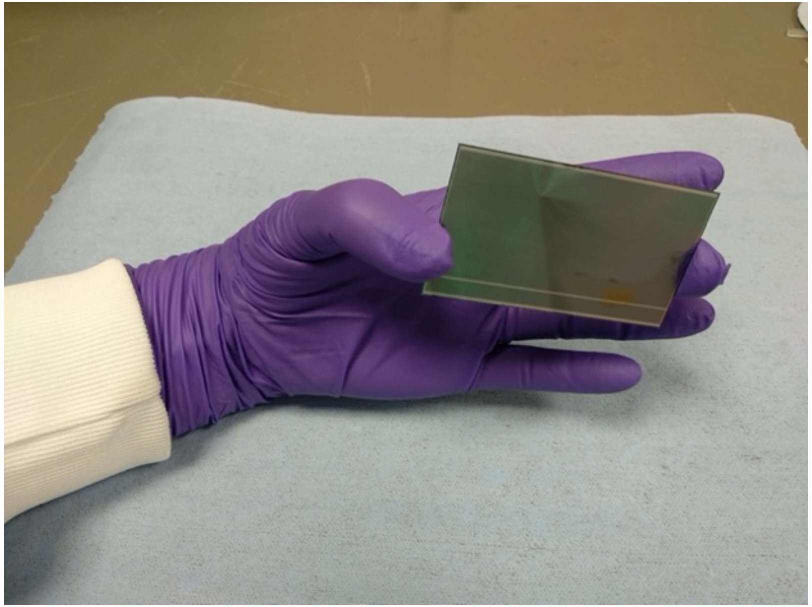
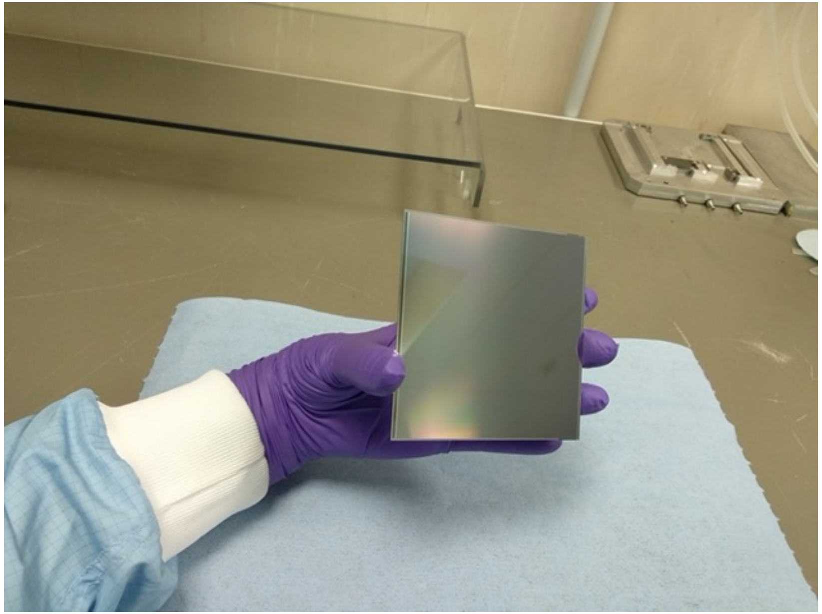
Silicon tracking detector for space-borne experiments

VERTEX 2019

G. Ambrosi
INFN Perugia

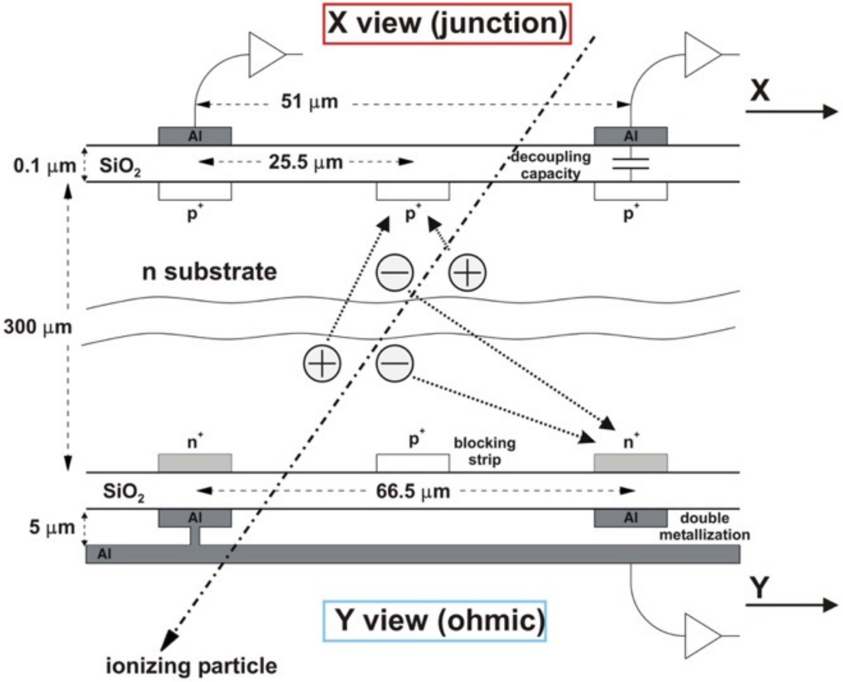
Silicon microstrip detector





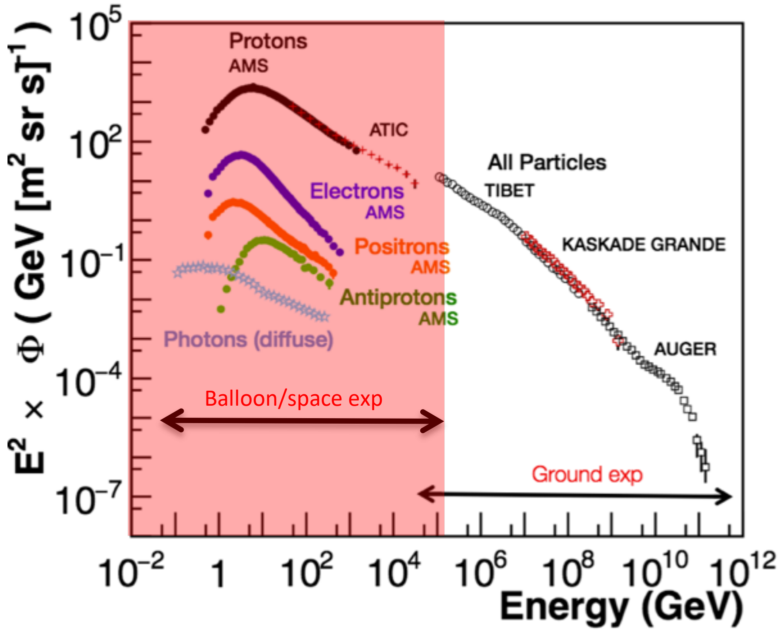
Spatial resolution driven by the pitch: strip pitch 25 – 200 µm, readout pitch 100 – 300 µm

Silicon microstrip detector



Spatial resolution driven by the pitch: strip pitch 25 – 200 μm, readout pitch 100 – 300 μm

The total Cosmic Ray flux

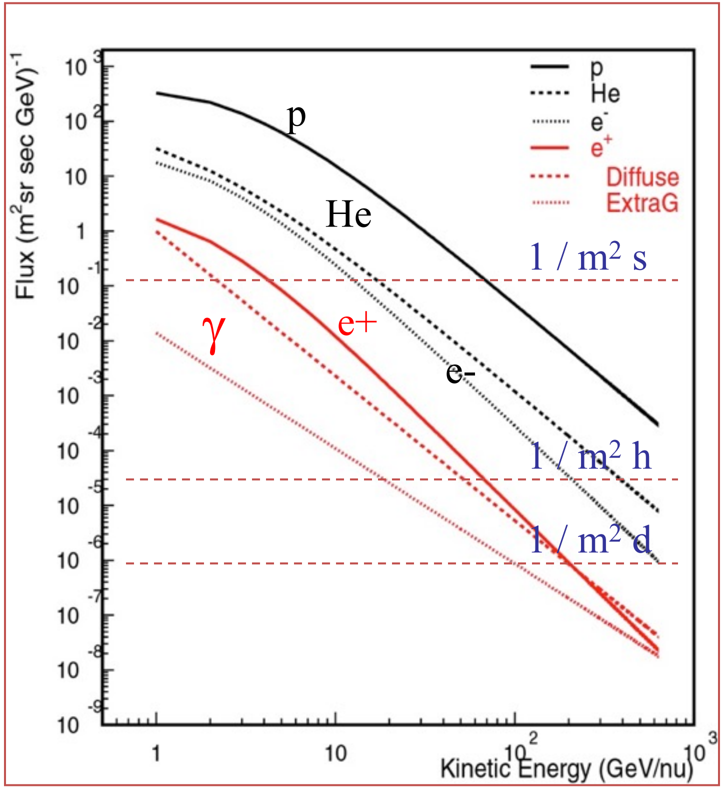


- Up to ~ 10^{20} eV;
- Energy density ≈ 1 eV / cm^3;
- Luminosity, L > 10^{40} erg/s;

$$\Phi(E)dE = kE^{-\gamma}dE \qquad \gamma \approx 2.6 - 2.7$$

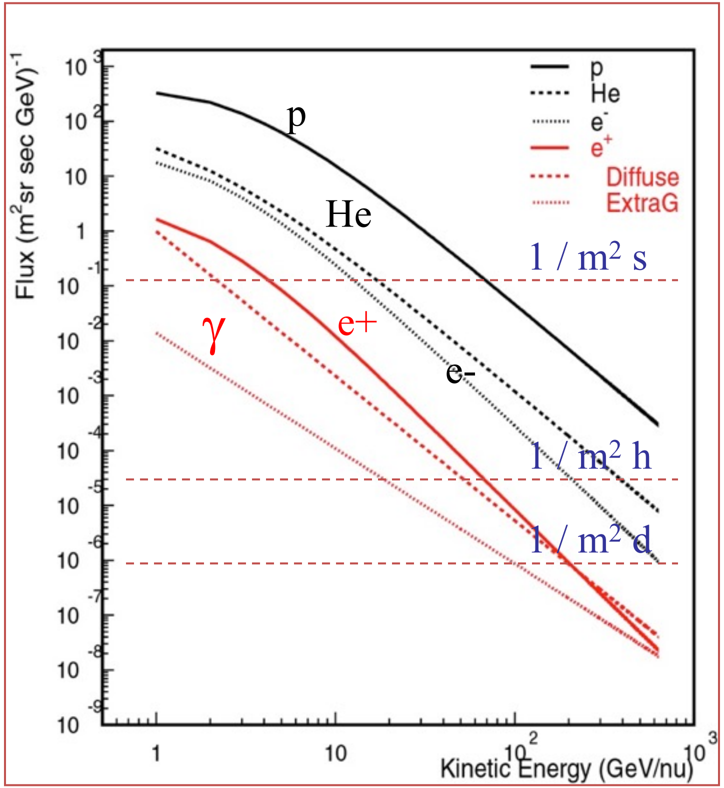
- energies much higher than reachable at accelerators on ground;
- to investigate the spectral and chemical composition accurate detector ('a la particle physics') are needed;
- to reach higher energies, bigger and bigger detectors are needed;

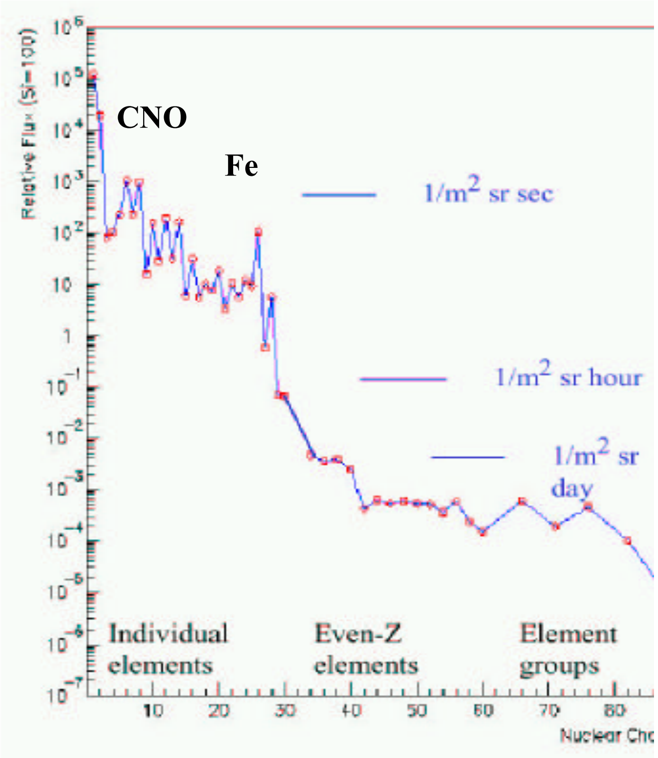
Cosmic Rays flux and composition



$$\Delta N = \Phi(E) \times \Delta(E) \times A \times T$$

Cosmic Rays flux and composition





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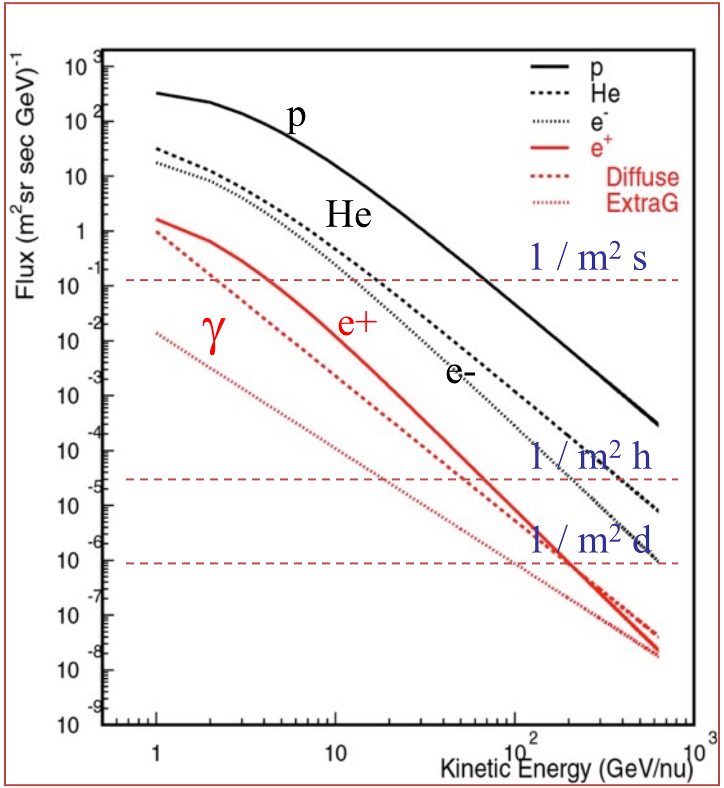
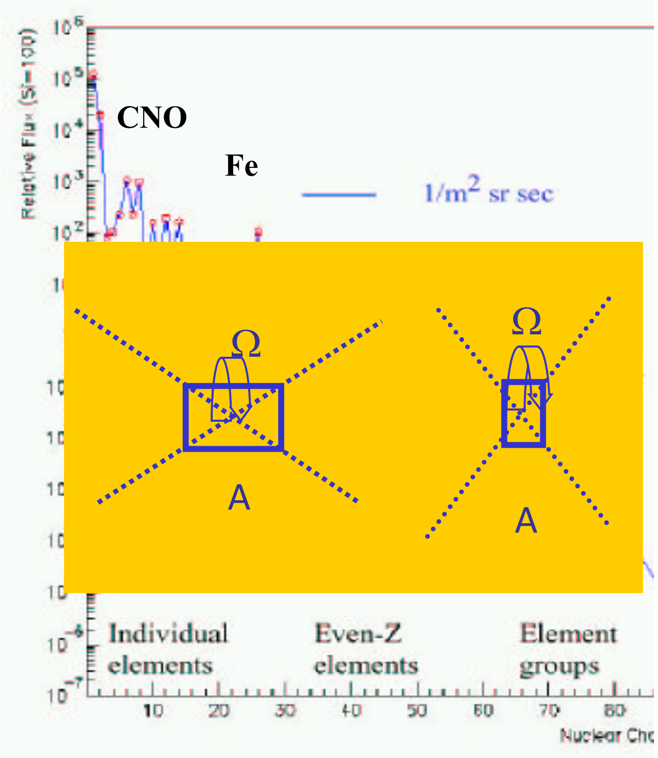
Cosmic Rays flux and composition





$$\Delta N = \Phi(E) \times \Delta(E) \times A \times T$$

The experimental challenge

No atmosphere: Stratospheric Balloons
Space

⇩ Limits on size / weight / time

- Detector design focused on specific measurements

p,He,e^-,anti-particles

⇩

<u>Magnetic spectrometers</u>
Energy reach on anti-particles limited by Maximum Detectable Rigidity

Primary spectra, Nuclei, $e^{\pm}$, γ

⇩

<u>Calorimeters</u>
Energy reach limited by statistics

$$\Delta N = \Phi(E) \times \Delta(E) \times A \times T$$

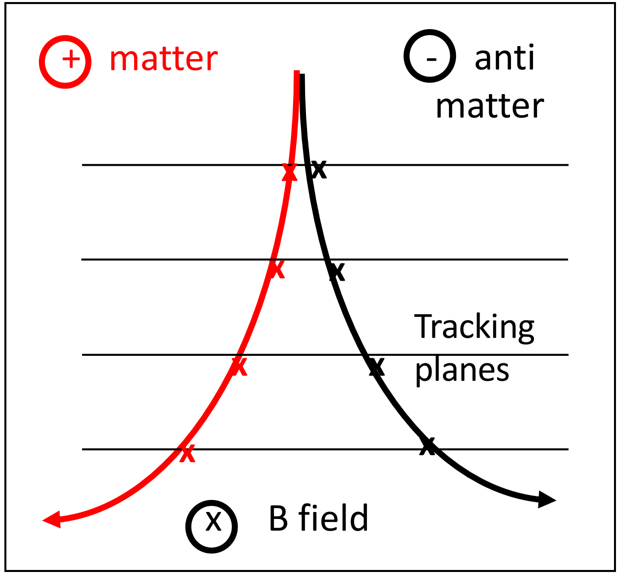
The instrument we need has …

- performance a la ‘particle physics’:
  - high resolution measurements of momentum, velocity, charge and energy
- characteristics to properly access and work in space:
  - Vibration (6.8 G rms) and acceleration (17 G)
  - Temperature variation (day/night $\Delta T = 100^{o}C$)
  - Vacuum (10^{-10} Torr)
  - Orbital debris and micrometeorites
  - Radiation (Single Event Effect)
- limitation in
  - weight (15000 lb)
  - power (3KW), bandwidth and maintenance
- Compliant with EMI/EMC specs

exact stress numbers depend from the details of the mission,here AMS-02 values are reported

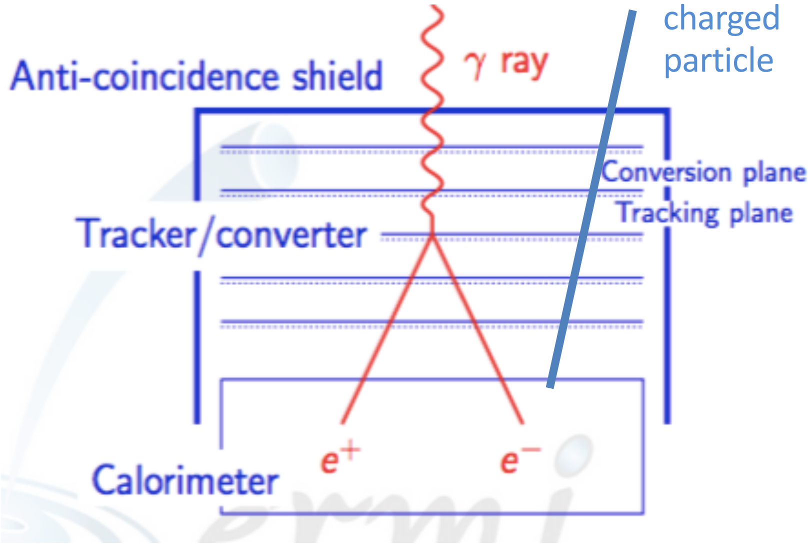
Tracking in space: Spectrometer vs Calorimeter

Magnetic spectrometer



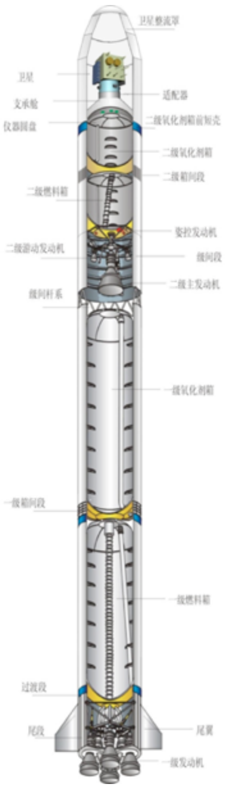
Spatial resolution: 3 – 10 μm

Calorimetric detector



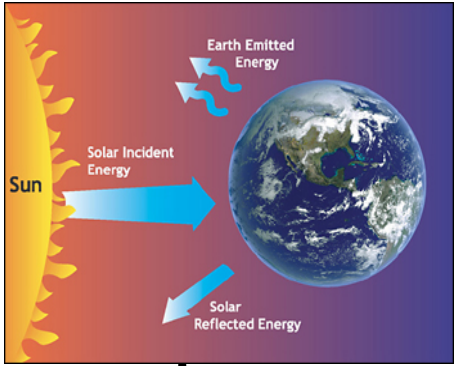
Spatial resolution: 30 – 70 μm

HEP detectors in Space



Mechanical stress at launch:

- Static acceleration
- Random vibration
- Sinusoidal vibration
- Pyroshock

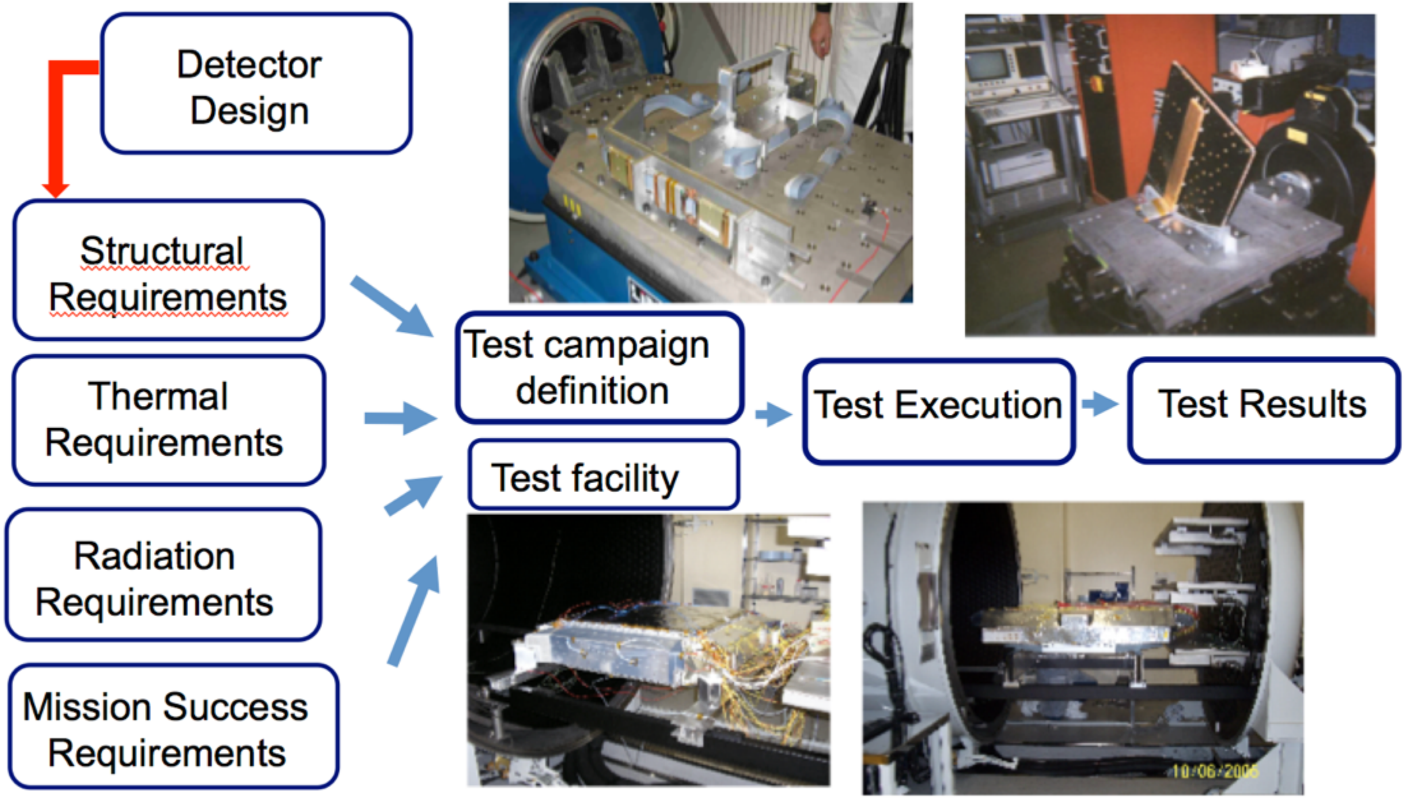


Life in space:

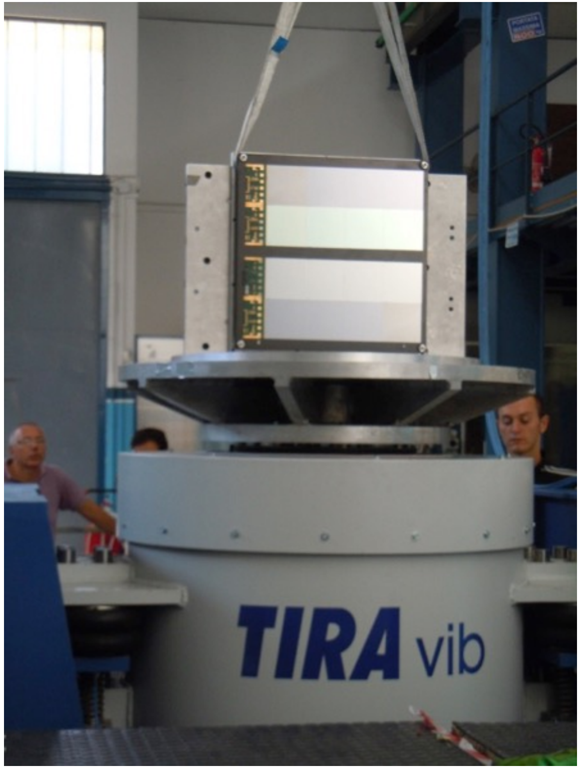
- **Thermal stresses due to Sun-light (seasonal / day-night effects)**
- **Vacuum**
- **Radiation**

Careful Design, Model validation and Qualification are needed to ensure *highest possible reliability*

(very) Simplified test flow-chart



DAMPE prototype test

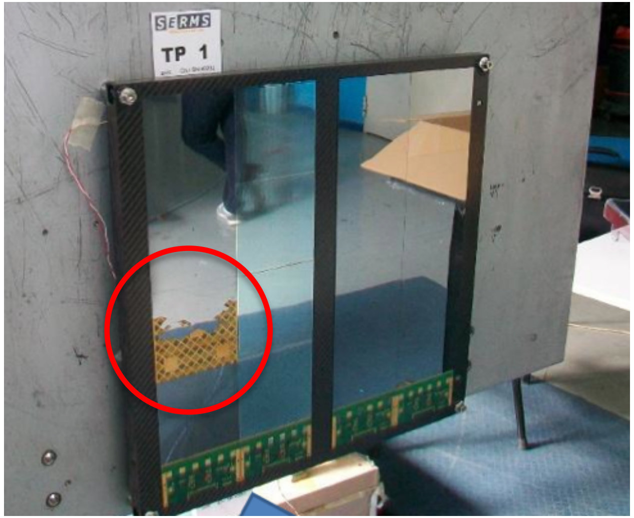


SERMS laboratory in Terni

- 3 mechanical and one electrical ladder prototypes mounted on the plane
- vibration test
- thermal cycling
- shock test

- Preliminary results:
  - electrical behaviour is unaffected by stress
  - Silicon detector ‘move’ by few microns

DAMPE prototype test



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- Preliminary results:
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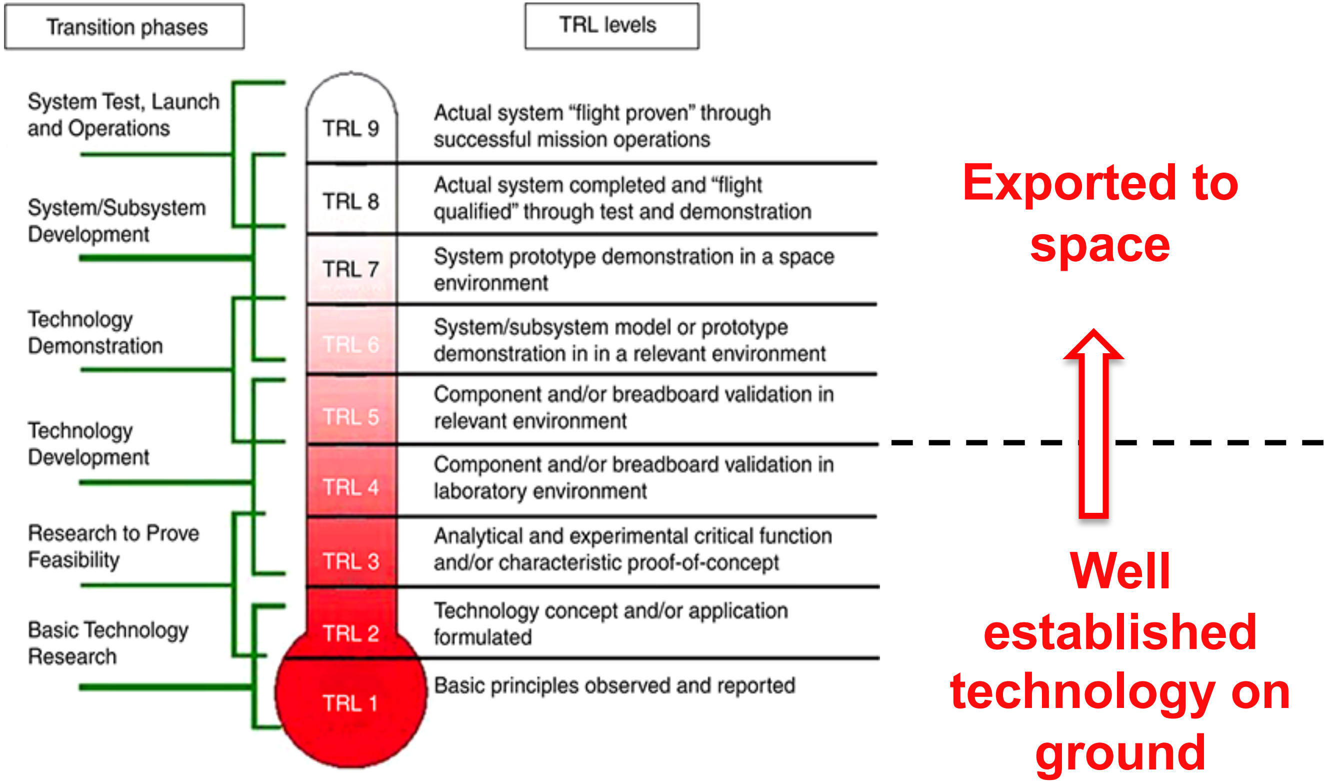
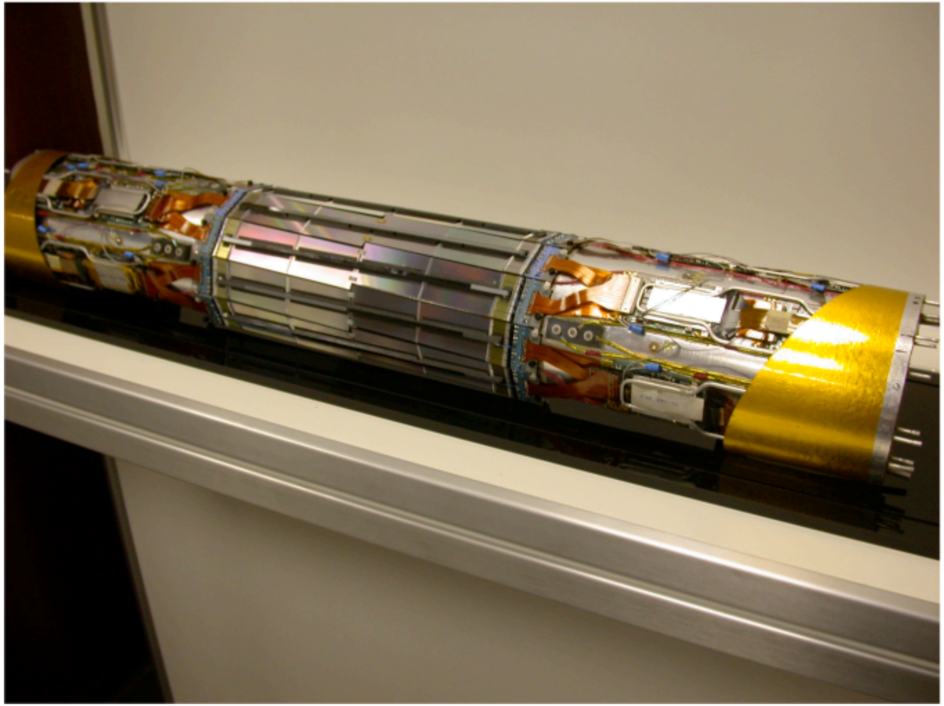
if you are good enough you can break a detector ;-)

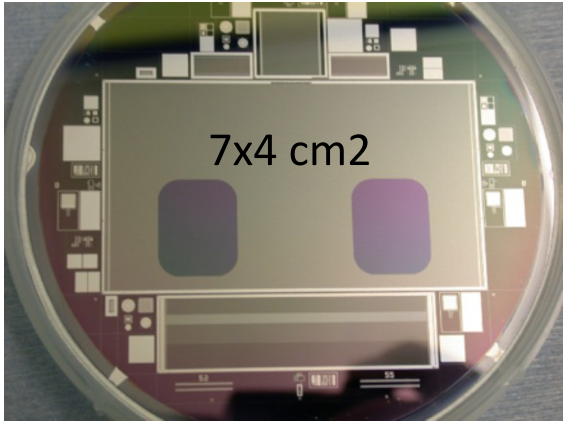
Technology Readiness Level

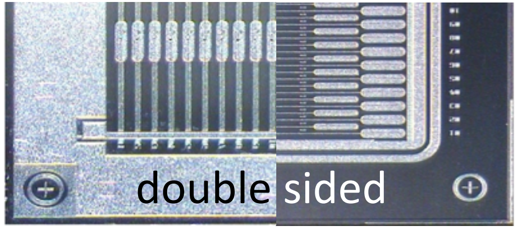


Source: Adapted from NASA and Mankins (1995)

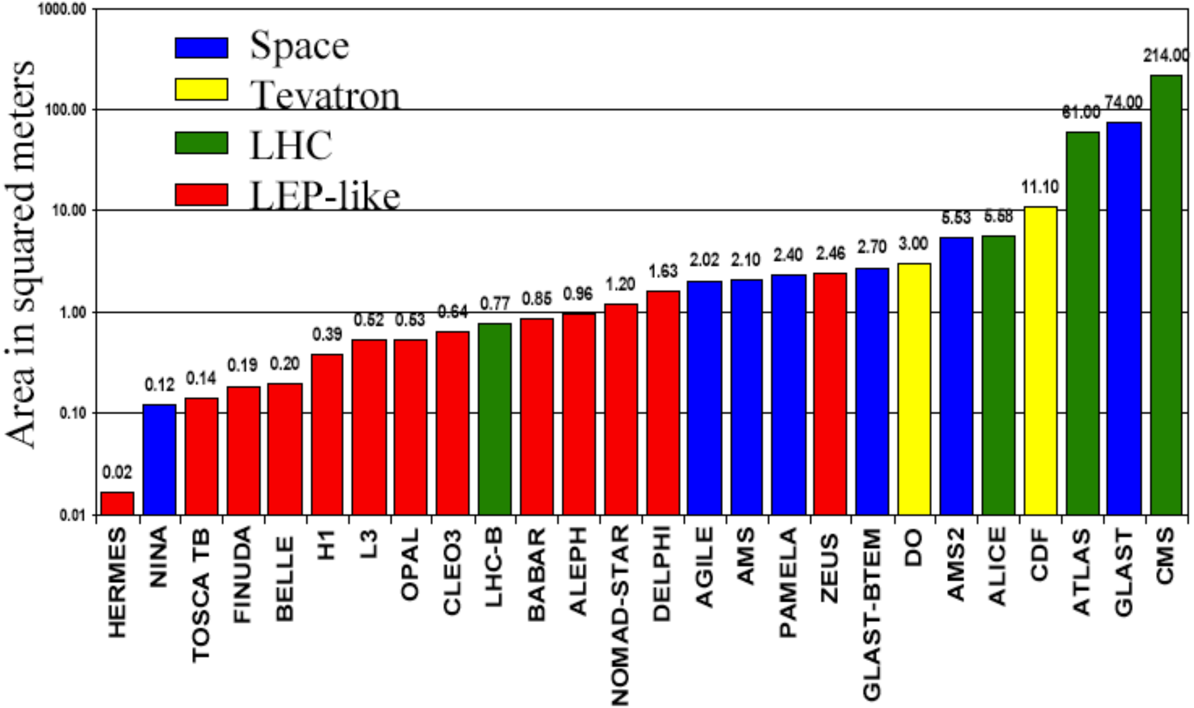
L3 Silicon Microvertex Detector at LEP (1993)







Experiments using silicon strip detectors



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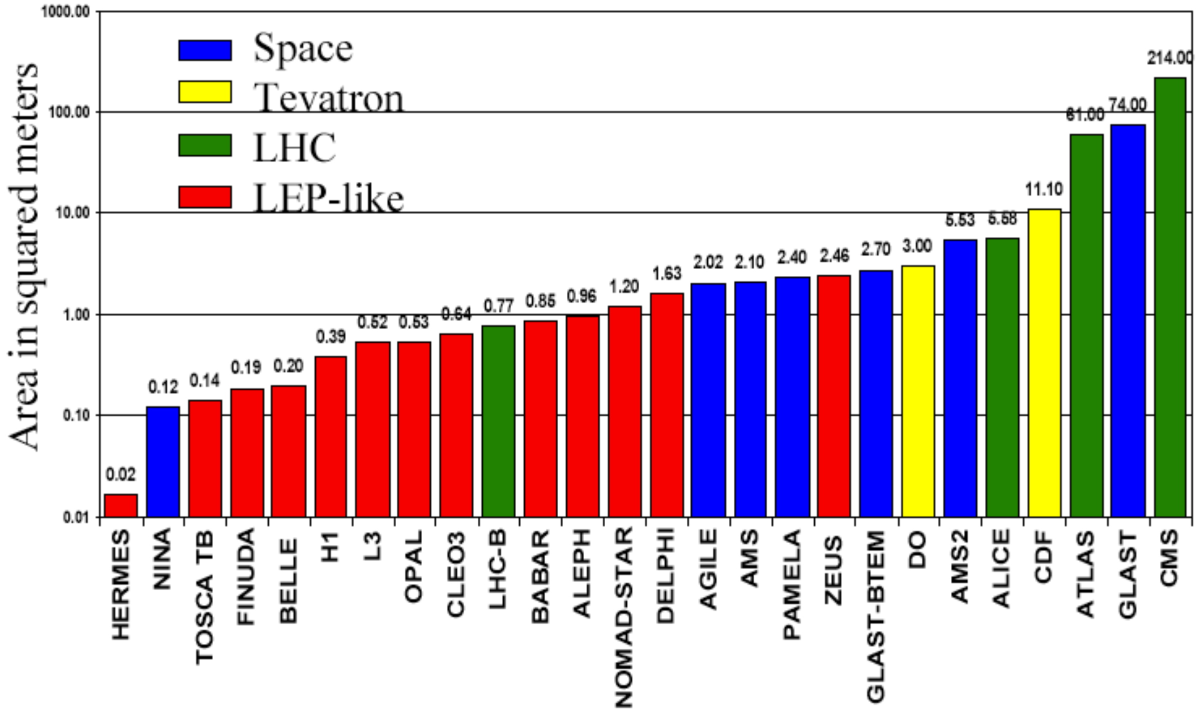

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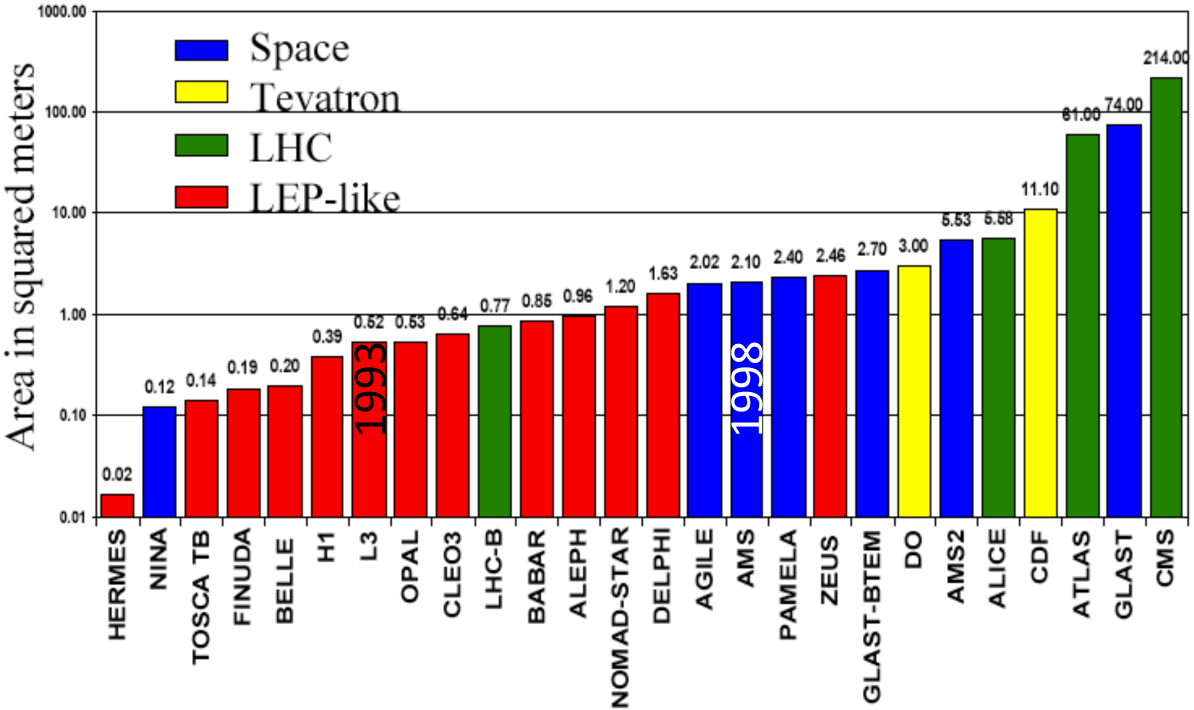

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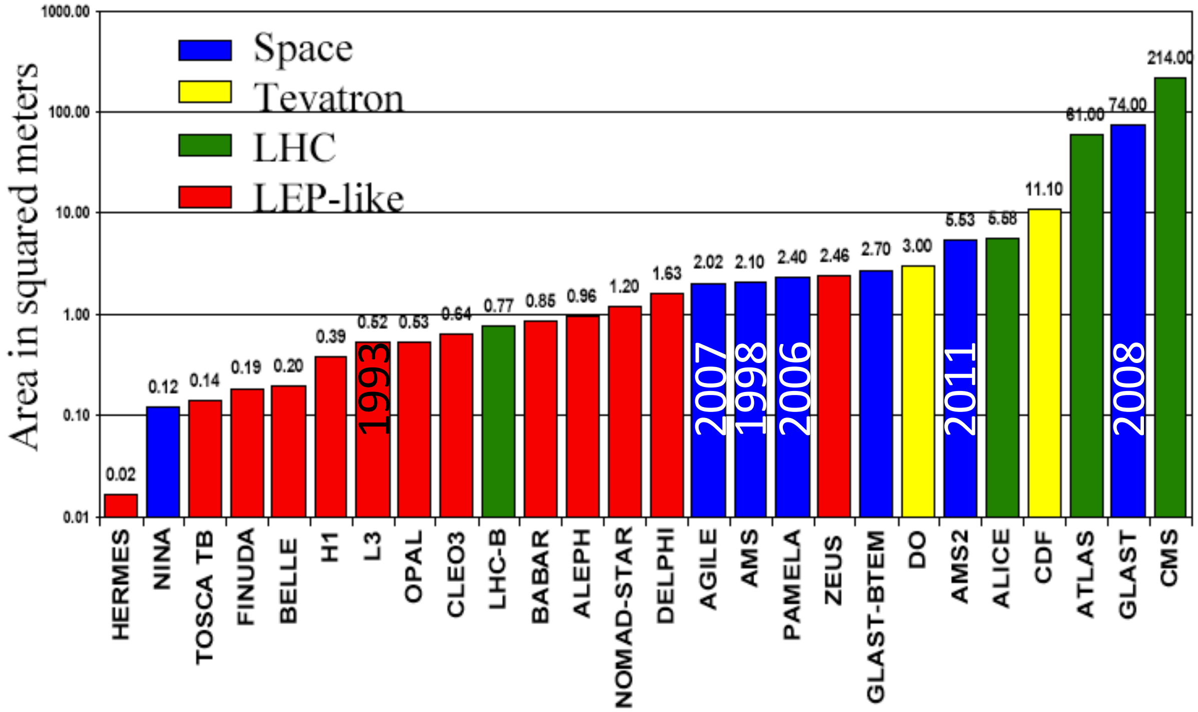
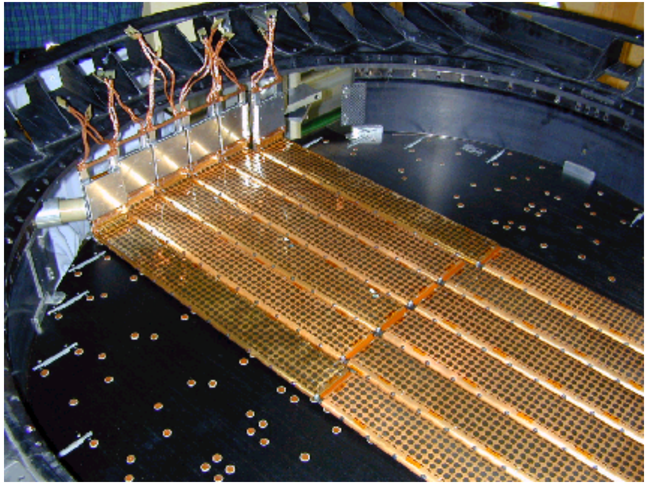


E. do Couto e Silva – SLAC/Stanford University

Vertex 2000, Sept 10-15, National Lakeshore, MI, USA

AMS-01 Silicon Tracker (1998)



- ✓ Aluminum honeycomb + carbon fiber reinforcement planes
- ✓ Front end electronics disposed vertically on the edge of the plane to save acceptance
- ✓ Thermal bars to dissipate the power on the magnet mass outside

Lightweight carbon fiber shell to hold the planes

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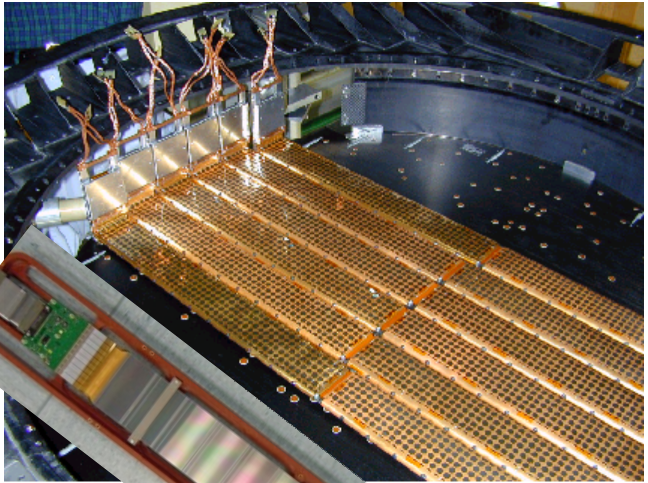

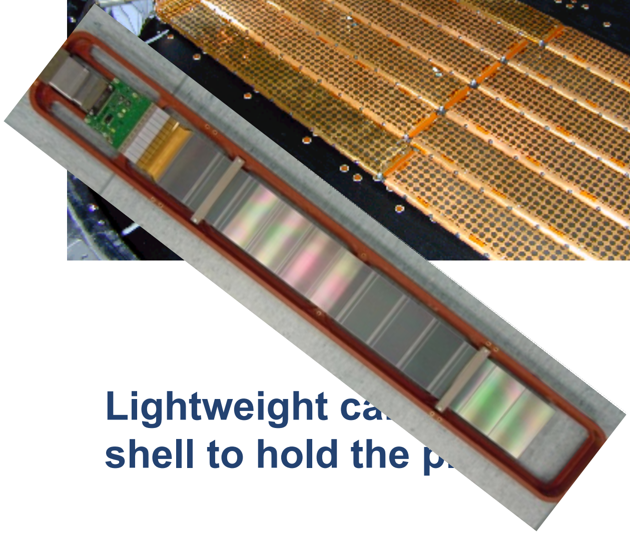

Lightweight ca
shell to hold the p

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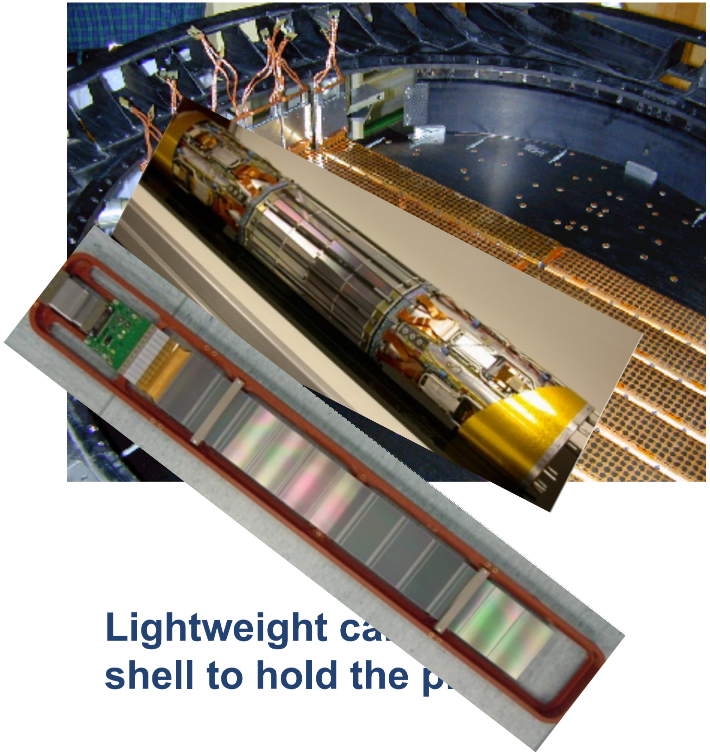
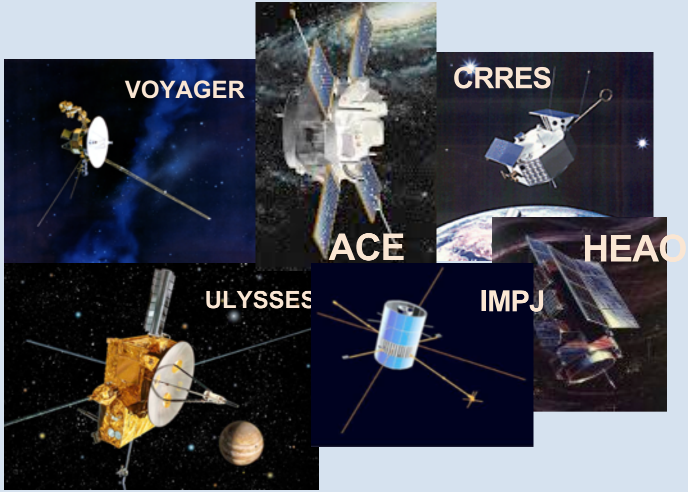


Lightweight ca
shell to hold the p

Space:



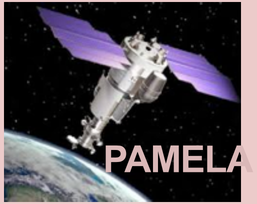
Long missions (years)
Small payloads
Low energies..

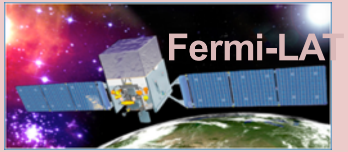
IMP series < GeV/n
ACE-CRIS/SIS Ekin < GeV/n
VOYAGER-HET/CRS < 100 MeV/n
ULYSSES-HET (nuclei) < 100 MeV/n
ULYSSES-KET (electrons) < 10 GeV
CRRES/ONR < (nuclei) 600 MeV/n
HEAO3-C2 (nuclei) < 40 GeV/n

Short missions (days)/ Larger payloads

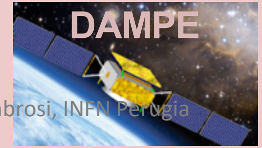
CRN on Challenger
(3.5 days 1985)

AMS-01 on Discovery
(8 days, 1998)



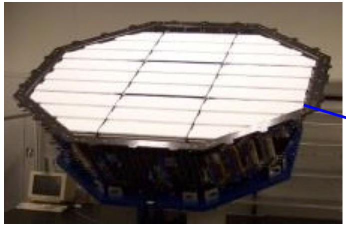


Long missions
Large payloads



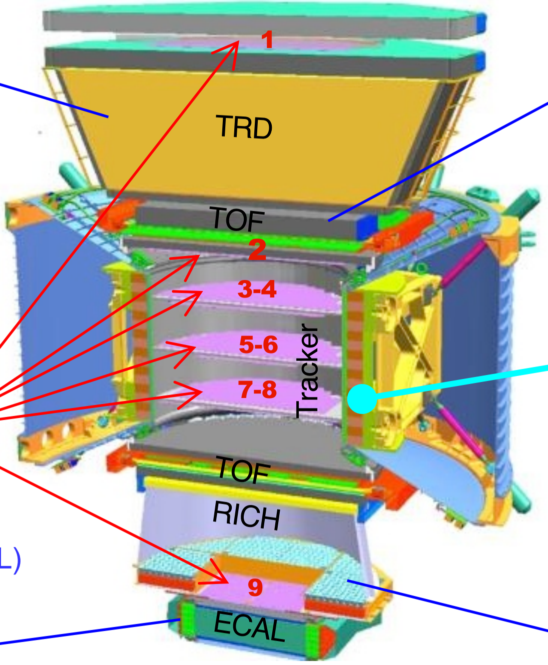
AMS-02: A TeV precision, multipurpose spectrometer

Transition Radiation Detector (TRD)
Identify e^+, e^-

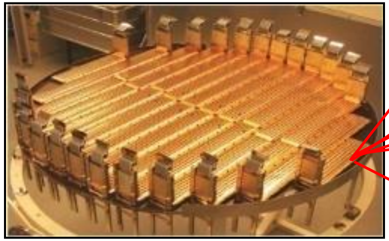


Particles and nuclei are defined by their charge (**Z**) and energy (E)

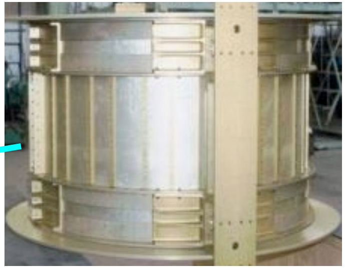
Time of Flight (TOF)
Z, E



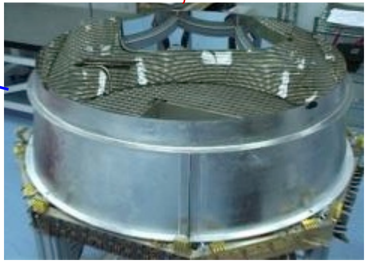
Silicon Tracker
Z, P



Magnet (0.15 T)
±Z



Ring Imaging Cherenkov (RICH)
Z, E

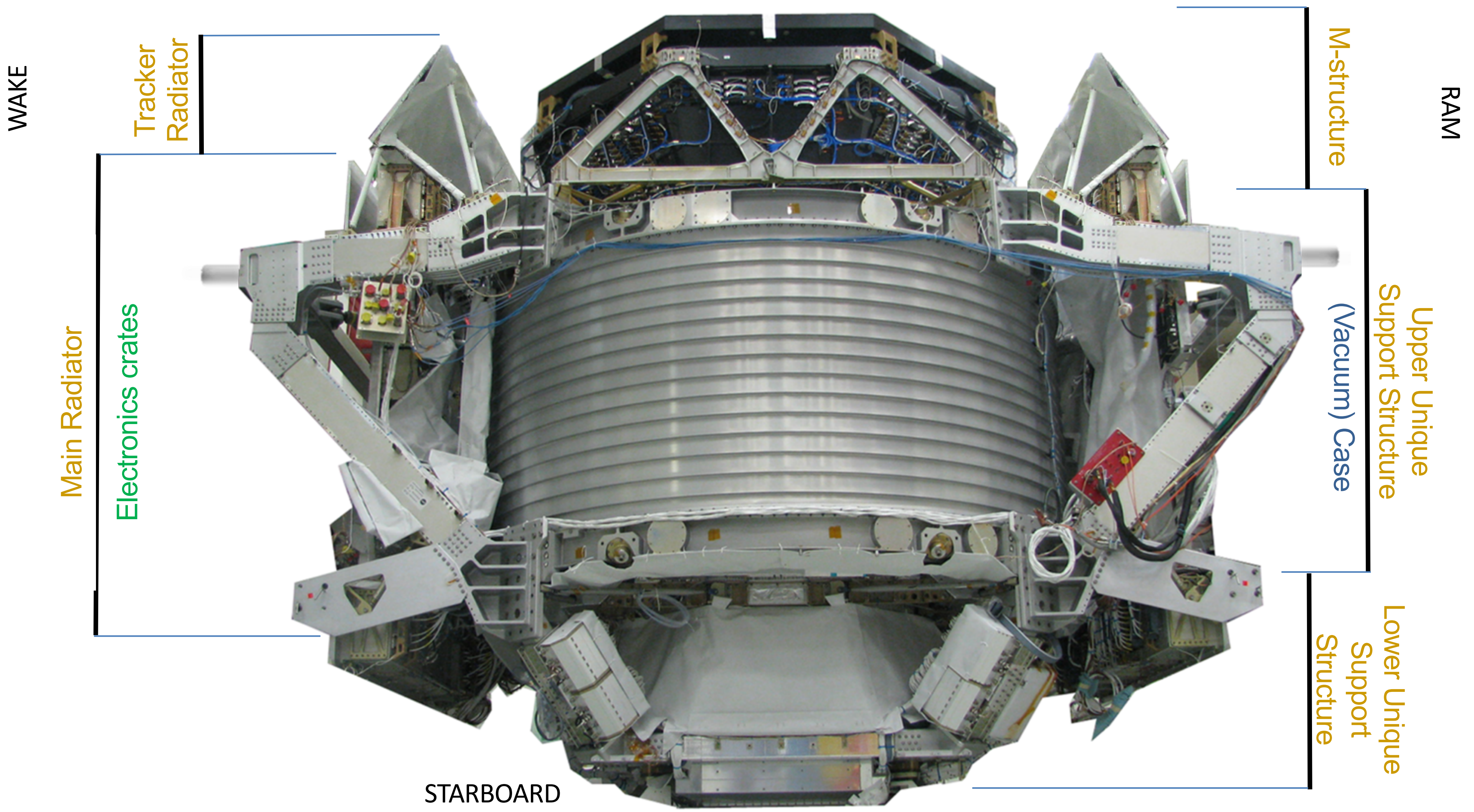


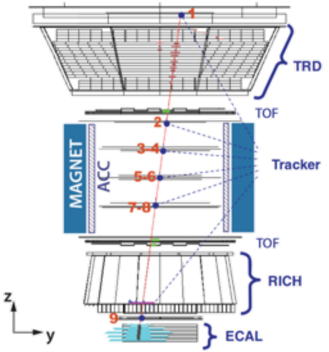
Electromagnetic Calorimeter (ECAL)
E of e^+, e^-, γ

Z, E, R, β

are measured independently by the Tracker, RICH, TOF and ECAL for the same CR

25

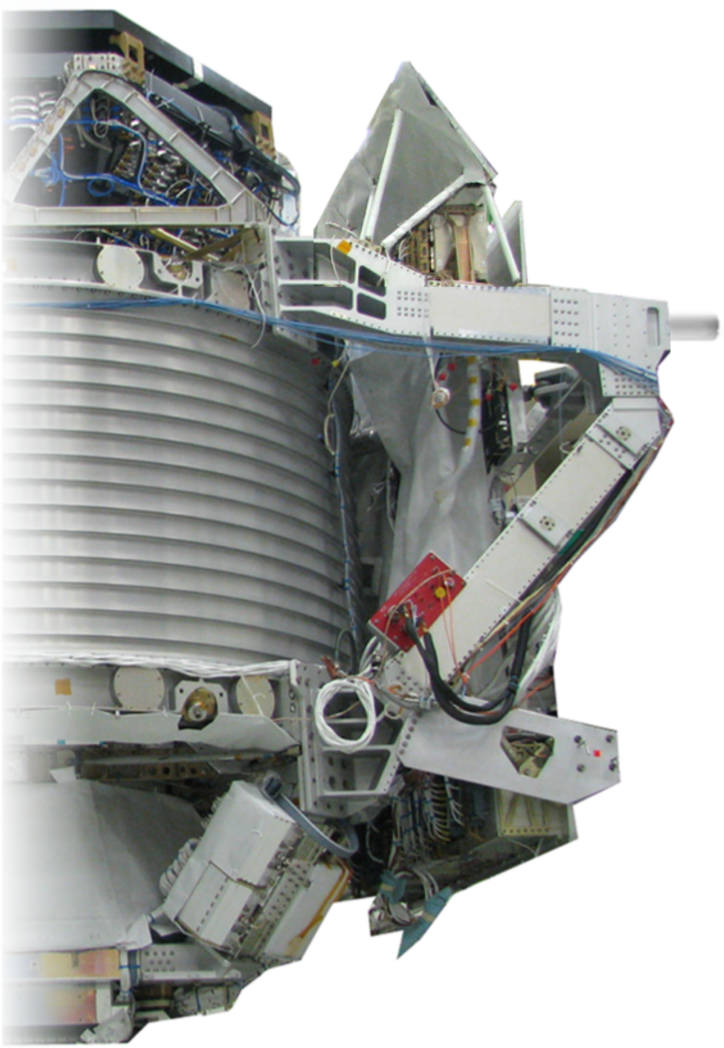

WAKE
Tracker Radiator
M-structure
RAM
Main Radiator
Electronics crates
Upper Unique Support Structure
(Vacuum) Case
Lower Unique Support Structure
STARBOARD



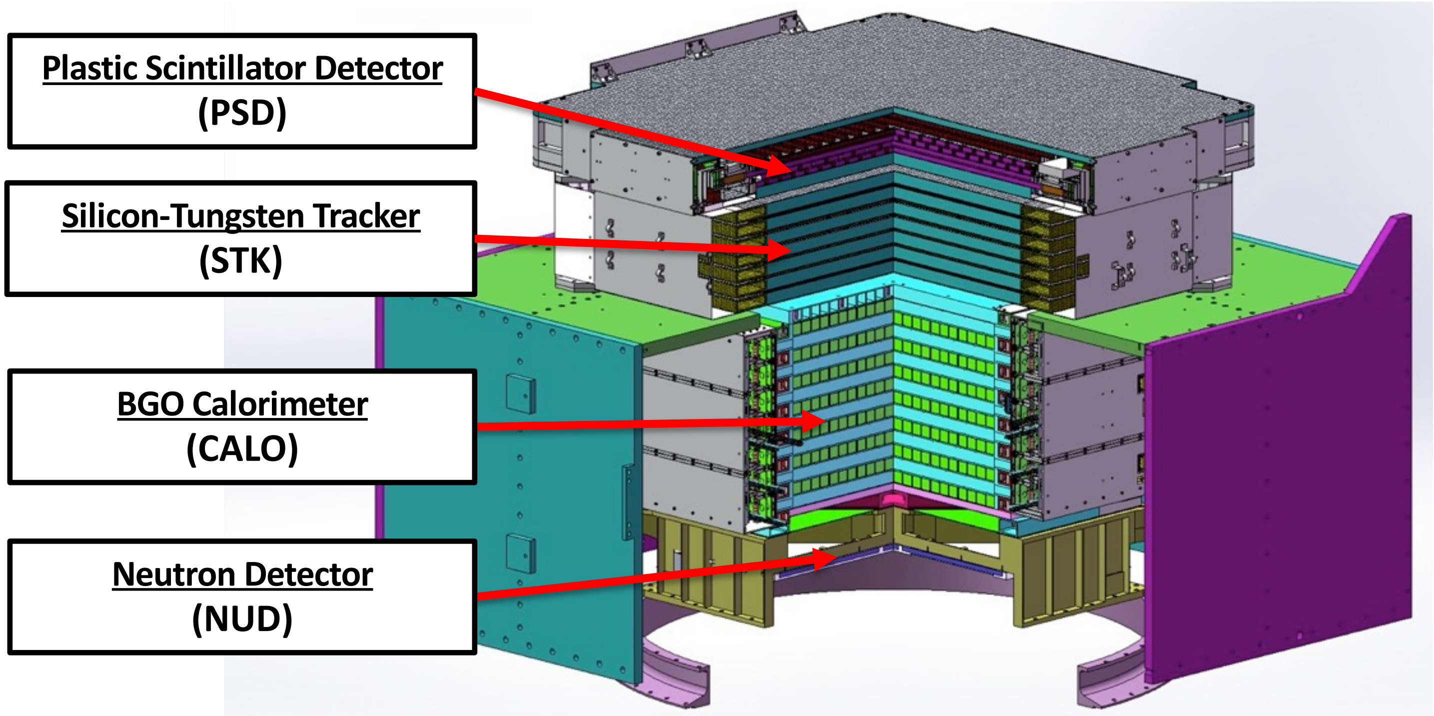
Tracker

planes

6.3 m^2 surface
2264 sensors
192 ladders
192 kchannels
190 W



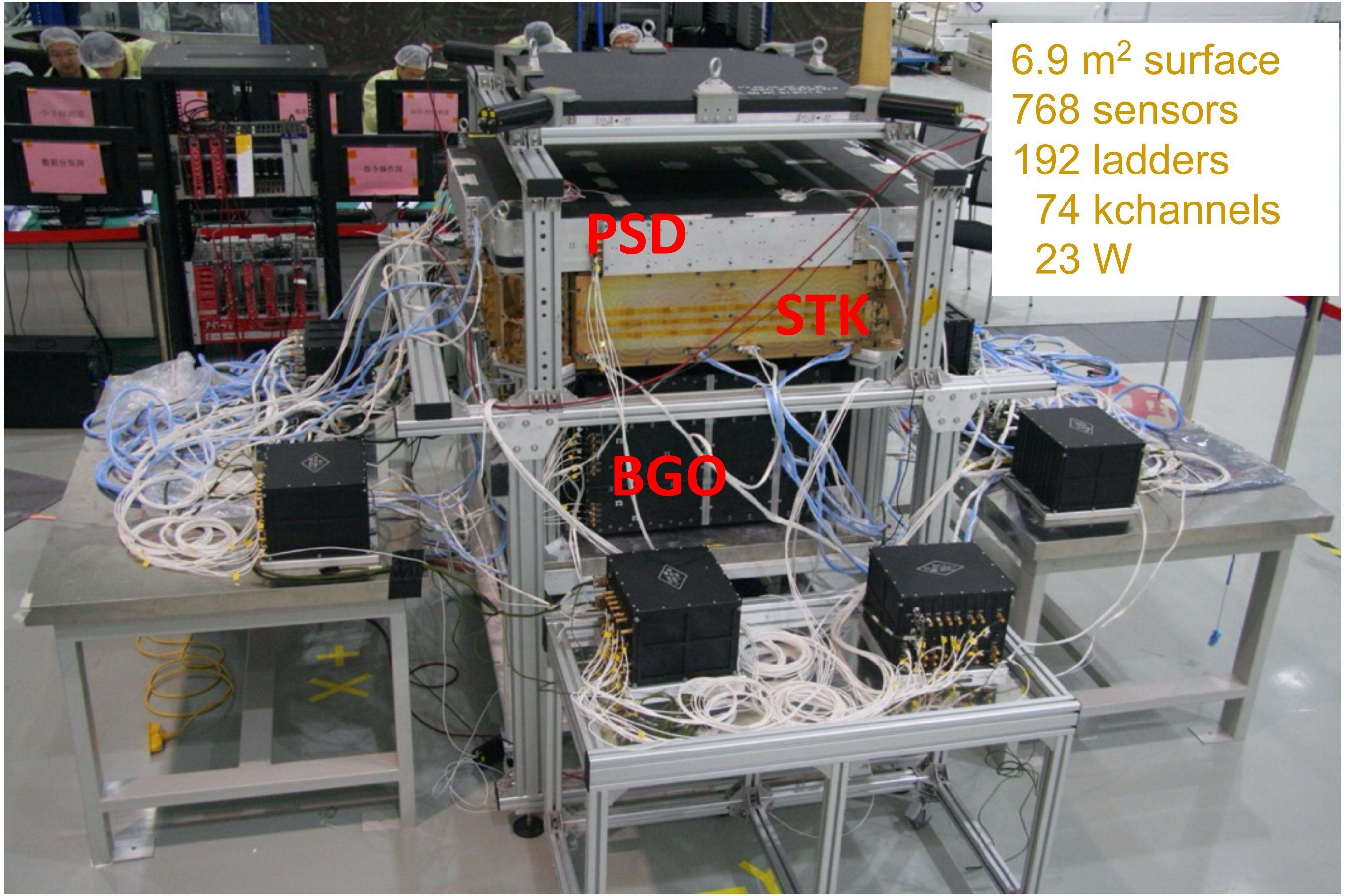
The DAMPE detector



- Charge measurement (dE/dx in PSD , STK and BGO)
- Tungsten converter (pair production)
- Precise tracking (silicon strips)
- Thick calorimeter (BGO bars)
- Hadron rejection (neutron detector)

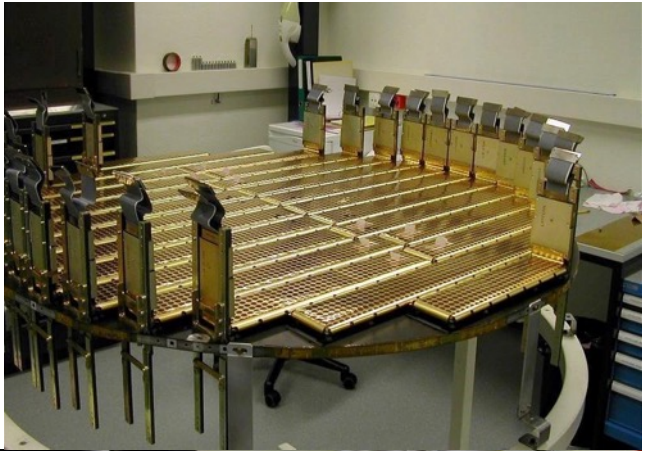
⇨ high energy γ-ray, electron and cosmic ray telescope

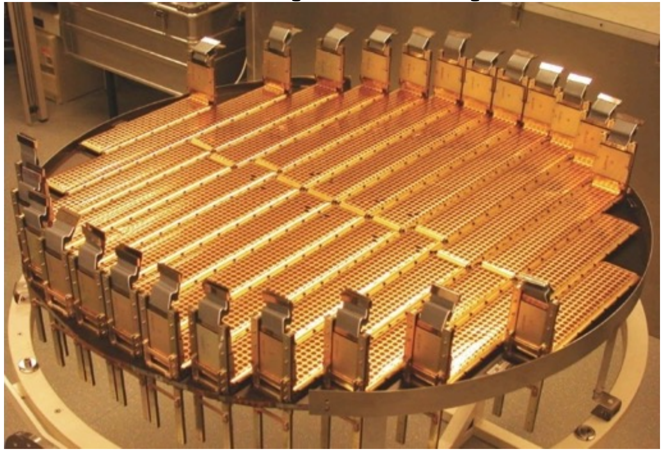
The DAMPE detector

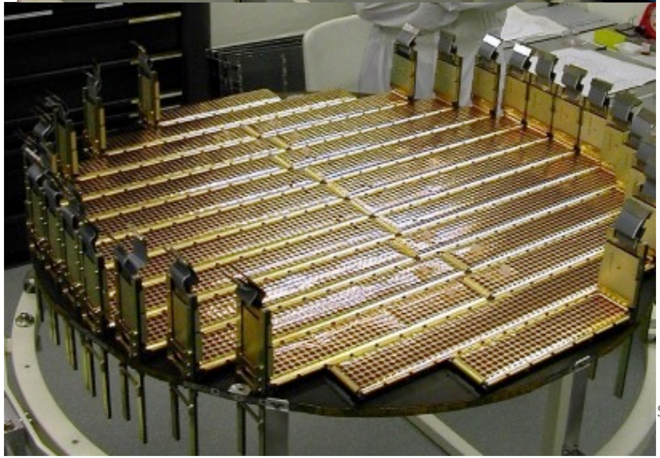


6.9 m^2 surface
768 sensors
192 ladders
74 kchannels
23 W

AMS-02 Silicon Tracker (2011)

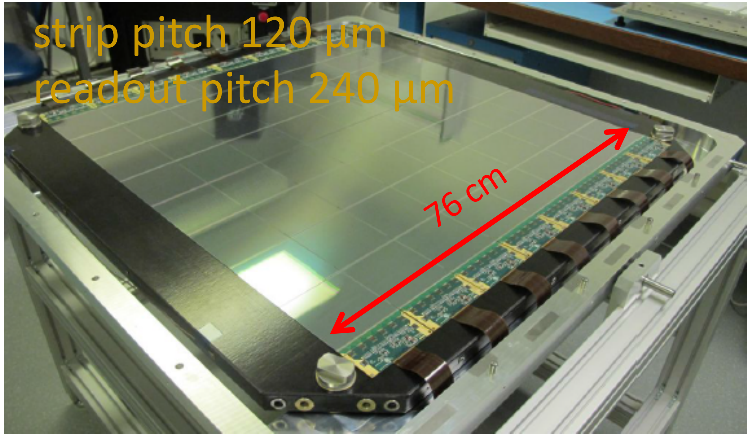


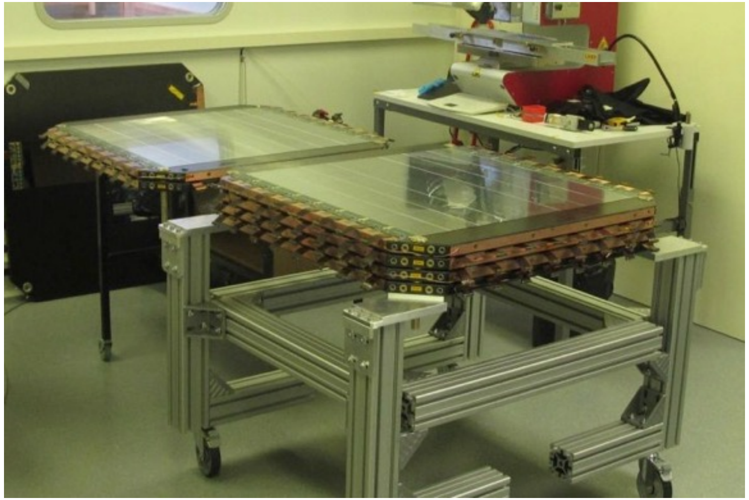


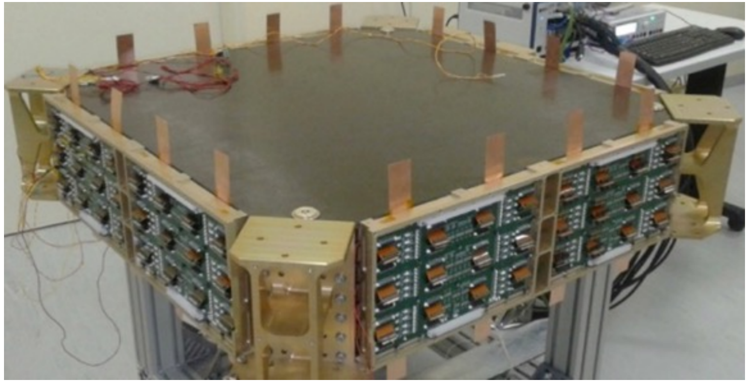


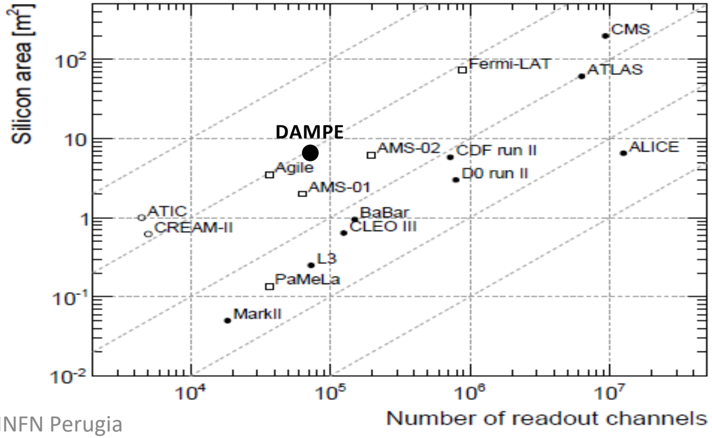
strip pitch 27.5 µm
readout pitch 110 µm

The DAMPE Silicon TracKer (2015)

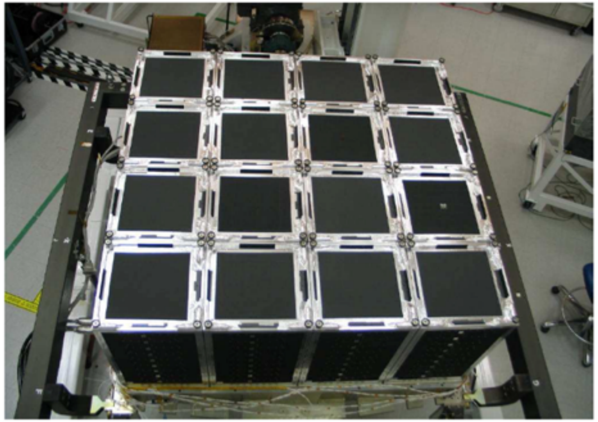


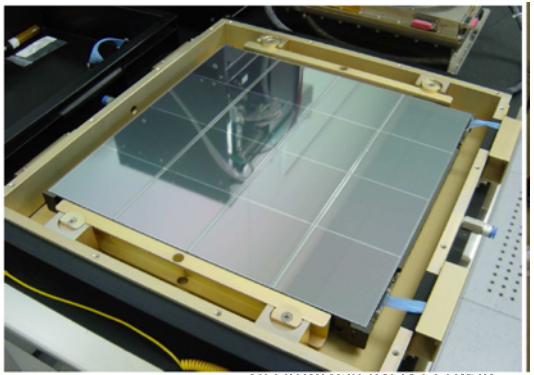


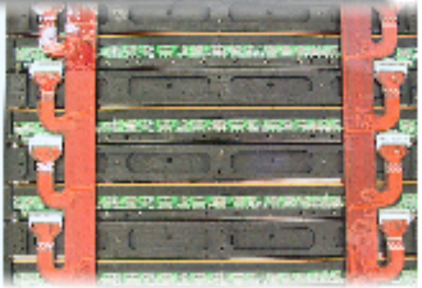




FERMI (2008)





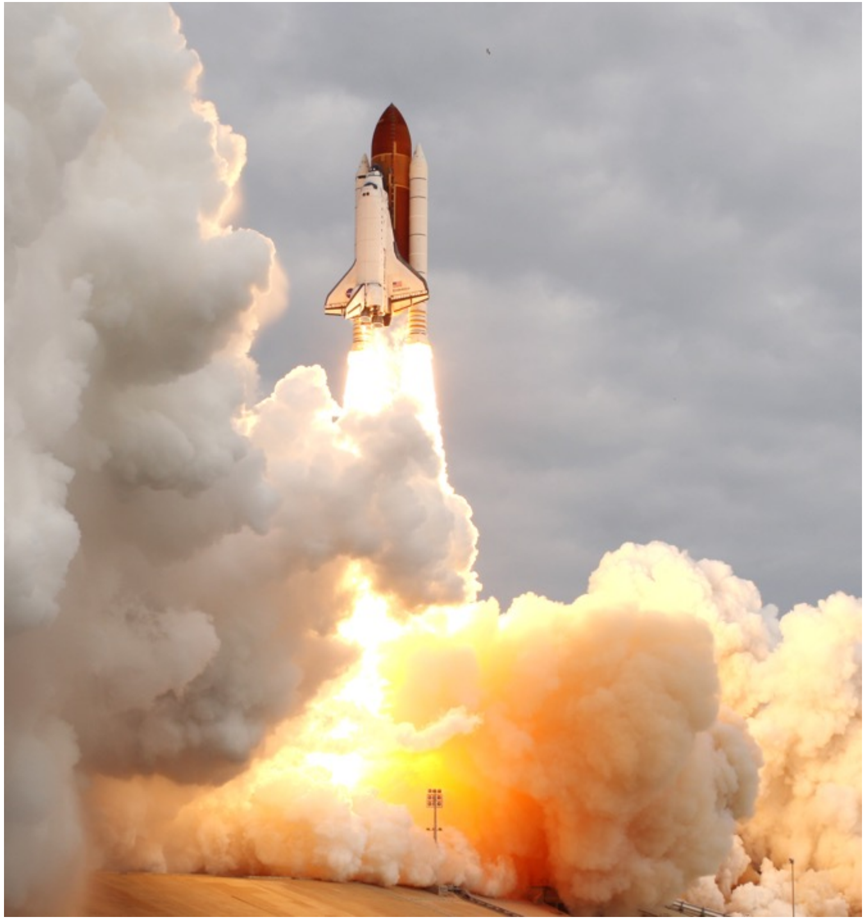


strip pitch 230 µm
readout pitch 230 µm

73 m^2 surface
9216 sensors
2304 ladders
221kchannels

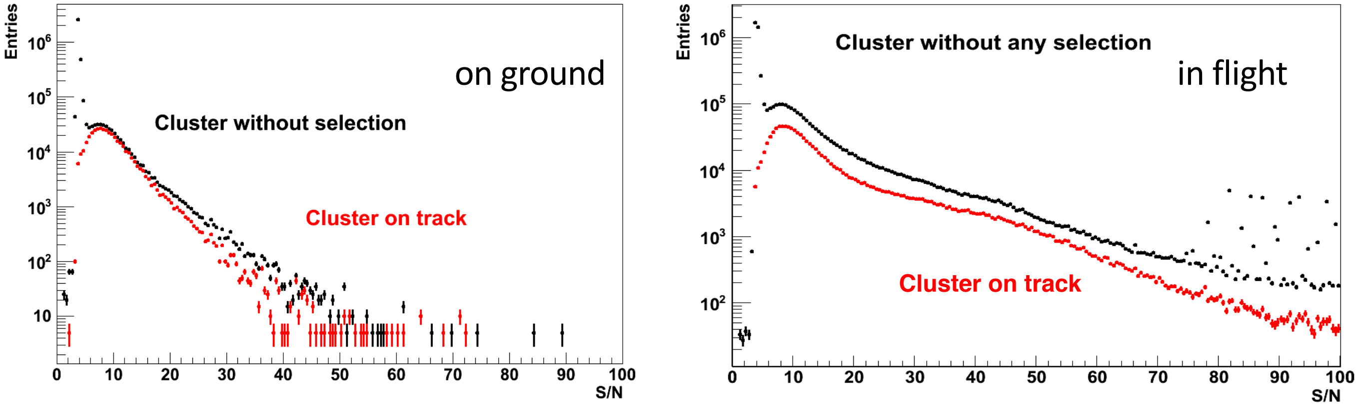
LAUNCH!


悟空号
Wukong
暗物质粒子探测卫星
Dark Matter Particle Explorer (DAMPE)
DAMPE



G.

Tracker signals and charge ID (AMS-02)



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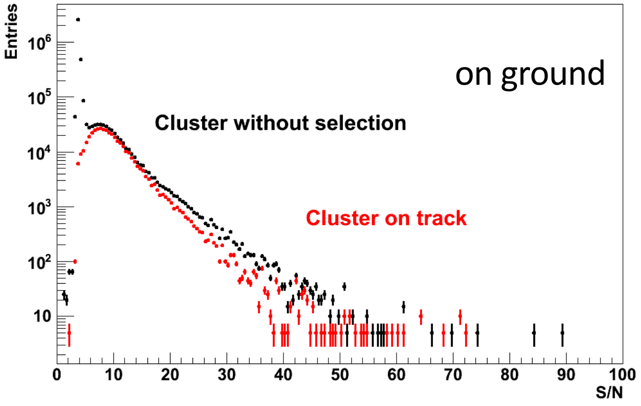
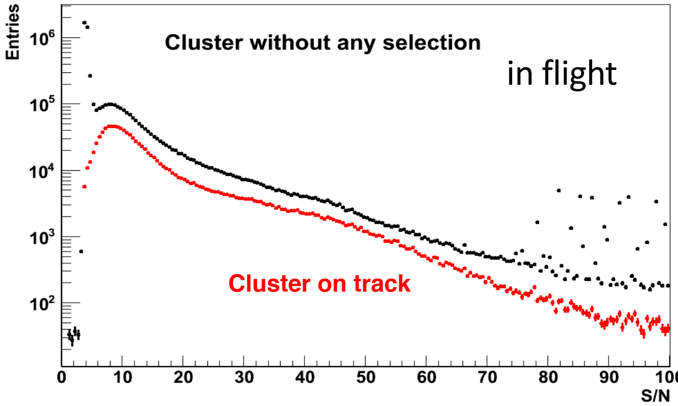
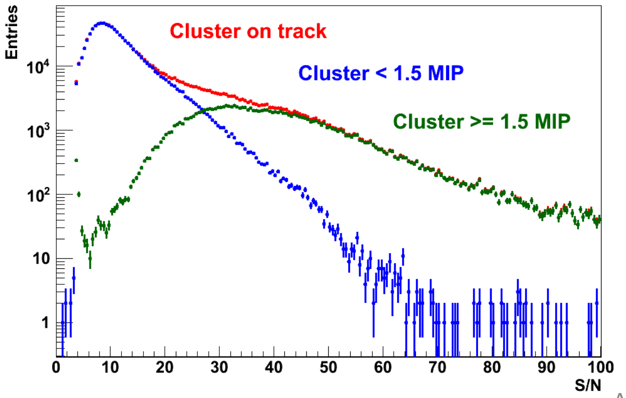
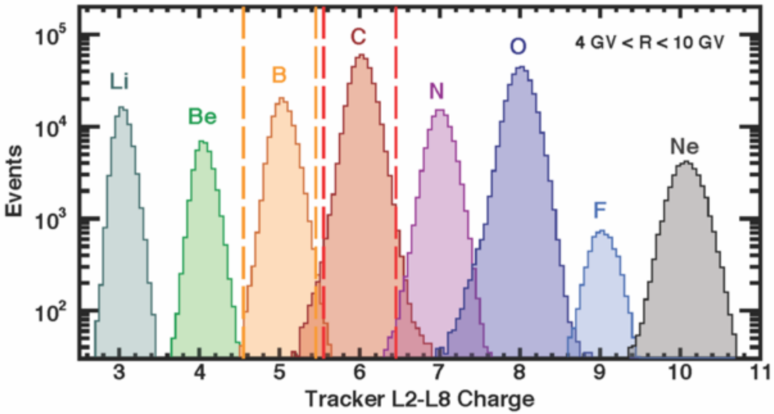
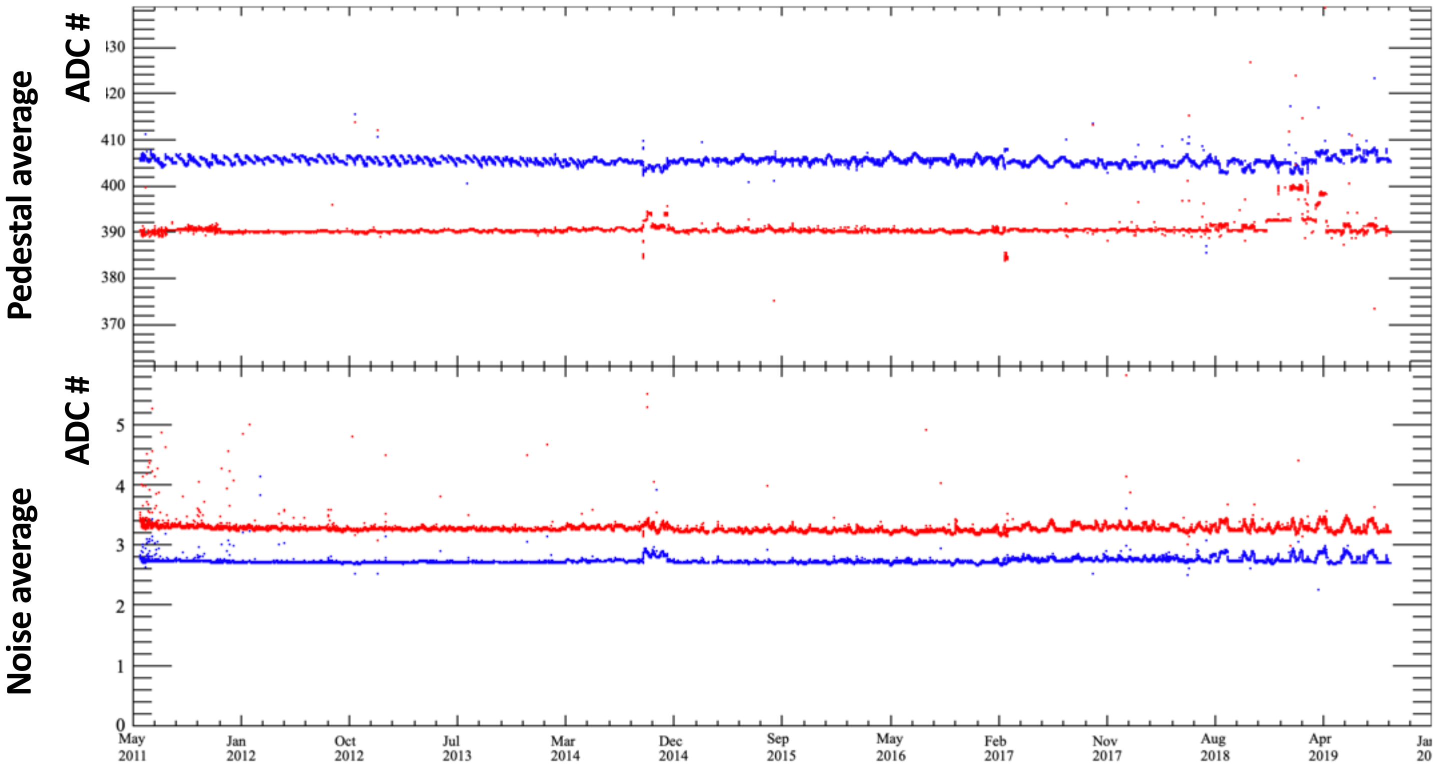






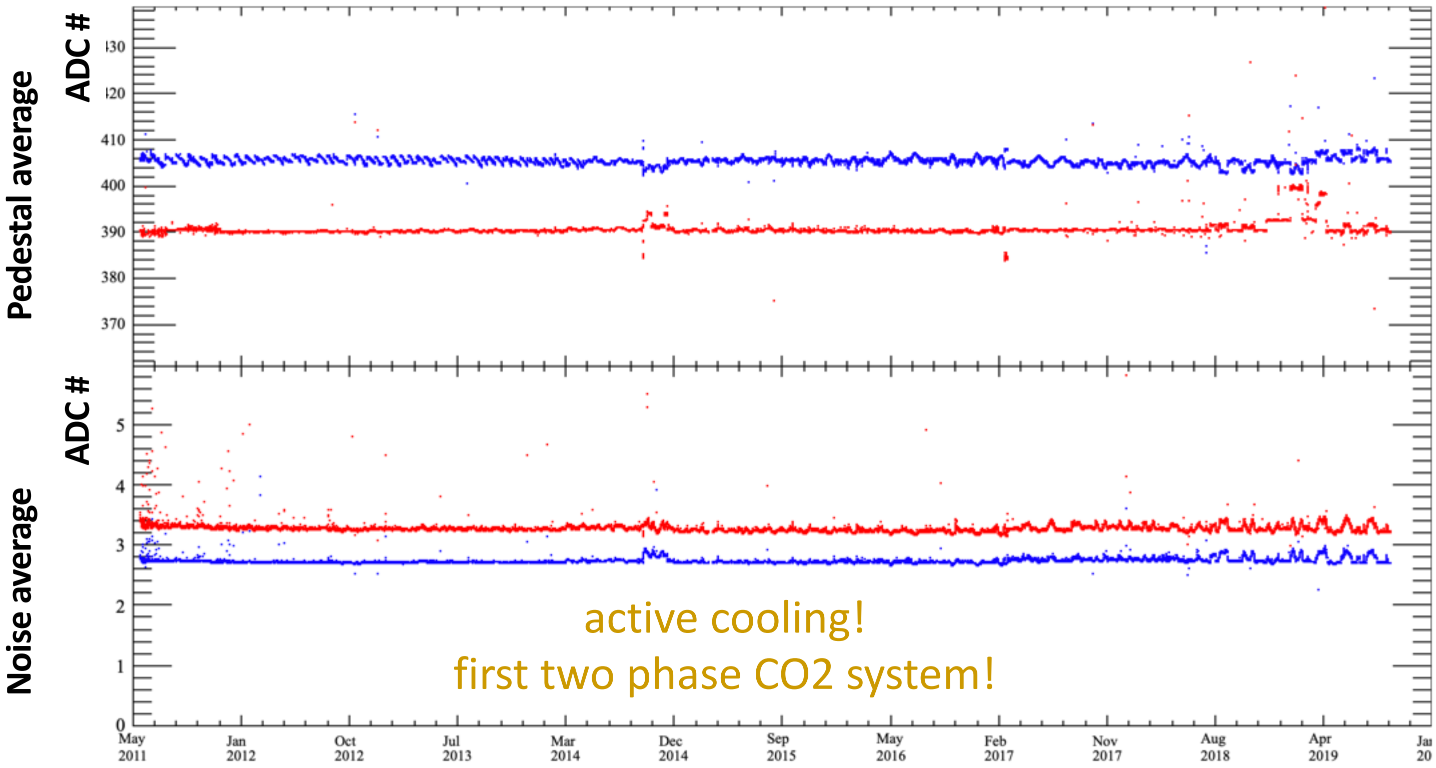


AMS-02 noise behavior vs time



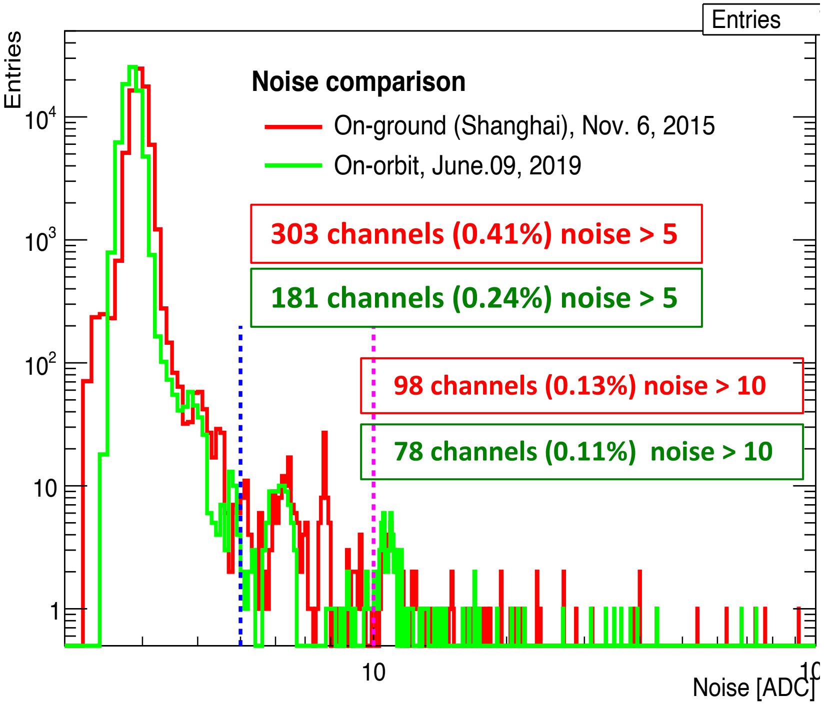
Calibrations done twice per orbit, close to equator, outside the SAA

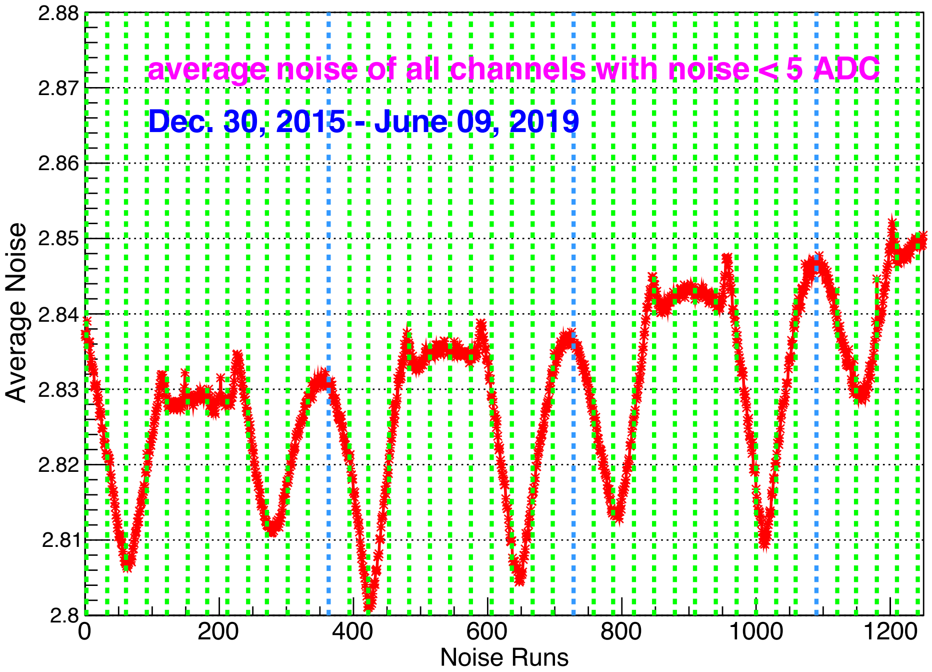
AMS-02 noise behavior vs time



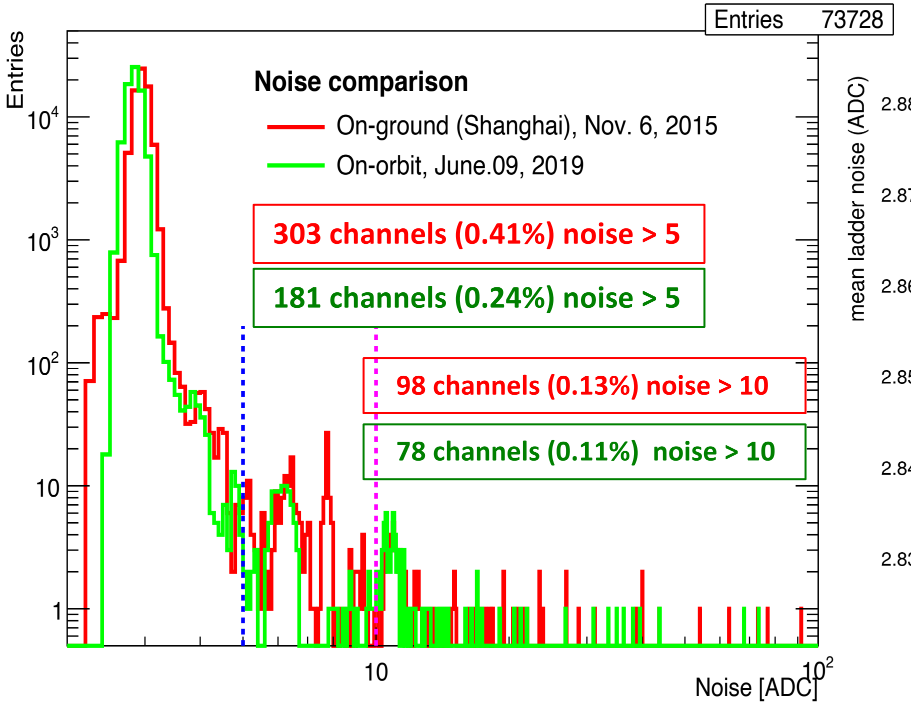
Calibrations done twice per orbit, close to equator, outside the SAA

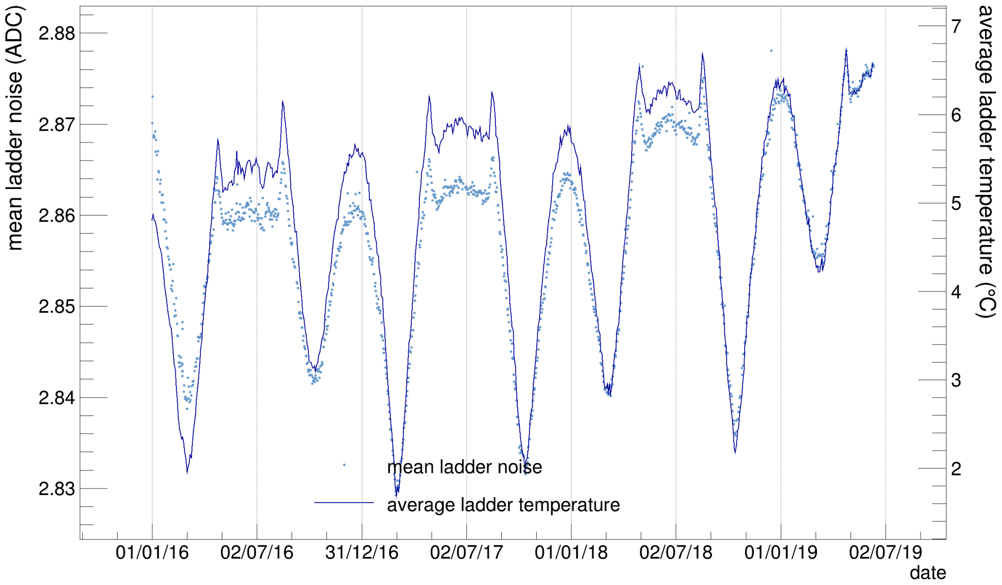
DAMPE STK noise in 42 months





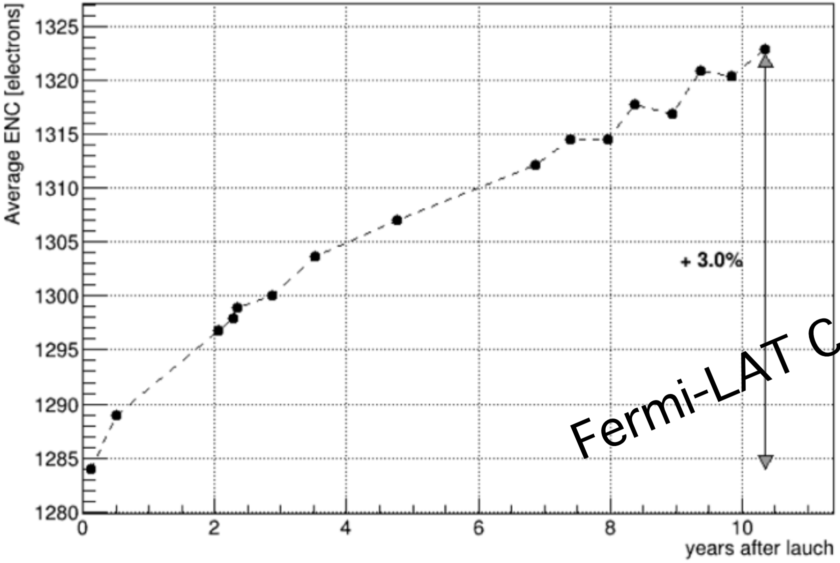
DAMPE STK noise in 42 months

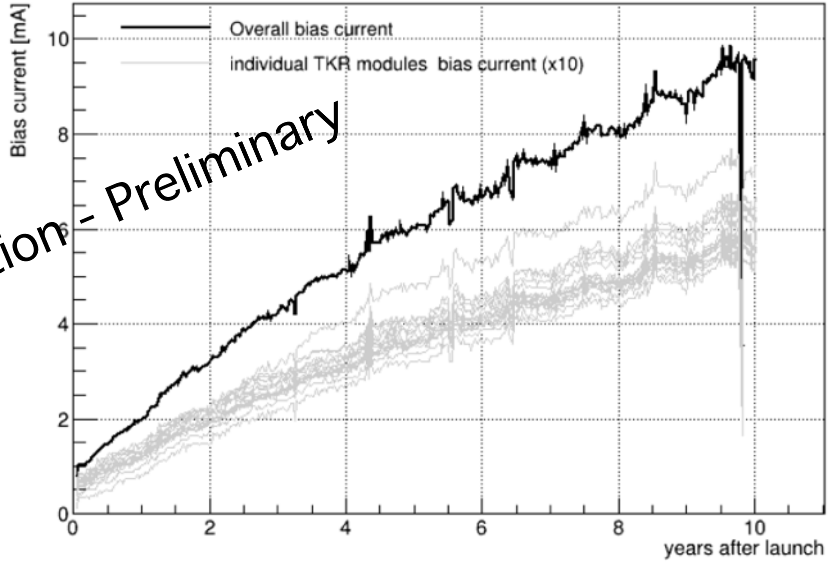




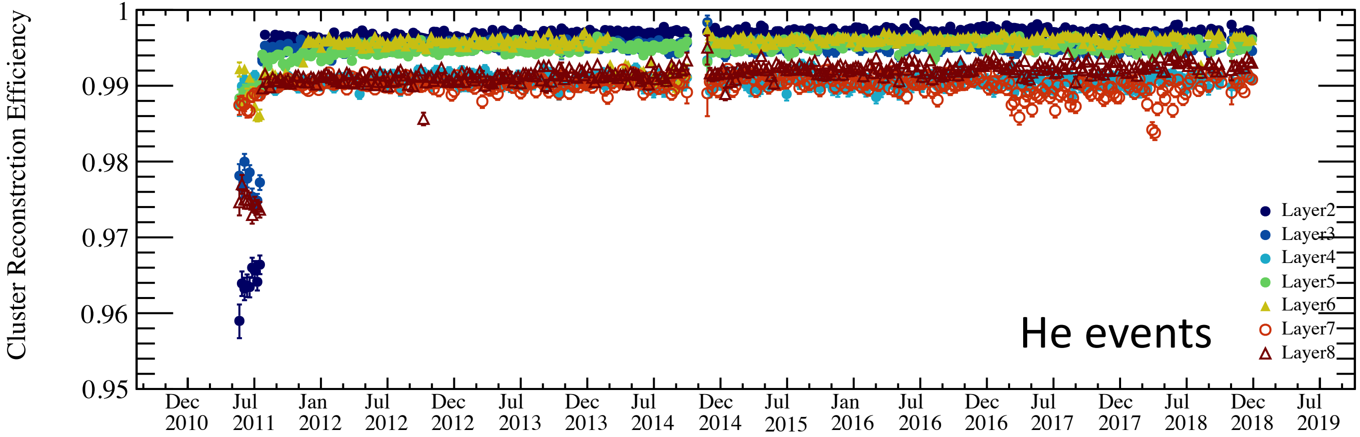
passive cooling!

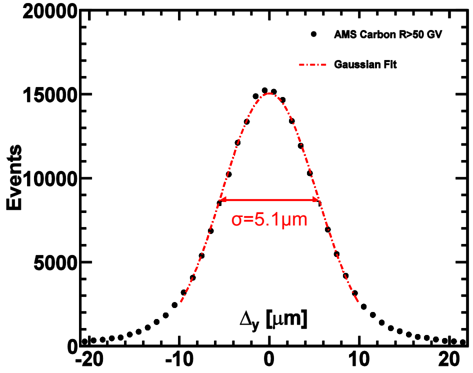
FERMI noise time evolution





AMS tracking efficiency and resolution

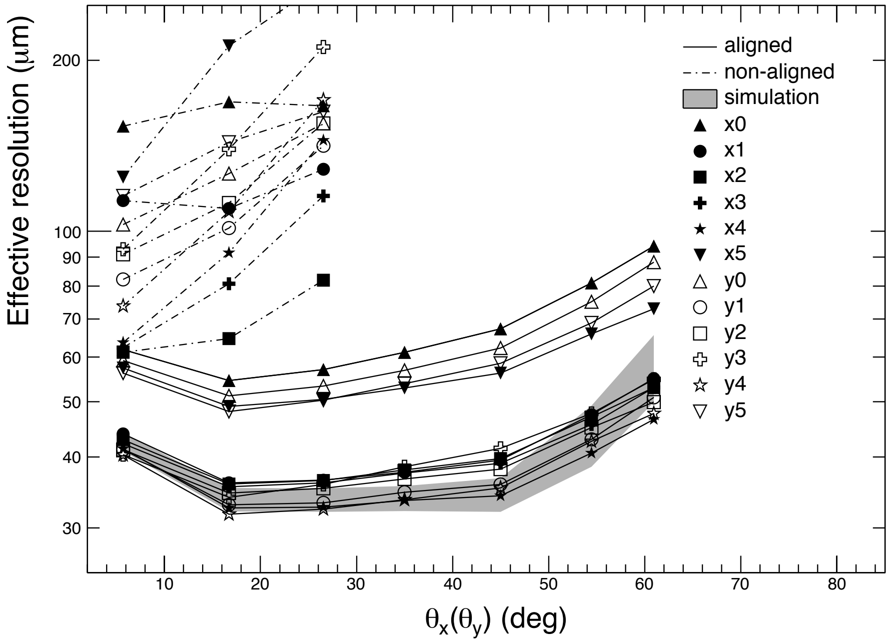




implantation pitch is 25 µm, readout pitch 100 µm

~5 µm intrinsic position resolution after on-orbit alignment

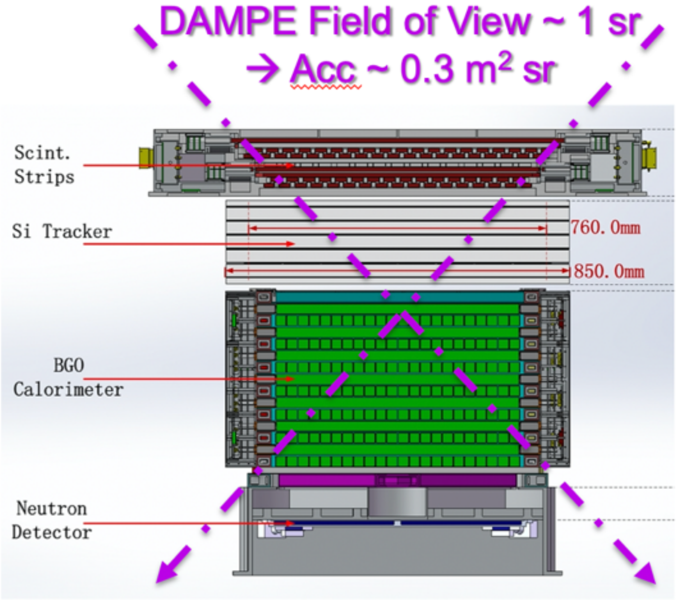
DAMPE STK position resolution

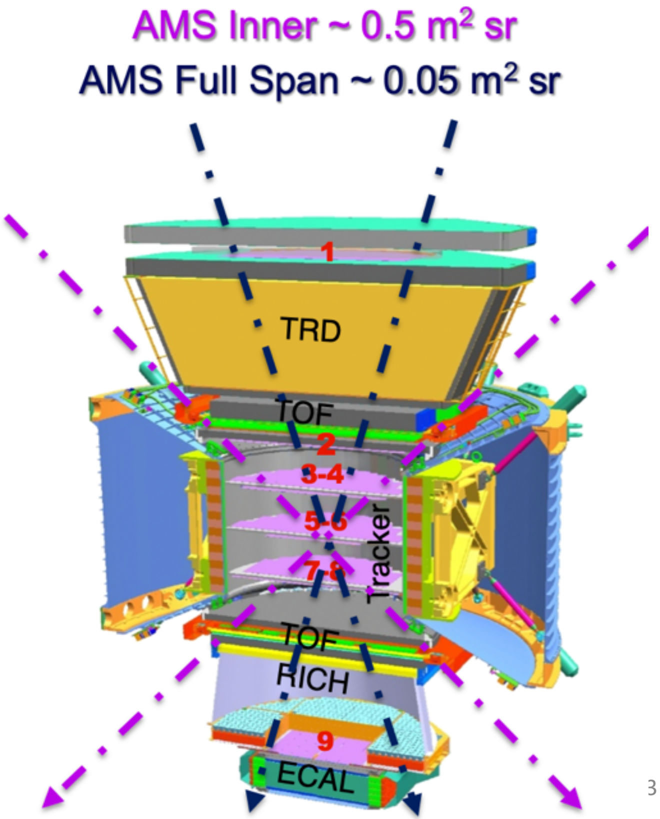


implantation pitch is 121 μm, readout pitch 242 μm

~40 μm intrinsic position resolution after on-orbit alignment

current experiments



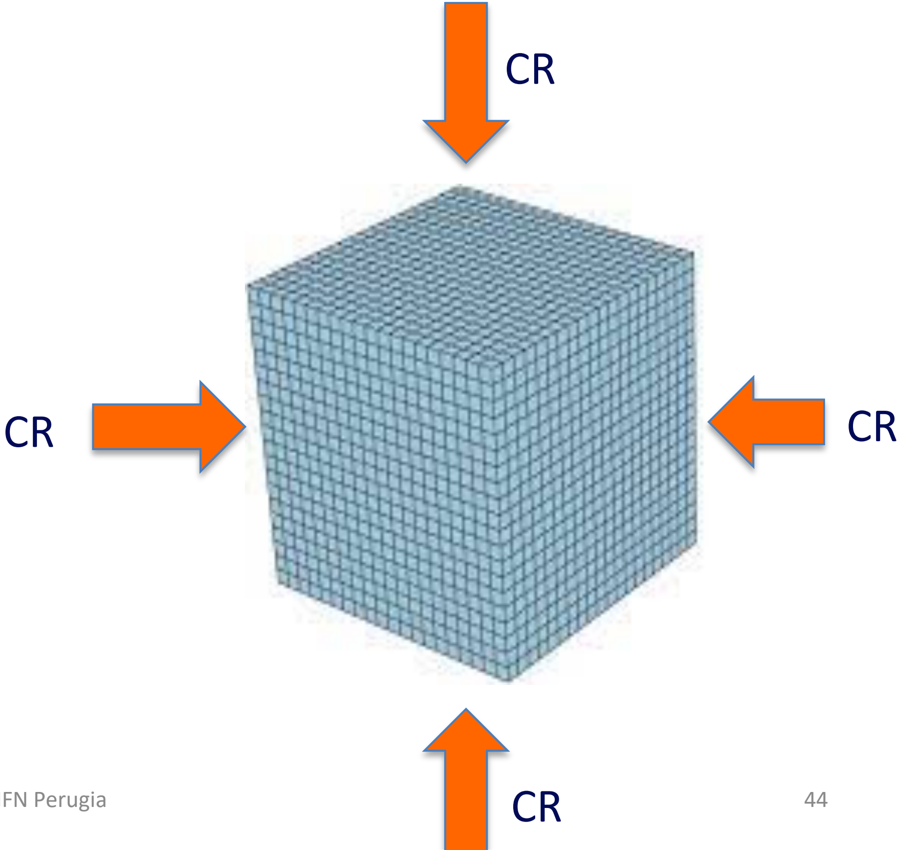


All the current and past detectors are designed as 'telescopes': they're sensitive only to particles impinging from "the top"

limited FoV → small acceptance

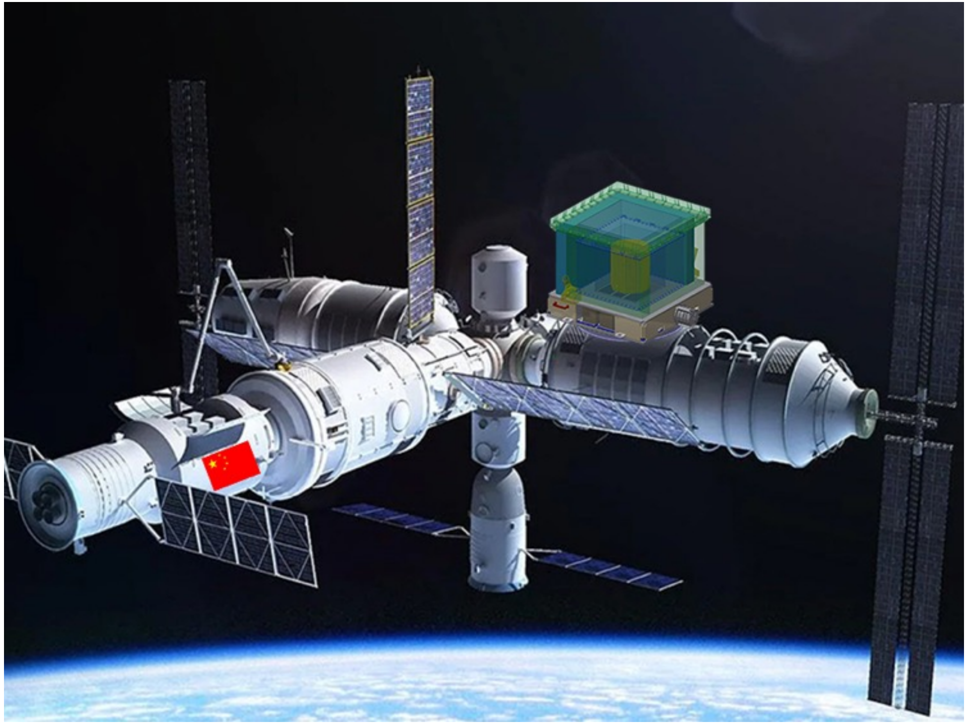
new paradigma: CALOCUBE

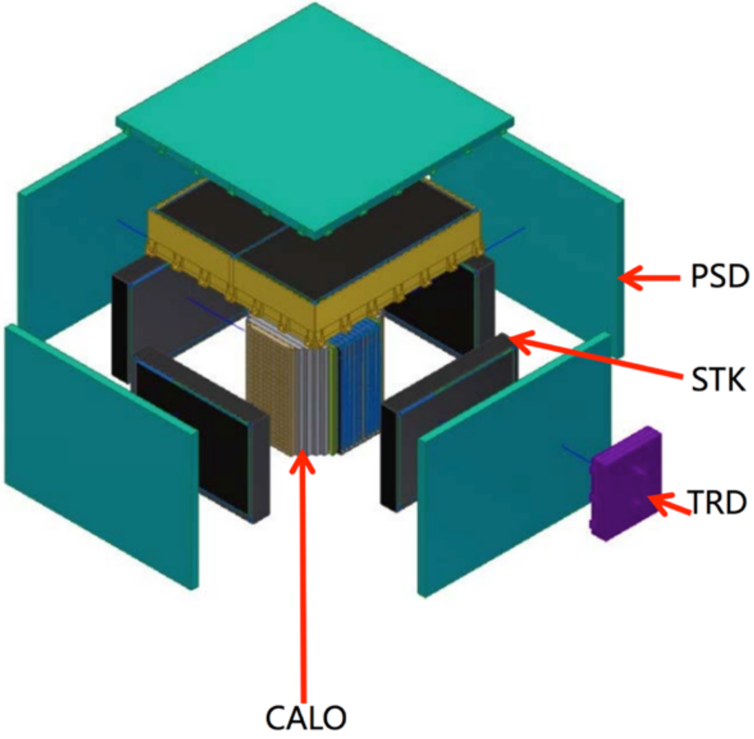
- Exploit the CR "isotropy" to maximize the effective geometrical factor, by using all the surface of the detector (aiming to reach $\Omega = 4\pi$)
- The calorimeter should be highly isotropic and homogeneous:
  - the needed depth of the calorimeter must be guaranteed for all the sides (i.e. cube, sphere, …)
  - the segmentation of the calorimeter should be isotropic



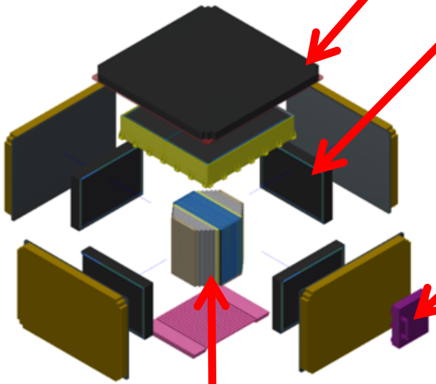
Development in the framework of the CALCUBE INFN initiative

HERD: cosmic ray detector on board the China Space Station





HERD: cosmic ray detector on board the China Space Station (2026?)



PSD, 6 sides
γ identification
Charge

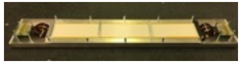
Tracker, 5 sides
Charge
CR trajectory
γ conv. & tracking

TRD
TeV CR calibration

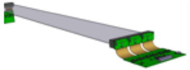
CALO: 3-D
Energy
e/p separation

~7500 LYSO crystals (55 R.L, 3 N.I.L.)
Trigger sub-system
Dual readout with IsCMOS & PD

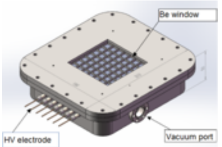
PS + SiPM
@INFN Bari, Lecce, GSSI, Pavia



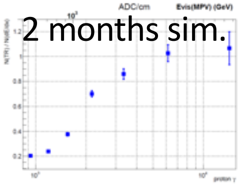
Silicon Track
@INFN Perugia



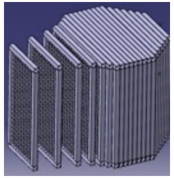
Fiber Tracker
@Univ. of Geneva



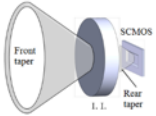
@Guangxi Univ.



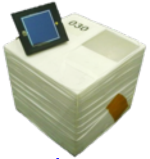
2 months sim.



@IHEP



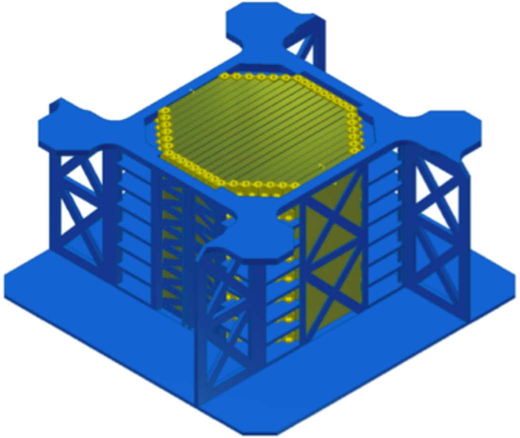
@XIOPM



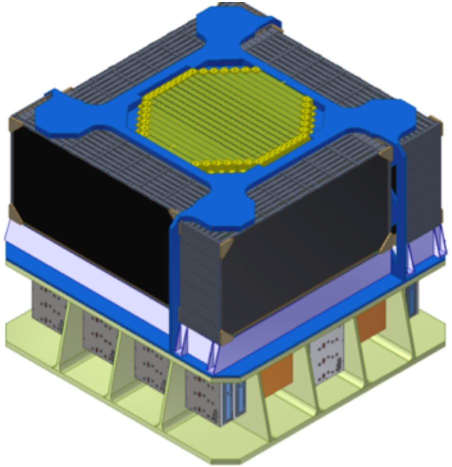
@INFN Florence

a Tracker for HERD

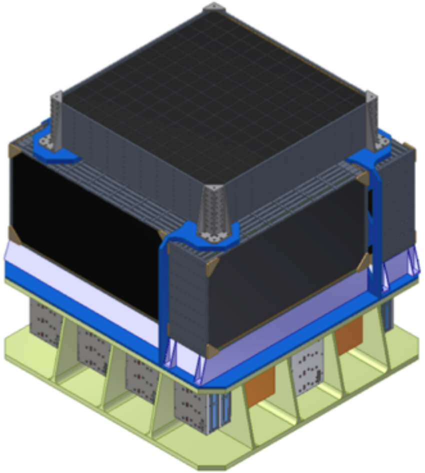
very preliminary design, work in progress



Calorimeter



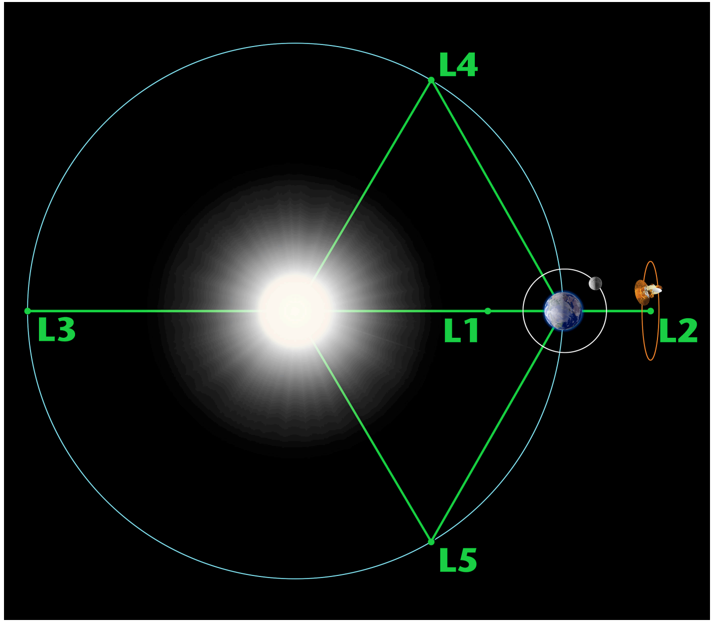
Side Tracker



Top Tracker

Total of about 6000 SSD, 240 kchannels, 300 kg, 100 W front end electronics

Lagrangian point 2: a nice place in space



https://en.wikipedia.org/wiki/List_of_objects_at_Lagrangian_points

tarted

L2 [edit]

L_2 is the Lagrangian point located approximately 1.5 million km from Earth in the direction opposite the Sun.

Past probes [edit]

- NASA's Wilkinson Microwave Anisotropy Probe (WMAP) observed the cosmic microwave background from 2001 until 2010. It was moved to a heliocentric orbit to avoid posing a hazard to future missions.
- NASA's WIND from November 2003 to April 2004. The spacecraft then went to Earth orbit, before heading to L_1.
- The ESA Herschel Space Observatory exhausted its supply of liquid helium and was moved from the Lagrangian point in June 2013.
- At the end of its mission ESA's *Planck* spacecraft was put into a heliocentric orbit and passivated to prevent it from endangering any future missions.
- CNSA's Chang'e 2[1] from August 2011 to April 2012. Chang'e 2 was then placed onto a heliocentric orbit that took it past the near-Earth asteroid 4179 Toutatis.

Present probes [edit]

- The ESA Gaia probe

Planned probes [edit]

- The joint Russian-German high-energy astrophysics observatory Spektr-RG
- The ESA Euclid mission, to better understand dark energy and dark matter by accurately measuring the acceleration of the universe.
- The joint NASA, ESA and CSA James Webb Space Telescope (JWST), formerly known as the Next Generation Space Telescope (NGST)
- The ESA PLATO mission, which will find and characterize rocky exoplanets.
- The JAXA LiteBIRD mission.
- The NASA Wide Field Infrared Survey Telescope (WFIRST)
- The ESA ARIEL mission, which will observe the atmospheres of exoplanets.
- The ESA Advanced Telescope for High ENergy Astrophysics (ATHENA)
- The NASA Advanced Technology Large-Aperture Space Telescope, which would replace the Hubble Space Telescope and possibly the JWST.

Cancelled probes [edit]

- The ESA Eddington mission
- The NASA Terrestrial Planet Finder mission (may be placed in an Earth-trailing orbit instead)

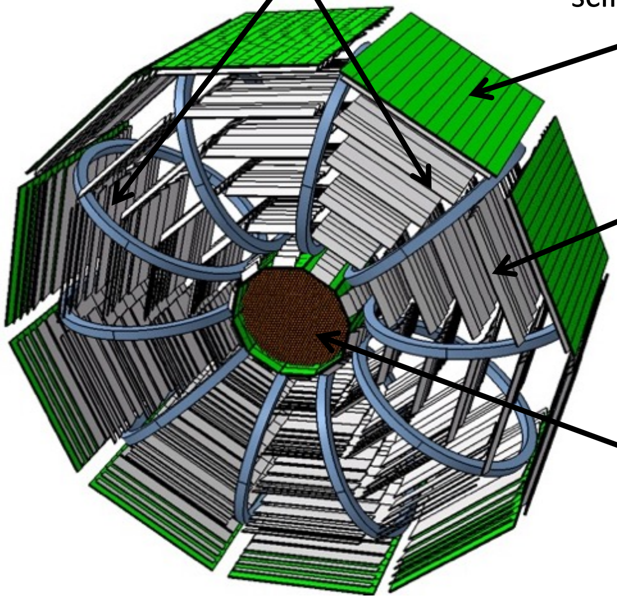
Aladino

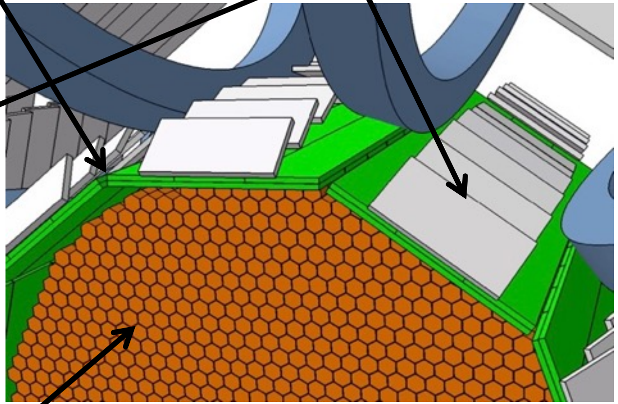
AntimatterLargeAcceptanceDetectorInOrbit

supercoducting coils: magnet

scintillators: ToF

Silicon ladders: tracking





CaloCube: energy
(INFN CSNV)

Diameter: 4.4 mt
Length: 2.2 mt
Acceptance: 3 m^2sr
MDR > 20 TV

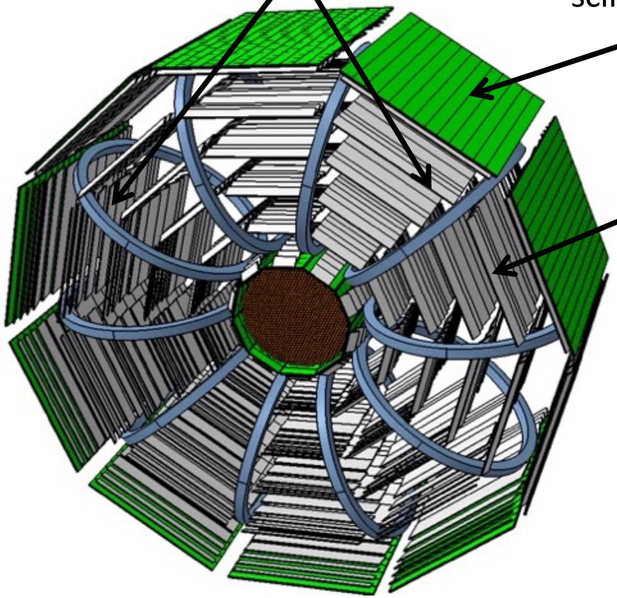
Aladino

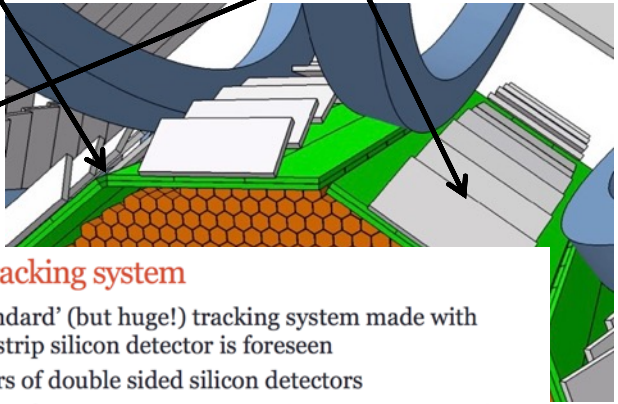
AntimatterLargeAcceptanceDetectorInOrbit

supercoducting coils: magnet

scintillators: ToF

Silicon ladders: tracking



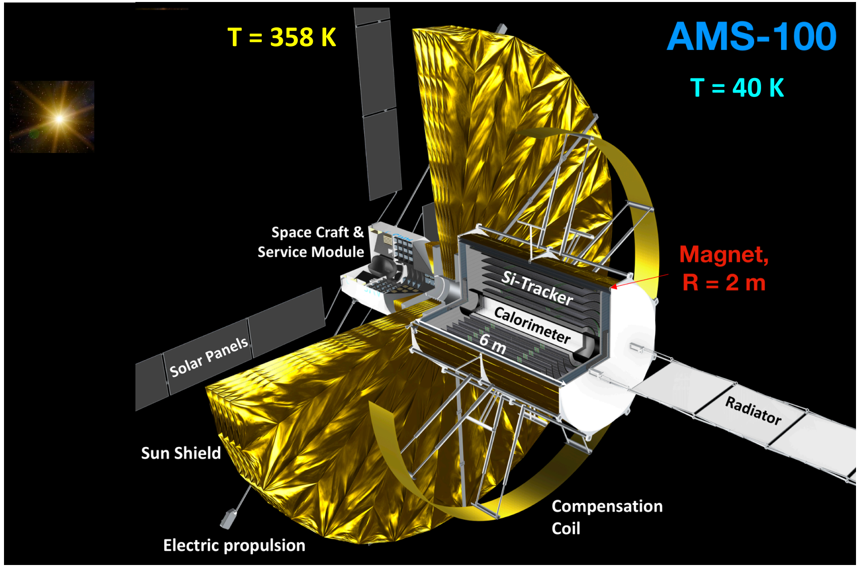


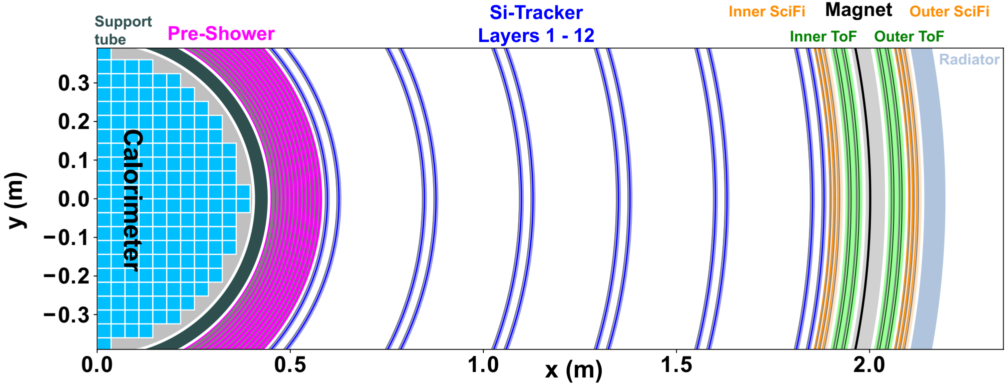
The tracking system

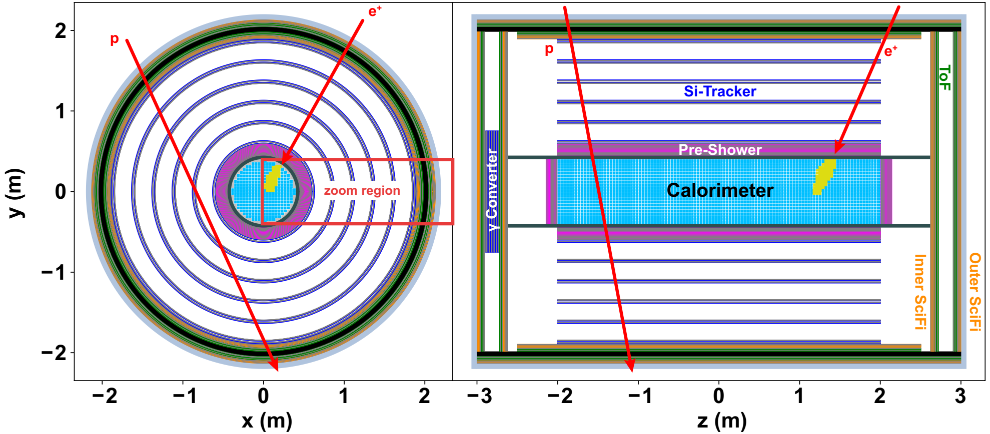
- A ‘standard’ (but huge!) tracking system made with microstrip silicon detector is foreseen
- 6 layers of double sided silicon detectors
- Total surface ~ 100 m² (Fermi-LAT~70 m²)
- # of channels: ~ 2 Millions (AMS ~ 200 k)
- Power consumption:
  - Based on reasonable extrapolation from current technologies we can expect 5 W/m²
  - Total power consumption <1000 W
- Spatial resolution (for the simulations):
  - ~5 μm for orthogonal tracks
  - ~15 μm for 60° incident angles

Diameter: 4.4 mt
Length: 2.2 mt
Acceptance: 3 m^2sr
MDR > 20 TV

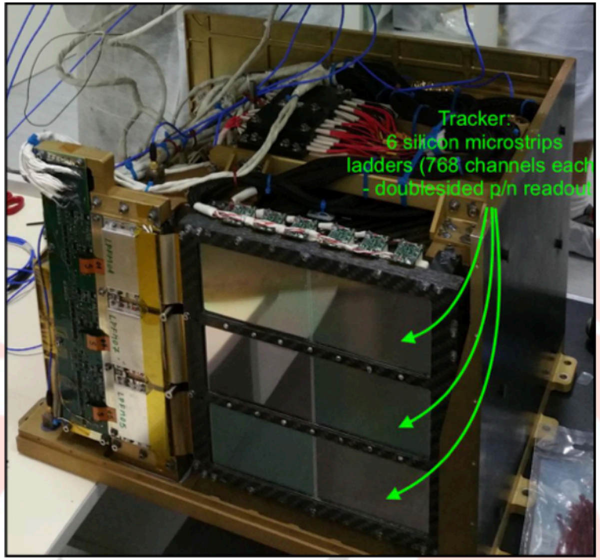
AMS-100


T = 358 K
AMS-100
T = 40 K
Space Craft &
Service Module
Magnet,
R = 2 m
Si-Tracker
Calorimeter
6 m
Solar Panels
Radiator
Sun Shield
Compensation
Coil
Electric propulsion


Support
tube
Pre-Shower
Si-Tracker
Layers 1 - 12
Inner SciFi
Magnet
Outer SciFi
Inner ToF
Outer ToF
Radiator
Calorimeter
y (m)
x (m)
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
0.0
0.5
1.0
1.5
2.0


p
e+
zoom region
y (m)
x (m)
Si-Tracker
Pre-Shower
Calorimeter
γ Converter
ToF
Inner SciFi
Outer SciFi
z (m)
2
1
0
−1
−2
−3
3

HEPD-02 tracker



From microstrips to MAPS:

ADVANTAGES

Low fake hit rates

Low cost

Small pitch

Thin detector

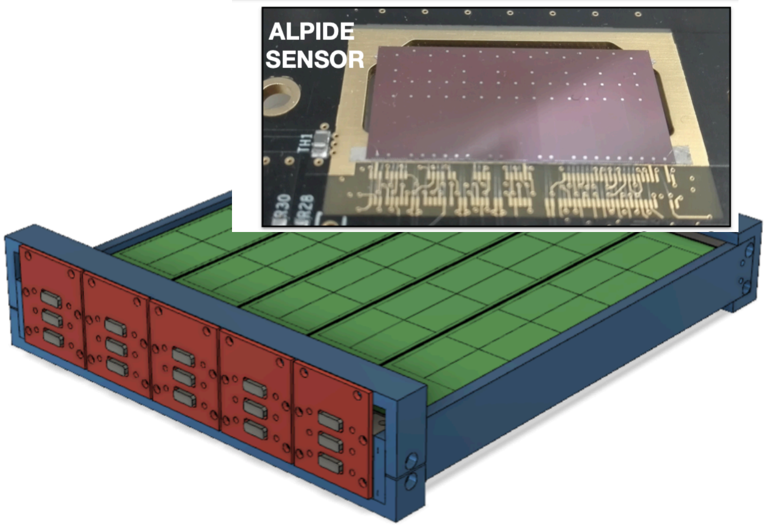
LIMITS

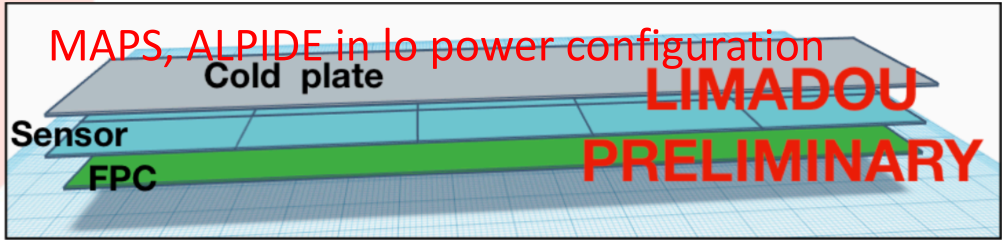
High power consumption

Temperature control

Increasing number of channels

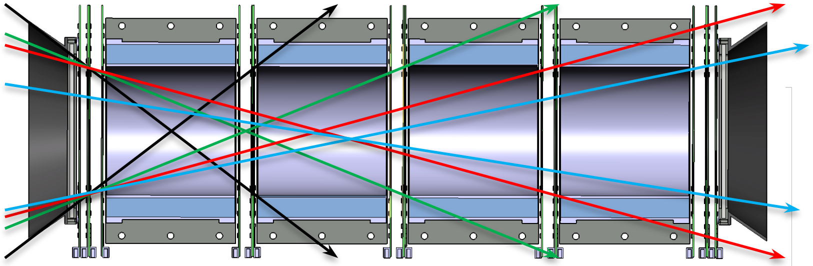
5 years and ~5M for development

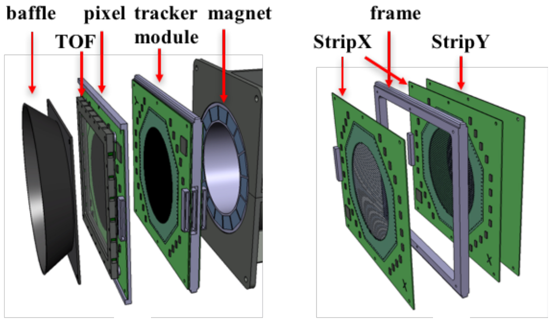




PAN detector modules

- **5 tracker modules, 2 TOF modules, 2 pixel modules**





- **Tracker module**
  - 2 StripX: 25 µm readout pitch, 150 µm thick, **2 µm resolution**, to measure both bending radius and bending angle, 40k channels, total power budget 8W
  - 1 stripY: 500 µm readout pitch, 150 µm thick, high dynamic range ASIC for Z = 1 – 26, trigger signal, time stamp (<100 ps resolution), 1k channels, total ~1 W
- **TOF module**
  - 3 mm thick scintillator, read out on all sides by SiPM: trigger, particle counter (max. ~10 MHz), charge measurement (Z = 1 -26), time (<100 ps), total ~1 W
- **Pixel module**
  - Avoid measurement degradation for high rate solar events
  - Issue to be resolved: total (static) power consumption ~2-4 W, for ~190 cm^2

ground demonstrator fully founded
H2020 FET-OPEN

G. Ambrosi

Conclusions

- Almost 100 m^2 of silicon tracking detector are taking data in orbit
- Silicon microstrip detector are playing a crucial role in running experiments:
  - tuning of spatial resolution vs power is simple (strip pitch)
  - excellent dE/dx measurement for ion identification
  - low power per active unit surface
- Although the technology is ‘from last century’ it is still optimal for future detector, of any dimension, in space!

Radiation 'hard' electronics

The problem are the SEE (Single Event Effect)

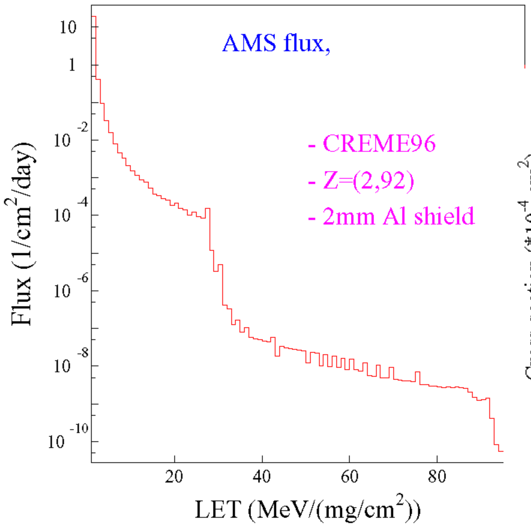


Figure 5: Expected fluxes on ISS in 2003.

Example: AMS-02 Tracker front end chip

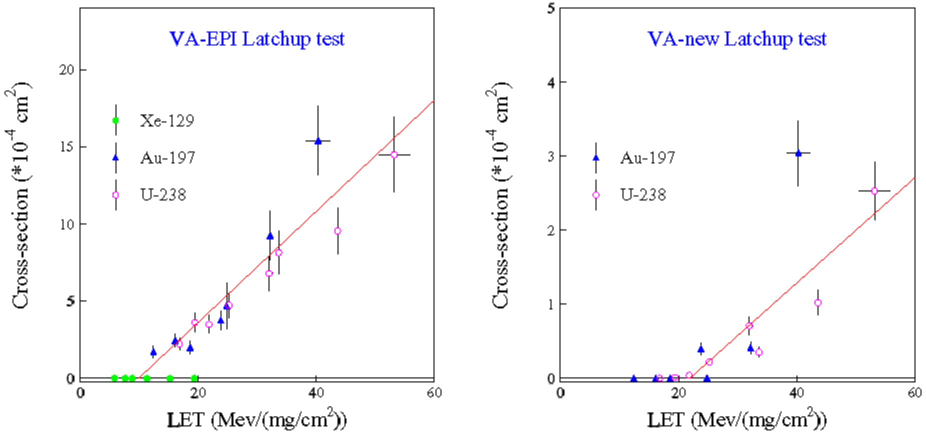
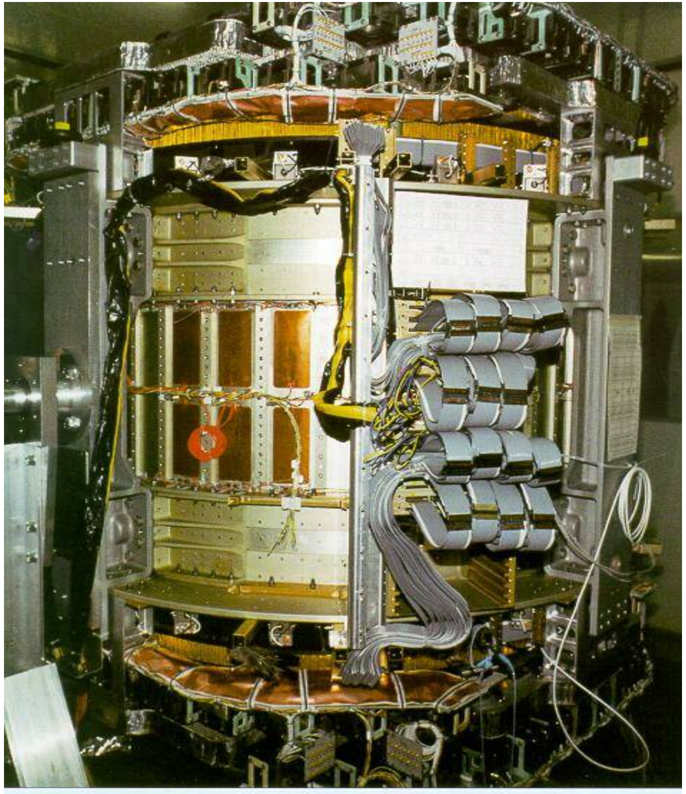


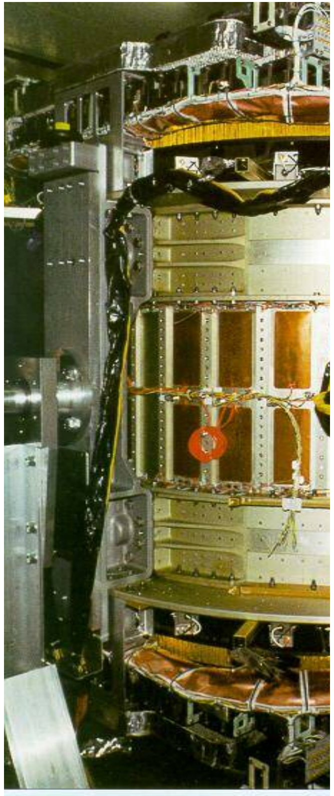
Figure 12: The new VA – SEL rates as measured in GSI

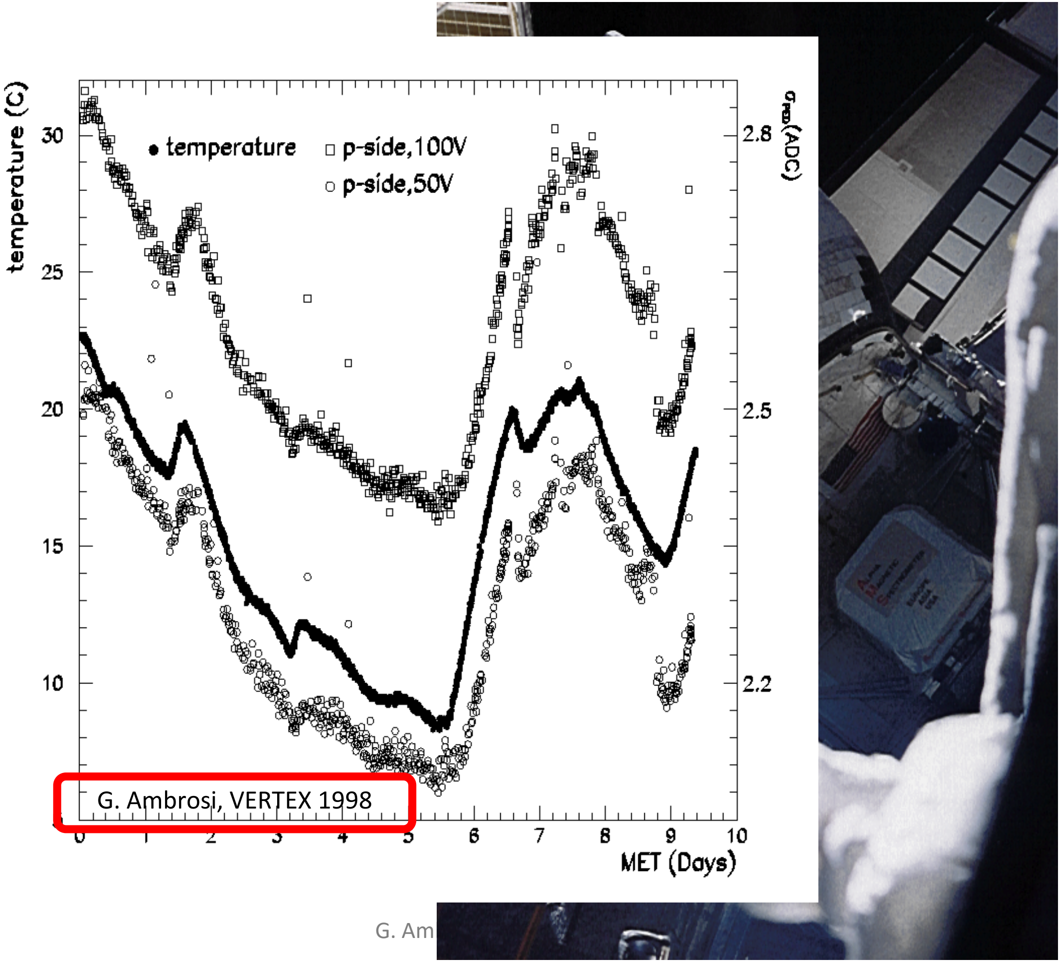
similar test on all active components
current limit protection is present for all active components

AMS-01 1998



AMS-01 1998




temperature (C)
30
25
20
15
10
● temperature
□ p-side,100V
○ p-side,50V
2.8
2.5
2.2
$\sigma_{\rm red}$(ADC)
0
1
2
3
4
5
6
7
8
9
10
MET (Days)
G. Ambrosi, VERTEX 1998