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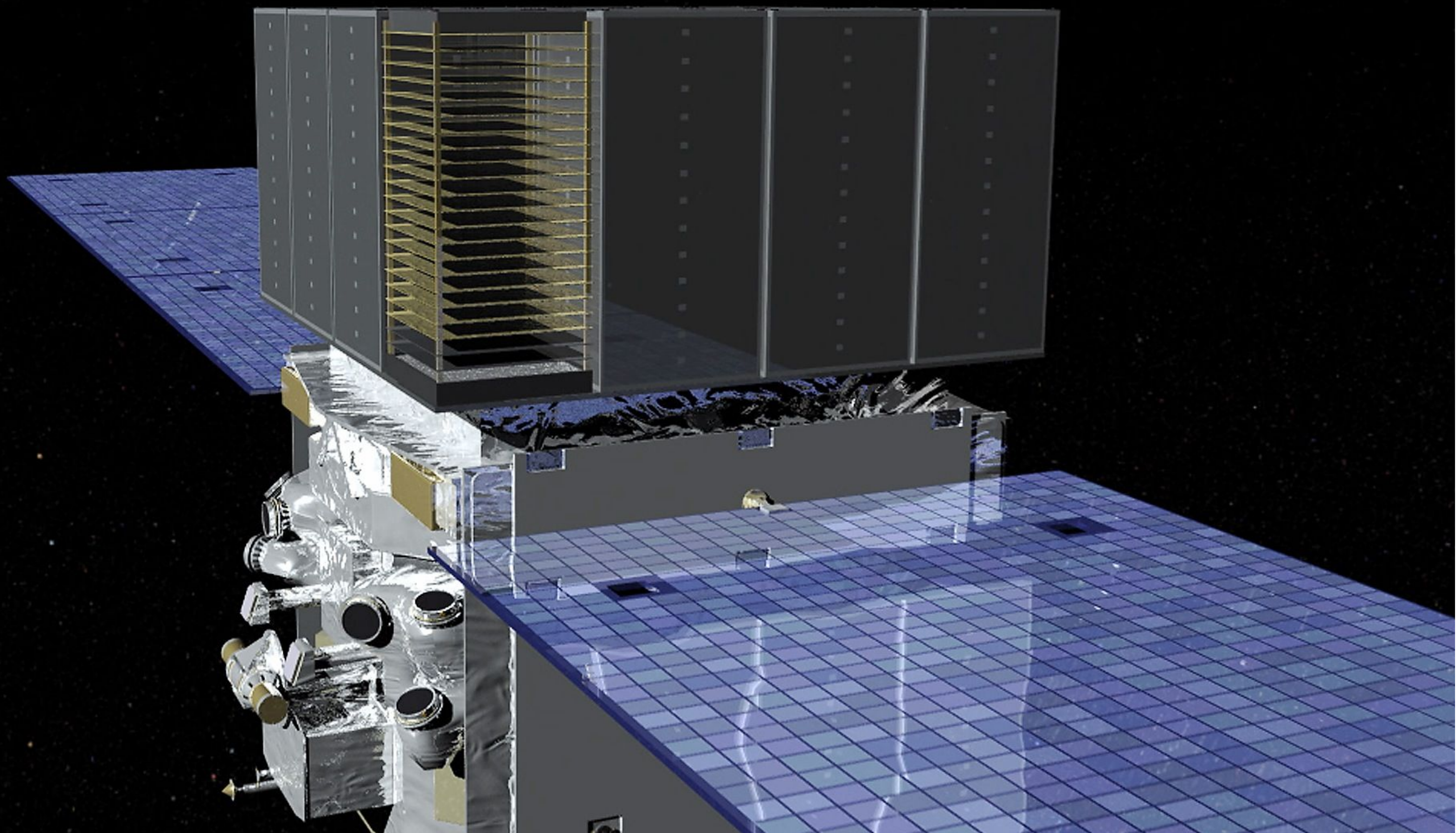
Fermi-LAT and the future of satellite gamma-ray experiments



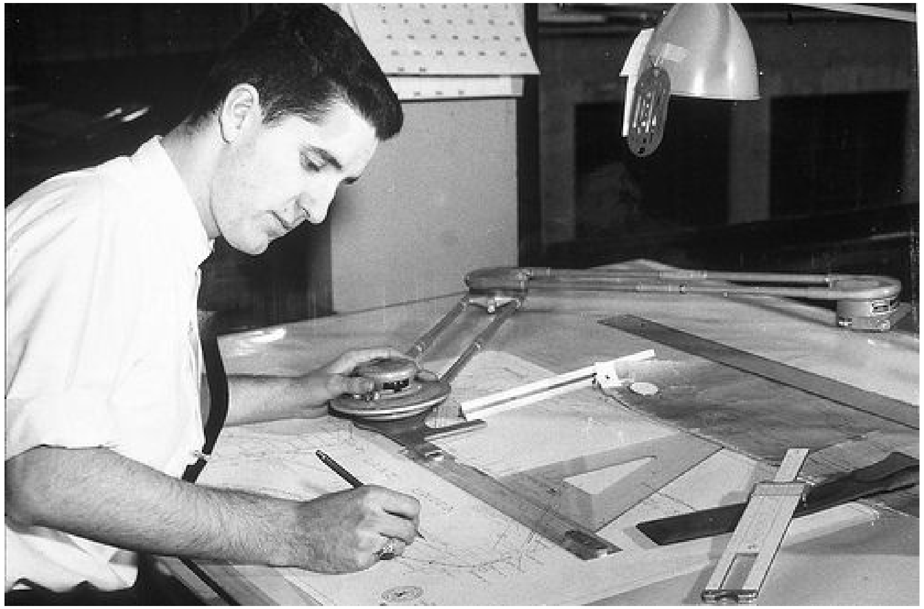
7th IDPASC School, Asiago,
20 - 30 June 2017

Outline

- **How to: Gamma-ray astrophysics**
- **Instrument design:**
  - **Case study: FERMI-LAT**
  - **The detector**
  - **Operation in space**
  - **Performance**
- **What next for GRA**
  - **Proposed missions**

Let us design a detector for gamma ray astrophysics
Say we want to observe remote sources of high energy gamma rays
Say also we want to **improve upon predecessors** using state-of-the-art high-energy-physics techniques

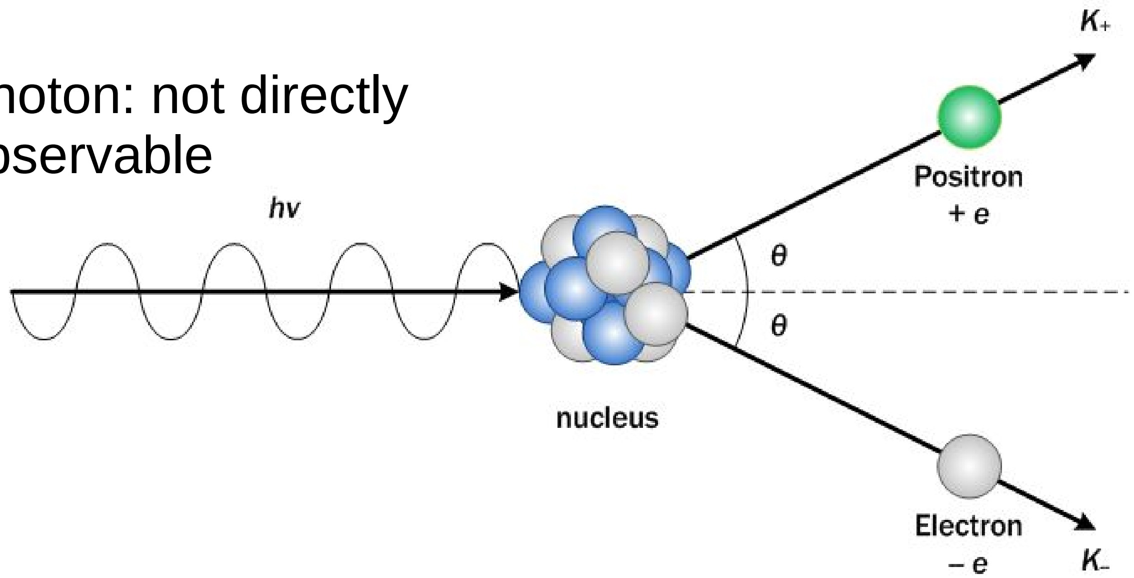
- How to detect the photons with **optimum performance**?
- What are the physical processes involved?
- What performance we can reasonably expect?
- How to successfully operate the instrument?



Let us not start from scratch:
Other experiments have flown before
No need to reinvent the wheel

At energies above a few 10 MeV pair production (in the nuclear field) is the main process by which photons interact with matter

Photon: not directly observable



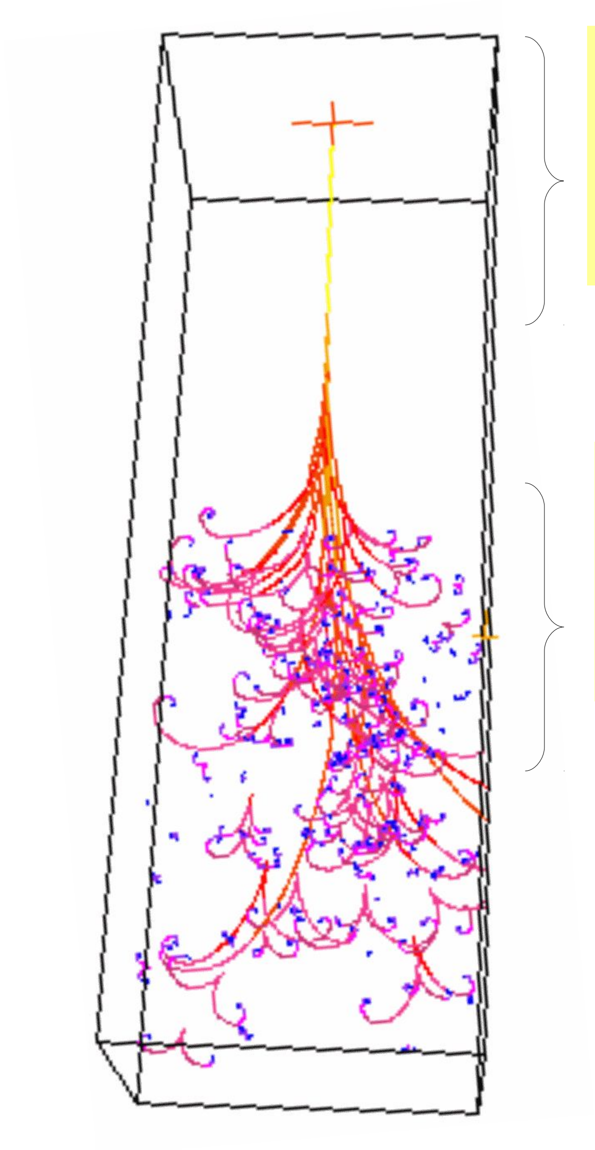
Secondaries:
Can be observed
Reconstruct the original direction
Absorb and score energy

Cross section increases with ~Z^2: high-Z materials are needed to have a good stopping power. Dense materials are also needed to completely absorb the gamma ray energy and properly measure it: reduce leakage.
This limits the tracking capabilities, because secondaries undergo **multiple scattering** in the detector. So requirements are at odds:

good efficiency and energy resolution ↔ good angular resolution

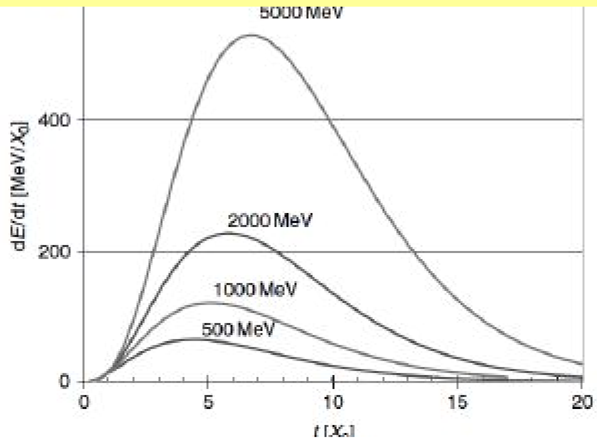
A design scheme

A solution is to do things one after another:



Start with the minimum amount of dense material
Thickness approx. **1 radiation length**: 7/9 of the mean path for a photon in the p-p regime
Segment it and place **good tracker in between**

After that: **a lot of dense material** to measure the energy
Several radiation lengths: some leakage is allowed, as long as the maximum is contained (so we can infer the amount lost)



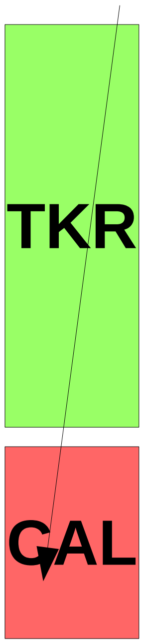
Putting it together

TKR

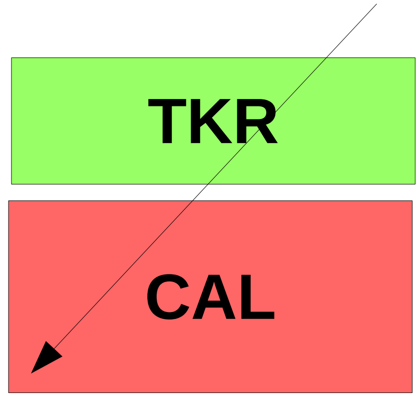
Low density
Relatively low efficiency
Excellent spatial resolution

CAL

High density
Good efficiency
Poor spatial resolution



Better angular resolution
Worse field of view

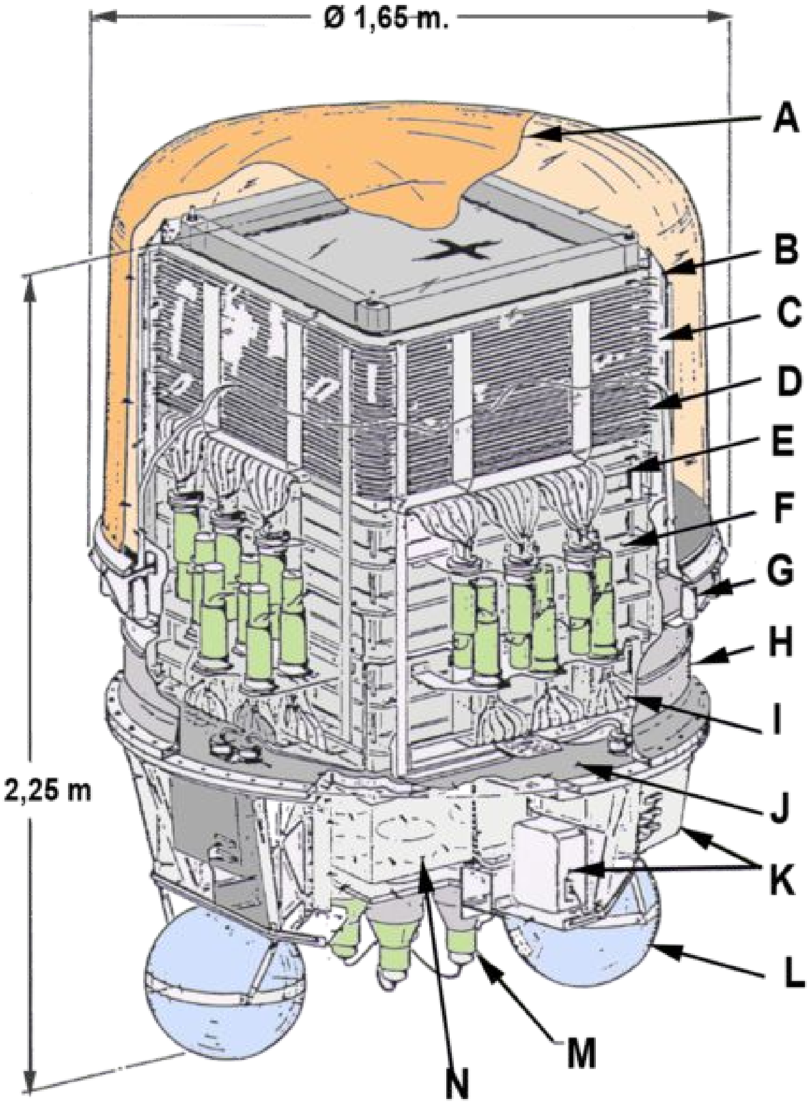


Worse angular resolution
Better field of view

For a good sky coverage, our detector will have a squat aspect ratio, for a good compromise

A HEP detector in space

Immediate predecessor: EGRET on CGRO



Anticoincidence dome:
Veto charged particles in orbit

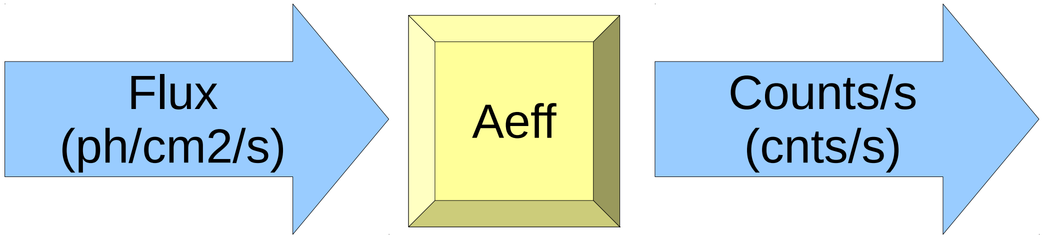
Spark chamber for tracking: get direction
Thin metal plates to promote pair production
Gas to track secondaries

Time-of-flight:
Identify and discard particles from below

Scintillator calorimeter:
Absorb completely the energy and score it

Detector parameters

Effective area
Efficiency for detection, in units of cm^2 (upper limit is geometric area)



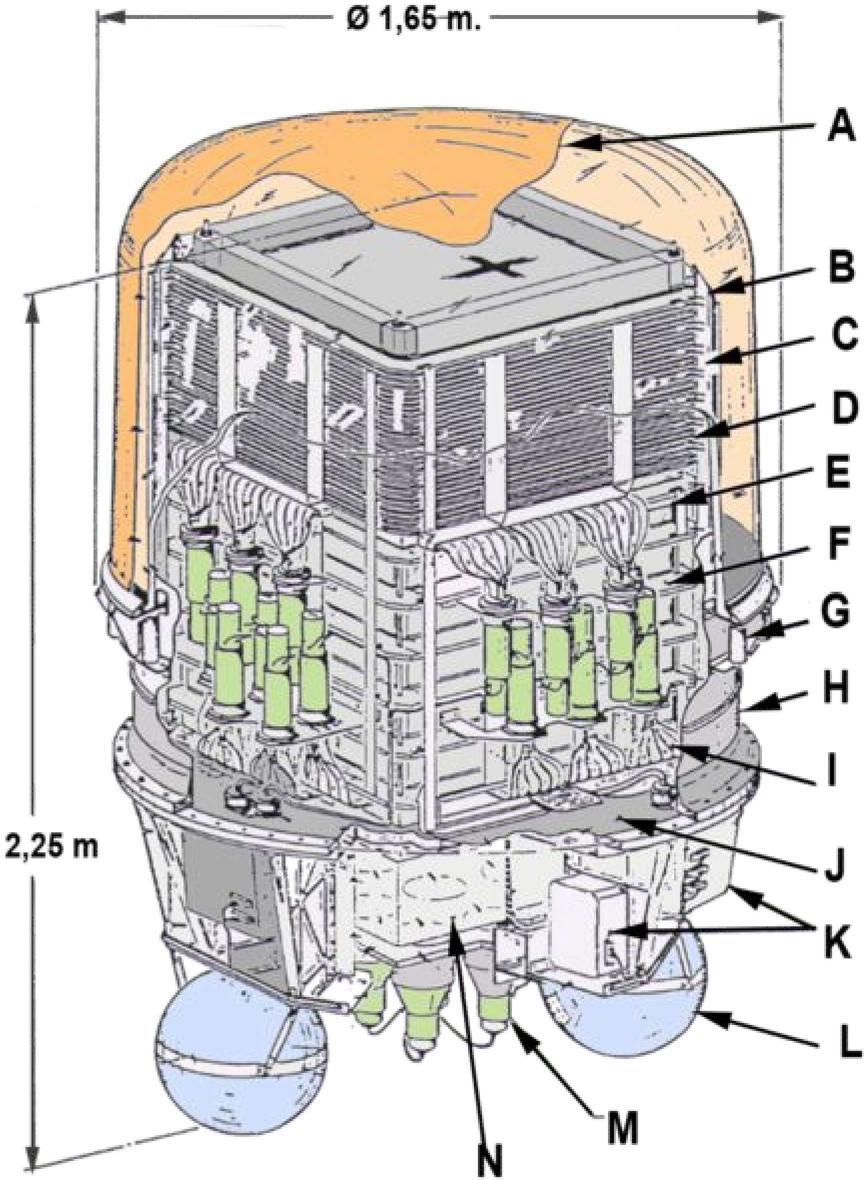
Energy resolution: measured energy vs. true energy
Gamma-ray sources typically have power-law spectrum
Rule of thumb: even a small overestimate is terribly bad

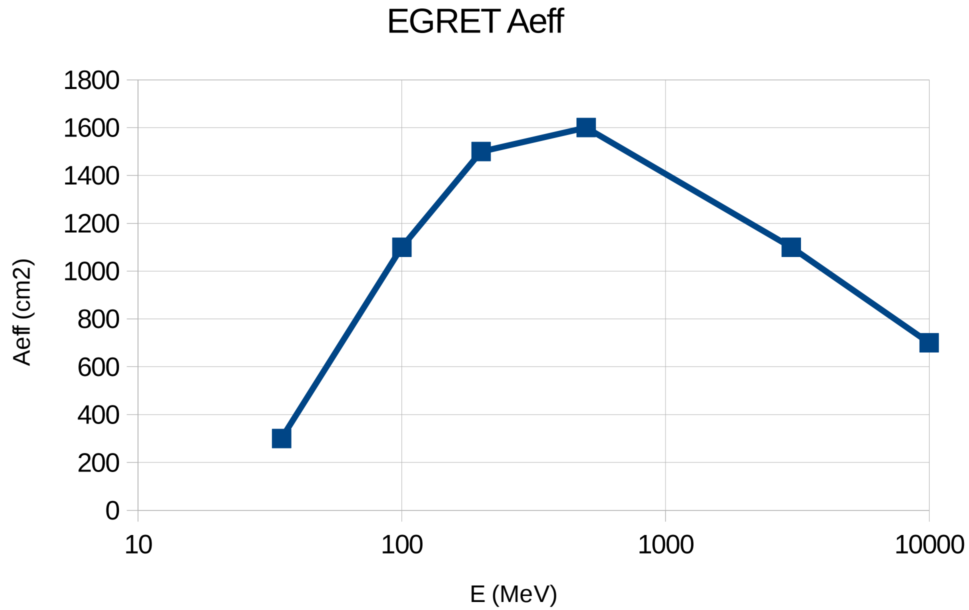
Point Spread Function (**PSF**) is the angular resolution (angle between measured & true direction)
Azimuthally symmetric? (fish-eye?)

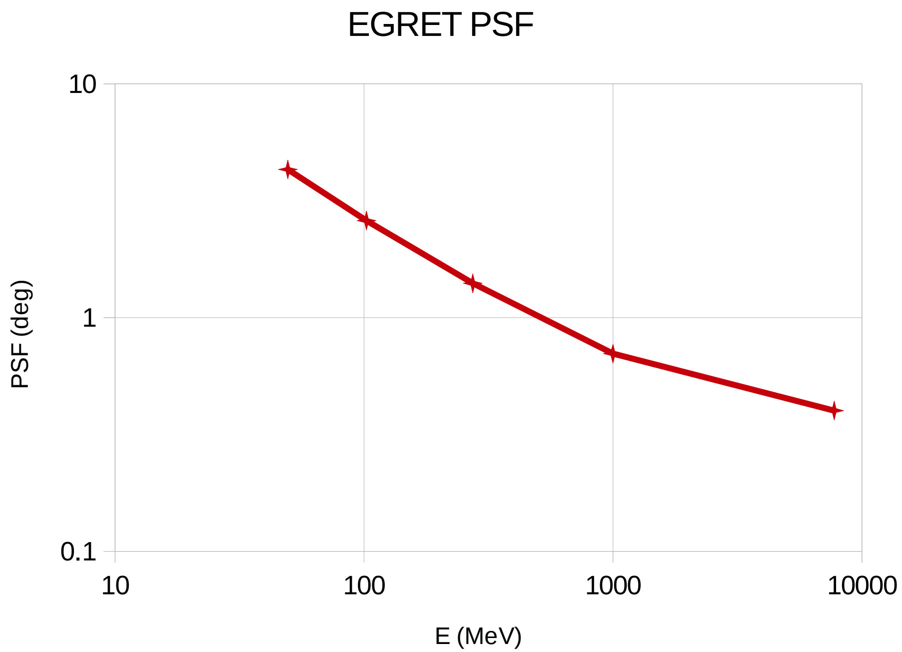
Exposure: aeff integrated over time, for a given certain direction in the sky (cm^2*s)

Livetime fraction: time the detector is ready to take data (as opposed to busy, offline, ...)

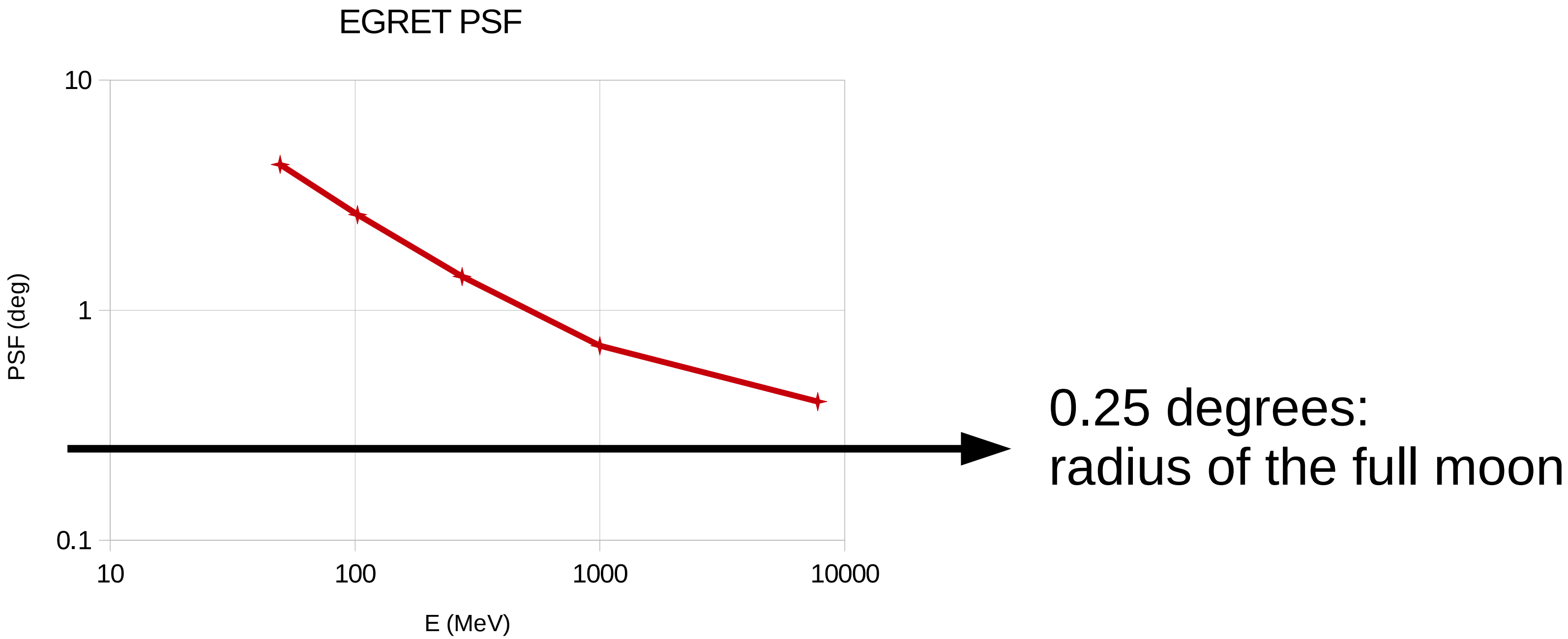
EGRET


Ø 1,65 m.
2,25 m
A
B
C
D
E
F
G
H
I
J
K
L
M
N


EGRET Aeff
Aeff (cm2)
1800
1600
1400
1200
1000
800
600
400
200
0
10
100
1000
10000
E (MeV)


EGRET PSF
PSF (deg)
10
1
0.1
10
100
1000
10000
E (MeV)

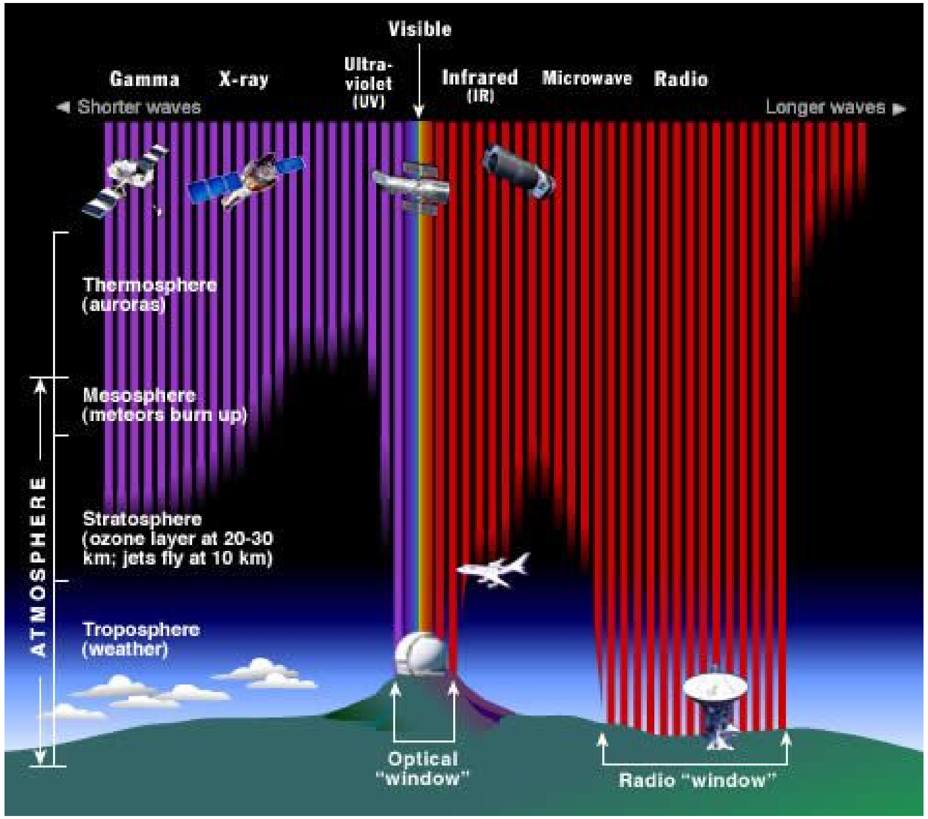
Full Moons



Not particularly impressive for optical or radio astronomers
Still allows to distinguish quite a few point sources:

Full moon: $6.67 \cdot 10^{-5}$ srad → full sky is 4π srad
Still 188k “pixels” in the sky (worse at low energy with PSF^2)

Observation of astrophysical sources of gamma rays (from ~100 MeV)



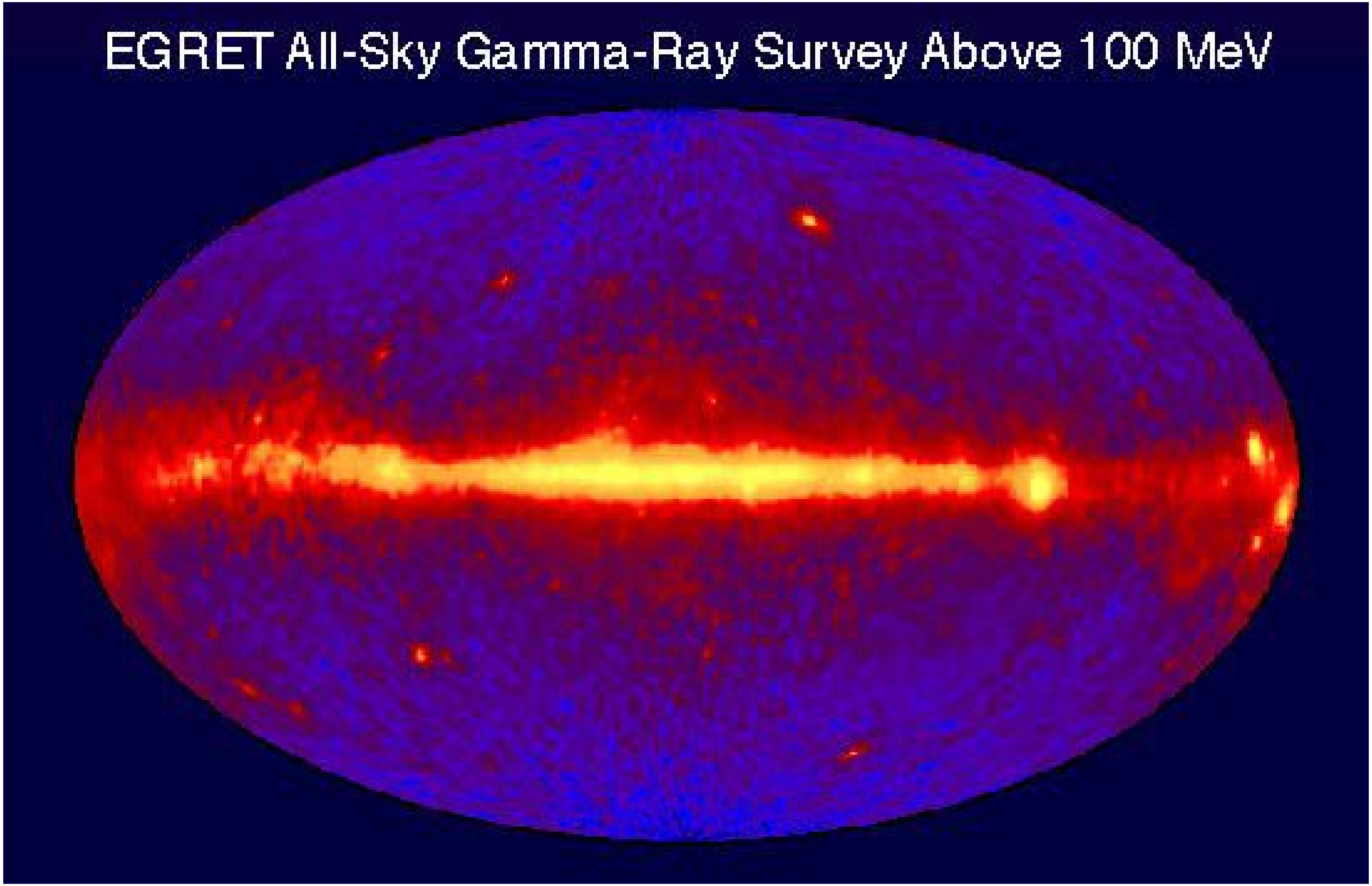
Absorption from atmosphere forces satellite
But: prof. Mariotti about VHE gamma

Space operation forces several additional constraints, mostly due to the impossibility of intervention (e.g. repairs) and mass/power limitations.

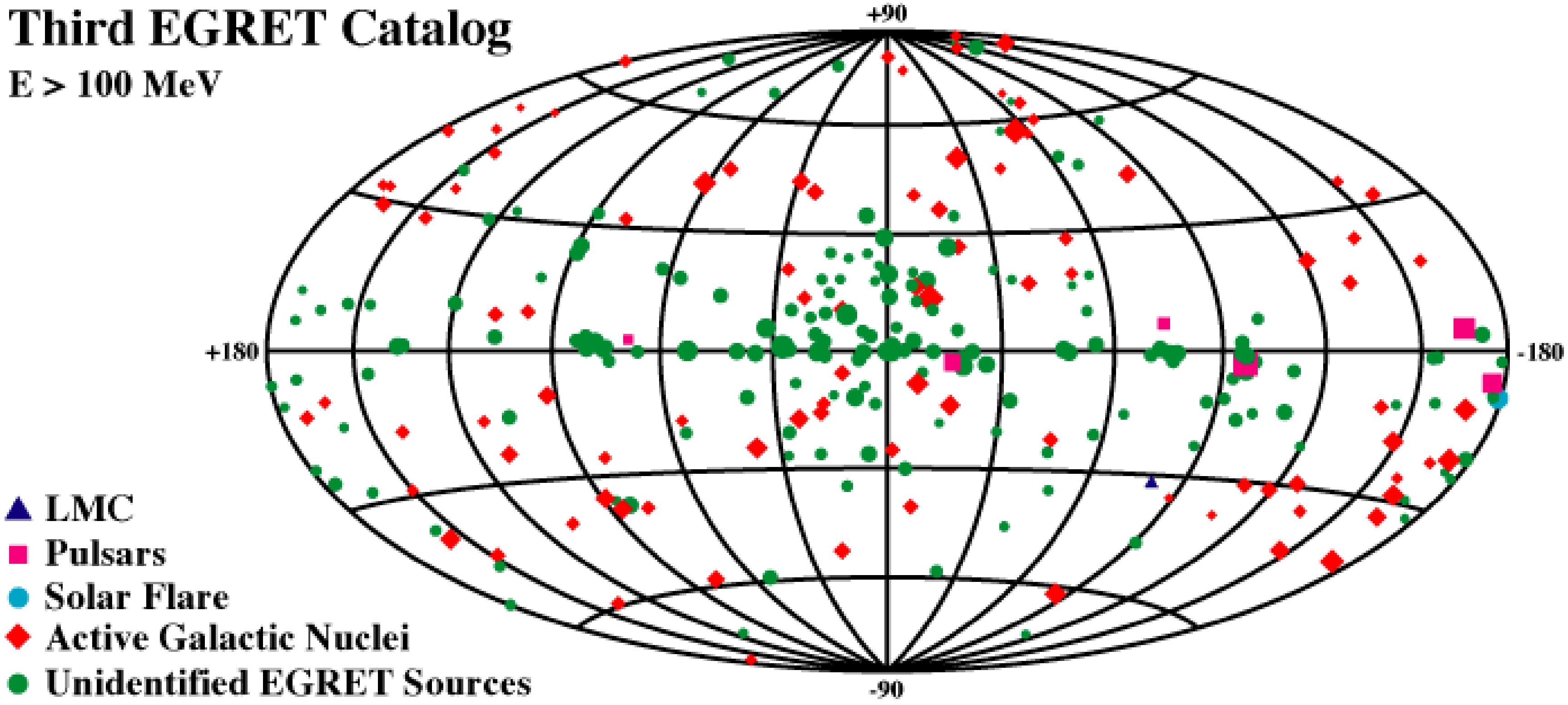
Also, harsh environment:
- Vacuum
- Radiation
- Heat

Even bringing data to ground is an issue

EGRET sky



EGRET results



271 sources
Discovered blazars
6 pulsars detected

Some requirements for the successor

Dictated by science:

- >5 year lifetime!
- All sky, with uniform coverage
- Wide FOV to observe a good fraction of the sky at all times
- Good resolution (angular and energetic)
- Good timing (us)
- Transient capabilities

Dictated by operation:

- 5 year lifetime!
- Lateral dimensions < 1.8 m
- Mass < 3,000 kg
- Power <650 W
- Downlink <300 kbps
- Unassisted
- No possibility of replacements

REQ

Quantity	*EGRET*	*GLAST Requirement*	*GLAST Goal*	*Science Driver*
Energy Range	20 MeV - 30 GeV	20 MeV - 300 GeV	10 MeV - >300 GeV	ALL
Energy Resolution	10%	10% (100 MeV–10 GeV) [1]	2% (E > 10 GeV)	ALL
Effective Area [2]	1500 cm^2	8000 cm^2	> 10,000 cm^2	ALL
Single Photon Angular Resolution - 68% [3] (on-axis)	5.8° (@100 MeV)	< 3.5° (@100 MeV) < 0.15° (E > 10 GeV)	< 2° (@ 100 MeV) < 0.1° (E > 10 GeV)	ALL
Single Photon Angular Resolution - 95% [3] (on-axis)		$< 3 \times \theta_{68\%}$	$2 \times \theta_{68\%}$	ALL
Single Photon Angular Resolution (off axis at FWHM of FOV)		< 1.7 times on-axis	< 1.5 times on-axis	ALL
Field of View [4]	0.5 sr	2 sr	>3 sr	ALL
Source Location Determination [5,8]	5 - 30 arcmin	1-5 arcmin	30 arcsec - 5 arcmin	Unidentified EGRET Sources, GRBs
Point Source Sensitivity [6,8] (> 100 MeV)	$\sim 1 \times 10^{-7}$ cm^{-2} s^{-1}	4×10^{-9} cm^{-2} s^{-1}	$< 2 \times 10^{-9}$ cm^{-2} s^{-1}	AGN, Unidentifieds, Pulsars, GRBs

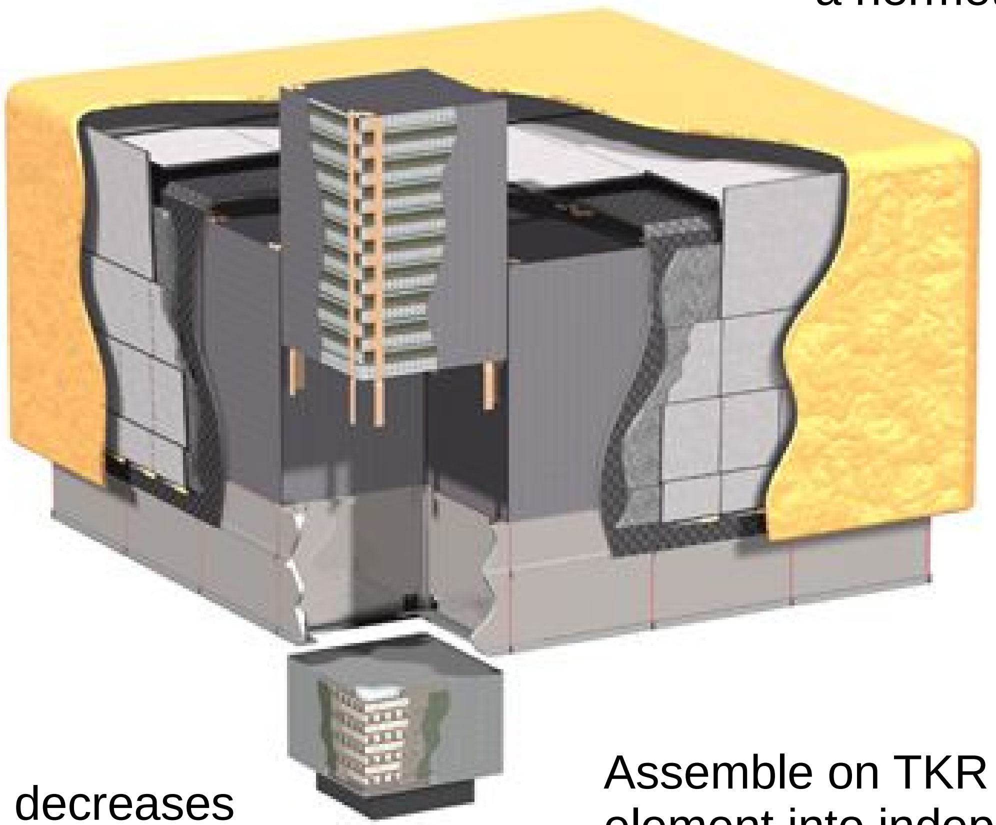
REQ2

Quantity	*EGRET*	*GLAST Requirement*	*GLAST Goal*	*Science Driver*
Time Accuracy	0.1 ms	10 μsec absolute [7]	2 μsec absolute [7]	Pulsars, GRBs
Background Rejection	$> 10^6$:1	$> 10^5$:1	$> 10^6$:1	ALL, Especially Diffuse
Dead Time	100 ms/event	< 100 μs /event	<10% instrument ave. for bursts up to 10kHz (<20 μs/event)	GRBs
Transients			Complementary low-energy observations Trigger and location for S/C repointing High efficiency recognition and reconstruction of multi-γ events	GRBs,Primordial BHs

Overall design

Squat aspect ratio – for a large FOV

ACD surrounding all as
a hermetic seal

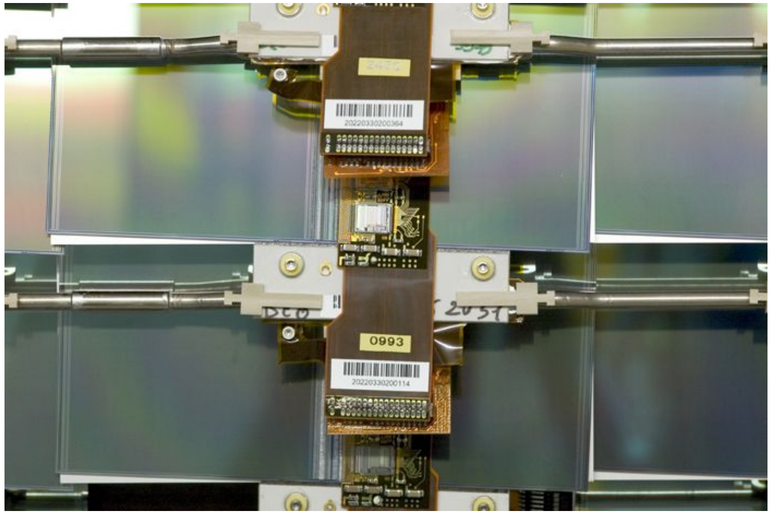


Modular design: decreases
risk of a major failure in
case of damage

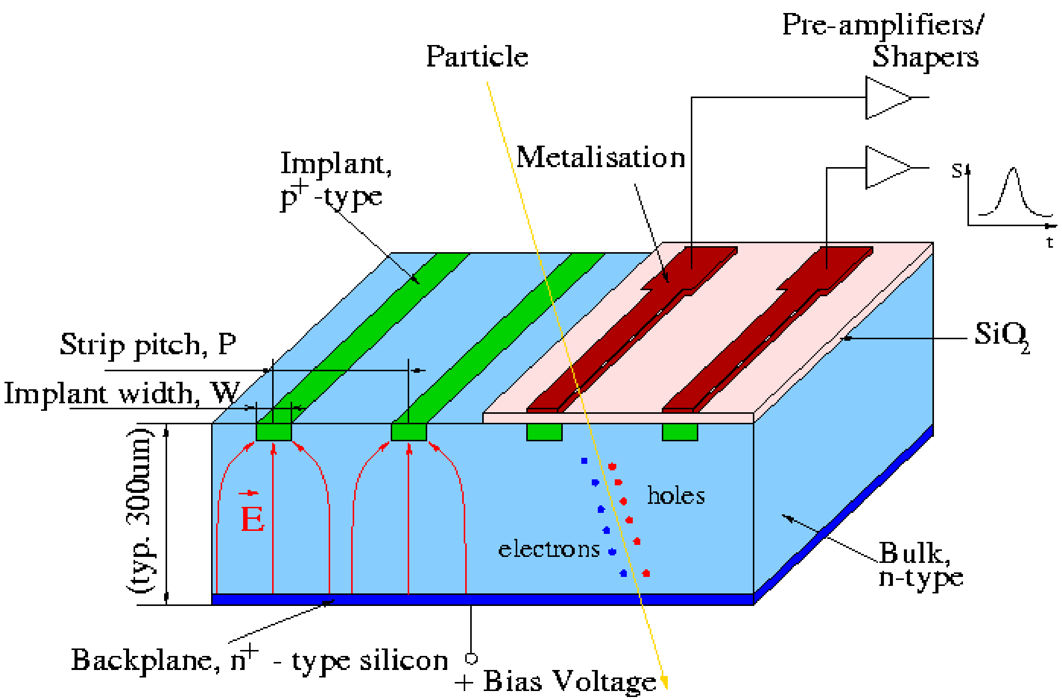
Assemble on TKR and one CAL
element into independent "tower"
structures

Tracker: basics

The TRACKER will be the core of our instrument
State-of-the-art: HEP detectors
Silicon microstrip detectors
Conversion foils to increase efficiency



Principles of operation



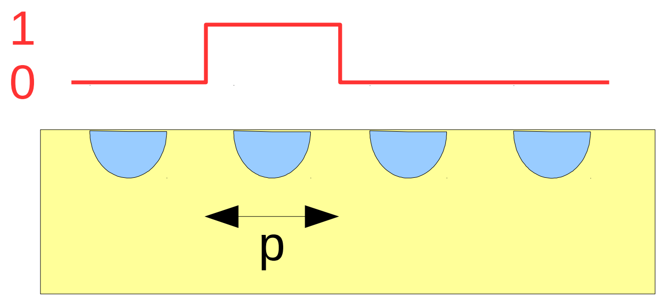
Need **2 layers** to measure x-y hit

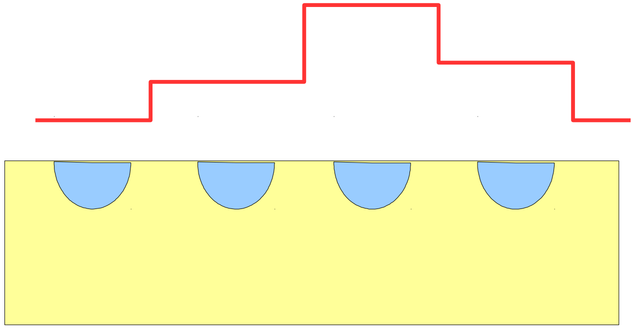
Double-sided: possible to limit the crossed material (and so MS)
Expensive, difficult to handle
Not necessary: the TKR material budget will be dominated by the conversion plates in any case

SSD hit resolution

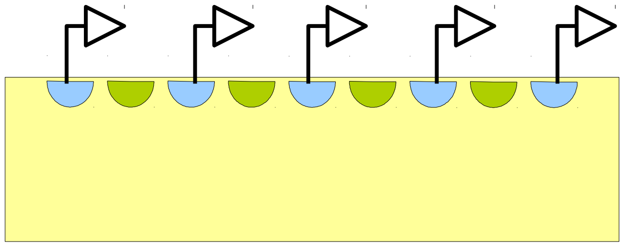
Baseline hit resolution is p/sqrt(12)
Assuming digital (1/0) readout
Decreasing pitch increases channel number

There are possible design improvements





1: analog readout
If several strips are hit, fit the profile
Requires fancier electronics
More complex, more power consumption



2: floating strips
Not connected to the readout, share charge with the neighbors
In addition to #1, improves resolution beyond readout pitch

E.g. AGILE has both, FERMI-LAT none

Tracker: advantages of silicon

2-hit resolution ~250 um
Compare: EGRET ~3 mm

Lower ionization energy than gas (2.6 eV versus ~30 eV)
More carriers are generated, more signal

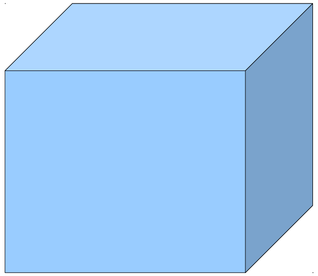
Higher density than gas
Large energy loss per distance: large signals

Self triggering
EGRET spark chamber needed an external trigger (issued from TOF)

Low voltage
100 V versus 1,000 V

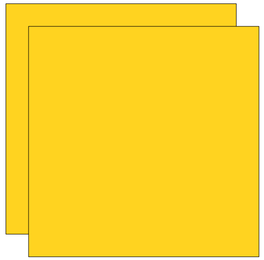
Tracker: budget

Even with single-sided detectors, grade-A silicon is expensive.
Let's assume (**not real figures**):



Lateral TKR size of 1.8 m
(fits into the big fairing of
a Delta-II launcher)

SSD lateral size of 9 cm
Two layers (x-y) needed per plane



We end up with an estimate of 20x20x2= 800 SSDs per plane!
Amounts to 5.8 m^2 of grade-A silicon per layer!
End message is:

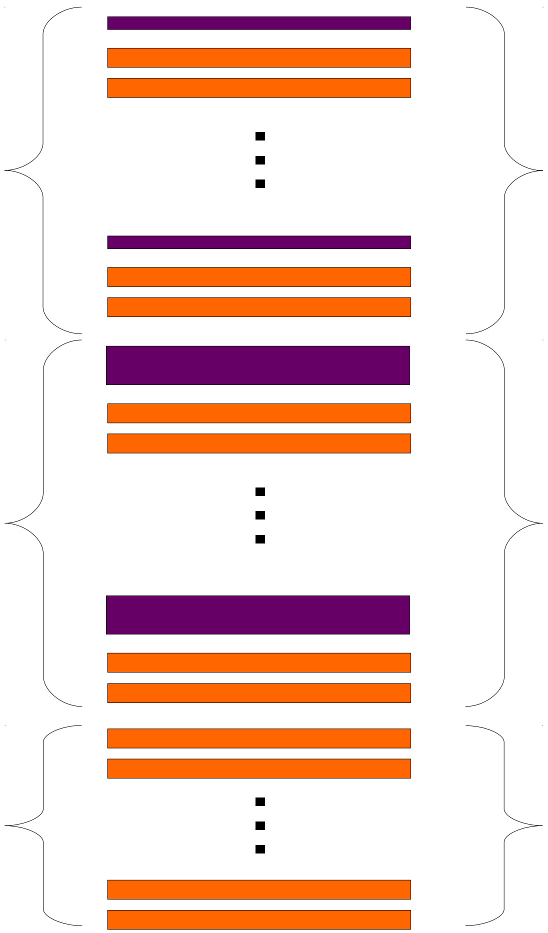
- TKR is really expensive (several 10^6 \$)!
- You can get a good discount for this amount !!!

Actual figures: 16x16x2 SSDs, times 16 layers

Tracker: conversion foils

Material: W
Aim: ~1 r.l.

properties	Si	W
Z	14	74
D (g/cm^3)	2.33	19.3
r.l. (cm)	9.37	0.35



12 layers with
0.03 r.l. of W
(0.01 of Si)

We try to have a good compromise
Significantly increase conversion prob.
without causing too much MS

4 layers with
0.1 r.l. of W

We are getting desperate
Give up a bit on the resolution,really try
to cause a p-p conversion

2 layers with
no W

We give up
(actually see later)

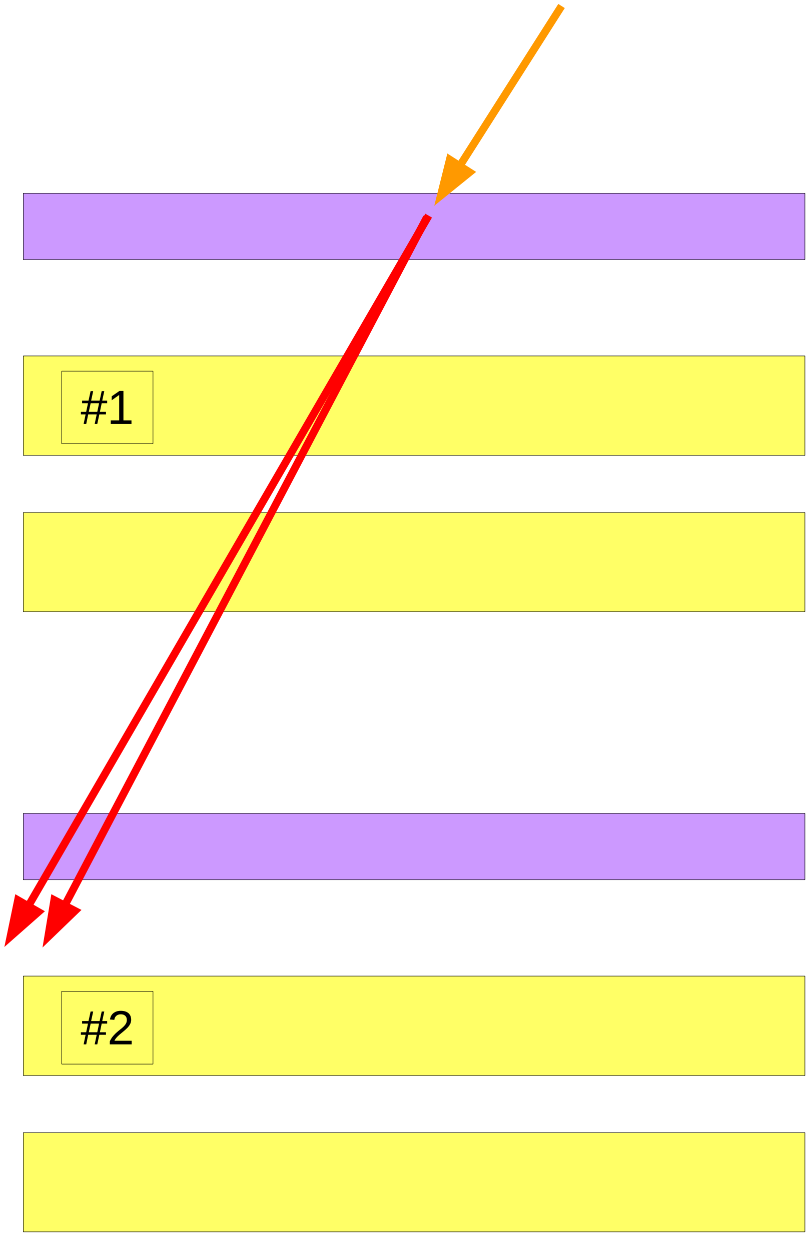
Tracker: spatial resolution

W thickness: 0.03 X_0
Causes multiple scattering
E.g. : gamma with 1 GeV
Assume secondary with 500 MeV each
Angled 45° wrt planes

$$\theta_{MCS} = \frac{13.6\,MeV}{\beta c\, p} z \sqrt{x/X_0}[1+0.038 \ln x/X_0]$$

#1: assume 3mm to the first silicon plane
Sigma of hit position is **<15 um**

#2: to the first silicon plane in second layer
Assume 3cm (W to W)
Material: 0.08 X_0 total
Sigma on hit position is **~250um**

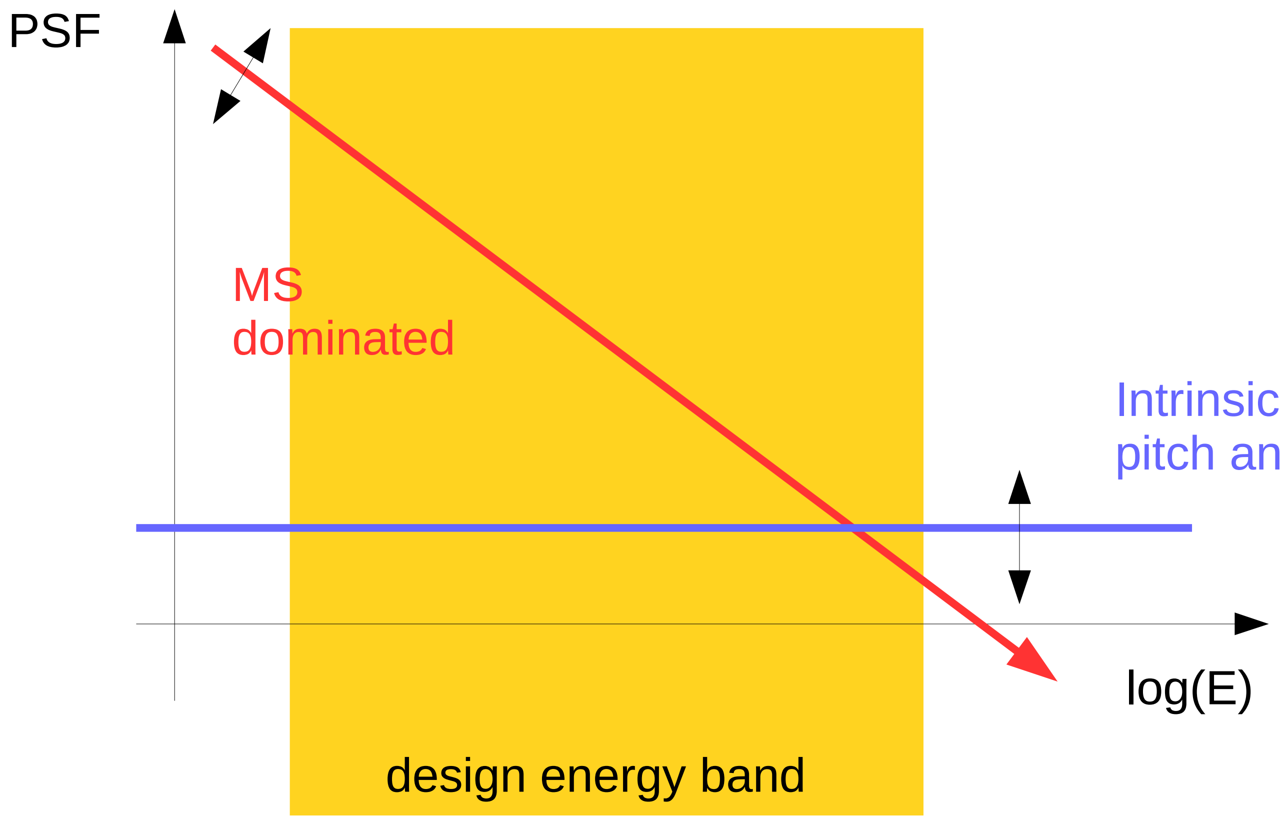


Due to MS, no need of high SSD hit resolution
A few 100 um is fine
Recording the first hit after conversion is vital
Miss causes a loss factor 2x in resolution!

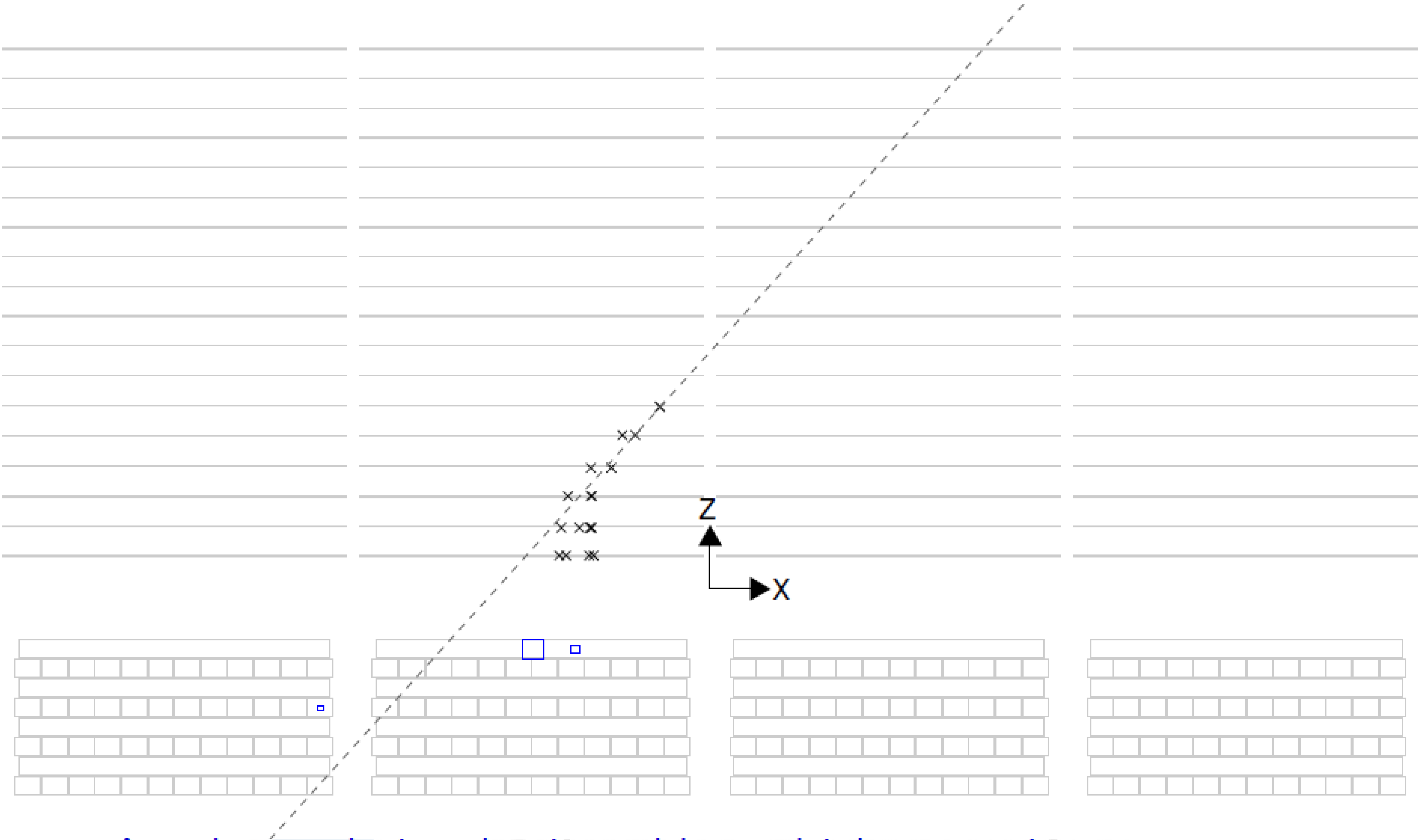
Tracker: spatial resolution 2

$$\theta_{MCS} = \frac{13.6\,MeV}{\beta c\, p}\, z \sqrt{x/X_0}\left[1 + 0.038 \ln x/X_0\right]$$

As long as MS dominates PSF will have a 1/E dependence
Set up so that at the highest energies this reaches the **intrinsic resolution** of the tracker, given by pitch+lever arm



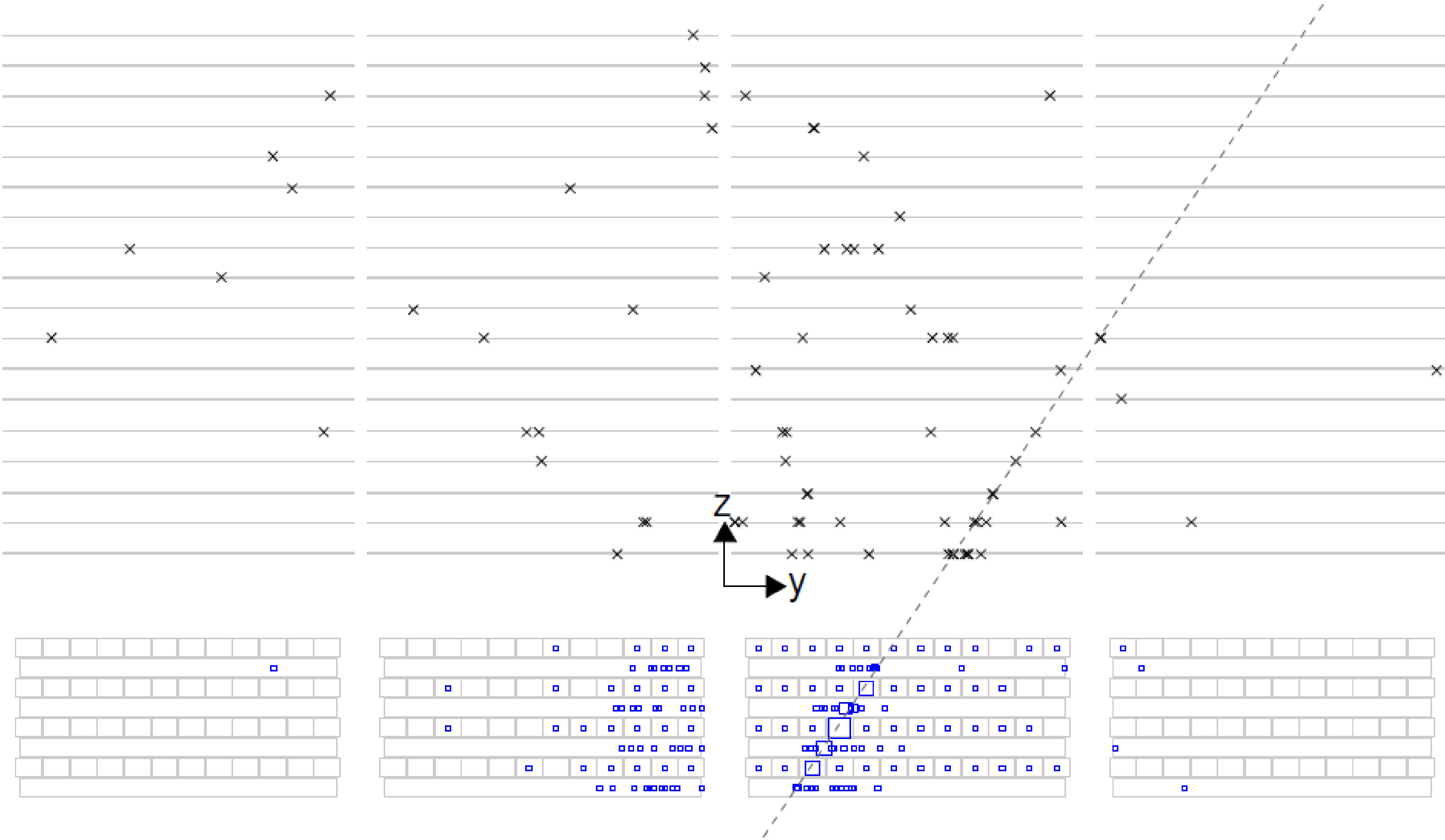
80 MeV



- Angular resolution dominated by multiple scattering:
  - call for *thin* converters;
  - but need material to convert the gamma-rays!

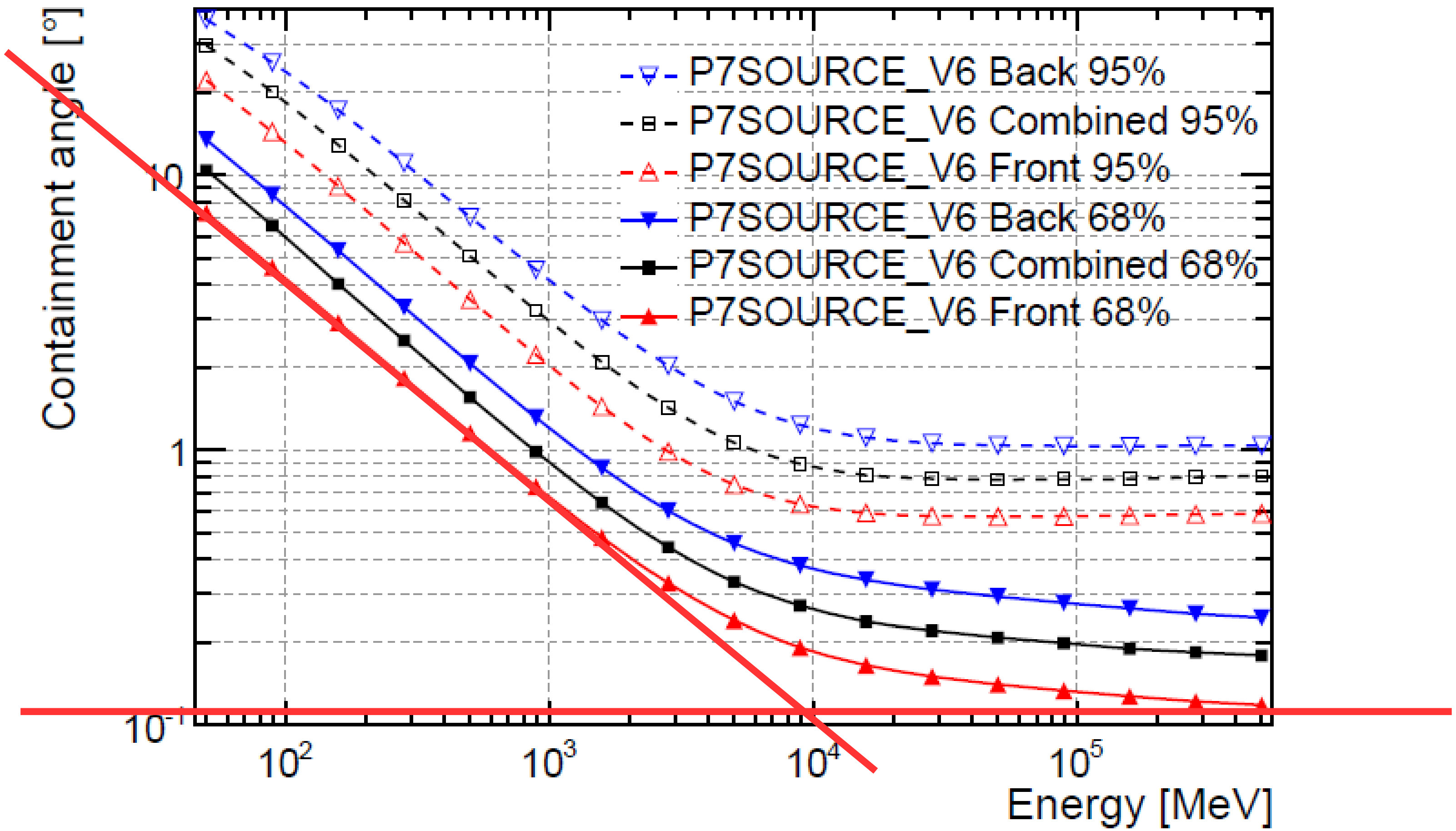
L. Baldini

150 GeV



- Angular resolution determined by hit resolution and lever arm:
  - call for fine SSD pitch, but power consumption is a strong constraint;
- backsplash from the calorimeter also a potential issue.

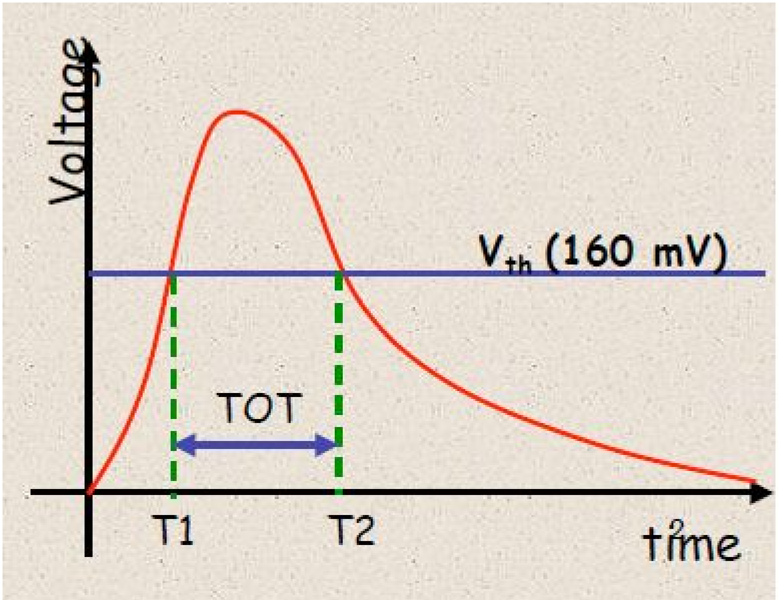
PSF dependence



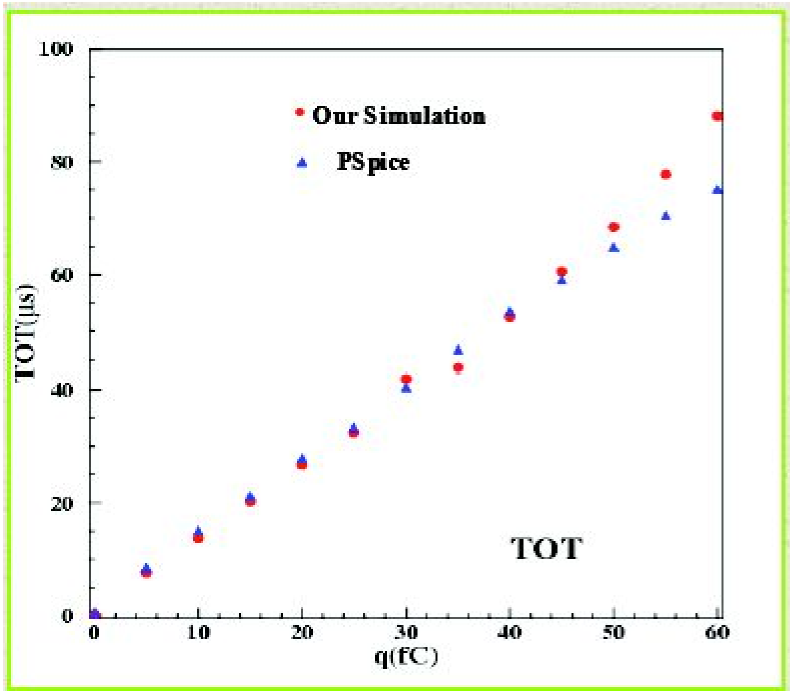
(*) actually, $E^{-0.78}$, due to missed hits and hard scattering (δ-rays)

ToT

Need estimate of energy deposited in TKR
TKR as a sampling calorimeter (sensitive material interleaved with dense material)
Complication: readout from TKR is fully digital (1/0), i.e. no pulse height information
Solution: Time-over-Threshold (TOT)



One can derive area from how long the channel is "up"
Shape of the curve is fixed by the shaping



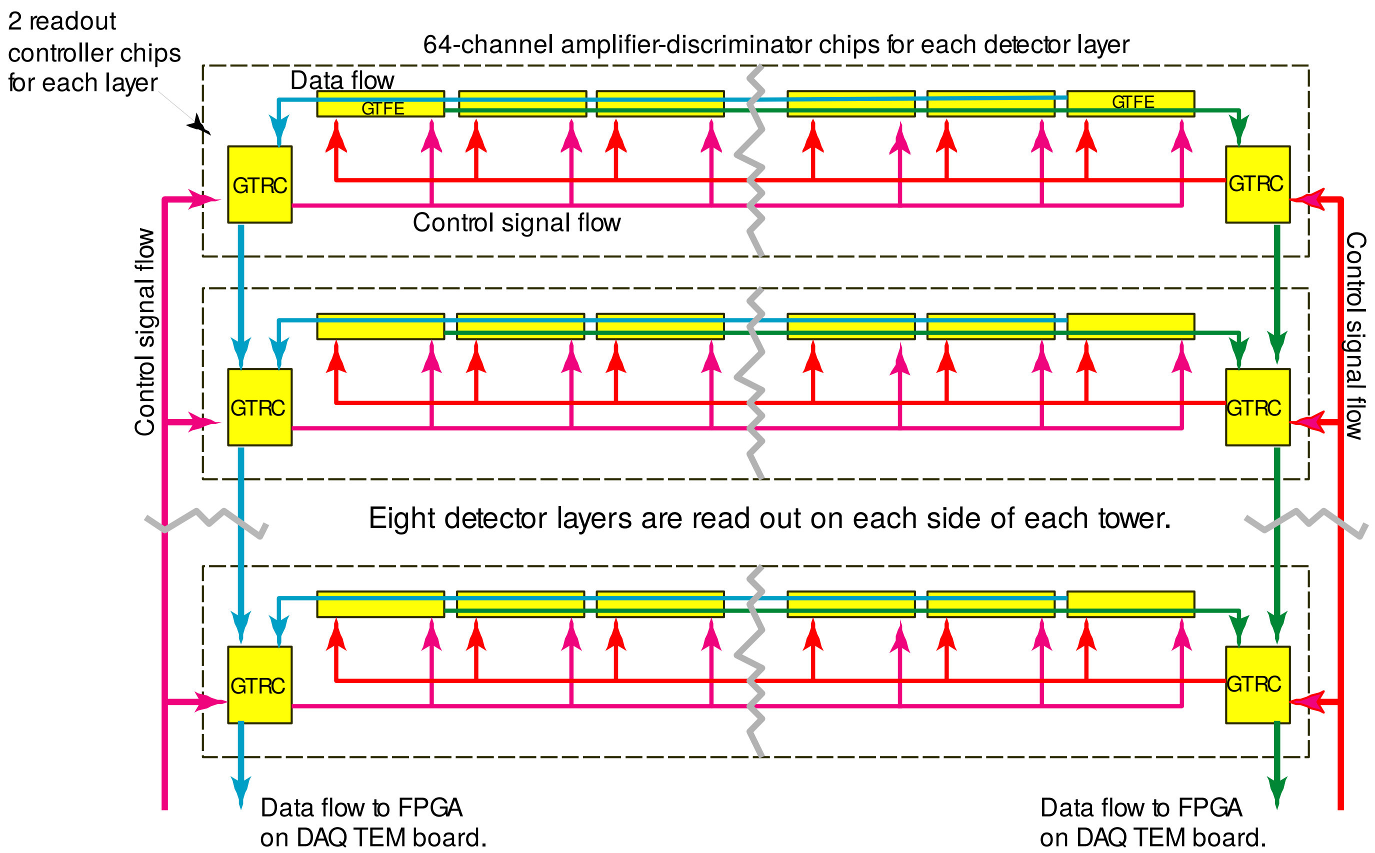
Dependence is reasonably linear up to saturation
Estimate for a MIP: 150 keV in 400um Si
→ ~4·10^4 e-h pairs, or ~7 fC
TOT ~ 8us
Calibration is ~1.6 us/fC

TKR readout

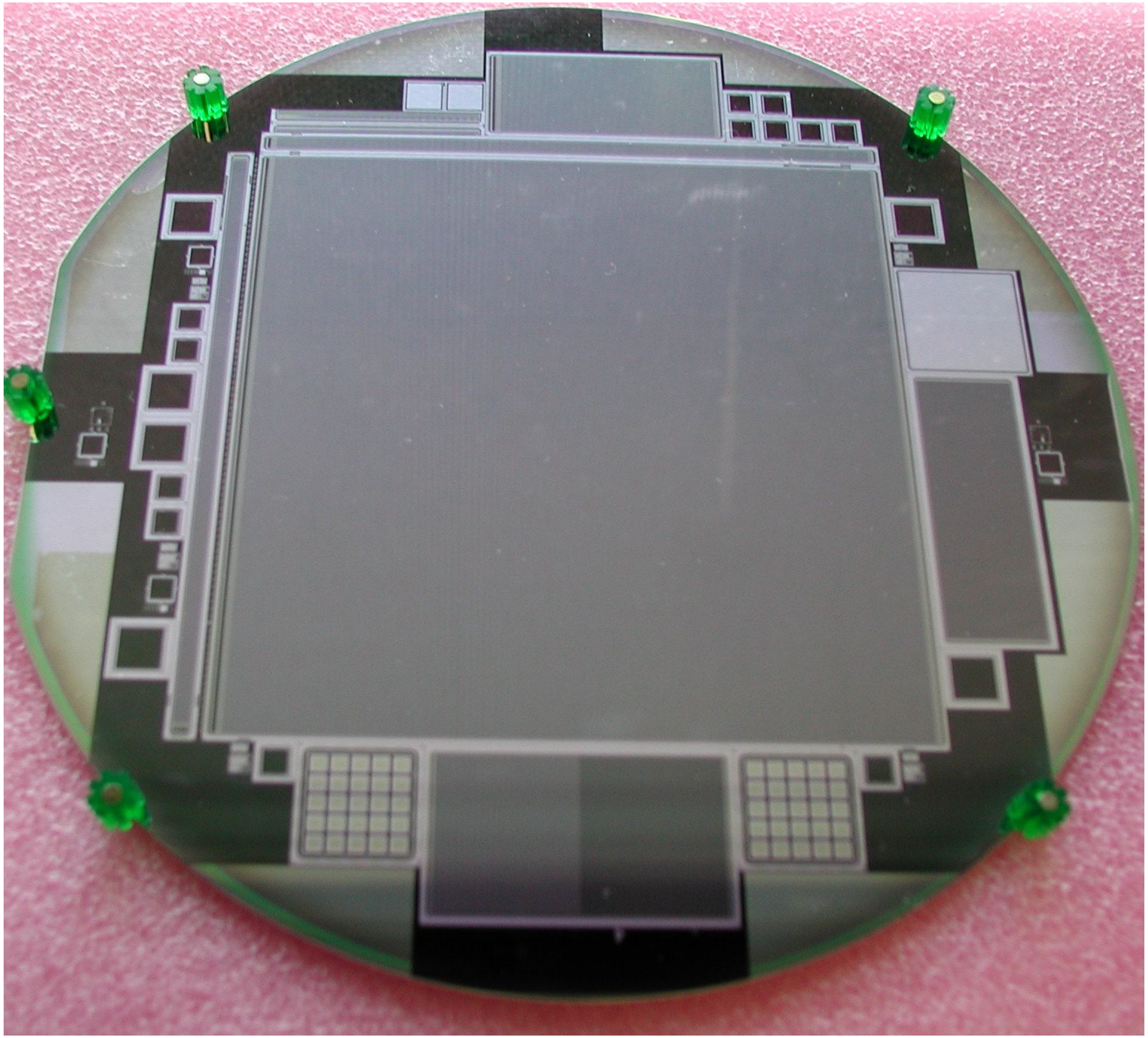
End up with **885k channels**! Long ladder: high input capacitance, noisy!
Go for simple, digital readout with amplifier/shaper/comparator
Require:

- Low power, <300uW/chn
- Self-triggering (fast-OR)
- Negligible dead time @ 10 kHz trigger rate
- Radiation hard
- Redundancy

2 ASICs developed
Analog front-end
Digital readout control



SSD

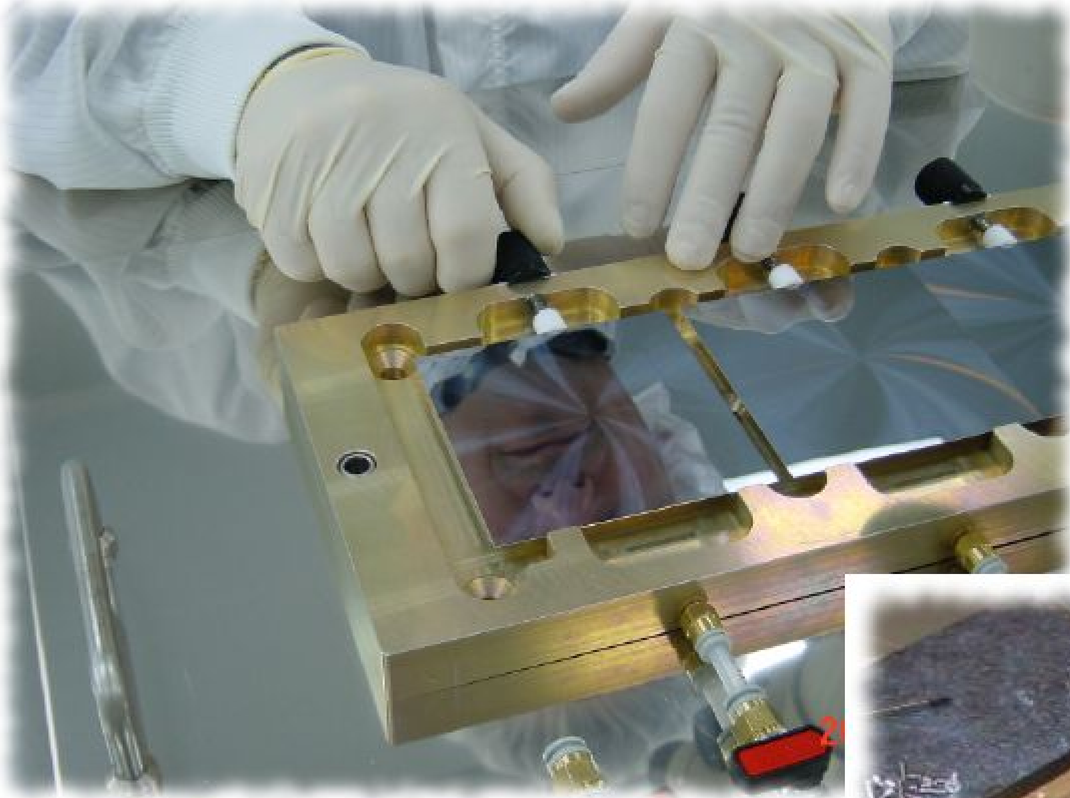


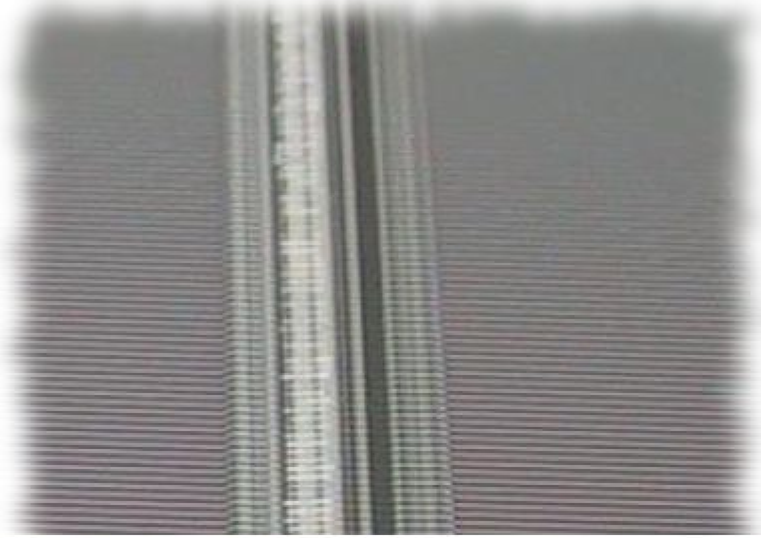
Single side SSD
228 um pitch
400 um thickness
384 strips

Outer side: 8.95 cm
Active: 8.76 cm

Depletion < 120 V

Tracker assembly at INFN Pisa





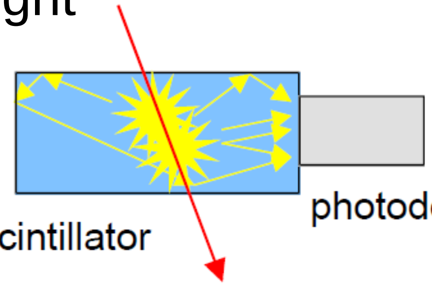
- Wafers glued and wire-bonded in 4×1 ladders.
- Four ladders integrated into a $\sim 36 \times 36$ cm^2 detection plane.
- Composite *trays* providing the mechanical structure and

Assembly at INFN Pisa

Calorimeter: basics

Inorganic scintillating material: convert ionizing energy into light

- High Z
- Up to several 10 photons/keV
- Radiation hard
- Stable in vacuum

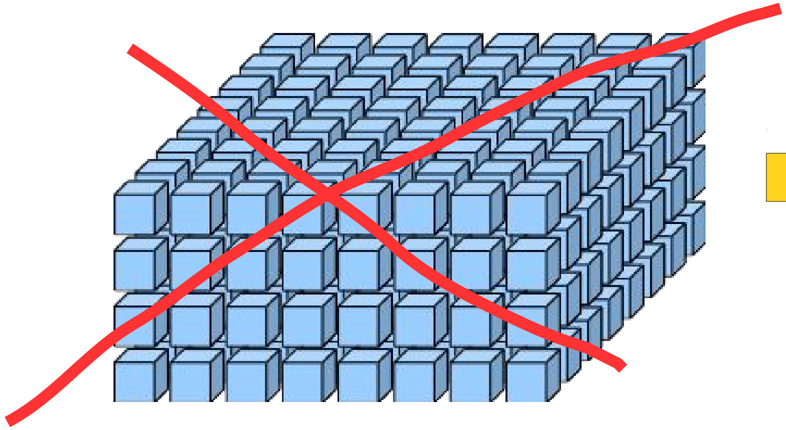


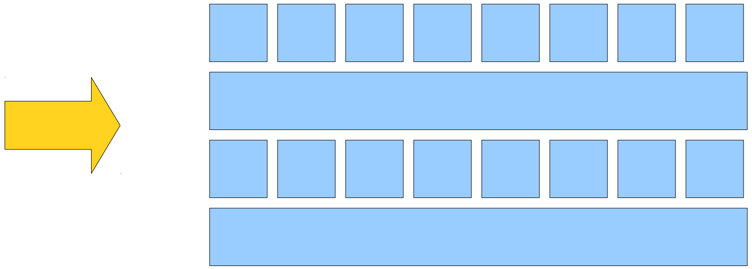
Doping: shift light emission to a wavelength the crystal is transparent to
Brochure for CsI(Tl) from Saint-Gobain:

> ...Because it has no cleavage plane, it is **quite rugged** – which makes it well-suited for well logging, **space research** or other applications where severe shock conditions are encountered. [...]
>
> The maximum of the broad emission is situated at **550nm** [....] Since CsI(Tl) has most of its emission in the long wavelength part of the spectrum, the material is **well-suited for photodiode readout**. CsI(Tl) has a light output of **54 photons/ keV and is one of the brightest scintillators known**. [...] CsI(Tl) is a **relatively slow scintillator with an average decay time of about 1µs** for γ-rays. Electronics with suitable shaping times (4-6µs) should therefore be used. [...] **Radiation damage** of CsI(Tl) scintillation crystals may become significant **above doses of 10 Gray (10^3rad)**. About 10 to 15% light loss has been measured. However, some of the damage is reversible.

Calorimeter: capabilities

Our design forces some additional requirement.
We must image the shower development, to calculate the fraction of energy leaking out (we are limited in depth, and modular structure comes at the cost of a lot of gaps).
Hodoscopic design: less channels and less leaks wrt cubes

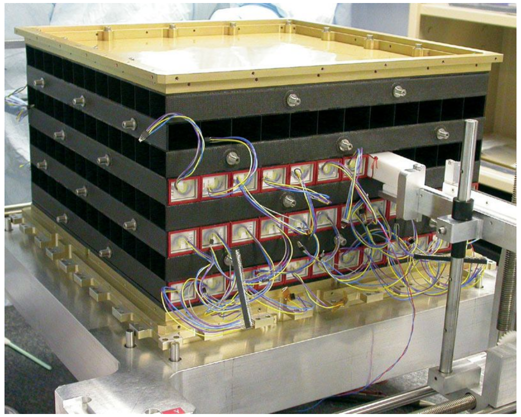




[...]

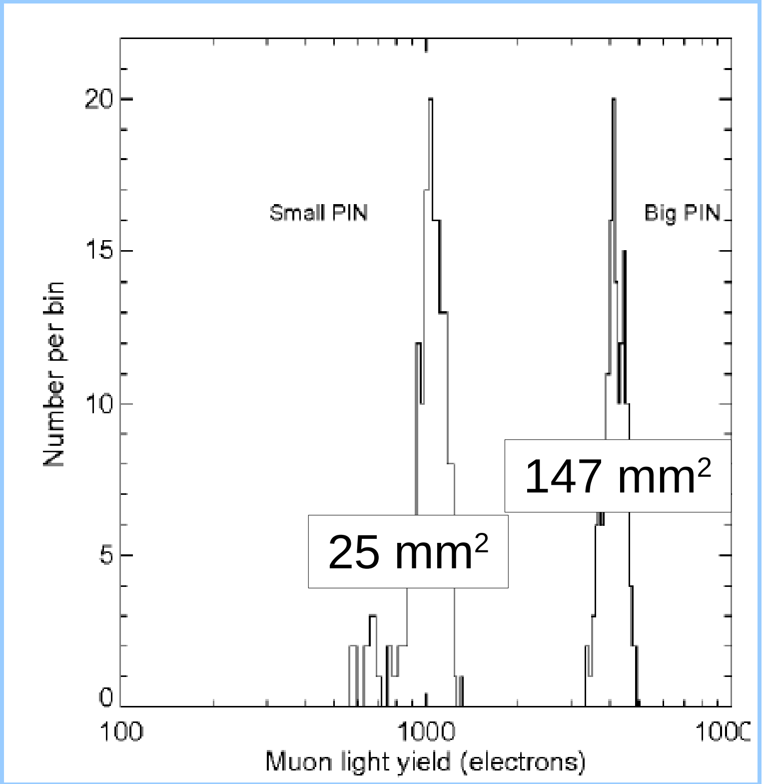
Crystals: 2.7x2.0x32.6 cm^3
8 layers: 8.5 X_0 normal

CsI	
D (g/cm^3)	4.51
X0 (cm)	1.86
Moliere r (cm)	3.53
MIP (MeV/cm)	5.6
Z	55/53

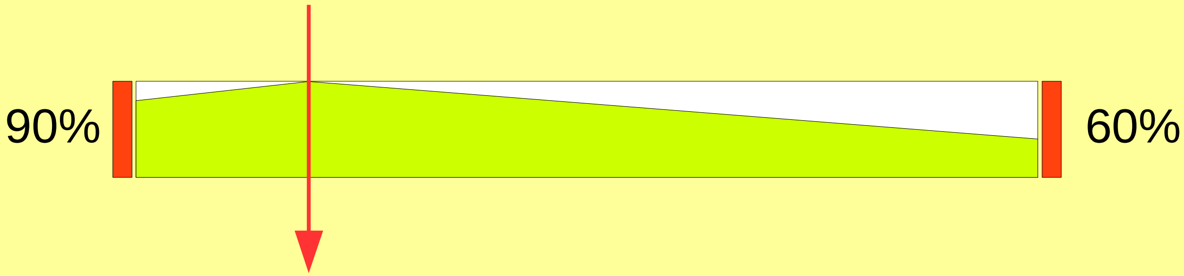


Light readout

Energy range is really large (>4 orders of magnitude)
Readout with 2 photodiodes: large area for small signals, small area for large signals
2 different gain paths in the electronics (LO-G/HI-G)
Cover ~2 MeV to 70 GeV deposit!

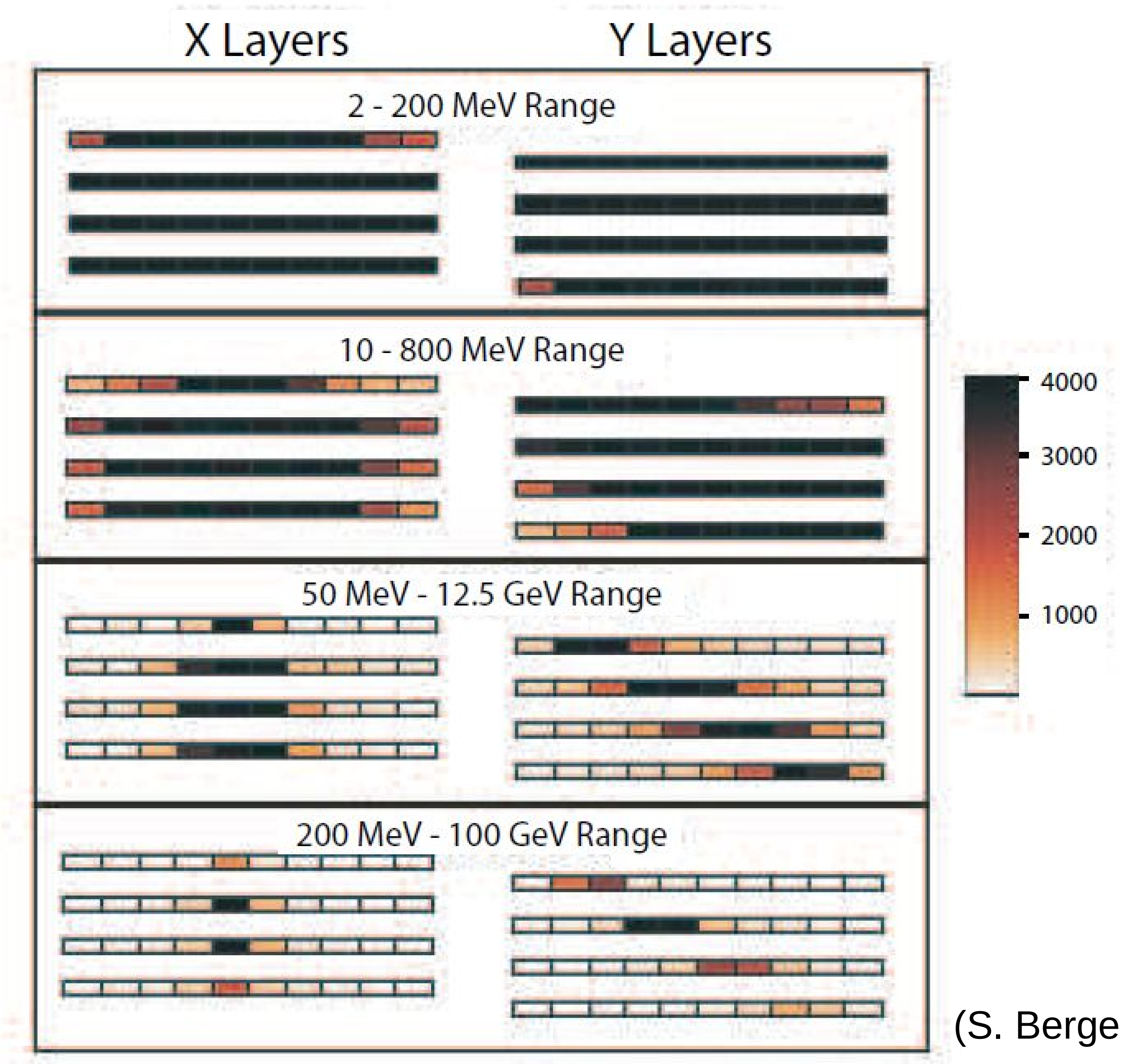


Reconstruct the peak of energy deposition along the crystal with "light tapering"
Readout at both ends, if light is lost along the way one can reconstruct the location of the initial emission by the asymmetry
Exaggerated:



Crystals are scratched to damage one long face, before being wrapped in reflective foil

Readout

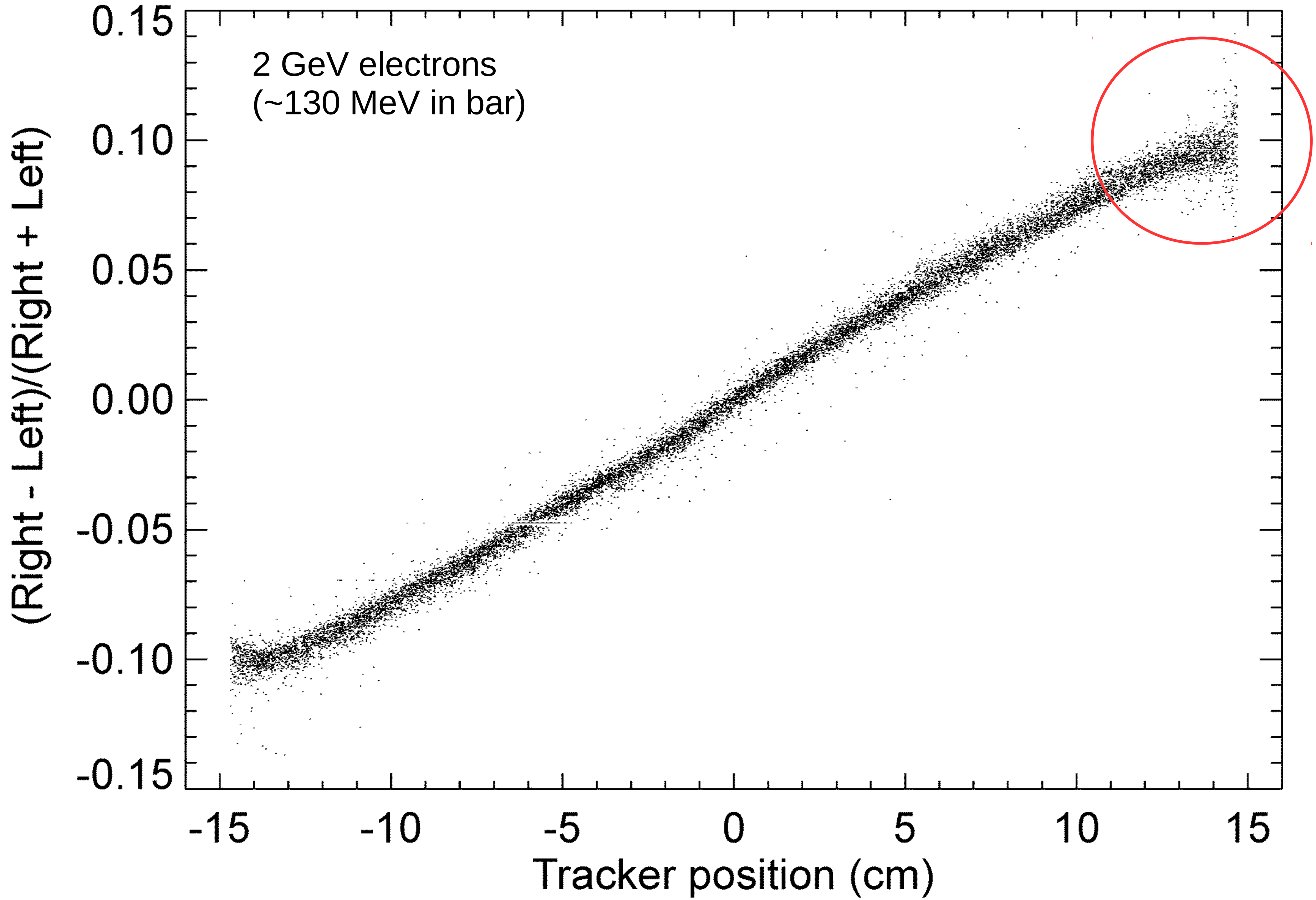


Readout of the same event (pulse of 20 GeV electrons, releasing ~300 GeV) with the 4 readout ranges

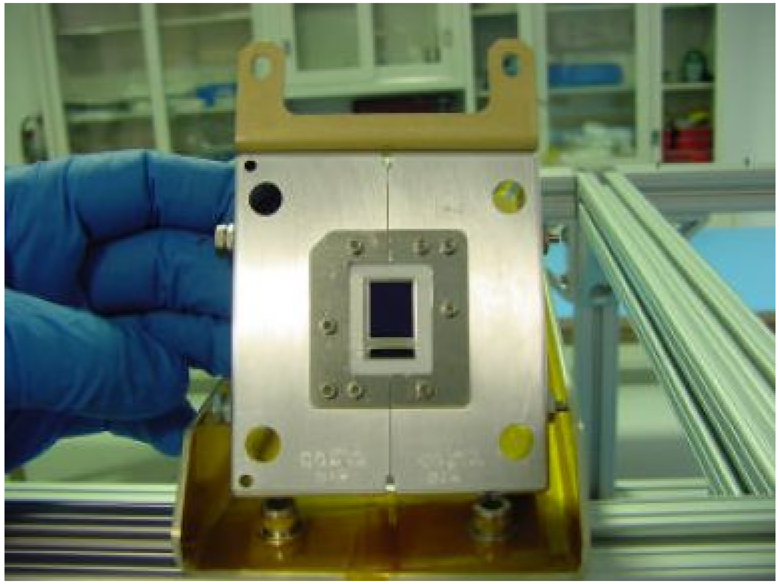
In DAQ, the highest-G non-saturated channel is selected

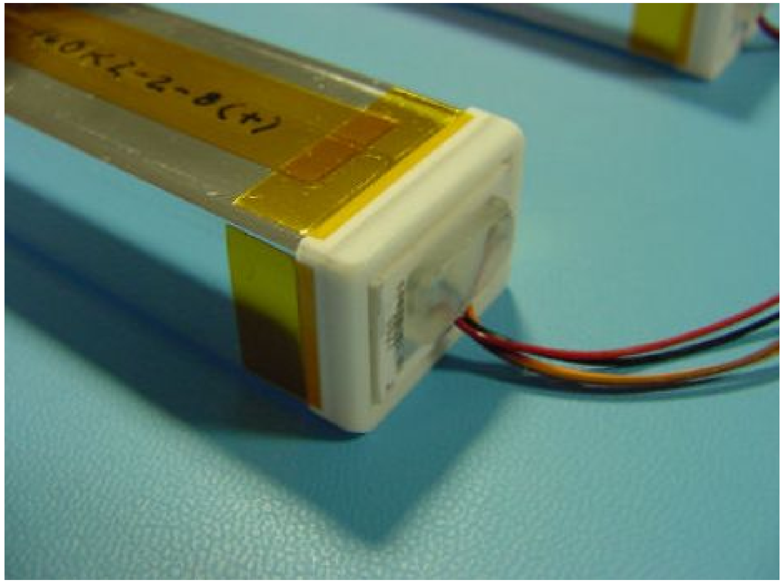
(S. Bergenius)

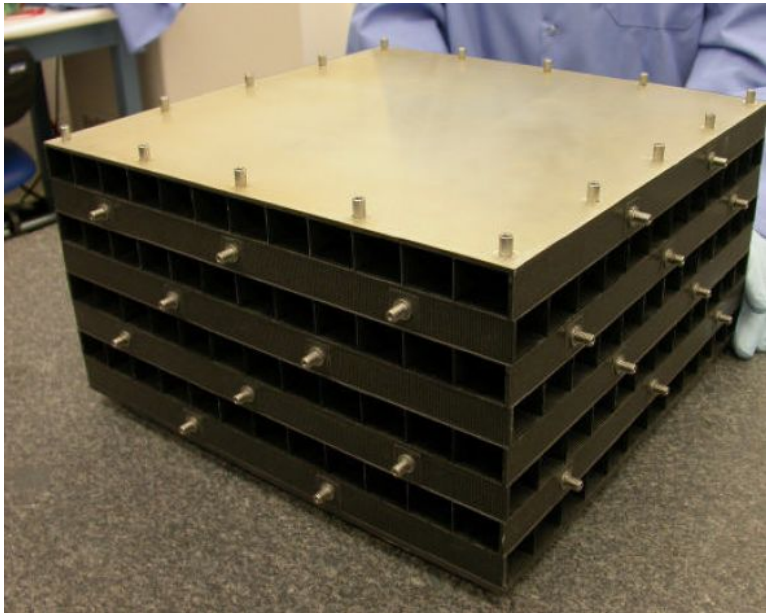
Light tapering

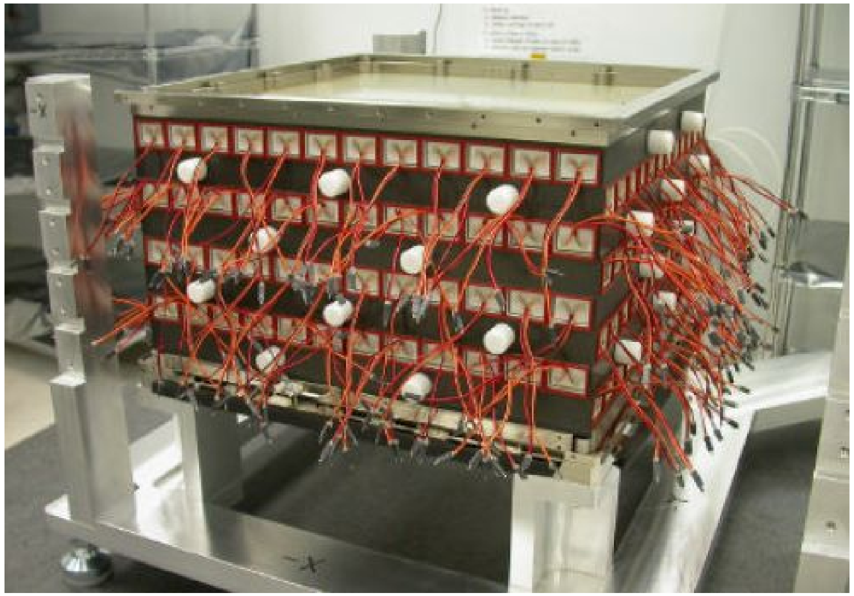


CAL assembly







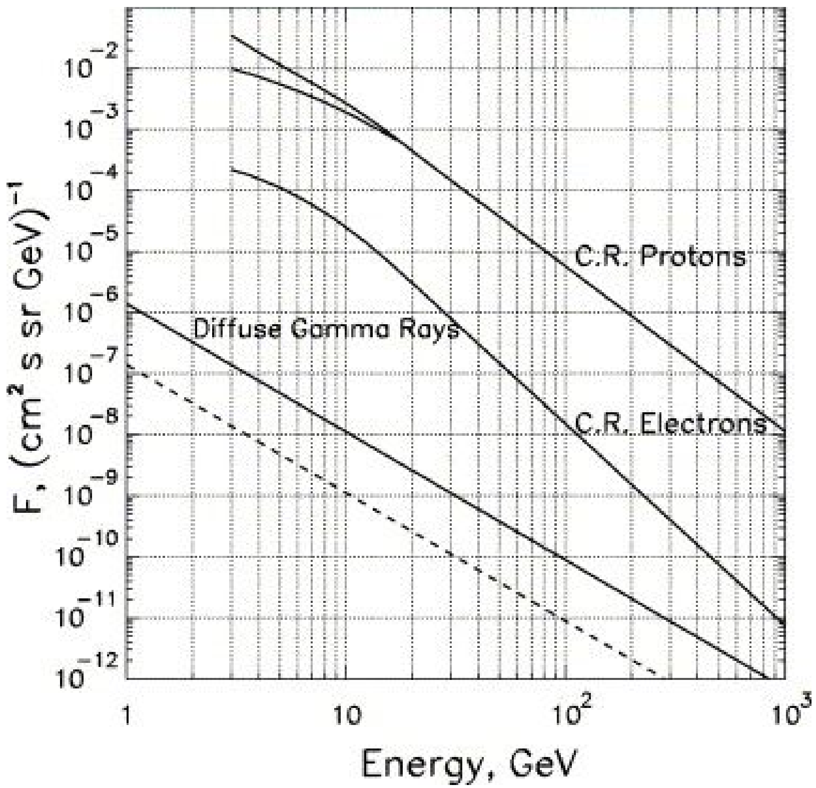


Signal and background

In the LEO, CR fluxes surpass gamma ray flux by a few orders of magnitude (3-5)
From the operational point of view:

- The telescope is **busy acquiring useless data**
- We transmit **garbage to the ground**

Protons are a lot (need a suppression 10^6) but **pattern** in TKR and CAL can be used to reject some (say a factor 10^3 in ACD and 10^3 in TLR+CAL)
Electrons are particularly worrisome: the EM shower is identical to a gamma, rejection is hard to impossible once inside the TKR
ACD must provide 10^4 suppression
Some help can come from TKR: tracks can be **extrapolated** to obtain the passage point through the ACD and match this with known regions of lesser efficiency (but angular resolution sets a limit). This **can be done on-board**!

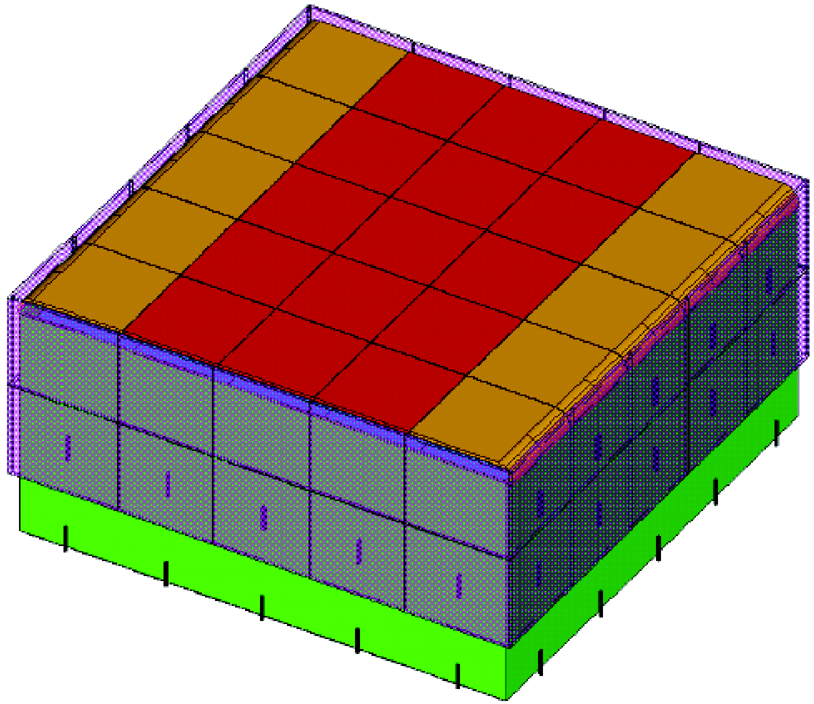


(Est. prior to launch)

Segmented anticoincidence detector

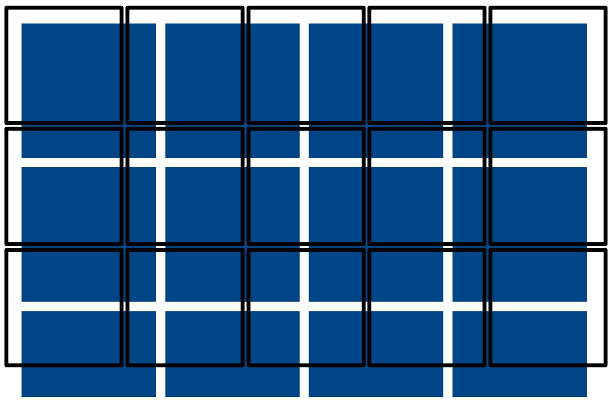
Plastic scintillator: inexpensive and reliable, can be machined in complex shapes
WLS fibers are embedded in the plastic tile, brings signal to a PMT
Well known technology:

- Large (LAT sides: ~8.6m^2)
- High-efficiency (~0.9997 avg.)

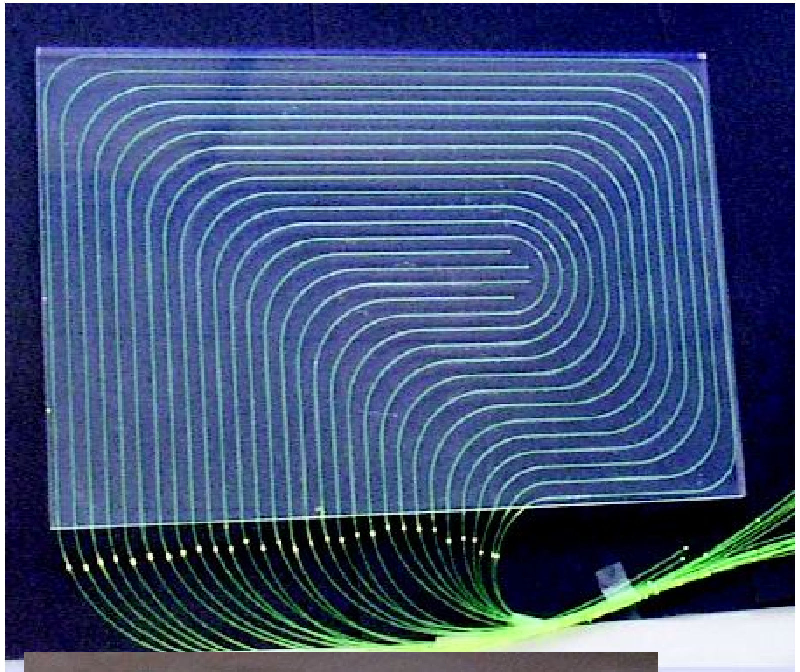


One known issue is the presence of CAL
Large mass of dense material (1.8 tons)
Lots of secondaries produced in the shower
These can escape and reach the ACD
→ **backsplash**
EGRET: effective area at 10 GeV down by a factor 2

Solution: **segmented** ACD
Also: modularity once again: every tile is individually sealed: a puncture can disable 1 at most
NB: 5x5 → does not match the 4x4 tower segmentation! Avoid risky alignments.

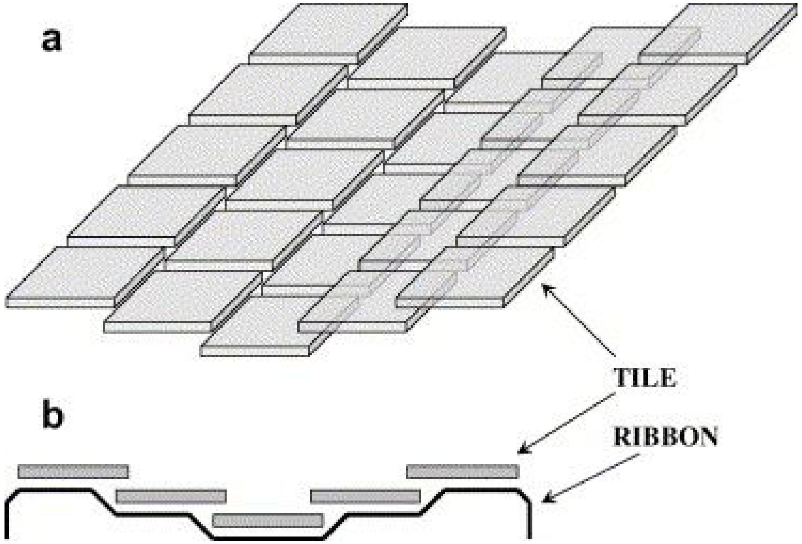


ACD tiles and ribbons

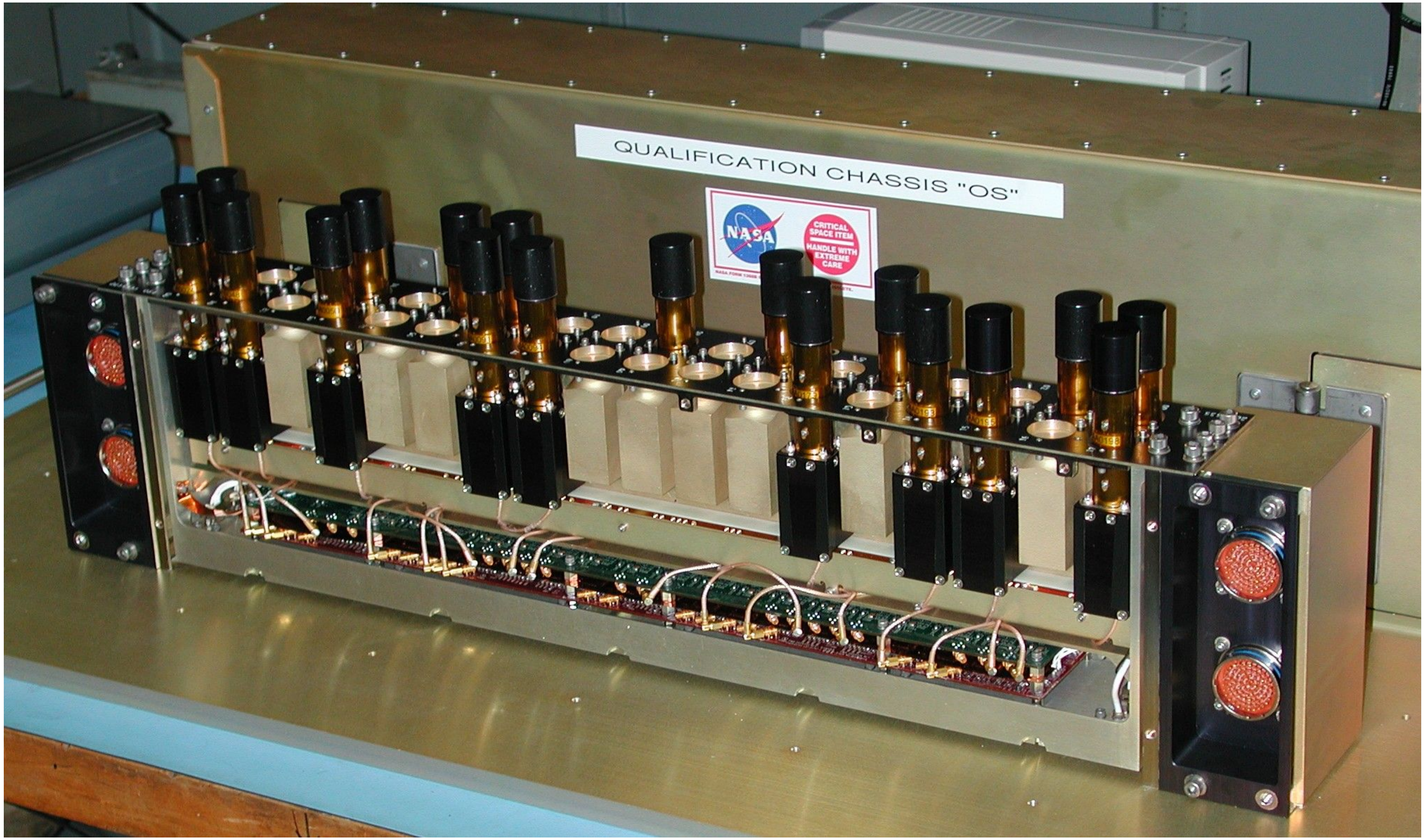


Thickness:
10-12 mm

Light yield of ribbons is low (8 phe per MIP vs ~20 for tiles)

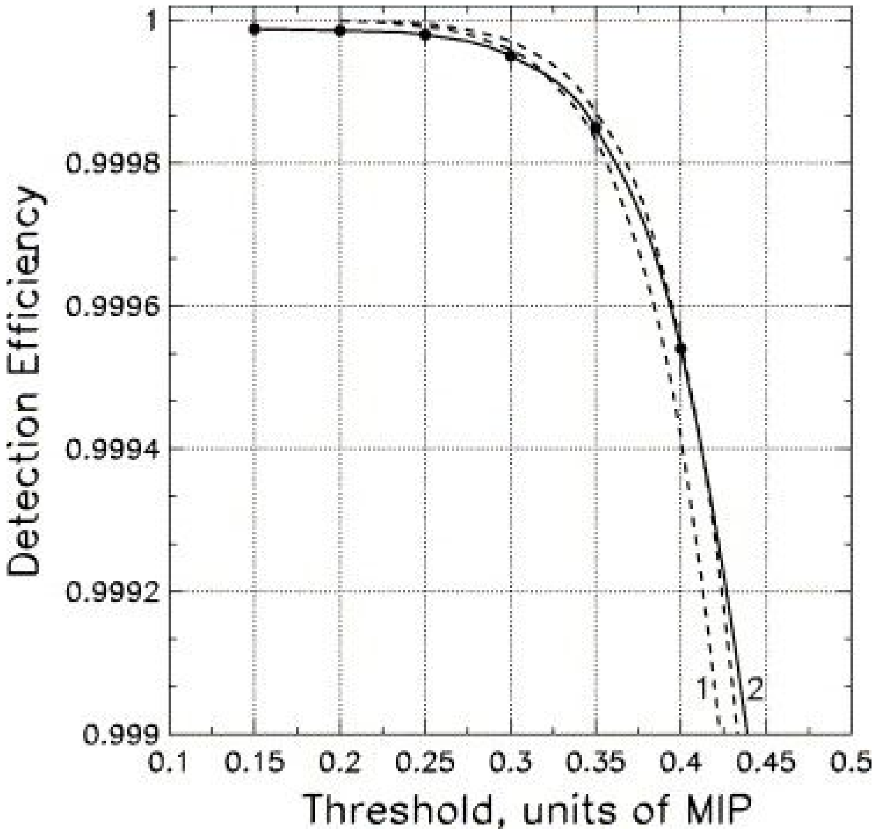


PMT readout

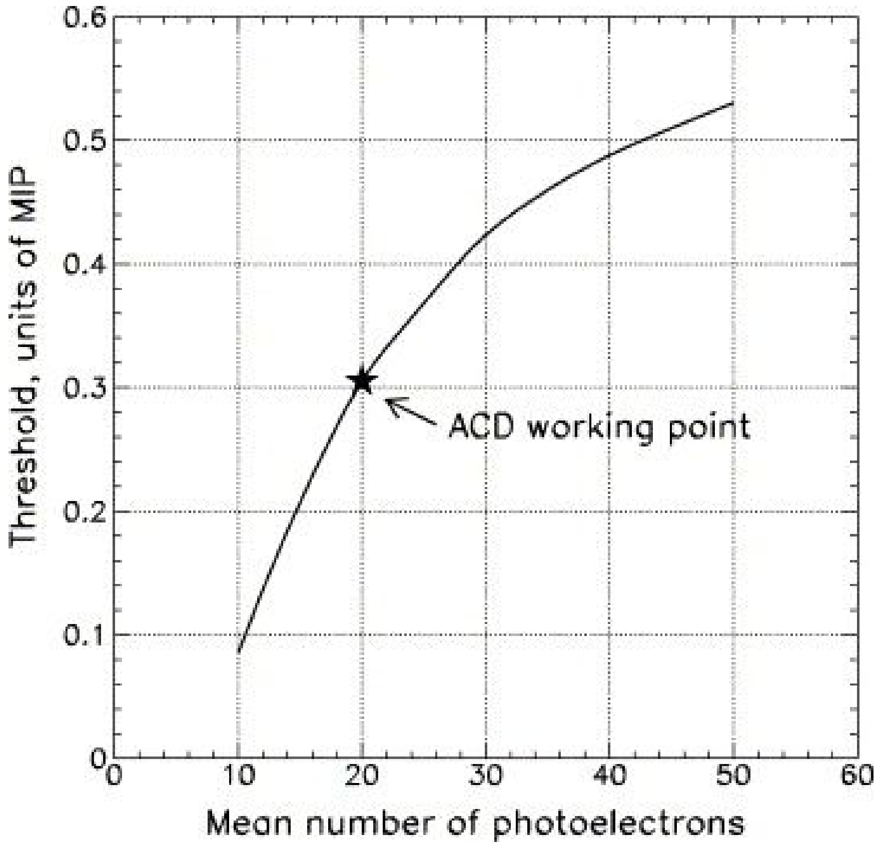


Away from the instrument aperture

Tuning the readout

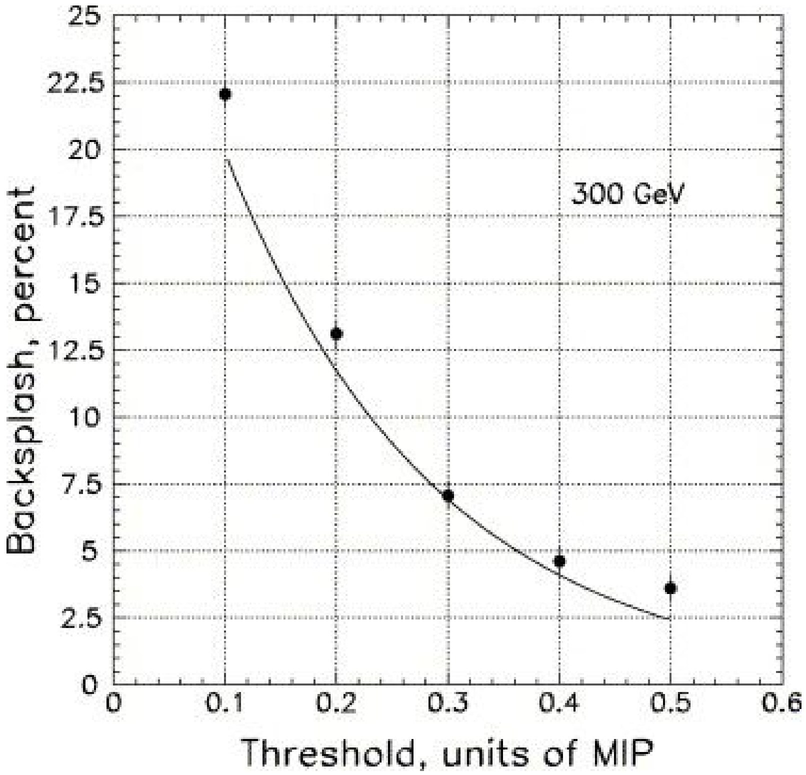


Threshold sets the efficiency

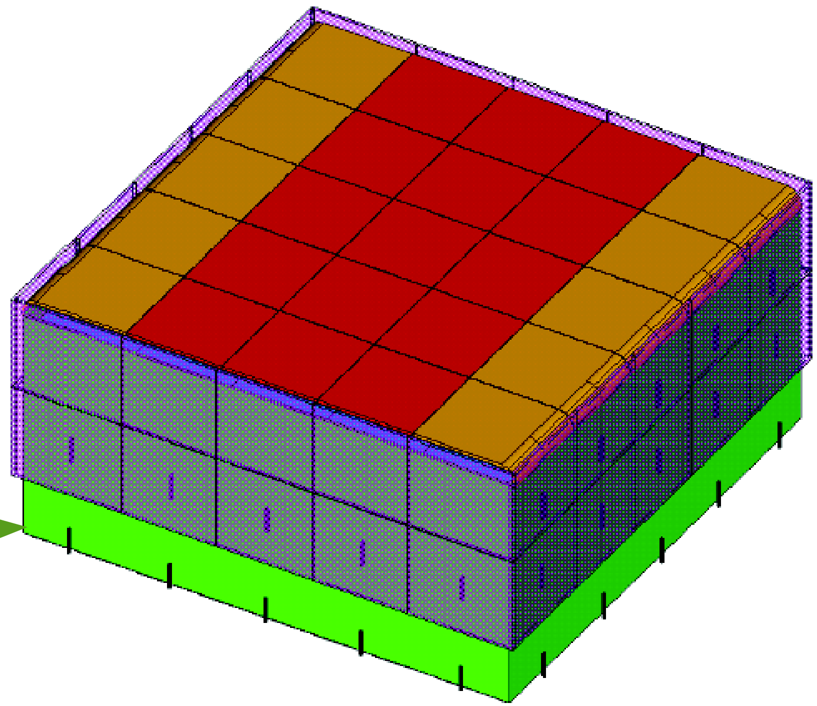


Gives no of photons needed at each PMT

Tuning 2

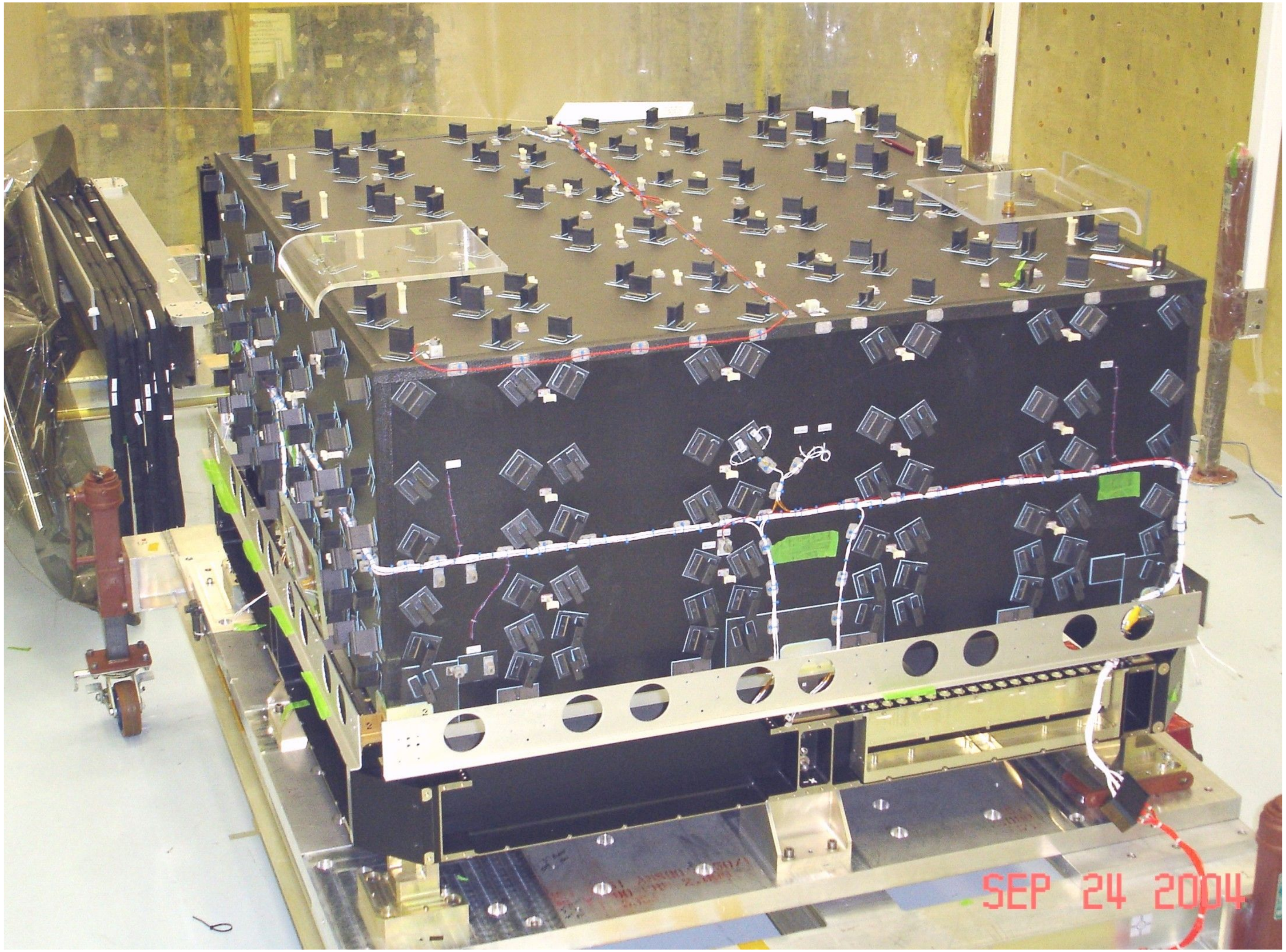


Check impact of backsplash
Depends strongly on tile size!



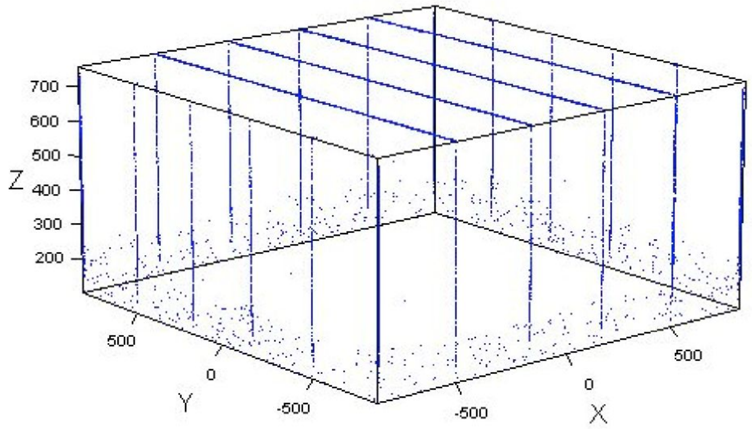
These are outside the design FOV: no event passing through here would be accepted

ACD



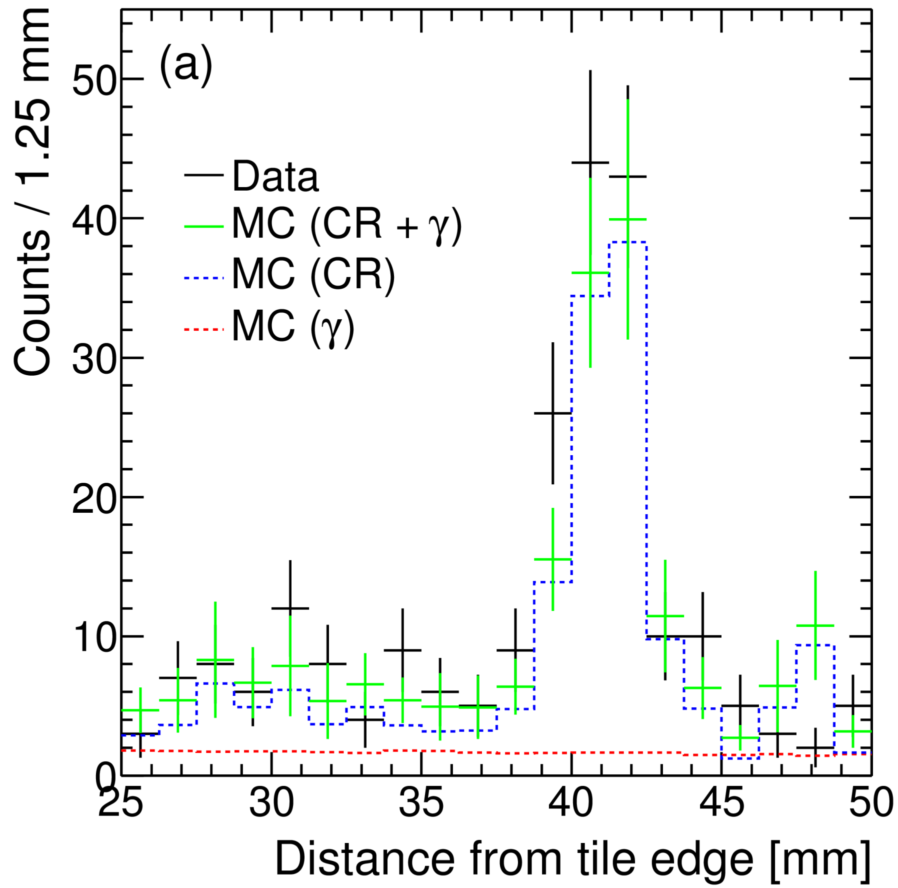
Hermeticity

As we turn the handles to enforce **hermeticity**, we see all (small) ACD inefficiencies (How effectively we can do this is a determined in part by event analysis)



MC simulation of events sent to ground: entry points of hadrons on the ACD box when **no background cuts** are applied (only on-board)
The gaps where ACD is not overlapping show (this is the small fraction of events that manage to pass the ribbons)

Extrapolated hit point on ACD: distance from border of tile, standard event class cuts applied. Peak corresponds to mounting bolts.



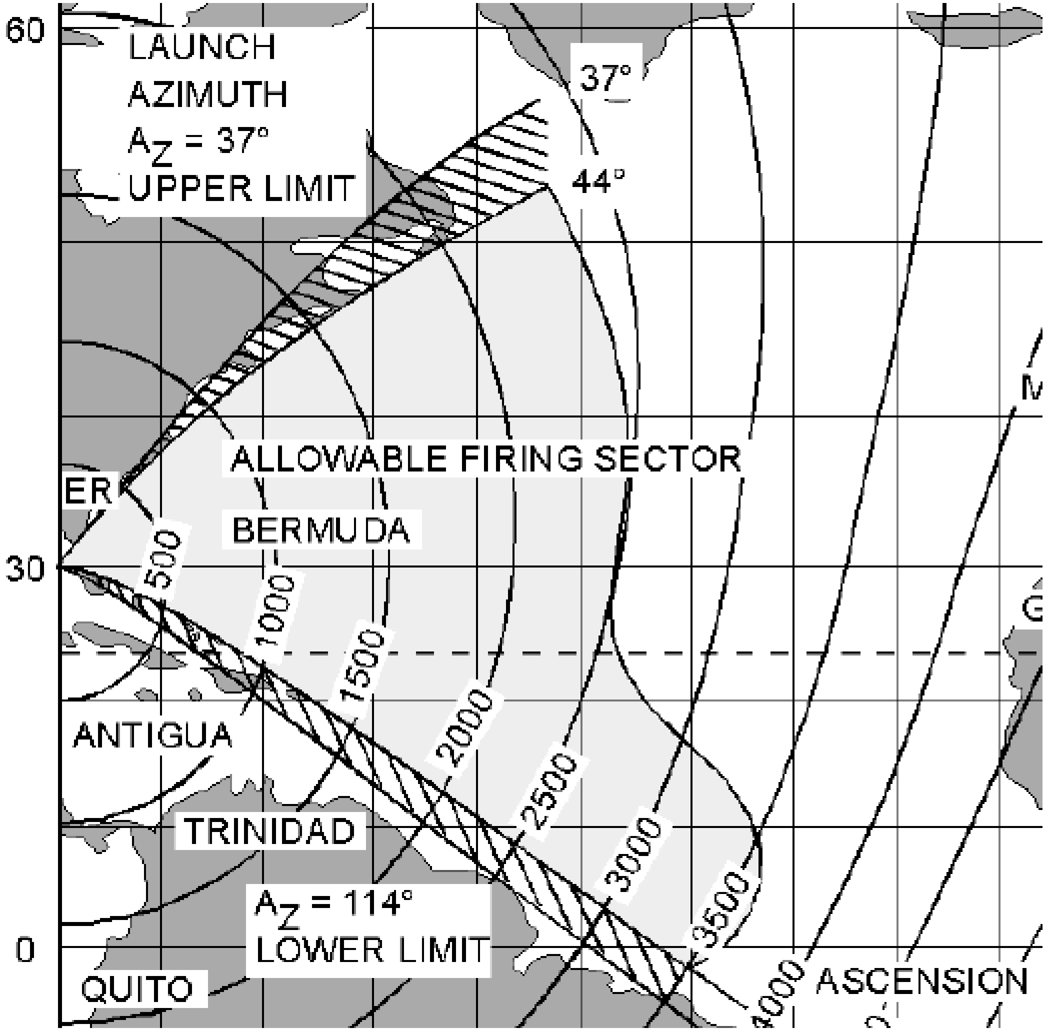
On the spacecraft

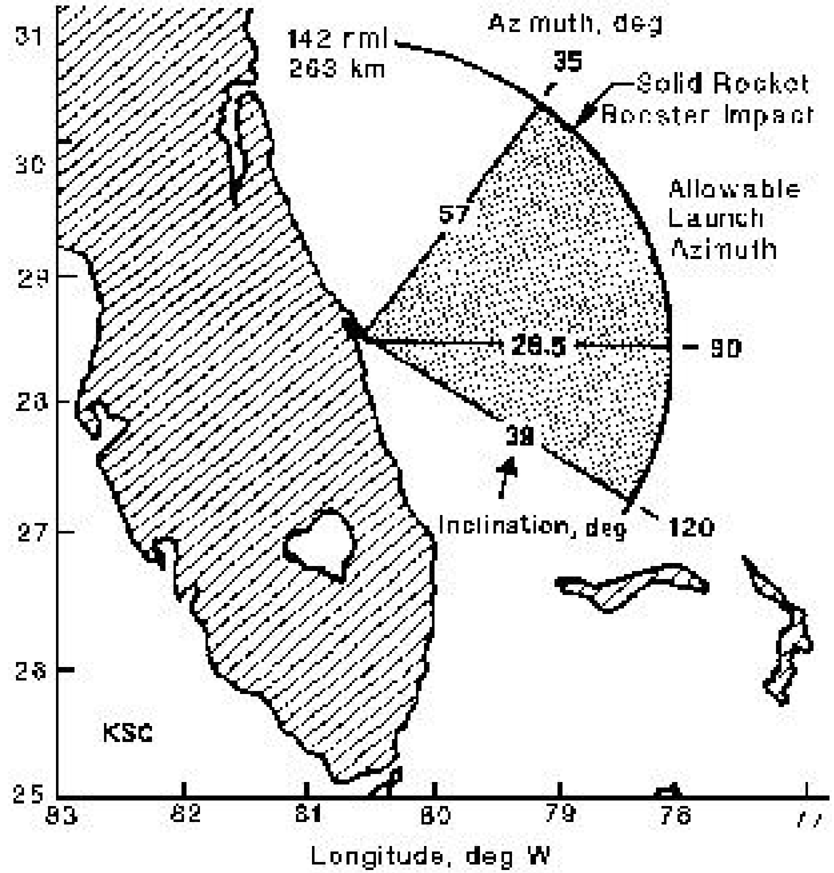
Loading

Inside fairing

Launch

Orbit: circular 565km, 25.5° inclination





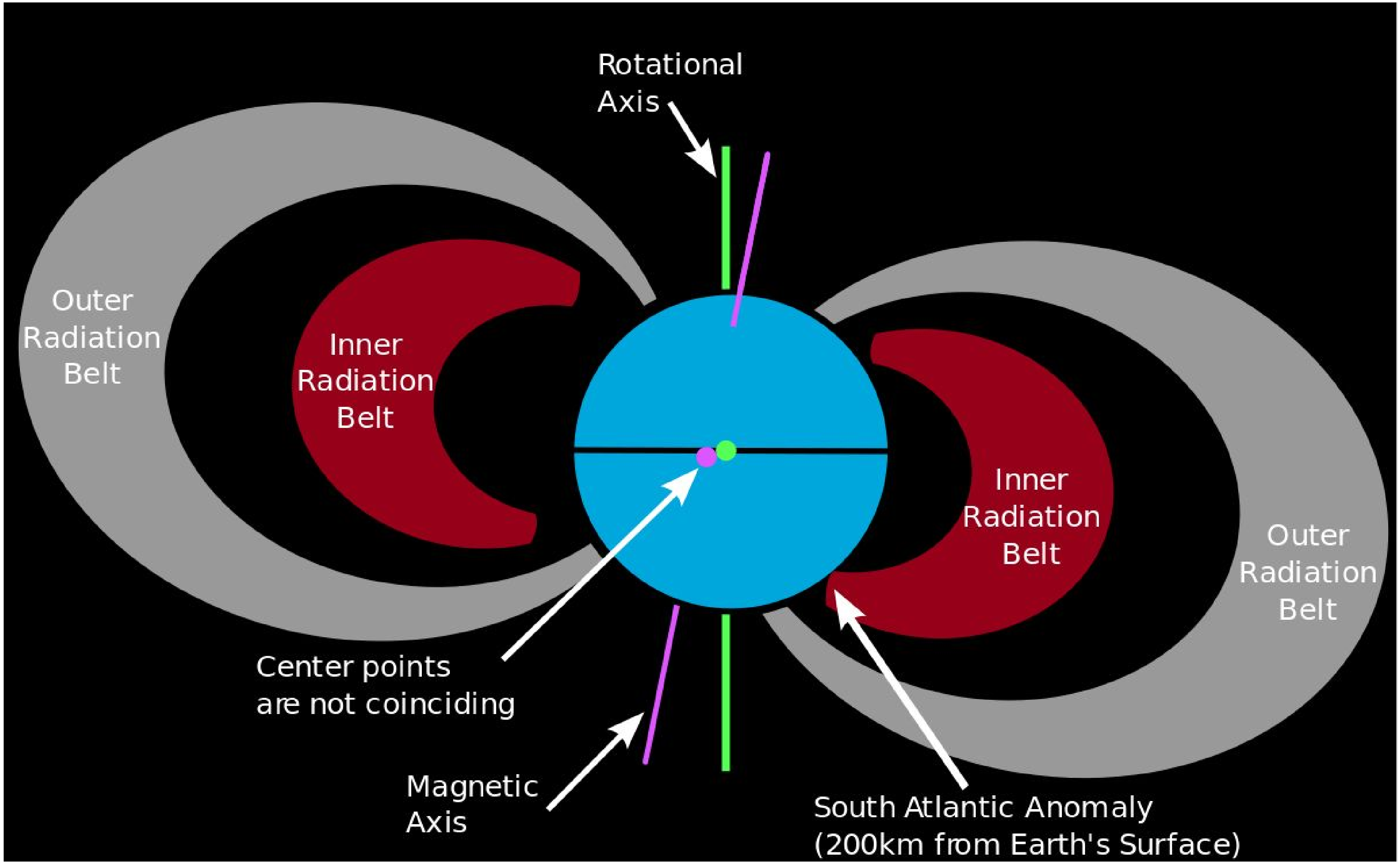
$$\cos(inc) = \cos(lat) \cdot \sin(azi)$$

With no maneuvers, minimum inclination is equal to latitude of launch site

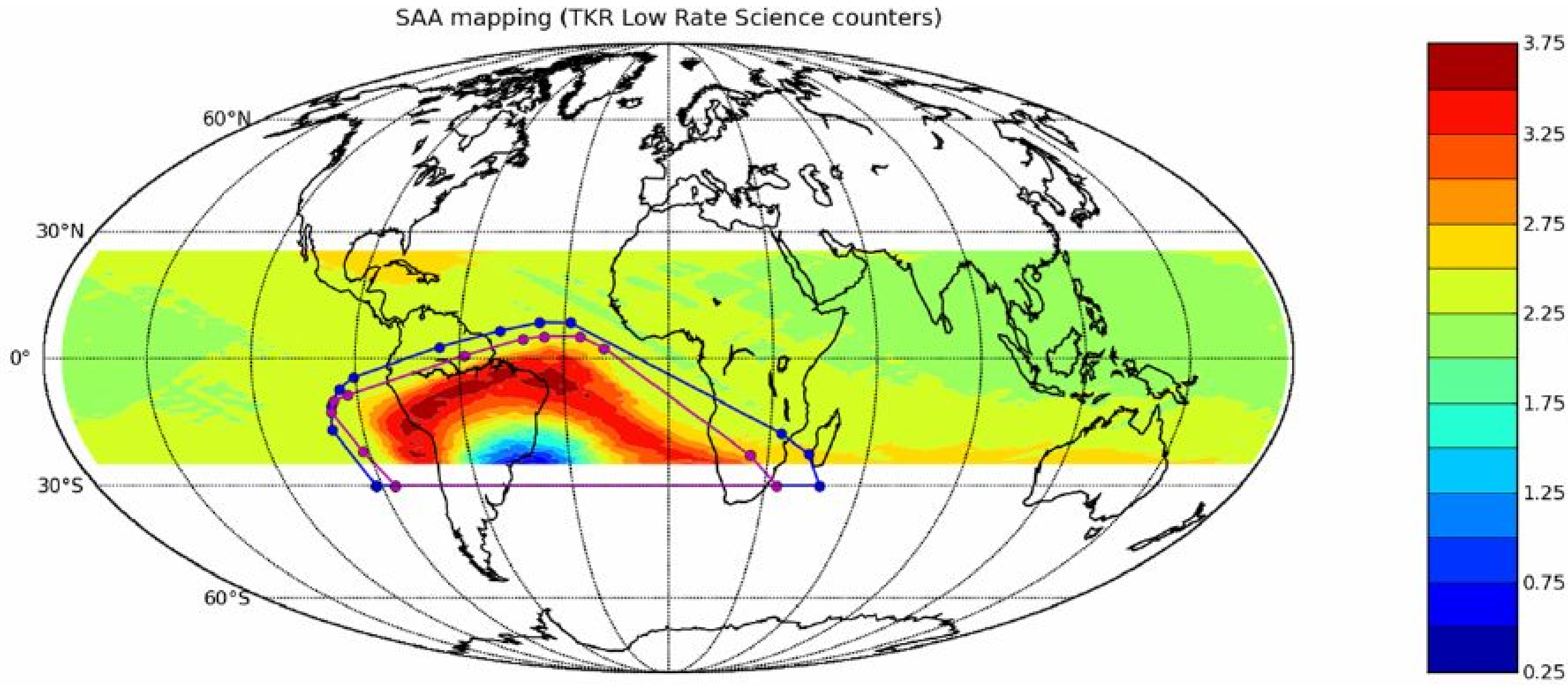
Orbit inclination was corrected to 25.5 deg, using every last drop of fuel

Impact of inclination

Impact of inclination mostly due to SAA
Region where magnetic fields are lower: more energetic particles
LAT HV supplies are turned off (some counters still operate)

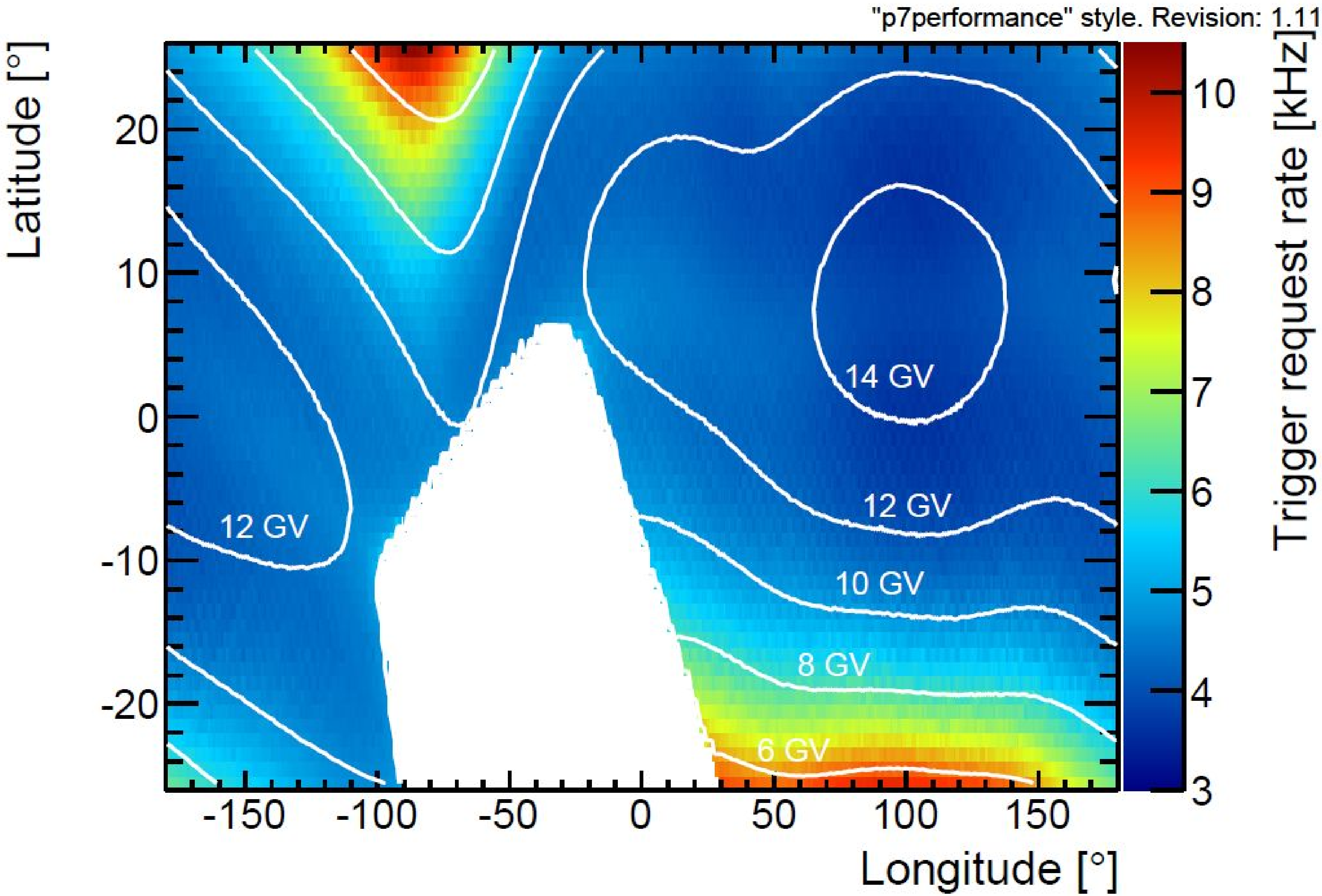


Trapped particles: SAA

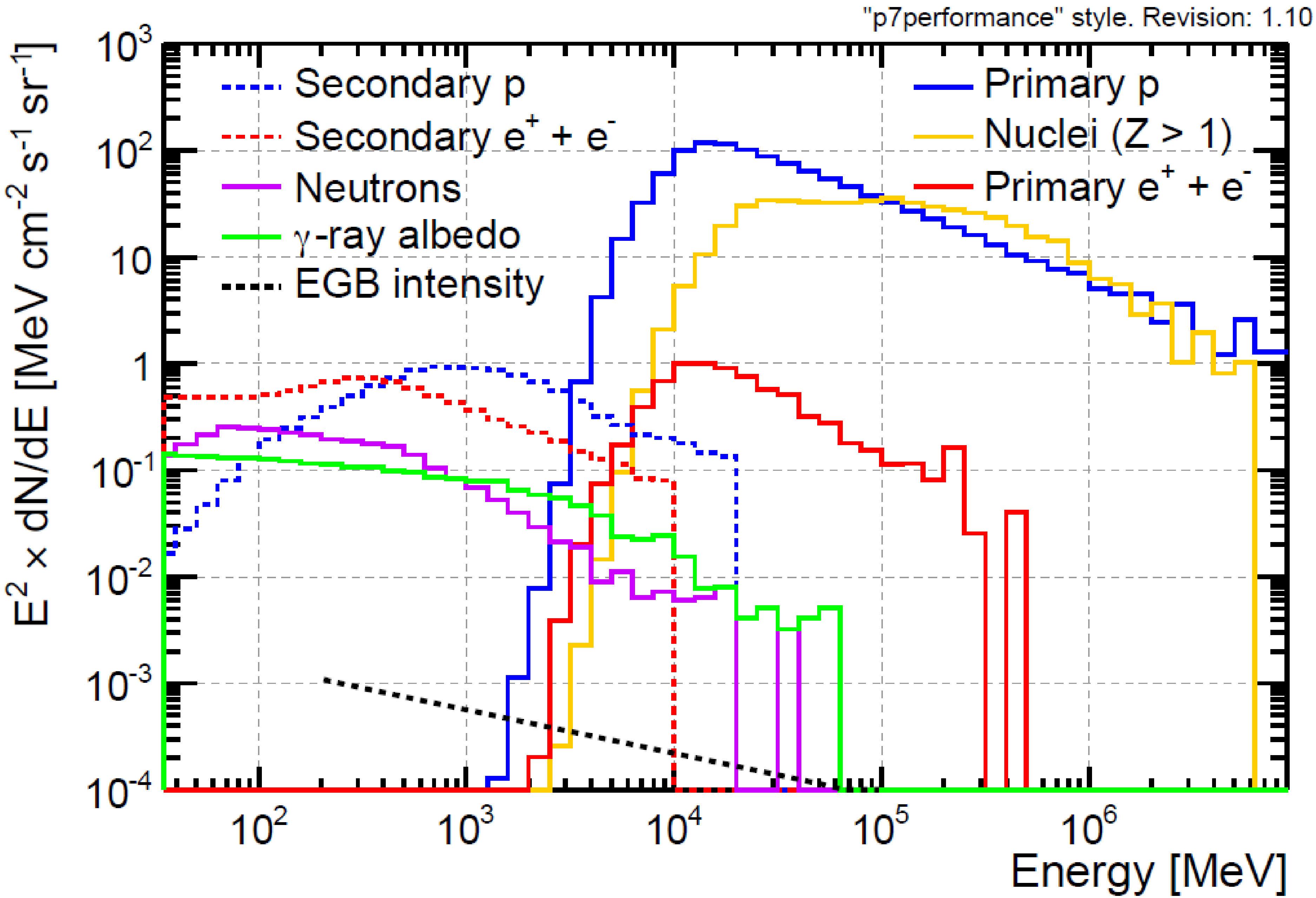


- The South Atlantic Anomaly is a region with a high density of trapped particles (mostly low-energy protons)
- We do not take physics data in the SAA (ACD HV is lowered) but we do record the trigger rate from CAL and TKR
- The mapping of the SAA was one of the goals of the commissioning phase, now routinely monitored

Primaries: geomag cutoff

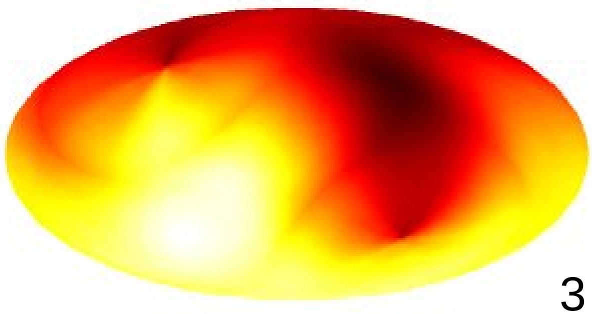


Background model

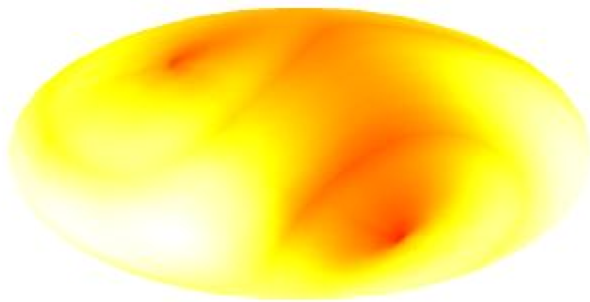


Gamma telescope: uniformity of exposure

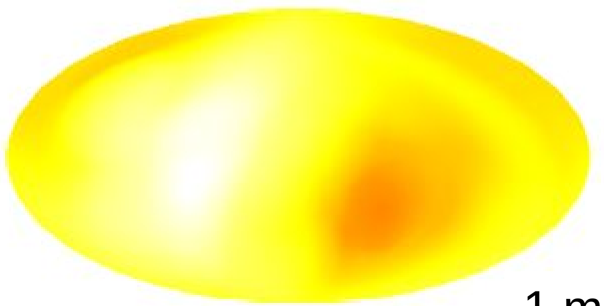
With no use of reaction wheels all sky is covered in 1 month
Need a **slew scheme to ensure good coverage of the sky** on short time scales!
Rocking: half orbit pointing northwards, half pointing southwards
Angle is a compromise
Initial: 35°, good coverage of N/S poles



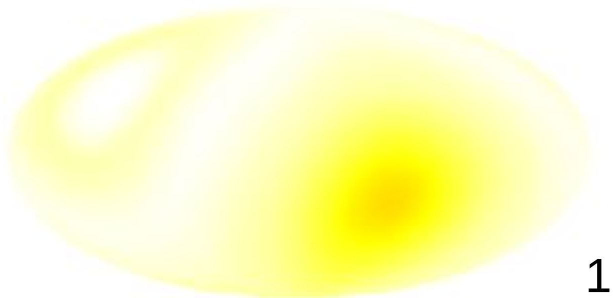
3 hours
(2 orbits)



1 day



1 month

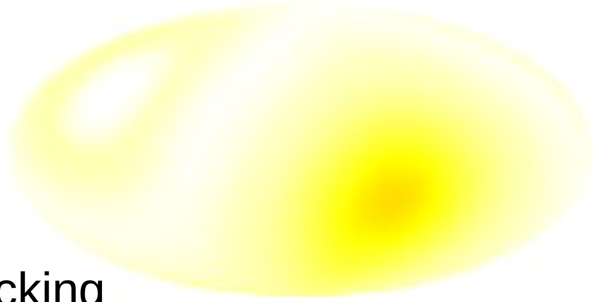


1 year

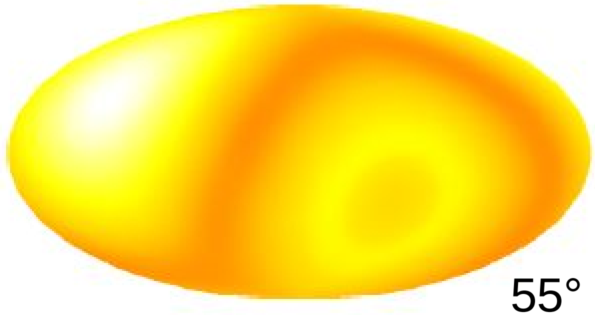
Underexposure of south pole is due to SAA

Exposure 2

Radiators and batteries on the back need pointing away from the bright Earth
Rocking was corrected to 50 degrees for a better cooling



1 year
35° rocking



1 year
55° rocking

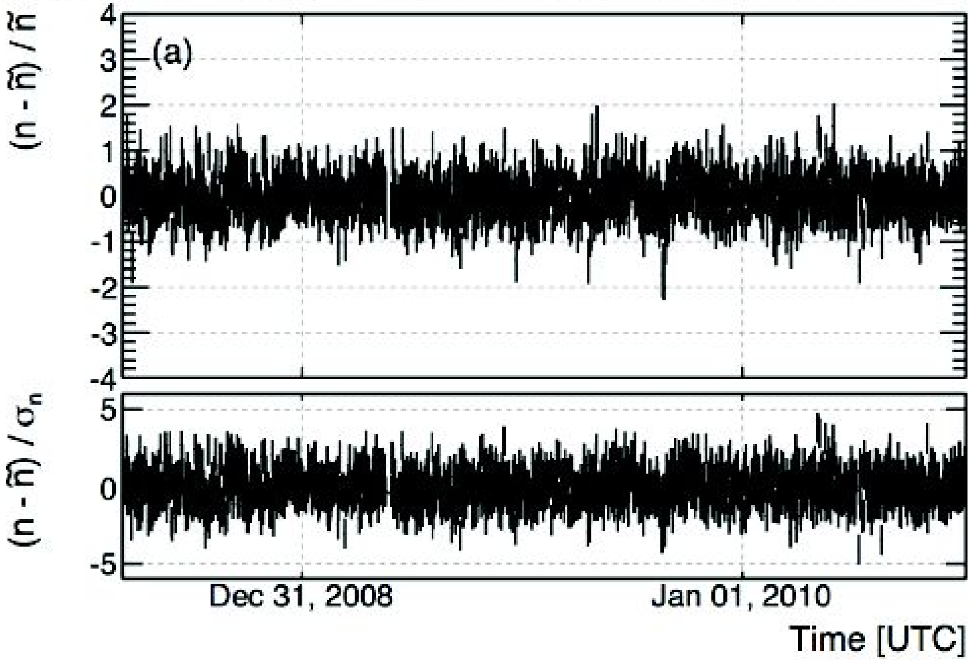
Equatorial region is a bit underexposed now (x2 dis-uniformity approx)
Still acceptable

Orbit and timing

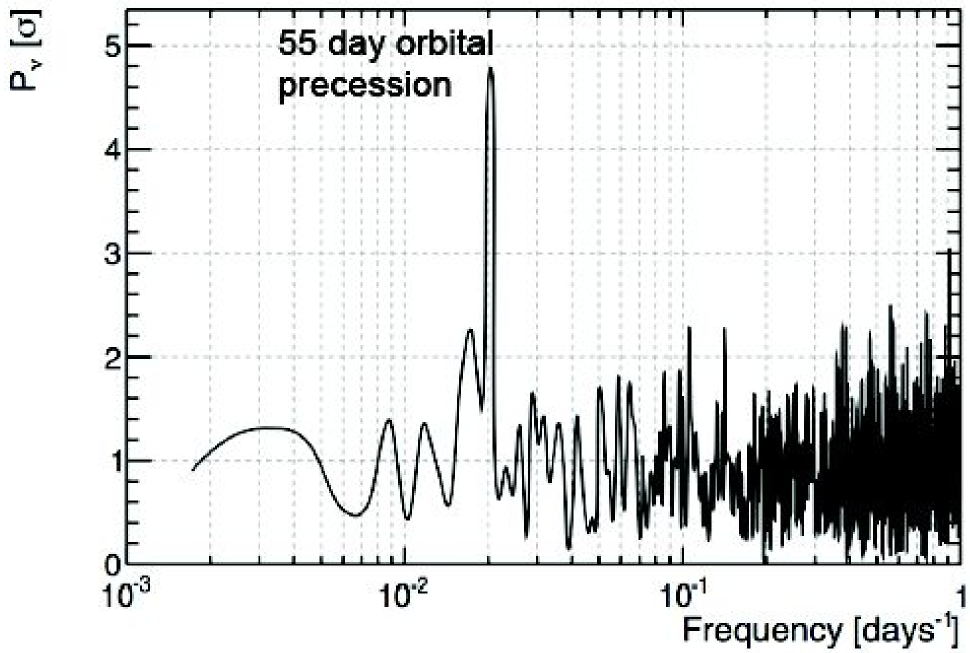
Orbit plane precedes around poles with period of ~55 days
Fermi attitude evolved accordingly: e.g. to keep solar panels pointing to the sun
Usually, small effects are ignored if they average out
This can cause a modulation in time analysis though

E.g. Vela: very bright, steady point source

Residuals from Vela pulsar flux measurement



Fourier spectrum of residuals

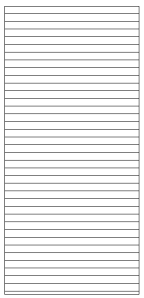


Trigger

Not one single trigger logic, need more flexibility
Each subsystem defines **trigger primitives** (“trigger requests”)
A table of allowed t**rigger conditions** is defined based on these
Each can be “prescaled”: accept only every n-th event

Several **channels**: gamma rays of course, but also ions for calibration of CAL,...
To keep in mind: after trigger minimum dead time is ~26 us, possibly much more

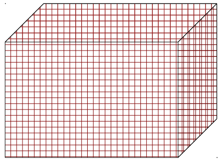
Trigger primitives:



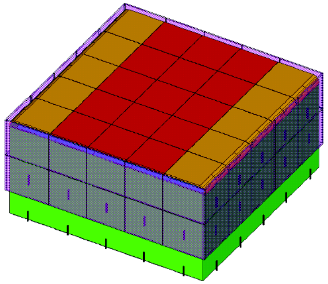
TKR: three x-y planes in a row (That's why the last 2 planes are without W converter: there would be no trigger

Ex. table	**Tr req 1**	**Tr req 2**	**Tr req 3**	**Tr req 4**
TRIG 1	Y	*	N	*
TRIG 2	N	*	*	Y
TRIG 3	Y	Y	*	*

Trigger 2



CAL_LO, CAL_HI: two thresholds for Edep
Low/high energy deposit in crystal (configurable, nominally 100 MeV & 1 GeV)



ROI: mostly used as veto
Each tower has a few “shadowing” ACD tiles assigned. If signal in those, raise veto
CNO: signal is compatible with passing ion (e.g.: C,N,O,...)

In addition 2 special ones, for diagnostics (not used in physics triggers):

- Sollicited, at beginning and end of a run
- Periodic, nominally 2 Hz

Example of 2 trigger engines:

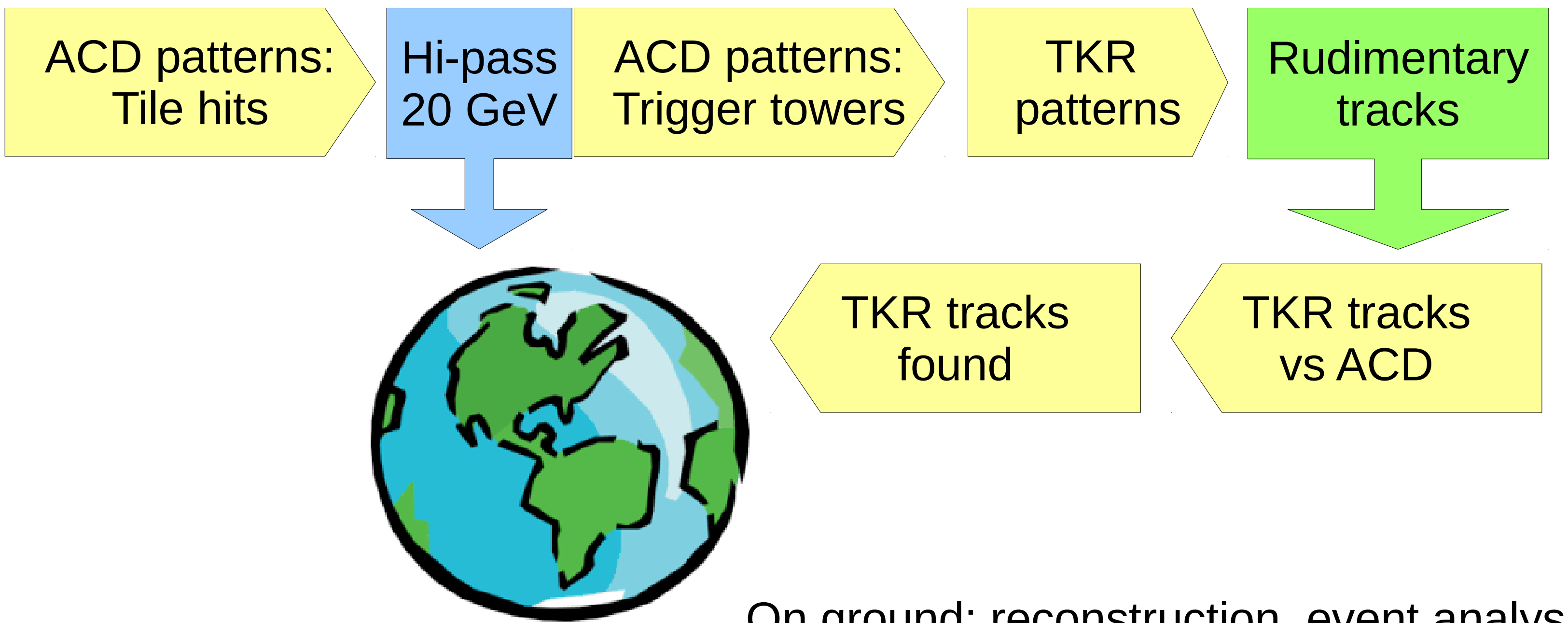
- For gamma: TKR && !ROI && !CNO
- For calibration: TKR && ROI && CNO && CAL_LO

On-board filter

It is time for downlink (1.5Mb/s avg), but still too many background events
Three paths to ground:

- Diagnostic: to monitor performance (periodic trigger, unbiased downscaled sample....)
- HIP: ions, for calibrations
- GAMMA

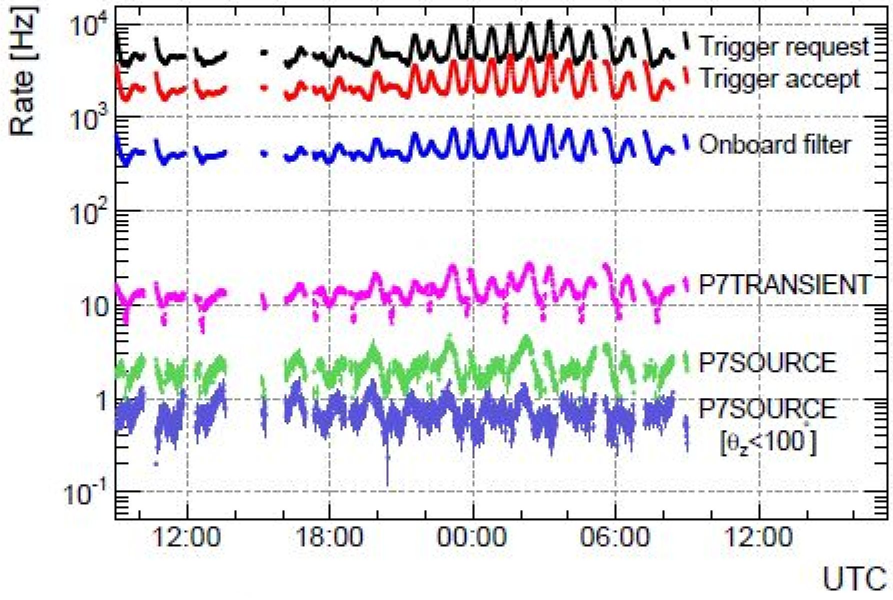
GAMMA:
On-board processor evaluates filter, series of veto tests, from least to most CPU-intensive



On ground: reconstruction, event analysis
Event classes: photon lists

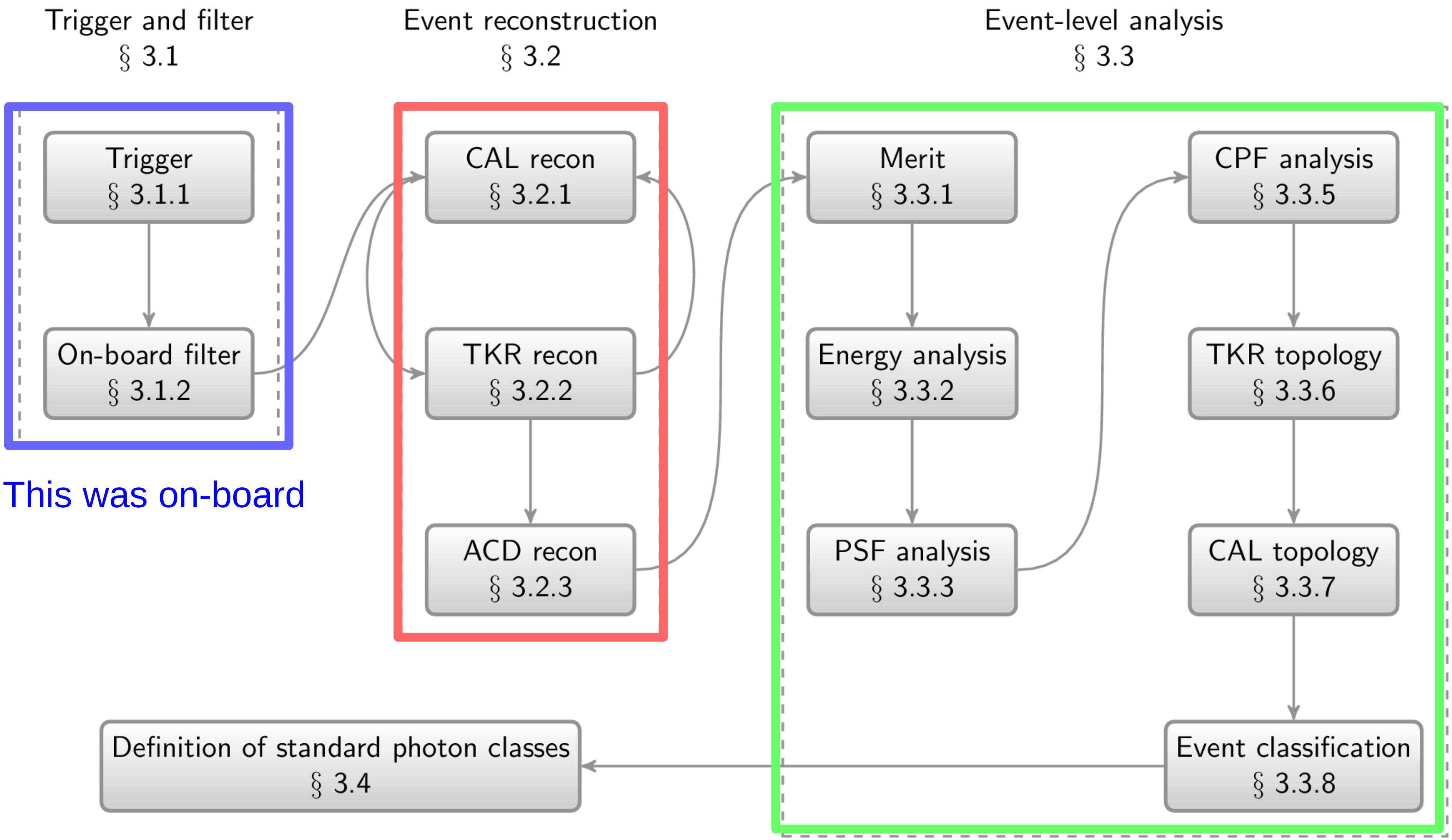
Rates

"Wiggle": SAA
As long as you see it, data are mostly bkg



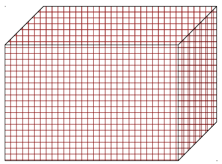
- All subsystems contribute to the L1 hardware trigger ($\sim$ 2.2 kHz):
  - TKR: three consecutive TKR x-y planes hit in a row;
  - CAL_LO: single CAL log with more than 100 MeV (adjustable);
  - CAL_HI: single CAL log with more than 1 GeV (adjustable);
  - ROI: MIP signal in the ACD tiles close to the triggering TKR tower;
  - CNO: signal in one of the ACD tiles compatible with a heavy.
- Adjustable hardware prescales to limit the deadtime fraction:
- Programmable on-board filter to fit the data volume into the allocated bandwidth ($\sim$ 1.5 Mb/s average).
  - Most of the $\sim$ 400 Hz of events passing the gamma filter and downlinked to ground are actually charged-particle background.

Event analysis

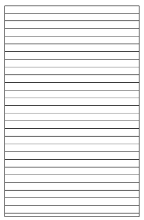


Recon (P7)

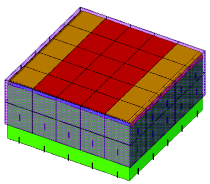
Translate electronic signals into physics



Find **shower shape** (principal axes), correct for **leakage**
Several E estimates, for several correction algorithms
→ shower profile, parametric, maximum likelihood.



(Can) use CAL as guide: track must point to centroid in CAL
Kalman filter: direction and full covariance
Repeat until all **tracks** are found
Assemble vertexes
Calculate energy deposited (particularly relevant at low E)



Associate hit tiles/ribbons with TKR tracks

Event analysis

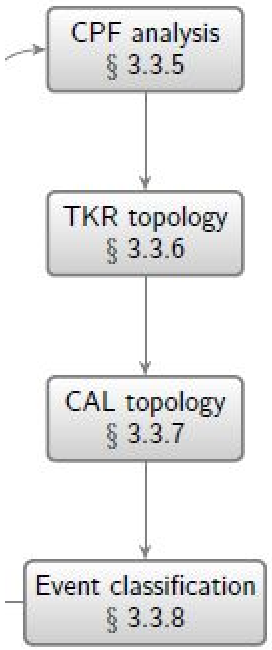
After recon, each event is a complex object, with several estimates for energy, direction, plus geometry information and other meaningful characteristics (number of hits per layer in TKR, shower axis in CAL, saturated crystals,...)

Event analysis does several things:

- **Select the best** energy/direction estimate
- Calculate likelihood that the former **estimates are correct**
- Calculate likelihood of being a gamma ray (for **background rejection**)

Trained on MC and **tuned on real events** (special “signal-” and “bkg-” rich sets)

Many many cuts and **machine learning** (classification trees)



Charged particles in FOV: seals ACD as tight as possible

Is TKR pattern “gamma-like”?

Is CAL pattern “gamma-like”?

“bad” events are not removed, only flagged

Final machine learning stage, using all above

Output is a series of knobs one can tweak to define event classes

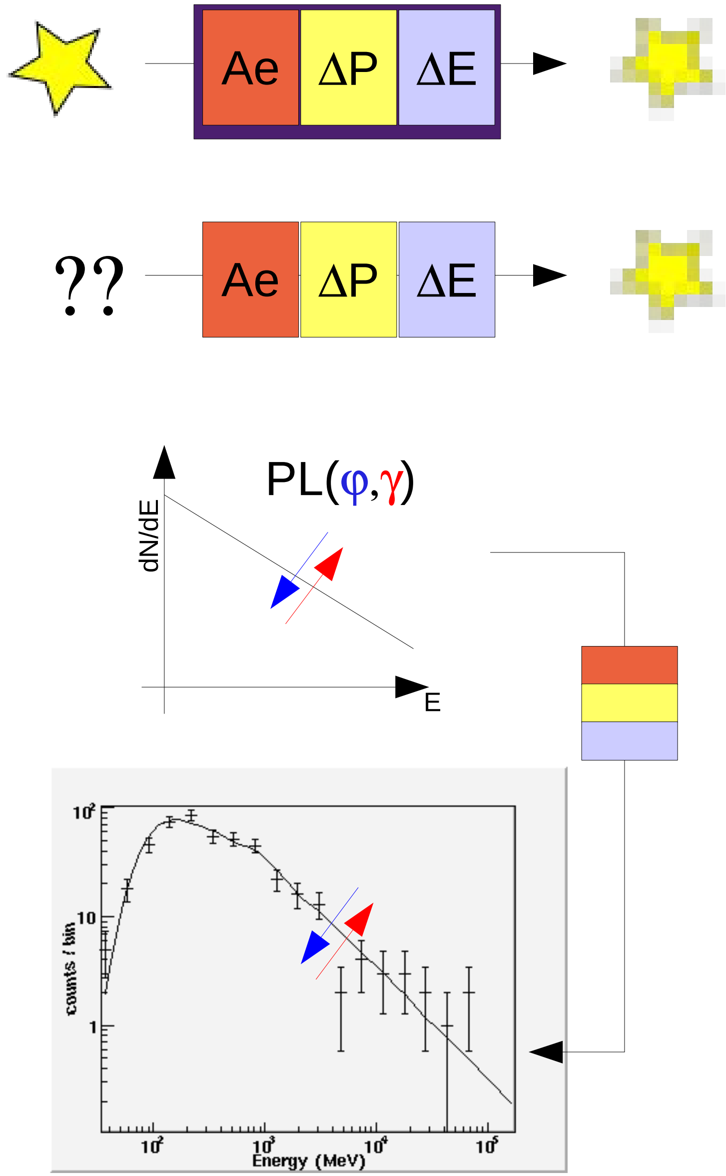
IRFs and science analysis

We have a list of events with **time, apparent location in sky, apparent energy**
We want **source properties: location, spectrum, ...**

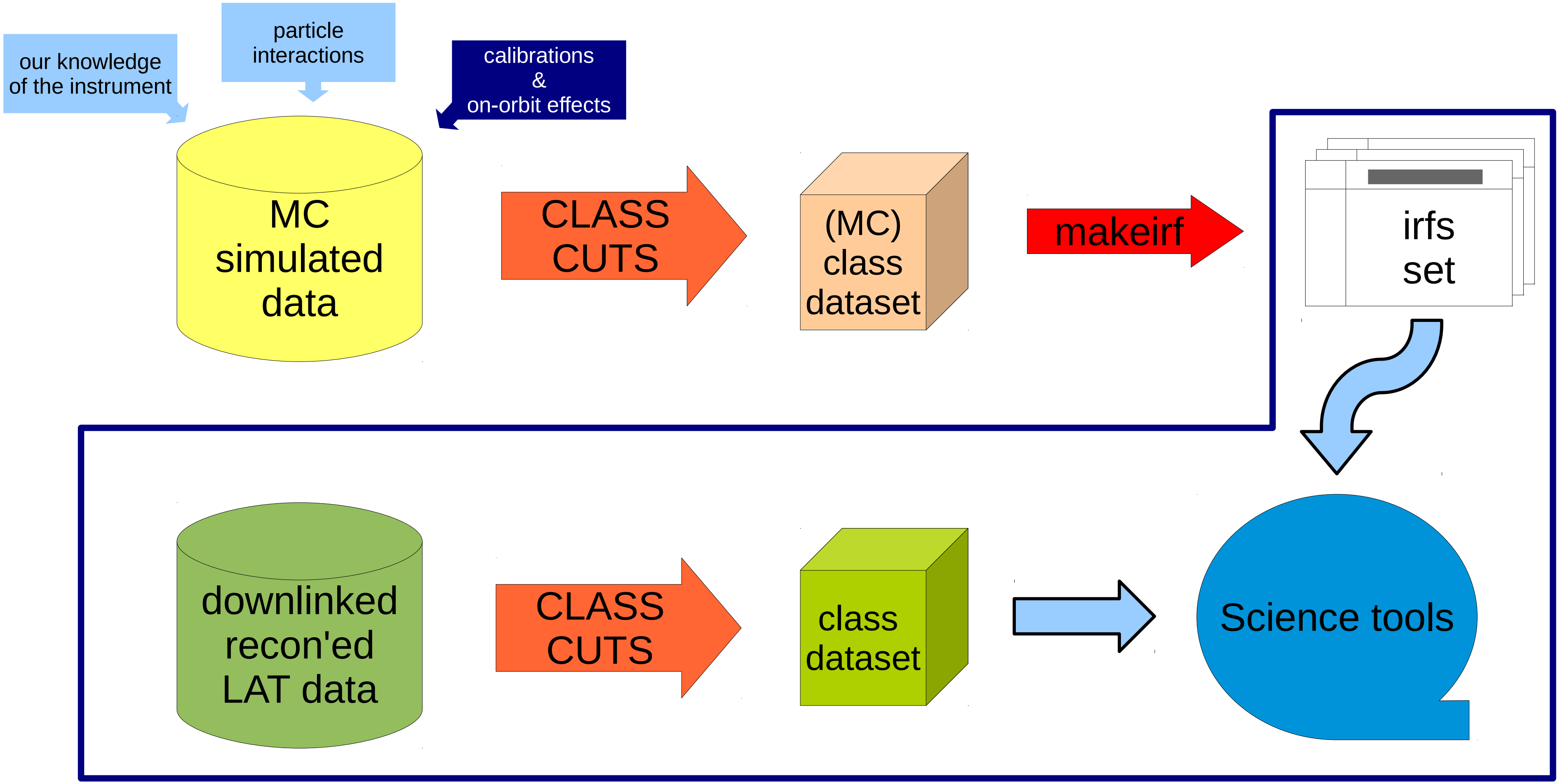
Unfolding in presence of non-negligible background is complex
We “forward-fold” with IRFs
Canonically: aeff, PSF, edisp.

Then use maximum likelihood to find the best parameters for a model describing a source
It is model-dependent, but uses 100% of the available information (IRFs are binned, but likelihood can be unbinned).
Easy to study systematics etc.

Cannot be used to discriminate different (non-nested) models!



Building IRFs

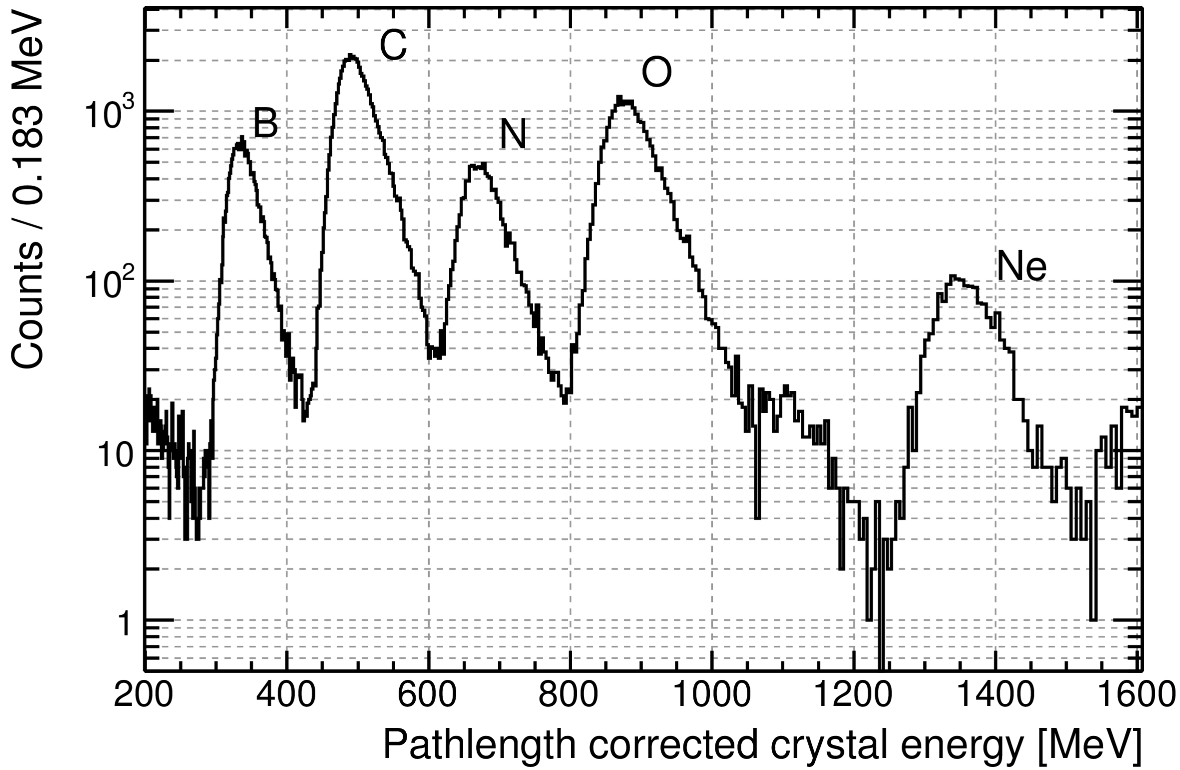


Must have vey high confidence in MC: can cross check with real data
E.g.; use 100% point sources (remote galactic nuclei) to evaluate angular resolution

On orbit calibrations

Calibrations must be kept up-to-date
Some small variation can be expected
Electronics not linear

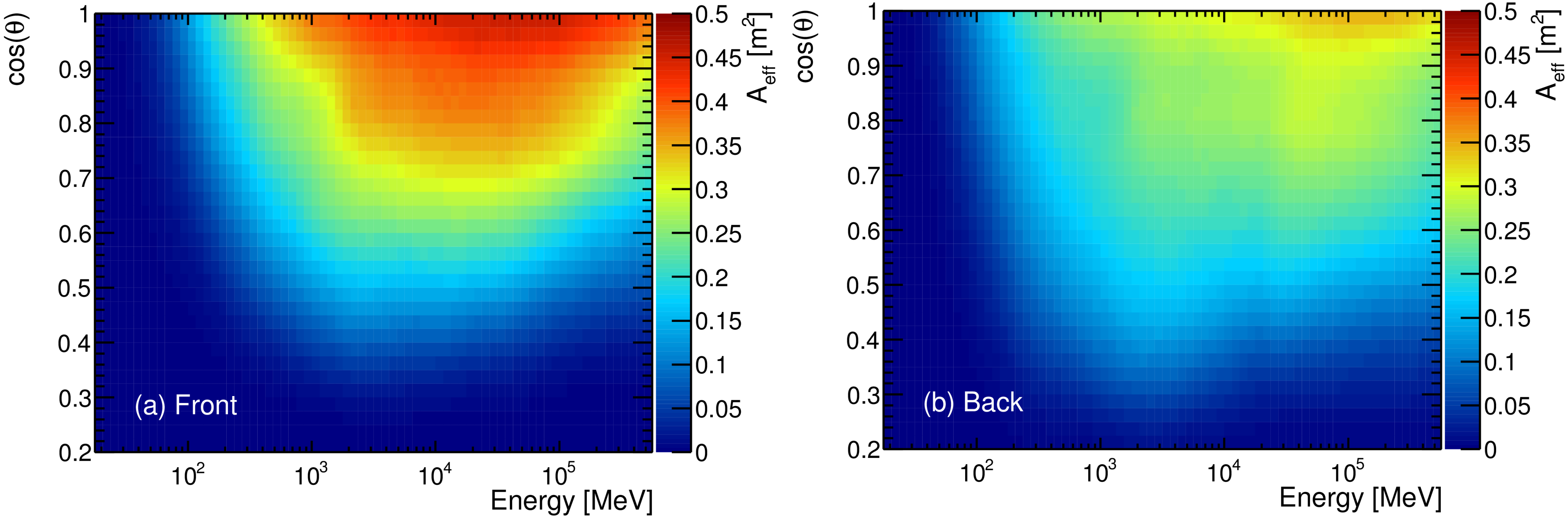
Dedicated trigger engines & filter
Dedicated data runs with special conf



Most obvious: CAL
Due to radiation hardness, CAL yield decreases: can monitor and fit data
Time constant ~2 years, 4.5% loss estimated after 10 years
Calibrations are routinely updated: used convert electric signal into charge

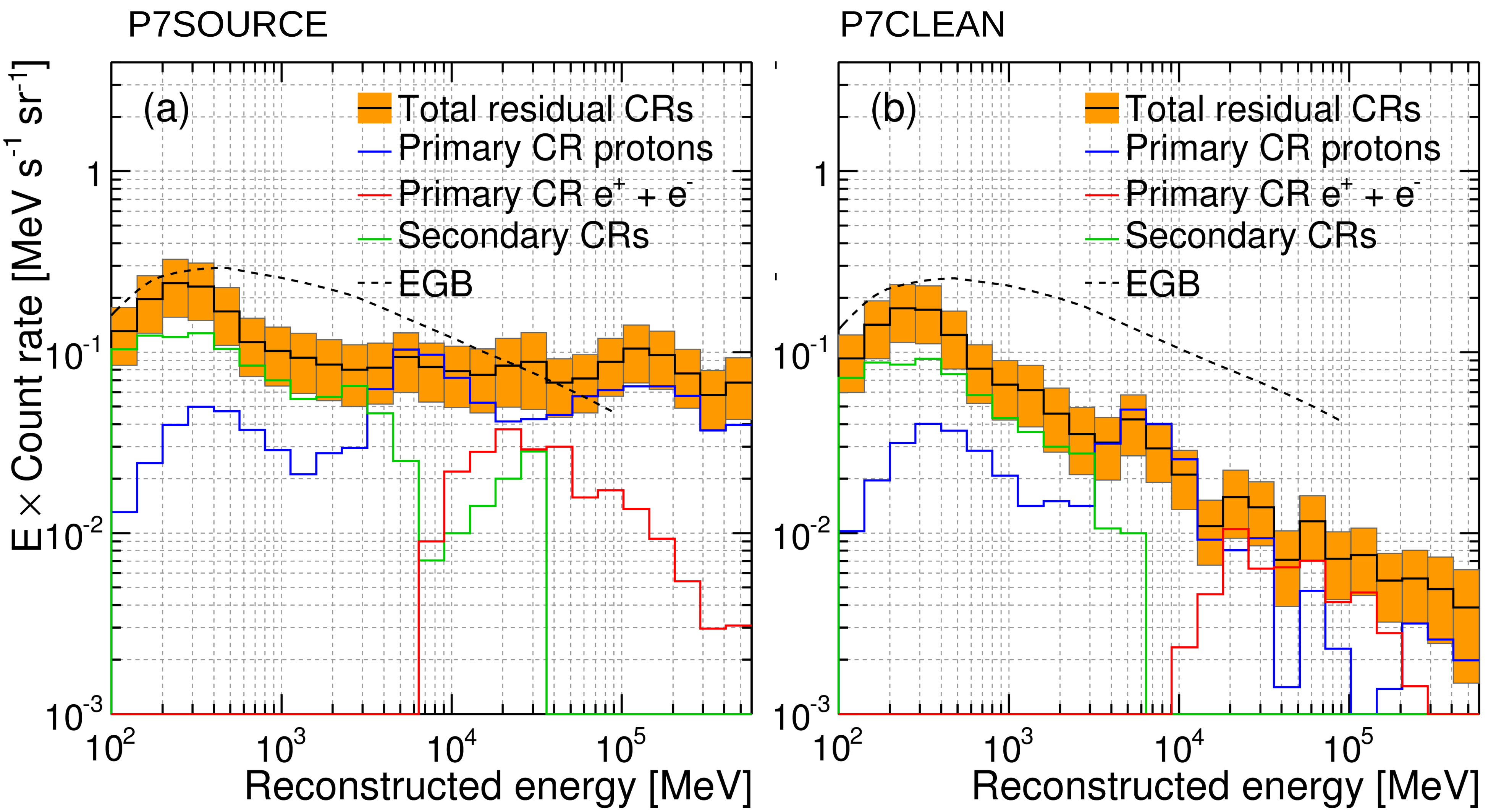
Aeff vs incidence angle

P7SOURCE

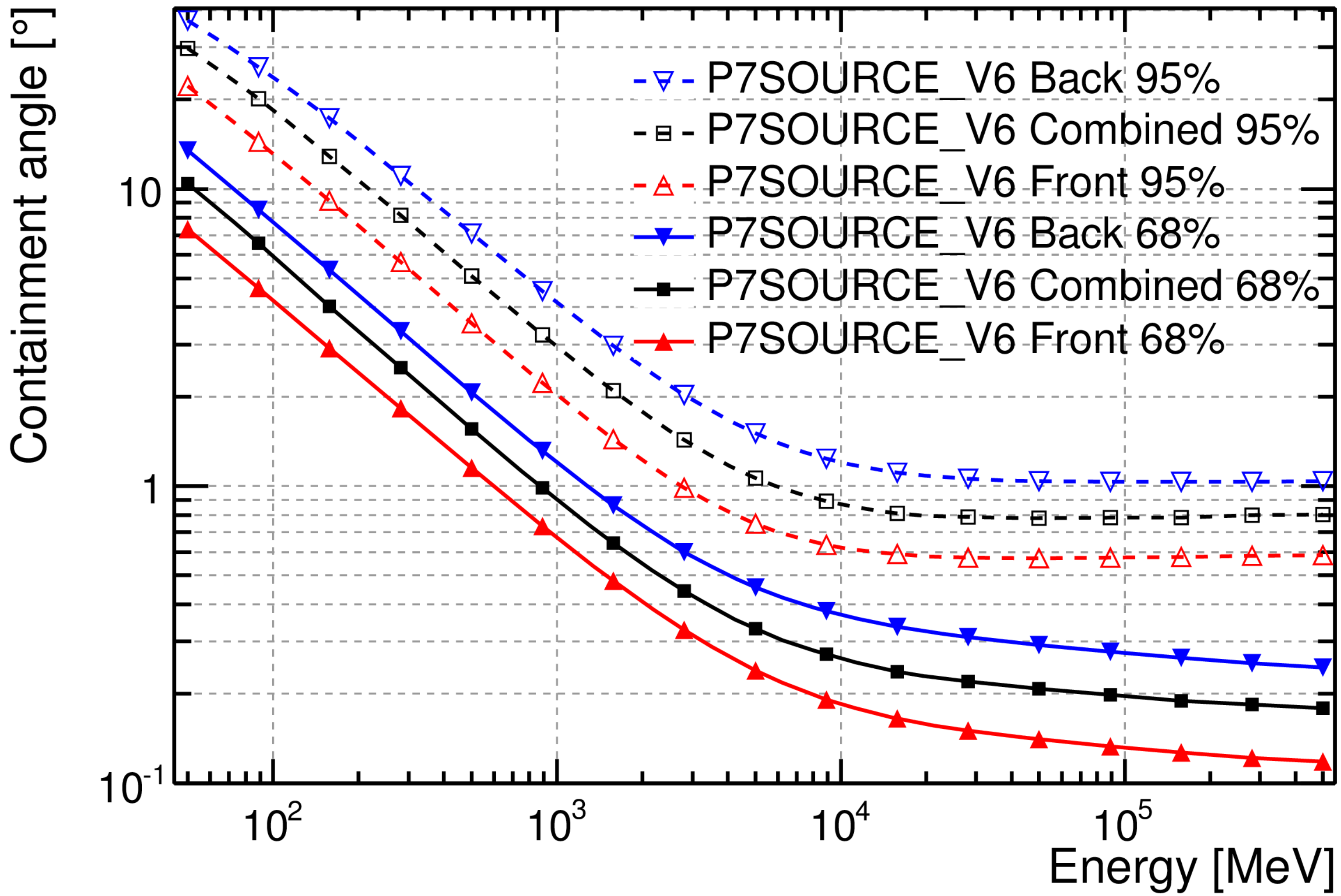


For up-to-date PASS8 performance:
https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

Background vs event class

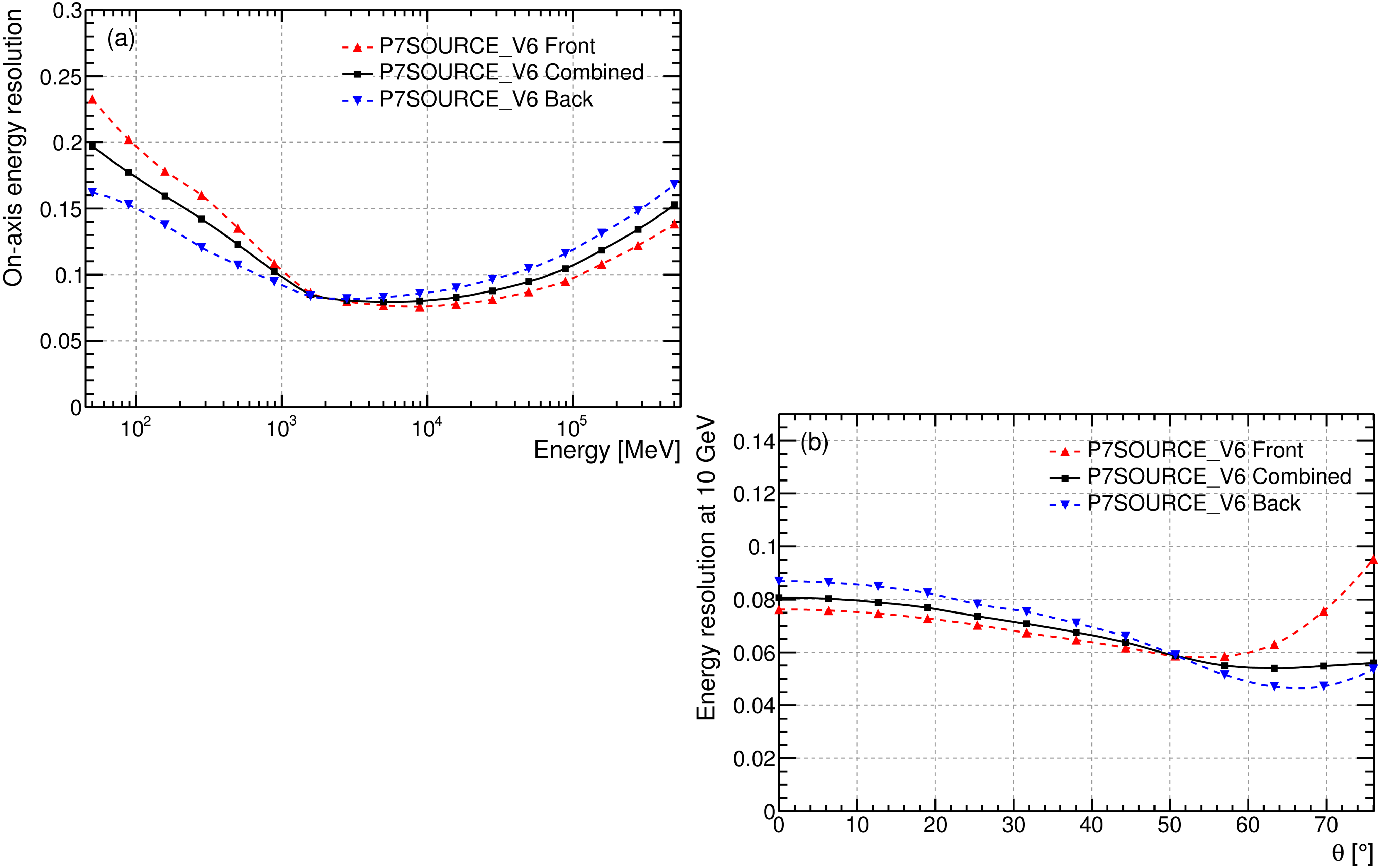


PSF

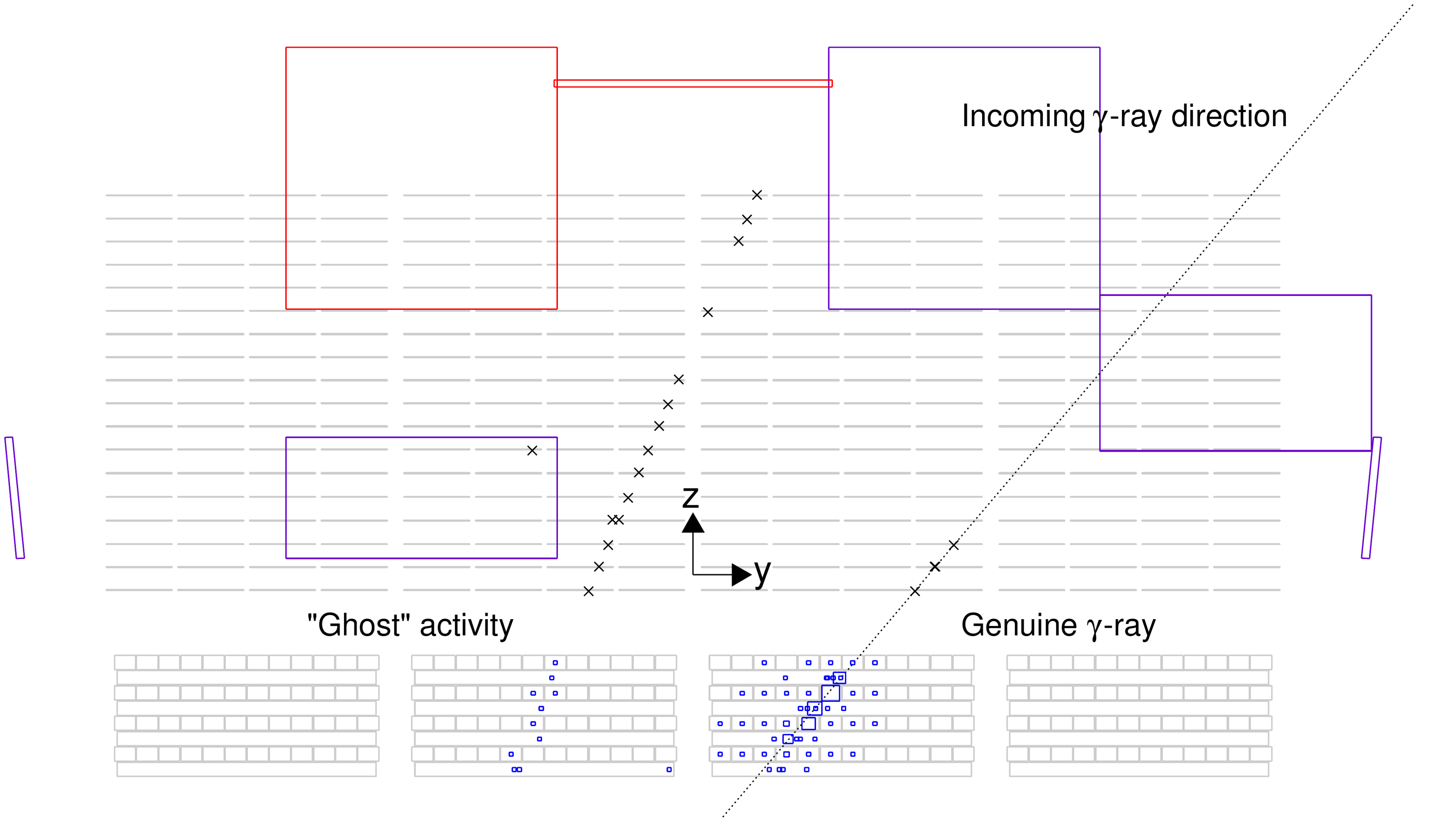


P7SOURCE_V6 Back 95%
P7SOURCE_V6 Combined 95%
P7SOURCE_V6 Front 95%
P7SOURCE_V6 Back 68%
P7SOURCE_V6 Combined 68%
P7SOURCE_V6 Front 68%
Containment angle [°]
10
1
10^{-1}
10^2
10^3
10^4
10^5
Energy [MeV]

Energy dispersion

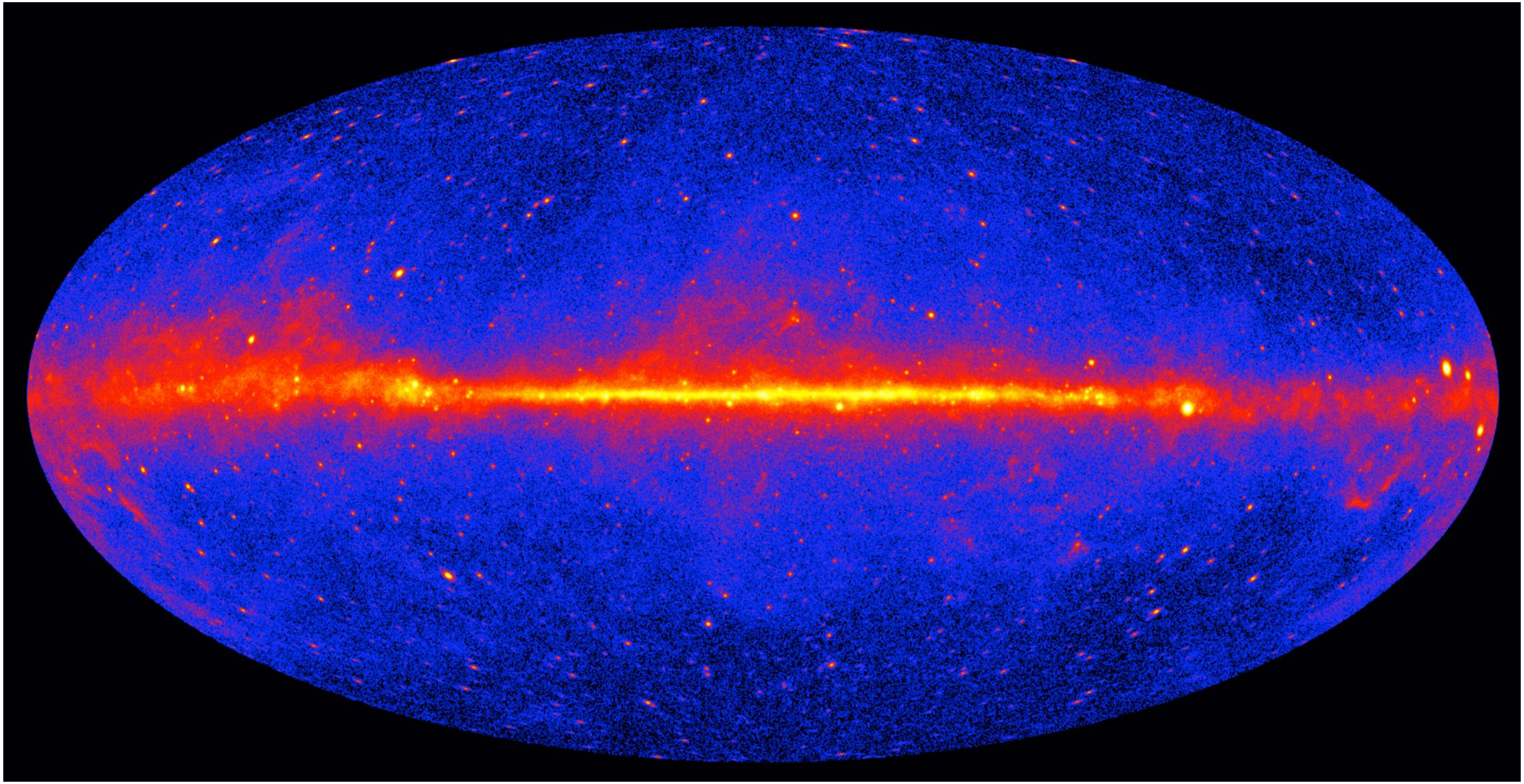


Issues: ghosts



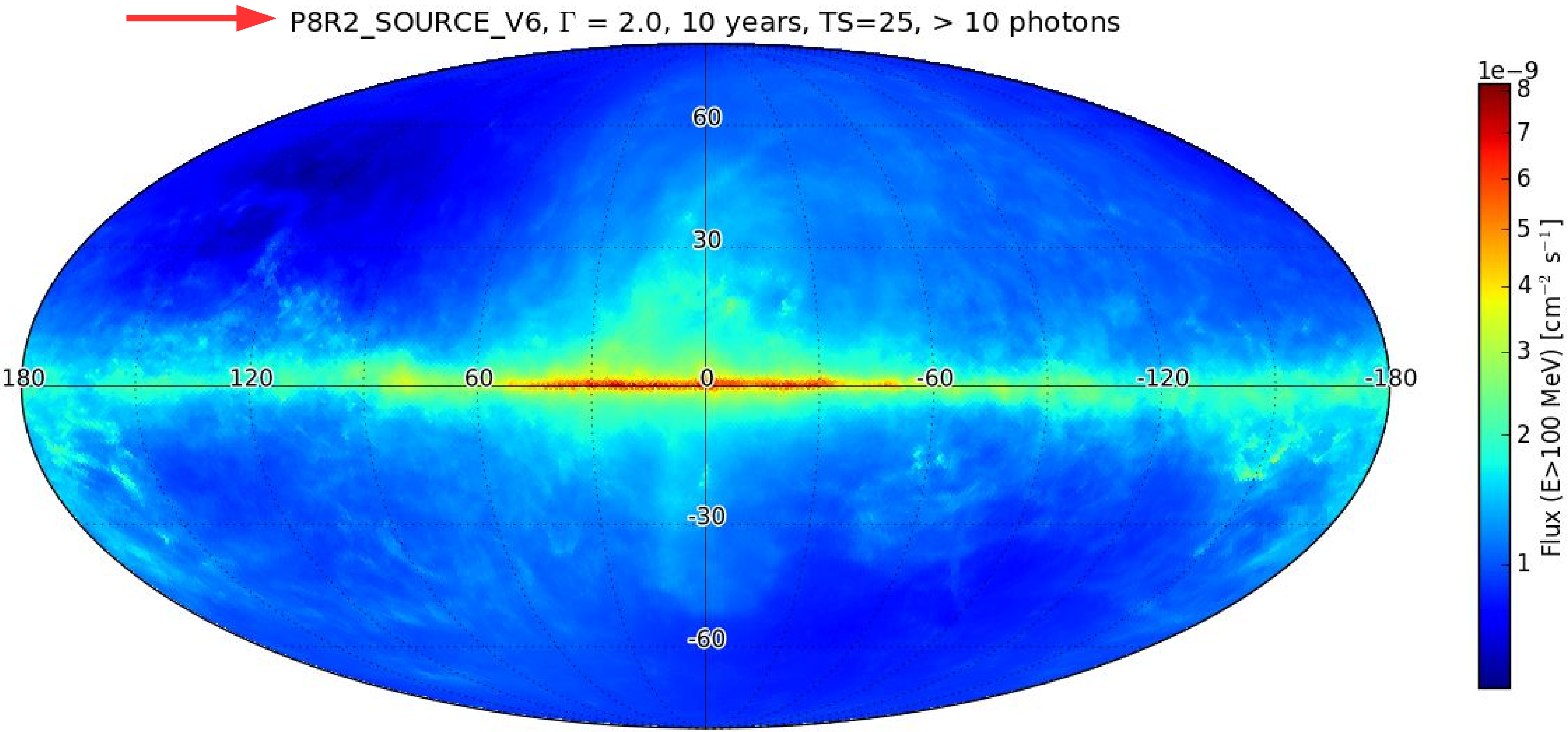
Observed very early, due to shaping time of electronics during readout and high bkg rate.
At first similar events were added to the MC simulation (overlay from periodic)
Now they are searched and flagged, goal is to recover the gamma information (Pass8)

Skymap



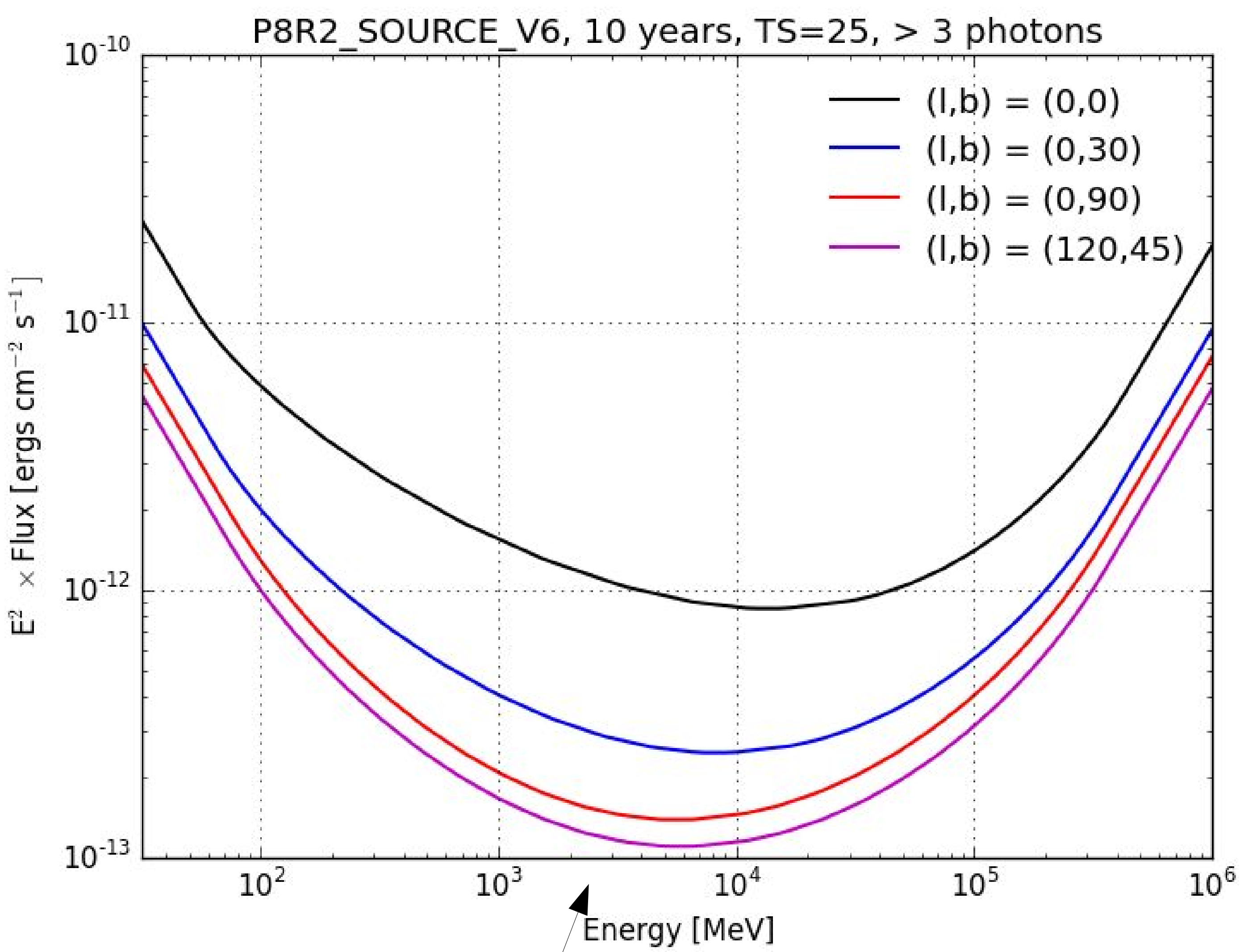
Just events

Sensitivity for point sources



Derived from IRFs, pointing history, and background models (galactic, isotropic)

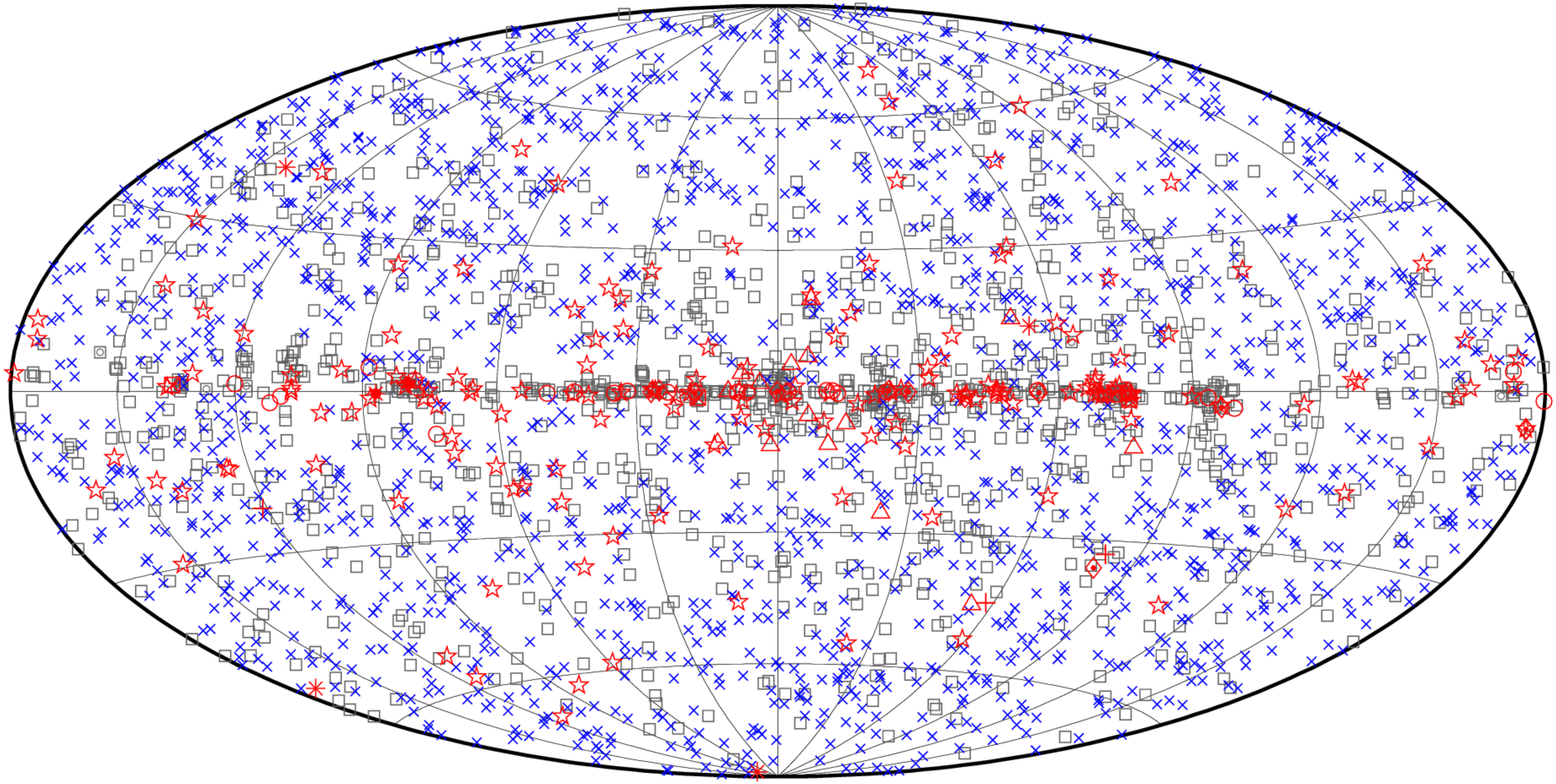
Spectral sensitivity



Flux limited (3 photons per energy bin)

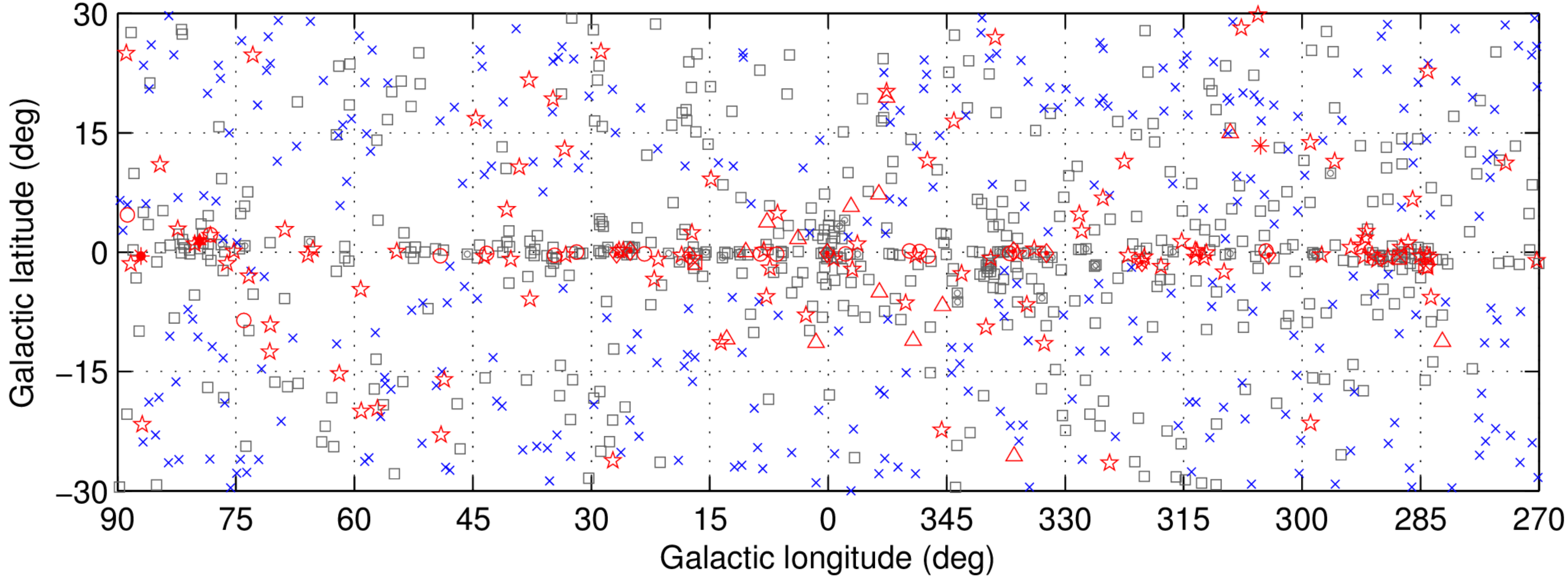
Sweet spot

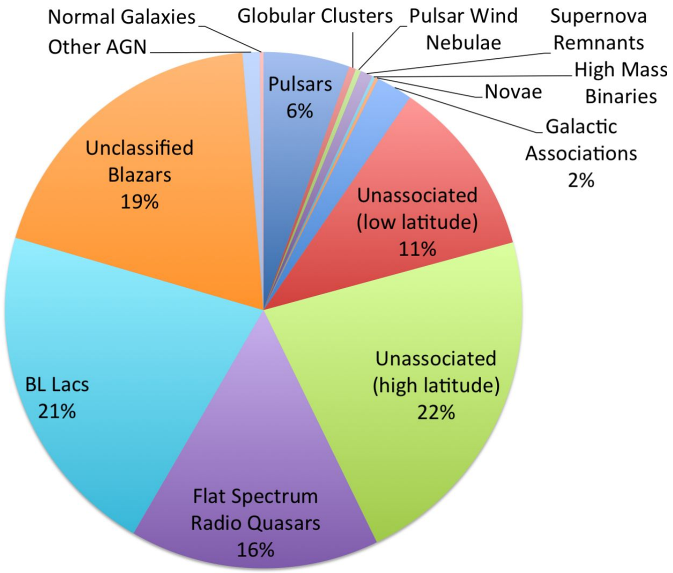
Point source catalog



3FGL (4-year catalog)
3033 sources
~1000 unidentified

Catalog: Galactic plane and overall





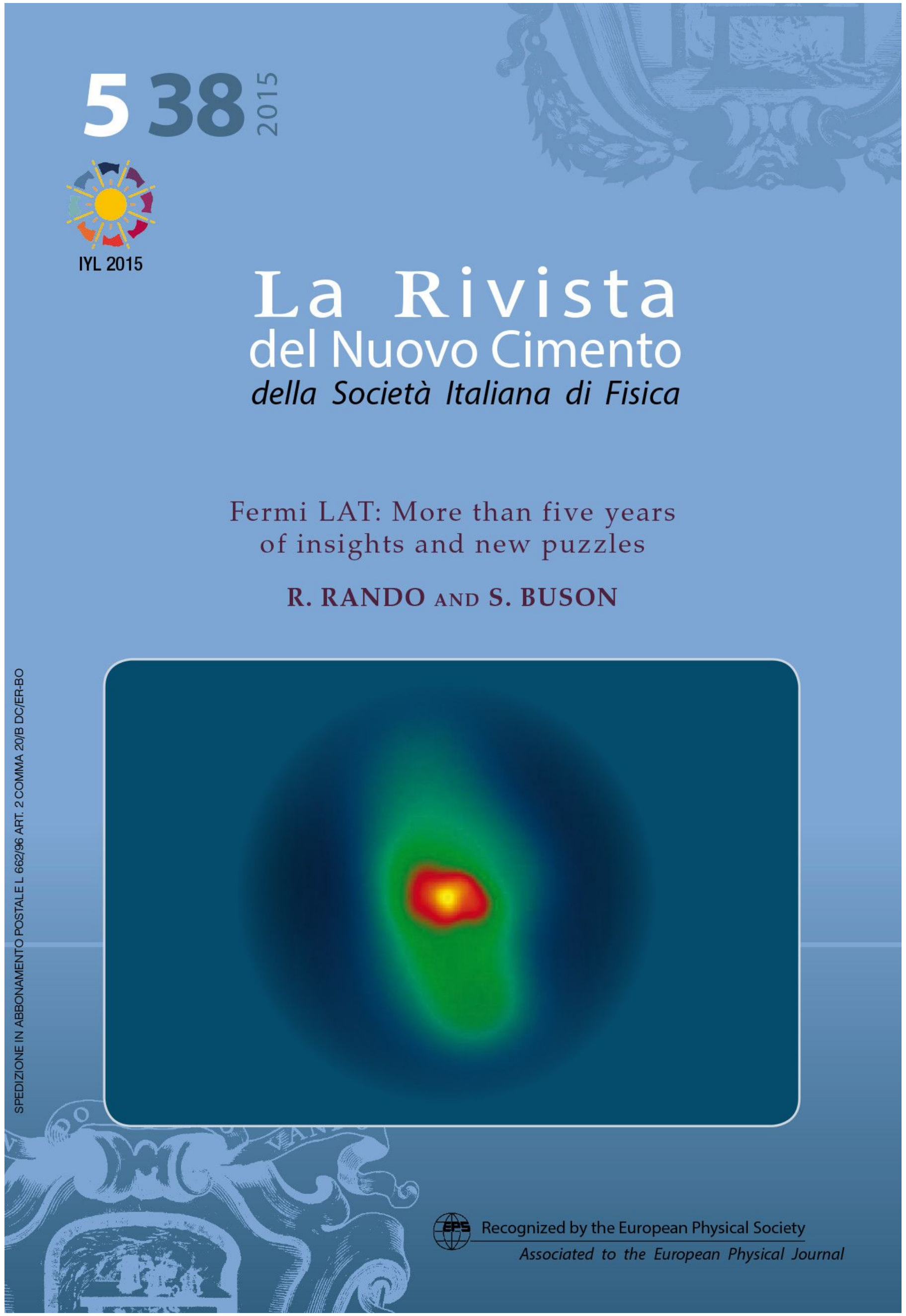
Scientific output

Solar Flares, 2015, ApJL, 805, L15,
Novae, 2014, Science, 345, 554,
DM lines, 2015, Phys. Rev. D, D91, 122002
Gamma-ray anisotropies and x-correlations, PRL 114, 241301 (2015)
Electrons/positrons: 2017 PhysRev D95; 2012, PRL, 108, 011103

Fermi *legacy*:
gamma-ray emission in PSR away from surface, e.g. 2013, ApJS, 208, 17
rejection of simplest single-zone emission in blazars, e.g. 2015, ApJ, 810, 14
Crab flares, e.g. 2011, Science, 331, 739
challenges to standard GRB afterglow model, e.g. 2014, Science, 343, 42
“Fermi bubbles”, 2010 APJ 724(2)
Novae

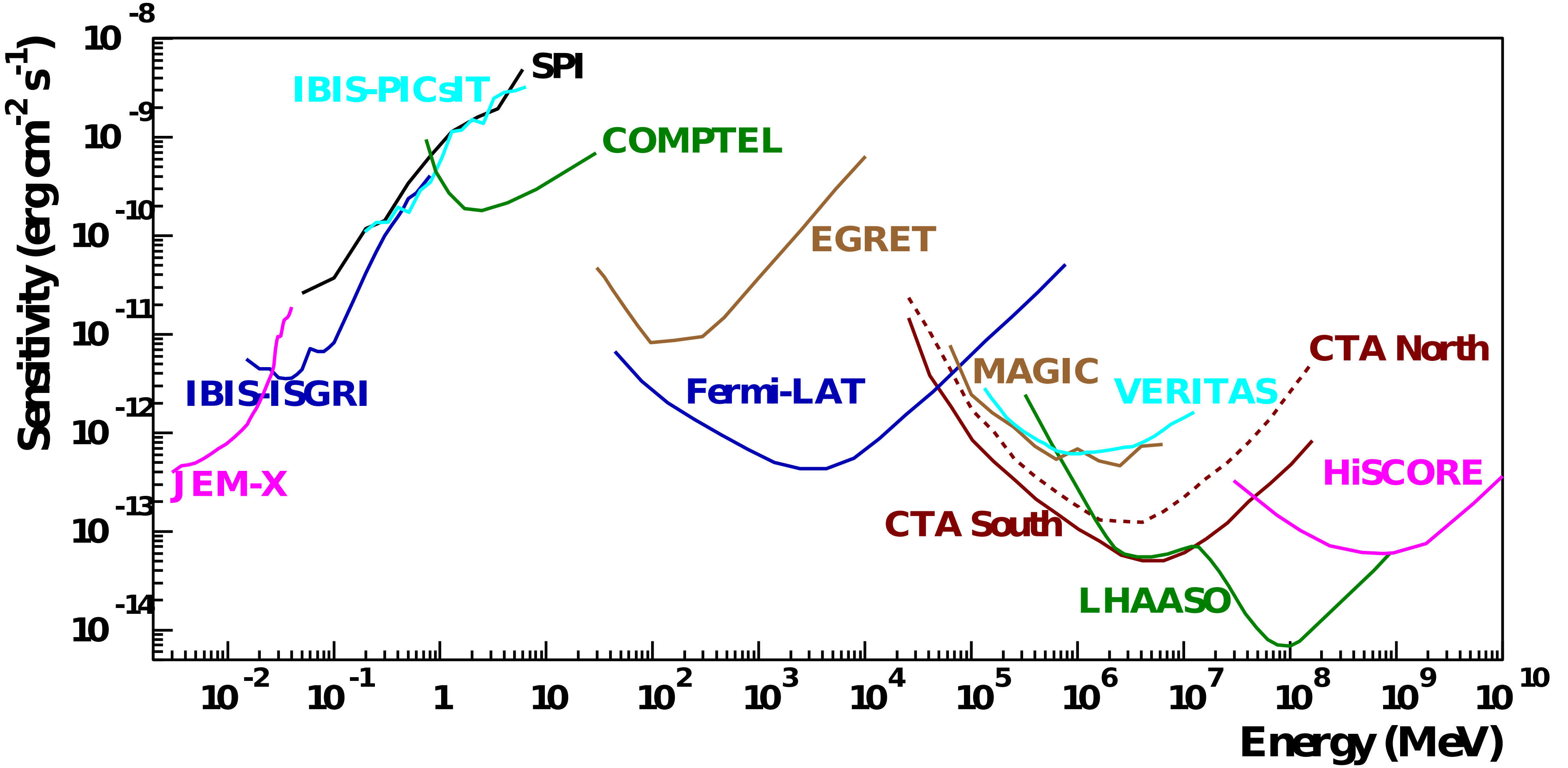
complete LAT Collab. publications at
https://www-glast.stanford.edu/cgi-bin/pubpub

For a summary of scientific results

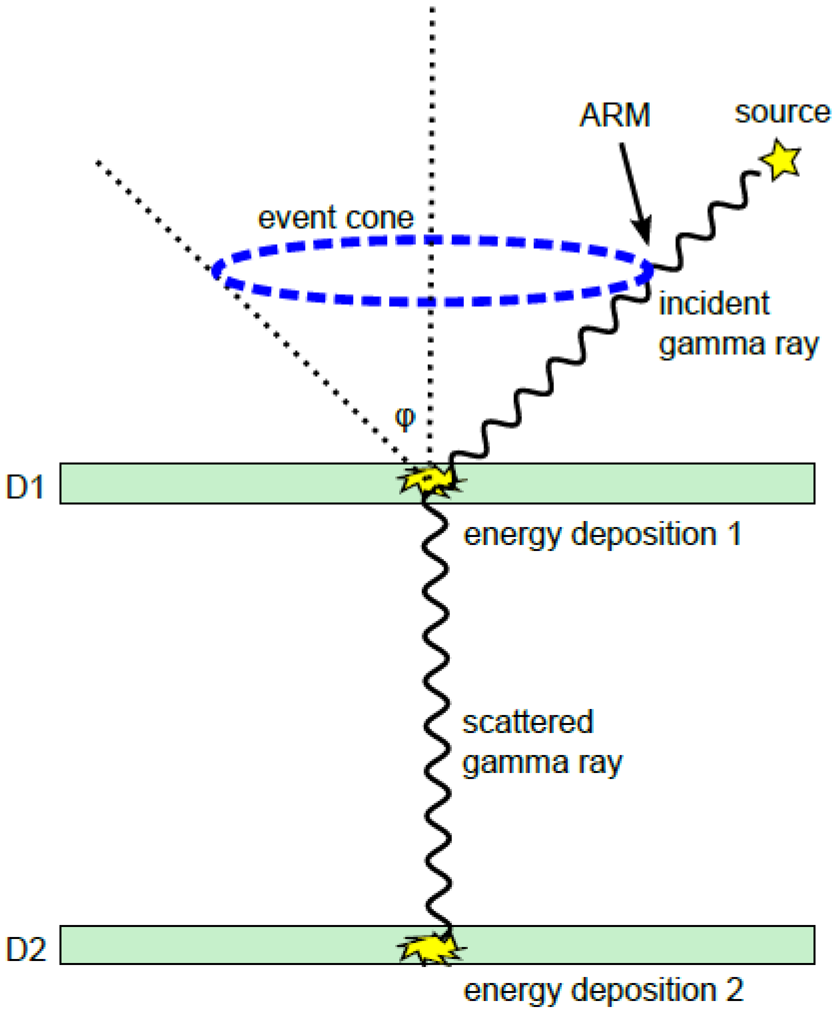


https://www.sif.it/riviste/ncr/econtents/2015/038/05

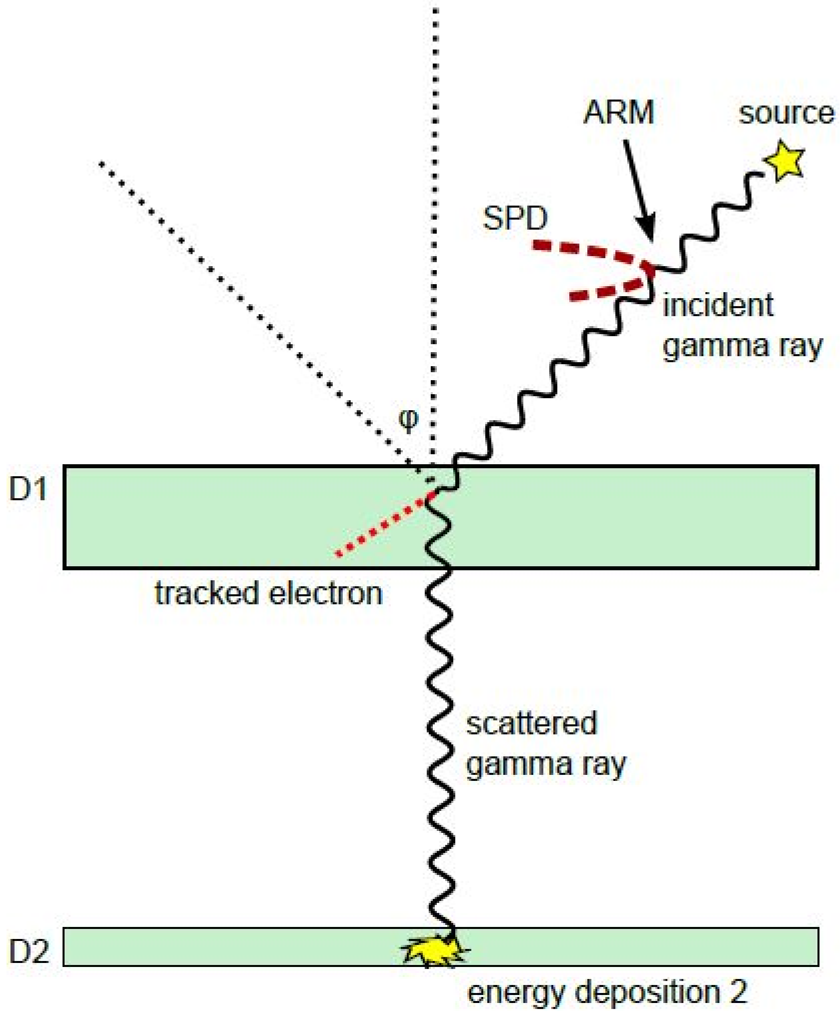
Onwards: the MeV domain



Future experiments: the MeV regime

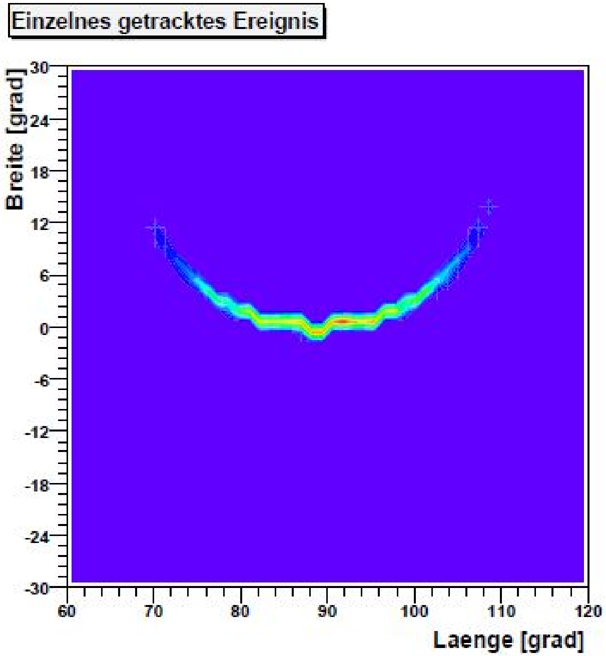


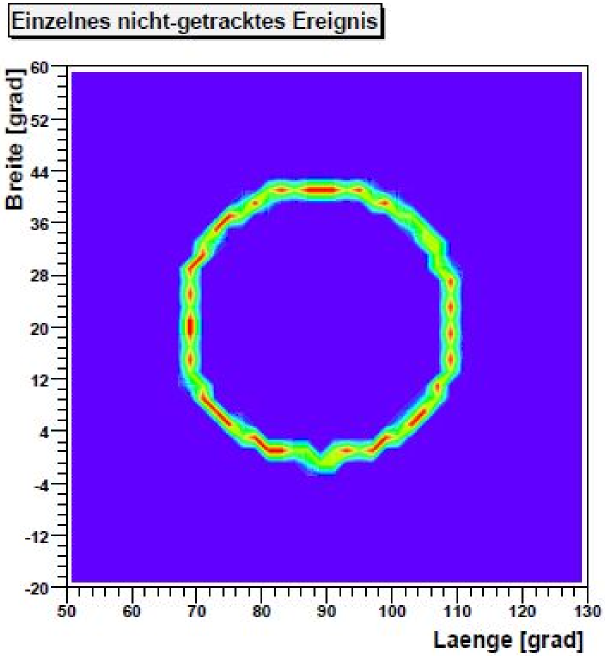
ARM: error on cone aperture

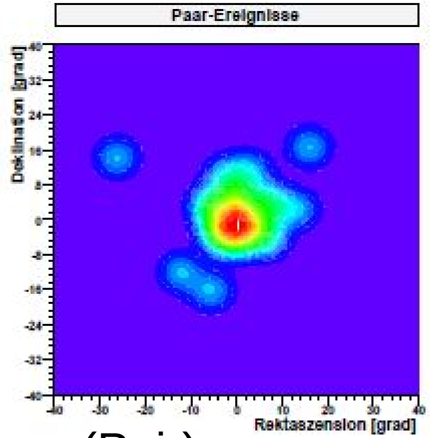


SPD: error on scatter plane

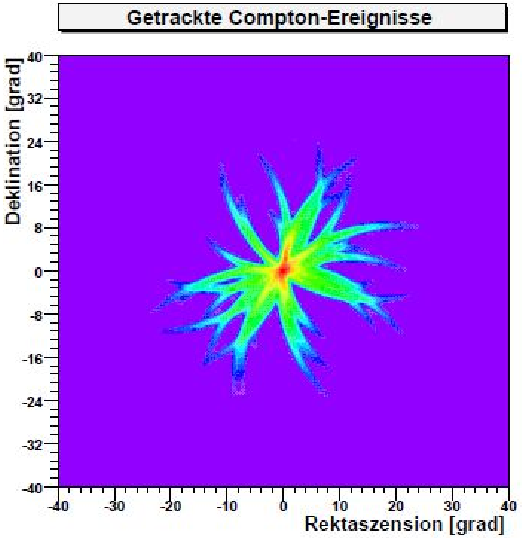
Compton events and point sources

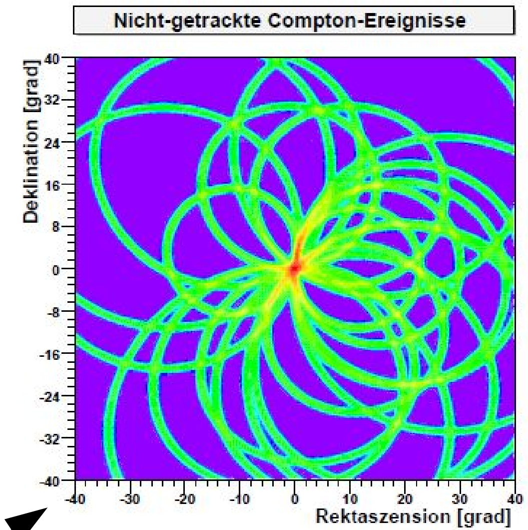






(Pair)





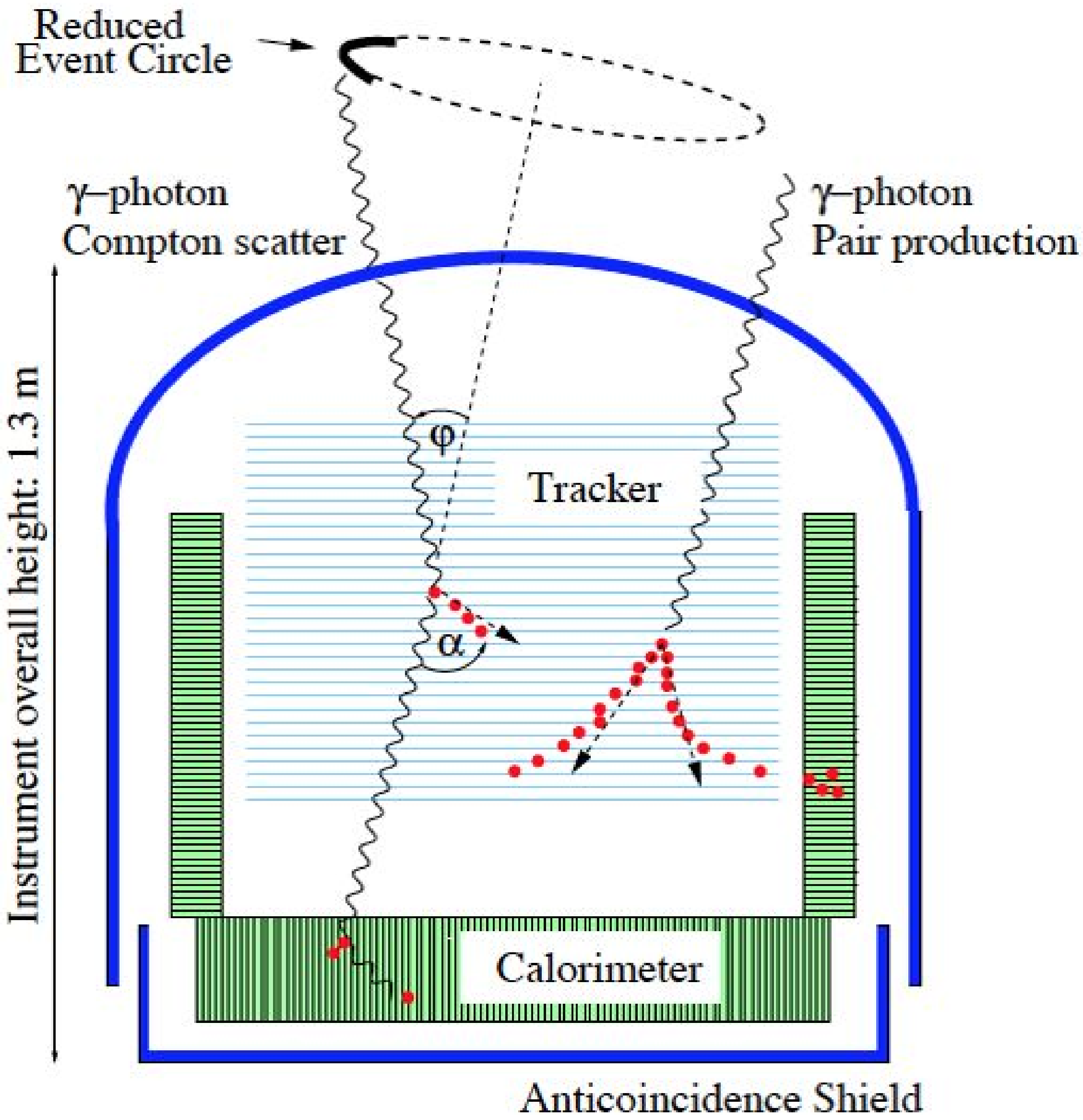
(A. Zoglauer)

Compton and pair

Tracker: unprecedented capability of observing the recoil electrons
Fine energy and position resolution

Calorimeter: thick to absorb the photon entirely
Fine energy and position resolution

ACD: reject particles
No significant backsplash wrt e.g. Fermi-LAT



Compton guidelines

Must get both hits:

- as little as possible passive material (in & around)
- calorimeter should be hermetic to leakage (in the design energy range)

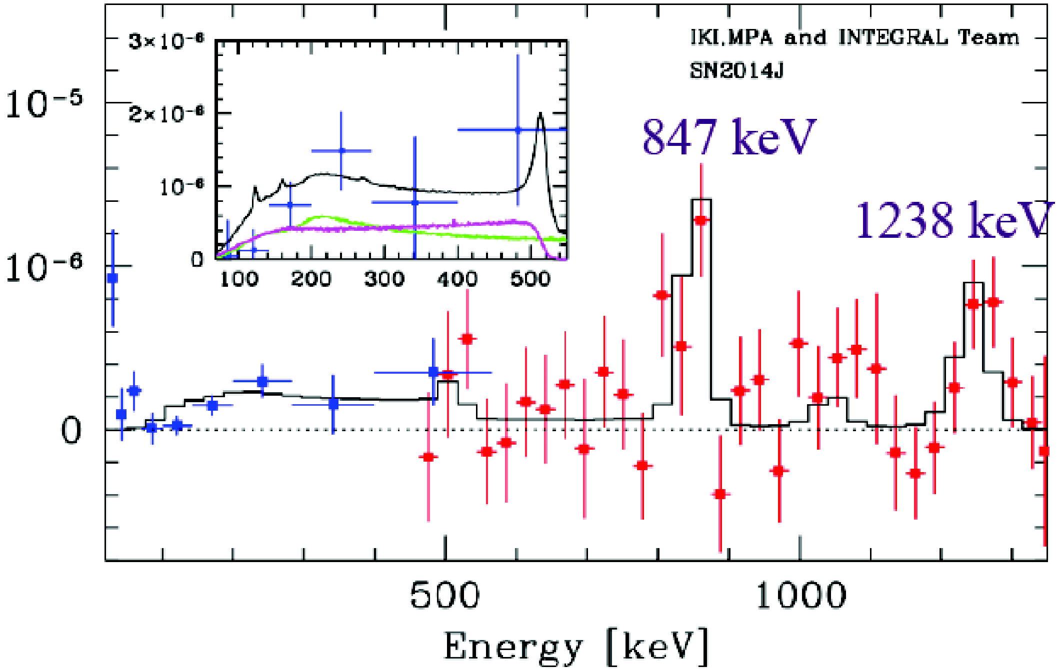
Multiple scattering MUST be limited

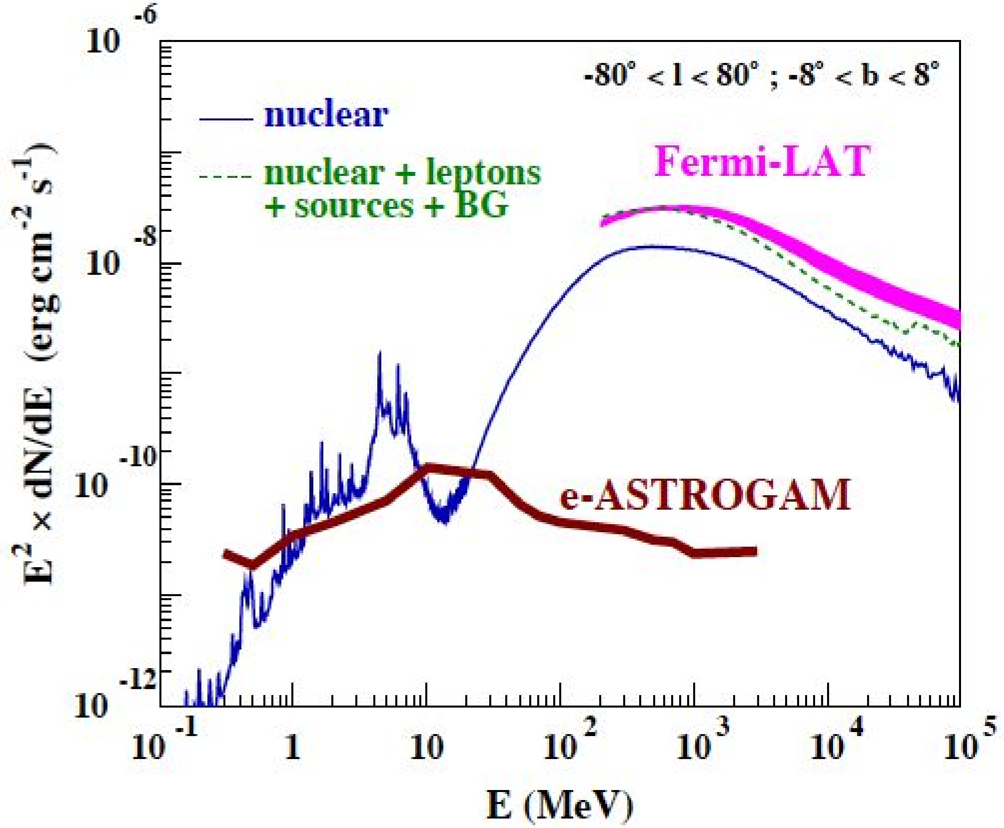
Tracker and calorimeter MUST have a good position resolution (TKR analog readout)

Good energy resolution:

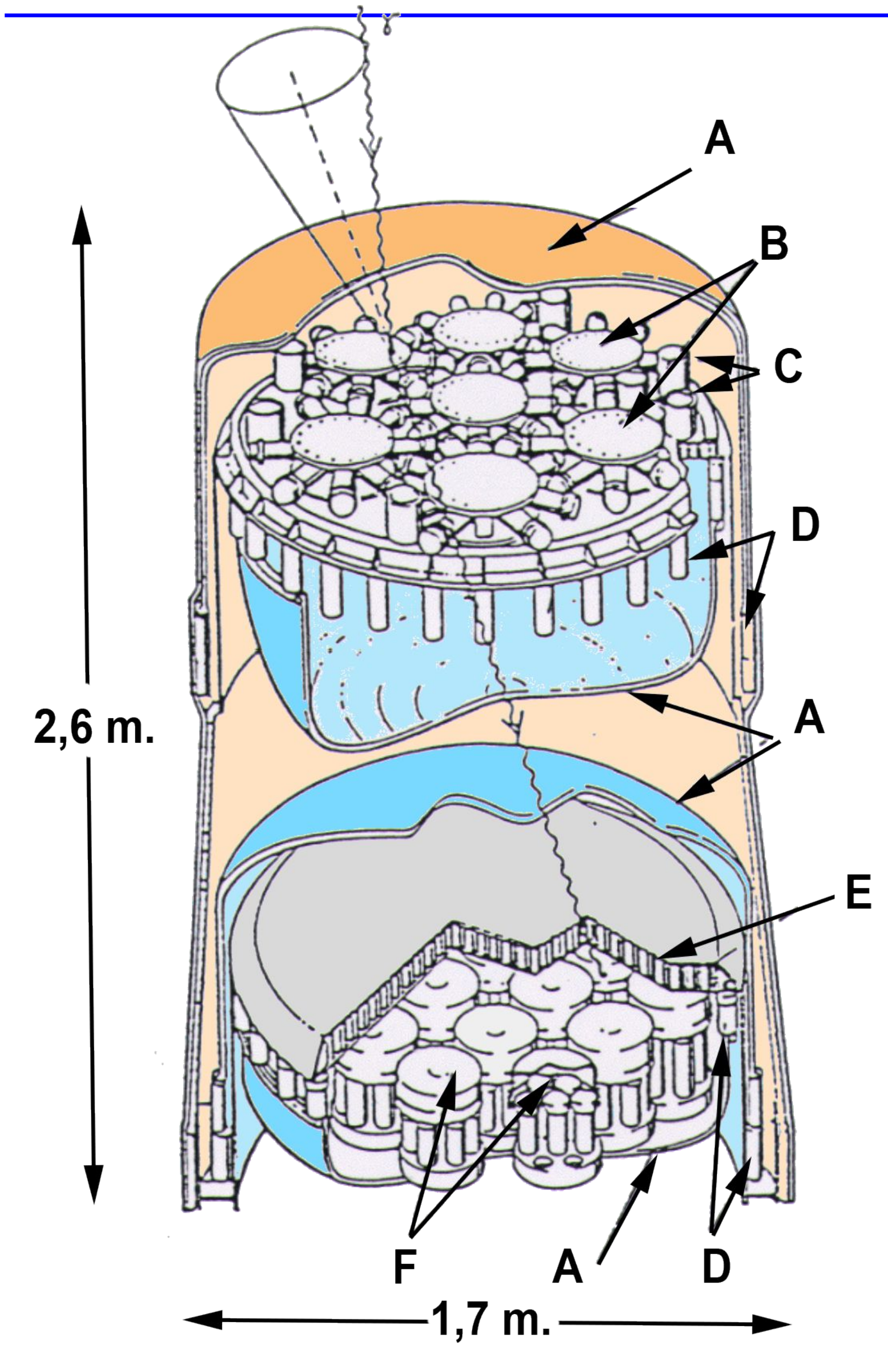
> The MeV regime is where nuclear lines are found
> A powerful tool to investigate the inner chemistry of gamma-ray sources

Earth's “albedo” gammas will be a pain





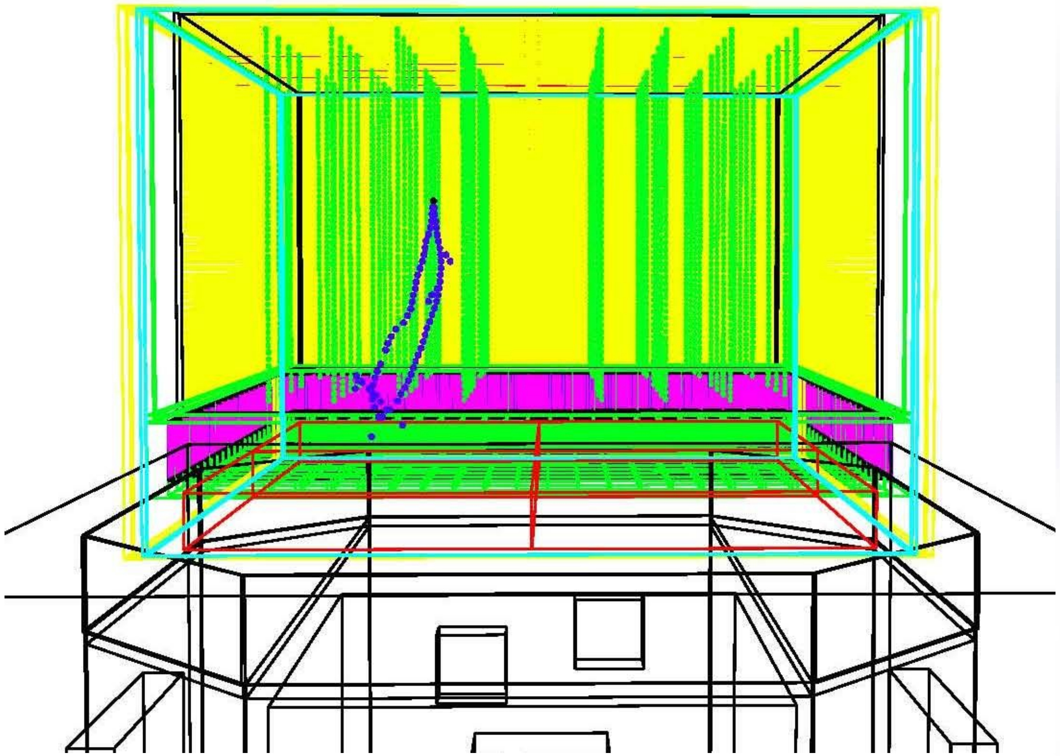
Predecessor: COMPTEL on CGRO

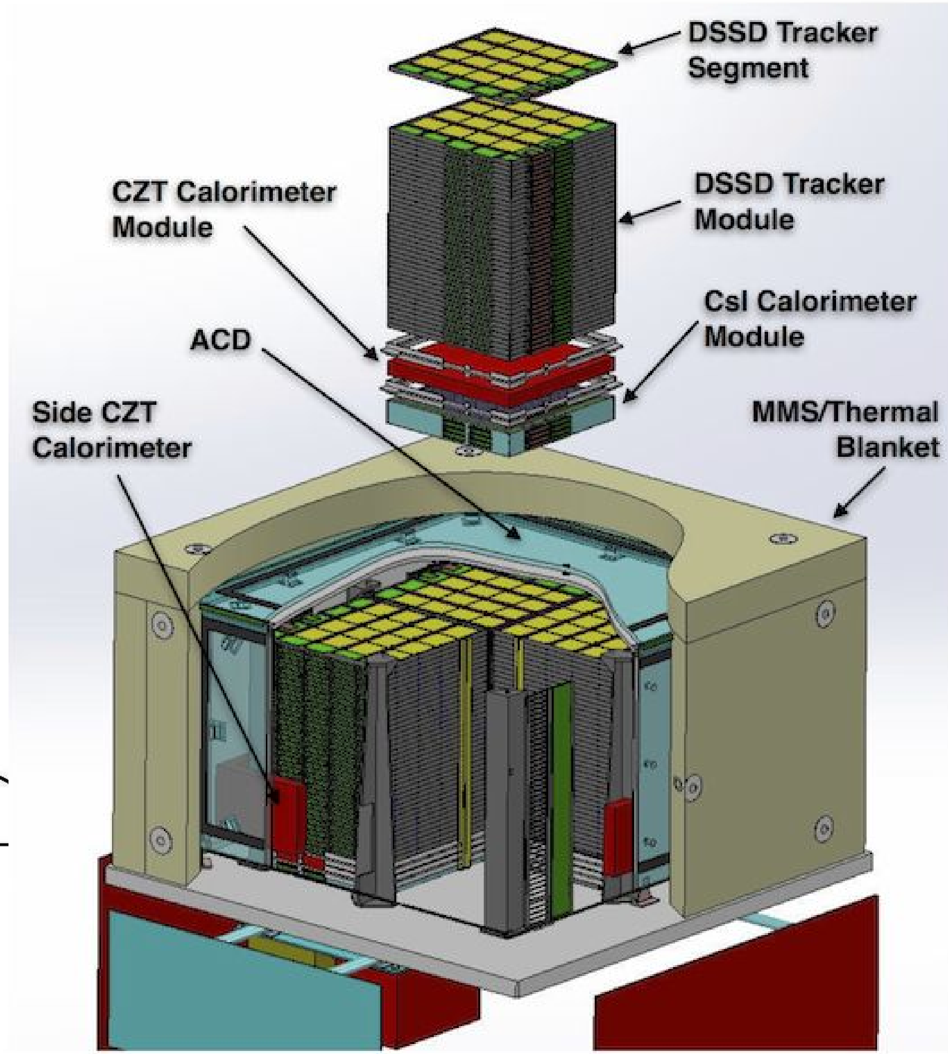


Proposed instruments

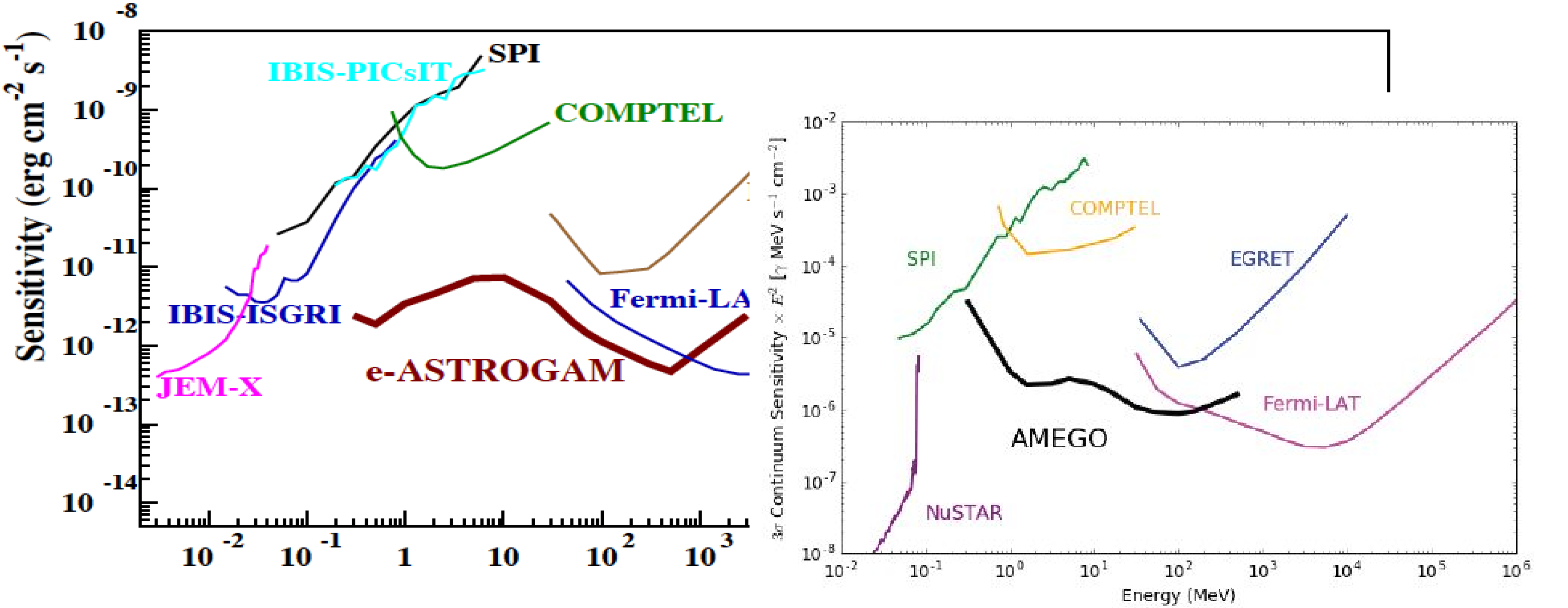
NASA: AMEGO Probe Class mission

ESA: e-Astrogam (M-class mission)



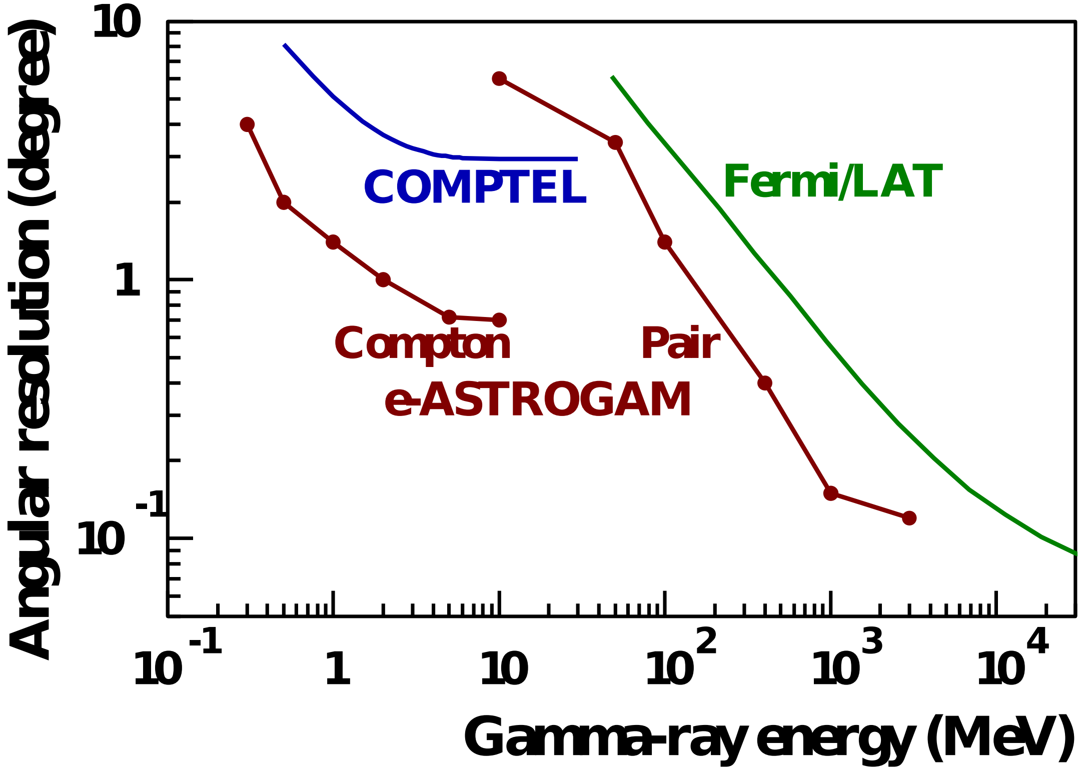


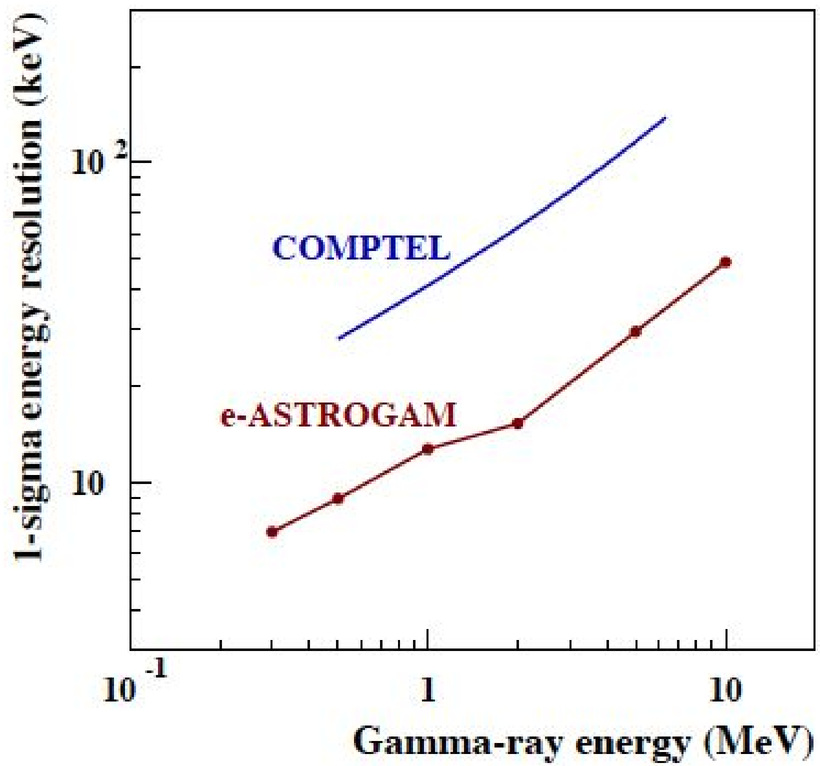
Design sensitivity



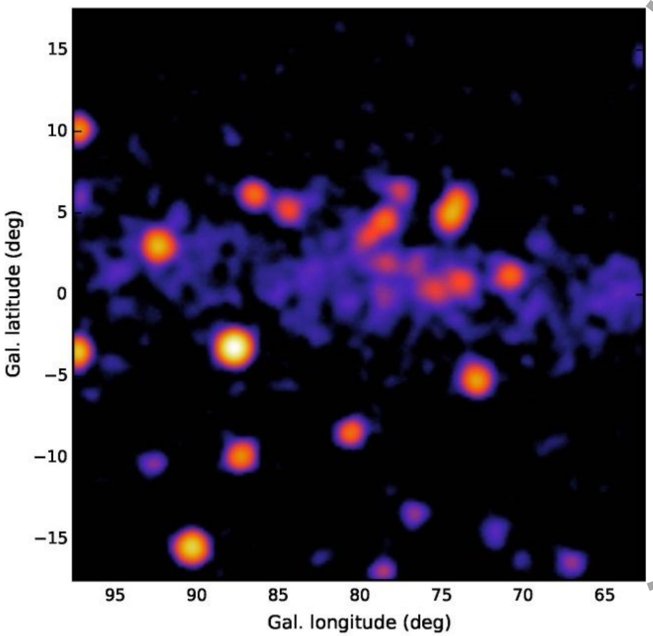
Sensitivity curve is composition of two similar curves, one for the Compton regime, one for pairs
Before the smaller calorimeter kills the sensitivity, better performance than FERMI-LAT (thanks to the finer angular resolution: no W !)

Design resolution

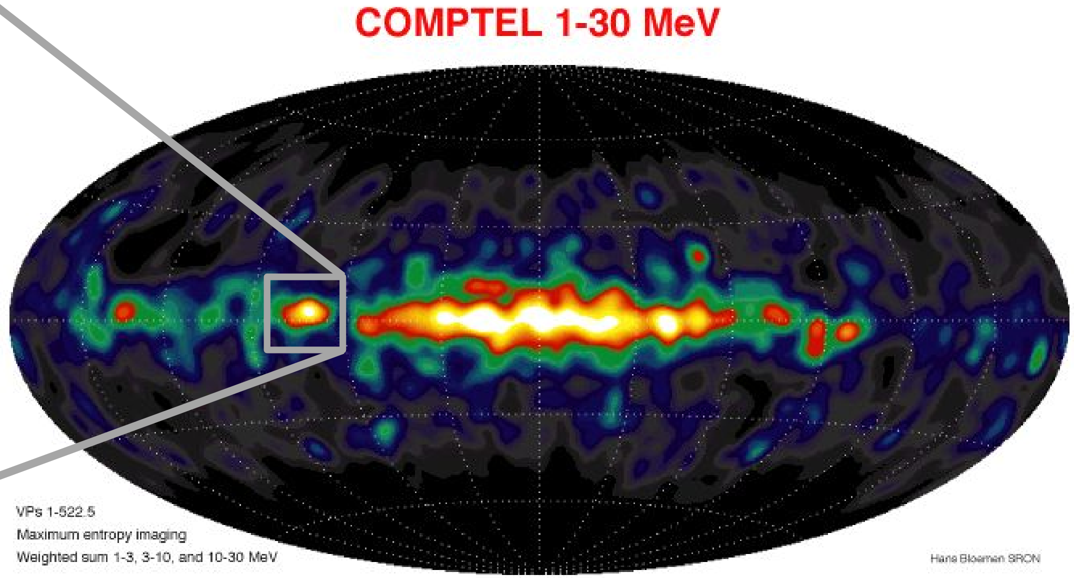


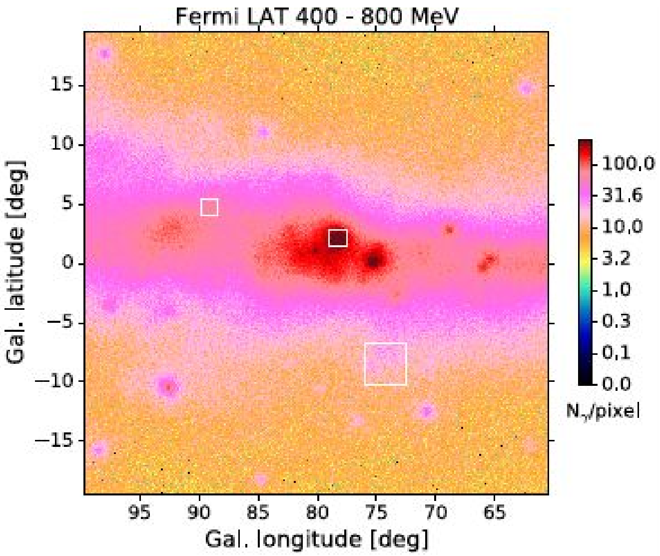


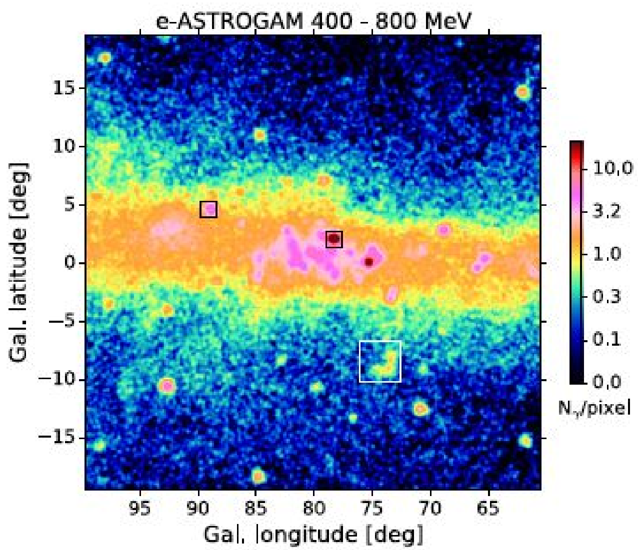
Simulated skymaps: e-Astrogam



<<Cygnus region in the 1 - 3 MeV energy band

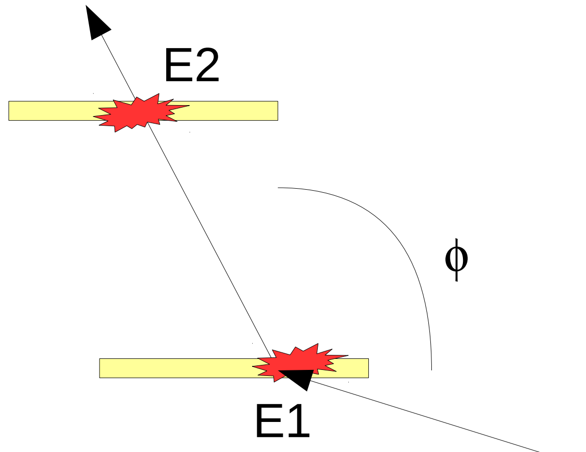


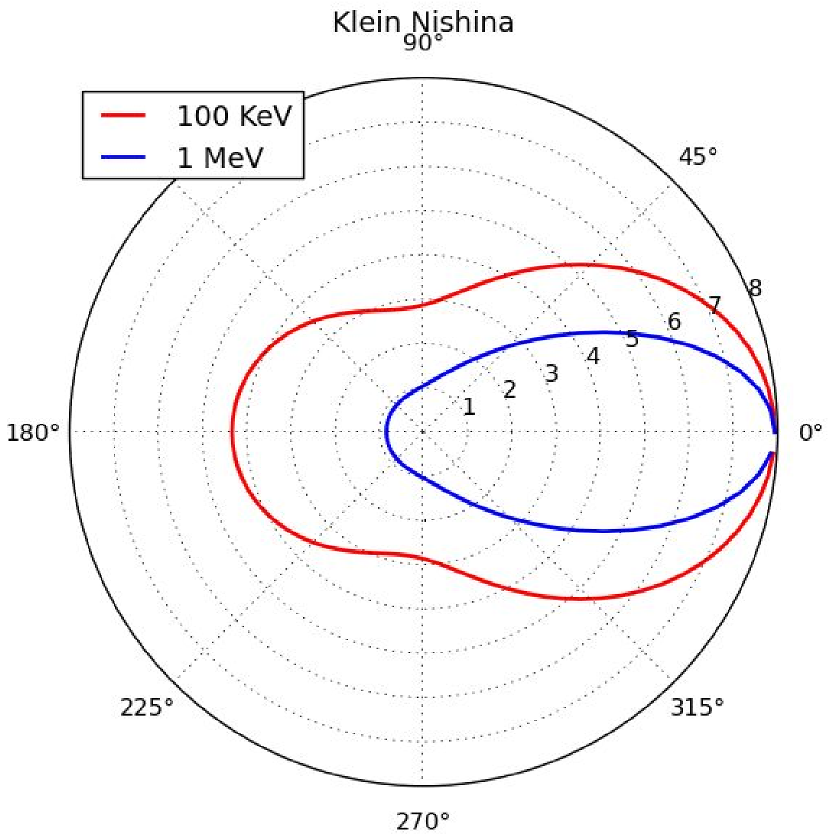




Event reconstruction

$$\cos\varphi = 1 - \frac{E_0}{E_g} + \frac{E_0}{E_g + E_e}$$



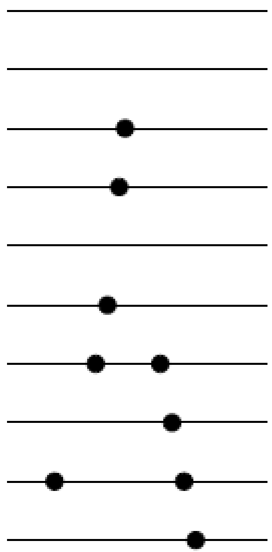


Energy and position concur in determining the event topology

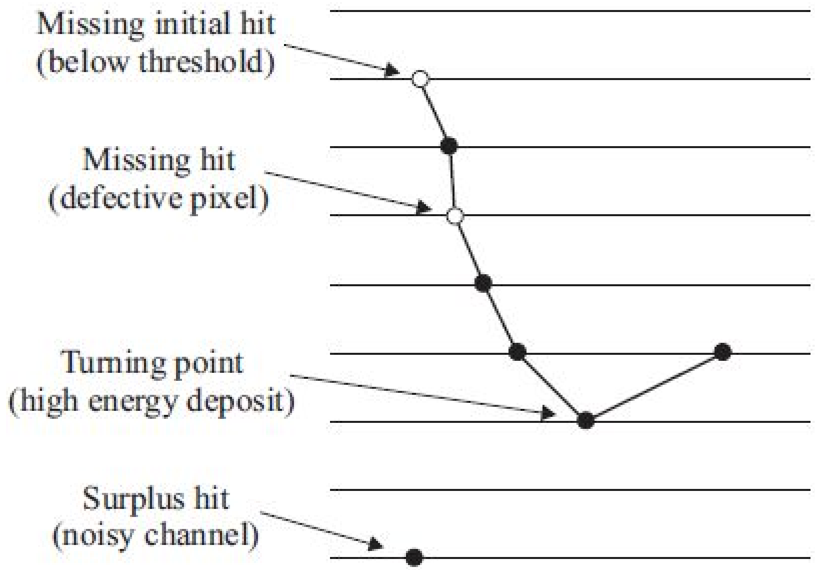
While pair signature is simple (secondaries “go forward”), the Compton sequence can be very complex

Hits in tracker

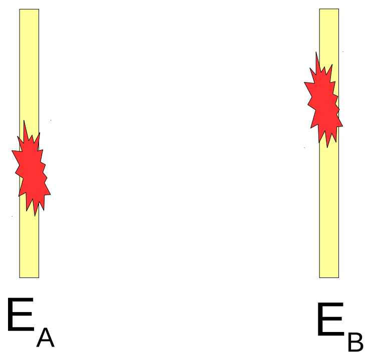
Pair



Compton

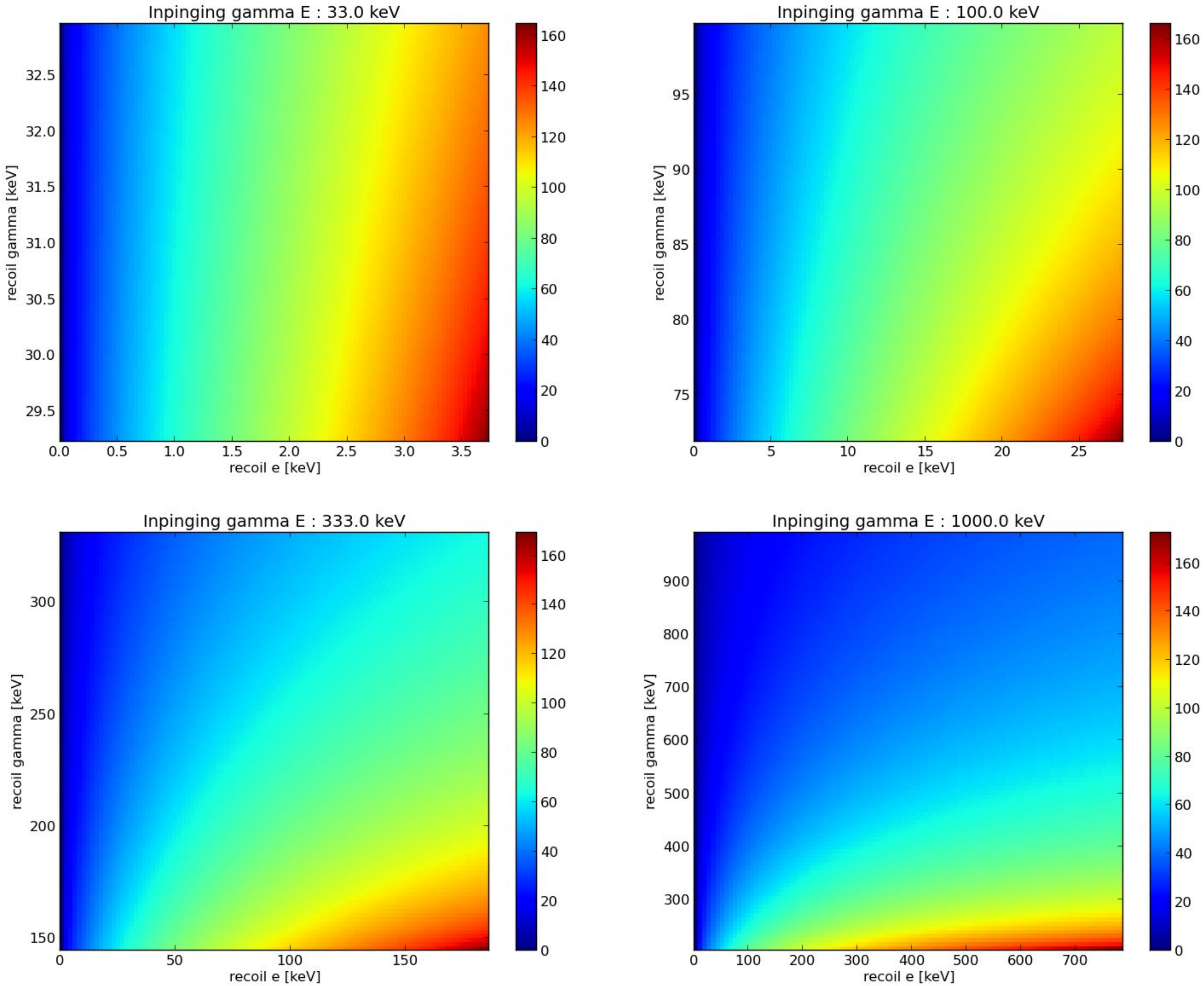


Adding energy information makes it worse: measurement errors can cause values to move out of kinematically allowed regions. This can lead to particle mid-ID, sequence mis-rec, etc.

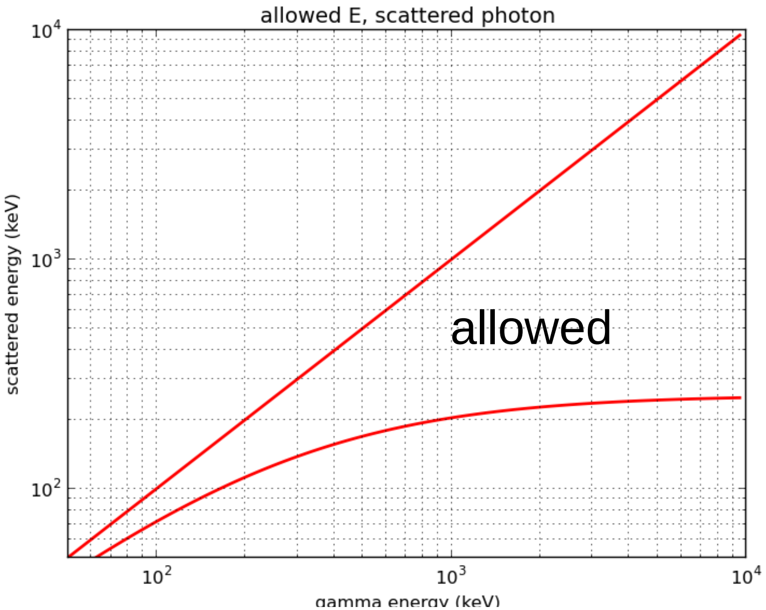


E.g. un-tracked event
Which is the Compton scattering (so the energy of the electron) and which the scattered gamma being absorbed?

Compton angle

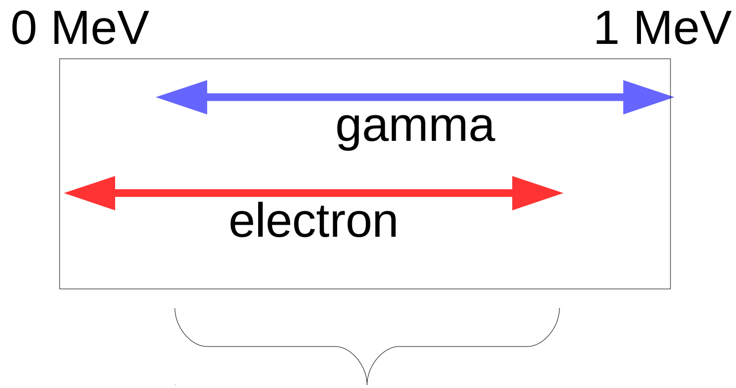


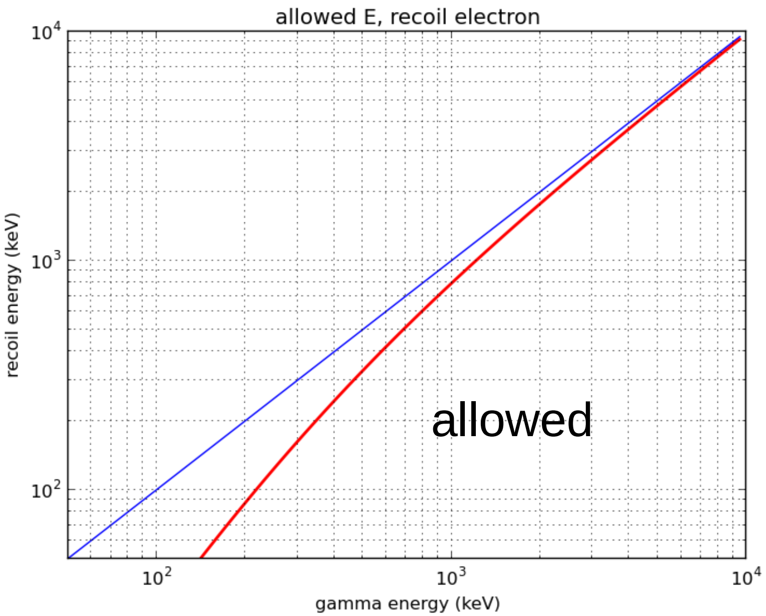
Compton: allowed energy



$$\frac{E_i E_0}{2E_i + E_0} < E_g < E_i$$

Ex: 1 MeV
Most probable:
forward scattering



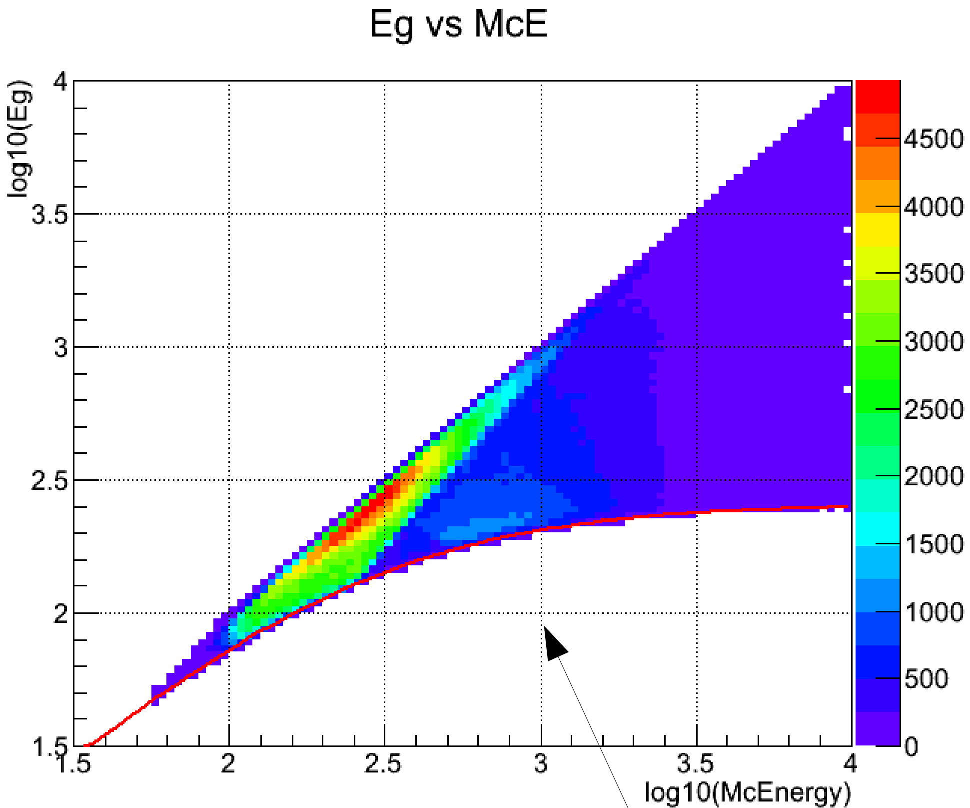


$$0 < E_e < \frac{2E_i^2}{2E_i + E_0}$$

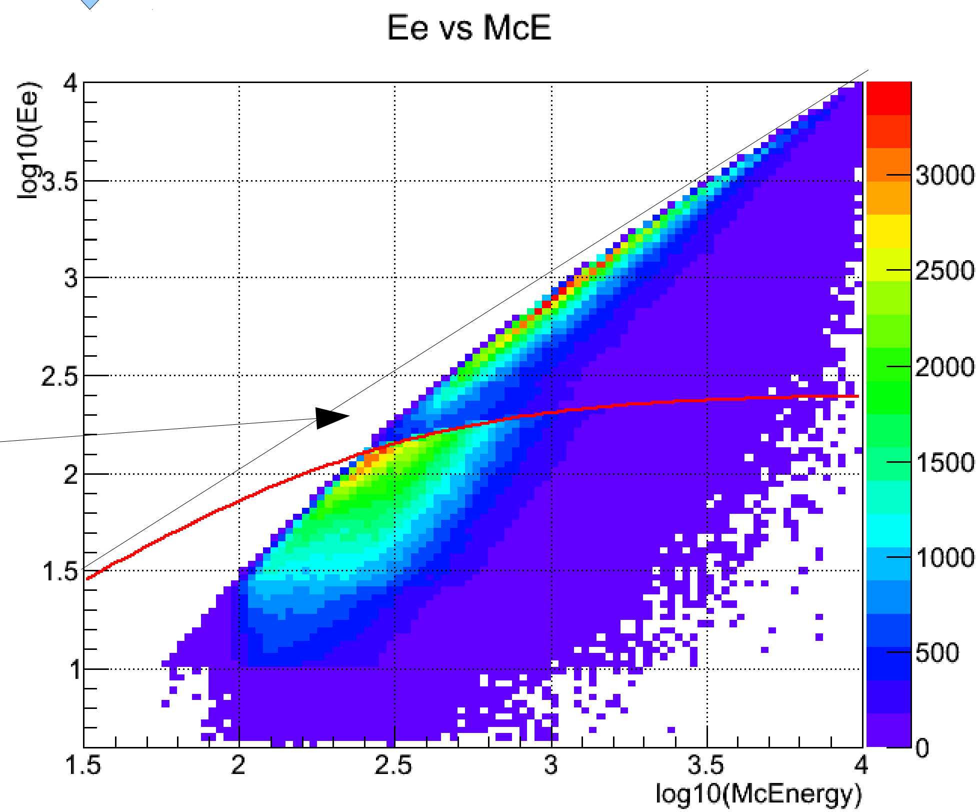
??

Large region of uncertainty
Beware of **E measurement errors**: can move into "unphysical" territory

Example: mis-Id for untracked events



Simulated gamma, power law spectrum, for a sample telescope with a **very thin calorimeter** (~1 cm CsI)

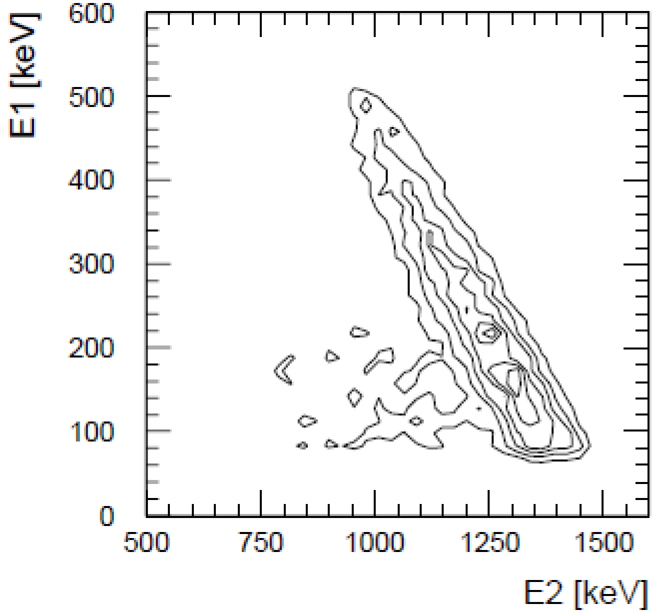


forbidden

Leakage leads to scattered gammas being confused with electrons. Event flips 180°, aperture of event cone is completely wrong ($E_g \leftrightarrow E_e$)

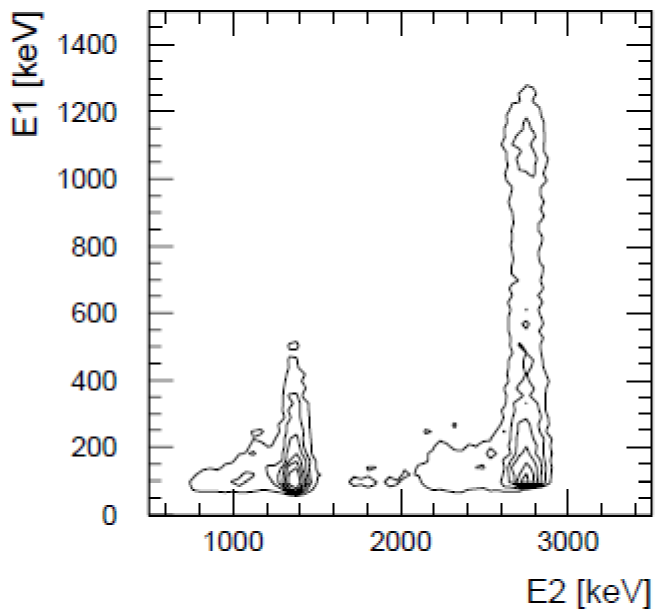
Activation

Materials exposed to space radiation
Protons and neutrons cause nuclear reactions: activation
Emission of lines from inside the ACD: no veto possible
No TOF in mission with a solid-state tracker + CAL
Activation will create a line background, troublesome for nuclear spectroscopy

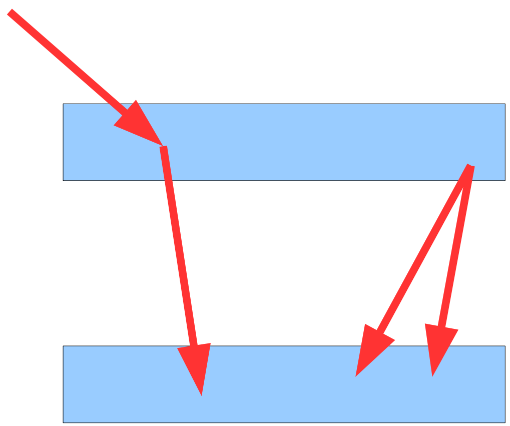


Single photon,
double hit

COMPTEL (simulations)
Left:
^{40}K events
Right:
^{24}Na events
(Weidenspointner)



Multiple photons



Avoid SAA!
~ equatorial orbit

COMPTEL isotopes

Isotope	Half-Life	Decay Modes and Photon Energies [MeV]	Main Production Channels
^{2}D	prompt	2.224	$^{1}H(n_{ther},\gamma)$
^{22}Na	2.6 y	β^+ (91%): 0.511, 1.275 EC (9%) : 1.275	$^{27}Al(p,3p3n)$, $Si(p,4pxn)$
^{24}Na	14.96 h	β^-: 1.37, 2.75	$^{27}Al(n,\alpha)$, $^{27}Al(p,3pn)$
^{28}Al	2.2 min	β^-: 1.779	$^{27}Al(n_{ther},\gamma)$
^{40}K	1.28×10^{9} y	EC (10.7%): 1.461	natural
^{52}Mn	5.6 d	EC (64%): 0.744, 0.935, 1.434 β^+ (27%): 0.511, 0.744, 0.935, 1.434	Fe(p,x), Cr(p,x), Ni(p,x)
^{57}Ni	35.6 h	β^+ (35%): 0.511, 1.377 EC (30%): 1.377	Ni(p,x), Cu(p,x)
^{208}Tl	1.4×10^{10} y (^{232}Th)	β^- (50%): 0.583, 2.614 β^- (25%): 0.511, 0.583, 2.614	natural

Design concepts & some issues

Tracker:

- Double sided SSD
- Lots of it! (60 layers)
- No conversion foils (still good for pairs in the lower Fermi-LAT band)
- Analog readout (best hit resolution)
- Minimal support structure (careful of strip readout both sides!)

Calorimeter:

- Thick, hermetic as possible
- Good hit resolution (small CsI blocks, CZT virtual Frisch grid [AMEGO])

Possible issues:

Tracker:

- Expensive!!!
- Many channels
- Power (per channel → total)
- Mechanical robustness

Calorimeter:

- Many channels
- Complex structure
- Mechanical robustness

Waiting for exciting new discoveries!