Status and Future Prospects for γ-Ray Polarimetry

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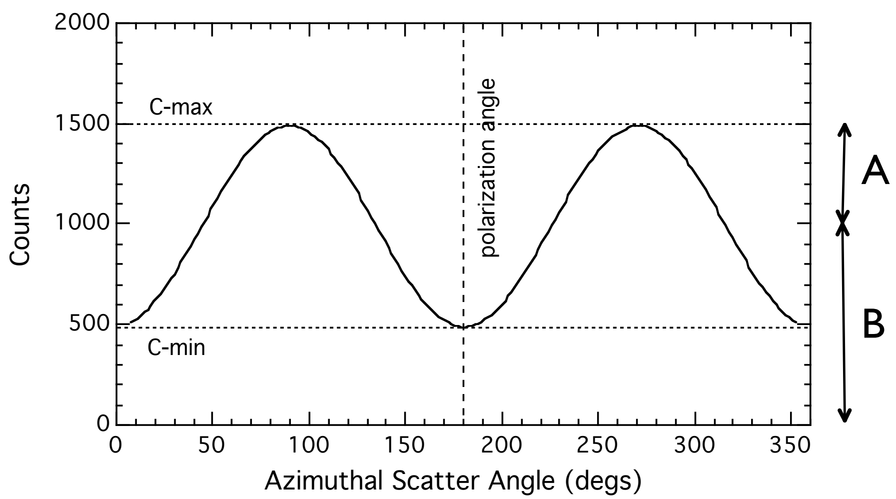
Overview

- Recent Results
  - RHESSI GRB
  - RHESSI Solar Flare
- Experimental Approach
  - Low Energy gamma-rays (50-500 keV)
  - Medium Energy gamma-rays (0.5-30 MeV)
  - High Energy gamma-rays (>30 MeV)

The Polarization Signature

For a fixed scatter angle (θ), the azimuthal distribution of scattered photons contains the polarization signature.



$$C(\eta) = A\cos 2(\eta - \varphi) + B$$

Modulation Factor for a 100% polarized beam represents a figure-of-merit for the polarimeter

$$\mu_{100} = \frac{C_{max} - C_{min}}{C_{max} + C_{min}} = \frac{A}{B}$$

Amplitude defines the *level* of polarization.

Minimum phase defines the *plane* of polarization.

GRB 921206

Polarization of the prompt γ-ray emission from the γ-ray burst of 6 December 2002

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Observations of the afterglows of γ-ray bursts (GRBs) have revealed that they lie at cosmological distances, and so correspond to the release of an enormous amount of energy[1,2]. The nature of the central engine that powers these events and the prompt γ-ray emission mechanism itself remain enigmatic because, once a relativistic fireball is created, the physics of the afterglow is insensitive to the nature of the progenitor. Here we report the discovery of linear polarization in the prompt γ-ray emission from GRB021206, which indicates that it is synchrotron emission from relativistic electrons in a strong magnetic field. The polarization is at the theoretical maximum, which requires a uniform, large-scale magnetic field over the γ-ray emission region. A large-scale magnetic field constrains possible progenitors to those either having or producing organized fields. We suggest that the large magnetic energy densities in the progenitor environment (comparable to the kinetic energy densities of the fireball), combined with the large-scale structure of the field, indicate that magnetic fields drive the GRB explosion.

is the azimuthal scatter angle, η is the direction of the polarization vector, and μ_m is the average value of the polarimetric modulation factor for the instrument. Although RHESSI has a small effective area (~20 cm^2) for events that scatter between detectors, it has a relatively large modulation factor in the 0.15–2.0 MeV range, $\mu_m \approx 0.2$, as determined by Monte Carlo simulations described below.

In comparison with other γ-ray instruments (COMPTEL, BATSE) that have attempted to measure polarization in the past[5,6], RHESSI has the major advantage of quickly rotating around its focal axis (centred on the Sun) with a 4-s period. Rotation averages out the effects of asymmetries in the detectors and passive materials that could be mistaken for a modulation. Because polarimetric modulations repeat every 180°, any source lasting more than half a rotation (2 s) will be relatively insensitive to the systematic uncertainties that typically plague polarization measurements. Finally, although the RHESSI detectors have no positioning information themselves, they are relatively loosely grouped on the spacecraft, allowing the azimuthal angle for a given scatter to be determined to within $\Delta\phi = 13°$ r.m.s. This angular uncertainty will decrease potential modulations by a factor of 0.95, which is included in our calculated modulation factor.

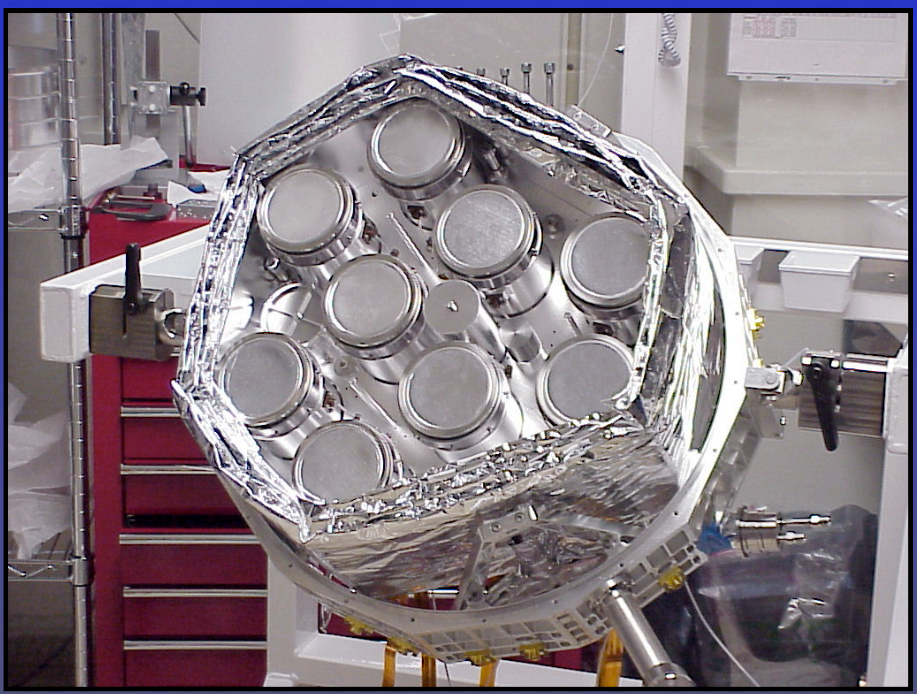
Prompt γ-ray emission from GRB021206 was detected with RHESSI on 6 December 2002 at 22:49 UT (Fig. 1). This GRB was also observed[7] with the Interplanetary Network (IPN), which reported a 25–100 keV fluence of 1.6×10^{-4} erg cm^{-2}, and a peak flux of 2.9×10^{-5} erg cm^{-2} s^{-1}, making this an extremely bright GRB. The IPN localized[8] GRB021206 to a 57 square-arcminute

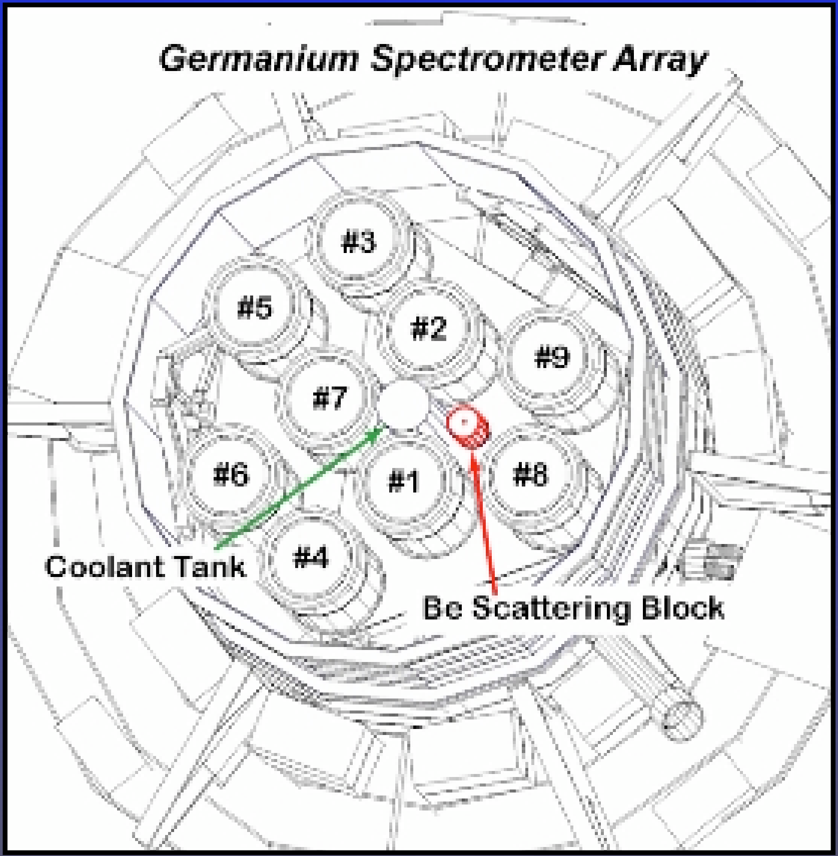
Recent Results

Ramaty High Energy Solar Spectroscopic Imager (RHESSI)

Low Energy Mode (BeGe): McConnell et al., Solar Physics, 210, 125 (2002)

High Energy Mode (GeGe): Coburn & Boggs, Nature, 423, 415 (2003)

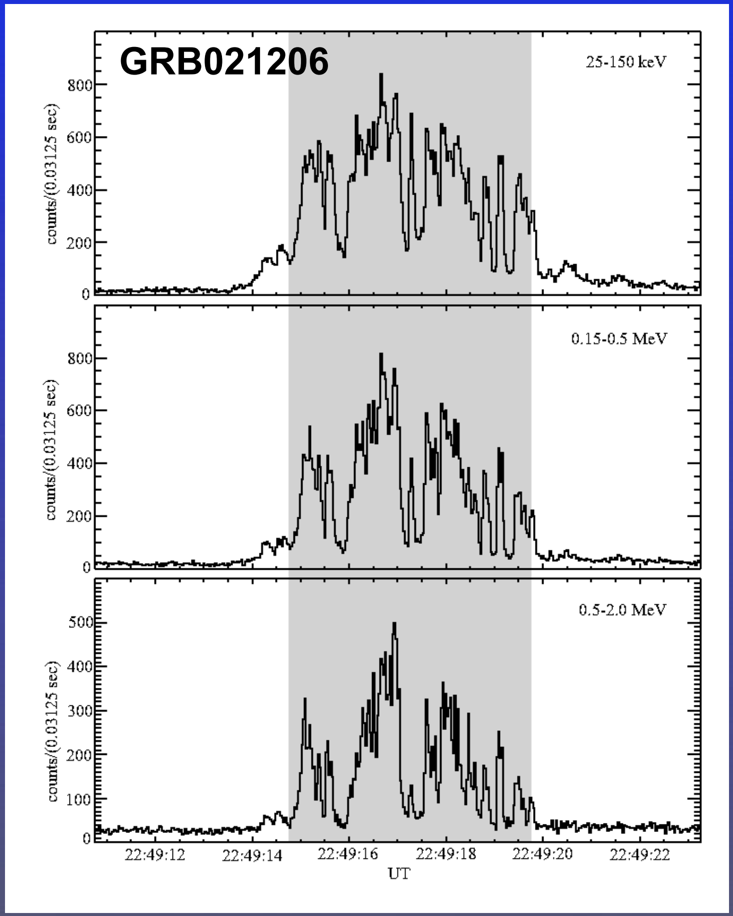




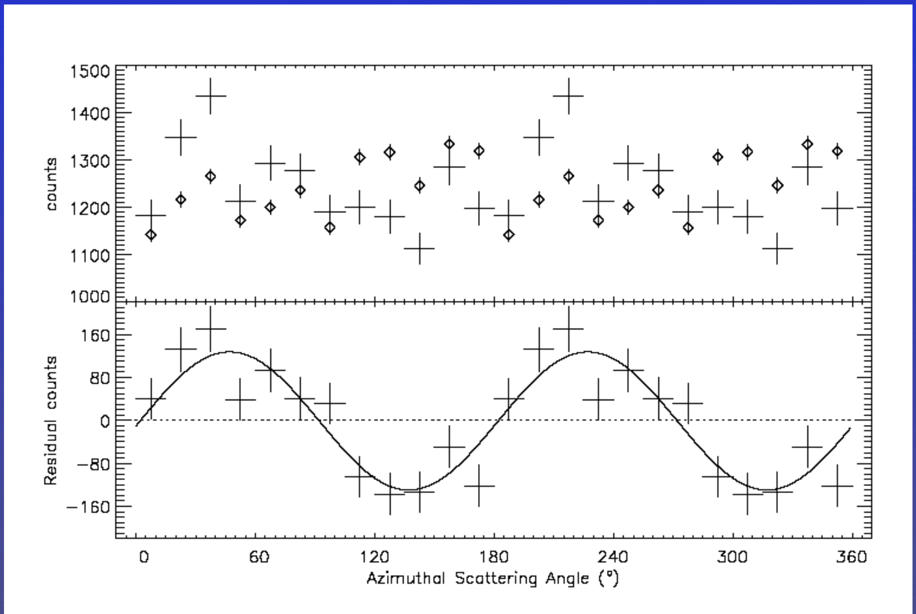
GRB Polarization

Coburn & Boggs, Nature, 423, 415 (2003)

RHESSI High Energy (double scatter - GeGe) Mode



P = 80(±20)%   0.15 - 2 MeV



crosses - data
diamonds - simulated (unpolarized)

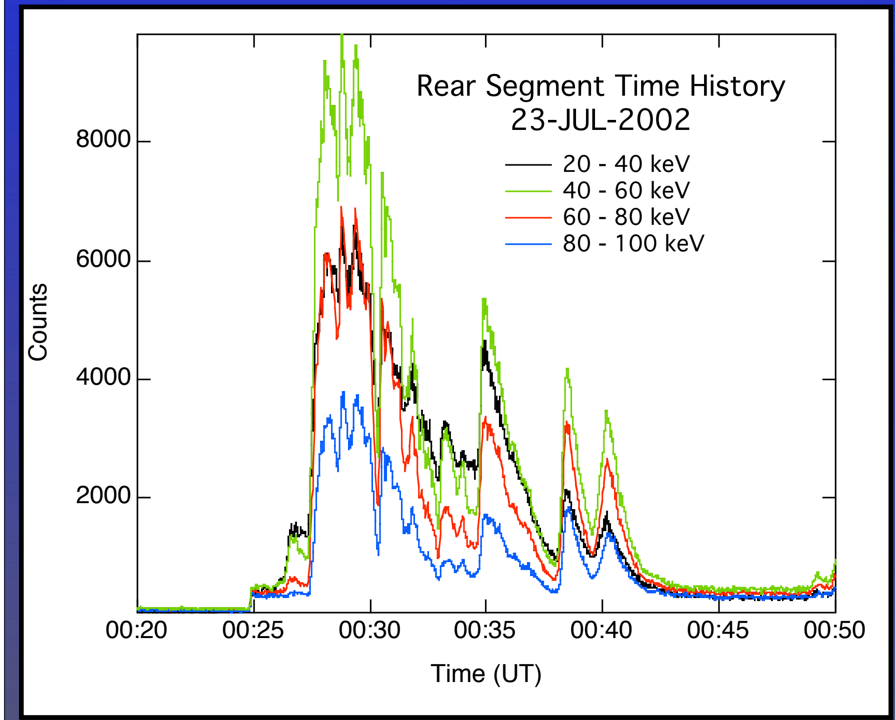
Solar Flare Polarization

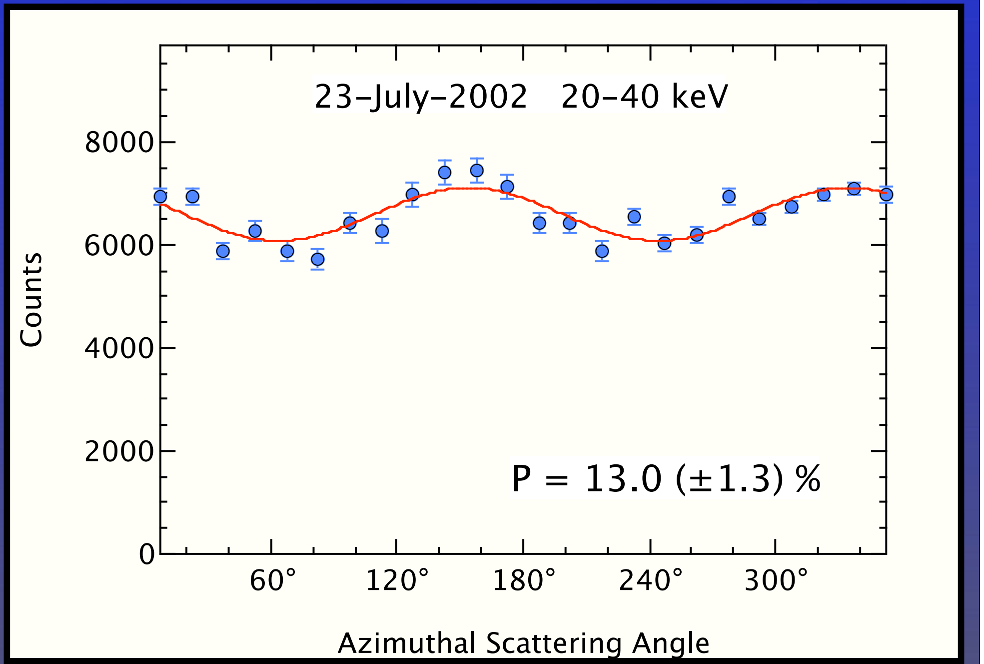
Smith et al., this workshop

McConnell et al., AAS-HEAD, 23-26 March 2003 (BAAS, 35, 616)

RHESSI Low Energy Polarimetry (Be Scatter) Mode

Solar Flare of 23-July-2002 (Class X4.8)



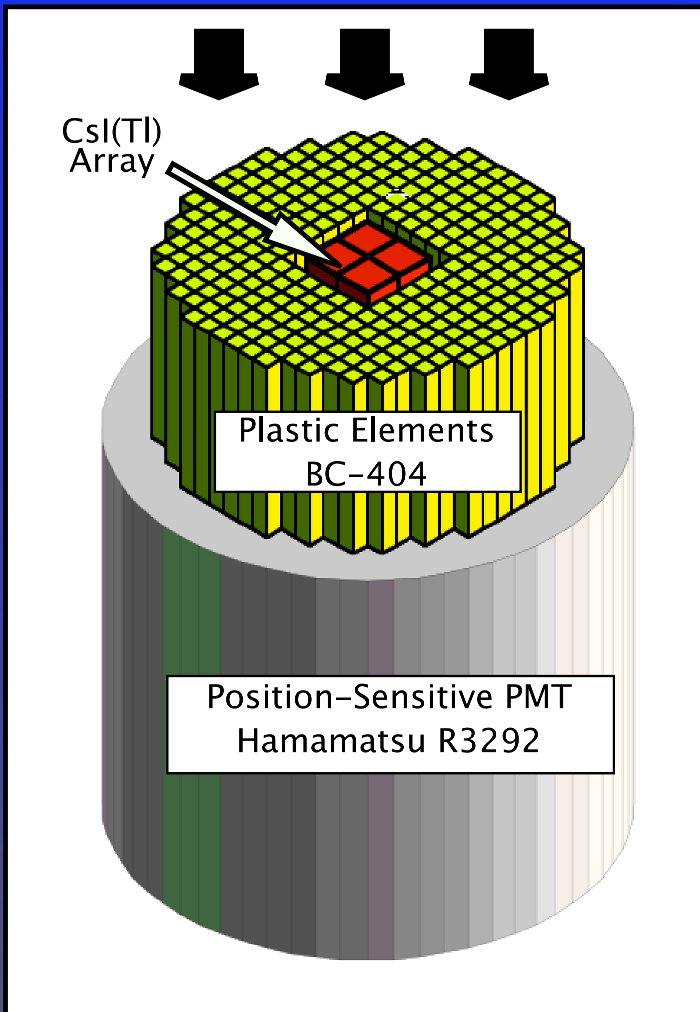


Low-Energy Gamma-Rays (50 – 500 keV)

Low-Z / High-Z Makes Things E-Z at low-E

High-Z / High-Z Makes Things E-Z at high-E

Gamma-Ray Polarimeter Experiment (GRAPE)

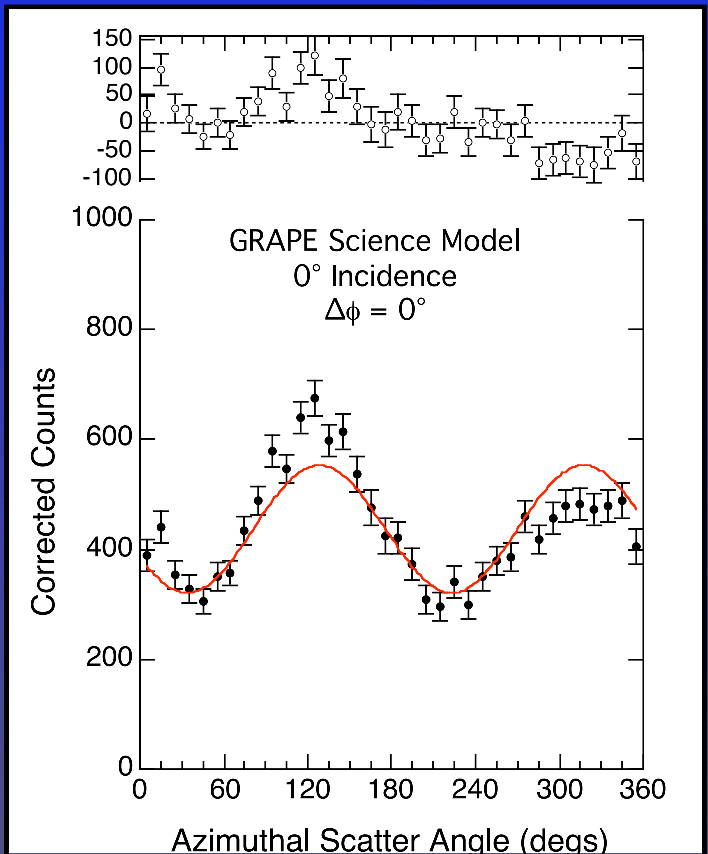


- Compact, modular design
- Prototype has been demonstrated
- Large field-of-view
- Useful for solar flares or γ-ray bursts
- MDP < 1% for X-class solar flares
- Could also be used in imaging systems

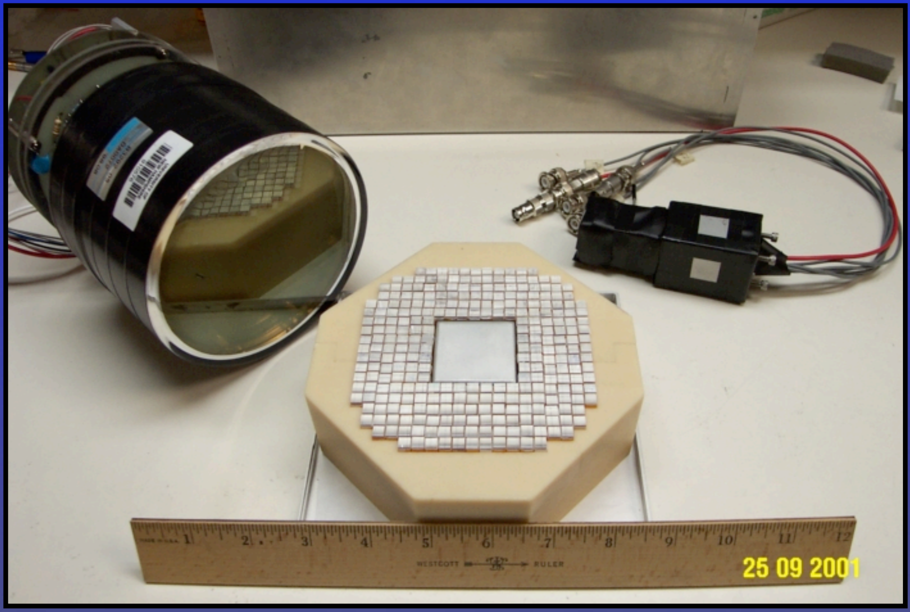
McConnell et al., SPIE Proc., 3764, 70 (1999)
McConnell et al., SPIE Proc, 5165, in press
McConnell et al., this workshop

GRAPE Laboratory Results

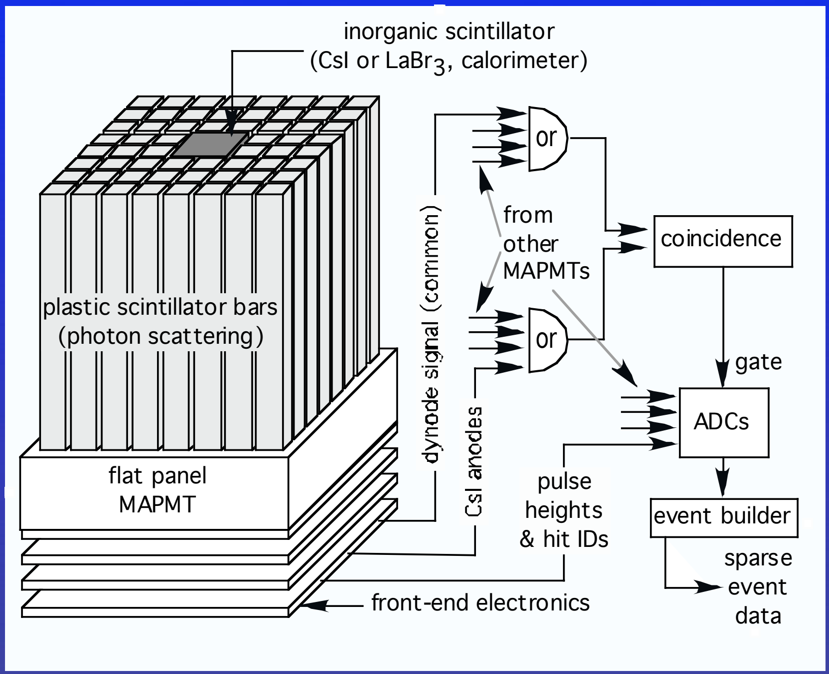
McConnell et al., SPIE Proc., 4851, 1382 (2003)

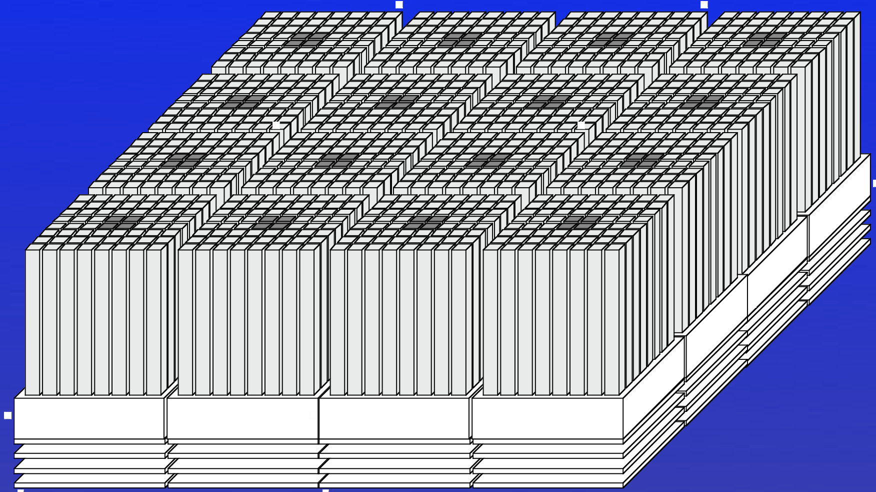


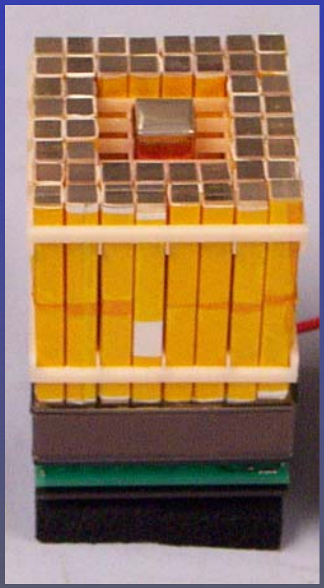
Partially Polarized beam at 288 keV



Gamma-Ray Polarimeter Experiment (GRAPE)







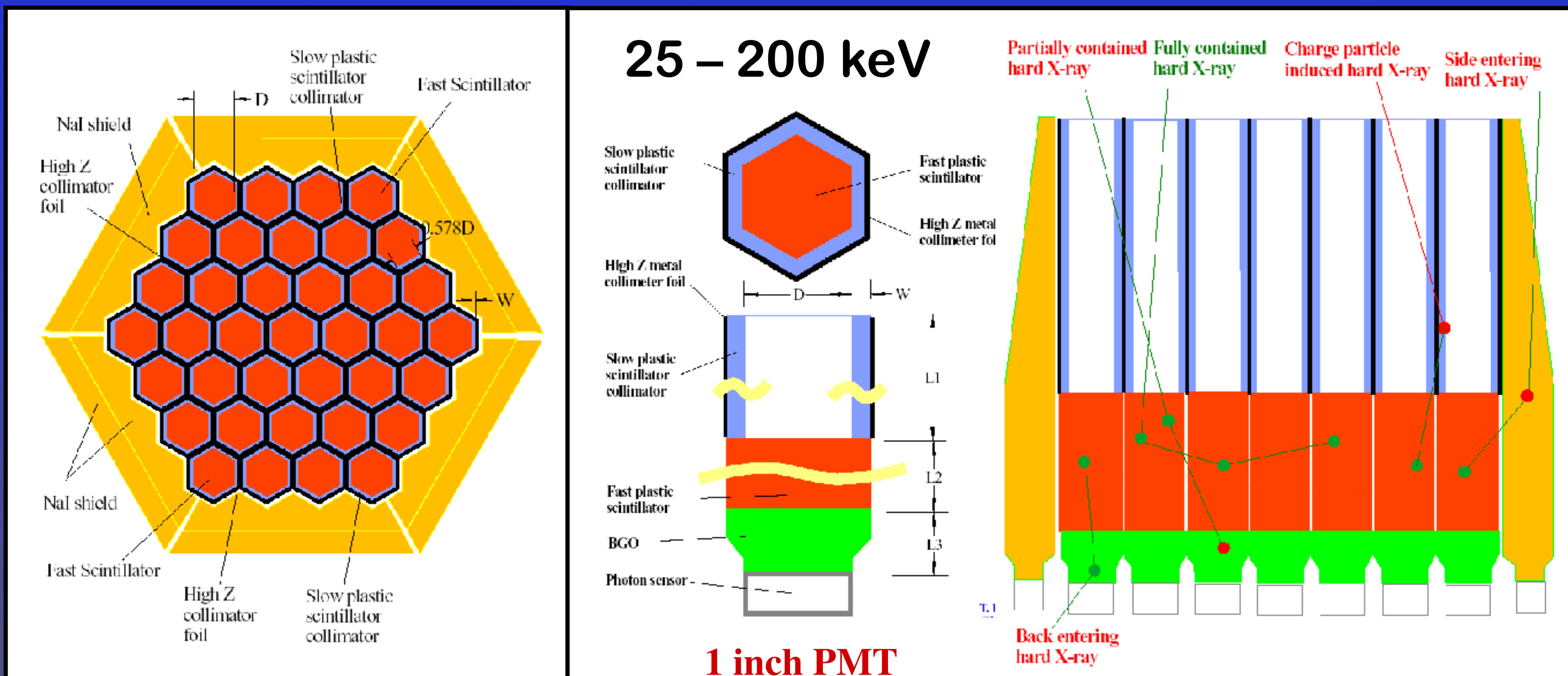
New version being tested.

Balloon flight ~2006.

Polarized Gamma-Ray Observer (PoGo)

Kamae, Mitchell, et al., this workshop

Modular design provides narrow FoV (~5°) for looking at individual sources with high S/B.



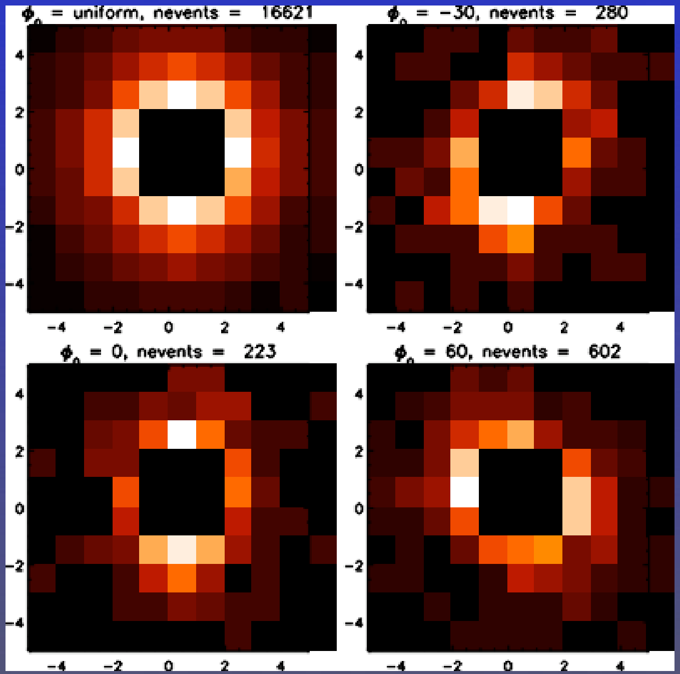
First balloon flight ~2007-2008

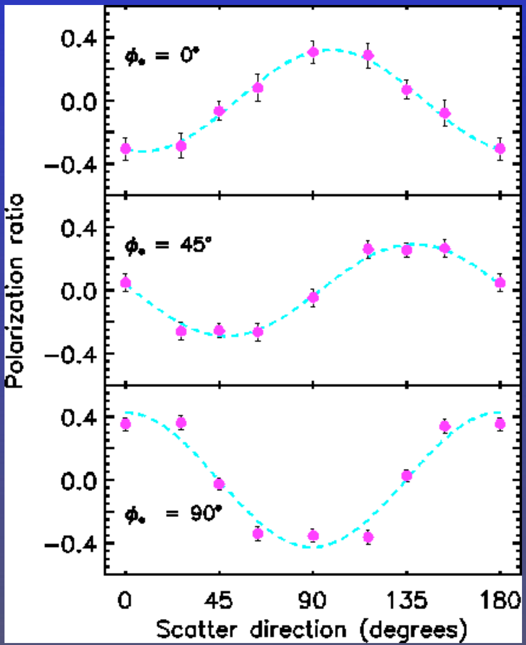
Gamma-Ray Instrument for Polarimetry, Spectroscopy and Imaging (GIPSI)

Kroeger et al., NIM, A436, 165 (1999)

Ge strip detectors, 1 cm thick, 2 mm strip pitch.

For a 400 cm^2 detector, polarization sensitivity < 5% on the Crab (70 -300 keV) for a two-week on-orbit exposure.



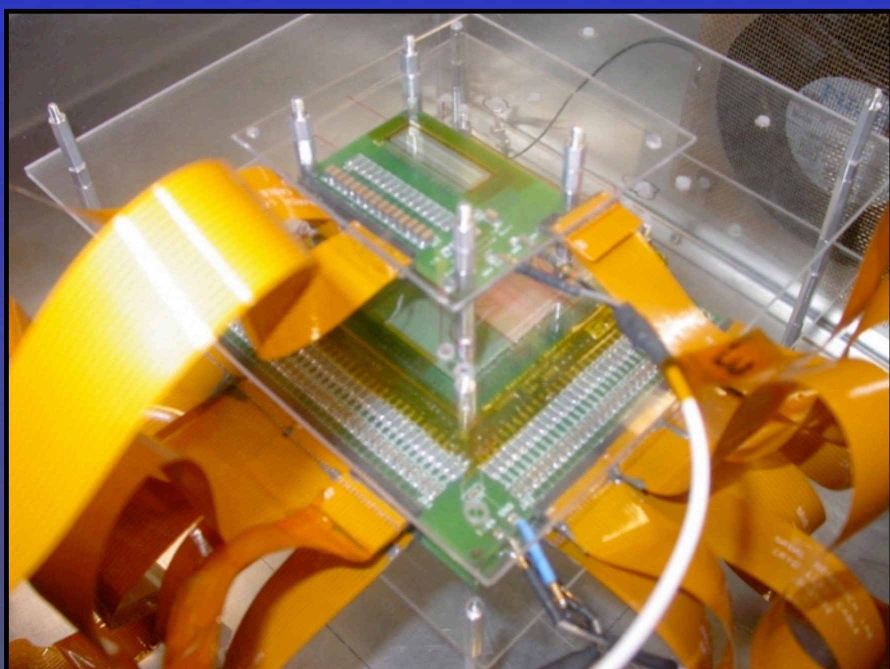


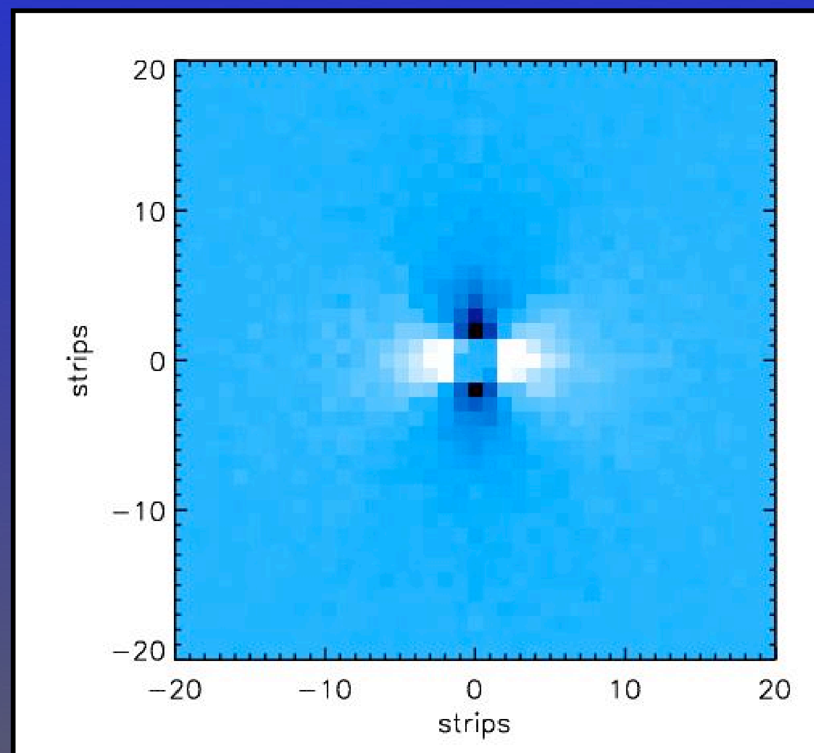
Laboratory results at 290 keV

Thick Silicon Polarimeter

Nelson et al., this workshop

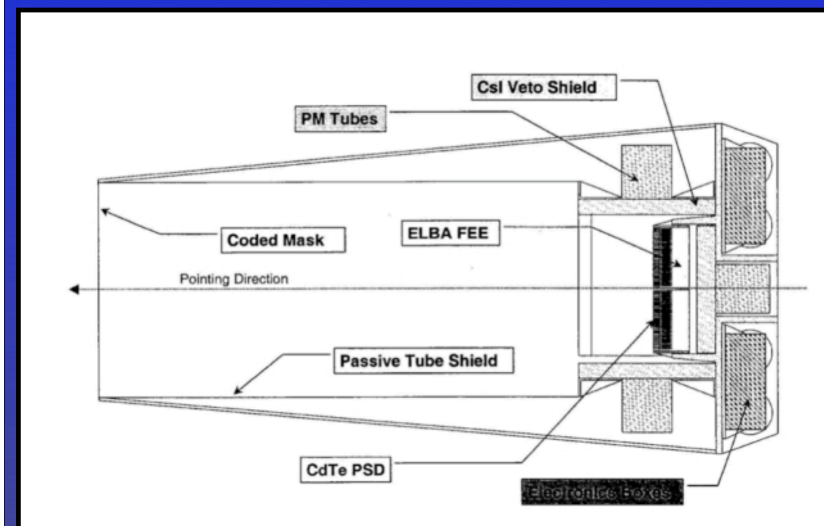
Recently tested using 122 keV photons polarized by scattering off a separate Si trigger detector.

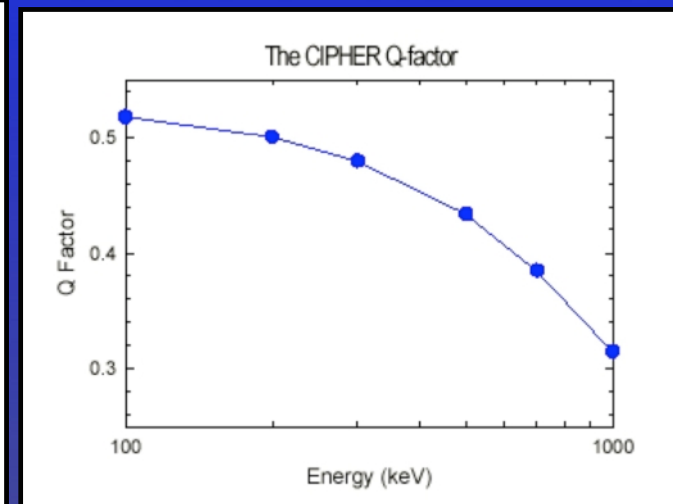


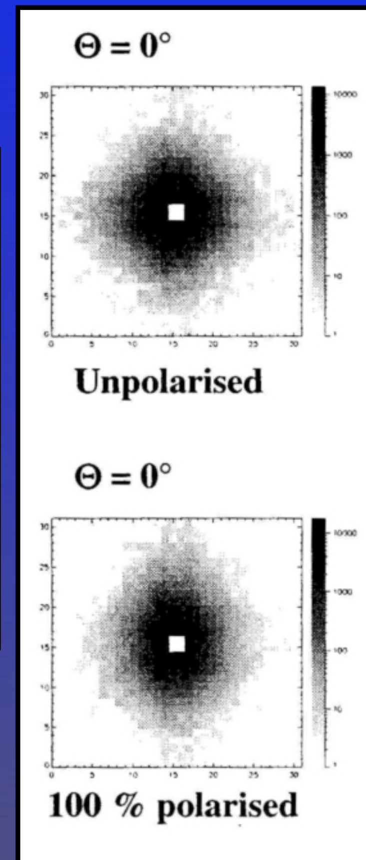


Coded Imager & Polarimeter for High Energy Radiation (CIPHER)

Caroli et al., SPIE, 4140, 573 (2000)
daSilva et al., SPIE, 4843, 543 (2003)



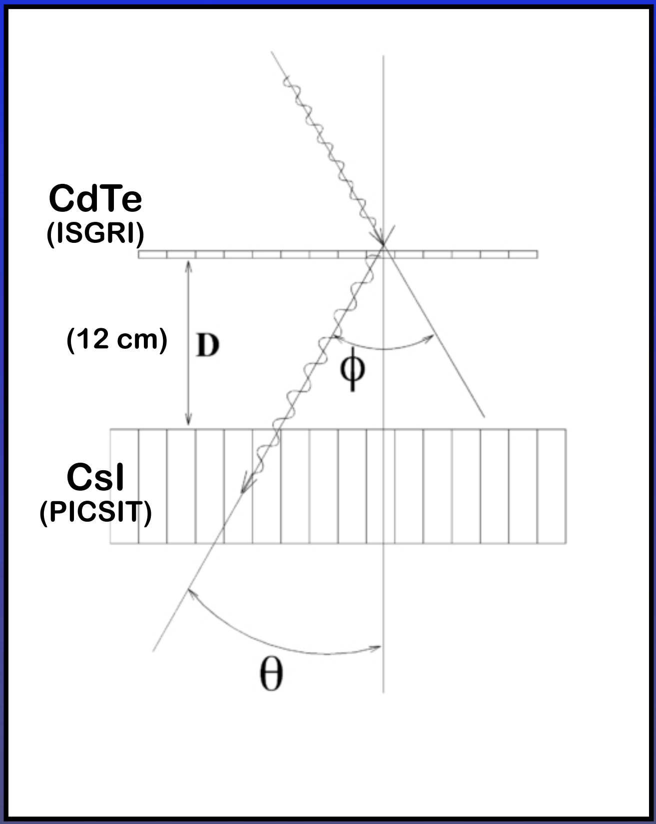




Coded Aperture Imager (10 keV – 1 MeV)
CdTe Imaging Plane
2mm pixels, 10 mm thick
Crab Sensitivity - 10 % (balloon), 1% (orbit)

INTEGRAL / IBIS

Lei et al., Proc. 2nd INTEGRAL Workshop, ESA SP-382, p. 643 (1997)
Stephen et al., GAMMA 2001 , AIP Conf. Proc. 587, 816 (2001)



PICsIT = PIxelllated CsI Telescope
ISGRI = Integral Soft Gamma Ray Imager

1) IBIS Compton mode

Events scatter from CdTe to CsI.

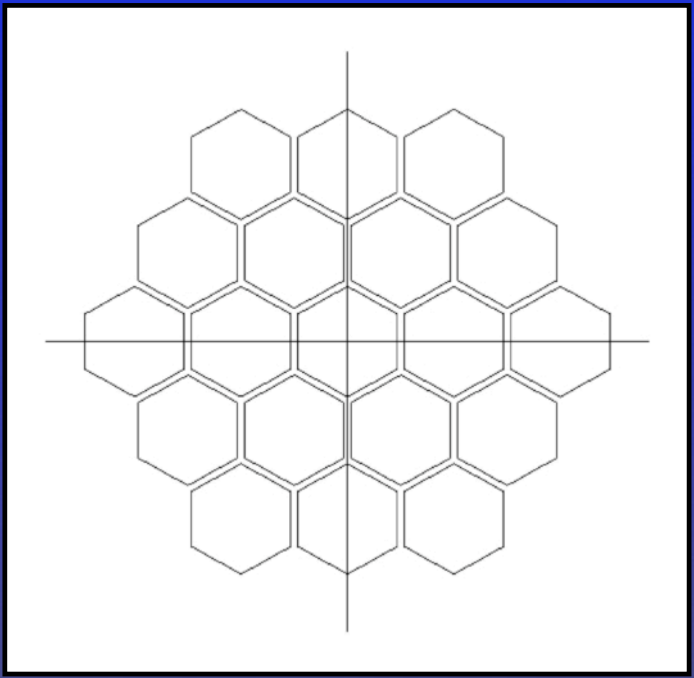
Only single interactions in CsI.

2) PICsIT Polarimetry mode

Events scatter from CsI to CsI.

INTEGRAL / SPI

Kalemci et al., this workshop



Layout of Ge detectors

Coincidence multiple events define azimuthal distribution.

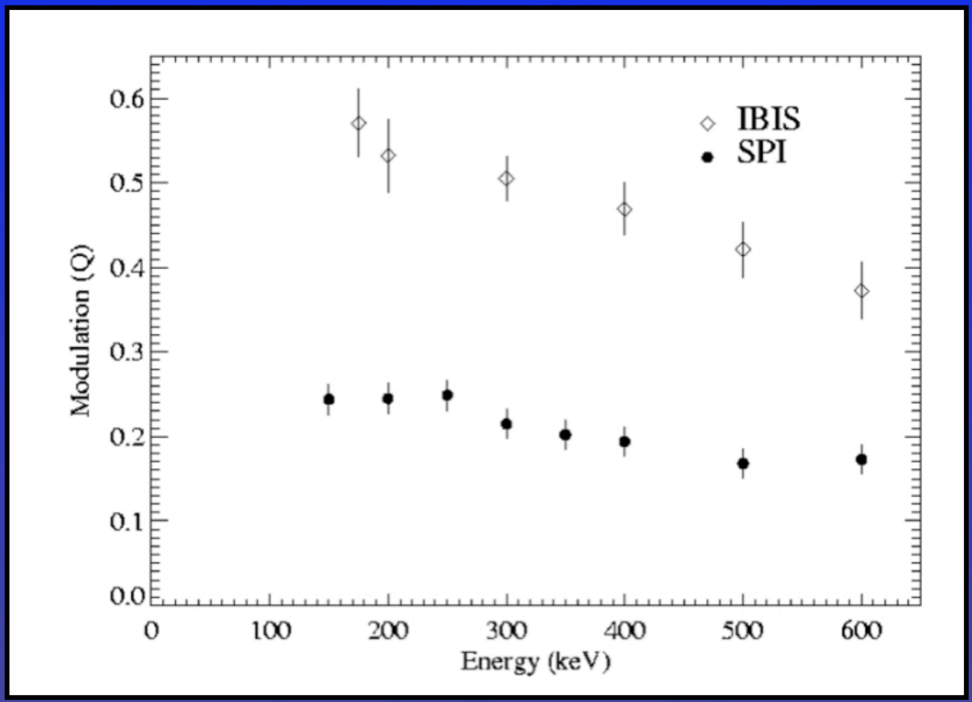
The azimuthal angle distribution is limited to 6 (center to center) angles.

For E < 511 keV, the first interaction generally is that with the smallest energy loss.

Systematics are tricky.

INTEGRAL Polarimetry

Kalemci et al., this workshop



Best opportunity for an INTEGRAL measurement would be to have a bright GRB within the FoV.

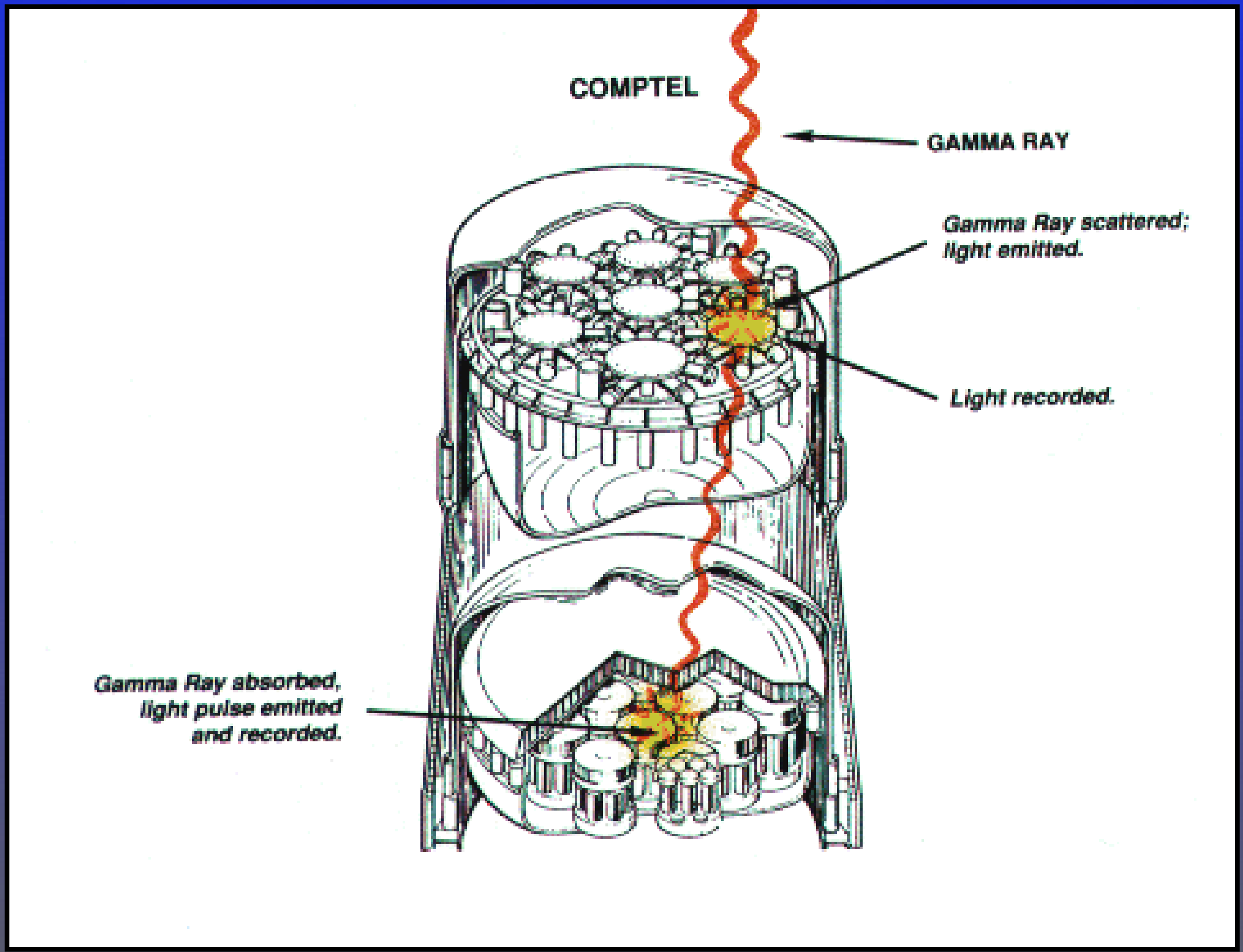
Medium-Energy Gamma-Rays (0.5 – 30 MeV)

The Domain of Compton Telescopes

Compton Telescopes

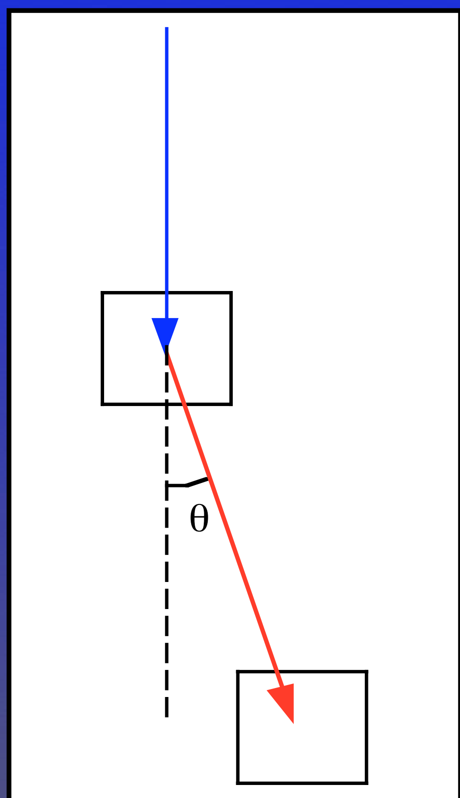
Prime example is CGRO/COMPTEL

Schönfelder et al., ApJS, (1993)

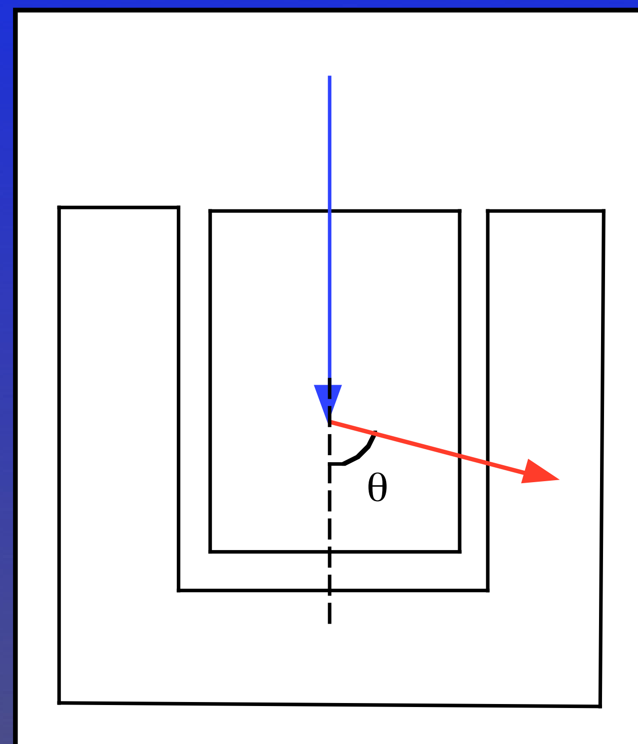


Compton Telescope Geometry

The polarization signature is most pronounced at certain energy-dependent scattering angles (45° < θ < 90°).



Poor Geometry
(COMPTEL)

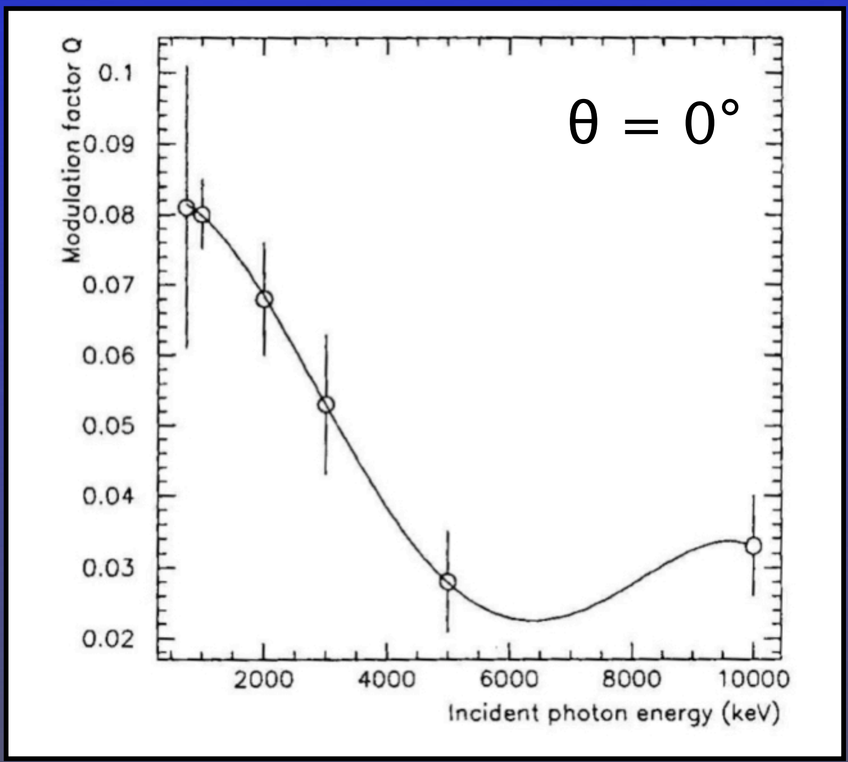


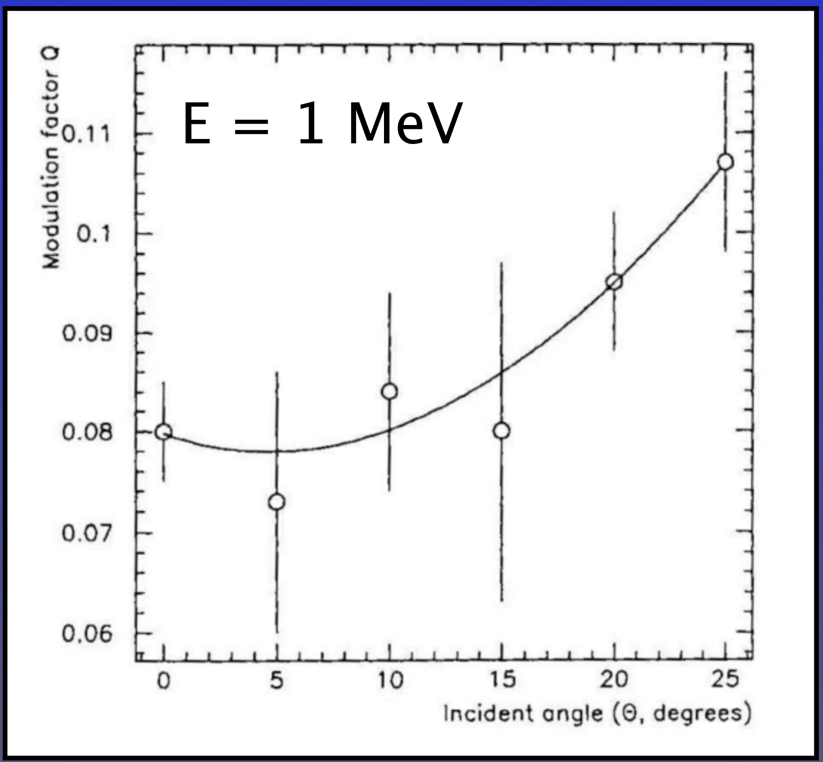
Good Geometry
(MEGA, TIGRE, LXeGRIT, NCT, SMCT, ACT)

CGRO/COMPTEL

Lei et al., A&AS, C120, 695 (1996)

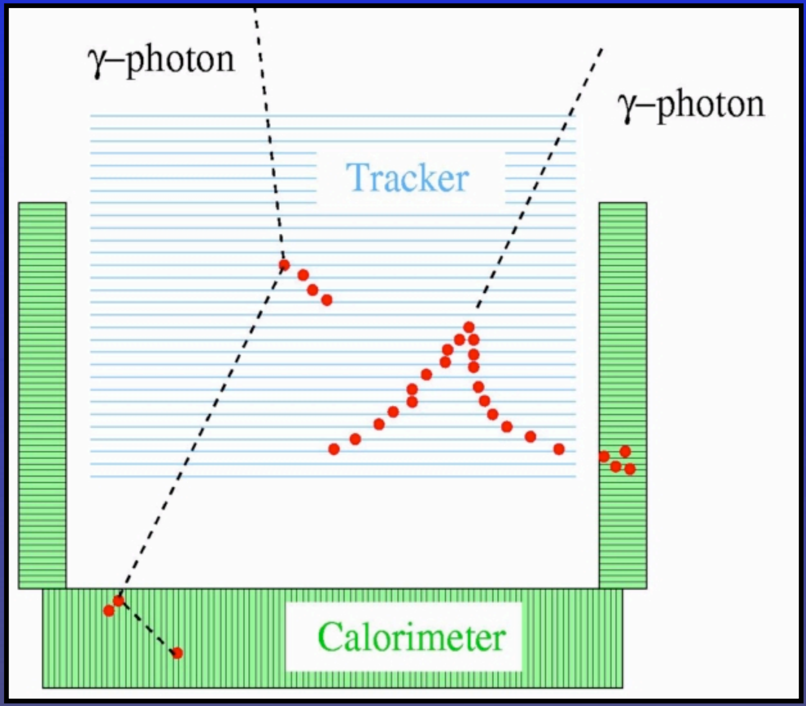
Poor geometry leads to small modulation factor. Attempts to measure polarization of GRBs and solar flares have so far been unsuccessful.





Recent Designs

Future designs all based on a well-type geometry.



Various detection technologies used for both the tracker and calorimeter components.

1) silicon strip detectors

2) Ge strip detectors

3) CdZnTe strip detectors

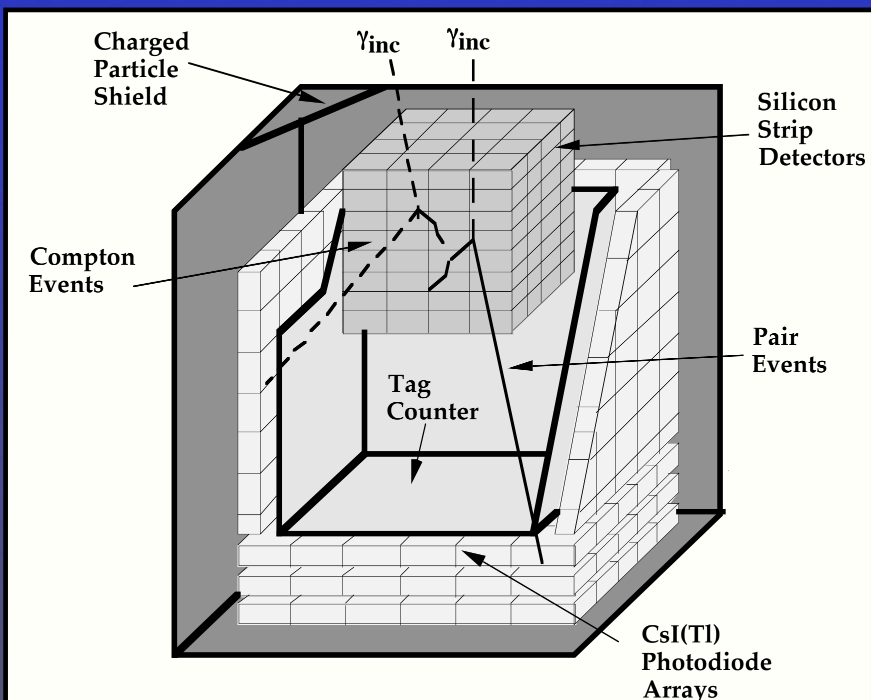
2) liquid Xenon

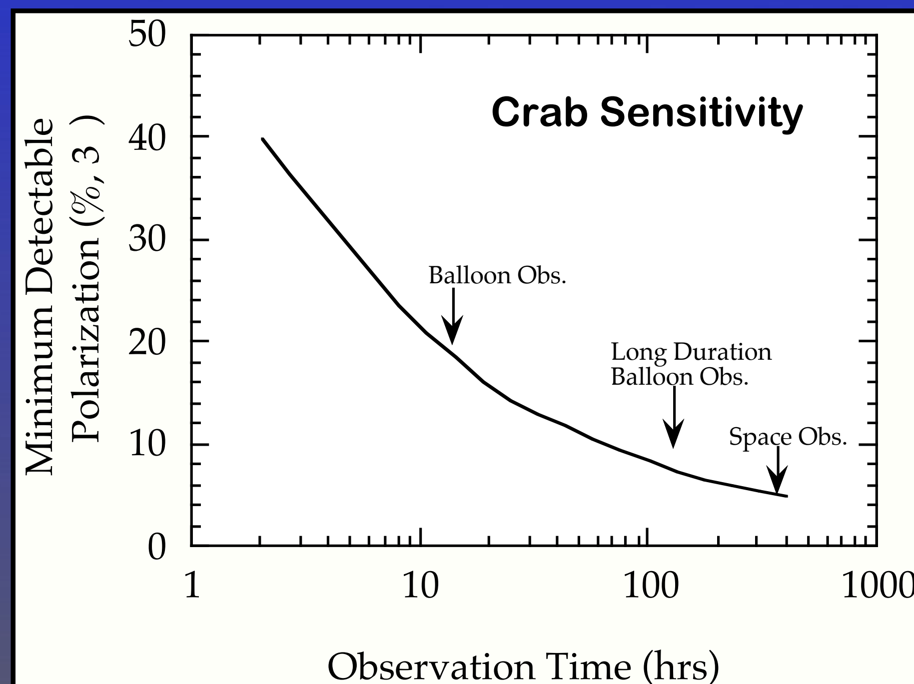
GREAT for Polarimetry !!!

Tracking and Imaging Gamma-Ray Experiment (TIGRE)

Akyüz et al., Experimental Astronomy, 6, 275 (1995)
O'Neill et al., A&AS, C120, 661 (1996)

Energy range 0.3 – 100 MeV
50 layers of Si strip detectors
Each layer 13 cm x 13 cm x 13 cm





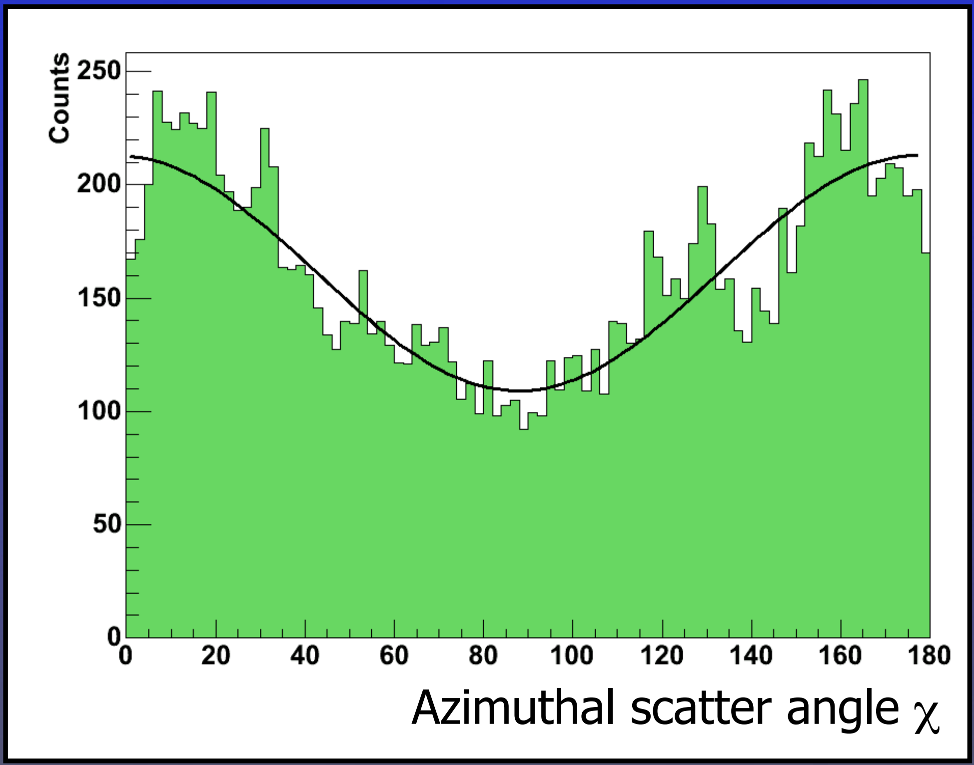
Medium Energy Gamma-ray Astronomy experiment (MEGA)

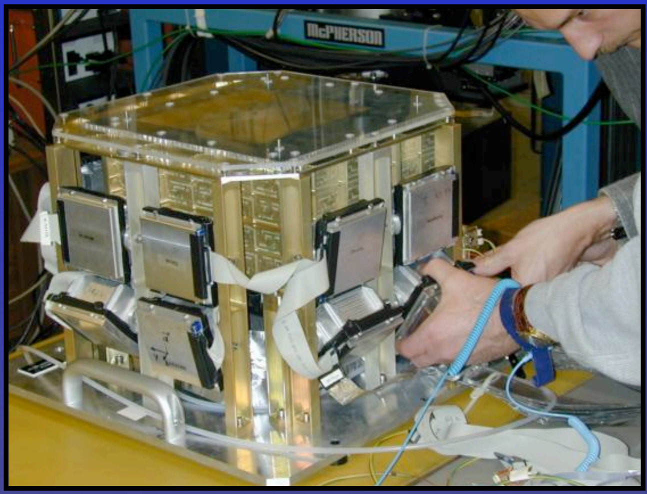
Kanbach et al., SPIE, 4851, 1209 (2003)
Bloser et al., New Astr. Rev., 46, 611 (2002)

A prototype is currently being prepared for a balloon flight in late 2004 / early 2005.
A spacecraft design has been developed.

MEGA Beam Calibration

Spring, 2003, Duke University
High Intensity Gamma-ray Source (HIGS)
0.7 to 50 MeV, 100% polarized

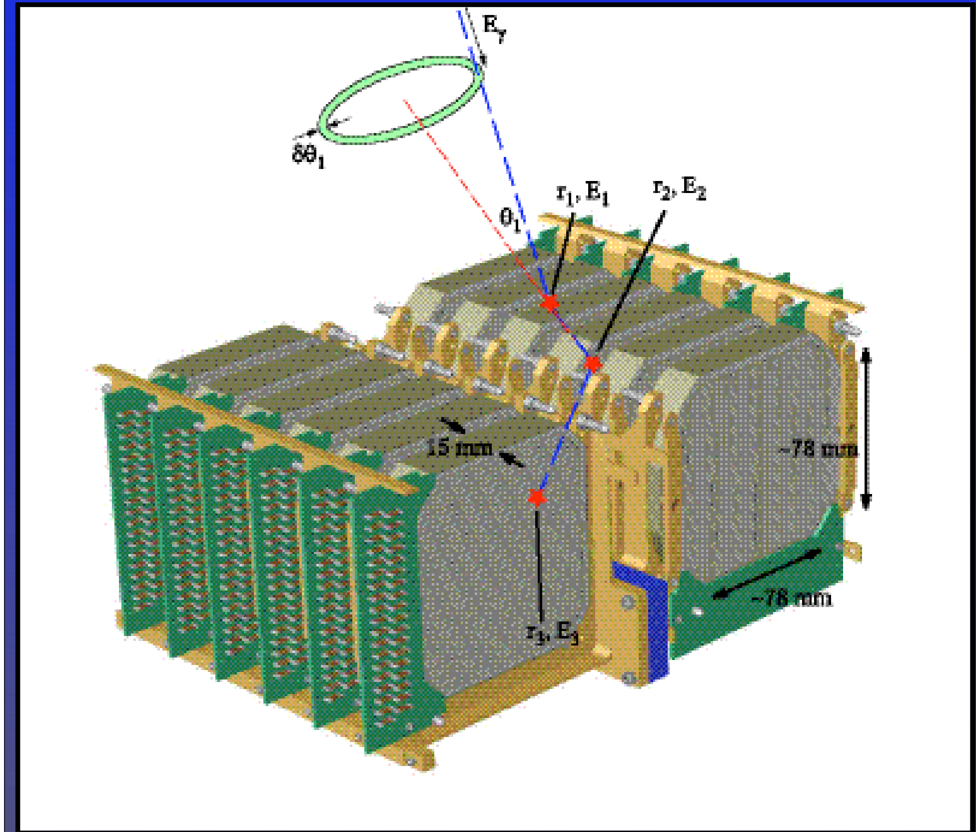




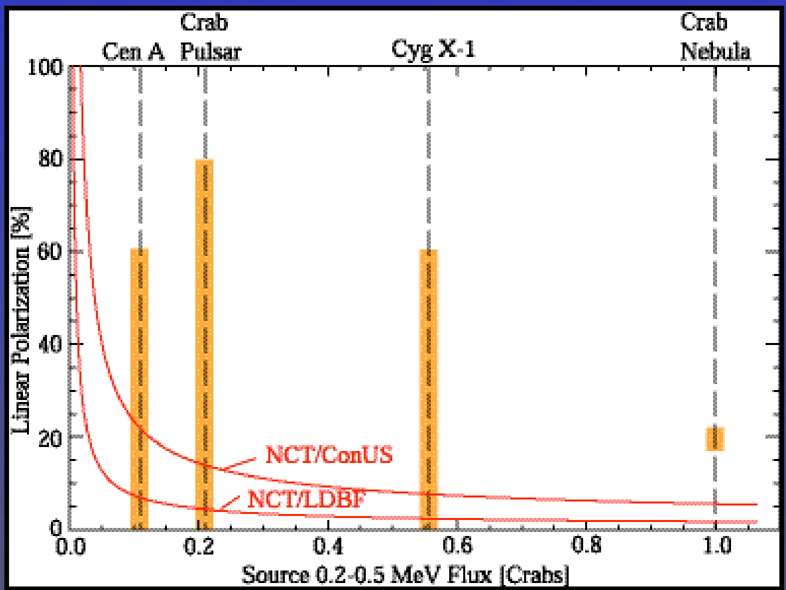
Incident Energy = 710 keV
Modulation = 0.31 ± 0.03

Nuclear Compton Telescope (NCT)

Boggs et al., this workshop
Boggs et al., SPIE, 4851, 1221 (2003)
Boggs et al., AIP 587, 877 (2001)



12 Ge strip detectors
(each 5400 mm^2 x 15 mm thick)
with active BGO well



200 - 500 keV

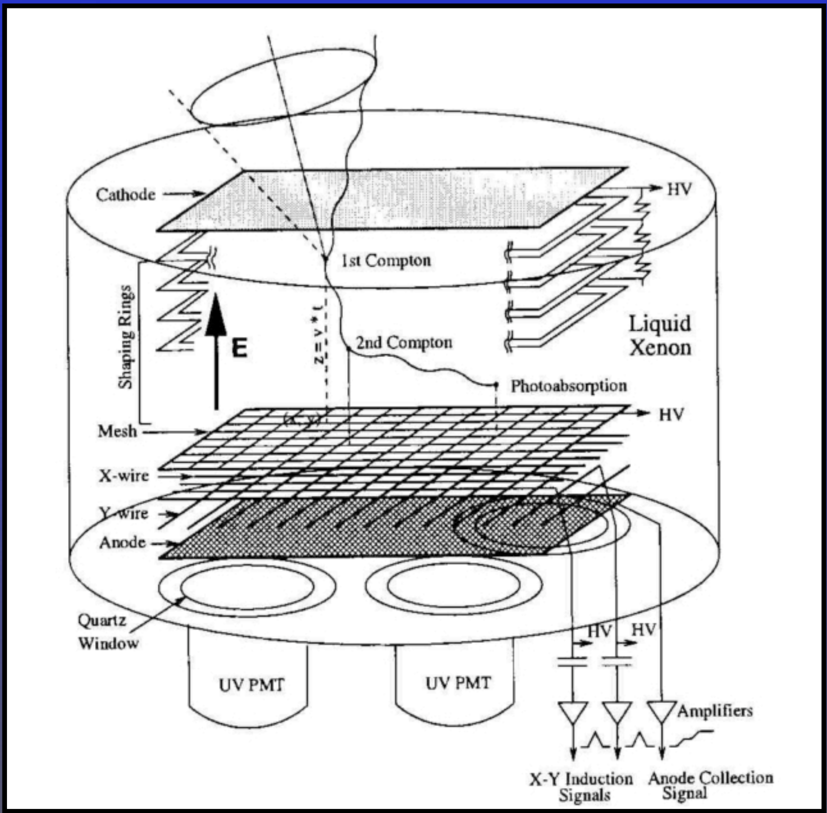
Liquid Xenon Gamma Ray Imaging Telescope (LXeGRIT)

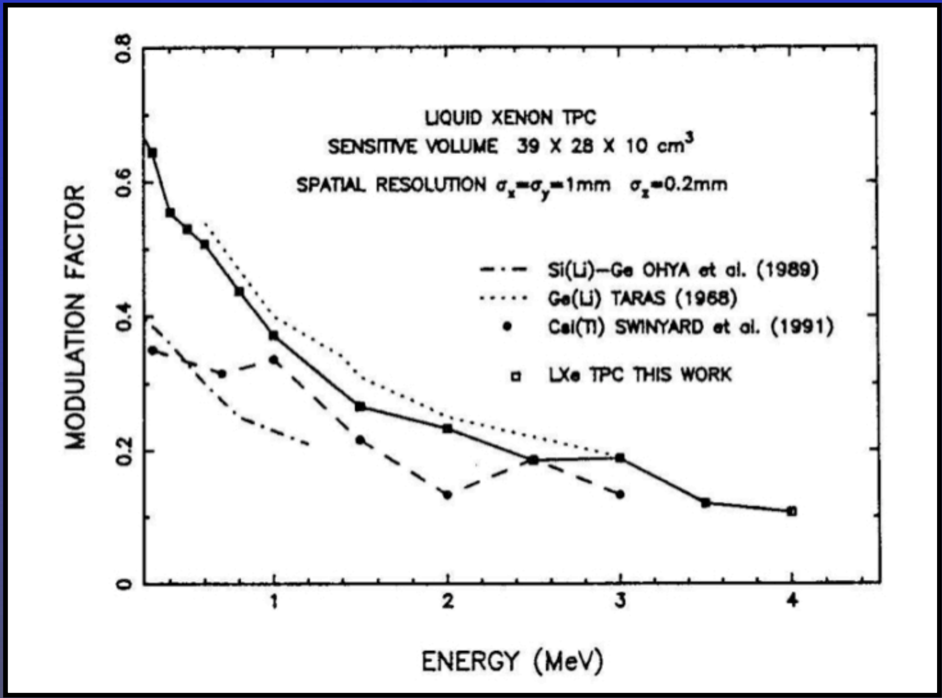
Aprile et al., this workshop

Aprile et al., ApJS, 92, 689 (1994)

3-d imaging in a liquid Xe time projection chamber

200 keV – 25 MeV

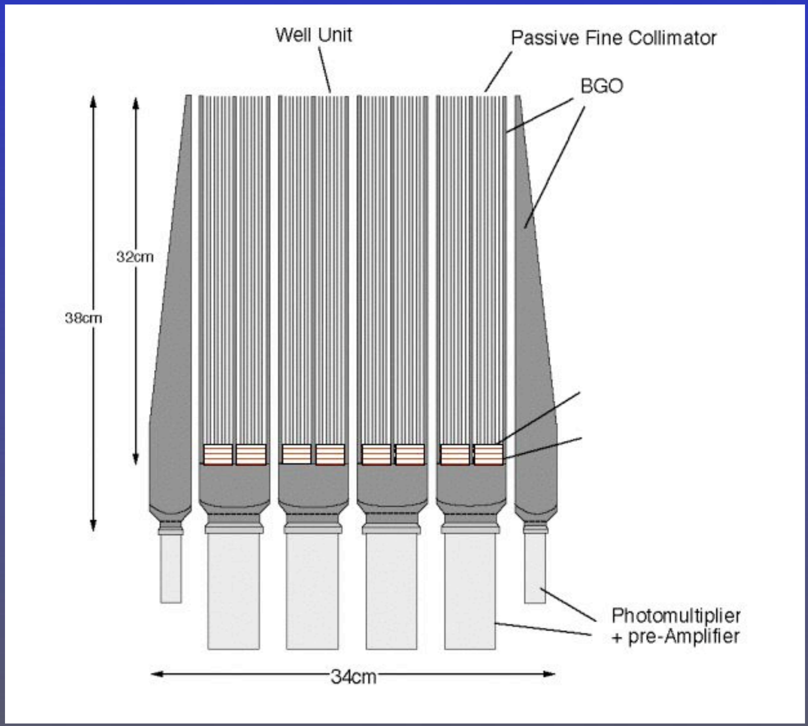


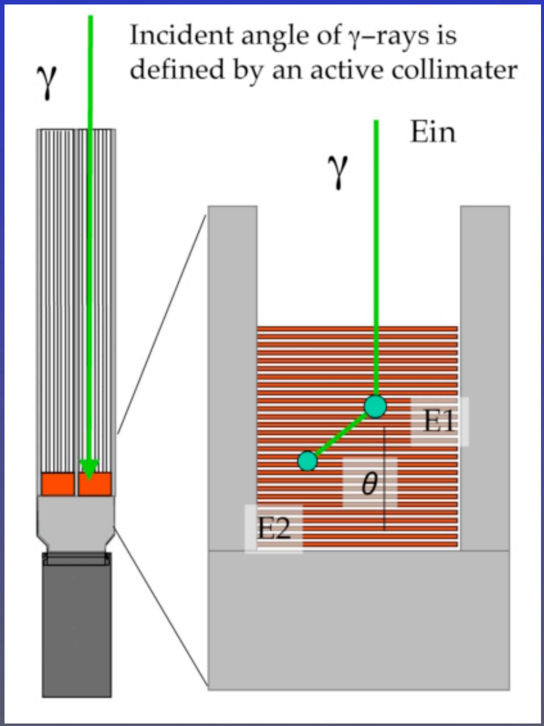


Semiconductor Multiple-Compton Telescope (SMCT)

Takahashi et al., this workshop
Tajima et al., Nucl. Instr. Meth., A511, 287 (2003)
Takahashi et al., SPIE, 4851, 1228 (2003)

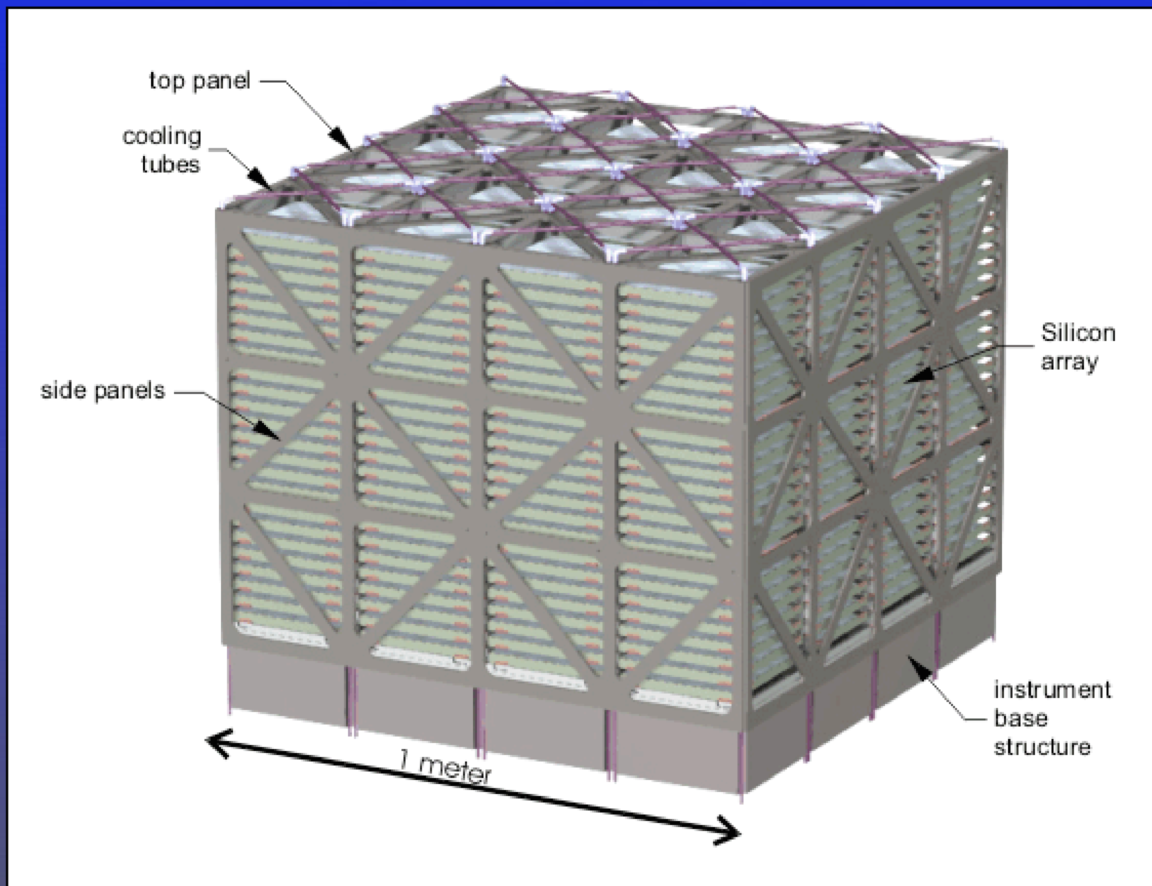
Based on a stack of Si or CdTe or CdZnTe detectors.
Collimated and multi-Compton designs have been studied.





Advanced Compton Telescope (ACT)

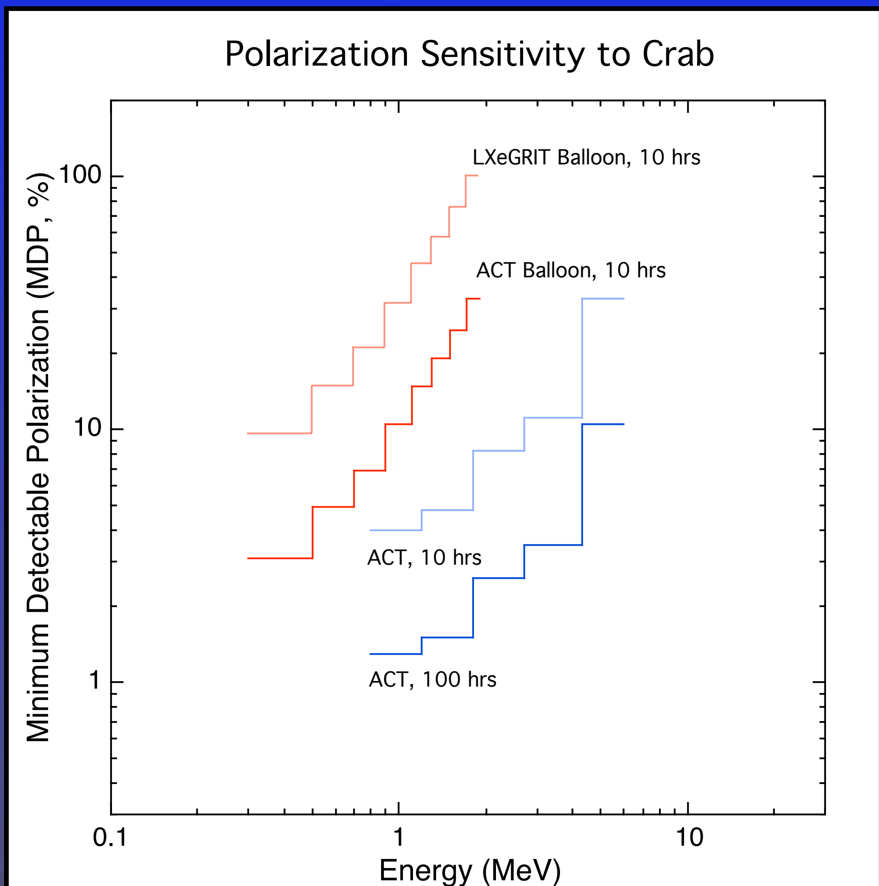
Several designs are currently under consideration, all of which have very favorable geometries for polarization.



This particular design is a large block of Si strip detectors.

Polarization Sensitivity of ACT

McConnell, ACT Workshop, 2001



Extrapolated results from Aprile et al. (1994).

Assumes 10,000 cm^2 for ACT vs. 1093 cm^2 for LXeGRIT.

Assumes both source and background scale as area.

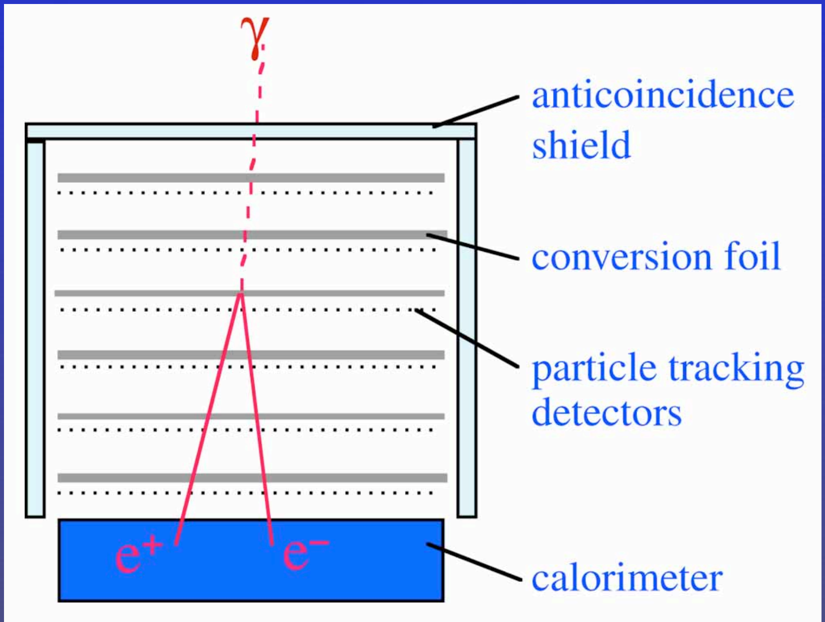
Assumes comparable efficiency and modulation factor.

High-Energy Gamma-Rays (> 30 MeV)

The Realm of Pair Production

Pair-Production Polarimetry

For pair production, the the plane of the electron-positron pair tends to lie parallel to the incident electric field vector.

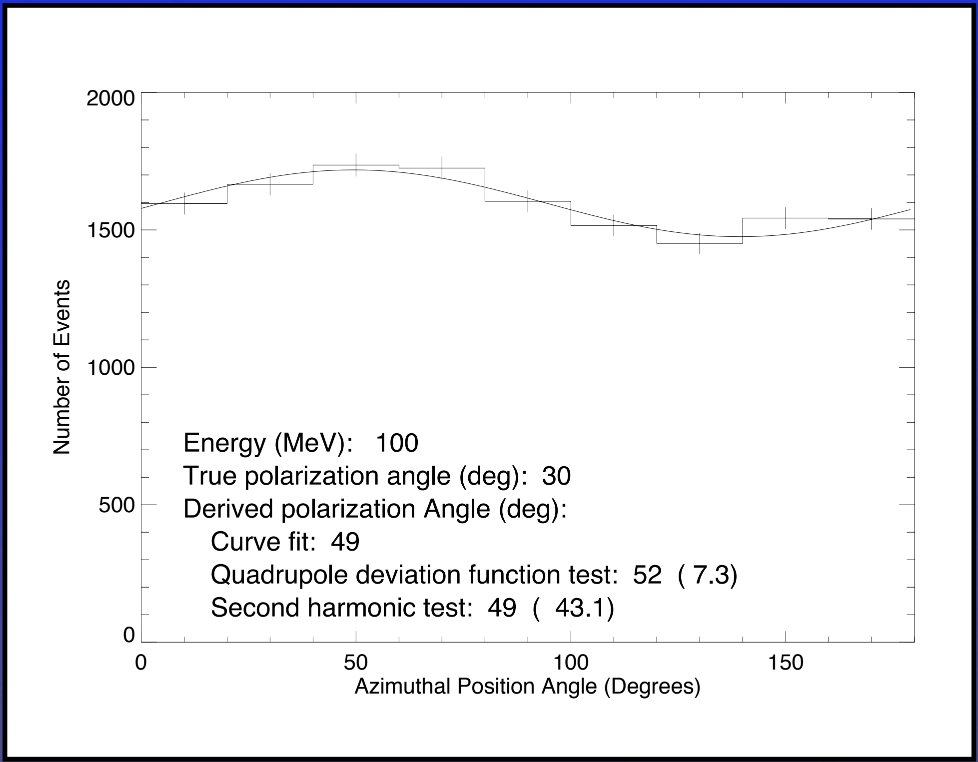


For both GLAST and AGILE, the thickness of the conversion plates leads to significant scattering.

Difficult to ascertain the initial particle directions.

A High Energy Gamma-Ray Polarimeter

Bloser et al., this conference
Bloser et al., SPIE, 5165, in press (2003)



Simulated result at 100 MeV

Uses pair production.

Uses gas micro-well detectors to track pairs.

~50 MeV to ~1 GeV

3σ MDP on Crab is 40% in 10^6 s (50-150 MeV).

… and Now for Something Completely Different

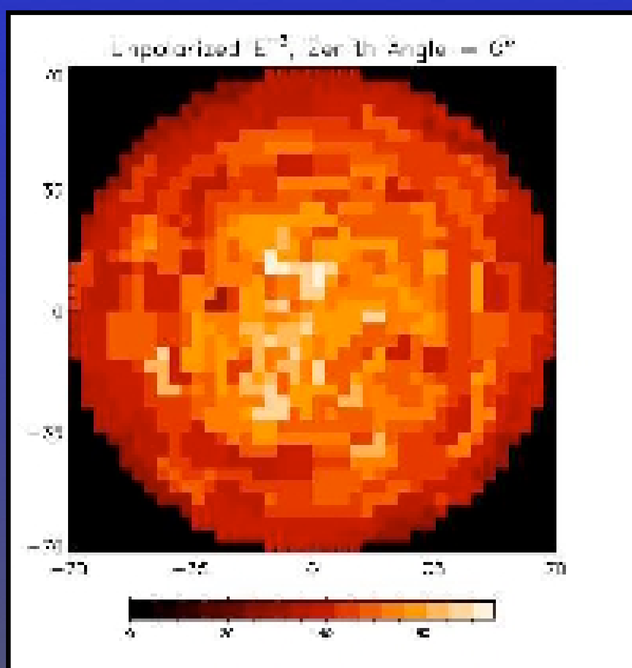
When Looking Down Means Looking Up

Albedo Polarimetry

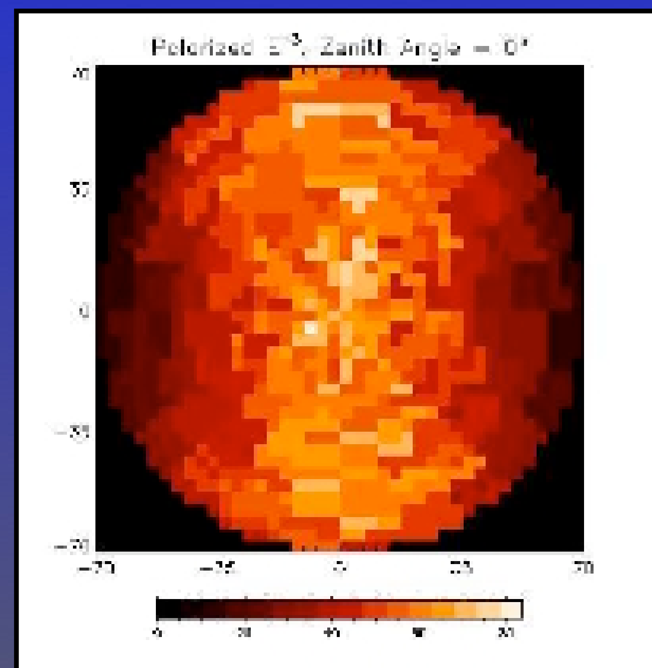
One can also measure polarization by looking down at the flux that is scattered off the atmosphere.

Very large FoV, limited spectral information.

unpolarized case



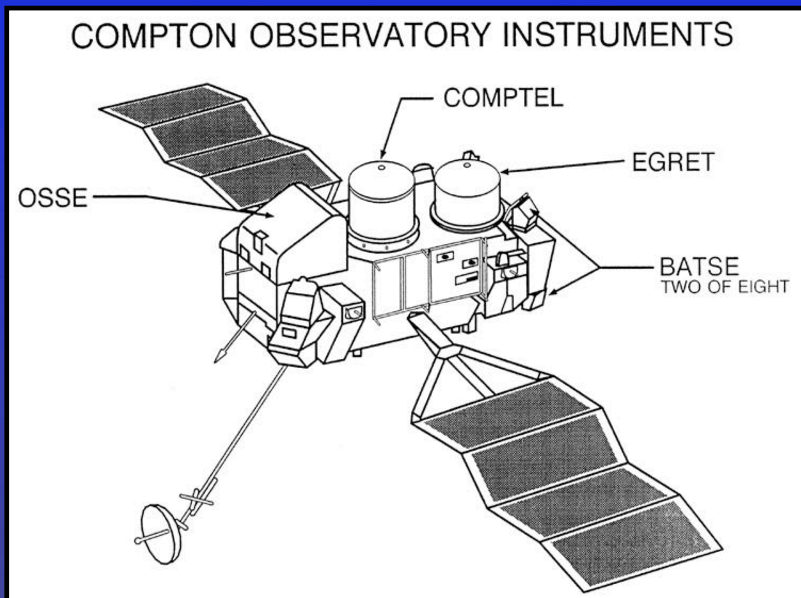
polarized case

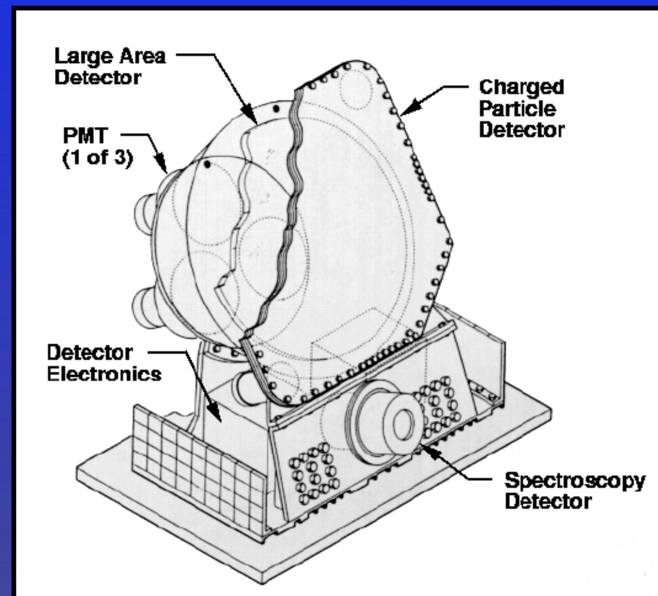


polarization vector

Albedo Polarimetry with BATSE

McConnell et al., AIP Conf. Proc. 374, 368 (1996)
McConnell et al., AIP Conf. Proc. 384, 851 (1996)





BATSE was not designed to do polarimetry.

Using albedo polarimetry,
we predicted ~10-15% MDP for the brightest GRB.

Summary

- One of the last unexplored avenues of high energy astrophysics.
- Recent results are very exciting.
- Many new experiments are on the horizon can be expected to add to the latest results.