Cosmic Rays, AMS-02 and beyond

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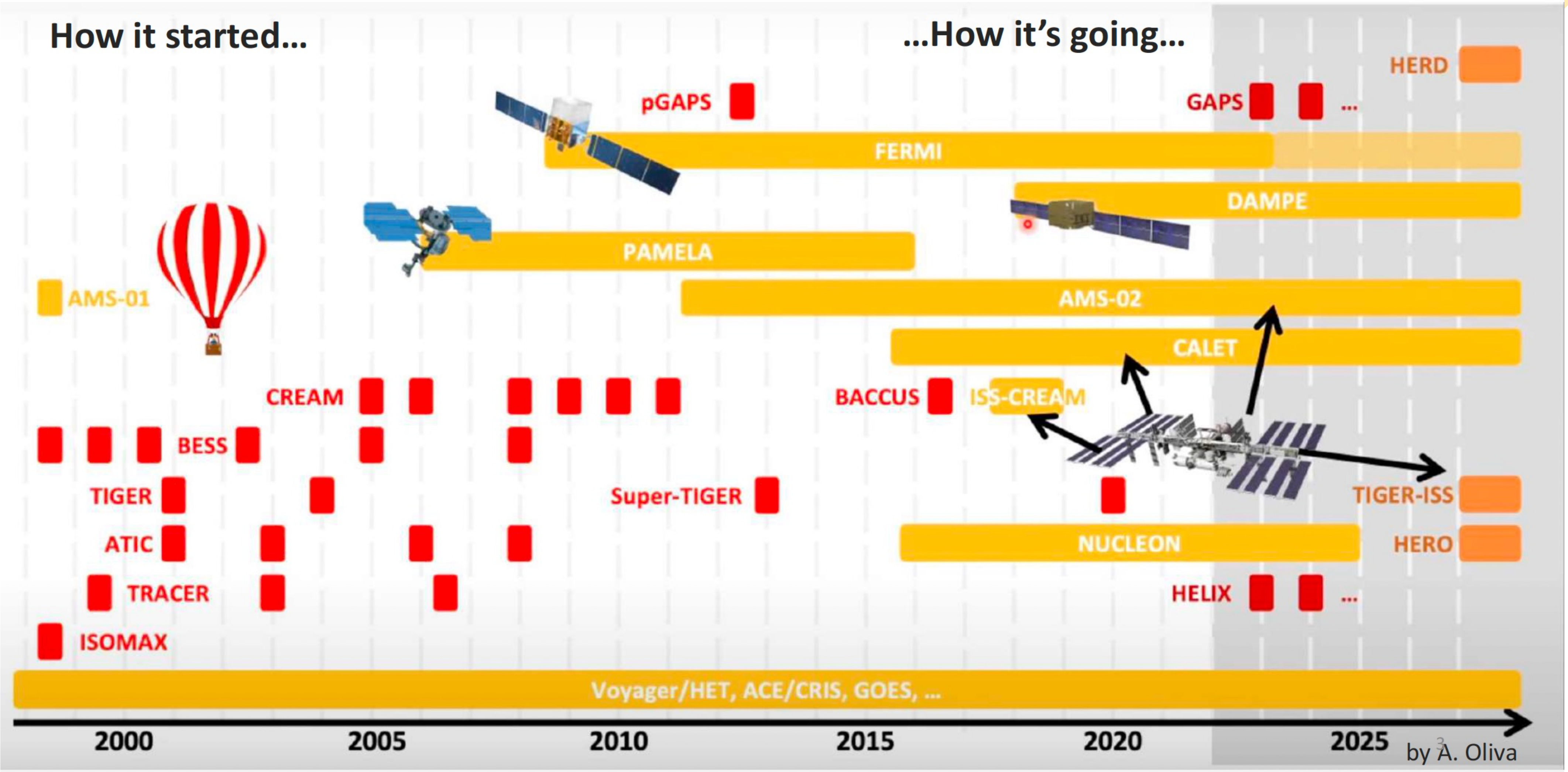
Cosmic Rays in the Multi-Messenger Era

Dec 5 -7, 2022, APC Laboratory (Paris)

a golden age of new cosmic ray measurements

Direct CR Measurements in the 3° millennium



by A. Oliva

A standard model of Galactic cosmic rays

General paradigm based on three pillars:

- Shock acceleration in SNRs: origin of primary CRS (p, C-N-O, Fe)
- Diffusive propagation in interstellar & interplanetary turbulence
- Collisions with ISM gas and production of secondaries: Li-Be-B, antimatter…

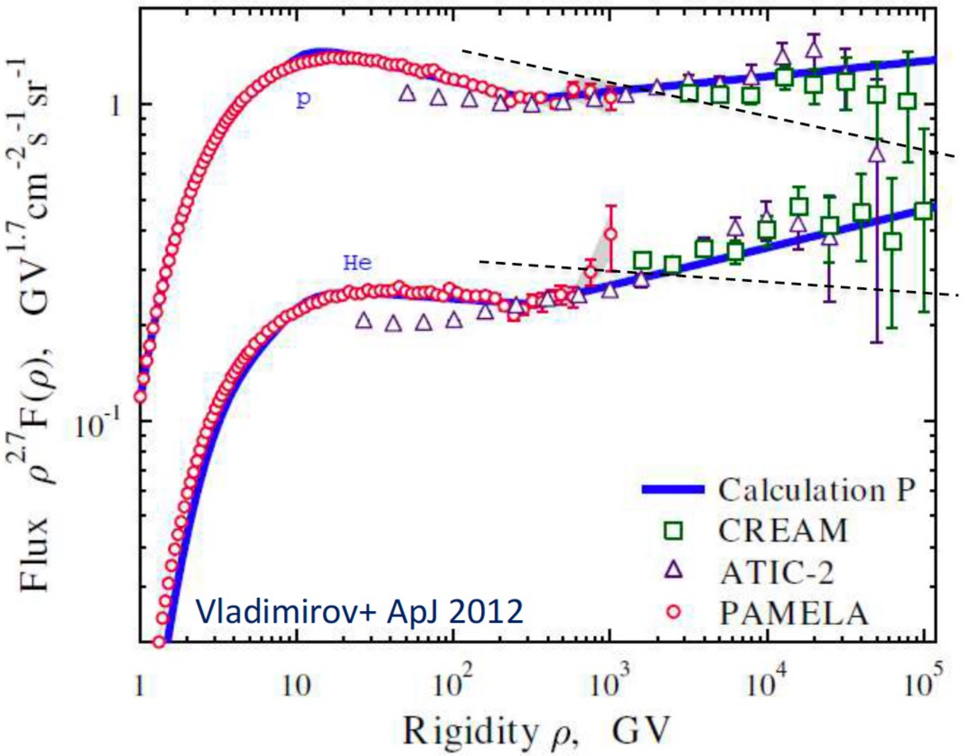
Questions:

- Which sources contributes at which energies?
- Are different CR types accelerated from the same sources?
- What's the CR composition in their sources?
- How's the acceleration mechanism works
- How CR propagation is related to the Galactic turbulence?

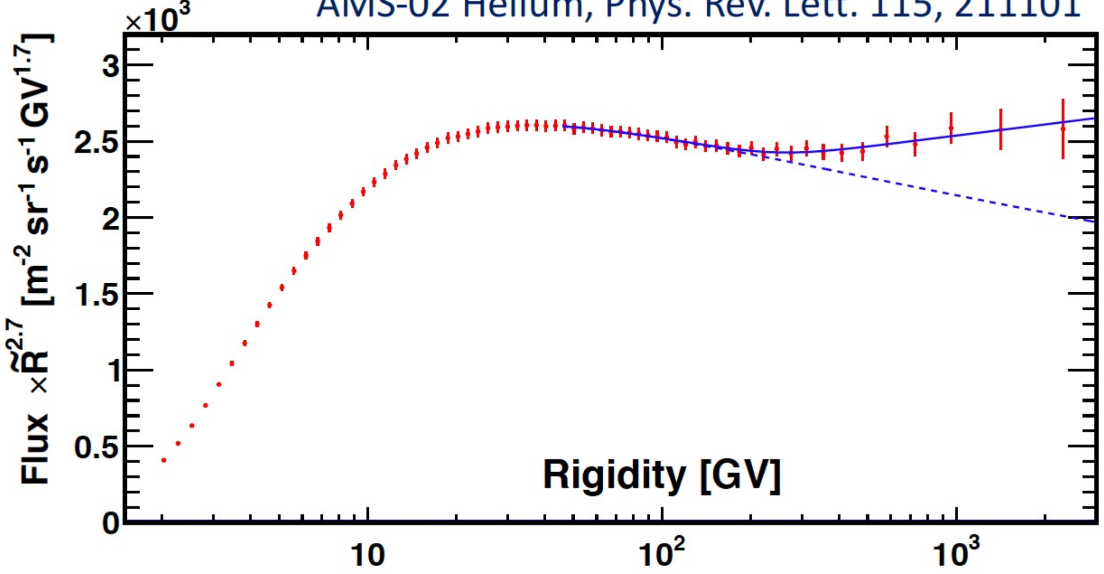
The high-energy spectral hardening

ATIC-2, CREAM, PAMELA (2011): the energy spectra of proton & helium become harder at high-rigidity (300 GV)

Spectral hardening at ~100 GeV energies



AMS-02 Helium, Phys. Rev. Lett. 115, 211101

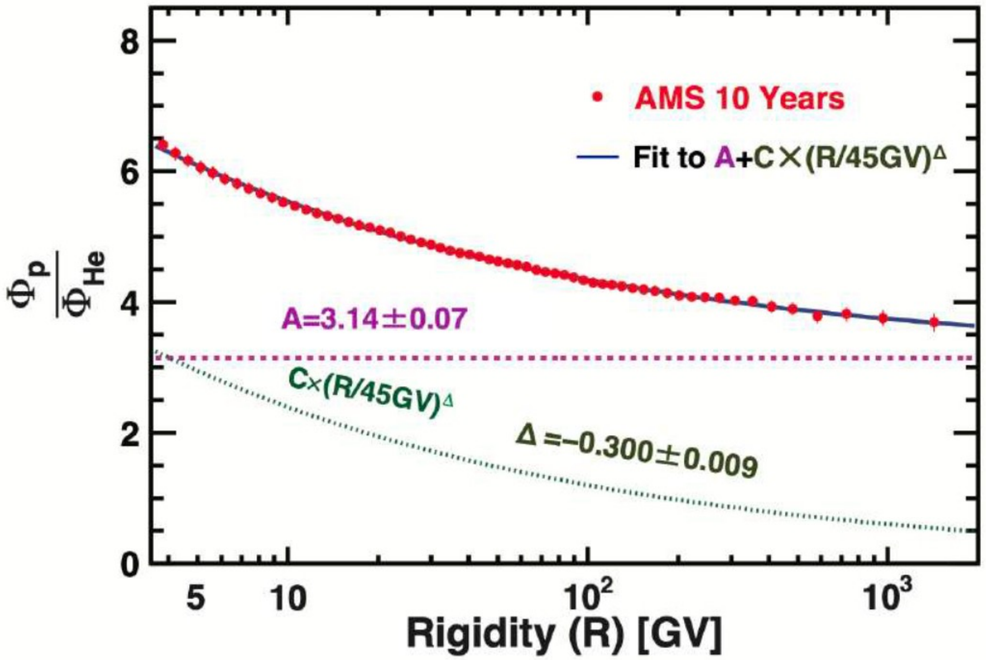


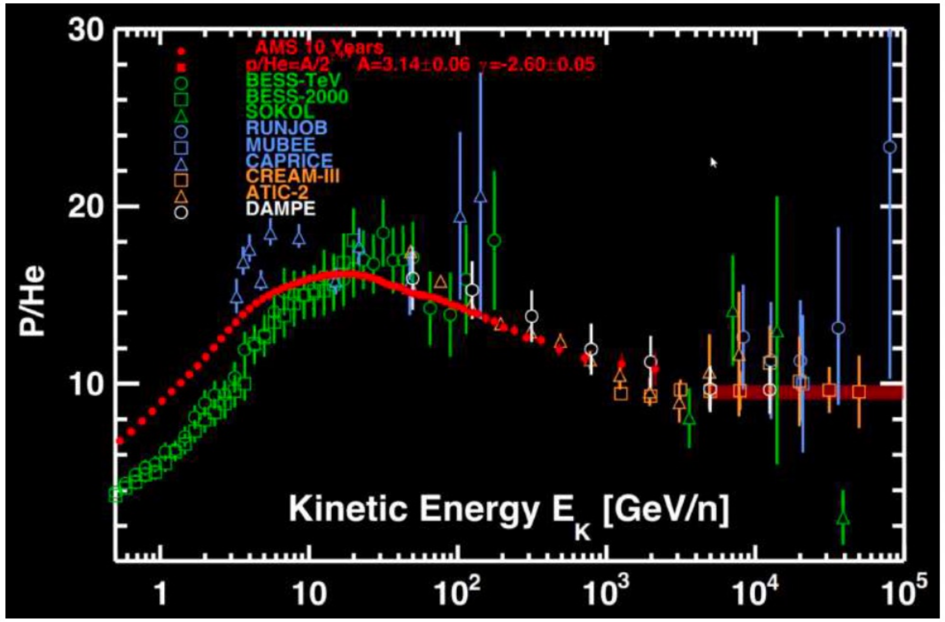
Challenge to the paradigm of CR acceleration & diffusive propagation

- New questions: is the spectral hardening universal? What's its origin?

p/He anomaly

- The He spectrum is harder than the proton on
- Both the spectra seems to have a kink at ~ 300 GV
- the p/He ratio decrease smoothly





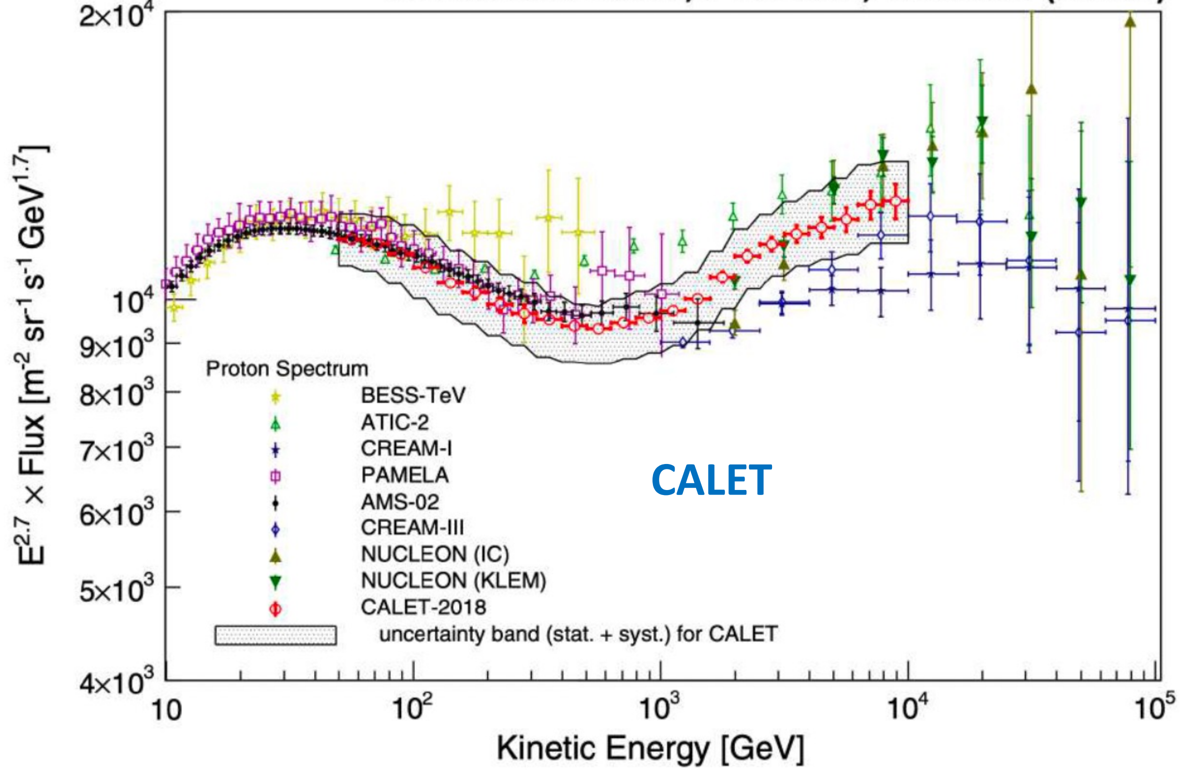
Not explained by standard CR propagation theory and in principle acceleration should be the same for p and He

Multi TeV proton flux features

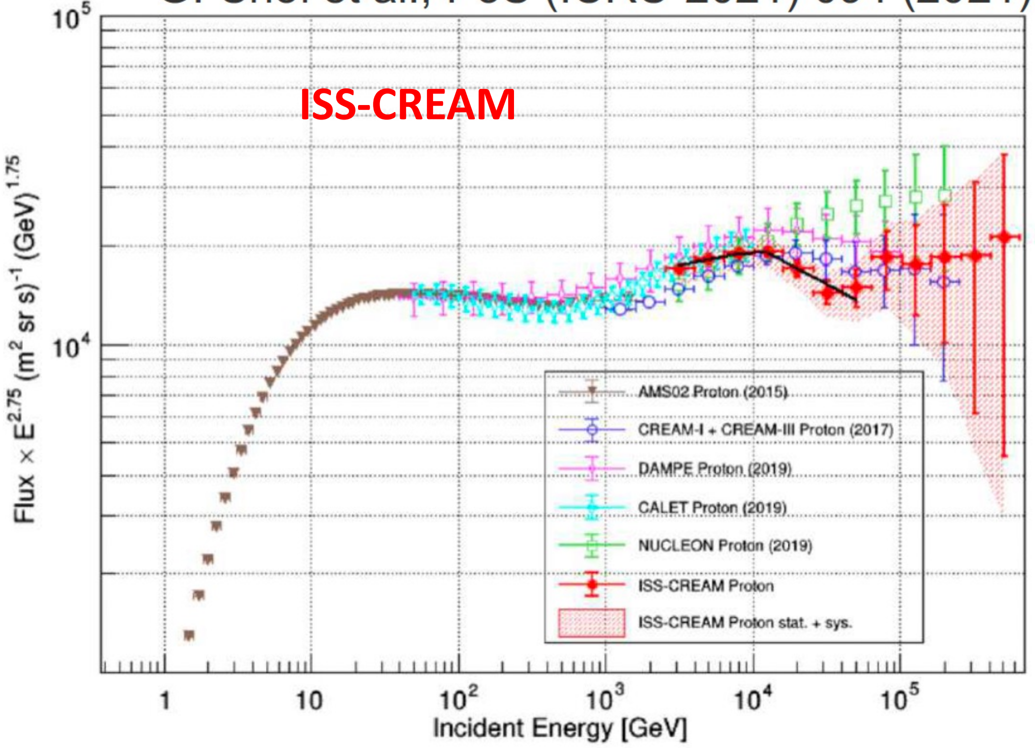
New bump-like structure reported by CREAM-I + III, NUCLEON, CALET, ISS-CREAM, DAMPE.

The CR proton spectrum is found to soften at about 10-20 TeV of energy.

O. Adriani et al., PRL 122, 181102 (2019)



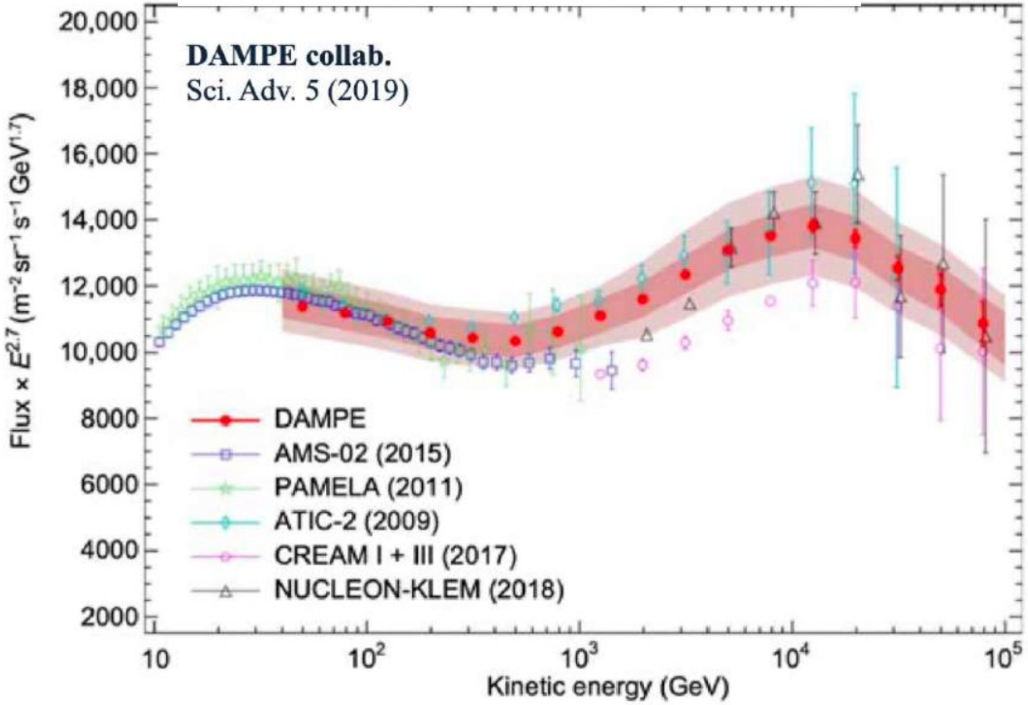
G. Choi et al., PoS (ICRC-2021) 094 (2021)



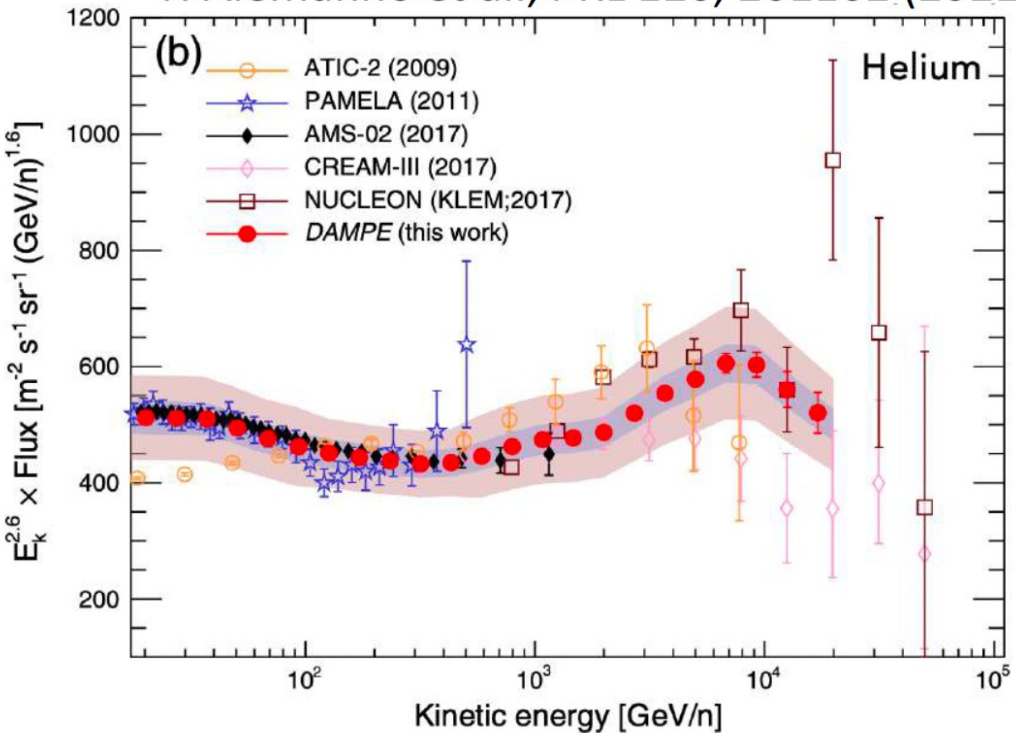
Multi TeV proton flux features

DAMPE: break at 20 TeV/n in both protons and helium, with $\Delta\gamma = -0.25 \pm 0.07$

Q. An et al., Sci. Adv. 5 (2019) 9



F. Alemanno et al., PRL 126, 201102 (2021)

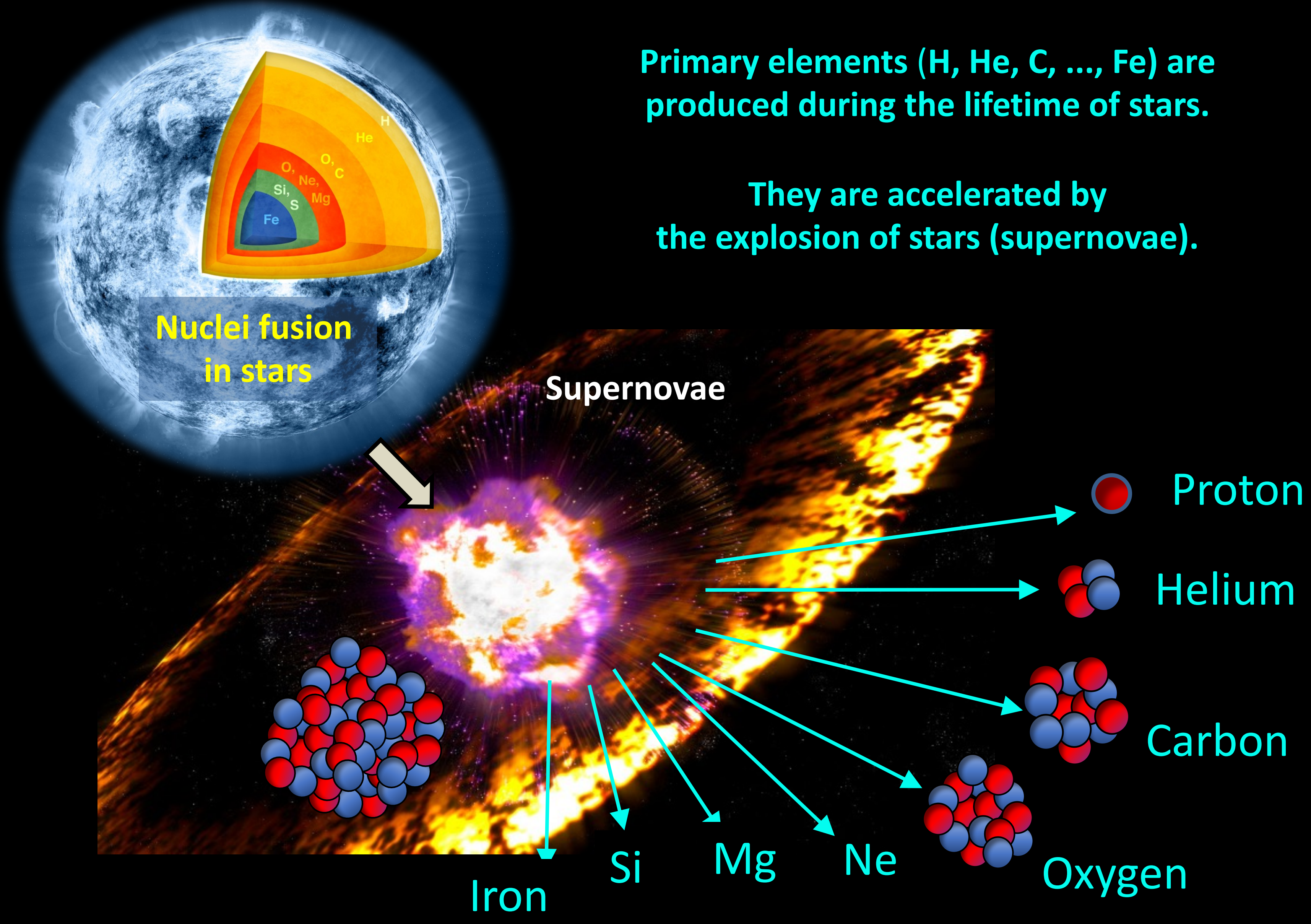


What is the origin of these structures
New features in the propagation?
Local sources ?

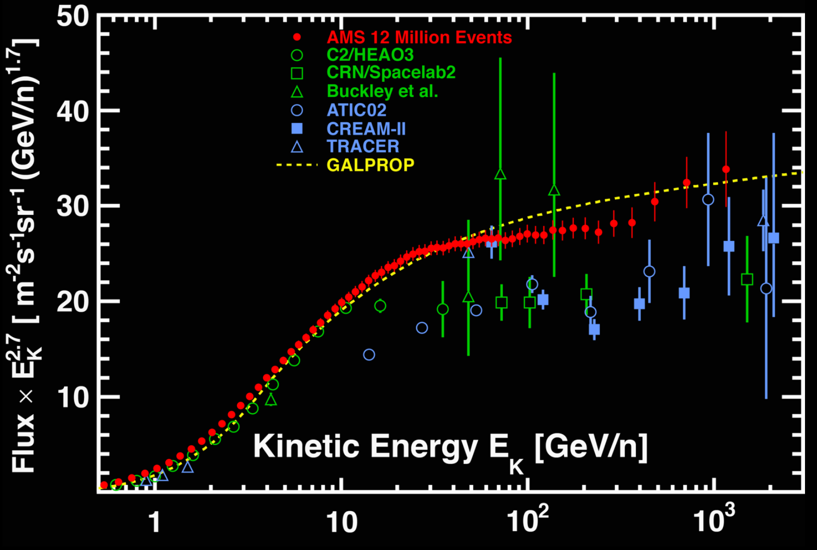
Properties of Primary Cosmic Rays

Primary elements (H, He, C, ..., Fe) are produced during the lifetime of stars.

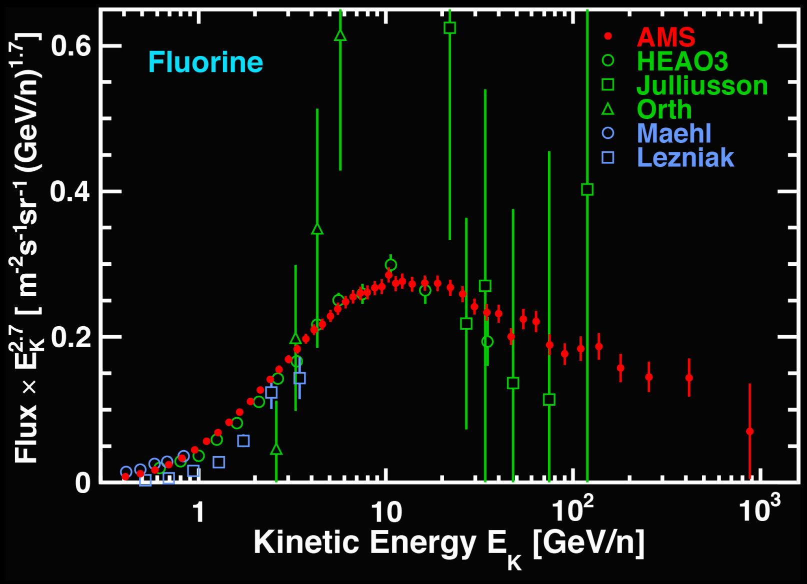
They are accelerated by the explosion of stars (supernovae).



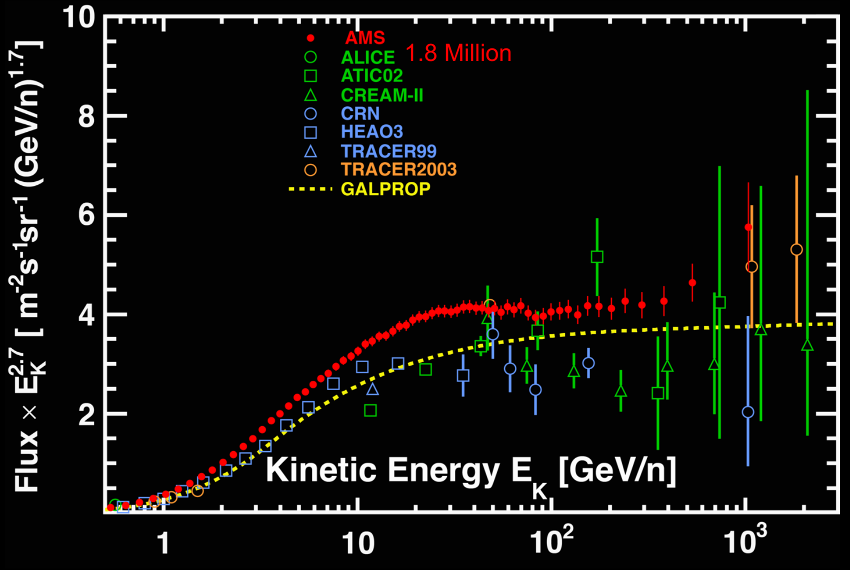
Oxygen (Z = +8)



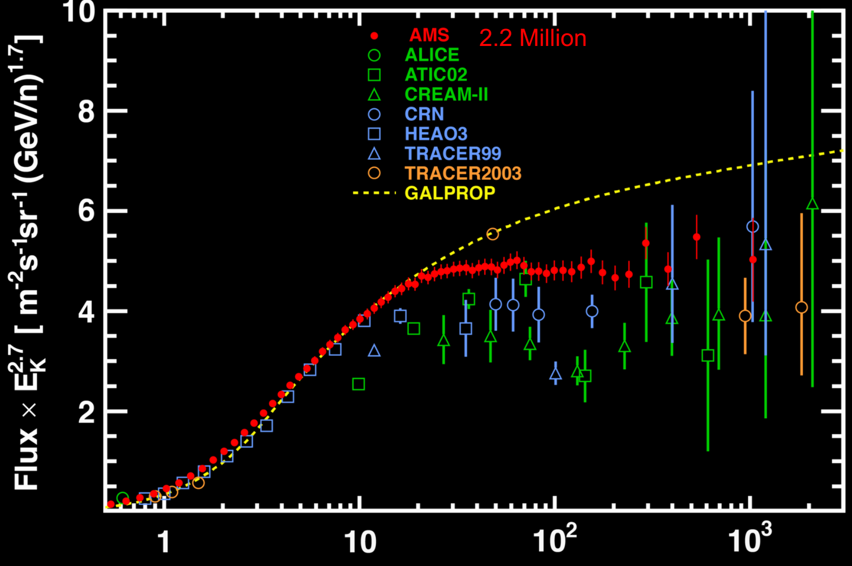
Fluorine (Z = +9)



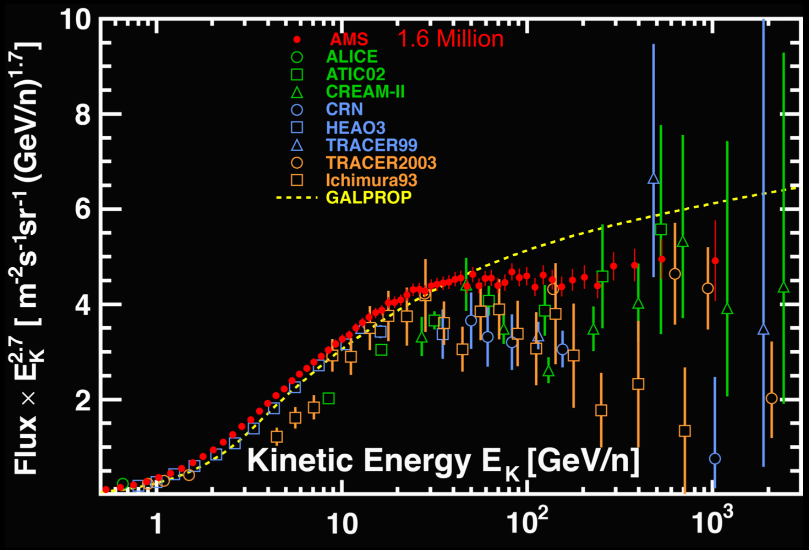
Neon (Z = +10)



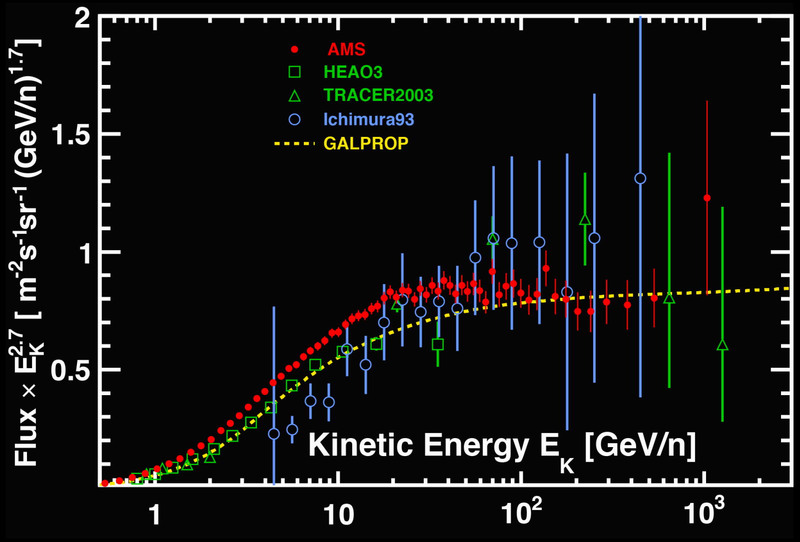
Magnesium (Z = +12)



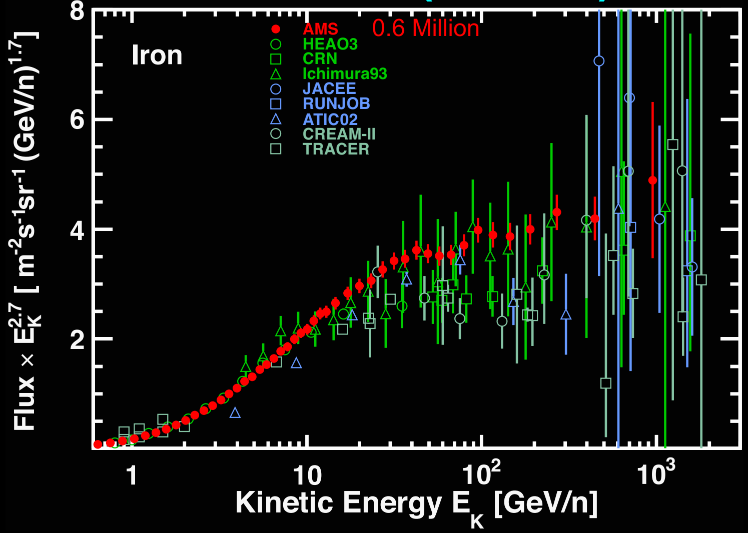
Silicon (Z = +14)



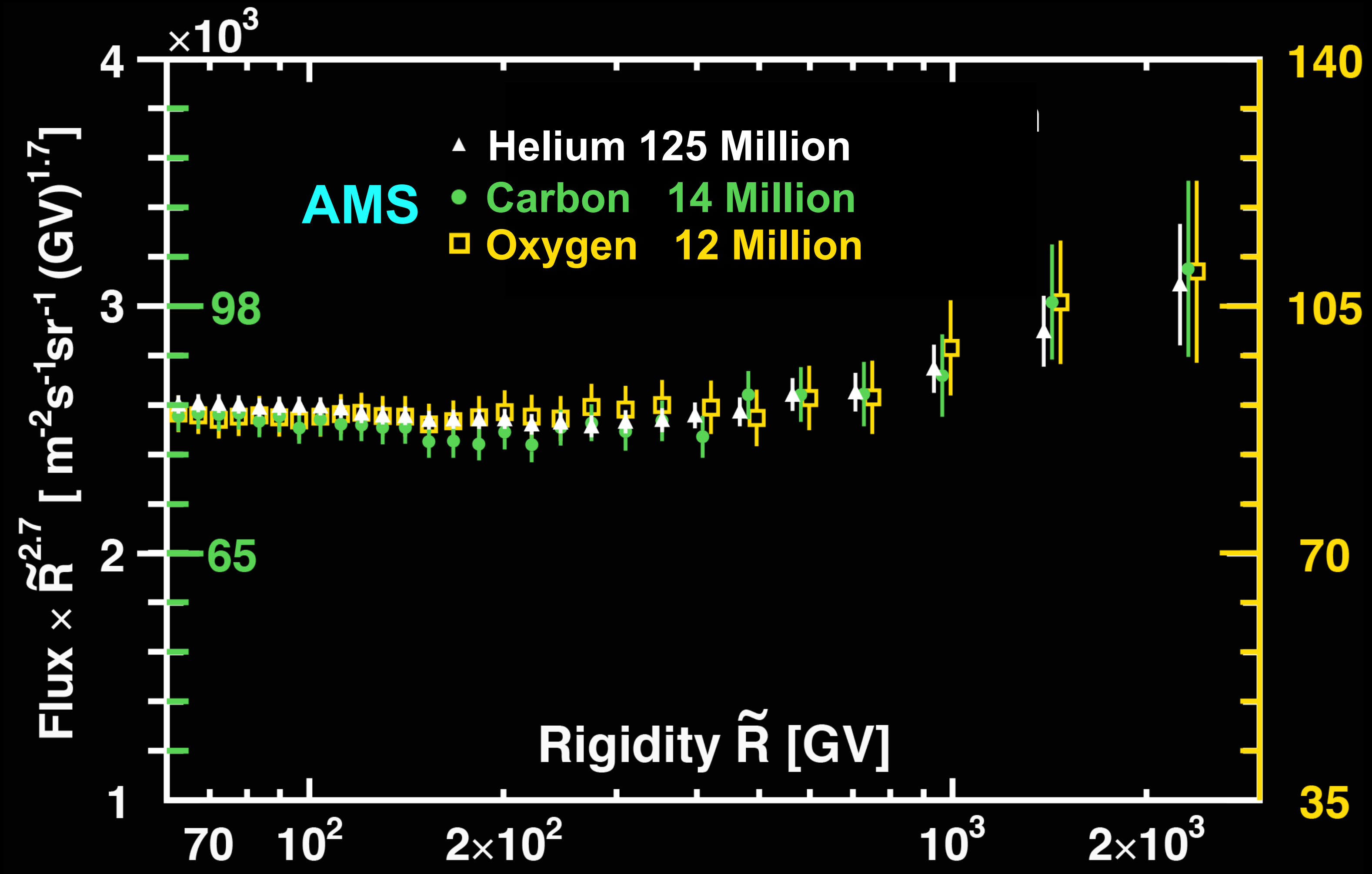
Sulfur (Z = +16)



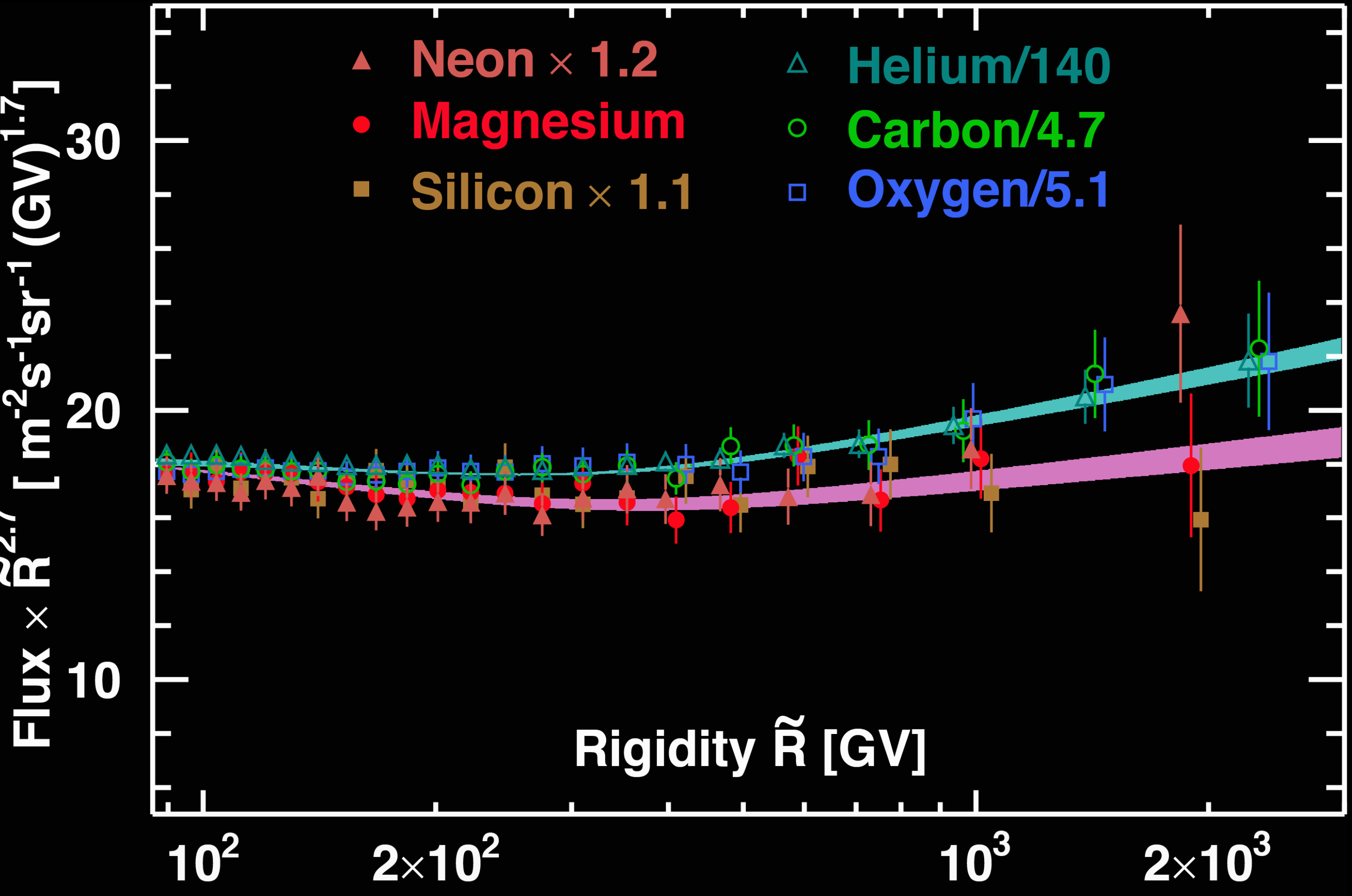
Iron (Z = +26)



Surprisingly, above 60 GV, the primary cosmic rays have **identical** rigidity (P/Z) dependence.

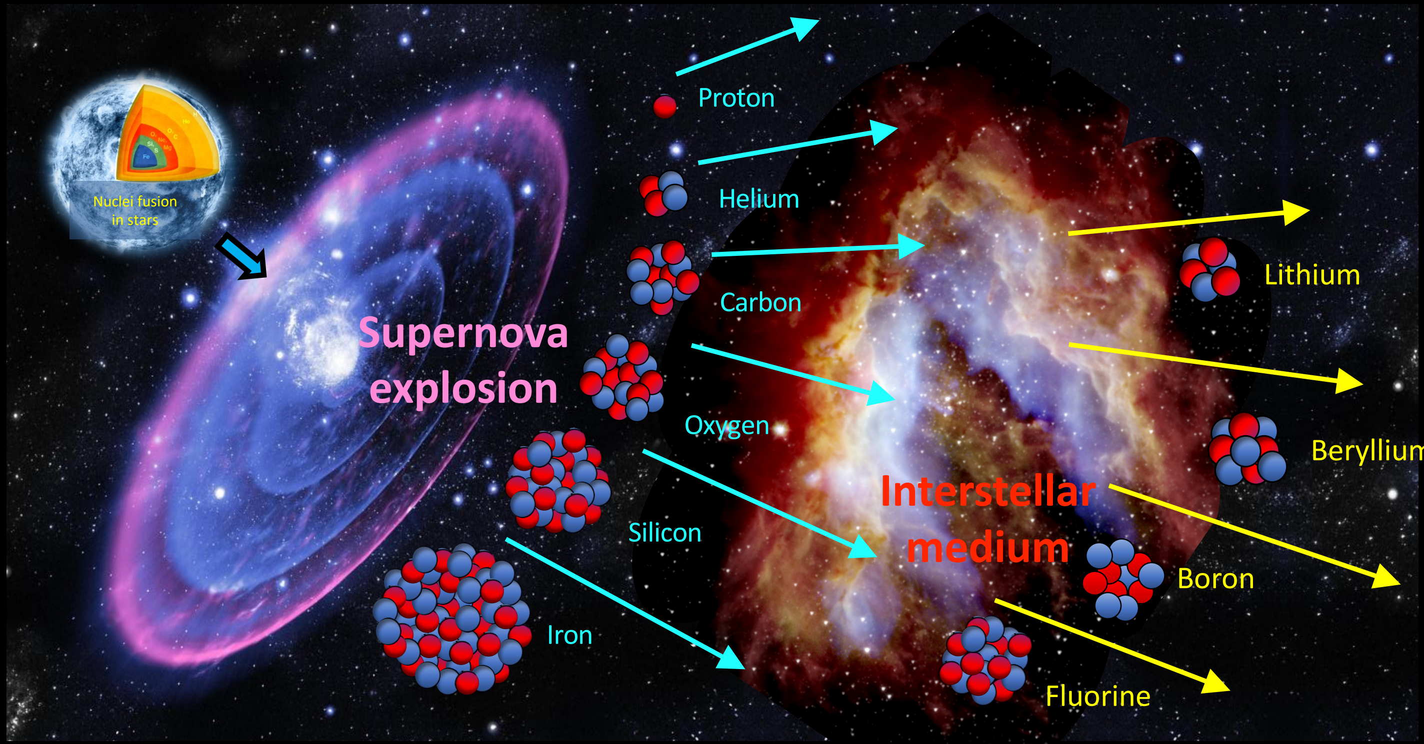


Heavier primary cosmic rays Ne, Mg, Si:
have their own identical rigidity behavior but different from He, C, O.
Primary cosmic rays have at least two classes.



Secondary Cosmic Ray Nuclei

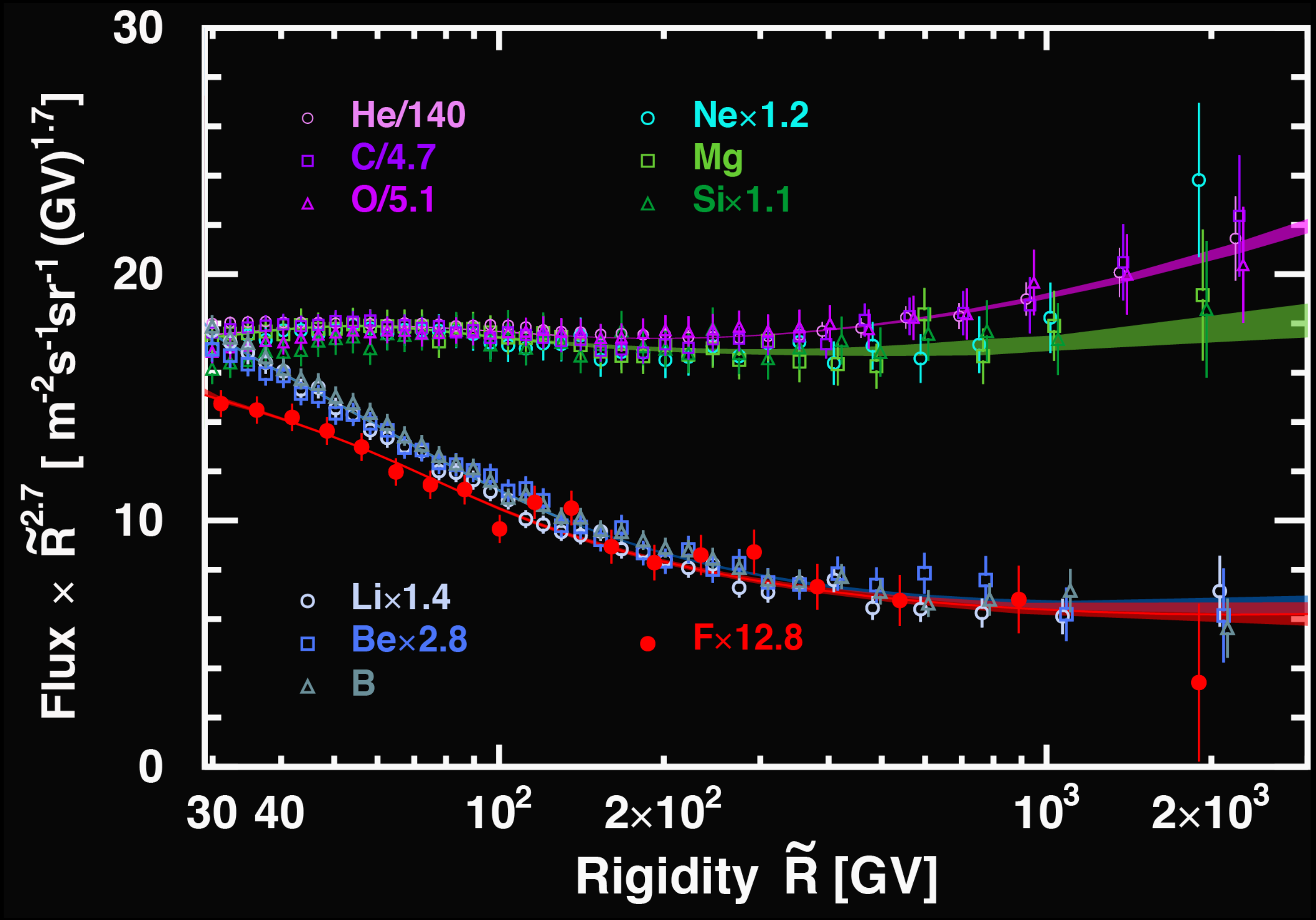
Secondary Li, Be, B, and F nuclei in cosmic rays are produced by the collision of primary cosmic ray C, O, Ne, Mg, Si, …, Fe with the interstellar medium.



Measurements of the secondary cosmic ray nuclei fluxes are important in understanding the propagation of cosmic rays in the Galaxy.

In fact, Lithium, Beryllium, Boron, and Fluorine on Earth are produced by cosmic rays.

Secondary Cosmic Rays also have two classes above 30 GV



A complex picture

Primary CRs group in two spectral classes:

- light (He-C-O) and
- heavy (Ne-Mg-Si)

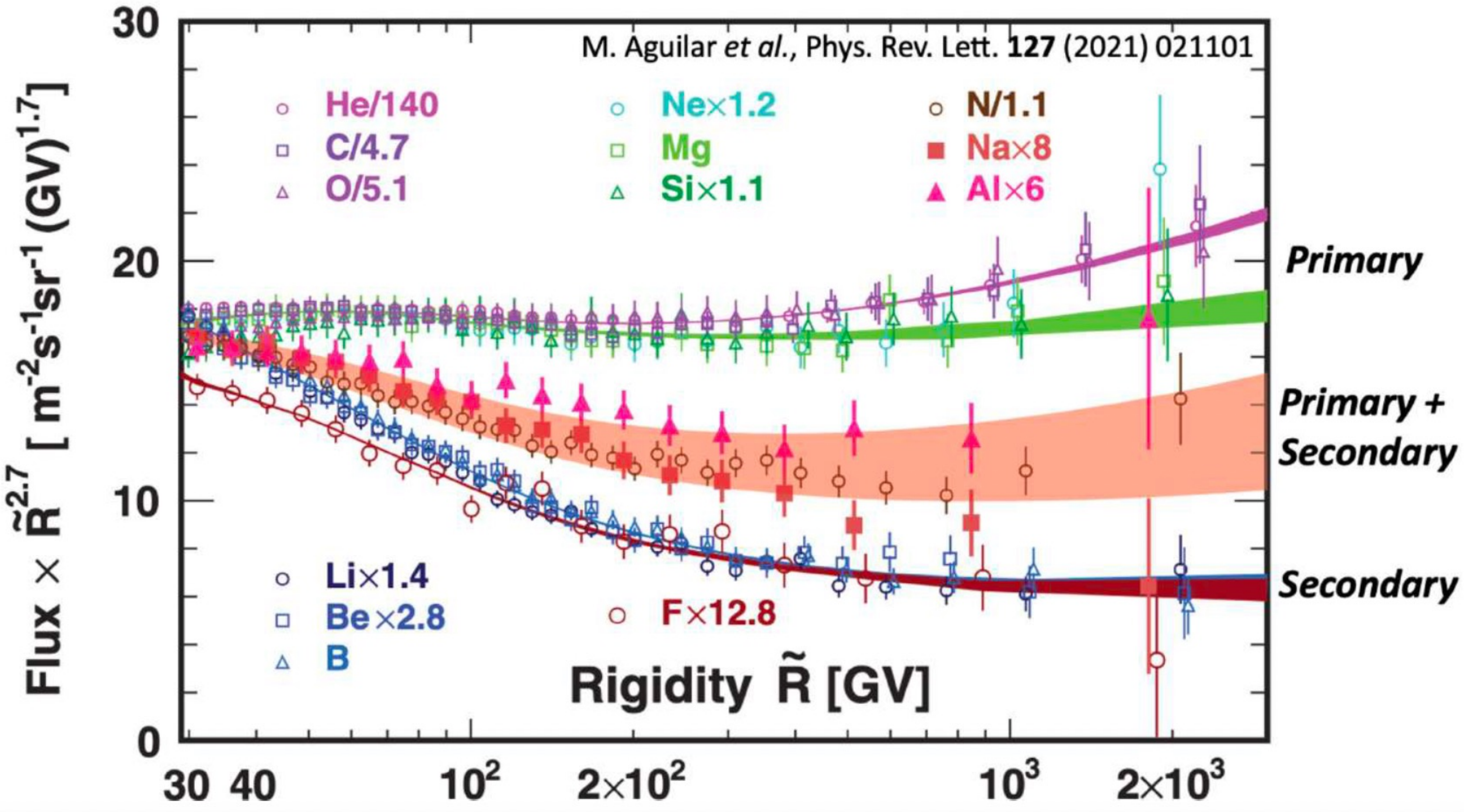
Mixed -> N, Na, and Al

- both primary and secondary CRs, mixed with different compositions

Iron

- appears to belong the same class of light primary nuclei.
- Ni looks similar to Fe.

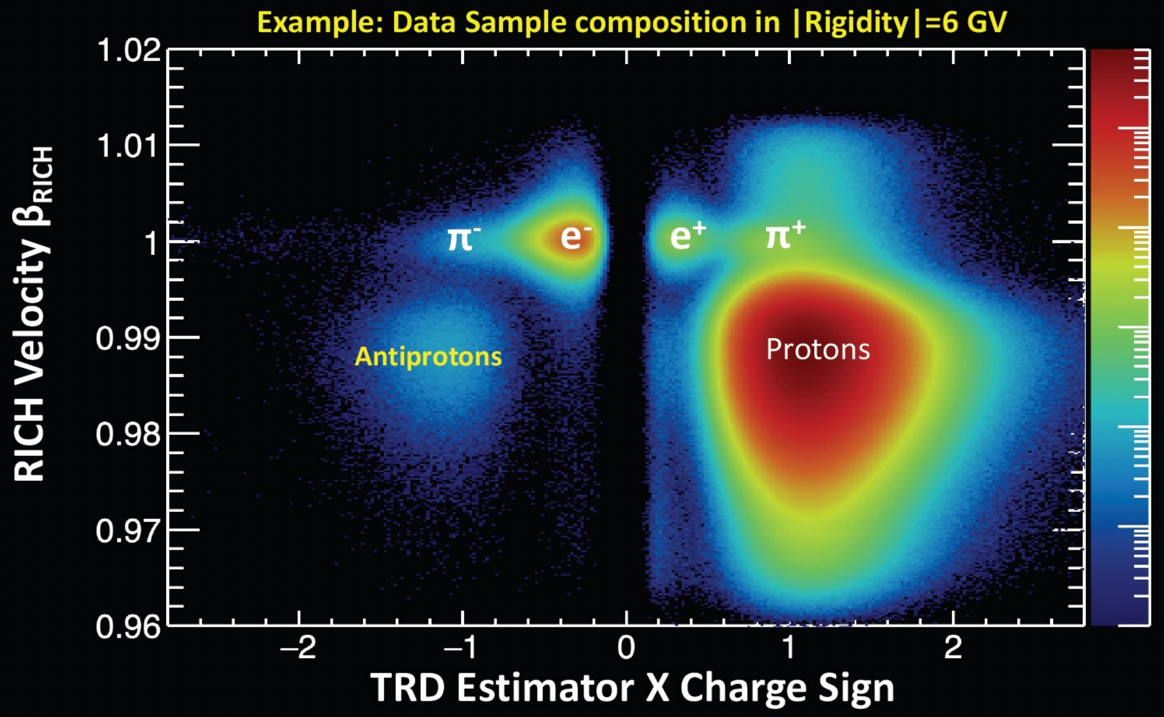
Along with p-He anomaly, hint for non-universal spectral indices for all Z>1 nuclei?

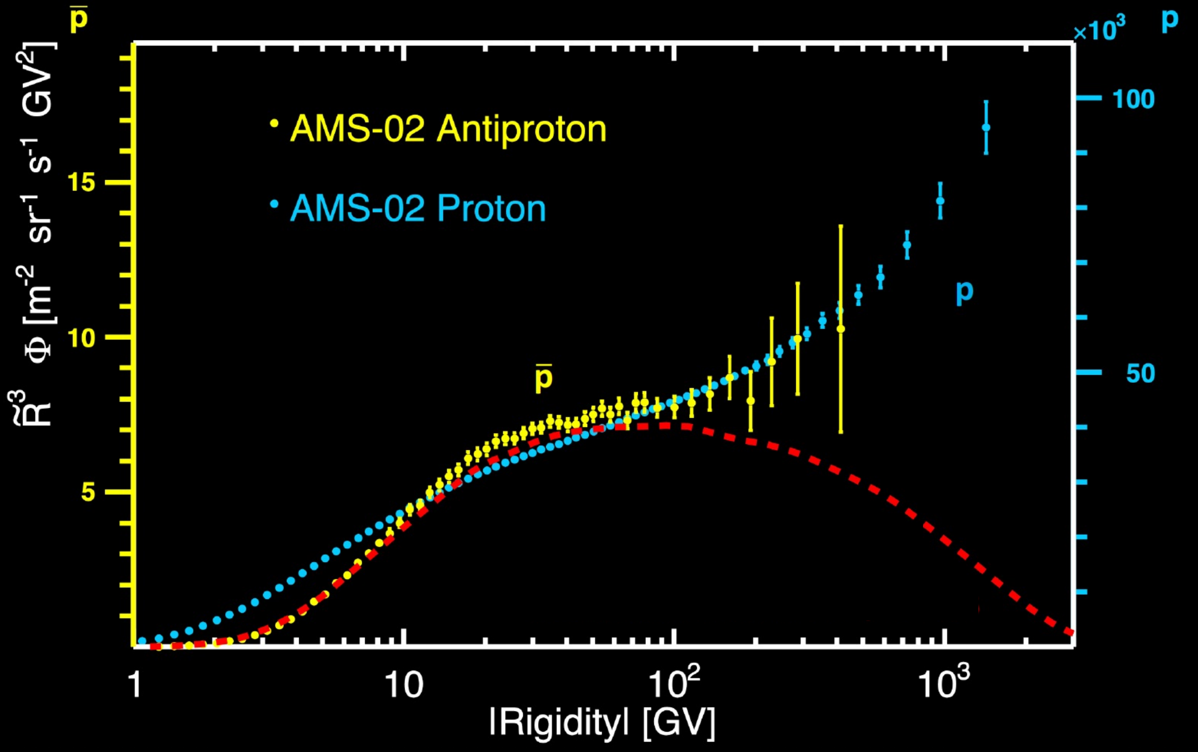


Interlude: anti-protons in CR

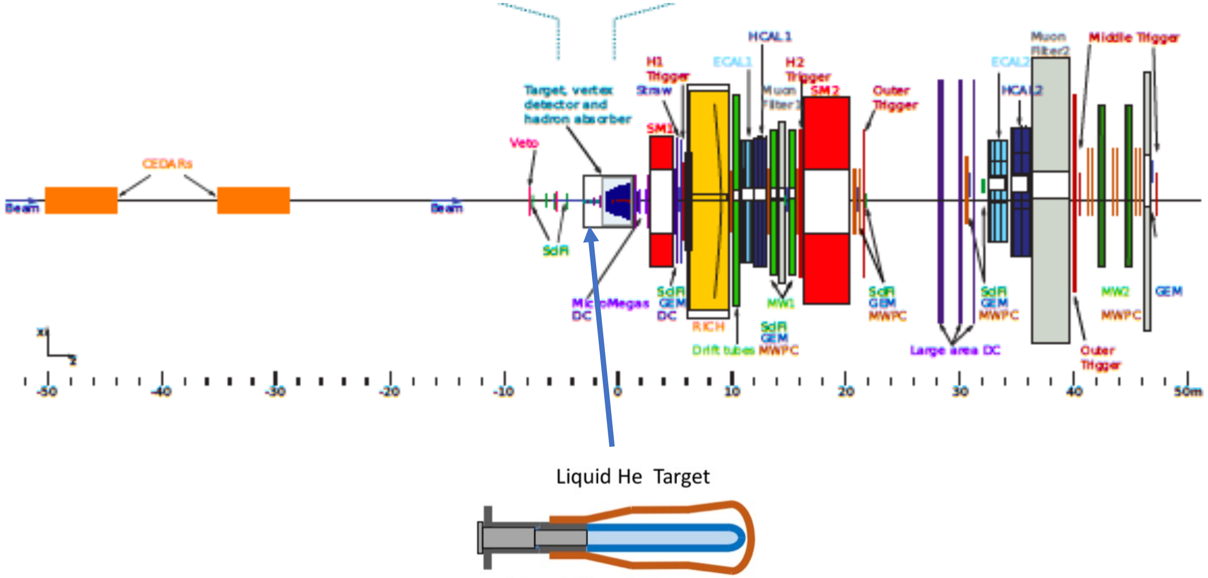
AMS anti protons

Use TOF, RICH, and TRD identify antiproton from backgrounds



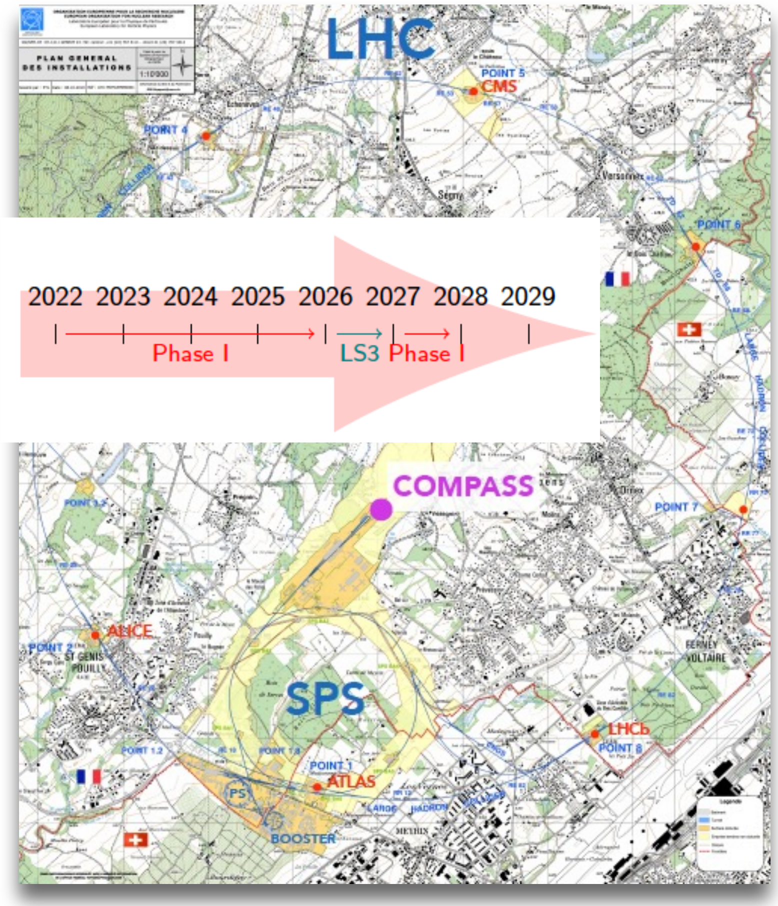


Antiproton production xsec measurement @ AMBER (NA66)



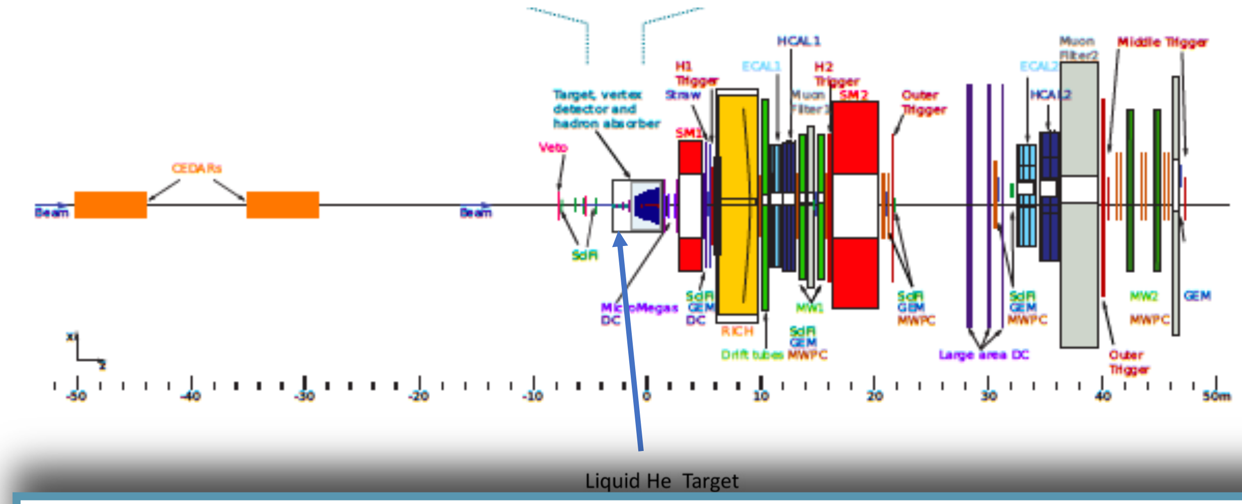
Pure LHe target :
23 % of interaction length

Measurement of p + He → pbar differential cross section
protons energies: 60, 100, 190, 250 GeV

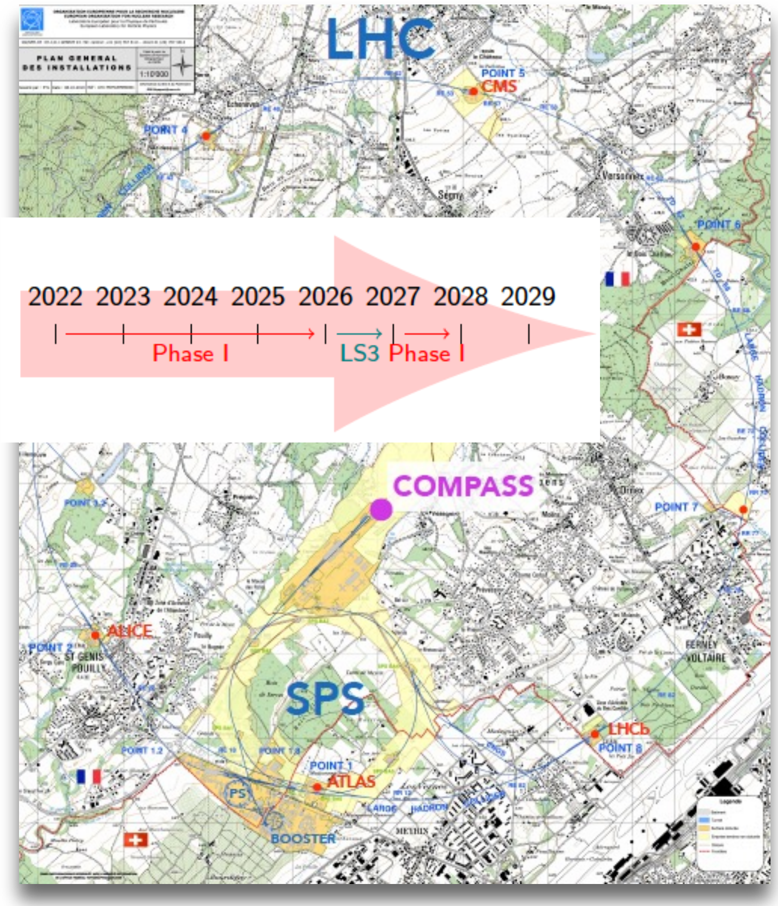


Antiproton production xsec measurement @ AMBER (NA66)

Apparatus for Meson and Baryon Experimental Research



Year	Activity	Duration	Beam
2021	Proton radius test measurement	20 days	μ
2022	Proton radius measurement Antiproton production test measurement **DONE !**	120 (+40) days 10 days	μ p
2023	Antiproton production measurement **MAY 2023** Proton radius measurement	20(+10) days 140 (+10) days	p μ
2024 2024+	Drell-Yan: pion PDFs and charmonium production mechanism	$\lesssim$ 2 years	p, K^+, π^+, $\bar{p}, K^-, \pi^-$



Anti – Matter in CR

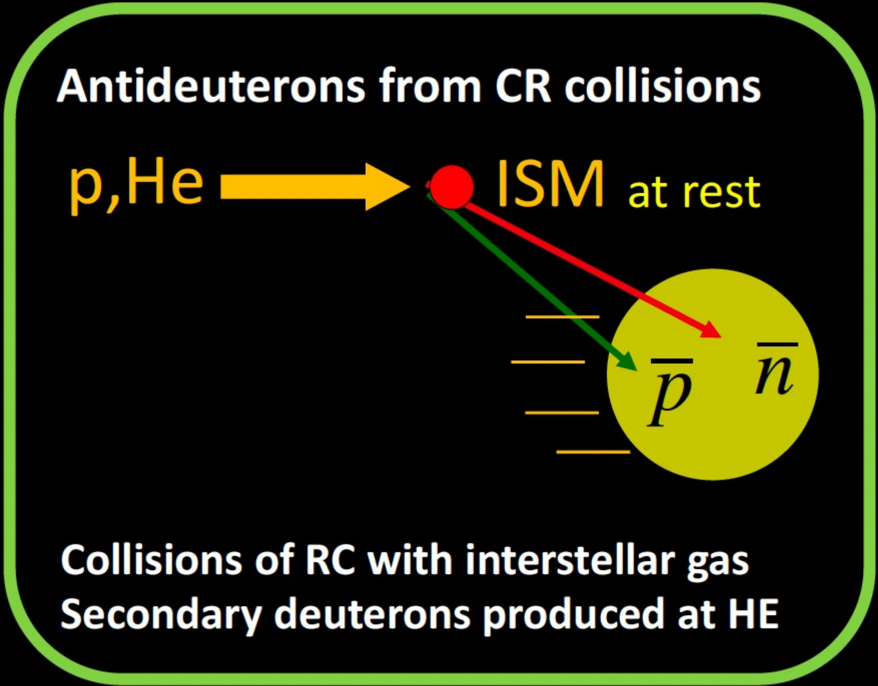
Anti-nuclei int Cosmic rays

Never detected so far in cosmic rays
May be hint of DM (anti-D and anti-^{3}He)
Are completely unexpected anti-^{4}He

AntiD searches:

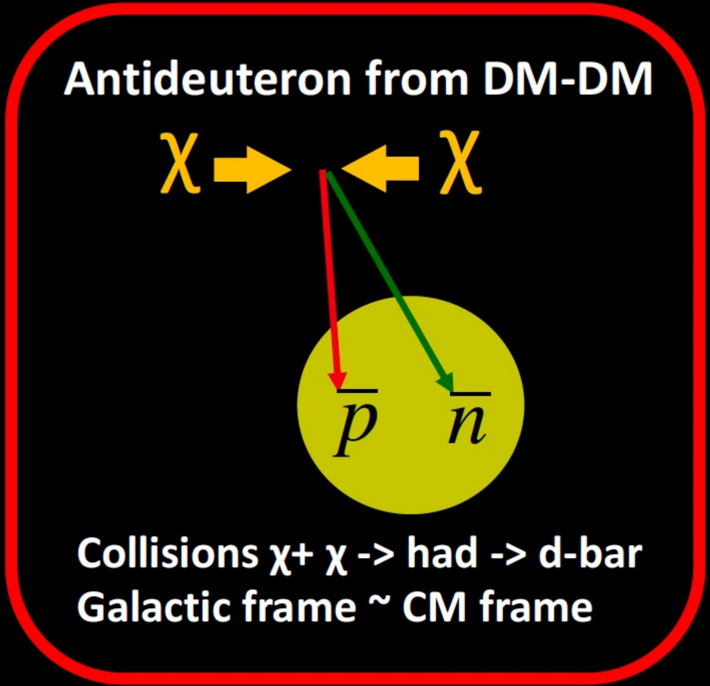
AMS-02:	above 1 GeV/n	direct
GAPS:	low energy	annihilation pattern

Example of anti-D as DM signature



Antideuterons from CR collisions

Collisions of RC with interstellar gas
Secondary deuterons produced at HE



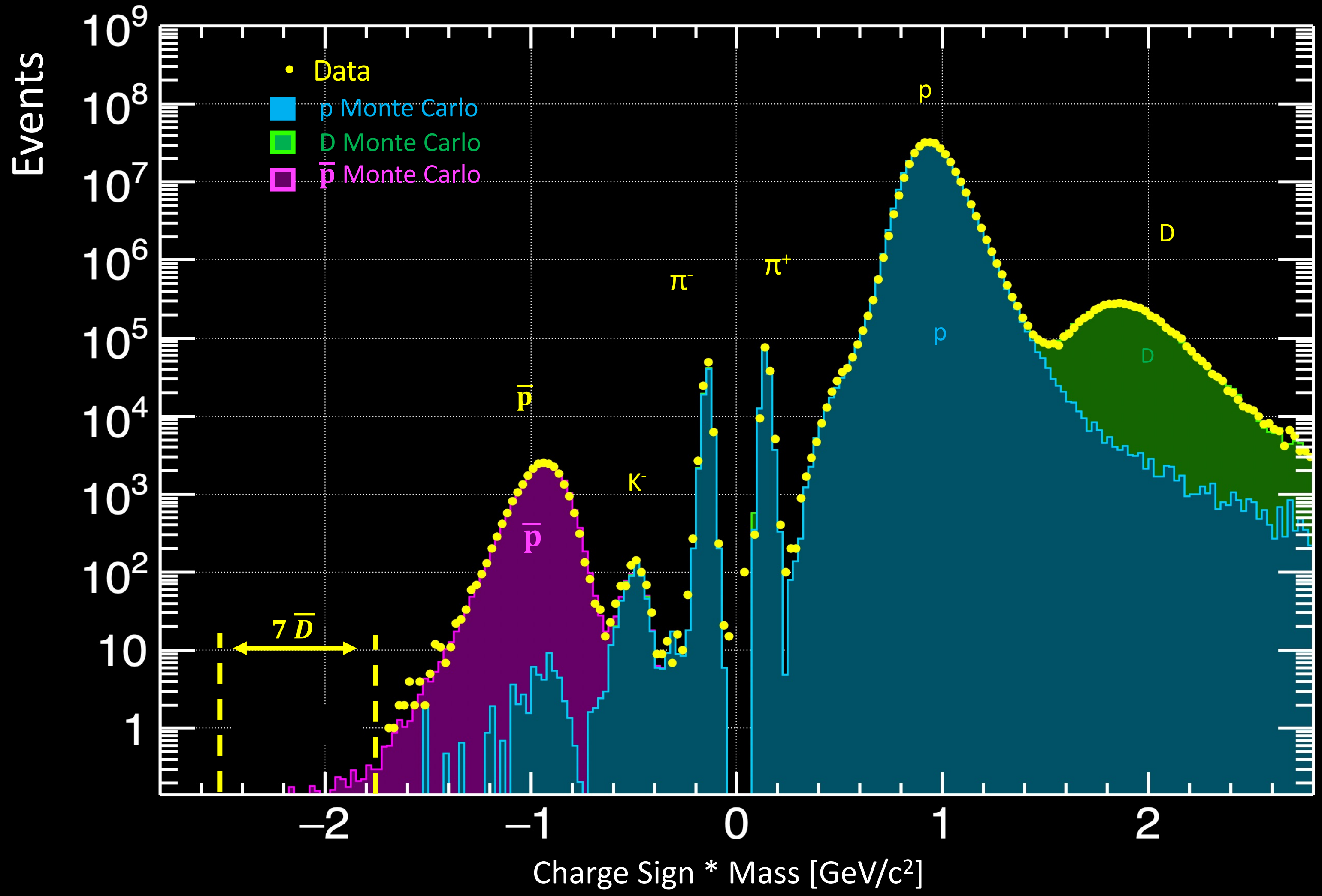
Antideuteron from DM-DM

Collisions χ+ χ -> had -> d-bar
Galactic frame ~ CM frame

AMS-02

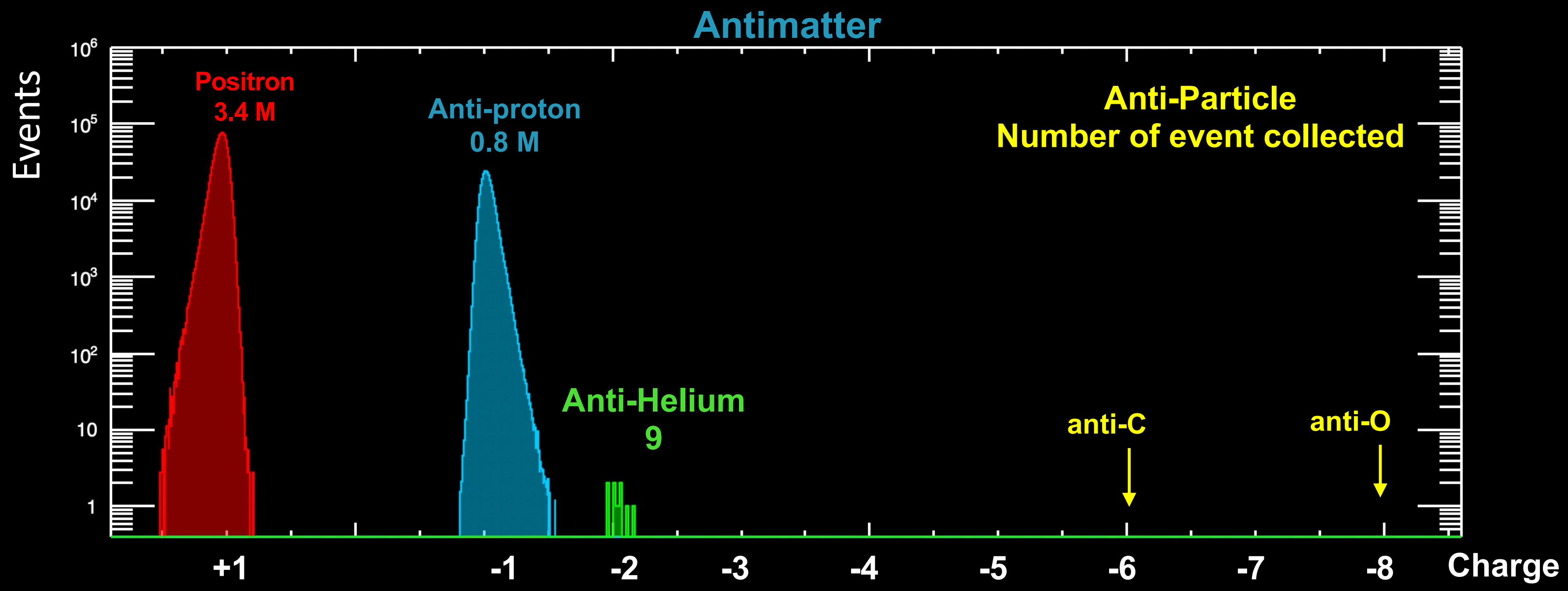
anti-D search

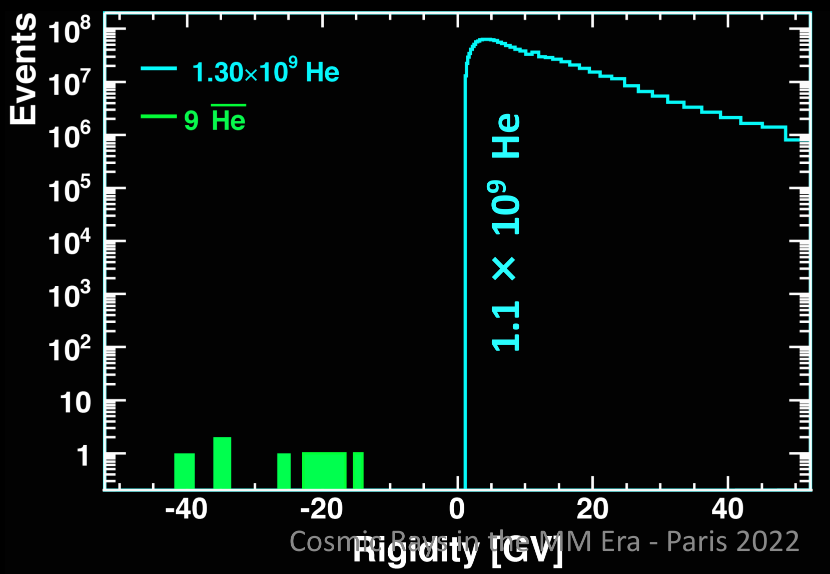
Current AMS Anti-Deuteron Status

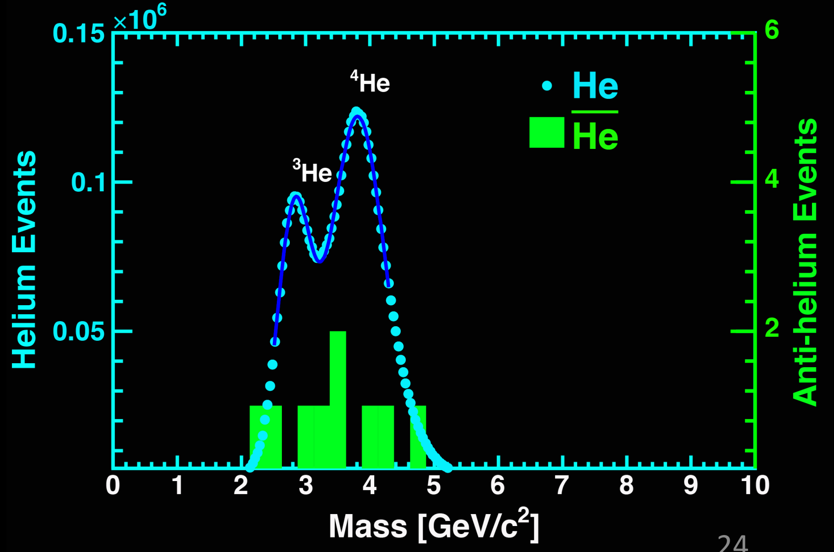


AMS-02

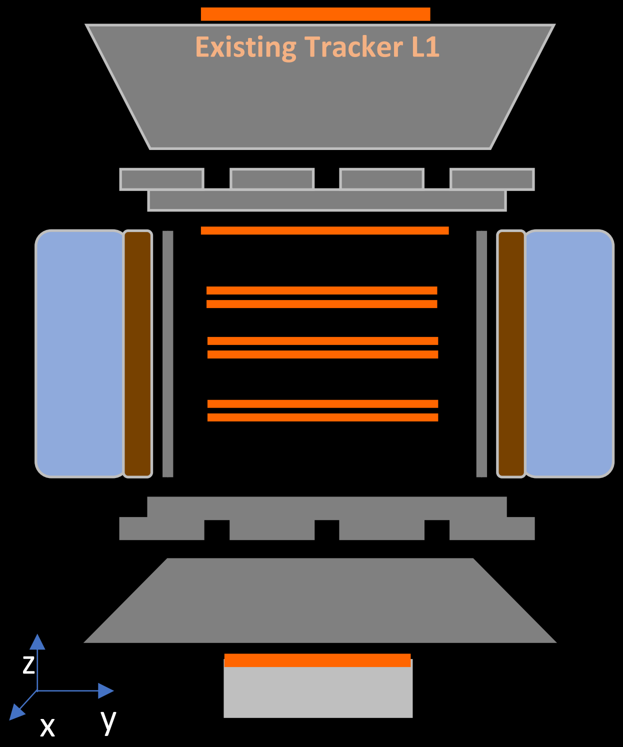
anti-He candidates up to 2020







How to improve event acceptance?

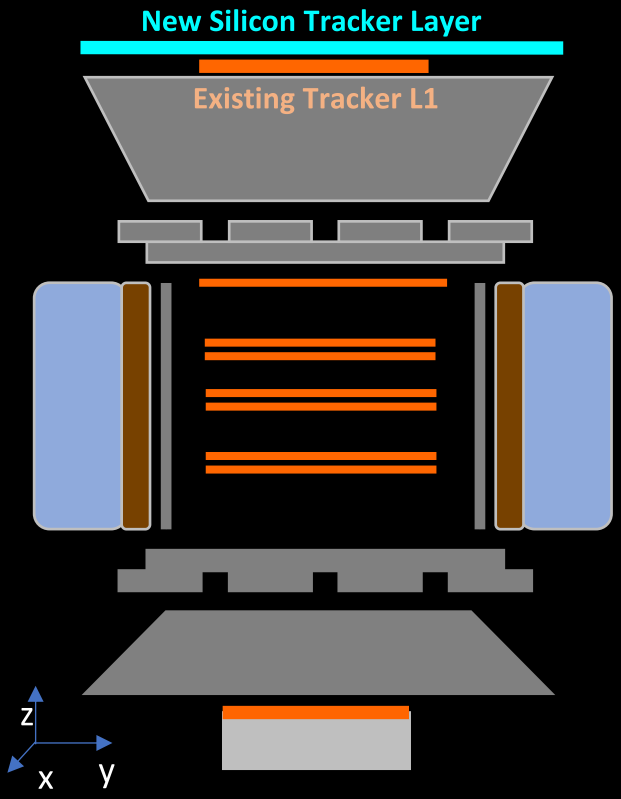


How to improve event acceptance?

3 fold acceptance improvement

The new L0 is:

- **a single mechanical object**
- **deliverable by several vectors**
- **a DAQ Slave, it just needs power, trigger/busy and a data connection**

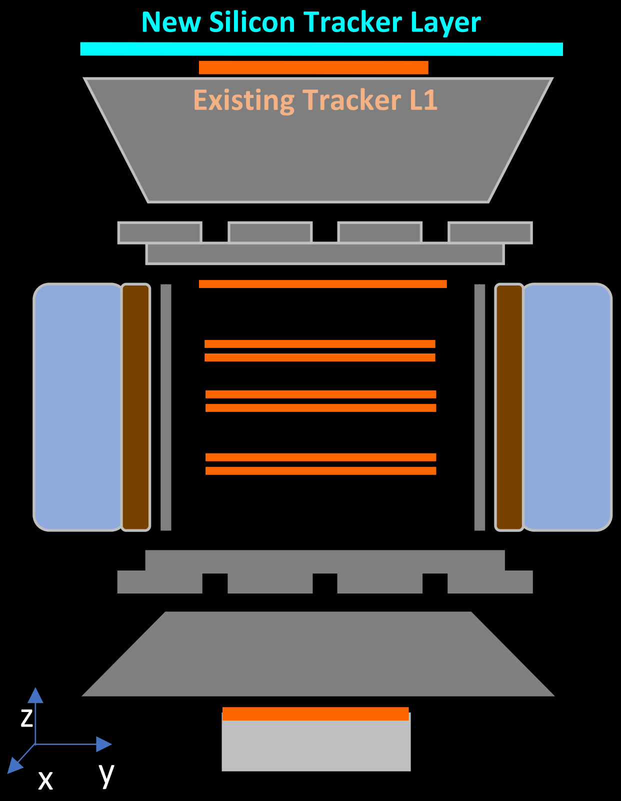


What to gain:

- **Improve positron DM search**
- **Improve anti-proton DM search**
- **Extend electron spectrum**
- **Sensitivity to anisotropies**
- **High Z elements Fe and sub-Fe**
- **Time dependence of CNO**

New Silicon Tracker Layer:
One layer, two planes, each ~ 4m^2

Acceptance increased to 300%
(10 years data becomes 30 years data)

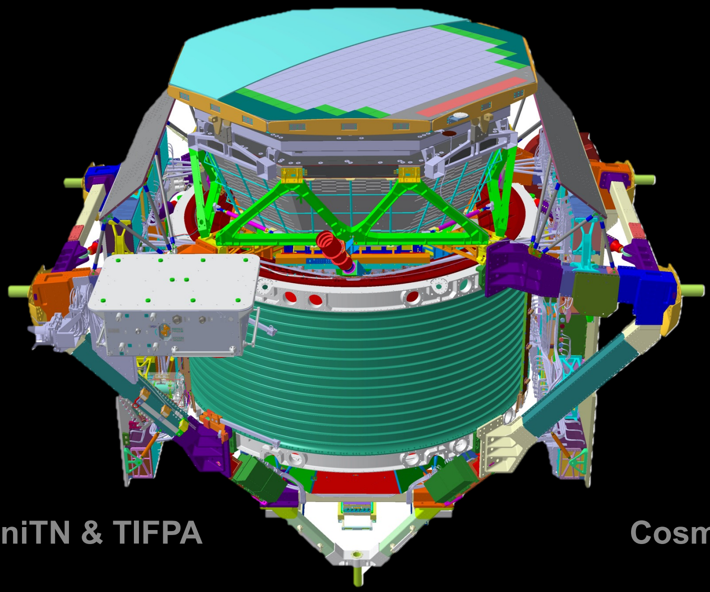


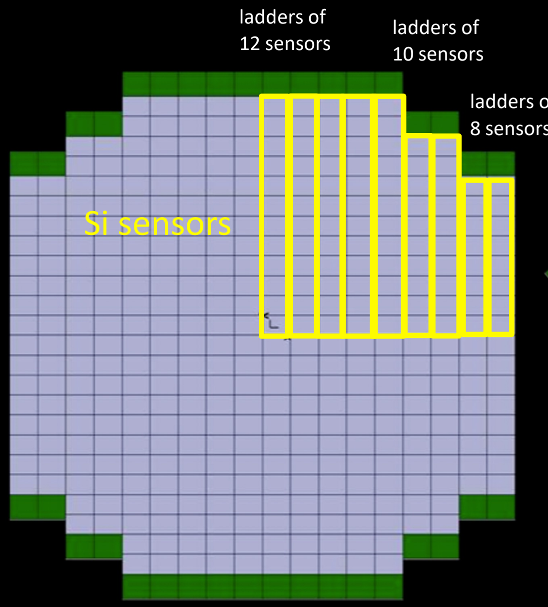
L0-Y

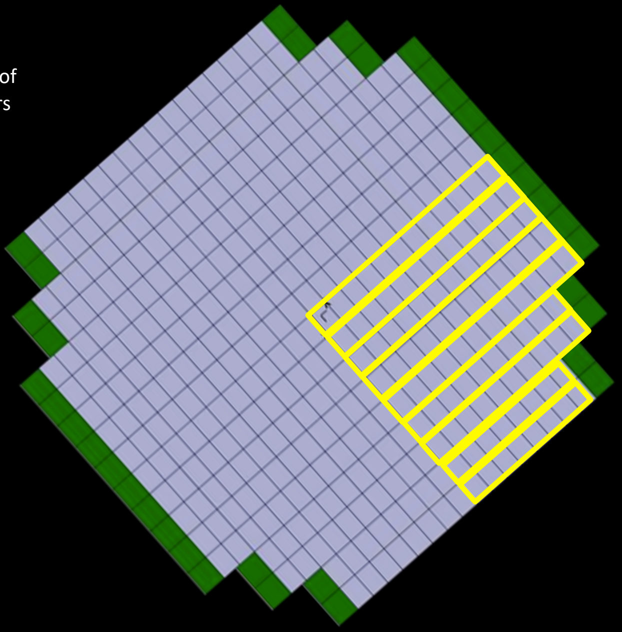
bending direction
7 micron

L0-U

rotated 45^o
10 micron bending
10 micron non-bending







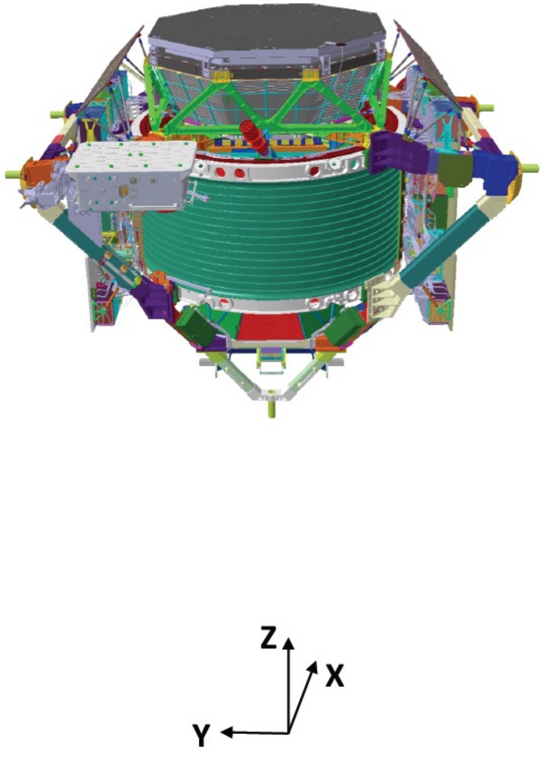
Front end electronics

L0 Real Dimensions

Layer 0 Mock-up in TERNI

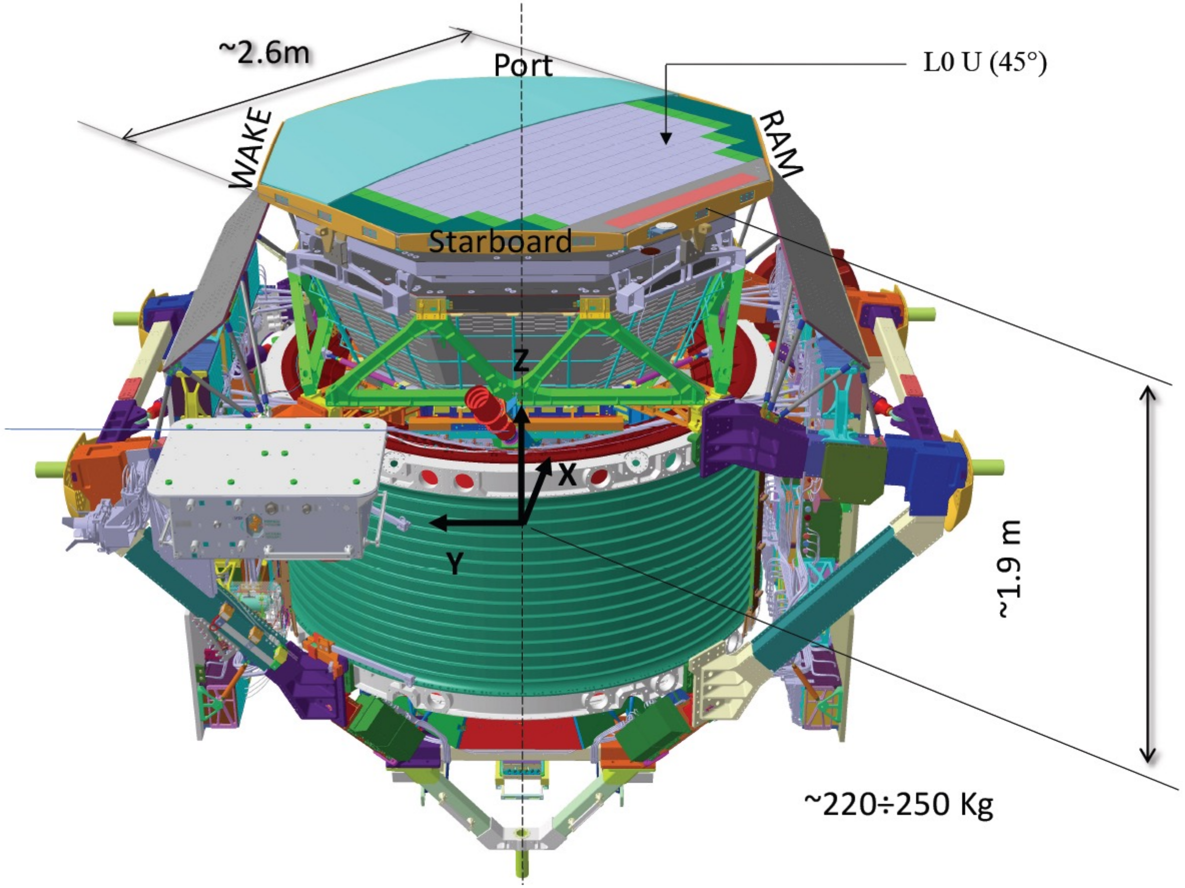
AMS Upgrade: New Tracker Layer

AMS-02 present layout



slide from Corrado

AMS Upgrade New Tracker layer



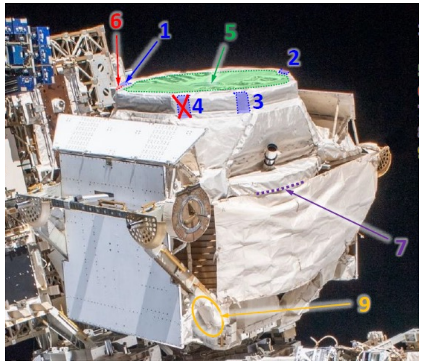
~220÷250 Kg

Initial/Notional EVA Development (cont.)

Stage 1a: Prep AMS for Tracker Install

Performed via EVA

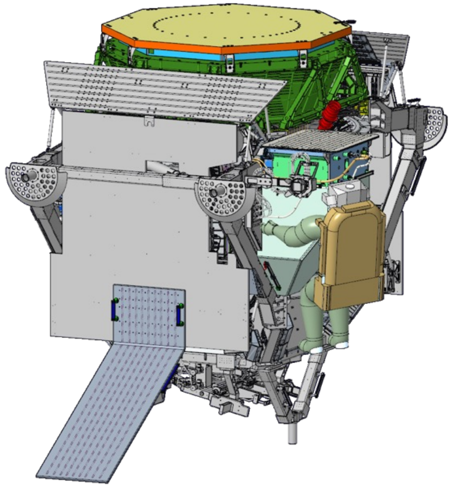
- Cut MLI
- Install Brackets
- Connect & route cables
- Relocate GPS



Stage 1b: Install Wake Radiator Supplement

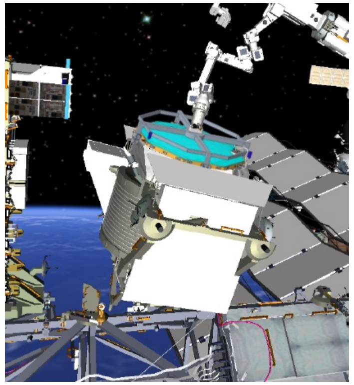
Performed via EVA

- Release 2 (of 50) – install studs
- Install bolt restraint block
- Release 48 bolts
- Retrieve Radiator
- Install



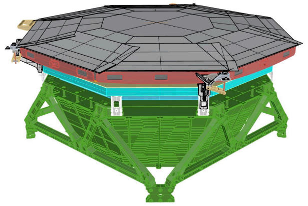
Stage 2: Install Tracker Layer 0

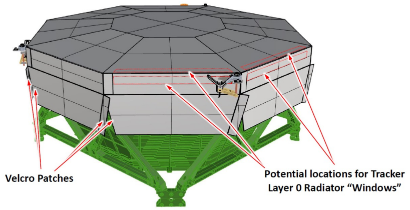
Performed Robotically between EVAs



Stage 3: Deploy MLI

Performed via EVA





Tasks distribution

NASA

- Payload integration
- ISS mechanics
- EVA and Installation
- Safety compliance

MIT

- Electronic design
- Electronic space qualification

CHINA

- SSD procurement
- Ladder integration

CERN/MIT

- General mechanic design
- Support procurement and construction
- Thermal analysis (with NASA)

TAIWAN

- Electronic procurement (VA)
- Electronic mass production and test

ITALY

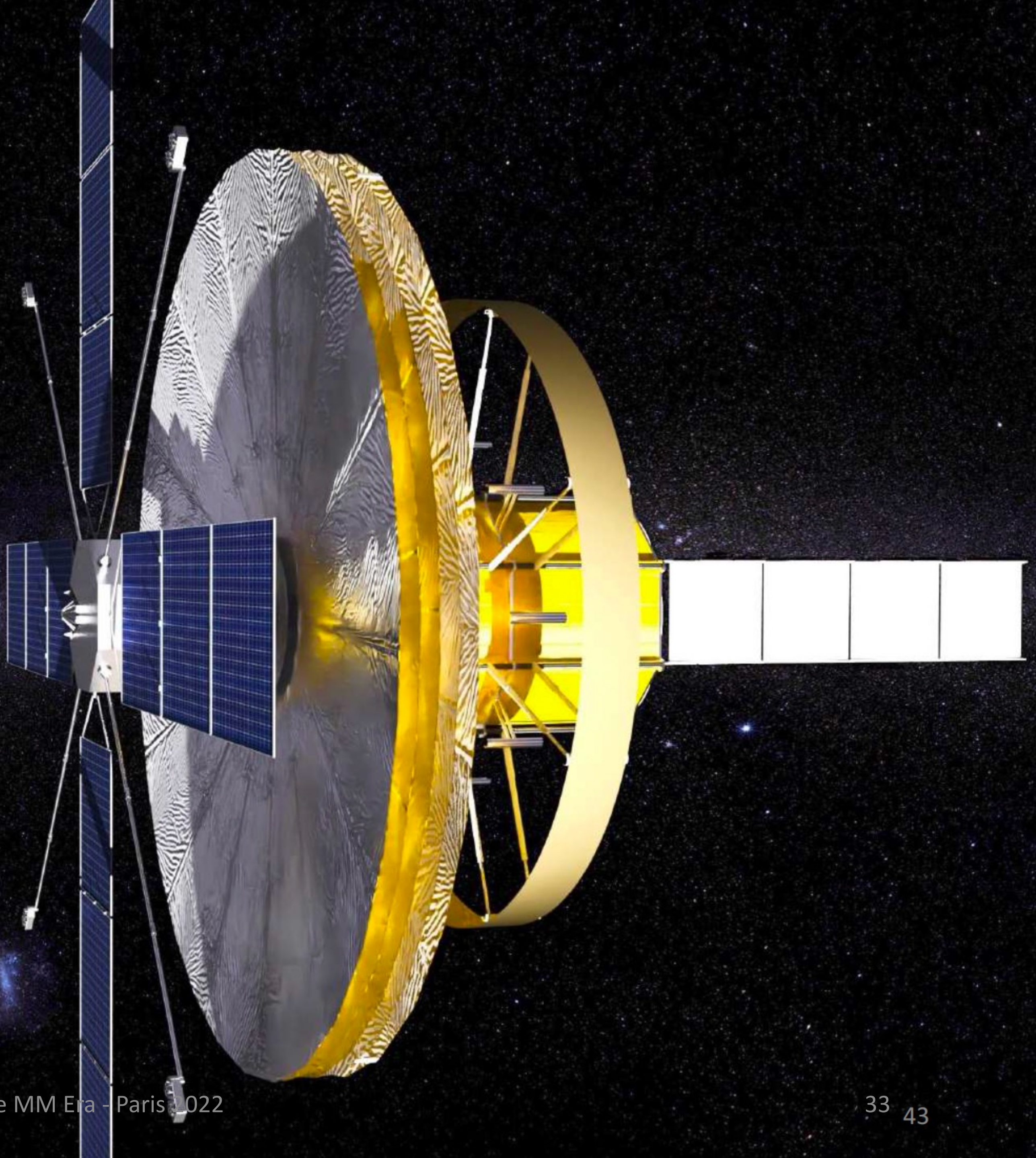
- Ladder qualification
- Ladder integration on plane
- System integration (with MIT & NASA)
- System space qualification
- Online Data Reduction

AMS Upgrade deployment 2025

Future Spectrometers

AMS-100

The Next Generation Magnetic Spectrometer



Presented at ESA call VOYAGE 2050

The Next Generation Magnetic Spectrometer in Space – An International Science Platform for Physics and Astrophysics at Lagrange Point 2

White paper: Shael et al. NIM A 944 162561 (2019)

https://arxiv.org/abs/1907.04168

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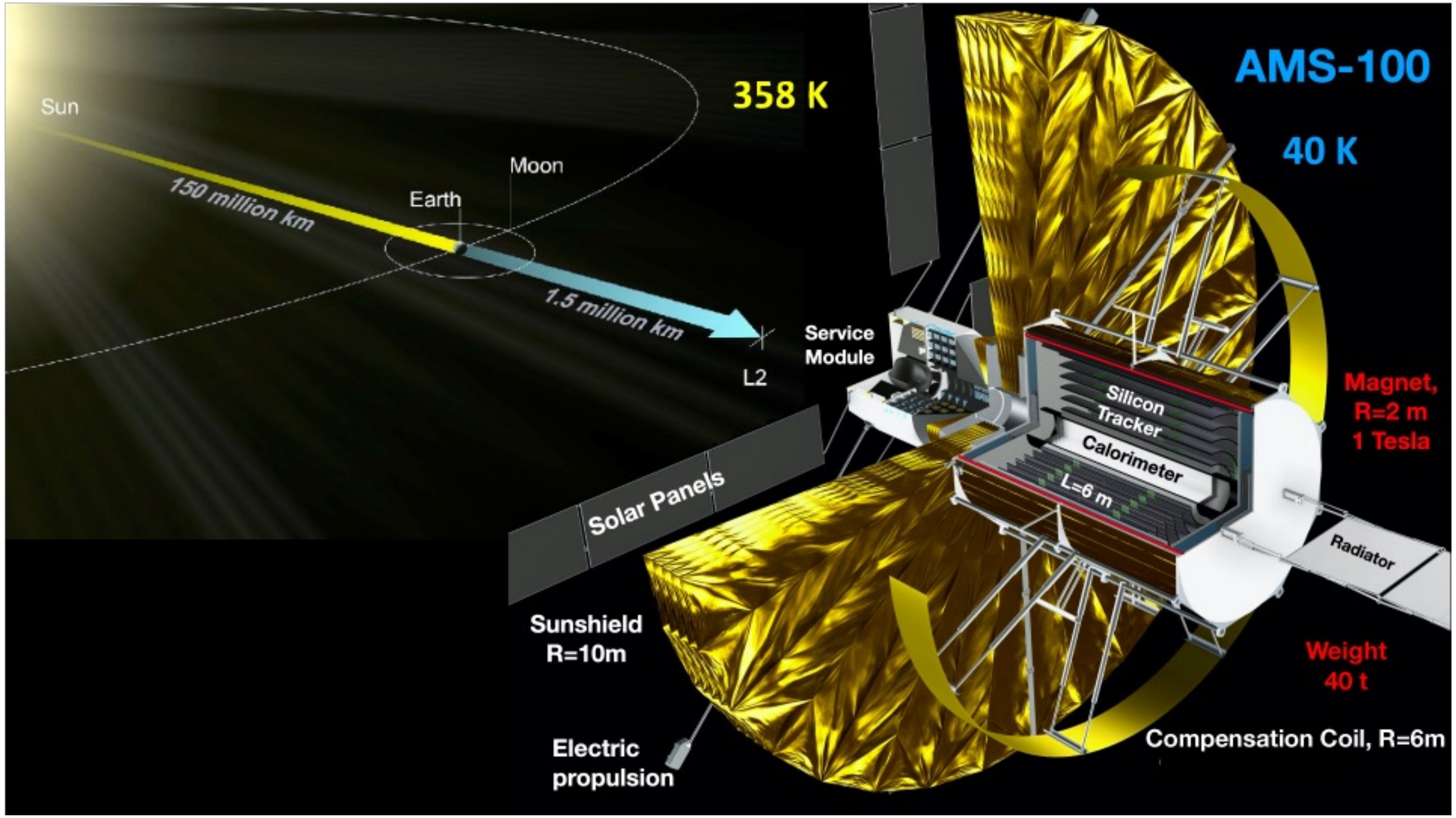
AMS-100

- AMS-100
- Lagrange point 2
- 1 Tesla magnetic, (6 Å~ 2) m
- Tracker, MDR = 100 TV
- Central calorimeter
- Targets e+, e-, nuclei (beyond the knee), antinuclei

- 40 tons -> needs heavy lifter rocket

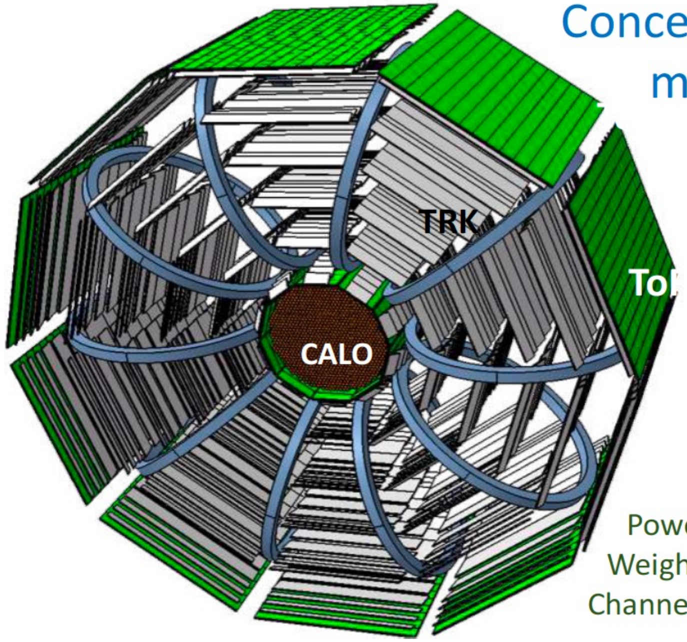


ALADInO: A Large Antimatter Detector In space

Concept for a new antimatter spectrometer to operate in L2 for measurement to extend the legacy of PAMELA and AMS-02

Core team members from IT, FR, DE, SE, CZ, CH

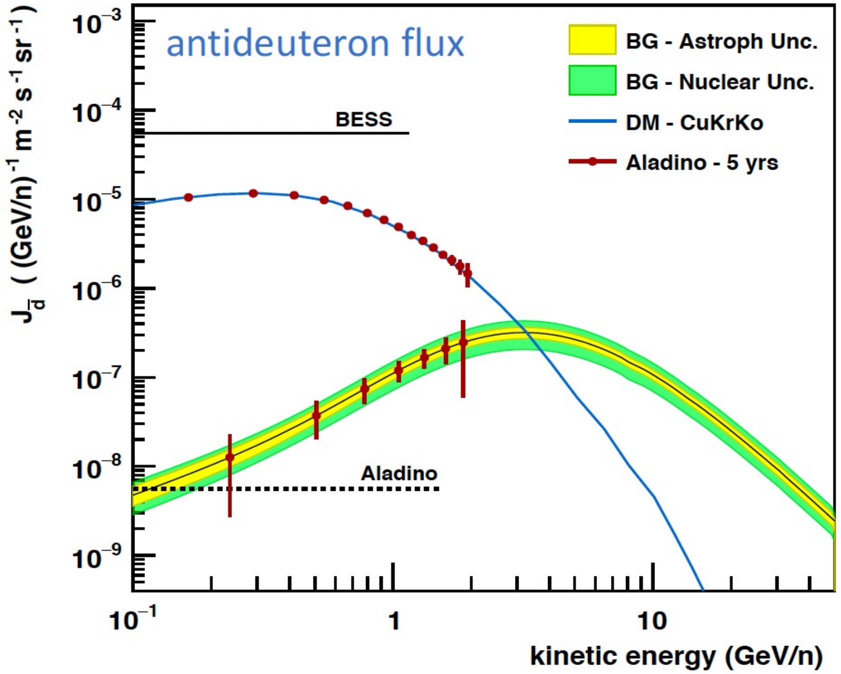
- Isotropic 3D calorimeter surrounded by a toroidal tracker & TOF
- Tracking system within high-T superconducting coils (B= 0.8 T)



Power: 4 kW
Weight: 6 Tons
Channels: 2.5 M

Total acceptance	10 m^2sr	Calo resolution	2% (e) – 30% (N)
MDR	20 TV	TOF resolution	100 ps

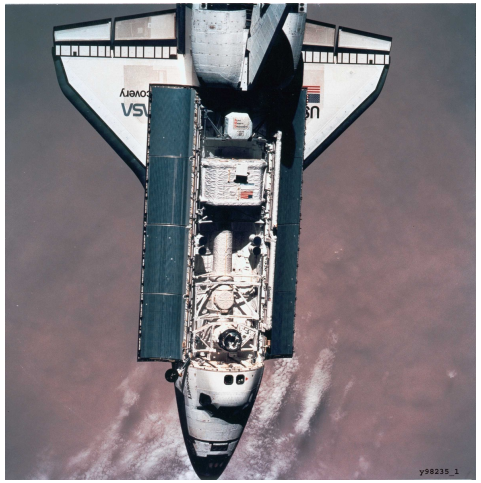
- Concept and science case: Battiston+ Exp Astr 51, 1299 (2021)
- Instrumental performance: Adriani+ Instruments 6(2), 19 (2022)



The quest for antimatter: near future

Alpha Magnetic Spectrometer - 01 (AMS-01)

- ~ 2 tons
- Same orbit of the ISS and of AMS-02
- 10 days of mission on board the Space Shuttle Discovery mission STS-91, June 1998



Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA)

- 470 Kg
- On board Resurs-DK1 satellite
- 15 June 2006 – 7 February 2016

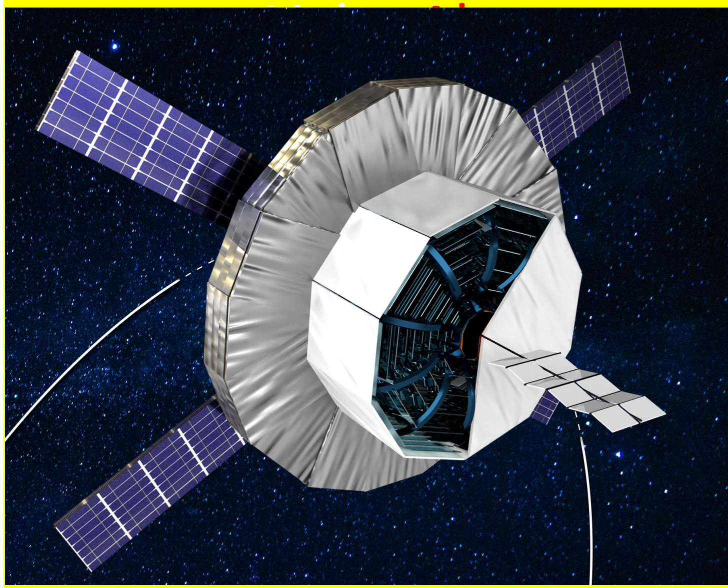
Alpha Magnetic Spectrometer - 02 (AMS-01)

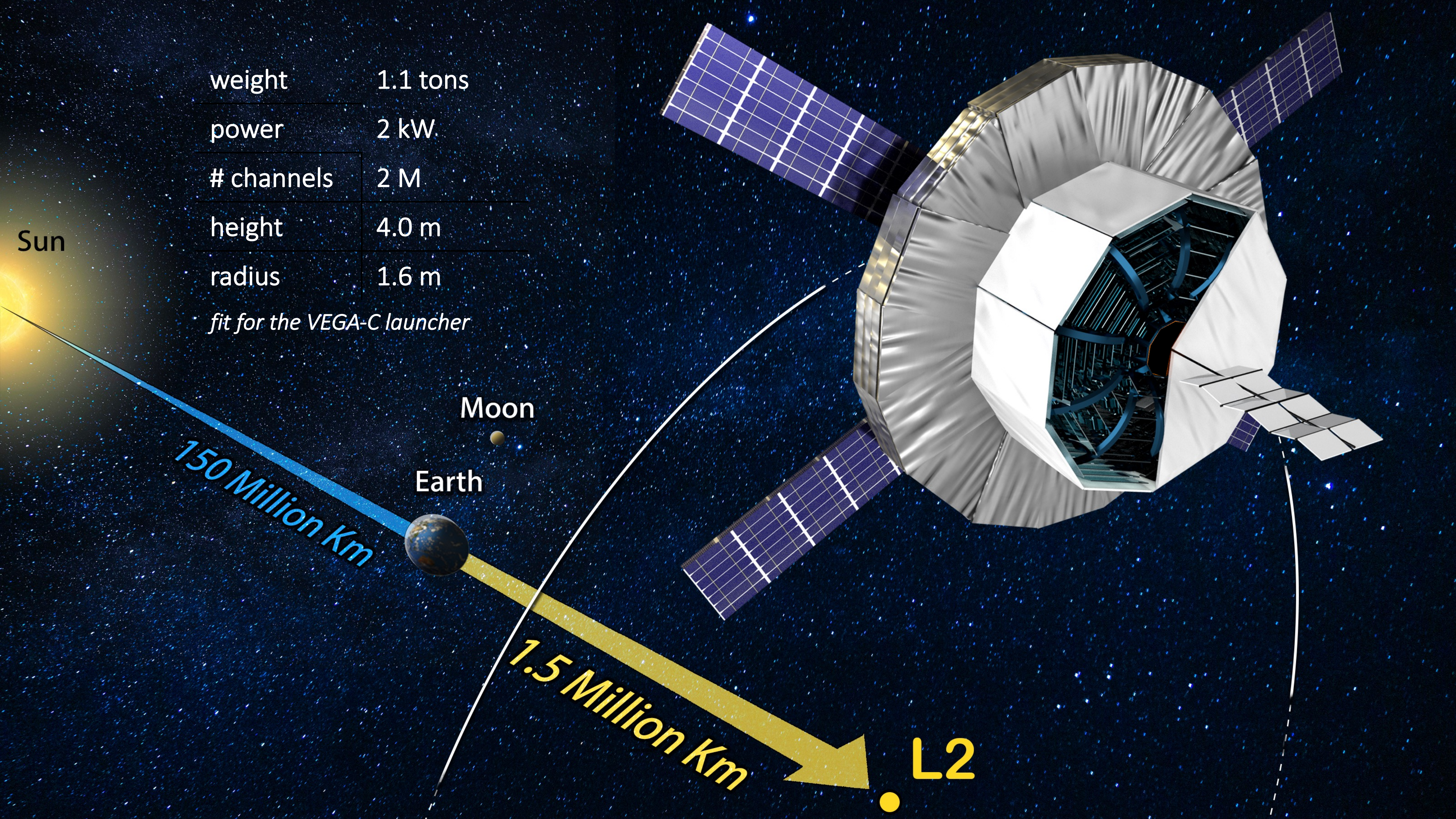
- ~ 6.7 tons
- on-board the ISS
- in operation since 2011. Operations expected to last until **2030**

Light Aladino-like Magentic sPectrometer

LAMP

- ~ 1.1 tons
- L2 or LEO
- Launch by 2032.
- 10 years of operations



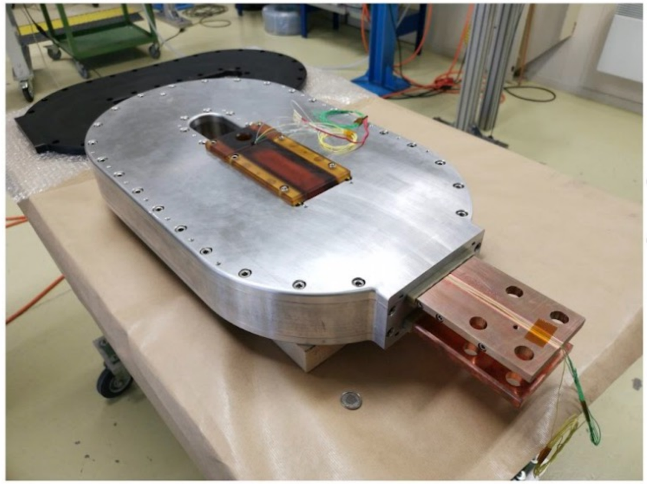


weight	1.1 tons
power	2 kW
# channels	2 M
height	4.0 m
radius	1.6 m

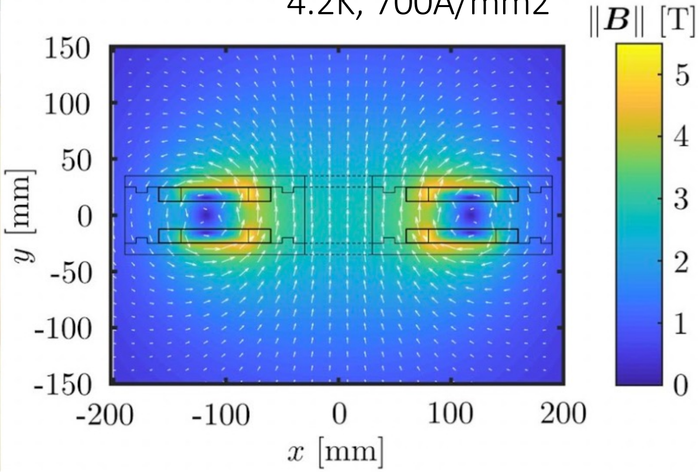
fit for the VEGA-C launcher

Magnet

Measuring the momentum means tracking inside a magnetic field. The field is also the only way to measure the sign of the charge, i.e. to distinguish from antimatter. For a compact experiment, high-fields are needed, attainable with superconducting magnets.



4.2K, 700A/mm2



Demonstrator coil constructed within the **HDMS project, funded by** **ASI and CERN**. **Innovative self-protection concept** against quenching. It is built with metal-insulated cable, to allow current sharing between winding turns. Metal insulation technique makes the winding self-protected, a key feature in a space environment. Metal-Insulation also enhances the turn-turn thermal conductivity, favoring the cooling of the magnets, so that cryocoolers of a few W at 10-20 K are sufficient to guarantee safe operation.

High Temperature Superconducting (HTS) magnets (YBCO or MgB2) could be operated in space at 20 K, greatly simplifying the problem of cryogenics, even allowing to rely exclusively on cryocoolers. **The use HTS magnets for space is unprecedented and it has no state-of-the-art reference to compare with.**

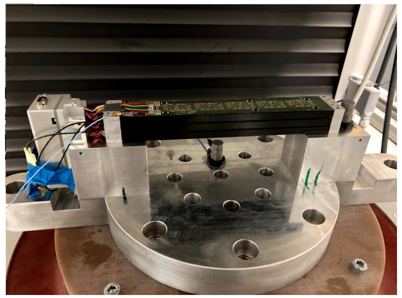
Concerning the cooling system, it is worth recalling that cryocoolers have been already used in space missions and the AMS-02 collaboration itself designed and fully qualified commercial Stirling-cycle devices.

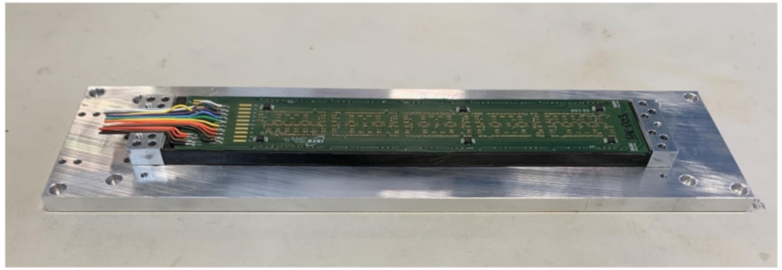
Tracker

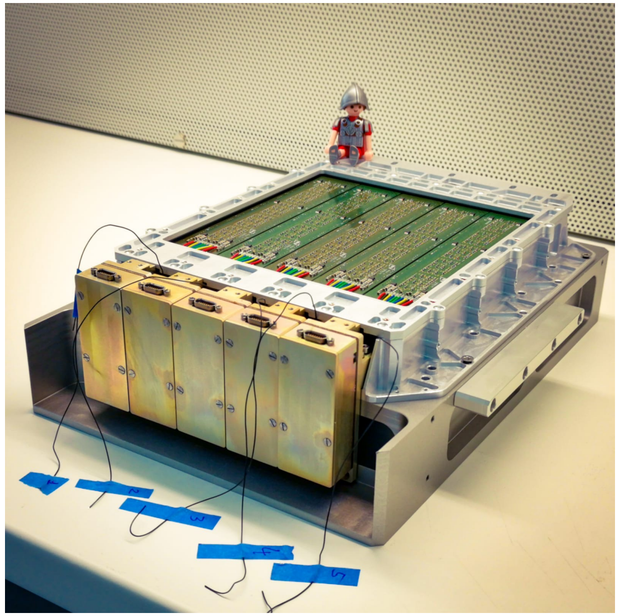
Measuring the momentum is a key-feature for cosmic-ray antimatter physics. Single hit resolution, and large acceptance and magnetic field are the figures to maximize.

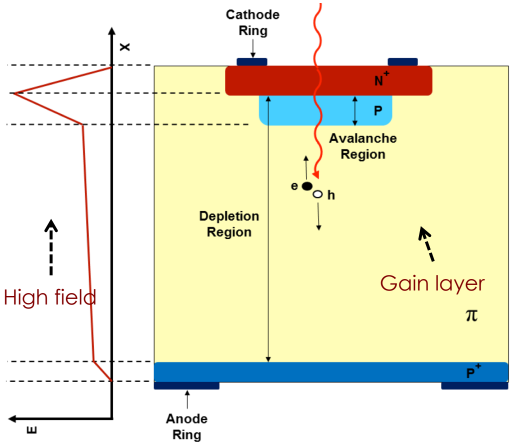
Monolithic Active Pixel Sensors (MAPS) are one of the most innovative approaches to particle tracking. CMOS-fabricated, they feature in-pixel electronics, with unparalleled low-noise and O(um) single hit precision.
Spatialized for the INFN-ASI project HEPD for the CSES-02 mission. Current developments focus on (i) lowering power consumption, (ii) enabling timing capability and (iii) increasing the sensor area.

Low Gain Avalanche-Diodes (LGAD) are a promising apporoach to particle tracking. Ultra Fast Silicon Detectors have been developed by INFN-TO (N. Cartiglia) and the R&D is carried forward in collaboration with FBK. Current developments focus on enhanced timing capability.

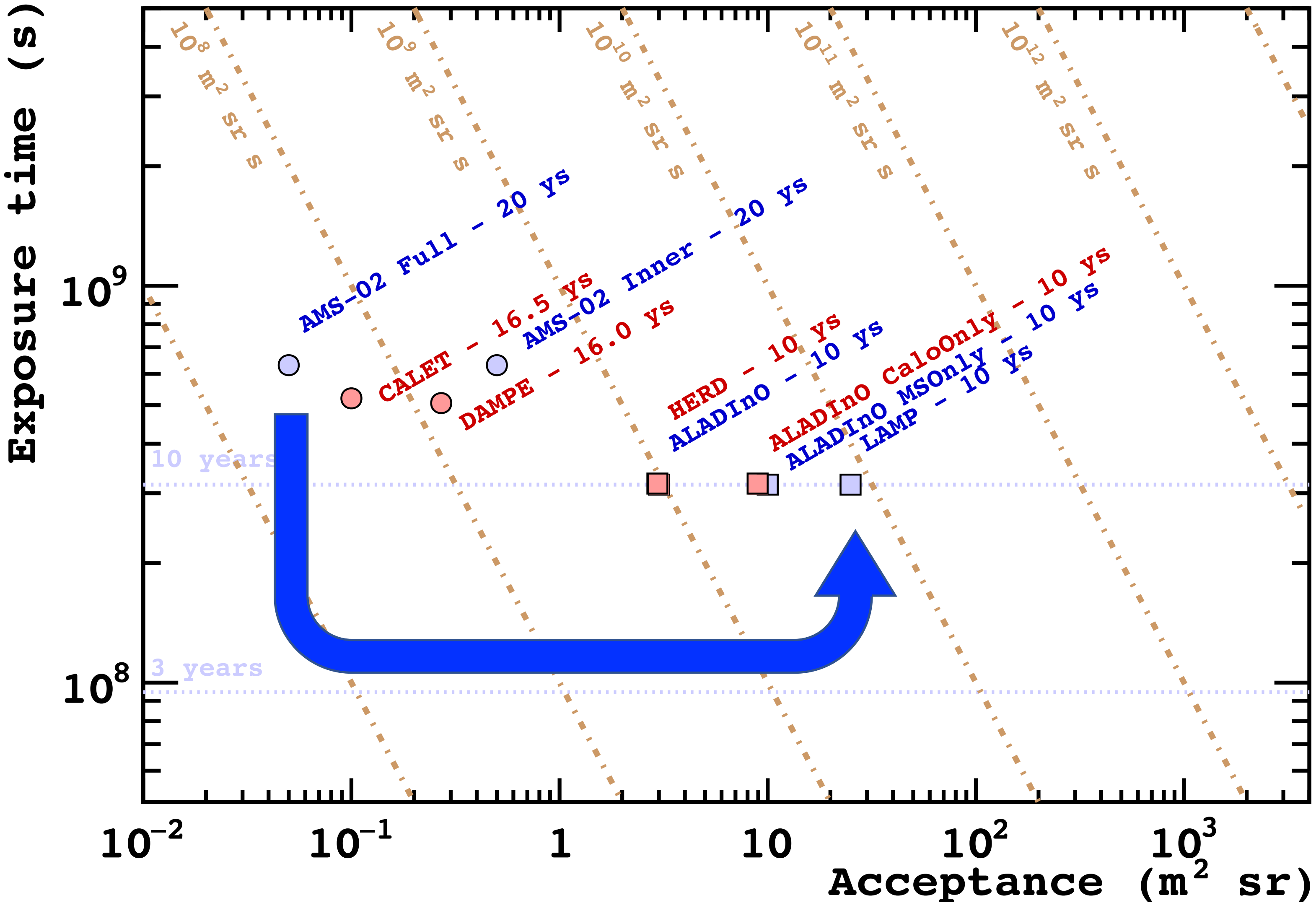








Light Aladino-like Magnetic sPectrometer



LAMP maintains the geometry of ALADInO, but **focuses on nuclear antimatter**. It features increased acceptance for the magnetic spectrometer and auxiliary detectors (TOF, Cherenkov), saving mass with a calorimeter-free approach. **More than a factor of 30 is gained in acceptance over AMS-02.**

Summary

- We live in the era of precision Cosmic Rays physics
- Current experiments provide a lot of accurate data about elementary particle and nuclei fluxes and new windows open at high energies
- new hints about cosmic anti-matter are fascinating -> dedicated mission ?
- we need a wide effort to launch in space the next generation magnetic spectrometer