Polarization measurements of GRBs and axion (ALP)-photon coupling

Alexander Sakharov & Andre Rubbia

ETH, CERN

4th Patras Workshop, June 19, DESY Hamburg

Summary

- *Axion-photon mixing, polarization effects*
- *Astrophysical and cosmological effects of axion-photon mixing*
- *Phenomenology of GRBs, polarization measurements*
- *Polarized prompt emission and axion-photon mixing*
- *Future prospects*
- *Conclusions*

Invisible axion (ALP)

Non-perturbative QCD effects violate CP

$$\mathcal{L}(\theta) = \theta \frac{g^2 F_a^{\mu\nu} \tilde{F}_{a\mu\nu}}{32\pi^2}$$

Additional CP violating source

$\mathcal{M}_q \longrightarrow$ diagonal

The total strong CP violation $\bar{\theta} = \theta + \text{Arg det } \mathcal{M}_q$

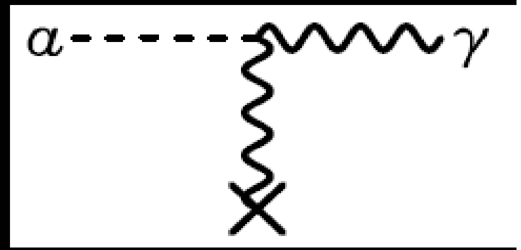
Consistency with the experimental bound $|d_n| \leq 3 \times 10^{-26}\ e \cdot \text{cm}$ $|\bar{\theta}| < 10^{-9}$

Strong CP problem $\text{U}(1)_{\text{PQ}} \longrightarrow \theta$ rotates away

$\theta \longrightarrow a$

(Peccei & Quinn, 1977)

Axion-photon mixing



Two photon vertex interaction

(Raffelt & Stdolsky, 1988)

(Maiani, Petronzio & Zavattini, 1986)

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma\gamma} \mathbf{E} \cdot \mathbf{B}_0 a$$

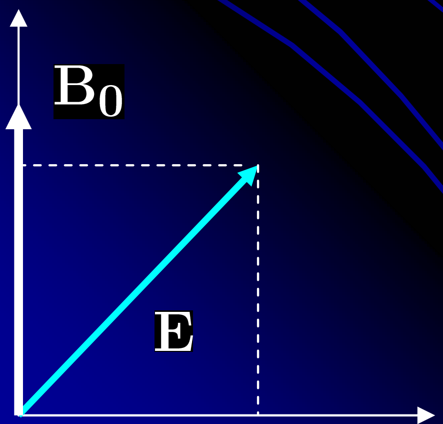
KSVZ, DFSZ

$$g_{a\gamma\gamma} = \xi \frac{\alpha}{2\pi} \frac{1}{f_a}$$

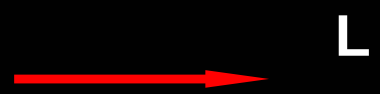
Additional contribution into refractive index of mode parallel to the **[B k]** plane

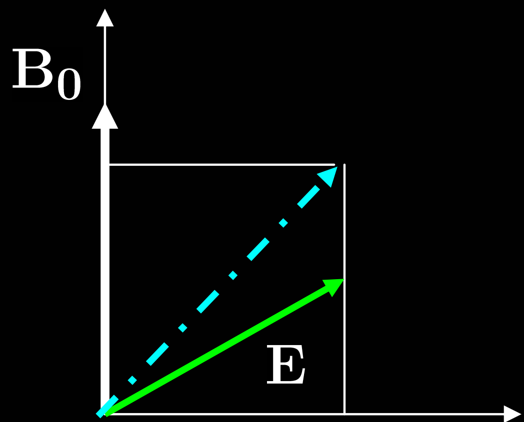
$$n_{\text{perp}}^{\text{axion}} = n_{\text{perp}}^{\text{QED}}$$

$$n_{\text{par}}^{\text{axion}} = n_{\text{QED}}^{\text{par}} + \frac{1}{2\omega}\left(\left[\left(\frac{B_0 \sin\theta}{M}\right)^2 + \left(\Delta_{\text{osc}} + \frac{m_a^2}{2\omega}\right)^2\right]^{1/2} - \left(\Delta_{\text{osc}} + \frac{m_a^2}{2\omega}\right)\right)$$



Dichroism





$$\epsilon = \frac{g_{a\gamma\gamma}^2}{m_a^2} \omega^2 B_0^2 \sin^2\left(\frac{m_a^2 L}{4\omega}\right) \sin 2\varphi$$

Astrophysical and cosmological consequences

- Polarization properties and shape of distant radio galaxies (Harari & Sikivie 1992); quasars (Hutsemekers et al 2005, Gnedin, Pitrovich & Natsvlishvili 2006)

- The diffuse x-ray background (Krasnikov 1996; Fairbairn et al 2007)

- Ultra and very high energy gamma rays (Gorbunov, Raffelt & Semikoz 2001; Csaki et al 2001, de Angelis & Roncadelli 2007)

- Dimming of distance sources by photon-ALP conversion (Csaki, Kaloper & Terning 1996)

- CMB distortions (Chen 1995, Mirizzi, Raffelt & Serpico 2005)

- ALP-photon conversion in Sun spots (Carlson & Tseng 1995; Zioutas et al 2007) in magnetic field of pulsars (Dupays, Rizzo, Roncadelli & Bignami 2005)

Gamma ray burst (GRB)

GRBs – sudden and unpredictable burst of high energy X / soft gamma rays of huge intensity and typical duration of tens of seconds coming from random direction in the sky

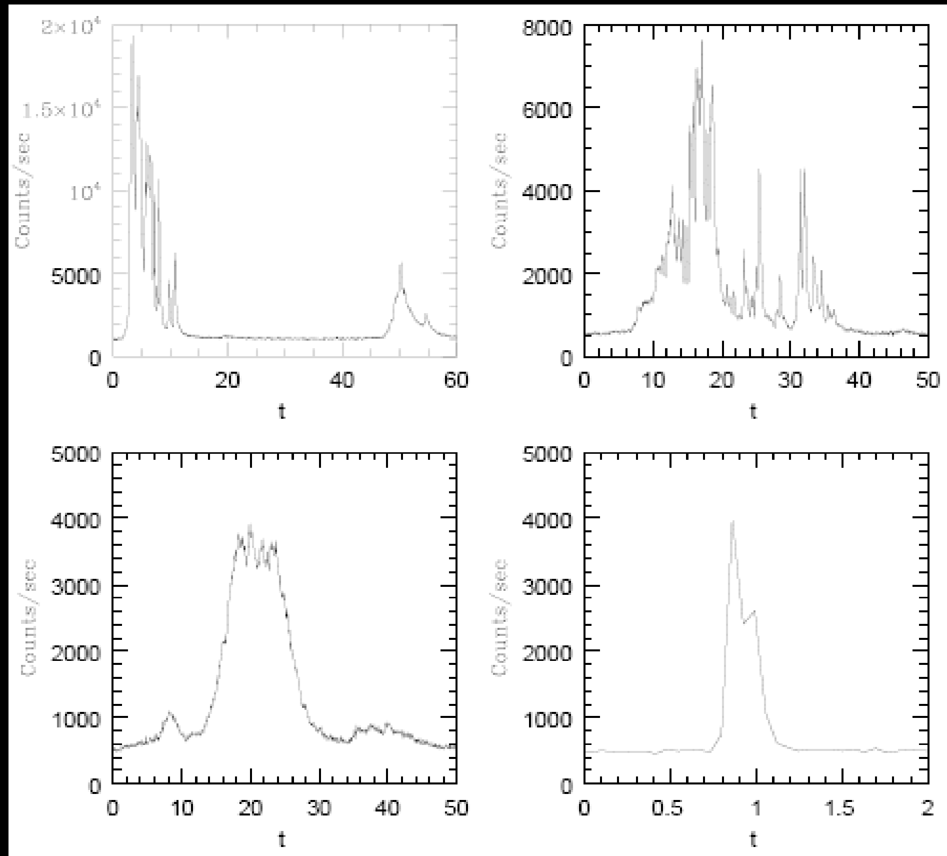
Most of the flux detected from 10KeV to 1-2 MeV

Very transient, unclassifiable time profiles

Estimated rate 1.8 burst/day

X ray and optical afterglow

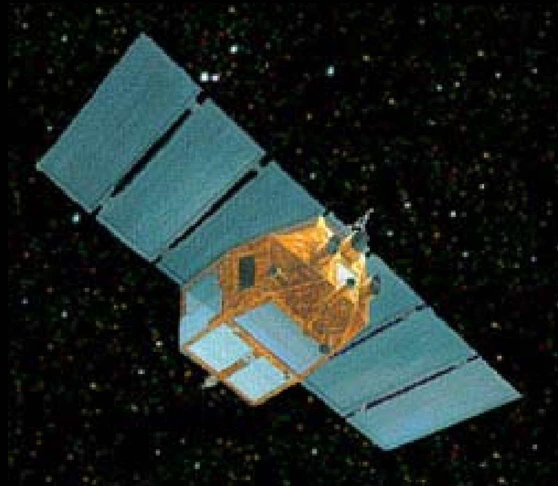
Redshift z=0.03-6.3 (>70 measured)



High energy prompt emission (up to 100 MeV) EGRET

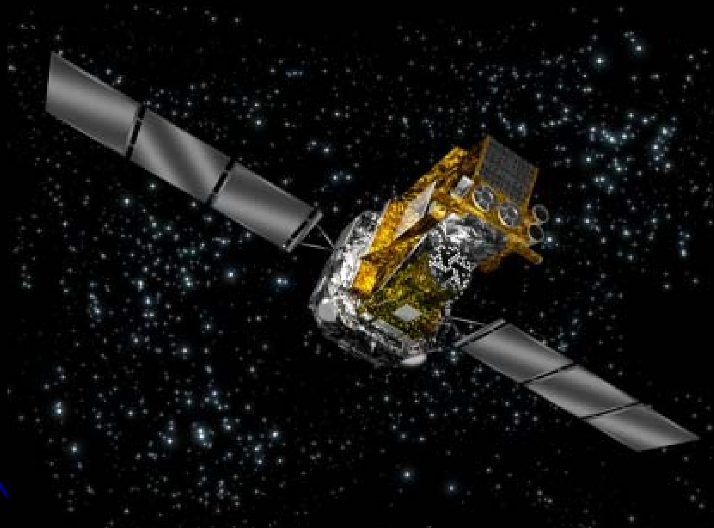
BATSE (GRO)

Beppo-SAX

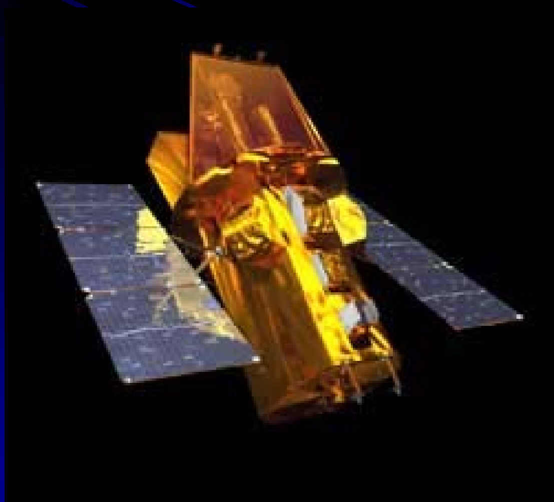


HETE

INTEGRAL



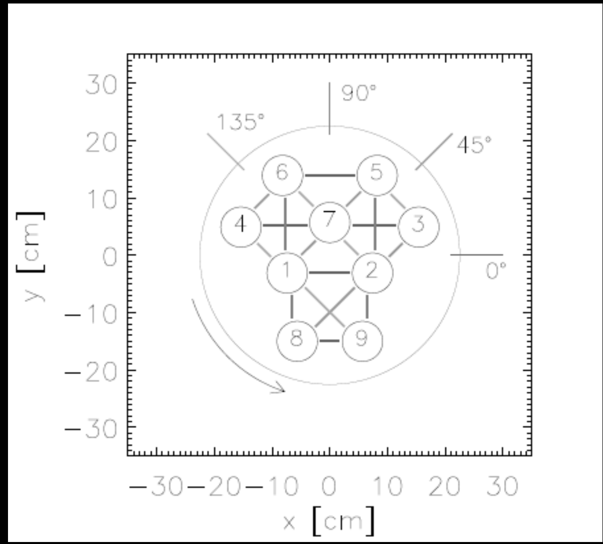
SWIFT



GLAST

Polarized prompt emission from GRB 021206 !?

RHESSI



GRB 021206

Prompt emission from GRB021206 found to be linearly polarized at 0.15-2 MeV

$\Pi = (80 \pm 20)\%$ (Coburn & Boggs 2003)

The analysis has been challenged

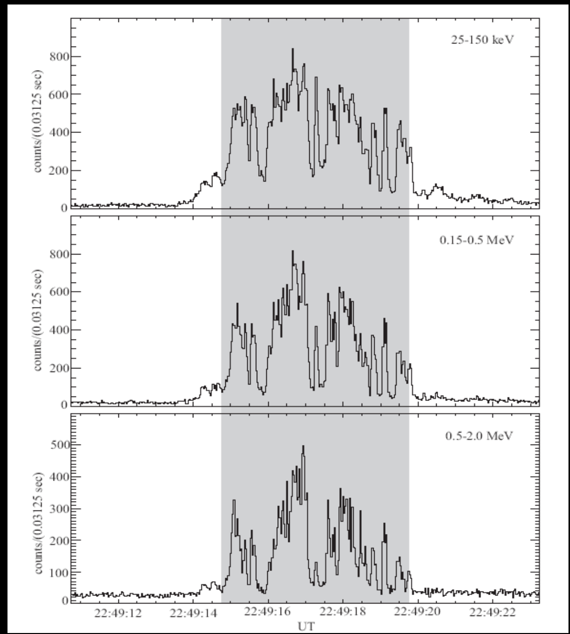
(Rutledge & Fox 2003)

The analysis has been defended

(Coburn & Boggs 2003)

Les significant signal has been found

$\Pi = 41^{+57}_{-44}\%$ (Wiggler at al 2004)



Other evidence of polarized GRBs (BATSE)

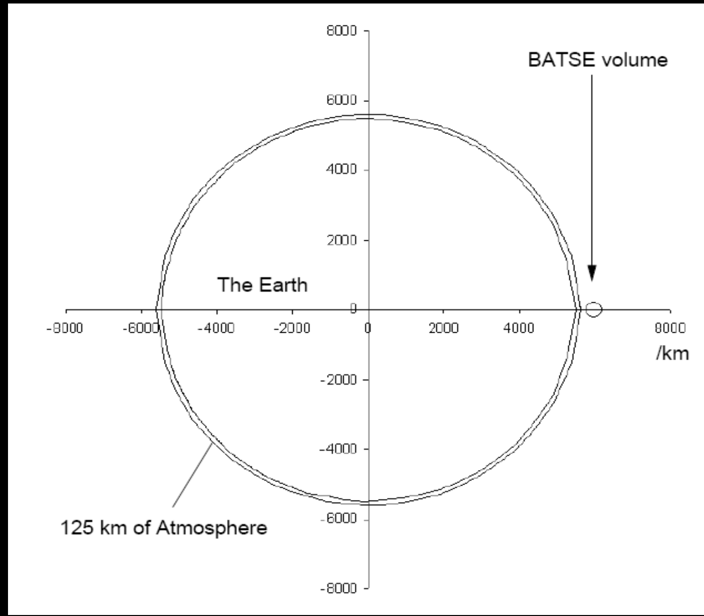
BATSE Albedo Polarimetry System (BAPS)

(Willis, et al 2003)

GRB 930131 $\Pi > 35\%$

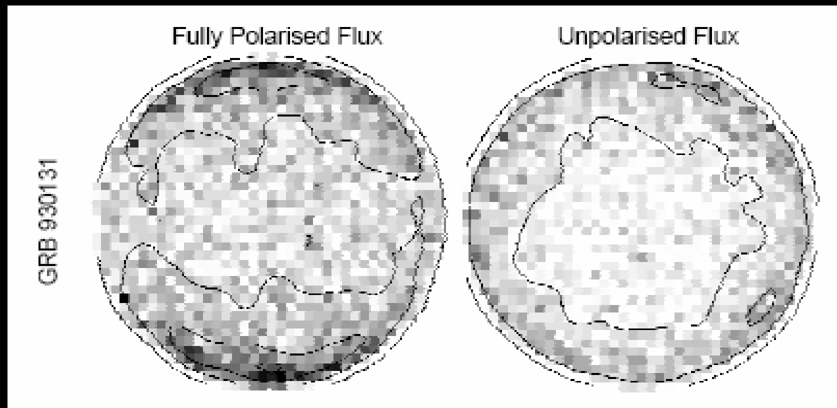
3-100 keV

GRB 960924 $\Pi > 50\%$



GRB flux scatters off the atmosphere; the distribution is recorded as it passes through a volume equivalent to where BATSE was at the time of the burst.

- Polarized flux preferentially scatters perpendicular to the direction of the polarization vector.

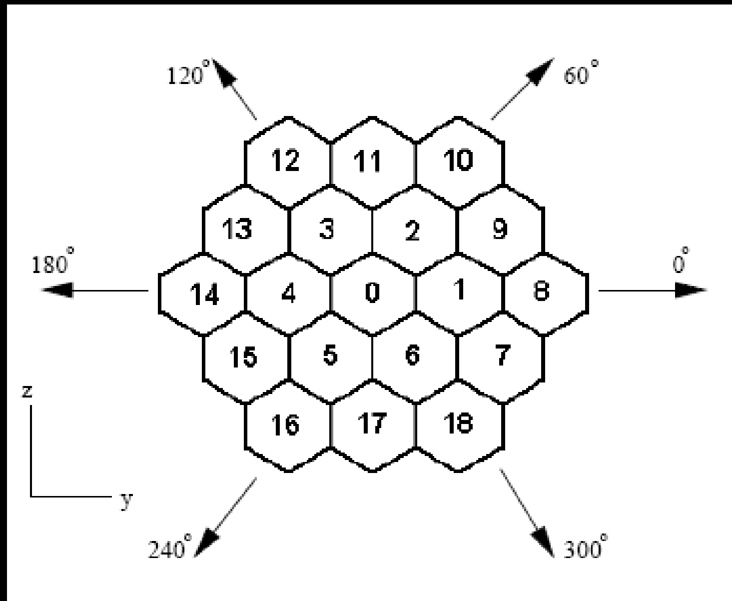


Any distribution produced as a result of polarized flux will appear as an anti-phase excess toward the limbs of the Earth.

Polarization studies by INTEGRAL

Masked spectrometer abord INTERGAL as a polarimeter (McGlynn, et al 2007)

GRB 041219a $\Pi = 96^{+39}_{-40}\%$ 100-350 keV



For each simulation run the polarization angle was set between 0 and 180 degree n 10 degree step. Compatible with $\Pi \simeq 60\%$

Similar fluence but over shorter time

A spectral harder burst, which would produce more multiple events and stronger polarization signature

DOCTOR FUN

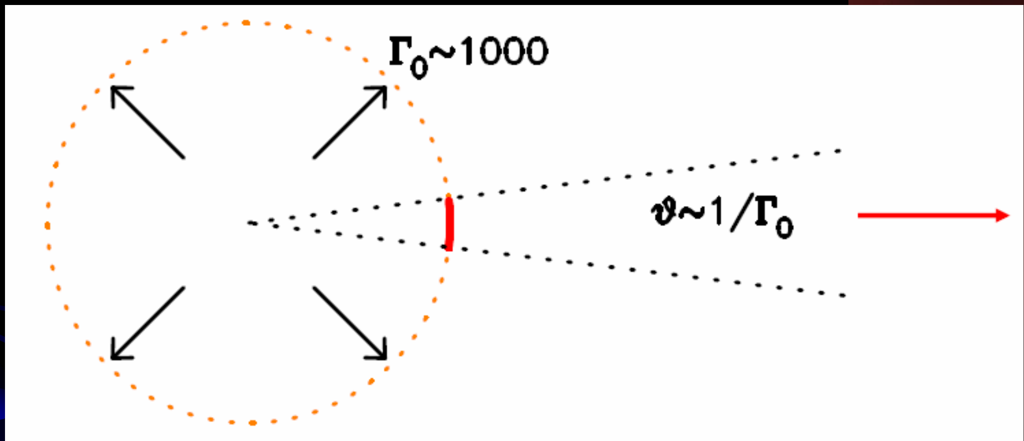
Despite funding cuts, research into the origin of gamma-ray bursts continues as best it can.

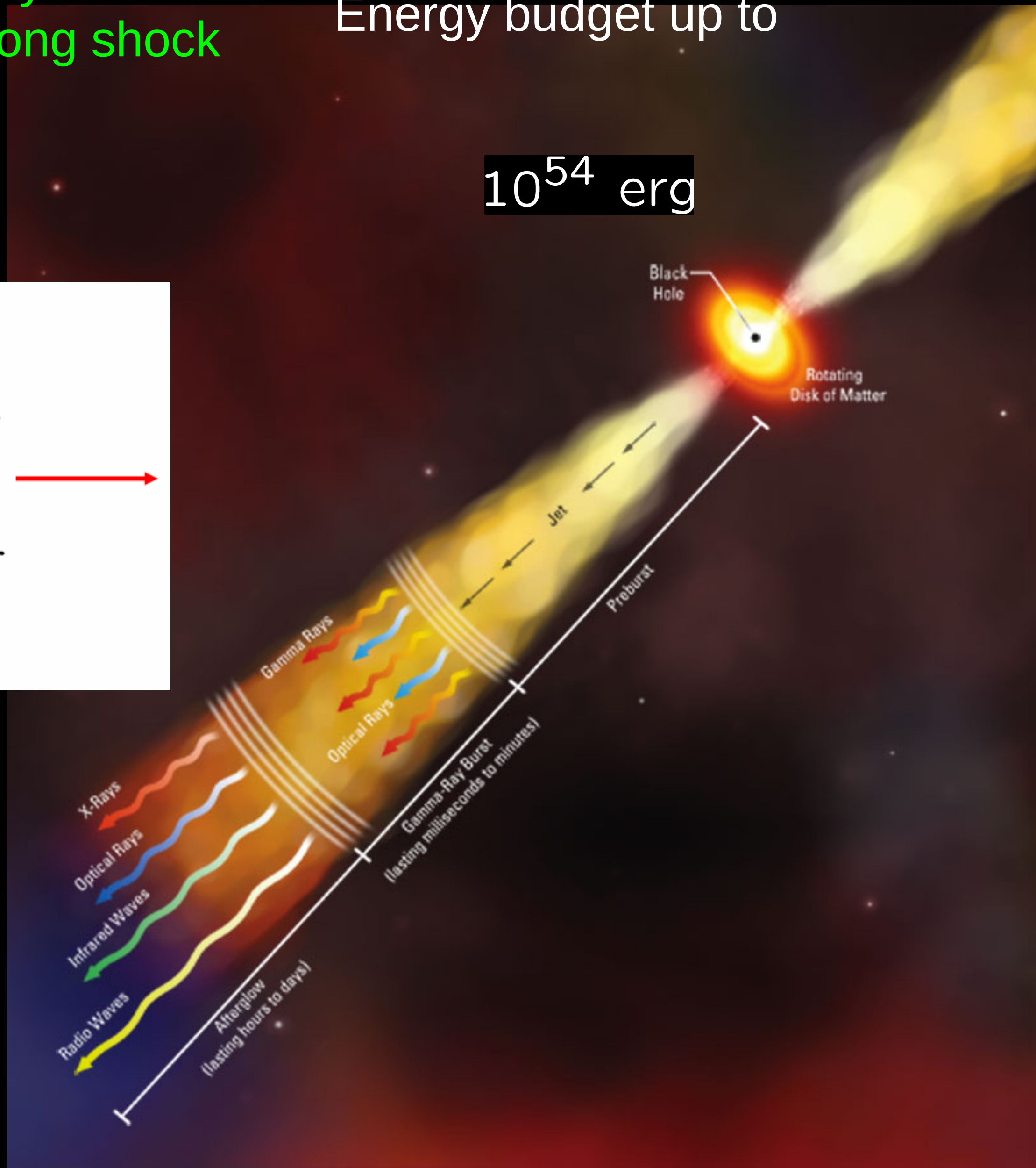
Relatvistic fireball (beamed)

The simplest model for the gamma-ray emission assumes that a proton crossing a strong shock front

Energy budget up to

10^{54} erg



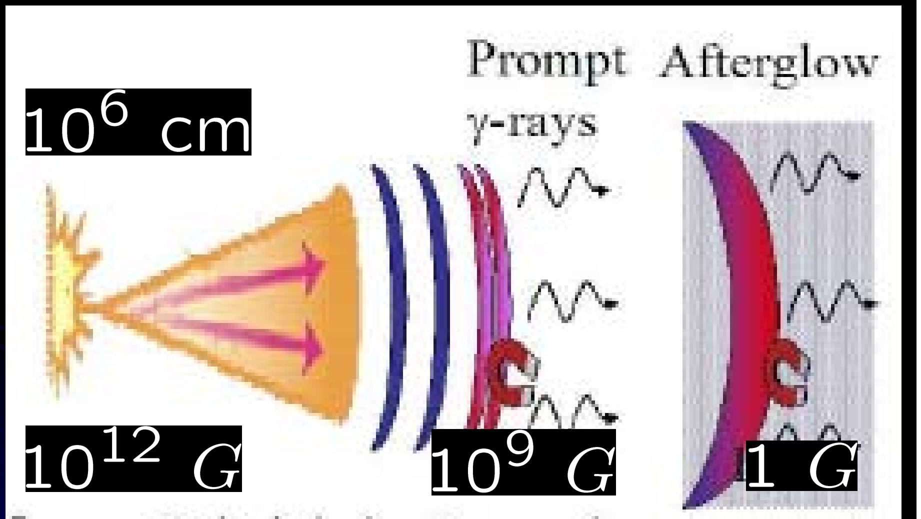


"General" GRB modeling elements

Relativistic flow

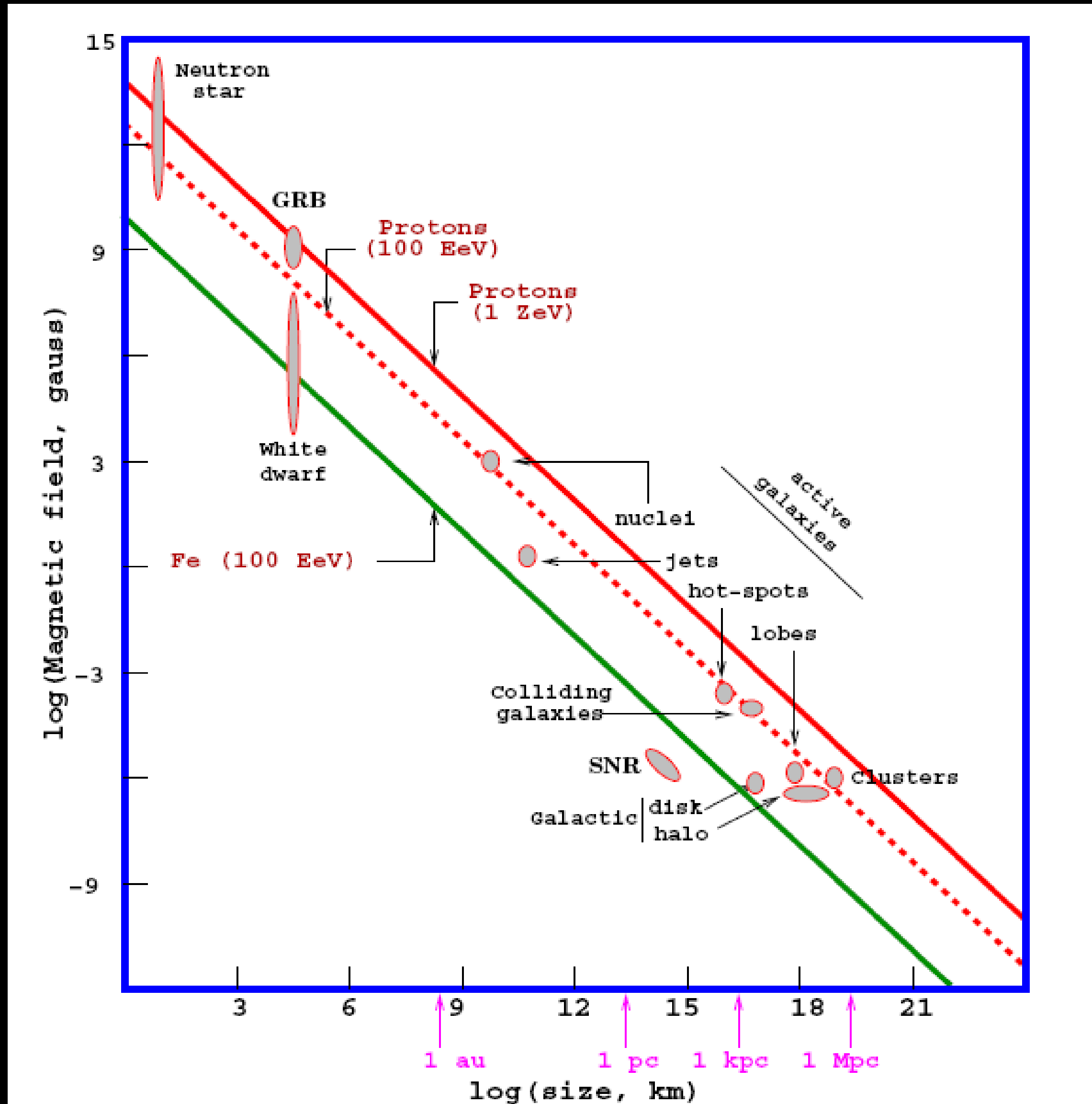
relativistic fireball (Goodman, 1986; Paczynski, 1990; Piran & Shemy 1993)

cannon ball (Dar & De Rujula; 2000)

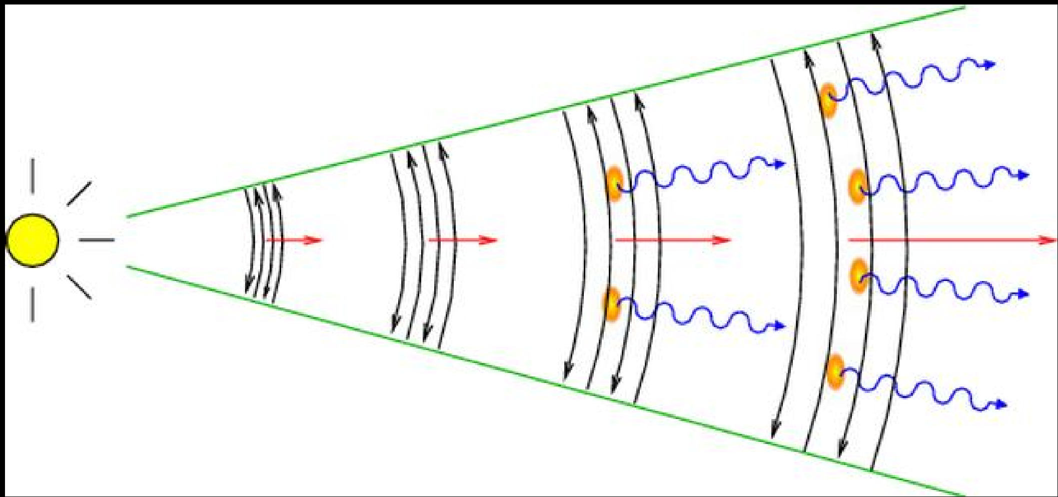


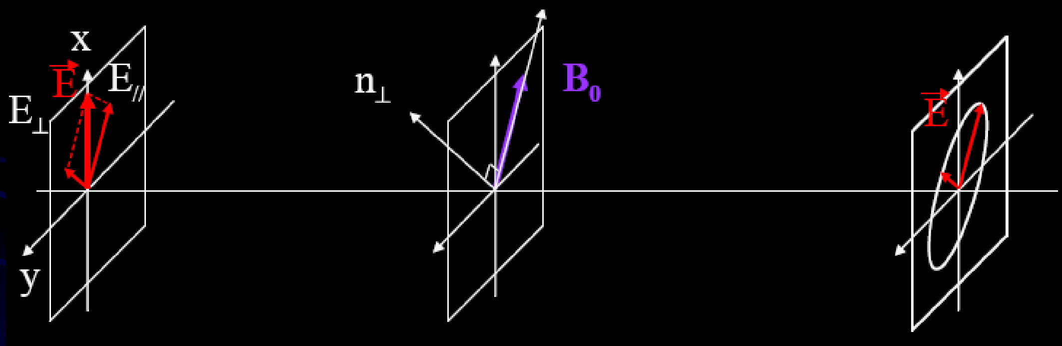
Hillas diagram

(Hillas, 1984; Anchordoqui,2003)



Axionic induced dichroism in GRB





$$\Delta^2_{\rm osc} = \left(\frac{m_a^2 - \omega_{\rm pl}}{2\omega}\right)^2 + B^2 g^2_{a\gamma\gamma}$$

$$\omega_{\rm pl} = \sqrt{4\pi\alpha n_e/m_e} \simeq 3.7 \cdot 10^{-11}\sqrt{n_e/{\rm cm}^{-3}}\ {\rm eV}$$

minimal variability 100 ms

$$L_{\rm GRB} \simeq 10^9\ {\rm cm}$$

central engine

$$r_0 \simeq 10^6\ {\rm cm} \qquad B_0 \simeq 10^{12}\ {\rm G}$$

$$4\pi r_0^2 B_0^2 = 4\pi L^2_{\rm GRB} B^2$$

$$L_{\rm GRB} \simeq 10^9\ {\rm cm} \qquad B_0 \simeq 10^9\ {\rm G}$$

Axion mass dominated

$$n_e \simeq 10^{10}{\rm cm}^{-3}$$

$$m_a \simeq 10^{-4}{\rm eV}$$

The polarization signature

All photon interaction mechanisms relevant to high-energy astrophysics are sensitive to linear polarization

Distribution in the emission direction of the interaction products

$$f(\phi) = A + B\cos^2\phi$$

The modulation

$$\mu = \frac{(f_{\text{max}} - f_{\text{min}})}{(f_{\text{max}} - f_{\text{min}})} = \frac{B}{2A + B}$$

The sensitivity of a polarimeter depends on both its analyzing power and its quantum efficiency

$$\Pi_{\text{MDP}} = \frac{1}{\mu\epsilon}\frac{n_\sigma}{S}\left(\frac{2\epsilon S + B}{t}\right)^{1/2}$$

A lost of statistics increases the minimal detectable polarization

Relative misalignment

The polarization rotation angle

$$\Delta\epsilon \approx \frac{L_{\text{GRB}}}{2\pi}\frac{g^2_{a\gamma\gamma}}{m_a^2}\Delta\omega B^2$$

Magnetic field strengths $B \simeq 10^9$ G

Extension $L_{\text{GRB}} \simeq 10^9$ cm

The energy difference $\Delta\omega = |\omega_2 - \omega_1| \approx 1$ MeV

Preserve the statistical pattern of the time integrated polarization signal from a GRB in a detector for the energy range ω_1 - ω_2

$$\Delta\epsilon \leq \frac{\pi}{2}$$

$$g_{a\gamma\gamma} \leq \pi\frac{m_a}{B\sqrt{\Delta\omega L_{\text{GRB}}}}$$

GRB021206 (RHESSI) $\omega_1 \approx 0.2$ MeV $\omega_1 \approx 1.3$ MeV

$$g_{a\gamma\gamma} \leq 2.2 \cdot 10^{-8}\frac{m_a}{1\text{ eV}}\ (\text{GeV})^{-1}$$

$$m_a \leq \sqrt{\frac{2\pi\omega}{L_{\mathrm{GRB}}}}$$

$\omega_1 \approx 1.3$ MeV

$m_{cr1} \approx 3.5 \times 10^{-4}$ eV

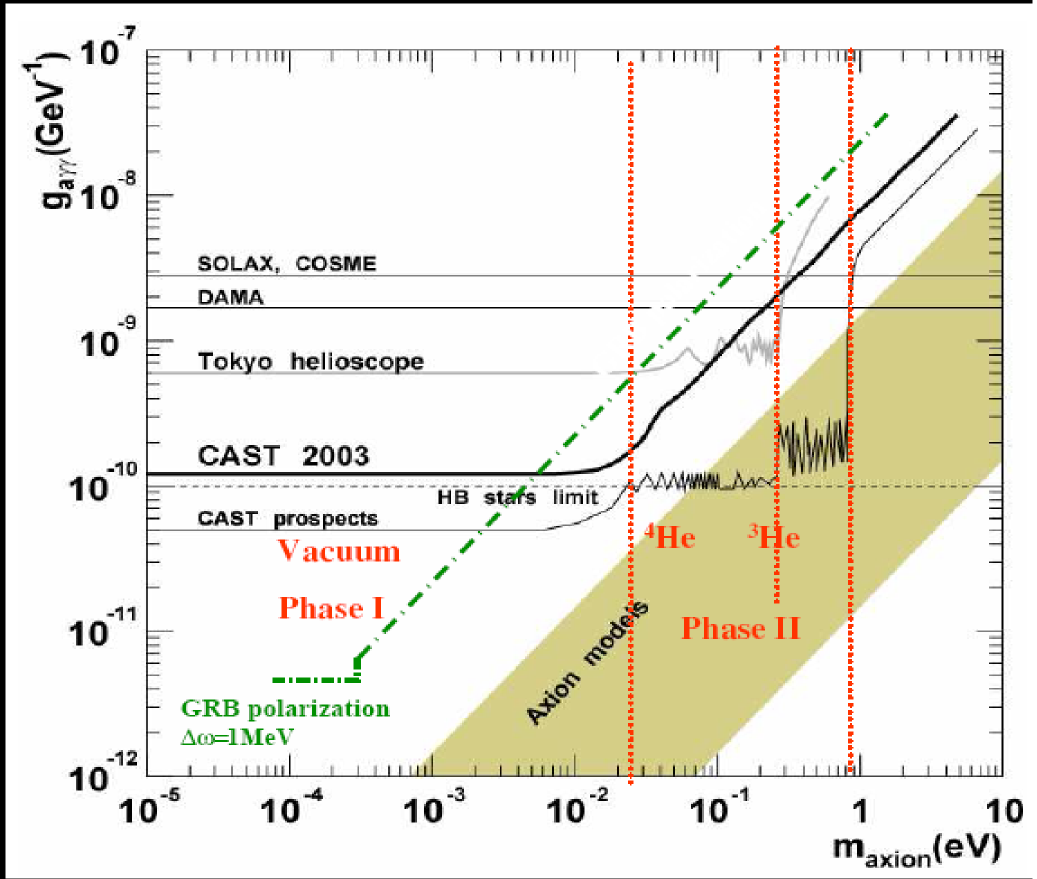
$$\epsilon = \frac{g_{a\gamma\gamma}^2}{16}(BL_{\mathrm{GRB}})^2$$

$$\Delta\epsilon = B^2 g_{a\gamma\gamma}^2 L_{\mathrm{GRB}} \left(\frac{L_{\mathrm{GRB}}}{16} - \frac{\omega_1}{2\pi m_a^2} \right)$$

$m_{cr1} \approx 8 \times 10^{-5}$ eV

$$g_{a\gamma\gamma} \leq \frac{2\sqrt{2\pi}}{BL_{\mathrm{GRB}}} \approx 5 \cdot 10^{-12}\ (\mathrm{GeV})^{-1}$$

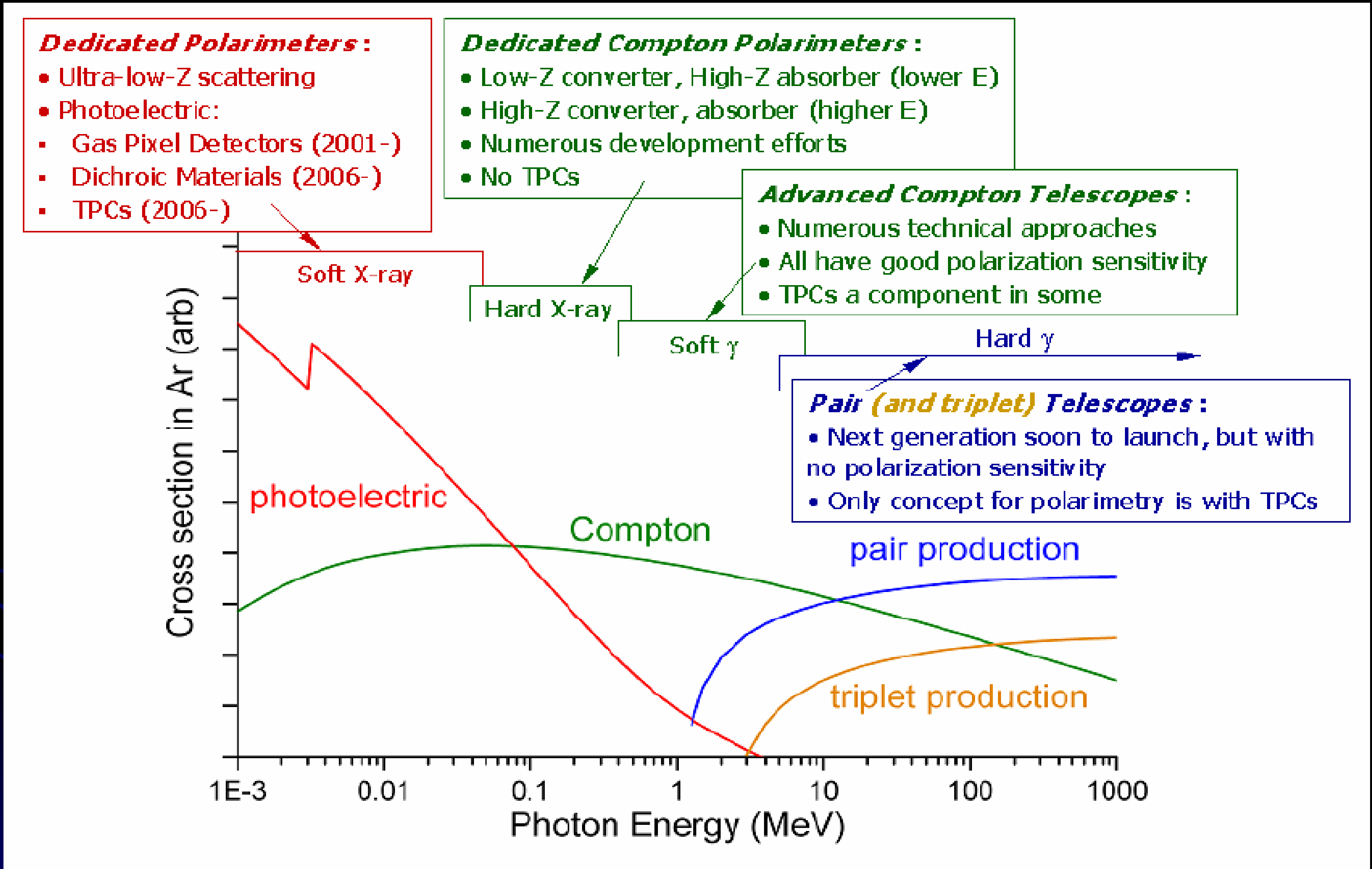
$$\sqrt{\frac{1\ \mathrm{MeV}}{\Delta\omega_{\mathrm{I,B}}}}$$



(Zioutas et al, 2003)

Future prospects

(Black, 2007)



ACT

(McConnell & Ryan, 2004)

POLAR

(Produit et al, 2005)

POLAR

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Nuclear Physics B (Proc. Suppl.) 166 (2007) 273–275

NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS

www.elsevierphysics.com

POLAR: A compact detector for GRB polarization measurements

J.P. Vialle [a], F. Barao [b], C. Casella [c], K. Deiters [d], S. Deluit [e], C. Leluc [c], A. Mchedlishvili [d], M. Pohl [c], N. Produit [e], D. Rapin [c], E. Suarez-Garcia [d], Ch. Tao [f], R. Walter [e], C. Wigger [d], A. Zehnder [d]

[a]LAPP/IN2P3/CNRS, Annecy, France

[b]LIP, Lisboa, Portugal

[c]DPNC, Université de Genève, Switzerland

[d]PSI, Villigen, Swizerland

[e]Université de Genève, Switzerland

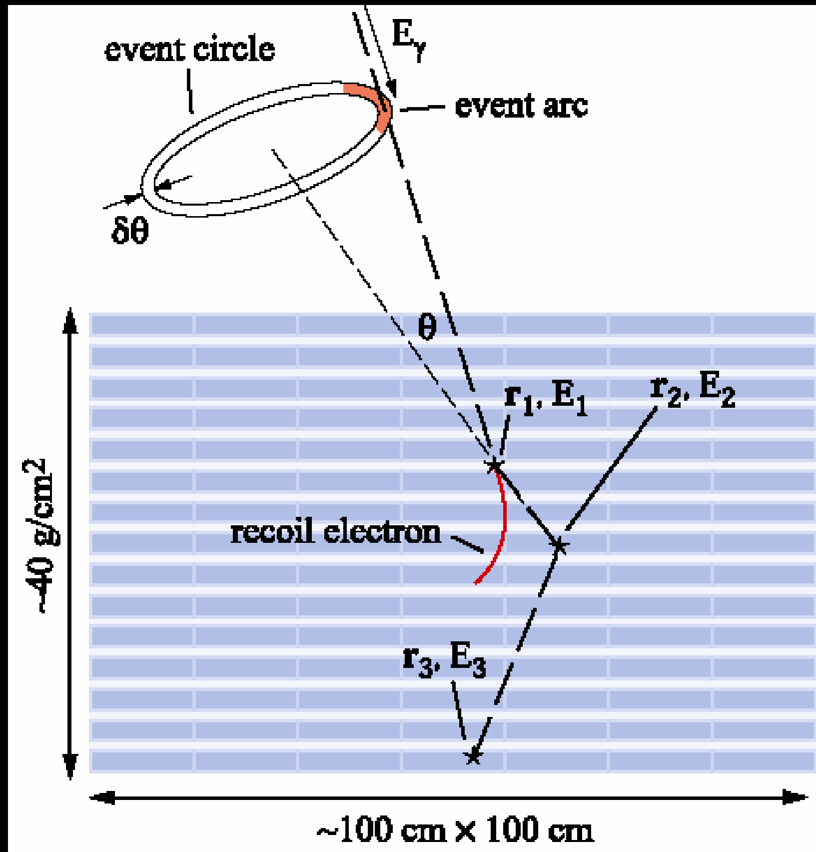
[f]CPPM, Université de la Méditerrannée, France

Though polarization measurements of X-rays can provide essential information for identifying processes responsible of their emission by astrophysical objects, almost no experimental data exist yet. We propose here a novel wide field compact detector for hard X-ray polarization measurements based on Compton scattering process and made of low-Z fast scintillators.

Advanced Compton Telescopes

ACT Enabling Detectors

- 1 mm^3 resolution
- $\Delta E/E \sim 0.2\text{-}1\%$
- 10-20% efficiency
- background rejection
- polarization, wide FoV



Conclusions

- A polarized gamma ray emission spread over a sufficiently wide energy band from a strongly magnetized astrophysical object like GRBs offers an opportunity to test the hypothesis of ALP

- Any evidence of polarized gamma rays coming from a GRB could be interpreted as a constraint on axion-photon coupling

- Future space based polarimeters like ACT and POLAR are very relevant for ALP physics