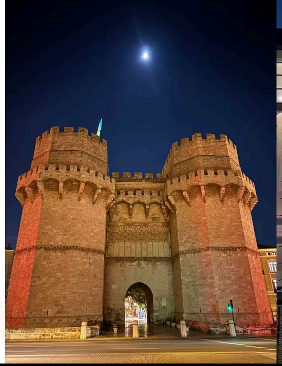
TeV Particle Astrophysics
TeVPA
Valencia 2025




Recent Results in Cosmic Rays Direct Detection

An Incomplete Experimental Review

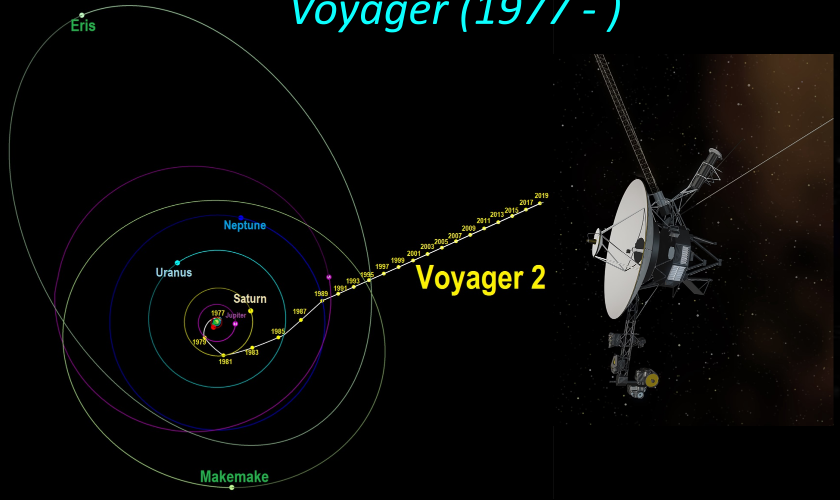
Weiwei Xu / SDU & SDIAT

Nov. 4, 2025

Examples of Current Experiments in Space

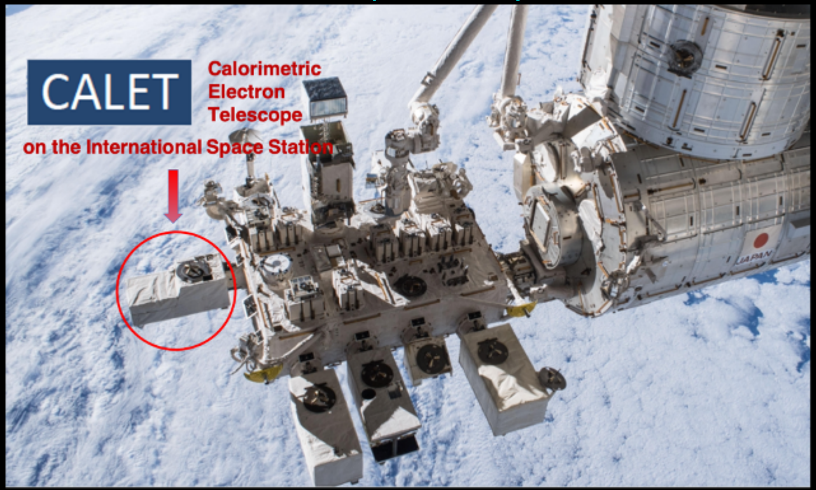
Non-magnetic calorimeters

Voyager (1977 -)

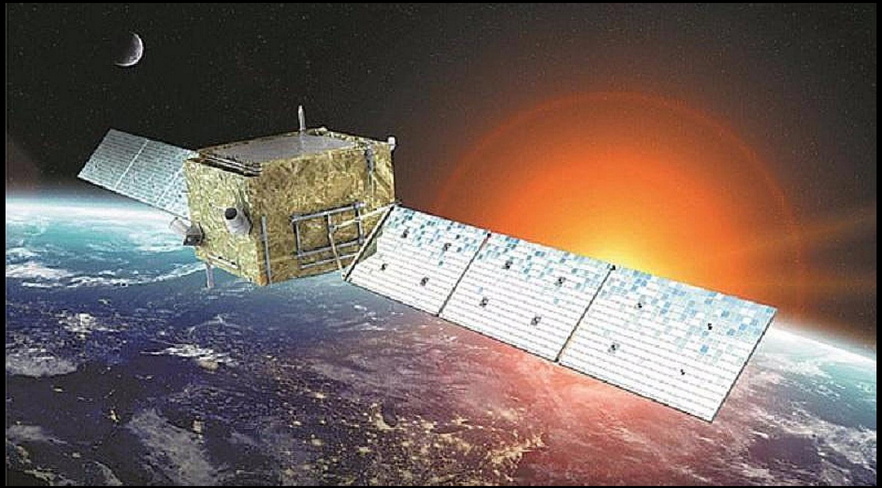


Fermi-LAT (2008 -)

CALET (2015 -)



DAMPE (2015 -)

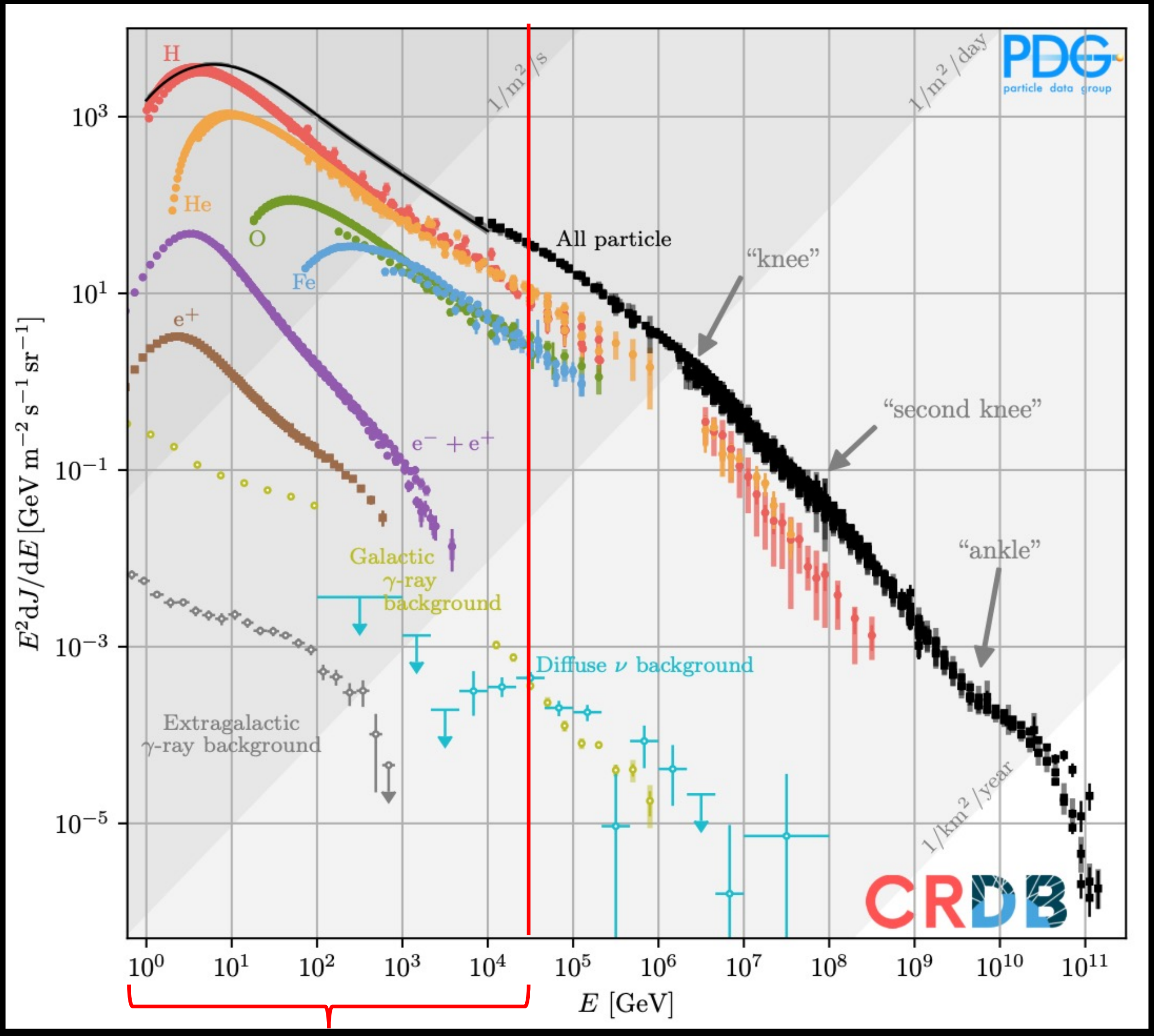


Magnetic detector

AMS (2011 -)

There are also may experiments and proposals: ISS-CREAM, GAPS, TIGER, HELIX, GRAMS, …

Overall Picture of Cosmic Rays



Energy Reach of Current CRD experiments

Lepton

- Electrons, Positrons

Antimatter

- Antiproton
- Antideuteron, Antihelium

Nuclei (Periodic Table)

- Proton, Helium
- Heavy Primary Nuclei
- Secondary Nuclei
- Mixed (Primary + Secondary)
- Ultra-heavy (Z>28) nuclei

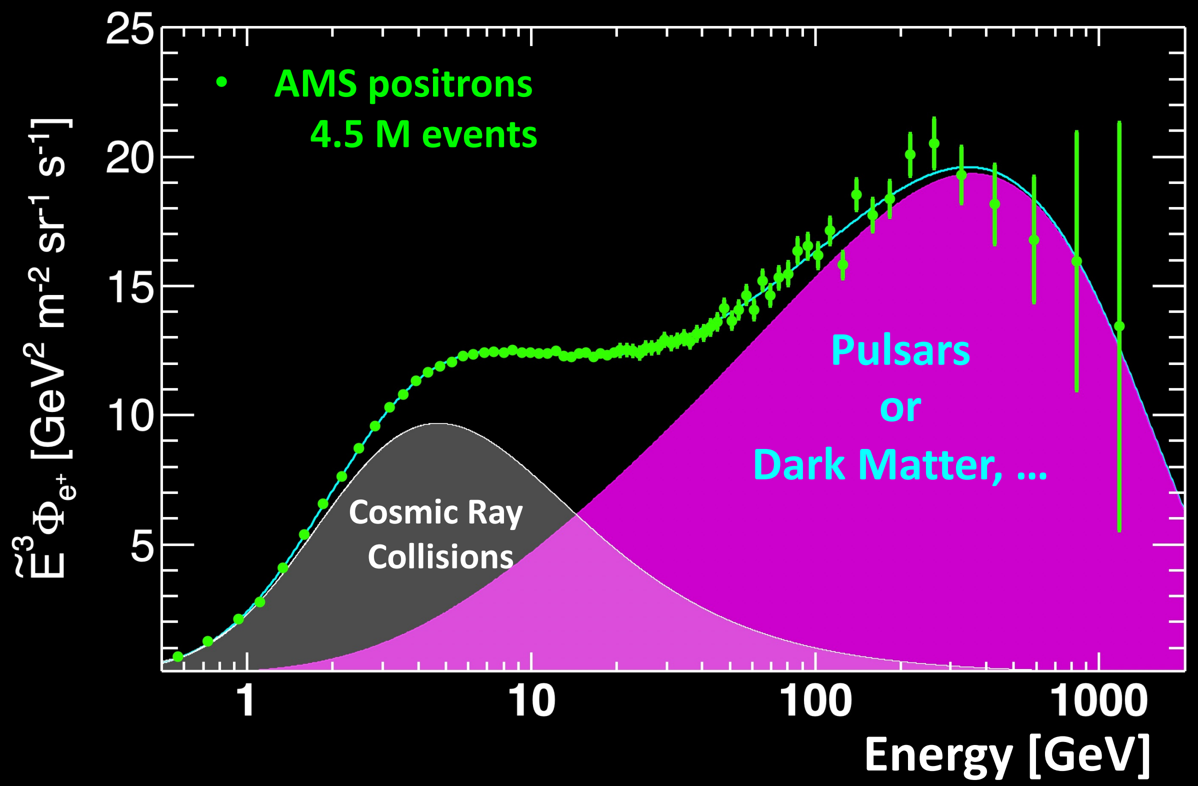
Isotopes

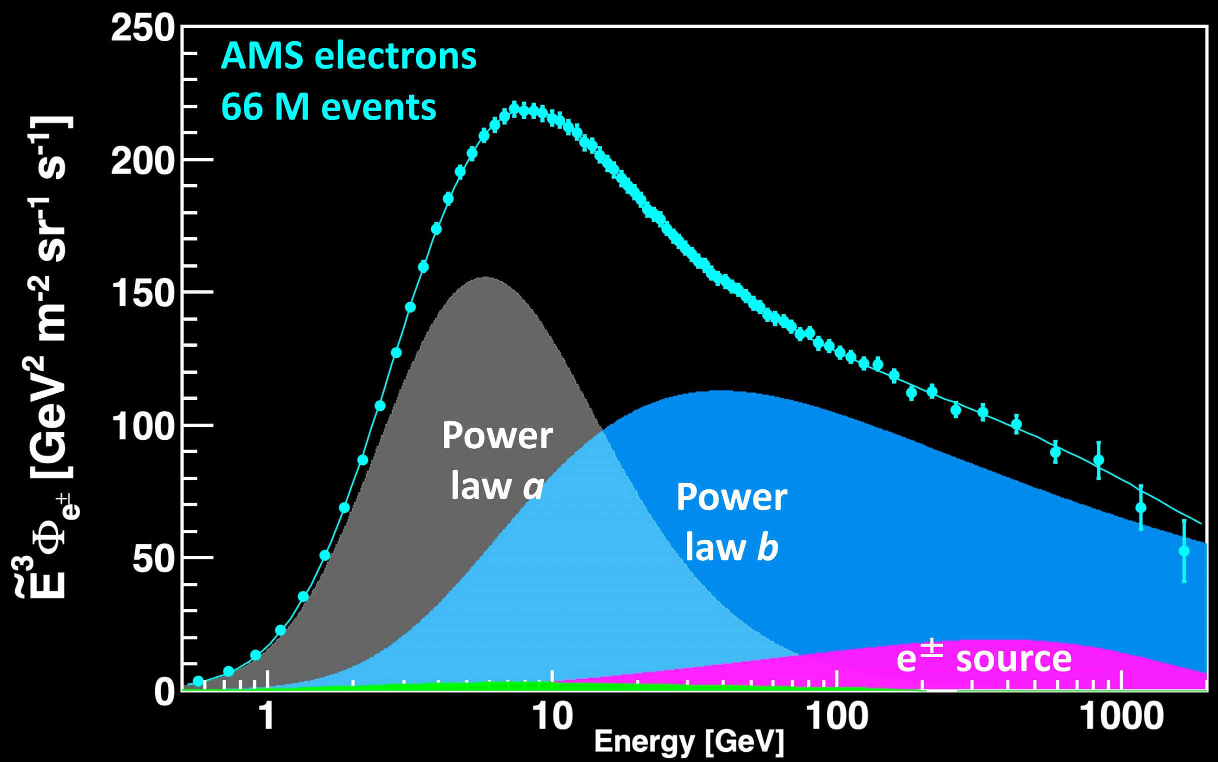
- Deuteron, Lithium, Beryllium

Heliosphere Physics (solar modulation)

- Time variation of cosmic ray fluxes

Cosmic Positrons and Electrons





AMS Empirical model for positrons:

$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$

Solar Collisions Pulsars or Dark Matter

Low energy High energy

Existence of a finite cutoff energy E_s is determined to be 5σ

AMS Empirical model for electrons:

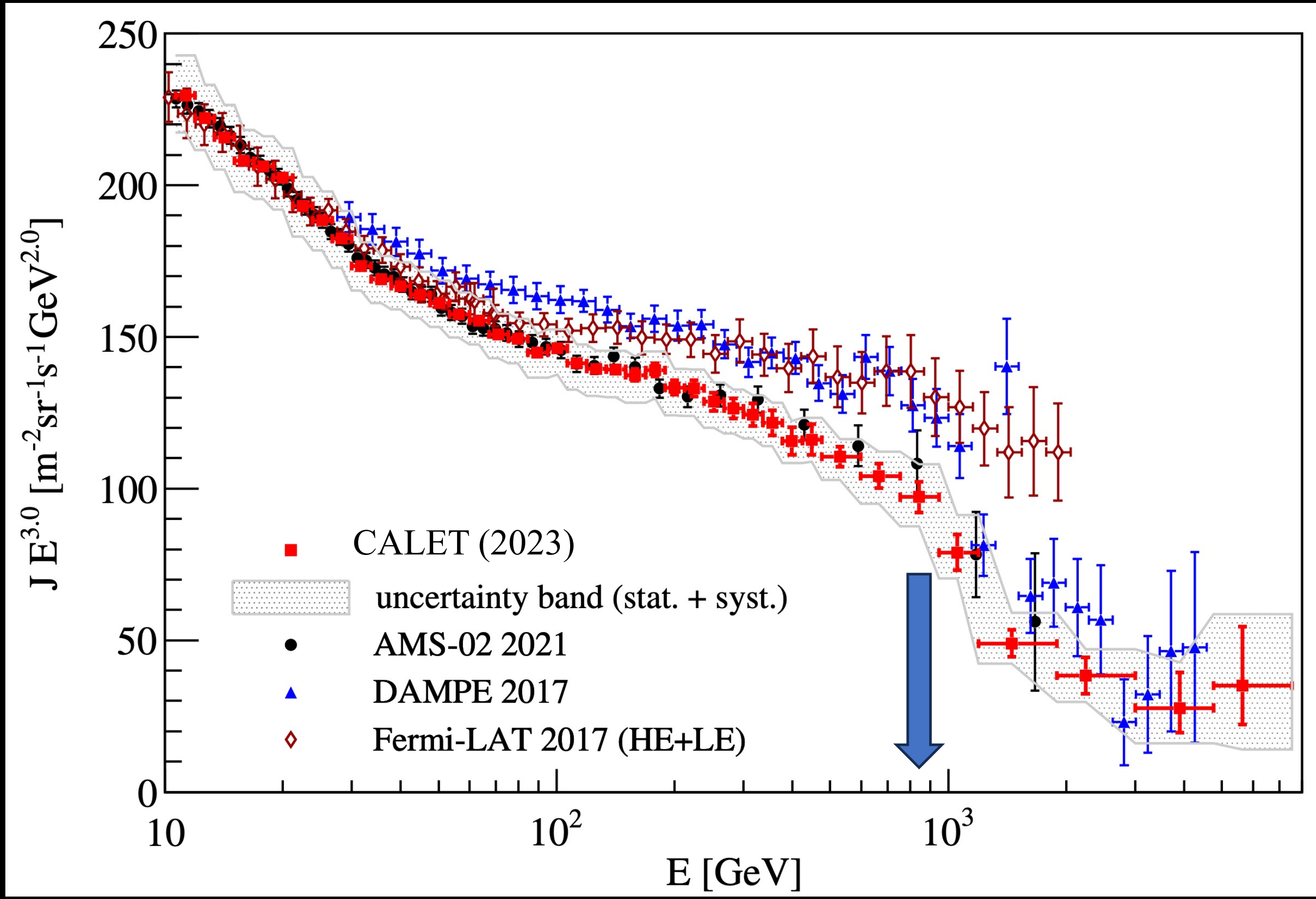
$$\Phi_{e^-}(E) = \frac{E^2}{\hat{E}^2}(C_a \hat{E}^{\gamma_a} + C_b \hat{E}^{\gamma_b} + \text{Positron Source Term})$$

Solar Power law *a* Power law *b*

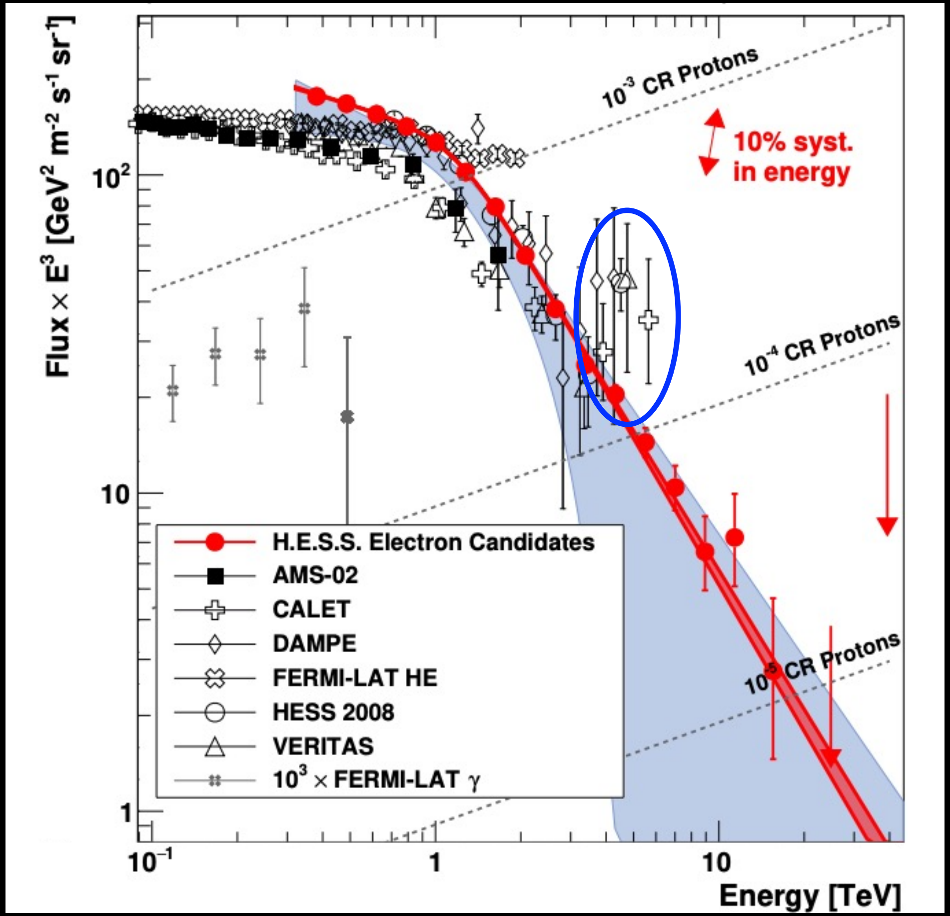
Emergence of charge symmetric source at 99.1% CL

Cosmic (Positrons + Electrons)

Extension to beyond 1 TeV energy with calorimeter experiments



CALET: PRL 131, 191001 (2023). Updates in ICRC 2025



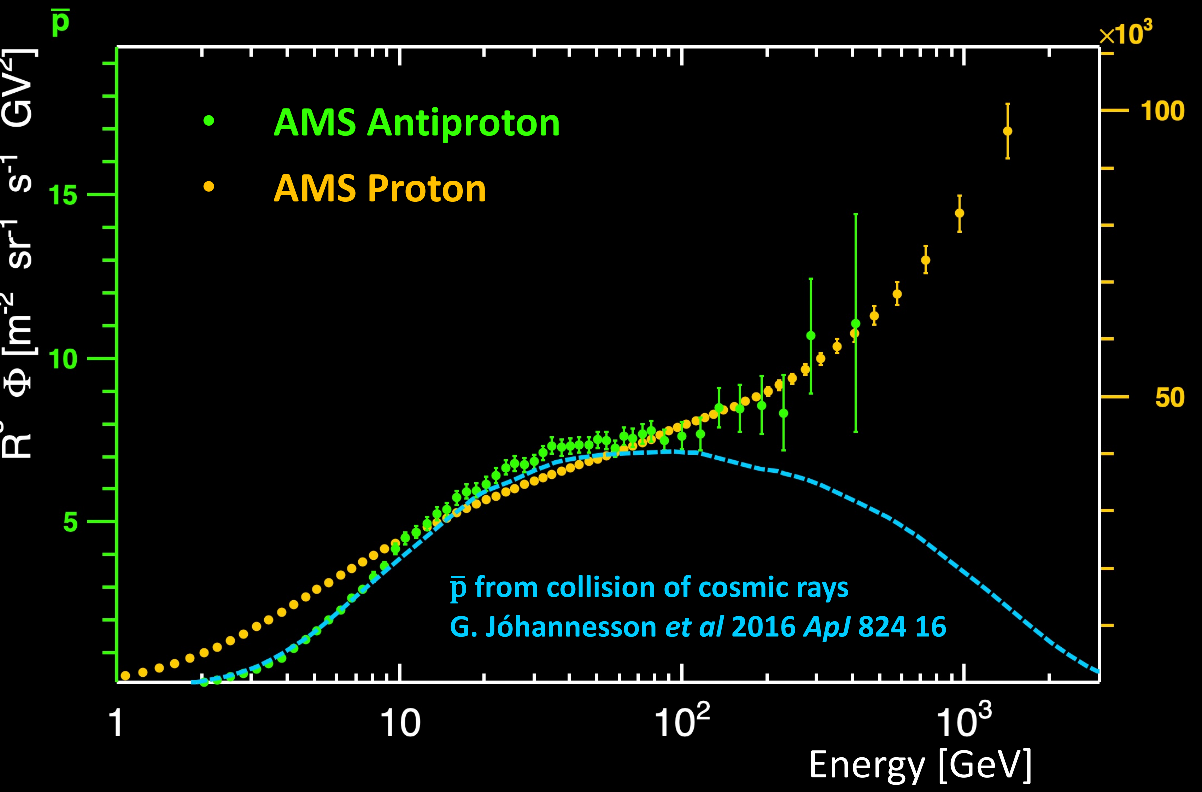
HESS: PRL 133, 221001 (2024)

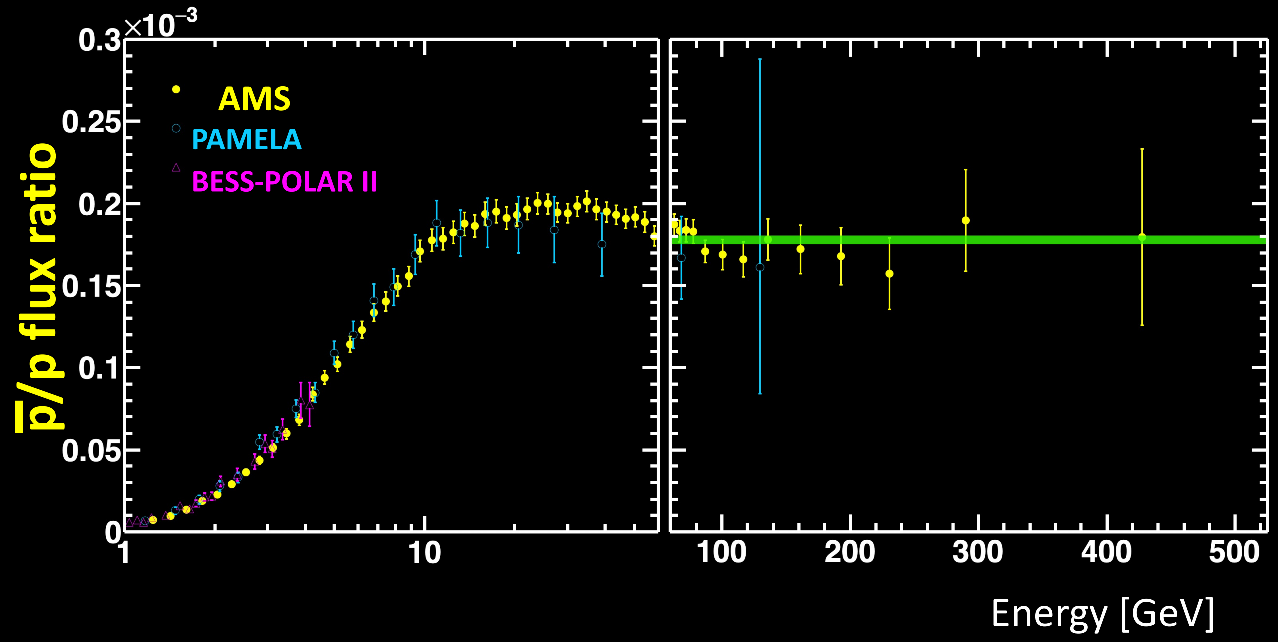
AMS, CALET, DAMPE: Spectral break at ~ 1 TeV

HESS: Continue with sharp drop above 3 TeV

Key question: Spectral structure caused by nearby e- sources? → Future measurements

Cosmic Antiprotons





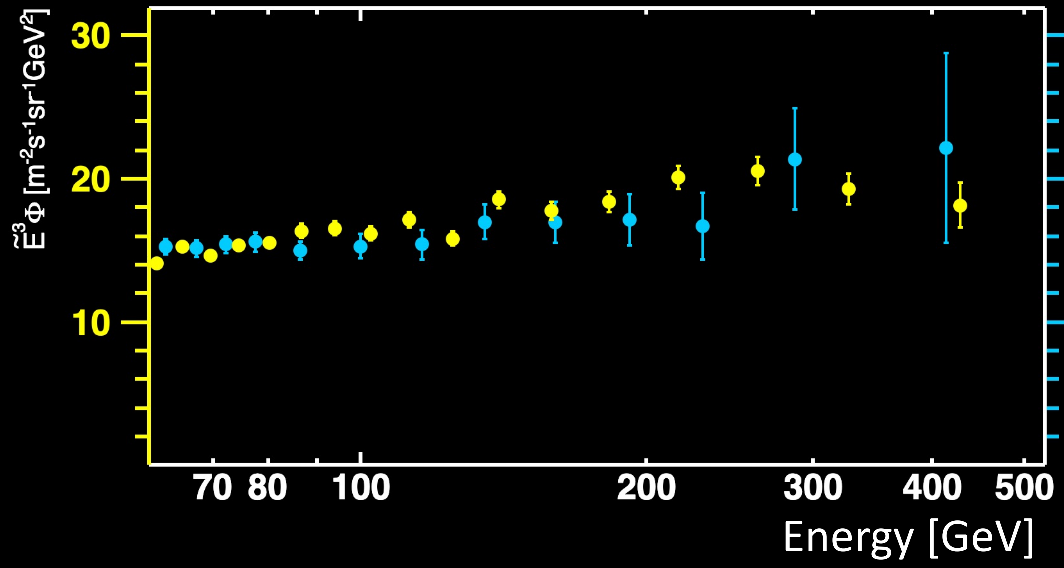
AMS observation: p and p̄ have identical rigidity dependence above 60 GV, p̄/p ratio is energy independent

This challenges the models with only secondary antiprotons (from cosmic ray collision with interstellar medium)

Cosmic Antiprotons and Positrons

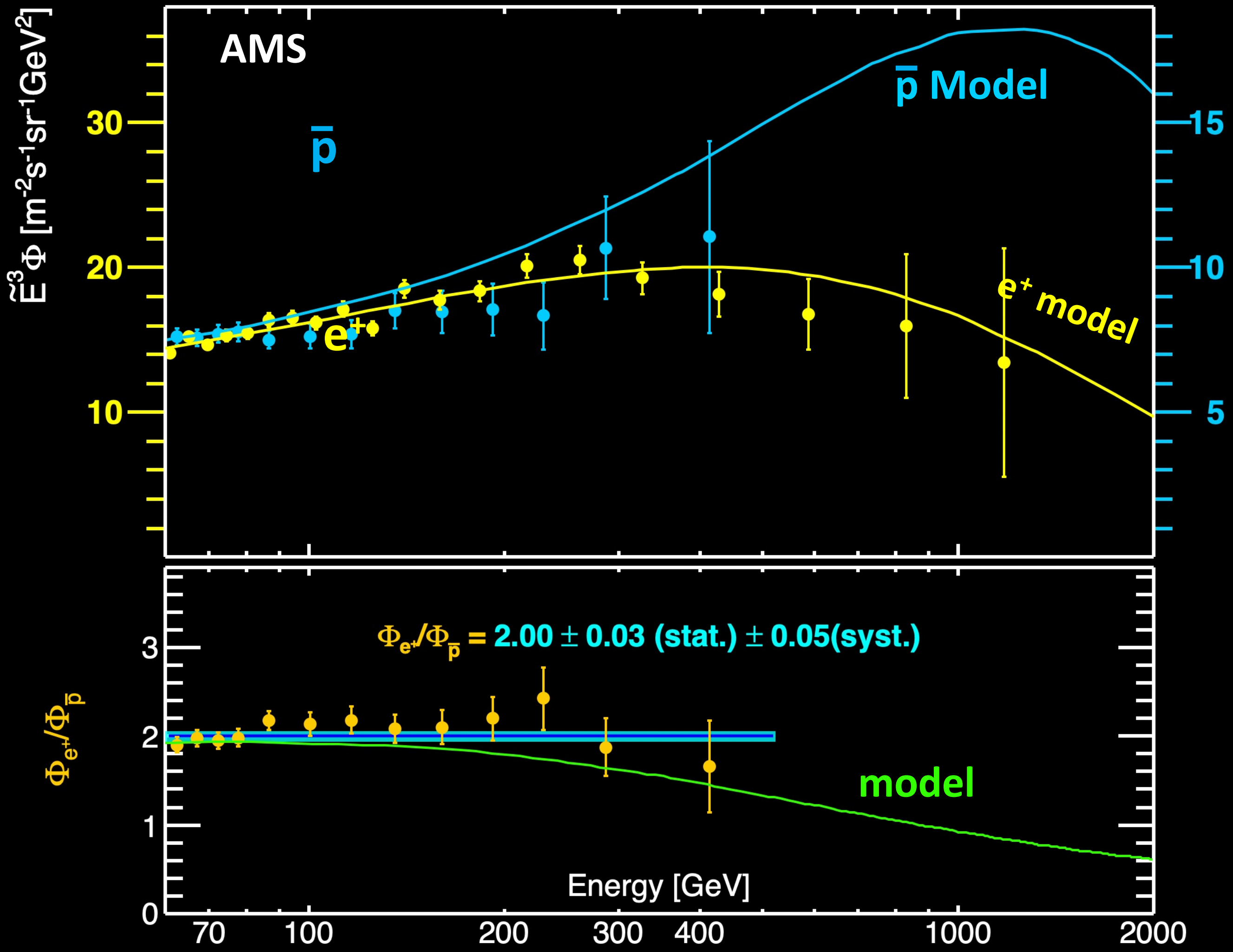
AMS observed striking similarity in the energy spectra of positron and antiproton.

Above 60 GV, $e+/\overline{p}$ = 2.00 ± 0.03 ± 0.05



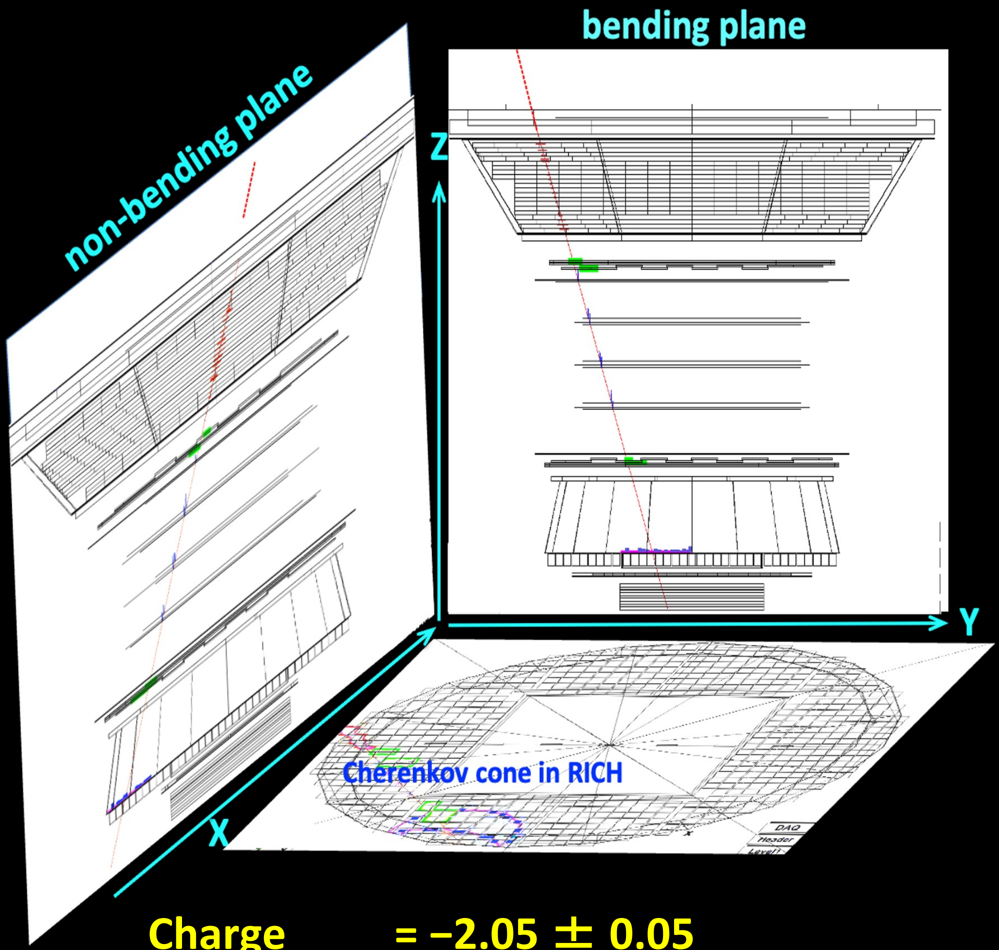
The extended measurements to higher energy is the key to address their origin.

Comparison with a model of old supernova:
P. Mertsch, A. Vittino, S. Sarkar, PRD 104 (2021) 103029



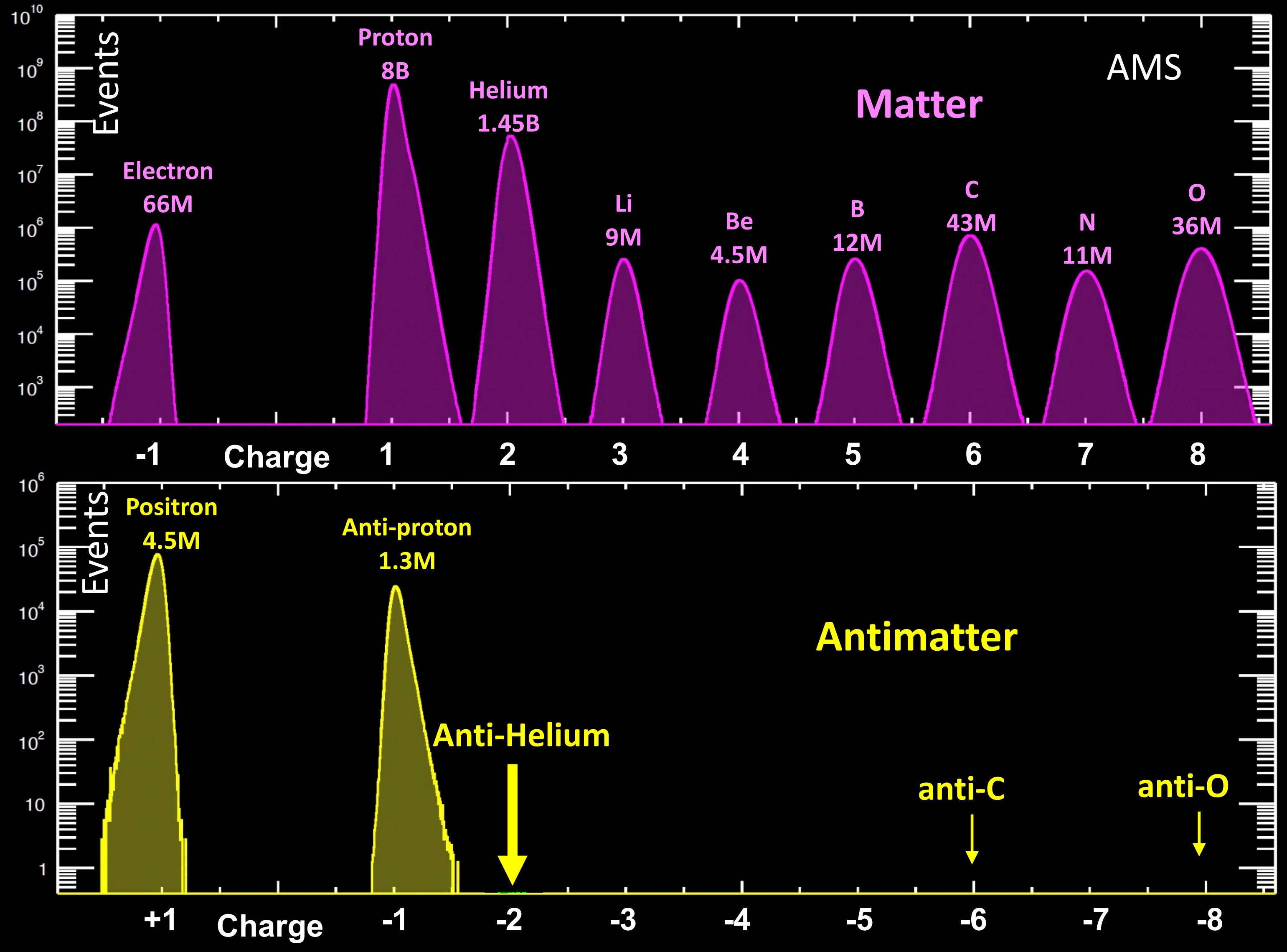
Heavier Antimatter in Cosmic Rays

A few antideuteron and antihelium candidates have been reported by AMS.



Charge = −2.05 ± 0.05
Mass = 3.81 ± 0.29 GeV/c^2

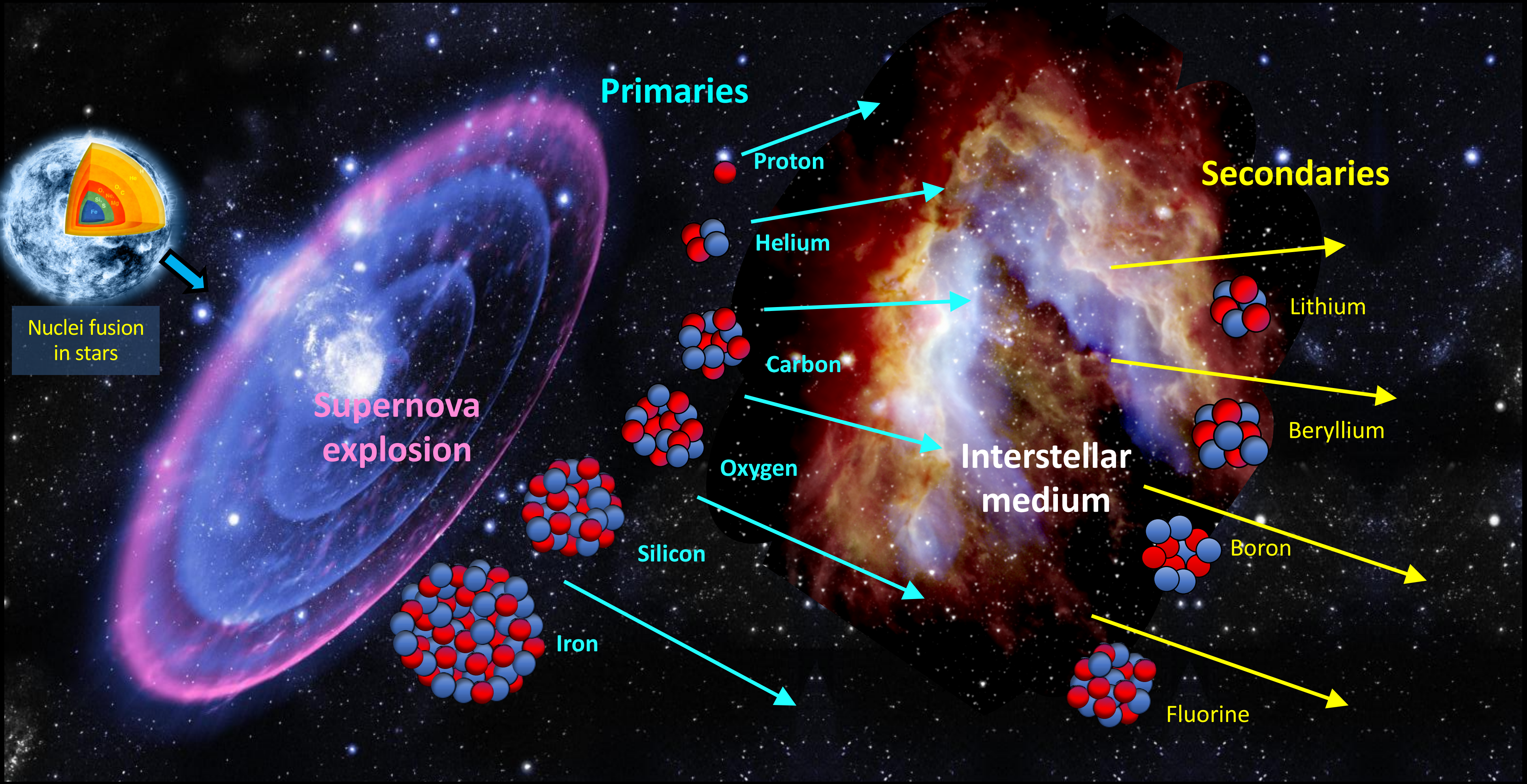
^{4}He: Mass = 3.73 GeV/c^2
Charge = +2



Further experimental verification is being conducted.

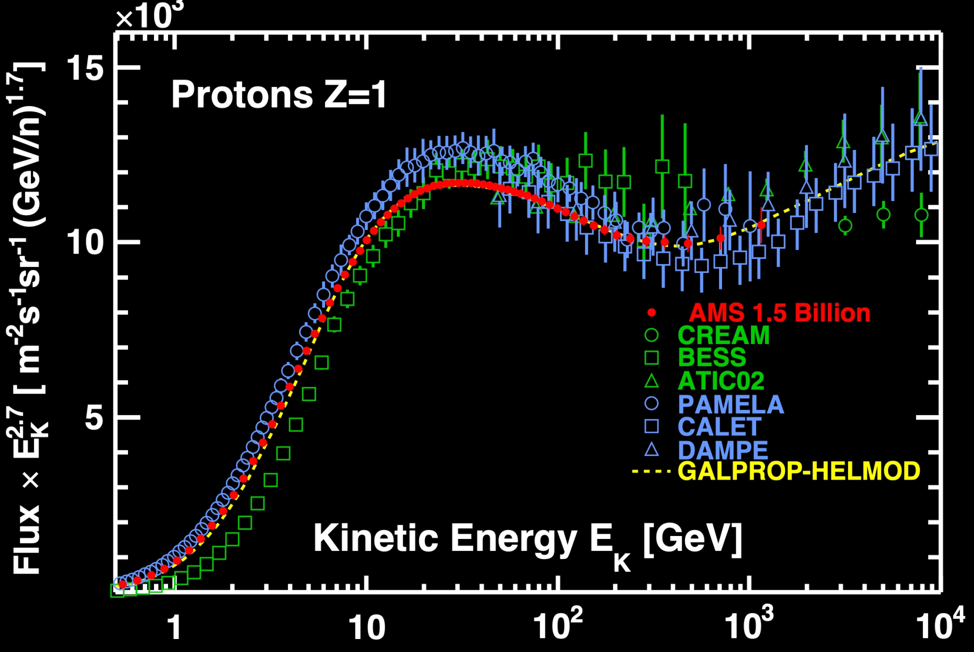
The Origin of Elements in Cosmic Rays

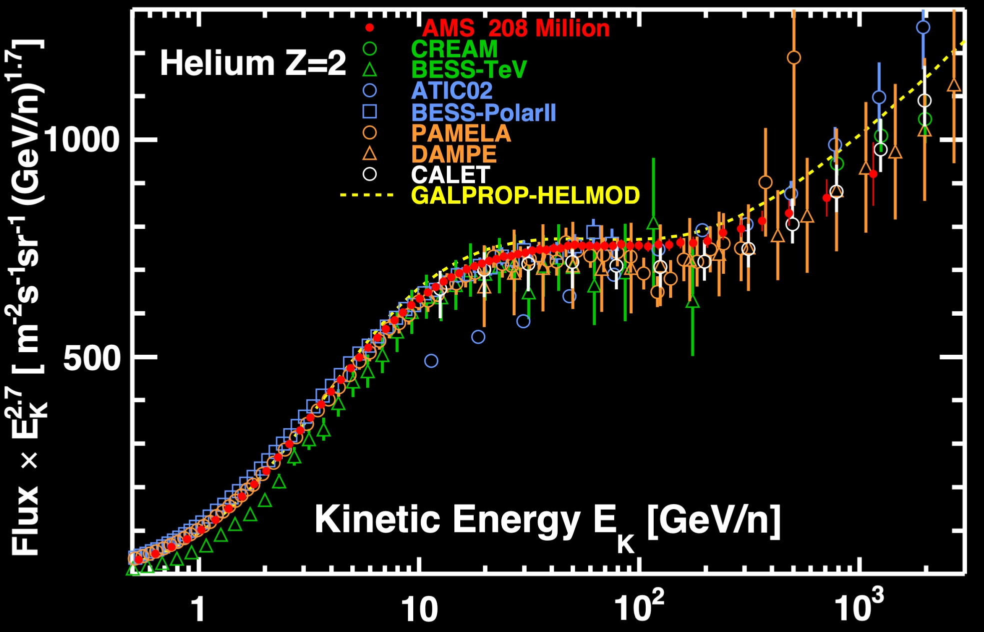
Primaries p, He, C, O, Si, …, Fe are produced in stars and accelerated by supernovae.
Secondaries Li, Be, B, and F are produced by the collision of Primaries with the interstellar medium



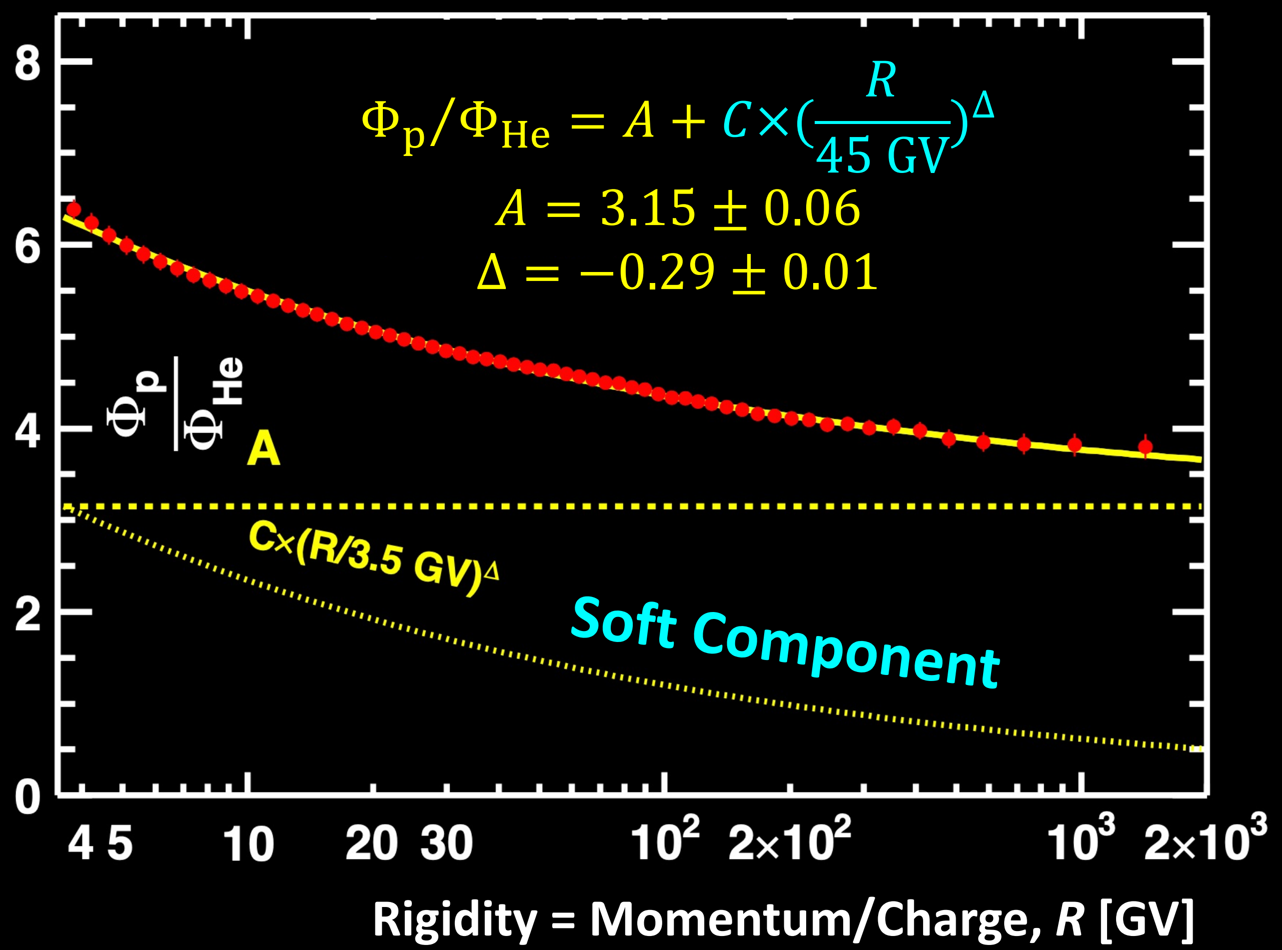
Measurements of the cosmic ray nuclei fluxes are important in understanding their origin, acceleration, and propagation processes in the Galaxy.

Cosmic Proton and Helium: The Most Abundant Element



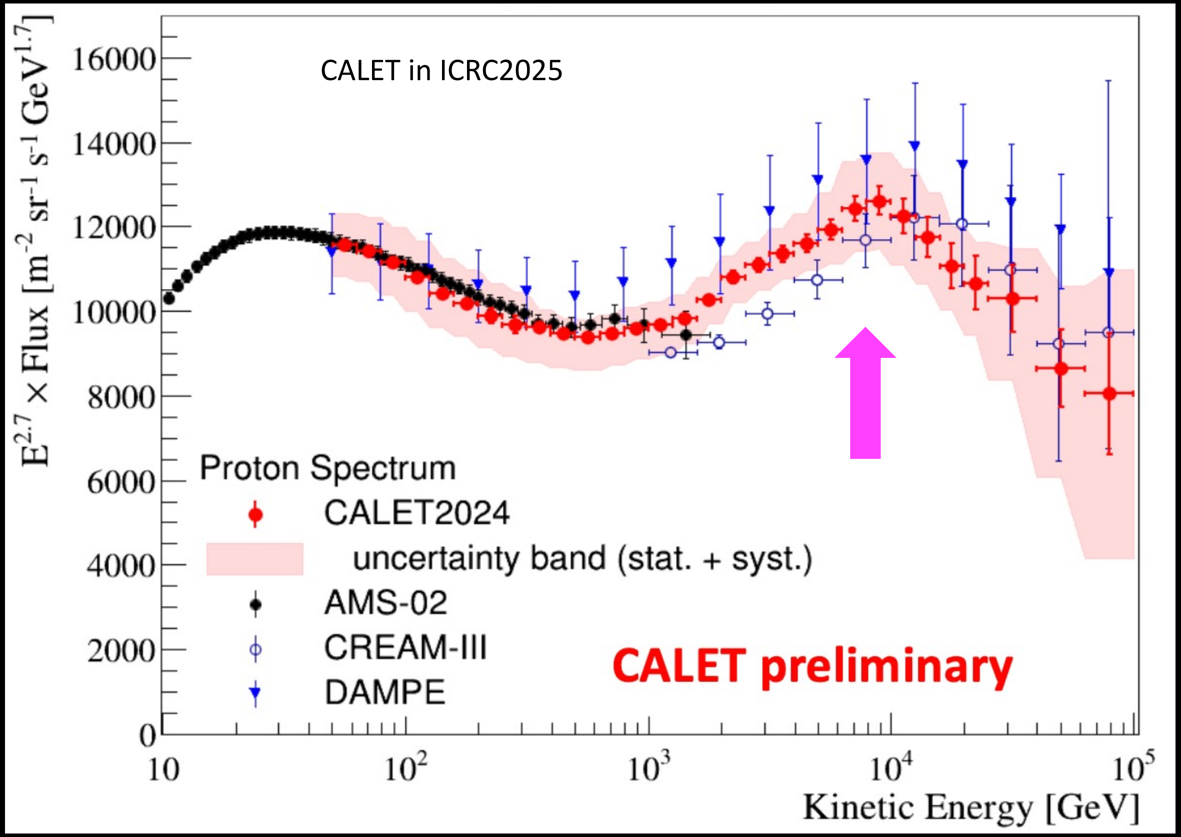


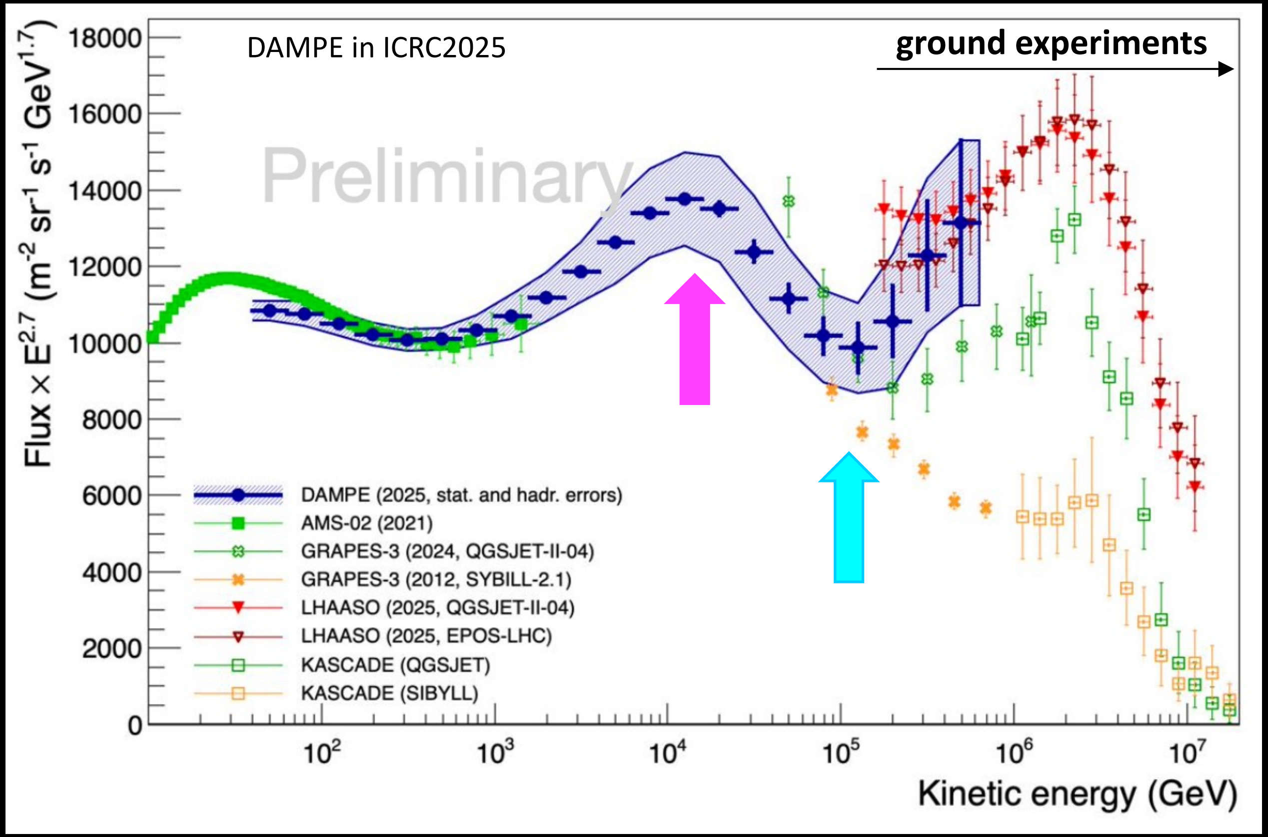
Proton/Helium Flux Ratio and A Soft Component in Proton



What is the origin of the soft component?

Cosmic Proton above 10 TeV Energies



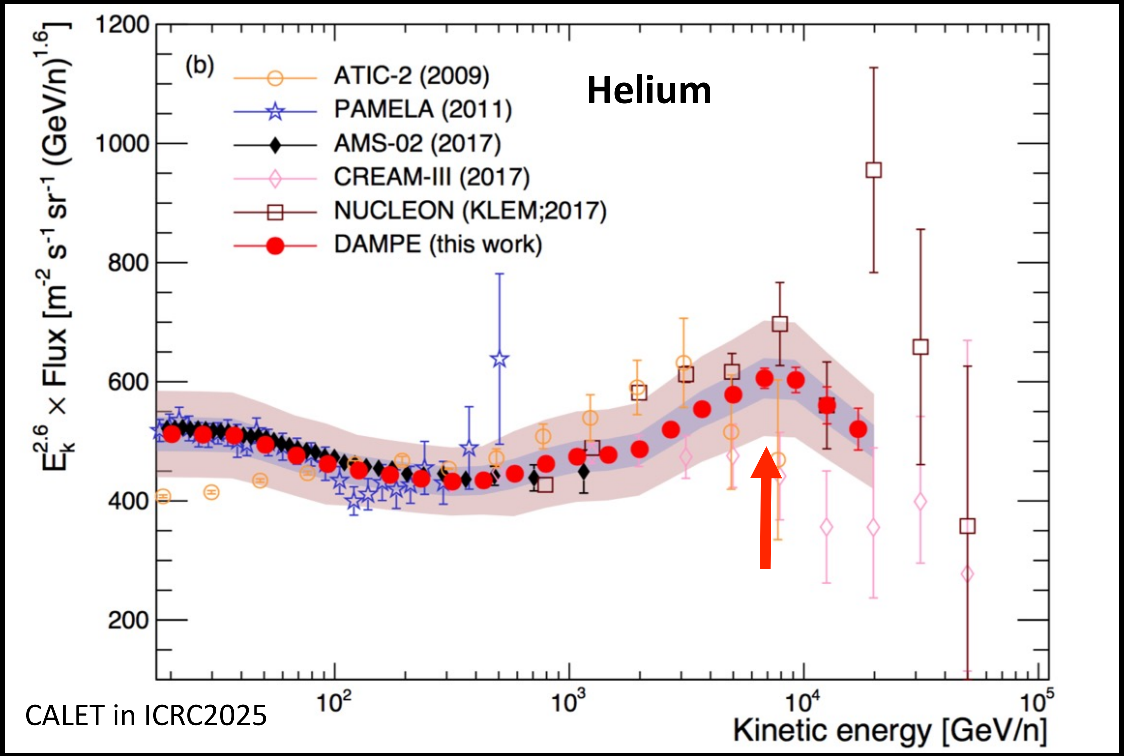


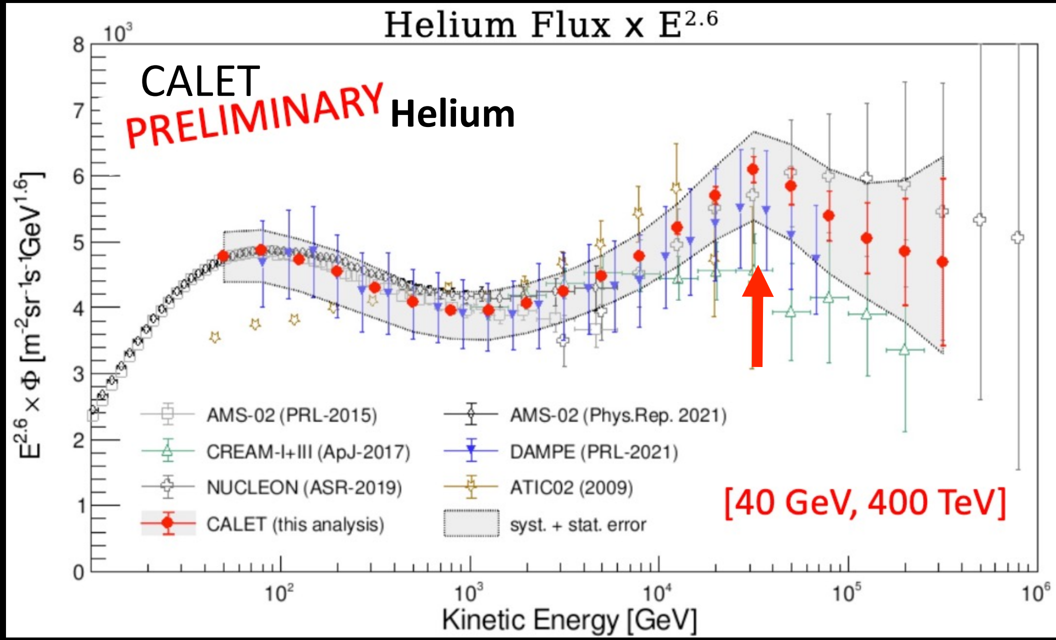
DAMPE, CALET, CREAM:
softening at ~10 TeV

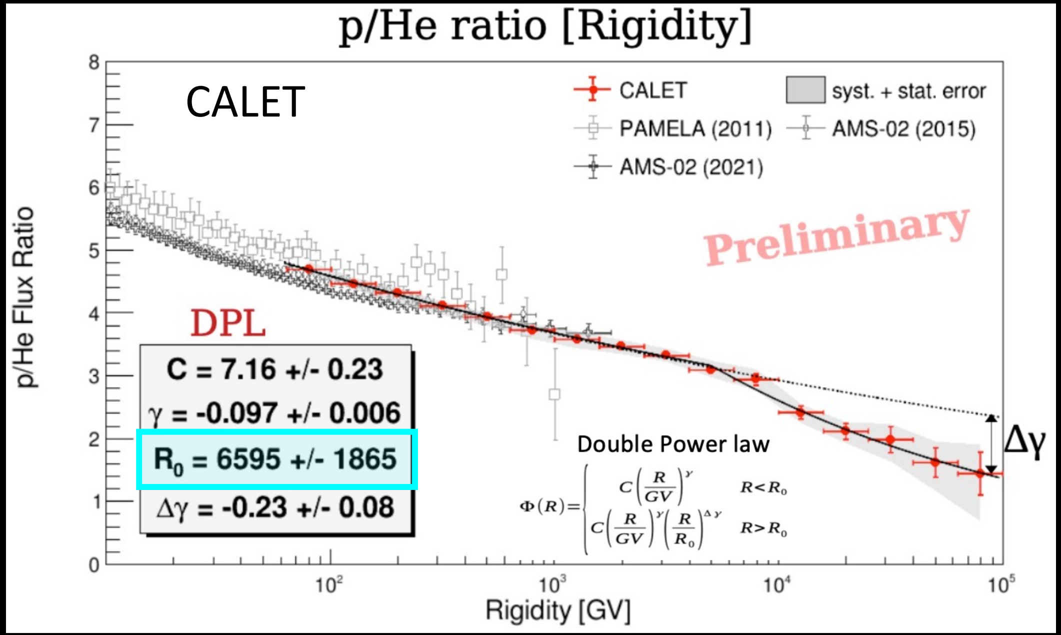
DAMPE:
"second break" at ~100 TeV

The direct measurement in space is touching the energy boundary of ground experiments.

Cosmic Helium: The Second Most Abundant Element



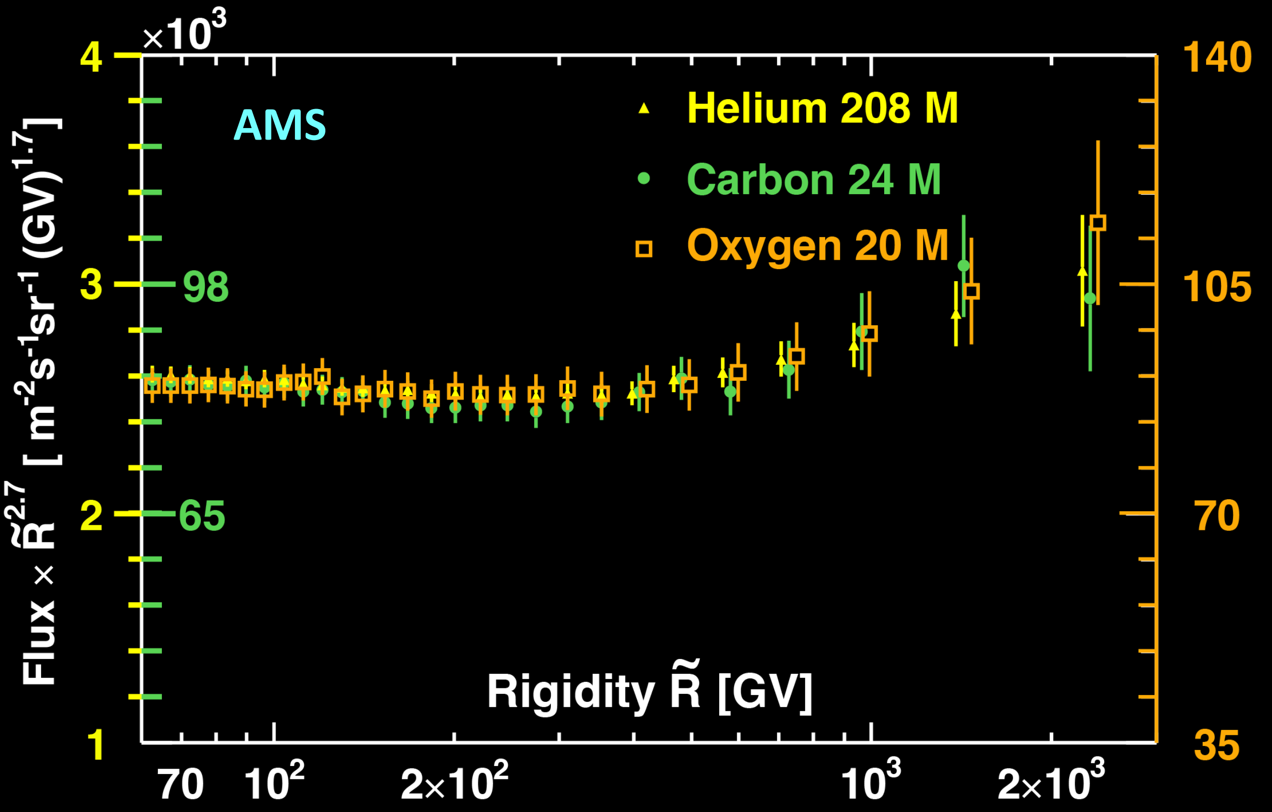


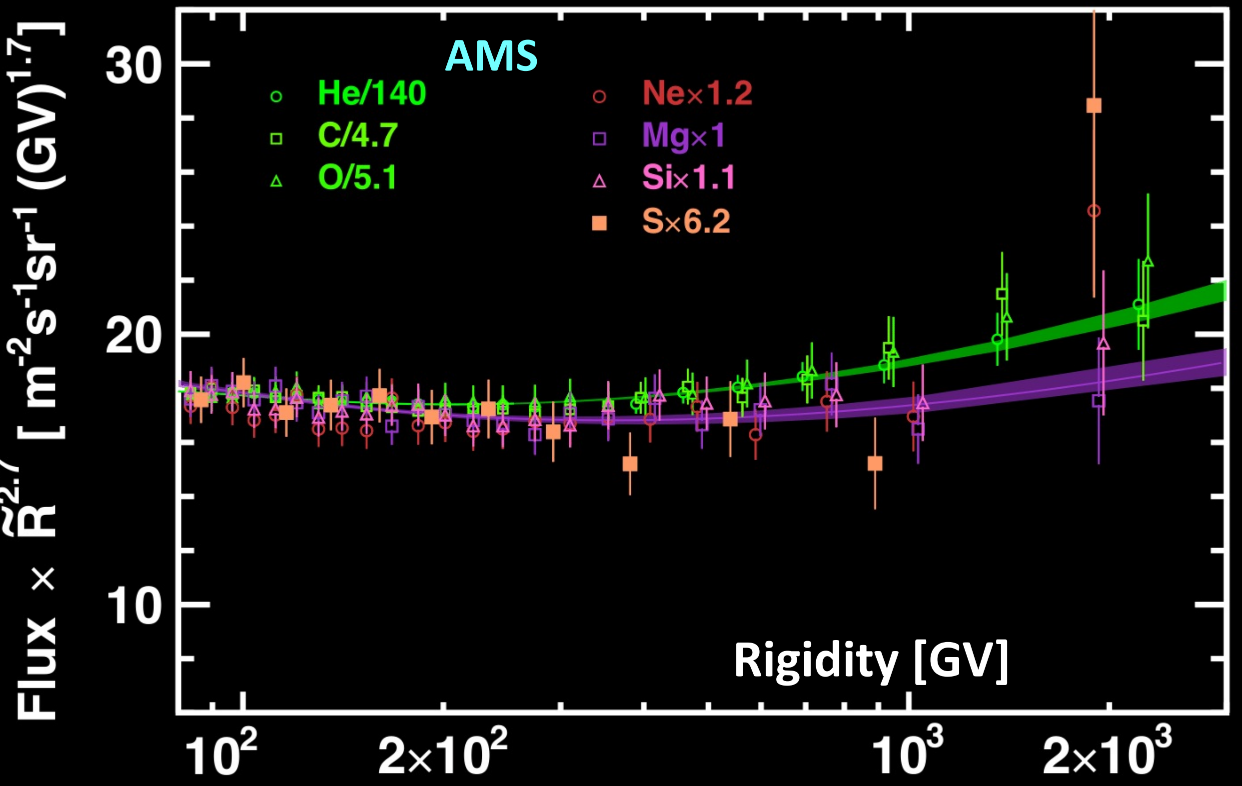


CALET, DAMPE (+ CREAM, NUCLEON):
Helium spectrum softening at ~34 TeV (~9 TeV/n),

CALET reported a faster decrease in p/He ratio beyond ~7 TV, i.e., proton spectrum softens more than helium.

Primary Cosmic Ray Nuclei



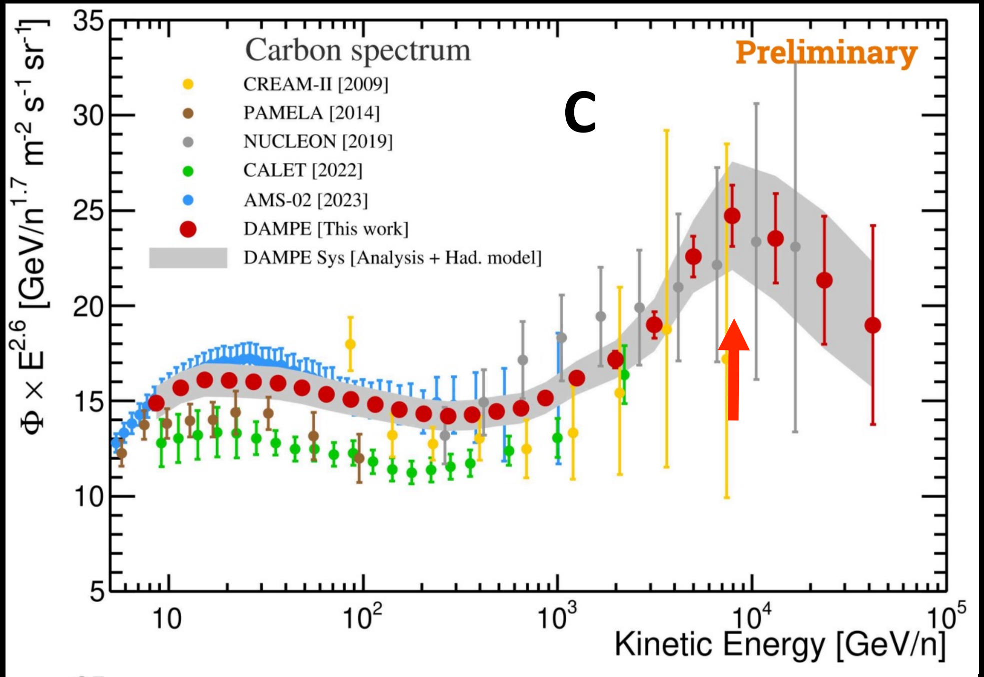


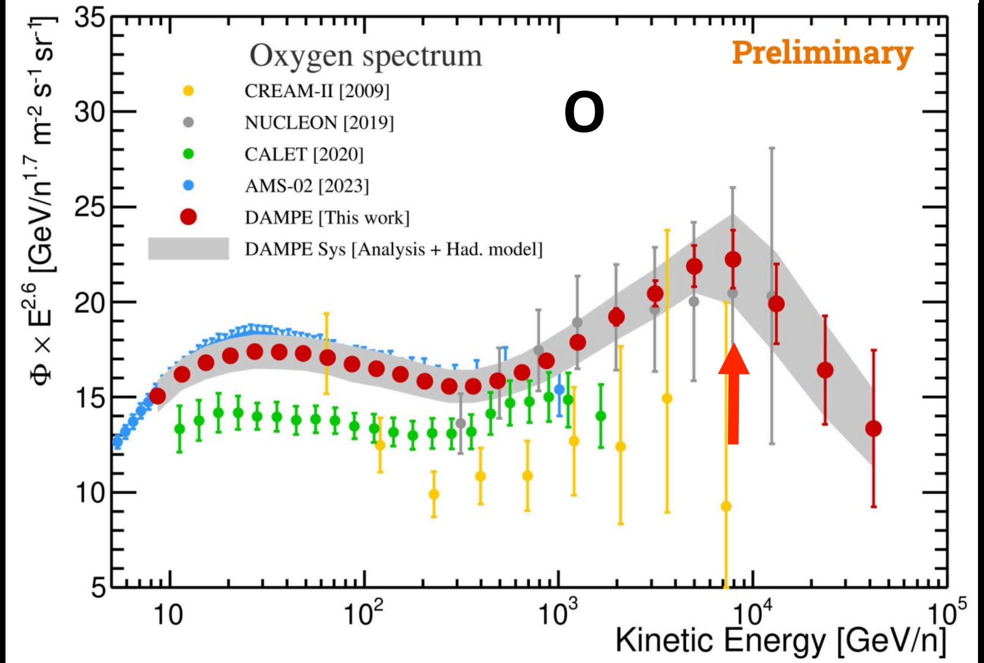
AMS: above 60 GV, the light primary cosmic rays He-C-O have identical rigidity (R=P/Z) dependence.

Heavier elements Ne-Mg-Si-S have identical rigidity dependence, but different than He-C-O

Primary cosmic rays have at least two classes

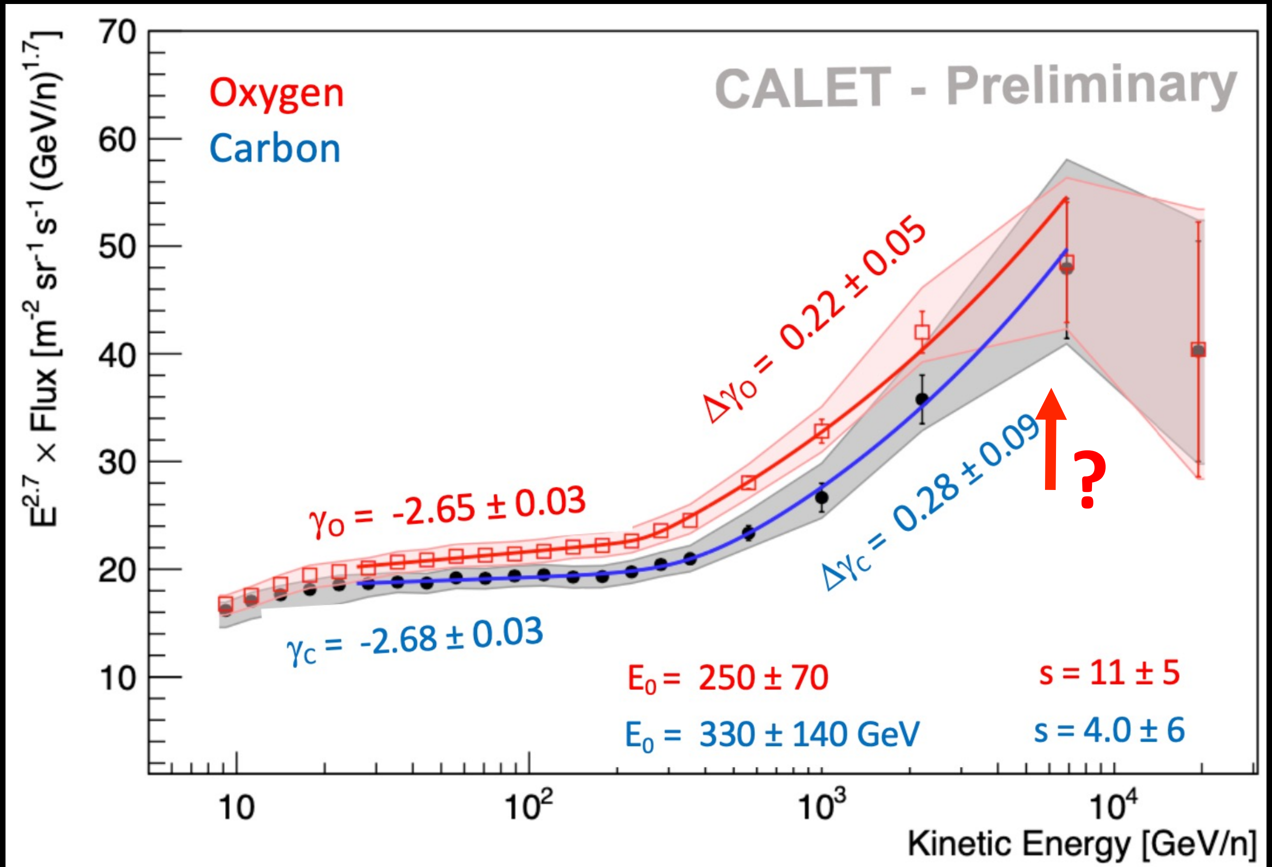
Carbon and Oxygen Spectral Feature at 10 TeV



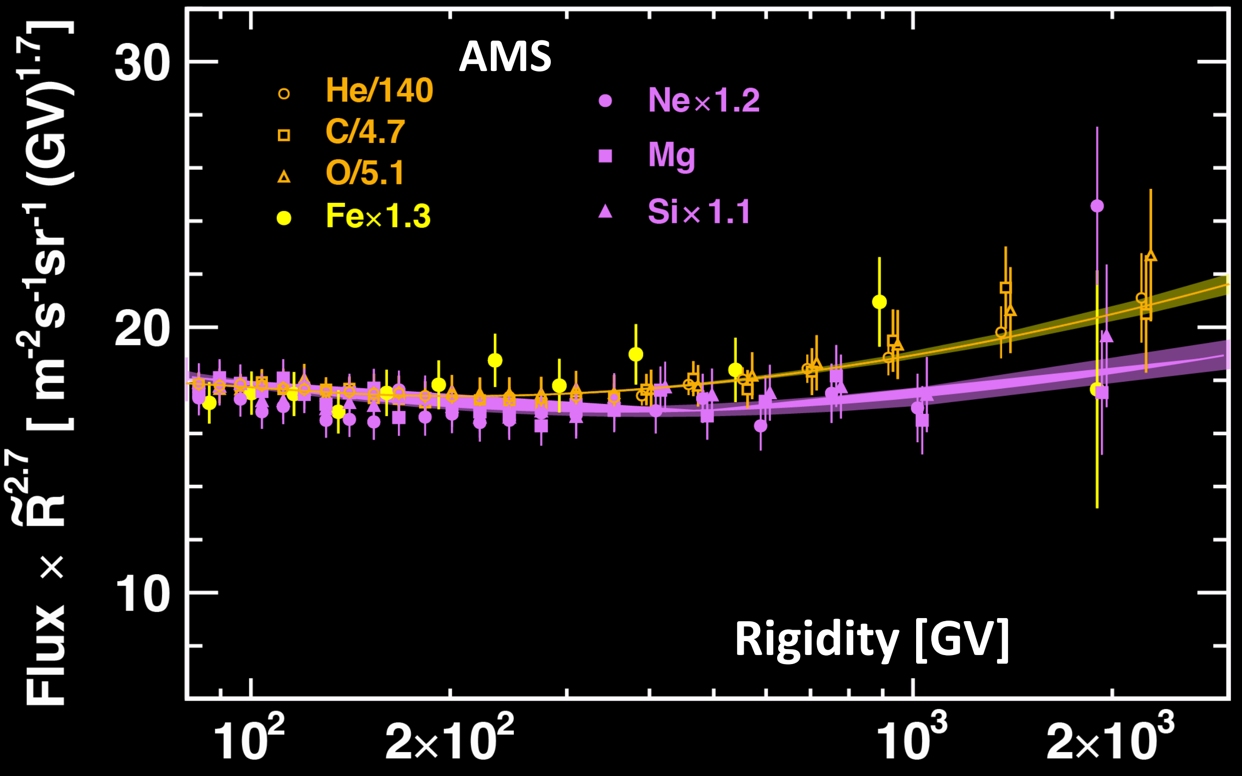


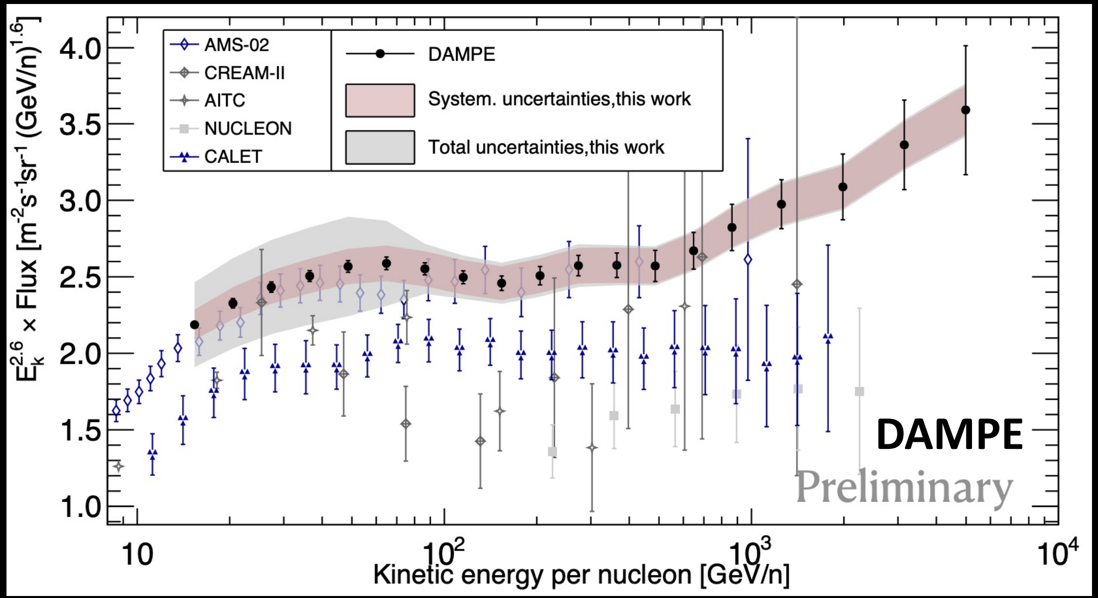
DAMPE reported results on C and O, which show softening at ~9 TeV/n, at the similar energy of proton and He softening.

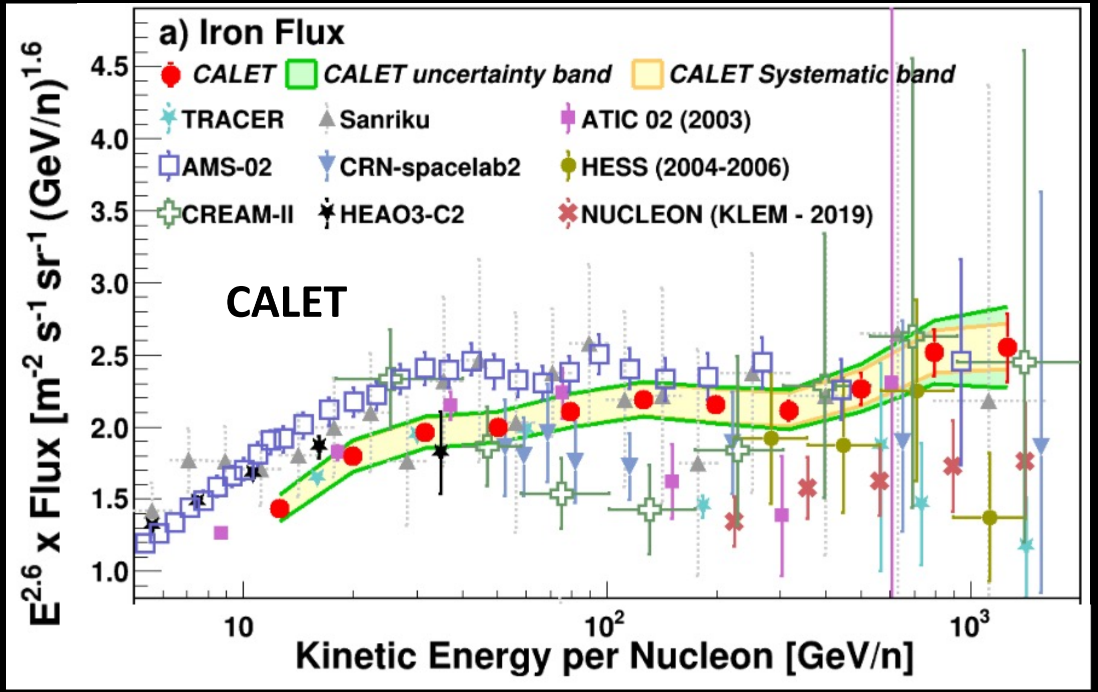
Awaiting the results from CALET.



The Heaviest side: Iron (Fe)







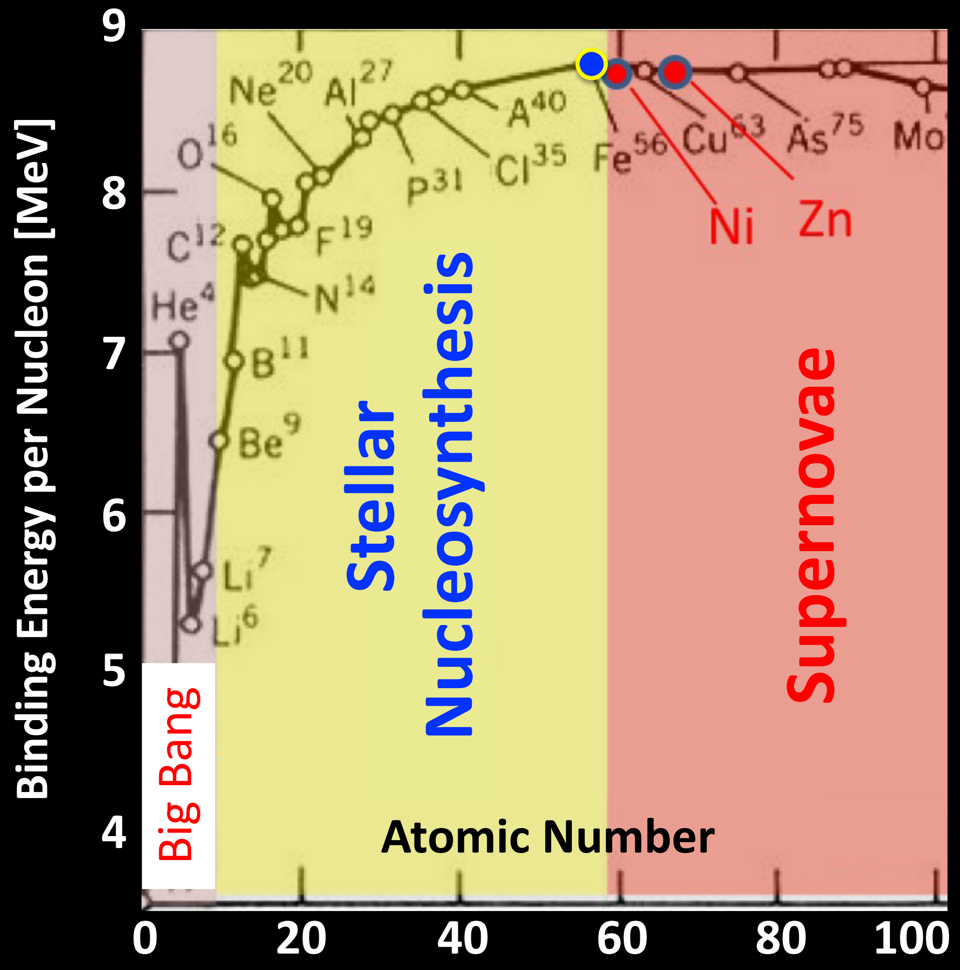
AMS found that, Unexpectedly,
Fe is in the He-C-O primary cosmic ray group,
not Ne-Mg-Si group.

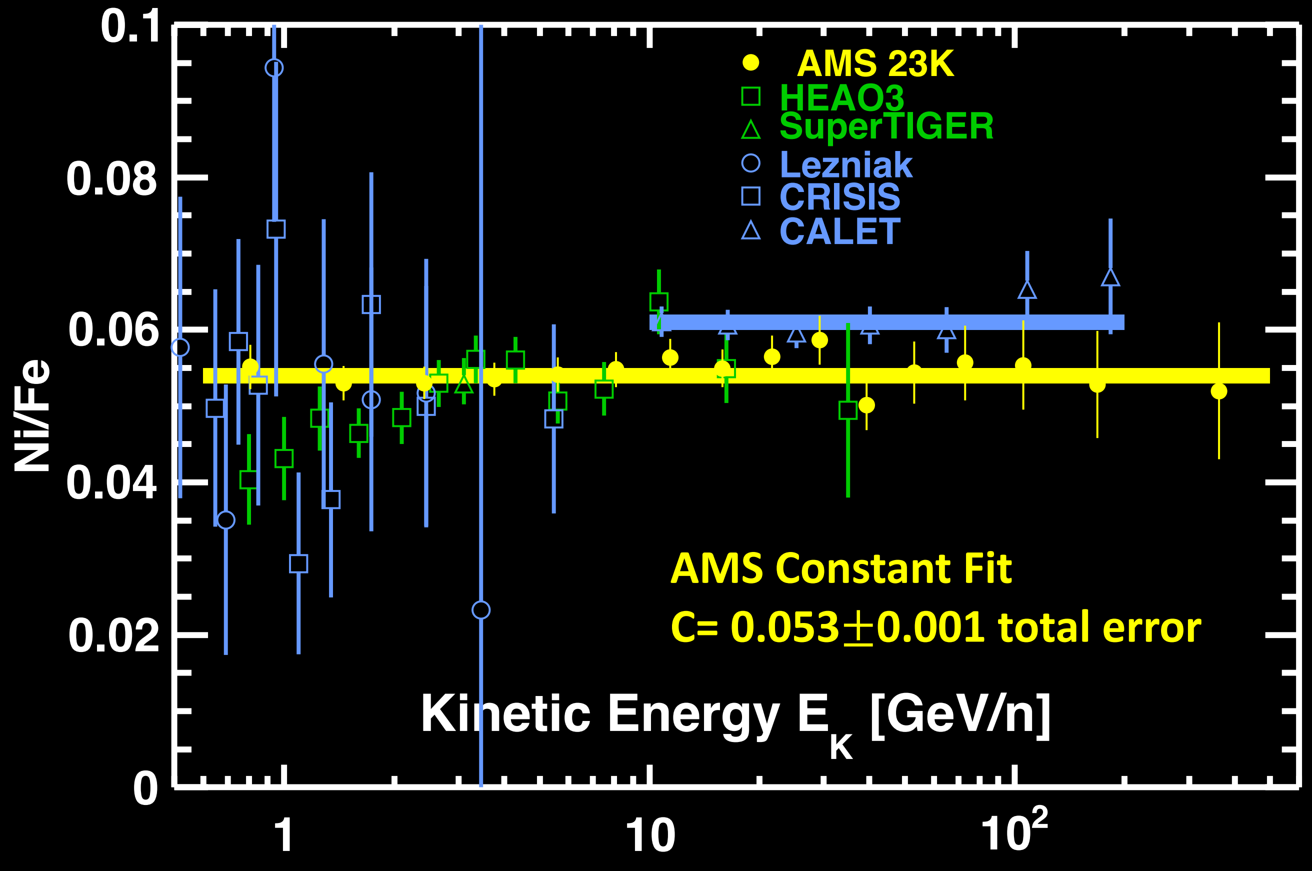
Hardening in Fe spectrum has been observed
by DAMPE and CALET.

The Heaviest side: Nickel

Iron is the heaviest element produced by Stellar Nucleosynthesis

Nickel is the lightest element created by supernovae.

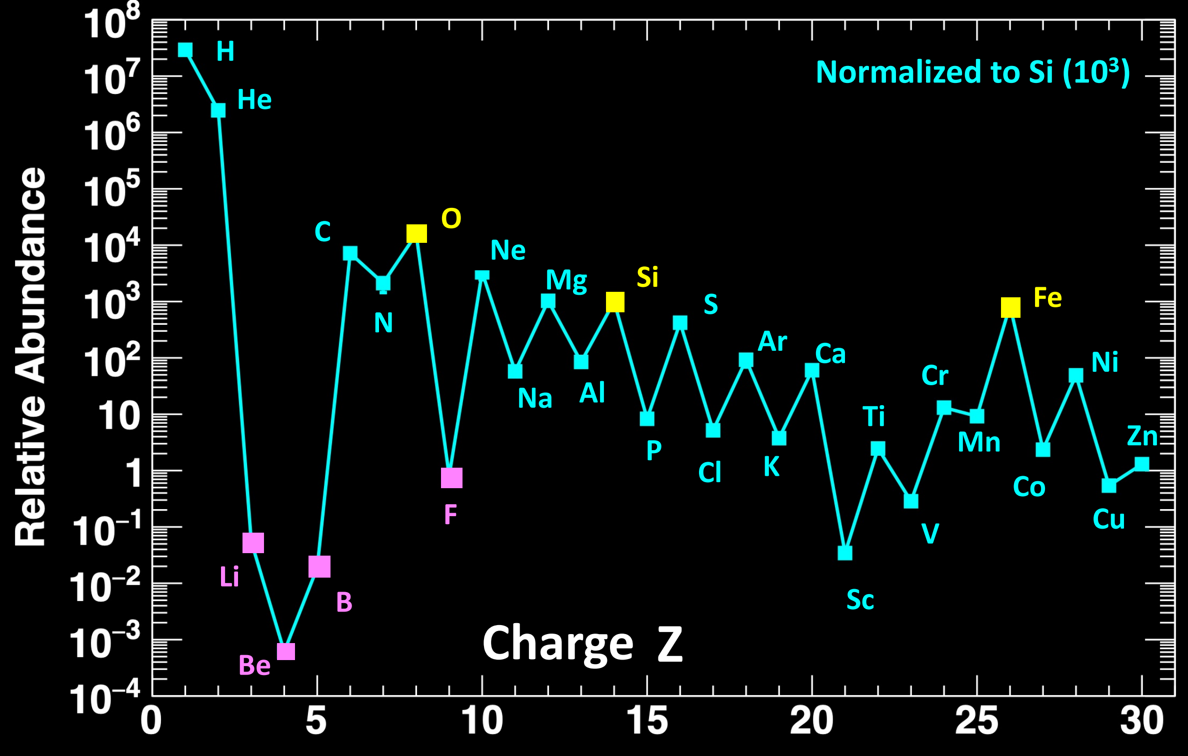




Current results show that the rigidity dependence of Ni is identical to Fe

Secondary Cosmic Ray Nuclei

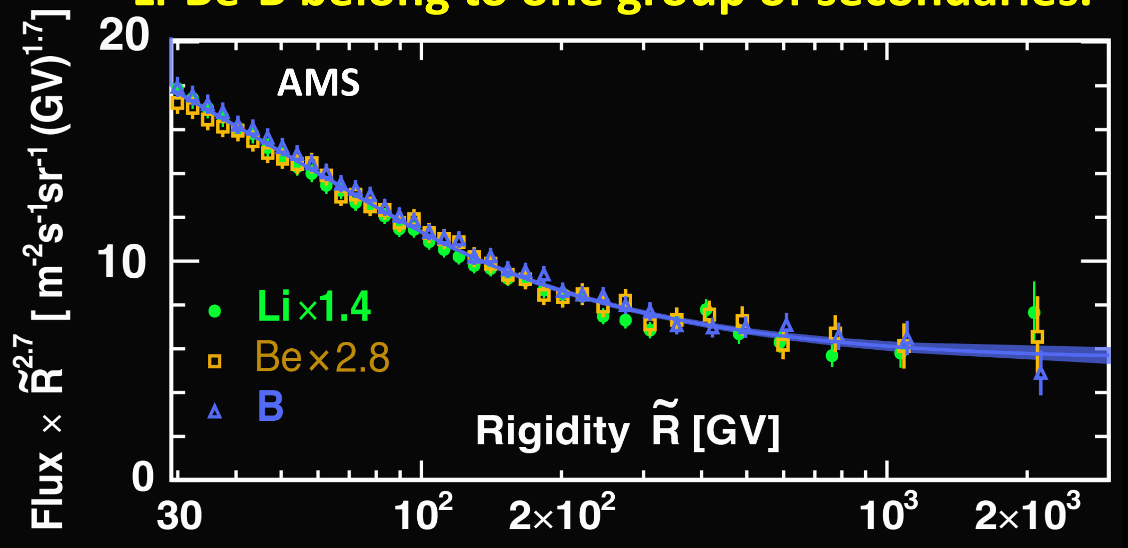
Abundance in the solar system
from the Sun wavelength analysis and meteorites

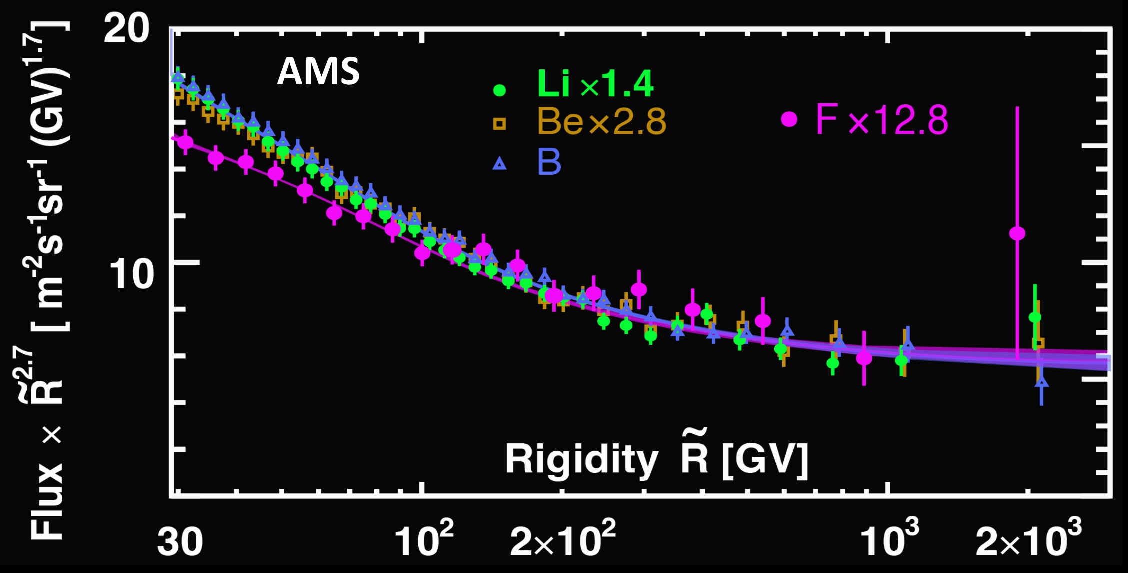


Li, Be, B, and F are secondary cosmic rays produced by the collision of Primaries with the interstellar medium.

Two groups of secondary cosmic nuclei: Li-Be-B, F

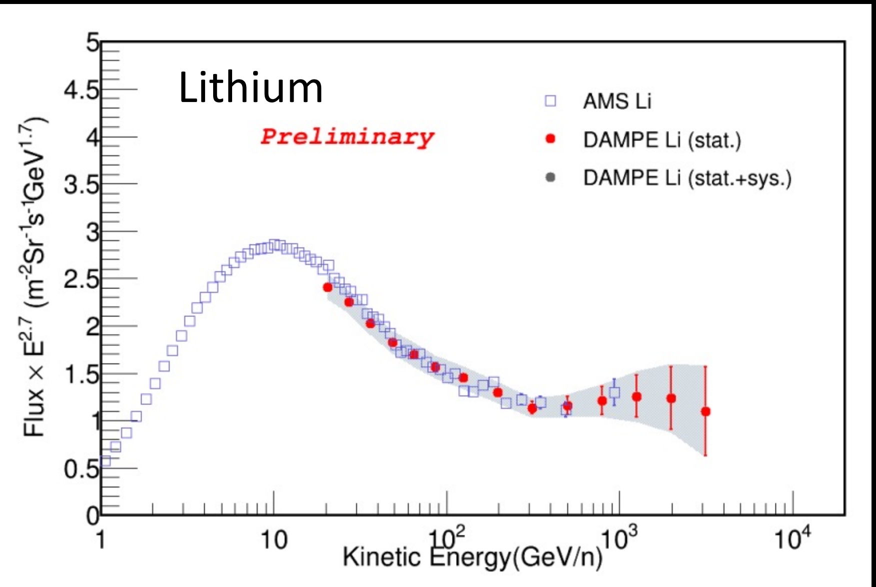
Li-Be-B belong to one group of secondaries.

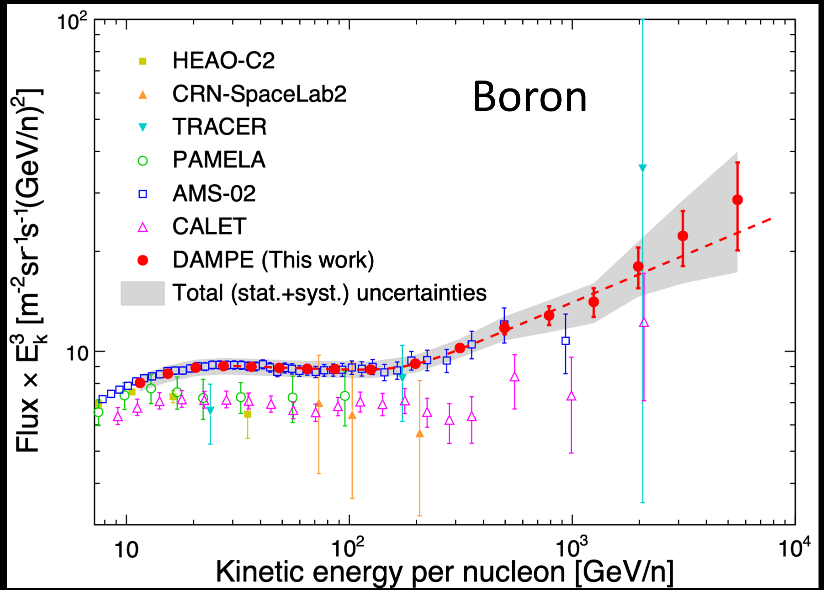


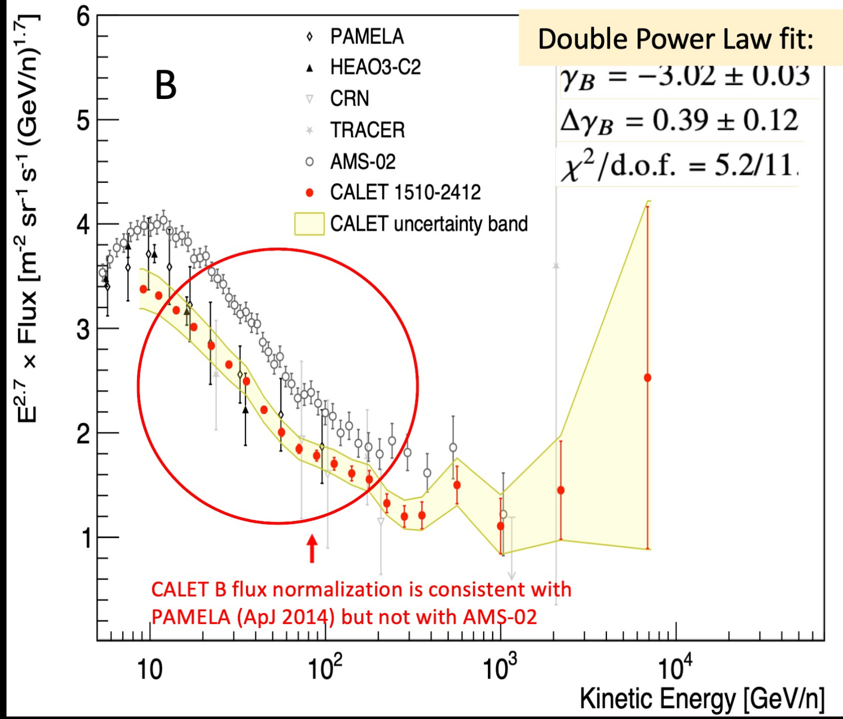


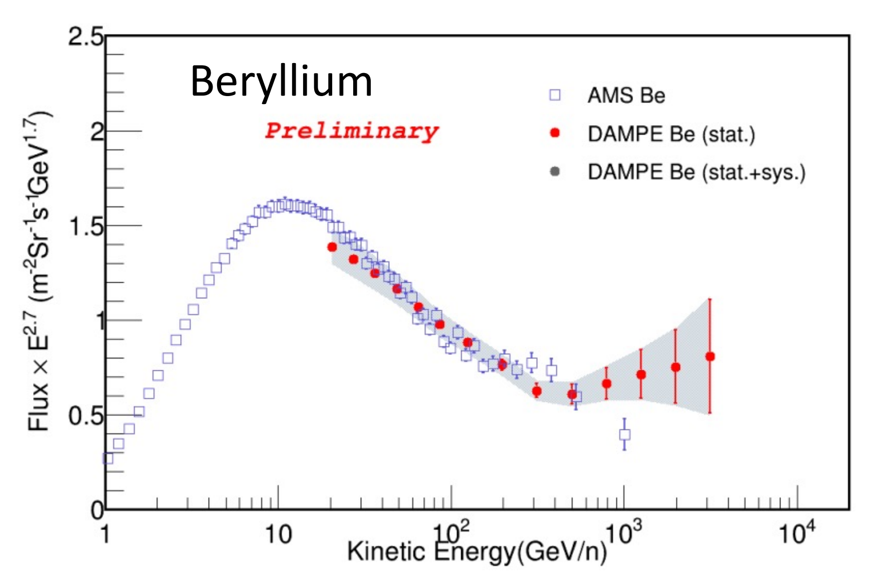
F(Z=9) belong to the second group of secondaries.

Secondary Cosmic Ray Nuclei









DAMPE and CALET also measured the Li, Be, and B spectra.

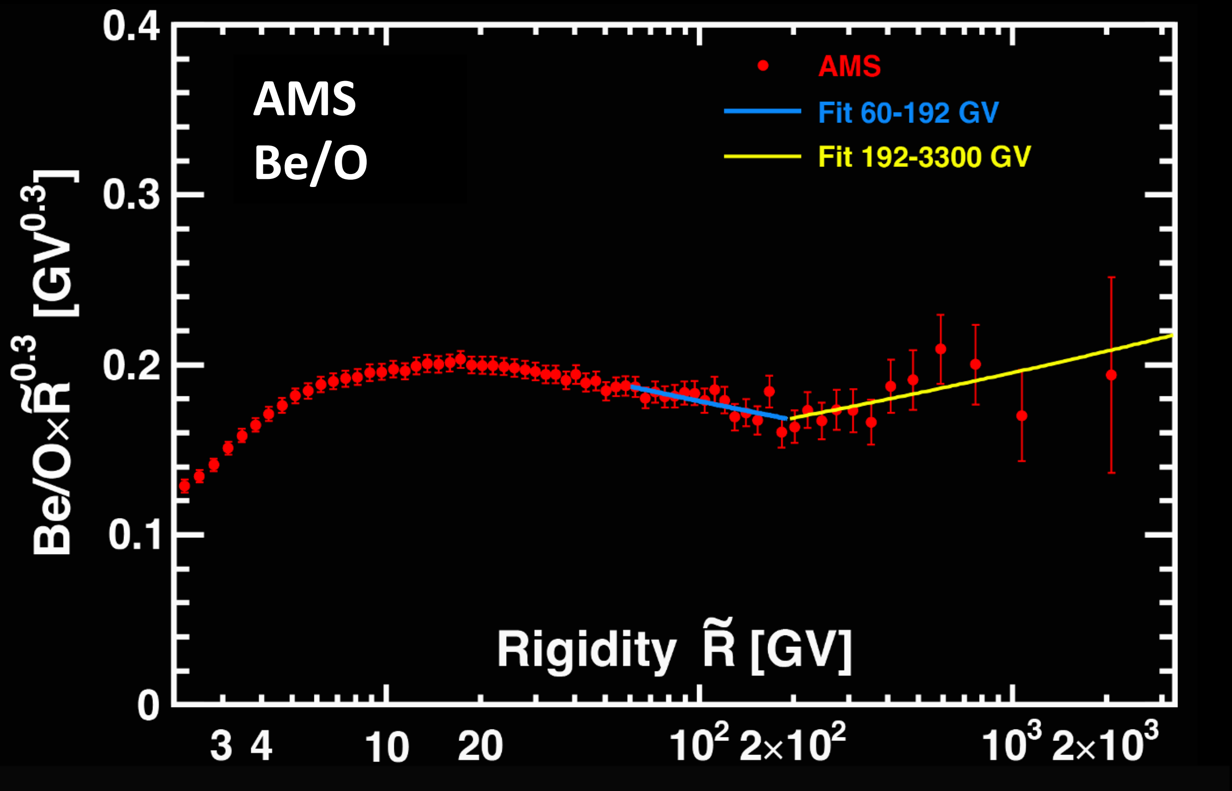
The hardening in secondary nuclei are confirmed.

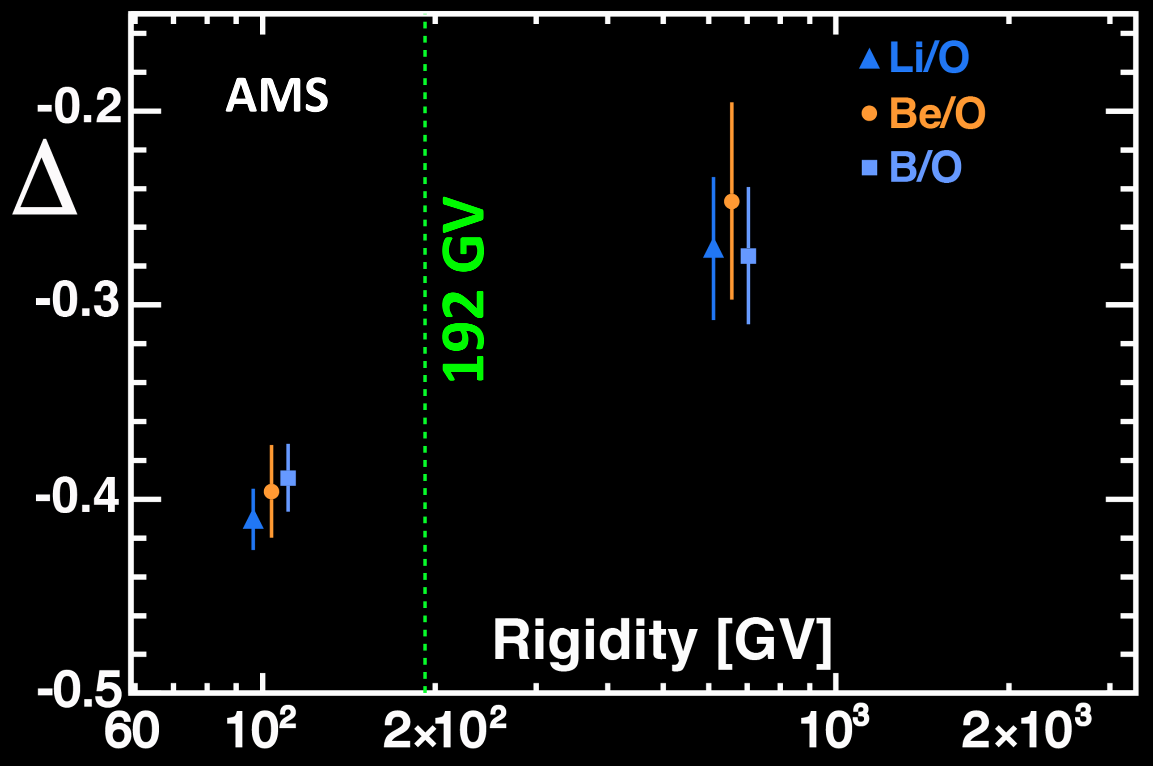
Possible origins of the spectral hardening:

(1) Source --> same hardening in secondaries and primaries

(2) Propagation --> twice hardening in secondaries as in primaries

Secondary-to-Primary Flux Ratio

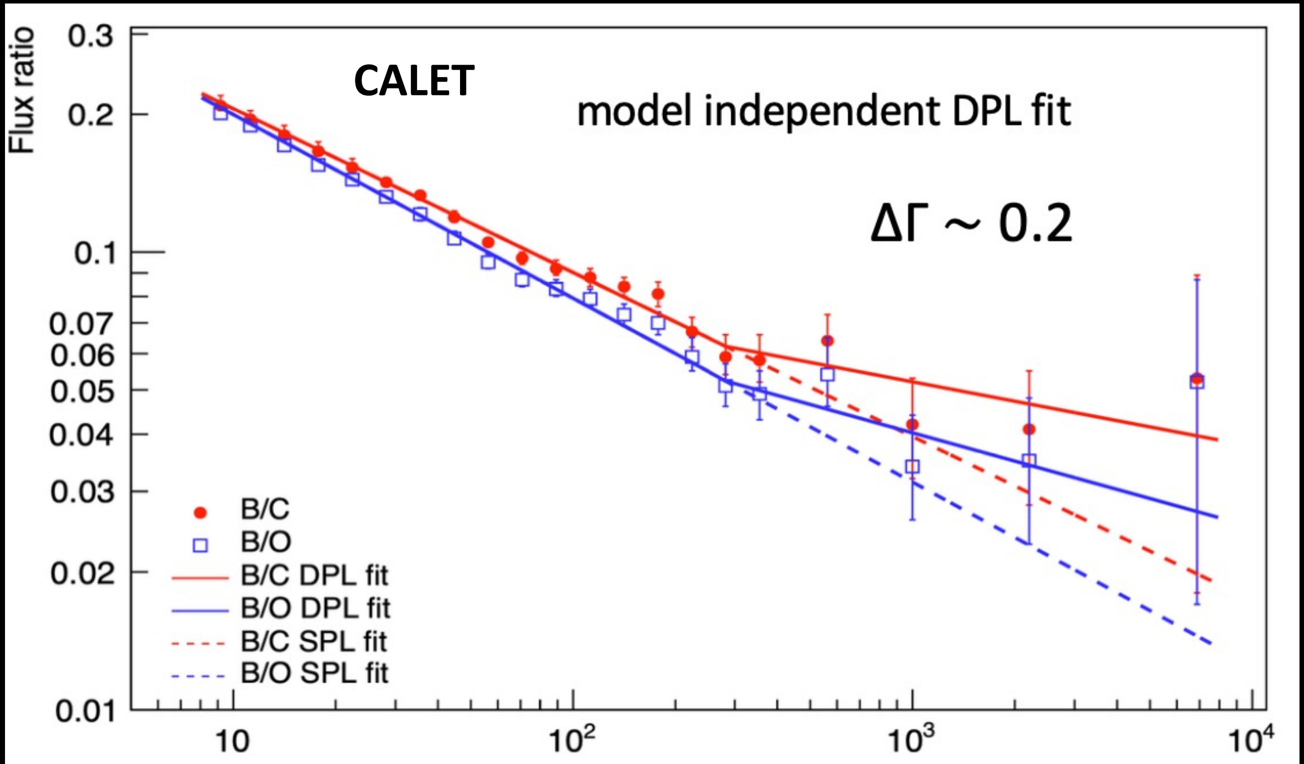


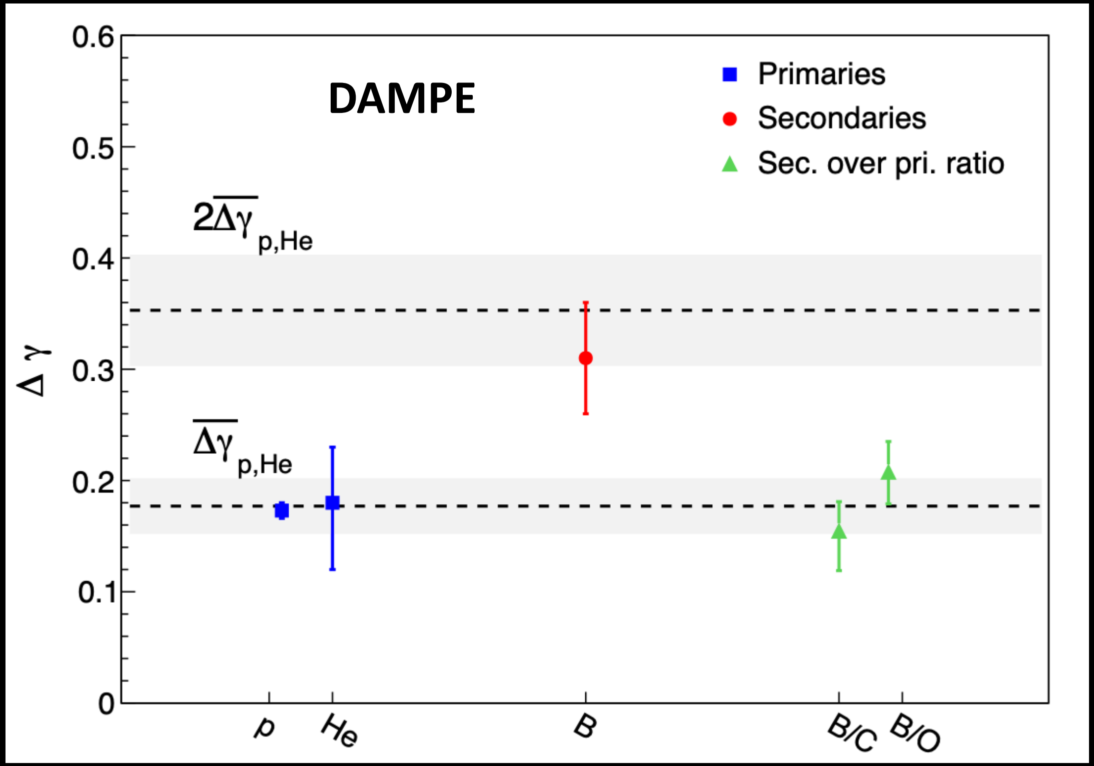


Δ in two rigidity intervals (60 – 192 GV and 192 – 3300 GV) exhibit an average hardening of $\Delta_{192-3300\,GV} - \Delta_{60-192\,GV} = 0.11 \pm 0.02$ (5.5σ effect).

Above ~200 GV secondary cosmic rays harden twice as much as primaries.
This strongly supports that the spectral hardening is related to propagation in the Galaxy.

Secondary-to-Primary Flux Ratio



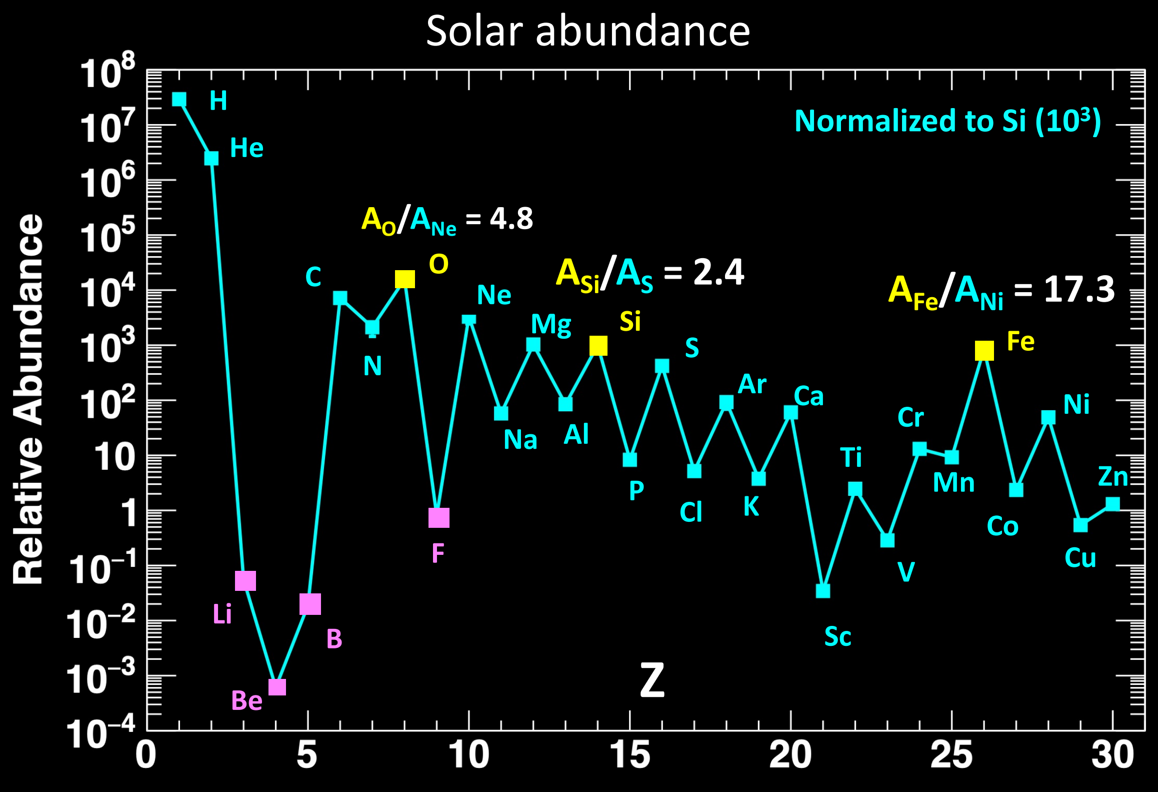


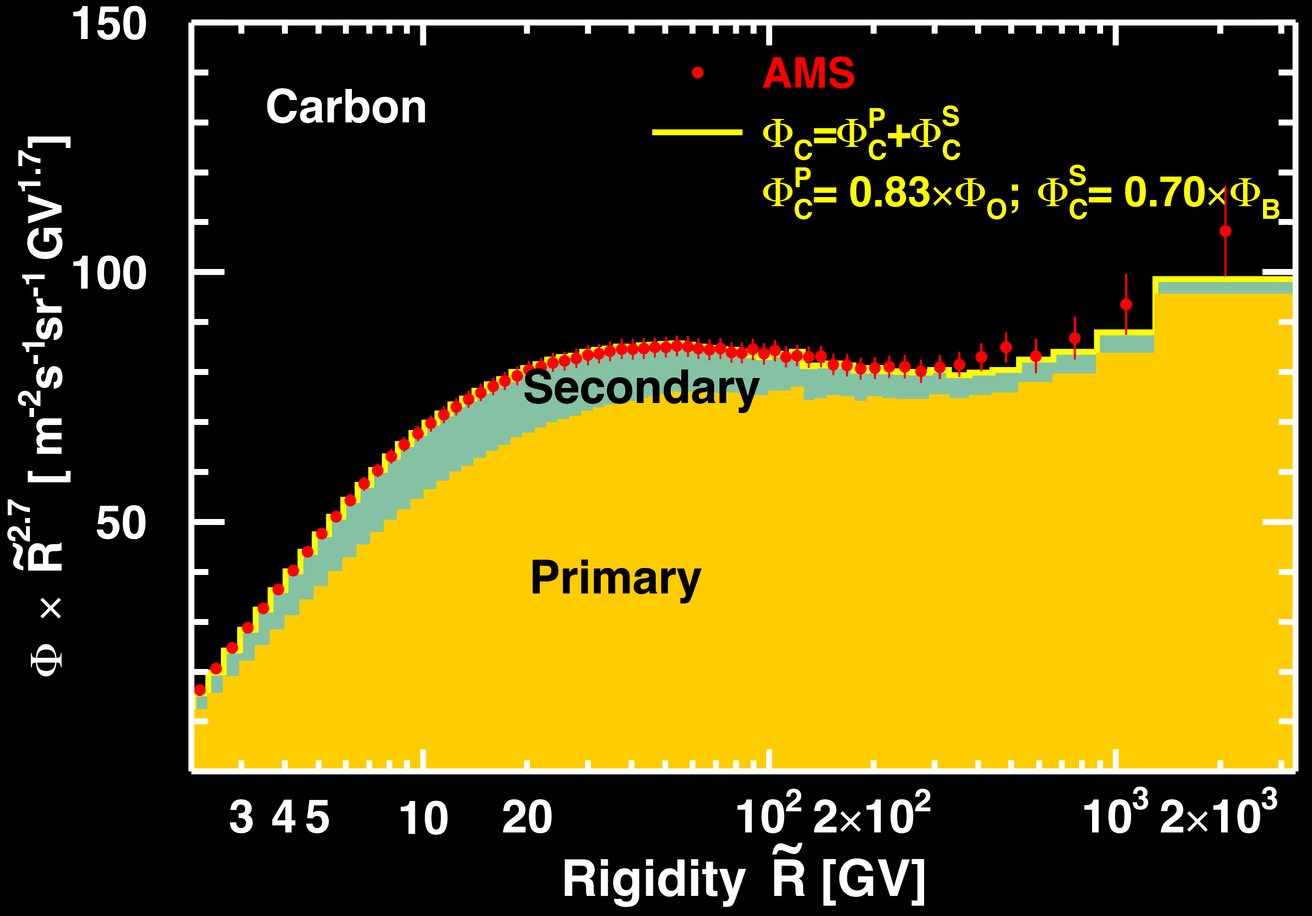
CALET observed that secondary-to-primary ratio (B/C and B/O) hardens at ~200 GeV/n.

DAMPE observed that secondary cosmic rays harden twice as much as primaries.

These results also support that the hardening at ~200 GV is related to propagation in the Galaxy.

The Element Abundance at Cosmic Rays Source



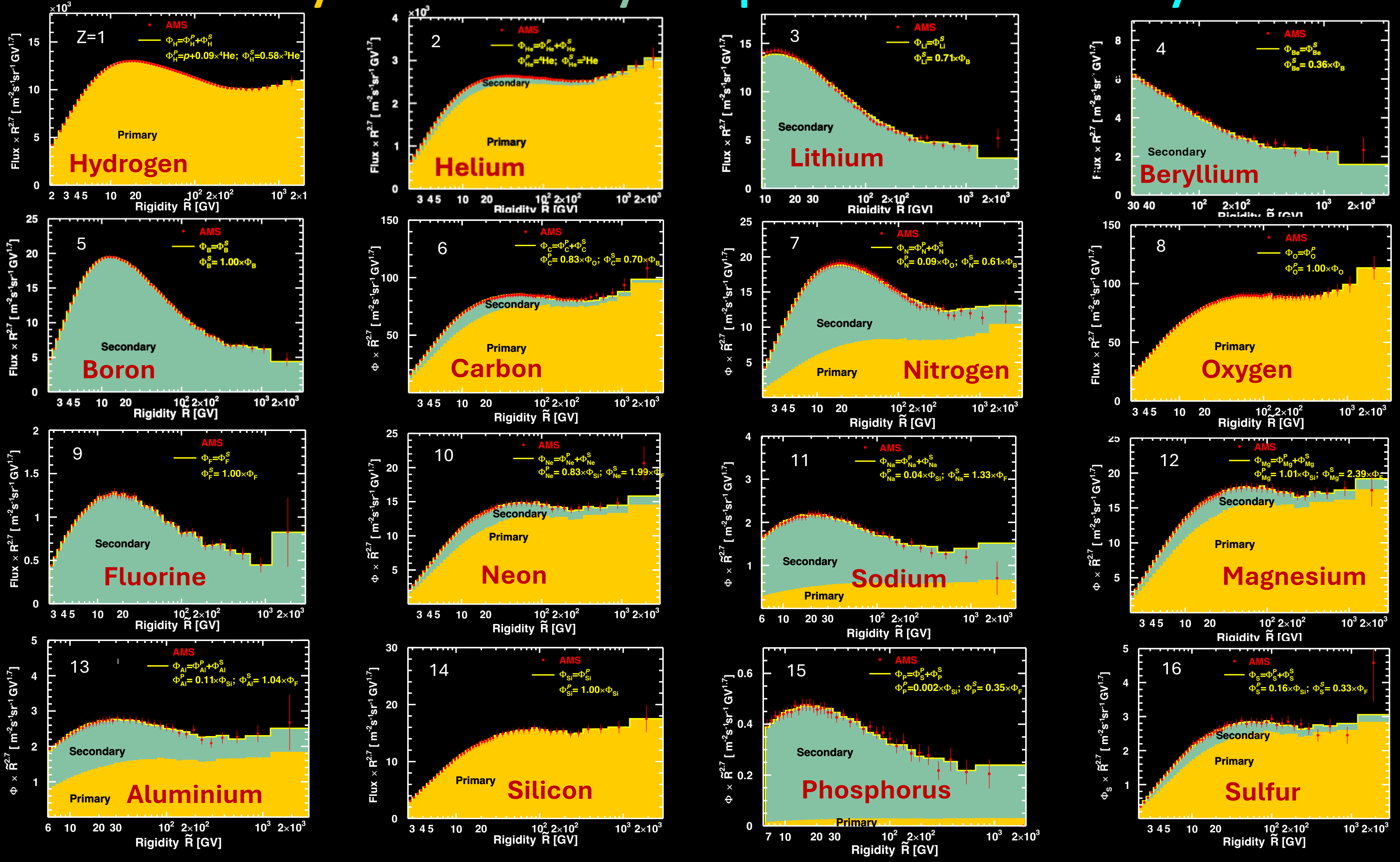


Characteristic primary cosmic rays: O, Si, and Fe

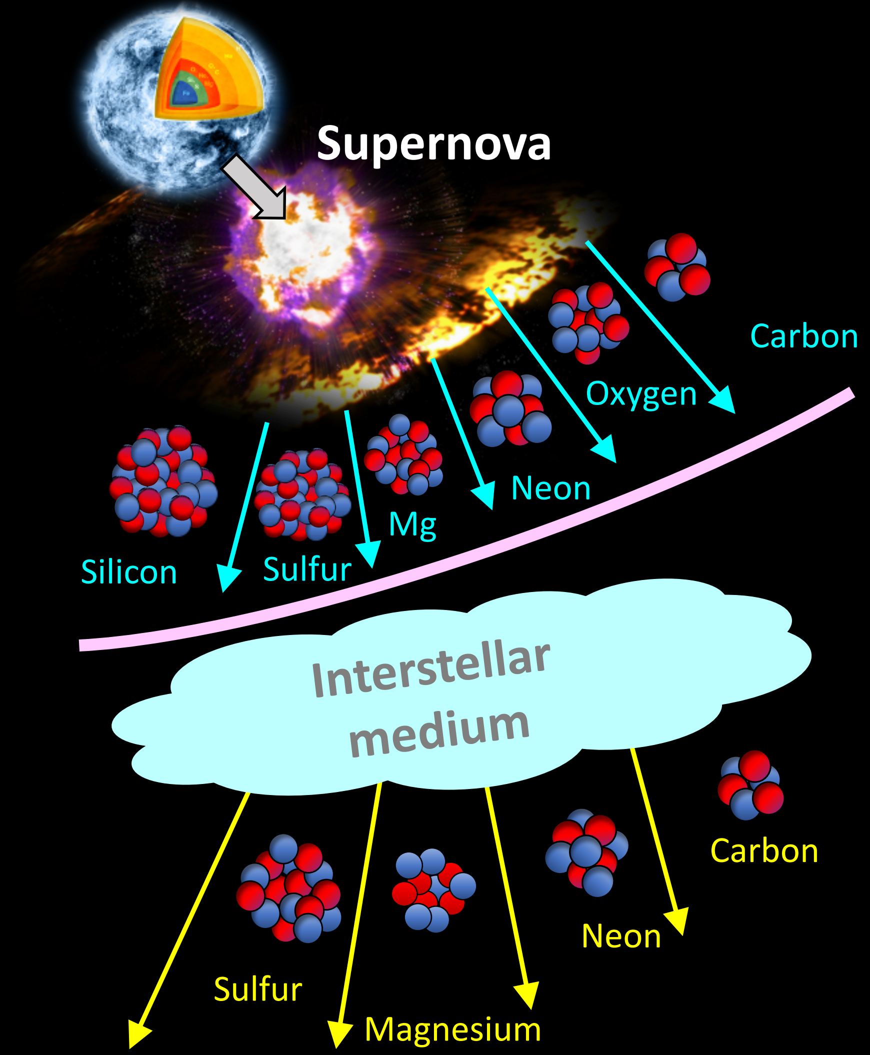
Characteristic secondary cosmic rays: Li, Be, B, F

C/O at source = 0.83

Primary and Secondary Composition of Cosmic Rays



AMS Model-independent measurements of the relative abundances at the source (before cosmic ray propagation)



Abundance Ratio at the Source

Φ_C / Φ_O	0.83 ± 0.025
Φ_N / Φ_O	0.09 ± 0.002
Φ_{Ne} / Φ_{Si}	0.83 ± 0.025
Φ_{Mg} / Φ_{Si}	1.01 ± 0.025
Φ_{Na} / Φ_{Si}	0.038 ± 0.003
Φ_{Al} / Φ_{Si}	0.105 ± 0.004
Φ_S / Φ_{Si}	0.16 ± 0.006
Φ_{Ar} / Φ_{Si}	0.021 ± 0.002
Φ_{Ca} / Φ_{Si}	0.076 ± 0.003

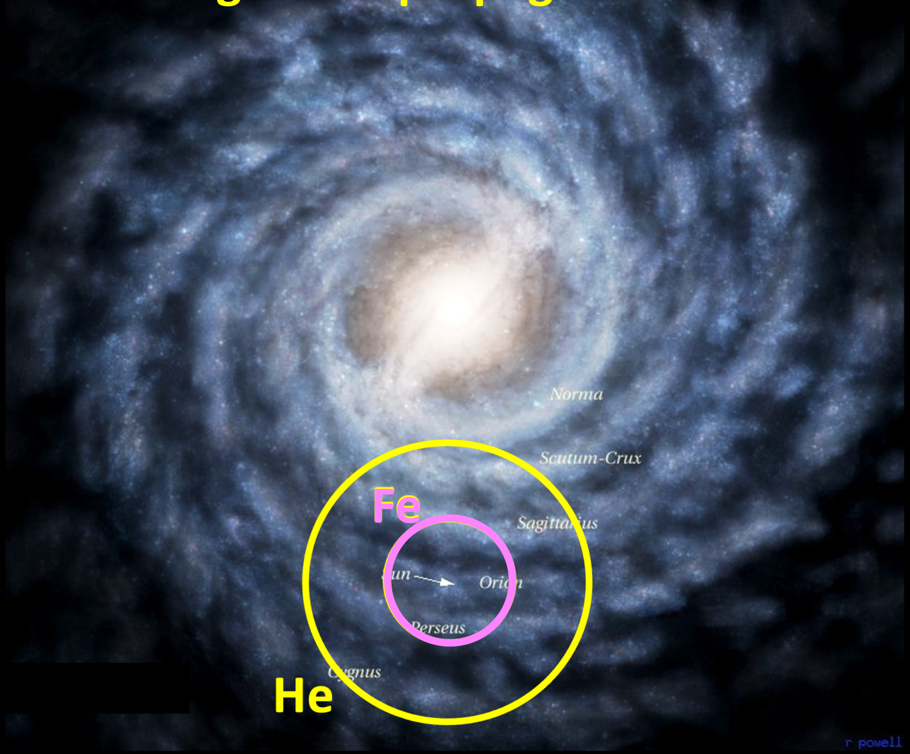
Earlier measurements are from HEAO, ULYSSES, Voyager-1, ACE/CRIS

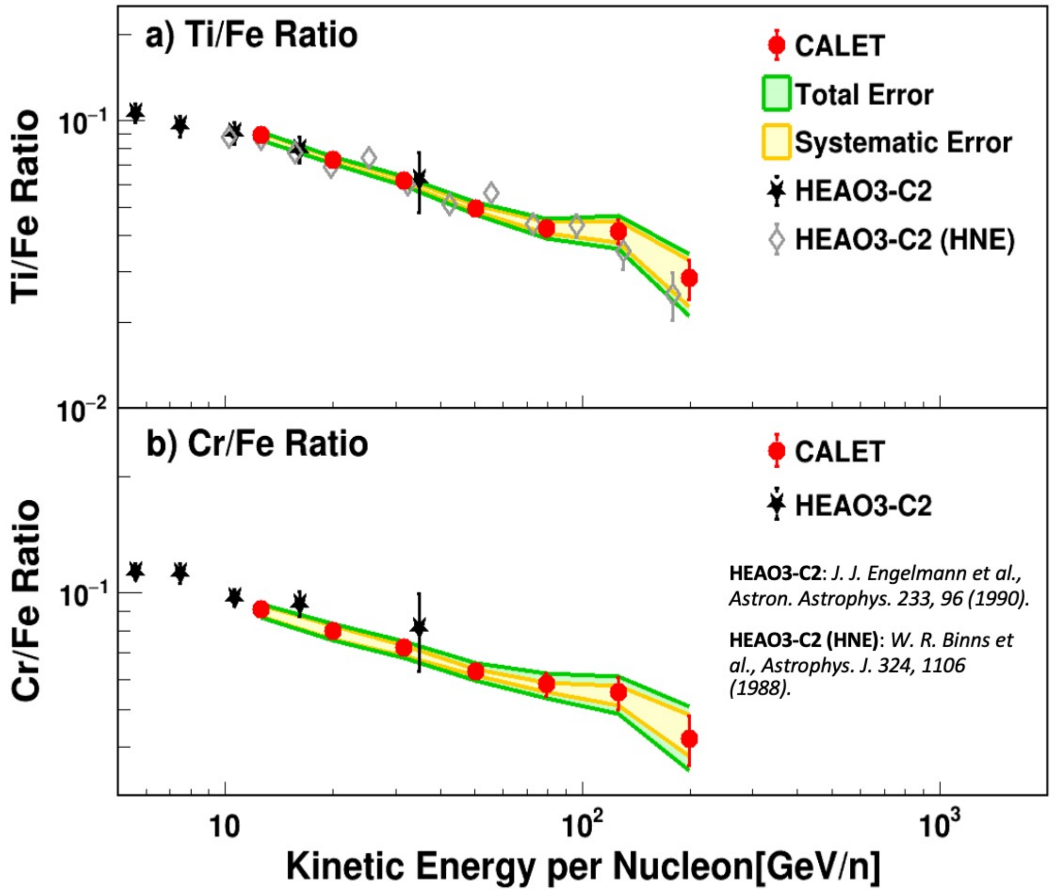
Sub-Iron group (Z=21 ~ 25)

Sub-Iron group (Sc, Ti, V, Cr, Mn) contains secondaries from Fe interaction with interstellar medium.

Secondary components of Sub-Iron are produced in the closer part of the Galaxy

Measuring their fluxes are important for the understanding of the propagation of heavier nuclei.

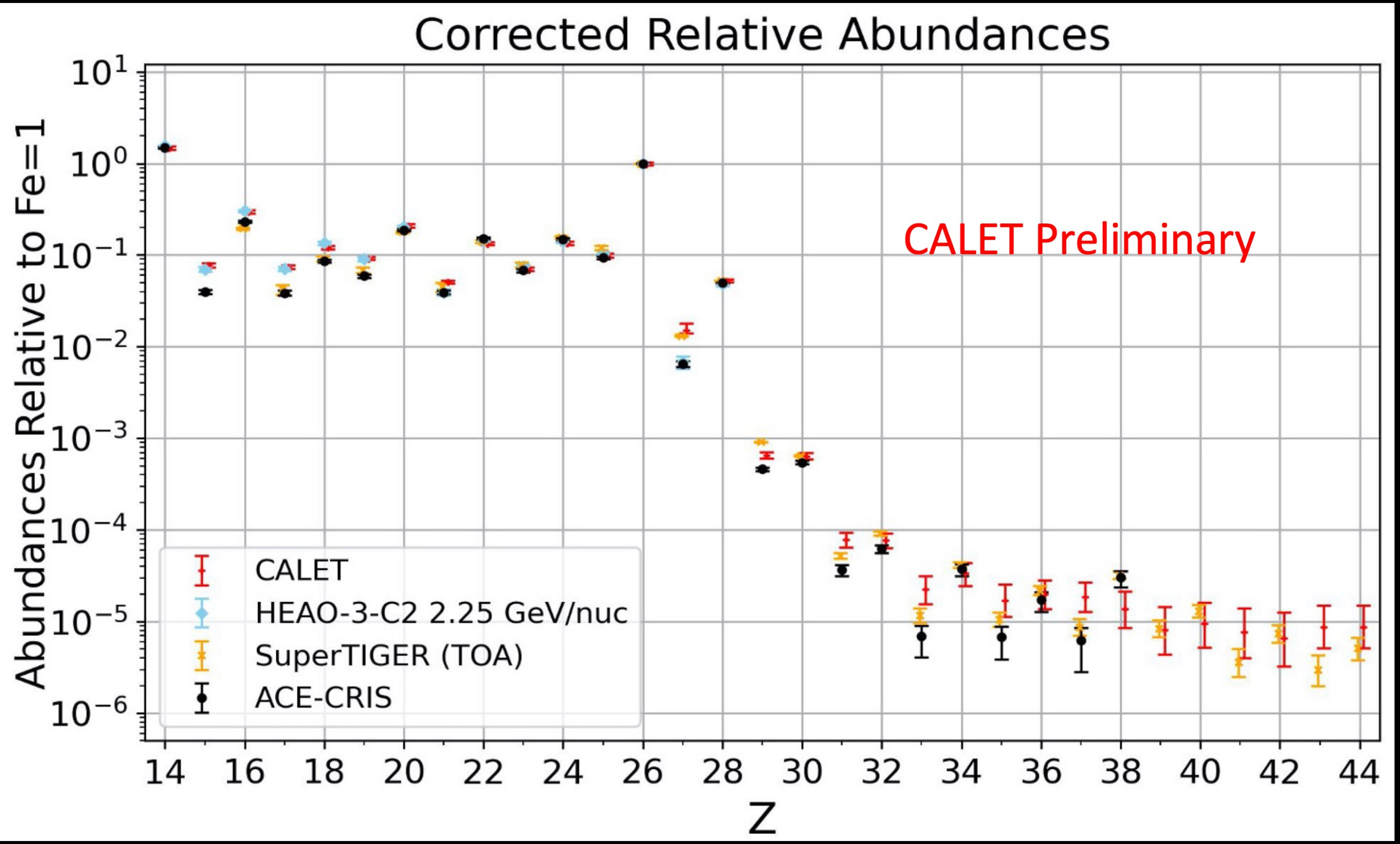


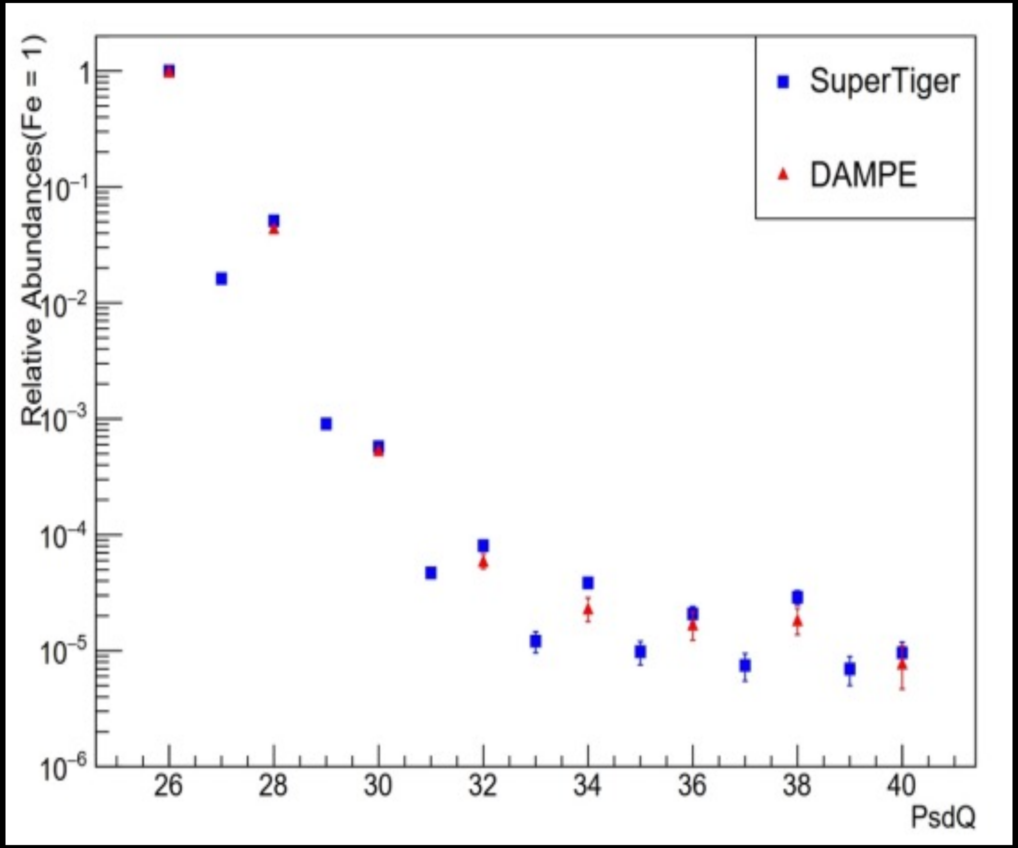


CALET and HEAO results on Ti and Cr show consistent energy dependence.

AMS will provide precise individual measurement of sub-Iron nuclei in the coming years.

Ultra Heavy Nuclei Abundance





CALET and DAMPE results on the abundance of Z>28 nuclei agree with earlier measurements from ACE-CRIS and SuperTiger.

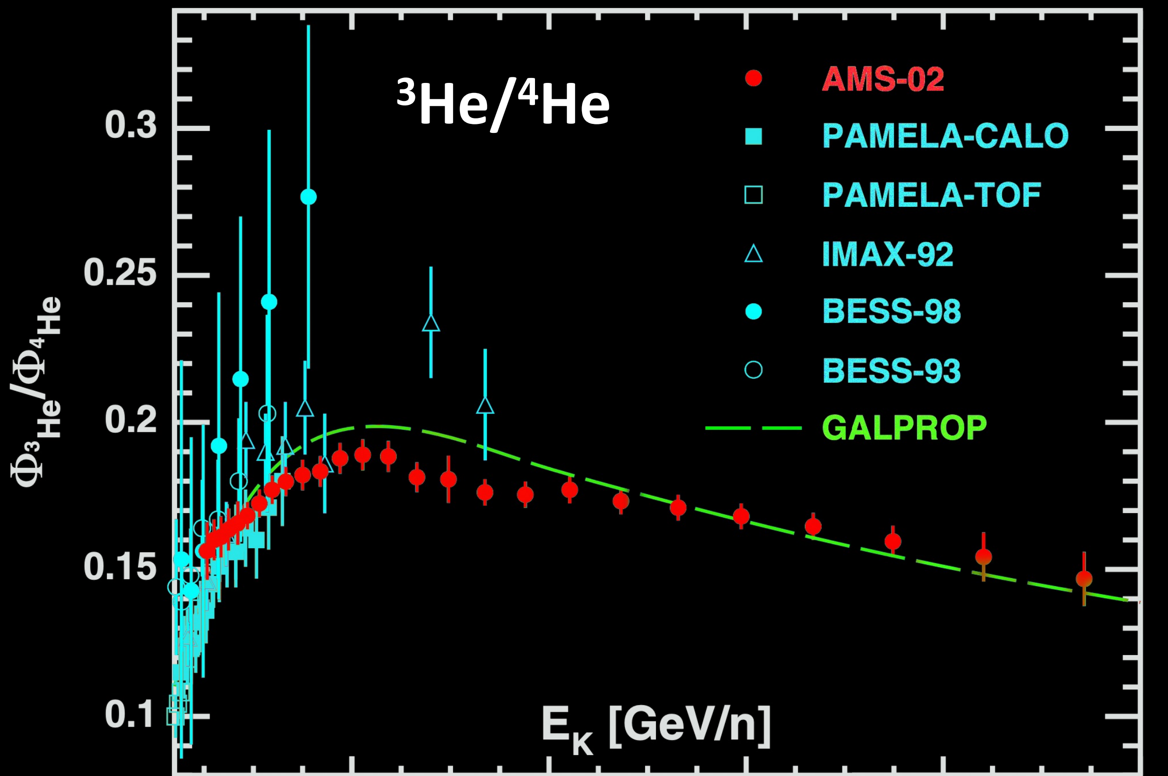
Note these experiments cover different energy range.

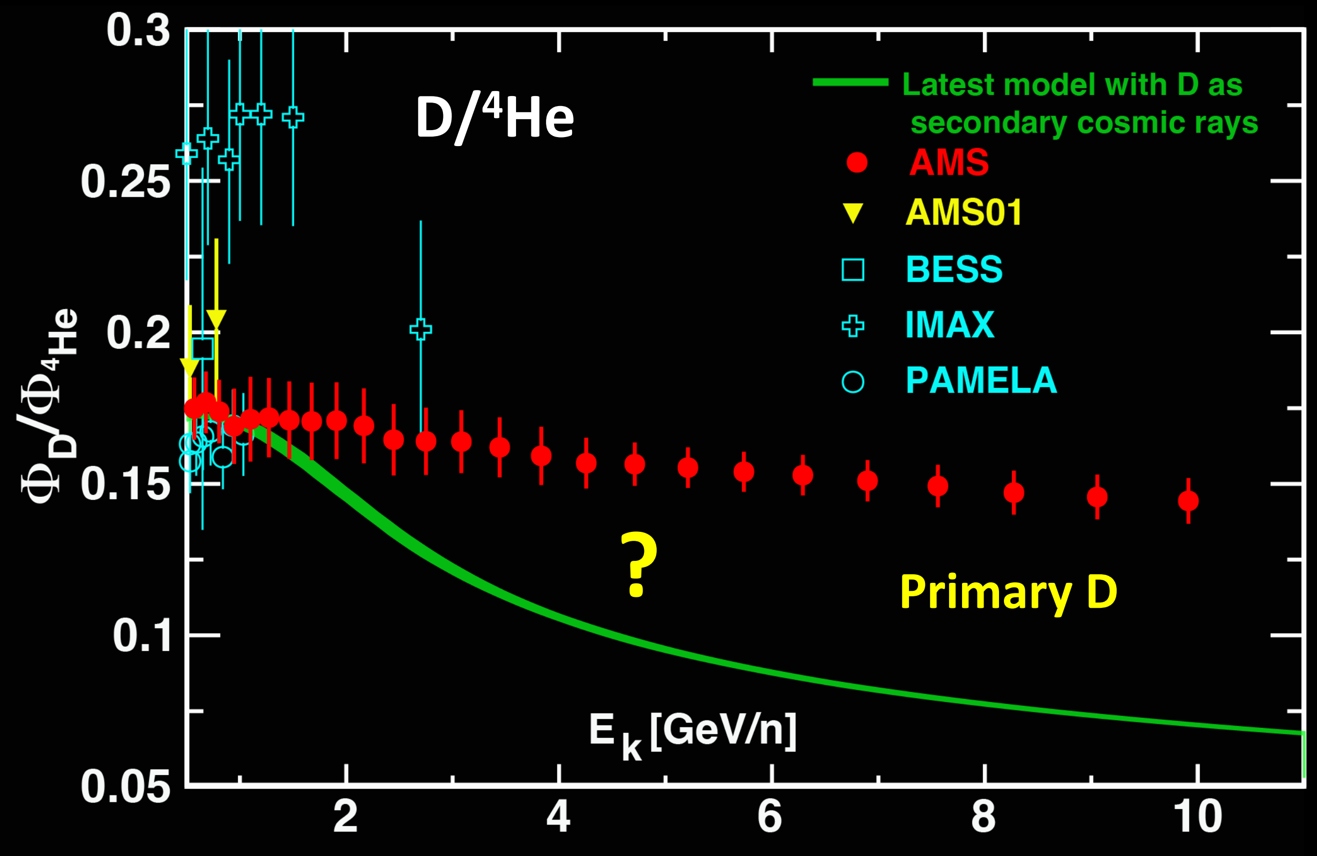
Future experiments: Energy spectrum of ultra heavy nuclei.

Cosmic Isotopes: Deuteron

D and ^{3}He are considered to be secondary cosmic rays.

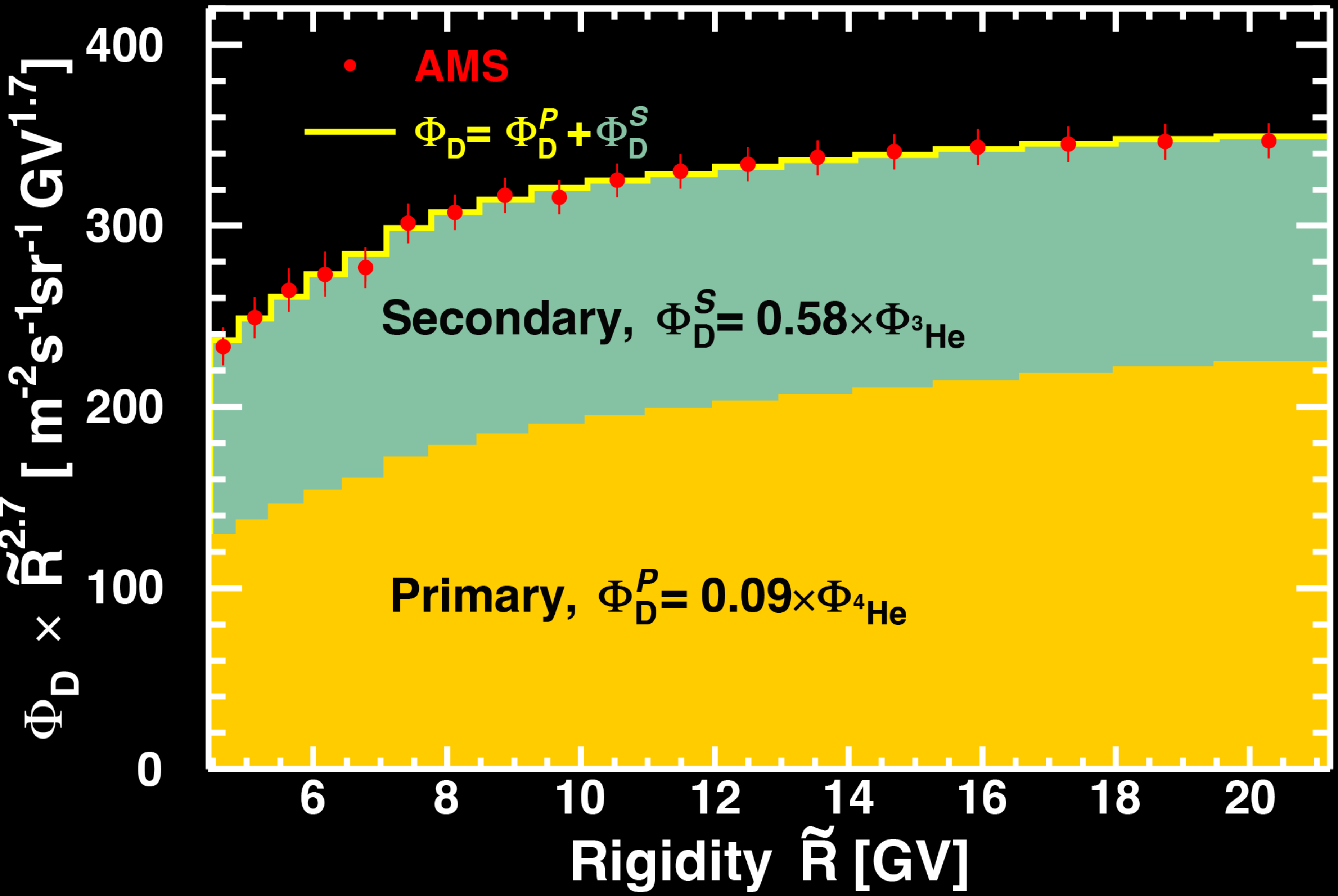
(^{4}He, C, O, …) + Interstellar Medium → (D, ^{3}He, …) + X

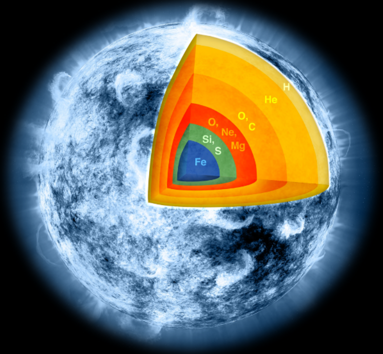




AMS results are consistent with secondary ^{3}He, but disagree with secondary D.

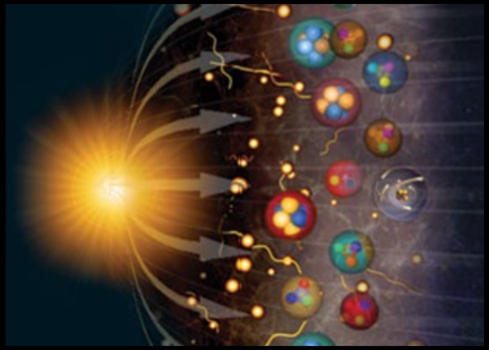
Deuterons have a significant primary component



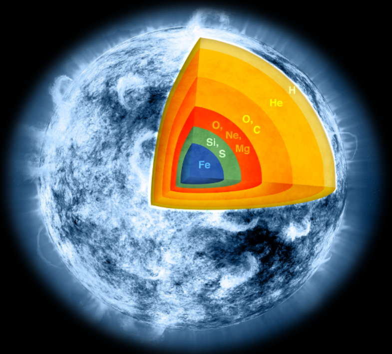


Results on Cosmic Lithium Li

Li has 3 or more possible sources in the cosmos.

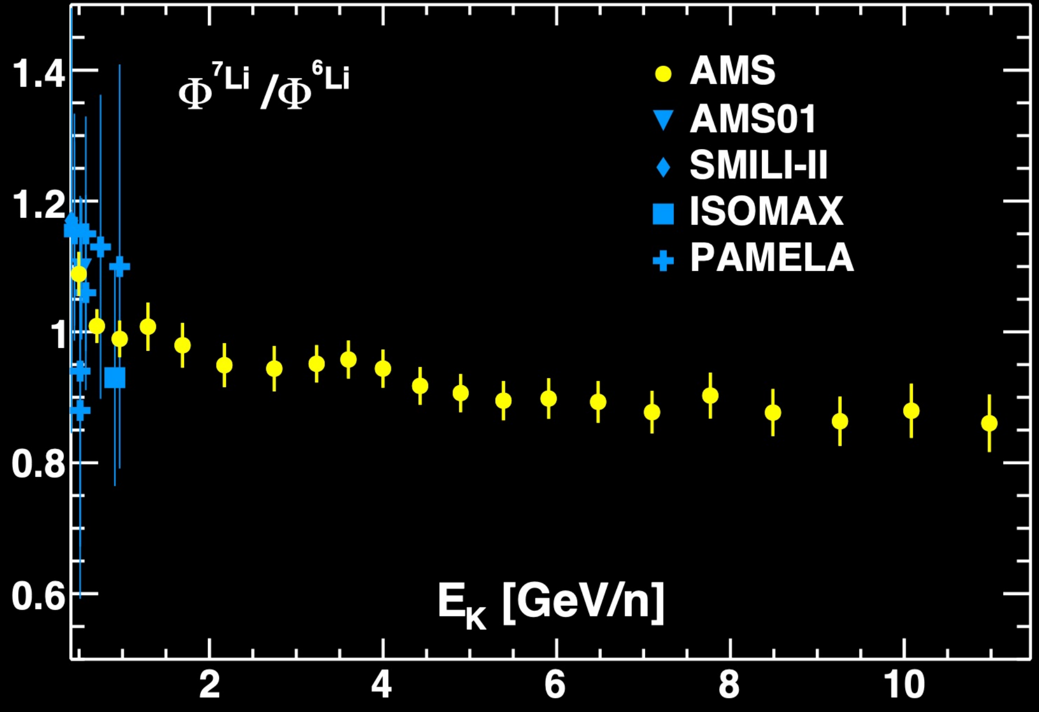


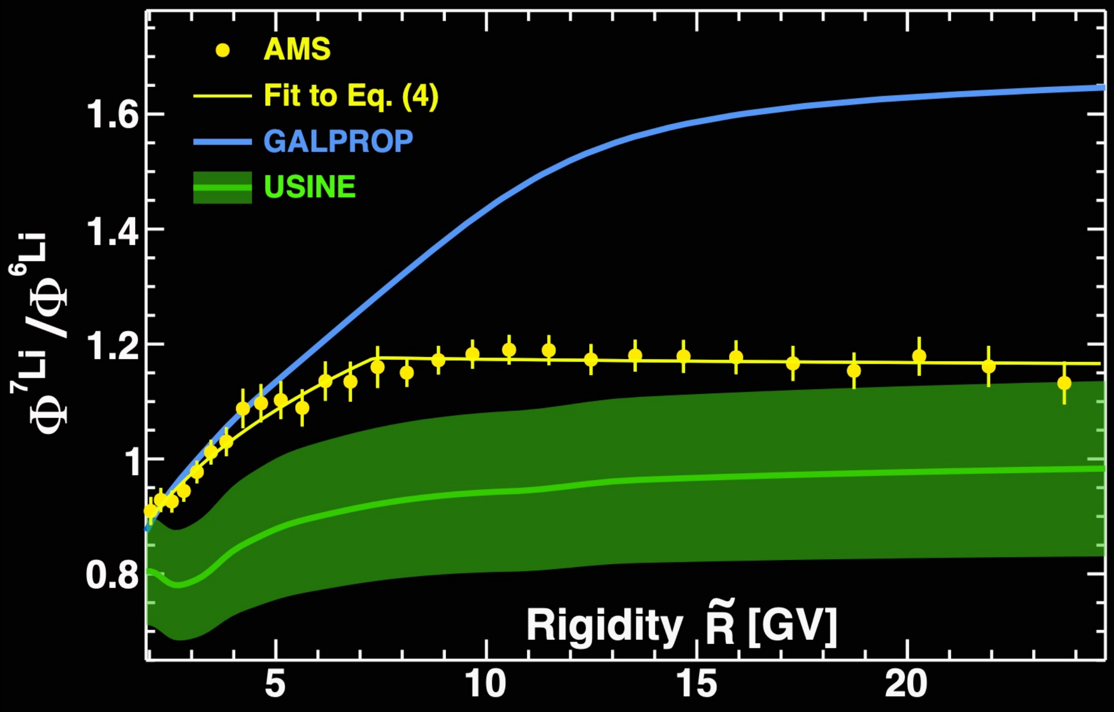
Big Bang Nucleosynthesis



Stellar Evolution (Nova)

Cosmic ray collision with Interstellar Medium





Model assuming a primary component in the ^{7}Li flux

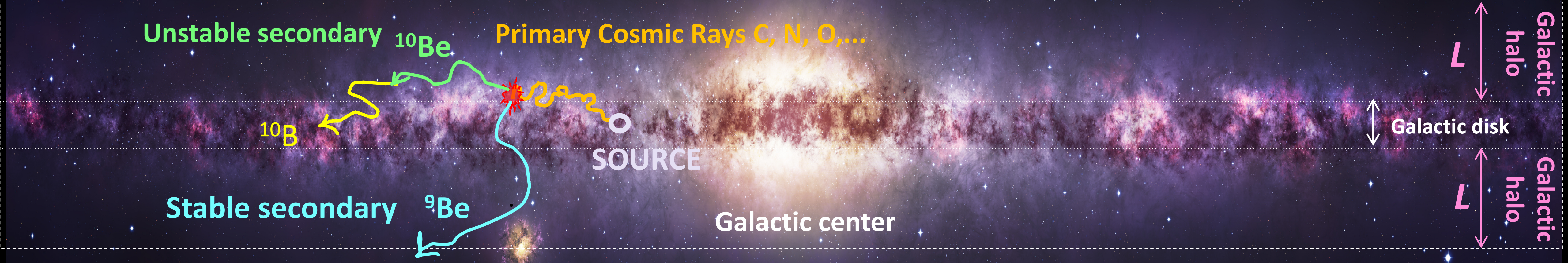
Model assuming secondary origin of ^{6}Li and ^{7}Li

Excludes the existence of a sizable primary component in the ^{7}Li flux

Physics of Beryllium Isotopes

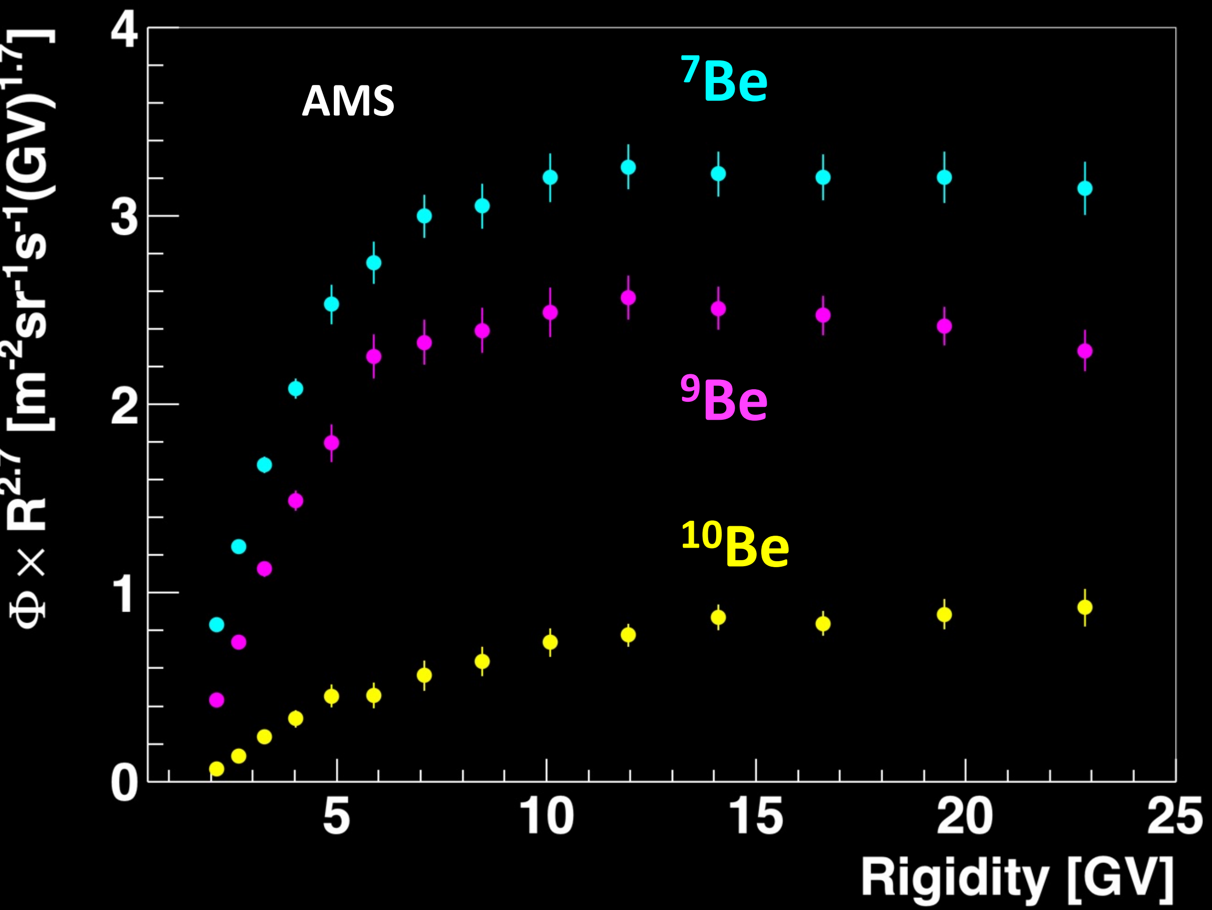
^{7}Be, ^{9}Be, and ^{10}Be

Stable ^{9}Be propagate in the entire galactic halo while ^{10}Be decay to ^{10}B before reaching the boundary of the Galaxy.

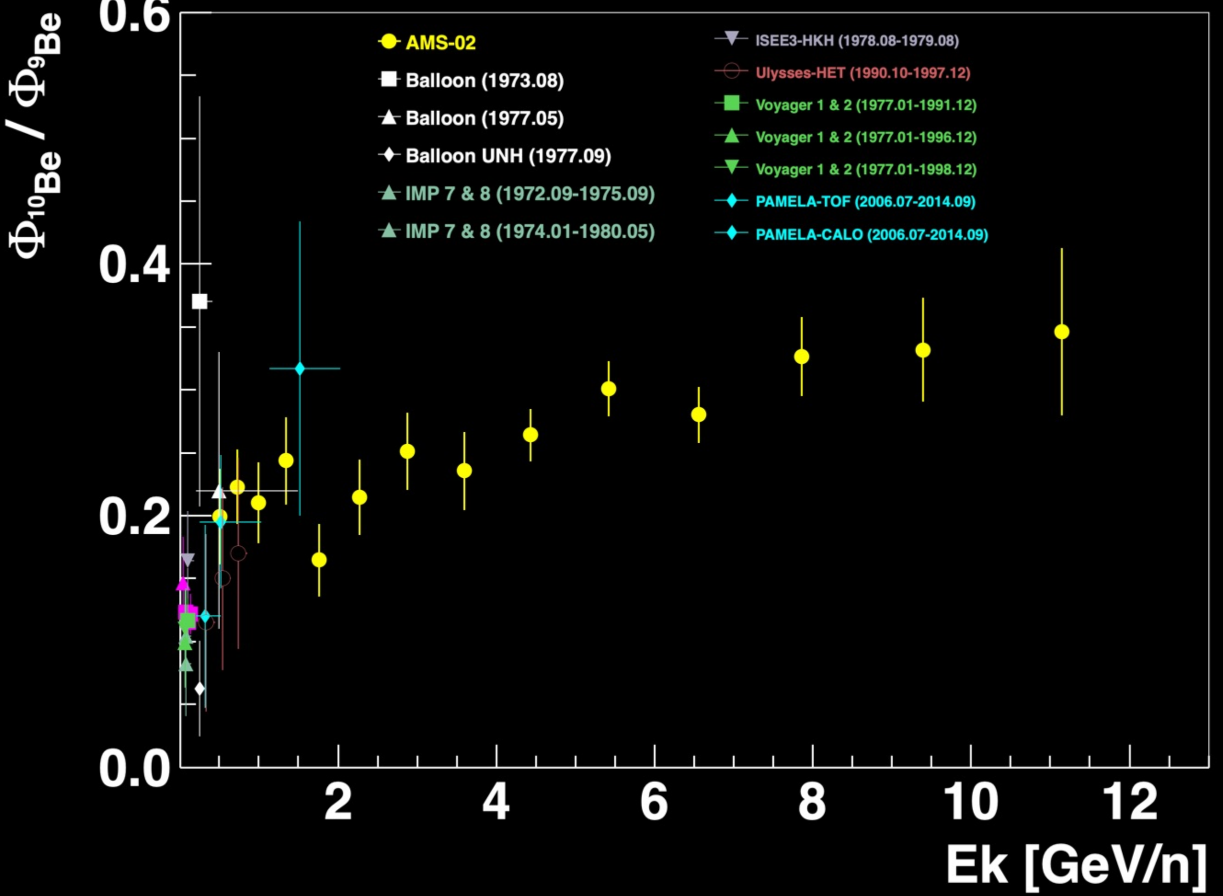


The ratio of unstable-to-stable, $^{10}Be/^{9}Be$, measures the Galactic halo size ***L***

Beryllium isotopes



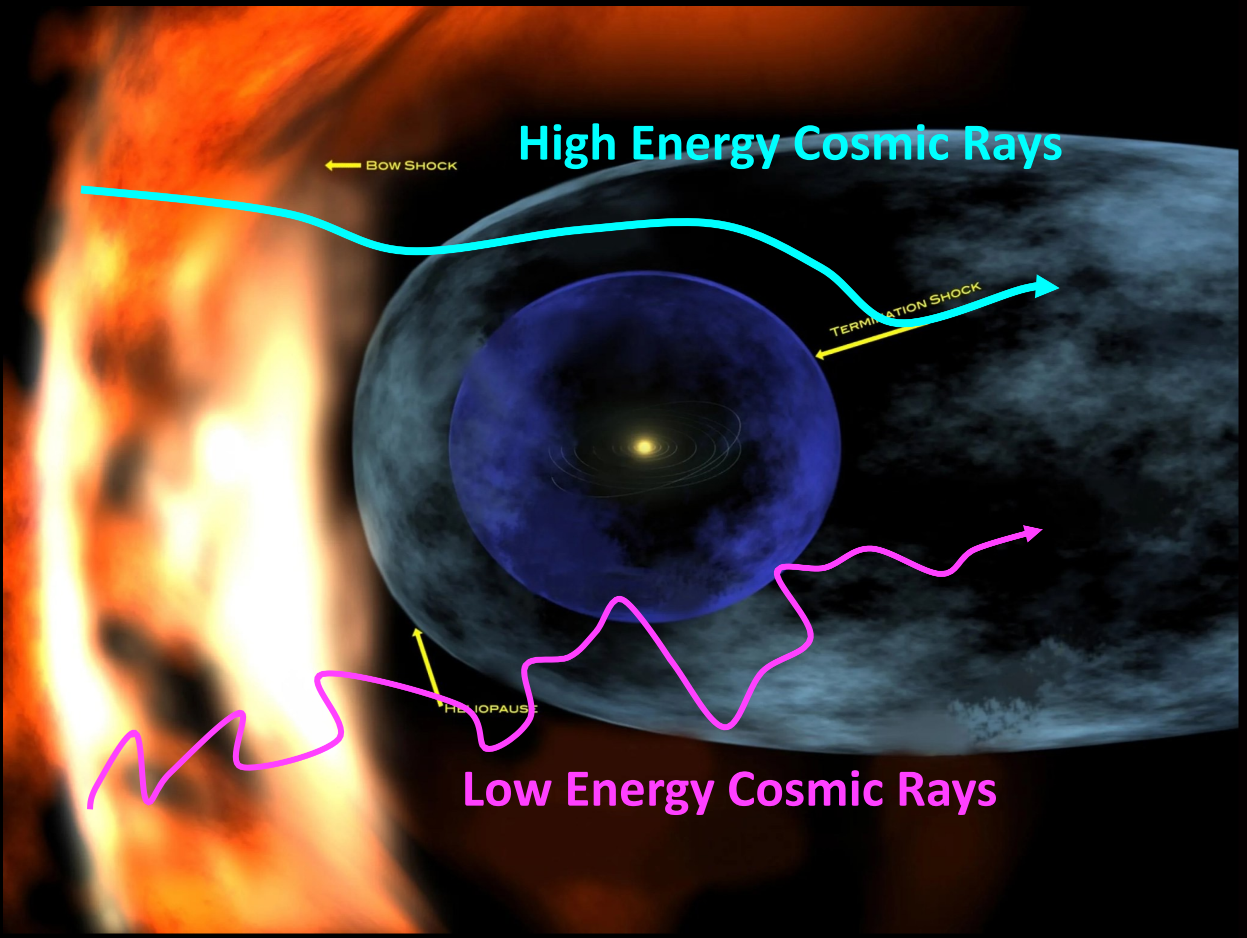
^{10}Be/ ^{9}Be Flux Ratio

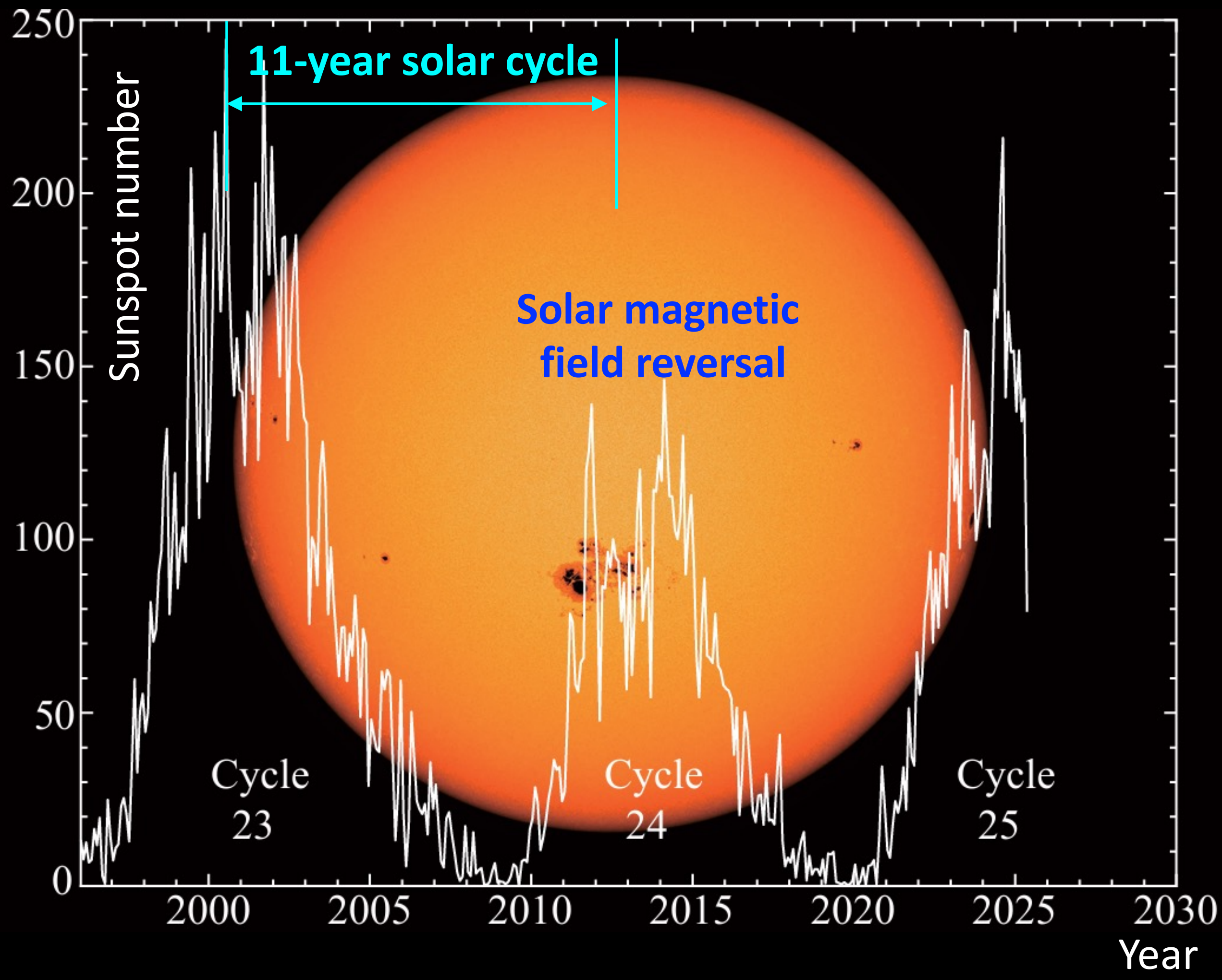


AMS results provide unique insights to the asymptotic behavior of ^{10}Be/^{9}Be at high energy

Expect to have important results from HELIX

Cosmic Ray Propagation in the Heliosphere

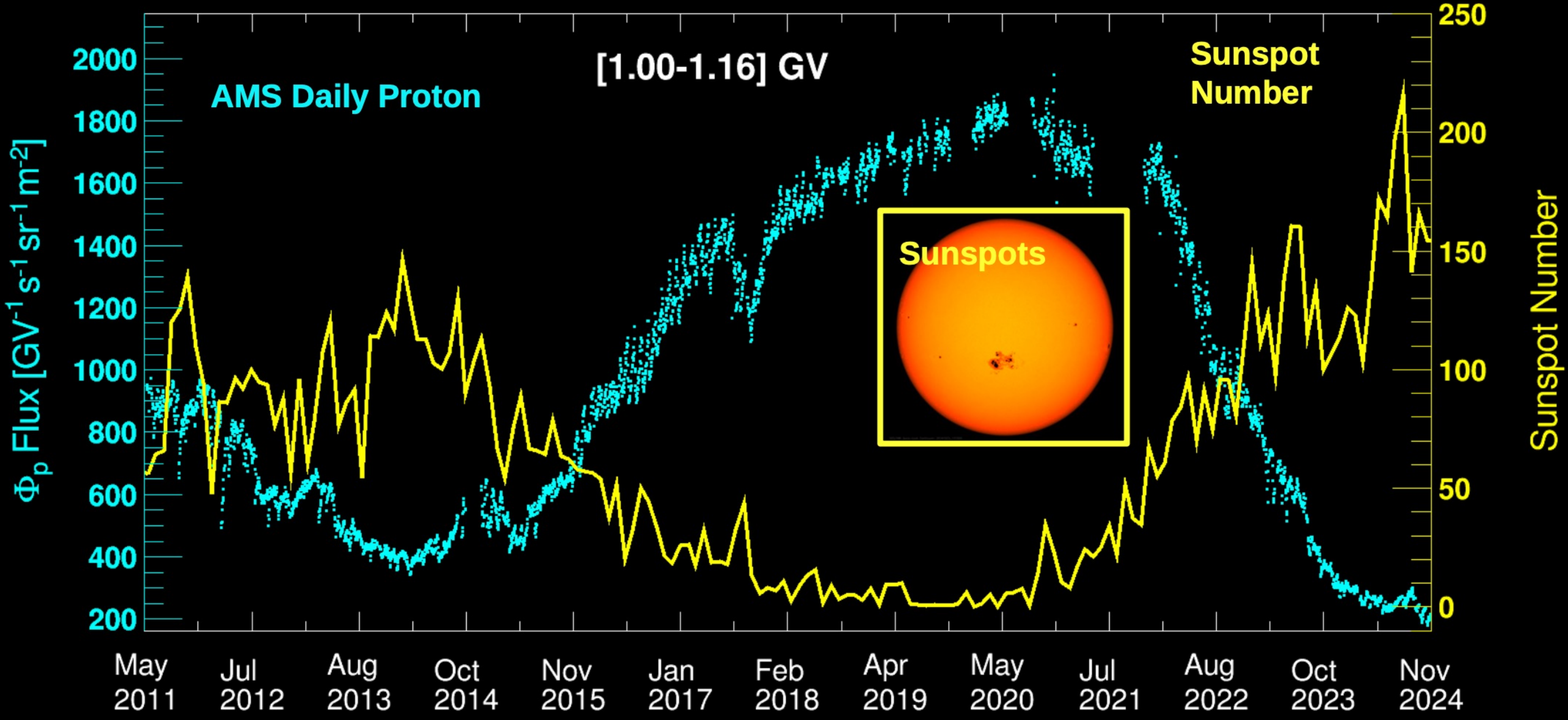




Low energy cosmic rays are more affected by the magnetic field in the solar system.
Solar magnetic field changes with time due to solar activities. --> Cosmic ray fluxes changes with time.

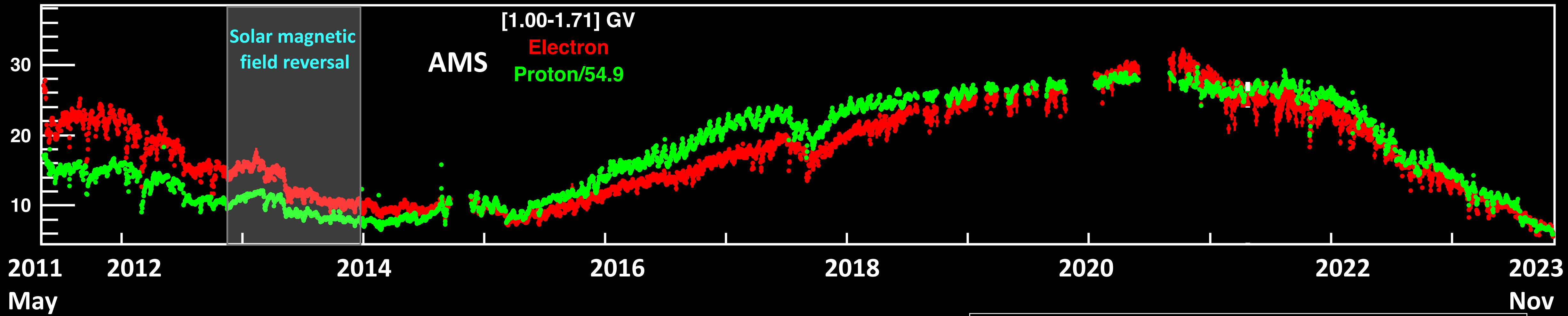
The propagation mechanism (parker equation) is identical in solar system and in the Galaxy.

Daily Proton Flux over an 11-year Solar Cycle



Larger solar activity (more sunspots number), lower proton fluxes

Cosmic Ray Propagation in the Heliosphere



Electron and proton carry opposite charge;

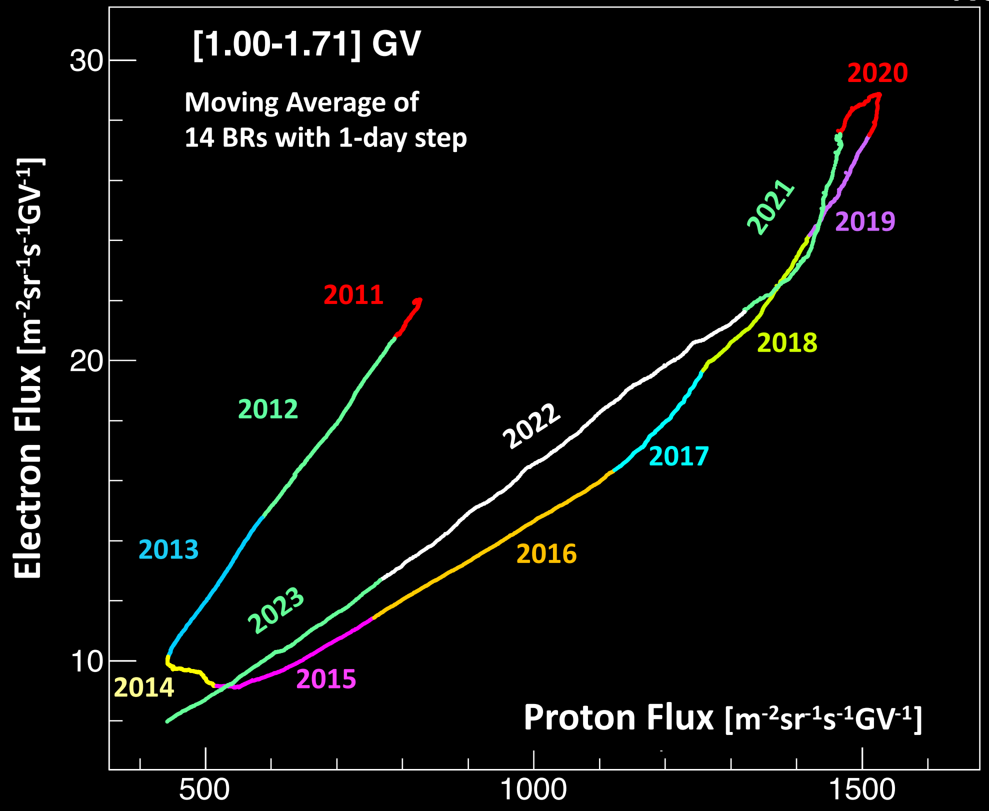
their fluxes show different time dependence.

(Hysteresis)

Hysteresis is also observed in electron vs positron.

--> Charge sign dependent solar modulation.

Also reported by CALET using $(e^{+}+e^{-})$ vs proton.



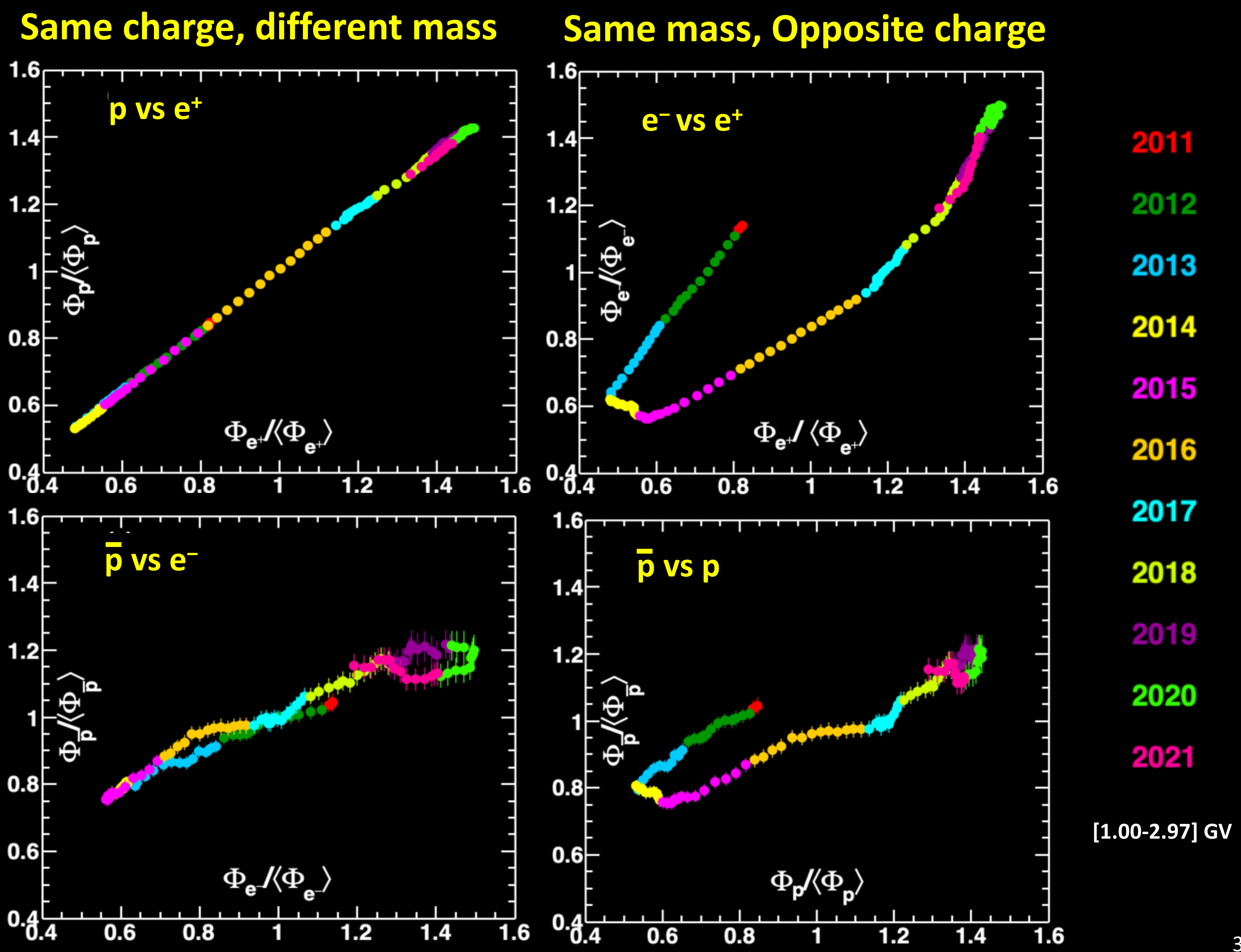
Cosmic Ray Propagation in the Heliosphere: Based on four elementary particles

Results from AMS

Linear relation between particles with same charge, different mass

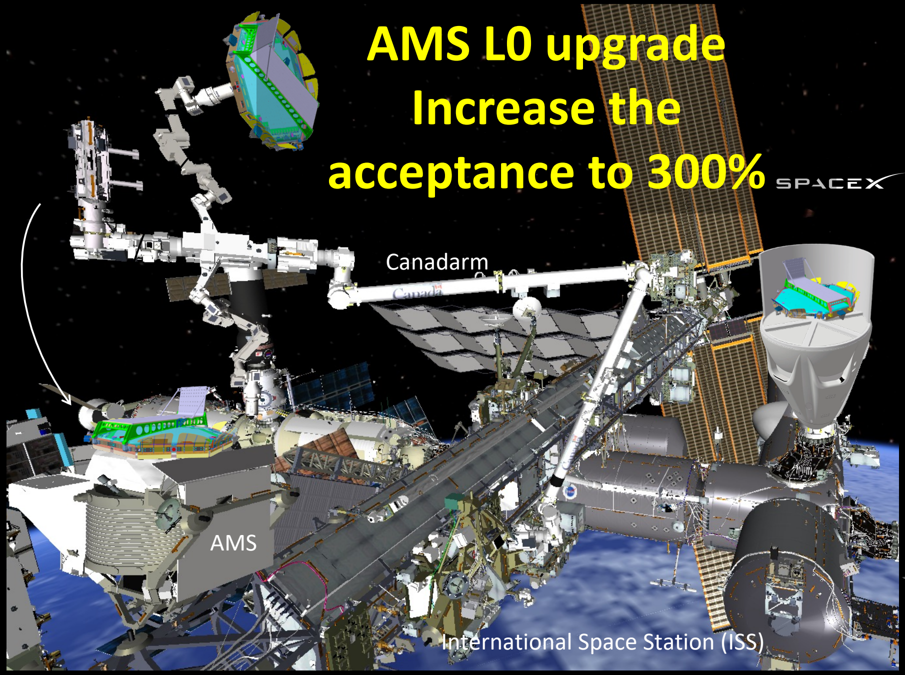
Hysteresis between particles with opposite charge and same mass

The magnitude of flux variations during the 11 years, are affected by their **spectral shape**

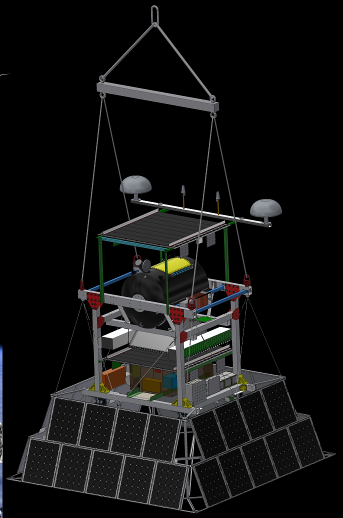


Prospects in the coming years

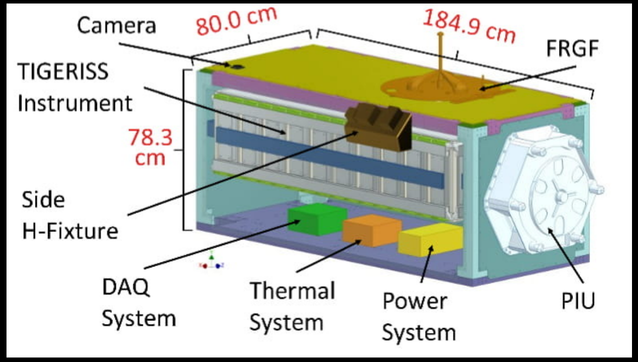
AMS L0 upgrade
Increase the acceptance to 300%



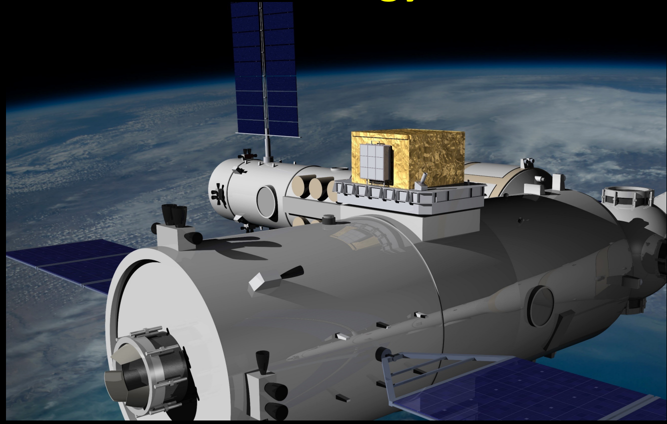
HELIX (Isotope)



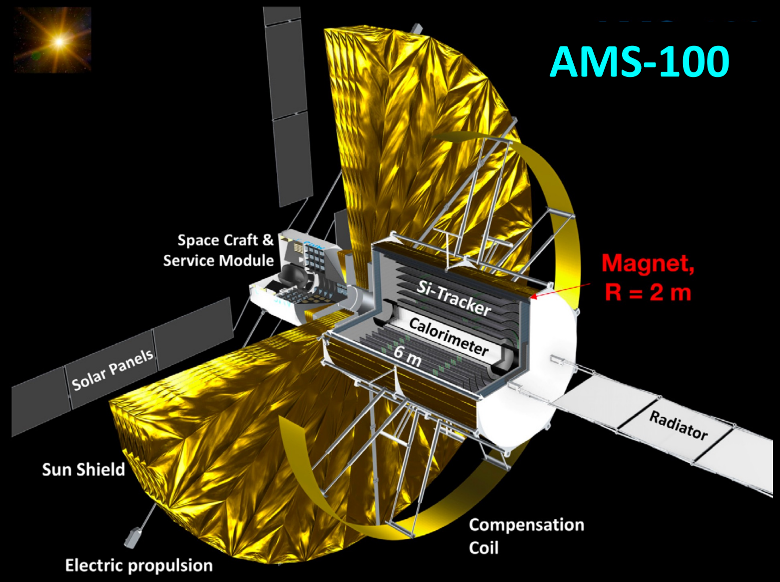
TIGERISS (High Z elements)



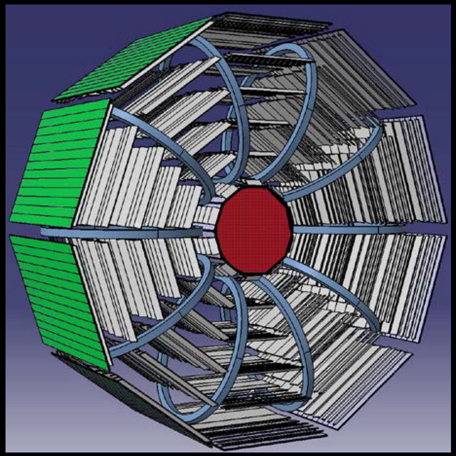
HERD on CSS (~2028)
PeV energy



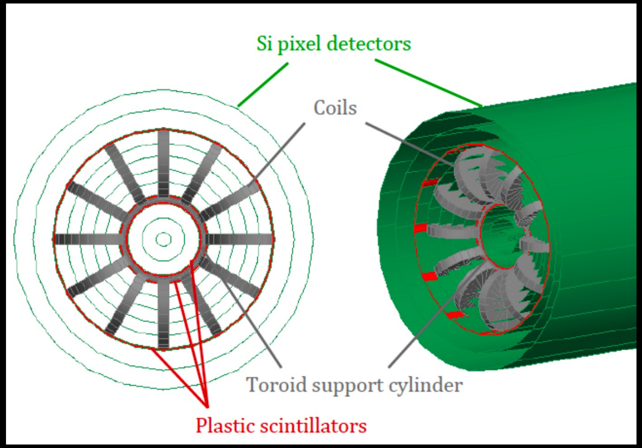
AMS-100



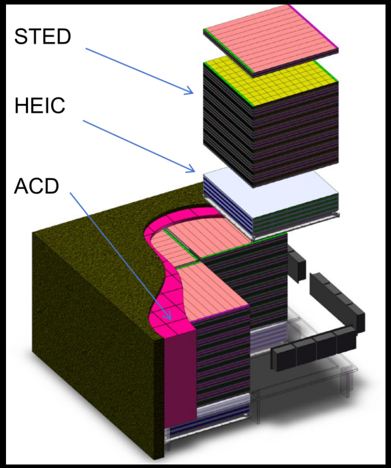
ALADINO



ARCOS



VLAST (Nonmagnetic)



+ many more proposals and R&D efforts

Summary and Prospects

- **Cosmos is the ultimate laboratory providing particles and nuclei to the highest energy.**
- **The direct detection in space bring the cosmic ray study to a precision era.**
- **Our understanding of the cosmic rays are being re-shaped by the discoveries of new phenomena and call for the development of a comprehensive cosmic ray model.**

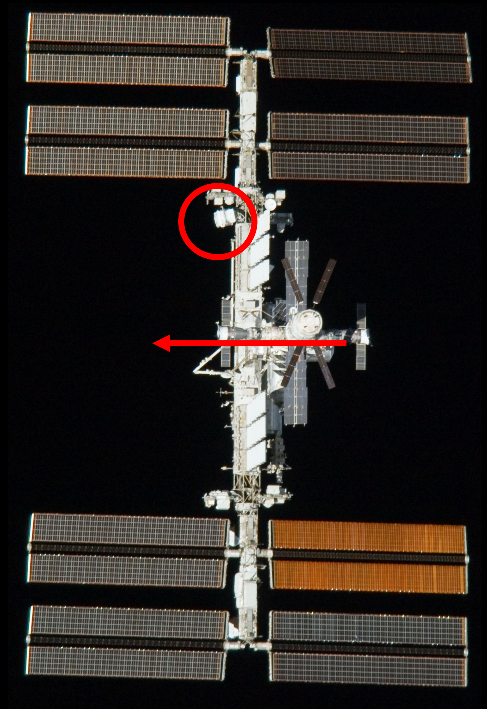
- **In the coming future, we expect more unexpected results from the current experiments.**
- **The R&D efforts are pushing next generation experiments (both magnetic and non-magnetic) on the horizon.**

Backup

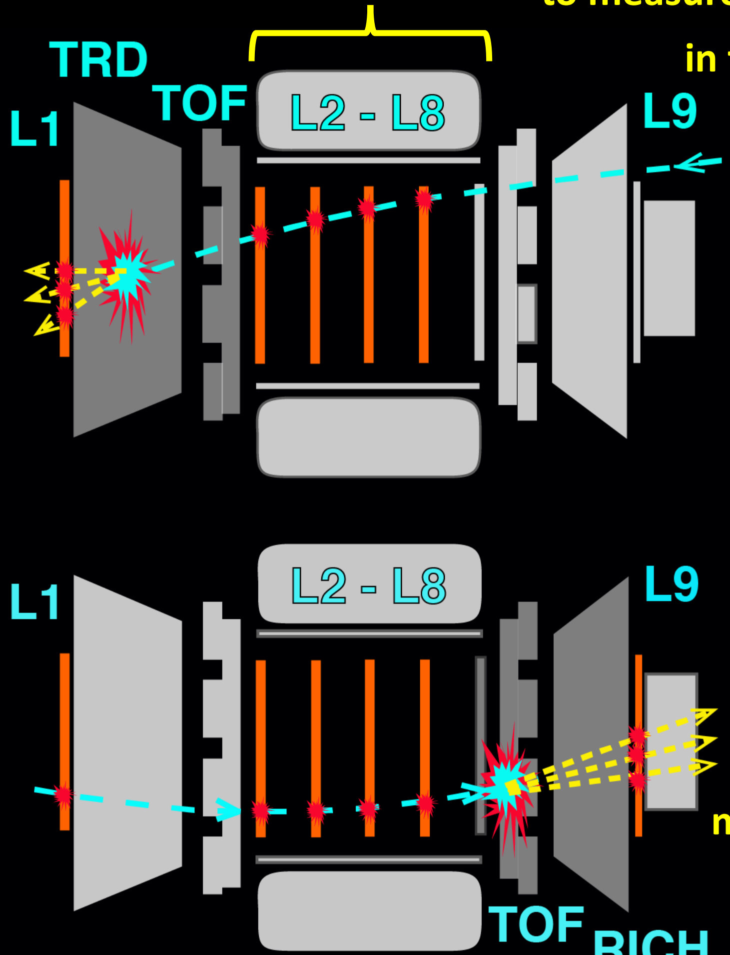
Increasing Attention to Cross-sections

Interaction cross section is one of the most important source of uncertainty for cosmic ray measurements.

AMS systematically measured the inelastic cross-section of nuclei with material, using the "beam" from space.

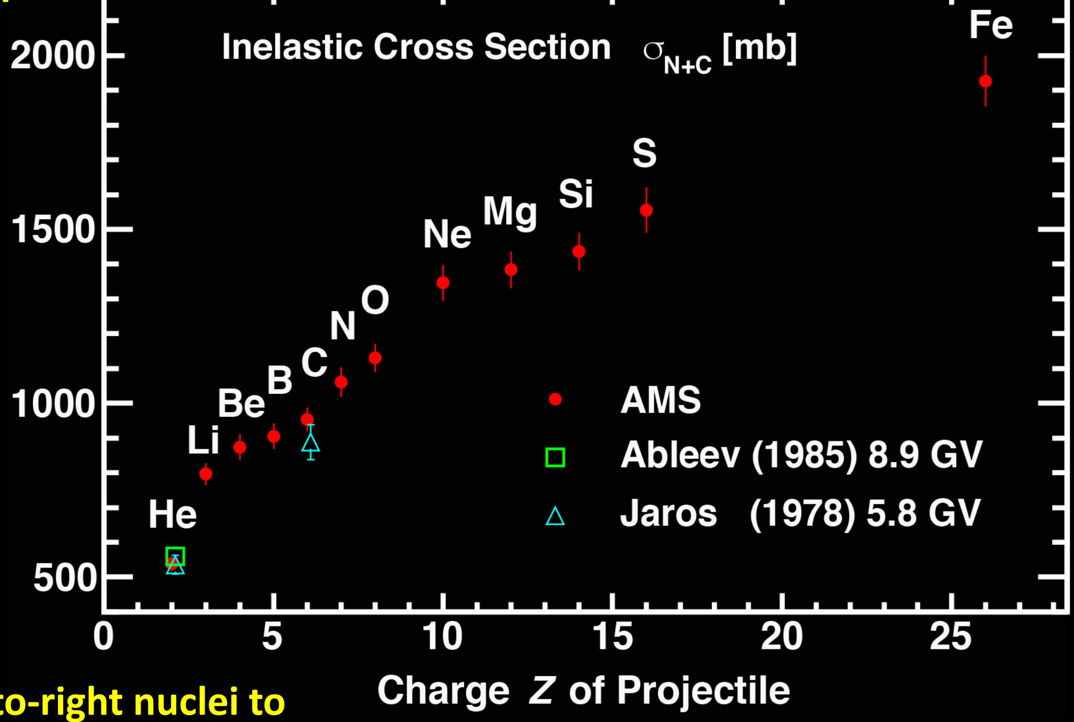


AMS horizontal



Use right-to-left nuclei to measure nuclear interactions in the TRD+TOF

Use left-to-right nuclei to measure the nuclear interactions in the TOF+RICH



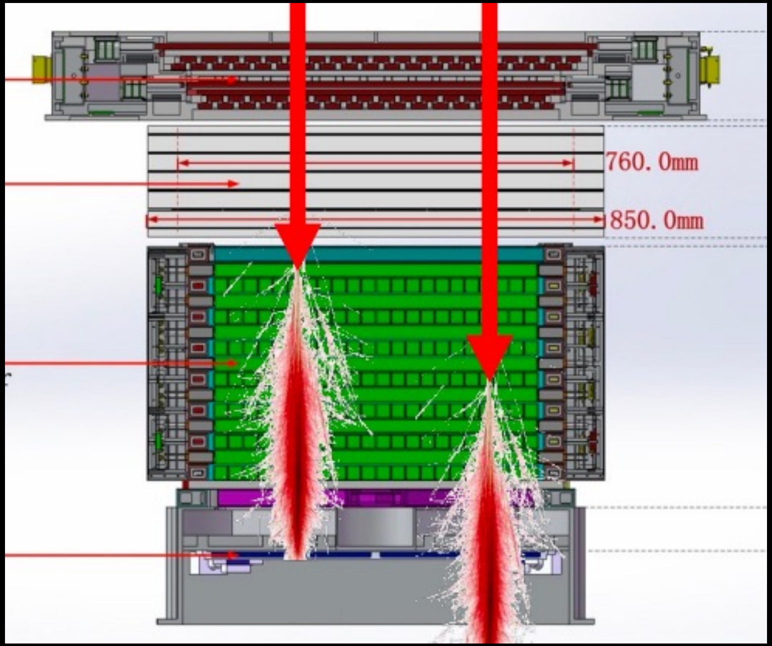
Increasing Attention to Cross-sections

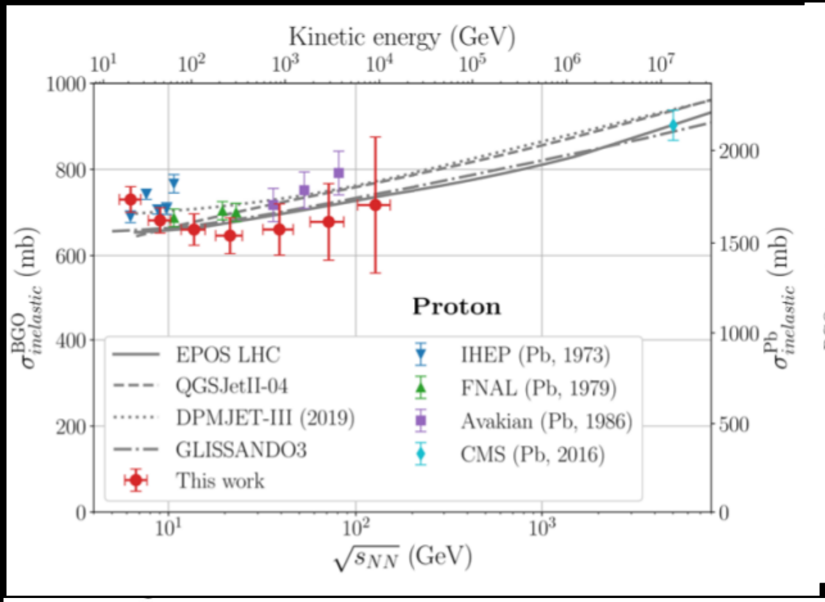
Examples of DAMPE studies of inelastic cross-section on BGO target.

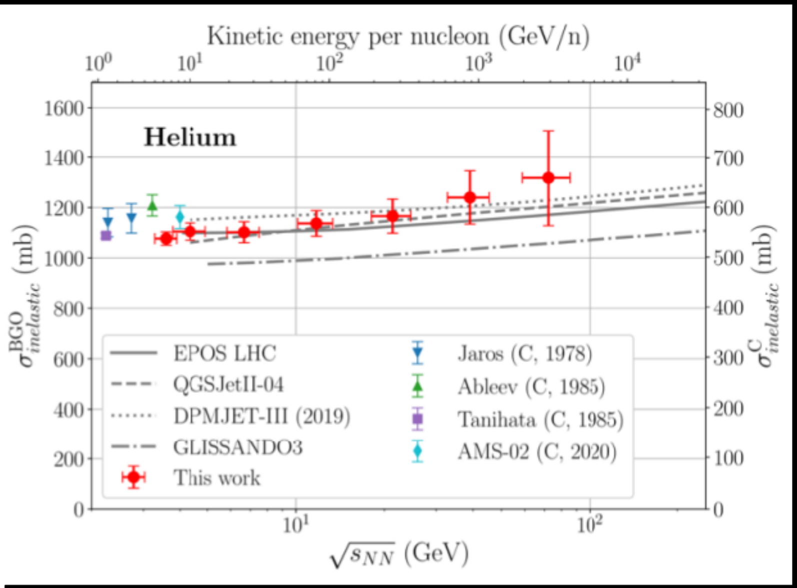
A beam-target experiment

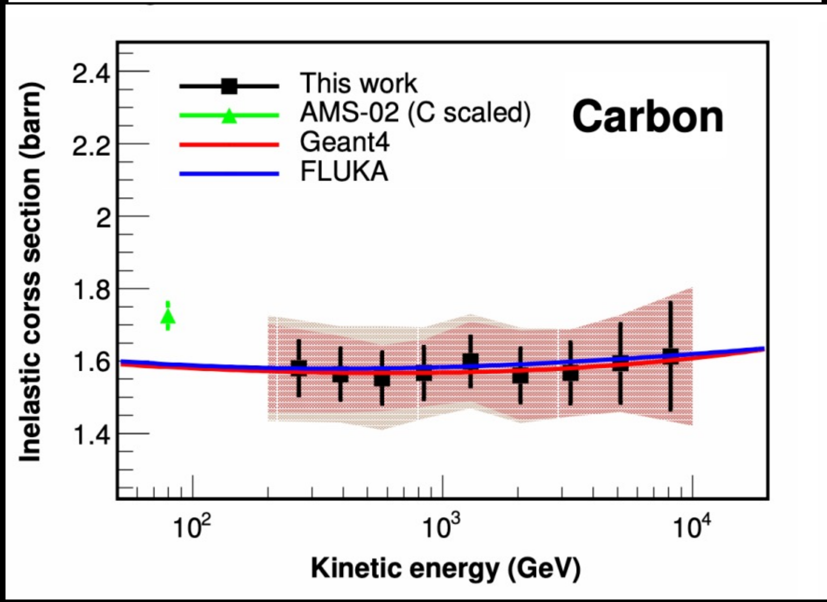
Beam: CR particles

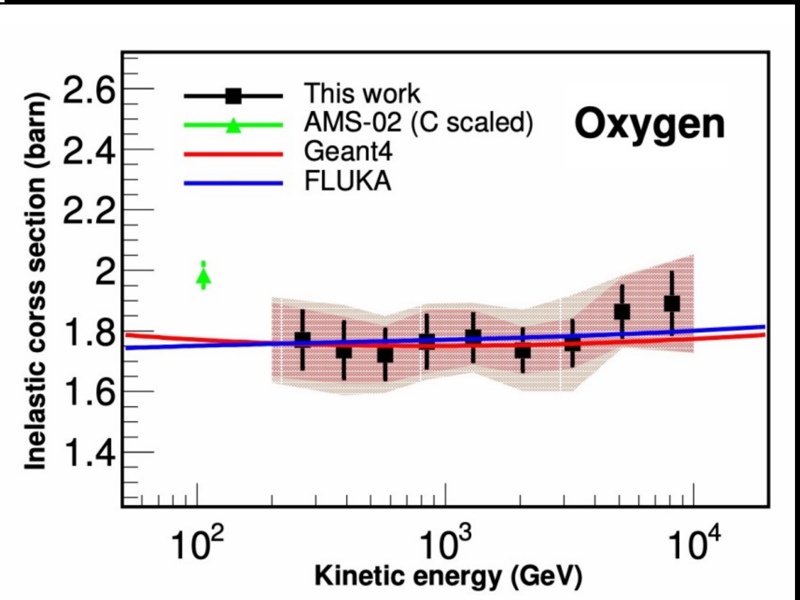
Target: BGO ($Bi_4Ge_4O_{12}$)



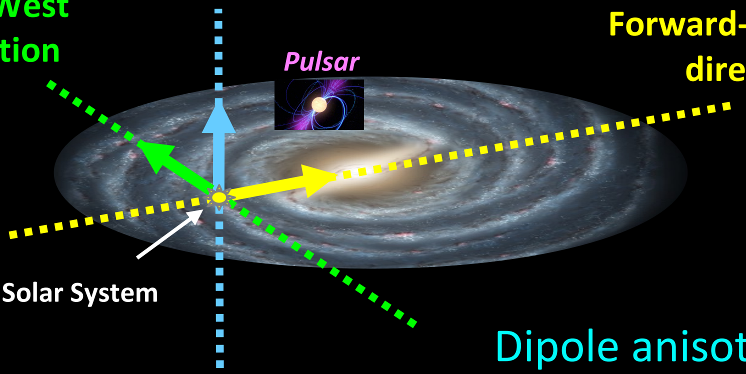






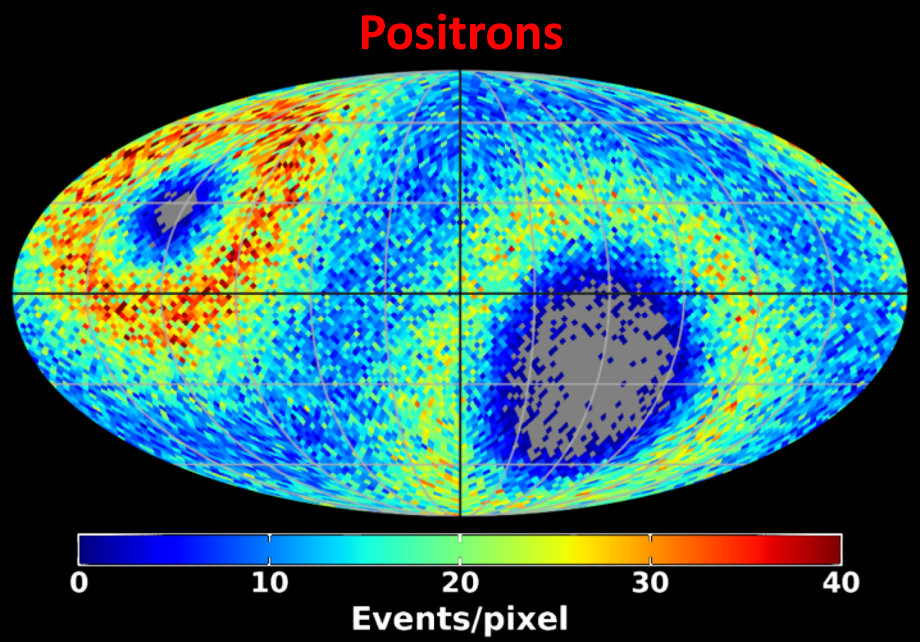


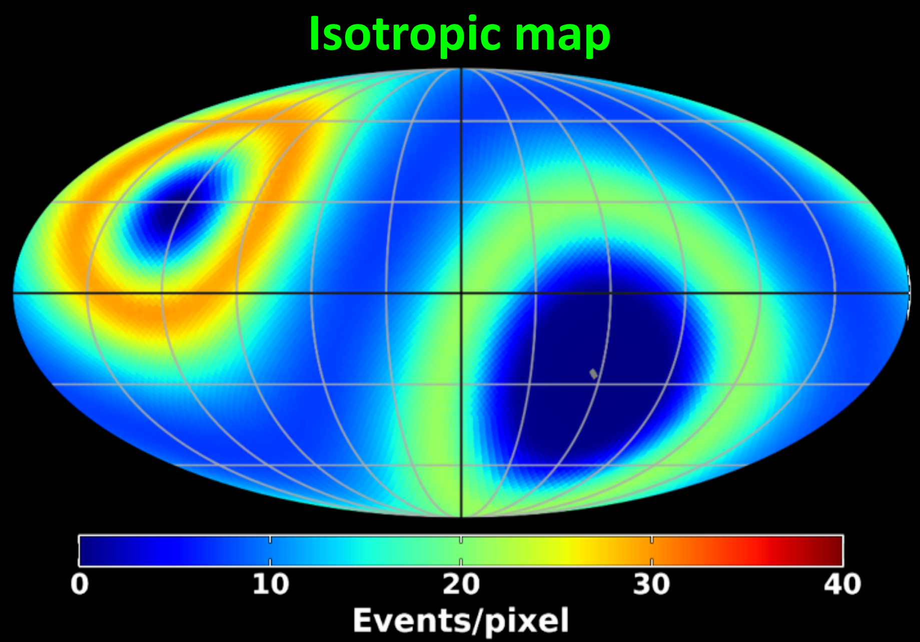
Positron Anisotropy



Astrophysical point sources will imprint a higher anisotropy on the arrival directions of energetic positrons than a smooth dark matter halo.

Dipole anisotropy: $\delta = 3\sqrt{C_1/4\pi}$ C_1 is the dipole moment



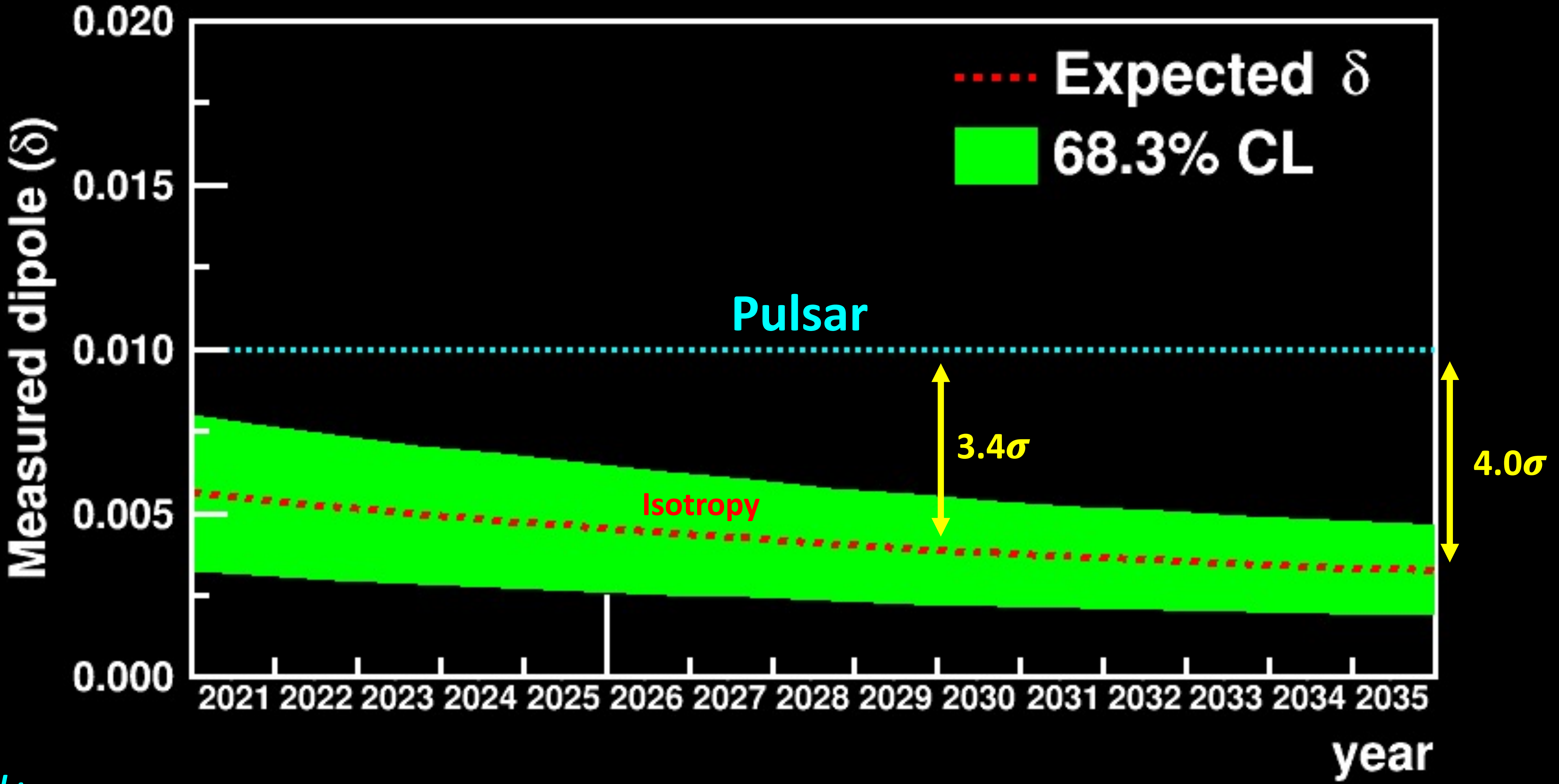


AMS **Currently at 95% C.I.:** $\delta_{e+} < 0.0144$

for 16 < E < 500 GeV

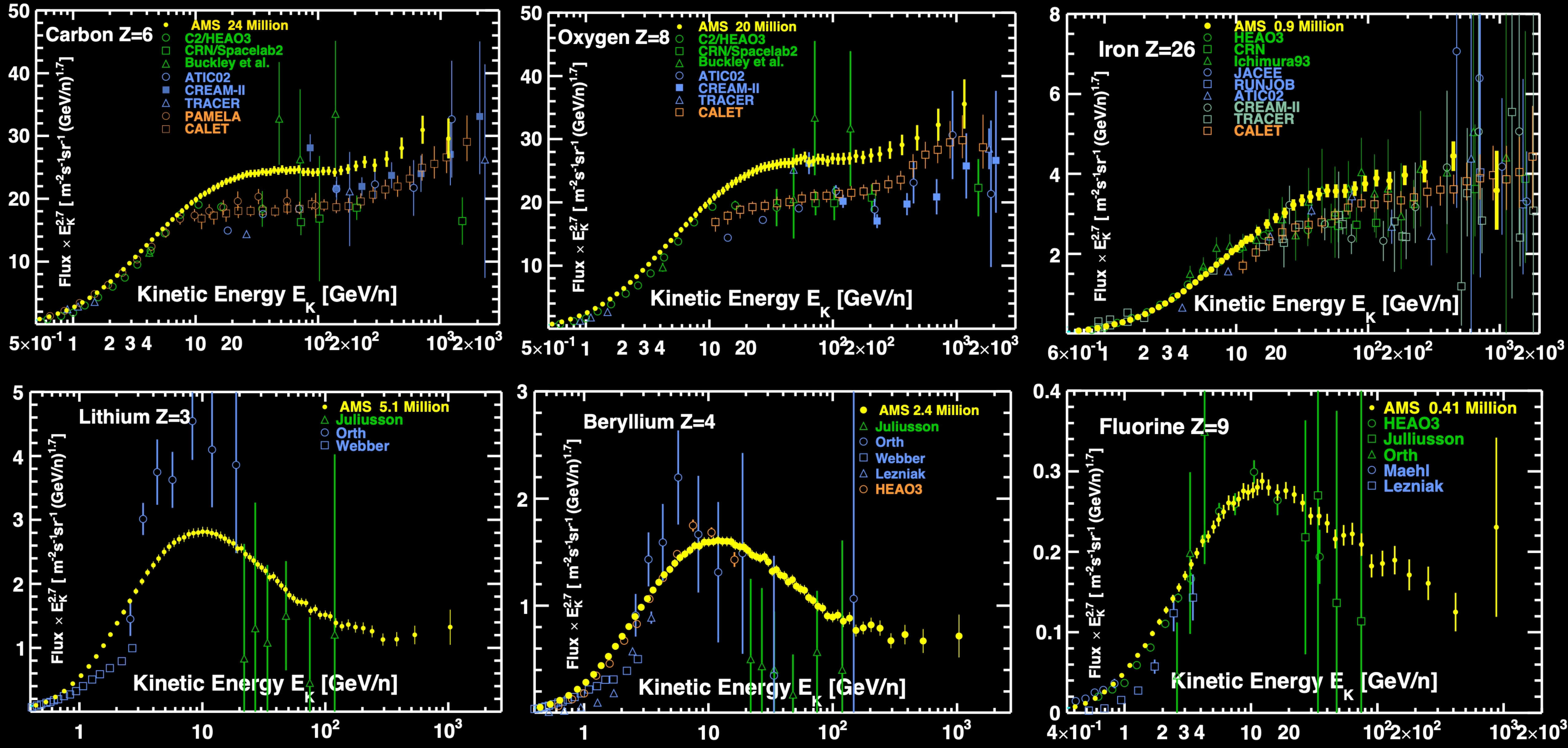
Poster by Iñaki Rodriguez Garcia

Future AMS measurement with improved positron statistics will allow us to distinguish dark matter and pulsars origin at the 99.93% C.L. in 2030, and at 99.99% C.L. in 2035



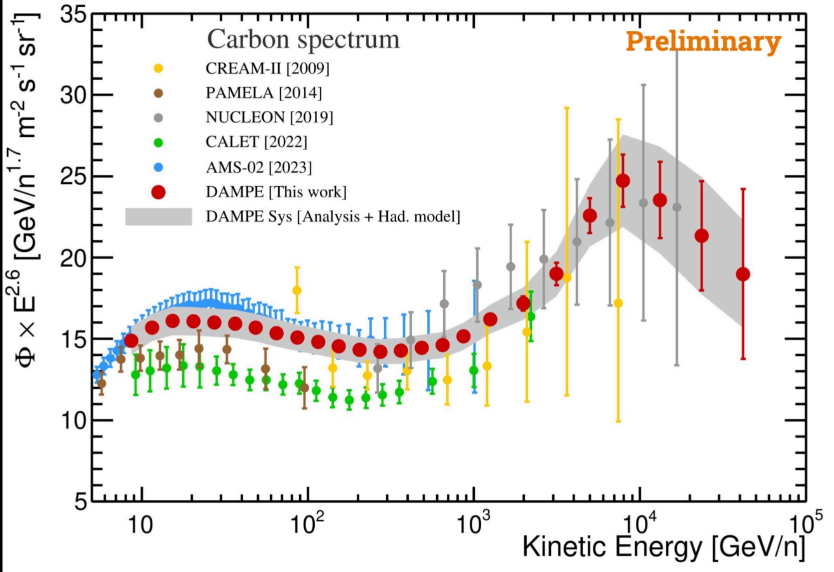
Pulsar Model :
D. Hooper, P. Blasi & P. D. Serpico, JCAP 0901(2009)

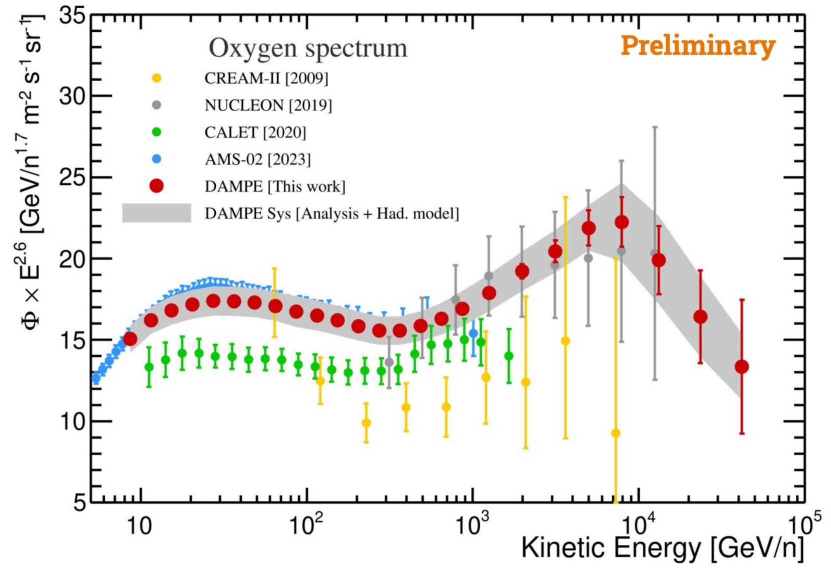
AMS provides the most accurate measurement in the GeV-TeV energy range



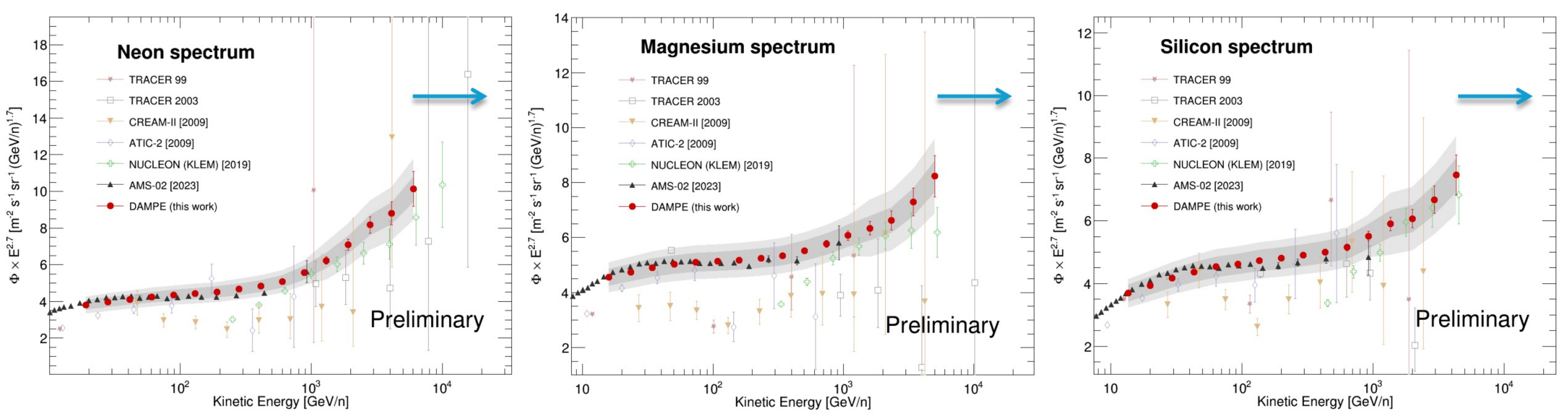
Primary Cosmic Ray Nuclei

DAMPE at ICRC 2025

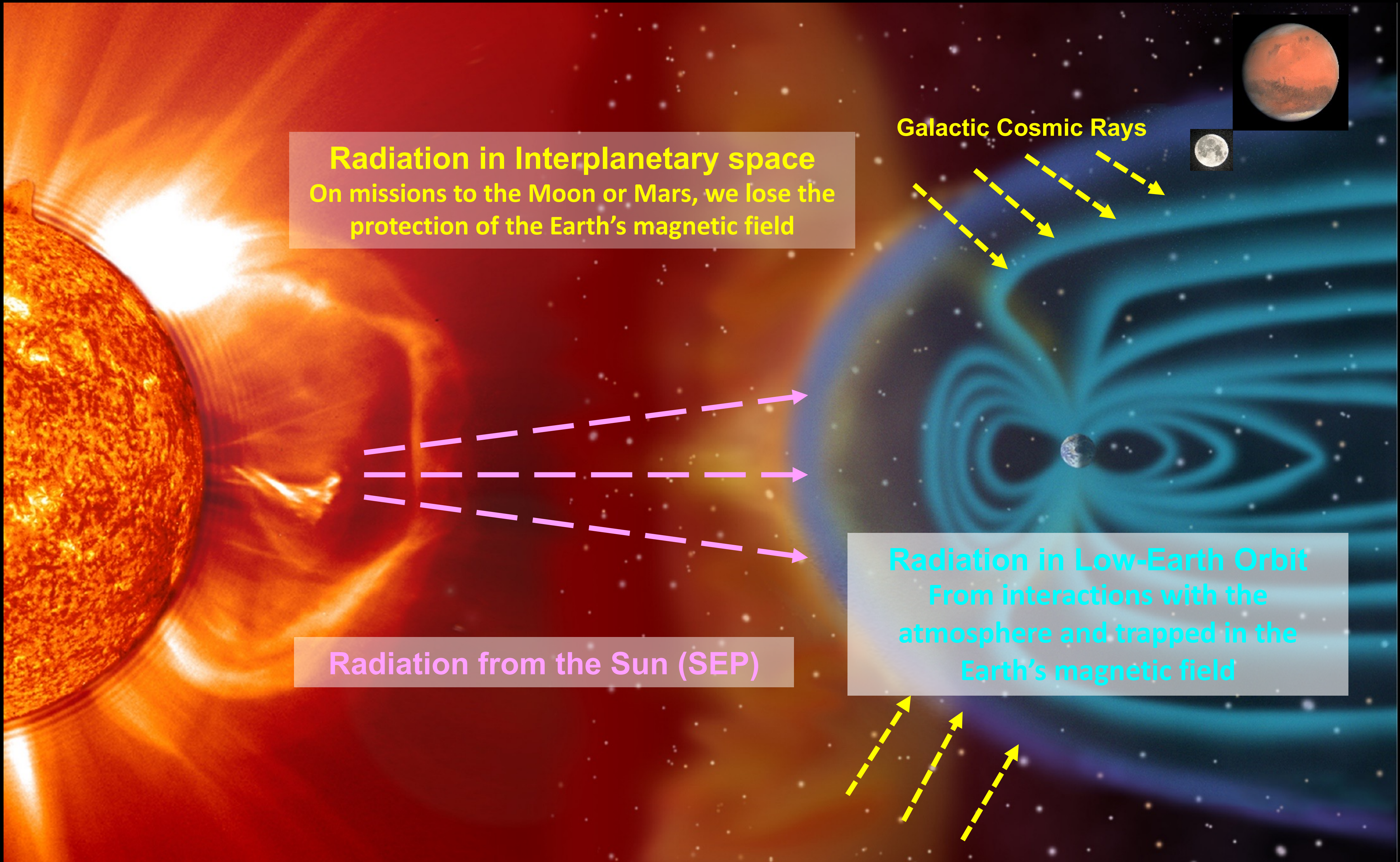




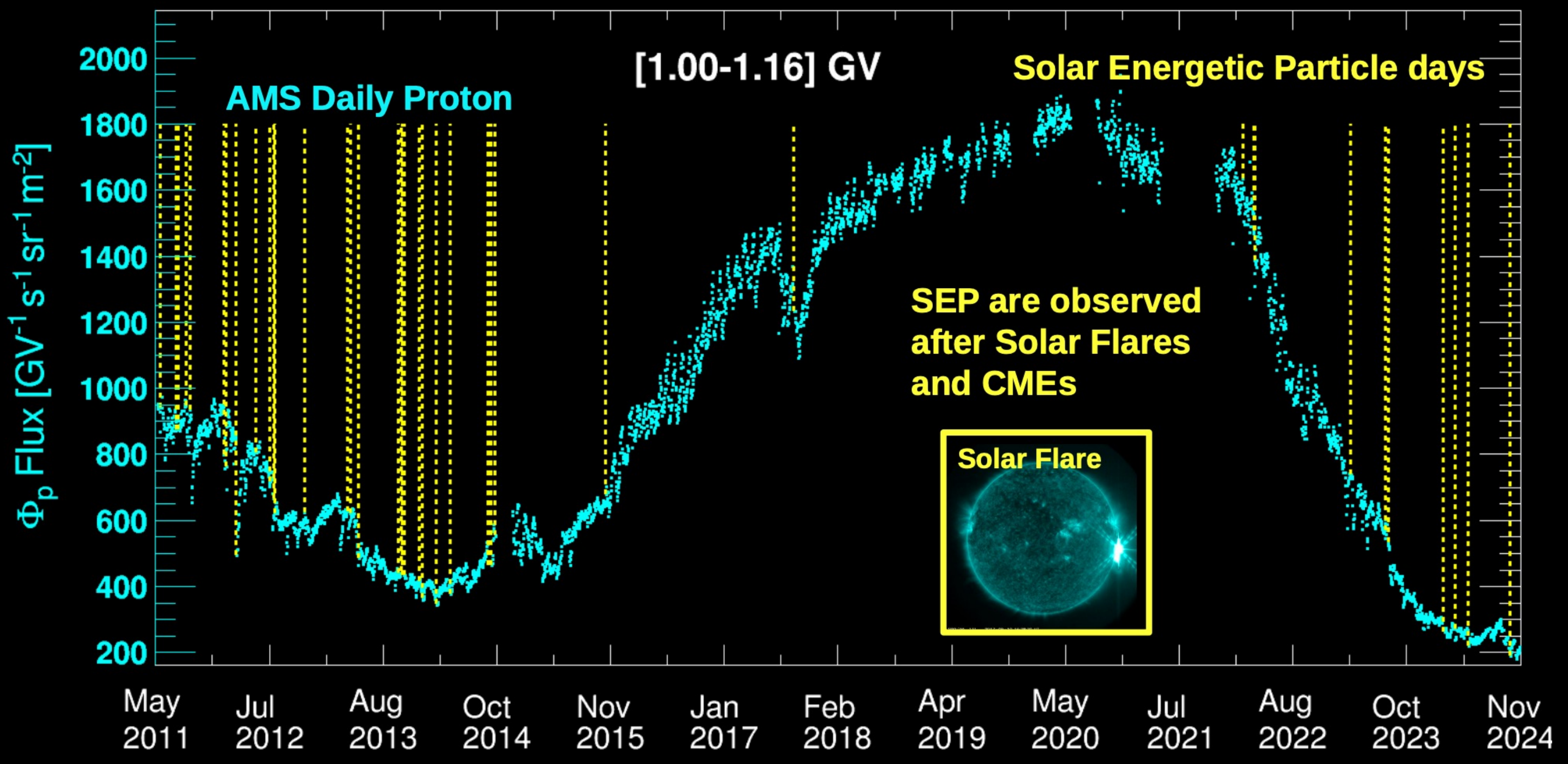
DAMPE: C and O spectra show a softening at ~ 7.5 GeV/n (15 TV)

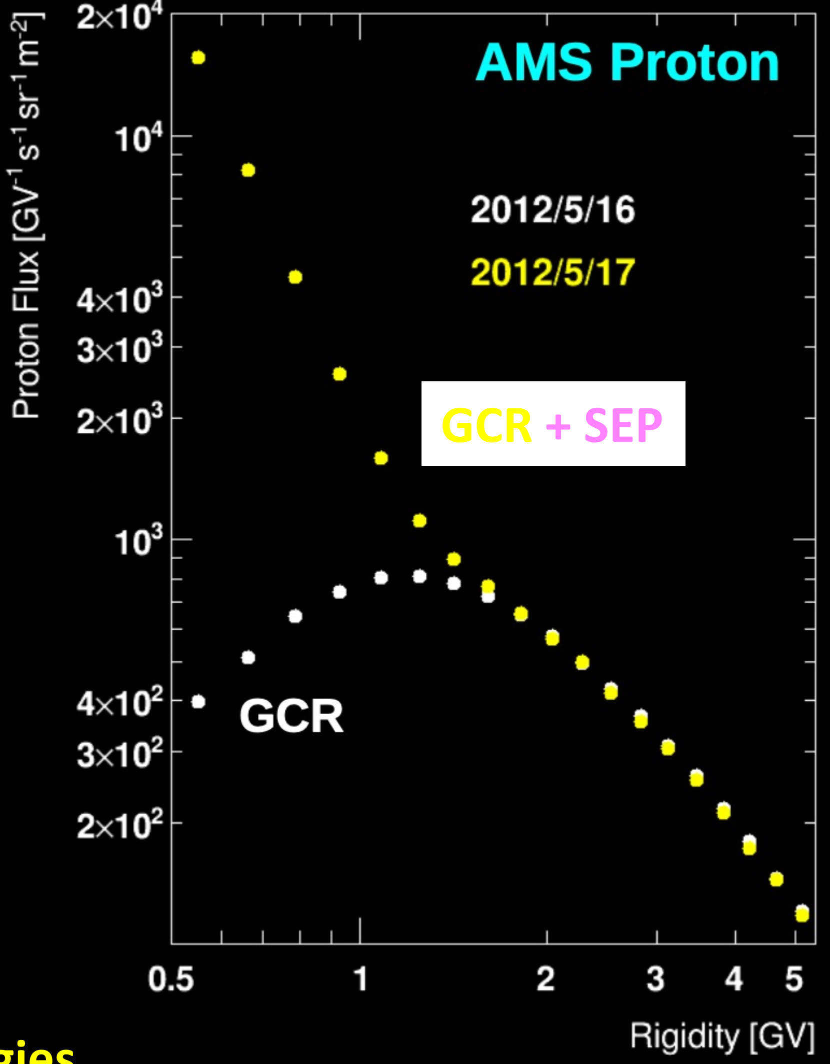


Cosmic Rays and Space Radiation



Particle Emission from the Sun (Solar Energetic Particles)



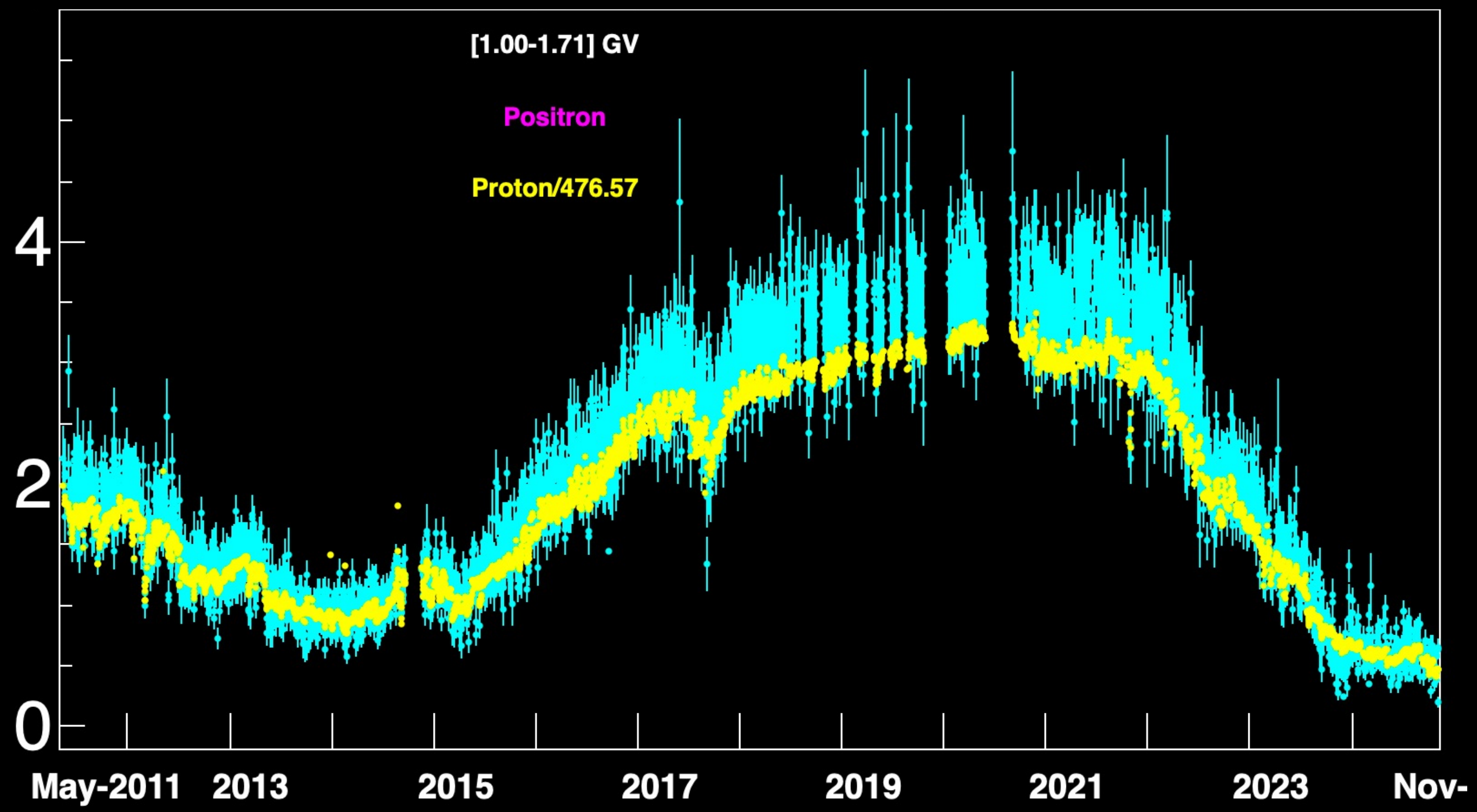


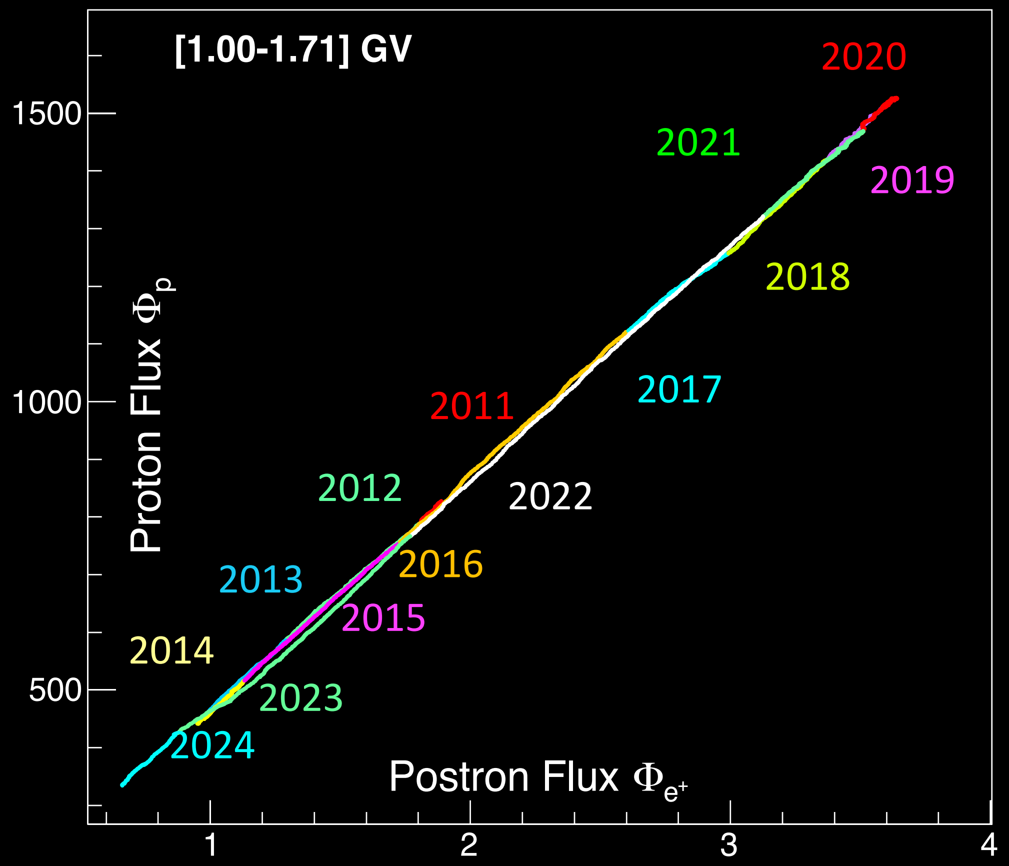
Unique measurement of the spectrum at GeV energies.

The SEP spectrum carries information of the acceleration mechanism.

Cosmic Ray Propagation in the Heliosphere

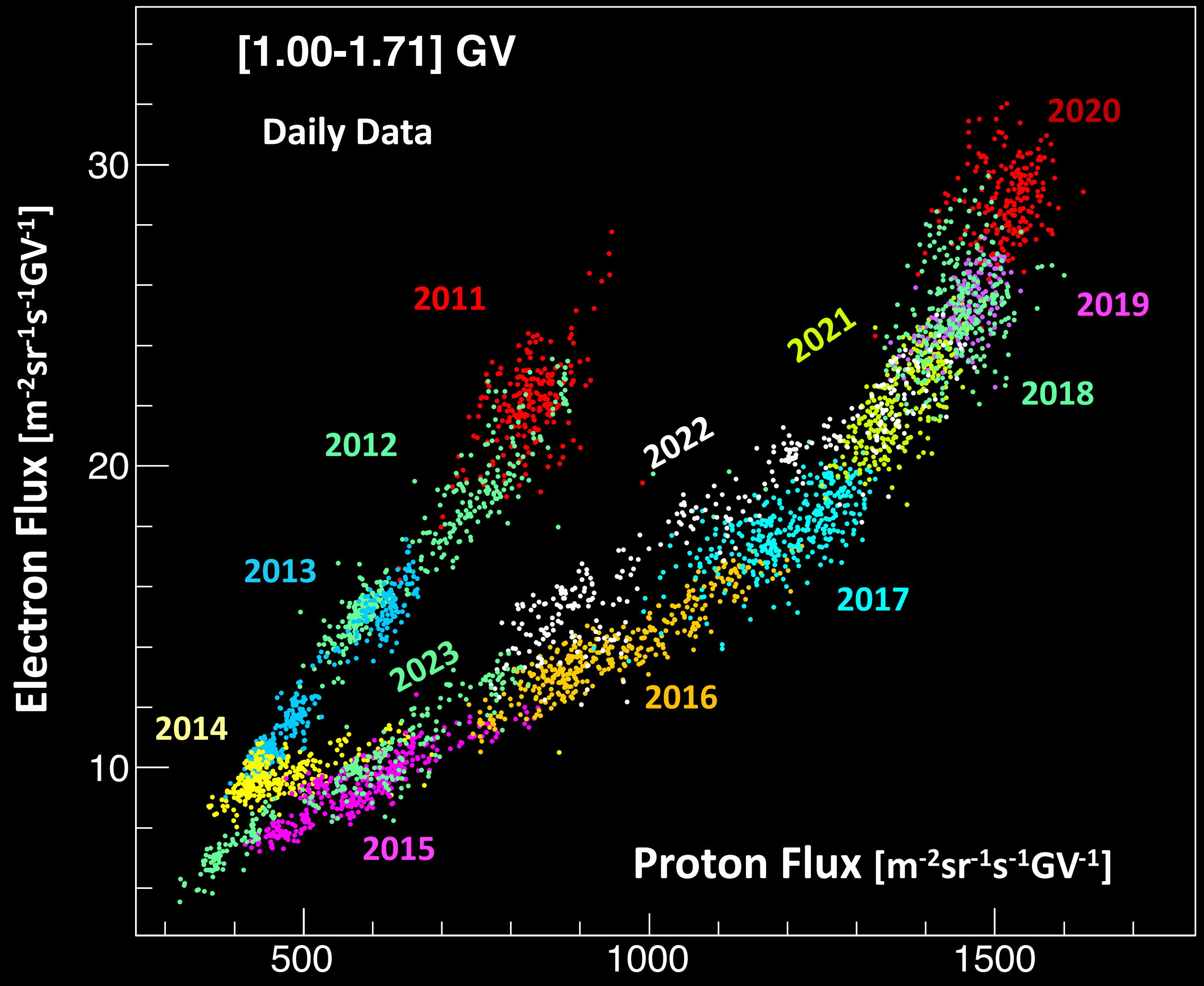
Positrons and Protons carry the same charge, though different mass;
Their fluxes show nearly identical time variation.

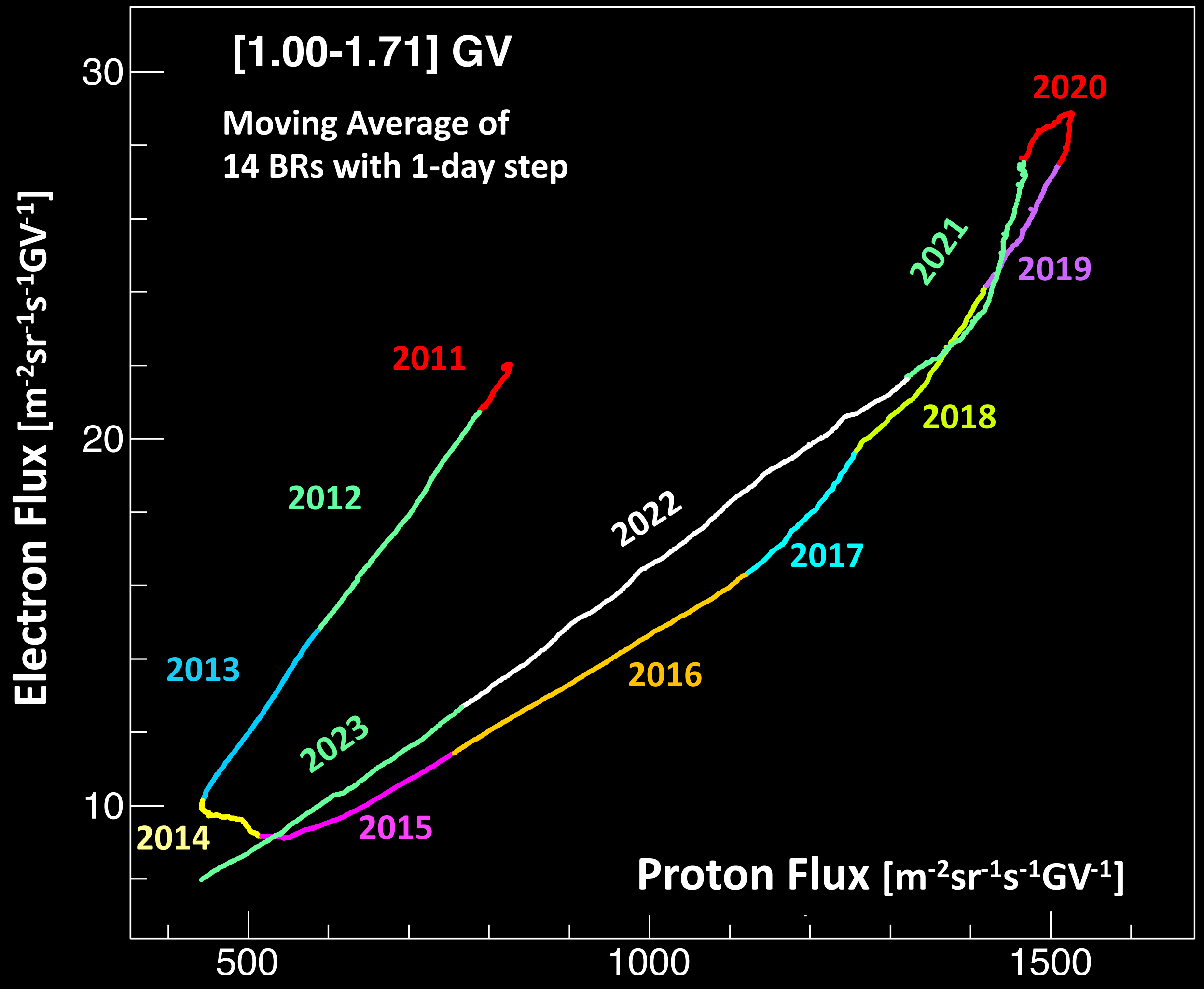




Linear relationship

Electron vs Proton
Opposite charge sign





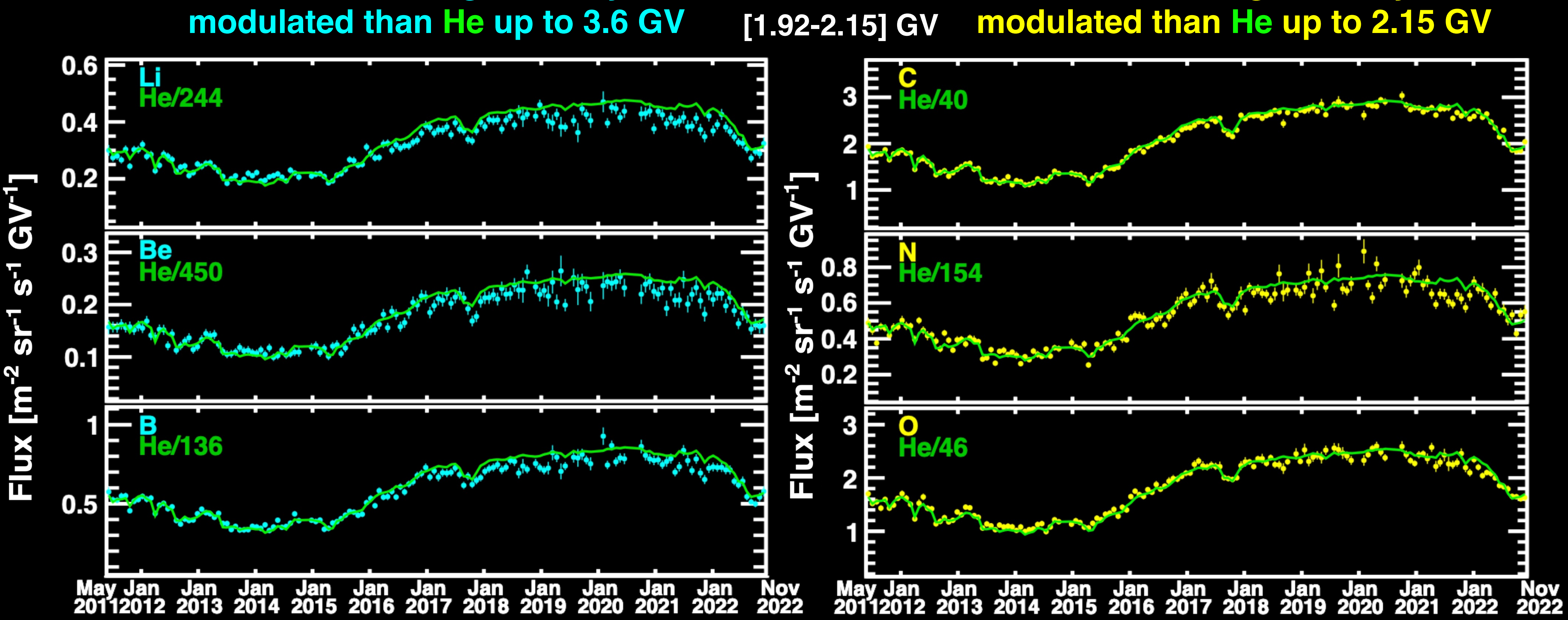
Cosmic Nuclei over an 11-year Solar Cycle

Talk by J. Tian

Phys. Rev. Lett. 134, 051001 (2025)

Li, Be and B are significantly less modulated than He up to 3.6 GV

C, N and O are significantly less modulated than He up to 2.15 GV

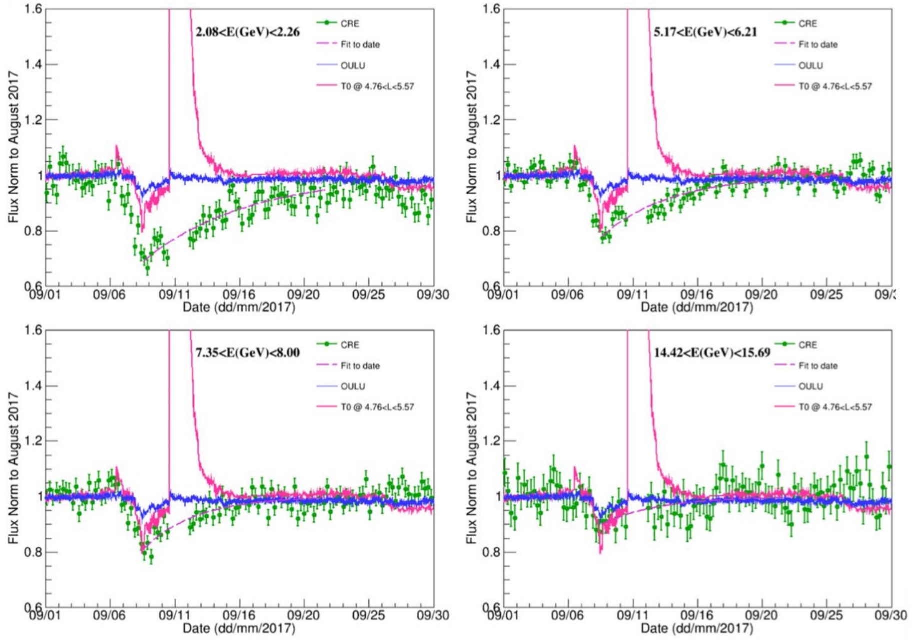


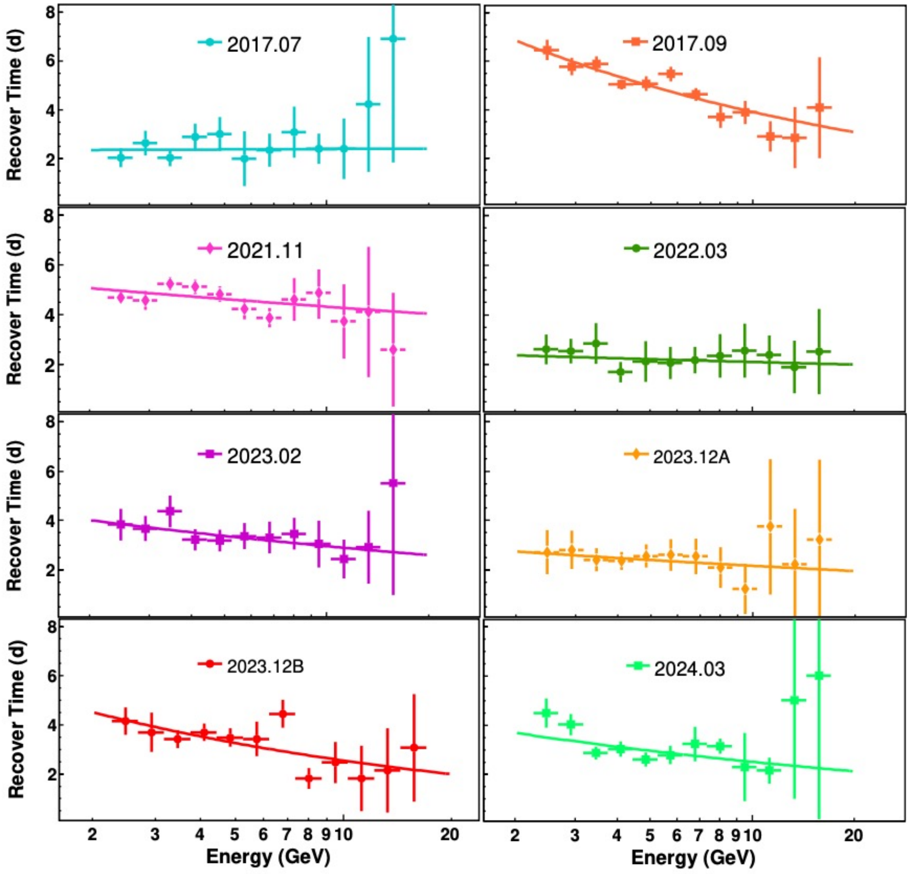
By 2030, AMS will provide unique information for understanding particle transport in the heliosphere over 22-year Solar Cycle

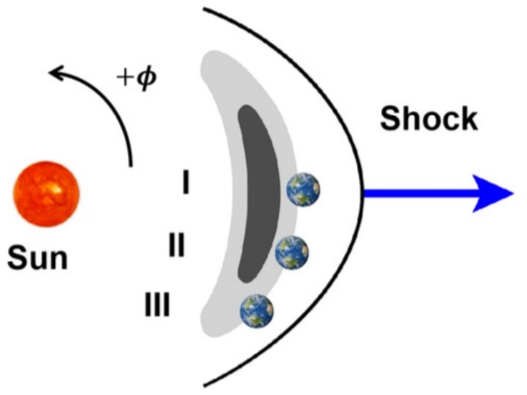
Heliophysics with DAMPE

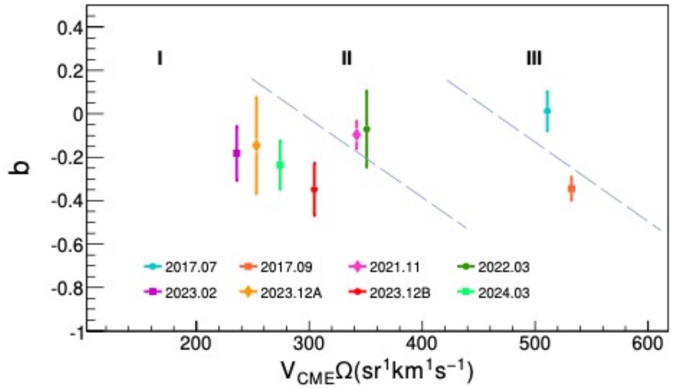
- **Forbush Decrease (FD) — CR follow-up of explosive solar activity, e.g. CME**
- Large acceptance and polar orbit of DAMPE— allows precise FD measurement

DAMPE collaboration, ApJL. 920 L43 (2021)









New FD features for the relation: **recovery time** vs. **decrease amplitude —> diverse properties of FDs**

Heliophysics with CALET

electron and proton count rates at an average rigidity of 3.8 GV