Probing the GRB Prompt Emission Mechanism through the γ- and X-ray polarimetry

(Toma 2013, in preparation)

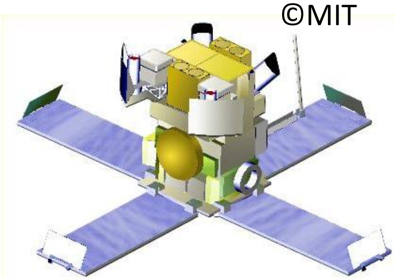
Kenji Toma
(Osaka Univ → Tohoku Univ)

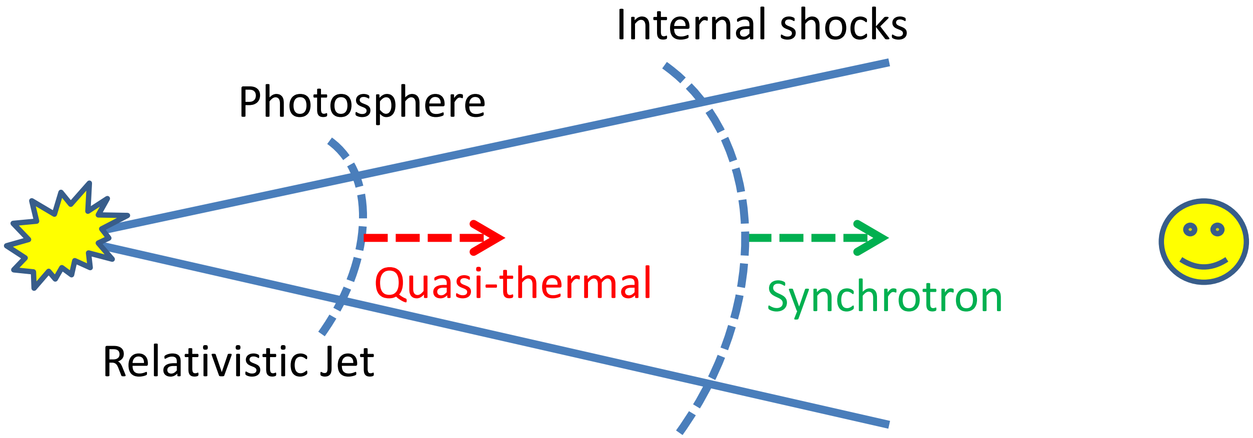
Supernovae and Gamma-Ray Bursts in Kyoto, Nov 11-15, 2013

Prompt Emission Mechanism

- In spite of extensive light-curve and spectral observations in the keV-MeV band as well as in the GeV band with Fermi, the GRB emission mechanism is still open.
- Polarimetric observations can give us some critical information for solving the problem (e.g. Lazzati 2006; KT 2013)

©NASA

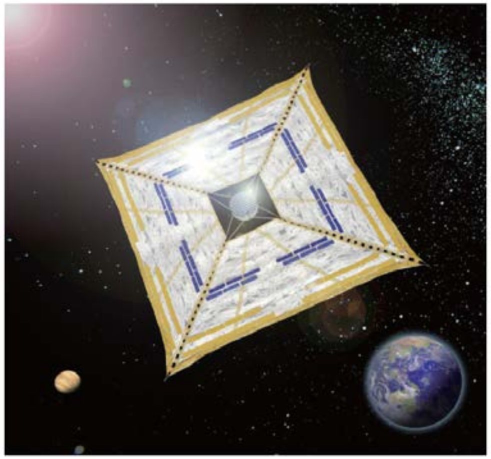


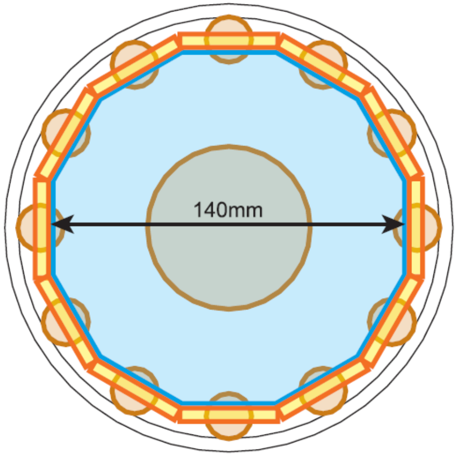


Gamma-ray Polarization

- GAP aboard IKAROS *(See Yonetoku's talk)*
- 70-300keV
- $\Pi_L = 27 \pm 11\%$ (GRB 100826A),
  $\Pi_L > 30\%$ at 2σ (110301A, 110721A)
- These are three brightest bursts observed by GAP
- Favor synchrotron emission model with ordered magnetic field (Yonetoku, Murakami, Gunji, Mihara, KT et al. 2011; 2012; KT, Mukohyama, Yonetoku et al. 2012; KT 2013)
- INTEGRAL-IBIS observations of GRB 041219A & 061122 are consistent (Gotz et al. 2009; 2013)

IKAROS ©JAXA

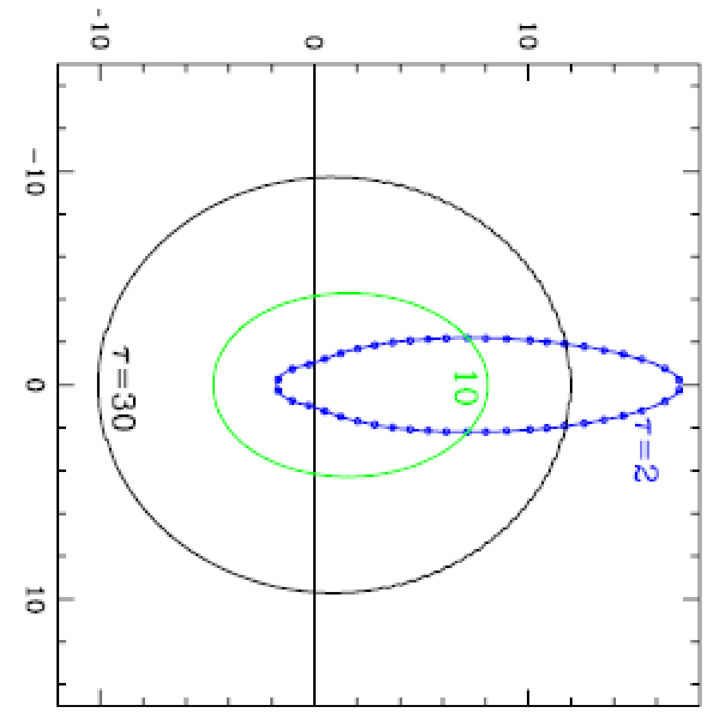




GAP detector (Compton-type)

Photospheric Emission Model?

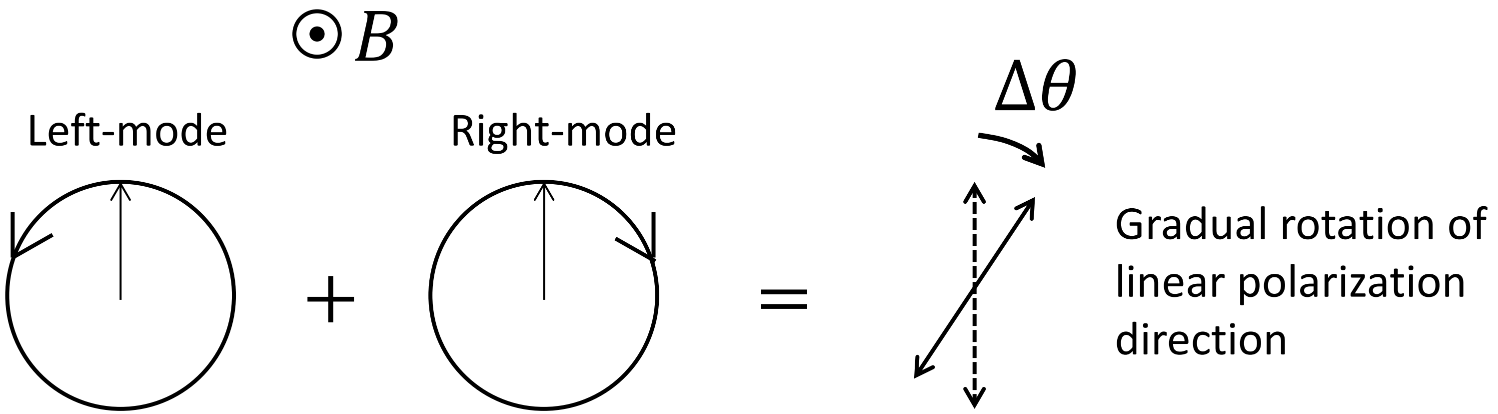
- If the fluid is matter-dominated at the photosphere, high Π_L arises (Compton scattering of anisotropic radiation)
- High Π_L from $\theta \sim 1/\Gamma$ (intensity relatively weak)
- Unlikely that all the bright bursts have high net Π_L
- Appear to be inconsistent with the GAP data



Angular distribution of radiation intensity *in the fluid frame*
(Beloborodov 2011)
(see also Lundman, Pe’er & Ryde 2013)

Faraday Rotation in the Source

- Detections of high linear polarization → synchrotron, B field structure
- Detections of Faraday effects in the source → B field strength

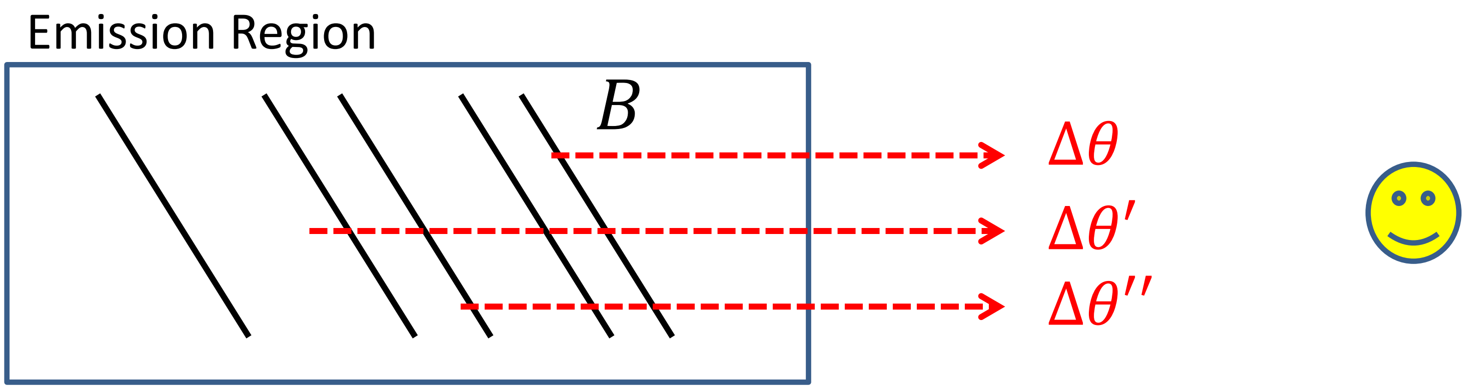


$$\Delta\theta = \frac{e^3}{\pi m_e^2 c^2} n B \cos\theta \, \nu^{-2} \Delta l$$

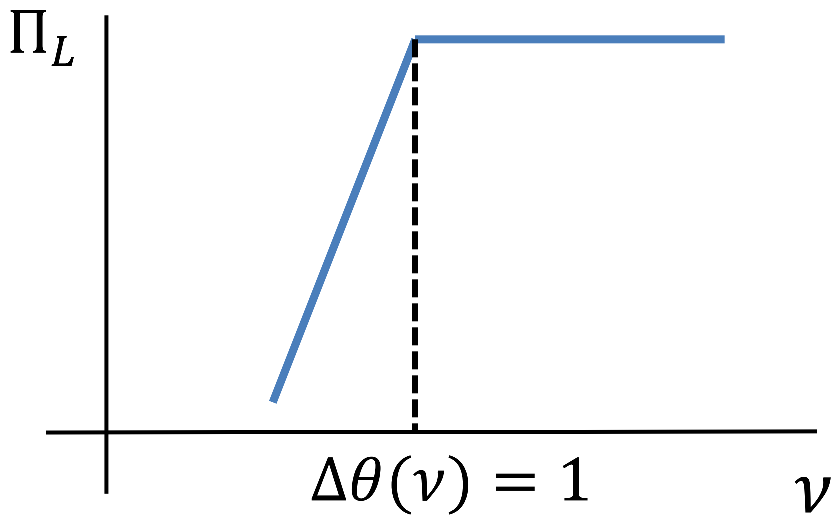
(Rybicki & Lightman 1979)

Faraday Depolarization

$$\Delta\theta = \frac{e^3}{\pi m_e^2 c^2} nB \cos\theta \, \nu^{-2} \Delta l \gg 1$$



- Linear polarizations with different rotation angles are canceled out
- Net Π_L decreases at energy range $\Delta\theta(\nu) \gg 1$



Relativistically-Hot Plasma

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

(Sazonov 1969; Melrose 1980)

- The Faraday rotation effect by relativistically-hot plasma is much smaller than that by cold plasma
- Not remarkable in the source where all the electrons keep accelerated

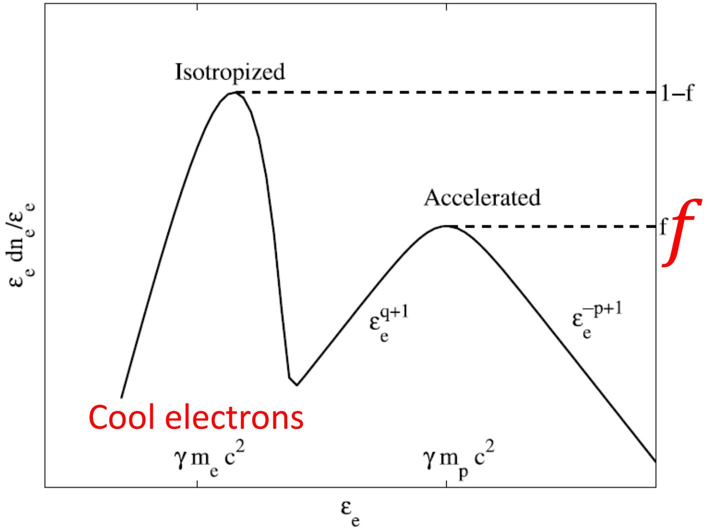
Cool Electrons in Prompt Emission Region

Predicted peak energy (e.g. Meszaros 2006)

$$E_p = \frac{3heB}{4\pi m_e c}\gamma_m^2\Gamma \simeq 600 f_{-1}^{-2}\epsilon_{e,-1}^{2}\epsilon_{B,-1}^{1/2}L_{52}^{1/2}r_{13}^{-1}\ \mathrm{keV}$$

- Dissipation energy has to be converted into only a small fraction of electrons.
- A large fraction of electrons are just isotropized by shock, remaining cool.

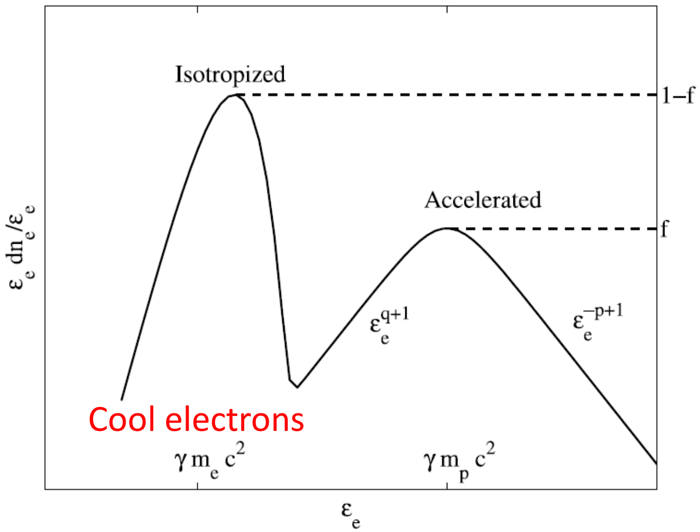
Electron energy distribution with acceleration efficiency < 100%



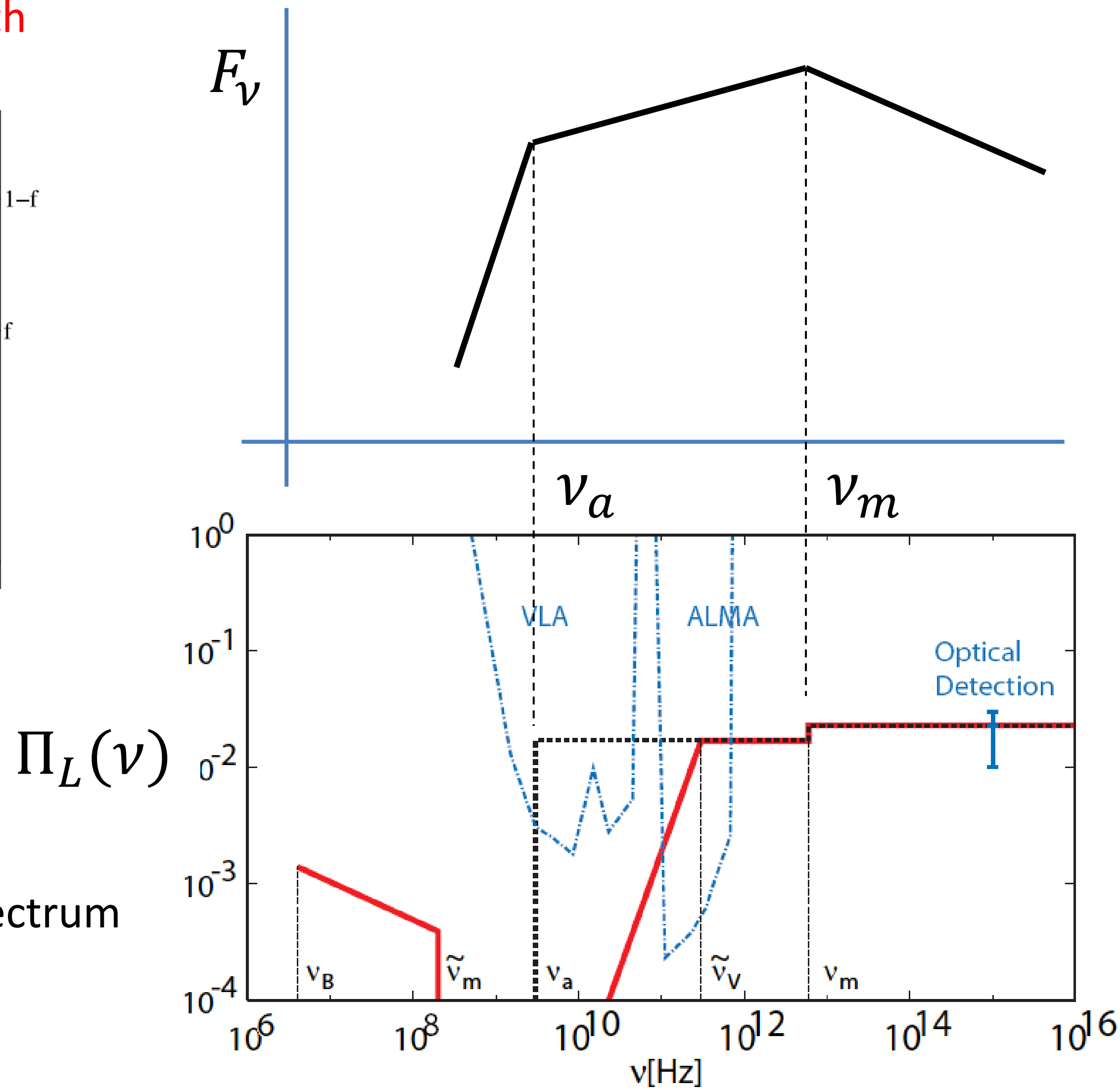
(Eichler & Waxman 2005)

Radio Afterglow

Electron energy distribution with acceleration efficiency < 100%



(Eichler & Waxman 2005)



Predicted late-time polarization spectrum
(KT, Ioka & Nakamura 2008)

Faraday Depolarization in Prompt Emission

- High Π_L detection → Ordered B field model
- Prompt emission models usually predict a large amount of cold electrons → Strong Faraday rotation

$$\Delta\theta(\nu_V) = 1 \quad \Rightarrow \quad \nu_V \simeq 100\, \epsilon_B^{1/4} L_{52}^{3/4} r_{12}^{-1} \Gamma_{2.5}^{-1}\ \mathrm{keV}$$

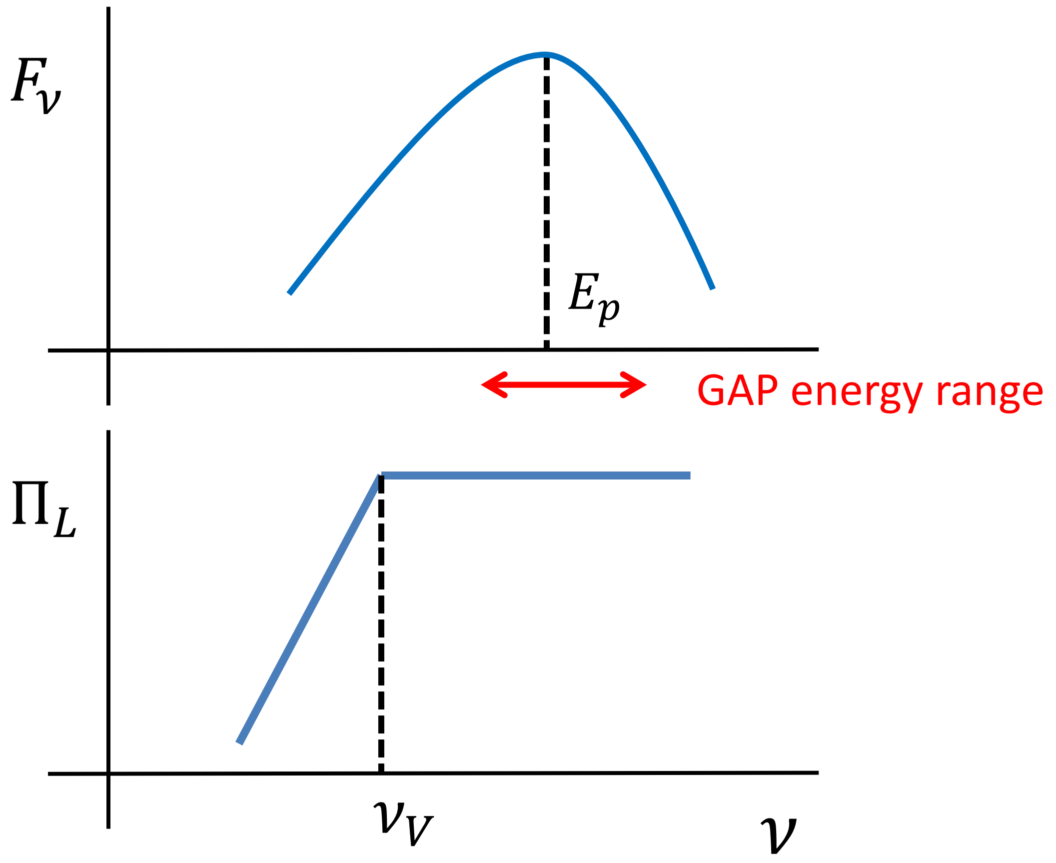
- High Π_L detection by GAP $\Rightarrow \nu_V \lesssim 70$ keV

$$\Rightarrow \quad r \gtrsim 10^{12}\, \epsilon_B^{1/4} L_{52}^{3/4} \Gamma_{2.5}^{-1}\ \mathrm{cm}$$

Future X-ray polarimetry (identification of ν_V ?) would constrain the emission radius more strongly.

Case Study (1)

- Synchrotron
- Ordered B field
- Cold electrons
- $r \sim 10^{13}$cm ($E_p \sim 1$MeV)

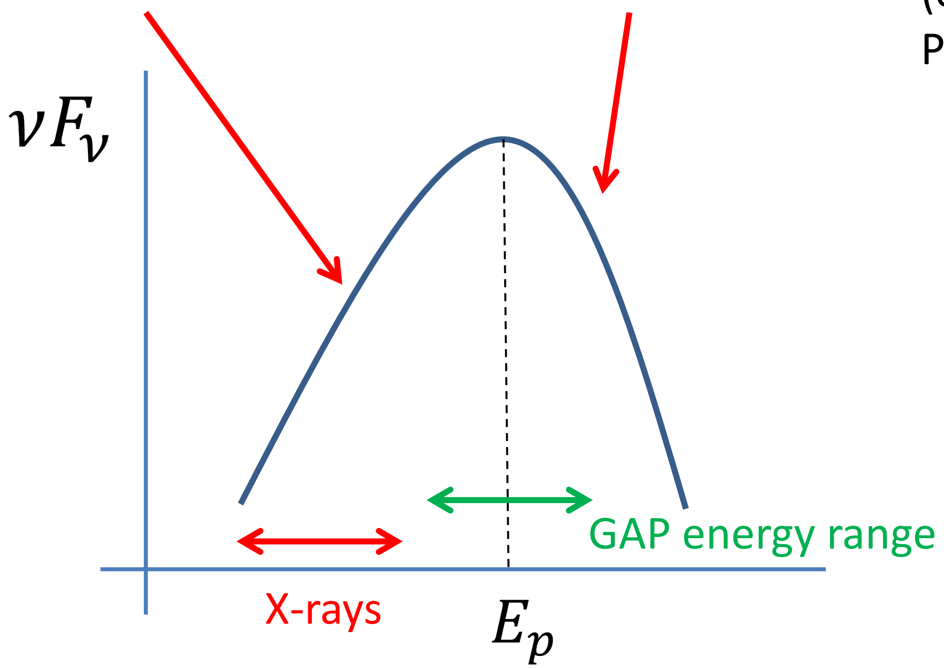


- If Faraday depolarization detected in X-rays ⇒ Disfavor the quasi-thermal emission model

Case Study (2)

- Synchrotron + quasi-thermal ?

(e.g. Vurm, Beloborodov, & Poutanen 2011)



- If high X-ray Π_L in many bright bursts ⇒ Ordered B field
- If Faraday depolarization detected ⇒ A small fraction of positrons (strong constraint on the model)

Summary

- Detections of linear polarization by GAP in bright bursts favor the synchrotron model with ordered B field
- Detection of Faraday depolarization in X-rays would imply [ordered B field], [electron-proton plasma], [existence of cool electrons]
- More quantitative calculations are in progress

Gamma-ray Polarization

Event name	T_{90} [s]	fluence [erg cm^{-2}]	E_p [keV]	Π	2σ limit
GRB 100826A	$\simeq 150$	$(3.0 \pm 0.3) \times 10^{-4}$	606^{+134}_{-109}	$27 \pm 11\%$	$> 6\%$
GRB 110301A	$\simeq 5$	$(3.65 \pm 0.03) \times 10^{-5}$	$106.8^{+1.85}_{-1.75}$	$70 \pm 22\%$	$> 31\%$
GRB 110721A	$\simeq 24$	$(3.52 \pm 0.03) \times 10^{-5}$	393^{+199}_{-104}	$84^{+16}_{-28}\%$	$> 35\%$

- Three GRBs are among the brightest bursts observed by GAP