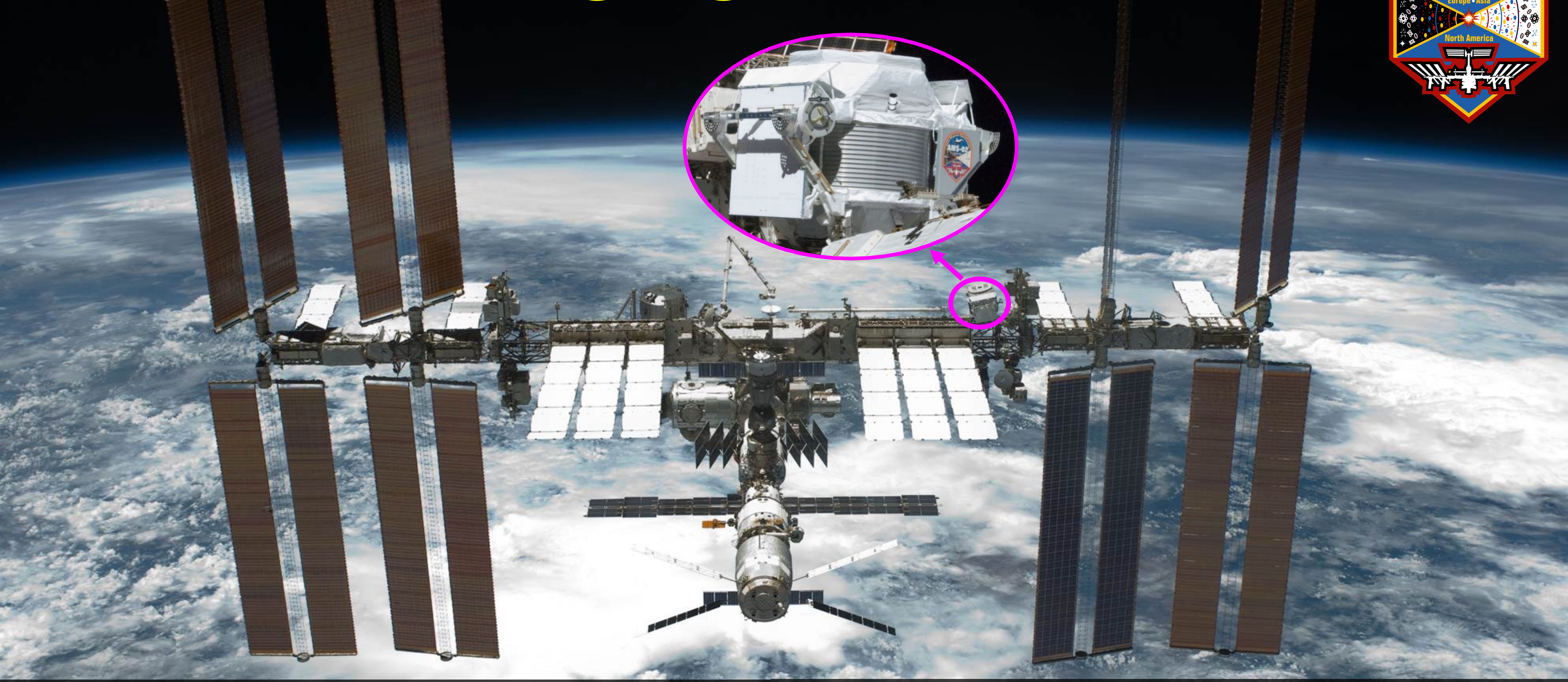
Recent Highlights from AMS-02

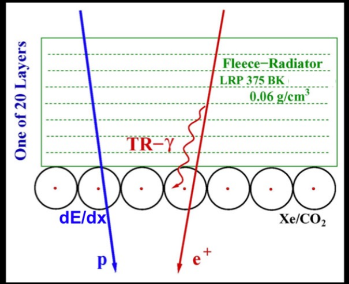


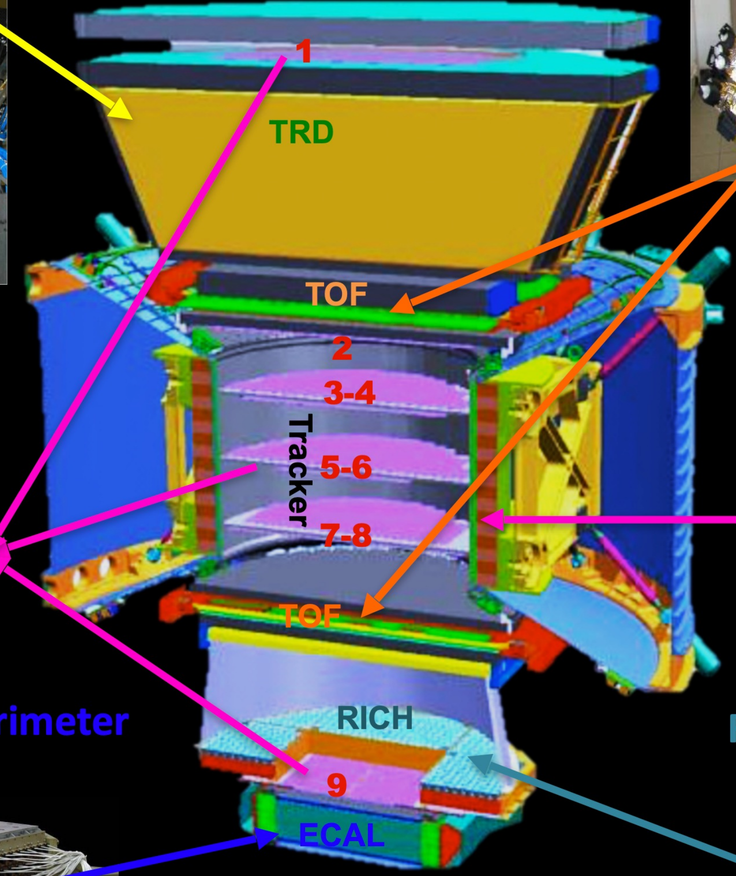
TMEX-2023
Quy Nhon, Vietnam

Hsin-Yi Chou
Institute of Physics, Academia Sinica

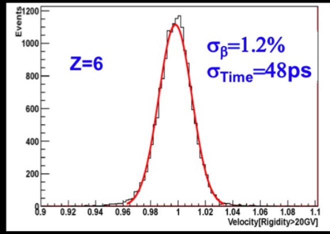
AMS-02: A TeV precision magnetic spectrometer in space

Transition Radiation Detector
Identifies e⁺, e⁻

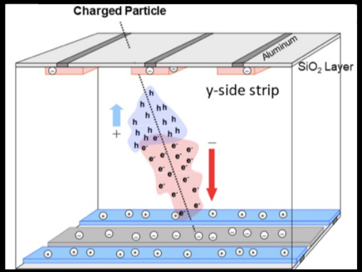


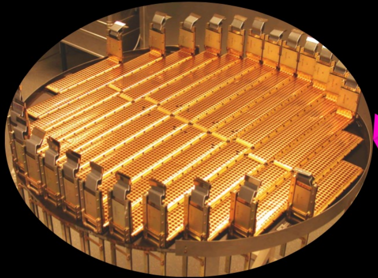


Time Of Flight
Z, β

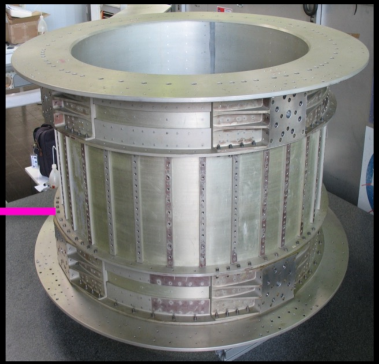


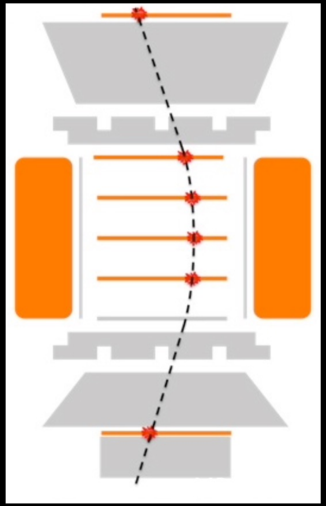
Silicon Tracker
Z, Rigidity=p/Ze



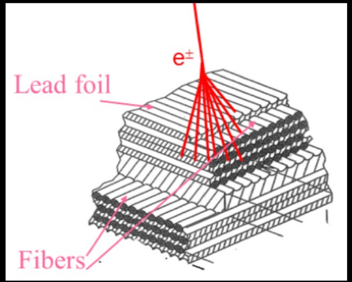


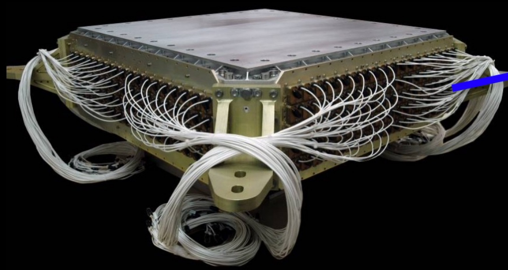
Magnet
±Z



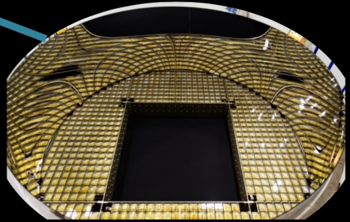


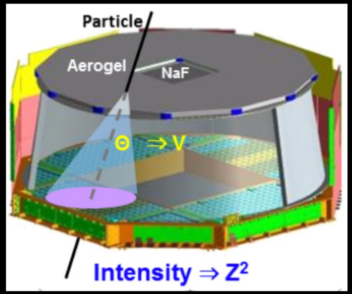
Electromagnetic Calorimeter
Energy of e⁺, e⁻





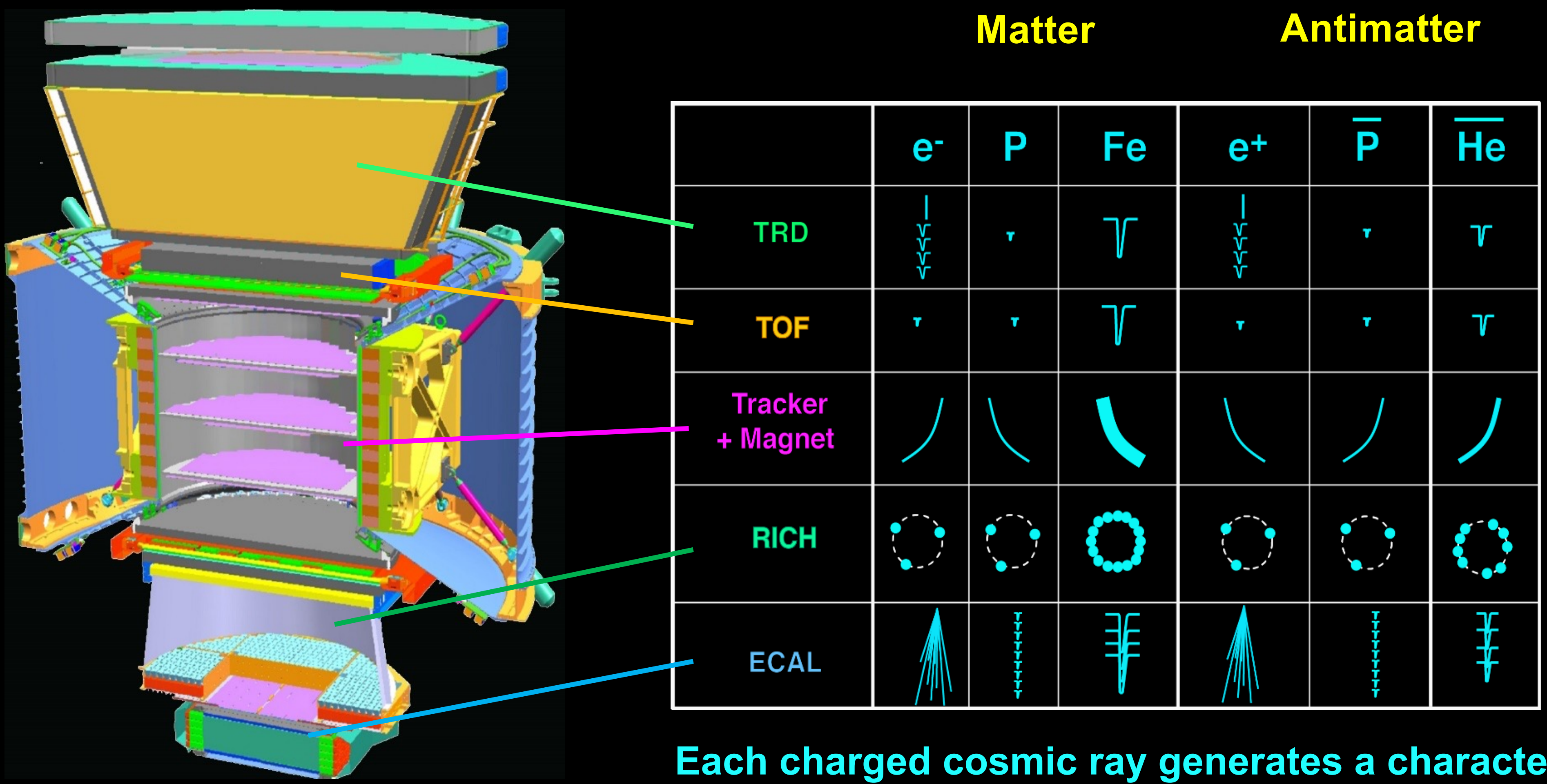
Ring Imaging Cherenkov
Z, β
Isotopic composition





- Energy (E in units of GeV) measured by ECAL.
- Rigidity (R=P/Z in units of GV) measured by Tracker+Magnet.

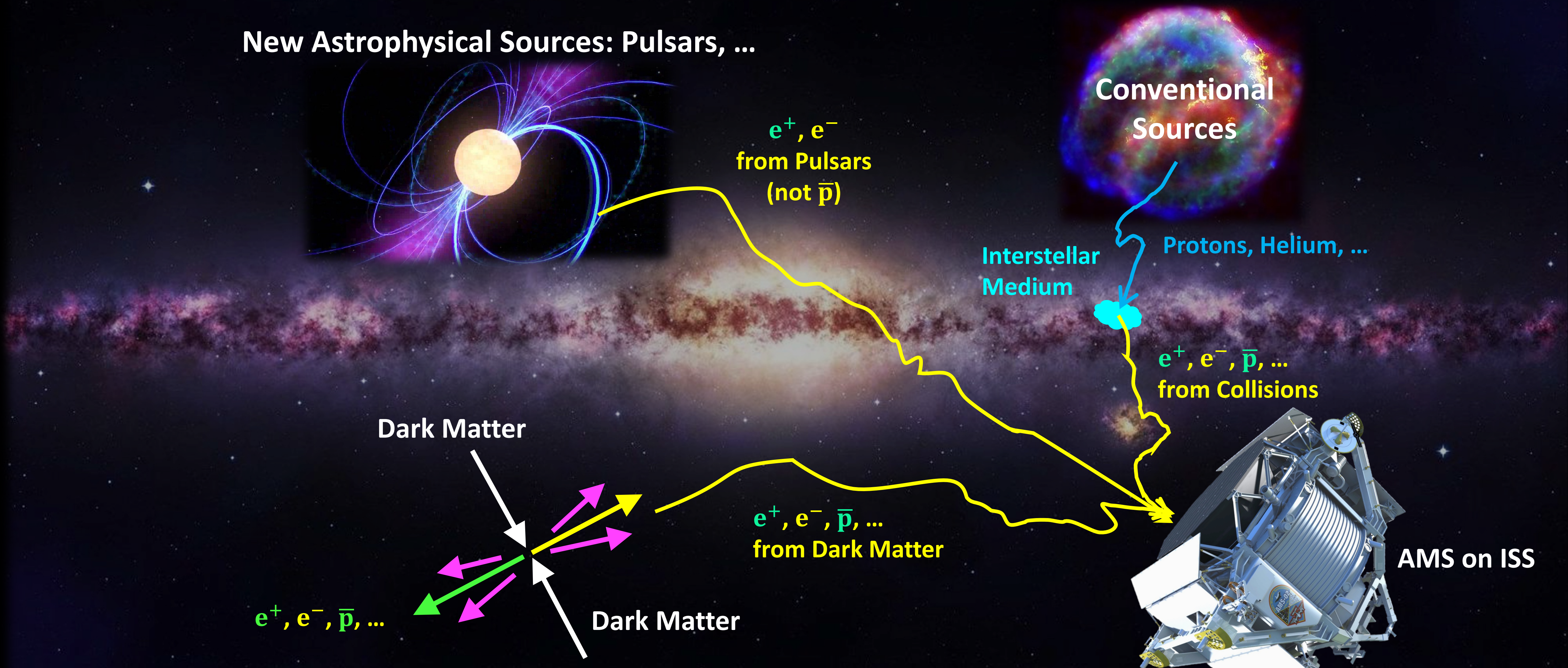
Measurement of Cosmic Rays



Each charged cosmic ray generates a characteristic response in the five detectors (TRD, TOF, RICH, …). Analysis of these responses provides probability distributions for each type of charged cosmic ray,

Origins of Elementary Particles

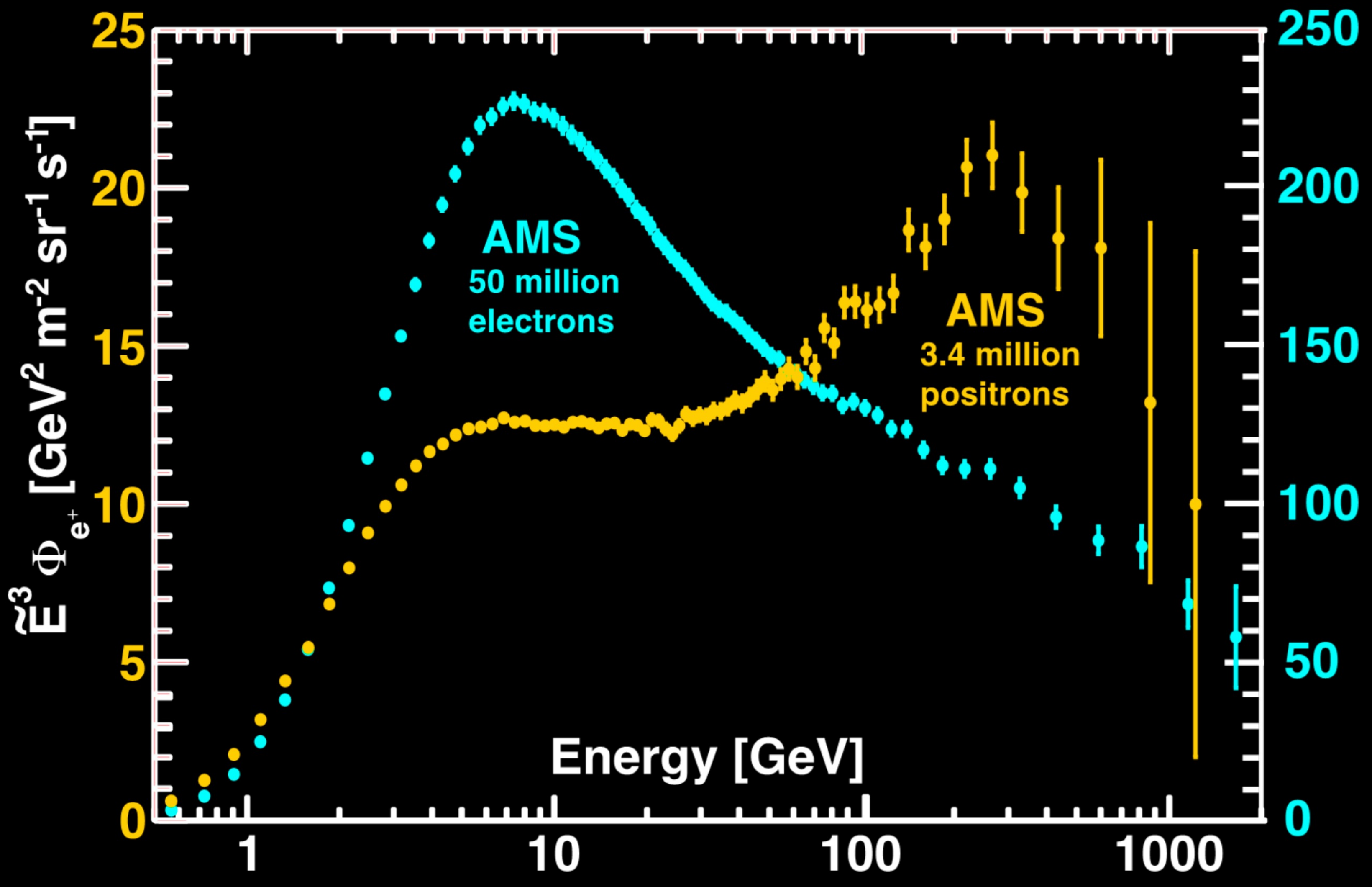
(Positrons e^+, Electrons e^-, Antiprotons $\bar{p}$, Protons p)



Measurement of these elementary particles (e^-, e^+, p, $\bar{p}$)
is a major tool to study new physics in space

Latest Electron and Positron Results

In the entire energy range the electron and positron spectra have distinctly different magnitudes and energy dependences.



Origin of Cosmic Positron

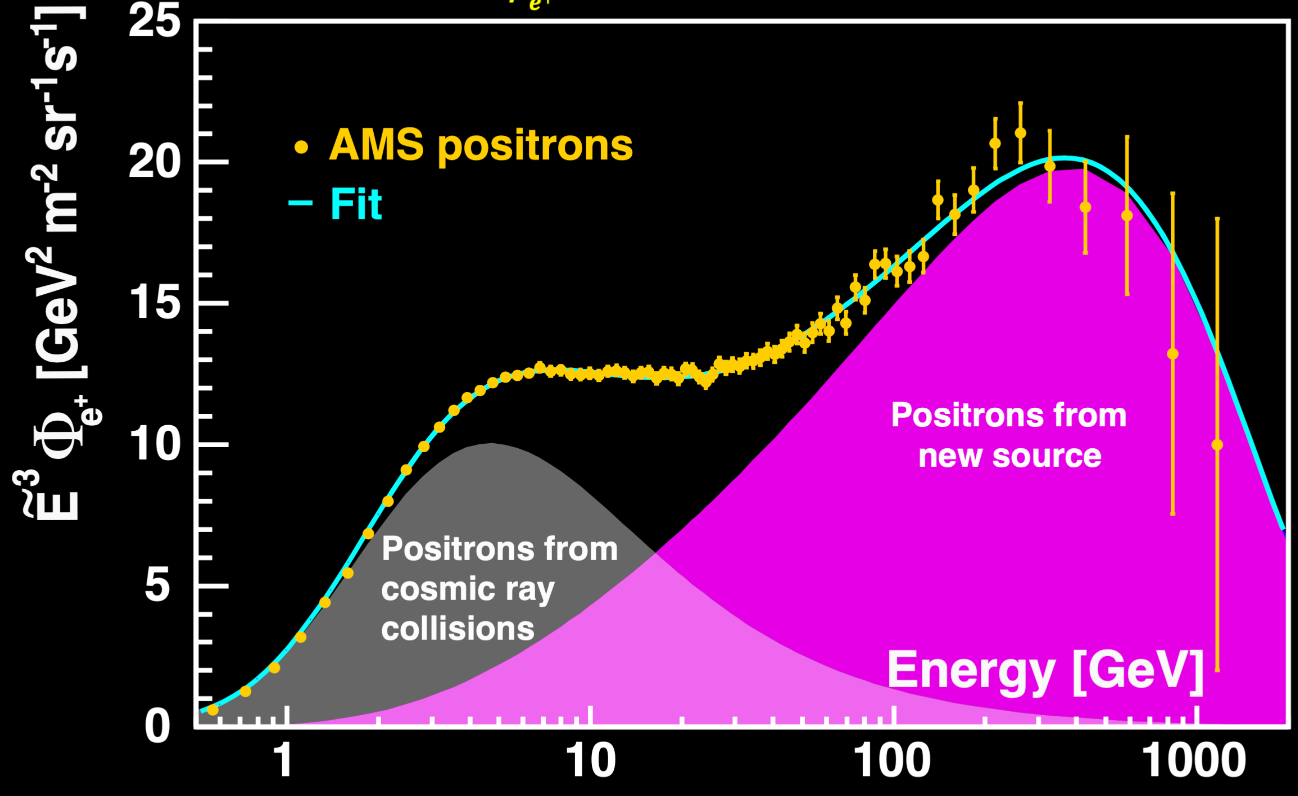
The positron flux is the sum of a low-energy part from cosmic ray collisions and a high-energy part from a new source.

Most importantly, the high energy spectrum must have a cutoff energy.

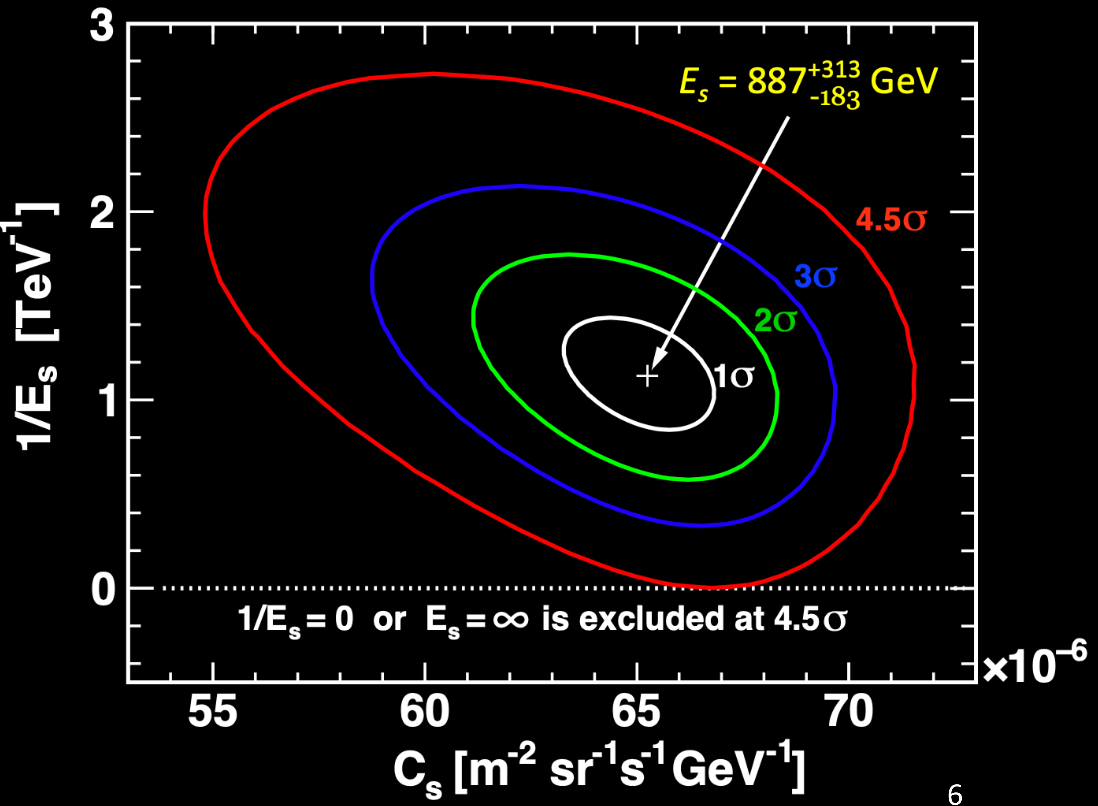
Solar Collisions New Source

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

$$\hat{E} = E + \varphi_{e^+}$$

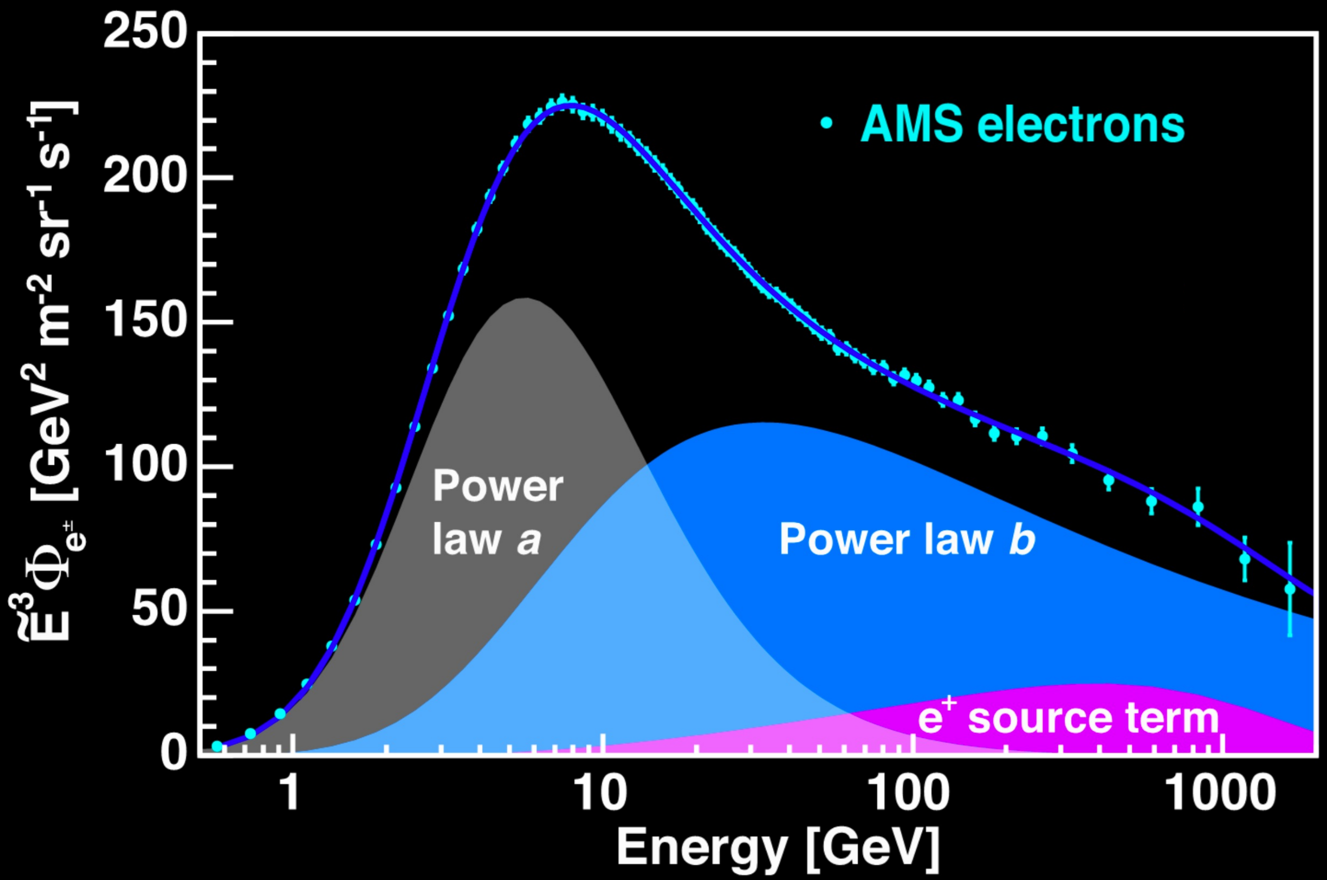


A cutoff energy ~1TV is observed with 4.5σ C.L.



Origin of Cosmic Electrons

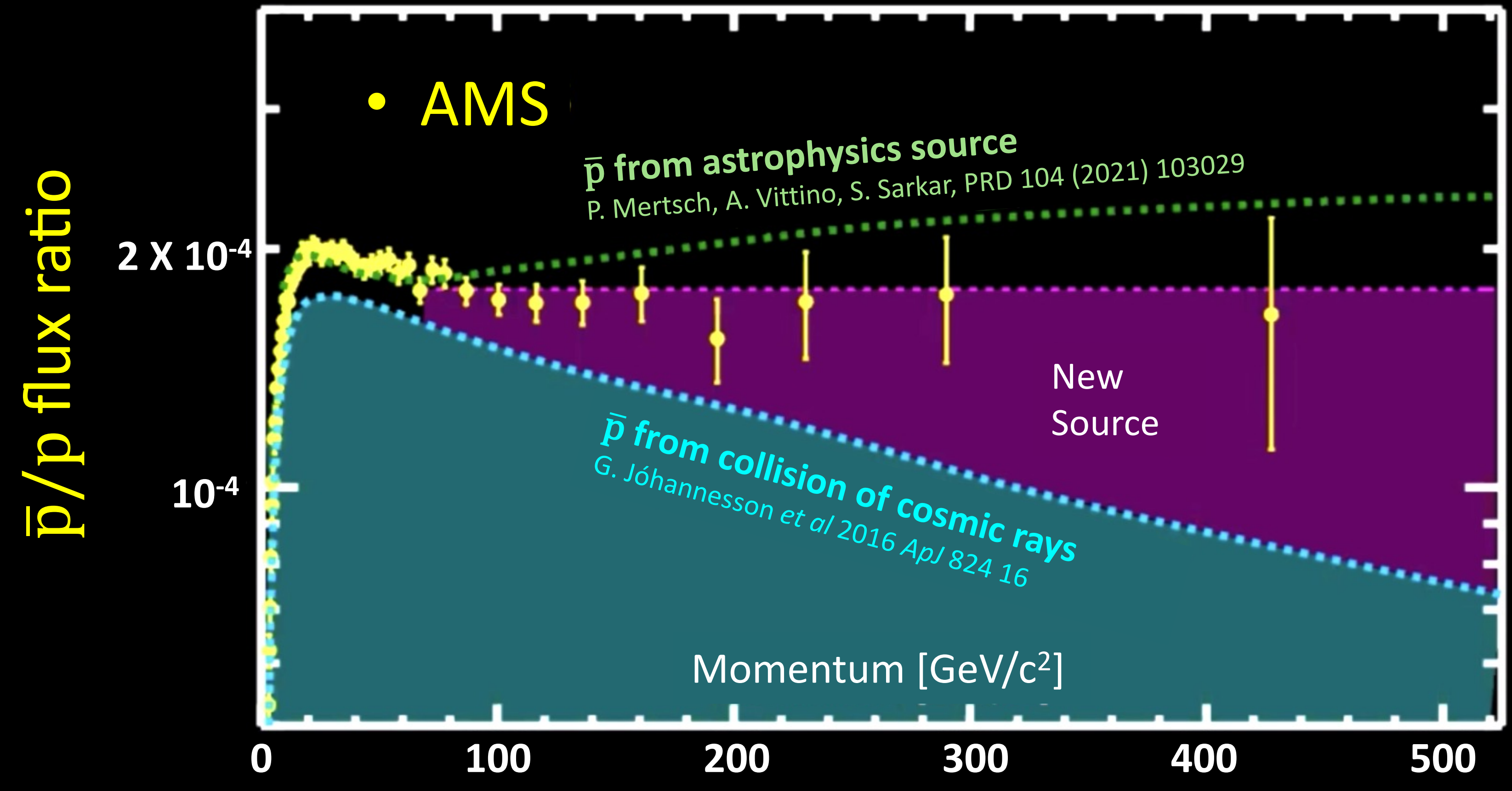
The electron spectrum has three origins. Two can be described by traditional power law sources and one new, high-energy electron source is identical to the new positron source.



Thus, there exists a cosmic source which produces equal amounts of high-energy positrons and electrons.

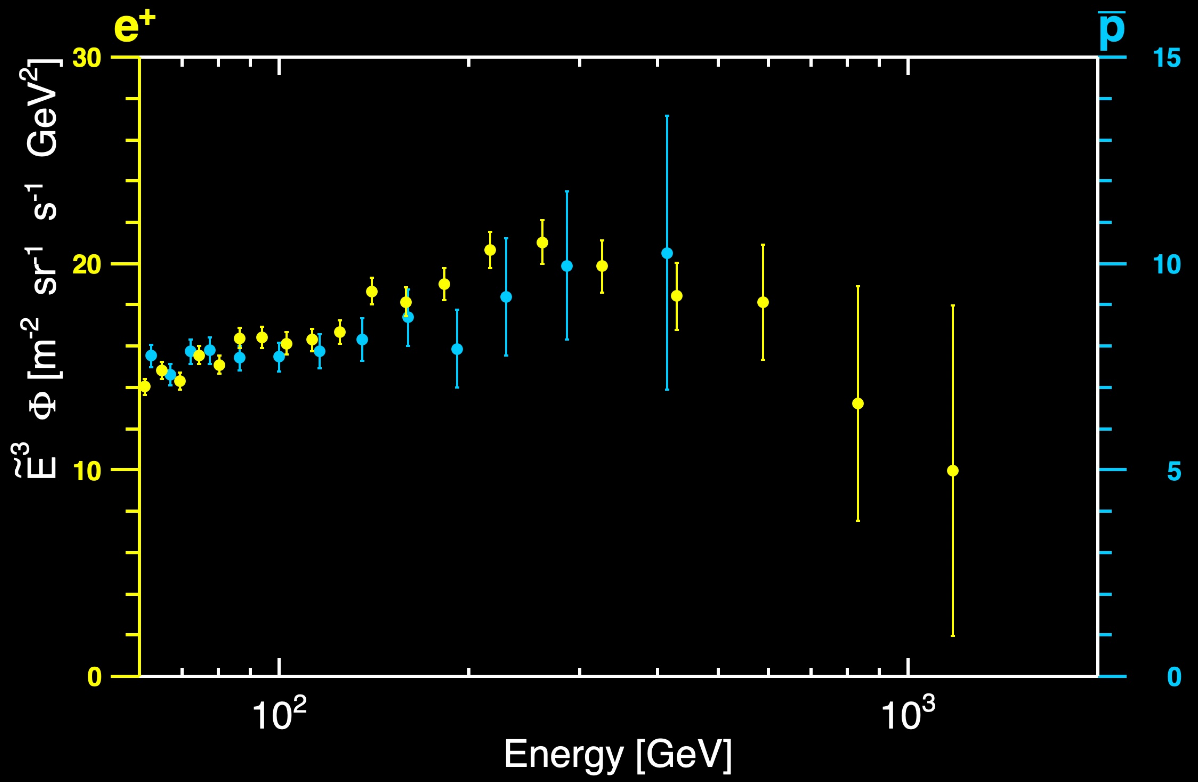
Properties of Cosmic Antiprotons (I)

The antiproton-to-proton flux ratio is
energy independent above 60 GV.

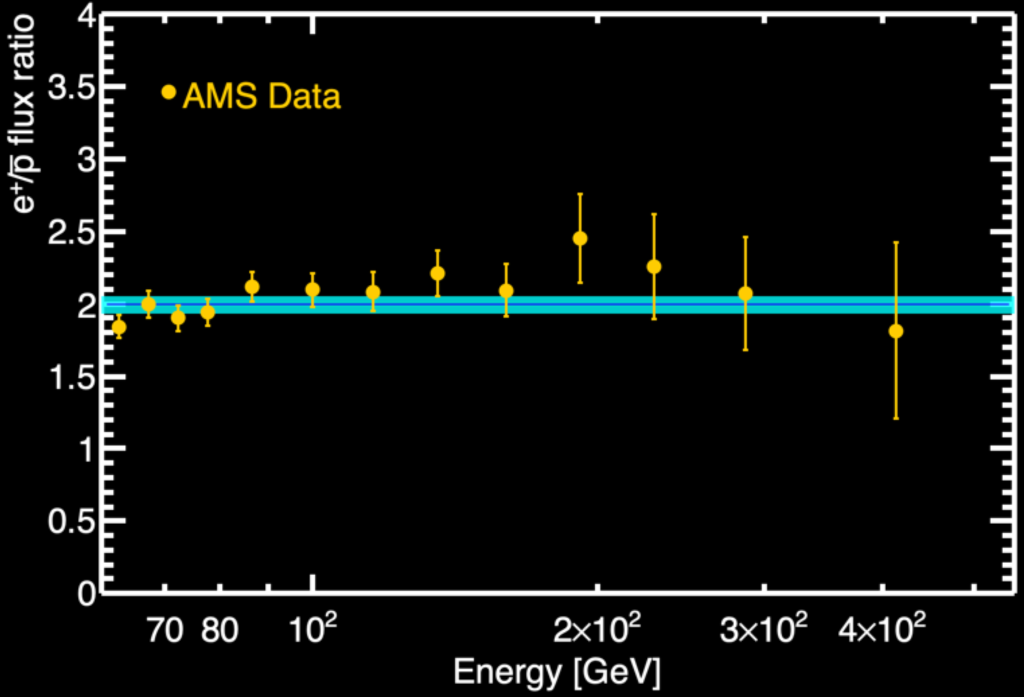


Properties of Cosmic Antiprotons (II)

The positron-to-antiproton flux ratio shows that above 60 GV the ratio is energy independent



The $\bar{p}$ and e^+ fluxes have identical rigidity dependence.

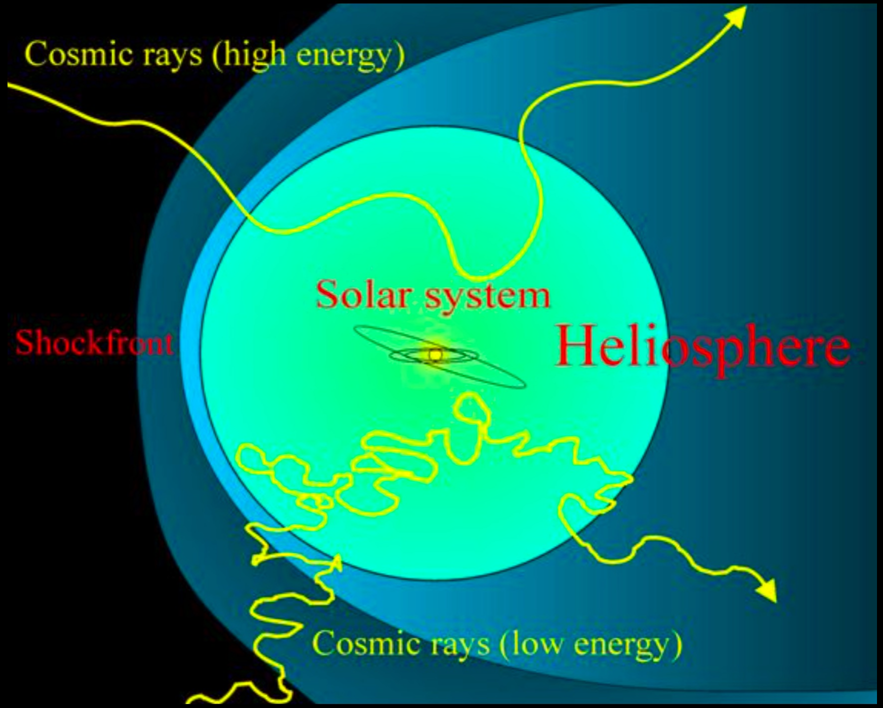


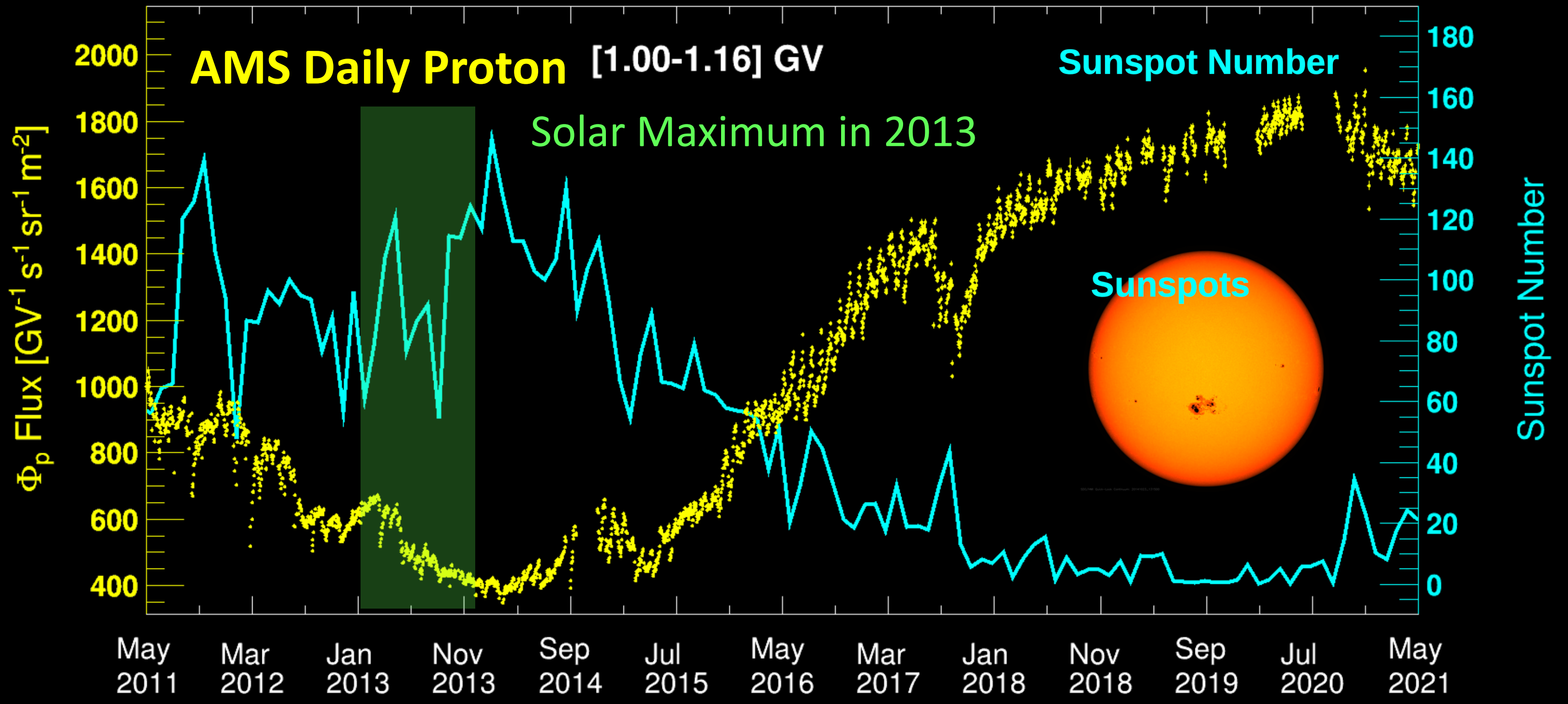
$e^+/\bar{p}$ flux ratio
1.99±0.03(stat.)±0.05(syst.)

$\bar{p}$ are not produced by pulsar.

Solar Modulation of Low Energy Cosmic Rays

The time evolution of the interplanetary space environment causes cosmic-ray intensity variations (i.e. solar modulation).



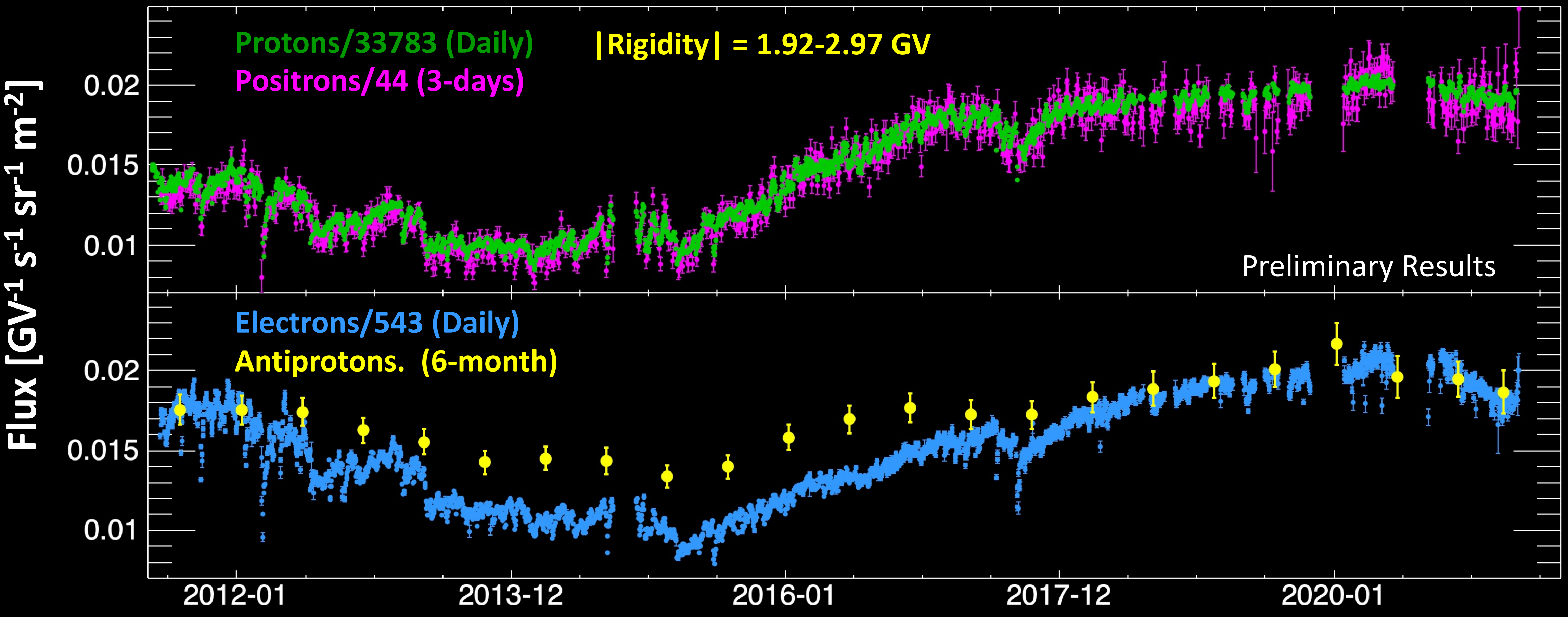


Sunspots are darker regions of the Sun with lower temperatures and higher magnetic fields.

The solar modulation is particularly visible at rigidities below 100 GV, and its long-scale variation changes with the 11-year solar cycle.

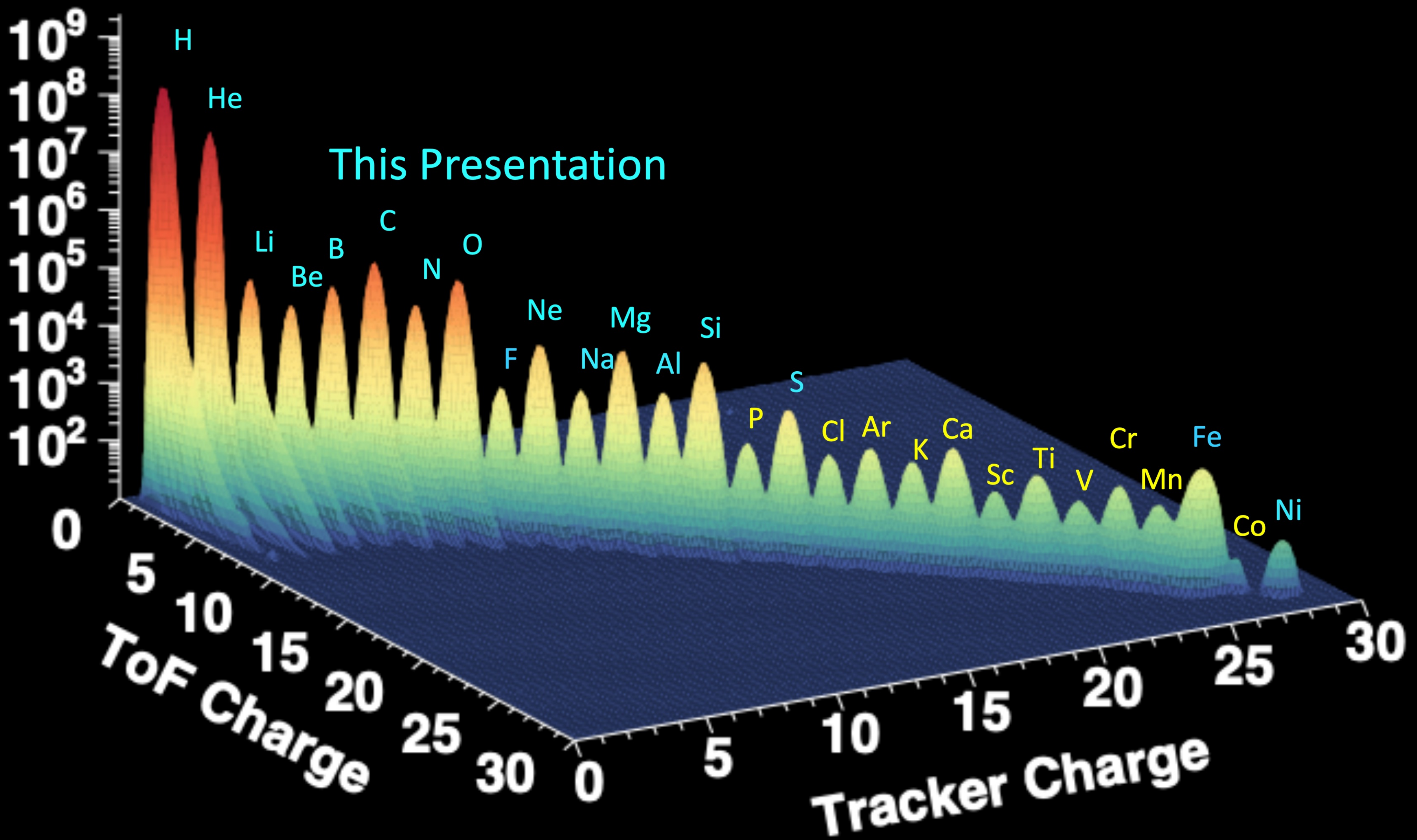
Unique Measurements of Time Evolution of Elementary Particles

AMS is the only instrument to measure antiproton and other elementary particle's flux across the entire solar cycle.



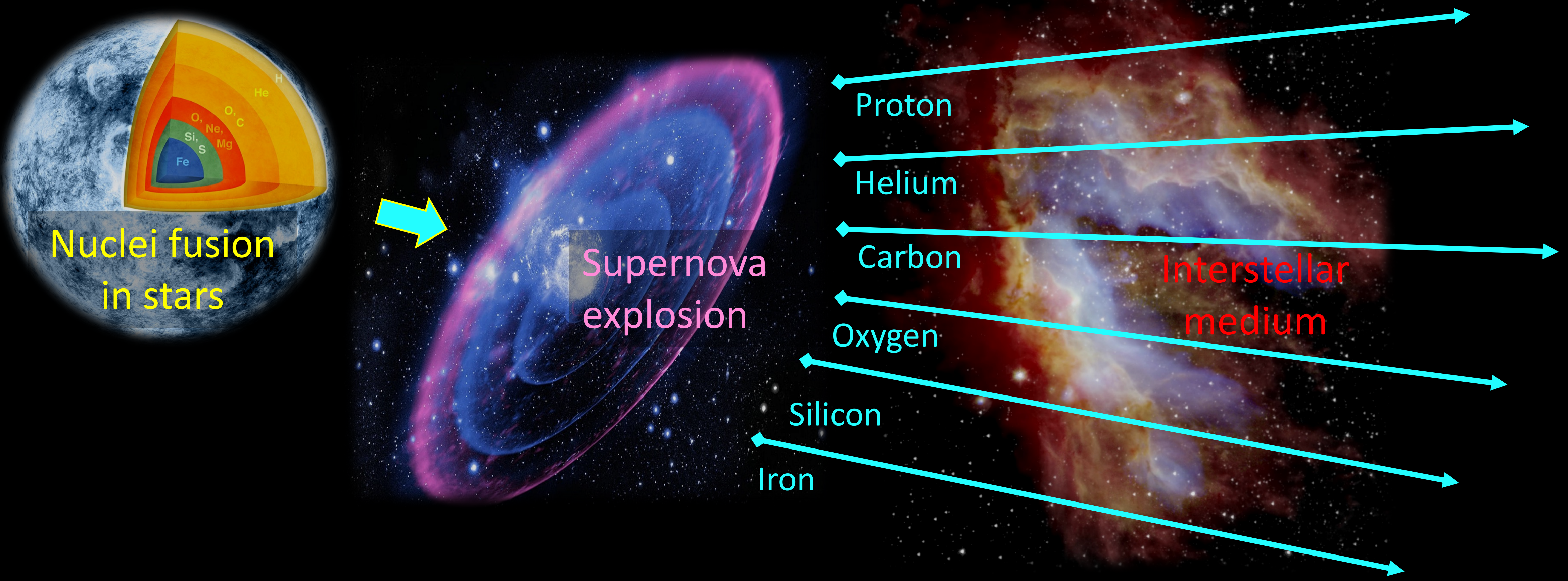
Measurements of the time evolution of elementary particles are important to understanding the low-energy cosmic rays affected by solar activities.

AMS Study of Cosmic Nuclei



Primary Cosmic Rays

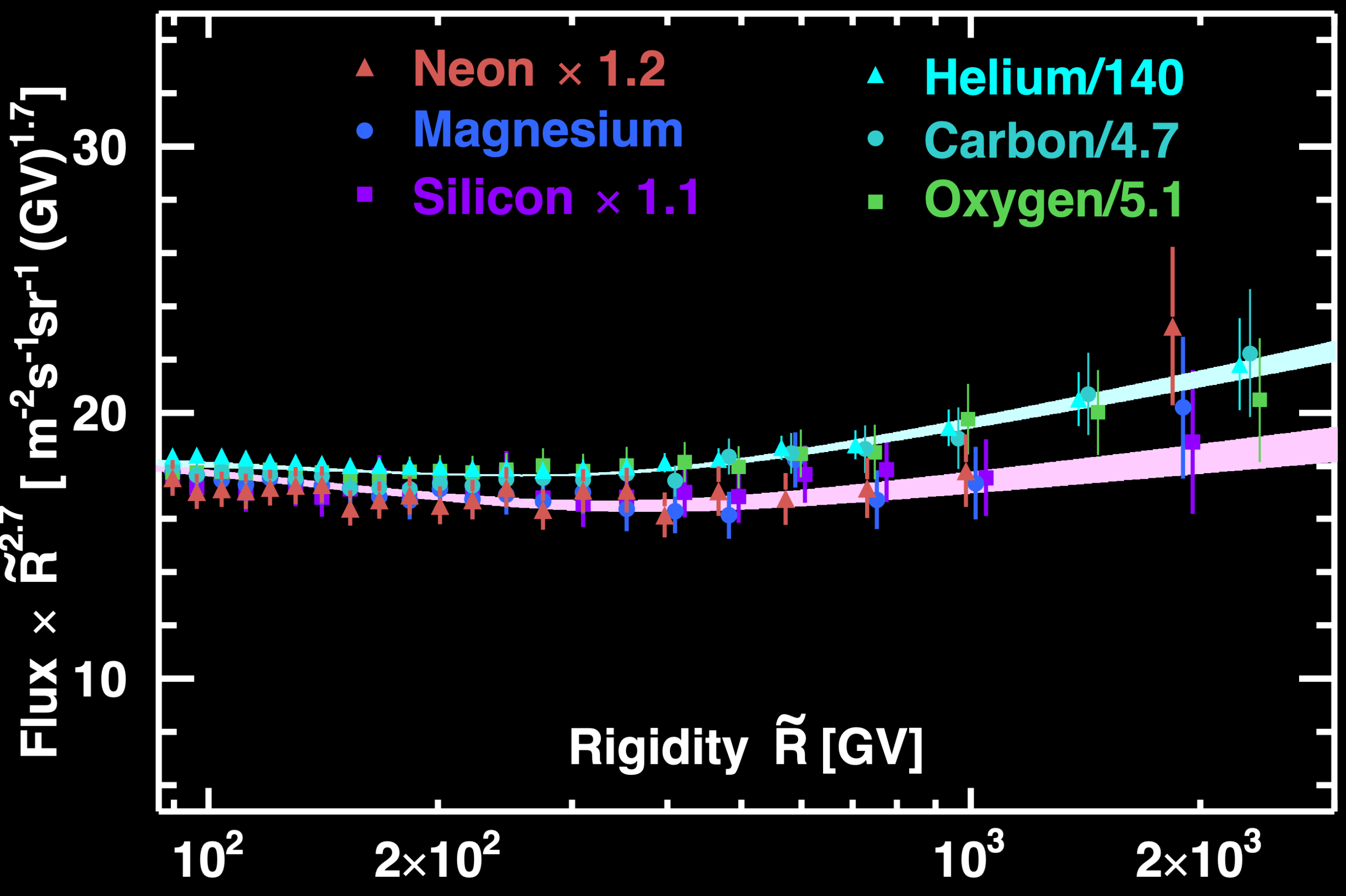
Primary cosmic rays p, He, C, O, …, Si, …, Fe are produced during the lifetime of stars and accelerated by supernovae. They propagate through interstellar medium before they reach Earth.



Measurements of primary cosmic ray fluxes are fundamental to understanding the origin, acceleration, and propagation processes of cosmic rays in the Galaxy.

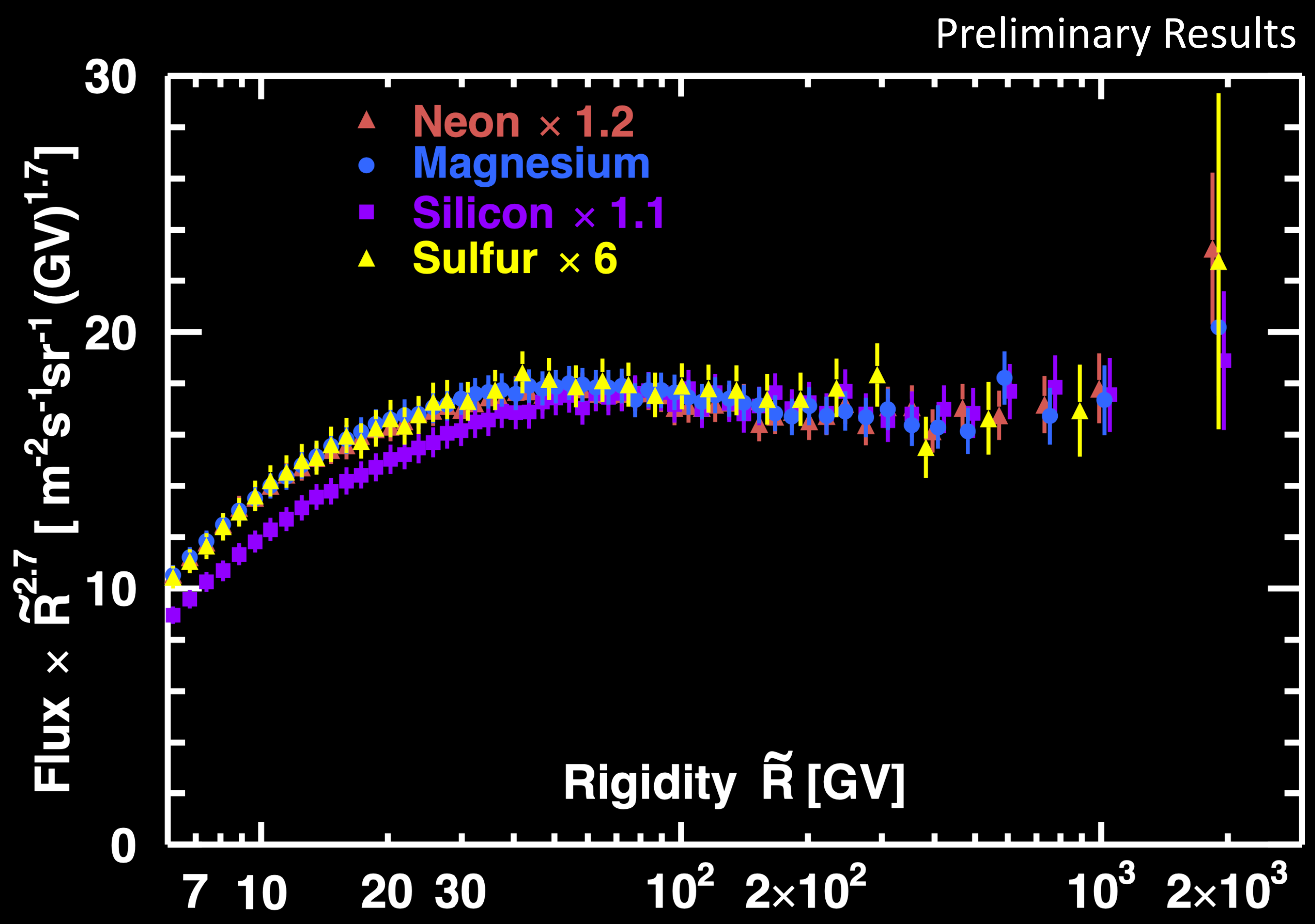
AMS Results: Primary cosmic rays have at least two classes

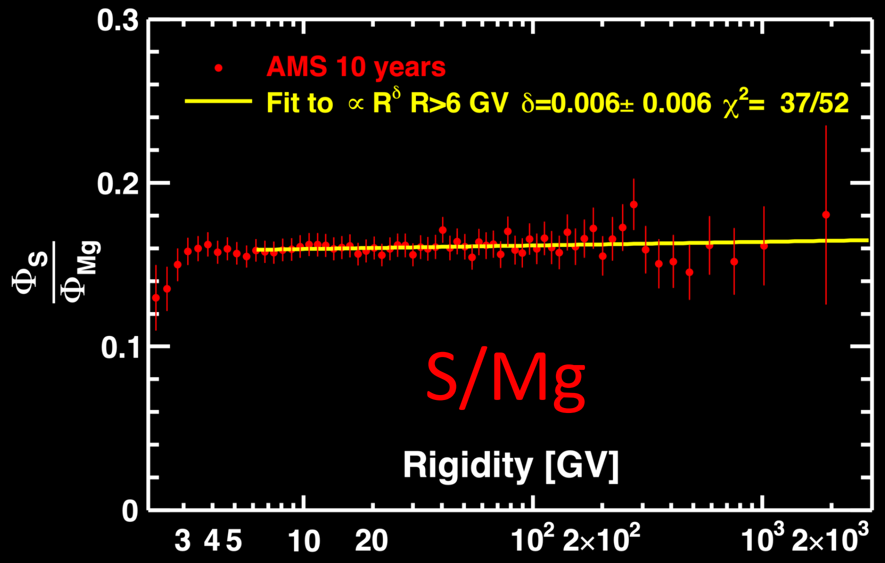
Above 60 GV, the primary cosmic rays, He, C, O have identical rigidity dependence.
Heavier primary cosmic rays Ne, Mg, Si have their own identical rigidity dependence but different from He, C, O.

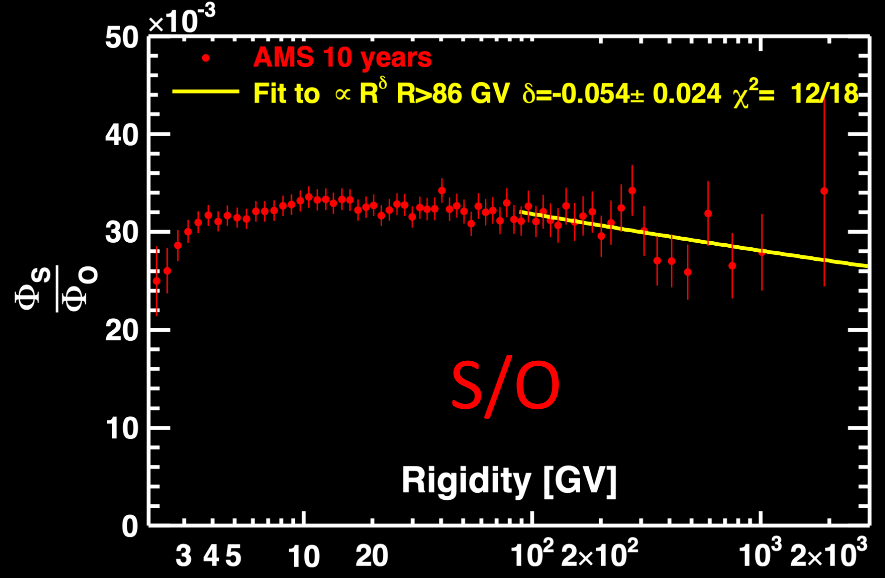


AMS Results: Cosmic Sulfur

Sulfur belongs to the same class as Ne-Mg-Si.

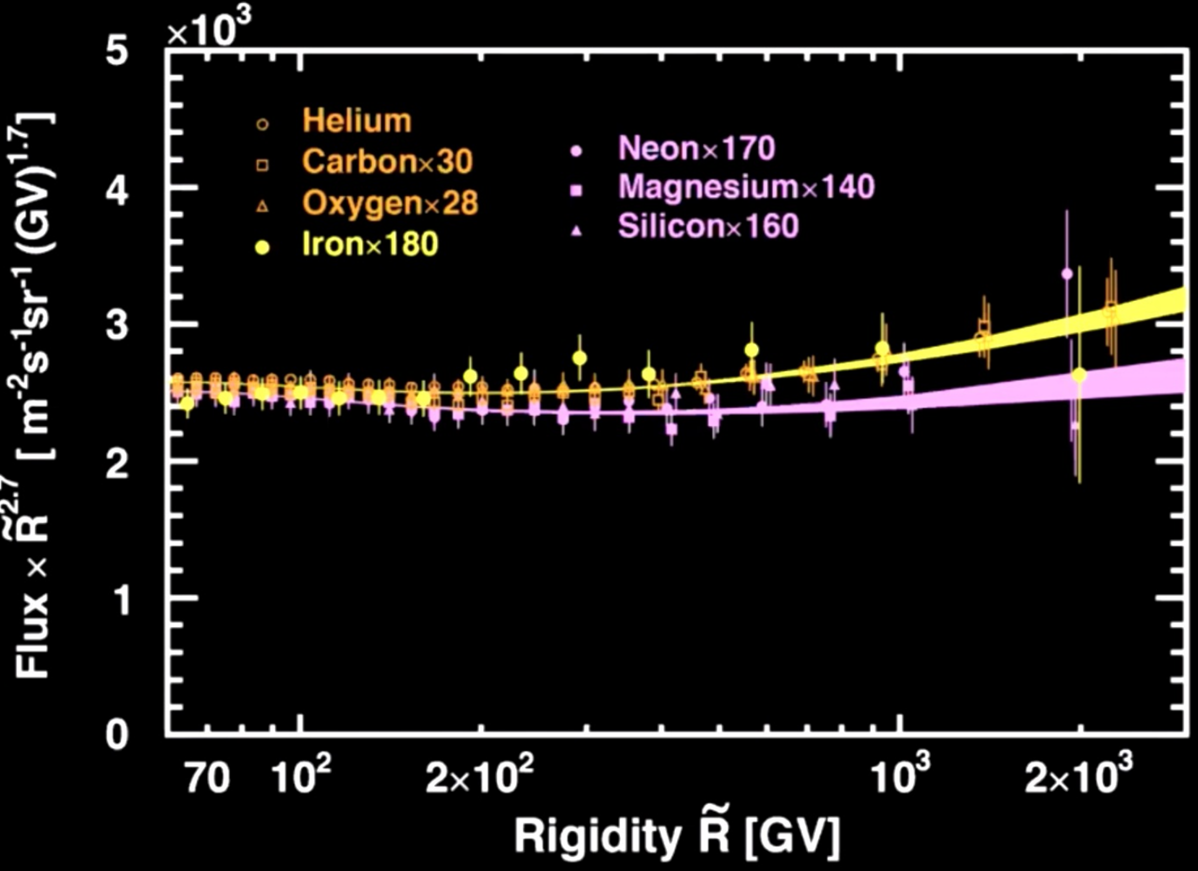






Measurement of the Heaviest Primary Cosmic Ray

Iron is a very important element in cosmic ray theories because it is the heaviest element produced during stellar evolution.

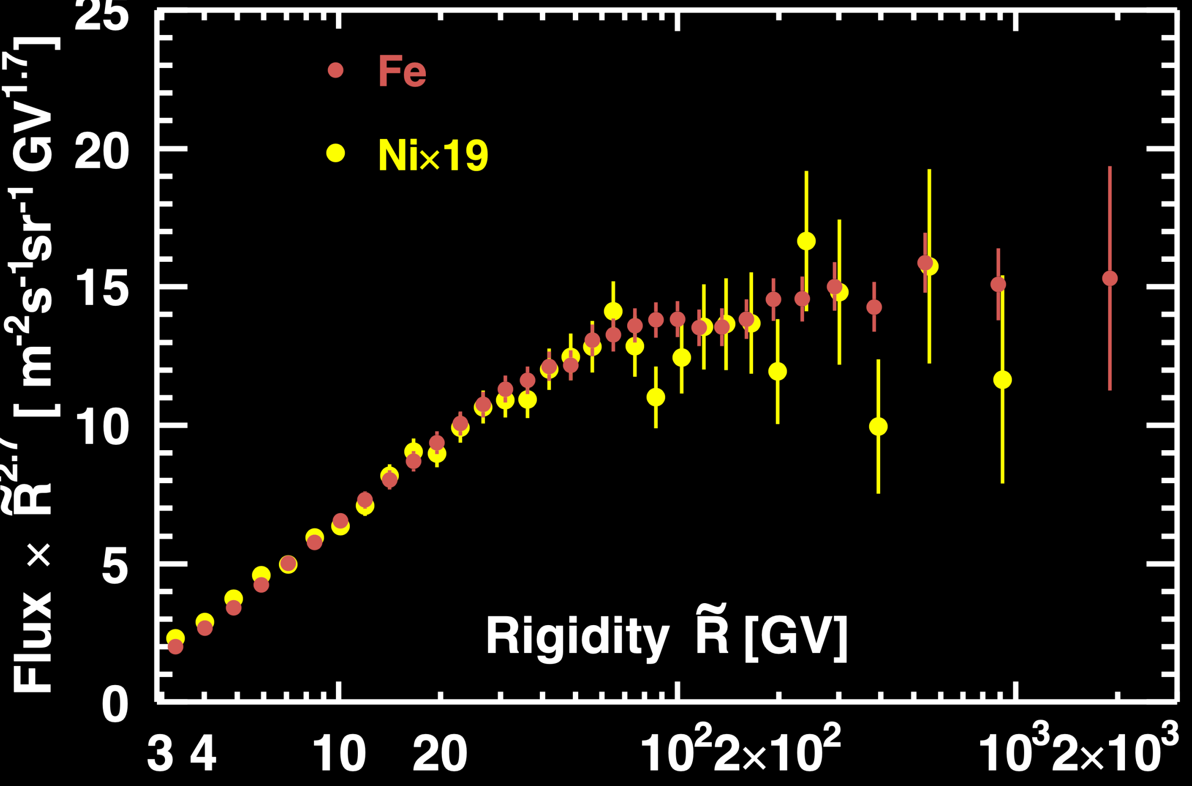


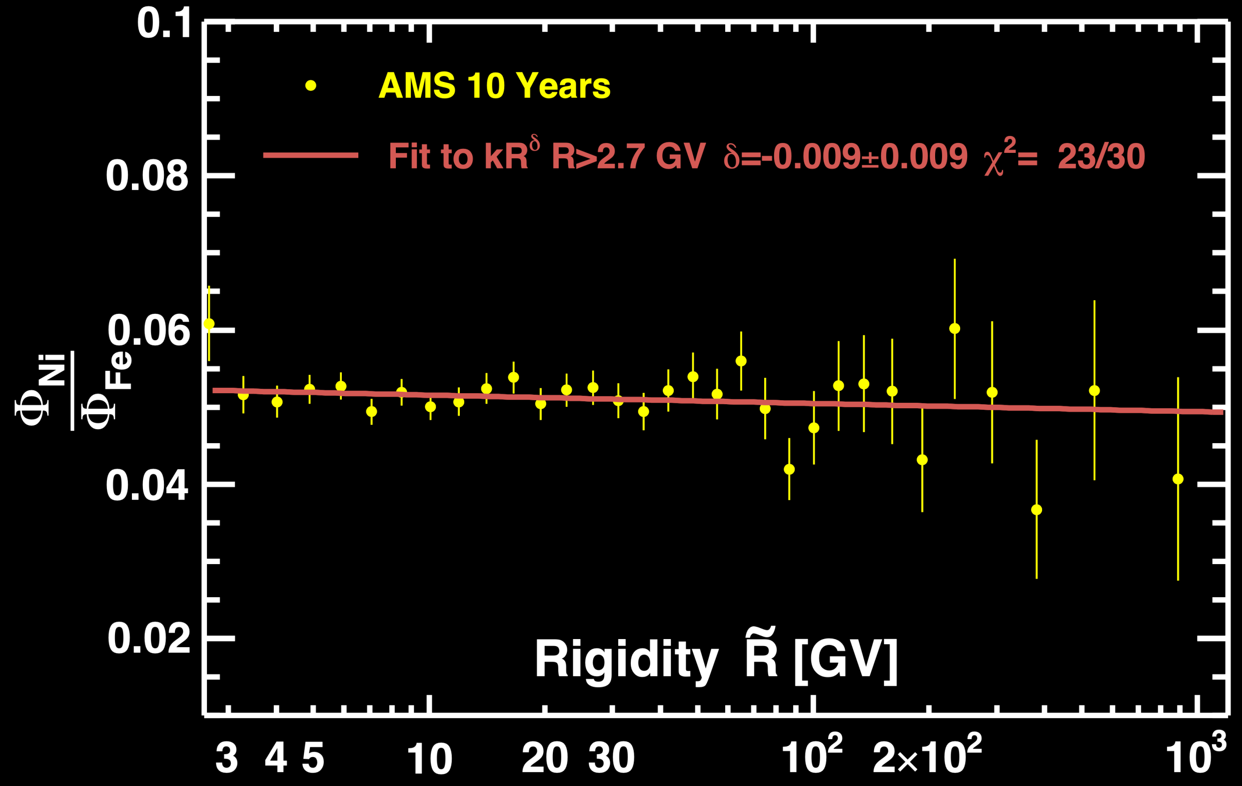
Unexpectedly, iron is in the He-C-O primary cosmic ray class instead of the nearby heavier Ne-Mg-Si class.

AMS Results: Cosmic Nickel

Rigidity dependence of Nickel (Z=28) flux is similar to Iron (Z=26).

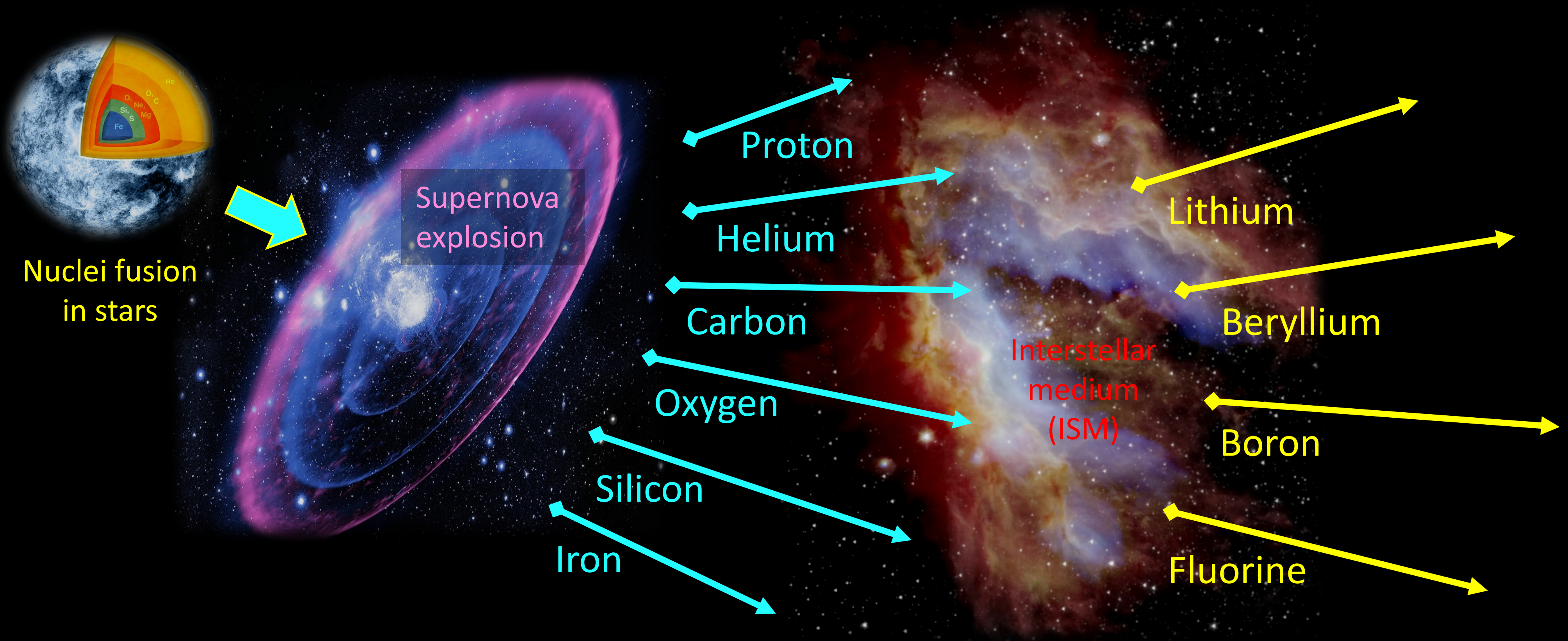
Preliminary Results





Secondary Cosmic Ray

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

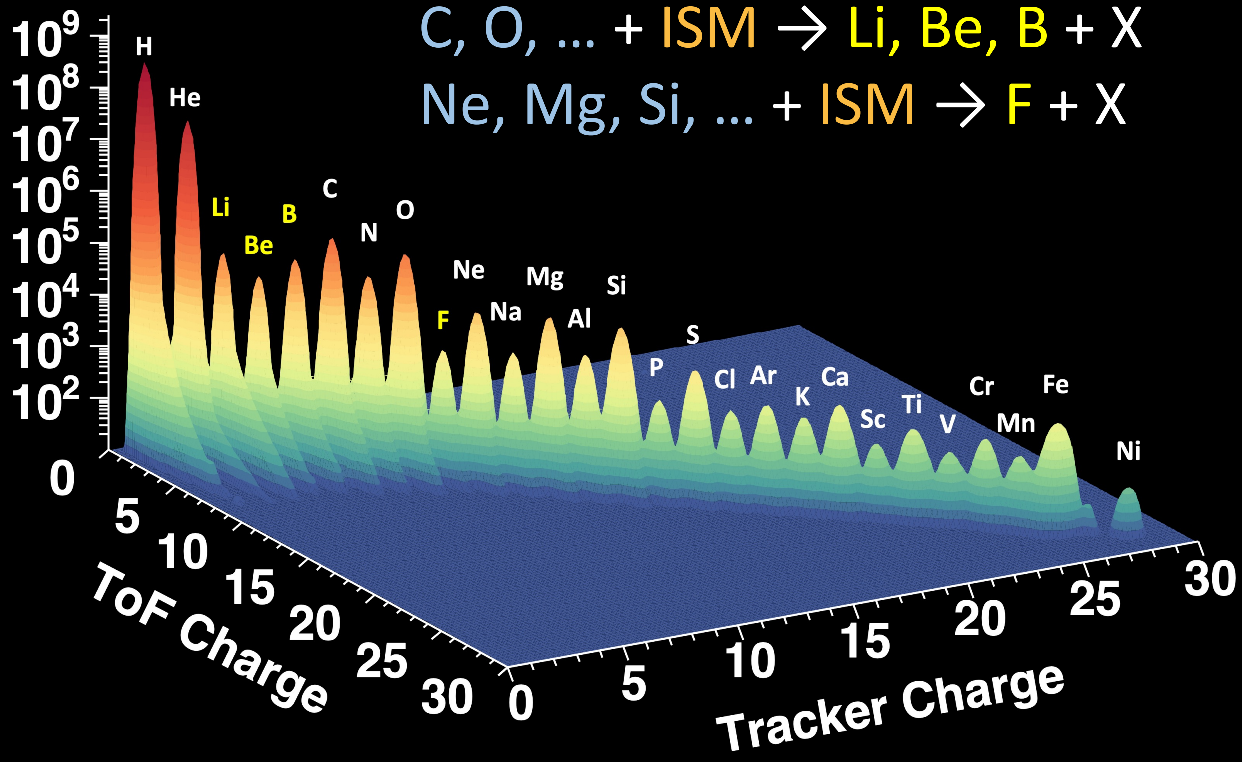


Measurements of secondary cosmic ray nuclei fluxes are important in understanding the propagation processes of cosmic rays in the Galaxy.

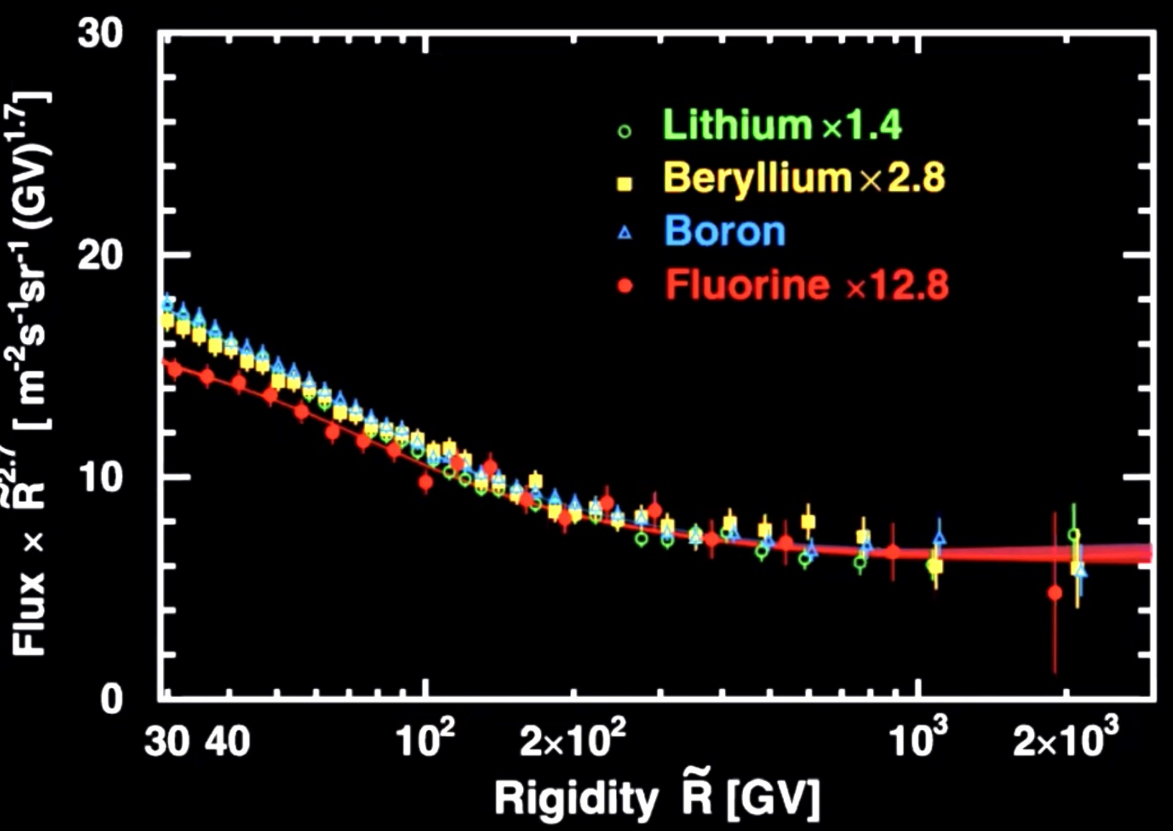
AMS Results: Cosmic Li-Be-B and F

Secondary cosmic rays Li, Be, and B have identical rigidity dependence

Secondary cosmic rays have two classes: Li-Be-B and F
Both classes are different from primaries.

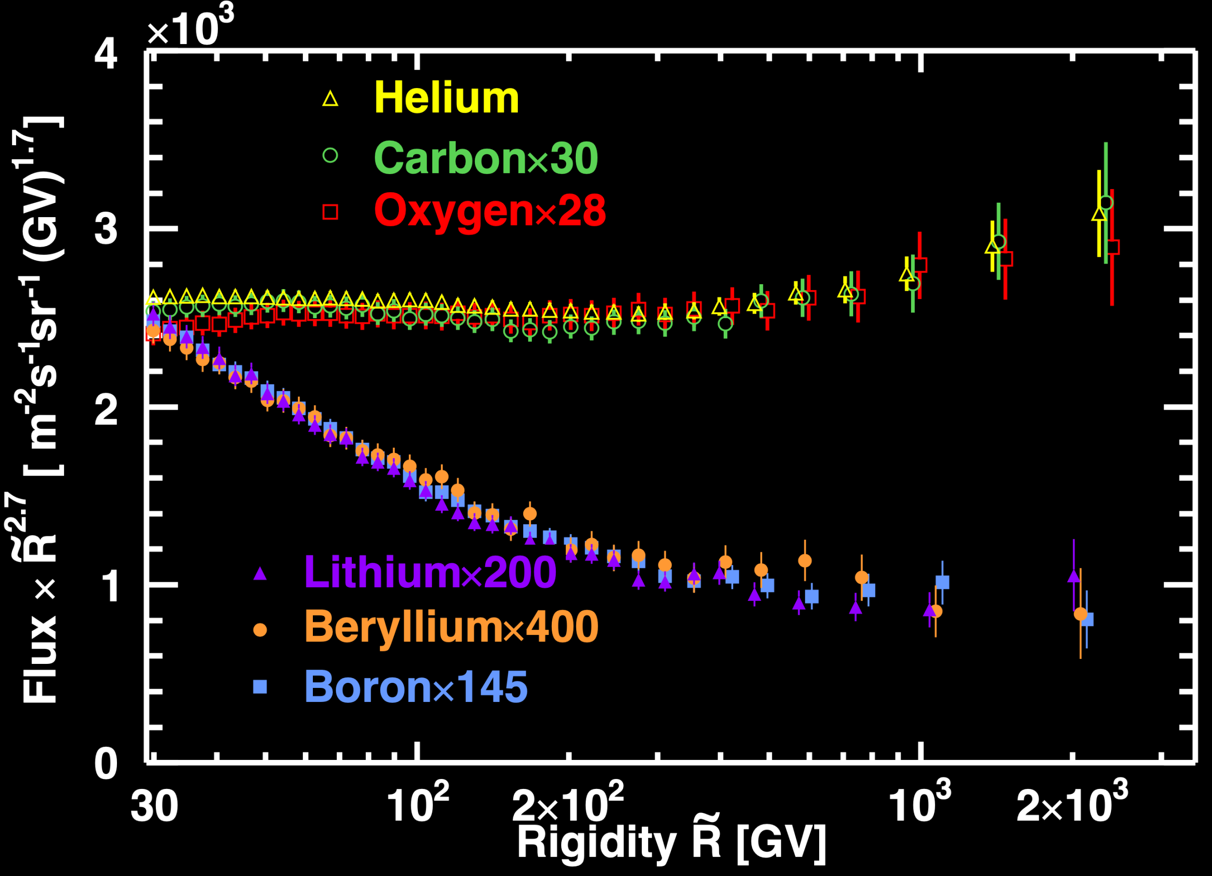


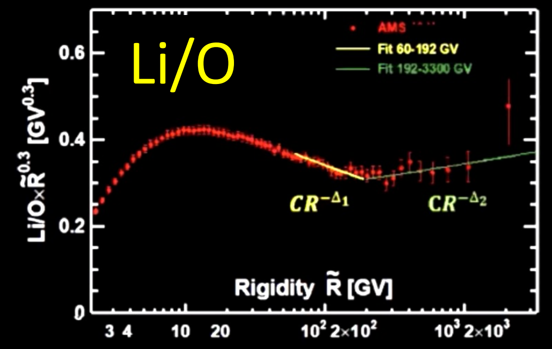
C, O, … + ISM → Li, Be, B + X
Ne, Mg, Si, … + ISM → F + X

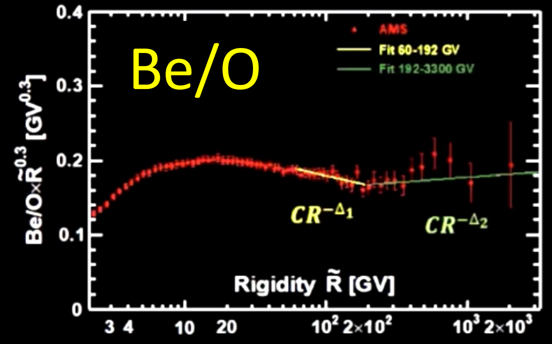


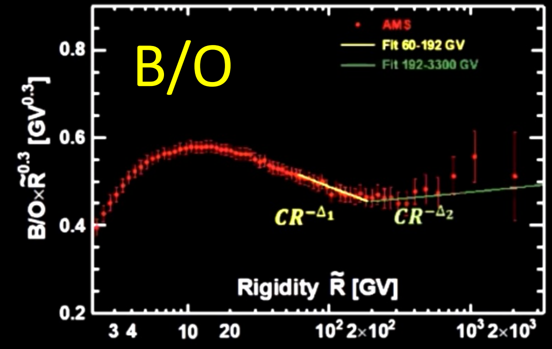
Light Ions Primary (He, C, O) and Secondary Fluxes (Li, Be, B)

The ratio of secondary flux to primary flux (B/C, …) directly measures the amount and properties of intersteller medium.









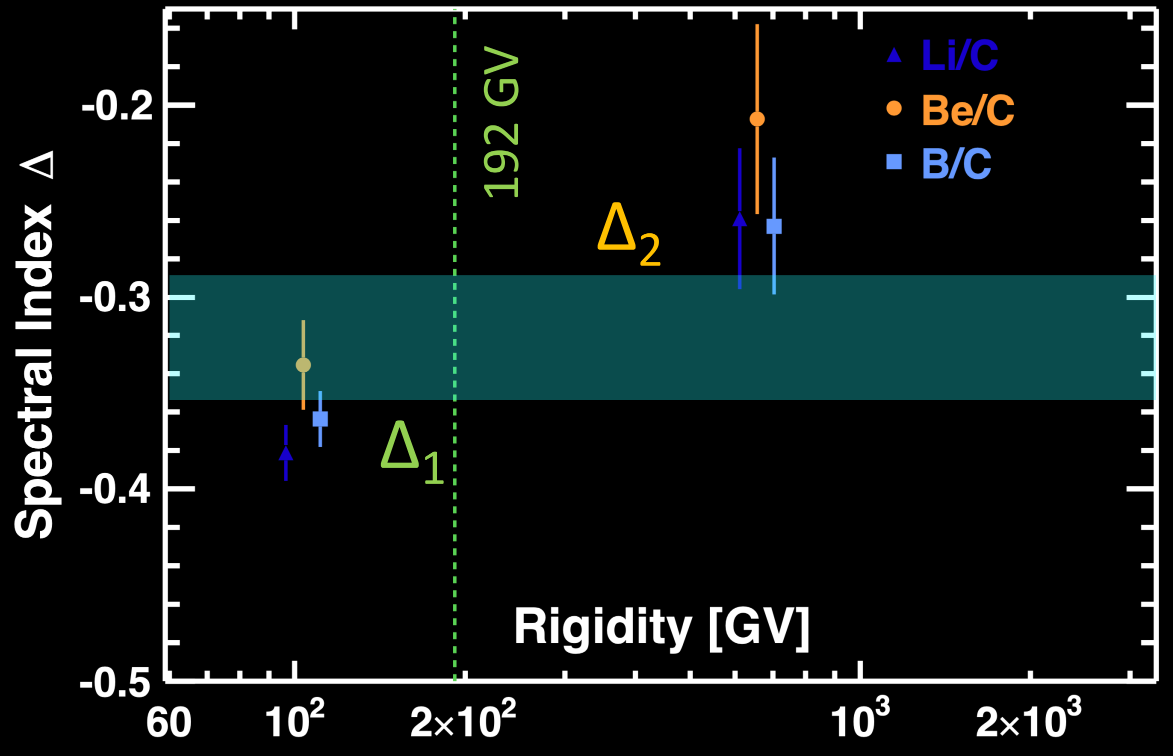
The Li/O, Be/O, and B/O flux ratios were fitted to:

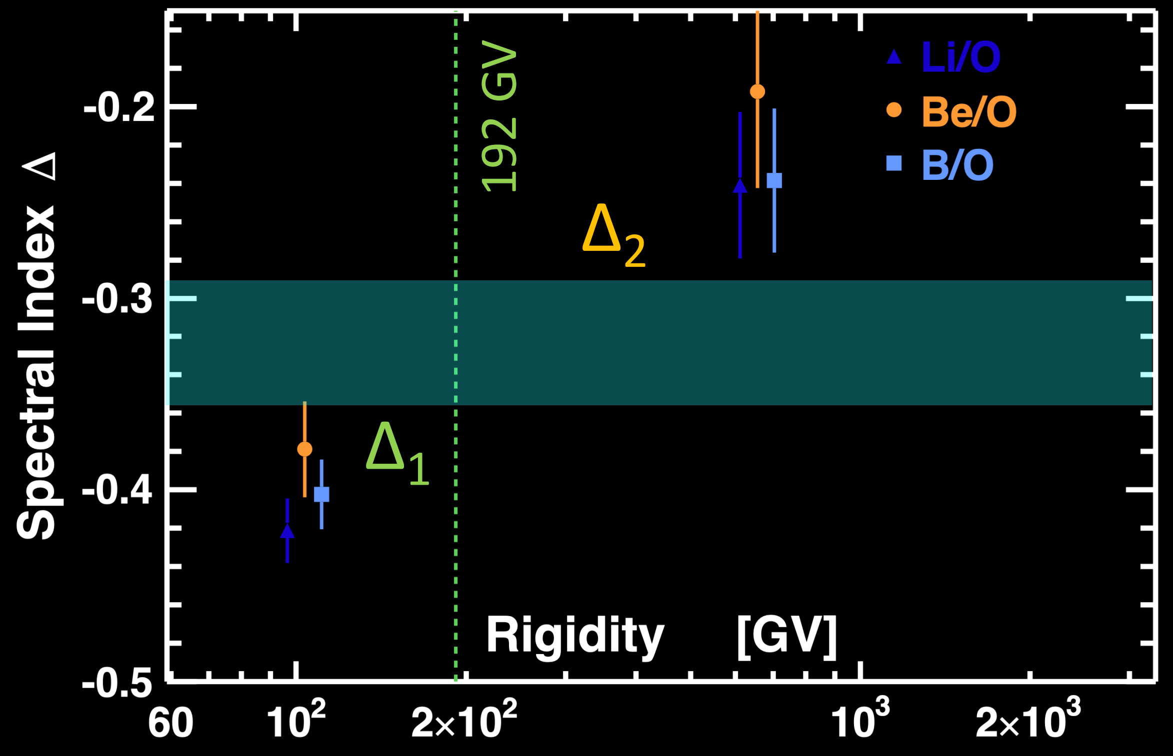
$$\begin{cases} C_1(R/192\ \text{GV})^{-\Delta_1}, & R \le 192\ \text{GV} \\ C_2(R/192\ \text{GV})^{-\Delta_2}, & R > 192\ \text{GV} \end{cases}$$

Secondary (Li, Be, B) to Primary (C, O) Flux Ratios Indices

The new observation strongly favours the hypothesis that the observed spectral hardening is due to a propagation effect

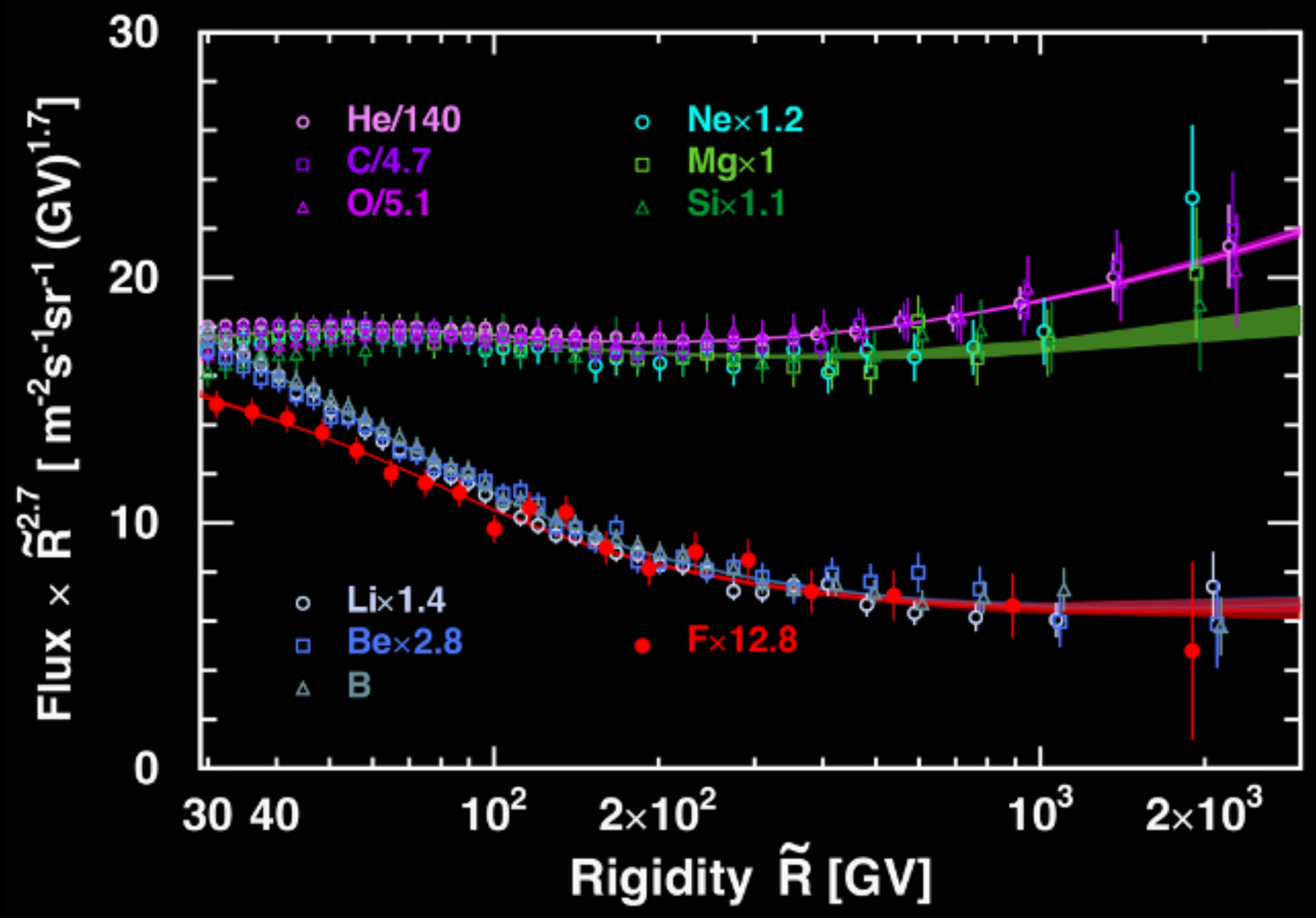
Predictions of modern cosmic ray theory

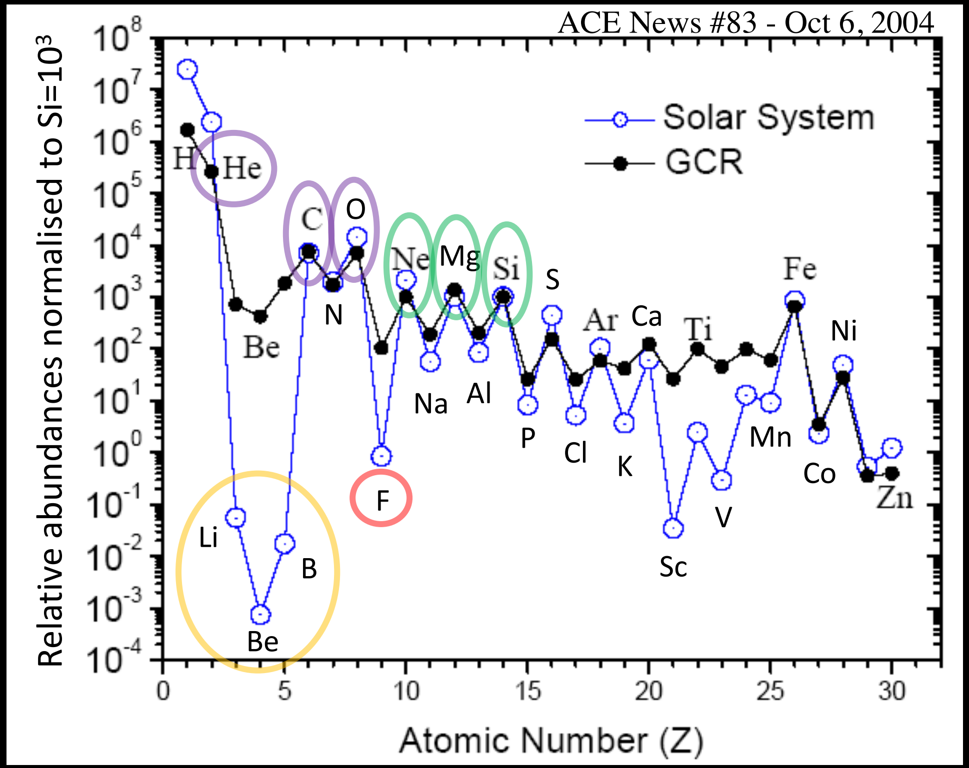




Average hardening $\Delta = \Delta_2$ (R>192 GV) - Δ_1 (R≤192 GV) = 0.145 ± 0.022, significance: 6.5σ

AMS Results: Primary and Secondary Cosmic Rays





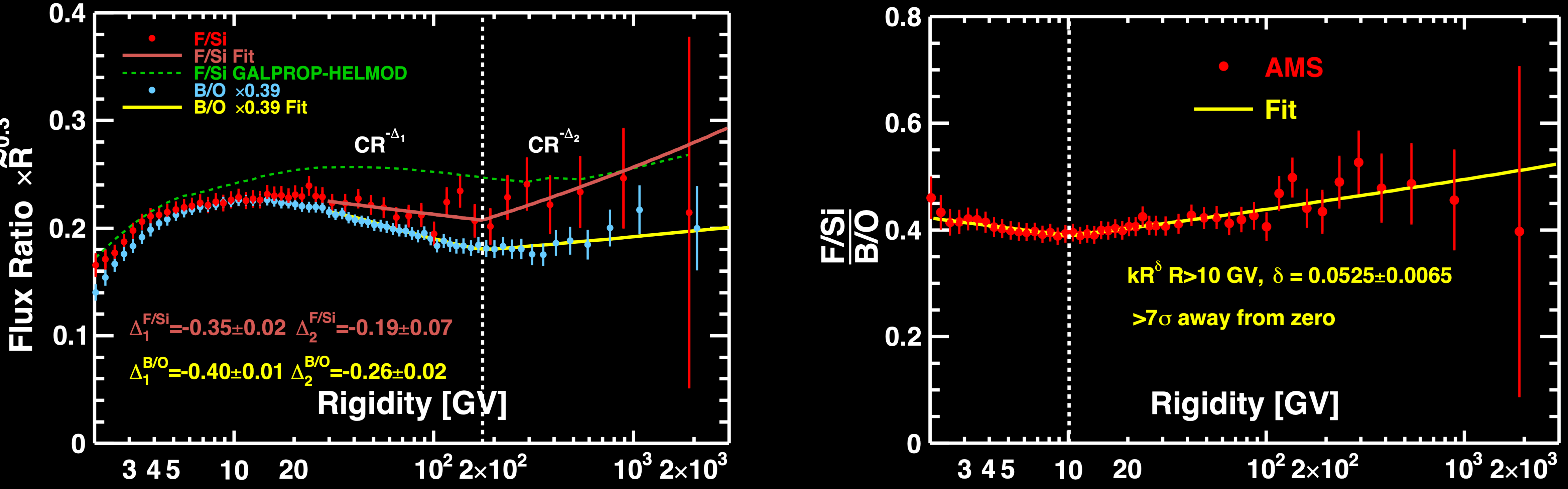
C, O, … + ISM → Li, Be, B + X

Ne, Mg, Si, … + ISM → F + X

Secondary-to-Primary Flux Ratios

Traditional Theory: light cosmic rays and heavy cosmic rays have

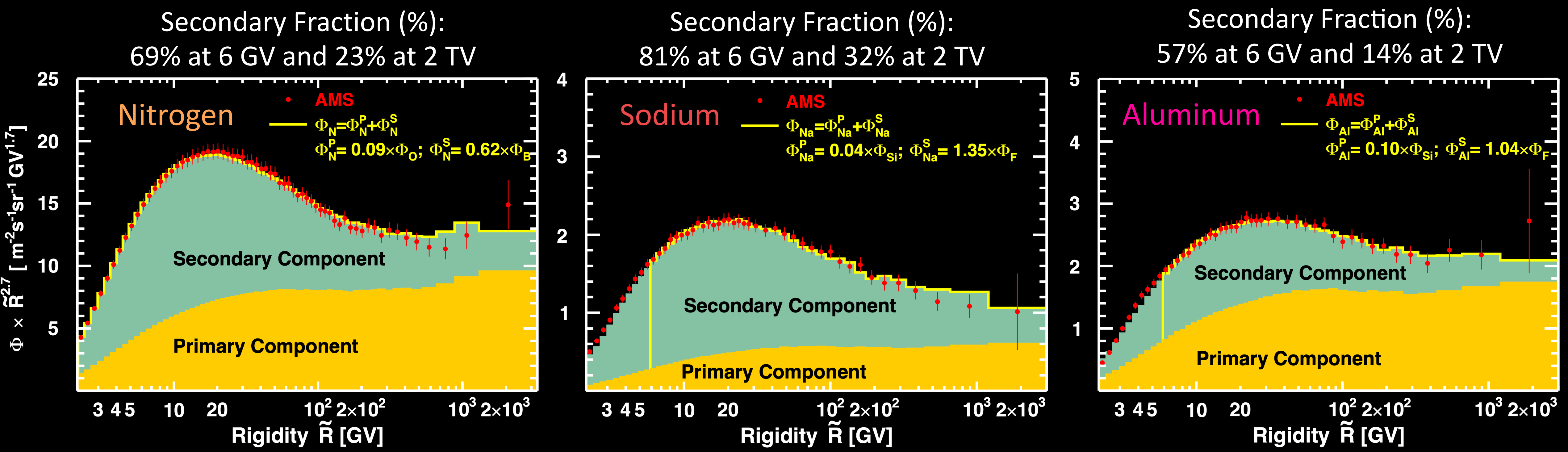
the same propagation properties, thus $\frac{F(Z=9)/Si(Z=14)}{B(Z=5)/O(Z=8)}$ is constant.



At >7σ-level, the propagation properties of heavy cosmic rays are different from those of light cosmic rays.

The Third Group of Cosmic Rays: Nitrogen, Sodium and Aluminum

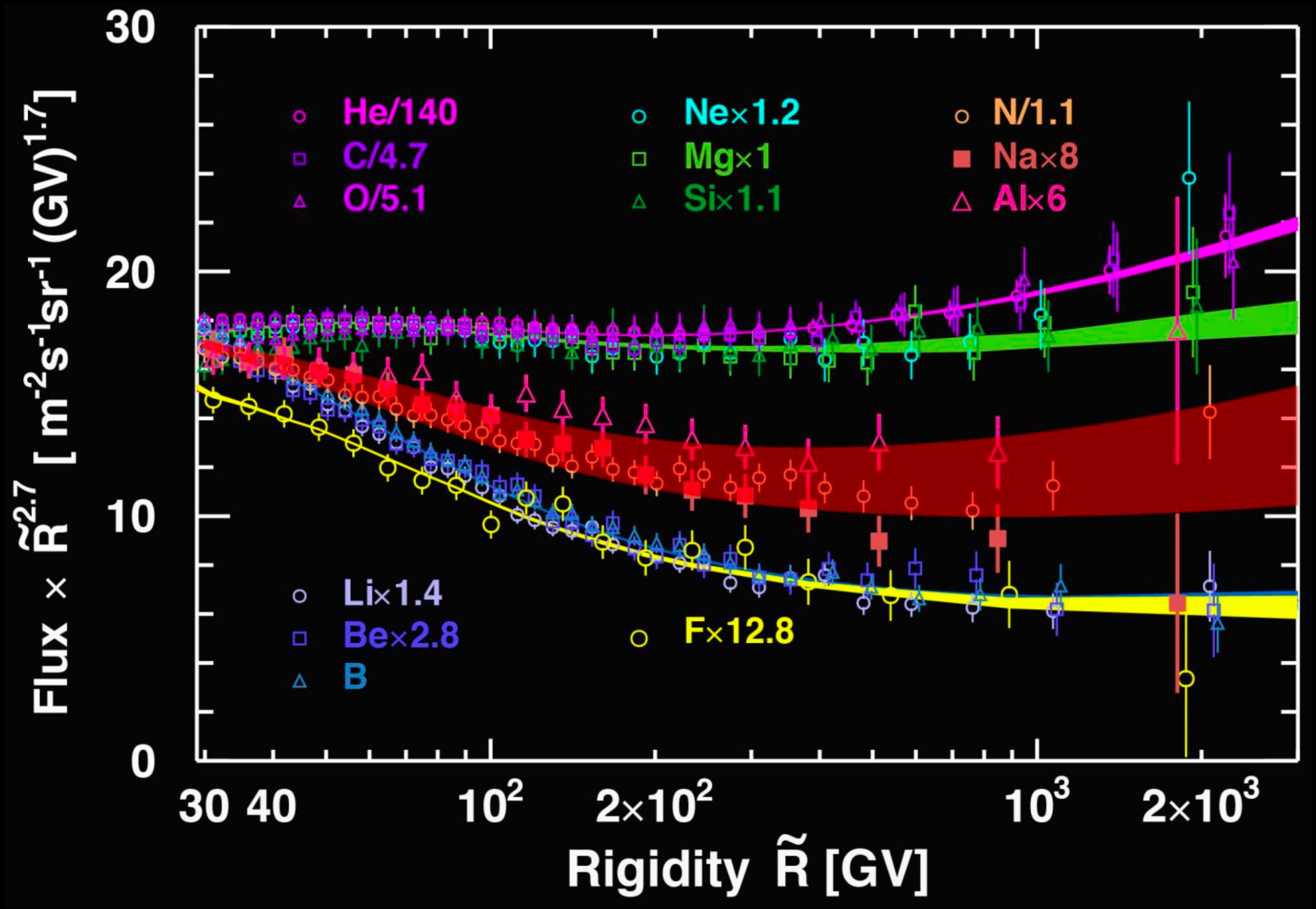
Cosmic nuclei with both primary and secondary components (N, Na, Al, …)



- Primary components come from accelerated in supernovae explosions.
- Secondary components come from produced by the collision of primary cosmic rays and the interstellar medium.

The Third Group of Cosmic Rays: Nitrogen, Sodium and Aluminum

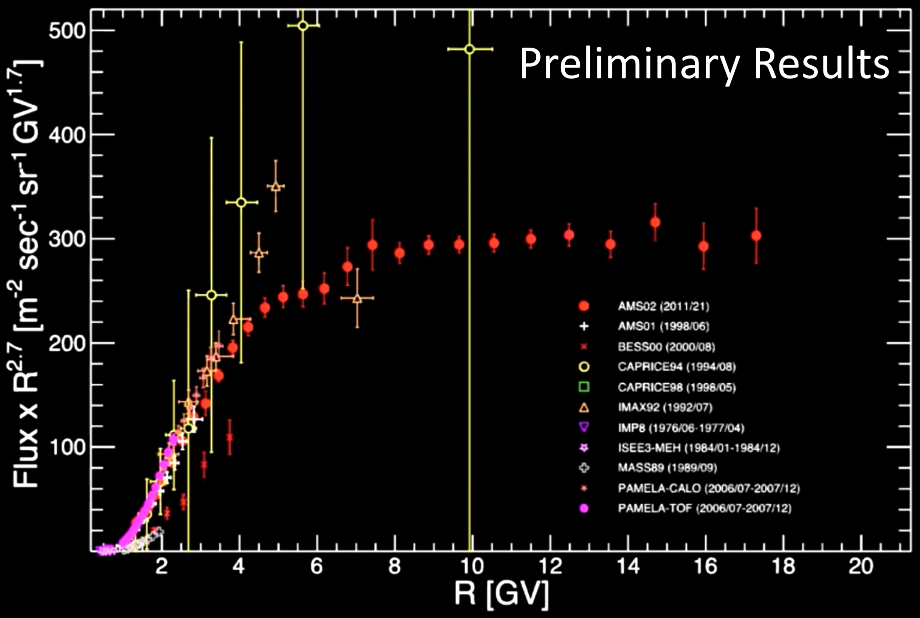
N, Na, and Al, belong to a distinct group and
are combinations of primary and secondary cosmic rays.



Secondary-to-Primary Flux Ratios for the lightest nuclei, Z=1 and Z=2

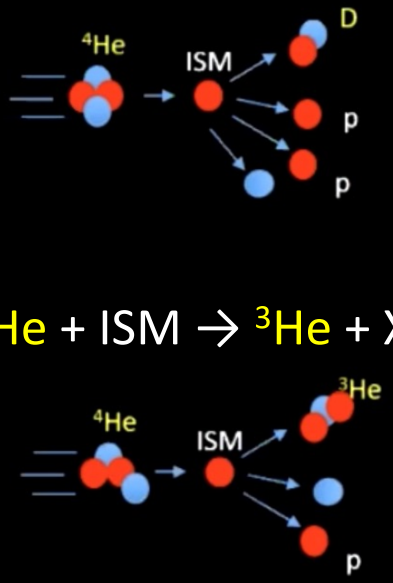
D(Z=1) and ^{3}He(Z=2) are mostly produced by the fragmentation of ^{4}He.

AMS Deuterno Flux

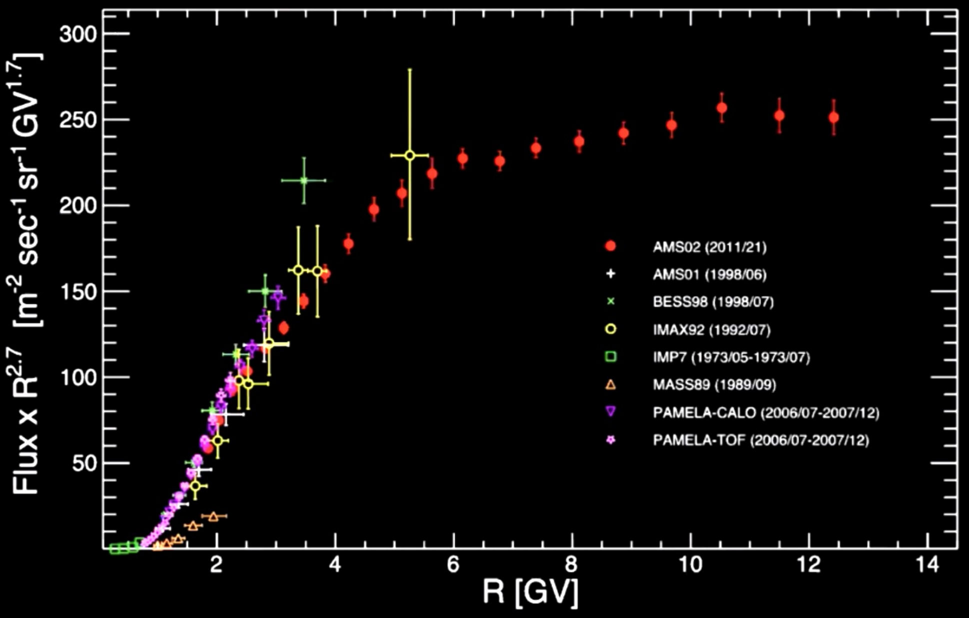


^{4}He + ISM → D + X

^{4}He + ISM → ^{3}He + X

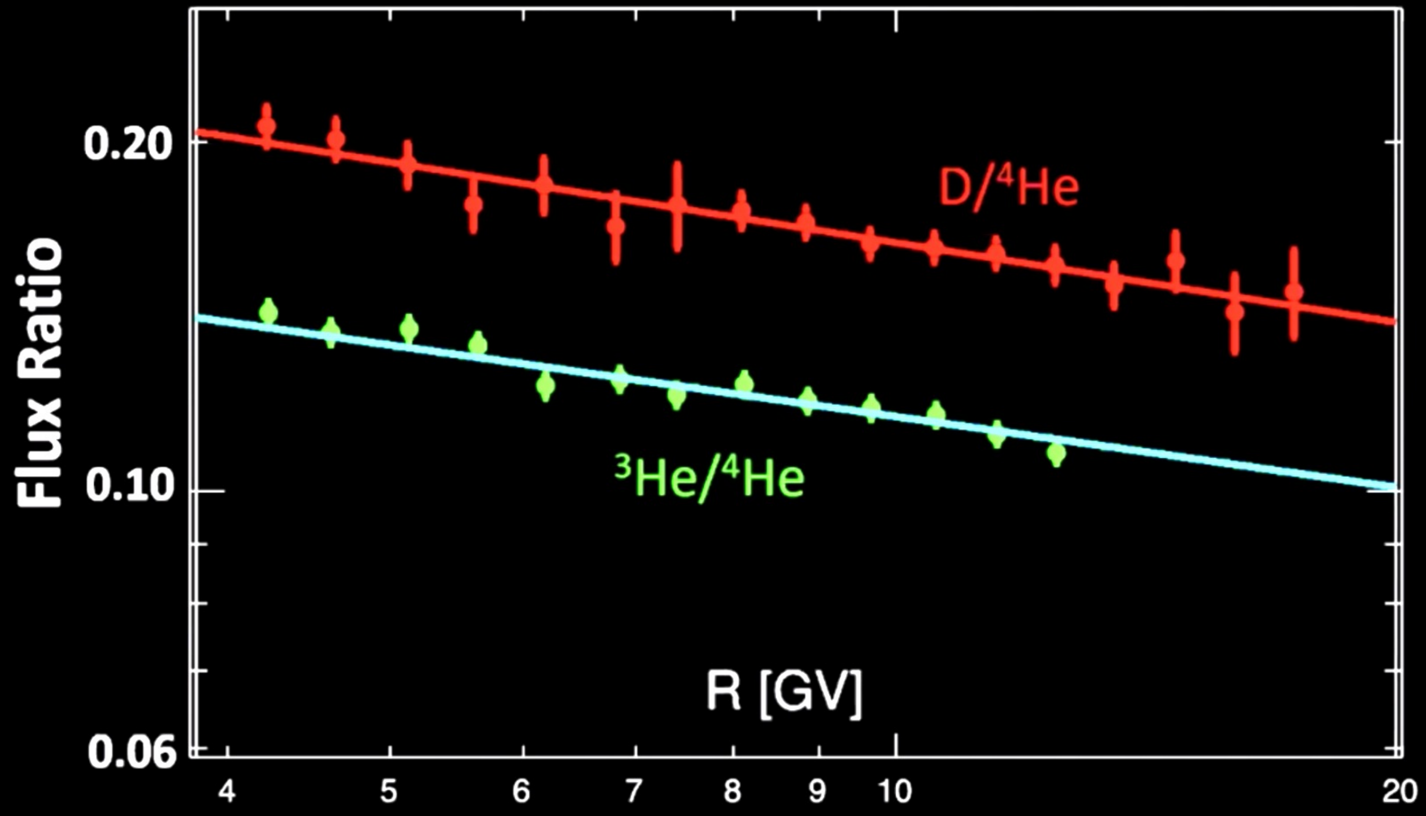


AMS ^{3}He Flux



Smaller cross-section of He with the interstellar medium:
D/^{4}He and ^{3}He/^{4}He probe the properties of diffusion at larger distances.
Provides comparison with B/C propagation models.

$D/^4He$ and $^3He/^4He$ Flux Ratios



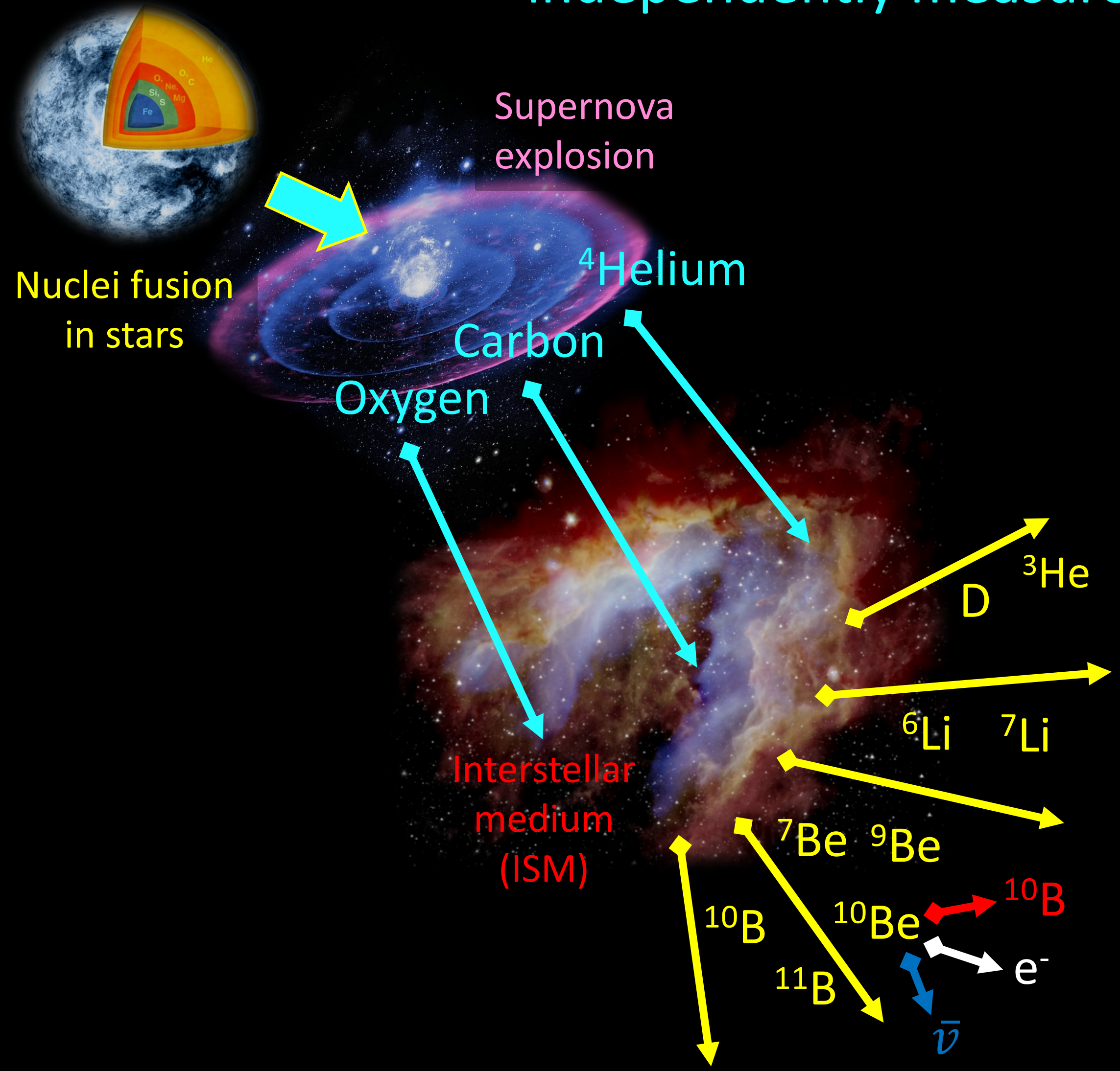
$D/^4He$ and $^3He/^4He$ have the same rigidity dependence

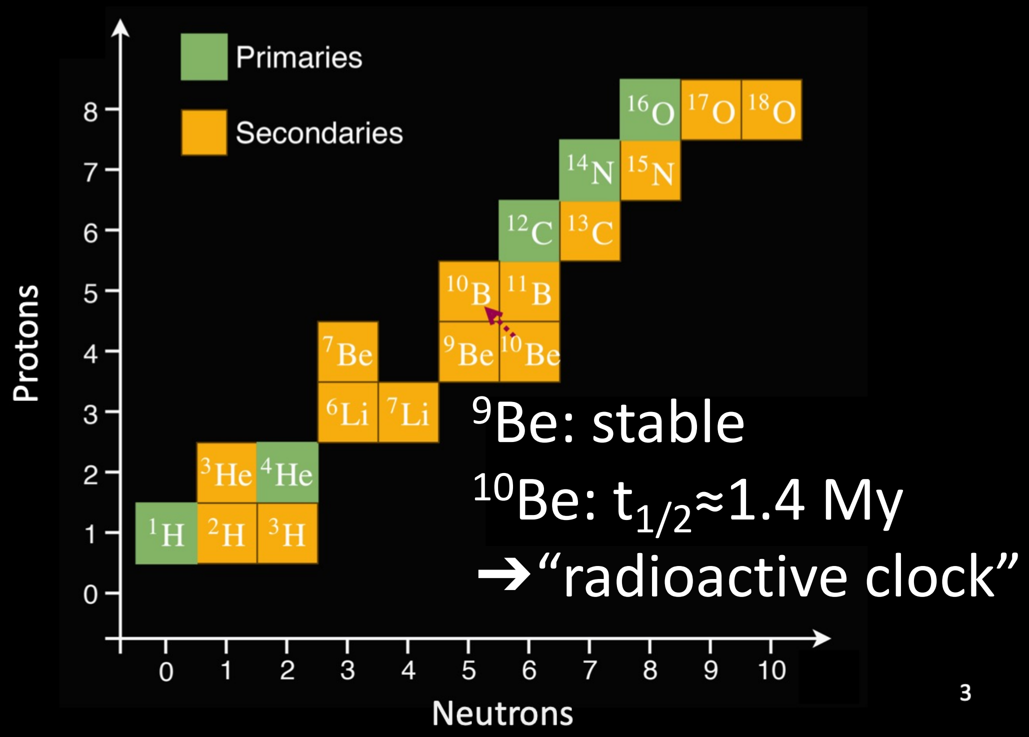
↓

D and ^3He have the same production and acceleration mechanism

Cosmic Light Isotopes

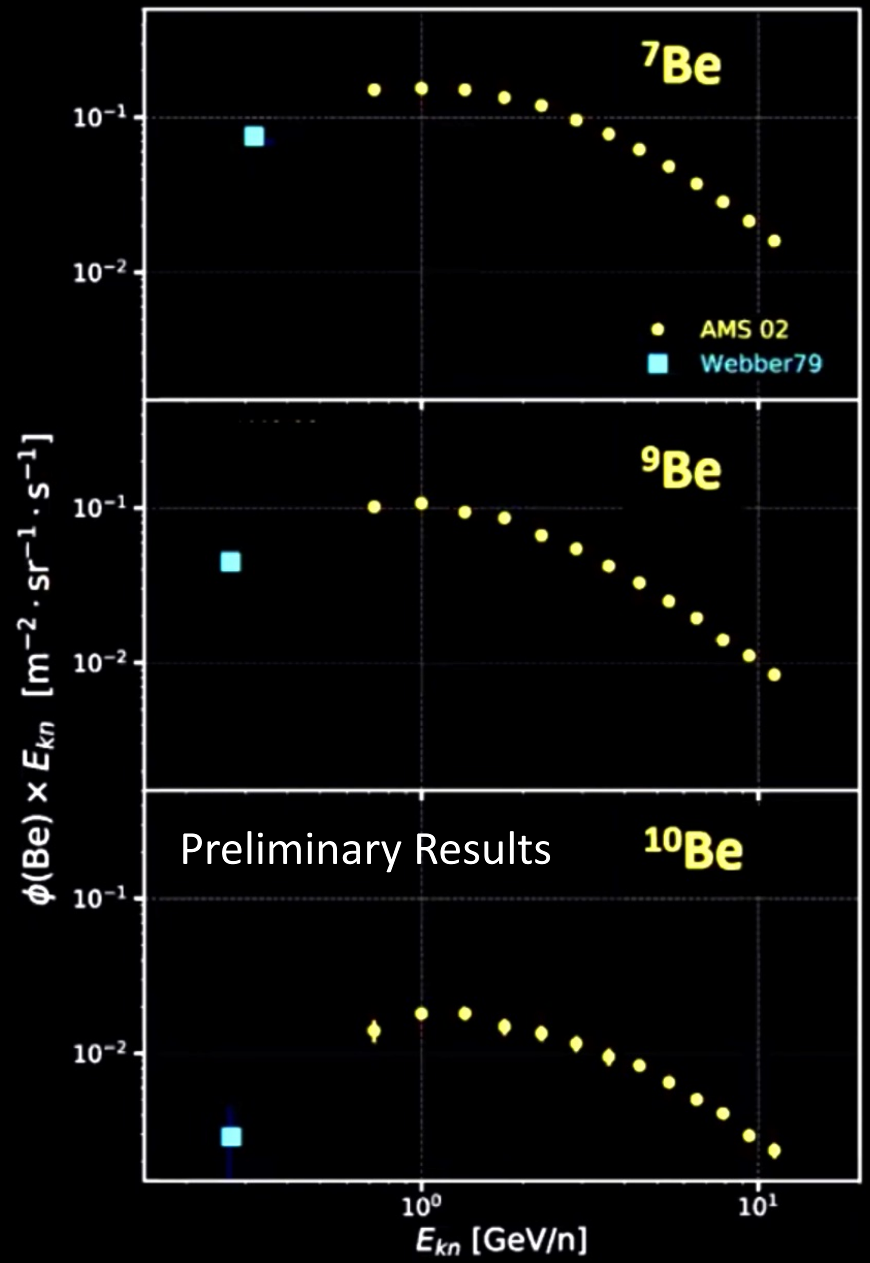
Isotope studies give unique information on propagation (D, ^{3}He), production mechanism (^{6,7}Li, ^{7,9}Be) and independently measure age of cosmic rays (^{9,10}Be)





- ^{10}Be is unstable with a half-life of 1.4 million years.
- The amount of ^{10}Be is used as a radioactive clock to determine the confinement time in the galaxy.

AMS Results: Cosmic Beryllium Isotopes

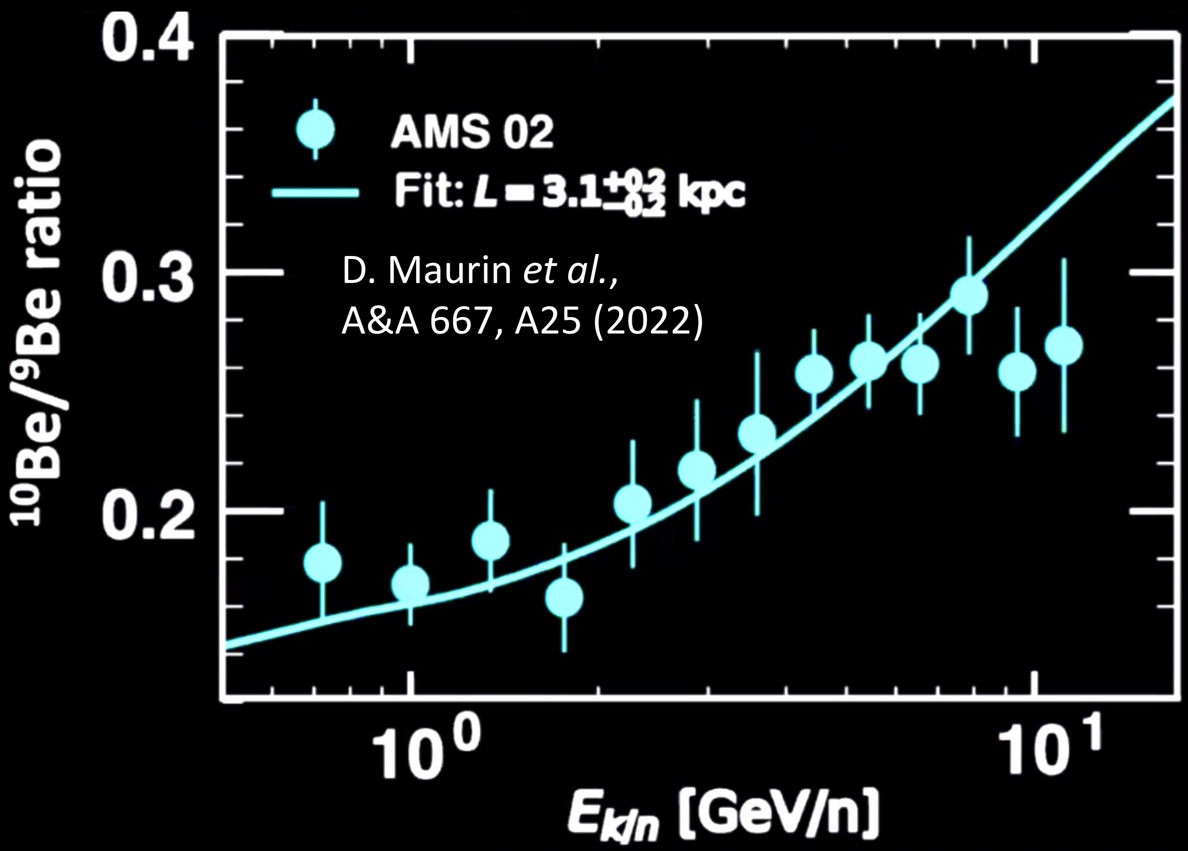


An accurate determination of the size of the galactic diffuision halo L

Lastest L estimations based on AMS Be/B data:

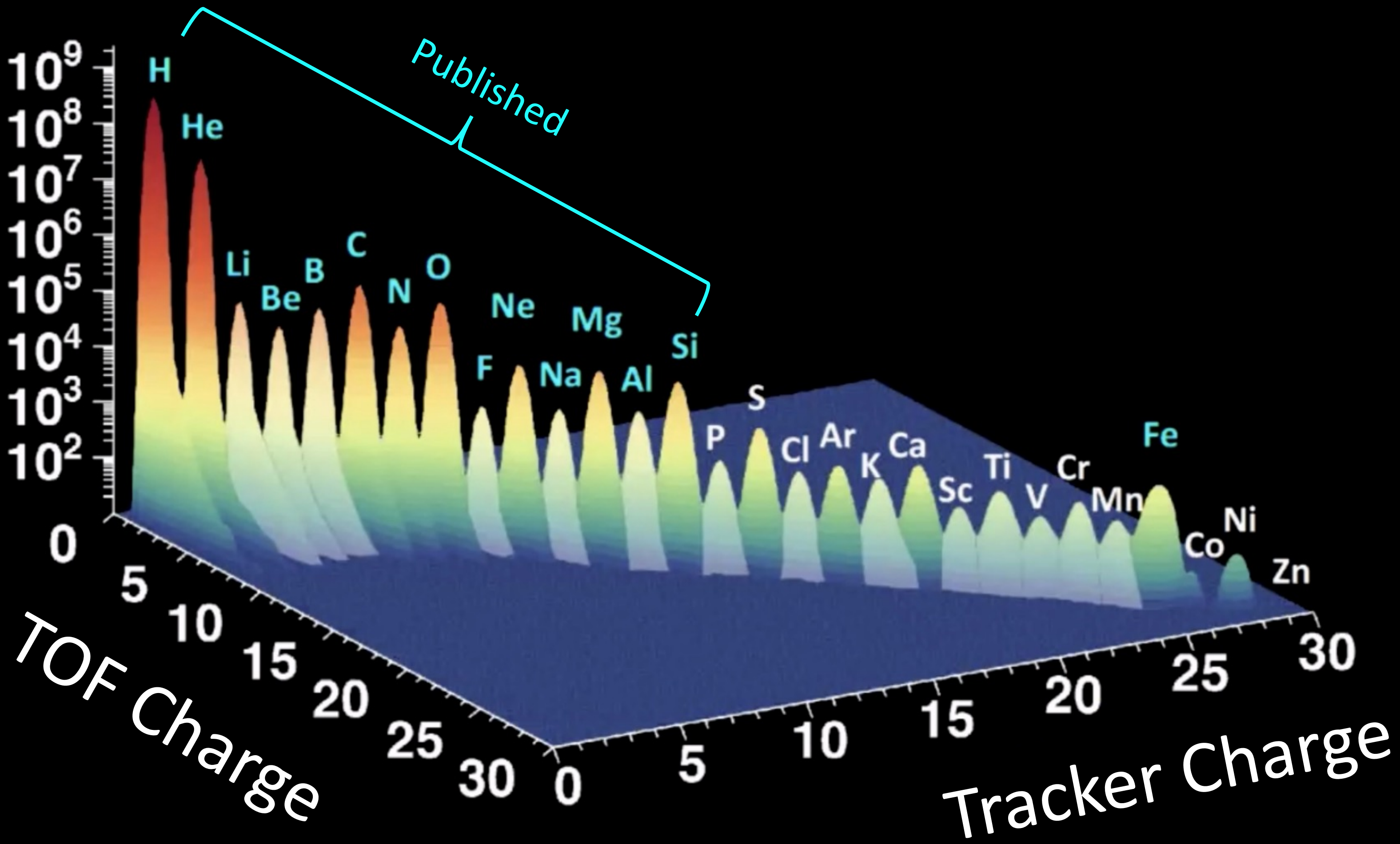
Evoli 2020: L ∽ 2−7 kpc and Weinrich 2020: L ∽ 3−8 kpc

Using ^{10}Be/^{9}Be directly determines L = 3.1 ± 0.2 kpc



In the first ten years, we studied 15 elements. None fits any cosmic ray model.

We will continue to measure all 29 elements.
This will provide the foundation for a comprehensive theory of the cosmos.



Antimatter Stars

Matter is defined by its mass M and charge Z.
Antimatter has the same mass M but opposite charge –Z.

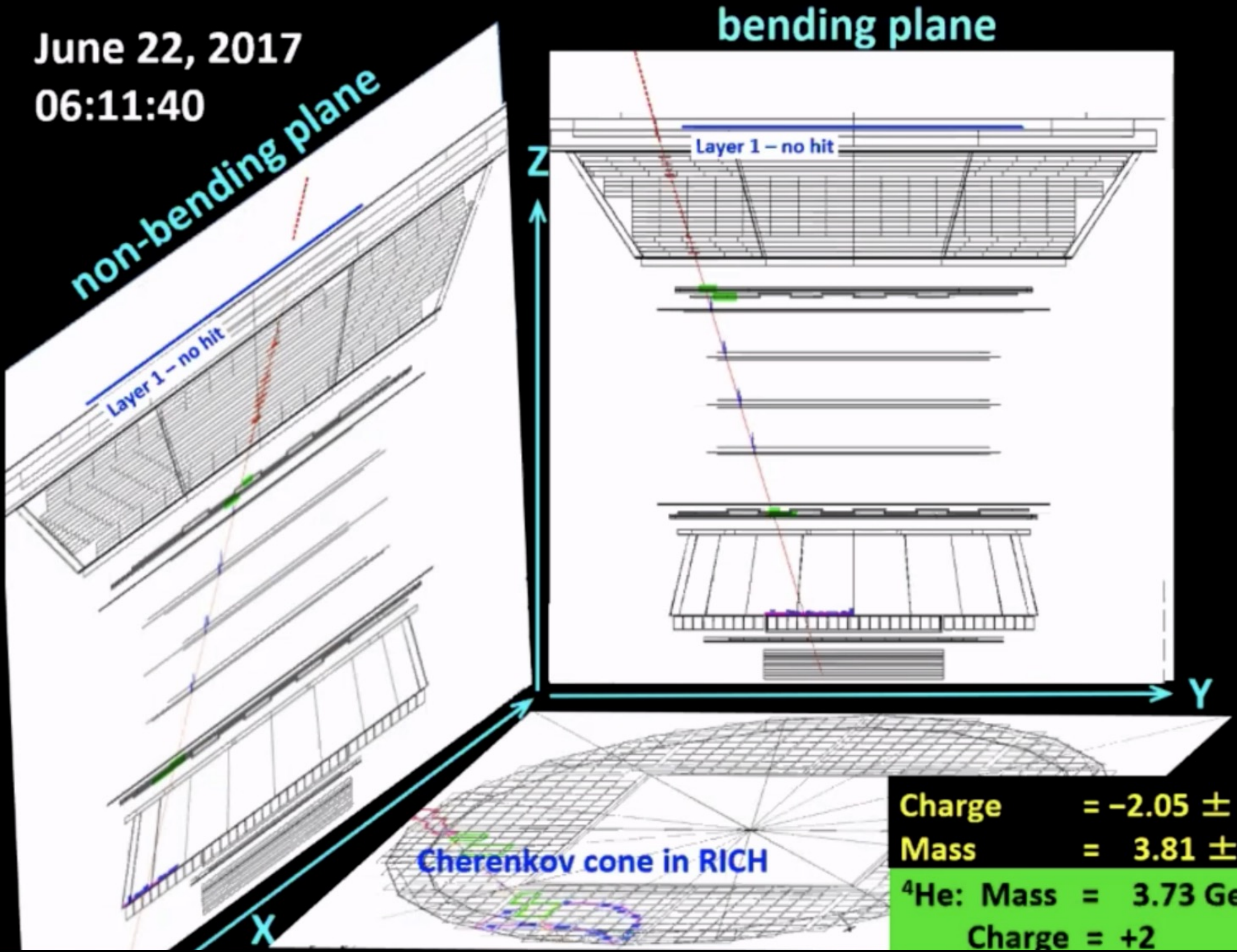
Antimatter Star

$\overline{\mathrm{D}}$, $\overline{\mathrm{He}}$, $\overline{\mathrm{C}}$, $\overline{\mathrm{O}}$, …

AMS on ISS

AMS is a unique antimatter spectrometer in space

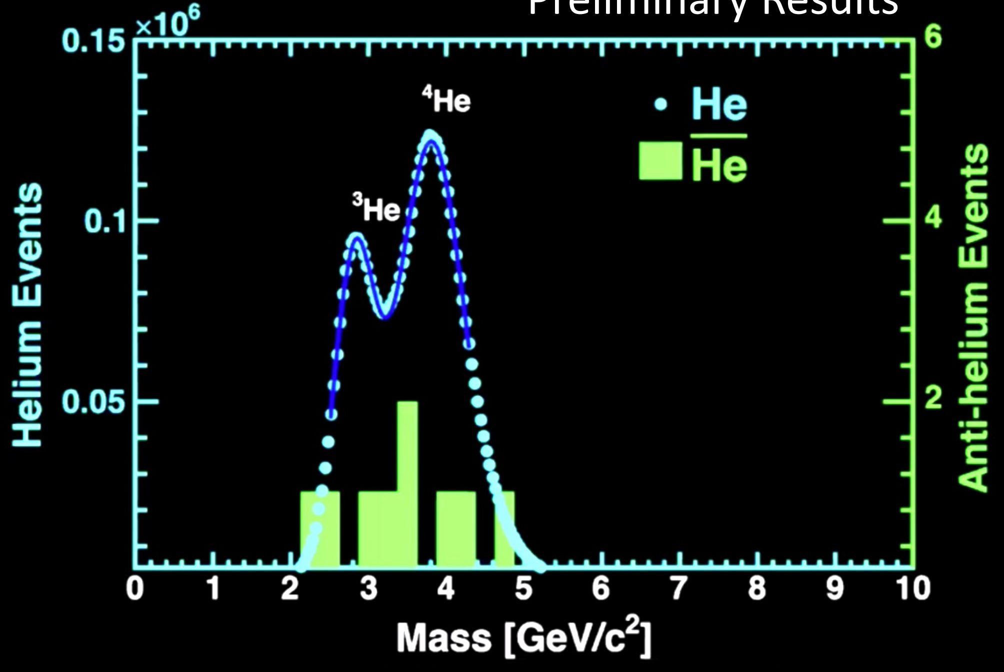
Example: Anti-Helium Candidate



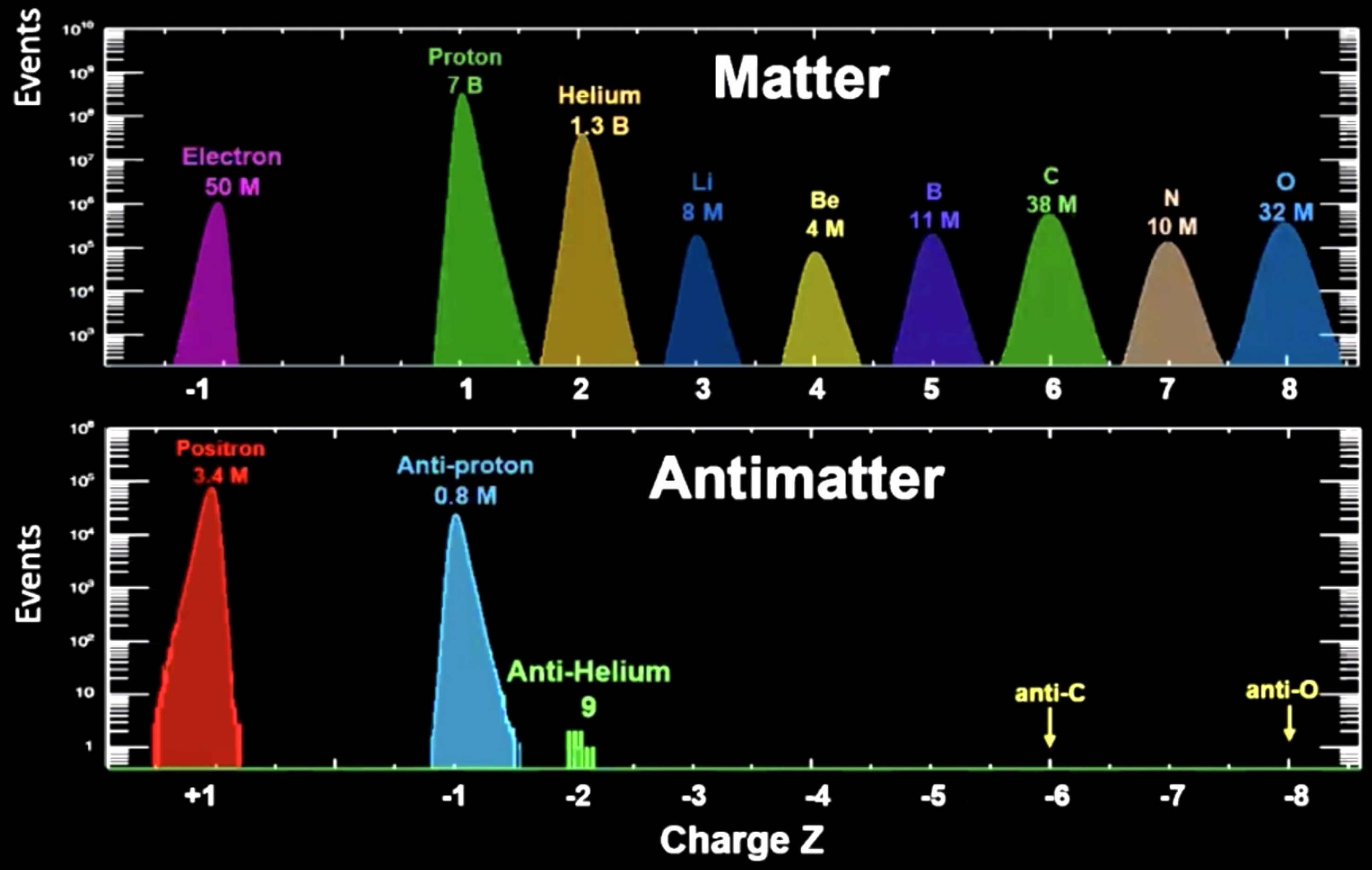
Charge	$= -2.05 \pm 0.05$
Mass	$= 3.81 \pm 0.29$ GeV/c^2
^{4}He: Mass	$= 3.73$ GeV/c^2
Charge	$= +2$

Antimatter

During the first 10 years of data taking,
AMS has collected 9 anti-helium candidates.



Mass from 0 to 10 GeV/c^2,
there are no other signal.



Summary

We have measured

- Properties of four elementary particles
- Cosmic nuclei and their flux relations
- Antimatter measurement

We will continue to measure cosmic rays till the lifetime of ISS, 2030.