Polarization of GRB Prompt Emission

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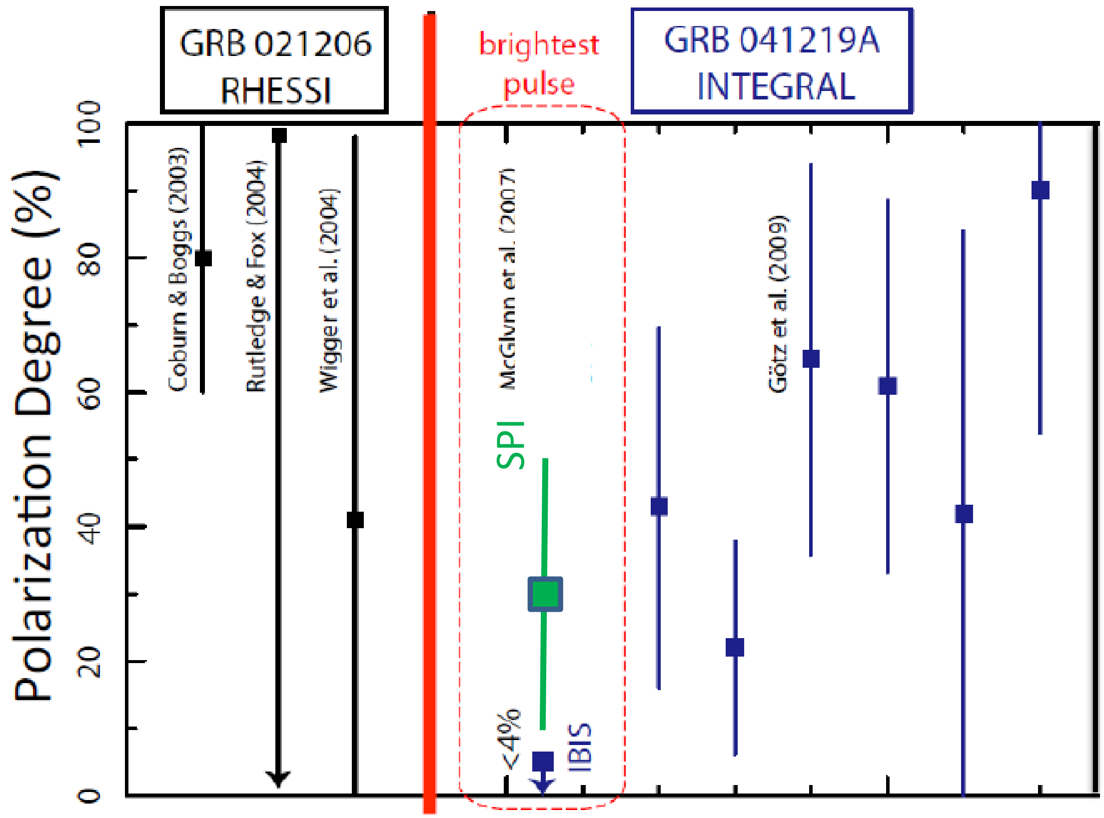
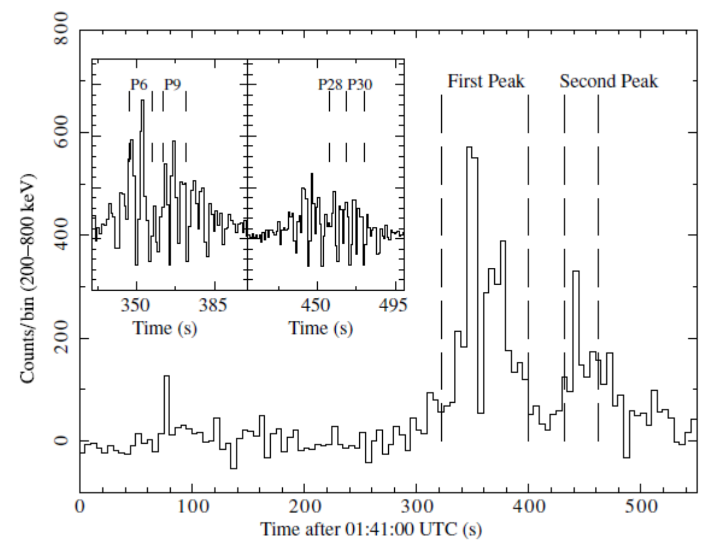
Outline

I. Brief history of prompt emission polarimetry
II. γ-ray polarimetry with GAP (and INTEGRAL)
III. Implications for emission mechanism
IV. Verification of Lorentz- and CPT-invariance
V. Summary

History of GRB Polarimetry



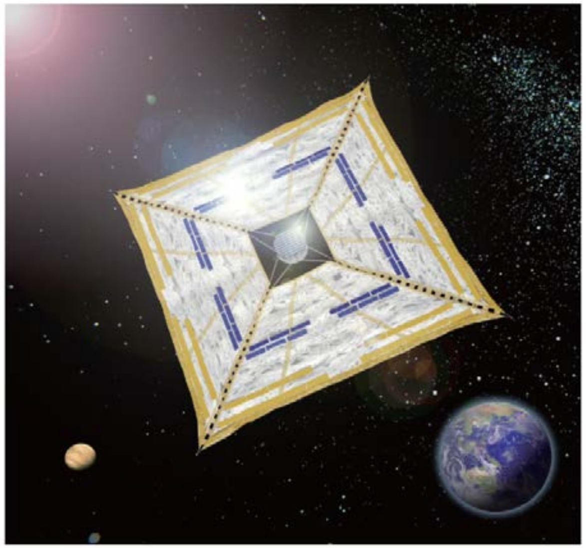


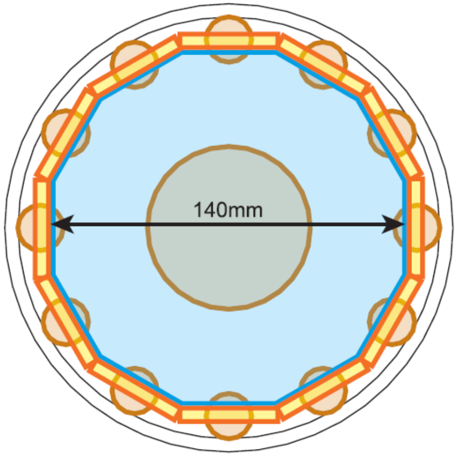
GRB 041219A analyzed by INTEGRAL (Gotz et al. 09)

RHESSI claim is controversial. INTEGRAL SPI and IBIS include results inconsistent with each other.

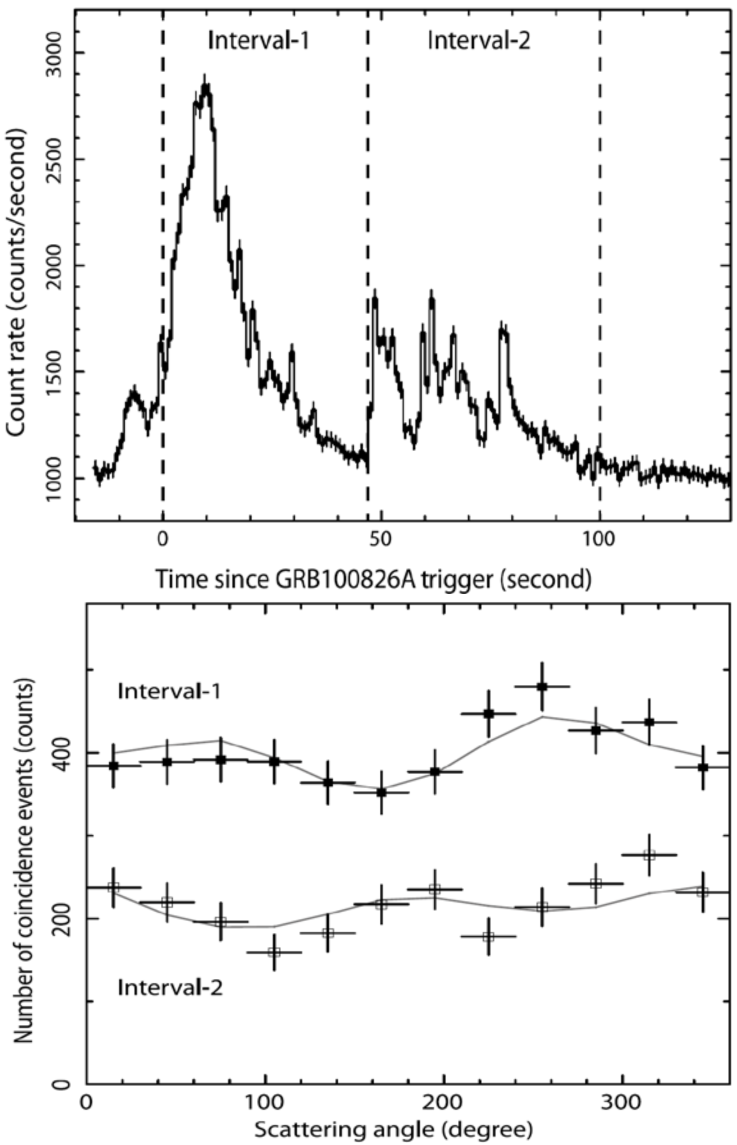
GAmma-ray burst Polarimeter (GAP)

- Gamma-ray burst polarimeter (GAP) aboard IKAROS launched in 2010
- Designed for prompt emission polarimetry, w/ small systematic uncertainty of 1.8% (Yonetoku et al. 2011)
- 70-300keV
- 3 GRB polarizations detected





GRB 100826A



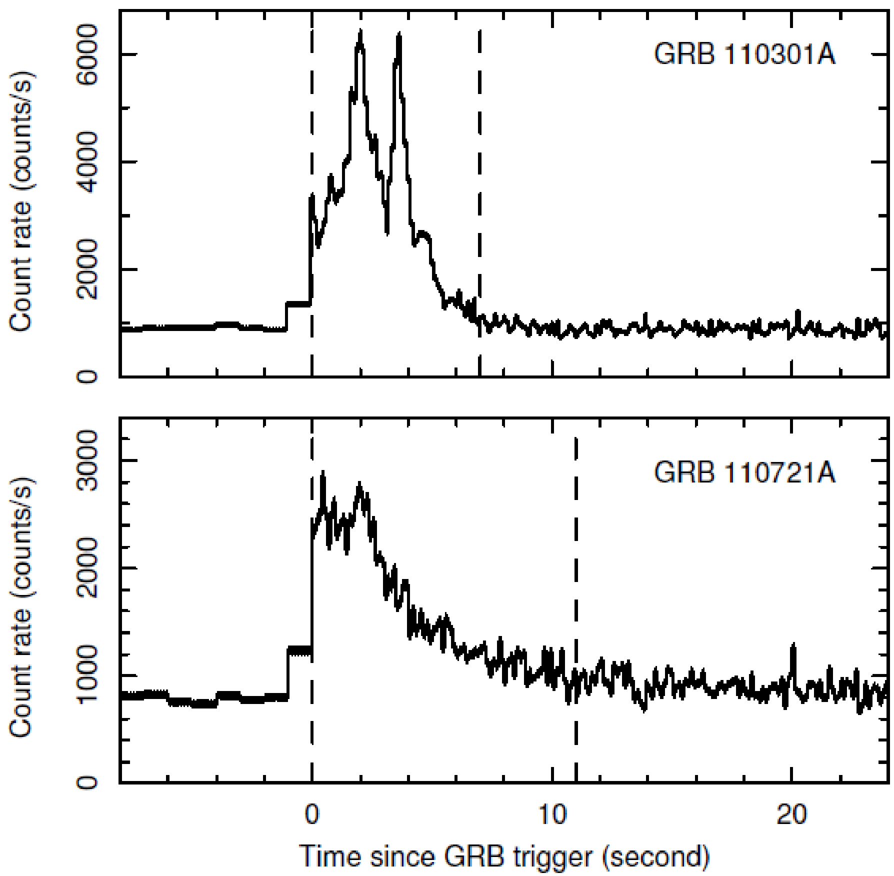
- $\Pi_L = 27 \pm 11\%$
- Non-zero at 2.9σ
- Polarization angle (PA) changed at 3.5σ

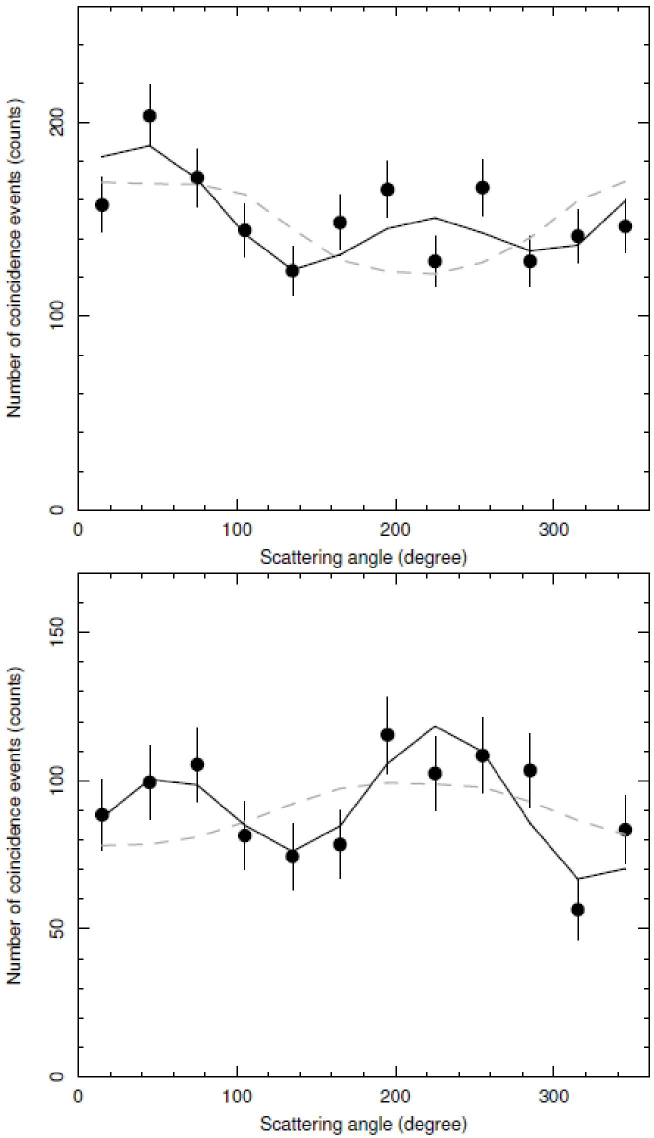
- Duration T ~ 100s

- $E_p = 606^{+134}_{-109}$ keV
- GAP energy range < E_p
- $\alpha = -1.31^{+0.06}_{-0.05}$

(Yonetoku, Murakami, Gunji, Mihara, KT+11)

GRB 110301A & GRB 110721A



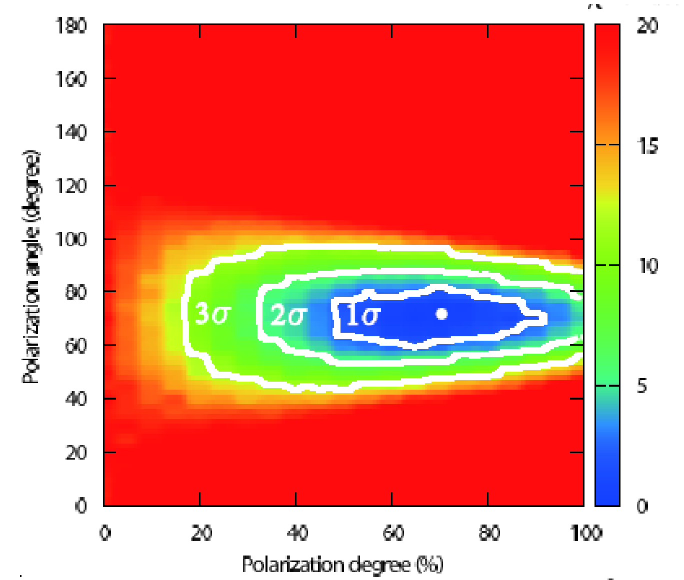


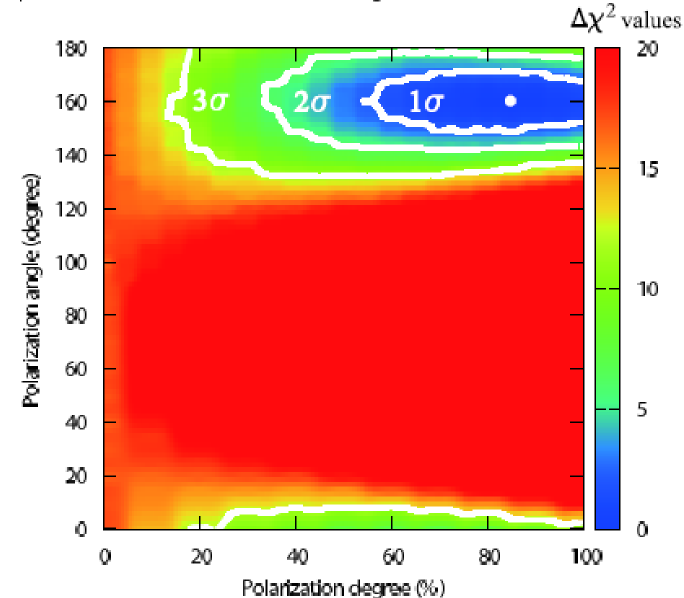
Duration: T ~ 10s

GRB 110301A & GRB 110721A

- 110301A
  - $\Pi_L = 70 \pm 22\%$
  - >~30% at 2σ, non-zero at 3.7σ
  - PA not changed
  - E_p = 107keV (GAP range > E_p)
- 110721A
  - $\Pi_L = 84^{+16}{}_{-28}\%$
  - >~30% at 2σ, non-zero at 3.3σ
  - PA not changed
  - E_p = 390keV (GAP range < E_p)

(Yonetoku, Murakami, Gunji, Mihara, KT+12)





Observations Summary

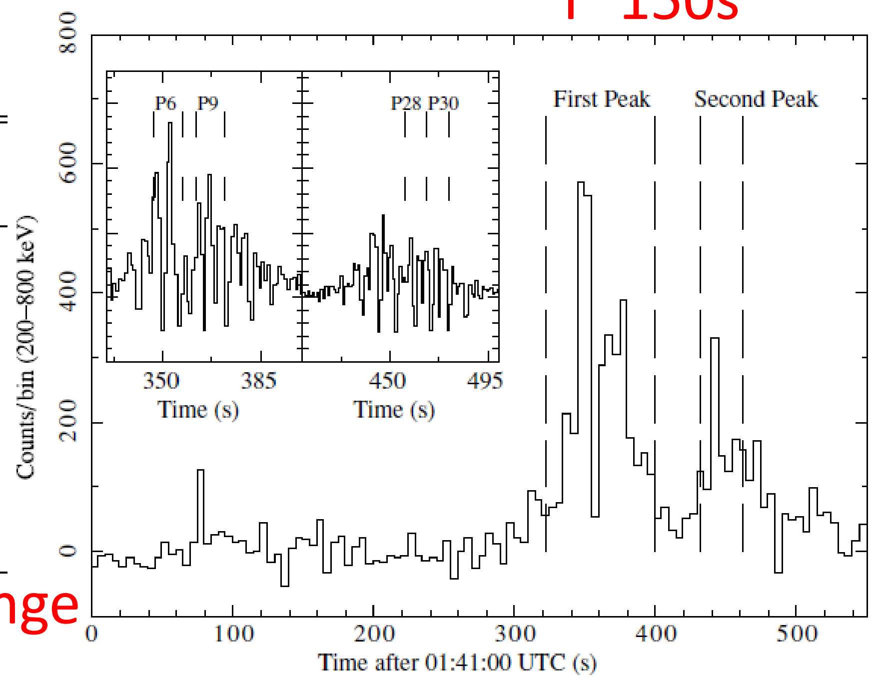
- There are cases with and without a significant PA change
- GRB 100826A, with long duration T ~ 100s, has a PA change, and $\Pi_L = 27 \pm 11\%$
- GRBs 110301A & 110721A, with short durations T ~ 10s, has no significant PA change, and $\Pi_L \gtrsim 30\%$ (2σ)
- INTEGRAL-IBIS results for GRB 041219A & 061122 appear consistent

IBIS on INTEGRAL

GRB 041219A (Gotz+09)

Name	T_{start} (UT)	T_{stop} (UT)	Π %	P.A. (deg)
First peak	01:46:22	01:47:40	<4	...
Second peak	01:48:12	01:48:52	43 ± 25	38 ± 16
P6	01:46:47	01:46:57	22 ± 13	121 ± 17
P8	01:46:57	01:27:07	65 ± 26	88 ± 12
P9	01:47:02	01:47:12	61 ± 25	105 ± 18
P28	01:48:37	01:48:47	42 ± 42	106 ± 37
P30	01:48:47	01:48:57	90 ± 36	54 ± 11

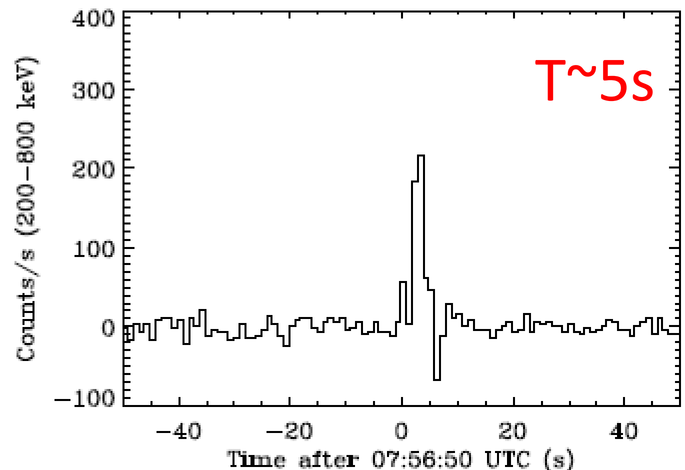
T~150s



PA change

GRB 061122 (Gotz+13)

Energy band (keV)	Π (%) (68% c.l.)	P.A. (°) (68% c.l.)	Π (%) (90% c.l.)	P.A. (°) (90% c.l.)
250–800	>60	150±15	>33	150±20
250–350	>65	145±15	>35	145±27
350–800	>52	160±20	>20	160±38



- P>~30% at 2σ, non-zero at ~3σ, consistent with GAP results

Emission Models

Polarimetric information would distinguish the emission models that have been debated

- Synchrotron

  ✓ Globally-ordered B field (SO model): advected from central engine through the jet

  ✓ Random B field on plasma scales (SR model): produced by some plasma instabilities at internal shocks

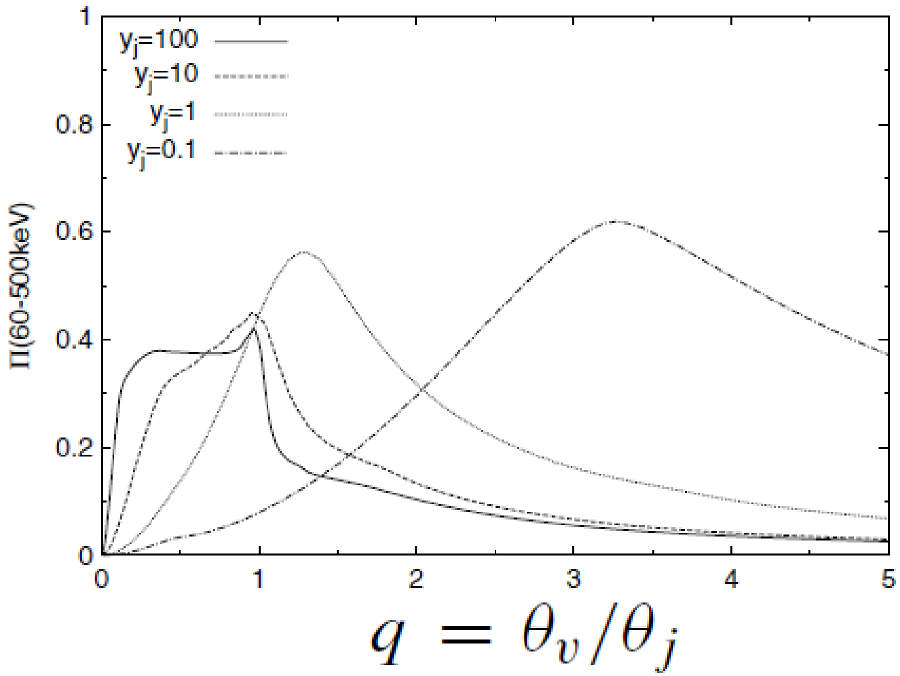
  ✓ Random B field on hydrodynamic scales (SH model): produced by MHD instability at internal shocks

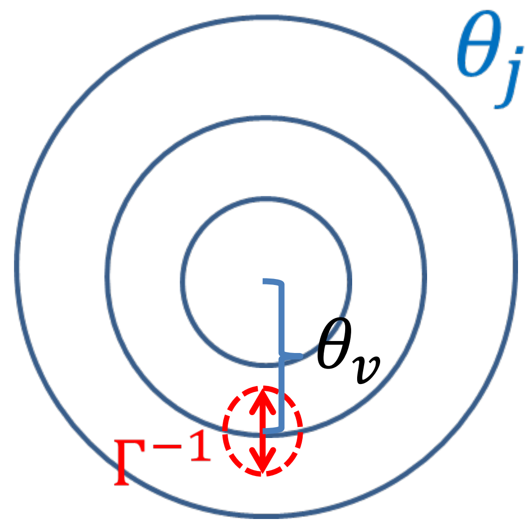
- Photospheric quasi-thermal (Ph model)

SO model

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

(Lyutikov 03; Granot 03; KT, Sakamoto, Zhang et al. 09)

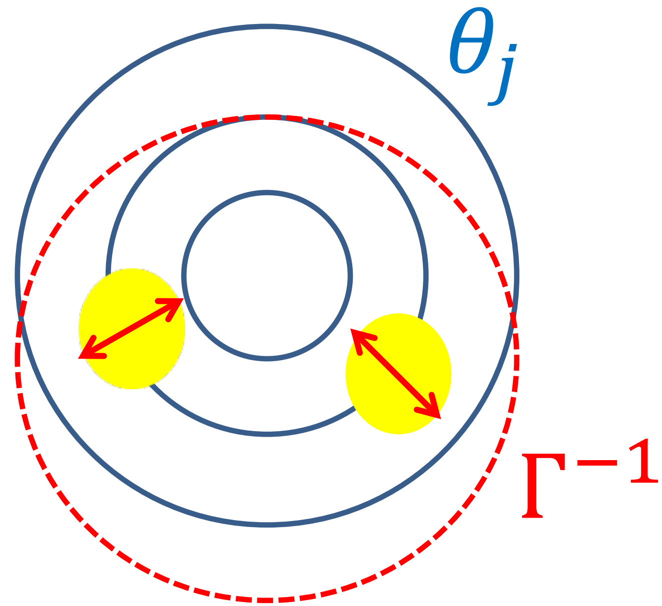




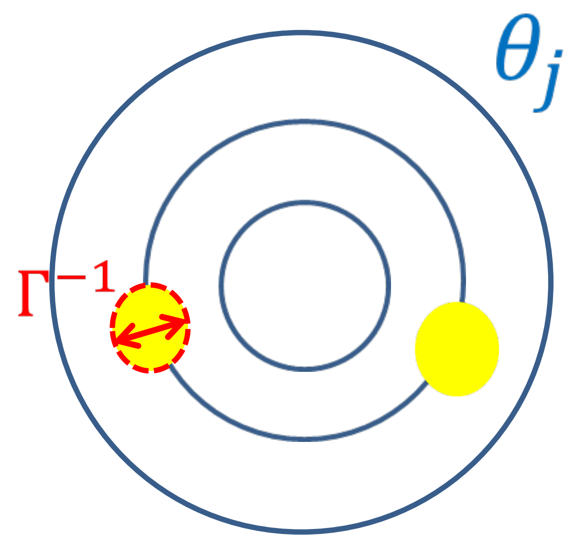
- Helical B fields
- PA does not vary for different Γ for SO model
- Patchy-like emission required to have PA change

SO model

- Patchy emission model
- If $\Gamma^{-1} \sim \theta_j$ → PA change
- If $\Gamma^{-1} \ll \theta_j$ → no PA change & $\Pi_L \sim 40\%$



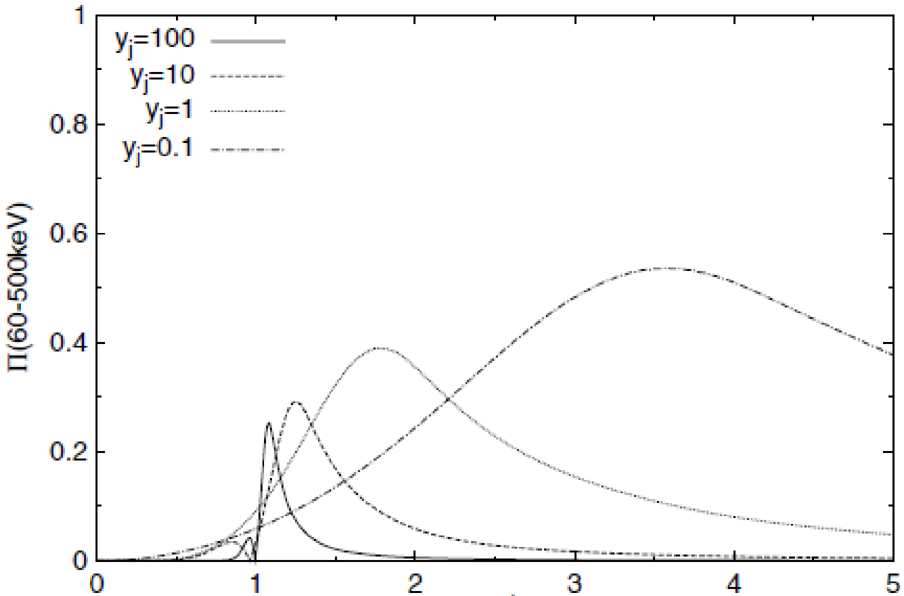
- Other ideas
  - Temporally distorted B fields (e.g, Zhang & Yan 11)
  - Multiple shells with ordered B fields of different directions (Granot+12)



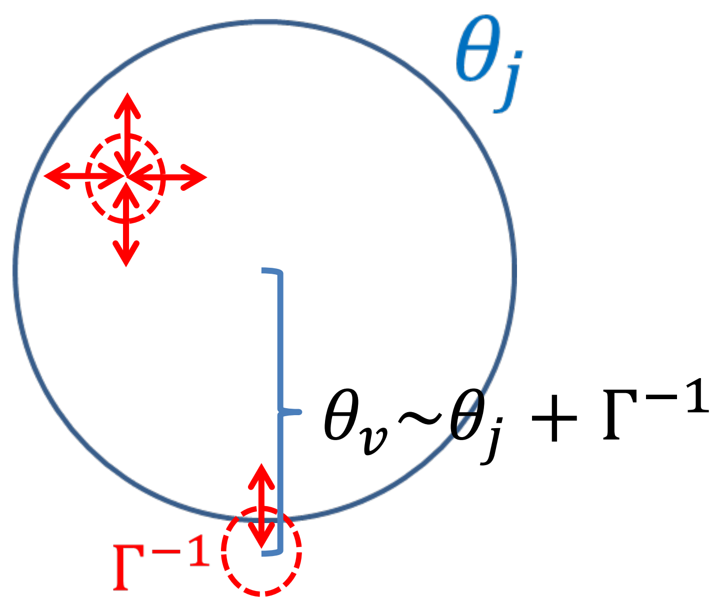
SR model

(Granot 03; Nakar & Piran 03; KT, Sakamoto, Zhang et al. 09)

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



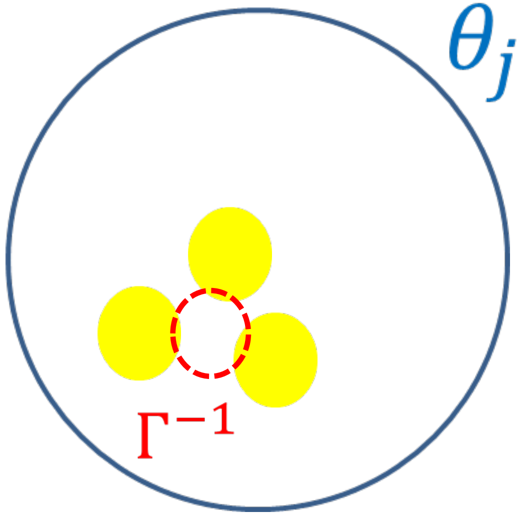
$q = \theta_v / \theta_j$



- B fields random on plasma scales, mainly parallel to the shock plane
- PA does not vary for different Γ either for SR model
- Patchy-like emission required to have PA change

SR model

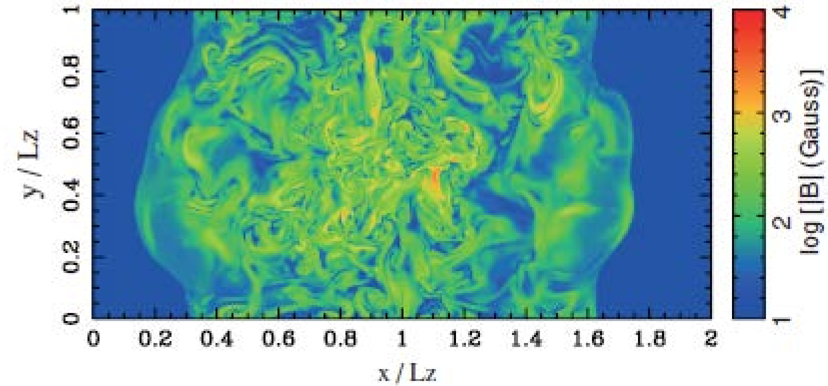
- PA can change if emission is patchy
- But Π_L > 30% requires fine tuning of parameters ($\theta_v \sim \theta_p + \Gamma^{-1}$)

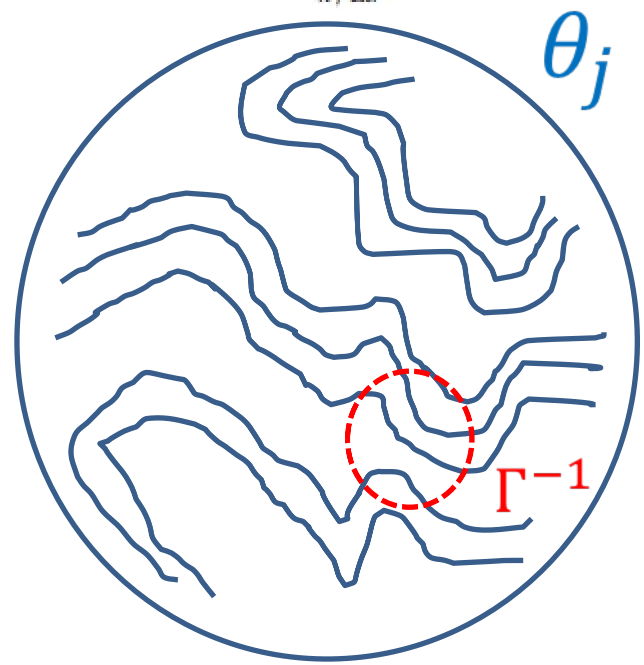


SH model

- B fields with random directions on hydrodynamic scales >> plasma scales (Inoue, Asano & Ioka 11, Gruzinov & Waxman99)
- PA change is natural
- $\Pi_L \sim 60\%/\sqrt{N}$
- However, numerical simulations indicate $N \sim 10^3$, too high

Simulation of internal shock with inhomogeneous density

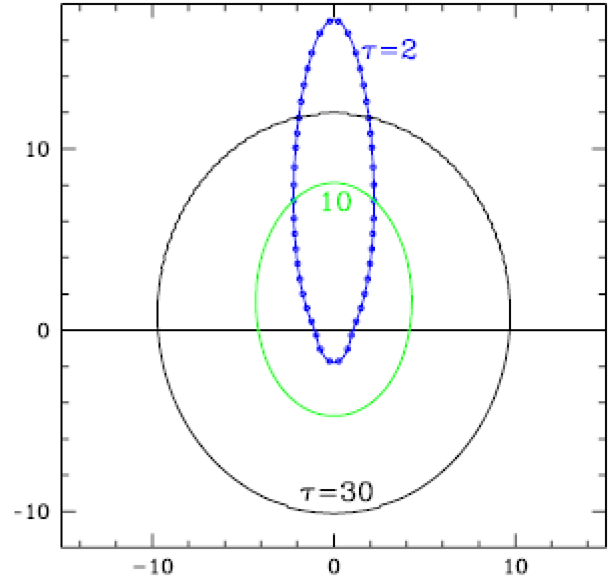


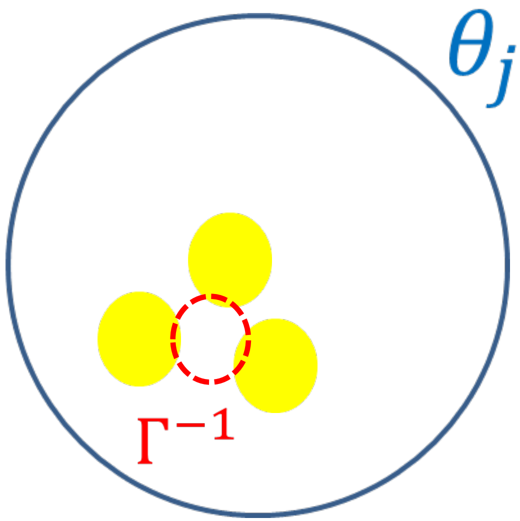


Ph model

- Prompt emission at $E \gtrsim E_p$ could be quasi-thermal radiation
- Π_L can be high if matter-dom. at photosphere (Beloborodov 11)
- Polarization properties are similar to the SR model
- Π_L > 30% requires fine tuning of parameters ($\theta_v \sim \theta_p + \Gamma^{-1}$)

Intensity dist. in the fluid frame





Implications for Emission Mechanism

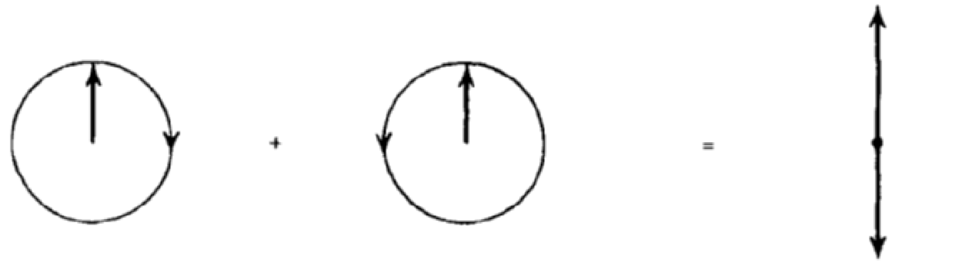
1. The SR, SH, and Ph models are not favored to reproduce all of the GAP results for 3 GRBs
2. The SO model could explain all of the GAP results, although even these models do not easily produce polarization as high as $\Pi_L \gtrsim 40\%$
3. Theories have to reconcile high dissipation efficiency with high polarization degree!
4. Anyway, more accurate observational data are needed and essential to solve the problem. Particularly, detection of a bright burst with low polari would be interesting.

QG effect on polarization propagation

- $m_{pl} \equiv \sqrt{\frac{\hbar c}{G}} \simeq 10^{19}$GeV, $l_{pl} \equiv \sqrt{\frac{\hbar G}{c^3}} \simeq 10^{-33}$cm
- Superstring theory, Loop quantum gravity, …
- Lorentz invariance may be broken.
- CPT theorem does not hold
- If CPT symmetry is broken, velocities of left and right circular polarization of light would be slightly different
- Effects on linear polarization accumulating for *cosmological distances* may be measured

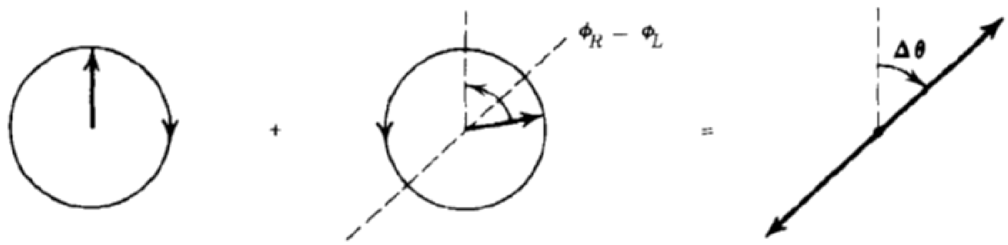
Dispersion relation

- Lorentz- and CPT-violating dispersion relation of photons derived from effective field theory (Myers & Pospelov 03)
- ${E_{\pm}}^2 = p^2 \left[1 \pm 2\xi \left(\frac{p}{M_{pl}}\right)\right]$
- $\pm$ denotes two circular polarization states -> different phase velocities -> gradual rotation of direction of linear polarization (like Faraday rotation in uniform B field, but effect stronger for higher energy)



(a)

Figure 8.1a ***Decomposition of linear polarization into components of right and left circular polarization.***



(b)

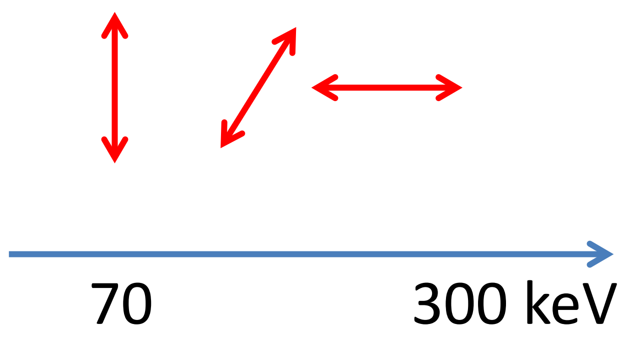
Figure 8.1b ***Faraday rotation of the plane of polarization.***

(Rybicki & Lightman 79)

- $\pm$ denotes two circular polarization states -> different phase velocities -> gradual rotation of direction of linear polarization (like Faraday rotation in uniform B field, but effect stronger for higher energy)

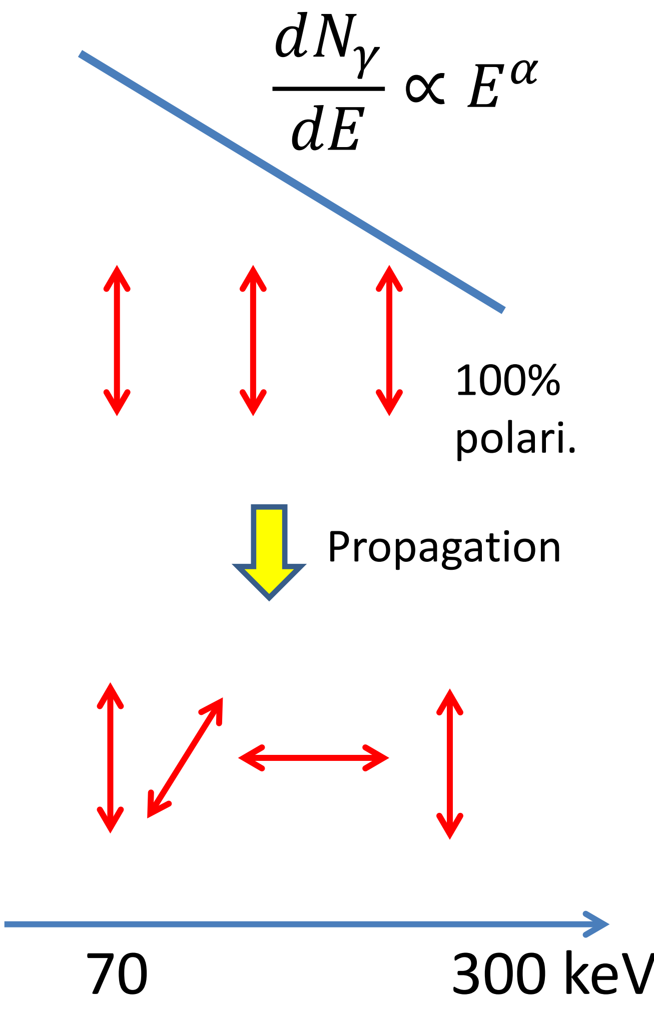
Rotation depends on energy

- $d\theta = (E_+ - E_-)dt/2 \simeq \xi p^2 dt/M_{pl}$
- $\Delta\theta(k,z) \simeq \xi \frac{k^2}{M_{pl}H_0} \int_0^z \frac{(1+z')dz'}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}$
- $k = p/(1+z)$: comoving momentum
- Polarization averaged over 70-300 keV reduces



Upper limit on coefficient ξ

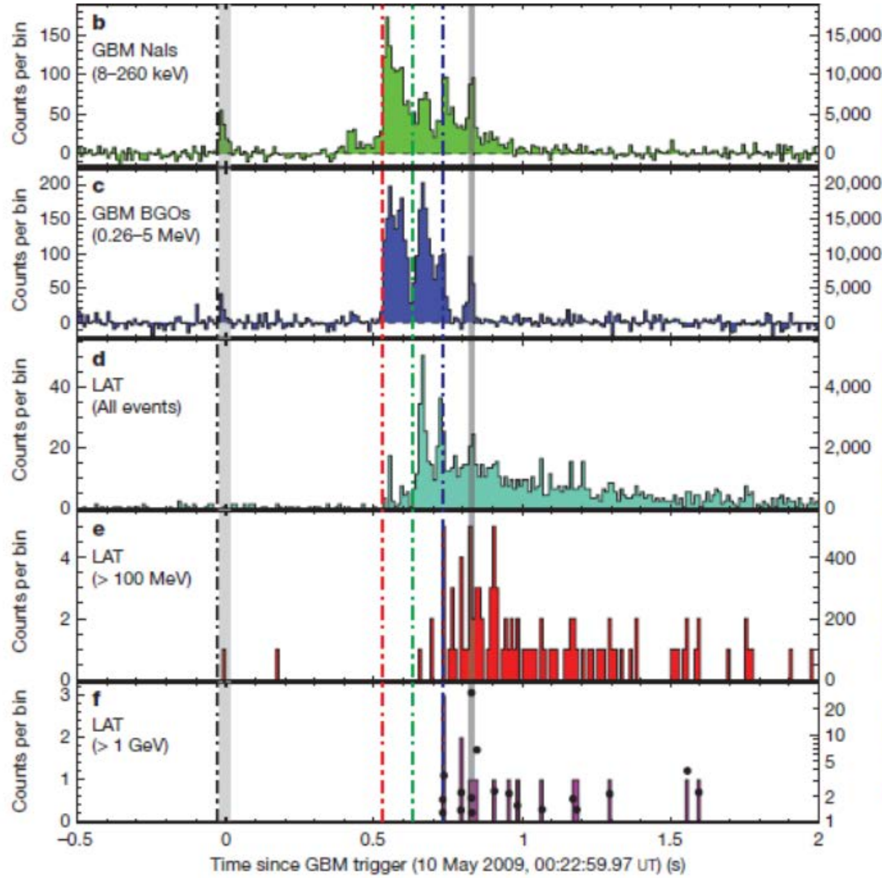
- $P = \sqrt{Q^2 + U^2}/I > P_{min} \sim 30\%$ at 2 σ
- $|\xi| < 2 \times 10^{-15}$ for GRB 110721A with redshift estimated by $E_p - L$ relation (KT, Mukohyama, Yonetoku et al. 2012)
- $|\xi| < 3 \times 10^{-16}$ for GRB 061122 with spectroscopic redshift (Gotz et al. 2013)



Constraint from Photon Arrival Times

- $E_{\pm}{}^{2} = p^{2}\left[1 \pm 2\xi\left(\frac{p}{M_{pl}}\right)\right]$
- Light curves depend on energy
- $|\xi| < O(1)$ for GRB 090510
- Much weaker constraint than polarimetry

- $E_{\pm}{}^{2} = p^{2}\left[1 + \xi_{2}\left(\frac{p}{M_{pl}}\right)^{2}\right]$
- CPT conserved. Cannot be tested by polarimetry
- $|\xi_2| < O(10^{18})$ for GRB 090510



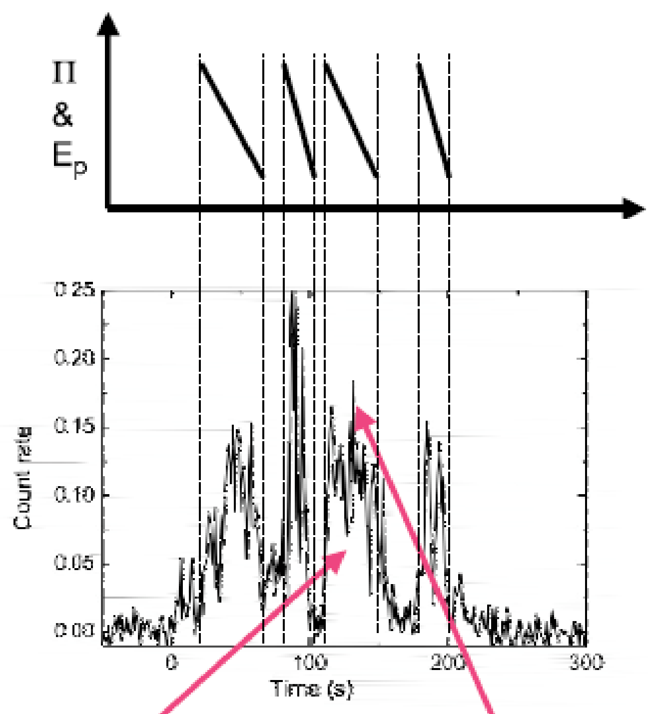
(Abdo et al. 2009, Nature)

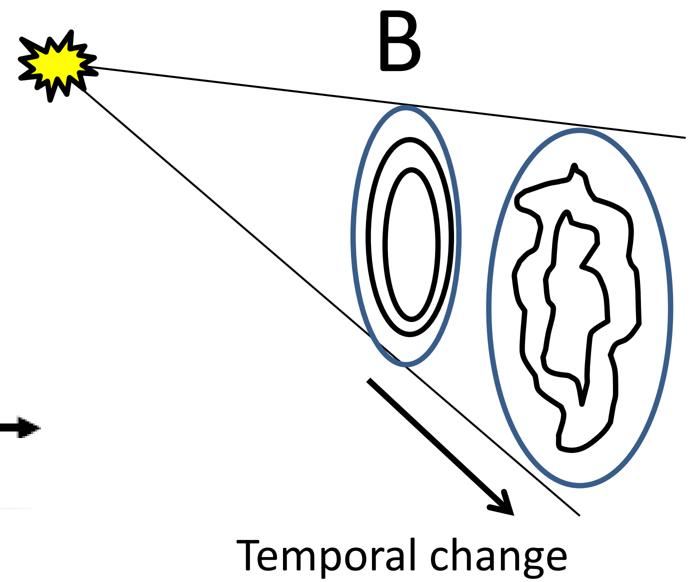
Summary

- γ-ray polarimetry is powerful to constrain prompt emission models
- SR, SH, and Ph models are not favored
- SO model is suggested, but more detailed modeling (dissipation & emission structure, spectrum, variability, …) are needed
- Extended amount of more accurate data (TSUBAME, PETS, PolariS etc.) and data in optical, X-rays, GeV, … useful
- Detections of γ-ray polarization from the cosmological distances verify the Lorentz- and CPT-invariance in the photon sector

Non-Steady SO model

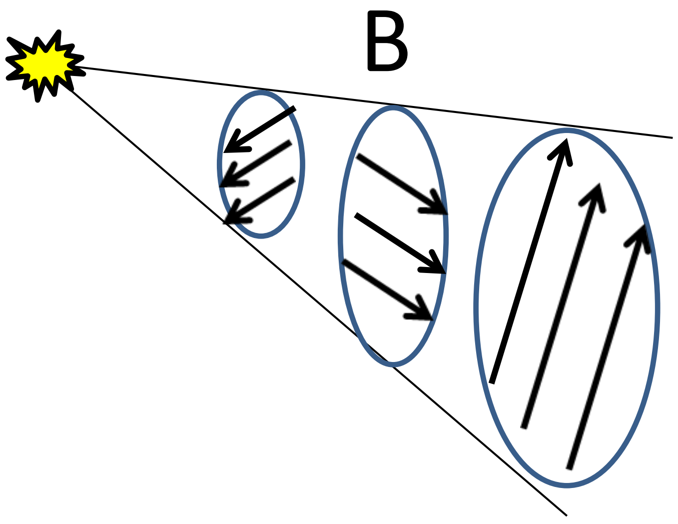
- Magnetic fields being distorted with energy dissipation (e.g., Zhang and Yan 11)





Non-Steady SO model

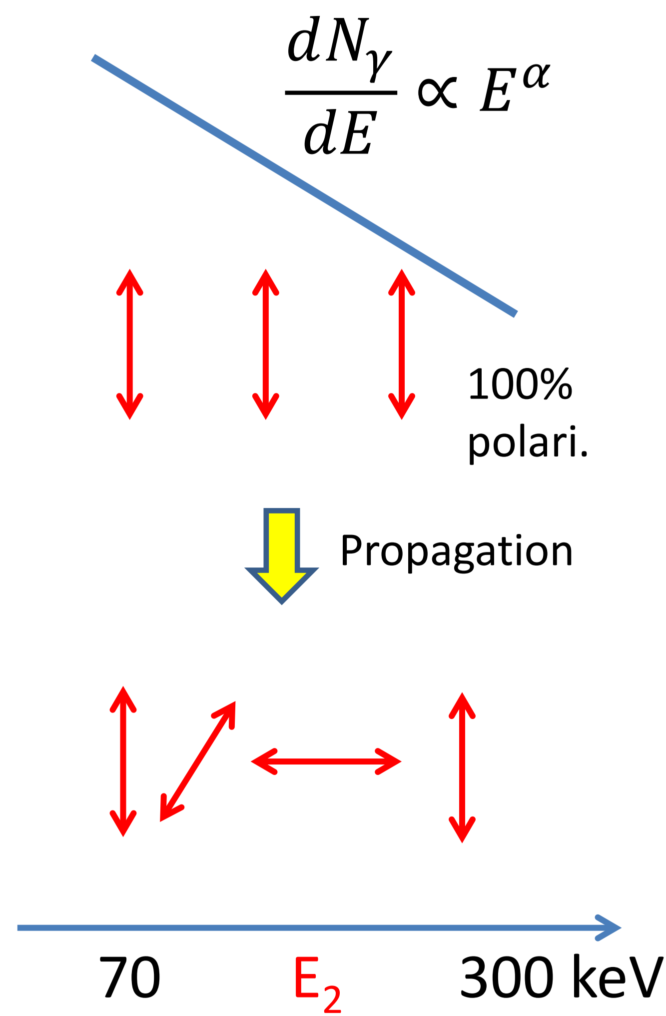
- Multiple impulsive shells with globally-ordered transverse B fields of different directions
- Such flows can accelerate (Granot+12)
- PA change is natural
- But not necessary if T is short
- $\Pi_L \sim 60\%/\sqrt{N}$
- N = number of shells with different field directions



Upper limit on ξ from P_{min} (at 2σ)

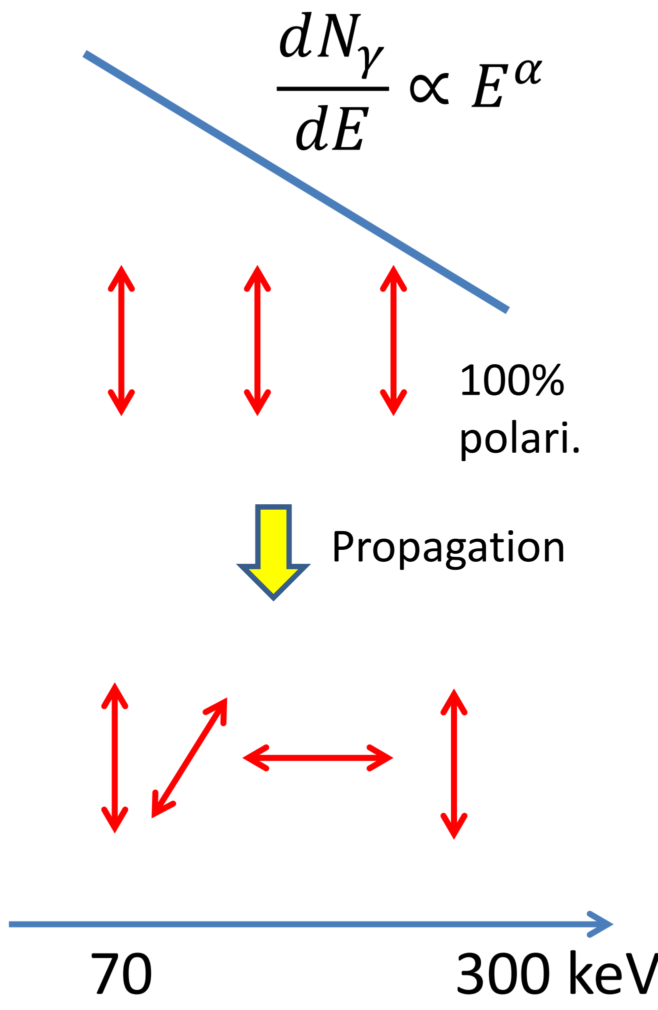
- Rough estimate
- $|\Delta\theta(E_2, z) - \Delta\theta(E_1, z)| \leq \pi/2$
- $E_1 = 70$ keV
- $\int_{70}^{E_2} E^{\alpha}\, dE / \int_{70}^{300} E^{\alpha} dE = P_{min}$
- P_{min}: 2σ lower limit observed

- For GRB 110721A, $\alpha > -0.98$, $P_{min} = 35\%$ -> $E_2 \sim 120$ keV
- -> $|\xi| < 7 \times 10^{-15}$



More accurate constraint

- $P = \sqrt{Q^2 + U^2}/I > \ P_{min}$
- $I = \int_{70}^{300} E^{\alpha} dE$
- $Q = \int_{70}^{300} E^{\alpha} \cos(2\Delta\theta(E))\, dE$
- $U = \int_{70}^{300} E^{\alpha} \sin\big(2\Delta\theta(E)\big) dE$
- For GRB 110721A
- $|\xi| < 2 \times 10^{-15}$



GAmma-ray burst Polarimeter

Yonetoku et al. (2011)

- Angular distribution of Compton Scat.
- Geometrical symmetry

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\frac{E^2}{E_0^2}\left(\frac{E_0}{E} + \frac{E}{E_0} - 2\sin^2\theta\cos^2\phi\right)$$

r_0 : classical electron radius
E_0 : energy of incident photon
E : energy of scattered photon