PROCEEDINGS OF SCIENCE

Detector Simulation Studies for the Proposed Gamma Ray and AntiMatter Survey (GRAMS)

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GRAMS is a proposed balloon and satellite-borne gamma ray and antimatter detector aimed at exploring the MeV energy bandgap as well as indirectly detecting dark matter. This study addresses the MeV detection capabilities of GRAMS via truth-level GEANT4 simulations, as a function of detector geometry and response. In particular, we examine Compton scattering as the vehicle for point source detection. As a first study, we applied the simple backprojection algorithm of Compton cameras to accurately reconstruct point source location and energy and examined the all-sky angular resolution of GRAMS, using truth-level detector information. We also calculated the point source sensitivity against a power-law isotropic background spectrum as observed by COMPTEL.

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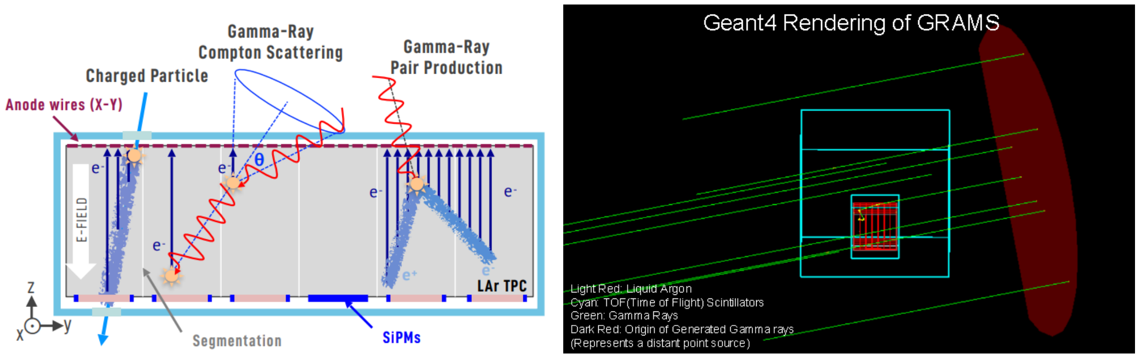
1. Introduction



(a) **(b)**

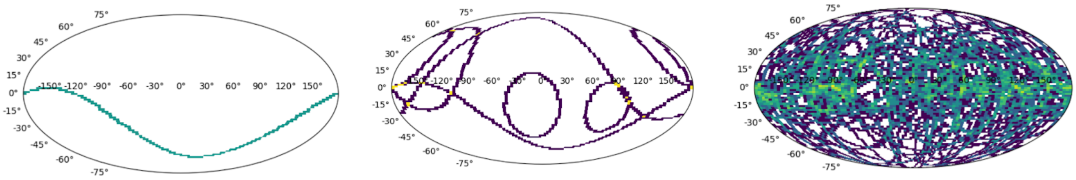
Figure 1: GRAMS detector concept. (a) Detection of MeV gamma rays and charged particles in the GRAMS LArTPC. (b) GEANT4 rendering of GRAMS, using the alternate 'cubic' design, showing gamma rays being produced from a disk surface which illuminates the entire detector.

GRAMS (Gamma Ray and Antimatter Survey) is a proposed balloon/satellite-borne experiment aimed at illuminating the MeV energy band as well as serving as an indirect dark matter search instrument. Using a liquid argon time projection chamber (LArTPC), GRAMS can record the energy deposits and the location of a series of Compton scatters in order to reconstruct the energy and direction of incoming gamma rays, which in turn enables reconstruction of the energy spectrum and location of the original MeV source (see Sec. 2).

LArTPCs work by drifting charged particles into a collection plane via an electric field (see Fig. 1a). The deposited charge on the collection plane is used to measure the x and y position as well as the energy of each interaction. In order to measure the z position, one must record the time difference between prompt scintillation light and the arrival of charge on the collection plane and use the drift velocity in liquid Argon to convert this time difference to a z coordinate.

The preliminary study reported in these proceedings investigates the detector response to MeV gamma rays at a variety of energies and source locations (see Fig. 1b). The results reported in these proceedings assume a cubic LArTPC geometry with dimensions of 70×70×80 cm^3; studies with additional varying detector geometries are in progress. The baseline design for GRAMS assumes a “flat” LArTPC detector geometry with dimensions of 140×140×20 cm^3.

2. MeV Gamma-Ray Source Reconstruction



(a) **(b)** **(c)**

Figure 2: MeV gamma-ray reconstruction via Compton scattering. (a) Projected Compton cone onto the full sky map indicating the likely position of a single reconstructed MeV gamma ray. (b) Projected Compton cones from several MeV gamma rays. (c) Projected Compton cones from many MeV gamma rays; the resulting heat map is interpreted as a probability distribution for the original MeV gamma-ray source location.

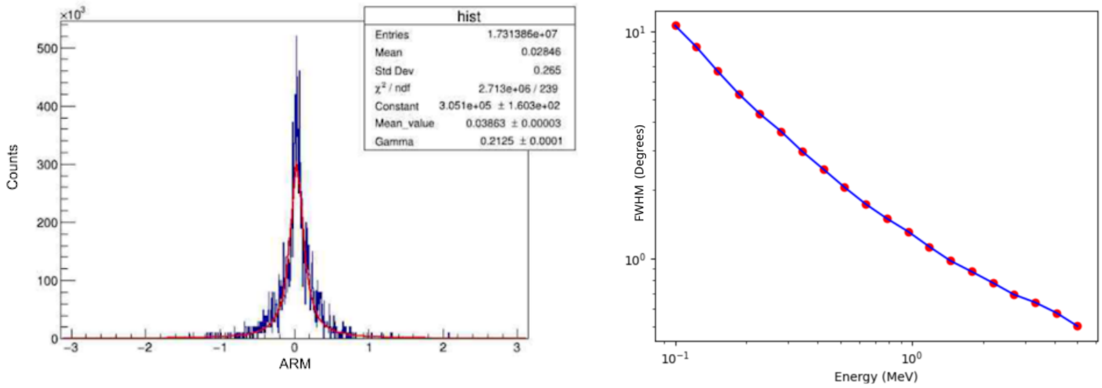
We can reconstruct the source location via detecting and correlating multiple Compton Cones using the backprojection algorithm. A Compton cone is defined by its principle axis (calculated via measuring the location of the first two Compton scatters) and the semi-angle of the cone (calculated via relativistic kinematics from energy deposits) [2]). Each ray along the surface of a Compton cone represents a potential candidate direction of an incoming gamma ray. By projecting these candidate directions on a sky map from many Compton cones, we can generate the so-called simple backprojection image. The source location can be inferred by the intersection of the Compton cones (see Fig. 2). While statistical methods, such as the Richardson-Lucy algorithm, are often used for quantitative image reconstruction, the backprojection algorithm is the gold standard for Compton Camera reconstruction and is the simplest to implement.

In addition to source location, source energy can be reconstructed by adding up the energy of all the energy deposits recorded in the LArTPC. For this study, we consider only events with at least two localized ionization energy depositions in the LArTPC (either from Compton scattering or from photoabsorption), where the first deposit is always required to be in the LArTPC. We further assume (optimistically) that the time ordering of the energy deposits is known. We make use of the true position of each deposit, as well as the true deposited ionization energy in the backprojection algorithm.

The above source and energy reconstruction is not perfect, since the incident gamma ray can often escape the detector, or can scatter in other parts of the GRAMS instrument before entering the active LArTPC volume. These types of events modify the predicted initial scattering angle and reconstructed energy. Although it is outside the scope of this study, event reconstruction methods which can also identify these escape events have been proposed (see algorithms using neural networks [3] and a probabilistic model [5]).

It should be emphasized that this study currently makes use of truth-level information (ie. we have perfect knowledge of the ionization energy depositions, locations for the Compton scatters and the order of the Compton scatters). Therefore, this study represents the “perfect reconstruction” scenario capabilities of the GRAMS detector. The effect of realistic detector response, which modifies detection efficiency and resolution, is currently being investigated.

3. All-Sky Point Resolution Maps

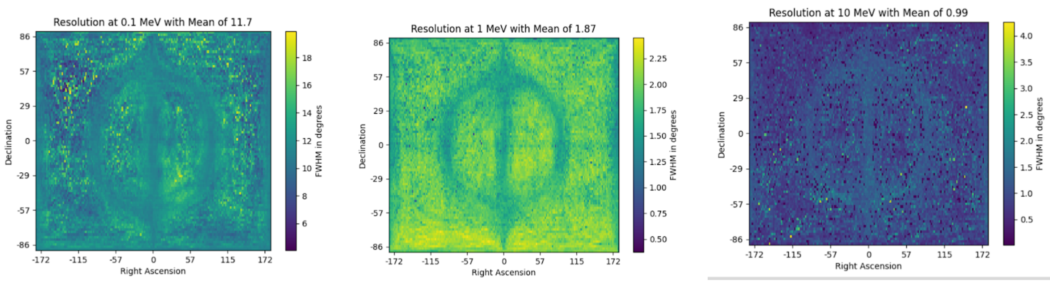


(a) **(b)**

Figure 3: Calculating ARM from reconstructed Compton cones. (a) Example fit of a Lorentzian function to the ARM distribution from a monoenergetic source. (b) Log-log plot of ARM, in degrees, as a function of energy of the incident gamma rays. The source location is along the x-axis.

One of the major advantages of GRAMS is that it is a wide field-of-view Compton camera. In light of this, one can examine the Angular Resolution Measure (ARM) of GRAMS across the entire sky. ARM is a standard means of quantifying point resolution of Compton cameras, and is defined as the difference between the true initial scattering angle versus reconstructed initial scattering angle as calculated from the Compton cones, defined in units of radians or degrees [1].

Making use of the same idealized reconstruction for Compton cones as described in Sec. 2, we evaluate a distribution of ARM values from many Compton cones that all share gamma rays of the same initial energy. We then fit a Lorentzian/Voigt function to the distribution and take its full width half maximum (FWHM) (ie. Γ) as a measure of the angular resolution at that particular energy and position. The results are shown in Fig. 3a, for ∼0.1 MeV gamma rays. This procedure can the be applied across a range of energies, as shown in Fig. 3b.



(a) **(b)** **(c)**

Figure 4: Preliminary all-sky ARM maps. (a) 0.1 MeV incident gamma rays. (b) 1.0 MeV incident gamma rays. (c) 10 MeV incident gamma rays.

If we instead fix the source energy and vary the source location, we can construct the all-sky maps shown in Fig. 4. The ARM at each energy is relatively constant across the entire sky (which is approximately 11.7° at 0.1 MeV, 1.87° at 1 MeV, and 0.99° at 10 MeV). It should be emphasized that these angular resolutions are optimistic, due to the use of idealized reconstruction.

4. Effective Area

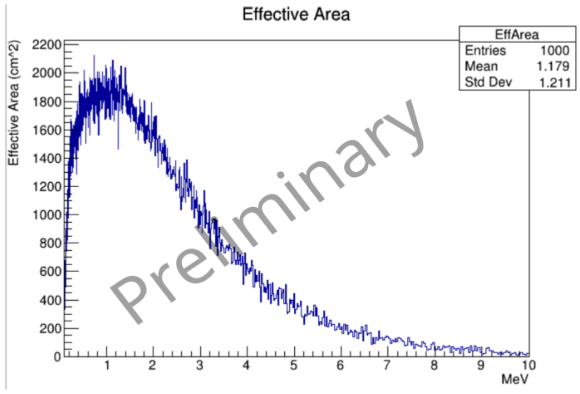


Figure 5: Preliminary evaluation of the effective area for the GRAMS detector for MeV gamma rays; accounts only for Compton scattering and assumes an idealized detector response. See text for more details.

Effective area is defined as the convolution of a detector's efficiency with its cross-sectional area. This is calculated computationally using a given gamma-ray flux by taking the number of reconstructable events, dividing by the total number of produced events, and then multiplying by the area of the generating surface used to produce the events.

The following selection criteria were applied to determine if an event can be reconstructed (using truth-level information):

- The incoming gamma ray produces at least two energy deposits inside the active LArTPC (either from Compton scattering or photoabsorption).
- No other processes (pair production, bremsstrahlung etc.) occur inside the active LArTPC.
- The first Compton scatter must occur inside the active LArTPC.
- Each successive Compton scatter must occur in an optically isolated region of the LArTPC (see Fig. 1a and original GRAMS paper for more details[1]).

As shown in Fig. 5, the effective area reaches a maximum of 2000 cm^3 around 1 MeV, and then exponentially tappers off at higher energy; this is consistent with the cross-section of Compton scatters, which rapidly falls off past 2 MeV. Note that GRAMS can use pair-production for the study of gamma rays in this regime [1]; this study considers only Compton scattering.

5. Point Source Sensitivity

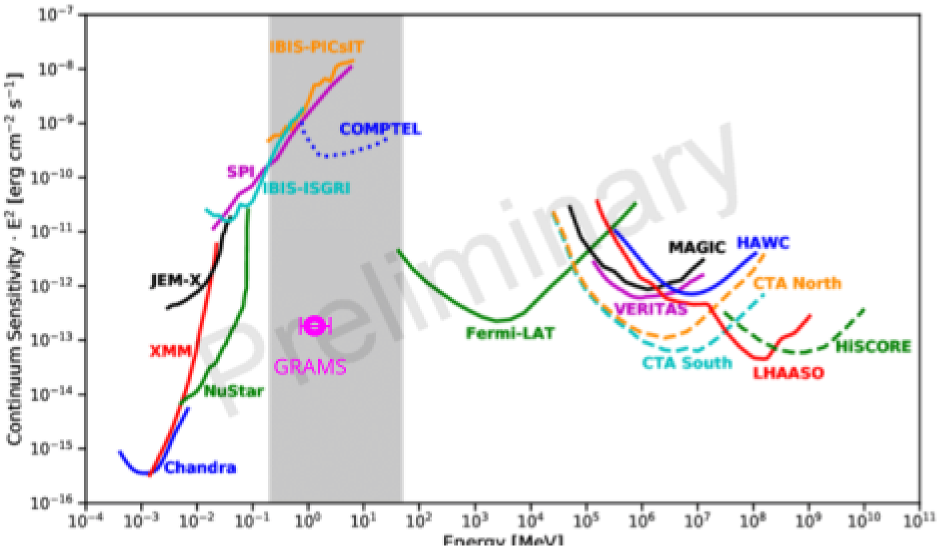


Figure 6: Preliminary Sensitivity Plot of GRAMS (Exposure time of 365 days)

With the cubic LArTPC design (active LArTPC dimensions of 70×70×80 cm^3), and using truth-level information from the GRAMS Geant4 simulation, we can evaluate a preliminary sensitivity of GRAMS to a point-like 1 MeV gamma-ray source. The sensitivity assumes Poisson statistical-only uncertainties, and an exposure of 365 days to both the source and background, with the former assumed to be fixed along the x axis, and the latter assumed to be isotropic with a broken power-low energy spectrum [4]. We further assume no additional atmospheric background. The resulting sensitivity (3.79e-13 $\frac{E^2 ergs}{cm^2 s}$) is shown in Fig. 6, and contrasted to other existing and planned projects.

It is important to note that this result is highly optimistic since it does not take into account physical processes that would alter observables (ionization charge recombination, attenuation, diffusion etc.), and further assumes perfect detector response. Moreover, in this work we did not consider radioactivation induced by cosmic-rays, which can be a dominant background component in a satellite mission. All these effects have the potential to impact the sensitivity, and are currently being incorporated in the simulation.

6. Conclusion

To summarize, we were able to apply the commonly used Compton telescope backprojection algorithm to examine GRAMS' capabilities in reconstructing MeV gamma-ray point sources (location and energy). We examined the all-sky angular resolution of GRAMS in terms of its spatial and energy dependence. We evaluated the effective area of the detector using optimistic assumptions. Finally, we calculated the statistical-only sensitivity of GRAMS for a 1 MeV gamma-ray point source against a power-law isotropic background spectrum as observed by COMPTEL. Further work involves evaluating the point-source sensitivity over a broader energy range, as well as incorporating detector response for the entire analysis, for more realistic estimates.

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