# Perspectives in Direct Measurements of GCRs

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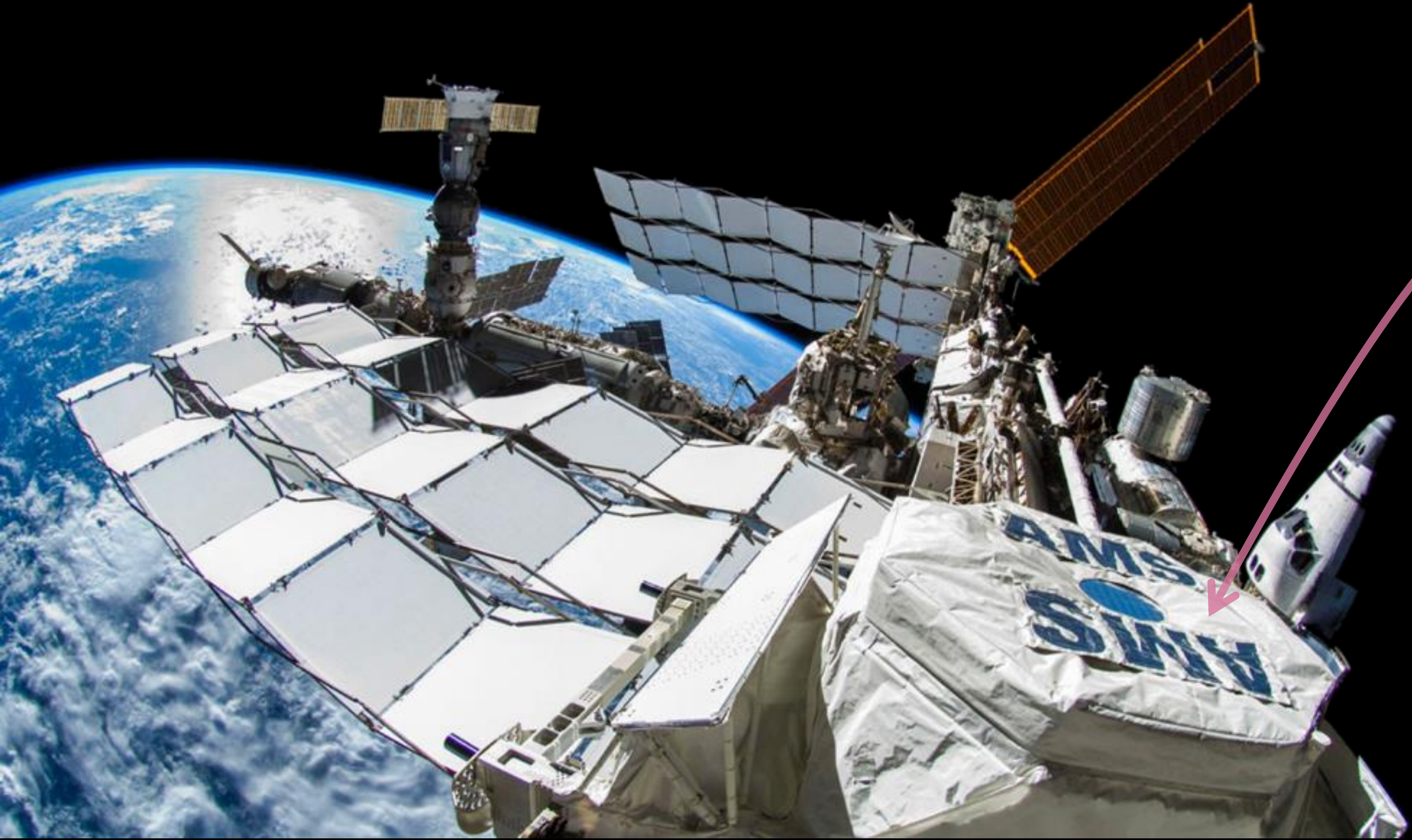
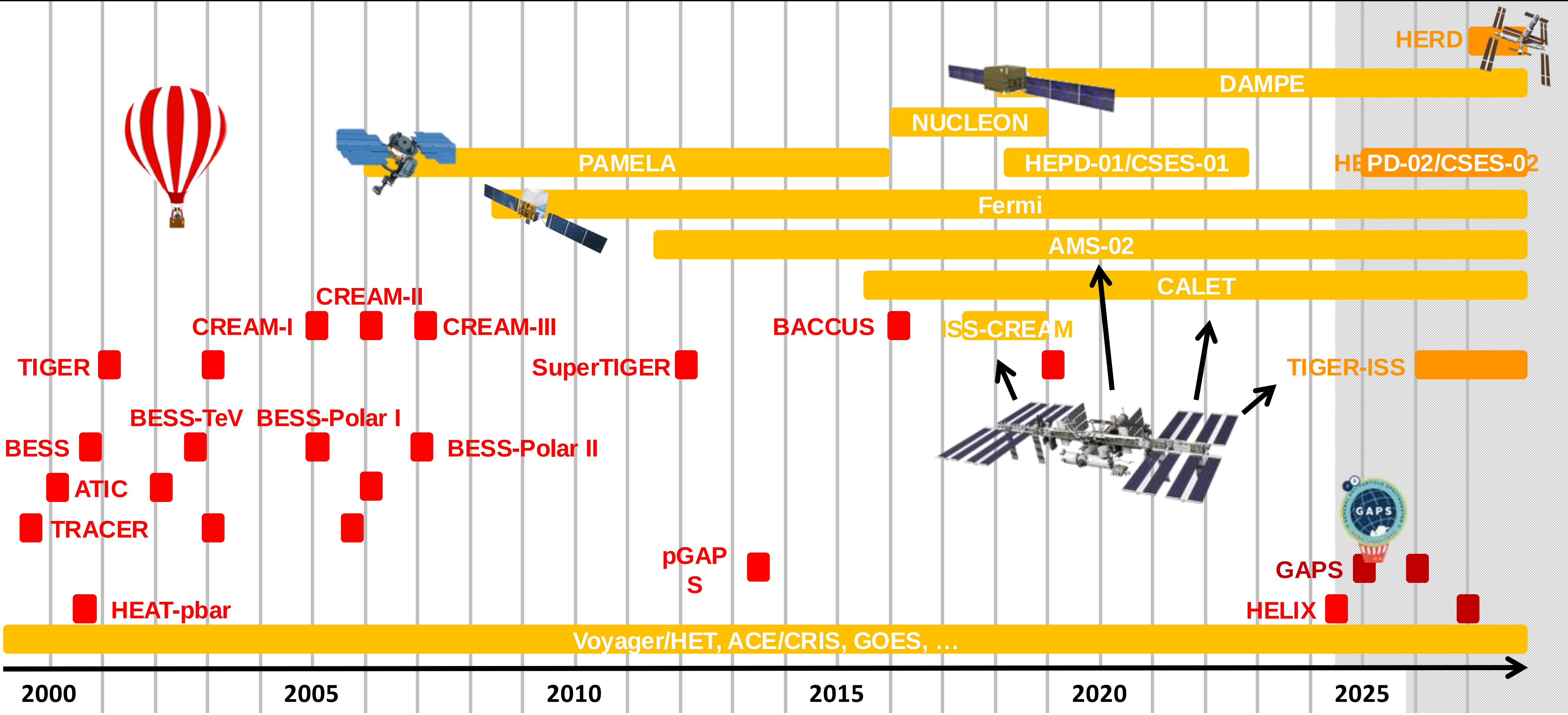



Cross Sections for Cosmic Rays,
XSCRC2024,
CERN, 18/10/2024

# Timeline of Direct Measurement of CRs from 2000






**Great legacy from the past (<2000)**, here we focus on the latest ones. Not all experiments displayed (sorry).
Many different experimental techniques employed, frequently focusing on some specific CR species or energy range.

# CRs Directly from the International Space Station

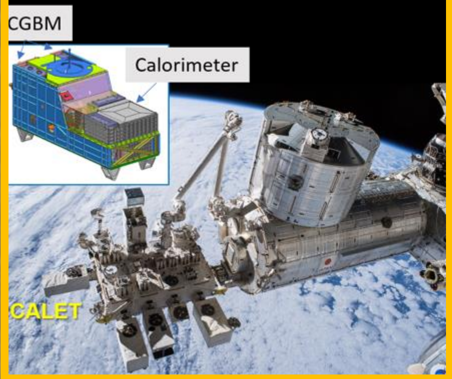


**International Space Station**

| | |
|---|---|
| Altitude | ~ 400 km |
| Inclination | 51° |
| Period | 93 min |
| Construction | 1998 - … |
| Dimensions | 73 × 109 $m^2$ |
| Weight | 420 t |

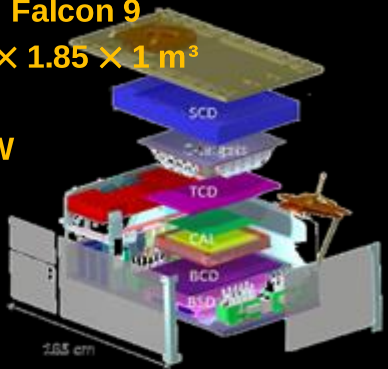
**CALET**

| | |
|---|---|
| Launch | 19/08/2015, H2-B |
| Dim. | 1.9 × 0.8 × 1.0 $m^3$ |
| Weight | 650 kg |
| Power | 650 W |



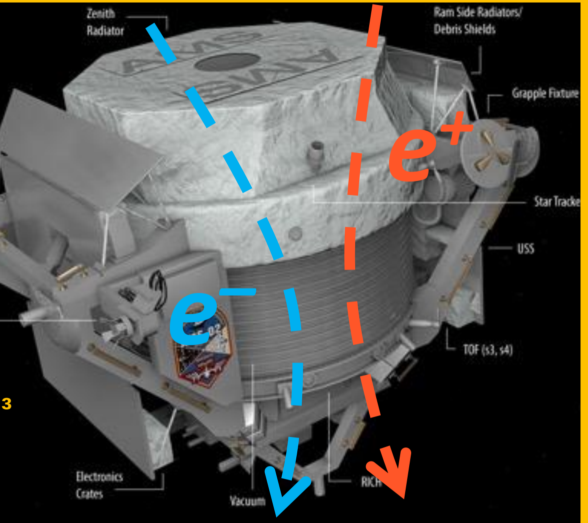

**ISS-CREAM**

| | |
|---|---|
| Launch | 14/8/2017 SpX, Falcon 9 |
| Dim. | 0.95 × 1.85 × 1 $m^3$ |
| Weight | 1.3 t |
| Power | 600 W |




**AMS-02**

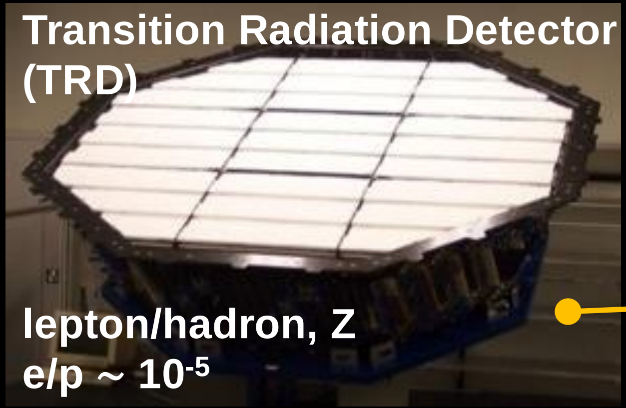
| | |
|---|---|
| Launch | 16/5/2011 STS-134 Endeavour |
| Dimensions | 3 × 4 × 5 $m^3$ |
| Weight | 7.5 t |
| Power | 2500 W |

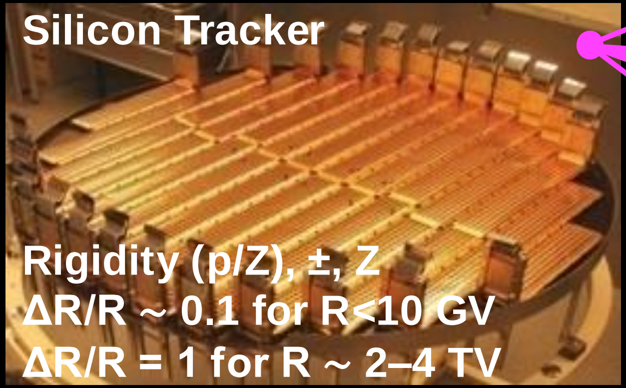


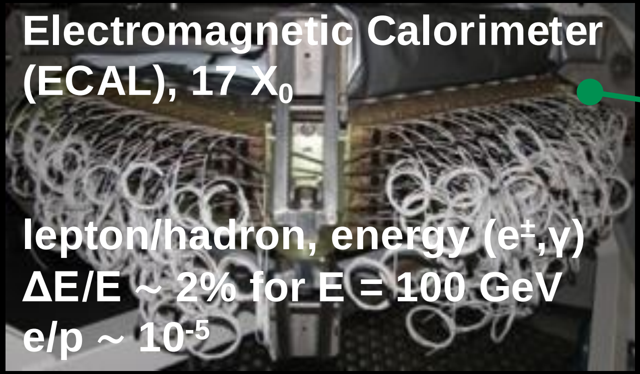
# AMS-02: Alpha Magnetic Spectrometer

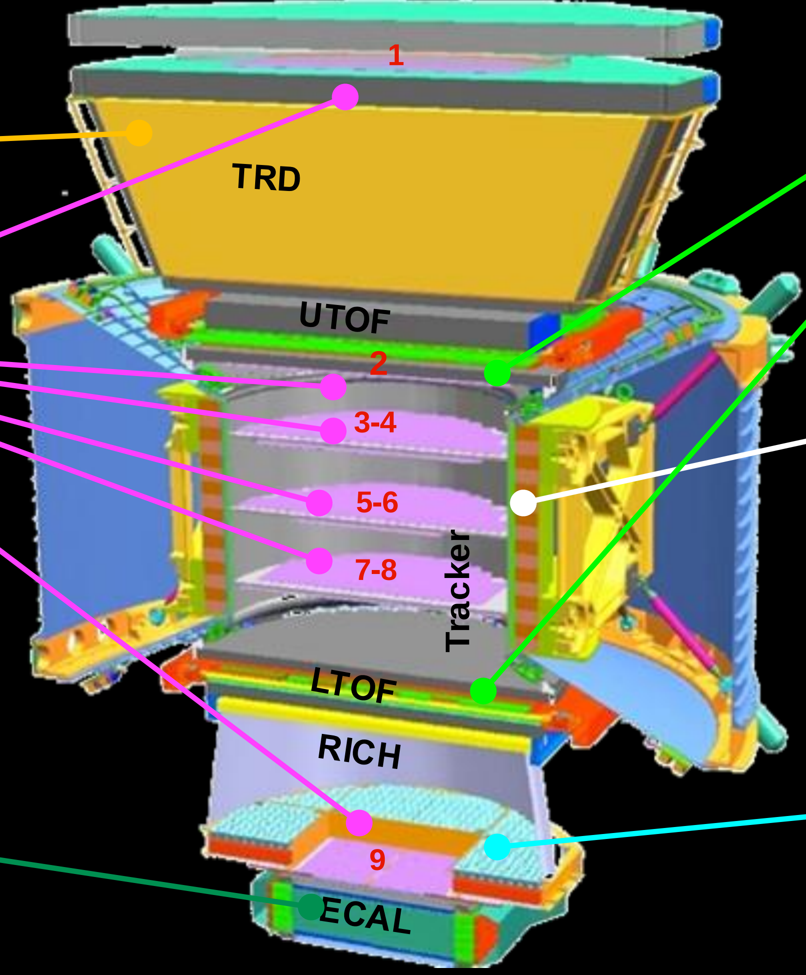


AMS-02 multi-purpose **magnetic spectrometer**. It separates hadrons from leptons, matter from anti-matter, chemical and isotopic composition from fraction of GeV to multi-TeV.

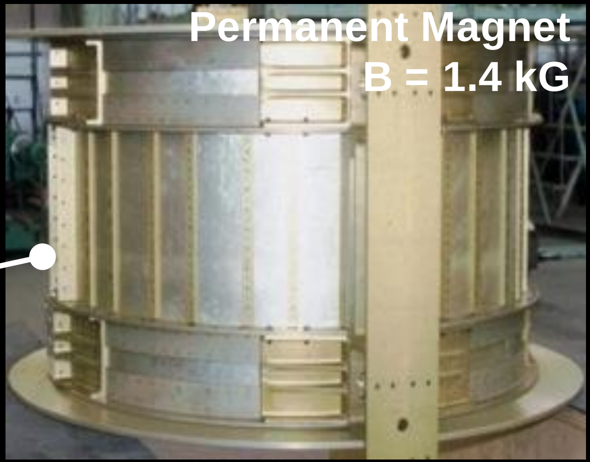


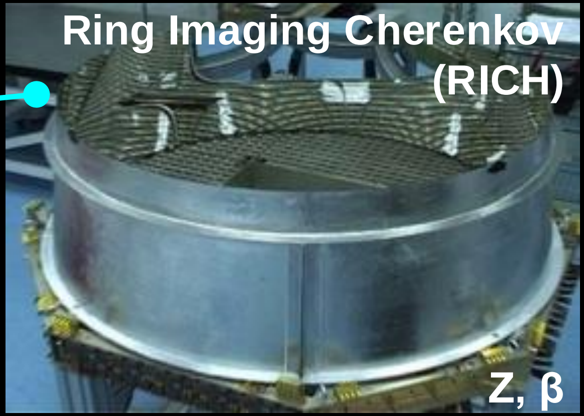







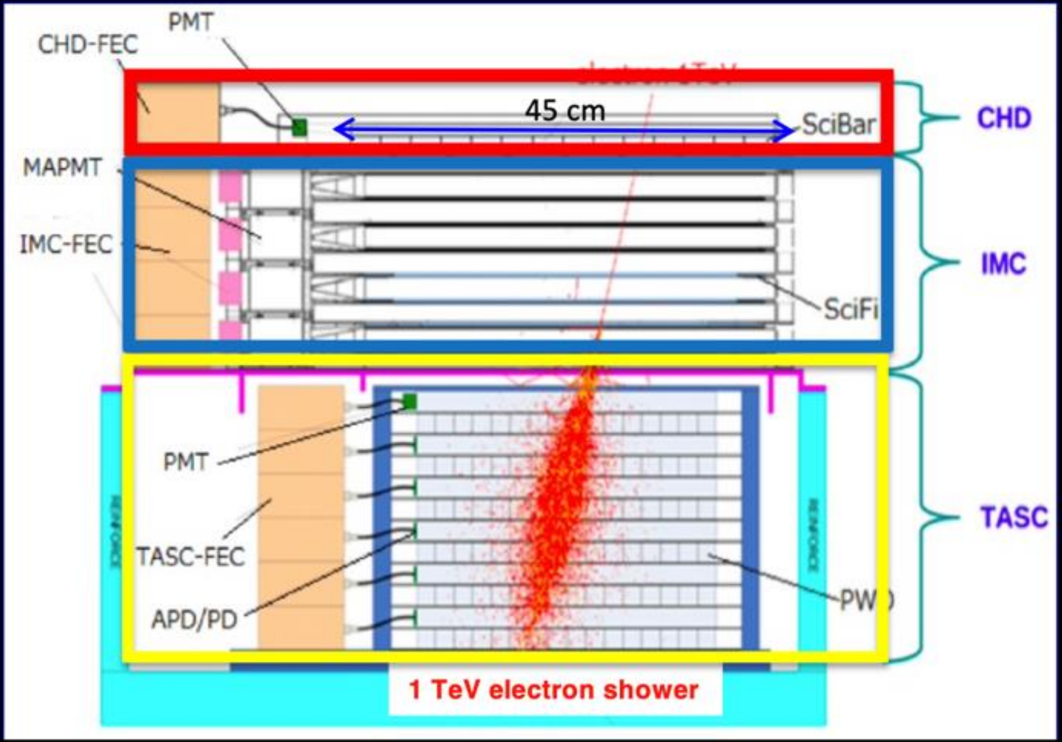




Multiple and/or Independent Measurement of Charge (Z), Energy (β, p, E) and Charge Sign (±).

# CALET: Calorimetric Electron Telescope



Field of view: ~ 45 degrees (from the zenith) Geometrical Factor: ~ 1,040 $cm^2 sr$ (for electrons) Thickness: 30 $X_0$, **1.3** $\lambda_I$




## CHD – Charge Detector

- 2 layers x 14 plastic scintillating paddles
- single element charge ID from p to Fe and above (Z = 40)
- charge resolution ~0.1-0.3 e

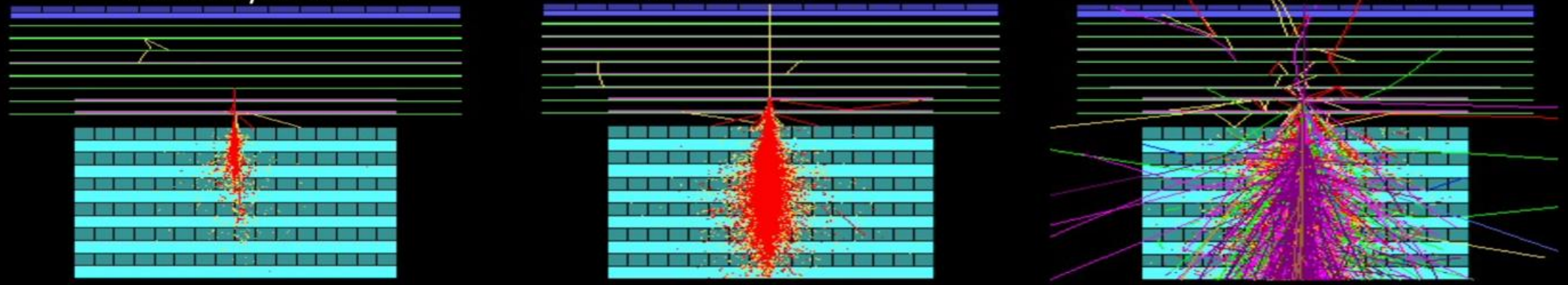
## IMC – Imaging Calorimeter

- Scifi + Tungsten absorbers: 3 $X_0$ at normal incidence
- 8 x 2 x 448 plastic scintillating fibers (1mm) **readout individually**
- **Tracking** ( ~0.1° angular resolution) + **Shower imaging**

## TASC – Total Absorption Calorimeter 27 $X_0$, 1.2 $\lambda_I$

- 6 x 2 x 16 lead tungstate ($PbWO_4$) logs
- **Energy resolution:** ~2 % (>10GeV) for e , γ ~30-35% for p, nuclei
- **e/p separation:** ~$10^{-5}$

Gamma-ray 10 GeV Electron 1 TeV Proton 10 TeV

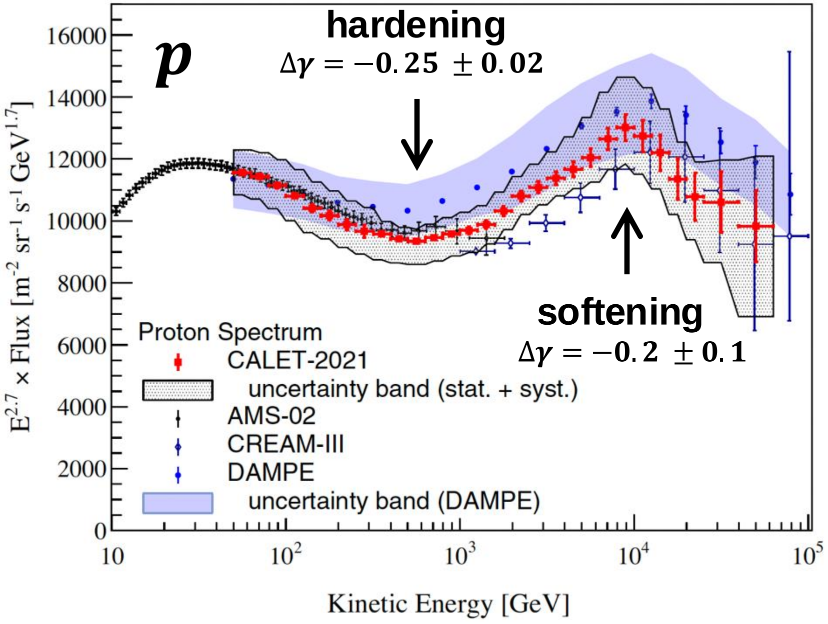


# What's Next: the Energy Frontier

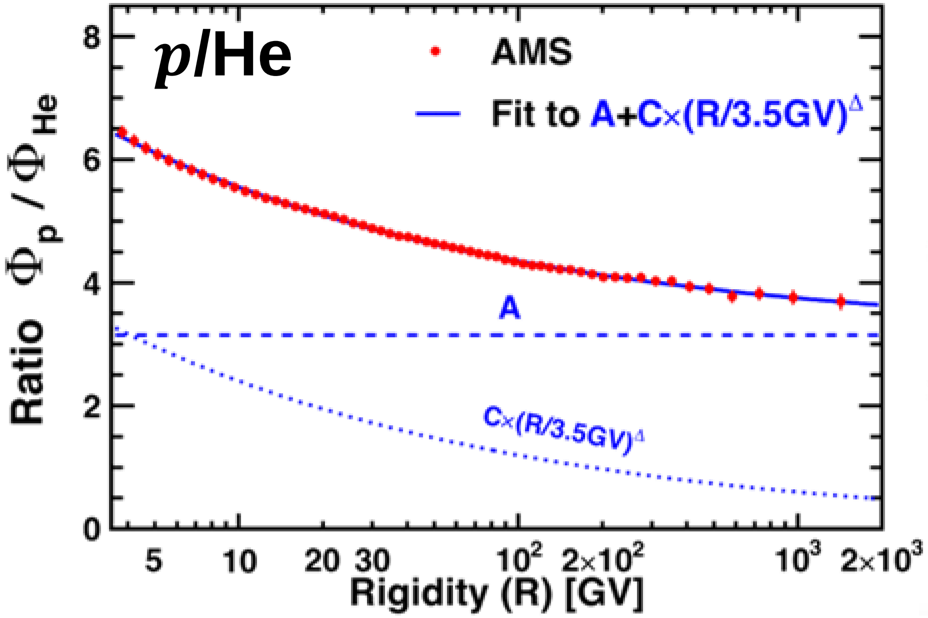
Data in the last decade are based on much larger statistics than the past and revealed many new details.

- **Significant structures** above 100 GeV have been found in all hadronic species.
- A **hardening** above few hundreds of GeV, and a **softening** above 10 TeV. What's their origin?
- Why the $p$/He ratio has a slope **without features**?
- Why the **sharp structure in** $(e^{-} + e^{+})$ at 1 TeV?

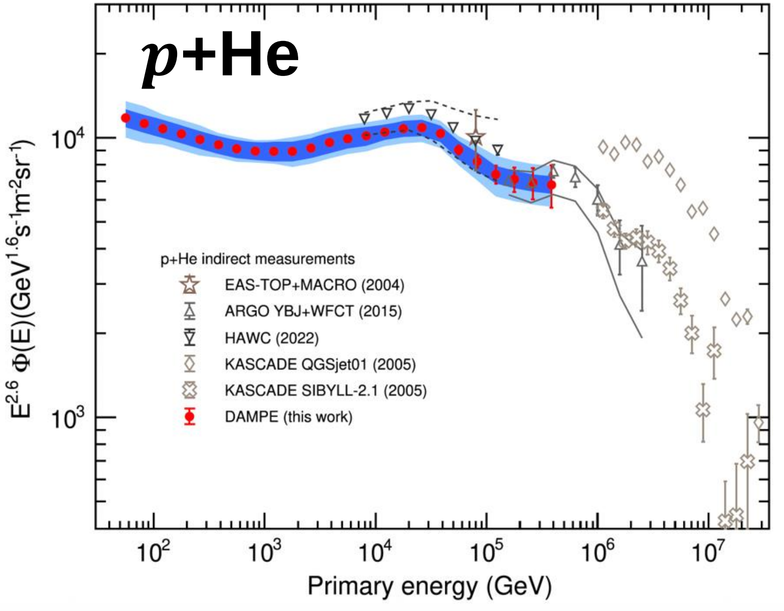
O. Adriani *et al.*, Phys. Rev. Lett. **129** (2022) 101102.




M. Aguilar *et al.*, Phys. Rep. **894** (2021) 1-116.




F. Alemanno *et al.*, Phys. Rev. D **109** (2024) L121101.



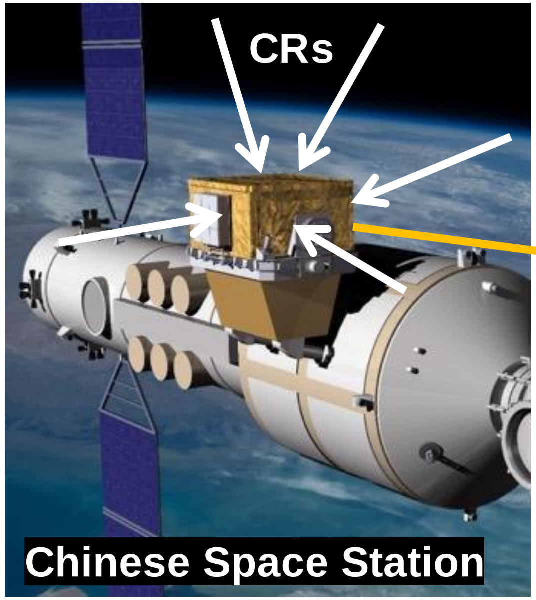

Experimental questions:

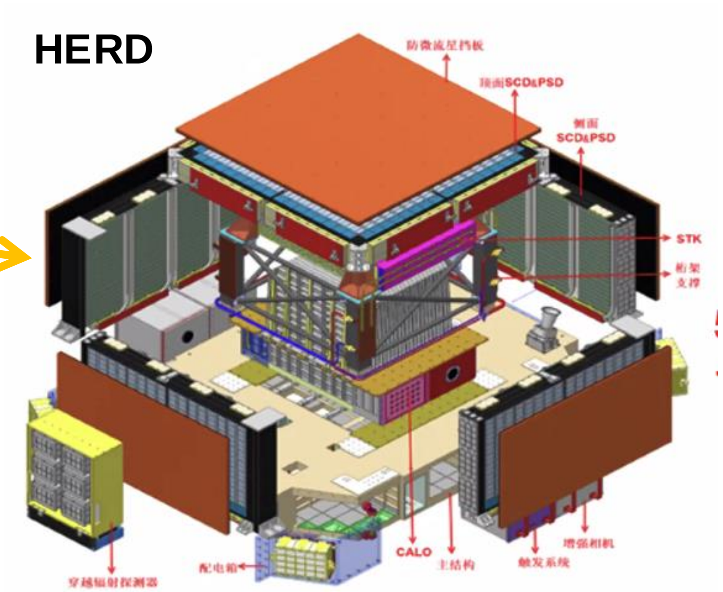
→ Can we study all proton, nuclei and electron spectra at higher energies?

→ Can we **study the knee with a direct cosmic ray experiment**?

# What’s Next: HERD, Towards the Knee



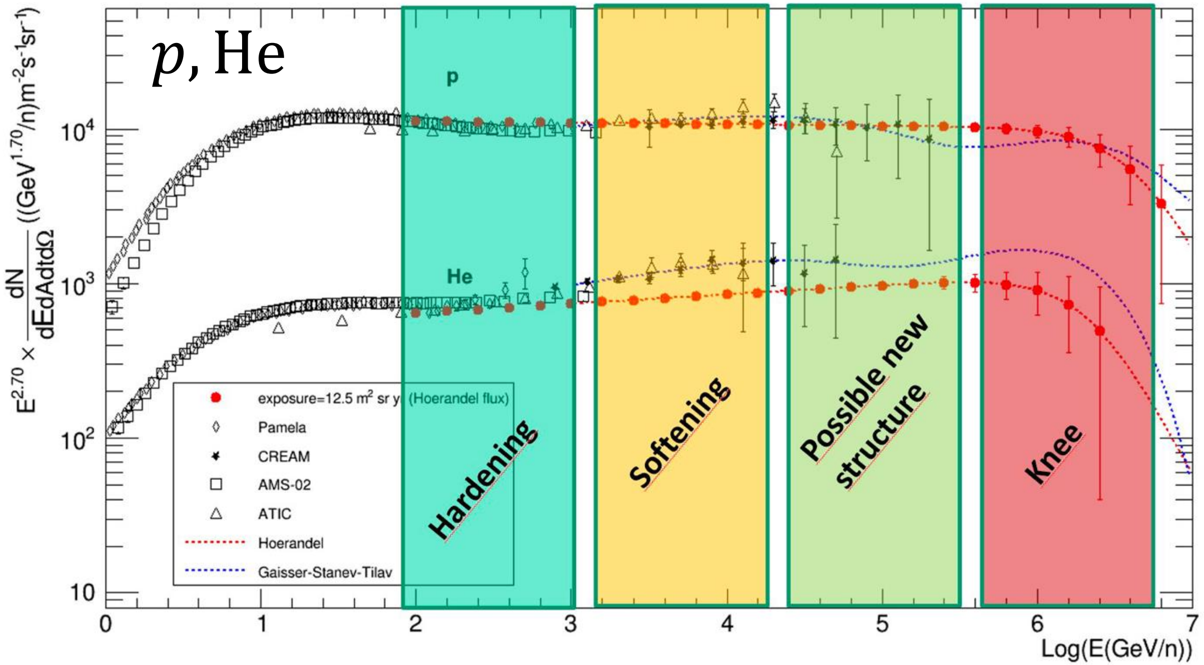


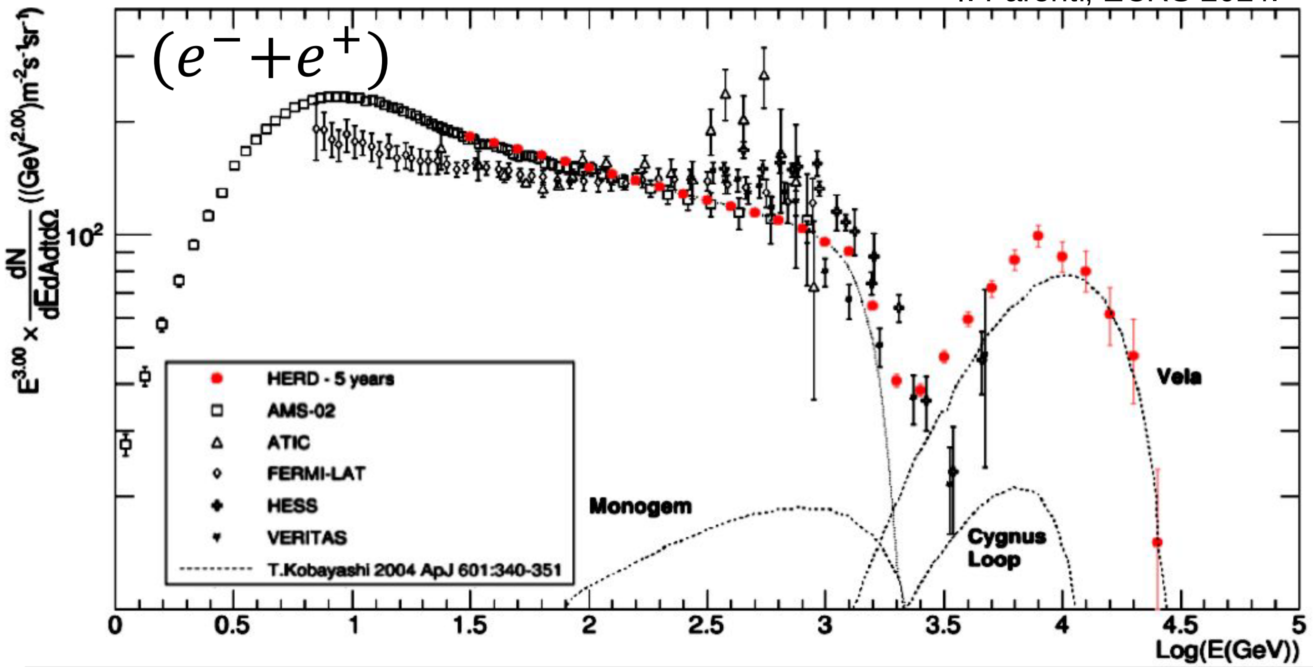




**High Energy Cosmic Radiation Detector (HERD)**
Based on a 3D, homogeneous, finely-segmented calorimeter of 55 $X_0$ with a wide field of view (2π).
Complemented by other detectors for PID (charge, veto, tracking, …).
Installation foreseen in 2027.

- Measurement of cosmic-rays up to the **knee** (~PeV).
- All-electron spectrum up to 10 TeV.
- Anisotropy of the all-electron.
- Full sky $\gamma$-ray monitoring (up to 100 TeV).
- Indirect dark matter search (all-electron, $\gamma$-ray).

I. Parenti, ECRS 2024.



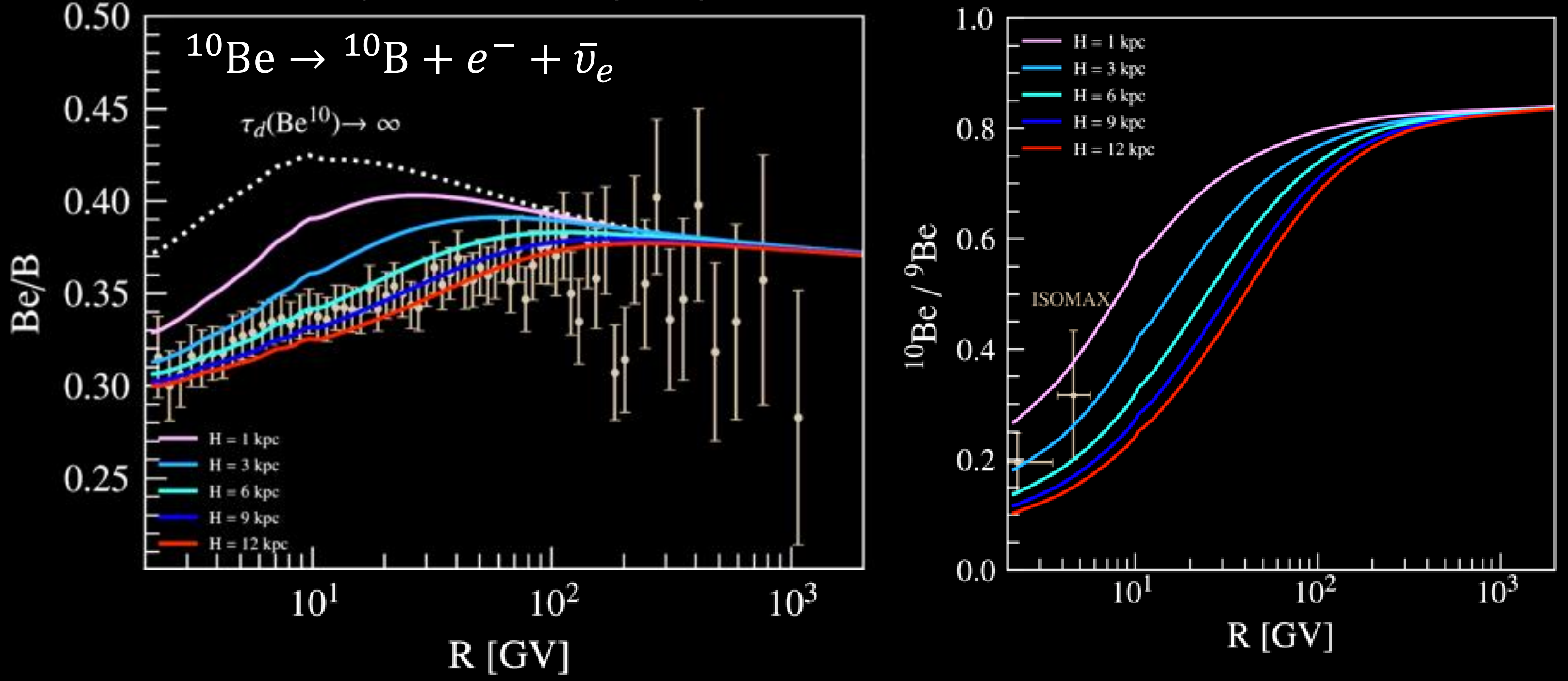



# What’s Next : the Composition Frontier

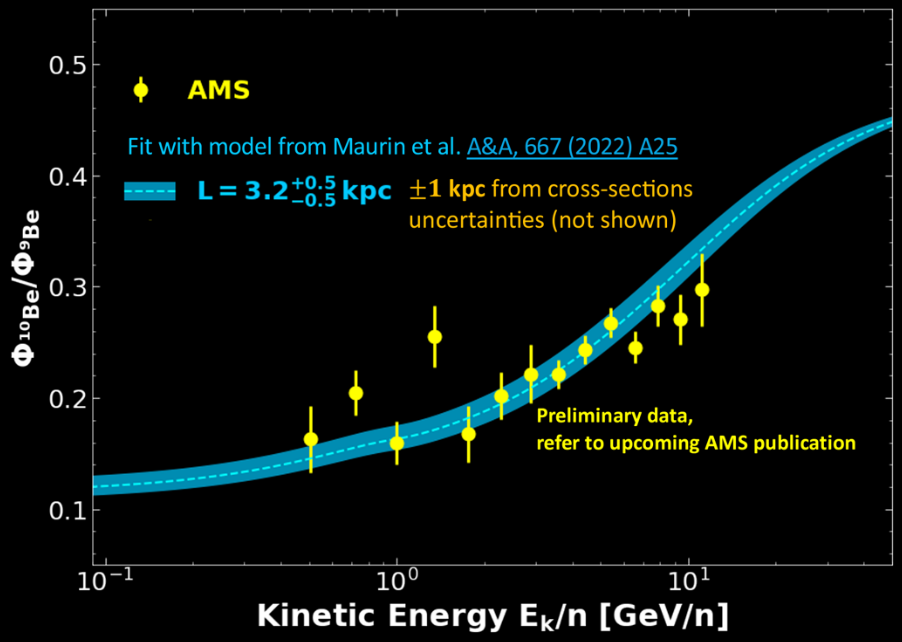


- The **galactic halo size** is the principal “unknown” of the cosmic ray diffusion models.
- Unstable elements are free to decay in the halo and can be used to measure it.
- The $^{10}\mathrm{Be}$ decay $^{10}\mathrm{Be} \rightarrow {}^{10}\mathrm{B} + e^{-} + \bar{\nu}_e$ with a half-life of $t_{1/2}$ = 1.4 My, is the most studied one.
- The interpretation of the data seems to be severely limited by isotopes production cross section knowledge.

C. Evoli *et al.*, Phys. Rev. D **101** (2020) 023013.




M. Paniccia, XSCR 2024.



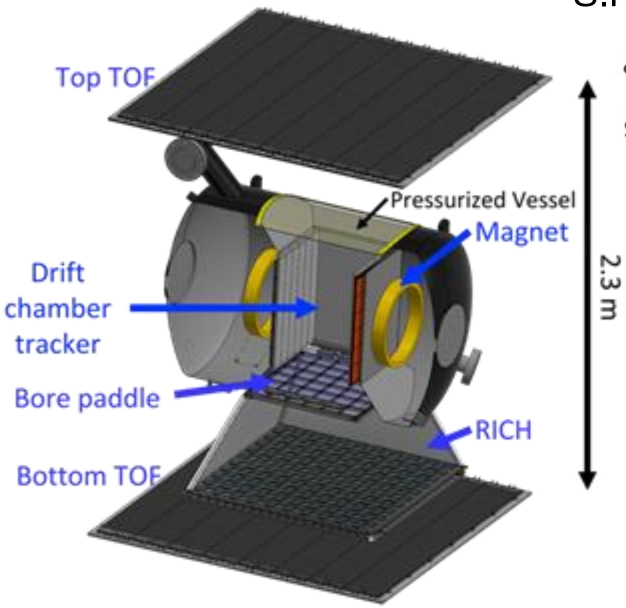

Experimental questions

→ Can we measure **isotopic composition** of cosmic rays up to **high energy**? (in some sense, if pushed to enough high energies the XS problem would be solved).

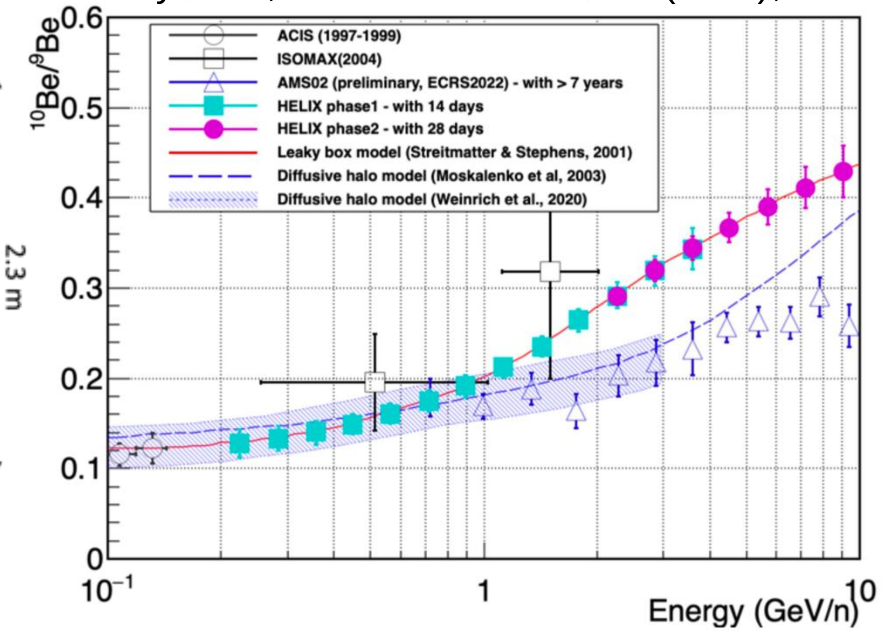
# What’s Next: $^{10}Be/^{9}Be$ with HELIX



**High Energy Light Isotope Experiment (HELIX)**
HEAT Superconducting Magnet, B = 1T.
Drift-Chamber Tracker (DCT), $\Delta R/R < 2\%$.
Ring Imaging Cherenkov (RICH), 1 to 10 GeV/n.
Time-of-Flight (TOF), 0.2 GeV/n to 1 GeV/n.
Velocity systems have $\gamma^2\,\Delta\beta/\beta < 2\%$.




S.P. Wakely *et al.*, Proc. of the 38th ICRC (2023), 118.





First HELIX campaign
Launched 28/05/2024
Landed 03/06/2024

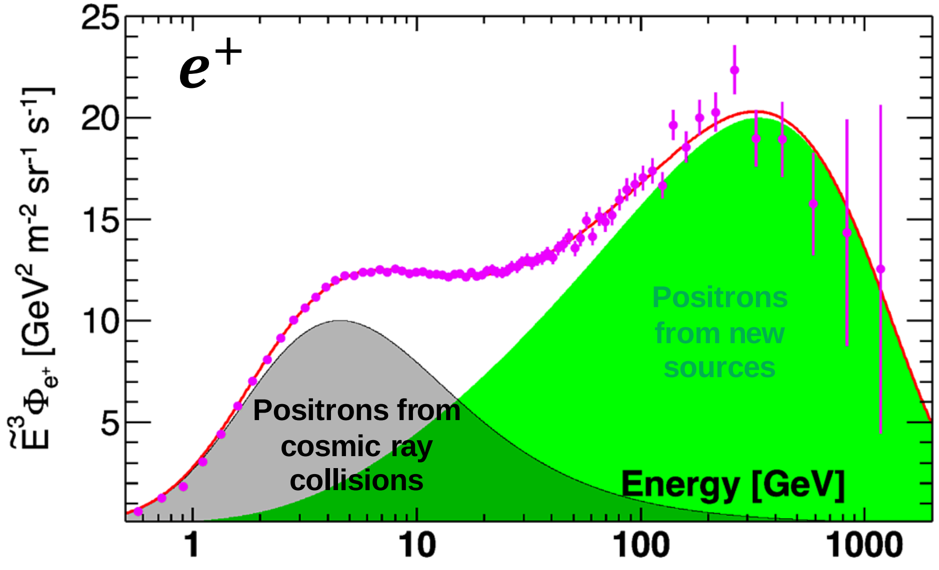
# What’s Next: the Antimatter Frontier



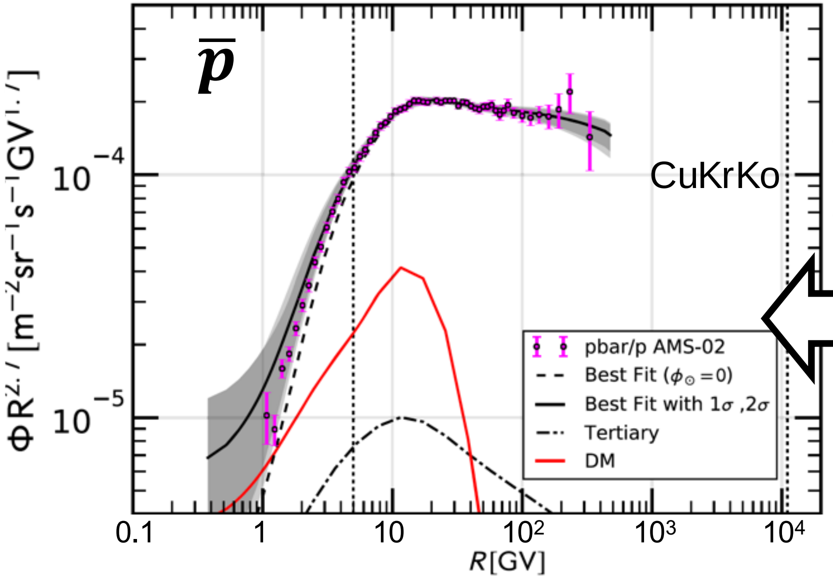
Antimatter is rare in cosmic rays, but it is important for the study of **new physics**.

- The **positrons** show an **excess with a cutoff** not compatible with cosmic ray production.
- Presence of a possible **excess in $\bar{p}$ flux** at ~10 GV. Modelling of **astrophysical background** is a limiting factor in the interpretation (uncertainties in propagation, production, and solar modulation).
- A signal in antiproton implies a corresponding antideuteron signal and viceversa.
- Antideuterons are believed to be a **clean channel for indirect dark matter search** at 1 GeV/n.
- Antihelium nuclei claimed by AMS-02, if confirmed, may have large impact.

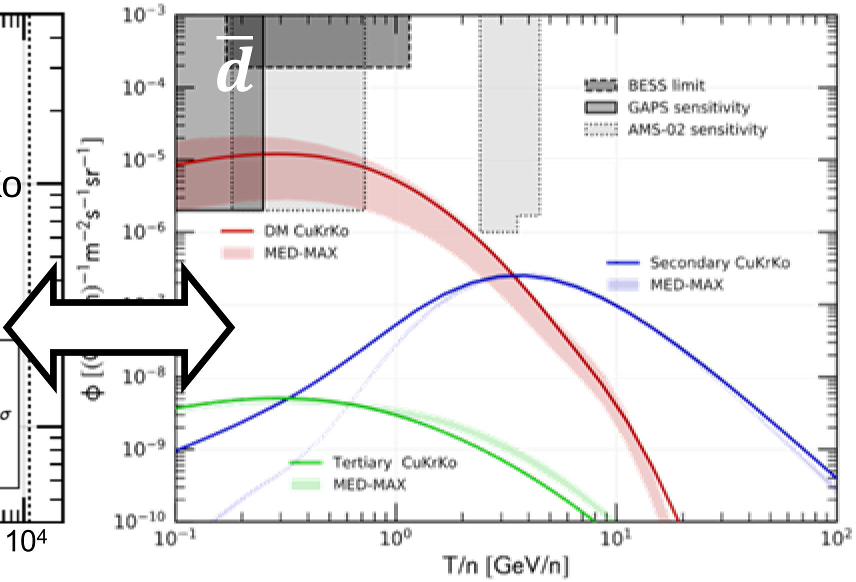
M. Aguilar *et al.*, Phys. Rep. **894** (2021) 1-116.




A. Cuoco *et al.*, Phys. Rev. Lett. **118** (2017) 191102.




M. Korsmeier *et al.*, Phys. Rev. D **97** (2018) 103011.




Experimental questions:

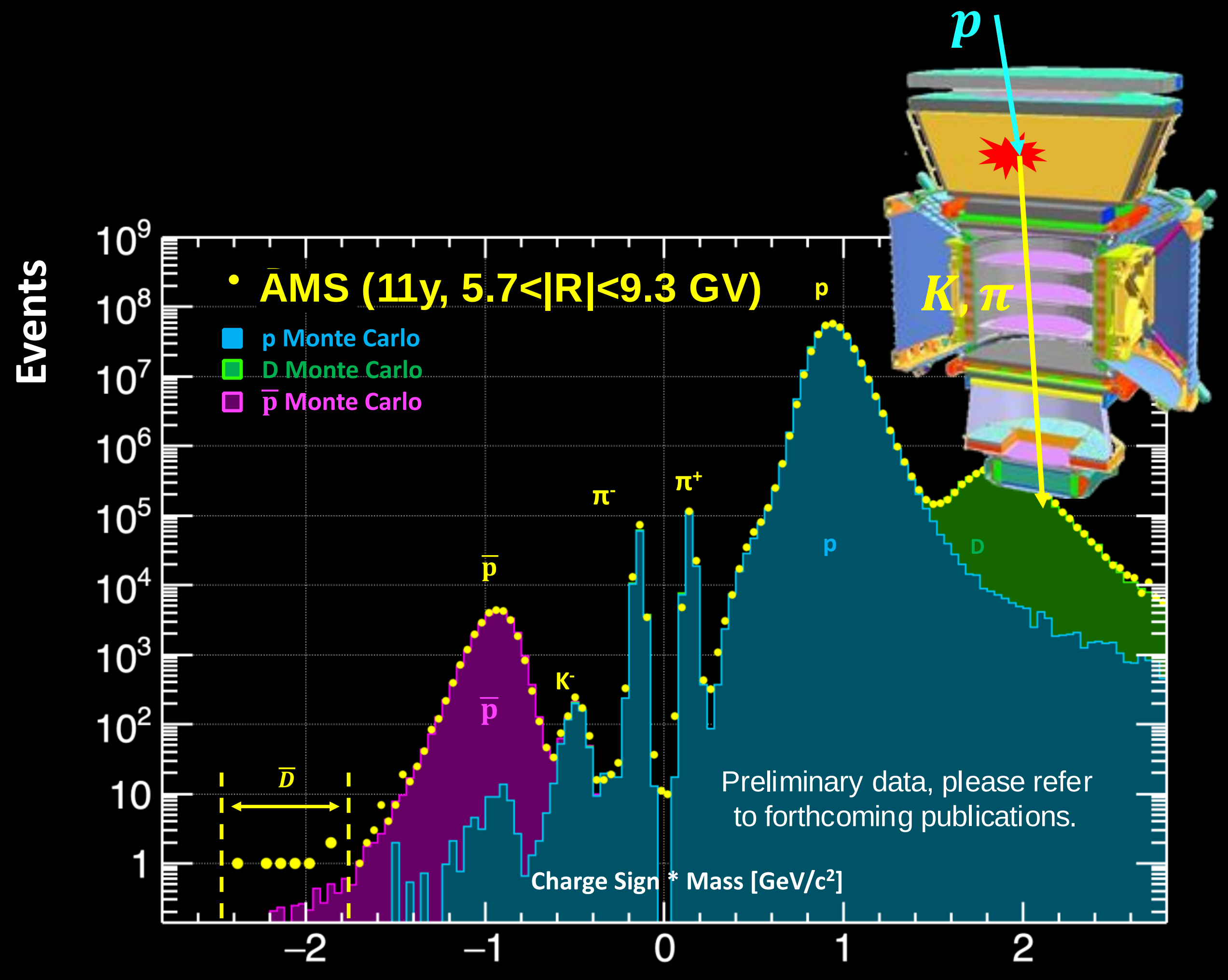
→ Can we measure positrons structure above the **observed cutoff**?

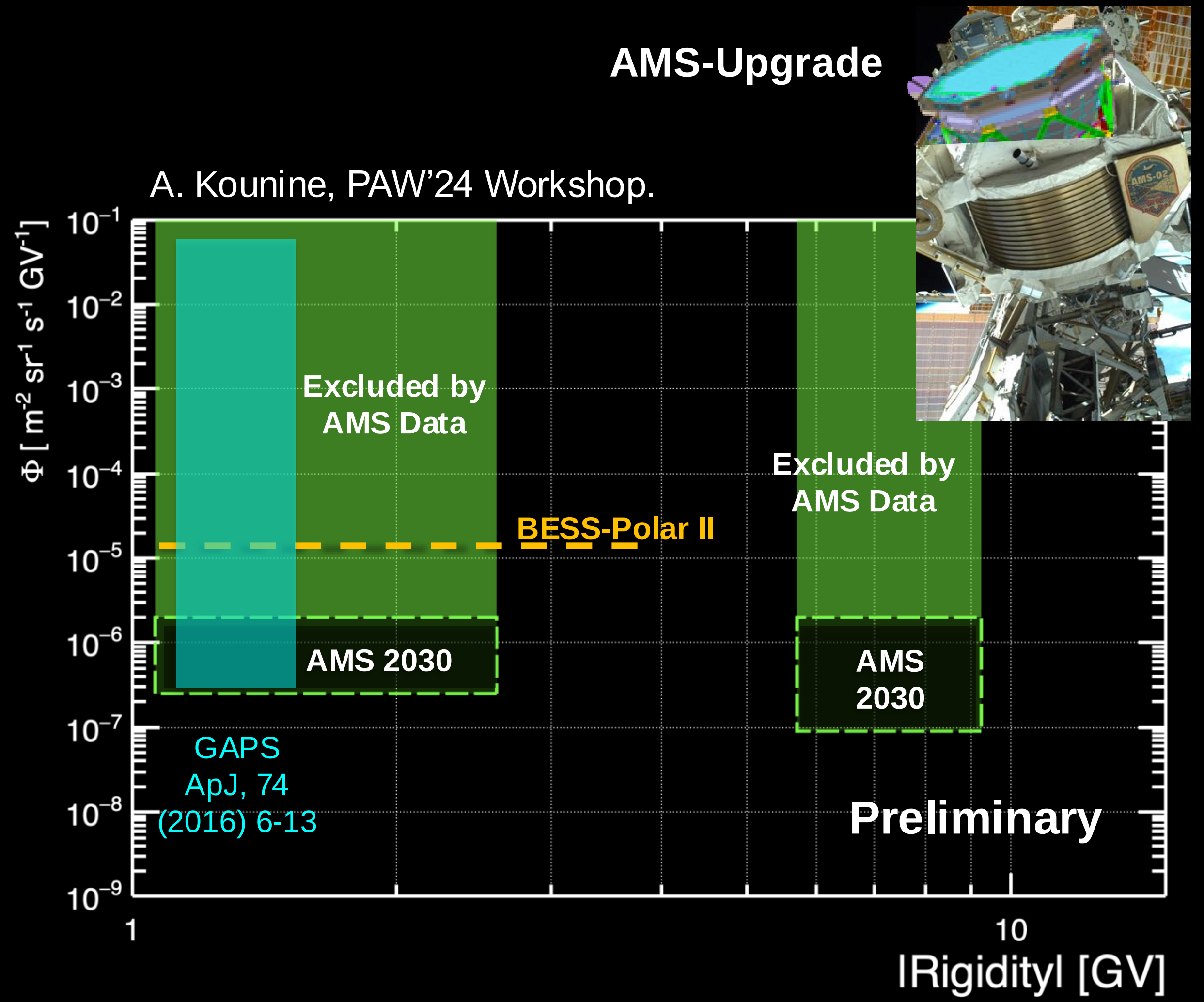
→ Can we do an experiment with **high sensitivity for antimatter** search in cosmic rays?

# What’s Next: The AMS-02 Upgrade



The **AMS-02 Upgrade** consist in the additional installation of a large tracking plane (diameter 2.6m) on top of AMS to be installed in 2026. This additional detector will allow to enlarge the field of view of the experiment increasing by a factor 3 the collection power (nuclei, positrons, antideuterons).

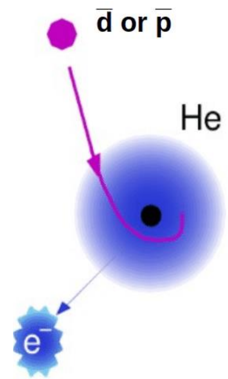


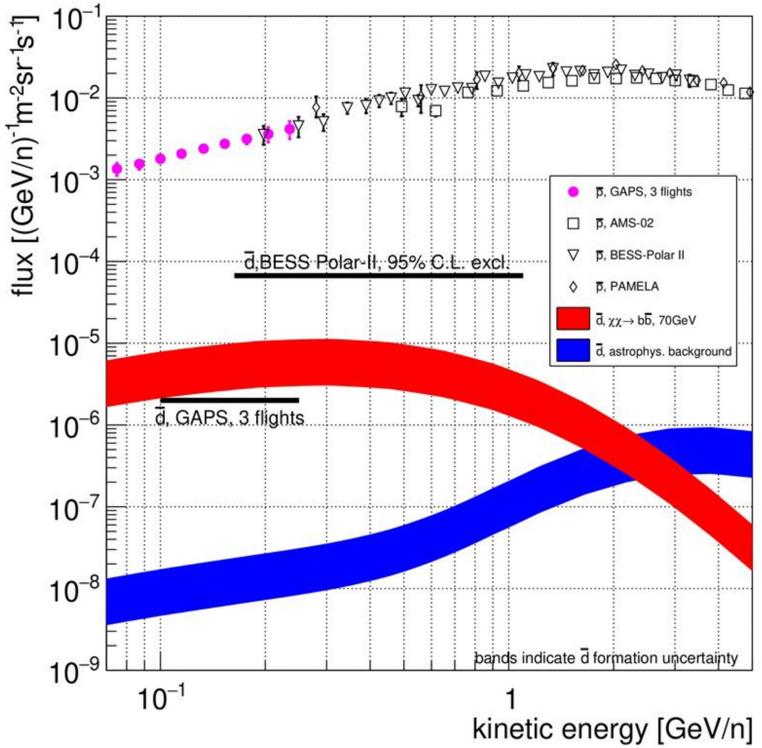
# What’s Next: GAPS



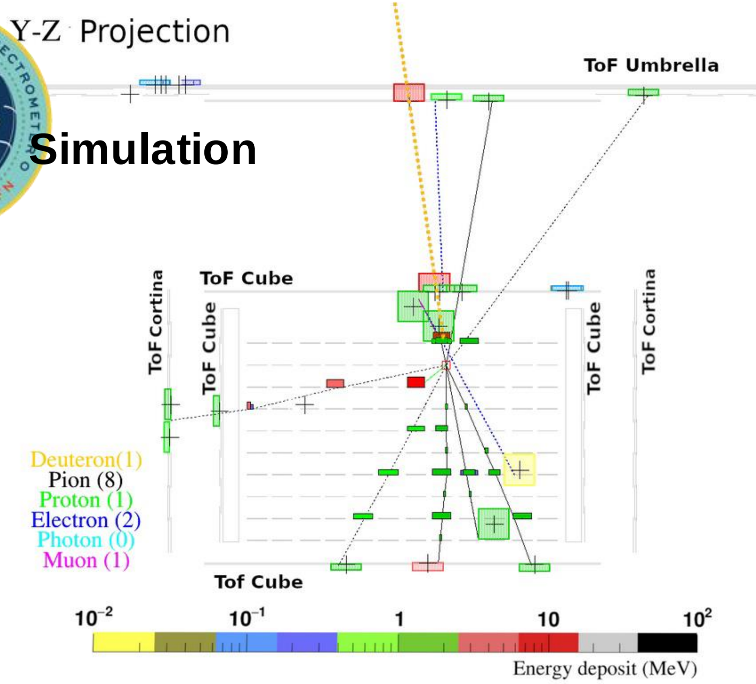
- General Anti-Particle Spectrometer (GAPS) is a balloon-borne instrument.
- The detection of antiparticles is based on an innovative experimental technique:
  - antiparticles are stopped in the material and form exotic atoms.
  - characteristics X-ray are emitted from orbital transitions of the exotic atom.
  - Pion-“star” produced by the final annihilation of the antiparticle on the nucleus.
- Finalized, foreseen the first balloon campaign in Antarctica starting from the end of this year.
- Will measure $\bar{p}$ and $\bar{d}$ in the interval between 100 MeV/n and 250 MeV/n.




P. Von Dotinchem, JENAA Workshop @ CERN 2024.








→ Other projects as the **ADHD**, and **GRAMS** have been proposed to profit of the same experimental principle but with very different designs. This is a new experimental field in its own.

# Ideas for the Next Generation: ALADInO

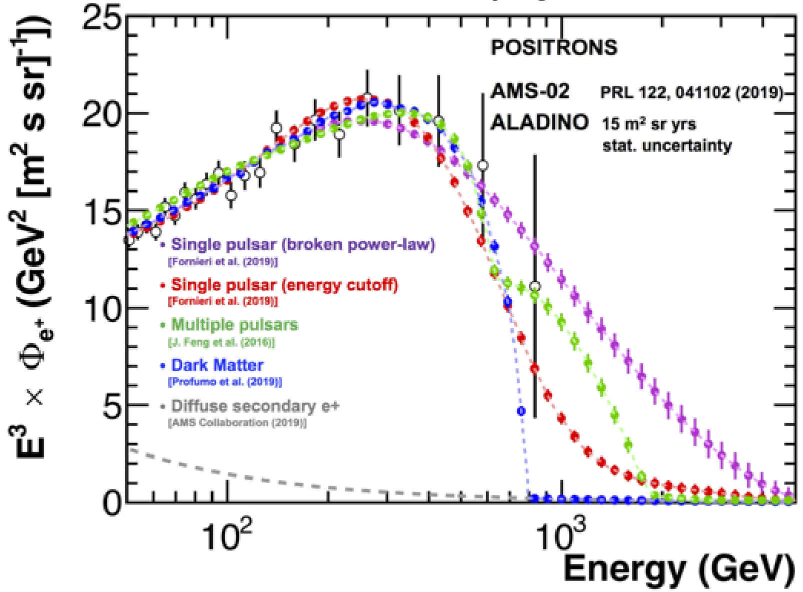


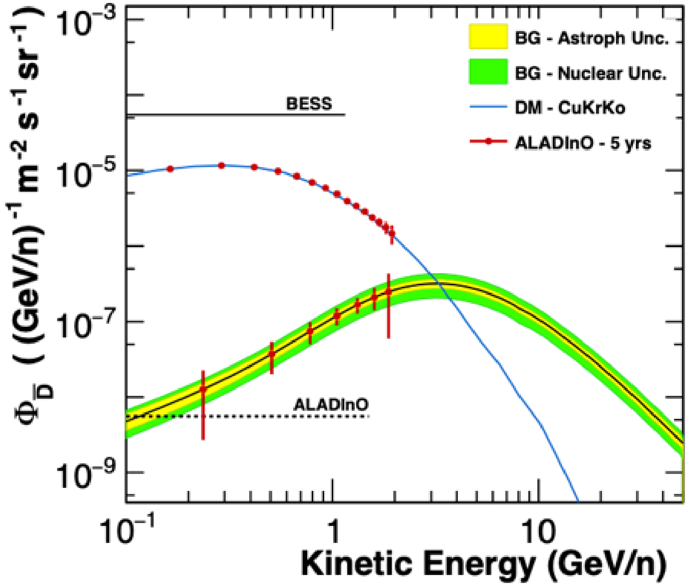
| | |
|---|---|
| Location | Lagrange Point $L_2$ |
| Installation | >2030 |
| Dimensions | ⌀ = 4.4 m, L = 2 m |
| Det. weight | 6.5 t |
| Power | 3 kW |
| Magnetic Field | 0.8 T |
| Acceptance | >10 $m^2$sr |
| MDR | >20 TV |
| Cal. thickness | 61 $X_0$ |

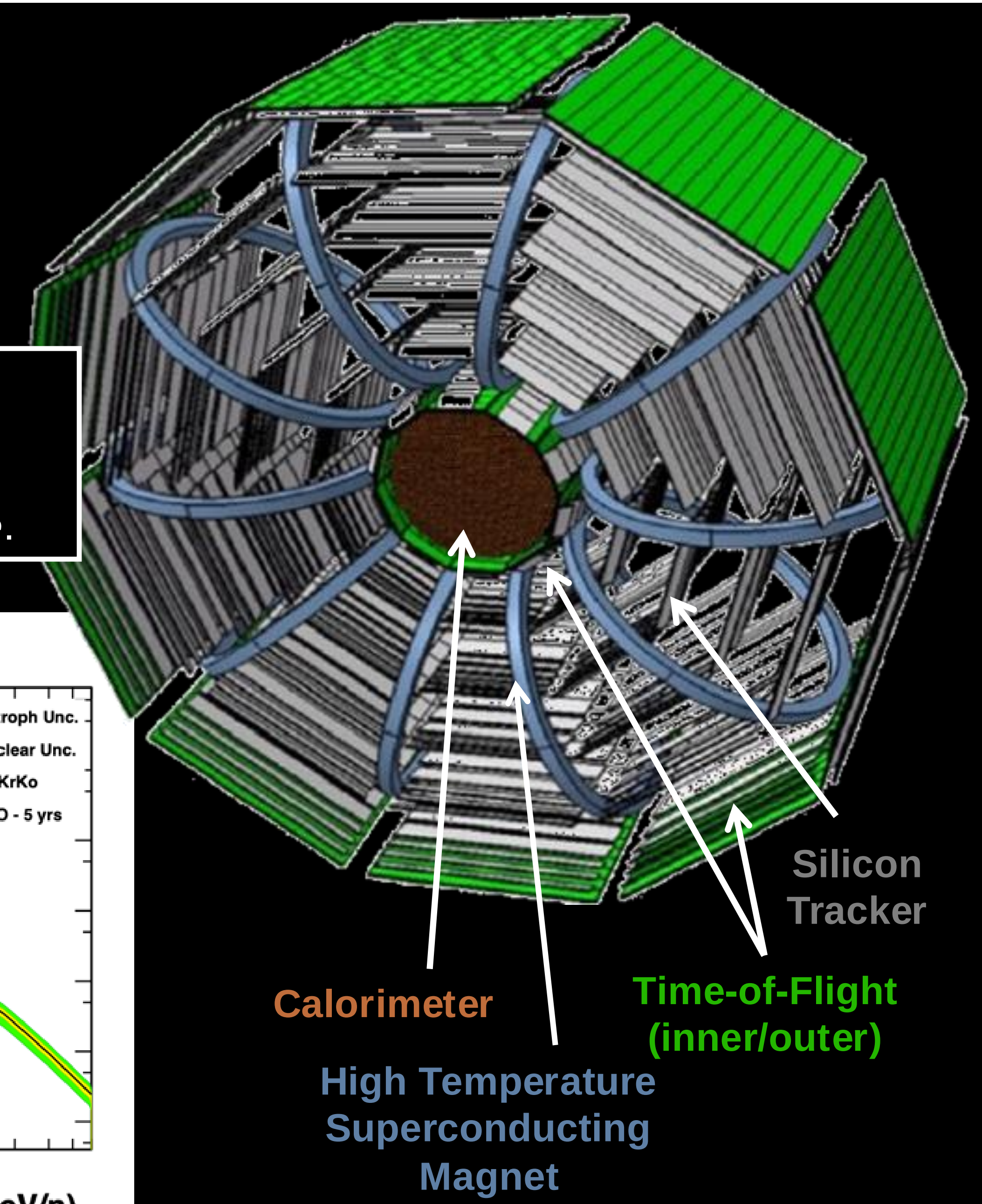
Physics objectives:

- anti-nuclei;
- $e^{\pm}$ up to 10 TeV;
- Cosmic ray comp. up to *knee*.

R. Battiston *et al.*, Voyager 2050 White Paper (2021).

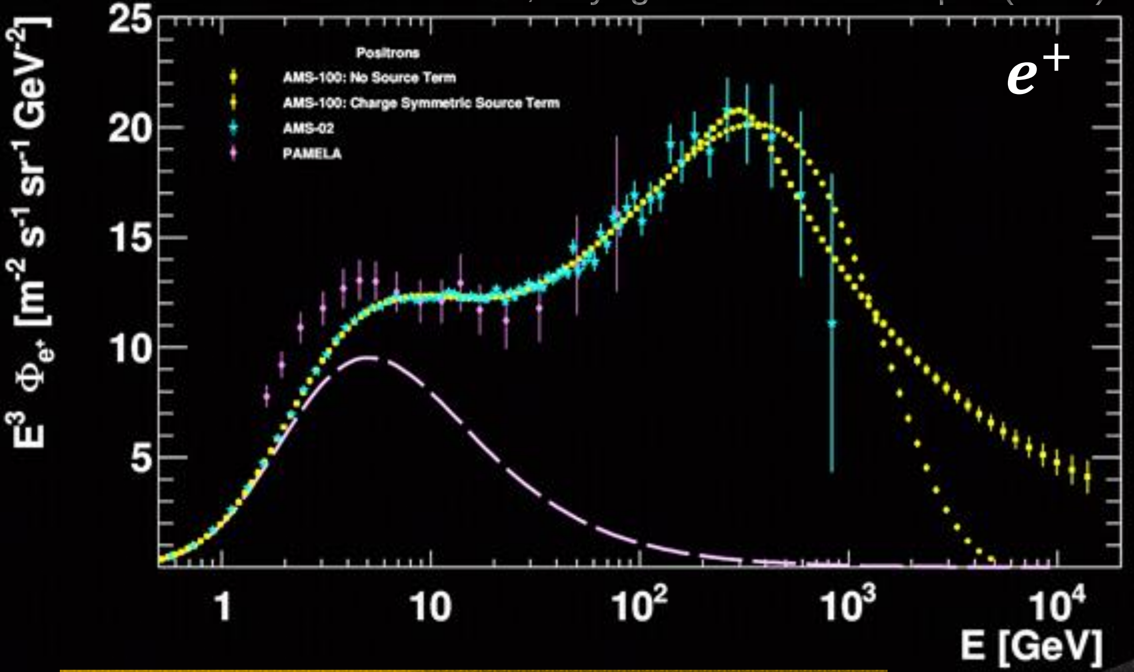


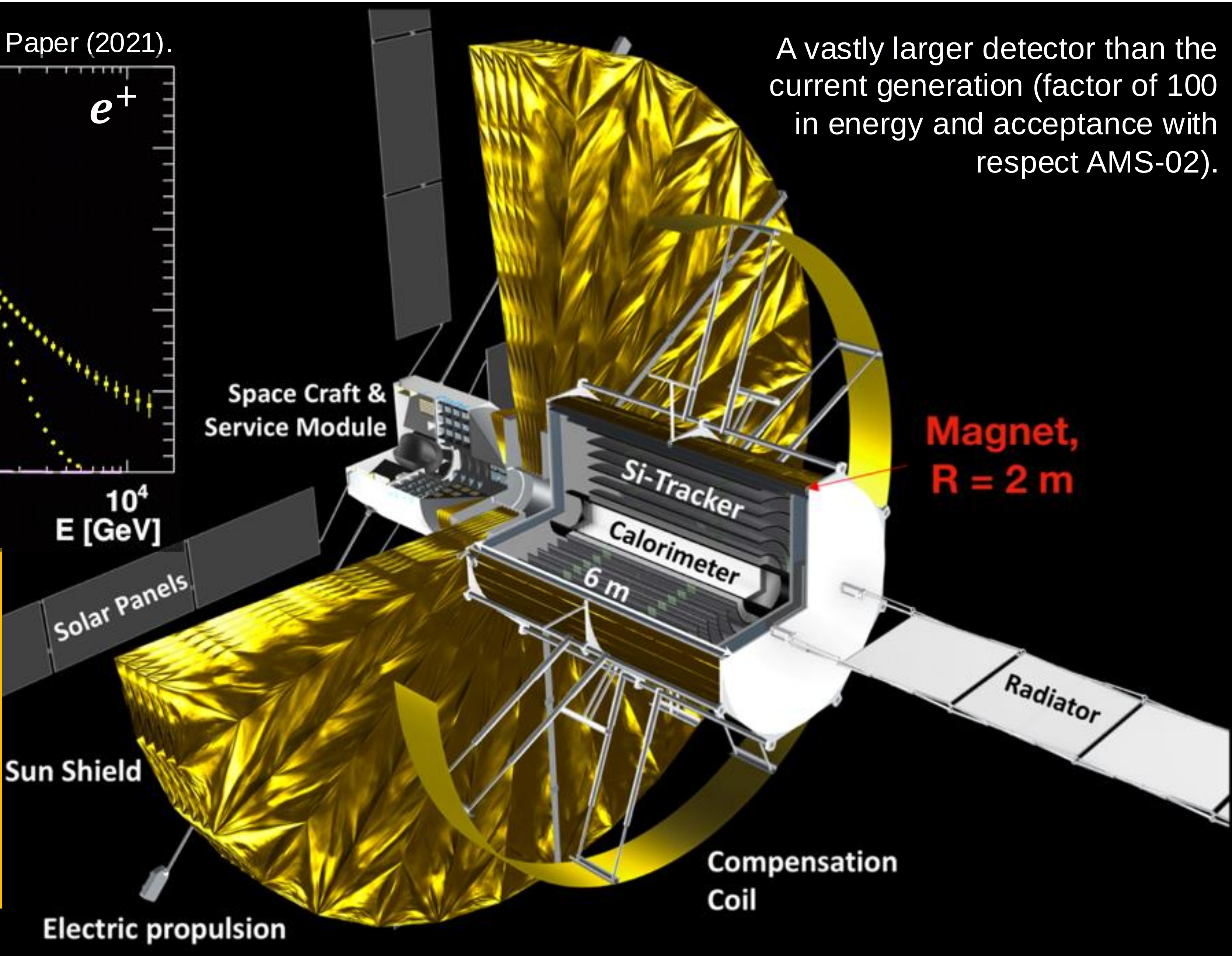



# Ideas for the Next Generation: AMS-100

S. Shael *et al.*, Voyager 2050 White Paper (2021).




A vastly larger detector than the current generation (factor of 100 in energy and acceptance with respect AMS-02).




| | |
|---|---|
| **Location** | **Lagrange Point $L_2$** |
| **Installation** | **>2030** |
| **Dimensions** | **⌀ = 4.4 m, L = 6 m** |
| **Weight** | **40 t** |
| **Power** | **15 kW** |
| **Magnetic Field** | **1 T** |
| **Acceptance** | **100 $m^2$ sr** |
| **MDR** | **100 TV** |
| **Cal. thickness** | **70 $X_0$** |

# Conclusions



- **Direct measurement** of CRs is a **precision measurement** field.
- **Many missions** are currently taking data at the same time, several of which are on the ISS.
- **Many new observations** were made in the last decade, and many still need an understanding.
- For the development of the field an important dependence with **ground experiment** has emerged (cross section measurements), that is the subject of this workshop.
- **New CR direct measurement projects in space and on ballons** are under realization. They will expand the field in terms of addressing specific problems (as ex, $^{10}$Be/$^{9}$Be), extending the energy range (as ex. towards the knee), or improving sensitivity (as ex. to antimatter search).
- **Experiments for the next generation** have been proposed. The effort is mainly dedicated in the increase of the TRL of new technologies, and to realize a pathfinder mission to test them with a strong physics case (antimatter).

# Calorimeters/Spectrometers Comparative Performances



Future (HERD, ALADInO, AMS-100)

| | | FERMI | PAMELA | AMS-02 | CALET | DAMPE | HERD | ALADInO | AMS-100 |
|---|---|---|---|---|---|---|---|---|---|
| Spectrometer | Magnetic Field [T] | | 0.43 (PM) | 0.14 (PM) | | | | 0.8 (SM) | 1 (SM) |
| Spectrometer | **MDR (ΔR/R = 100%) [TV]** | | **1** | **2-4** | | | | **>20** | **100** |
| Spectrometer | Acceptance [$m^2sr$] | | 0.0021 | 0.5 | | | | >10 | 100 |
| Calorimeter | e/γ Energy resolution @100 GeV [%] | 10 | 5.5 | 3 | 2 | 1.5 | <1 | 2 | $<1^{*}$ |
| Calorimeter | e/γ Angular resolution @100 GeV [°] | 0.1 | 0.3 | 0.3 | 0.2 | 0.1 | <0.1 | $<0.1^{*}$ | <0.01 |
| Calorimeter | e/p discrimination | $10^3$ | $10^5$ | $10^5$ | $10^5$ | $10^5$ | $>10^6$ | $>10^5$ | $>10^{5*}$ |
| Calorimeter | **Thickness [$X_0$]** | **8.6** | **16.3** | **17** | **27** | **32** | **55** | **61** | **70** |
| Calorimeter | Acceptance [$m^2sr$] | 1 | 0.06 | 0.09 | 0.104 | 0.3 | >3 | 9 | 30 |
| Comb. | Acceptance [$m^2sr$] | | 0.0021 | 0.09 | | | | 3 | 30 |

**Not all experiments and techniques displayed (sorry).**

**(*) Educated guess.**