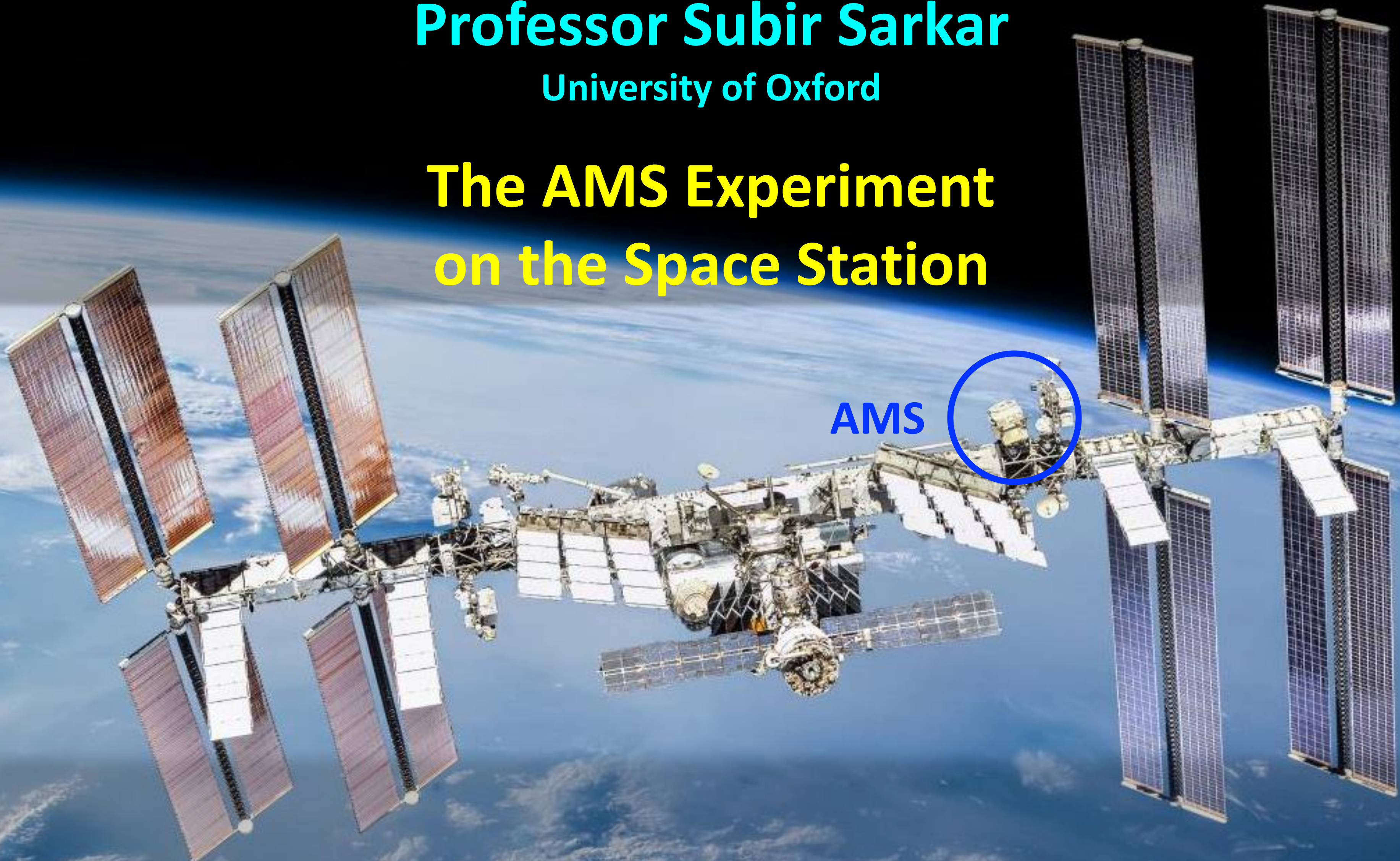
In honor of

Professor Subir Sarkar

University of Oxford

The AMS Experiment on the Space Station

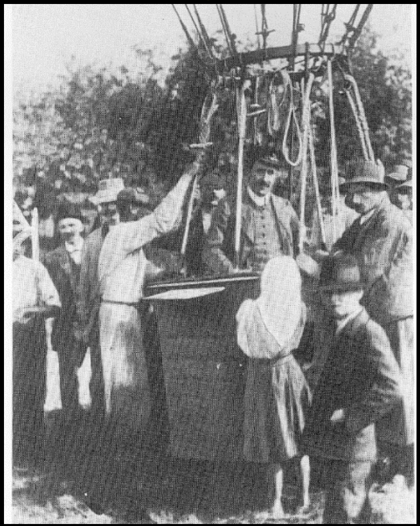


September 12, 2023

S. Ting

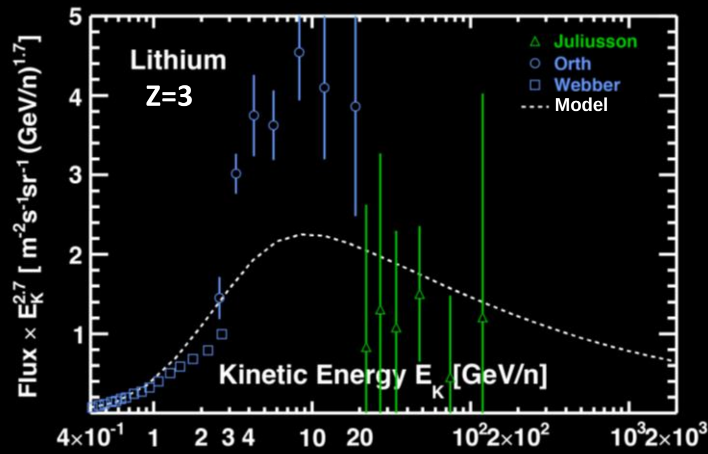
Cosmic Rays in the last 100 years

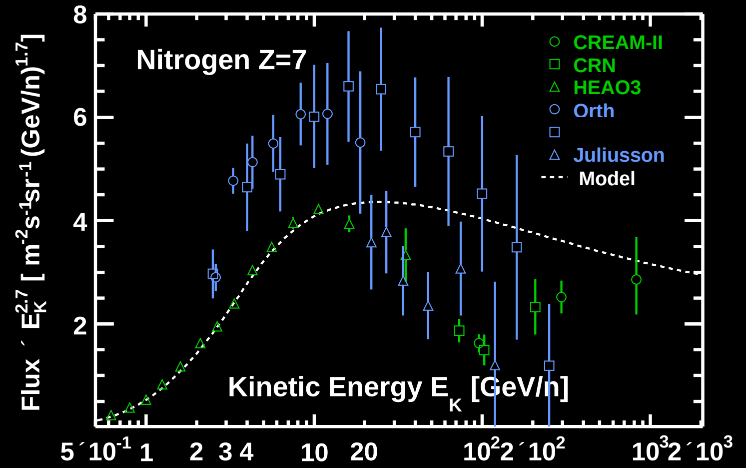
1912: Discovery of Cosmic Rays

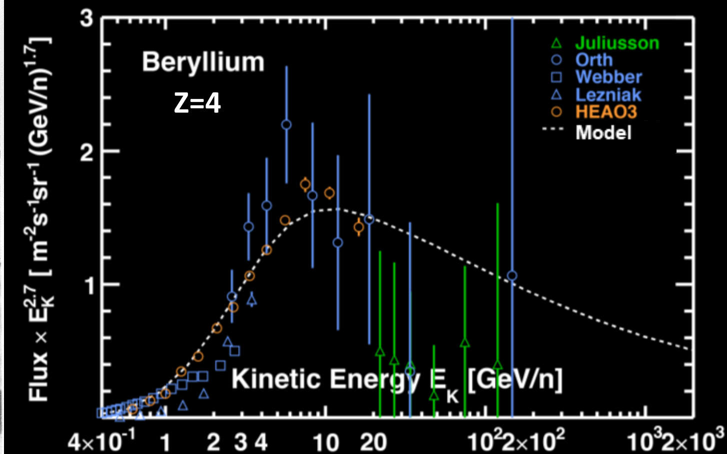


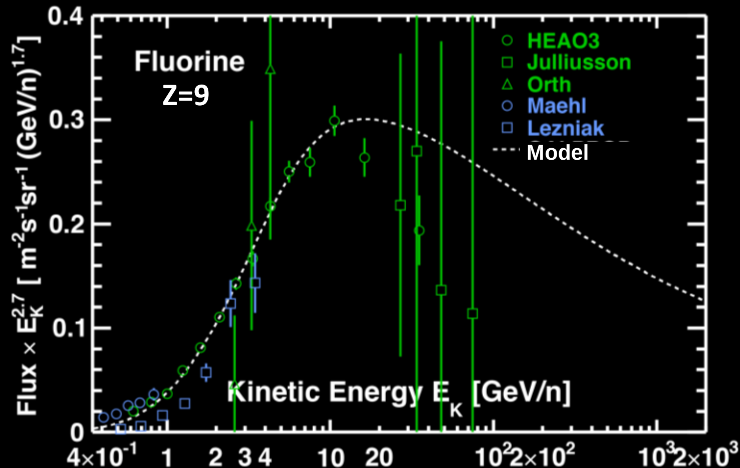
Victor Hess Nobel Prize (1936)

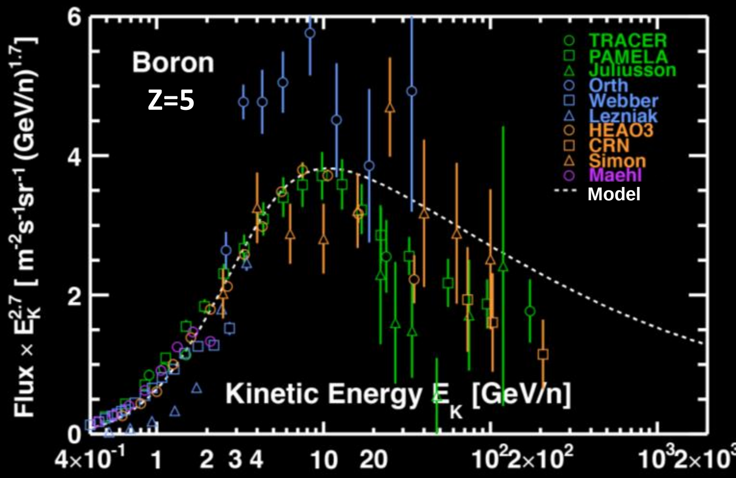
Before AMS: Many theoretical models agree with experimental data

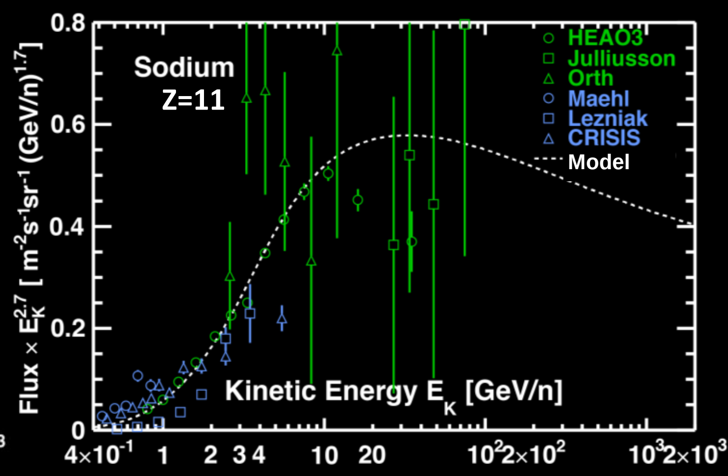






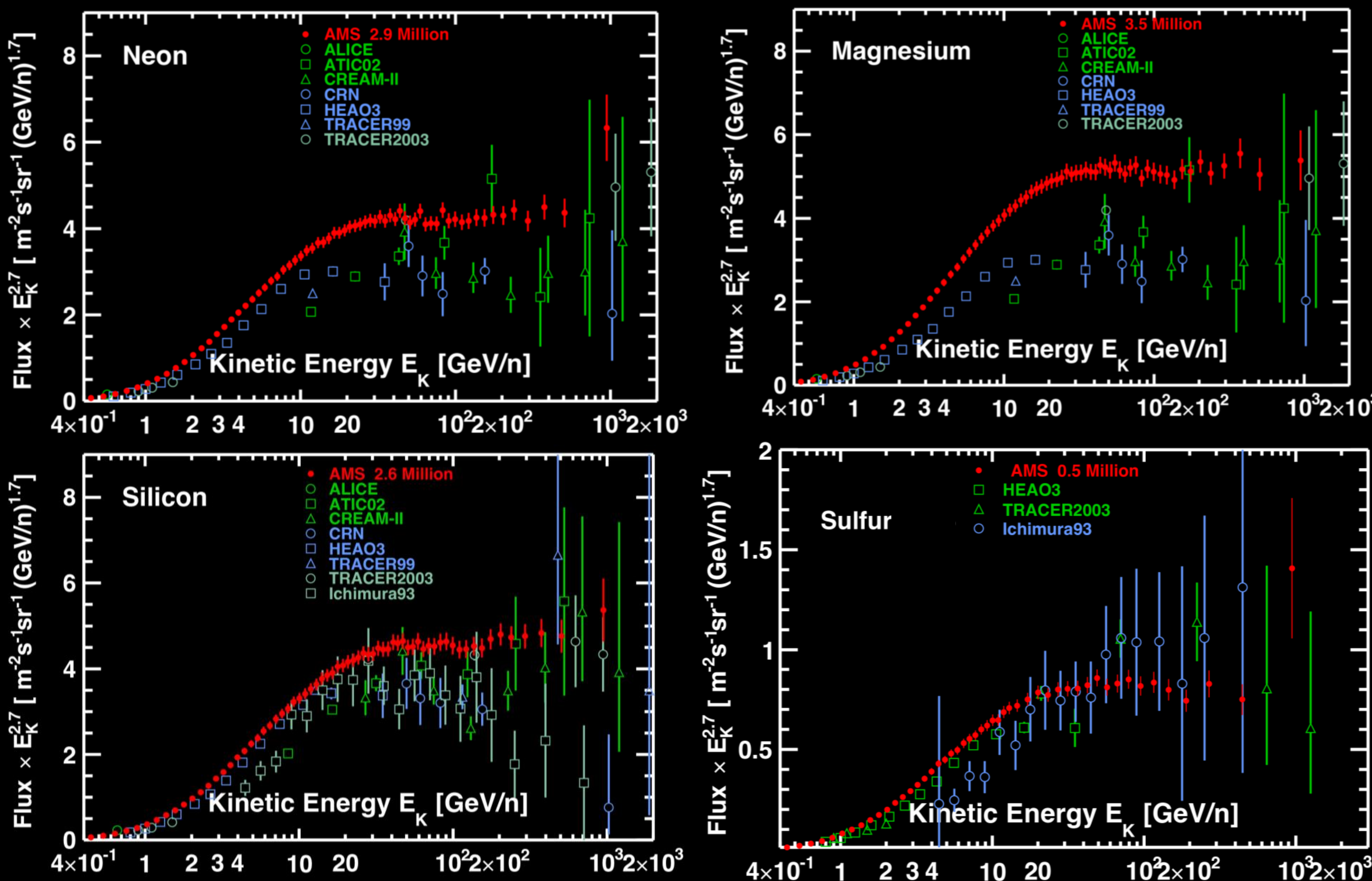






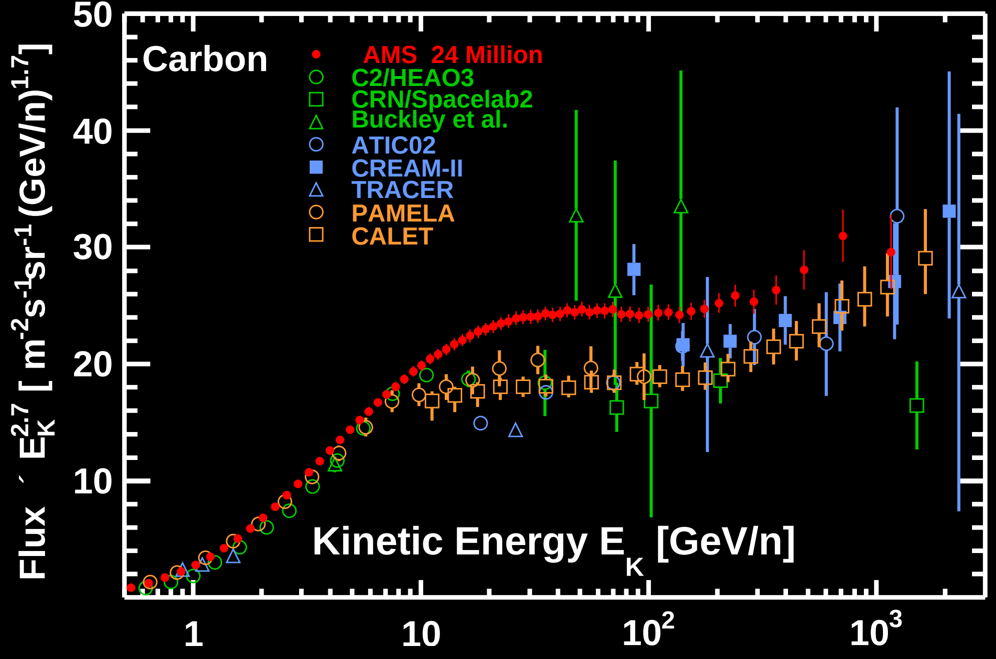
AMS Results compared with earlier measurements

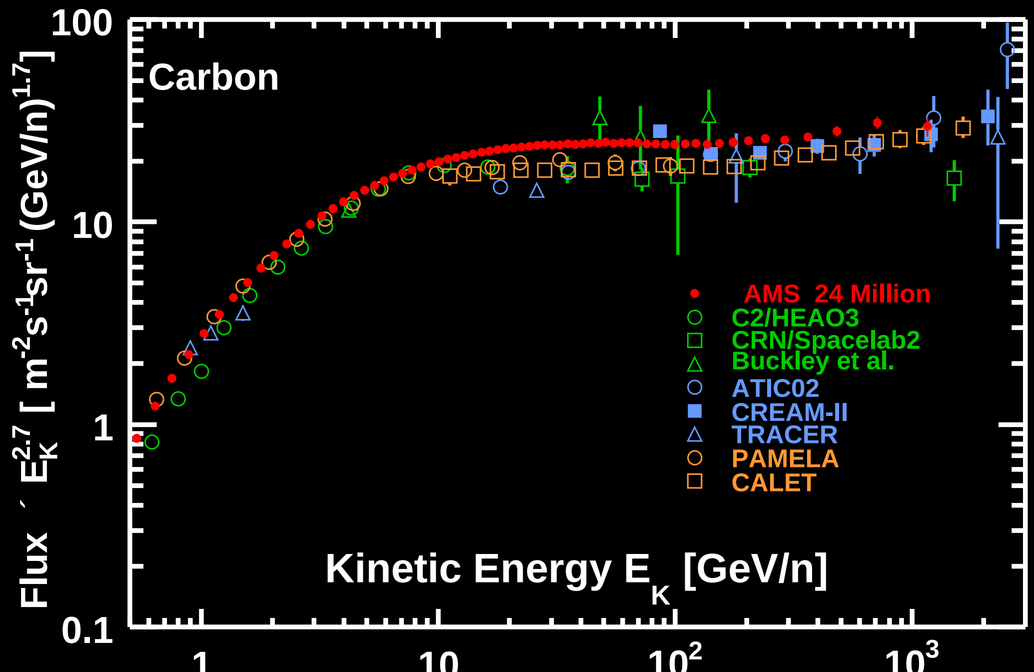
The precision AMS results cannot be explained by current models.



Today, I will summarize the 11.5-year results from AMS

AMS Results compared with earlier measurements





In Celebration of Subir Sarkar's Scientific Achievements by Sunil Gupta

The research of Subir Sarkar spans a whole spectrum of astroparticle physics. Subir began his career in cosmic ray physics that included an experimental study and their theoretical interpretation about five decades back. He has played a key role in defining and promoting the interdisciplinary areas of astroparticle physics that has now acquired a central place and came to be known as multi-messenger physics.

Subir has extended our understanding of cosmic ray acceleration and propagation. He showed that the magnetic field in young supernova remnant Cas-A was significantly amplified over the compressed interstellar field – as required for efficient acceleration of cosmic rays up to the "knee". He also showed that the second-order Fermi acceleration by plasma turbulence generated through the deceleration of the shock wave naturally yields the observed power-law spectrum of electrons. He also showed that the spectrum and morphology of gamma-ray emission from the `Fermi Bubbles' can be explained as inverse-Compton scattering by the electrons being accelerated by MHD turbulence. He has also argued that a nearby shock wave accelerating cosmic rays may be responsible for the positron excess in high energy cosmic rays seen by PAMELA. If so, then the antiproton-to-proton and boron-to-carbon ratios should also start flattening with increasing energy – which is being tested by the AMS-02 detector. Subir has clearly shown that a better understanding of Galactic cosmic ray transport and Galactic diffuse emissions is essential for ongoing fundamental physics investigations on inflation and on dark matter.

Subir's contributions to the early universe cosmology have been wide-ranging and influential, from deriving constraints on new phenomena beyond the Standard Model via considerations of big bang nucleosynthesis and the cosmic microwave background, to developing and testing field-theoretical models for cosmic inflation using astronomical data to quantify the primordial perturbations that have grown to create the large-scale structure in the universe. He has been an insightful critic of the astronomical evidence for the accelerated expansion of the universe and dark energy.

In Celebration of Subir Sarkar's Scientific Achievements - continued

Subir is highly regarded for his theoretical work which is firmly grounded in experimental considerations enhances its relevance and credibility. He has worked on the Pierre Auger Observatory for high energy cosmic rays which established the suppression of the energy spectrum at the `GZK cutoff'. He is also a member of the IceCube Neutrino Observatory which has recently detected cosmic high energy neutrinos. His main contribution to these experiments has been to provide state-of-the-art theoretical inputs for science analyses, e.g. searches for ultrahigh energy neutrinos require knowledge of their deep inelastic scattering cross-section which he has computed using the latest QCD parton distribution functions.

But what I really treasure is the recent participation of Subir in a special session during the 38th ICRC in Nagoya. There the implications of the precision measurements of fluxes and energy spectra by the AMS-02 detector of antimatter particles such as the positrons, antiprotons, antidueteron, antihelium as well as the matter particles from protons to the first 27 nuclei in the periodic table from helium right up to nickel were discussed. I greatly look forward to Subir's continued participation in the interpretation of these measurements for, (1) the presence of dark matter in the galaxy, (2) the sources of antimatter if any, (3) the sources of galactic cosmic rays, their acceleration and propagation in the galaxy, and finally (4) a precision study of the heliosphere and space weather with different nuclei of matter and antimatter. I wish the best of health and a productive future for Subir Sarkar.

A few of the latest Subir Sarkar’s papers on charged cosmic rays:

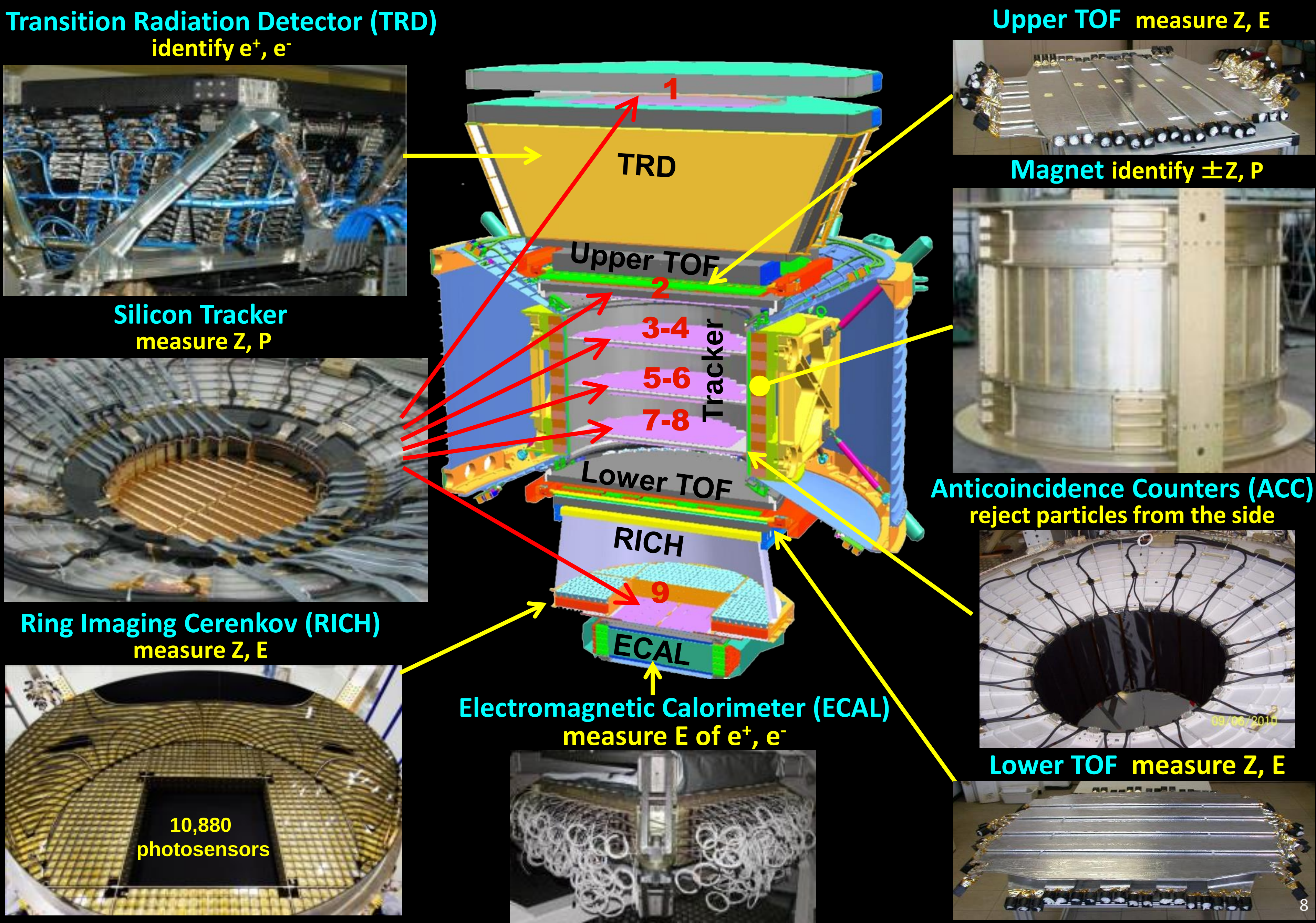
“Testing Astrophysical Models for the PAMELA Positron Excess with Cosmic Ray Nuclei”
Philipp Mertsch and Subir Sarkar, Phys. Rev. Lett. **103** (2009) 081104

“Cosmic ray acceleration in supernova remnants and the FERMI/PAMELA data”
Markus Ahlers, Philipp Mertsch, and Subir Sarkar, Phys. Rev. **D 80** (2009) 123017

“AMS-02 data confront acceleration of cosmic ray secondaries in nearby sources”
Philipp Mertsch and Subir Sarkar, Phys. Rev. **D 90** (2014) 061301(R)

“Explaining cosmic ray antimatter with secondaries from old supernova remnants”
P. Mertsch, A. Vittino, S. Sarkar, Phys. Rev. **D 104** (2021) 103029

AMS is a space version of a precision magnetic spectrometer used in accelerators



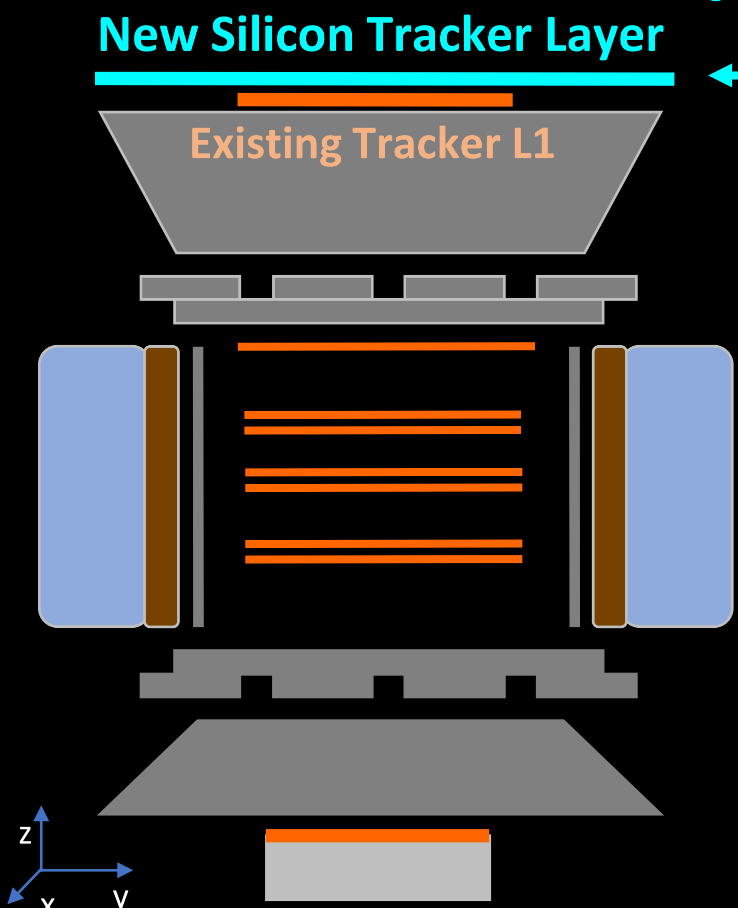
Upgrade with new Silicon Tracker Layer

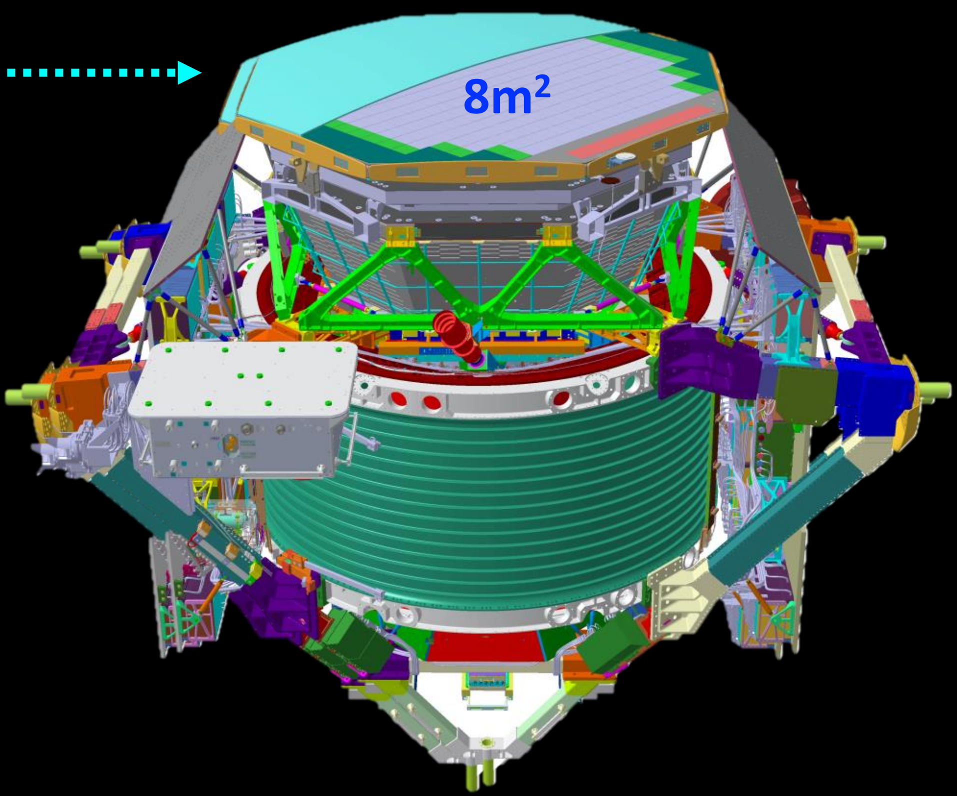
Acceptance increased to 300%

The upgrade should be accomplished before the end of 2025

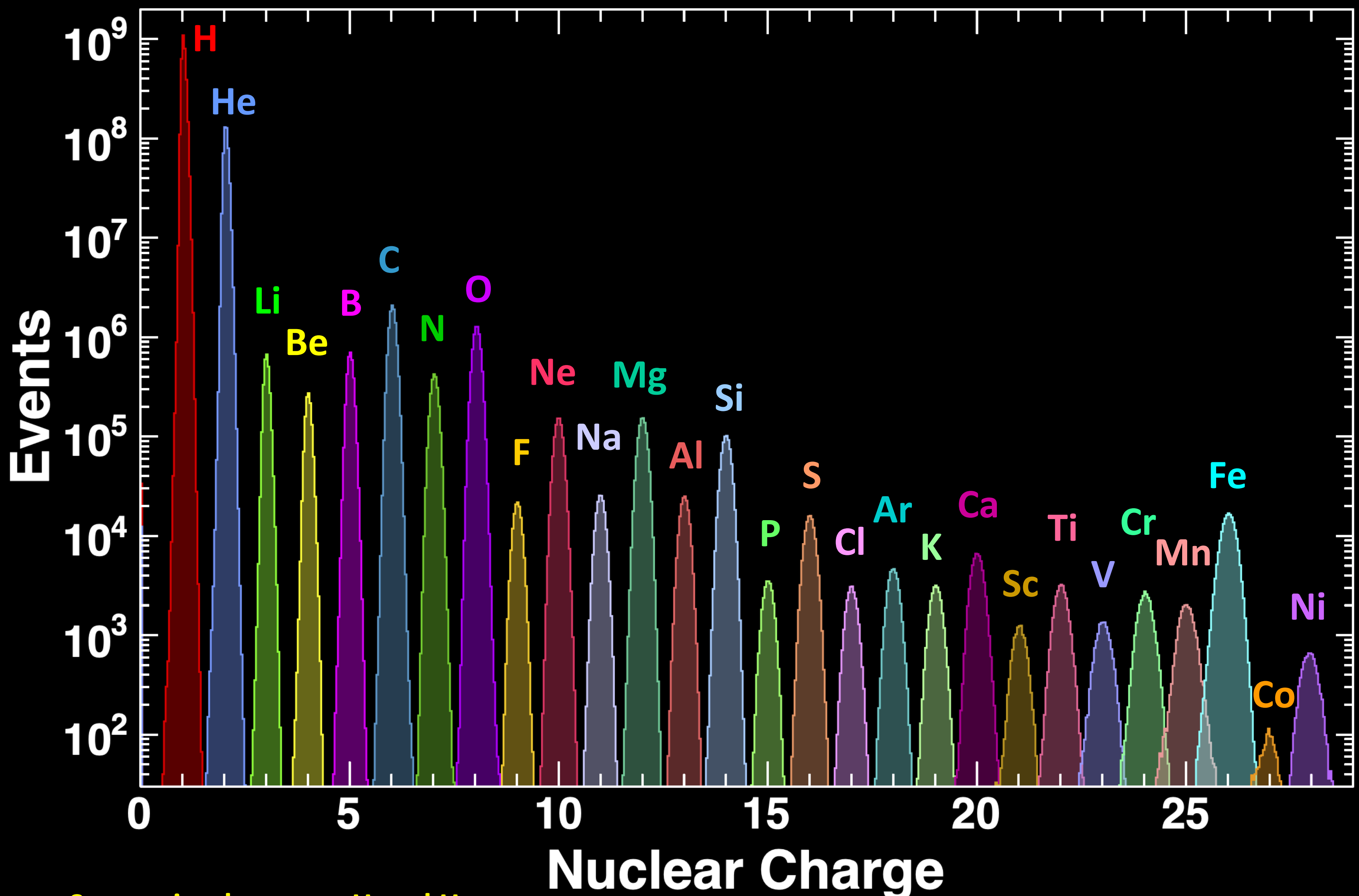
Without Upgrade 2026-2030 = 5 years

With Upgrade = 15 years





Cosmic Nuclei Measurement in 11.5 years

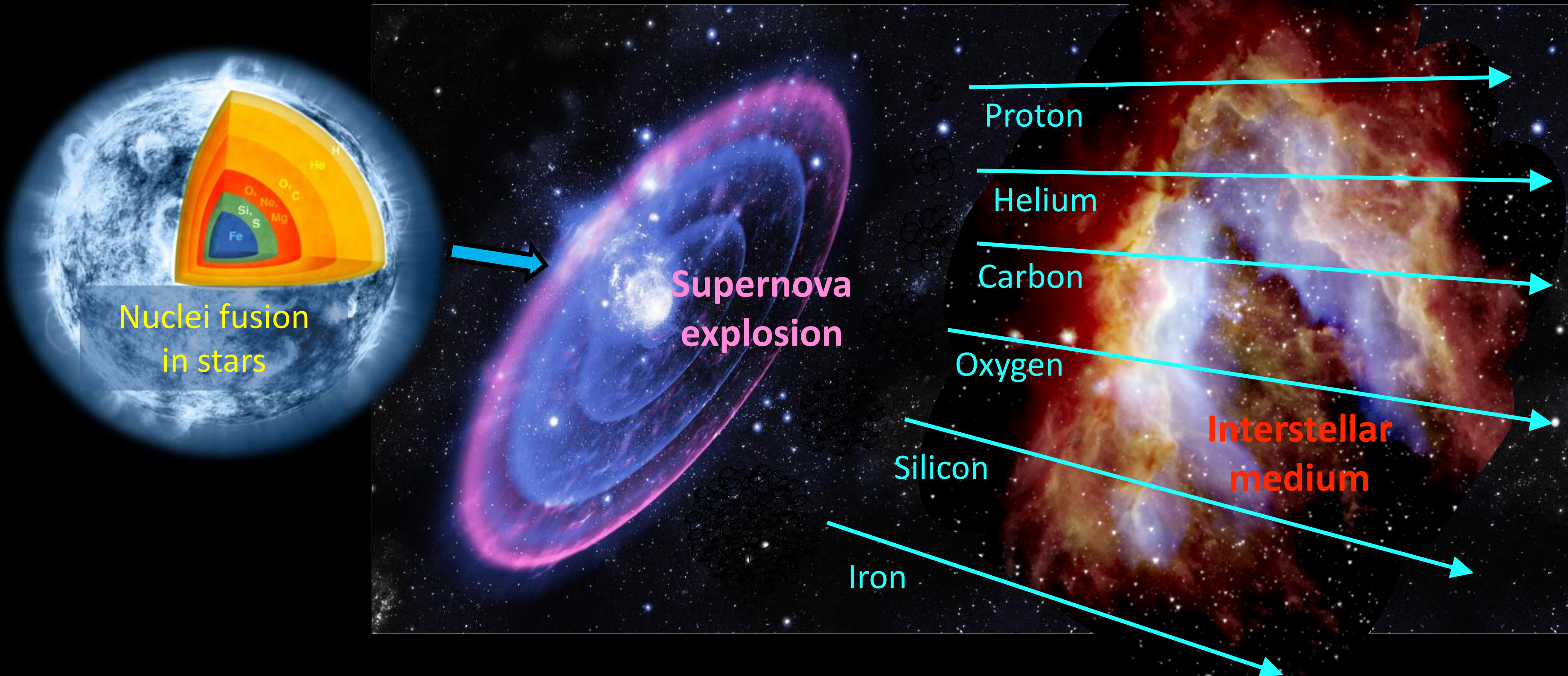


Separation between H and He is better than 1 in 10^9

Separation between Fe and Co is better than 1 in 10^2

Latest AMS Results (11.5 years) on Primary Cosmic Rays

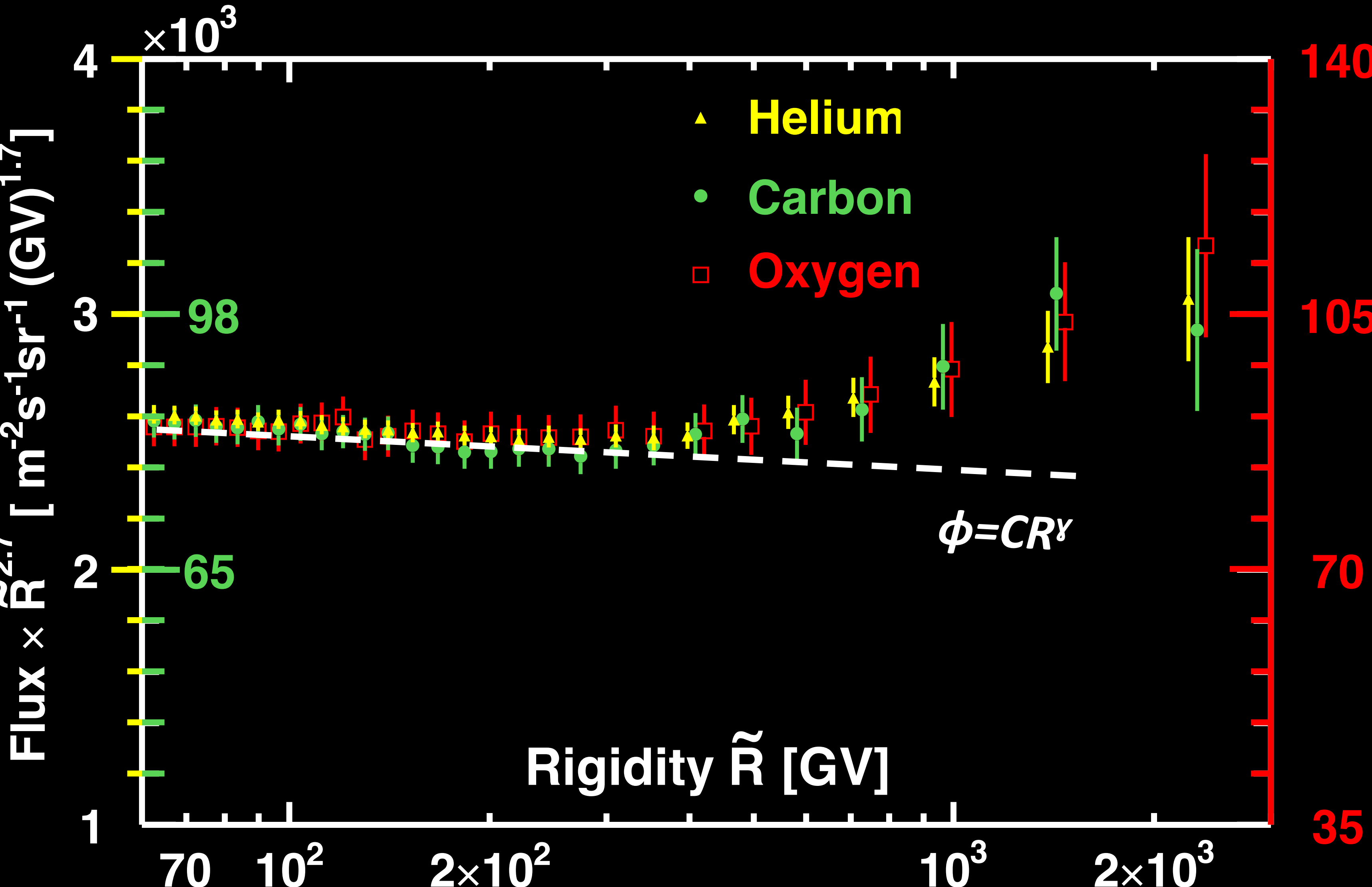
Primary cosmic rays p, He, C, O, ..., Si, ..., Fe
are produced during the lifetime of stars and accelerated by supernovae.
They propagate through interstellar medium before they reach AMS.



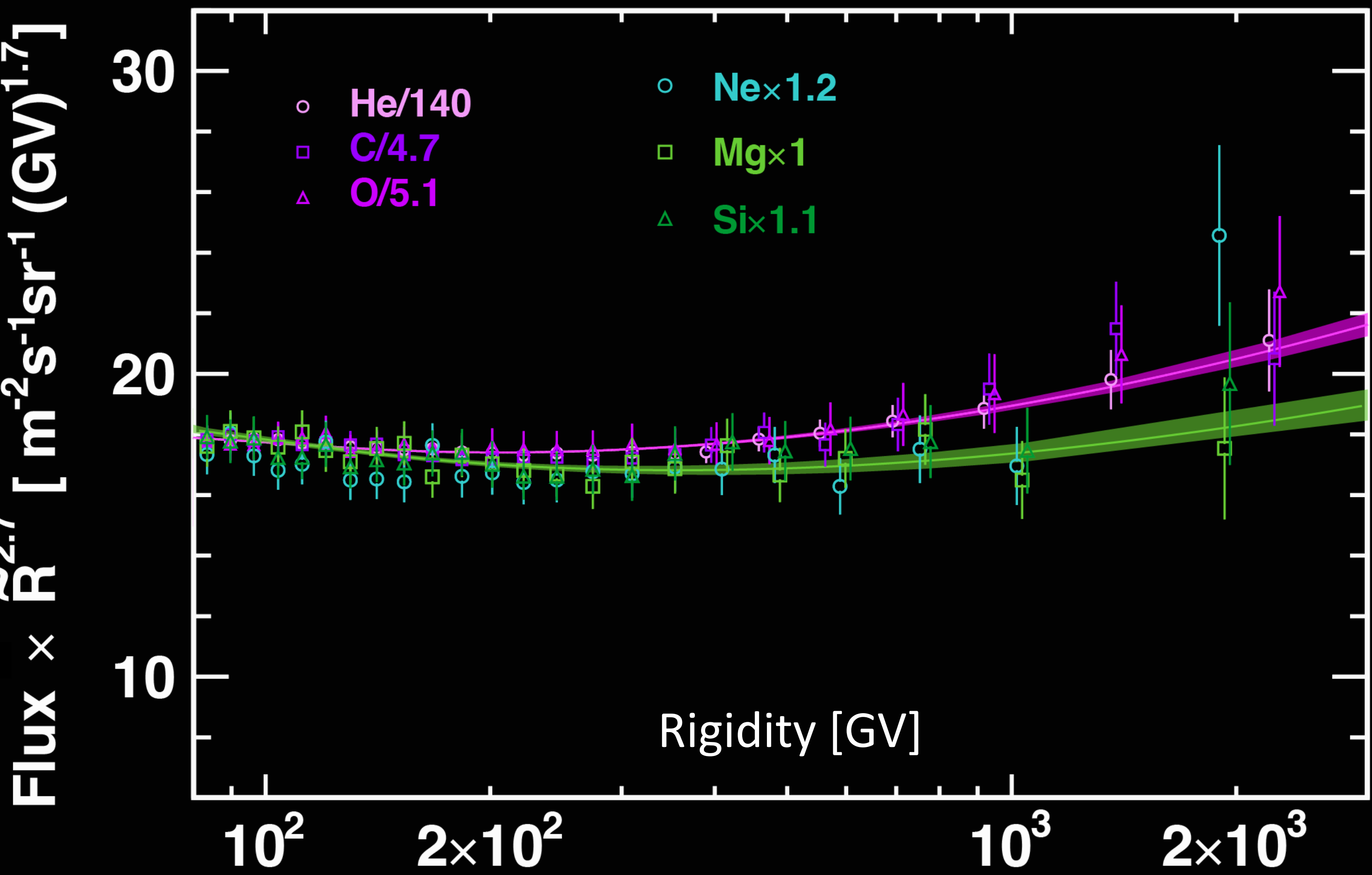
Measurements of primary cosmic ray fluxes are fundamental to understanding the origin, acceleration, and propagation processes of cosmic rays in the Galaxy.

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

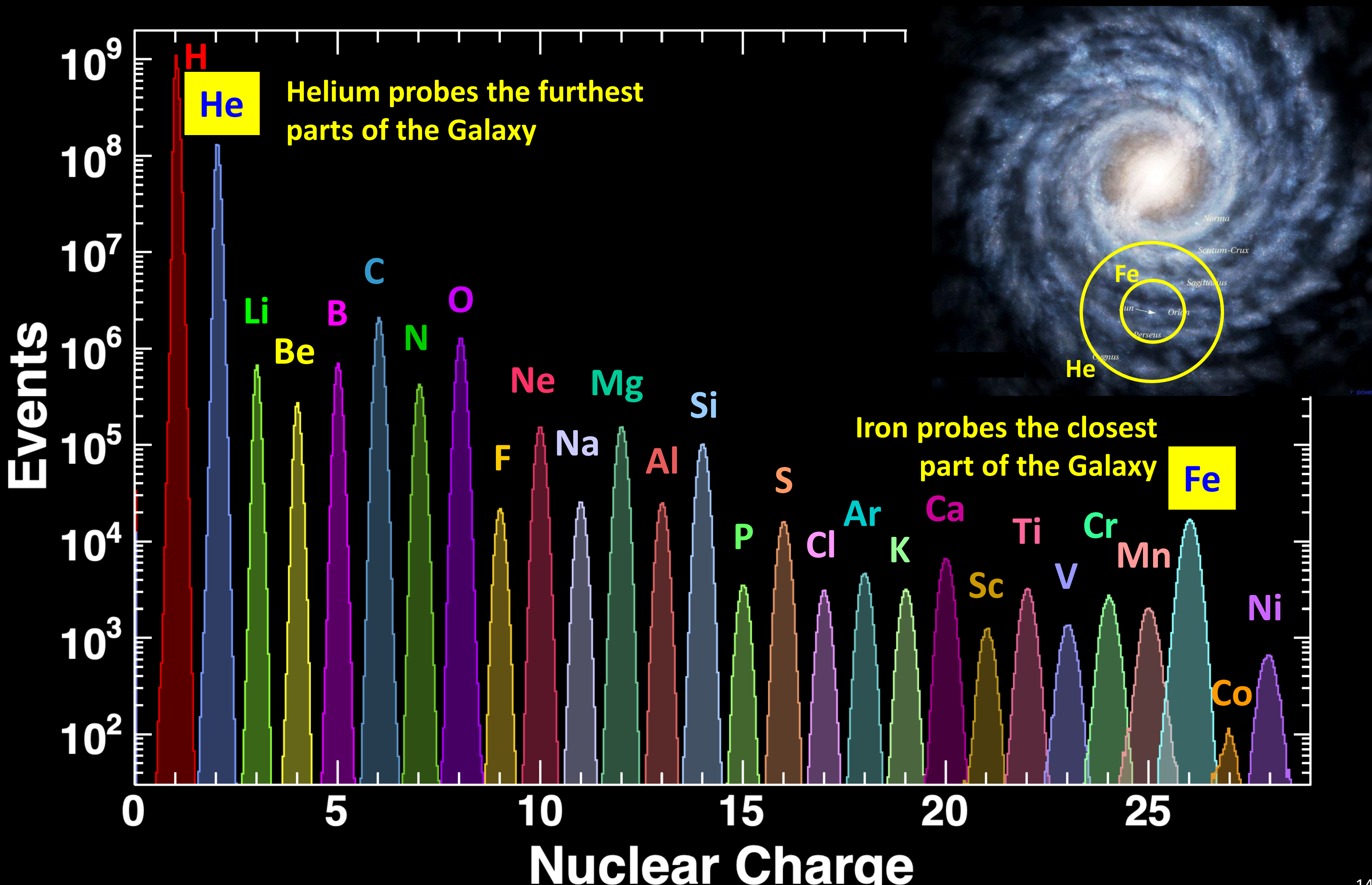
In the traditional understanding $\phi=CR^{\gamma}$,
AMS found that He-C-O **harden** in the same way above ~200 GV.



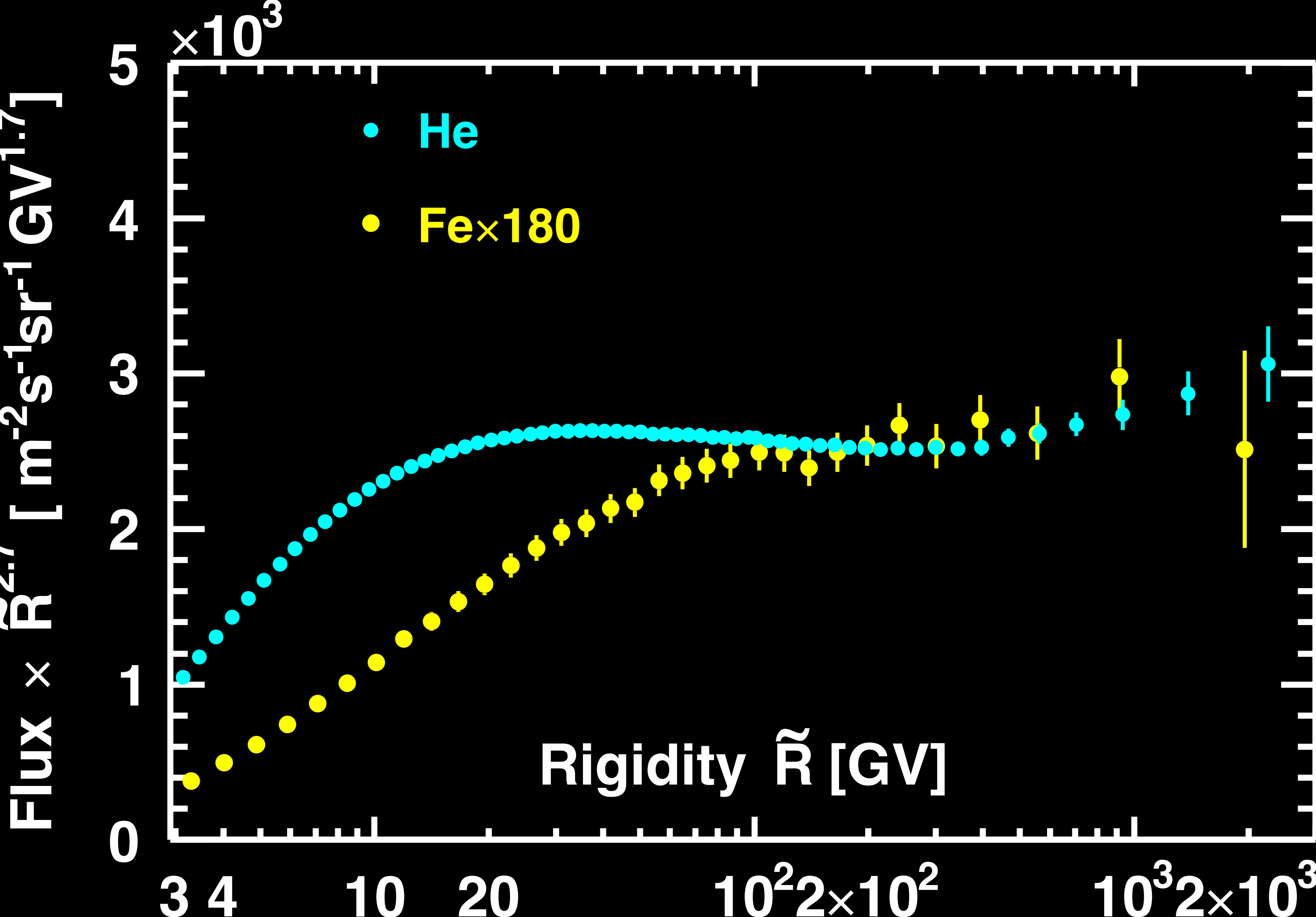
Heavier elements Ne-Mg-Si have their own rigidity dependence, different than the dependence of light elements He-C-O.



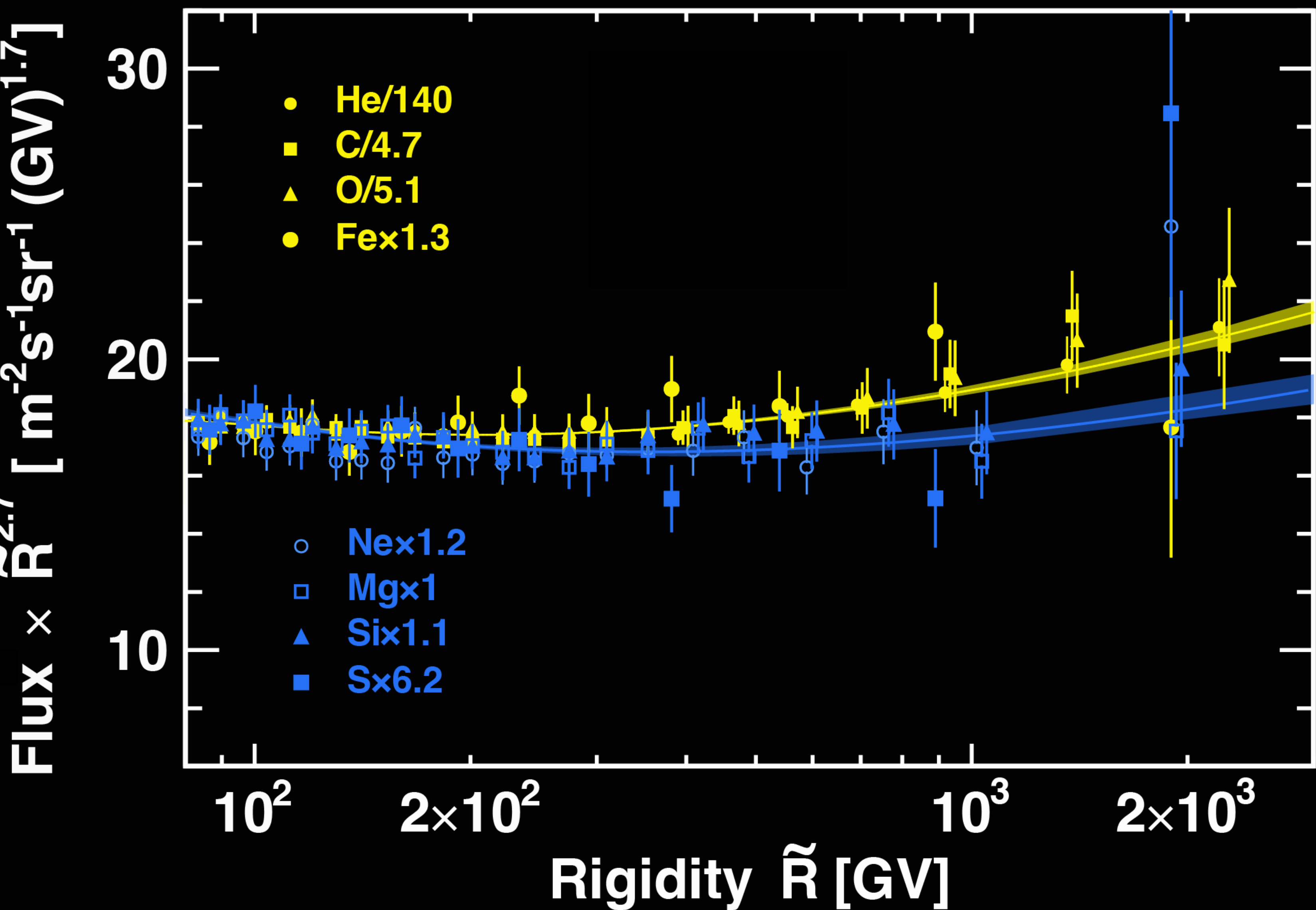
Iron is a very important element in cosmic ray theories because it is the heaviest element produced during stellar evolution. Iron has a large interaction rate with the interstellar medium and comes from the closest part of the Galaxy.



Iron is in the He-C-O primary cosmic ray group instead of the expected heavy Ne-Mg-Si group.

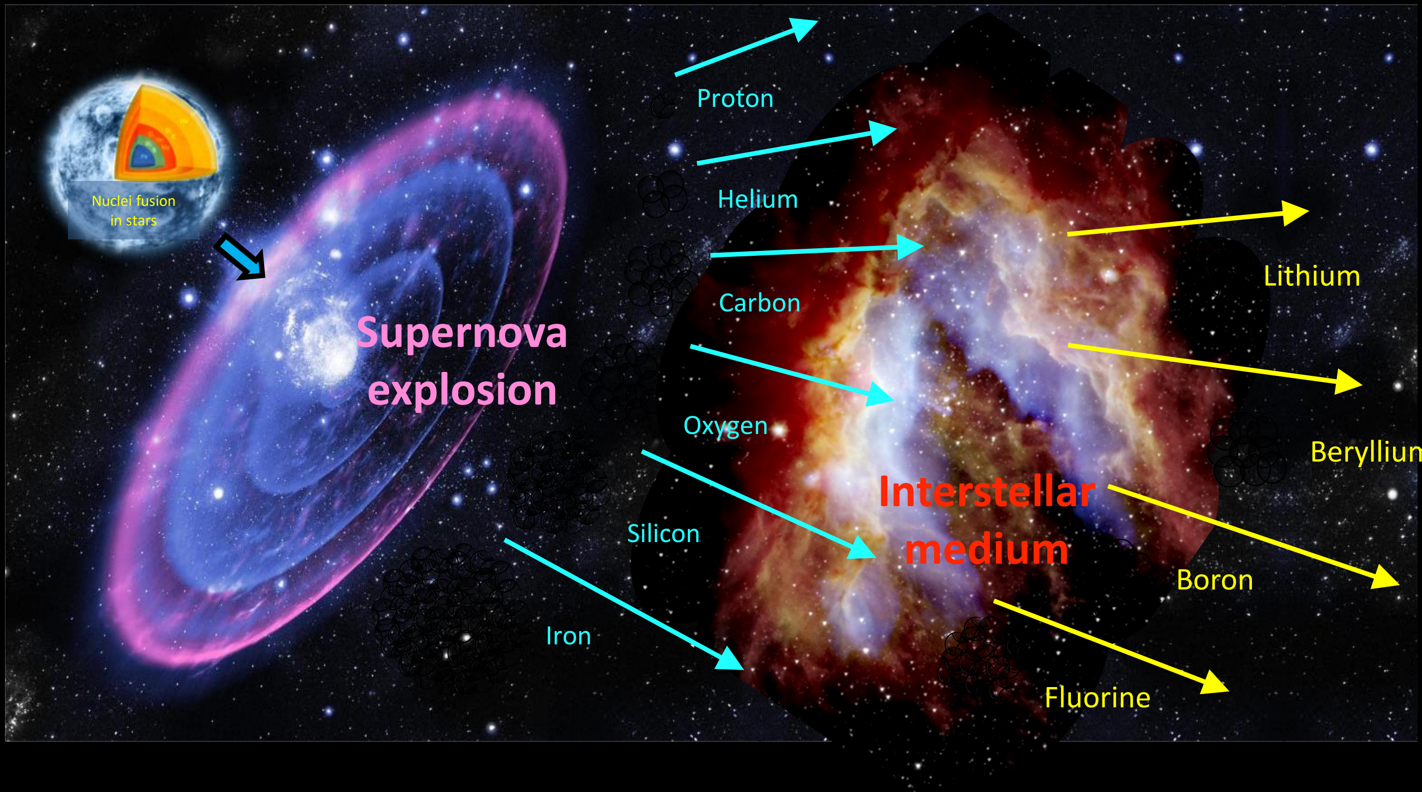


AMS Results on all 8 primary elements: They are in two classes



Latest AMS Results (11.5 years) on Secondary Cosmic Ray Nuclei

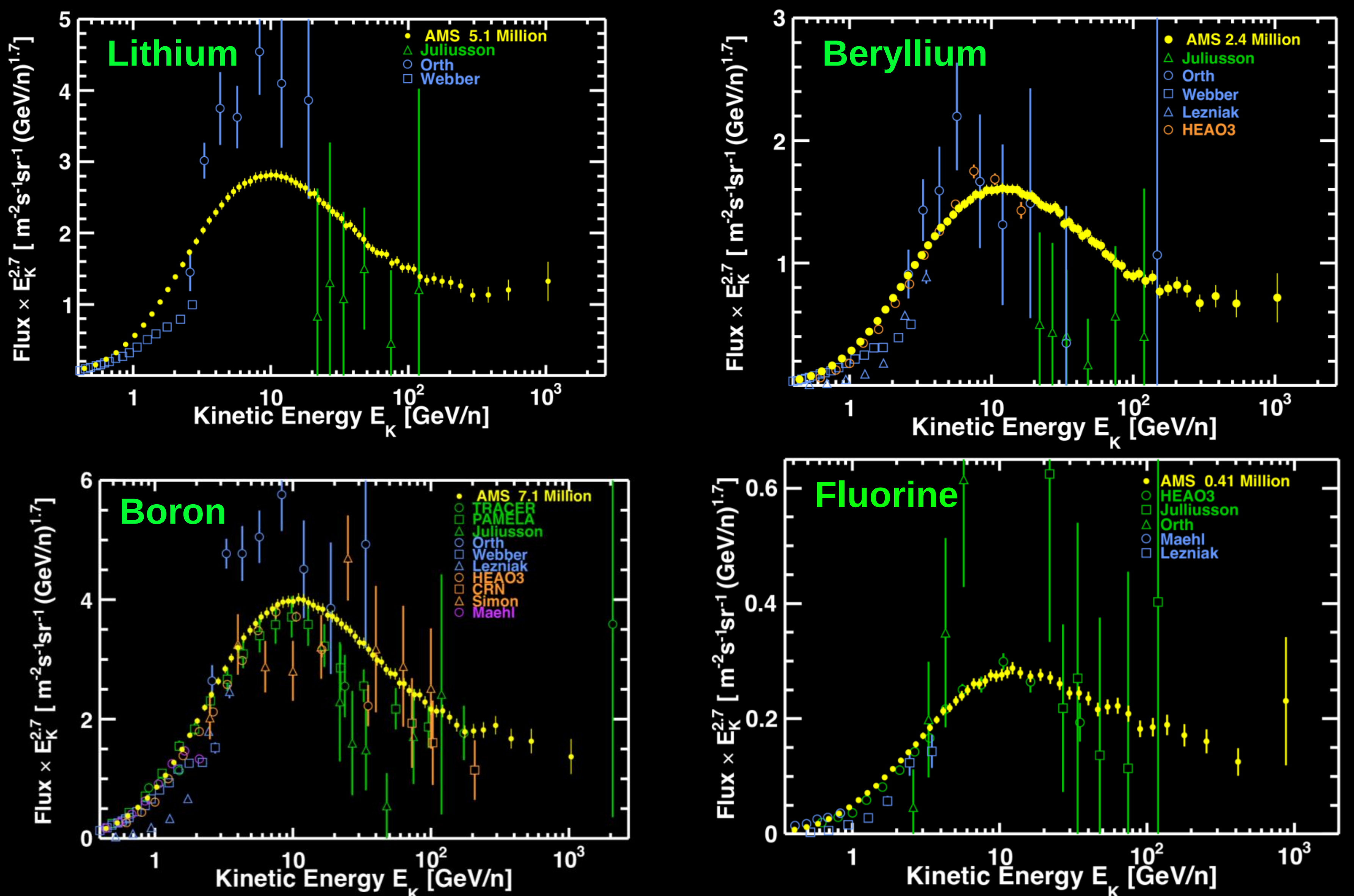
Secondary Li, Be, B, and F nuclei in cosmic rays are produced by the collision of primary cosmic ray C, O, Ne, Mg, Si, …, Fe with the interstellar medium.



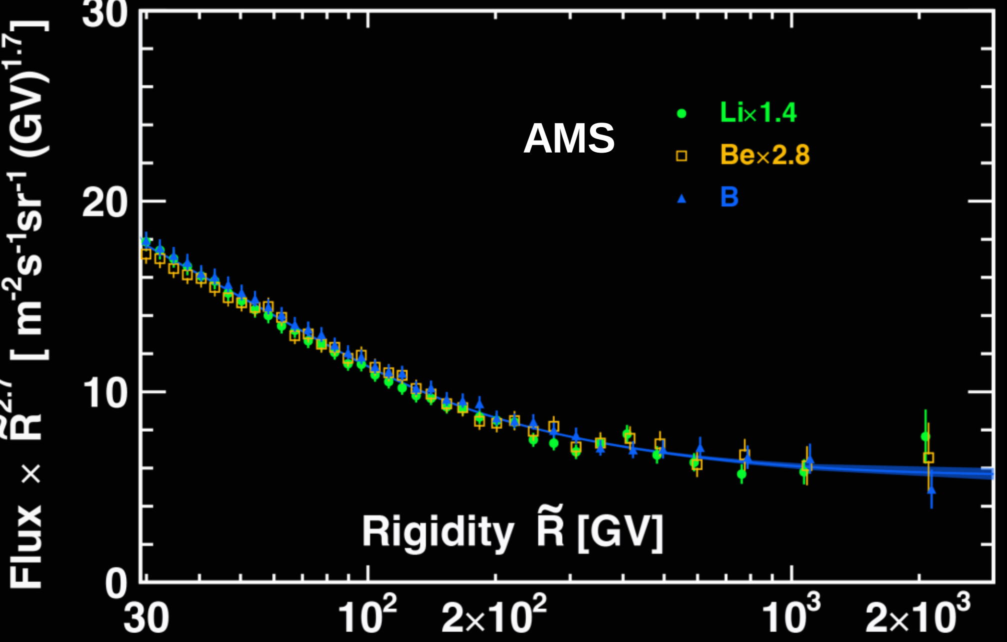
Measurements of the secondary cosmic ray nuclei fluxes are important in understanding the propagation of cosmic rays in the Galaxy.

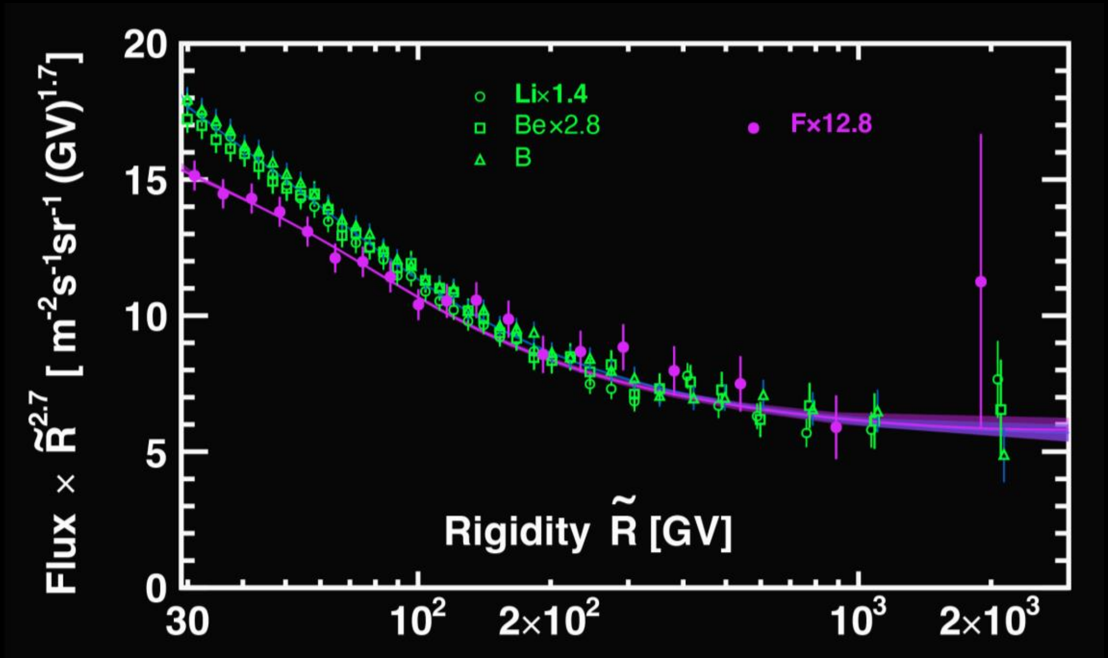
Secondary Nuclei are rare and difficult to measure.

AMS Secondary nuclei results compared with earlier measurements

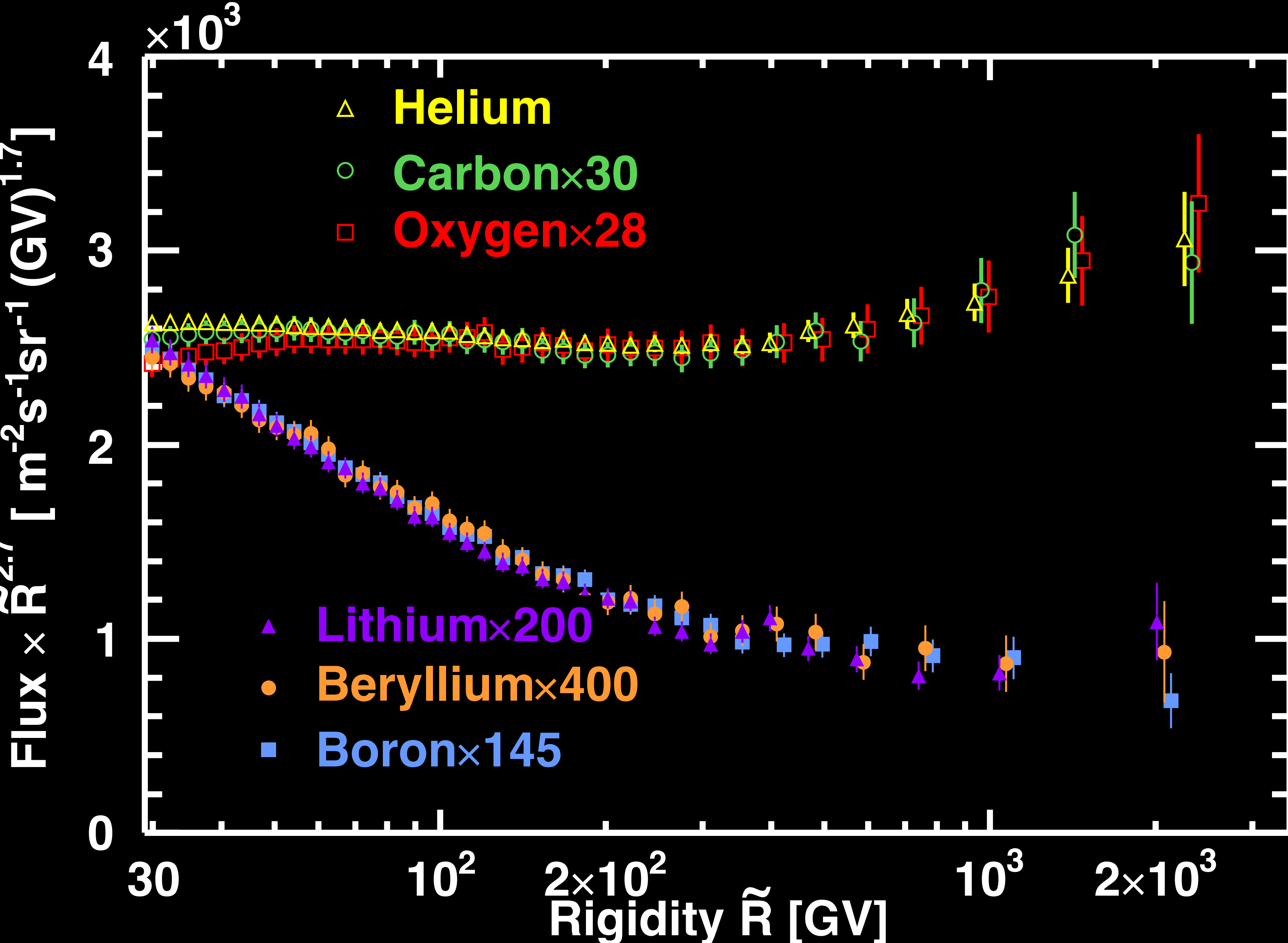


Secondary cosmic rays also have two classes of rigidity dependence

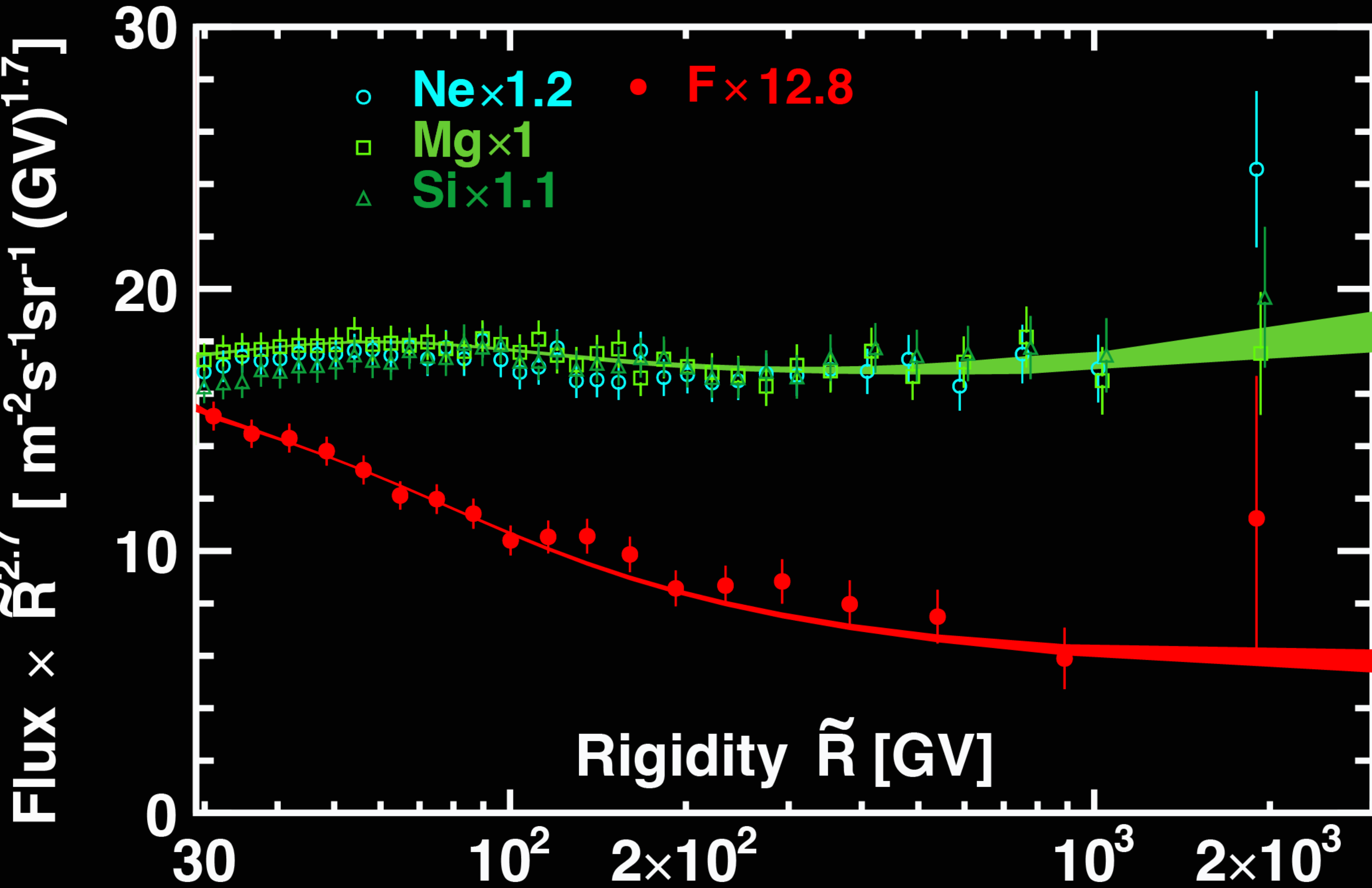




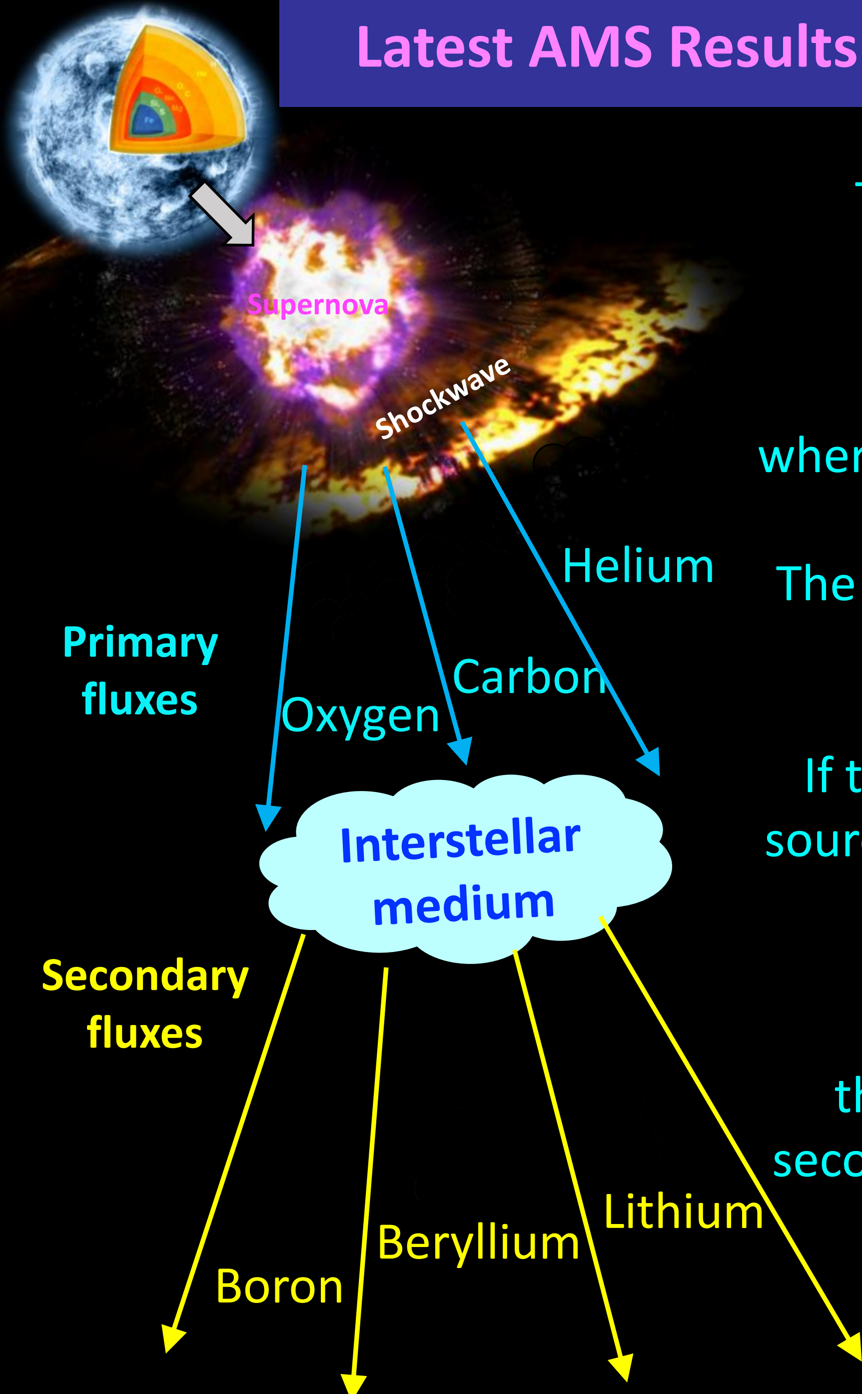
He-C-O primaries compared with Li-Be-B secondaries



Ne-Mg-Si primaries compared with F secondaries
High-Z nuclei also have two distinct classes



Latest AMS Results on Secondary-to-Primary Flux Ratios



The secondary-to-primary flux ratio is a key parameter in all models of cosmic rays.

Secondary/Primary = kR^{Δ}

where Δ was assumed to be independent of R and Z.

The increase of Δ with R is described as hardening.

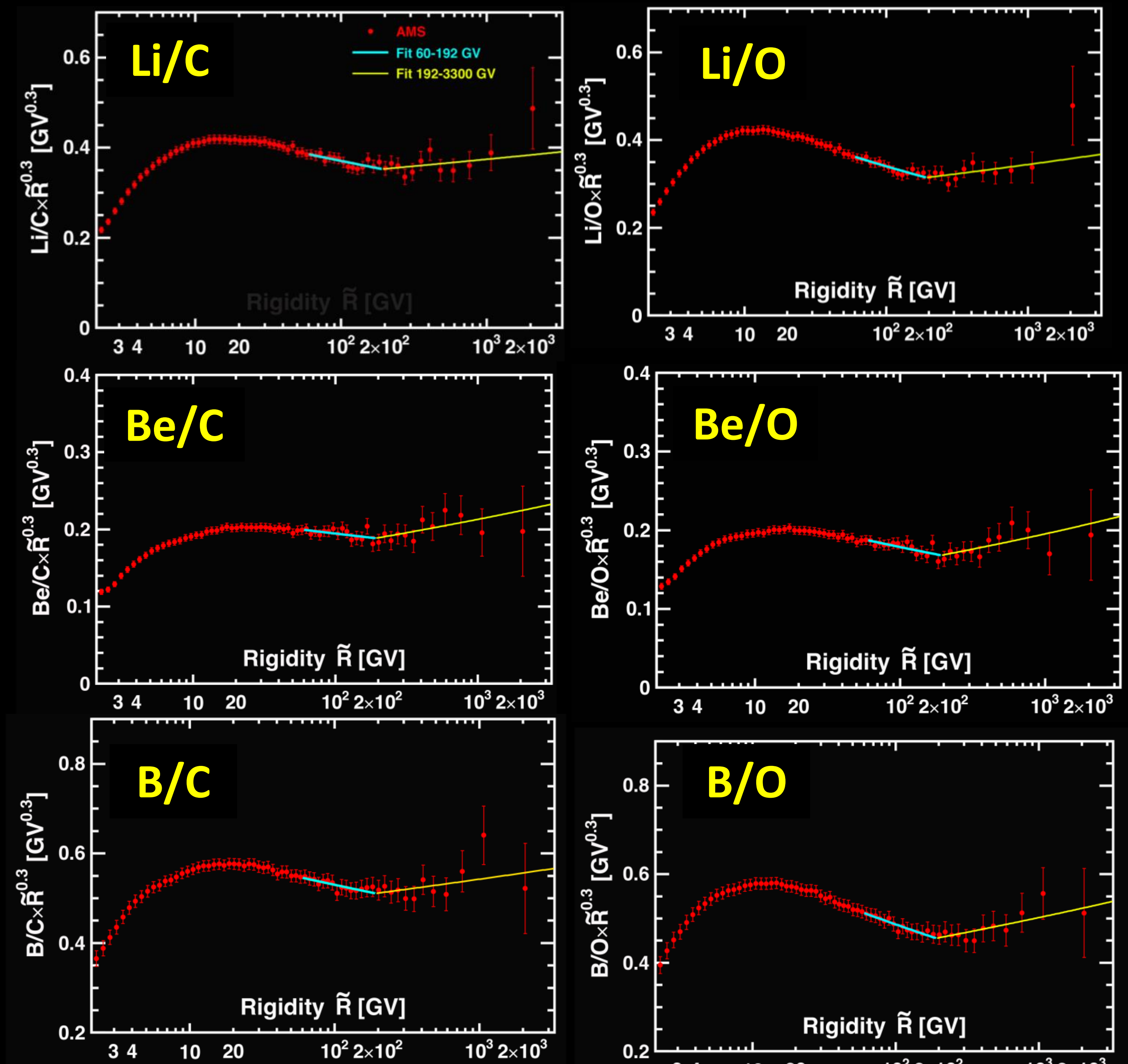
If the hardening is related to the injection at the source, then similar hardening is expected for both.
Δ is independent of R.

If the hardening is related to propagation, then a stronger hardening is expected for the secondary with respect to the primary cosmic rays.
Δ increases with R.

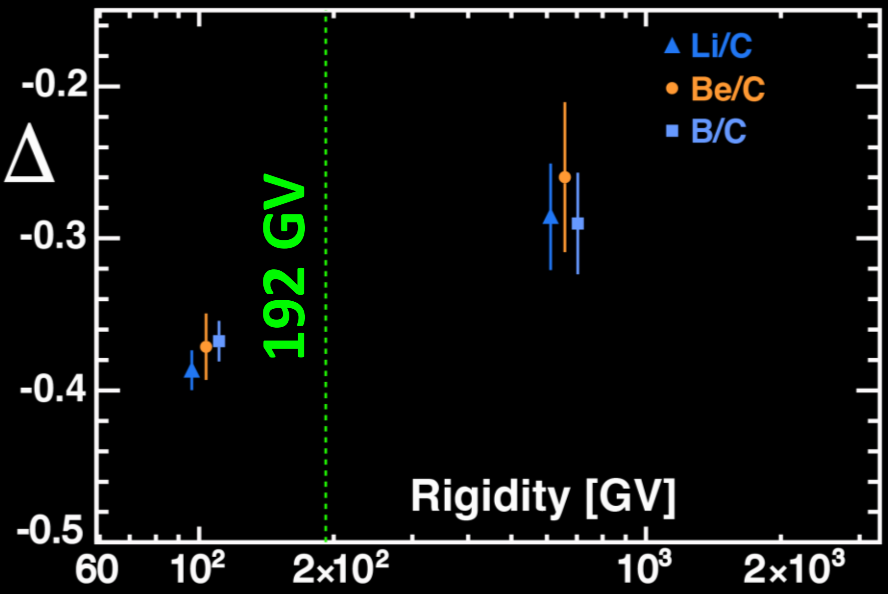
Secondary to Primary Flux Ratios = kR^{Δ} are rigidity dependent

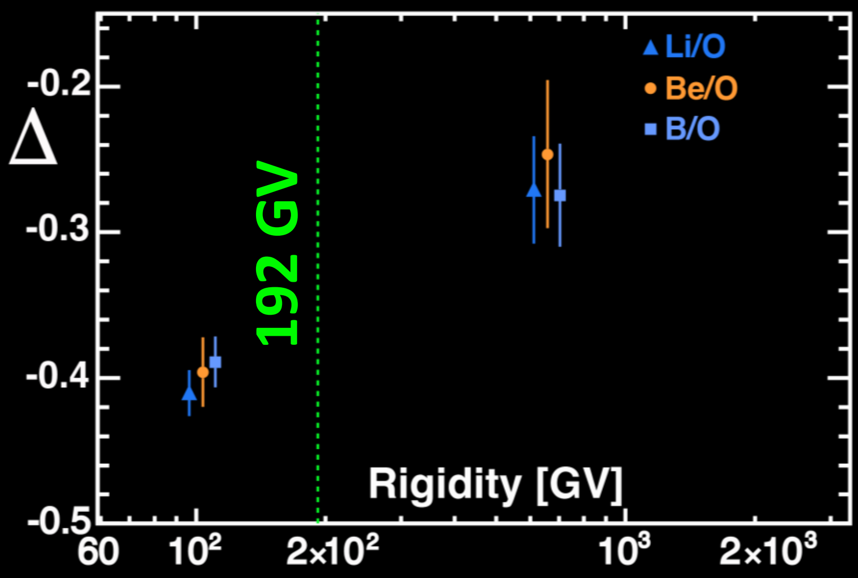
and

Δ increases with R



Rigidity dependence of the Secondary/Primary Flux Ratios = kR^{Δ}



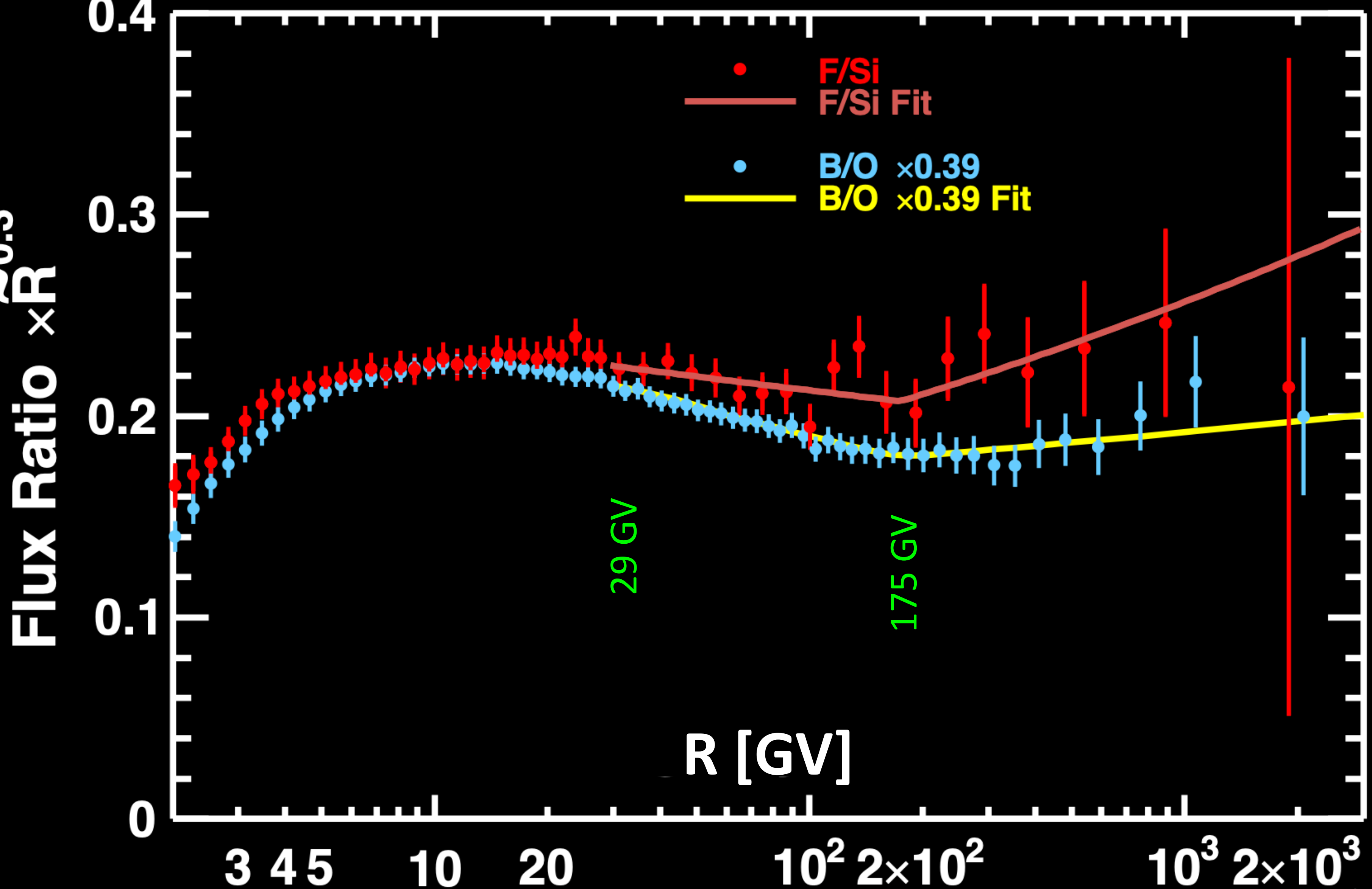


Δ in two rigidity intervals (60 − 192 GV and 192 − 3300 GV) exhibit an average hardening of 0.11±0.02.
The significance of this change is 5.5σ.

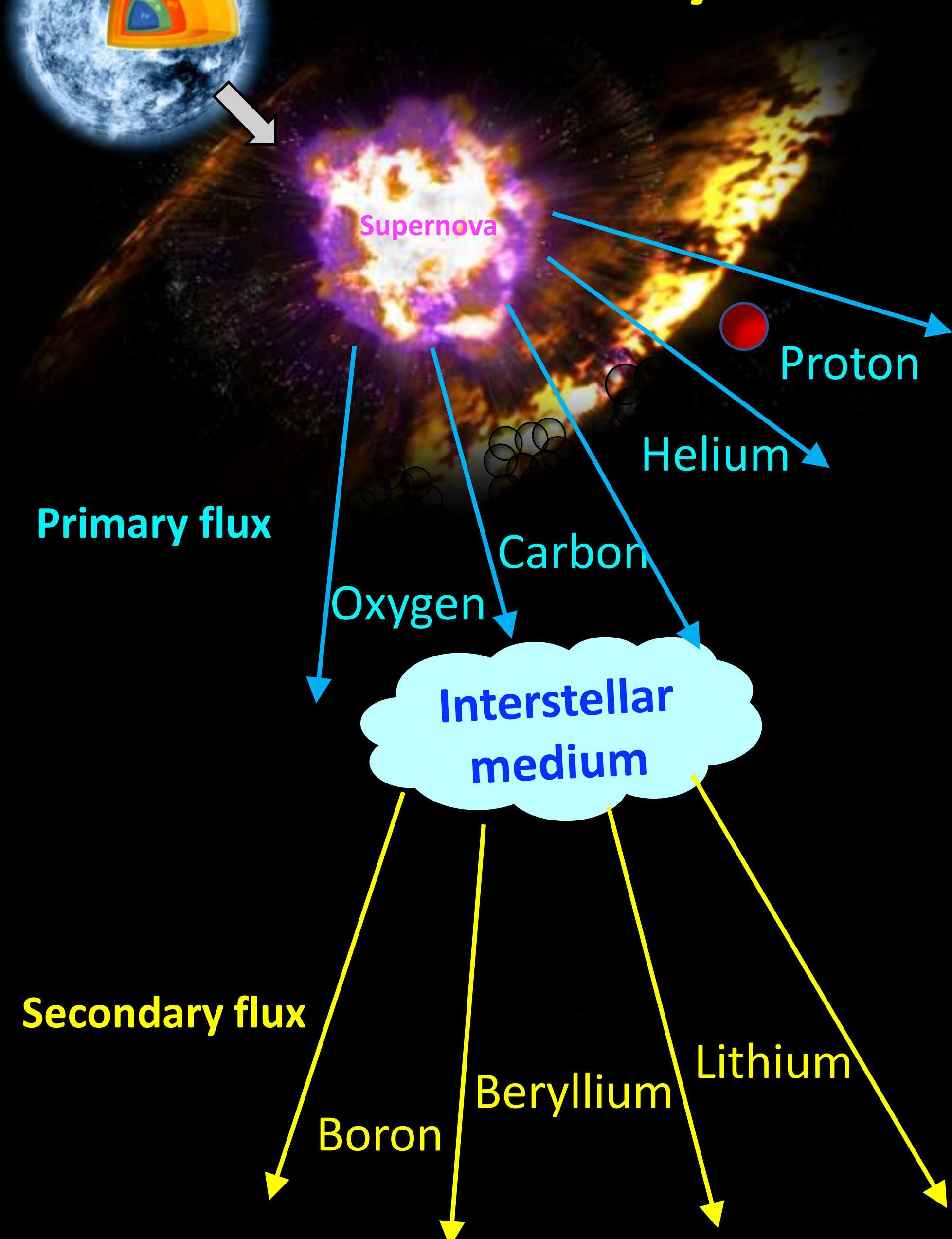
Above ~200 GV secondary cosmic rays harden twice as much as primaries.
This shows that the hardening is related to propagation properties in the Galaxy.

Z dependence of the Secondary-to-Primary flux ratios

F/Si (high-*Z*) compared to B/O (low-*Z*)



Secondary-to-Primary Flux Ratios



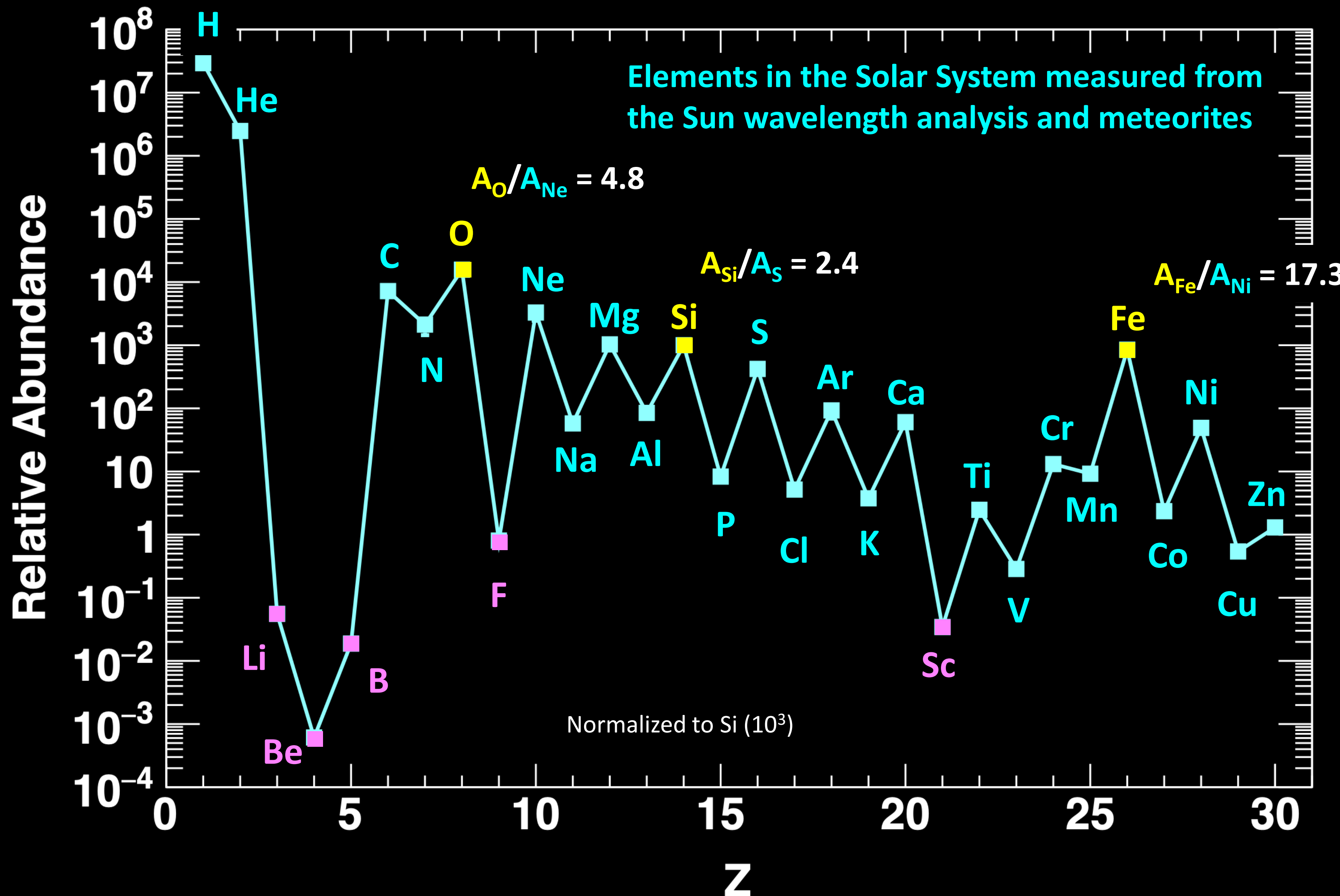
Before AMS, the secondary-to-primary flux ratios (B/C …) were assumed to be = kR^{Δ} with Δ a constant.

AMS results:

Δ depends on Z
Δ depends on R

The traditional B/C measurement does not describe the Interstellar Medium

Abundance of elements in the Solar System

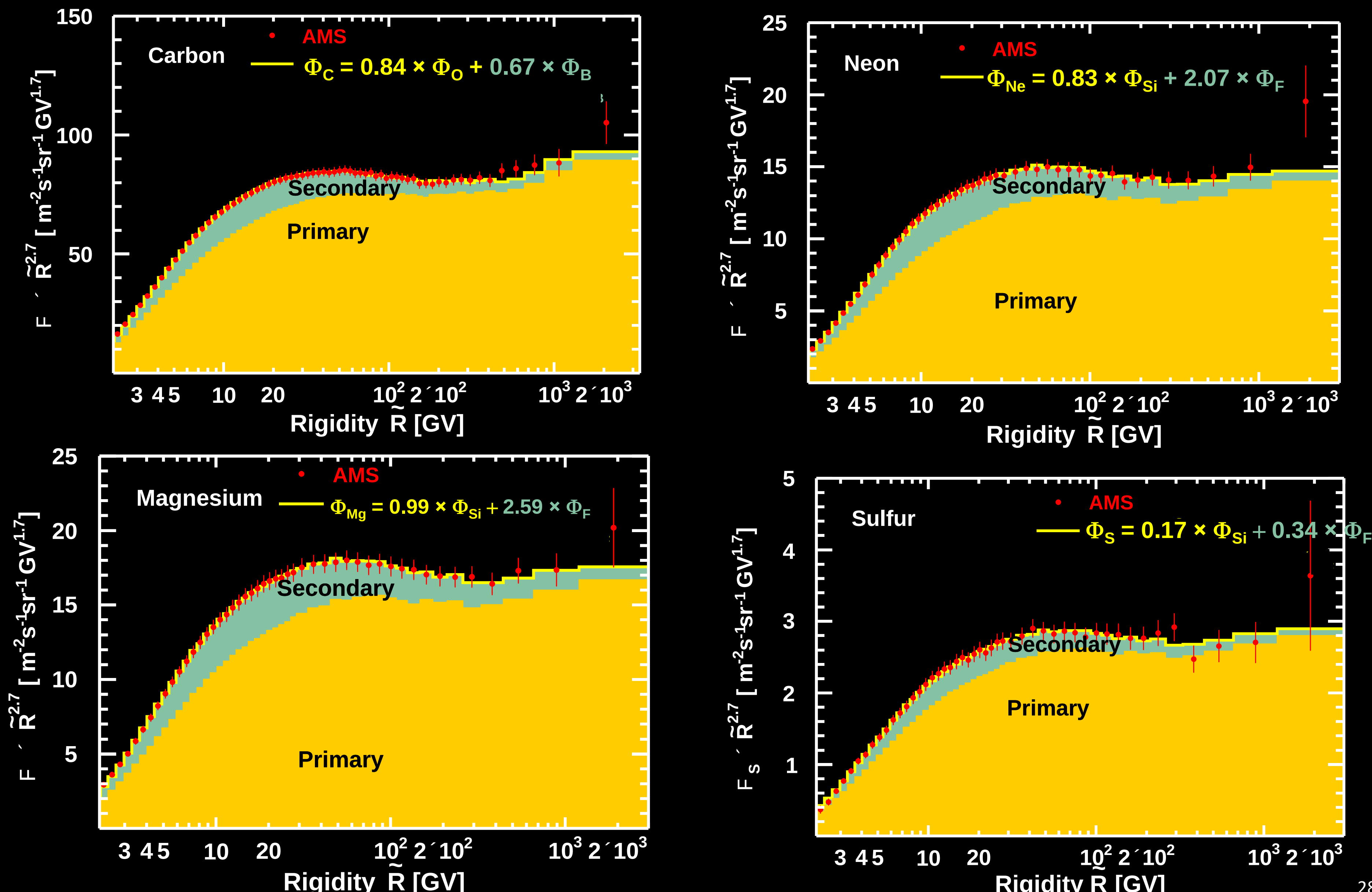


O, Si, and Fe are characteristic primary cosmic rays

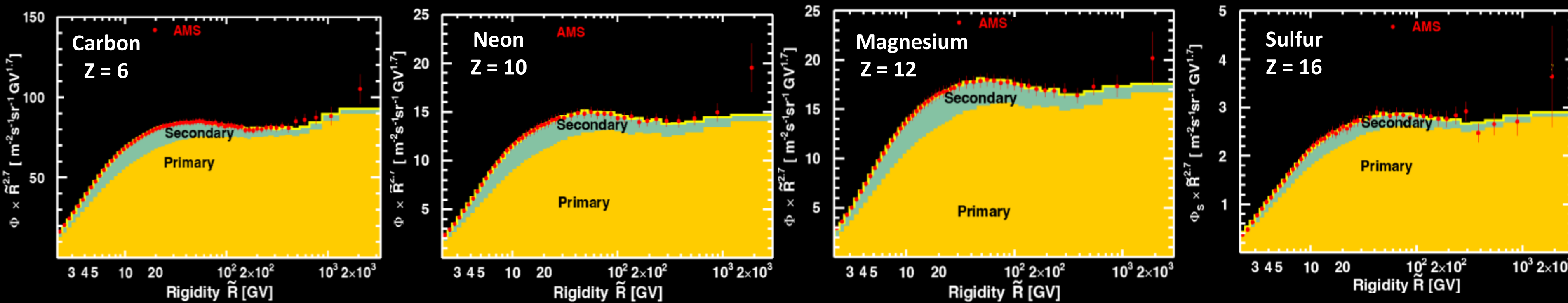
Li, Be, B, F, and Sc are characteristic secondary cosmic rays

New, unexpected observation:

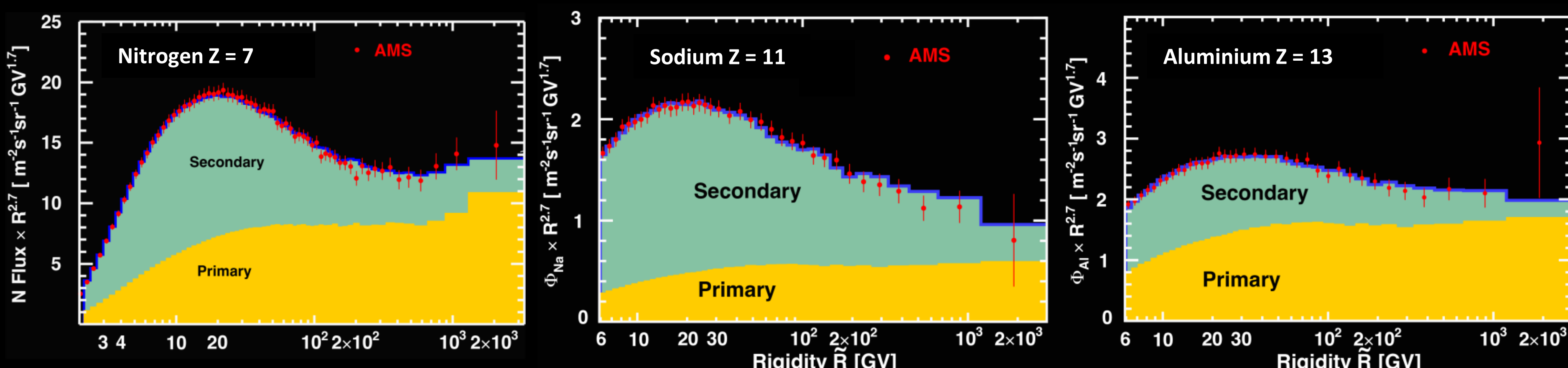
Traditional primary cosmic rays C, Ne, Mg, and S fluxes are not pure primary; they all have a significant secondary component



Even-Z nuclei and Odd-Z nuclei have distinctly different primary and secondary composition

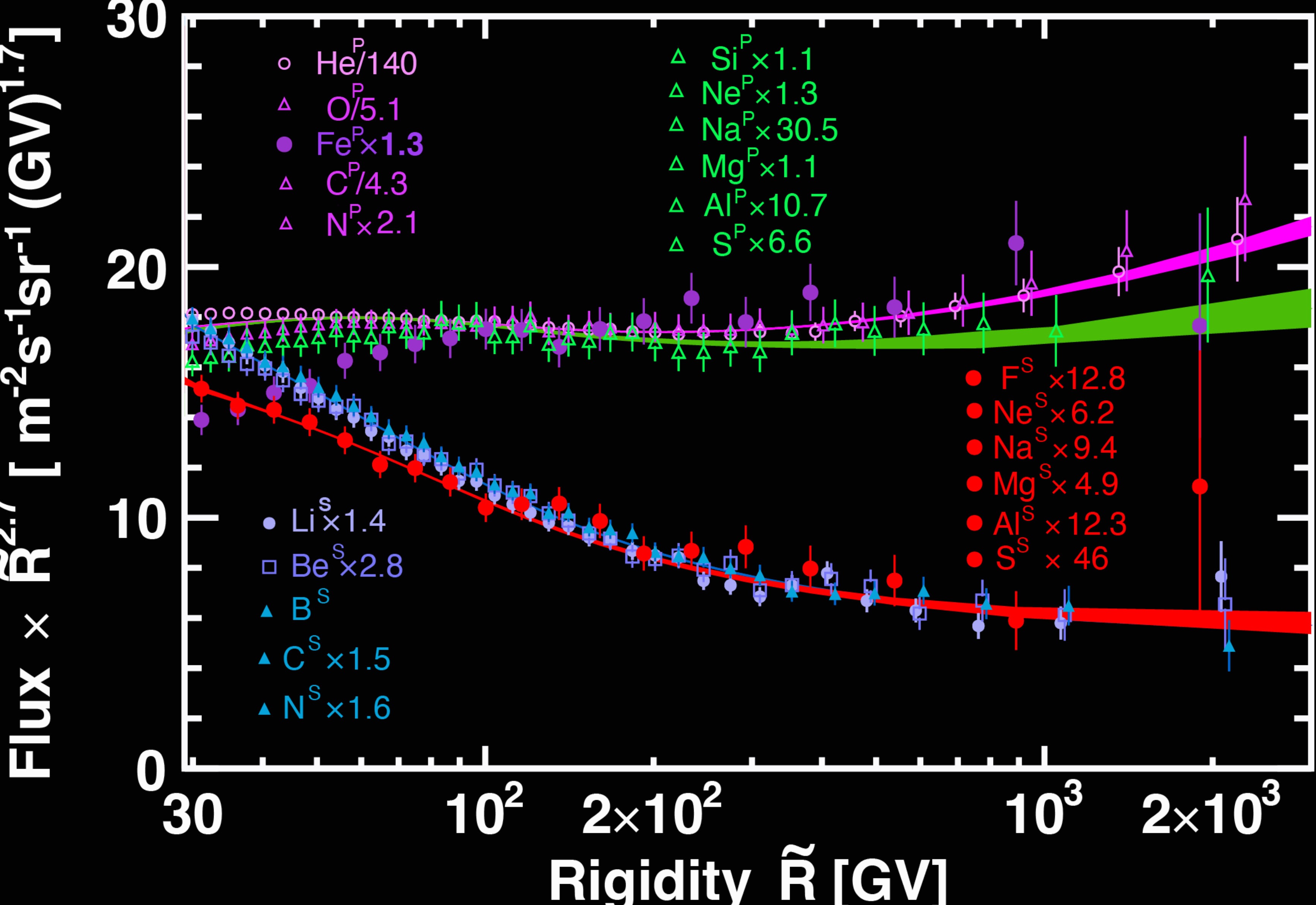


Even-Z nuclei are dominated by primaries

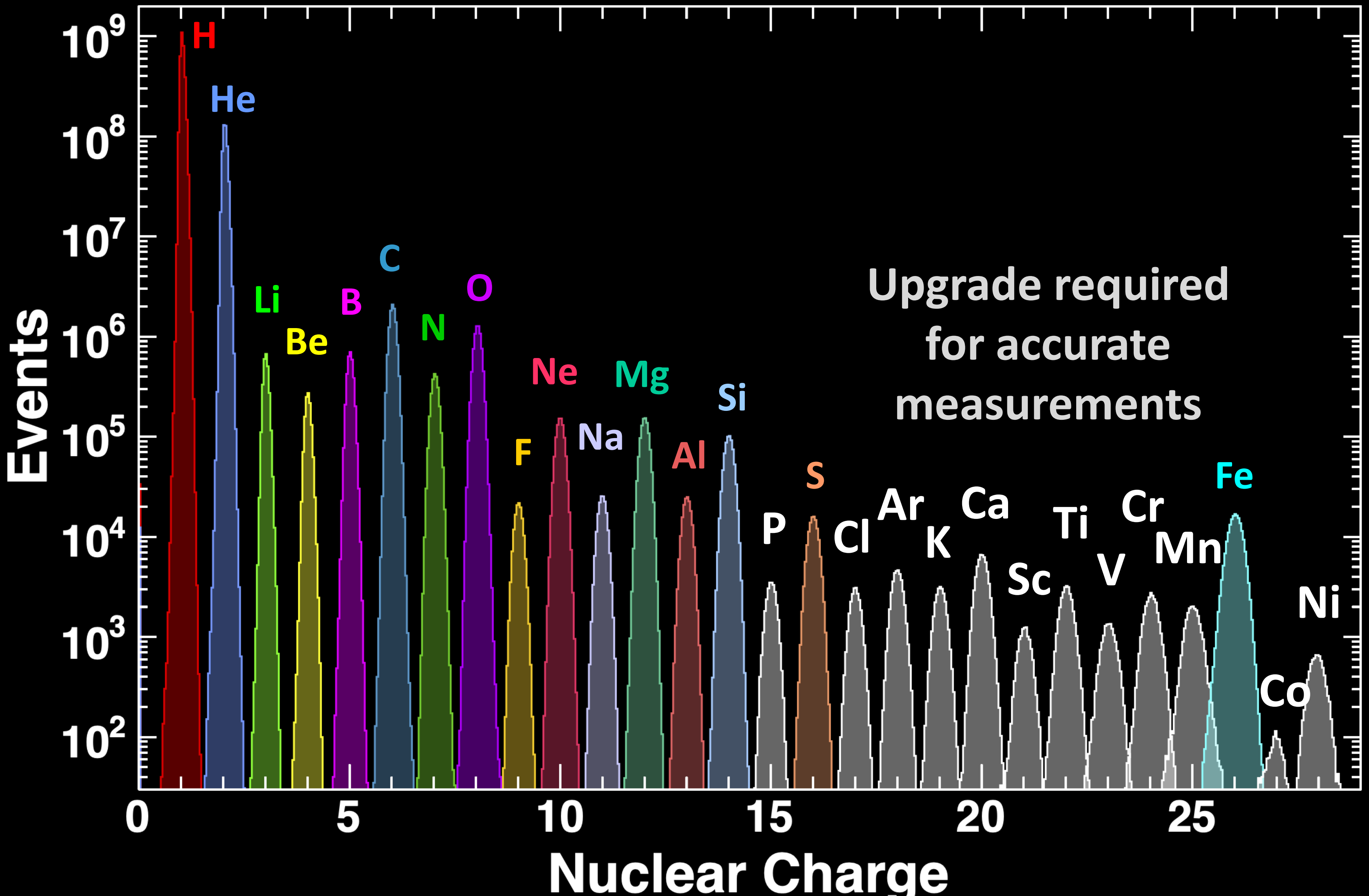


Odd-Z nuclei have more secondaries than even-Z

AMS Cosmic Ray data shows that all of the cosmic rays can be described by two Primary classes and two Secondary classes from 30 to 3000 GV

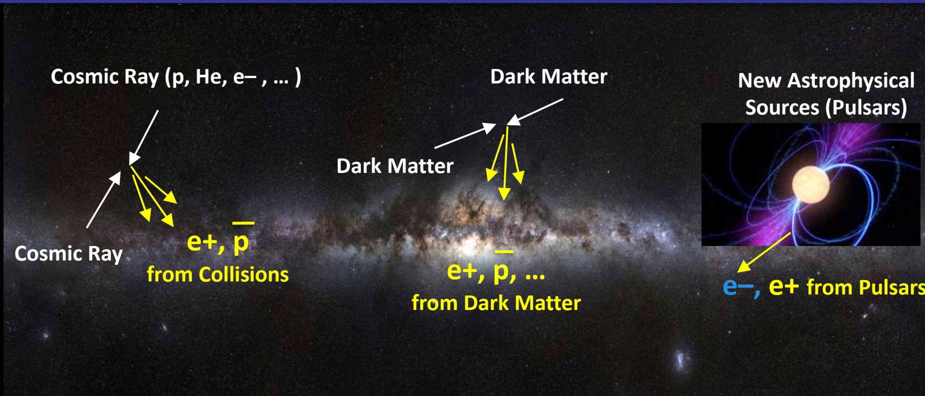


Current AMS Cosmic Ray Data (11.5 years)



By 2030 AMS will provide complete and accurate spectra for the 28 elements and will provide the foundation for a comprehensive theory of cosmic rays.

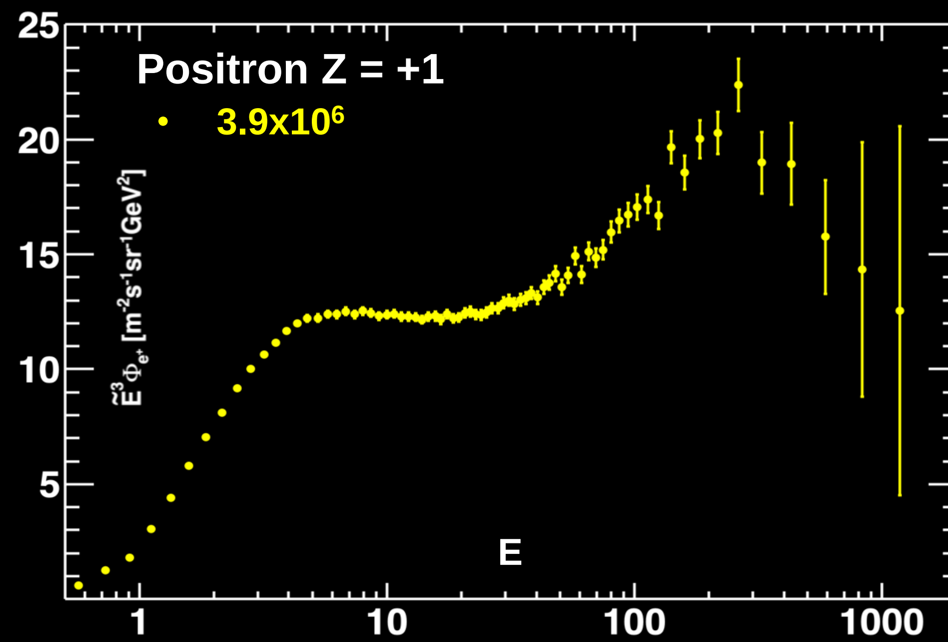
Latest AMS Results (11.5 years) on cosmic e+, e−, and $\bar{p}$

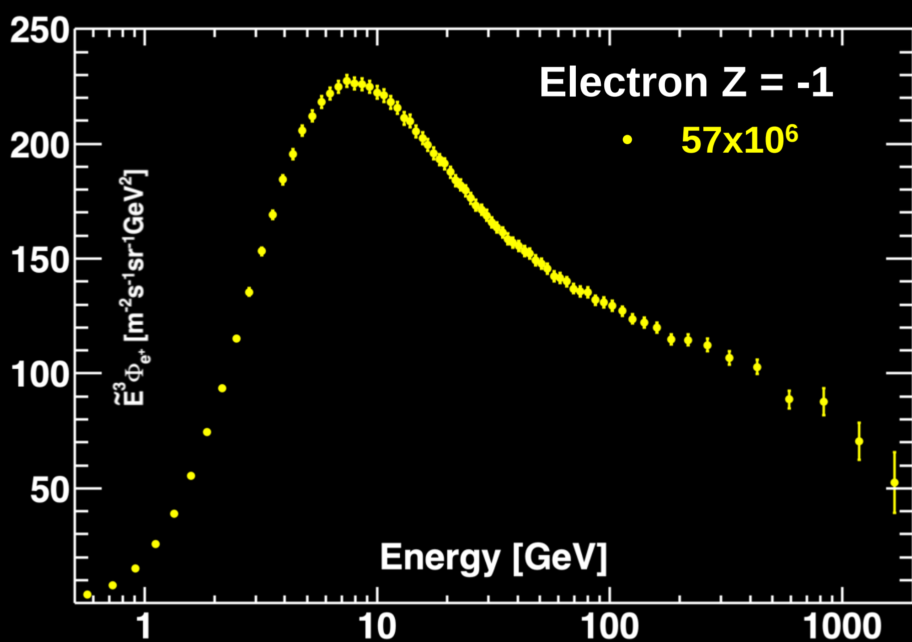


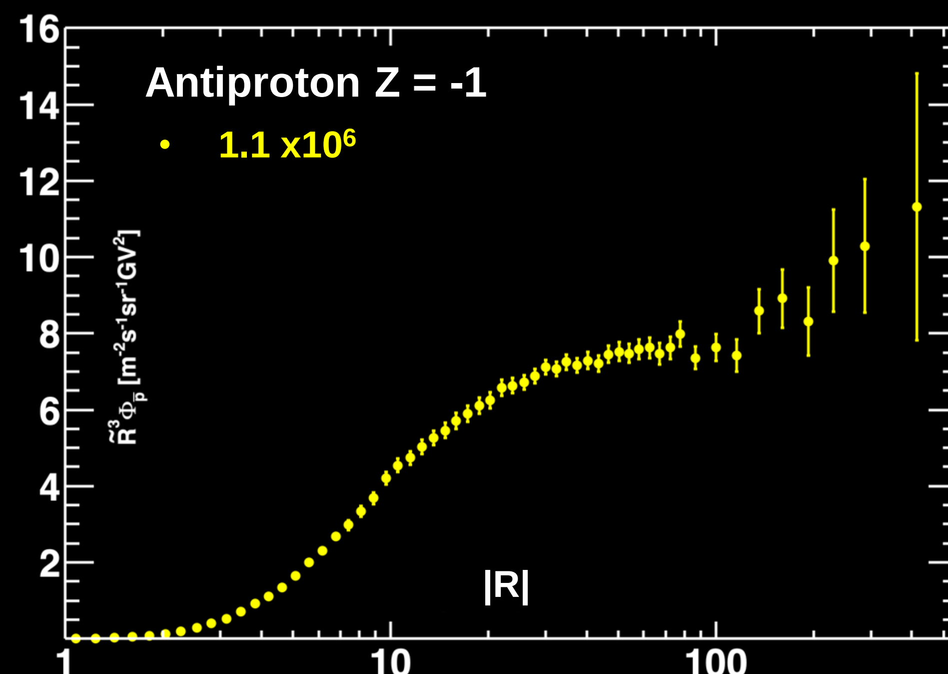
J. Ellis *et al.* , Nuclear Physics B. 238 (1984)

M. Turner and F. Wilczek, Phys. Rev. D42 (1990) 1001

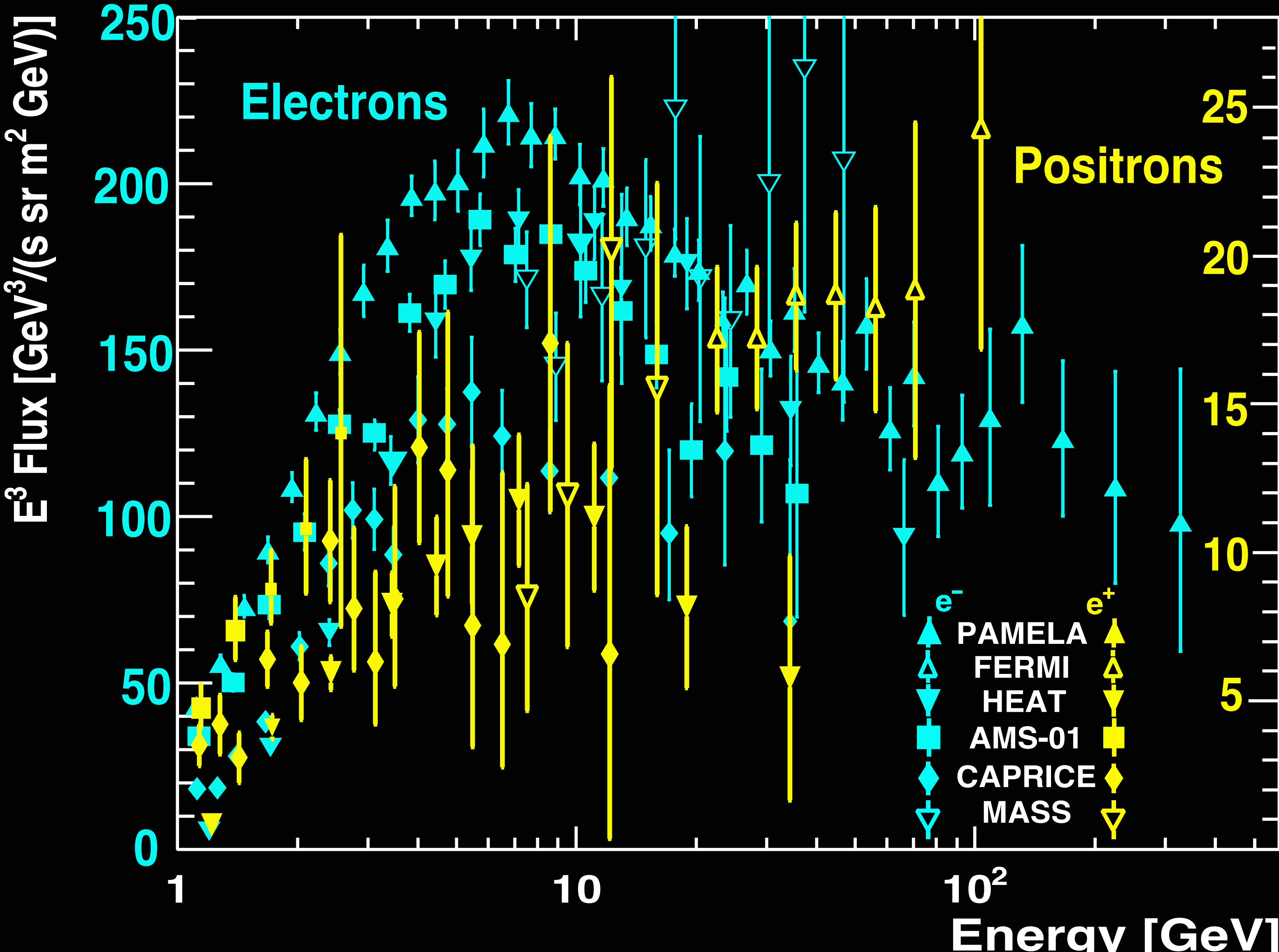
J. Ellis 26th ICRC (1999)



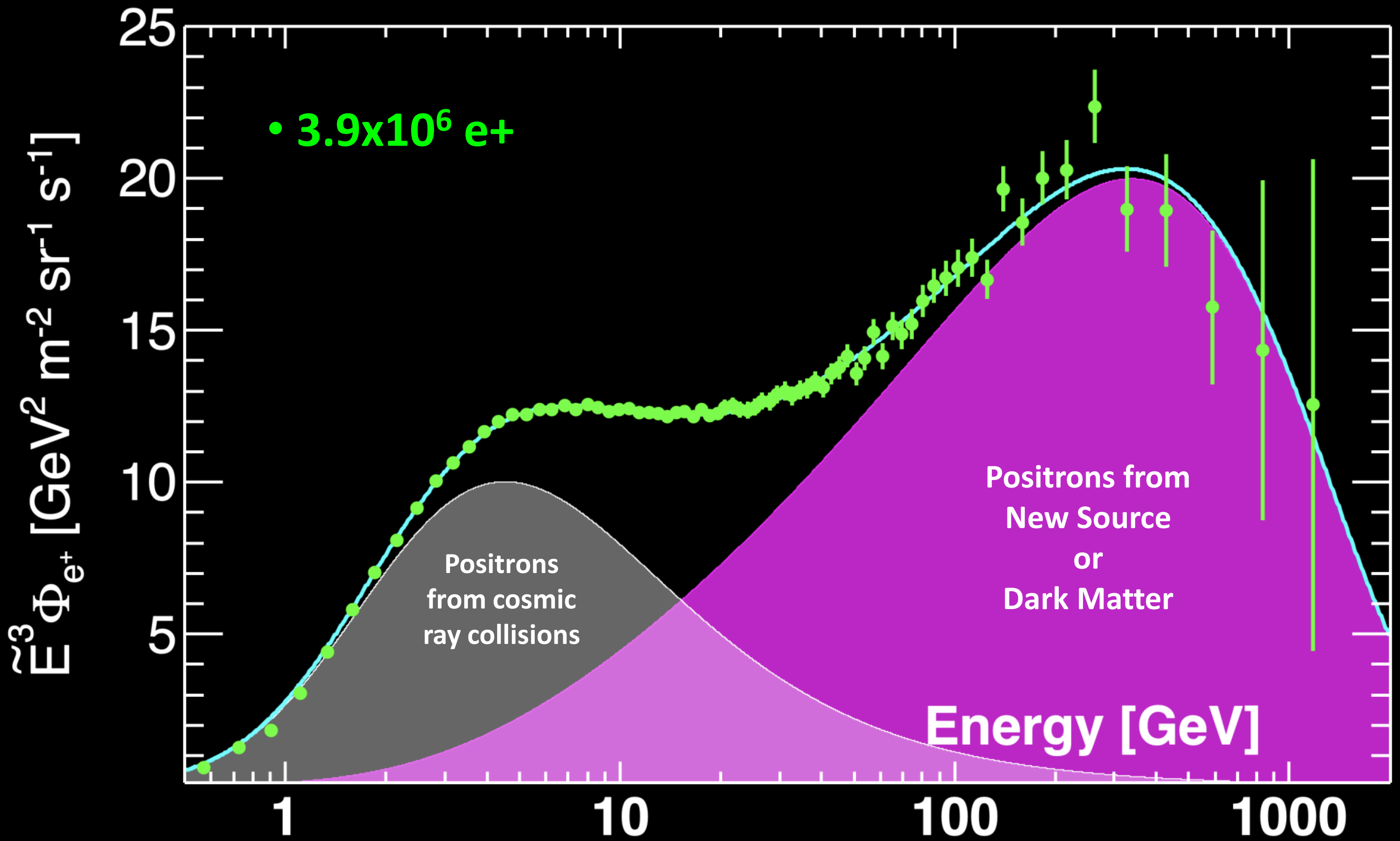




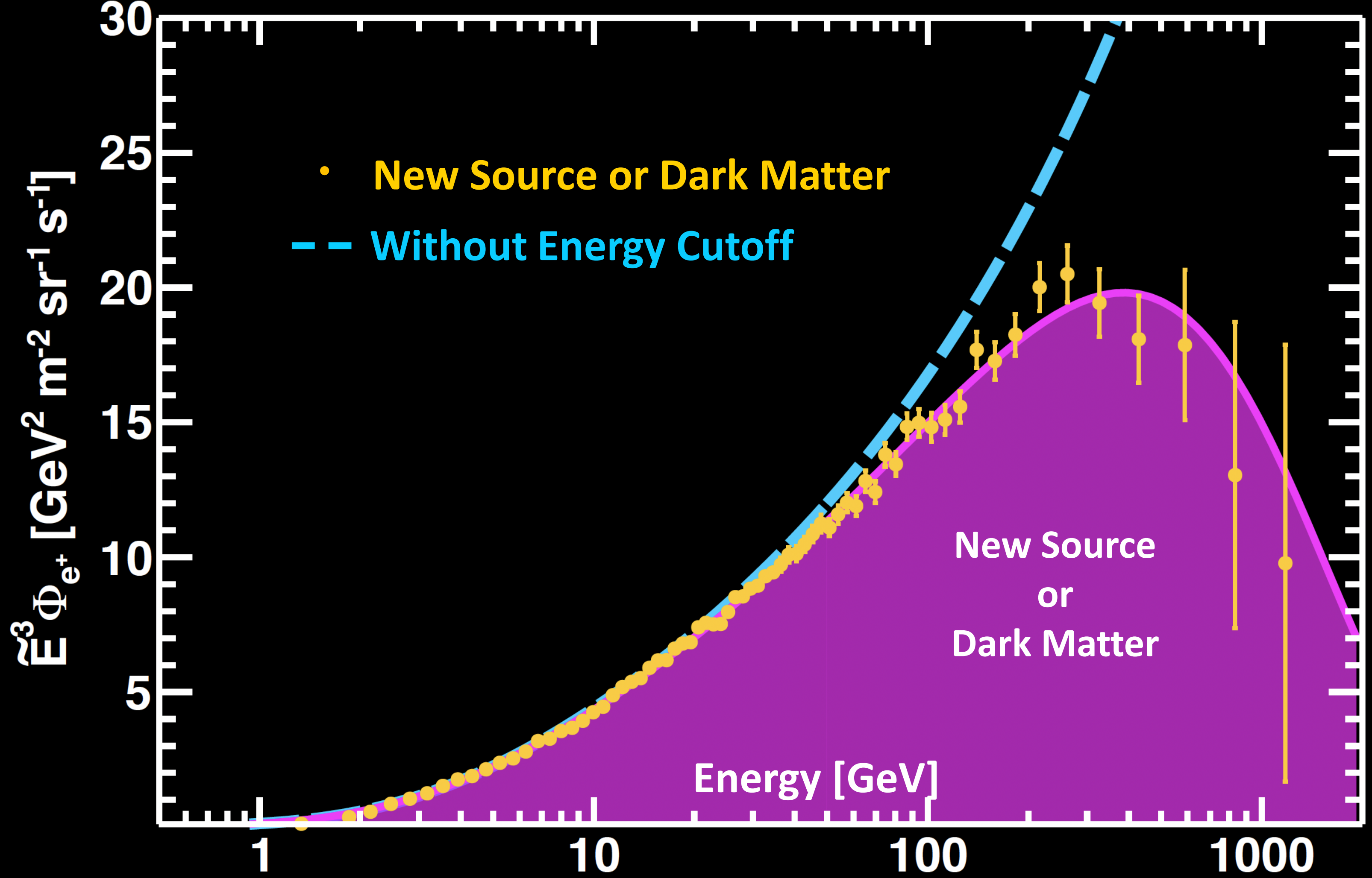
Measurements of positrons and electrons before AMS



The positron flux is the sum of low-energy part from cosmic ray collisions plus a high-energy part with a cutoff energy from new source or dark matter



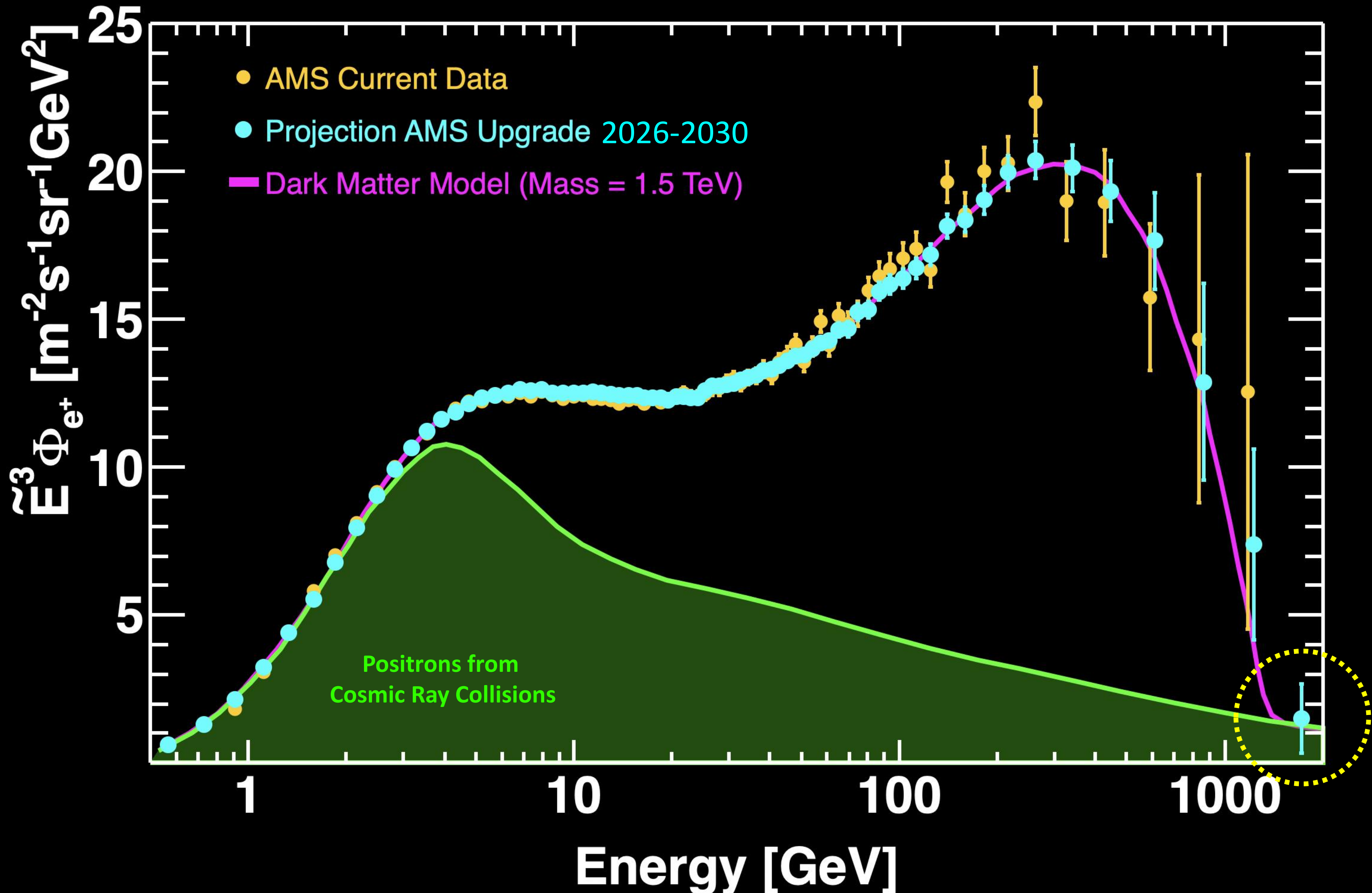
The excess of positrons with a cutoff energy



The finite cutoff energy is established with a confidence level of more than 99.999%.

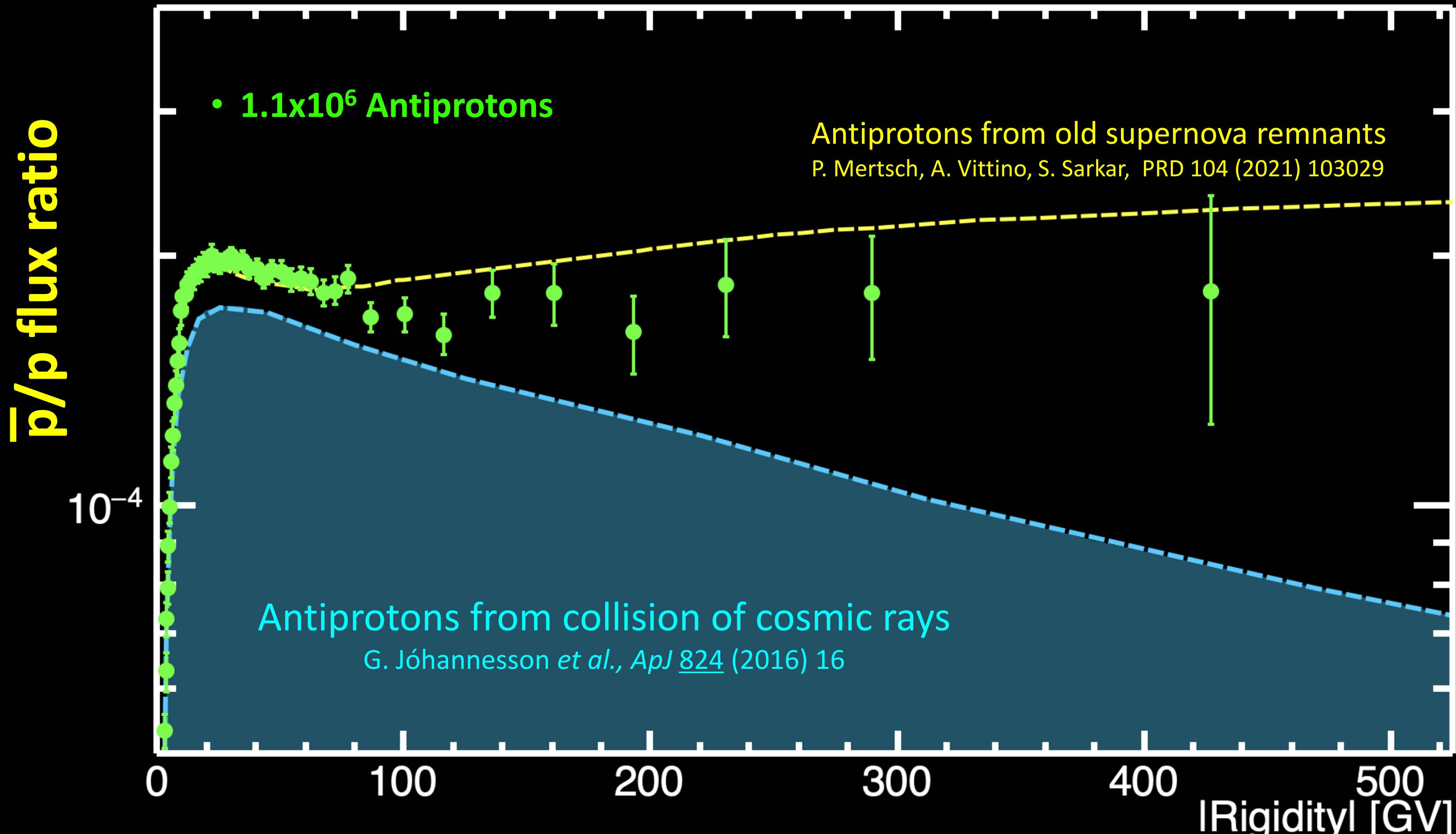
Determination of the Origin of Cosmic Positrons

The Upgrade will ensure that the measured high energy positron spectrum drops off quickly and, at the highest energies, the positrons only come from cosmic ray collisions as predicted by dark matter models



Properties of Cosmic Antiprotons

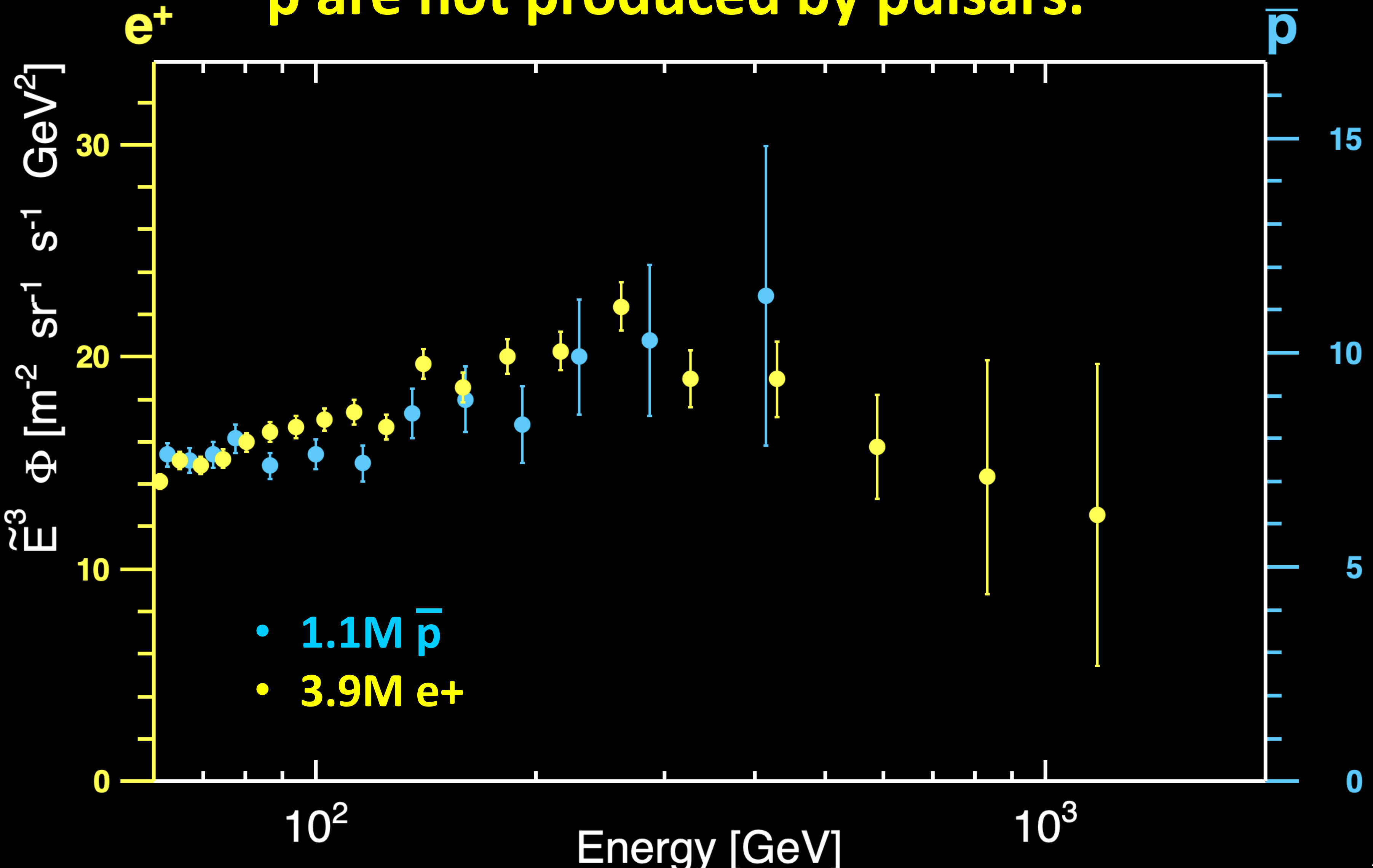
The antiproton-to-proton flux ratio shows that above 60 GV the ratio is energy independent.



Latest Results of Cosmic Antiprotons

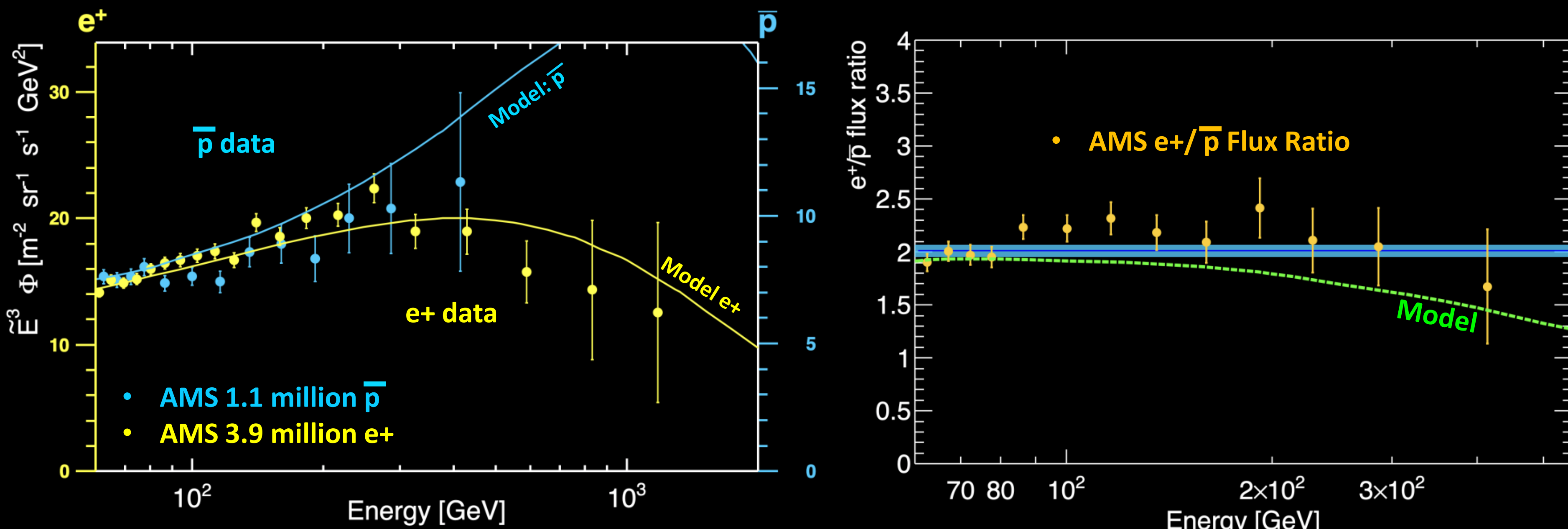
The $\bar{p}$ and e^+ fluxes have identical rigidity dependence.

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

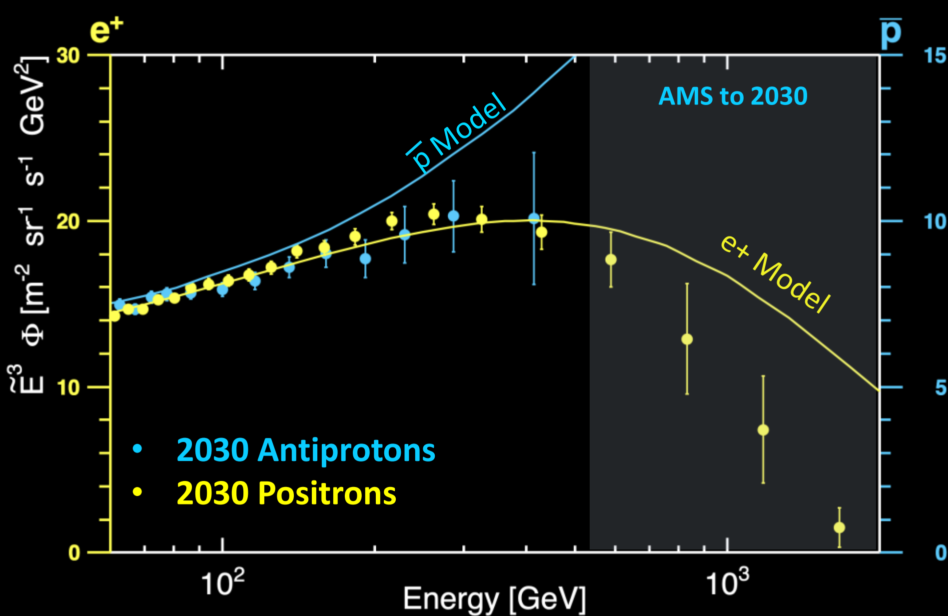


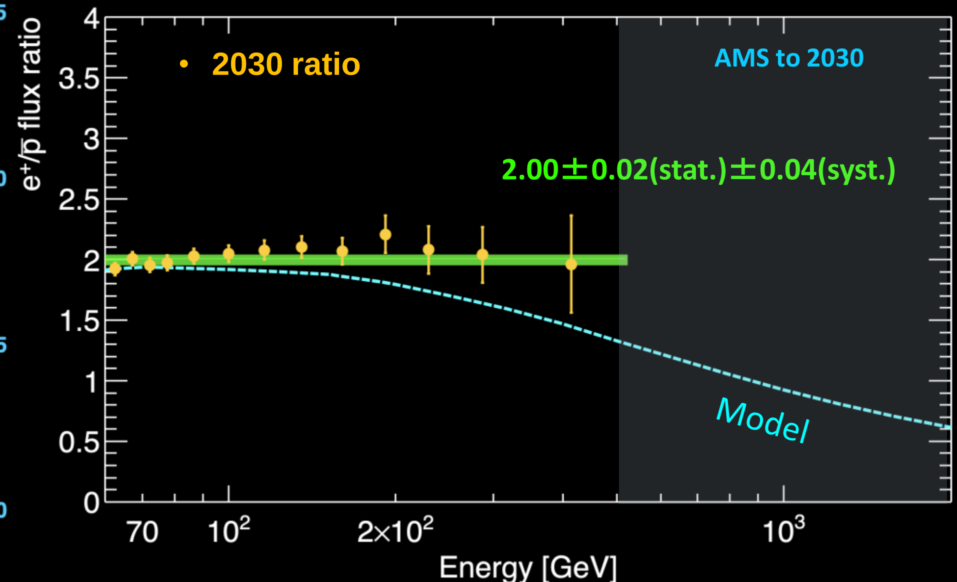
Comparison of the latest AMS e+ and $\bar{p}$ spectra with a recent model:

P. Mertsch, A. Vittino, S. Sarkar, "Explaining cosmic ray antimatter with secondaries from old supernova remnants" PRD 104 (2021) 103029



Comparison of the 2030 AMS e+ and p̄ spectra with a recent model:



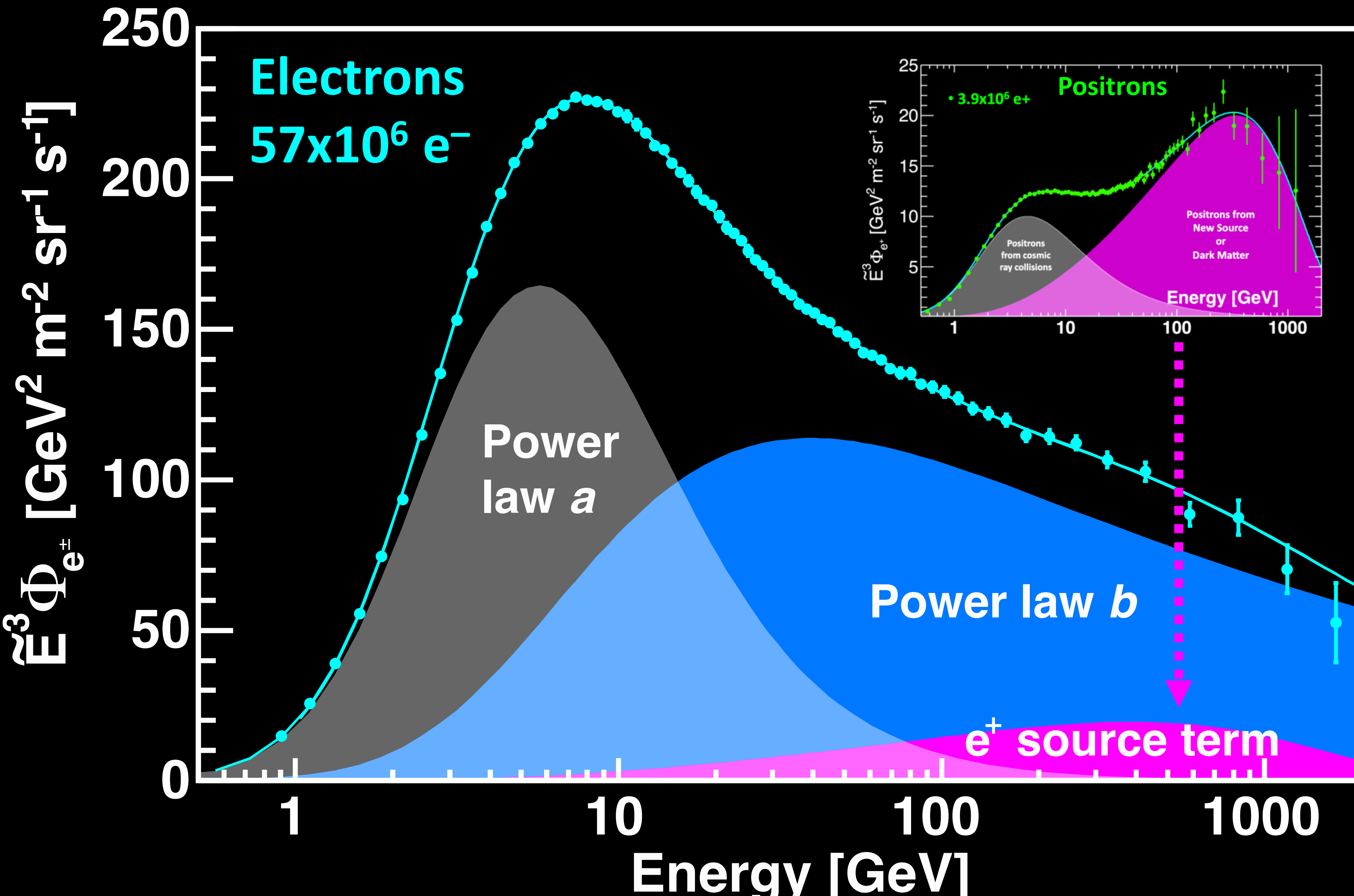


The identical behavior of positrons and antiprotons excludes the pulsar origin of positrons

Latest AMS Result on the electron spectrum

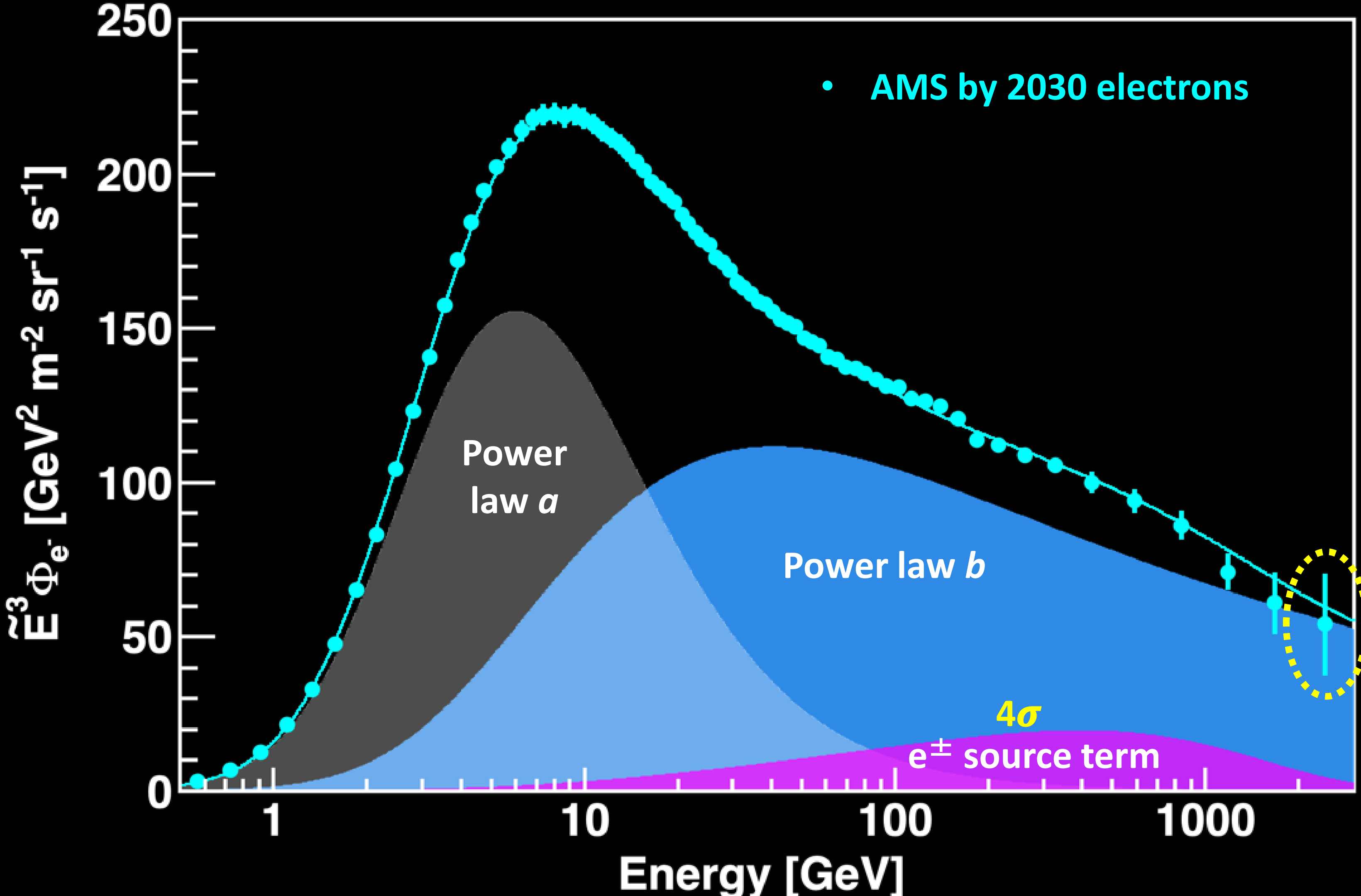
The spectrum fits well with two power laws (*a*, *b*) and

a source term identical to the positron excess

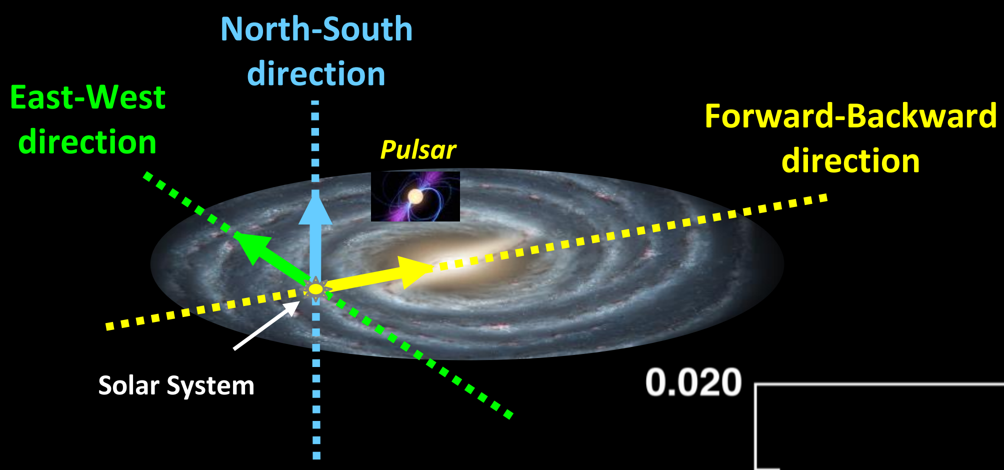


By 2030, the charge-symmetric nature of the high energy source will be established at the 4*σ* level

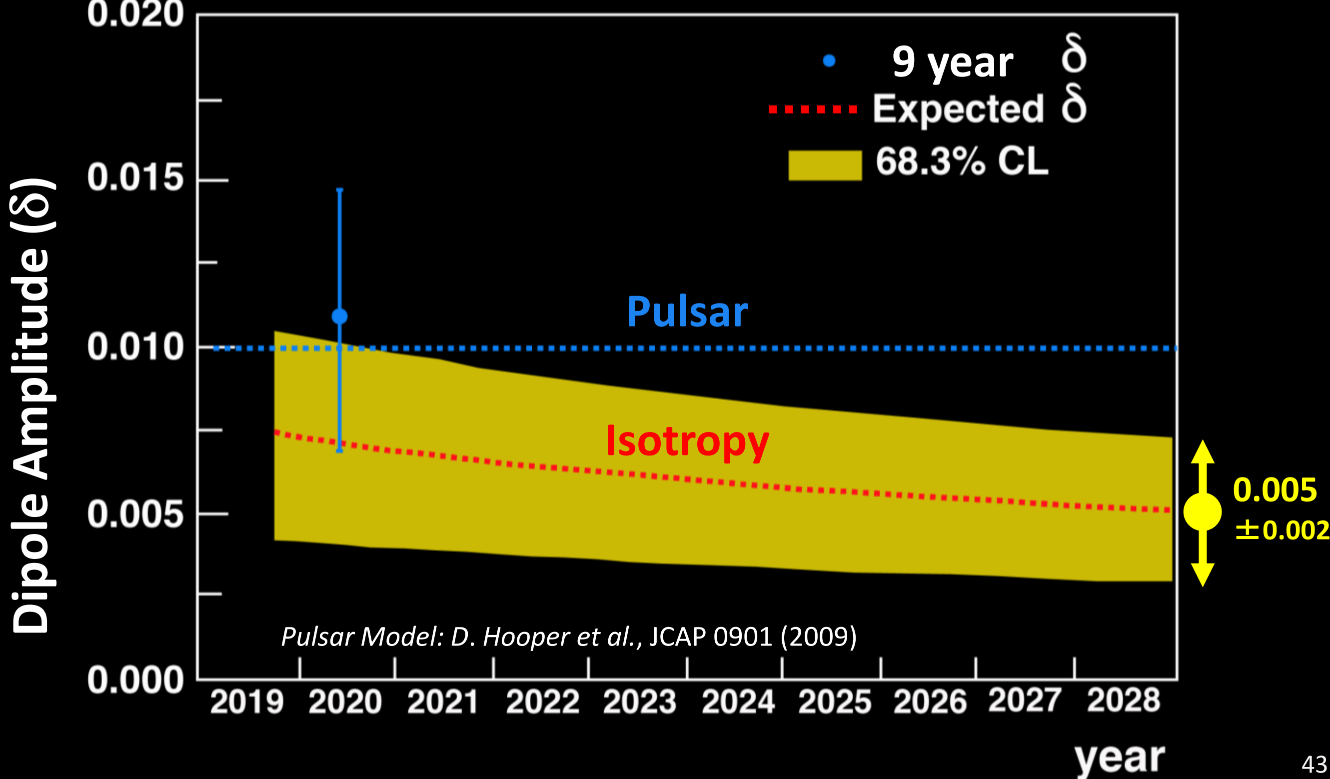
New sources, like Dark Matter or Pulsars, produce equal amounts of e+ and e–



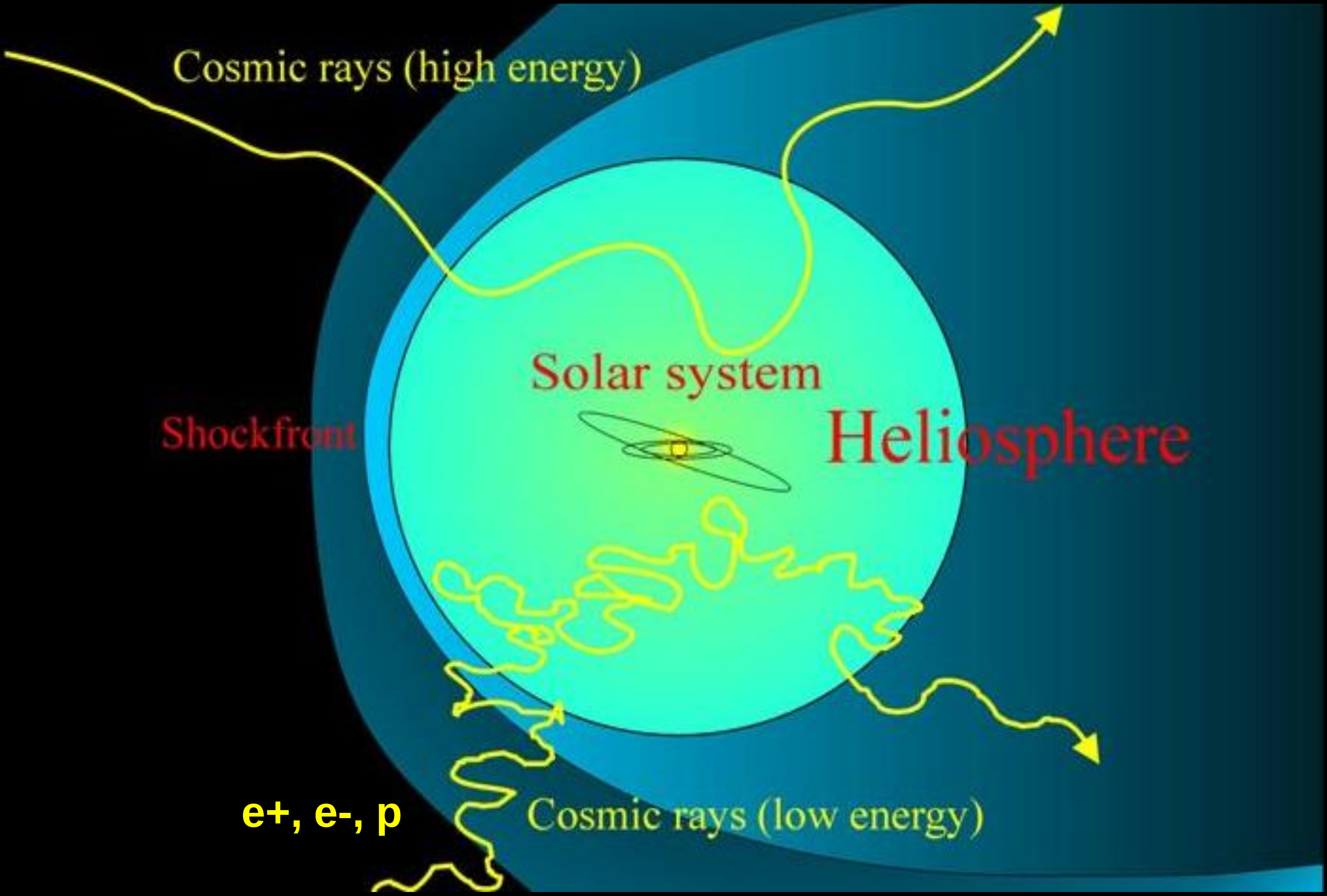
By 2030, the positron statistics will allow us to measure the anisotropy accurately to permit a separation between dark matter and pulsars at the 99.93% C.L.



Positrons from a pulsar would have a preferential direction



Latest AMS Results on Elementary Particles (e+, e-, p, …) in the Heliosphere over an 11-year Solar Cycle (2011-2022)

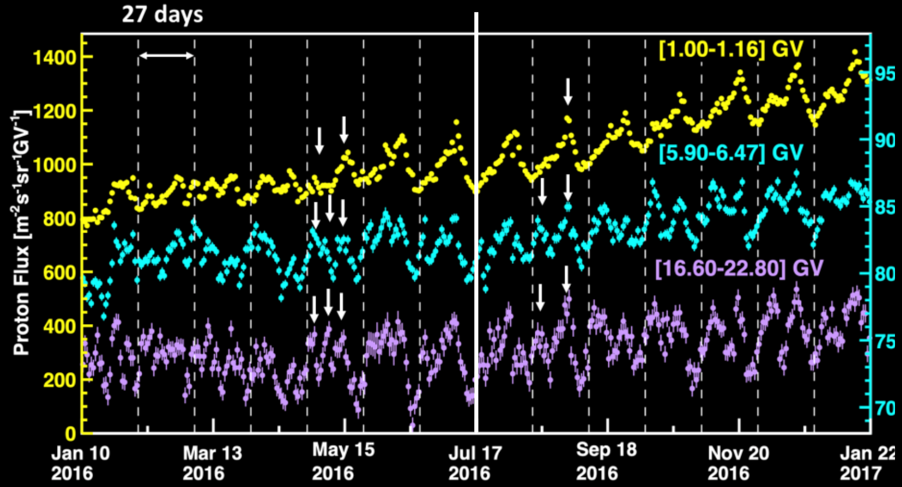


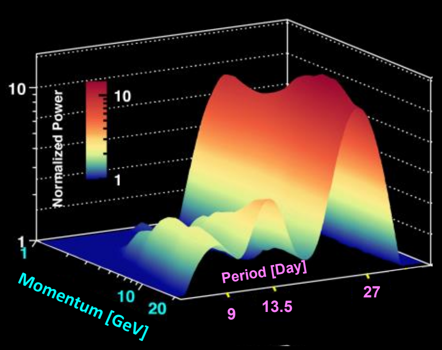
By 2030, AMS will study Heliosphere physics over 22-year Solar Cycle

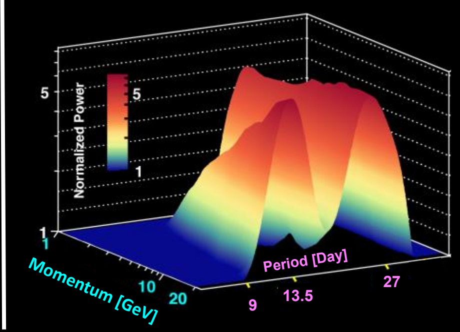
Daily Protons in the Heliosphere

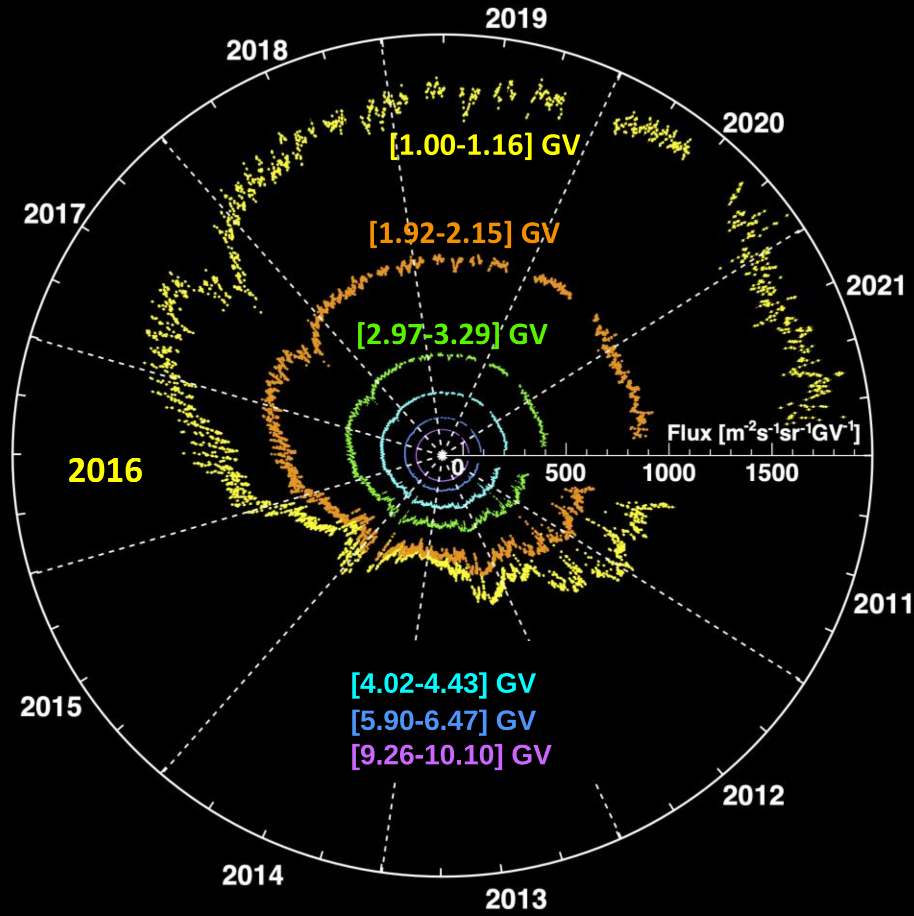
Frequency Analysis of daily fluxes in 2016

Double-peak and triple-peak structures are visible





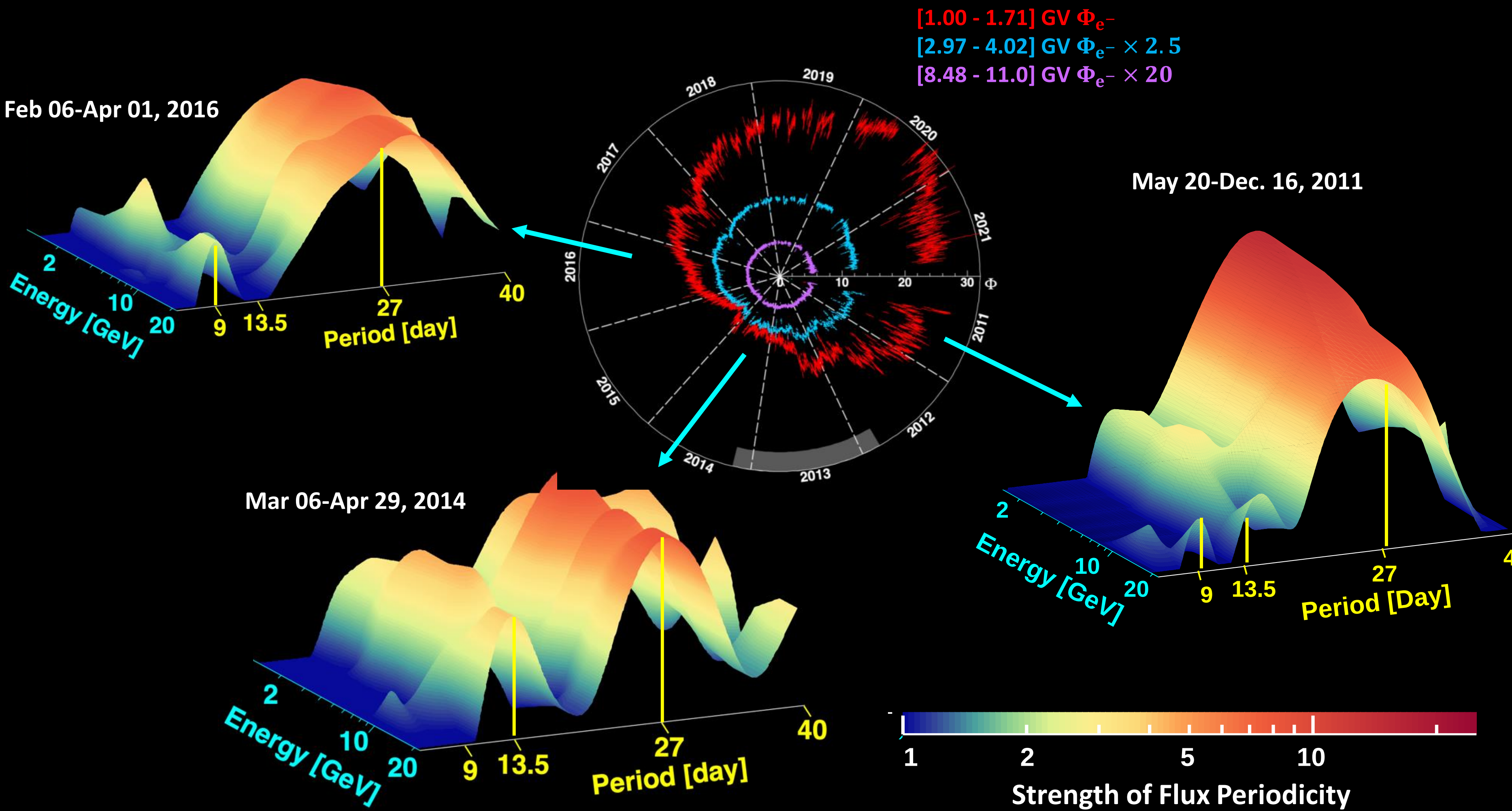




Recurrent variations with periods of 27, 13.5, and 9 days are observed.
Unexpectedly, in 2016, the strength of the 9- and 13.5-day periodicity increases with increasing rigidity.

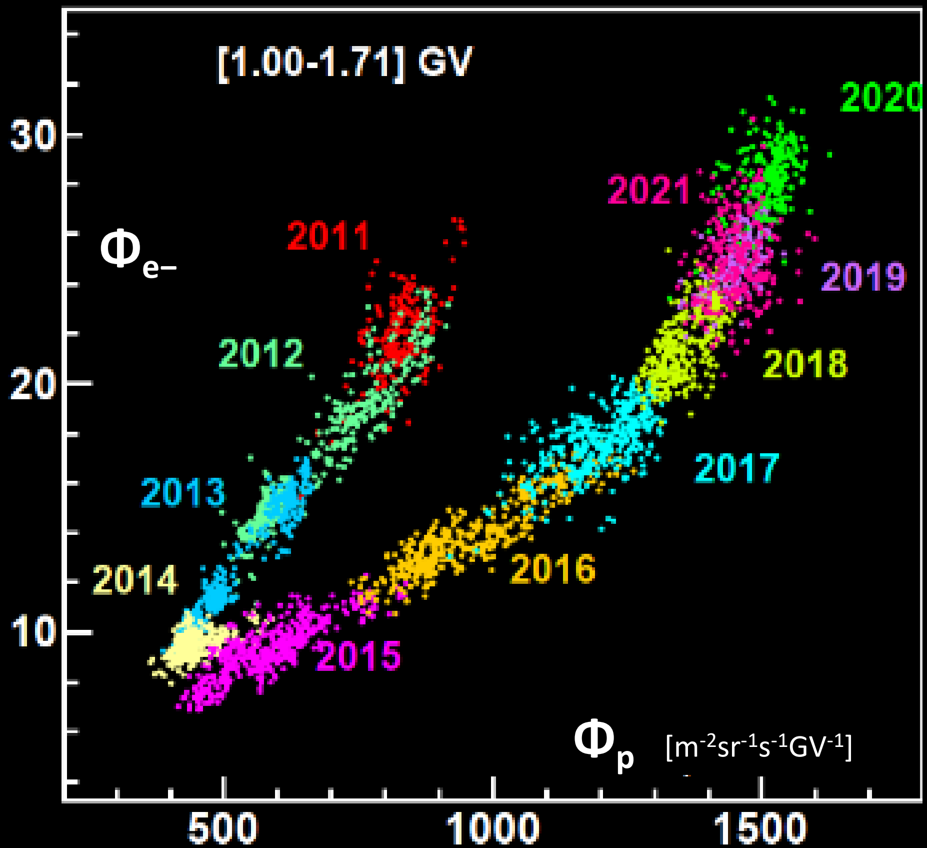
The models predict that the strength of the periodicity decreases with increasing rigidity.

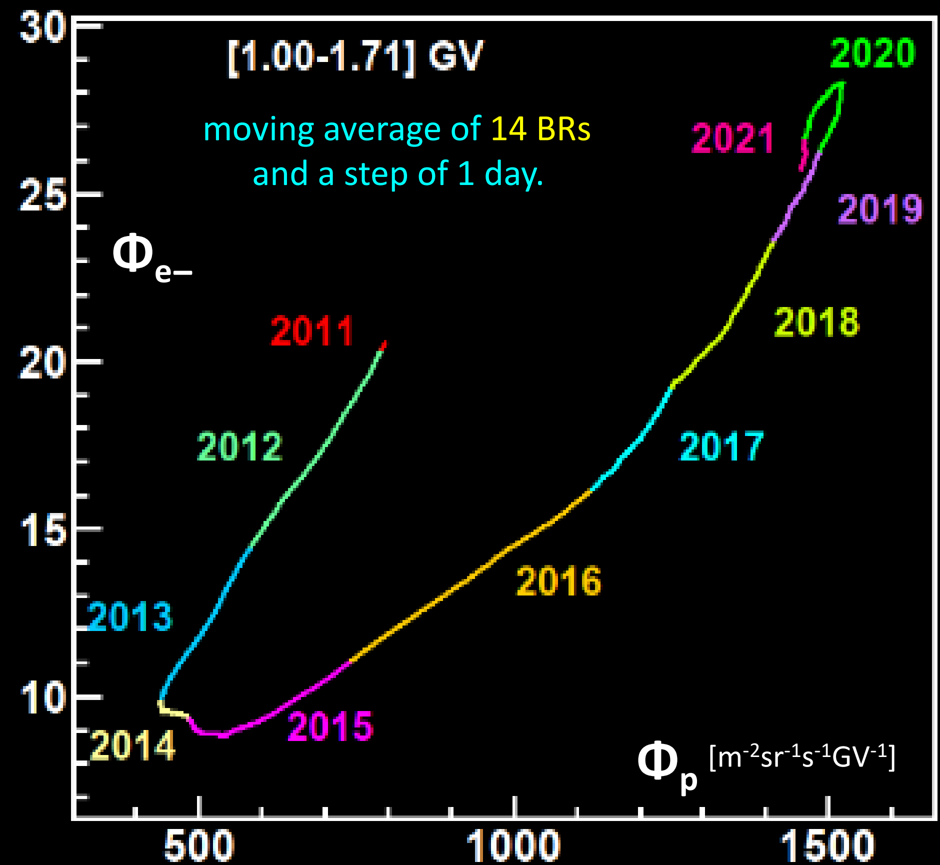
First Observation of Periodicity in the Daily Electron Flux in the Heliosphere



Elementary Particles in the Heliosphere

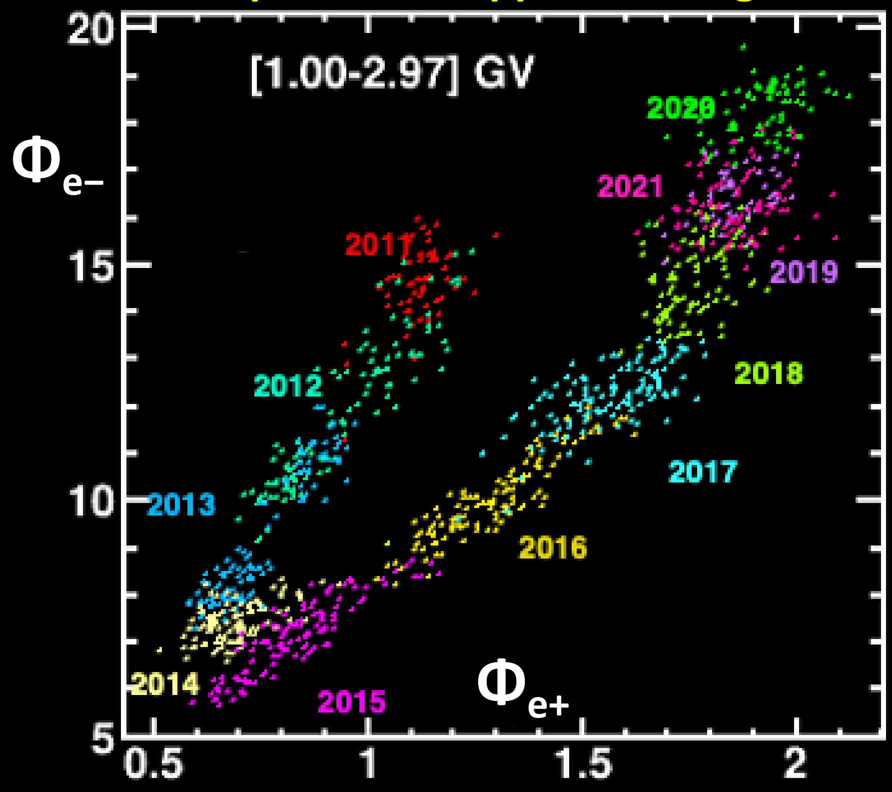
Observation of a hysteresis between daily electron flux Φ_{e-} and daily proton flux Φ_p



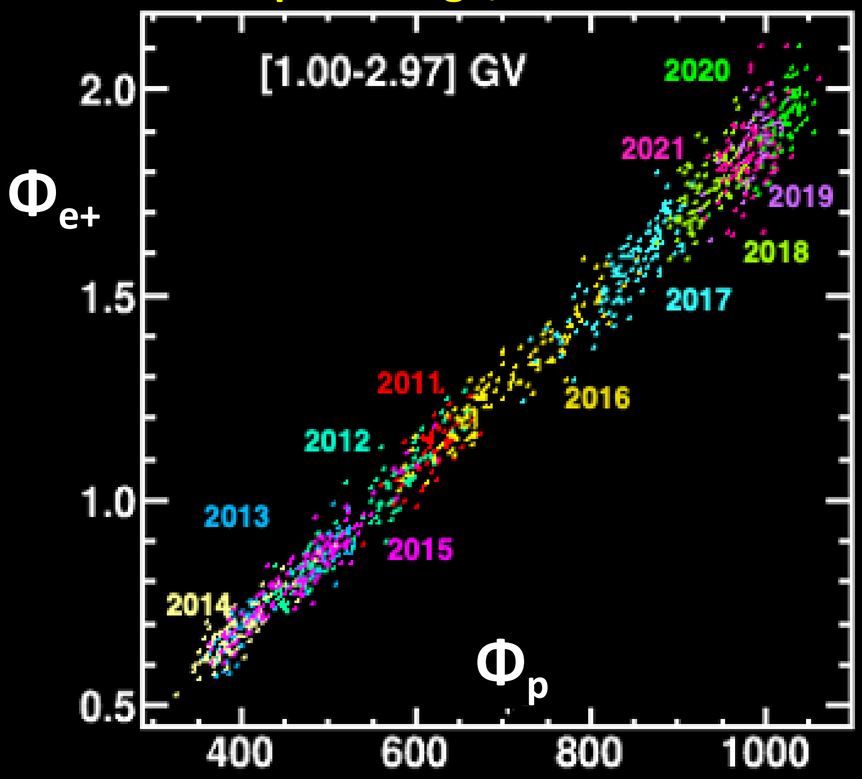


Relationship between charge and mass

Equal mass, Opposite charge



Equal charge, different mass



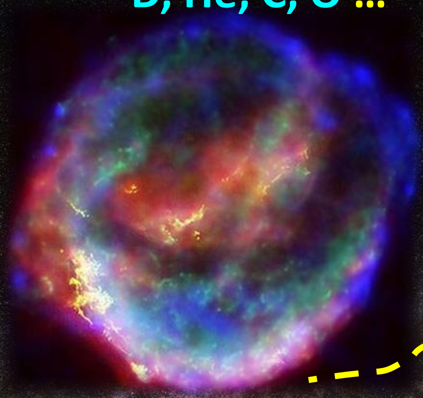
Latest AMS Results on Heavy Antimatter

Matter is defined by its mass *M* and charge *Z*.

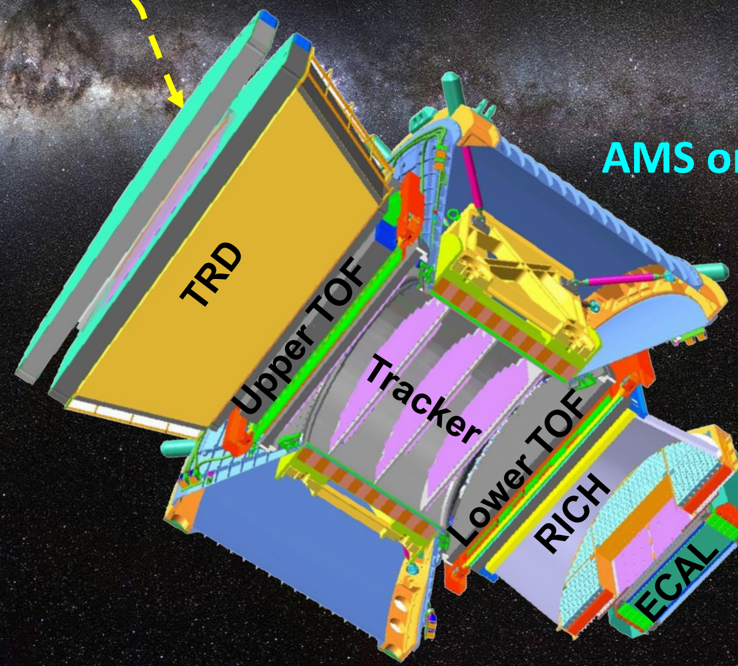
Antimatter has the same mass *M* but opposite charge *–Z*.

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

Antimatter Star

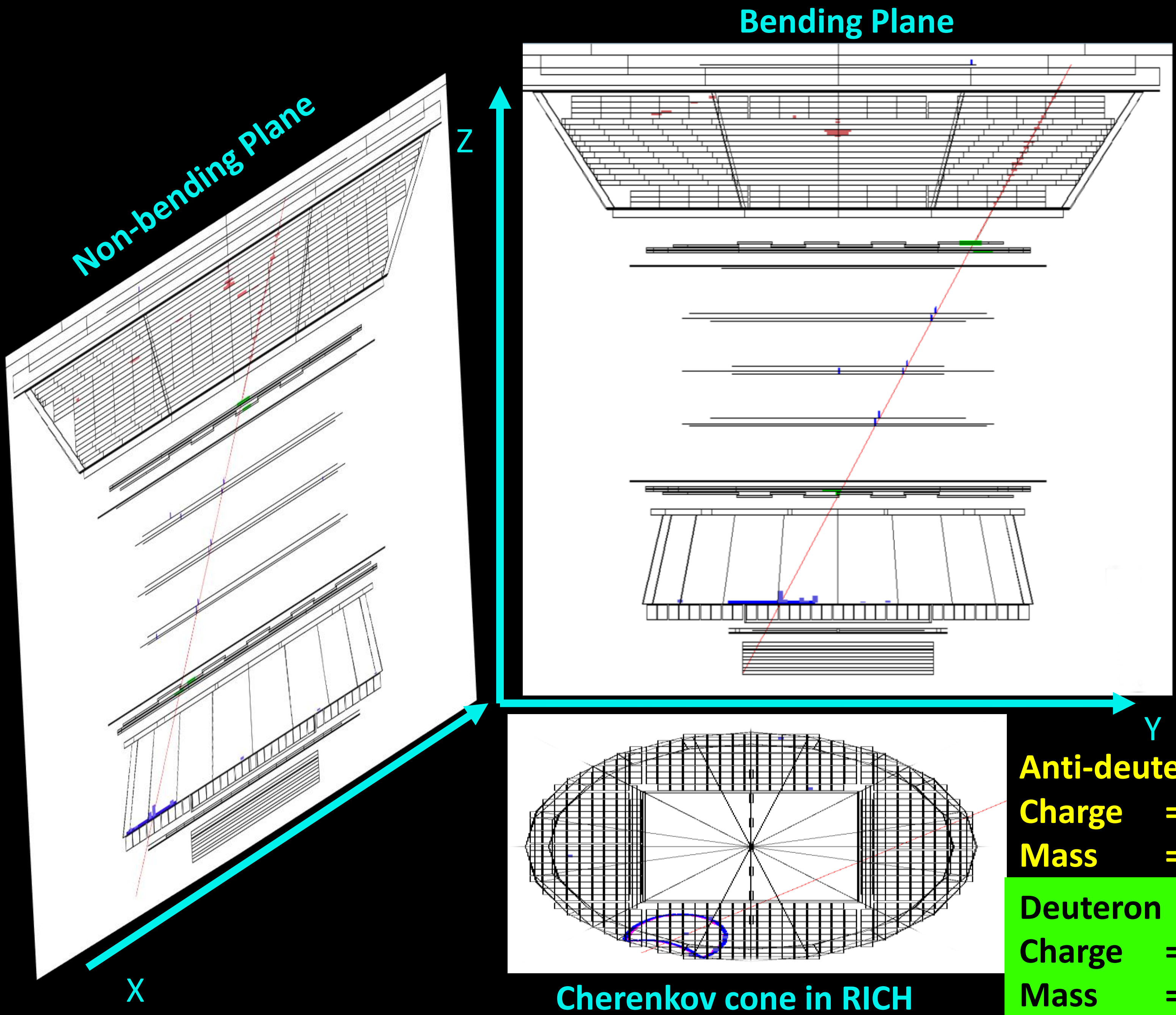


AMS on ISS



AMS is a unique antimatter spectrometer in space

An Anti-Deuteron Candidate from ~100 million deuterons and ~10 billion protons

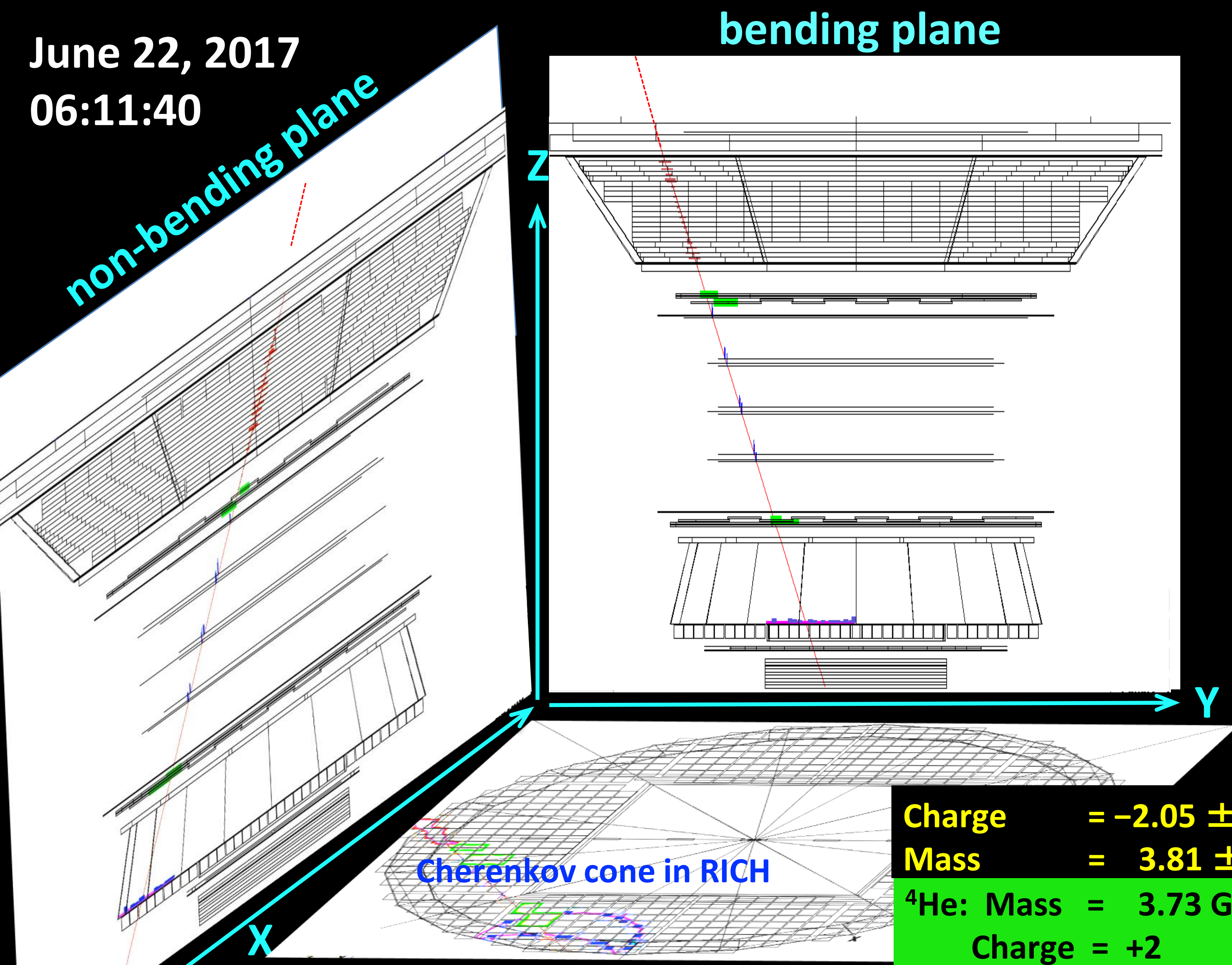


Anti-deuteron Candidate
Charge = −1.02 ± 0.05
Mass = 1.9±0.1 GeV/c^2

Deuteron
Charge = +1
Mass = 1.88 GeV/c^2

Anti-^{4}Helium Event

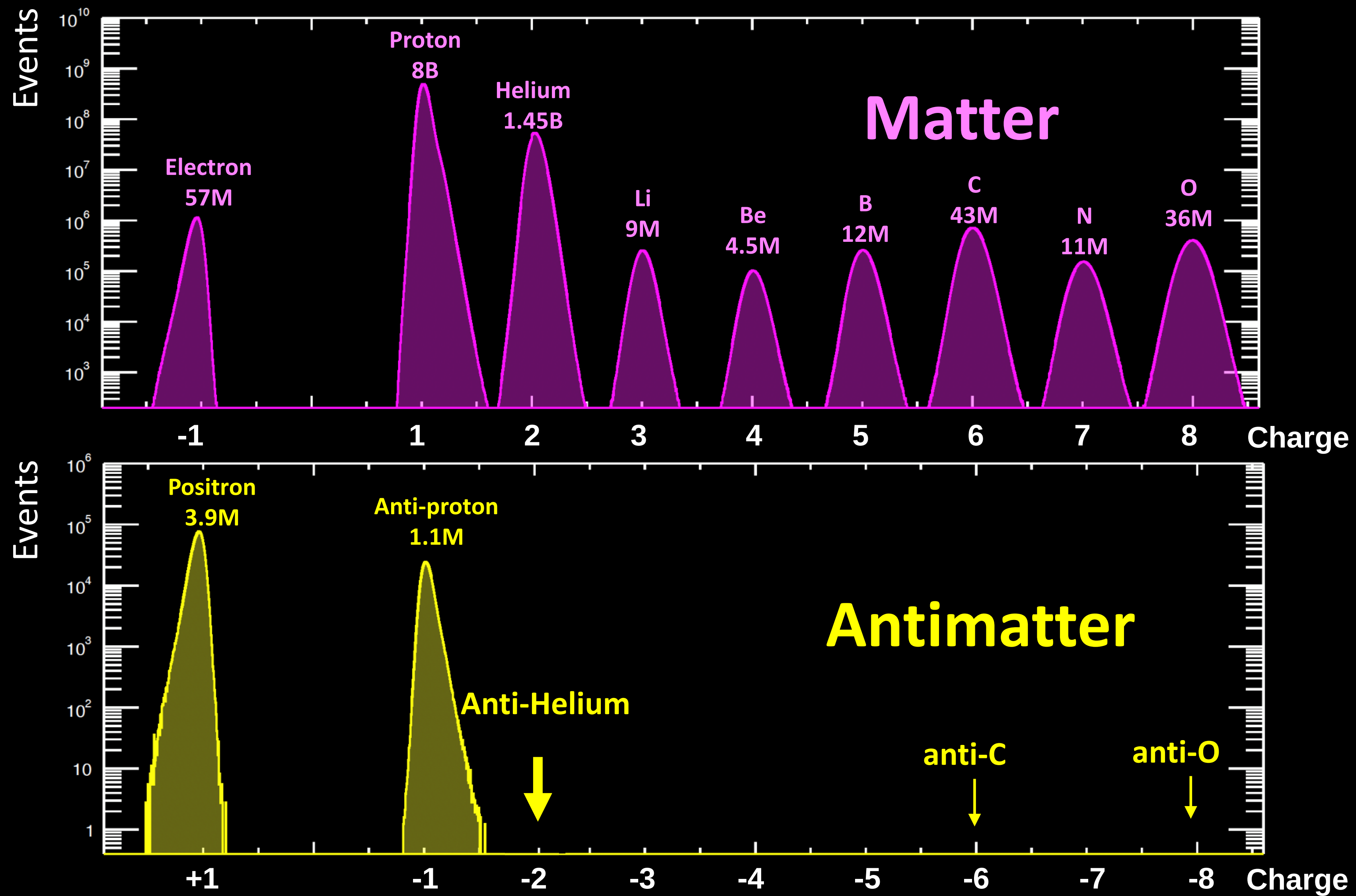
June 22, 2017
06:11:40



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

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

Current Matter and Antimatter Statistics

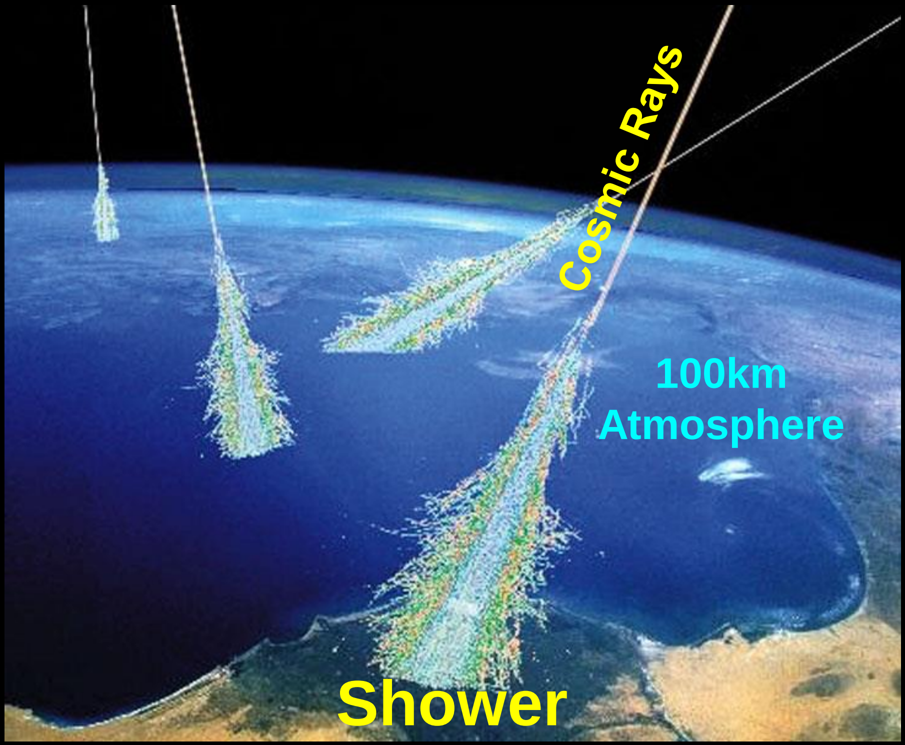


By 2030, with the Upgrade AMS will have additional measurement points in the study of antimatter: anti-deuterons, anti-helium, anti-carbon, and anti-oxygen.

Unique features of AMS on the Space Station:

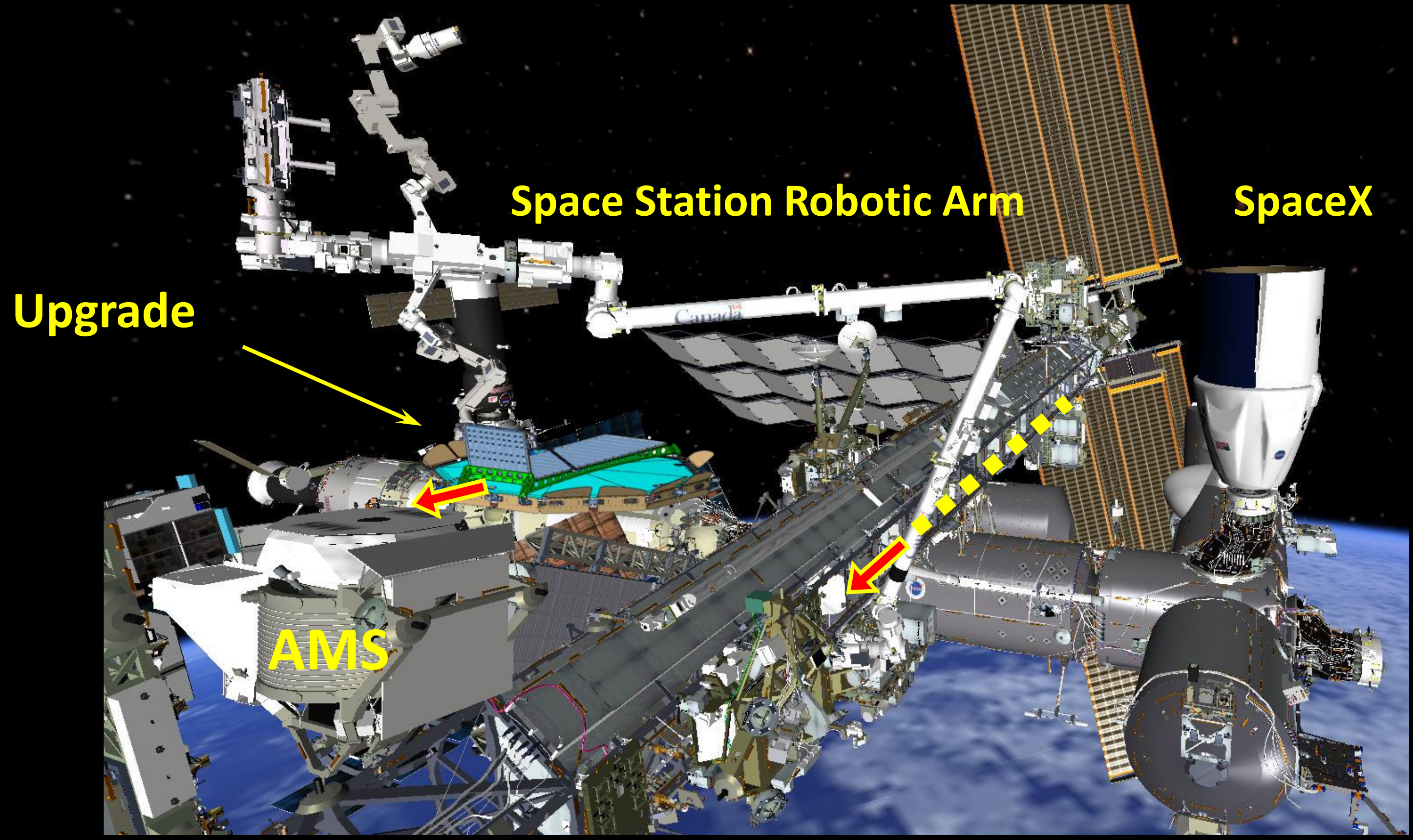
Charged cosmic rays have mass.
They are absorbed by the
100 km of Earth's atmosphere
(10m of water).
The properties ($\pm Z$, P) of charged
cosmic rays cannot be studied on the
ground.

To measure cosmic ray
charge and momentum
requires
a magnetic spectrometer
in space



AMS is providing cosmic ray information with ~1% accuracy.
The improvement in accuracy and extension of the energy range is providing new insights.

The AMS results contradict current cosmic ray theories and require the development of a new model of the universe.



AMS will continue to collect data to 2030 with an upgraded detector.

Subir Sarkar has made a fundamental contributions to astrophysics, cosmology, and particle physics through both in theoretical exploration and experimental discovery