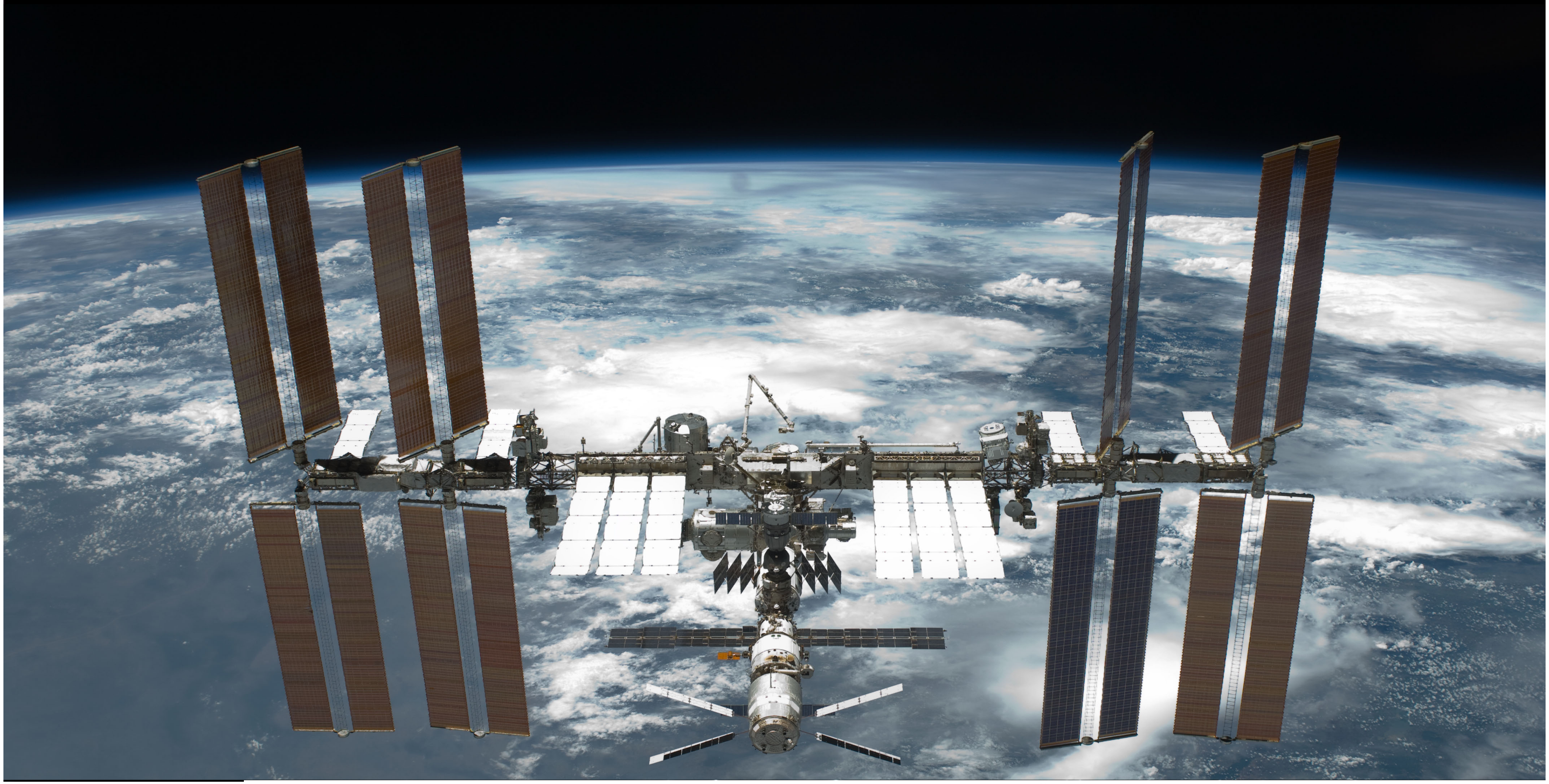
Heritage and challenges for next generation charged cosmic-ray space missions



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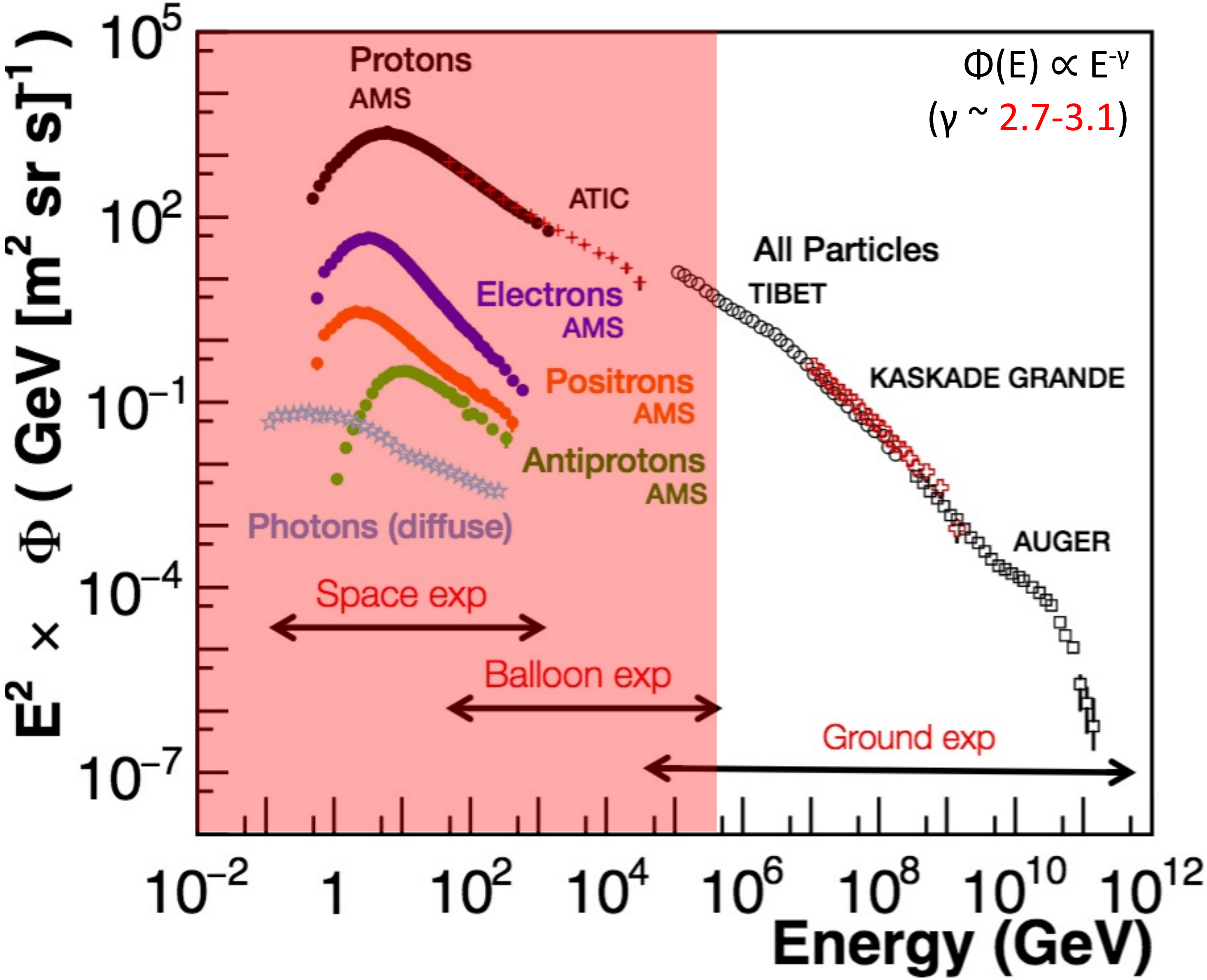
Istituto Nazionale di Fisica Nucleare

TeVPA Chicago 2024

26–30 ago 2024
University of Chicago

Cosmic Rays



measuring in Space (or balloon) allows to measure at single particle level

→ precise composition and spectra measurement

BUT

cosmic ray spectra are tipically power laws:

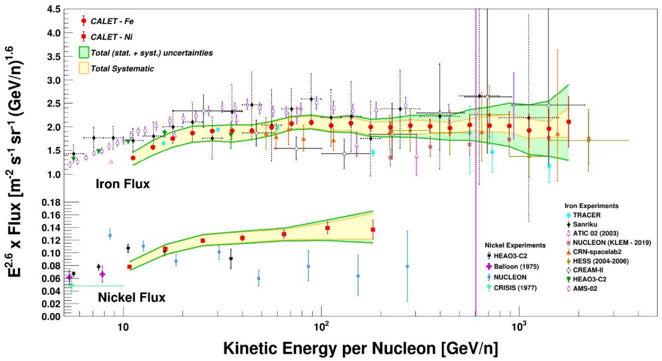
1 order of magnitude in energy

→ 3 orders of magnitude in flux

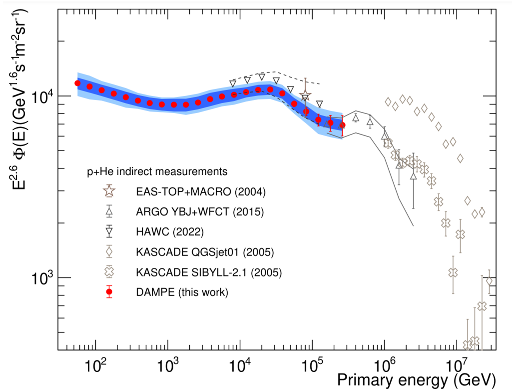
→ 2 orders of magnitude in collected counts (i.e. in statistics)

Charged CRs: state of the art & challenges

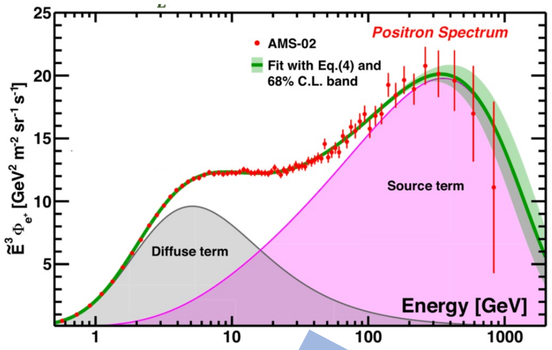
***CALET coll.**, O. Adriani et al., Phys. Rev. Lett. 128, 131103 (2022)*



***DAMPE coll.**, F. Alemanno et al., PoS (ICRC2023) 138*



***AMS coll.**, M. Aguilar et al., Phys. Rev. Lett. 122, 041102 (2019)*



S. Gabici @ ICRC 2023
CR direct rapporteur

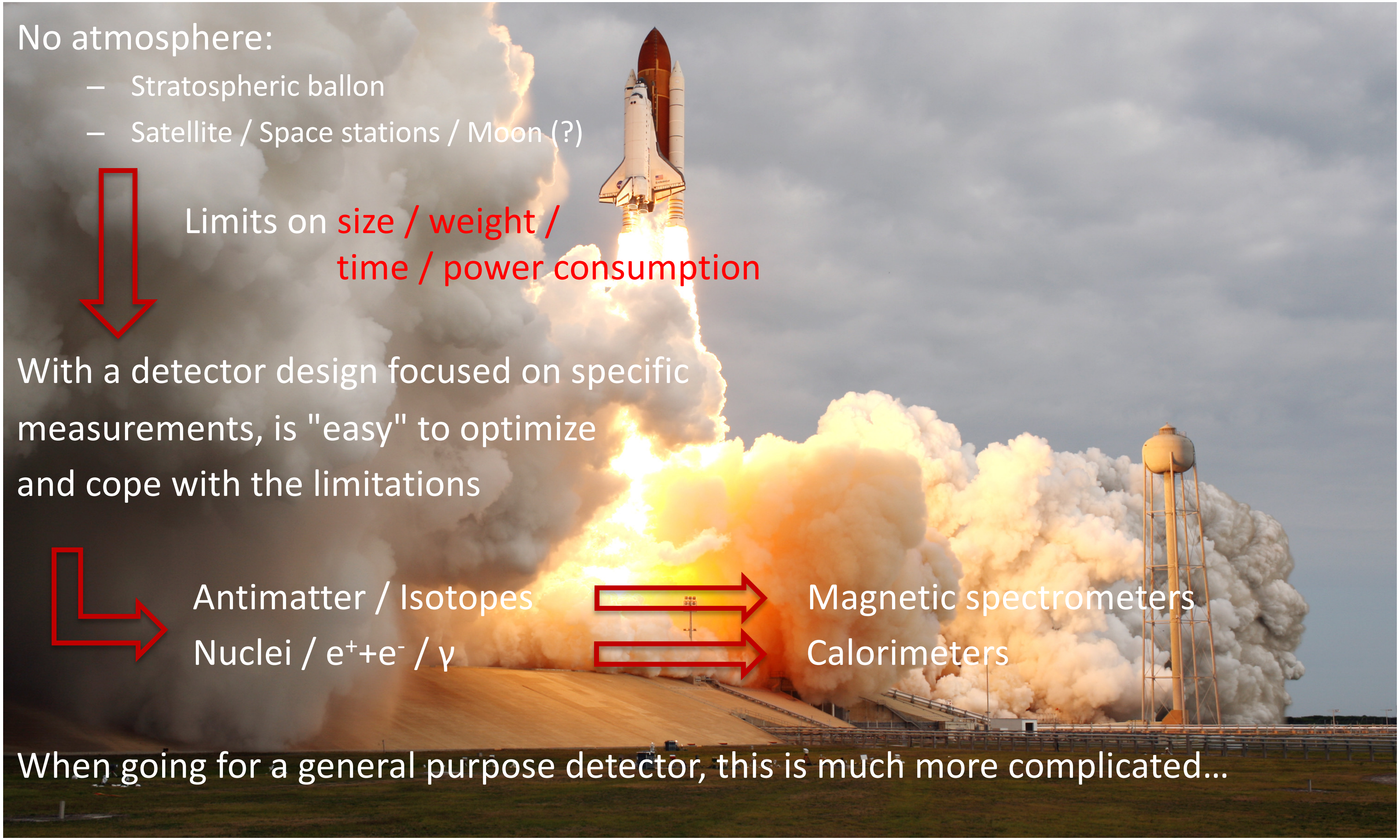
I. What is the origin of the **hardening observed in the spectra of CR nuclei** at rigidity of 300 GV and ~10 TV?
II. Why is the slope of the spectrum of CR **proton and helium different**?
III. What is the origin of the prominent **break** observed at a particle energy of **1 TeV in the electron spectrum**?
IV. Why do the **proton, positron, and antiproton** spectra have roughly same slopes at particle energies larger than 10 GeV?
V. What is the origin of the **rise in the positron fraction** at particle energies above 10 GeV?

COMPOSITION frontier	ENERGY frontier	ANTIMATTER frontier

In general the goal is:

- measurement of CR nuclear composition in the 100 TeV - PeV energies for a comprehensive assessment of CR origin, acceleration and transport mechanisms
- Measure CR electron anisotropies and flux beyond 10 TeV (search for nearby astrophysical electron sources)
- Extend measurements of isotopic composition of CRs above 10 GeV/n (determination of halo size, high energy interactions, …)
- Ultra-heavy trans-Iron CR composition (association of neutron-rich CR sources, ..)
- Search for new physics signatures in CR measurements:
  - New physics signatures in low-energy nuclear antimatter fluxes (e.g., anti-D, anti-He)
  - New physics signatures in high-energy antiprotons and positron/electron fluxes
  - Measurement of secondary positrons above the TeV break
  - Search for exotica or Beyond-Standard-Model physics

The experimental challenge



No atmosphere:

- Stratospheric ballon
- Satellite / Space stations / Moon (?)

Limits on size / weight / time / power consumption

With a detector design focused on specific measurements, is "easy" to optimize and cope with the limitations

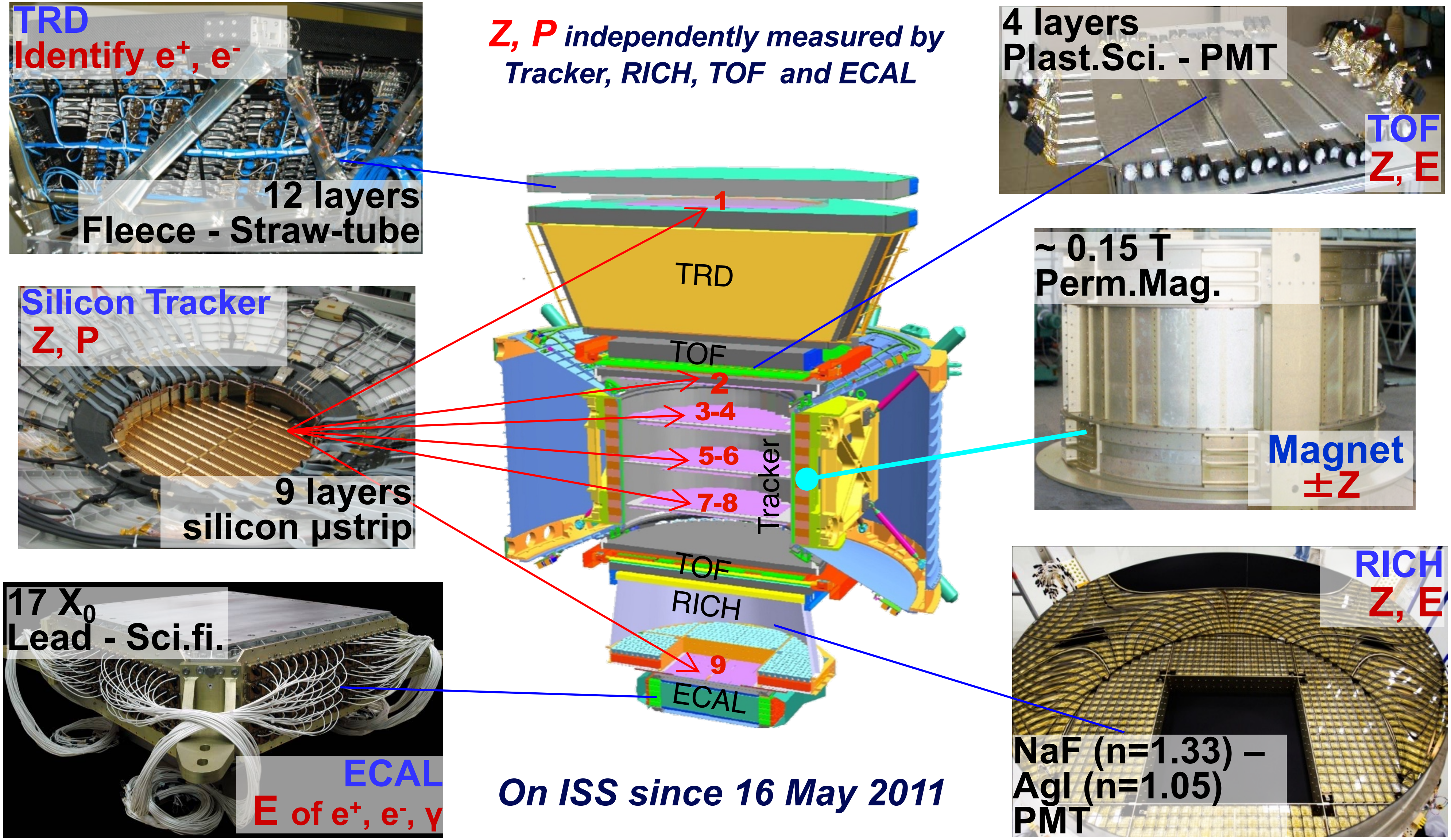
Antimatter / Isotopes → Magnetic spectrometers

Nuclei / e^{+}+e^{-} / γ → Calorimeters

When going for a general purpose detector, this is much more complicated…

Current experiments – key concepts/detectors (AMS, mainly, and DAMPE used as examples)

Current operating experiments – AMS-02



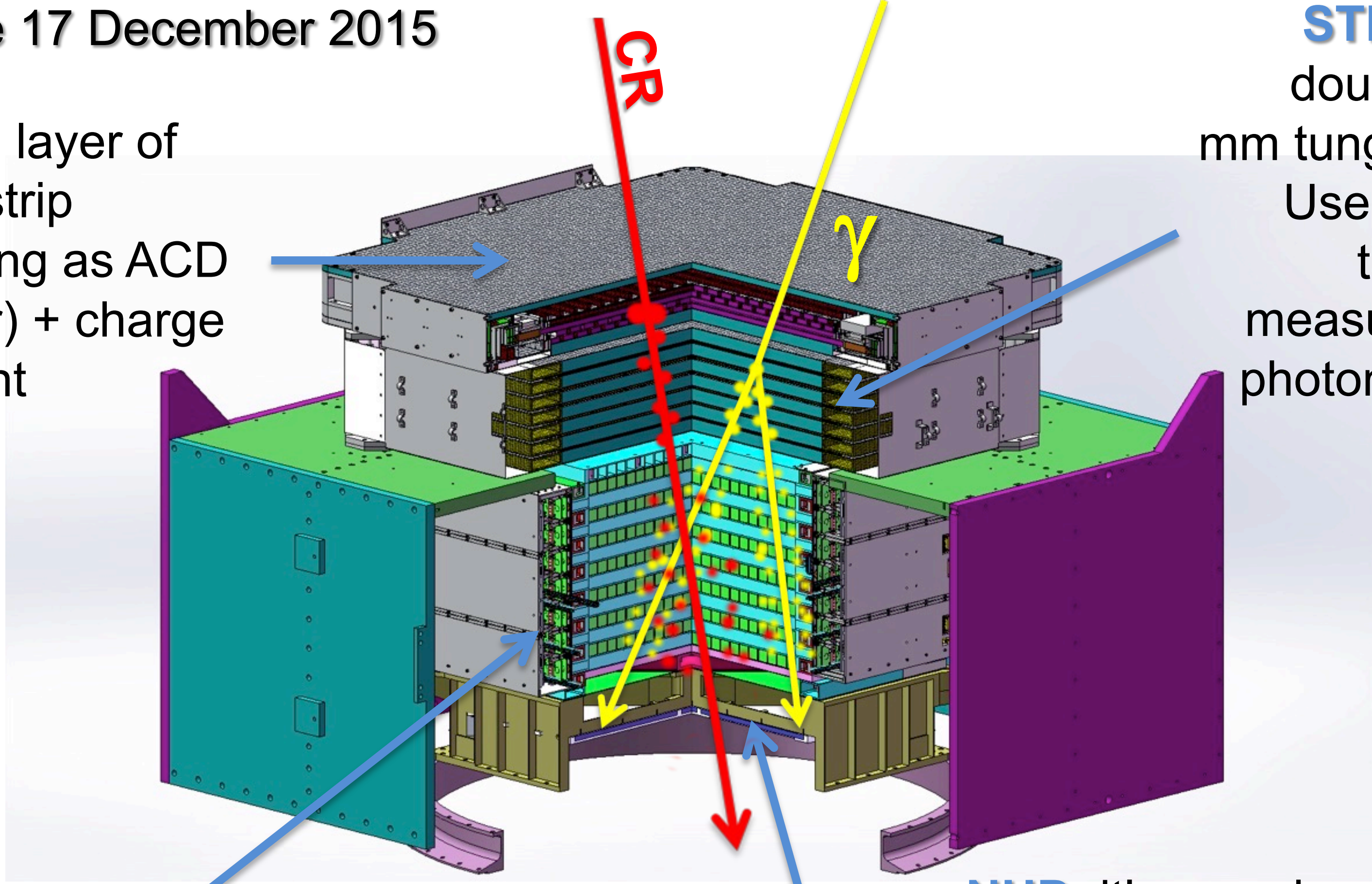
On ISS since 16 May 2011

Current operating experiments - DAMPE

In orbit since 17 December 2015

PSD: double layer of scintillating strip detector acting as ACD (anti-counter) + charge measurement

STK: 6 tracking double layer + 3 mm tungsten plates. Used for particle track, charge measurement and photon conversion (~ 2 X_0)



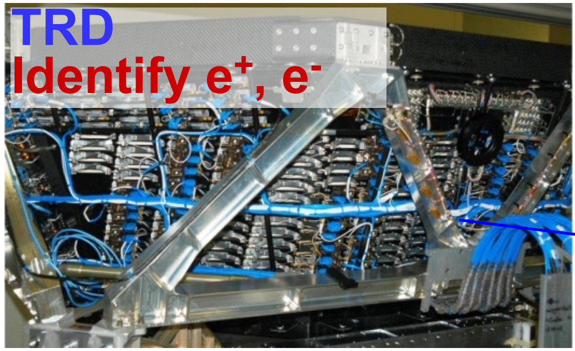
BGO: the calorimeter is made of 308 BGO bars in hodoscopic arrangement (~31 X_0). Performs energy measurements, hadron/lepton identification (*e/p rejection*), and trigger

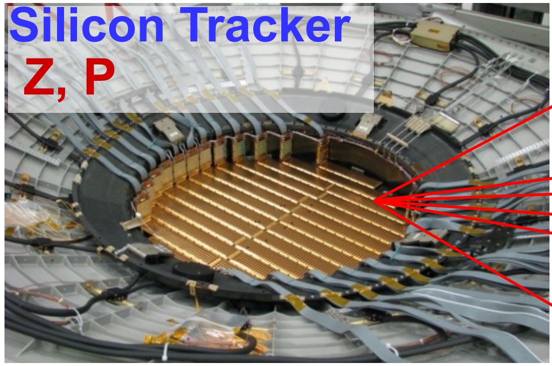
NUD: it's complementary to the BGO e/p rejection, by measuring the thermal neutron shower activity. Made up of boron-doped plastic scintillator

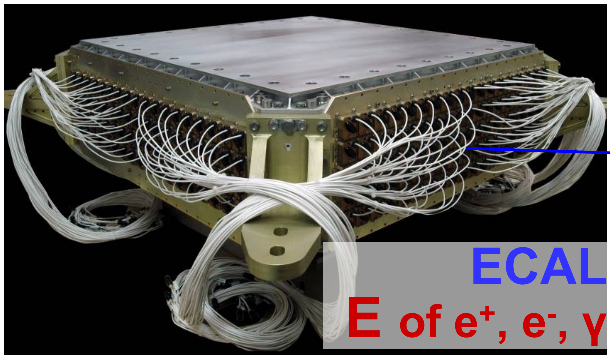
How to identify&measure

- measure energy/momentum:
  - calorimetry
  - magnetic spectrometry
  - ~~time of flight~~
  - ~~Cherenkov~~
  - transition radiation
- measure sign of charge:
  - magnetic spectrometry + time of flight
  - topology of annihilation (tracking/calorimetry)
- measure charge:
  - dE/dx (tracking/scintillation)
  - number of photons in Cherenkov radiation
- measure mass (β/γ + E/p):
  - time of flight
  - Cherenkov
  - transition radiation
- hadron/lepton separation:
  - transition radiation
  - shower development topology (imaging calorimetry)
  - energy/momentum match
  - neutron produced in hadronic shower (neutron detector)
  - calorimeter back-scattering timing measurement ?

Key concepts/detectors



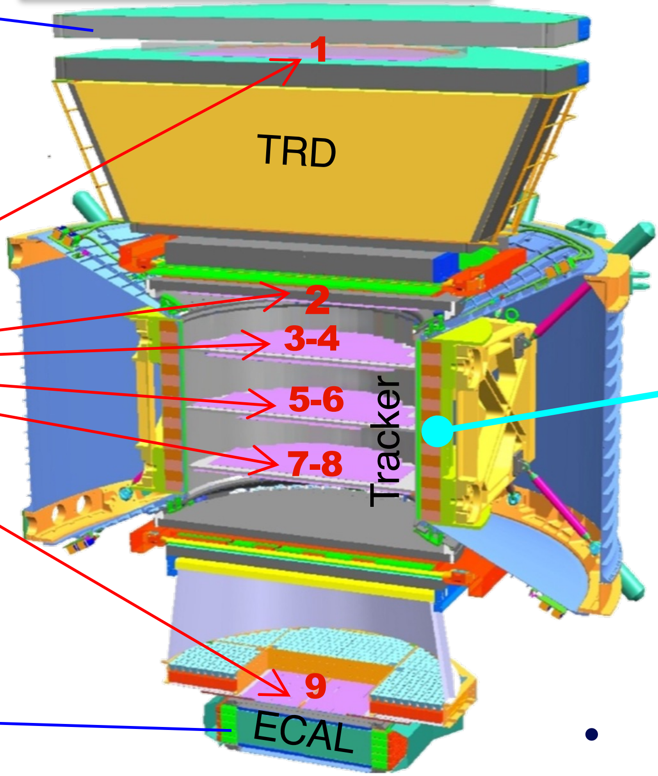


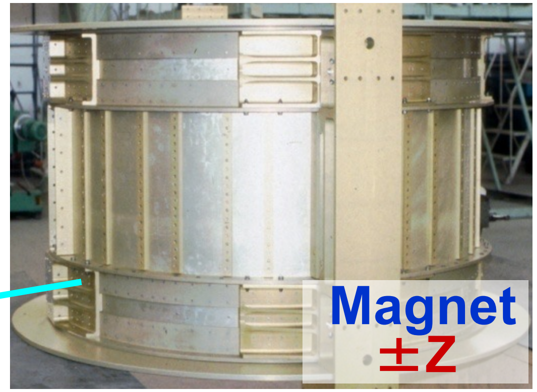


Techniques:

- Transition Radiation
- Shower development topology

- Energy/Momentum (E/p) match
- neutrons produced in the hadronic shower

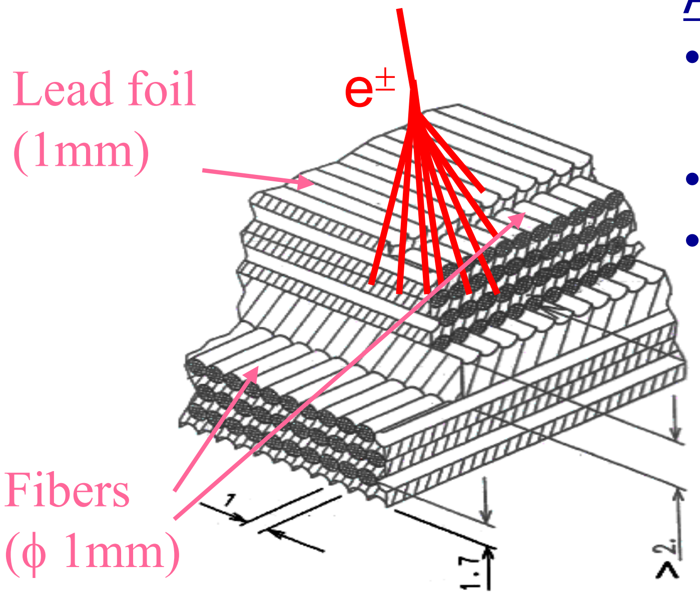


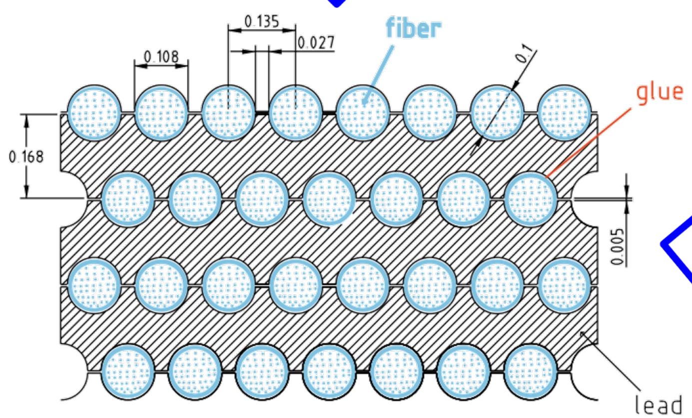


Electron/proton separation:

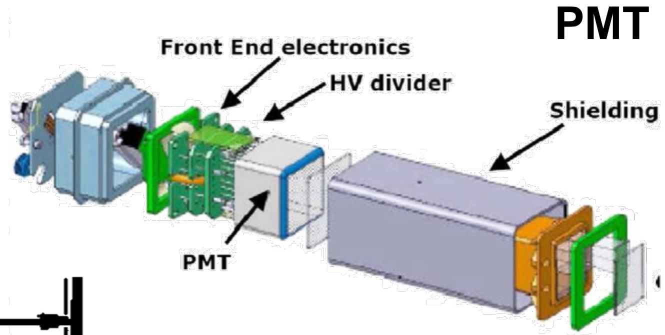
- e^- wrt the p background
- e^+ wrt to the p background
- anti-p wrt to the e^- background
- γ's wrt the p background

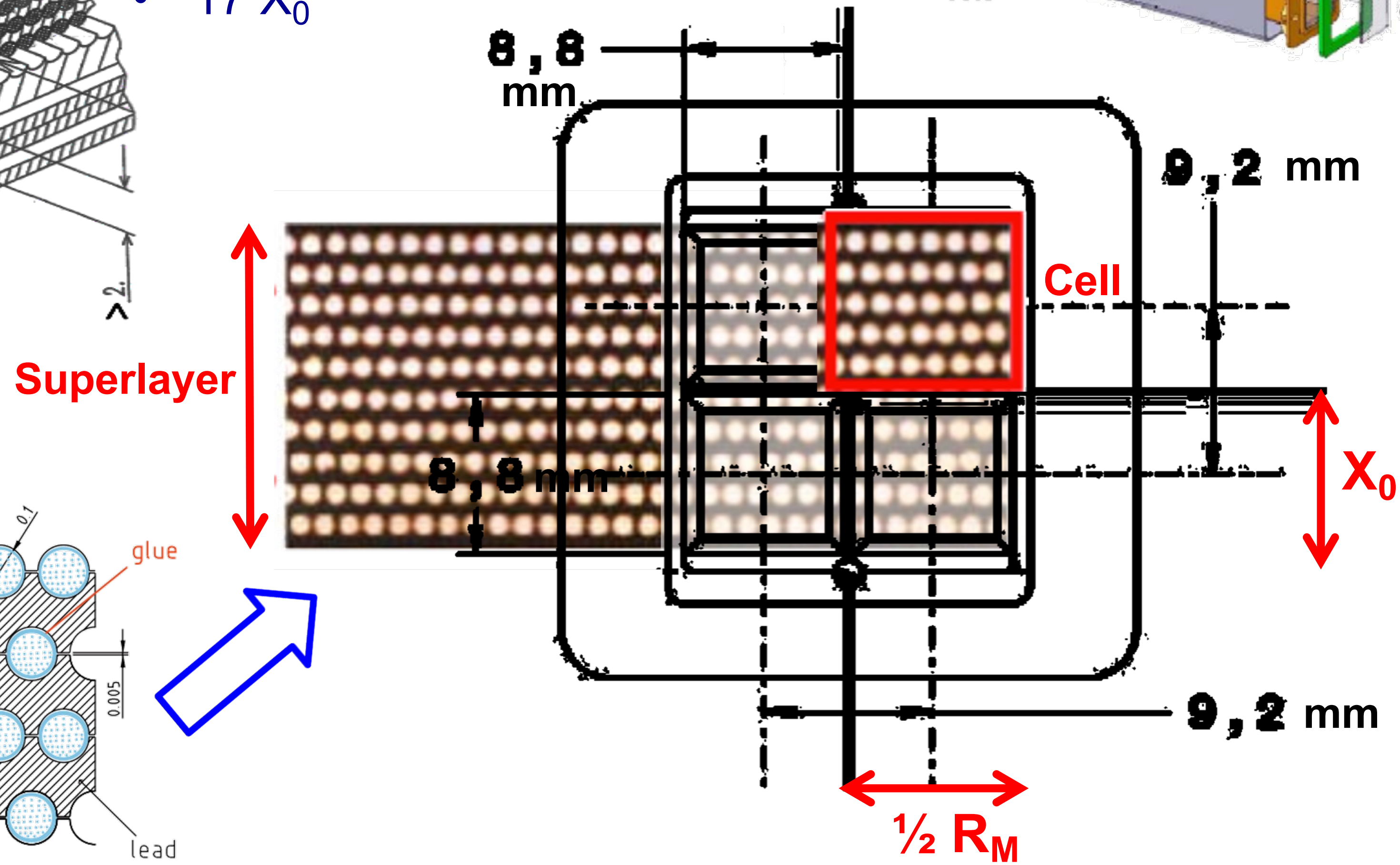
Shower development topology: segmentation (longitudinal and lateral)





AMS ECAL:
- Lead-SciFi sampling calorimeter
- 18 layers (9 super-layers)
- 17 X_0

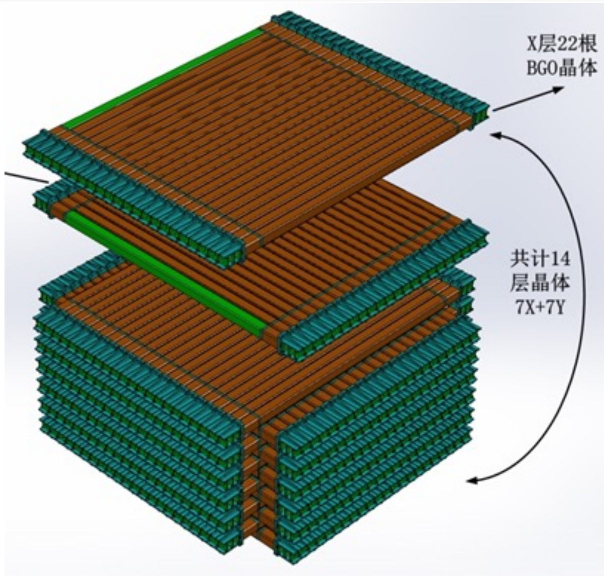


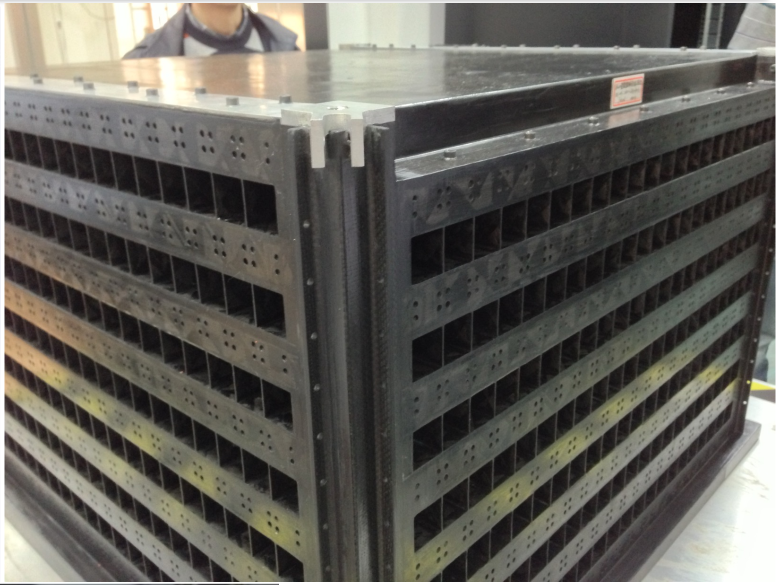


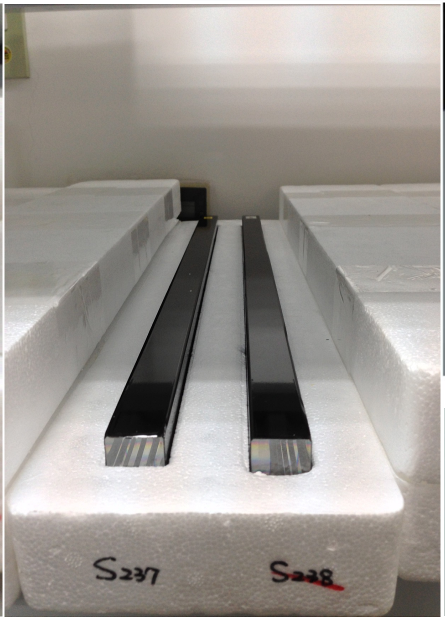
Shower development topology: segmentation (longitudinal and lateral)

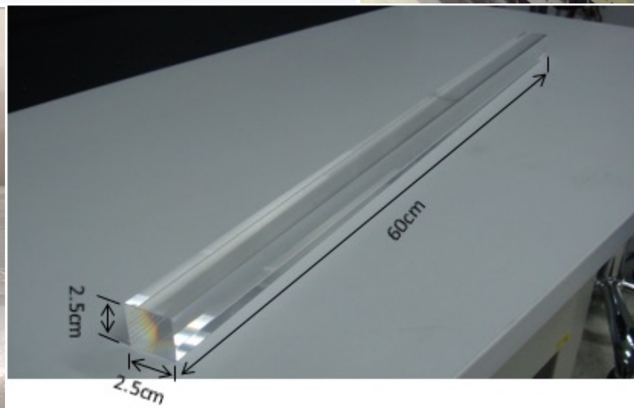
INFN PERUGIA

DAMPE BGO:
- homogeneous calorimeter
- ~ 31 X_0
- 14 layers (~ $2X_0$ per layer)



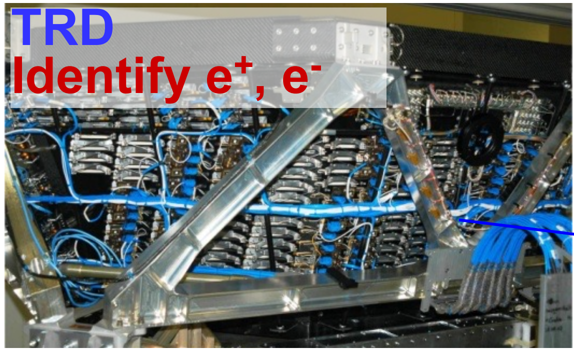






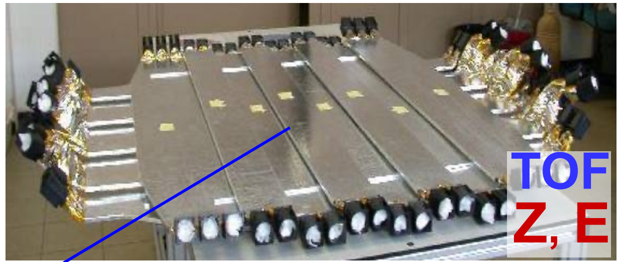
308 bars
616 PMTs

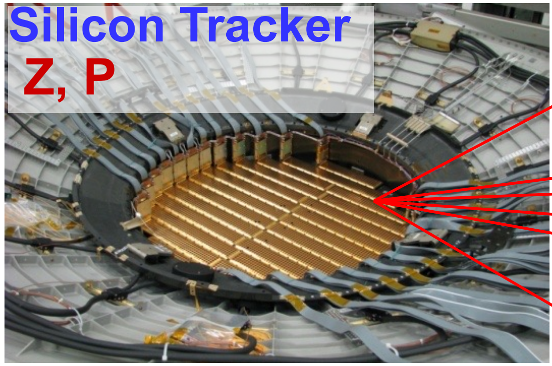
Key concepts/detectors

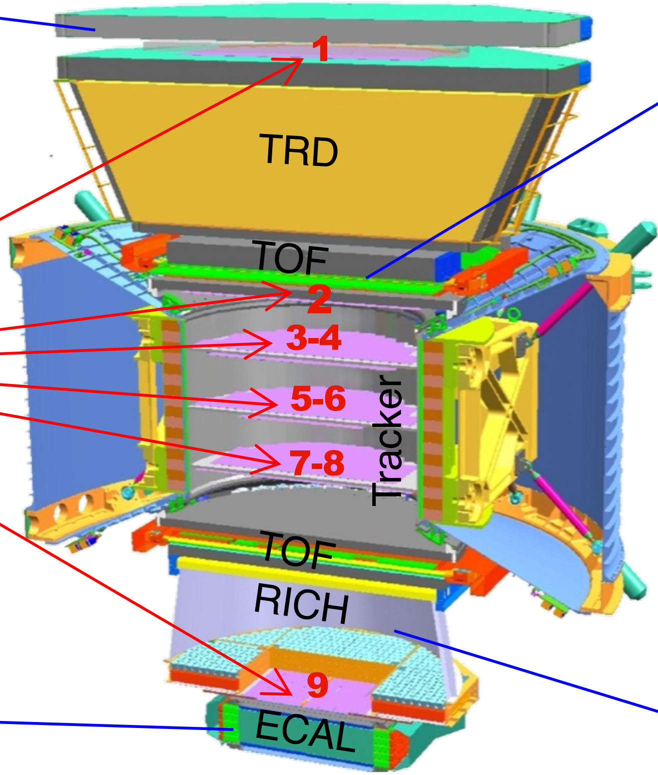


Techniques:

- dE/dx
- number of photons in the Cherenkov radiation

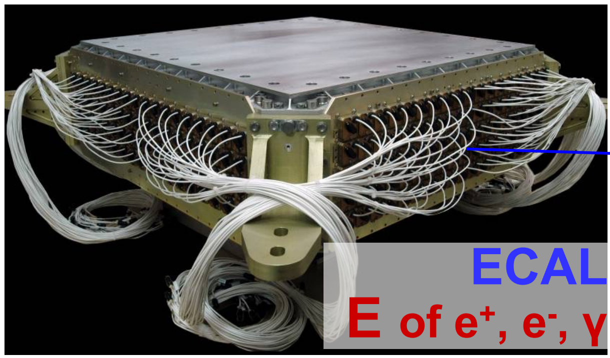


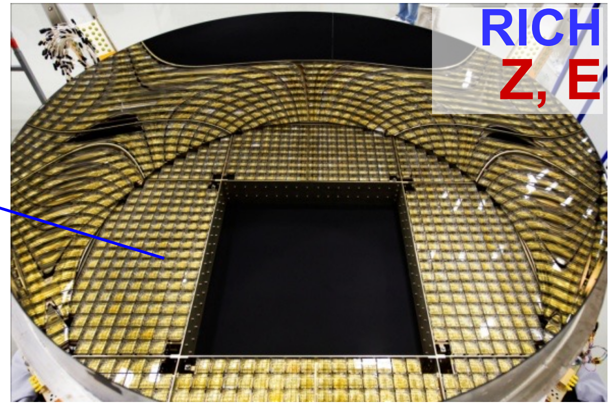




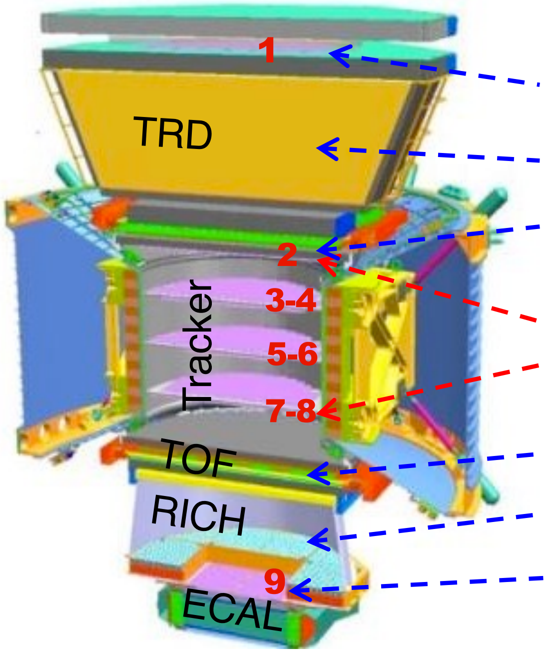
Charge measurement:

- identify the different nuclear species
- control the fragmentations (if multiple measurements along the detector)



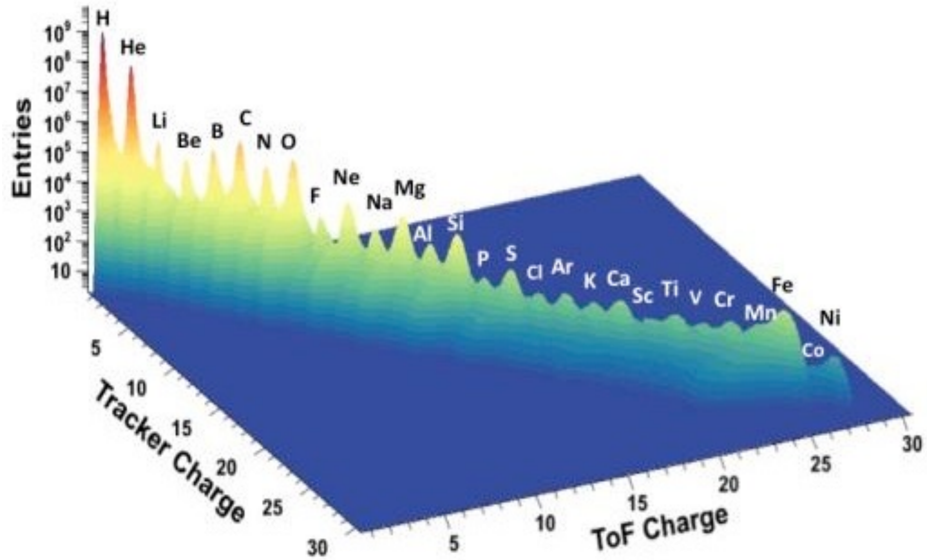


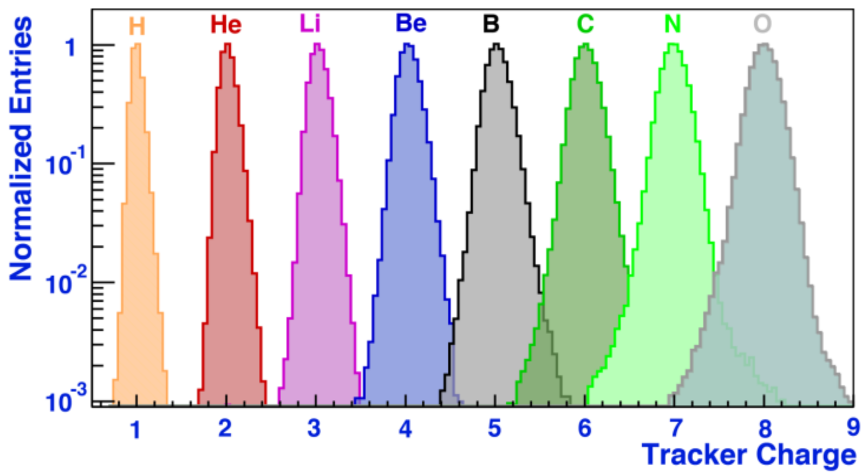
Key concepts/detectors



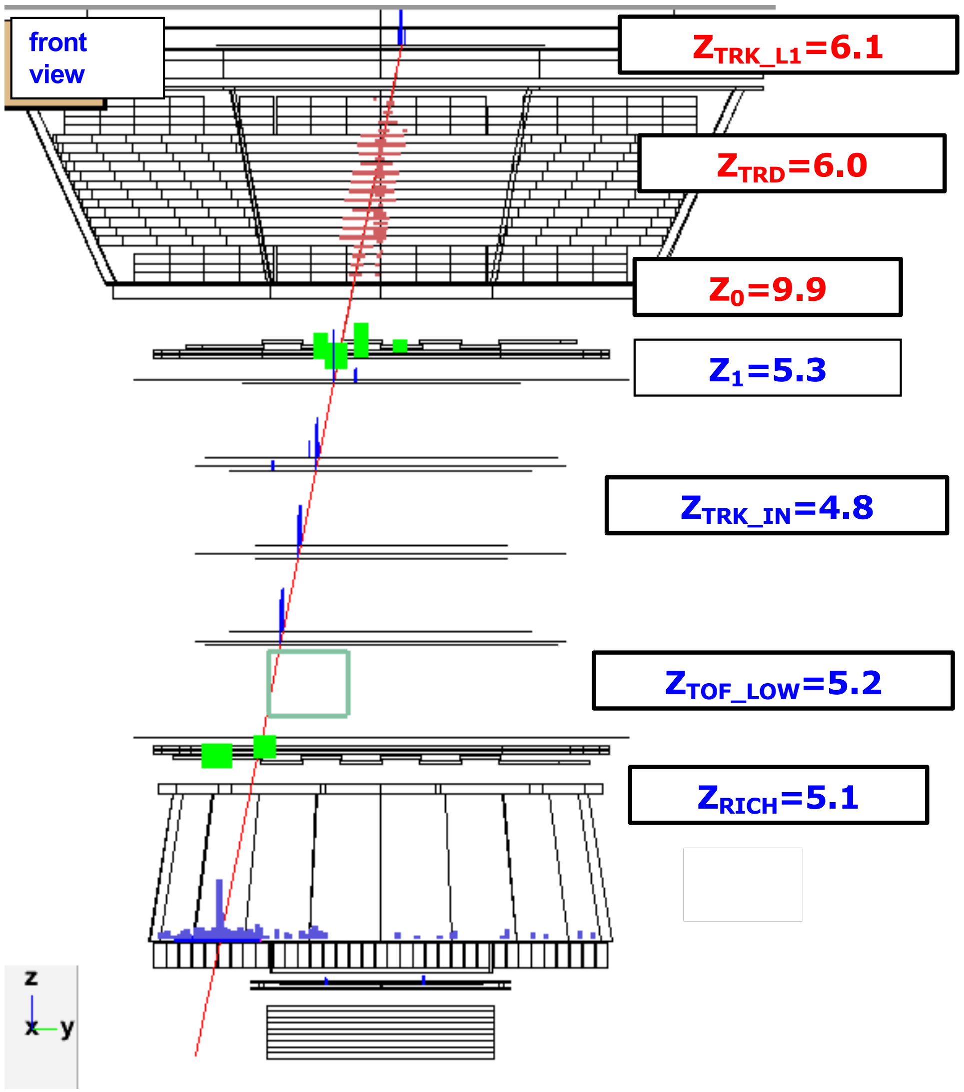
Charge Resolution (Z=6)

Tracker Plane 1	0.30
TRD	0.33
Upper TOF	0.16
Inner Tracker 2-8	0.12
Lower TOF	0.16
RICH	0.32
Tracker Plane 9	0.30

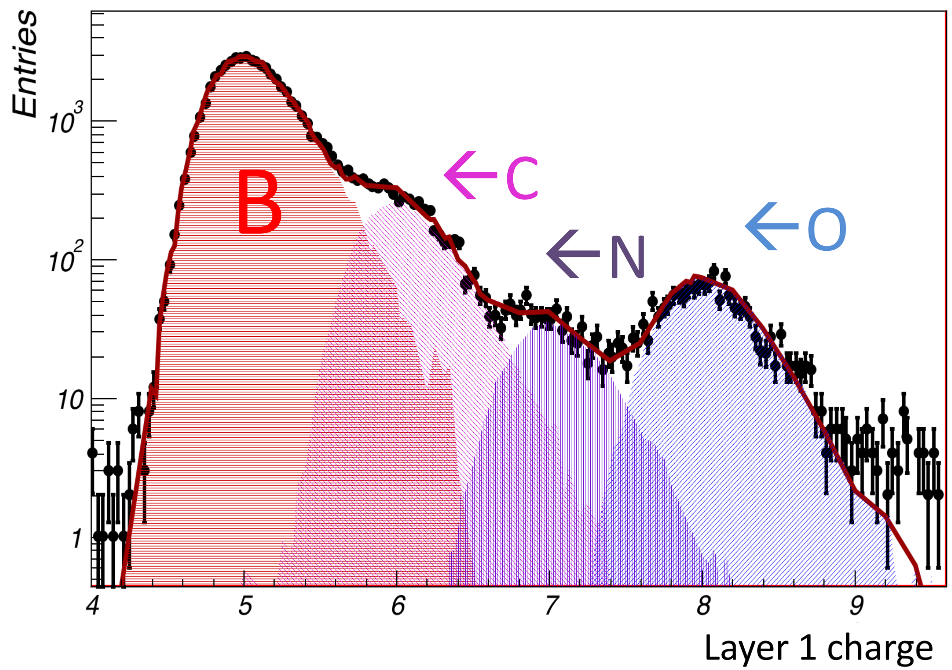




Control of fragmentation inside the detector



Selecting, for example, a Boron sample, with the full apparatus (i.e. the "inner tracker") is not enough to guarantee a genuine Boron sample...

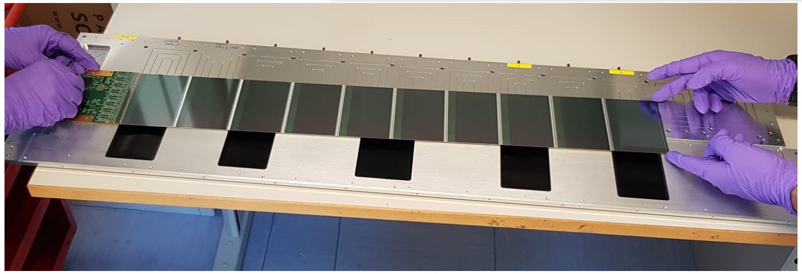


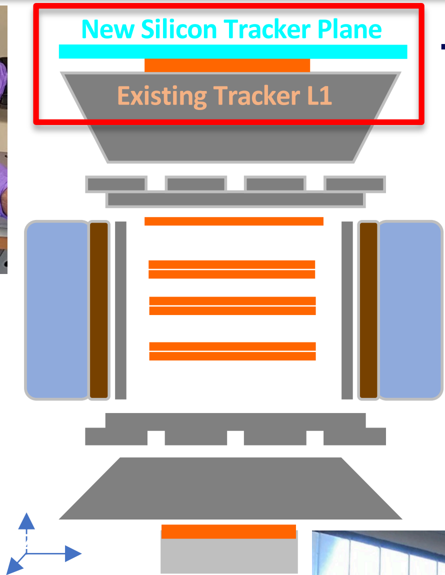
You keep systematics well under control if you:

→ control the fragmentation inside the detector

→ <u>measure the charge "as TOI as possible"</u>

AMS-02 Layer0 upgrade

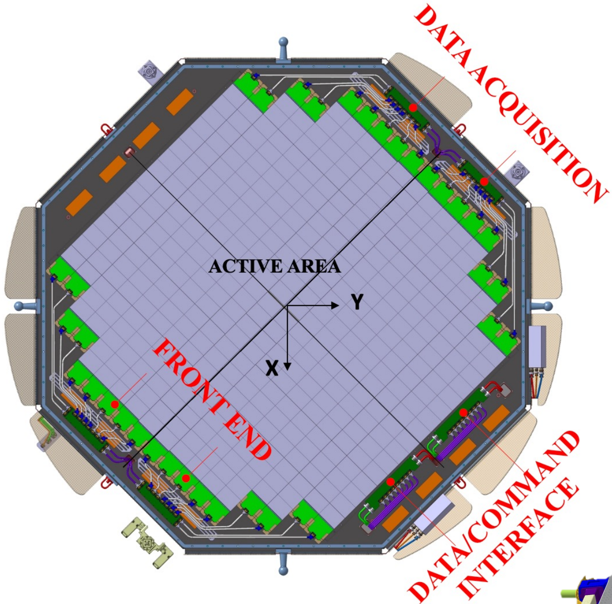


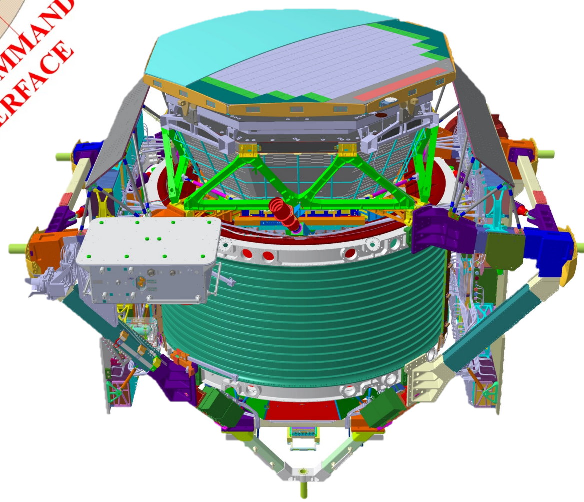


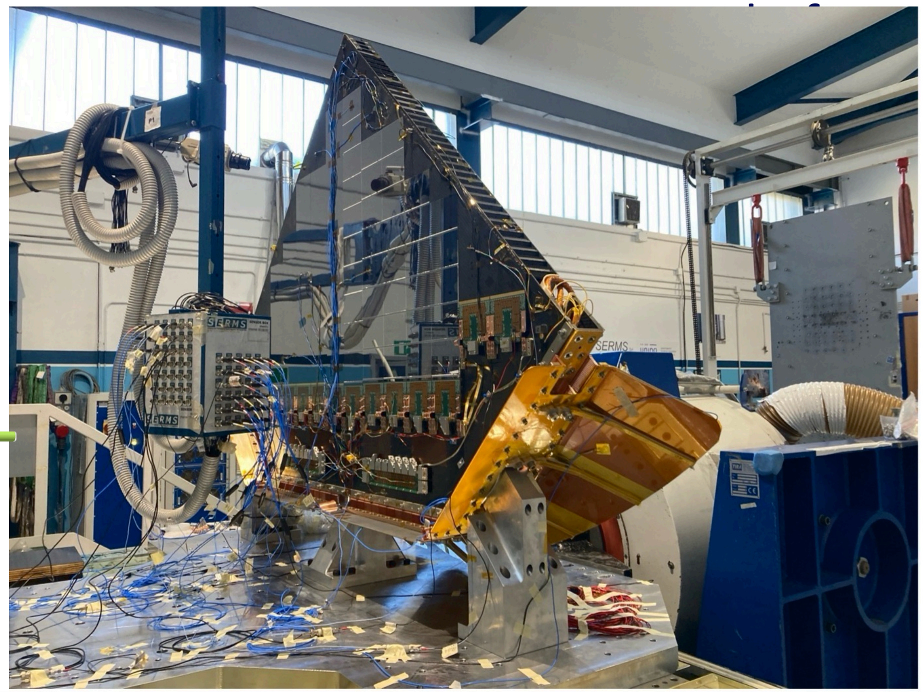
→ add (early 2026) an as large as possible outermost layer

to increase lever arm and measure charge before fragmentation

→ "lightest" possible cover, "cupola", to avoid fragmentation





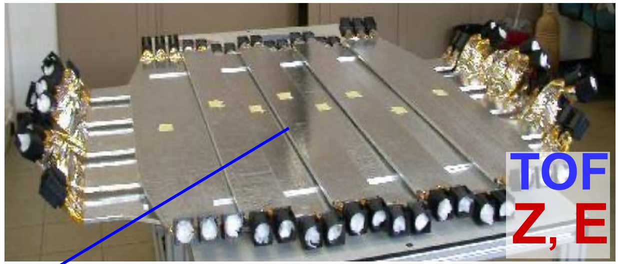


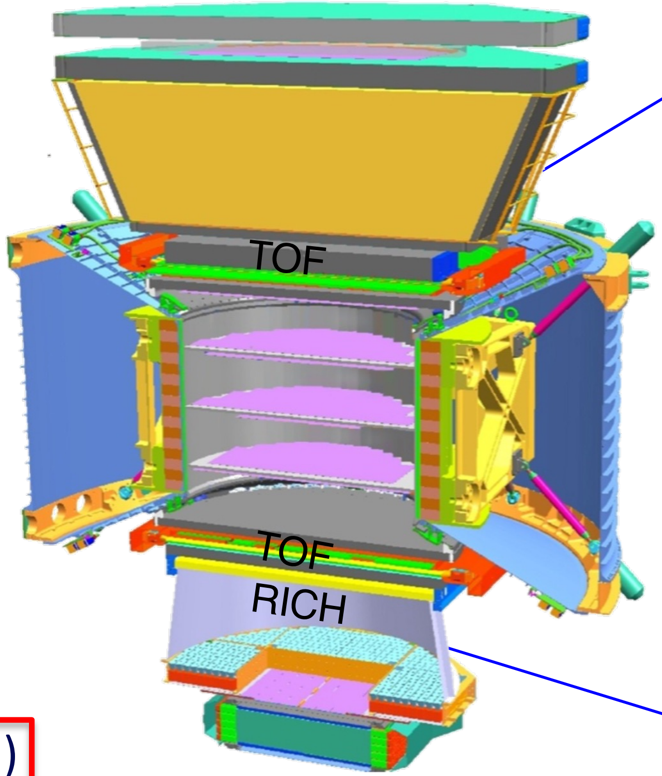
~ 8 m^2 surface
2 layers (45° stereo)
768 sensors
72 ladders
72k channels
~ 120 W

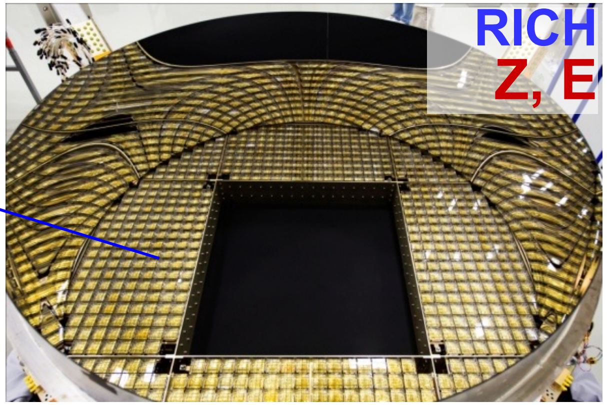
Key concepts/detectors

<u>β measurement:</u>

- identify the different isotopes (d/p, $^3He/^4He$, $^7Li/^6Li$, $^{10}Be/^9Be$, $^{27}Al/^{26}Al$, …)
- control the quality of the momemtum/energy measurement (e.g. check on the mass)



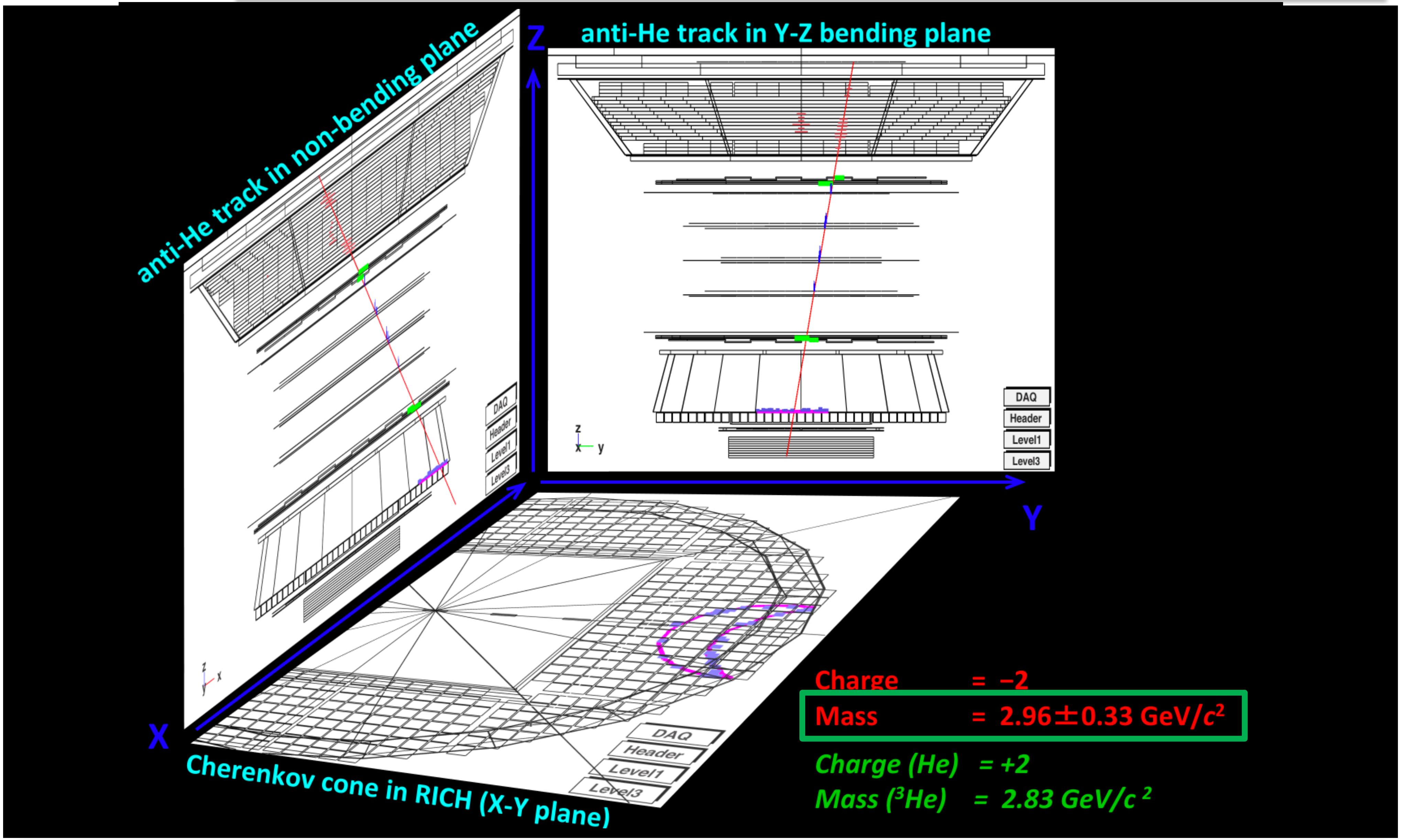




<u>Techniques:</u>

- Time of Flight (ToF)
- Cherenkov (ring or threshold)
- Transition Radiation (measuring γ)

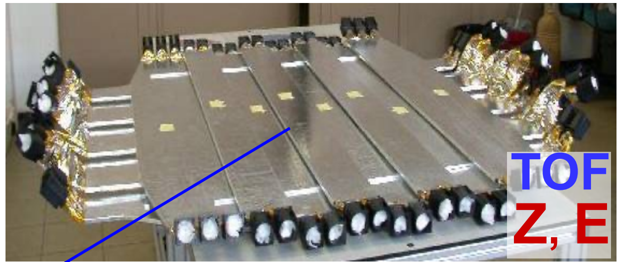
Key concepts/detectors

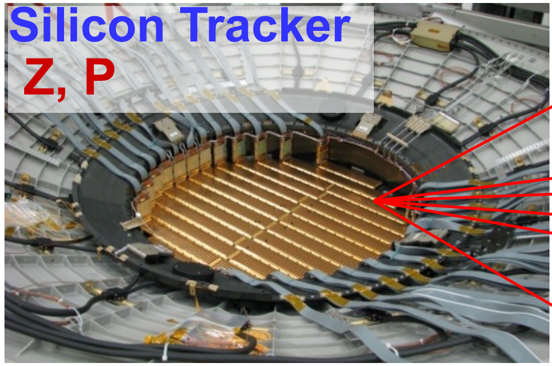


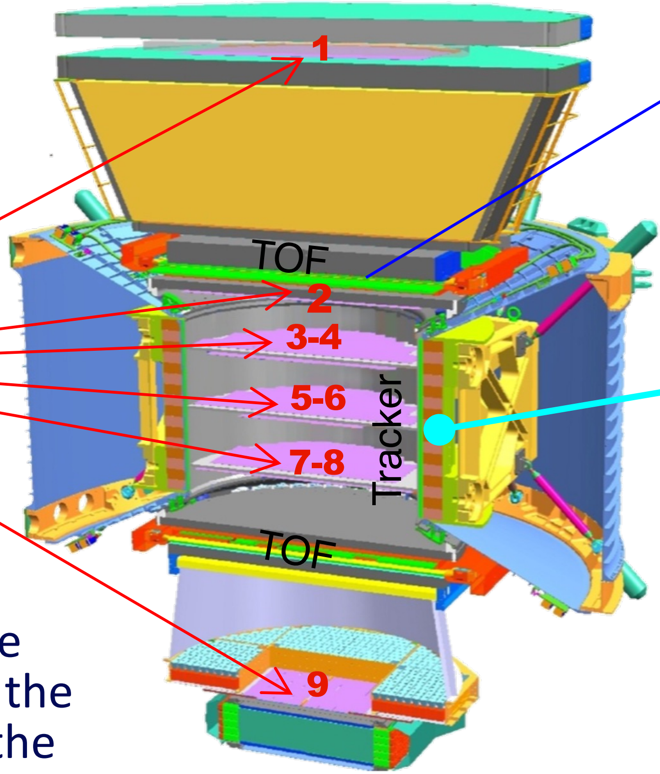
Key concepts/detectors

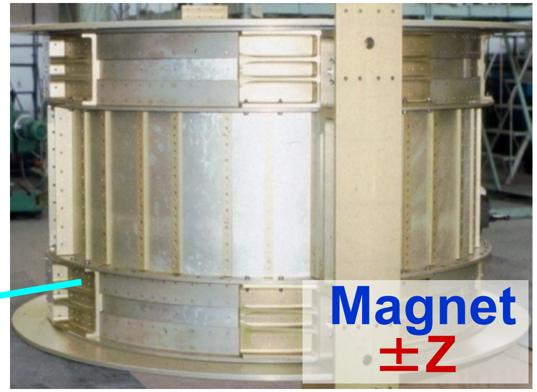
Charge sign measurement:

- matter/anti-matter









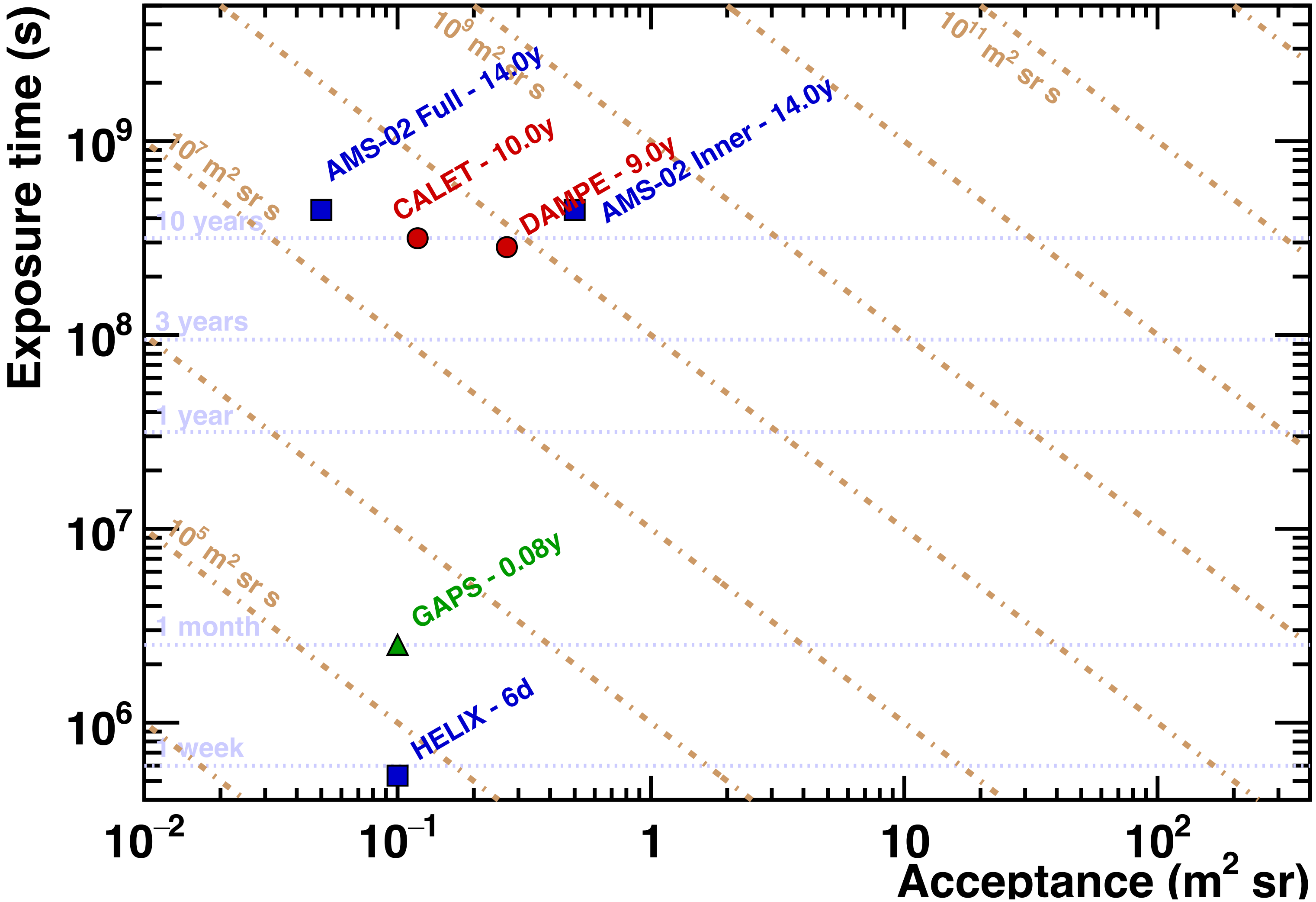
The intensity of the magnetic field (B), the lever arm (L) and the spatial resolution (σ_x) determine the momentum resolution (δp) and the detector Maximum Detectable Rigidity, MDR ($\delta p/p=1$):

$$MDR \propto B\,L^2 / \sigma_x$$

Techniques:

- Spectrometry + ToF

Current operating experiments (end 2024)

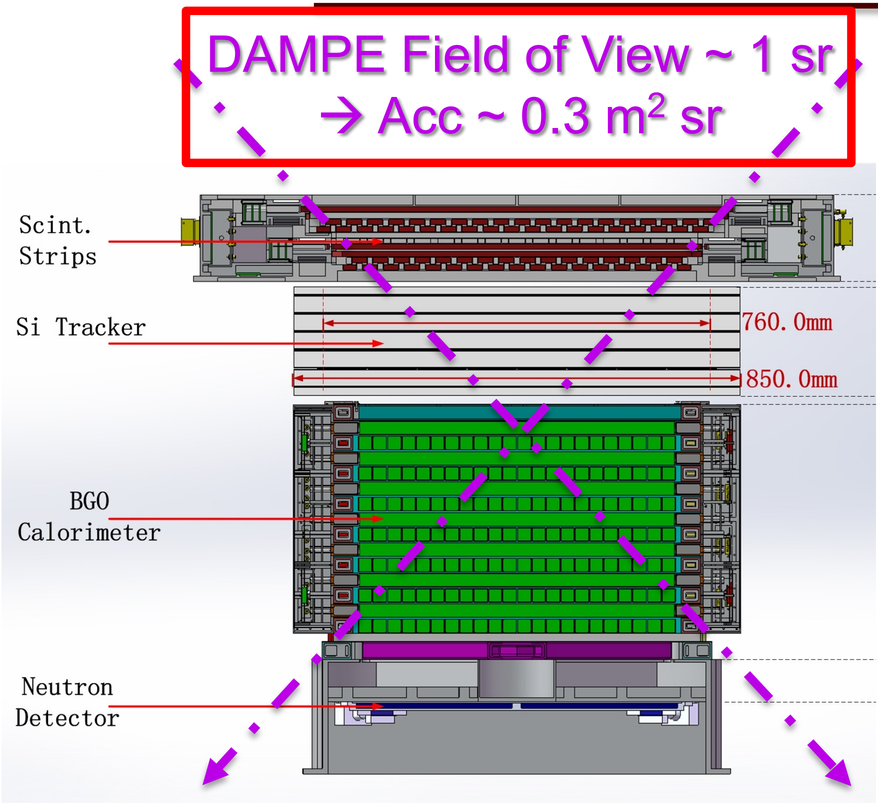


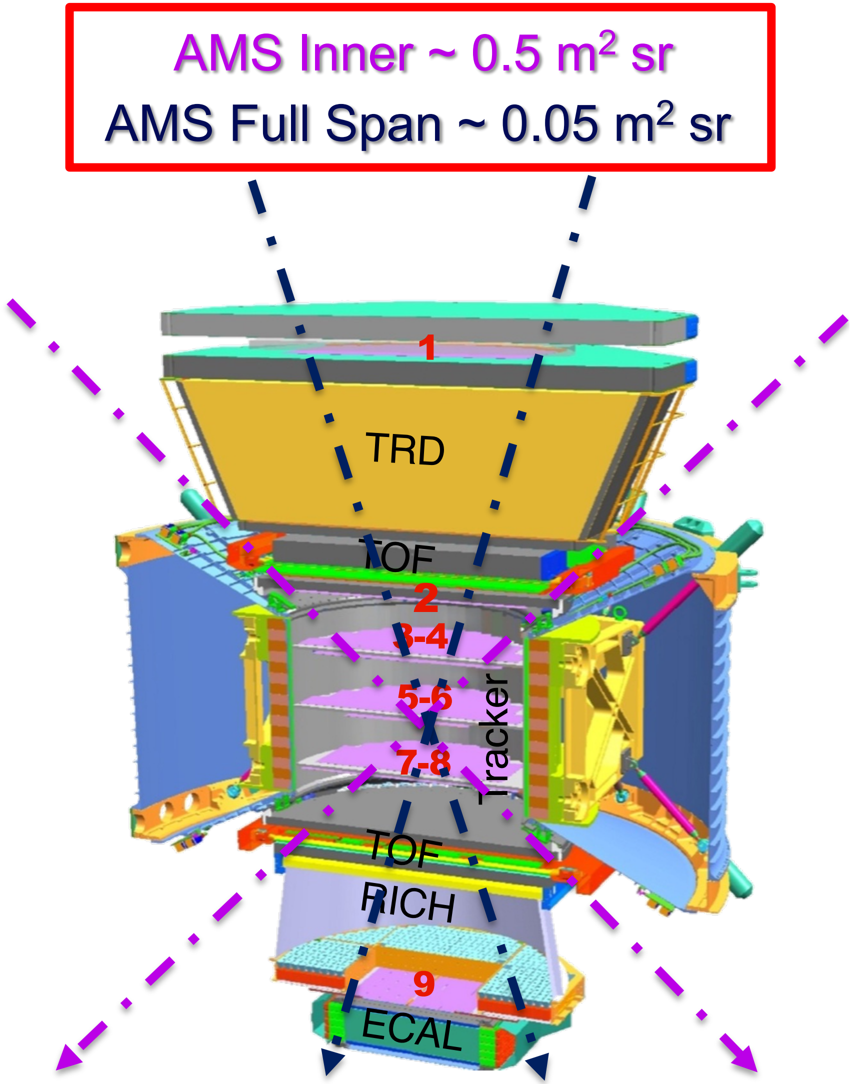
* focusing on direct "high energy", so not mentioning detectors like CSES-01 & CSES-02 or NUSES…

Future/proposed 4π experiments

– HERD
– ALADInO
– AMS-100
– balloon?

Current operating "telescopes"





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

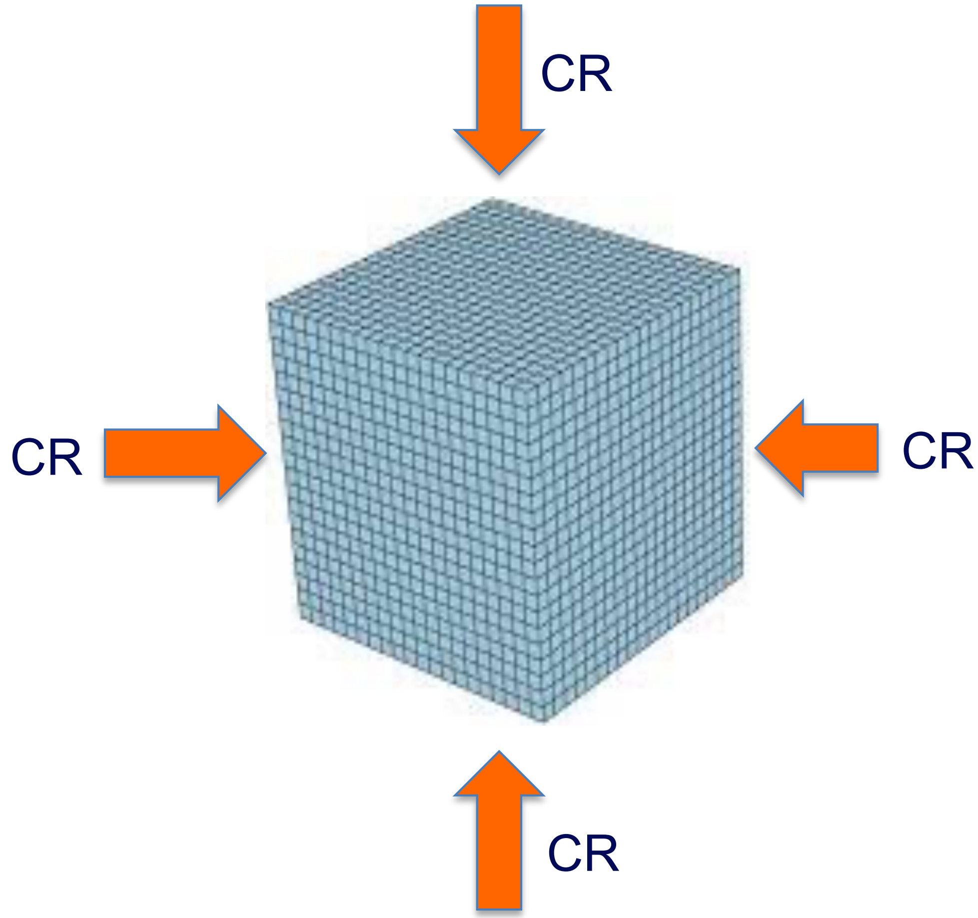
limited FoV → small acceptance

New paradigma - CaloCube

- Exploit the CR "isotropy" to maximize the effective geometrical factor, by using all the surface of the detector (aiming to reach $\Omega = 4\pi$)

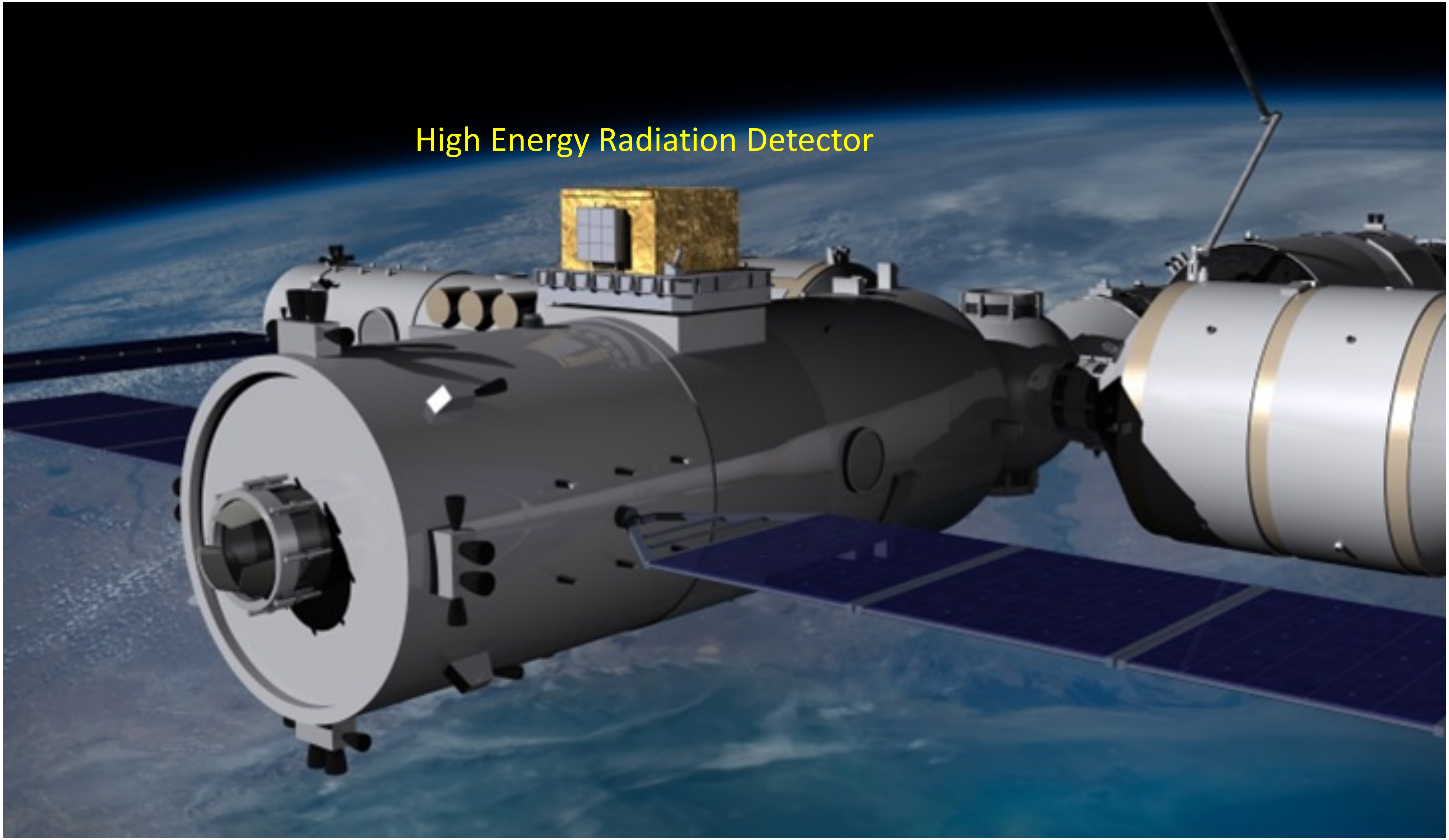
- The calorimeter should be highly isotropic and homogeneous:
  - the needed depth of the calorimeter must be guaranteed for all the sides (i.e. cube, sphere, …)
  - the segmentation of the calorimeter should be isotropic

→ this is in general doable just with an homogeneous calorimeter



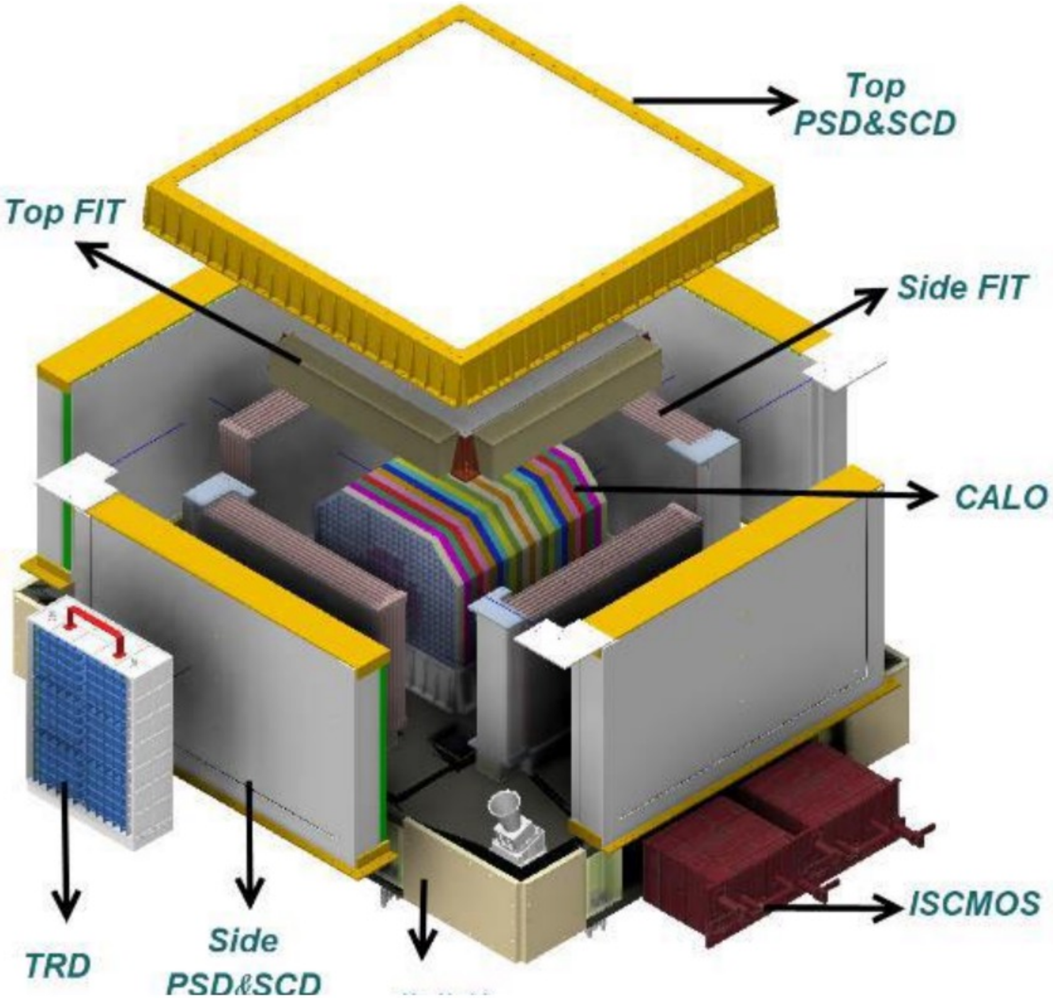
CaloCube is an INFN R&D initiated in Florence (Adriani et al.), almost always inspiring the next generation of large space cosmic rays detectors

HERD on the CSS



HERD detector

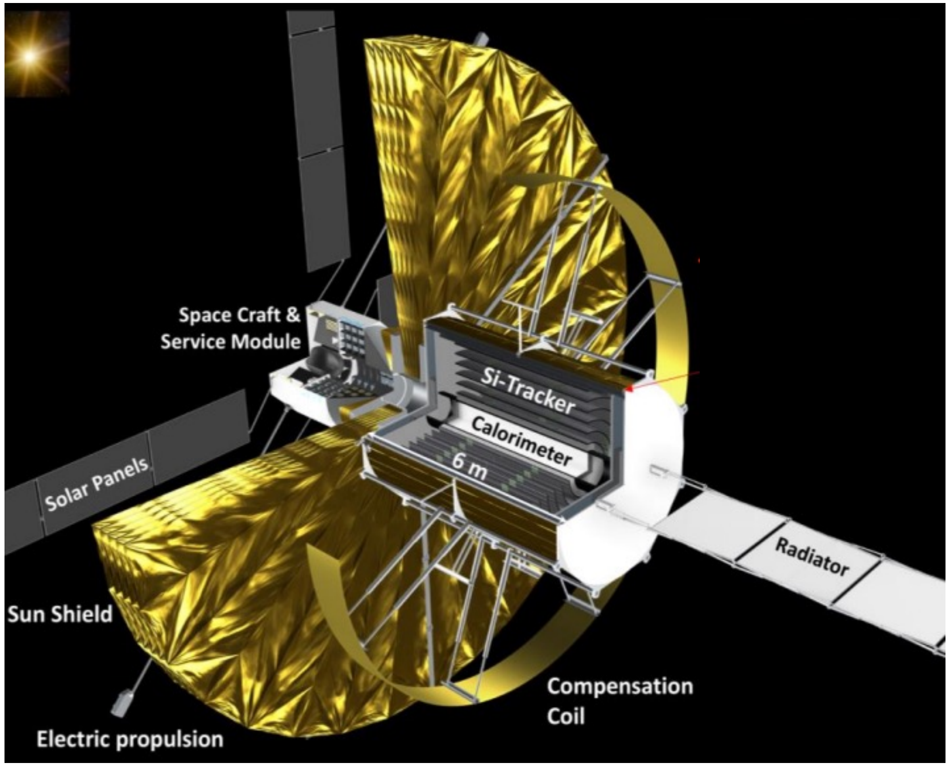
~ 300k readout channels



operative from 2027 on the CSS

Item	Value
Energy range (e/γ)	10 GeV - 100 TeV (e); 0.5 GeV-100 TeV (γ)
Energy range (nuclei)	30 GeV - 3 PeV
Angle resolution	0.1 deg.@10 GeV
Charge resolution	0.1-0.15 c.u
Energy resolution (e)	1-1.5%@200 GeV
Energy resolution (p)	20-30%@100 GeV - PeV
e/p separation	~10^{-6}
G.F. (e)	>3 m^2sr@200 GeV
G.F. (p)	>2 m^2sr@100 TeV
Field of View	~ 6 sr
Envelope (L*W*H)	~ 2300*2300*2000 mm^3
Weight	~ 4000 kg
Power Consumption	~ 1400 W

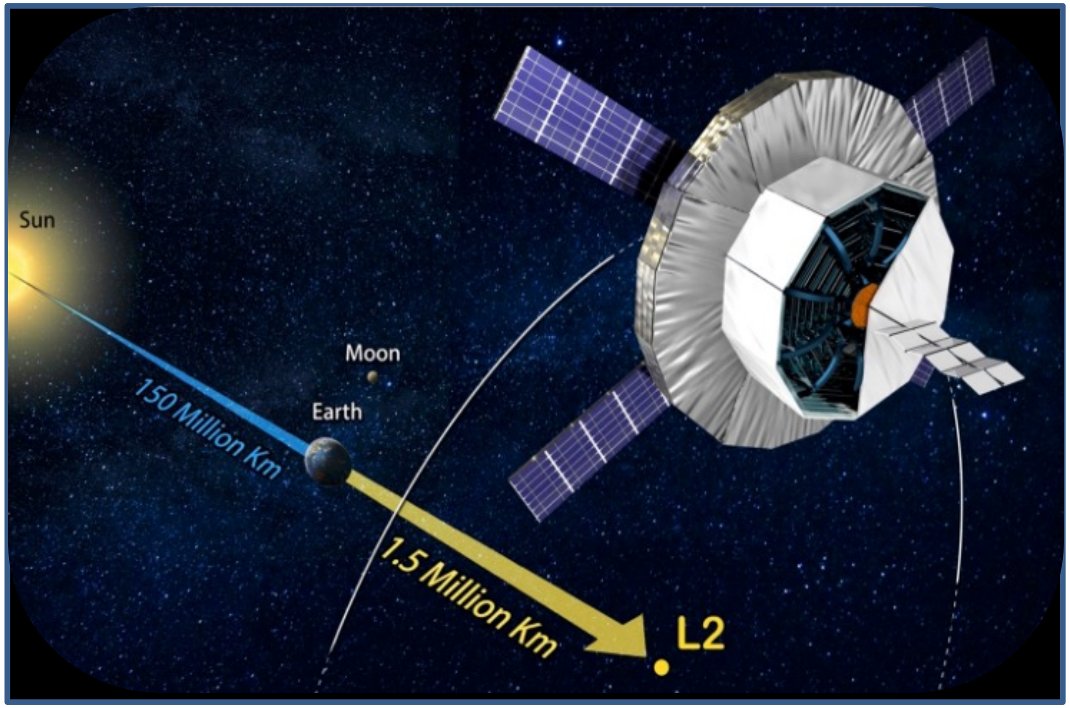
“ future CR detection in space “



AMS-100: The next generation magnetic spectrometer in space – An international science platform for physics and astrophysics at Lagrange point 2

S. Schael [a], A. Atanasyan [b], J. Berdugo [c], T. Bretz [d], M. Czupalla [e], B. Dachwald [e], P. von Doetinchem [f], M. Duranti [g], H. Gast [a], W. Karpinski [a], T. Kirn [a], K. Lübelsmeyer [a], C. Maña [c], P.S. Marrocchesi [h], P. Mertsch [i], I.V. Moskalenko [j], T. Schervan [k], M. Schluse [b] ... J. Zimmermann [k]

https://doi.org/10.1016/j.nima.2019.162561



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Design of an Antimatter Large Acceptance Detector In Orbit (ALADInO)

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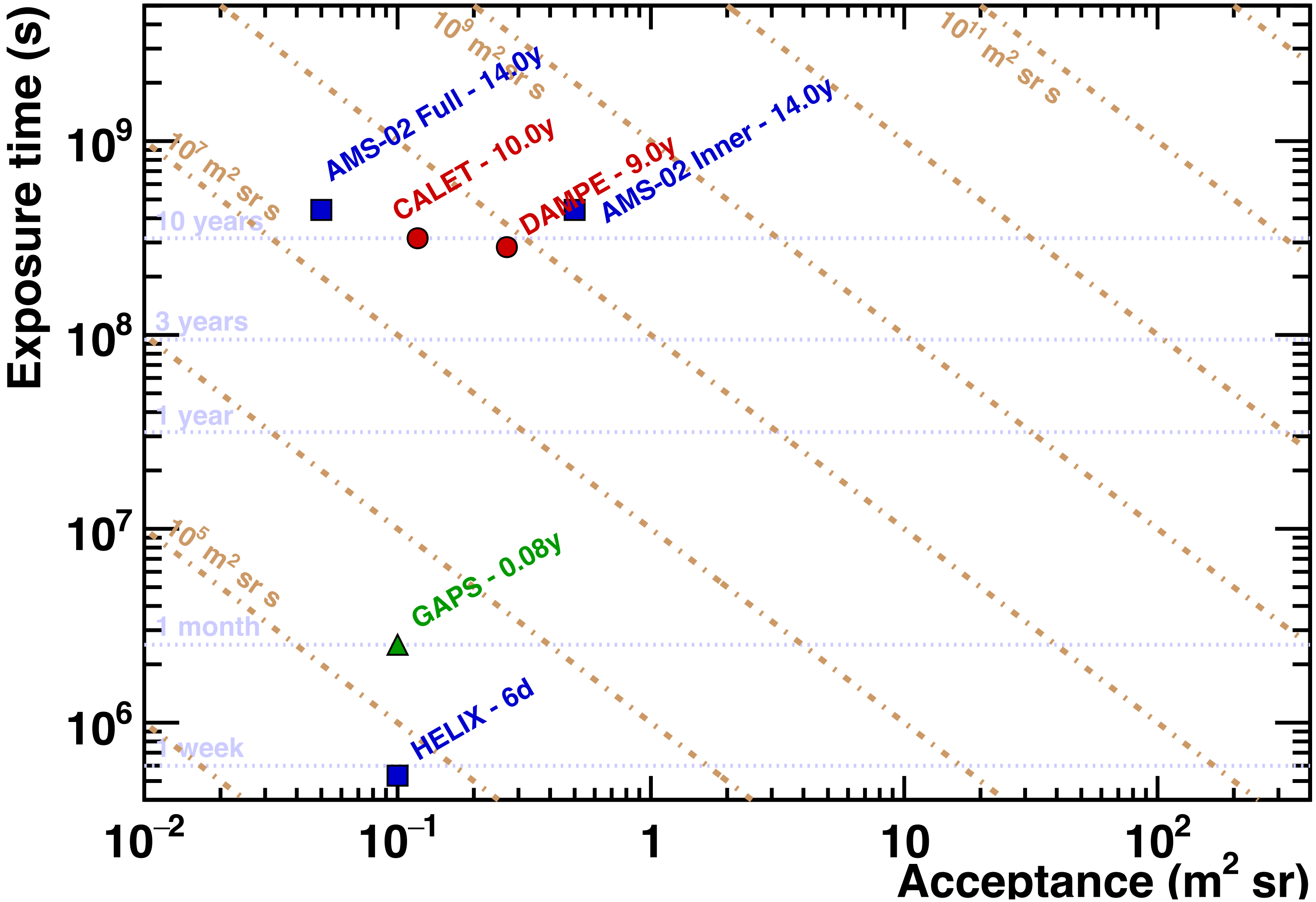
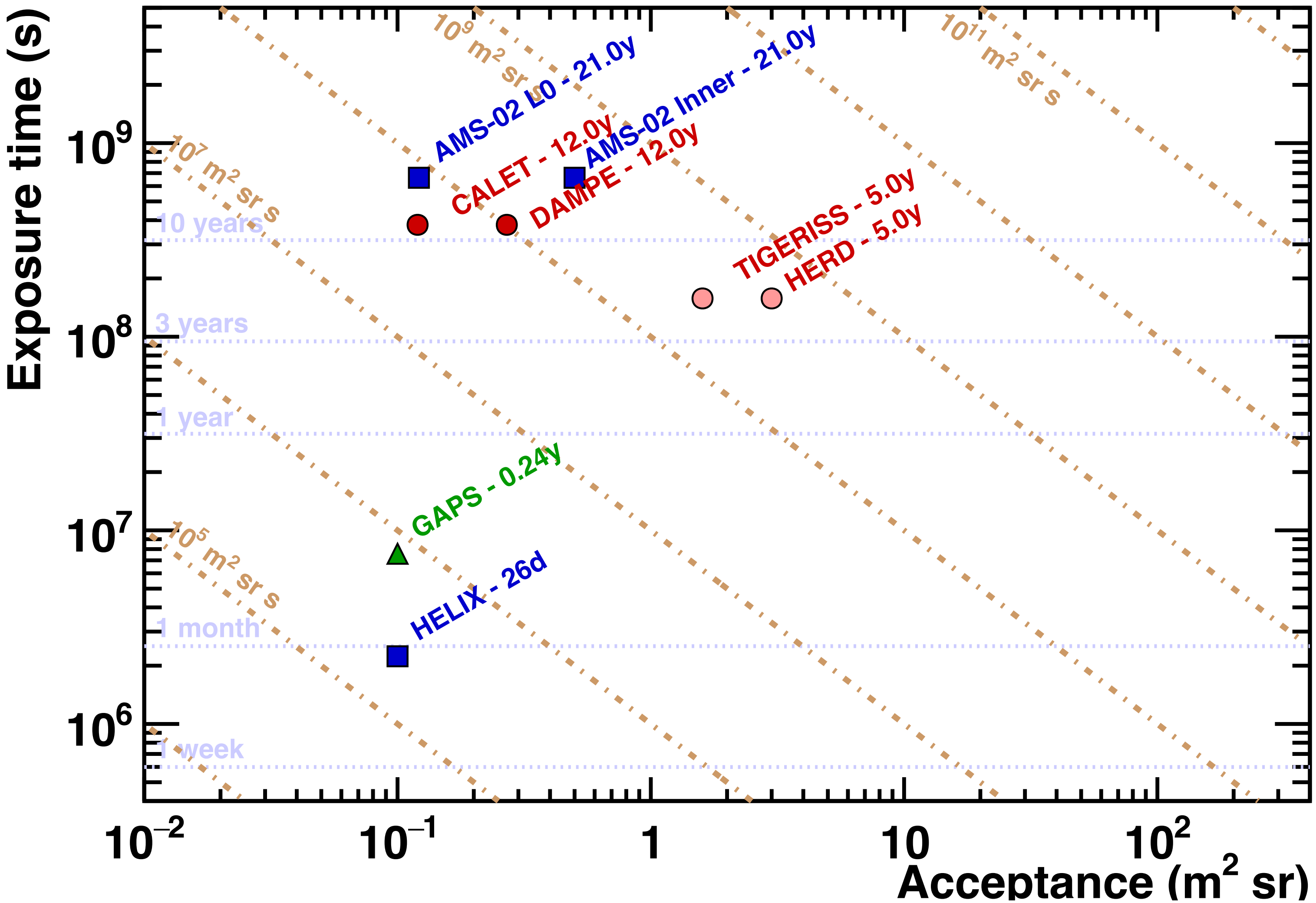
https://doi.org/10.3390/instruments6020019

Current operating experiments (end 2024)



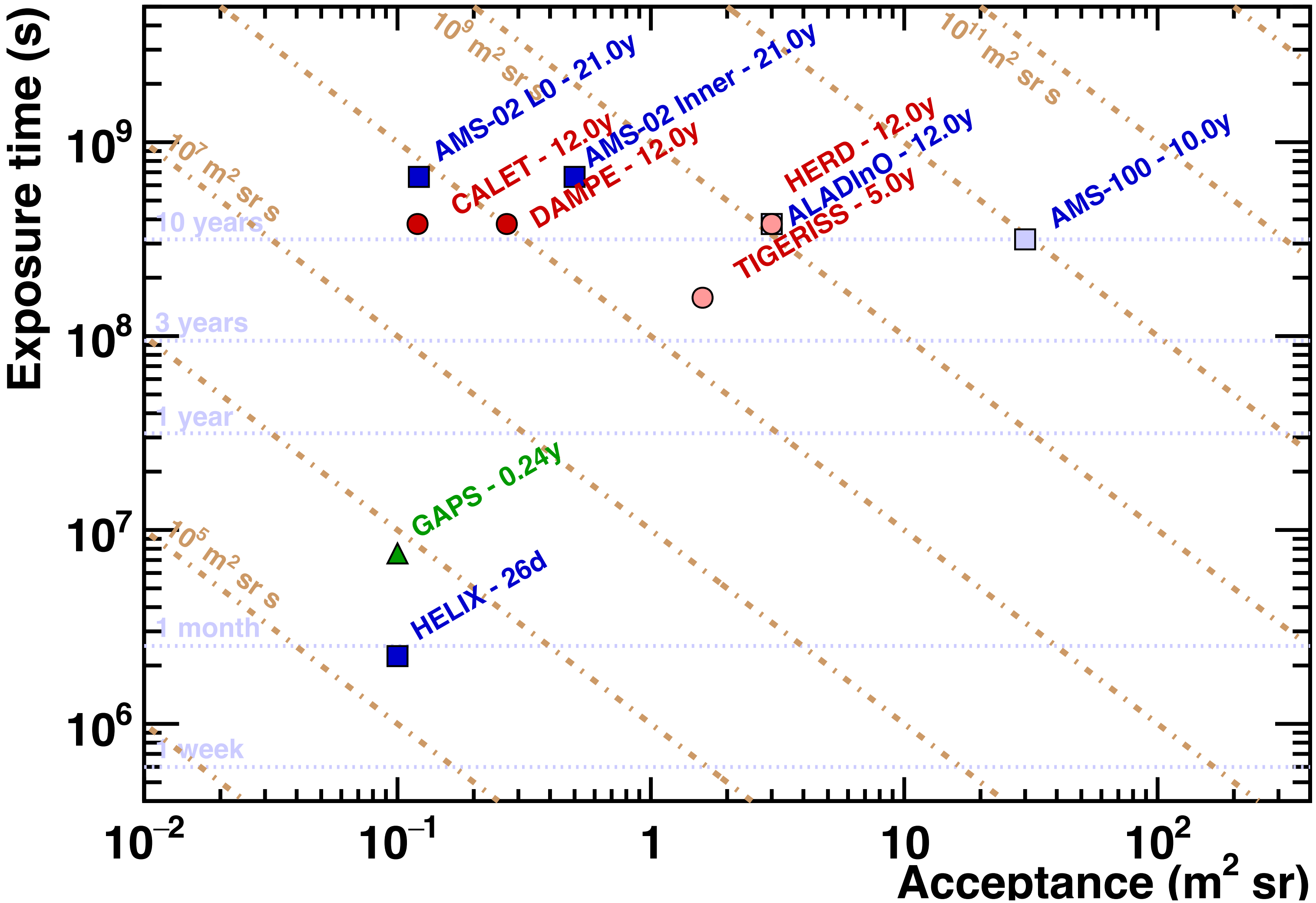
* focusing on direct "high energy", so not mentioning detectors like CSES-01 & CSES-02 or NUSES...

Current operating experiments (2032)



* focusing on direct "high energy", so not mentioning detectors like CSES-01 & CSES-02 or NUSES…

Current operating experiments (2060)



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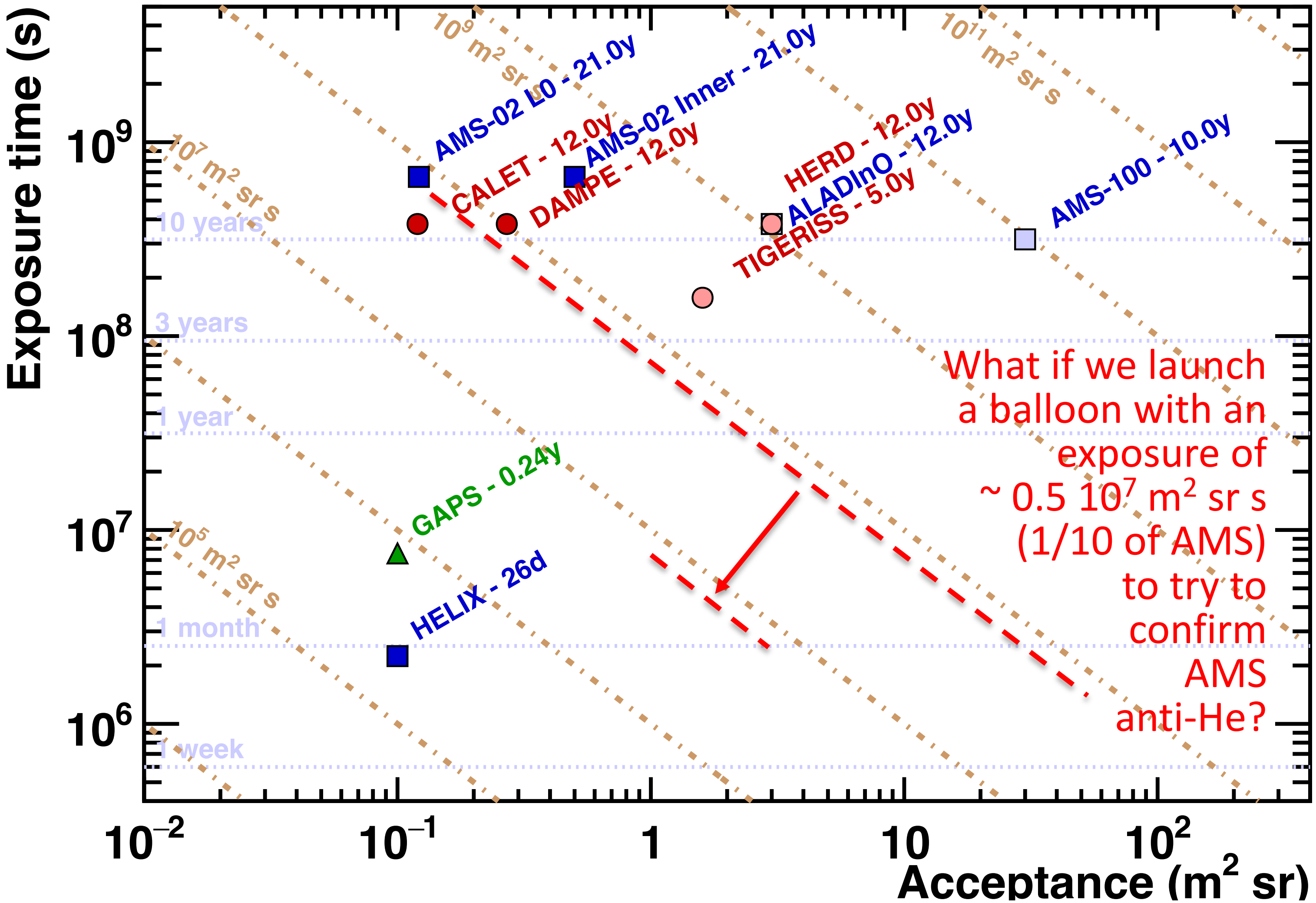
Current operating experiments (2060)



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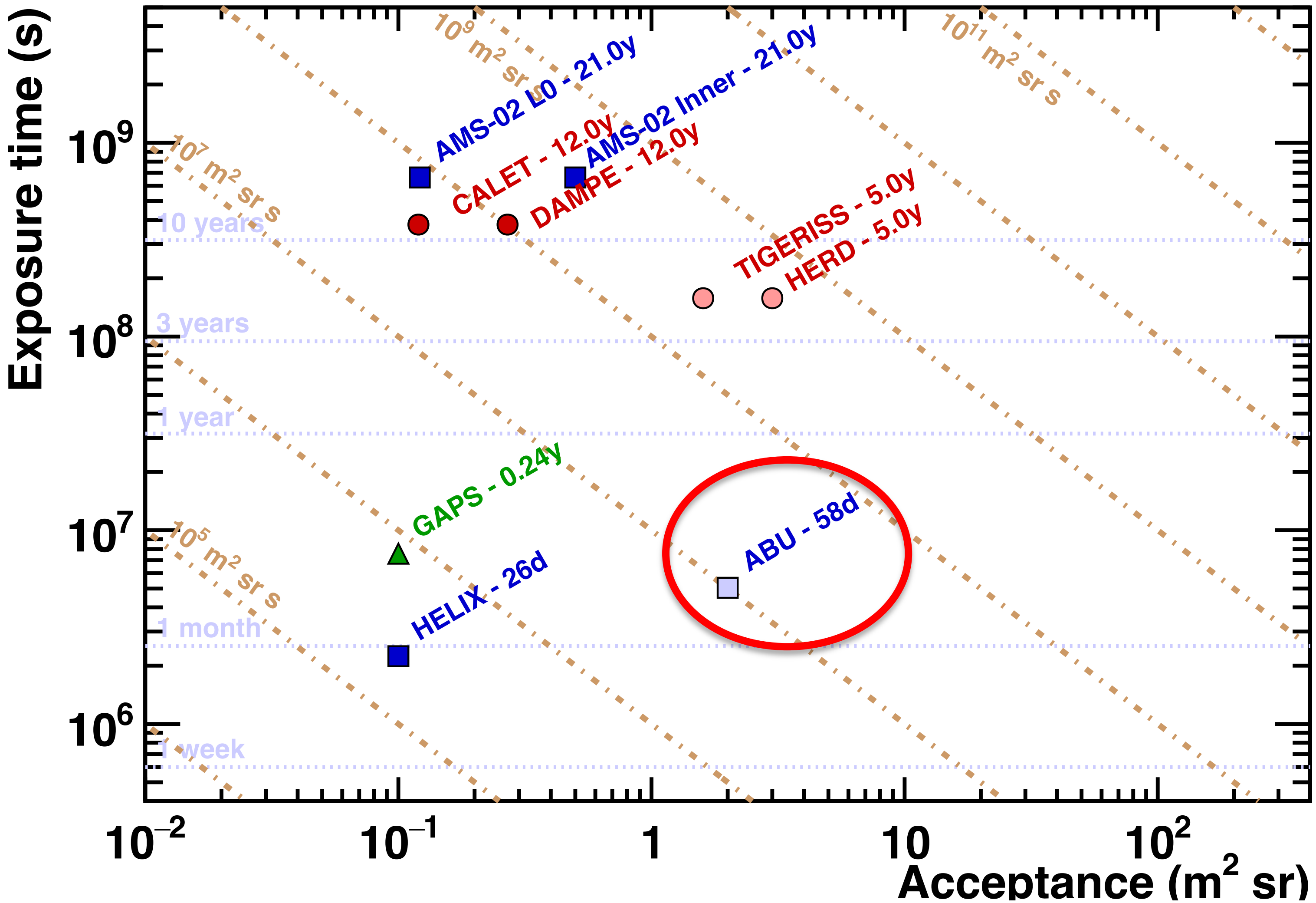
Current operating experiments (2032)



* focusing on direct "high energy", so not mentioning detectors like CSES-01 & CSES-02 or NUSES…

What we need?

- measure energy/momentum:
  - calorimetry
  - HTS magnetic spectrometry + high resolution tracking system (MAPS?)
  - time of flight
  - ...ation
- measure sign of charge:
  - magnetic spectrometry + time of flight
  - topology of annihilation (tracking/calorimetry)
- measure charge:
  - dE/dx (tracking/scintillation)
  - number of photons in Cherenkov radiation

- measure mass (β/γ + E/p):
  - time of flight (20 ps: plastic scintillator + SiPMs? LGAD tracker?)
  - Cherenkov (DIRC?)
  - transition radiation
- ...ration:
  - transition radiation
  - shower development (calorimetry)
  - energy/momentum match
  - neutron produced in hadronic shower (neutron detector)
  - calorimeter back-scattering timing measurement ?

Trento/Milano groups:
Supercond. Sci. Technol. 36 (2023) 014007
Aachen/Geneva groups:
Volume 1040, 1 October 2022, 167215

Trento/Torino groups:
Volume 1063, June 2024, 169281

Perugia/Roma/Bologna groups:
Instruments 2021, 5(2), 20

Aachen/PSI groups:
Instruments 2022, 6(1), 14

Darmstadt/Frankfurt/Mainz groups:
NIMA, Volume 952, 1 February 2020, 161790

Stay tuned...