A Combined Compton and Coded Mask Telescope for Gamma-Ray Astrophysics

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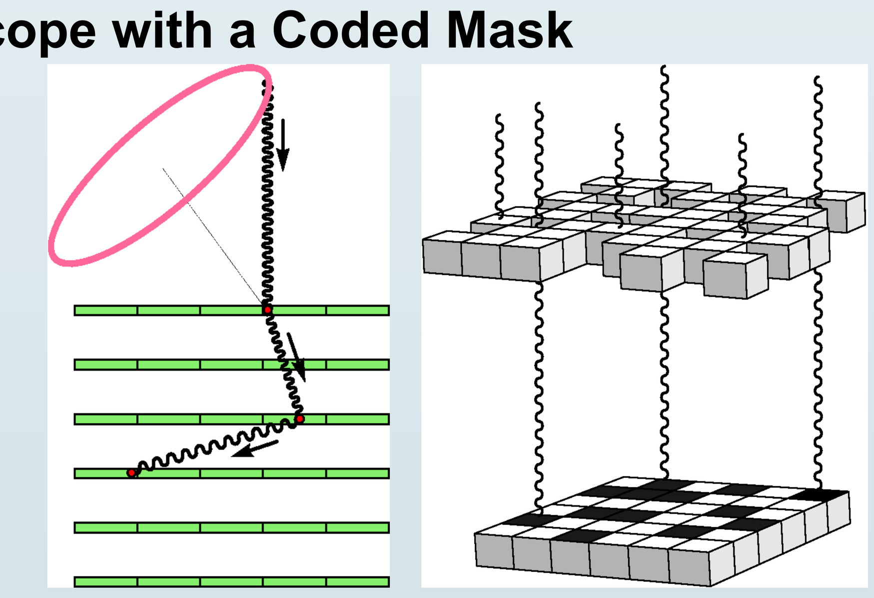
Motivation

Several factors need to be considered in the design of a next generation telescope for medium-energy gamma-ray astrophysics. A future instrument requires a good angular resolution in order to resolve and accurately locate potential point sources while remaining sensitive to diffuse emission. It needs a good energy resolution for resolving the shape of nuclear lines. In addition, in order to achieve a high sensitivity it should also have a large effective area and good background rejection capabilities. These requirements can be achieved by combining a Compton telescope with a coded mask. Here we describe a combined Compton and coded mask instrument which utilizes a Silicon detector array as a gamma-ray tracker and large volume cadmium zinc telluride (CdZnTe) detectors with good energy resolution (< 1.5% FWHM at 662 keV) as absorbers.

Combining a Compton Telescope with a Coded Mask

Mating a Compton telescope with a narrow field-of-view coded mask combines the advantages of both telescopes:

- The Compton telescope brings good background rejection and thus high sensitivity.
- The coded mask provides the high angular resolution albeit at the cost of ~50% of the event rate in the field-of-view of the mask.
- Since the narrow field-of-view coded mask only obscures a small part of the sky, the Compton telescope can observe the rest of the sky in normal Compton mode with reduced angular resolution. Many science targets (such as diffuse line emission, AGNs, pulsars) only require a moderate angular resolution.



Left: Event reconstruction using Compton interactions. Right: Coded mask reconstruction uses the shadow from photo-absorbed photons in the mask to reconstruct the source position.

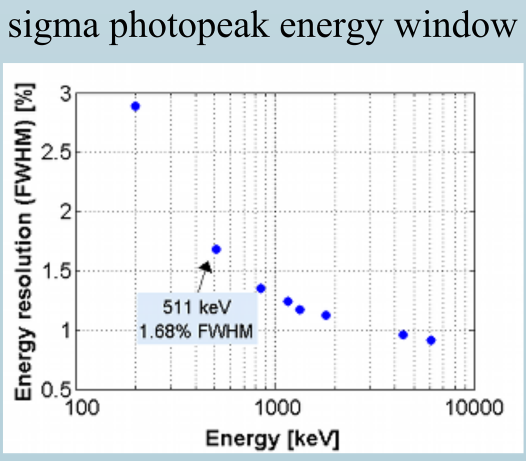
Simulations and Data Analysis

The data analysis including event and image reconstruction for the telescope were performed using the MEGAlib [1] software package. Simulations were performed using Cosima, a Geant4-based Monte Carlo package in MEGAlib. A series of monoenergetic line sources from 200 keV to 6.1 MeV were simulated, as well as a 511 keV broadened source (sigma of 1.25 keV from Jean, et al. [2]) at various incident angles and a Crab-like continuum source. Images were reconstructed using Mimrec.[3]

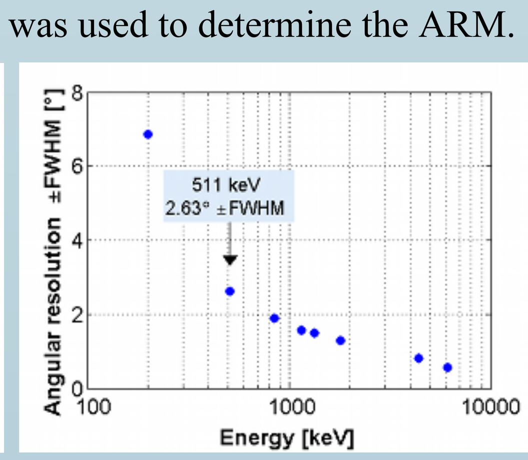
Energy Resolution and Angular Resolution

The simulated performance parameters for CdZnTe detectors were based on an energy resolution of 1.5% FWHM at 662 keV. The silicon detectors were assumed to have an energy resolution of 2.4 keV FWHM at 59.5 keV. The simulated photopeak energy resolution for the telescope is shown below.

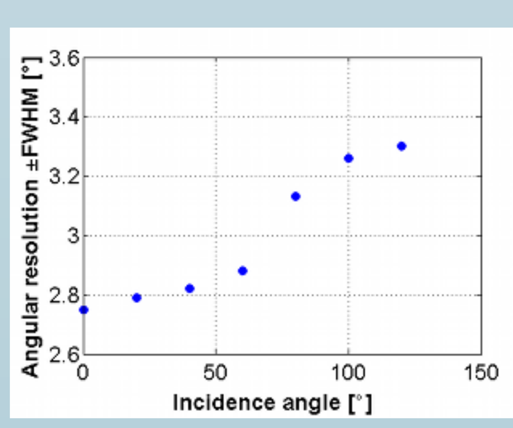
For Compton events, the angular resolution measurement (ARM) is defined as the distance between the known source position and the closest reconstructed position on the Compton cone (i.e. the ARM is the width of the Compton cone). It is a function of energy resolution, position resolution, and Doppler broadening. The position resolution is determined by the 0.5 mm strip pitch of the silicon detectors and the 1 cubic centimeter voxel size of the CZT detectors. For the plots shown below, a 3 sigma photopeak energy window was used to determine the ARM.



Simulated photo-peak energy resolution for the telescope.



Angular resolution measurement +/- FWHM as a function of energy for on-axis monoenergetic line sources.



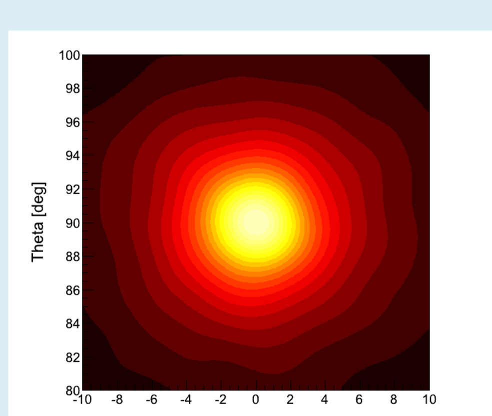
Angular resolution measurement +/- FWHM as a function of zenith angle for a broadened 511 keV source.

Resolving Point Sources with Compton-Coded Mask Imaging

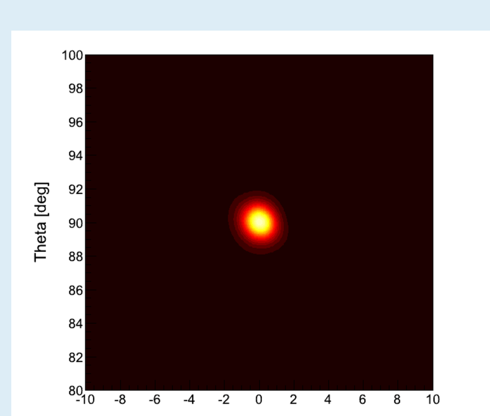
The images to the right were reconstructed from simulations of two 511-keV point sources separated by 0.2 degrees.

The top two images show a Compton-only reconstruction before and after deconvolution. Clearly those two sources are not separable. The image reconstruction in the bottom two images takes into account the absorption probabilities of the initial photons through the coded mask. The image before the deconvolution shows some additional "noise" which is actually the overlapping coded-mask patterns superimposed onto the Compton cones. However, the list-mode likelihood deconvolved image clearly shows that the two sources can be separated (note that the scales shift from ±10 deg to ±1 deg).

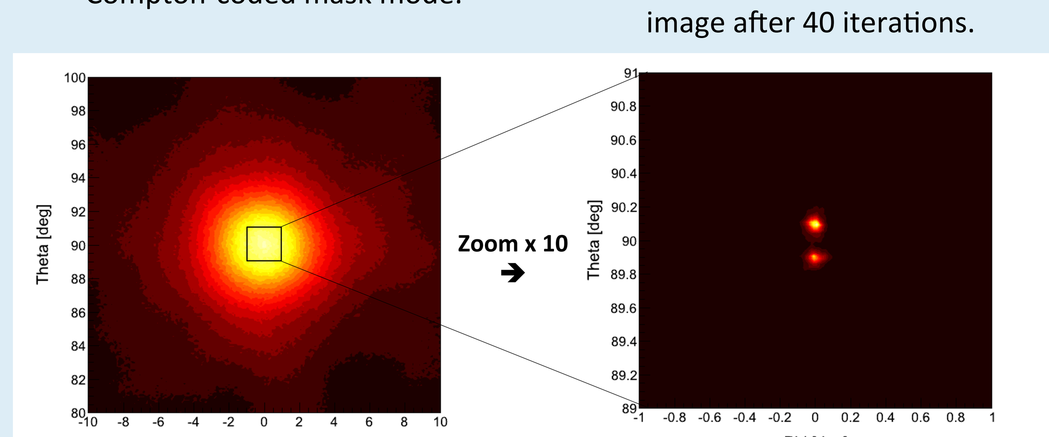
Imaging of two 511 keV point sources separated by 0.2 degrees



Above: Back projection using Compton mode only. Below: Back projection using a combined Compton-coded mask mode.

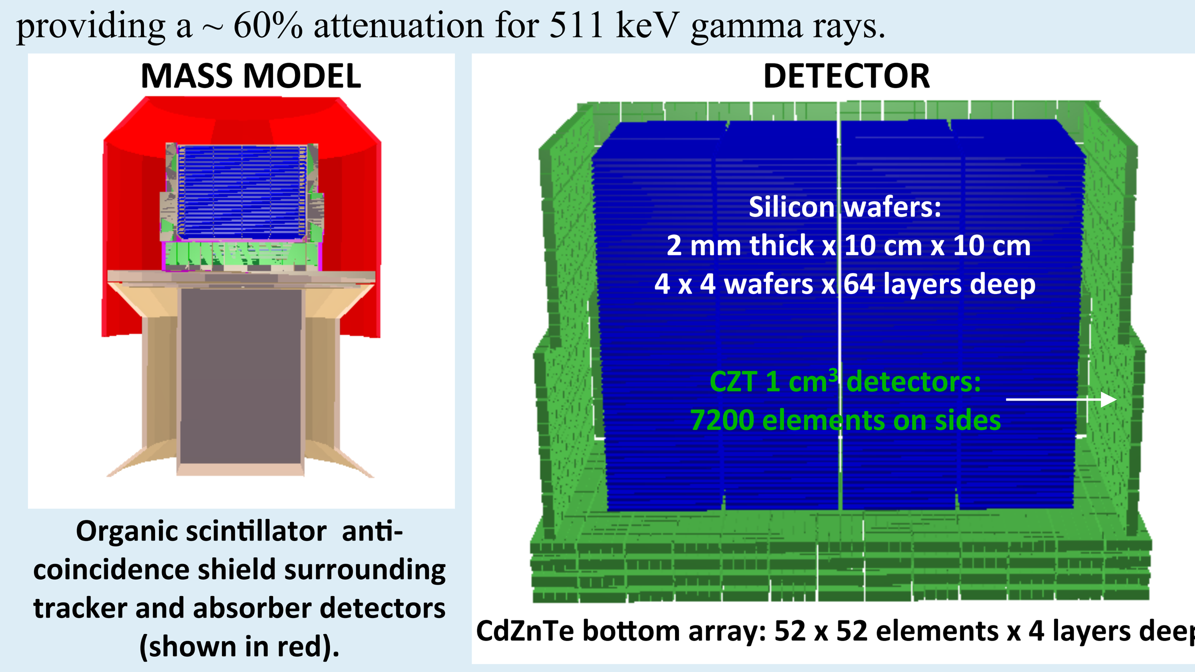


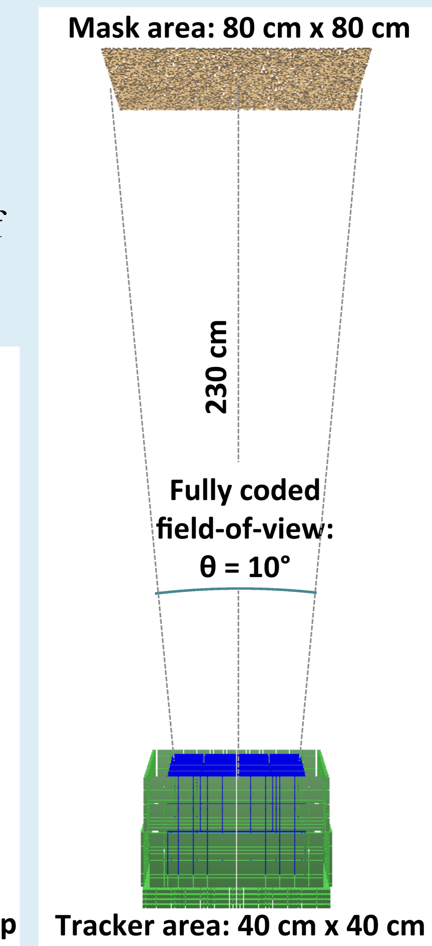
Above: Deconvolved image in Compton mode only after 40 iterations. Below: Combined Compton and coded mask mode image after 40 iterations.



The Simulated Instrument

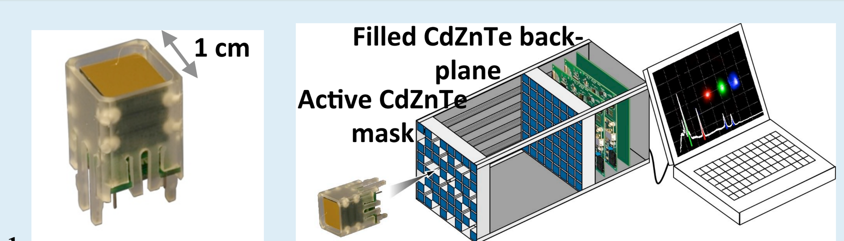
The mass model consists of 4 elements: a silicon tracker in which the first Compton interaction takes place, a CdZnTe absorber surrounding the tracker, an organic scintillator used as an anti-coincidence shield for charged particles, and a coded mask above the tracker. The mask consists of 0.5 cubic centimeter tungsten pixels in a 160 x 160 random mask pattern, providing a ~ 60% attenuation for 511 keV gamma rays.



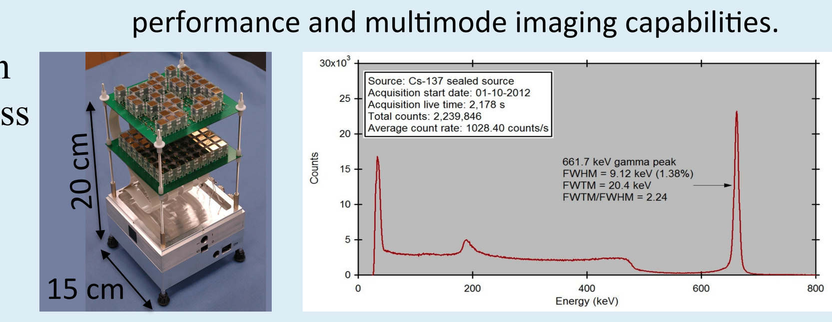


CdZnTe Detector Development

The CdZnTe detectors are commercially produced large volume coplanar-grid detectors that utilize ASIC based (minimal) electronics with low power consumption.[4] They were developed for a combined Compton and (active) coded mask prototype instrument, the High Efficiency Multimode Imager (HEMI).[5] The measured spectral energy resolution of some of the best of these detectors is currently less than 1.5% FWHM at 662 keV. Because CdZnTe operates at ambient temperature, passive material surrounding the detectors is minimal, subsequently reducing background events.



Top left: CdZnTe detector element. Top right: The HEMI instrument concept used to demonstrate CdZnTe performance and multimode imaging capabilities.

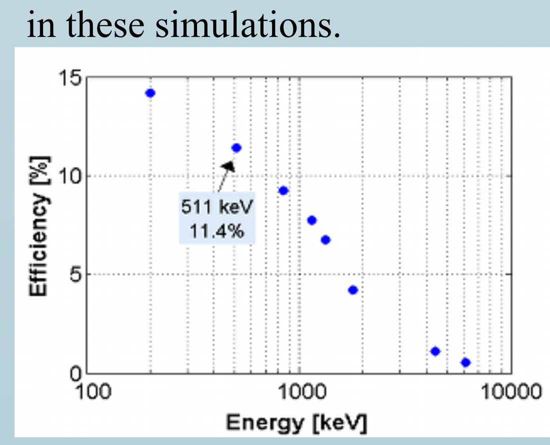


Left: The ~100 detector HEMI prototype instrument. Right: Measured energy resolution of a high performance CdZnTe detector.

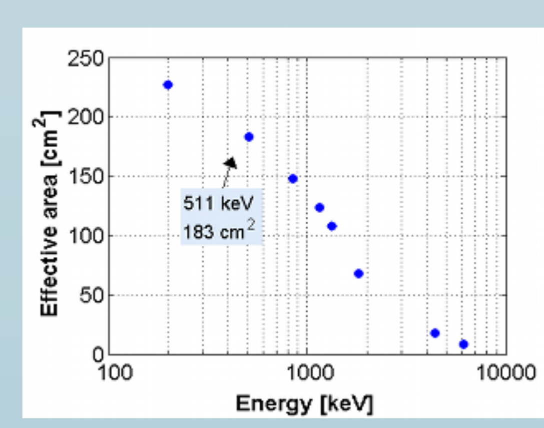
Efficiency and Effective Area for Untracked Compton Events

The effective area (A_{eff}) is the detection area that is reduced from the actual geometric area (A_{geo}) due to the detection efficiency and the event cuts required for Compton reconstruction. No mask was included in these simulations.

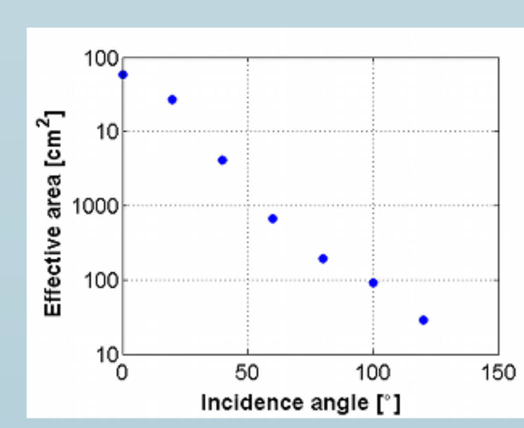
$$A_{eff}(E, \theta, \varphi) = A_{geo}\,\frac{N_{detected\ photons}}{N_{incident\ photons}}$$



Detection efficiency as a function of energy for the telescope without mask.



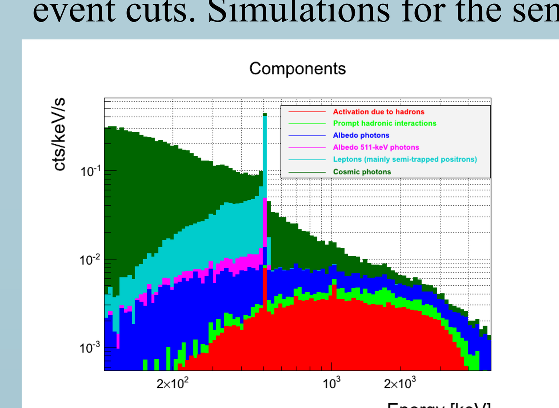
Effective Area as a function of energy for monoenergetic narrow line sources.



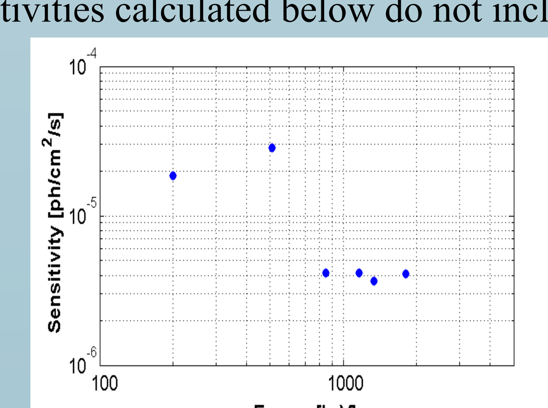
Effective Area for a broadened 511 keV source as a function of incidence angle.

Sensitivity

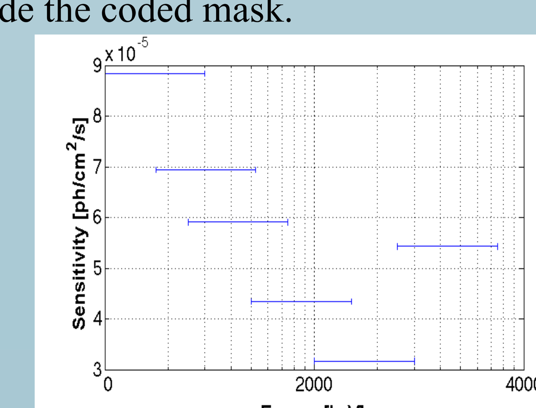
The telescope sensitivity is a description of the minimum flux which can be measured by the instrument within a given significance above background. Shown below are calculated sensitivities with optimized event cuts. Simulations for the sensitivities calculated below do not include the coded mask.



Reconstructed background after sensitivity optimized event cuts for a 575 km orbit with a 6° inclination.



Sensitivity as a function of energy for monoenergetic narrow line sources. Observation time is 1 megasecond.



Continuum sensitivity for a simulated Crab-like source (power law index of 2) using a 1 megasecond observation time.

The all-sky sensitivity of a 511 keV broadened line source is 3.6×10^{-6} ph/cm²/s for a 2 year observation time.

Conclusions

We have demonstrated that combining a coded mask with a Compton imager improves point source localization for positron detection. With a silicon tracker and a CdZnTe calorimeter, an all-sky sensitivity of 3.6×10^{-6} ph/cm²/s for a 2 year observation of 511 keV gamma-rays can be achieved.

References

[1] Zoglauer, et al., NewAR 50, 2006
[2] Jean et al., A&A 407, 2003
[3] Zoglauer, et al., NIMA 652, 2011
[4] P. N. Luke, et al., IEEE Trans. Nucl.Sci. 42, 1995
[5] M. Amman, et al., NSS 2009

Acknowledgements

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With questions, please contact Michelle Galloway : shell@ssl.berkeley.edu