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

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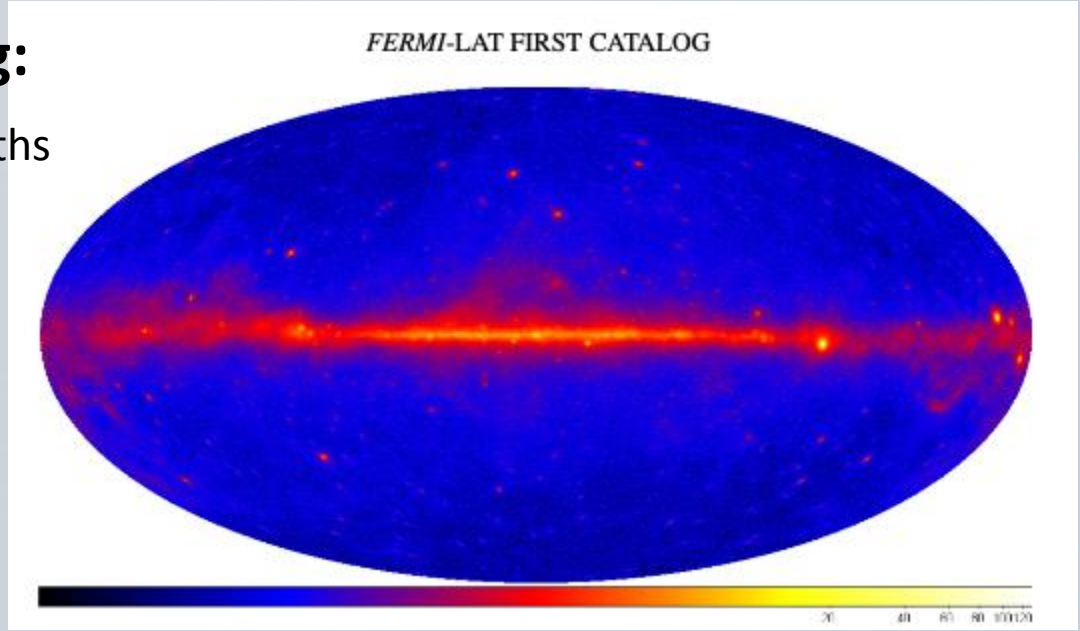
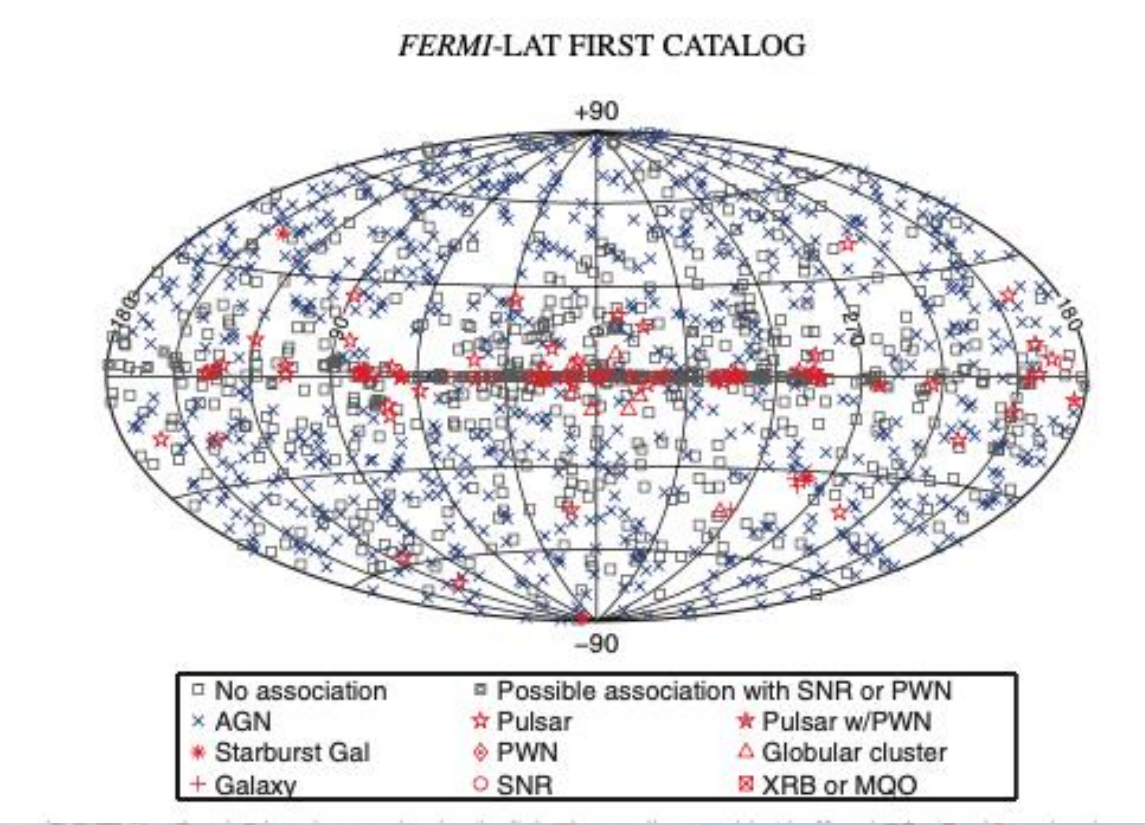
For the GECCO Team

One who wants to do something will find a way;
one who does not will find an excuse
(Socratus, Confucios,… Abraham Lincoln, Russian saying)

Motivation, First push: ~2010, Fermi-LAT 1st Catalog:

- 1,451 sources, **630 sources are unassociated** with other wavelengths
- Dense source population in Galactic plane
- Un-associated sources in Galactic plane and Galactic Center





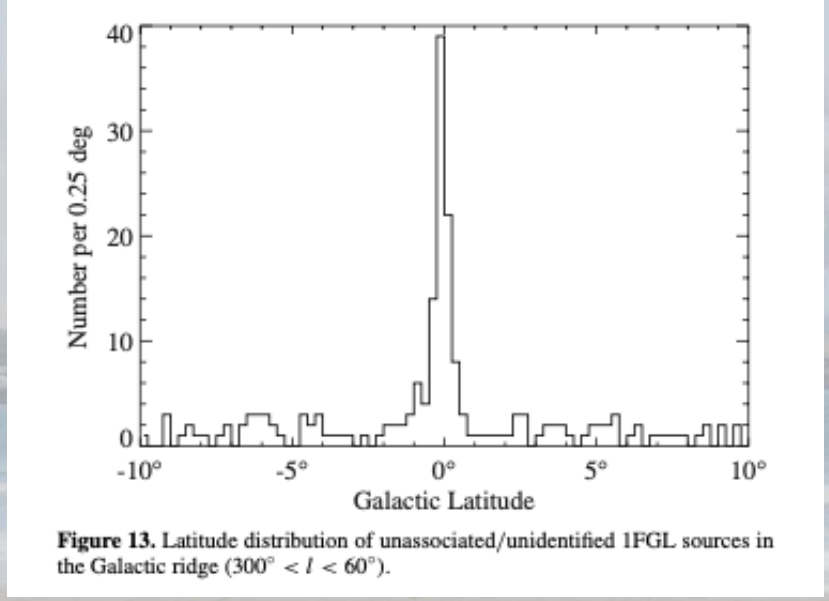
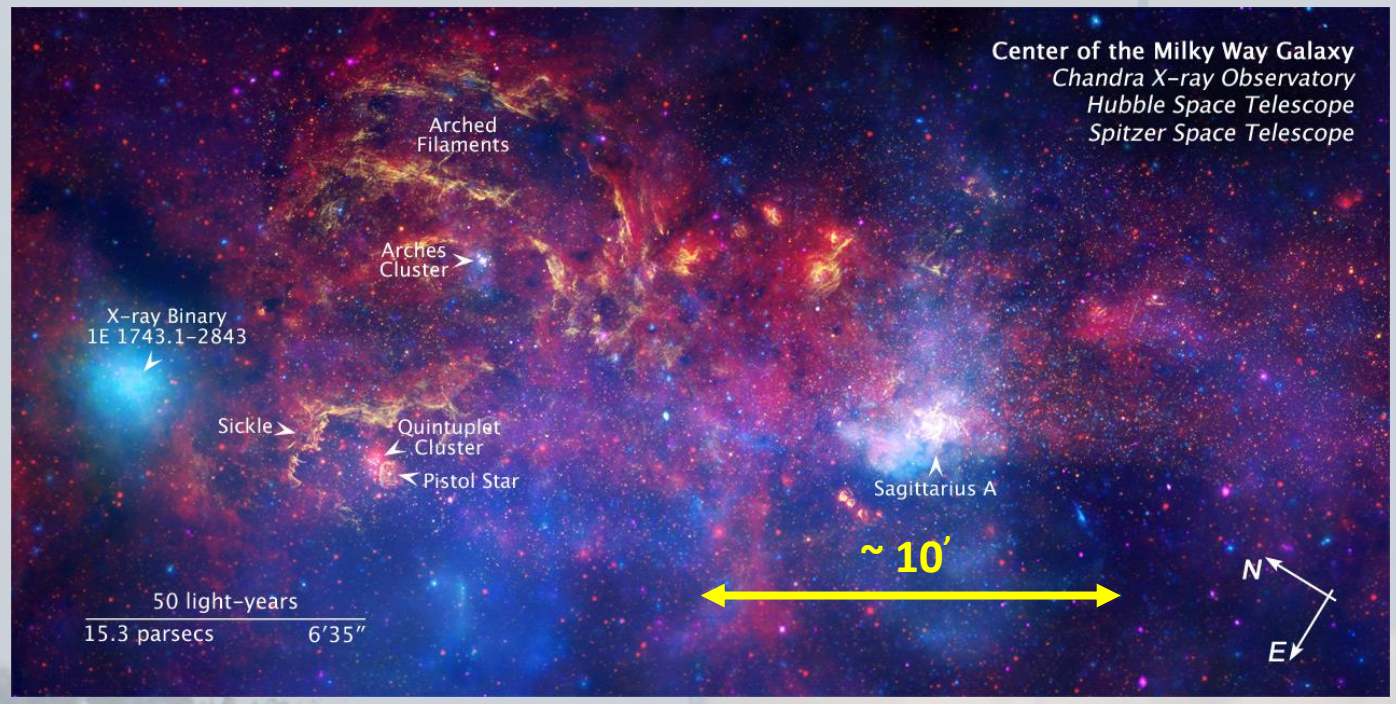


Figure 13. Latitude distribution of unassociated/unidentified 1FGL sources in the Galactic ridge ($300^\circ < l < 60^\circ$).

A. Abdo et al., 1FGL, 2010

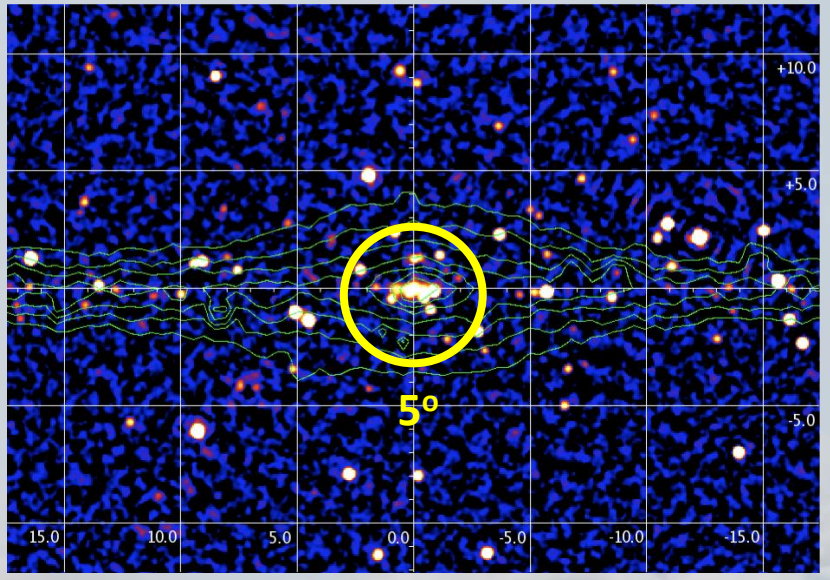
At the same time: “our own” supermassive black hole environment needs more measurements



Source population density in the GC (Chandra/Hubble/Spitzer data) **is <arcsec.**

We need angular resolution of ~arcmin to resolve high-energy source population in heavy populated sky regions

INTEGRAL/IBIS observations

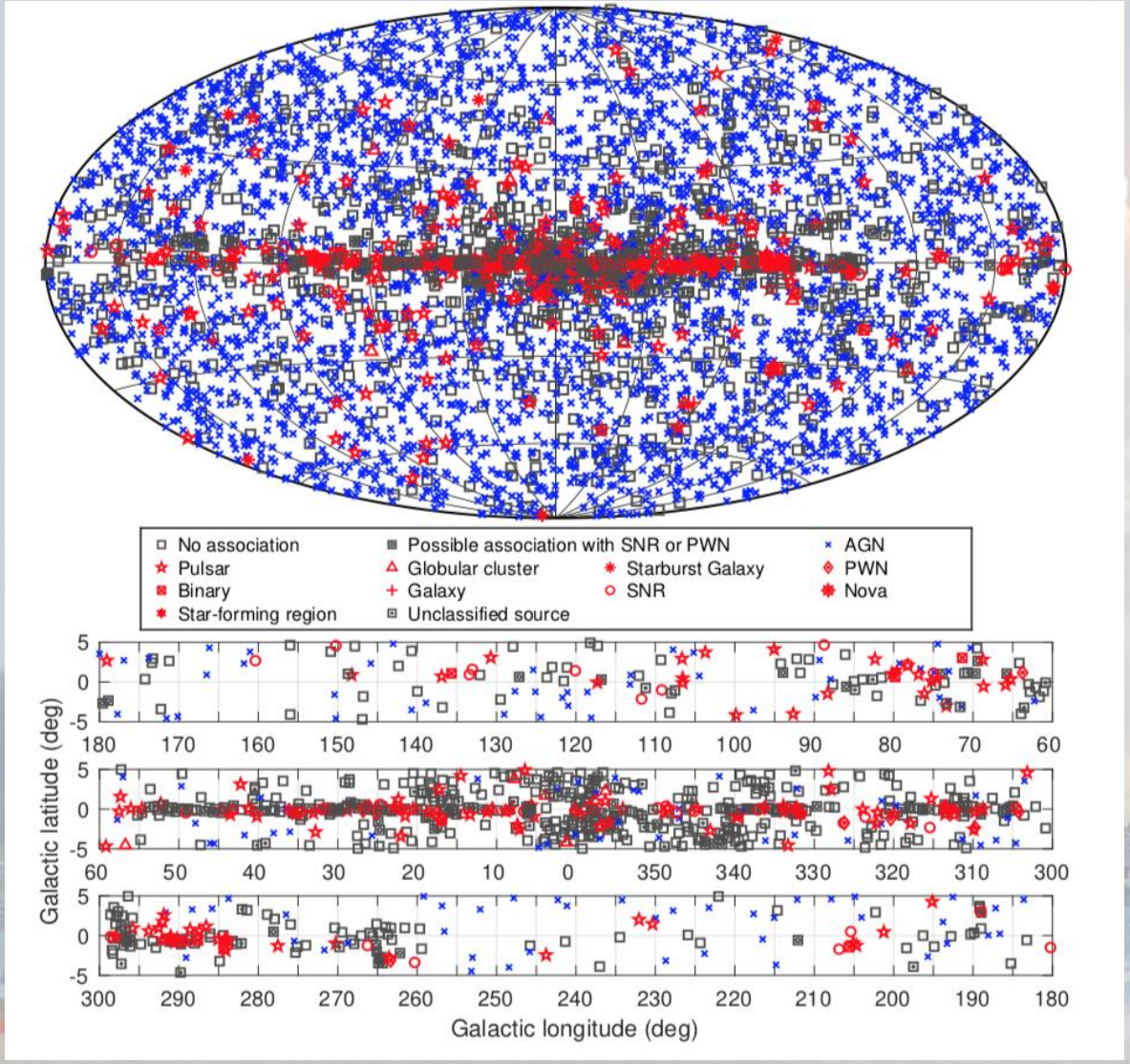


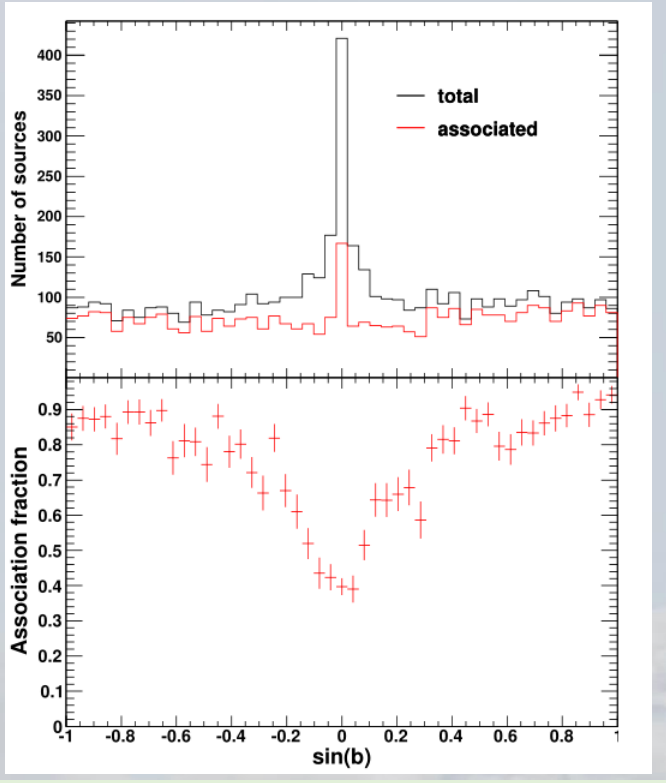
Central part of the Galaxy as measured by INTEGRAL / IBIS 17-60 keV (Krivonos et al., 2010). IBIS angular resolution is 12 arcmin.

521 source, 485 are identified

Presently more exciting measurements from NuSTAR

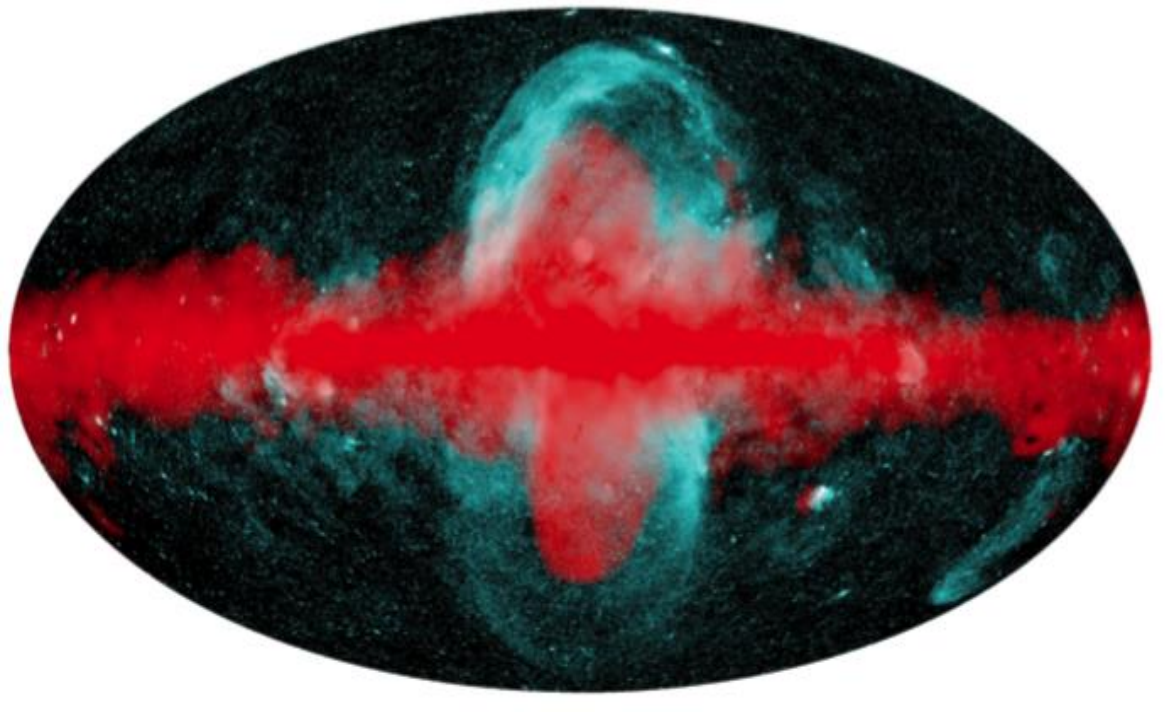
2019: Better, but still: Fermi-LAT 4FGL: 5,065 sources, 1,323 unassociated

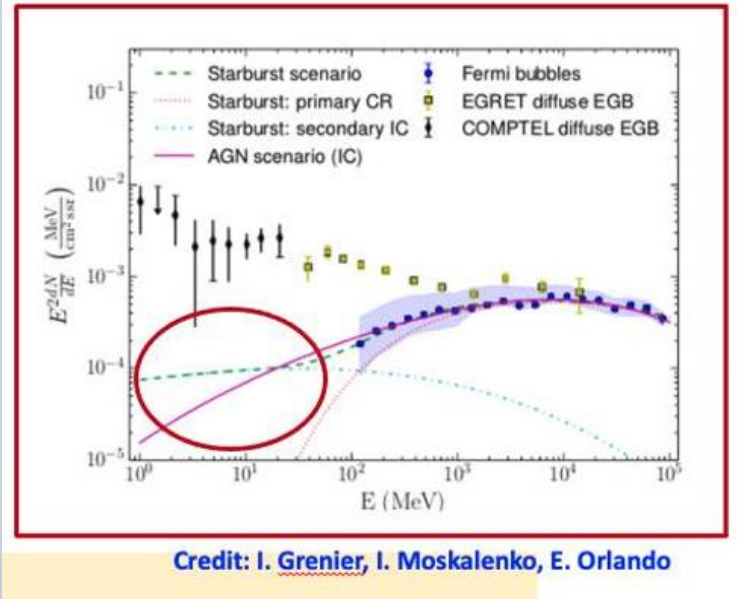




- **1,323 sources (~25%) do not have associations with other wave-length sources, with majority in GP and GC: Why not associated? and Who Are They?**
- **Position resolution of ~arcmin will help to resolve**

The Fermi Bubbles: one of the most unexpected (?) and spectacular discoveries by Fermi LAT, and now - eROSITA !!!





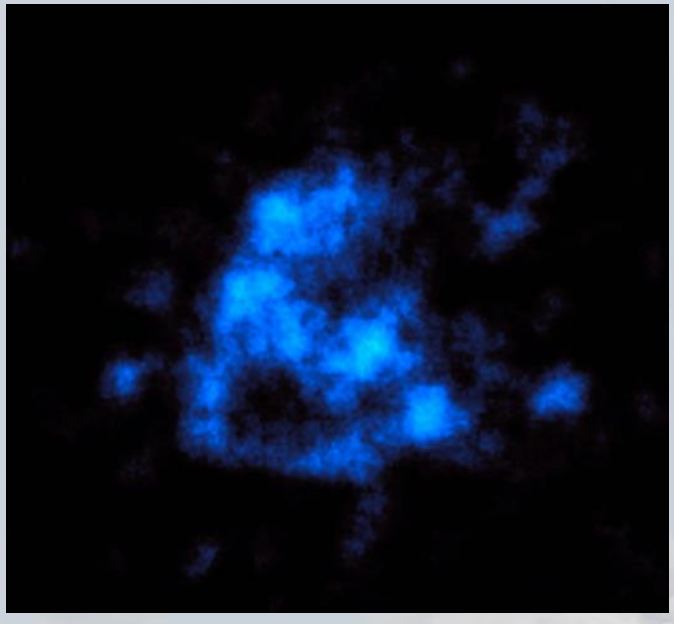
Credit: I. Grenier, I. Moskalenko, E. Orlando

Comparison of the morphology of the γ-ray (Fermi-LAT, >50 MeV, shown by red) and X-ray (eROSITA, 0.6-1 keV, shown by cyan color) Bubbles (P. Predehl et al., Nature 2020)

- Do the Fermi and eROSITA Bubbles have the same nature?
- What to expect in sub-MeV (GECCO) energy range?

CasA supernovae

Spitzer, Chandra and Hubble images.
Map of heated non-radioactive materials (iron)



NuSTAR image in ~70 keV line (^{44}Ti)
Map of radioactive material in SNR

B. W. Grefenstette et al., Nature 12997, 2014

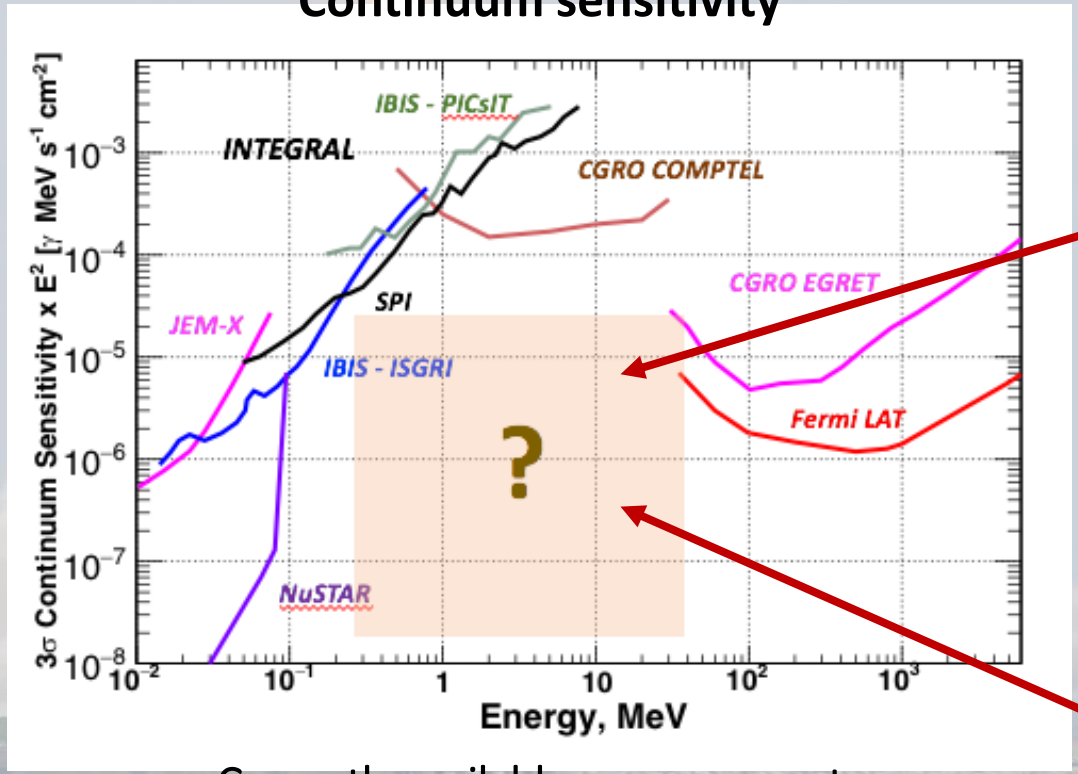
These images do not match up well → ???

"GECCO has to find CasA missing ^{44}Ti cousins"
Dieter Hartmann

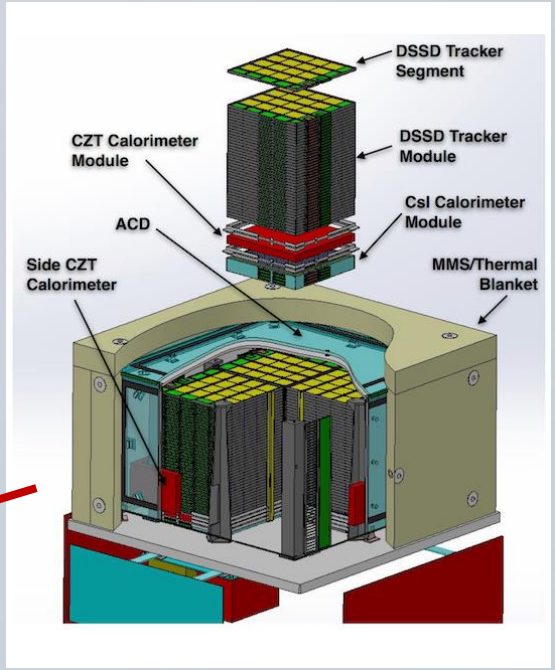
Where are we in MeV-GeV γ–ray Astronomy?

Fermi-LAT (GLAST): 2008 – currently operating

Continuum sensitivity



Currently available measurements



AMEGO, to be proposed as NASA/Probe mission

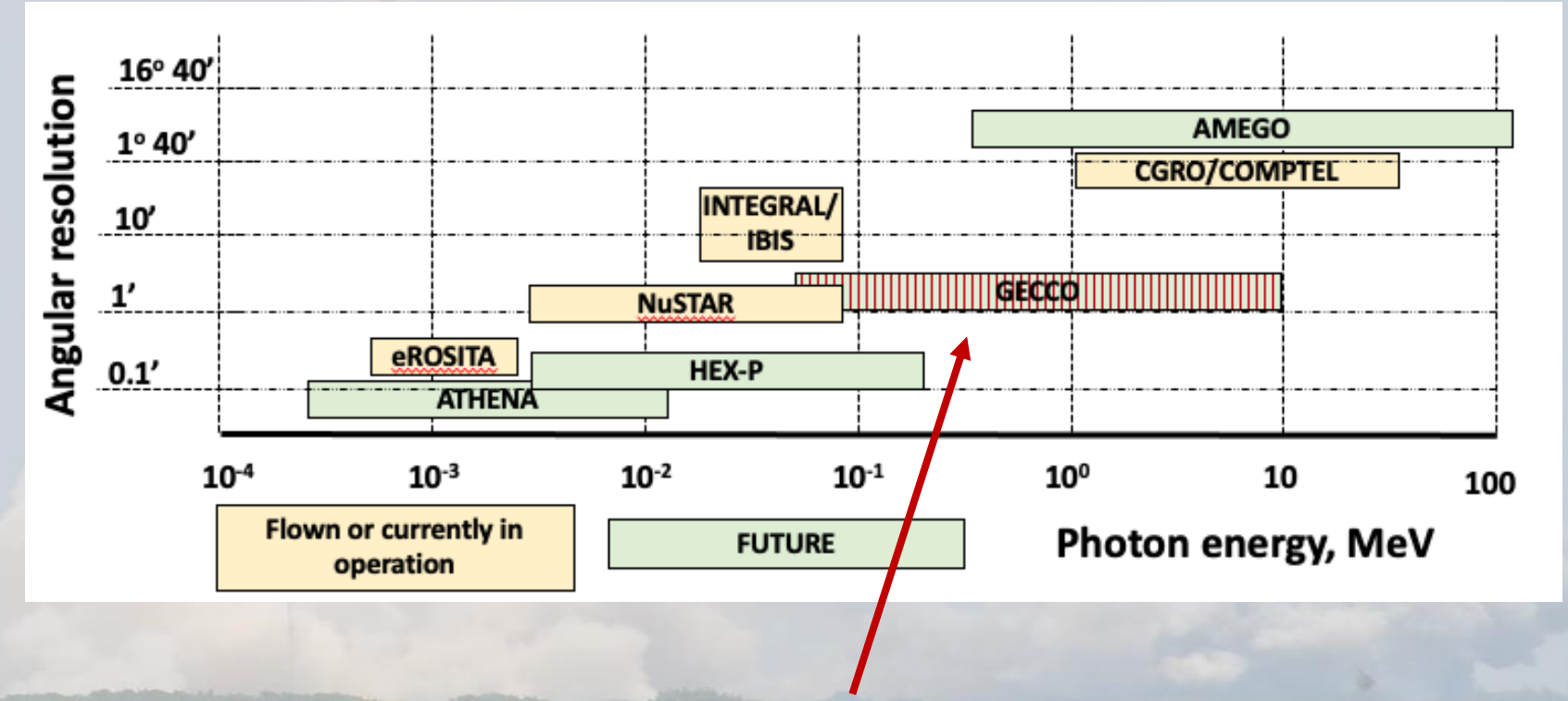
Spatial resolution is a big problem in this energy range

GECCO

Where are we in MeV-GeV γ–ray Astronomy?

Fermi-LAT (GLAST): 2008 – currently operating

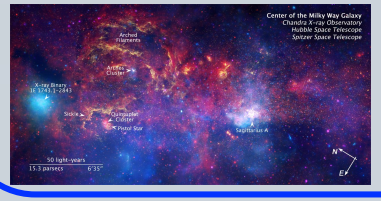
Angular resolution

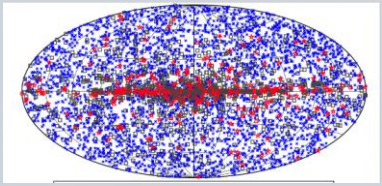


GECCO will conduct high-sensitivity measurements of the cosmic γ-radiation in the energy range 50 keV - 10 MeV and create intensity maps with high spectral and spatial resolution

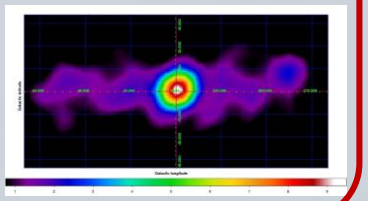
GECCO Science and Observations objectives

Understand the nature of the central supermassive black hole environment and sources, including >1,000 unassociated Fermi sources at the Galactic Center; address the enigma of Galactic Center excess (a bulge)

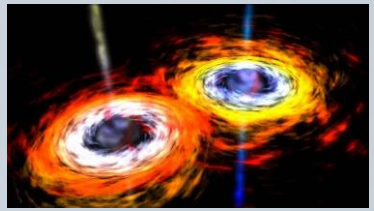


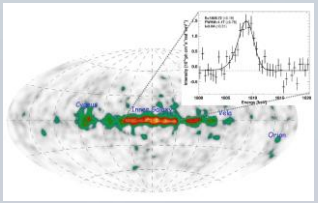


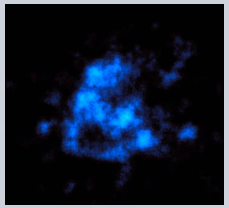
Localize and clarify the origin(s) of the 511 keV positron annihilation line



Identify and precisely localize t the source of the gravitational wave and neutrino events

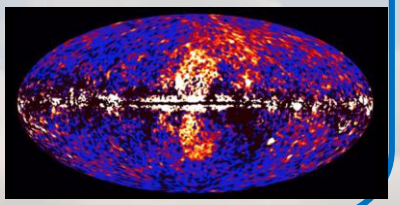






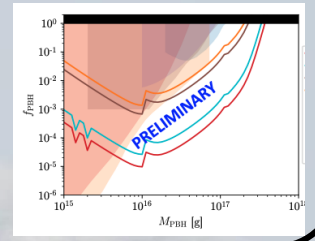
Resolve Galactic chemical evolution and sites of explosive element synthesis

Investigate the origin(s) of the Fermi Bubbles by mapping them, especially their bases near the GC

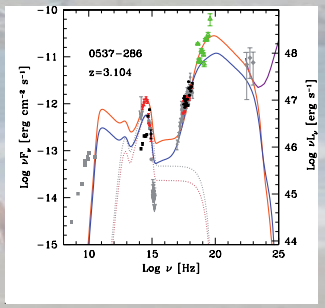


Resolve heavily populated sky regions, including tangential directions to the spiral arms in the Galactic plane

Test as-yet unexplored candidates for the dark matter



Detection and identification of high-redshift blazars



Prioritization of the science objectives, as well as the observation strategy will be made closer to the Proposal time to be aligned with newest developments and standing problems

Galactic Center Environment: Measurements approach

Galactic Center γ-ray excess (a bulge) has been recently confirmed by Fermi LAT

To understand its Origin, the contribution from unresolved point sources has to be identified and separated. Spatial resolution of arcmin-level is needed.

The Goal: reach the "Bottom" of the GC γ-radiation, or actual diffuse, or continuum, radiation. After subtraction of known contributors: is there going to be any residual, unexplainable component?

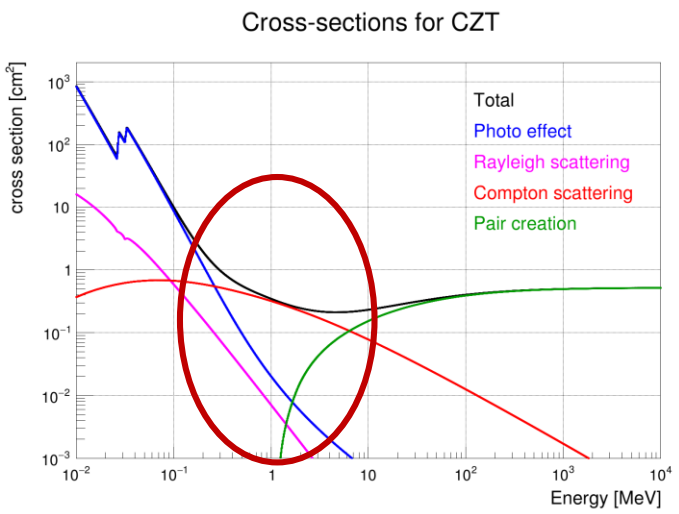
Potential contributors: MSP, PBH, binaries, DM, what else?

Expected ~1,000 pulsars within 1^o around GC, or **~ 0.3 pulsar/arcmin^2**

Star-forming regions (LMC, M31): also γ-ray excess: need to resolve sources within fraction of degree

Mission Concept and Requirements for GECCO:

1. **Investigation of fine structure and the composition of inner Galaxy in γ-rays: requires ~arcmin angular resolution for the point sources, capability to measure diffuse radiation, and 1-2 % energy resolution**
2. **Probing Galactic chemical evolution and sites of explosive element synthesis: requires ≲1% energy resolution**
3. **Contribution to the multimessenger astrophysics (GW and neutrino events): requires quick re-pointing to the target area**
4. **In GECCO concept we make all possible efforts to reduce all known backgrounds to maximize its sensitivity**



Credit: A. Zoglauer

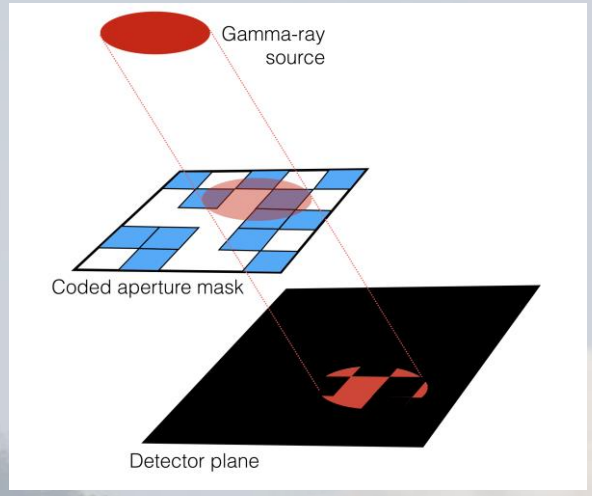
Angular Resolution: Even 1 degree of angular resolution is extremely difficult, or impossible to achieve in direct photon detection in energy range ~ 0.2-10 MeV with use of Compton effect

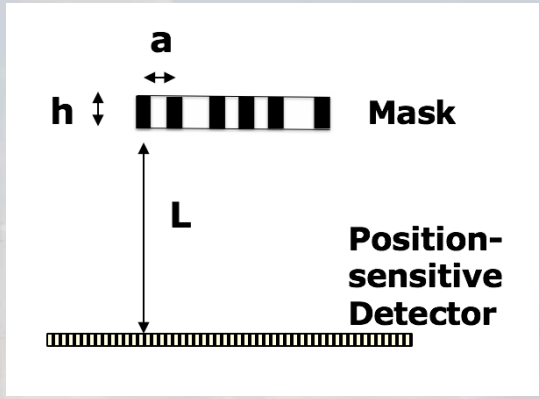
Below ~200 keV photoabsorption starts dominate: no photon direction can be obtained!

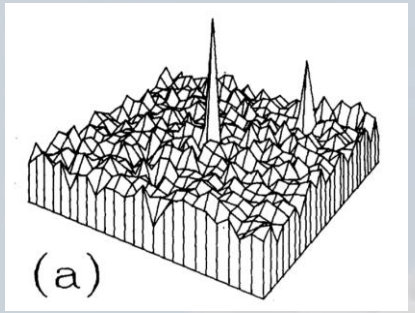
Moving to indirect measurement of photon arrival direction with a Coded Aperture method: cross-correlation of the coded mask pattern with its image on the detector plane, created by the parallel flux from point source

Coded Aperture Mask: the only feasible way to provide arcmin-level resolution in this energy range.

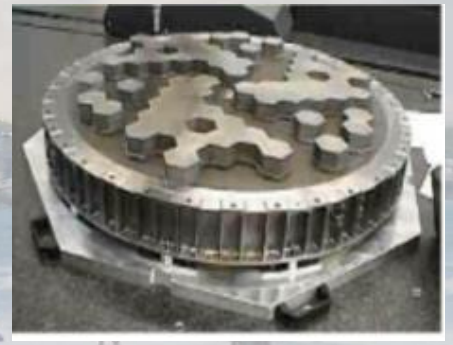
A Coded Aperture Mask (array of transparent and opaque elements) modulates the incident photon flux and creates its shadow (image) on the detector.



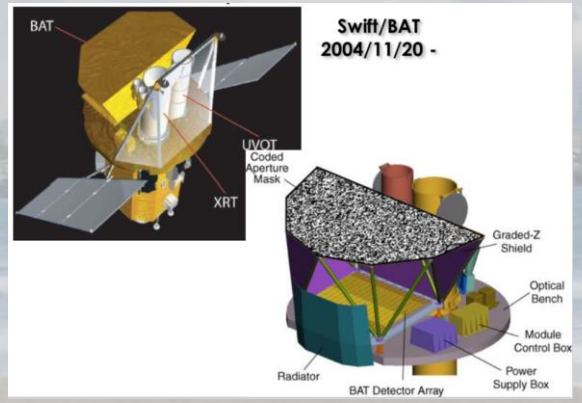




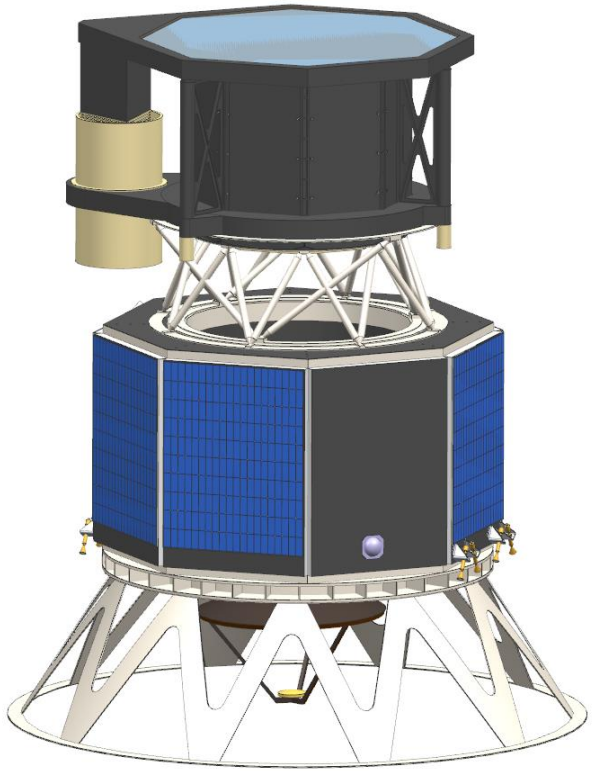
Angular resolution of the system is ~a/L. It can be made as good as we want if the Mask is placed at a large distance from the detector.



INTEGRAL - SPI



GECCO Conceptual Design: Compton telescope with deployable coded aperture mask

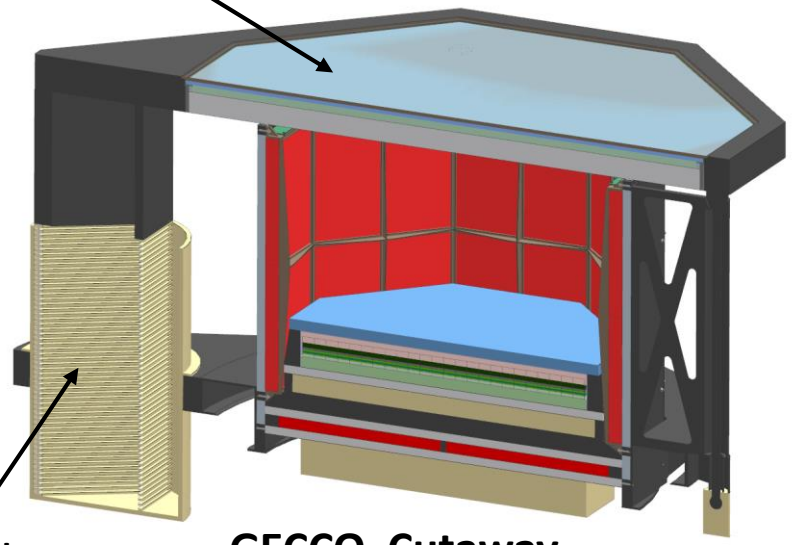


GECCO with Mask in stowed position, and notional SC bus

Coded Aperture Mask

Mask deployment cylinder

Incident photon flux is modulated while passing through the **Mask** and creates an image on the **CdZnTe** detector plane.



GECCO, Cutaway

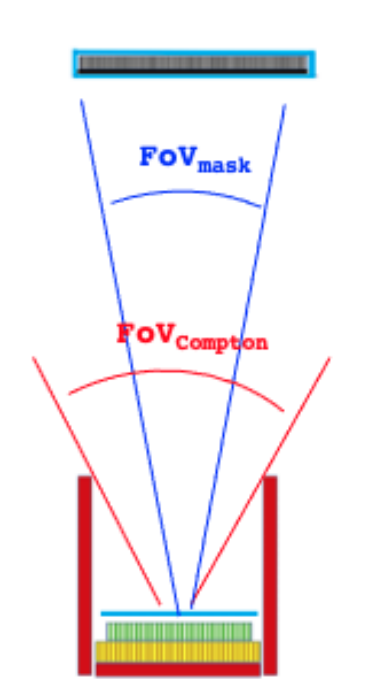
Plastic scintillator **anticoincidence detector** above the CdZnTe Imager provides protection against charged cosmic rays

The **CdZnTe** Imager provides detection of incident photons with a position resolution of <1mm and with energy resolution of ~1%.

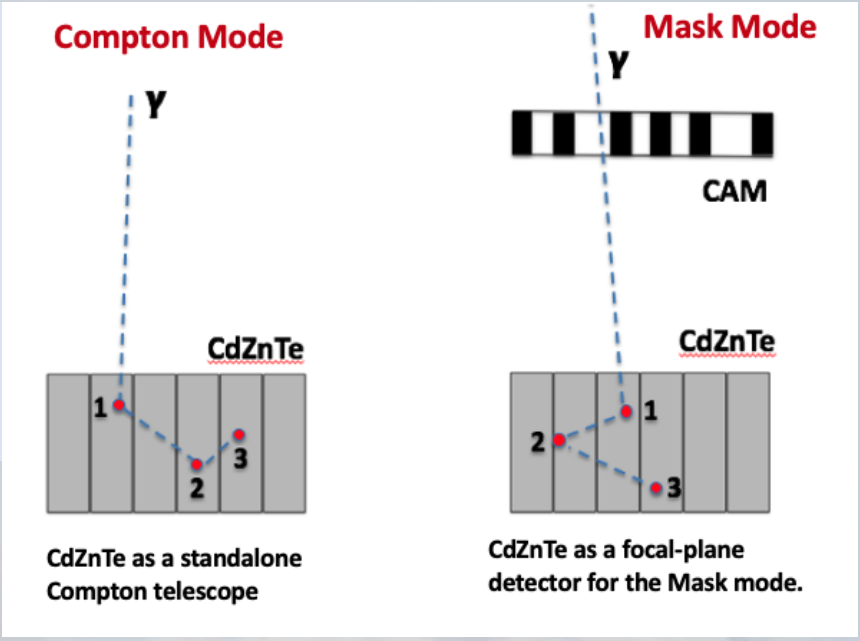
BGO shield provides absorption of natural background photons and vetoes production of background photons by charged cosmic rays

CsI 5-cm thick log calorimeter measures energy escaping from **CdZnTe Imager**

GECCO principle of operation: Compton Telescope + Coded Aperture Mask Telescope



- **Compton mode to measure large-scale diffuse**: CZT as a Compton telescope with 3-5° direction reconstruction accuracy and Field-of-View (FoV) ~ 1 sr
- **Mask mode to measure point sources and small-scale diffuse:** angular resolution ~1 arcmin and FoV ~ 4° (with Mask at 20 meters)



Why deployable Mask: angular resolution is inverse proportional to the Mask-detector separation

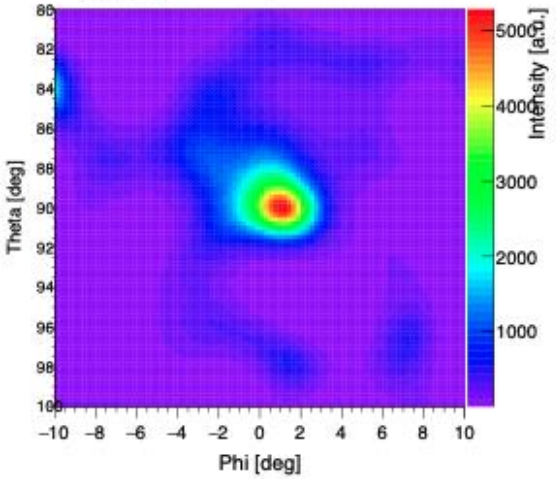
BUT the problem: huge side-entering background radiation.

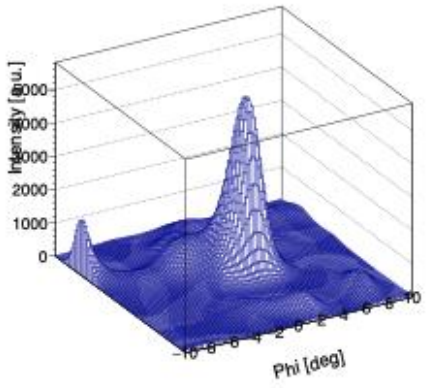
GECCO: Compton telescope is used to select photons arrived from the Mask area. Most of side-entering background photons are eliminated

BGO shield helps to veto not fully-contained events

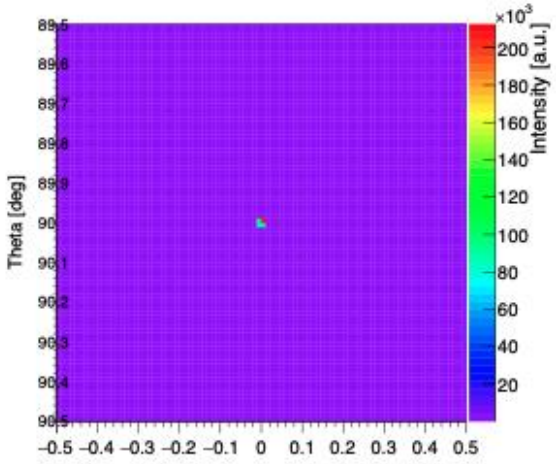
Simulated GECCO performance: imaging of the point source

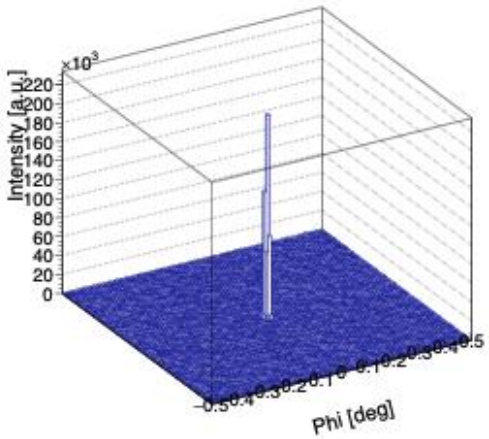
Compton analysis (FoV ~ 60°)



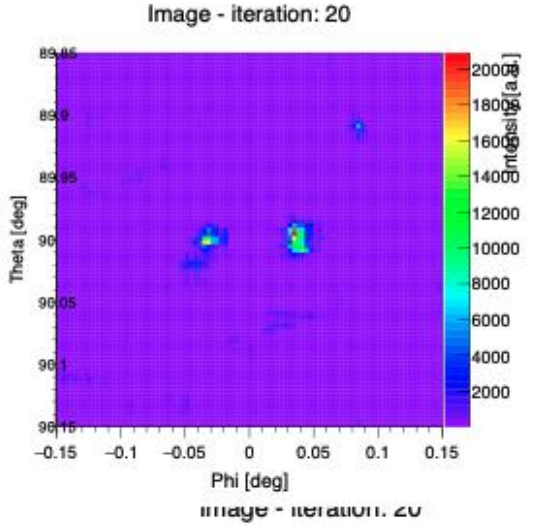


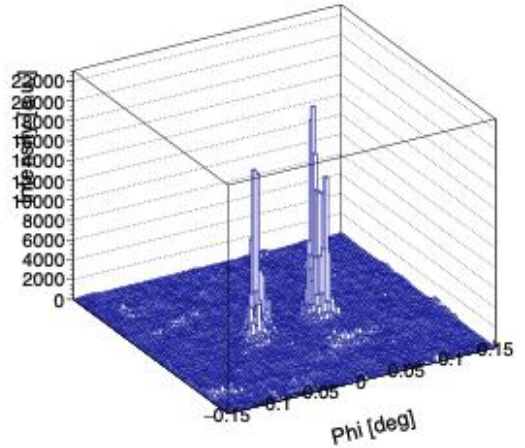
Mask analysis (FoV ~ 4°)





Two sources separated by 4’





Why deployable/retractable Coded Mask?

The fine structure of small-size extended objects (*e.g.*, SNR) can be mapped if the angular resolution of the Coded Mask system is comparable with the size of the object

Detection of extended sources by the Coded Aperture Mask INTEGRAL/IBIS

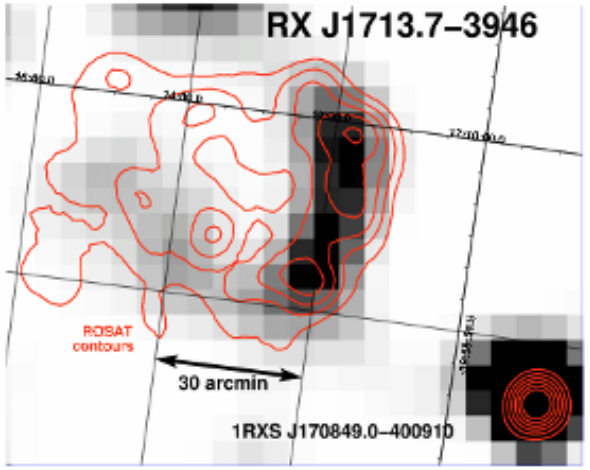


Fig. 4. INTEGRAL/IBIS hard X-ray (17–60 keV) image of the supernova remnant RX J1713.7–3946. The gray scale on the map is proportional to the hard X-ray flux. The map obtained by ROSAT in the soft X-ray (0.5–2.5 keV) band is shown by contours.

R. Krivonos et al., A&A 475, 775, 2007

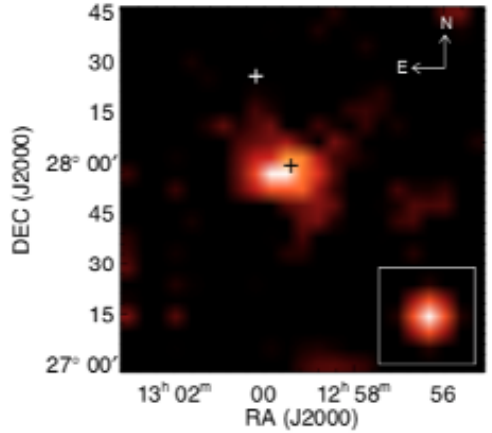
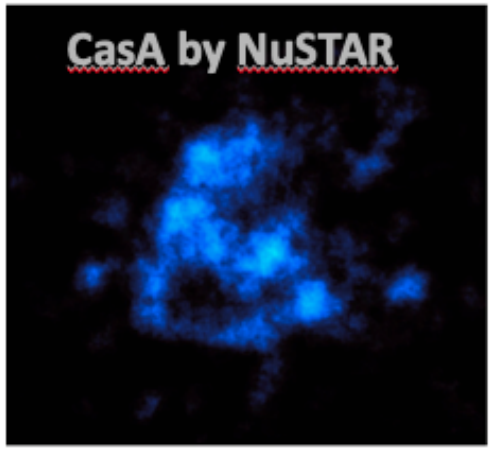


Fig. 1. IBIS/ISGRI significance image of the Coma cluster in the 18–30 keV energy range. The black cross indicates the position of NGC 4874, near the center of the X-ray emission from Coma (Briel et al. 2001). The white cross shows the location of X Comae, a bright Seyfert galaxy at ~30′ from the cluster. The colour scale is linear, with black corresponding to 1σ and white to 8σ. The IBIS SPSF is also shown in the lower right corner.

M. Renaud et al., A&A 453, L5, 2006

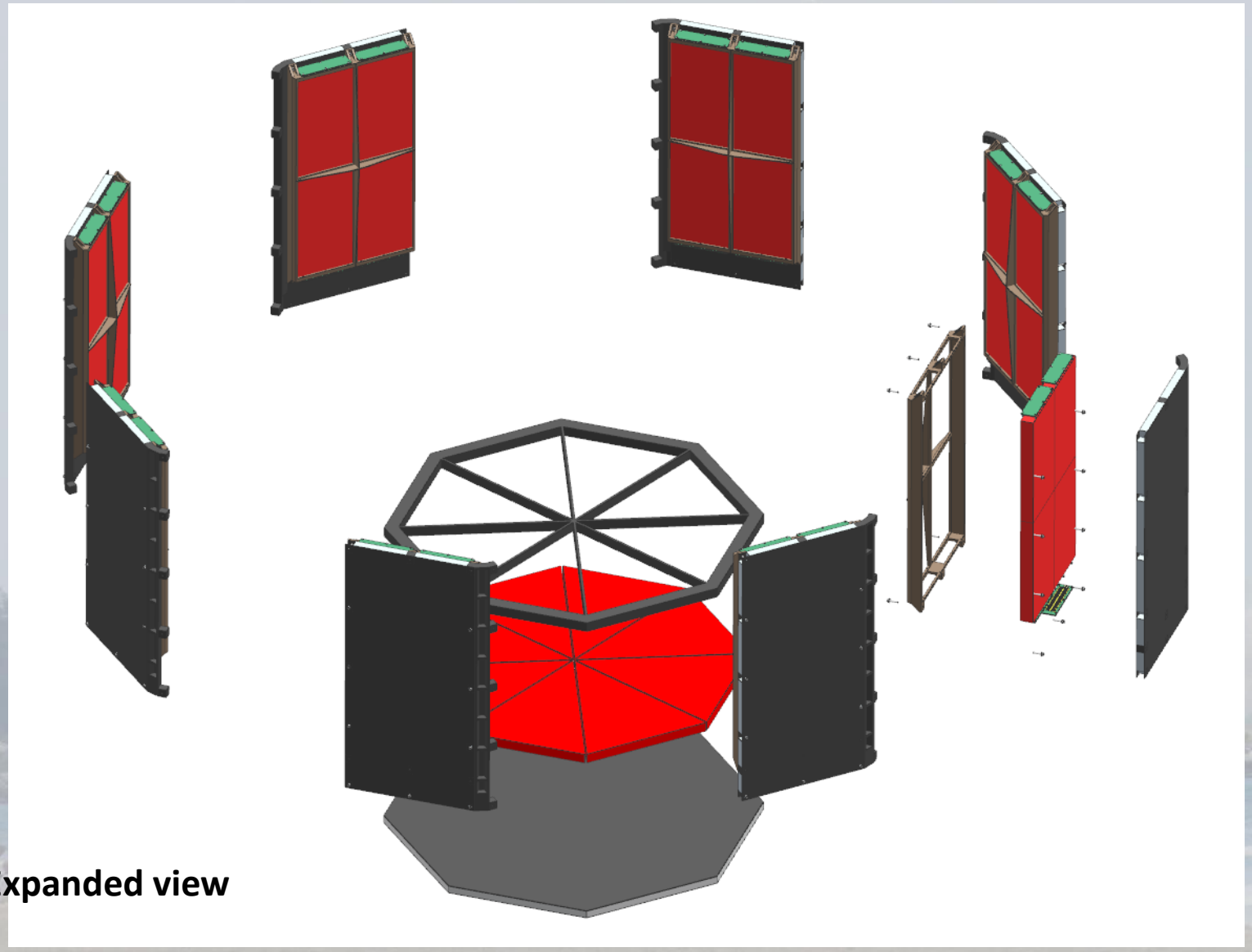


NuSTAR image in ~70 keV line (^{44}Ti)
Map of radioactive material in SNR

B. W. Grefenstette et al., Nature 12997, 2014

There is a list of high-energy extended sources in 4FGL catalog with >40 sources smaller than 30-40 arcmin. The morphology of extended sources can potentially be explored by GECCO. This feature is enabled by GECCO retractable Coded Mask

BGO shield as GRB monitor: Burst Octagon



Expanded view

8 panels ~3,000 cm each + CZT Calorimeter: 9 directions for GRB detection and location with expected angular precision sufficient to re-point GECCO and use a full power of the Mask-provided source localization

GECCO Expected Performance

Energy Range: 50 keV – 10 MeV range,

Energy resolution: < 1% at 0.5 – 5 MeV.

Angular resolution:

~1 arcmin in the Mask mode with 3^o – 4^o field-of-view,

3^o – 5^o in the Compton mode with a 60^o field-of-view

Sensitivity: 10^{-4} - 10^{-6} MeV cm^{-2} s^{-1} over the entire energy range, depending on the observation time and analysis specifics

GECCO can be operated in either scanning or pointed mode, to be optimized according to the given science objective.

- In scanning mode it will be observing mainly the Galactic Plane,
- it can change to the **pointed mode** to either increase observation time for special regions of interest, e.g., to observe the **Galactic Center**, or to observe **transient events**, e.g., flares of different origin or gamma-ray bursts.

SUMMARY

GECCO is a modern combination of already proven approaches:

- MeV low-background measurements (INTEGRAL/SPI),
- Coded Aperture Mask X- and **γ**-ray telescopes (SWIFT, INTEGRAL, several balloon payloads),
- Compton+Mask telescope (INTEGRAL/IBIS, also M. Galloway et al. 2017),
- Coded Mask for small-scale diffuse (XRT, IBIS),
- Diffuse-Point source separation (COMPTEL, Fermi LAT, D^3PO, other works),
- Compact solid-state detector as a standalone Compton telescope (COSI)

- **Main science objectives and observation strategy have been identified**
- **Baseline instrument concept is developed, main detectors are identified**
- **We are looking for the options to realize this ambitious project (scale of MidEx)**

THANK YOU!