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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 1), 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 5), INTE- GRAL 6), AGILE 7), and Fermi-LAT (Fig.1).

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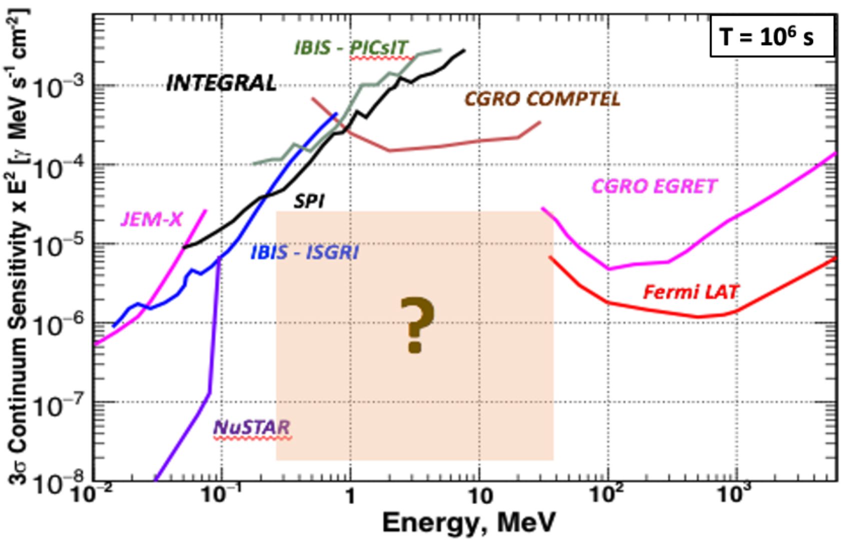

Figure 1: *Currently available capabilities in MeV γ-ray astronomy. GECCO focuses on the highlighted under-explored energy range.*

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[8] review of the scientific targets in MeV γ-ray astronomy. In addition, the rapidly widening search for the sources of gravitational waves[9] and high-energy neutrinos[10] requires their accurate and precise localization and identification, which can be provided by X-ray and γ-ray instruments.

There are several unresolved problems connected with the dynamic structure and composition of the inner Galaxy, including the Galactic Center region and active star-forming regions that require high spatial resolution to address: the nature of unassociated Fermi-LAT sources (approximately one third of all detected sources, primarily in the Galactic plane), the nature of the Fermi-eROSITA Bubbles, the nature of the Galactic Center GeV-excess, the origin of the 511-keV positron annihilation line, and the origin of enigmatic dark matter. High-sensitivity measurements of nuclear lines in the MeV range will also lead to resolving Galactic chemical evolution and sites of explosive element synthesis, such as supernova. High angular resolution and good spectral resolution, along with high sensitivity, are critical in these studies.

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[11], future HEP-X[12]), and high-energy γ-ray instruments (Fermi-LAT, AGILE, ground-based γ-ray telescopes). An important argument is also that the operation of the ESA mission INTEGRAL, the only one currently providing measurements in high keV-low MeV energy range, can be terminated in 2023. COSI[13], 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[14, 15].

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[3, 12]. 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” (Fig.2a). 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.

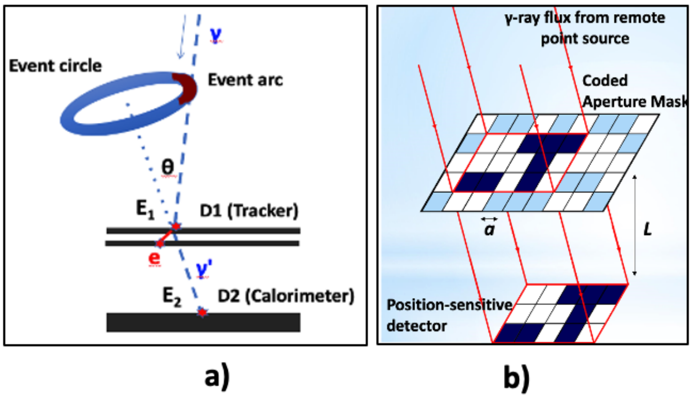

Figure 2: *a) Principle of operation of the Compton telescope. Incident photon undergoes Compton scattering in D1 and then is detected in D2; b) CA principle of operation. The angular resolution is constrained by the Mask element size "a" and Mask-Focal Plane detector separation "L"*

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 [16, 17]. 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 (Fig.2b). 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. The pixel size is constrained by the PSD position resolution, and is usually set 2-3 times larger to provide reasonable signal-to-noise ratio (SNR). The availability of a PSD with high-position resolution is one of the cornerstones of CA-based instruments. The other key parameter is the distance between the mask and the PSD. For space-borne instruments this distance is constrained by the launcher geometry and cannot exceed 3-4 meters.

The challenges for an MeV-energy CA Imager. At MeV energies, CA imagers face difficulties not present in X-ray applications. The amount of material required to significantly attenuate MeV photons is much thicker than is needed for X-rays, with a minimal mask thickness on the order of a few cm of tungsten. The resulting mask will be heavy, with a fully-coded FoV that is limited by the ratio of the mask pixel size to its thickness (that is, the opening angle of a given transparent mask element), as well as by the ratio of the mask size to the FPD size. The effective change in mask thickness with photon incidence angle furthermore creates non-uniformity in the system response (self-collimation effect). If the CA design for X-ray instruments is rather straightforward, for MeV energies it requires careful design and fabrication optimization to maximize the instrument performance.

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[18, 19]. 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.3). 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[18].

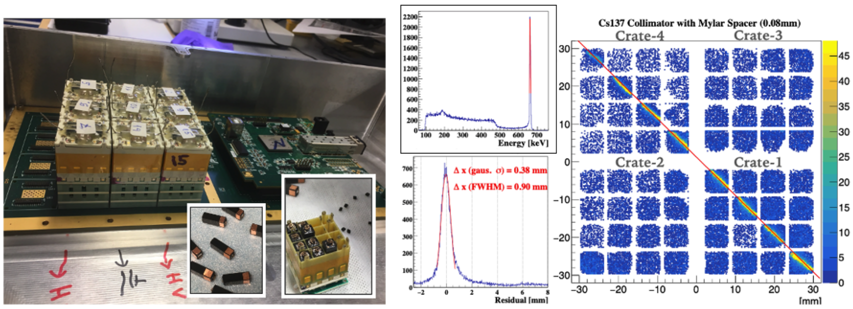

Figure 3: *Left: 9-crate prototype assembled, with inserts: CZT bars with copper sensing pads attached, and crate, half-populated with bars. Upper middle: the ^{137}Cs spectrum with ~0.9% FWHM energy resolution, obtained with IDEAS readout. Right: image of 0.08mm wide collimator obtained with 4 crates, 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*

Crate Design. The CZT bars are tightly packed inside the cells of the egg-crate structure (Fig.3). As a result of joint GSFC-BNL efforts, we have integrated a fully functional prototype of the Imaging Calorimeter comprised of 3×3 crates. The crates are plugged into a motherboard, which also carries low-voltage power regulators, ADCs, an FPGA, and a fiber-optics communication interface.

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While good spectroscopic performance has been achieved with this prototype, measurements clearly indicated that the analog ASICs used previously have inherent limitations for the reconstruction of the X and Y event locations. To address this problem, we chose to use a new "smart" ASIC concept based on waveform sampling of the unshaped signals. With the digitized data, we can use time-correlated samples of the signals captured from pads for reconstructing X and Y coordinates with much higher accuracy. To develop the waveform digitizing approach, we integrated and tested a 2×2 prototype crate with a customized GDS-100 front-end readout system provided by IDEAS[20]. The results obtained with radioactive sources in the laboratory, and in our recent test at the TUNL/HIGS polarized photon beam encouraged our team to use the GDS readout system as the baseline for the GECCO ImCal (Fig.3).

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. 5), with direct application in GECCO[14] and AMEGO[21]. 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[14, 15], its baseline design is shown in Fig.4. 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).

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.6. In the GECCO baseline design we assume the CA mask to be deployed at 20m, with the mask pixel size 3mm. These numbers provide ~0.5 arcmin angular resolution and $2° \times 2°$ fully-coded field-of-view. It is critical for achieving high sensitivity CA observations and its efficacy and efficiency have been validated in simulations performed by our team. The method of "Compton pointing" has been demonstrated earlier in simulations[22, 23], and tested with INTEGRAL/IBIS data[24], but the mature concept has never been implemented as the central motivation for a telescope design.

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 ~200 keV, as a standalone Compton telescope (Fig.5). 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

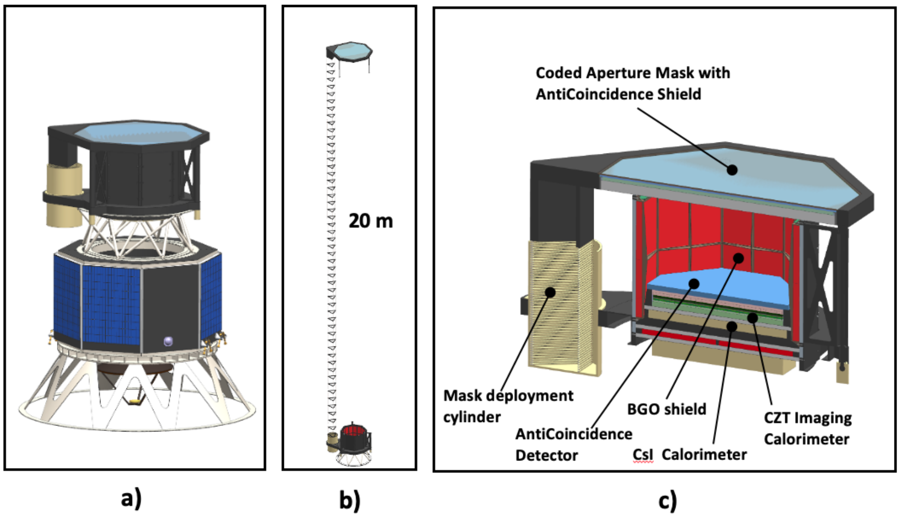

Figure 4: *GECCO conceptual design: a) GECCO with the mask in stowed position and notional spacecraft bus, b) GECCO with the mask in deployed position, c) GECCO, cutaway.*

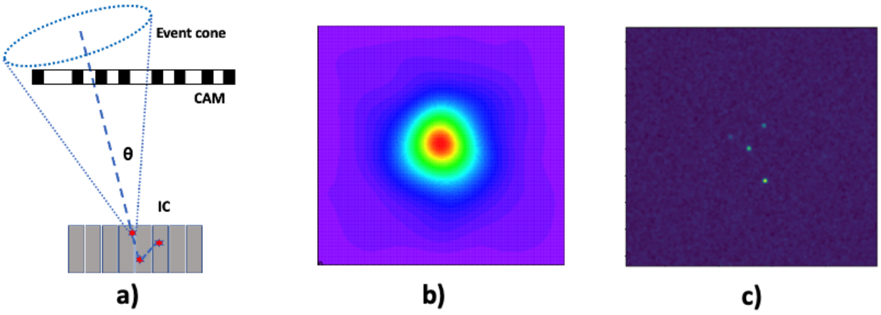

Figure 5: *a): Illustration of ImCal dual imaging capability. Red stars show the points of photon interactions detected in the ImCal, which are used to reconstruct the cone of possible incident photon directions, enabling Compton imaging. The point of the first photon interaction is used to create the 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).*

and so cannot be correctly reconstructed. Monte Carlo simulations of the instrument have been performed by our team with the MEGAlib toolkit[25].

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[13] is taking.

The GECCO BGO shield consists of eight, thick BGO detectors configured to create an octagonal well (shown in dark red in Fig.4). 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

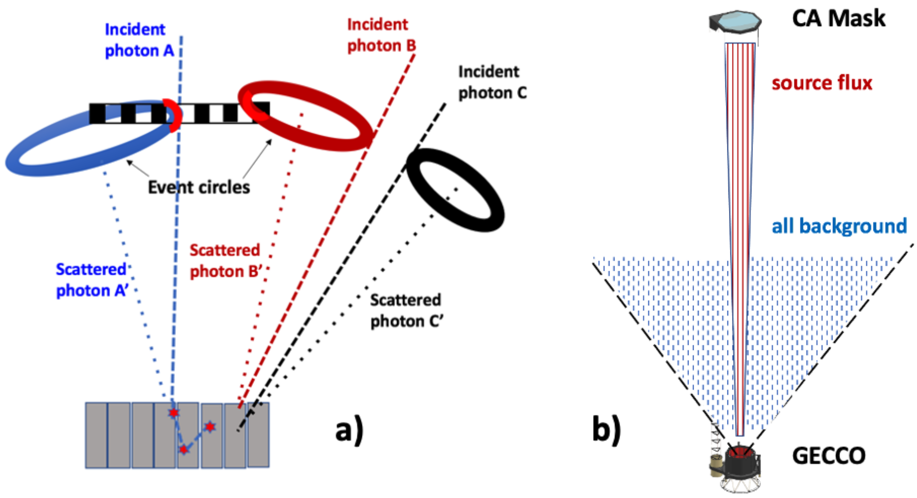

Figure 6: *Background removal method: a) Photon A, shown in blue - accepted good photon from the source, with its event circle crossing the CA mask location. Photon B, shown in red - accepted background photon, because its event circle crosses the CA mask location. Photon C, shown in black - rejected 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.*

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). If the GRB is in a heavy-populated sky region where such resolution is insufficient, GECCO can be re-pointed in that direction for more accurate localization using the full power of the CA mode.

Presently, our team is developing the GECCO prototype, called ProtoGECCO, to test and demonstrate the performance and conduct the design optimization if found necessary[26].

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[27]. GECCO will operate in the 100 keV - 10 MeV energy range, with energy resolution of $\approx$ 1% in 0.5 - 5 MeV. The Coded Aperture Mask provides the angular resolution of $\approx$0.5 arcmin with a $2^\circ \times 2^\circ$ fully-coded FoV, while the Compton telescope provides the angular resolution of 4° - 8° with a $\approx$ 2 sr FoV, see [15] 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.

In order to exploit GECCO's unique (for this energy range) angular resolution and pursue its main science objective of resolving heavily-populated sky regions, its primary mode of observation is fixed pointing, with extended exposure of such regions. Also, the pointed mode will be used to either increase observation time for special regions of interest, or to observe transient events such as flares of various origins or gamma-ray bursts. However, as a standalone Compton telescope with wide FoV, ImCal will simultaneously provide wide-area sky exploration, significantly broadening GECCO's observational scope.

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[15]. 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.

GECCO will be able of addressing practically all of the science problems described in the Section 1, but will be focused on two primary objectives. One is to explore heavily populated sky regions, mainly the Galactic Center (the illustration of GECCO's capability to detect closely situated sources is shown in Fig.5c). Here, the important goals are to resolve the nature and environment of the central massive black hole, and to understand if some emissions are due to dark matter, or multiple point sources. The presence of dark matter in close vicinity of the GC has been advocated in numerous papers and GECCO will be able to resolve this[27]. GECCO is the only instrument, able to investigate this problem at MeV energies by resolving potentially contributing point sources, that would have an expected ~arcmin population density[4, 28, 29]. The other primary objective for GECCO will be large FoV monitoring for transient events, detected with high sensitivity, and accurate localization, performing multimessenger investigations to support GW and neutrino discoveries.

5. Acknowledgements

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6. GECCO Team

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