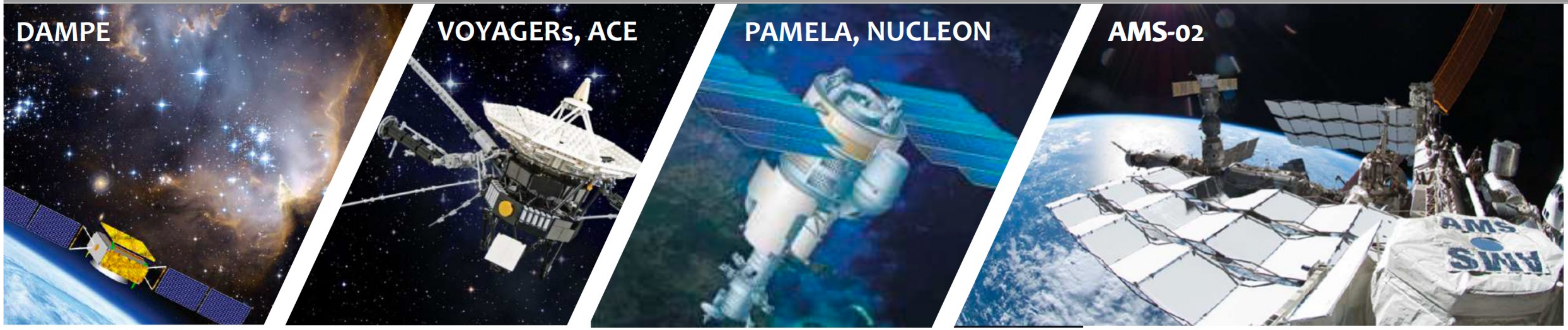
12th Cosmic Ray International Seminar
Naples, Italy, September 12 -16, 2022

Direct Cosmic Rays Measurements from Satellite

P. Zuccon – Trento University and TIFPA

Outline

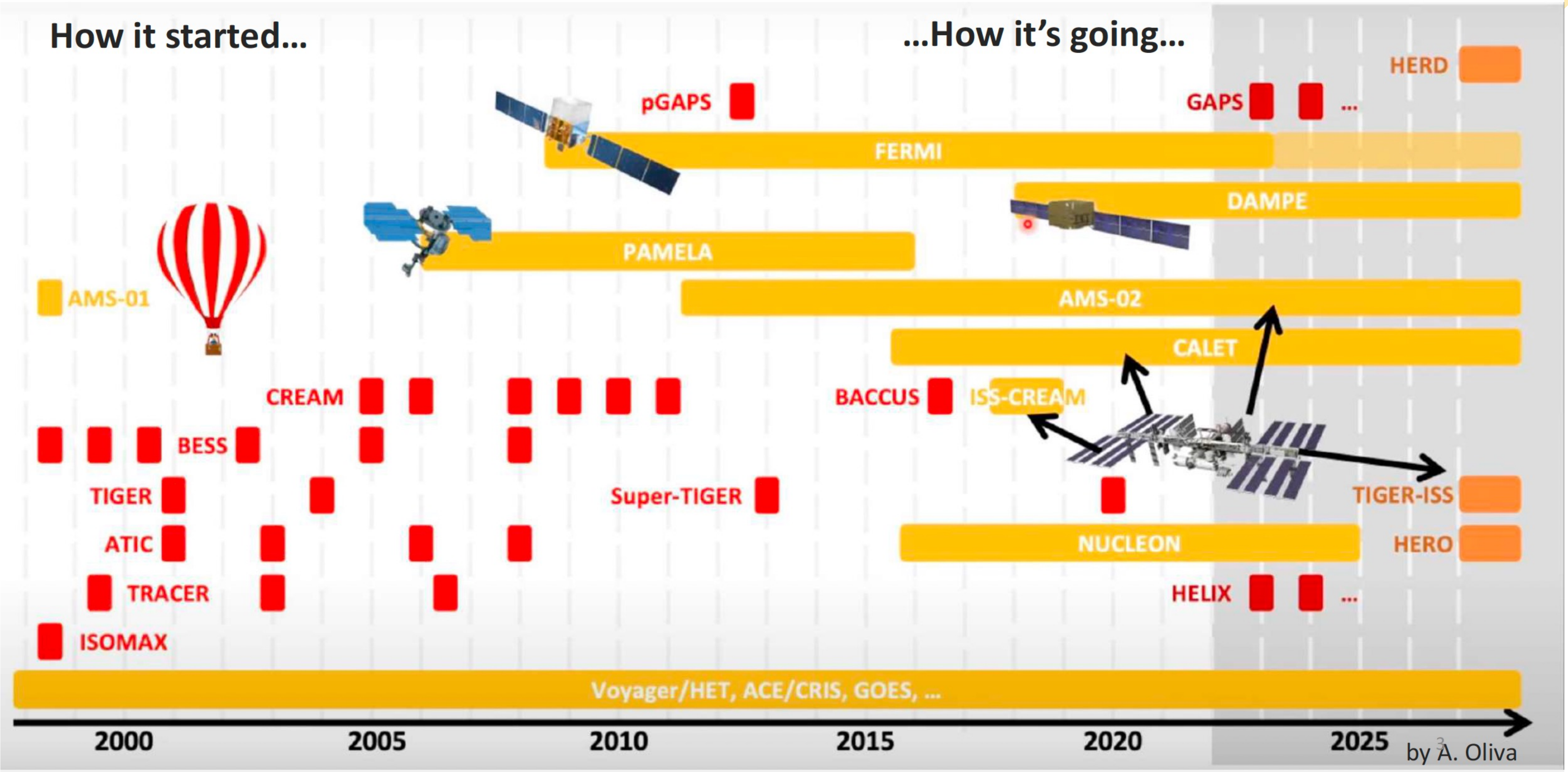
- scenery of the current missions
- Primary & secondary nuclei and their spectra;
- Secondary nuclei (non isotopes) and their spectra;
- Antimatter;
- Incoming experiments
- Future proposed missions
- Conclusions



a golden age of new cosmic ray measurements

2

Direct CR Measurements in the 3° millennium



A standard model of Galactic cosmic rays

General paradigm based on three pillars:

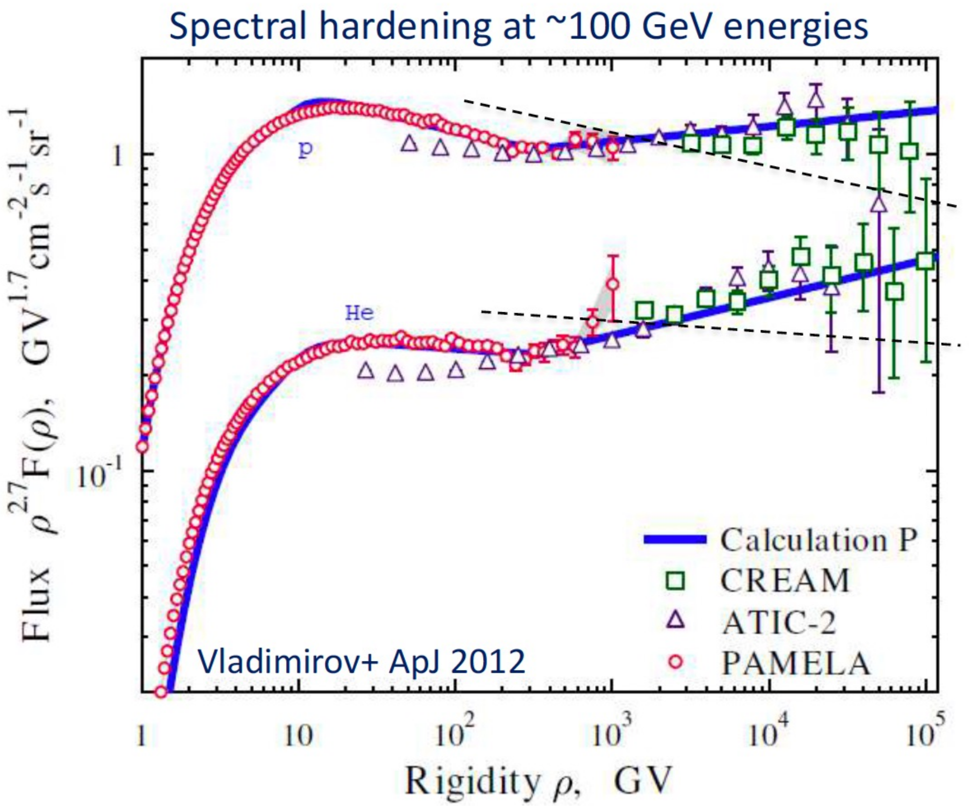
- Shock acceleration in SNRs: origin of primary CRS (p, C-N-O, Fe)
- Diffusive propagation in interstellar & interplanetary turbulence
- Collisions with ISM gas and production of secondaries: Li-Be-B, antimatter…

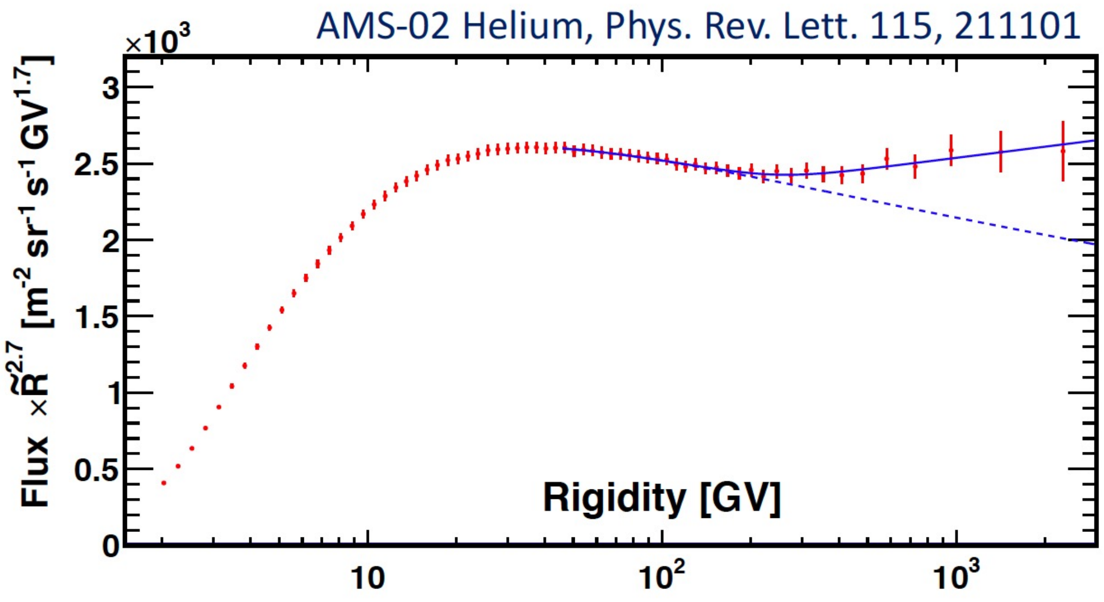
Questions:

- 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)



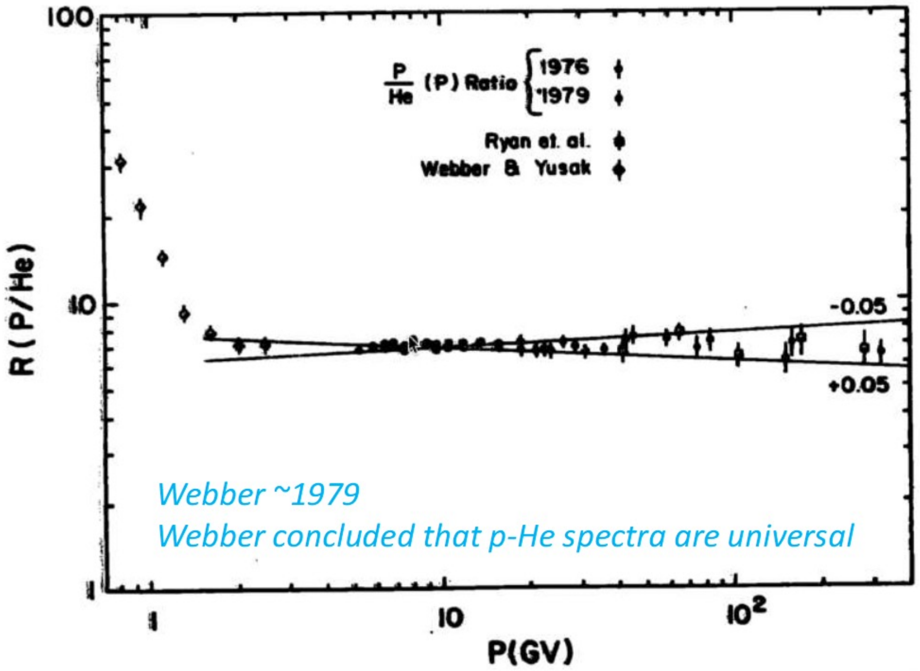


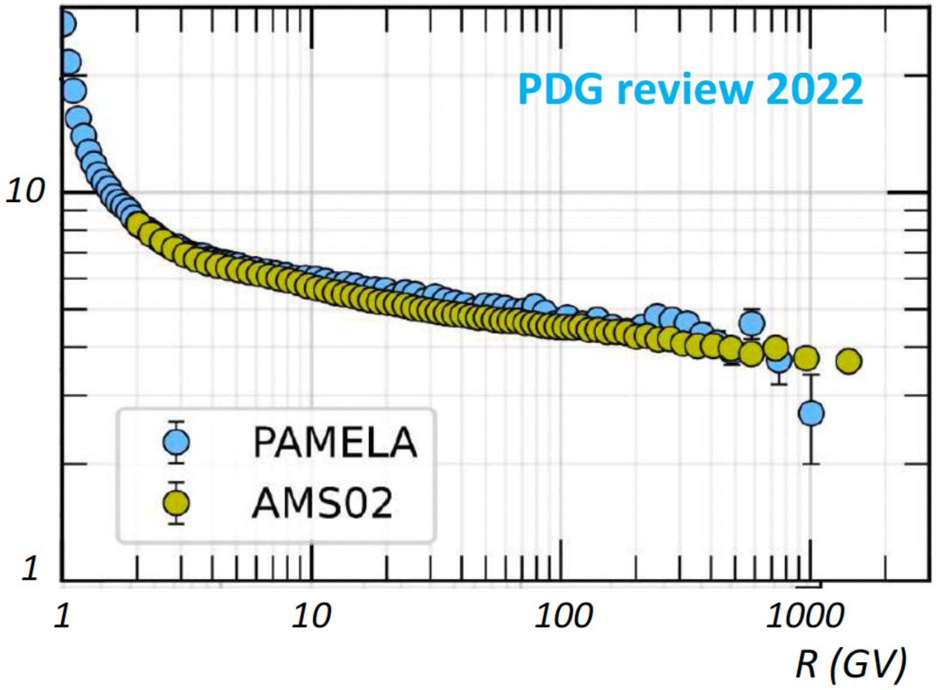
Challenge to the paradigm of CR acceleration & diffusive propagation

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

The p/He anomaly

- The He spectrum is harder than the proton spectrum. [CREAM, PAMELA, AMS02, BESS]
- The p/He ratio decreases without structures, while the p and He spectra harden at ~300 GV



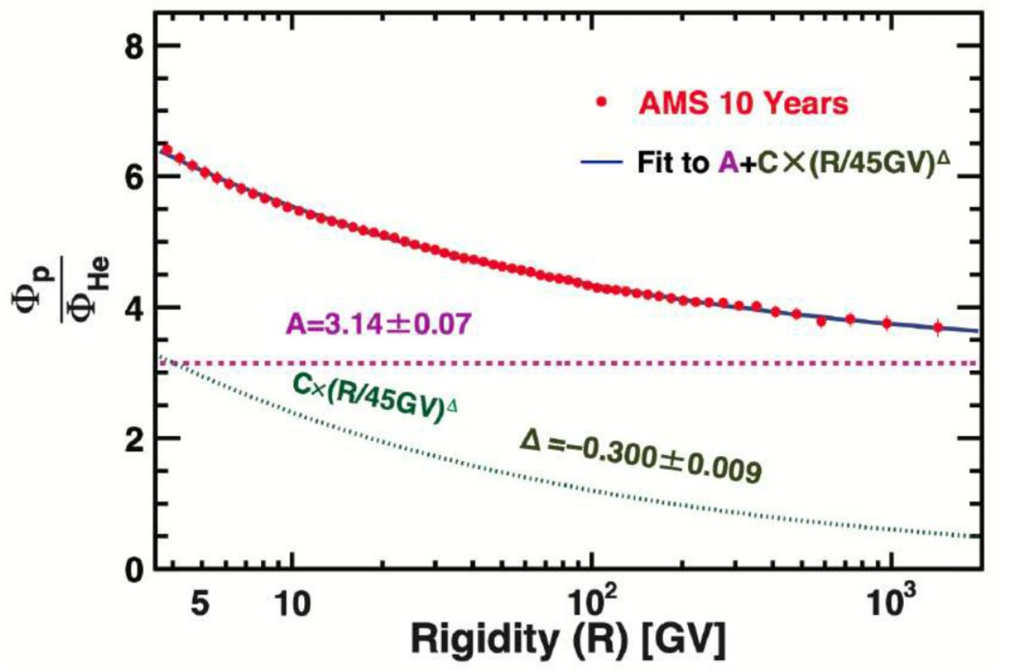


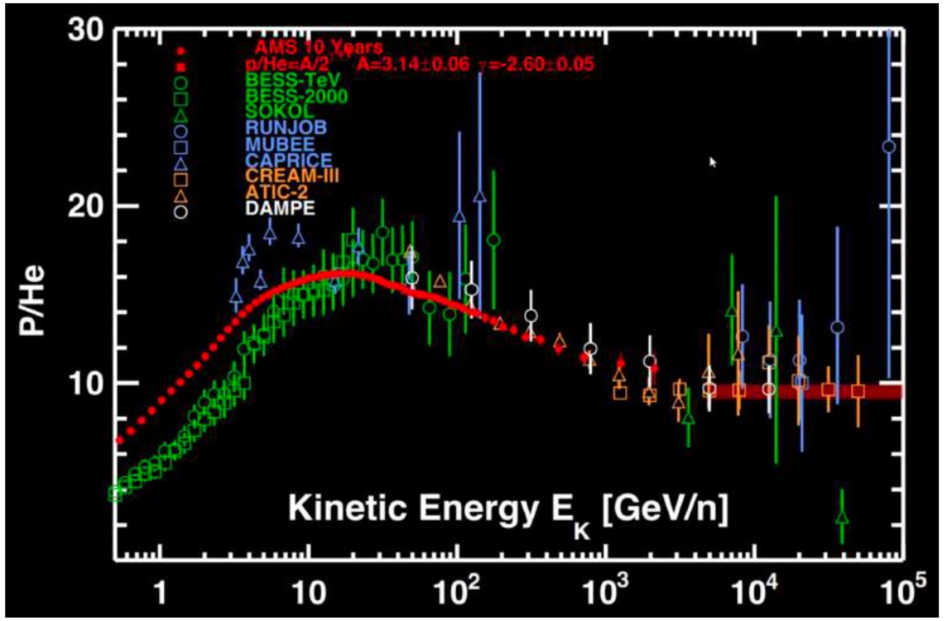
Not explained by (basic) diffusive-shock-acceleration theory. DSA is composition blind!

New question: is this behaviur hardening universal? What's its origin?

The p/He anomaly

- The He spectrum is harder than the proton spectrum. [CREAM, PAMELA, AMS02, BESS]
- The p/He ratio decreases without structures, while the p and He spectra harden at ~300 GV
- The p/He ratio seems to flatten at TV rigidity (AMS, see talk by V. Choutko)



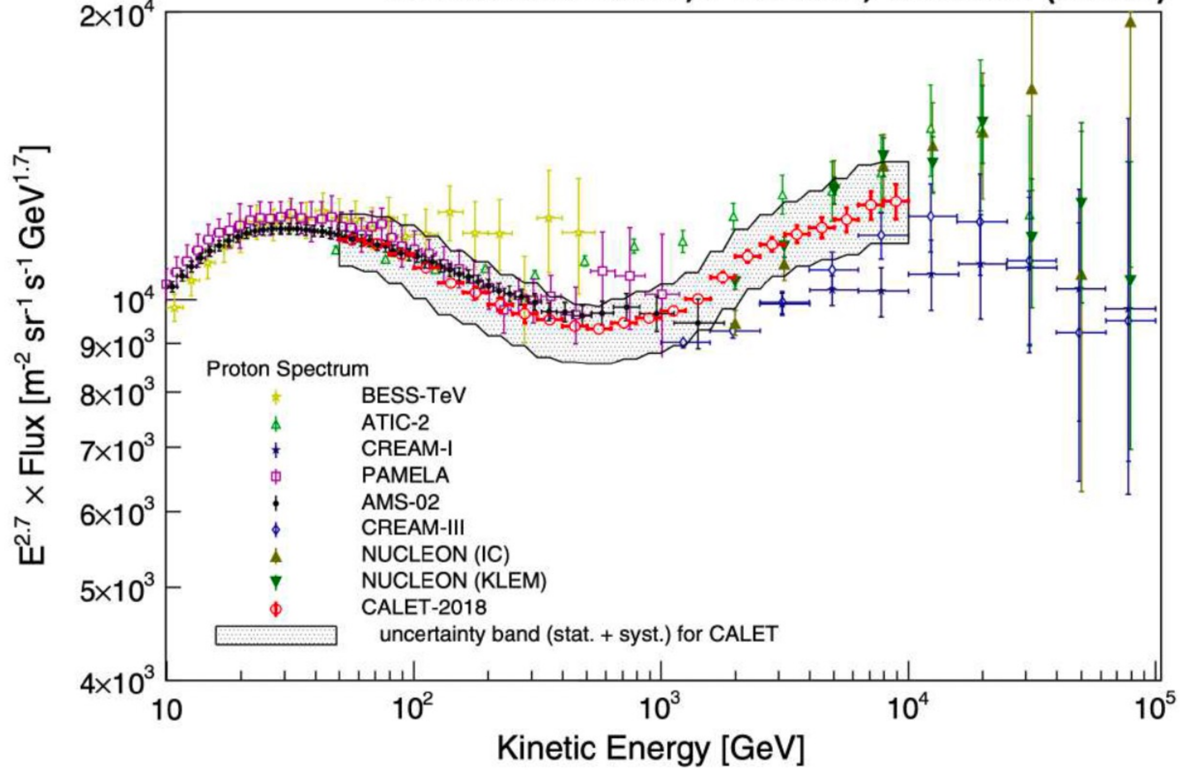


(NT ApJL 815, L1 (2015)[astro-ph/1511.04460] «A distinctive signature of our scenario is the high-energy flattening of the p/He ratio at multi-TeV energies, which is hinted at by existing data and will be resolutely tested by new space experiments ISS-CREAM and CALET».)

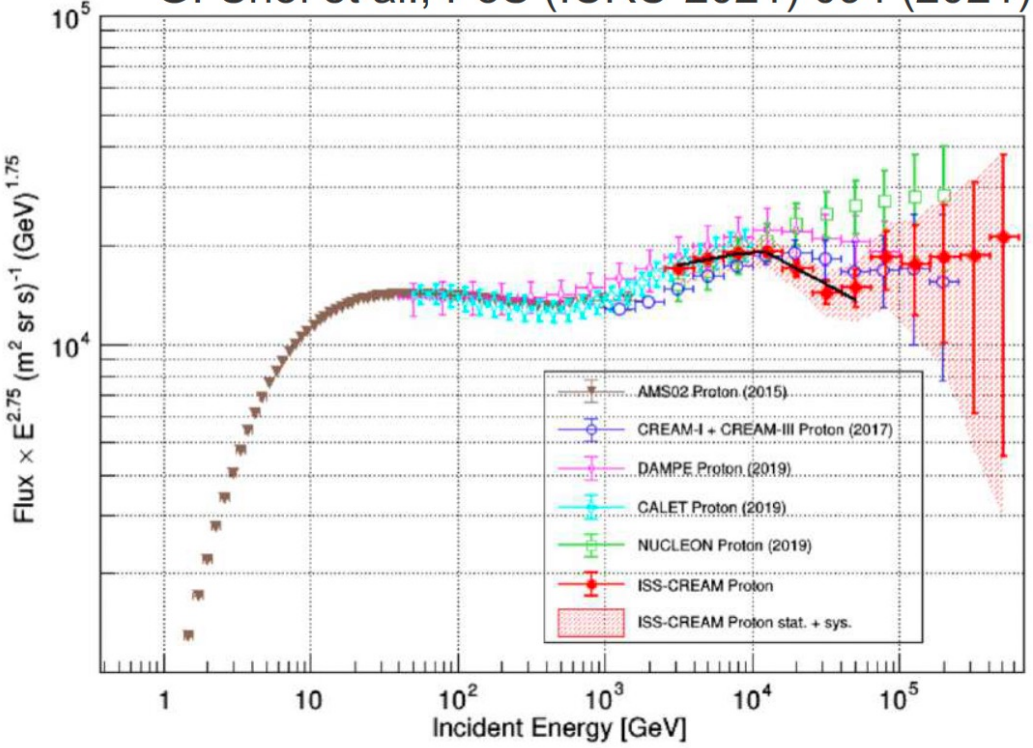
New features in the multi-TeV proton flux

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)



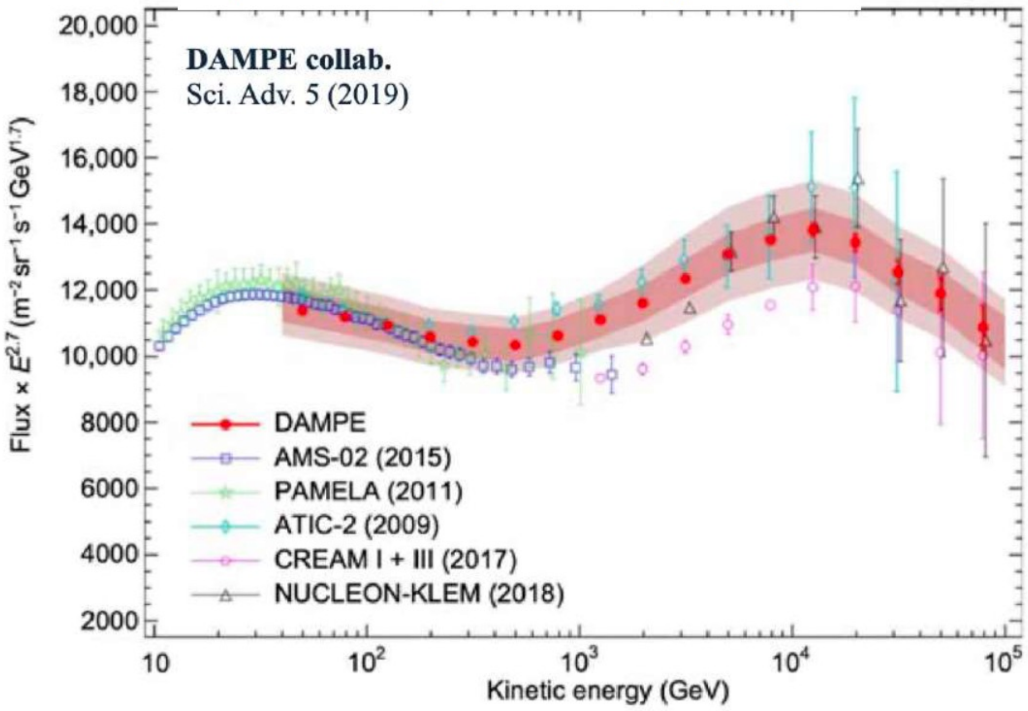
G. Choi et al., PoS (ICRC-2021) 094 (2021)



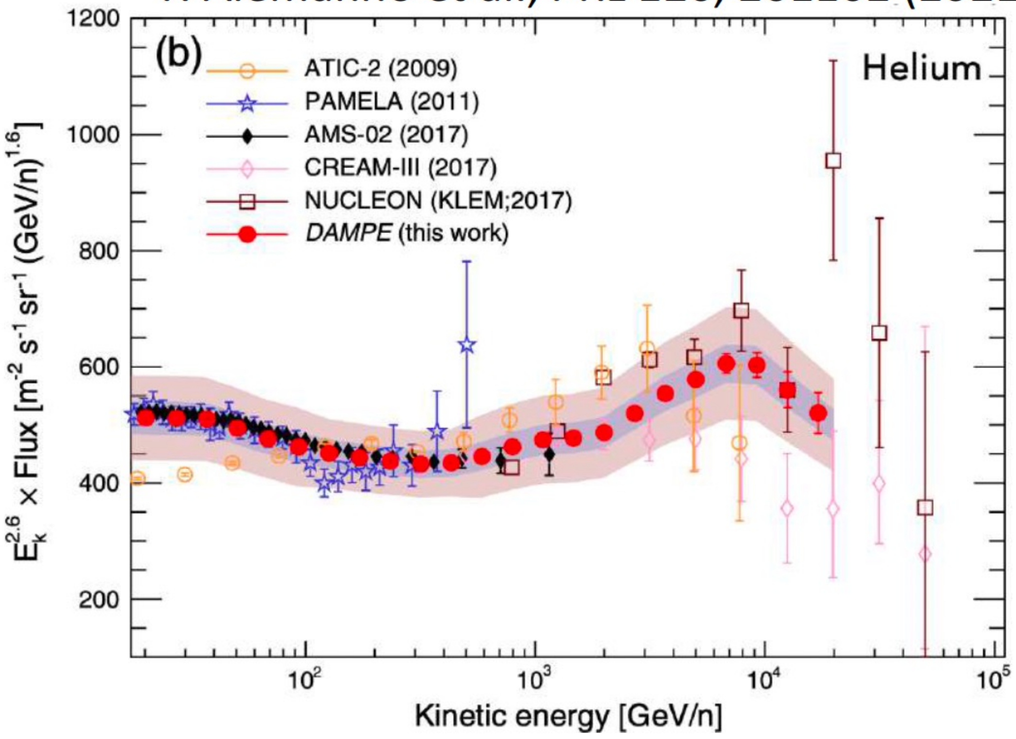
New features in the multi-TeV proton flux

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



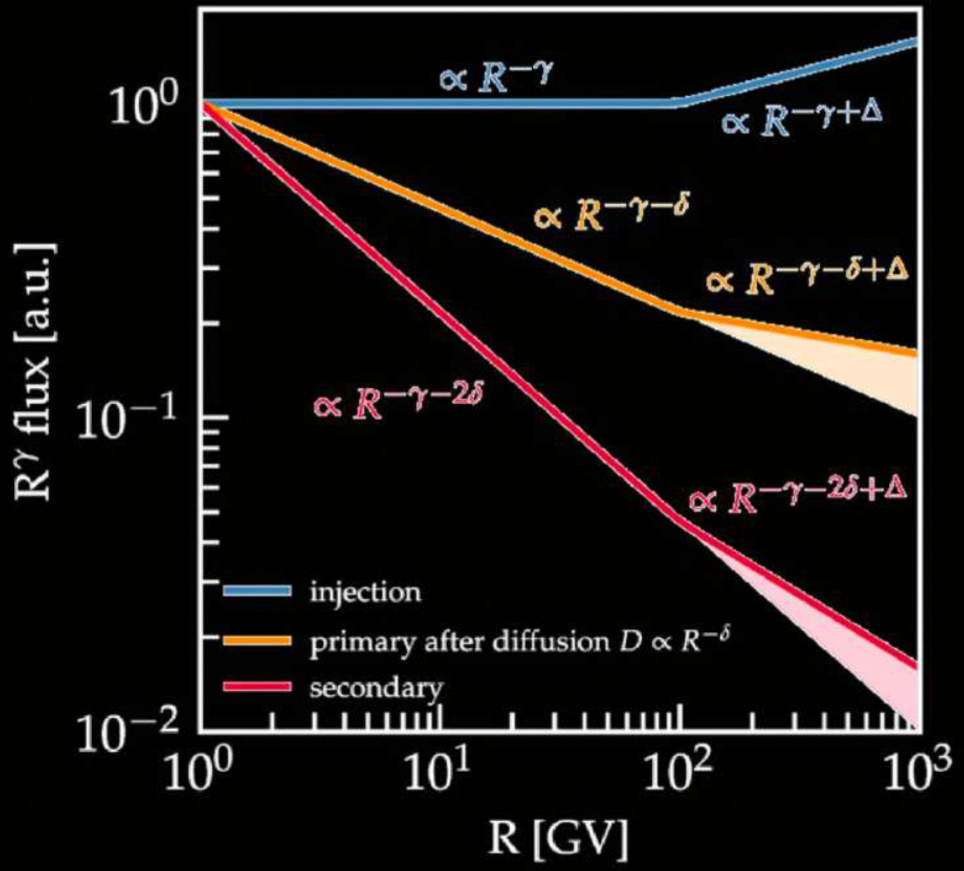
F. Alemanno et al., PRL 126, 201102 (2021)

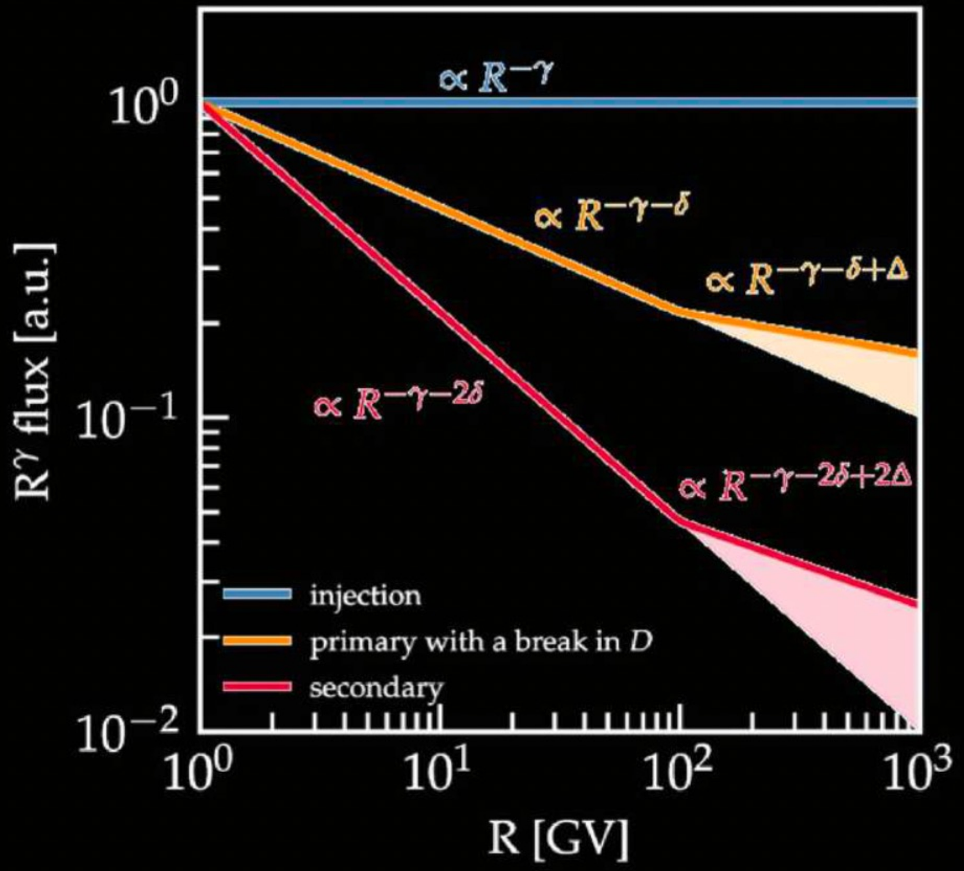


- **Indication of local source of GCRs appearing in the high-energy part of the spectrum?**
- **Possible indication of a further change of regime in the diffusive propagation of CRs?**

Origin of the CR spectral hardening

From C. Evoli (2019).





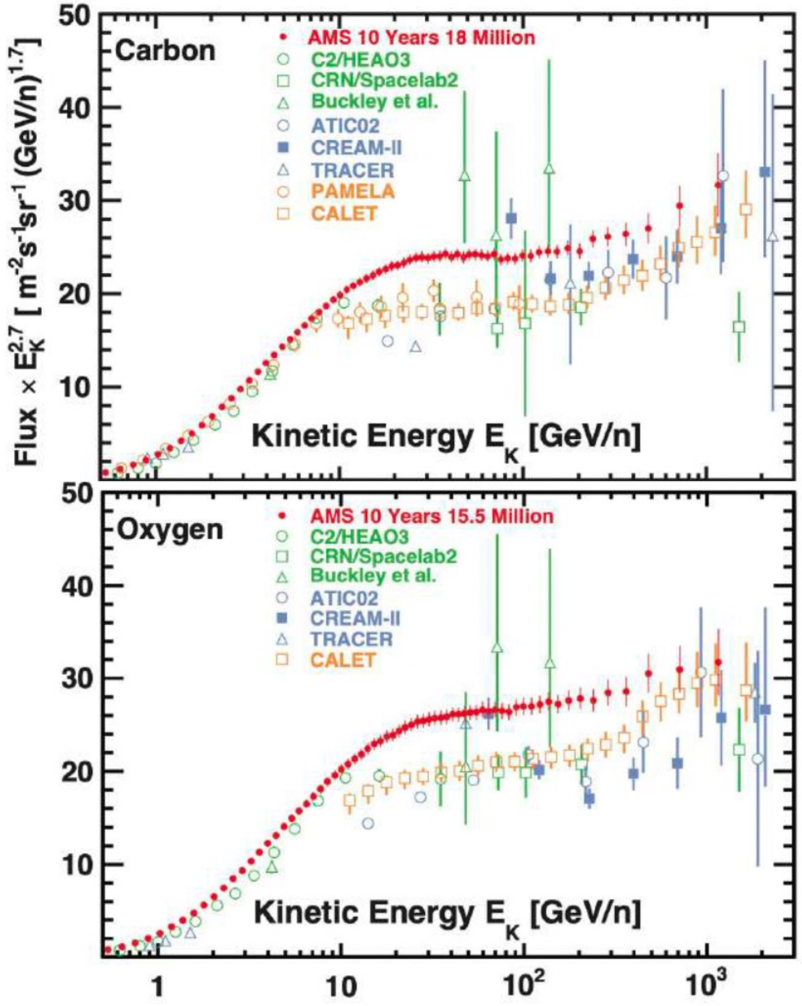
If the hardening is related to CR **acceleration**, we will observe a **similar hardening** for **secondary** and **primary**

(Ptuskin+ ApJ 2011 [1212.0381], Ohira & Ioka ApJ 2011 [1011.4405]…)

If the hardening is related to **propagation** in the Galaxy, then a **stronger hardening** is expected for the **secondary** CRs

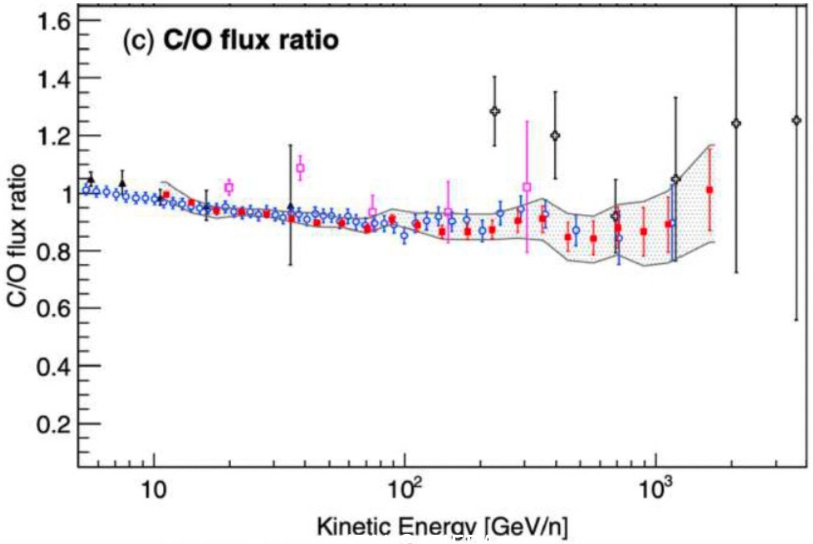
(NT ApJ 2012 [1204.4492], Blasi+ PRL 2012 [1207.3706]…)

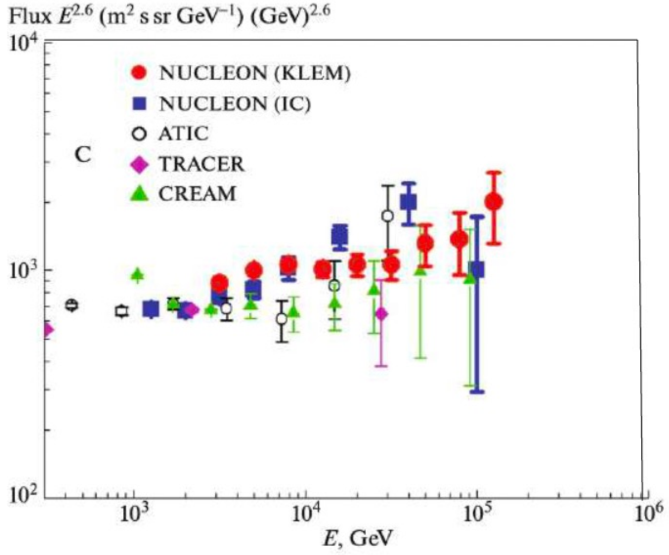
Spectral hardening in Carbon and Oxygen



- ✓ **Other primary nuclei are seen to harden**
- ✓ **Similar spectral breaks in all primaries (R~200 GV)**

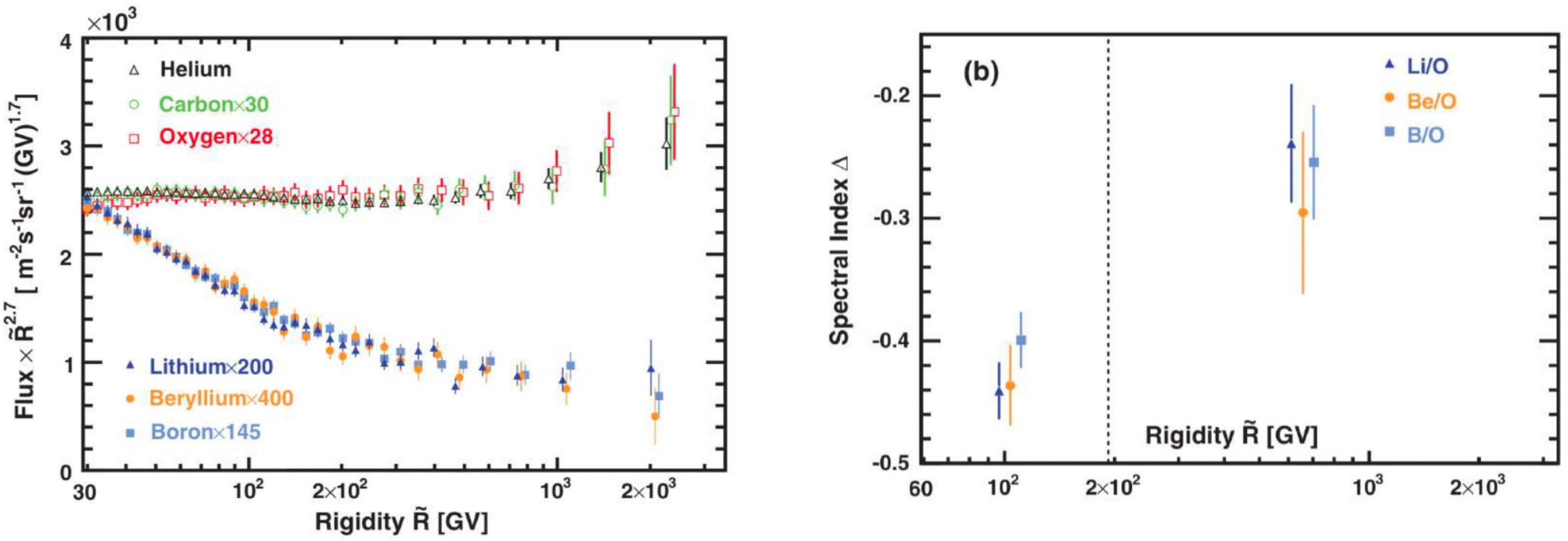
- CALET/AMS flux normalization discrepancy
- Similar spectral behaviour and ratio C/O
- Multi-TeV slope from Nucleon





Spectral hardening in secondary Li-Be-B nuclei

the rigidity dependence of primary and secondary cosmic rays are unique and distinct

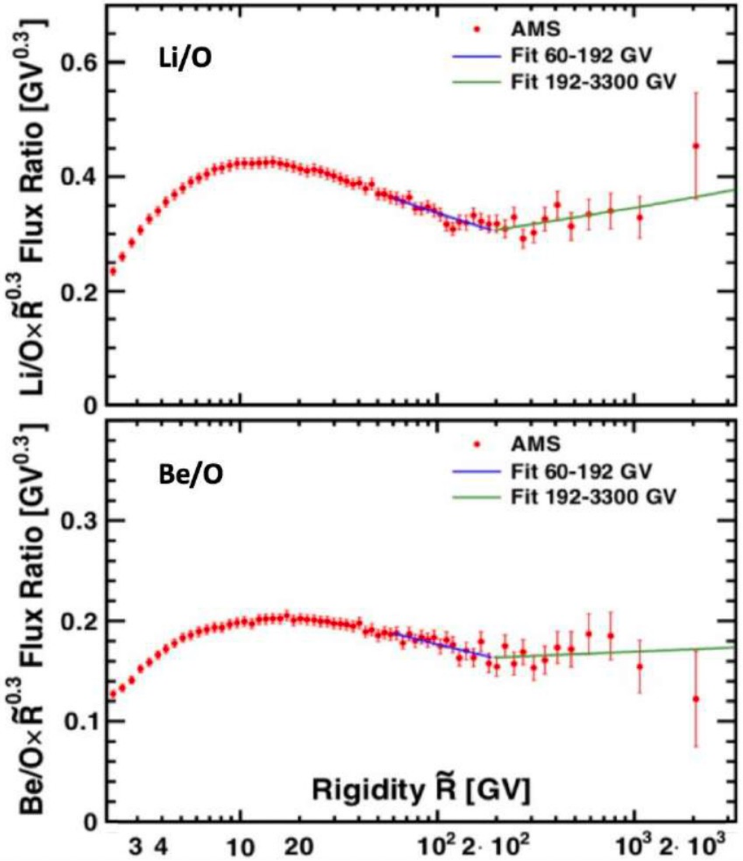


- He-C-O and Li-Be-B lie in two distinct spectral groups: primary and secondary CRs
- All species (and both pri and sec) are subjected to spectral hardening at rigidity R~300 GV
- Different change of slope: the Li-Be-B hardening is more pronounced. => S/P ratio hardening

Spectral hardening in secondary/primary ratios

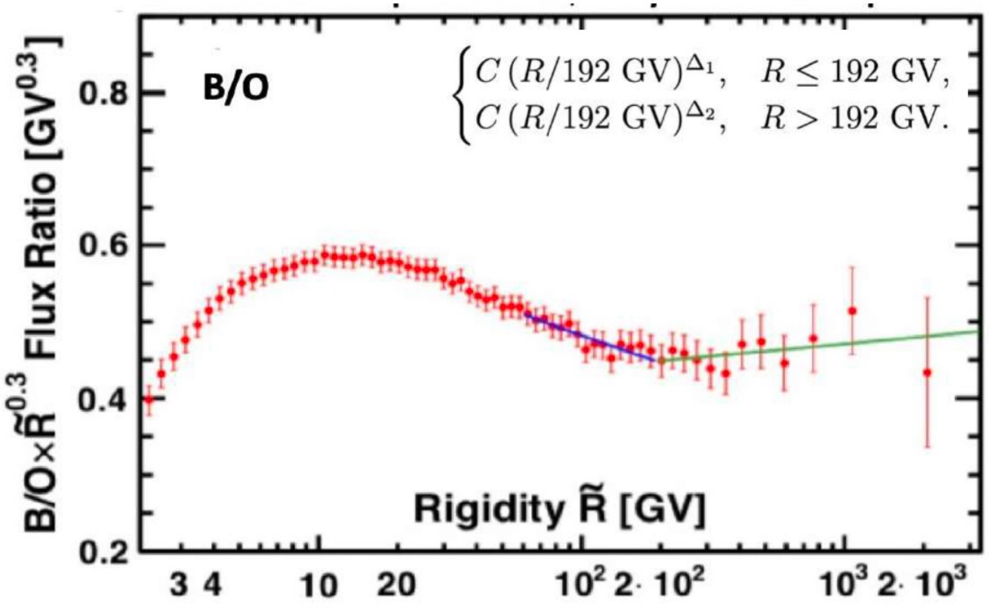
The break is seen not only in secondary CRs, but also in **secondary/primary** ratios.

The hardening seems not related to CR injection/acceleration, but to **CR propagation**



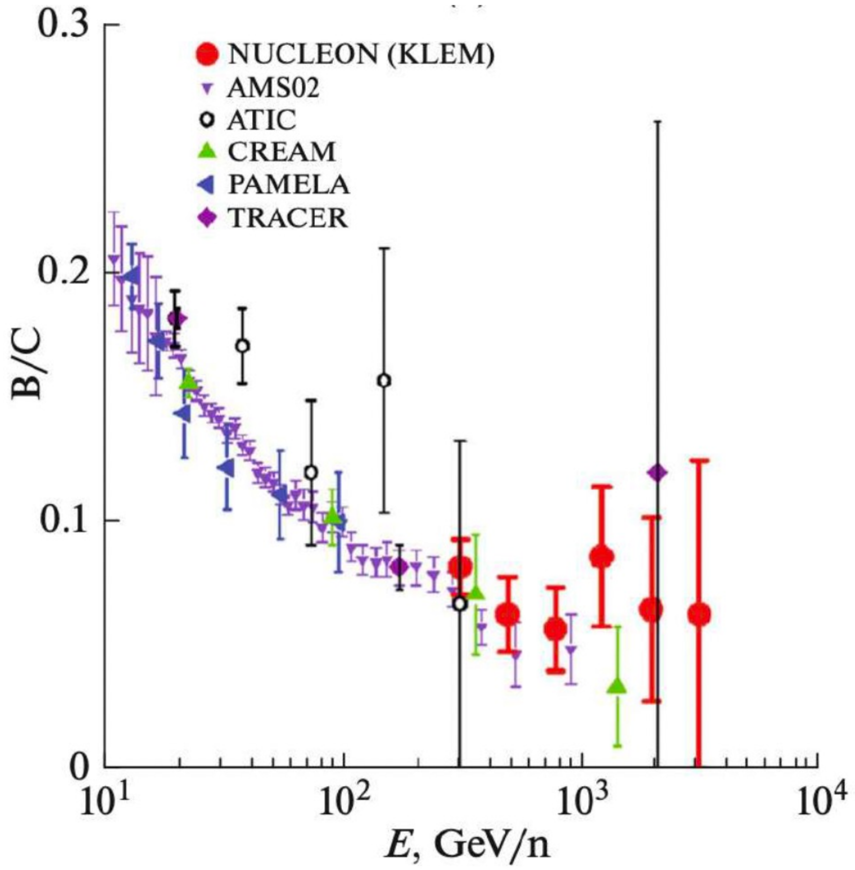
The diffusive origin of the breaks is discussed in many models:

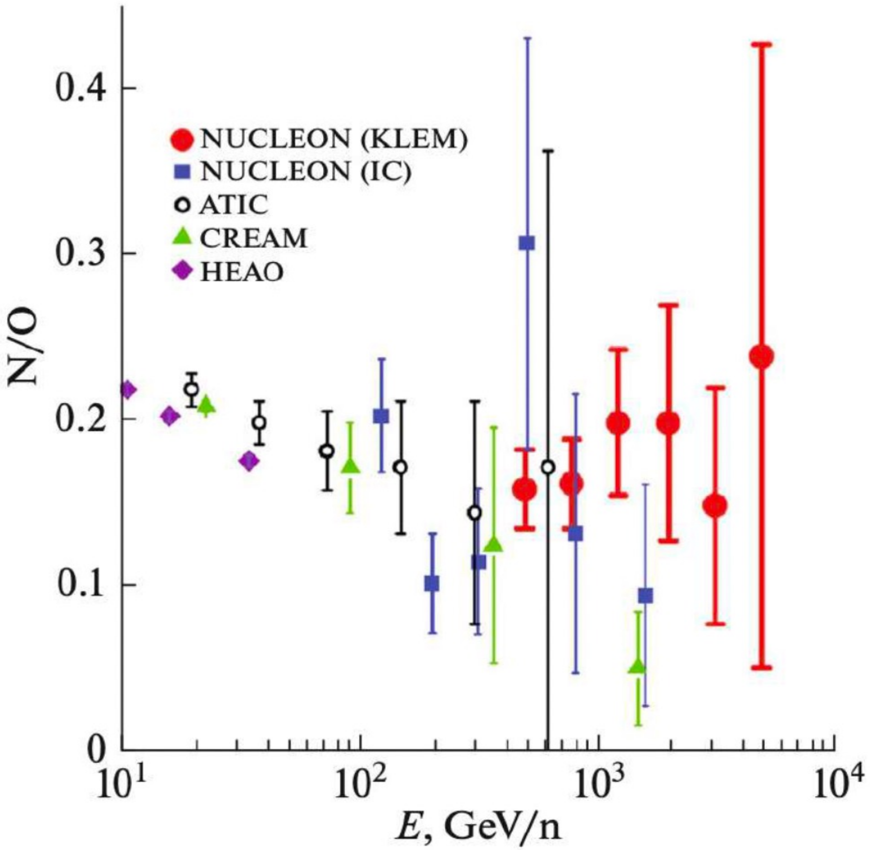
- NT, ApJL 715, L13 (2012) [arXiv:1204.4492],
- Blasi et al., PRL 109, 061101 (2012) [arXiv:1207.3706]
- Evoli et al. PRL 121, 021101 (2018) [1806.04153]



Spectral hardening in secondary/primary ratios

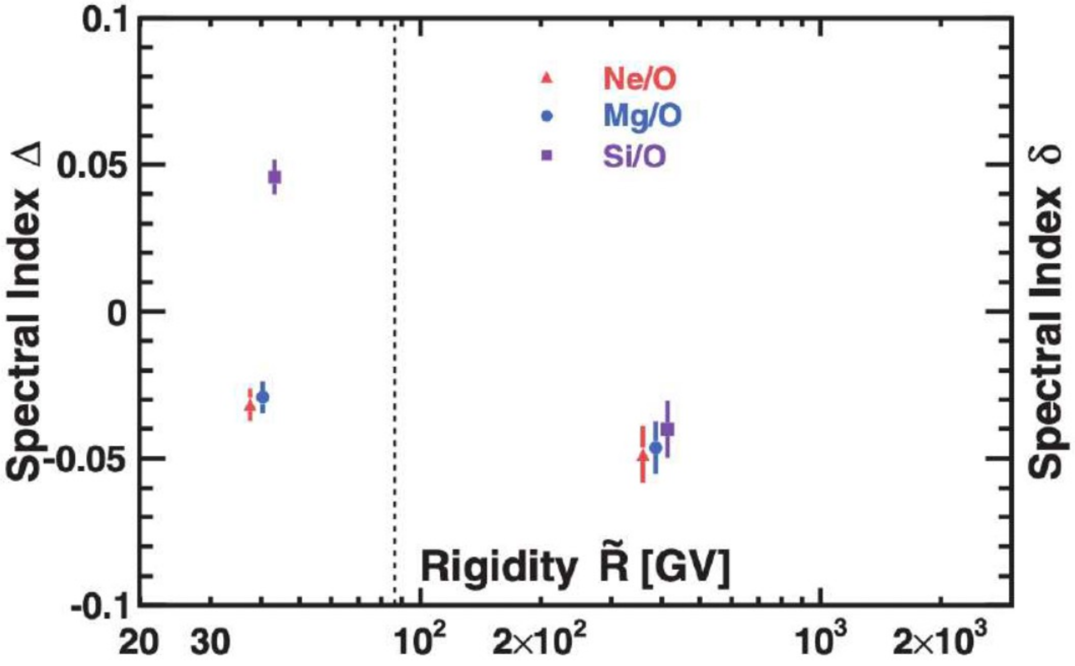
Measurements from NUCLEON also suggest harder secondary/primary ratios in the multi-TeV region.



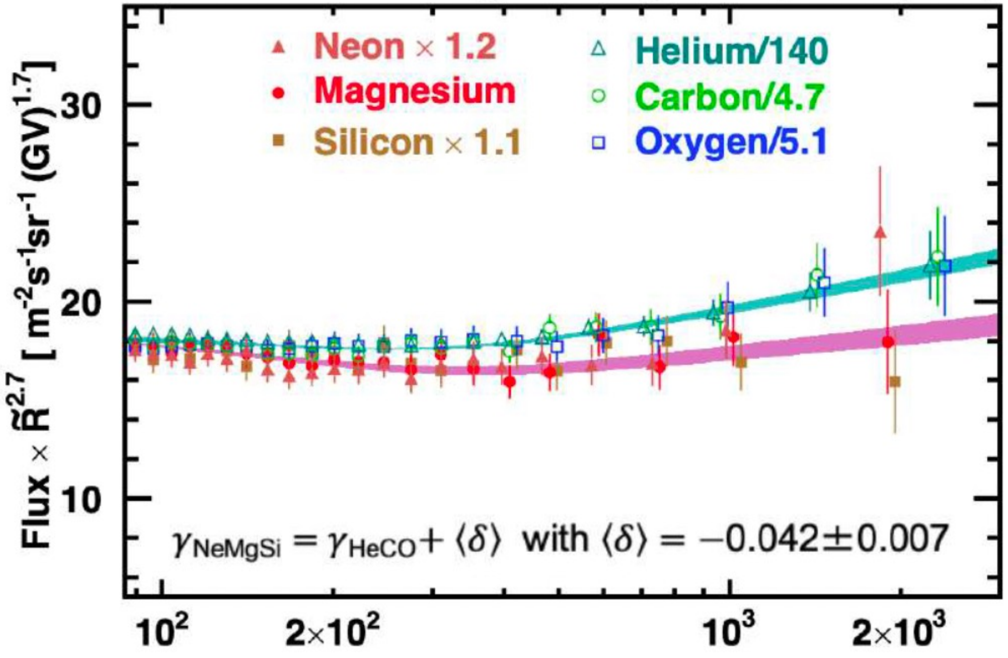


High-energy spectra of other nuclei: Ne Mg Si

At high rigidity (R>85 GV) the spectra of Ne, Mg, Si are **different** from light primary CRs such as He, C, and O. Simiarly, Sulfur seems to belong to this class of intermediate nuclei.



M. Aguilar et al., PRL 124, 21102 (2020)

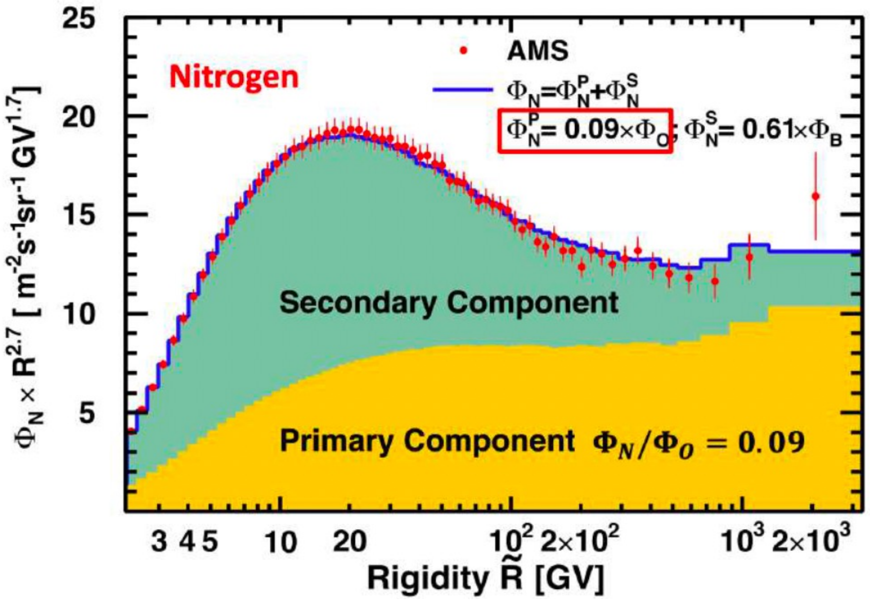


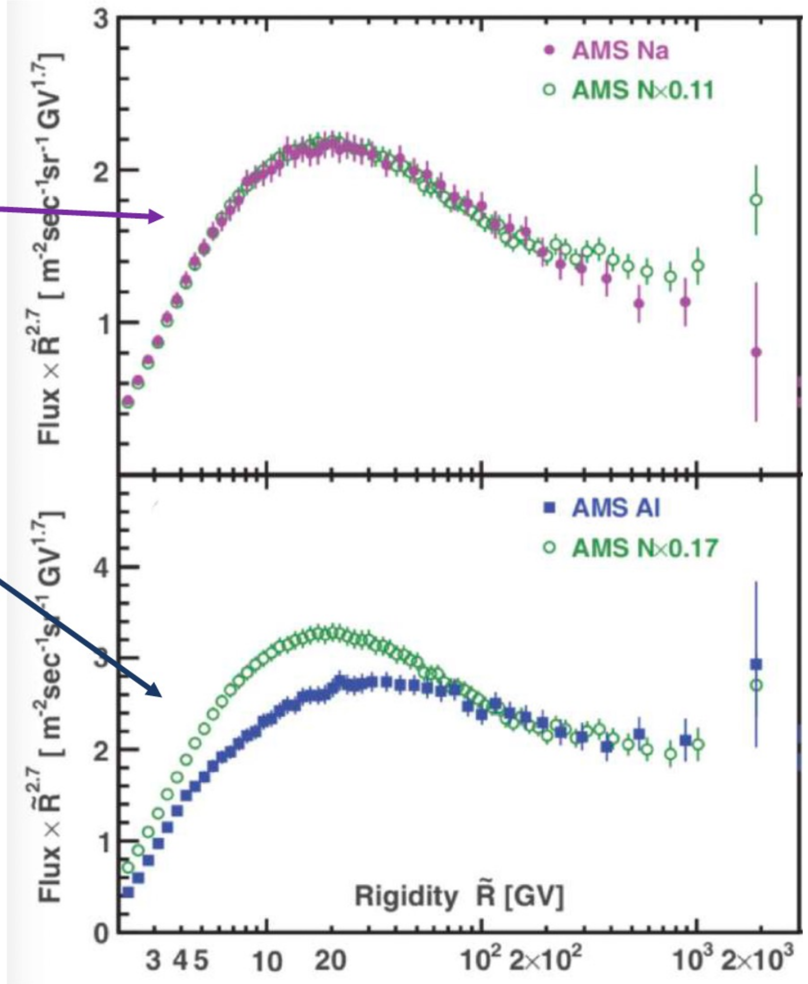
Primary cosmic rays have at least two different classes (of sources?)

High-energy spectra of other nuclei: N, Na & Al

Nitrogen is a known mix of primary & secondary CRs. Similarly for Na and Al, but with different mixtures.

- Below 100 GV, the Sodium flux and its spectral index are similar to Nitrogen
- Above 100 GV, the Aluminum flux and its spectral index are similar to Nitrogen

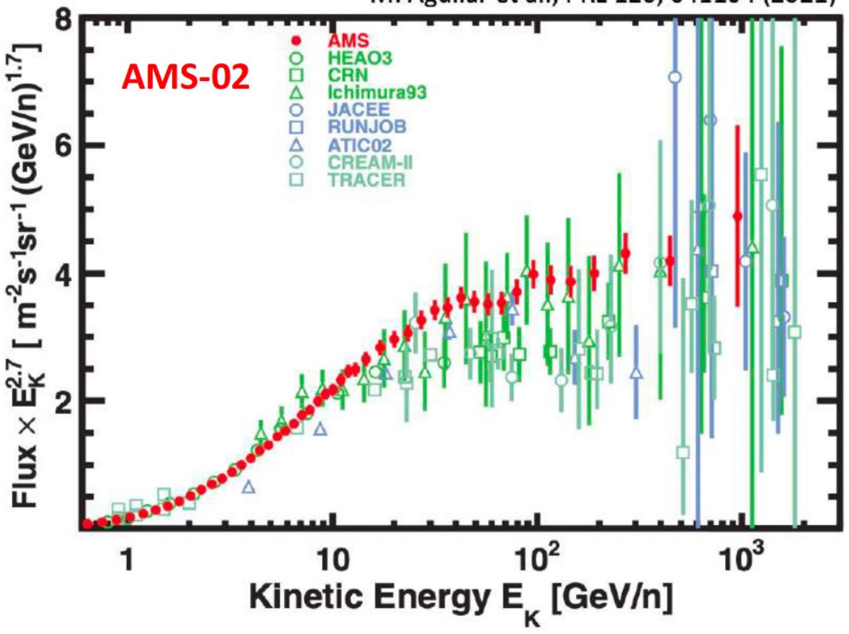




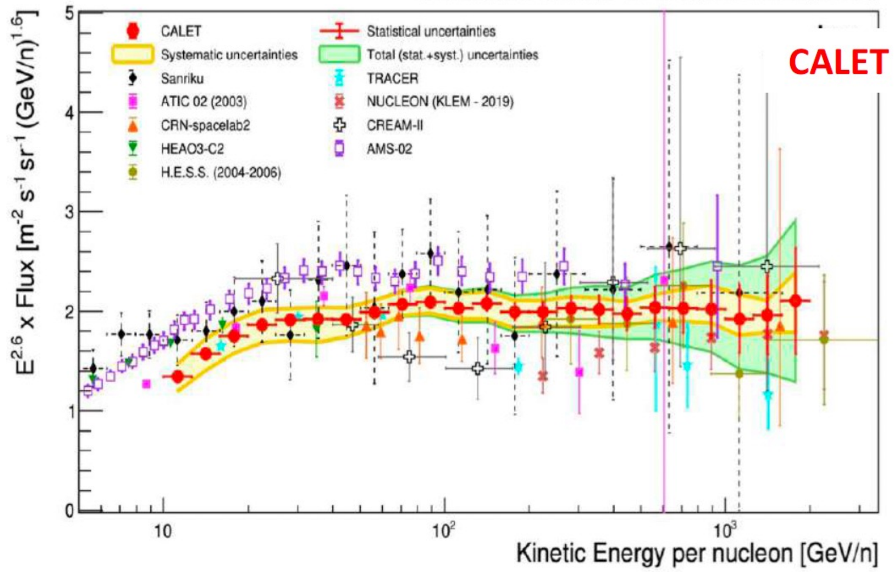
Heavy metals: the Iron spectrum

The high-energy Iron flux is now measured by AMS-02, CALET, NUCLEON.

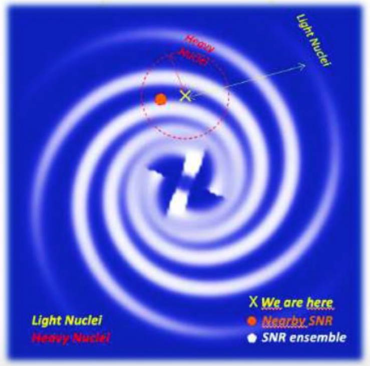
M. Aguilar et al., PRL 126, 041104 (2021)



O. Adriani et al., PRL 126, 241101 (2021)



- CR propagation in our local environment (~ few 100 pc).
- Unique spectrum, not described by existing CR propagation models.
- AMS Iron: the Fe spectrum at HE behave like the «light» primary class (He-C-O)

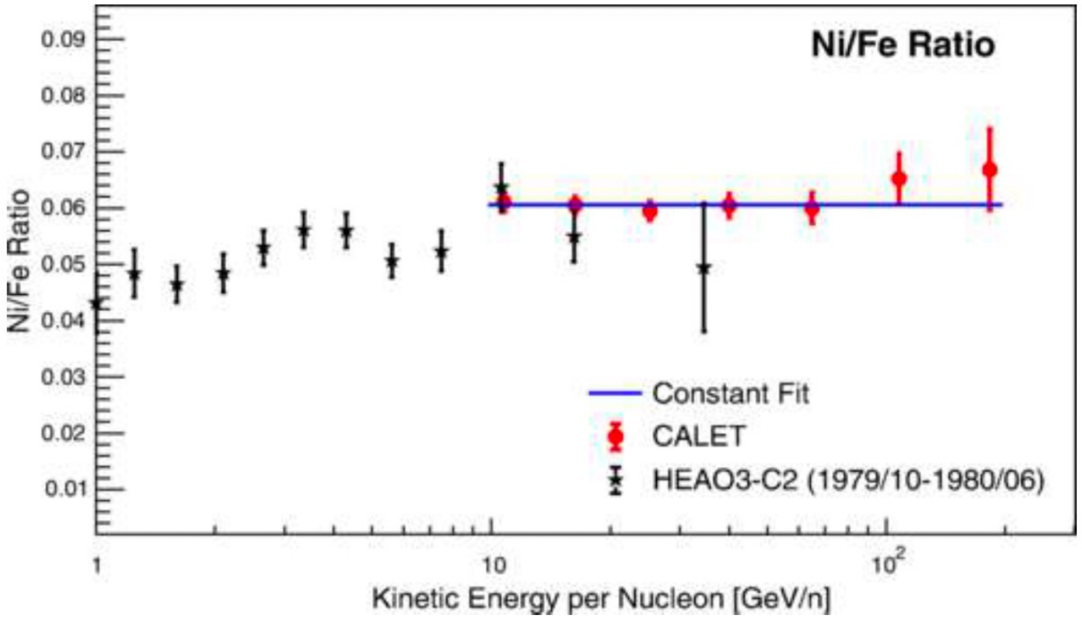


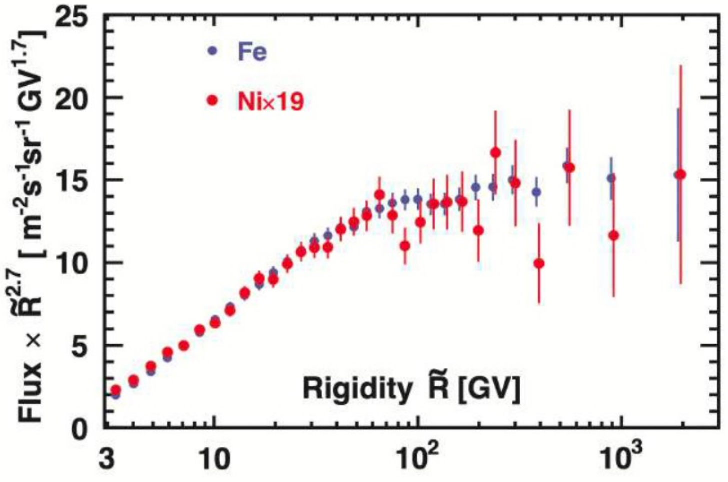
Heavy metals: the Nickel spectrum

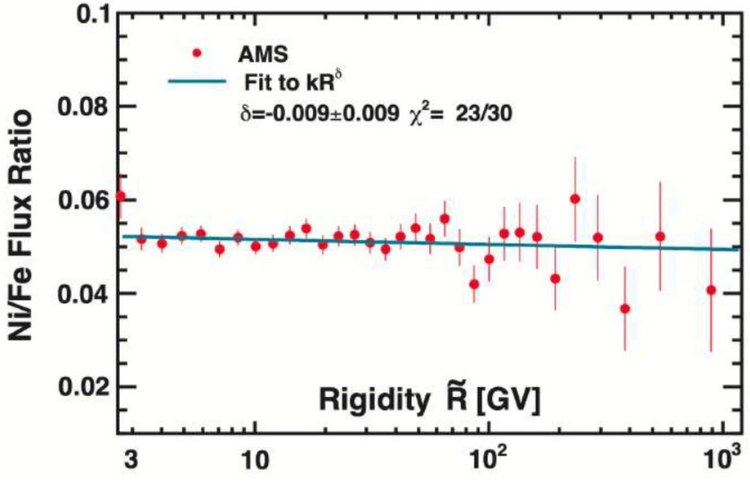
New Nickel measurements by CALET and AMS-02

The Nickel spectrum look pretty similar to the Iron spectrum, but its flux is 20 times weaker

Ni/Fe ratio at the 10 GeV/n – TeV/n energy scale is consistent with a constant behavior







A complex picture

Primary CRs group in two spectral classes:

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

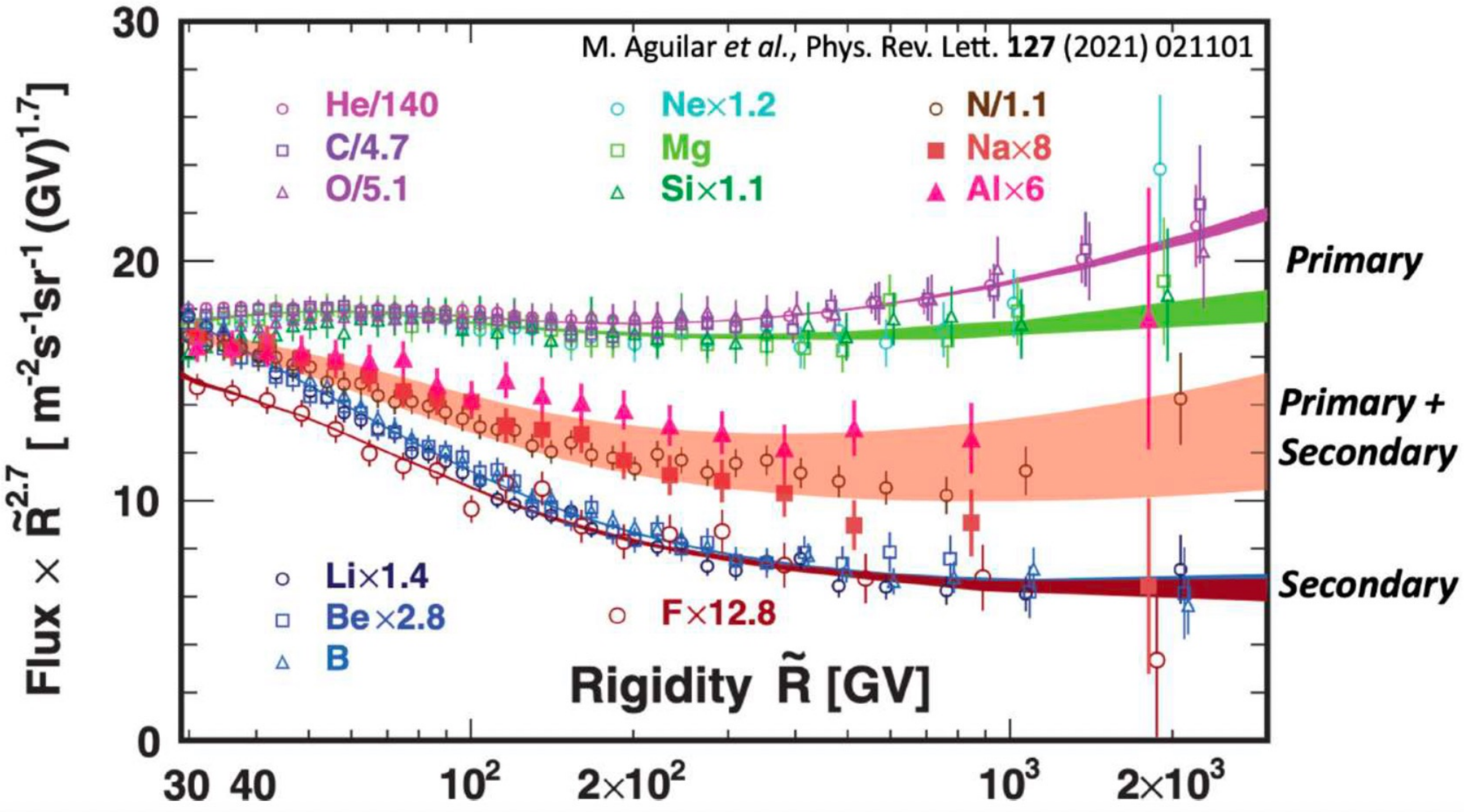
Mixed -> N, Na, and Al

- 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.

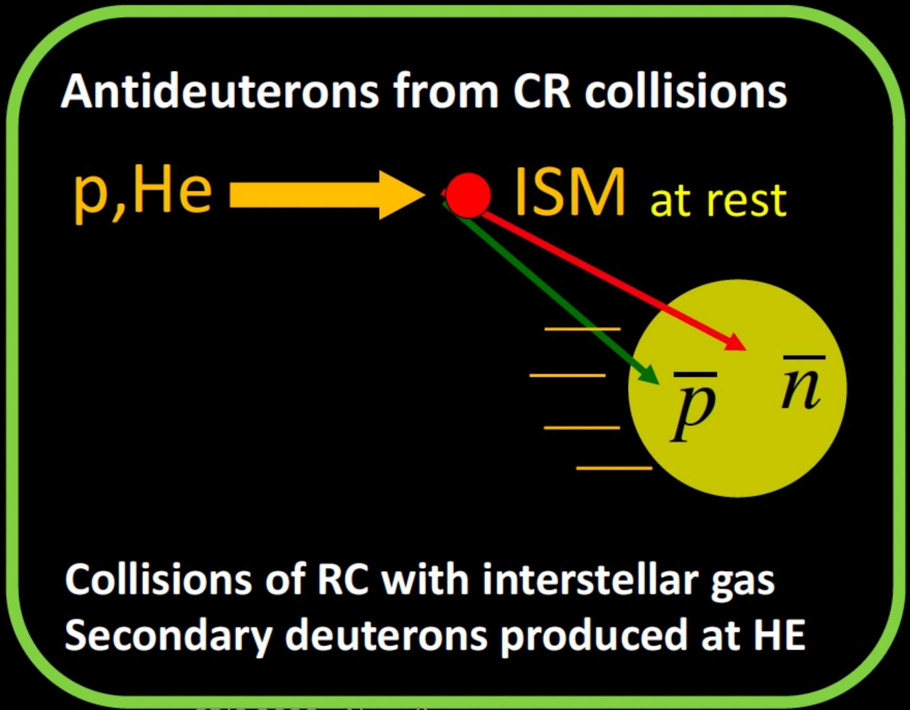
Along with p-He anomaly, hint for non-universal spectral indices for all Z>1 nuclei [Korsmeier 2022]

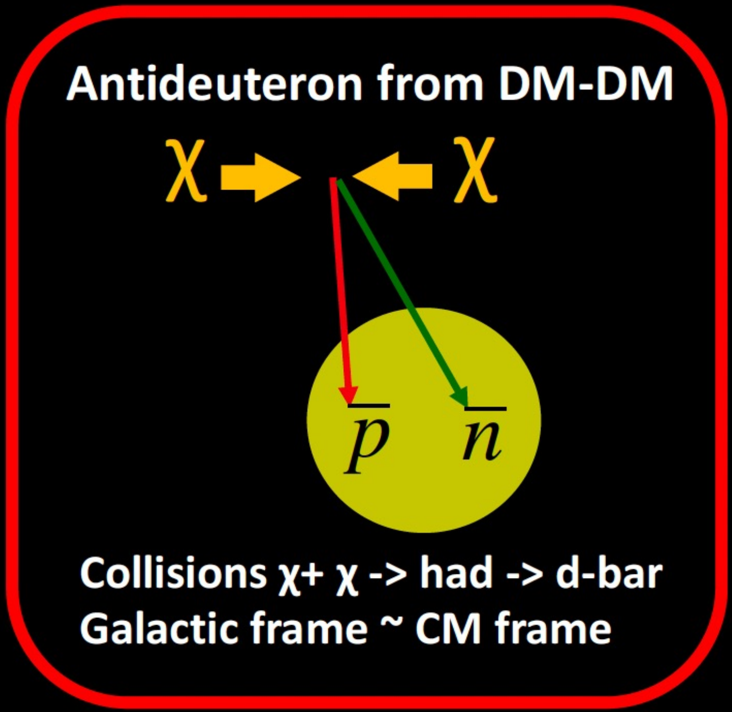


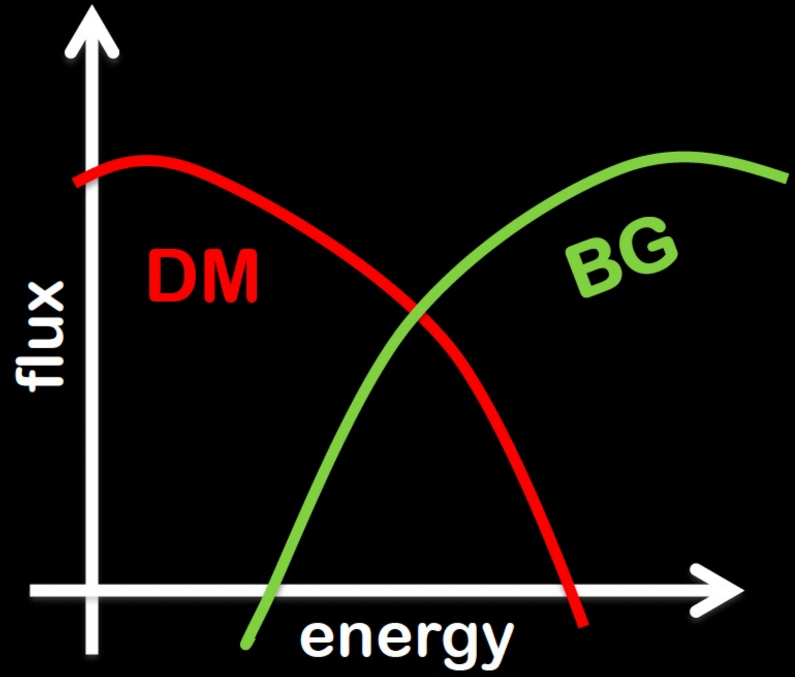
Next milestone: antinuclei

Never detected in cosmic rays → Next milestone [→ AMS-02, GAPS]
Nuclear coalescence of antinucleons: $\bar{d}=\{\bar{p},\bar{n}\}$, $\overline{He}=\{\bar{p},\bar{p},\bar{n}\}$ [→ ALICE]

Favorable signal/background ratio, due to kinematics

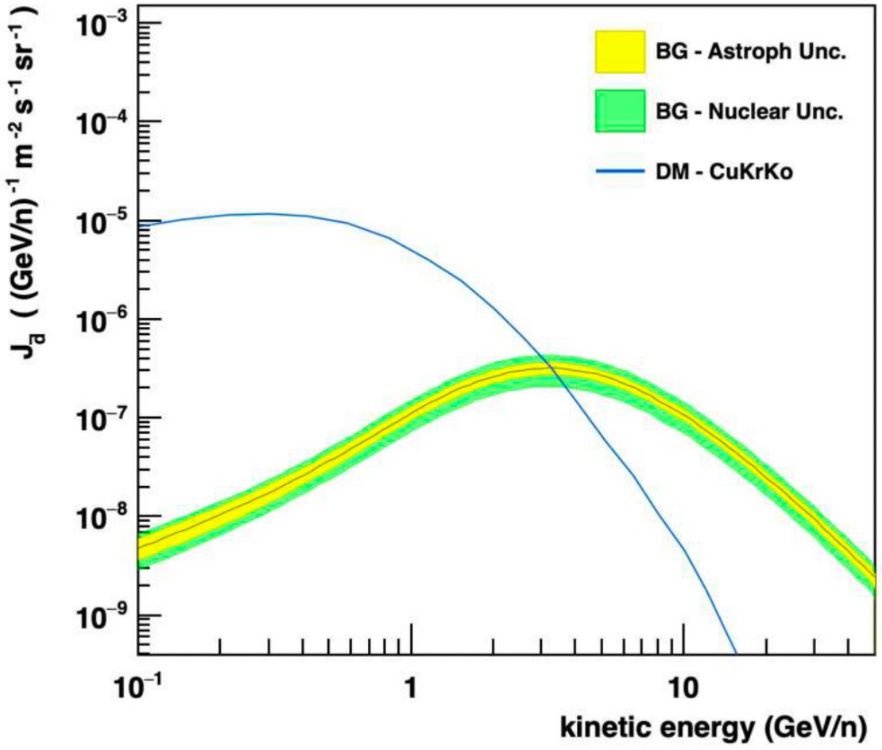




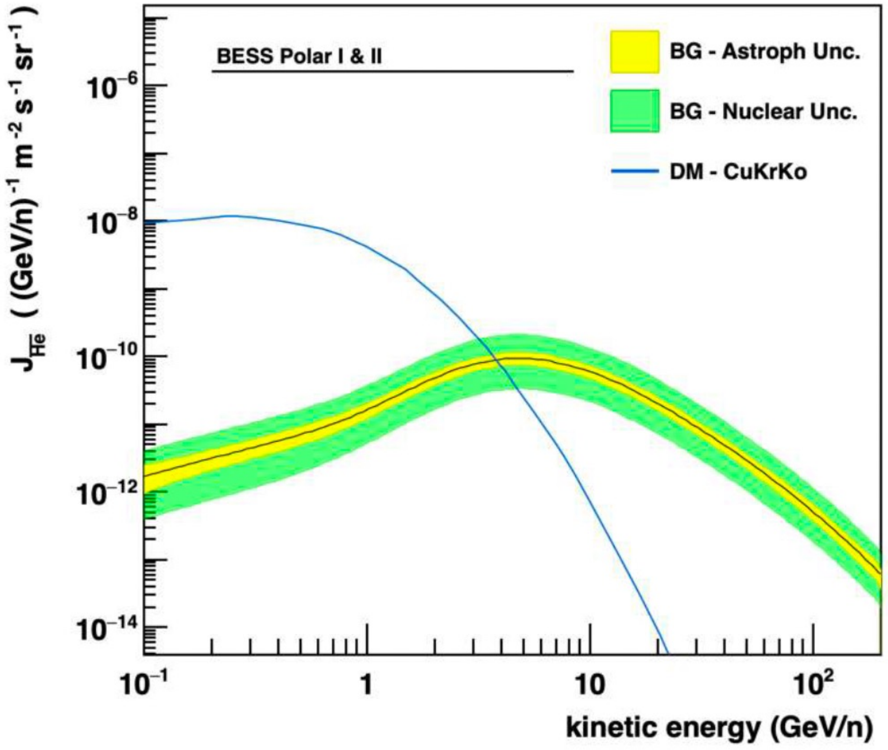


Anti-deuteron and anti-helium

antideuteron flux



antihelium flux

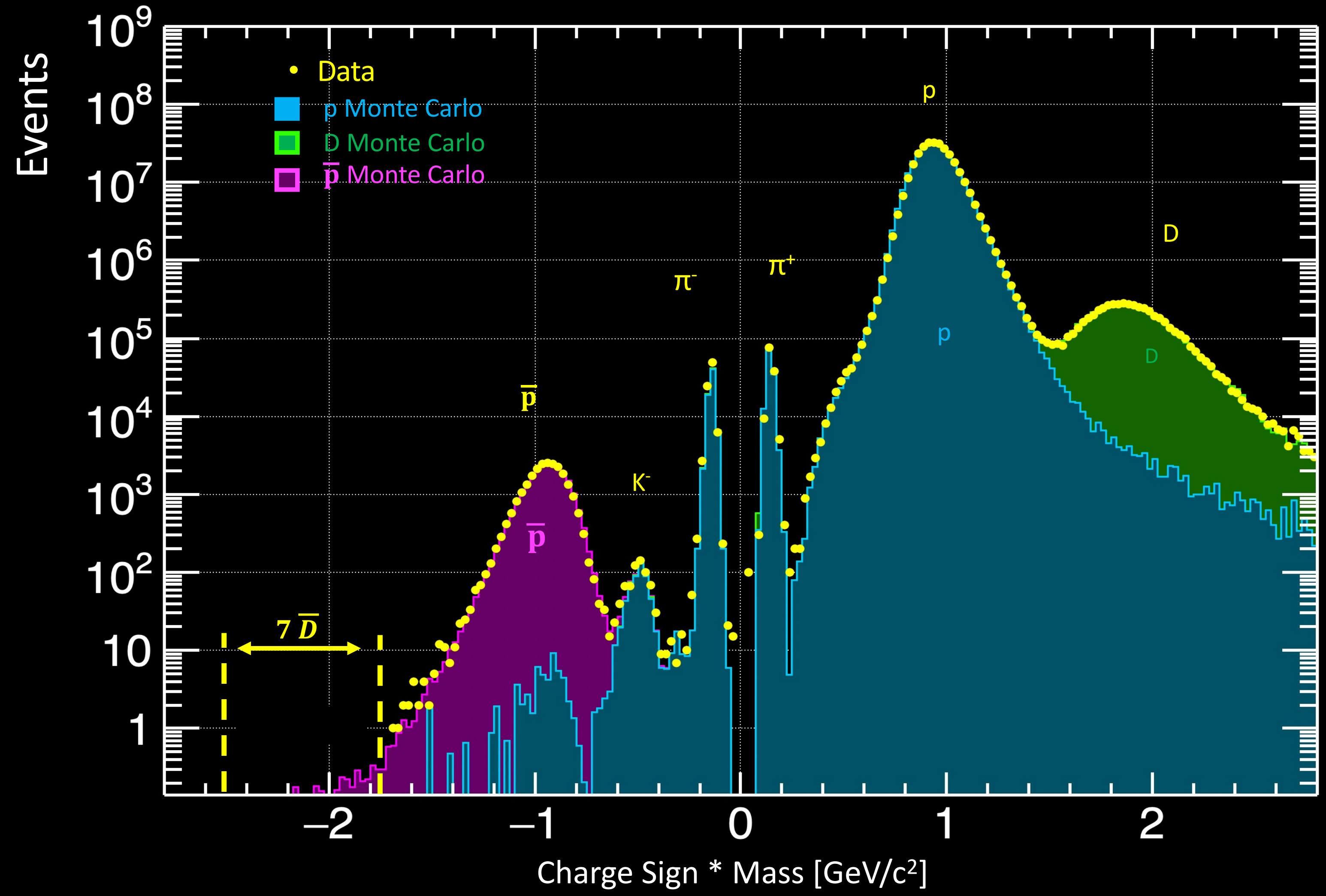


DM model from A. Cuoco et al. 2017, Phys. Rev. Lett. 118, 191102, M. Korsmeier et al., 2018, Phys. Rev. D 97 n.10, 103011
BKG model from N. Tomassetti and A. Oliva, 2017, ApJ Lett. 844

AMS-02

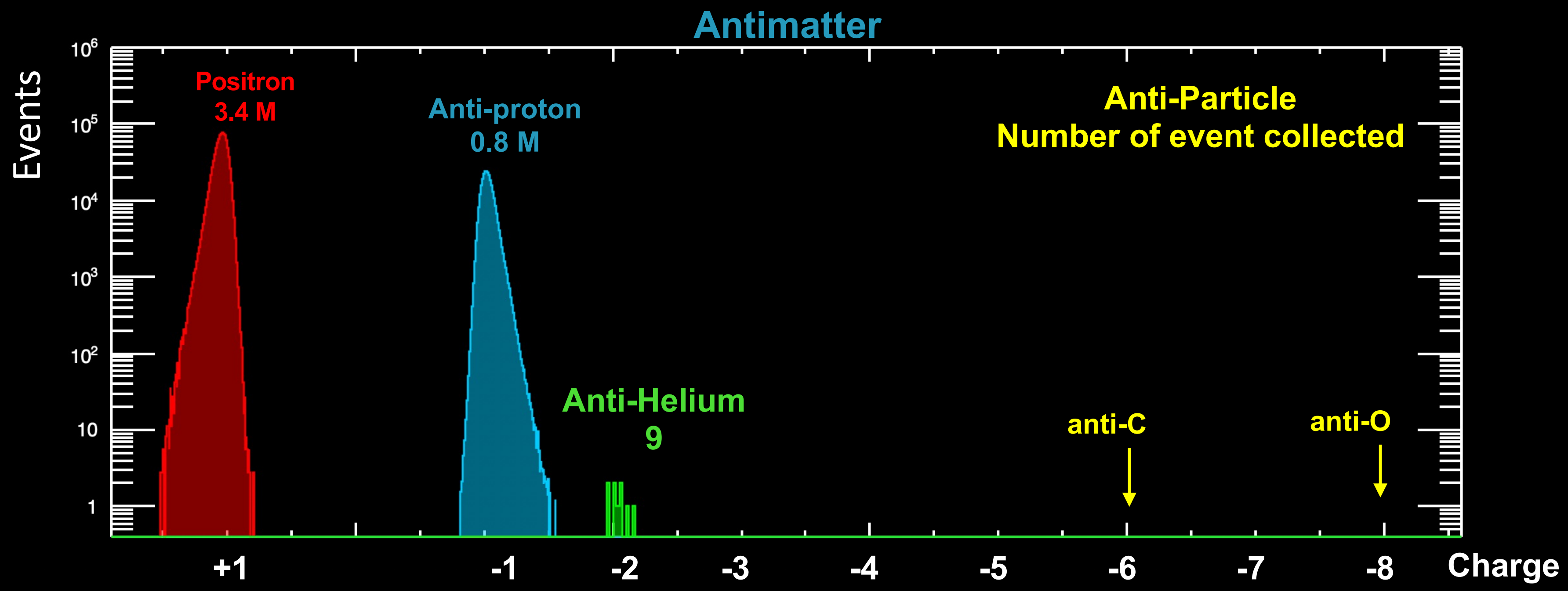
anti-D search

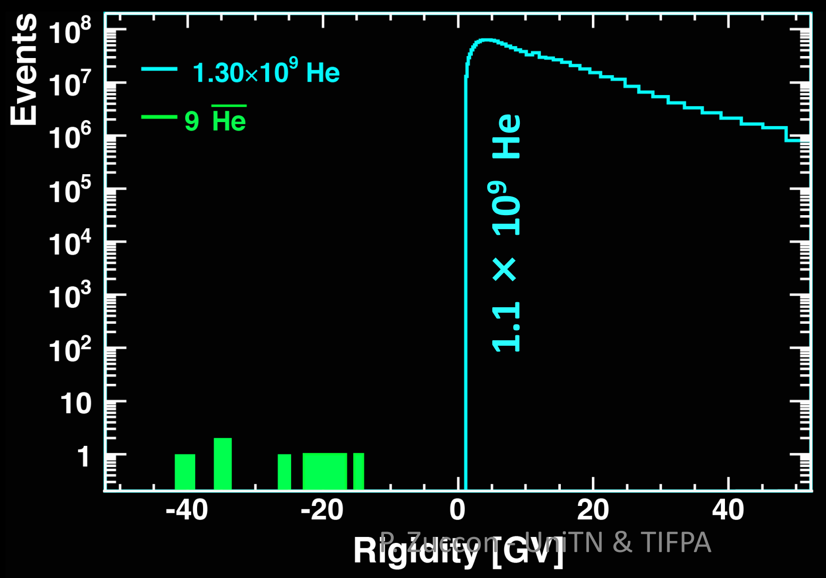
Current AMS Anti-Deuteron Status

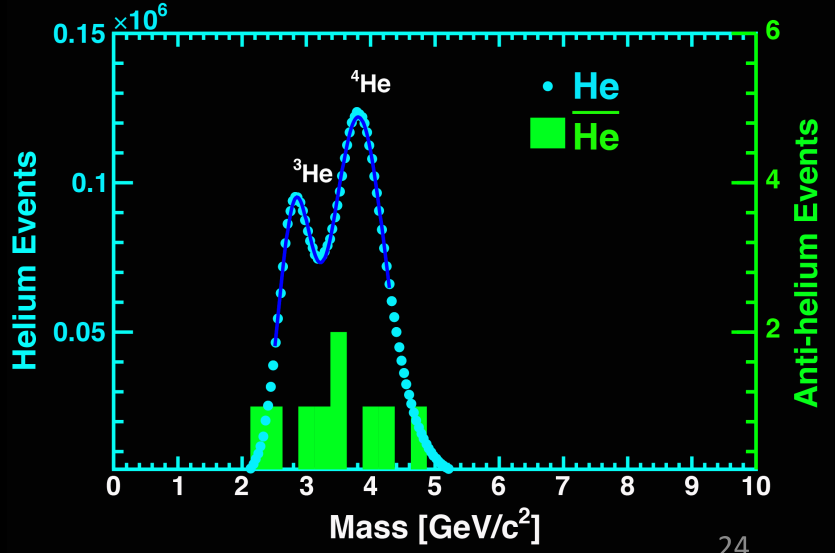


AMS-02

anti-He candidates up to 2020







Upcoming Experiments

GAPS: General AntiParticle Spectrometer

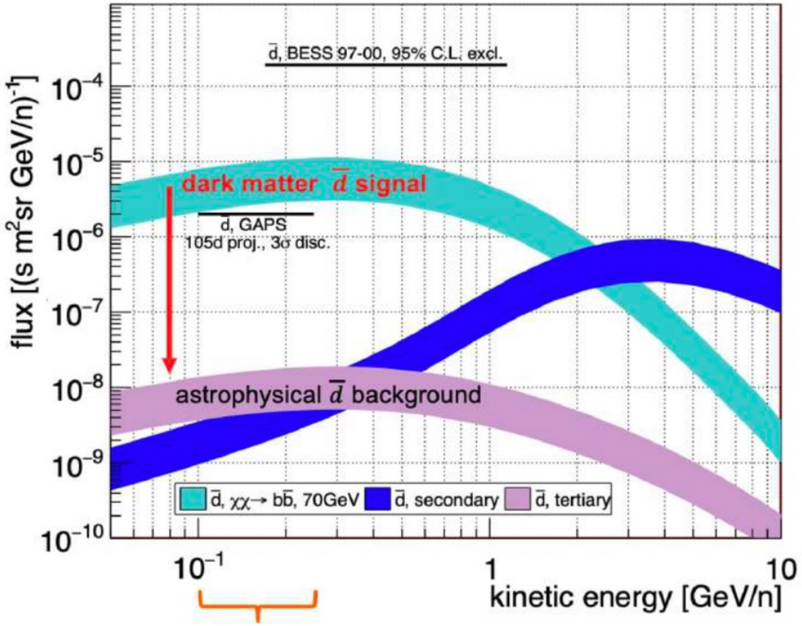
USA-Italy-Japan experiment for the detection of antinuclei: $\overline{p}$, $\overline{d}$, $\overline{He}$ $(100 - 250$ MeV/n).

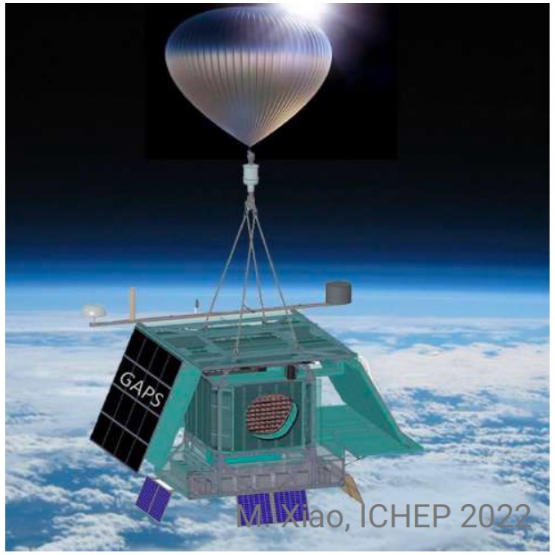
Non-magnetic spectrometer: the detection id based on **exotic atom formation** with **X/π emission**

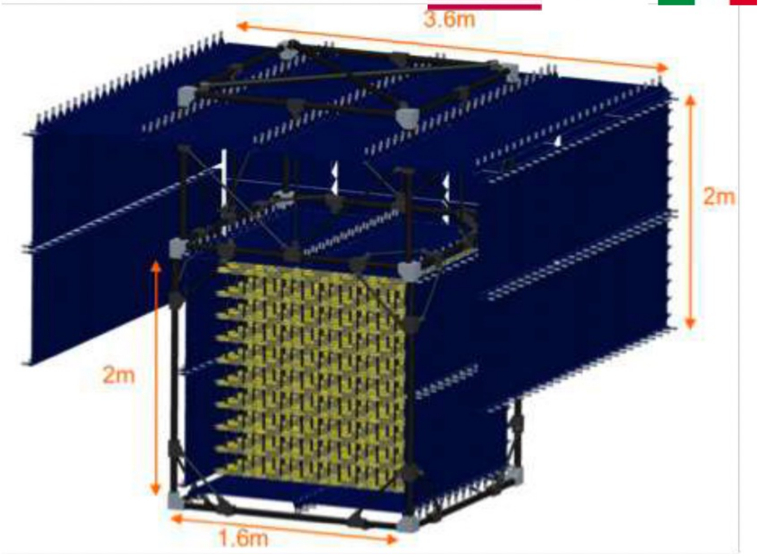
ToF system (A,B) and a 10-layer SiLi tracker (C)

First of a series of Antarctic balloon flights scheduled for late-2023.

3 x 35-day flights: sensitivity to antideuteron (2 10^{-6} [m^2 s sr GeV/n]$^{-1}$)

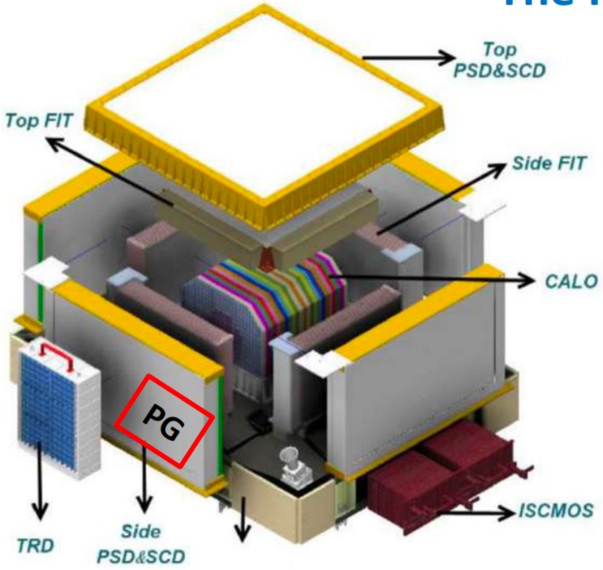




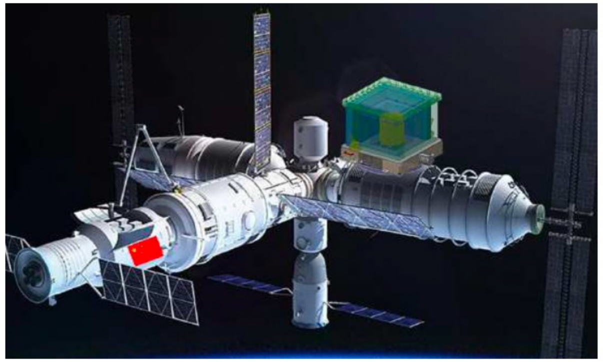


The HERD Experiment in the Chinese Space Station

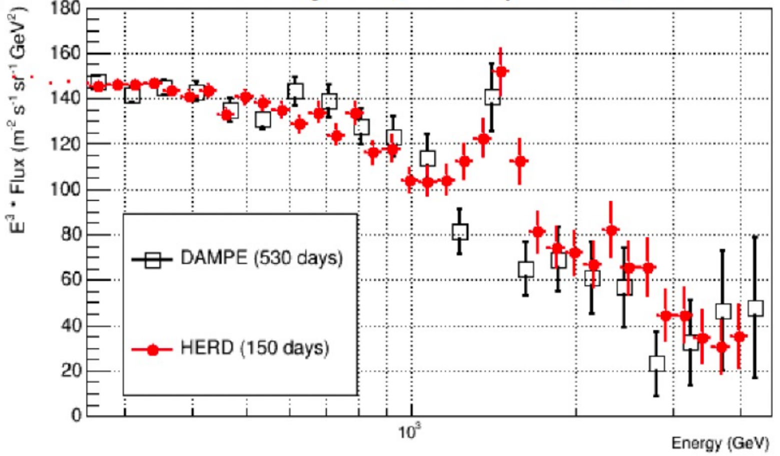
The High Energy cosmic Radiation Detection facility



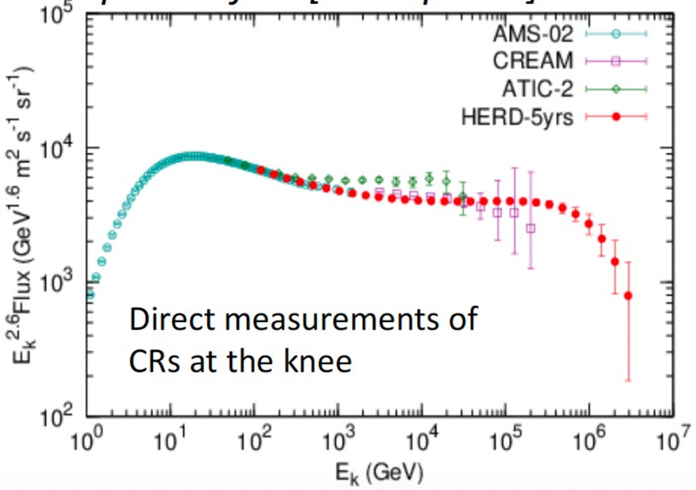
- HERD consortium: 130+ from China, Italy, Switzerland, Spain
- Long-term mission ~10 yrs (Exp ~ 20 m^2 sr yrs), NET 2027.
- Calorimetric measurements of leptons (multi-TeV) & nuclei (PeV!)



all-electron flux [anticipated]



proton flux [anticipated]



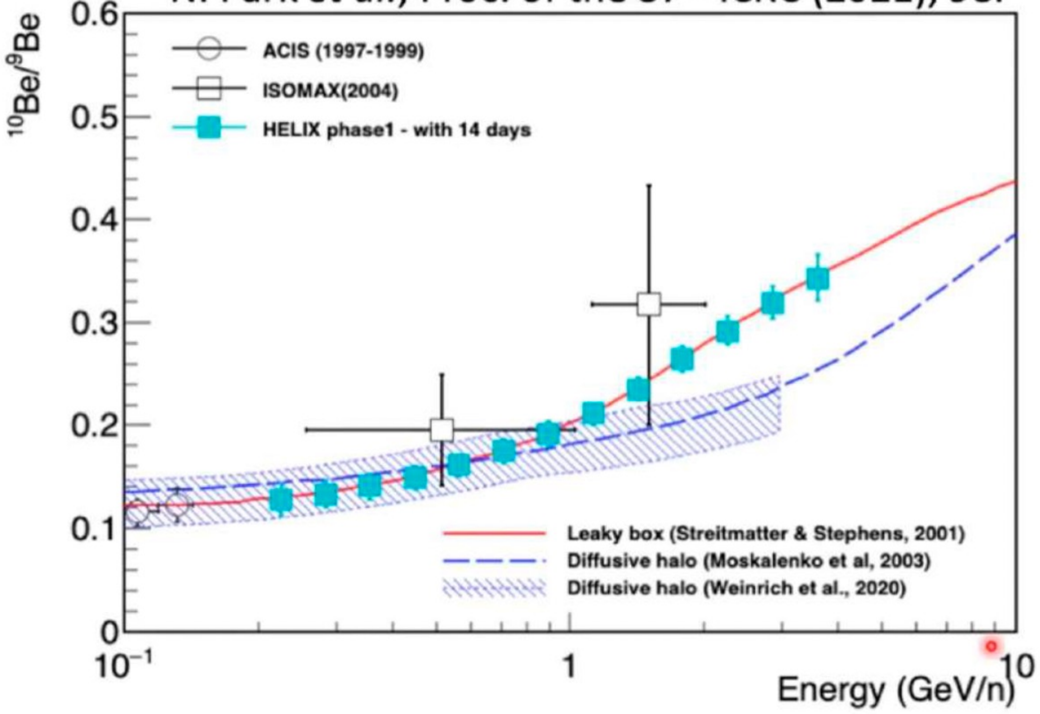
HELIX: High Energy Light-Isotope Experiment

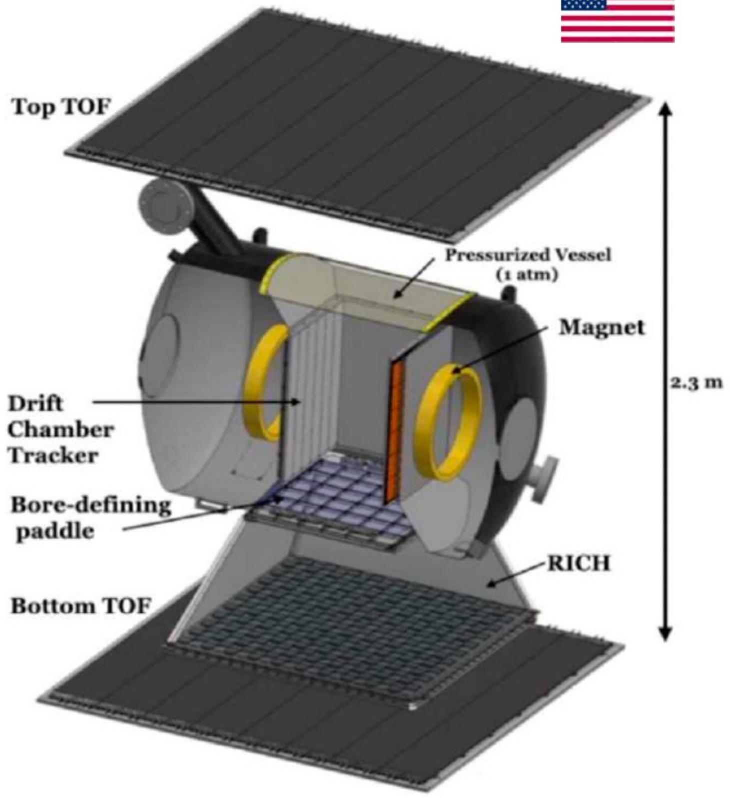
Experiment of CR isotopic composition measurement. Prime goal: $^{10}Be/^{9}Be$

Isotopic separation up to Neon. Basic spectrometer with drift chamber, B=1T, mass resolution <3%

HELIX is moving forward to be ready for integration in 2023

N. Park *et al.*, Proc. of the 37th ICRC (2021), 98.





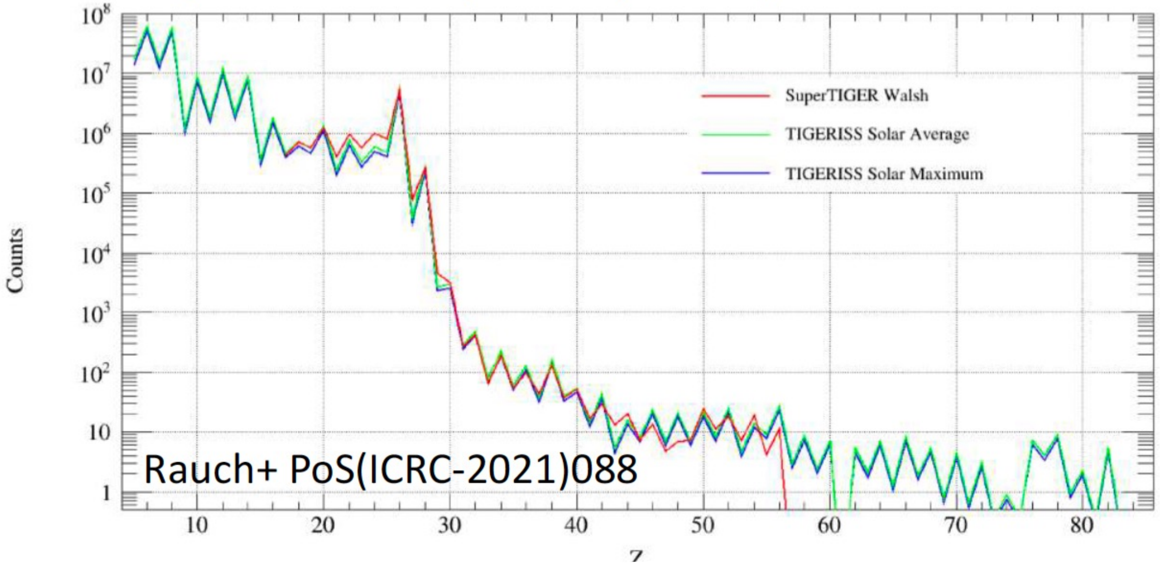
TIGERISS: Super-Heavy CRs from the ISS

TIGERISS: The Trans-Iron Galactic Element Recorder for the International Space Station

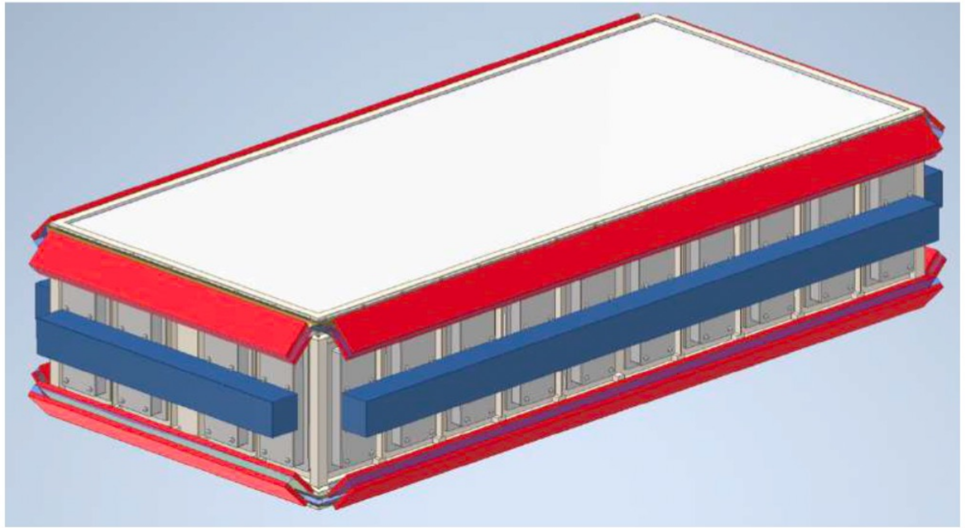
Based on SuperTIGER, to be installed on the ISS for a long-term mission.

Composition of the ultra-heavy CRs with single-element resolution from Z=6 (C) to Z=82 (Pb) or even Z=96 (Cm).

Projected counts for one year exposure on the ISS



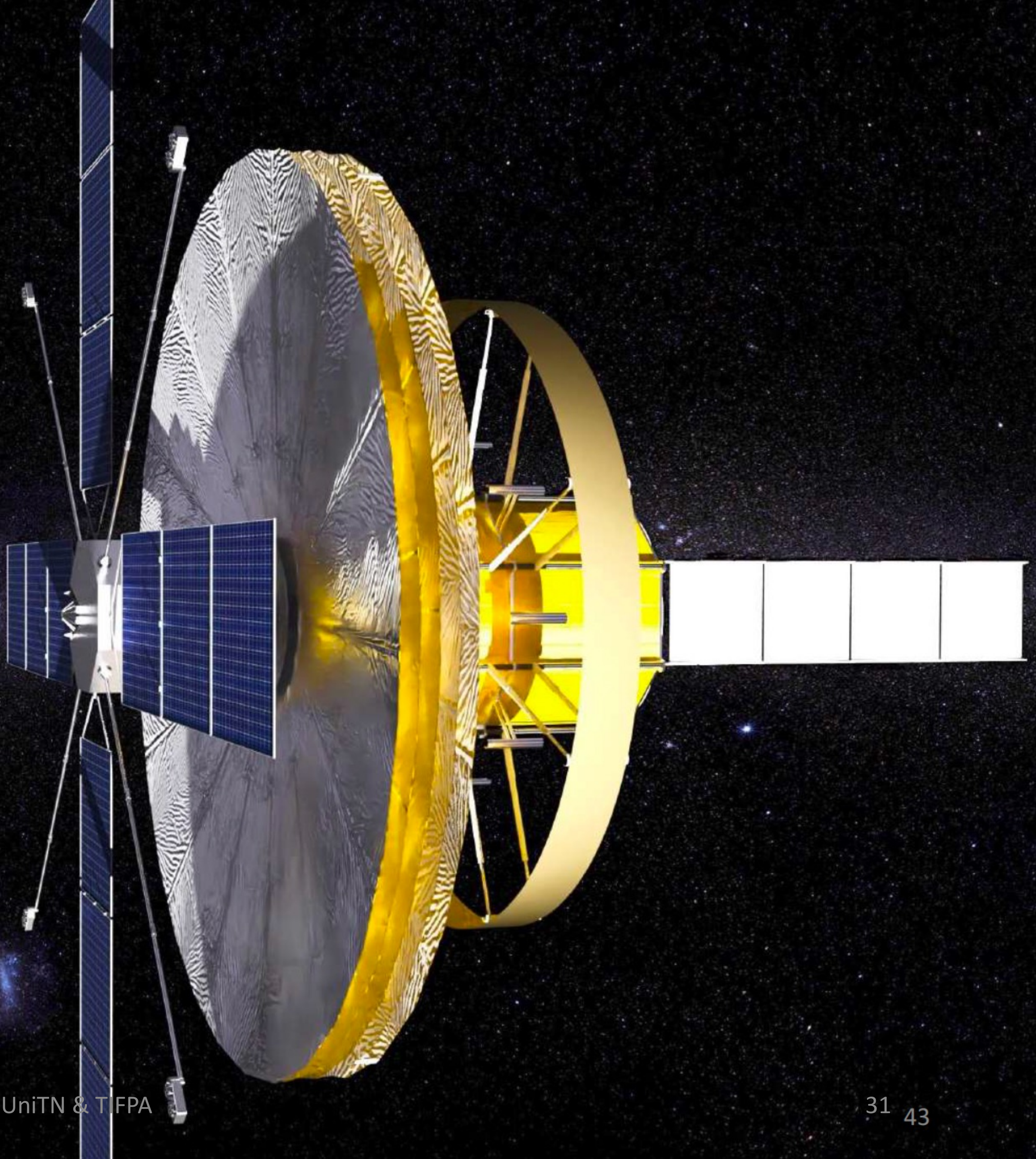
Technical model of the detector stack



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

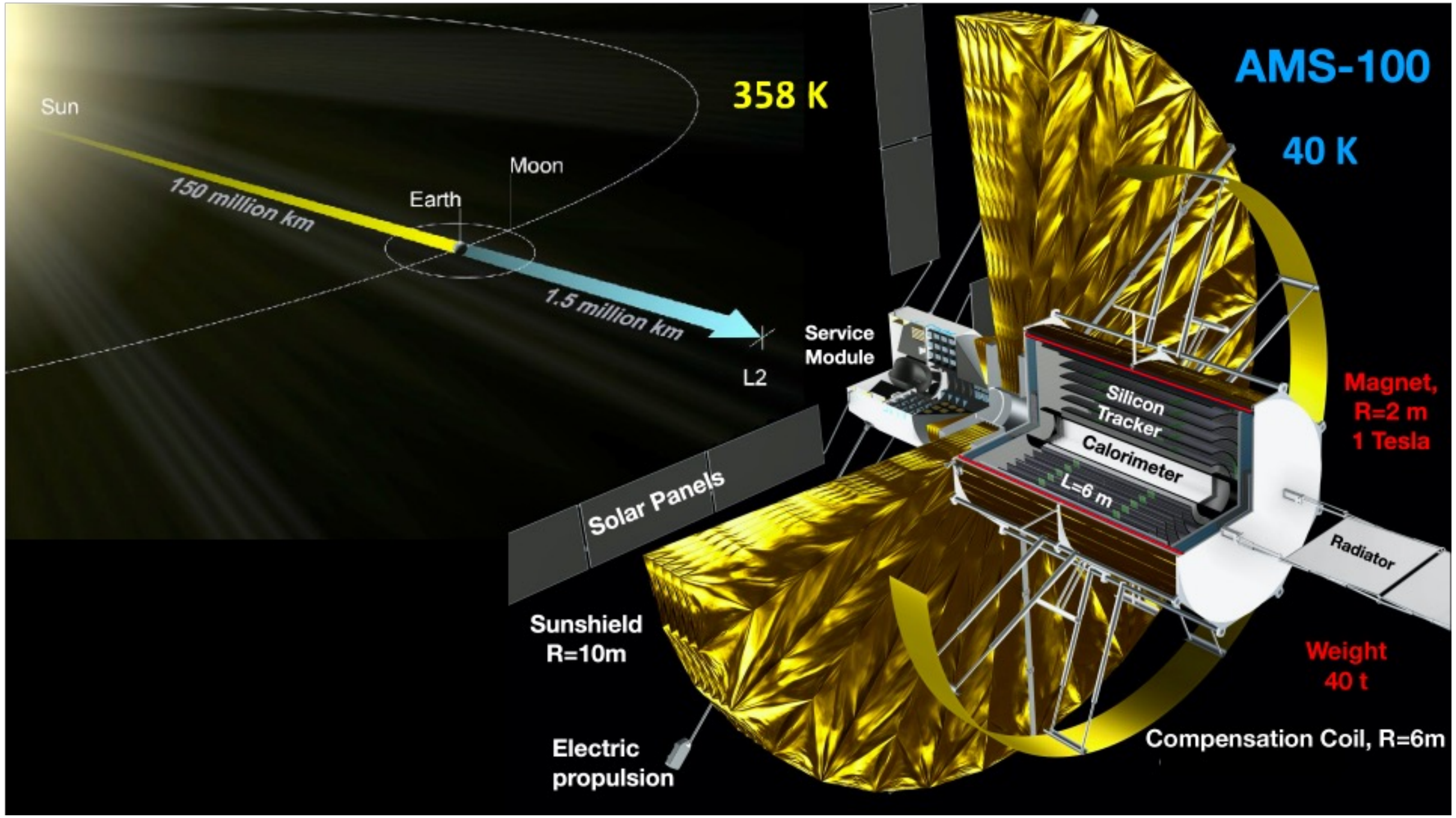
White paper: Shael et al. NIM A 944 162561 (2019)

https://arxiv.org/abs/1907.04168

AMS-100

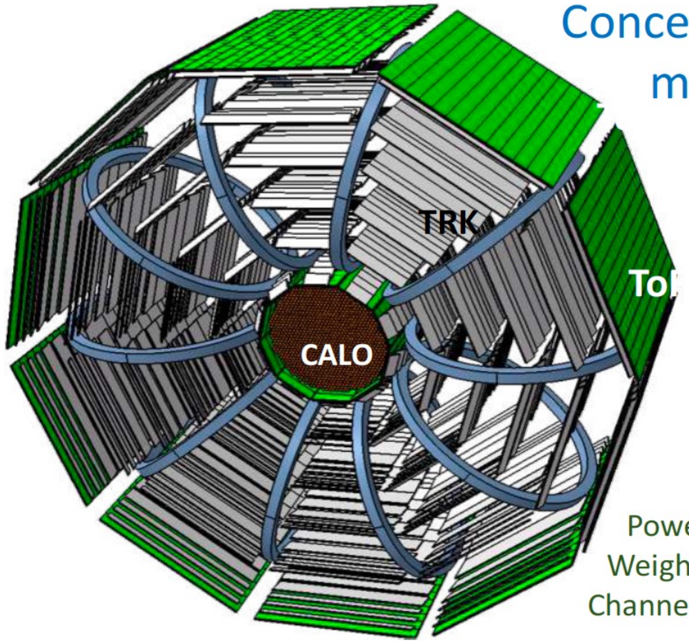
- AMS-100
- Lagrange point 2
- 1 Tesla magnetic, (6 Å~ 2) m
- Tracker, MDR = 100 TV
- Central calorimeter
- Targets e+, e-, nuclei (beyond the knee), antinuclei

- 40 tons -> needs heavy lifter rocket



ALADInO: A Large Antimatter Detector In space

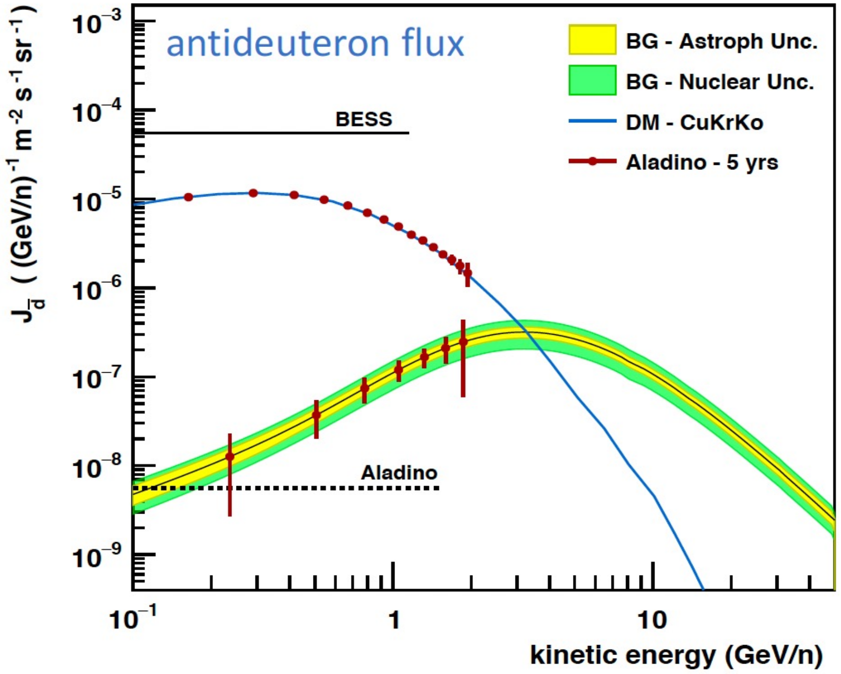
Concept for a new antimatter spectrometer to operate in L2 for measurement to extend the legacy of PAMELA and AMS-02



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



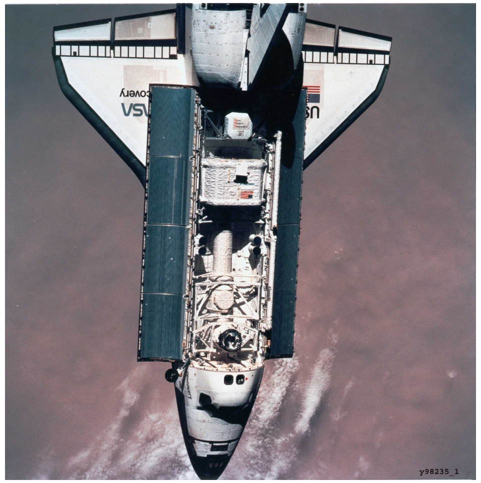
Total acceptance	10 m^2sr	Calo resolution	2% (e) – 30% (N)
MDR	20 TV	TOF resolution	100 ps

- 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

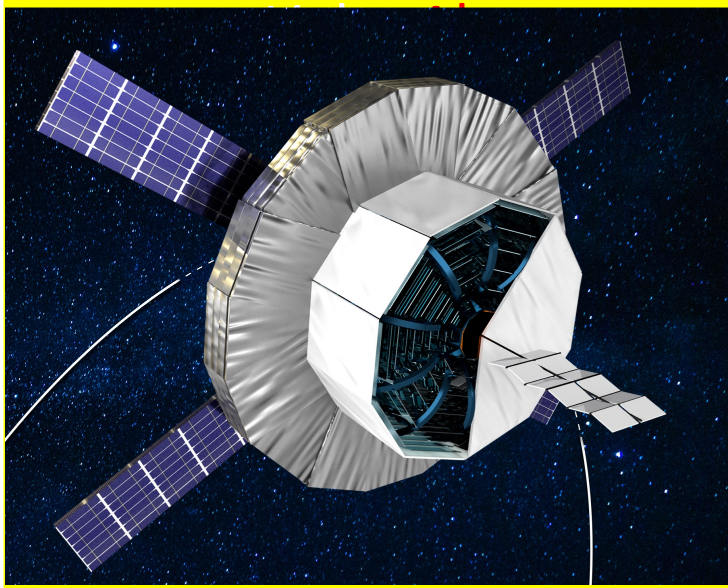
Alpha Magnetic Spectrometer - 02 (AMS-01)

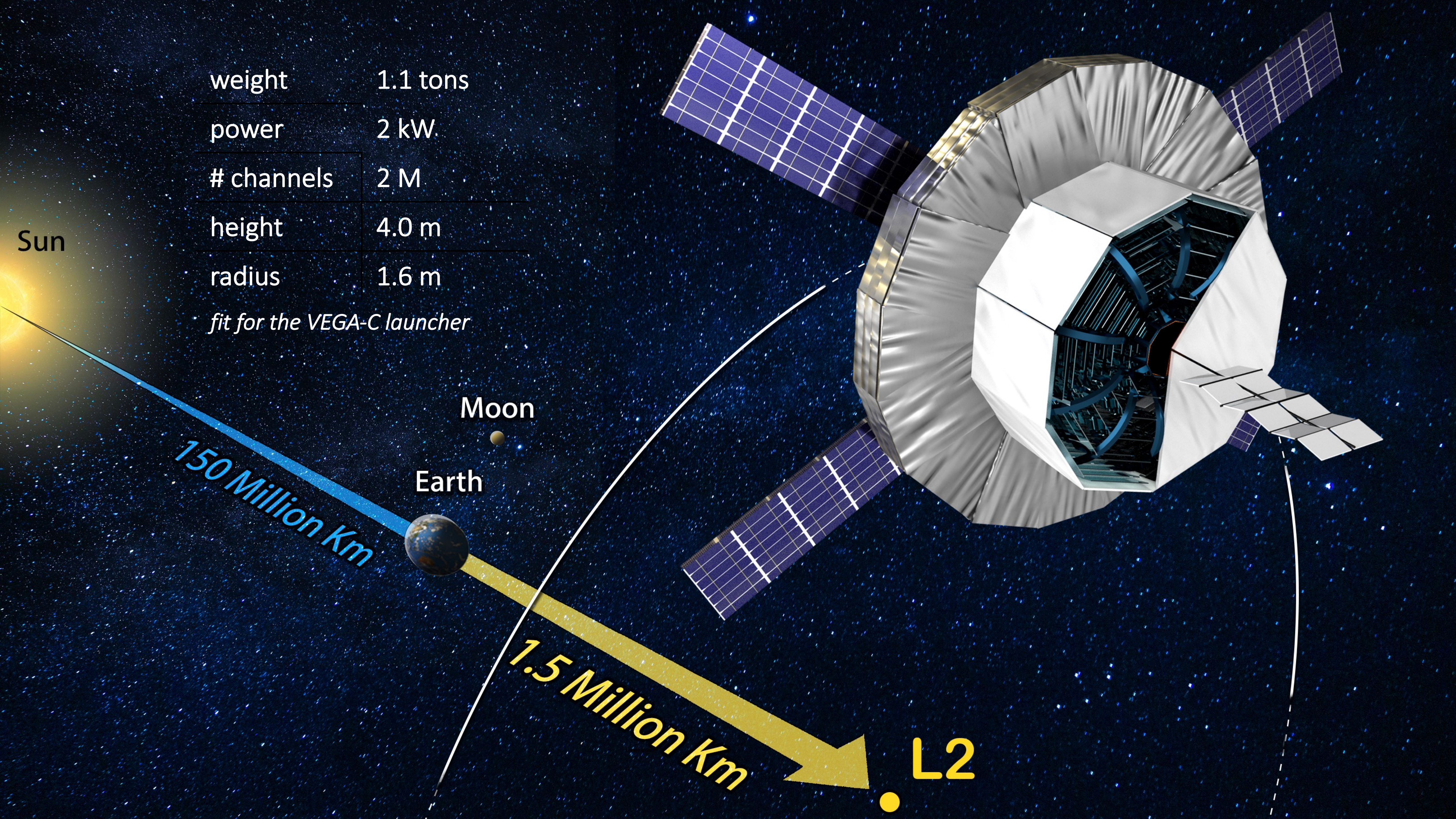
- ~ 6.7 tons
- on-board the ISS
- in operation since 2011. Operations expected to last until 2028.

Light Aladino-like Magentic sPectrometer

LAMP

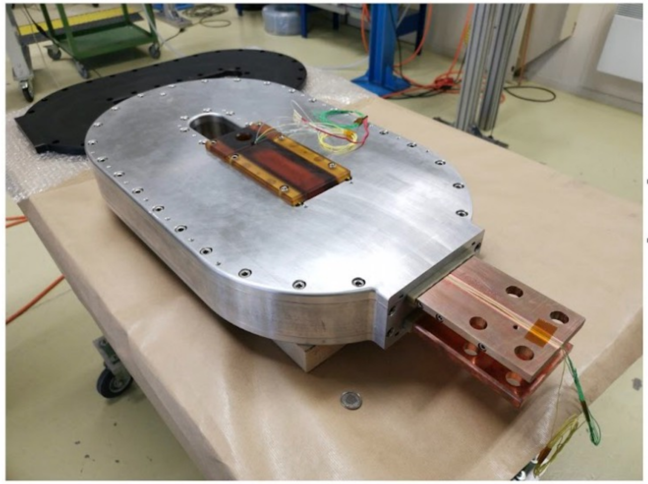
- ~ 1.1 tons
- L2 or LEO
- Launch by 2032.
- 10 years of operations

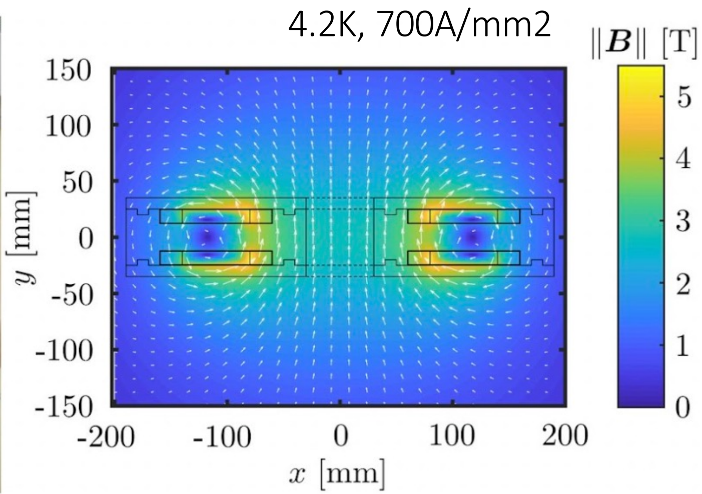



weight 1.1 tons
power 2 kW
channels 2 M
height 4.0 m
radius 1.6 m
fit for the VEGA-C launcher
Sun
Moon
Earth
150 Million Km
1.5 Million Km
L2

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.





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.

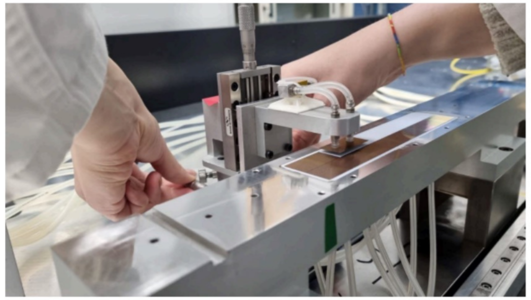
High Temperature Superconducting (HTS) magnets (YBCO or MgB2) could be operated in space at 20 K, greatly simplifying the problem of cryogenics, even allowing to rely exclusively on cryocoolers. **The use HTS magnets for space is unprecedented and it has no state-of-the-art reference to compare with.**

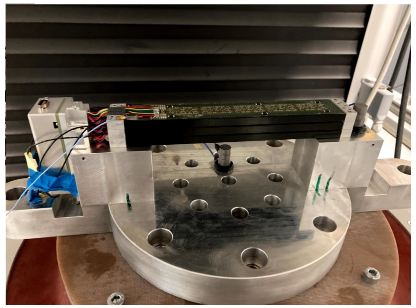
Concerning the cooling system, it is worth recalling that cryocoolers have been already used in space missions and the AMS-02 collaboration itself designed and fully qualified commercial Stirling-cycle devices.

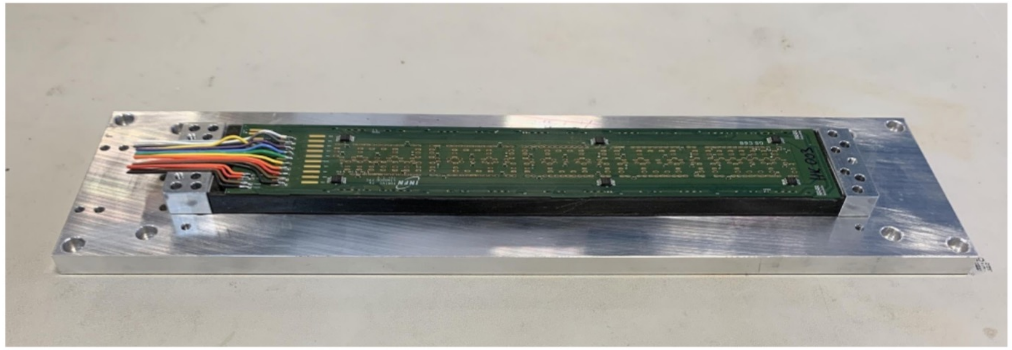
Tracker

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.

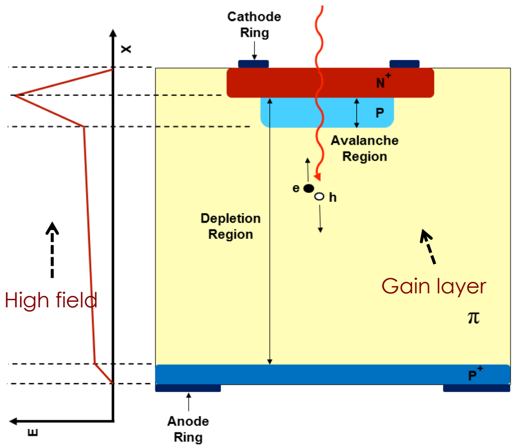
Monolithic Active Pixel Sensors (MAPS) are one of the most innovative approaches to particle tracking. CMOS-fabricated, they feature in-pixel electronics, with unparalleled low-noise and O(um) single hit precision.
Spatialized for the INFN-ASI project HEPD for the CSES-02 mission. Current developments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

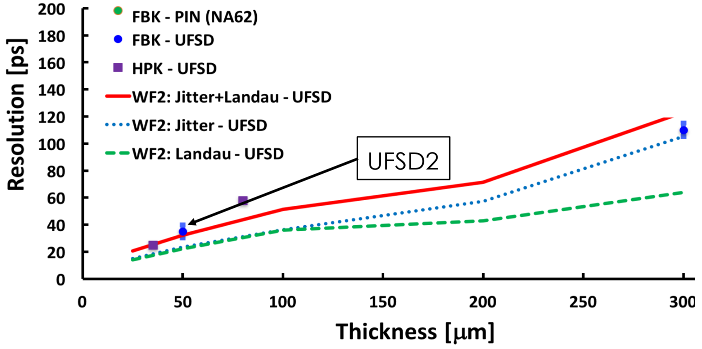






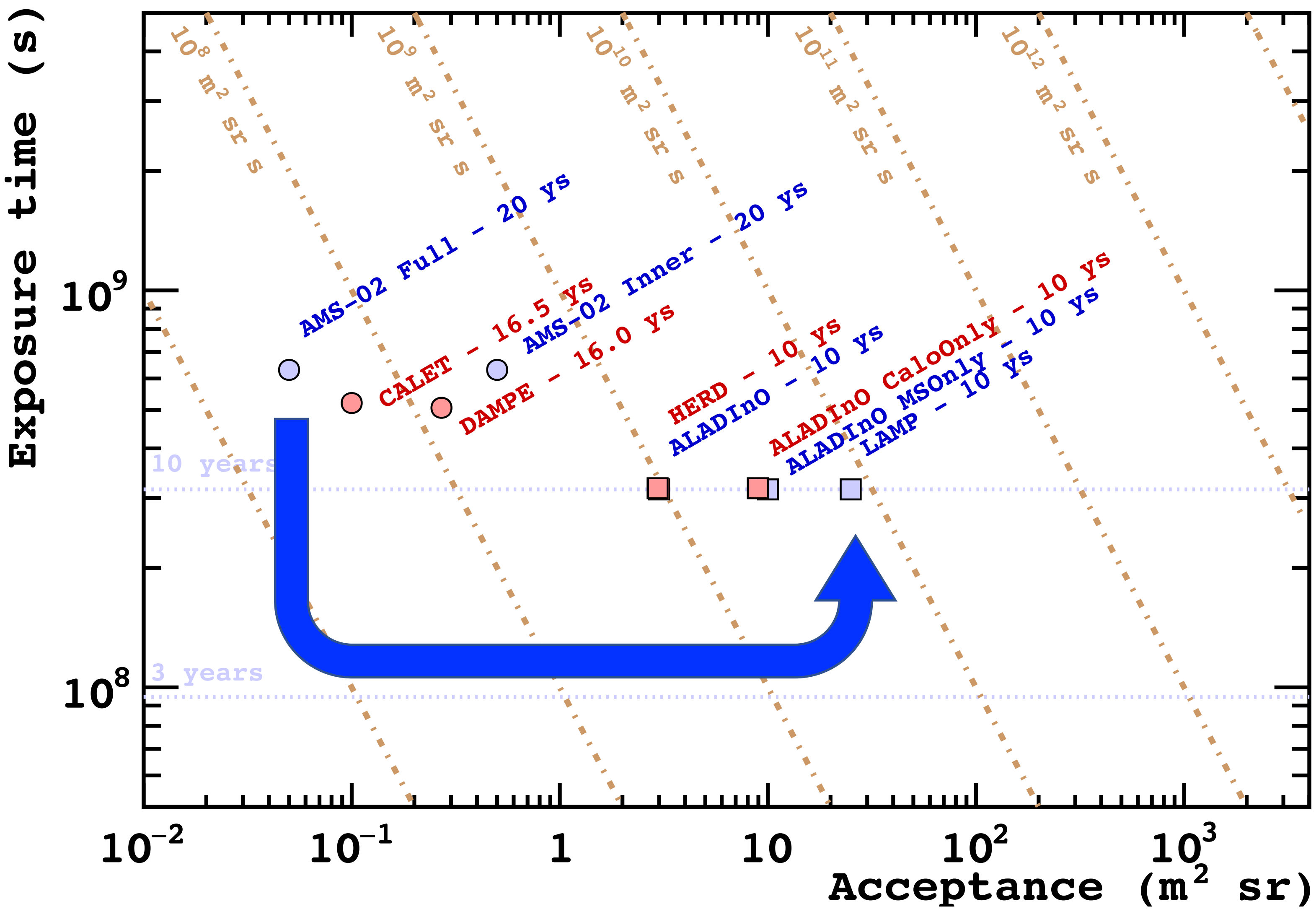
Low Gain Avalanche-Diodes (LGAD) are a promising apporoach to particle tracking. Ultra Fast Silicon Detectors have been developed by INFN-TO (N. Cartiglia) and the R&D is carried forward in collaboration with FBK. Current developments focus on enhanced timing capability.





Roberto Iuppa
P. Zuccon - UniTN & TIFPA

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.**

Roberto Iuppa

Istituto Nazionale di Fisica Nucleare

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