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New Mission Concept: Compton Telescope with Coded Aperture Mask (GECCO) for MeV Gamma-ray Astronomy

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The Galactic Explorer with a Coded Aperture Mask Compton Telescope (GECCO) is a novel Explorer-class concept for a next-generation telescope covering the poorly explored hard X-ray and soft gamma-ray energy regimes. The instrument is based on a novel CdZnTe imaging calorimeter and a deployable coded aperture mask, which enable it to reach 1 arcmin angular resolution and 1% energy resolution. GECCO will connect the arcminute angular resolution observations from X-ray telescopes to high-energy images of the Galactic plane provided by Fermi-LAT, and will focus on the exploration of heavily populated sky regions such as the Galactic Center and the Carina and Cygnus regions to decipher the nature of their emission. These measurements will probe with unprecedented capabilities the possible origin of this emission as dark matter, new types of sources, or currently unresolved populations of point sources. Uncoded observations with GECCO's Compton telescope will provide wide field-of-view sky monitoring for transient events, synergizing with gravitational wave and high-energy neutrino facilities. In addition, GECCO will conduct a high-sensitivity search for the positron sources in the Galactic Center responsible for the enigmatic 511 keV positron annihilation line excess, will search for as-yet untested candidates for dark matter, will detect and identify high-redshift blazars with excellent angular resolution, and will explore Galactic chemical evolution and sites of explosive element synthesis.

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1. Science Motivation

The coming of age of modern gamma-ray astronomy, in particular by the ground- breaking achievements of Fermi-LAT, has dramatically increased the breadth and depth of our understanding of a variety of sources which radiate at gamma-ray energies and the underlying fundamental mechanisms of their operation. However, as usual, newly revealed information has resulted in the appearance of deeper questions. The gamma-ray energy range from a few hundred keV to a few tens MeV has remained largely unexplored since the pioneering but limited observations by COMPTEL [2] on CGRO (1991- 2000), while the neighboring energy ranges have been deeply investigated by NuSTAR [3], Gehrels-Swift [4], INTEGRAL [5], AGILE, and Fermi-LAT [1] (Fig.1).

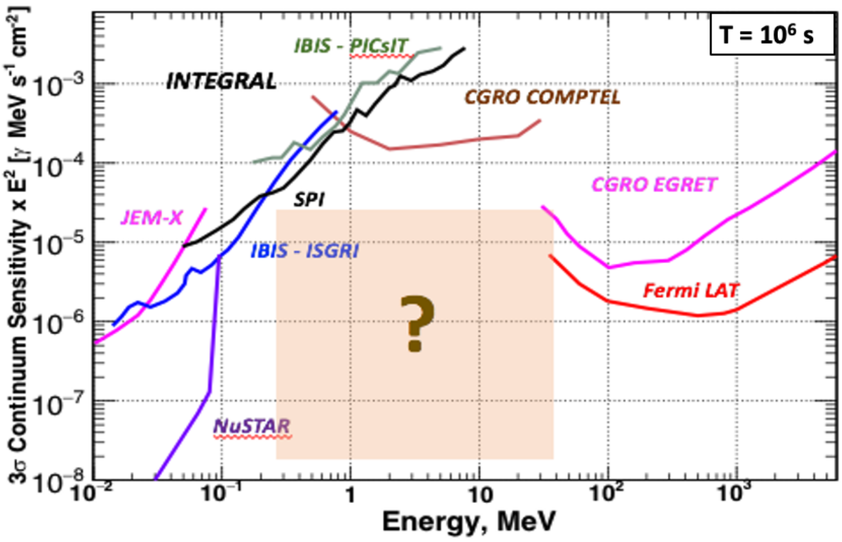

Figure 1: *Currently available capabilities in MeV γ-ray astronomy. GECCO focuses on the highlighted under-explored energy range.*

However, the lack of measurements in this band results not from a paucity of interesting science, since many sources of great astrophysical interest have energy output that peaks in the MeV-range, with expected spectral and temporal features, but rather from technological constraints that limit instrumental performance. In fact, this energy range offers great potential for astrophysics discovery in the areas of nucleosynthesis, multimessenger/gravitational waves, jets, and compact objects, see *e.g.*, an excellent eASTROGAM[6] review of the scientific targets in MeV γ-ray astronomy. In addition, the rapidly widening search for the sources of gravitational waves[7] and high-energy neutrinos[8] requires their accurate and precise localization and identification, which can be provided by X-ray and γ-ray instruments.

The arguments and science objectives listed above prove the need for a wide-aperture, high angular and energy resolution MeV-instrument, to fill the poorly explored yet full of scientific potential energy gap between X-ray optics instruments (NuSTAR, eROSITA[9], and high-energy γ-ray instruments (Fermi-LAT, AGILE, ground-based γ-ray telescopes). COSI[10], with excellent energy resolution but limited sensitivity and Compton-only modest angular resolution, is planned for a 2026-2027 launch and should provide results that will set the stage for a GECCO mission[11, 12].

2. GECCO concept inputs

2.1 Limits to Compton telescope angular resolution at MeV energies

The measurement concepts for X- and γ-ray instruments are different, depending on the photon energy of interest. Below 200 keV focusing optics provide the best performance. For energies above 10 MeV and up to the TeV range, pair-production is suitable for direct detection, competing at the high end with ground-based Cherenkov and large-array detectors. For high-keV and low-MeV energies, Compton scattering is the dominant photon interaction mechanism with matter, and photon detection using the Compton effect is a well-established observation method ([2] and references therein). Unlike pair-production telescopes like Fermi-LAT[1], the photon arrival direction can only be constrained to an "event circle". The uncertainty in the event circle is reflected in its thickness and is due to uncertainties in the scattering angle arising from energy and location measurement uncertainties, as well as Doppler broadening. The direction of a point source can be determined by the overlap from combining the event circles (or arcs) of many detected photons. While the measurement uncertainties can be improved, the resulting point source resolution is ultimately limited by "Doppler" broadening. This effect is due to uncertainty in the initial electron momentum, where the incident photon Compton scattering occurs. This effect imposes a fundamental limit on the angular resolution for Compton telescopes that for semiconductor detectors (*e.g.*, Si, Ge, or CdZnTe) varies in the range 0.4 – 3.5 degrees for energies 0.2 – 10 MeV. For this reason, arcminute angular resolution cannot be achieved in a Compton telescope alone, and arcminute resolution is typically needed in order to associate a source confidently with a multiwavelength counterpart.

2.2 Coded Aperture Imaging

Spatial modulation of the incident flux and deconvolution of the measurement from a position-sensitive detector at the detector plane is an established method for imaging with fine angular resolution, and usage of coded-aperture (CA) masks is widespread in X-ray instruments [13, 14]. A mask is an array of opaque and transparent elements set between the source field and a position-sensitive detector plane (PSD), also called the Focal Plane Detector (FPD). Every source within the instrument's FoV projects a shadow image of the mask onto the PSD. There are several data analysis approaches for such systems that are widely discussed in the literature, many based on Fourier-based deconvolution. The fundamental angular resolution of the system is determined by the ratio of the mask pixel size to the distance from the mask to the FPD.

2.3 CZT Imaging Calorimeter

During last several years, our team has been developing a modular, crate-based architecture for the CZT Imaging Calorimeter (ImCal). ImCal is based on combining many position-sensitive Virtual Frisch-grid (VFG) CZT bar detectors with a large geometrical aspect ratio, e.g., 6×6×20 or 8×8×30 mm^3[15]. These are oriented with the long axis parallel to the incident γ-ray direction, making the detector effective thickness equal to the bar length, providing high detection efficiency.

The distinguishing feature of the detector is the use of four conducting pads attached to the sides of the encapsulated CZT crystal bar near its anode (Fig.2). The pads are virtually grounded through the ASIC front end and act as a virtual Frisch-grid. The induced signals on the pads, anode, and the cathode (6 signals in total per bar) are read out to provide X, Y, and Z coordinates by combining the signal ratios. An important advantage of the position-sensitive VFG detectors is the ability to correct for non-uniformity of the response caused by crystal defects. Such a correction allows us to use standard grade crystals produced with higher acceptance yields and, thus, to reduce the overall cost of the instrument.

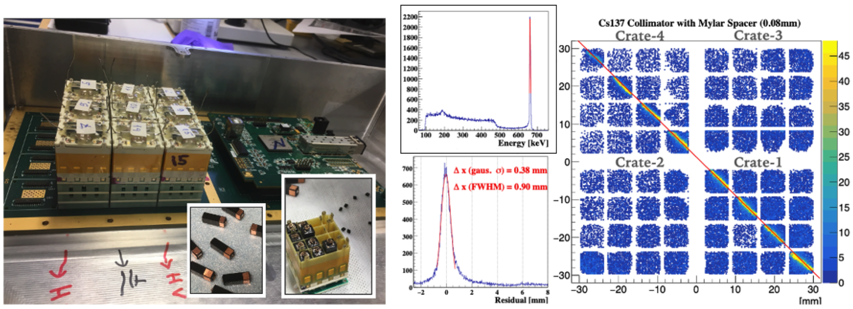

Figure 2: *Left: 9-crate prototype assembled, with inserts: CZT bars with copper sensing pads attached, and crate, half-populated with bars. Upper middle: the ^{137}Cs spectrum with ~0.9% FWHM energy resolution, obtained with IDEAS readout. Right: image of 0.08mm wide collimator obtained with 4 crates, each blue square corresponds to cross-section of CZT bar (6×6mm^2). The red line is the best fit linear function. Bottom middle: corresponding residual distance of the reconstructed hit from the red line (position resolution), 0.9mm FWHM*

With the ImCal prototype built and tested, we demonstrated the basic principles and benefits of this technology for γ-ray space telescopes, and its ability to measure with high efficiency both the photon interaction sites and the deposited energy with good accuracy: $<$ 1mm for the 3D position resolution, and $\leq$ 1% FWHM for the energy resolution. Arrays of such detectors have been recognized as promising for use in various γ-ray telescopes as a stand-alone Compton detector and as a focal-plane detector for CA instruments (Fig. 4), with direct application in GECCO[11] and AMEGO[16]. Furthermore, using the crate-based modular design allows for flexibility in selecting array configurations and sizes for large-area detector systems.

3. GECCO Concept

The GECCO concept combines the best of the Compton and CA imaging modalities, mutually enhancing the performance of each modality and enabling previously inaccessible measurements[11, 12], its baseline design is shown in Fig.3. Compton telescopes provide good, low-noise performance over a wide FoV, while CA telescopes achieve arcmin-level and better angular resolution but have no inherent background rejection. In GECCO we are developing a novel approach, over most of GECCO energy band, where CA imaging will be performed using only Compton-scattered γ-rays, whose rings of incidence cross the CA mask, allowing significant background rejection and improved signal-to-noise ratio (SNR).

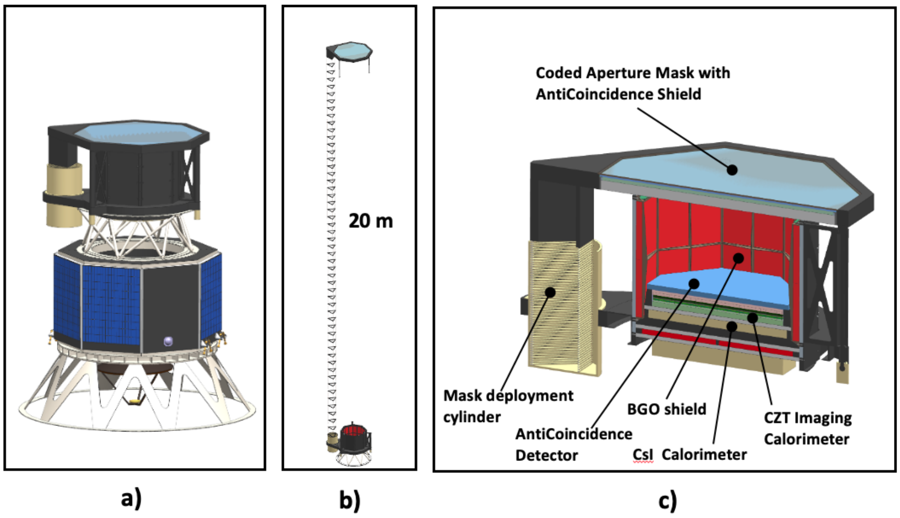

Figure 3: *GECCO conceptual design: a) GECCO with the mask in stowed position and notional spacecraft bus, b) GECCO with the mask in deployed position, c) GECCO, cutaway.*

This approach will enable the use of a longer focal length to achieve sub-arcminute angular resolution without requiring heavy, full side shielding, by deploying the mask post-launch on an extensible boom, similar to the well-developed designs used in NuSTAR and other X-ray optics instruments. The method of using Compton imaging to suppress side-entering background (bright off-angle sources, diffuse γ-radiation) is illustrated in Fig.5.

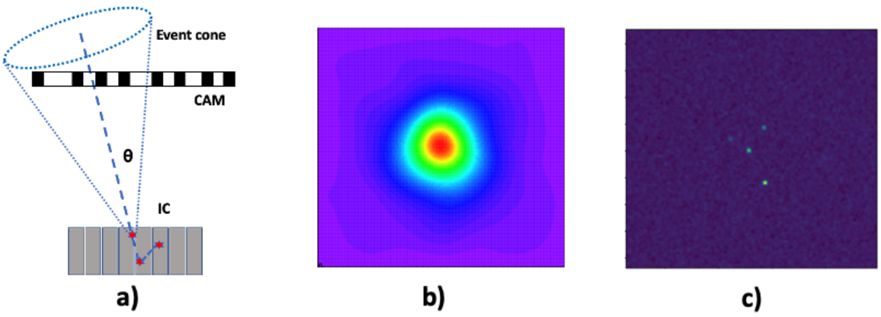

Figure 4: *a): Illustration of ImCal dual imaging capability. Red stars show the points of photon interactions detected in the ImCal, which are used to reconstruct the cone of possible incident photon directions, enabling Compton imaging. The point of the first photon interaction is used to create the CA image, with ImCal operation as the CA FPD. The dashed line shows the scattered photon direction detected by ImCal. The dotted lines show the event cone. b) Compton observation of 4 point sources of different intensities, separated by 3'-5', and c) – the same 4 point sources as detected by the CA (simulations).*

In GECCO the ImCal detects γ-rays from 50 keV to 10 MeV providing the (multi-site) energy and location of interactions. It serves as the detector plane for the CAM telescope and, above $\sim$200 keV, as a standalone Compton telescope (Fig.4). The CsI Calorimeter supports the ImCal by measuring the energy and interaction positions of radiation escaping from the ImCal: 2-10 MeV photons have the lowest attenuation length and most of them are not fully contained in the ImCal and so cannot be correctly reconstructed. Monte Carlo simulations of the instrument have been performed by our team with the MEGAlib toolkit[17].

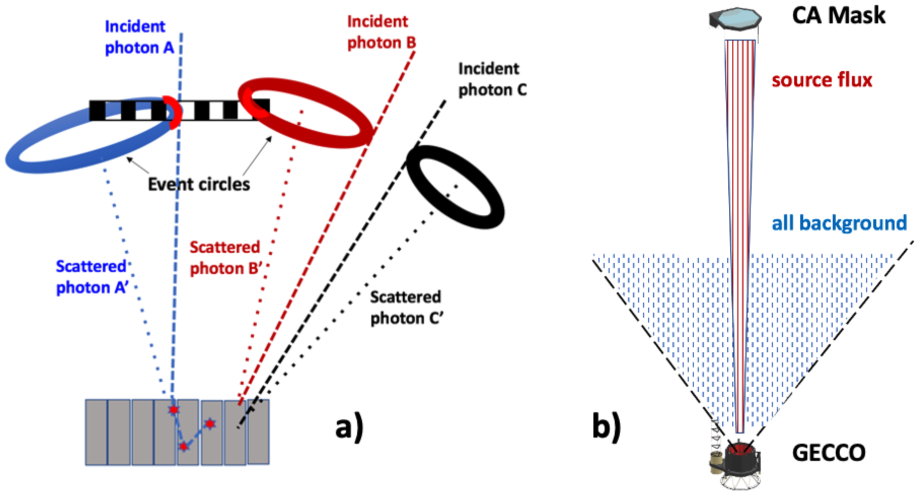

Figure 5: *Background removal method: a) Photon A, shown in blue - accepted good photon from the source, with its event circle crossing the CA mask location. Photon B, shown in red - accepted background photon, because its event circle crosses the CA mask location. Photon C, shown in black - rejected background photon. b) Source and background fluxes, shown in red, entering the GECCO ImCal FoV within the CA mask FoV, accepted for the analysis. The background flux, entering the GECCO ImCal FoV but outside of the CA mask FoV, is shown in blue and is rejected by the Compton pointing method.*

The ImCal, serving for GECCO as a standalone Compton telescope and as a FPD, is also a powerful tool to measure the γ-radiation polarization. The first results of our simulations are very encouraging, and we will pursue this topic for GECCO, following the steps COSI[10] is taking.

The GECCO BGO shield consists of eight, thick BGO detectors configured to create an octagonal well (shown in dark red in Fig.3). It shields the detectors from the bright Earth radiation, and serves as a veto detector for incident charged cosmic rays and for vetoing not-fully contained and otherwise accepted Compton events. The BGO shield will also serve as an excellent γ-ray burst (GRB) detector (BurstOctagon), capable of locating GRBs with 1-2 degree accuracy (burst type, location, and brightness dependent, our team simulations).

Presently, our team is developing the GECCO prototype, called ProtoGECCO, to test and demonstrate the performance and conduct the design optimization if found necessary.

4. GECCO Expected performance and Conclusions

GECCO's observational capabilities will be of paramount importance for disentangling astrophysical and dark matter explanations of emission from the Galactic Center and potentially providing a key to discovering as-of-yet unexplored dark matter candidates. GECCO will operate in the 100 keV - 10 MeV energy range, with energy resolution of ≈ 1% in 0.5 - 5 MeV. The Coded Aperture Mask provides the angular resolution of ≈0.5 arcmin with a 2° × 2° fully-coded FoV, while the Compton telescope provides the angular resolution of 4° - 8° with a ≈ 2 sr FoV, see [12] for the details. The 3σ, $10^6 s$ sensitivity is expected to be about $10^{-5} MeV \times cm^{-2} \times s^{-1}$ over the entire energy range.

With the unprecedented angular resolution of the coded mask telescope combined with the sensitive Compton telescope, GECCO will be able to disentangle discrete sources from truly diffuse emission, contributing to understanding the gamma-ray Galactic Center excess and the Fermi Bubbles, and to tracing low-energy cosmic rays and their propagation in the Galaxy[12]. Nuclear and annihilation lines will be spatially and spectrally resolved from continuum emission and from sources, addressing the role of low-energy cosmic rays in star formation and galaxy evolution, the origin of the 511 keV positron line, fundamental physics, and Galactic chemical evolution. Of special interest will be the exploration of sites of explosive element synthesis by conducting high-sensitivity measurements of nuclear lines from Type 1a supernovae and from other objects.

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