Compton Telescopes:

Goals, Design Options, Data Analysis

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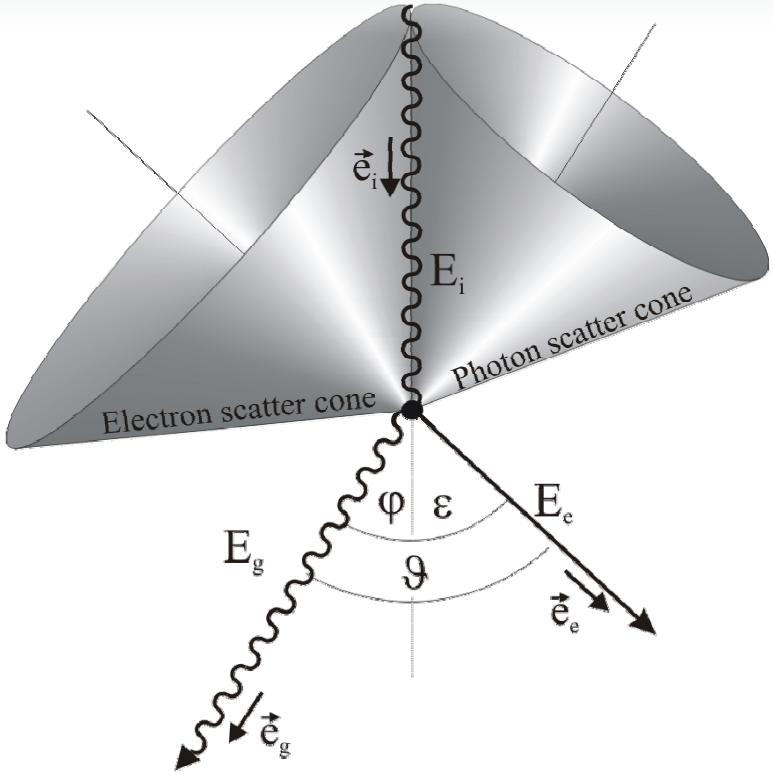
Prologue:
Details about Compton scattering

A Compton Scattering Primer



E_i	Energy of initial gamma ray
E_e	Energy of the recoil electron
E_g	Energy of the scattered gamma ray
E_0	Rest energy of the electron
E_e^{rel}	Total relativistic energy of the electron
φ	"Compton scatter angle" of the gamma ray
ε	"Electron scatter angle" of the recoil electron
ϑ	Total scatter angle
$\vec{e}_i$	Direction of the initial gamma ray
$\vec{e}_e$	Direction of the recoil electron
$\vec{e}_g$	Direction of the scattered gamma ray

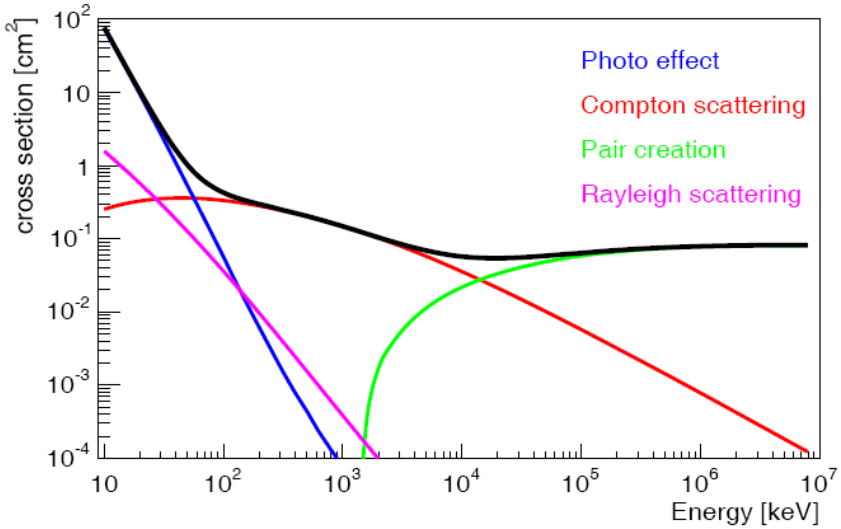
Compton equation: $\cos\varphi = 1 - \frac{E_0}{E_g} + \frac{E_0}{E_e + E_g}$ "Compton cone"

In the case the electron direction is known: $\vec{e}_i = \frac{\sqrt{E_e^2 + 2E_eE_0}\,\vec{e}_e + E_g\vec{e}_g}{E_e + E_g}$

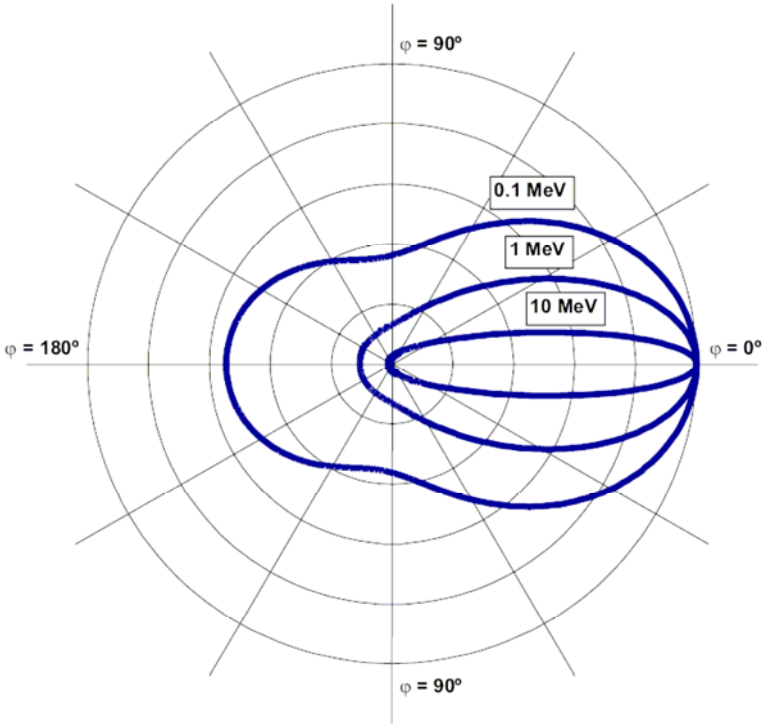
The Klein-Nishina cross-section

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

for Silicon:



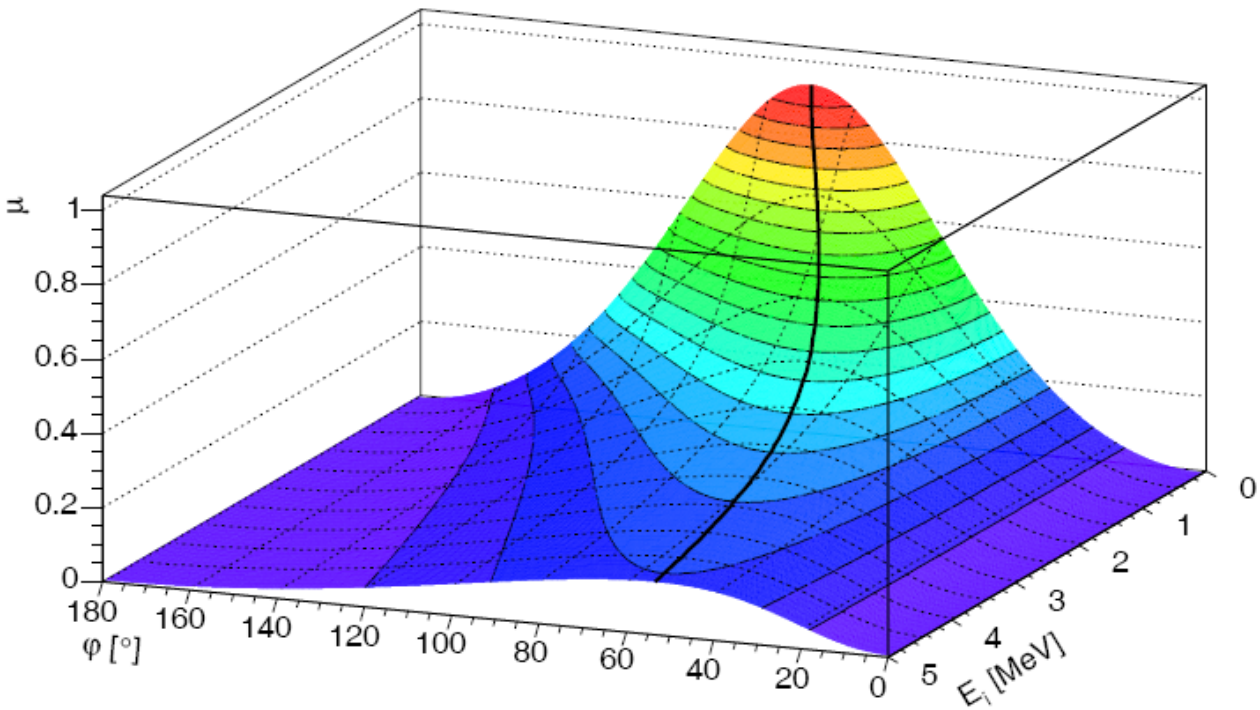
Compton scattering is the dominant interaction mechanism between ~100 keV and ~10 MeV (in Si)

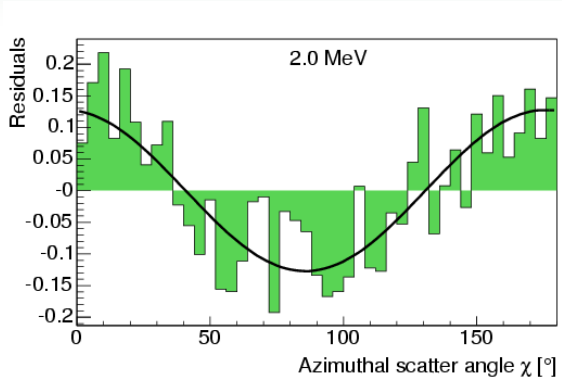


Normalized Klein-Nishina cross-section as a function of scatter angle: The higher the energy, the stronger is the forward scattering.

Compton Scattering Preserves Polarization

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





Cosine shaped modulation of azimuthal scatter angle

Modulation as a function of energy and and scatter angle

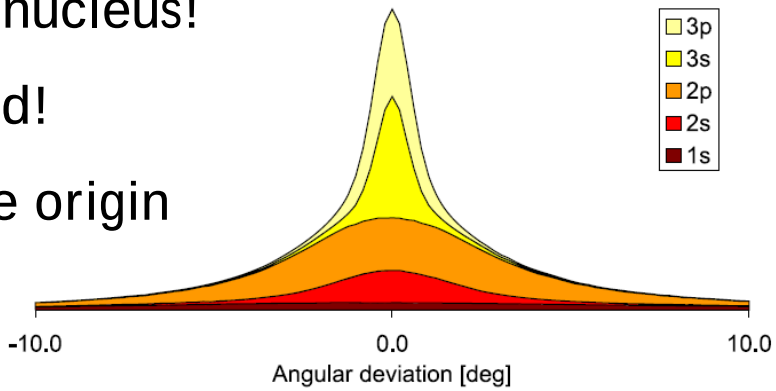
→ Most polarization information is preserved at low energies and medium scatter angles (60-90 degrees)

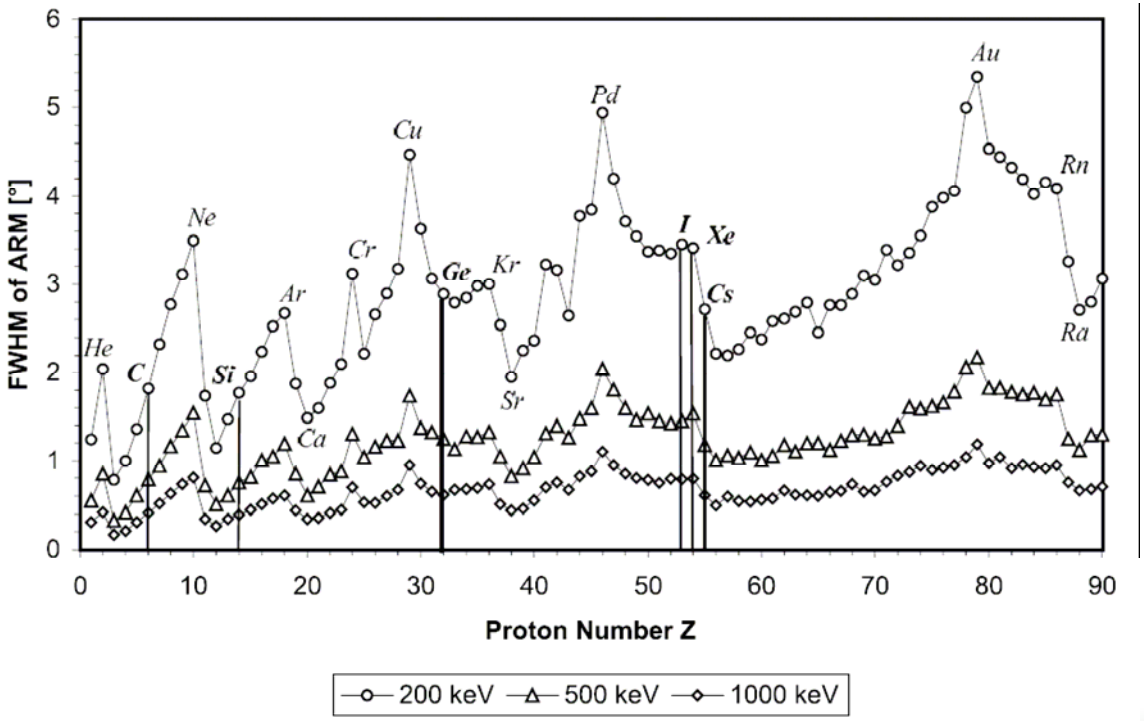
Doppler-broadening as fundamental limit

The electron is not at rest, but bound to a nucleus!

→ Electron momentum cannot be measured!

→ Using Compton equation(s) to determine origin of γ-ray is only an approximation!





The angular resolution of any Compton telescope is fundamentally limited by this so called "Doppler-broadening"

Chapter One:
What are Compton cameras good for?

Application areas

Physics

Astrophysics: medium-energy gamma-ray astronomy

Dark matter search

Medical imaging

SPECT – Single Photon Emission CT

“Homeland security”

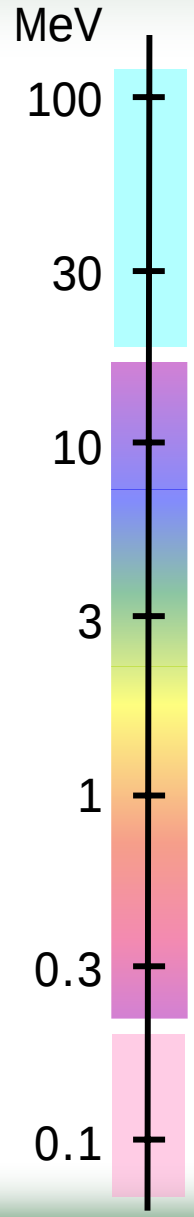
nuclear thread detection & nuclear waste monitoring

Astrophysics in the Compton regime

High-energy γ-ray range
(pair regime)

Medium energy γ-ray range
(Compton regime)

Low-energy γ-ray range/
Hard X-ray range
(photo effect regime)



Pair telescopes:

EGRET, AGILE, GLAST

Compton telescopes:

COMPTEL

Spatial & temporal modulators:

SPI, Swift, RHESSI

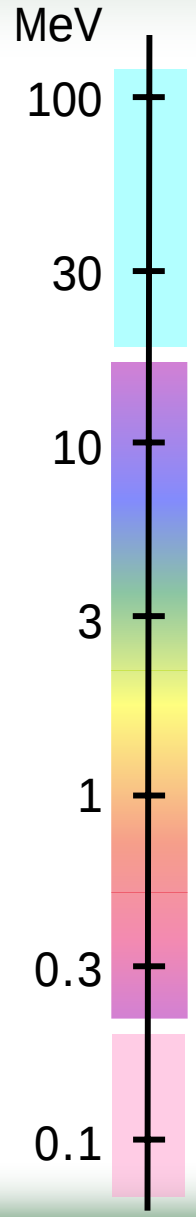
Focusing: GRI

Collimators: HXD, SGD

Astrophysics in the Compton regime

Nucleosynthesis

nuclear γ-lines
$\leq$8 MeV



Cosmic Accelerators

non-thermal continuum:

- Bremsstrahlung
- synchro-cyclotron radiation
- inverse Compton scattering

Astrophysics in the Compton regime

Nucleosynthesis

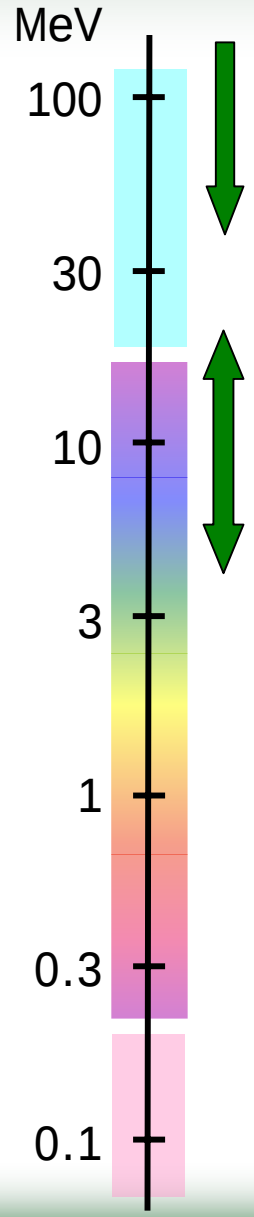
SN/massive stars:
nuclear reactions/isotopes

Extended galactic radioactivity:
^{26}Al, ^{60}Fe

Young SNRs: ^{44}Ti

847 keV: SN Ia

511 keV: novae, supernovae,
dark matter ??



Cosmic Accelerators

Unidentified EGRET Sources

Galactic and extragalactic
diffuse background

Spectral luminosity maxima of some
EGRET/COMPTEL Blazars

non-thermal spectra
in black-hole binaries,
micro-quasars

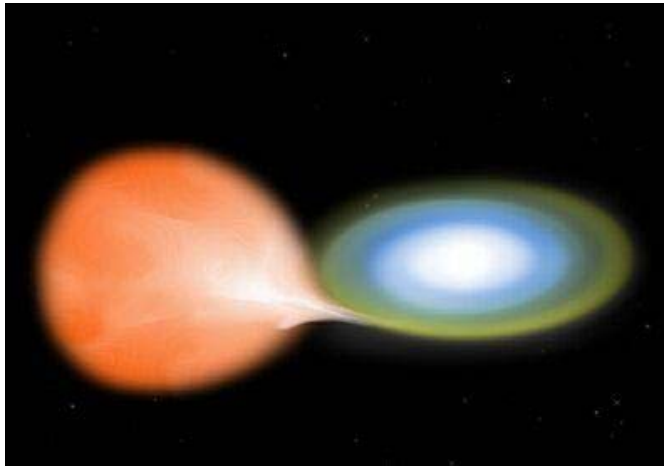
GRB spectra
polarization

847 keV: Are SN Ia Standard Candles?

Supernovae of type Ia are presumed to be standard candles and used for cosmology

However, many competing models for their explosion mechanism exists:

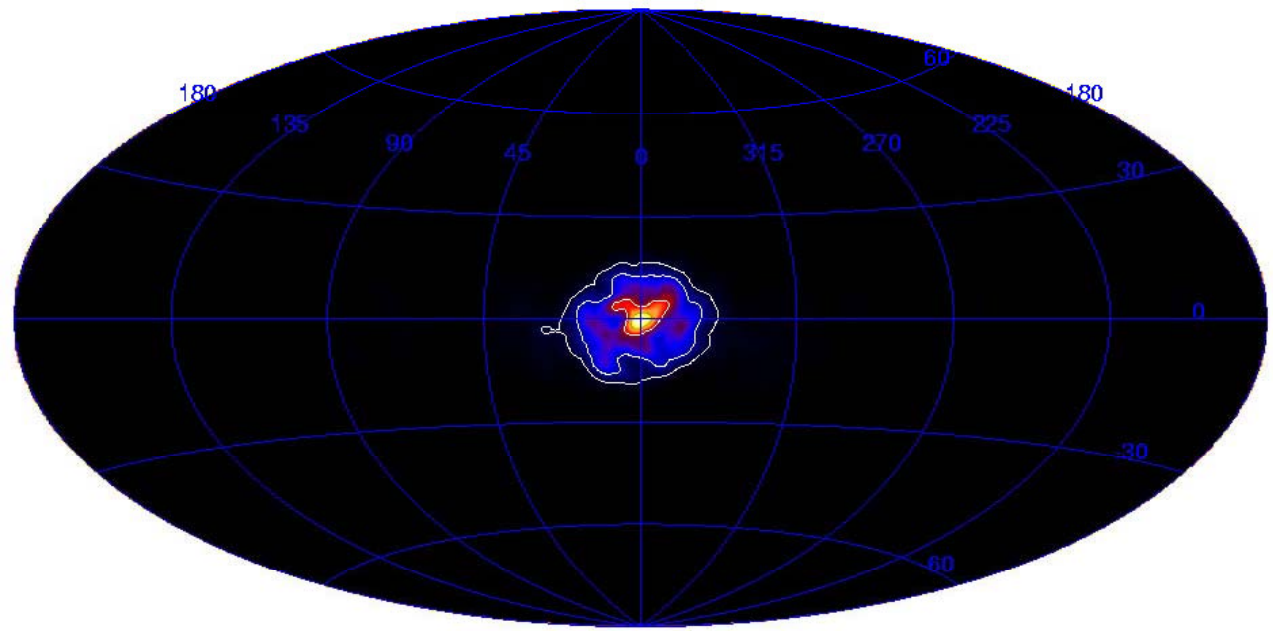
- Speed of burning front:
  - subsonic (deflagration model)
  - supersonic (detonation model)
  - mixture
- Does the explosion only happen if the white dwarf exceeds the Chandrasekhar limit, or also while it it is still a sub-Chandrasekhar white dwarf



Goal:

Discriminate between the models through measurements of the production rate and ejection velocities of ^{56}Ni decay chain (847 keV, 1238 keV, 812 keV)

511 keV: Electron-Positron Annihilation



INTEGRAL/SPI 511 keV measurement

(Knödlseder et al., 2005)

What is the origin of the 511 keV line at the galactic center:

- Unresolved SN Ia, novae, black holes ?
- Positrons transported in the galactic magnetic field to the center ?
- MeV dark matter annihilation/decay ?
- Or something else ?

Polarization: GRBs, pulsars

GRBs:

How does the inner engine work and what are the γ-ray emission processes:

- synchrotron/inverse Compton
- hadron related emission via pion production and decay

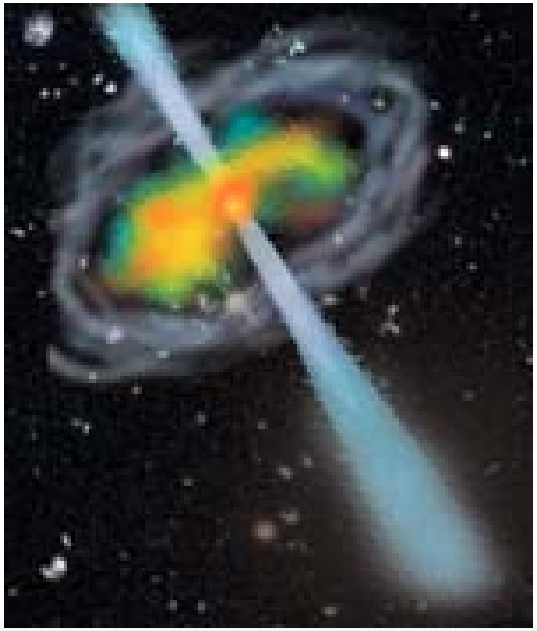
Pulsars:

What are the production sites

- polar cap
- outer gap
- two-pole caustic model

Goal:

Solve most of the open questions by high-sensitivity, high-bandwidth measurements including polarization



Science summary

Enable high sensitivity γ-ray spectroscopy, imaging and polarization measurements from 0.2 up to 10 MeV

Life Cycles of Matter

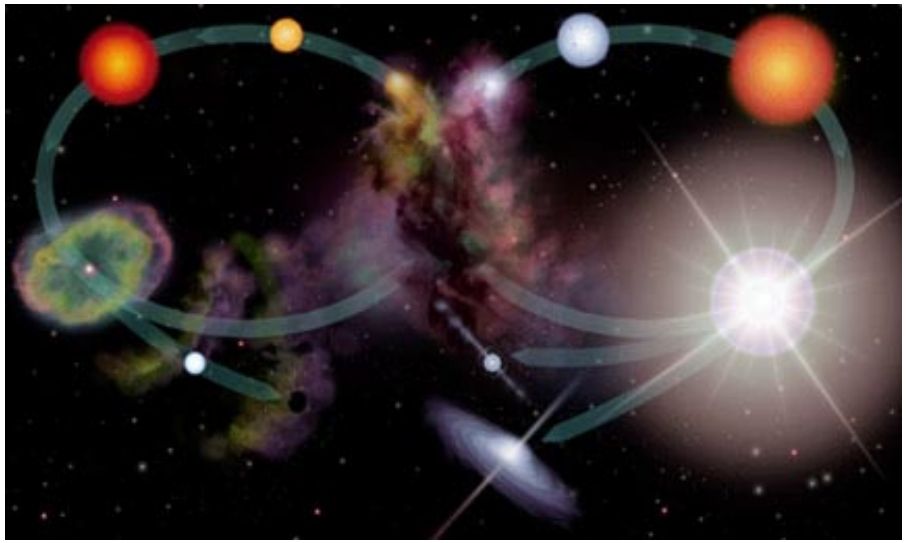
- ✓ Supernovae & nucleosynthesis
- ✓ Supernova remnants & interstellar medium
- ✓ Neutron stars, pulsars, novae

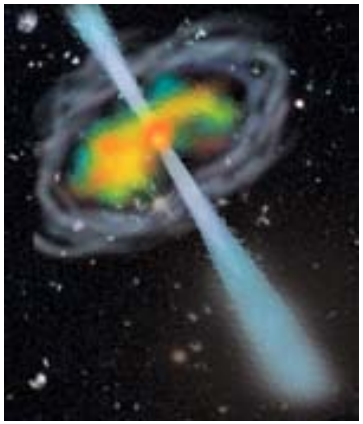
Black Holes

- ✓ Creation & evolution
- ✓ Lepton vs. hadron jets
- ✓ Deeply buried sources

Fundamental Physics & Cosmology

- ✓ Gamma-ray bursts & first stars
- ✓ History of star formation
- ✓ MeV dark matter





Chapter Two:
Designing a next generation Compton telescope

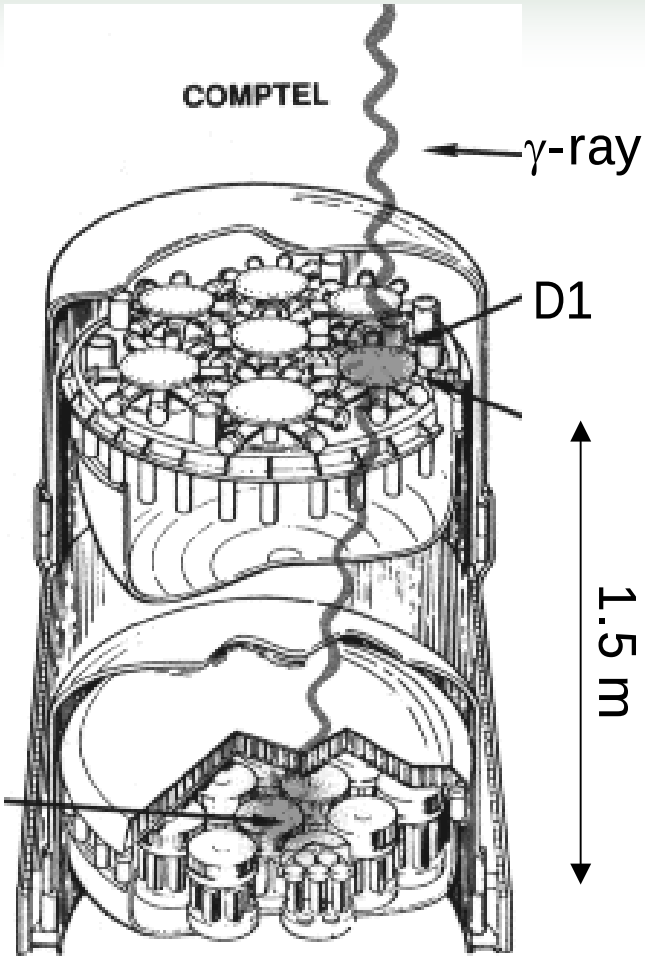
Compton Gamma-Ray Observatory (1991-2000)

COMPTEL
(0.8-30 MeV)

OSSE
(50 keV – 10 MeV)

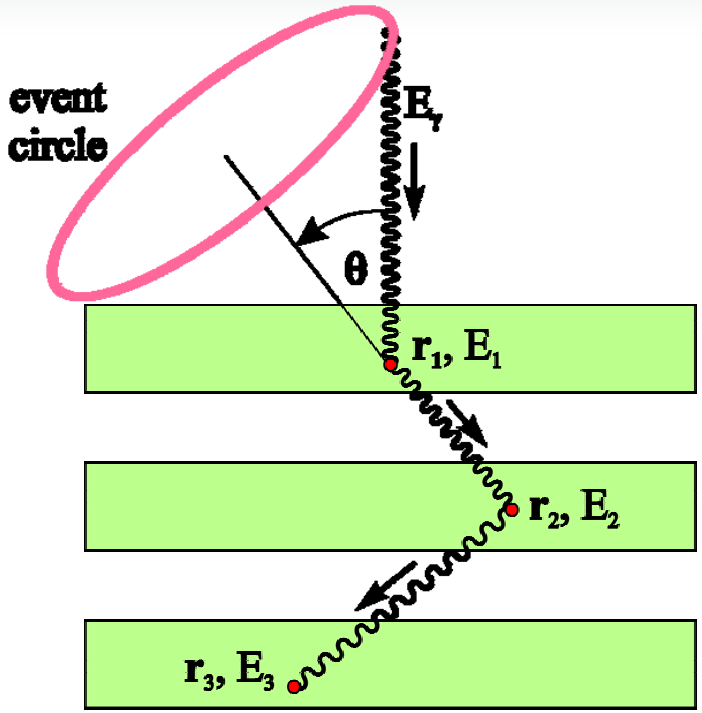
BATSE
(20-600 keV)

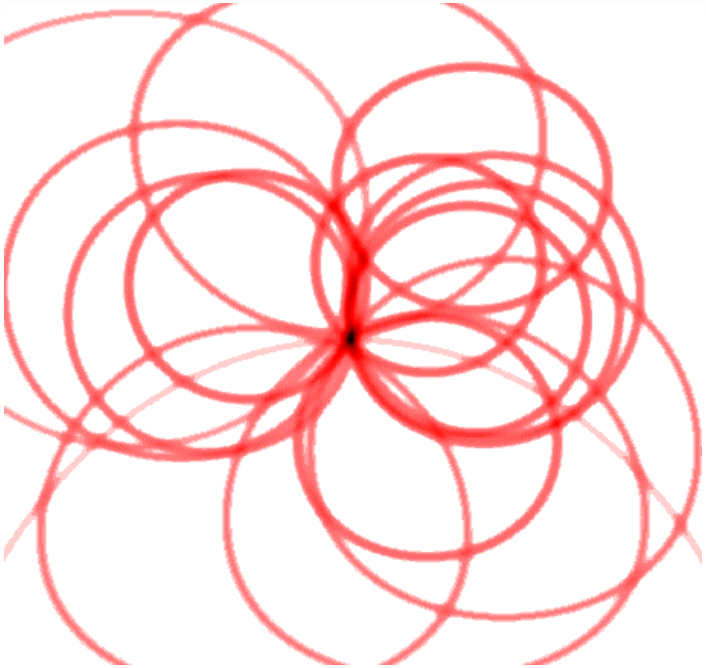
EGRET
(20 MeV – 30 GeV)



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

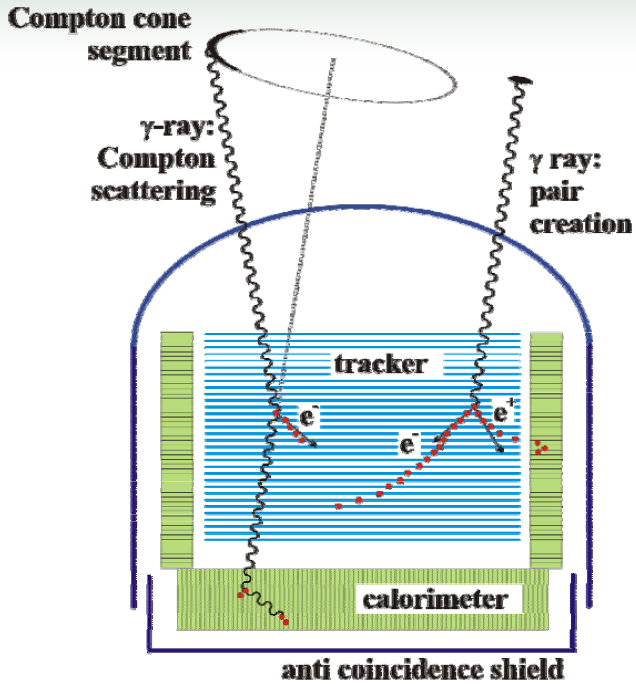
NCT/ACT-style Compton telescopes

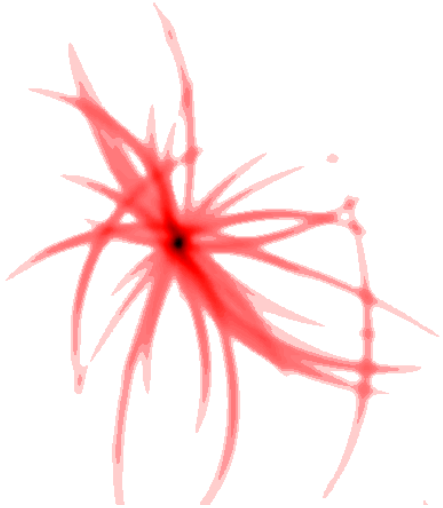




- Photons interact multiple times in active detector (Si, Ge, CdTe, CZT, Xe, etc).
- The interaction sequence can be determined from redundant information (scatter angles).
- The origin of a single not-tracked event can be restricted to the so called "event circle".
- The photon originated at the point of all overlap.

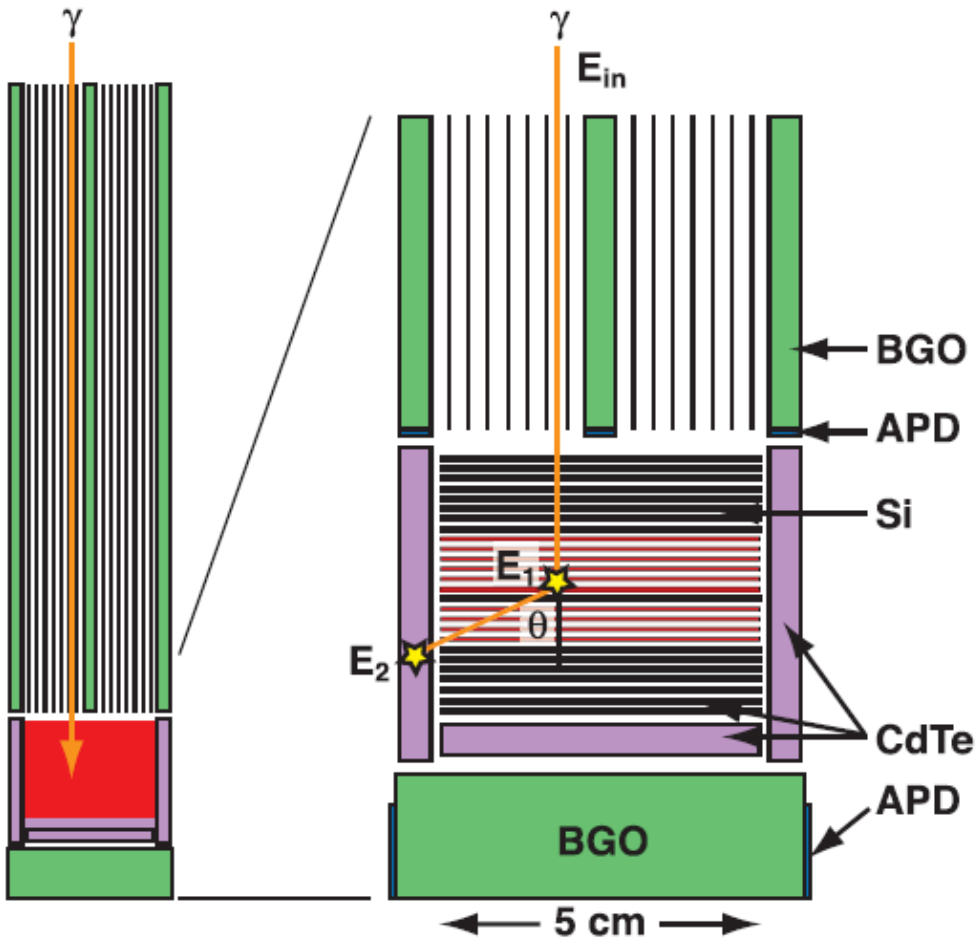
MEGA-style Compton telescopes





- First interaction occurs in an electron tracking detector (here: Si double-sided strip).
- The interaction sequence can be determined from redundant information (total scatter angles, multiple Compton interactions).
- The origin of a single tracked event can be restricted to the so called “Compton arc” whose length is determined by Molière scattering.
- The photon originated at the point of overlap.

A Compton Telescope for Improved Background Rejection With a Collimator (SGD for NeXT)

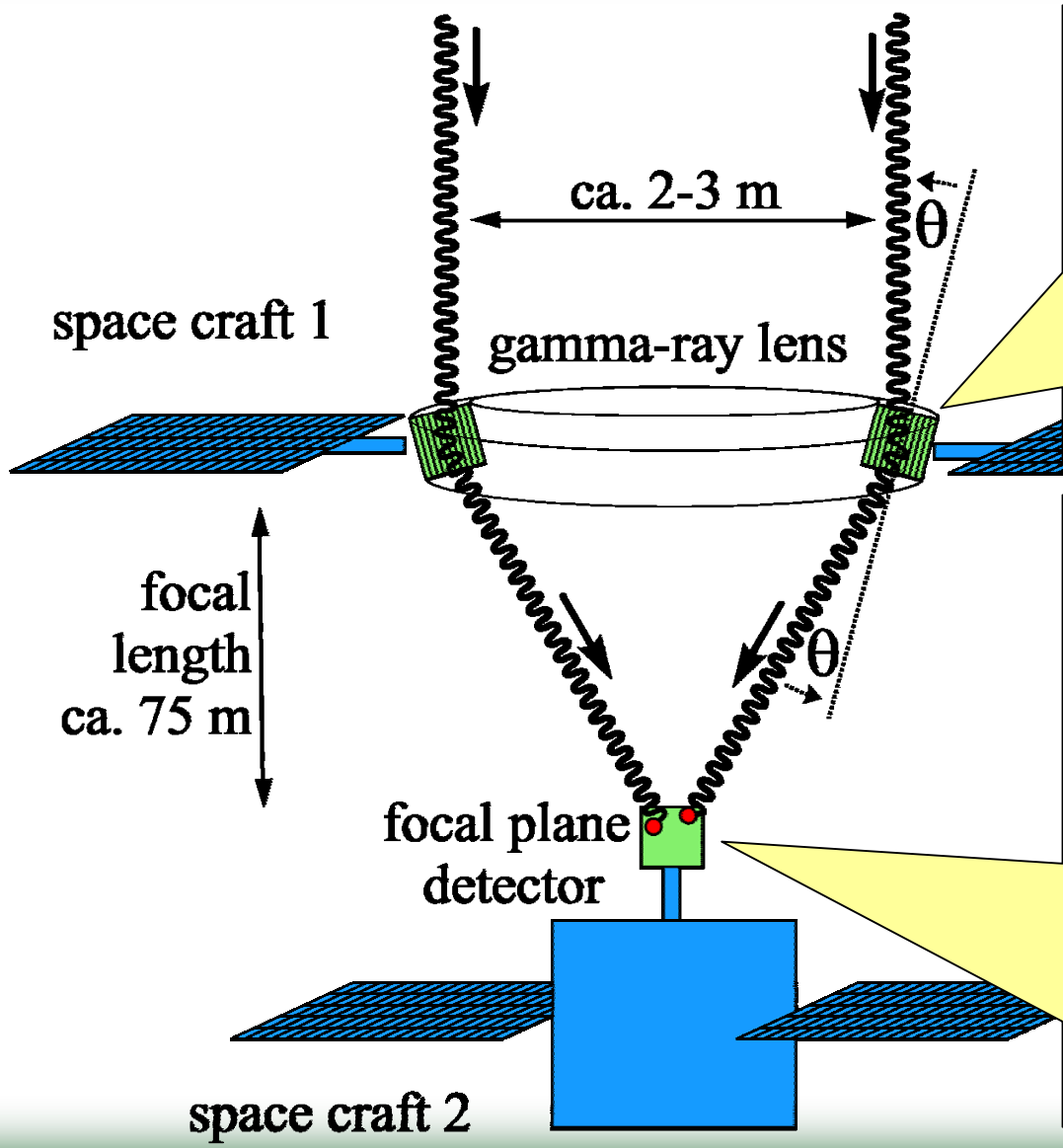


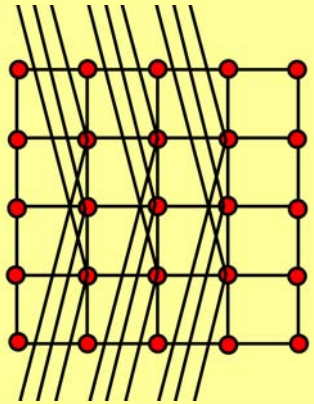
Takahashi et al. 2004

Characteristics:

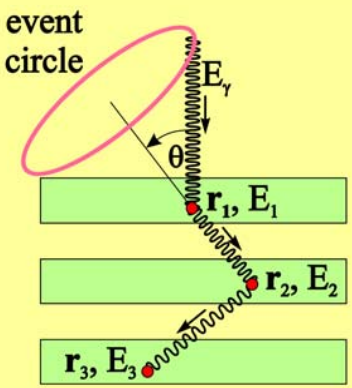
- Small field-of-view
- (Almost) no imaging capabilities ?
- Additional background rejection compared to collimation alone (activation!)
- Polarization measurements

A Compton Telescope As Focal Plane Detector of the Gamma-ray Lens Imager GRI





Laue diffraction of gamma rays within the crystal's volume under Bragg condition



Compton scatter detector

- Improved background rejection
- Polarization measurements
- Small all-sky monitor

What Limits the Sensitivity of a Compton Telescopes?

Sensitivity = Minimum flux in photons / cm^2 / s (/ keV) from a source which your telescope can significantly detect

Background!

COMPTEL (first Compton telescope in space): Source:Background ≈ 1:100

MEGA at sensitivity limit (2 MeV continuum): S:B=1:15

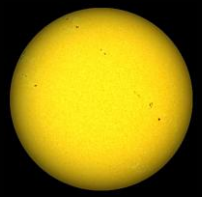
Science with Compton telescopes is background limited due to:

- External background (photons)
- Internal background (activation and subsequent decay)
- Incompletely absorbed events (first interaction in passive material, or photon escapes detector)
- Chance coincidences
- For strongly collimated/focused telescope: Requirement of on-off-measurements

With exception of: gamma-ray bursts & solar flares

- short time scales (seconds to minutes) – as long as satellite is not directly within the radiation belts…

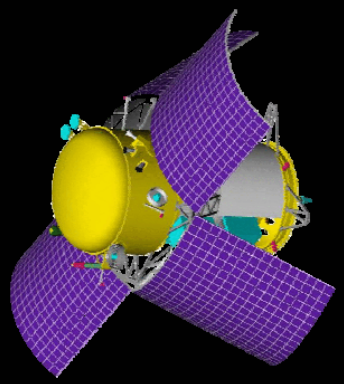
The Space Radiation Environment



Sun through solar flares: photons, charged particles

Radiation belts:

Trapped protons (SAA) & resulting activation, electrons



Cosmic rays:

- Protons
- Alpha particles
- Ions
- Electrons
- Positrons

For some applications cosmic photons are also background

Secondaries induced by cosmic ray interaction with upper atmosphere:

Albedo photons, neutrons, electron, positrons

How to Reduce Background in a Compton Telescope?

By prevention

- Choose orbit wisely
  - ✓ Stay within magnetosphere
  - ✓ Avoid radiation belts
    - → Equatorial low Earth orbit
- Minimize passive material → "fly your detector naked"
  - ✓ Less activation
  - ✓ Less chance of interactions in passive material
- Choose your materials wisely
  - ✓ Use elements/isotopes with low neutron/proton interaction cross sections
  - ✓ Choose materials whose activations lines don't interfere with your science (e.g. no Aluminum if you want to do ^{26}Al science)

How to Reduce Background in a Compton Telescope?

By shielding and (hardware) rejection

- Use plastic anti-coincidence shield
  - ✓ Vetoes charged particles (+)
  - ✓ Increases the low-energy detection threshold (-)
- Use a heavy BGO, CsI, etc. shield
  - ✓ Protects against low-energy photon events, e.g. from Earth's atmosphere, or satellite activation (+)
  - ✓ Allows vetoing escaping events (+)
  - ✓ Increases activation, especially 511 keV and above (-)
  - ✓ Can narrow field-of-view (-)
  - ✓ Increases overall satellite weight (-)

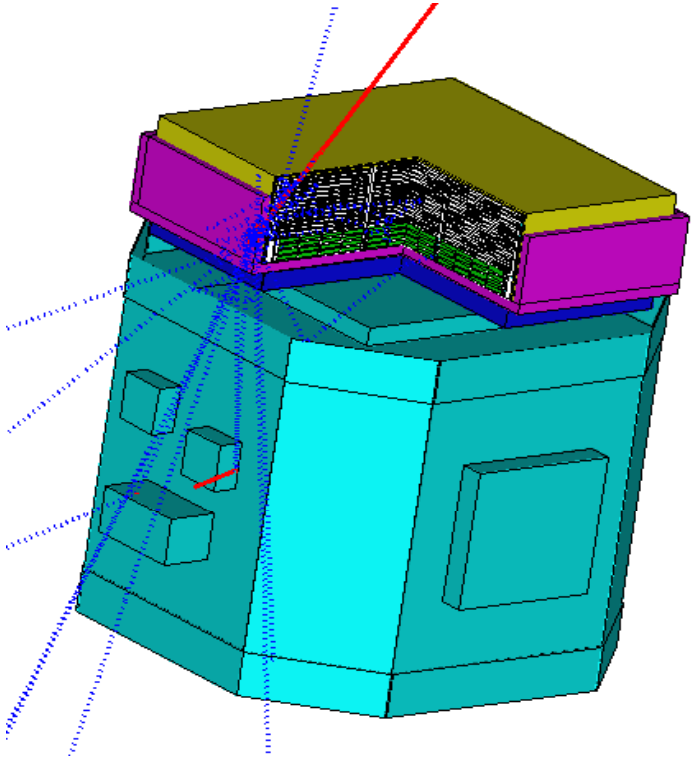
How to Reduce Background in a Compton Telescope?

By increasing the data space & narrowing the point spread function

- Adding more dimensions in data space, over which background can spread
  - ✓ Using electron tracks adds another dimension
- By measuring as much information as possible
  - ✓ Ideal Compton telescopes would measure:
    - Electron tracks,
    - Time-of-flight between individual interactions
    - Multiple Compton interactions
- By improving energy resolution
- By improving angular resolution
  - ✓ Through improved energy and position resolution, as well as low-z materials for minimized Doppler-broadening
- By minimizing coincidence window

The Baseline Advanced Compton Telescope (ACT) Instrument Concept

as defined by the ACT vision mission study



ACT mass model on GLAST bus.

D1: 27 layers of 2 mm thick Si DSD

- 10x10 cm^2, 64x64 strips
- 3888 detectors, 248 832 channels
- -30°C, Stirling cycle cooler

D2: 4 layers, 16 mm thick Ge DSD

- 9.2x9.2 cm^2, 90x90 strips
- 576 detectors, 103 680 channels
- 80 K, Turbo-Brayton cooler

BGO: 4 cm thick shield (anti coincidence)

ACD: plastic scintillator (anti coincidence)

More details about ACT: Boggs et al. 2005, 2006

Chapter Three:
The data analysis chain

Data analysis

All data has to pass through 4 level of analysis

Level:	source: detector / simulation	calibration & low level data analysis	event reconstruction	image recon-struction and high level data analysis
Data:	hits: strips, pixels, AD units	hits: position & energy	events: Compton, pair, Myon, etc.	Images, spectra, distributions, etc.

→ Most challenging: event & image reconstruction

Event Reconstruction

Main goals are to

reconstruct the path of the original photon

determine if the event originated from a completely absorbed photon (i.e. that it is not background)

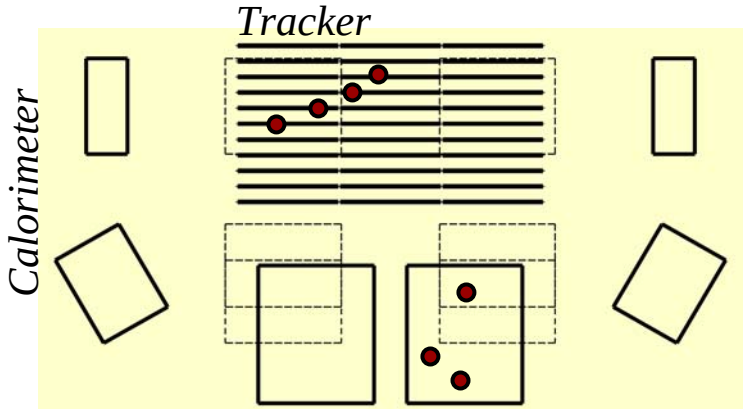
from the measured energies and positions, by utilizing:

- The kinematics of the events, i.e. the redundant Compton scatter information (electron track and/or multiple Compton interactions)
- The known response of the detector to incident gamma-ray (absorption probabilities, etc.)

The result of this analysis step are Compton, pair creation, charged particle, photo-effect events, etc. as well as an overall quality factor, describing the probability that the event was caused from an completely absorbed photon.

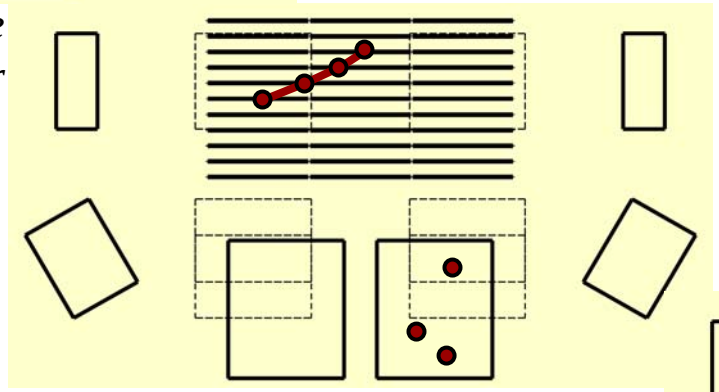
Event reconstruction: Basics

All event reconstruction algorithms have the following analysis steps in common to find the correct ordering of the hits:

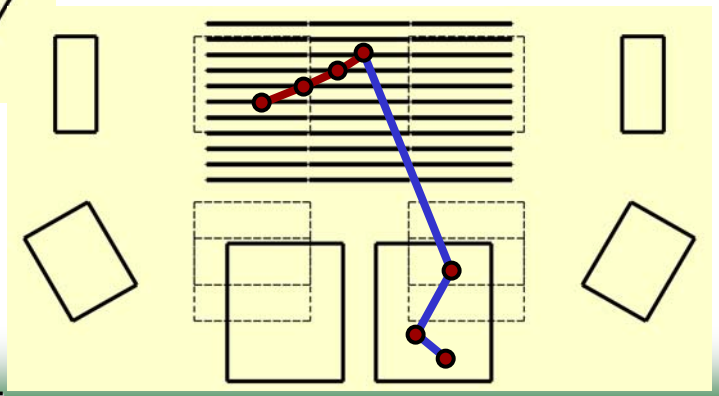


Start with a set of hits and clusterize the hits of adjacent voxels

Sketches of the MEGA detector



Find charged particle tracks of e.g. Compton or pair events



Finally find the overall Compton hit sequence and determine the quality of the event.

Electron Track Evaluation

Identify tracks for MEGA type Compton telescopes

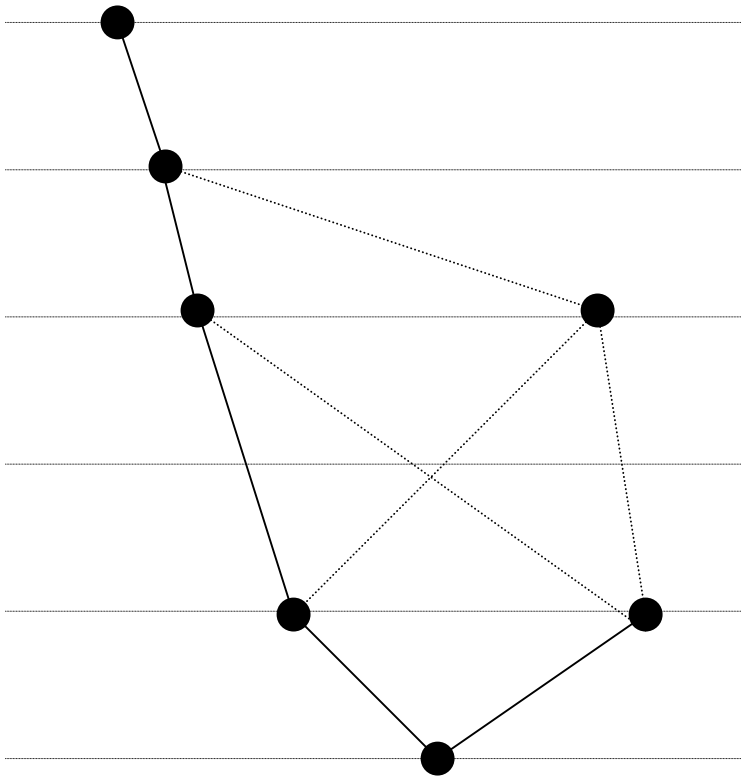
Four steps:

A. Find all possible/reasonable paths of the electron track(s)

B. Evaluate them

C. Choose the track with the highest probability of having the correct direction of motion based on the measured data points

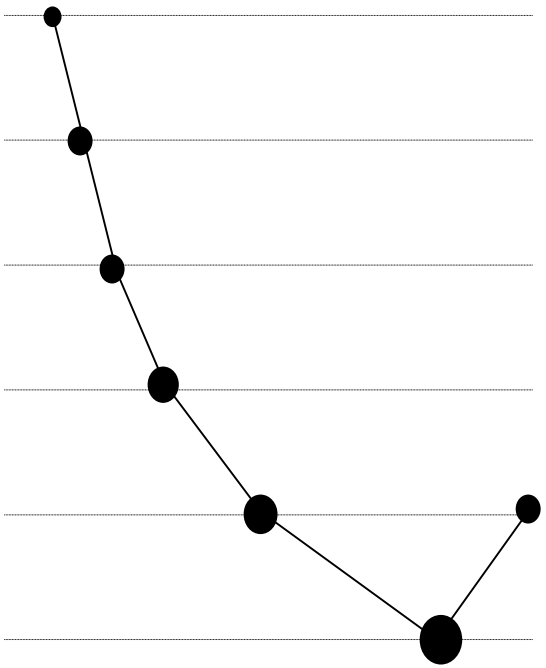
D. Append bremsstrahlungs hits, check if the track leaves the tracker, correct for bad strips, etc.



Electron Track Evaluation

Characteristics of a good track

- Angle change according to Molière-scattering
  - → Increase of scattering at end of track (decreasing energy of electron)
- Energy deposits follow Bethe-Bloch-Equation
  - → Increase of deposits at end of track
  - → Large deposit at turning points
- First deposit likely to be lower than average deposit (interaction takes place somewhere within layer)



The event reconstruction has to assign to each possible track a quality factor, which describes the compliance of the track with the underlying physics!

Electron Track Evaluation

Statistical means: Pearson correlation

Goal:

Prove that for the correct track direction the energy deposits increase at the end of the track and also the angular change

Simpler:

$$\Delta E \sim n \quad \& \quad \Delta\alpha \sim n$$

Where n is the hit number along the track

Electron Track Evaluation

Statistical means: Pearson correlation

„Pearson correlation“:

covariance devided by the variances of the involved variables

$$P_c\left(E_{dep}, n\right) = \frac{\overline{E_{dep} \cdot n} - \overline{E_{dep}} \cdot \overline{n}}{\sqrt{\overline{E_{dep}^2} - \overline{E_{dep}}^2}\sqrt{\overline{n^2} - \overline{n}^2}} \qquad P_c\left(\Delta\alpha, n\right) = \frac{\overline{\Delta\alpha \cdot n} - \overline{\Delta\alpha} \cdot \overline{n}}{\sqrt{\overline{\Delta\alpha^2} - \overline{\Delta\alpha}^2}\sqrt{\overline{n^2} - \overline{n}^2}}$$

The final quality factor is:

$$Q = 1 - \frac{P_C\left(E_{dep}, n\right) + P_C\left(\Delta\alpha, n\right)}{2}$$

Electron Track Evaluation

Statistical means: Bayesian model testing: an example

Example: Email Spam filtering

Assume we want to find out the probability that an email containing the word „Casino“ (C) is spam (ham = $\overline{\text{spam}}$)

$$p(Spam|C) \overset{\text{Bayes rule}}{=} \frac{p(C|Spam)\cdot p(Spam)}{p(C|Spam)\cdot p(Spam)+p(C|Ham)\cdot p(Ham)}$$

From previous emails we know:

From the last 200 Spams, 50 contained the word „Casino“

From the last 100 Hams, 1 contained the word „Casino“

$$p(C|Spam)=50/200; \quad p(Spam)=200/(100+200);$$
$$p(C|Ham)=1/100; \quad p(Ham)=100/(100+200);$$

$$p(Spam|C)=50/51=0.98$$

Electron Track Evaluation

Bayesian model testing

What we want to know:

How probable is it that the track direction is correct („Ok“), given a set of measured parameters M (energy deposit, angular deviation, etc.)

$$p(Ok|M) \overset{\text{Bayes rule}}{=} \frac{p(M|Ok)\cdot p(Ok)}{p(M|Ok)\cdot p(Ok) + p(M|Not\ Ok)\cdot p(Not\ Ok)}$$

Transition from emails to tracks:

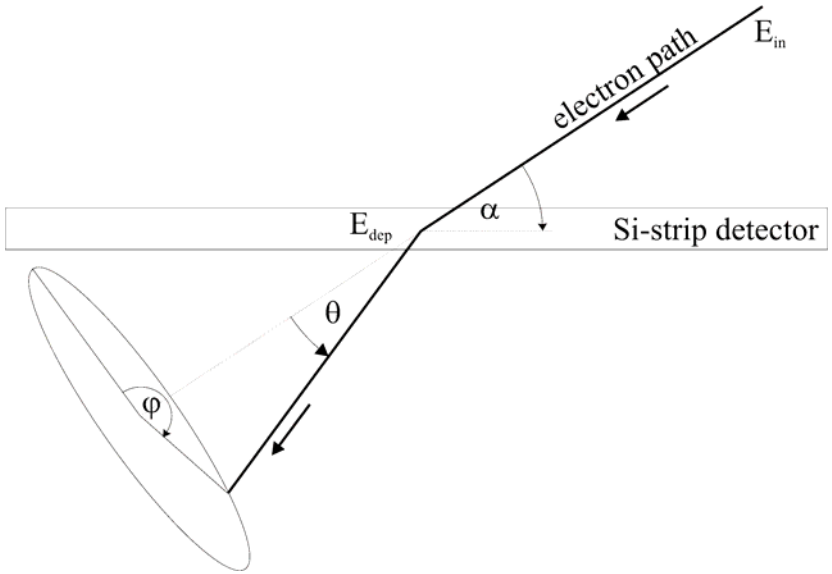
Spam ↔ Track element Ok; Ham ↔ Track element Not Ok;
„Casino“↔ Measurement Point

We need two types of matrices, spanning the complete data-space M:

The first one contains the numbers, how often the measured parameters M occur under the condition, that the track element has the correct direction, the other that the track element has the wrong direction

Electron Track Evaluation

Bayesian model testing: The data spaces



3 parameters describe the start of a track: E_{in}, α_{out}, E_{dep}

5 parameters describe a central hit: E_{in}, α_{in}, E_{dep}, θ_{out}, φ_{out}

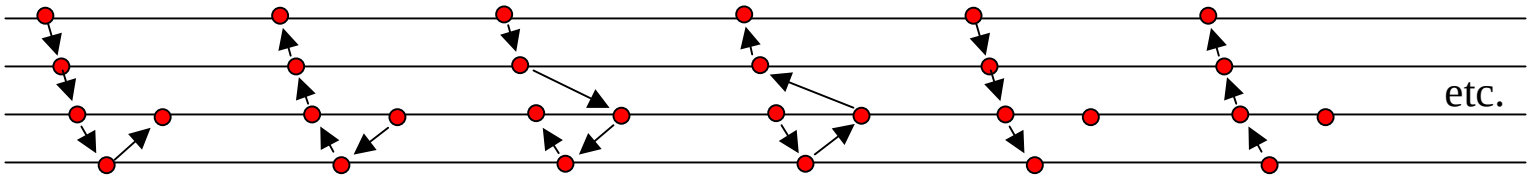
2 parameters describe a final hit: α_{in}, E_{dep}

→ 3x2 data-space matrices needed

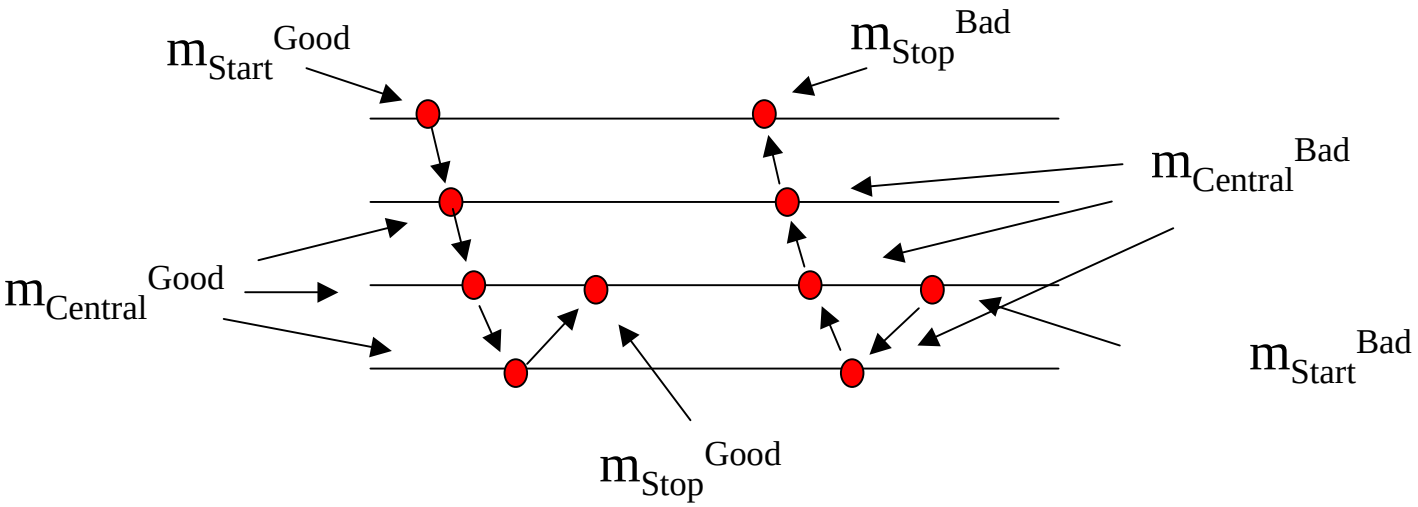
Electron Track Evaluation

Bayesian model testing: Fill the data space

Evaluate each possible track combination in the same way as during tracking:

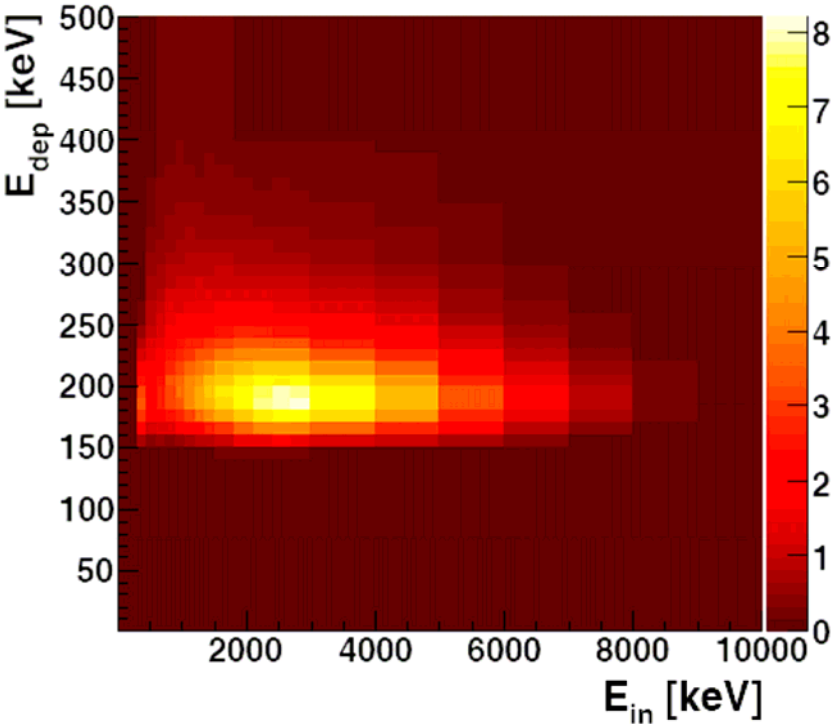


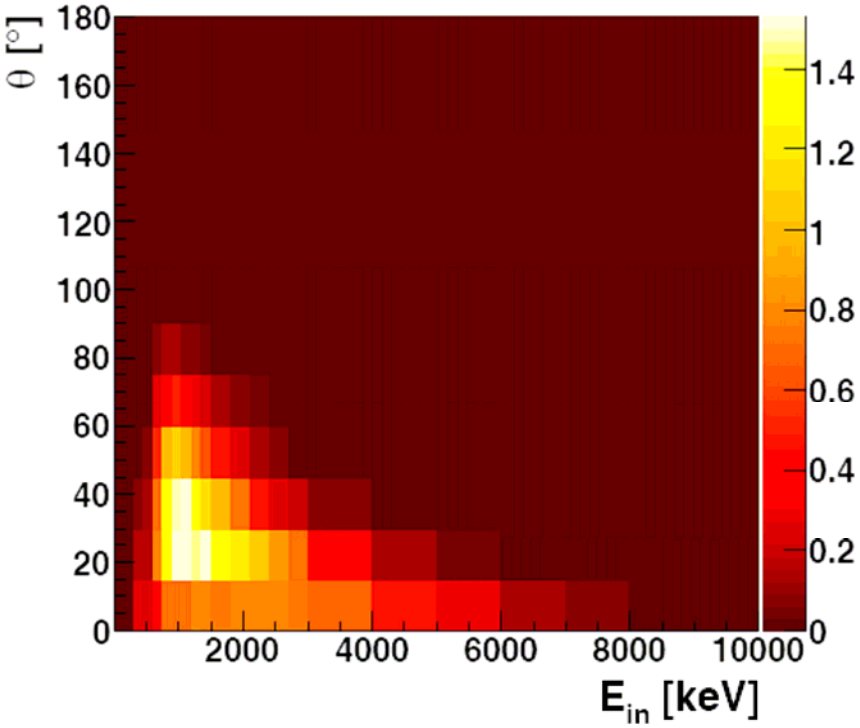
Enter each measurement point of a track ONCE into its matrix



Electron Track Evaluation

Bayesian model testing: Two data space representations





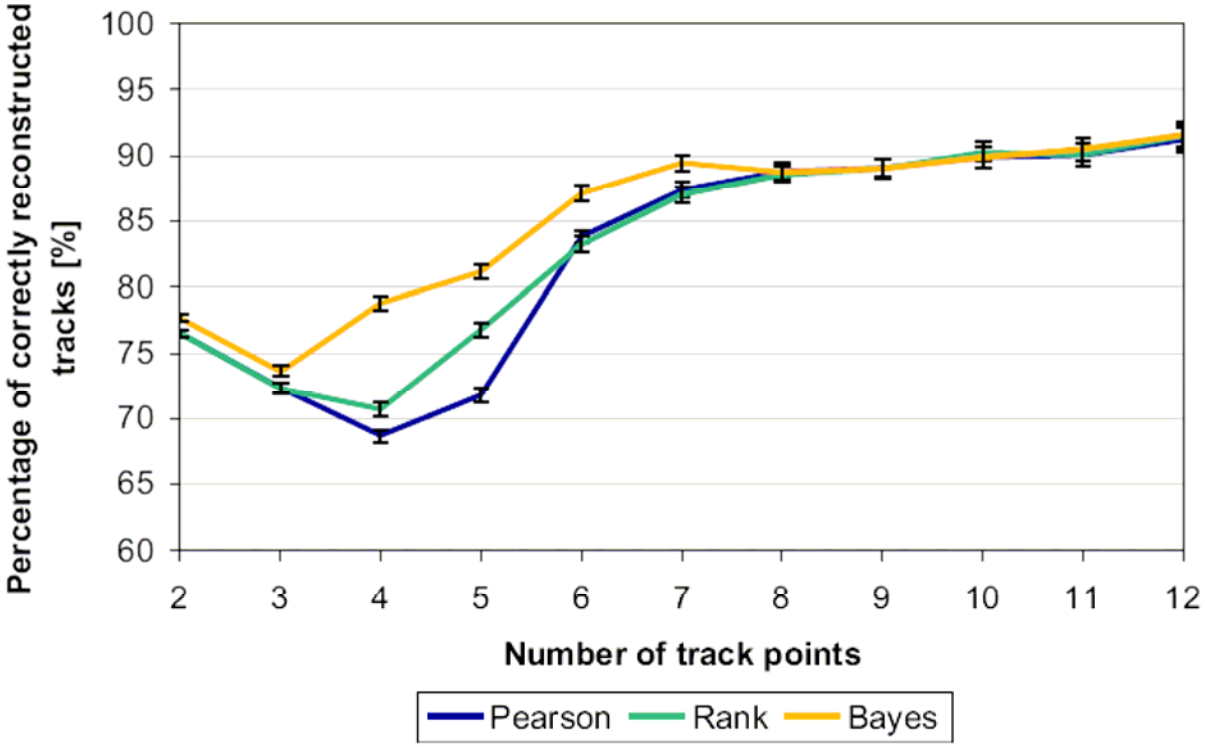
Deposited energy per layer as a function of electron energy:

Shaped as a Landau-distribution

Change of flight direction as a function of electron energy:

Dominated by Molière-scattering

Electron Tracking: Performance

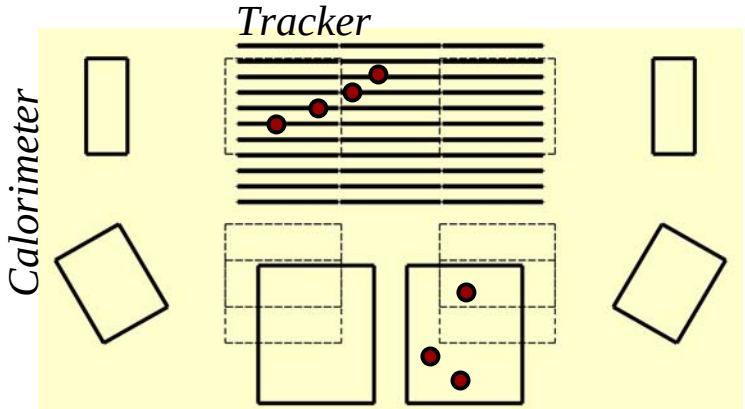


Performance comparison for MEGA

Most of the wrongly reconstructed events can be rejected/recovered later on using also the Compton sequence

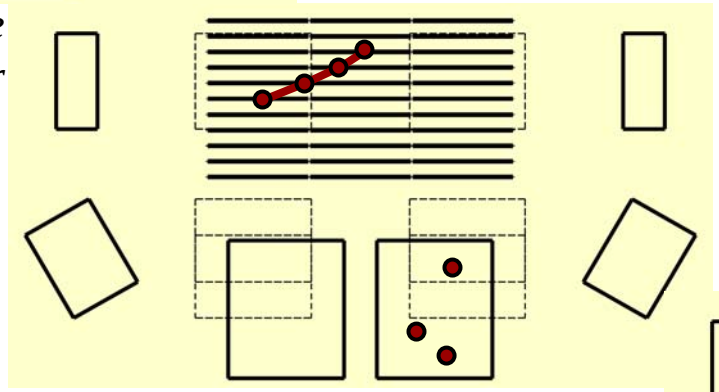
Event reconstruction: Basics

All of event reconstruction algorithms have the following analysis steps in common to find the correct ordering of the hits:

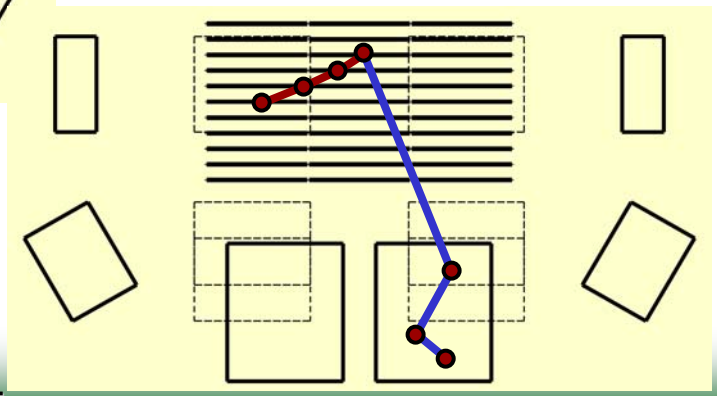


Start with a set of hits and clusterize the hits of adjacent voxels

Sketches of the MEGA detector



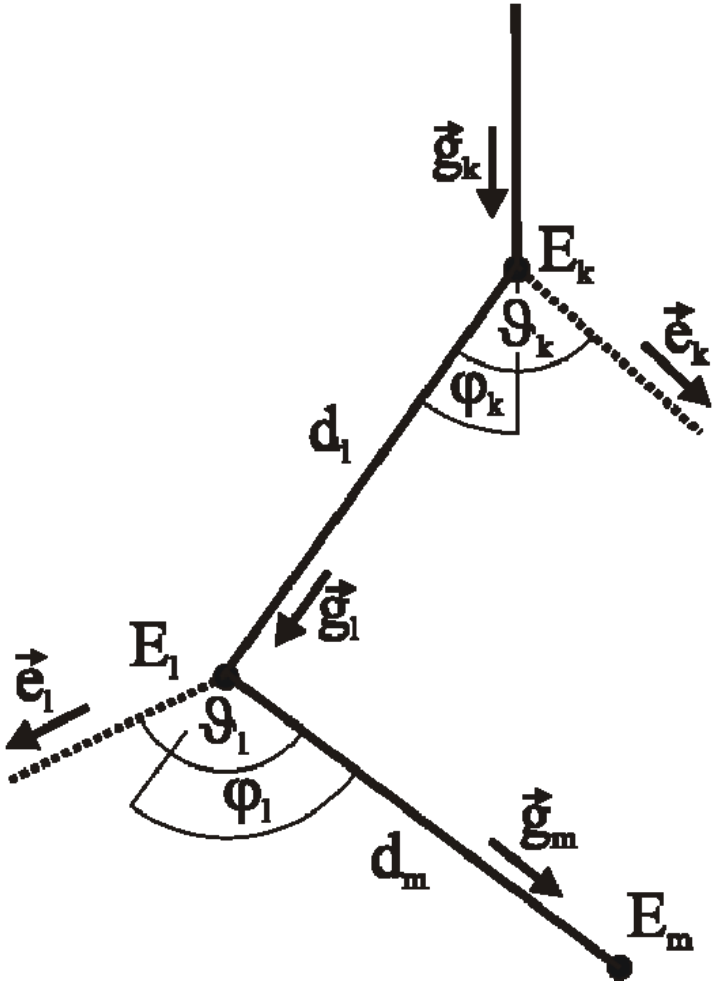
Find charged particle tracks of e.g. Compton or pair events



Finally find the overall Compton hit sequence and determine the quality of the event.

Compton sequence evaluation

Find the sequence of Compton interactions



Use redundant information to determine Compton sequence:

Angles φ_l, ϑ_l can be determined via geometry and via Compton kinematics!

Compton sequence evaluation

Statistical means: „Pseudo“-χ^2 for completely absorbed events

Compare central Compton scatter angles, calculated via

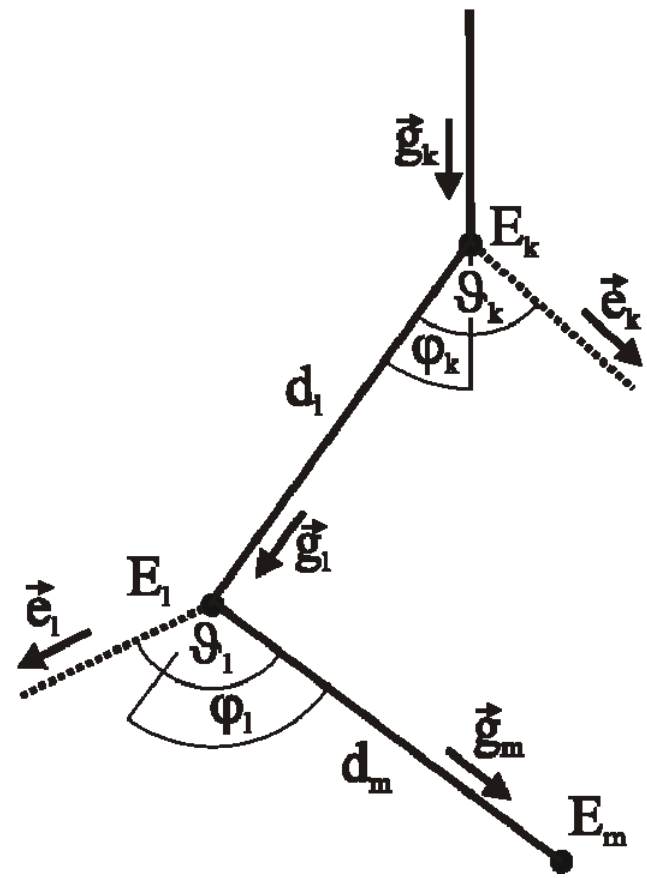
Geometry: $$\cos\varphi_{i,geo} = \frac{\vec{g}_{i-1} \circ \vec{g}_i}{\left|\vec{g}_{i-1}\right| \cdot \left|\vec{g}_i\right|}$$

Kinematics: $$\cos\varphi_{i,kin} = 1 - \frac{E_0}{E_i} + \frac{E_0}{E_{i+1}^{+}}$$

$$\chi_P^{\,2} = \sum_{i=2}^{I-1} \frac{\left(\cos\varphi_{i,geo} - \cos\varphi_{i,kin}\right)^2}{\sigma^2_{\varphi_{i,geo}} + \sigma^2_{\varphi_{i,kin}}}$$

Degrees of freedom N := Number of „redundant informations“

$$Q = 1 - P(\chi_P^2, N)$$



Compton sequence evaluation

Statistical means: Bayesian model estimation

Theory: see electron tracking

The goals:

- Use all dimensions which Compton scattering provides as *one multidimensional* data space – not several one-dimensional approximations!
- Get a handle on the background: Where in the data space is our background?
- Get one *absolute* quality factor of the event:

  Probability that the current sequence originated from a completely absorbed non-background photon

Compton sequence evaluation

Bayesian model estimation: The data space dimensions

1. The difference of the redundant Compton scatter angles: $\Delta\varphi = \varphi_E - \varphi_G$
2. A distance factor d, which describes the geometrical error of $\Delta\varphi$, resulting from pixelation of the detectors.
3. The Compton scatter angle φ_E, since larger scatter angles result in larger measurement errors and increased Doppler-broadening. In addition the Klein-Nishina equation influences φ_E.
4. The total energy E_{tot}, since the distribution of φ is given by the Klein-Nishina equation and depends on the total energy of the photon.
5. The total number of interactions, because this determines the number of combinations which have to be investigated.
6. The Compton absorption probability p_A on the photon´s path to the next interaction point. For the last interaction point the photo absorption probability is used.
7. The target material where the interaction takes place, because this determines the degree of Doppler-broadening.

Compton sequence evaluation

Bayesian model estimation: The data space dimensions

8. The difference of the redundant total scatter angle in case of electron tracking: $\Delta\alpha = \alpha_E - \alpha_G$
9. The total scatter angle α_E

→ **Luckily, some of those dimensions are independent**

→ **Several, smaller data spaces are ok**

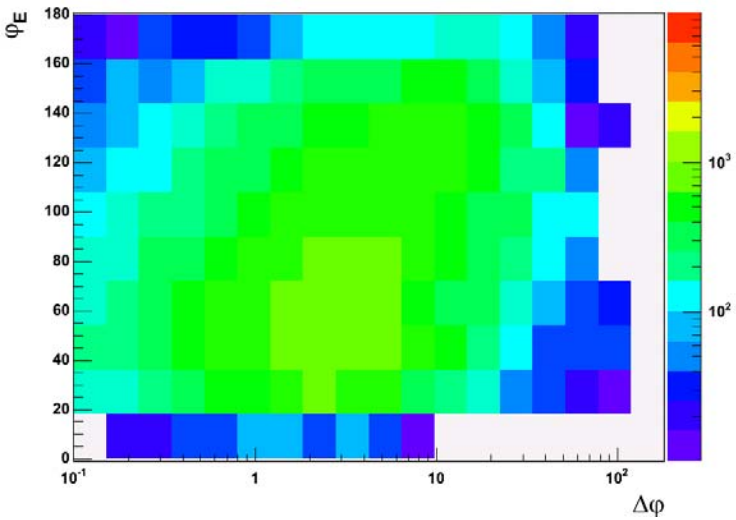
Compton sequence evaluation

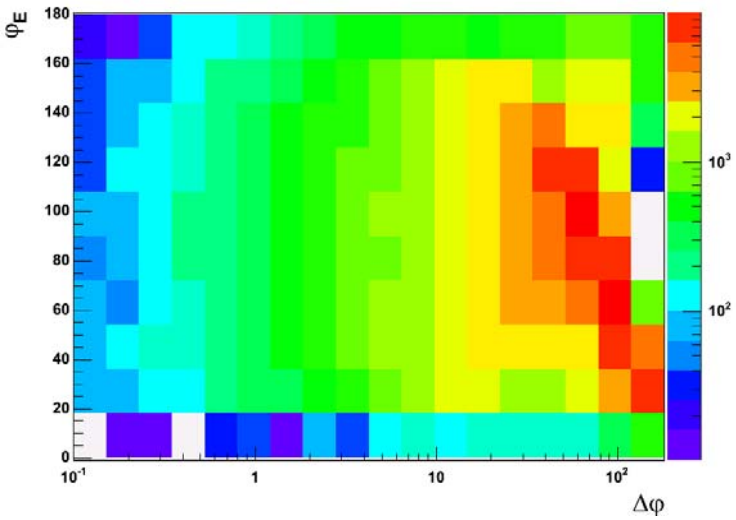
Bayesian model estimation: The data space dimensions

Start	Central	Track	Absorption	Stop
N hits	N hits	N hits	N hits	N hits
Material	Material	Material	Material	Material
E_{tot}	E_{tot}	E_e	E_{tot}	E_{tot}
$\cos \varphi$	$\cos \varphi$	$\cos \alpha$	$p_{abs,\ Compton}$	$p_{abs,\ Photo}$
	$\Delta\varphi$	$\Delta\alpha$		
	distance	distance		

Compton sequence evaluation

Bayesian model estimation: The data space dimensions



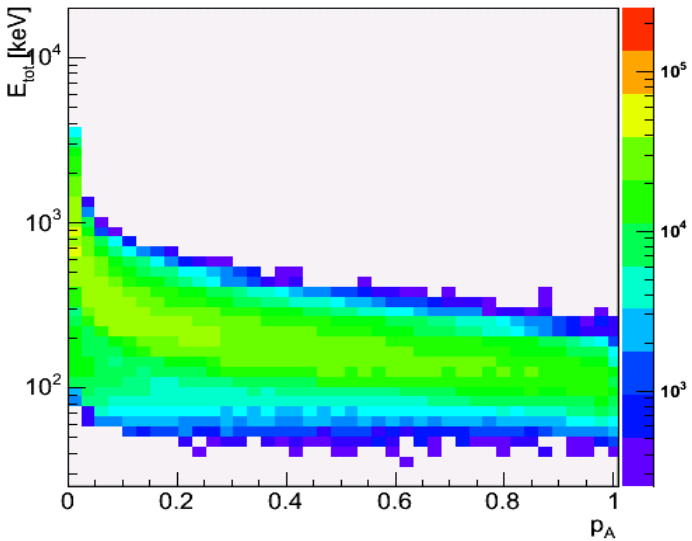


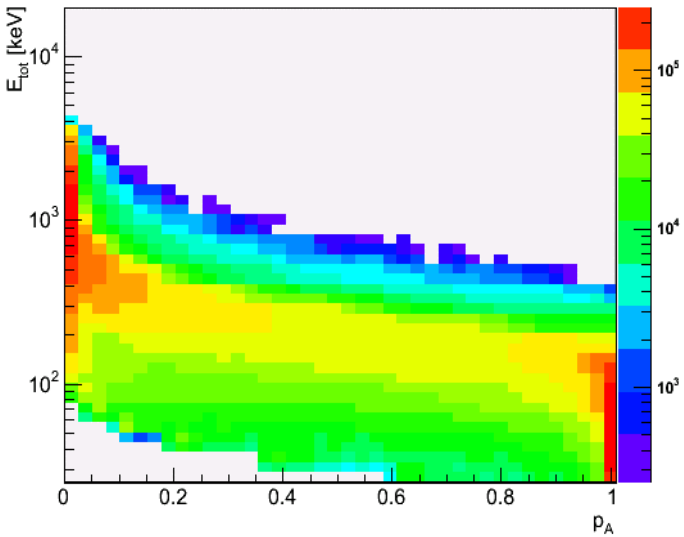
Event density in the φ_E-$\Delta\varphi$ data space for the correct sequences. The other dimensions of the data space are fixed to: d = 2.6-5 cm, E_{tot} = 200-500 keV, events with four hits. No other dimensions are used.

All wrong sequence points gather at larger $\Delta\varphi$ values. Nevertheless there is an overlap between good and bad sequences in the data space which results in wrongly reconstructed events.

Compton sequence evaluation

Bayesian model estimation: The data space dimensions





The data space of the final measurement point contains only the photo-absorption probability p_A and the deposited energy E_{tot}. Here, the events are roughly evenly distributed over all absorption probabilities.

A significant amount of the wrong sequence points gather at large and small probability values p_A, since their energy is either too high or too small for a reasonable photo absorption.

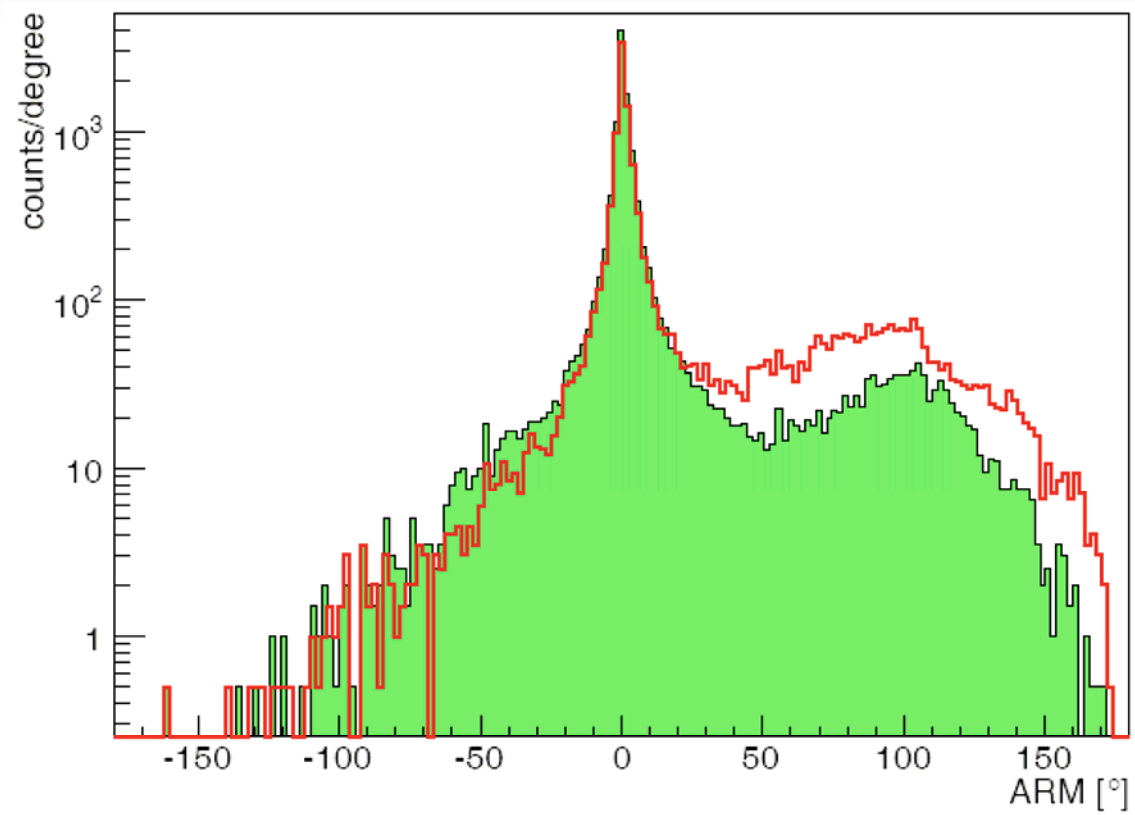
Comparison of the Approaches

Classical approach	Bayesian
Uses only projections of the data space	Uses all dimensions of the data space → Better performance
Gives only a „figure-of-merit“	Results in an absolute measurement on the quality of the track/sequence → Advantages in background reduction
Simple adaptions to modified angular resolution / geometry	Matrices fixed to one geometry and one angular resolution
Fast	Large matrices → **Extensive** simulations
Likely to fail during strange conditions	Can better cope with strange conditions (turning tracks, etc.)

Fast & good enough for terrestrial applications

Space applications!

Event Reconstruction Performance



Red-line: Classic approach

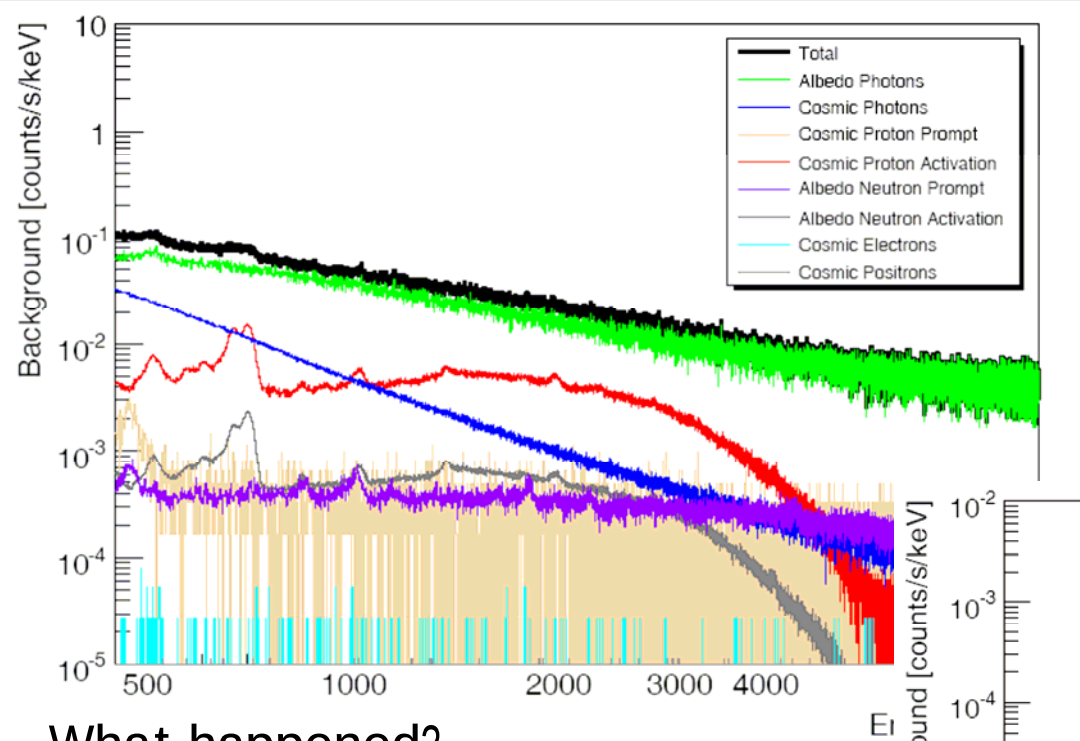
Green: Bayesian approach

ARM distribution (2 MeV photo peak events, MEGA simulation)

Wrongly reconstructed events (large angles) are reduced by roughly a factor 2

General: Bayesian reconstruction results for MEGA in a sensitivity improvement in a space radiation environment by a factor of 1.2 for 511 keV and 1.7 for 1809 keV!

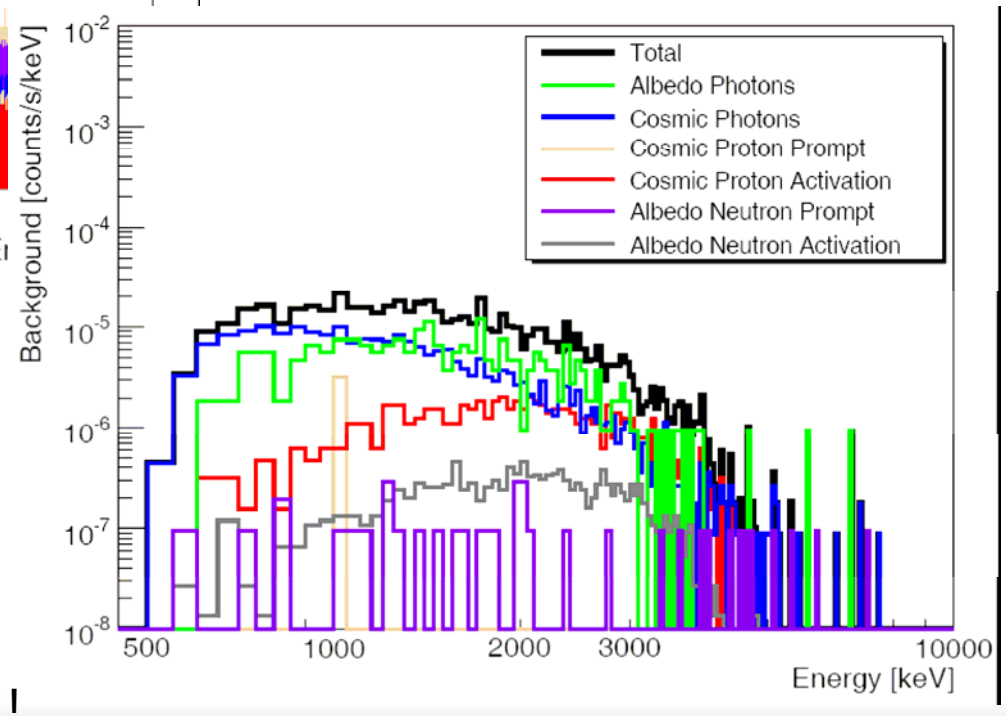
Background – before/after - MEGA



Simulation of MEGA (modest energy resolution – no lines) telescope in equatorial LEO:

Left: all triggered events

Bottom: Within psf after reconstruction and background rejection



What happened?

- Background identification and rejection through event reconstruction and selections
- Spreading of background in tracked Compton data space
- Improvement S/B: x 450 (1809 keV) !

Data analysis

All data has to pass through 4 level of analysis

Level:	data source: detector / simulation	calibration & low level data analysis	event reconstruction	image recon-struction and high level data analysis
Data:	hits: strips pixels, AD units	hits: position & energy	events: Compton, pair, Myon, etc.	Images, spectra, distributions, etc.

→ Most challenging: event & image reconstruction

What does a non-tracking Compton camera measure?

Step 1:

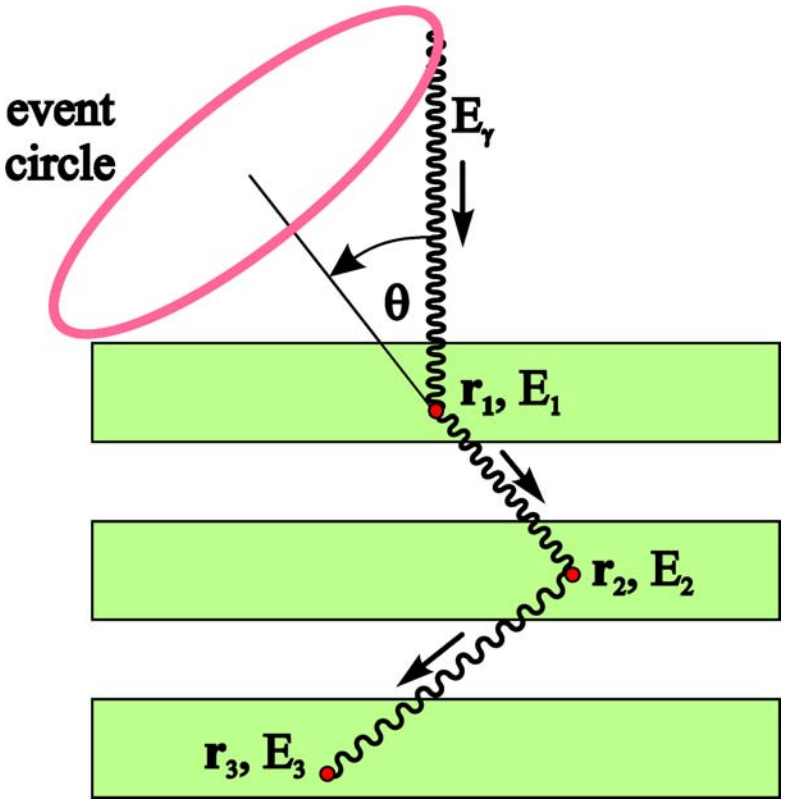
Set of channel numbers, AD converter units and timings, which are converted into energies and positions during calibration:

$$N \times (\mathbf{r}_i, E_i)$$

Step 2:

Event reconstruction, i.e. find the interaction sequence and thus the parameters of the original Compton interaction:

$$E_e, \mathbf{r}_1 \text{ and } E_g, \mathbf{r}_2$$



The basic imaging algorithm: ML-EM

t_{nm}: Probability that an event emitted in image bin m is detected as event n
"Response"
(system matrix)

c_n:
List mode: portion of the event that intersects the image
Binned mode: Number of events in bin n

$\lambda_m^{(l)}$: Image bin m at iteration level l

$$\lambda_m^{(l+1)} = \frac{\lambda_m^{(l)}}{s_m} \sum_n \frac{t_{nm} \cdot c_n}{\sum_k t_{nk} \cdot \lambda_k^{(l)} + b_n \cdot h}$$

b_n: Background

h: Scaling factor

s_m: Probability that an event emitted in image bin m is detected

Projection:

Data space → image space

"Maximize the expectation of the log-likelihood"

Projection:

Image space → data space

"Expectation of log-likelihood"

List mode vs. binned mode

Imaging detector response (system matrix) t_{nm}:

$$(E_\gamma, \lambda, \nu) \rightarrow (E_e, E_g, \mathbf{r}_1, \mathbf{r}_2)$$

Imaging space → Data space

Two approaches to span data space: list and binned mode:

- List mode: list of events containing each event's parameters
- Binned mode: multi-dimensional matrix

Advantages of list mode:

- Requires less memory when number of events smaller than required bins
- Most detailed handling of data (no bins!)

Disadvantages:

- Very difficult to handle background and absolute normalization

Requirements for astrophysics – 1

1. **Correct reconstruction of the spatial distribution of point and extended sources**

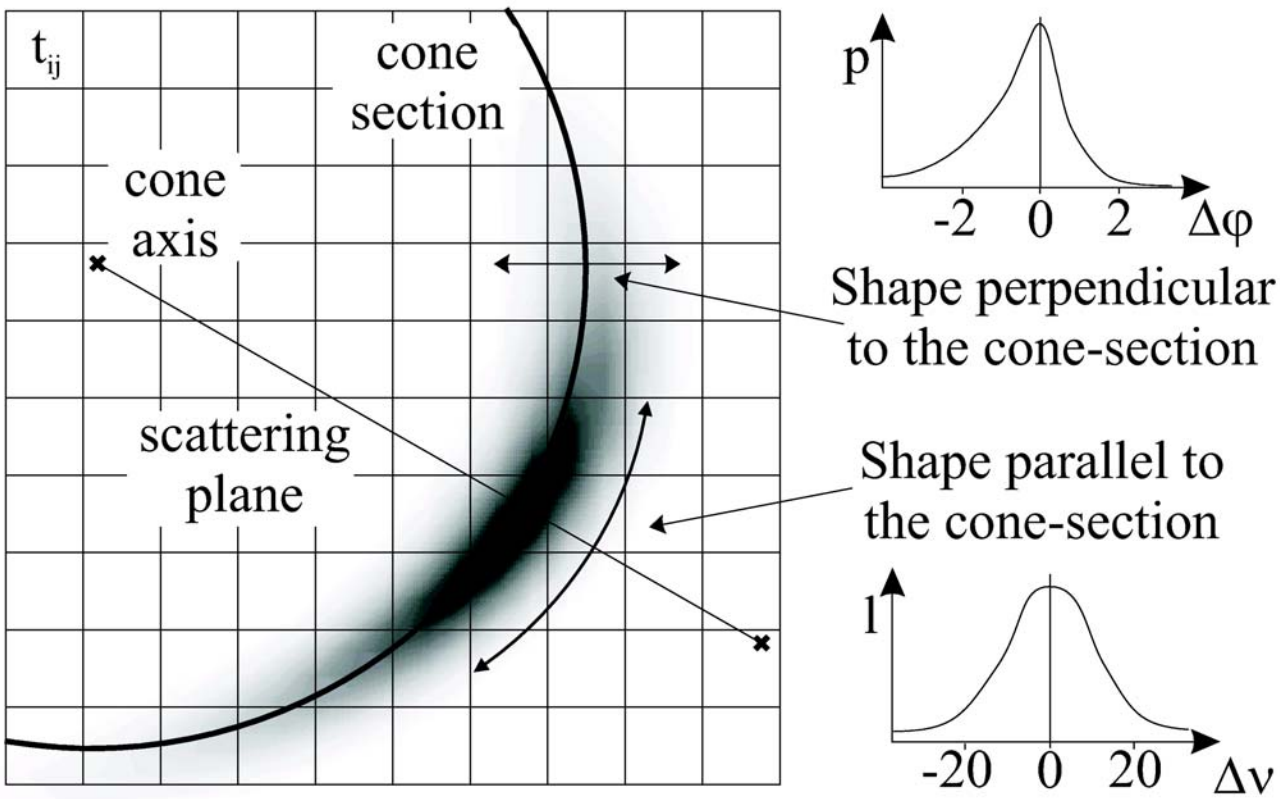
→ Single most important requirement for most terrestrial applications (medical imaging, nuclear monitoring), besides optimizing noise vs. contrast ratio

Achieved by correctly modeling the shapes of the Compton cones and arcs.

A list-mode response model - basics

Compton cone axis, Compton scatter angle, and electron direction are known

→ Fit shapes perpendicular and parallel to cone section

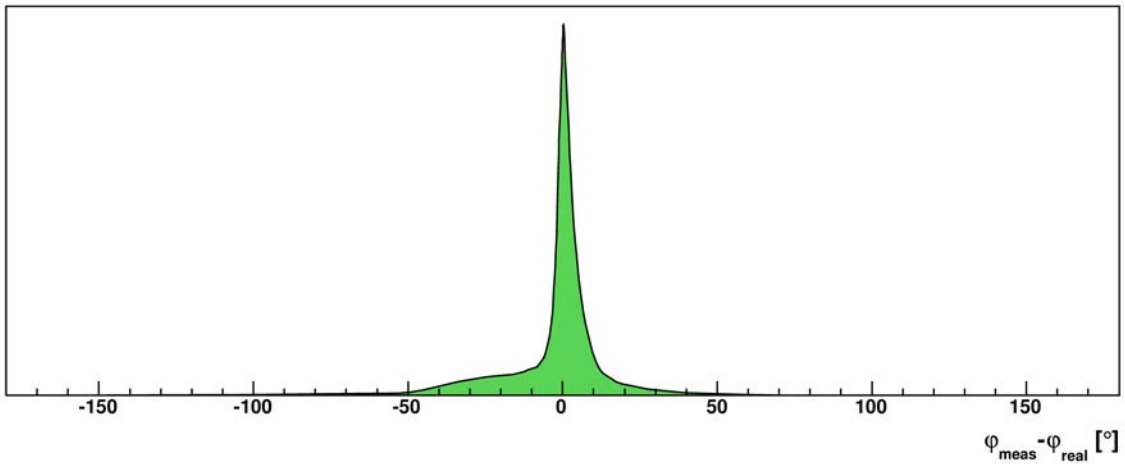


A list-mode response model – the model

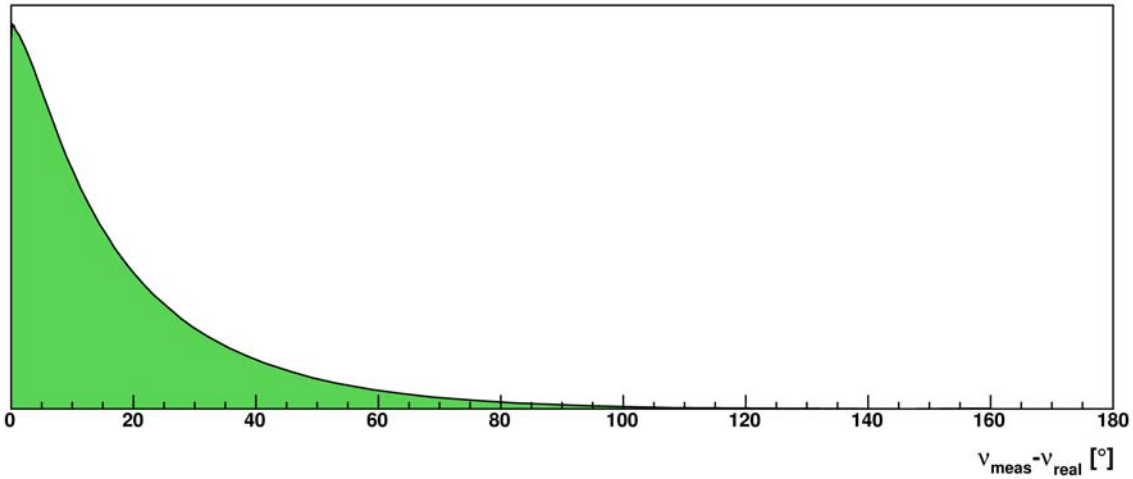
From simulations determine the difference between real and measured scatter angles as a function of the measured energies: "Response"

Shapes include most measurement uncertainties, incomplete absorption, etc. but constitute a simplification to 1D

Perpendicular shape



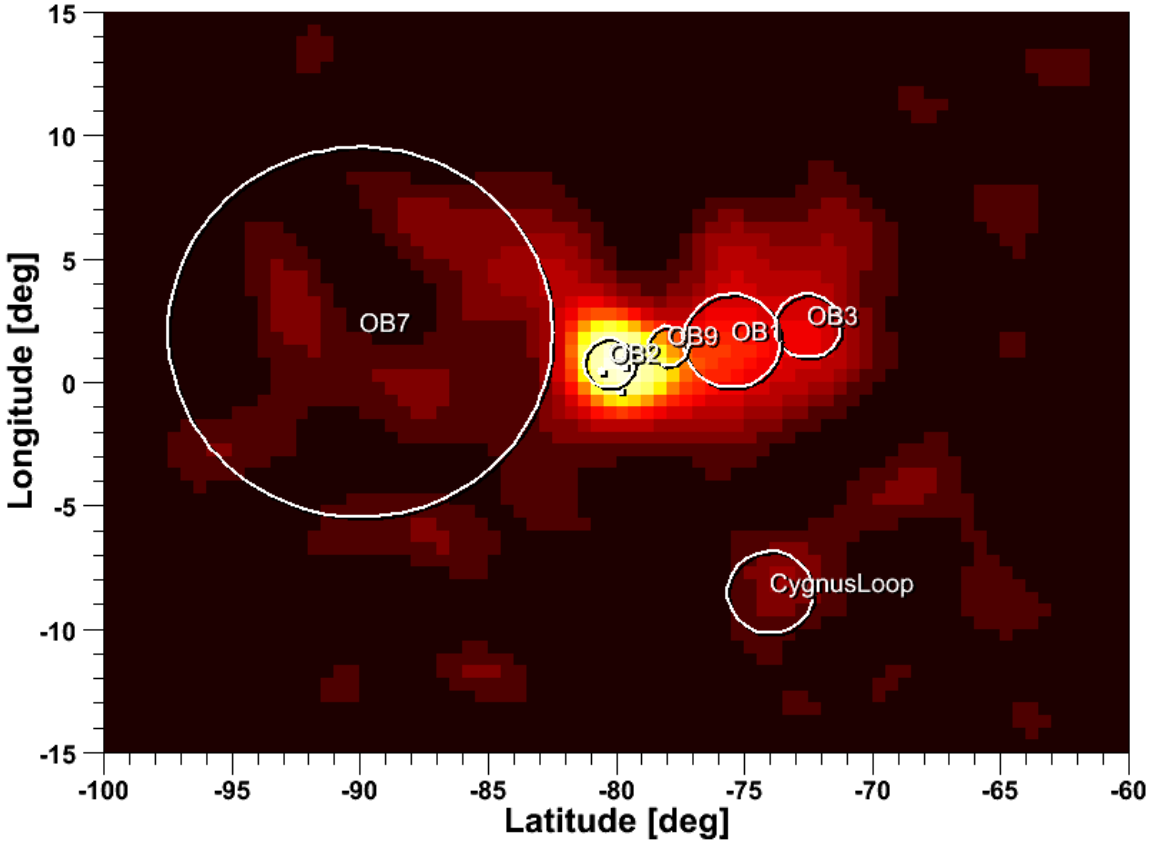
Parallel shape



An Astrophysical Application

Simulation of the Cygnus region in the light of radioactive ^{26}Al (1.8 MeV)

Telescope: MEGA, 2 yrs observation



Simulation includes OB-associations, Wolf-Rayet stars and supernova remnants as well as an appropriate amount of background.

Requirements for Astrophysics - 2

1. Correct reconstruction of spatial distribution of point and extended sources

2. **Correct retrieval of absolute source fluxes [ph/cm^2/s/keV/sr]**

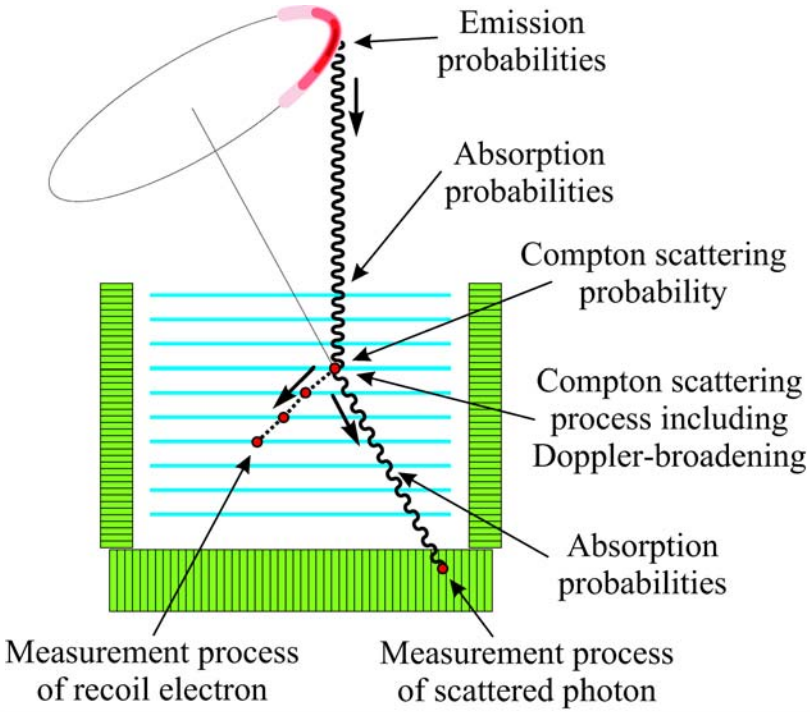
   This requires:

   (a)

   Get all probabilities correct!

   → Extremely time consuming in list-mode

   → Requires extremely detailed models of the detector and its characteristics as a function of event selections



Requirements for Astrophysics - 2

1. Correct reconstruction of spatial distribution of point and extended sources

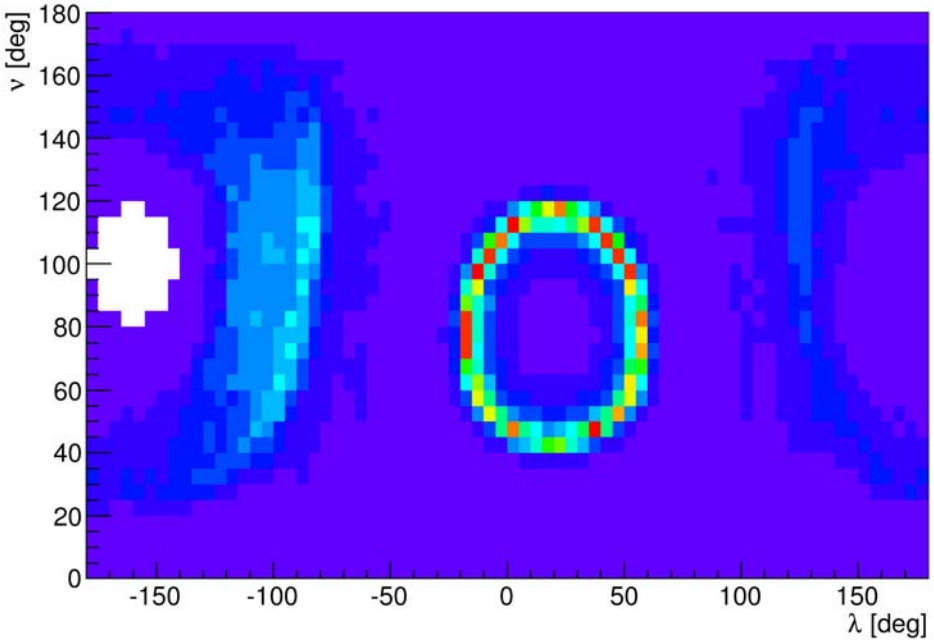
2. **Correct retrieval of absolute source fluxes [ph/cm^2/s/keV/sr]**

(b)

Include all detector, calibration, event reconstruction, etc. imperfections in the response!

Image space projection of response for one fixed bin in the data space.

i.e. pick one (E_e, E_g, r_1, r_2)



Requirements for Astrophysics - 2

1. Correct reconstruction of spatial distribution of point and extended sources

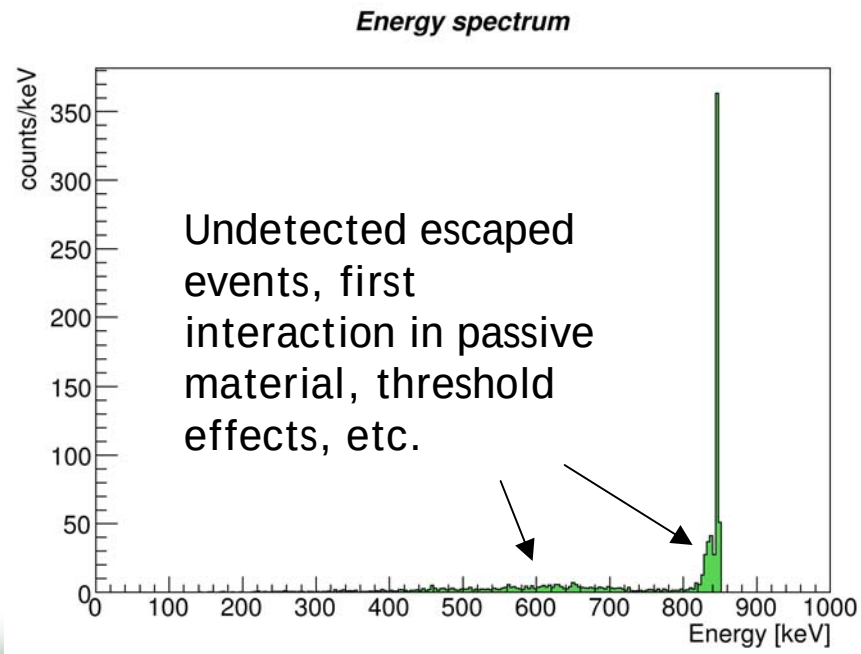
2. **Correct retrieval of absolute source fluxes [ph/cm²/s/keV/sr]**

(c)

Incomplete absorption results in wrong energy and wrong spatial distribution

Spatial & spectral components are linked

→ 3D problem: Combined spatial and spectral deconvolution



Requirements for Astrophysics - 3

1. Correct reconstruction of spatial distribution of point and extended sources
2. Correct retrieval of absolute source fluxes [ph/cm^2/s/keV/sr]
3. **Correct modeling of background**

Simulations and experience from COMPTEL show:

Up to 99% of all photons originate from background!

Source-independent part is a complex (non-analytic) distribution in data-space and best handled during reconstruction.

$$\lambda_m^{(l+1)} = \frac{\lambda_m^{(l)}}{s_m} \sum_n \frac{t_{nm} \cdot c_n}{\sum_k t_{nk} \cdot \lambda_k^{(l)} + b_n \cdot h}$$

Requirements for Astrophysics - 4

1. Correct reconstruction of spatial distribution of point and extended sources
2. Correct retrieval of absolute source fluxes [ph/cm^2/s/keV/sr]
3. Correct modeling of background
4. **Handle large amounts of events**

Si-Ge based ACT (Boggs et al., 2005) will measure ~1,500 valid Compton events per sec

→ ~5 x 10^{10} events per year

→ Estimate on a 1.6 GHz Pentium-M: 200,000 CPU days with current algorithm (50 iterations, unable to store backprojected events, all-sky, 0.5 degree resolution)

→ Number will get significantly larger, when "perfect" response is implemented

Requirements for Astrophysics – 5

1. Correct reconstruction of spacial distribution of point and extended sources
2. Correct retrieval of absolute source fluxes [ph/cm^2/s/keV/sr]
3. Correct modeling of background
4. Handle massive amounts of events
5. **Optimize "noise vs. contrast" ratio**

If points 1-4 are implemented, it is only a question of finding the perfect imaging algorithm:

- Expectation Maximization
- Maximum Entropy
- Pixon
- Etc.

Requirements for Astrophysics – 5

1. Correct reconstruction of spacial distribution of point and extended sources
2. Correct retrieval of absolute source fluxes [ph/cm^2/s/keV/sr]
3. Correct modeling of background
4. Handle massive amounts of events
5. Optimize “noise vs. contrast“ ratio
6. **Correct handling of all the technical details:**
   - **Allow for multiple observations, etc. (i.e. non-homogeneous exposure)**
   - **Easy handling of different event selections (earth horizon cuts, background cuts, etc.)**
   - **…**

Status

Currently no algorithm exists which fulfills *all* requirements!

The approximations done for COMPTEL do not hold for large field-of-view telescopes

→ Required data spaces for binned mode are to large to be handled on today's hardware

→ In list-mode the absolute normalization is far to time consuming

However…

Imaging Examples

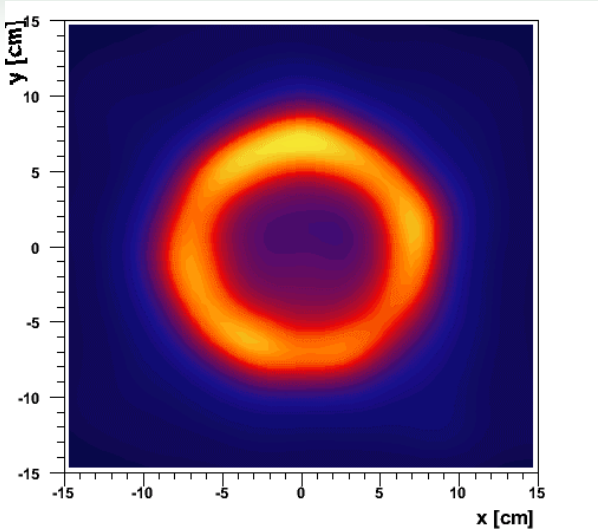
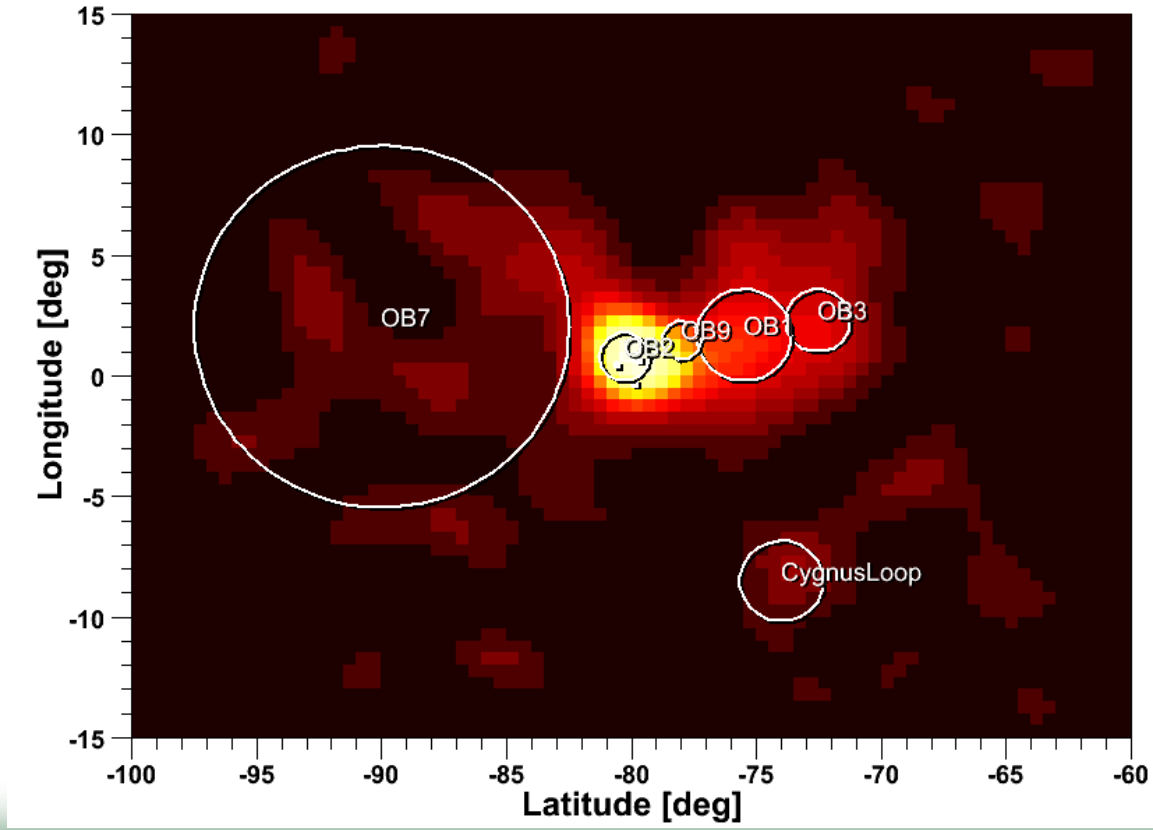


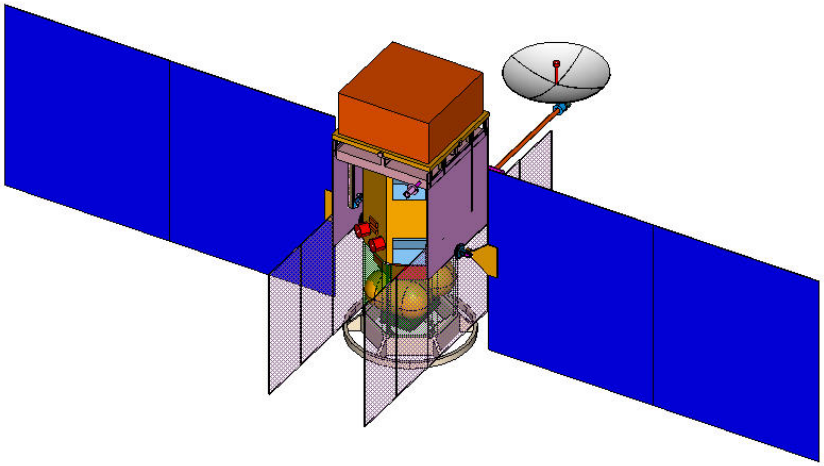
Illustration of the LM-EM algorithm recovering the image of a ring (Real measurement with MEGA prototype)

Image of the Cygnus region in the light of ^{26}Al after 2 years exposure (MEGA detector)

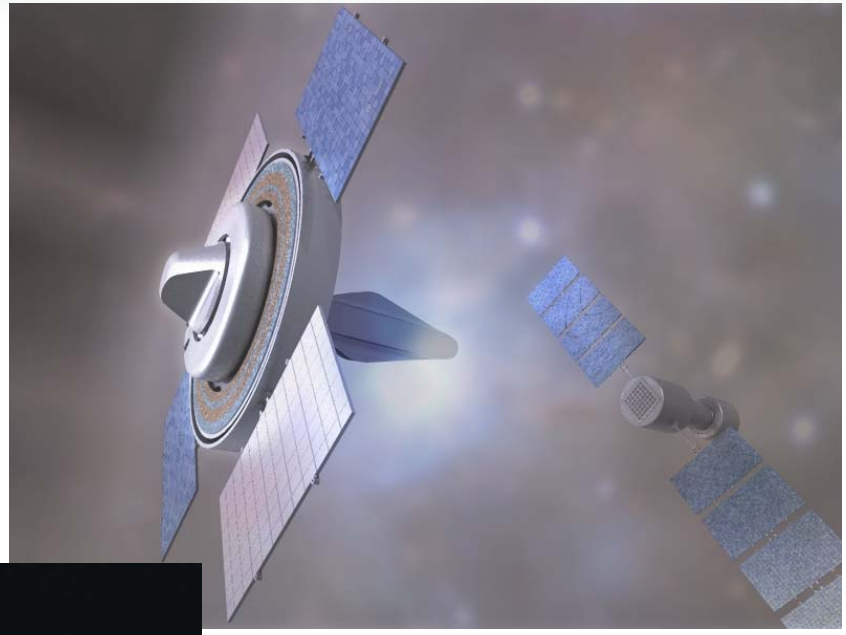


Epilogue:
The future

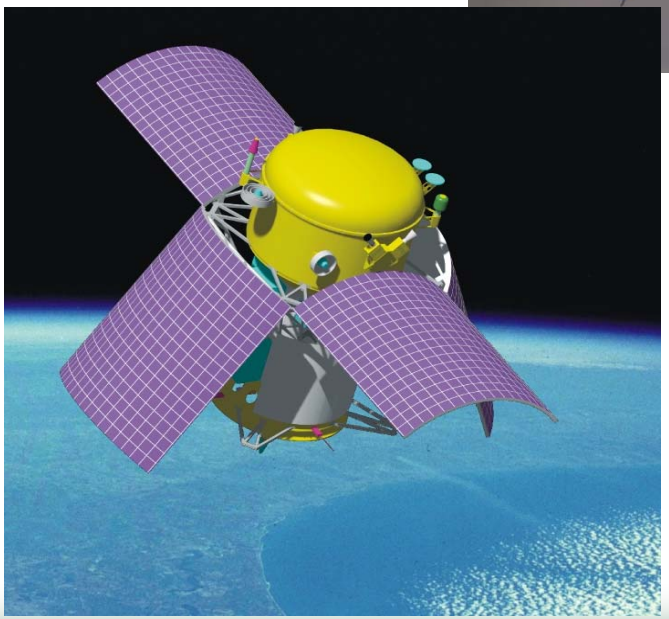
One day there will be a mission... perhaps...



ACT ?



GRI ?



MEGA ?

2020... 2025... ??