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L'esperimento di Astrofisica GLAST – il Large Area Telescope

Scuola Nazionale "Rivelatori ed Elettronica per Fisica delle Alte Energie, Astrofisica e Applicazioni Spaziali"
INFN Laboratori Nazionali di Legnaro
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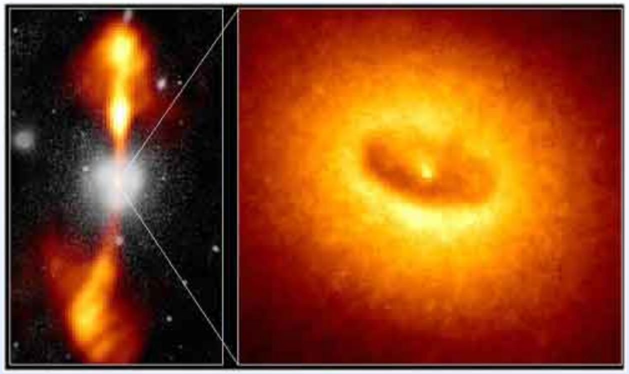
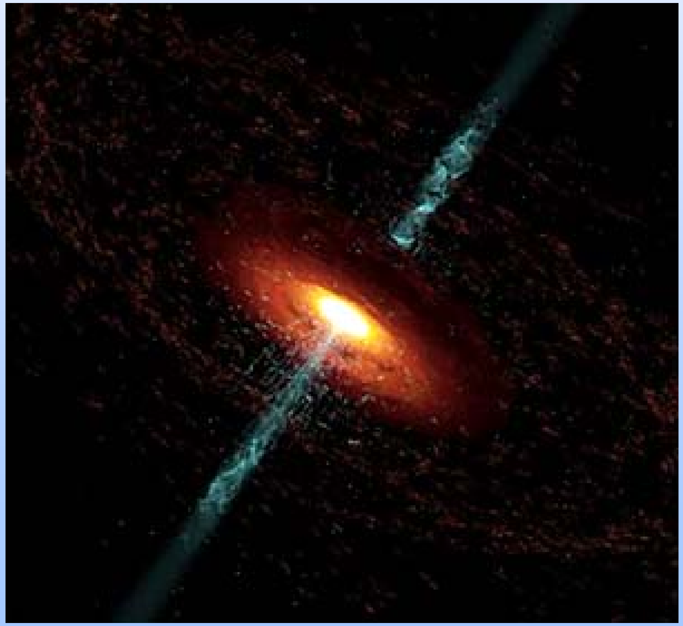
Outline

- Gamma astrophysics: sources & detection
- Tracking telescopes
- LAT
- LAT subsystems (ACD,TKR,CAL)
- GLAST Trigger and Data Acquisition
- Status & conclusions

High Energy Astrophysics

- gamma rays: highly penetrating
- γ's are not affected by the galactic magnetic field
- provide insight on the most energetic phenomena in the universe
- interface between cosmology and high-energy particle physics
- investigate the birth and evolution of the Universe
- requirements:
  - reconstruct energy,direction
  - timing informations
  - reject (lots of) background events





AGN/PSR

• **AGN: stellar-like engine, beamed emission of energy**

• **spectra: from radio to gamma**

• **different models for inner engine (leptonic, hadronic)**

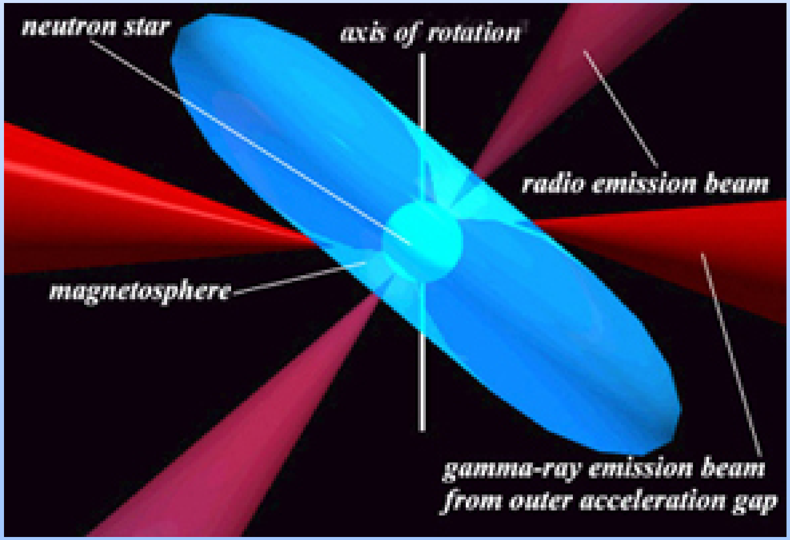
• **b*road energy coverage, sensitivity***

• **PSR: magnetized rotating neutron stars**

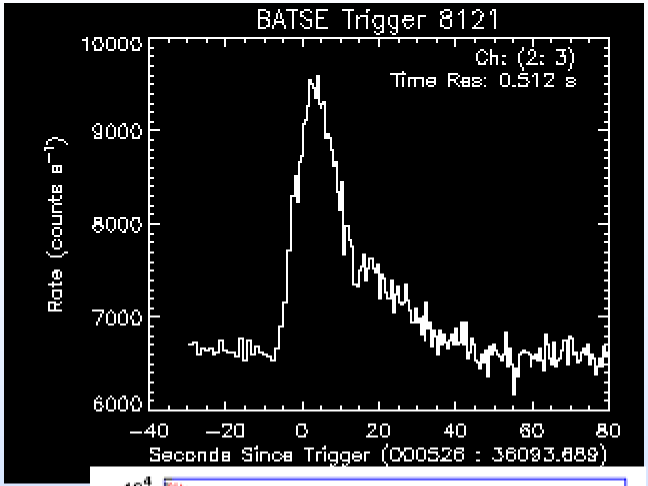
• **30 pulsars known at gamma energies**

• ***sensitivity and time response* to identify the periodic signal**

• **different models describe emission of accelerated particles, *multiwavelength analysis* to discriminate by spectral analysis**

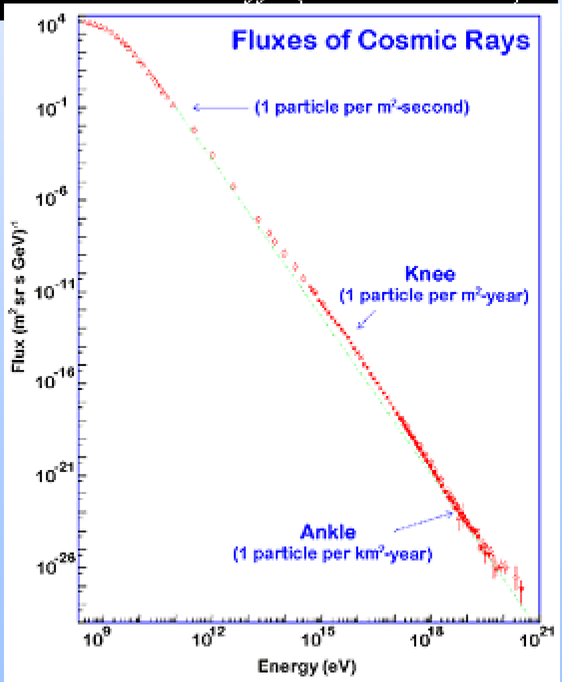


GRB/CRs



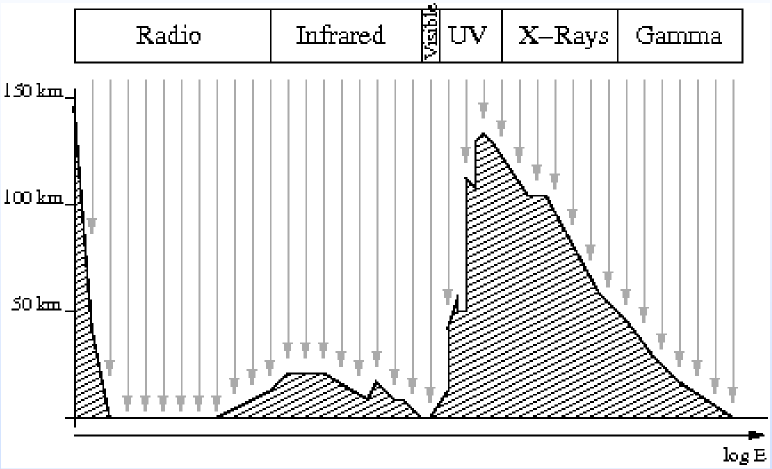
- **GRBs: gamma flashes, discovered in 1967**
- **BATSE measured 2704 GRBs in 9 years, isotropic distribution in the sky**
- **different spectral characteristics, time structure: 1000 s down to sub-ms features**
- **model involves the collision of blobs of relativistic matter ejected from a central engine, *broad energy coverage* and *fast time response* are required**

- **CRs: known since 1912, Nobel prize (Hess) in 1936**
- **unknown origin (yet)**
- **89% H, 10% He, 1% all heavier elements**
- **energies up to 10^{20} ev ( at 250 km/h!)**
- **supernovae are candidate sites of CR acceleration**
- **observations of interactions of CR and ISM near a supernova remnant could settle the issue: *resolution***



Detecting Cosmic Gamma Rays

- though gamma rays are penetrating, atmospheric integrated density is ~ 1 kg/cm^2
- at higher energy (TeV) the whole atmosphere is the detecting medium (Cerenkov, ACT)
- at lower energies: balloons / satellites are required to avoid the atmospheric attenuation



Instruments

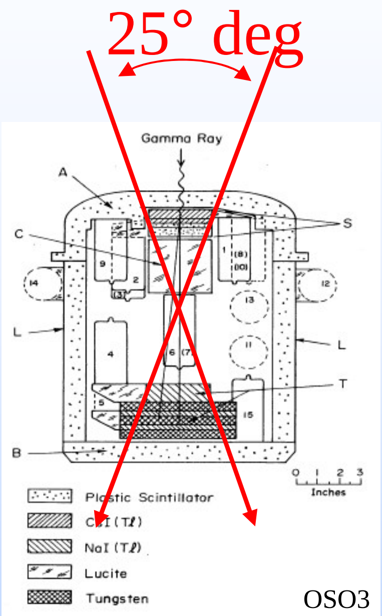
• scintillators (CsI, NaI, BGO, ...)

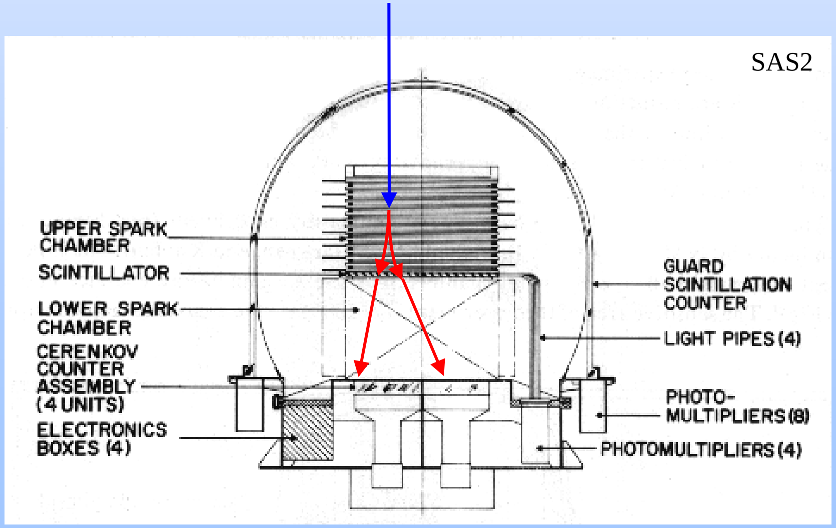
• Cerenkov counters

• collimators (as in X-ray telescopes) are not suitable

• early: active collimation, the active elements define a pointing direction with their arrangement

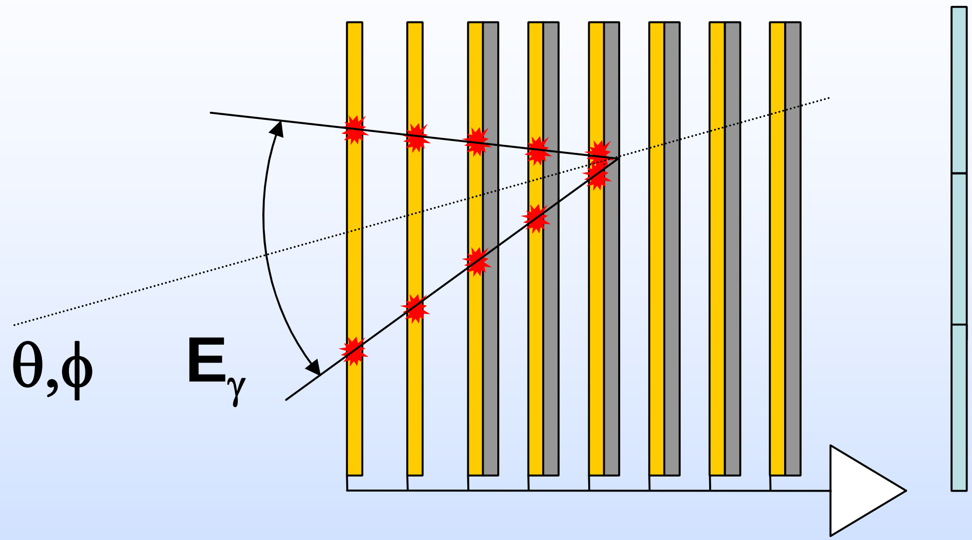
• currently: trackers (spark chambers, silicon), direction is reconstructed from secondaries

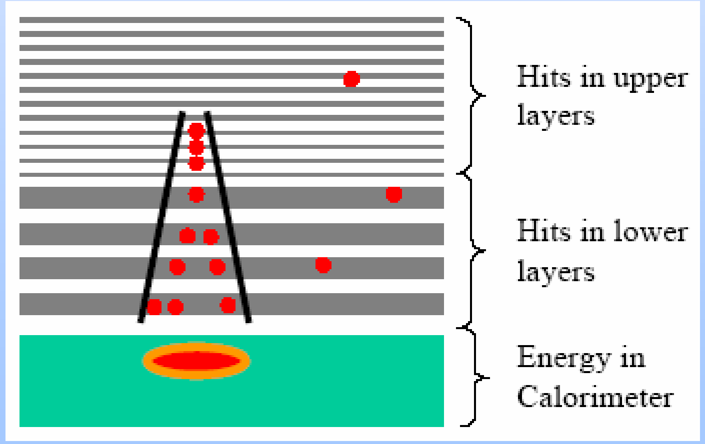




Photons are converted...

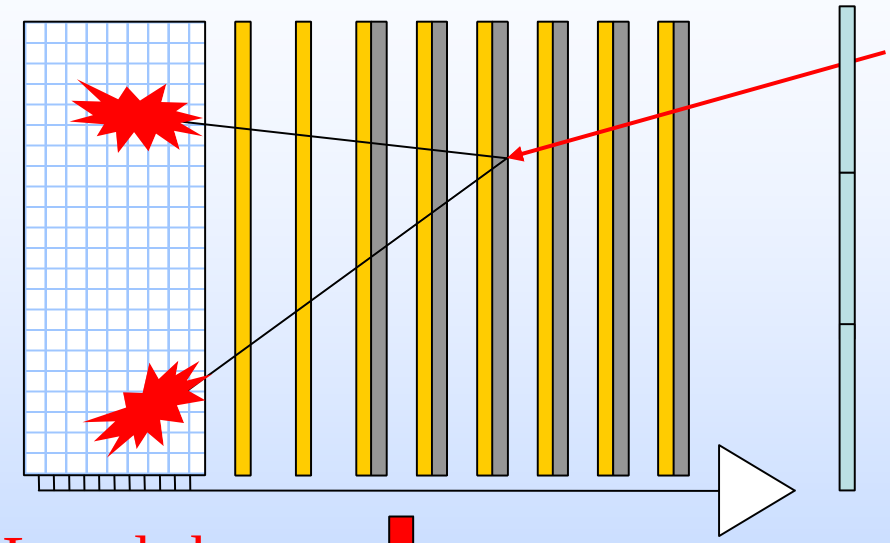
- above 20 MeV pair-production is by far the most probable interaction a photon will experience
- photons are converted into electron-positron pairs in the high-density layers within the tracker (every X_0: prob 78%)
- e^+/e^- are tracked (track recon, vertexing)
- γ direction is recovered
- tracker is used as a sampling calorimeter to measure energy loss in the converter foils



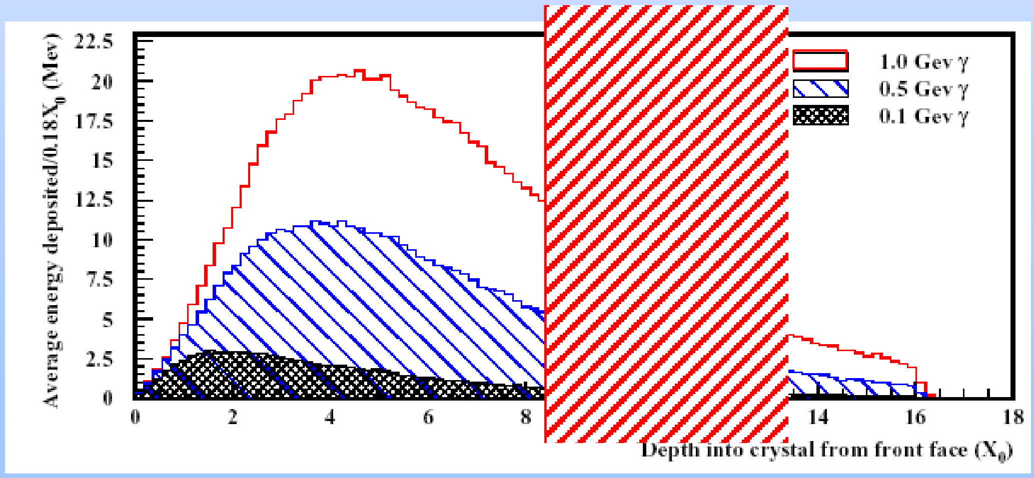


...and secondaries are scored

- in the remaining layers the electrons lose energy
- in the calorimeter an EM shower develops
- due to satellite constraints, a lot of energy will be lost! (calorimeter is small, made of non-adjacent blocks)
- complicated energy reconstruction procedures will be required:
    - loss from the back
    - loss from the sides
    - loss in gaps
    - loss in the TKR



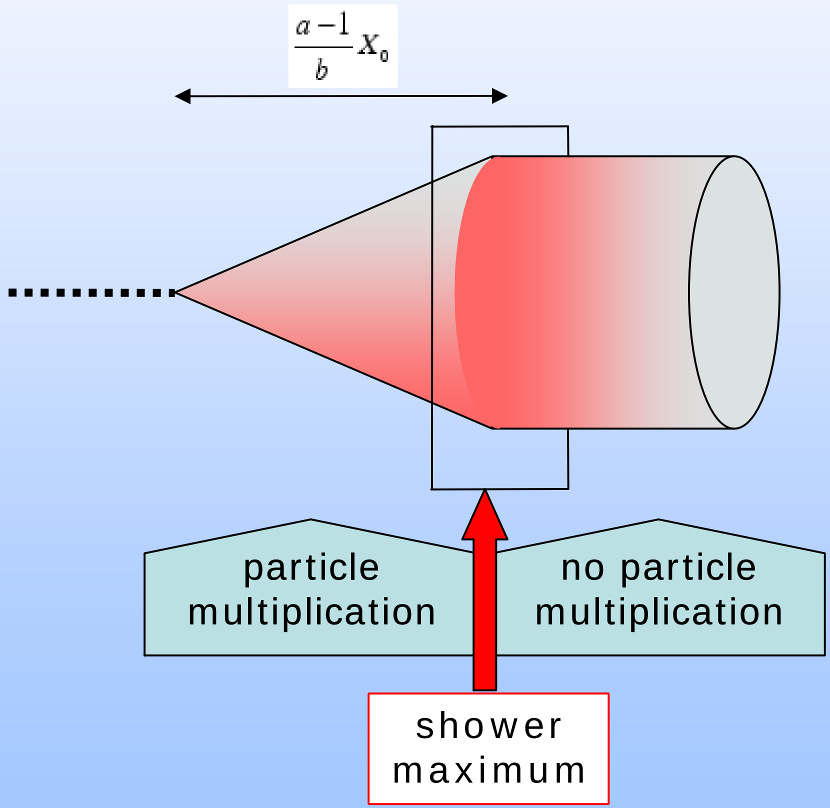
CAL ends here



CAL E losses

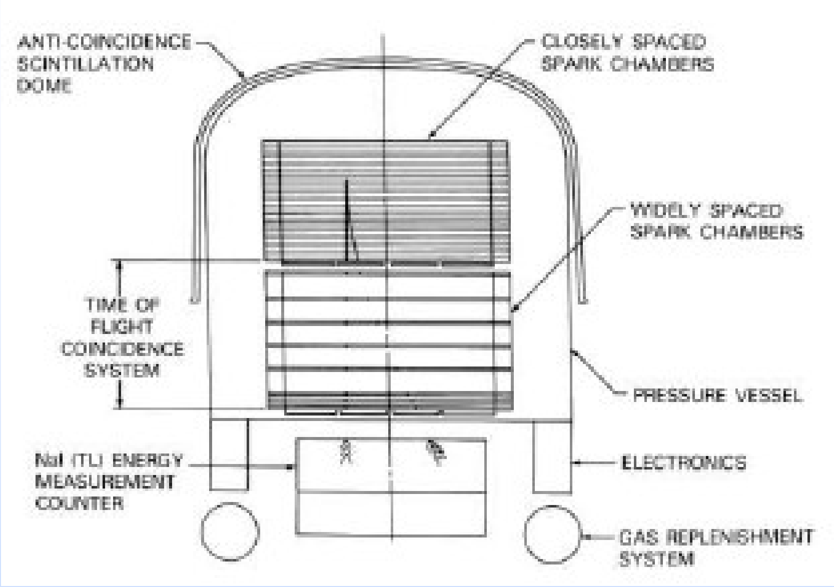
- longitudinal modelling: cone, saturating to a cylinder at shower maximum
- transverse modelling, function of Moliere radius
- if shower maximum is NOT contained shower longitudinal profile is fitted to reconstruct energy leaked from the bottom
- if shower maximum is contained the procedure is much easier: the number of escaping particles is proportional to the energy released in the last layer (8^{th})
- leakage from the edges depend on (reconstructed) angle and hit position
- $\Rightarrow$ exceedingly complicated energy reconstruction algorithm!

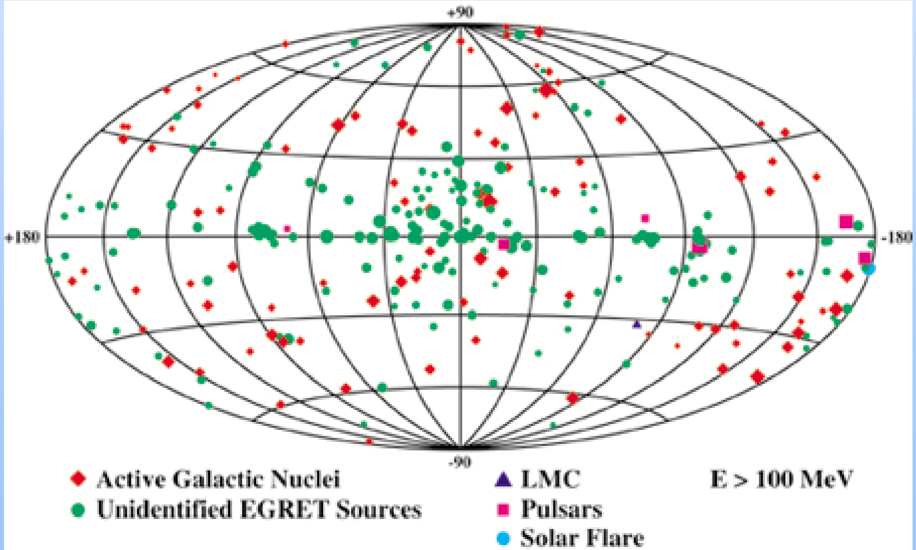
$$\frac{dE}{d(bt)} = E_0 \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$



Last flown: Egret

- closely spaced spark chamber for tracking
- widely spaced spark chamber for TOF
- NaI(Tl) calorimeter (7.7 X_0)
- plastic anticoincidence dome
- energy resolution ~10%
- angular res. 10° (60 MeV) to 1° (10 GeV)
- problems from backsplash from the CAL: the anticoincidence was too close
- map of the galactic background
- 3EG catalogue, 271 point sources (most blazars, 5 pulsars, 170 still unidentified)

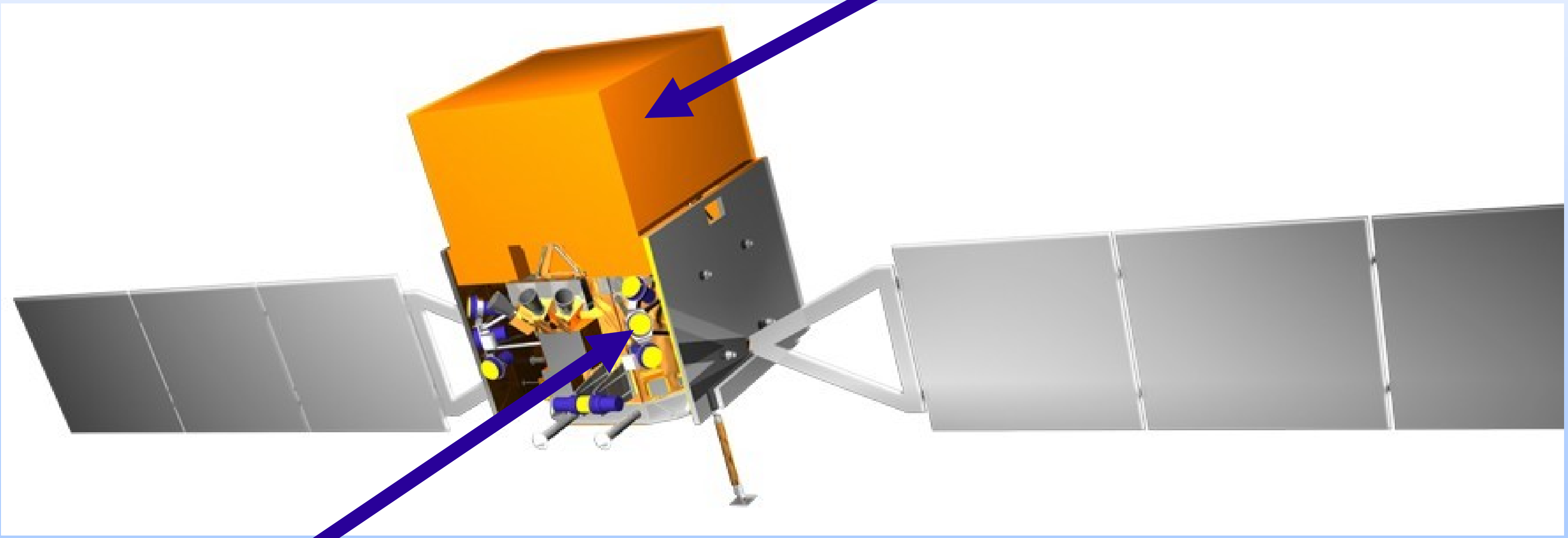




GLAST

- Large Area Telescope: a silicon pair-conversion tracking telescope
- GLAST Burst Monitor: scintillating detectors
- Spacecraft

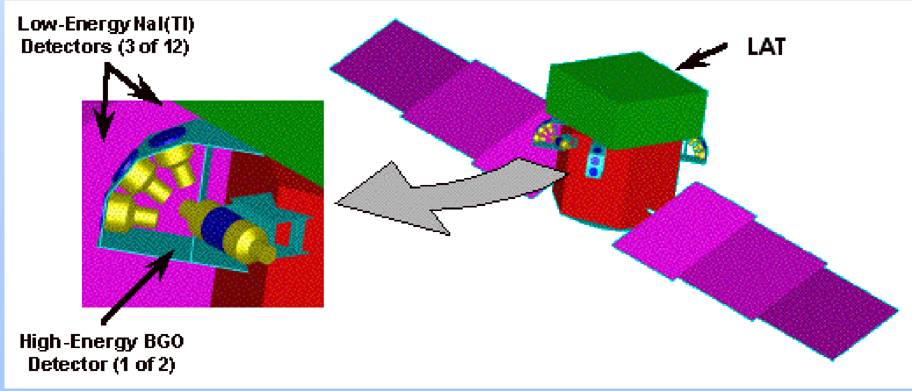
LAT



GBM

GBM

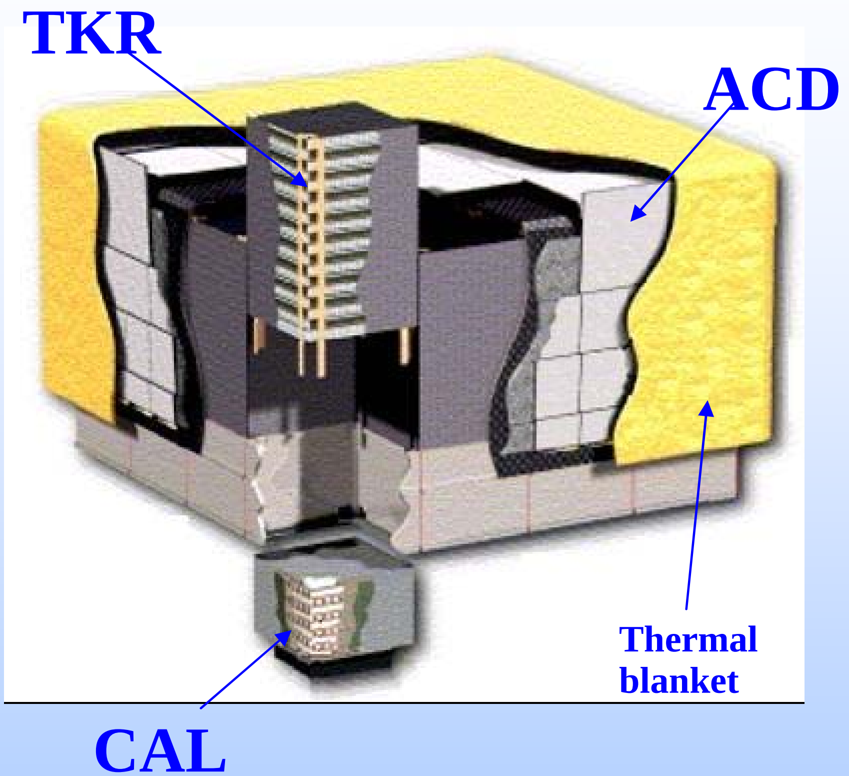
- 12 Low Energy Detectors (NaI, few keV to 1 MeV)
- 2 High Energy Detectors (BGO, 10 keV to 25 MeV)
- GBM covers the low energy end, overlapping with the LAT at high energy
- field of view ~ 8 srd
- time resolution 2 μs, GRB fast detection in ~2 s
- energy resolution 20% at 511 keV, 7% at 2 MeV



Parameter	GBM requirement	BATSE
Energy range	8 keV - 1 MeV (LED) 150 keV - 30 MeV (HED)	10 keV - 1.8 MeV (LAD) 15 keV - >30 MeV (SD)
Energy resolution	20% FWHM at 511 keV	~20% FWHM at 511 keV
Time resolution	10 μs	2 μs
On-board GRB locations	20° accuracy (1σ) within 2 s	none
Rapid ground GRB locations	5° accuracy (1σ) within 5 s	10° within 5 s 3° within 5 min
GRB sensitivity	0.5 ph/(cm^{2}s) (peak flux, 50-300 keV)	0.1 ph/(cm^{2}s) (peak flux, 50 300 keV)
Field of view	8 srad	4π srad
Deadtime	<10 μs/count	~10 μs/count

LAT

- silicon tracker, W converter foils
- CsI calorimeter
- plastic ACD
- DAQ electronics
- modular design
- 4 towers, each with TKR, CAL
- segmented ACD



Quantity	LAT Spec.	EGRET
Energy Range	20 MeV - 300 GeV	20 MeV - 30 GeV
Peak Effective Area	> 8000 cm^2	1500 cm^2
Field of View	> 2 sr	0.5 sr
Angular Resolution (100 MeV)	< 3.5°	5.8°
Angular Resolution (10 GeV)	< 0.15°	
Energy Resolution	< 10%	10%
Dead Time	< 100 μs	100 ms
Source Location Determination	< 0.5′	1.5′
Point Source Sensitivity	$< 6 \times 10^{-9} cm^{-2} s^{-1}$	$\simeq 10^{-7} cm^{-2} s^{-1}$

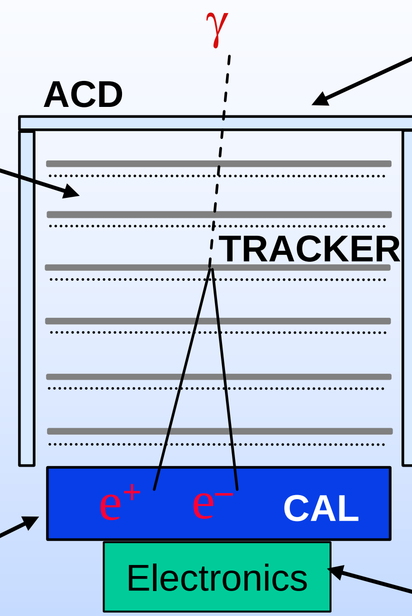
Science drivers on design

Effective area and **PSF** requirements drive the converter thickness and layout. PSF requirements also drive the sensor performance, layer spacing, and the design of the mechanical supports.

FRONT 3 $\%X_o$
BACK 18 % X_o
PITCH 228 µm

Energy range and **energy resolution** requirements bound the thickness and layout of calorimeter

8.5 X_o
HODOSCOPIC, GRANULAR

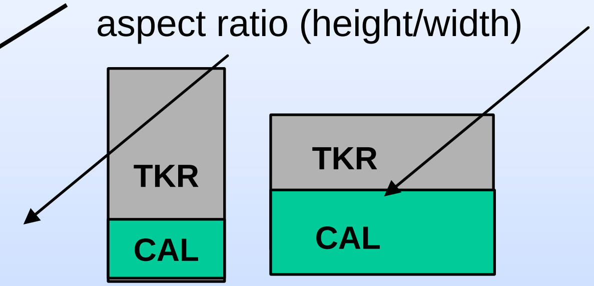


On-board transient detection requirements, and **on-board background rejection** to meet telemetry requirements are relevant to the electronics, processing, flight software, and trigger design.

Background rejection requirements drive the ACD design (and influence the calorimeter and tracker layouts).

0,9997 EFFICIENCY
SEGMENTED,REDUNDANT

Field of view sets the aspect ratio (height/width)



Time accuracy provided by electronics and intrinsic resolution of the sensors.

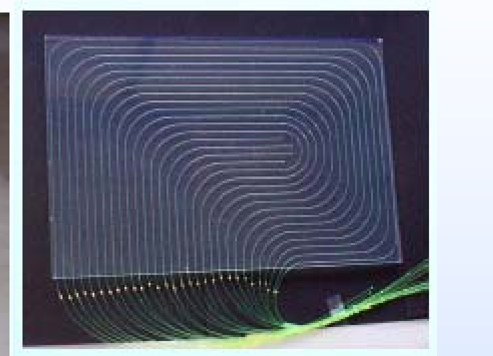
NO DEAD _TIME FROM SILICON SENSORS

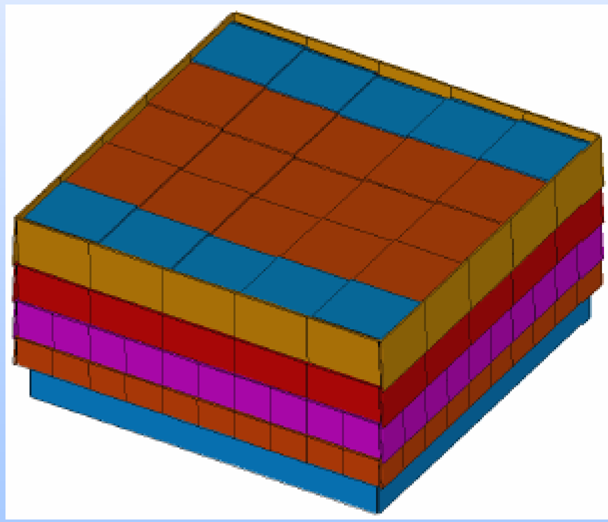
Instrument life has an impact on detector technology choices (NO CONSUMABLES). Derived requirements (**source location determination** and **point source sensitivity**) are a result of the overall system performance.

From: L. Latronico, ICATPP03

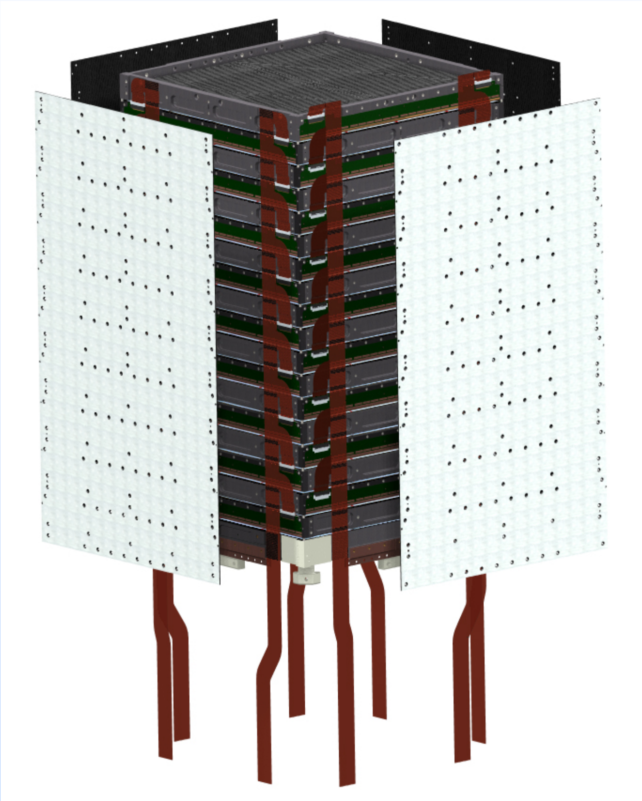
AntiCoincidence Detector

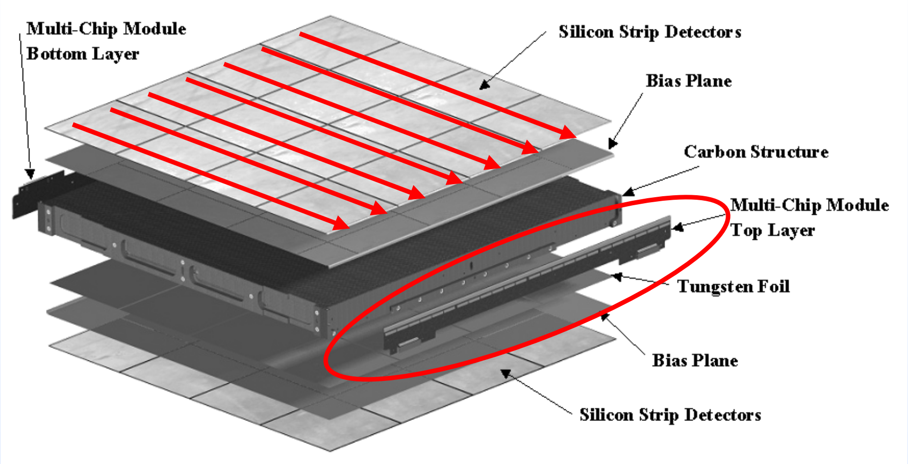
- tiles of plastic scintillator, wavelength shifting fibers, photomultiplier tubes
- light-tight case for each tile to limit impact of micrometeorite damage
- power < 31 W
- reject charged particles (10^5 more than γ's)
- low energy photons from CAL (0.2÷2 MeV) give Compton signal comparable to a MIP
- 50% less A_{eff} in EGRET!! (at 10 GeV, with respect to 1 GeV)
- segmentation can associate this events to CAL backsplash and avoid self-vetoing (to less than 20% of “dangerous” events)





Tracker

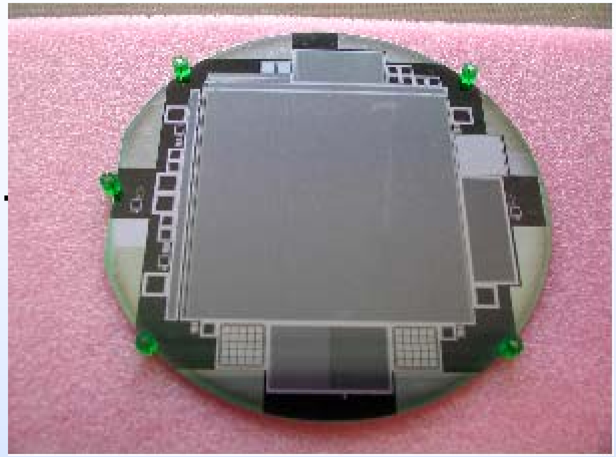




- electronic modules tested at INFN Pi, assembles on two sides of tray (top/bottom)
- each tray is stacked on the others, rotated by 90 degrees
- a tower is composed by 19 trays, 12 with a thin W foil (0.03 X_0), 4 with a thick foil (0.18 X_0) and 3 w/o converter

Silicon detectors

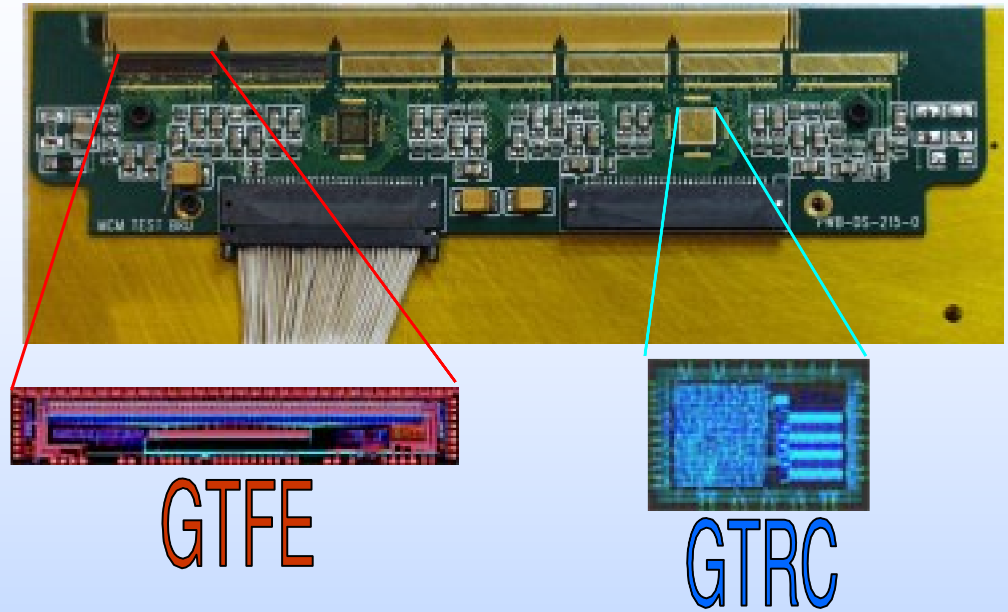
- Hamamatsu: qualified producer for HEP experiments
- 11,500 SSD delivered (10,368 for assembly [83 m^2] + spares + wastage + prototypes)
- 885,000 channels!!!
- tested at HPK
- quality is so high that no search for bad strips is needed: only sum current is checked
- rejection rate at INFN lower than 0.6%
- after ladder assembly: loss rate ~2% (1% for mishandling), 0.03% bad strips

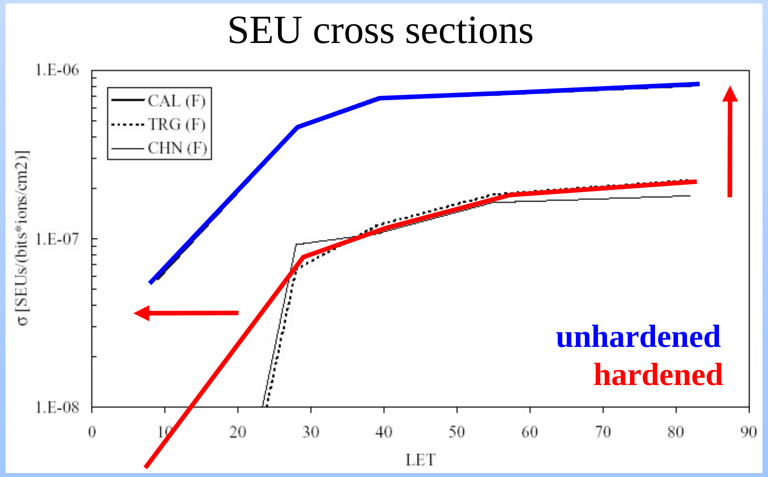


Parameter	Specification
Thickness	400 μm
Outer size	$8.95 \times 8.95\ cm^2$
Active area	$8.76 \times 8.76\ cm^2$
Strips per detector	384
Strip pitch	228 μm
R_{bias}	>20, <80 MΩ
$C_{interstrip}$ at 150 V, 1 MHz	<1.5 pF/cm
$C_{coupling}$	> 500 pF
Depletion voltage	< 120 V
Breakdown voltage	> 175 V
I_{leak} at 200 V	< 600 nA
Bad strips	<0.2%

TKR electronics

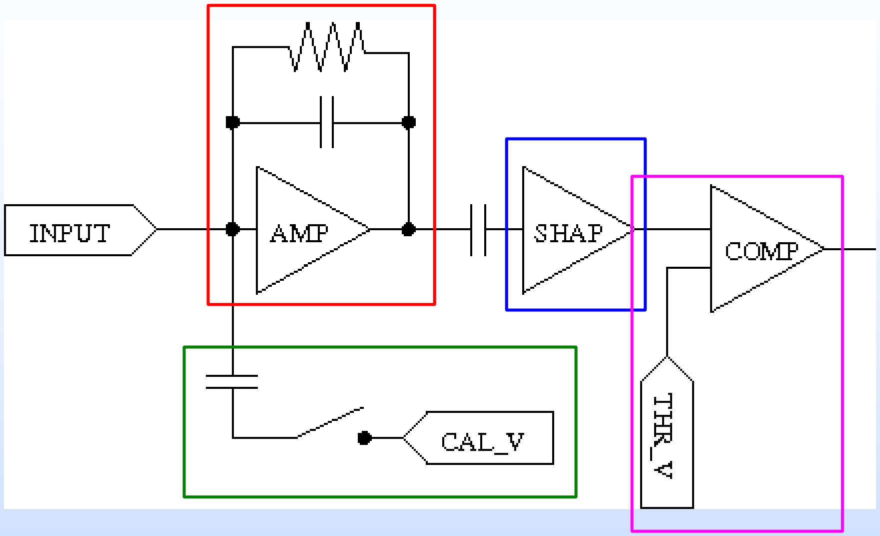
- 1536 channels per tower plane: 24 FE ASICs with 64 strips each
- 2 Readout Controllers, one on each side, manage communications
- GTFE pads bonded to a pitch adapter and to the silicon sensors
- GTRC connected with a flex cable to the DAQ cable controllers on the Tower Electronics Module, below TKR
- registers hardened against SEU (Rockett, 1988)
- ASICs hardened against SEL (thin epi-layer)
- tests with heavy ions, gamma rays

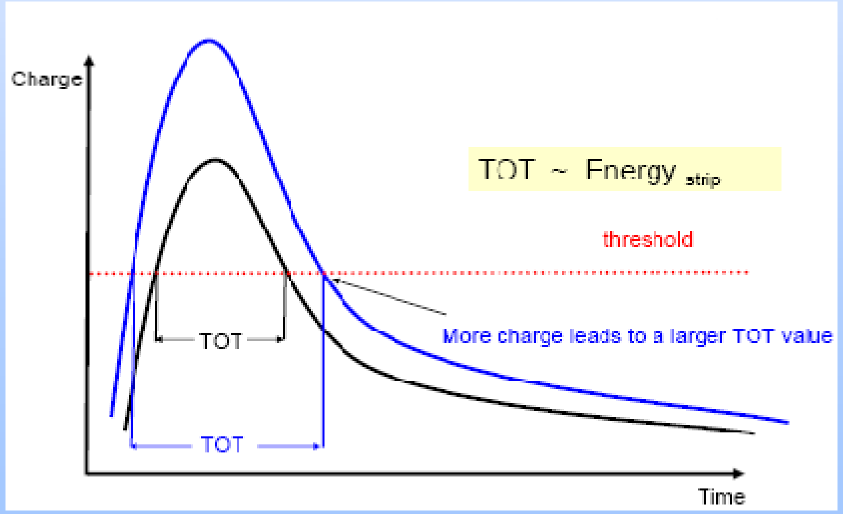




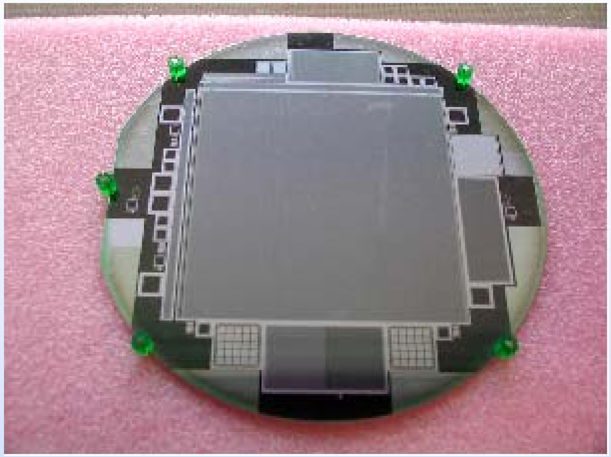
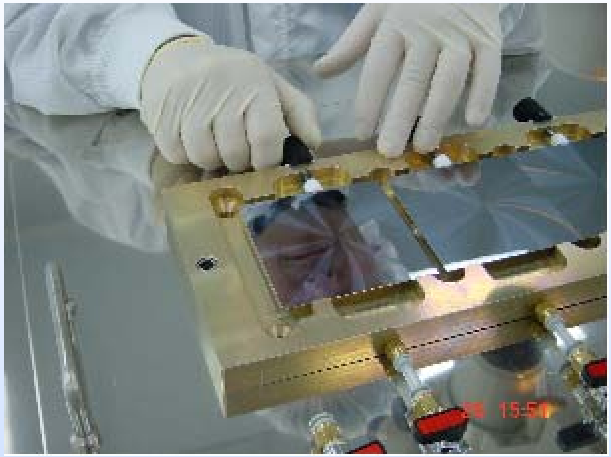
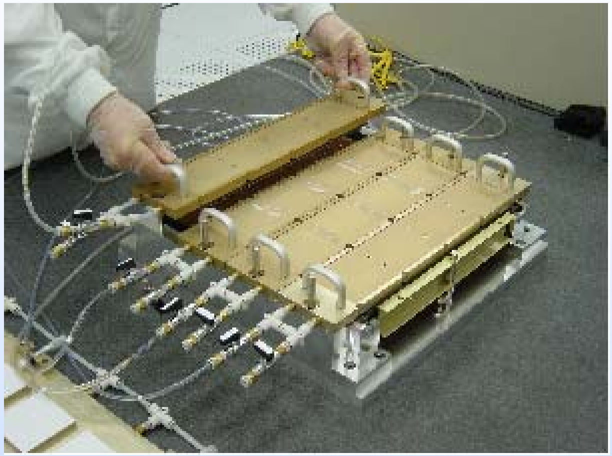
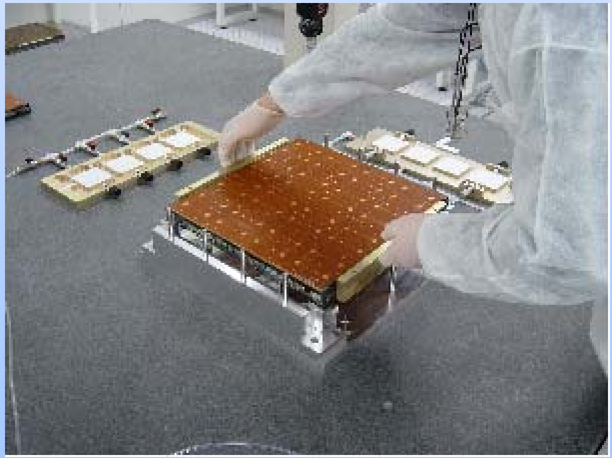
GTFE structure

- low power cascode amplifier, 37 mV per MIP
- RC-CR shaper, 1.5 μs
- single-threshold comparator
- a calibration capacitor allows for charge injection for testing
- all channels in a GTFE are OR-ed, OR is propagated to other GTFEs to generate a fast trigger request for an entire layer
- pulse height is not measured: it can be obtained measuring time-over-threshold
- low power (<250 μW per channel)
- low noise occupancy ($<10^{-4}$ ch/trg)
- complete zero-suppression

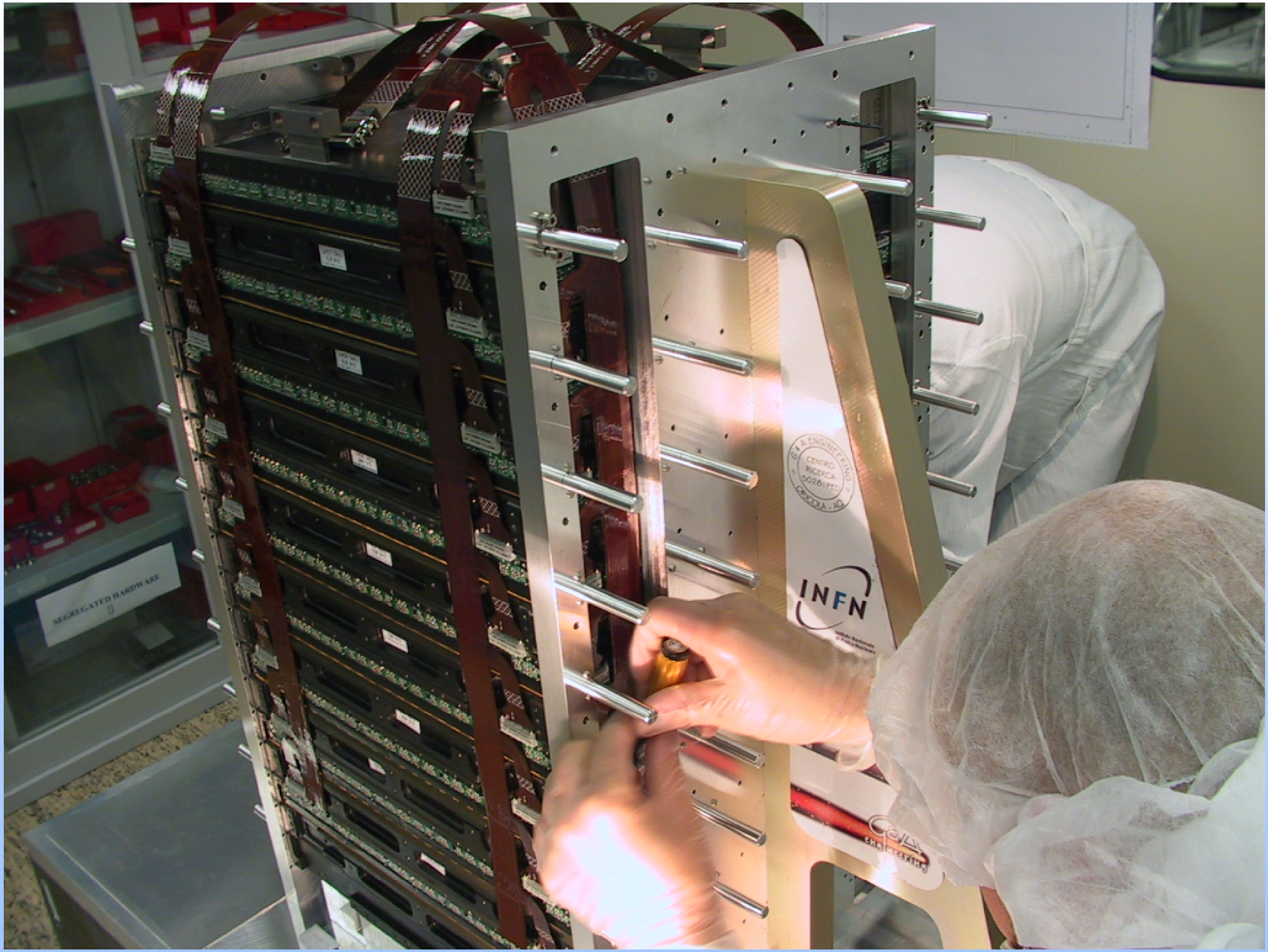




TKR assembly

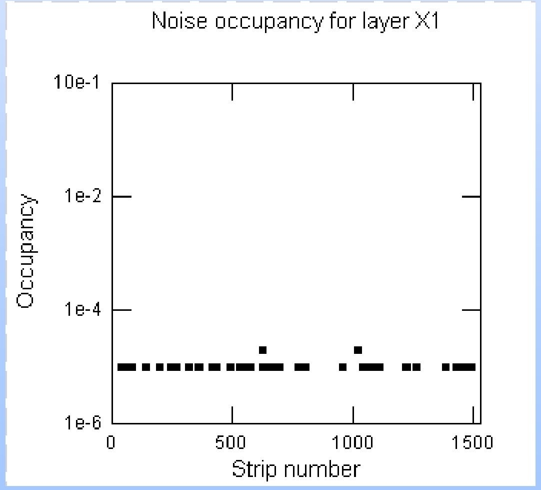





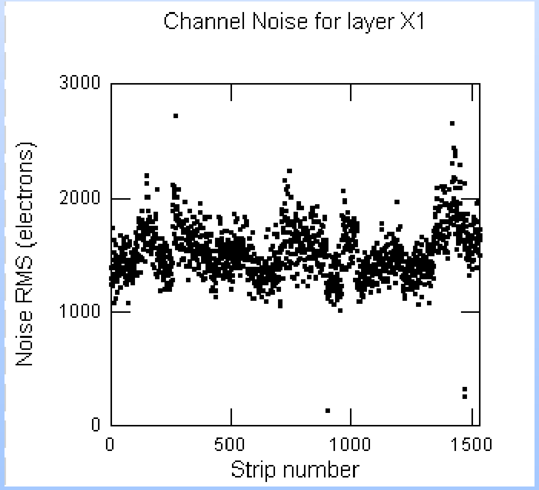
Tower!

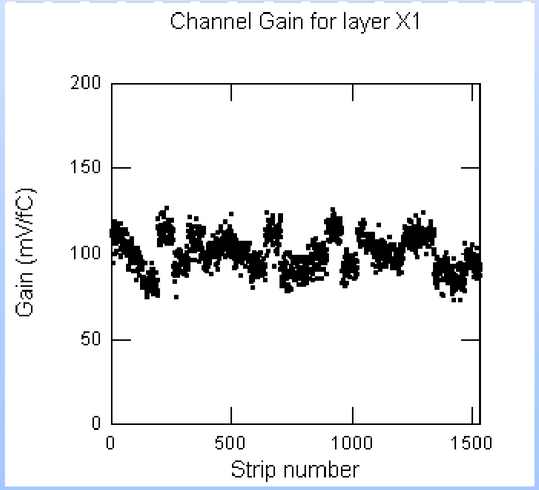


Integration

- INFN Pisa receives TKR flight parts
- MCMs are tested, before and after being assembled in a TKR tray
- complete trays are tested
- trays are assembled in a stack configuration and a self-triggering data acquisition is performed
- flight trays are assembled into a tower!

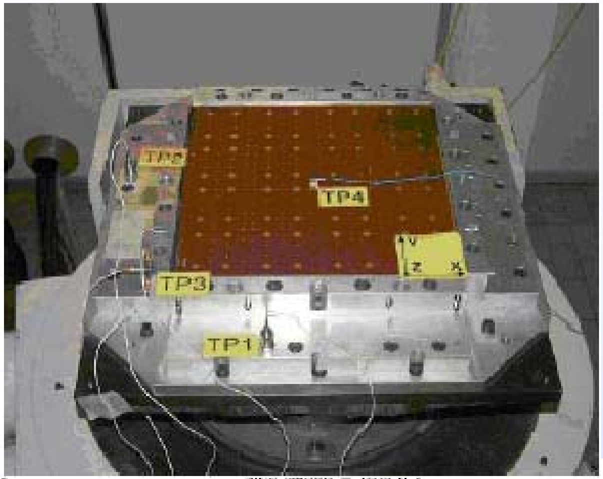


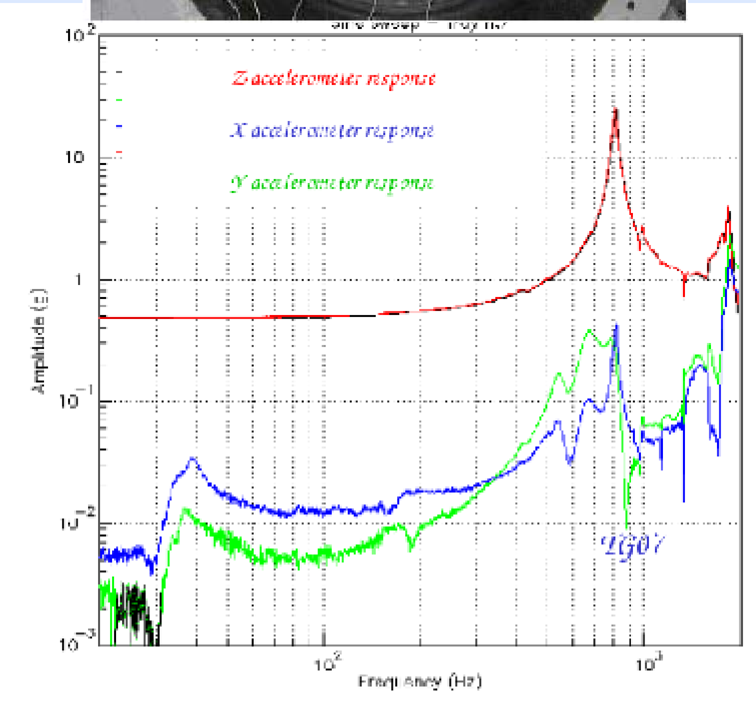




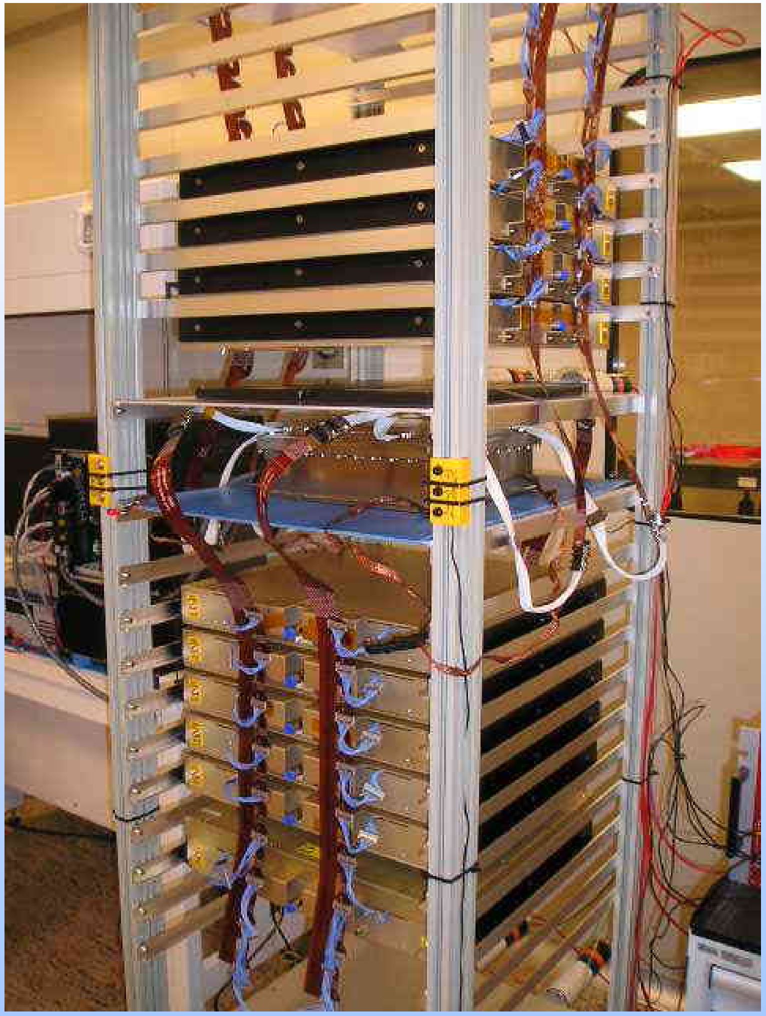
TKR vibrational tests

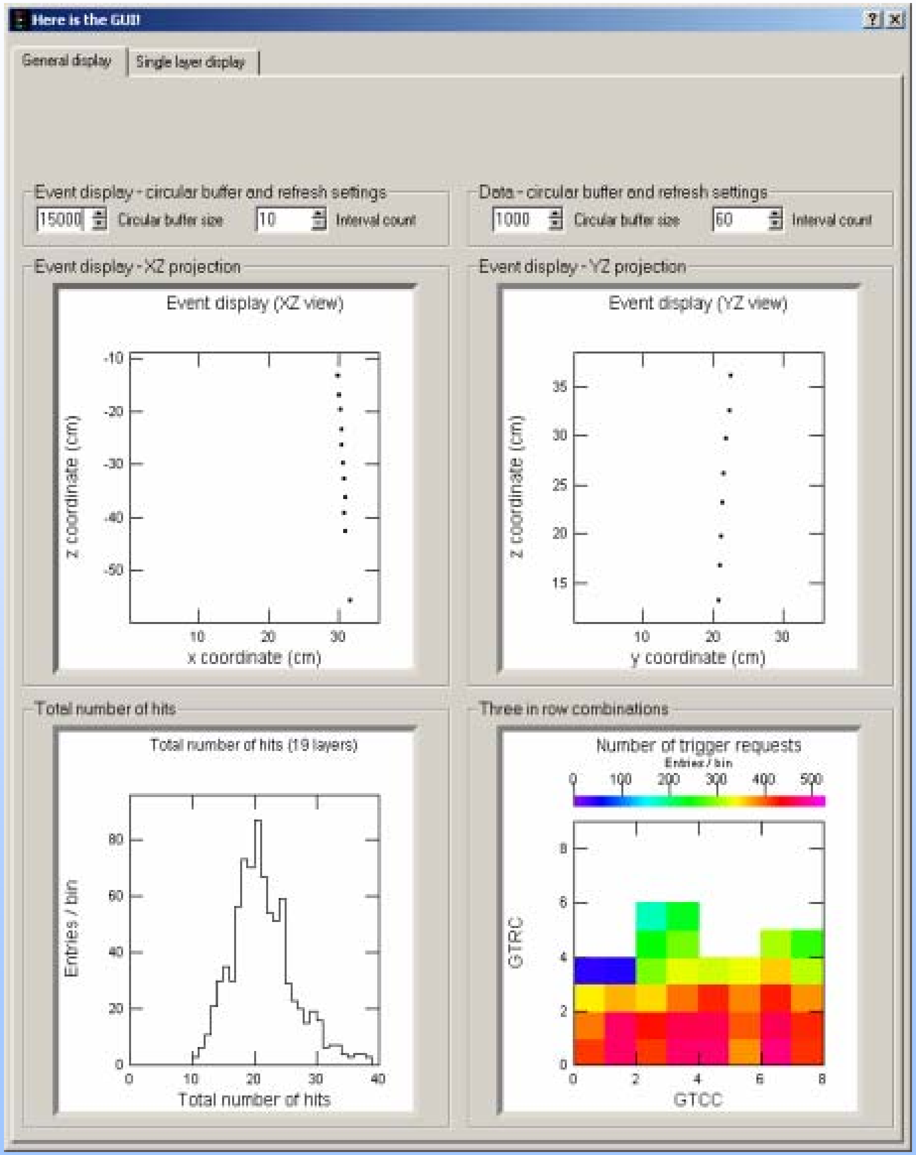
- measure normal mode resonances of trays and full towers
- sweep: 5-2000 Hz, 0.15 g
- verify workmanship by exposing items to random vibrations (6.8 g rms) and then re-checking response
- look for lowest resonances
- differences after random vibration must be less than 3%
- no damages (cracks, delamination...)





Stack test





Here is the GUI!
General display
Single layer display
Event display - circular buffer and refresh settings
15000
Circular buffer size
10
Interval count
Data - circular buffer and refresh settings
1000
Circular buffer size
60
Interval count
Event display - XZ projection
Event display (XZ view)
z coordinate (cm)
x coordinate (cm)
Event display - YZ projection
Event display (YZ view)
z coordinate (cm)
y coordinate (cm)
Total number of hits
Total number of hits (19 layers)
Entries / bin
Total number of hits
Three in row combinations
Number of trigger requests
Entries / bin
GTRC
GTCC

TKR thermo-vacuum tests

• trays must withstand the thermal gradients with no loss in functional properties: test addressing, data taking, noise,....

• T from -30°C to +55°C

• change rate ±40°C/hr, 2.5 hrs at the extremes

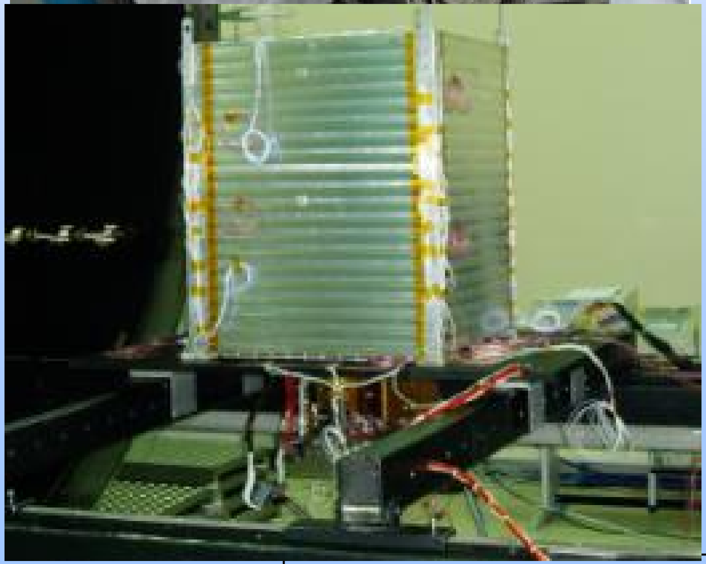
• trays are tested in N atmosphere in an environmental chamber

• full towers are tested at the Alenia laboratories ☞

• full "on-ground" DAQ setup

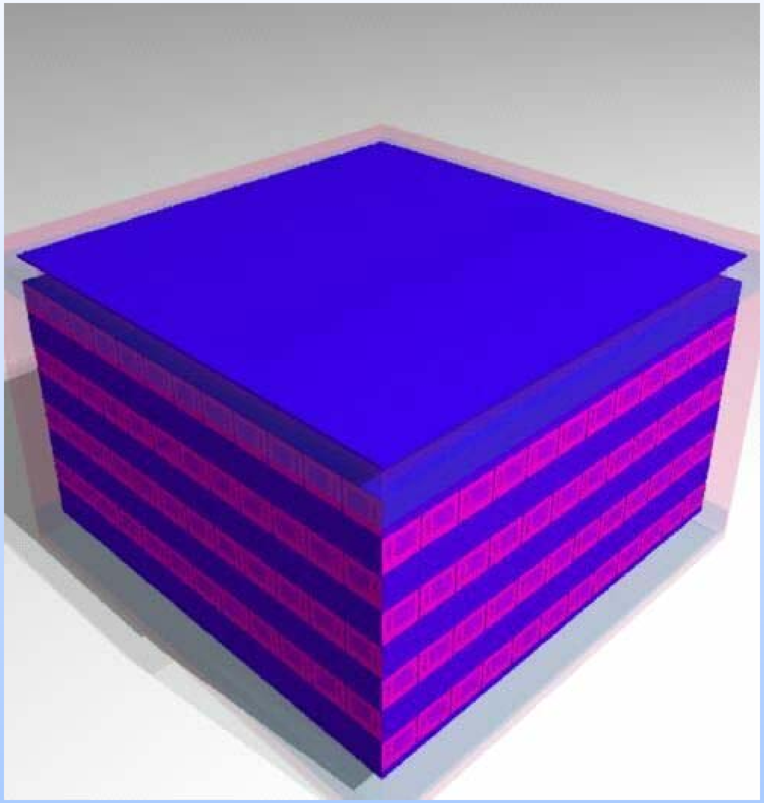
• vacuum: 10^{-5} torr

• 4 thermal cycles like specified above



Calorimeter

- hard constraints on mass (payload)
- power budget in the space telescope must be checked carefully
- 16 towers, 8 layers, 12 xtals per layer : 1536 crystals
- weight is 1500 kg, P < 91 W !
- self-triggering



CsI crystals

The boule is cut...

... again ...

... and again.

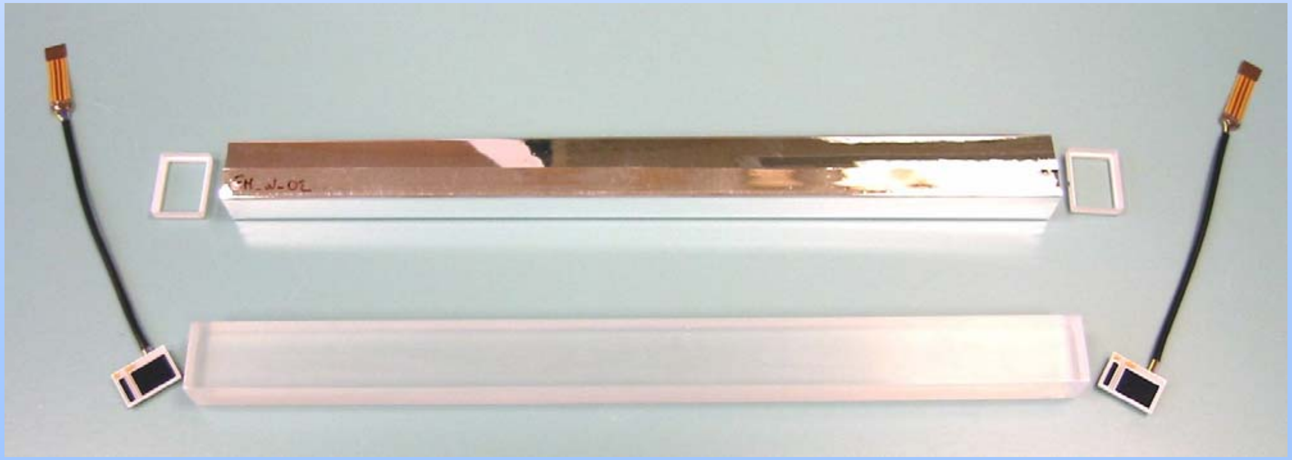
Each crystal is polished...

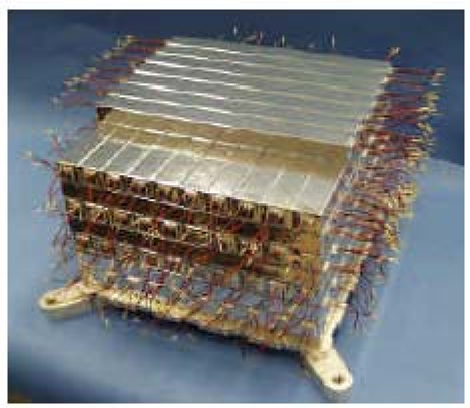
... then a side is scratched ... (tapering)

... and it's put in a safe.

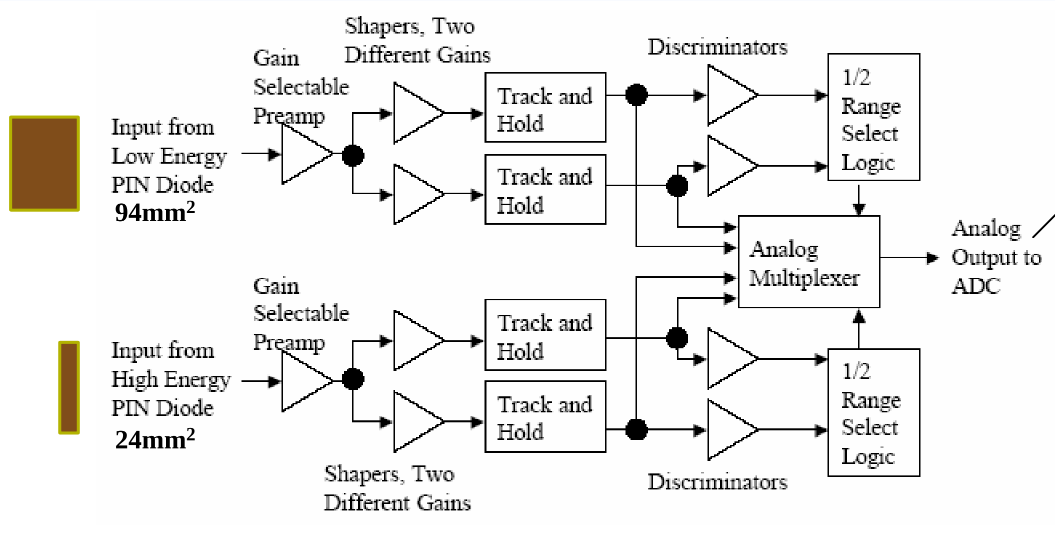
CAL assembly

- each XTAL: a Dual Diode Package at each side
- two PIN diodes: low/high energies, depending on the area
- XTAL wrapped in VM2000 reflective foil (2× increase in light collection)
- flex cables added, positioned in tray
- connected to electronics (FE)
- added TEM and connected



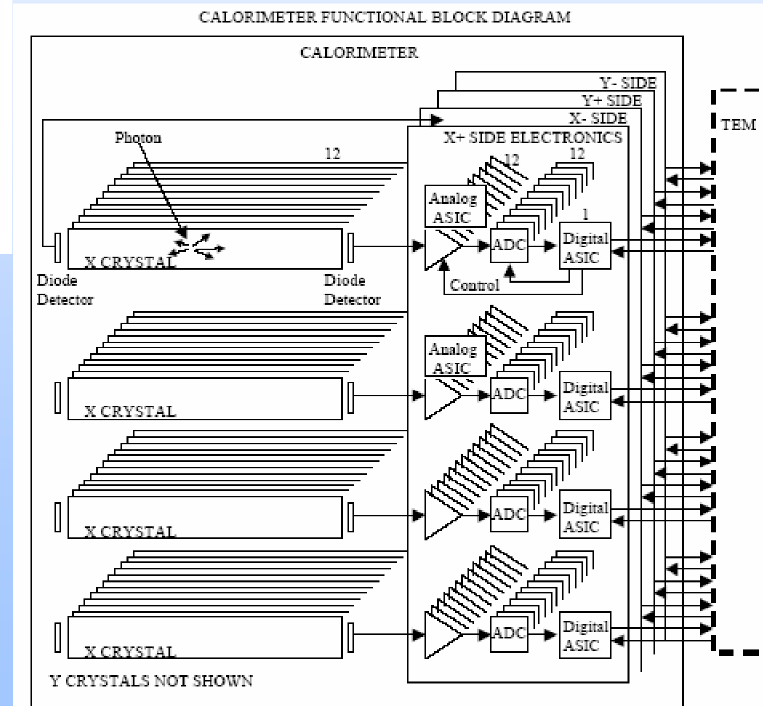


CAL electronics



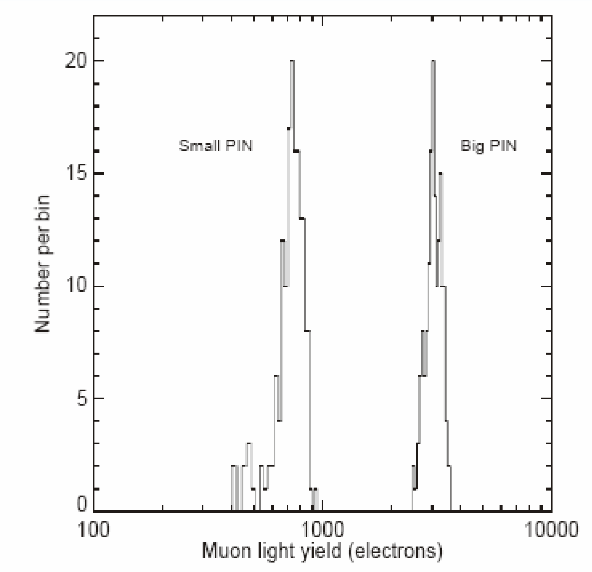
12 bit, successive approssimation
COTS as fast ADC
dead time<20μs

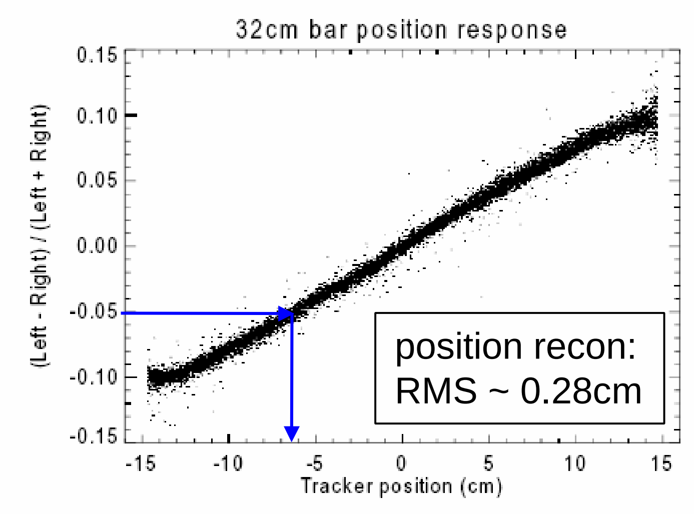
Low energy range: 2÷800 MeV
High energy range: 100 MeV ÷ 100 GeV



CAL calibration & test

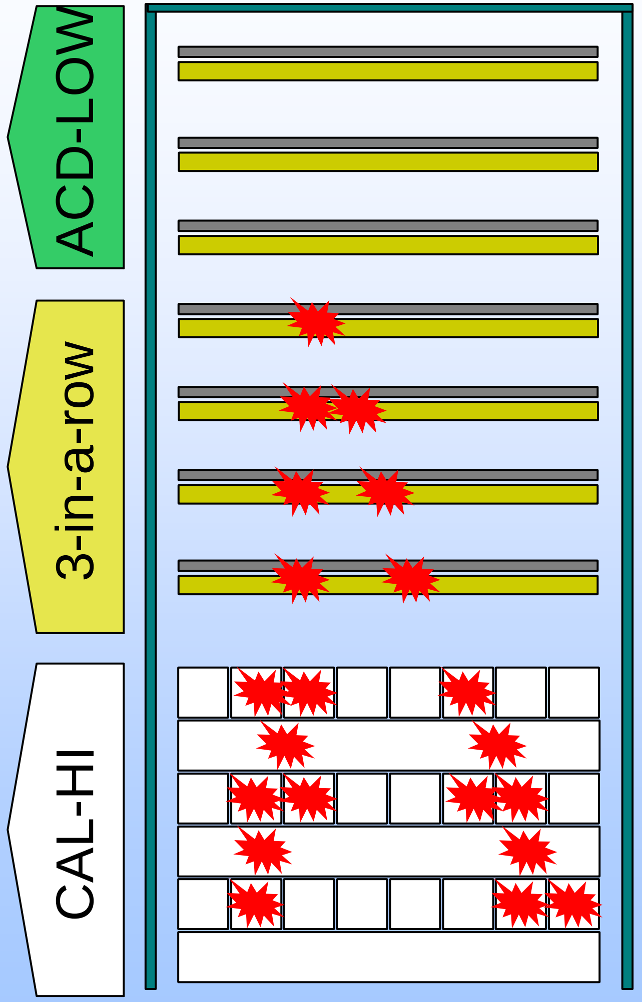
- 511 kev ^{22}Na source used as light source
- yield: >5000 e/MeV to be accepted
- beam test: muons
  - 750 e/MeV from small diode
  - 3000 e/MeV from large diode
- light tapering allows position reconstruction along crystal
- tapering: ~40% loss across XTAL length





DAQ system

- triggers the LAT, read out events, process them into the downlink stream.
- GLAST Global Trigger receives signals from the LAT electronics and creates trigger primitives: 3-in-a-row in the TKR (= 6-fold coincidence), ACD tile above threshold,...
- primitives are processed into high-level named primitives (“*3-in-a-row with CAL-HI*”,...) used for L1T
- L1T: tower level, rate is 6 kHz (peak: 9 kHz)
- L2T: still tower level, loose cuts on background, 1 kHz (peak: 2 kHz)
- L3T: full instrument-wide reconstruction, should drop to 15 Hz
- OK for telemetry, but a significant background rejection still needs to be done on ground



Status

• TKR towers being assembled at the INFN labs in Pisa

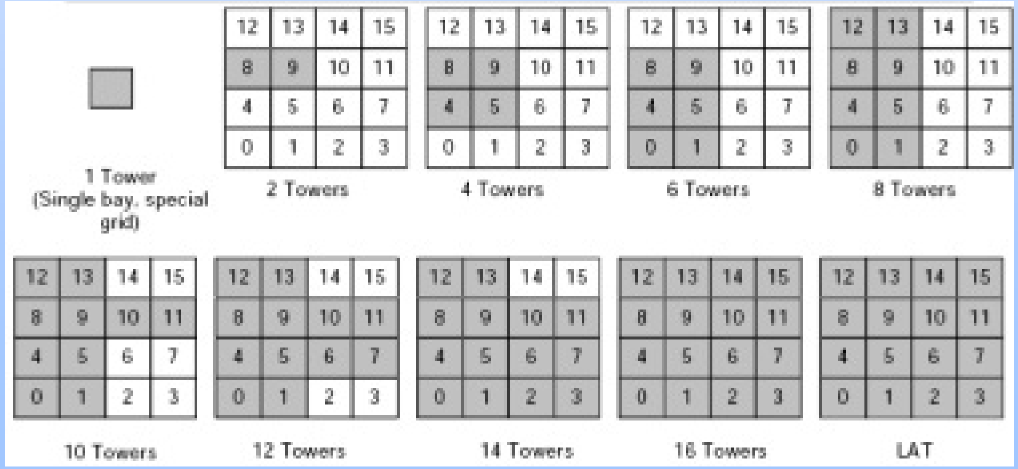
• tests (DAQ, vibrational, thermo-vacuum)

• towers are sent to SLAC for Integration & Test

• tests with cosmic rays, Van de Graaff gamma's

• tray alignment is checked

• towers (TKR+CAL+DAQ) will be placed in the support grid, LAT assembled



Conclusions

- Astrophysics borrowed detector technology from high energy physics
- Si microstrip tracker, CsI EM calorimeter
- INFN: expertise in the field: design, assembly, test...
- Key aspects of LAT assembly are entrusted to industrial partners (quality control and certification, insurances, overtime fees, ...)
- Production has reached the stage of subsystem integration
- Test results validated key aspects of detector design
- Novel problems were encountered and solved
- Focus shifts on data analysis and science issues

Some spare slides...

TKR digital ASICs

- GTRC interfaces GTFEs and TEM
- The layer ID is set by 4 pads, it's hardcoded in the flex cable
- 2 registers regulate the operations:

➢ REG: see right! 22 bits to store configuration, 6 error bits, 5 enable, 1 readonly

➢ SYNC: 8 bit, controls synchronization in communications with GTFEs

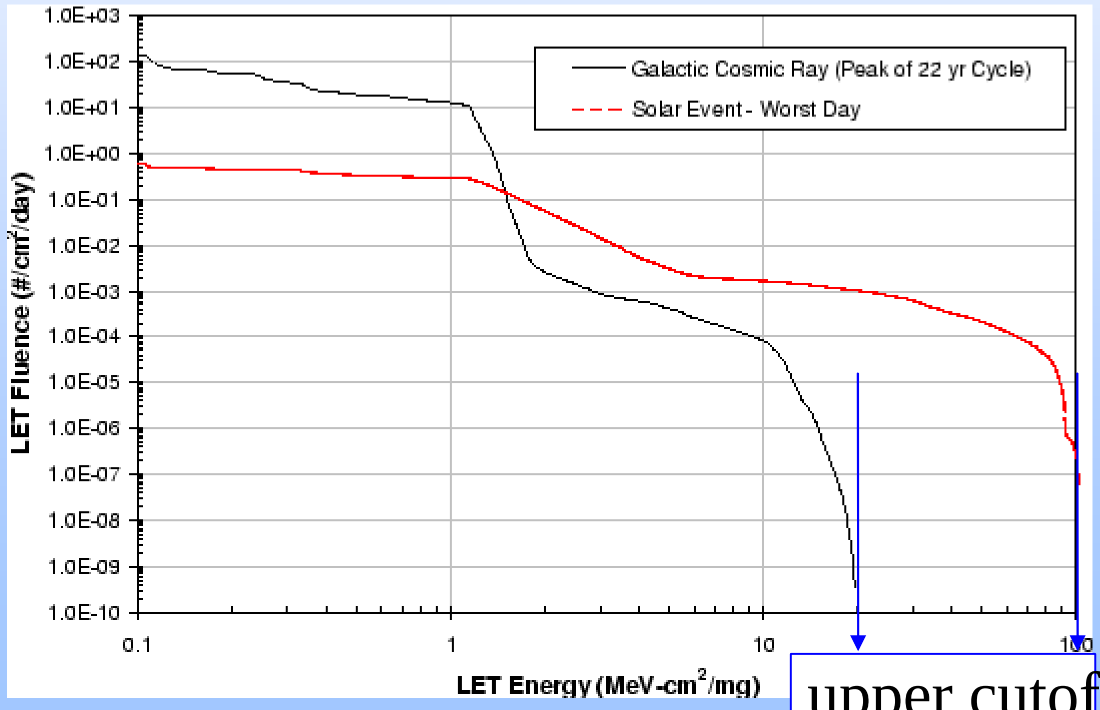
- Only the "CONF" 22 bits and the SYNC affect the ASIC functionalities
- 2 buffers to download data frames and store them
- TOT counter: time over threshold is ~ proportional to the injected charge

GTRC Control Register Format			
Bit	**Name**	**Definition**	**Default**
33	LD_FT	Enable loading FORCE and TOT bits	
32	LD_DELAY	Enable loading READ_DELAY	
31	LD_STRETCH	Enable loading STRETCH	
30	LD_CNT	Enable loading GTFE_CNT	
29	LD_SIZE	Enable loading SIZE	
28	SUM_ERR	Read only Logical OR of TAG, TRIG, DAT and CMD errors Cleared by reading Control Register	
27	CMD_ERR	Read only Sum Cmd Parity Error Set if there is a Cmd Parity Error Clear by reading Control Register	
26	DAT_ERR	Read only Sum Data Parity Error. Set if there is a Data Parity Error Cleared by reading Control Register	
25	TRIG_ERR	Read only Sum Trigger Parity Error Set if there is an L1T Parity Error Cleared by reading Control Register	
24	TOK_ERR	Read only Sum Token Parity Error Set if there is a Token Parity Error Cleared by reading Control Register	
23	TAG_ERR	Read only Sum Tag Error Set if there is a comparison failure in the TAG from the GTFE's. Cleared by reading Control register	
22	SHIFT_MODE	Read only. Bonded pad to determine side	
21	TOT_EN	1 => Enable TOT Delay	1
20	FORCE_NO_ERR	0 => Normal operation 1 => Forces Normal Event readout	0
[19..17]	READ_DELAY	Delay from Read Event to start of Read Command in 6.4us steps	0
[16..12]	OR_STRETCH[4..0]	Fast-OR Stretch in 50ns steps. 0 => No Deglitch, No Stretch	10
[11..07]	GTFE_CNT	Number of GTFE chips to read	12
[06..00]	SIZE	Number to set maximum number of Hits from GTFE	64

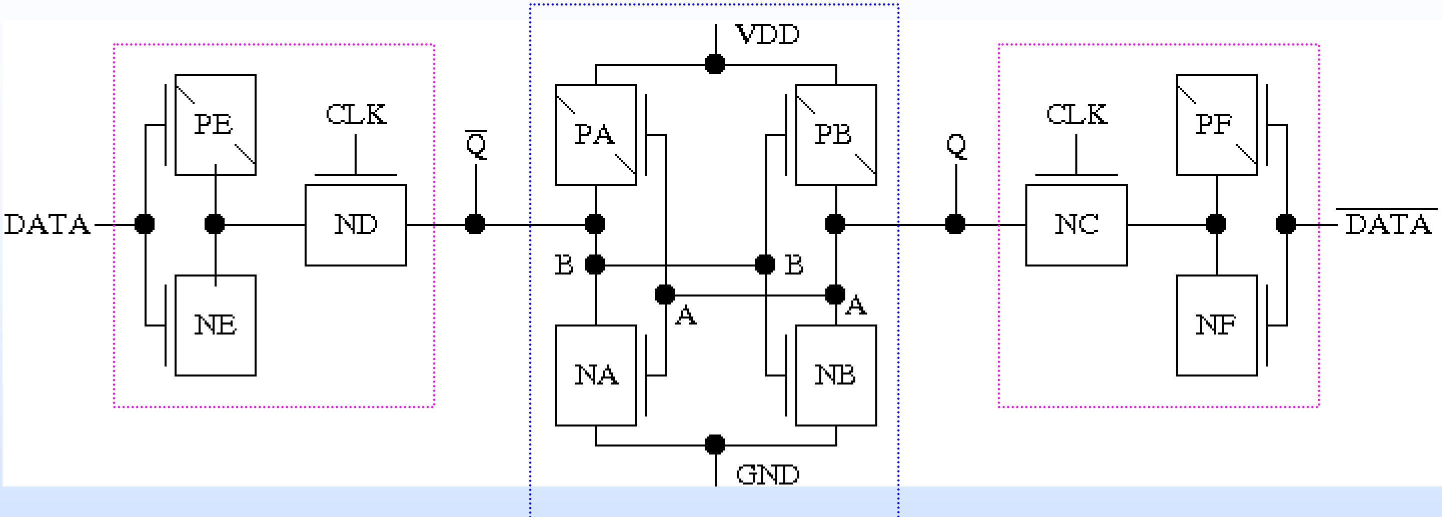
LET spectra and dose for GLAST

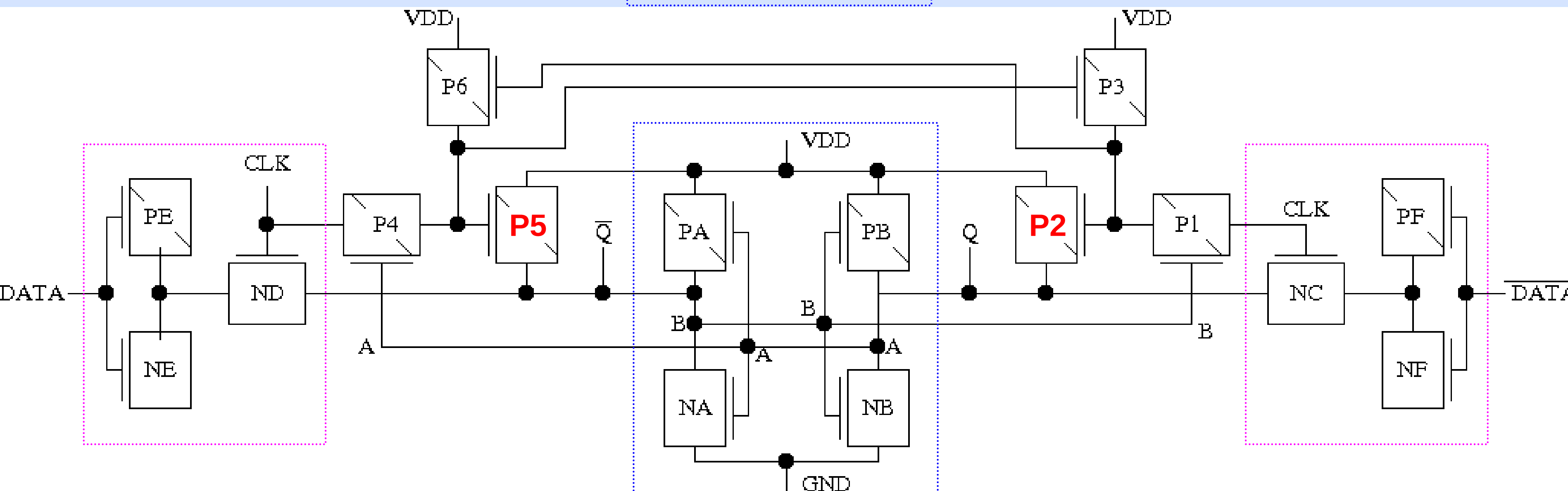
- GLAST orbital parameters:
  - ➢ 565 km asl, circular orbit
  - ➢ 28.5° inclination, ~1.6 hr orbital period
  - ➢ 5 year mission
- CREME96 simulation gives LET spectra, integrated doses given magnetic cutoff, shielding, ...
- Biggest contribution to dose is passage into SAA
- Maximum total dose is **0.8 krd** in most exposed devices in a 5 year mission
- 5X engineering limit
- We added another 2X safety margin
- GCR+SPE < **0.3 ions/cm^2**

10 krd, 1 ion/cm^2 (5 years)



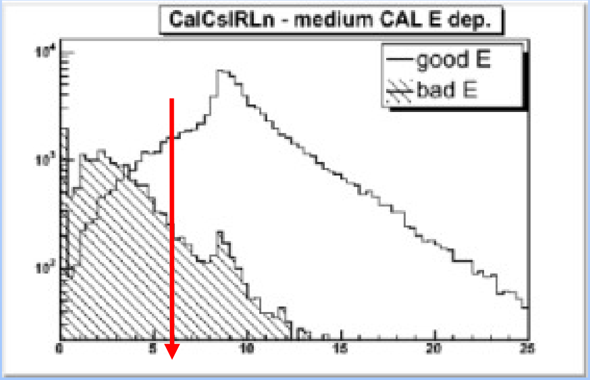
Rockett cell





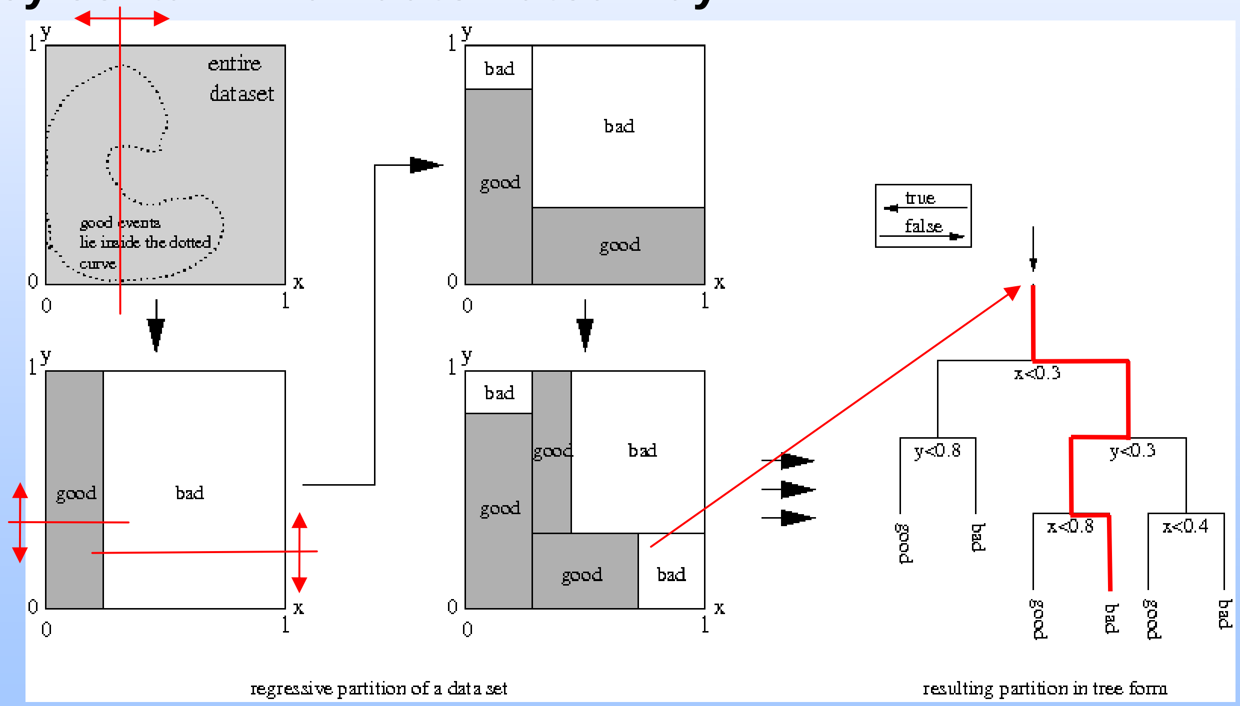
Background

- γ / background events ratio is ~ 1:10^5
- A rejection factor ~100 should be obtained on-board after L3T and OnboardFilter
- Another factor ~100 is required on ground to prepare dataset for science analysis
- This requirement was demonstrated with the tools available at the time of the AO / Flight Inv.
- Being carried on with the official LAT Software
- Standard path: investigate useful cuts on highly-discriminating variables:



Background rejection

- Current implementation uses *regression trees*, approach taken from soft sciences
- A training (simulated) data set is used to grow a predictor, recursively partitioning the data in categories (signal/noise, good/bad, ...) with cuts on the variables they contain in an automated way



- The predictor can then be applied to other data to classify them