Frontier Research Institute for Interdisciplinary Sciences
Tohoku University

Theoretical Astrophysics
Tohoku University

GRB Polarization

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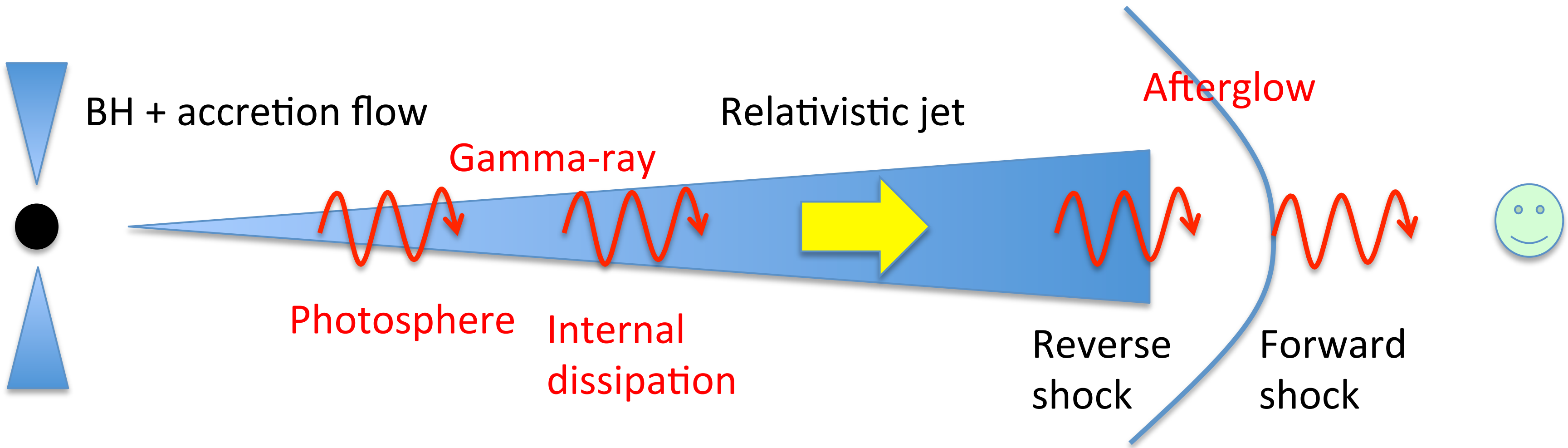
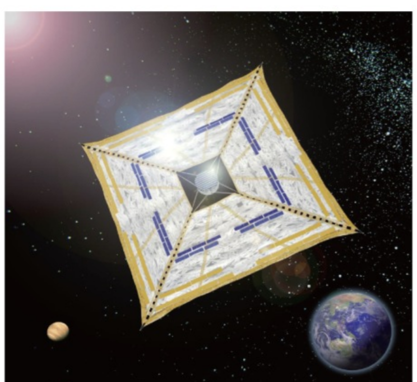
(Tohoku Univ.)

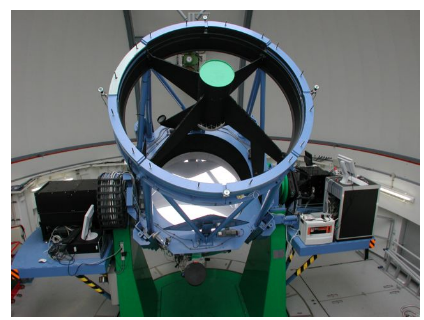
“GRB workshop 2015” @ RIKEN, Aug 31 – Sep 2, 2015

GRB Polarization: another frontier



Recent reports of detections
(e.g. Yonetoku+11;12; KT 13)





Late-time afterglow
Π_L ~ 1-3%
(Covino+03)
Π_C ~ 0.6 % !!
(Wiersema+14)

Early-time afterglow
Π_L ~ 30% !! (Mundell+13), Π_L ~ 10% (Steele+09),
Π_L ~ 10% (Uehara, KT, Kawabata+12)
Π_L < 8% (Mundell+07)

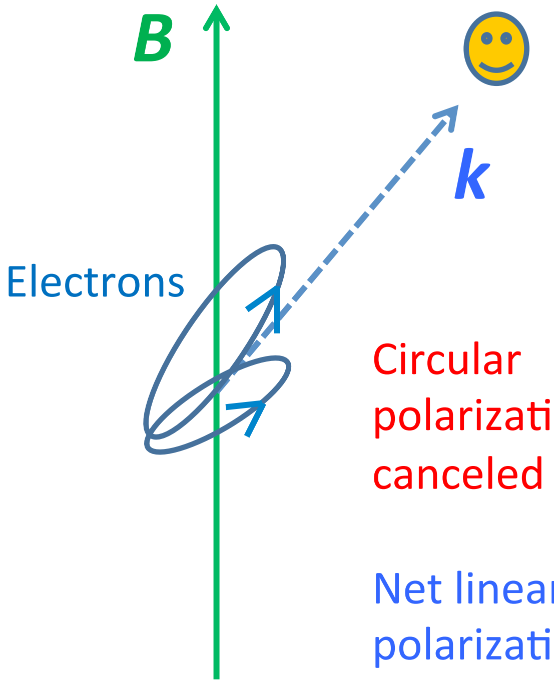
Synchrotron emission

- Relativistic electrons with isotropic pitch-angle distribution
- Ordered B field (on scales larger than electrons' gyro-radii)

$$\ell_{\rm gy} \simeq 3 \times 10^6 \gamma_e B^{-1} \ {\rm cm}$$

- Linear polarization $\Pi_L \sim 70\%$
- Circular polarization $\Pi_C \sim 1/\gamma_e << 1$

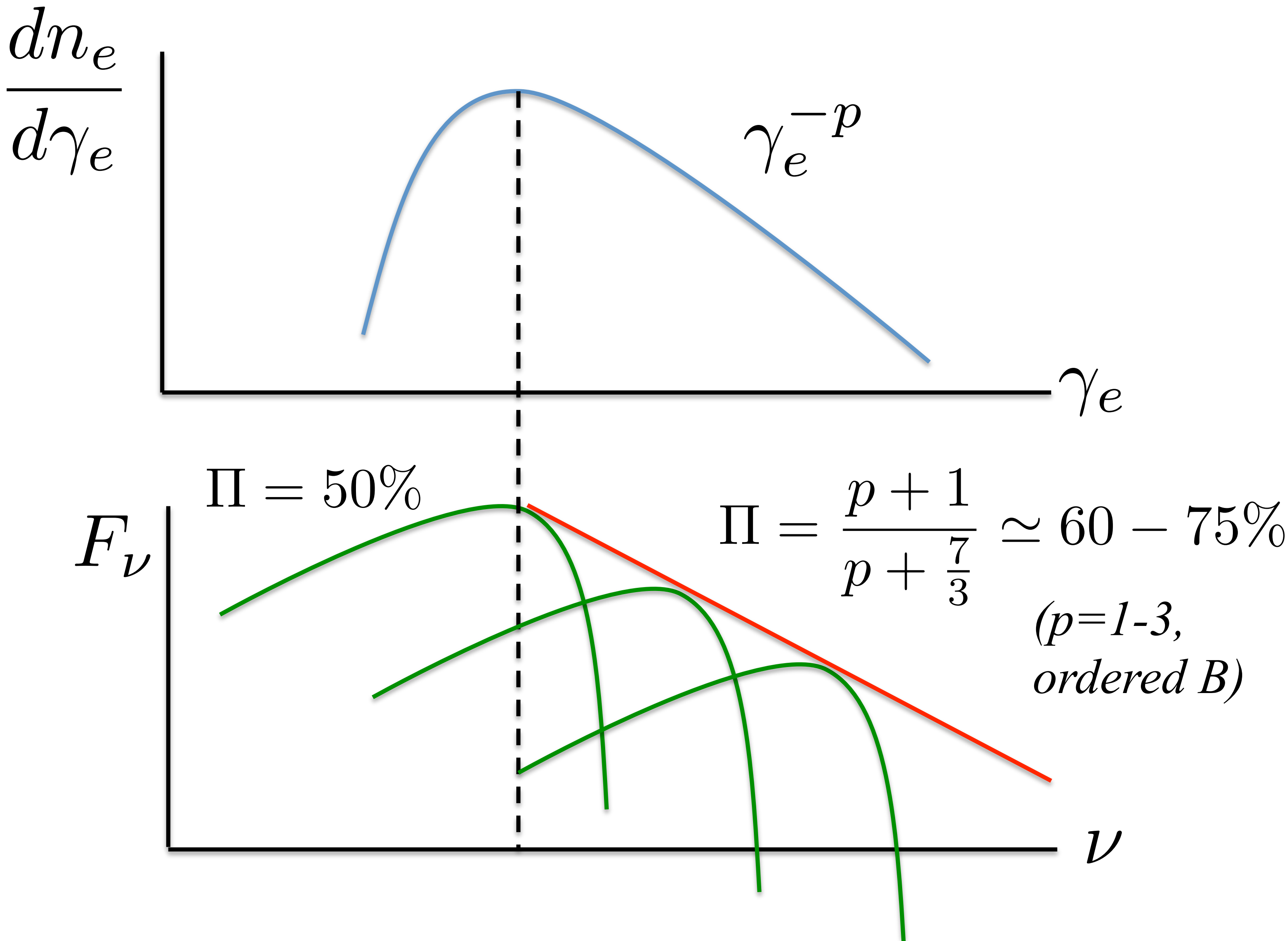
(Rybicki & Lightman 79; Melrose 80)



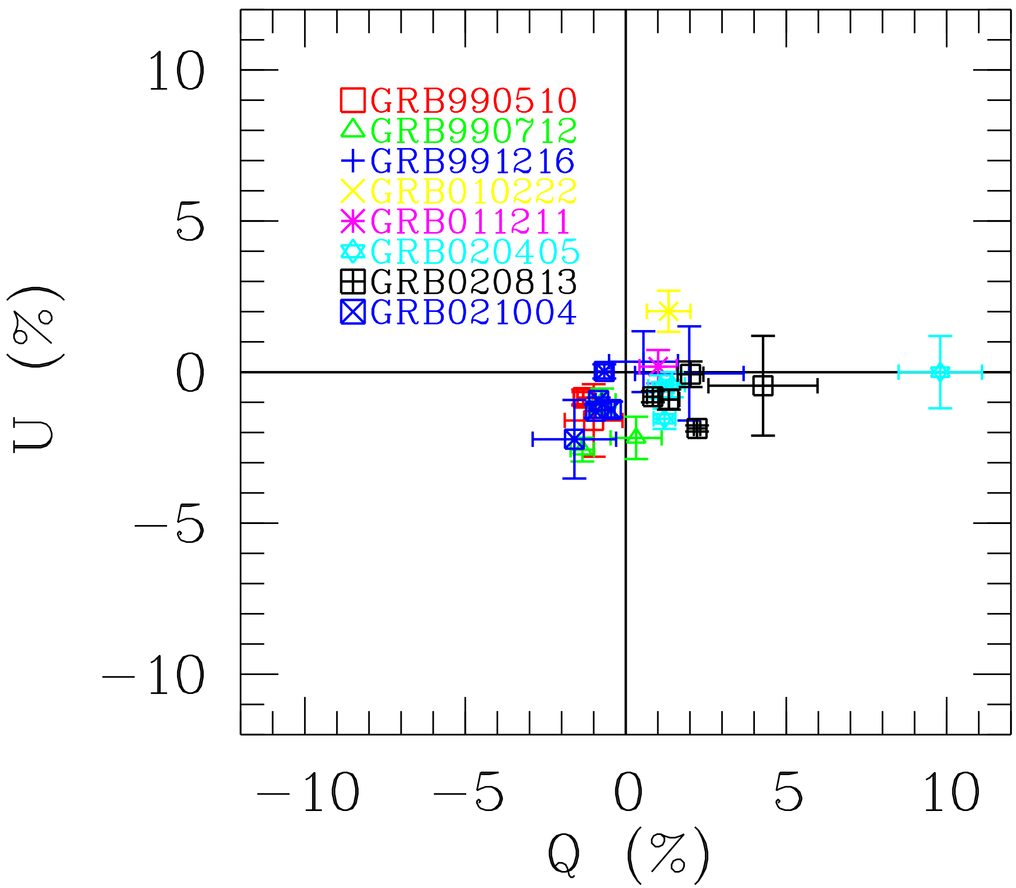
Circular polarizations are canceled out

Net linear polarization is perpendicular to B and k

Afterglow model



Late-time afterglow polarization

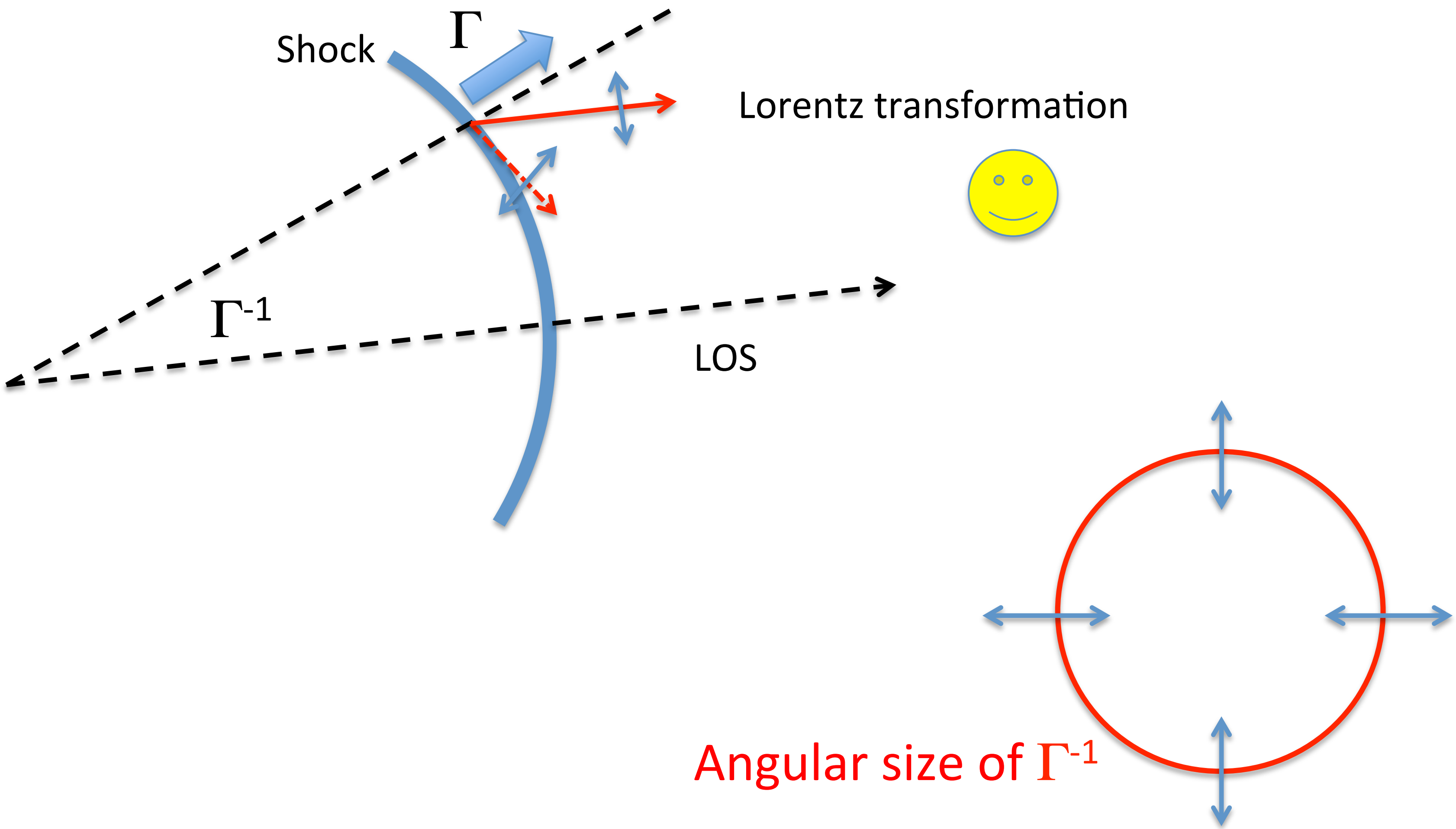


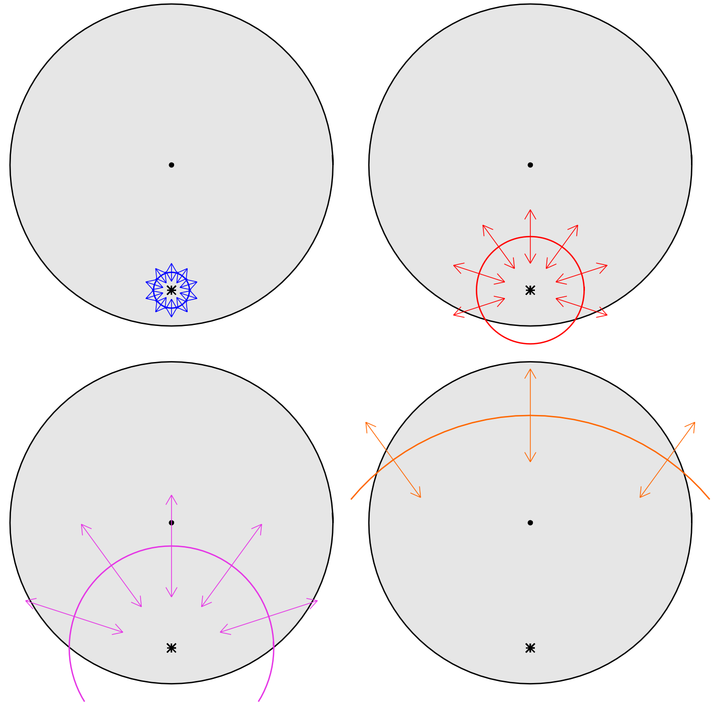
(Covino+03)

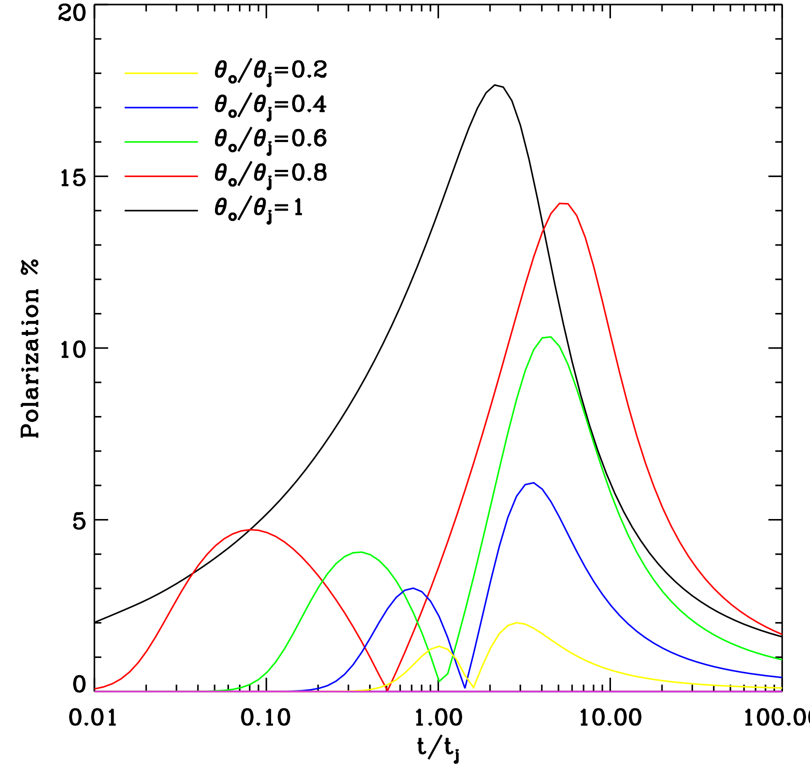
Π ~ 1-3% at *T ~ 1* day ➔ B field is not ordered

Constraining B field structure

Case of random B field parallel to the shock plane



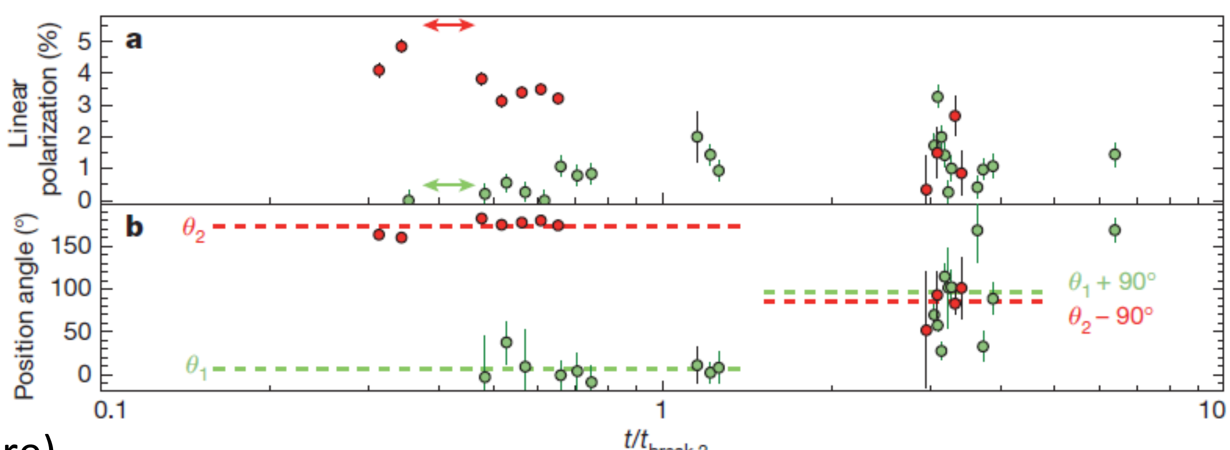




(Sari 99; Ghisellini & Lazzati 99; Lazzati 06)

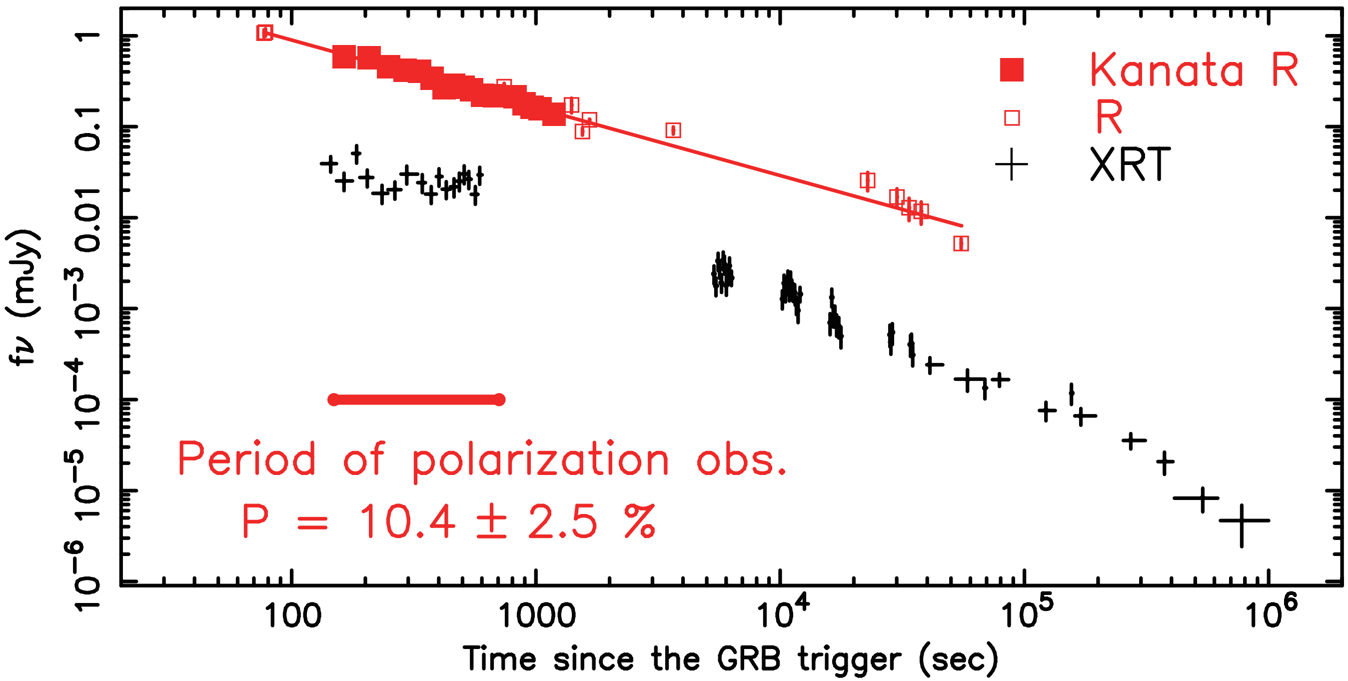
GRB 121024A, GRB 091018

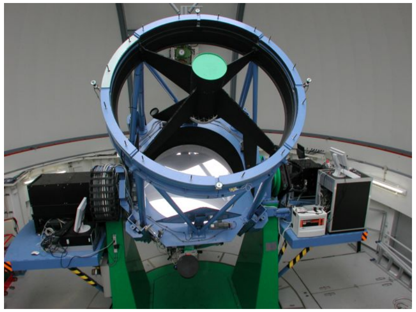
Consistent with the observed temporal change of pol. angle



(Wiersema, Covino, KT+14, Nature)

Early-time afterglow polarization





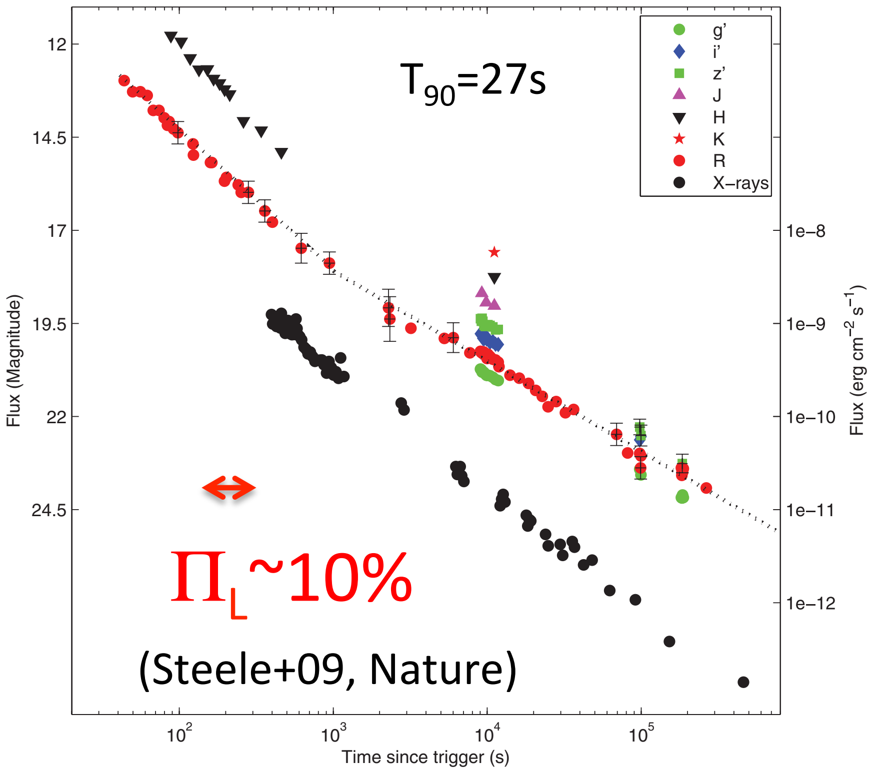
Kanata Telescope
at Hiroshima U

Early-time polarization from the forward shock is high!!

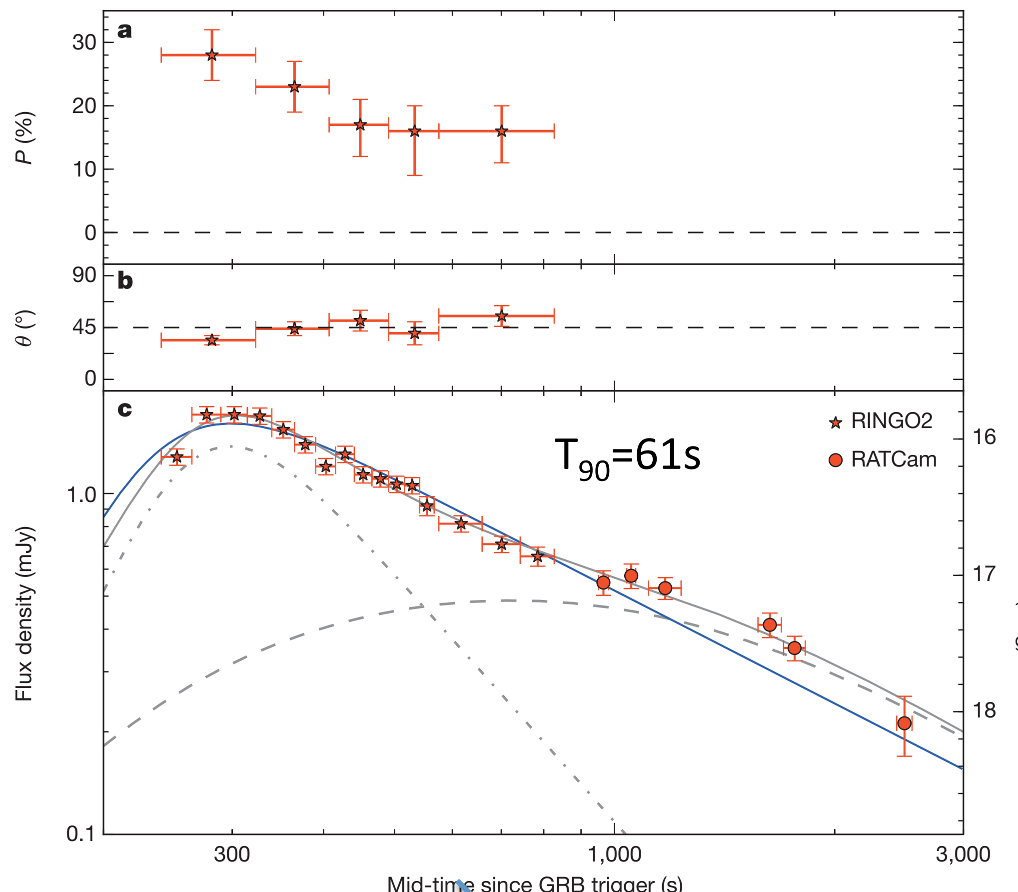
This implies the forward shock involves large-scale B fields

(Uehara, KT, Kawabata+12)

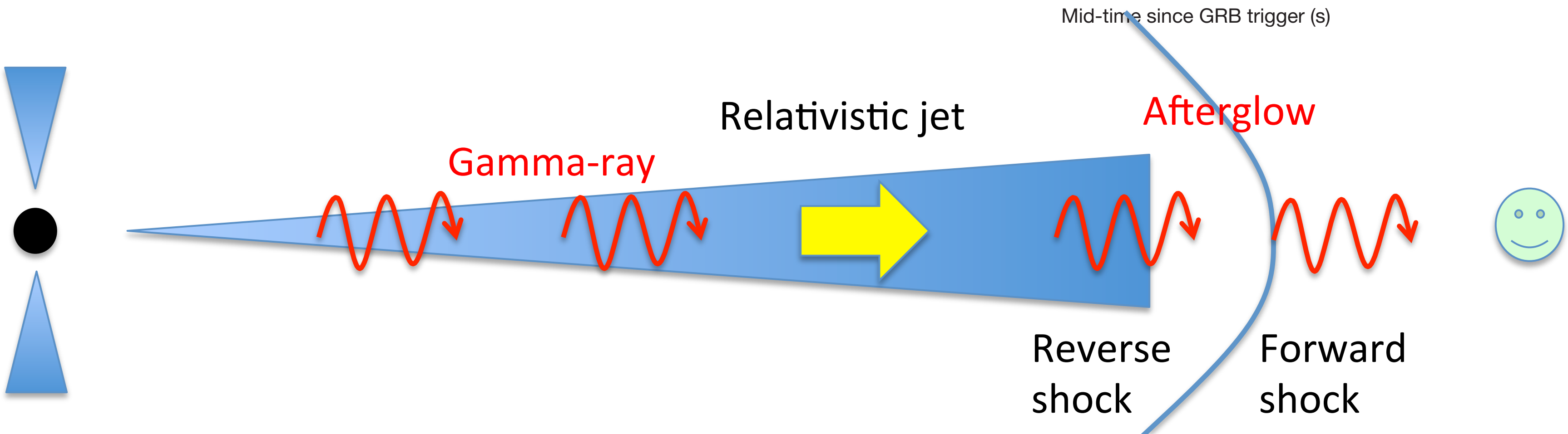
GRB 090102 (Gendre+10)



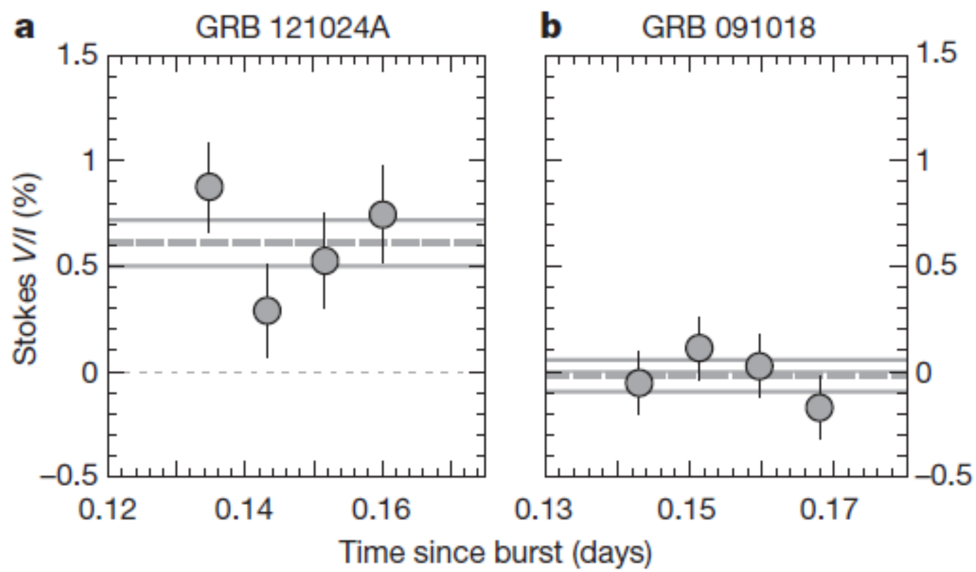
GRB 120308A (Mundell+13, Nature)



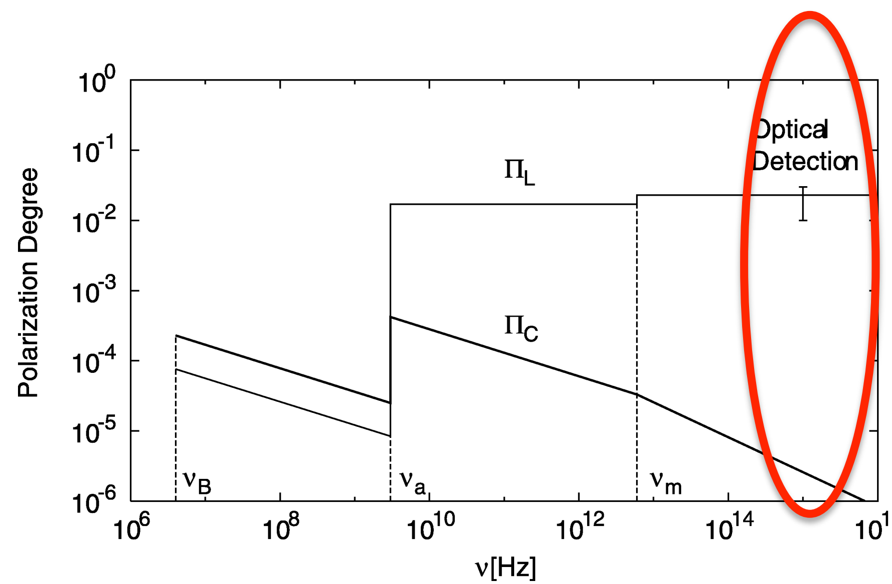
Reverse shock emission?



Detection of circular polarization



- One of the two observed bursts has Π_C ~ 0.6%!!
- Propagation effect is weak



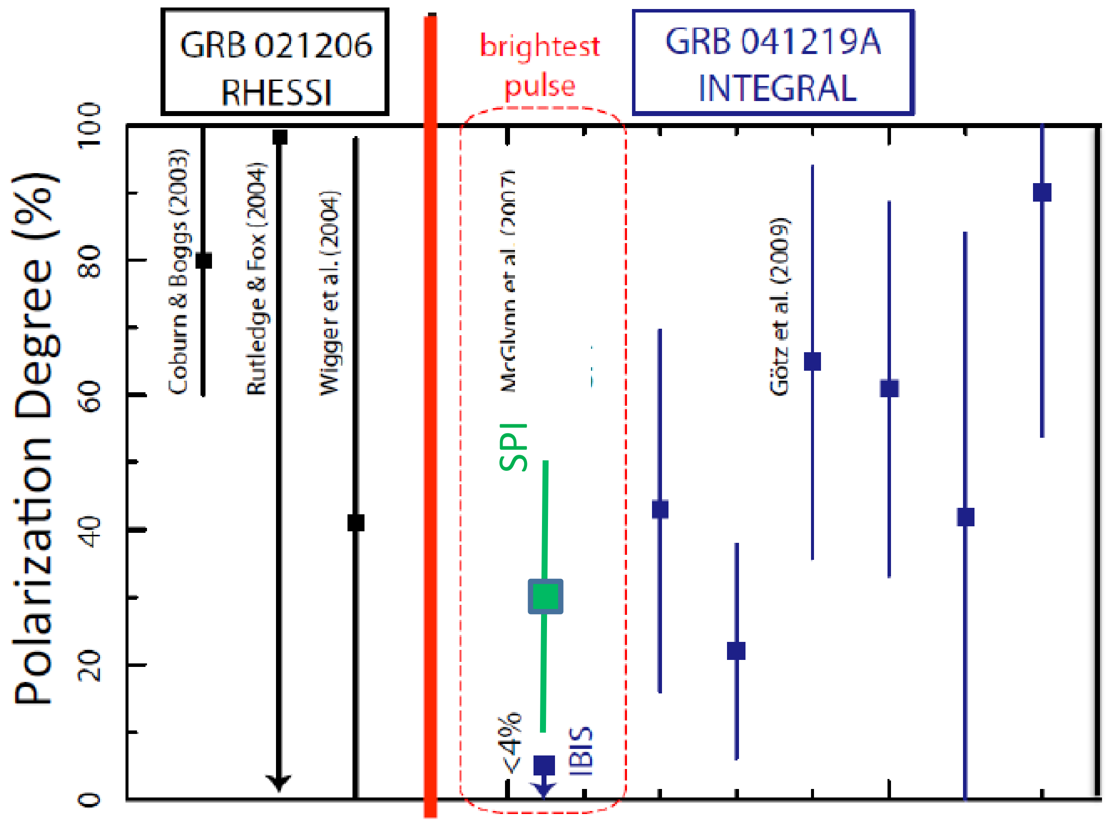
- Highly anisotropic electron distribution?

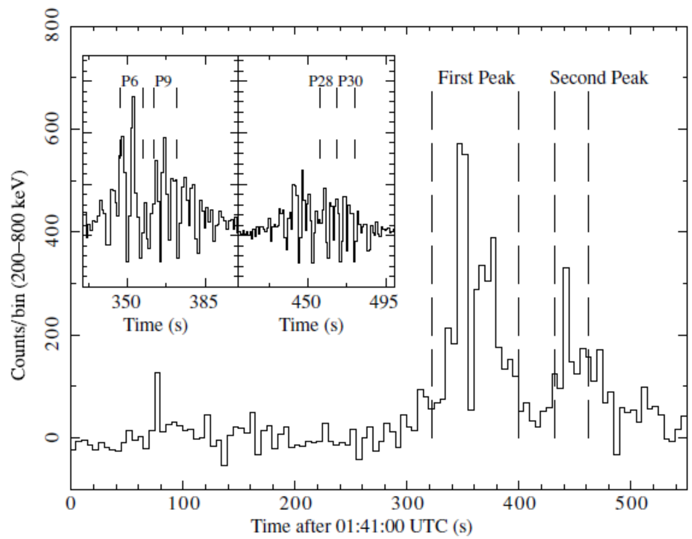
$$g(\theta) \equiv \frac{1}{f(\theta)} \frac{\mathrm{d}f(\alpha)}{\mathrm{d}\alpha}\bigg|_{\alpha=0} \quad \sim 10^3$$

(Wiersema, Covino, KT+14, Nature)

(KT, Ioka & Nakamura 08)

History of gamma-ray polarimetry



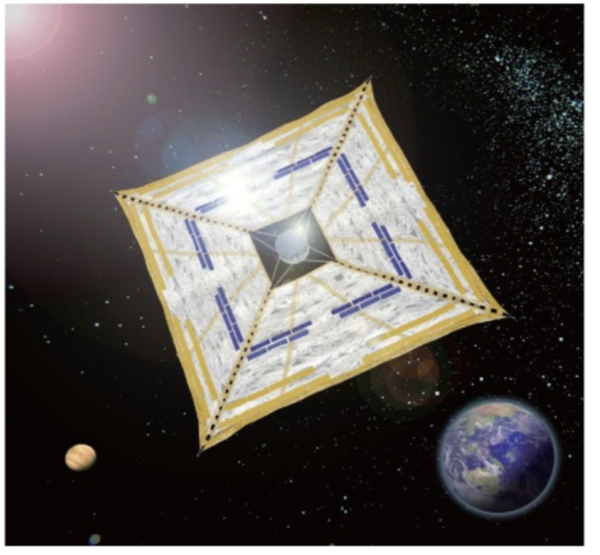


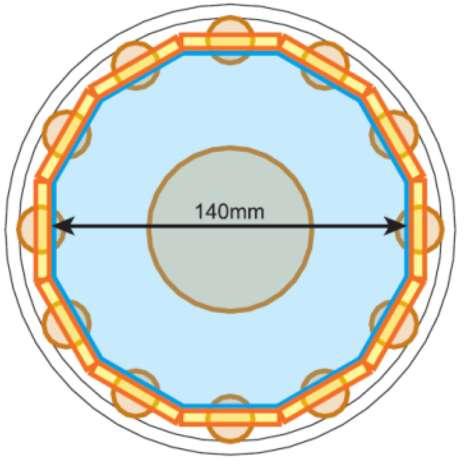
GRB 041219A analyzed by INTEGRAL (Gotz et al. 09)

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

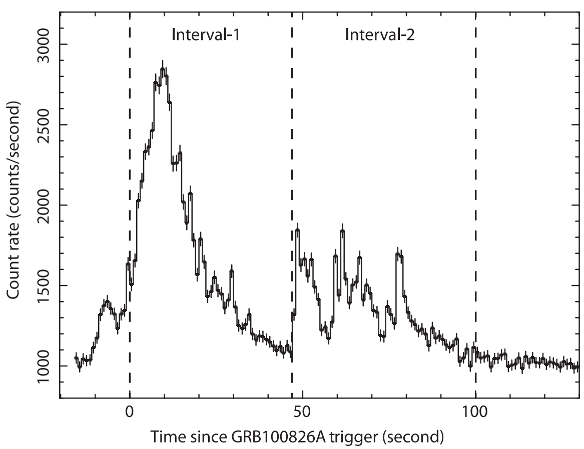


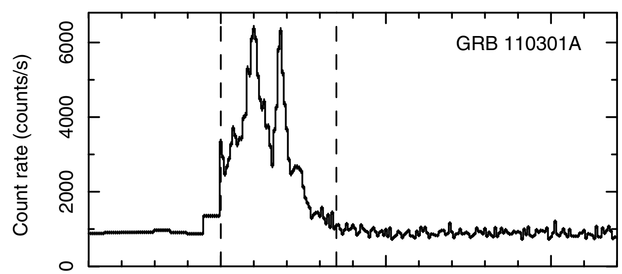


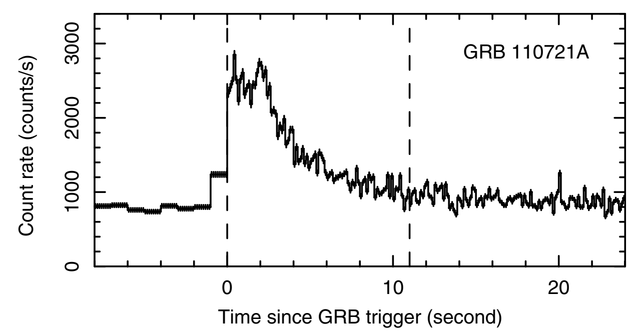
Observational results

Event name	Π	2σ limit	Detection significance	PA change
GRB 100826A	$27 \pm 11\%$	$> 6\%$	2.9σ	yes
GRB 110301A	$70 \pm 22\%$	$> 31\%$	3.7σ	no
GRB 110721A	$84^{+16}_{-28}\%$	$> 35\%$	3.3σ	no

Event name	T_{90} [s]	fluence [erg cm^{-2}]	E_p [keV]
GRB 100826A	$\simeq 150$	$(3.0 \pm 0.3) \times 10^{-4}$	606^{+134}_{-109}
GRB 110301A	$\simeq 5$	$(3.65 \pm 0.03) \times 10^{-5}$	$106.8^{+1.85}_{-1.75}$
GRB 110721A	$\simeq 24$	$(3.52 \pm 0.03) \times 10^{-5}$	393^{+199}_{-104}







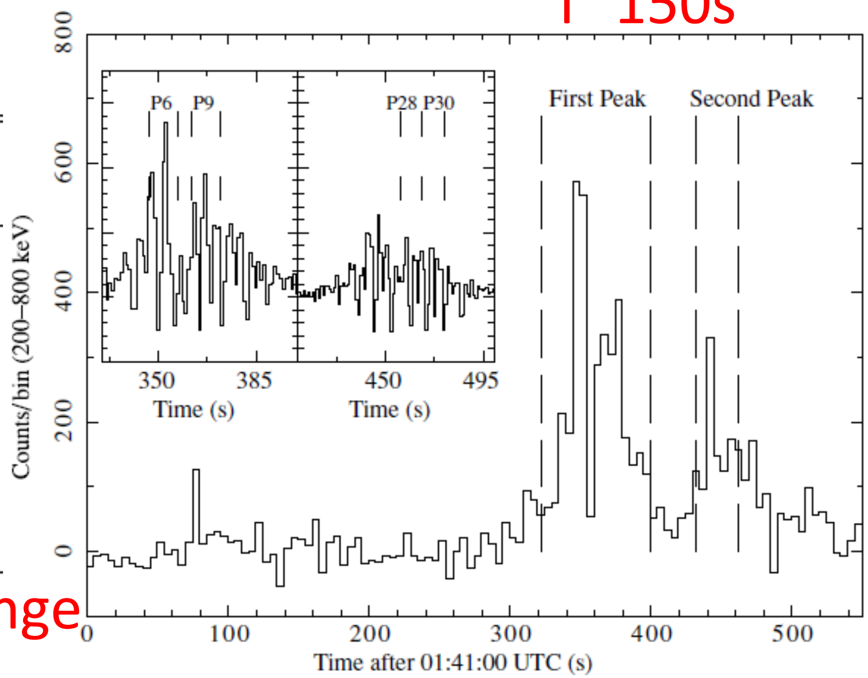
(Yonetoku+11;12; KT 13)

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

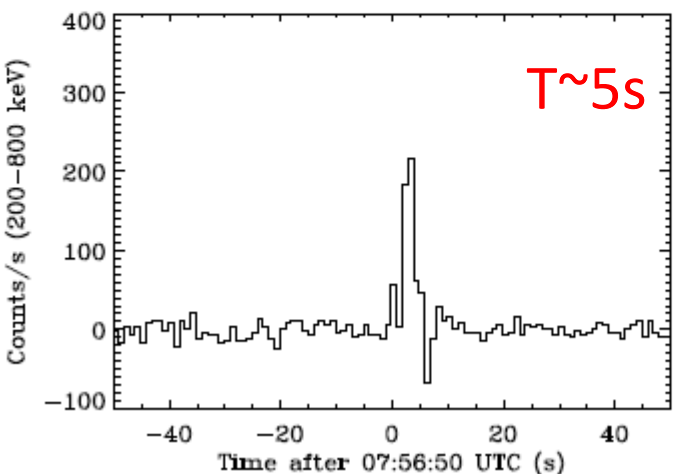
T~150s



PA change

GRB 061122 (Gotz+13)

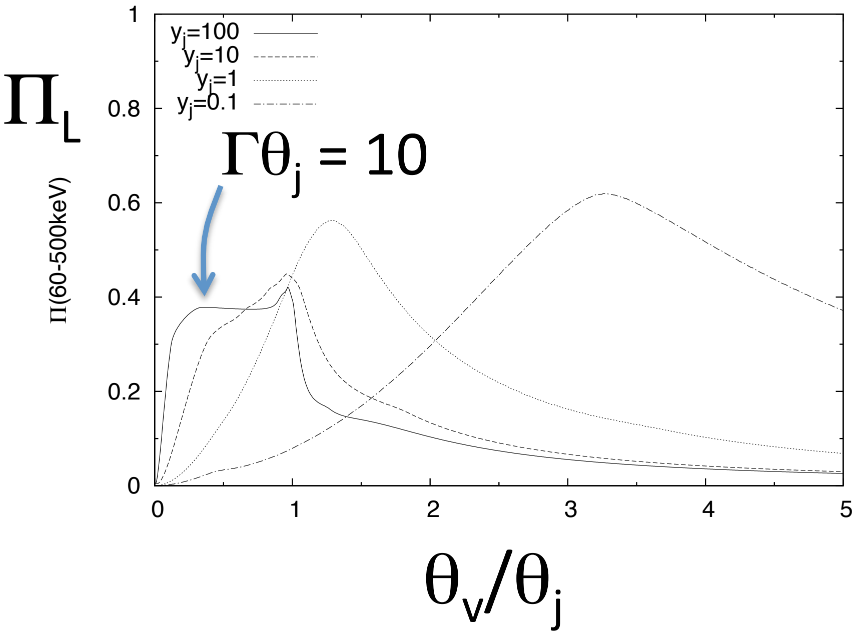
Energy band (keV)	Π (%) (68% c.l.)	P.A. (°) (68% c.l.)	Π (%) (90% c.l.)	P.A. (°) (90% c.l.)
250–800	>60	150±15	>33	150±20
250–350	>65	145±15	>35	145±27
350–800	>52	160±20	>20	160±38

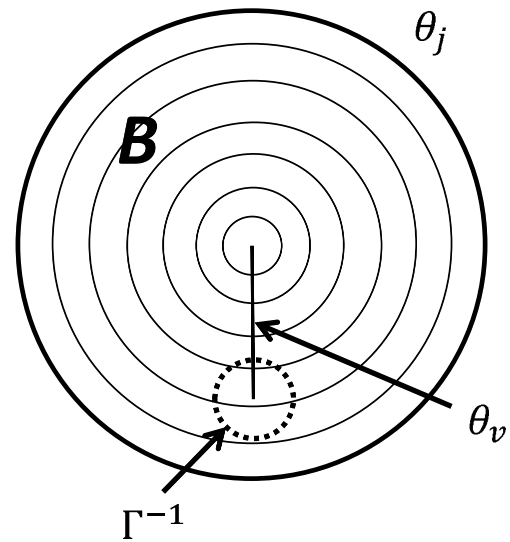


- P>~30% at 2σ, non-zero at ~3σ, consistent with GAP results

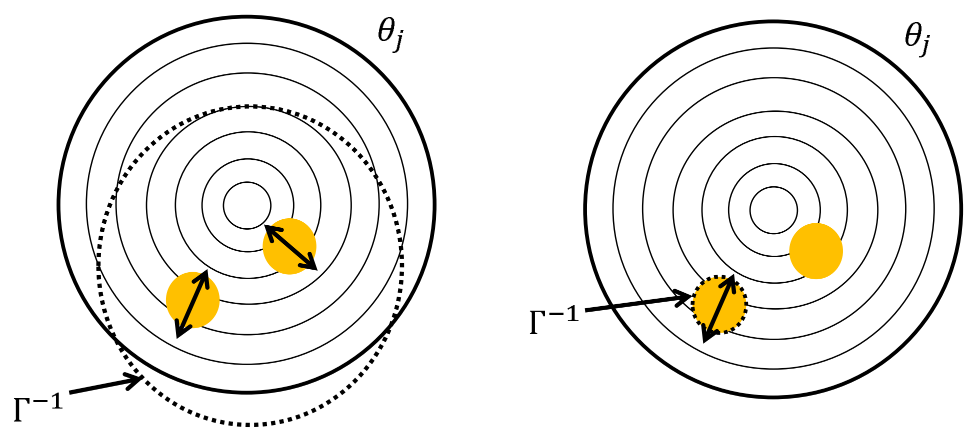
SO model (syn ordered B)

(Lyutikov+03; Granot 03; KT, Sakamoto, Zhang+09; KT13)



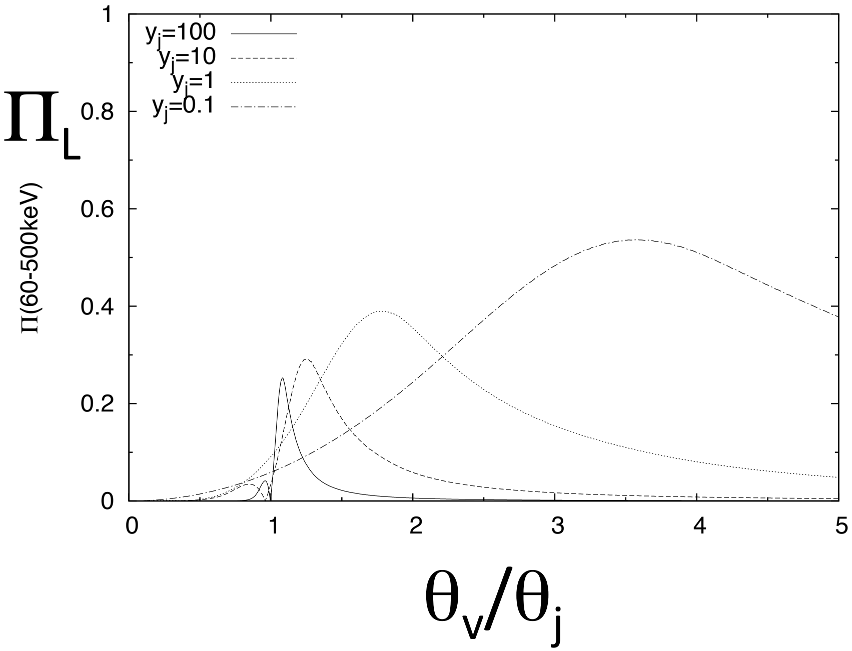


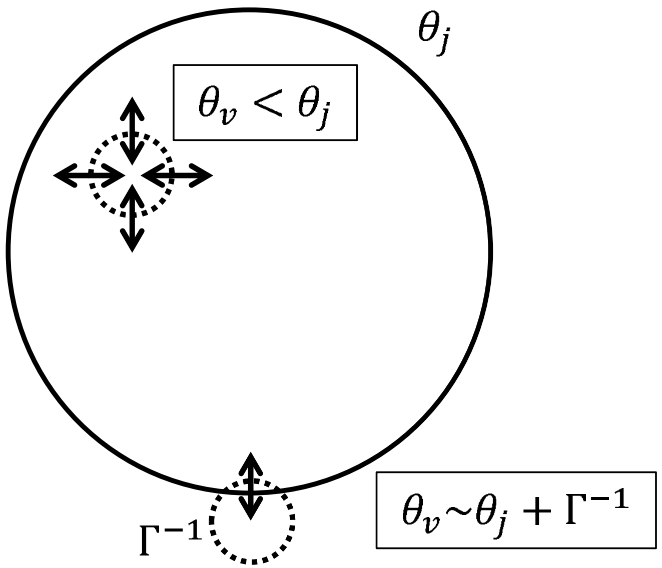
- Polarization degree is sufficient
- Patchy emission may lead to PA changes
- Other B structures possible



SR model (syn random B)

(Granot 03; Nakar & Piran 03; KT, Sakamoto, Zhang+09; KT13)

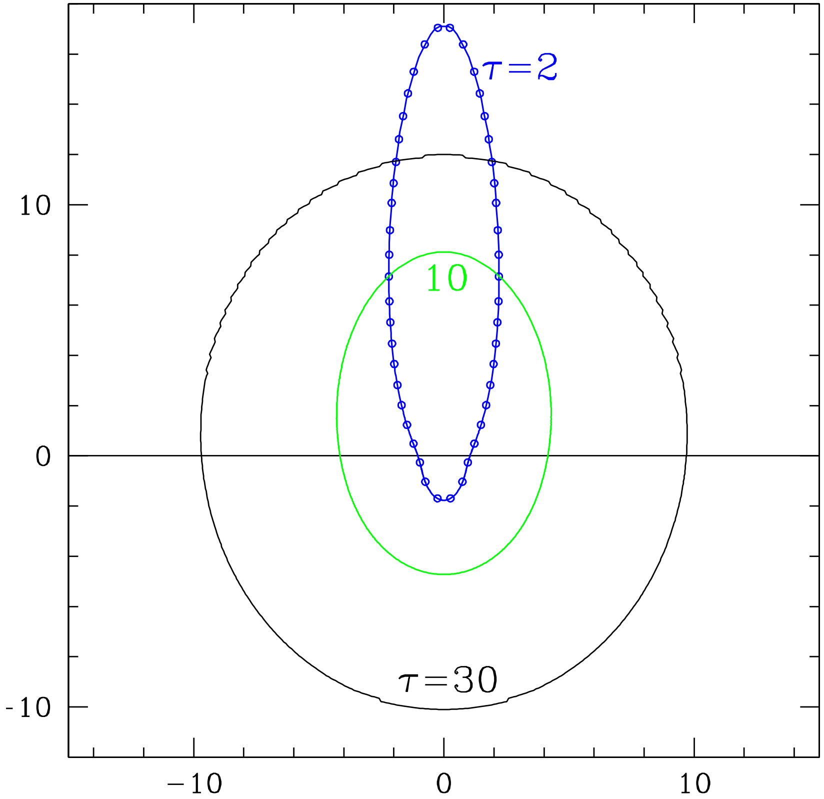




- Random B field parallel to the shock plane
- Π_L > 30% requires a fine tuning of parameters

Photospheric model

(Beloborodov 11)



Radiation intensity is highly anisotropic in the fluid frame

- Prompt emission could be quasi-thermal emission
- Π_L can be high if matter-dom. at photosphere (Beloborodov 11)
- Polarization properties similar to SR model
- $\Pi_L > 30\%$ requires a fine tuning of parameters
- See also Ito, Nagataki+14; Lundman+13

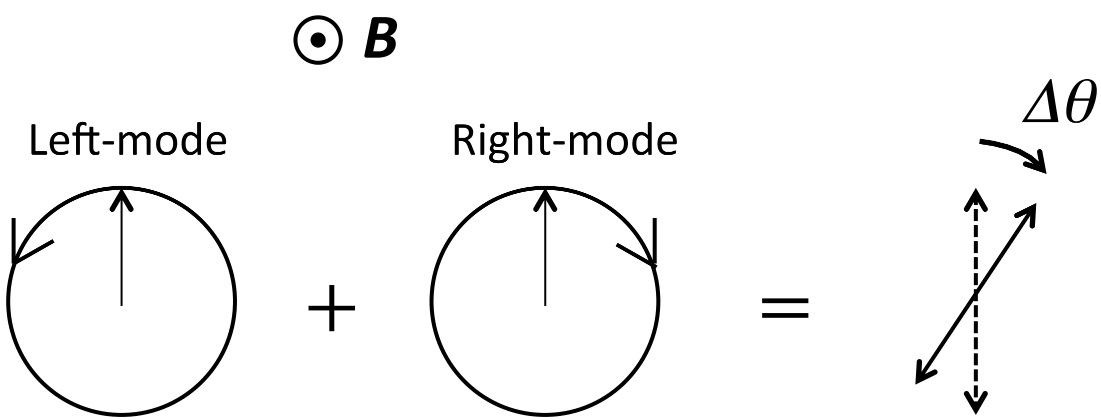
Implications for emission mechanism

- Only the SO model can explain all of the observational results

- Major concern: prompt emission has high efficiency (implying global field distortion), which looks incompatible to high polarization degree
- More accurate, more statistics needed
- Any bright bursts with low Π_L?
- Correlation with spectral shape? (see Axelsson's talk)

Faraday effects

- Polarization degree ➔ B field structure (if synchrotron)
- Faraday effects in the source ➔ B field strength



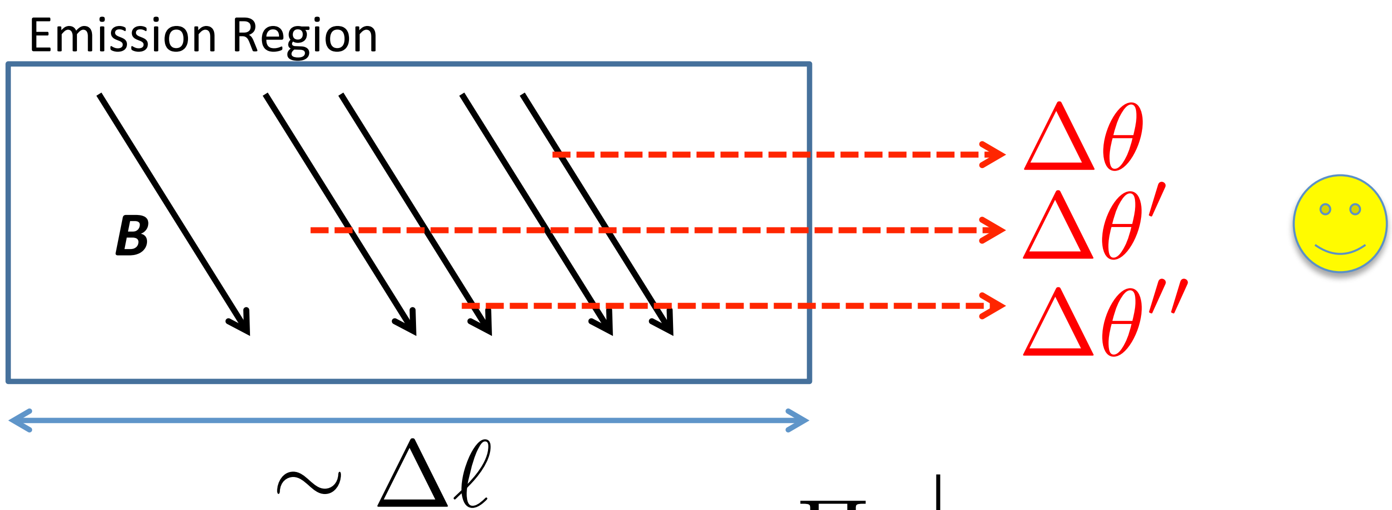
Gradual rotation of linear polarization direction

$$\Delta\theta = \frac{e^3}{\pi m_e^2 c^2} n B \cos\theta \frac{1}{\nu^2} \Delta\ell$$

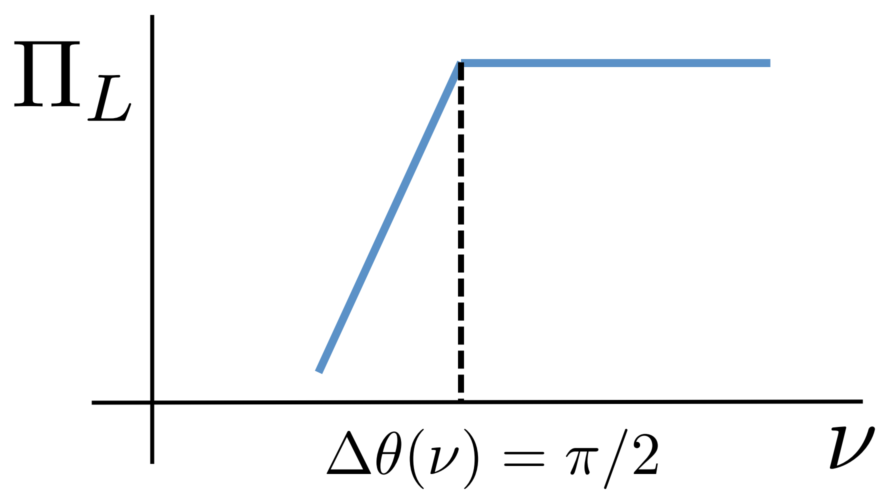
(cf. Rybicki & Lightman 79)

Faraday depolarization

$$\Delta\theta = \frac{e^3}{\pi m_e^2 c^2} n B \cos\theta \frac{1}{\nu^2} \Delta\ell \gtrsim \frac{\pi}{2}$$



- Linear polarizations with different rotation angles are cancelled out

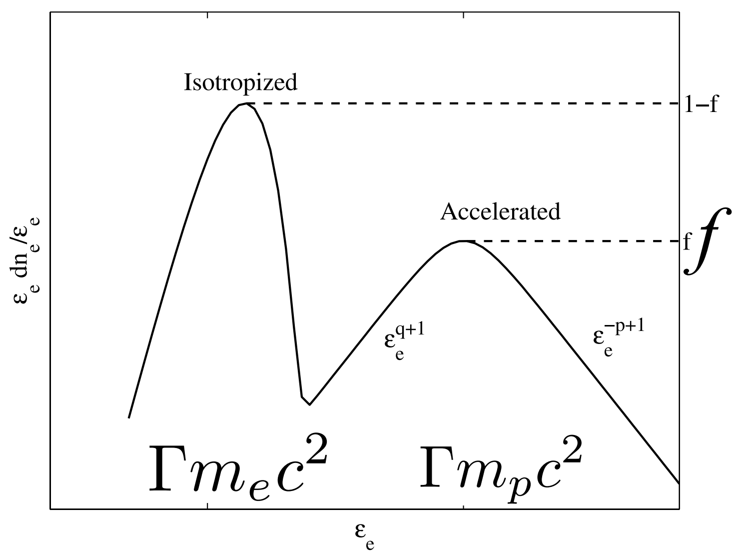


Late-time radio afterglow

For the relativistically-hot source

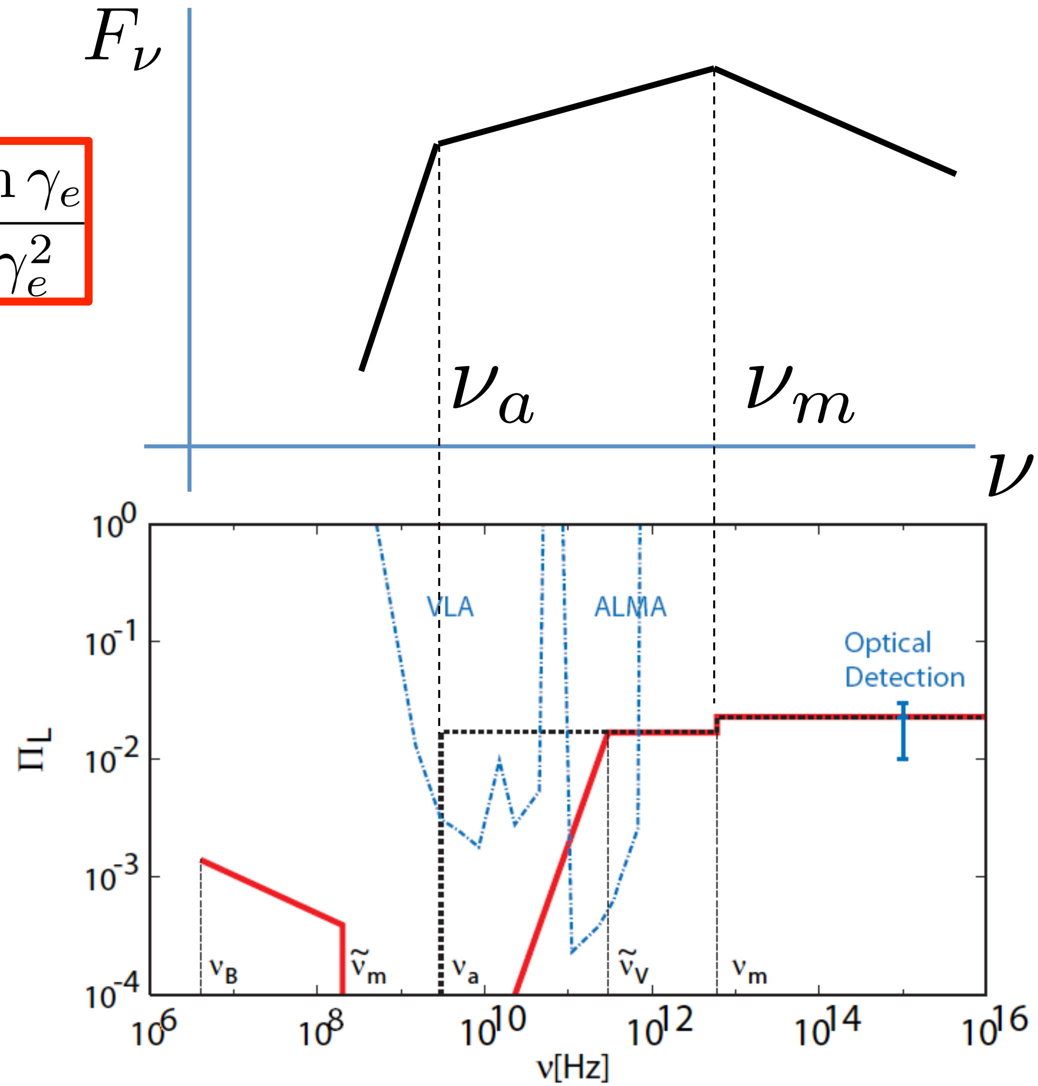
$$\Delta\theta = \frac{e^3}{\pi m_e^2 c^2} nB \cos\theta \frac{1}{\nu^2} \Delta\ell \frac{\ln \gamma_e}{\gamma_e^2}$$

Electron energy distribution



E_{iso} ➔ E_{iso}/f

(Eichler & Waxman 05; see also Warren's talk)

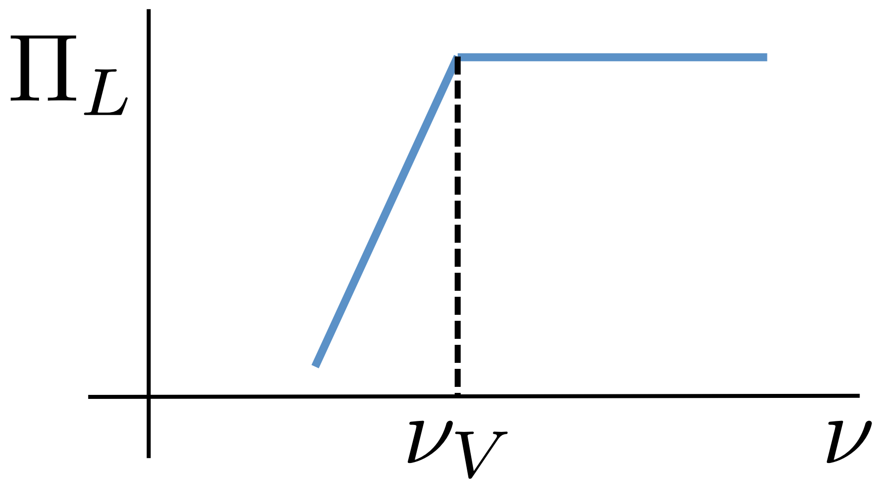


Target of ALMA!!

(KT, Ioka & Nakamura 08)

Faraday effects on prompt emission

- High PL detection ➔ synchrotron with ordered B field
- High efficiency, high Ep ➔ large amount of low-energy electrons ($\gamma_e \sim 1$) ➔ strong Faraday rotation



$$\nu_V \simeq 100\ \epsilon_B^{1/4} L_{52}^{3/4} r_{12}^{-1} \Gamma_{2.5}^{-1}\ \mathrm{keV}$$

Future X-ray polarimetry would further constrain the emission mechanism

(KT in prep.)

Verification of CPT symmetry

Superstring theory, loop quantum gravity, …
➔ Lorentz invariance may be broken ➔ CPT theorem not hold

Lorentz- and CPT- violating dispersion relation of photons (Myers & Pospelov 03)

$$E_{\pm}^2 = p^2 \left[1 \pm 2\xi \left(\frac{p}{M_{\rm pl}}\right)\right]$$

Faraday depolarization can reduce Π_L averaged over 70-300 keV range (GAP)

$$|\xi| < 2 \times 10^{-15}$$

For GRB 110721A; luminosity distance estimated by Yonetoku relation

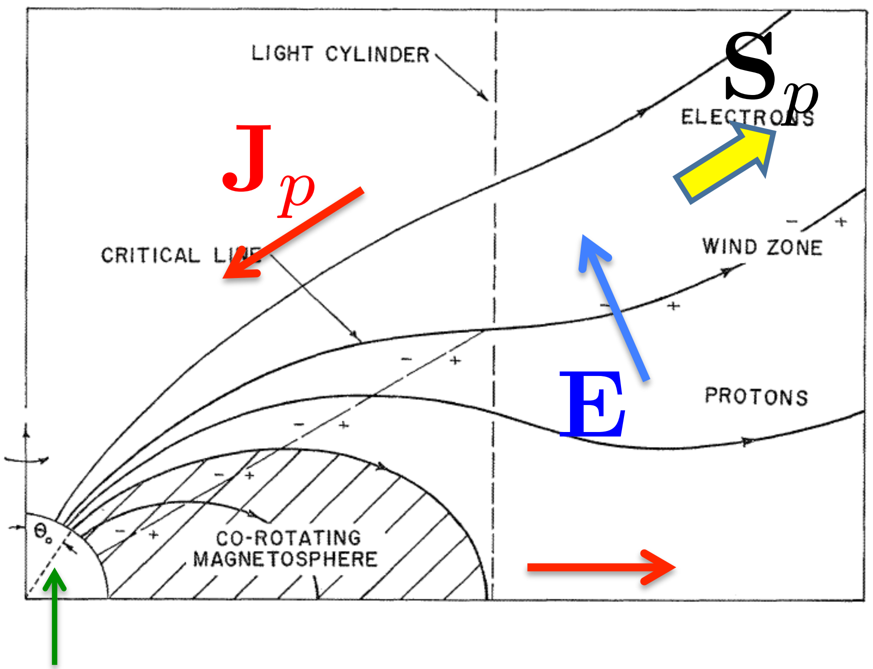
(KT, Mukohyama, Yonetoku+12)

$$|\xi| < 3 \times 10^{-16}$$

For GRB 061122 with confirmed redshift (Gotz+13)

Jet production: theoretical issues

Pulsar winds (Goldreich & Julian 69)

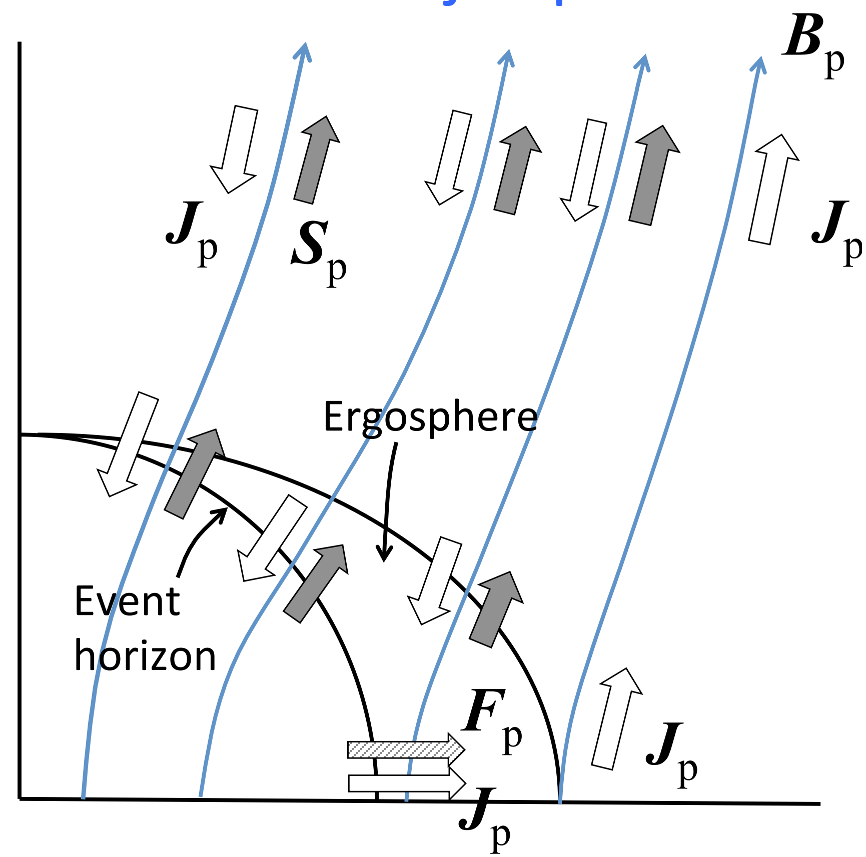


Matter-dominated region

$$\mathbf{E} = -\mathbf{V} \times \mathbf{B}$$

$$\nabla \cdot \mathbf{S}_p = -\mathbf{E} \cdot \mathbf{J}_p$$

Blandford-Znajek process



No matter-dominated region

(KT & Takahara 14; 15 submitted;
Komissarov 04; 09; Blandford & Znajek 77)

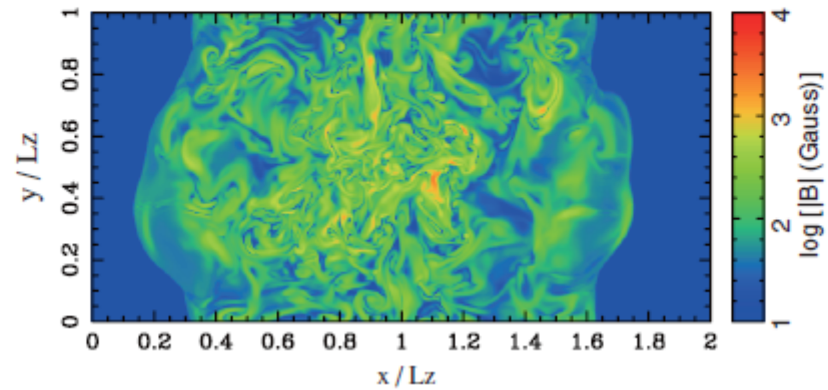
Summary

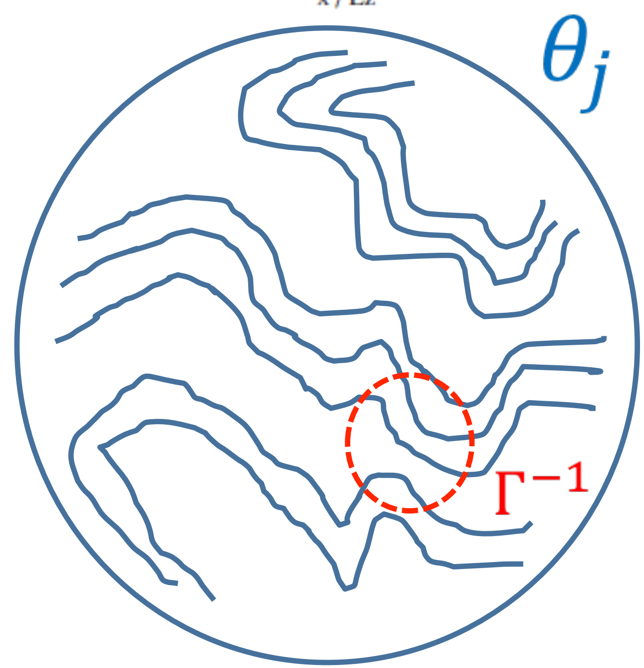
- High-energy polarization study is another frontier (in addition to ν, CR, GW)
- Late-time AG
  - Π_C detection
  - Radio AG: Faraday effects. ALMA!
- Early-time AG: high Π_L detections
- Prompt emission: critical for emission mechanism. More data needed

SH model

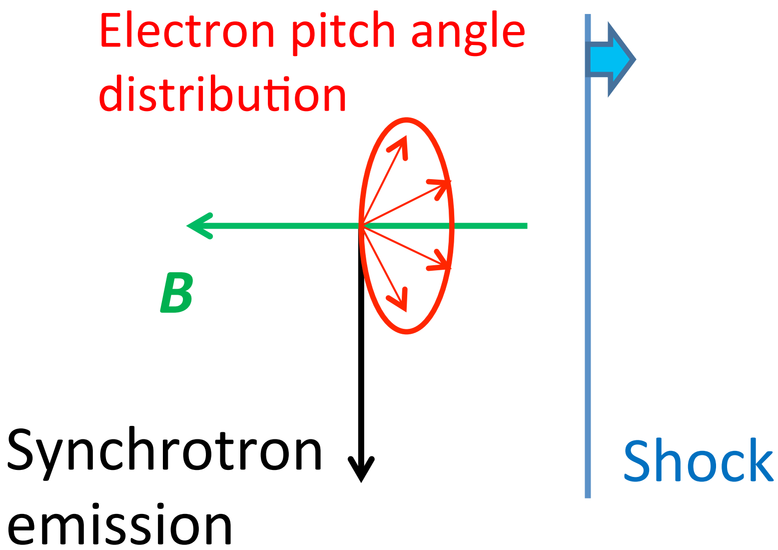
- Random B fields on hydrodynamic scales >> plasma scales (T. Inoue, Asano & Ioka 11; Gruzinov & Waxman 99)
- PA change is natural
- Π_L ~ 70%/√N
- But numerical simulations indicate N ~ 10^3, too high

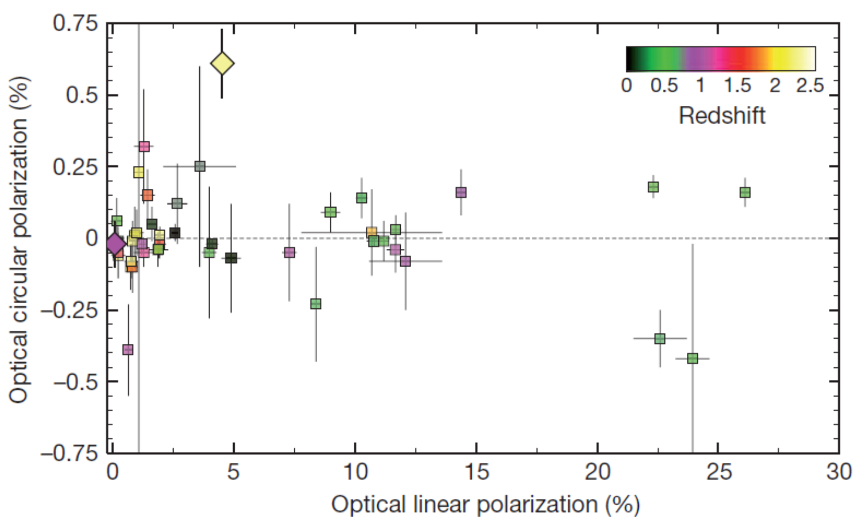
Simulation of internal shock with inhomogeneous density





Highly anisotropic pitch angles?

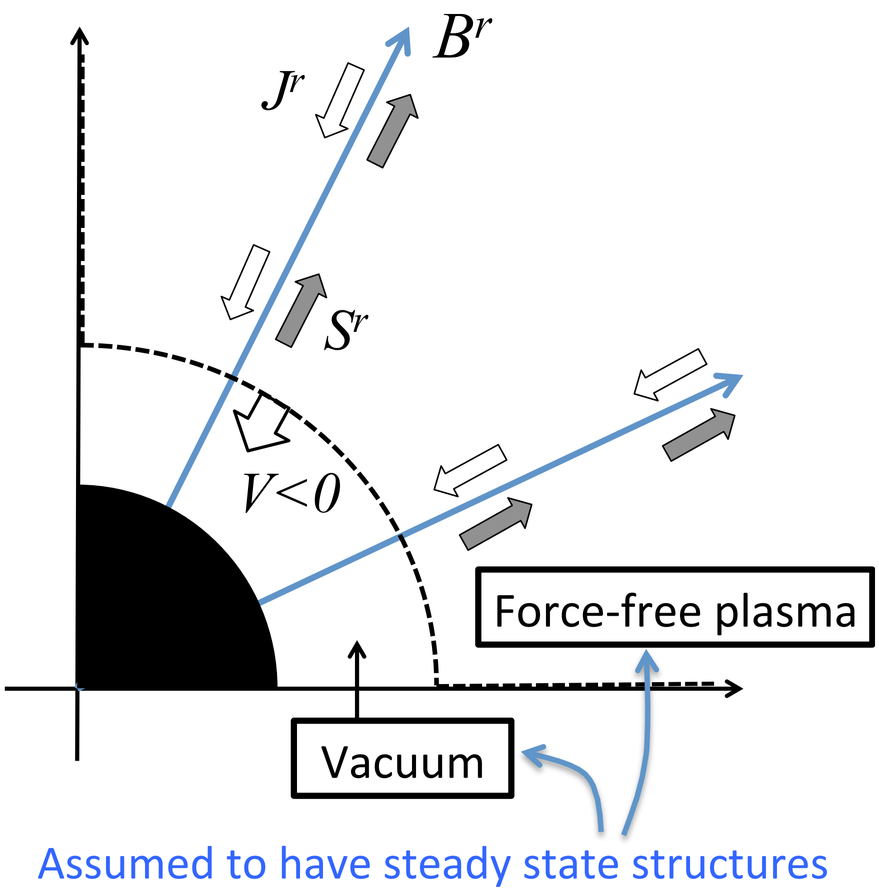




Optical circular polarizations in QSOs

Process toward steady state

We try to understand the time-dependent process with a toy model



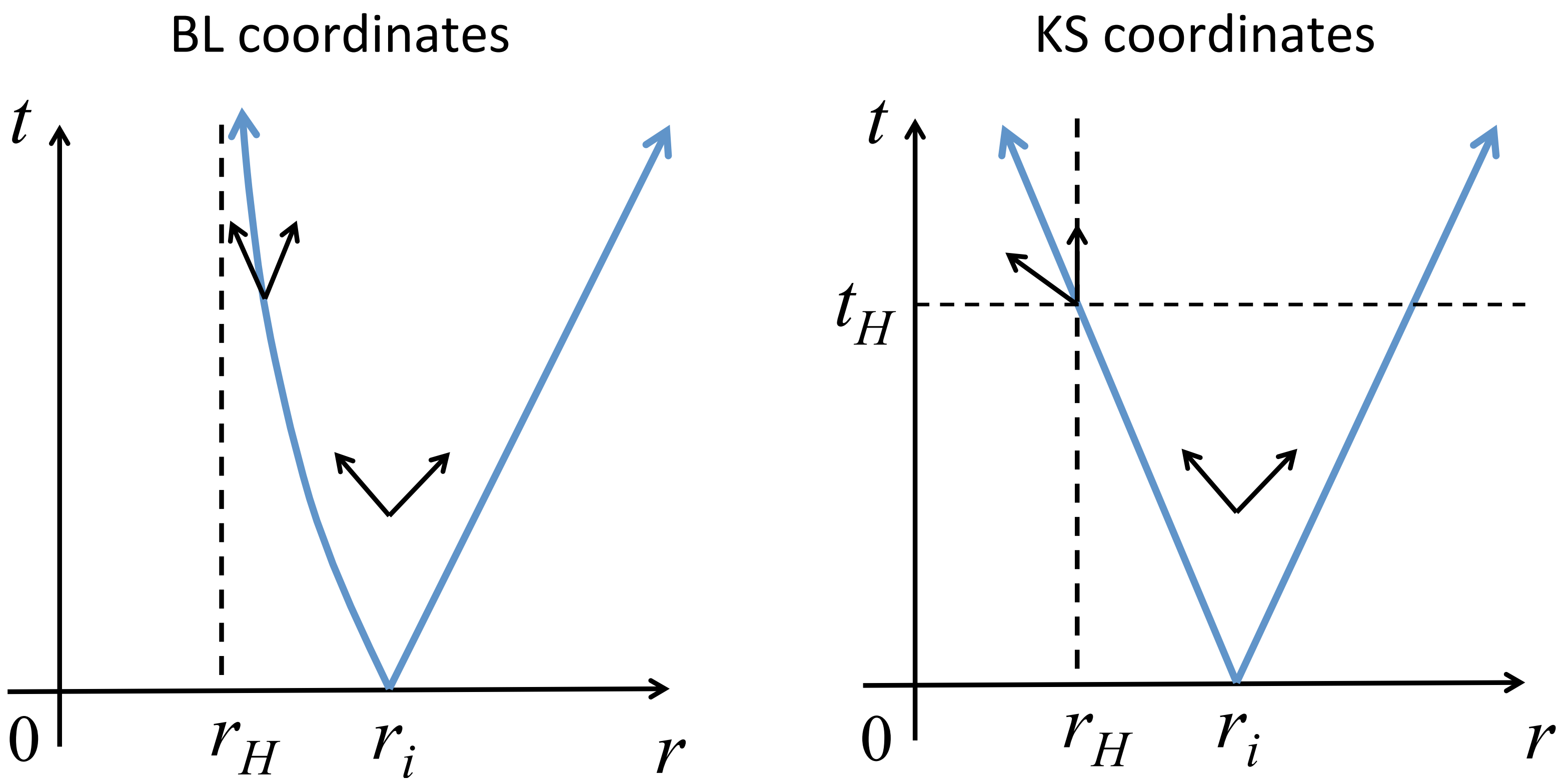
- We obtain junction conditions from the Maxwell equations
- If $J^\theta = C^\theta \delta(R) = 0$, V becomes null speed (in both BL & KS coordinates)
- ➔ $J^\theta > 0$ at the boundary
- The fluxes are causally built at the in-going boundary

$$\nabla \cdot \mathbf{L}_p = -\partial_t l - (\mathbf{J}_p \times \mathbf{B}_p) \cdot \mathbf{m}$$

$$\nabla \cdot \mathbf{S}_p = -\partial_t e - \mathbf{E} \cdot \mathbf{J}_p$$

(KT & Takahara 2015 submitted)

Space-time diagram



In the steady state, no electromagnetic source of the Poynting flux is required (in the case of no resistivity)