# Polarization and the Magnetic Field Structure in GRB Outflows

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# Outline of the Talk:

- GRB theory: Fireball model vs. Poynting flux
- GRB polarization: an unresolved relativistic jet
- Afterglow pol.: variable vs. smooth light curves
- Polarization in the **prompt γ-ray emission**
- Polarization of the **optical flash & radio flare**
- **New:** upper limits on the Pol. of the radio flare
- Implication for B-field structure + jet structure
- Conclusions

# Theory: Fireball vs. Poynting Flux

*Meszaros & Rees 92, Katz 94, Sari & Piran 95

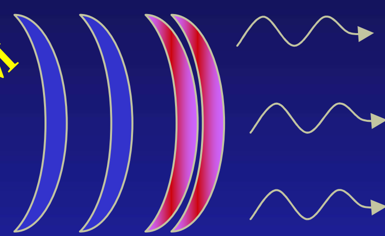
† Shemi & Piran 90, Goodman 86, Paczynski 86,…

Compact Source

**Matter dominated**† outflow $E_{kin} \gtrsim E_{EM}$

**Poynting flux**† dominated flow $E_{EM} \gg E_{kin}$

**Prompt GRB**



Internal Shocks

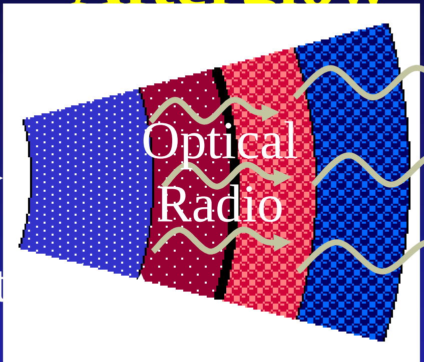
Particle acceleration

⇒ synchrotron γ-rays

reconnection (or other EM instability)

**Afterglow**

ejecta



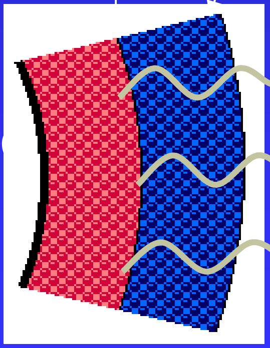

X-rays
Optical
Radio

Reverse shock*

Forward Shock (Rees & Meszaros 92)

External medium

Magnetic bubble

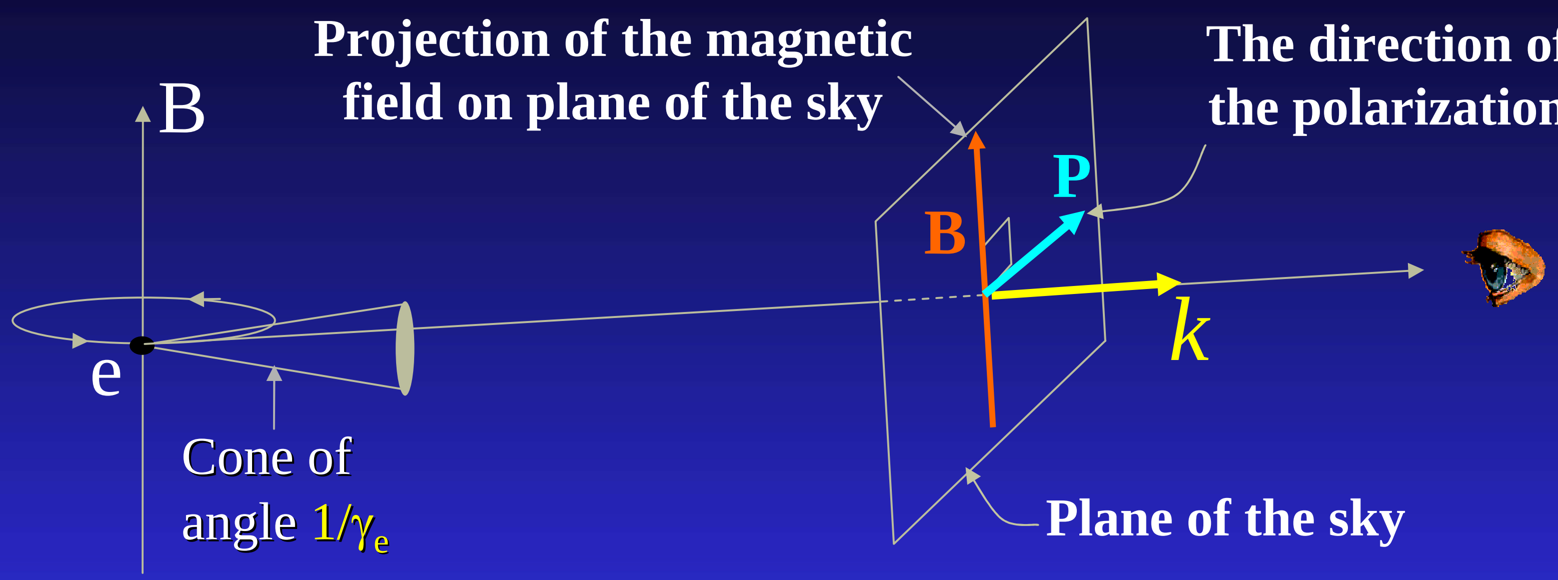


X-rays
Optical
Radio

†Thopson 94, Usov 94, Meszaros & Rees 97, Katz 97,…

Lyutikov & Blandford 02,03

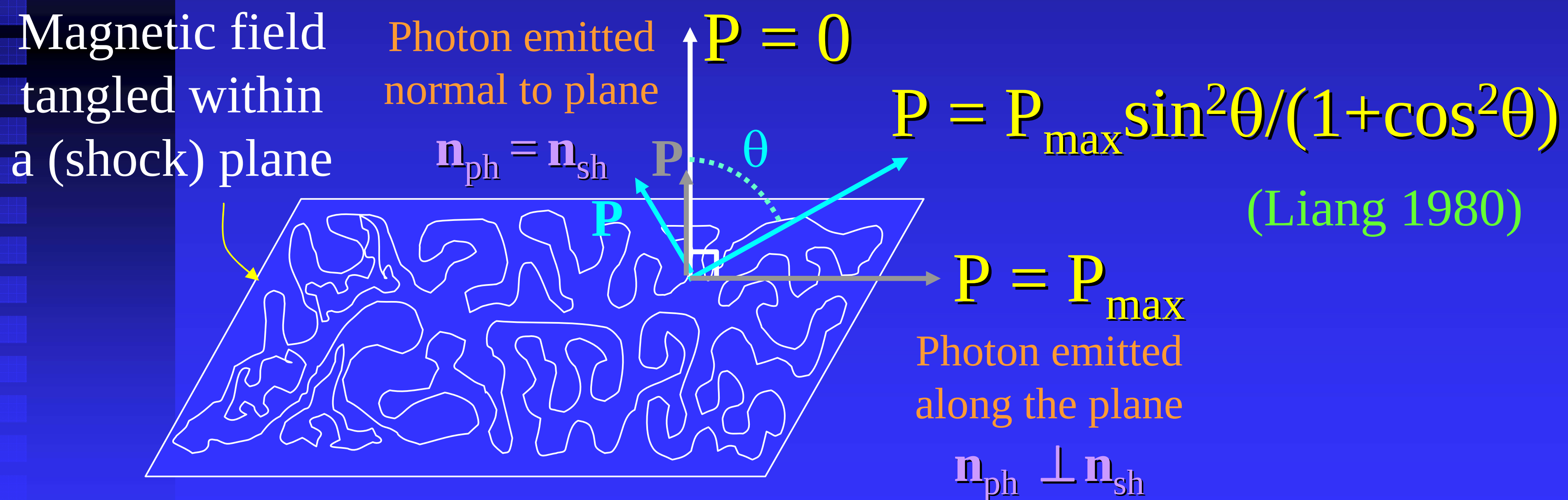
# Polarization of Synchrotron Emission




- **linear polarization** perpendicular to the projection of **B** on the plane of the sky (+ **residual elliptical pol.** $\lesssim 1/\gamma_e \ll 1$)
- 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)

# Shock Produced Magnetic Field:

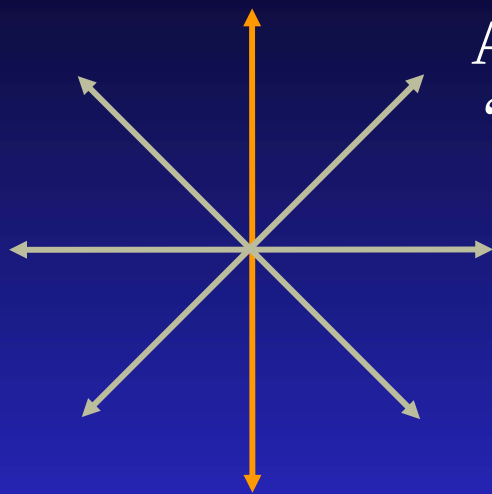
- A magnetic field that is produced at a relativistic collisionless shock, due to the two-stream instability, is expected to be **tangled within the plane of the shock** (Medvedev & Loeb 1999)



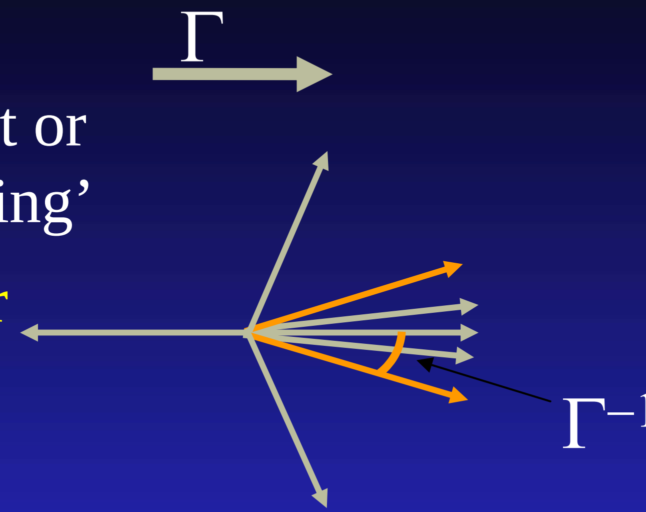
# Relativistic source:

Aberration of light or ‘relativistic beaming’

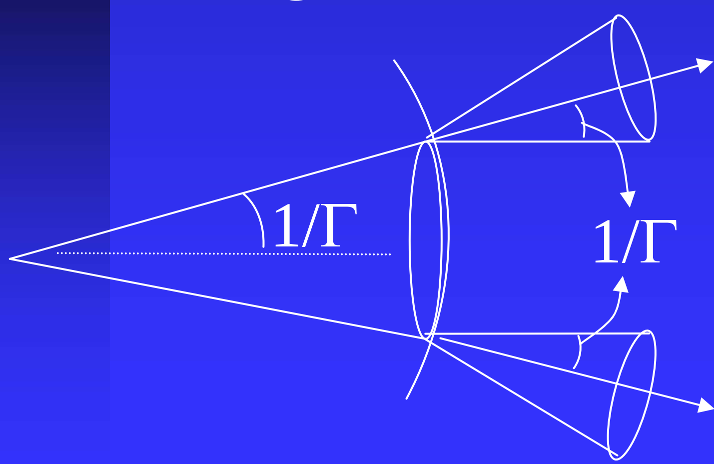
Source frame



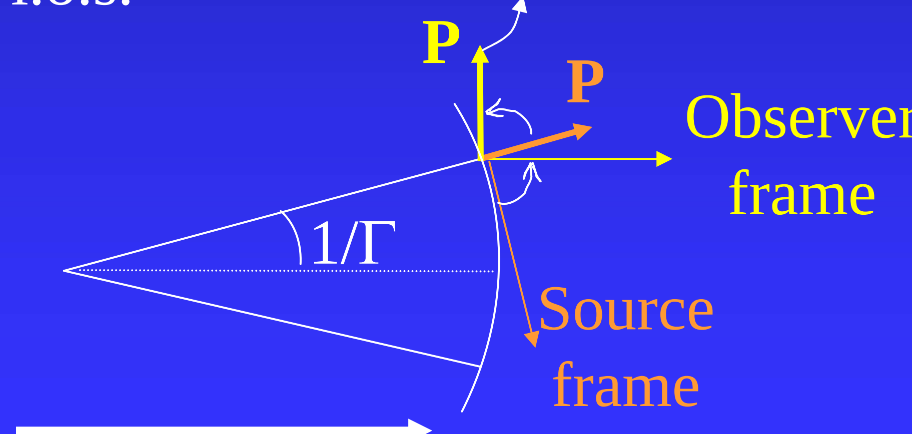
Observer frame




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



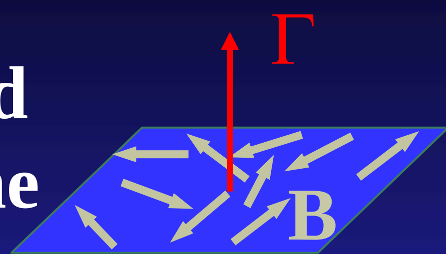

Direction of Polarization



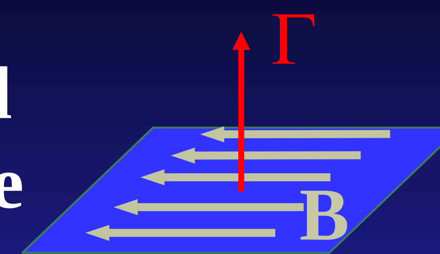

Direction to observer

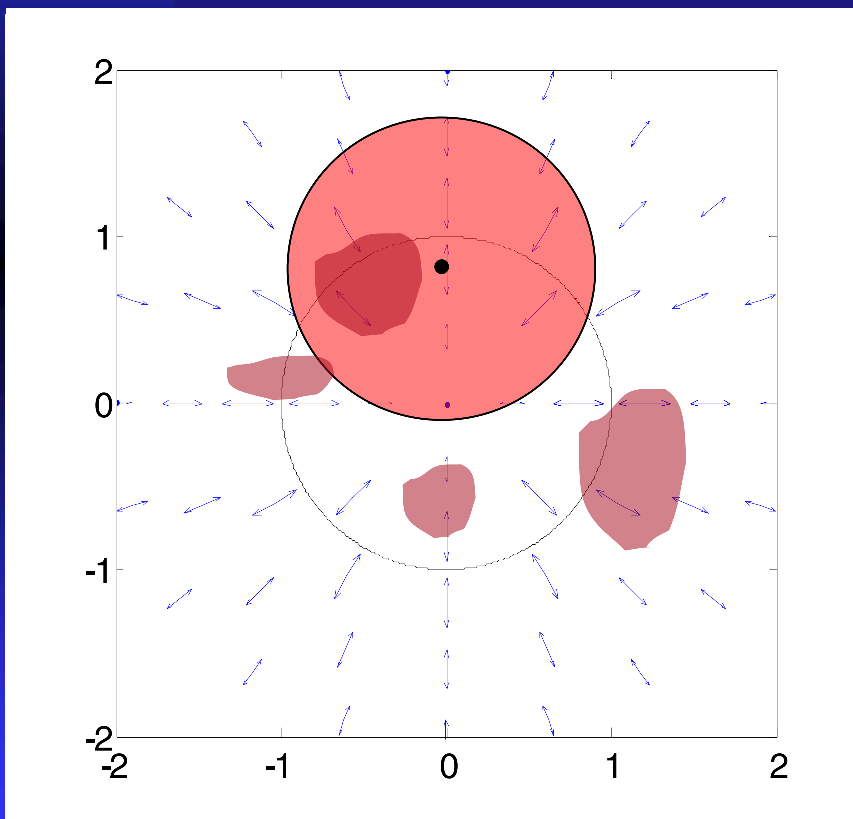
# Polarization in the observer frame

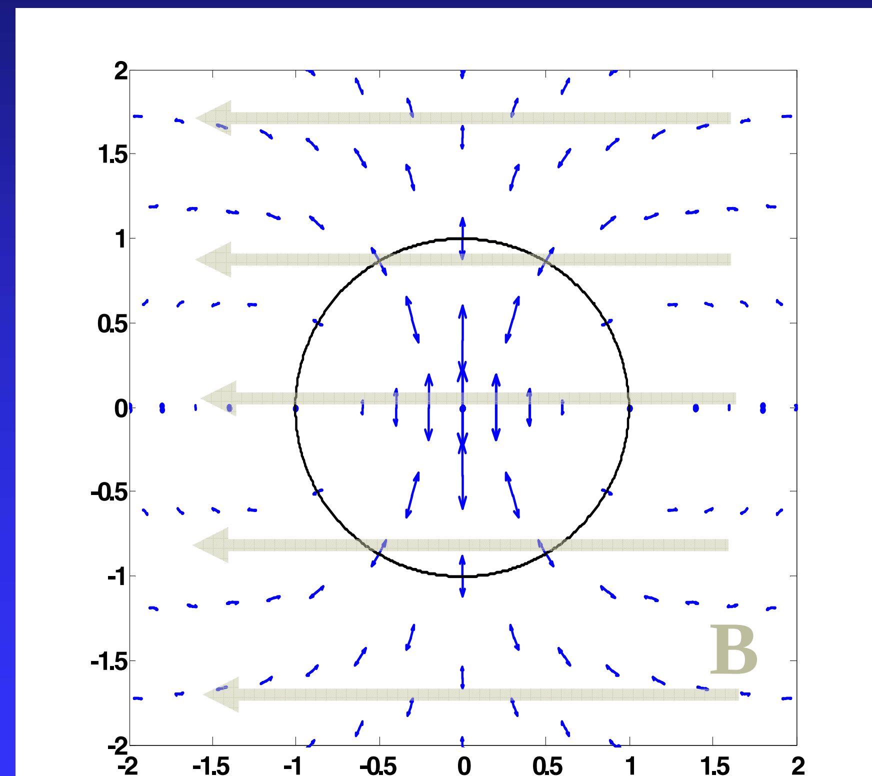
**Random field in shock plane**




**Ordered field in shock plane**




Sari 99; Ghisellni & Lazzati 99

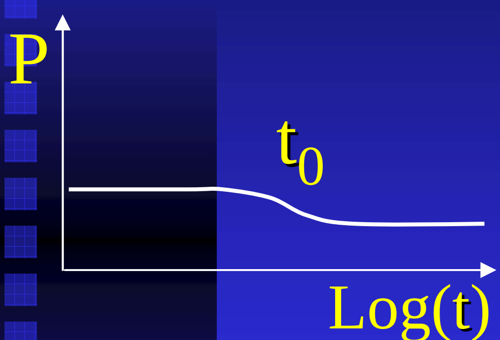
Granot & Königl 03

$P \sim P_{max}$

# Smooth Afterglow Light Curves:

## the polarization is usually attributed to a jet geometry

## Ordered B-field*:




$\theta_p$ = const

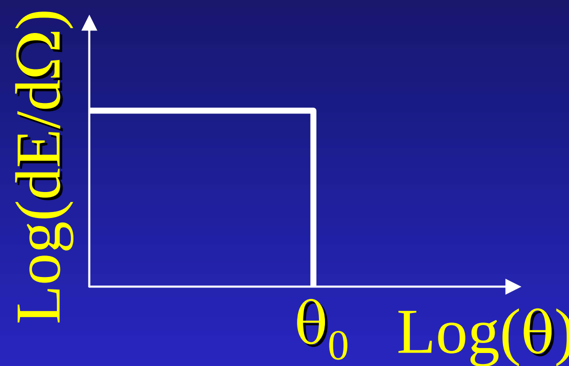
- $P(t \ll t_j) \sim P(t \sim t_j)$

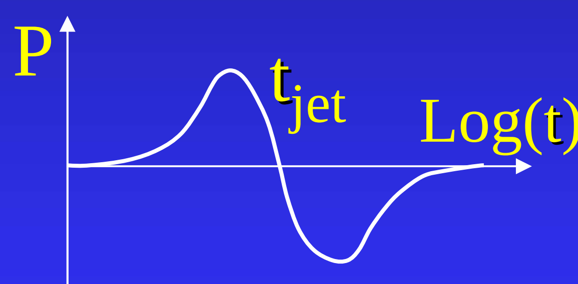
while for jet models

$P(t \ll t_j) \ll P(t \sim t_j)$

* Granot & Königl 03

## Uniform jet†:



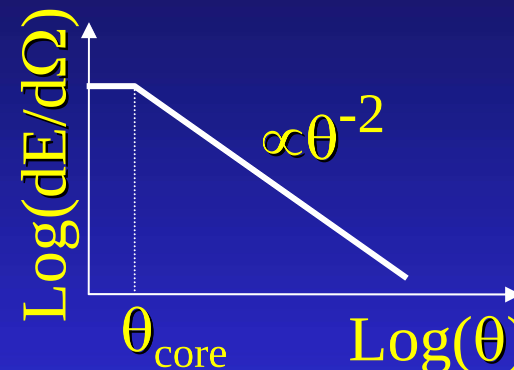



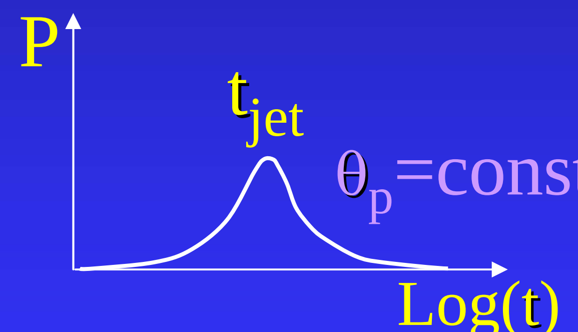

$\theta_p$ flips by $90^o$ at $t_{jet}$

(Ghisellini & Lazzati 99; Sari 99)

† Rhoads 97,99; Sari et al. 99, …

## Structured jet††:



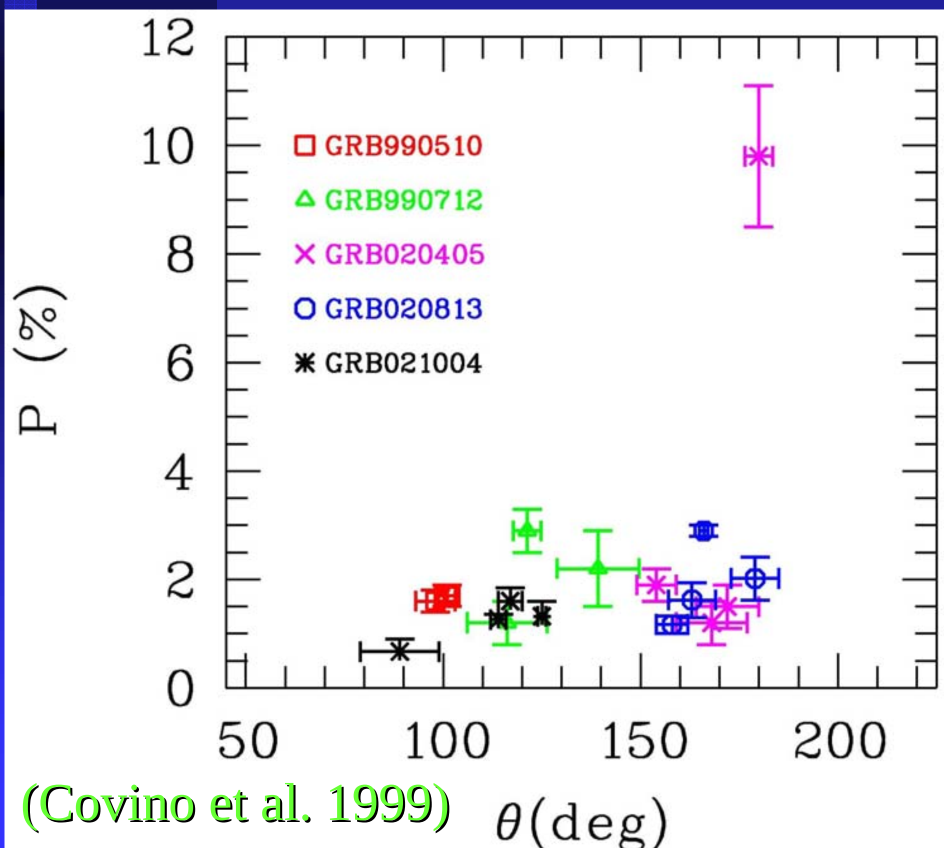




(Rossi et al. 2003)

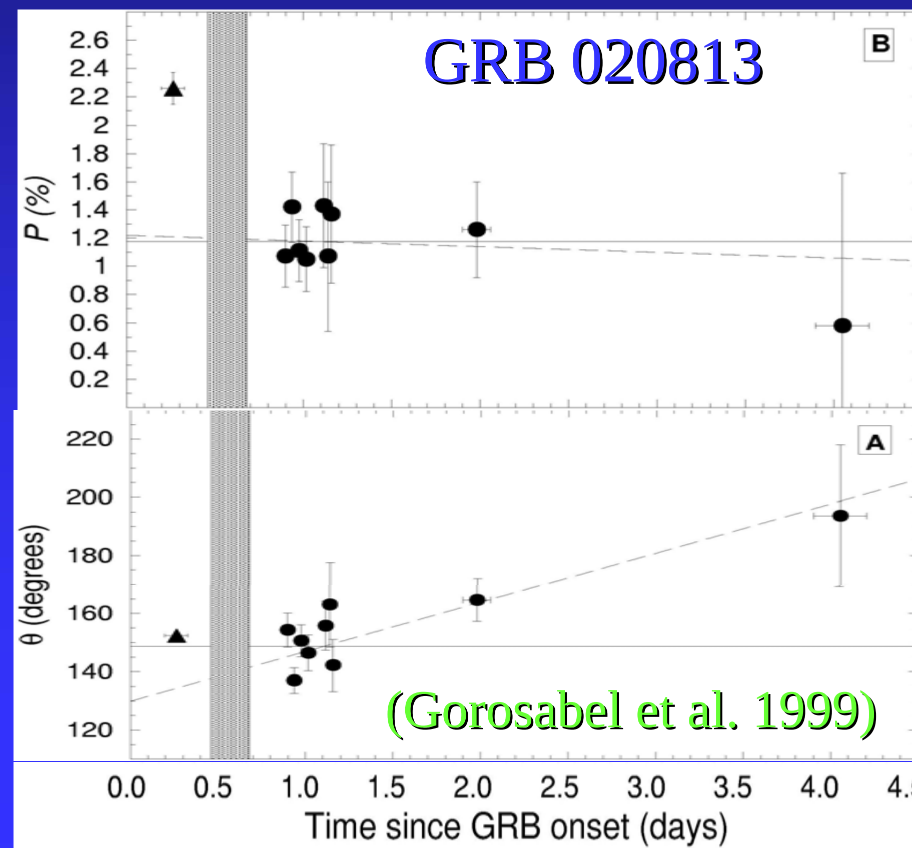
†† Postnov et al. 01; Rossi et al. 02; Zhang & Meszaros 02

# Afterglow Polarization: Observations

- 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)

# Polarization of prompt γ-ray emission:

- **GRB 021206** P = 80% ± 20% (Coburn & Boggs 2003)
- Controversial♣: measuring pol. in γ-rays is very difficult
- $P \sim P_{max}$ can be achieved in the following ways:

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

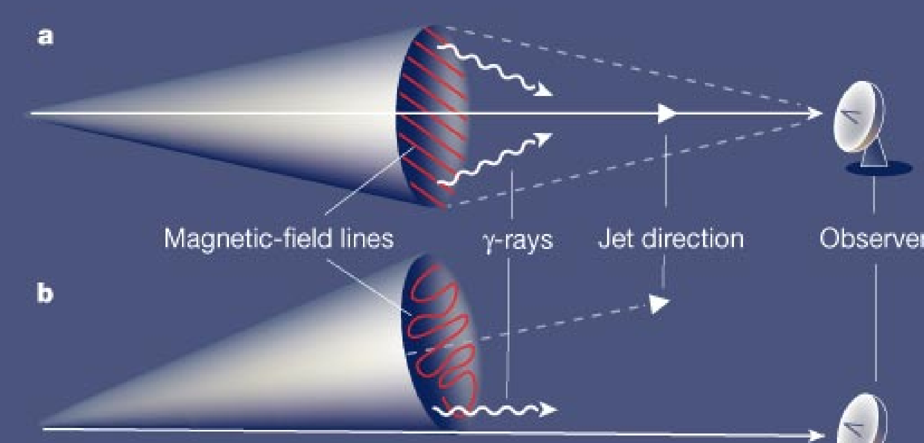
(2) **special geometry**: $\theta_j < \theta_{obs} \lesssim \theta_j + 1/\Gamma \Rightarrow$ narrow jet: $\theta_j \lesssim 1/\Gamma$ (works with **shock produced magnetic field**♠ or **inverse Co**

♣Rutledge & Fox 03

†JG & Königl 03,
Coburn & Boggs 03,
Lyutikov et al. 03, JG 03

♠Waxman 03,
Nakar et al. 03

♦♦Lazzati et al. 03,
Eichler & Levinson 03



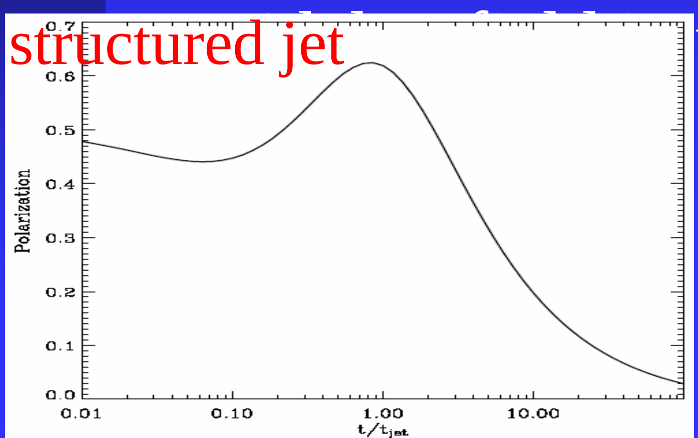

Waxman (2003)

# Reverse shock Pol.: B-field in ejecta

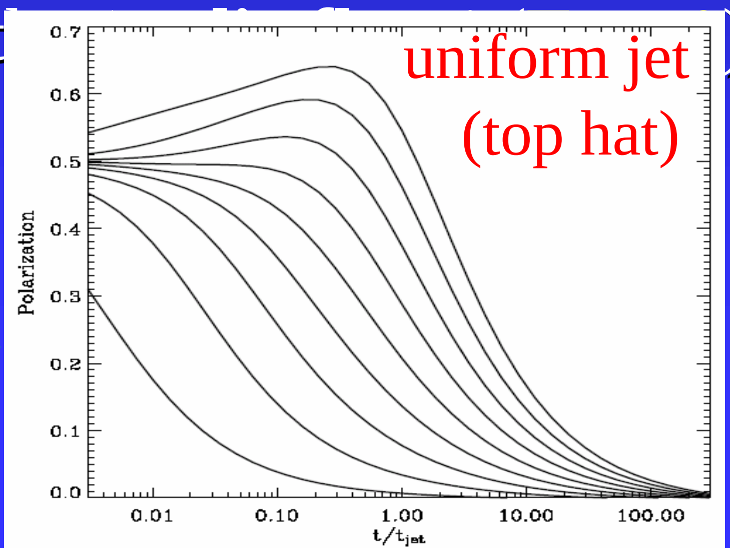
- The **existence** of a reverse shock $\Rightarrow$ $E_{EM} \lesssim E_{kin}$ (♦ $\lesssim$ 1)
- In the '**optical flash**' the **pol.** should be **similar** to that in $\gamma$**-rays**, but much **easier to measure** & more **reliable**
- If $B_{ord}$ in the ejecta is ordered on angles $1/\Gamma_0 \lesssim \theta_B < \theta_j$ 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 $\theta_p$ in t

  the ejecta:




(Lazzati et al. 2004)



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

# New: Upper Limits on Polarization of Radio Flare Emission (JG & Taylor 04)

| GRB | t (days) | $t_j$ (days) | $\Pi_L$ (3 $\sigma$) | $\Pi_C$ (3 $\sigma$) |
|---|---|---|---|---|
| 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

# 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 ($\theta_B$) | $P \sim P_{max} \times \min(1, \Gamma\theta_B)$ | $\theta_B \leq P_{lim}/\Gamma P_{max} \sim 10^{-2}$ |
| Toroidal | structured jet: $P \sim P_{max}$<br>top hat: $P \sim P_{max}(\theta_{obs}/\theta_j)^2$ | X<br>$\theta_{obs}/\theta_j \lesssim 0.4 - 0.55$ |

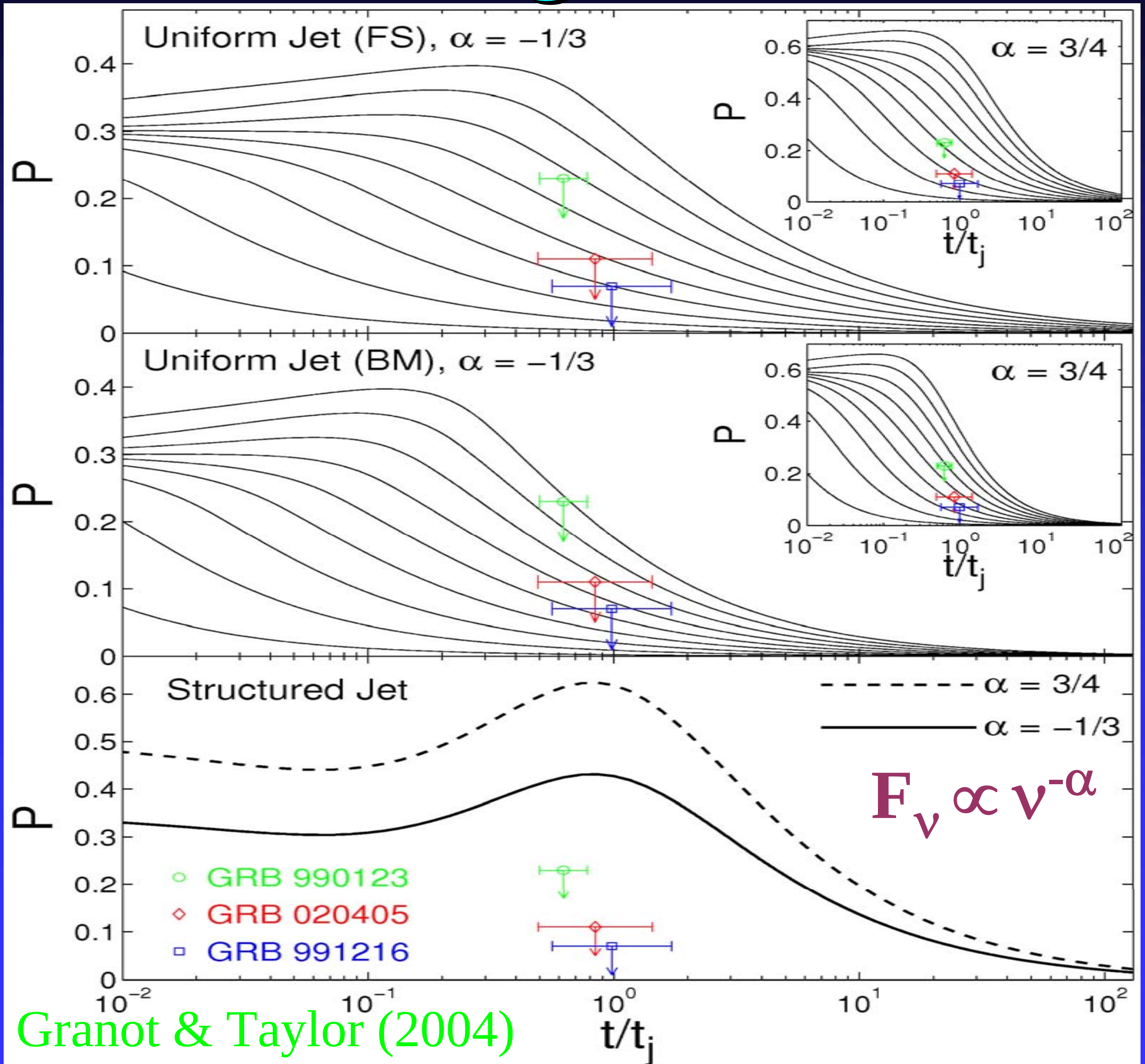
# Toroidal Magnetic Field:

**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 (2004)

# Magnetic field Structure in the Source

- **Poynting flux dominated** outflow (♦ **≫ 1**): naturally produces a **structured jet** + **toroidal magnetic field**
- **Reverse shock** ⇒ ♦ ≲ 1 ⇒ maybe due to **dissipation**
- **Dissipation** can also cause a **random field component**
- If Poynting flux is sub-dominant (♦ **≲ 1**):
  - Axial symmetry ⇒ toroidal magnetic field
  - B-field tangled on small scales ⇒ tangled in 2D
- Shock produced B-fied can give rise to a random field component $\mathbf{B}_{\mathbf{rnd}}$ on top of an initislly ordered one $\mathbf{B}_{\mathbf{ord}}$ ⇒ lowers pol. by a factor $\sim\eta/(1+\eta)$; $\eta \approx \langle B_{ord}^2\rangle/\langle B_{rnd}^2\rangle$
- For GRB 991216: $\eta/(1+\eta) \lesssim 1/6 \Rightarrow \eta \lesssim 0.2$
- For ♦ **≫ 1** one might naturally expect $\eta \gtrsim 0.5$

# Conclusions:

- The most promising way to probe the magnetic field structure in GRB outflows is by measuring the **optical flash** or **radio flare** polarization
- **New upper limits** on the radio flare polarization are **hard to reconcile** with a **structured jet + a predominantly toroidal magnetic field**
- $\Rightarrow$ for GRB 991216: $\langle B_{ord}{}^2\rangle/\langle B_{rnd}{}^2\rangle \lesssim 0.2$
- A **toroidal** magnetic field + a **uniform jet** is possible for viewing angles $\theta_{obs}/\theta_j \lesssim 0.4 - 0.55$
- If the magnetic field is ordered on patches of angular scale $\theta_B$ then: $\theta_B \lesssim P_{lim}/\Gamma P_{max} \sim \mathbf{10^{-2}}$