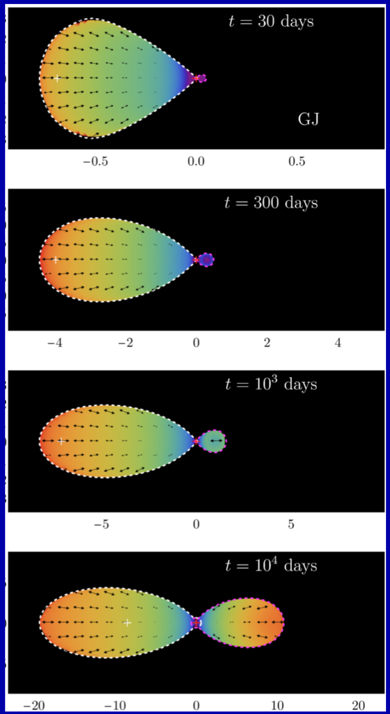
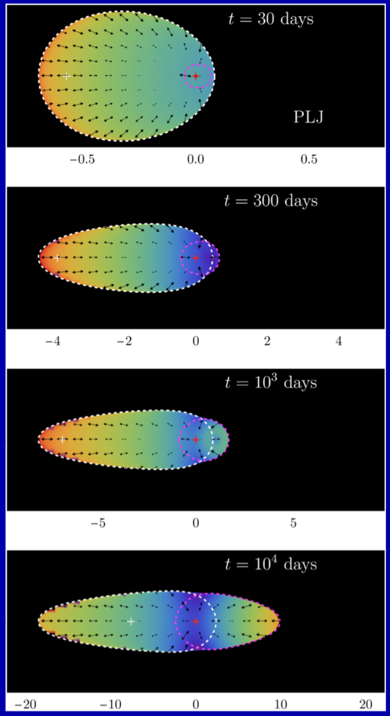
Gamma-Ray Burst Polarization: Status and Perspectives

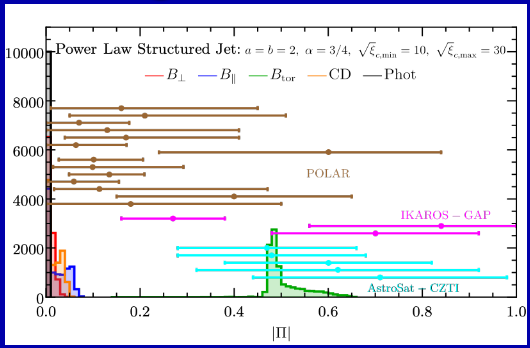
Jonathan Granot

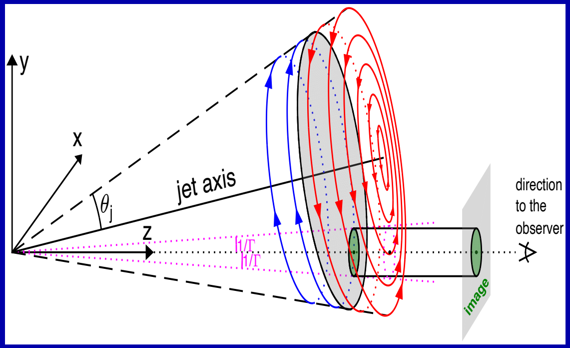
Open University of Israel & George Washington University

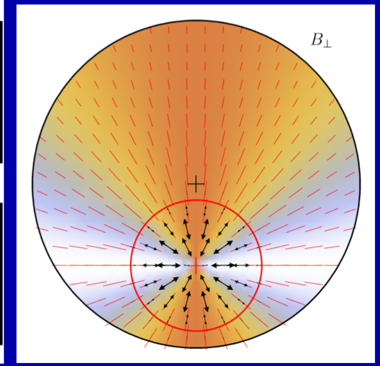
Collaborators: R. Gill, A. Königl, M. Kole, P. Kumar, T. Laskar

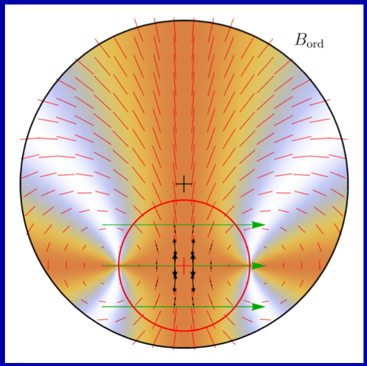


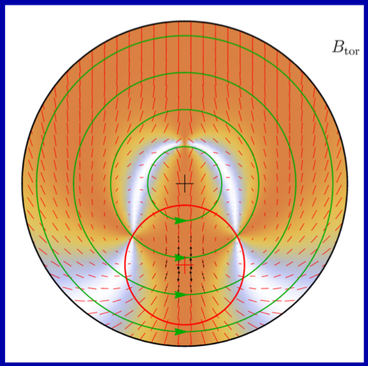






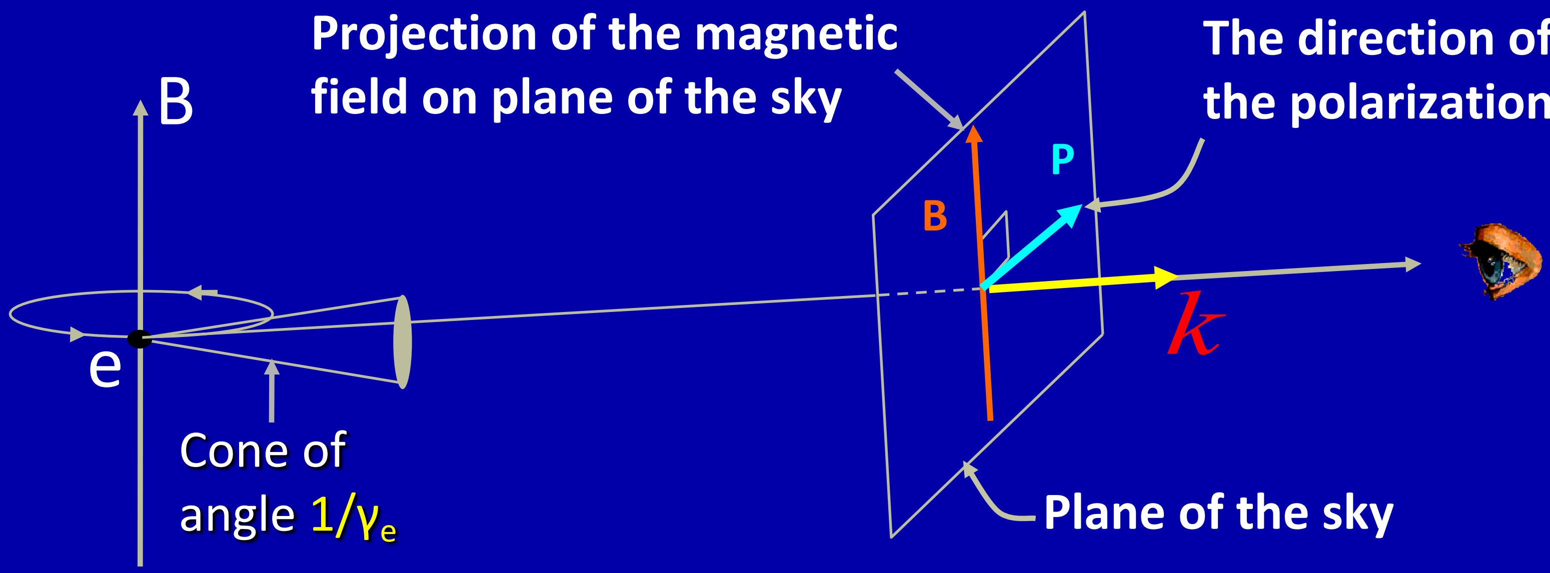






Astrophysical Polarimetry in the Time-Domain Era, Lecco, Italy, 1/9/22

Polarization of Synchrotron Emission

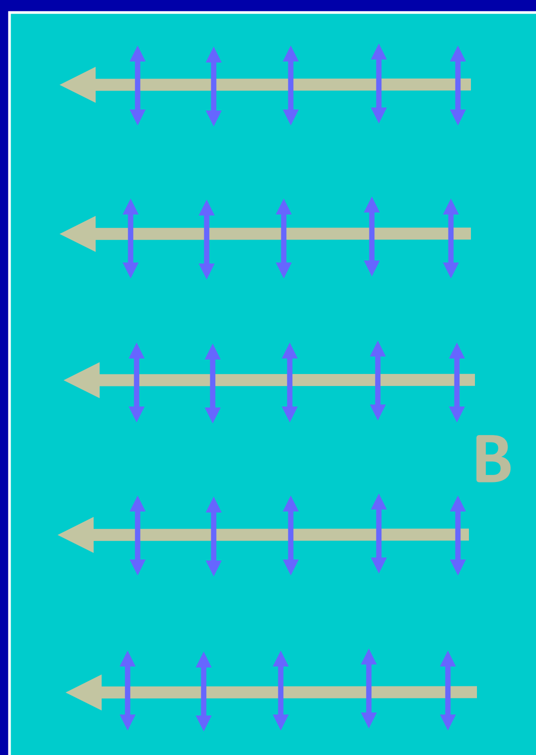


- **linear polarization** is perpendicular to the projection of **B** on the plane of the sky (normal to the wave vector)
- The maximal polarization is for the local emission from an ordered **B**-field: $P_{max} = (\alpha+1)/(\alpha+5/3)$ where $F_\nu \propto \nu^{-\alpha}$, $-1/3 \leq \alpha \lesssim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

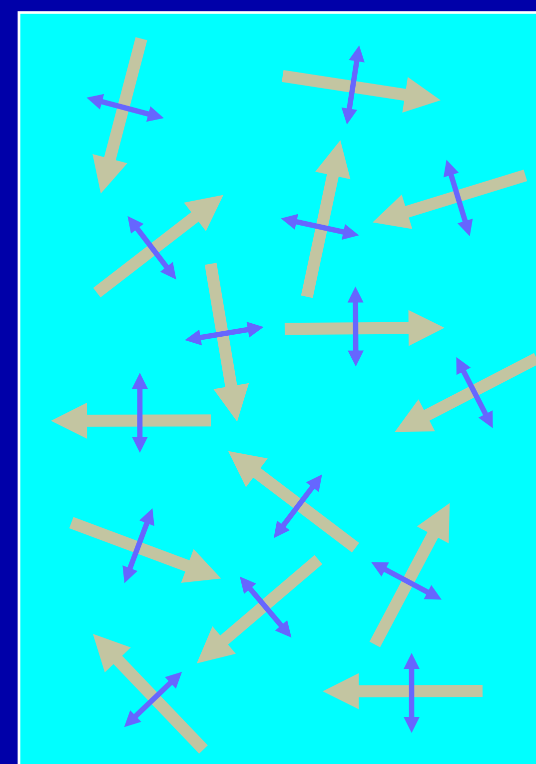
In the source rest frame:

- 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

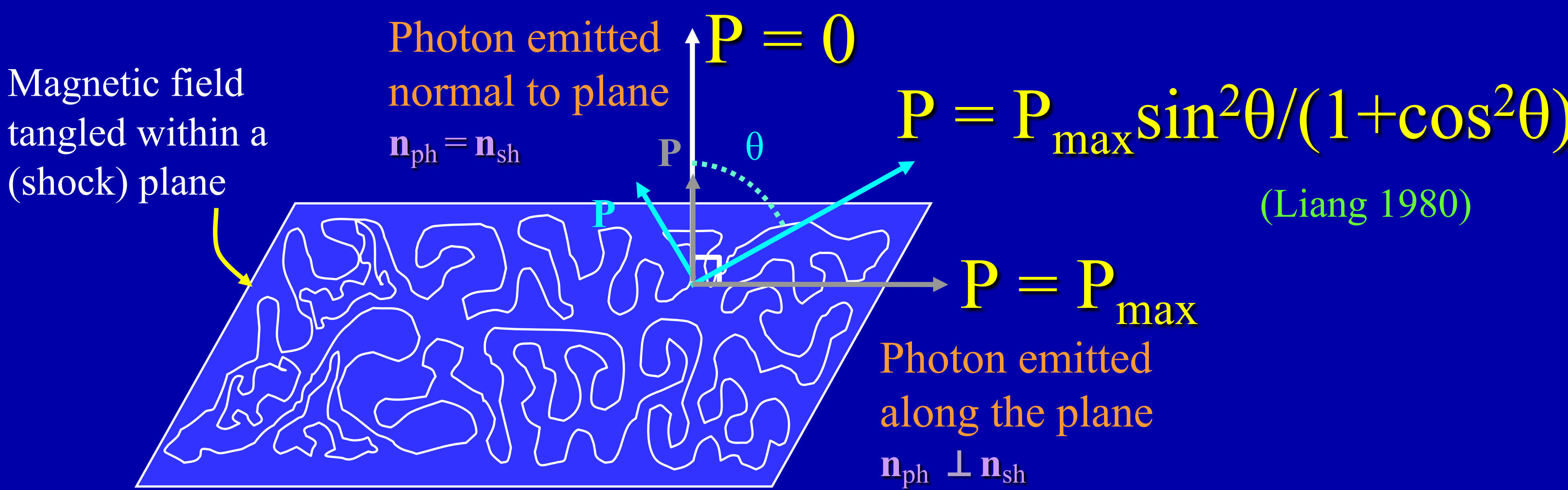


Random B

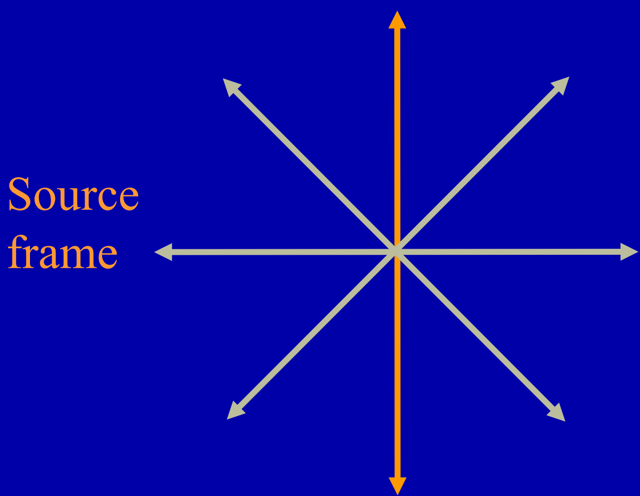


Shock Produced Magnetic Field:

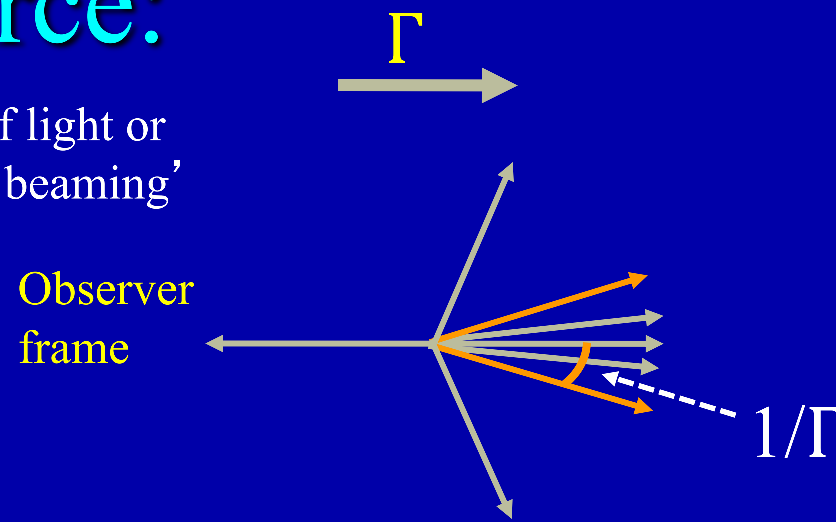
- A magnetic field produced at a relativistic collisionless shock, due to the two-stream instability, is **naively** expected to be **tangled within the plane of the shock** (Medvedev & Loeb 1999)



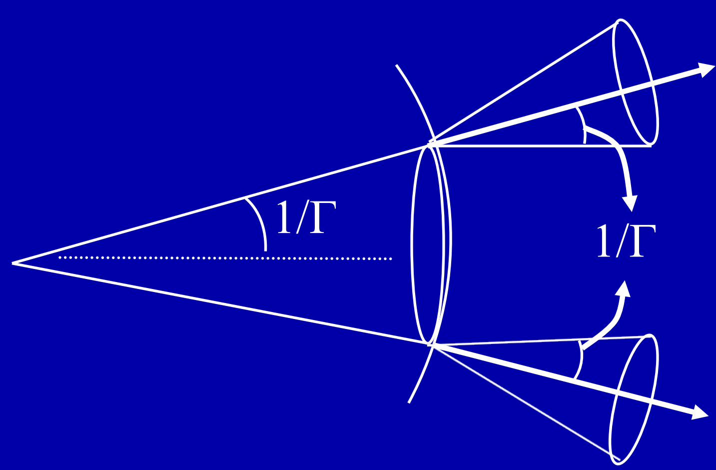
Relativistic source:

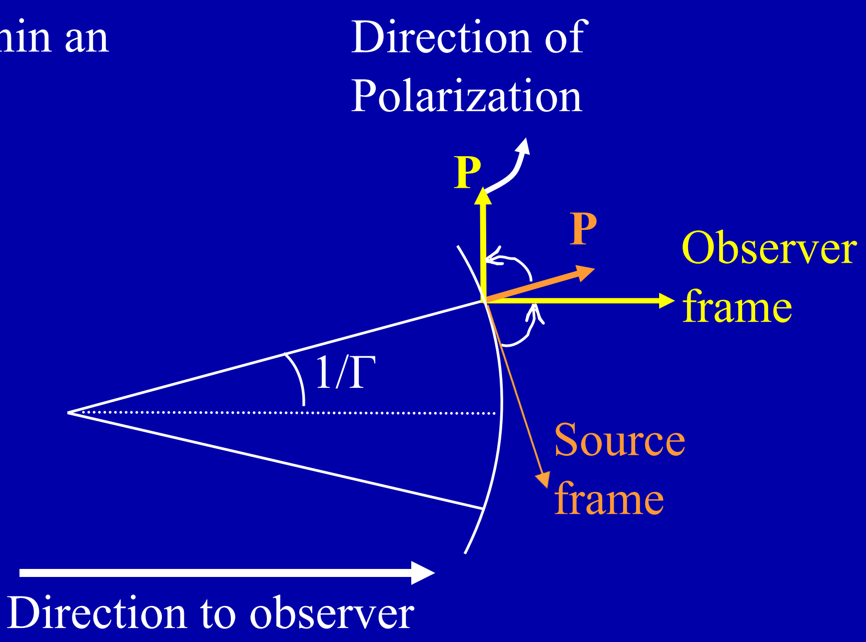


Aberration of light or 'relativistic beaming'



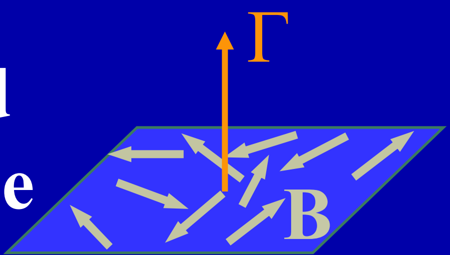
The observer sees mostly emission from within an angle of 1/Γ around the l.o.s.

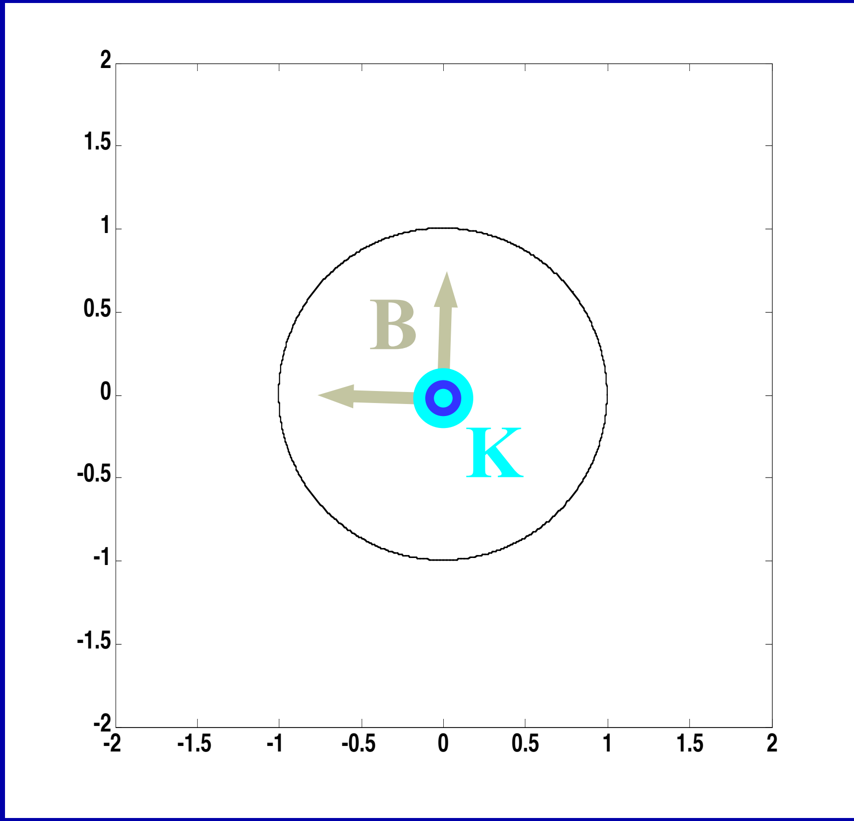




Polarization in the observer frame

Random field in shock plane

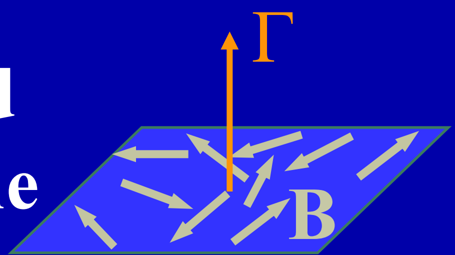


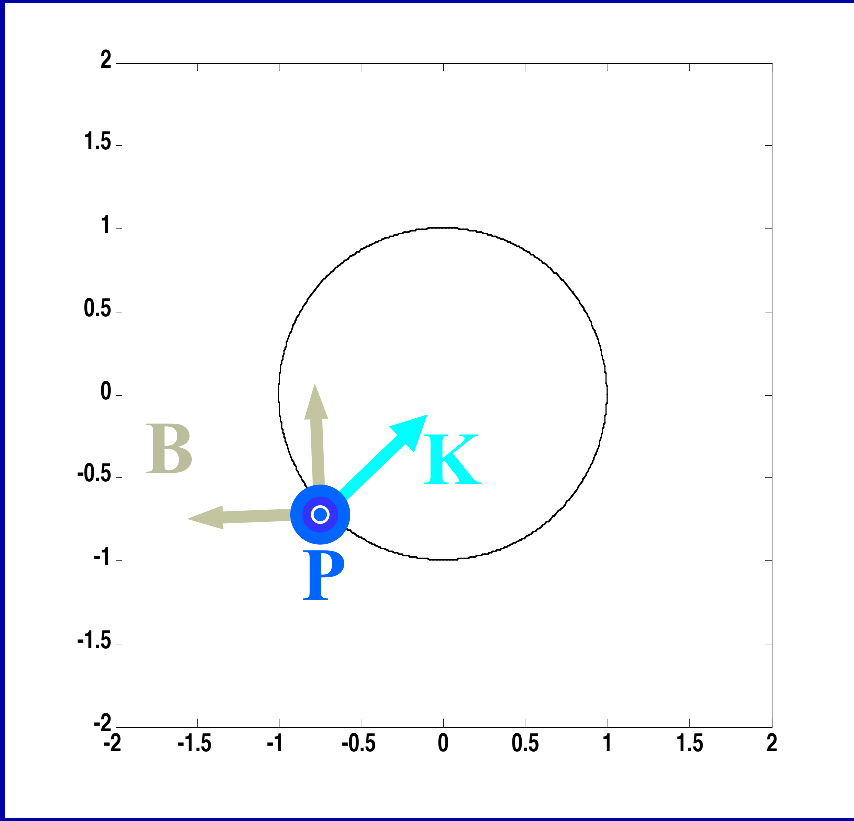


Sari 99; Ghisellni & Lazzati 99

Polarization in the observer frame

Random field in shock plane

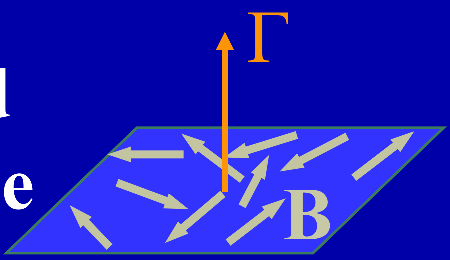


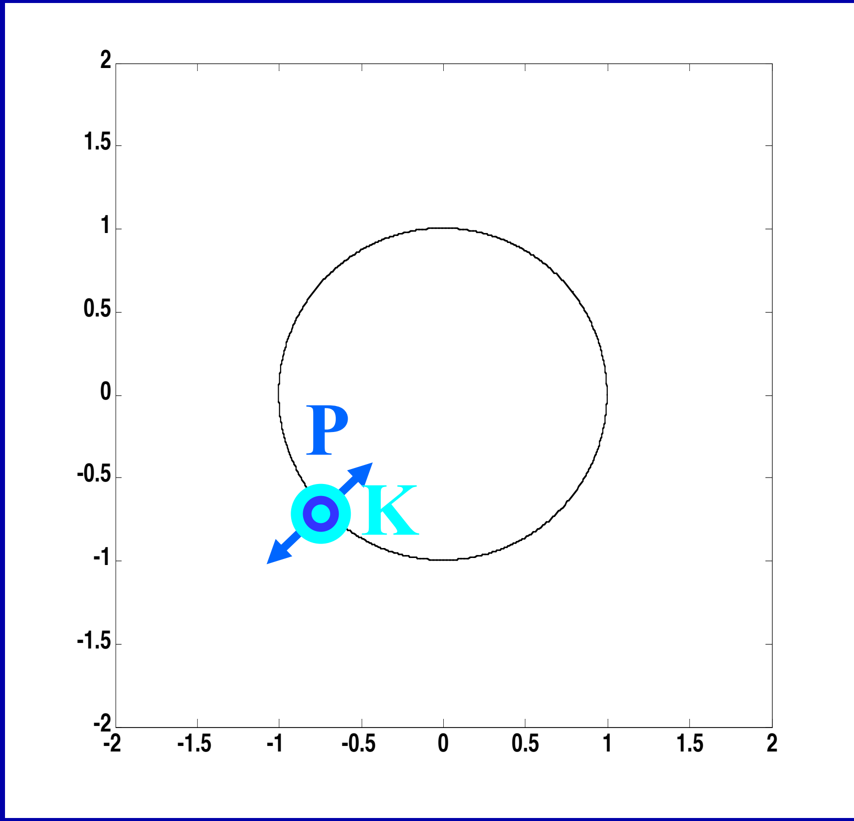


Sari 99; Ghisellni & Lazzati 99

Polarization in the observer frame

Random field in shock plane

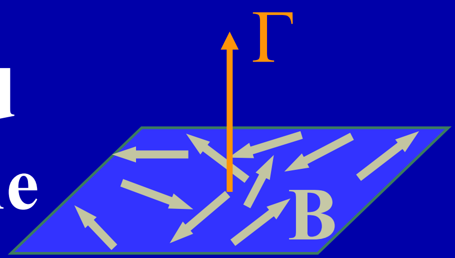


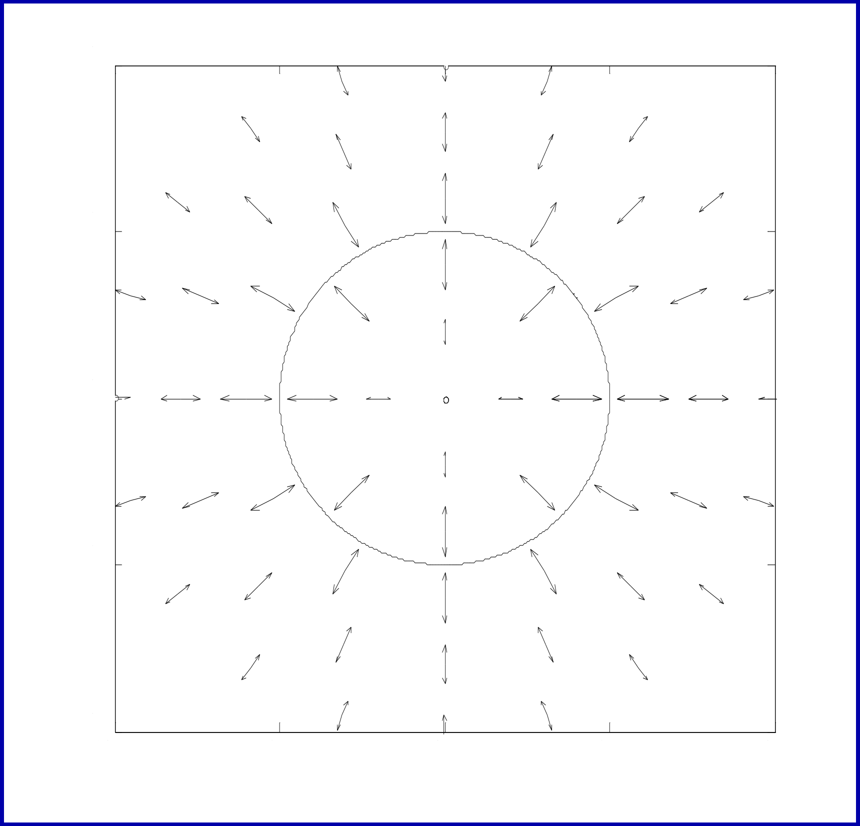


Sari 99; Ghisellni & Lazzati 99

Polarization in the observer frame

Random field in shock plane

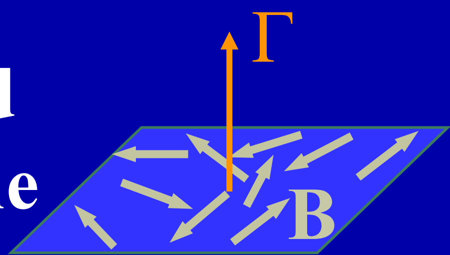


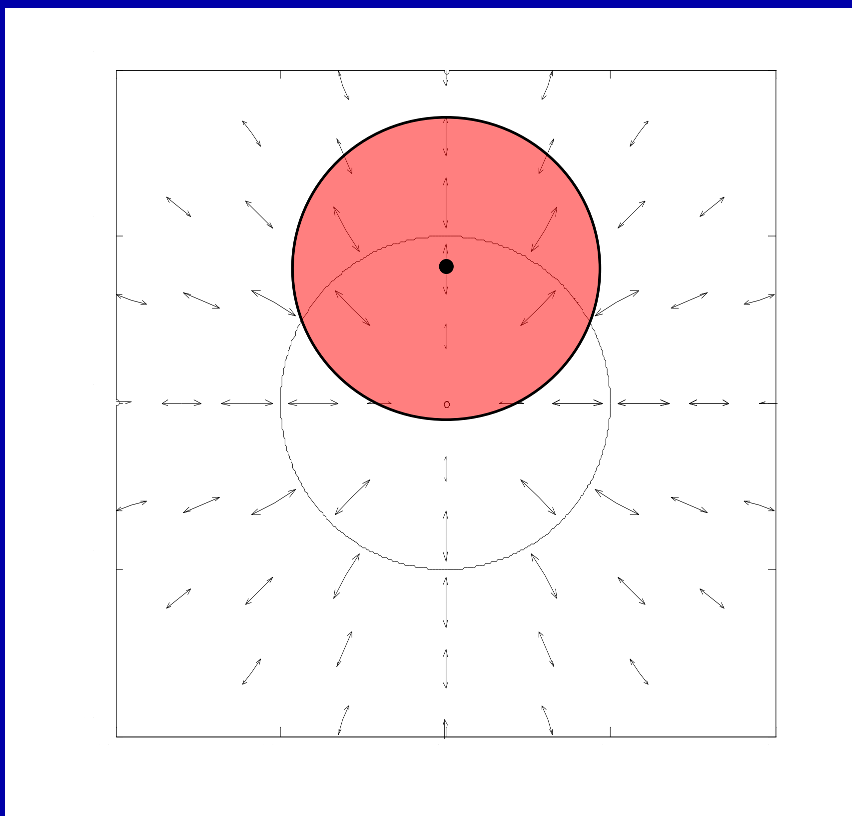


Sari 99; Ghisellni & Lazzati 99

Polarization in the observer frame

Random field in shock plane

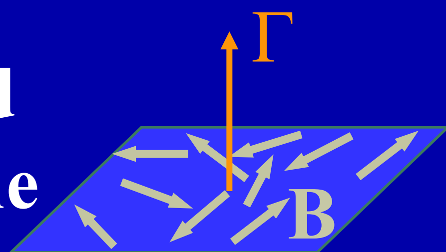


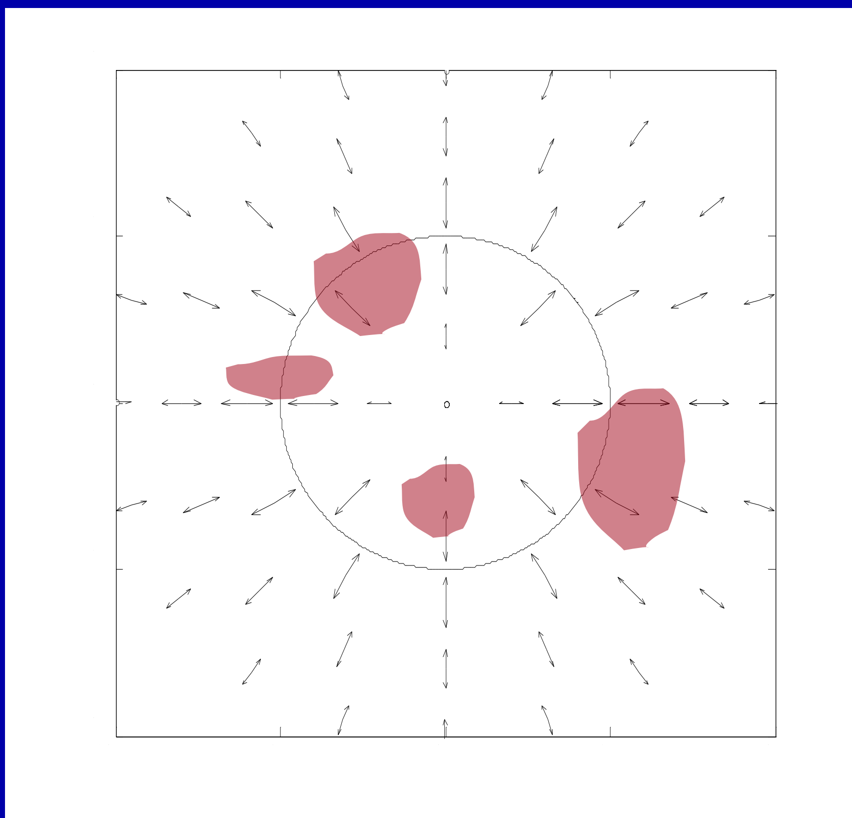


Sari 99; Ghisellni & Lazzati 99

Polarization in the observer frame

Random field in shock plane

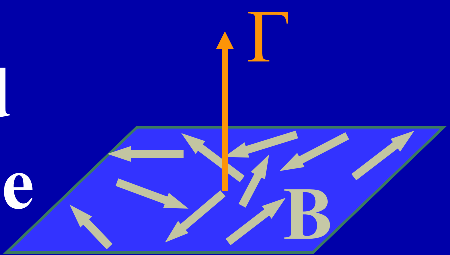


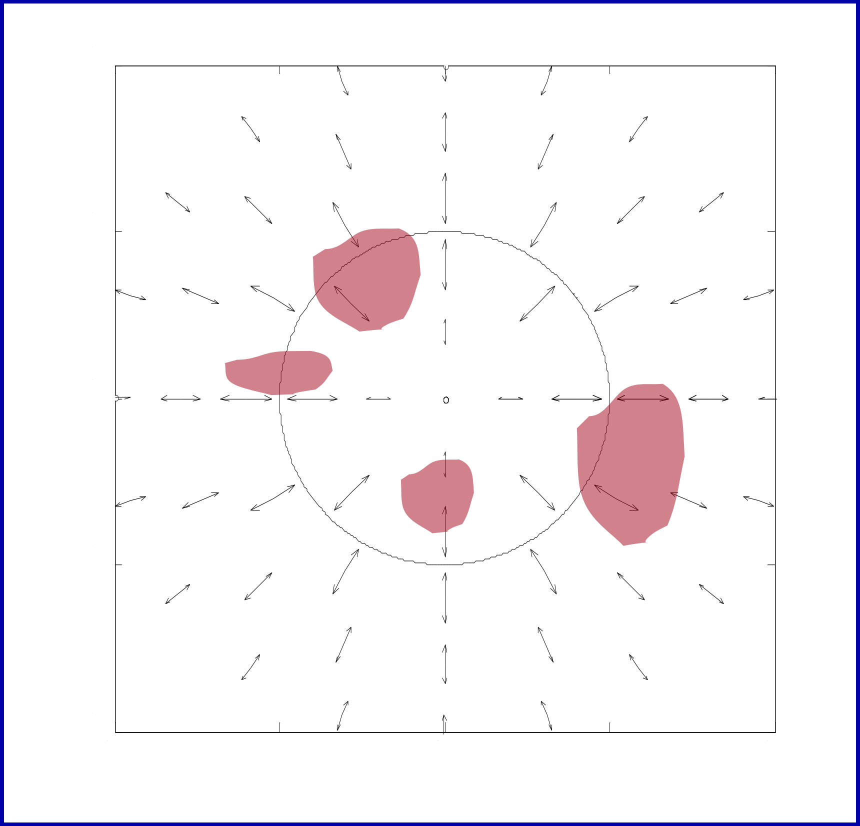


Sari 99; Ghisellni & Lazzati 99

Polarization in the observer frame

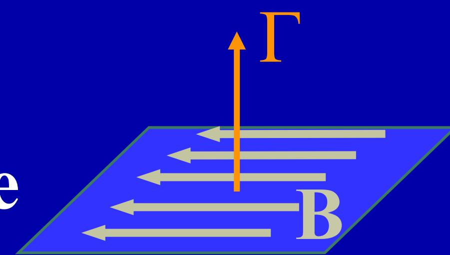
Random field in shock plane

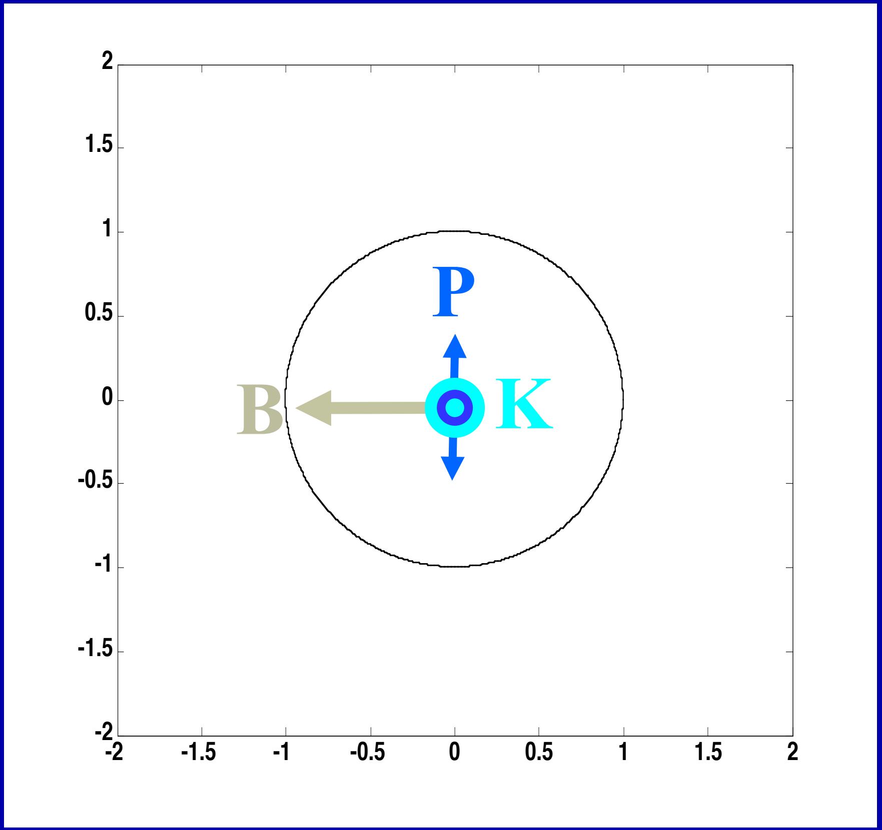




Sari 99; Ghisellni & Lazzati 99

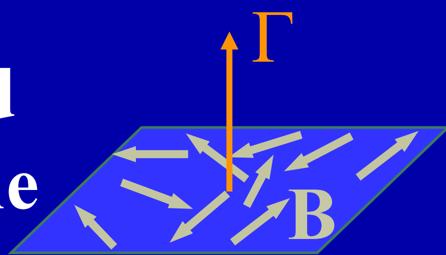
Ordered field in shock plane



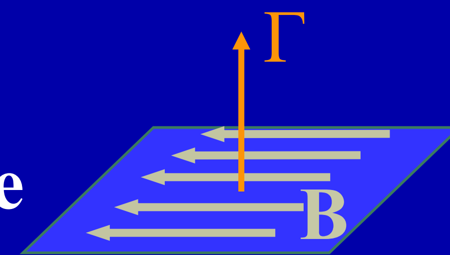


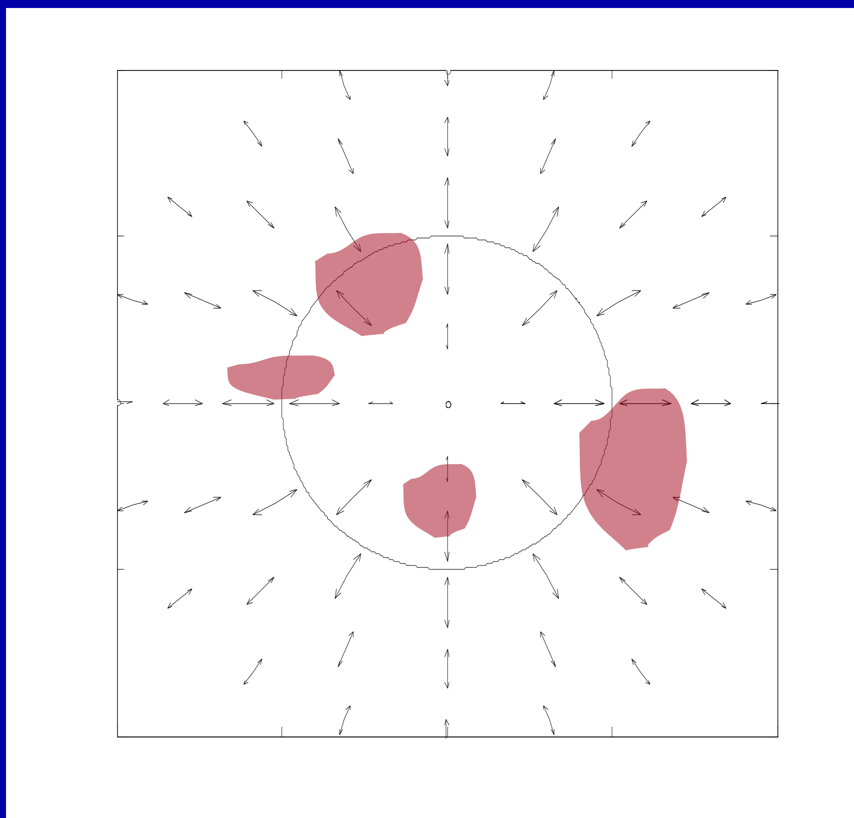
Polarization in the observer frame

Random field in shock plane

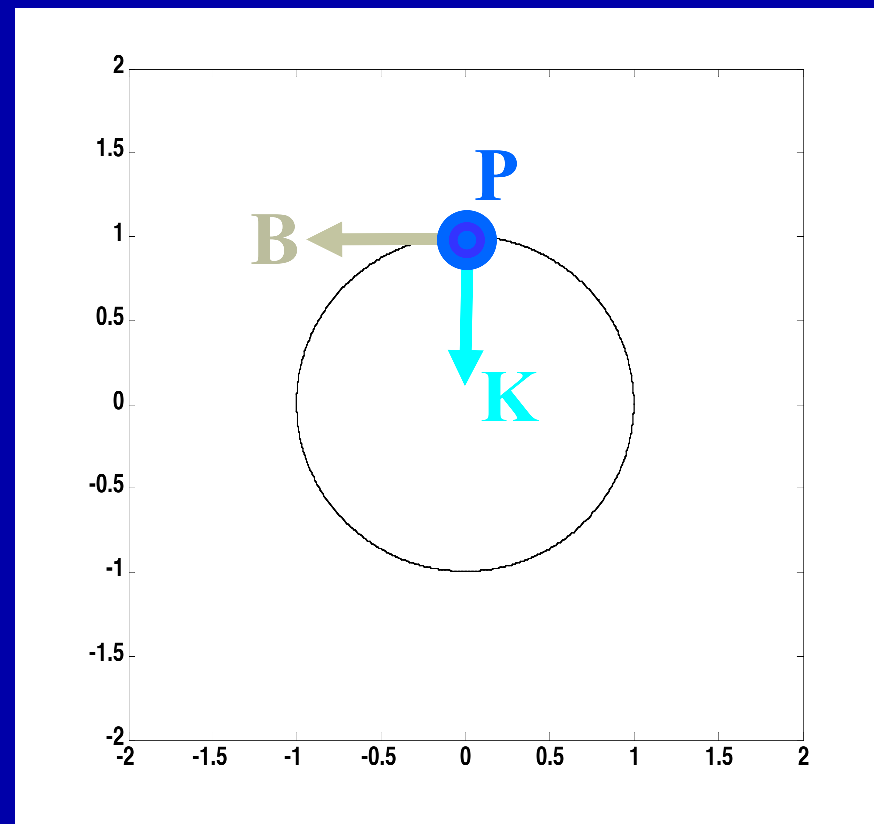


Ordered field in shock plane



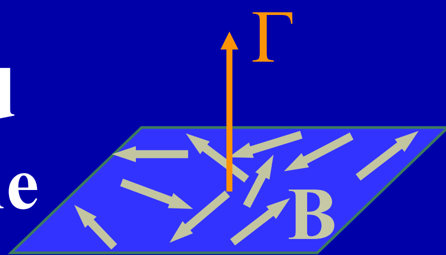


Sari 99; Ghisellni & Lazzati 99

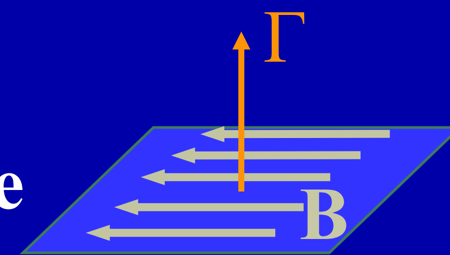


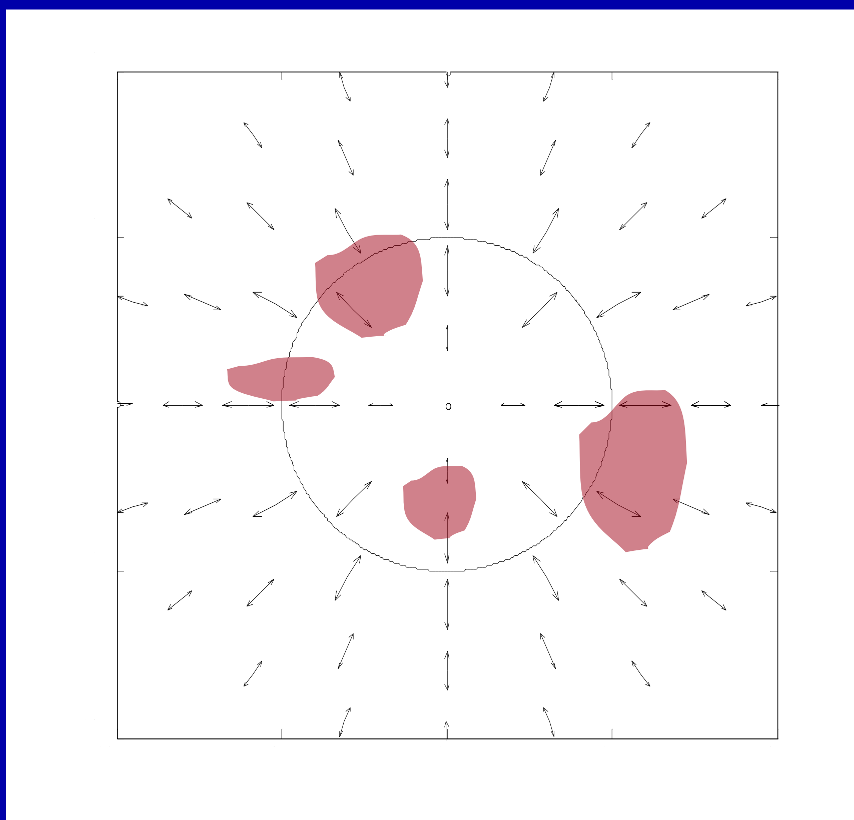
Polarization in the observer frame

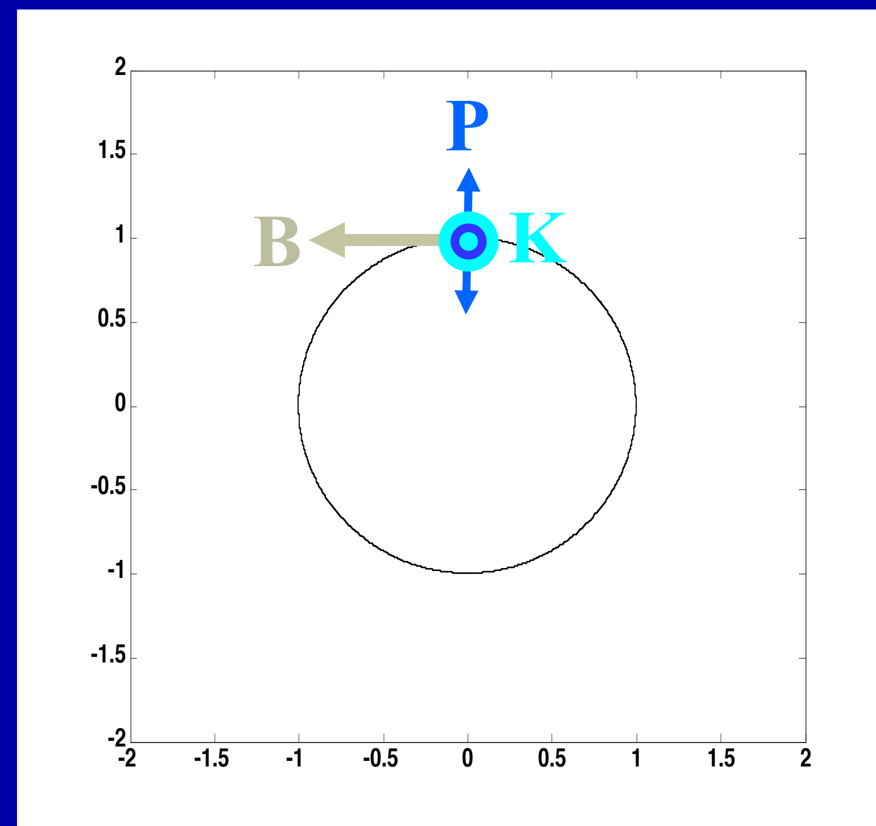
Random field in shock plane



Ordered field in shock plane



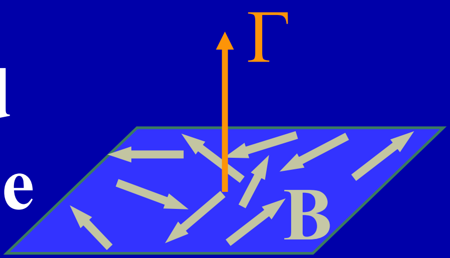




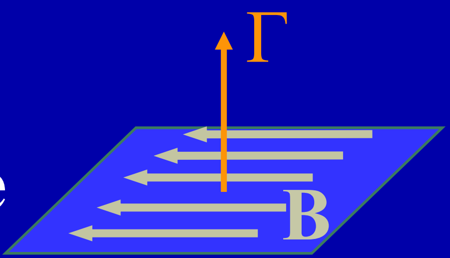
Sari 99; Ghisellni & Lazzati 99

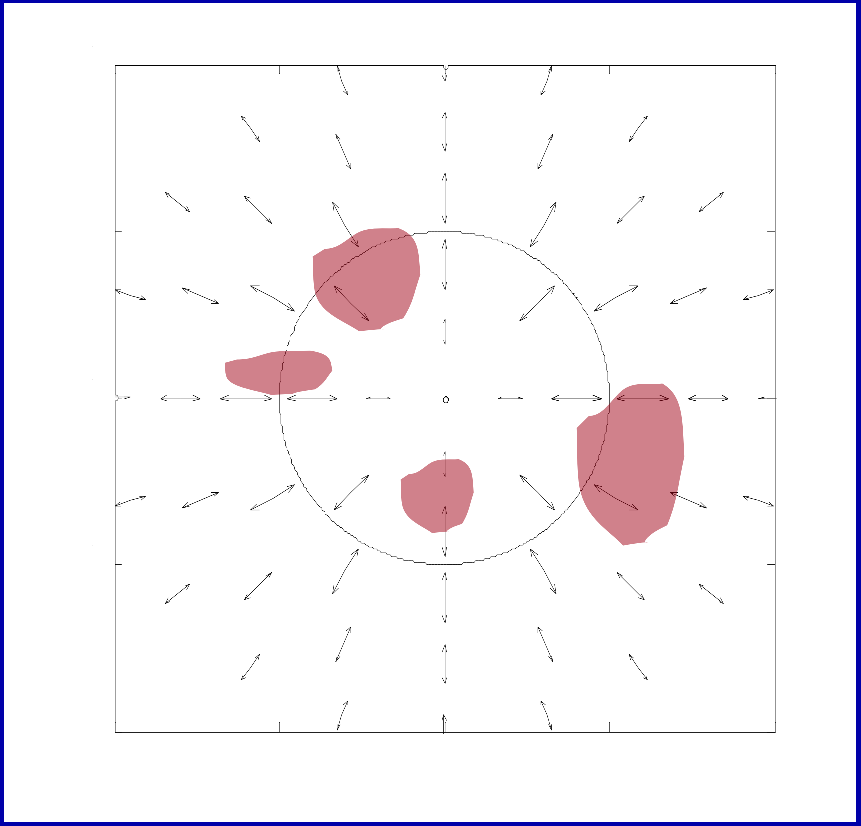
Polarization in the observer frame

Random field in shock plane

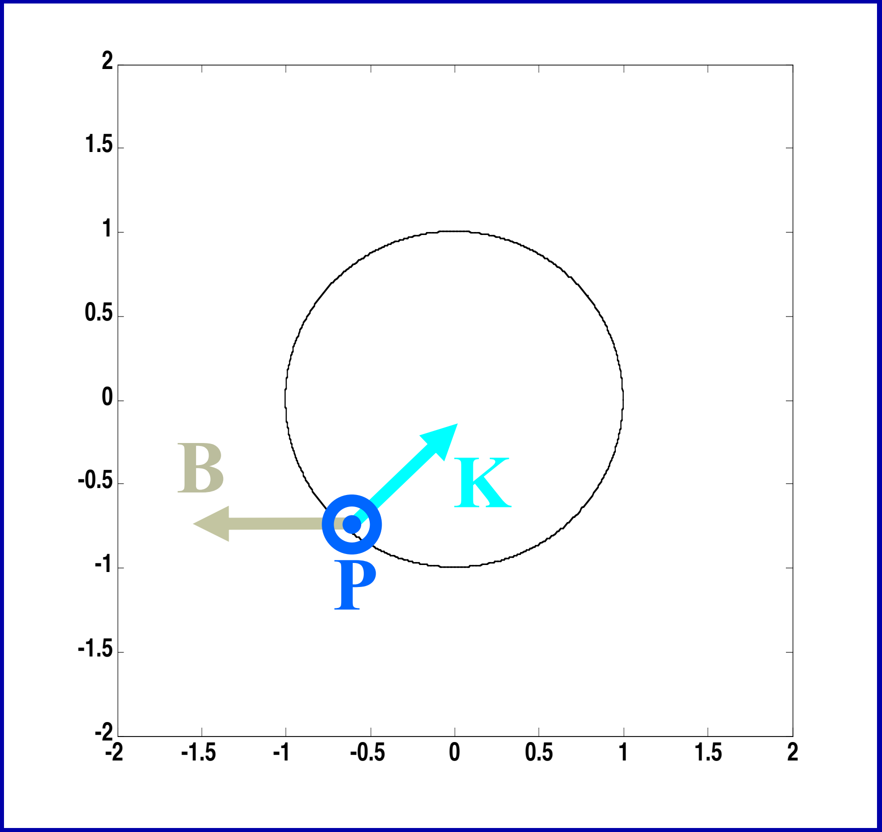


Ordered field in shock plane



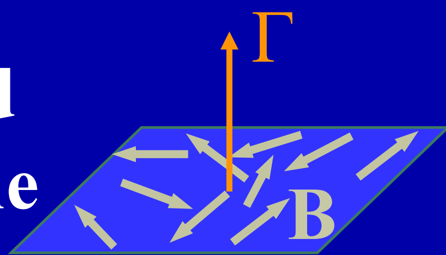


Sari 99; Ghisellni & Lazzati 99

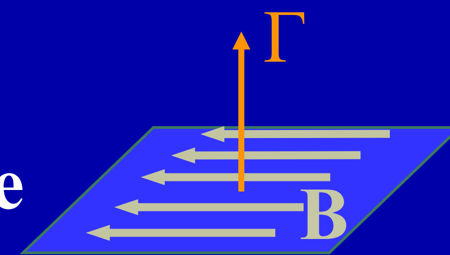


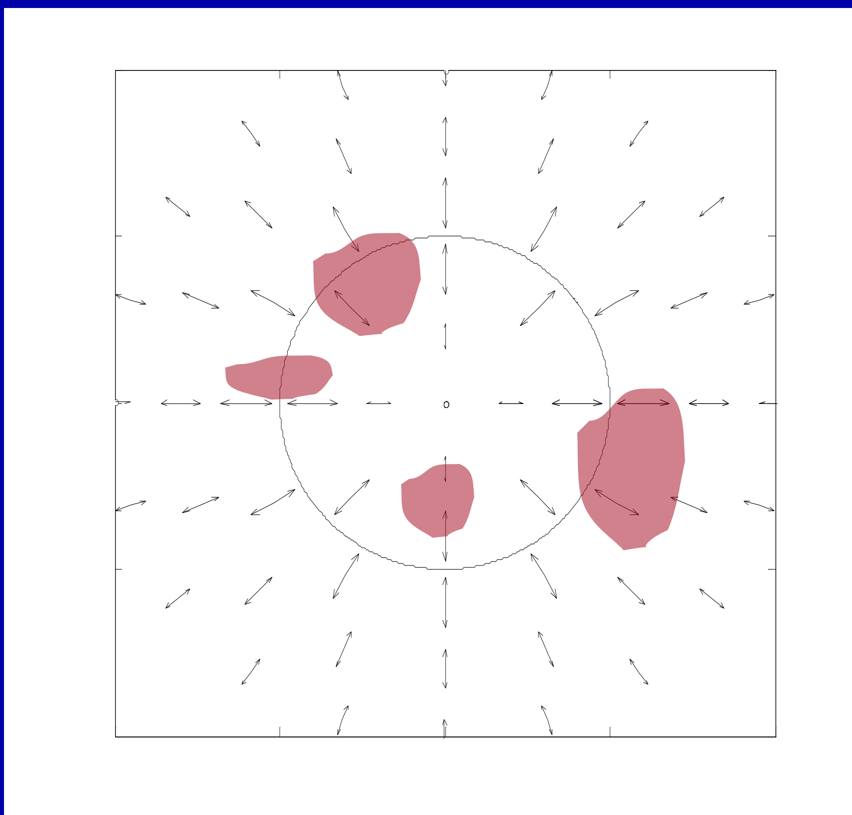
Polarization in the observer frame

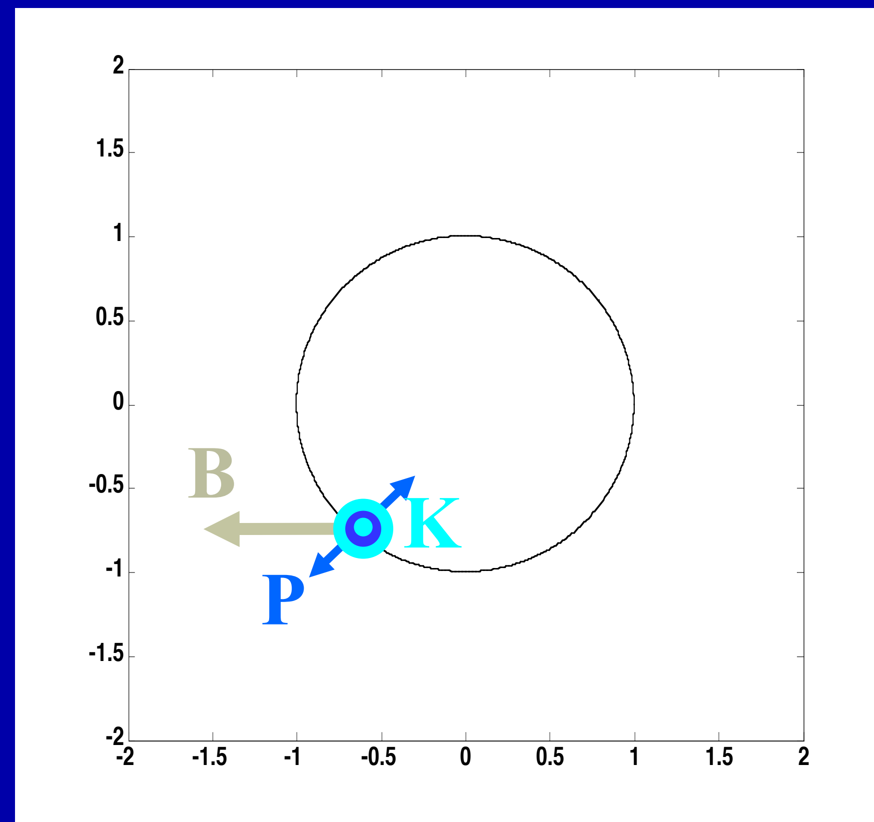
Random field in shock plane



Ordered field in shock plane



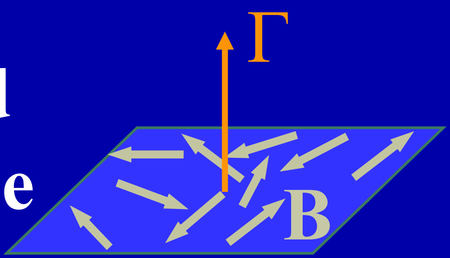




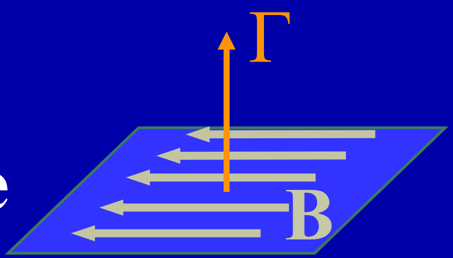
Sari 99; Ghisellni & Lazzati 99

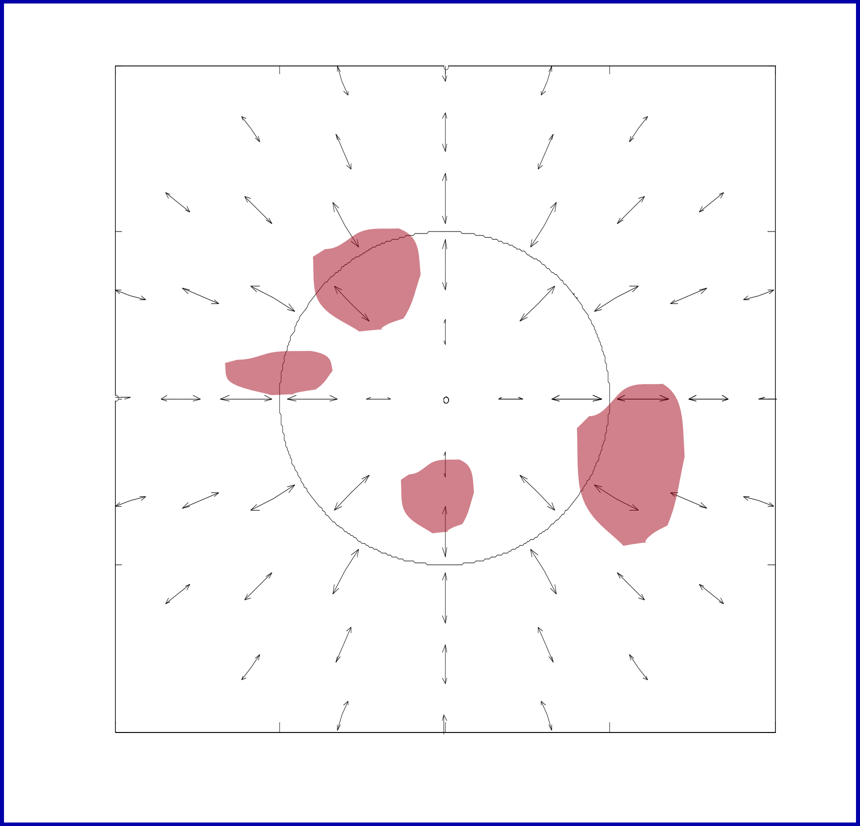
Polarization in the observer frame

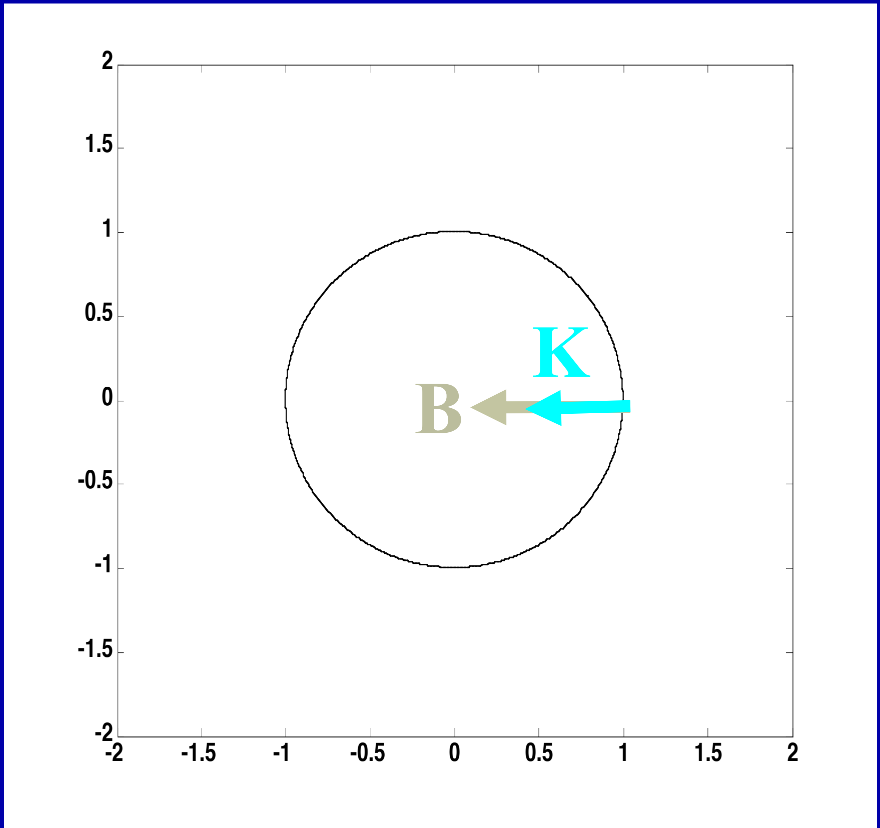
Random field in shock plane



Ordered field in shock plane



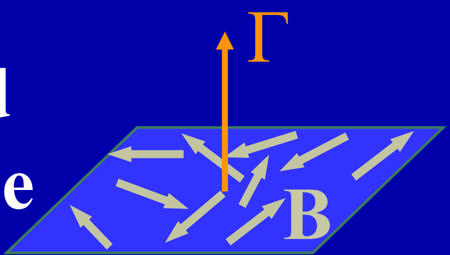




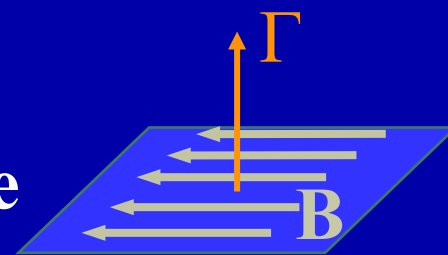
Sari 99; Ghisellni & Lazzati 99

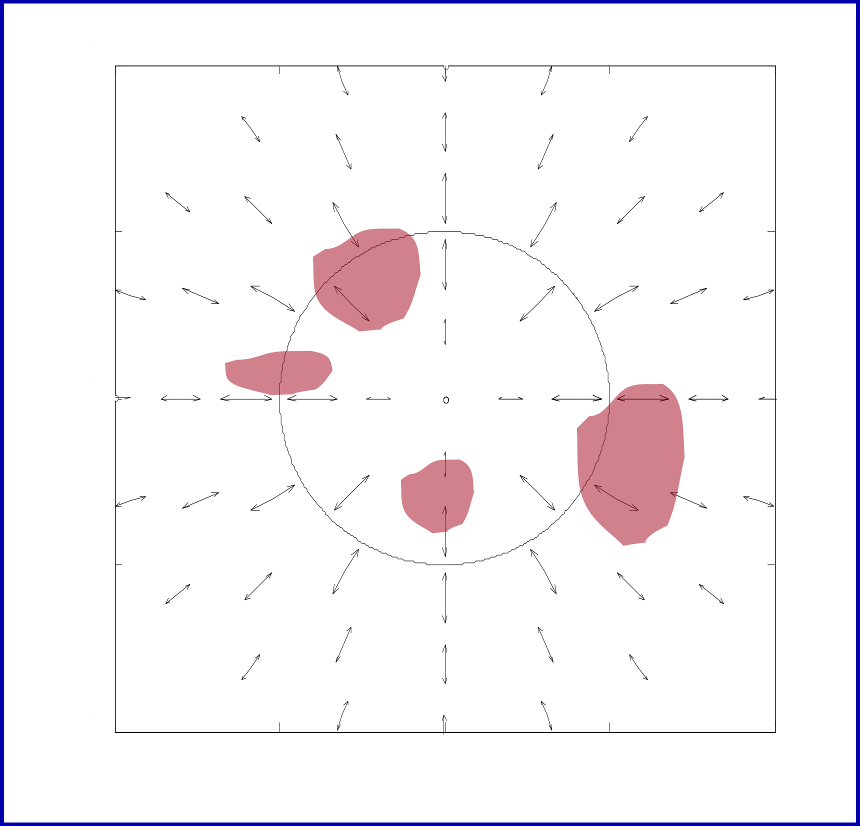
Polarization in the observer frame

Random field in shock plane

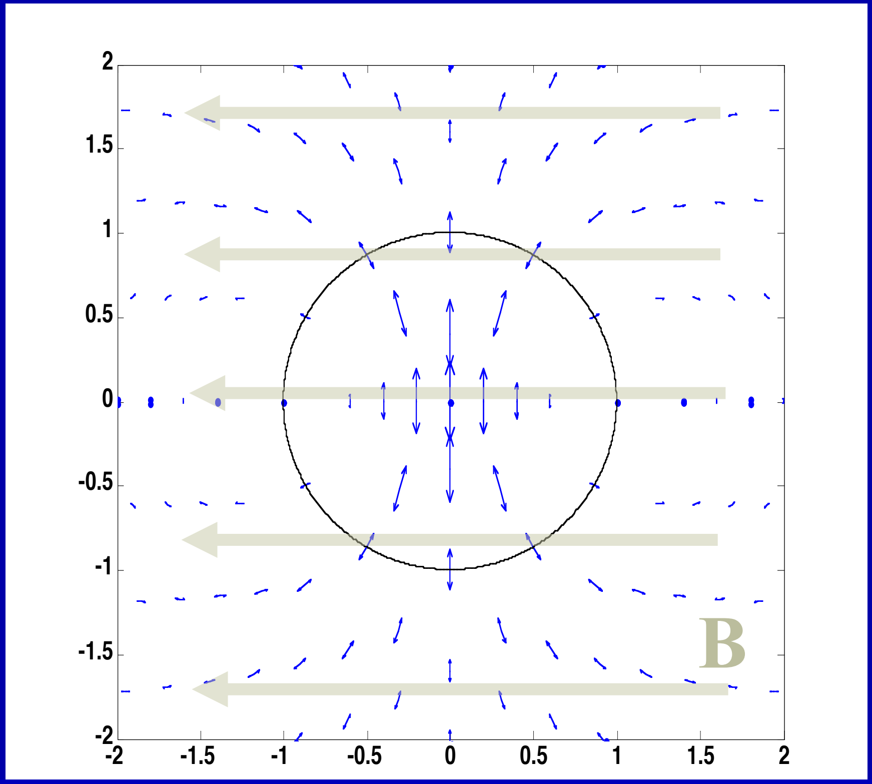


Ordered field in shock plane





Sari 99; Ghisellni & Lazzati 99

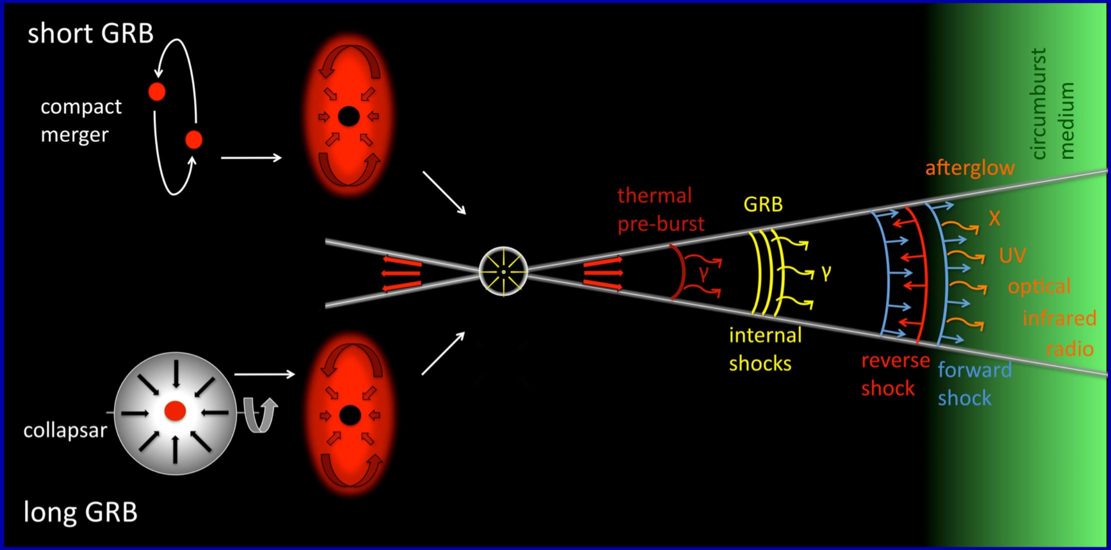


Granot & Königl 03

$P \sim P_{max}$

GRB Theoretical Framework:

- **Progenitors**:
  - ◆Short: binary mergers
  - ◆Long: massive stars
- **Jet Acceleration** to $\Gamma > 100$: P_{rad} / B-field?



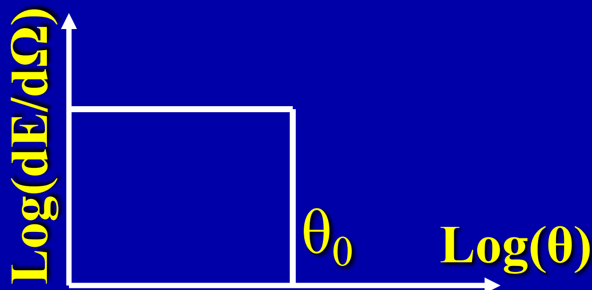
- **γ-rays**: dissipation: shocks/B? emission mechanism?
- The jet **decelerates** as it sweeps up the external medium,

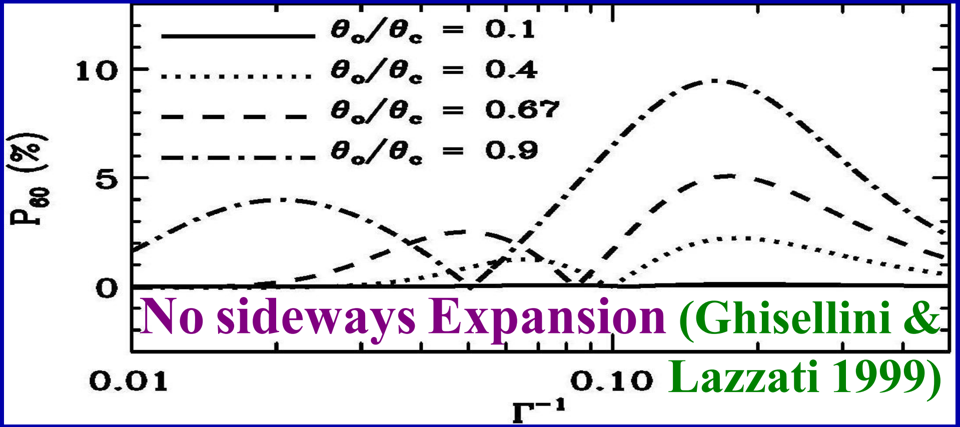
  by a **reverse shock** (for $\sigma \lesssim 1$) ⇒ optical flash, radio flare
- ⇒ **afterglow** from the long-lived forward shock going into the external medium: X-ray → optical → radio

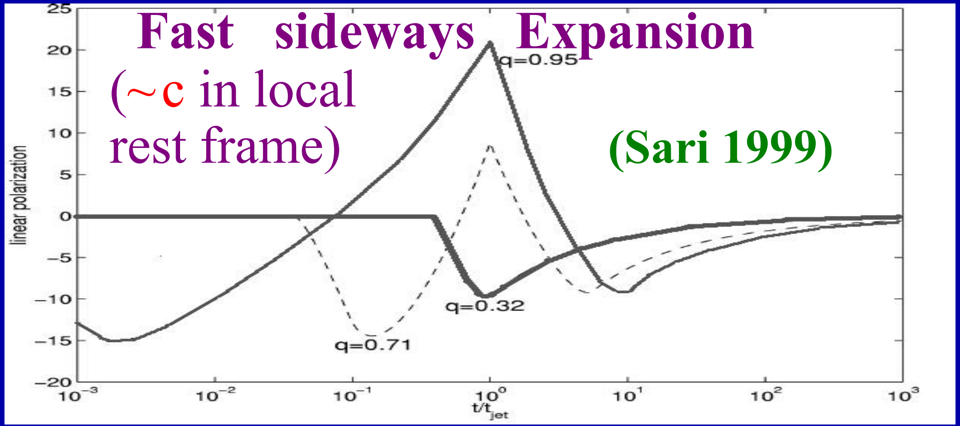
Afterglow: Two "Traditional" Jet Structures

Uniform (top hat) jet:

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







Main Prediction:

P vanishes & reappears with θ_p rotated by 90°

Is not clearly observed

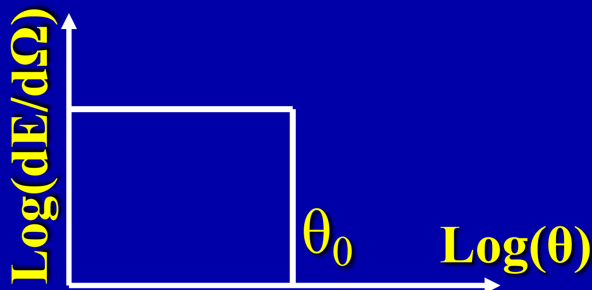
Also: $P \lesssim 10\%$-20%

While $P_{obs} \sim 1$-3%

Afterglow: Two "Traditional" Jet Structures

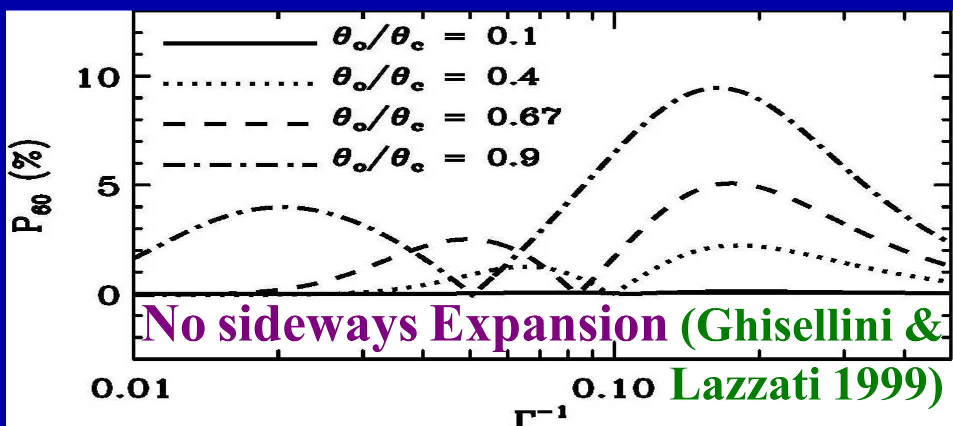
Uniform (top hat) jet:

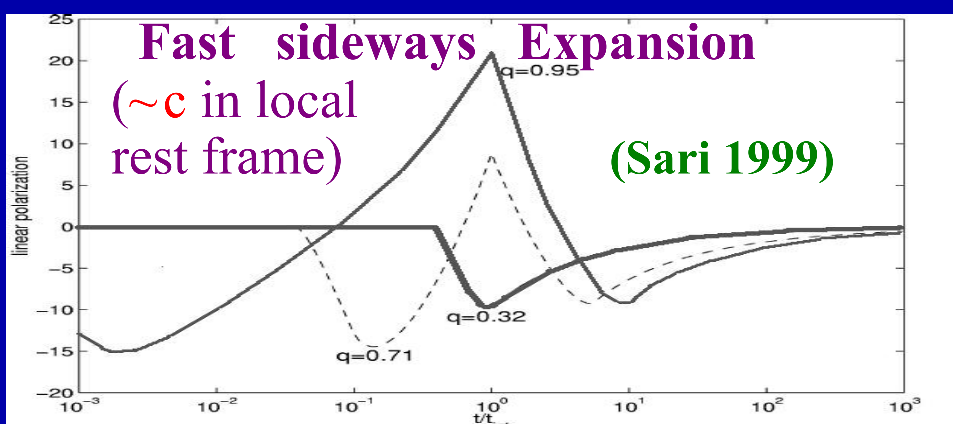
(Rhoads 97,99; Sari+99, ...)

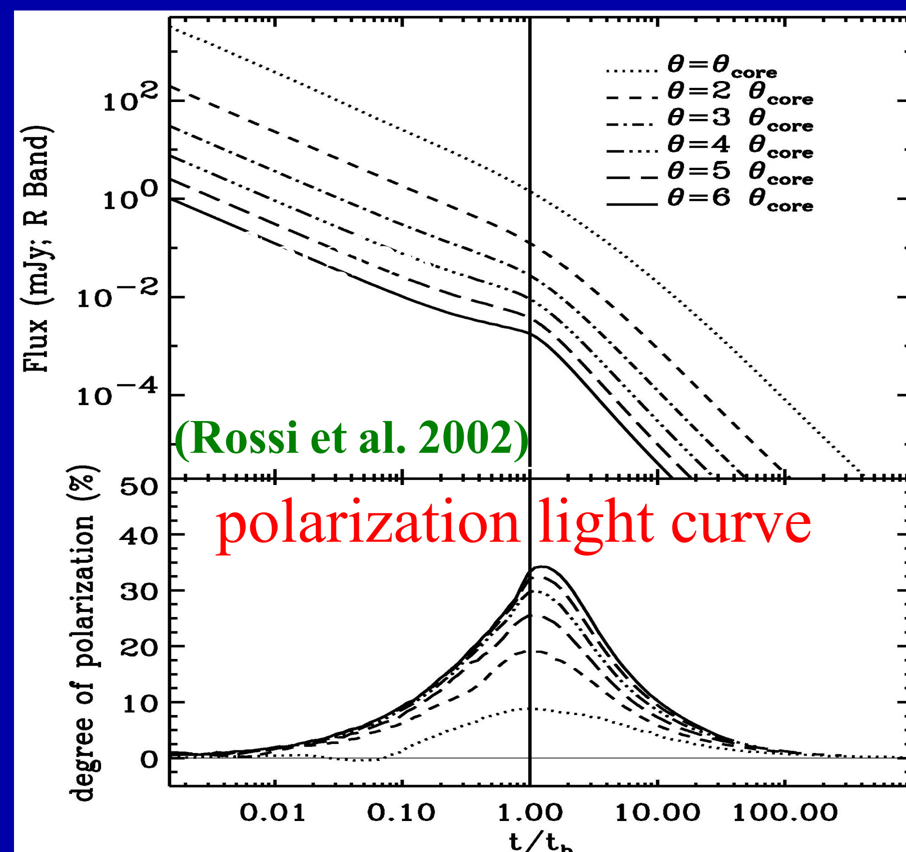


Structured jet:

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

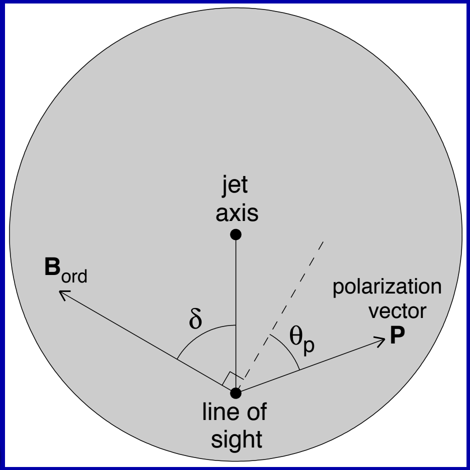




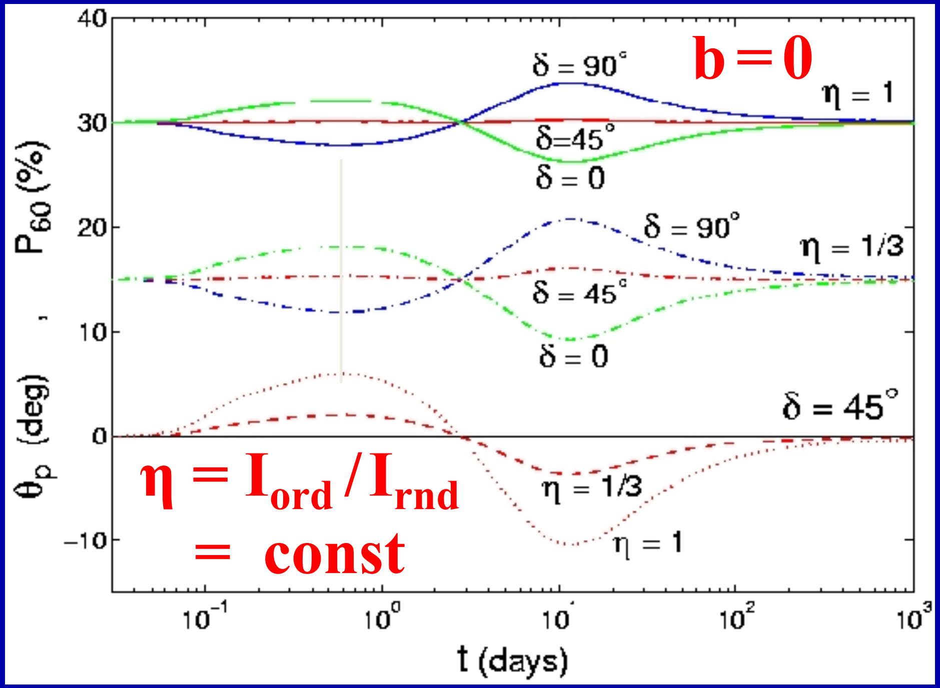


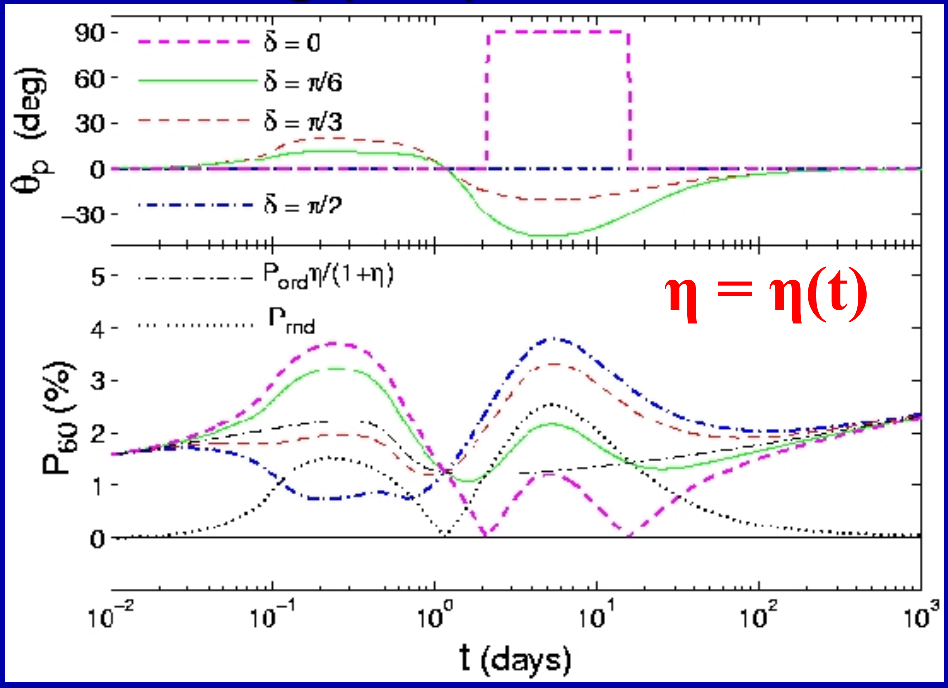
Combining Ordered B_{ord} & Random B_{rnd} Fields

- $P_{ord} \sim P_{max} \sim 60\%$ & $\theta_p = 90°$ 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}



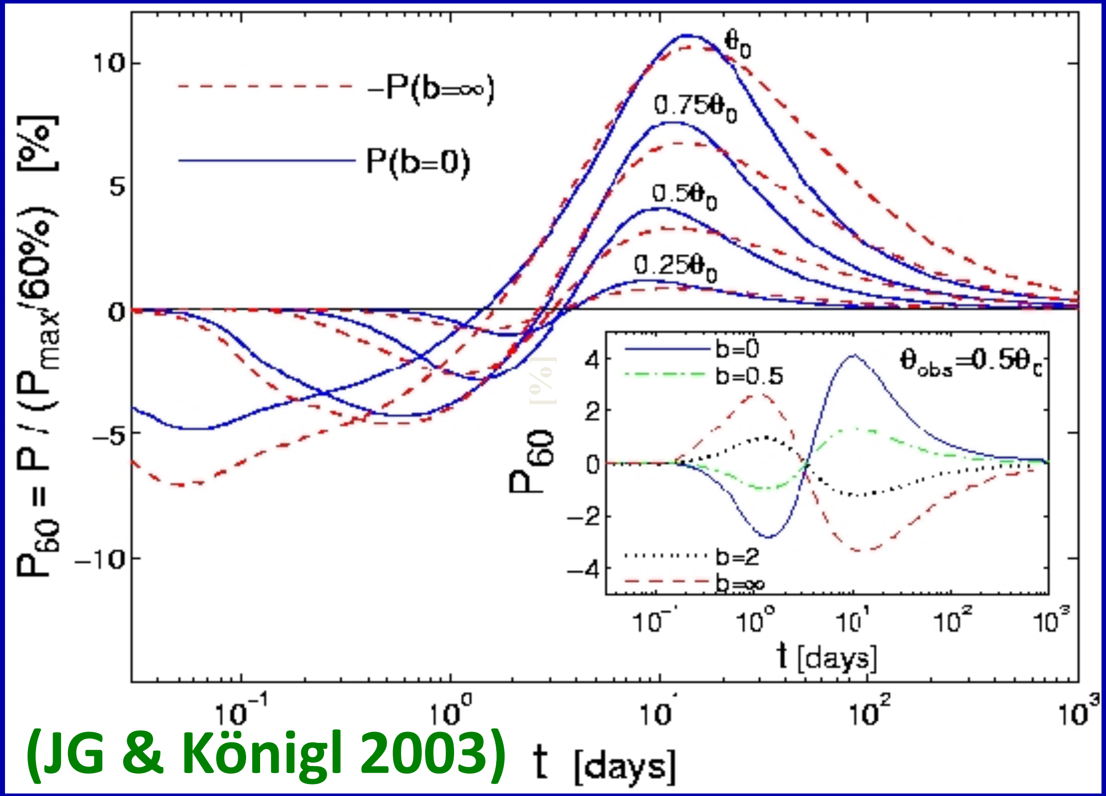
JG & Königl (2003)





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 $\Rightarrow 0.5 \lesssim b \lesssim 2$

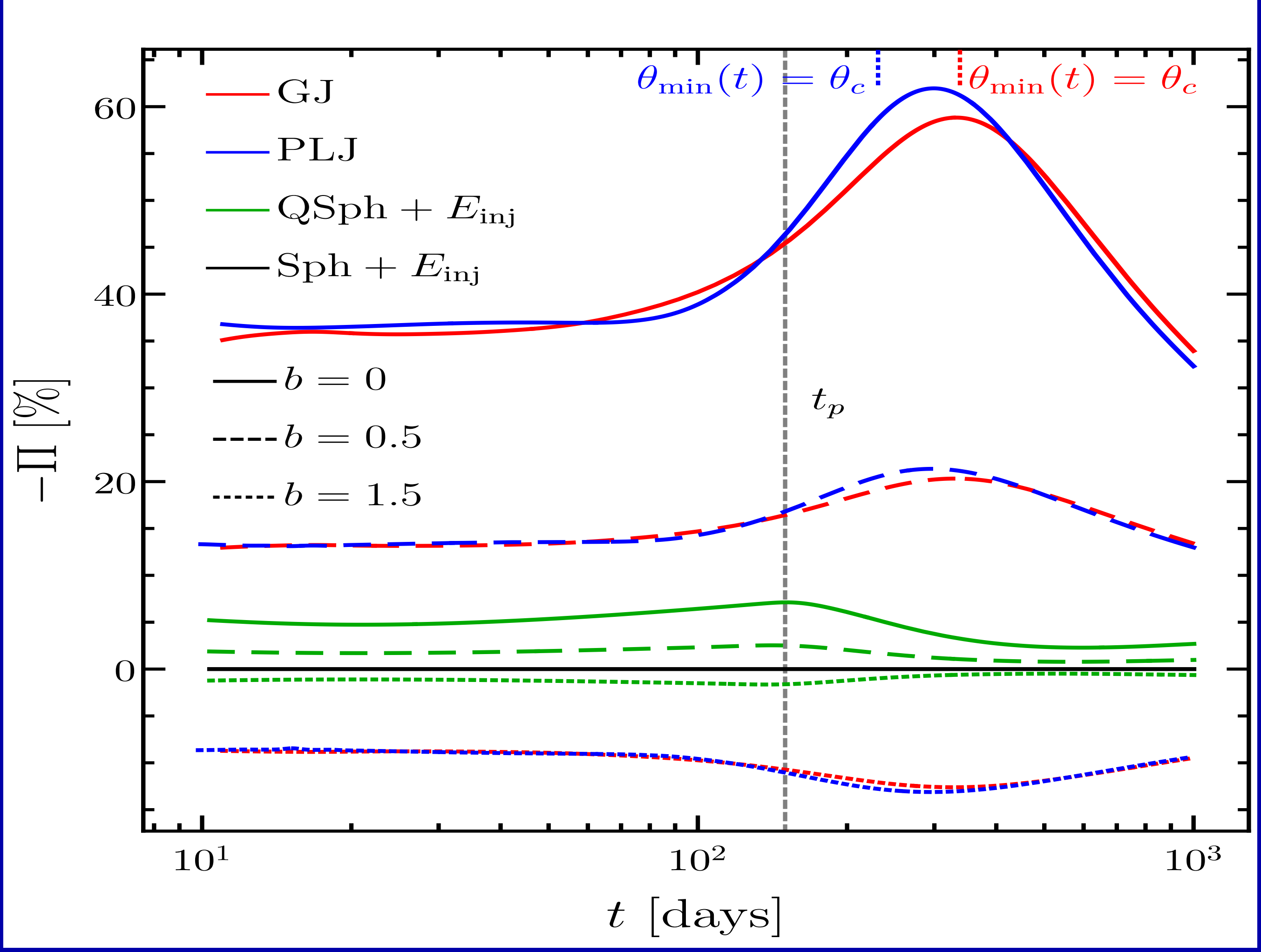


$P = P_{max}/[1+2/(b-1)\sin^2\theta']$
(valid for $j'_{\nu'} \propto [B' \sin\chi']^2$)

$\theta_0 = 5^o$
$E_{jet} = 3 \times 10^{51}$ erg
$n = 1\ cm^{-3}$
$z = 1$
$p = 2.5$
$\varepsilon_e = 0.1$
$\varepsilon_B = 0.01$

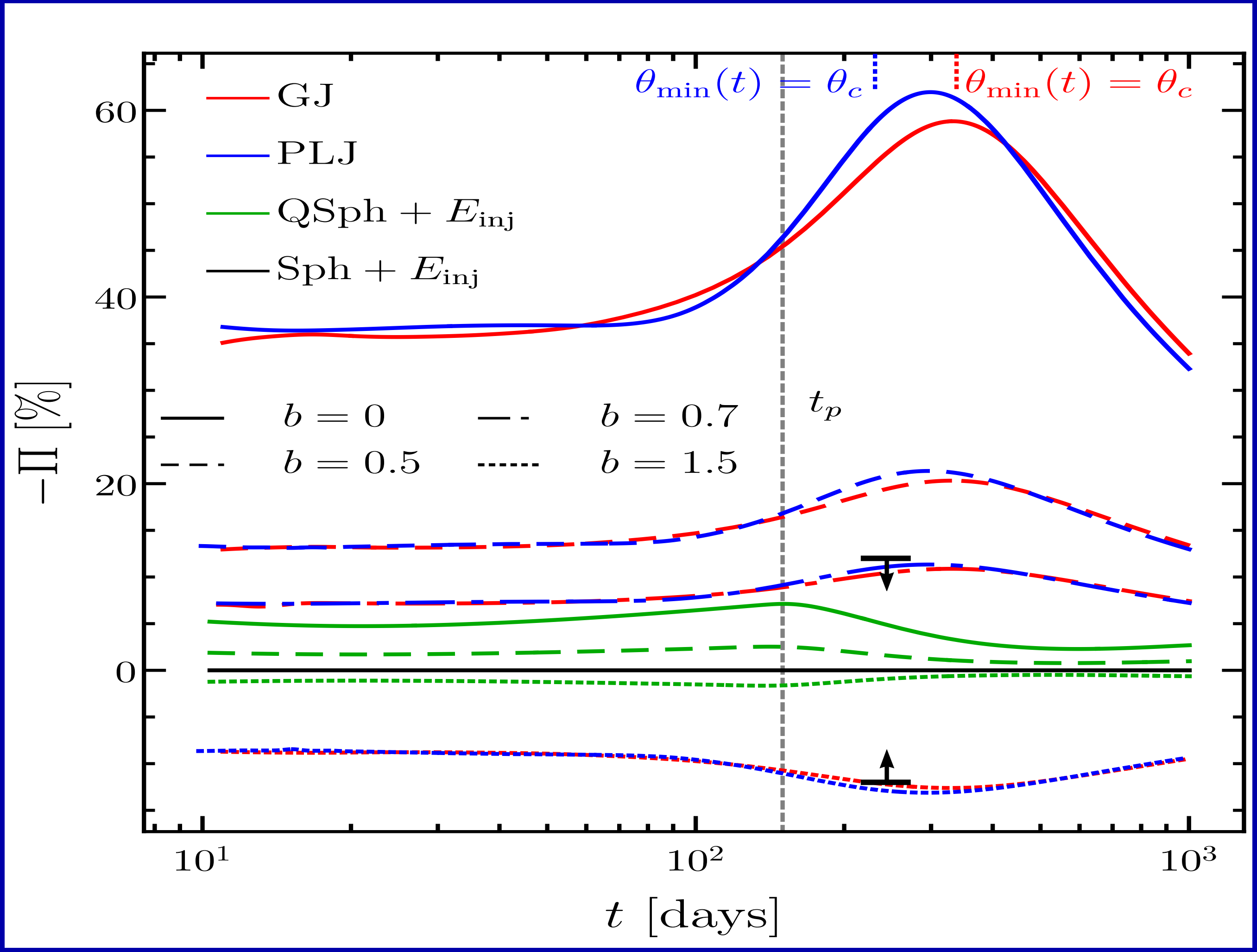
GW170817/GRB170817A Afterglow (Gill & JG 18)

- 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)



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)



$0.66 \lesssim b \lesssim 1.49$ for jet models

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

GW170817/GRB170817A Afterglow (Gill & JG 19)

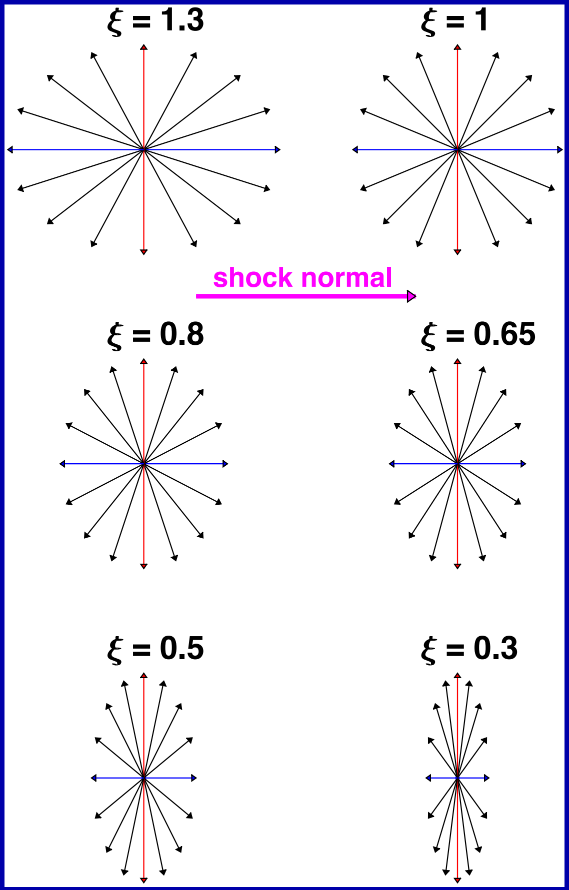
More realistic assumptions ⇒ B-field in collisionless shocks:

- 2D emitting shell → 3D emitting volume (local BM76 radial profile)

GW170817/GRB170817A Afterglow (Gill & JG 19)

More realistic assumptions ⇒ B-field in collisionless shocks:

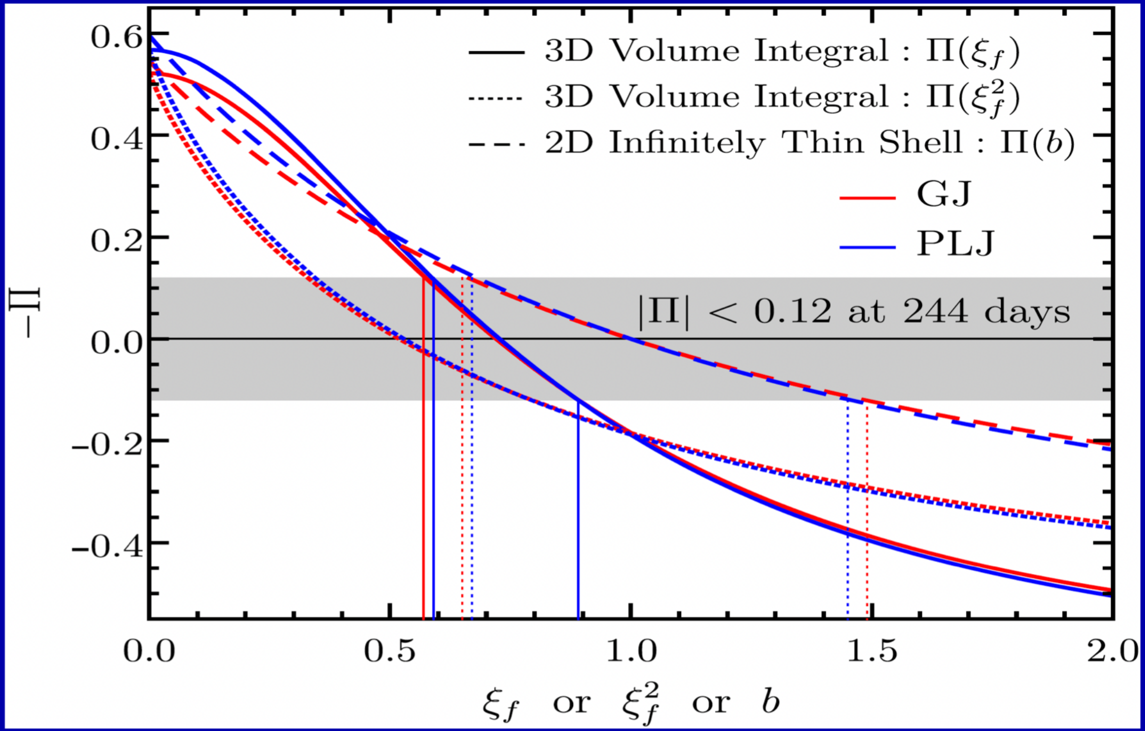
- 2D emitting shell → 3D emitting volume (local BM76 radial profile)
- B-field evolution by faster radial expansion: $L'_r / L'_{\theta,\varphi} \propto \chi^{(7-2k)/(8-2k)}$
  B-field isotropic in 3D with $B'_r \to \xi B'_r$ (Sari 1999); $\xi = \xi_f \chi^{(7-2k)/(8-2k)}$

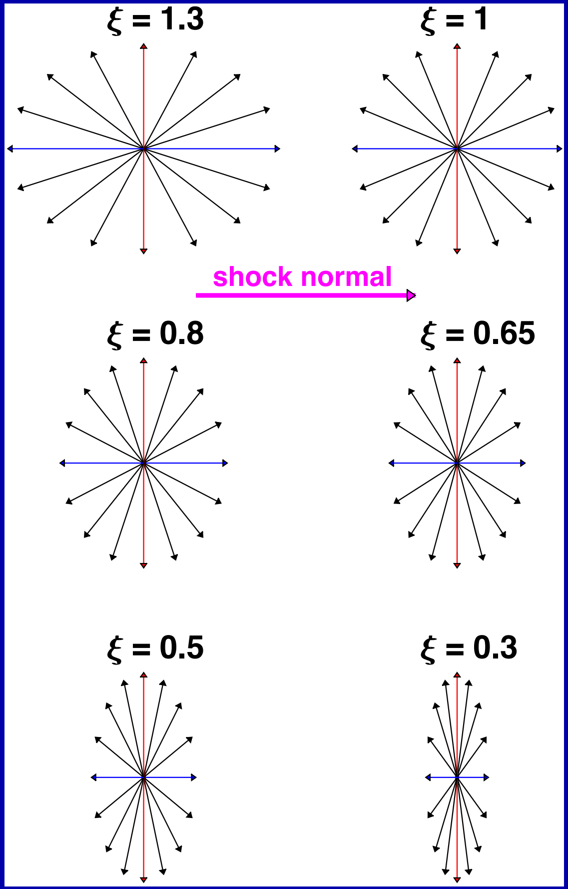


GW170817/GRB170817A Afterglow (Gill & JG 19)

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 $B'_r \rightarrow \xi B'_r$ (Sari 1999); $\xi = \xi_f \chi^{(7-2k)/(8-2k)}$

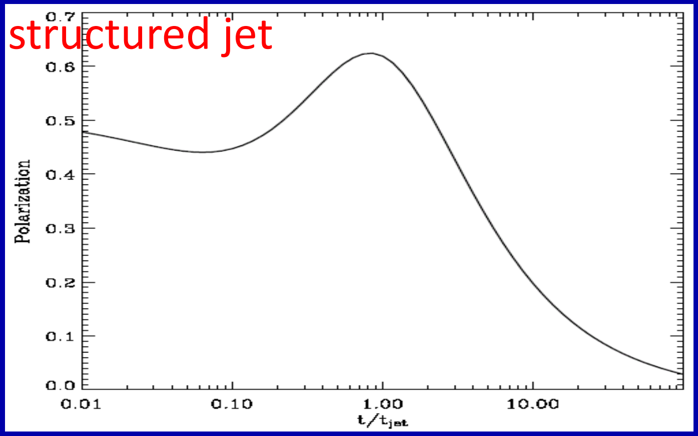




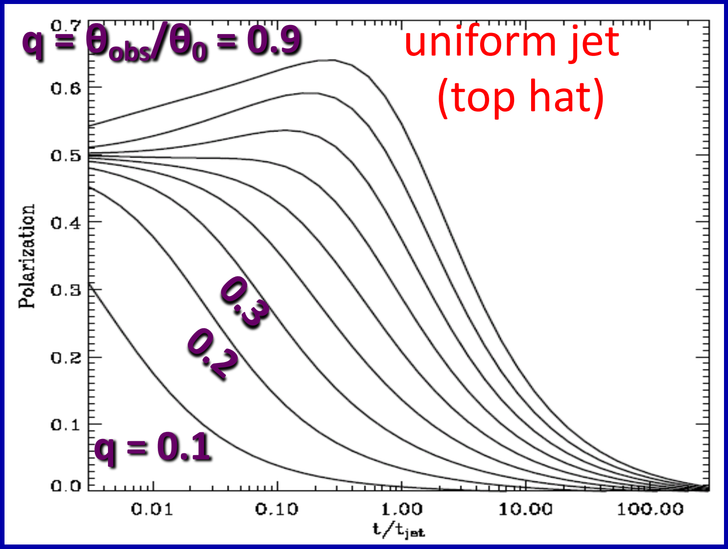
$0.57 \lesssim \xi_f \lesssim 0.89$

Reverse shock Pol.: B-field in ejecta

- The **existence** of a reverse shock ⇒ $E_{EM} \lesssim E_{kin}$ ($\sigma \lesssim 1$)
- 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) ⇒ 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 (3σ)	Π_C (3σ)
990123	1.25	**≈ 2**	< 23%	< 32%
	1.49		< 11%	< 17%
991216	2.68	~ 2	< 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

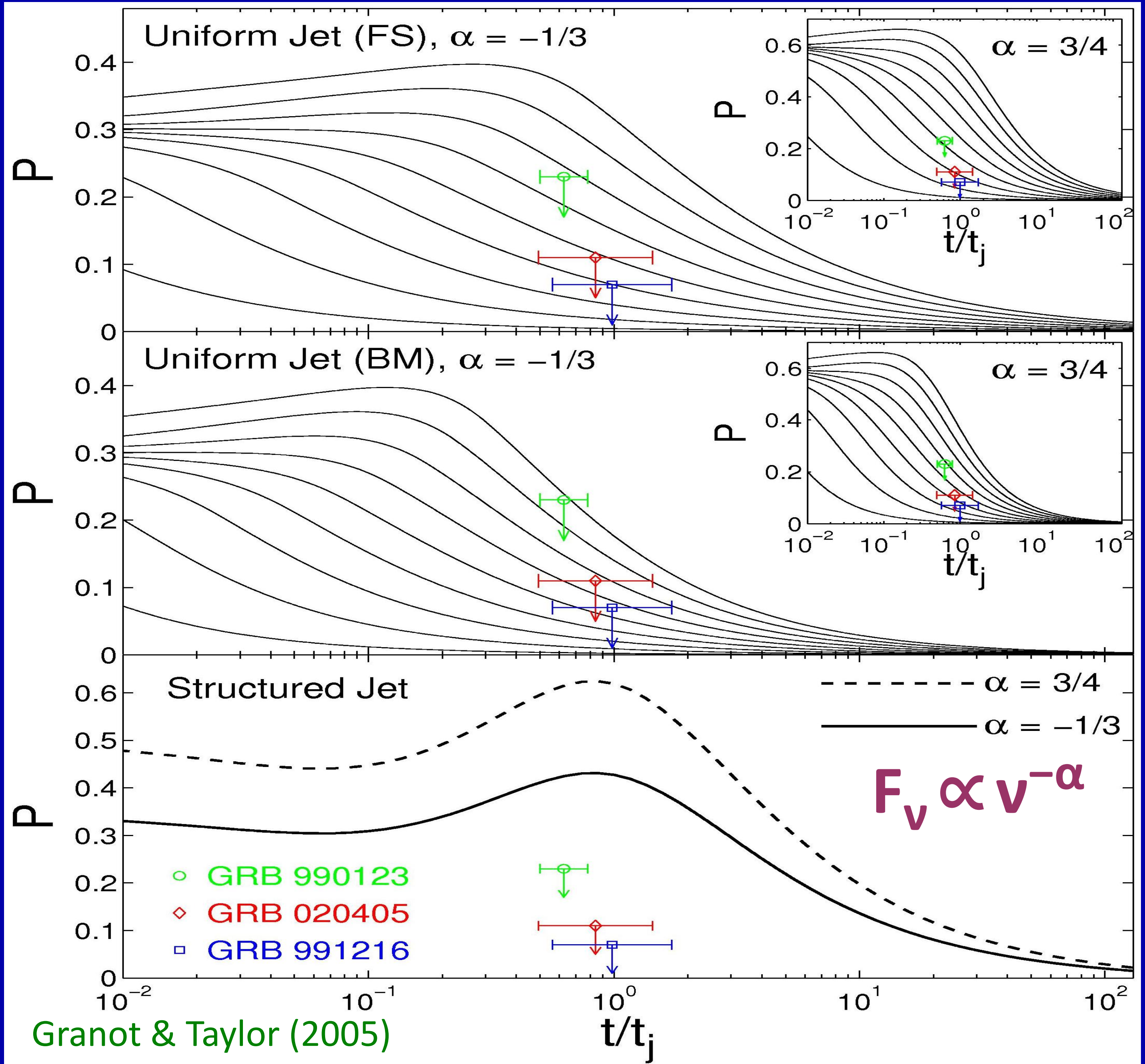
Toroidal Magnetic Field:

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



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

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 ⇒ 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 $\theta_{obs}/\theta_j \lesssim 0.4 - 0.55$

Implications of the Upper limits on the Radio Flare Polarization

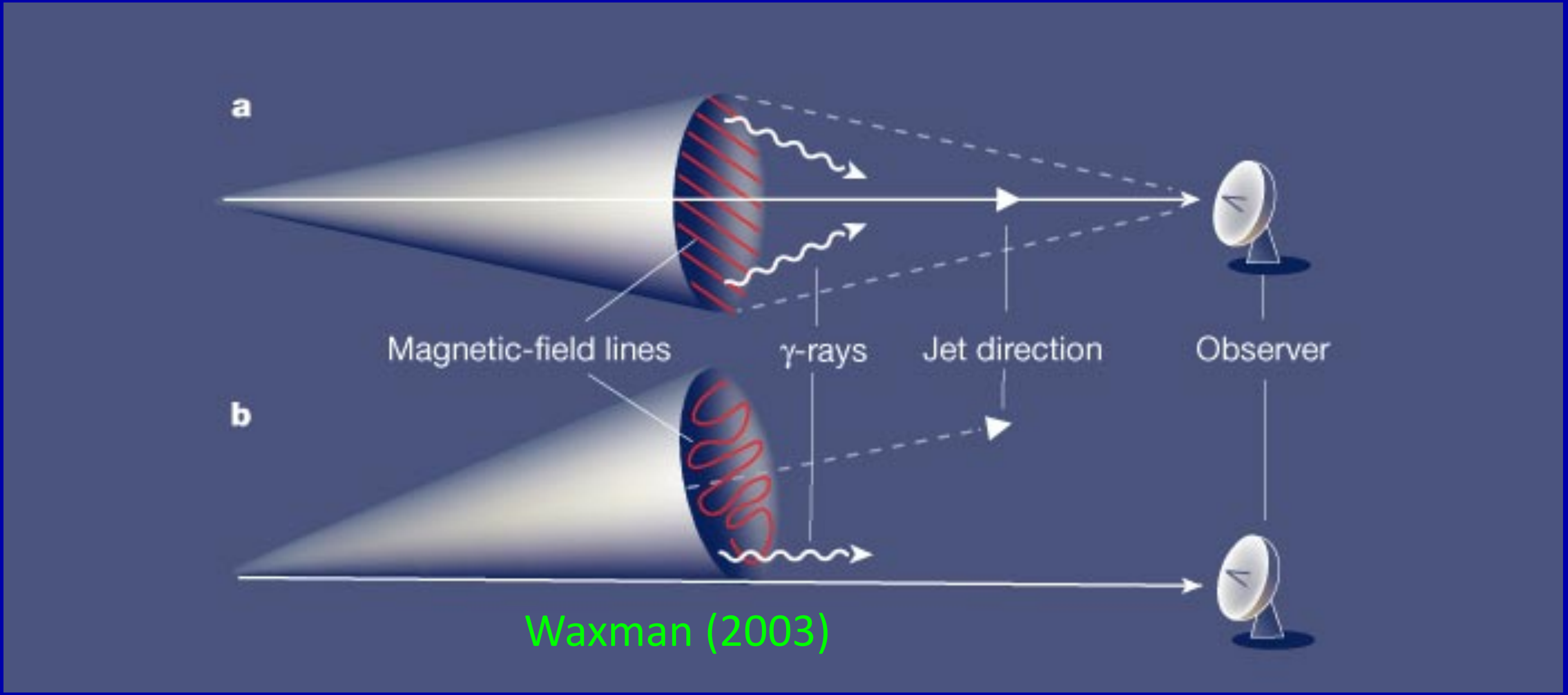
New Results: Tanmoy Laskar's talk

B-field structure	Theoretical prediction	Theory vs. Observation
Shock Produced	pol. due to jet structure ⇒ 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 $\theta_{obs}/\theta_j \lesssim 0.4 - 0.55$

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 θ_{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

Narrow Jet + shock produced B-field

- High polarization + reasonable flux ⇒ $\theta_j < \theta_{obs} \lesssim \theta_j + 1/\Gamma$
- A reasonable probability for such θ_{obs} ⇒ $\Gamma\theta_j \lesssim$ 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)

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 %)

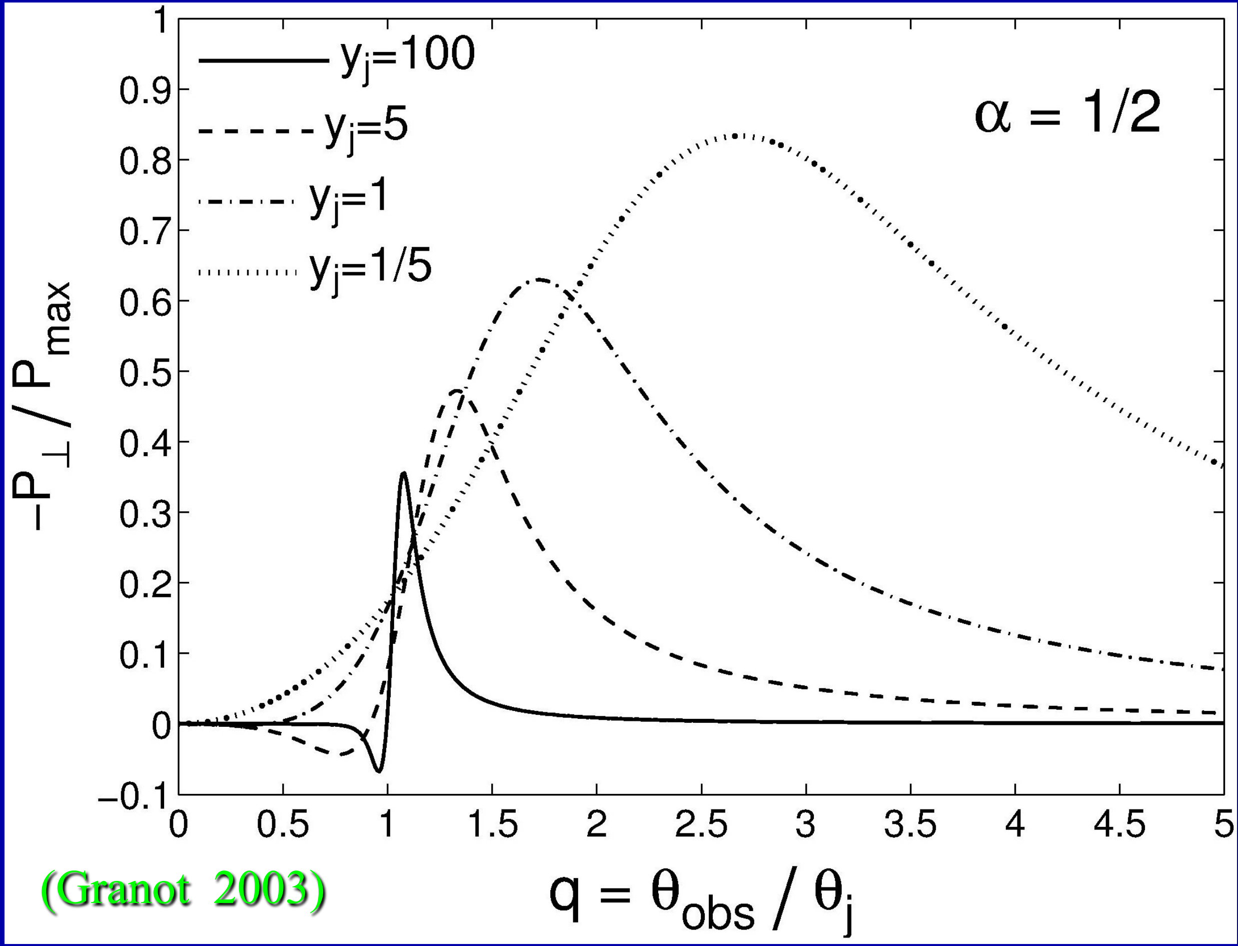
Narrow Jet + shock produced B-field

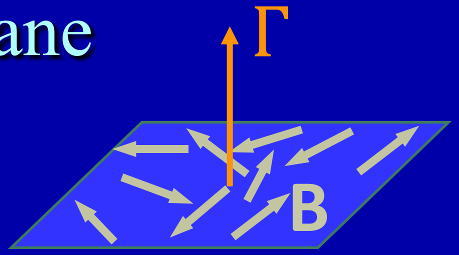
- High polarization + reasonable flux $\Rightarrow \theta_j < \theta_{obs} \lesssim \theta_j + 1/\Gamma$
- A reasonable probability for such $\theta_{obs} \Rightarrow \Gamma\theta_j \lesssim$ a few
- Since $\Gamma \gtrsim 100$ & $\theta_j \gtrsim 0.05$, $\Gamma\theta_j \gtrsim 5$ and is typically larger
- 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

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}: $0.57 \lesssim \xi_f \lesssim 0.89$

Adding pulses: Random B-field in shock plane





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

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

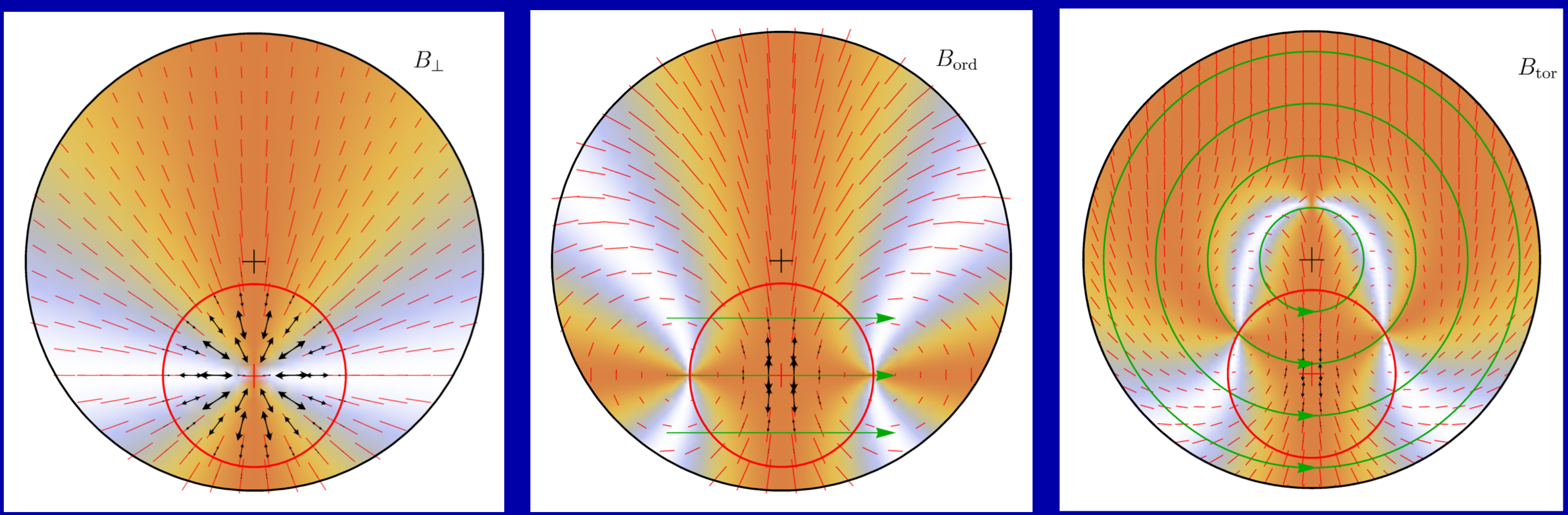
- $\Delta\Gamma \sim \Gamma$ between different shell collisions (different pulses in GRB light curve) reduces P by a factor ~ 2

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} $(0.57 \lesssim \xi_f \lesssim 0.89)$ $\Delta\theta_j \lesssim 1/4\Gamma$

Prompt GRB Polarization (Gill, JG & Kumar 2020):

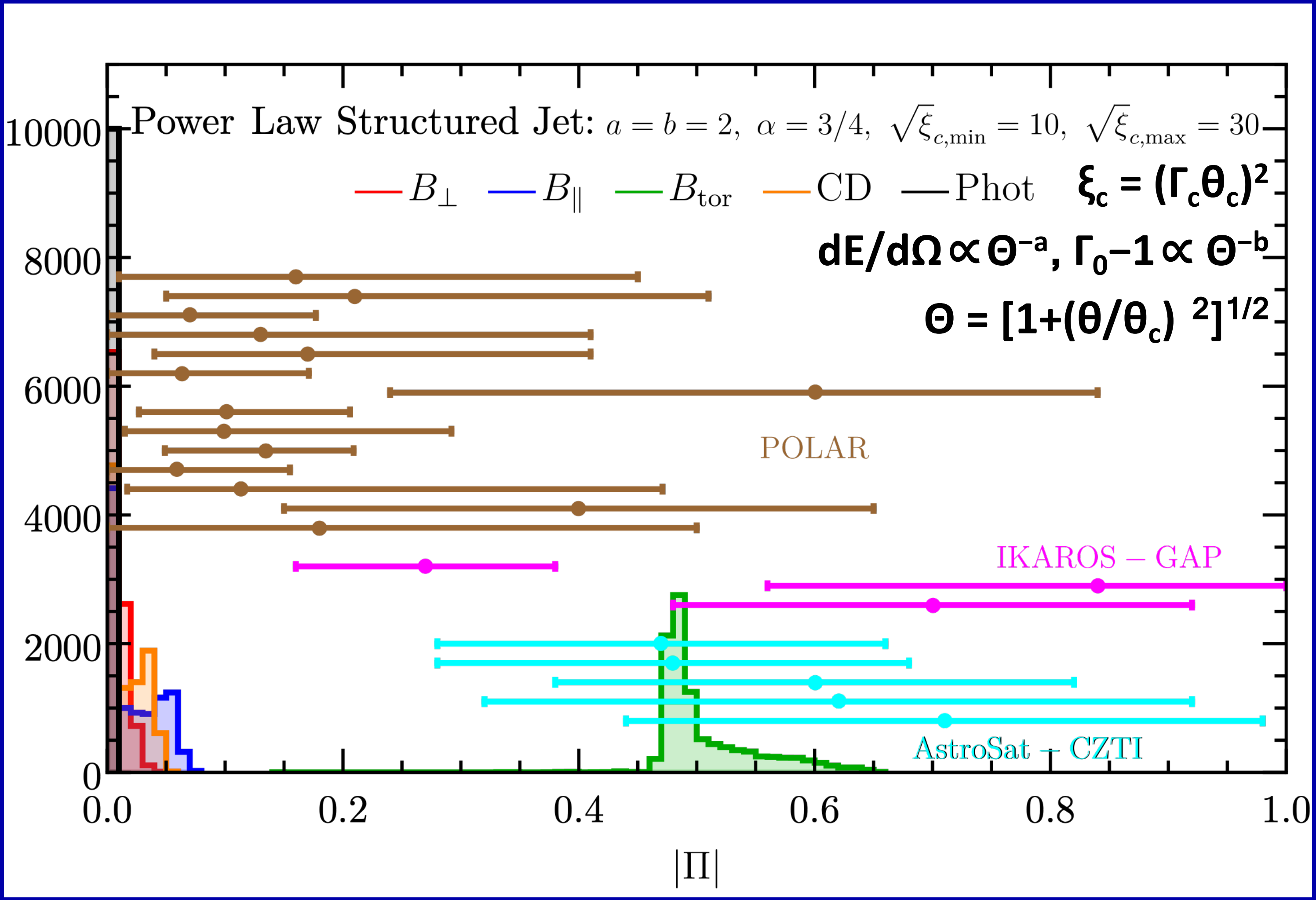
- Comprehensive study in view of γ-ray polarimetry missions
- Jet structure: top hat (sharp/smooth), Gaussian, core+power-law
- Emission mechanism: synchrotron, photospheric, Compton drag
- **Time integrated** over single or multiple pulses



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 $P \sim 50\text{-}65\%$ in 1 ($\gtrsim 20\%$ in most) GRBs

Prompt GRB Polarization (Gill, Kole & JG 2022):

Colour scale: 0% – 100%

		Synchrotron $B_\perp$	Synchrotron $B_{\|}$	Synchrotron $B_{\rm tor}$	Photospheric	Compton Drag
Structured Jet	$\theta_{\rm obs} \gtrsim \theta_c$	7% - 18%	14% - 35%	38% - 52%	5% - 15%	10% - 25%
Structured Jet / Top-Hat Jet	$\theta_{\rm obs} \ll \theta_c$ / $\theta_{\rm obs} \ll \theta_j$	0%	0%	0% - 50%	0%	0%
Top-Hat Jet	$\theta_{\rm obs} \approx \theta_j$	4% - 28%	10% - 56%	10% - 60%	4% - 20%	5% - 50%

Conclusions:

- **Afterglow polarization** probes jet structure & dynamics + the B-field structure behind relativistic collisionless shocks
  - ⇒ GW170817: $0.57 < \xi_0 < 0.89$ (B_{rnd}) + core-dominated jet
    (talks by Brivio, Jordana-Mitjans, Laskar)

Conclusions:

- **Afterglow polarization** probes jet structure & dynamics + the B-field structure behind relativistic collisionless shocks
  - ⇒ GW170817: $0.57 < \xi_0 < 0.89$ (B_{rnd}) + core-dominated jet
    (talks by Brivio, Jordana-Mitjans, Laskar)
- 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
  - Optical / Radio results: talks by Jordana-Mitjans / Laskar

Conclusions:

- **Afterglow polarization** probes jet structure & dynamics + the B-field structure behind relativistic collisionless shocks
  - ⇒ GW170817: $0.57 < \xi_0 < 0.89$ (B_{rnd}) + core-dominated jet (talks by Brivio, Jordana-Mitjans, Laskar)
- 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
  - Optical / Radio results: talks by Jordana-Mitjans / Laskar
- 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 (talks by Kole, Gill, Parsotan, De Angelis)