A Low Energy Compton Imager for GRB Polarization Studies

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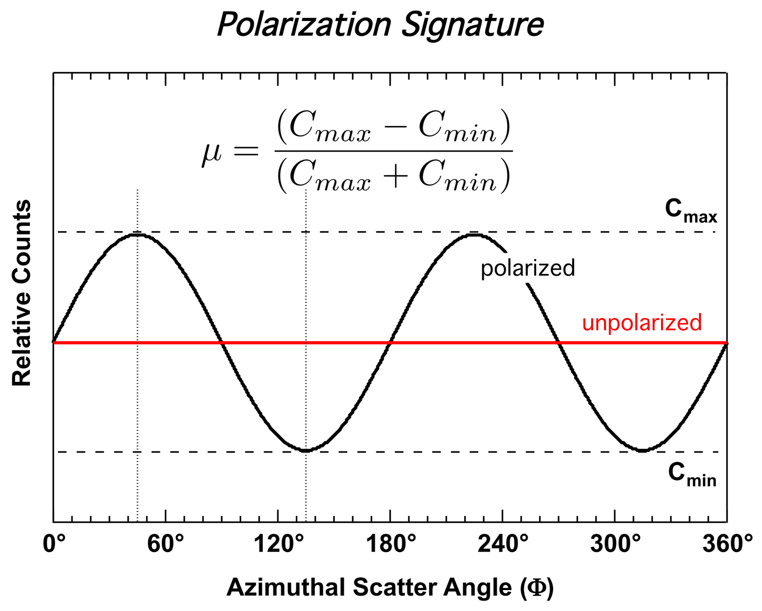
The Gamma Ray Polarimeter Experiment (GRAPE) is designed to investigate one of the most exotic phenomena in the universe – gamma-ray bursts (GRB). There has been intense observational and theoretical research in recent years, but research in this area has been largely focused on studies of time histories, spectra, and spatial distributions. Theoretical models show that a more complete understanding of the inner structure of GRBs, including the geometry and physical processes close to the central engine, requires the exploitation of gamma-ray polarimetry. Over the past several years, we have developed the GRAPE instrument to measure the polarization of gamma-rays from GRBs over the energy range of 50 to 500 keV. Our experience with two balloon flights (in 2011 and 2014), coupled with further design efforts focused on orbital payloads, has led to an improved polarimeter concept. The new concept employs a large number of small (~1 cm), optically-isolated scintillator cubes, each of which is read out by its own silicon photomultiplier (SiPM). These cubes are stacked in a three-dimensional arrangement that allows the determination of event interaction locations in three dimensions within the sensitive volume. The resulting three-dimensional location data provides a moderate level of Compton imaging capability (1 sigma angular resolution of 10-15°). Imaging can be used to significantly reduce the instrumental background by limiting the influence of the cosmic diffuse flux, resulting in an improved polarization sensitivity. A prototype balloon flight of this design will be conducted in either 2020 or 2021 from Palestine, TX.

Compton Polarimetry

In Compton scattering, the incident photon tends to scatter at right angles to the incident electric field vector. For a an unpolarized flux of Compton scattered photons, the distribution of the azimuthal scatter angles (the scatter angle distribution in the plane of the detector) will be uniform. For a polarized flux of Compton scattered photons, the distribution of azimuthal scatter angles will be non-uniform and be sinusoidally distributed. This polarization signature can be used to determine the fractional polarization and the polarization angle of the incident flux. The energy-dependent *modulation factor* (μ) characterizes the polarization signature and can be used to estimate the *minimum detectable polarization* (MDP). This represents the minimum level of polarization that can be detected

Polarization Signature



At the 99% confidence level, the MDP associated with an observation is given by,

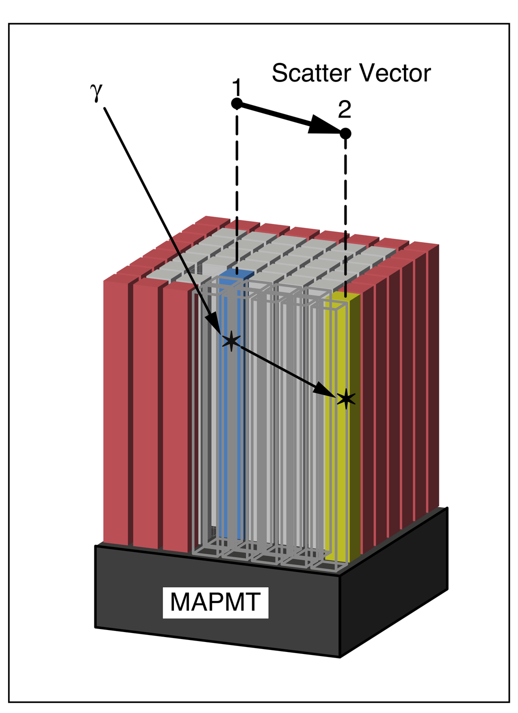
$$MDP = \frac{4.29}{\mu_{100}\, C_{src}}\sqrt{C_{src} + C_{bgd}}$$

where μ_{100} is the modulation factor corresponding to fully polarized radiation, C_{src} is the total number of source counts during the observation time interval, and C_{bgd} is the total number of background counts during the observation time interval.

Evolution of GRAPE

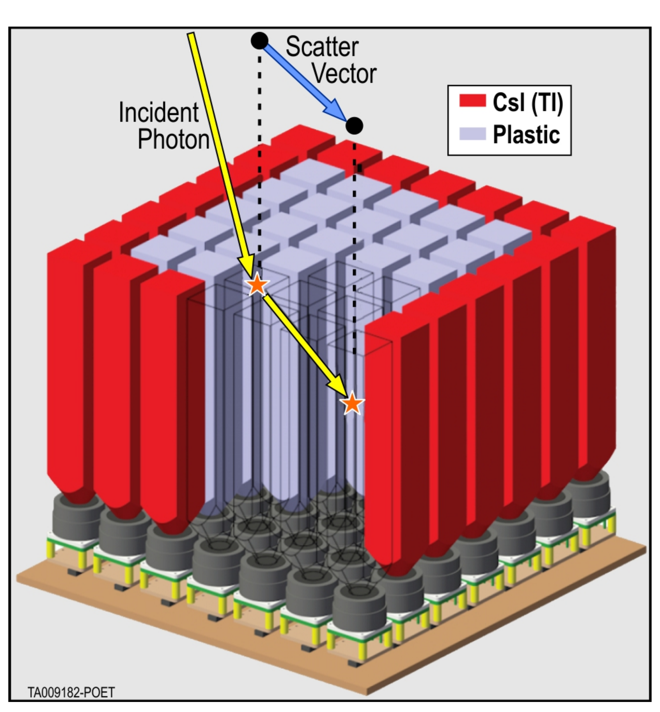
The original version of GRAPE placed an array of scintillator elements on a single MAPMT. A later version considered an array of (larger) scintillator elements with individual PMT readout. The current version (under development) is a cubic array of small scintillator elements with individual SiPM readouts. The latest version is designed to eliminate crosstalk issues and provide 3d locations. In each case, the combination of high-Z and low-Z scintillator optimizes the design for low energy Compton scatters with complete energy absorption.

2011



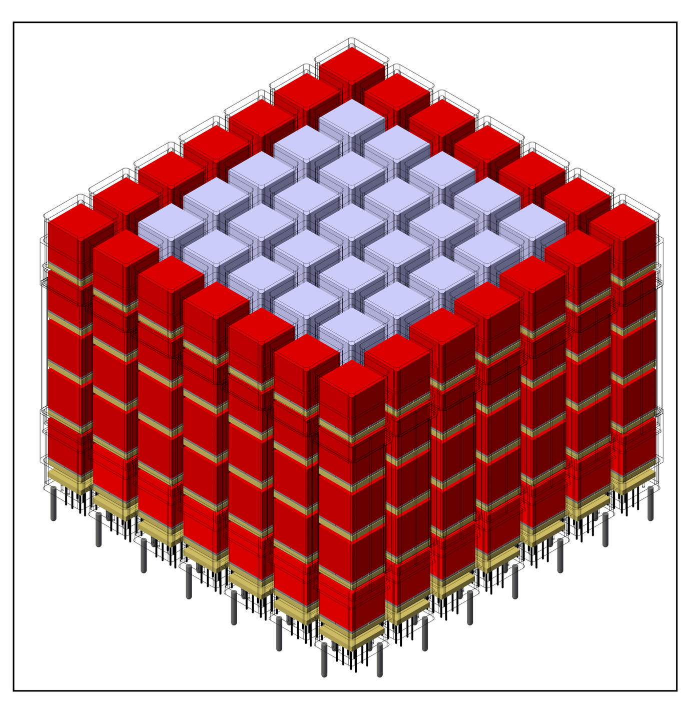
GRAPE Balloon
64 elements (8x8)
5 mm x 5 mm x 50 mm
single MAPMT

2014



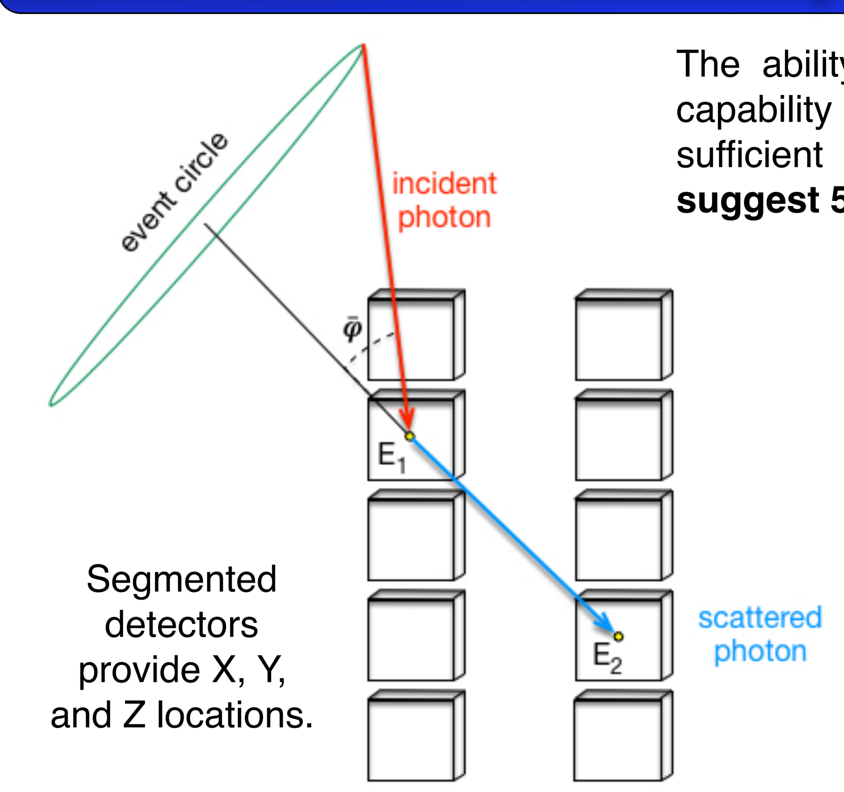
GRAPE SMEX
49 elements (7x7)
17 mm x 17 mm x 100 mm
49 PMTs

2018



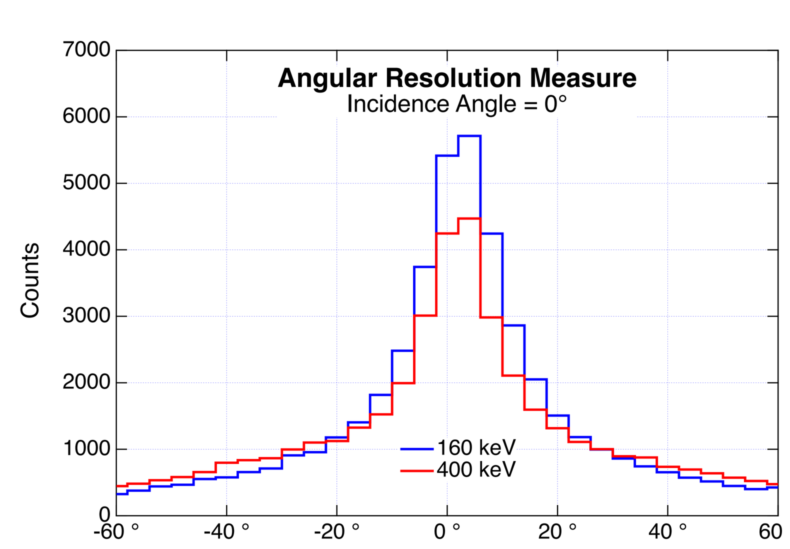
NG-GRAPE
245 elements (7x7x5)
12.5 mm x 12.5 mm x 12.5 mm
245 SiPMs

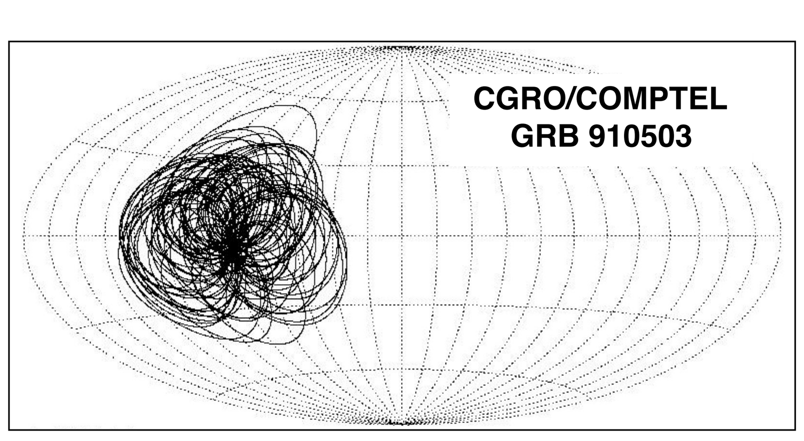
Compton Imaging

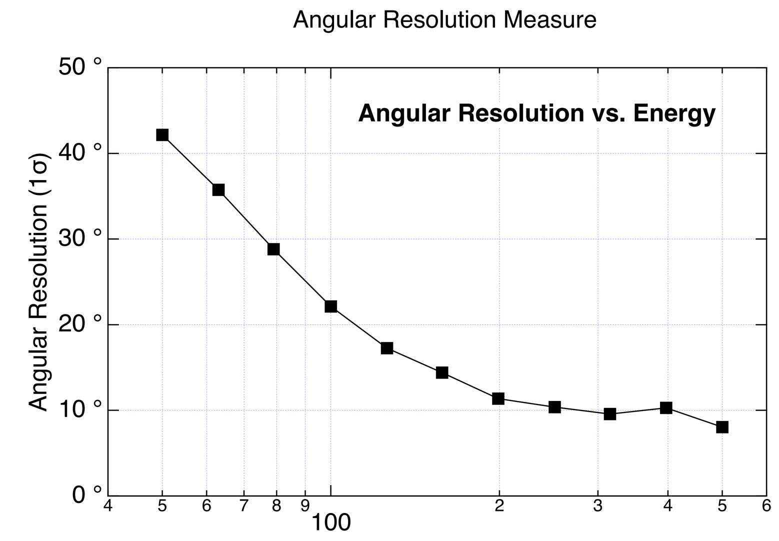


Segmented detectors provide X, Y, and Z locations.

The ability to measure 3d locations for each interaction provides the capability of doing Compton imaging. The limited angular resolution is sufficient to reduce a large fraction of the background. **Estimates suggest 5x improvement in sensitivity for GRBs.**

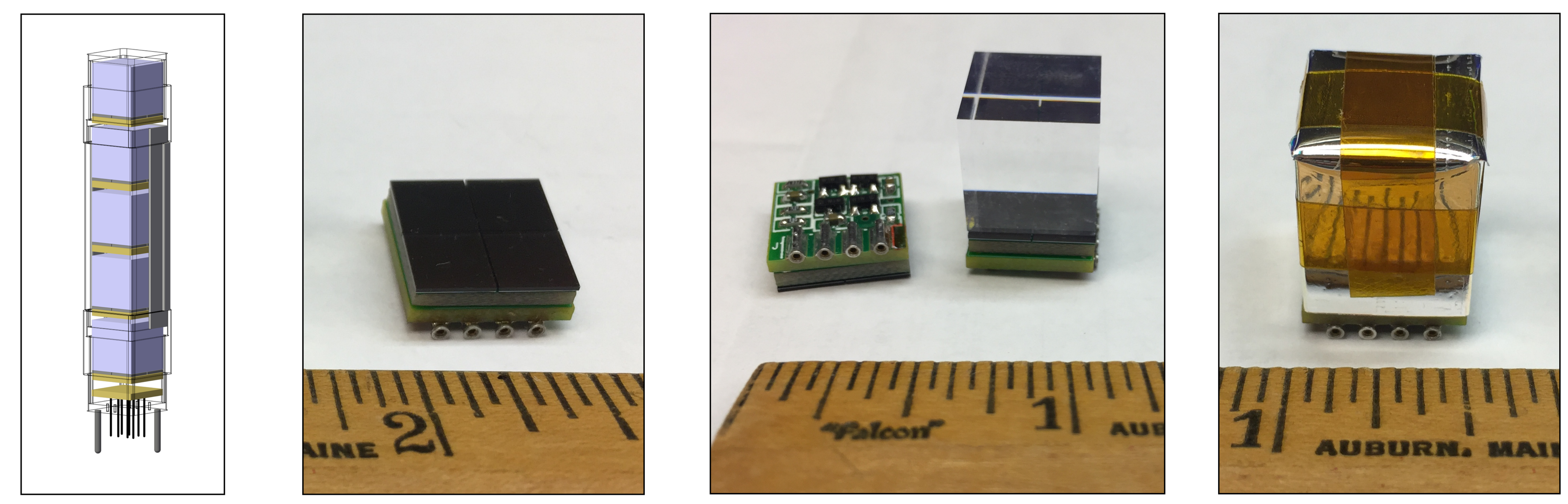


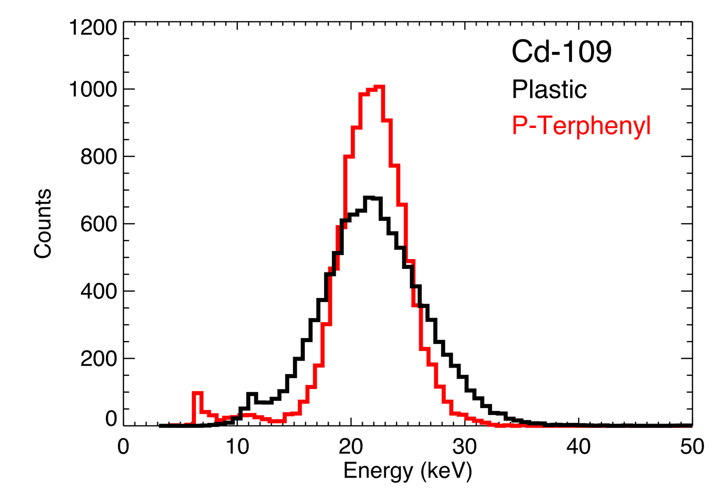




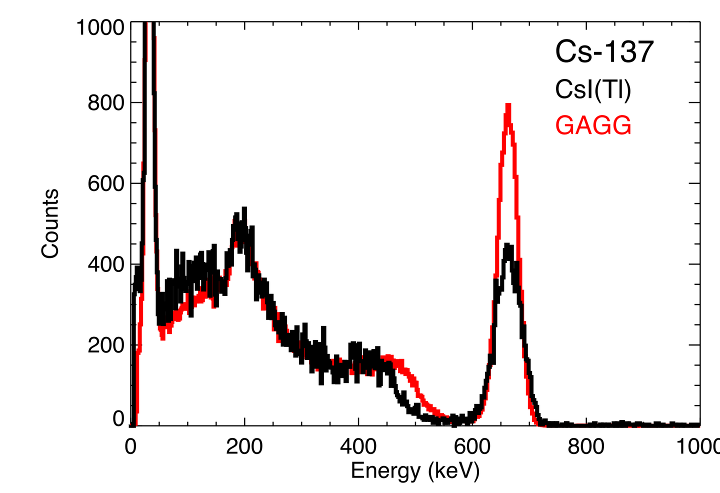
Scintillator Elements

Lab measurements with a variety of low-Z and high-Z scintillators demonstrate the performance of a single scintillator cell. All scintillators shown here are non-hygroscopic to facilitate instrument assembly. The 12.5 mm size of each scintillator element is chosen to match the size of a Sens-L J-series 2x2 SiPM array.



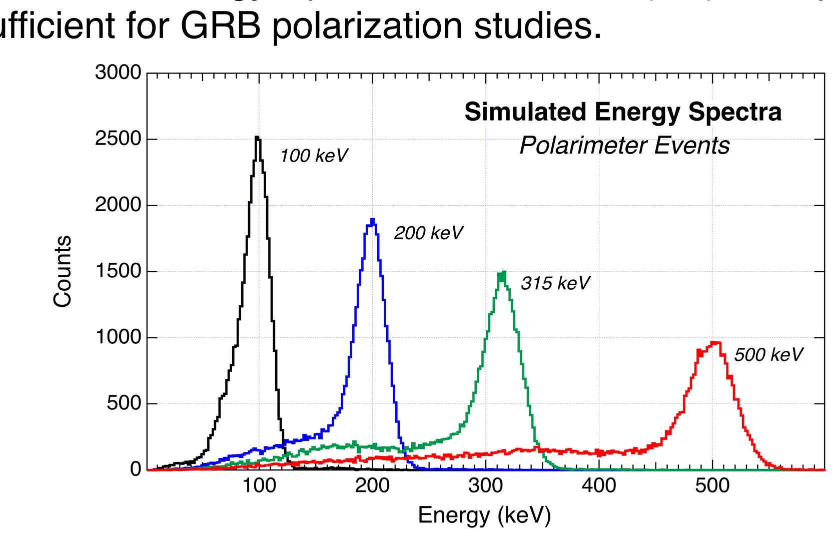


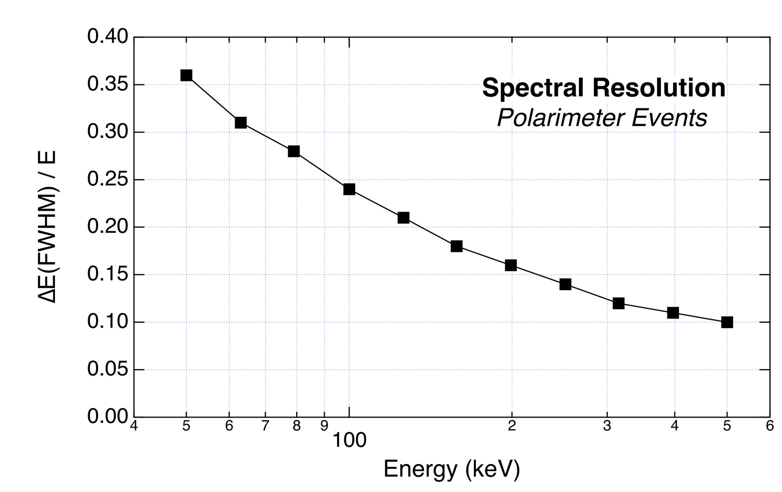
plastic threshold ~11 keV
P-Terphenyl threshold ~7 keV



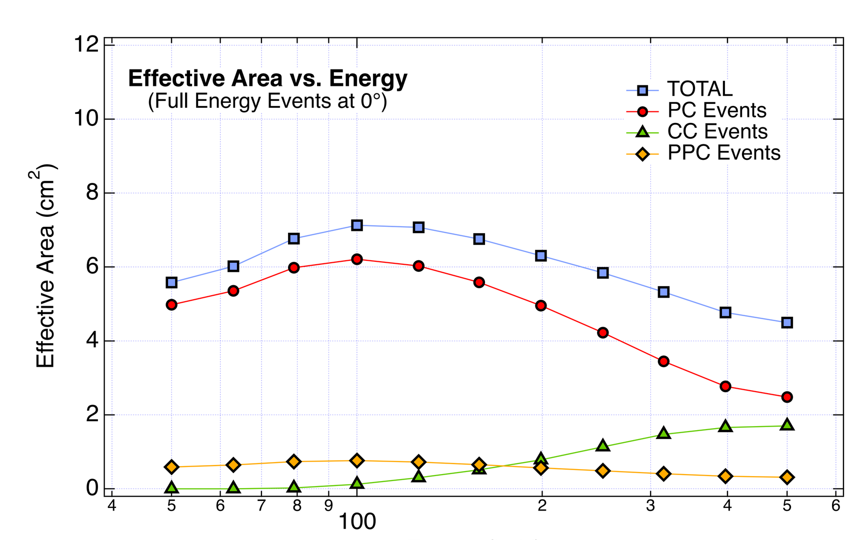
thresholds < 20 keV

Simulated energy spectra for two-site (PC) Compton events illustrate a moderate level of angular resolution, sufficient for GRB polarization studies.



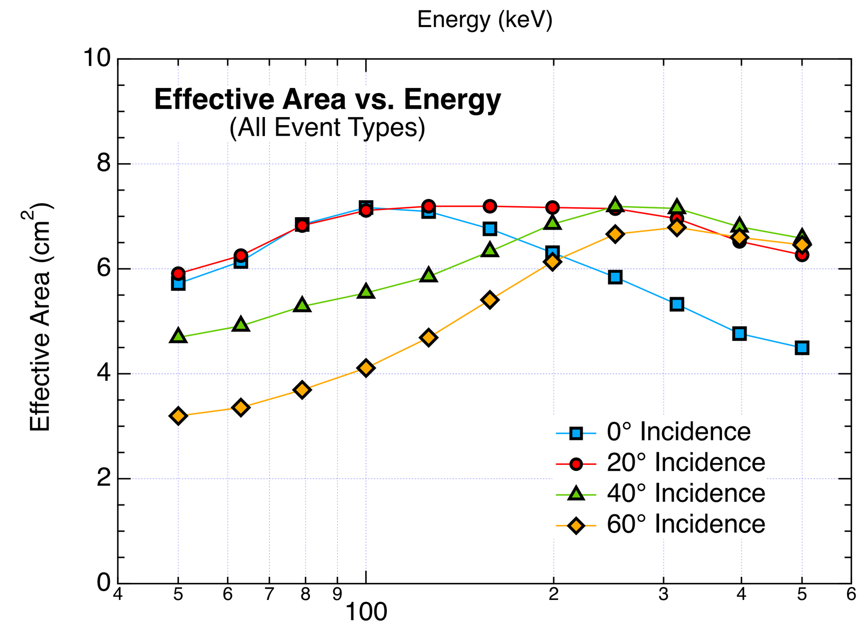


Simulated Response



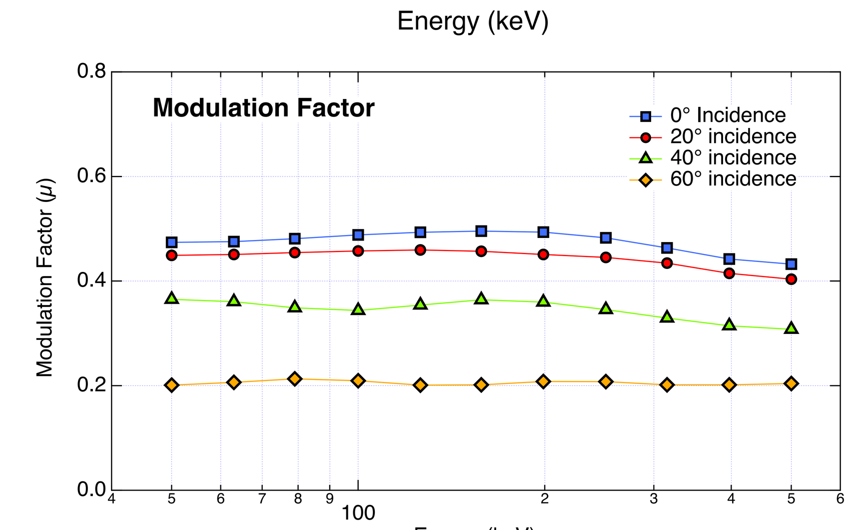
Effective area vs. energy for various event types at 0° incidence.

Valid polarimeter events come in various types
PC - Plastic / Calorimeter
CC - Calorimeter / Calorimeter
PC - Plastic / Plastic / Calorimeter
PC events dominate. CC events can be important at energies ≥ 200 keV.



Effective area vs. energy for all event types at various incidence angles.

At larger incidence angles, there is larger efficiency at high energies (due to the larger contribution of CC events). Best response occurs around 20° off-axis.



The modulation factor is an important figure-of-merit that plays a significant role in the polarization sensitivity.

This design exhibits very good response out to at least 20-30° off-axis, with significant response out to at least 60°.

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