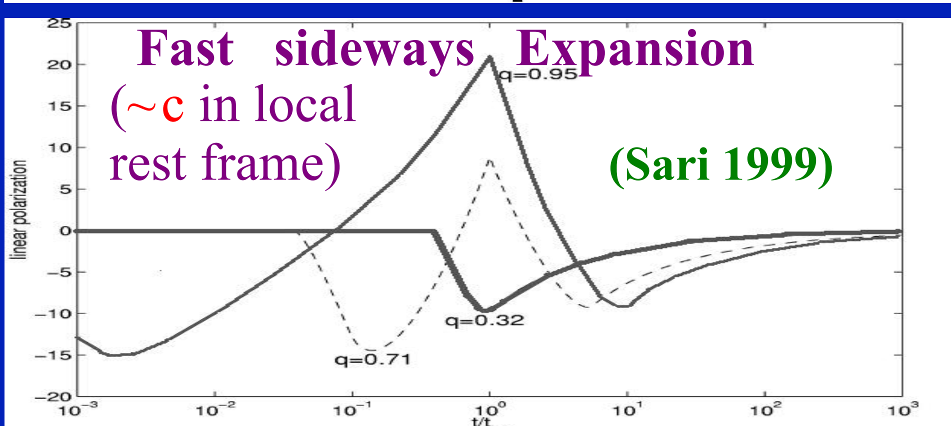
Afterglow: Two "Traditional" Jet Structures

Uniform (top hat) jet:

(Rhoads 97,99; Sari+99, …)







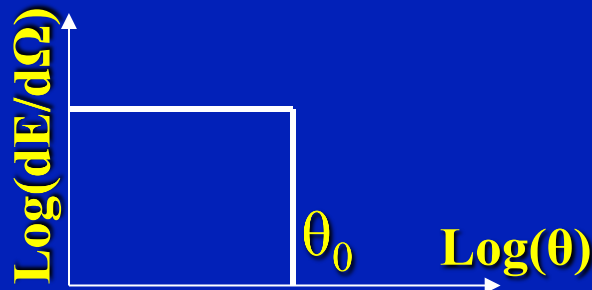
Main Prediction:
P vanishes & reappears with θ_p rotated by 90°
Is not clearly observed

Also: $P \lesssim 10\%-20\%$
While $P_{obs} \sim 1-3\%$

Afterglow: Two "Traditional" Jet Structures

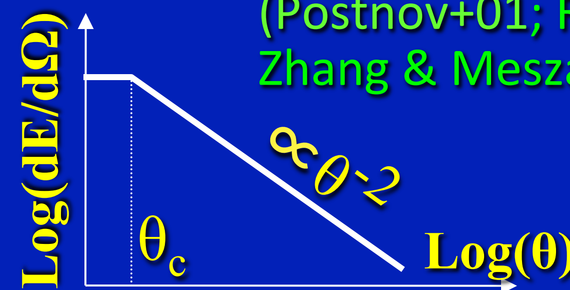
Uniform (top hat) jet:

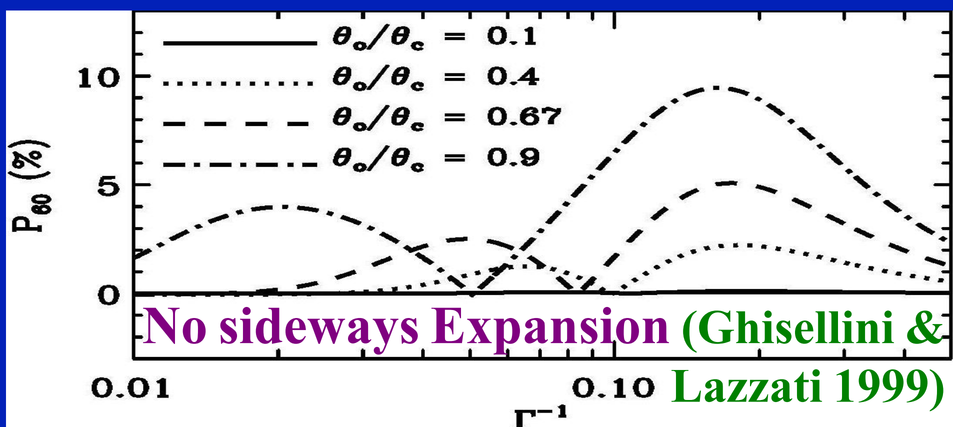
(Rhoads 97,99; Sari+99, ...)

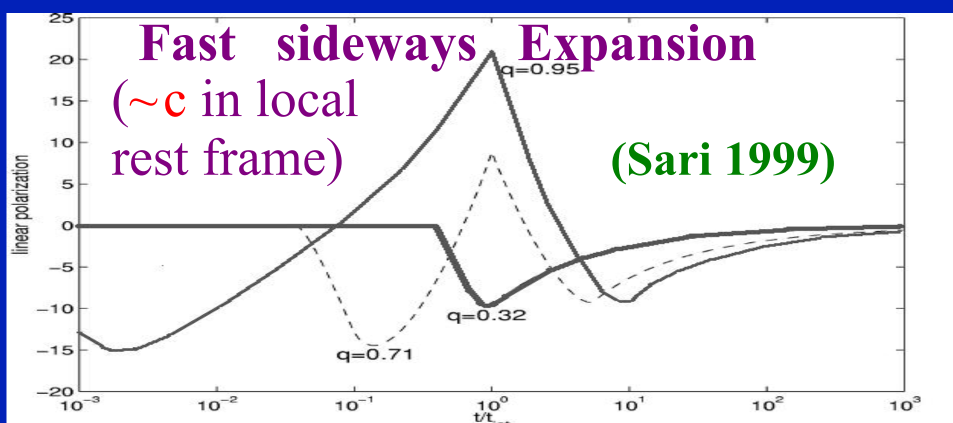


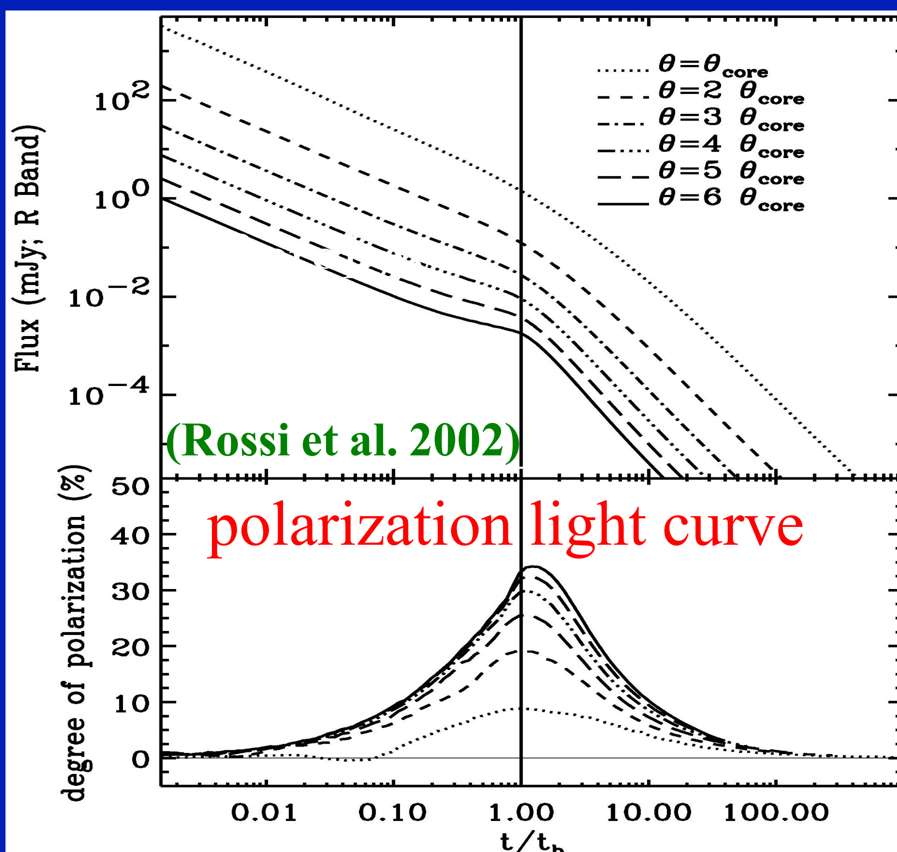
Structured jet:

(Postnov+01; Rossi+02; Zhang & Meszaros 02)



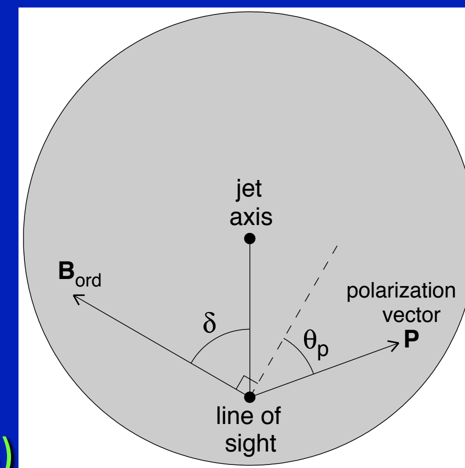




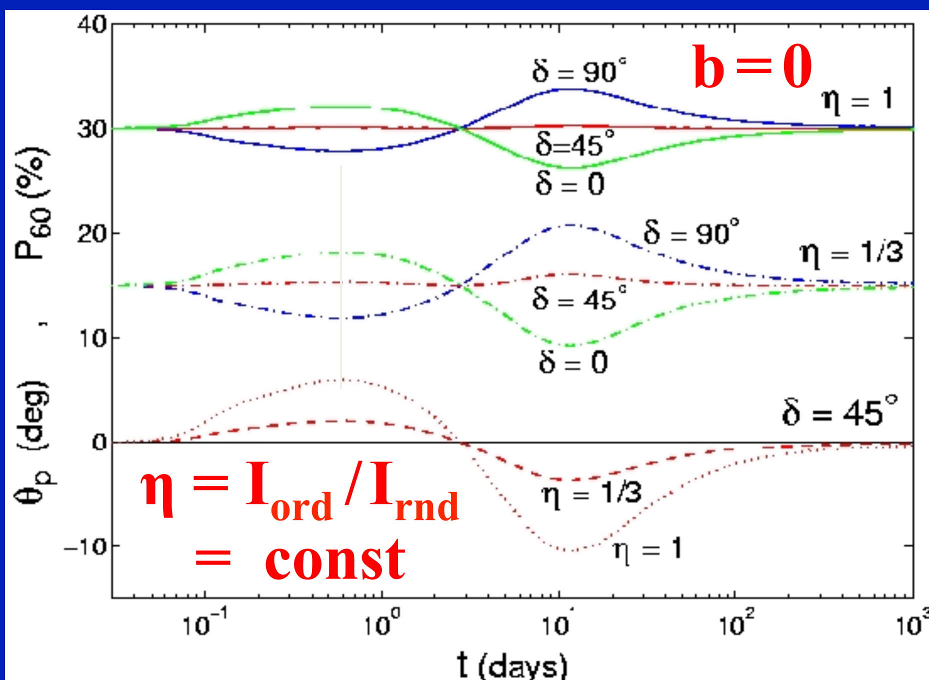


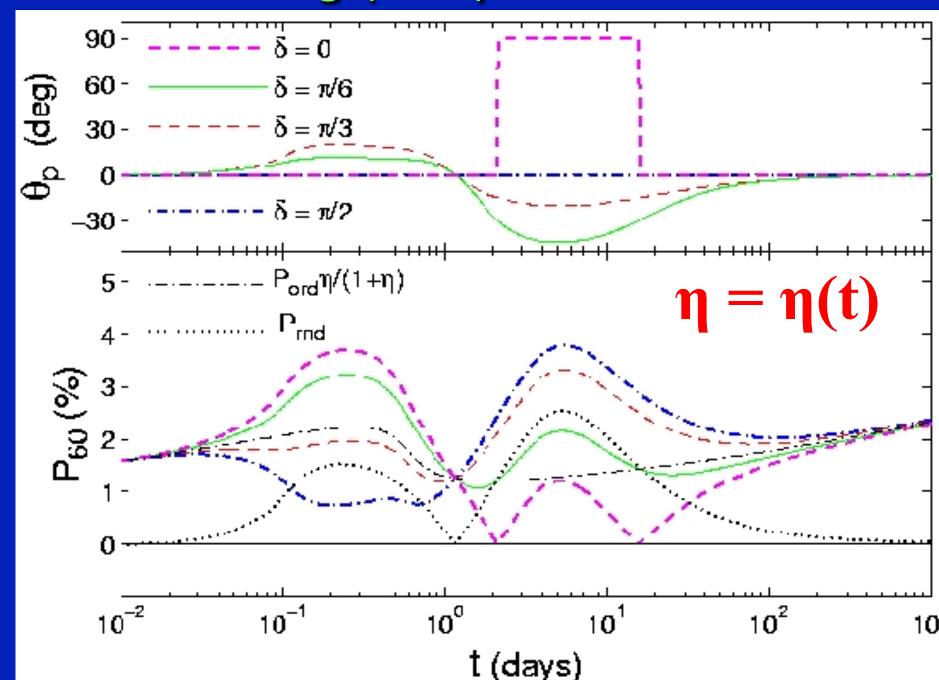
Combining Ordered B_{ord} & Random B_{rnd} Fields

- $P_{ord} \sim P_{max} \sim 60\%$ & $\theta_p = 90°$ w.r.t. the direction of $\mathbf{B}_{ord}$
- In the afterglow $P \lesssim 3\% \Rightarrow I_{ord} \ll I_{rnd}$
  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}



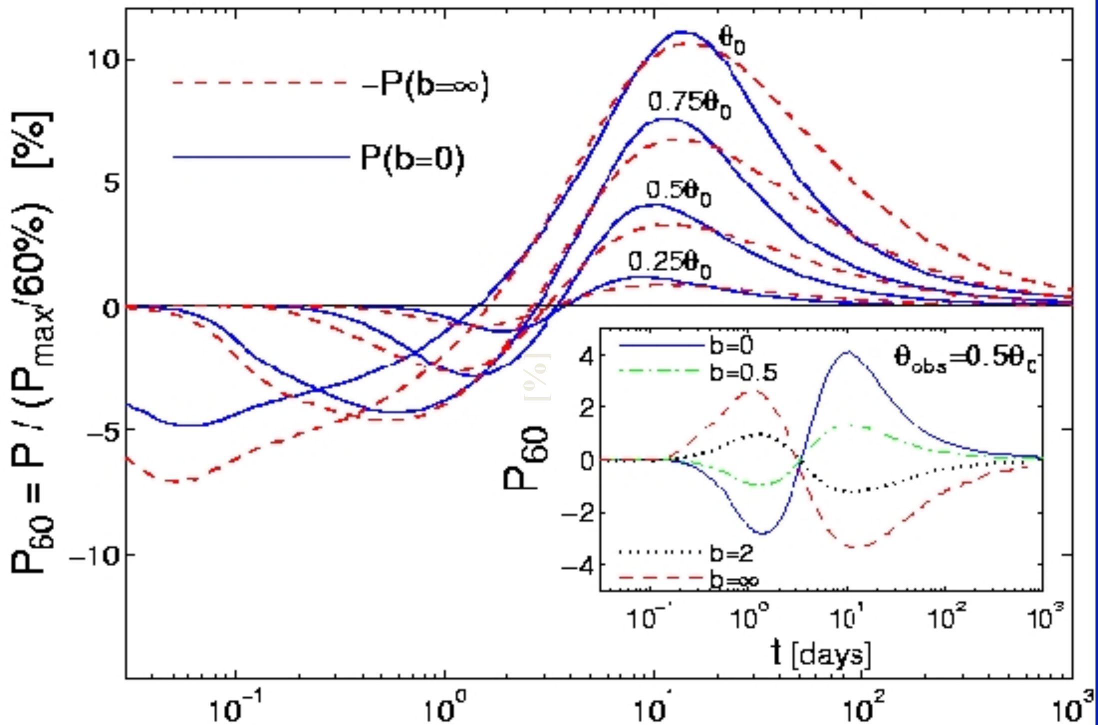
JG & Königl (2003)





The Random B-field's Degree of Anisotropy:

- $b = 2\langle B_{||}^2\rangle/\langle B_{perp}^2\rangle$ 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 $\Rightarrow 0.5 \lesssim b \lesssim 2$



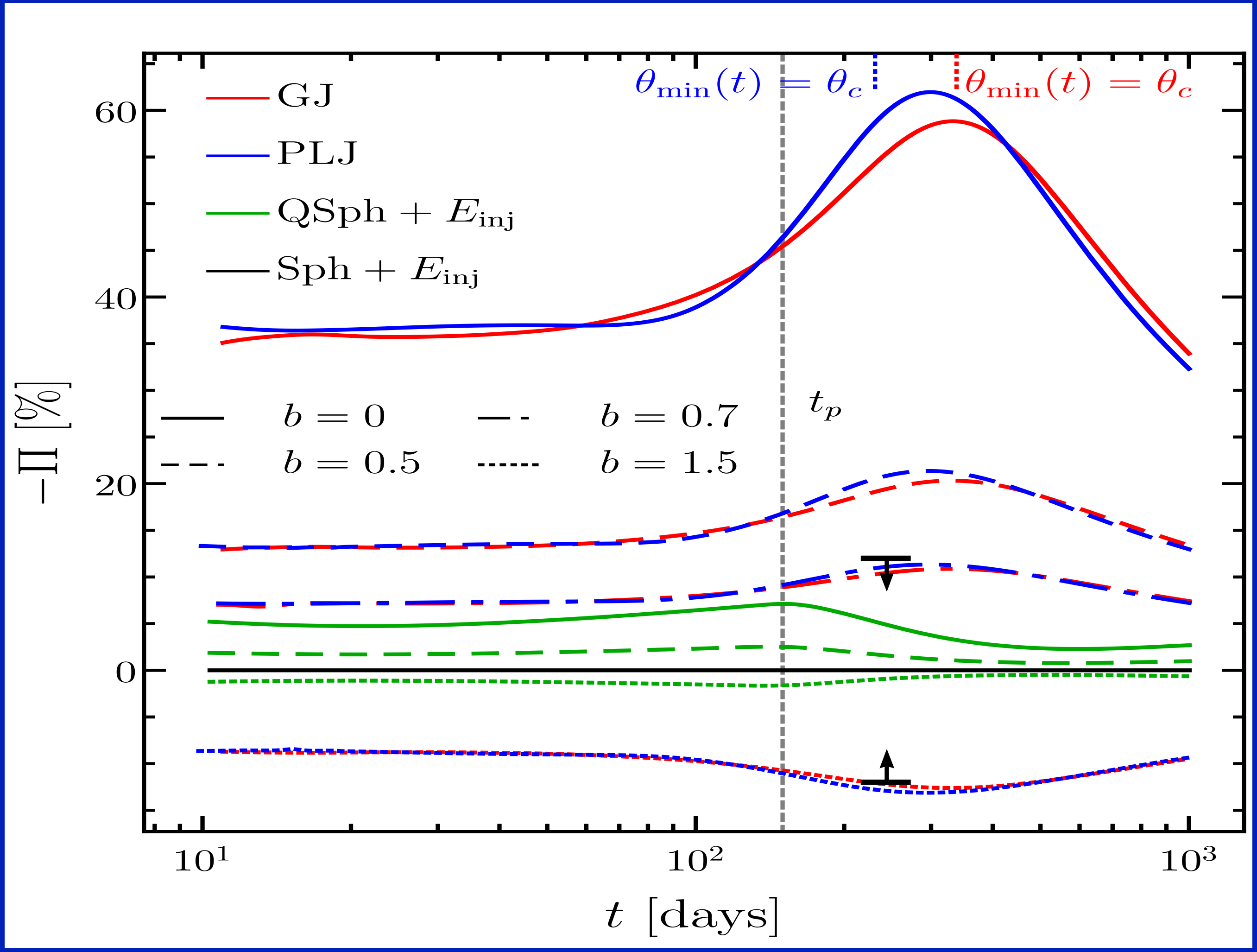
(JG & Königl 2003)

$P = P_{max}/[1+2/(b-1)\sin^2\theta']$
(valid for $j'_{\nu'} \propto [B'\sin\chi']^2$)

$\theta_0 = 5^o$
$E_{jet} = 3\times10^{51}$ erg
$n = 1\ cm^{-3}$
$z = 1$
$p = 2.5$
$\varepsilon_e = 0.1$
$\varepsilon_B = 0.01$

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)



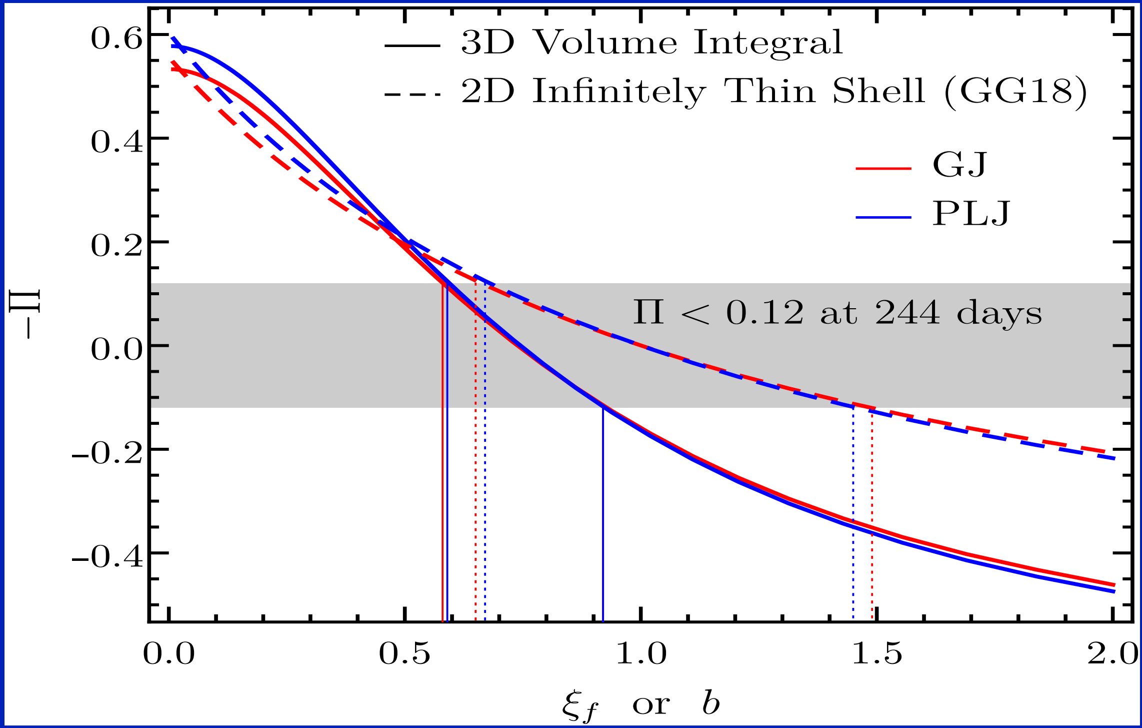
$0.7 \lesssim b \lesssim 1.5$ for jet models

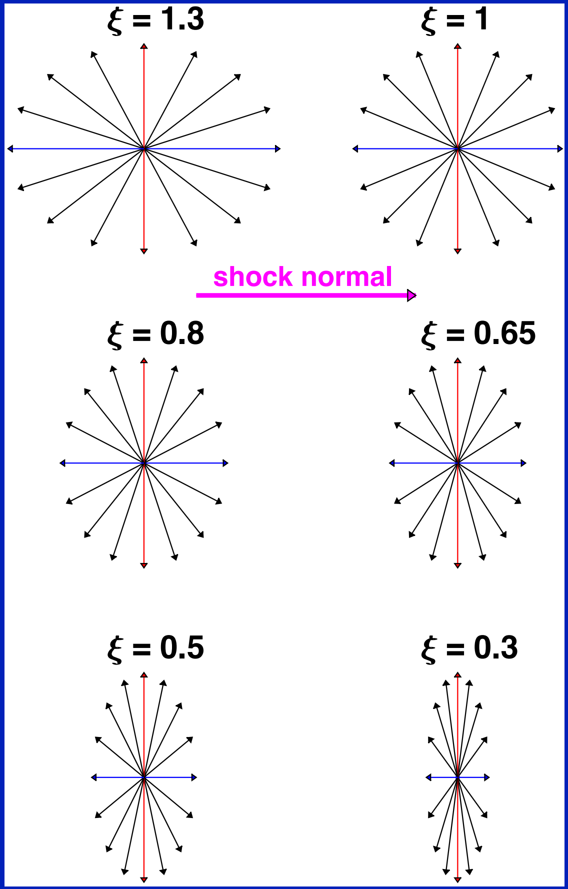
New: upper limit $P_{lin} < 12\%$ @ $\nu = 2.8$ GHz, t = 244 days (Corsi + 2018)

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); $\xi = \xi_0 \chi^{(7-2k)/(8-2k)}$

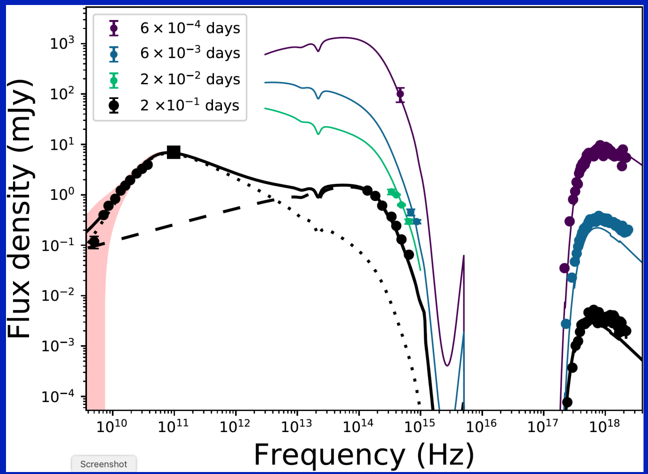


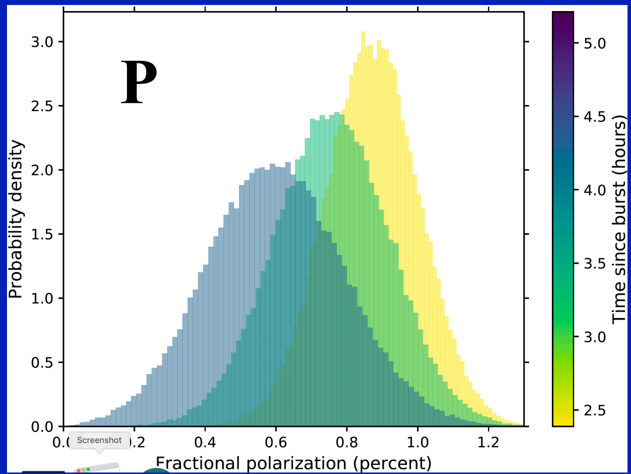


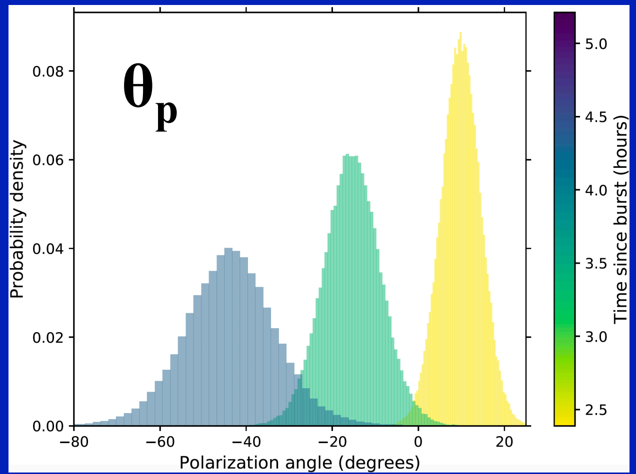
$0.58 \lesssim \xi_f \lesssim 0.92$

Reverse shock Pol.: Ejecta B-field (Laskar + 2019)

- ALMA observed GRB 190114C reverse shock @97.5 GHz: $P \approx 0.9 \rightarrow 0.6\%$, $\Delta\theta_p \approx 54°$ ($2.2 \rightarrow 5.2$ hr); 1st GRB radio pol.
- Low P: rules out B_{ord} (with $\theta_B \gtrsim 1/\Gamma$) for which $P \sim P_{max}$
- $B_{ord}+B_{rnd}$: $|P|_{rnd}/|P|_{ord} \sim 1$ & $I_{ord} \ll I_{rnd}$; ~~FS~~ ($t \ll t_j$), ~~RS+FS~~
- $N \sim (\Gamma_{ej}\theta_B)^{-2}$ incoherent patches: $\Gamma_{ej} \approx 15$, $P \sim P_{max}/N^{1/2} \Rightarrow$ $\theta_B \sim P/P_{max}\Gamma_{ej} \sim 10^{-3}$ & $\Delta\theta_p \sim 1$ expected over $\Delta t \sim t$ ✓
- $\Delta\theta_p \approx 54°$ rules out an axi-symmetric configuration (e.g. a global toroidal B-field in the original jet; A patchy shell?







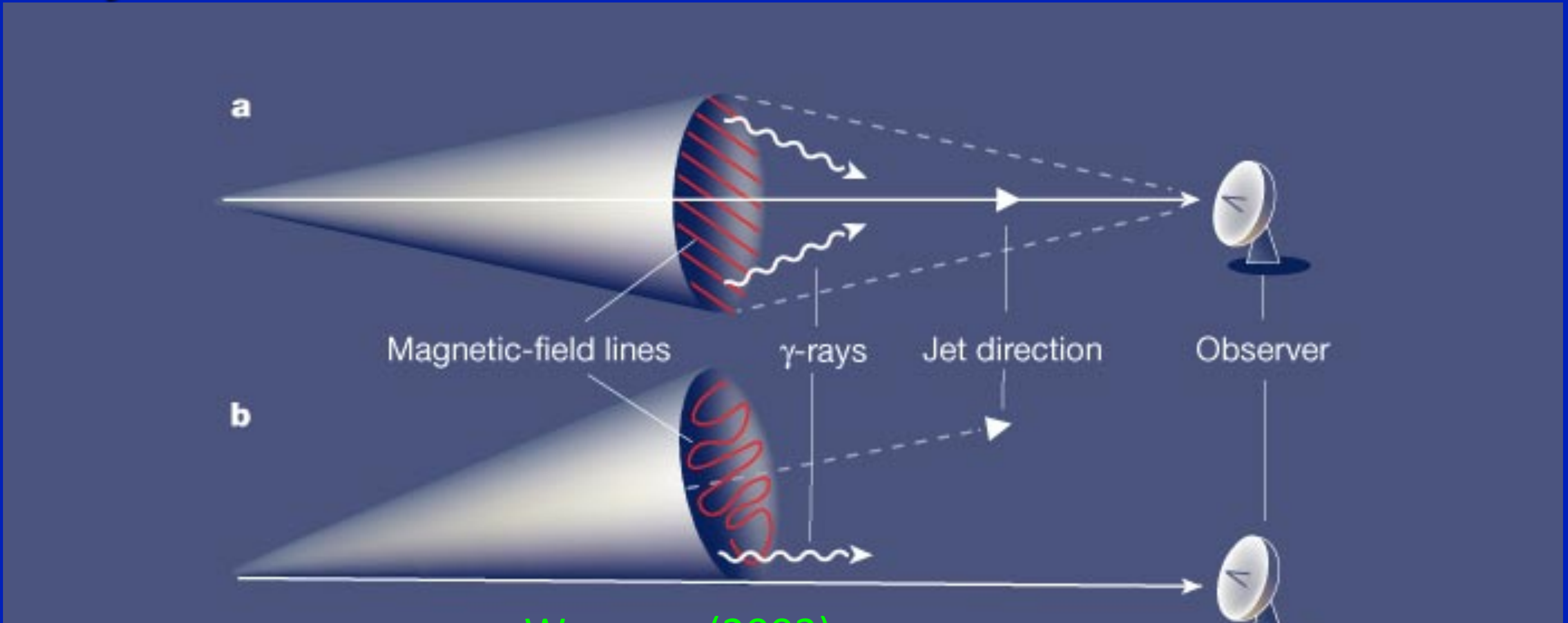
Prompt γ-ray Polarization: hard to measure

First consider synchrotron emission:

- Shock produced B-field + $\theta_{obs} \lesssim \theta_j - 1/\Gamma \Rightarrow P \approx 0$
- $P \sim P_{max}$ can be achieved in the following ways:

  (1) **ordered magnetic field** in the ejecta,

  (2) **special geometry**: $|\theta_{obs} - \theta_j| \lesssim 1/\Gamma \Rightarrow$ favors narrow jets: $\theta_j \lesssim 1/\Gamma$ (works with a shock produced B-field)

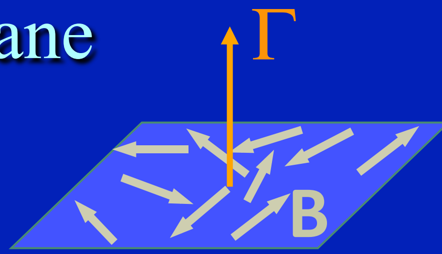


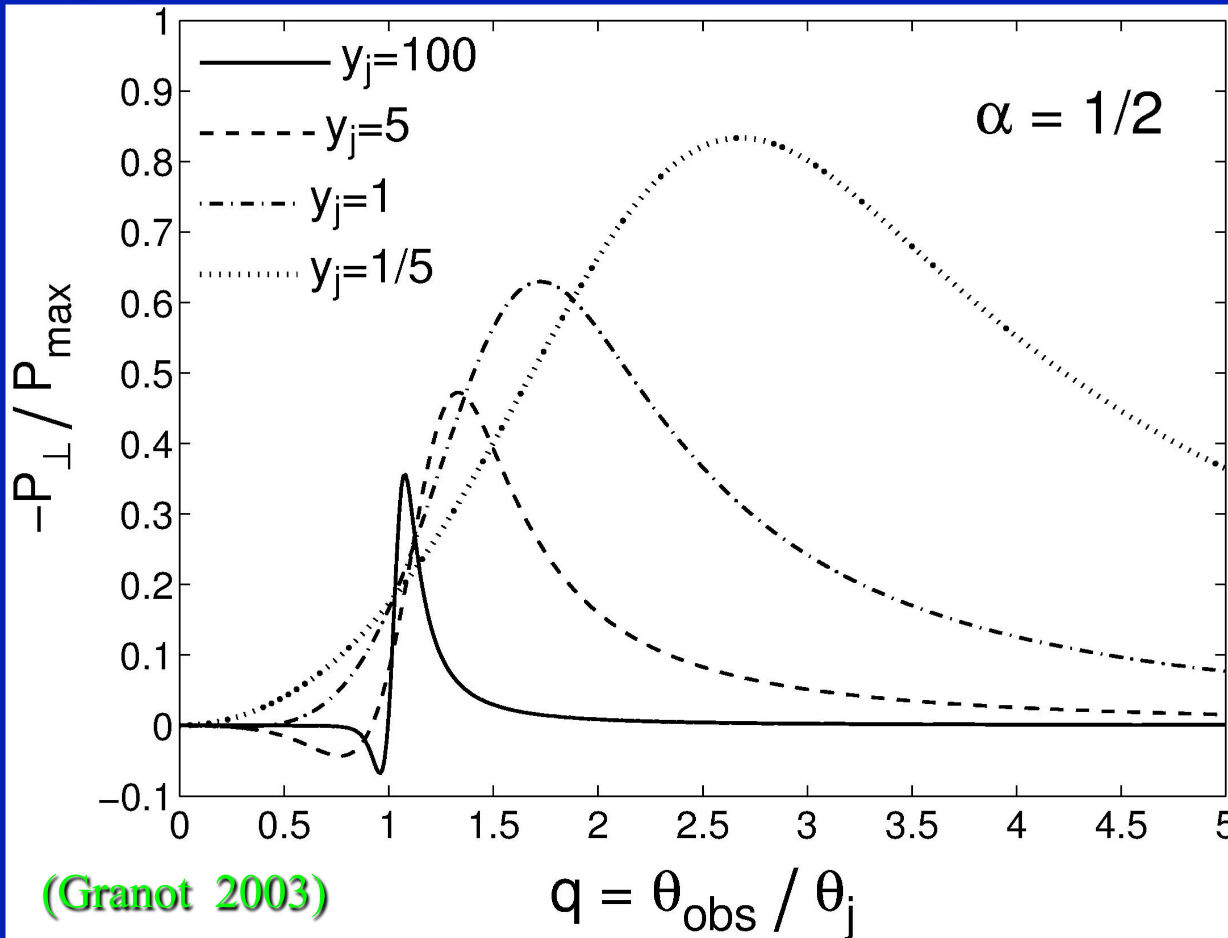
Waxman (2003)

Narrow Jet + shock produced B-field

- High polarization + reasonable flux $\Rightarrow \theta_j < \theta_{obs} \lesssim \theta_j + 1/\Gamma$
- A reasonable probability for such $\theta_{obs} \Rightarrow \Gamma\theta_j \lesssim$ a few
- Since $\Gamma \gtrsim 100$ & $\theta_j \gtrsim 0.05$, $\Gamma\theta_j \gtrsim 5$ and is typically larger
- The **jet** must have **sharp edges**: $\Delta\theta_j \lesssim 1/4\Gamma$ (Nakar et al. 03)
- a 'structured jet' produces low polarization (several %)
- Most GRBs are viewed from $\theta_{obs} < \theta_j$ and are expected to have a very low polarization in this scenario
- Afterglow obs. imply more random B_{rnd}: $0.58 \lesssim \xi_f \lesssim 0.92$

Adding pulses: Random B-field in shock plane





$y_j = (\Gamma\theta_j)^2$

$F_\nu \propto \nu^{-\alpha}$

- $\Delta\Gamma \sim \Gamma$ between different shell collisions (different pulses in GRB light curve) reduces P by a factor ~ 2

Prompt γ-ray Polarization: short summary

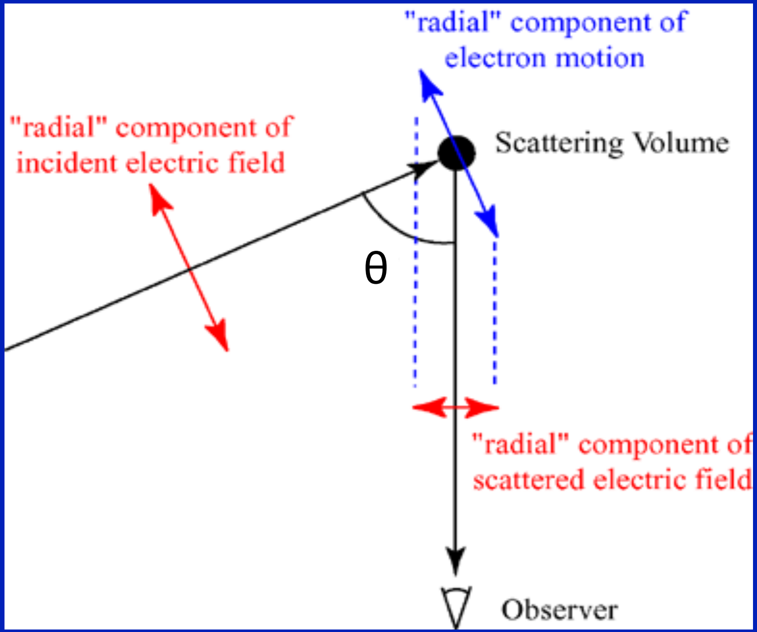
	Ordered Field	Sharp-edge Jet
$P \sim 80\%$	X	X
$P \sim 50\%$	✓	X
$P \sim 25\%$	with $B_{rnd} \lesssim B_{ord}$	✓
$P \lesssim 10\%$	$B_{rnd} > B_{ord}$	with $B_{rnd} \gtrsim B_{ord}$
statistics	High P in all GRBs	low P in most GRBs
Potential problems	Some B_{rnd} required for Fermi acceleration	$\Gamma\theta_j \lesssim$ a few, $\Delta\Gamma \sim \Gamma$, B_{rnd} $(0.58 \lesssim \xi_f \lesssim 0.92)$ $\Delta\theta_j \lesssim 1/4\Gamma$

Alternative to Synchrotron: Compton Drag

(Bulk Inverse Compton Scattering of External photons)

(Lazzati et al. 2003; Dar & De Rujula 2003, Eichler & Levinson 2003)

- Requires special geometry/viewing angle, $\theta_j < \theta_{obs} \lesssim \theta_j + 1/\Gamma$
- Polarization properties similar to synchrotron + B_{rnd} with an advantage: **local polarization** $P = (1-\cos^2\theta)/(1+\cos^2\theta)$ can reach up to 100% while $P_{max} \sim 70\%$ for synchrotron
- Shares drawbacks of shock produced field + narrow jet



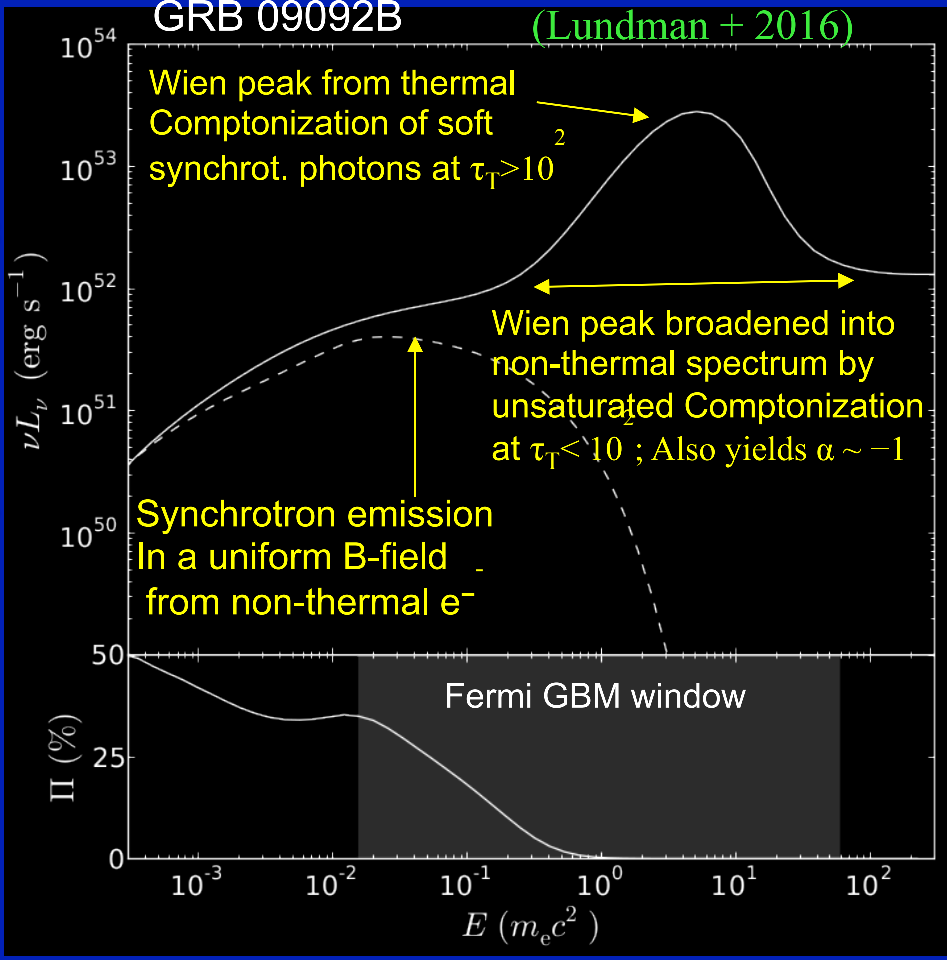
Alternative to Synchrotron: **Photospheric Emission**

(Comptonized radiation advected from optically thick to thin region of the jet)

(Beloborodov 11; Thompson & Gill 14; Lundman + 14; Vurm & Beloborodov 16; Lundman + 16)

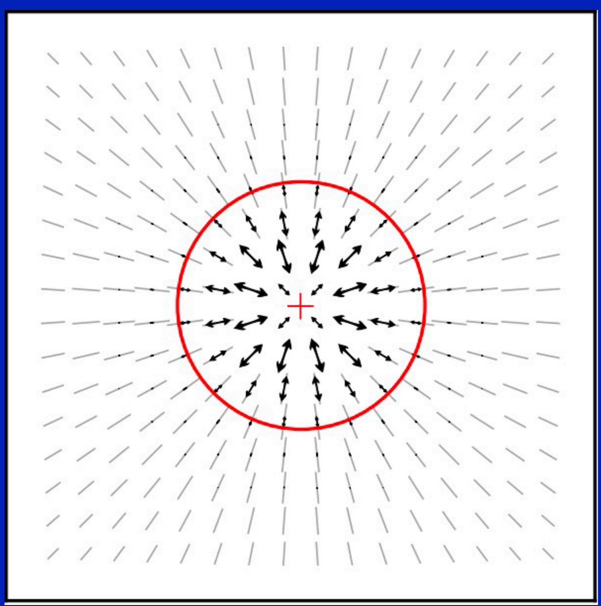
- Need to integrate radiation transfer equations for the Stokes parameters $I(r,\mu)$ & $Q(r,\mu)$ from $\tau_T \gg 1$ to $\tau_T \ll 1$.
- $P = 0$ seed photons become anisotropic at $\tau_T \lesssim 10 \Rightarrow P \approx 0.45 P_{\text{Compton-drag}}$
- This requires symmetry breaking e.g.
  - special viewing angle: $|\theta_{obs} - \theta_j| \lesssim 1/\Gamma$
  - θ-dependent bulk-Γ and/or luminosity (in structured jets $P \leq 40\%$)

- Synchrotron + B_{ord} (spherical flow): Unscattered syn. photons emitted at $\tau_T \sim 1$ dominate at $E \ll E_{pk} \Rightarrow P \sim P_{syn,max}$

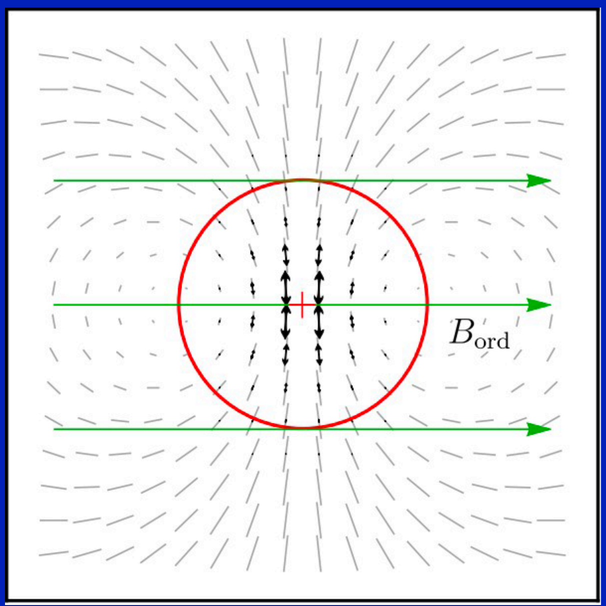


Prompt GRB Polarization (Gill, JG & Kumar 2018):

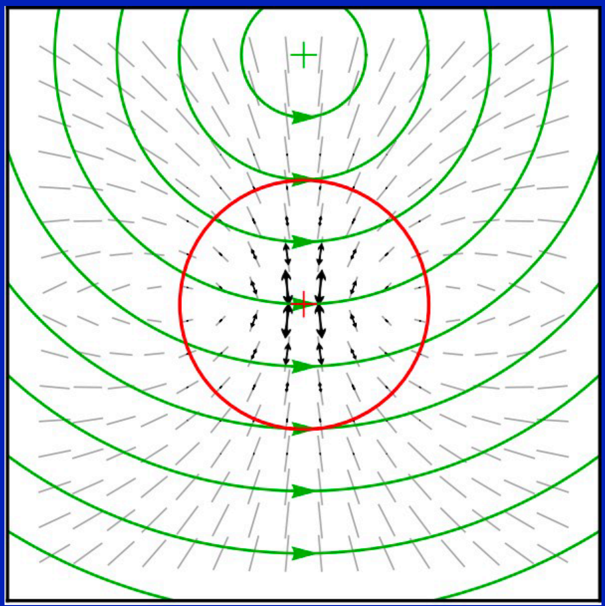
- Comprehensive study in view of γ-ray polarimetry missions
- Jet structure: top hat (sharp/smooth), Gaussian, core+power-law
- Emission mechanism: synchrotron, photospheric, Compton drag
- Time resolved, integrated over single or multiple pulses



Random B-field in 2D



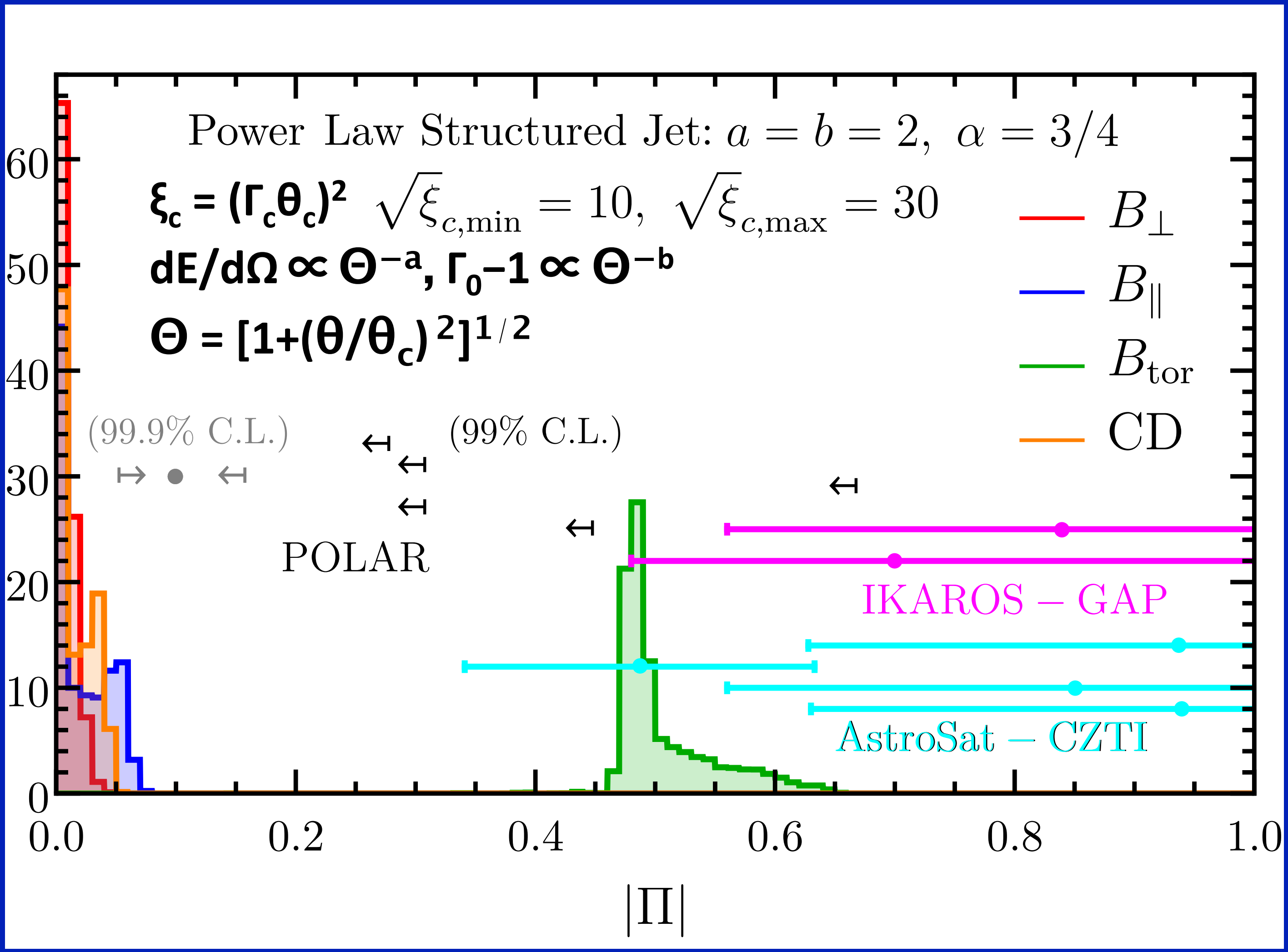
Ordered B-field



Toroidal B-field

Prompt GRB Polarization (Gill, JG & Kumar 2018):

- Model comparison: **structured jet, integrating 10 pulses**



- B_{tor}/B_{ord} is favored if P ~ 50-65% in 1 ($\gtrsim$20% in most) GRBs

Conclusions:

- **Afterglow polarization** probes jet structure & dynamics + the B-field structure behind relativistic collisionless shocks
  - ◆ ⇒ GW170817: $0.58 < \xi_0 < 0.92$ (B_{rnd}) + core-dominated jet
- 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
  - ◆ GRB190114C: ~~B_{ord}~~, ~~axisymmetric~~ (~~B_{tor}~~, ~~B_{rnd}~~), $B_{ord}+B_{rnd}$ X patchy shell?, incoherent patches: $\theta_B \sim 10^{-3}$ ✓
- Prompt GRB pol. probes emission mechanism & jet structure
  - ◆ Observations are improving & new planned missions
  - ◆ Theory is improving to match the upcoming observations
  - ◆ B_{ord}/B_{tor} favored if $P \sim 50\text{-}65\%$ in 1 ($\gtrsim 20\%$ in most) GRBs