Future Missions And Mission Concepts for MeV Gamma-ray Astrophysics

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Science in the MeV domain

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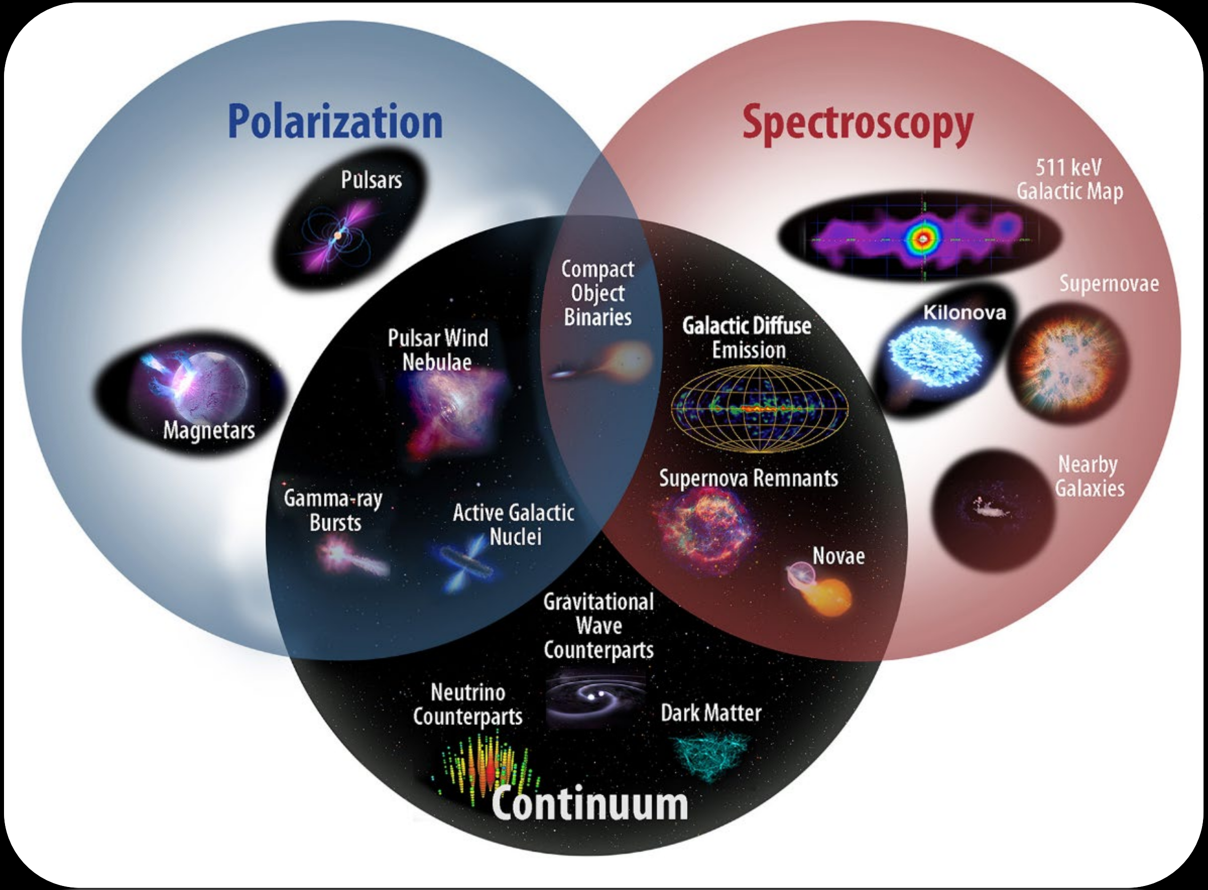
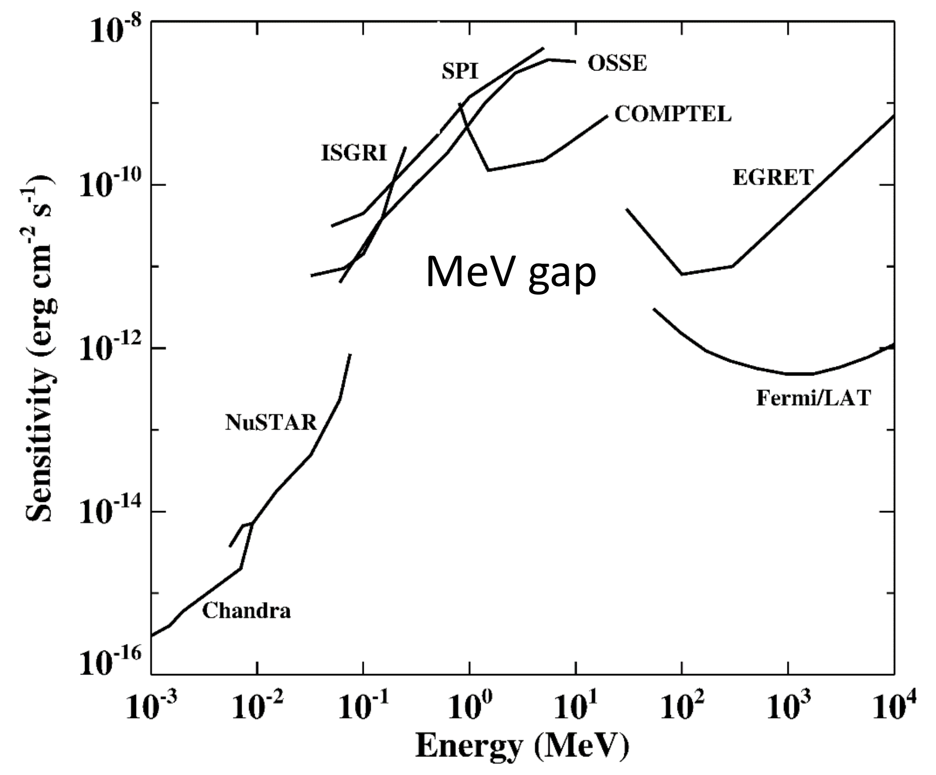


McEnery+ 2019

The MeV Gap

- Previous missions have had relatively poor sensitivity in the MeV range
- Large discovery space where there is known to be interesting physics
  - 511 keV e^-e^+ annihilation line
  - Nucleosynthesis and supernovae
  - High levels of polarization
  - Multi-messenger astrophysics



511-keV e^-e^+ Annihilation Line

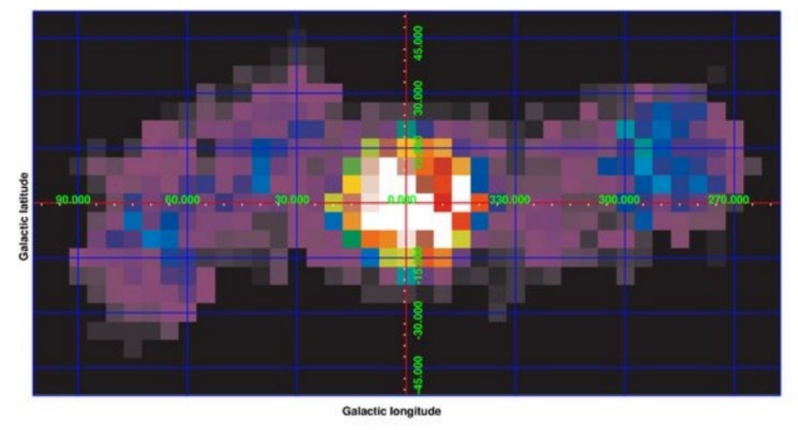
SPI observations (2002 - present):

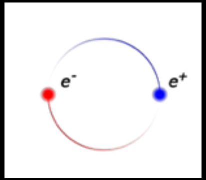
Very extended 511-keV emission from positron annihilation centered around galactic center/bulge and around the galactic disk

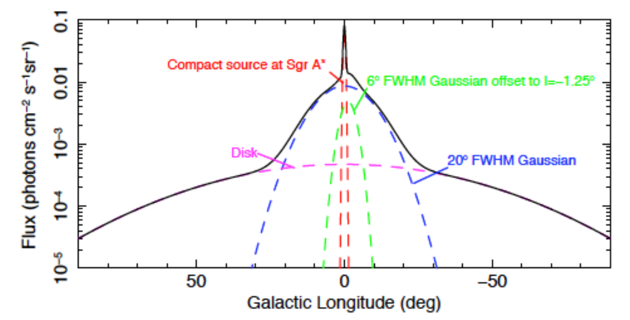
Contributors (how much TBD):

- Nuclear decays
- Core-collapse supernovae
- X-ray binaries
- Novae
- dark matter?

INTEGRAL/SPI map of the 511 keV emission (Bouchet+10)







Skinner+14, Siegert+16

Nucleosynthesis

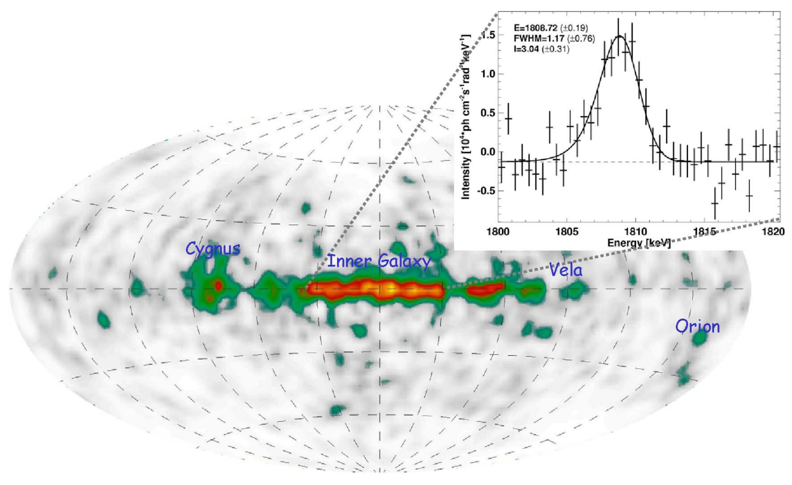
Creation and release of new elements:
Stars, supernovae, novae, and mergers

Each nuclear line tells a different story:
^{26}Al: History of star formation over last million years
^{60}Fe: History of core-collapse supernova
^{44}Ti: Tracer for young supernova remnants
^{56}Ni: How do type Ia supernovae explode?
^{22}Na & ^{7}Be: How do nova explosions work?

Observe:

- Location
- Fluxes
- Line width & shift
- Temporal evolution

SPI spectrum

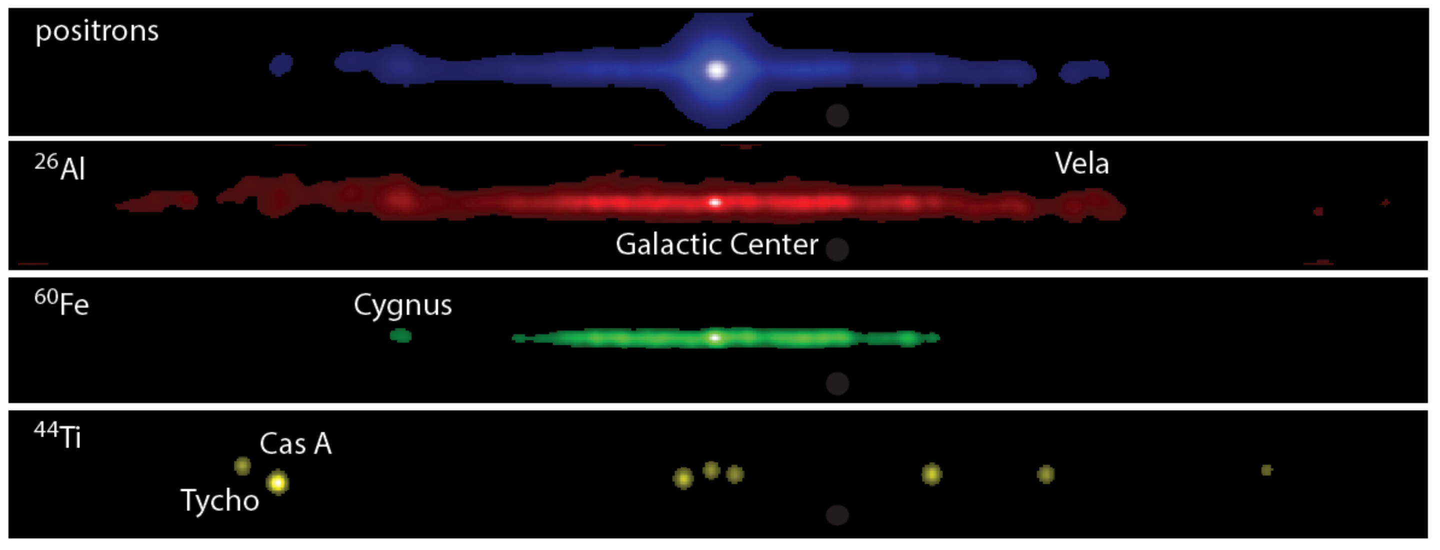


COMPTEL map

Roland Diehl et al.

Nucleosynthesis

Each line tells a different story



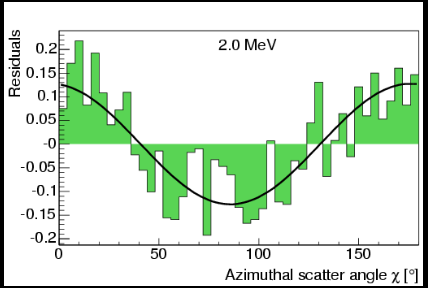
0.511 MeV	Locations of positron annihilation
1.809 MeV	Star forming regions
1.173, 1.333 MeV	History of core-collapse supernovae
1.157 MeV	Young supernovae remnants

Maps based on COSI simulations
View in Galactic coordinates with Galactic center in the middle

Open a New Dimension: Polarization

Compton scattering preserves information about the linear polarization of the gamma rays.

$$\left(\frac{d\sigma}{d\Omega}\right)_{C,\,unbound,\,pol} = \frac{r_e^2}{2}\left(\frac{E_g}{E_i}\right)^2 \Big(\frac{E_g}{E_i}+\frac{E_i}{E_g}-2\sin^2\varphi\,\boxed{\cos^2\chi}$$



Zoglauer 2005

Polarization helps to better understand / constrain the geometry and emission processes with which the gamma rays are created, for example in:

- Pulsars: Crab nebula and pulsar measurements at 0.1-1 MeV
  - 46-98% (Dean+08; Forot+08; Moran+16)
- Accreting black holes, e.g., Cyg X-1:
  - 67±30% (0.4-2 MeV) (Laurent et al. 2011)
  - >75% (0.37-0.85 MeV) (Jourdain et al. 2012)
- Gamma-ray bursts
  - Wide range of observed polarization levels

Crab pulsar (X-rays, Chandra)

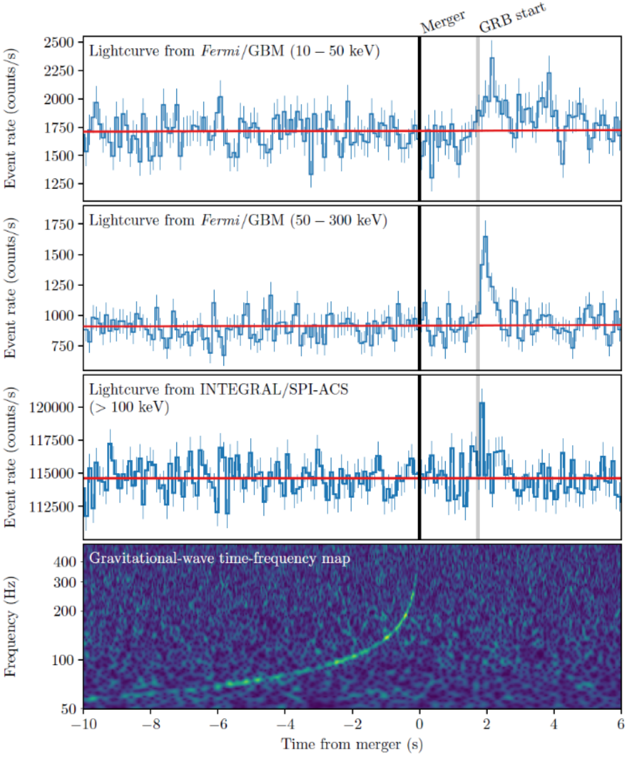
Multi-Messenger Astrophysics

Gravitational waves and gamma-rays:

- GW 170817 neutron star merger seen with LIGO
- Coincident (2 sec delay) GRB 170817A seen with Fermi/GBM and INTEGRAL

High-energy neutrinos and gamma-rays:

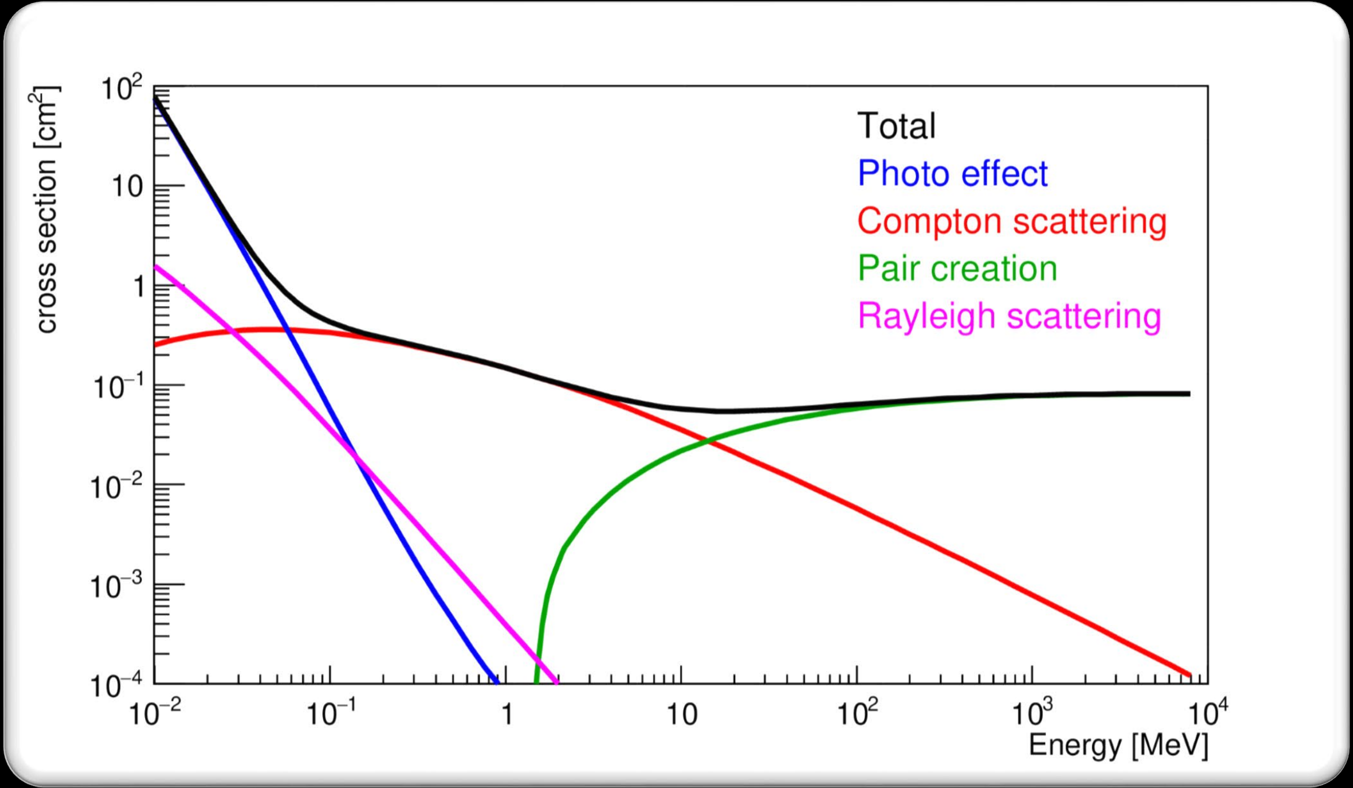
- IC 170922A IceCube neutrino event
- Coincident gamma-ray flare from TXS 0506+056 blazar seen with Fermi/LAT



GW 170817 followed by GRB 170817A (LIGO collaboration)

Measurement Challenges in the MeV Domain

Two Dominating Processes & Small Interaction Cross Sections

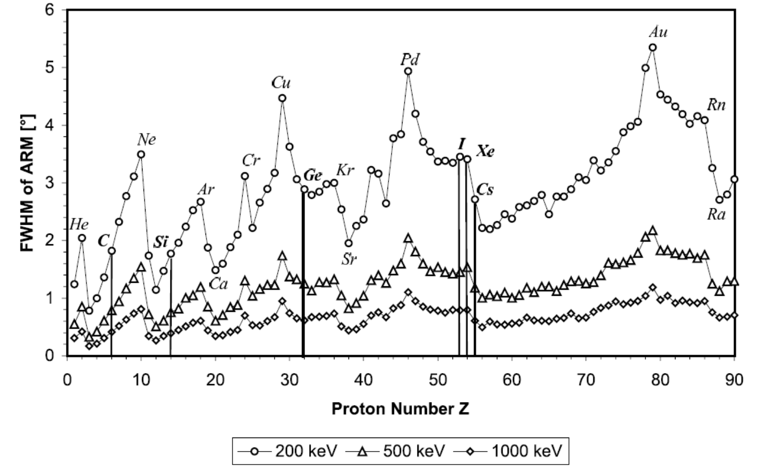


Dominant cross sections in silicon

Angular Resolution Limits

Compton regime: Doppler broadening

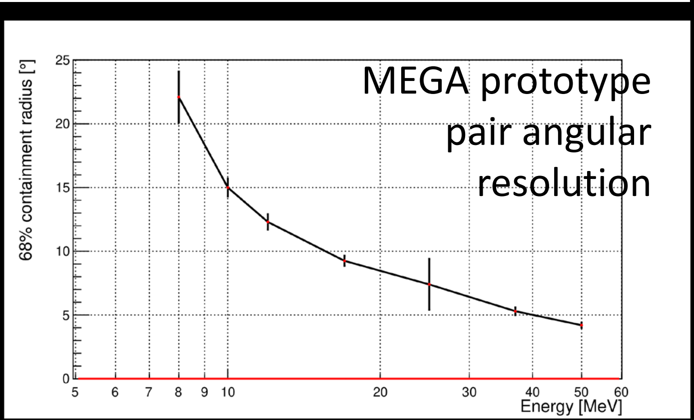
- The electron on which the scatter happens is not at rest but bound to a nucleus
- Electron momentum cannot be measured
- Using Compton equations to determine origin of the gamma ray is only an approximation



Pair regime:

The angular resolution for pair events is limited by:

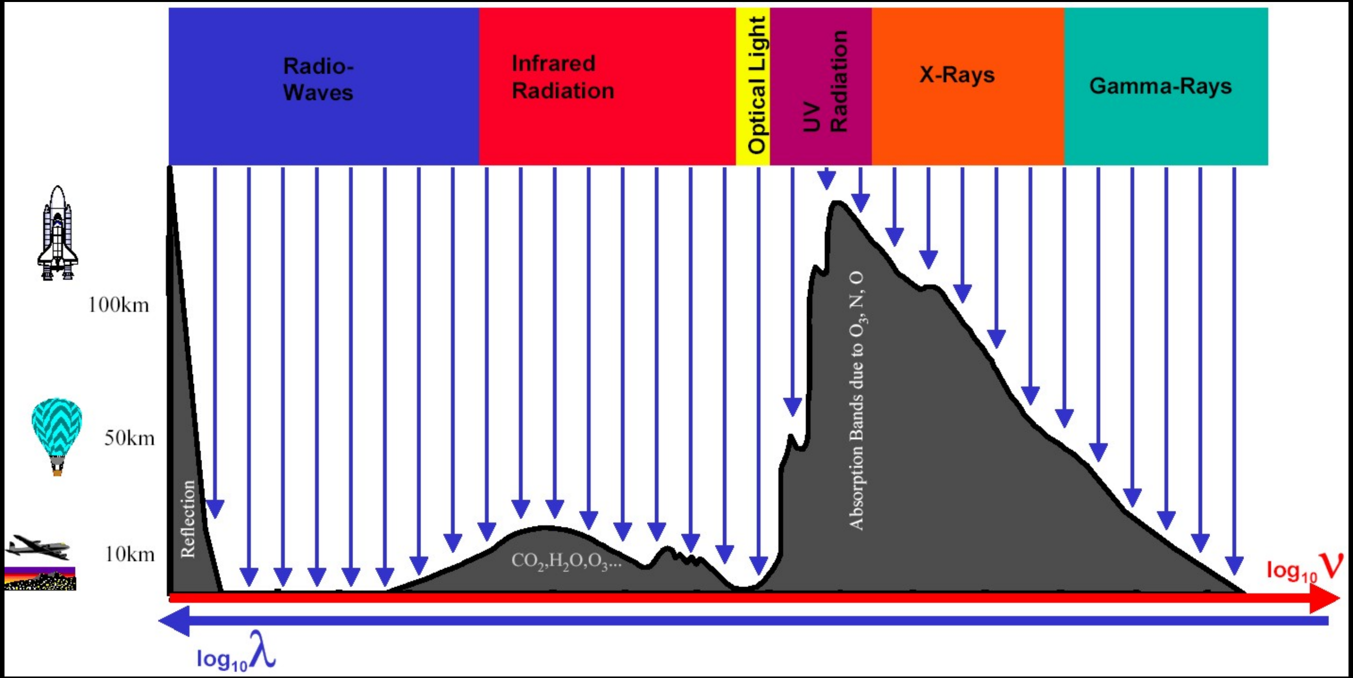
- The unknown recoil of the nucleus
- Electron / Positron small angle scattering in the interaction medium



MEGA prototype pair angular resolution

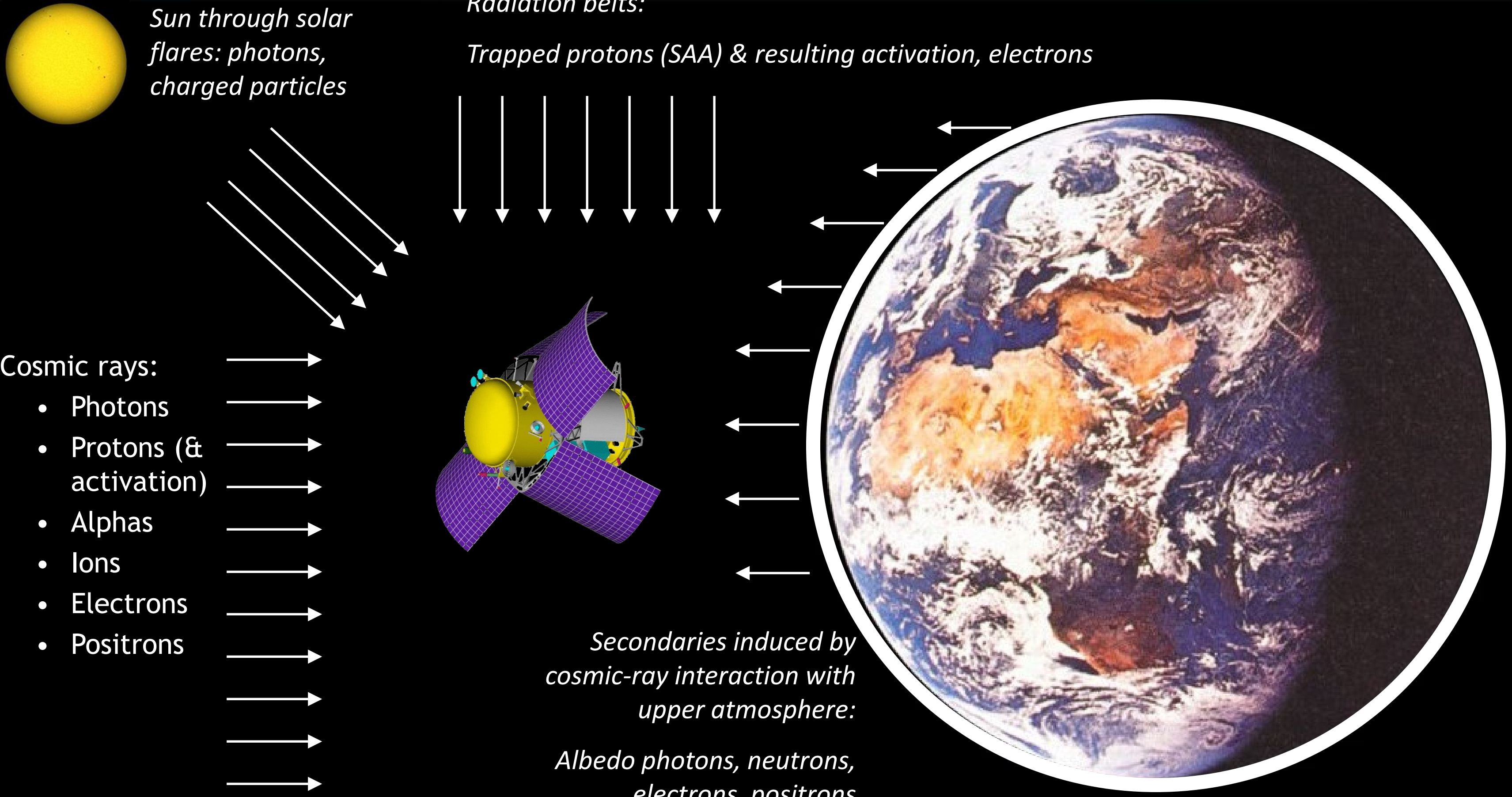
Both: Zoglauer 2005

Leaving the Atmosphere



Schönfelder+, 2001

The Space Radiation Environment



Sun through solar flares: photons, charged particles

Radiation belts:

Trapped protons (SAA) & resulting activation, electrons

Cosmic rays:

- Photons
- Protons (& activation)
- Alphas
- Ions
- Electrons
- Positrons

Secondaries induced by cosmic-ray interaction with upper atmosphere:

Albedo photons, neutrons, electrons, positrons

Background Mitigation Options

- Anti-coincidence system: Detect charged particle background
- Minimize activating materials:
  - Minimize passive mass
  - Select low-Z, low-activation materials close to detector
  - Put detector on a boom away from space craft
- Orbit:
  - Low-Earth Equatorial minimizes activation from cosmic rays and radiation belts
  - “Interplanetary” (e.g. L2) eliminates Albedo and radiation-belt components
- Active or passive shielding:
  - Most effective for lower energy particles, e.g., Earth-Albedo photons
  - “Self-shielding” for tracking telescopes: Surround the electron tracker with an active absorber
- For Compton events:
  - Time-of-flight can eliminate upward moving gamma rays from atmosphere
  - Multiple interactions
  - Recoil electrons: Reduce PSF (cones to arcs to direct localization)
  - Pulse-shape discrimination: Eliminate, e.g., neutrons

Future Missions and Concepts

Caveats

There are many MeV mission concepts out there.
Here I will talk about a representative sample.
I have unfortunately no time to talk about them all.

I will not talk about sensitivity – it depends on too many changeable parameters such as orbit, size, observation time, the chosen detector material, read-out quality, thresholds, analysis tools, etc.

Key Detector Types/Materials: Scintillators, Semi-conductors, TPC's

Scintillators:

- Many options: BGO, NaI, CsI, $LaBr_3$, $CeBr_3$, GAGG, P-Terphenyl, etc.
- Read out with PMT's, Silicon-diodes, or, nowadays, SiPM's
- Achieve usually less good voxilization and less good energy resolution than semi conductors
- In many cases cheaper, and easier to build and scale

Semi conductors:

- Several options: Si, Ge, CdTe, CZT, etc.
- Read out via pixel, (double-side) strips, Frisch-grids, and a few more
- Can achieve better energy resolution and finer voxelization than scintillators
- Usually more expensive, harder to build and scale

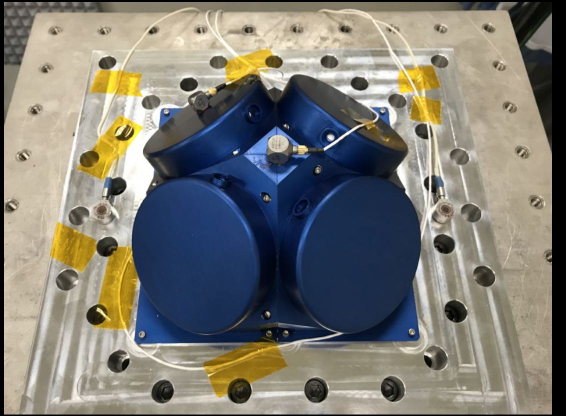
TPC's:

- Several options gas or liquid: Ar, Xe, etc.
- Read-out, e.g., via gas electron multiplier (GEM), micro-pixel chamber
- Can have excellent track resolution (depends on gas pressure) and a large volume without passive material

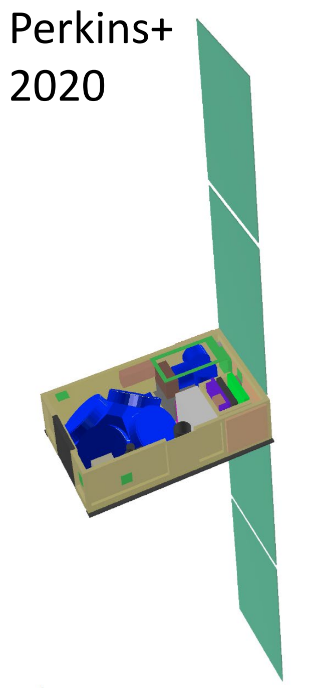
Key MeV Instrument Types

- Intelligently arranged simple detectors: **BurstCube, Glowbug**
- Collimators: HXT on Suzaku
- Laue Lenses: MAX
- Occultors: **LOX**
- Coded masks: INTEGRAL, SWIFT
- Rotators: RHESSI, GRIPS
- Compton telescopes: COMPTEL, FACTEL, **SMILE**, GRAMS, **COSI**
- Pair telescopes: EGRET, FERMI
- And combinations of the above:
  - Laue Lens with Compton telescope: GRI, DUAL
  - Compton telescope with Collimator: SGD on Hitomi
  - Coded mask in front of Compton telescope: **GECCO**
  - Combined Compton and pair telescopes: MEGA, eASTROGAM, **AMEGO-X**

BurstCube – a cubesat GRB detector



BurstCube consists of 4 cylindrical CsI modules arranged to optimize the all-sky field-of-view and the source localization. The picture shows the prototype for the shake-test.



Full MEGAlib simulation model of the 6U cubesat.

Key science objectives:
- Spectra & light curves of GRB’s and other short transients

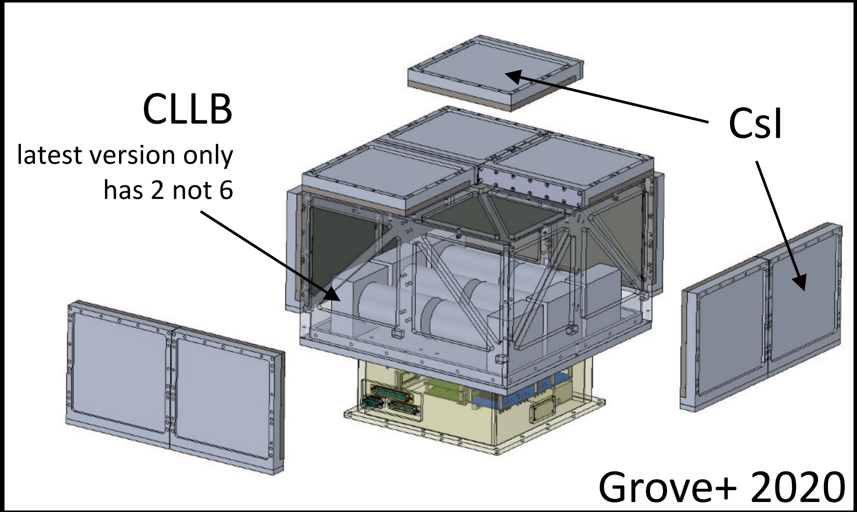
Status:
- Expected launch in 2022

Energy range:
- 50 keV to ~1 MeV

Localization accuracy:
- < 30 degrees

Background rejection:
- None

Glowbug – a GRB telescope



Grove+ 2020

Exploded view of Glowbug:
12 CsI scintillators (low-energy sensitivity) surround 2 CLLB ($Cs_2LiLaBr_6$) scintillators (high-energy sensitivity)

Key science objectives:

- GRBs and other short transients

Status:

- Assembly and testing for launch to ISS in 2023. Will be located beside MAXI.

Energy range:

- ~30 keV to ~ 2 MeV

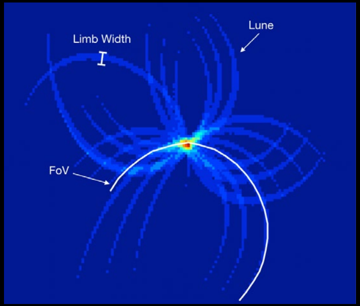
Localization accuracy for GRBs:

- Depends on source strength and incidence angle, ~5 degrees
- ~8 sr field-of-view

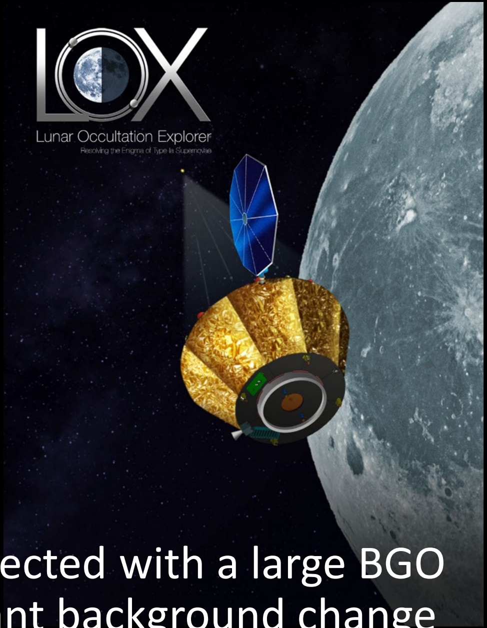
Background rejection:

- Active and passive shielding

LOX – The Lunar Occultation Explorer



Miller+ 2019



Gamma ray are detected with a large BGO array. Each significant background change is considered an occultation event. In image space those are “event arcs”. The point of overlap of all those arcs (occultation ensembles) is the source location.

Key science objectives:

- Point sources: deep all-sky survey and monitoring
- Supernovae, especially type Ia

Status:

- Concept development
- Will be proposed as MIDEX end of this year

Background suppression:

- Optimized, stable background environment

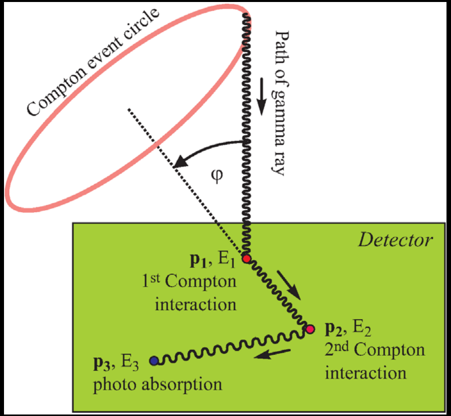
Energy range:

- ~ 0.1-10 MeV

Localization accuracy:

- Dependent on implementation parameters (altitude above moon, acquisition cadence)
- ~1 arcmin achievable

COSI – The Compton Spectrometer and Imager



Gamma rays interact via multiple Compton interactions in the Germanium detectors, allowing to determine the direction-of-motion of the gamma ray, and ultimately to determine the origin of sources.

COSI 2x2x3 Germanium detector array

Key science objectives: Everything within energy and sensitivity range but especially:

- 511-keV and nuclear line science

Status:

- Competitive NASA SMEX Phase A study with expected launch in 2025

Background suppression:

- Compton cone in data space
- Multiple-Compton events
- Fine pixelation (absorption probabilities)
- Active BGO shield

Energy range:

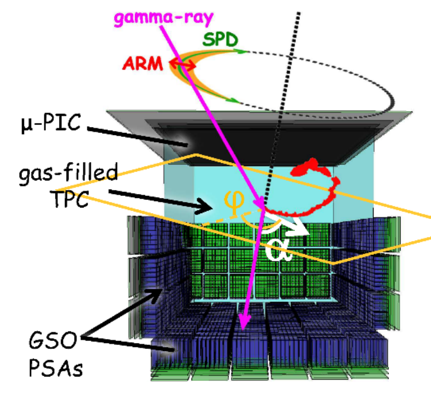
- 200 keV to 5+ MeV

Angular resolution:

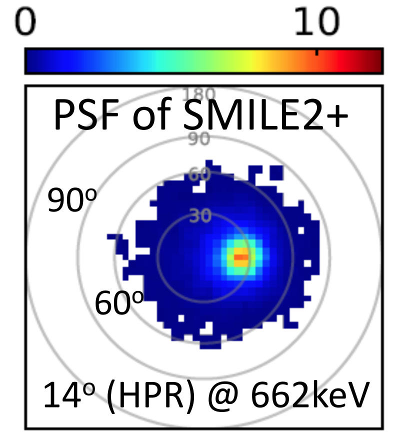
- Depending on energy range and event cuts, down to below 2 degrees

Further details see presentation by John Tomsick.

SMILE: An electron-tracking Compton Telescope



Hamaguchi, 2019, SMILE-2+



Ikeda+ 2021

The Compton interactions occur in a gas-filled TPC (Ar, 2 atm) enabling the tracking of the recoil election. This significantly reduces the area occupied by the PSF, and as consequence improves the sensitivity compared to a non-tracking Compton telescope.

Key science objectives:

- All MeV science within range of energy and sensitivity

Status:

- Active development with balloon flights

Background suppression:

- Full Compton kinematics with recoil electron direction and redundantly measured total scatter angle
- Some multiple-Compton events
- High resolution (absorption probabilities)

Energy range:

- ~200 keV to ~5 MeV

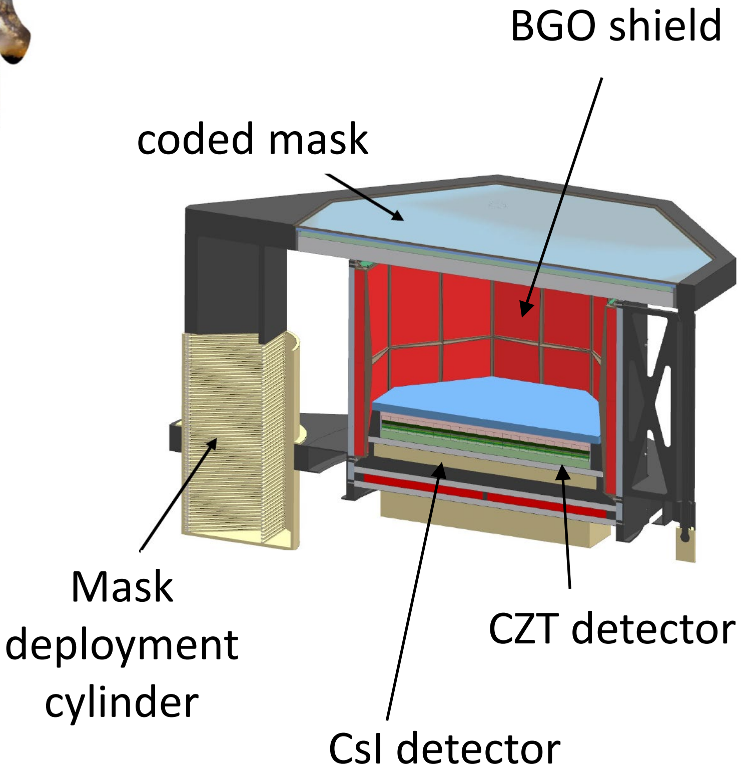
Angular resolution (HPR):

- Down to ~5 degree @ 1 MeV for SMILE-3

GECCO – a combined Compton Telescope and Coded Mask

GALACTIC COMPTON AND
GECCO
CODED APERTURE MASK EXPLORER

GECCO with mask deployed.



Best suited science objective:
- Point sources in Galactic Center region using coded-mask mode
- Everything else in Compton mode

Status:
- Getting ready to propose as MIDEX

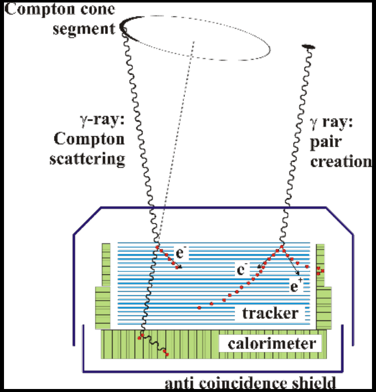
Background suppression:
- Compton cone
- Multiple-Compton events
- Fine pixelation (absorption probabilities)

Energy range:
- 50 keV – 10 MeV

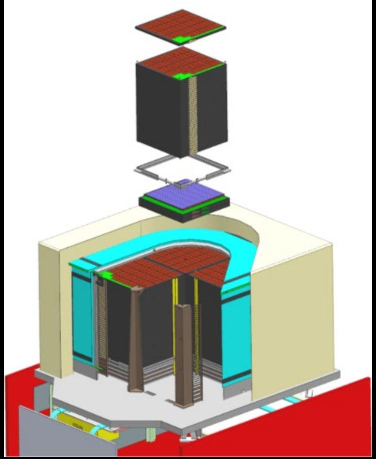
Angular resolution:
- Mask-mode: 1 arcmin
- Compton-mode: Down to 3 degrees

Further details see presentation by Alex Moiseev.

AMEGO-X – a combined Compton and Pair Telescope



General principle of a combined Compton and pair telescope



3 detector systems:

- Tracker consisting of pixel detectors (AstroPix)
- Calorimeter consisting of CsI bars
- Plastic anticoincidence shield

Fleischhack+ 2021

Science:

- Everything in the MeV range within sensitivity limits
- Focus on multi-messenger astrophysics

Status:

- Balloon flight with prototype in 2022/23
- Will be proposed as MIDEX end of this year

Background suppression:

- Compton arcs & pairs
- Multiple-Compton events
- Fine pixelation (absorption probabilities)
- Absorber for self-shielding when zenith pointing
- Si has very low activation

Energy range (size and threshold dependent):

- ~100 keV up to ~ 1 GeV (4 orders of magnitude!)

Angular resolution:

- Compton: Down to a few degrees
- Pair: Degrees to below 1 degree at higher energies.

Further details see presentation by Henrike Fleischhack

The typical data-analysis pipeline of a future MeV mission using COSI as example

The Compton Spectrometer and Imager

Current COSI: APRA balloon

46-day flight from Wanaka, New Zealand, 2016 – 1st science flight of NASA new super-pressure balloon platform

Future COSI: SMEX satellite

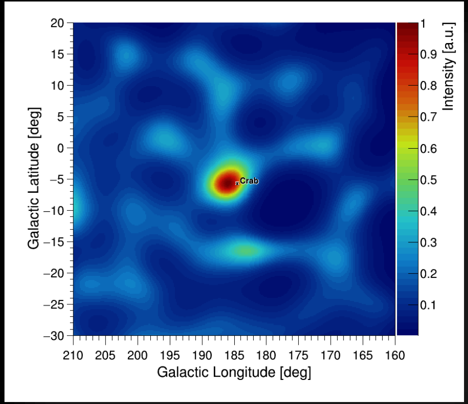
Currently in competitive Phase A study for NASA space mission

Detector System

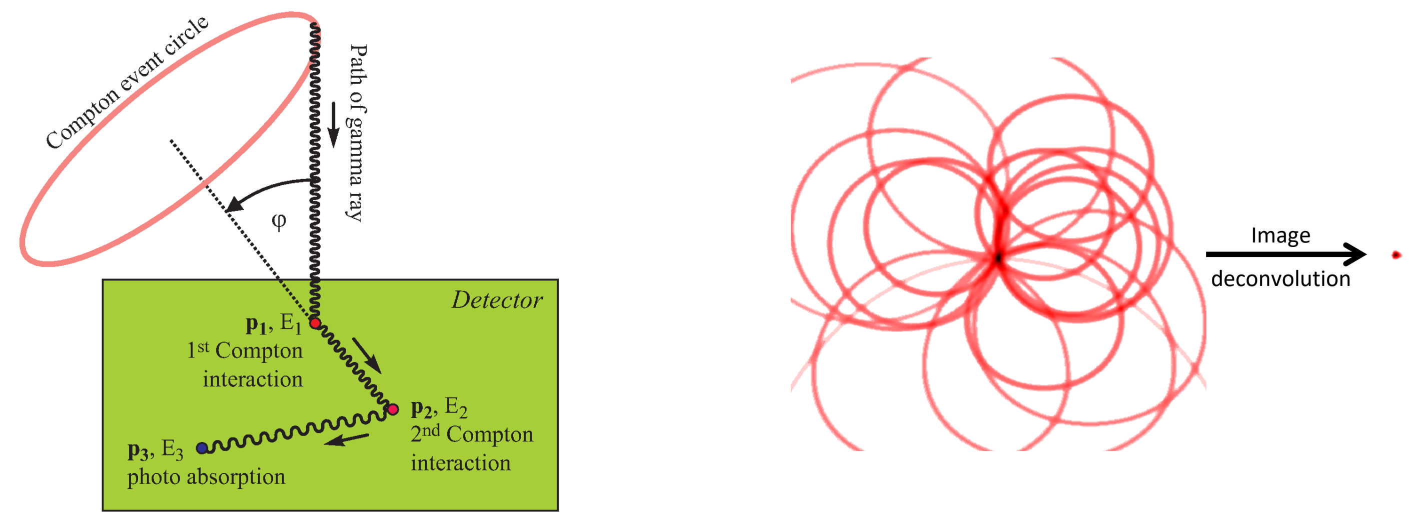
- Compton telescope
- Energy range: 0.2 – 5.0 MeV
- High-purity Germanium double-sided strip detectors
- Excellent energy resolution (few keV FWHM)
- Good angular resolution (up to below 2° FWHM for space mission)
- All-sky exposure for satellite mission

Science Objectives

- Origins of Positrons in our Galaxy
- Life cycle of matter in our Galaxy
- The most violent events and the most extreme environments in our Universe



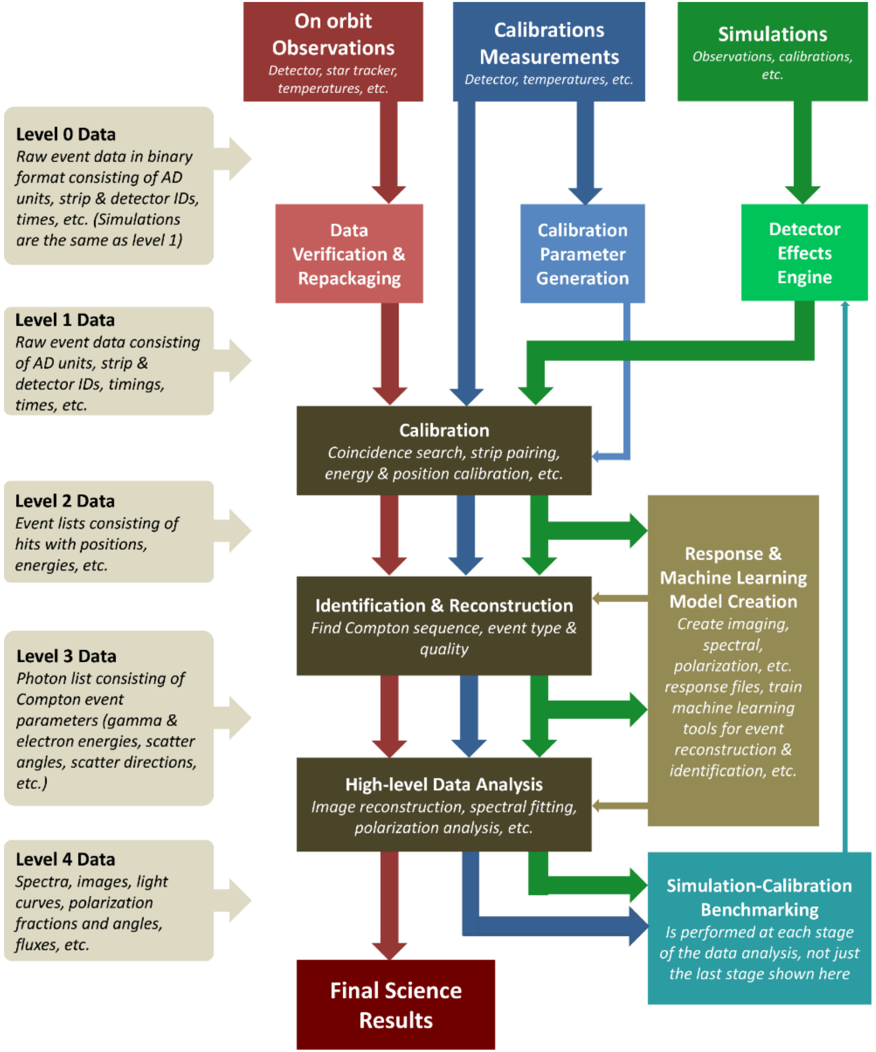
COSI Overview: Operating Principle



- Photons interact multiple times in active Germanium detectors via Compton scatters
- The interaction sequence has to be determined from information such as scatter angles, absorption probabilities, scatter probabilities.
- The origin of a single not-tracked Compton event can be restricted to the so called “event circle”.
- The photons originate at the point of all overlap.
- Deconvolution creates sky maps.

The COSI Data Analysis Pipeline

- COSI data-analysis pipeline fully implemented (Zoglauer 2021+)
- Based on MEGAlib & COSIpy
- Continued work on refinements and ease of use
- Next year:
  - Public data challenge using simulated data to teach COSI data analysis planned for autumn 2022
  - Release of pipeline along with all COSI balloon flight data in November 2022



On orbit Observations
Detector, star tracker, temperatures, etc.

Calibrations Measurements
Detector, temperatures, etc.

Simulations
Observations, calibrations, etc.

Level 0 Data
Raw event data in binary format consisting of AD units, strip & detector IDs, times, etc. (Simulations are the same as level 1)

Data Verification & Repackaging

Calibration Parameter Generation

Detector Effects Engine

Level 1 Data
Raw event data consisting of AD units, strip & detector IDs, timings, times, etc.

Calibration
Coincidence search, strip pairing, energy & position calibration, etc.

Level 2 Data
Event lists consisting of hits with positions, energies, etc.

Response & Machine Learning Model Creation
Create imaging, spectral, polarization, etc. response files, train machine learning tools for event reconstruction & identification, etc.

Identification & Reconstruction
Find Compton sequence, event type & quality

Level 3 Data
Photon list consisting of Compton event parameters (gamma & electron energies, scatter angles, scatter directions, etc.)

High-level Data Analysis
Image reconstruction, spectral fitting, polarization analysis, etc.

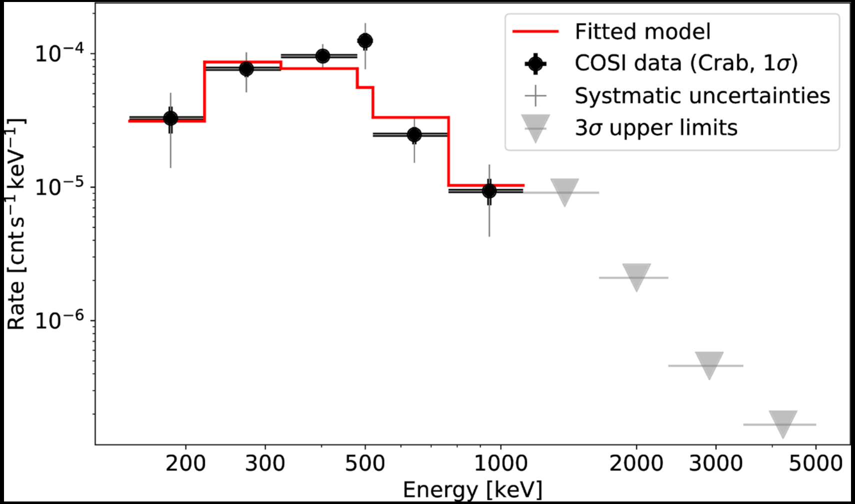
Level 4 Data
Spectra, images, light curves, polarization fractions and angles, fluxes, etc.

Simulation-Calibration Benchmarking
Is performed at each stage of the data analysis, not just the last stage shown here

Final Science Results

Crab Observations

Crab was visible for a few days during the 2016 flight when balloon reached its northern-most location under high zenith angles (40 degrees and more)



Spectral detection significance:
~16 sigma

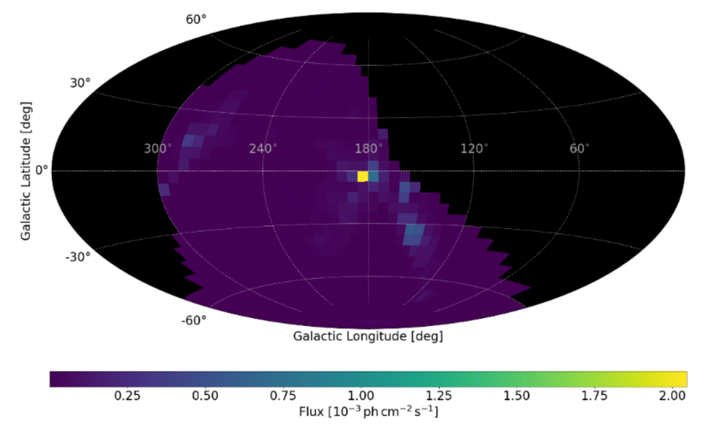
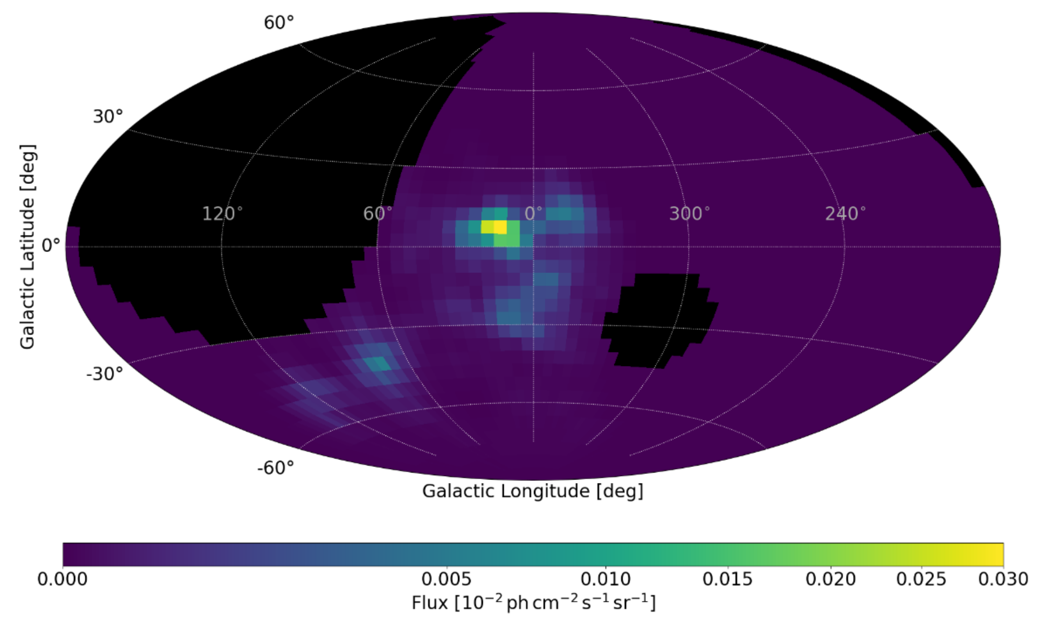


Image detection significance:
~8 sigma in 325 to 480 keV band
Illuminated pixels around Crab are from Crab photons scattering in the atmosphere (not included in response)

Details: Zoglauer+ 2021

Galactic Positron Annihilation Observations



Best 25 days (with least background) Galactic center observations during balloon flight
Image reconstruction using modified Richardson-Lucy approach
Corresponds to ~1.5 days of COSI-SMEX observations.
Details: Siegert+ 2020 ApJ

Summary

The MeV domain is one of the least explored regions in the electromagnetic spectrum and home to many exciting research topics ranging from the origins of the Galactic positrons, to nuclear-line science, to multi-messenger astrophysics via short GRBs and neutrino sources.

Many new missions and mission concepts are ready to fill this void in the next decade and will significantly advance MeV gamma-ray astrophysics.

Thank you!