X-ray & γ-ray Polarization in Gamma-Ray Bursts

Jonathan Granot

Institute for Advanced Study, Princeton

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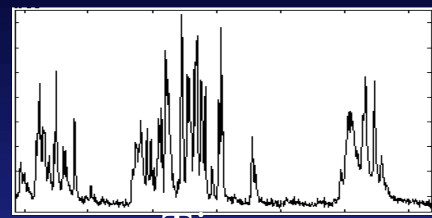
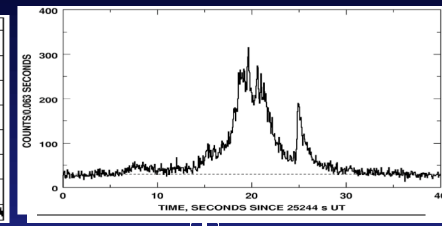
Outline of the Talk:

- Short Overview of GRBs
- Why is GRB polarization interesting
- GRB polarization: an unresolved relativistic jet
- Polarization of the prompt γ-ray emission: theoretical expectations (relatively in detail)
- Polarization of early X-ray afterglow (brief)
- Conclusions

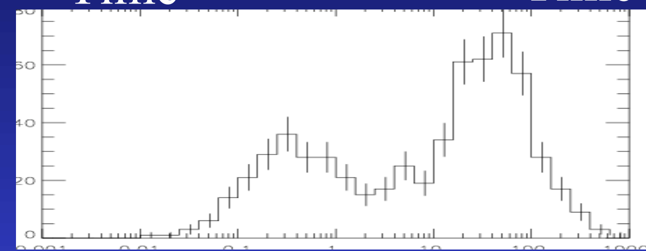
Observations: Prompt GRB

- Variable light curve

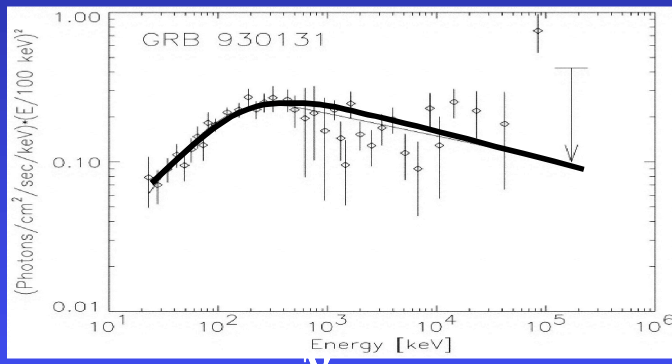




- Duration: ~$10^{-2} – 10^{3}$ sec



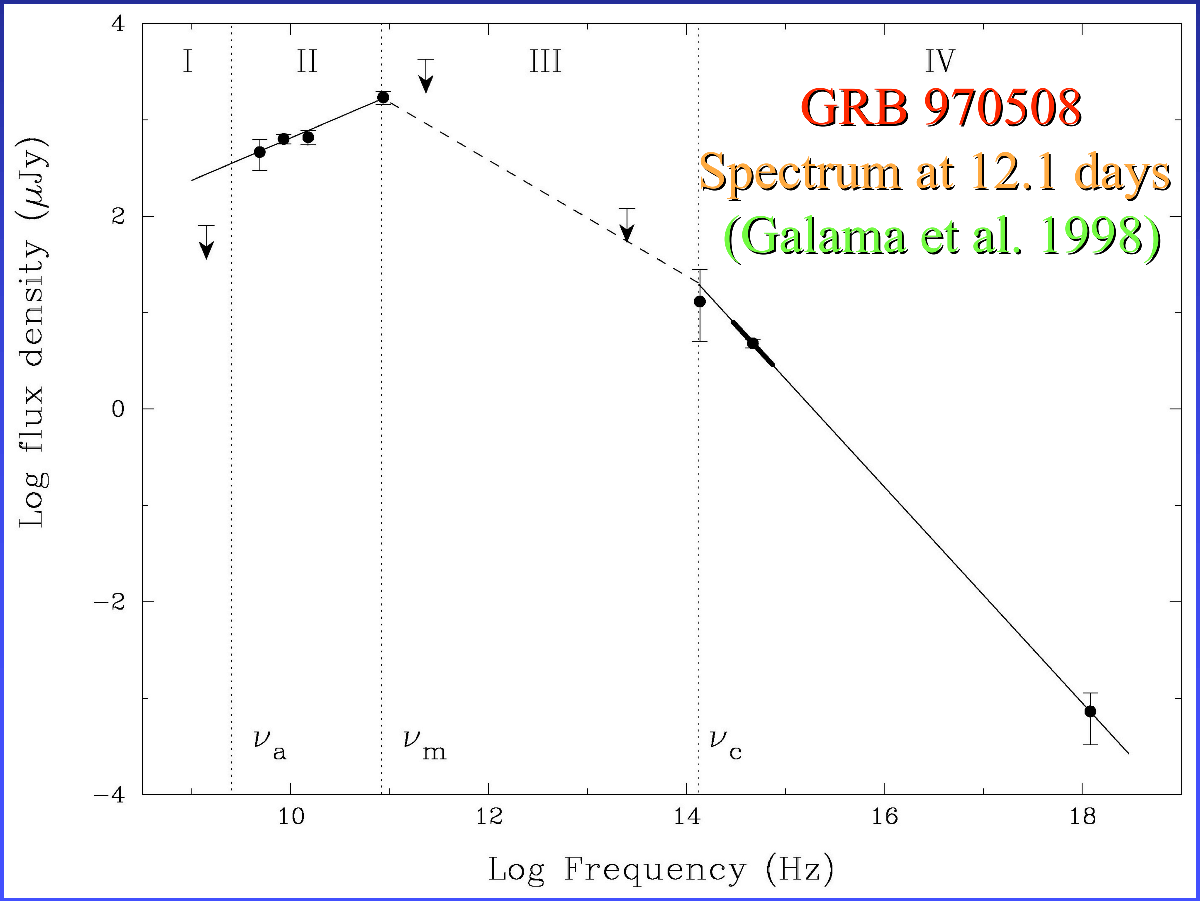
- Spectrum: non-thermal
  νF_ν peaks at E_p~0.1-1 MeV
  $E_p \propto (E_{\gamma,iso})^{1/2}$ (Amati et al. 03)



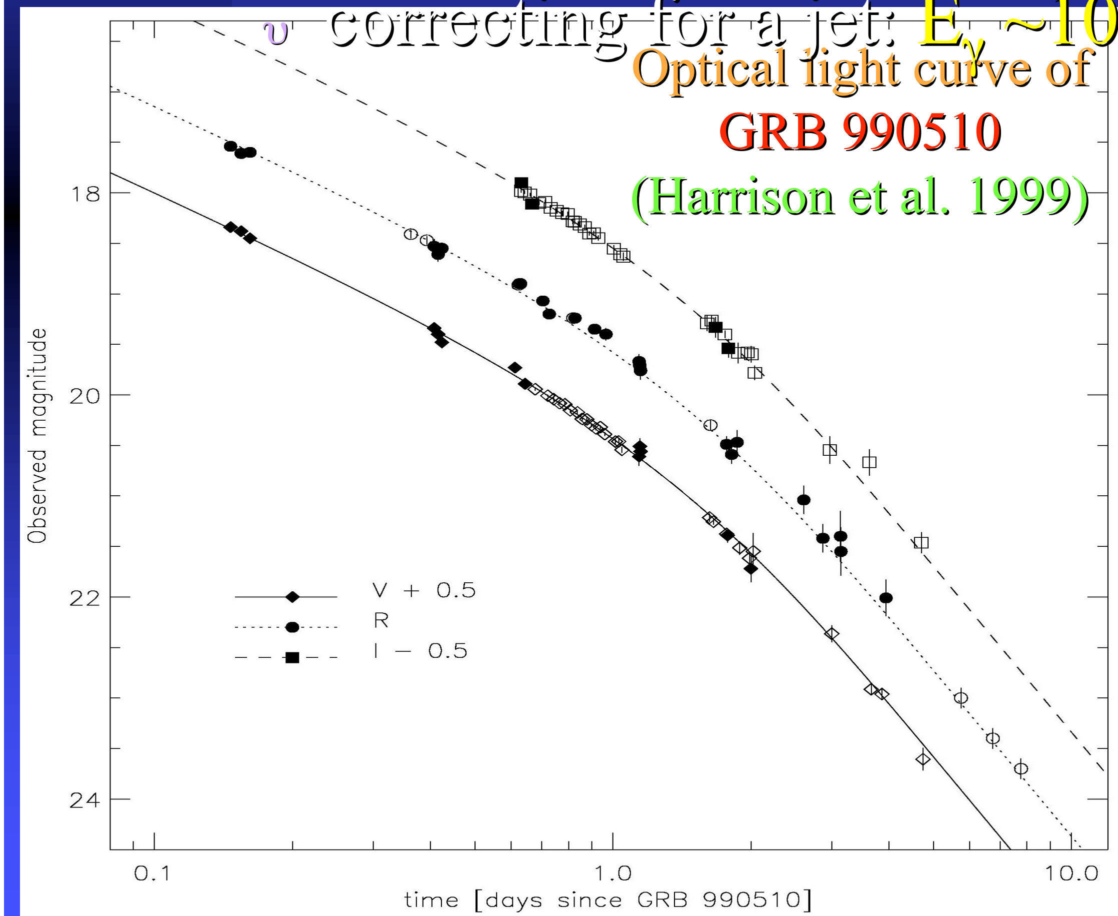
- Rapid variability, non thermal spectrum & z~1 ⇒ relativistic source (Γ _ 100) (compactness problem: Schmidt 1978; Fenimore et al. 1993; Woods & Loeb 1995;…)

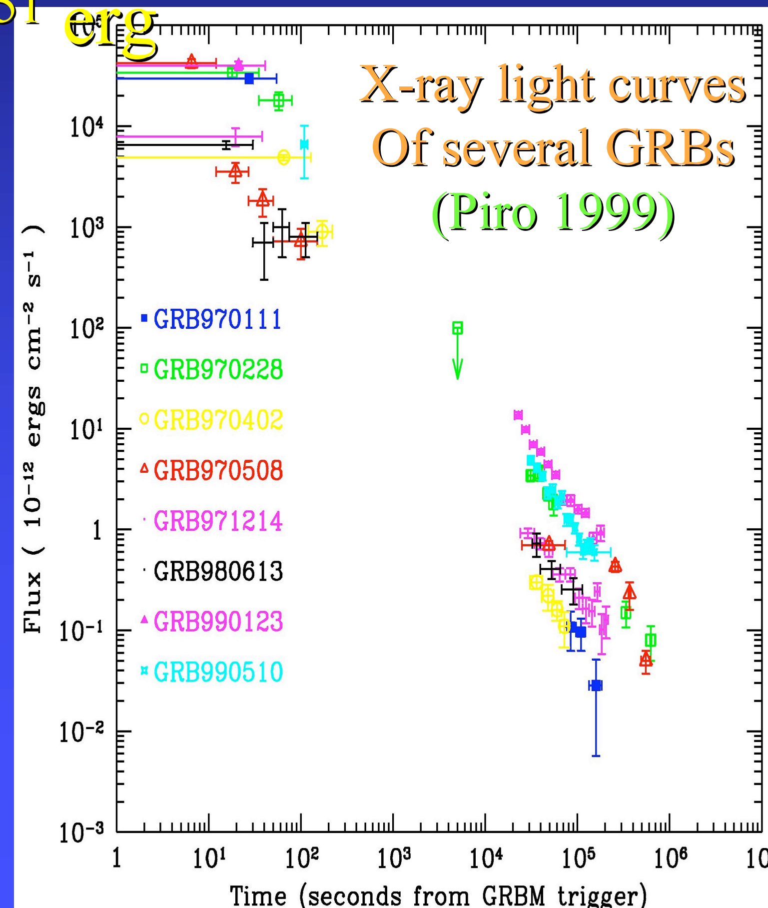
Observations: Afterglow

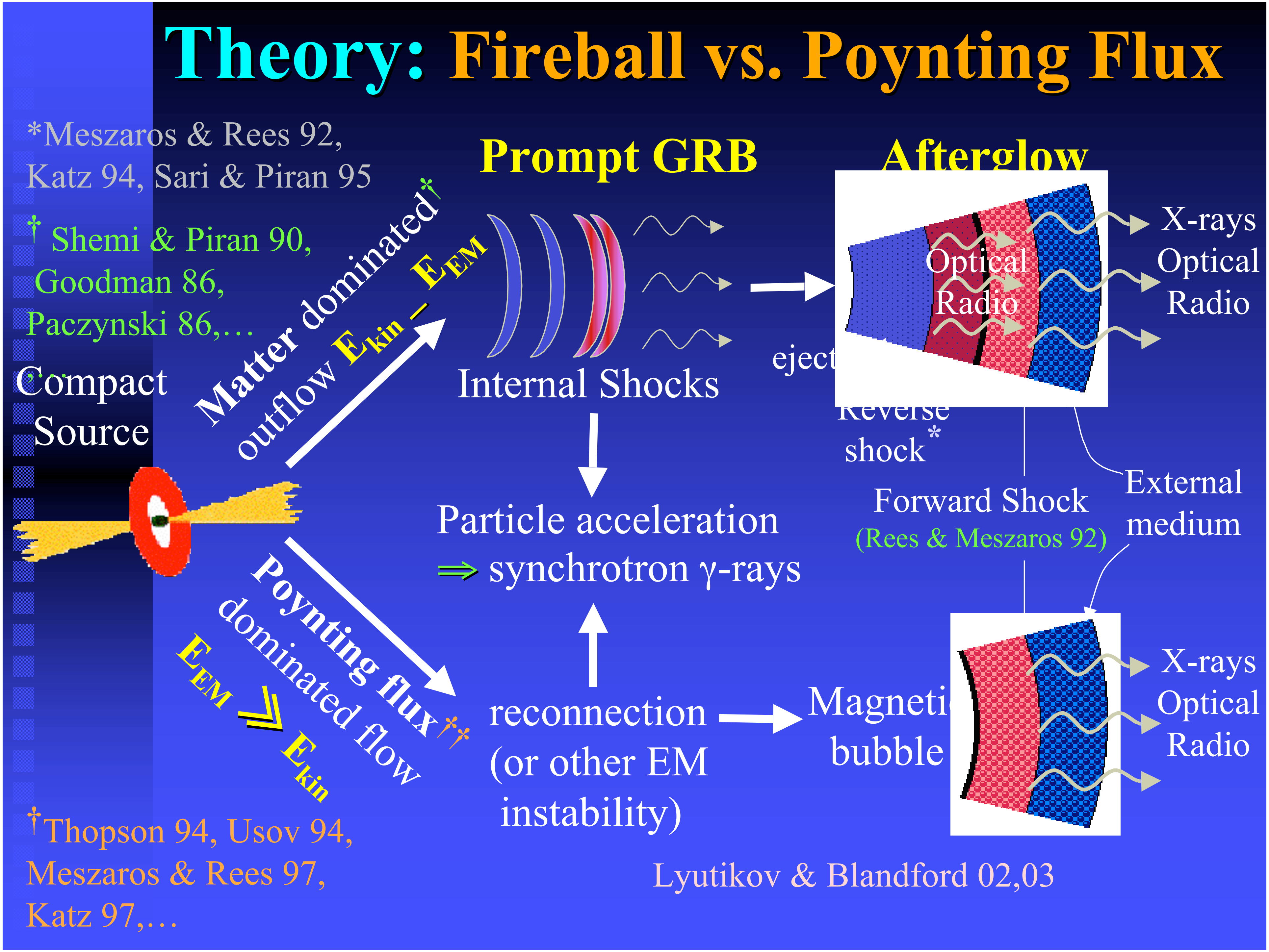
- X-ray, optical & radio emission over days , weeks & months, respectively, after a GRB
- **Spectrum:** consists of several power law segments & is well fit by synchrotron emission



- **Light curve:** power law decay; some afterglows show an achromatic steepening of the light curve ('jet break')
- $z \sim 1$ + fluence $\Rightarrow$ energy output in γ-rays:
  - assuming isotropic emission: $E_{\gamma,iso} \sim 10^{52}$-$10^{54}$ erg
  - correcting for a jet: $E_{\gamma} \sim 10^{51}$ erg



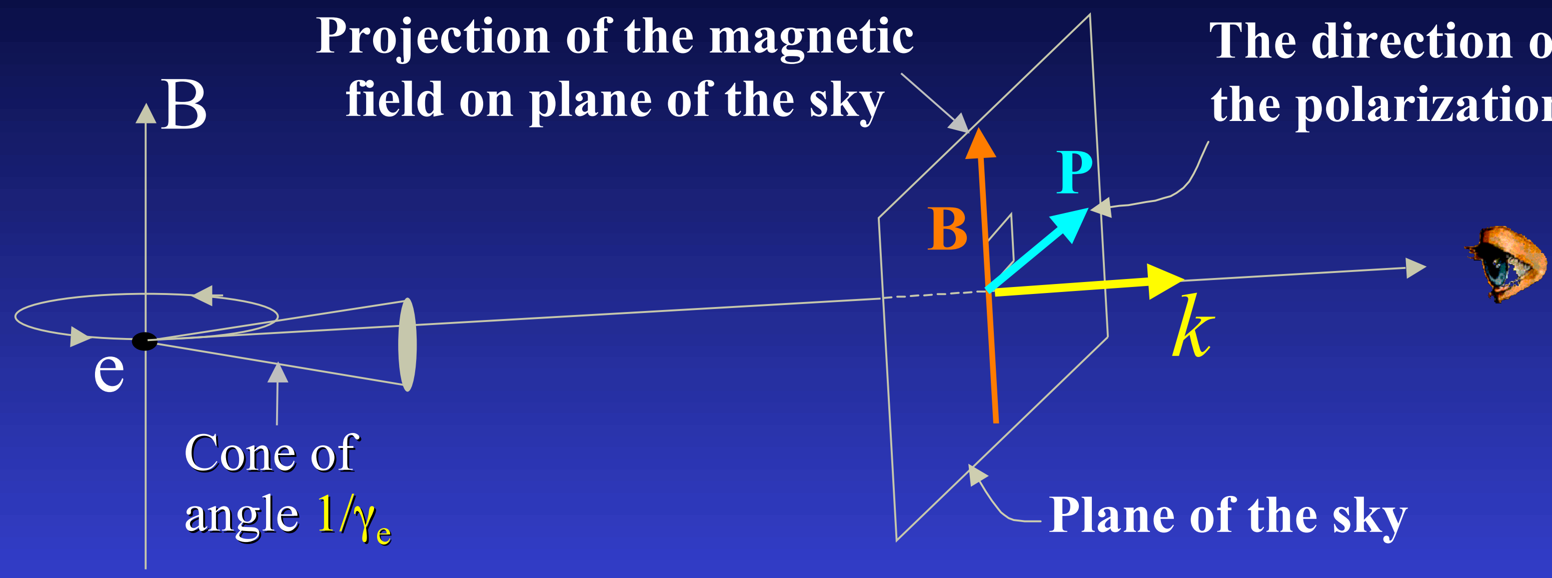



Theory: Fireball vs. Poynting Flux
*Meszaros & Rees 92,
Katz 94, Sari & Piran 95
† Shemi & Piran 90,
Goodman 86,
Paczynski 86,…
Compact
Source
Matter dominated*†
outflow $E_{kin} \sim E_{EM}$
Prompt GRB
Internal Shocks
Afterglow
Optical
Radio
X-rays
Optical
Radio
eject
Reverse
shock*
Forward Shock
(Rees & Meszaros 92)
External
medium
Particle acceleration
⇒ synchrotron γ-rays
Poynting flux*†
dominated flow
$E_{EM} \gg E_{kin}$
reconnection
(or other EM
instability)
Magnetic
bubble
X-rays
Optical
Radio
†Thopson 94, Usov 94,
Meszaros & Rees 97,
Katz 97,…
Lyutikov & Blandford 02,03

Why is GRB Polarization Interesting

- It teaches us about the magnetic field structure in the GRB ejecta & provides clues as to whether most of energy is in **Poynting flux** or **kinetic energy**:
  - $\mathbf{E_{EM} \gg E_{kin}} \Rightarrow$ ordered magnetic field is expected
  - $\mathbf{E_{kin}}$ _ $\mathbf{E_{EM}} \Rightarrow$ ordered & random fields are possible
- Provides a strong test for the structure of GRB jets, both in the prompt GRB & in the afterglow
- Probes magnetic field structure behind afterglow shock
- Helps pin down cause of time variability in afterglows

Polarization of Synchrotron Emission

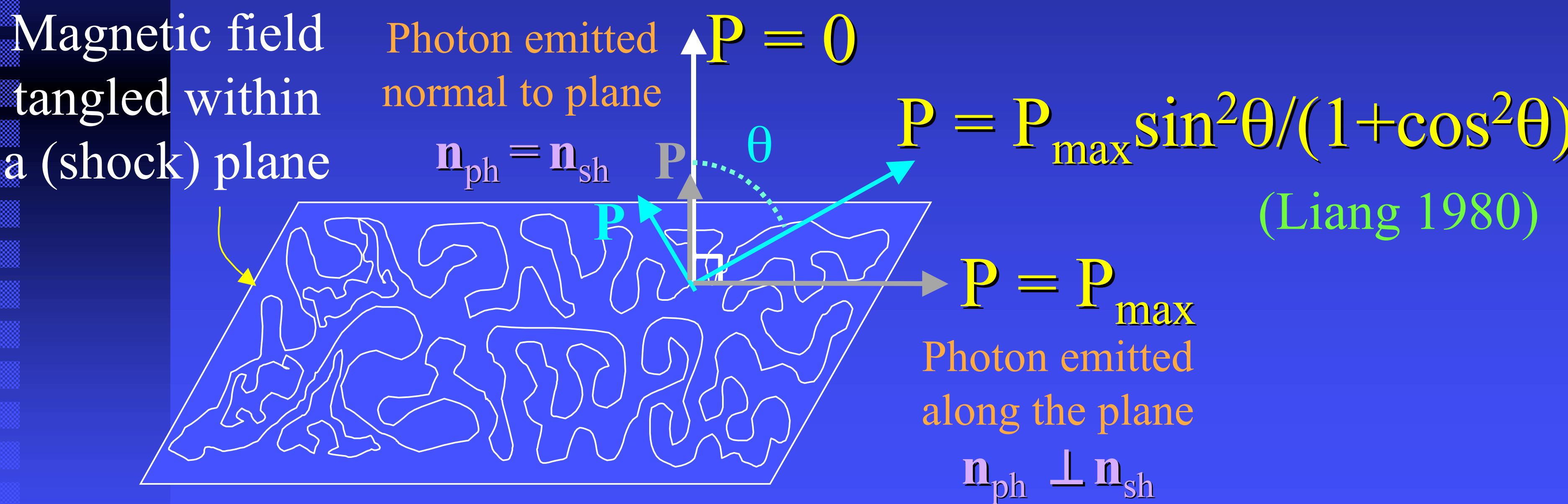


ν **linear polarization** perpendicular to the projection of **B** on the plane of the sky

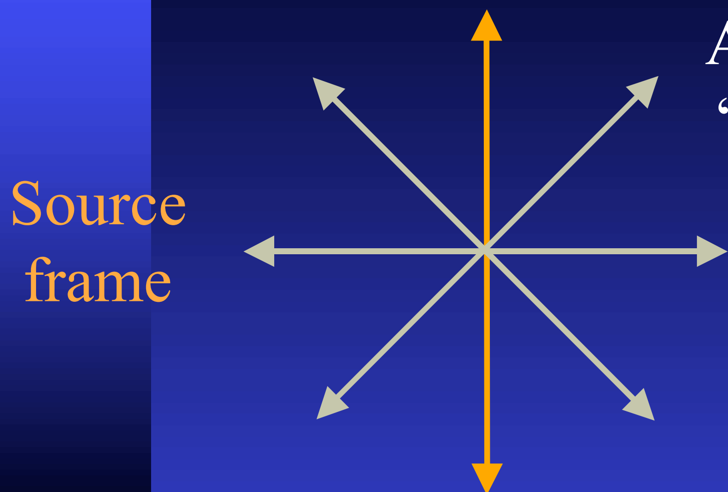
- The maximal polarization is for the local emission from an ordered **B**-field: $P_{max}=(\alpha+1)/(\alpha+5/3)$ where $F_\nu \propto \nu^{-\alpha}$, $-1/3 \leq \alpha$ _ $1.5 \Rightarrow 50\% \leq P_{max}$ _ 80%
(Rybicki & Lightman 1979; Granot 2003)

Shock Produced Magnetic Field:

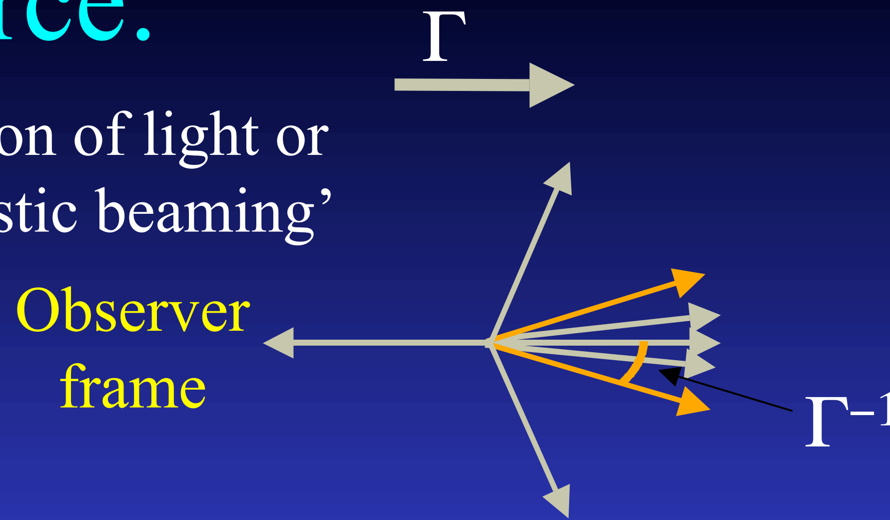
- A magnetic field that is produced at a relativistic collisionless shock, due to the two-stream instability, is expected to be **tangled within the plane of the shock** (Medvedev & Loeb 1999)



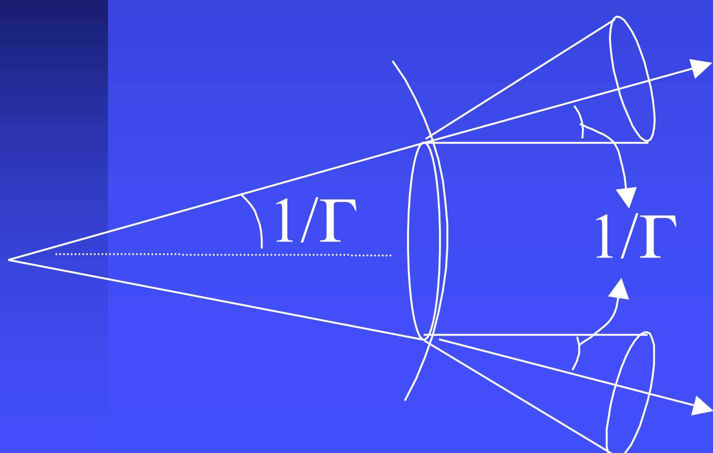
Relativistic source:

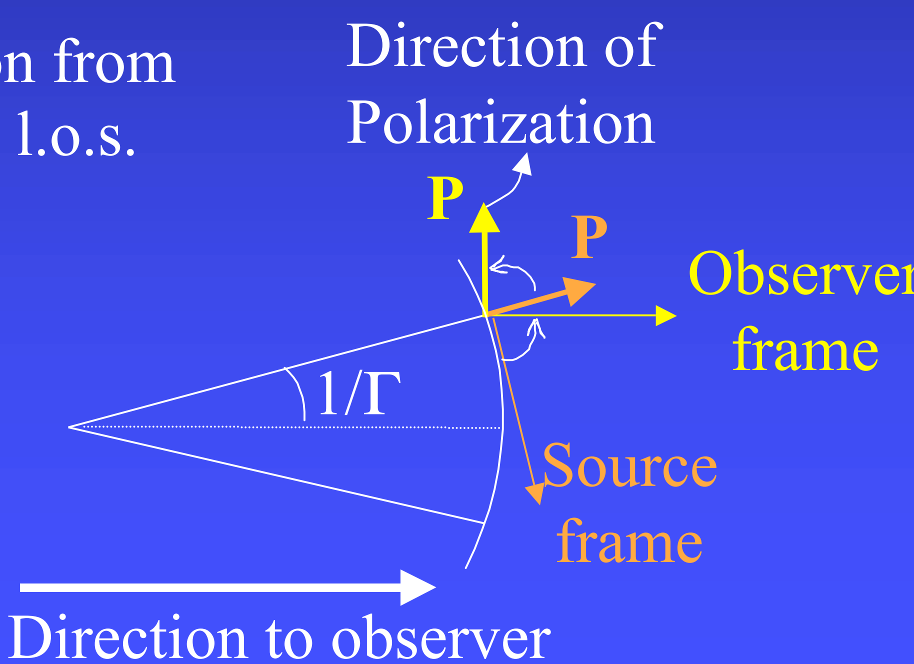


Aberration of light or
'relativistic beaming'



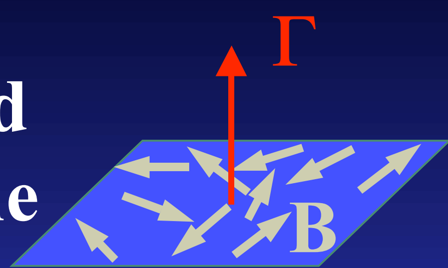
The observer sees mostly emission from within an angle of 1/Γ around the l.o.s.



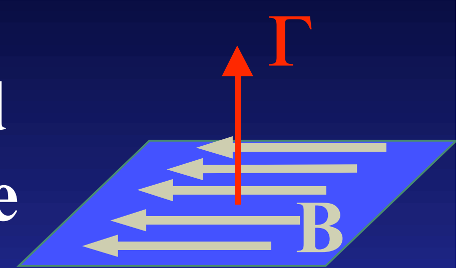


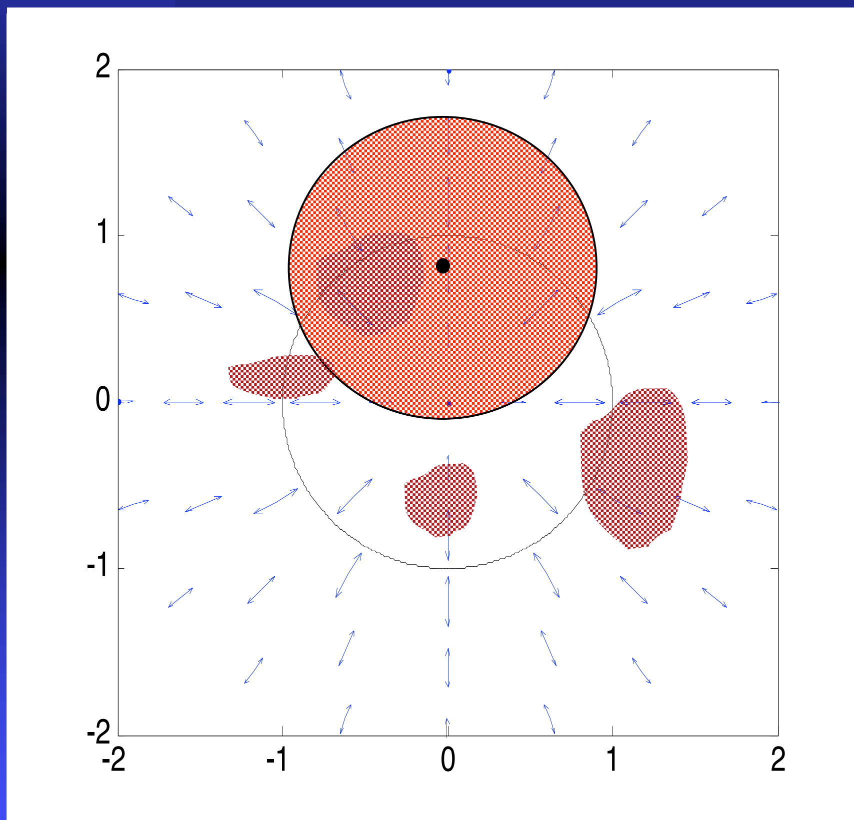
Polarization in the observer frame

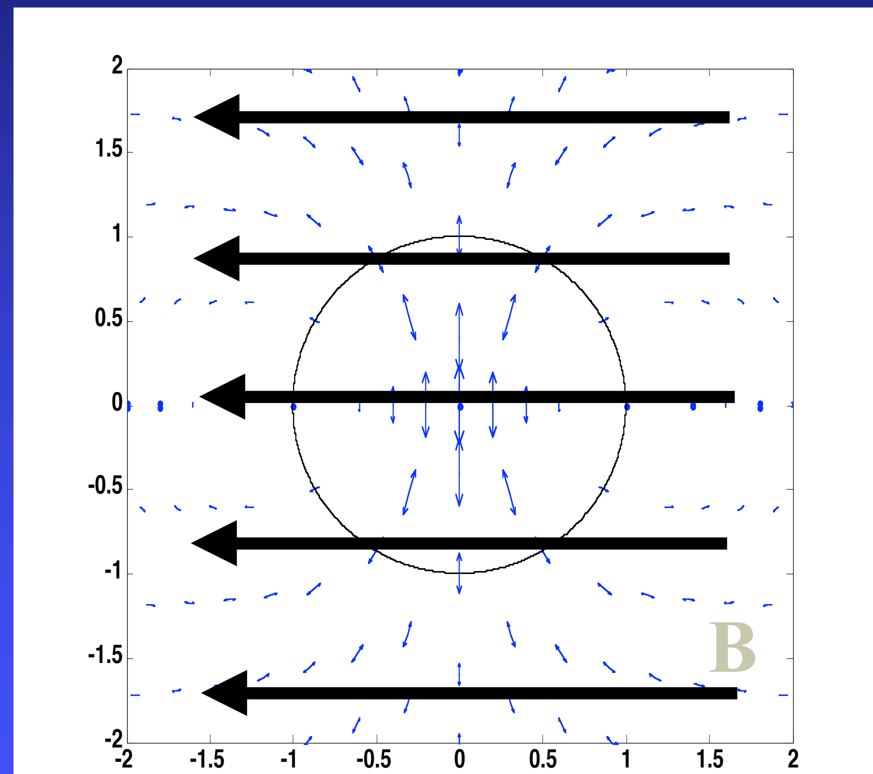
Random field in shock plane



Ordered field in shock plane







Sari 99; Ghisellni & Lazzati 99

Granot & Königl 03

$P \sim P_{max}$

Polarization of Prompt γ-ray emission:

GRB 021206 P = 80% ± 20% (Coburn & Boggs 2003)

Extremely bright GRB, 18° from the sun ⇒ favorable for measuring polarization with RHESSI

However: this result is **controvertial**

Rutledge & Fox (2003) claim:

A factor of ~10 less relevant photon scattering events in the detector ⇒ P cannot be constrained

There is an ongoing controversy

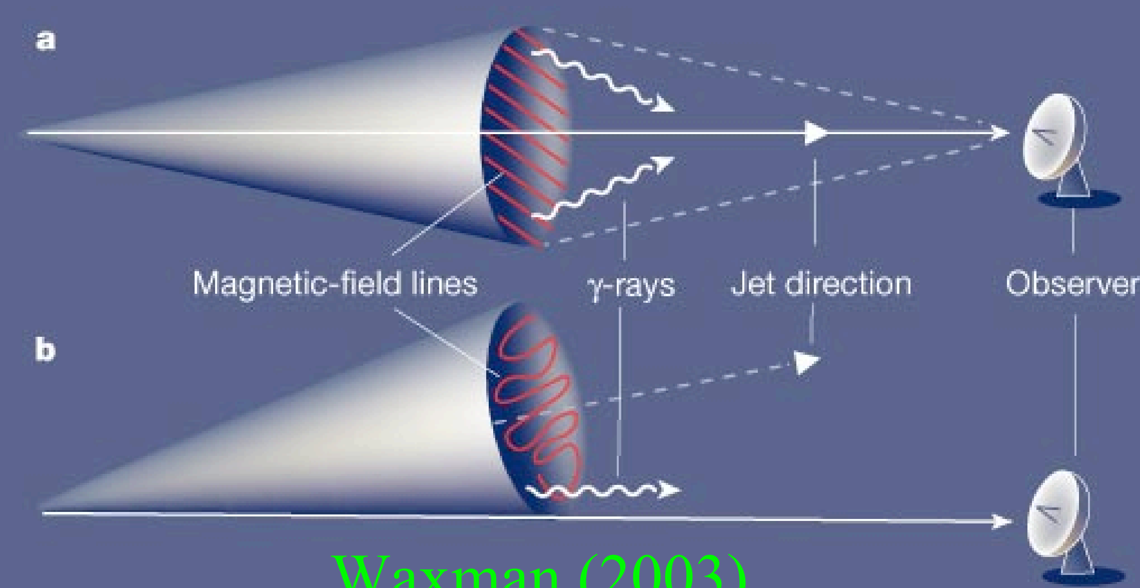
(stay tuned for the next two talks)

Polarization of prompt γ-ray emission: **Theoretical Expectations**

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

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

(2) **special geometry**: $\theta_j < \theta_{obs}$ _ $\theta_j + 1/\Gamma \Rightarrow$ narrow jet: θ_j _ $1/\Gamma$ (works with a shock produced magnetic field)



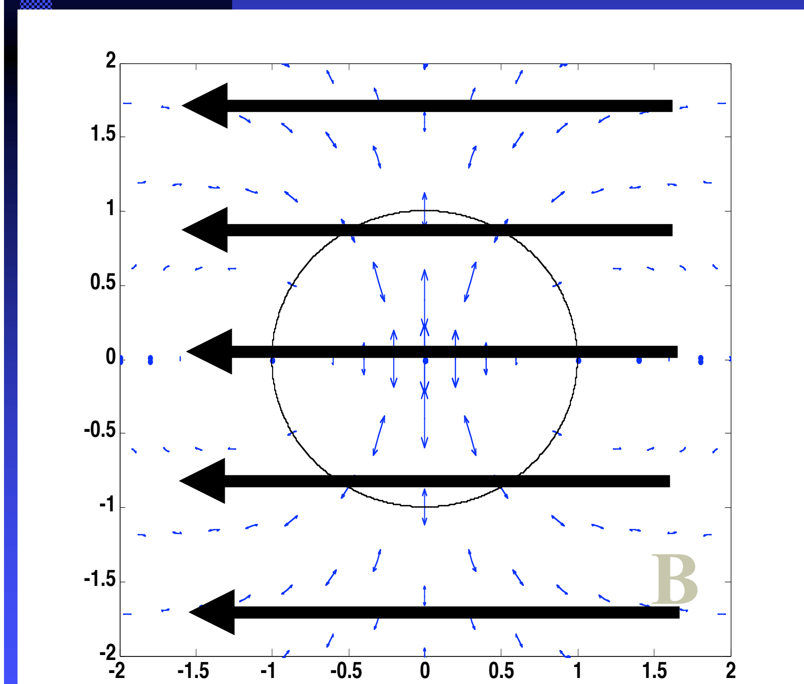
Waxman (2003)

Ordered Magnetic Field in the Ejecta:

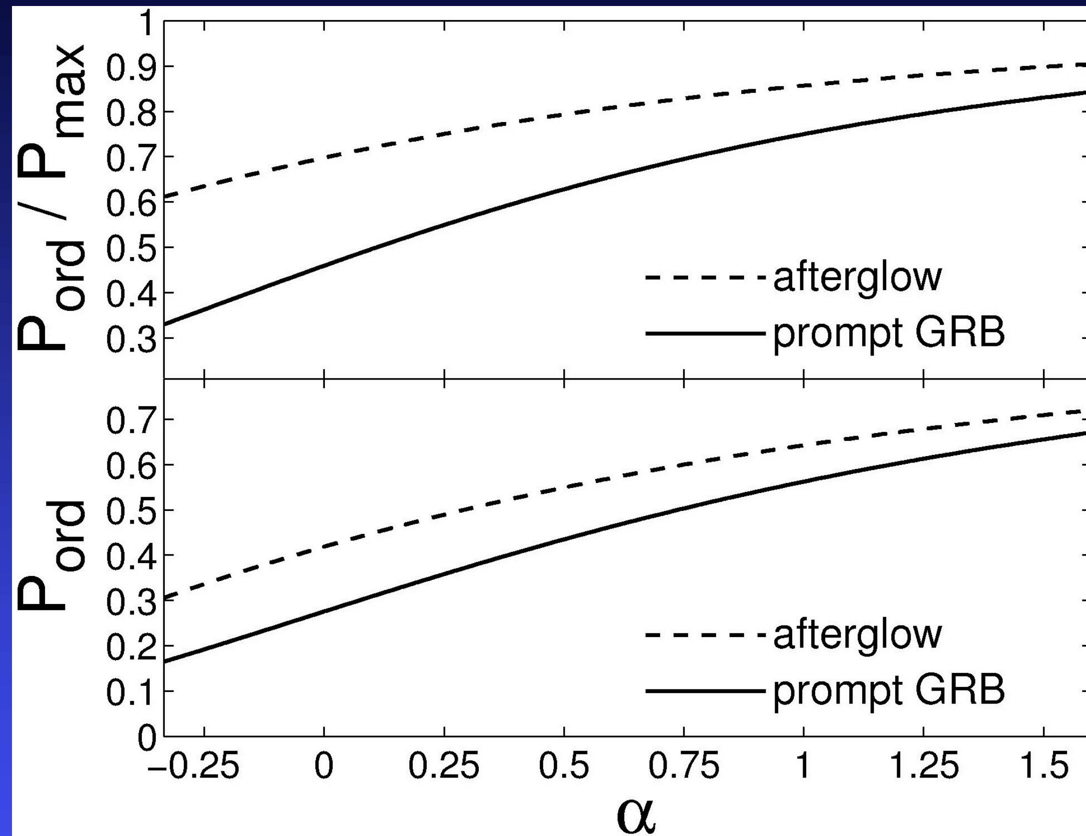
Total emission from jet

Afterglow:
instantaneous emission

Prompt GRB:
time integrated emission



Granot & Königl 03



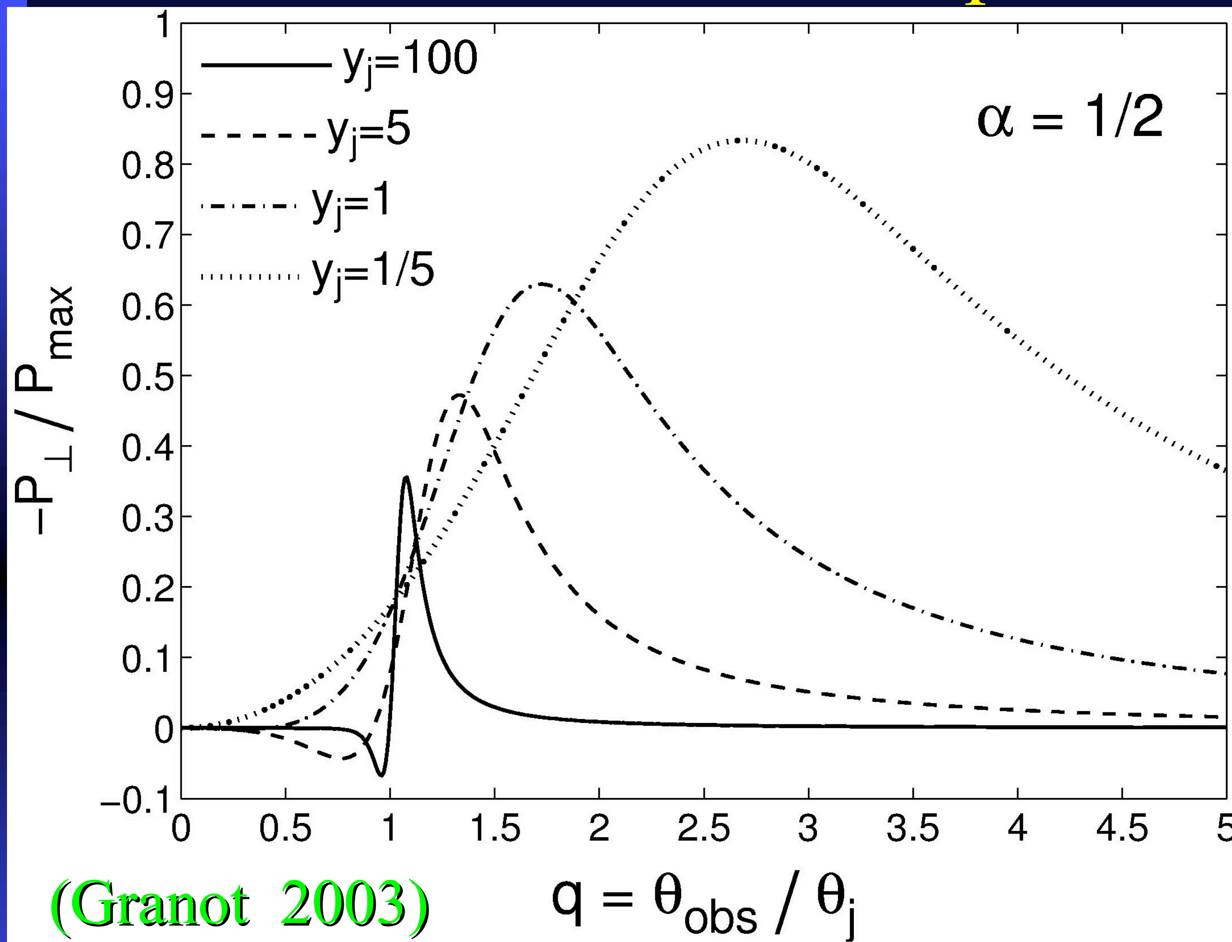
(Granot 2003)

- $F_\nu \propto \nu^{-\alpha}$, P increases with α
- P from an ordered B-field is slightly larger in afterglow

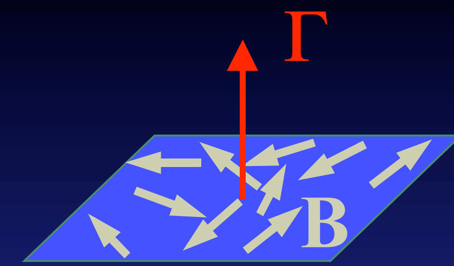
Narrow Jet + shock produced B-field

- High polarization + reasonable flux $\Rightarrow \theta_j < \theta_{obs} \_ \theta_j + 1/\Gamma$
  - ν A reasonable probability for such $\theta_{obs} \Rightarrow \Gamma\theta_j \_$ a few
  - ν Since $\Gamma \_ 100$ & $\theta_j \_ 0.05$, $\Gamma\theta_j \_ 5$ and is typically larger
- However GRB 021206 was very bright, suggesting a very narrow jet: $f = 1.6\times10^{-4}$ erg which for $z\sim1$ implies $E_{iso}\sim10^{54}$ erg & $\theta_j \sim (10^{51}\text{erg}/E_{iso})^{1/2} \sim 0.03$ (Frail et al. 01)
  - ν $\Rightarrow \Gamma\theta_j \sim 3(\Gamma/100) \Rightarrow \Gamma\theta_j \_$ a few is possible (Waxman 03)
- The jet must have sharp edges: $\Delta\theta_j \_ 1/4\Gamma$ (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

Random B-field in sock plane



(Granot 2003)



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

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

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

	Ordered Field	Narrow Jet
$P \sim 80\%$	X	X
$P \sim 50\%$	✓	X
$P \sim 25\%$	with B_{rnd} _ B_{ord}	✓
P _ 10%	with $B_{rnd} > B_{ord}$	with B_{rnd} _ $B_{\perp}$
statistics	High P in all GRBs	low P in most GRBs
Optical flash	High P - similar to the prompt GRB	Similar to prompt GRB (low P in most GRBs)
Potential problems	Some B_{rnd} required for Fermi acceleration	$\Gamma\theta_j$ _ a few, $\Delta\Gamma \sim \Gamma$, B_{rnd} (afterglow obs.)

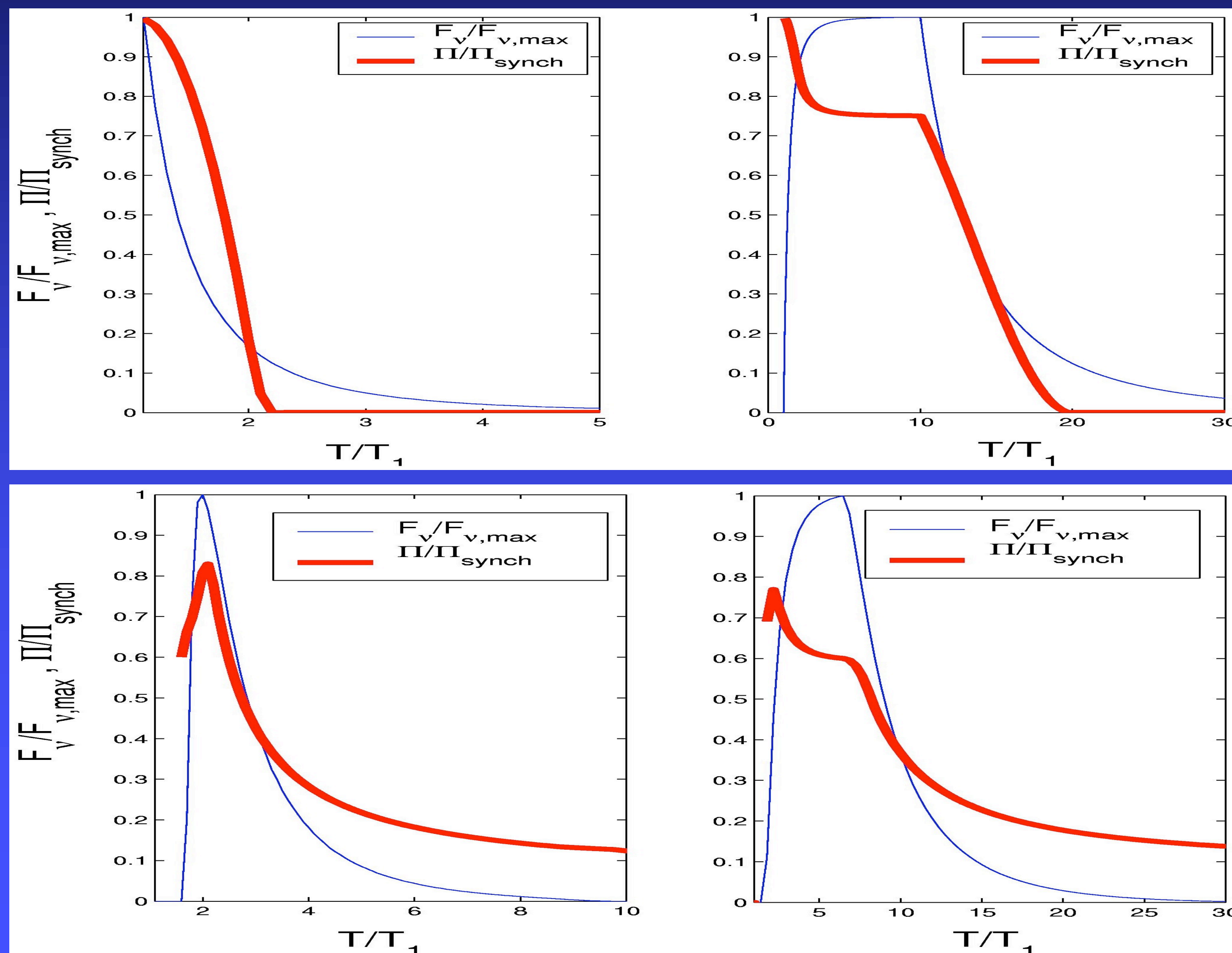
Temporal evolution of Polarization within a pulse in the GRB liht curve:

‘short pulse’ ($\Delta R<R$) ‘long pulse’ ($\Delta R>R$)

Ordered B-field:

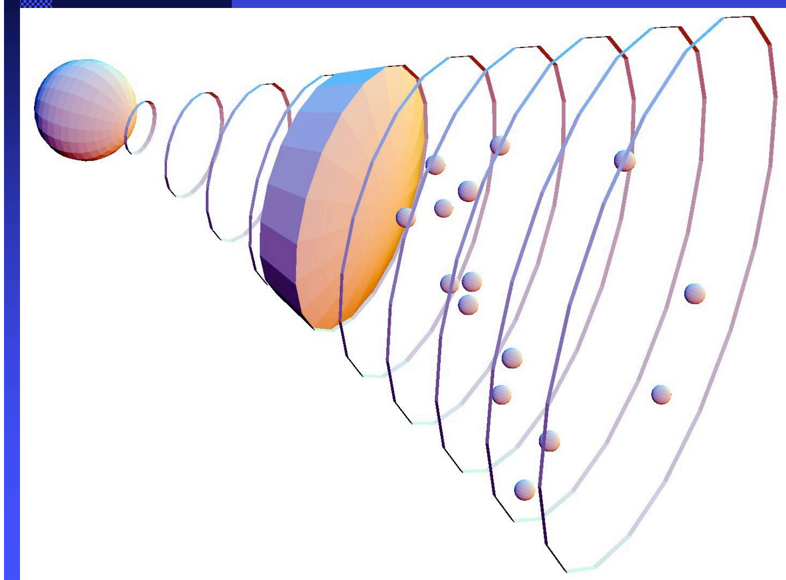
(Nakar, Piran & Waxman 2003)

Random field in shock plane:

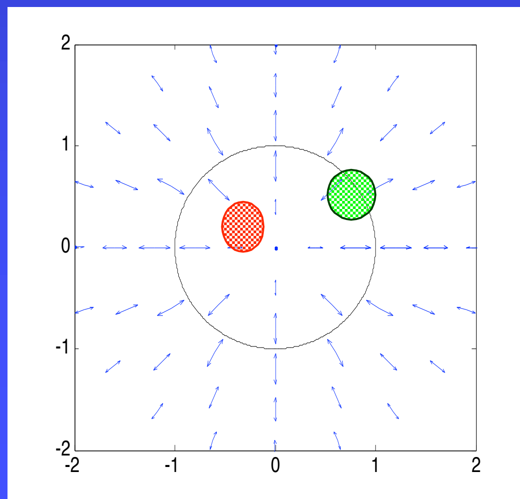


Position Angle in Different Pulses:

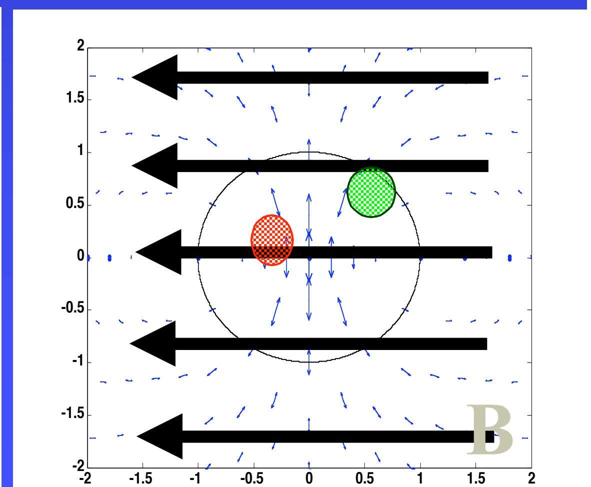
- In the **internal shocks** model, the polarization position angle θ_p is expected to remain constant between different pulses in the GRB light curve, both for B_{ord} or narrow jet+shock produced field
- For the **external shocks** model θ_p is expected to vary between different the pulses



B_{rnd} in shock plane



Ordered field B_{ord}



Alternative to Synchrotron: Compton Drag

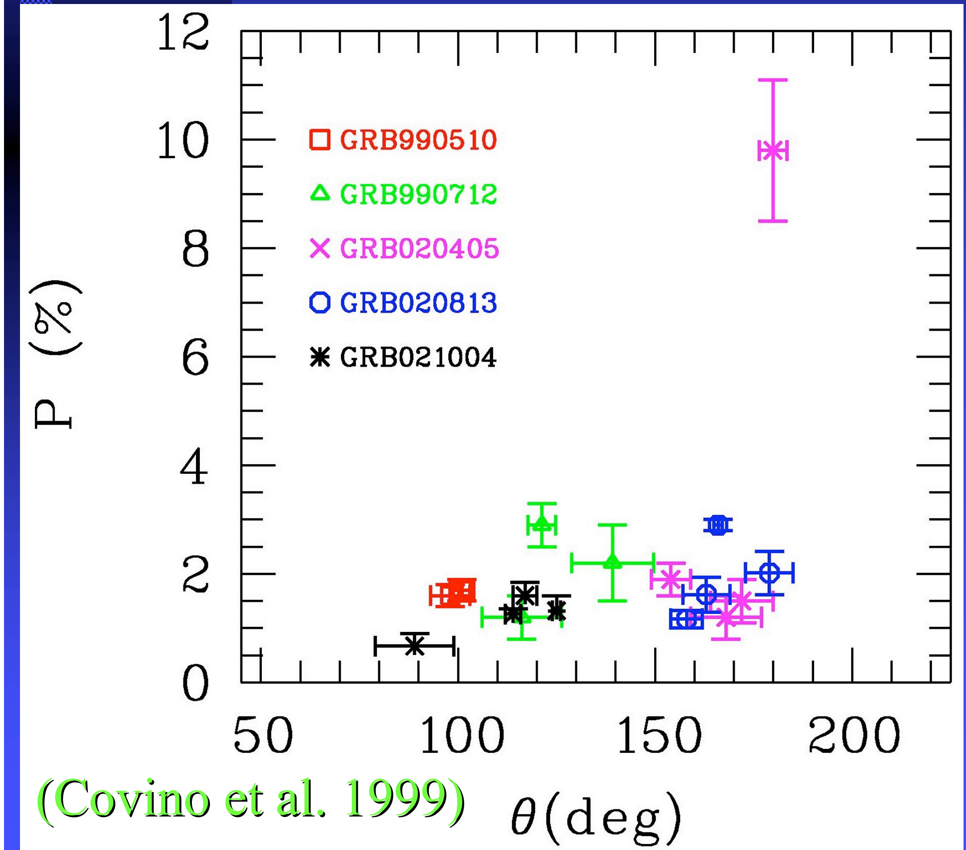
(Bulk Inverse Compton Scattering of External photons)

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

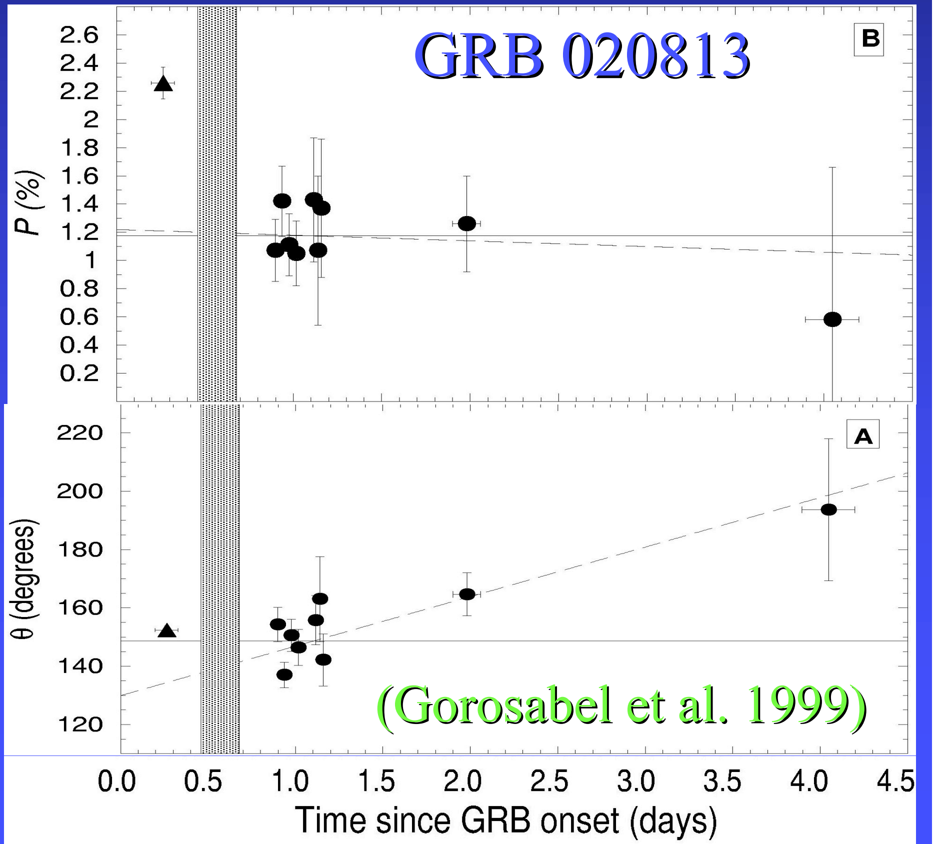
- Requires a special geometry and/or viewing angle, $\theta_j < \theta_{obs}$ _ θ_j+1/Γ
- Similar polarization properties as a shock produced B-field with one relative advantage: the local polarization $P=(1-\cos^2\theta)/(1+\cos^2\theta)$ can reach up to 100% while $P_{max} \sim 70\%$ for synchrotron
- Shares drawbacks of shock produced field + narrow jet
- It has additional problems, unrelated to polarization:
  - Explaining the prompt GRB spectrum
  - Supplying external photons for all the ejected shells
  - High photon density $\Rightarrow$ small radii $\Rightarrow$ high $\tau_{\gamma\gamma}$

Afterglow Polarization: Observations

- Linear polarization at the level of $P \sim 1\%$-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)

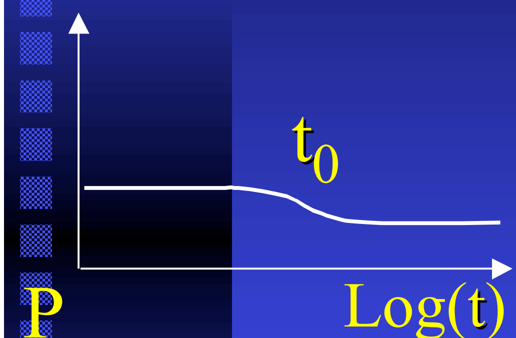


(Gorosabel et al. 1999)

Afterglow Polarization: Theory

the polarization is usually attributed to a jet geometry

Ordered B-field*:



$\theta_p = \text{const}$

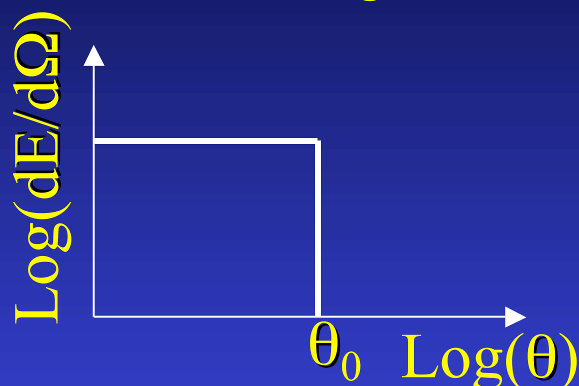
- $P(t \ll t_j) \sim P(t \sim t_j)$

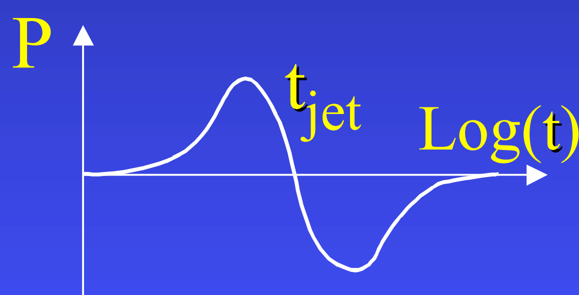
while for jet models

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

* Granot & Königl 03

Uniform jet†:



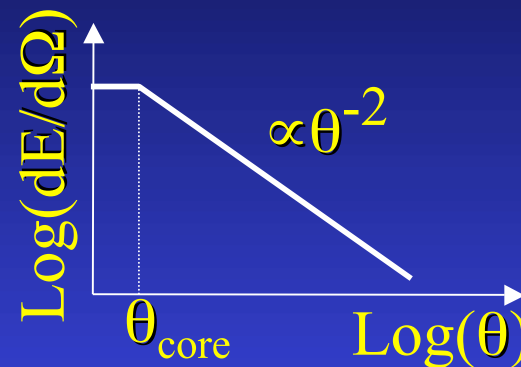


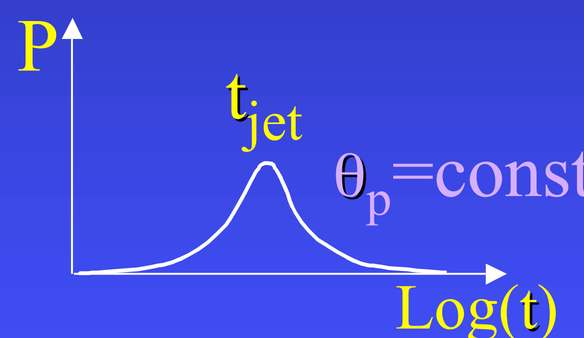
θ_p flips by 90° at t_{jet}

(Sari 99; Ghisellini & Lazzati 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

Conclusions:

- Ordered magnetic field in the ejecta naturally produces $P \sim 30\%-65\%$, for **all GRBs** (all θ_{obs}) & **reverse shock**
- P should increase with the spectral index α ($F_\nu \propto \nu^{-\alpha}$)
- Narrow jet + shock produced B-field or Compton drag naturally produce $P \sim 20\%-30\%$ for $\theta_j < \theta_{obs} \_ \theta_j + 1/\Gamma$

  but **for most GRBs** $\theta_{obs} \_ \theta_j$ and $\mathbf{P \approx 0}$
- ν The temporal evolution of P within a single pulse can help distinguish between ordered B-field & a shock produced B-field or Compton drag
- ν The pol. **position angle** θ_p in different pulses can help distinguish between **internal** & **external** shocks
- ν Polarization measurements in **early X-ray afterglow** can test the GRB **jet structure** & the possible role of **ordered magnetic field** component: $P(t \ll t_{jet}) \sim P(t \_ t_{jet})$