# Instrumentation for the MeV Domain

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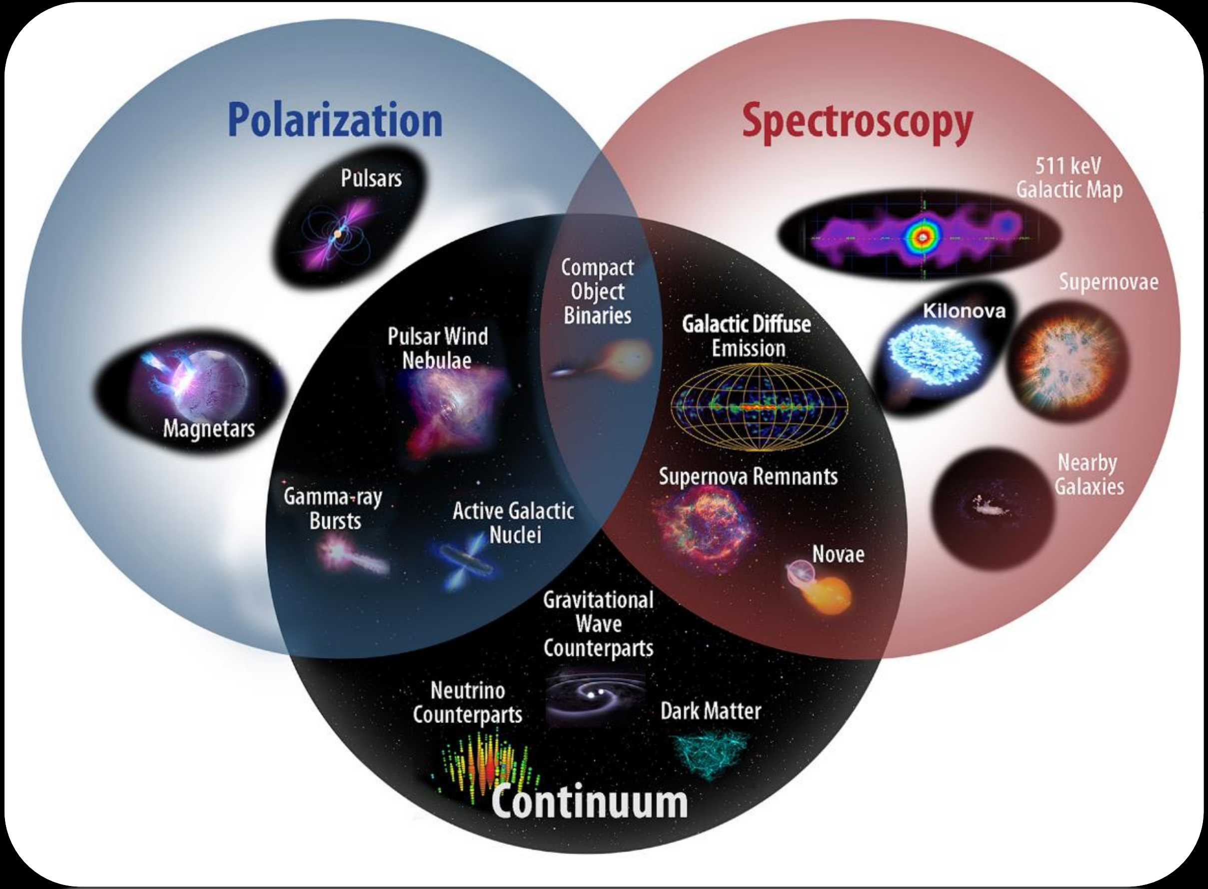
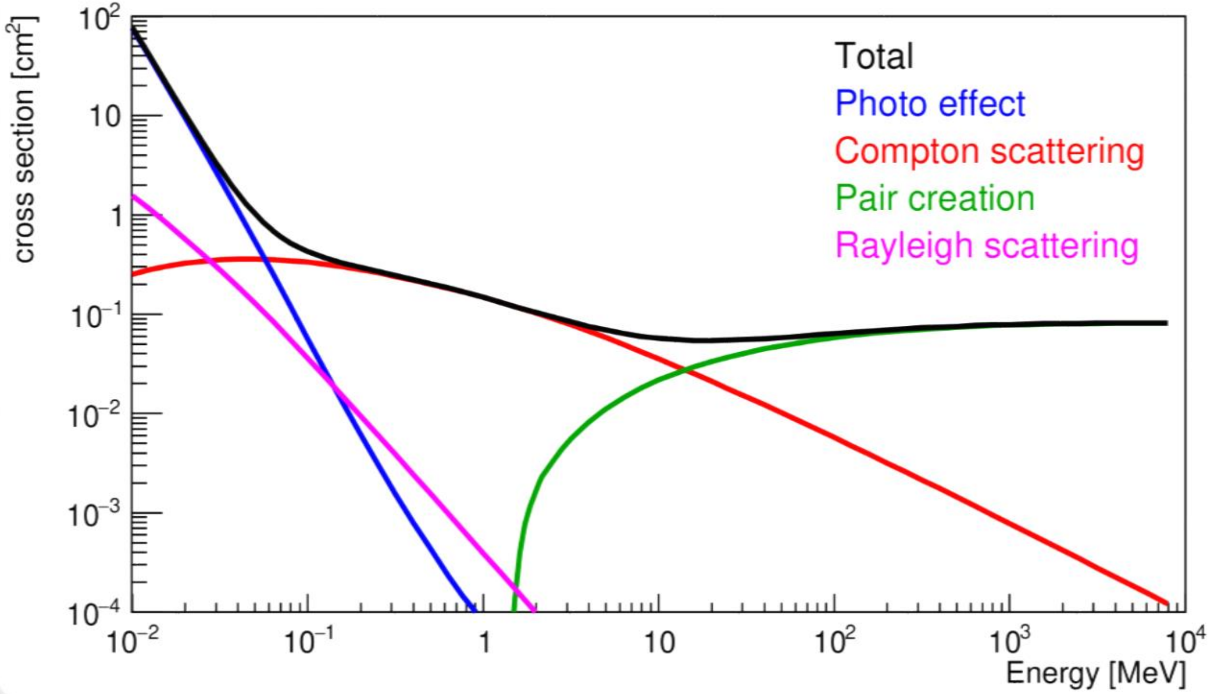
# Science in the MeV Domain




McEnery+ 2019

# Measurement Challenges in the MeV Domain

# Two Dominating Processes & Small Interaction Cross Sections

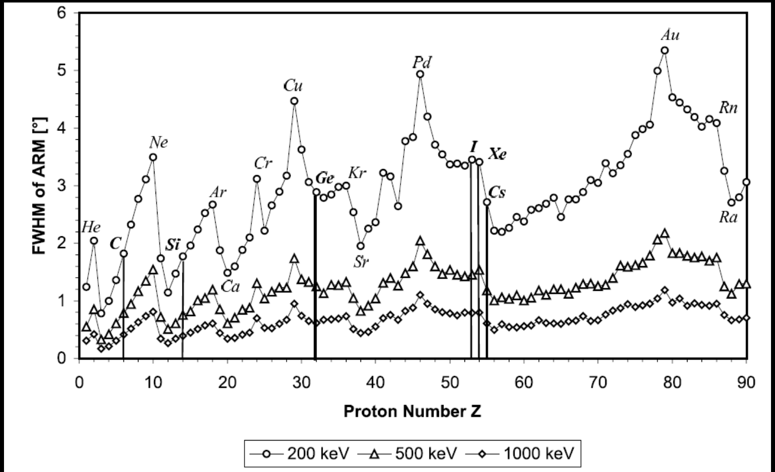



Dominant cross sections in silicon

# Angular Resolution Limits

## Compton regime: Doppler broadening

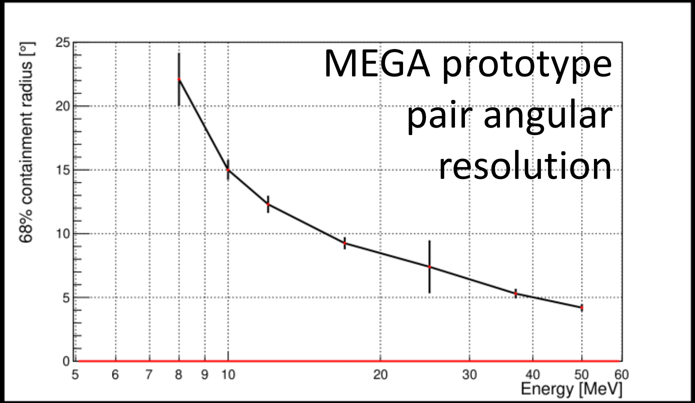
- The electron is not at rest but bound to a nucleus!
- Electron momentum cannot be measured!
- Using Compton equation(s) to determine origin of the gamma ray is only an approximation!



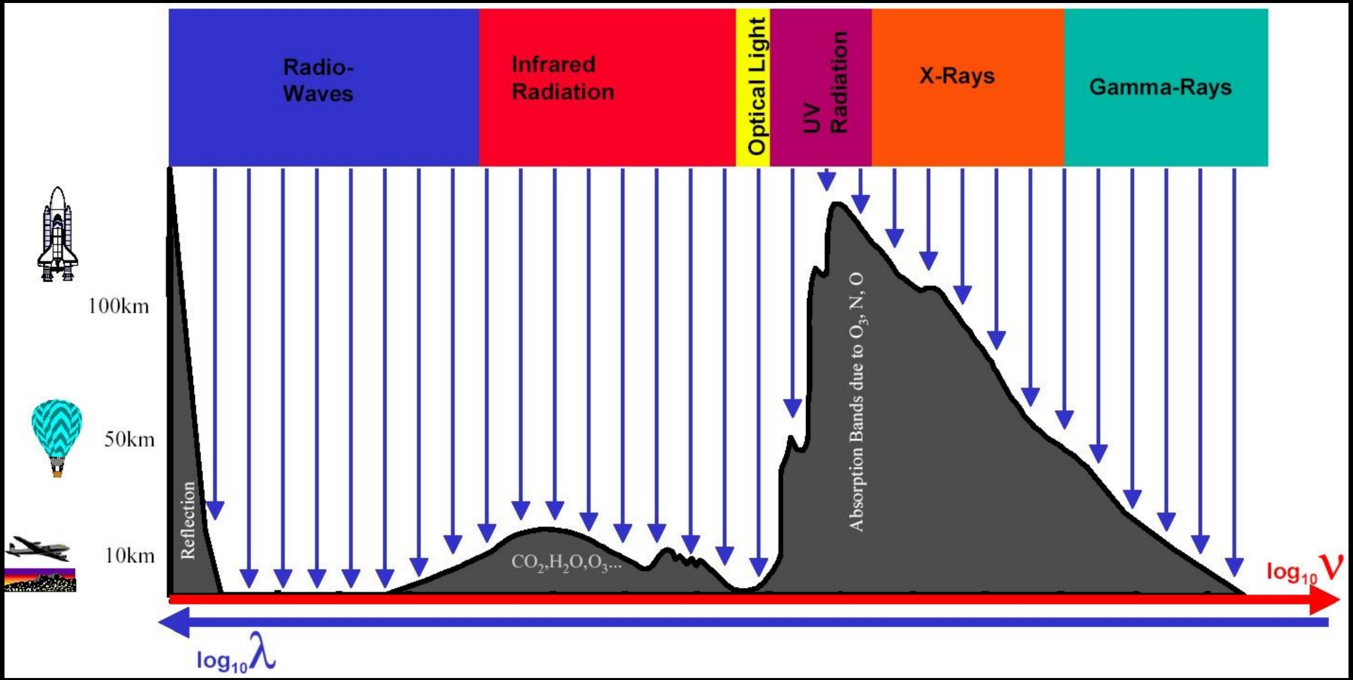

## Pair regime:

The angular resolution for pair events is limited by:

- The unknown recoil of the nucleus
- Electron / Positron small angle scattering in the first layer of interactions

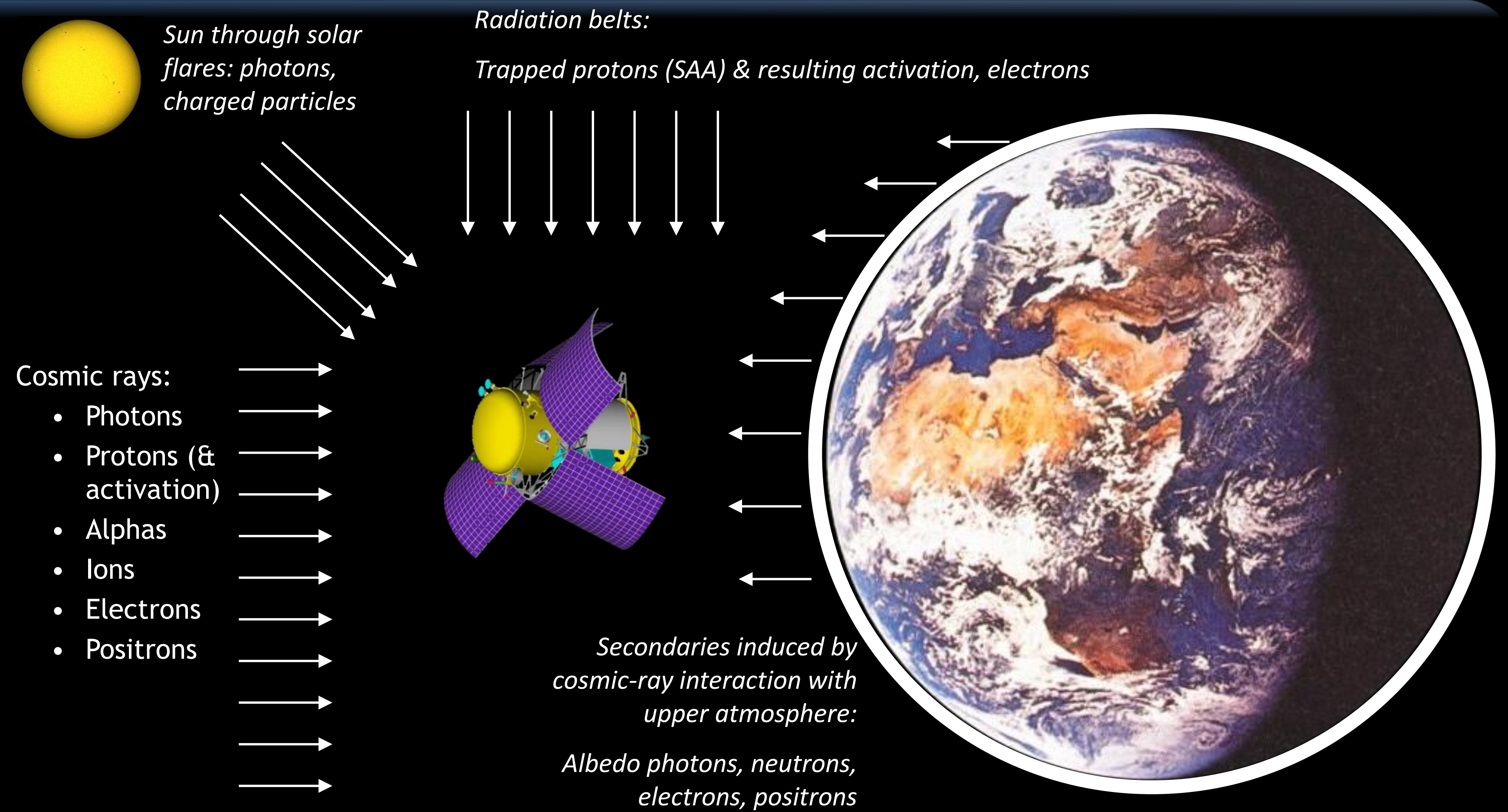


# Leaving the Atmosphere




Schönfelder+, 2001

# The Space Radiation Environment



# 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-Compton events
  - Tracked Compton events: Reduce PSF (cones to arcs)
  - Pulse-shape discrimination: Eliminate, e.g., neutrons

# Instrument Types

# 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 gas options: Ar, Xe, etc.
- Read-out, e.g., via gas electron multiplier (GEM)
- Can have excellent track resolution (depends on pressure)

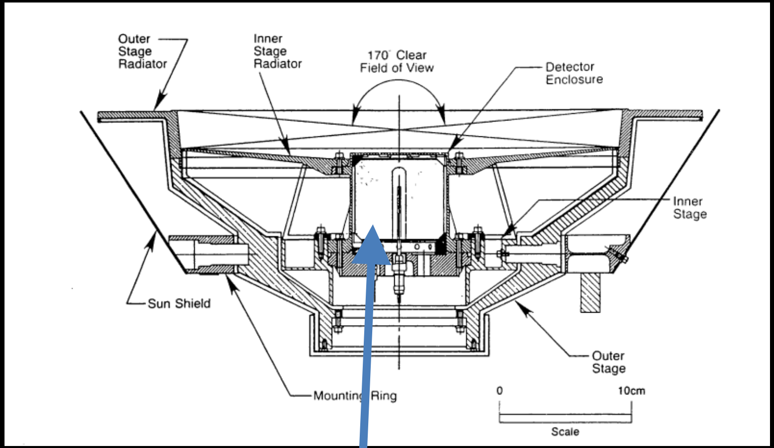
# Caveats

I will show at most ONE example per instrument types – although there might be many more similar detectors out there.

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.

# Just a Volume of Active Detector Material

Example: TGRS on Wind




Owens+ 1991

Single coaxial Germanium detector

Background rejection:

- Not really

Energy range (material, size, threshold, etc. dependent):

- Several keV up to 10's of MeV

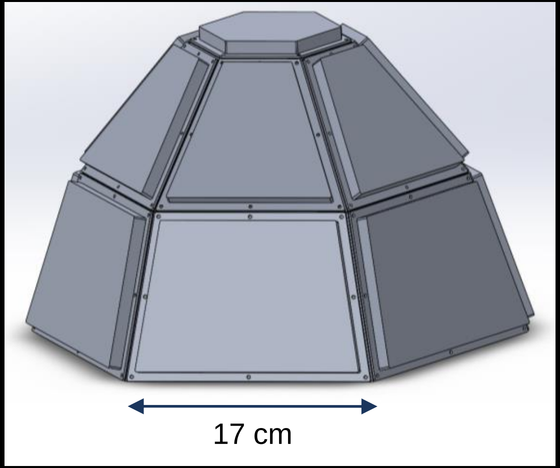
Angular resolution:

- None

Best suited science:

- Spectra / light curves of fast transients: GRB's & solar flares, all-sky

# Intelligently Arranged Detector Volumes




Example: Glowbug concept, Eric Grove, NRL

Arranging the simple detectors intelligently, allows a certain degree of transient localization due to orientation towards the GRB and (self-) shielding (i.e. for different directions the detectors see unique source intensity)

Background rejection:

- Not really

Energy range (material, size, threshold, etc. dependent):

- Several keV up to 10’s of MeV

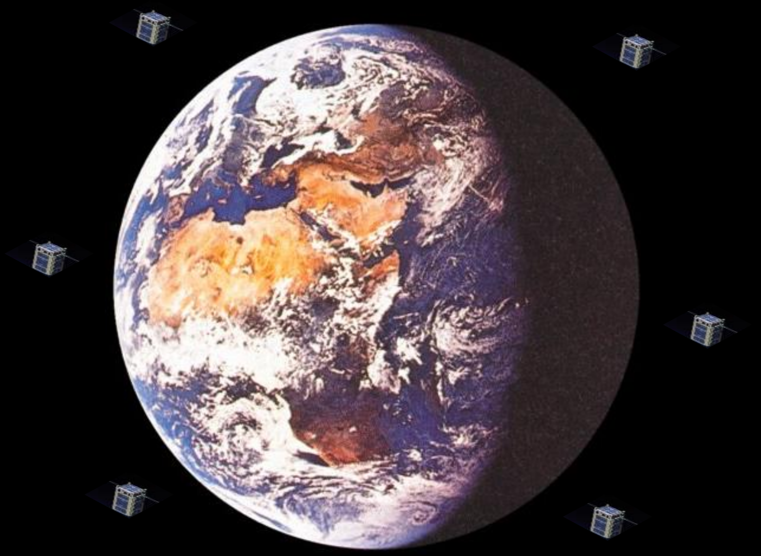
Angular resolution (68% containment):

- Depends on number of detectors, arrangement, statistics & systematics
- Few degrees to 10’s of degrees

Best suited science:

- GRB’s, all-sky

# Constellation of Simple Detectors



Using a fleet of, e.g., low-cost cube-sats with single channel scintillators allows to triangulate the origin of fast transients with well-defined features (spikes, start times, etc.)

Background rejection:

- Not really

Energy range (material, size, threshold, etc. dependent):

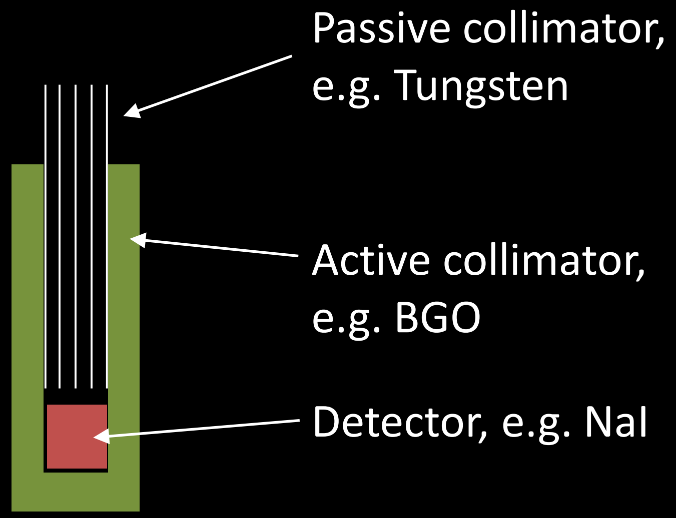
- Several keV up to 10's of MeV

Angular resolution for fast transients depends on spacecraft separation, statistics, systematics, etc.

Best suited science:

- GRB's, all-sky

# Collimator using simple detectors




Collimation eliminates some of the background, and restricts the field-of-view to a small spot on the sky, e.g., your point source

Background rejection:
- Collimation

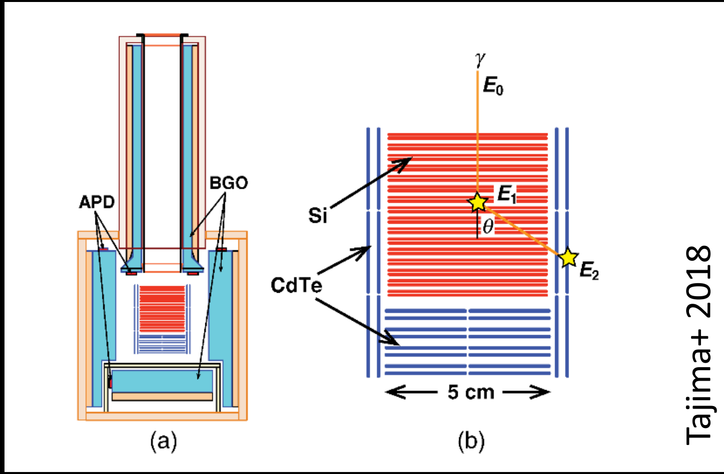
Energy range (size and threshold dependent):
- Several keV up to whenever your collimator gets transparent (few MeV)

Angular restriction:
- Opening of collimator

Best suited science:
- Spectral properties of individual, known point sources

# Collimators with Compton Detector

Example: Soft Gamma-ray Detector (SGD) on Hitomi




The Compton camera enables the rejection of the background not compatible with an origin visible through the opening of the collimator

Background rejection:

- Collimation
- "Compton collimation"

Energy range (size and threshold dependent):

- Several keV up to whenever your collimator gets transparent (few MeV)
- Hitomi: 60 keV – 600 kev

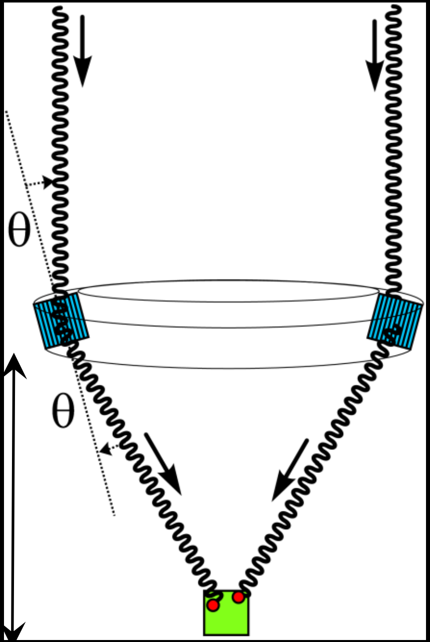
Angular restriction:

- Opening of collimator

Best suited science:

- Spectral and polarization properties of point sources

# Laue Lenses




Example: Max


*Crystals, e.g., Ge, Si, Ag, Au, etc.*

Collection:

- Laue diffraction of gamma rays under Bragg-condition

Detection:

- Gamma rays are focused on small detector - usually shielded and with very good energy resolution (Ge)

Background collection area for point sources:

- Focal spot

Energy range (depends on crystal, its orientation, and focal length):

- Many keV up to ~2 MeV
- But: In bands (one per crystal and orientation) not continuously

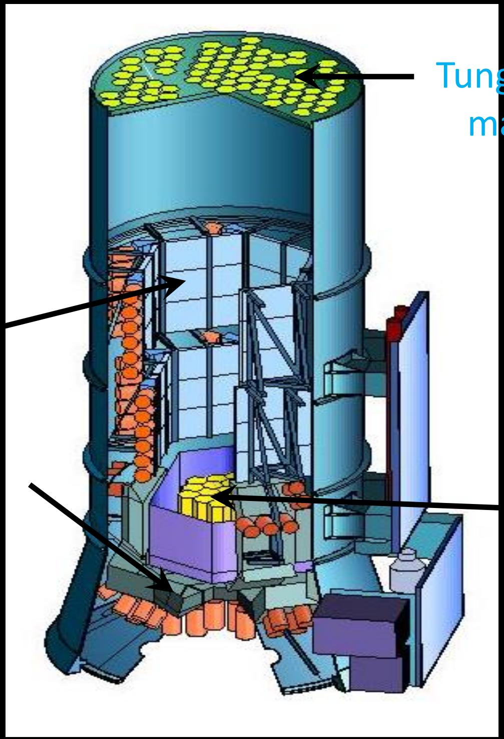
Angular restriction (depends on focal length, quality of lens element arrangement, lens elements)

- Not real imaging but focusing
- Below 1 arcmin may be achievable

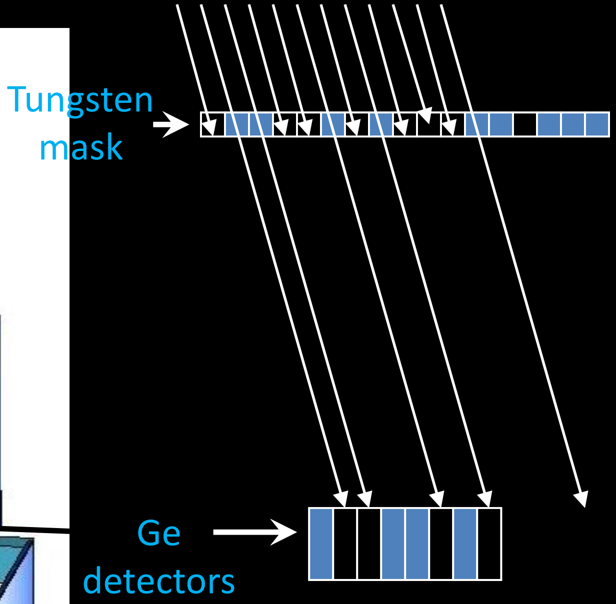
Best suited science:

- Single known point sources

# Spatial & Temporal Modulation: Coded Masks



*Example: SPI onboard INTEGRAL*




Unique mask/shadow pattern for each photon direction (angular resolution element)

→ Direction can be reconstructed

Background collection area for point sources:

- Whole detector

Energy range (size and threshold dependent, collimator design):

- Several keV up to few MeV

Angular resolution:

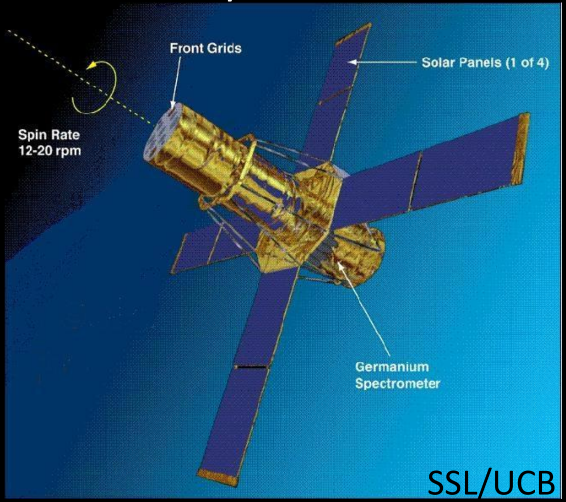
- Opening of collimator & detector pixel size
- Degrees to arcsec achievable

Best suited science objective:

- Point sources

# Spatial & Temporal Modulation: Rotators

Example: RHESSI




One or two planes of grids rotate in front of a detector. Fourier analysis can be applied to derive the source location from the temporally modulated source signal.

Background collection area for point sources:

- Whole detector

Energy range (size and threshold dependent):

- Several keV up to whenever your grids gets transparent (few MeV)

Angular resolution:

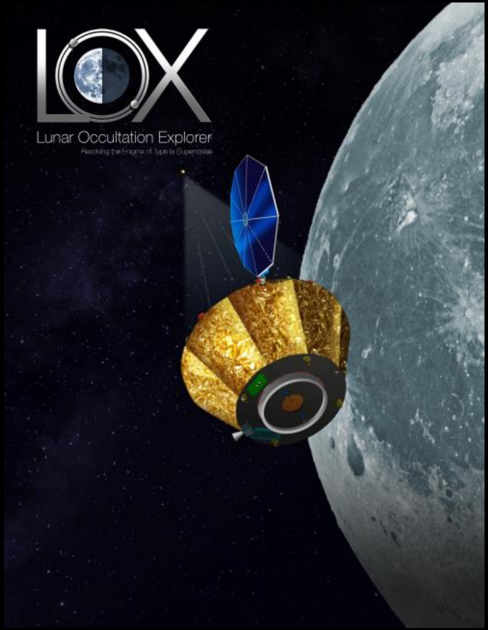
- Depends on grid pitch(es): arc second range achievable

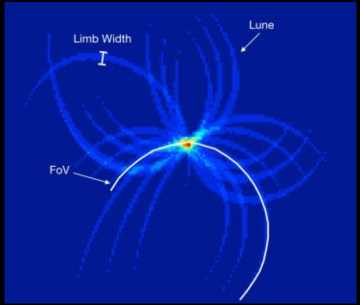
Best suited science objective:

- Point sources

# Spatial & Temporal Modulation: Occultations

Example:




Miller+ 2019

Each significant background change is considered an occultation event. In image space those are “event arcs”. The point of overlap of all those arcs is the source position.

Background collection area for point sources:

- Whole detector

Energy range (material, size and threshold dependent):

- Several keV up to 10’s of MeV

Angular resolution:

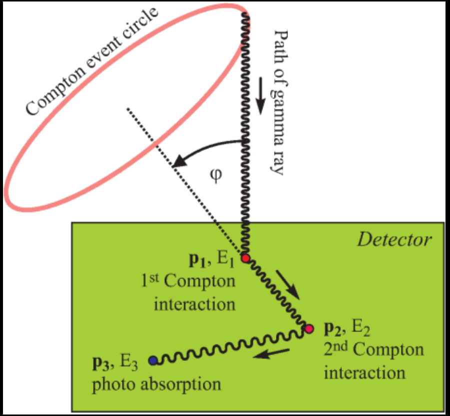
- Depends on systematics, sharpness (atmosphere / terrain knowledge) of object
- Arcmin achievable

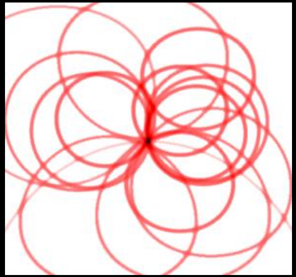
Best suited science:

- Point sources / all-sky monitoring

# Single-Volume Multiple-Interaction Compton Telescopes

Example: COSI



Gamma rays interact via multiple Compton interactions in the active detector material, allowing to determine the direction-of-motion of the gamma ray.

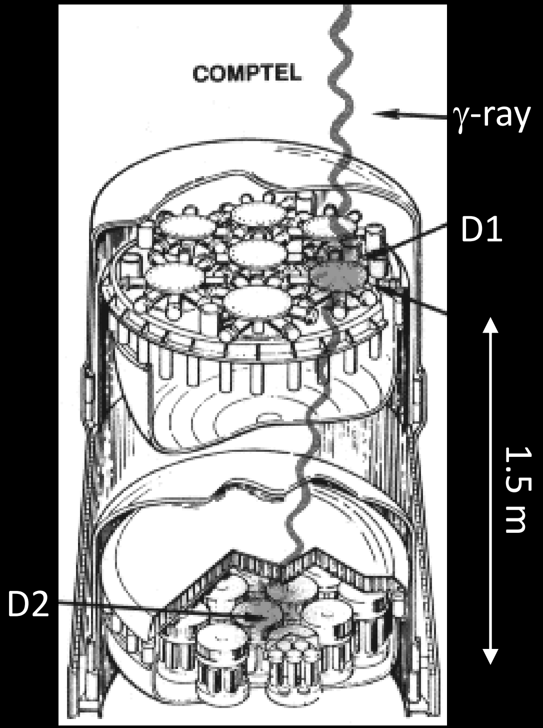
Background suppression:
- Compton cone in data space
- Multiple-Compton events
- Fine pixilation (absorption probabilities)
- COSI-specific: Active shield

Energy range (size and threshold dependent):
- ~100 keV up to 10's of MeV
- COSI: 200 keV to 5 MeV

Angular resolution:
- Can reach aground 1 degree, but very difficult (limited by energy & position resolution, Doppler-broadening)
- COSI balloon: 4 degree

Best suited science objective:
- Everything within range of sensitivity
- COSI-specific: Ge-detectors optimized for nuclear line science

# Time-of-flight Compton Telescopes




Interaction sequence is determined by time-of-flight measurement between detector planes

Background suppression:
- Compton cone in data space
- Time-of-flight

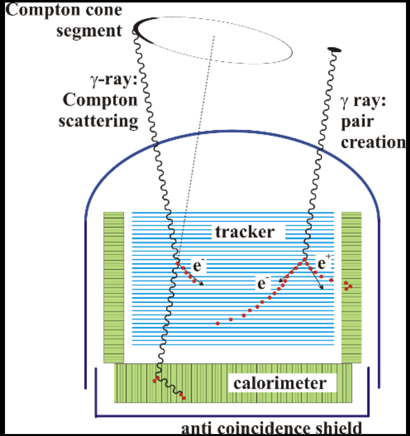
Energy range (material, size and threshold dependent):
- 100 keV up to 10's of MeV
- COMPTEL: 0.75 – 30 MeV

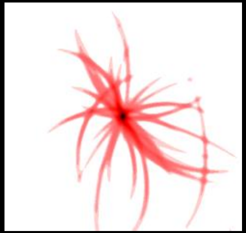
Angular resolution:
- Can reach aground 1 degree, but very challenging (limited by energy & position resolution, Doppler-broadening)
- COMPTEL: up to 3 degrees

Best suited science objective:
- Everything within range of sensitivity

# Electron-tracking Compton Telescopes

Example: MEGA



The tracker allows to determine the direction of motion of the recoil electron, which reduces the Compton cone to an arc, and subsequently reduces the PSF and the background below it.

**Also detects pair events**

Background suppression:

- Compton arcs
- Some multiple-Compton events
- Fine pixilation (absorption probabilities)

Energy range (size and threshold dependent):

- ~100 keV up to …

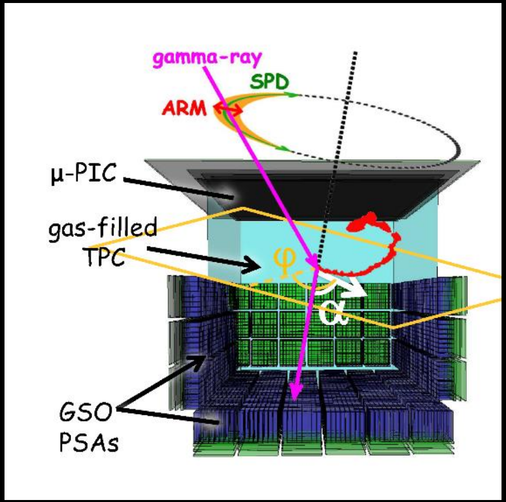
Angular resolution:

- Can reach aground 1 degree, but difficult (limited by energy & position resolution, Doppler-broadening)

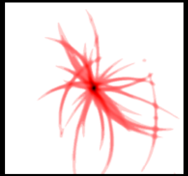
Best suited science objective:

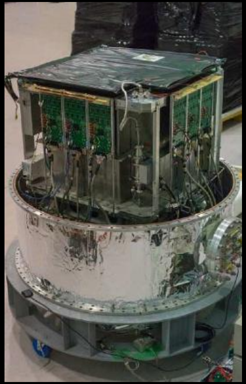
- Everything within range of sensitivity

# Electron-tracking Compton Telescopes




Hamaguchi, 2019, SMILE-2+





The Compton interaction occurs in a gas-filled TPC, enabling tracking of the recoil election.

**Also could detect pair events**

Background suppression:

- Compton <u>arcs</u>
- Some multiple-Compton events
- Fine pixilation (absorption probabilities)

Energy range (size and threshold dependent):

- 10’s of keV up to …

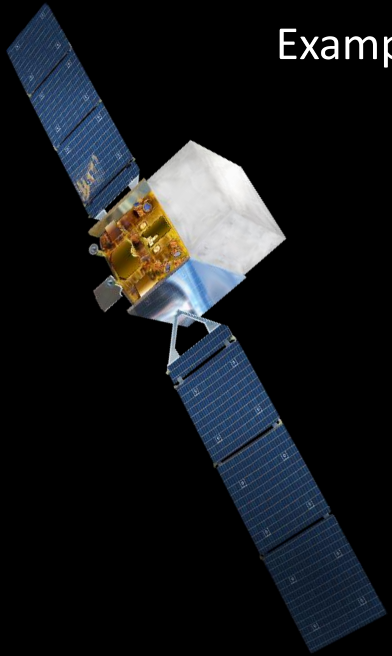
Angular resolution:

- Can reach aground 1 degree, but very difficult (limited by energy & position resolution, Doppler-broadening)

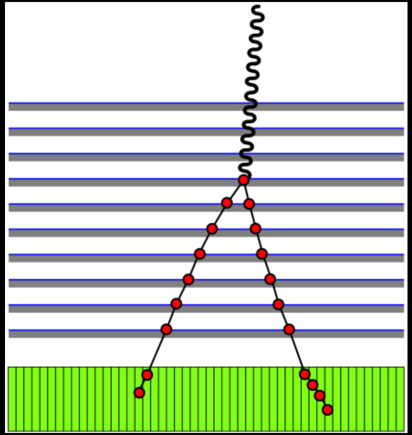
Best suited science objective:

- Everything within range of sensitivity

# Pair Telescopes



Example: FERMI



Gamma rays undergo pair creation in the tracker. From the path of the electron-positron pair the origin of the gamma ray can be determined.

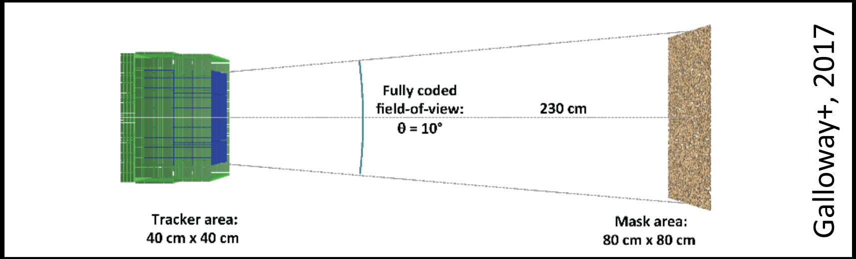
Background suppression:
- Pair events

Energy range (size and threshold dependent):
- ~20 MeV until effective area is too small

Angular resolution:
- Several degree up to several arcmin

Best suited science objective:
- Everything within range of sensitivity

# Combined Compton Telescope and Coded Mask

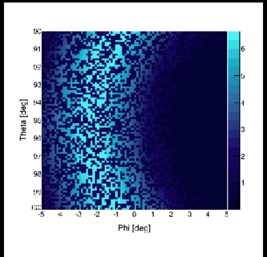



Background suppression:

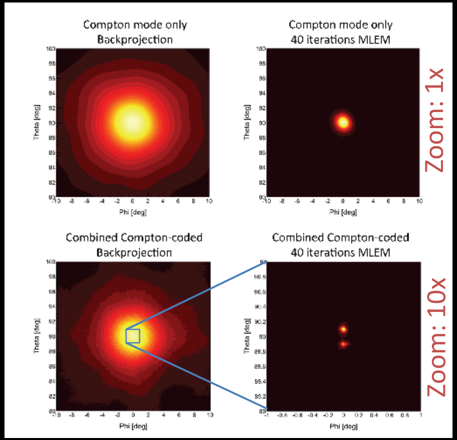
- Compton cone
- Multiple-Compton events
- Fine pixilation (absorption probabilities)

Energy range (size and threshold dependent):

- Defined by mask and Compton telescope, up to a few MeV




Coded-mask pattern is imprinted on Compton cones




Deconvolution results in the angular resolution determined by the mask.

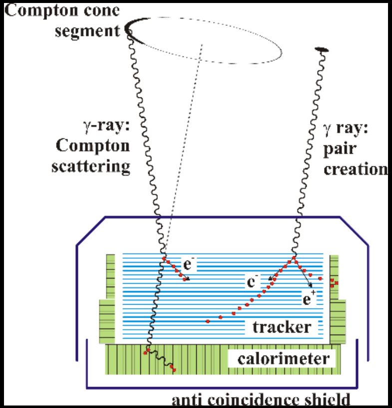
Angular resolution:

- Defined by mask, up to arcmin or better

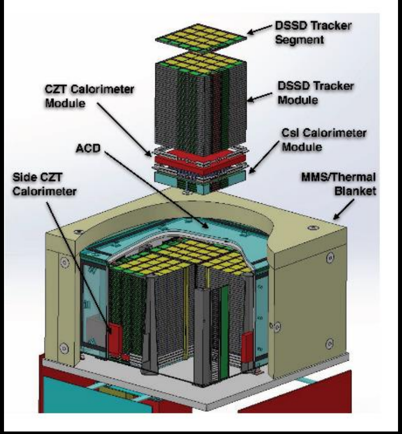
Best suited science objective:

- Point sources in coded-mask mode
- Everything else in Compton mode

# Combined Compton and Pair Telescopes




Tracker can do both: Compton & pair events




Several different incarnations: MEGA, GRIPS, e-ASTROGAM & AMEGO

McEnery+ 2019

Background suppression:

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

Energy range (size and threshold dependent):

- ~100 keV up to ~ 10 GeV (5 orders of magnitude!)

Angular resolution:

- Compton: Up to 1 degree (Si lowest Doppler broadening)
- Pair: Degrees to several arcmin's (better than FERMI due to missing conversion foils)

Science:

- Everything in the MeV range within sensitivity limits

Thanks!