Direct Measurements of Cosmic Rays

and what we can learn from them

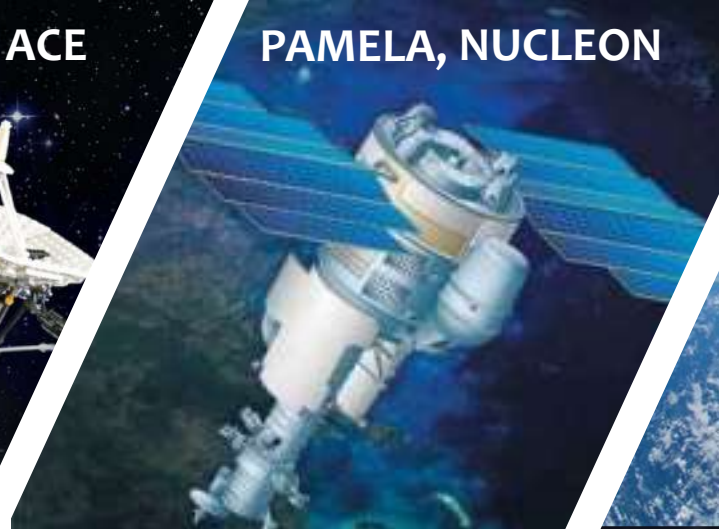
Nicola Tomassetti
Università degli Studi di Perugia

European Cosmic Ray Symposium ECRS 2022
Nijmegen, The Netherlands, 25-29 July 2022

A.D. 1308 unipg
DIPARTIMENTO
DI FISICA E GEOLOGIA

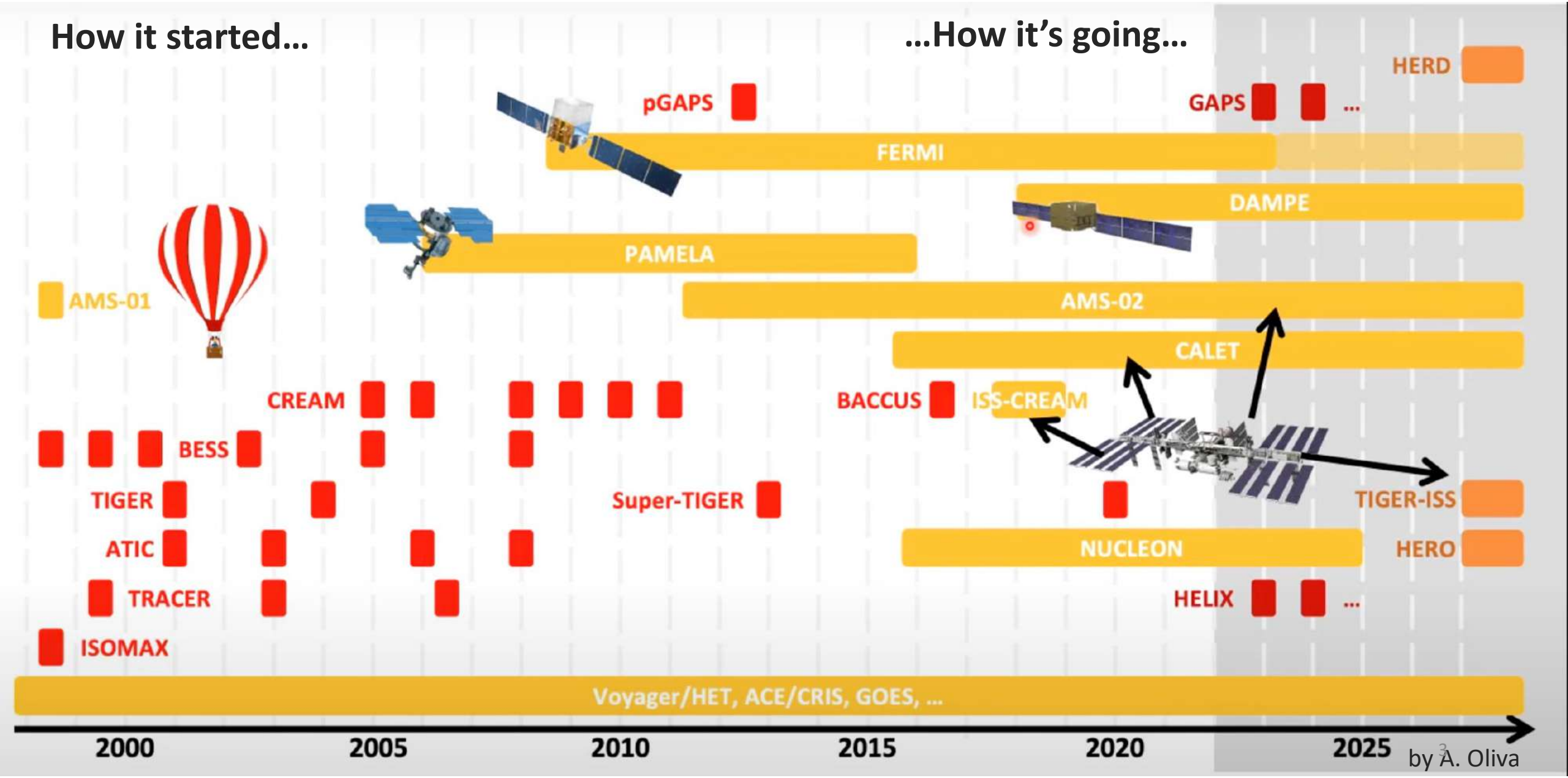
INFN

Università degli Studi di Perugia
C.R.I.S.P. ASI-UniPG 2019-2-HH.0



a golden age of new cosmic ray measurements

Direct CR Measurements in the 3° millennium

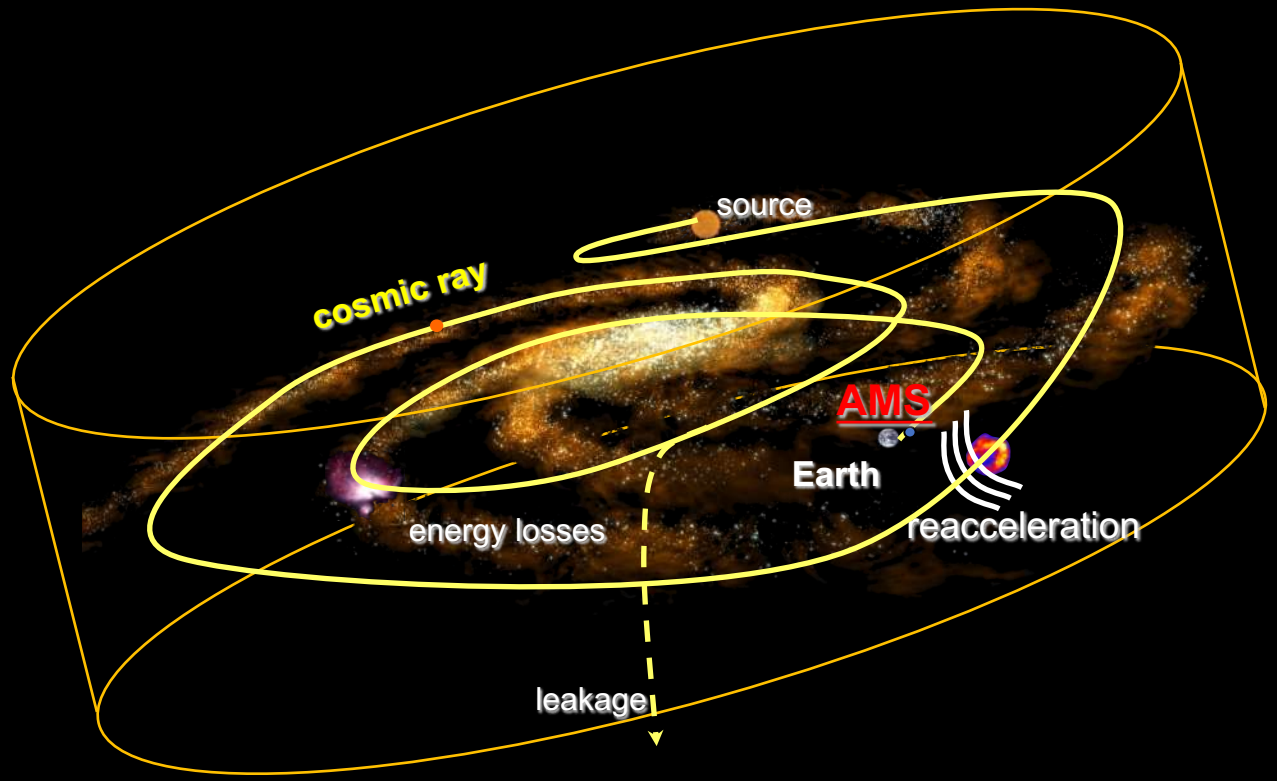


by A. Oliva

The 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…



The concrete models rely on simplifying assumptions: symmetry, homogeneity, isotropy, stationarity, linearity…

The 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…**

Classical 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?

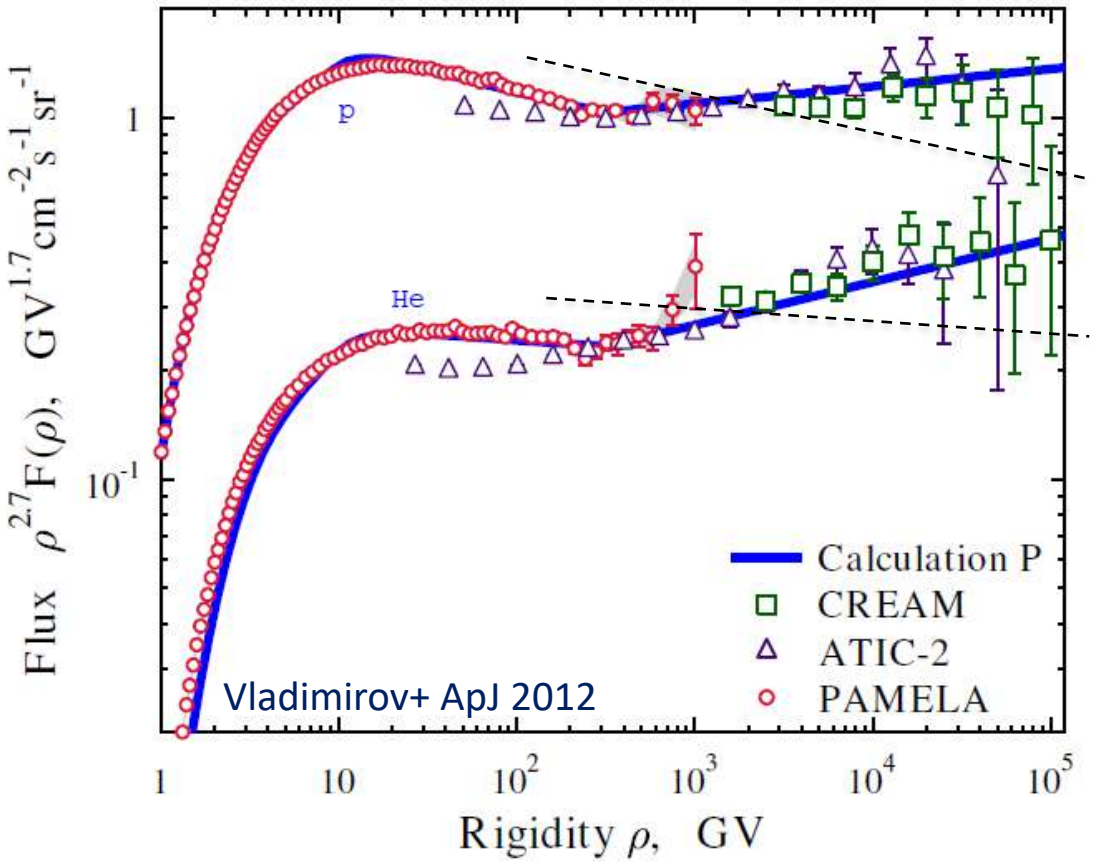
The high-energy spectral hardening

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

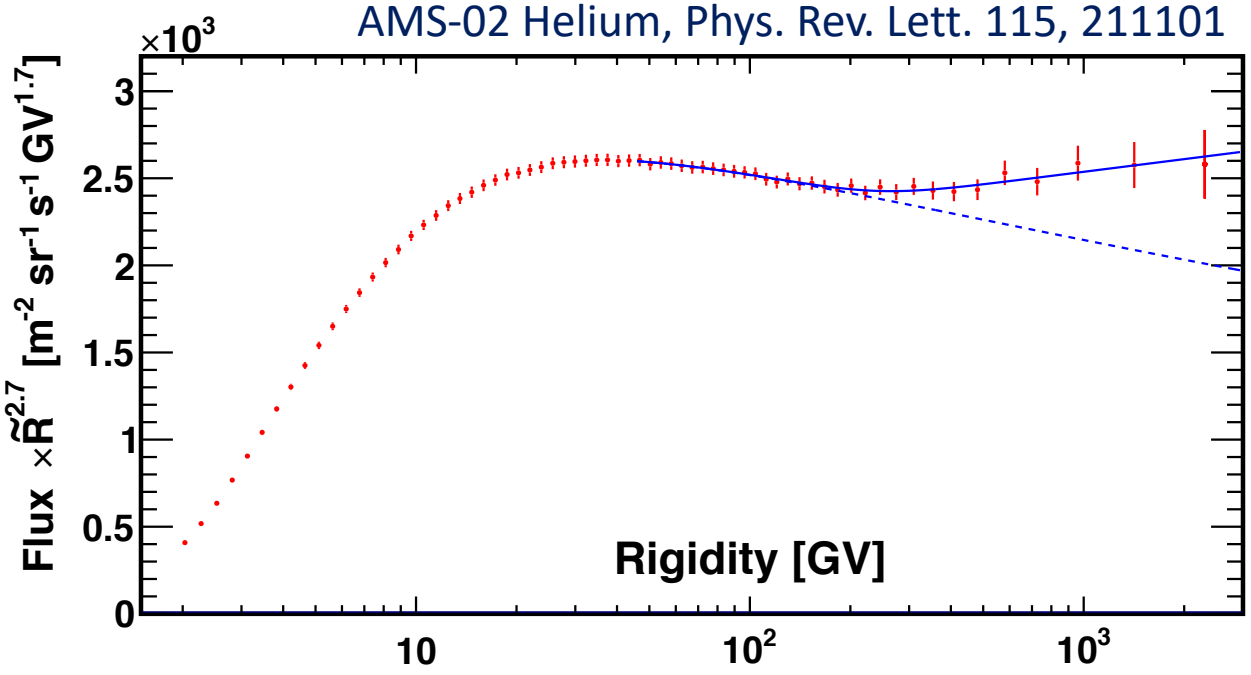
Challenge to the paradigm of CR acceleration & diffusive propagation

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

Spectral hardening at ~100 GeV energies

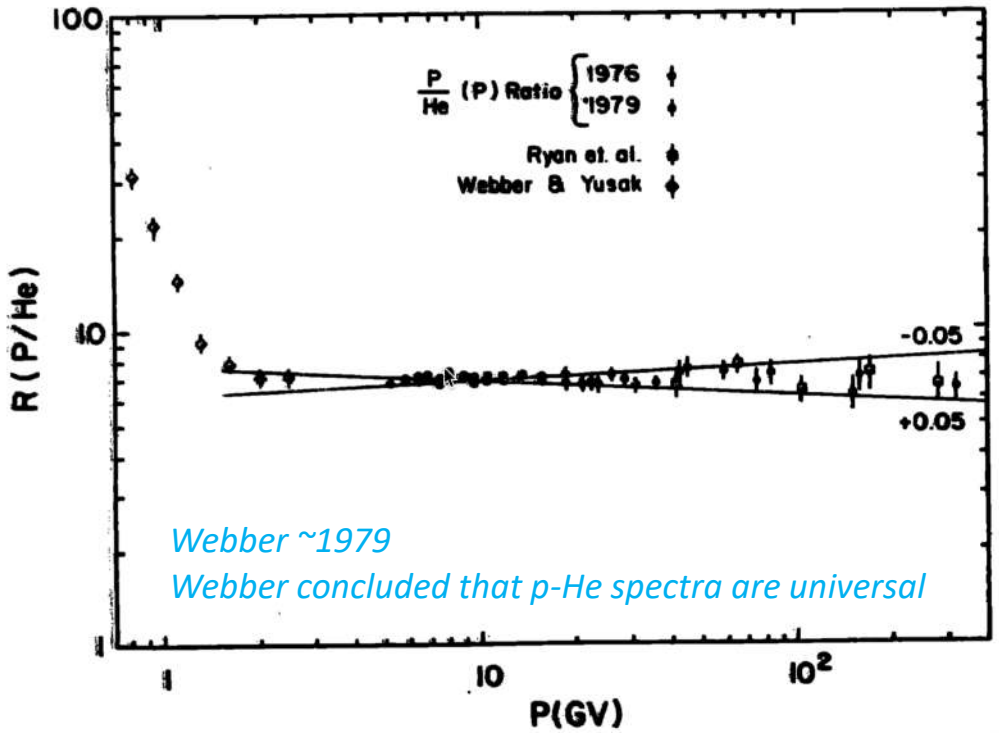


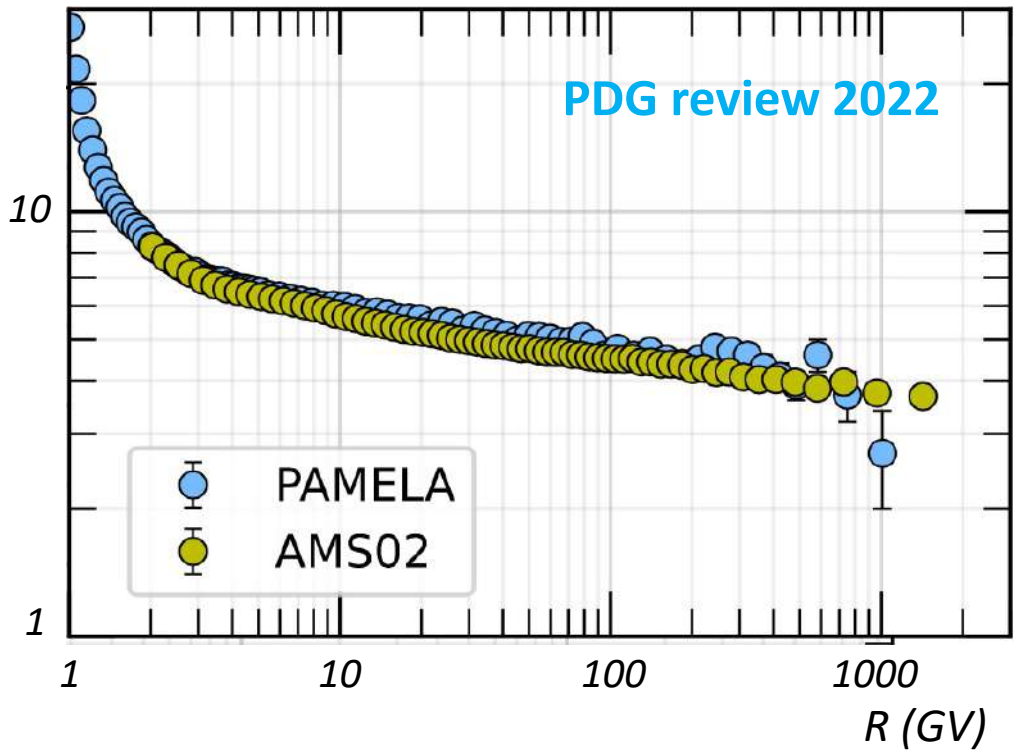
AMS-02 Helium, Phys. Rev. Lett. 115, 211101



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



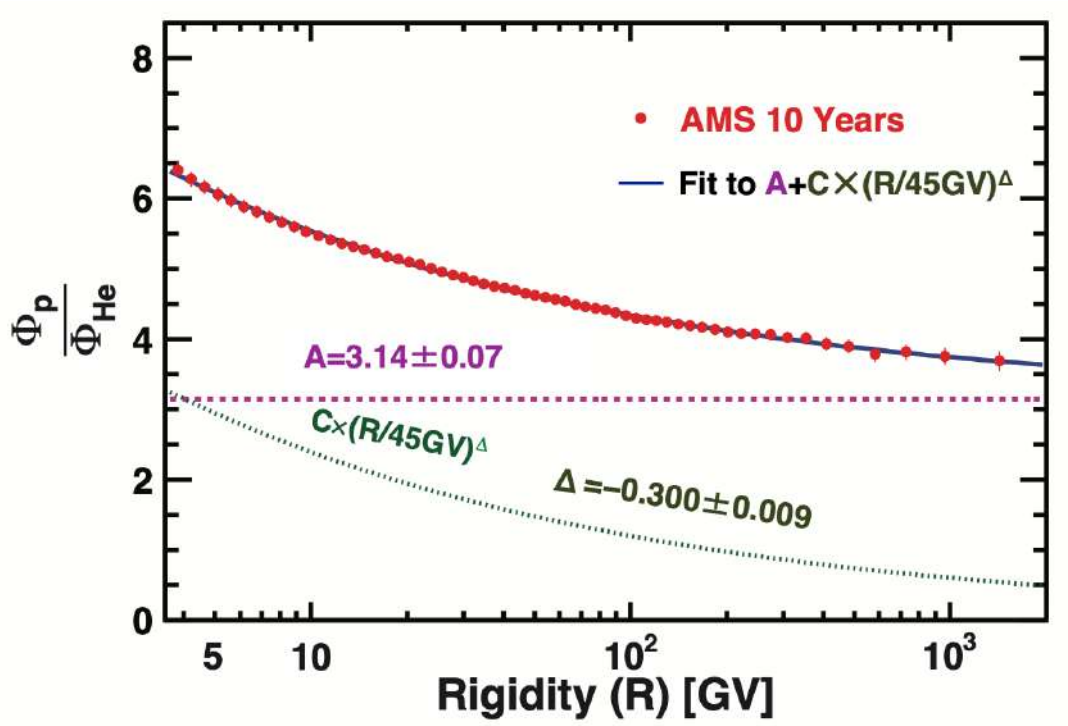


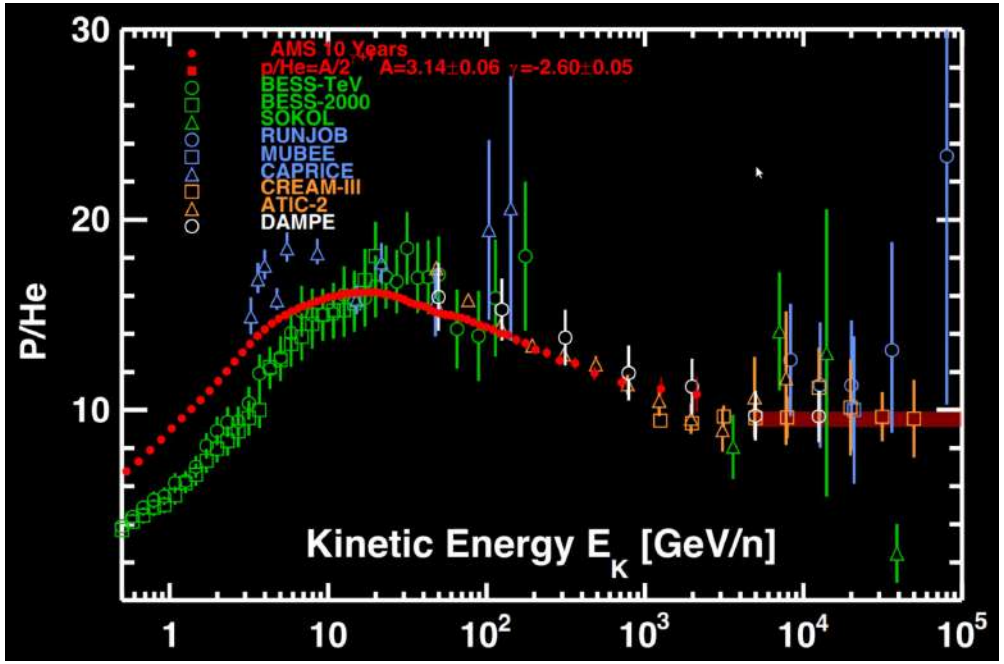
Not explained by (basic) diffusive-shock-acceleration theory. DSA is composition blind!

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)

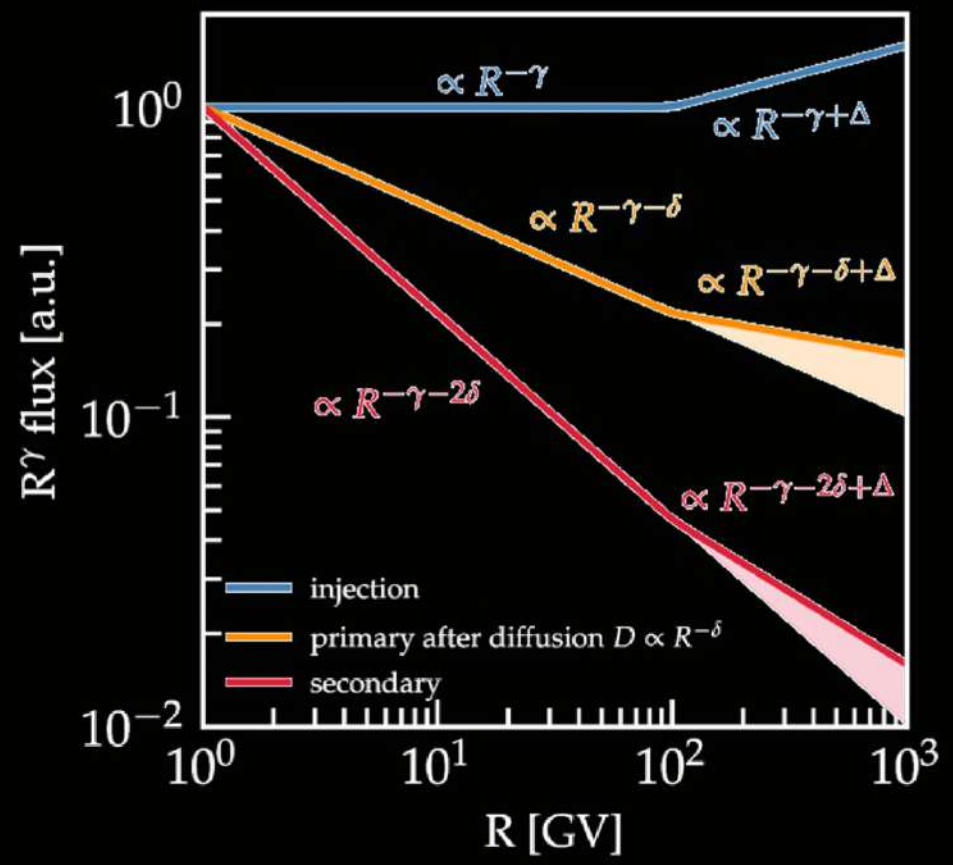


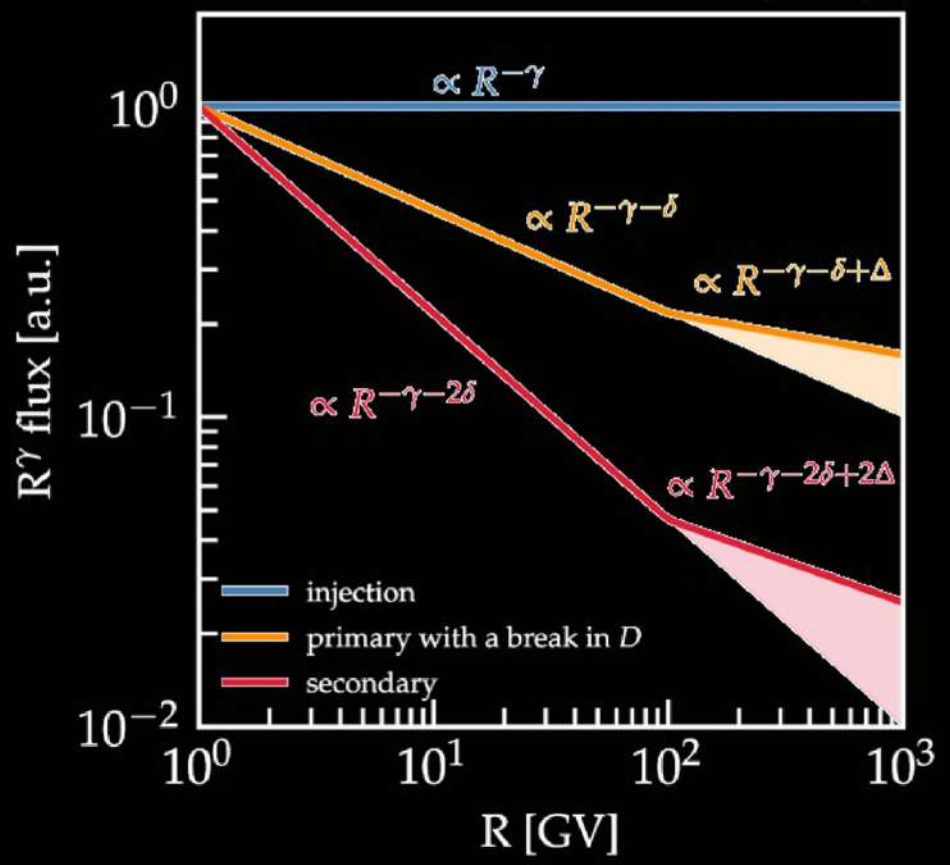


(NT ApJL 815, L1 (2015)[astro-ph/1511.04460] «A distinctive signature of our scenario is the high-energy flattening of the p/He ratio at multi-TeV energies, which is hinted at by existing data and will be resolutely tested by new space experiments ISS-CREAM and CALET».)

Origin of the CR spectral hardening

From C. Evoli (2019).





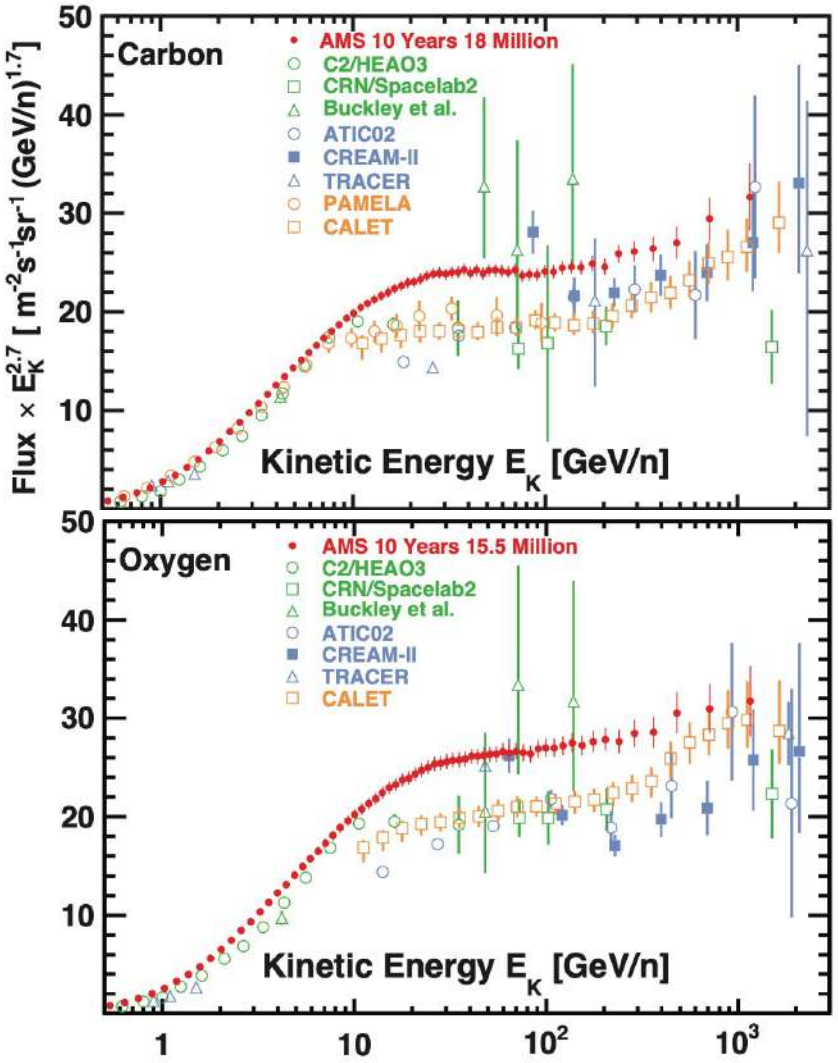
If the hardening is related to CR **acceleration**, we will observe a **similar hardening** for **secondary** and **primary**

(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

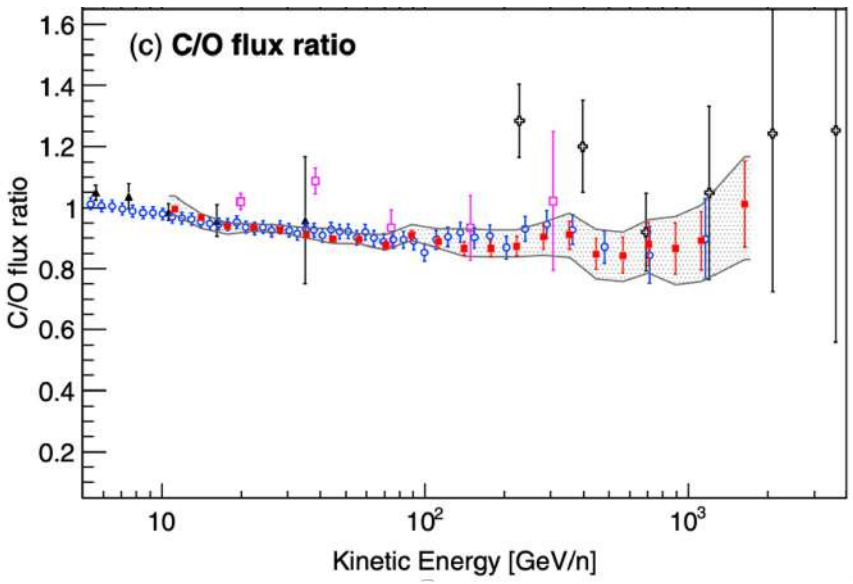
(NT ApJ 2012 [1204.4492], Blasi+ PRL 2012 [1207.3706]…)

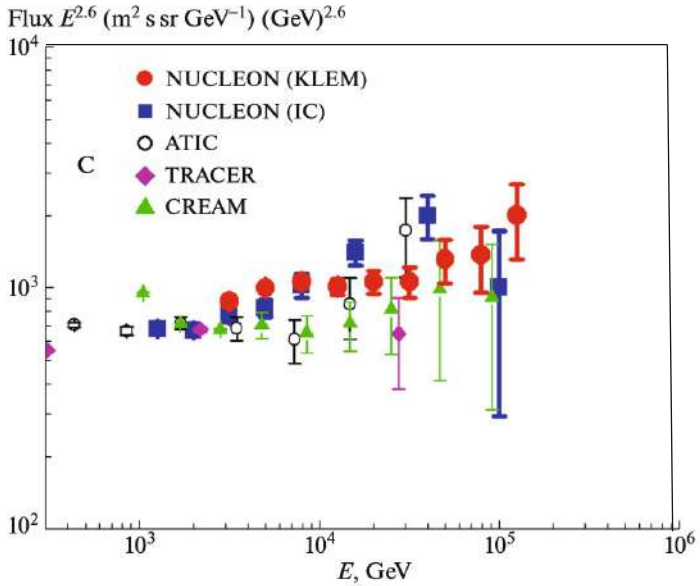
Spectral hardening in Carbon and Oxygen



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

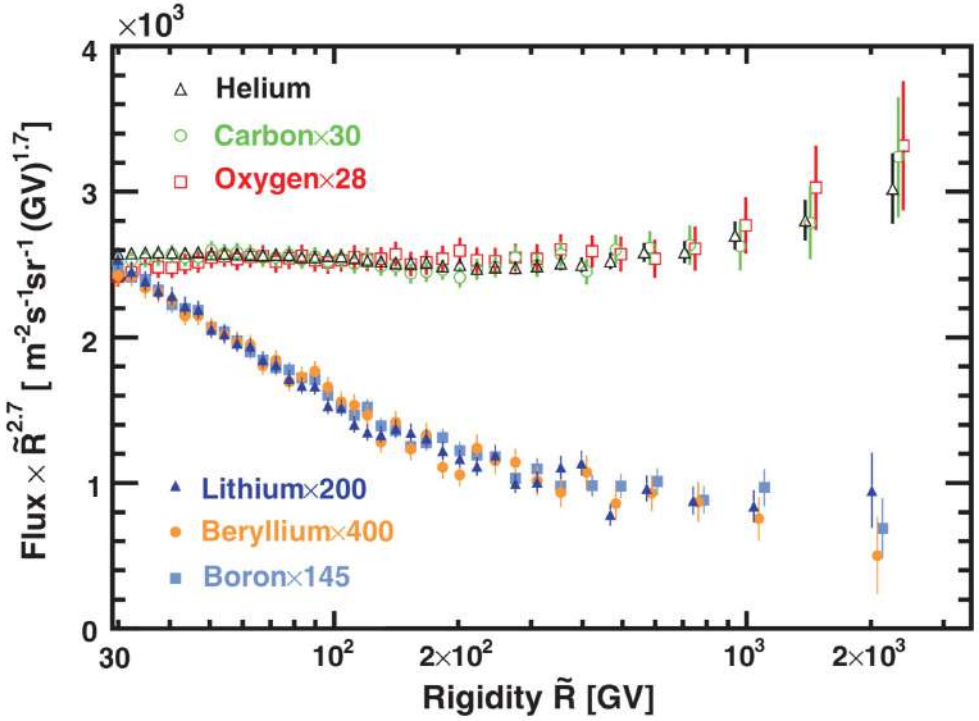
- CALET/AMS flux normalization discrepancy
- Similar spectral behaviour and ratio C/O
- Multi-TeV slope from Nucleon

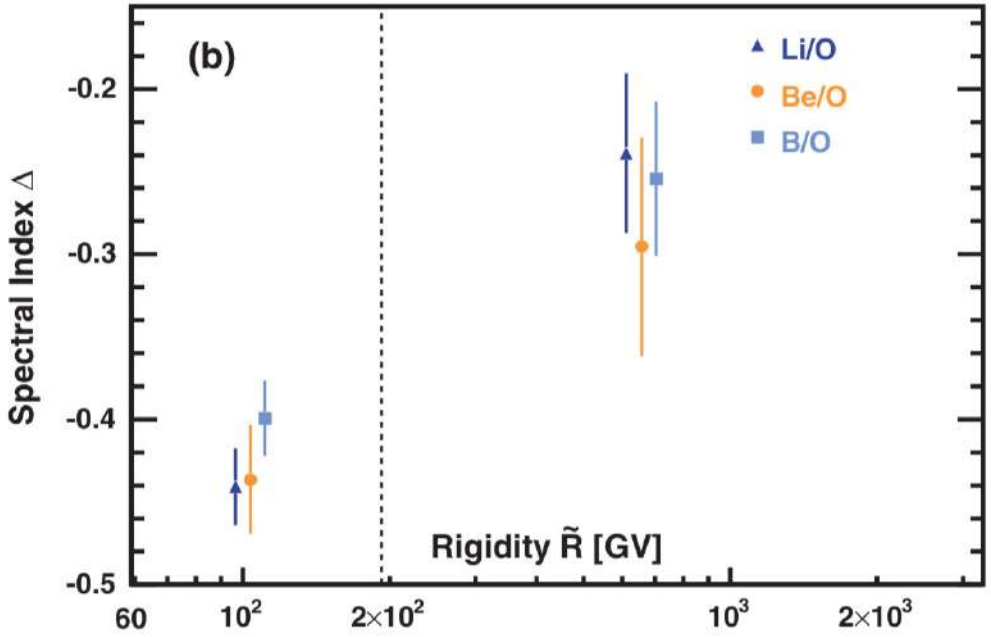




Spectral hardening in secondary Li-Be-B nuclei

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



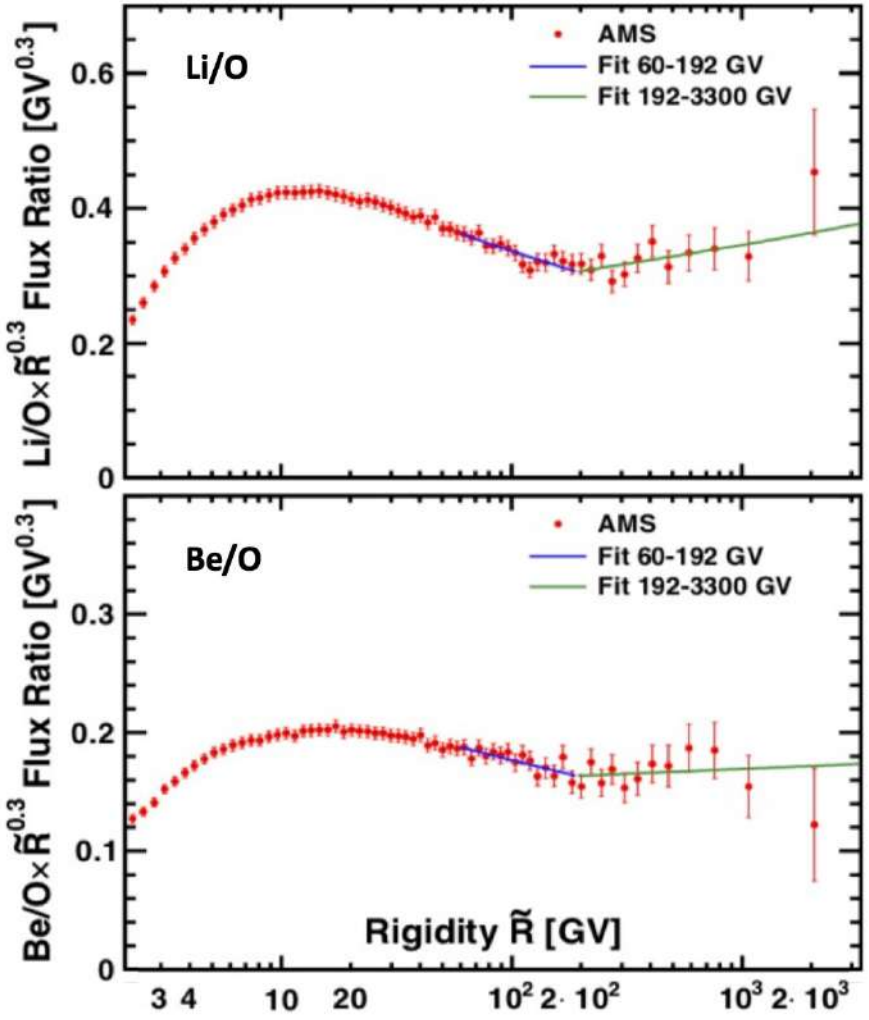


- He-C-O and Li-Be-B lie in two distinct spectral groups: primary and secondary CRs
- All species (and both pri and sec) are subjected to spectral hardening at rigidity R~300 GV
- Different change of slope: the Li-Be-B hardening is more pronounced. => S/P ratio hardening

Spectral hardening in secondary/primary ratios

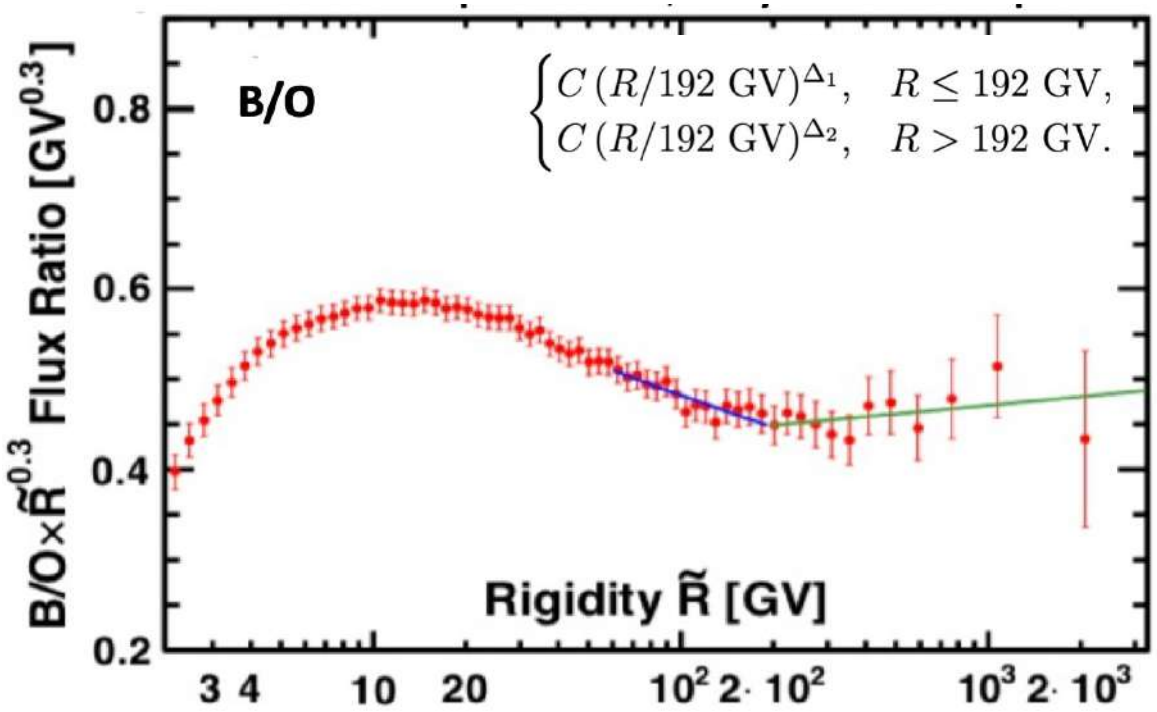
The break is seen not only in secondary CRs, but also in **secondary/primary** ratios.

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



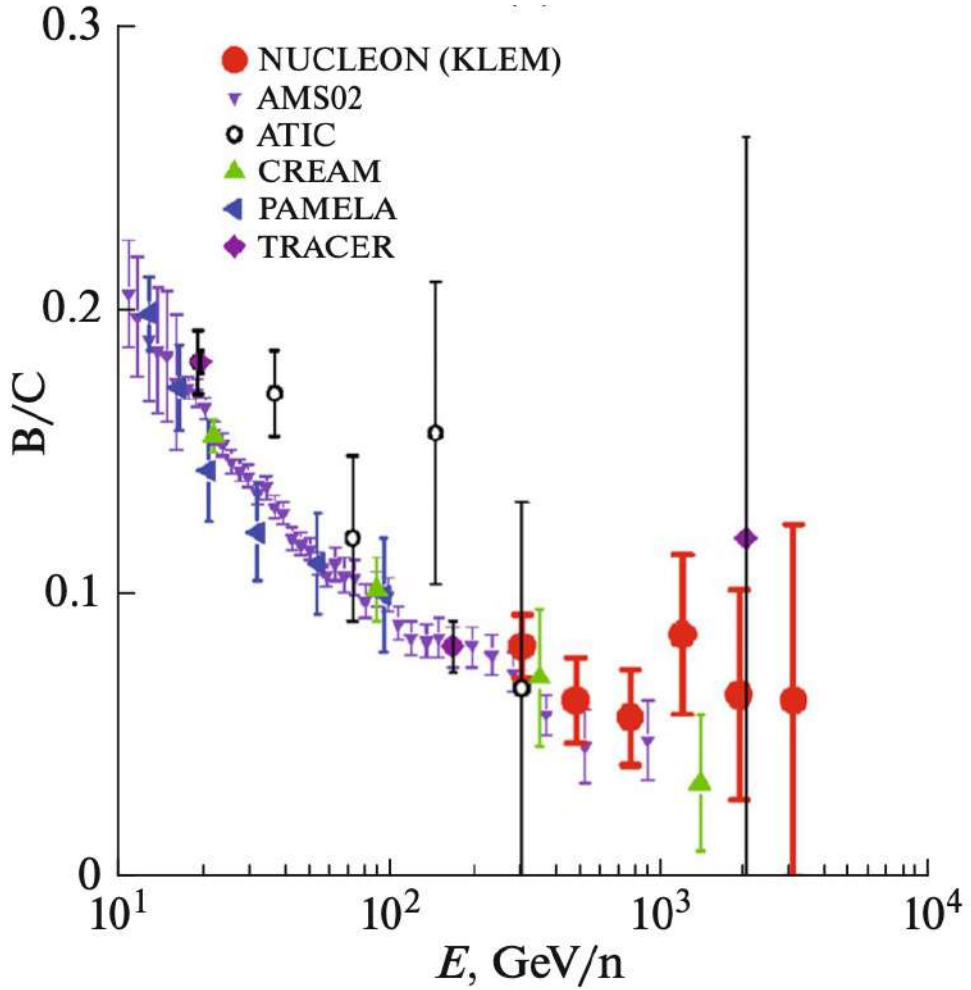
The diffusive origin of the breaks is discussed in many models:

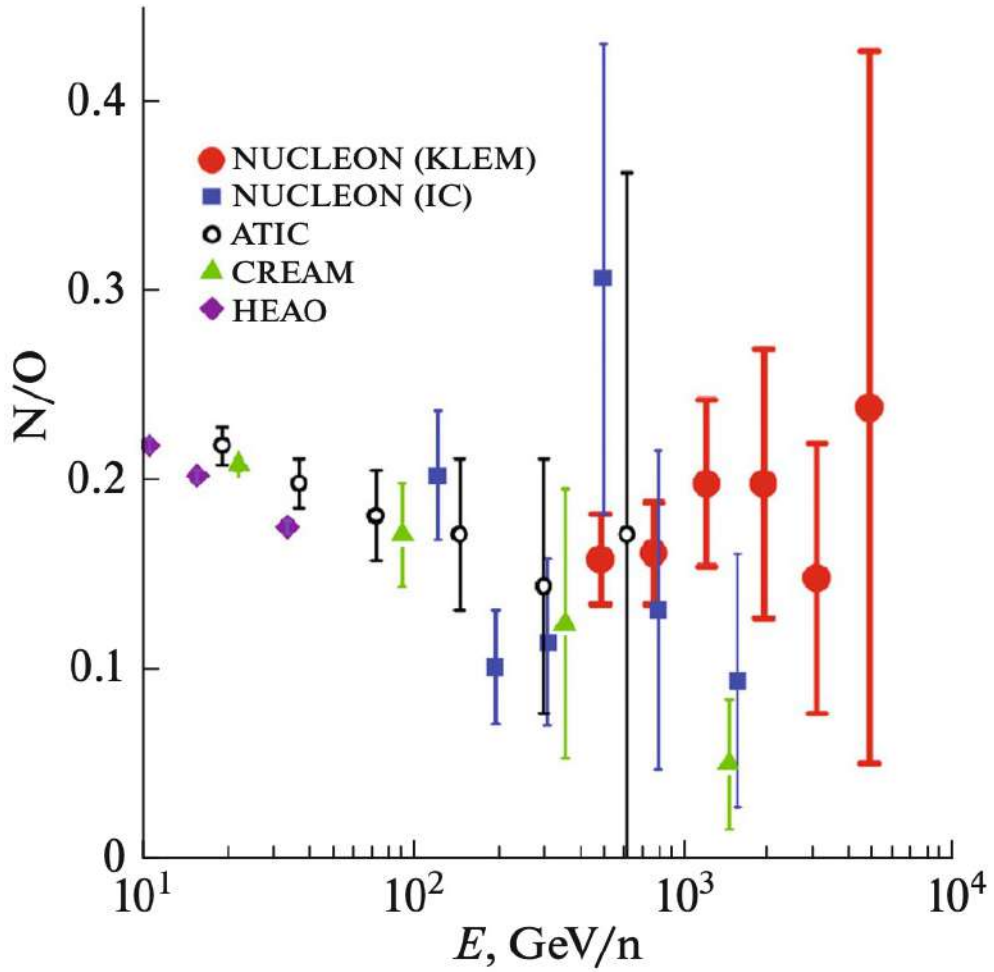
- NT, ApJL 715, L13 (2012) [arXiv:1204.4492],
- Blasi et al., PRL 109, 061101 (2012) [arXiv:1207.3706]
- Evoli et al. PRL 121, 021101 (2018) [1806.04153]



Spectral hardening in secondary/primary ratios

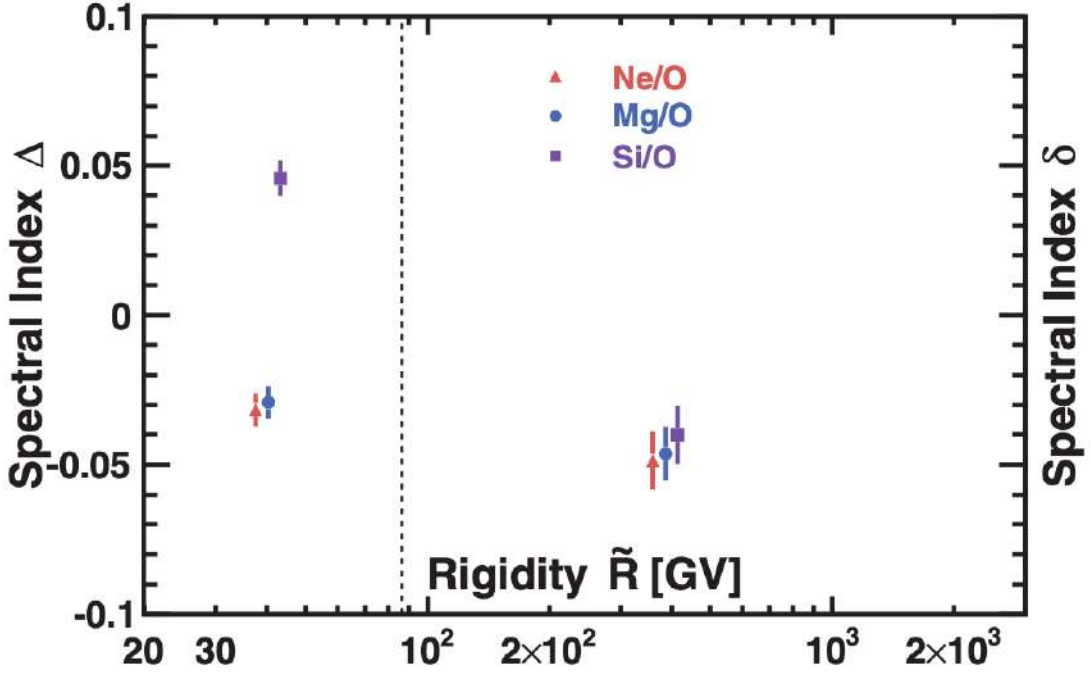
Measurements from NUCLEON also suggest harder secondary/primary ratios in the multi-TeV region.



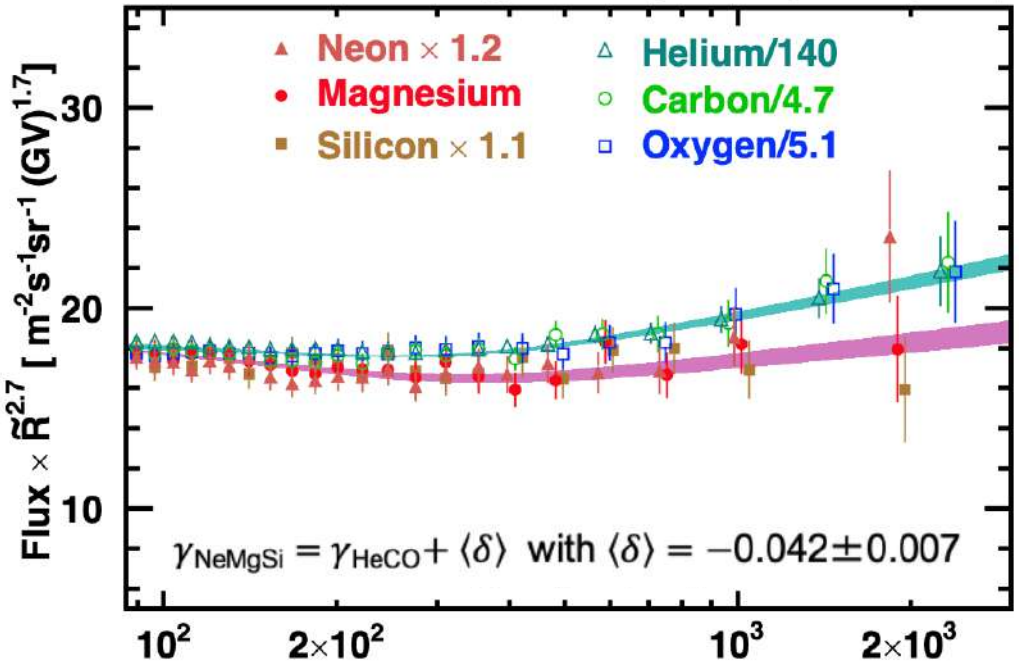


High-energy spectra of other nuclei: Ne Mg Si

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.



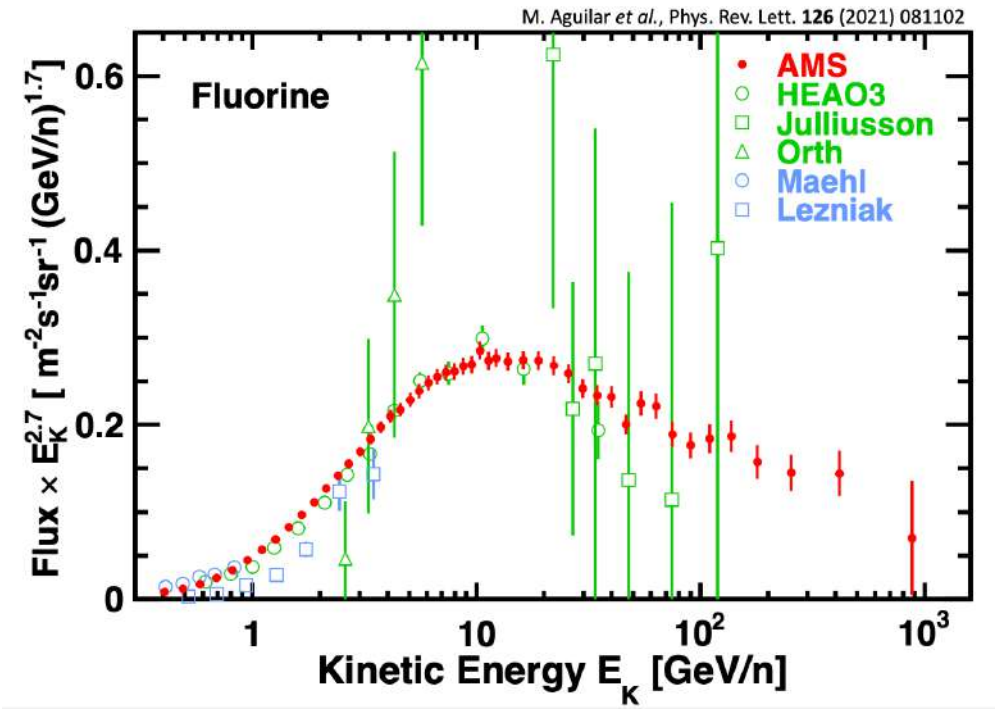
M. Aguilar et al., PRL 124, 21102 (2020)

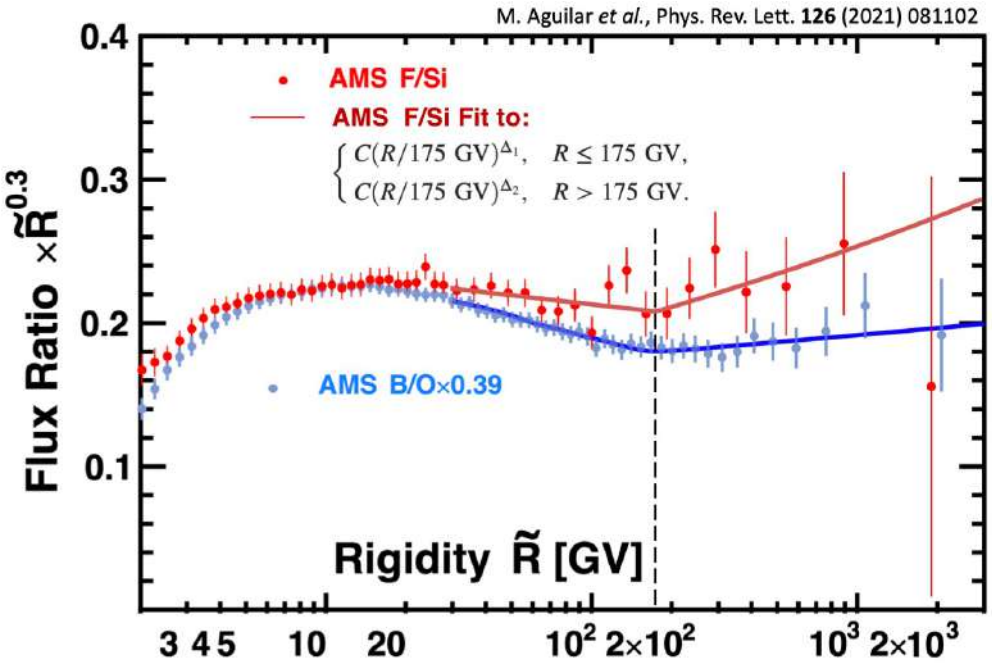


Primary cosmic rays have at least two different classes (of sources?)

High-energy spectra of other nuclei: Fluorine

- Fluorine is purely secondary. The F/Si ratio above 1175 GV hardens by 0.15 ± 0.07
- The Fe/Si hardening is compatible with other sec/pri ratios, but the F flux is harder than Li-Be-B





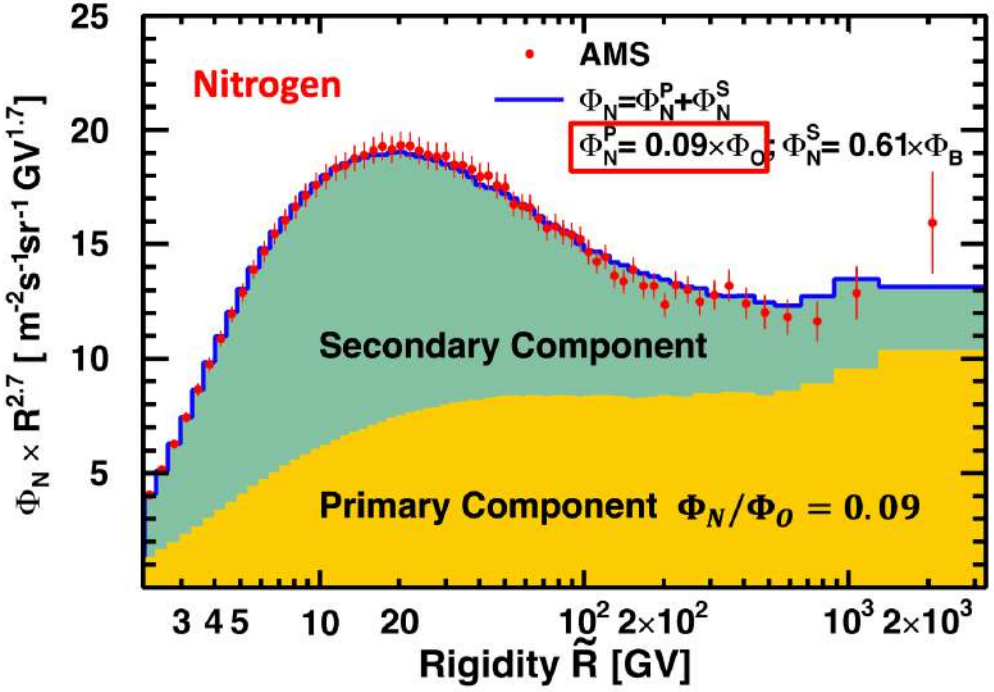
?

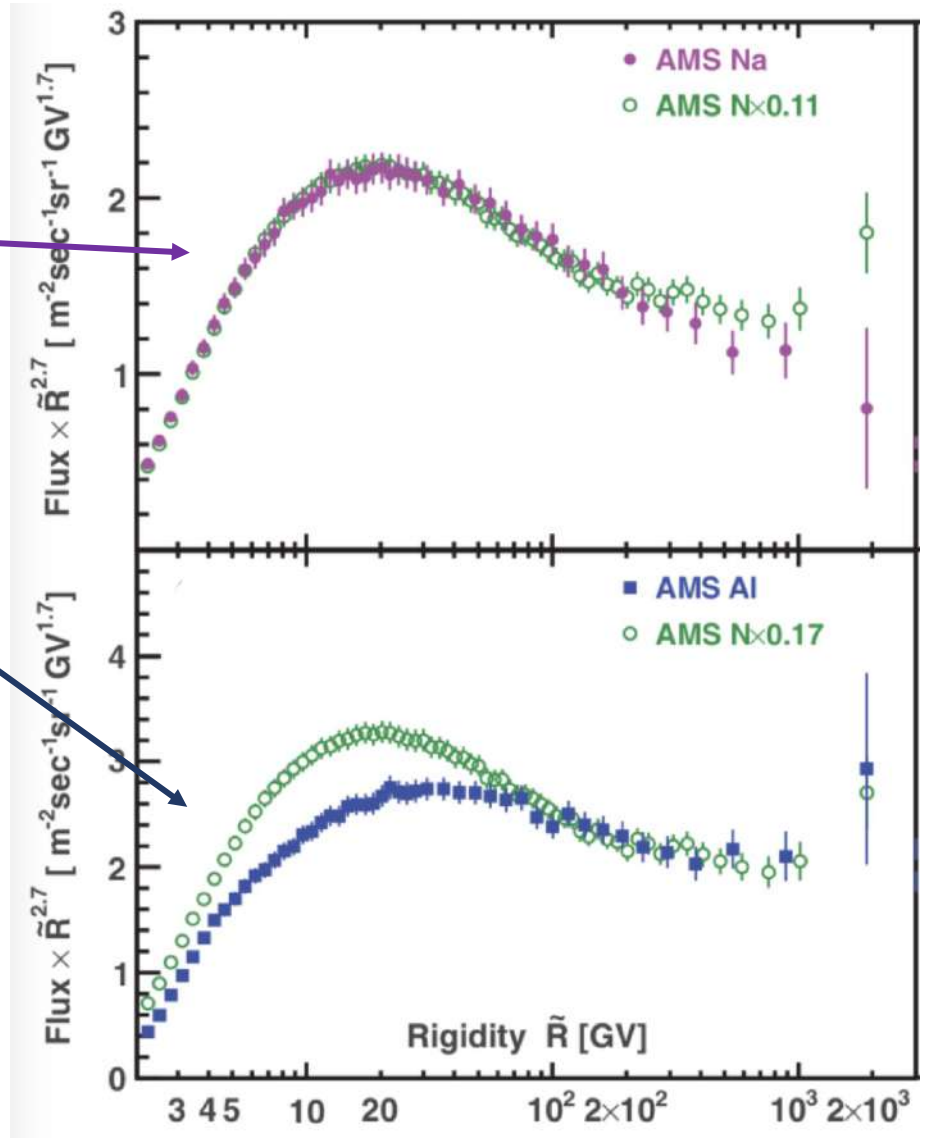
>> See e.g. the ratio betwee F/Si and B/O, talk by V. Choutko.

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

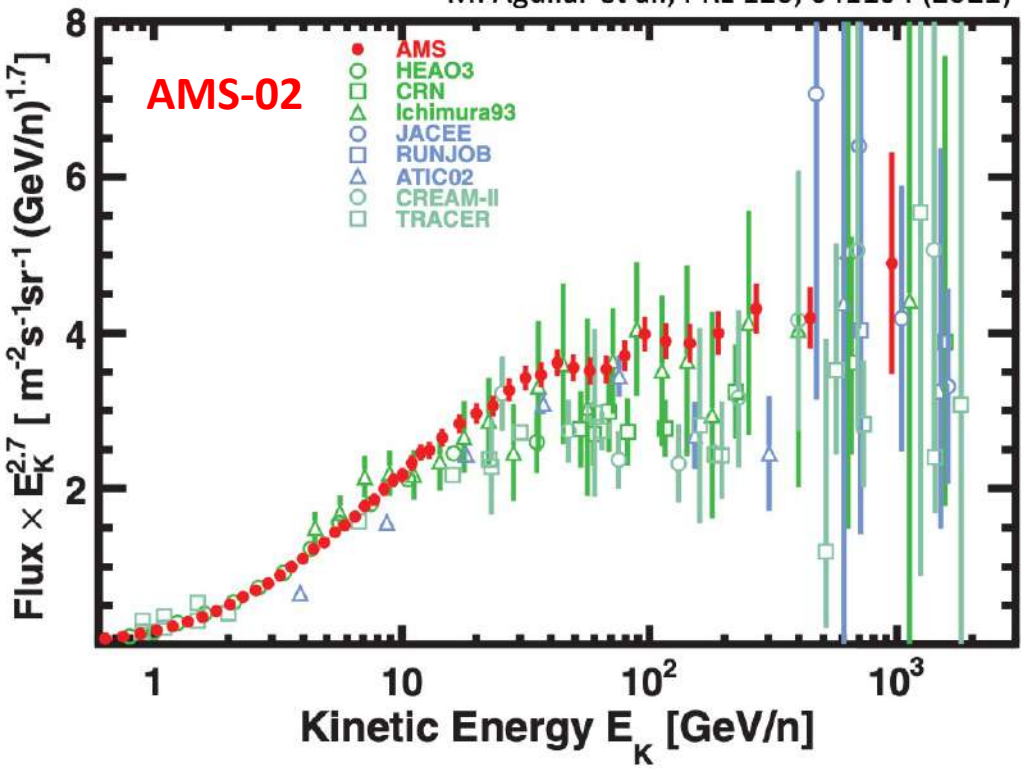




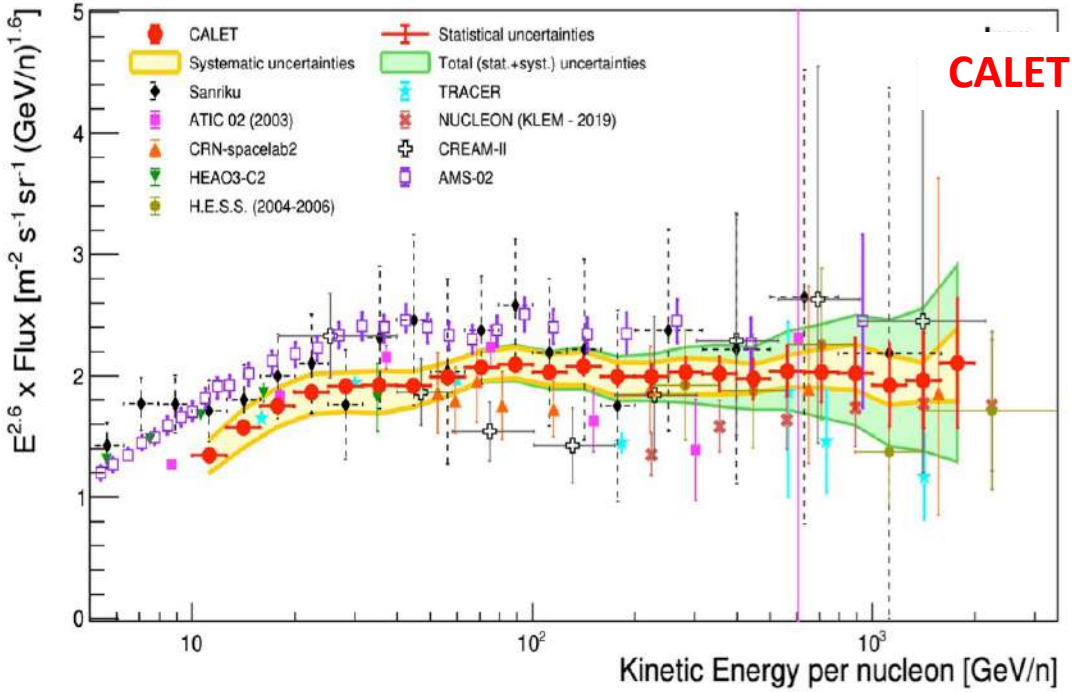
Heavy metals: the Iron spectrum

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

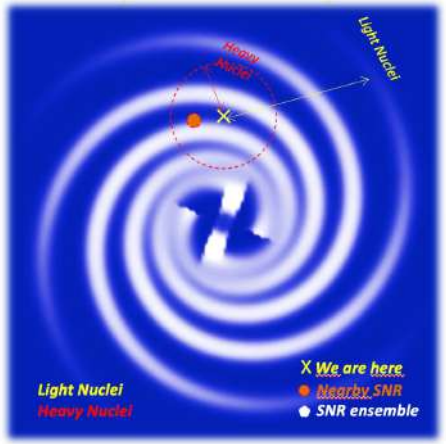
M. Aguilar et al., PRL 126, 041104 (2021)



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)

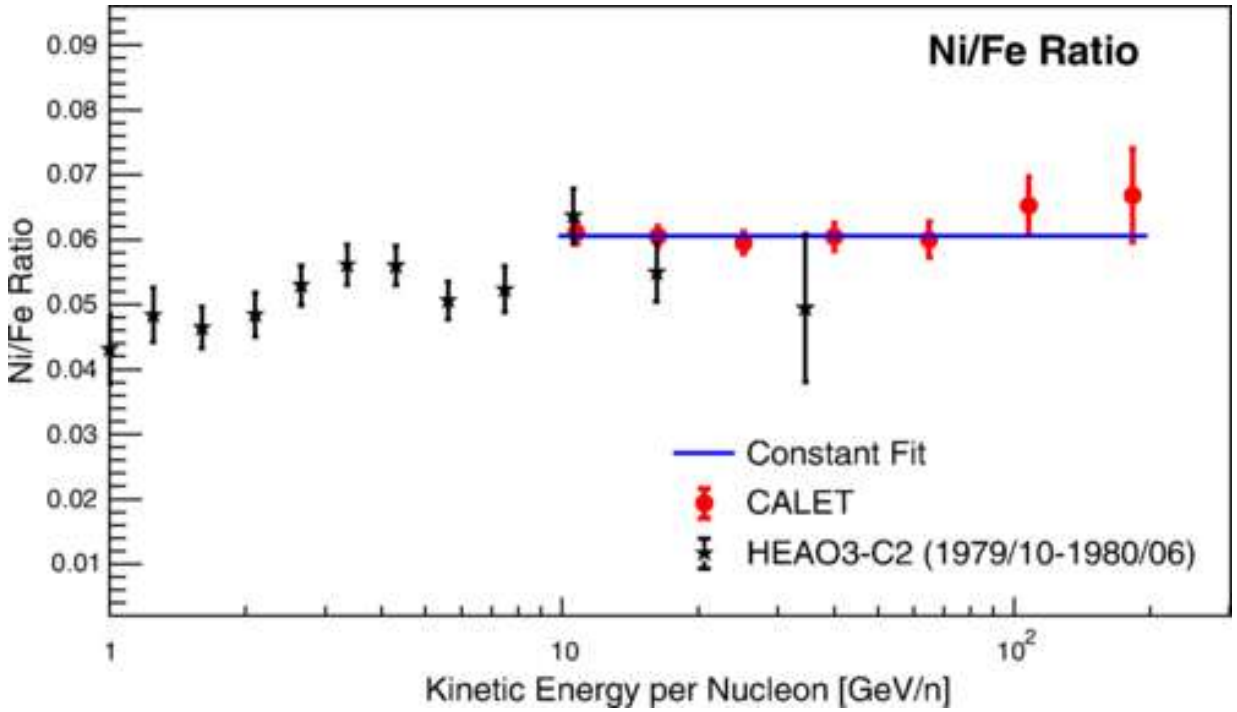


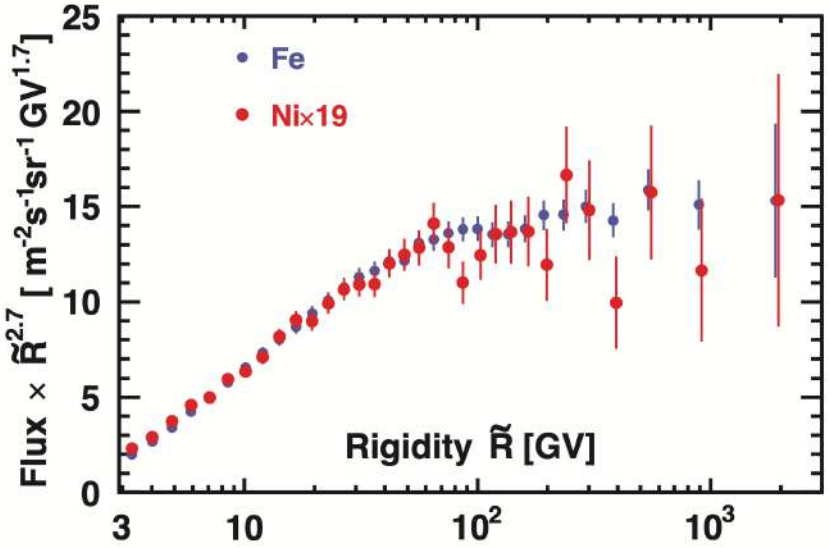
Heavy metals: the Nickel spectrum

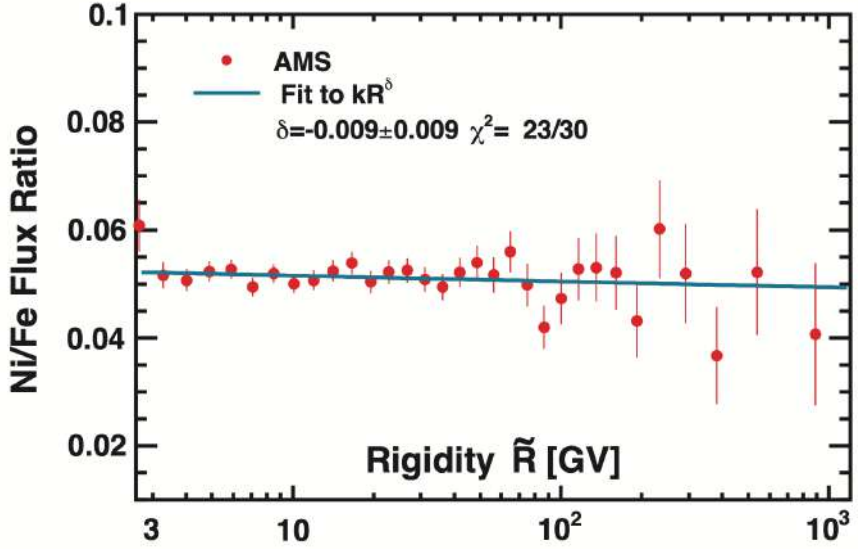
New Nickel measurements by CALET and AMS-02

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

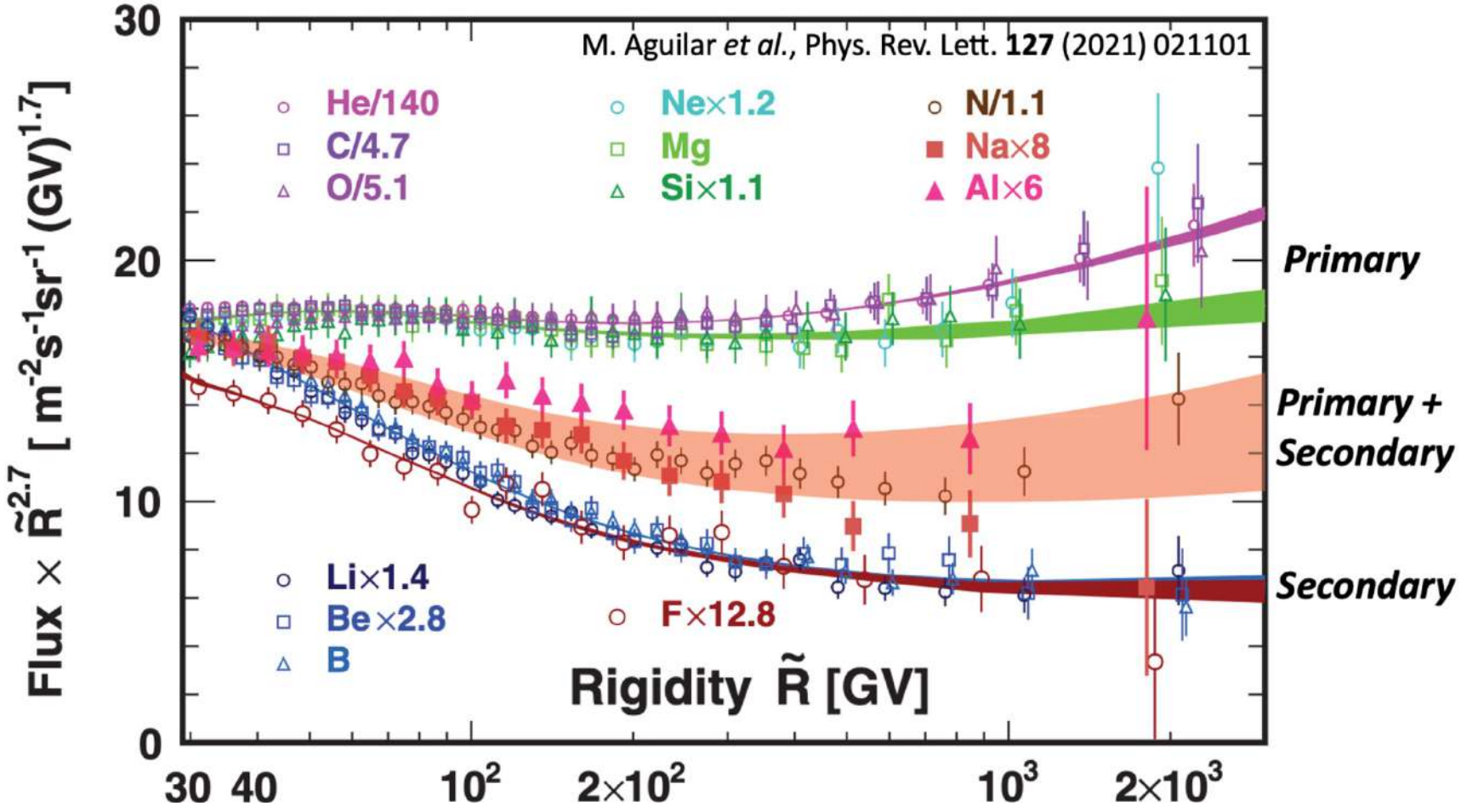






The emergence of a complex picture

- Primary CRs group **in two spectral classes**: light (**He-C-O**) and heavy (**Ne-Mg-Si**)
- **N, Na, and Al** are both primary and secondary CRs, mixed with different **compositions**
- The Iron spectrum 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]

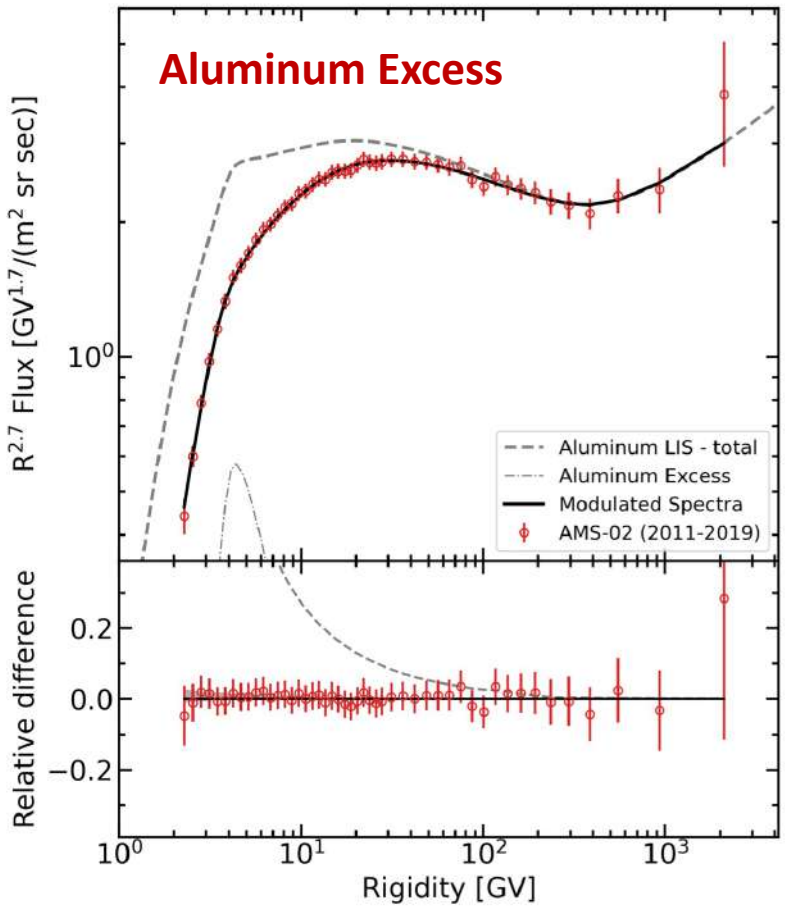


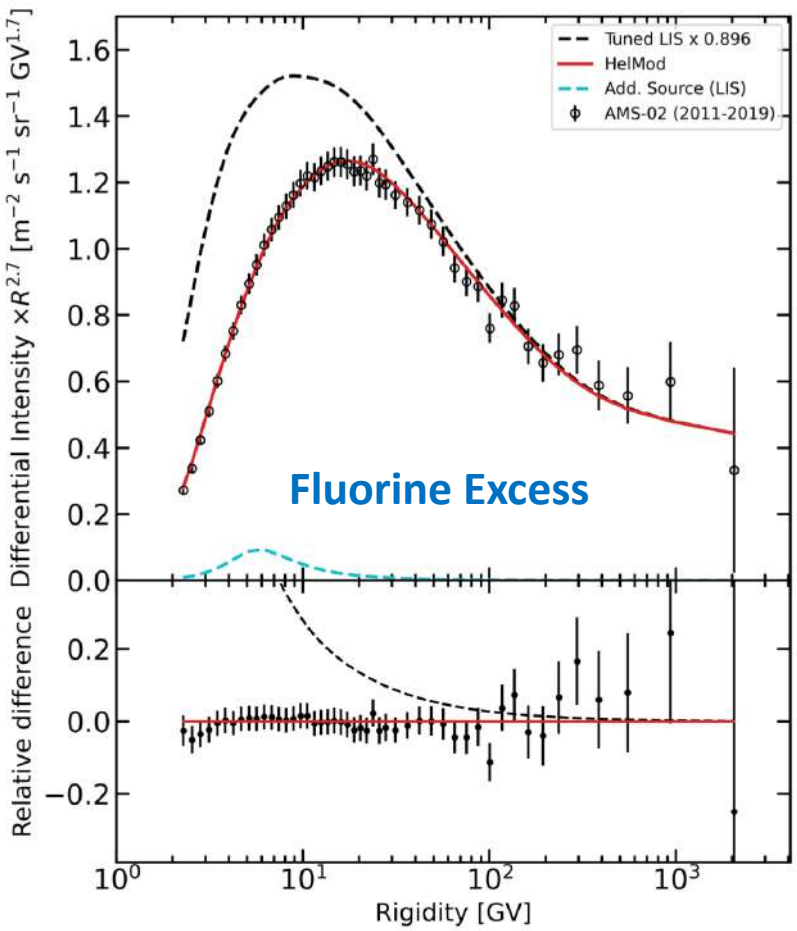
Anomalies at low-energy: evidence for local sources?

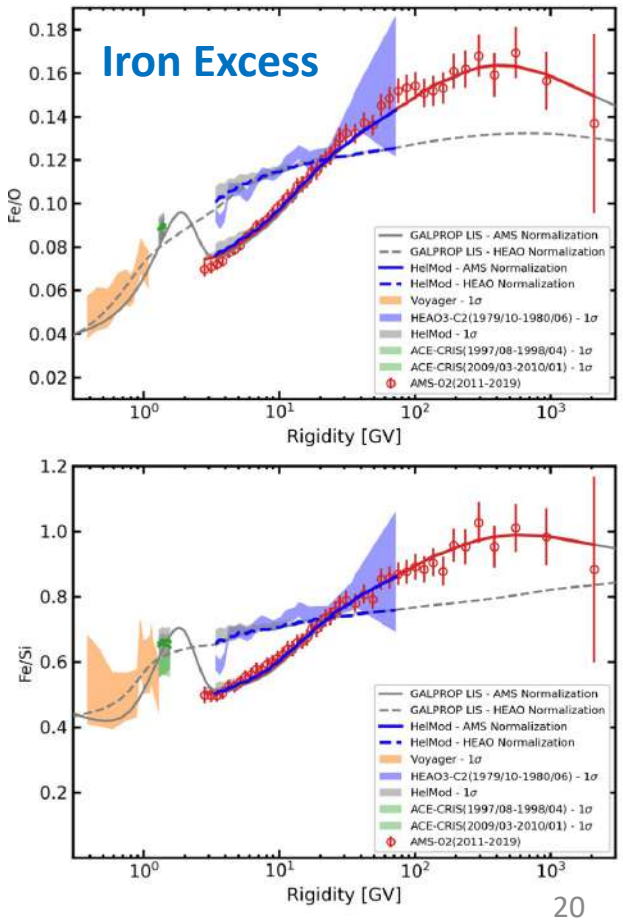
Boschini et al. 2202.09928: Spectra of Cosmic Ray Sodium and Aluminum and Unexpected Aluminum Excess

Boschini et al. 2106.01626: A Hint of a Low-Energy Excess in Cosmic-Ray Fluorine

Boschini et al. 2101.12735: A discovery of a LE excess in CR iron: an evidence of the past SN activity in the Local Bubble



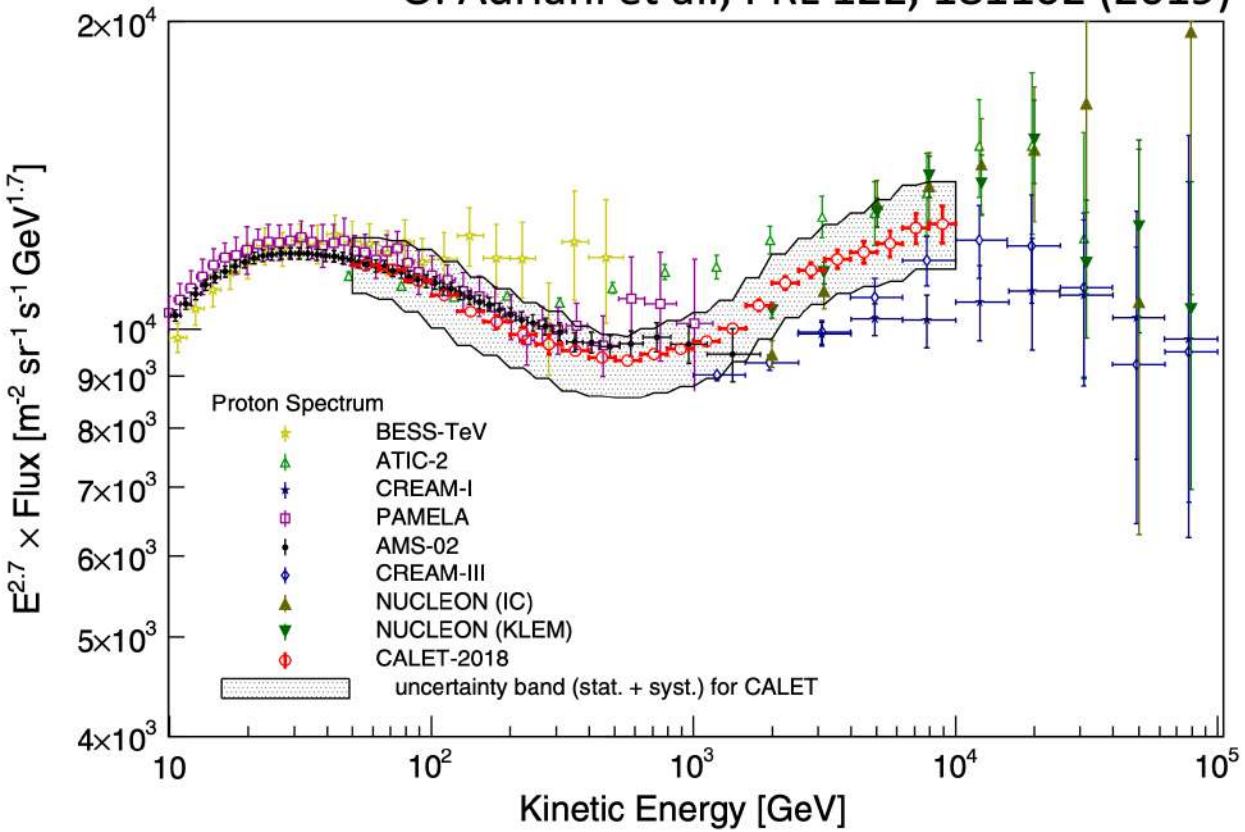




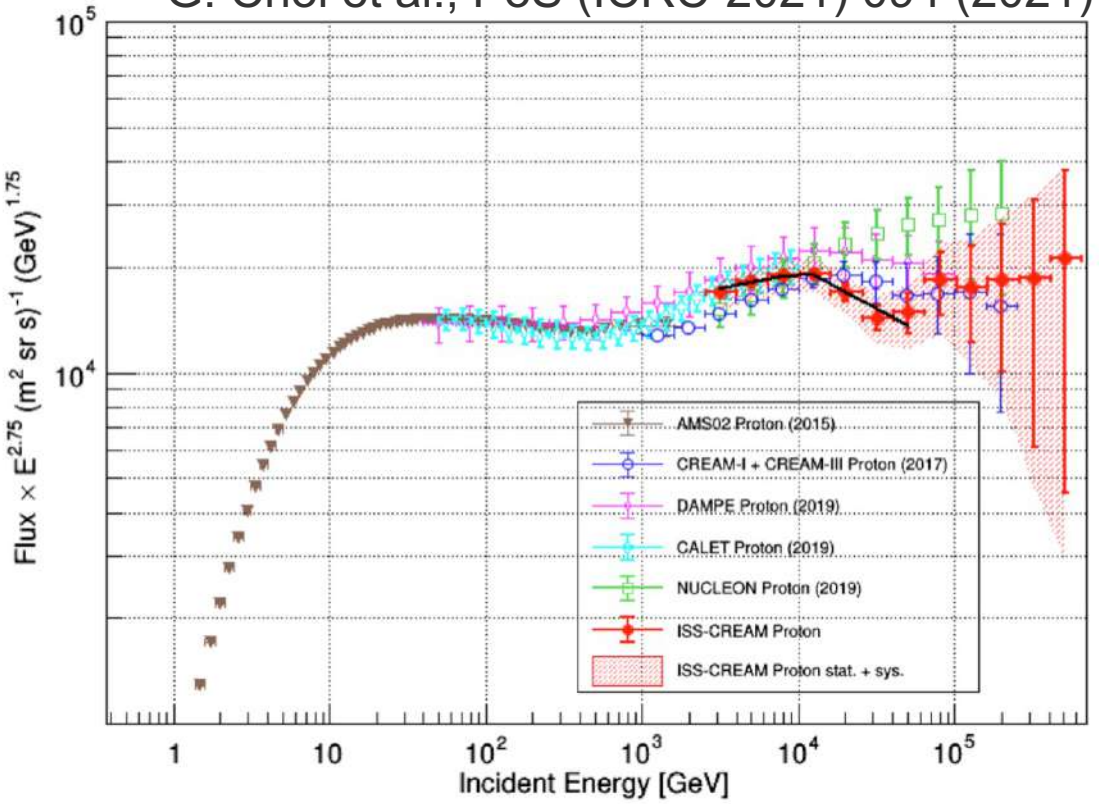
New features in the multi-TeV proton flux

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)



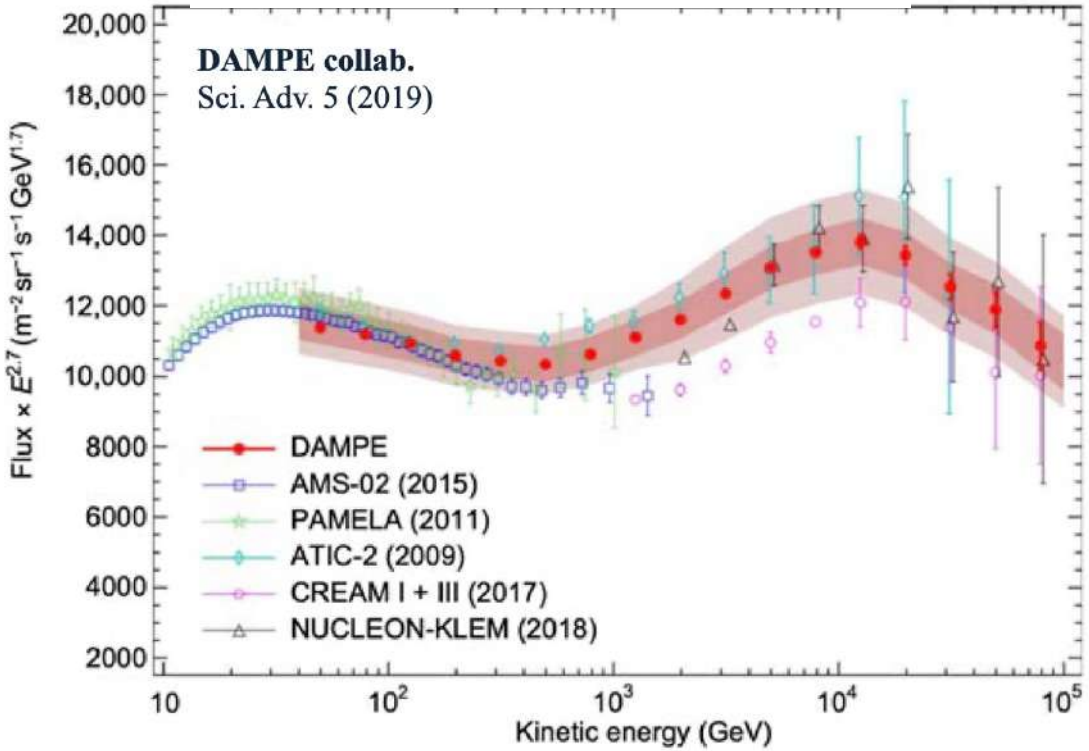
G. Choi et al., PoS (ICRC-2021) 094 (2021)



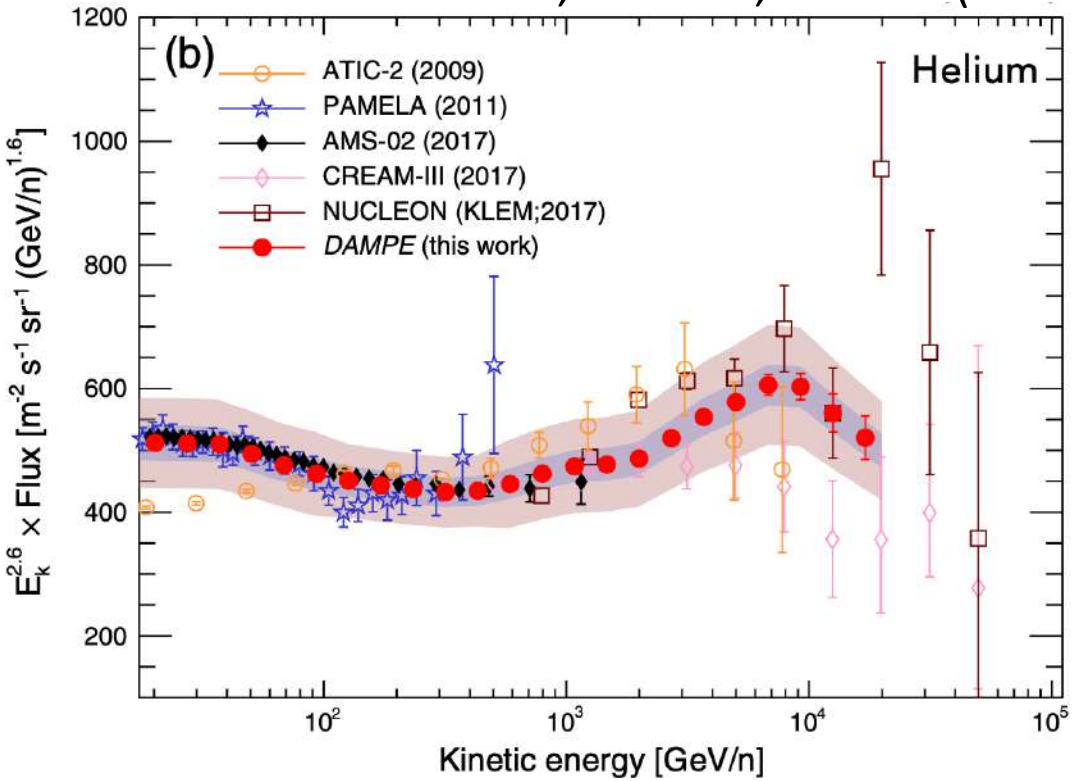
New features in the multi-TeV proton flux

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



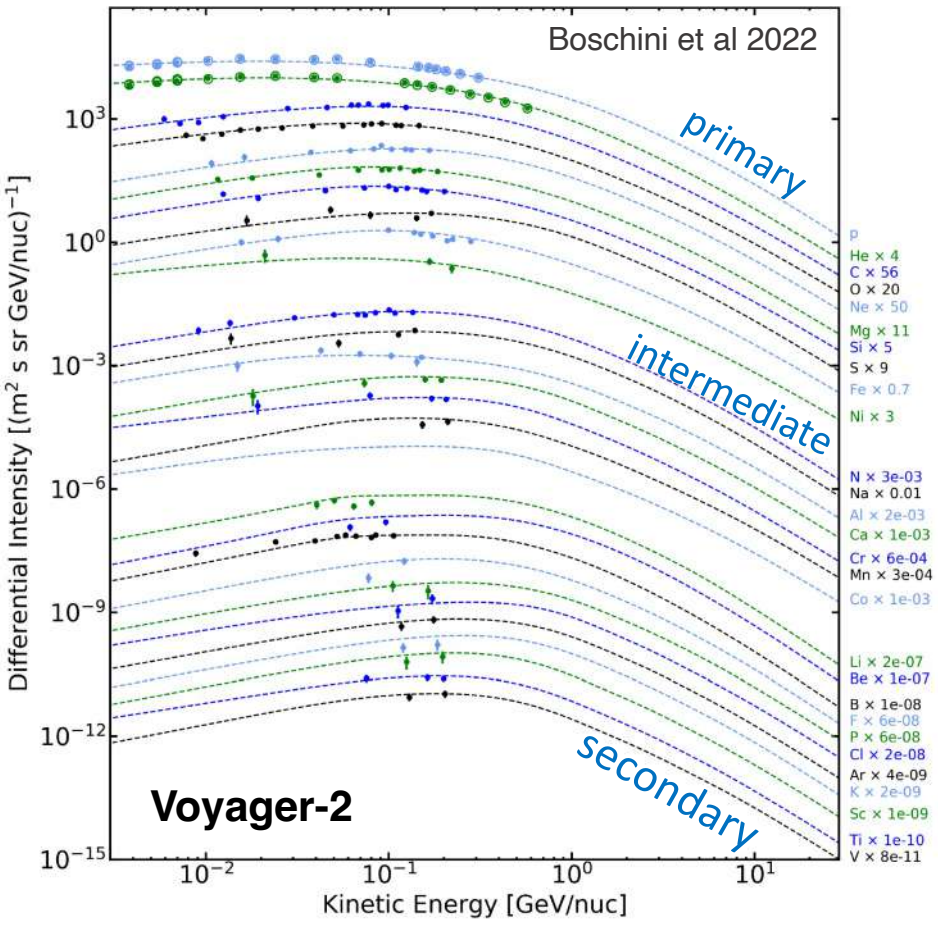
F. Alemanno et al., PRL 126, 201102 (2021)



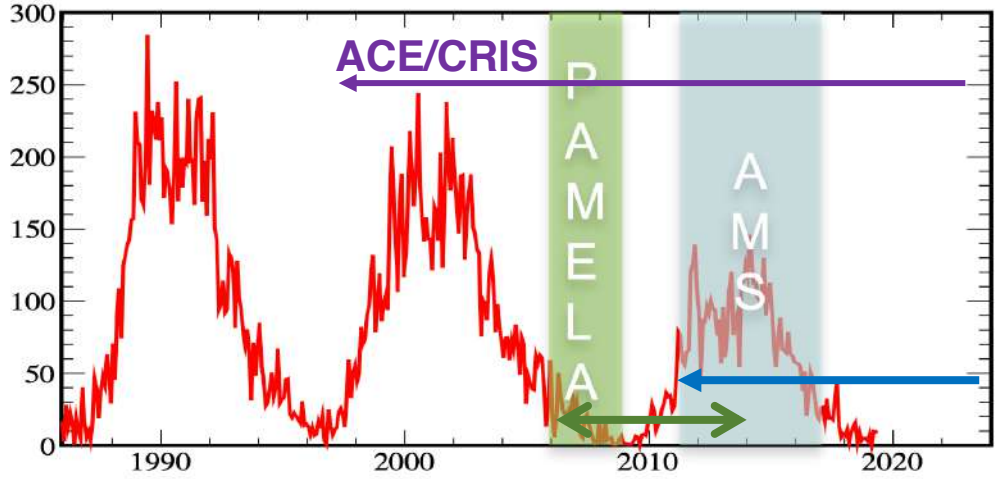
- **Indication of local source of GCRs appearing in the high-energy part of the spectrum?**
- **Possible indication of a further change of regime in the diffusive propagation of CRs?**

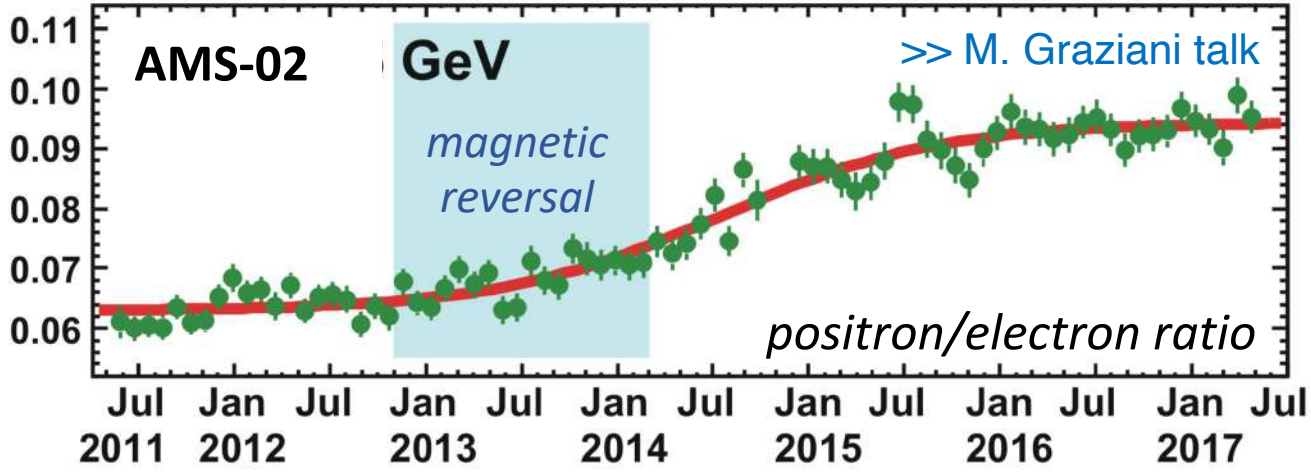
Low-energy physics phenomena: solar modulation

- ✓ Voyager data on Interstellar Spectra for many CR species (Z=1-28)
- ✓ Continuous measurements of CRs over the last solar cycles (ACE/CRIS)
- ✓ Charge-sign and multichannel data from AMS and PAMELA



>> N. Masi talk



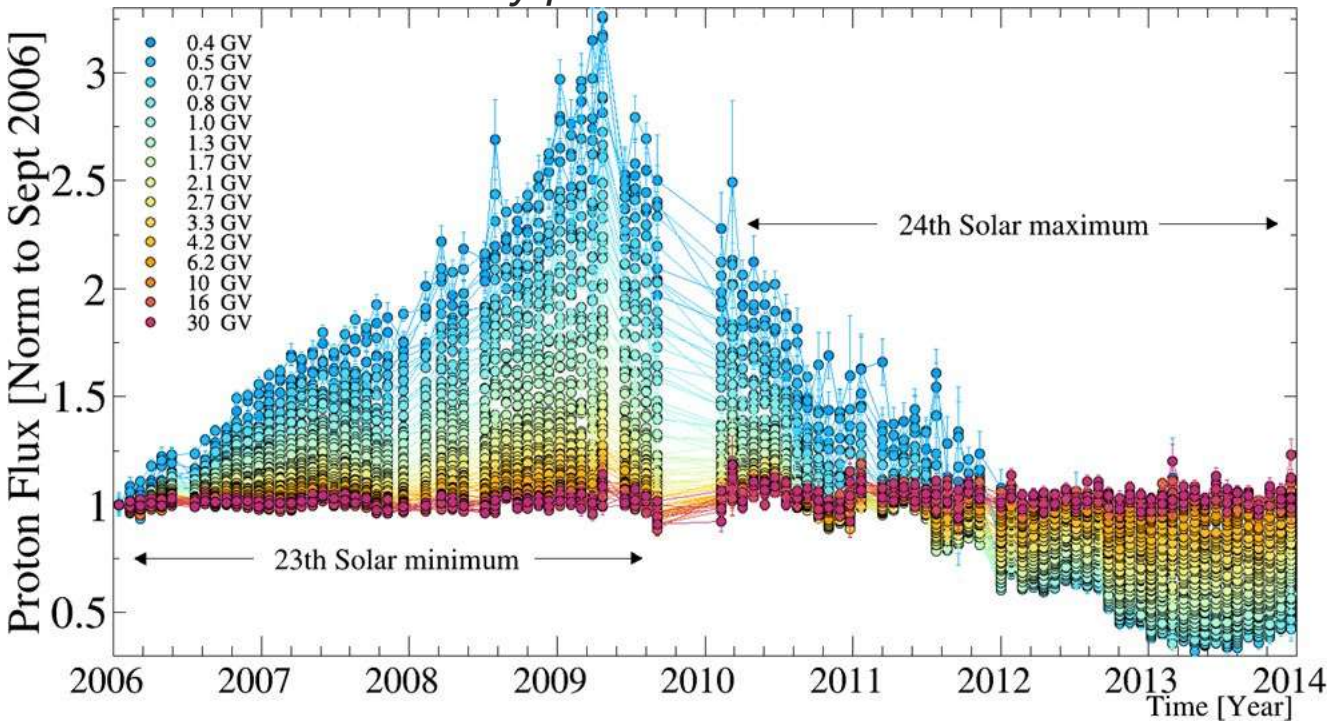


>> M. Graziani talk

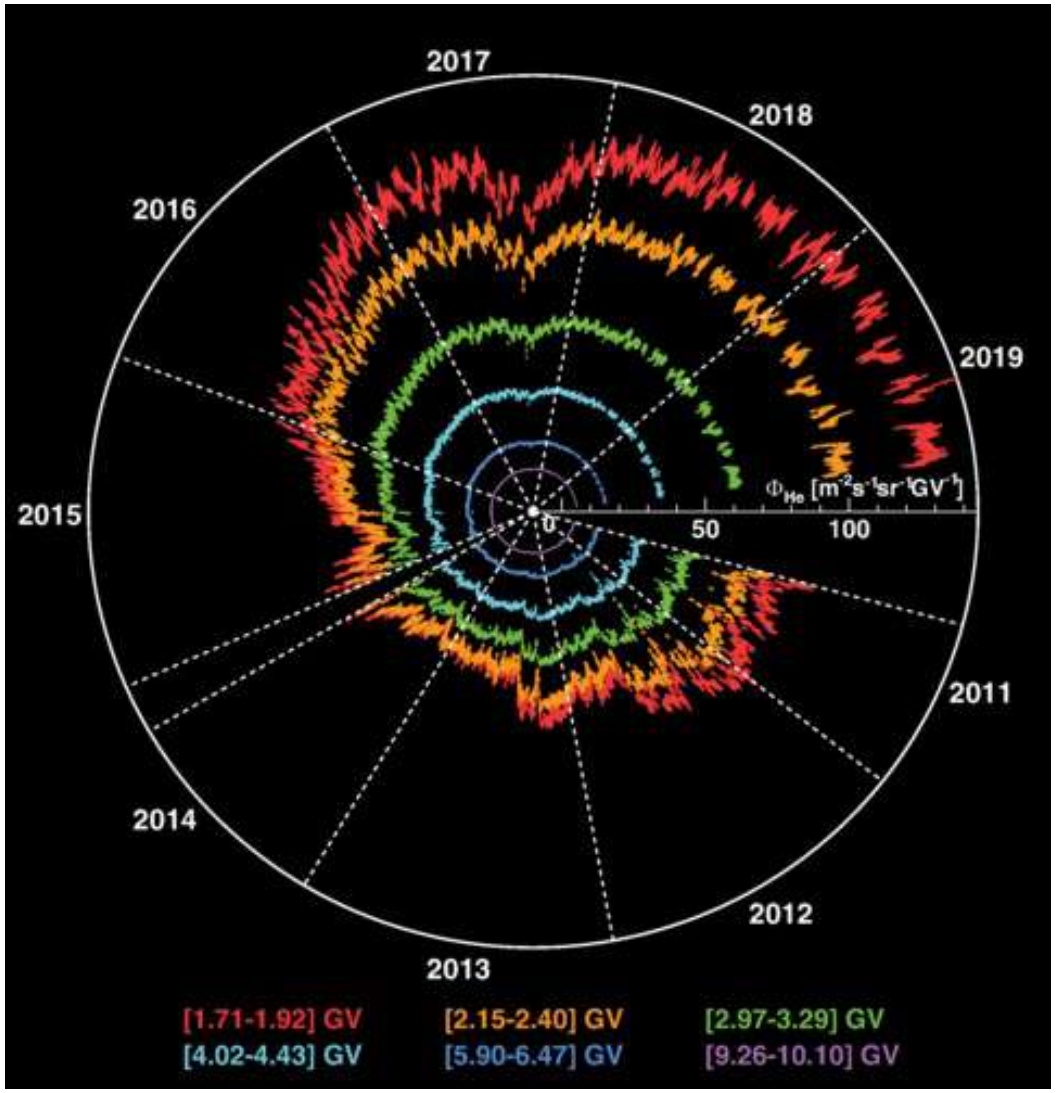
Low-energy physics phenomena: solar modulation

Precision CR data from AMS and PAMELA are particle-, energy-, and time-resolved, are revealing new fine structures of the solar modulation phenomenon

PAMELA – daily proton fluxes from 2006 to 2014

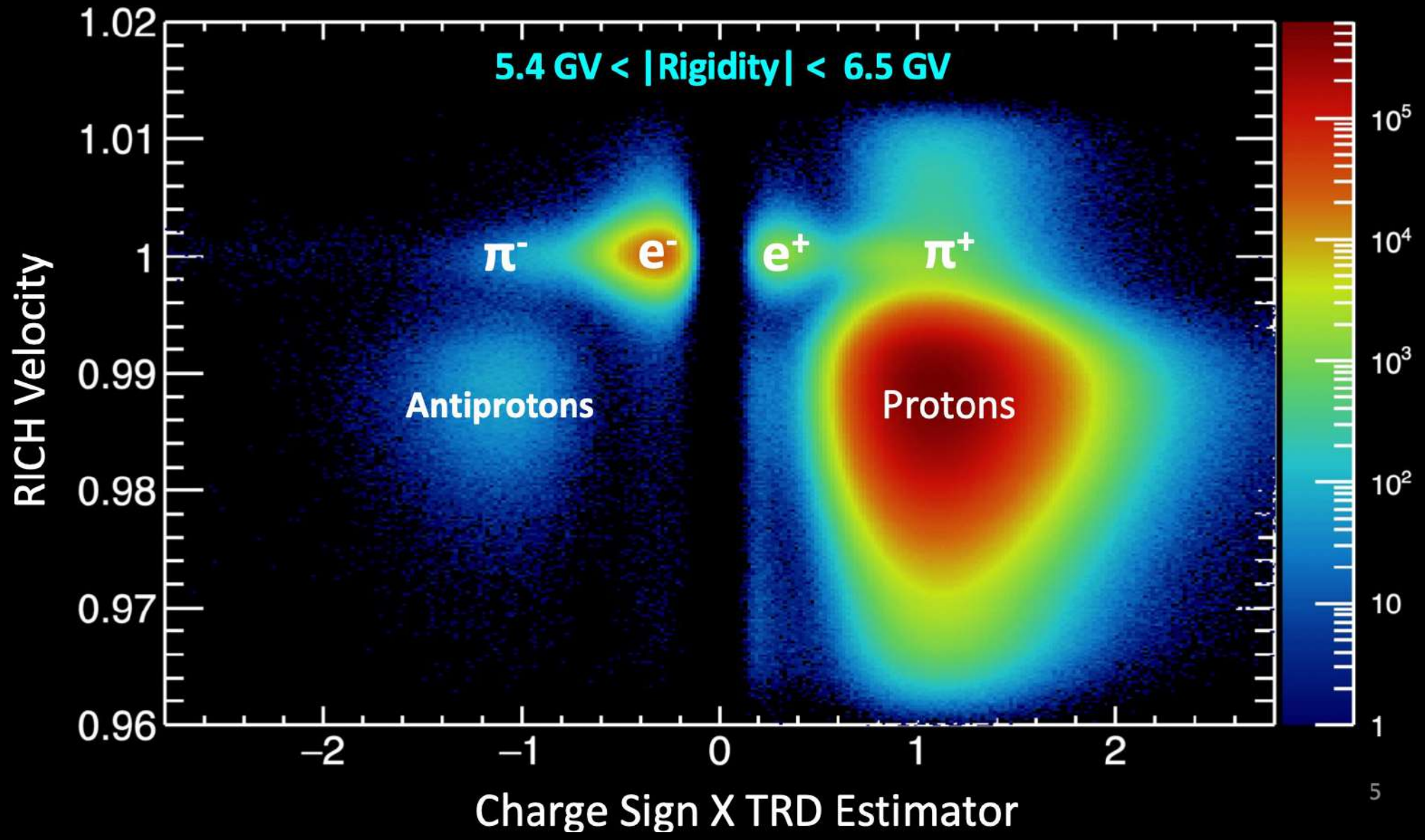


AMS – daily helium fluxes from 2011 to 2020



M. Aguilar et al. PRL 128, 231102 (2022)

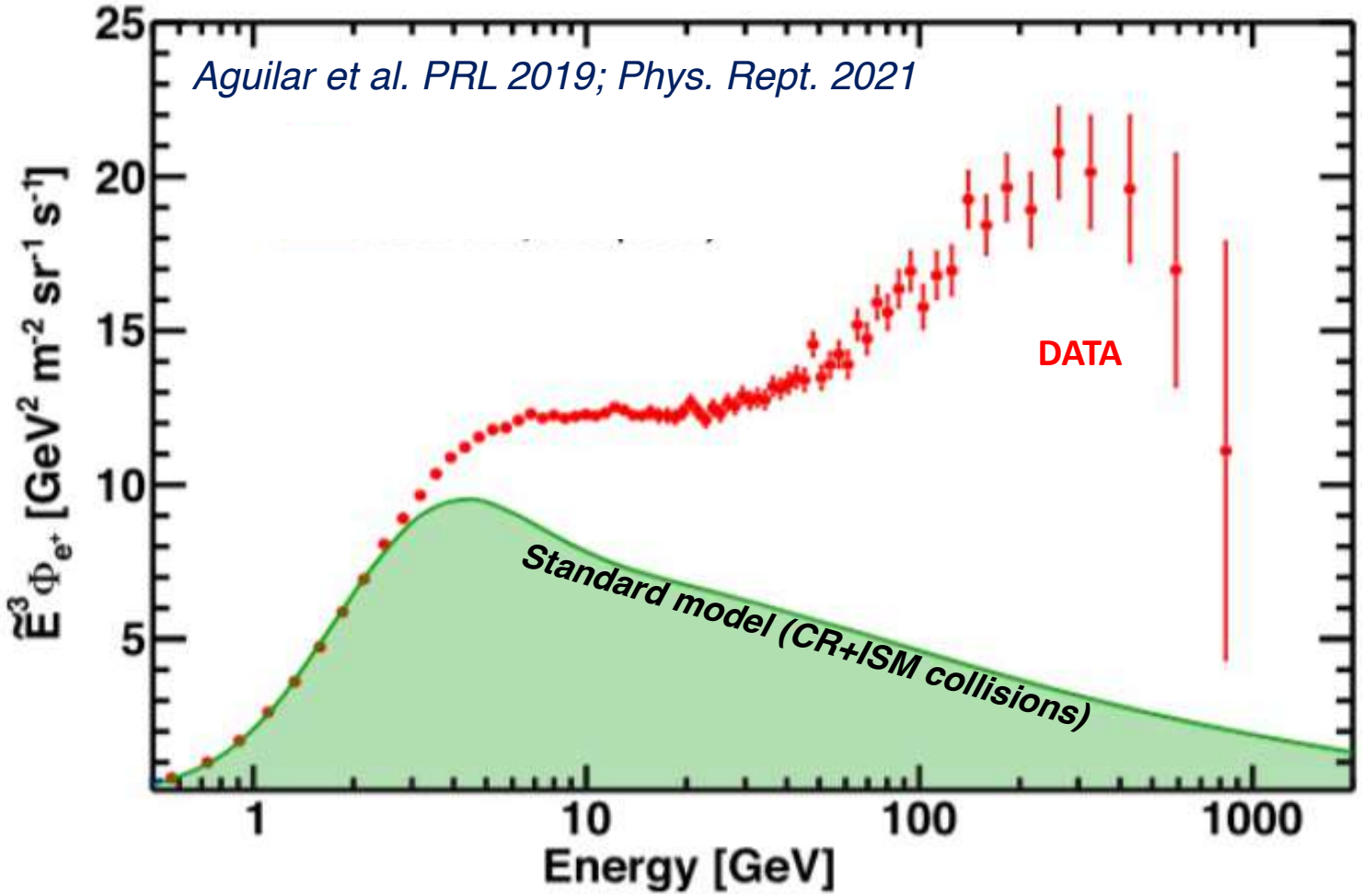
The antimatter sector



5

The antimatter sector

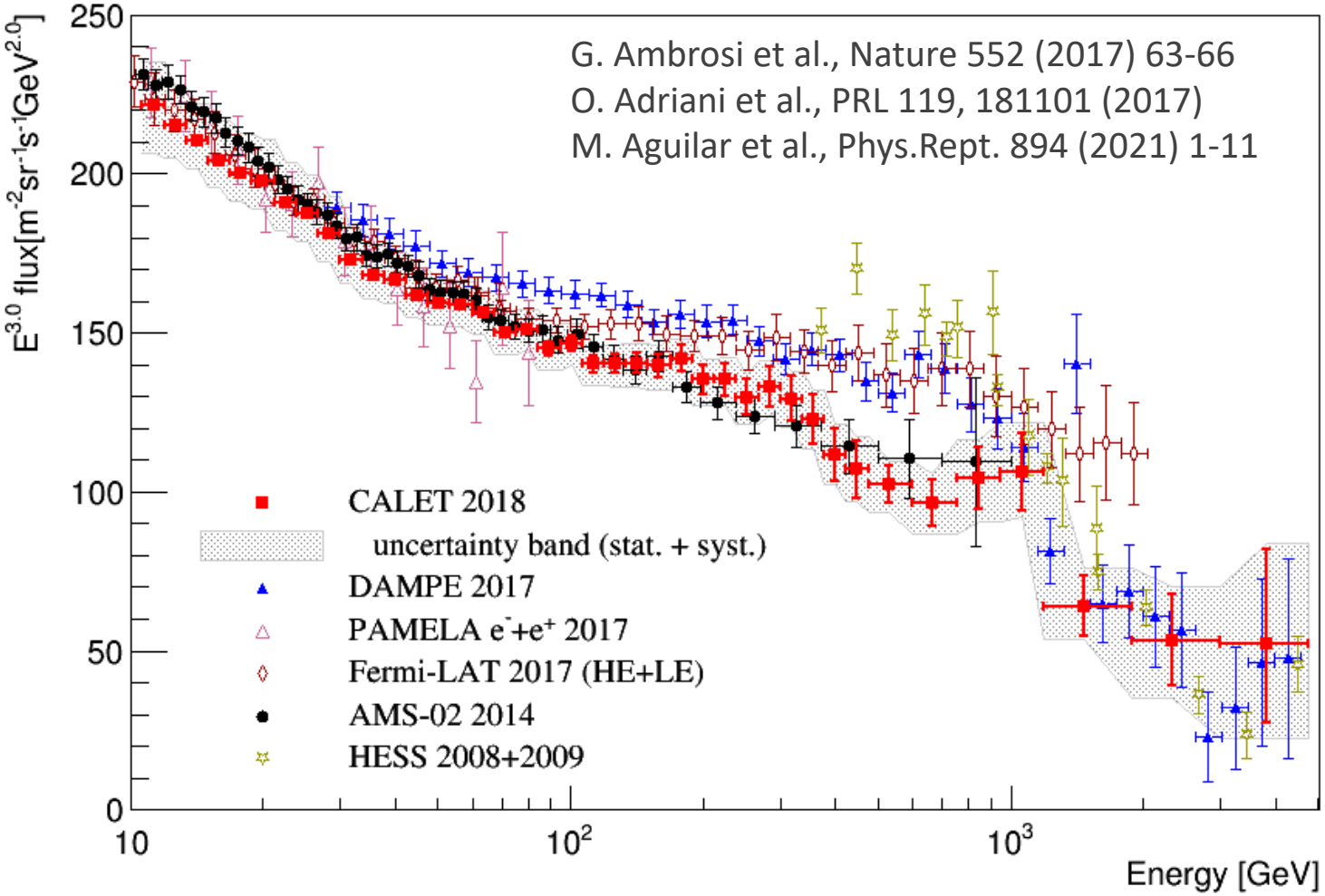
- 2008, PAMELA: unexpected positron excess. Rise of the e+ fraction at ~1-100 GeV.
- 2019, AMS-02: observation of peak in the positron flux (xE^3) at ~300 GeV.
- The excess of CR positrons (wrt secondary production) is unequivocal



See talk by D. Krasnopevtsev

The antimatter sector

Meanwhile, in the «all electron» spectrum…



The data cluster into two groups:

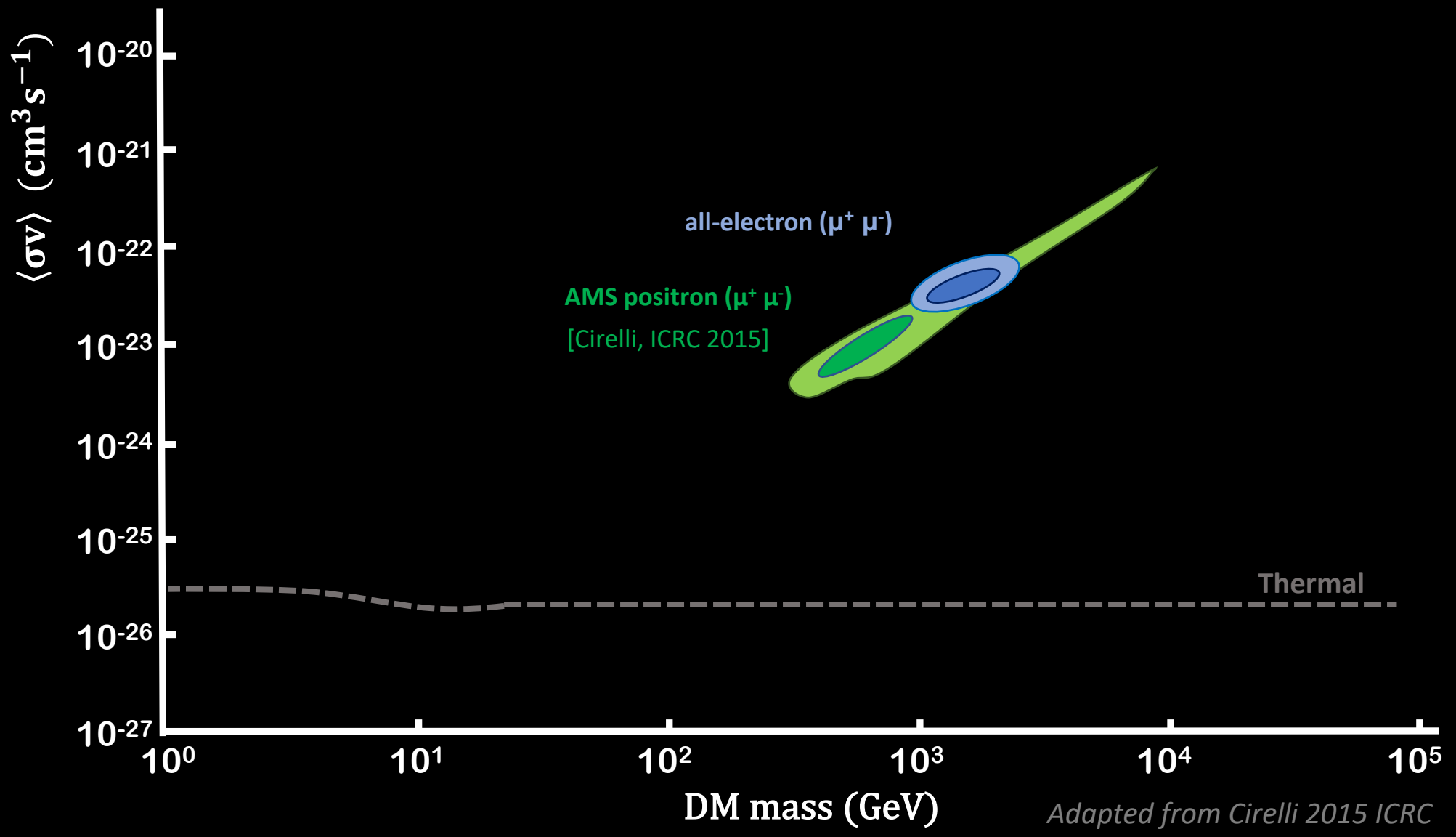
- ISS group: AMS-CALET,
- Satellite group: Fermi-DAMPE

Both CALET and DAMPE found a flux reduction (break) above 1 TeV

The positron excess is also present in CR «all electrons» too.

Comparing dark matter bounds

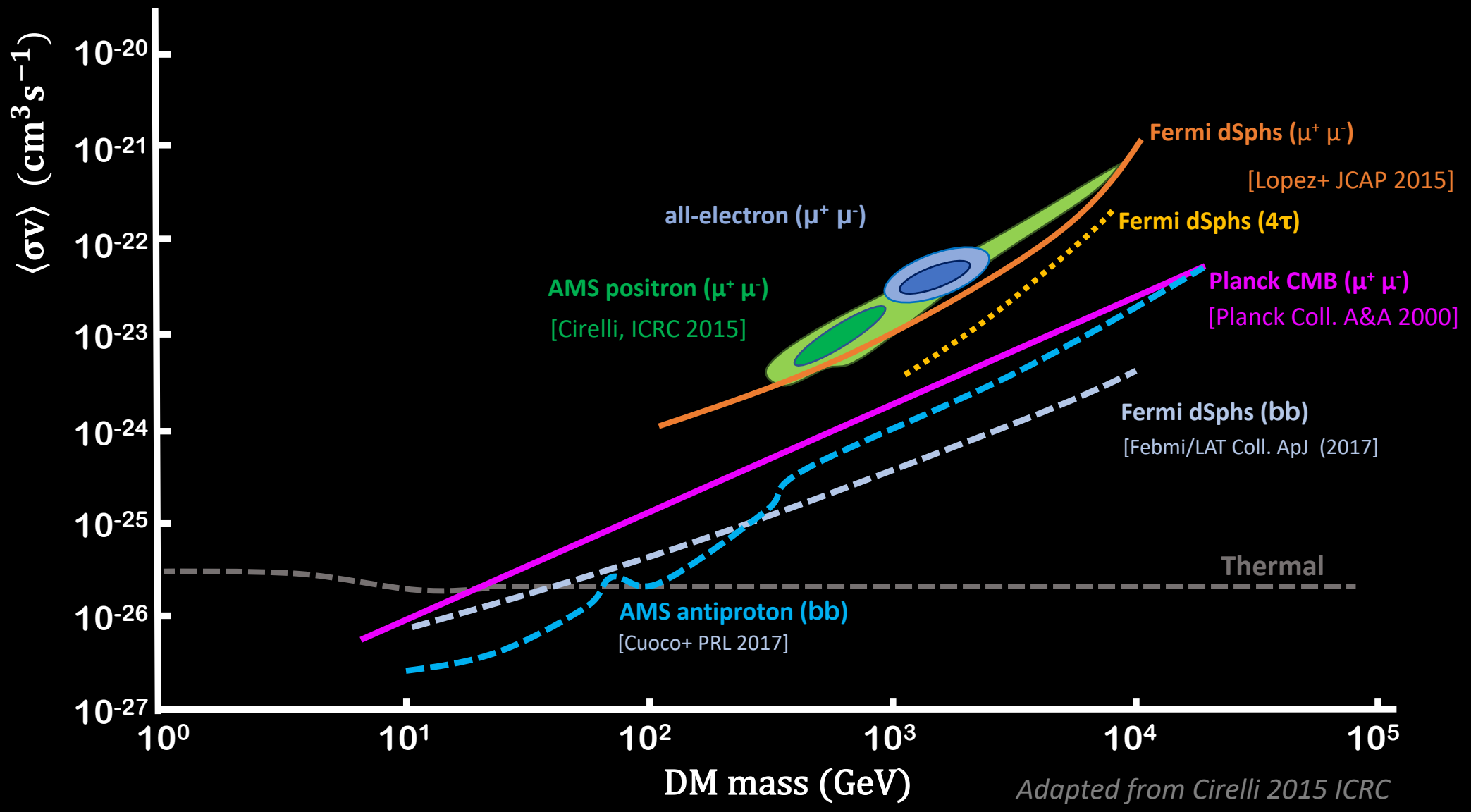
Dark matter interpretation => TeV-scale mass, leptophilic, strong ann. rate: $\langle\sigma v\rangle \sim 10^{23}$ cm^3/s



Adapted from Cirelli 2015 ICRC

Comparing dark matter bounds

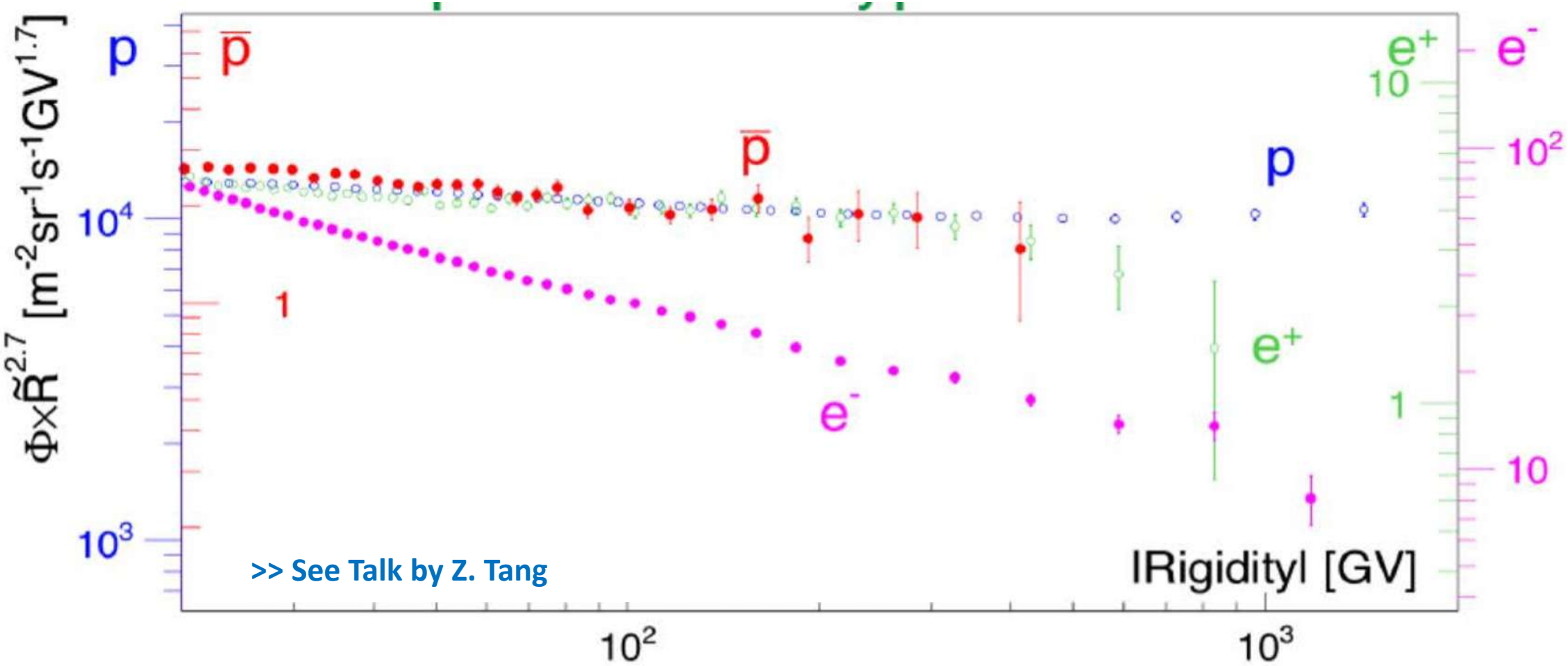
Dark matter interpretation => TeV-scale mass, leptophilic, strong ann. rate: $\langle\sigma v\rangle \sim 10^{23}$ cm^3/s



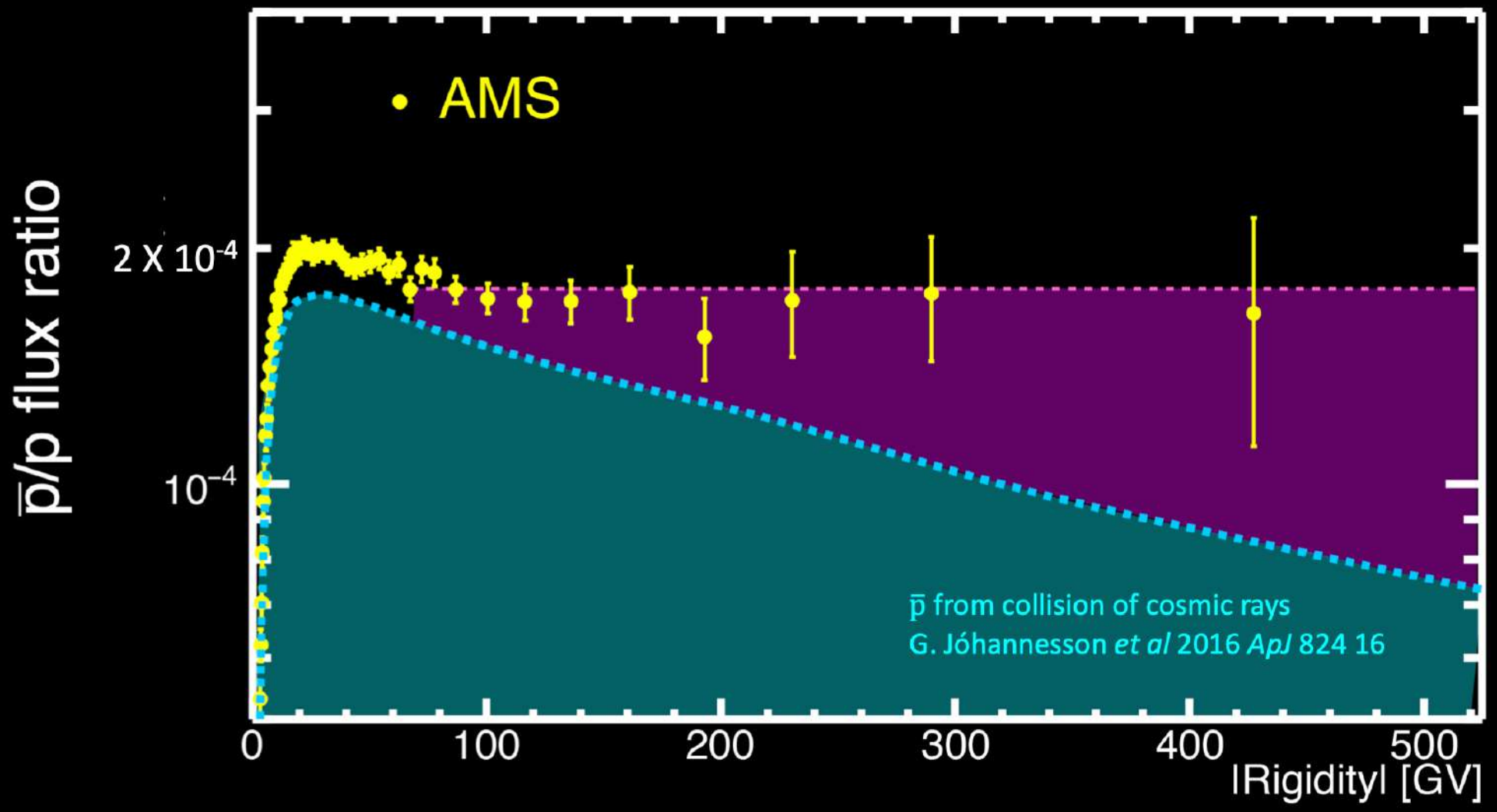
Adapted from Cirelli 2015 ICRC

Antiprotons

The spectra of positrons, antiprotons and protons are nearly identical in a large range. The positron spectrum shows a drop-off at ~300 GV. The electron spectrum is steeper.

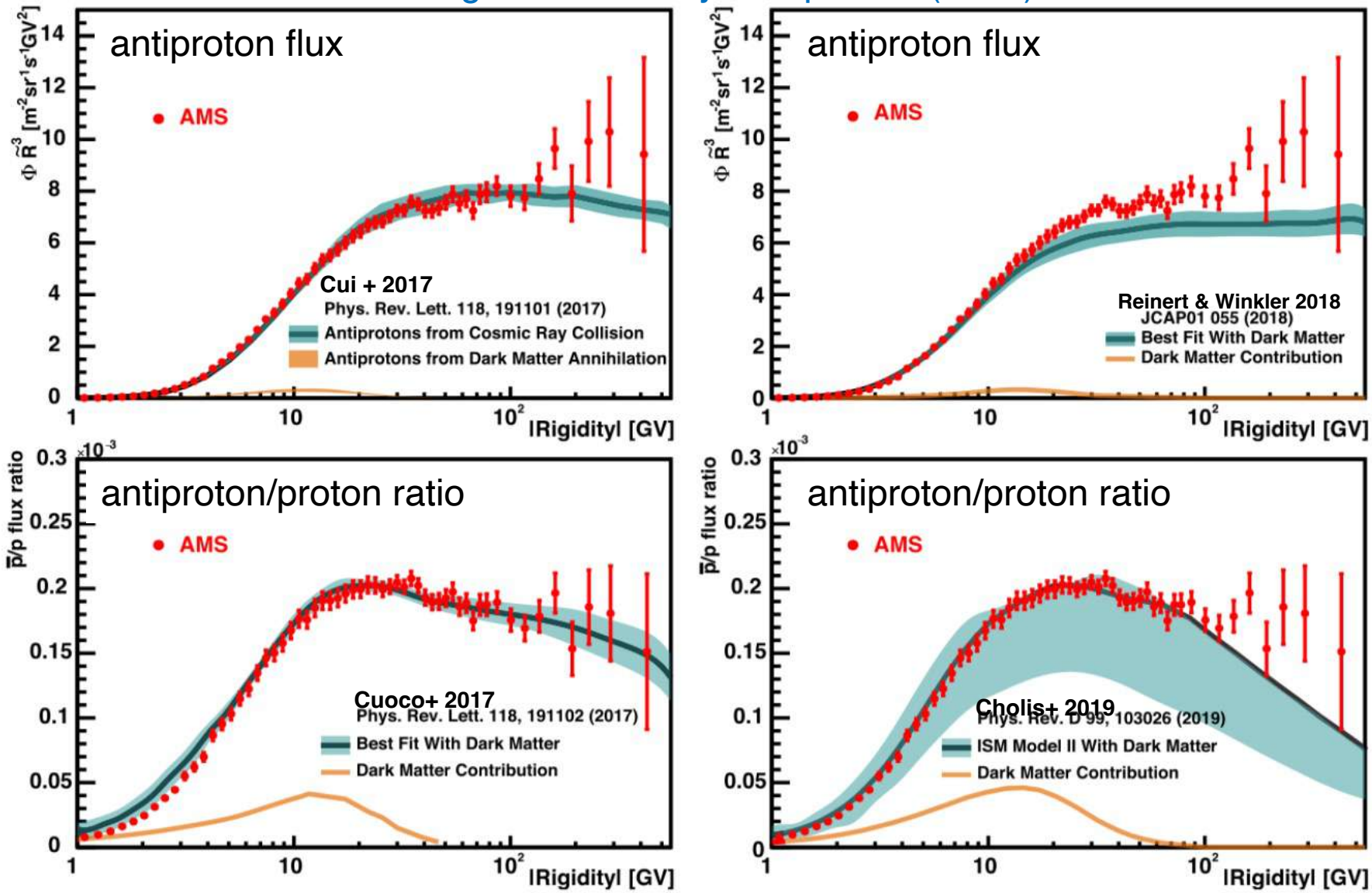


Antiproton excess?

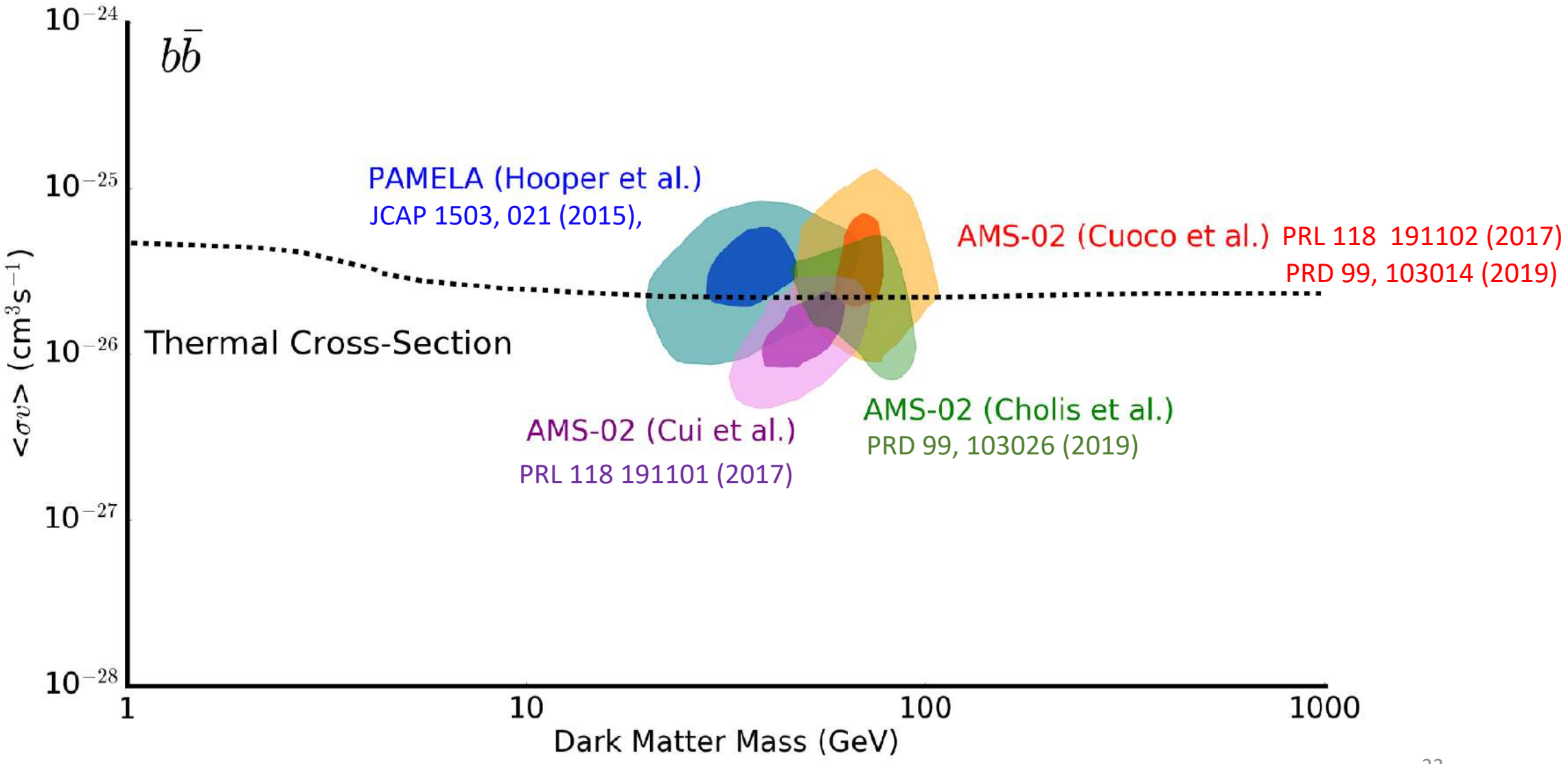


Antiproton excess?

Aguilar et al. Phys. Rept. 894 (2021)



Antiprotons and Dark Matter



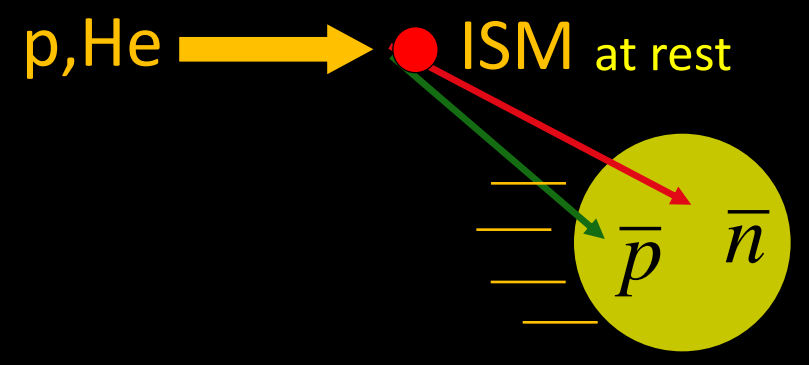
From Tim Linden

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]

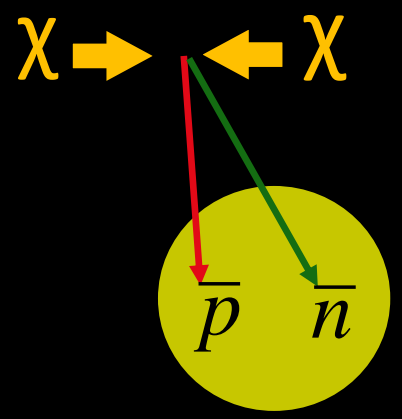
Favorable signal/background ratio, due to kinematics

Antideuterons from CR collisions

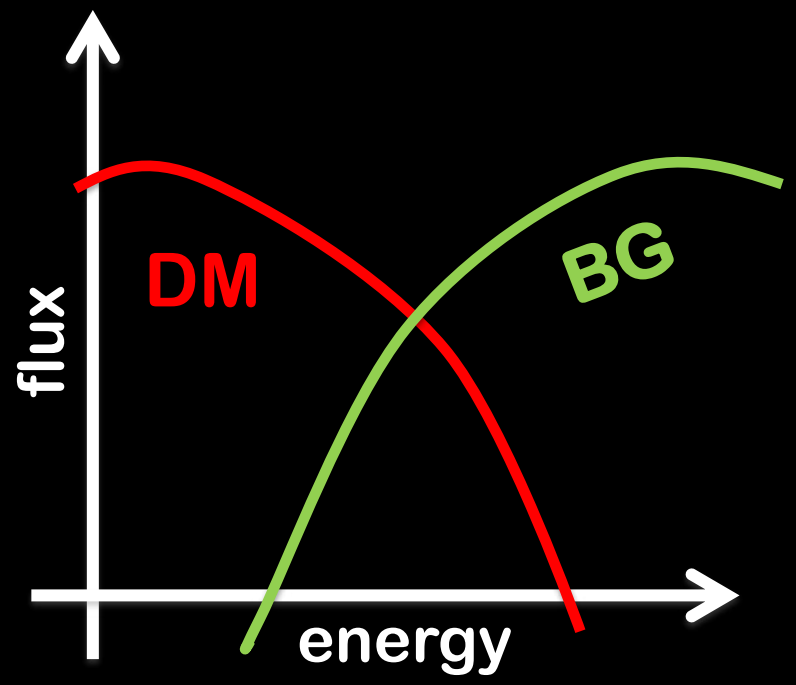


Collisions of RC with interstellar gas
Secondary deuterons produced at HE

Antideuteron from DM-DM

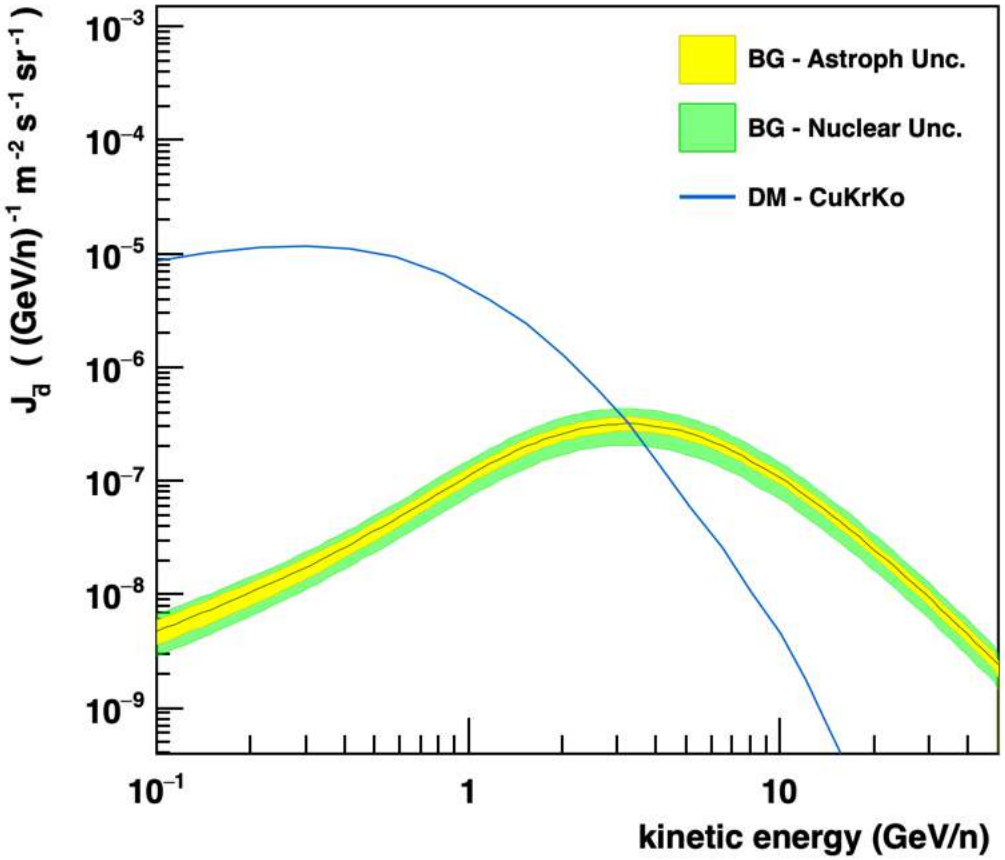


Collisions χ+ χ -> had -> d-bar
Galactic frame ~ CM frame

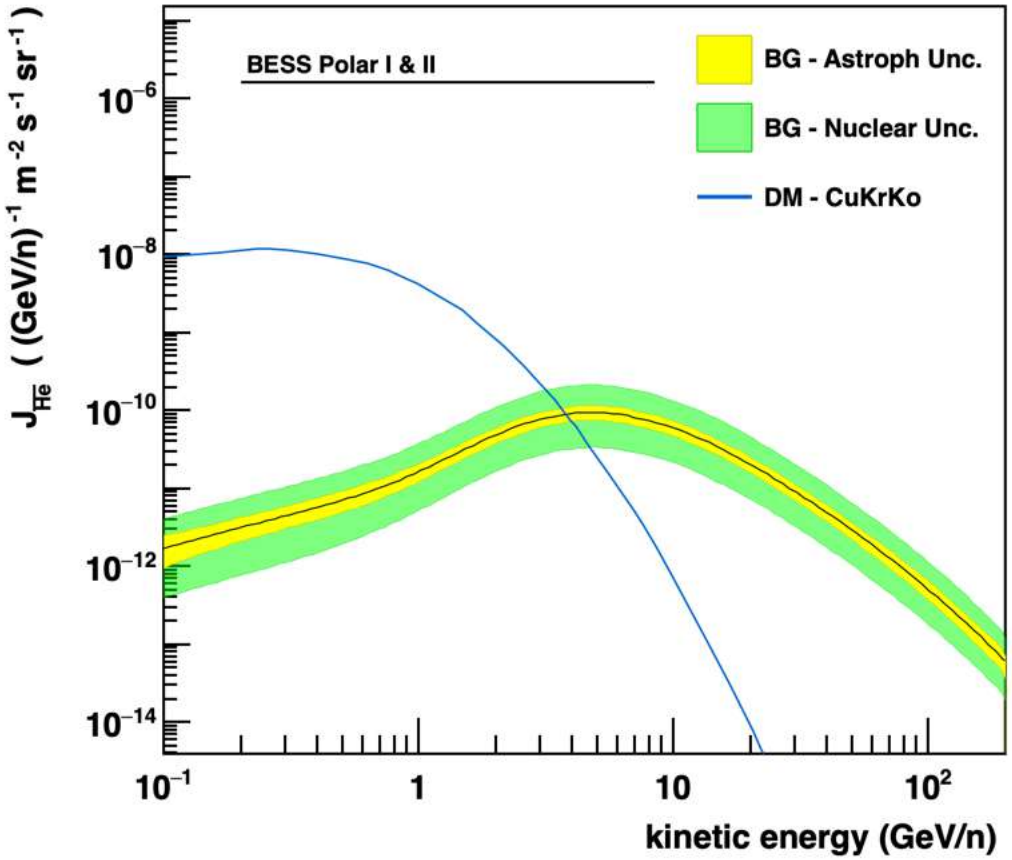


Anti-deuteron and anti-helium

antideuteron flux

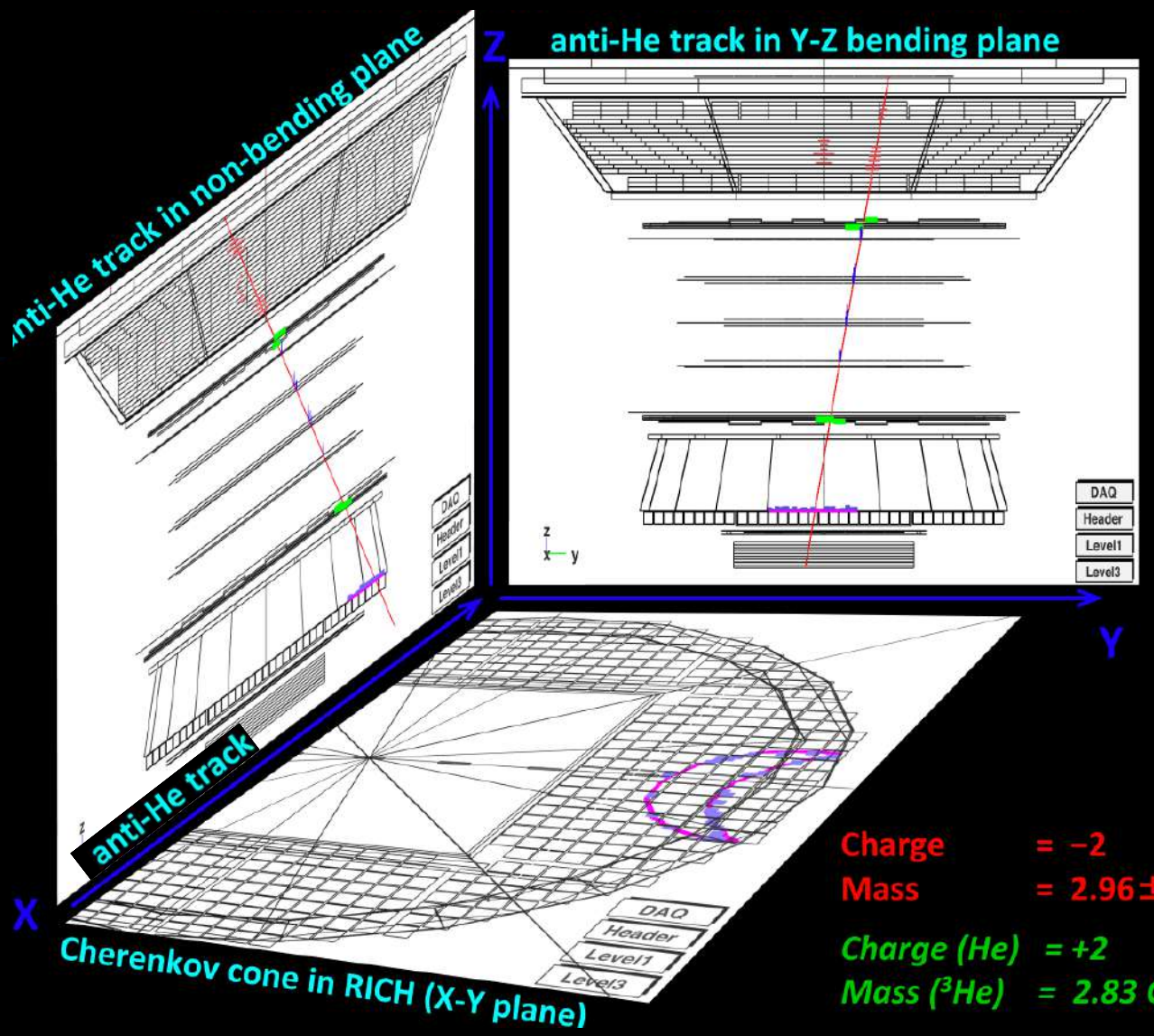


antihelium flux



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

Anti-deuteron and anti-helium



Charge = −2
Mass = 2.96±0.33 GeV/c^2

Charge (He) = +2
Mass (^{3}He) = 2.83 GeV/c^2

Search in progress by AMS-02, with 10+ years of cumulated exposure and a few candidates under analysis

New interesting projects for the near future

GAPS: General AntiParticle Spectrometer

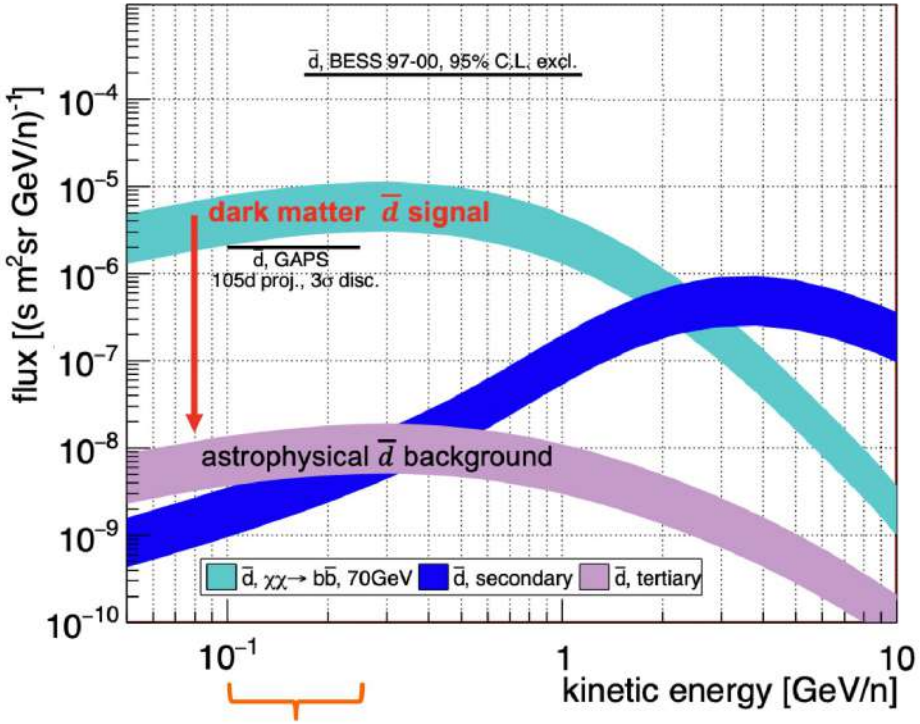
USA-Italy-Japan experiment for the detection of antinuclei: $\bar{p}$, $\bar{d}$, $\overline{He}$ $(100 - 250$ MeV/n).

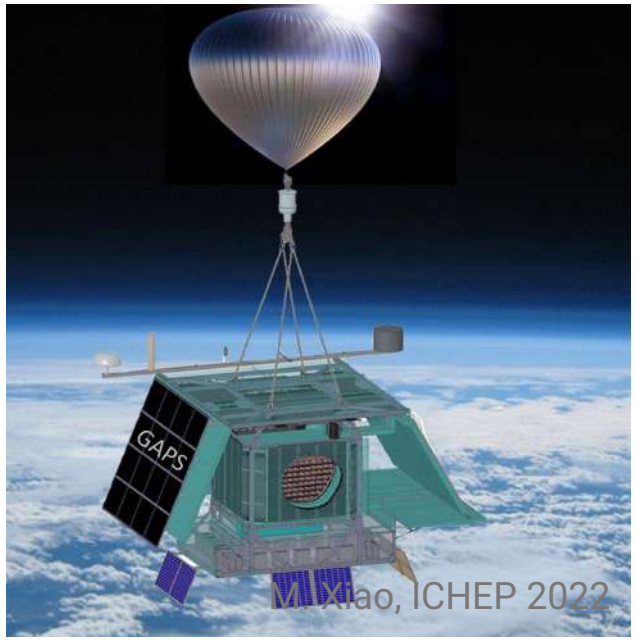
Non-magnetic spectrometer: the detection id based on **exotic atom formation** with **X/π emission**

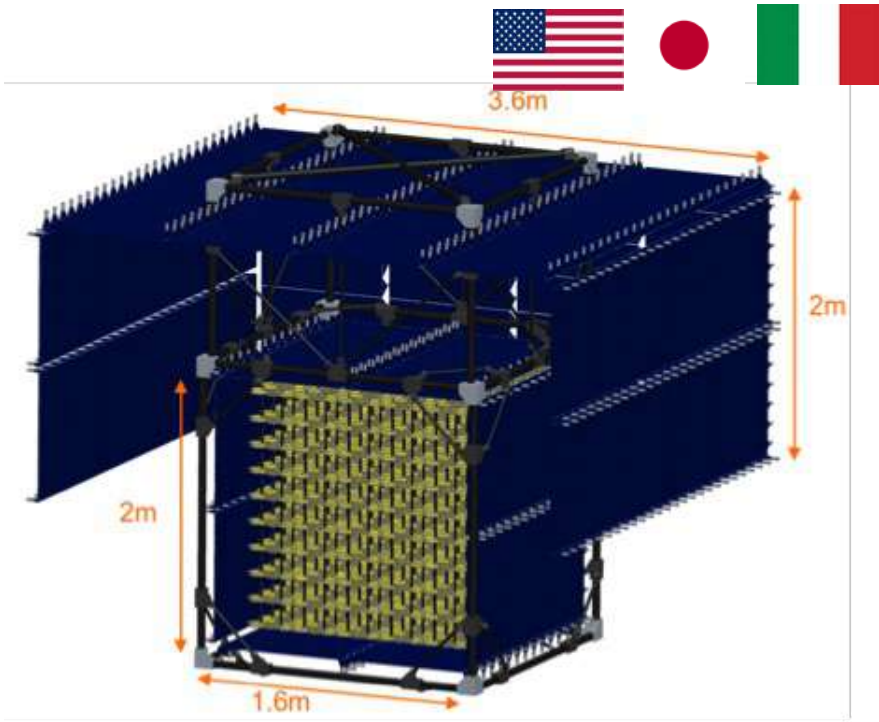
ToF system (A,B) and a 10-layer SiLi tracker (C)

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]$^{-1}$)





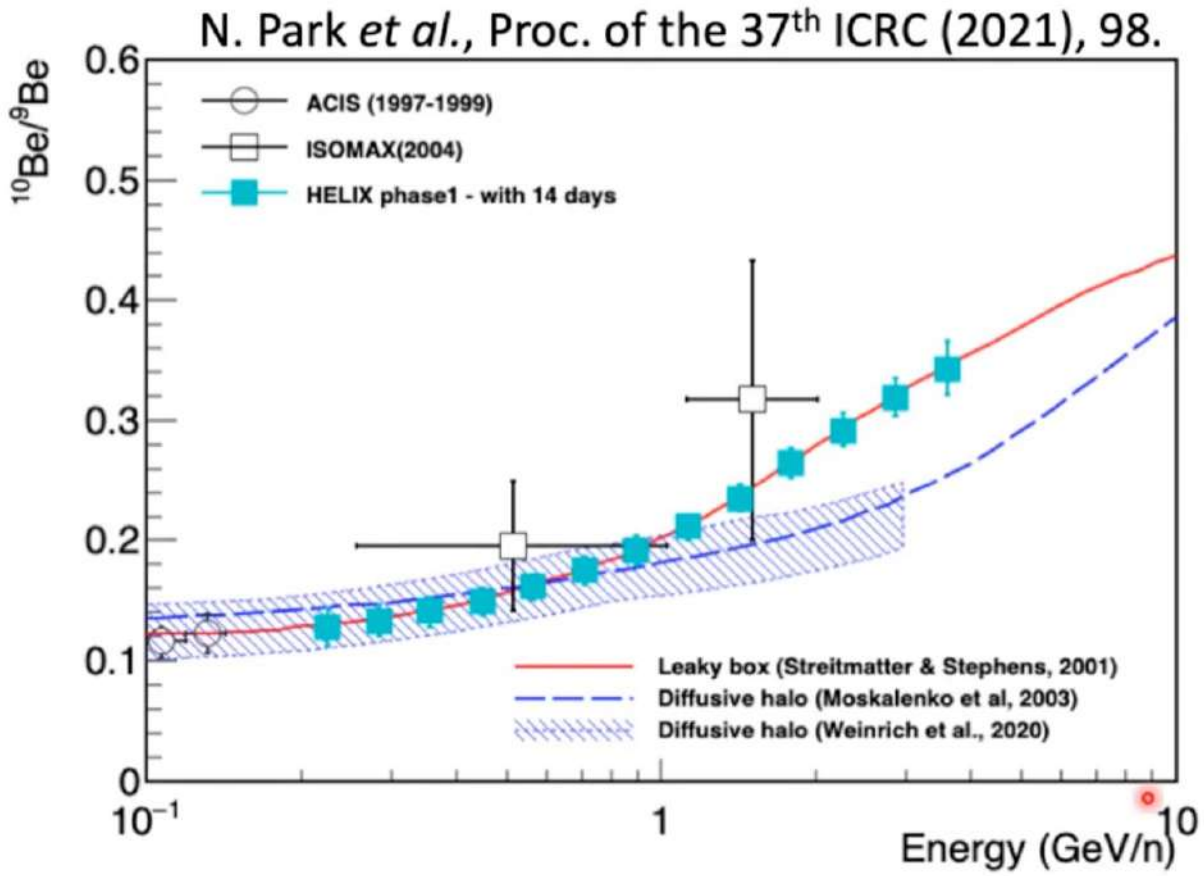


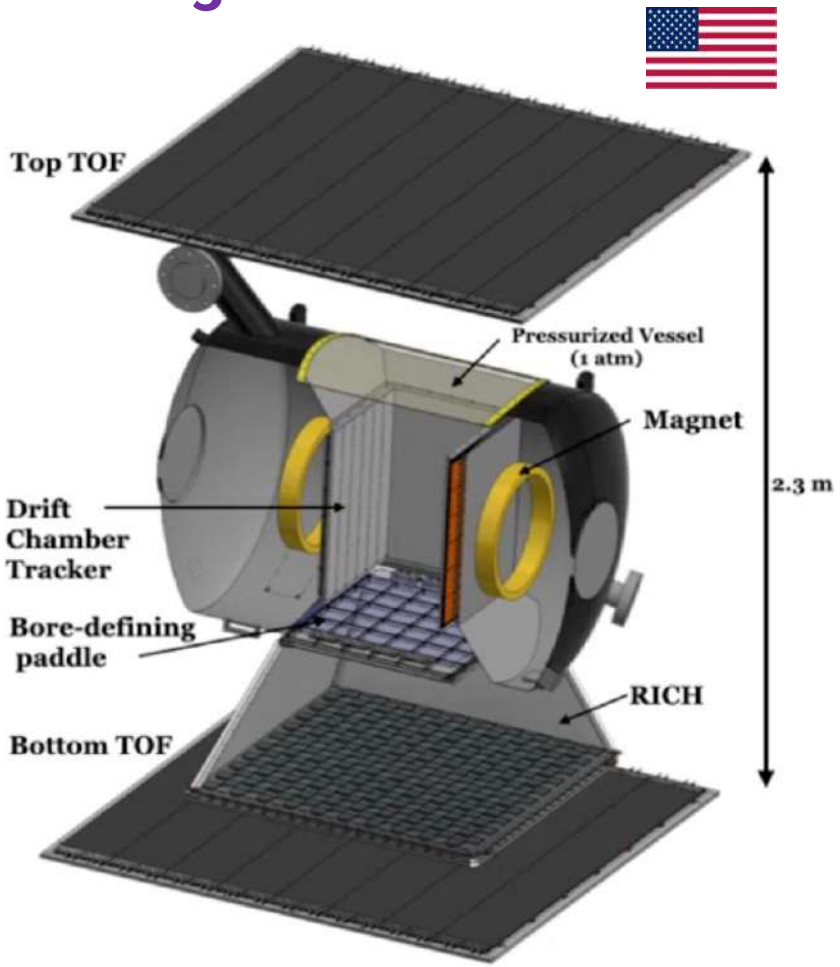
HELIX: High Energy Light-Isotope Experiment

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





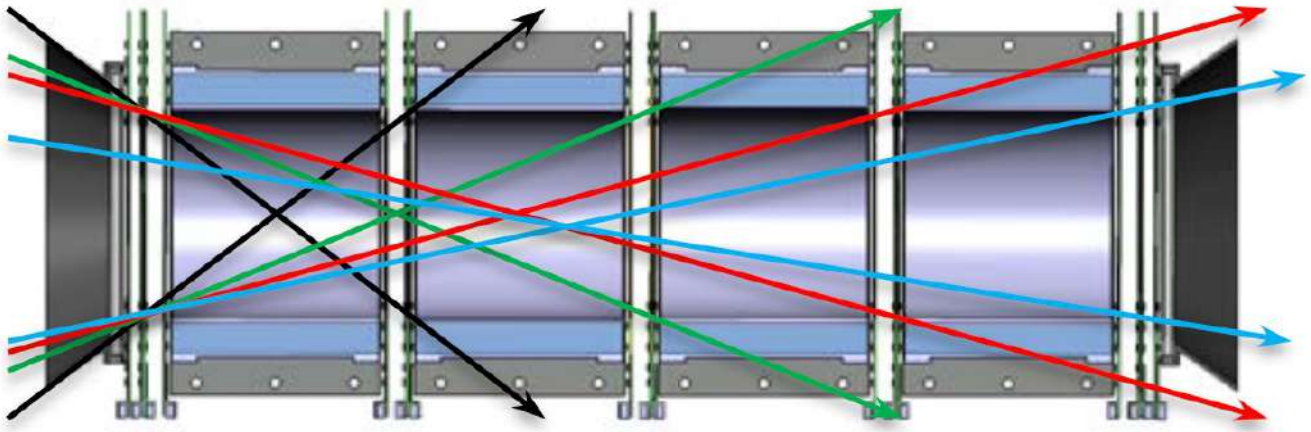
PAN: Penetrating particle ANalyzer

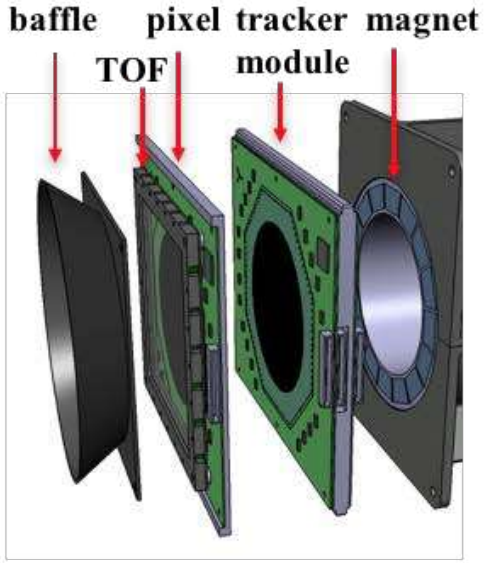
Compact and modular magnetic spectrometer for low-energy measurements

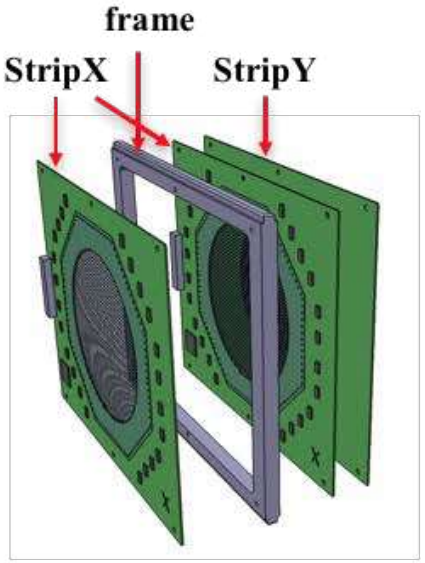
- U Geneva + INFN Italy + U Perugia + U Prague
- Cosmic rays, solar particle events, heliophysics, space weather
- Nuclei, leptons, antiparticles at 50 MeV – 20 GeV. Long-duration mission >> yrs
- Onboard instrument for real time monitoring in long-term missions

Precursor "Mini-PAN" (2020-23) project EU H2020 FET_OPEN GA 862044

White paper: *Wu et al. Adv Space Res. 63 (2019)*







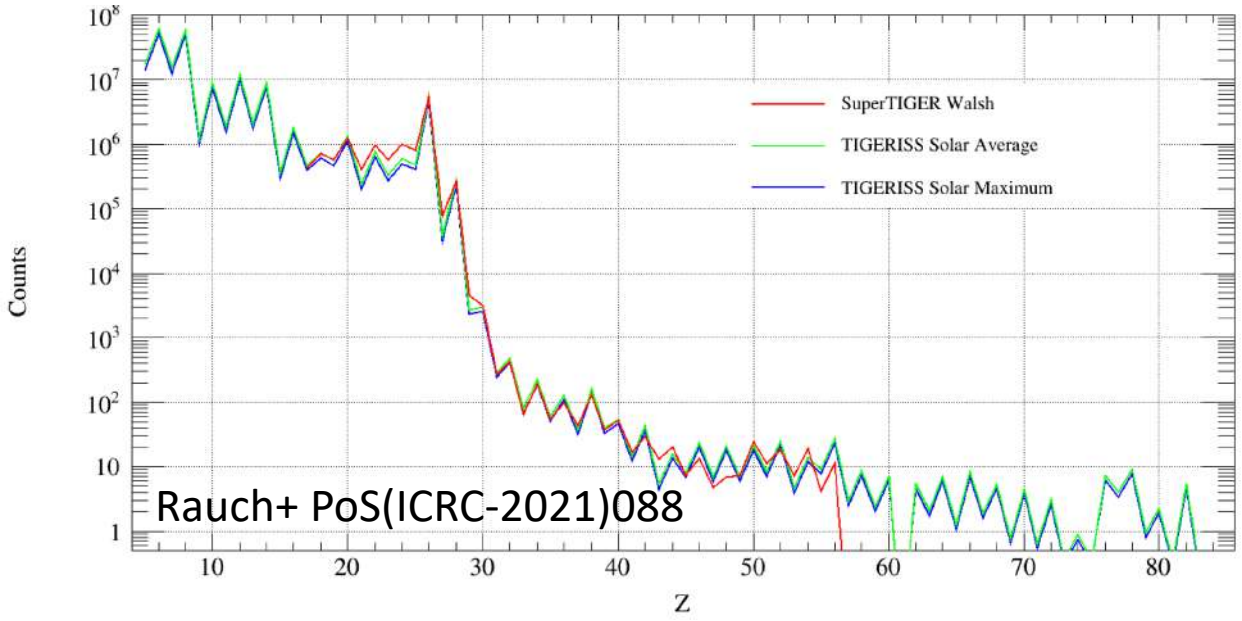
TIGERISS: Super-Heavy CRs from the ISS

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

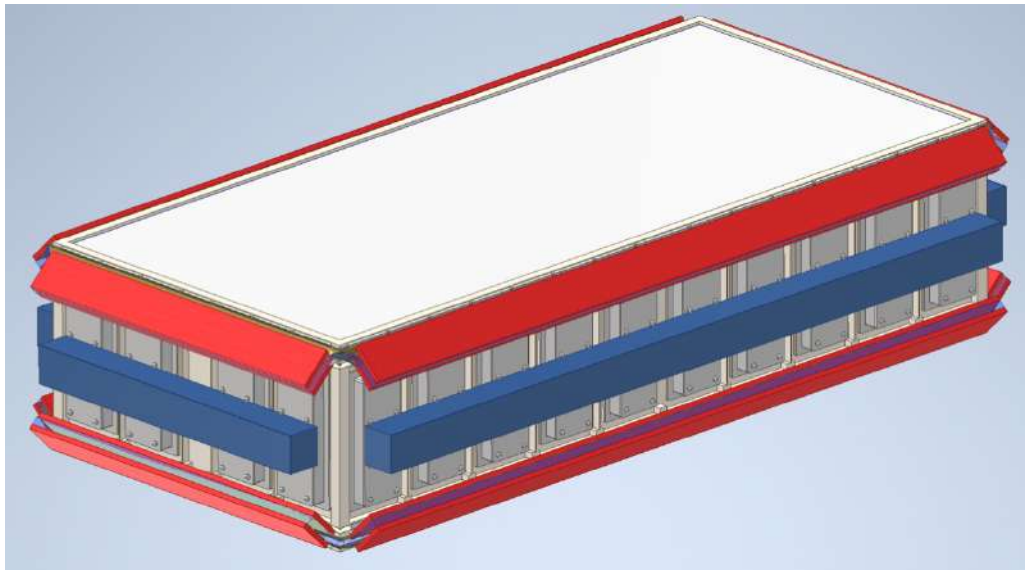
Based on SuperTIGER, to be installed on the ISS for a long-term mission.

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

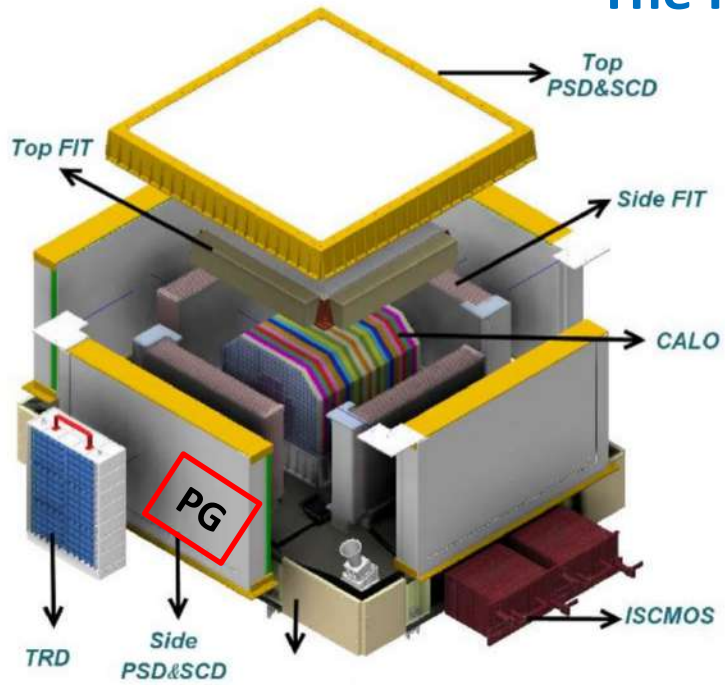


Technical model of the detector stack

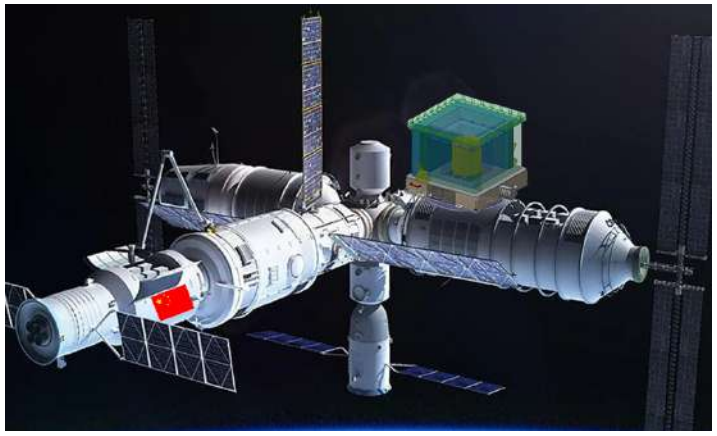


The HERD Experiment in the Chinese Space Station

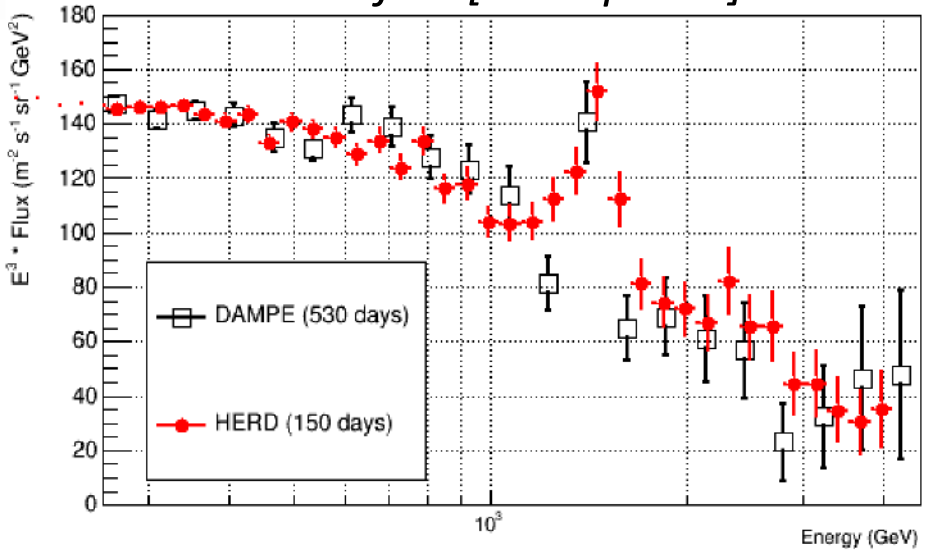
The High Energy cosmic Radiation Detection facility



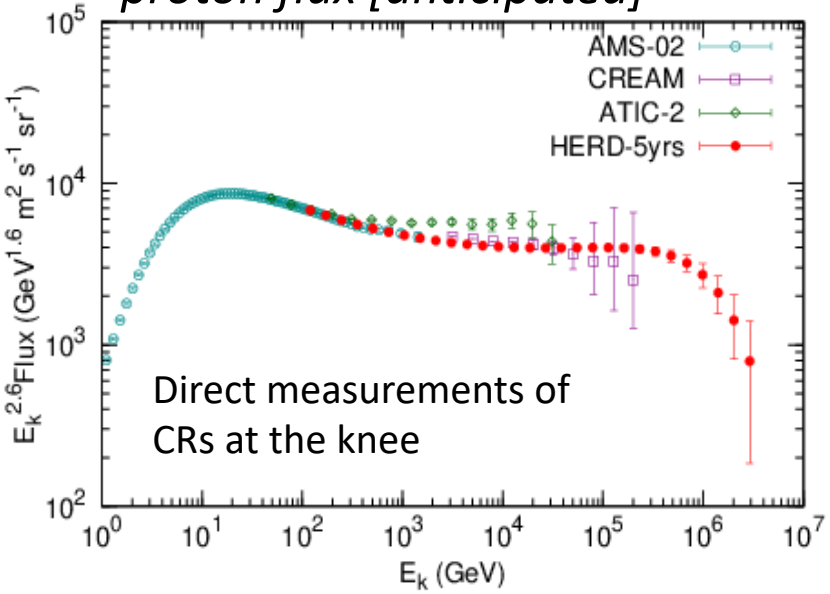
- HERD consortium: 130+ from China, Italy, Switzerland, Spain
- Long-term mission ~10 yrs (Exp ~ 20 m^2 sr yrs), NET 2027.
- Calorimetric measurements of leptons (multi-TeV) & nuclei (PeV!)



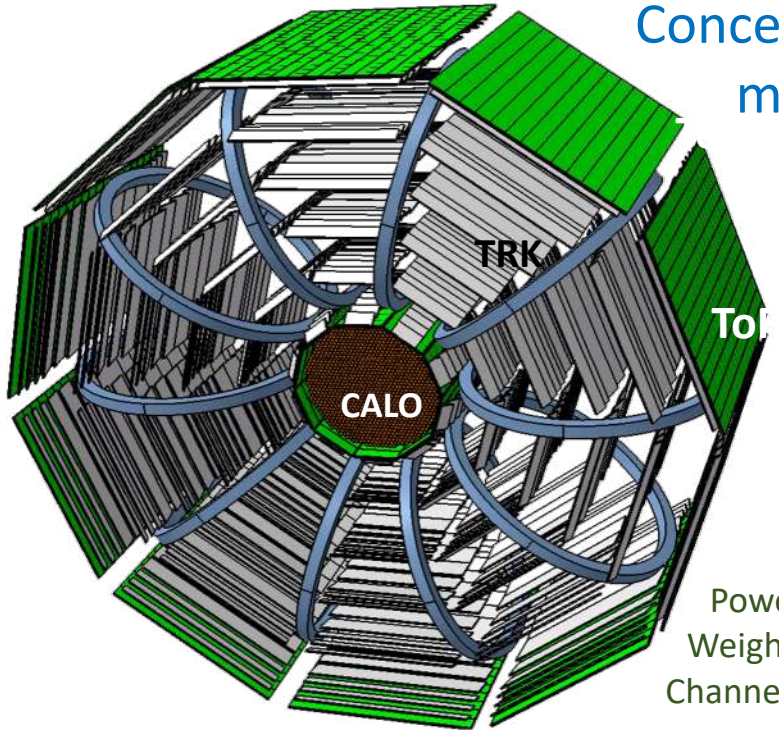
all-electron flux [anticipated]



proton flux [anticipated]



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

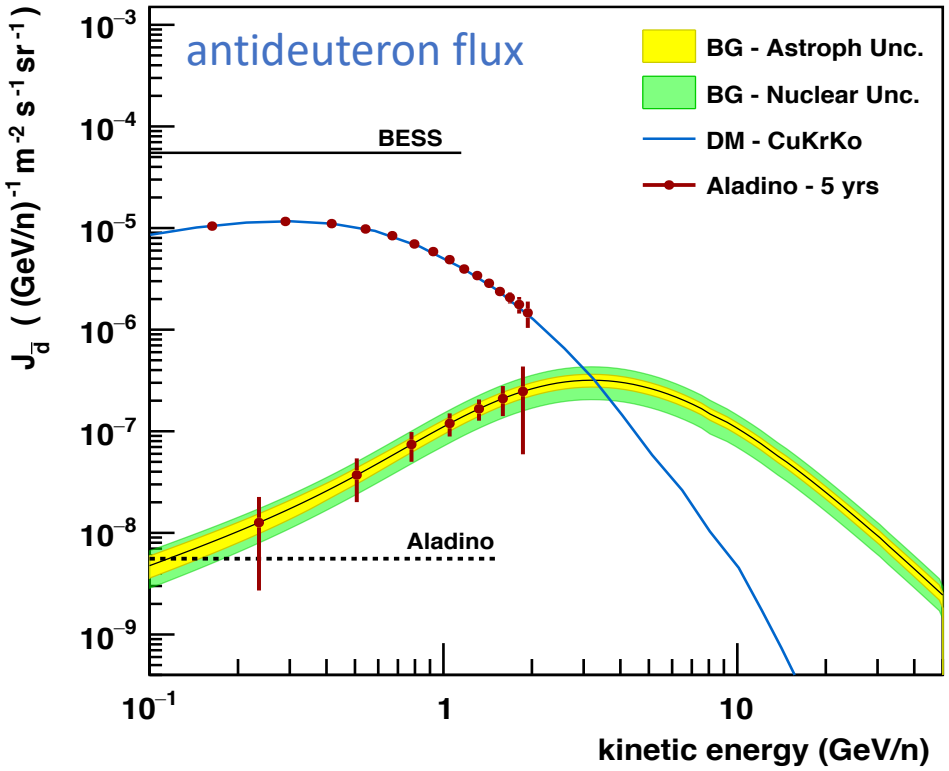
Core team members from IT, FR, DE, SE, CZ, CH

- 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

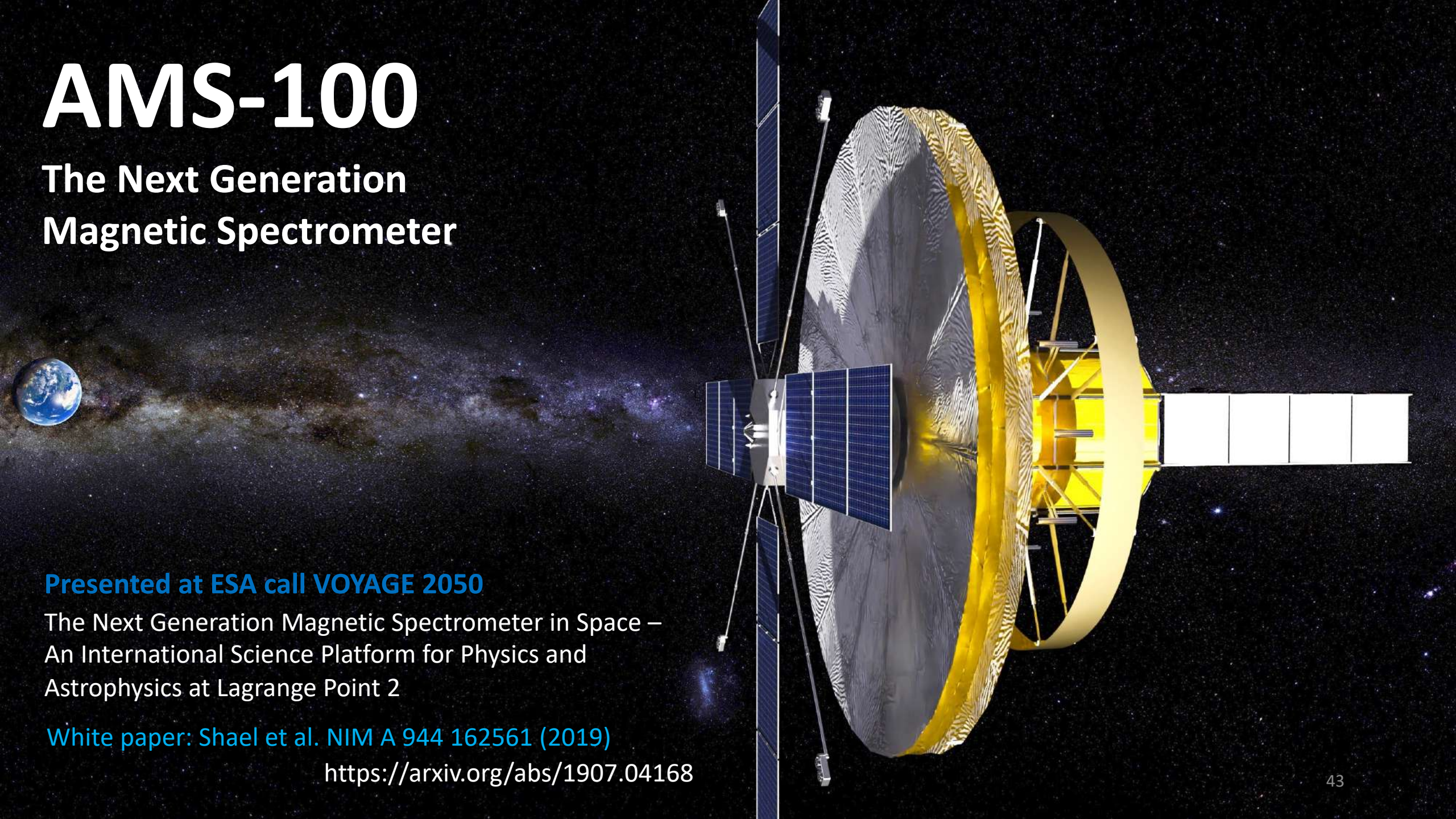
Total acceptance	10 m^2sr	Calo resolution	2% (e) – 30% (N)
MDR	20 TV	TOF resolution	100 ps

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



AMS-100

The Next Generation Magnetic Spectrometer



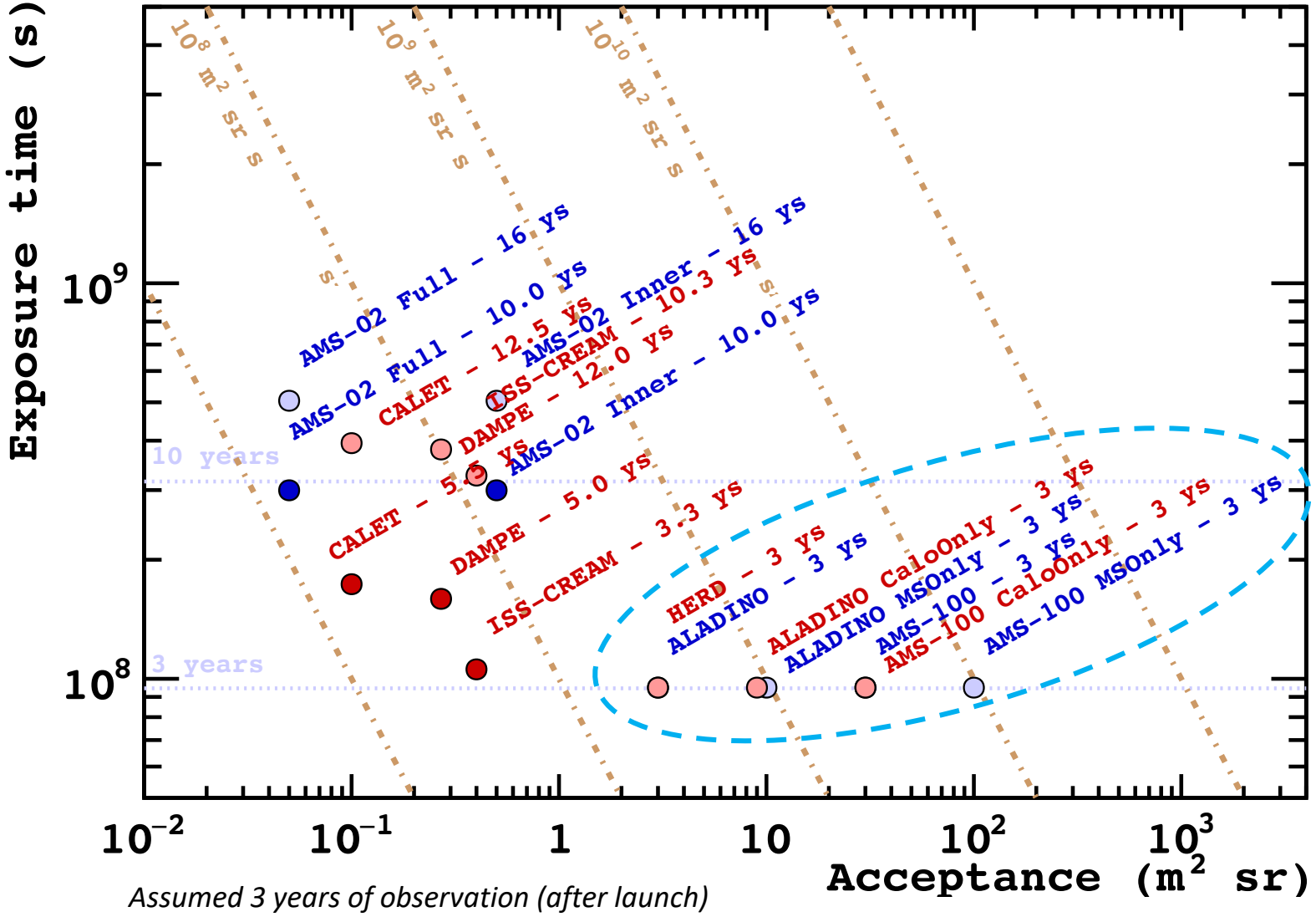
Presented at ESA call VOYAGE 2050

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

Future facilities w/ 3 yrs data



Assumed 3 years of observation (after launch)

Conclusions

- Precision era of CR measurements. High-quality data from many active experiments
- The recent data are changing our understanding of CR physics.
- End of the paradigm of simple and universal power-law
- The CR spectrum has several unexpected features, the origin of which is to be understood
- Anomalies have been found in many species and energies, from sub-GeV to multi-TeV

New questions triggered by the recent measurements

- What's the origin of the **hardening** in the spectra of all CR nuclei at ~300 GV?
- Why different species have different **slopes**? And why the **p/He ratio** flattens at TV scales?
- Why different secondary/primary ratios have different high-energy slopes?
- Why the spectrum of **Iron** is different to that of other primaries?
- What's the origin of the **20 TeV spectral softening** in proton and helium?
- What's the origin of the **TeV break** in the **electron** spectrum?
- What's the origin of the **positron excess**?
- Why the high-energy **antiproton** spectrum is as hard as the proton spectrum?