Frontier Research Institute for Interdisciplinary Sciences
Tohoku University

Theoretical Astrophysics
Tohoku University

GRBの偏光

當真賢二
（東北大　学際研/天文専攻）

『ガンマ線バースト研究の新機軸』@宇宙線研究所 2017/11/21-23

AGN Jet Workshop 2018

"Dawn of a New Era for Black Hole Jets in Active Galaxies"
Tohoku University, 1/25-27/2018
Registration Deadline: 12/17/2017

Event Horizon Telescope, East Asia VLBI Network, …

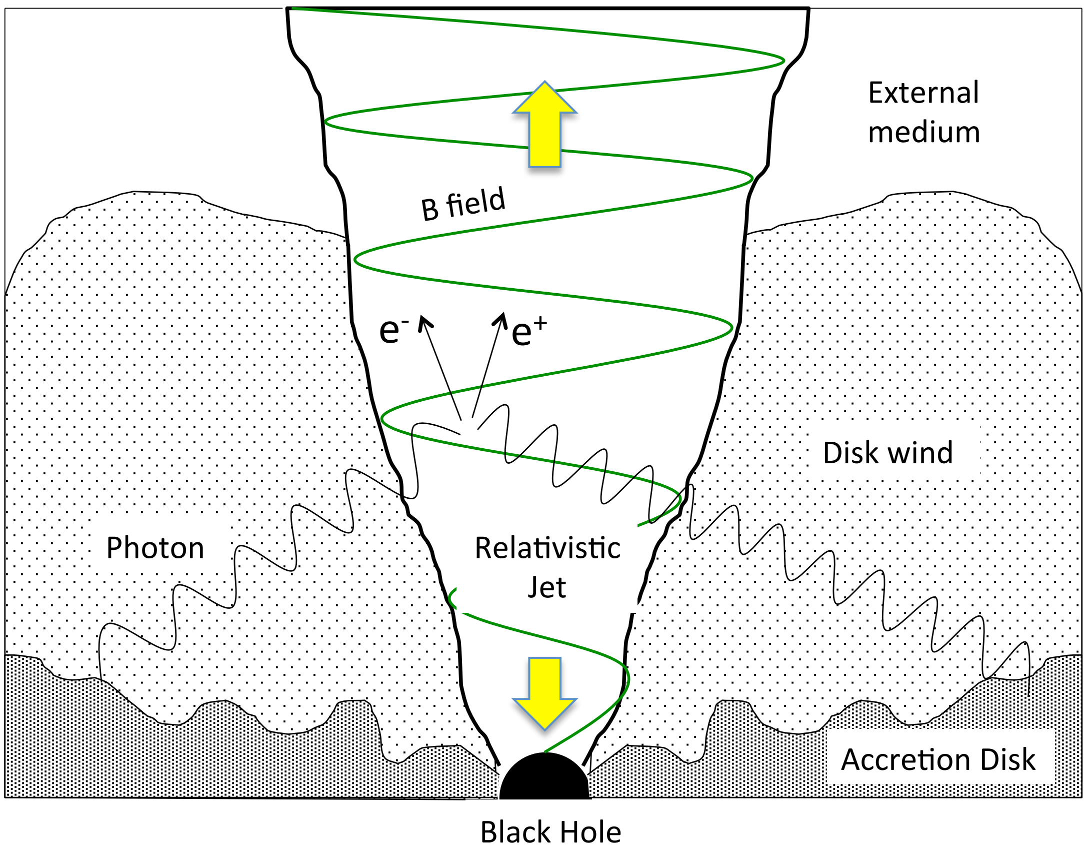
HST image credit: NASA and the Hubble Heritage Team

Outline

- Theoretical issues on relativistic jets
- Physics of GRB polarization
  - Late-time optical (& radio) afterglow
  - Early-time optical afterglow
  - Prompt γ-ray emission
- Macronova polarization
- Summary

Relativistic Jets

Fixed
- GR MHD simulations (e.g. Komissarov 01; Koide+ 02; McKinney & Gammie 04; Barkov & Komissarov 08; Tchekhovskoy+ 11)



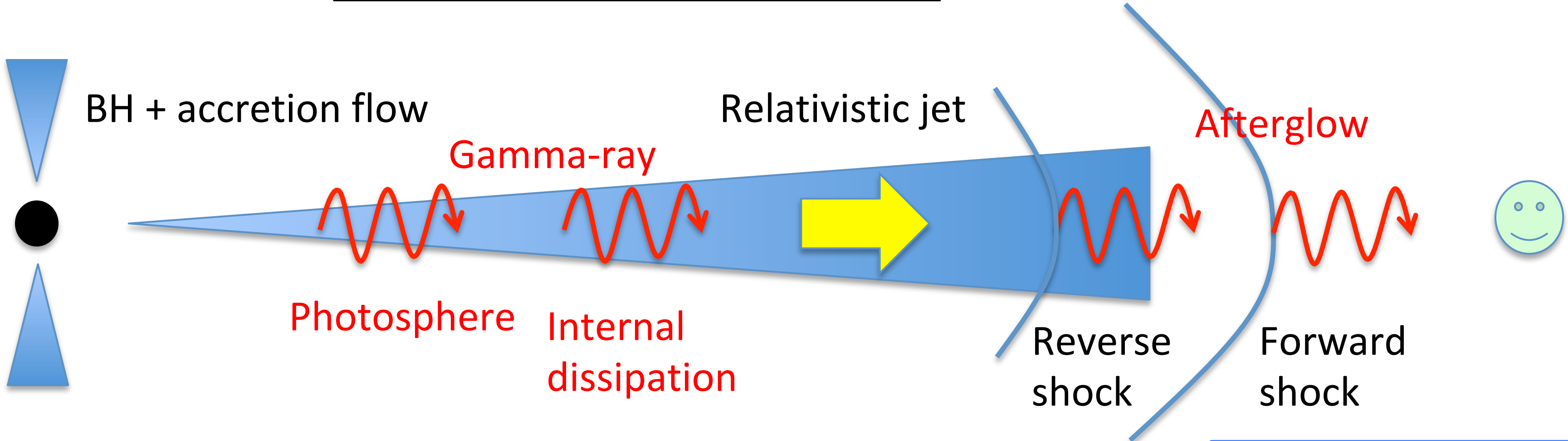
- Quasi-steady structure
- Poynting-dominated jet in funnel region
  - BH energy/AM extraction (Blandford & Znajek 1977)
  - $B_\phi >> B_p$ at far zone
  - Bulk acceleration by Lorentz force
  - Dissipation?
- Collimation by disk wind
- Outflow + inflow
  - Mass loading?
  - Density floor in simulations

(當真 2017, 物理学会誌)

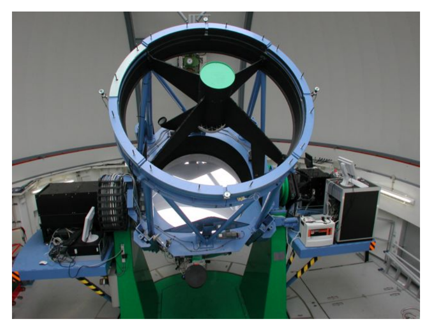
GRB Polarization

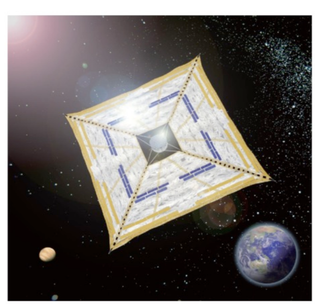
Jet driving & dissipation physics

Collisionless shock physics



Recent reports of detections:
GAP, INTEGRAL
(e.g. Yonetoku+11;12; KT 13)
AstroSat, POLAR, SPHiNX, LEAP,..

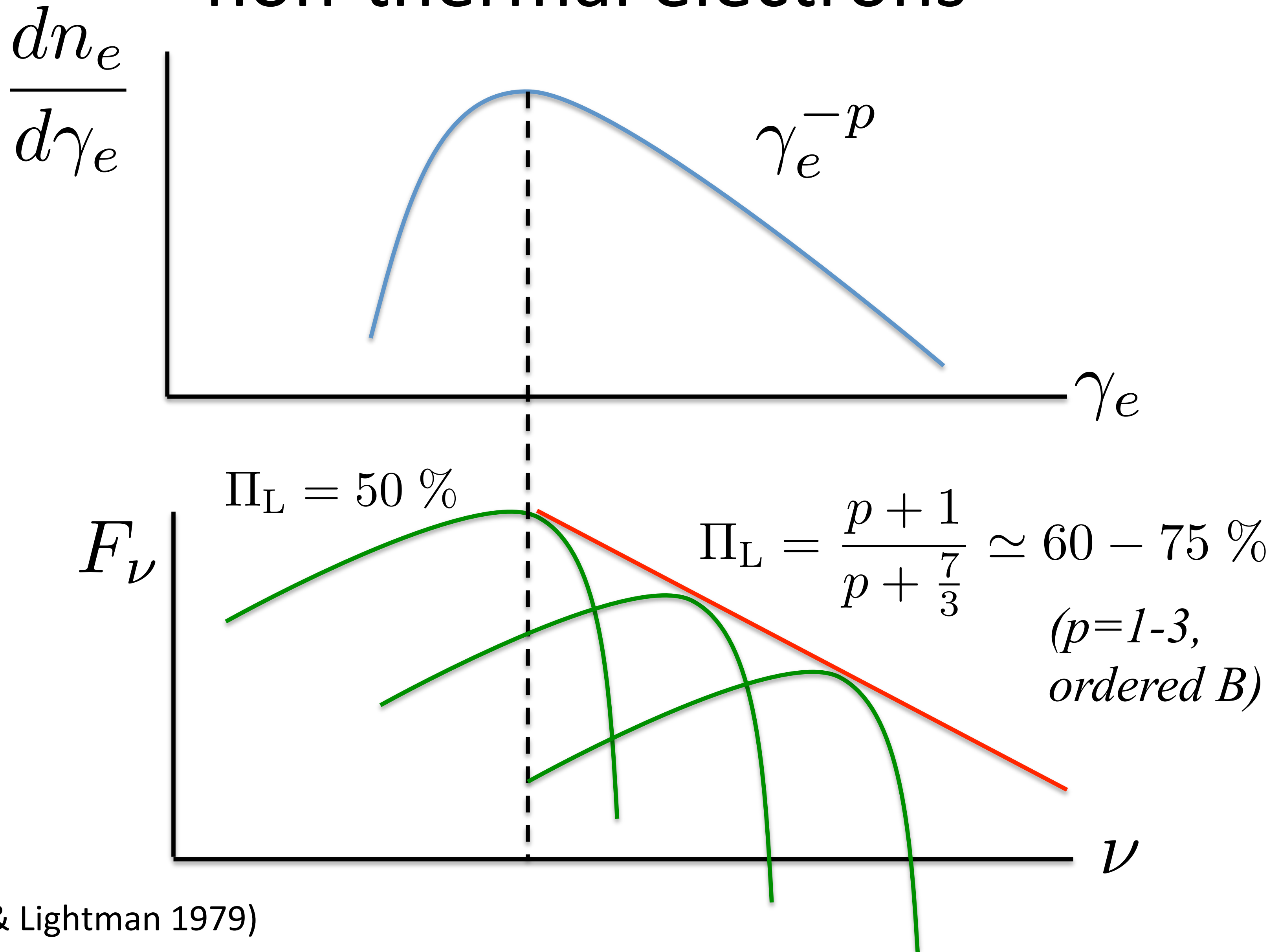




Late-time afterglow
Π_L ~ 1-3%
(Covino+03)
Π_C ~ 0.6 % !!
(Wiersema+14)
ALMA?

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

Synchrotron emission from non-thermal electrons



(Rybicki & Lightman 1979)

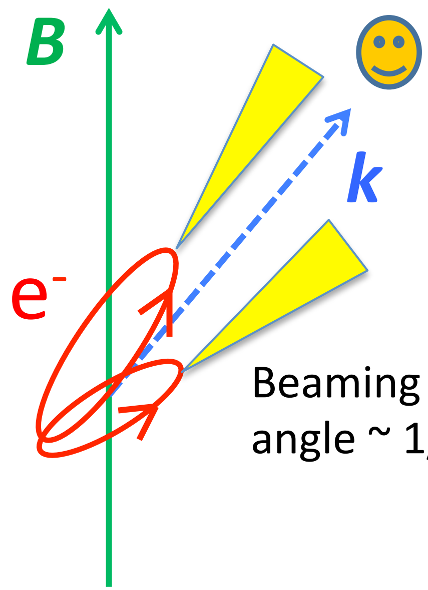
Synchrotron emission

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

$$\ell_e/\gamma_e \simeq 3 \times 10^3 \ B^{-1} \ \mathrm{cm}$$

- Linear polarization Π_L = p+1/(p+7/3) ~ 60-75%, with direction perpendicular to B & k

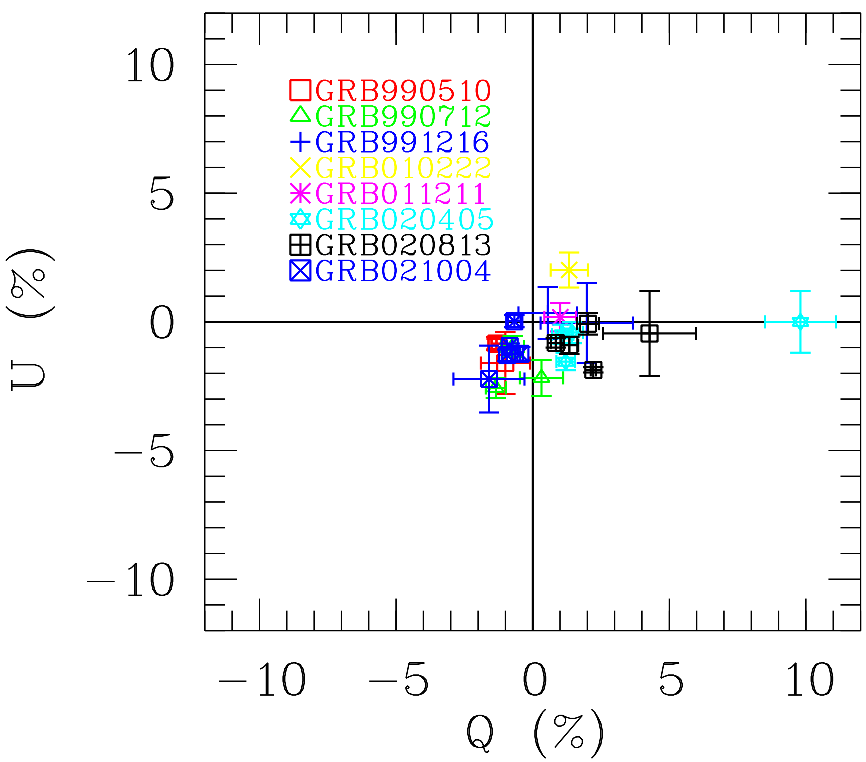
- Circular polarization is nearly canceled out: $\Pi_C \sim 1/\gamma_e << 1$



Beaming into angle ~ $1/\gamma_e$

(e.g. Rybicki & Lightman 79; Melrose 80)

Late-time afterglow polarization

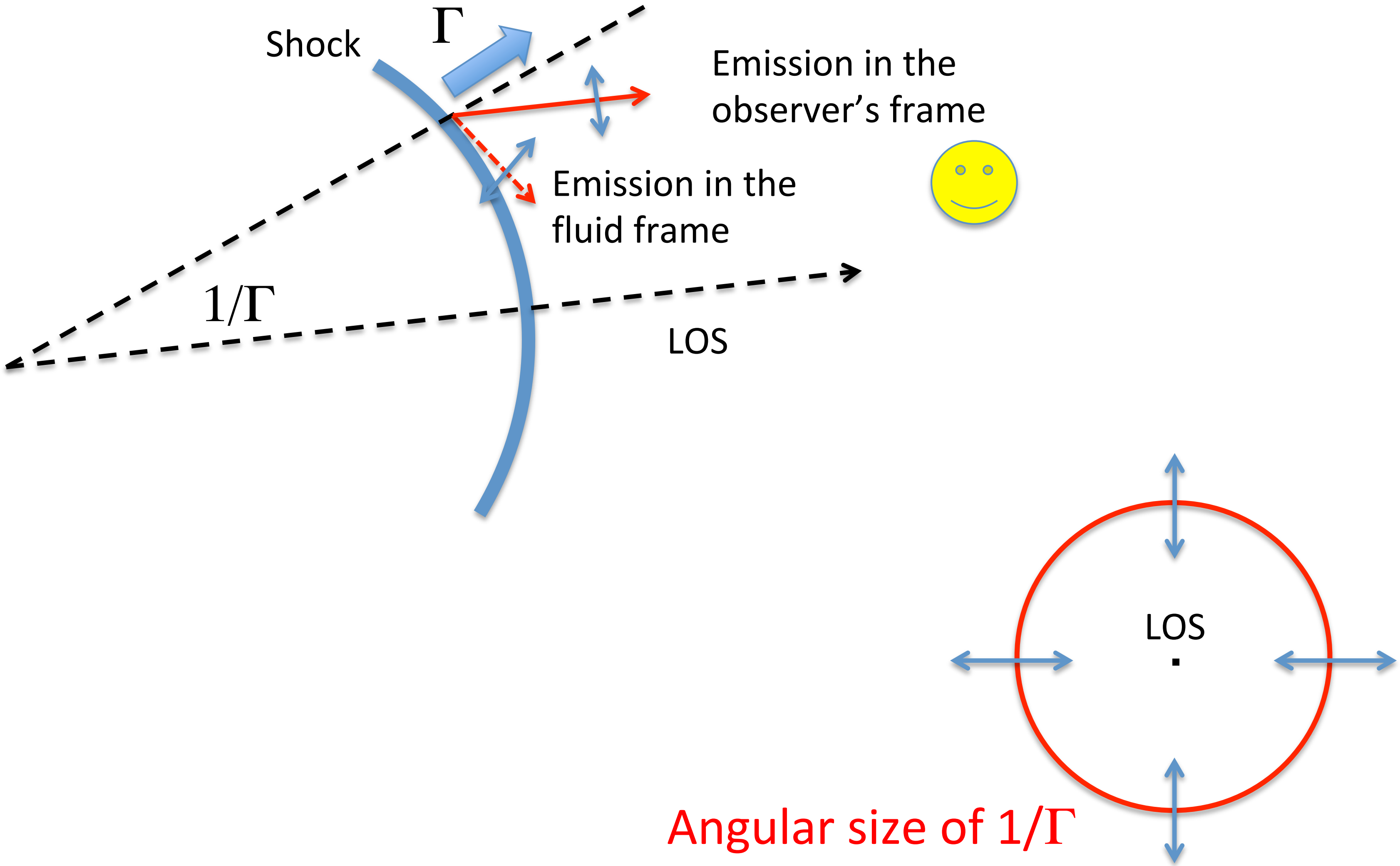


Burst	P (%)	ϑ (°)	Δt (hours)	Band
GRB 990123	< 2.3		18	R
GRB 990510	1.7 ± 0.2	101 ± 3	18	R
	1.6 ± 0.2	96 ± 4	21	R
	< 3.9		43	R
GRB 990712	2.9 ± 0.4	122 ± 4	11	R
	1.2 ± 0.4	116 ± 10	17	R
	2.2 ± 0.7	139 ± 10	35	R
GRB 991216	< 2.7		35	V
	< 5		60	V
GRB 010222	1.4 ± 0.6		22	V
GRB 011211	< 2.0		37	R
GRB 020405	1.5 ± 0.4	172 ± 8	29	R
	9.8 ± 1.3	180 ± 4	31	V
	2.0 ± 0.3	154 ± 5	52	V
	1.5 ± 0.4	168 ± 9	78	V
GRB 020813	$2.3 - 3.1$	$153 - 162$	6	SP
	1.2 ± 0.2	158 ± 5	24	V
	1.6 ± 0.3	163 ± 6	29	V
	2.0 ± 0.4	179 ± 6	50	V
	4.3 ± 1.7	177 ± 11	96	V
GRB 021004	< 5		11	J
	1.3 ± 0.1	114 ± 2	15	V
	1.3 ± 0.3	125 ± 1	16	V
	$1.4 - 2.3$	$111 - 126$	19	SP
	0.7 ± 0.2	89 ± 10	91	V

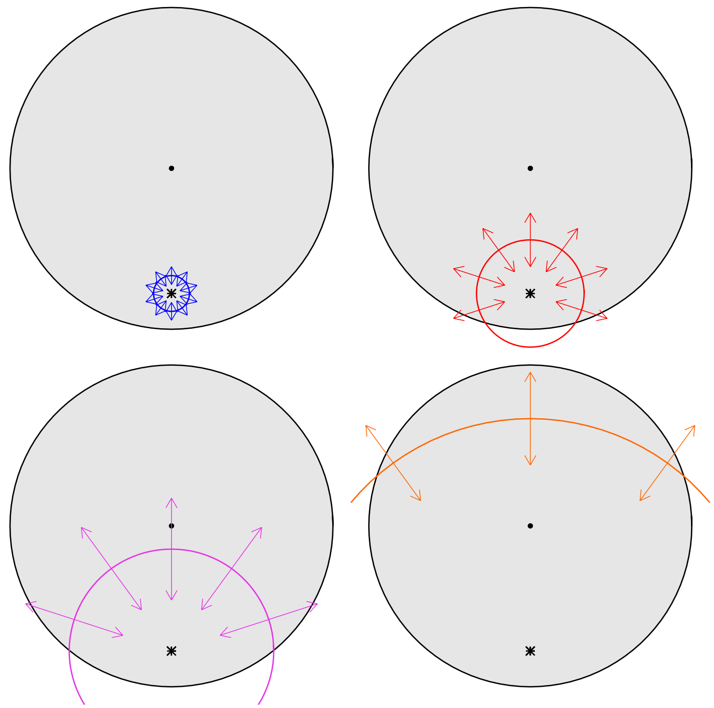
Π_L ~ 1-3% at *T* ~ *1* day ➔ B field is not ordered

(Covino+03)

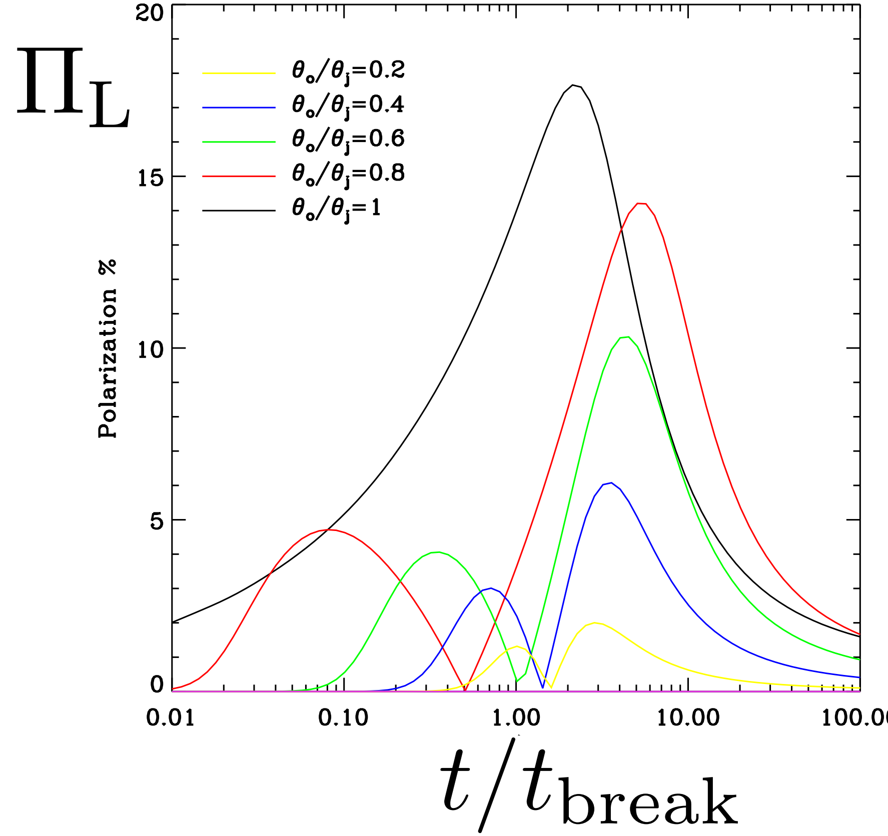
Random B field parallel to shock plane



(Sari 99; Ghsellini & Lazzati 99)

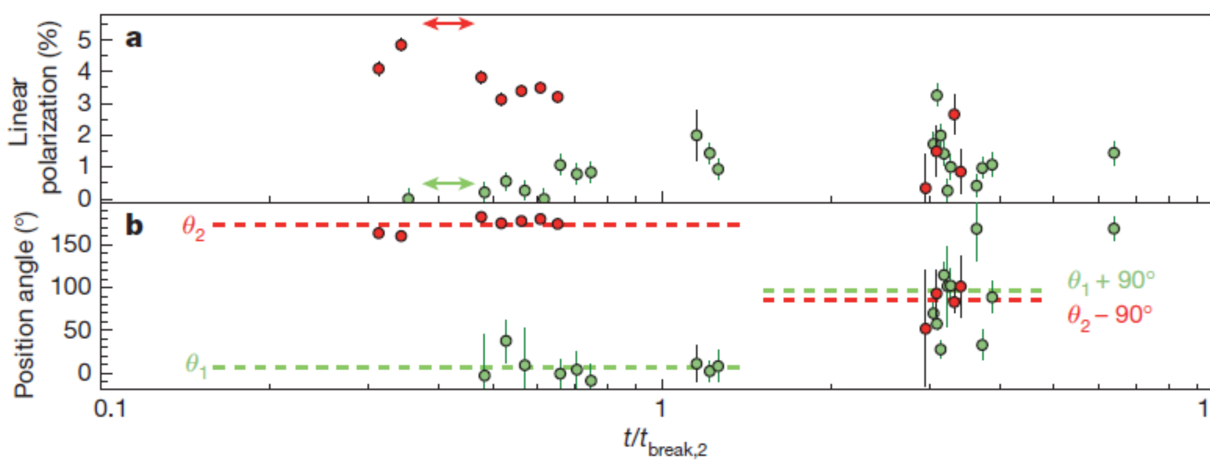


(Sari 99; Ghisellini & Lazzati 99; Lazzati 06)



GRB 121024A, GRB 091018

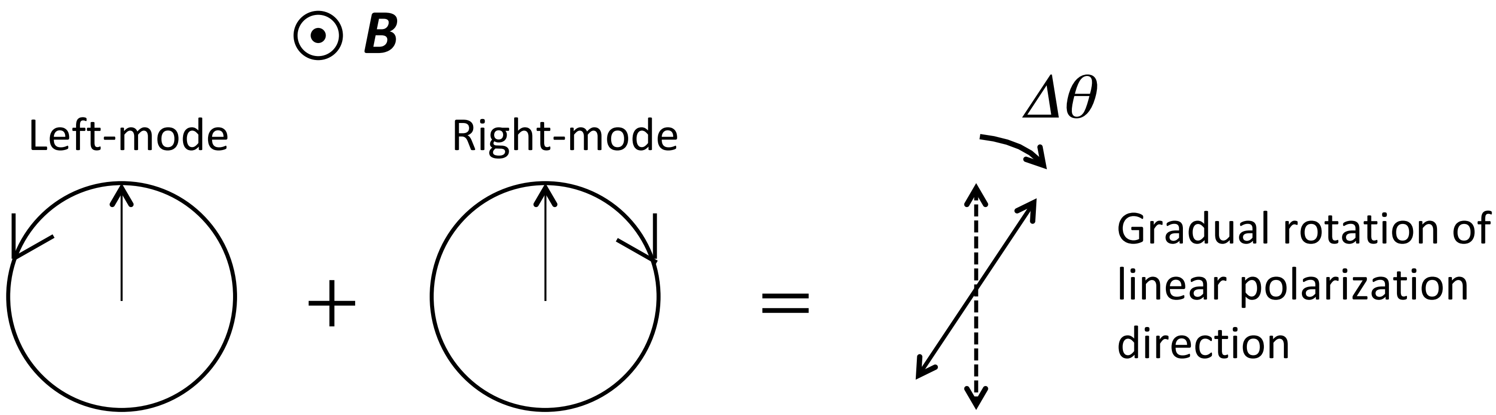
Consistent with the observed temporal change of pol. angle



(Wiersema, Covino, KT+14)

Faraday effects

- Polarization degree → B field structure (if synchrotron)
- Faraday effects in the source → B strength, density…

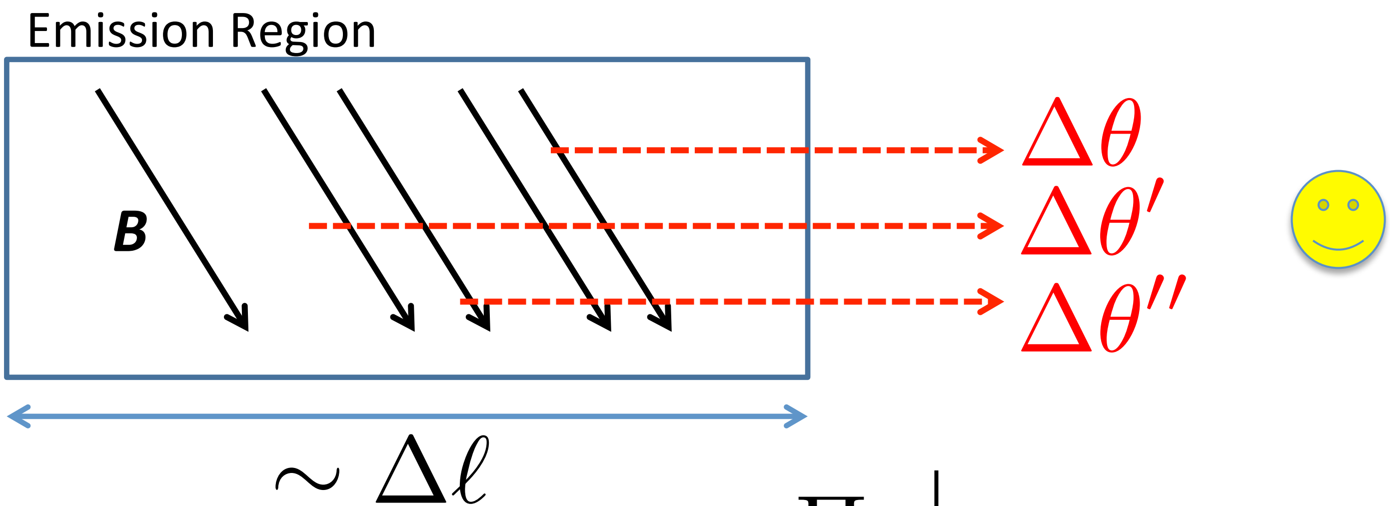


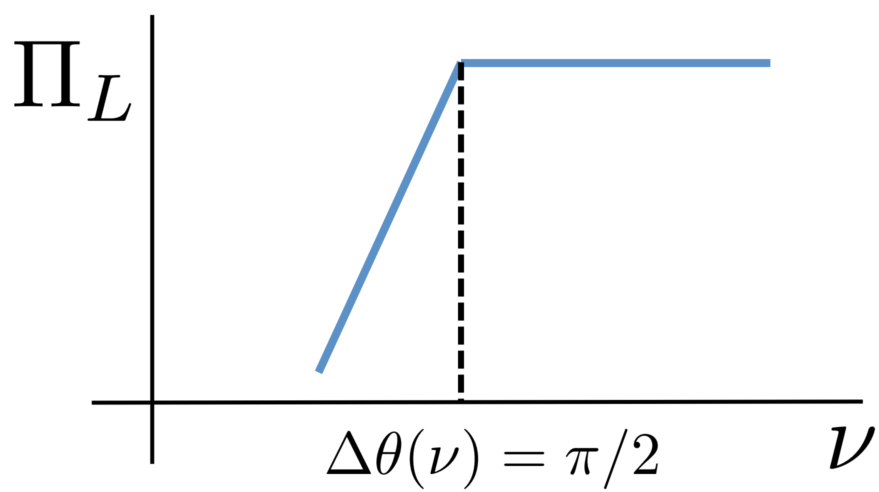
$$\Delta\theta = \frac{e^3}{\pi m_e^2 c^2} n B \cos\theta \frac{1}{\nu^2} \Delta\ell$$

(cf. Rybicki & Lightman 79)

Faraday depolarization

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





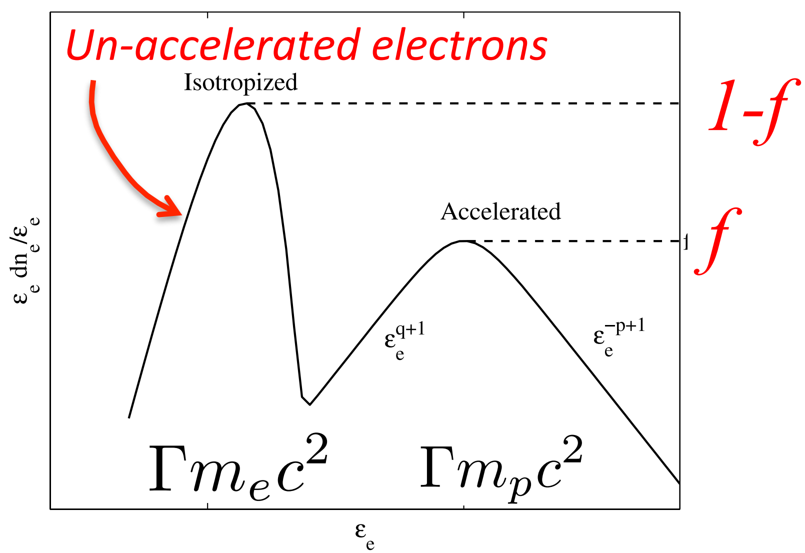
- Linear polarizations with different rotation angles are cancelled out

Late-time radio afterglow

For the relativistically-hot source
(e.g. Jones & O'Dell 77)

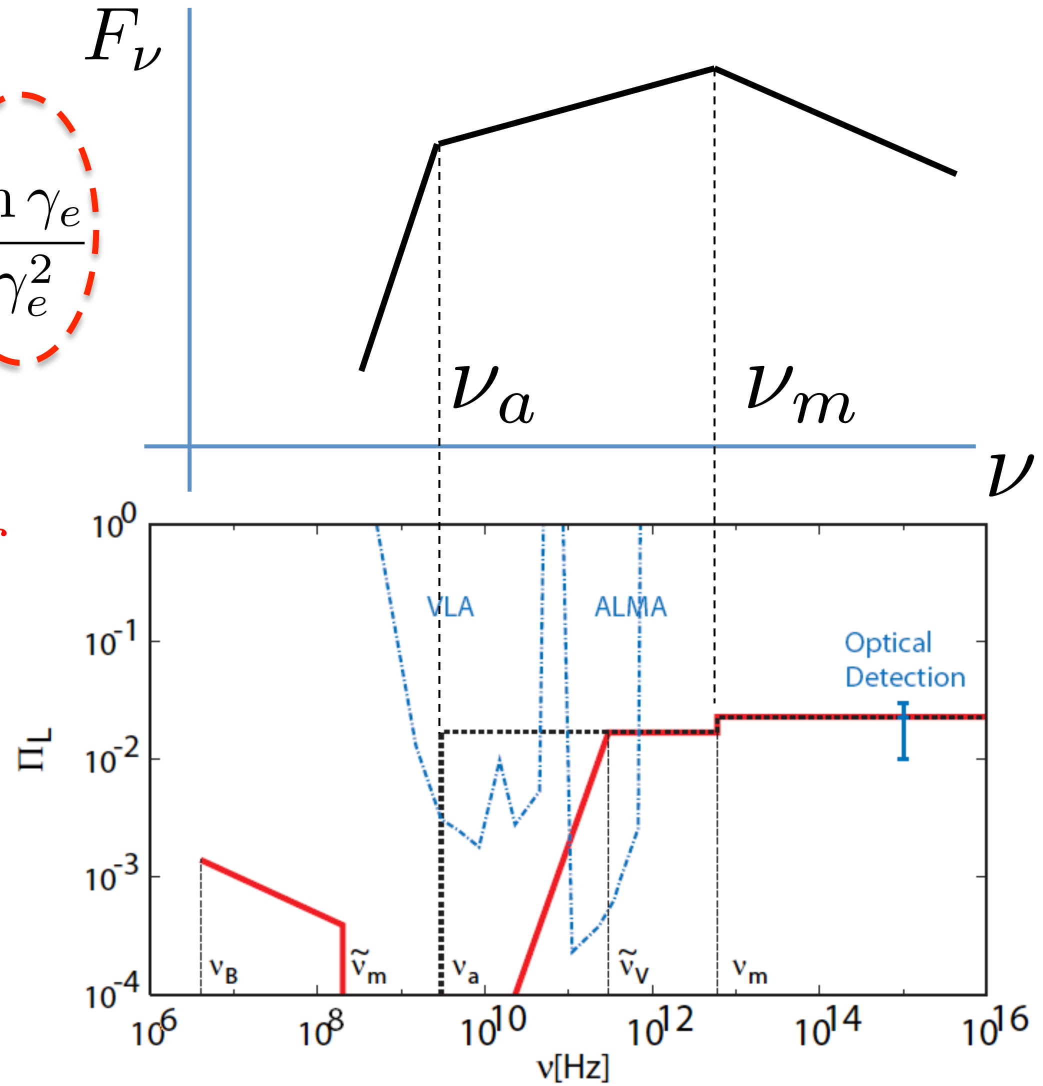
$$\Delta\theta = \frac{e^3}{\pi m_e^2 c^2} n B \cos\theta \frac{1}{\nu^2} \Delta\ell \frac{\ln \gamma_e}{\gamma_e^2}$$

Electron energy distribution



E_{iso} ➔ E_{iso}/f !!

(Eichler & Waxman 05)

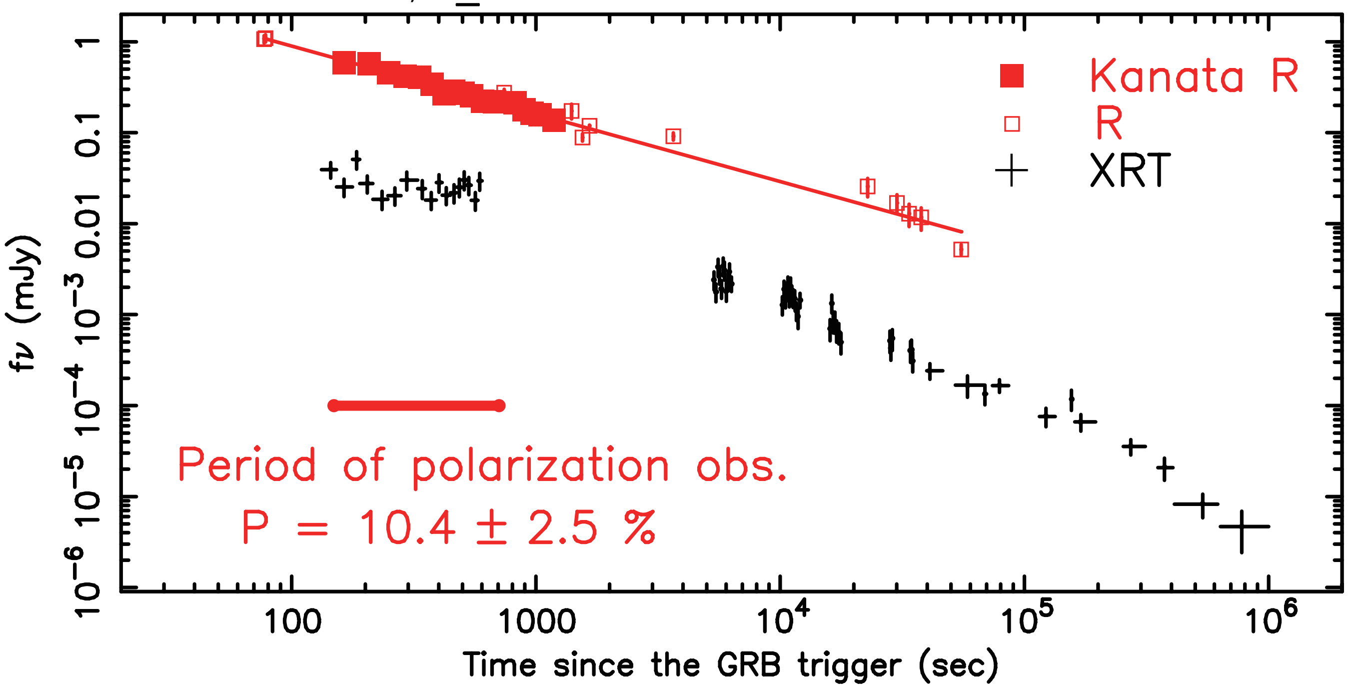


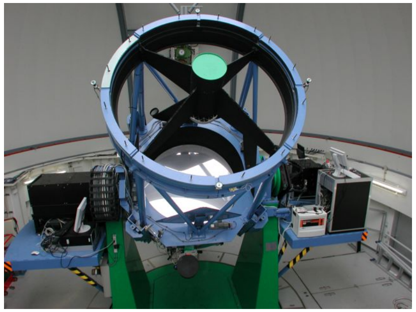
Target of ALMA!!

(KT, Ioka & Nakamura 08)

Early-time optical afterglow

GRB 091208B, T_90 = 14.9sec





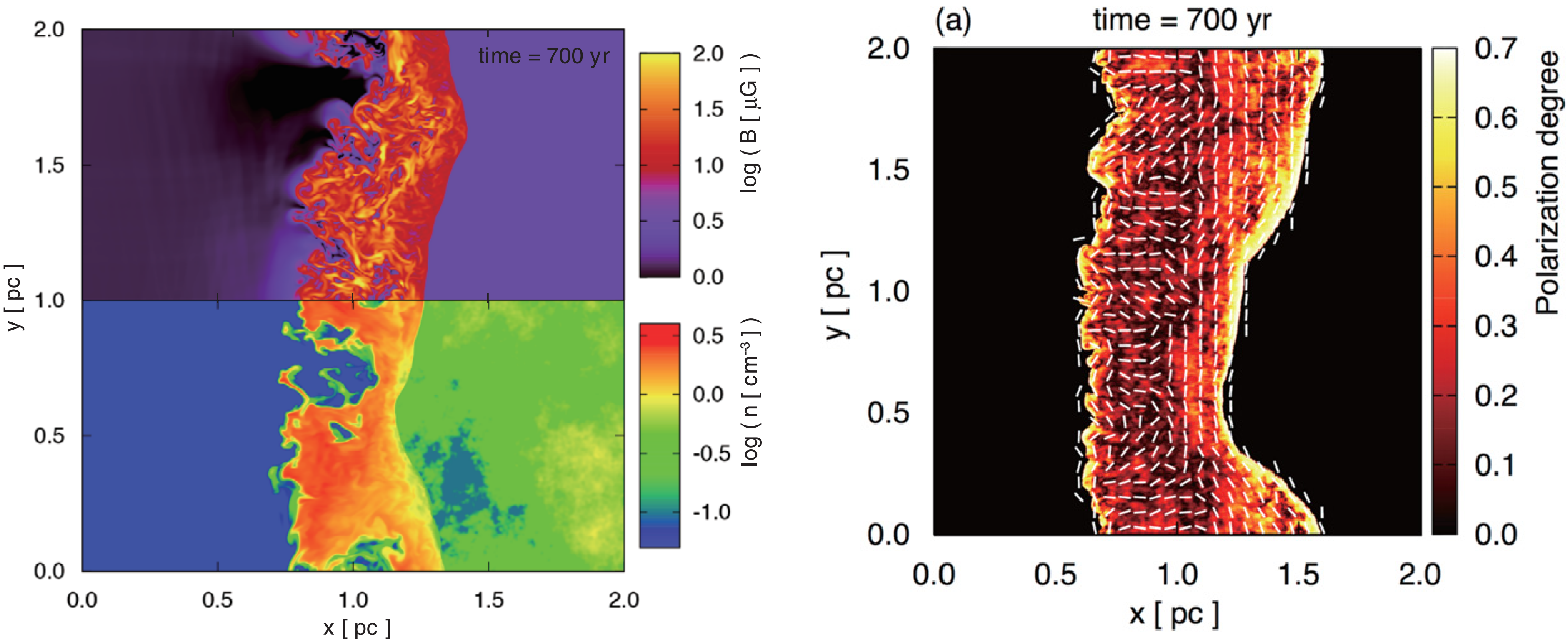
Kanata Telescope at Hiroshima U

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

This implies the forward shock involves large-scale B fields (hydro-scale rather than plasma-scale)

(Uehara, KT, Kawabata+12)

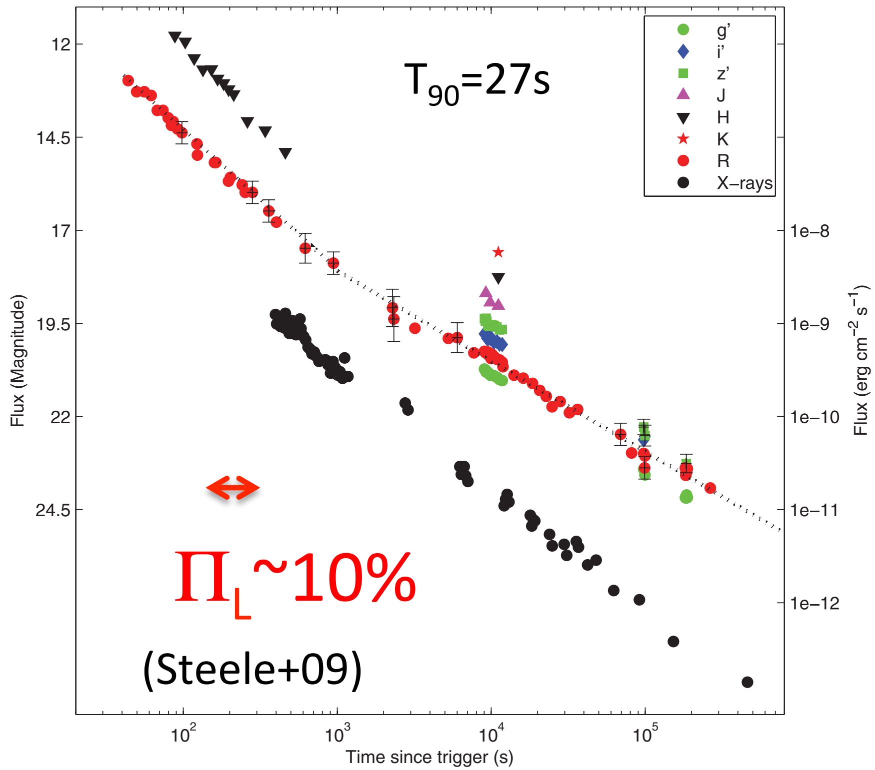
Simulations of supernova remnants



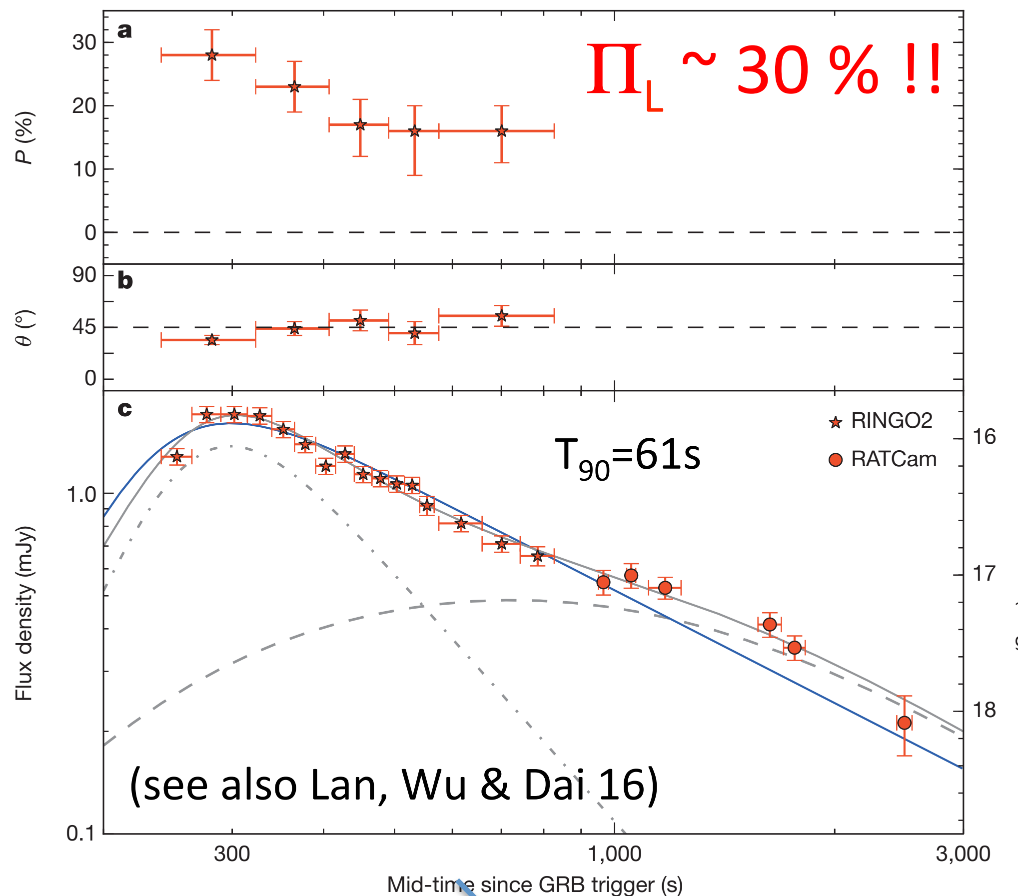
Shock propagation in inhomogeneous external medium amplifies B field with hydro-scale

(T. Inoue, Shimoda, et al. 2013)

GRB 090102 (Gendre+10)

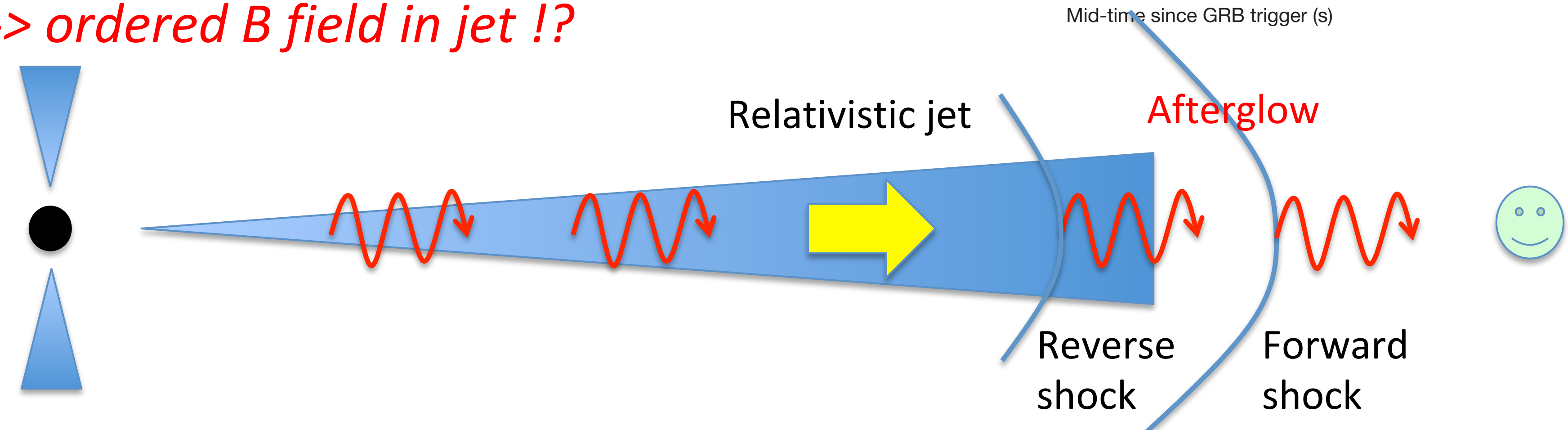


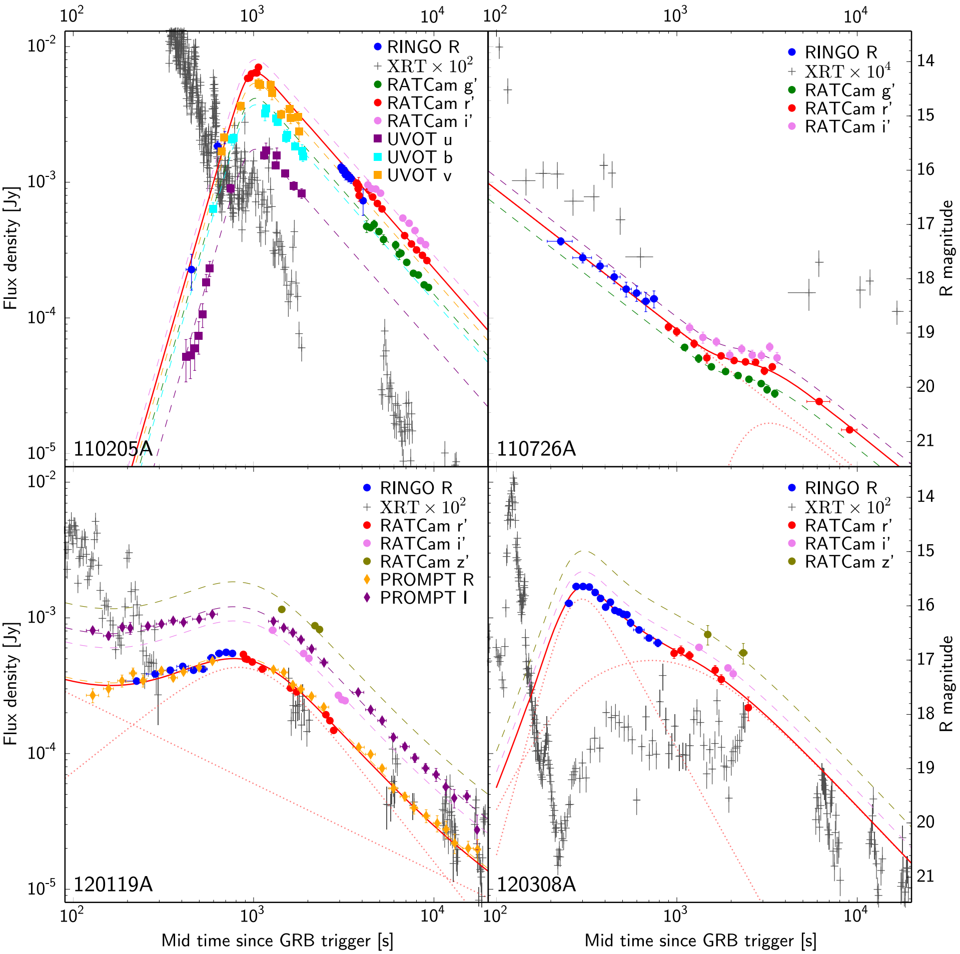
GRB 120308A (Mundell+13)

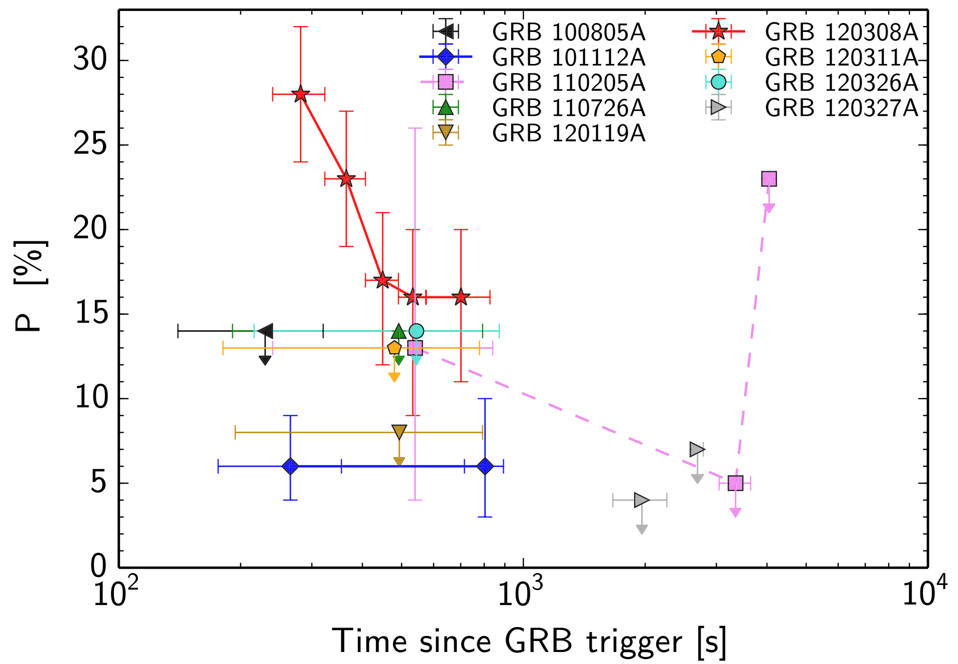


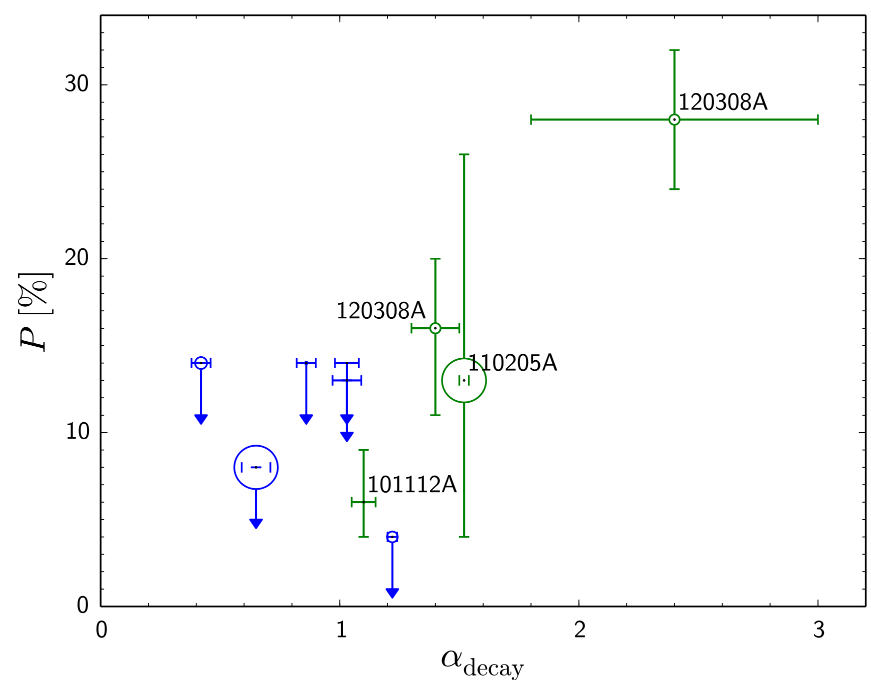
Reverse shock emission…!?

-> ordered B field in jet !?





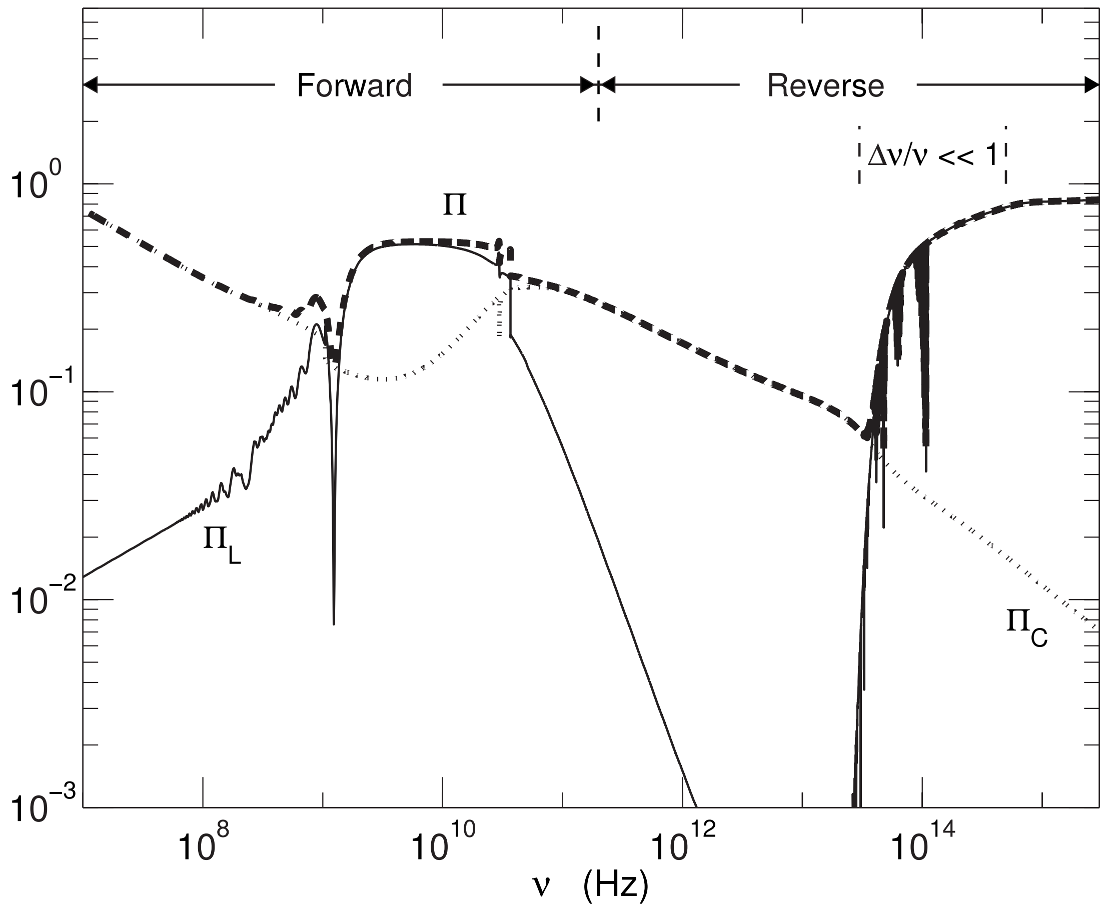




Steeper decay -> Reverse shock emission (?)

(Steele et al. 2017)

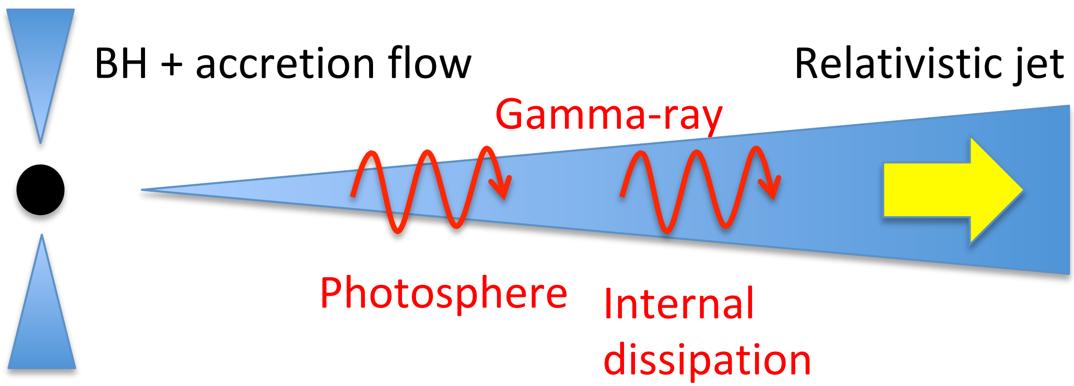
Faraday depolari for early afterglow?



$$\nu_V \simeq 2 \times 10^{14}\ \mathrm{Hz}\ E_{54}^{3/8} n_0^{7/16} T_1^{-15/16}$$

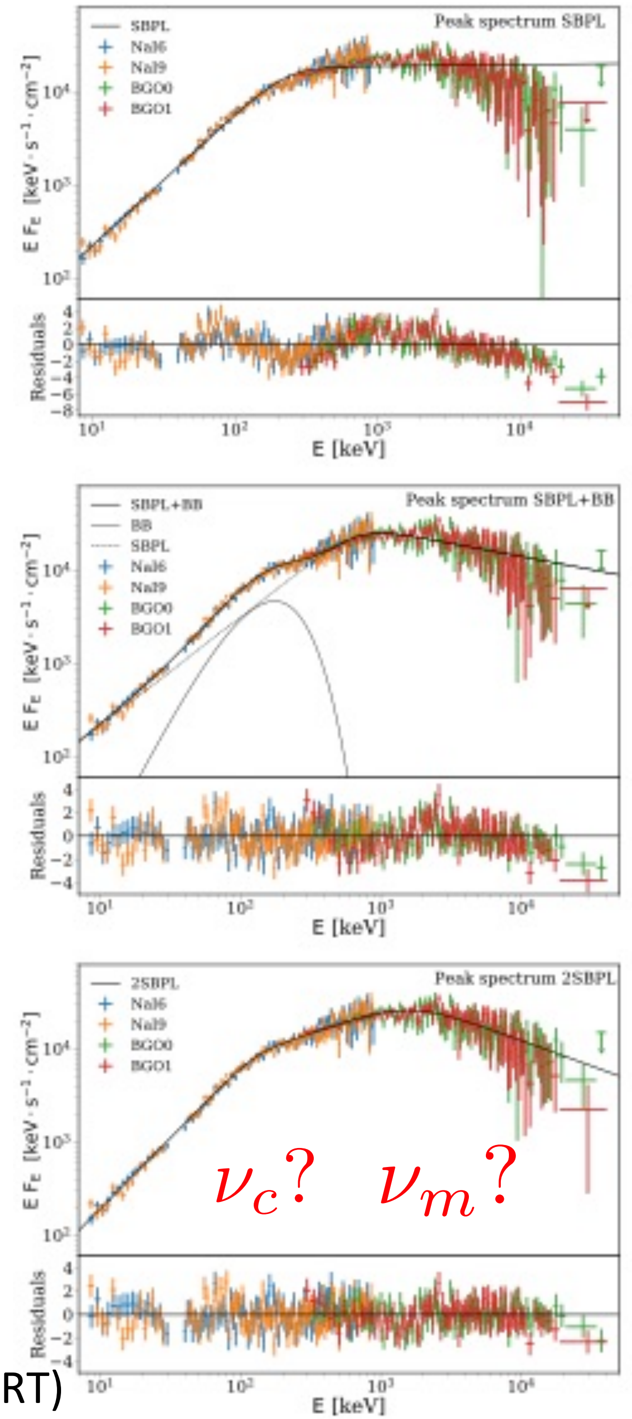
(Sagiv, Waxman & Loeb 2004)

Prompt emission

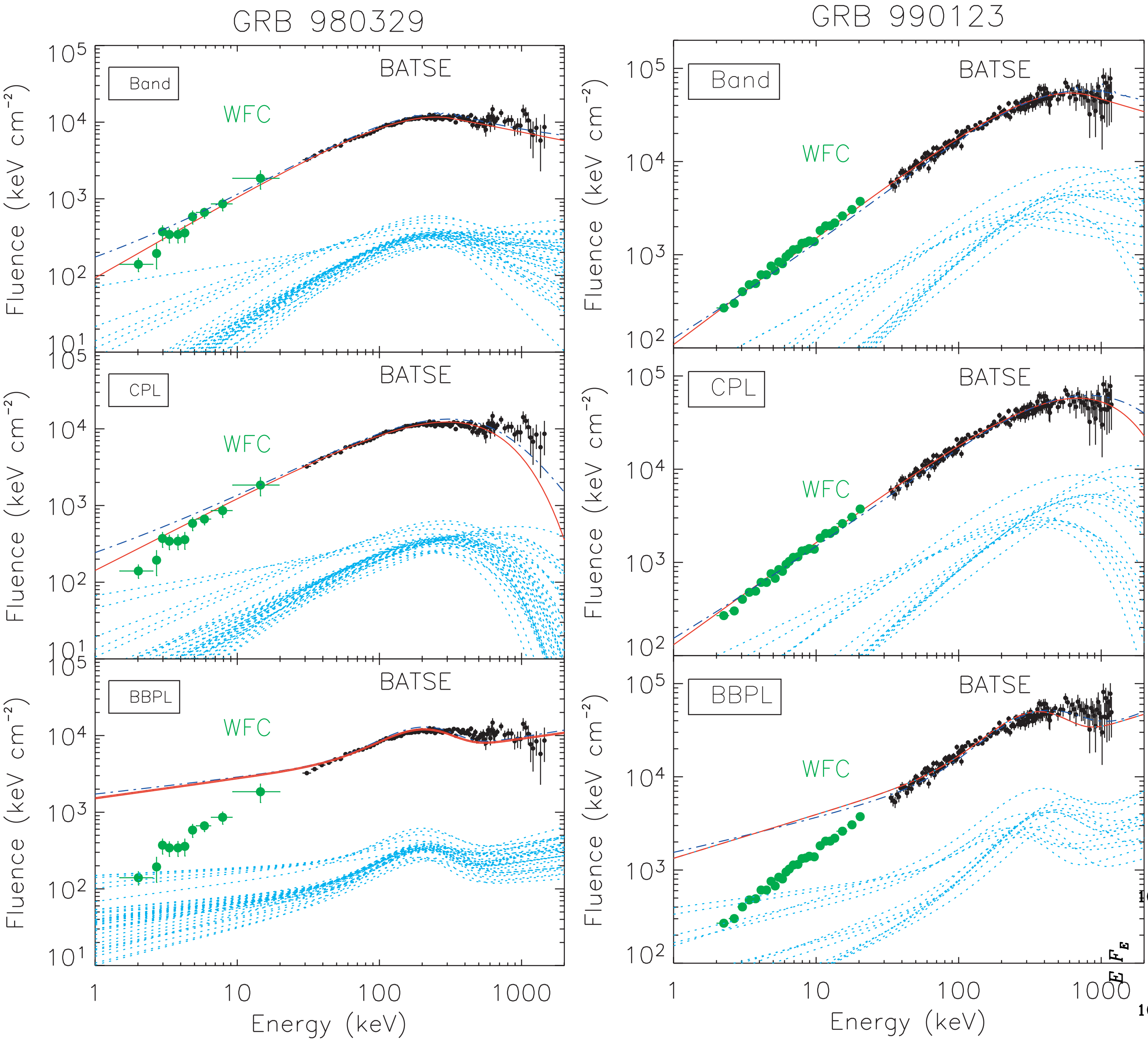


- Synchrotron emission?
  - ✓ Ordered B field (SO model)?
  - ✓ Random B field on plasma scale (SR model)?
- Photospheric emission?

α_1 = -0.62
α_2 = -1.50



(Ravasio et al. 2017 for GBM;
see also Oganesyan et al. 2017 for BAT+XRT)

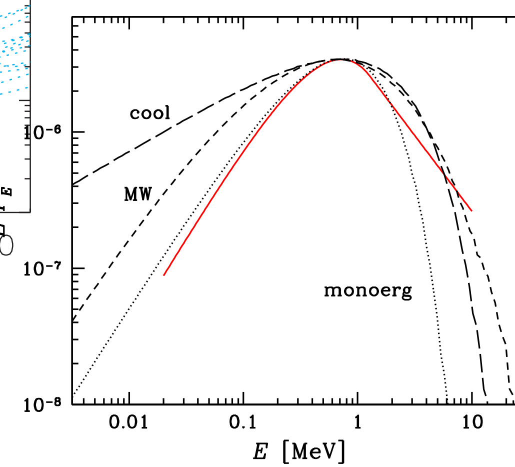


α = -0.64

α = -0.89

(Ghirlanda et al. 2007)

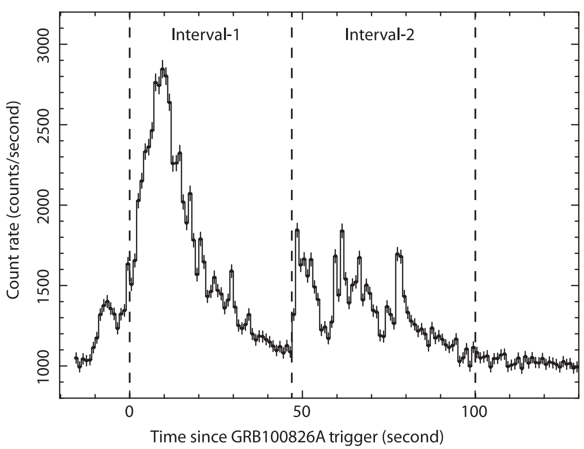
(Vurm & Beloborodov 2015)

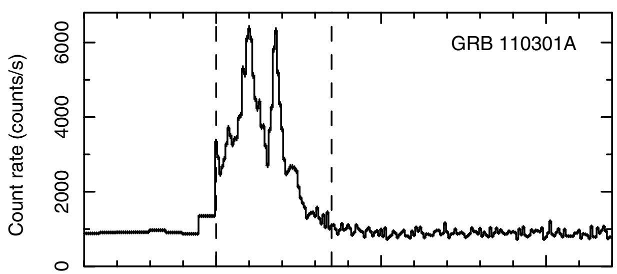


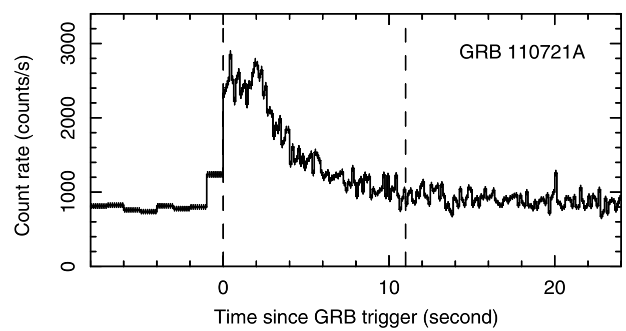
Observational results with GAP

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}



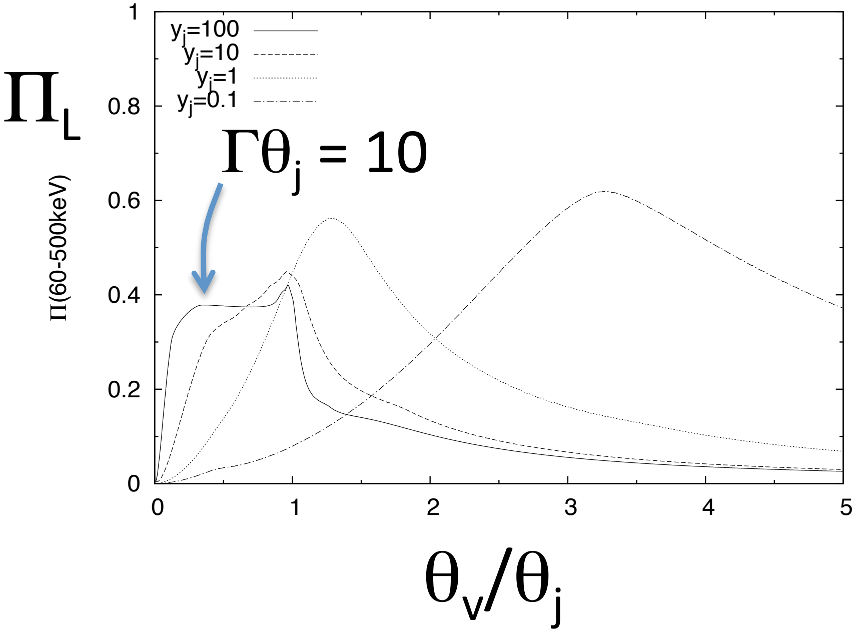


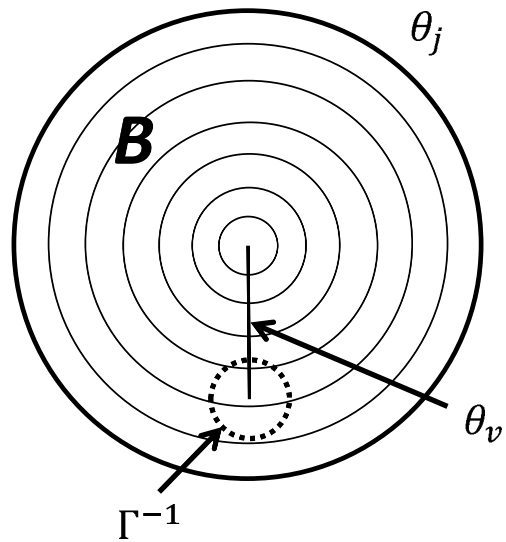


(Yonetoku+11;12; KT 13)

SO model (syn ordered B)

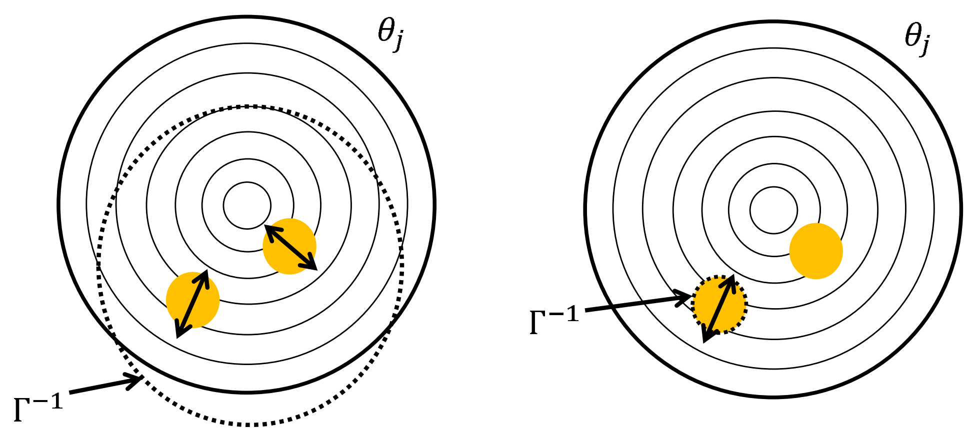
(Lyutikov+03; Granot 03; KT, Sakamoto, Zhang+09; KT13)





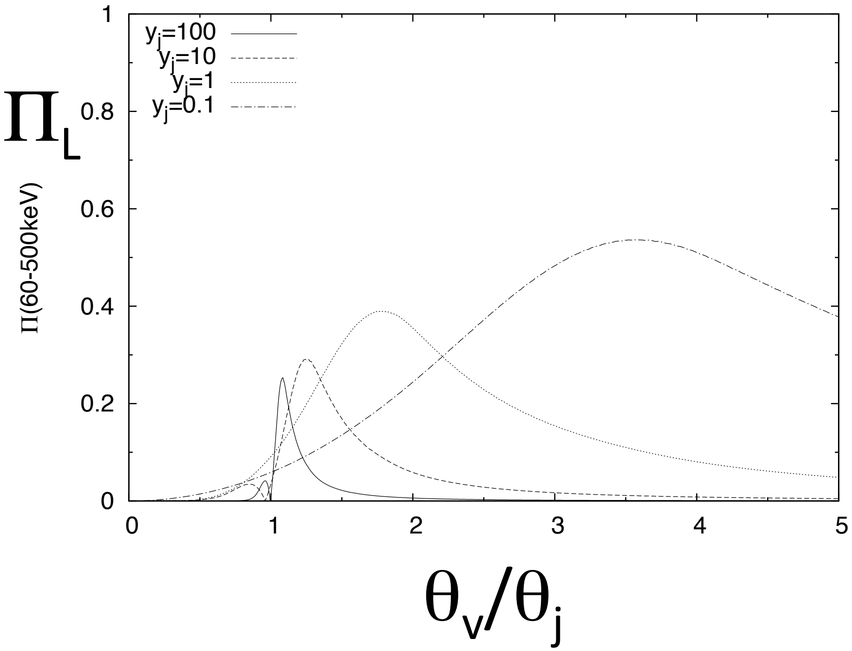
- Polarization degree is sufficient
- Patchy emission may lead to PA changes
- Other B structures possible

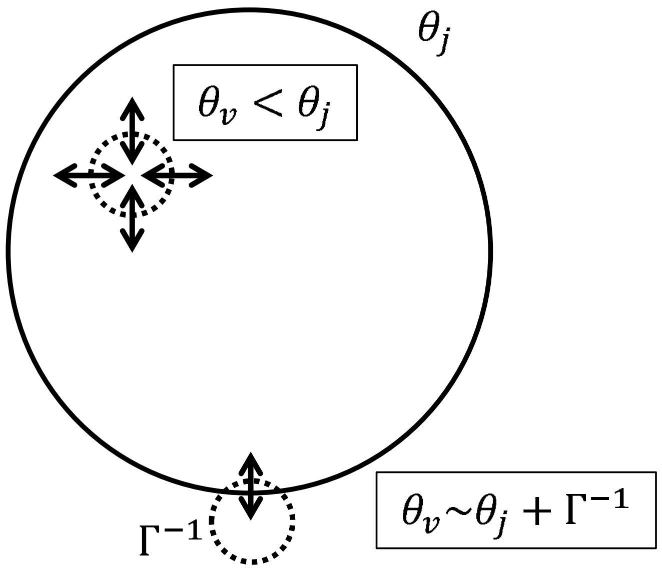
  (Granot+12; Zhang & Yan 11)



SR model (syn random B)

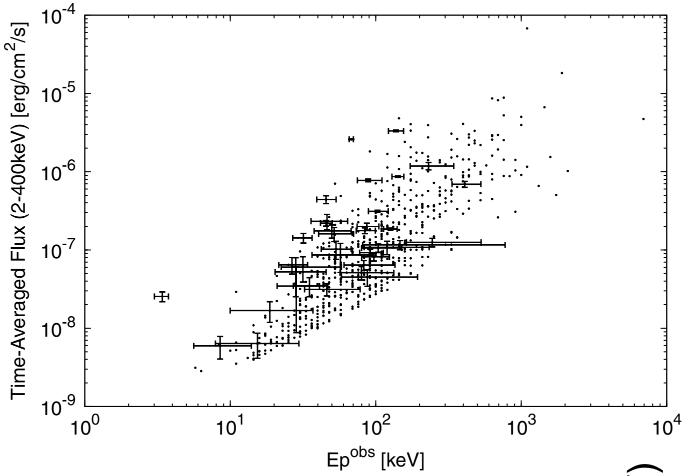
(Granot 03; Nakar & Piran 03; KT, Sakamoto, Zhang+09; KT13)



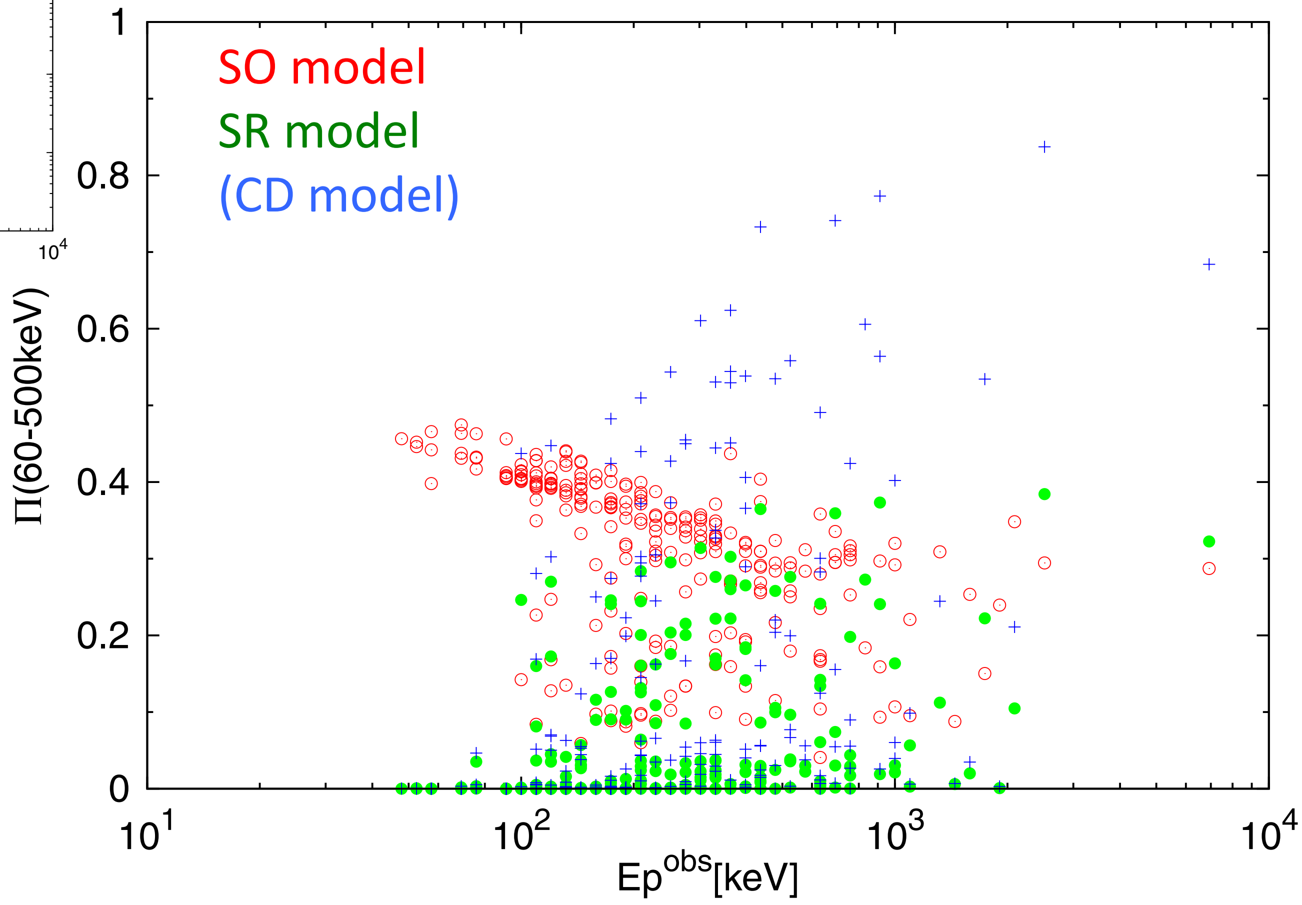


- Random B field parallel to the shock plane
- Π_L > 30% requires a fine tuning of parameters

Theoretical Monte Carlo simulation



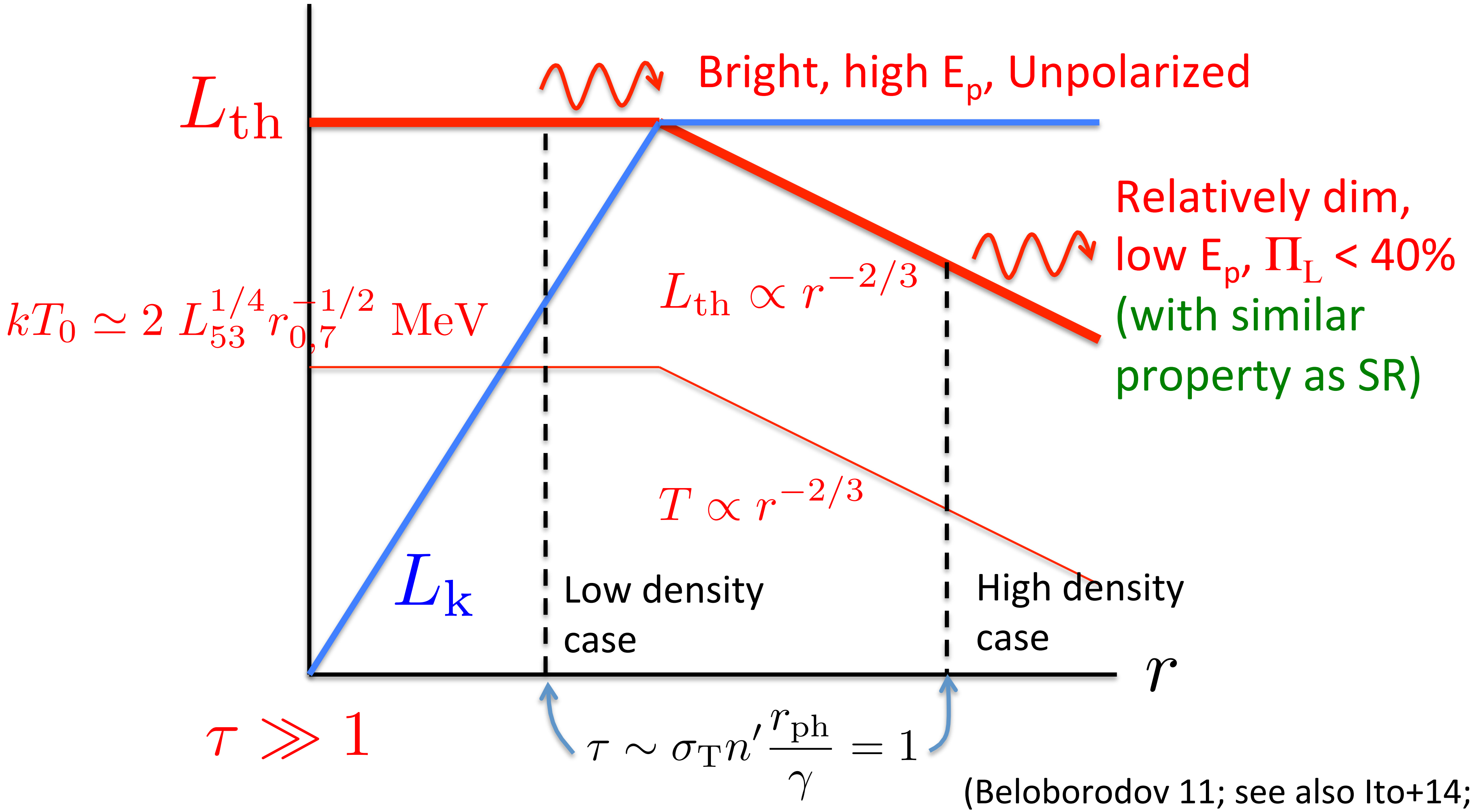
Uniform jet assumed.



(KT, Sakamoto, Zhang et al. 2009)

Photospheric emission

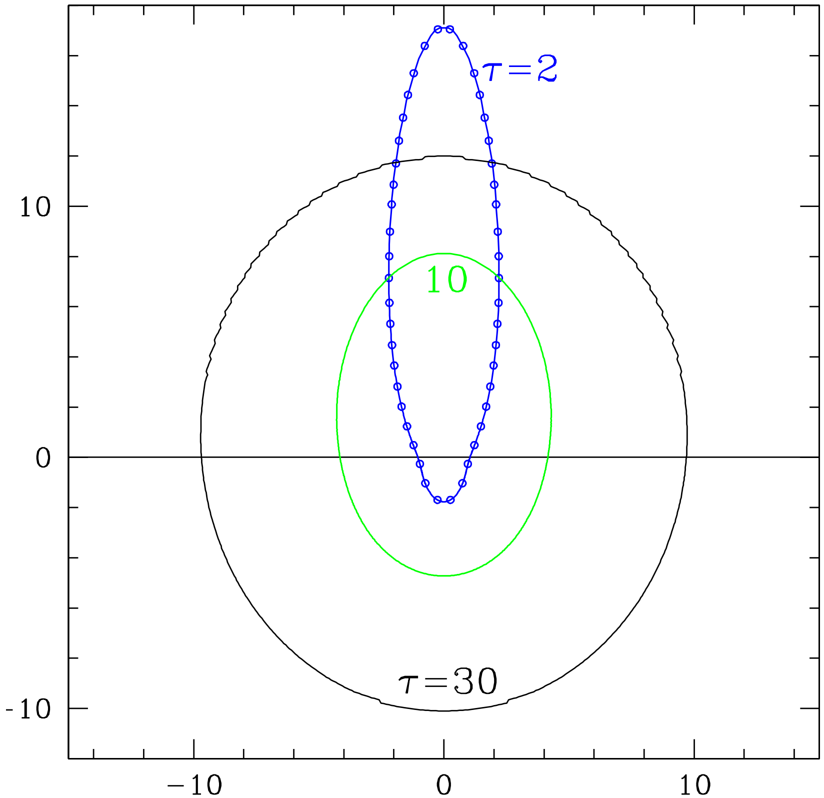
Optically-thick radiation-dom. gas expansion & acceleration



(Beloborodov 11; see also Ito+14; Lundman, Pe'er & Ryde 14)

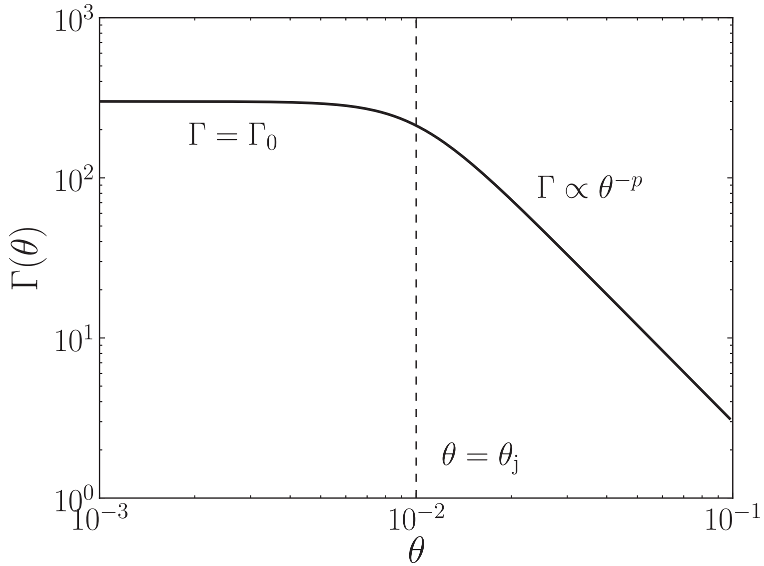
Photospheric model

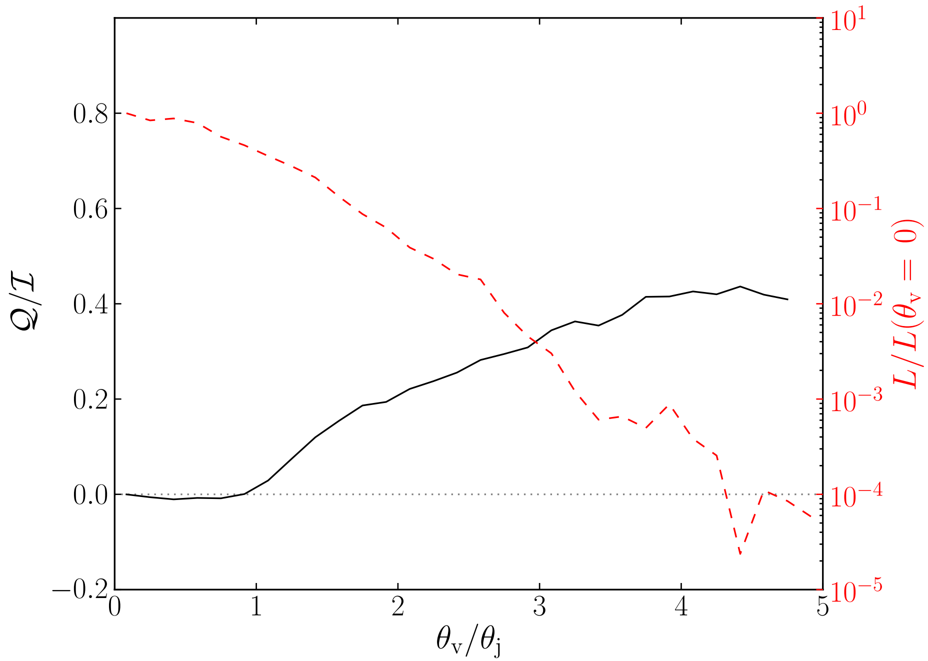
(Beloborodov 11)



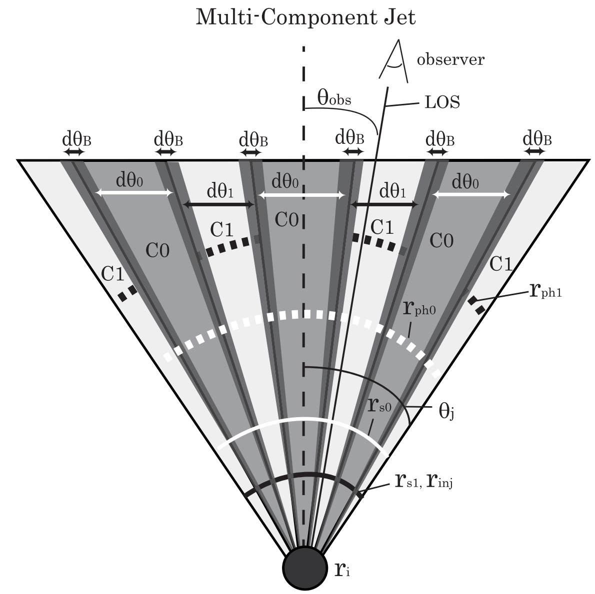
Radiation intensity is highly anisotropic in the fluid frame

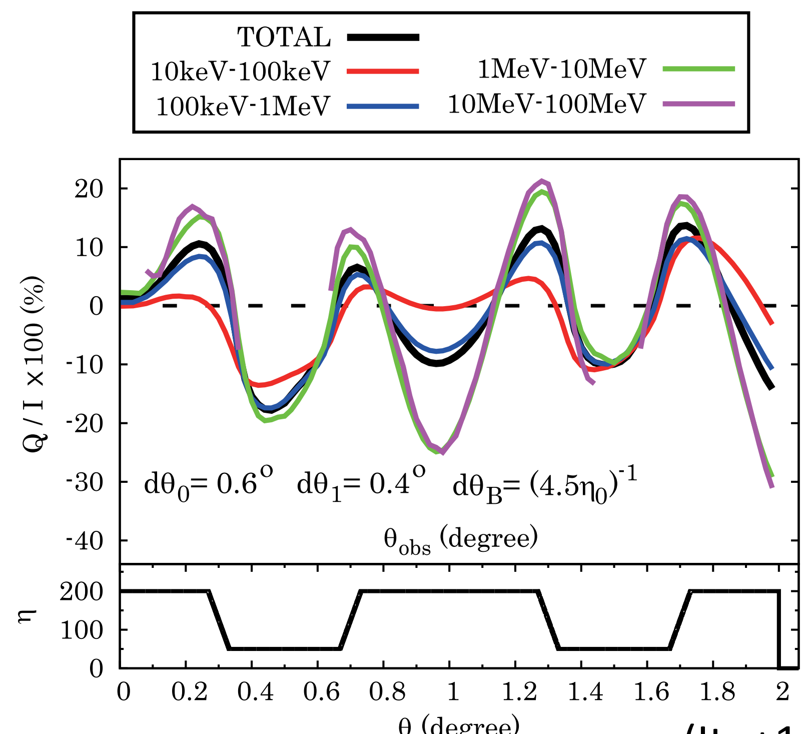
- Prompt emission could be quasi-thermal emission
- Π_L can be high if matter-dom. at photosphere (Beloborodov 11)
- Polarization properties similar to SR model
- Π_L > 30% requires a fine tuning of parameters
- See also Ito+14; Lundman+14





(Lundman+14)





(Ito+14)

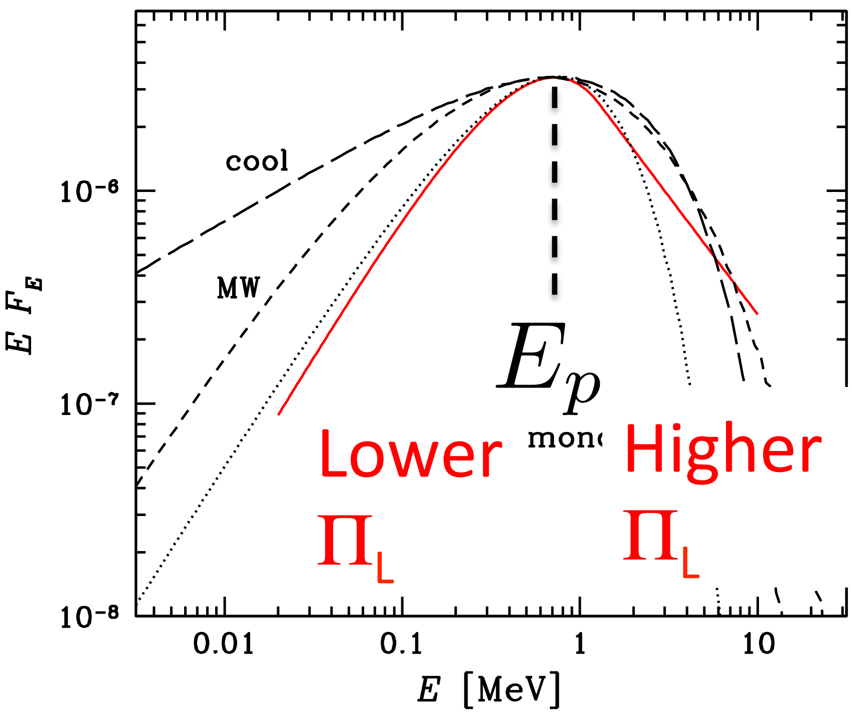
Implications for emission mechanism

- The SO model is favored, while the SR and photospheric emission requires fine tunings

- More accurate, more statistics needed
- Any bright bursts with low Π_L? -> photospheric
- Correlation with spectral shape?

Polarization spectrum

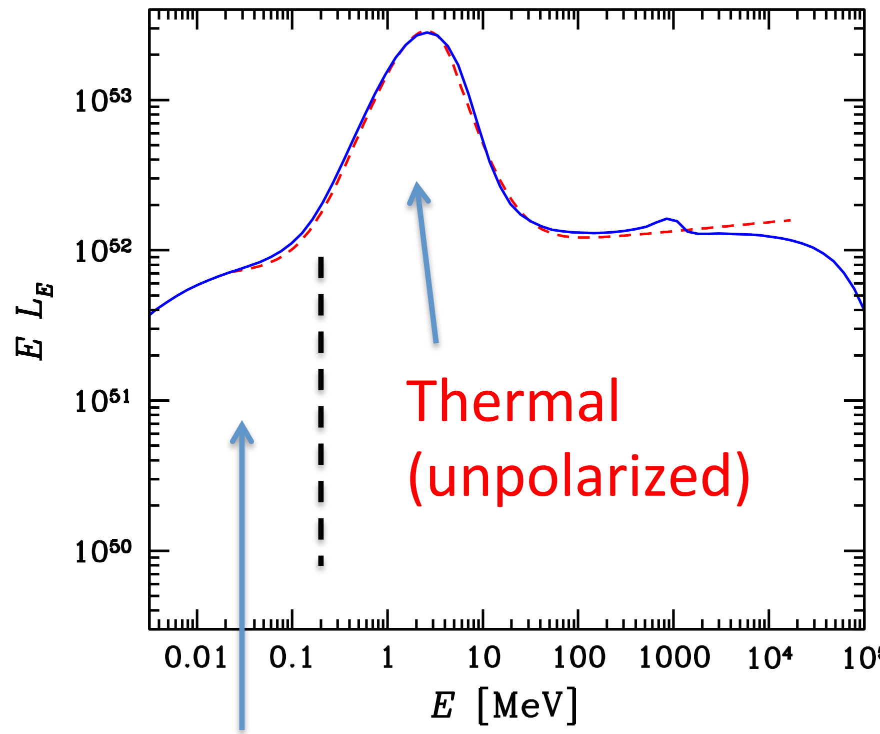
Synchrotron



$$\Pi_L = \frac{p+1}{p+\frac{7}{3}}$$

But maybe this difference is hard to detect

Photospheric

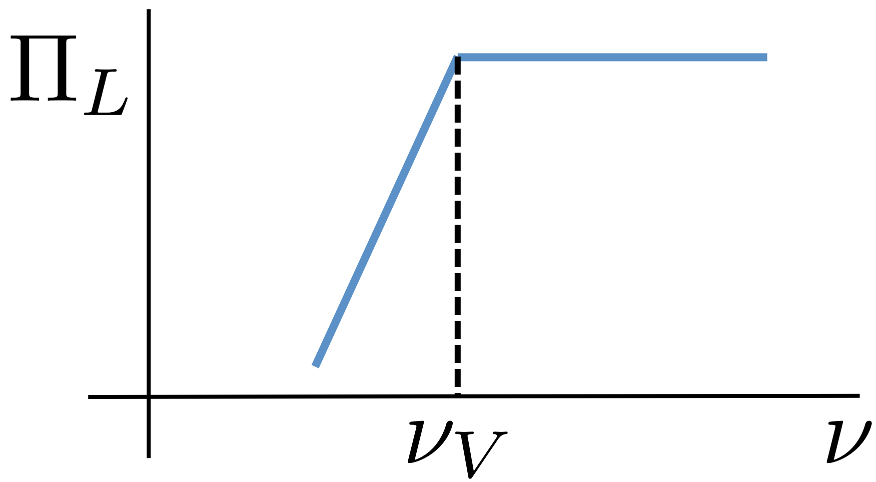


Synchrotron with possibly high Π_L

(Vurm & Beloborodov 15)

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

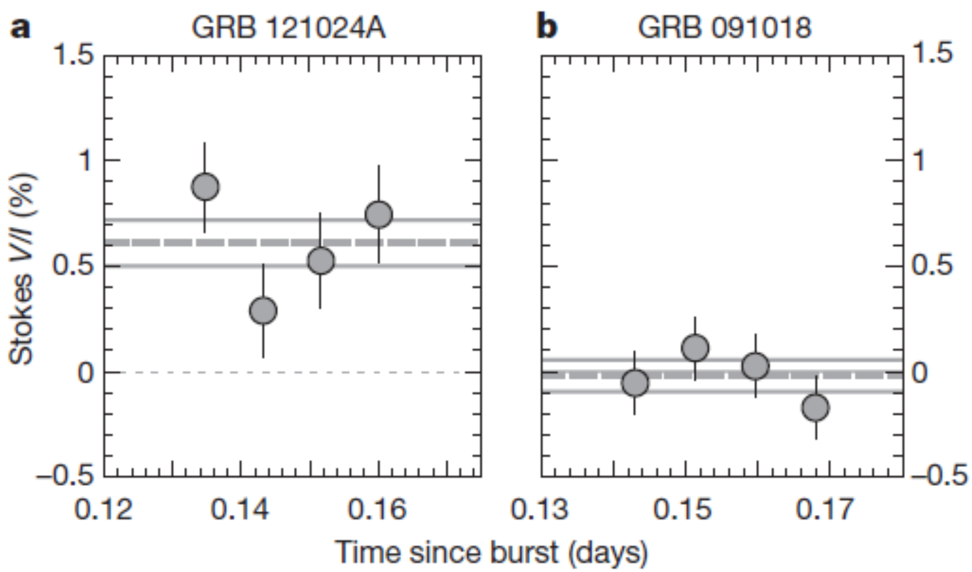


$$\nu_V \simeq 100\ \epsilon_B^{1/4} L_{52}^{3/4} r_{12}^{-1} \Gamma_{2.5}^{-1}\ \mathrm{keV}$$

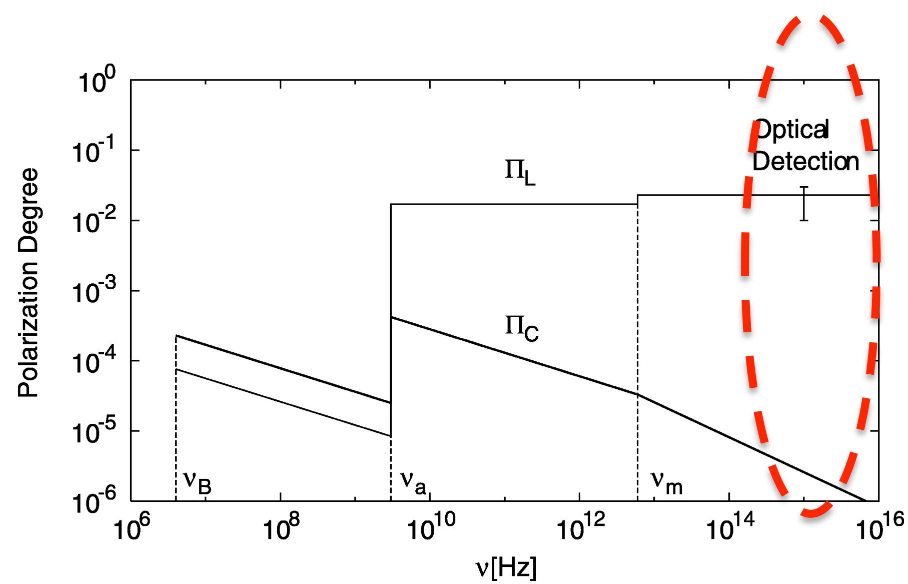
Future X-ray polarimetry would further constrain the emission mechanism

(KT & Kakuwa in prep.)

Detection of circular polarization



- One of the two observed bursts has Π_C ~ 0.6%!!
- Propagation effect appears to be weak -> intrinsic Π_c



- Highly anisotropic electron distribution?

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

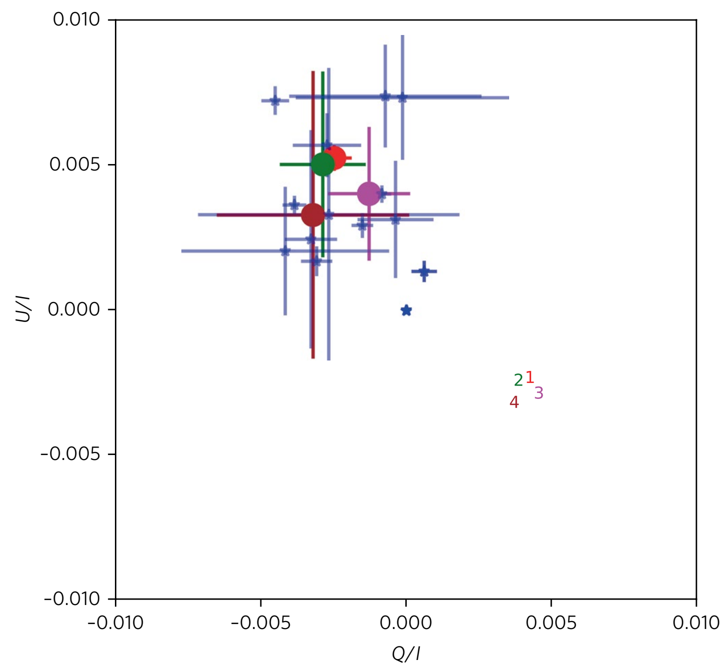
(Wiersema, Covino, KT+14; see also Nava, Nakar & Piran 16)

(KT, Ioka & Nakamura 08)

Macronova polarization

Table 1 | Results of the polarimetric campaign

T - T_{GW} (days)	*Q/I*	*U/I*	Polarization (%)
1.46	−0.0021 ± 0.0008	+0.0046 ± 0.0007	0.50 ± 0.07
2.45	−0.0025 ± 0.0016	+0.0044 ± 0.0032	<0.58
3.47	−0.0009 ± 0.0015	+0.0034 ± 0.0024	<0.46
5.46	−0.0029 ± 0.0033	+0.0026 ± 0.0050	<0.84
9.48	+0.0412 ± 0.0216	−0.0095 ± 0.0126	<4.2

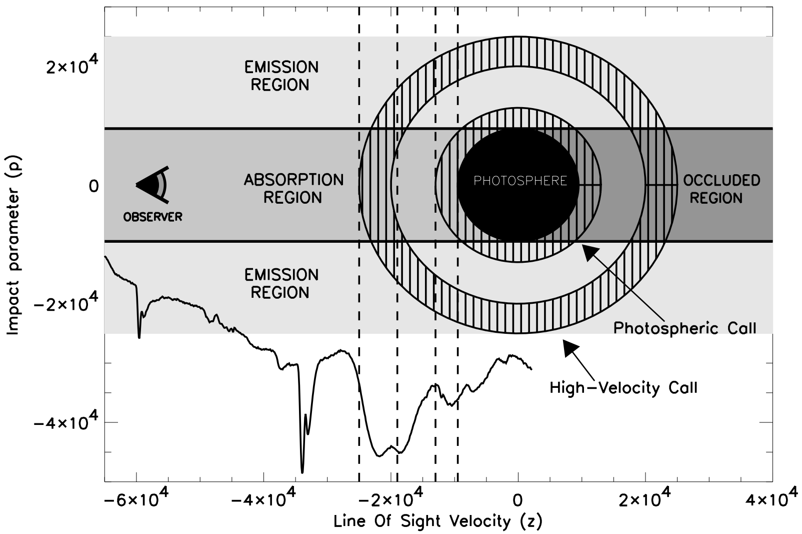


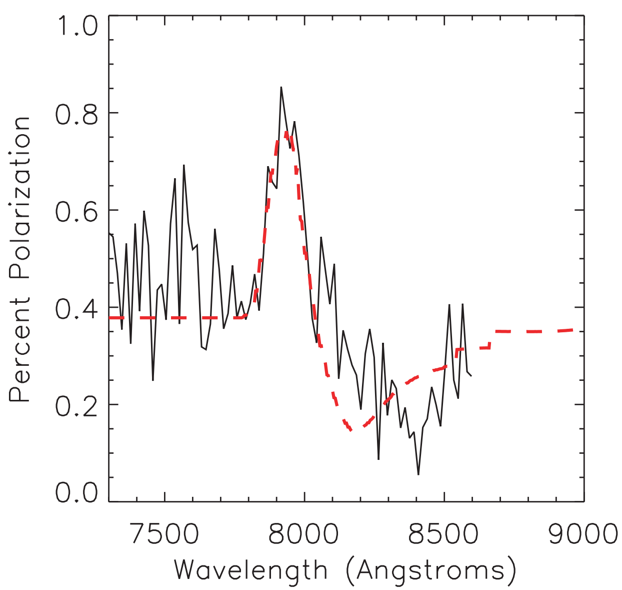
(Covino, Wiersema, Fan, KT et al. 2017; Kyutoku et al. 2013; 2015)

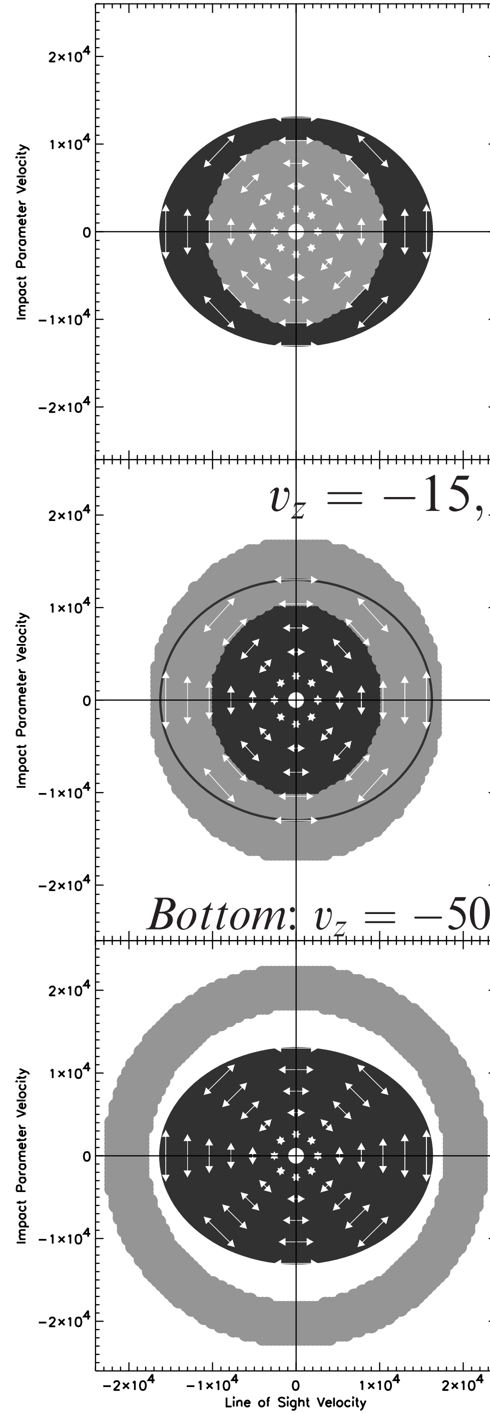
- Upper limit (<0.5%) on intrinsic optical polarization
  - ✓ Red phase: Not inconsistent with opacity dominated by r-nuclei b-b transition (not by electron scattering)
  - ✓ Blue phase: r-nuclei-free ejecta does not appear very asymmetric
  - ✓ Dim GRB optical afterglow

More quantitative calculations could constrain geometry & Θ_v

Type Ia SN polarization





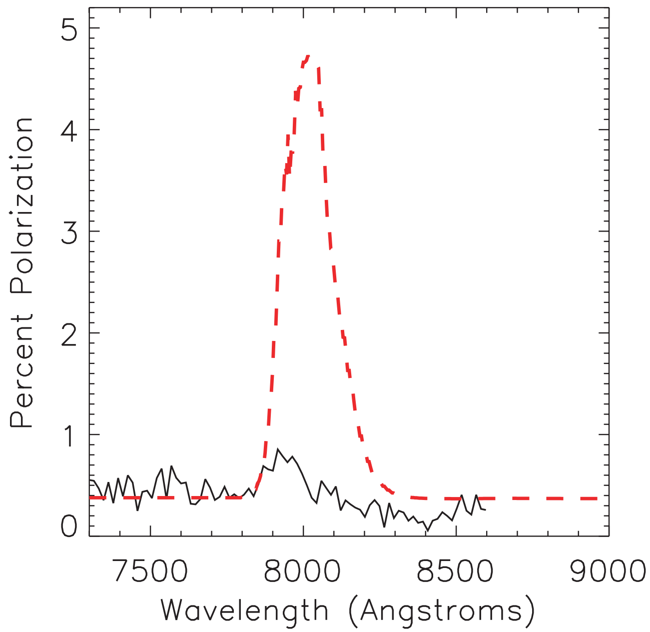


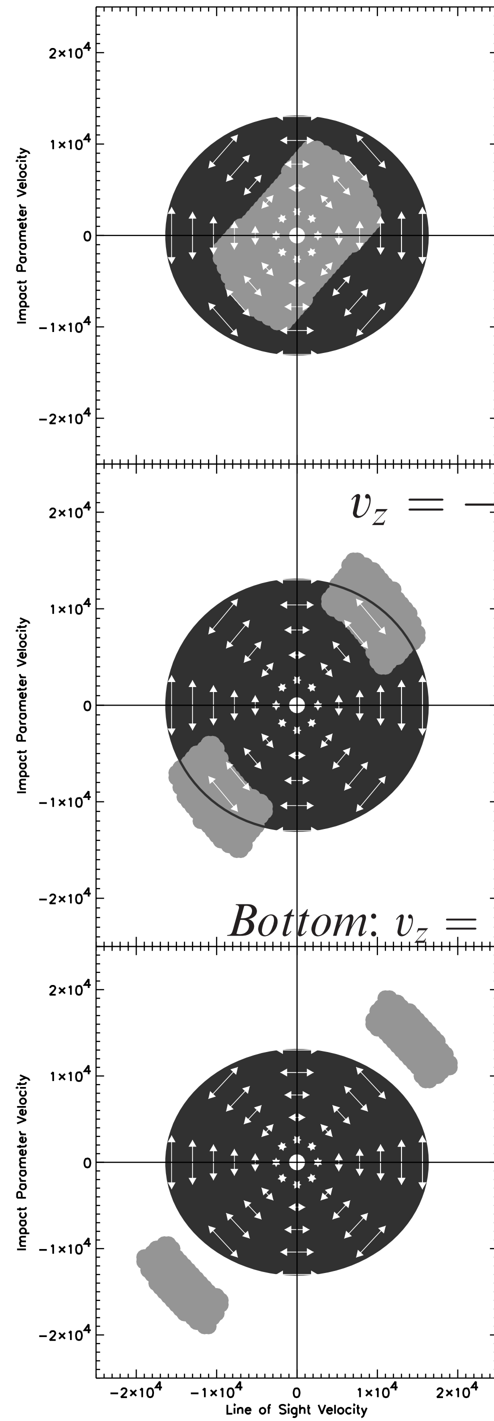
Top: $v_z = -22,500$ km $s^{-1} \rightarrow \lambda = 7900$ Å;

$v_z = -15,500$ km $s^{-1} \rightarrow \lambda = 8100$

Bottom: $v_z = -5000$ km $s^{-1} \rightarrow \lambda = 8400$ Å;

(Kasen+ 03)



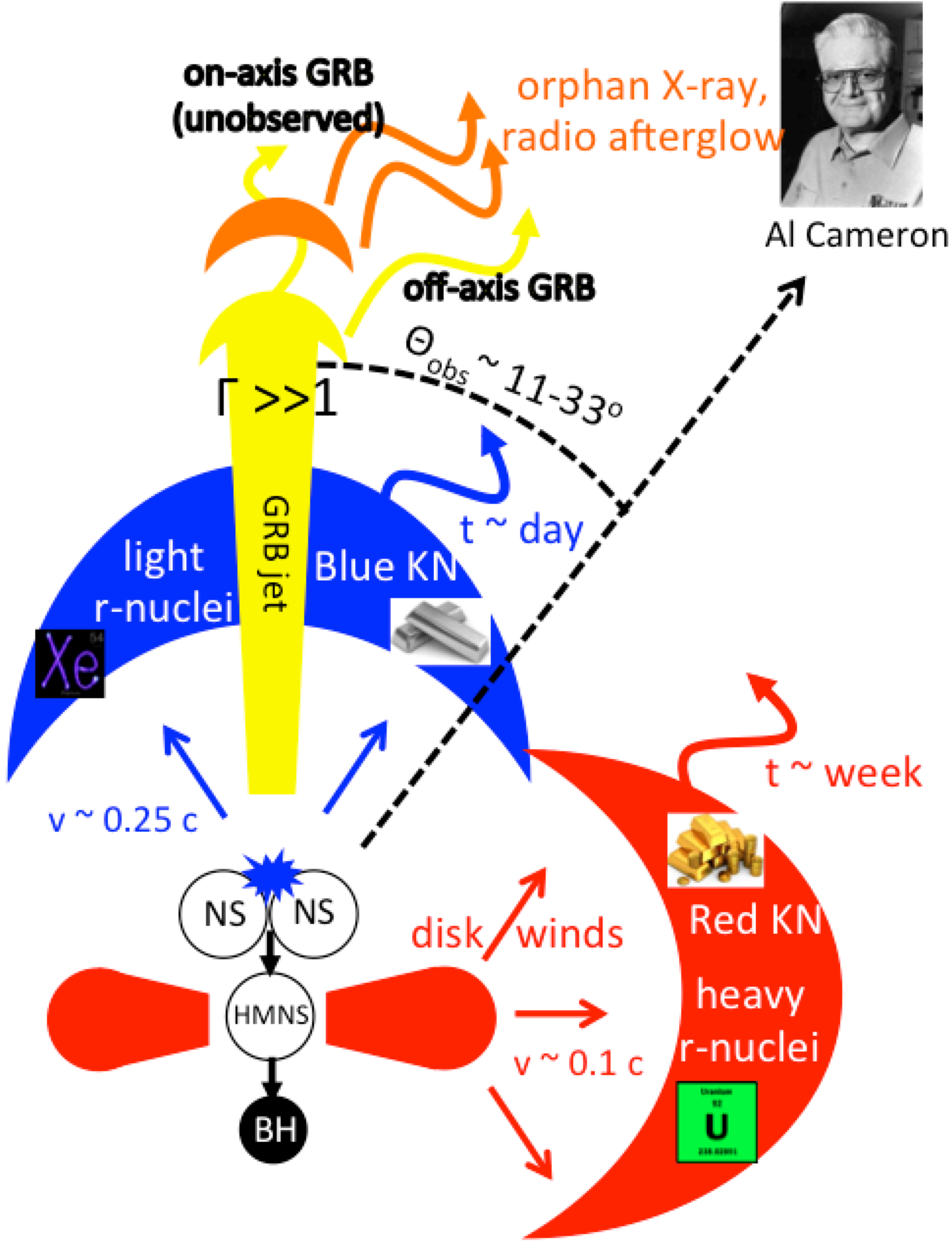


Top: $v_z = -22,500$ km s$^{-1} \rightarrow \lambda = 7900$ Å;

$v_z = -15,500$ km s$^{-1} \rightarrow \lambda = 8100$

Bottom: $v_z = -5000$ km s$^{-1} \rightarrow \lambda = 8400$ Å;

High polarization might be realized due to block by asymmetric line-opacity-dominant ejecta

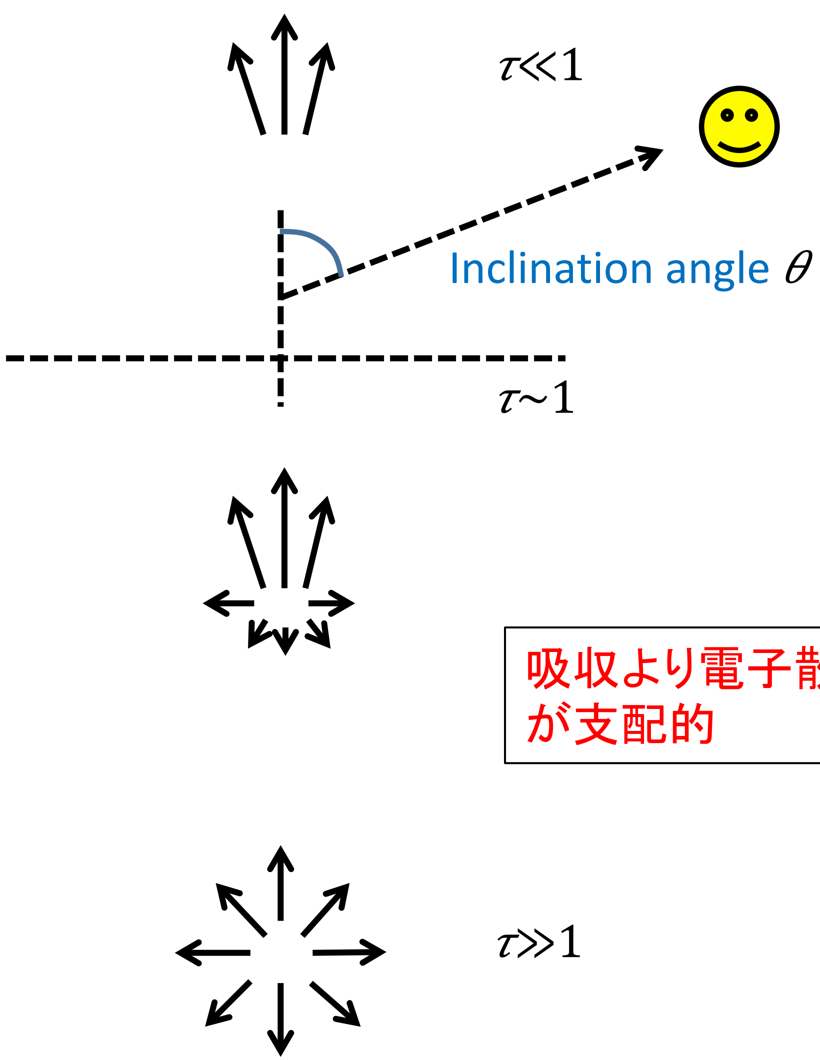


(Metzger 2017)

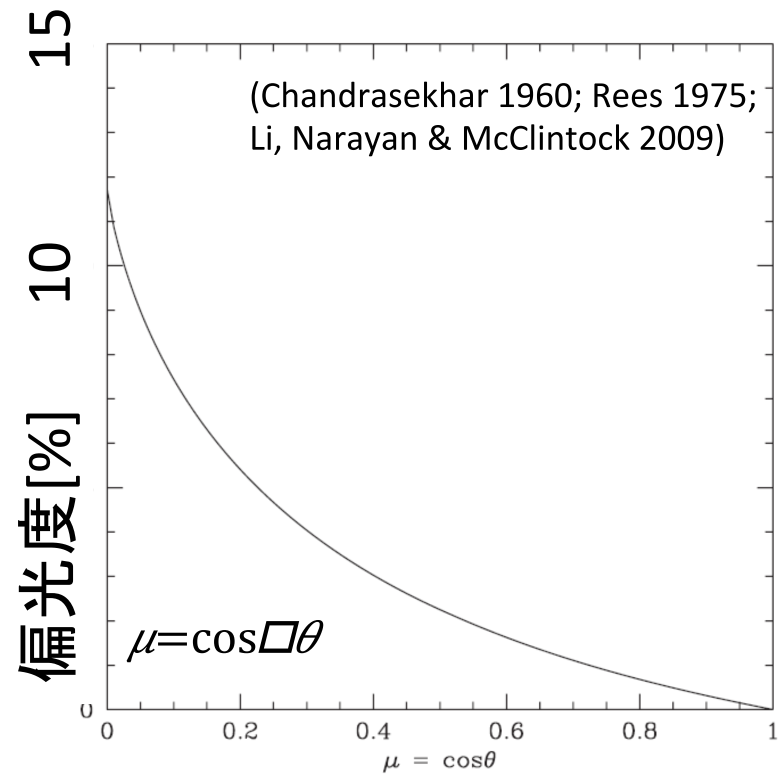
Summary

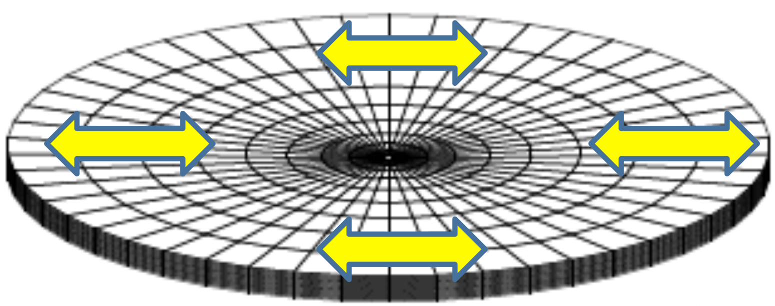
- Late-time AG
  - Π_C detection: mystery
  - Radio AG: Faraday effects, ALMA!
- Early-time AG
  - High Π_L implies ordered B field in jets
  - But some are not highly polarized
- Prompt emission
  - SO emission model & magnetically-dom. jet ? More data needed
- Macronova
  - Geometry & viewing angle could be constrained

降着円盤からの偏光

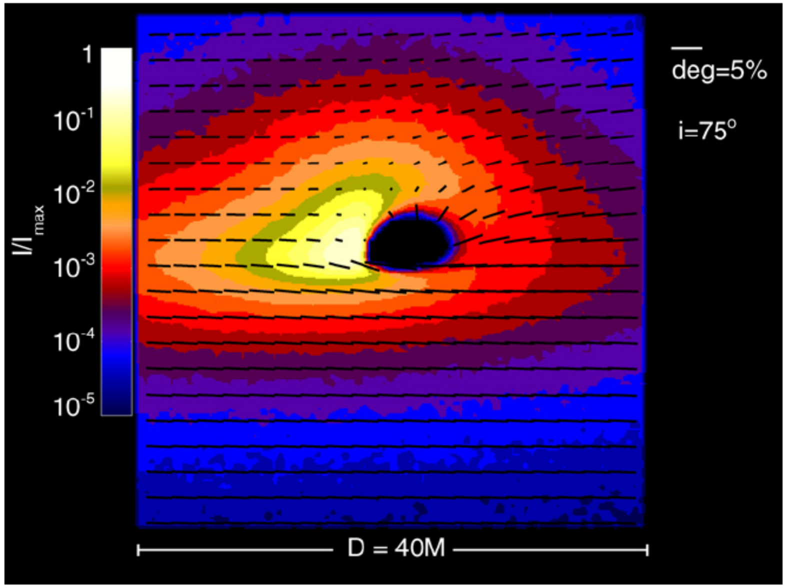


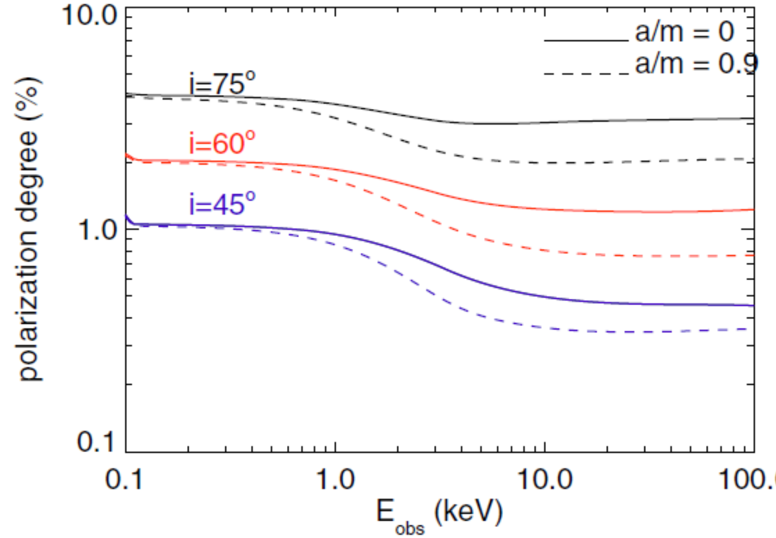
吸収より電子散乱が支配的

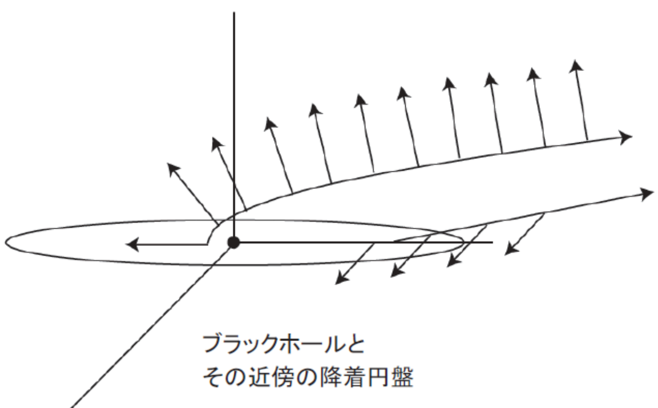


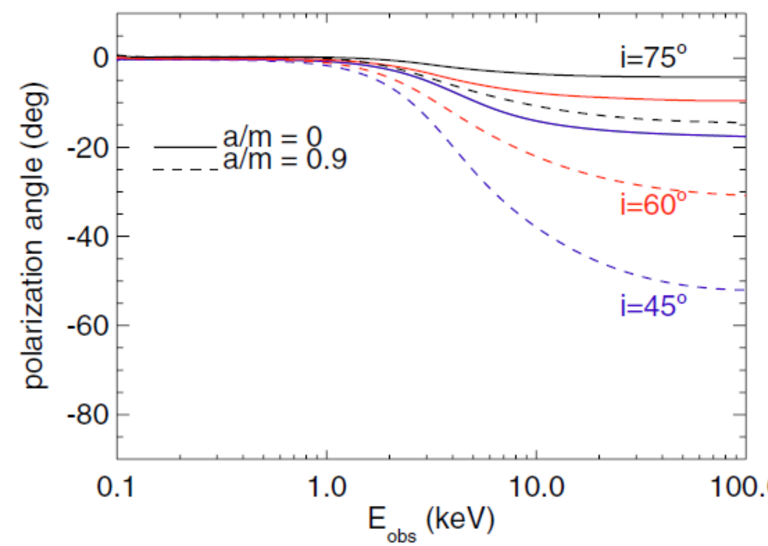


一般相対論的効果









(Stark & Connors 1977; Li+ 2009; Schnittman & Krolik 2009)

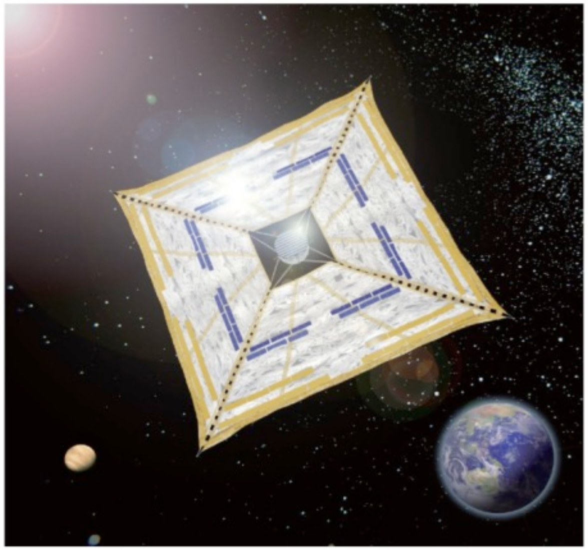
As will be discussed in § II, supernova atmospheres are likely to be scattering-opacity dominated. It is well known that scattering atmospheres can transform initially unpolarized light into partially linearly polarized light. Chandrasekhar (1960, 1946) calculated this effect for a plane-parallel electron scattering atmosphere and derived the degree of polarization of the emergent light as a function of the angle between the normal to the plane and the direction of view. An observation of a

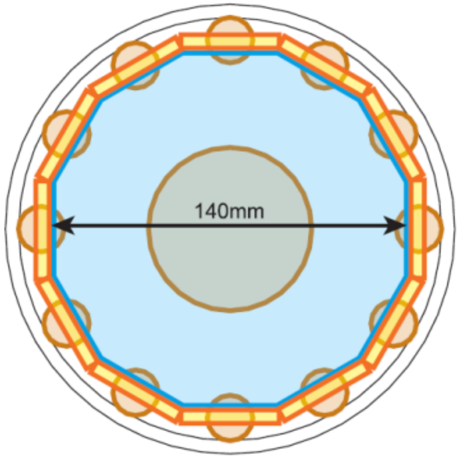
We discuss the net polarization which is to be expected as a function of the degree of this asphericity in the sections which follow. In § II, we summarize the

(P. Shapiro & Sutherland 1982)

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

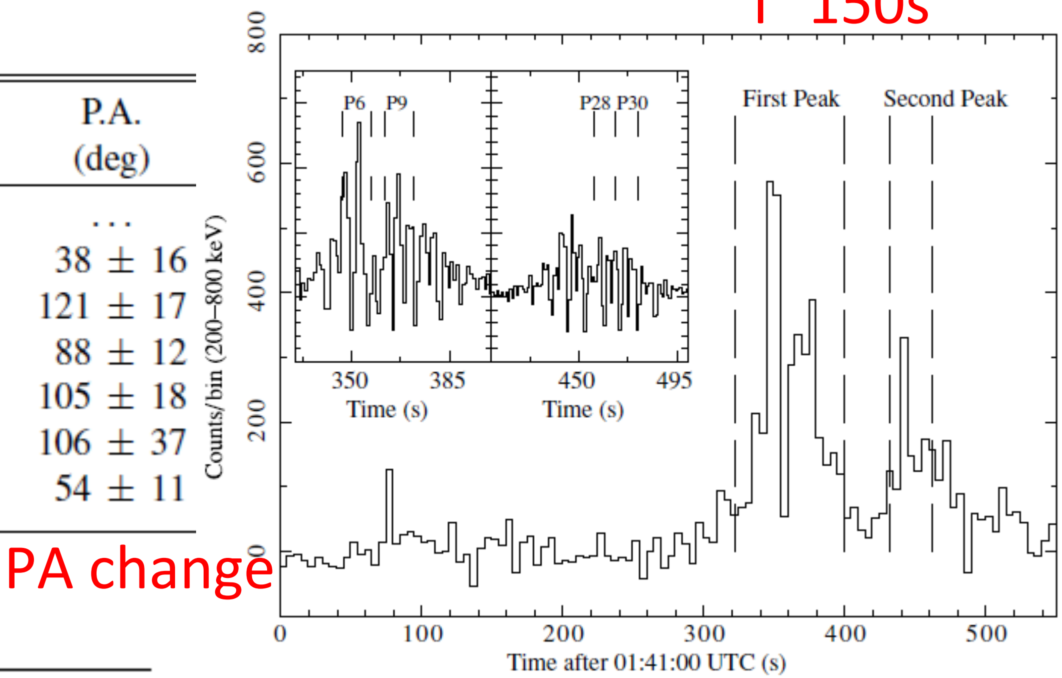




IBIS on INTEGRAL

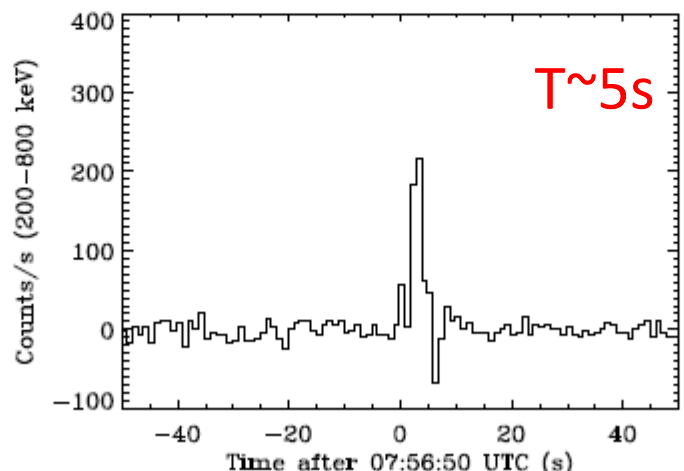
GRB 041219A (Gotz+09)

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



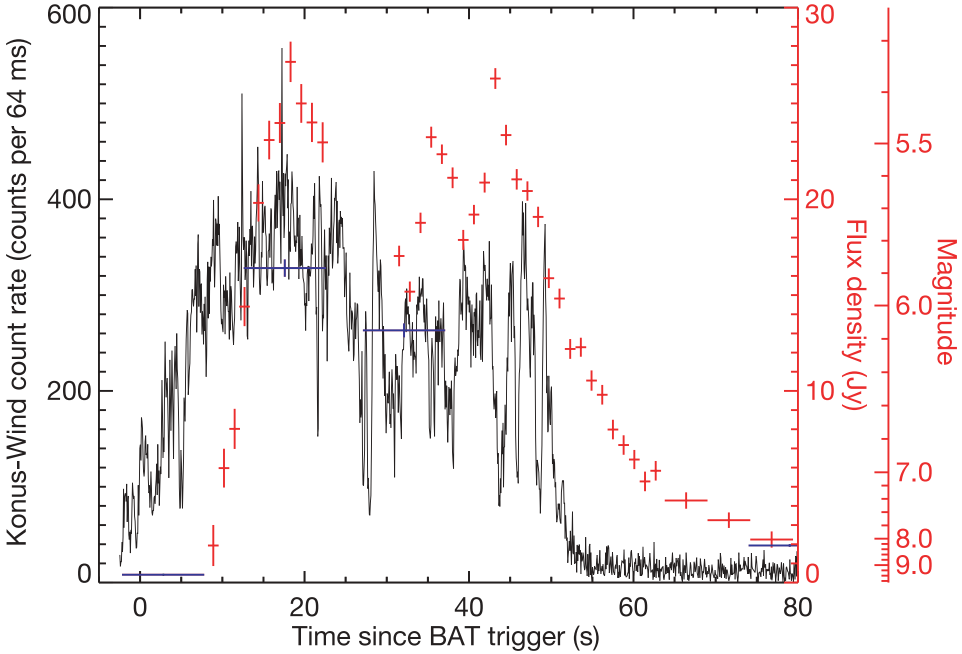
GRB 061122 (Gotz+13)

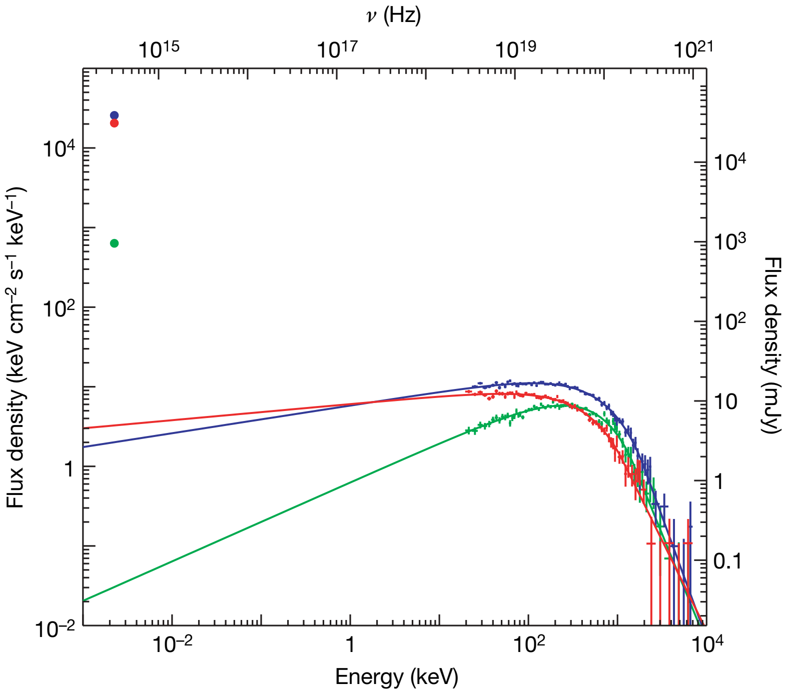
Energy band (keV)	Π (%) (68% c.l.)	P.A. (°) (68% c.l.)	Π (%) (90% c.l.)	P.A. (°) (90% c.l.)
250–800	>60	150±15	>33	150±20
250–350	>65	145±15	>35	145±27
350–800	>52	160±20	>20	160±38



- P>~30% at 2σ, non-zero at ~3σ, consistent with GAP results
- GRB 140206A (Gotz+14)

Prompt optical emission





(Racusin+08, Nature)

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

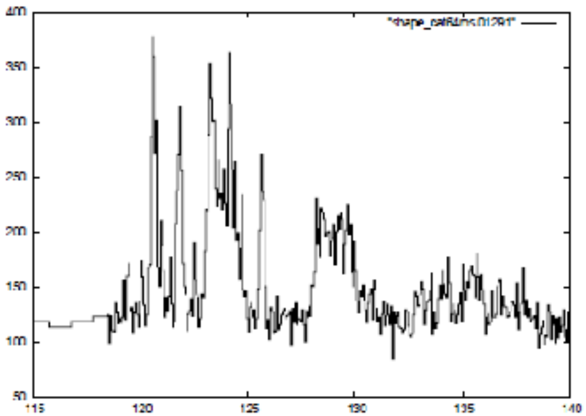
(KT, Mukohyama, Yonetoku+12)

$$|\xi| < 1 \times 10^{-16}$$

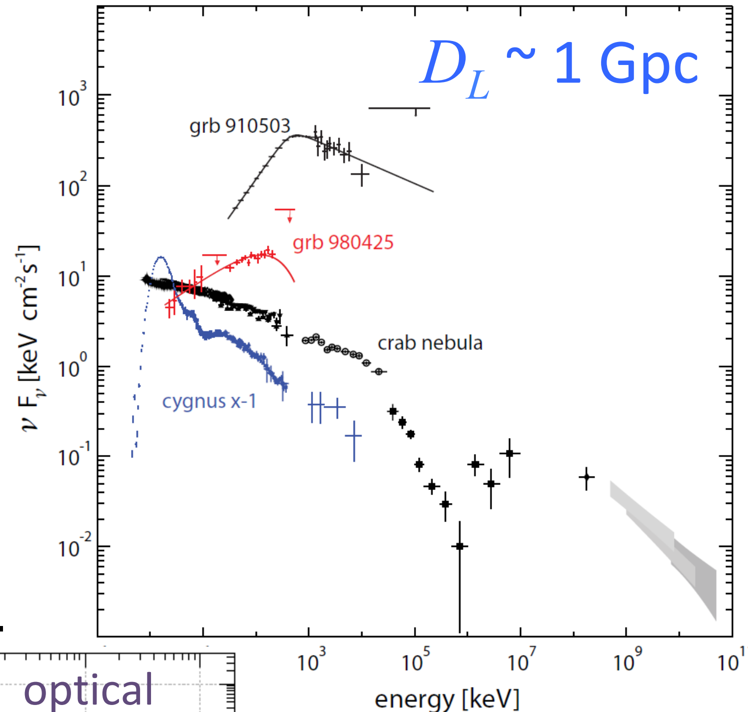
For GRB 140206A with confirmed redshift (Gotz+14)

Gamma-Ray Bursts (GRBs)

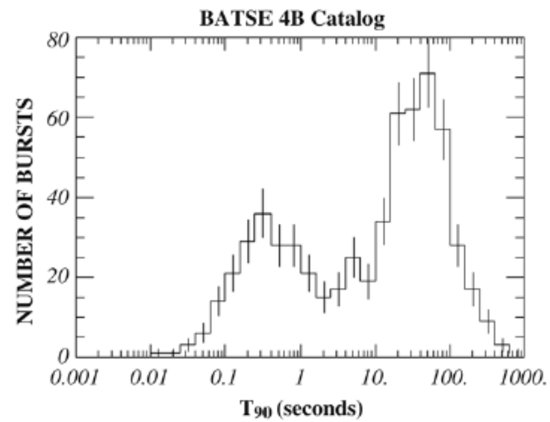
Prompt emission



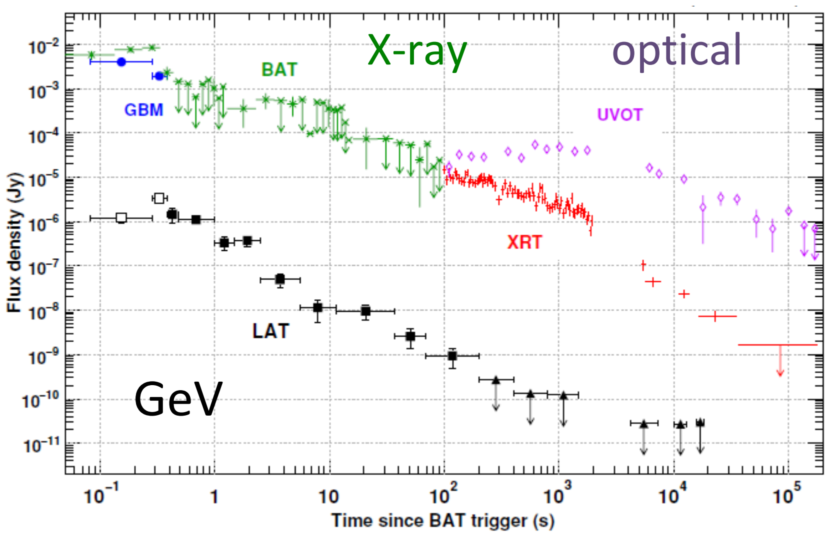
T (sec)



Distribution of prompt emission durations

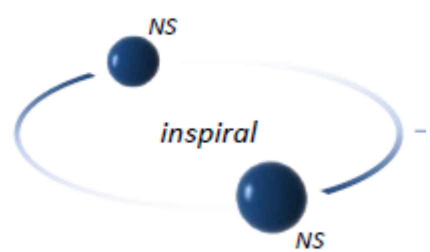


Afterglow lightcurve



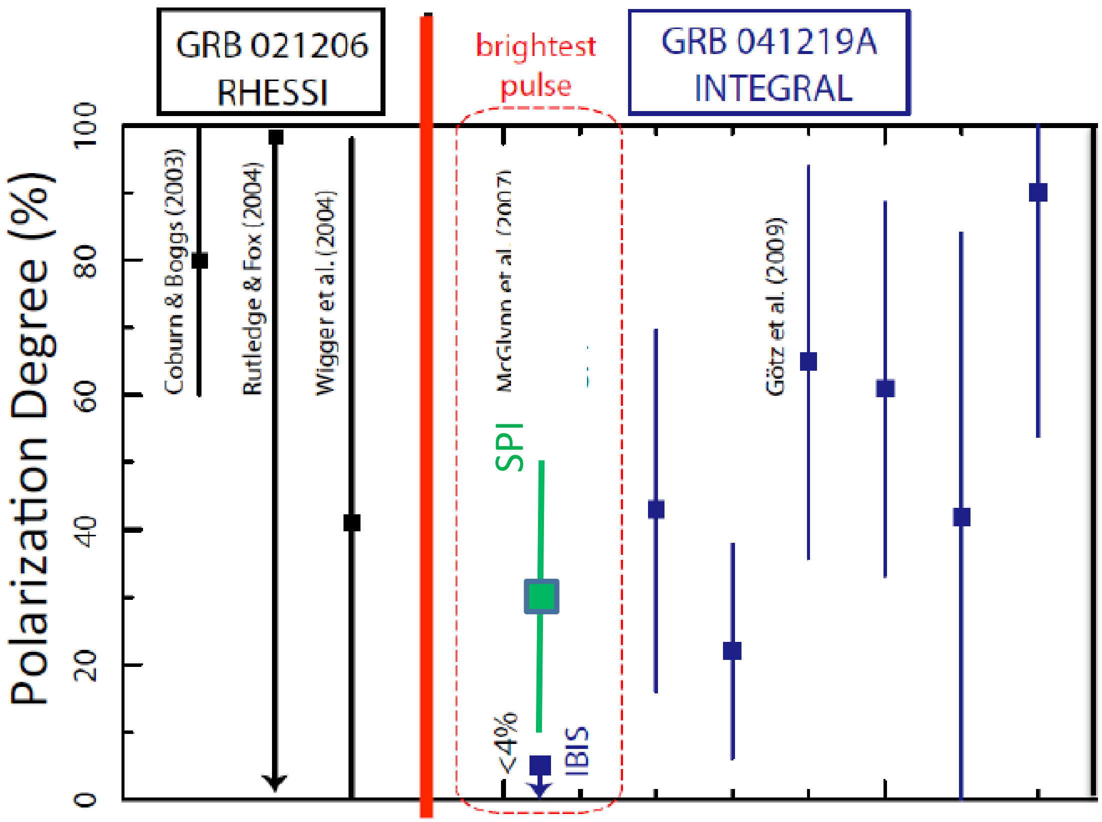
Short GRBs = Binary Mergers?

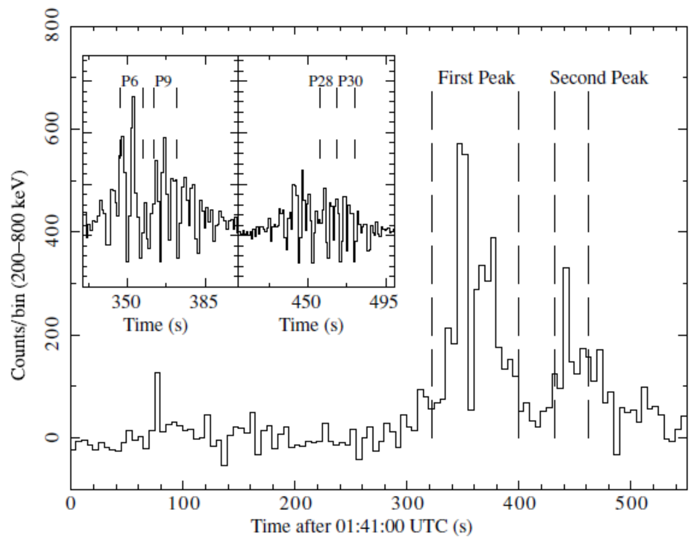
Long GRBs = Stellar Collapses



Gravitational wave emitters

History of gamma-ray polarimetry





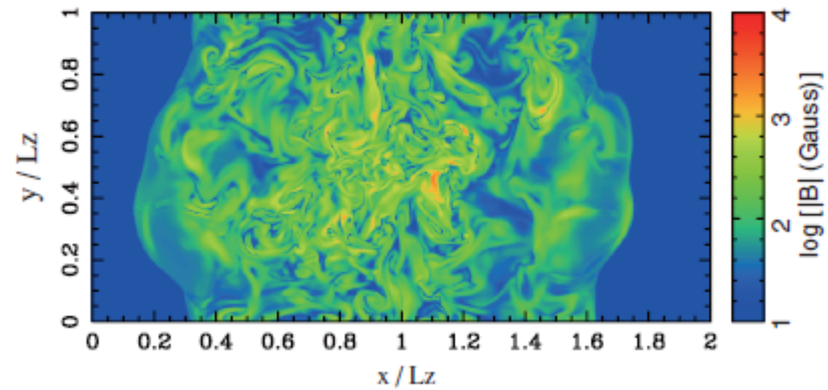
GRB 041219A analyzed by INTEGRAL (Gotz et al. 09)

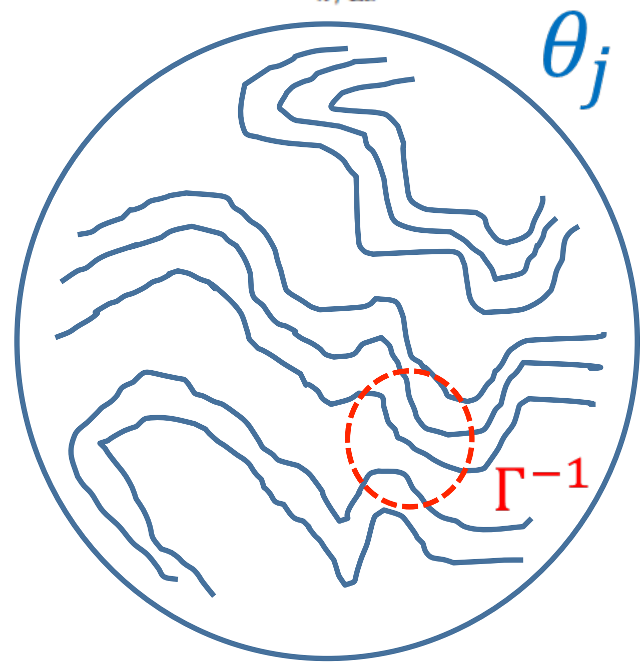
RHESSI claim is controversial. INTEGRAL SPI and IBIS include results inconsistent with each other.

SH model

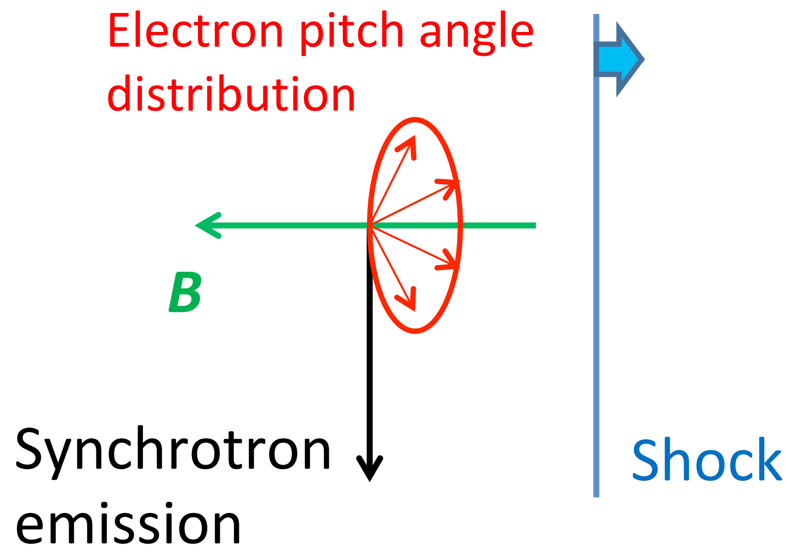
- Random B fields on hydrodynamic scales >> plasma scales (T. Inoue, Asano & Ioka 11; Gruzinov & Waxman 99)
- PA change is natural
- Π_L ~ 70%/√N
- But numerical simulations indicate N ~ 10^3, too high

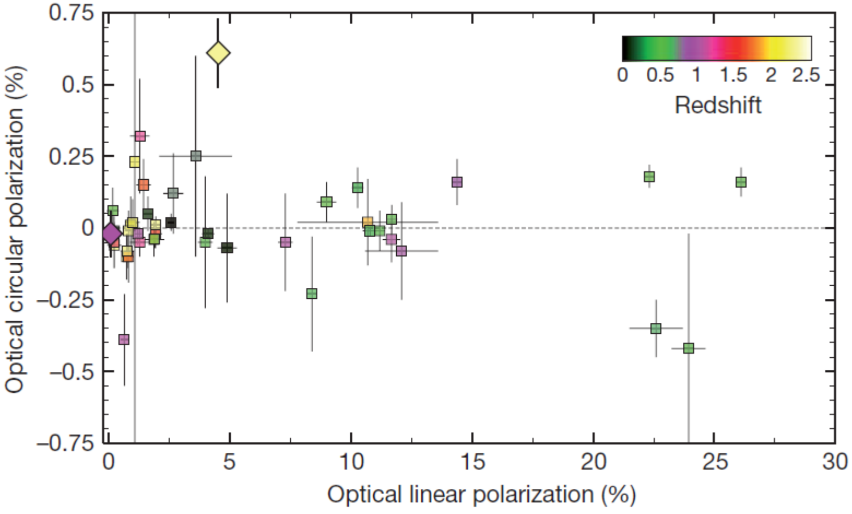
Simulation of internal shock with inhomogeneous density





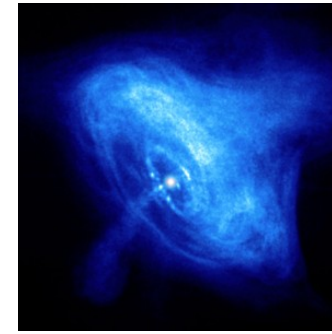
Highly anisotropic pitch angles?

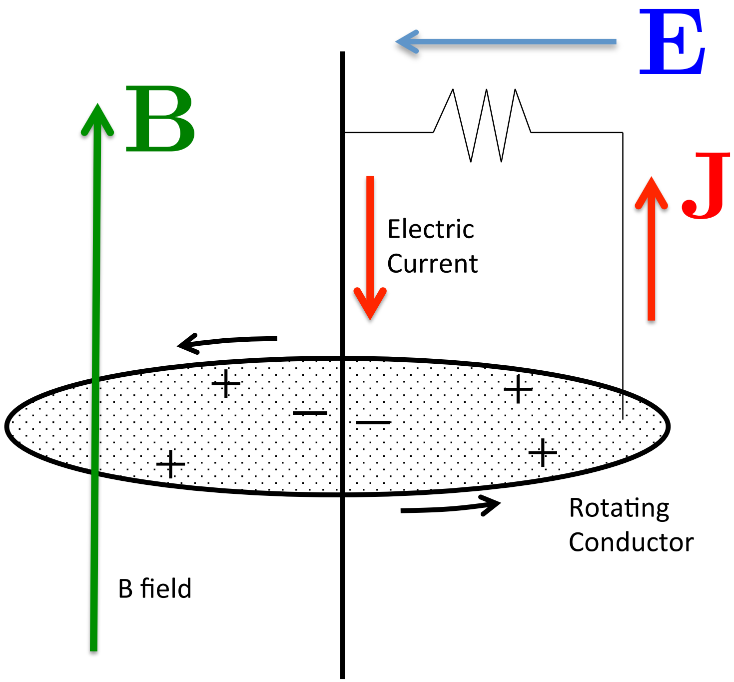




Optical circular polarizations in QSOs

Electromagnetic jet

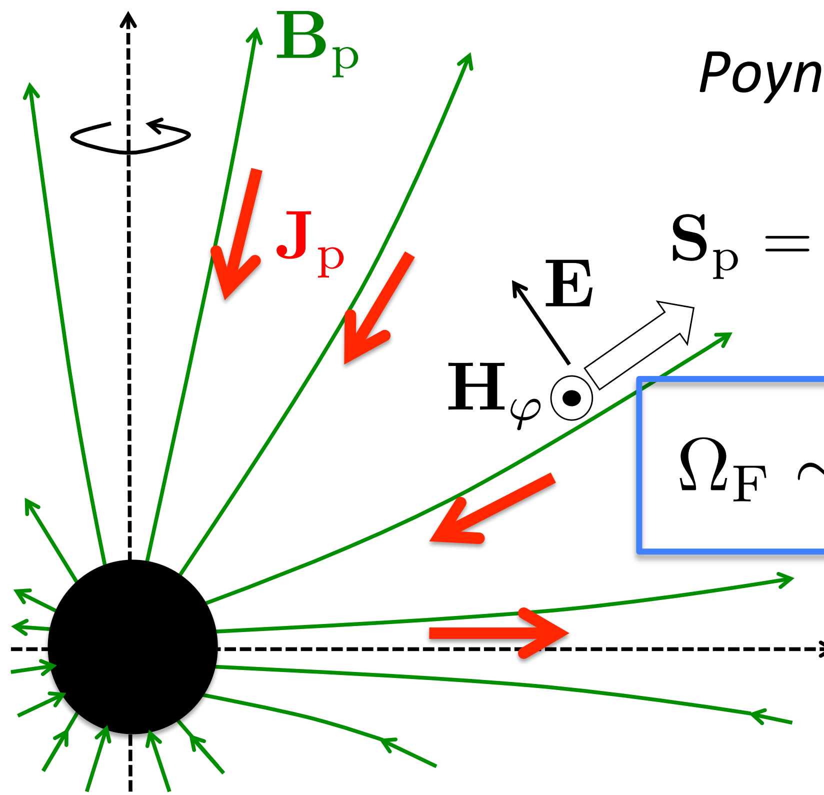




$$\Omega_{\rm F} = \Omega$$

$$\mathbf{E} = -\frac{r\Omega_{\rm F}}{c}\mathbf{e}_\varphi \times \mathbf{B}_{\rm p}$$

- Steady production of Poynting flux by rotating BH (Blandford & Znajek 1977)



Poynting flux

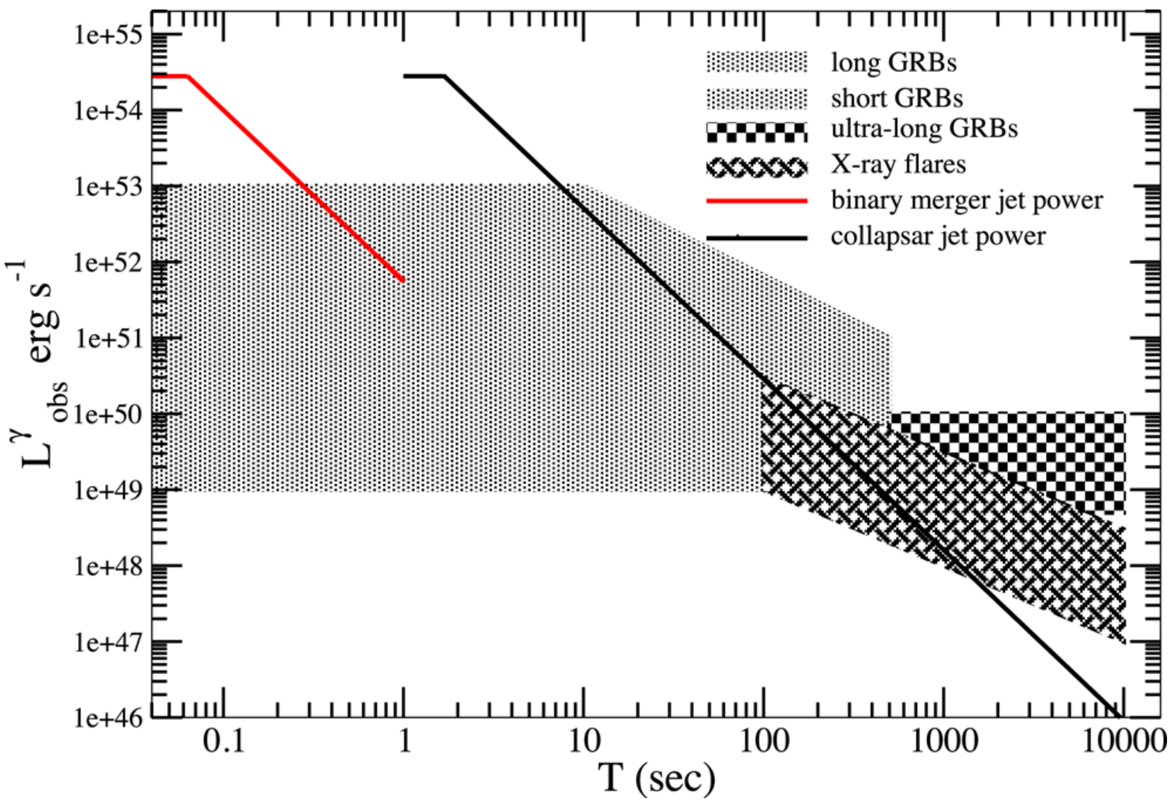
$$\mathbf{S}_{\rm p} = \frac{\mathbf{E}\times\mathbf{H}_\varphi}{4\pi}$$

$$\Omega_{\rm F} \sim \frac{1}{2}\Omega_{\rm H}$$

(KT 2016, IAU324, arXiv:1611.09447)

GRB jets

- AGN jets are optically thin, then cannot be driven thermally
- Thermal (neutrino driven) jets are not favored for GRB jets



$$\dot{M} \sim \frac{M_{\rm f} - M_{\rm i}}{T} \sim \frac{M_{\rm i}}{T} = 0.3 \frac{M_{\rm i}}{3\,{\rm M}_{\odot}} \left(\frac{T}{10{\rm s}}\right)^{-1} {\rm M}_{\odot}{\rm s}^{-1}.$$

This implies for the jet power that (see equation 1)

$$P^{\rm I}_{\nu\bar{\nu}} \sim 8.5 \times 10^{50} \left(\frac{M_{\rm i}}{3\,{\rm M}_{\odot}}\right)^{3/4} \left(\frac{T}{10\,{\rm s}}\right)^{-9/4} {\rm erg\,s}^{-1},$$

(Leng & Giannios 2014; see also Tchekhovskoy & Giannios 2015)