Solar Polarimetry : Status and Future Prospects

Mark McConnell

Space Science Center
University of New Hampshire
Durham, NH

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Outline of Talk

- Scattering Polarimetry
- Summary of Experimental Results
- Survey of Upcoming Experiments

Scattering Polarimetry

For any scattering angle ϑ we see that the scattering probability has its maximum value when $\eta = 90°$. Therefore, the scattered photon and the scattered electron tend to be ejected *at right angles to the electric vector* $\mathcal{E}_0$ *of the incident radiation.*

Equation (2.3) forms the operating basis for several types of practical γ-ray polarimeters. In one of these, shown schematically in Fig. 2.2, the scattered photons are observed at fixed values of the scattering angle ϑ as a function of the angle η. A minimum in the coincidence counting rate locates the angle $\eta = 0$, for which $\mathcal{E}_0$ is parallel to the scattering plane, while a maximum counting rate is observed at $\eta = 90°$. The asymmetry ratio between the maximum and minimum values of the scattering intensities depends on both $h\nu_0$ and ϑ and falls to unity for $\vartheta = 0$ or 180°. In general, the greatest asymmetry is found for scattering angles which are slightly less than 90°. For example, the optimum scattering angle ϑ is about 82° for 0.51-Mev photons, and about 78° for 1.0-Mev photons (M44). The maximum asymmetry ratio is 5 for 0.51-Mev photons in ideal geometry and decreases as the photon energy increases.

c. Differential Scattering Cross Section for Polarized Incident Radiation. Now let us turn our attention to the amount of *energy* carried by the scattered photons. Consider a broad incident beam, of area

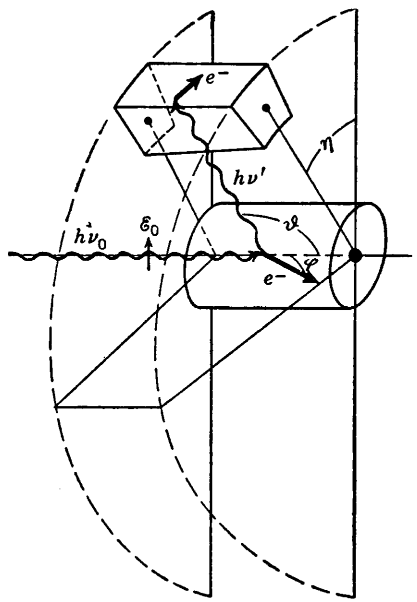


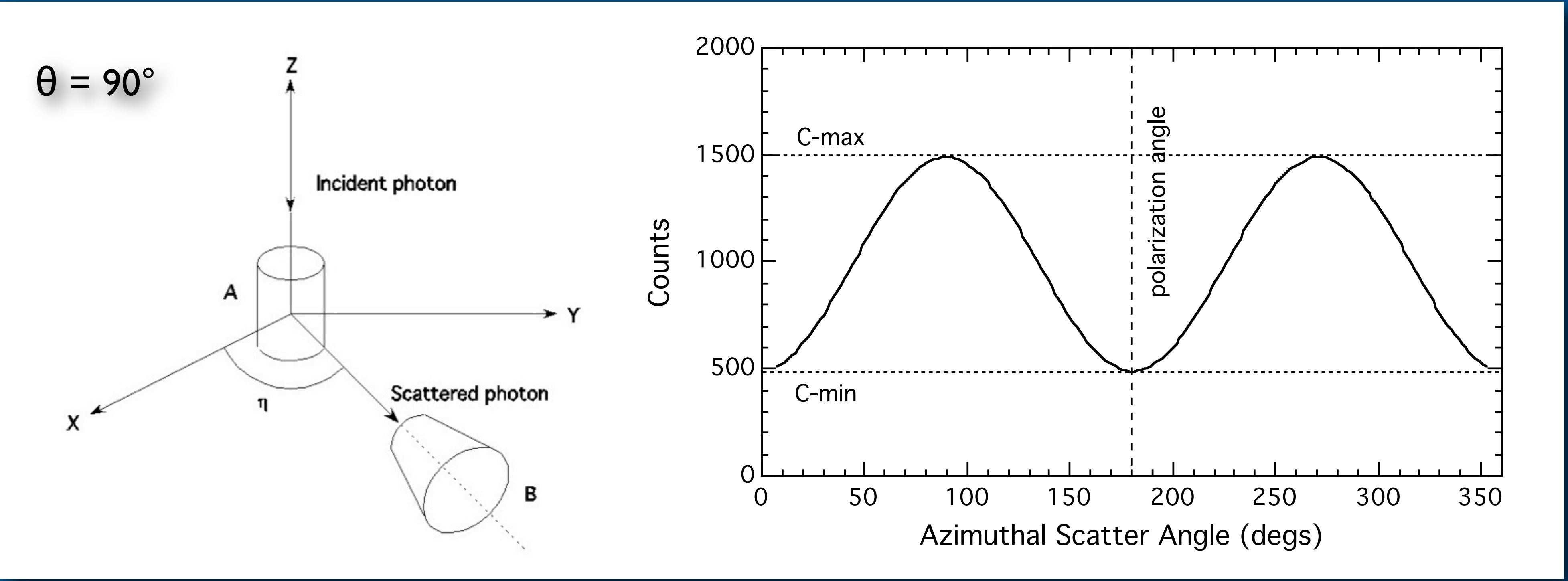
Fig. 2.2 Schematic illustration of a basic element for a γ-ray polarimeter. Two scintillation counters are used in a coincidence circuit. A coincidence is registered when the incident photon $h\nu_0$ produces a Compton recoil electron in one counter, while the photon scattered at ϑ, η is detected in a second counter, in which it produces a Compton electron or a photoelectron. At fixed scattering angle ϑ, the coincidences are minimum in the direction ($\eta = 0$) of the incident electric vector $\mathcal{E}_0$ and maximum in a direction ($\eta = 90°$) normal to $\mathcal{E}_0$. [*Metzger and Deutsch* (M44).]

The concept of using Compton scattering for measuring polarization is not new.

This figure is from Evans' The Atomic Nucleus (1955)

Scattering Polarimeter

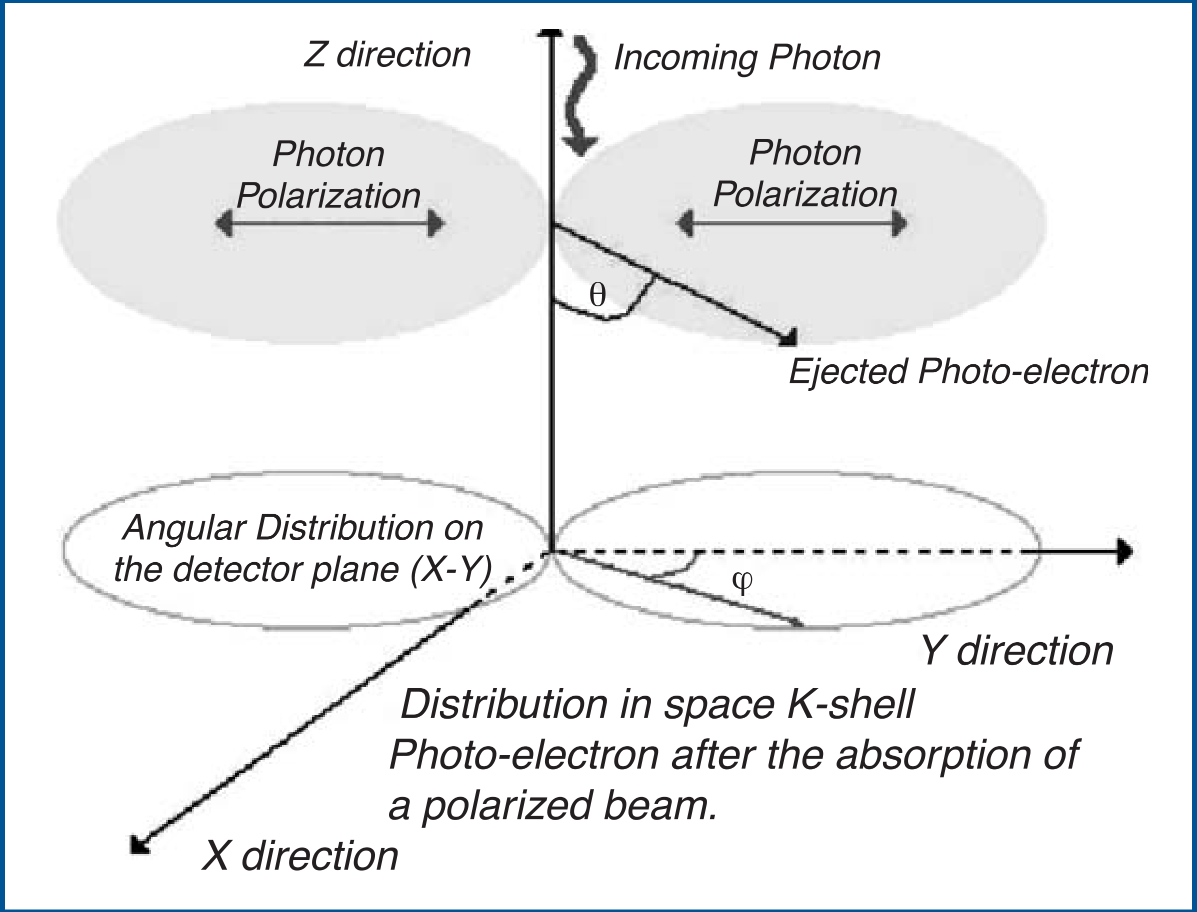
A detector (or series of detectors) surrounding a scattering element can be used to measure the azimuthal distribution of scattered photons.



Amplitude defines the level of polarization.
Minimum phase defines the plane of polarization.

Photoelectric Polarimetry

- Based on tracking of photoelectron.
- Photoelectron preferentially ejected parallel to the incident polarization vector.
- Effective at energies below ~30 keV.



Early Measurements (1969 - 1983)

Intercosmos Polarimeter

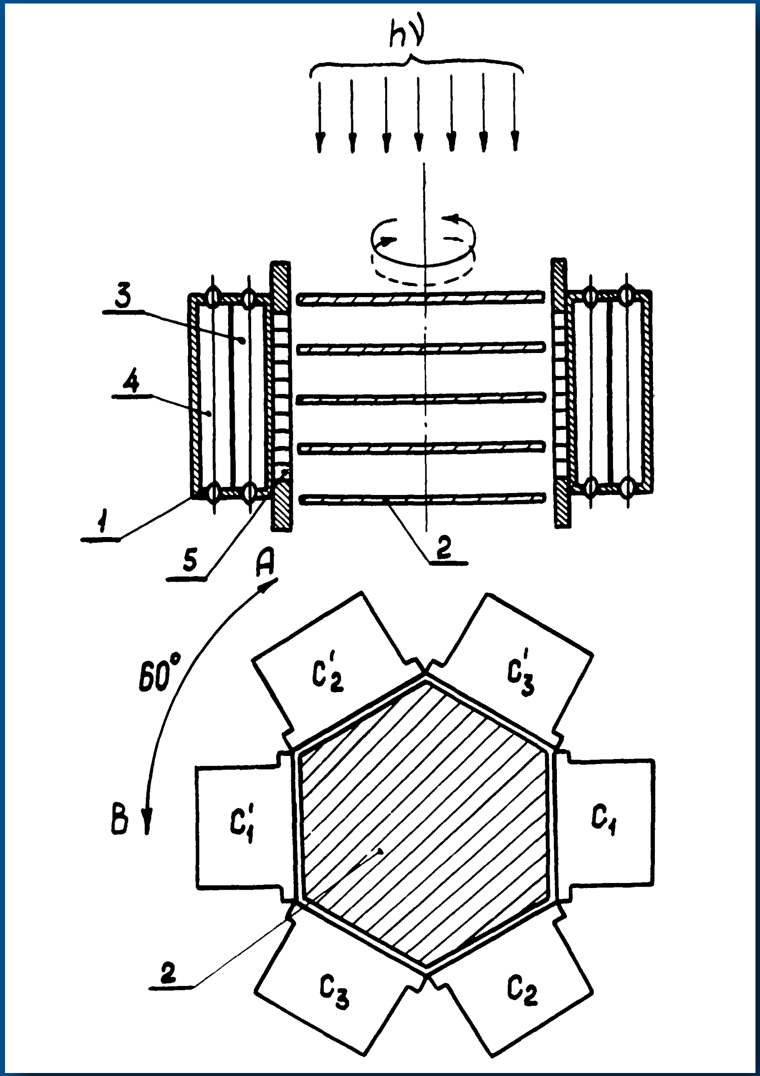
Tindo et al.
1970 - 1976

Be scatterer with proportional counters

E ~ 15 keV

4 different polarimeters

constant improvements



Intercosmos 7
polarimeter

Intercosmos Observations

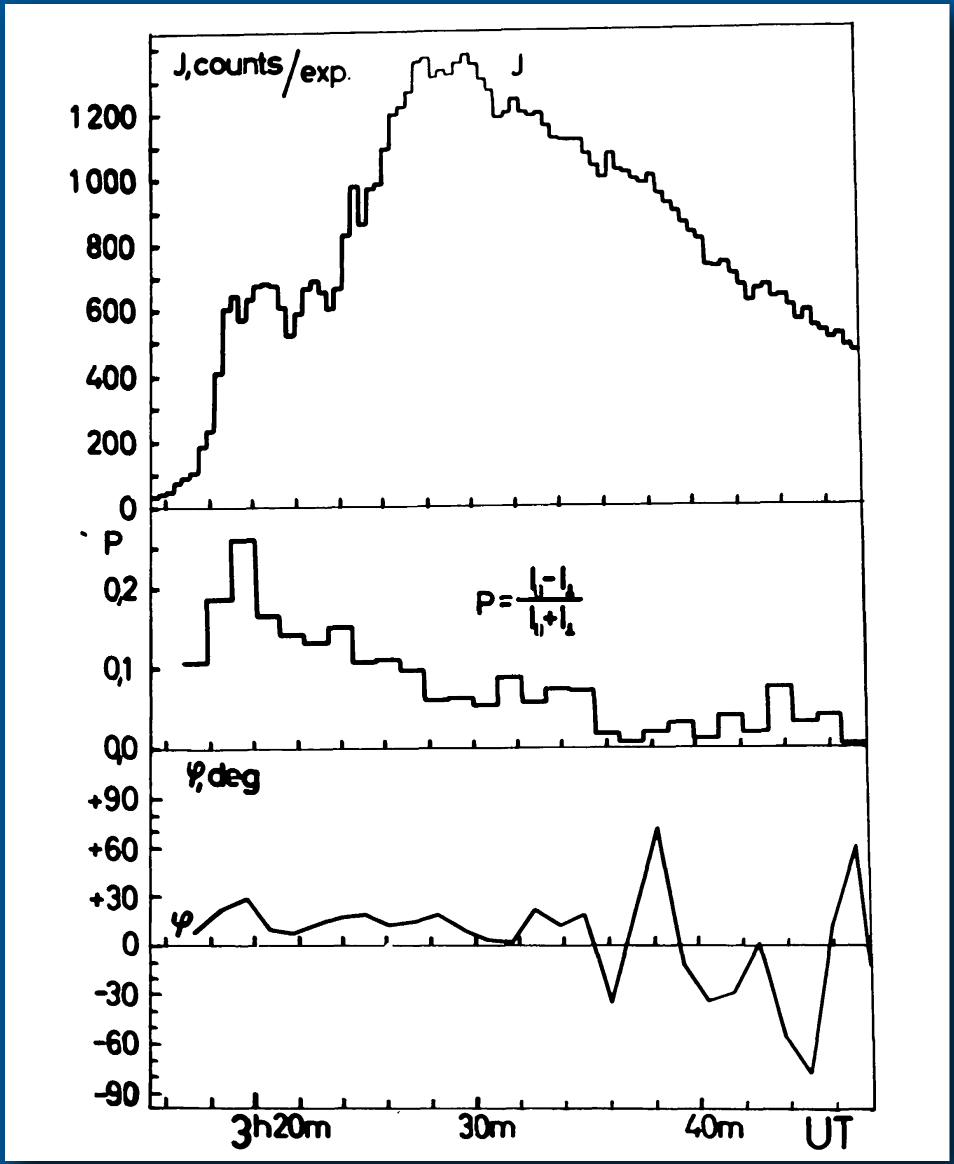
Tindo et al., Solar Physics, 14, 204 (1970)
Tindo et al., Solar Physics, 24, 429 (1972)
Tindo et al., Solar Physics, 27, 426 (1972)
Tindo et al., Solar Physics, 32, 469 (1973)

1969	Intercosmos 1	3 flares	P ~ 40%
1970	Intercosmos 4	3 flares	P ~ 15-20%
1972	Intercosmos 7	3 flares	P ~ 2-16%
1974	Intercosmos 11	3 flares	P < ~5%

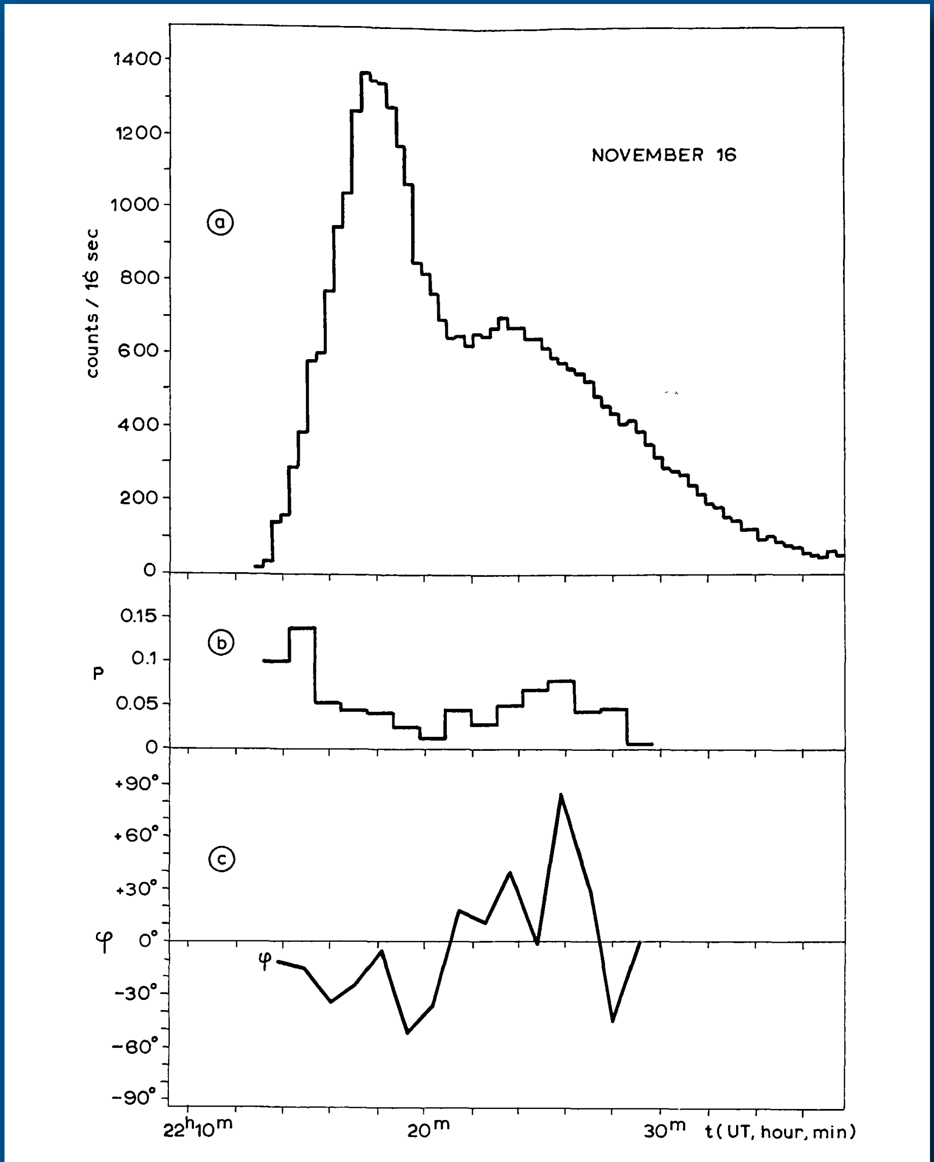
It is interesting to note that, as the instrumentation improved, the measured level of polarization decreased.

Intercosmos 4 Observations

November 5, 1970



November 16, 1970



OSO-7 Polarimeter

Nakada, Neupert & Thomas, Solar Physics, 37, 429 (1974)

Be scatterer with proportional counters

E ~ 15-30 keV

in-flight threshold changes

analysis shows P ~ 10% with large uncertainty

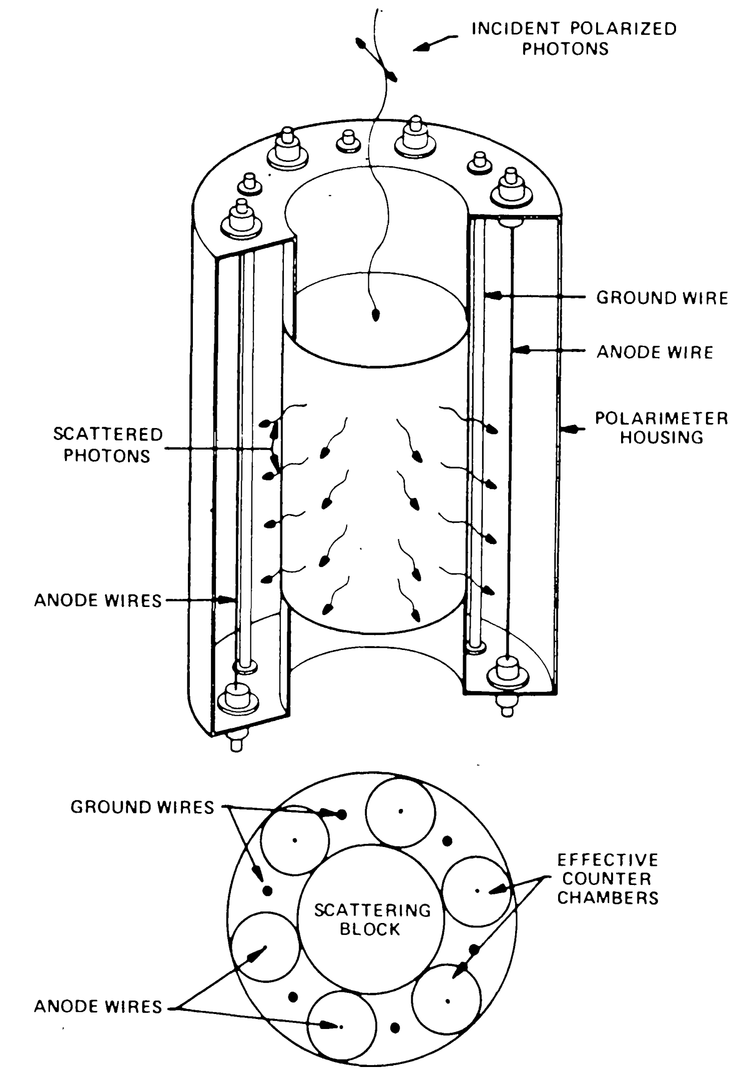


Fig. 1. Diagram of polarimeter on OSO-7.

Shuttle STS-3 Polarimeter

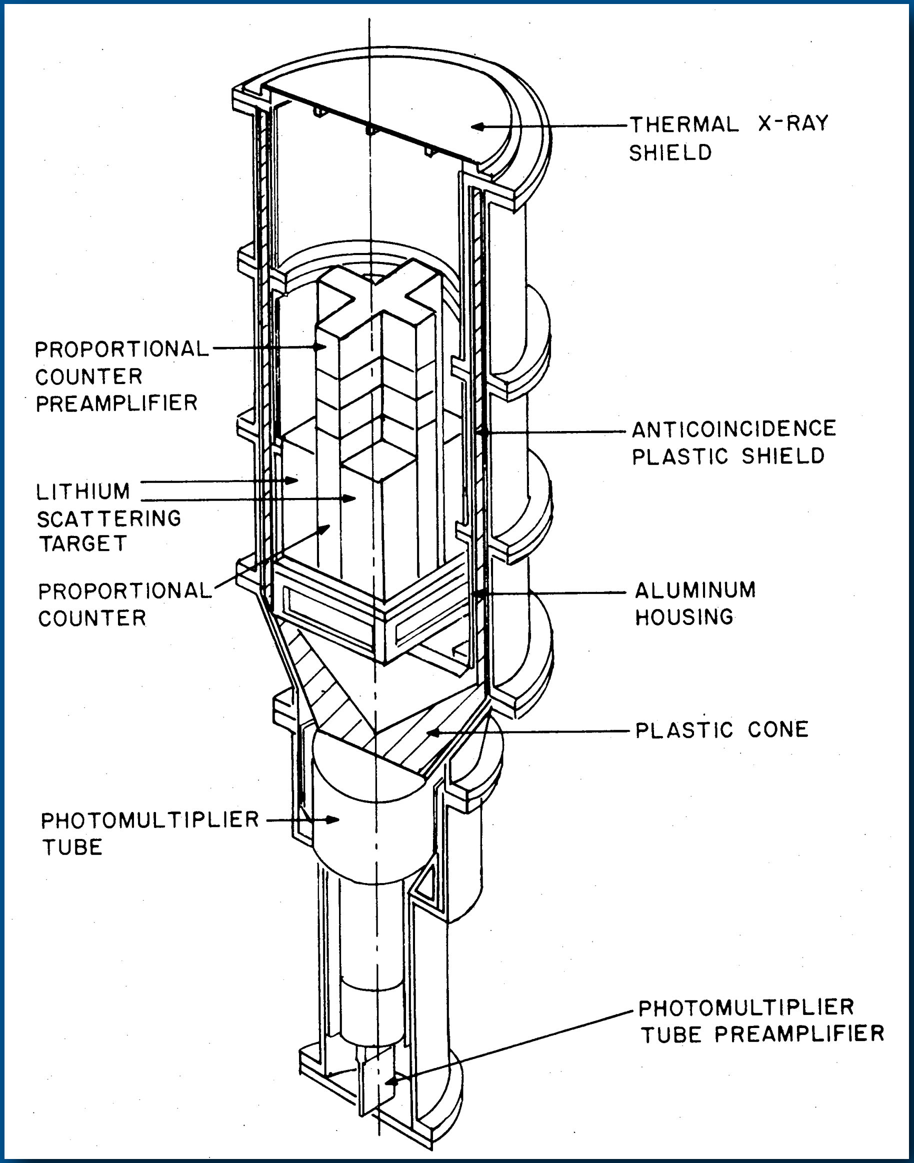
Lemen et al., Solar Physics, 80, 333 (1982)

March, 1982

Li scatterers with proportional counters

E ~ 5-30 keV

Several flares
P < 5 %



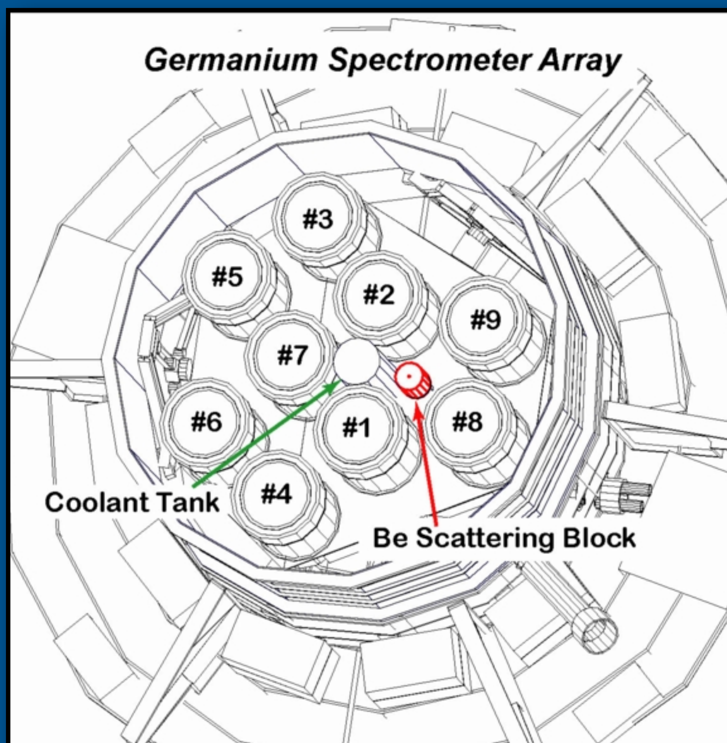
Early Measurements

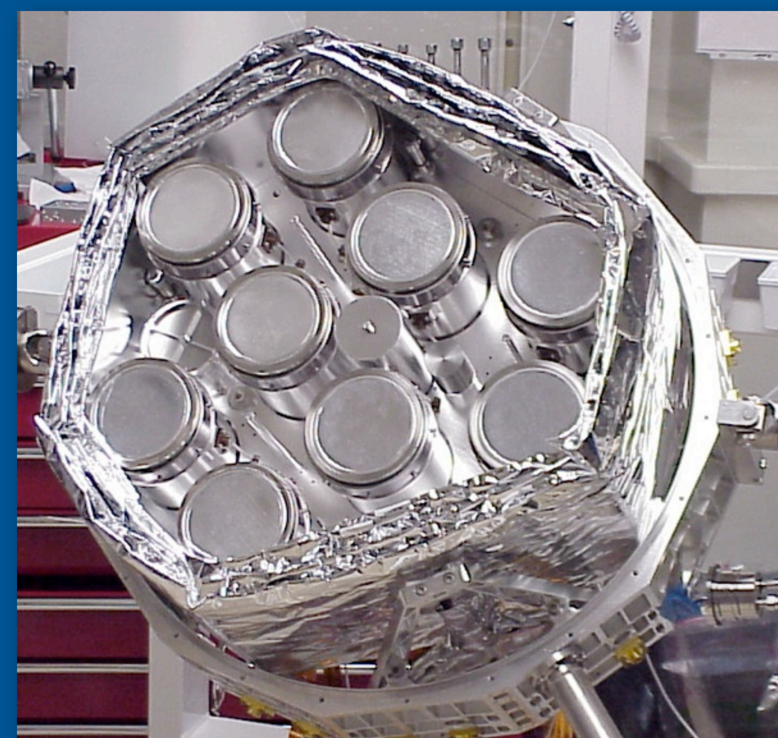
- All at low energies (< 30 keV)
- Low levels of polarization
- Dominated by thermal emission
- High levels of polarization are generally not expected

The RHESSI Era
(2002 - present)

RHESSI as a Polarimeter

Low-Energy Mode (Be-Ge, 20-100 keV)
High-Energy Mode (Ge-Ge, >200 keV)





Spacecraft rotation facilitates polarization measurements.

GRB 021206

Rejuvenated interest in polarimetry.

letters to nature

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

Wayne Coburn* & Steven E. Boggs*†

* *Space Sciences Laboratory, and † Department of Physics, University of California, Berkeley, California 94720, USA*

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 ($\sim$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.

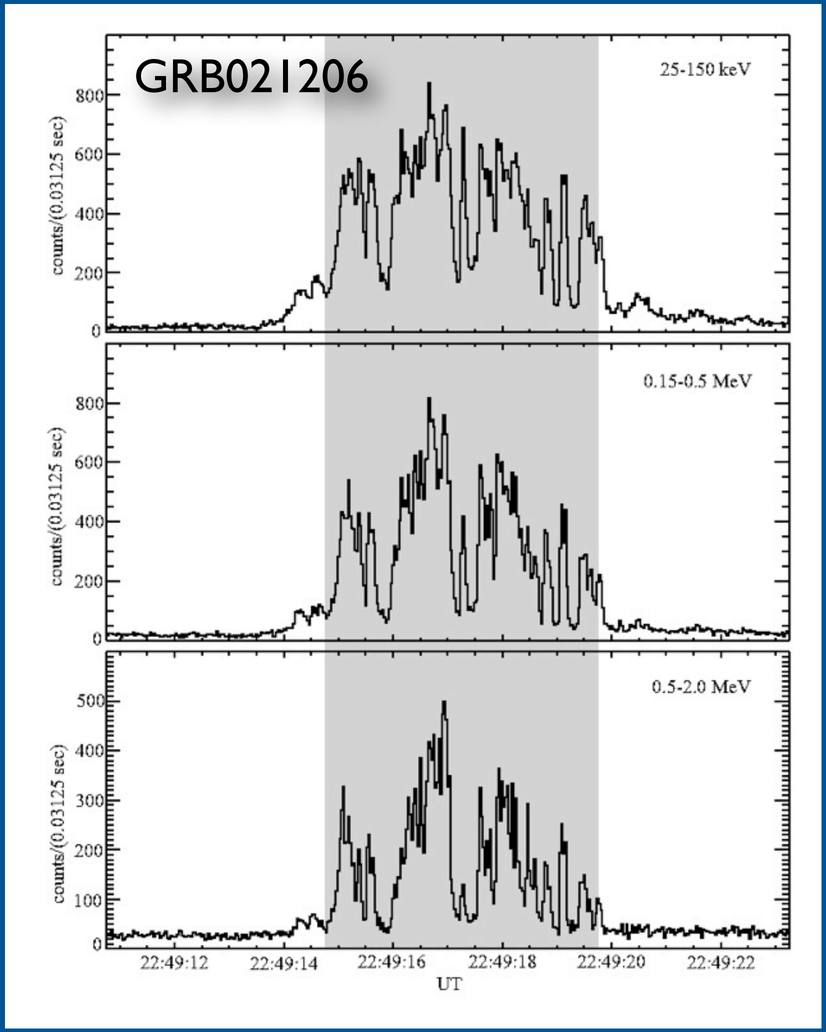
In comparison with other γ-ray instruments (COMPTEL, BATSE) that have attempted to measure polarization in the past[5,6], RHESSI has the major advantage of quickly rotating around its focal axis (centred on the Sun) with a 4-s period. Rotation averages out the effects of asymmetries in the detectors 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

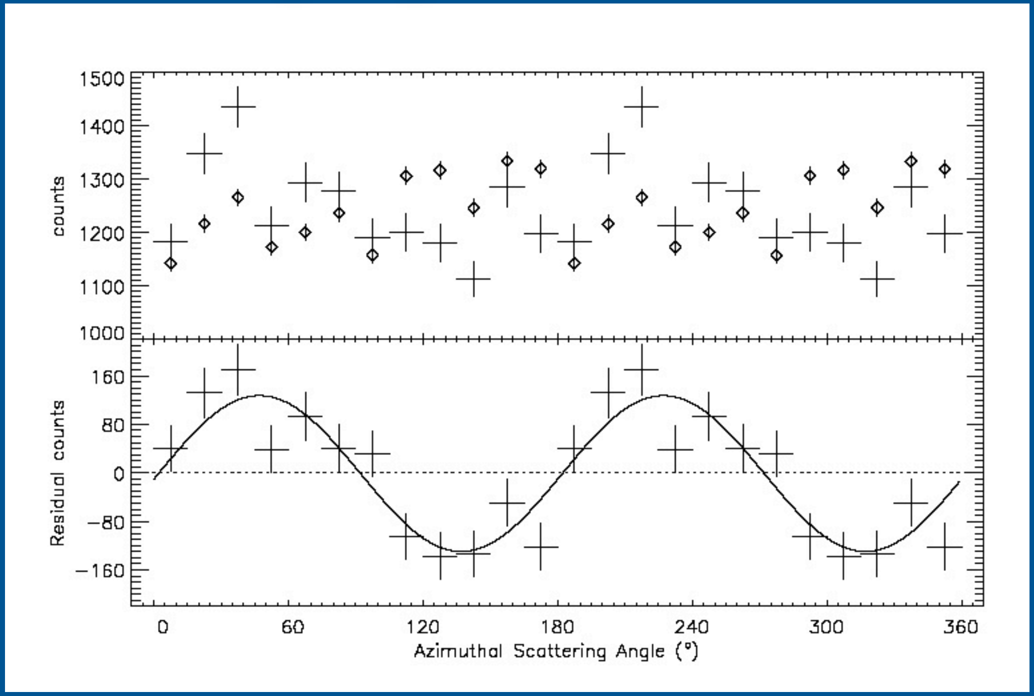
GRB Polarization

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)

GRB Result Met with Skepticism

Two subsequent publications (including one from the RHESSI team) found no significant evidence for polarization.

Mon. Not. R. Astron. Soc. **350,** 1288–1300 (2004) doi:10.111

Re-analysis of polarization in the γ-ray flux of GRB 021206

Robert E. Rutledge★ and Derek B. Fox★
Division of Physics, Mathematics and Astronomy, California Institute of Technology, MS 130-33, Pasadena, CA 91125, USA

Accepted 2004 January 23. Received 2004 January 22; in original form 2003 October 14

The Astrophysical Journal, 613:1088–1100, 2004 October 1

GAMMA-RAY BURST POLARIZATION: LIMITS FROM *RHESSI* MEASUREMENTS

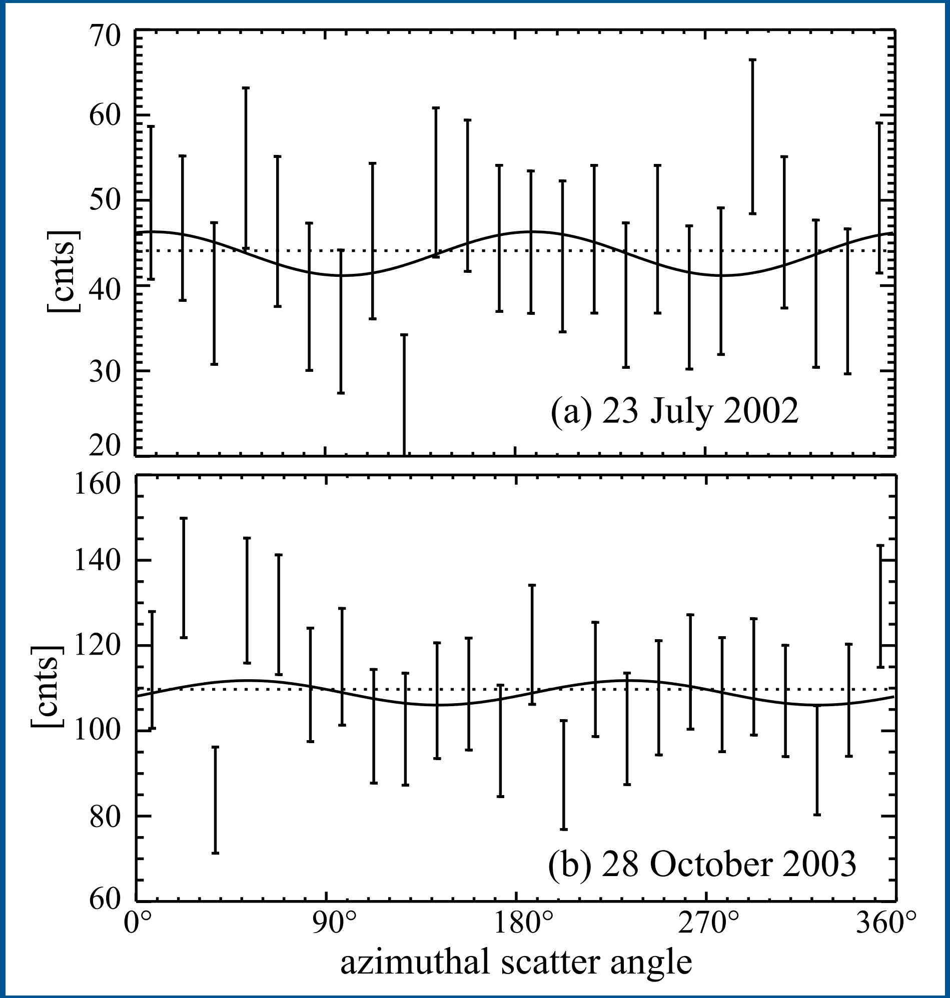
C. Wigger, W. Hajdas, K. Arzner, M. Güdel, and A. Zehnder
Labor für Astrophysik, Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland; claudia.wigger@psi.ch, wojtek.hajdas@psi.ch, arzner@astro.phys.ethz.ch, guedel@astro.phys.ethz.ch, alex.zehnder@psi.ch
Received 2004 February 14; accepted 2004 June 7

Solar Flare Polarization

Boggs et al., ApJ, 638, 1129 (2006)

RHESSI High Energy (double scatter - GeGe) Mode

200 keV - 1 MeV



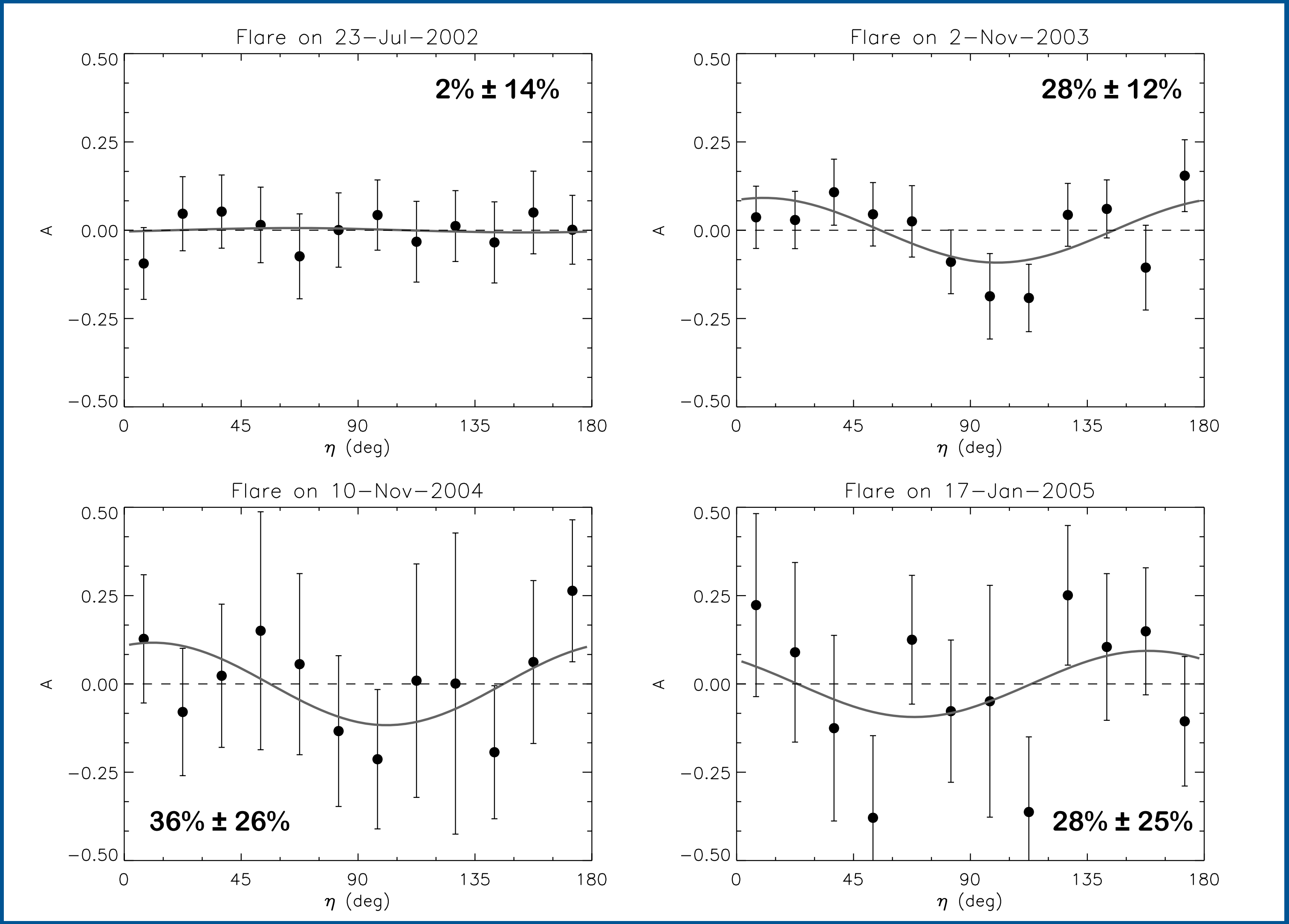
X4.8-class flare
$\Pi = 21\% \pm 9\%$

X17-class flare
$\Pi = 11\% \pm 5\%$

Solar Flare Polarization

Suarez-Garcia et al., Solar Physics, 239, 149 (2006)

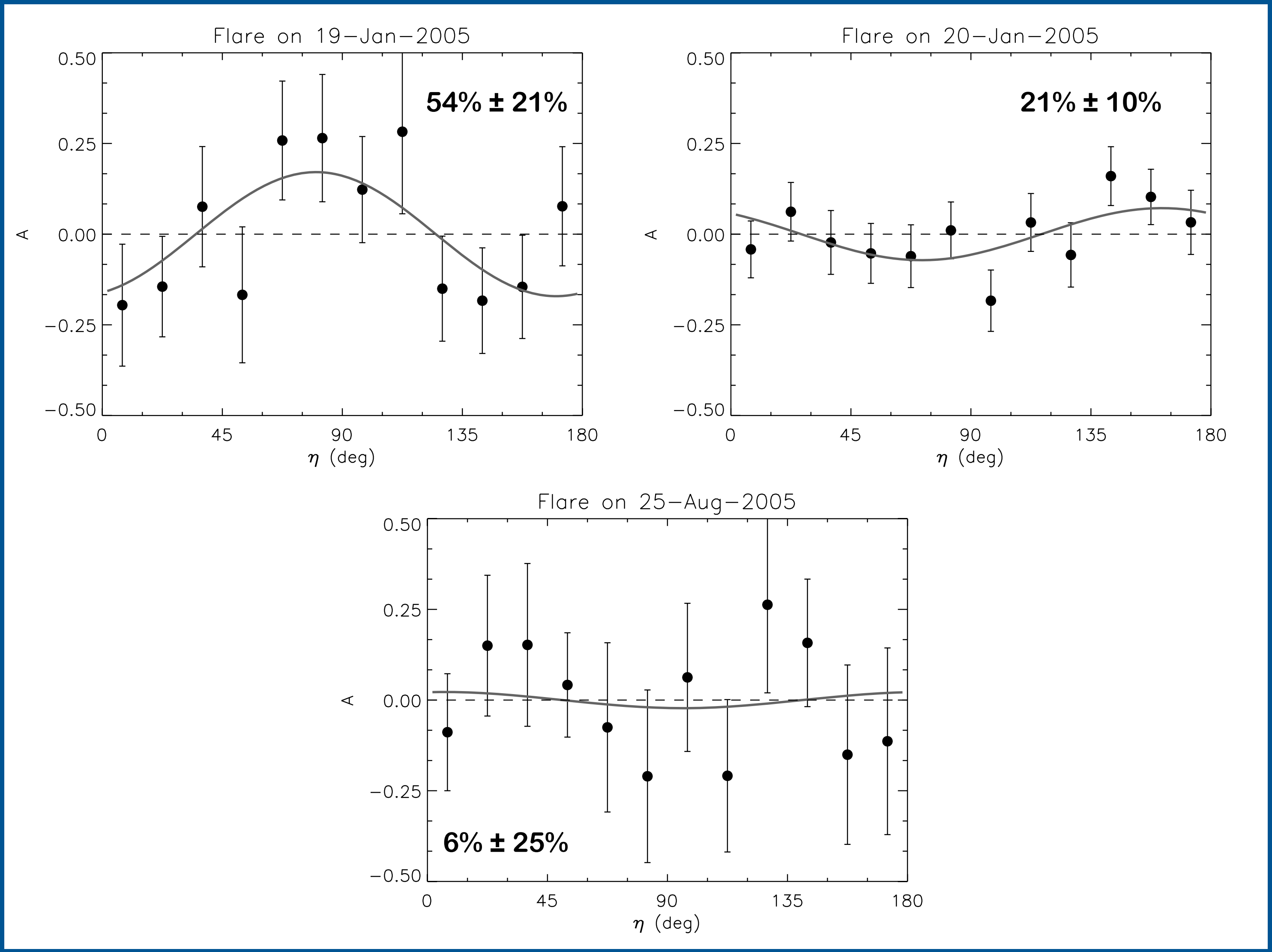
GeGe Mode / 100 - 350 keV / 7 events



Solar Flare Polarization

Suarez-Garcia et al., Solar Physics, 239, 149 (2006)

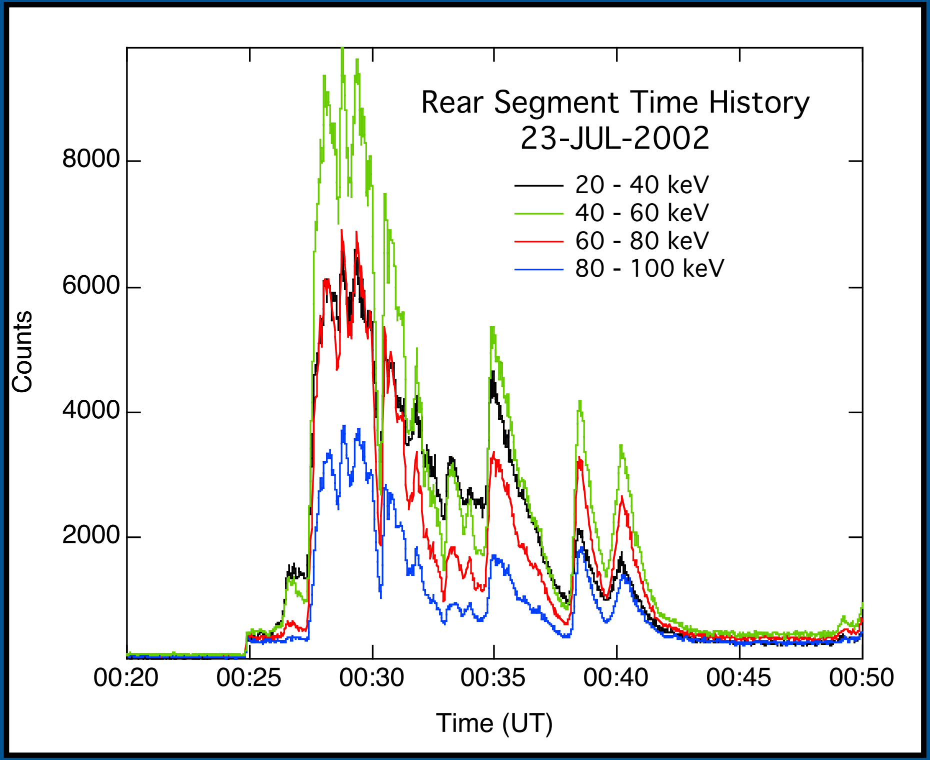
GeGe Mode / 100 - 350 keV / 7 events

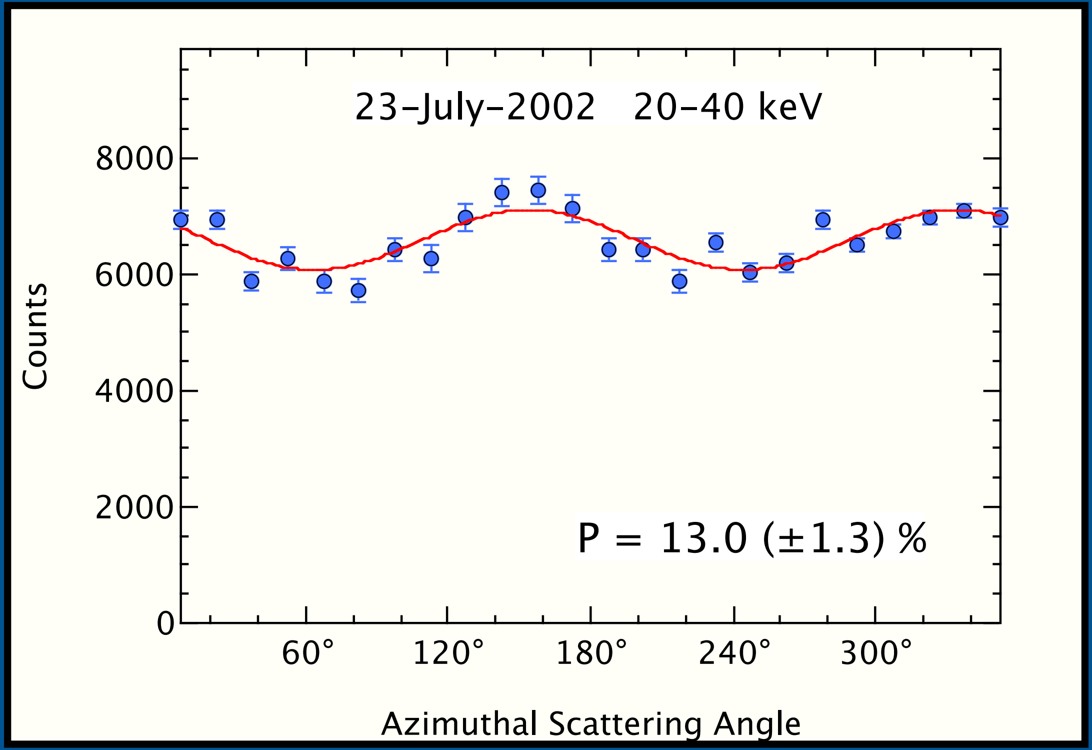


Solar Flare Polarization

McConnell et al., Solar Physics 210, 125 (2002)
McConnell et al., AAS-HEAD, 23-26 March 2003 (BAAS, 35, 616)

RHESSI Low Energy Polarimetry (Be Scatter) Mode





Never published. Result was not internally consistent.

CORONAS-F

Bogomolov et al., Space Sys. Res, 37, 112 (2003)
Bogomolov et al., IAU Symp., 223, 447 (2004)

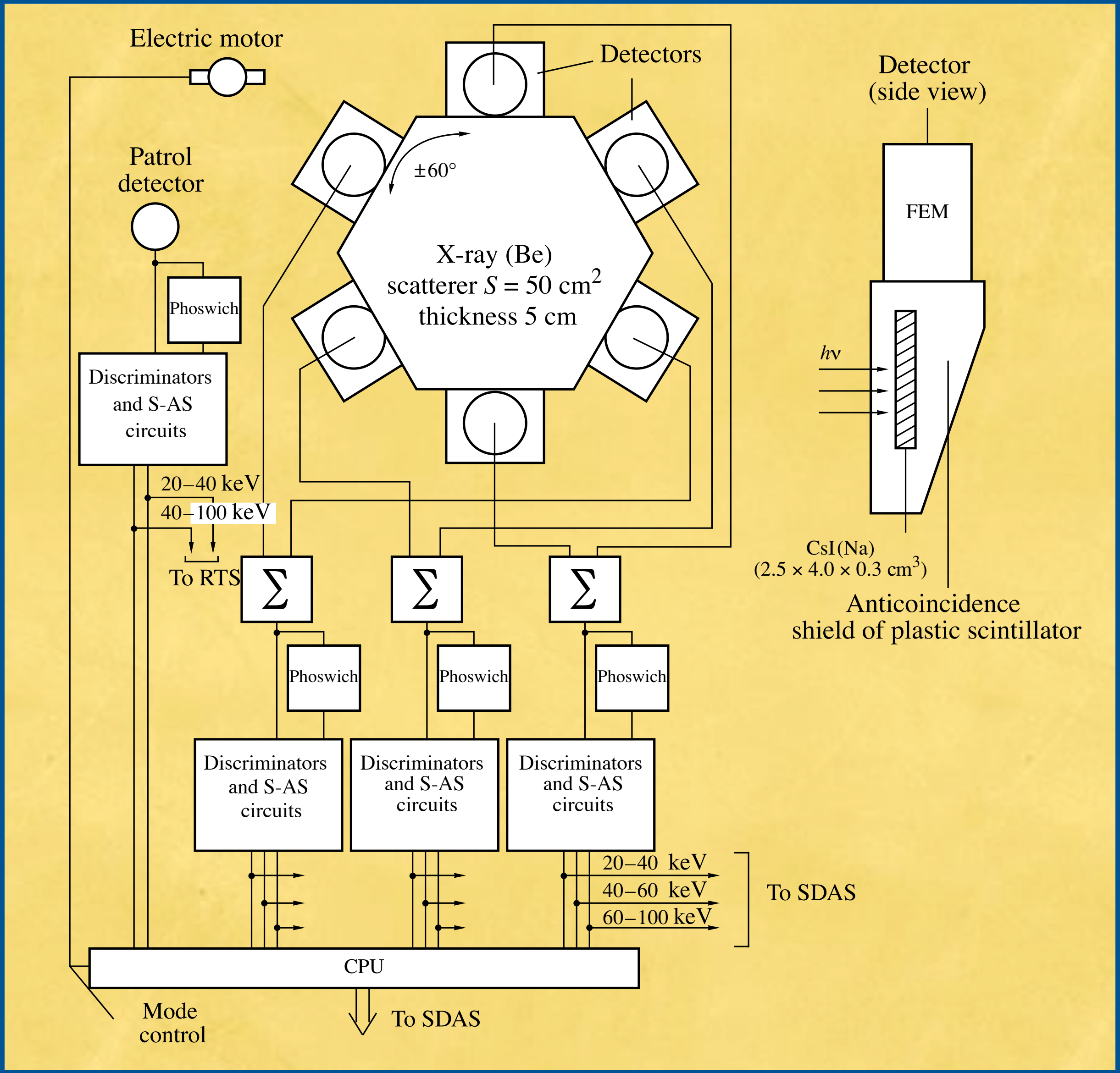
Be scatterer with CsI detectors

E ~ 20-100 keV

2001-2005

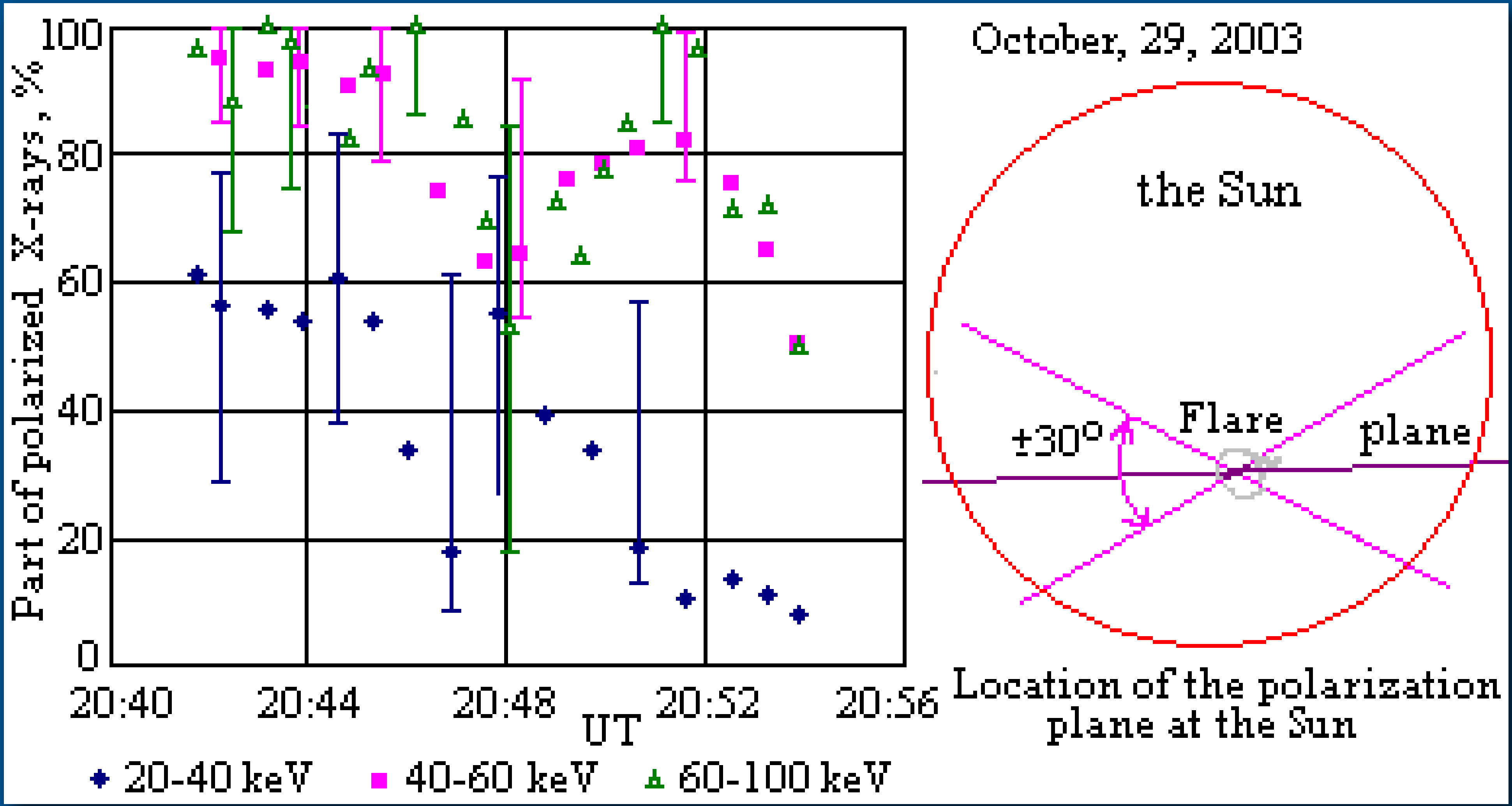
Claimed detection in one event (29-Oct-2003) at the 50-70% level.

Upper limits for ~25 events.



CORONAS-F

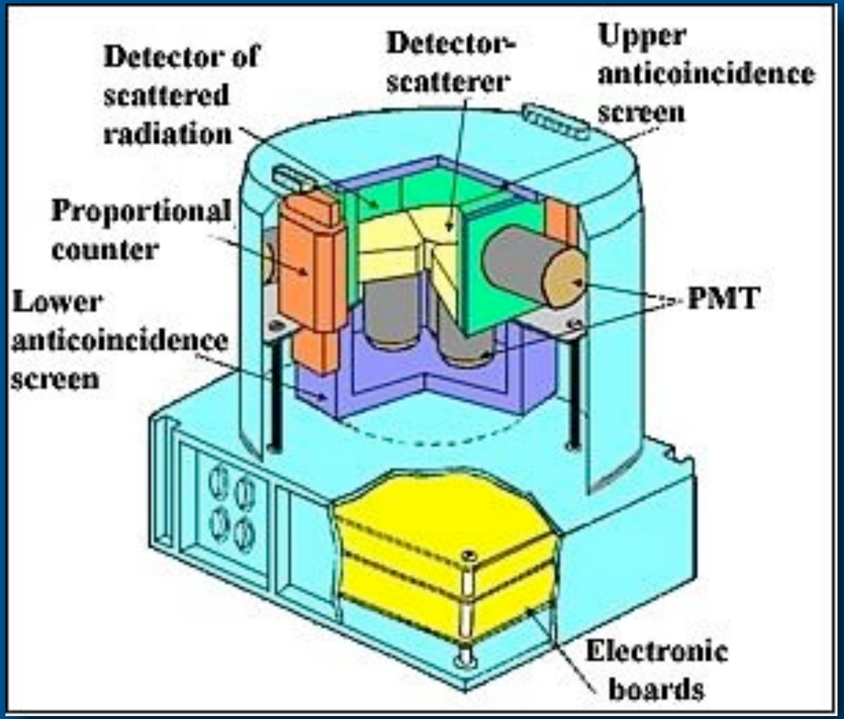
Bogomolov et al., IAU Symp. 223, 447 (2004)



Coronas-Photon

Launched Jan 30, 2009
Contact lost on Dec 1, 2009; never fully recovered.

PENGUIN-M, a hard X-ray polarimeter-spectrometer
20-150 keV polarimetry.

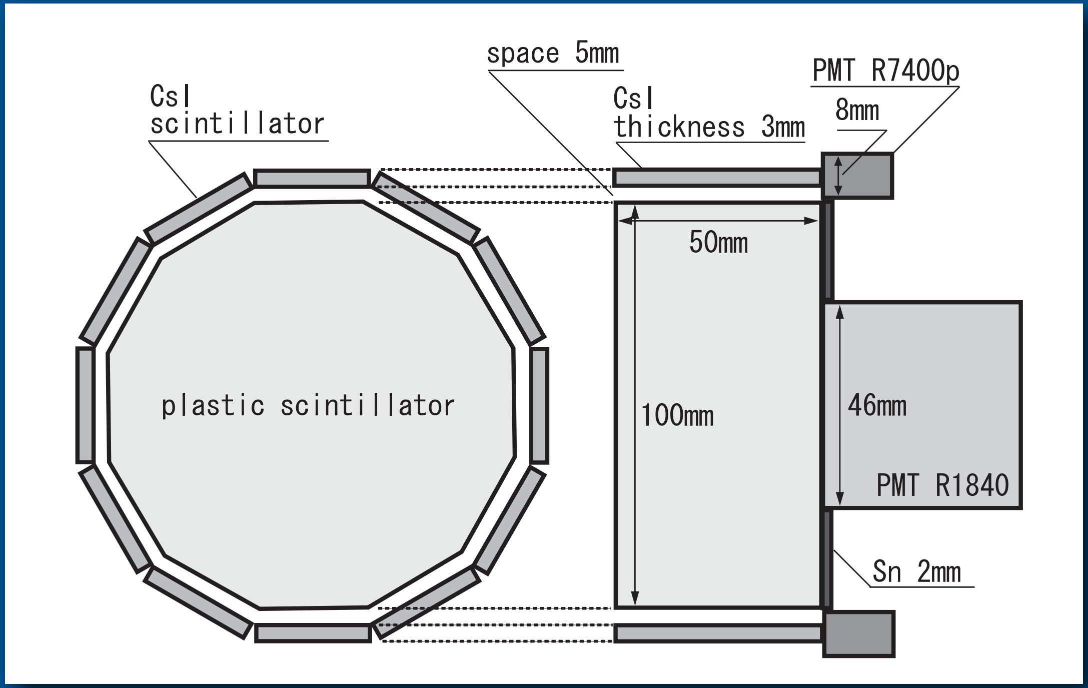


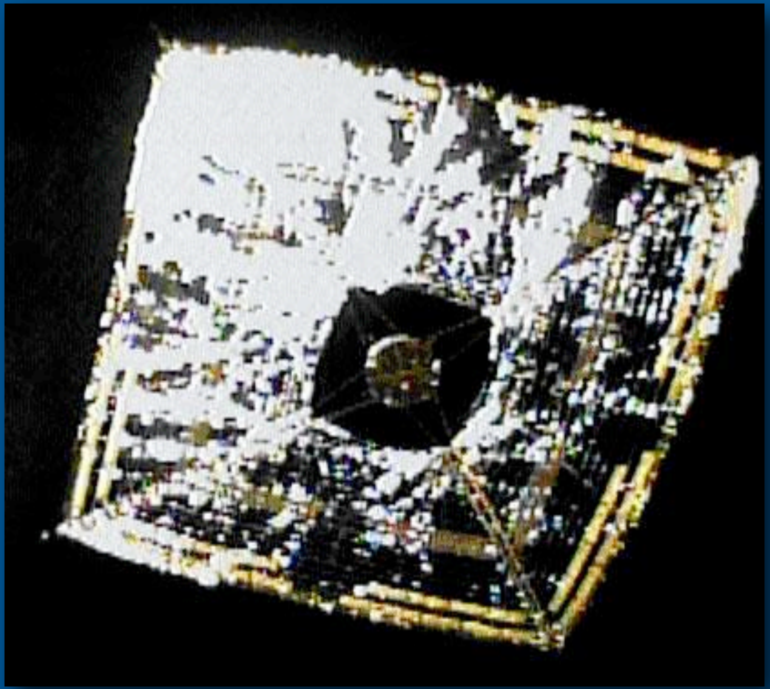
No reports of polarization measurements(?).

IKAROS – Solar Sail Mission

Yonetoku et al. , SPIE 6266 (2006)

Japanese engineering verification satellite was launched in May, 2010.
6 year cruise to Jupiter plus 5 years to Jovian L4 Trojan asteroids.
IPN detector (GAP) with polarization sensitivity.
Large plastic scintillator surrounded by 12 CsI detectors.



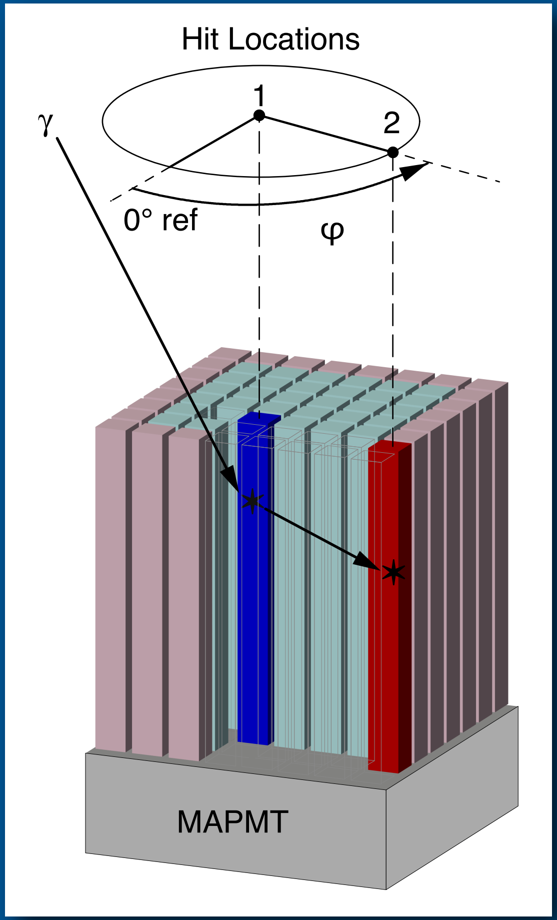


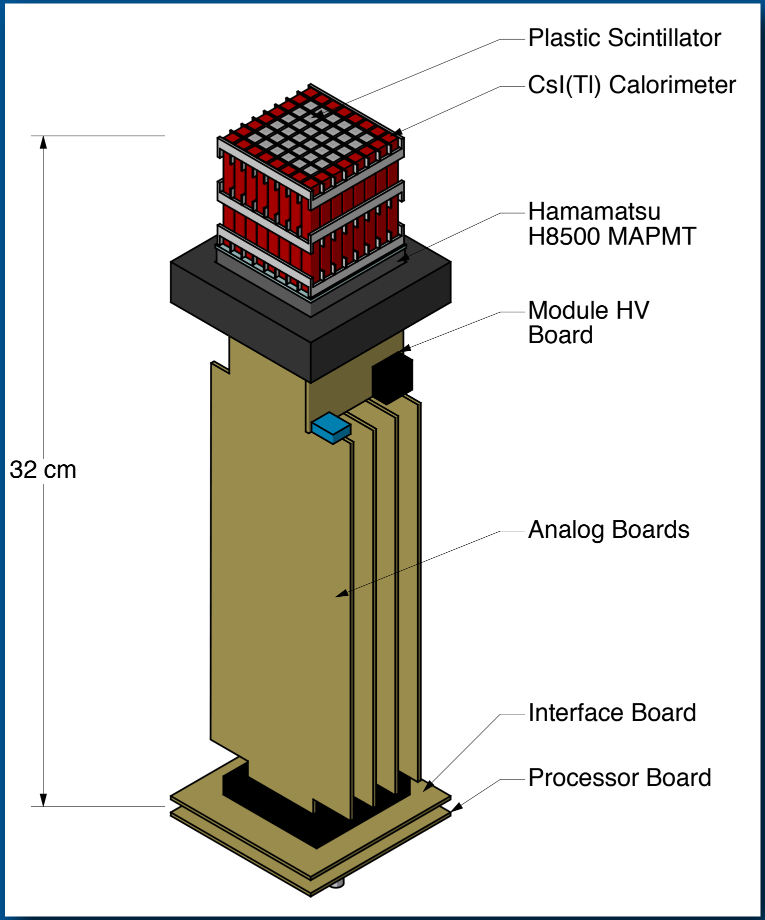
50-m solar sail

Future Prospects (in development)

Gamma-Ray Polarimeter Experiment (GRAPE)

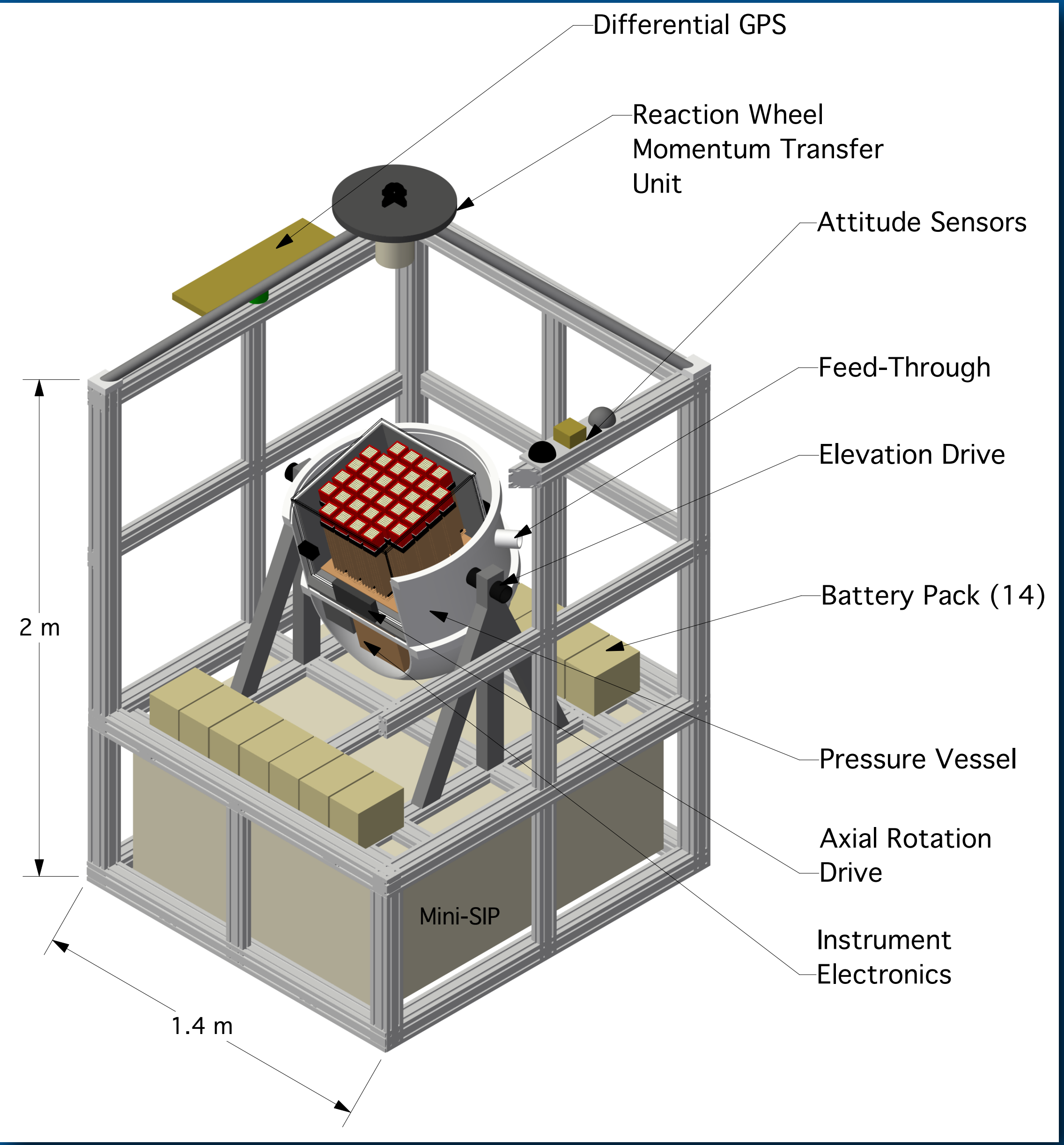
Bloser et al., NIM, 600, 424 (2009)
Legere et al.,SPIE 5898, 413 (2005)
McConnell et al., IEEE TNS 46, 890 (1999)





50 - 500 keV energy range

GRAPE Balloon Payload

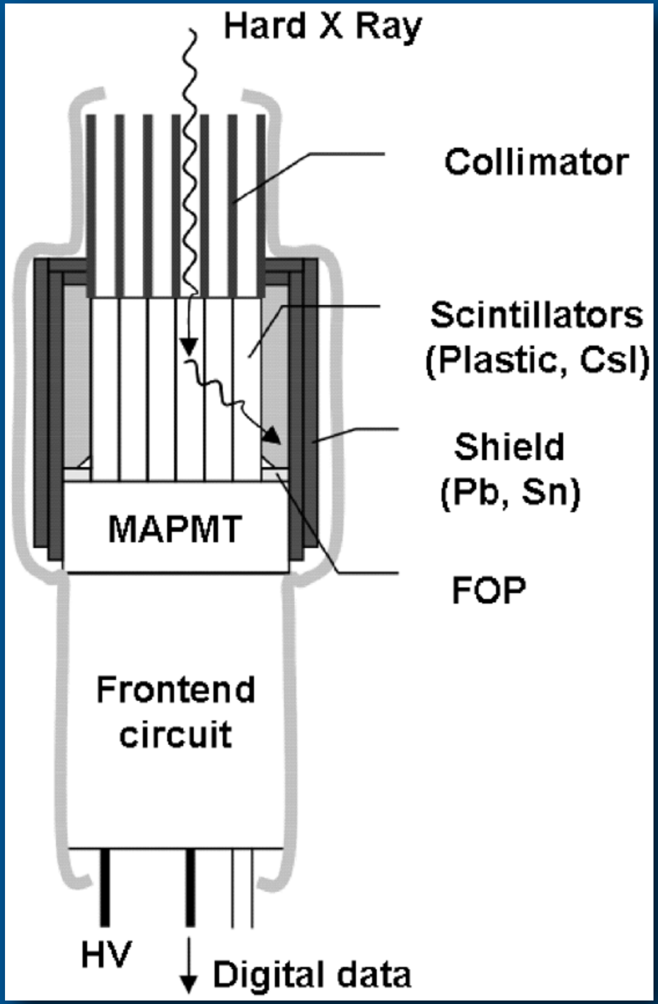


The balloon payload incorporates a design that provides for back-and-forth rotation of the detector array within the pressure vessel.

First flight in Fall, 2011 will look at Crab. Subsequent LDB flights from Antarctica for GRBs and solar flares.

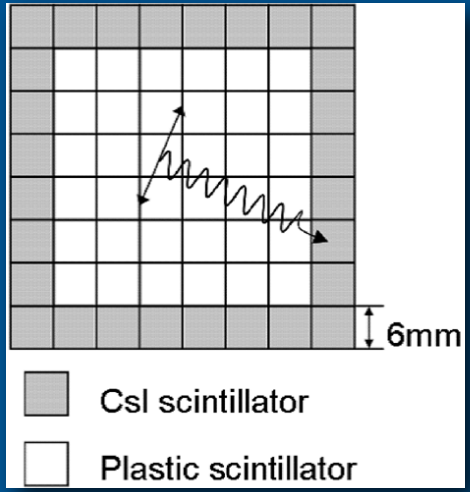
Polarimetry of High ENErgy X-rays (PHENEX)

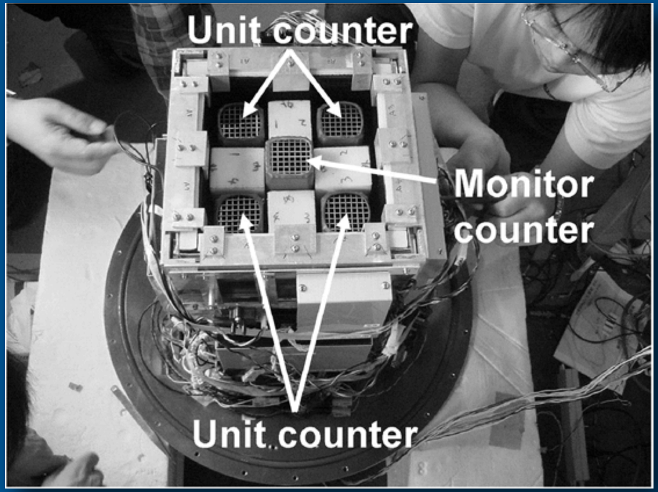
Kishimoto et al. , IEEE TNS, 54, 561 (2007)



Array of plastic and CsI (Tl) read out by a single MAPMT.

Polarimetry from 40 - 200 keV.

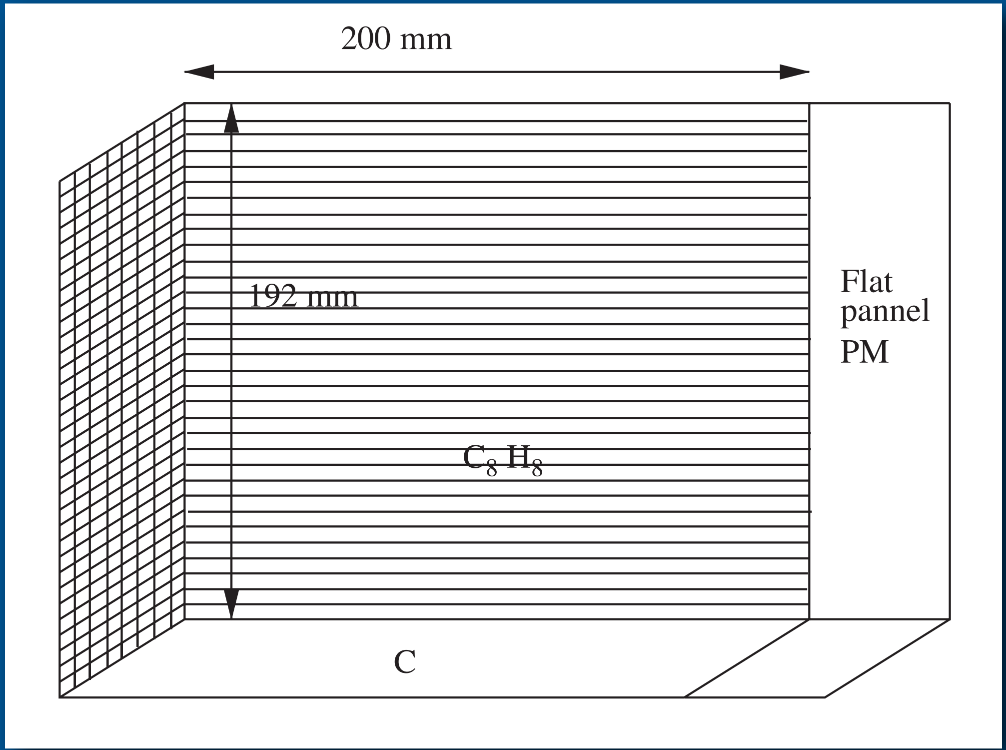


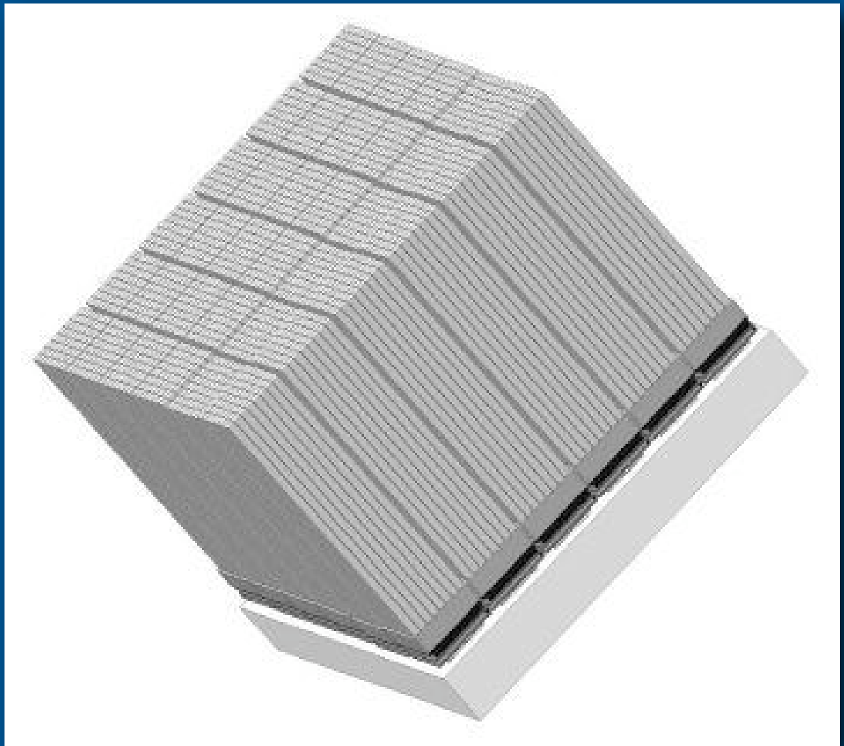


POLAR

Hajdas et al.,SPIE 6266 (2006)
Produit et al., NIM, 550, 616 (2005)

10 - 300 keV
Scattering between 5-mm plastic elements.
Plastic is read out by an array of MAPMTs.

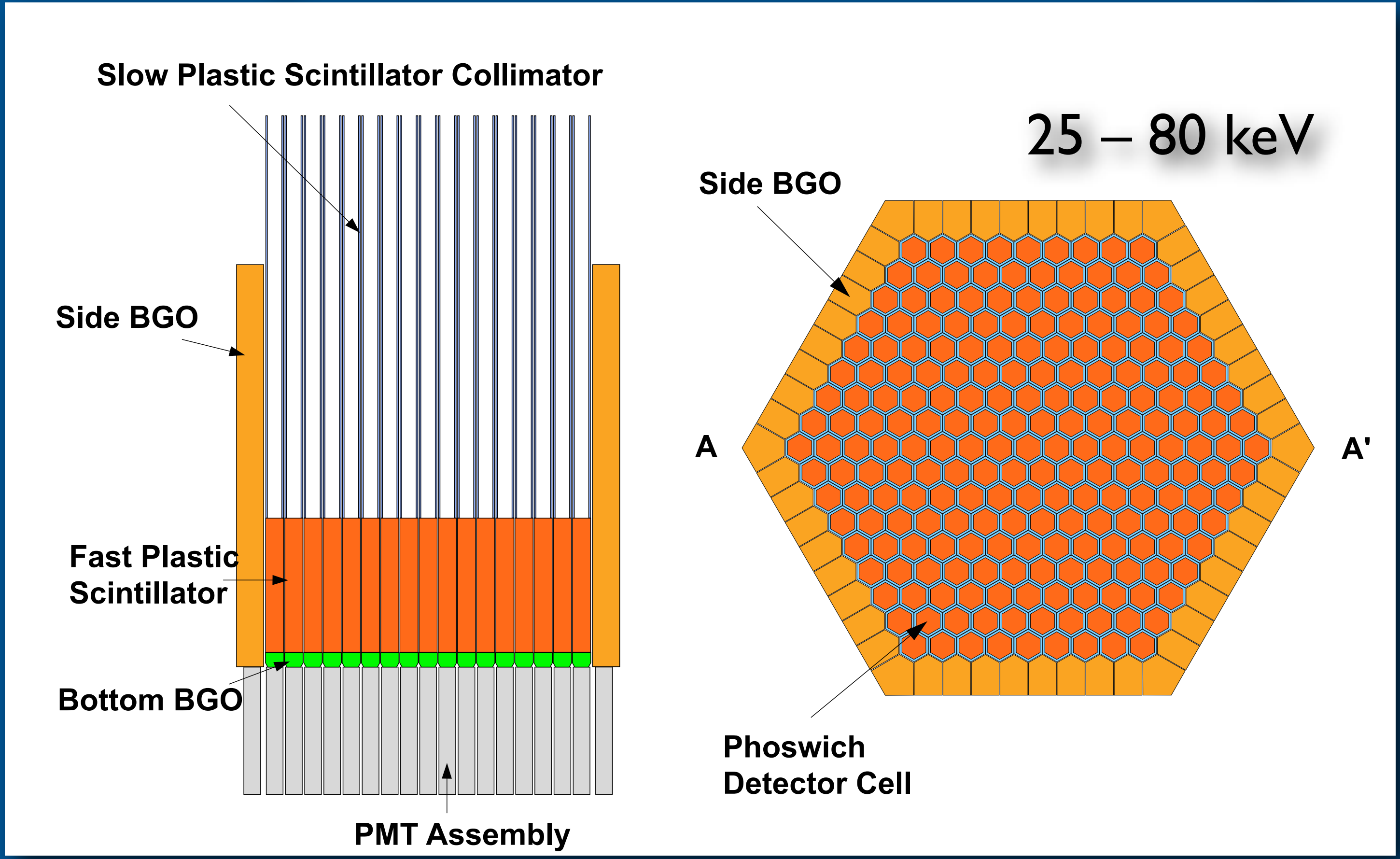




Polarized Gamma-Ray Observer (PoGoLite)

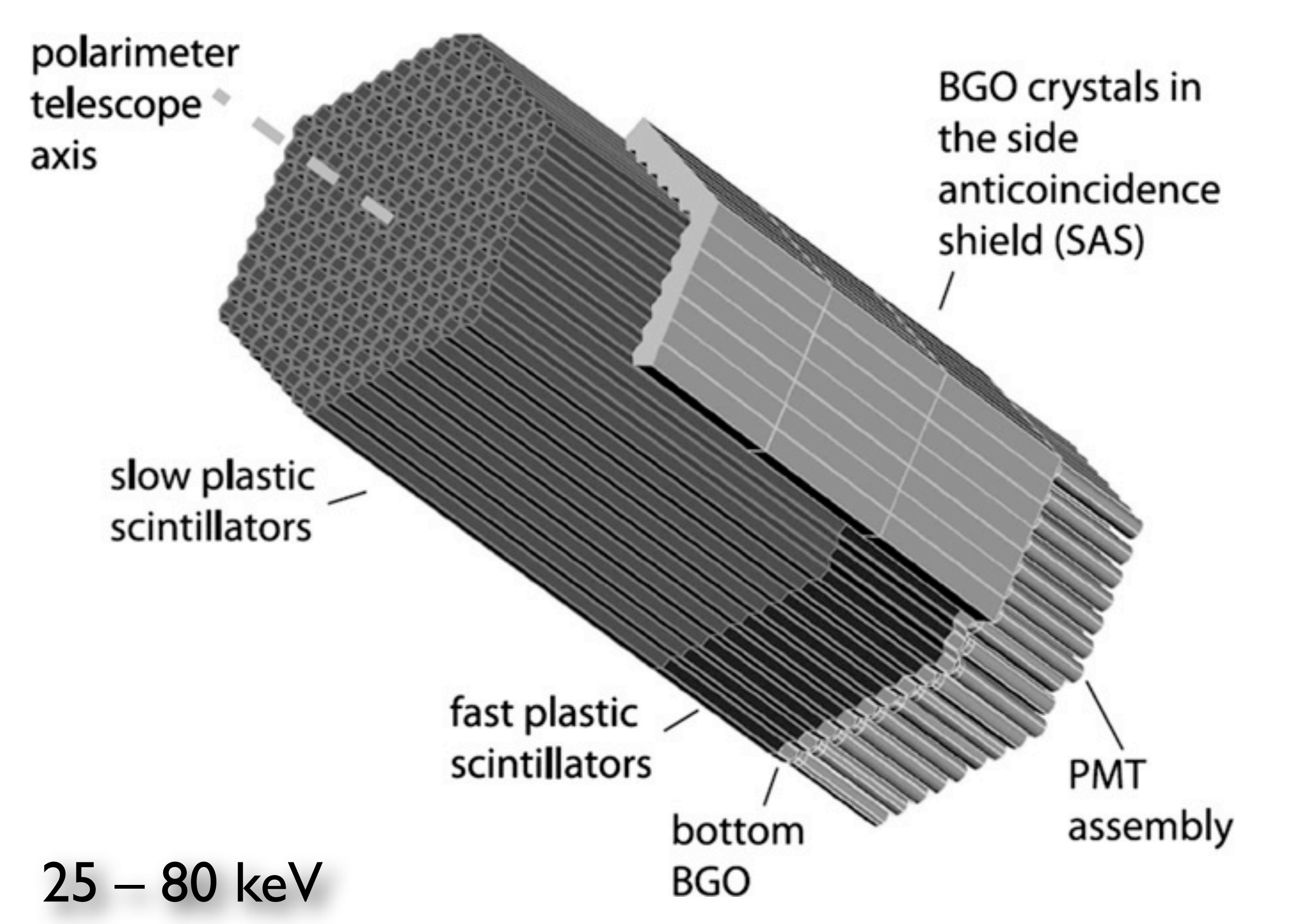
Kamae et al. , Astroparticle Physics, 30, 72 (2008)
Kanai et al., NIM, 570, 61 (2007)

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



Polarized Gamma-Ray Observer (PoGoLite)

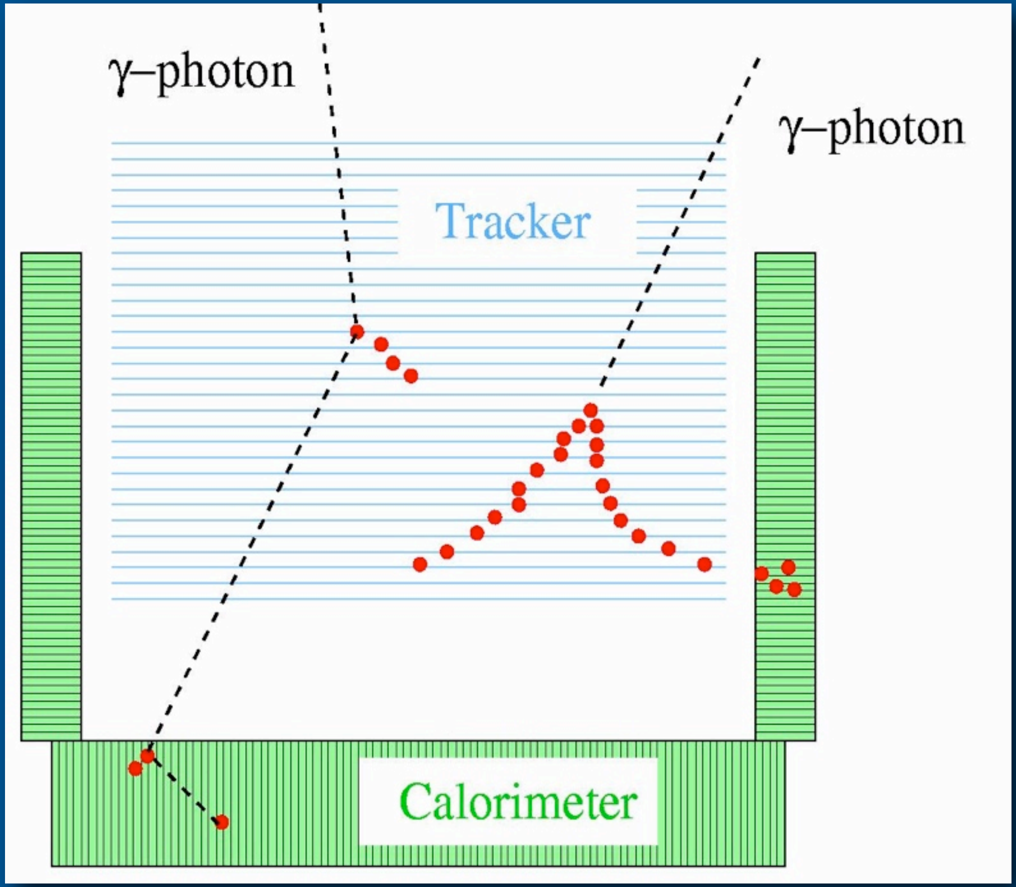
Kamae et al. , Astroparticle Physics, 30, 72 (2008)
Kanai et al., NIM, 570, 61 (2007)



10% polarization in 200 mCrab
6-hr balloon flight

Compton Telescope Designs

Many future designs are based on a well-type geometry.



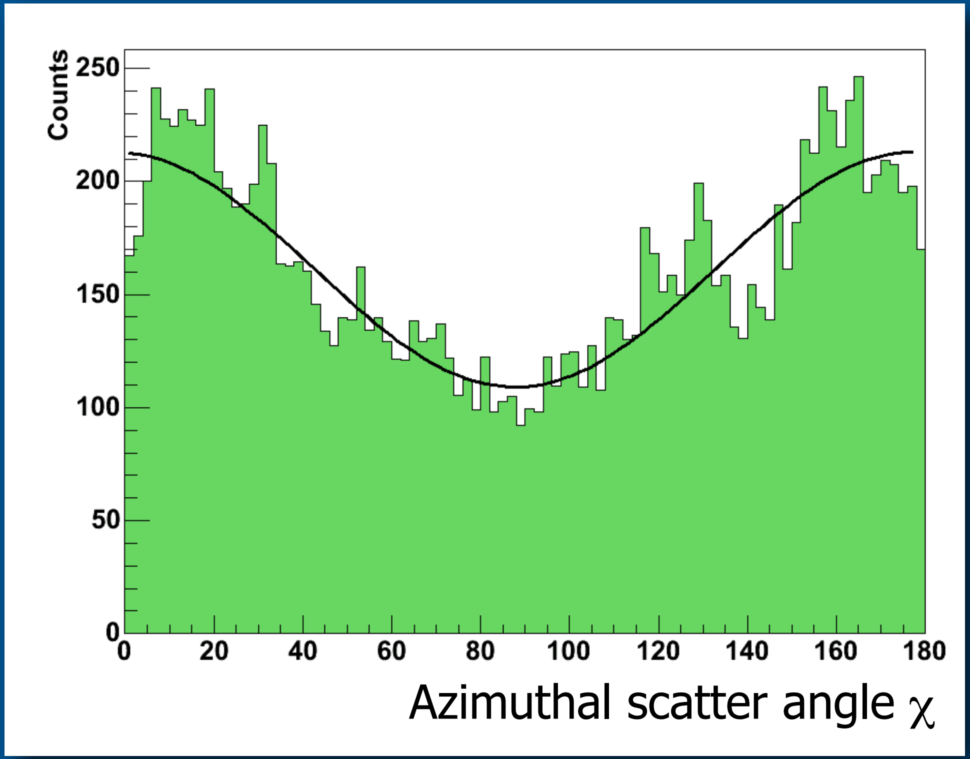
Various detection technologies used for both the tracker and calorimeter components.

1) silicon strip detectors
2) Ge strip detectors
3) CdZnTe strip detectors
2) liquid Xenon

Medium Energy Gamma-ray Astronomy experiment (MEGA)

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

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

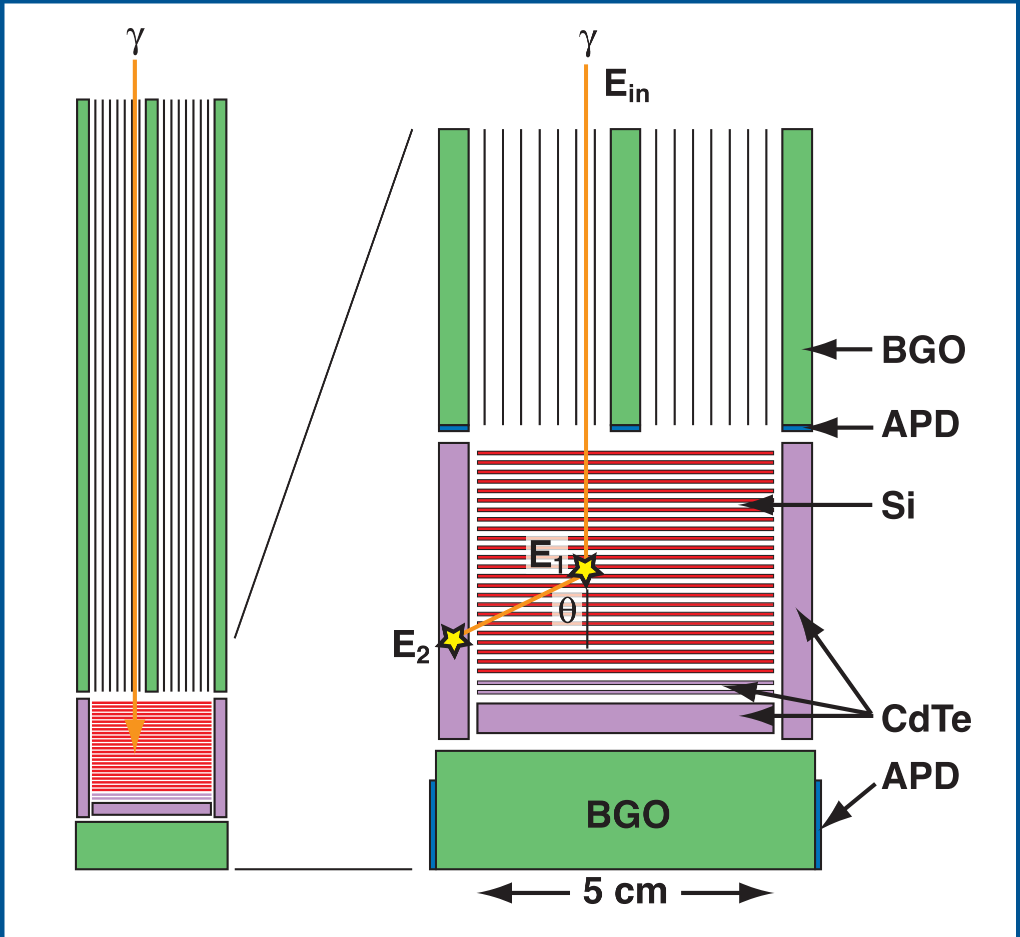


Incident Energy = 710 keV
Modulation = 0.31 ± 0.03

Semiconductor Multiple-Compton Telescope (SMCT)

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

Based on a shielded stack of Si detectors.

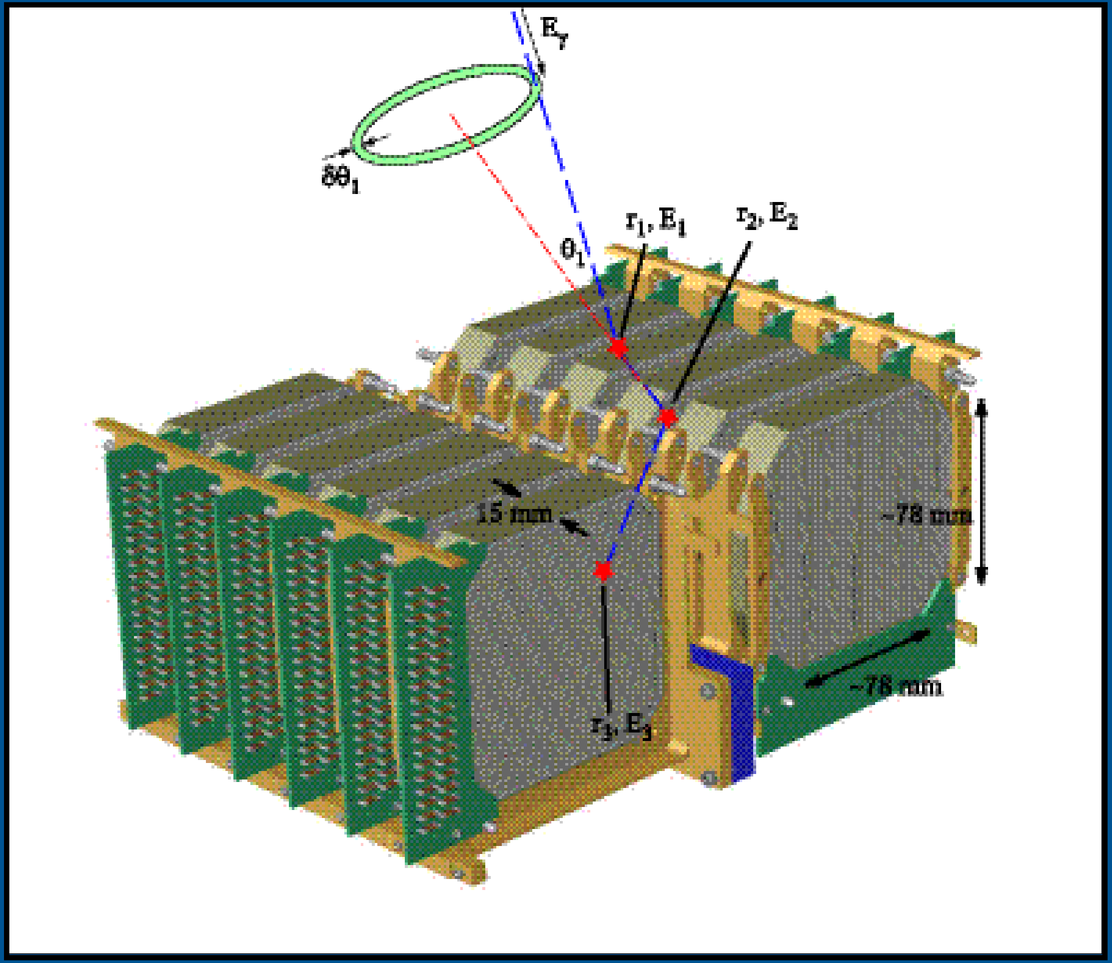


This design is to be used for the soft gamma-ray detector on Astro-H (also known as NexT), to be launched in 2013.

Also possibly for the CAST mission (2015-2020)

Nuclear Compton Telescope (NCT)

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



Ge strip detectors

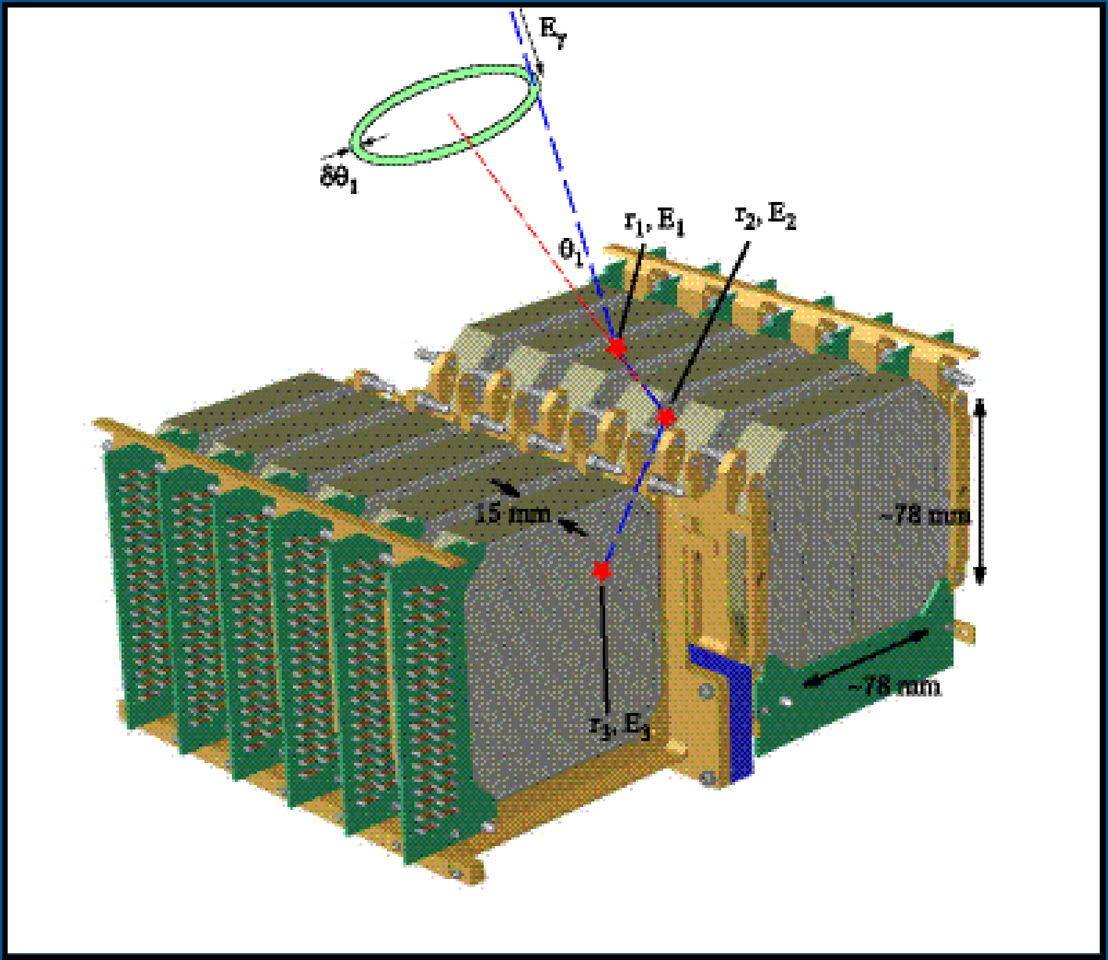
0.2-10 MeV

recently showed first image from the Crab

no polarization data

recent balloon launch failure

Gamma-Ray Imaging Polarimeter for Solar Flares (GRIPS)



200 keV - 10 MeV

modulation imaging

12 arcsec
angular resolution

first balloon flight
in 2013

Flare Polarization Measurements

- Observations to date of limited quality
- Considerable interest in polarimetry
- Several experiments in development
- Observations during current cycle?!?