The context of gamma-ray astronomy from space

Marco Tavani

(INAF and National Academy of Lincei)

Thanks to

- Andrea Bulgarelli, Nicolò Parmigiani, Martina Cardillo, Nicola Mazziotta (John Tomsik, Andreas Zoglauer)

Highest-Energy Astrophysics, a global view

- Today we can explore individual sources at the highest energies
- **Incredibly different and surprising situations**
- Particle acceleration under a large variety of conditions
- Fundamental Processes and Fundamental Physics
- Lots of still unknown mechanisms and surprises
- Relevance of time variability
- TeV Astronomy: a young sector of Astrophysics
- Multifrequency and necessity of synergy with space and ground detectors

TeV emission linked with GeV and PeV radiation

- Example of the Crab Nebula (Pevatron with power spectrum peak at 50 GeV)
- **TeV emission is most of the times inverse Compton out of energetic electrons**
- TeV emission also from hadronic processes (involve neutral pions produced by hadron beams interacting with photon or particle targets)
- In any case, **GeV information is crucial** (transition or peak) and going «deeper» in the process, **MeV, X-rays and optical, the realm of synchrotron emission !**

Understanding TeV emission therefore necessitates GeV and synchrotron information

- very often TeV information is not enough !
- Many examples
- SNR J1713
- GRB BOAT

Therefore, GeV -> MeV -> …

- Space gamma-ray missions
- 1980's **SAS-2 (GeV)**
- 1980's **COS-B (GeV)**
- 1990's **GRO (MeV and GeV)**
- 2010-2020's **AGILE (GeV)**, **Fermi (GeV)**
- 2027- … **COSI (MeV)**
- 2030's **?**

Therefore, GeV -> MeV -> …

- Space gamma-ray missions
- 1980's **SAS-2 (GeV)**
- 1980's **COS-B (GeV)**
- 1990's **GRO (COMPTEL - MeV; EGRET - GeV)**
- 2010-2020's **AGILE (GeV)**, **Fermi (GeV)**
- 2027- … **COSI (MeV)**
- 2030's **?**

Small vs. Large Missions

- The case of **AGILE** and **Fermi**
- In perspective, **SAS-2** as a precursor of **EGRET**
- **COSI** vs. a possible large MeV-GeV mission (**new-ASTROGAM**)
- **GEMMA**, a new proposed Small Mission (MeV-GeV)

Small vs. Large Missions

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- **GEMMA**, a new proposed Small Mission (MeV-GeV)

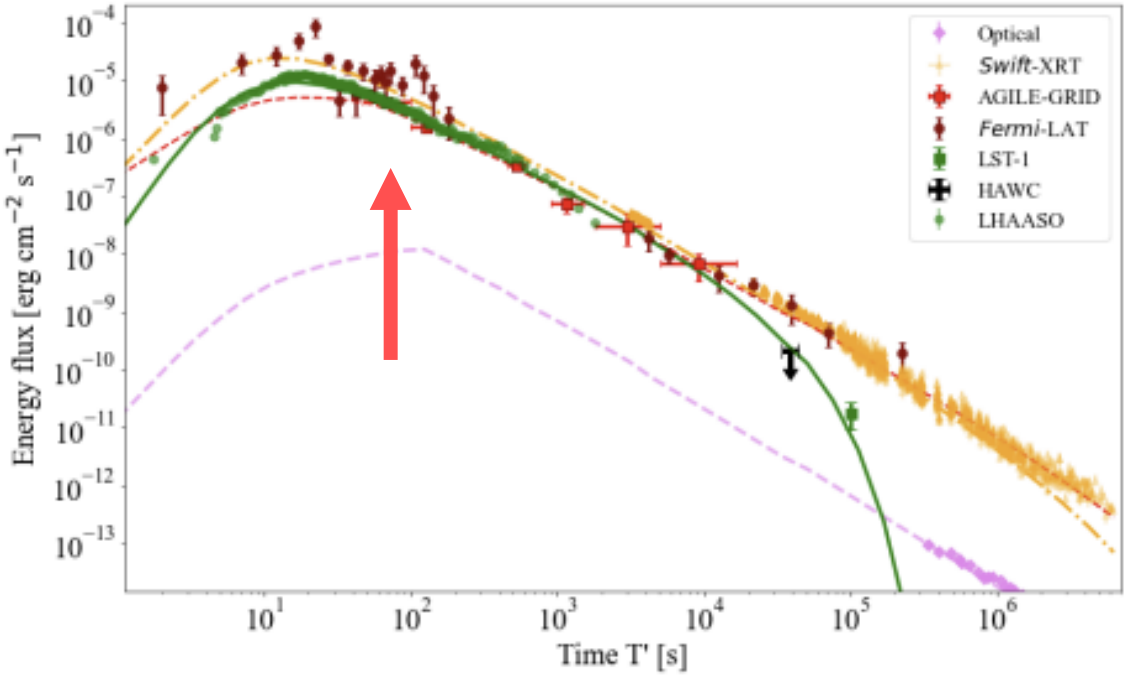
- **Small missions, 50 - 100 M$**
- **Large Missions, ½ - 1 G$**

GeV is clear, but what about MeV ?

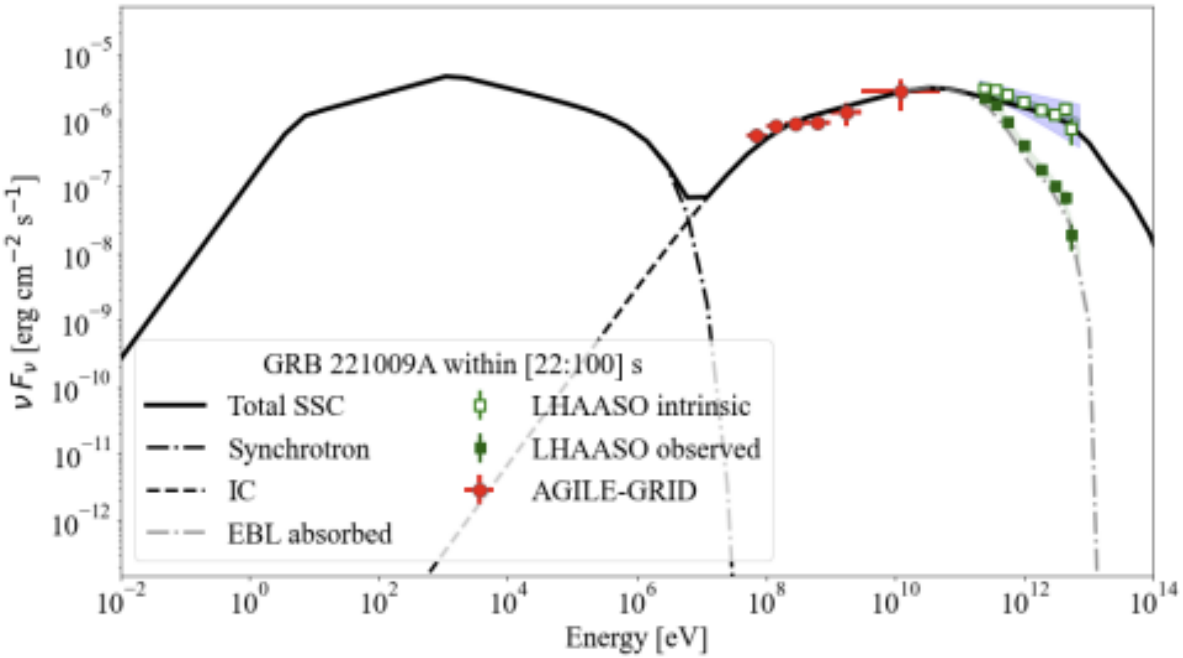
- MeV astrophysics
- Nucleosynthesis, nuclear lines
- 511 keV line
- Continuum emission (0.3 – 10 MeV)

- Continuum emission (1-100 MeV)
- Spectral cutoff, opt. thick
- Opt. thin emission, end of synchrotron, diagnostic on the largest particle energies
- ‘’V’’ in the spectral power, MeV-GeV

GRB 221009A, Foffano & Tavani 2025

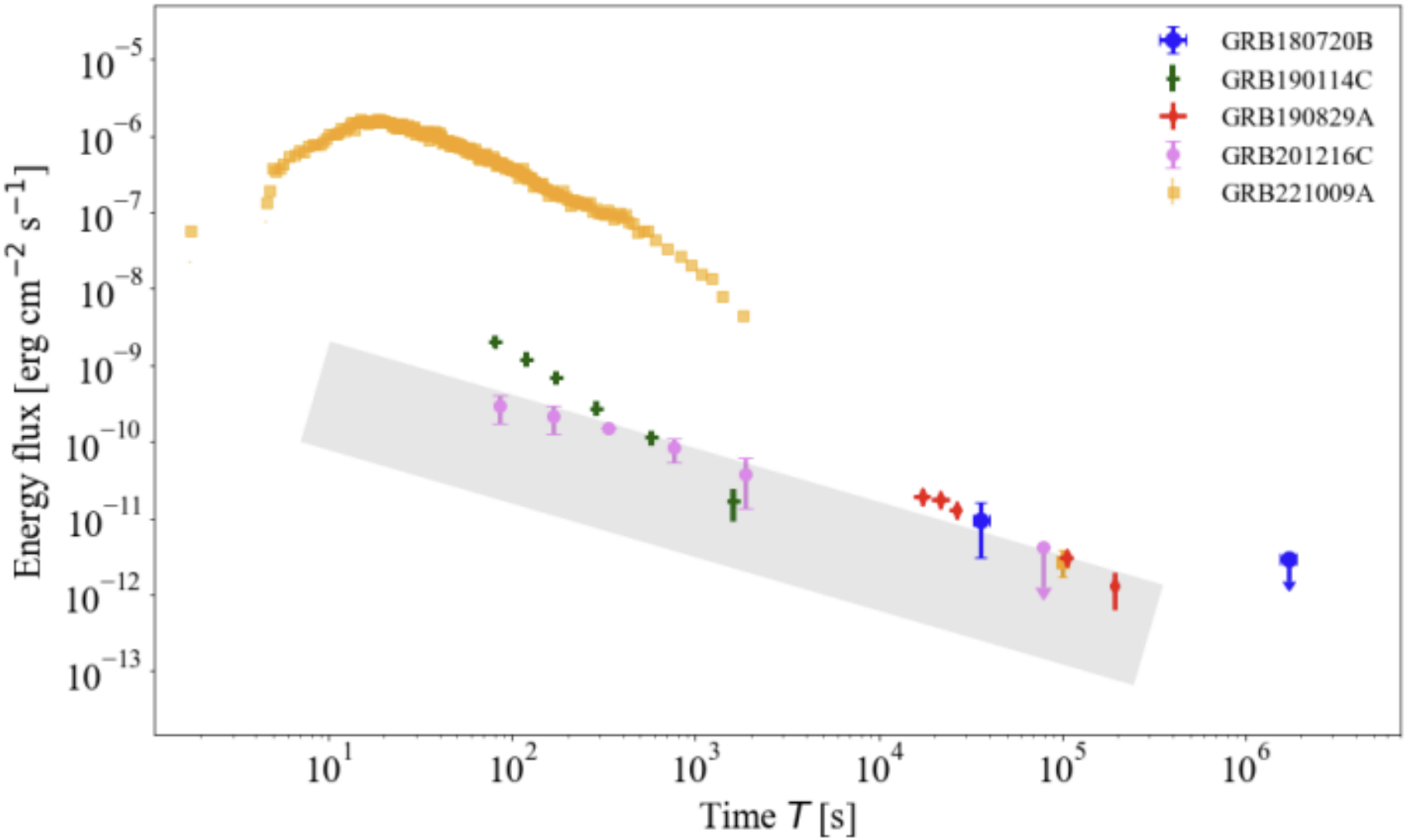


(a) Light curve.

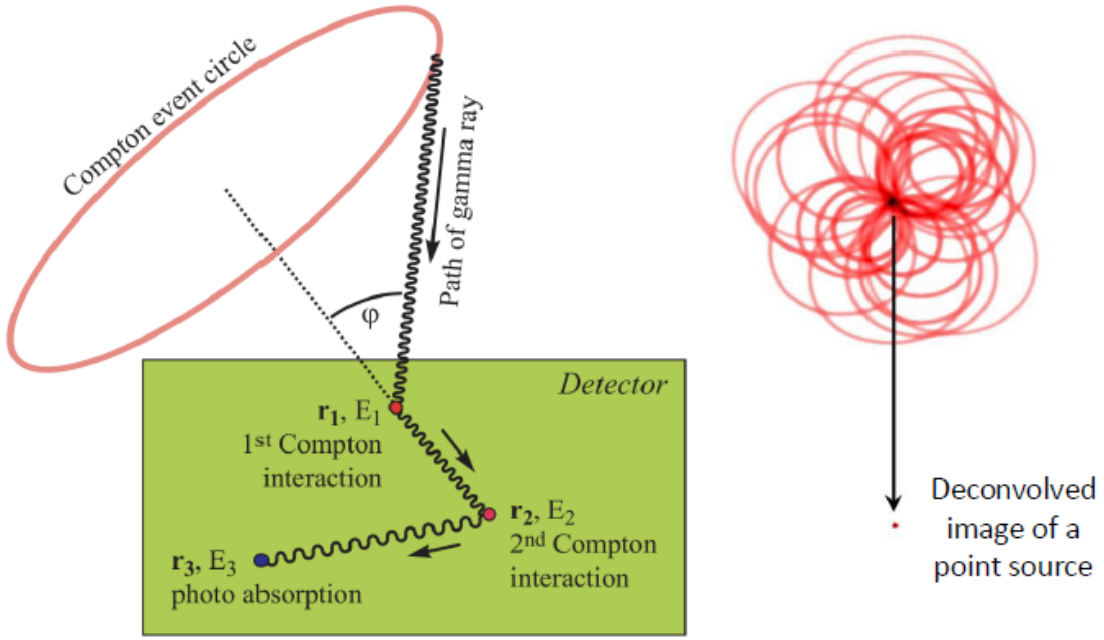


(b) Spectrum.

GRBs and TeV telescopes, Foffano & Tavani 2025

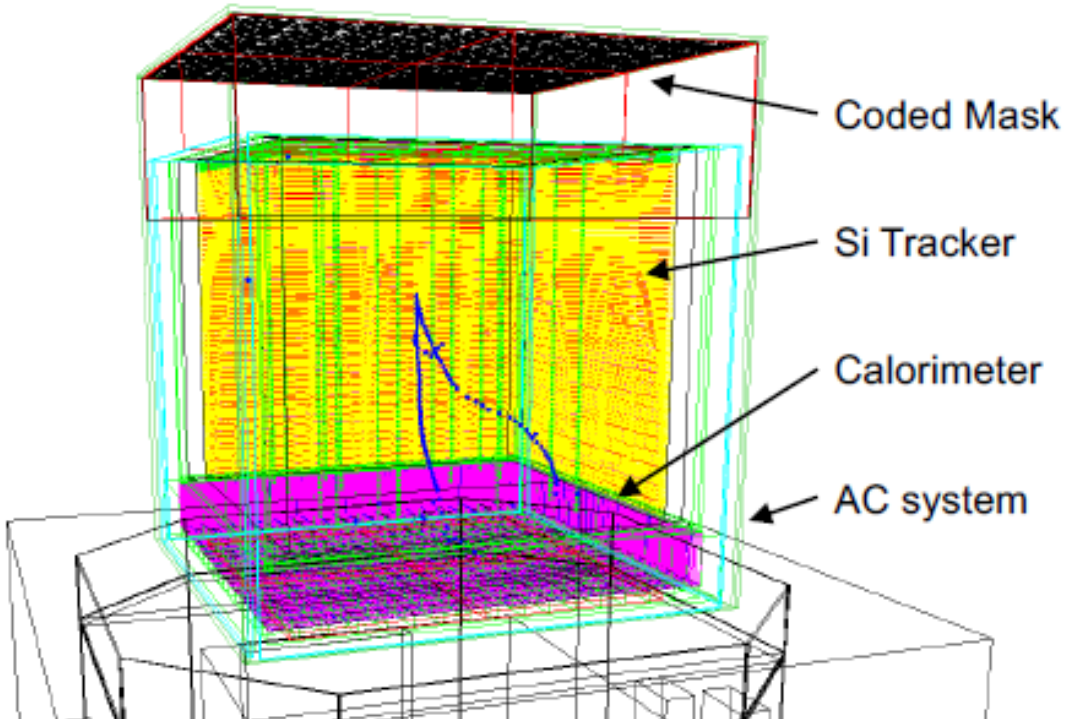


Compton telescope



- Multiple interactions in the instrument
- $E_\gamma = E_1 + E_2 + E_3 + \ldots$
- The gamma-ray origin can be restricted to the "event circle"
- Deconvolution creates all-sky images

Pair creation telescope



- **MeV detection**
- Difficult
- Small cross section
- Complicated kinematics reconstruction
- Background

- **GeV detection**
- Balance between absorber and pair tracking
- Large number of channels of the Tracker
- Background

The MeV Gap

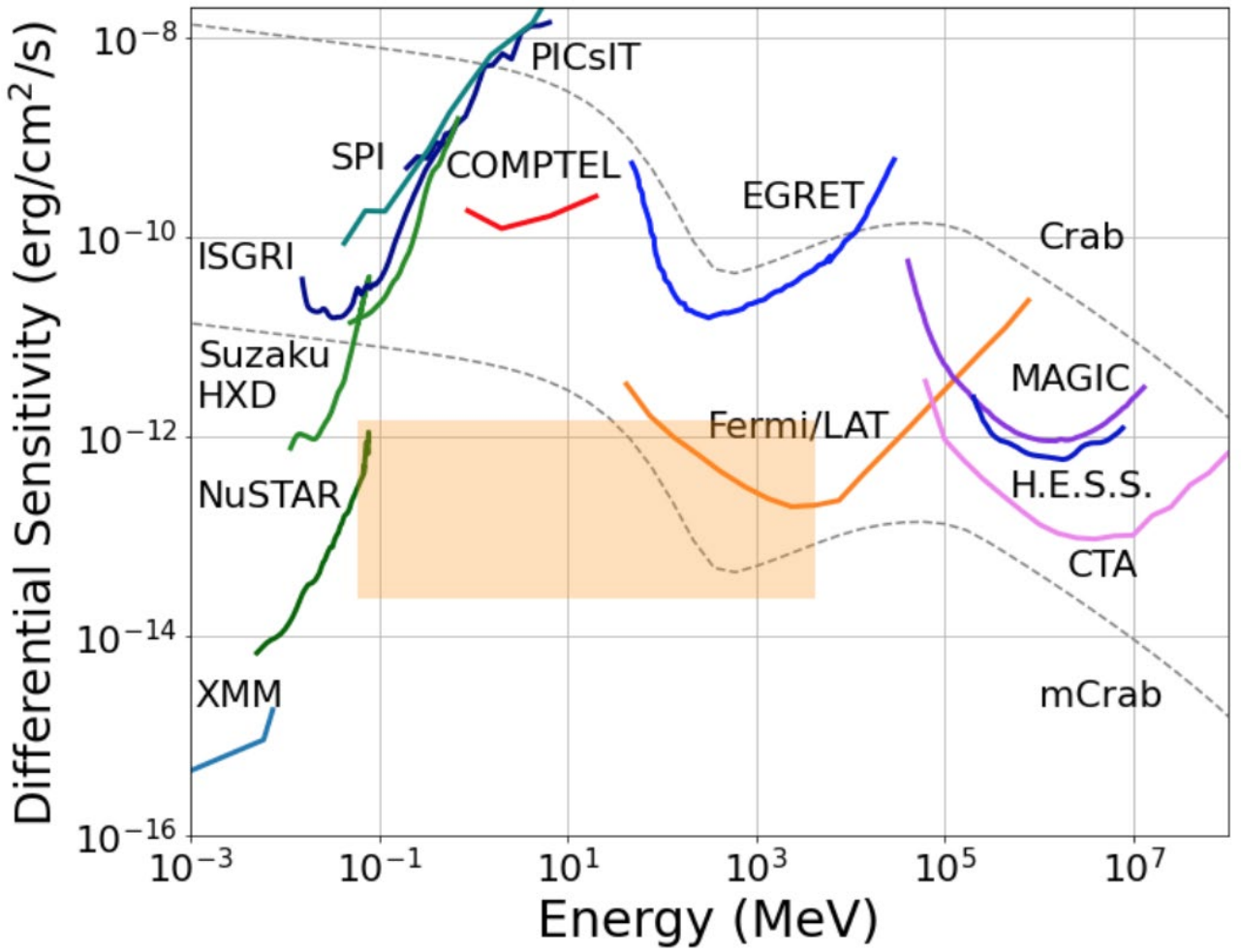
Largely Unexplored

The MeV domain remains a significant observational frontier in astrophysics.

Sensitivity Gap

Physics Explorer

Critical for understanding fundamental particle acceleration physics.



Post-Fermi Mission (ASTROGAM)

- Ambitious project
- **Combines MeV and GeV detection**
- Good sensitivity in the MeV and GeV ranges
- Large international collaboration
- ESA Medium Mission proposals
- So far, it didn’t go through

newASTROGAM

The New MeV to GeV Gamma-Ray Observatory

Step-1 proposal for the ESA M8 Mission Opportunity Call

21 May 2025

Image created from pictures of Adobe Stock, Dassault Systèmes SolidWorks Corp., Tony Liu Photography (mosaic of GUM 16, the Vela Supernova Remnant).

Lead Proposer: David Berge
Proposal co-PIs:
D. Berge (DESY and Humboldt-University of Berlin, Germany),
M.N. Mazziotta (INFN Bari, Italy),
U. Oberlack (Johannes Gutenberg University Mainz, Germany),
V. Tatischeff (University of Paris-Saclay, CNRS, IJCLab, France),
M. Tavani (INAF-IAPS Roma, Italy).

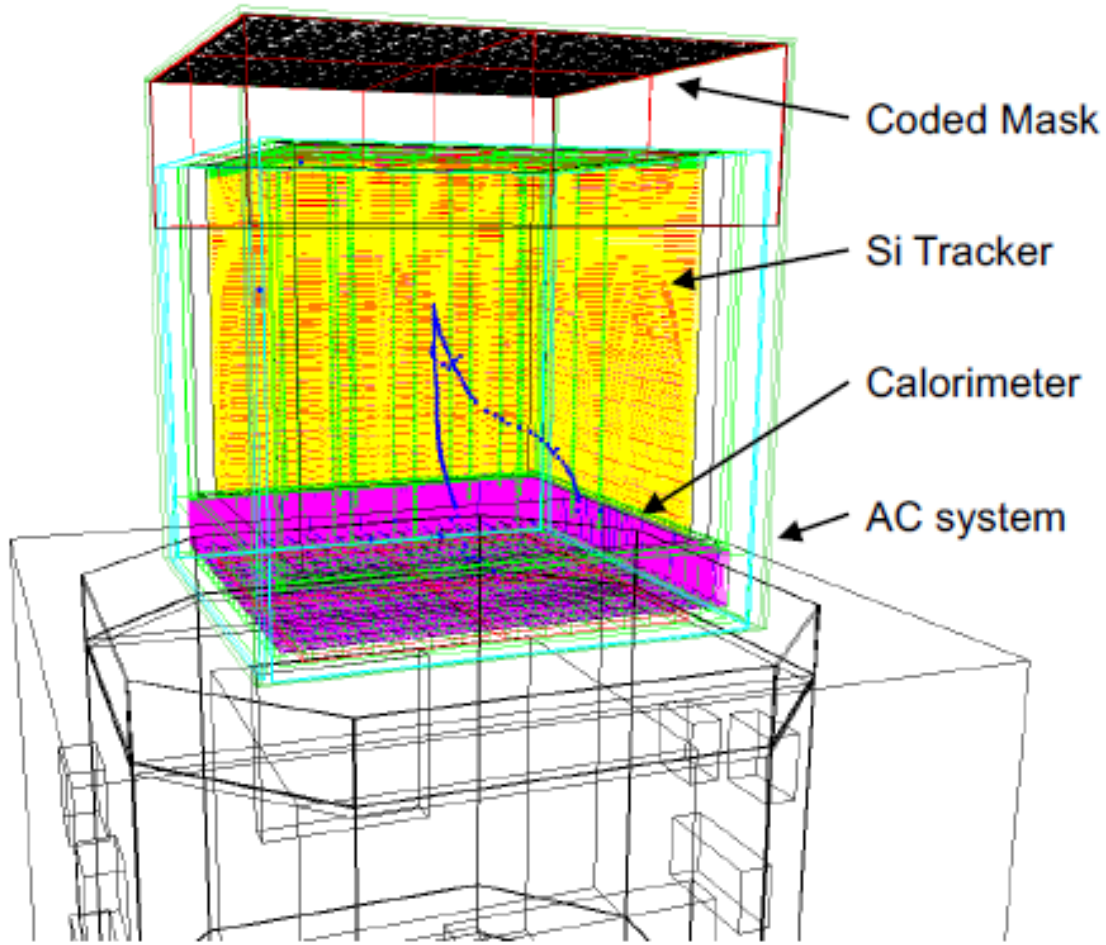


Fig. 5: Geant4/MEGAlib mass model of *newASTROGAM* with a simulated pair event produced by a 50-MeV photon.

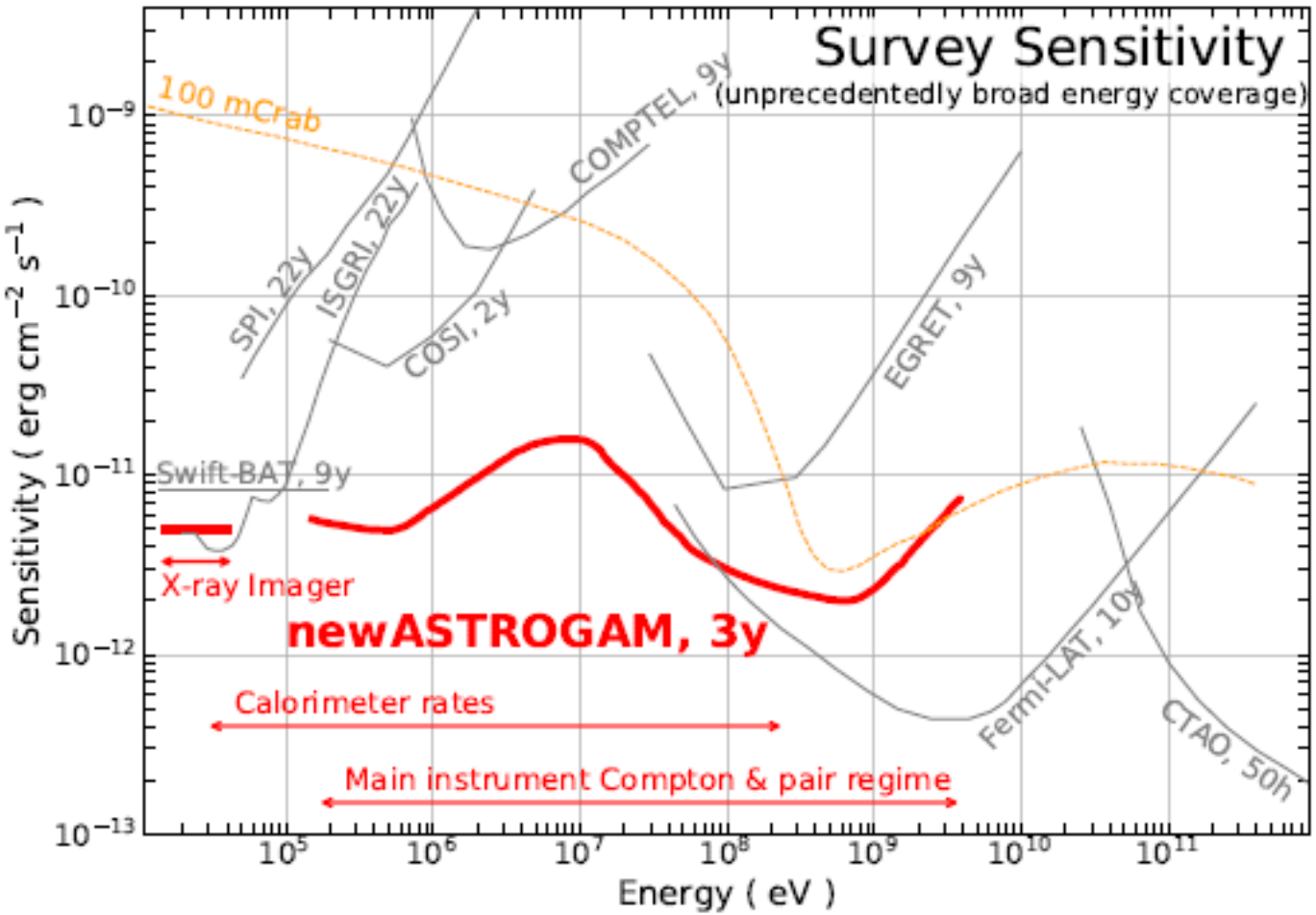


Fig. 1: Point-source (extra-galactic) continuum sensitivity of different X- and γ-ray instruments.

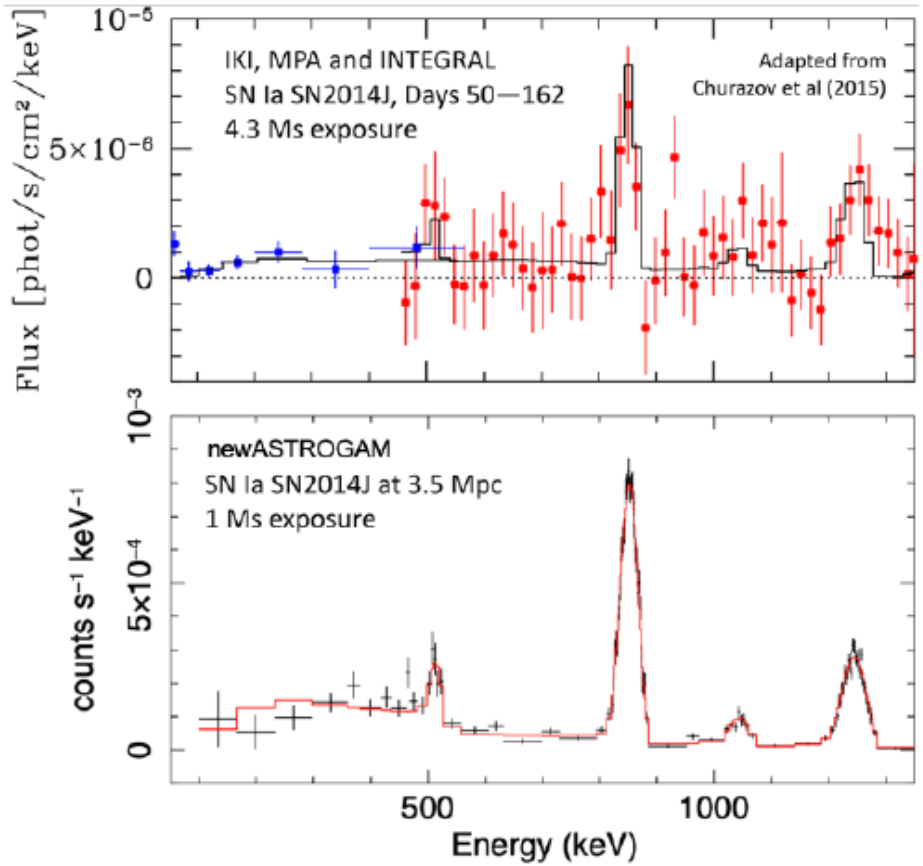


Fig. 2: Improvement over INTEGRAL (top, [13]) for a type-Ia SN. Lines from the ^{56}Ni decay chain will clearly be resolved (bottom), yielding the radioactive and total ejecta masses, a characteristic of the progenitors.

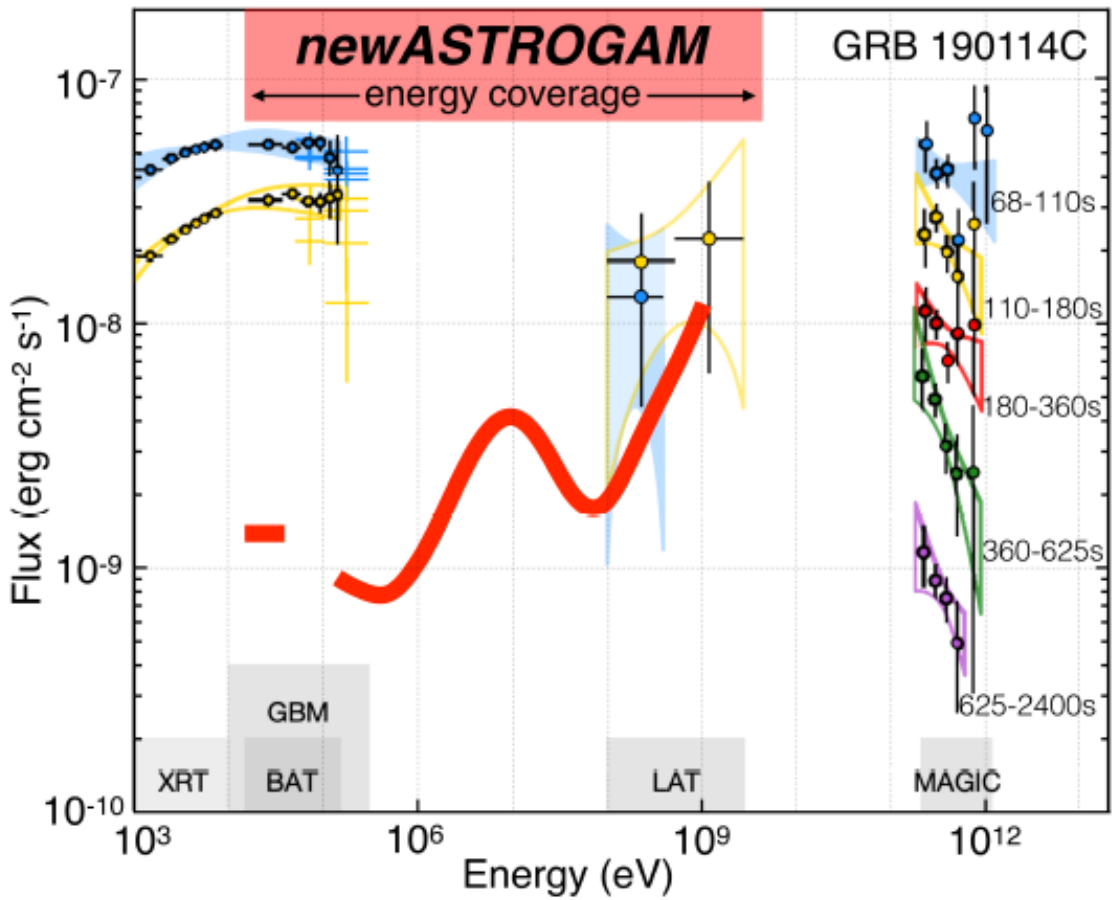


Fig. 3: X- and γ-ray afterglow spectrum of a long GRB [34]. *newASTROGAM* probes the poorly covered transition region, its sensitivity is shown in red here for 600 s exposure.

What’s next ?

- NASA studies of next MeV-GeV mission (AMEGO, …)
- Going back to Small Missions


COSI
Gamma-ray Space Explorer
NASA
UCB • UCSD • LSU • Clemson • NASA • NRL • NGSP • CNES • SDL • LBNL
NTHU • ASI • JMU • DLR • Nagoya • Kavli IPMU • INAF • IRAP • Mainz • LANL
The Compton Spectrometer And Imager

COSI overview

COSI
Gamma-ray
Space Explorer

- COSI is a NASA Small Explorer (SMEX) satellite with a planned launch in 2027
- Compton telescope operating in the 0.2-5 MeV gamma-ray bandpass
- Unique combination of capabilities
  - Uses germanium detectors cooled to cryogenic temperatures to provide ***excellent energy resolution***
  - Instantaneous field of view is ***>25%-sky*** and covers the whole sky every day
- History/Status
  - Successful COSI-balloon flights: 2005, 2009, 2014, 2016
  - COSI-SMEX proposed in 2019, and project started in 2020
  - Critical Design Review held in December 2024
  - Currently building flight model components

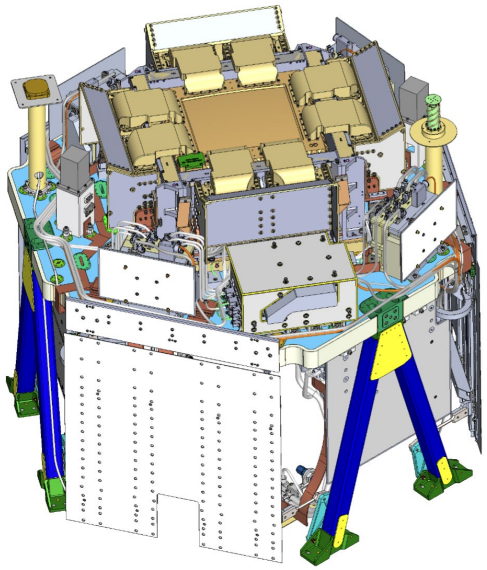
COSI Mission

- The **Compton Spectrometer and Imager (COSI)** is a NASA Astrophysics Small Explorer (SMEX) satellite mission.

- COSI is a **soft gamma-ray survey telescope** (0.2-5 MeV) planned for **launch in 2027**.

- PI: John Tomsick, international collaboration, important INAF participation

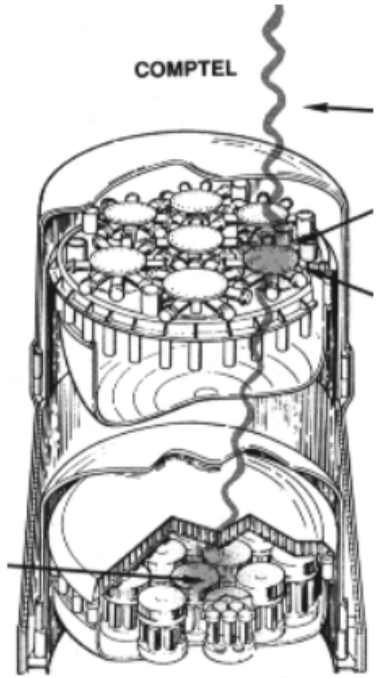
- Unique capabilities:
  - Uses germanium detectors for **excellent energy resolution**
  - Istantaneous **field of view is > 25% of the sky** and covers the entire sky every day



COSI Instrument

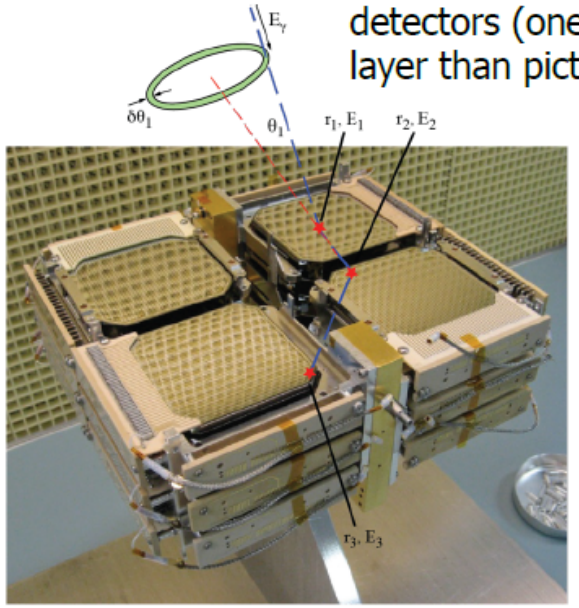
- Goals:
  - The origins of Galactic positrons
  - Uncover the sites of nucleosynthesis in the Galaxy
  - Perform pioneering studies of gamma-ray polarization
  - Find counterparts to multi-messenger sources.

Compton Telescopes: from COMPTEL to COSI



30+ years of development through NASA R&D

COSI-SMEX has 16 detectors (one more layer than pictured here)



Each detector is 8cmx8cm

CGRO/COMPTEL:

- ~40 cm^3 resolution
- $\Delta E/E$ ~10%
- up to 0.4% efficiency

COSI:

- <1 mm^3 resolution
- $\Delta E/E$ ~0.2-1%
- up to 16% efficiency
- bandpass covers 511 keV
- polarization

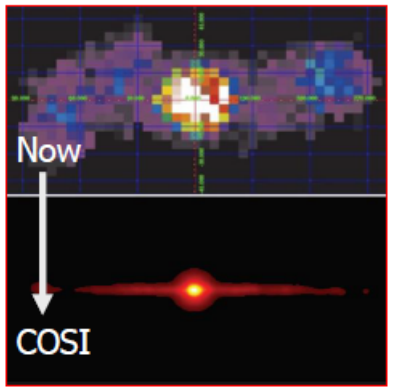
- Vastly improved performance with a fraction of the mass and volume

COSI's key science goals

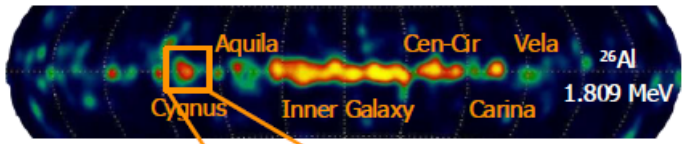
COSI
Gamma-ray
Space Explorer

A. Uncover the Origin of Galactic Positrons

e^-e^+ @ 511 keV

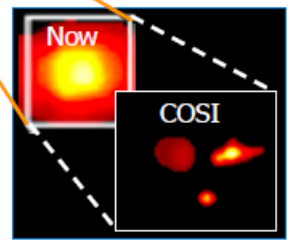


See talk by Sophie Haight



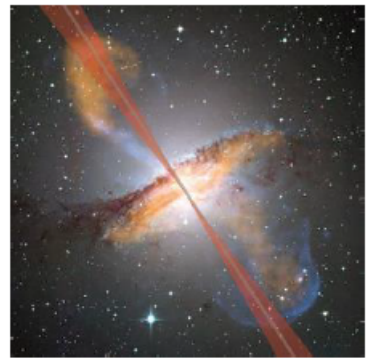
B. Reveal Galactic Element Formation

^{26}Al @ 1.809 MeV
^{60}Fe @ 1.173 and 1.333 MeV
^{44}Ti @ 1.157 MeV



More details: Thomas Siegert

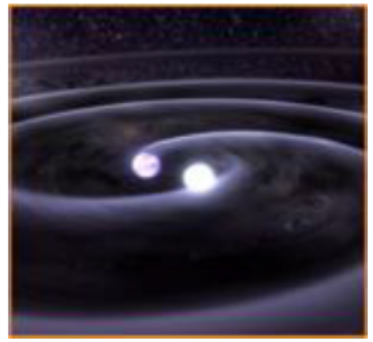
C. Gain Insight into Extreme Environments with Polarization



Active Galactic Nuclei (AGN) and Galactic black holes @ 0.2-0.5 MeV

See presentations by Marco Ajello, Hamta Farrokhi, Jarred Roberts, Haocheng Zhang, Krishna Vedula

D. Probe the Physics of Multimessenger Events



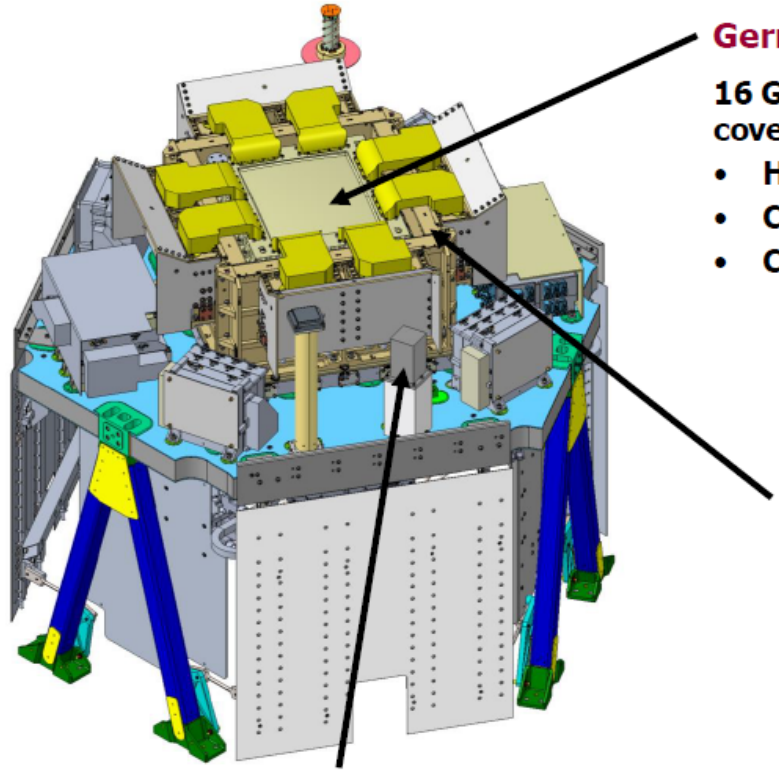
Gamma-ray burst (GRB) alerts

See talk by Eliza Neights

Plus: COSI dark matter presentations by Field Rogers, Yu Watanabe, Maíra Dutra, Robin Anthony Petersen

Payload design and instrument concept

COSI
Gamma-ray
Space Explorer

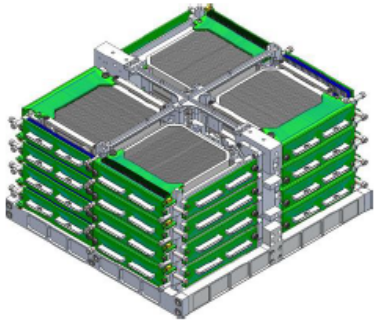


Germanium Detectors (GeDs)

16 GeDs in a cryostat cooled to ~90 K covering 0.2-5 MeV for:

- **High-resolution spectroscopy**
- **Compton imaging**
- **Compton polarimetry**

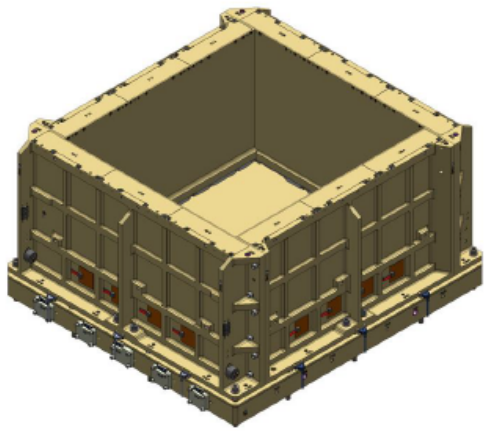
SUNPOWER / AMETEK



Anticoincidence Subsystem (ACS)

Bismuth germanium oxide (BGO) scintillator "shields" for:

- **Reducing external background**
- **Rejecting escaping events**
- **50 ms light curves at 80 keV - 2 MeV (for GRB alerts)**
- **Light curves at >2 MeV (for proton background monitoring)**



Background and Transient Observer (BTO)

- **Student Collaboration instrument**
- **2 NaI(Tl) scintillator detectors (>30 keV)**

For more information on BTO see talk & poster by Hannah Gulick

Path forward for COSI

COSI
Gamma-ray
Space Explorer

Activity	2022	2023	2024	2025	2026	2027	2028
	A S O N D	J F M A M J J A S O N D	J F M A M J J A S O N D	J F M A M J J A S O N D	J F M A M J J A S O N D	J F M A M J J A S O N D	J F M A M J J A S O N D
Key-Decision Points			4/16 KDP-C		10/5 KDP-D	4/30 KDP-E	
Mission Milestones		1/17 SRR	2/26 PDR	12/4 CDR	9/4 SIRPER	PSR 3/24	LRD 8/27 PLAR 10/1
COSI Instrument Milestones			2/9 IPDR	11/8 ICDR			

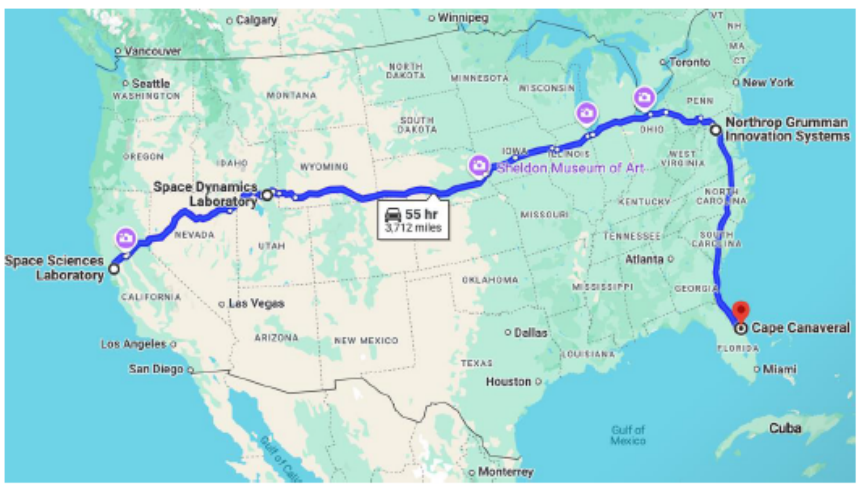
Now

Payload I&T | Observatory I&T

SSL | SDL | NG

LAUNCH!

What activity?	Where?	When?
Payload Integration & Testing (I&T)	SSL (Berkeley)	Mid-2025 to Early-2026
Payload I&T - environmental testing	SDL (Utah)	Mid-2026
Observatory I&T	NG (DC area)	Late-2026 to Early-2027
Launch (SpaceX Falcon 9)	Cape Canaveral	August 2027

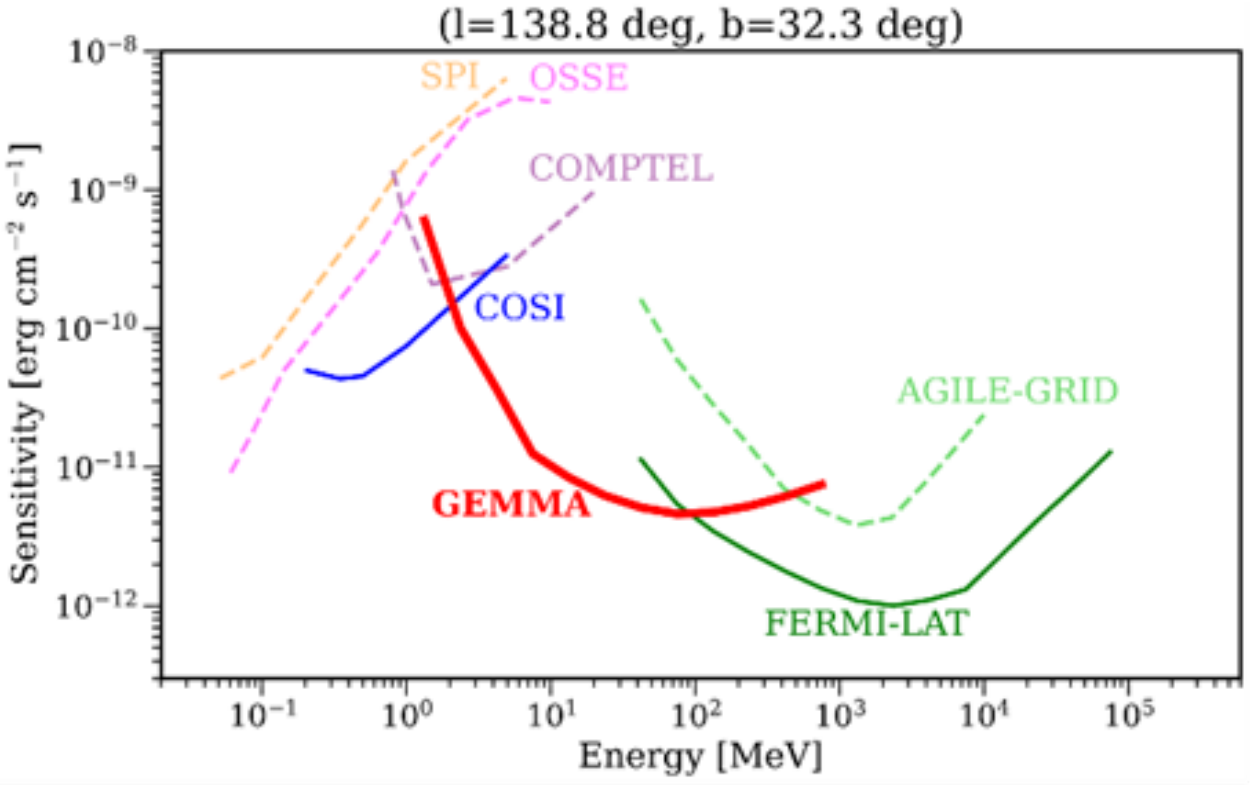


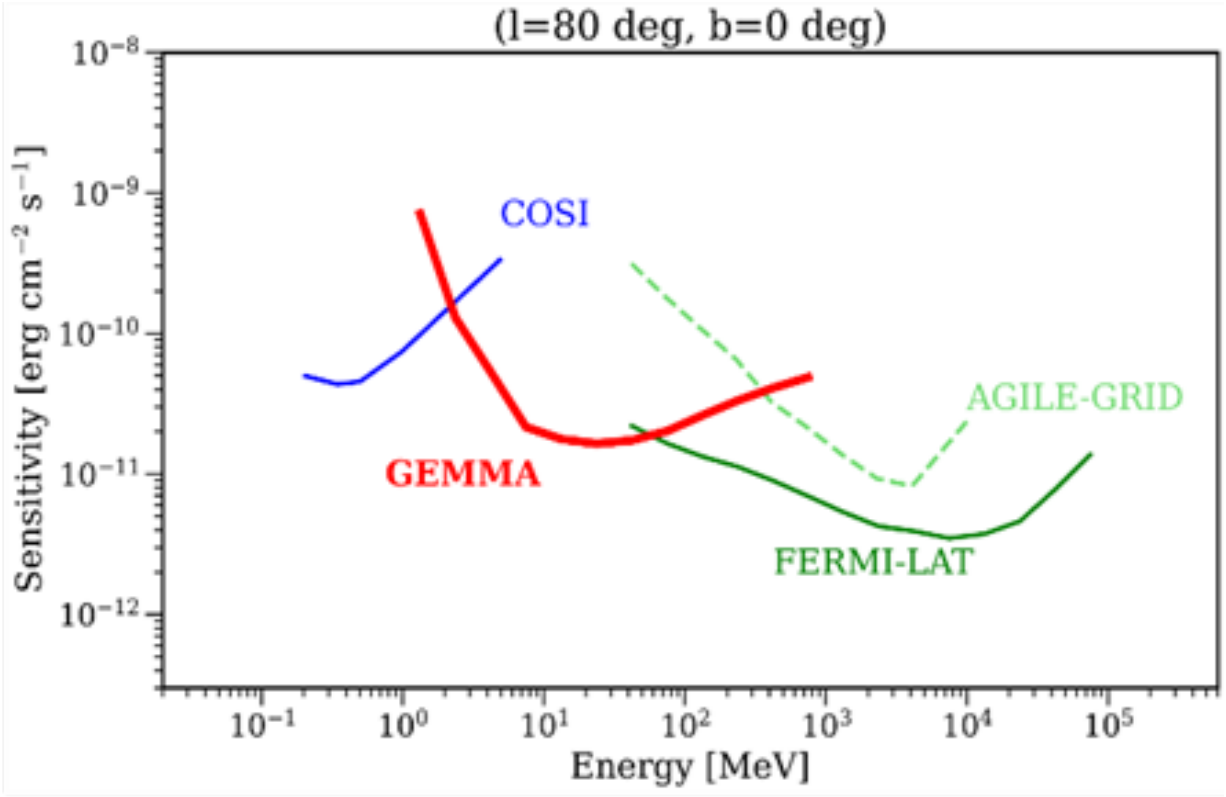
New opportunity: ASI Call for Small Missions

- New ASI call
- 100 kg payload, 50 Meuros
- proposals due in April 2026
- Proposals currently under review

- **The GEMMA Project**
- MeV-GeV Mission, innovative design
- PI: Andrea Bulgarelli (INAF);
- Co-PI's: Martina Cardillo (INAF), Nicola Mazziotta (INFN)

The GEMMA Window





Why now?

Imminent observational gap

No missions in the MeV-GeV range after AGILE/Fermi

Multi-messenger revolution

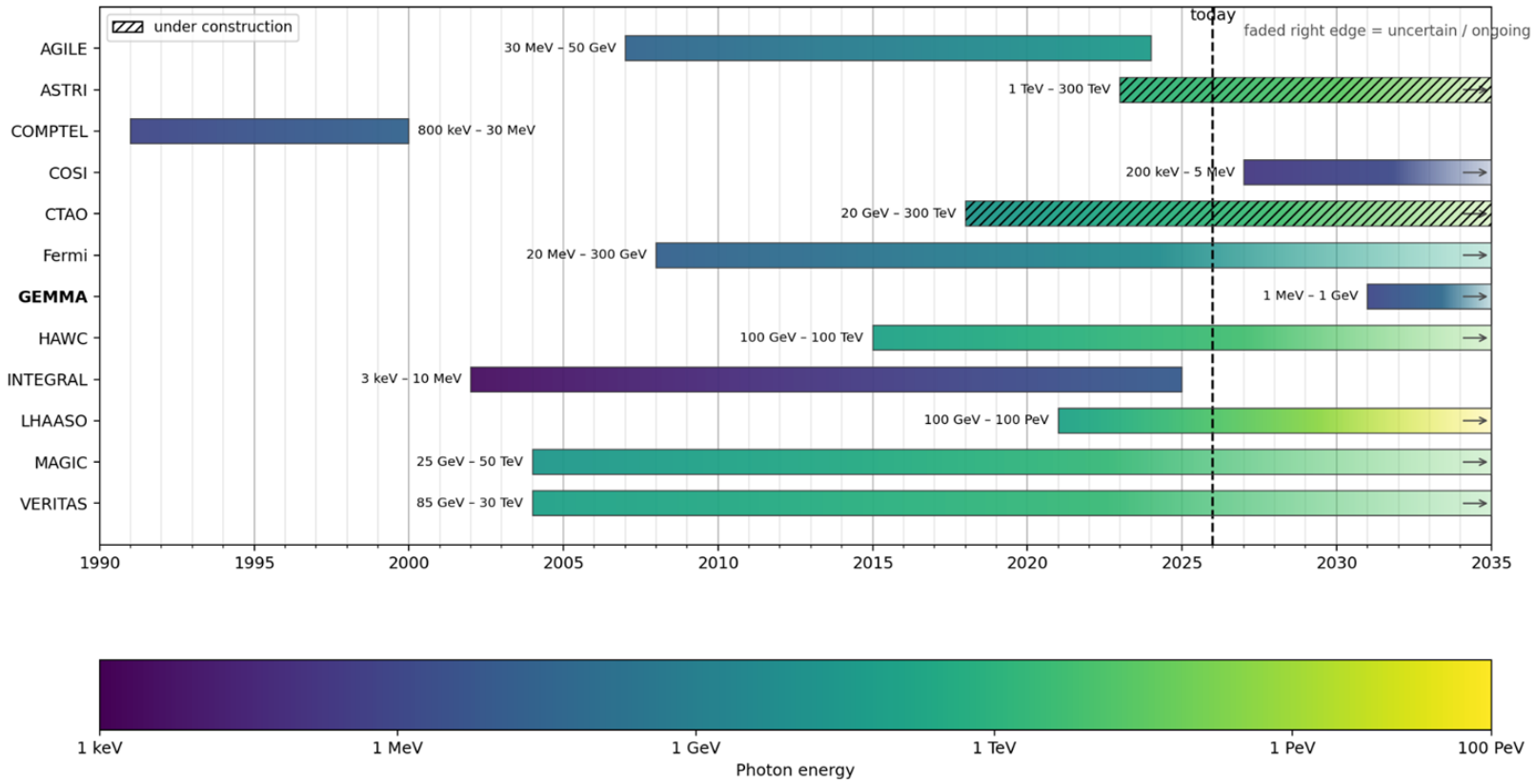
GW, neutrinos, TeV observatories → missing MeV link

Unique diagnostics

Only MeV reveals hadronic vs leptonic emission (“pion bump”)

Technology is ready

Strong heritage from AGILE, Fermi, NUSES

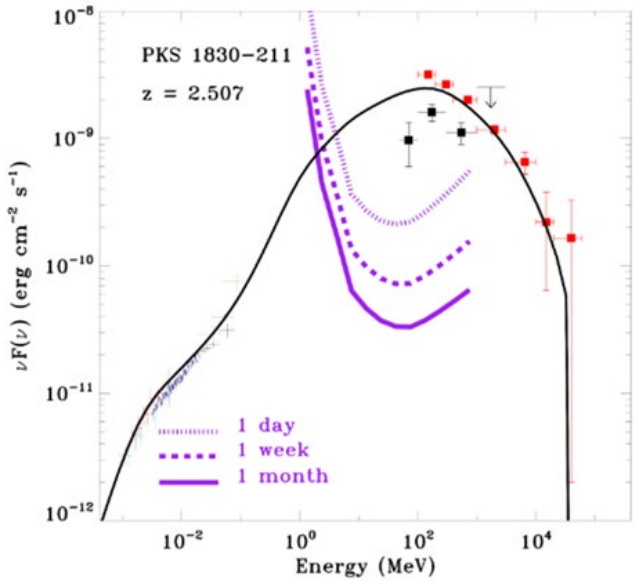


“Now” is the only window to fill the MeV gap

Why the MeV domain is essential?

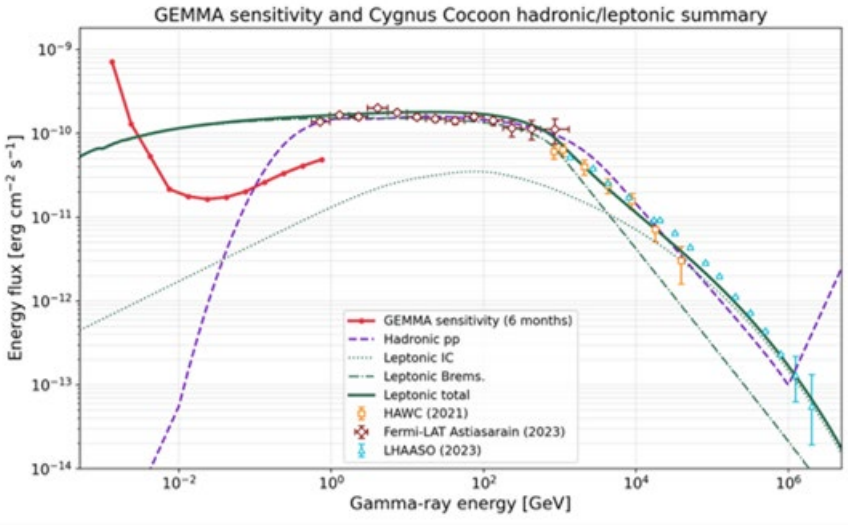
1. Cosmic-ray origin

- Origin of Galactic cosmic rays still unknown
- Hadronic vs leptonic processes unresolved
- **Pion bump (10–300 MeV) is the key diagnostic**



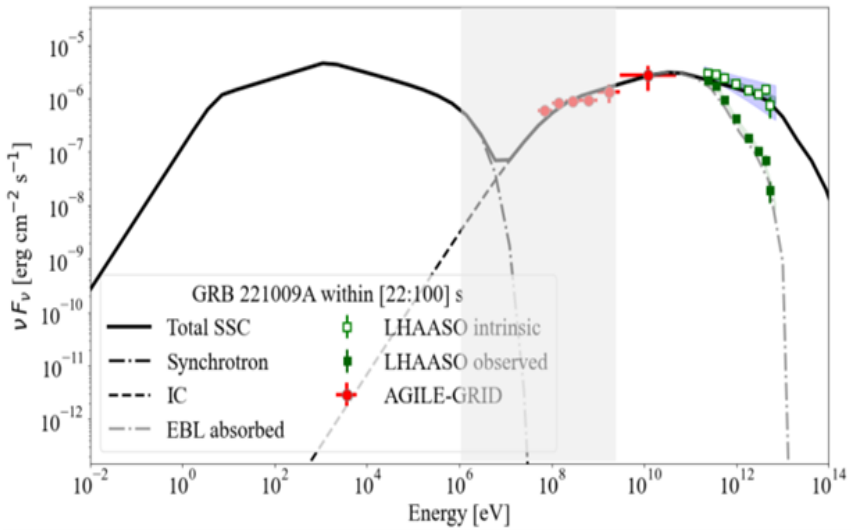
3. Multi-messenger astrophysics

- Counterparts of:
  - neutrinos
  - gravitational waves
- Hidden accelerators peak in MeV band



2. Jets & relativistic accelerators

- Transition between thermal and non-thermal emission
- Disentangling:
  - Bremsstrahlung
  - Inverse Compton
  - Hadronic emission



Only MeV observations disentangle particle acceleration processes

Conclusions

- Crucial relevance of the MeV-GeV space instruments for TeV Arrays
- **Fermi should last forever !**
- A large MeV-GeV Misssion at the moment is stalling

- **Opportunities from Small Missions !**
- **COSI**
- **Possibly GEMMA**