Simulation of a Compton Telescope with a Liquid Xenon TPC

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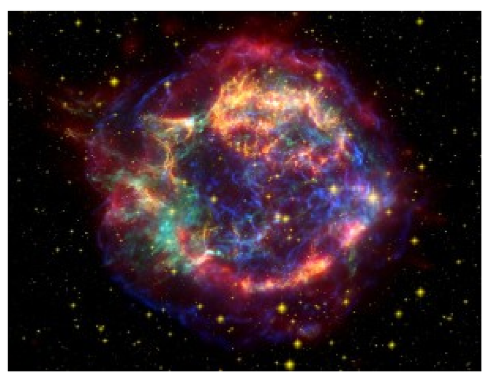
Motivation

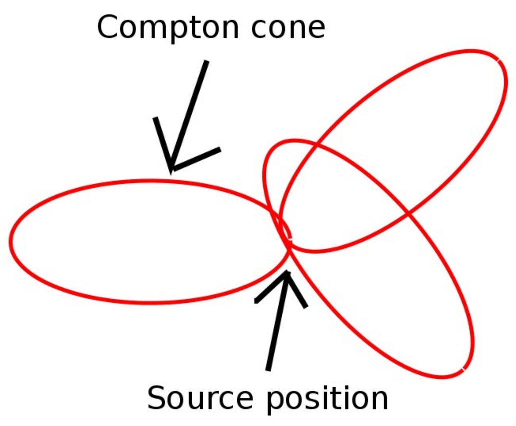

[1]

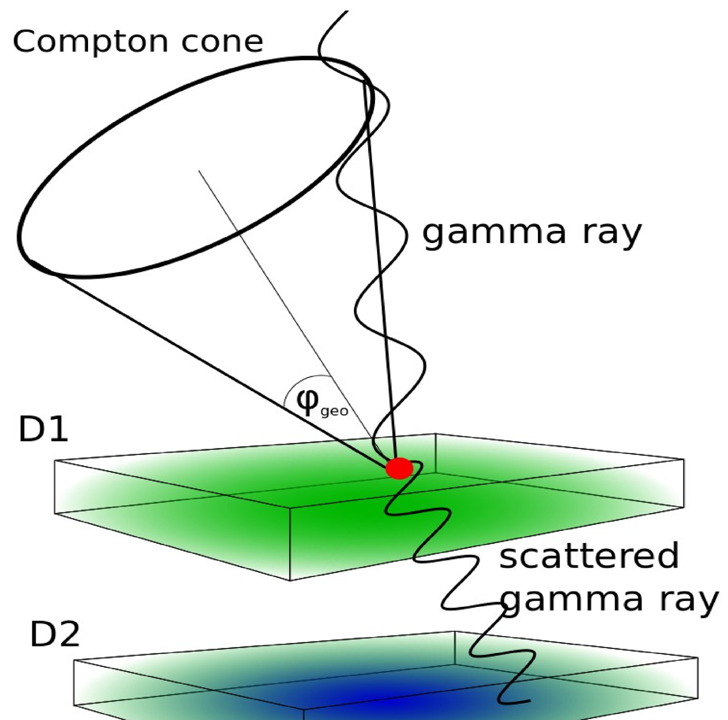
MeV gamma-ray astrophysics provides a little explored window into an energy regime which promises a multitude of new insights. It comprises gamma-ray bursts, MeV blazars, or extragalactic background radiation in the continuum, and it is the energy regime of positron annihilation and nuclear transitions. Gamma-ray lines from isotopes such as ^{56}Ni, ^{44}Ti, ^{26}Al or ^{60}Fe can provide unique insights into, e.g., the inner workings of supernova explosions and ongoing nucleosynthesis. Compton scattering is the dominant interaction in this energy range, making a Compton telescope the most promising detector principle. Here we present a Monte Carlo study of a combination of PVT as scatter detector and a liquid xenon TPC as position-sensitive calorimeter.

Direction reconstruction with Compton formula:

$$\cos(\bar{\varphi}) = 1 - m_e c^2 \left(\frac{1}{E_{after}} - \frac{1}{E_{before}}\right)$$

- Events are several hits, that have to be reconstructed
- With several photons of the same source, its position can be determined



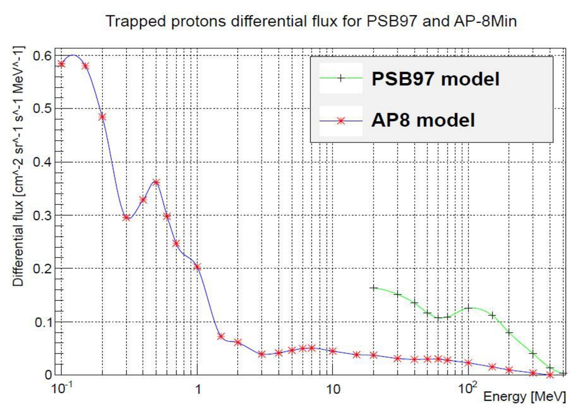


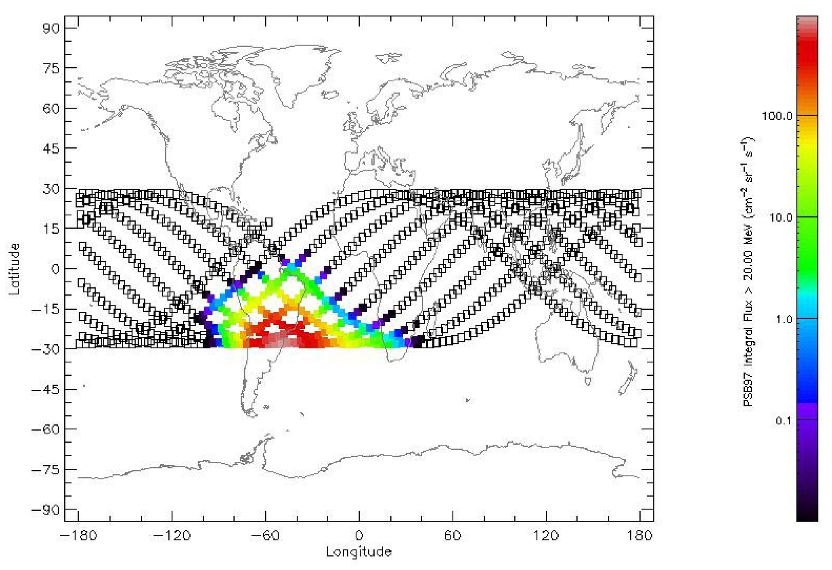
D1:
1.) Detector in which the incident Compton scattering should happen and will be measured
2.) Needed low Z material with good position and energy resolution
3.) possible candidates plastic scintillators, silicon

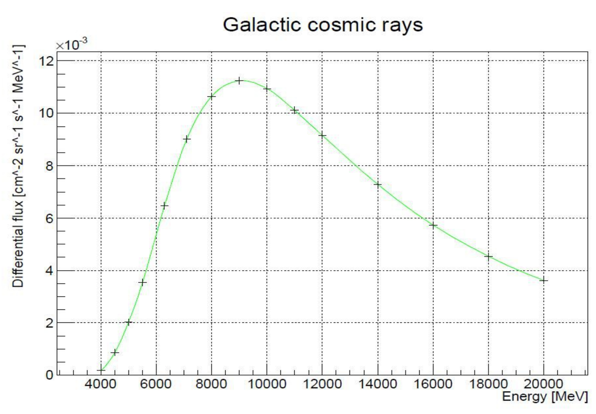
D2:
1.) Position sensitive detector to stop the gamma energy and measure its total energy
2.) Needed: high Z and density, good position and energy resolution
3.) liquid Xenon

Backgrounds (Input Spectra)

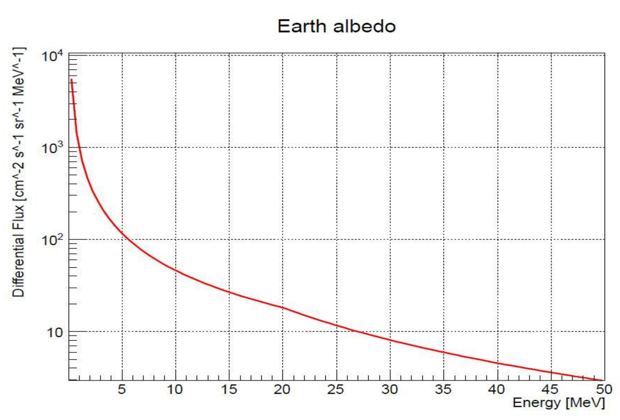
Proton backgrounds:
For a LEO 500km altitude and inclination of 28°
Models provided by SPENVIS [2]
- Trapped protons: trapped by Earth's magnetic field used model PSB97
- Solar protons: emitted during solar flares
- Galactic cosmic rays: emitted by SNs used model ISO15390
→ used for activation simulation







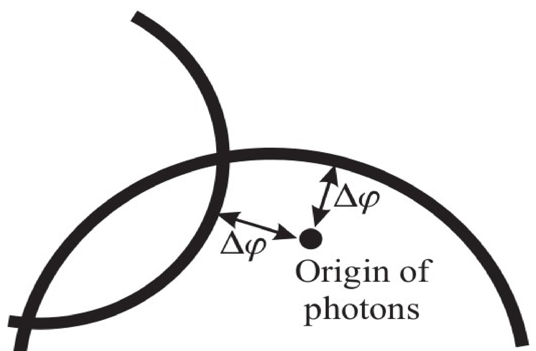
Gamma ray backgrounds:
- Diffuse gamma-ray background
- Earth albedo
- Activation induced gamma rays



Performance Parameters

The following parameters are used to characterize a Compton telescope:
- Angular resolution measure (ARM):

$$ARM = \varphi_{geo} - \bar{\varphi}$$



- Energy resolution
- Field-of-view (FOV)
- Sensitivity describes the minimal detectable flux for:
  - Line
  - Continuum
  - Point source
  - Diffuse

$$f = \frac{n^2}{2 A_{eff} t_{obs}} \left(1 + \sqrt{\left(1 + 4b \frac{t_{obs}}{n^2}\right)}\right)$$

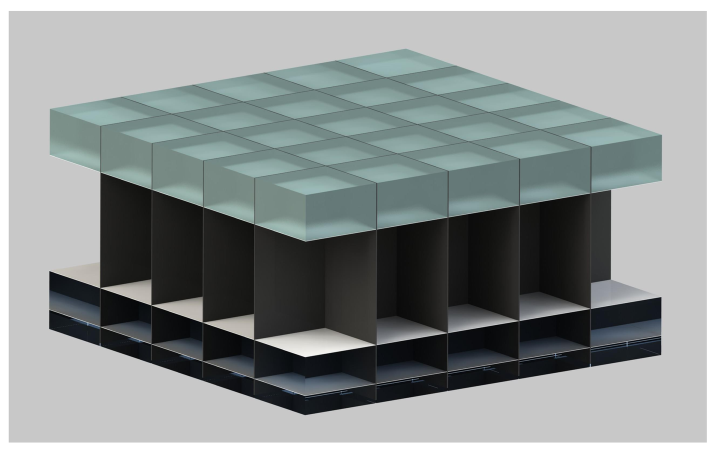
Background rate b; Observation time t_{obs}; Effective area A_{eff};
Number of standard deviations n

Monte Carlo Simulation Framework

Simulations are done with Geant4 [3] and MEGAlib [4]. The geometry used in these simulations consists of 5×5 modules of 22 ×22 cm² size. Each inherits a D1 detector (12cm Polyvinyltoluene (PVT)), a D2 detector (10cm LXe) and a veto (5cm LXe) with readout. Between D1 and D2 is a gap of 30cm.

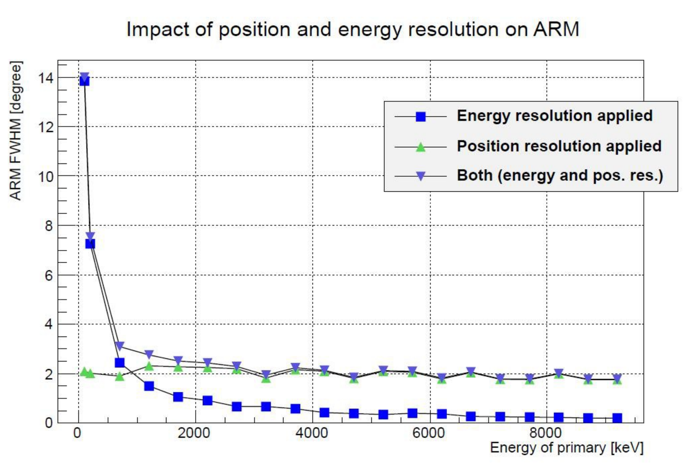
D1:
Position resolution 0.29cm
Energy resolution $\sigma(E) = 3.48\% \sqrt{(E/\mathrm{MeV})}\,\mathrm{MeV}$ [5]

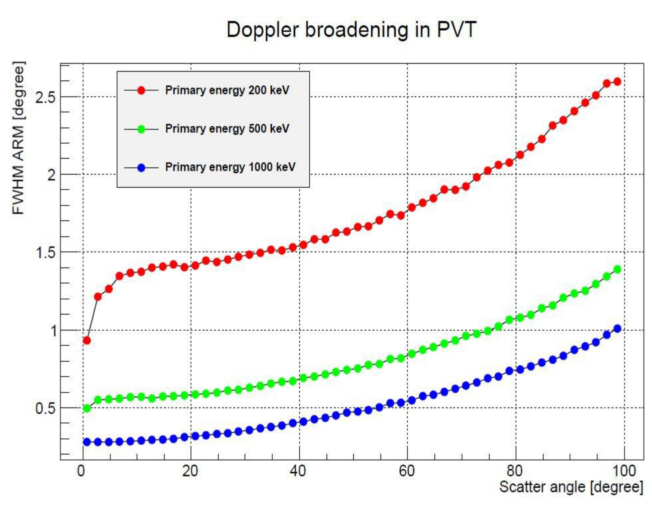
D2:
Position resolution in x-y 0.25mm; in z 0.1mm
Energy resolution $\sigma(E) = 1.9\% \sqrt{(E/\mathrm{MeV})}\,\mathrm{MeV}$ [6]



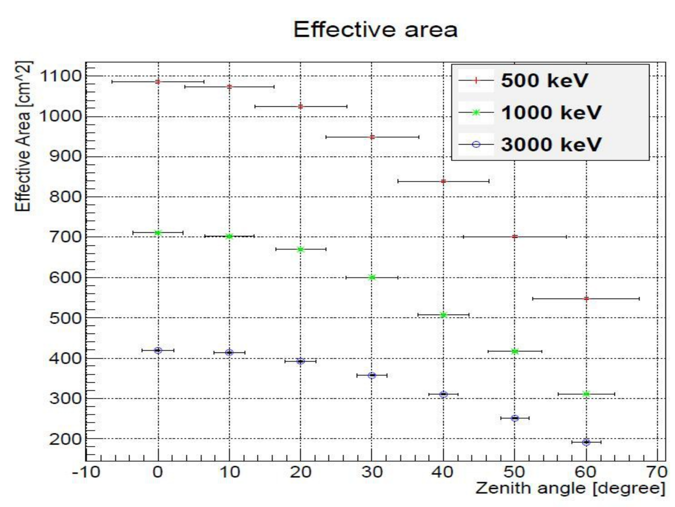
Monte Carlo Simulation Results

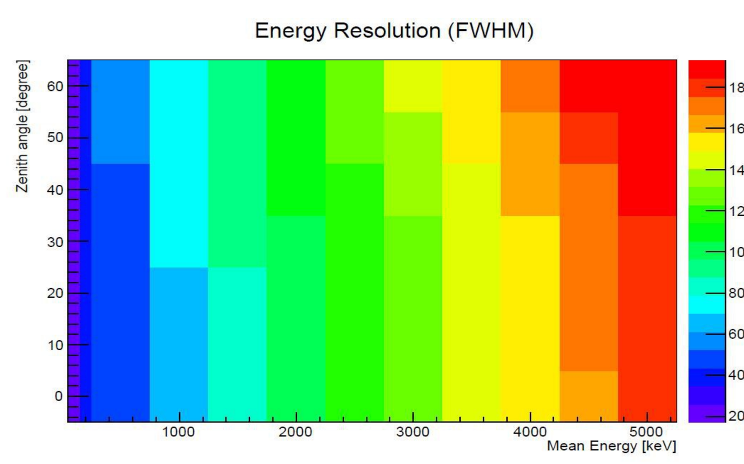
Measured positions + source position → φ_{geo}
Energy resolution + Doppler broadening + missing energy → $\bar{\varphi}$

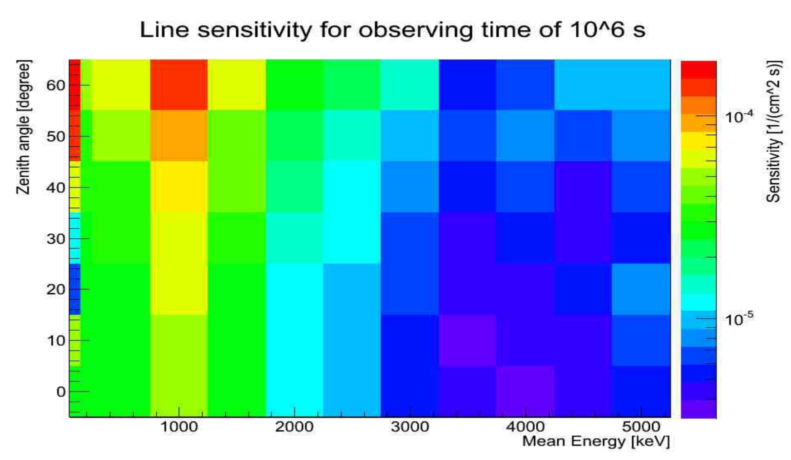


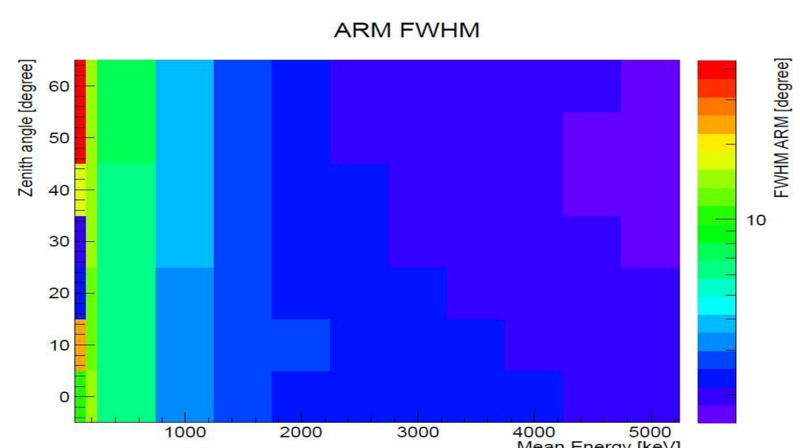


ARMs main contribution for high energies is the position resolution. For higher scatter angles increases the Doppler broadening.









Preliminary conclusions:
Only moderate sensitivity with PVT as D1, due to energy and position resolution.
Ongoing work: Effect of silicon or LXe D1 detectors.

References:
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[3] S. Agostinelli et al., Nucl. Instrum. Meth. A 506:250-303 (2003)
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[6] E. Aprile et al., Astrop. Phys. 35:573-590 (2012)