PROCEEDINGS OF SCIENCE

ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

# NEW MISSION CONCEPT: GALACTIC EXPLORER WITH A CODED APERTURE MASK COMPTON TELESCOPE (GECCO)

**Alexander Moiseev** [a,b,*], **for the GECCO collaboration**

(complete list of the authors can be found at the end of the paper)

[a] *University of Maryland, College Park, MD 20740, USA*

[b] *CRESST/NASA/GSFC, Greenbelt, MD 20771, USA*

*E-mail:* amoiseev@umd.edu

**Abstract.** We present a novel concept for a next-generation γ-ray telescope that will cover the hard X-ray to soft γ-ray domain. Despite the progress made by the European Space Observatory INTEGRAL, this energy range is still under-explored. GECCO will conduct high-sensitivity measurements of the cosmic γ-radiation in the energy range from 50-100 keV to ~10 MeV and will create intensity maps with high spectral and spatial resolution, focusing on a sensitive separation of diffuse and point-source components. These observations will enable the following major objectives:

a) explore the nature, composition, and fine structure of the inner Galaxy,

b) localize and discern the origin(s) of the positron annihilation 511 keV line,

c) explore Galactic chemical evolution and sites of explosive element synthesis,

d) provide identification and precise localization of gravitational wave and neutrino events,

e) test as-yet unexplored candidates for the dark matter

The instrument is based on a novel CdZnTe Imaging calorimeter and a deployable coded aperture mask. The unique feature of GECCO is that it combines the advantages of two techniques – the high-angular resolution possible with coded mask imaging, and a Compton telescope mode providing high sensitivity measurements of diffuse radiation. Expected GECCO performance is as follows: energy resolution <1% at 0.5-5 MeV, angular resolution ~1 arcmin in the Mask mode (3-4° field-of-view, ~2,000 $cm^2$ effective area), and 3-5° in the Compton mode (~60° field-of-view, ~500 $cm^2$ effective area). The continuum sensitivity is expected to be $10^{-6}$ – $10^{-5}$ MeV/$cm^2$/s over the energy range. GECCO can be considered for a future NASA Explorer mission.

*37th International Cosmic Ray Conference (ICRC 2021)*
*July 12th – 23rd, 2021*
*Online – Berlin, Germany*





PoS(ICRC2021)648

## 1. Introduction

Launched in 2008, the Fermi Gamma-ray Space Telescope has been providing groundbreaking results in γ-ray astronomy. Its main instrument, the Large Area Telescope (LAT), has been conducting high-sensitivity measurements in the photon energy range from about 50 MeV to above 300 GeV. Fermi's second instrument, the Gamma-ray Burst Monitor (GBM), measures photons above 8 keV and provides detection and localization of Gamma-ray Bursts (GRB), the most energetic phenomena in Universe. Both instruments cover practically all topics in high-energy astrophysics, ranging from terrestrial γ-ray flashes and solar flares to Galactic sources and further to extragalactic phenomena [1]. Fermi has, however, left problems requiring dedicated and focused investigations. Among them are: a) the Fermi LAT has discovered more than 5,000 point γ-ray sources (pulsars, active galactic nuclei, γ-ray binaries, novae, starburst galaxies, etc.) but about 30% of them do not have association with sources detected at other wavelengths. The reason for this lack of association is puzzling, primarily a result of limited spatial resolution; b) GBM detected the first association of a GRB with a gravitational wave source, GW 170817, but with insufficient angular resolution to clearly associate the source with a known stellar object; c) Fermi LAT provided the association of a high-energy neutrino source detected by IceCube with the active galaxy namely TXS 0506+056. Further multi-wavelength observations of these systems are needed to understand their nature; d) The exciting discovery of the Fermi Bubbles, mysterious bubble-shaped high-energy γ-radiation on both sides of the Galactic disc, and the recent discovery of similar but larger eROSITA features at ~1 keV have ignited numerous speculations but their nature is still unknown; e) The Fermi LAT discovery of γ-radiation excess in the Galactic Centre (GC) region suggests several scenarios involving cosmic-ray sources and/or the supermassive black hole, but their resolution requires more precise measurements. A key to resolving these problems may lie in the lower energy range at around 1 MeV where many active γ-ray sources have peak emission. For several reasons, this energy range from a couple of hundred keV to several tens of MeV remains largely unexplored, due to complicated and challenging measurement technology. The space telescopes OSSE and COMPTEL onboard CGRO (1991-2000) provided pioneering but limited observations in the 50 keV to 30 MeV energy band, which still are the only high significance measurements in this energy range, while neighboring energy ranges have been deeply investigated by NuSTAR, Gehrels-Swift, INTEGRAL, and Fermi (Fig. 1). Currently available results undoubtedly assert that there is a huge discovery space in this void.

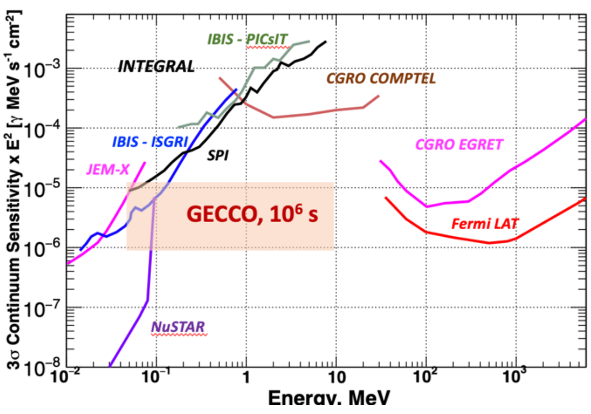


***Figure 1**: Sensitivity of currently available measurements in keV-GeV energy range*

In order to fill this gap, we are designing a Medium-Explorer-scale mission, Galactic Explorer with a Coded Aperture Mask Compton Telescope (GECCO) to provide high-sensitivity measurements with high angular and energy resolution and create high-resolution maps of densely populated sky regions (GC, Cygnus, Carina, etc.) in the energy range from 50 keV to 10 MeV. We are



PoS(ICRC2021)648

aiming to reach arcmin-level angular resolution and <1% energy resolution. The former is achieved by utilization of a coded-aperture technique, which is the only way to provide ~arcmin resolution at this energy. The latter is provided by CdZnTe detectors. CdZnTe performance is inferior only to germanium detectors, but does not require cryogenic temperature regulation, which is challenging for space borne instruments. At the same time, we aim to measure the diffuse γ-radiation, where a coded-aperture technique practically does not work. For this reason, GECCO also leverages a Compton telescope functionality provided by the 3D-sensitive CdZnTe Imaging Calorimeter (hereafter ImCal). The combined coded-aperture and Compton modes offers excellent potential to achieve the measurement objectives. Measurements in the MeV range must challenge various backgrounds, both natural and artificial. GECCO is designed to effectively suppress all known backgrounds, largely relying on the results from SPI and IBIS on INTEGRAL. Observation capabilities of GECCO will support the following science objectives:

a) explore the nature, composition and fine high energy structure of the inner Galaxy,
b) localize and discern the origin(s) of the positron annihilation 511 keV line,
c) explore Galactic chemical evolution and sites of explosive element synthesis,
d) provide identification and precise localization of gravitational wave and neutrino events,
e) test as-yet unexplored candidates for dark matter

## 2. GECCO concept and principle of operation

GECCO is a modern γ-ray telescope which has been designed according to two combined principles – Compton telescope and coded-aperture mask telescope. This combination mutually enhances the performance of each telescope and enables previously inaccessible measurements. GECCO consists of 6 subsystems: ImCal, CsI Calorimeter (hereafter CsICal), Bismuth Germanate heavy scintillator (hereafter BGO) shield, plastic scintillator Anticoincidence detector (hereafter ACD), Coded Aperture mask with plastic scintillator Anticoincidence shield (hereafter CAM), and data-acquisition system (DAQ) (Fig.2).

A classic example of a space-borne Compton telescope is COMPTEL onboard CGRO. A typical Compton telescope consists of two separated detectors, with the first photon interaction occurring in the “upper” one, and the second in the “lower” one. For a reliable event reconstruction, it is necessary to identify the sequence of interactions. In COMPTEL it was achieved by using a time-delay between the two interactions, requiring certain spacing between the detectors, which reduces the instrument aperture and detection efficiency. In GECCO ImCal and CsICal operate together making up a Compton telescope, which detects incident photons in the energy range from 50-100 keV to ~10 MeV by measuring their energy and incident direction. ImCal provides a measurement of photon interaction position (in 3 dimensions) and the energy released in each of those interactions, and the CsICal measures the energy and interaction positions of radiation escaping from the ImCal. As a result, an event interaction pattern is determined, which contains the “hits”, or points of energy deposition, with associated energy and 3D position. They are used to reconstruct the photon incident direction (a cone) based on the Compton formula, using the MEGAlib software package [2]. A similar approach is used in COSI, currently proposed as a Small Explorer NASA mission. **The GECCO Compton telescope provides a few degrees of angular resolution and 1 − 2% energy resolution, with a large ~1 sr field-of-view (FoV), capable of measuring diffuse γ-radiation.**

The angular resolution of Compton telescopes has an intrinsic limit of order of a degree due to Doppler broadening of the incident photon direction induced by the velocity of the electron on which the Compton scattering occurred. Limited position resolution for the interaction location used to reconstruct a Compton event pattern contributes to the angular resolution as well. In order to achieve arcmin angular resolution, a coded-aperture mask is placed in the instrument aperture. The incident photon flux creates a shadowgram of the mask in the detector, and the image of the source field is reconstructed by cross-correlating the shadowgram and the mask pattern [3]. The ImCal operates as a focal plane detector for the reconstruction of the coded-aperture mask image by the incident photon flux from a point source.

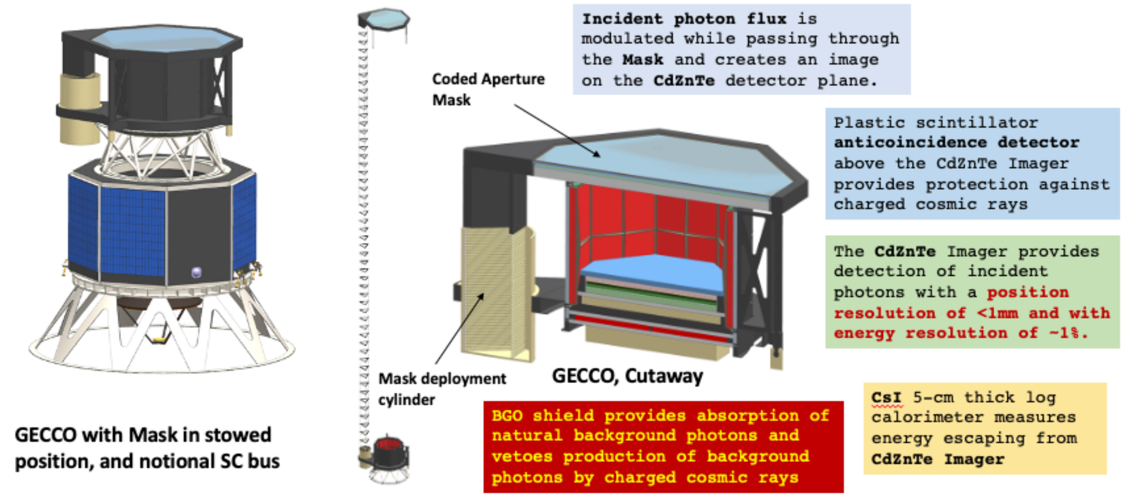


***Figure 2**: GECCO artistic image and its components*

Image reconstruction requires the knowledge of the point of the photon's first interaction, which is determined in the Compton reconstruction. The total event energy, which is the sum of all "hits", is needed for the spectral analysis of the data. Another set of data for the mask image reconstruction contains single hit events when there was only one interaction in the ImCal, which represents "classical" data for a coded mask telescope. These two (Compton reconstruction events and single-site events) sets of data include different backgrounds and can be analyzed either together or separately. Use of single-hit events, which are mainly photo-absorption events, extends the GECCO sensitivity down to an energy of ~50 keV, where the Compton event fraction becomes very small.

The angular resolution of a coded-aperture mask telescope is approximately equal to the ratio of the mask element size to the distance between the mask and the detector, so potentially can be as good as desired, defined by this distance. An attractive option to increase the distance between the mask and the detector beyond the launcher shroud is to deploy the coded mask after reaching orbit; however in this configuration the instrument aperture will be exposed to side-entering background radiation, which deteriorates the performance. **GECCO has a coded mask deployable to 20 meters and reduces the problem of side-entering background by selecting for analysis only events that might have originated from the coded mask location according to their measured Compton-scattered directions.** This unique feature of GECCO greatly improves its angular resolution while maintaining a high signal-to-noise ratio in coded mask imaging.

## 3. Instrument components

GECCO has an octagon shape with a medium diagonal of 90 cm (Fig. 2). Such a shape provides better operation of the coded mask instrument when compared to a rectangular shape. All the GECCO detectors, besides the CAM, are placed inside the BGO well.

### 3.1. The CdZnTe Imaging calorimeter

The ImCal is a key detector of GECCO, providing detection of incident photons with a 3D position resolution of $< 1mm$ and with energy resolution of $\sim 1\%$. It constitutes a stand-alone Compton telescope, and it enables measurements of nuclear $\gamma$-ray lines (Fig.3).

The ImCal has a modular structure and is based on the Virtual Frisch-grid drift CdZnTe bars approach developed at BNL [4]. Each detector element is a CdZnTe bar with dimensions of 8x8x30 $mm^3$. The bars are arranged in 4x4 modules which are integrated into a full-size calorimeter. In addition to providing critical interaction position information, the use of corrections based on the interaction position information within each bar solves a long-standing problem of CdZnTe detectors associated with material non-uniformities. Each module is served by an individual Application-Specific Integrated Circuit (ASIC) and plugged into a readout mother board. Each module is a low-level unit which can be easily replaced in a case of malfunction.

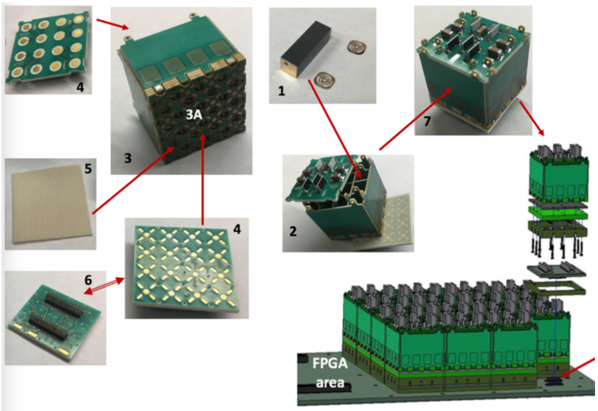


***Figure 3:*** *ImCal: single module components and 4x4 module array are shown*

As opposed to widely used pixelated detectors, in GECCO's calorimeter the X-Y positions of the photon interaction are determined by the ratio of the signals from side-attached sensitive pads. The Z-coordinate (along the bar height) is measured by the anode-to-cathode signal ratio and their relative timing. This approach greatly reduces the number of readout electronic channels while maintaining high position resolution [A. Bolotnikov, these Proceedings]

### 3.2. The CsI Calorimeter

The CsICal, situated below the ImCal, detects energy leaking from the ImCal and measures the position of that energy deposition. It is especially important to catch escaping 511 keV annihilation photons. The CsICal design is largely inherited from Fermi-LAT and is built from 30cm long CsI(Tl) logs with a 1.5cm x 1.5cm cross section. The ends of each log are viewed by silicon photomultipliers (SiPMs), and the sum of the signals from both ends of a log provides the energy measurement; their ratio gives the position of the center of gravity for the energy depositions in the log. There are 4 layers of alternatively orthogonal logs in this calorimeter.

### 3.3. The AntiCoincidence Detector

The 5-mm thick plastic scintillator anticoincidence detector (ACD) is positioned on the top of the ImCal to veto the charged cosmic rays which are 3-4 orders of magnitude more abundant than photons, from triggering the instrument. It is read out by SiPMs at its edges. The ACD provides rejection of charged cosmic rays with the efficiency of >99.9%.

### 3.4. The BGO shield

The stack of ImCal, CsICal, and ACD is surrounded on all 8 sides and at the bottom by a 4-cm thick BGO scintillator shield. This shield absorbs most of the side-entering photons, especially from the bright Earth limb. The BGO being an active detector, it also creates a signal to be used as a veto. The veto is particularly important for three backgrounds: a) secondary photons from Compton scattering events in the BGO which pass the ACD shield and enter the ImCal, b) side-entering charged cosmic rays, and c) incompletely contained ImCal photons, which have missing energy and otherwise could be mis-reconstructed. The BGO panels also serve as a powerful GRB detector with a few degrees accuracy for GRB localization.

### 3.5. The Coded-Aperture Mask

The CAM is an array of opaque (tungsten) and transparent elements, whose image in the ImCal is deconvolved by the Mask pattern. In the baseline design the ratio of transparent and opaque elements is 1:1, the mask thickness is 20 mm, and a single element size is 3x3 mm. The pattern in the baseline mask design is random, which provides optimal performance but is challenging to fabricate. The top surface of the mask is covered by a plastic scintillator ACD to veto the cases of photon generation in the mask material by incident charged cosmic rays or by neutrons. The mask footprint is two times larger than that of ImCal and CsICal, and it is positioned on top of the BGO shield octagon and can be placed at any distance vertically above the instrument, up to 20 meters away.

## 4. Background suppression.

Background reduction and suppression are critical to any telescope in the MeV energy range due to bright albedo and Earth limb radiation, background nuclear lines from the instrument and spacecraft, and nuclear lines produced by activation of the instrument and spacecraft by charged cosmic rays. The latter is especially dangerous and very hard to fight because this radiation usually is delayed after activation occurs. For low-Earth orbit the time spent by the spacecraft in the South-Atlantic Anomaly (SAA) region with very high fluxes of trapped charged particles causes most of the activation. Experience from SPI and IBIS onboard INTEGRAL is invaluable for the GECCO design optimization to reduce these backgrounds. We outline below the mitigation techniques implemented in GECCO:

a) bright albedo and Earth limb radiation: GECCO detectors are placed inside the effective and thick active BGO shield, covering the sides and the bottom of the instrument. They absorb most of side- and bottom-entering radiation and protect against dominating charged cosmic rays by creating a veto signal,
b) Material activation by charged cosmic rays: equatorial low-Earth orbit (550-600 km altitude, <5$^{\circ}$ inclination) is chosen as optimal to minimize the effect of SAA crossing. The GECCO design concept maximizes the use of composite and other non-metal materials in the instrument structure to reduce activation backgrounds,

c) Charged-particle cosmic rays: highly-efficient plastic-scintillator ACD is placed on the top of the ImCal, vetoing >99.9% of charged particles entering the detectors,
d) Secondary photons produced in the coded aperture mask by incident charged cosmic rays: the mask is covered by the highly-efficient plastic scintillator detector similar to the ACD design; it creates a veto signal to remove such background events from the analysis

## 5. GECCO observation and data analysis strategy

On orbit, GECCO will be capable of scanning or pointing, with the observation mode to be discussed and defined in the later stages of the project. In scanning mode, it will be observing the Galactic Plane, and will change to pointed mode to either increase observation time for special regions of interest, e.g., to observe the GC, or to observe transient events, e.g., flares of different origin or gamma-ray bursts. GECCO has two main observation configurations: the mask in stowed position, and the mask deployed at 20 meters away. The latter is the main configuration. As was described above, the GECCO data is divided naturally into two simultaneously obtained sets: the Compton data and the mask data.

**In the deployed mask configuration**, **the Compton data** provide ~ 1sr FoV practically unobscured by the mask in an energy starting at ~250 keV, with angular resolution 3-5º FWHM depending on energy. The main background components are the natural (diffuse) radiation in its FoV and artificial activation radiation.
The mask data consist of two parts. One is single-hit events (predominantly at low energy), and the second is made of Compton-reconstructed events. For the events with several hits in the CdZnTe Imaging calorimeter, the Compton reconstruction is necessary to determine which hit corresponds to the first interaction and can be used in the image reconstruction. This requirement reduces the number of events to be used in the image reconstruction, but so far this is the only viable way unless an alternative approach of finding the point of first interaction is found.

**The mask in stowed position**. This configuration provides the lowest contribution from external (natural) radiation and is very useful for benchmarking and calibration measurements because the detecting volume is effectively sealed from all directions. The Compton data will provide approximately the same continuum sensitivity; however the background contributors are different due to FoV occultation by the mask. For the mask data no Compton pointing is needed but still Compton reconstruction is necessary for multi-hit events to determine the point of 1$^{st}$ interaction. The single-hit events at low energy can provide higher sensitivity than for the deployed mask configuration but with poorer angular resolution of ~20 arcmin.

**The mask in intermediate position**. This feature can be useful for the mapping of extended sources with the mask data, when the instrument angular resolution is close to the angular size of the source of the interest. By positioning the mask at different distances from the imaging plane, its angular resolution can be adjusted accordingly.

**BGO panels as a GRB locator.** The presence of 8 large-size detectors (~3,000 cm$^2$ each) positioned at different angles, plus the ImCal at "zenith" angle, represents a great opportunity to



PoS(ICRC2021)648

detect GRBs. Our preliminary simulations show that a few degrees localization is feasible, depending on the brightness and direction of the GRB. With subsequent re-pointing of GECCO to the GRB direction its position can be determined with the full power of GECCO, that is at sub-arcmin precision. Unfortunately, the spacecraft slewing will take a few minutes, sometimes a few tens of minutes, depending on the required slewing angle, restricting accurate measurements for the majority of short GRBs.

**GECCO triggering.** The main GECCO trigger is provided by its main detector, the ImCal with the threshold of < 50 keV. The BGO, ACD and the mask ACD are used as veto detectors. Also, the GRB mode is enabled by an independent BGO trigger which will be readout independently.

**The expected performance of GECCO:** Energy range 50 keV−10 MeV, and energy resolution < 1% at 0.5−5 MeV. In the mask mode the angular resolution is ∼1 arcmin within $3^{\circ}-4^{\circ}$ field-of-view, while in the Compton mode the angular resolution is $3^{\circ}-5^{\circ}$ in a ~1sr FoV. The sensitivity calculation is not trivial for MeV instruments because it is strongly affected by the backgrounds and methods of their suppression, both in the instrument design and in continuously evolving data analysis. The sensitivity for the mask data analysis is similarly difficult to quote in the current phase of development as will strongly depend on the particular observation region, on the instrument configuration, and also on the data analysis. However, the sensitivity should be superior to all currently existing missions, with conservative estimates at $10^{-6}-10^{-5}$ MeV/cm$^2$/s level over the entire energy range for $10^6$ s observation time.

## 6. Acknowledgements

This work was supported by NASA under award numbers 80GSFC17M0002 (CRESST) and 80NSSC20K0573 (APRA).

## 7. References

[1] W.B. Atwood et al., *ApJ* **697**, 1071 (2007)
[2] A. Zoglauer et al., *New Astronomy Reviews* **50** (7-8), 629 (2006)
[3] G.K. Skinner, *NIM* **221**, 33 (1984)
E. Caroli et al., *Space Science Reviews* **45**, 349 (1987)
[4] A.E. Bolotnikov et al., *NIM* **A954**, 161036 (2020)

**GECCO collaboration:**

D.M. Asner[1], M.G. Baring[2], P.F. Bloser[3], A.E. Bolotnikov[1], E. Bottacini[4,5], T. Brandt[6], N. Cannady[7,8], G.A. Carini[1], W. Collmar[9], A. Coogan[10], G. DeNolfo[6], S. Digel[11], V. Eberle[9], T. Enßlin[9], I. Grenier[12], A. Harding[3], D. Hartmann[13], S. Hermann[1], D. Kazanas[6], M. Kerr[14], R. Krivonos[15], P. Laurent[12], F. Longo[16], J.W. Mitchell[6], A.A. Moiseev[8,17,*], L. Morrison[19], A. Morselli[18], I.V. Moskalenko[5], R.F. Mushotzky[17], M. Negro[7,8], E. Orlando[5,16], Stefano Profumo[19], M. Sasaki[8,17], C.R. Shrader[8,20], G.K. Skinner[21], F. Stecker[6], A.W. Strong[9], S. Sturner[7,8], P. Shawhan[17], L. Smith[17], H. Tajima[22], D. Thompson[6], J. Tomsick[23], Z. Wadiasingh[24], R. Woolf[14], E. Yates[17], K.-P. Ziock[25], A. Zoglauer[23]

[1] Brookhaven National Laboratory (BNL), USA
[2] Rice University, Houston, USA
[3] Los Alamos National Laboratory (LANL), USA
[4] University of Padova, Italy
[5] Stanford University, USA
[6] NASA/Goddard Space Flight Center, USA
[7] University of Maryland, Baltimore County, USA
[8] CRESST/NASA/Goddard Space Flight Center, USA
[9] Max Plank Institute, Germany
[10] GRAPPA, University of Amsterdam, the Netherlands
[11] Stanford Linear Accelerator Center (SLAC), USA
[12] CEA Saclay, France
[13] Clemson University, USA
[14] Navy Research Laboratory (NRL), USA
[15] Space Research Institute (IKI), Russia
[16] INFN Trieste, Italy
[17] University of Maryland, College Park, USA
[18] University of Rome Tor Vergata, Italy
[19] University of California at Santa Cruz, USA
[20] Catholic University, Washington DC, USA
[21] University of Birmingham, United Kingdom
[22] Nagoya University, Japan
[23] University of California, Berkeley, USA
[24] University Space Research Association (USRA), USA
[25] Oak Ridge National Laboratory, USA
[*] corresponding author, amoiseev@umd.edu