Silicon in Space

G. Ambrosi

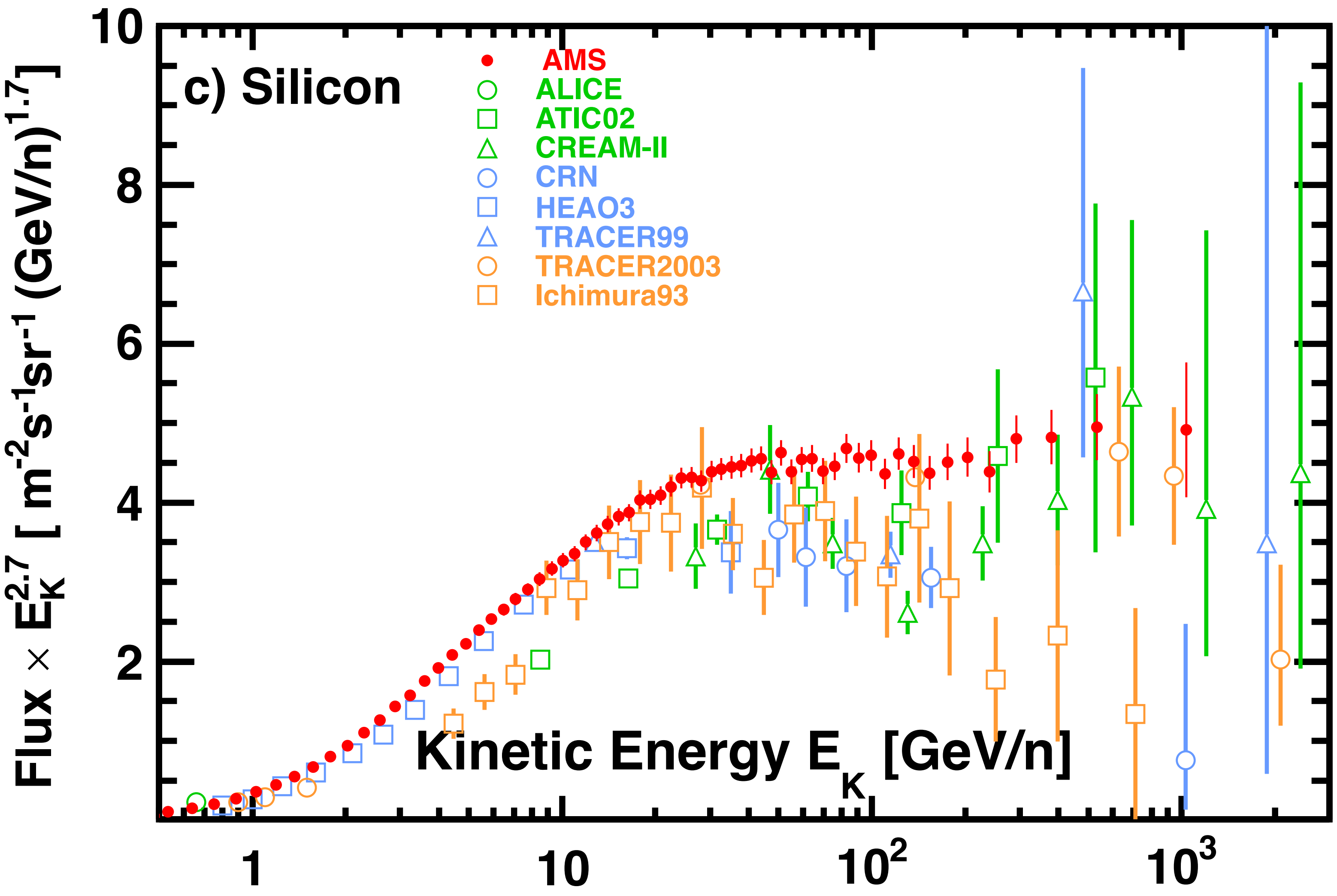
INFN Perugia

INFN

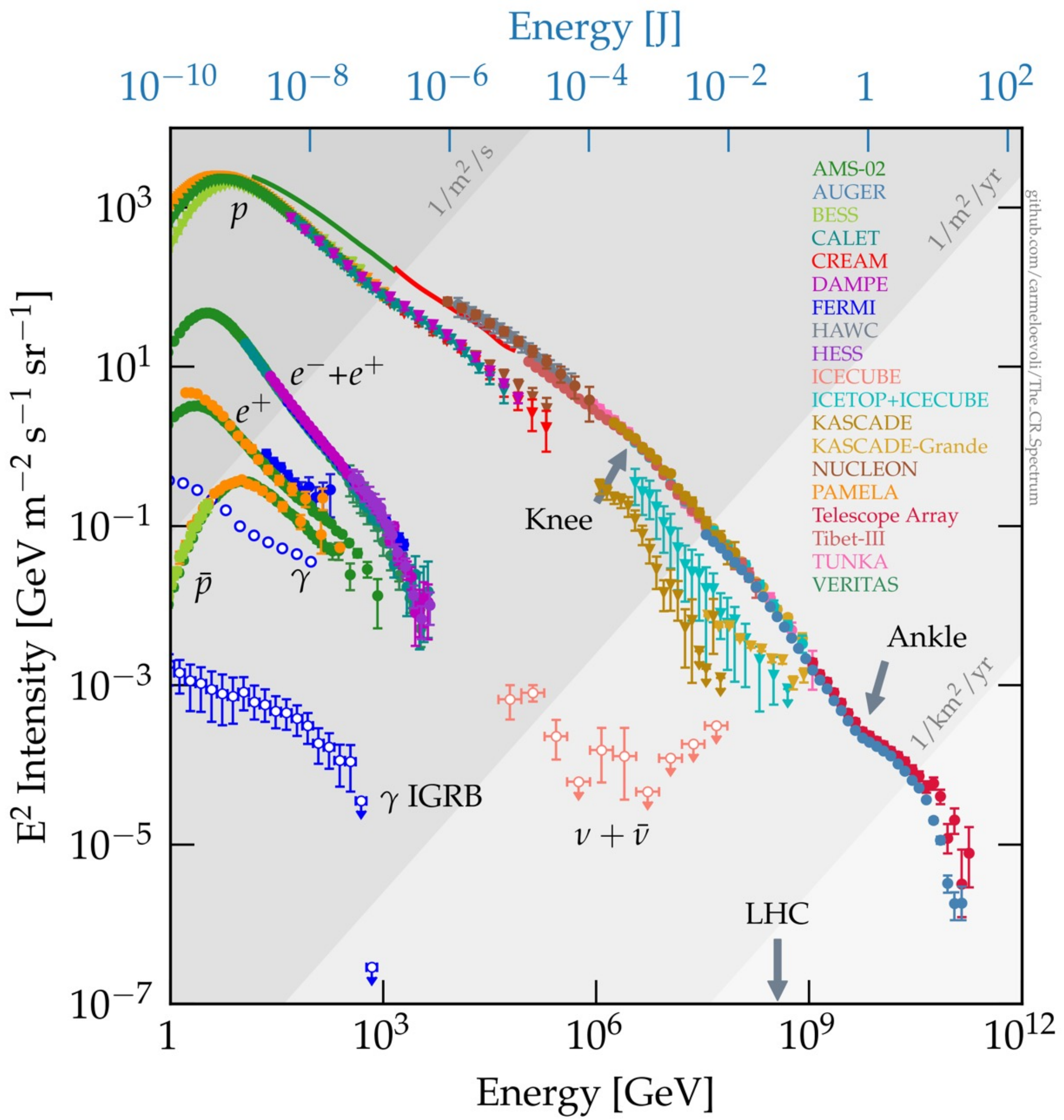
VERTEX 2023

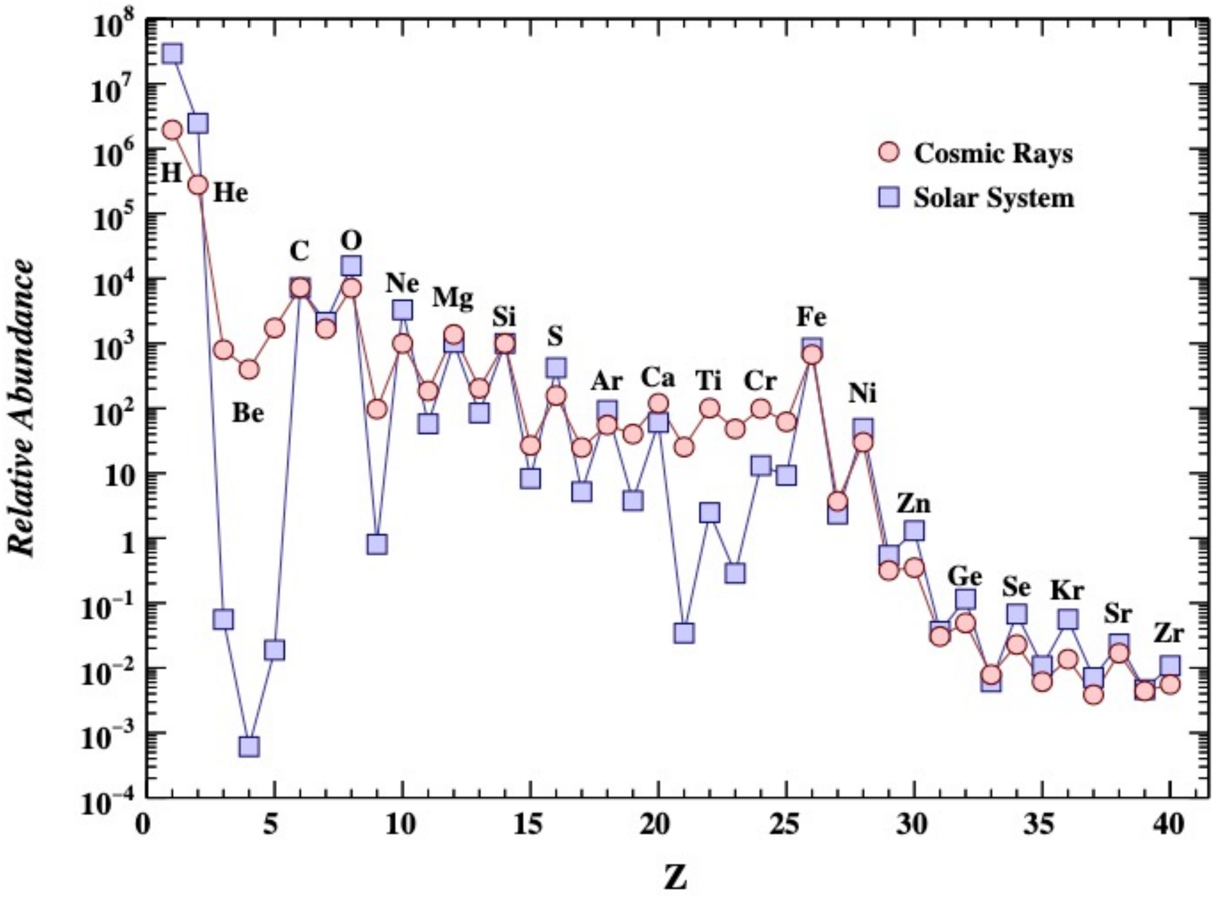
Si spectrum in cosmic rays

PhysRevLett.124.211102

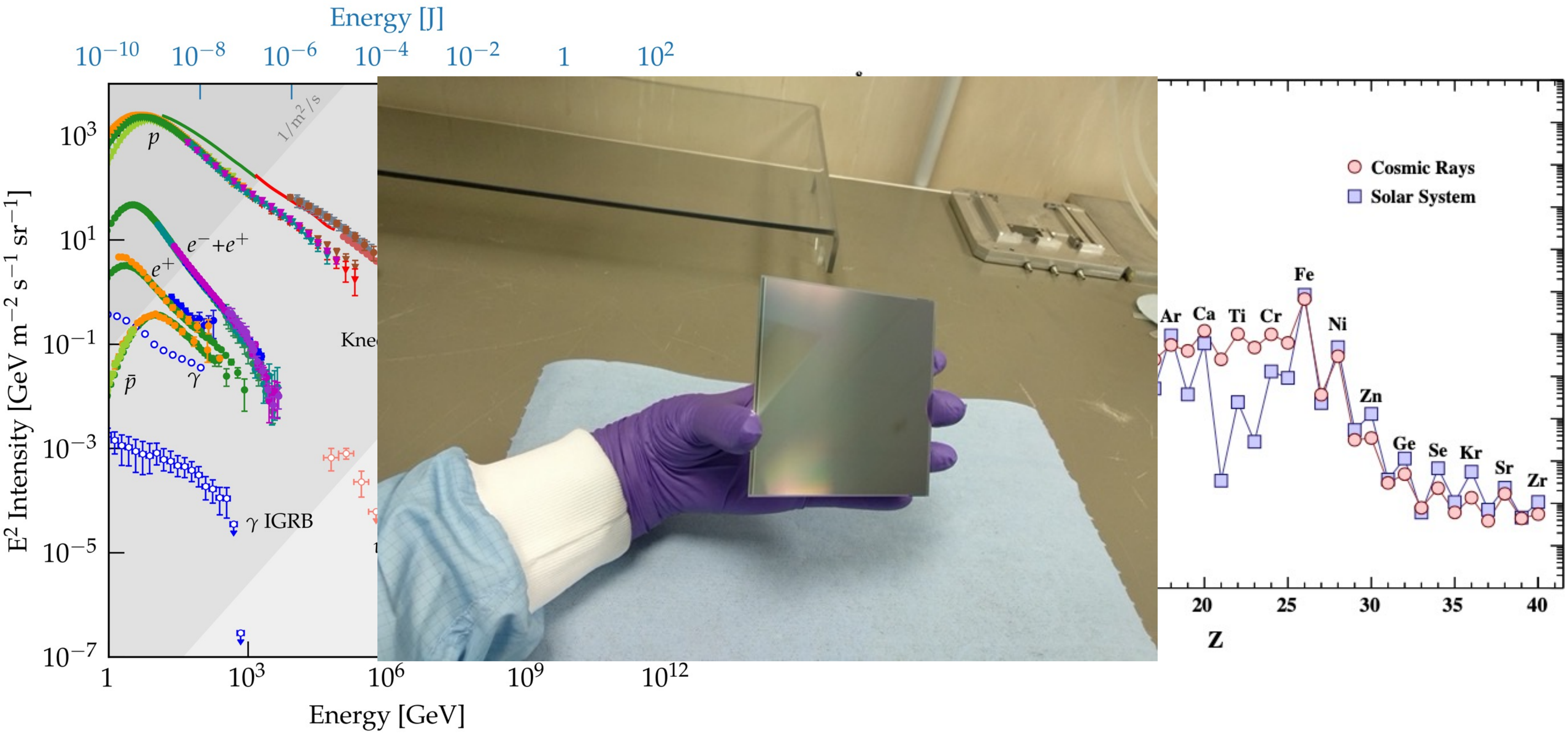


Cosmic ray flux and composition





Cosmic ray flux and composition



Silicon detectors: from the laboratory to space

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Silicon detectors: from the laboratory to space

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G. Ambrosi

strong bias (μstrip detector)

too much information in one talk

VERTEX 2023

Silicon detectors:
from the laboratory to space

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

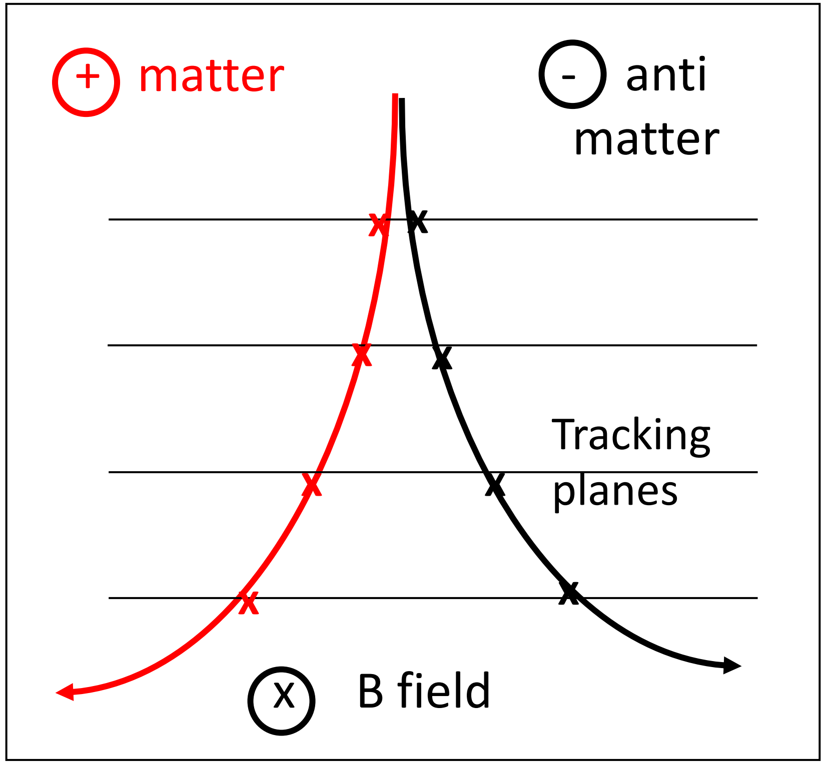
Primary spectra, Nuclei, e$^\pm$, γ

⇓

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

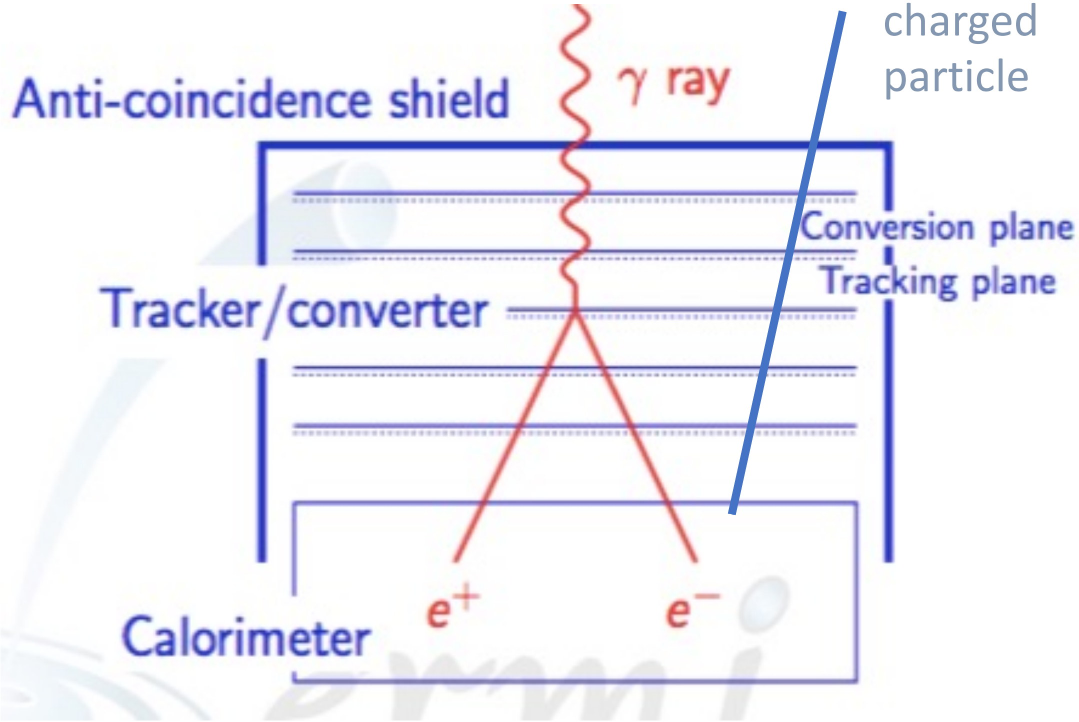
Tracking in space: Spectrometer vs Calorimeter

Magnetic spectrometer



Spatial resolution: 3 – 10 μm

Calorimetric detector



Spatial resolution: 30 – 70 μm

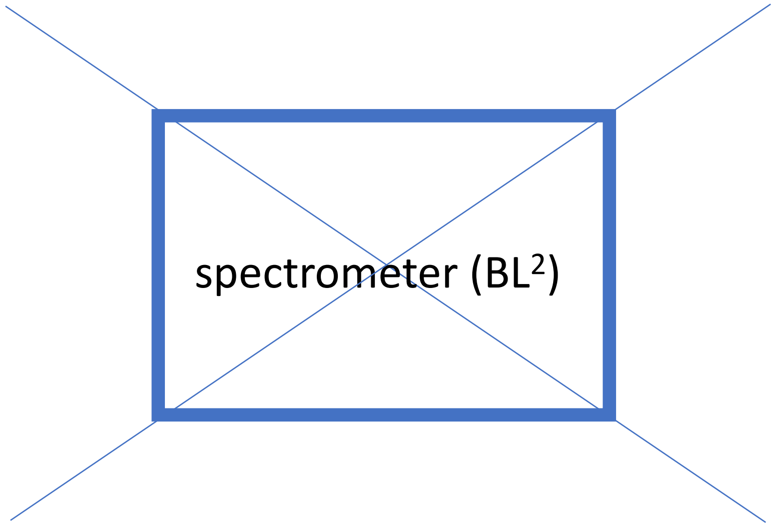
$$\Delta N = \Phi(E) \times \Delta(E) \times A \times T$$

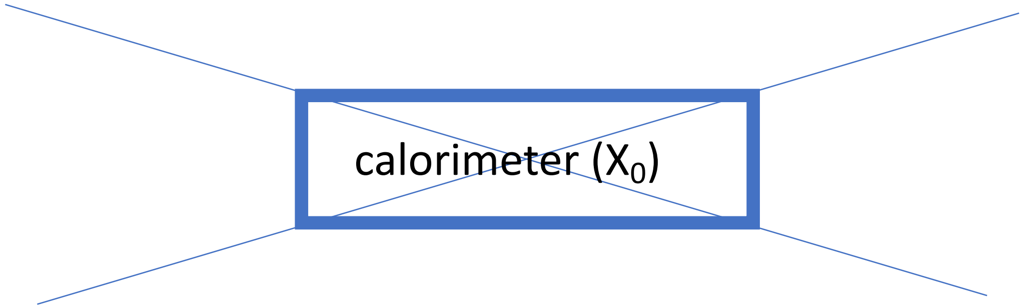
flux
(given by Nature)

Energy bin

exposure time

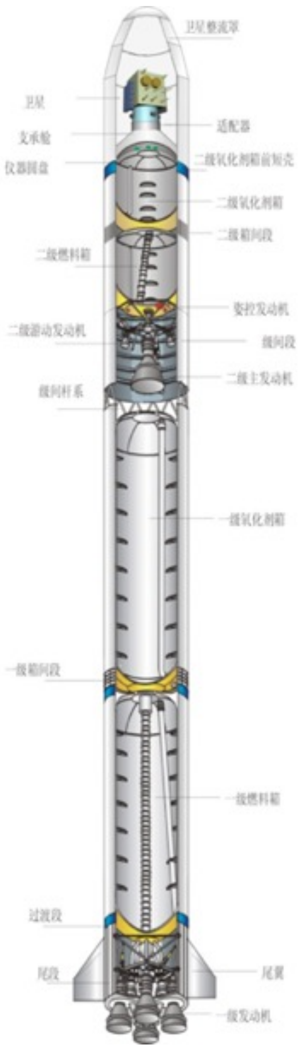
acceptance





surface AND solid angle

HEP detectors in Space

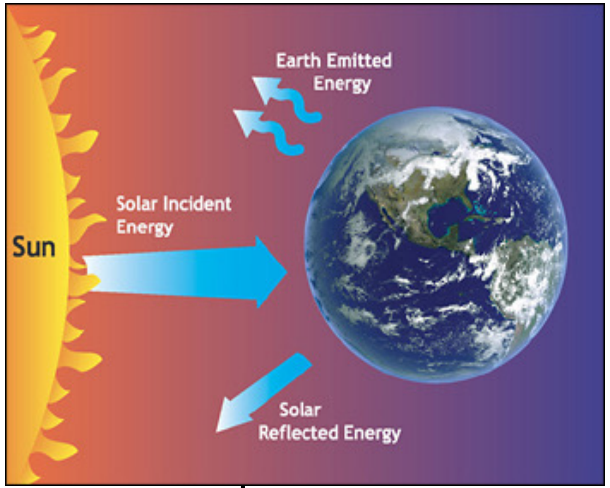


Mechanical stress at launch:

- Static acceleration
- Random vibration
- Sinusoidal vibration
- Pyroshock

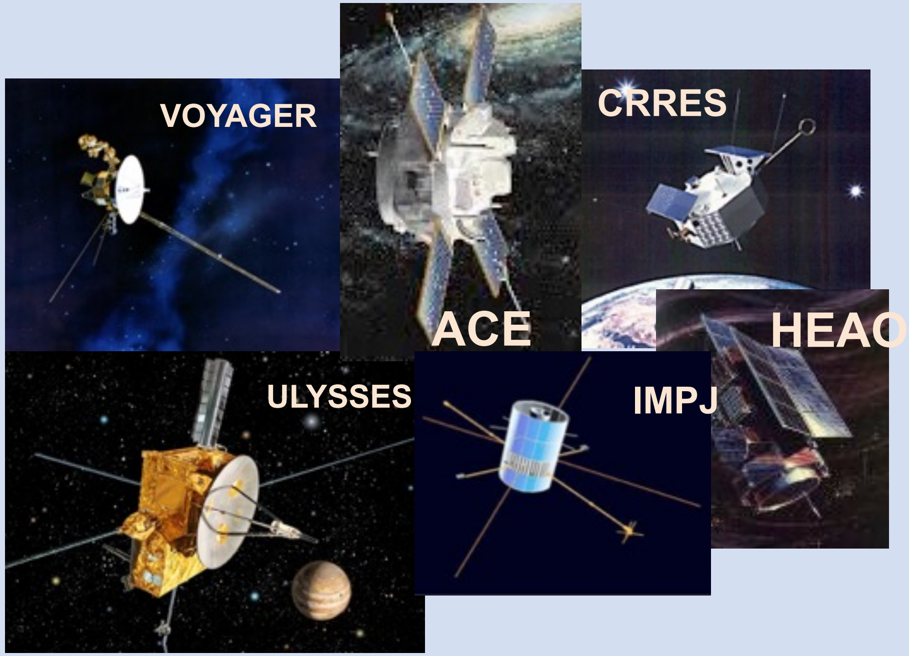
Life in space:

- **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*

Space



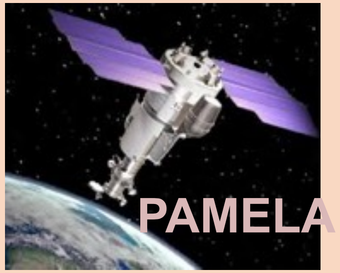
Long missions (years)
Small payloads
Low energies..

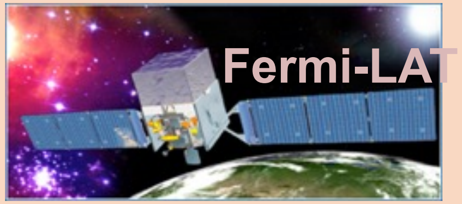
IMP series < GeV/n
ACE-CRIS/SIS Ekin < GeV/n
VOYAGER-HET/CRS < 100 MeV/n
ULYSSES-HET (nuclei) < 100 MeV/n
ULYSSES-KET (electrons) < 10 GeV
CRRES/ONR < (nuclei) 600 MeV/n
HEAO3-C2 (nuclei) < 40 GeV/n

Short missions (days)/ Larger payloads

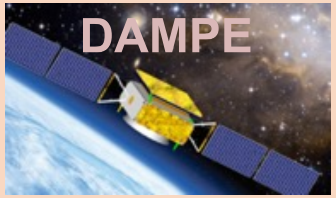
CRN on Challenger
(3.5 days 1985)

AMS-01 on Discovery
(8 days, 1998)



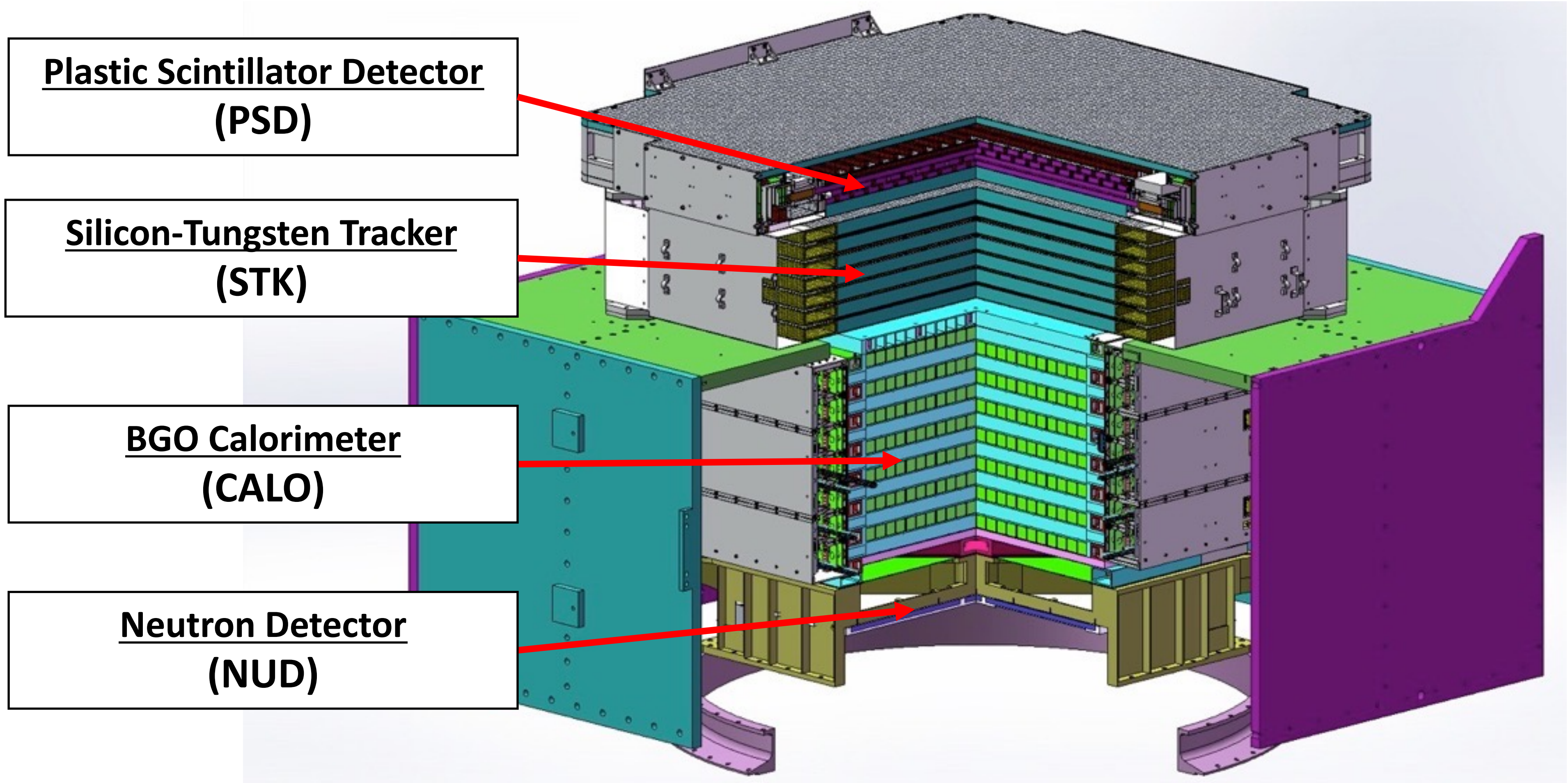


Long missions
Large payloads




LIMADOU
AMS-02
future experiments
DAMPE
APEL009

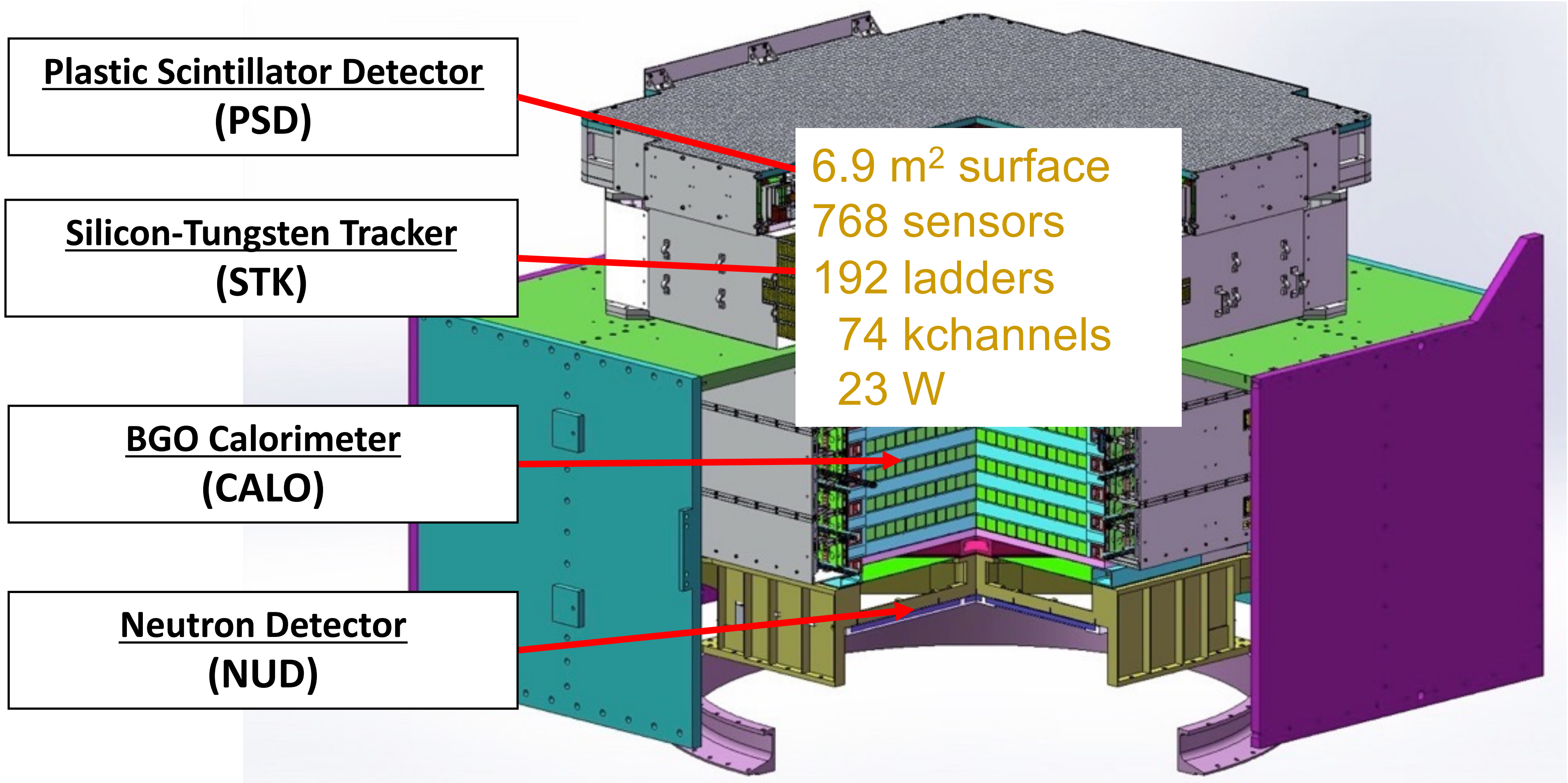
The DAMPE detector (calorimeter)



- 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 (calorimeter)



- Charge measurement (dE/dx in PSD , STK and BGO)
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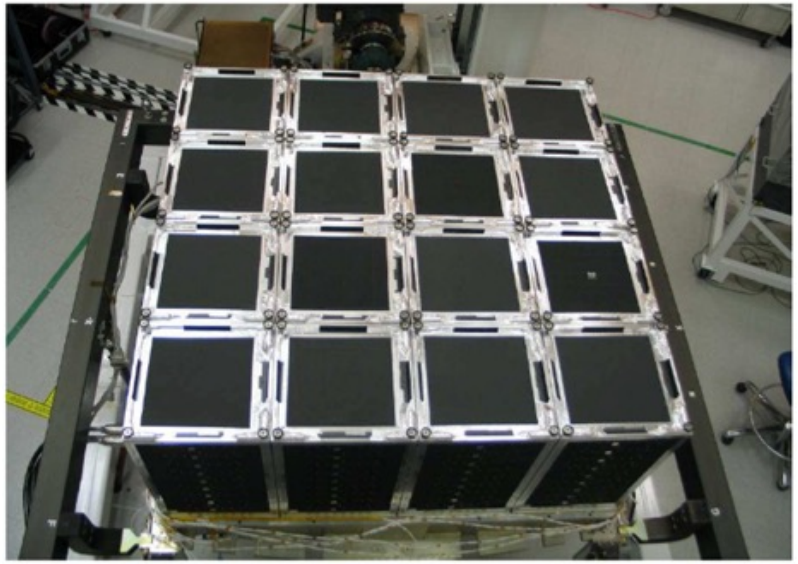
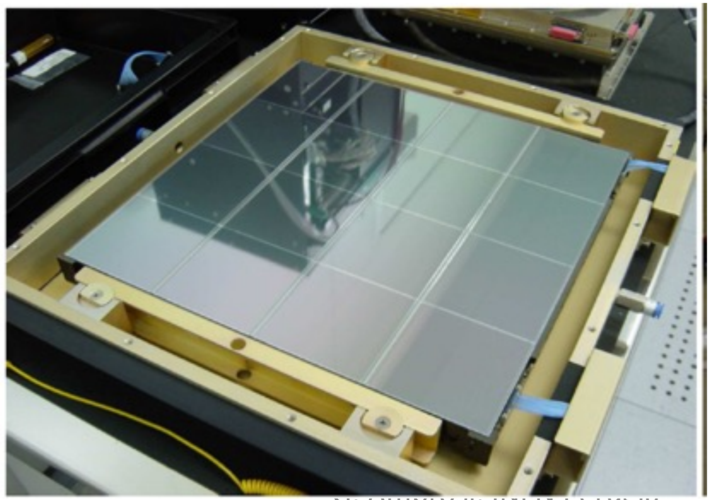
⇨ high energy γ-ray, electron and cosmic ray telescope

FERMI (2008)



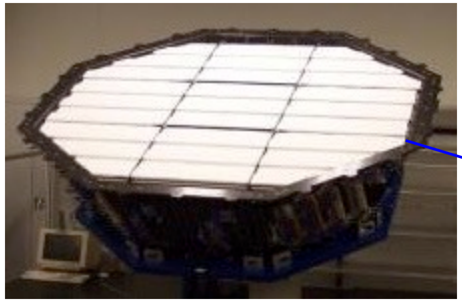


strip pitch 230 µm
readout pitch 230 µm

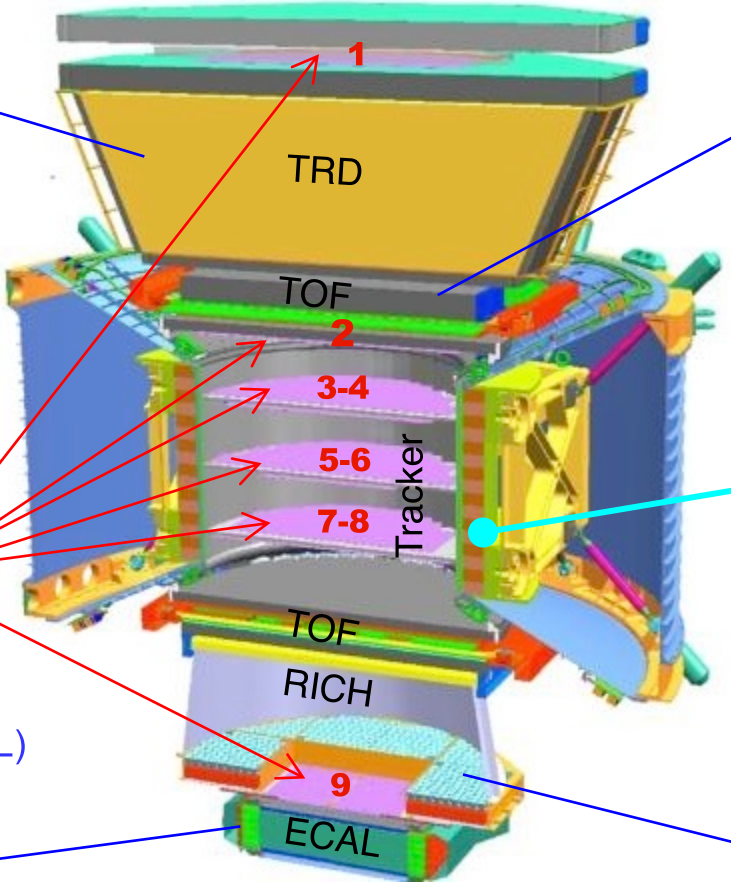
73 m² surface
9216 sensors
2304 ladders
221kchannels

AMS-02: A TeV precision, multipurpose spectrometer

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

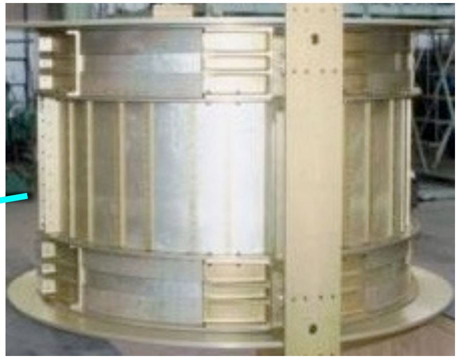


Particles and nuclei are defined by their charge (**Z**) and energy (E)

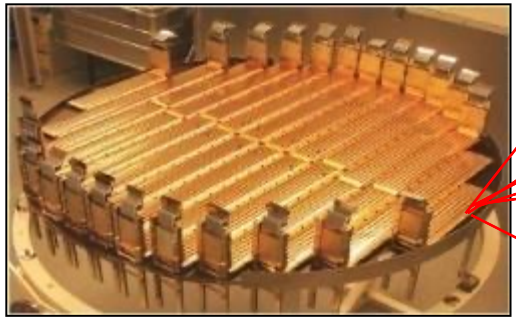


Time of Flight
(TOF)
Z, E

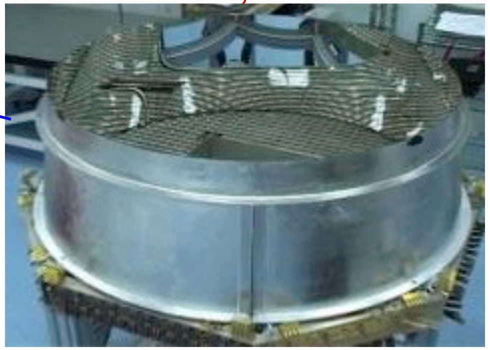
Magnet (0.15 T)
±Z



Silicon Tracker
Z, P



Ring Imaging Cherenkov
(RICH)
Z, E

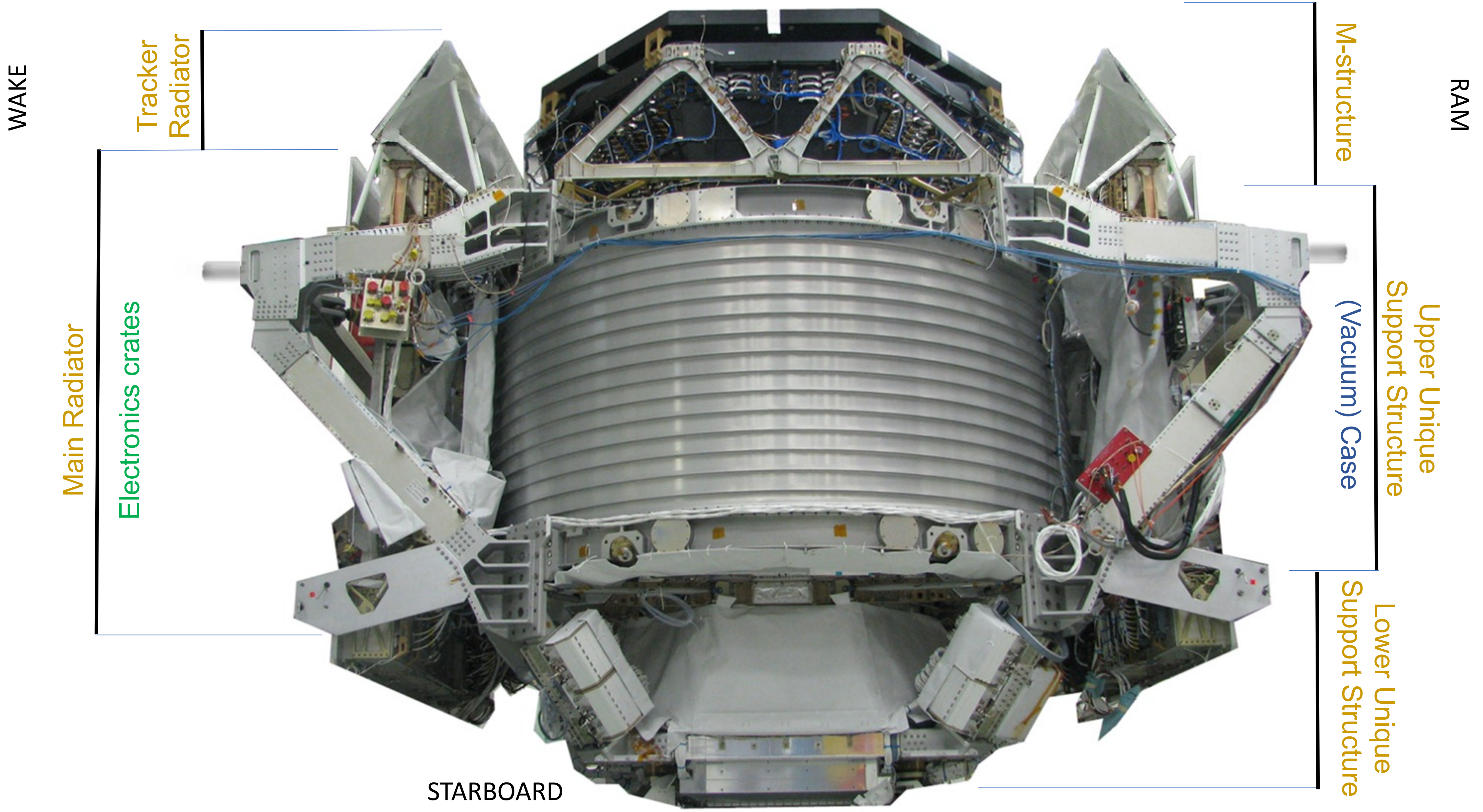


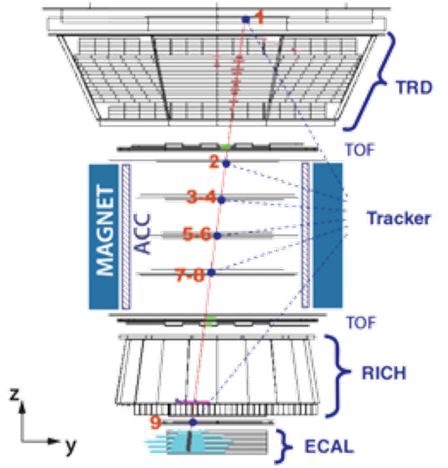
Electromagnetic Calorimeter (ECAL)
E of e^+, e^-, γ

Z, E, R, β

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

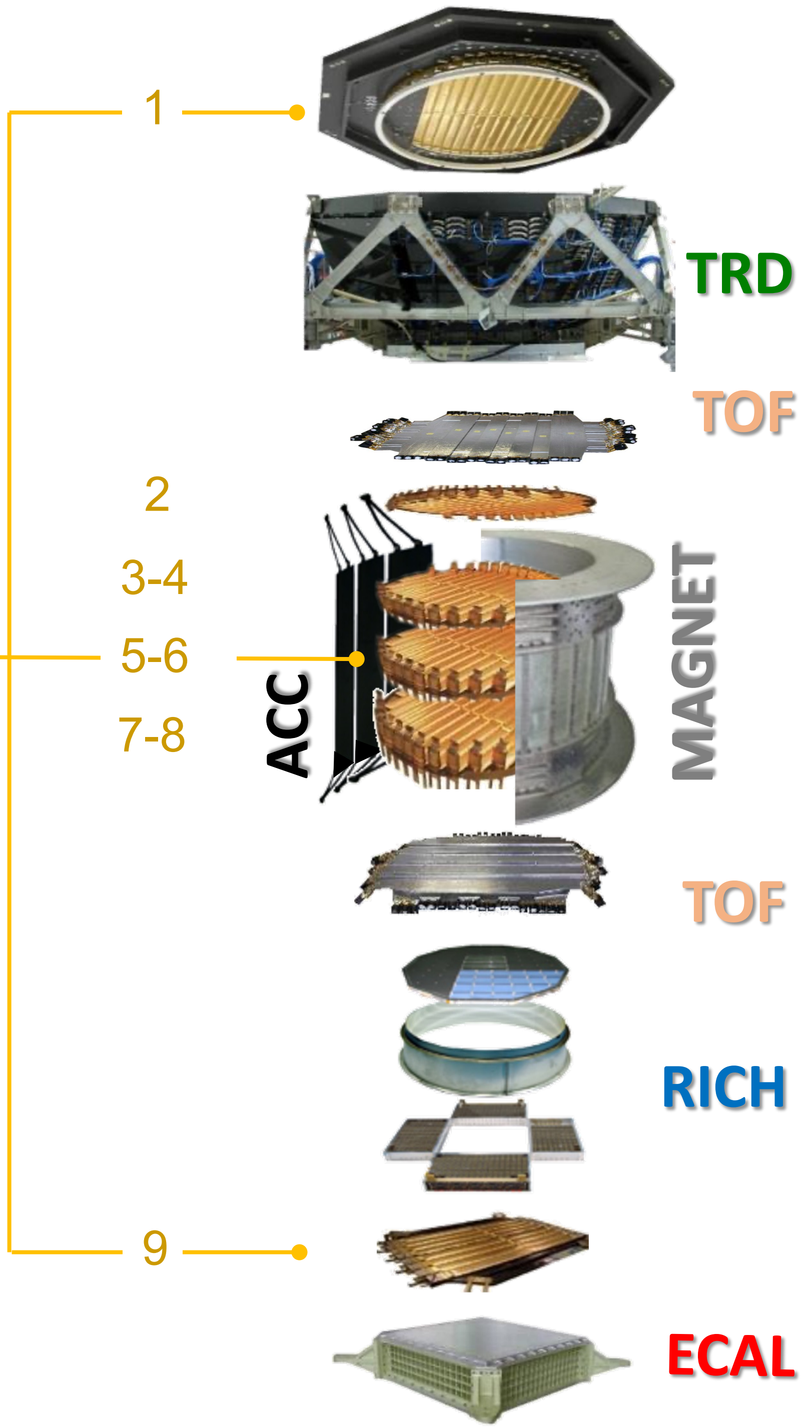
17


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

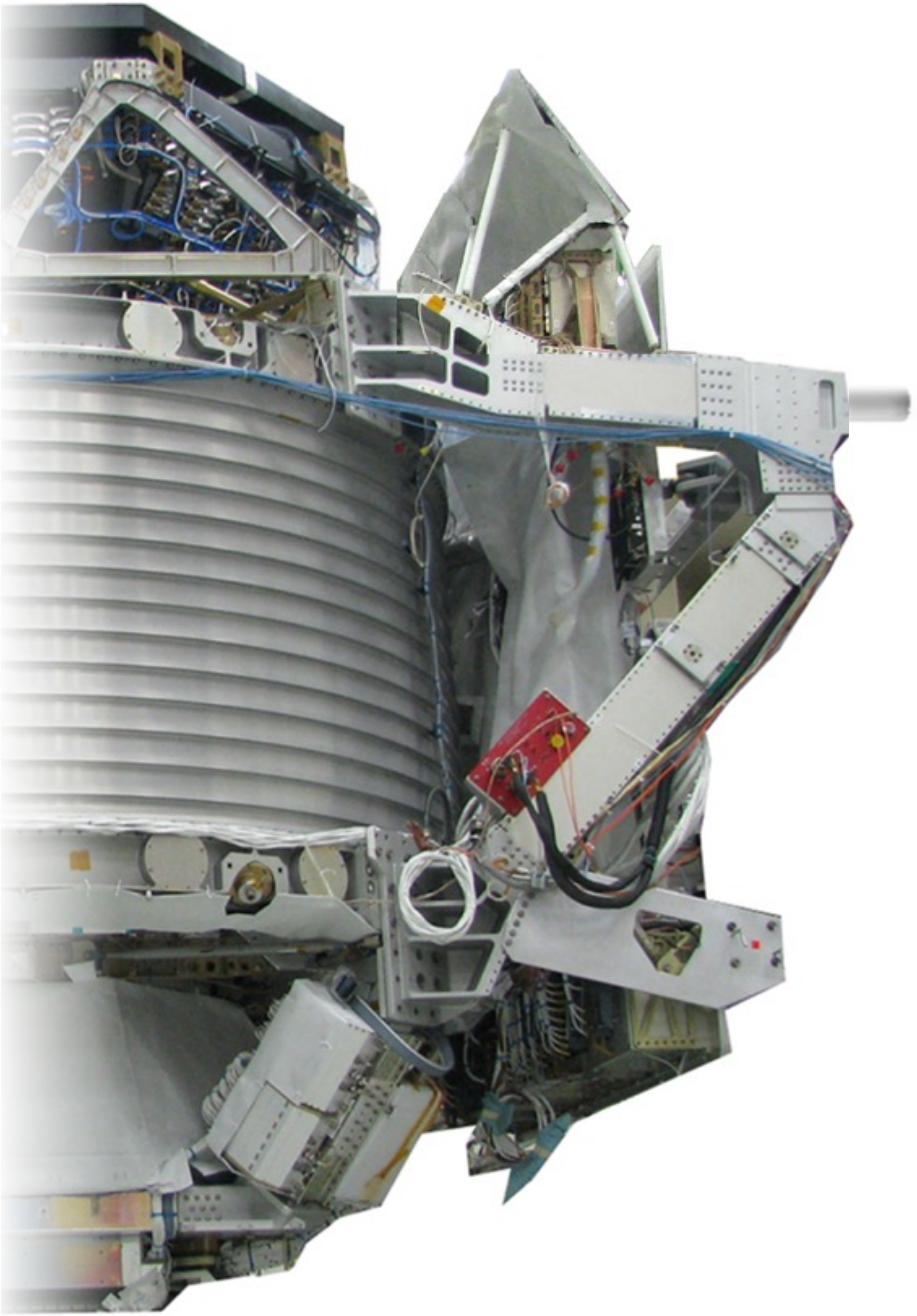


Tracker

planes



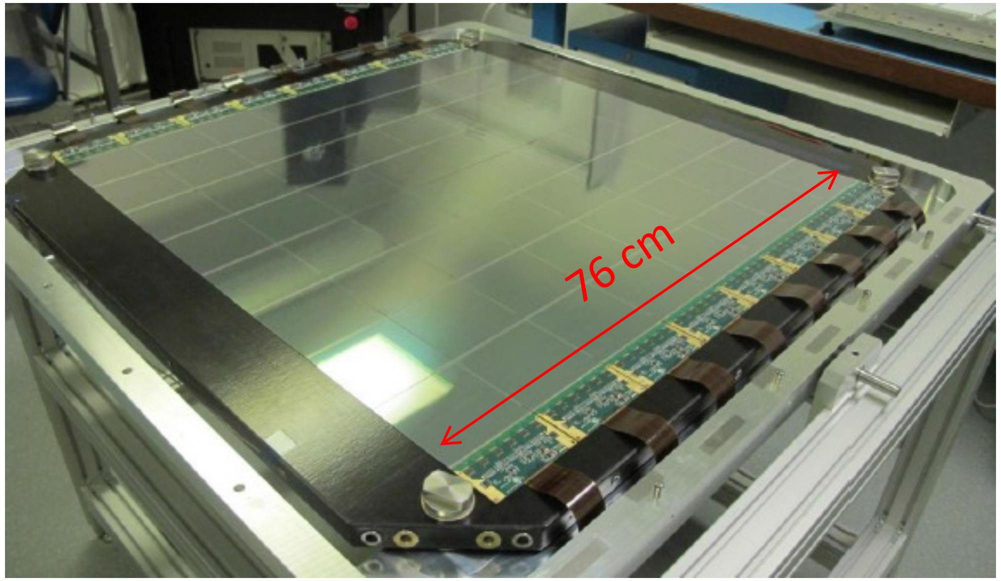
6.3 m² surface
2264 sensors
192 ladders
192 kchannels
190 W

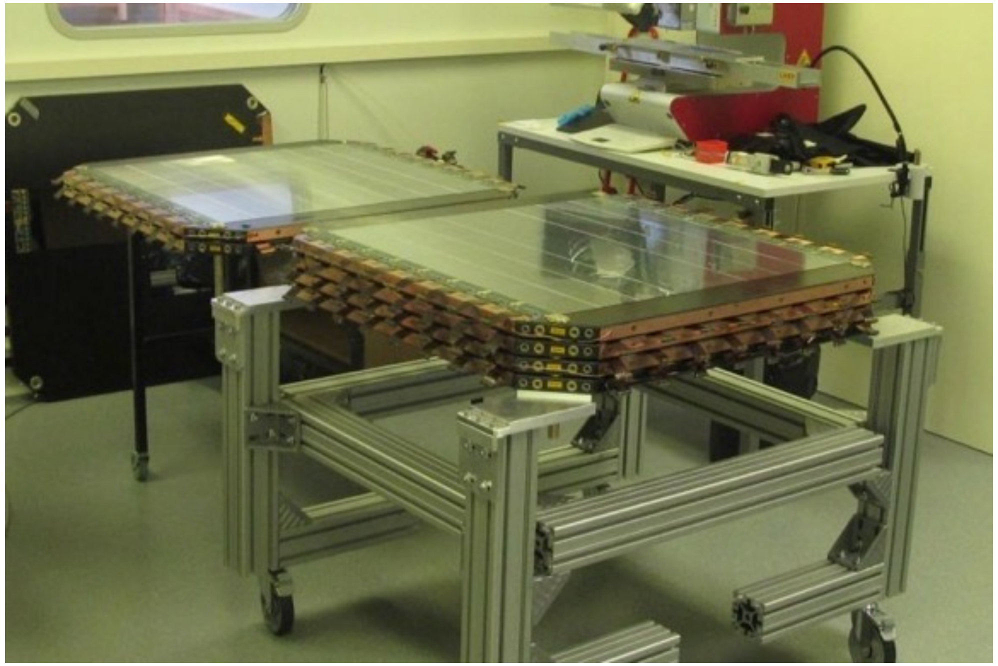


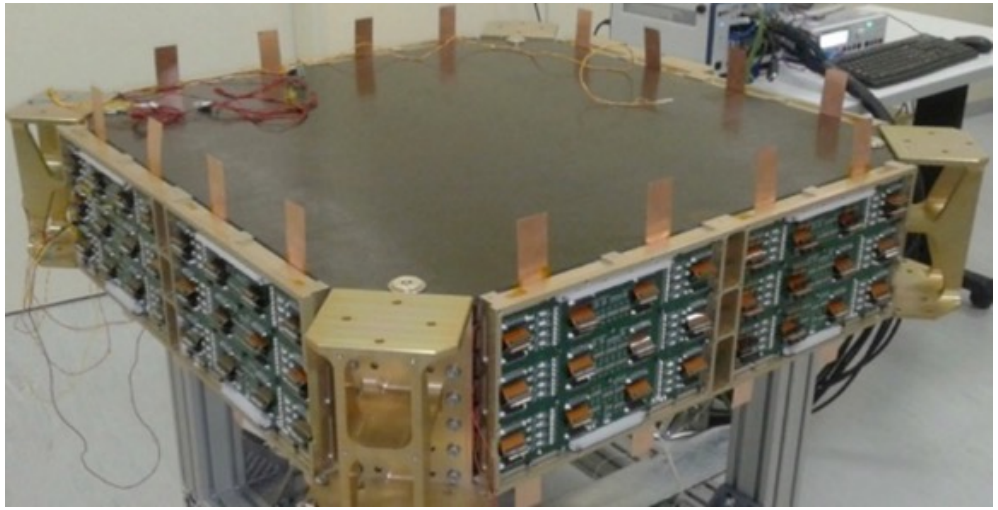

AMS
AMS

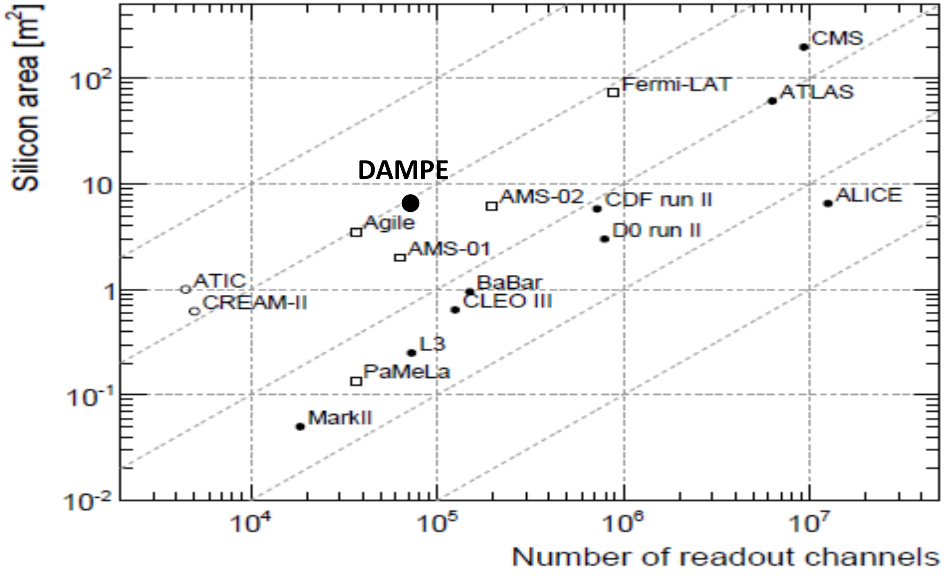
The DAMPE Silicon TracKer (2015)

strip pitch 120 µm
readout pitch 240 µm



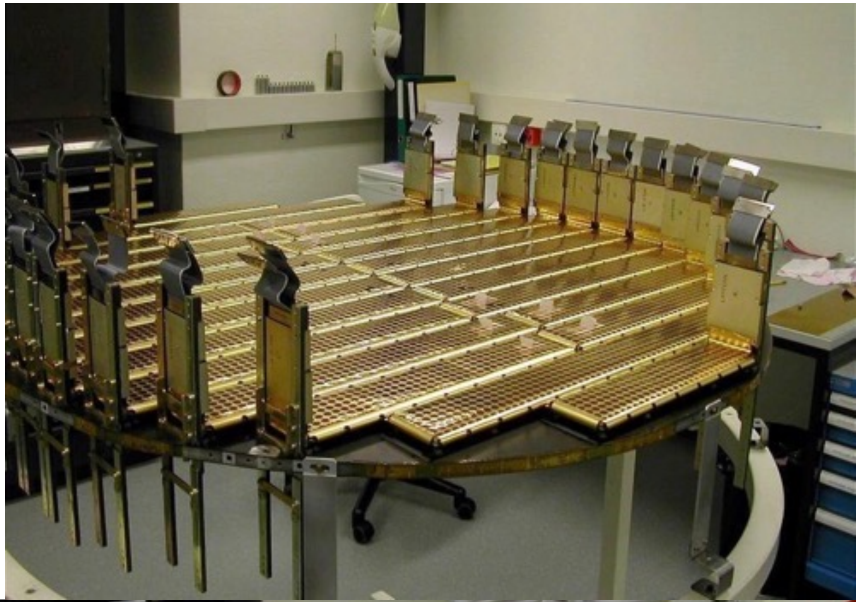
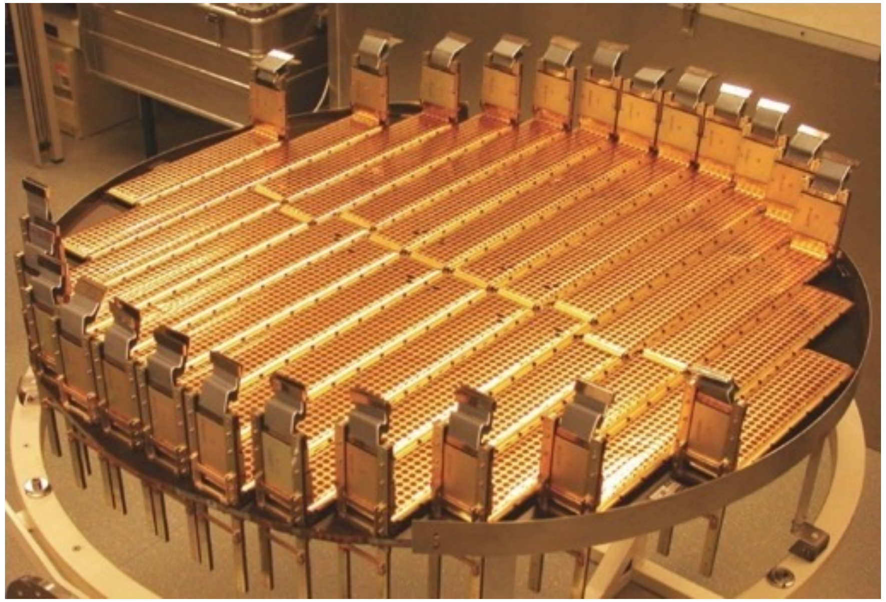
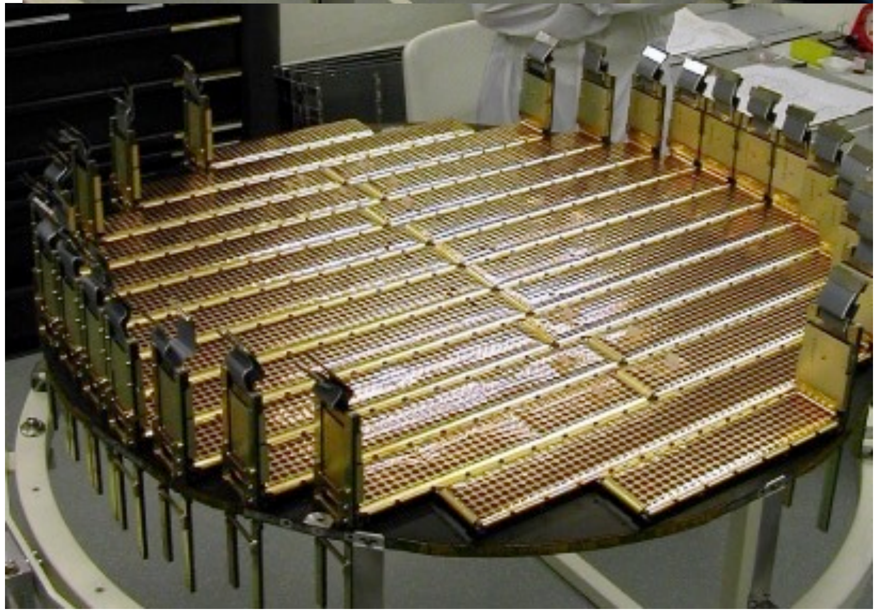




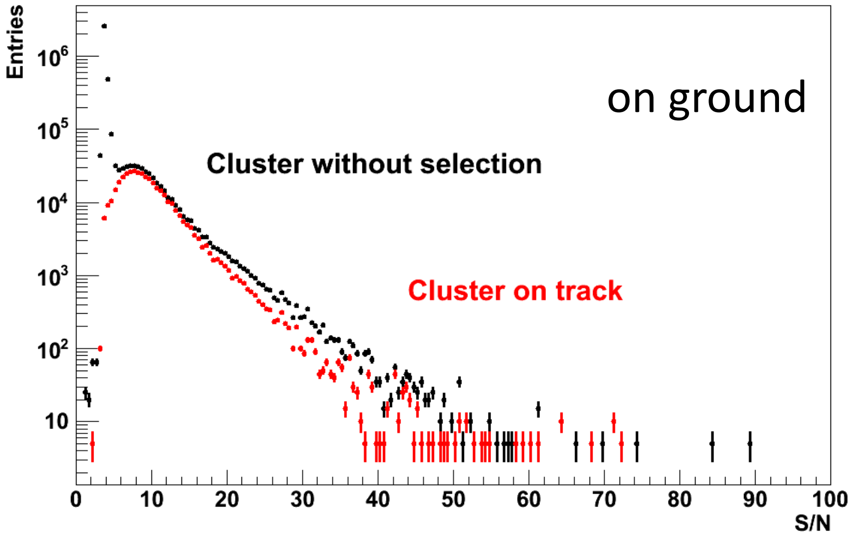


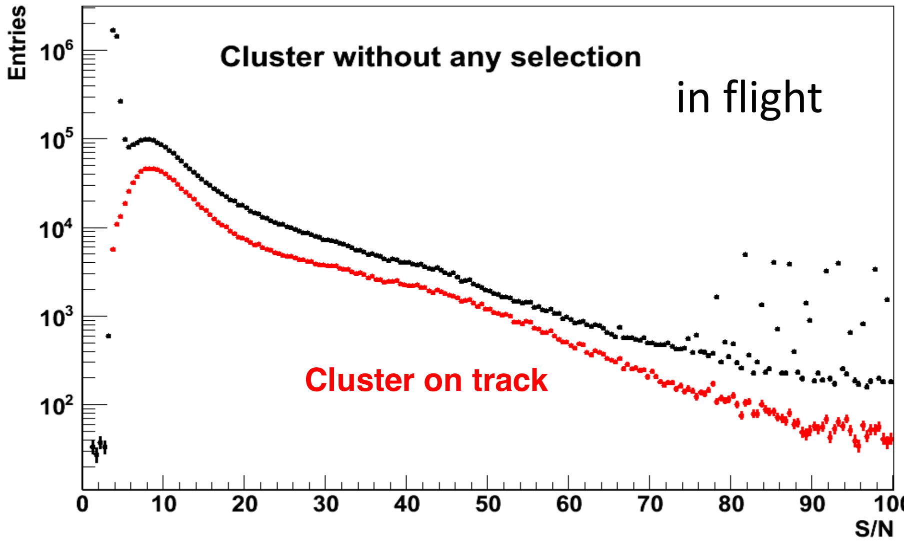
AMS-02 Silicon Tracker (2011)

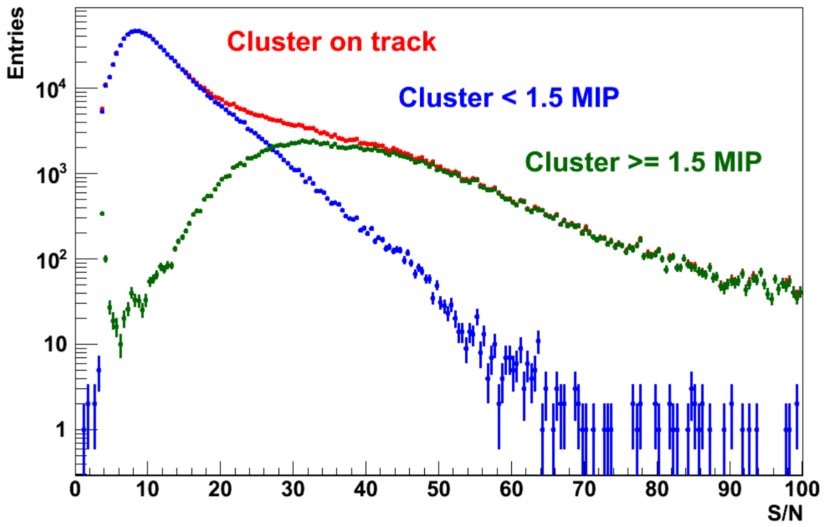
strip pitch 27.5 µm
readout pitch 110 µm

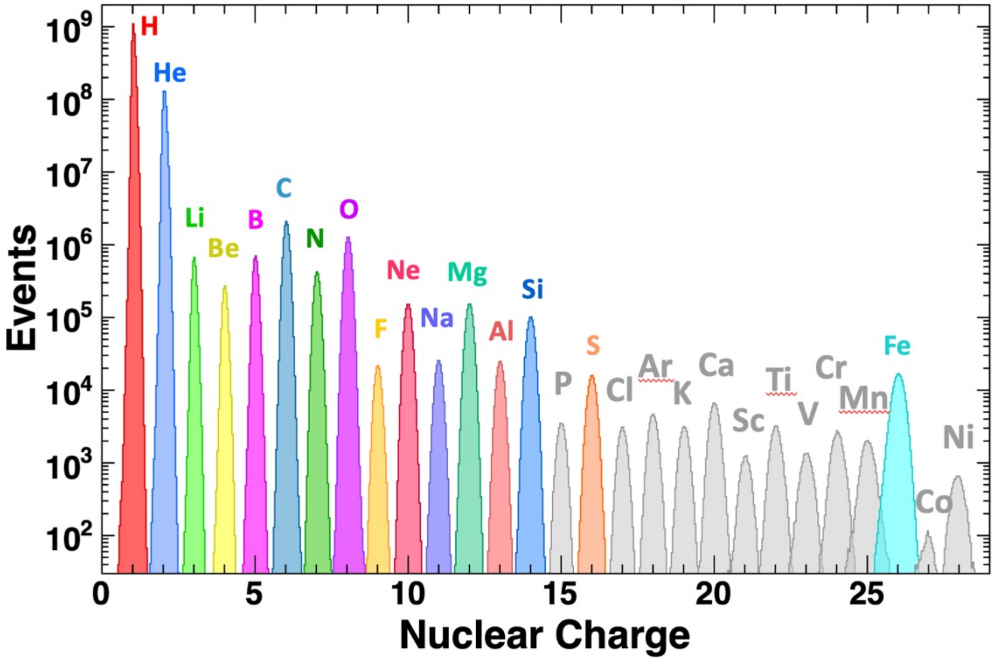





Tracker signals and charge ID (AMS-02)

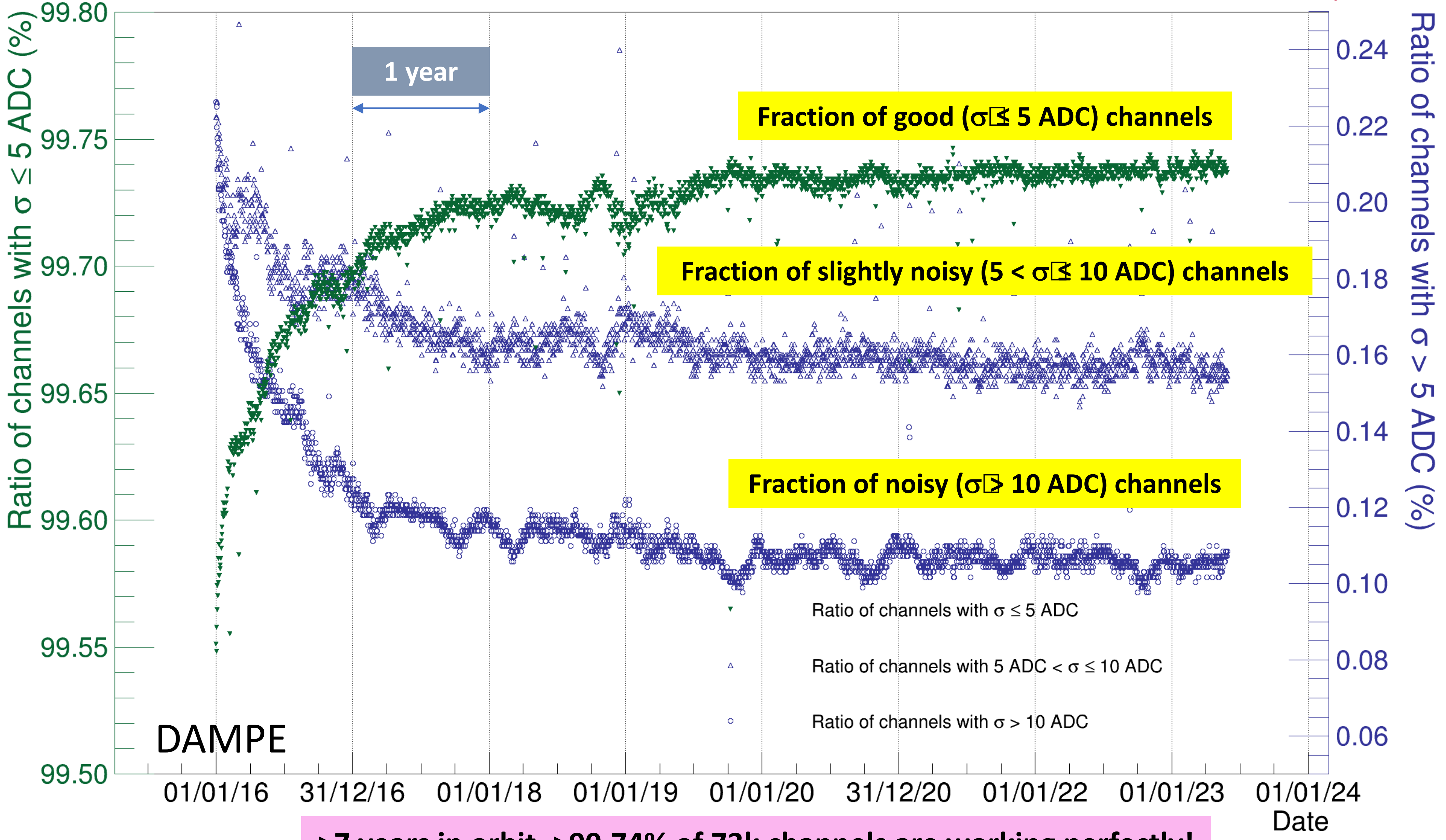








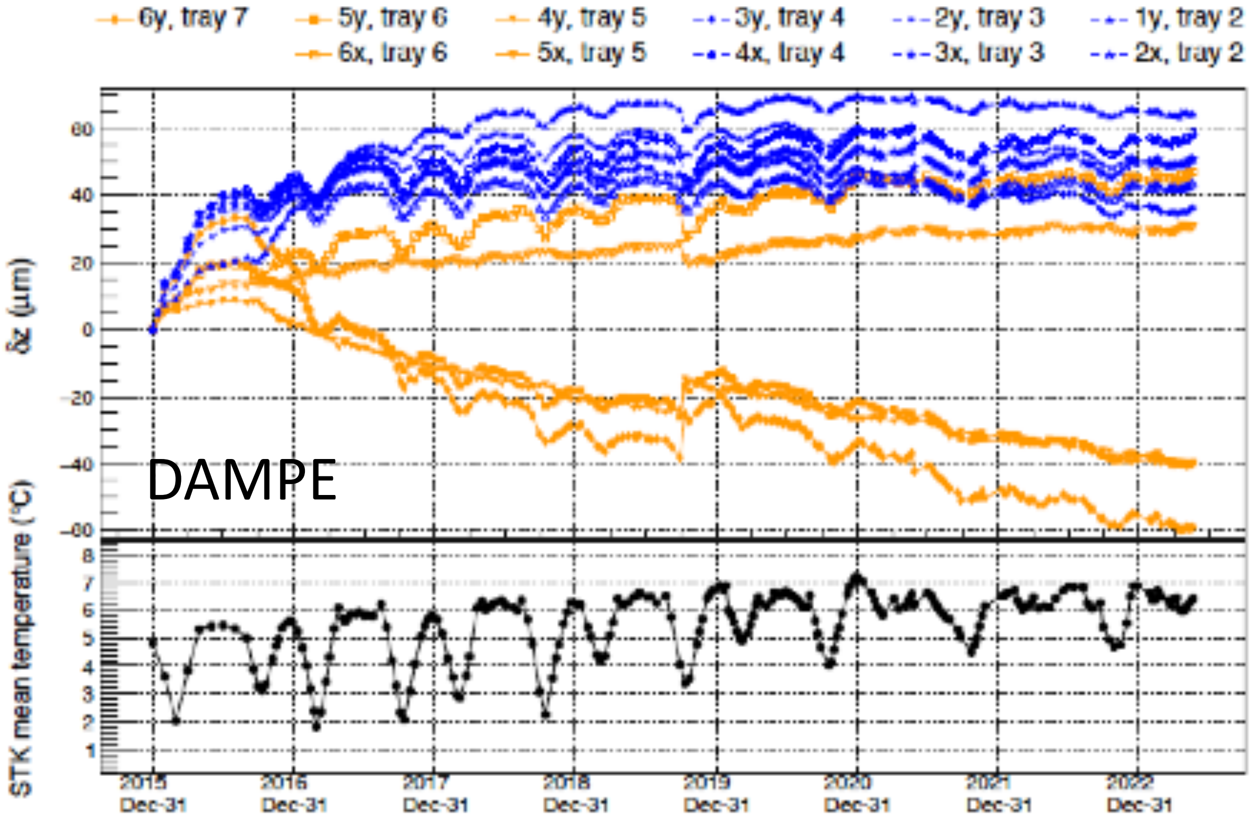
STK in excellent condition since launch, for more than 7 years!

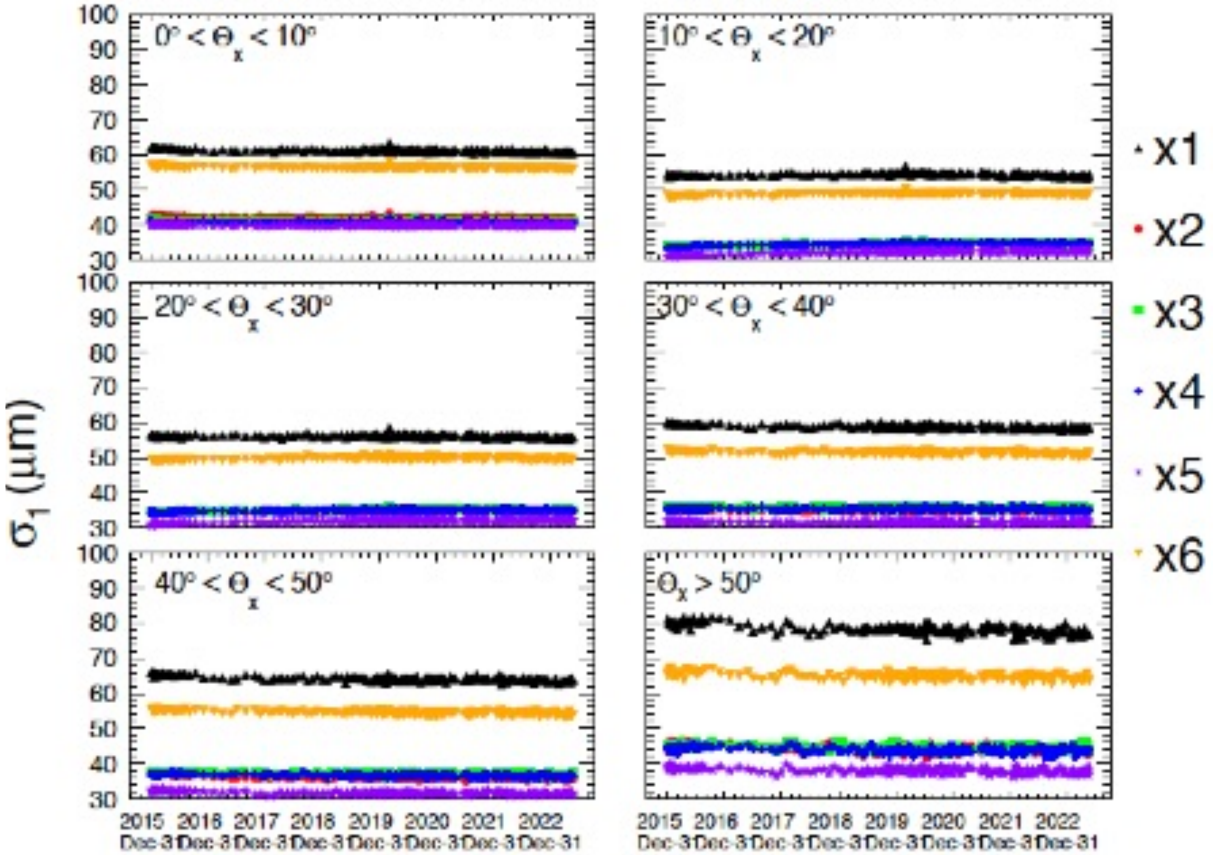


>7 years in orbit, >99.74% of 73k channels are working perfectly!

STK in-flight alignment

up to May 2023





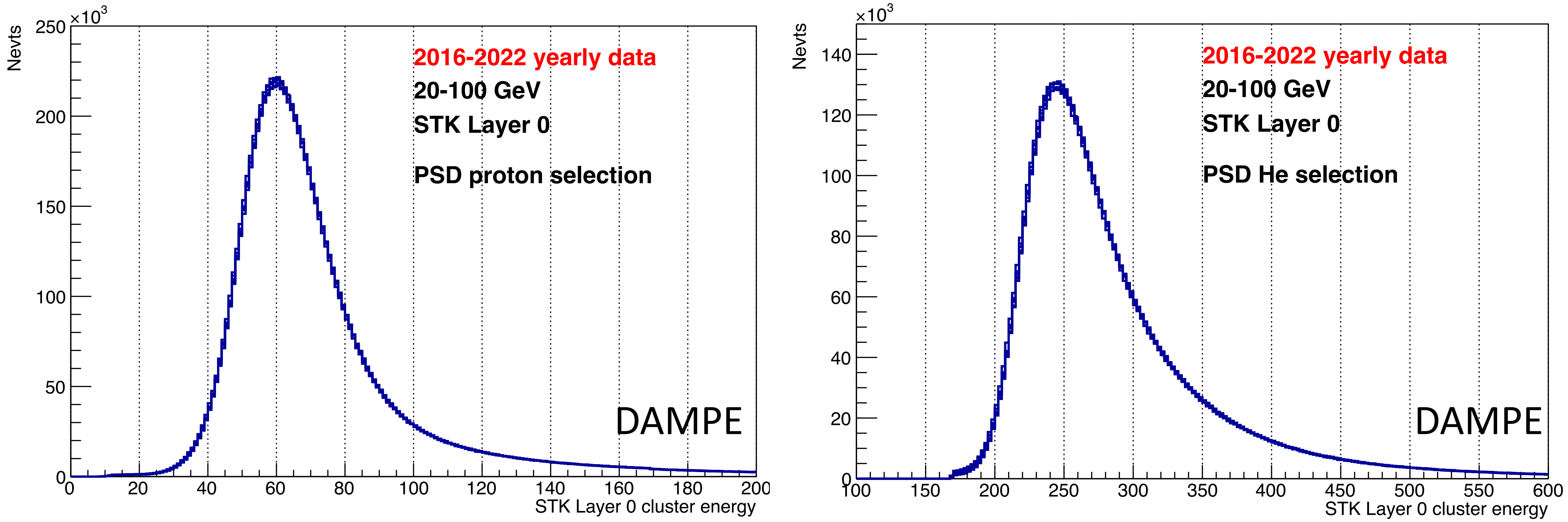
In 7 years detector position shifts in z are within 100 μm, < 1% of the support tray thickness

Re-align every 2 weeks to track long term shift

Intrinsic position resolution 30 -40 μm, better than 70-100 μm required

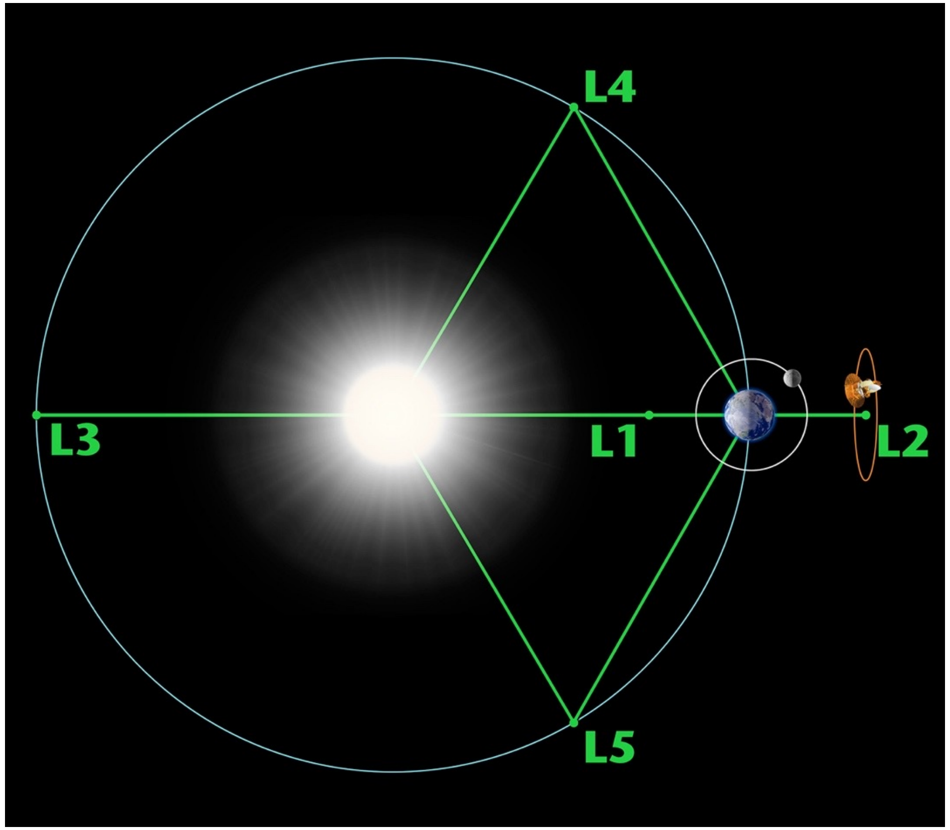
- STK is the “backbone” of experiment allowing to link precisely all the sub-detectors for alignment, calibration, particle identification, event classification, …

STK p/He MIP measurement stability: 2016 - 2022 yearly data



- 7 yearly histograms overlayed, not adjusted for live time!
  - Excellent stability: not only the charge measurements, but also the full chain of mission operation
  - Achieved also thanks to the robust STK calibration and alignment procedures running routinely
- Higher charge calibration in progress
  - More challenging due to readout ASIC nonlinearity and saturation

the (far) future is in L2, 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)

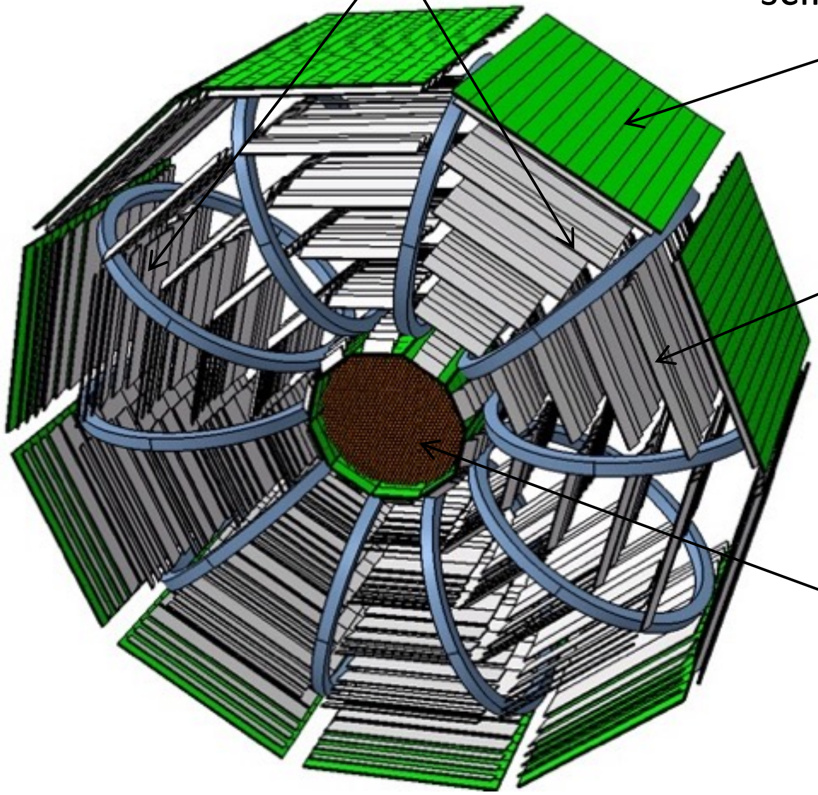
Aladino

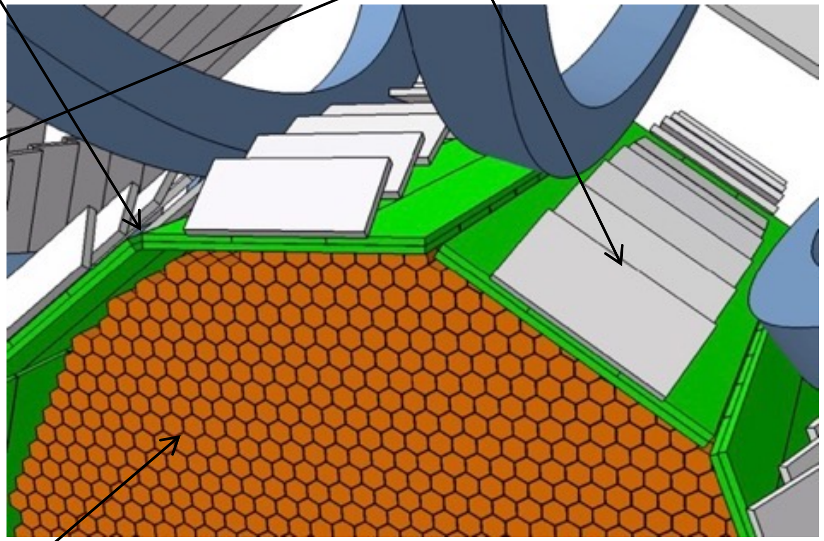
AntimatterLargeAcceptanceDetectorInOrbit

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

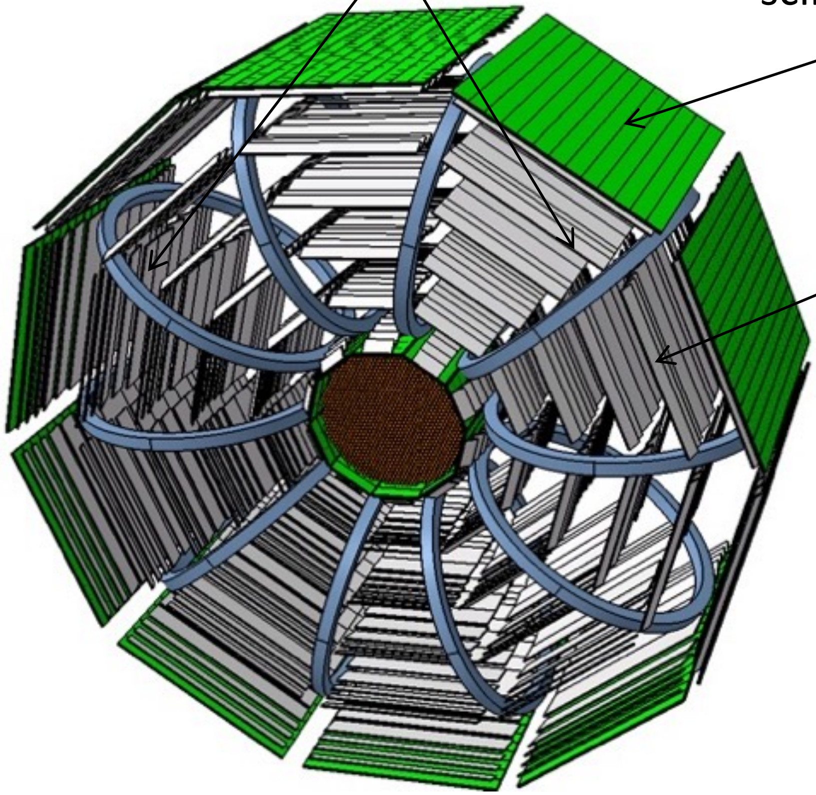
Aladino

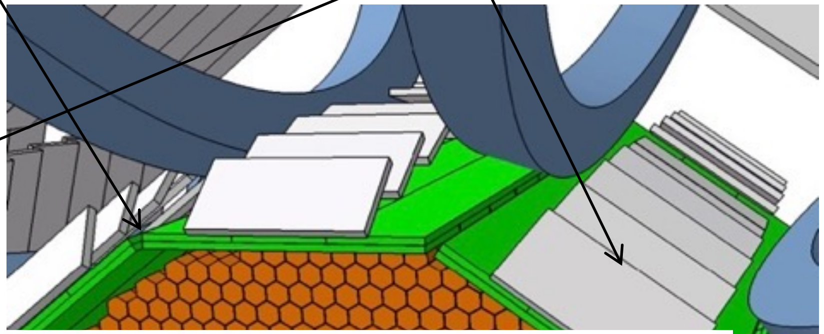
AntimatterLargeAcceptanceDetectorInOrbit

supercoducting coils: magnet

scintillators: ToF

Silicon ladders: tracking



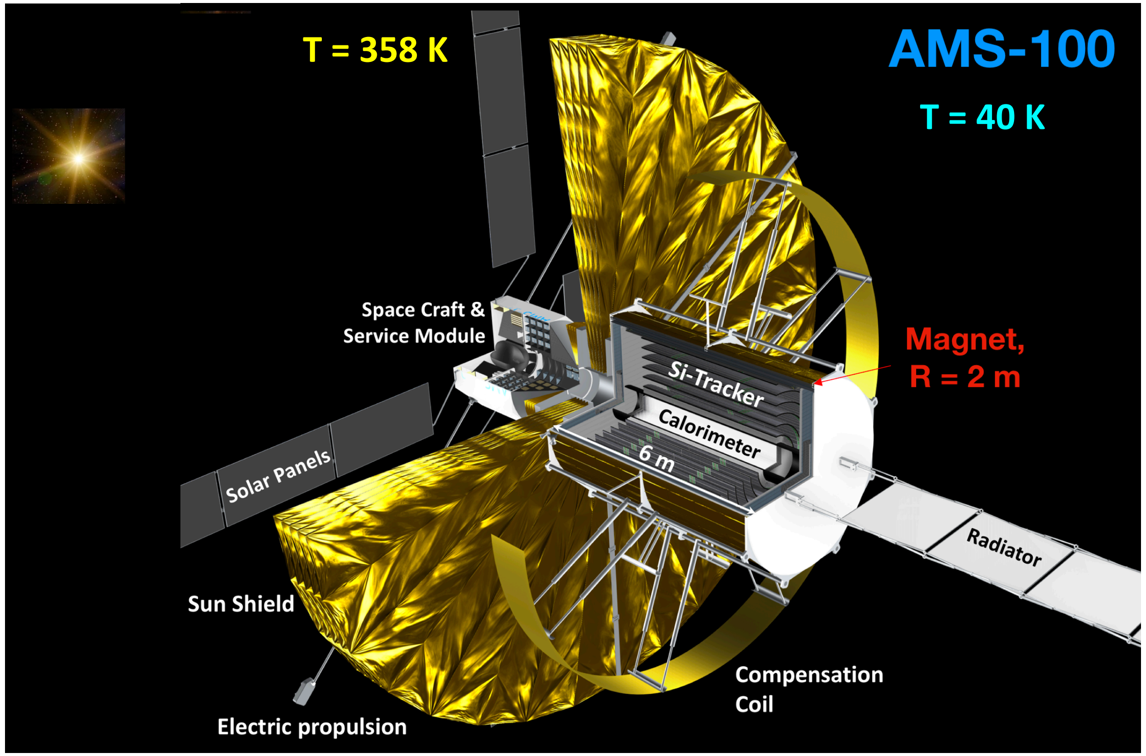


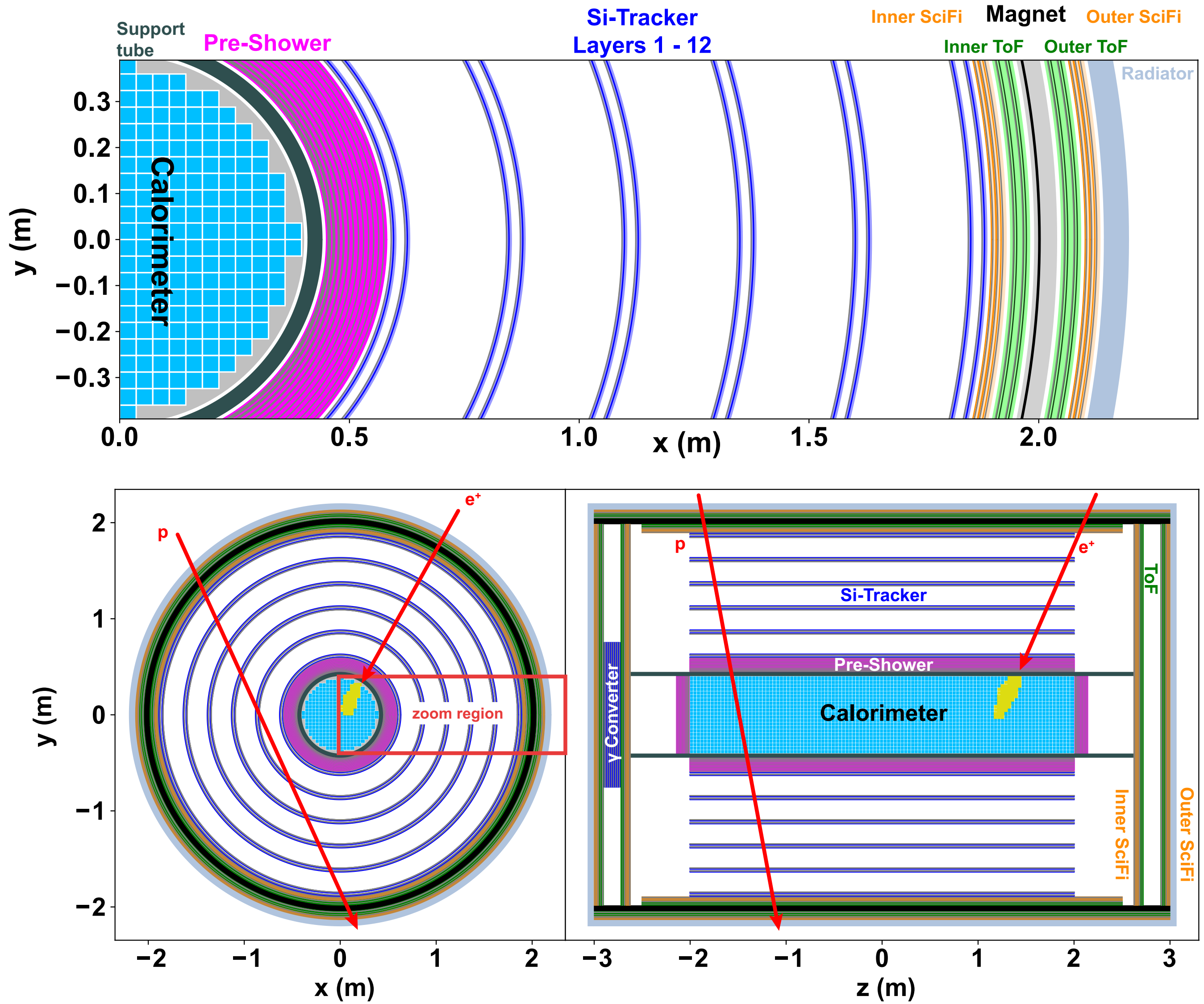
The tracking system

- 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

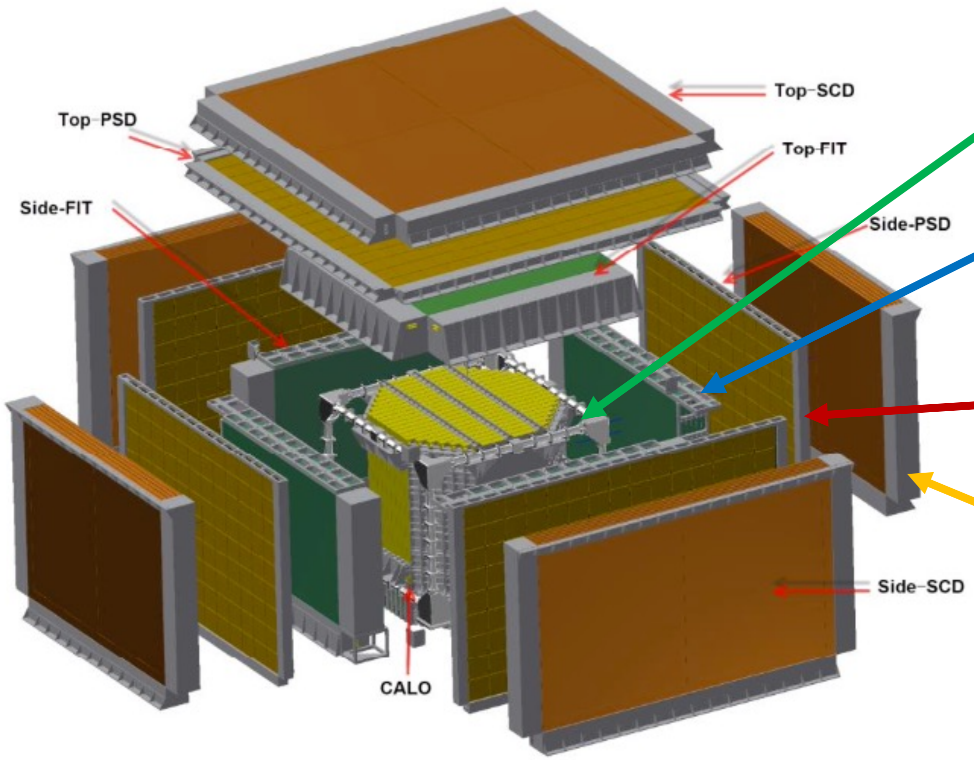
Diameter: 4.4 mt
Length: 2.2 mt
Acceptance: 3 $m^2 sr$
MDR > 20 TV

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)
p
e+
zoom region
Si-Tracker
Pre-Shower
Calorimeter
γ Converter
ToF
Inner SciFi
Outer SciFi
z (m)

intermediate future: HERD



Field of view	+/- 70° off the zenith
Power	< 1.5 kW
Mass	< 4 t

CALO: CALOrimeter
- Energy measurement
- Electron/proton separation

FIT: FIber Tracker
- Track reconstruction
- Low energy γ ray conversion ($\gamma \rightarrow e^+ e^-$)
- Charge measurement (|Z|)

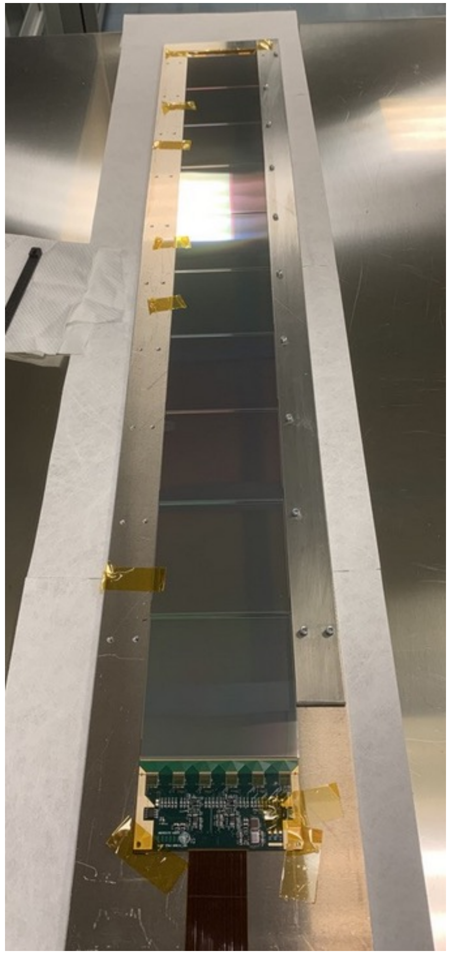
PSD: Plastic Scintillator Detector
- Charge measurement (|Z|)
- γ ray identification

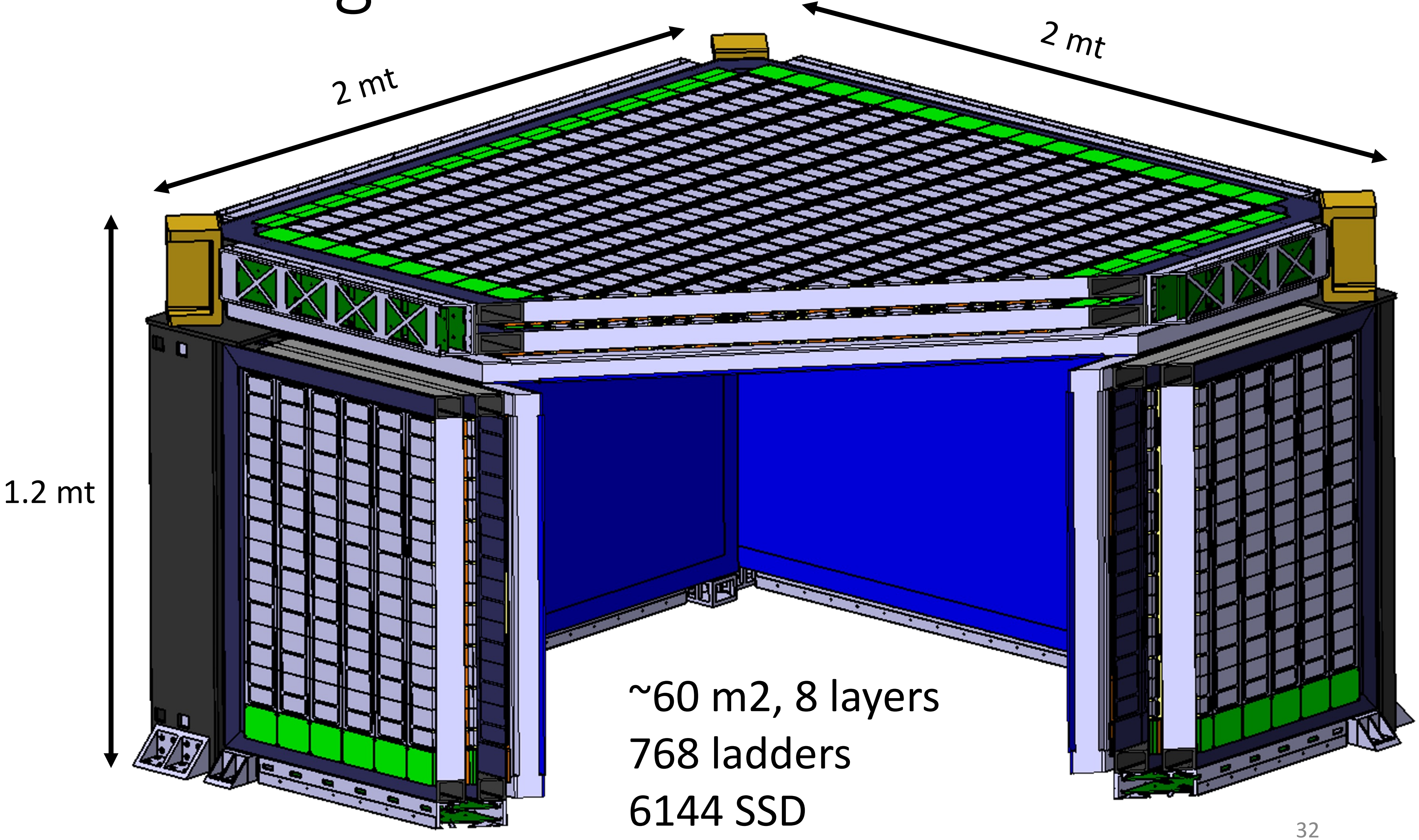
SCD: Silicon Charge Detector
- Charge measurement (|Z|)

TRD: Transition Radiation Detector
- Energy calibration of TeV nuclei

to be installed on board the Chinese Space Station (2027)

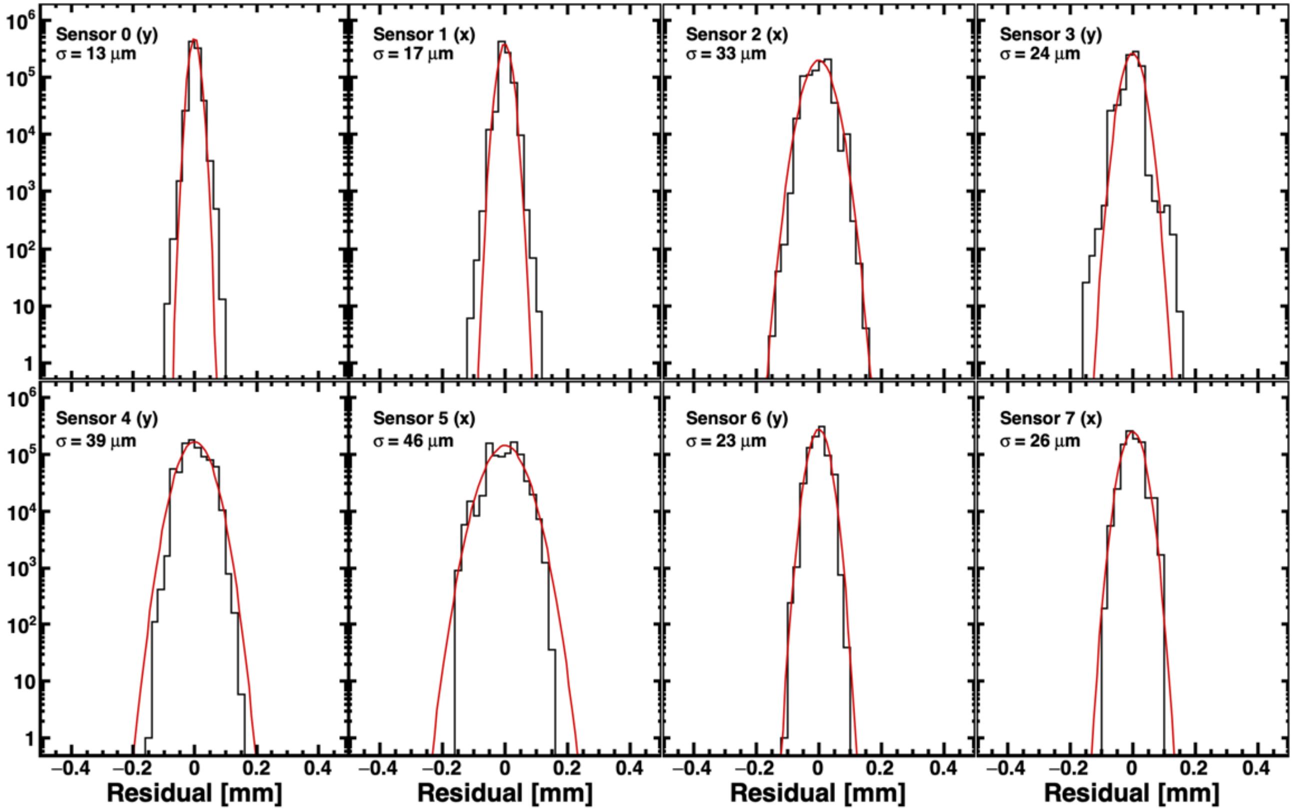
HERD Silicon Charge Detector



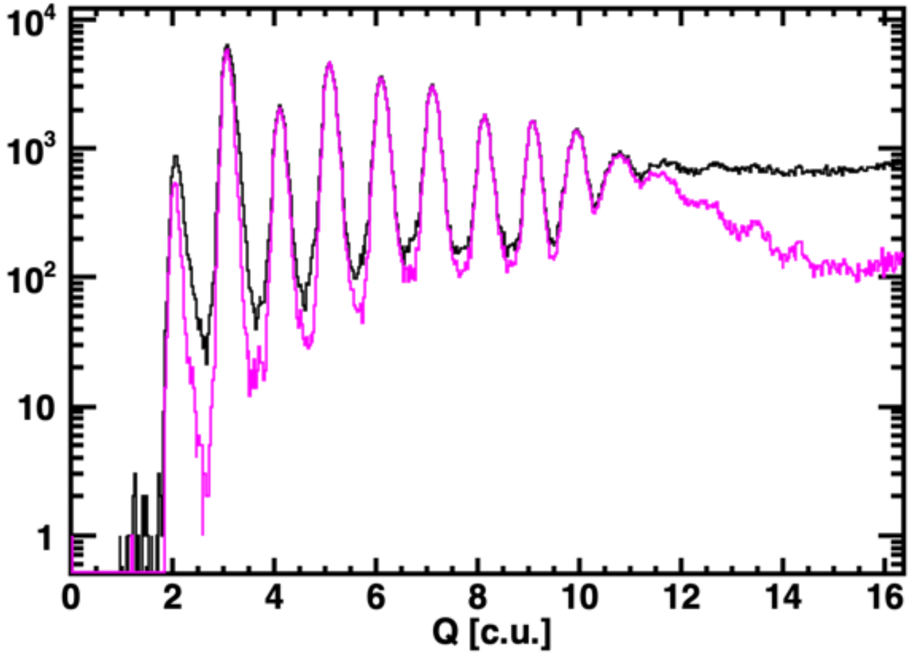


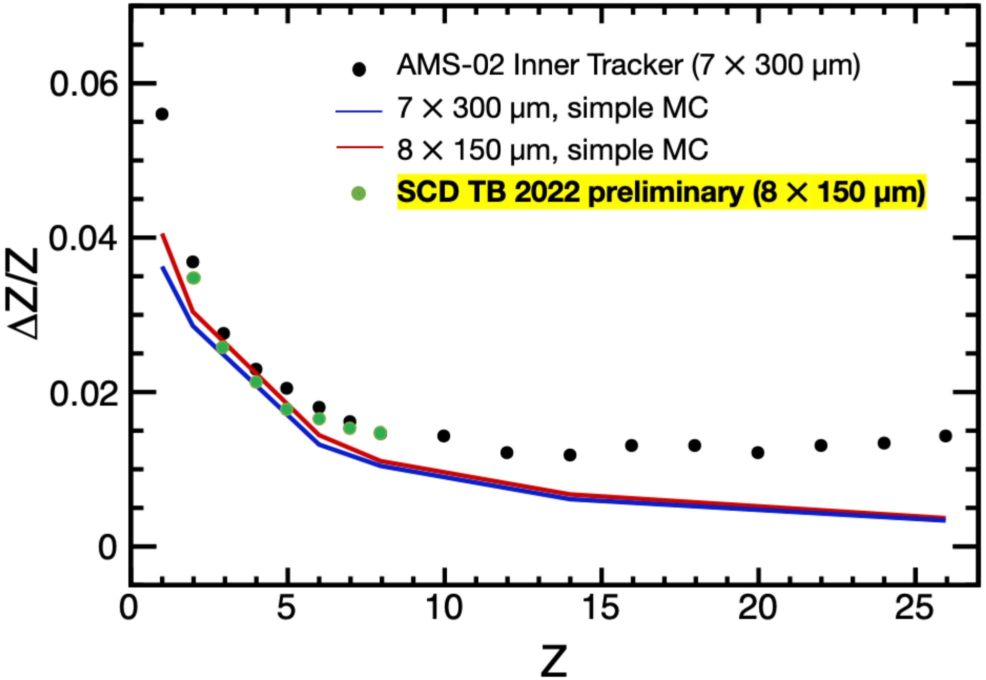
~60 m2, 8 layers
768 ladders
6144 SSD

2022 SCD results



Preliminary alignment procedure accounts for Δx, Δy and XY rotation



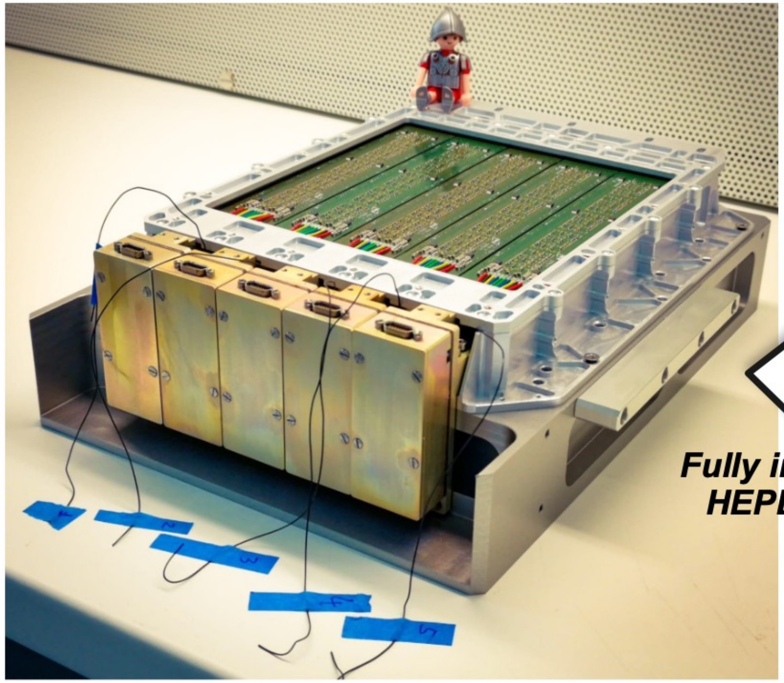


HEPD 2

First MAPS pixel tracker in space

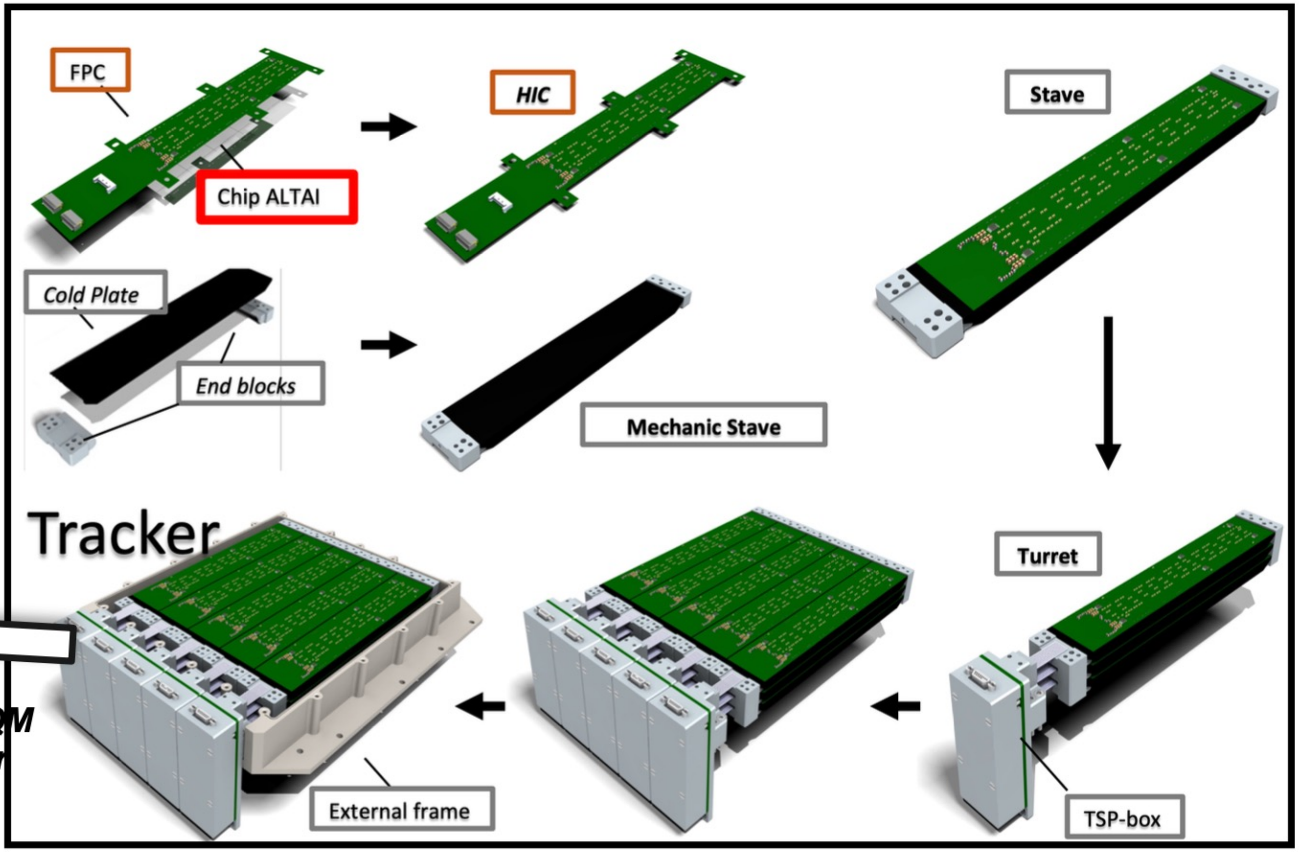
Based on the MAPS developed for ALICE experiment

- Pixel size 29.24 µm x 26.88 µm (~ 4 µm single-hit resolution)
- ALTAI: 512x1024 pixels -> 10 chips per stave;
- 5 turrets, each made of 3 staves with active area 15 x 3 cm² each;
- Low material budget ~ 0.015 X_0;



Fully integrated QM HEPD-02 tracker

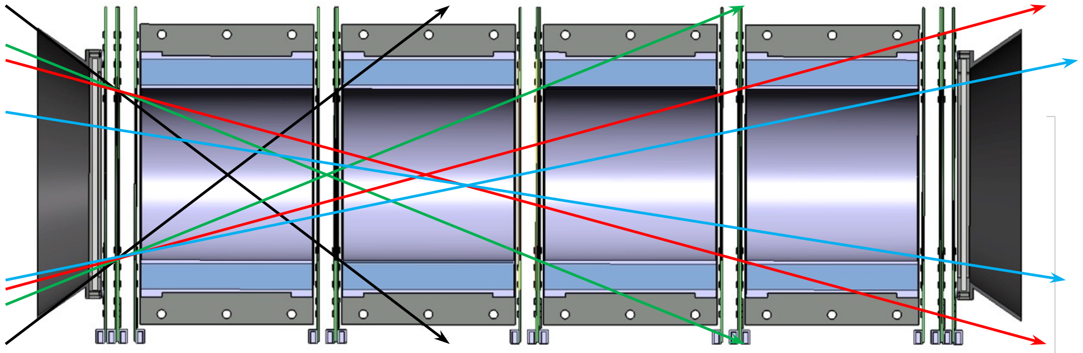
Tracker integration steps

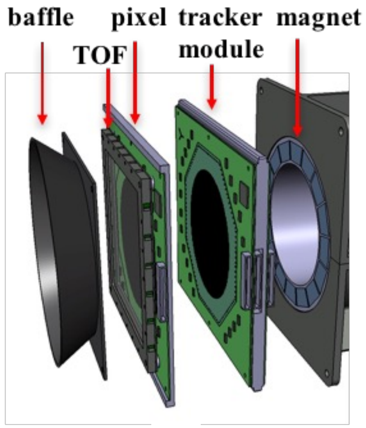


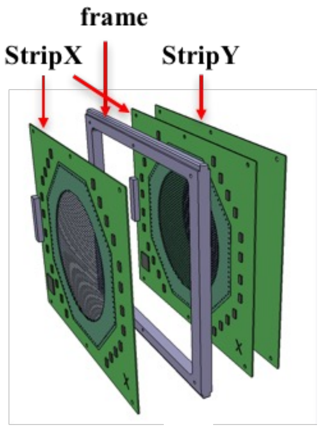
A 80 megapixel CMOS camera for charged radiation

PAN detector modules

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

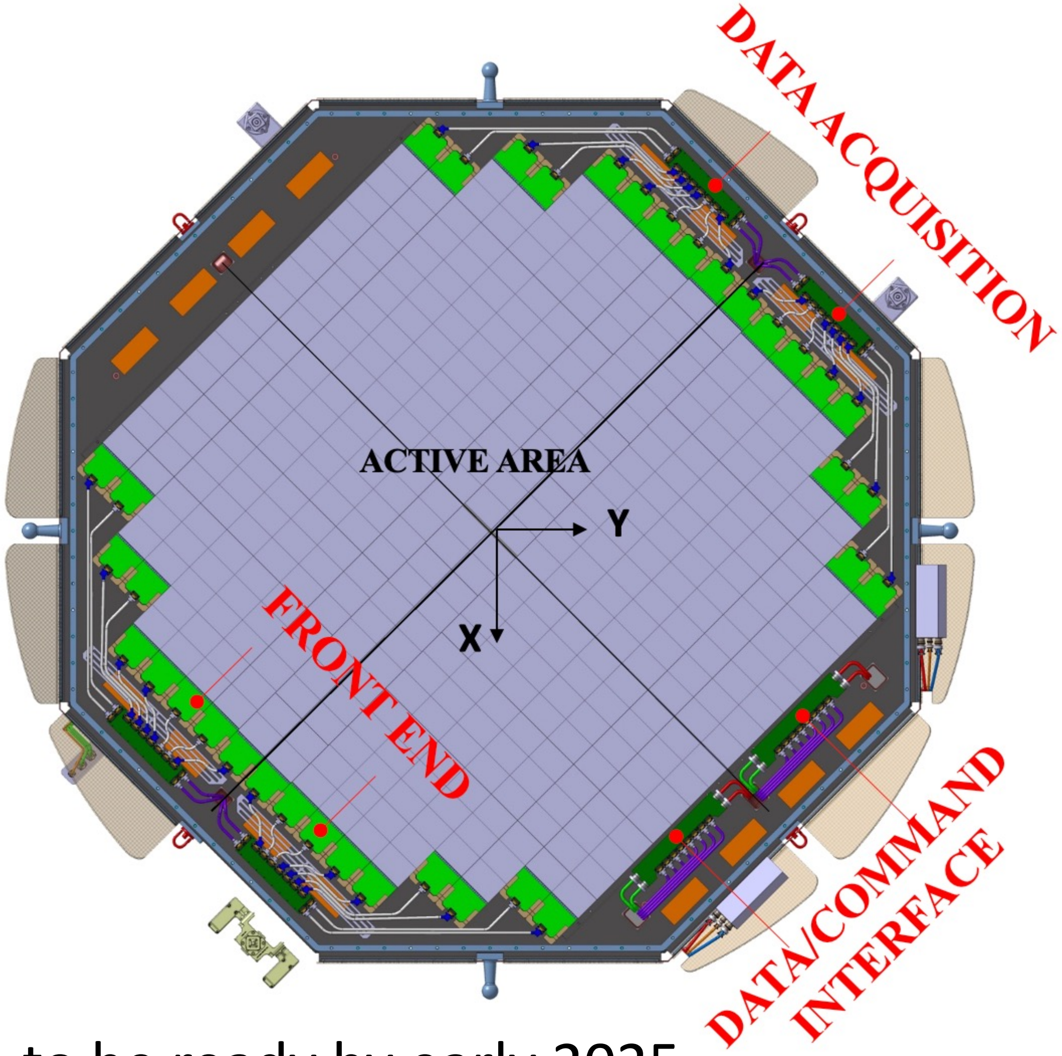




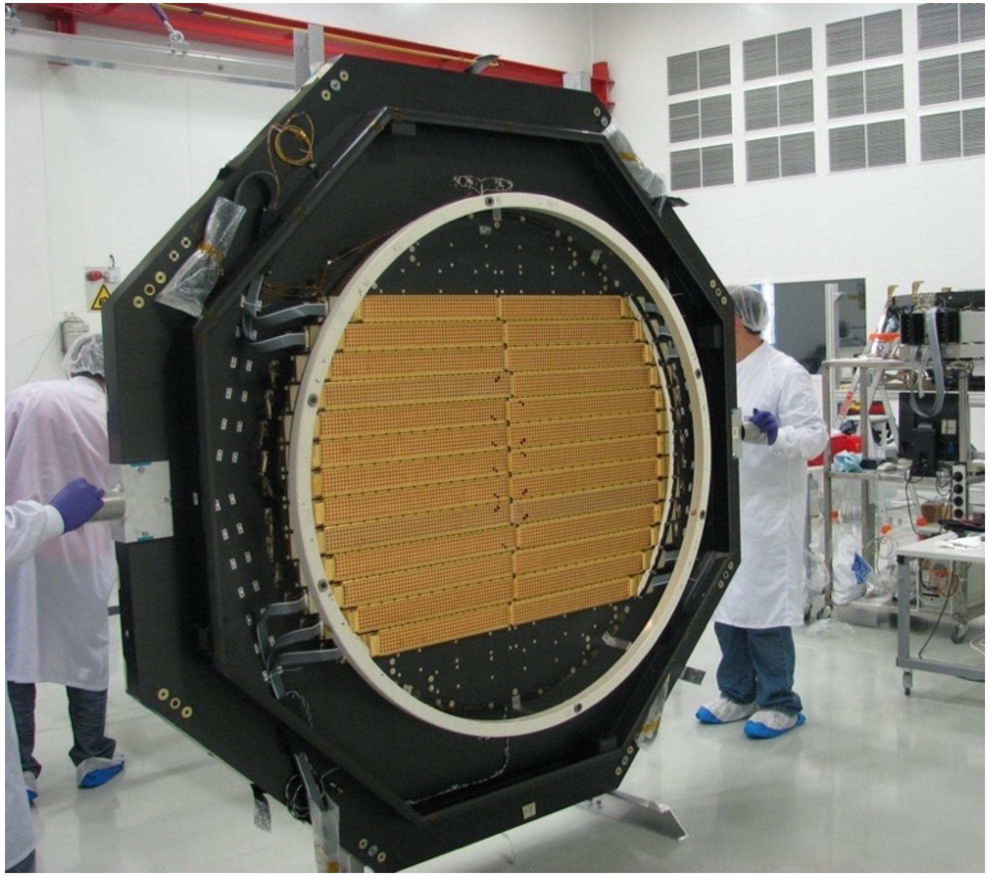


- **Tracker module**
  - 2 StripX: 25 µm readout pitch, 150 µm thick, **2 µm resolution**, to measure both bending radius and bending angle, 40k channels, total power budget 8W
  - 1 stripY: 500 µm readout pitch, 150 µm thick, high dynamic range ASIC for Z = 1 – 26, trigger signal, time stamp (<100 ps 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

the near future: AMS-02 L0 upgrade

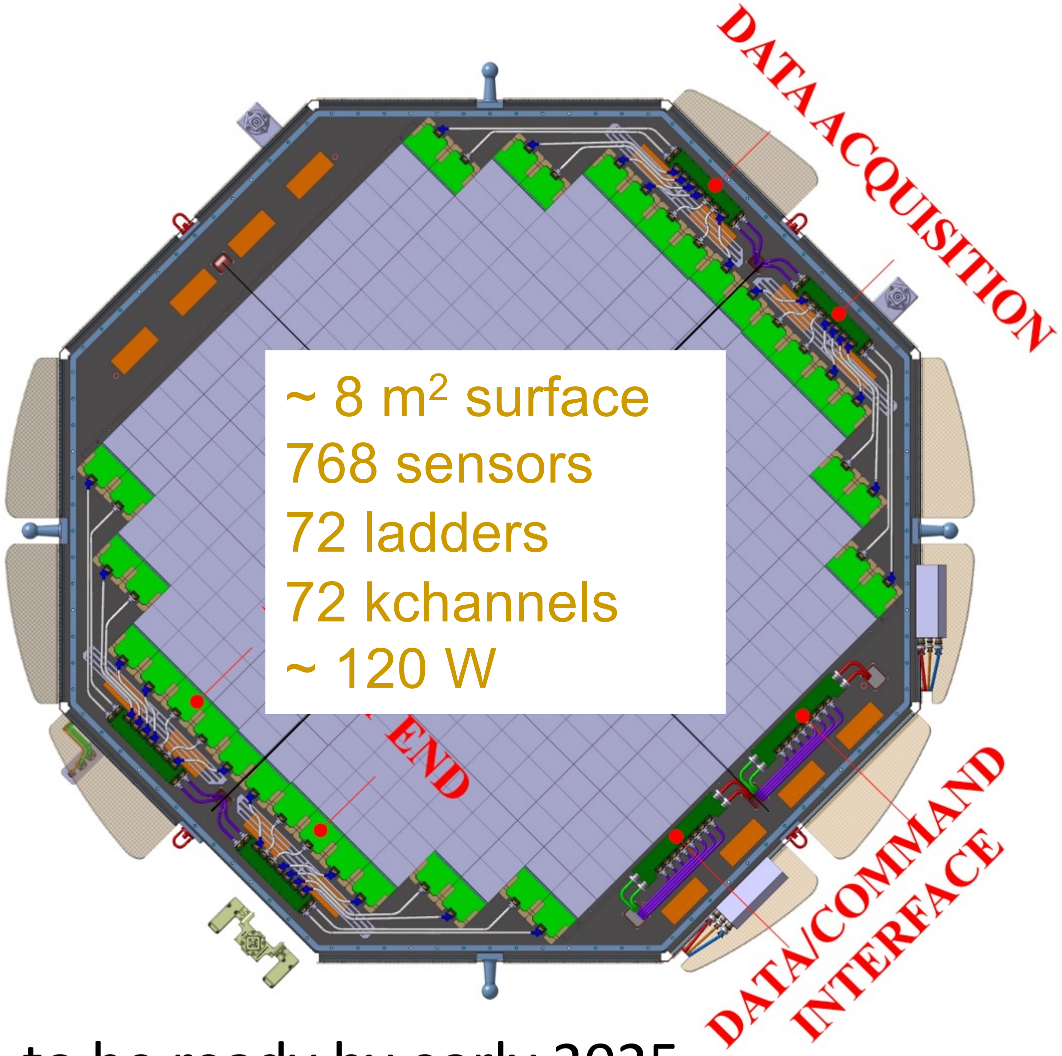


to be ready by early 2025



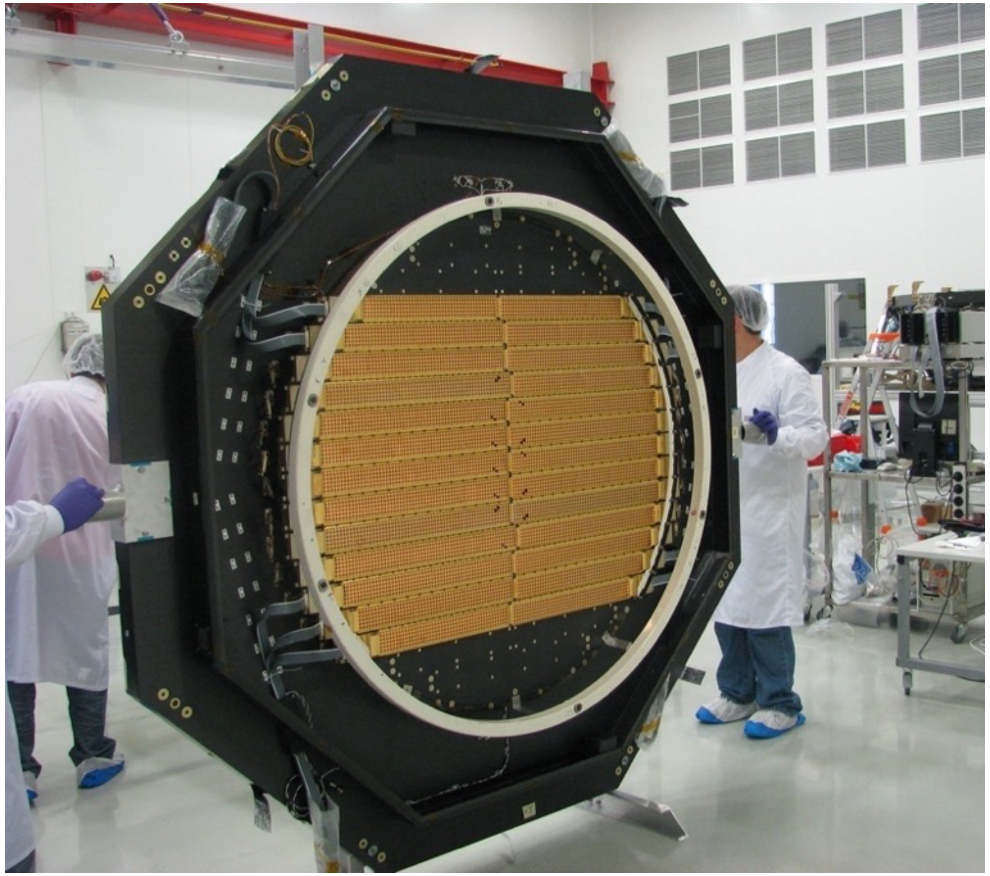
AMS-02 Layer1

the near future: AMS-02 L0 upgrade



~ 8 m^2 surface
768 sensors
72 ladders
72 kchannels
~ 120 W

to be ready by early 2025



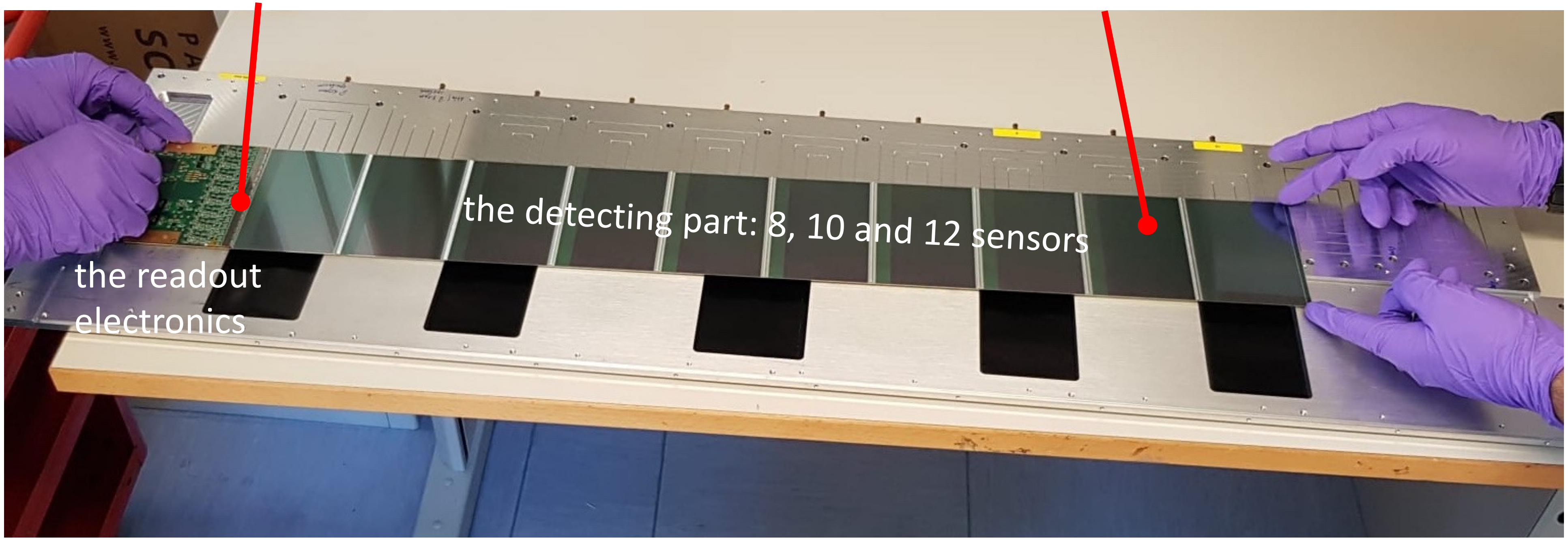
AMS-02 Layer1

the near future: AMS-02 L0 upgrade

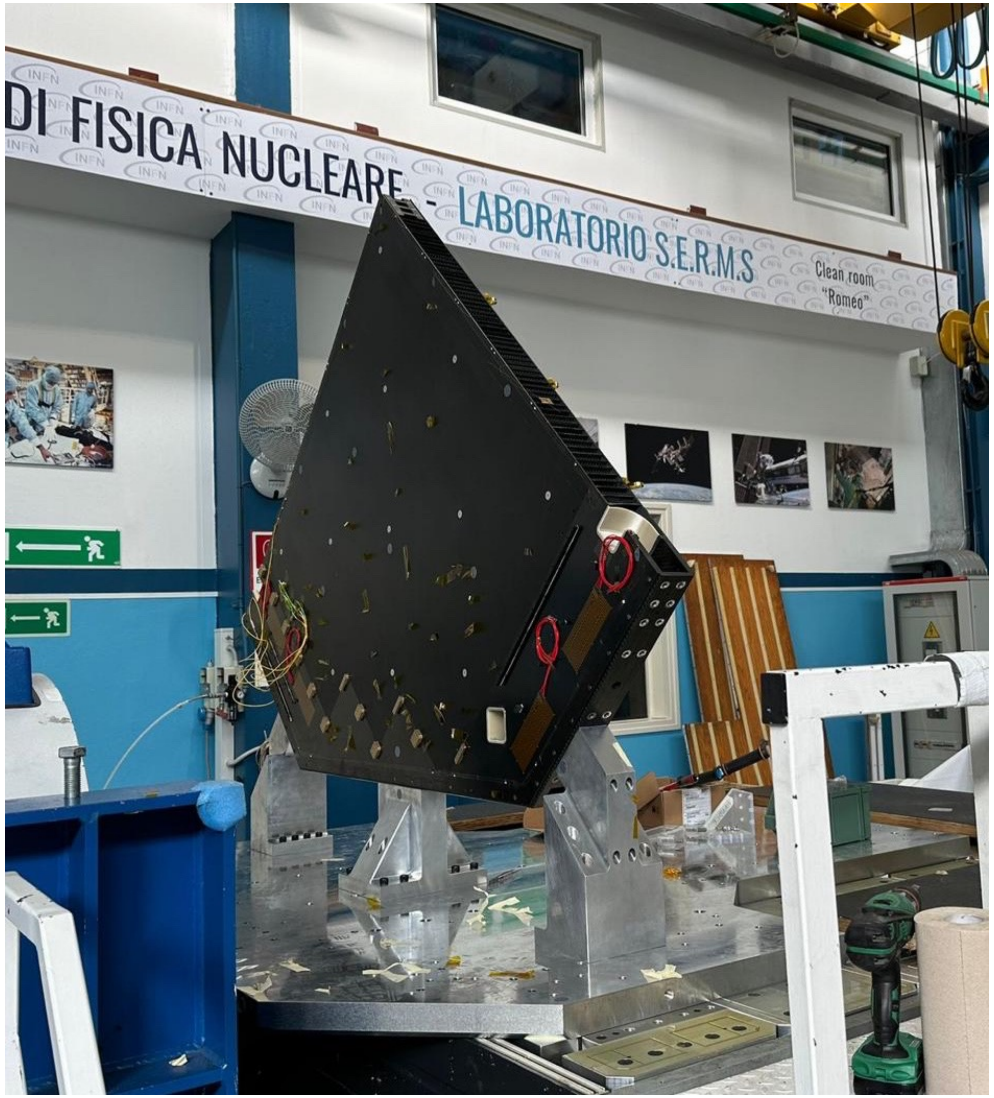
the basic element of the detector

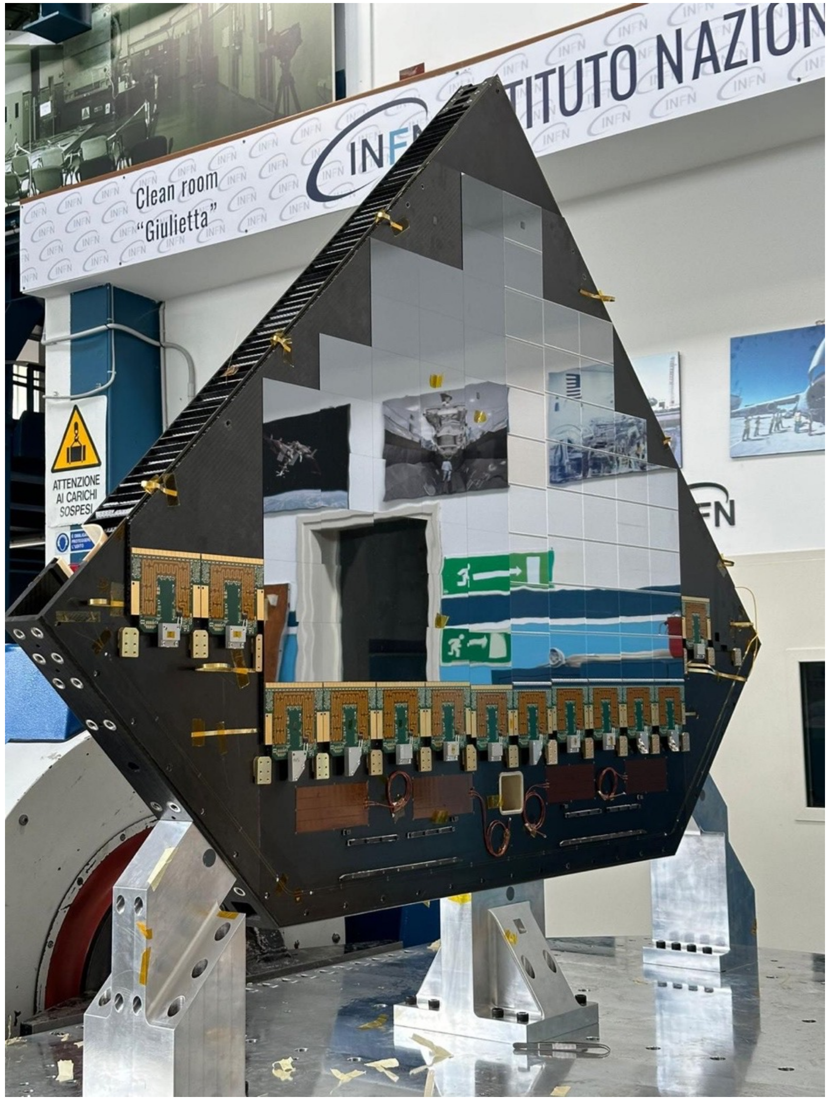
charge measurement:
high dynamic range FE

spatial resolution:
110 µm readout pitch

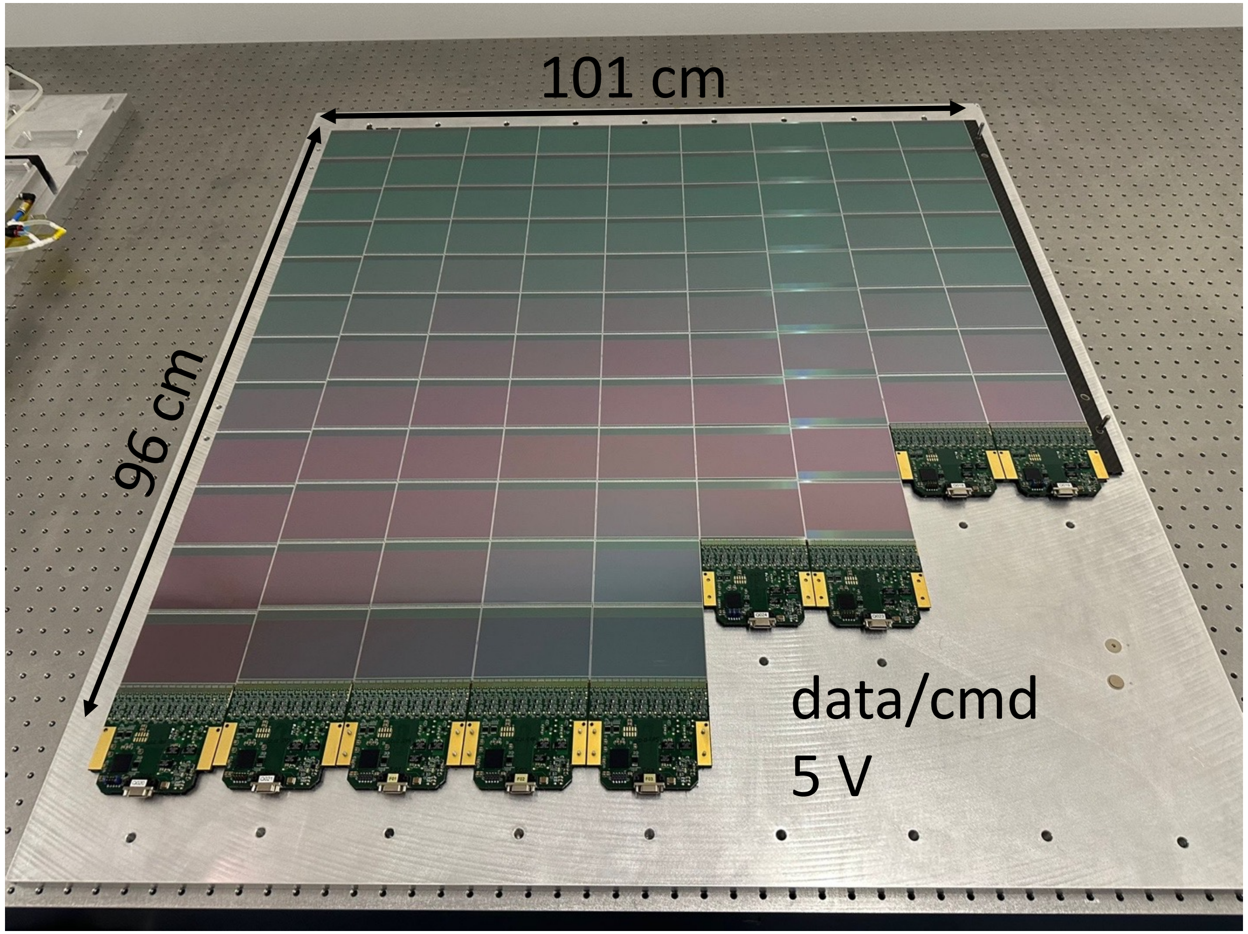


vibration test of a silicon detector

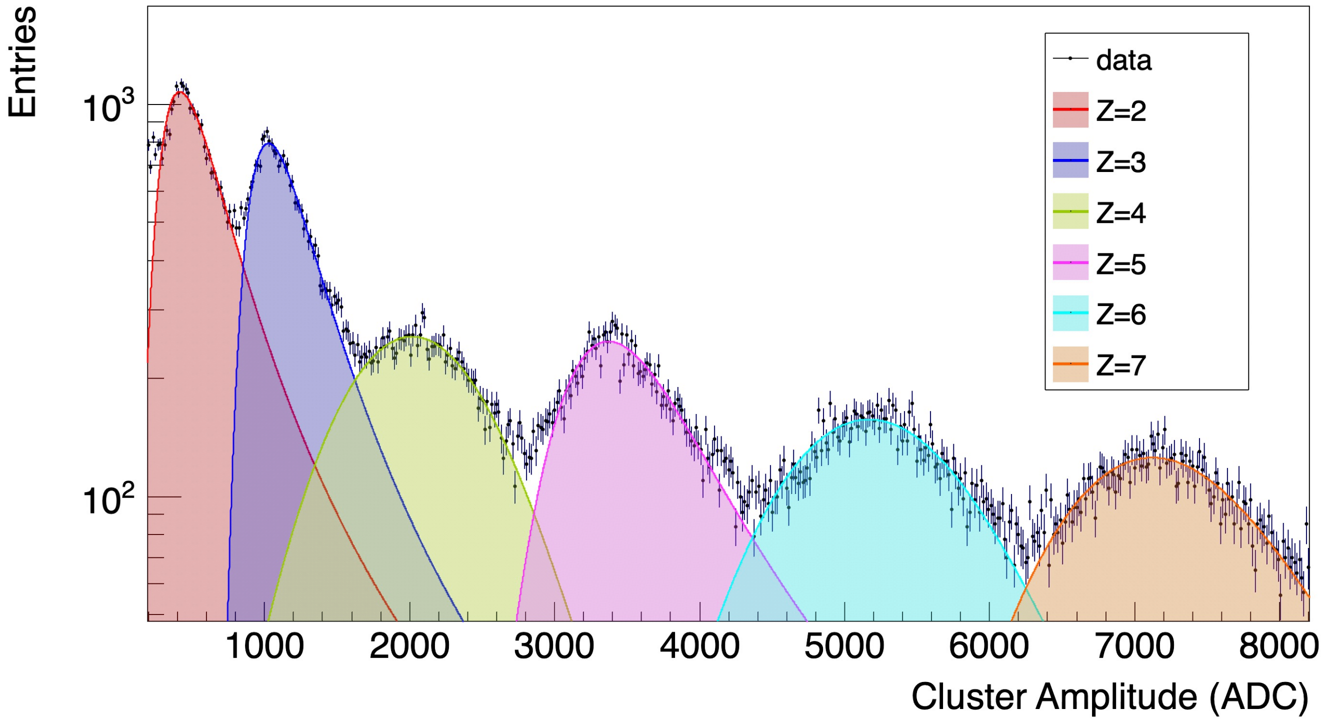


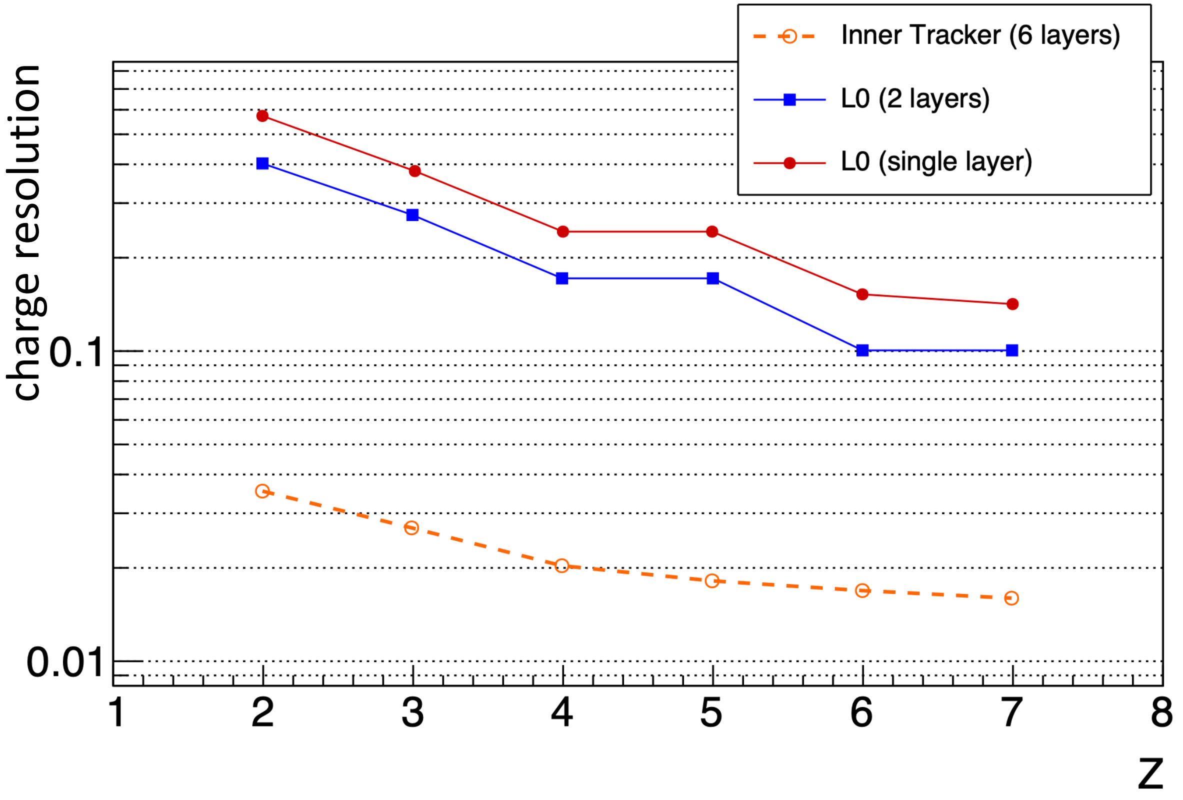


AMS-02 L0 upgrade



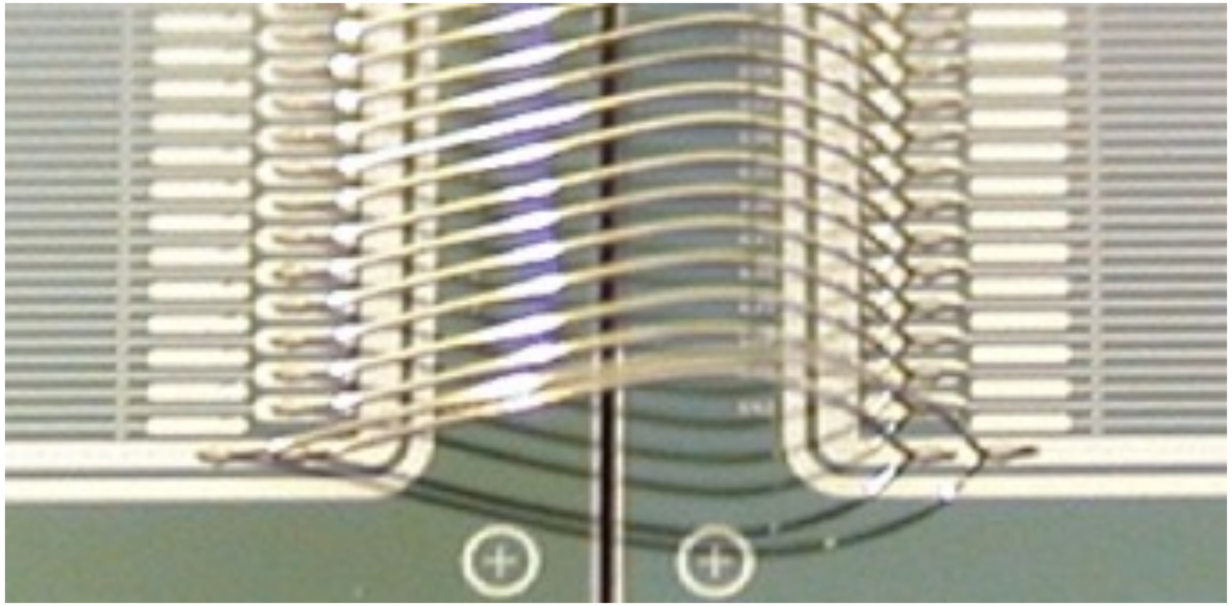
L0 detector performance (ion beam test)

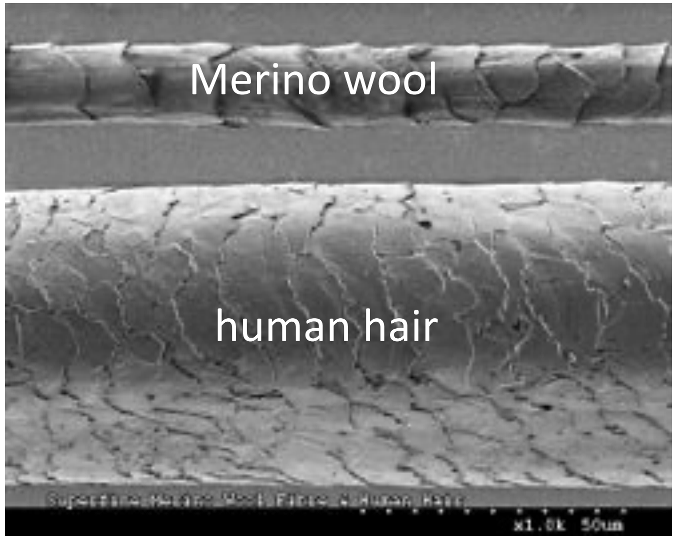


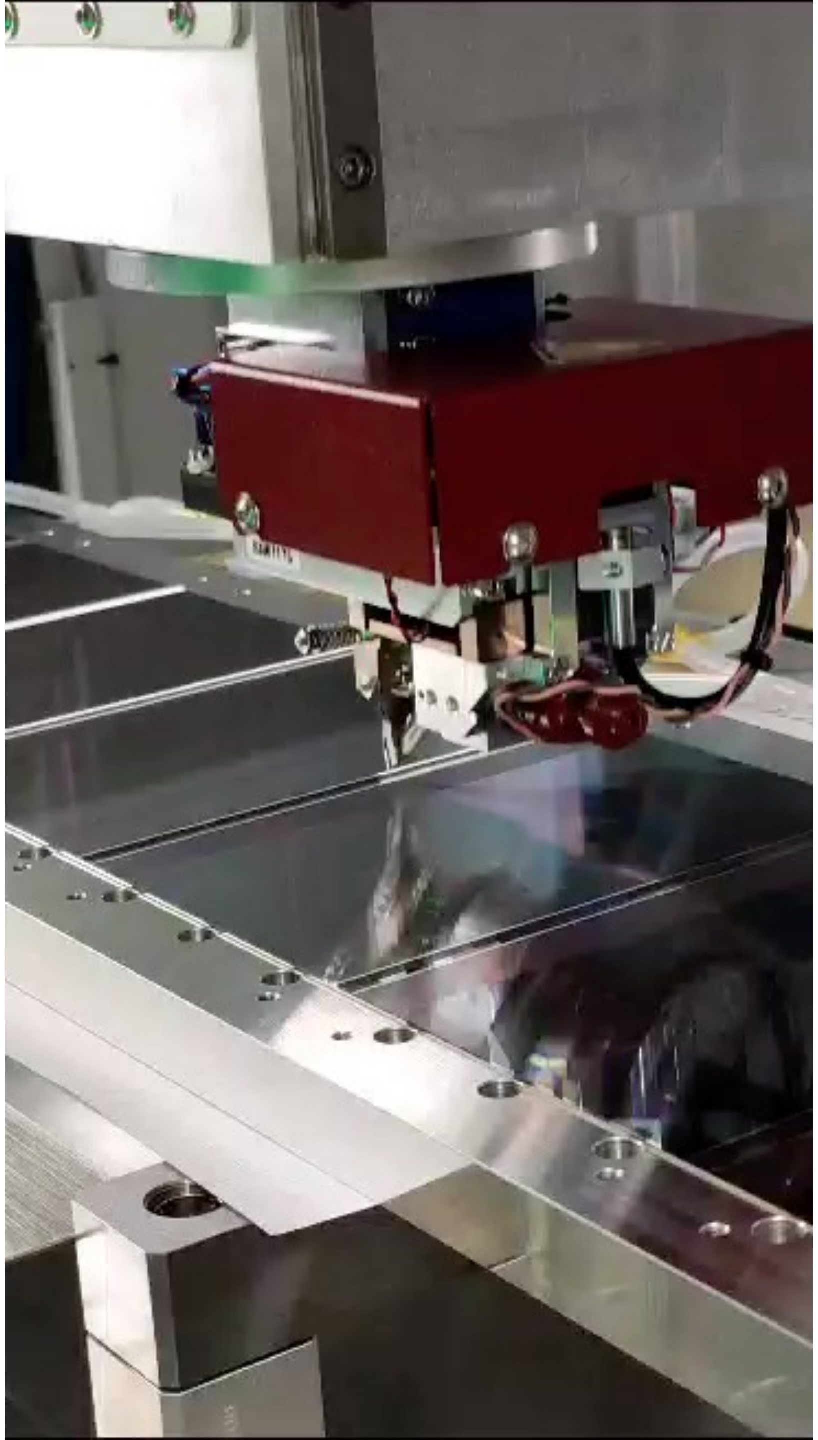


the measured signal can properly identify the ions

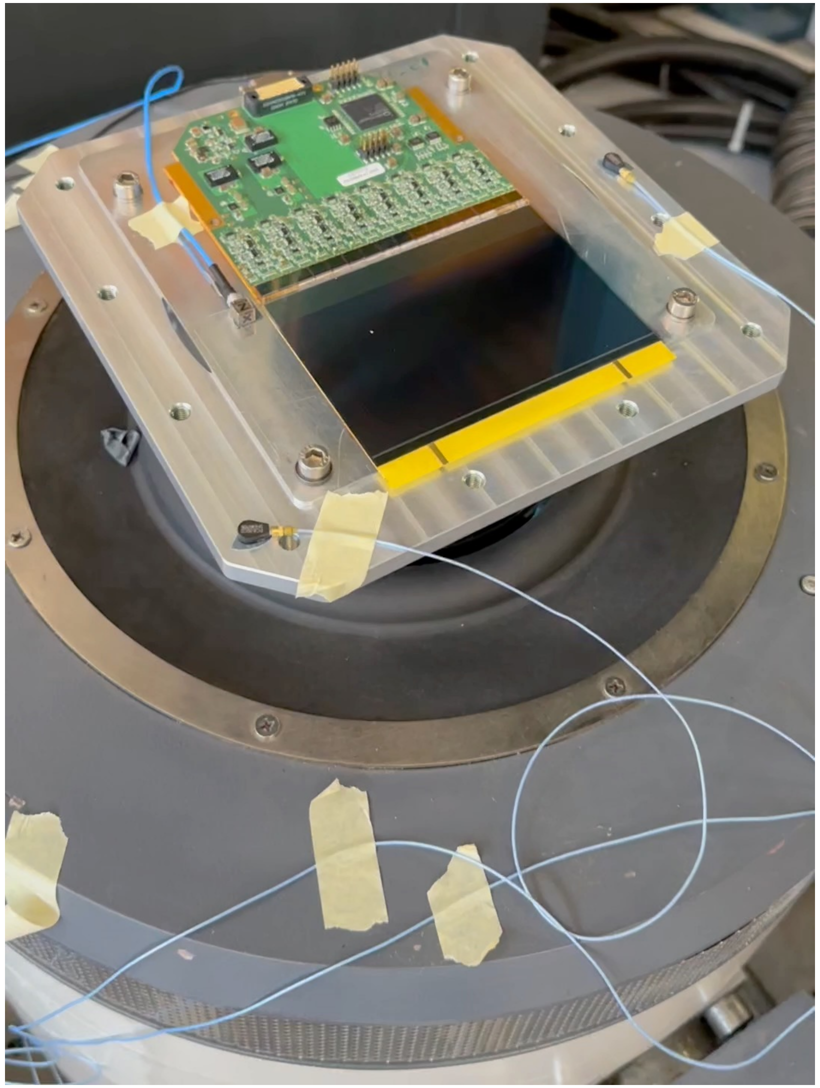
wire bonding







wire bonds vibration test

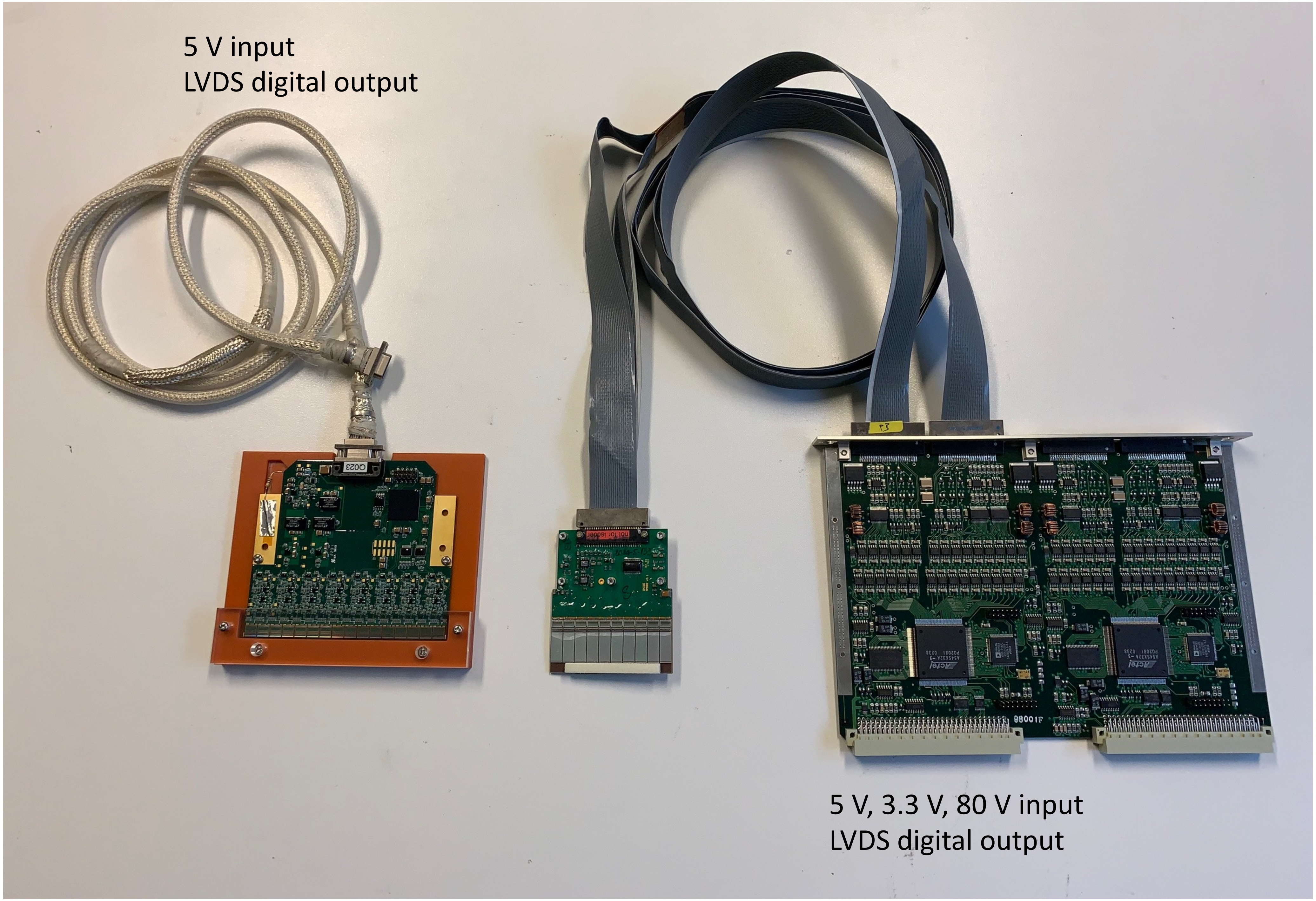


wire bonds vibration test

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 in space

- It is (not!) difficult to put a Silicon Detector in space!


5 V input
LVDS digital output
5 V, 3.3 V, 80 V input
LVDS digital output