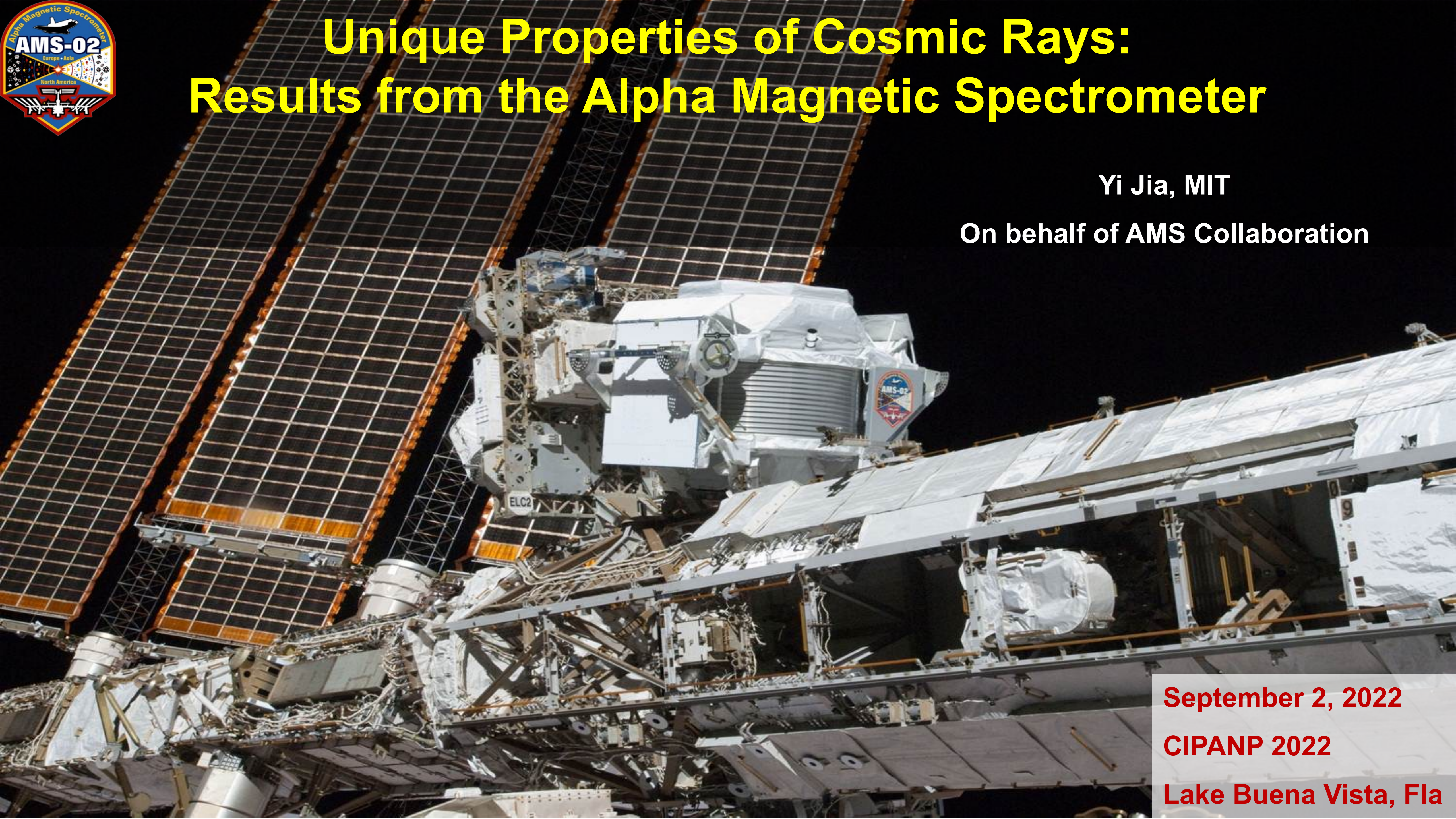
Unique Properties of Cosmic Rays: Results from the Alpha Magnetic Spectrometer

Yi Jia, MIT

On behalf of AMS Collaboration

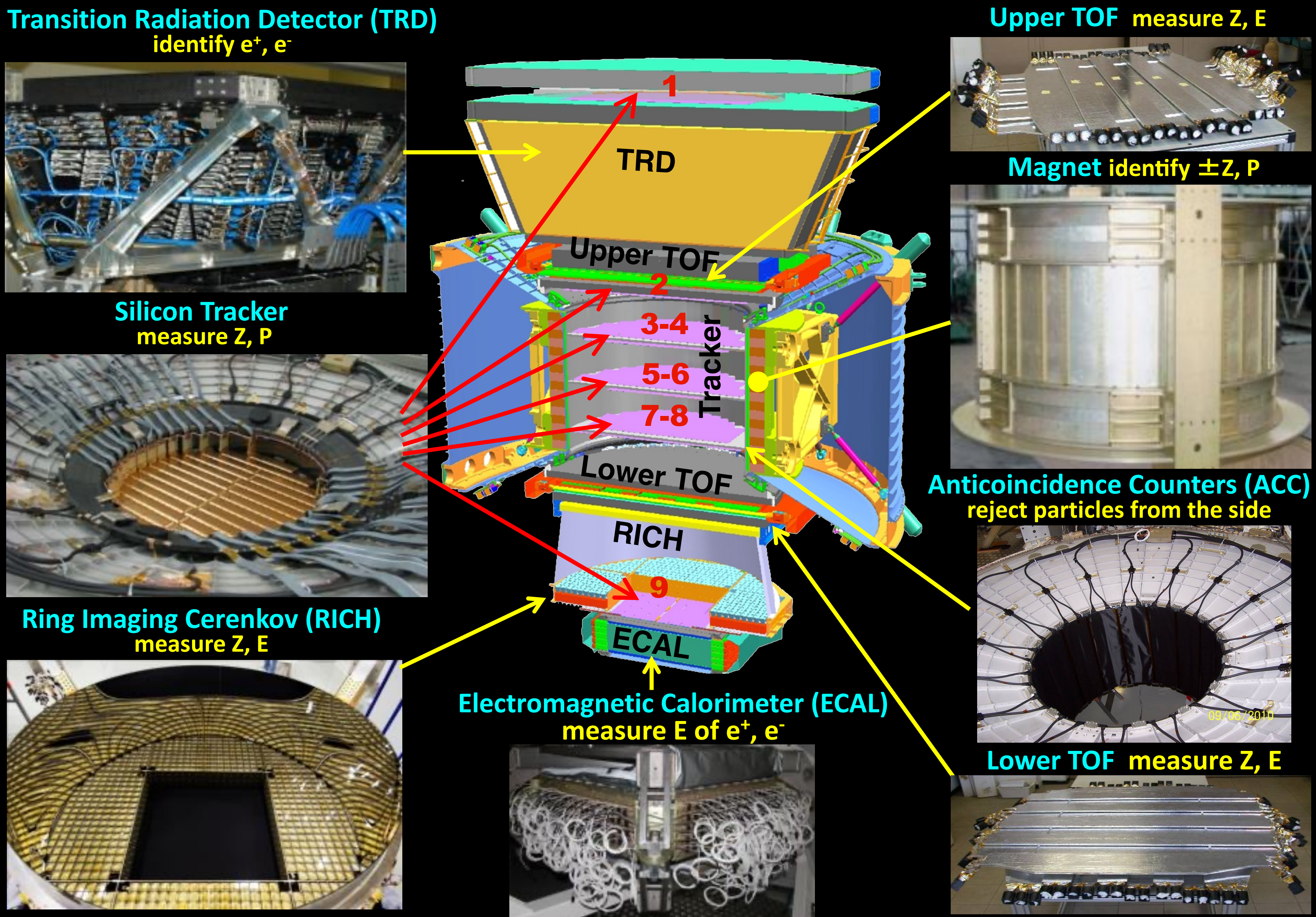


September 2, 2022

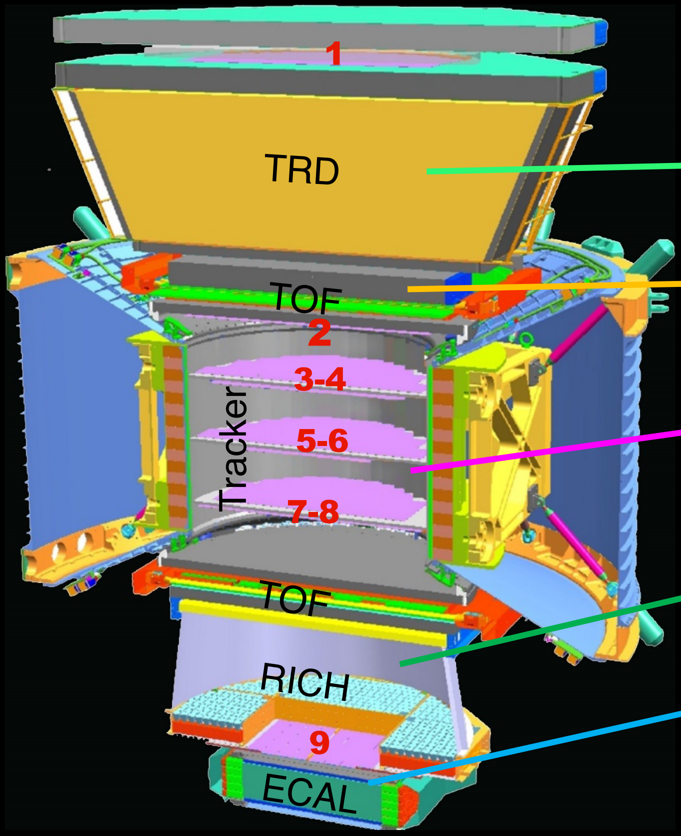
CIPANP 2022

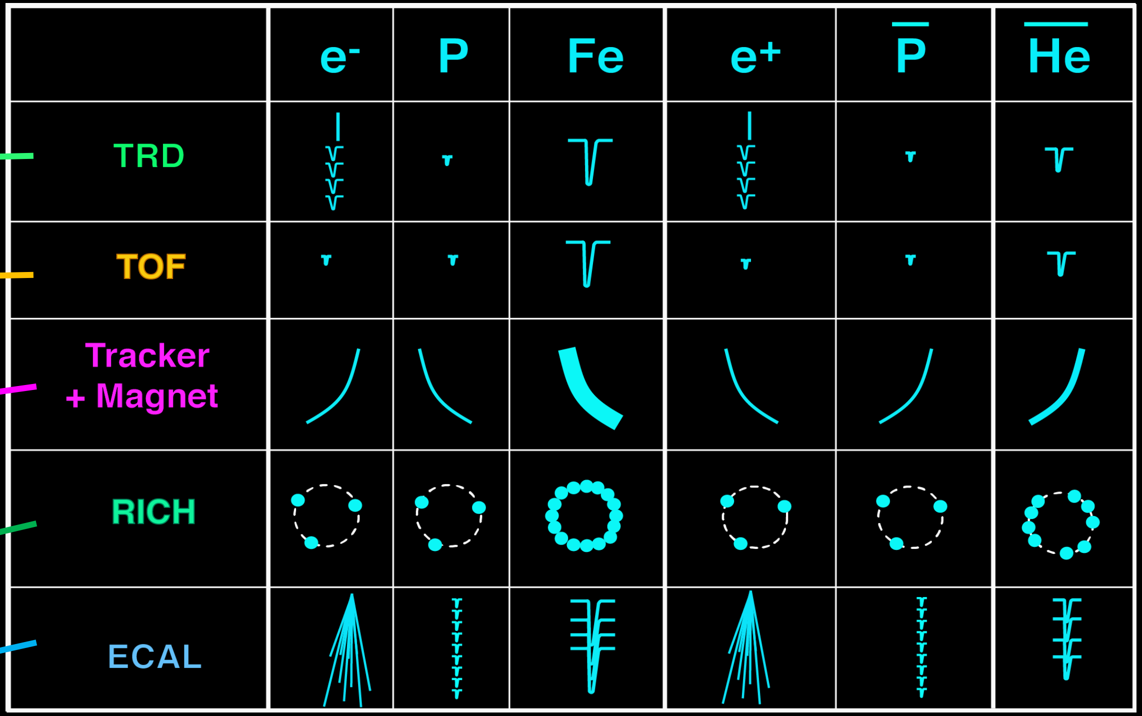
Lake Buena Vista, Fla

AMS is a space version of a precision detector used in accelerators



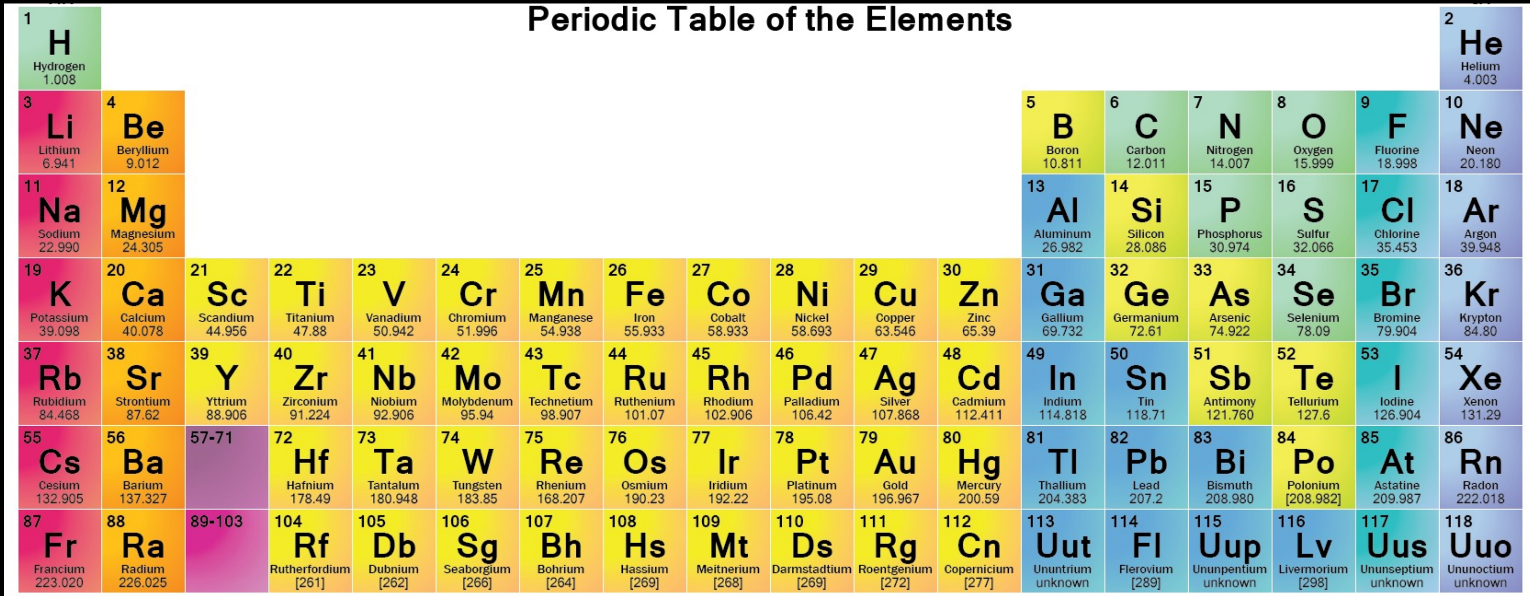
The detectors provide independent information of cosmic rays





AMS measures :

- Momentum (P, GeV/c)
- Charge (Z)
- Rigidity (R=P/Z, GV)
- Energy (E, GeV/A)
- Flux (signals/(s sr m^2 GeV))

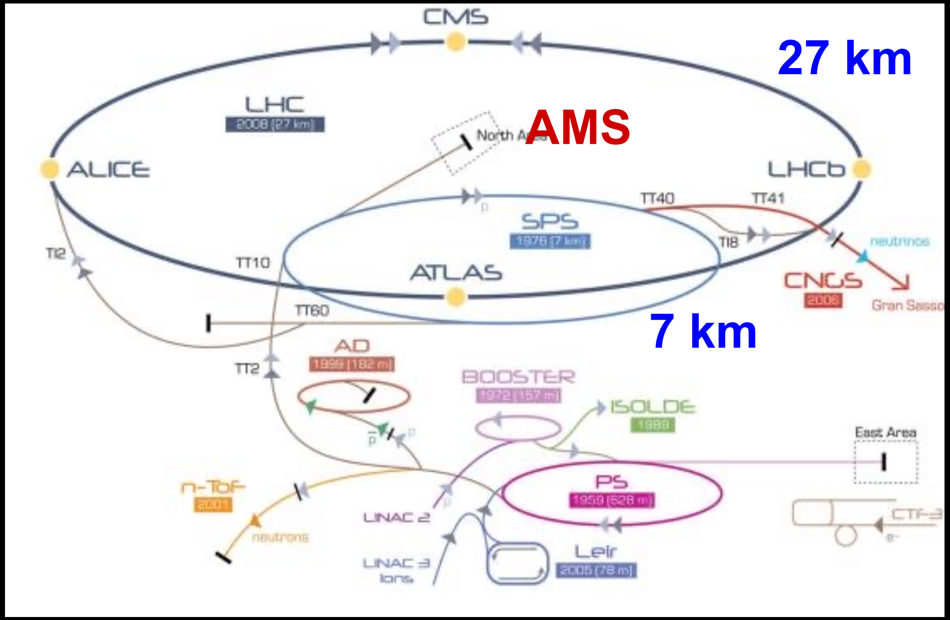


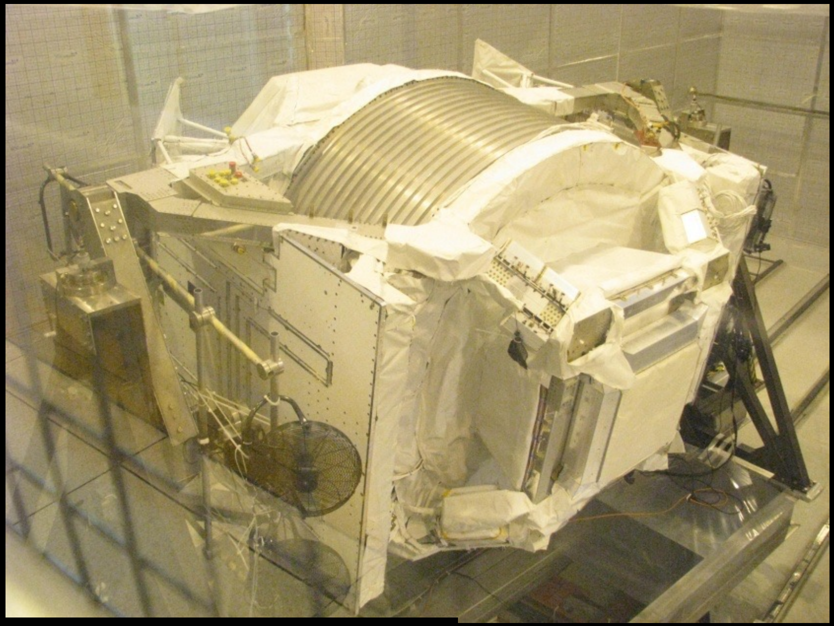
Periodic Table of the Elements

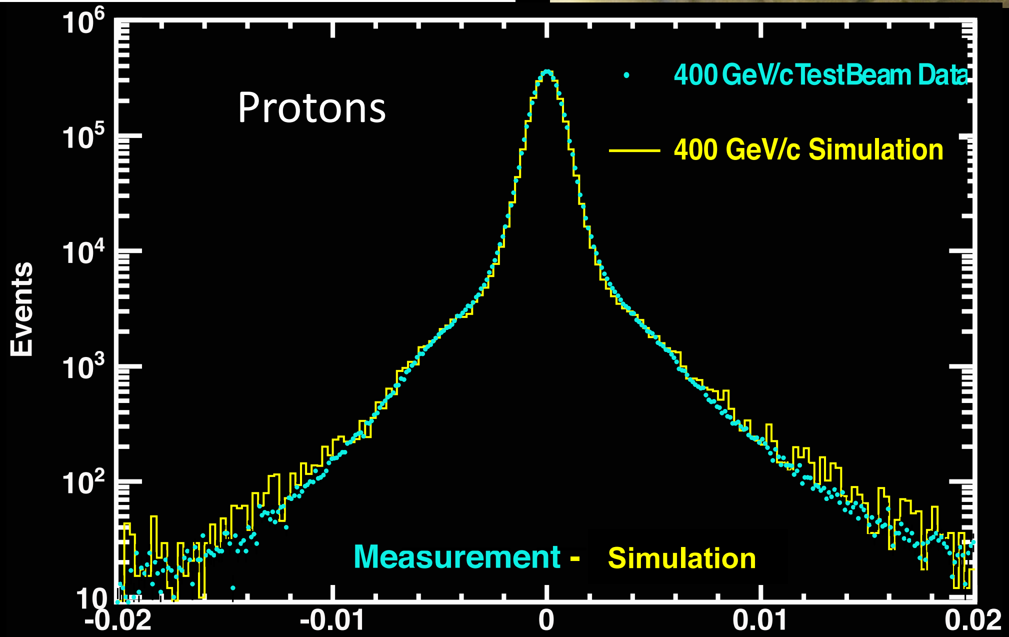
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.09	35 Br Bromine 79.904	36 Kr Krypton 84.80
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

Calibration at CERN

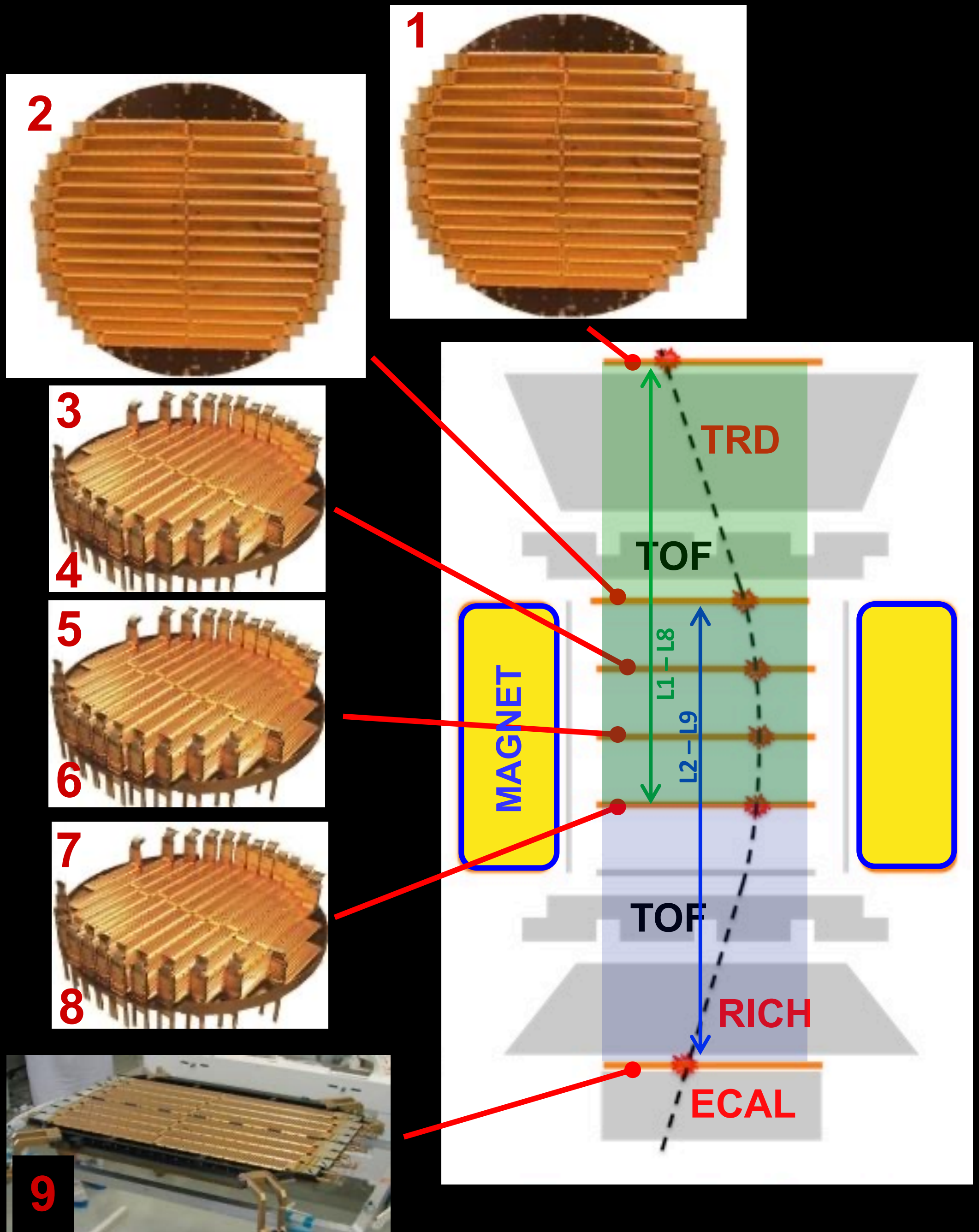
with different particles at different energies







Ten years of operation of AMS on the ISS: Continuous Calibration

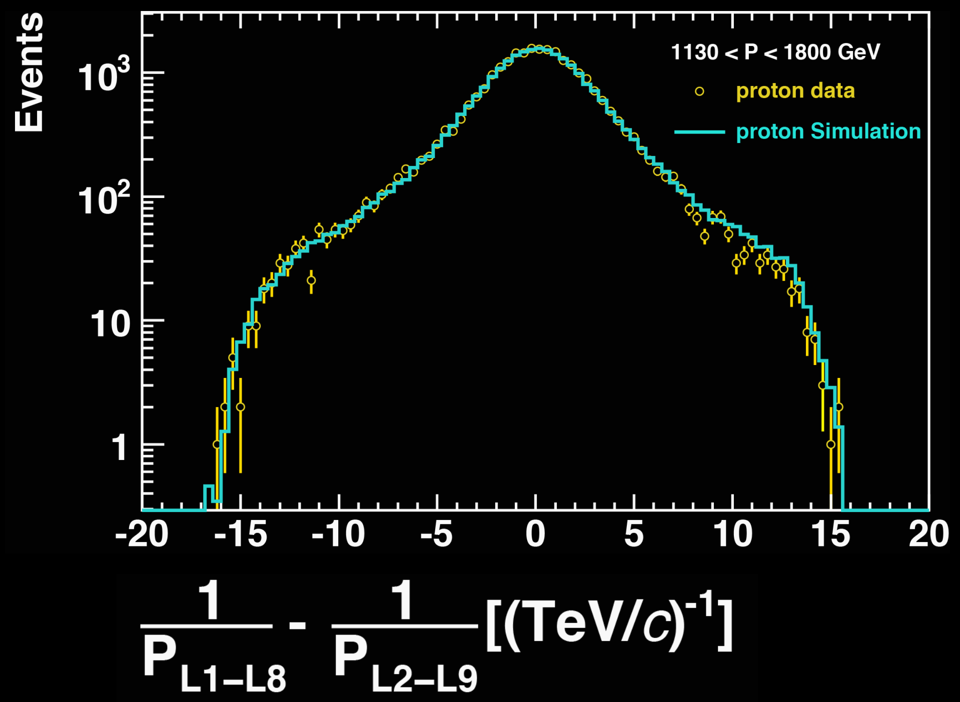


By comparing proton data and simulation from

the upper spectrometer (L1 to L8)

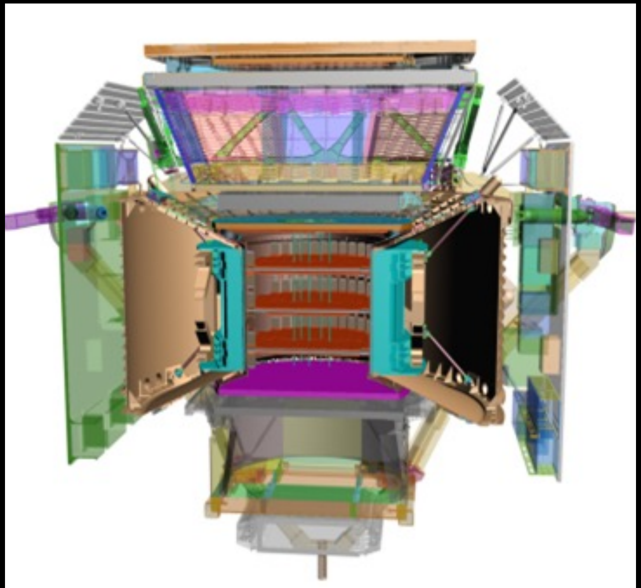
and

the lower spectrometer (L2 to L9)

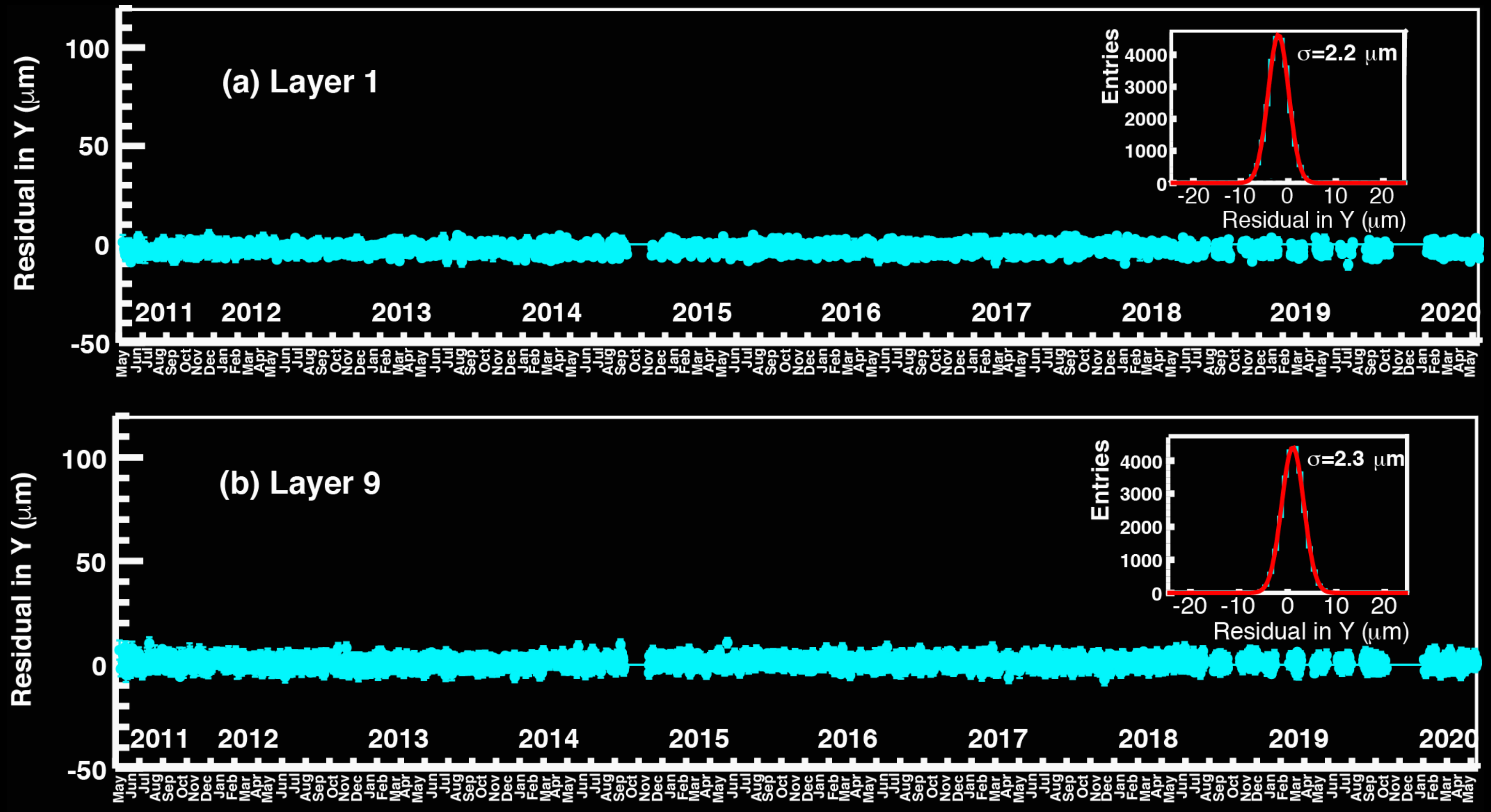


Examples of Detector Monitoring: Tracker Alignment

Monitored every 2 minutes by cosmic rays

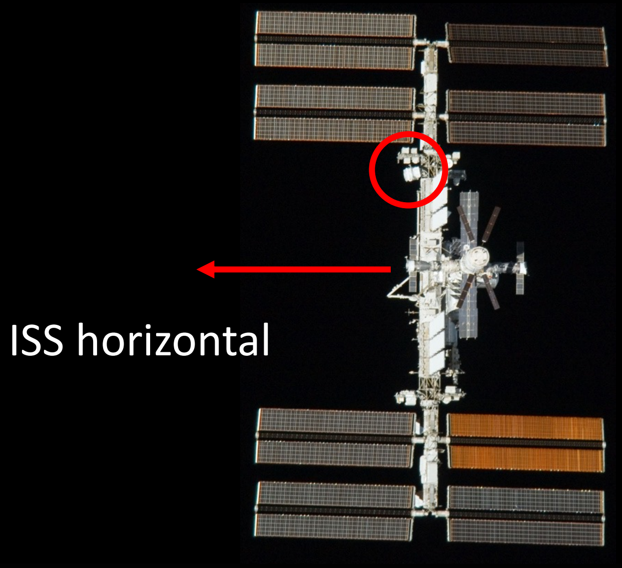


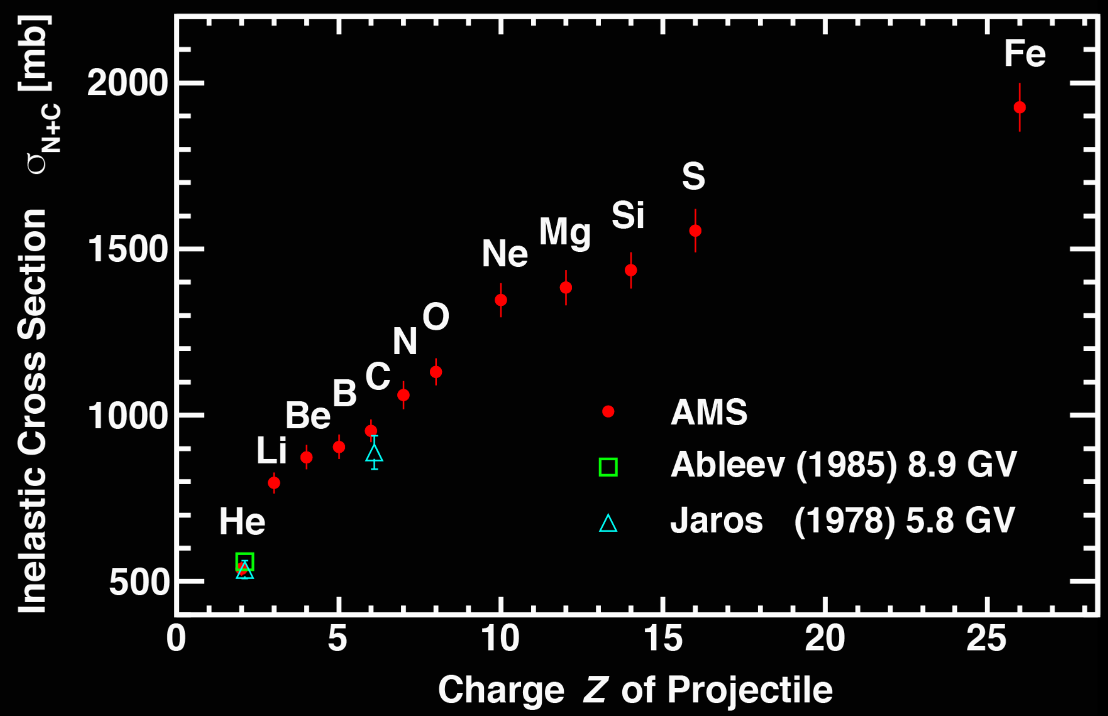
Inner tracker alignment
(< 1 micron)
monitored with IR lasers



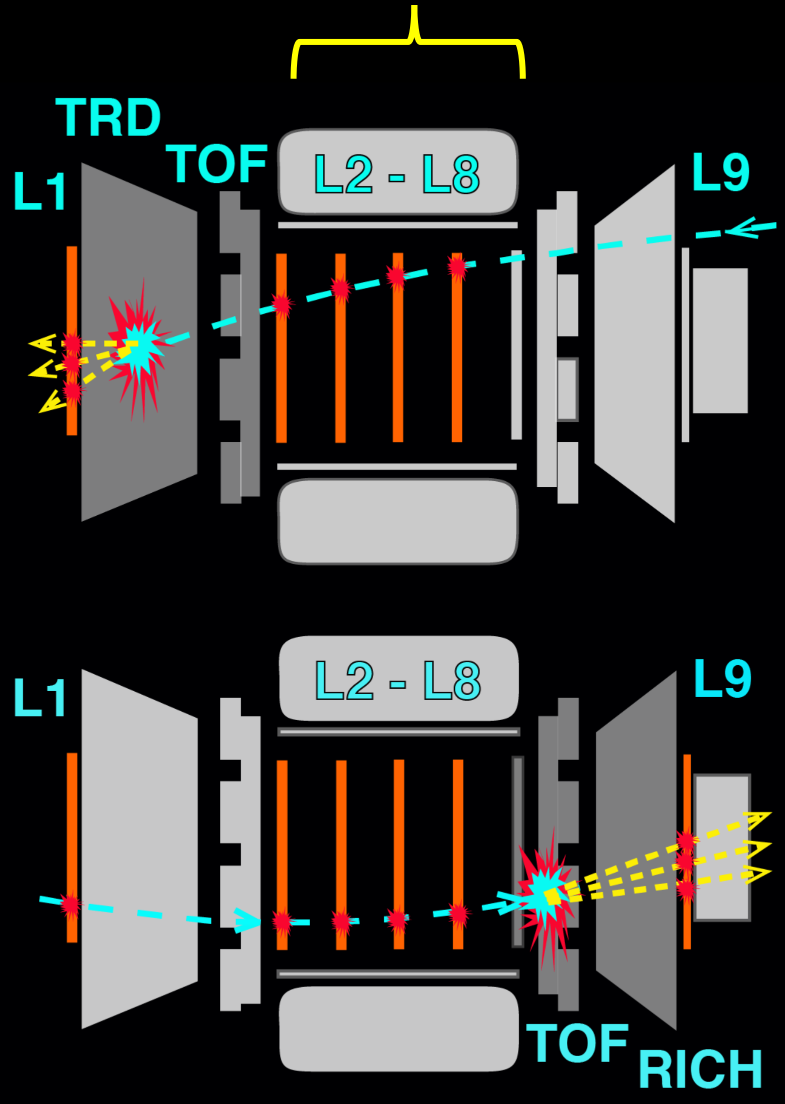
Outer tracker (a) Layer-1 and (b) Layer-9
stable to 2 micron over 9 years

Precision Measurements of Inelastic Cross Sections for Accurate Flux Determination

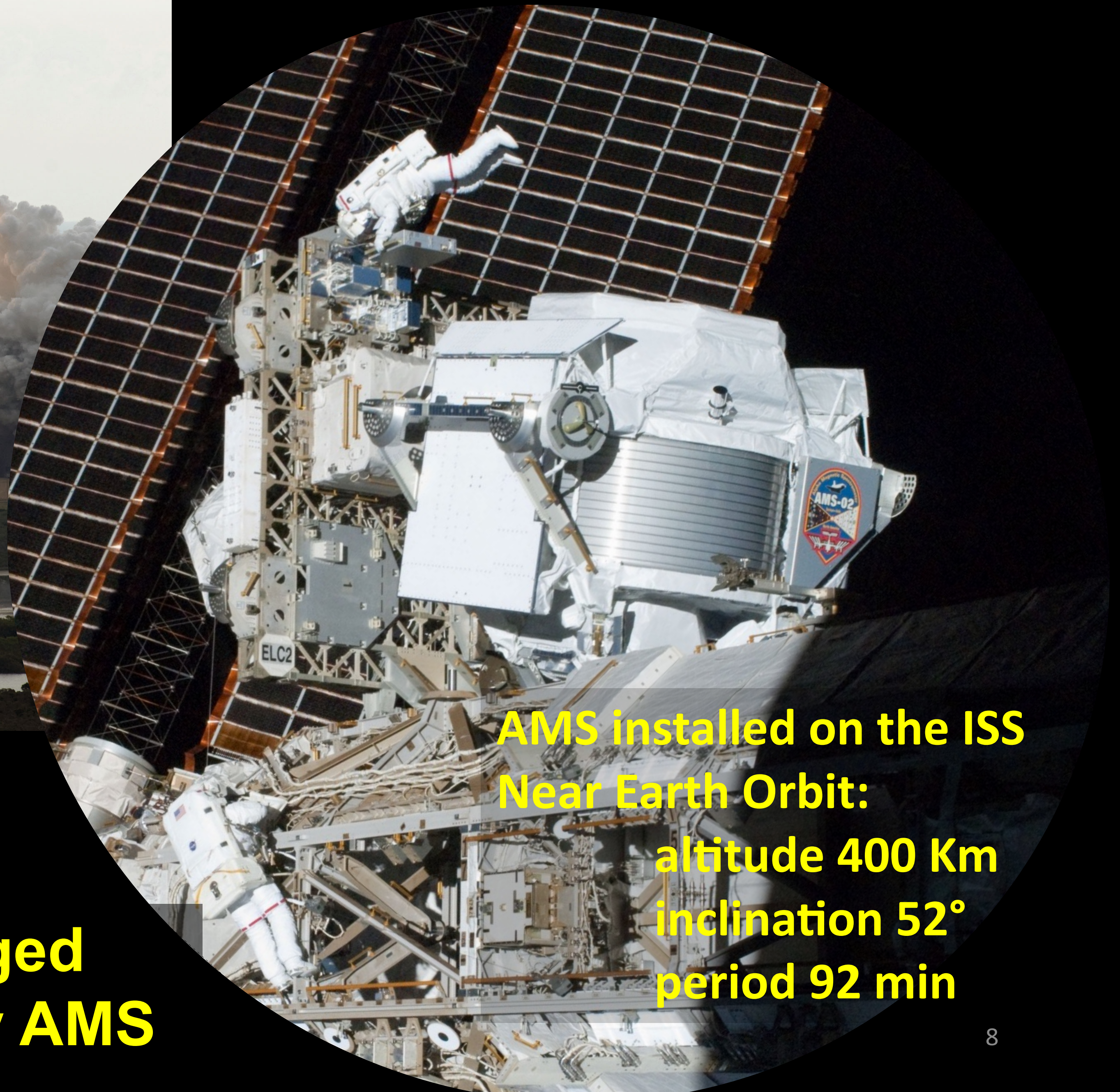




Define (P, Z) of the nuclei with the central spectrometer



AMS Launch May 2011
Space Shuttle Endeavour
Mission STS-134

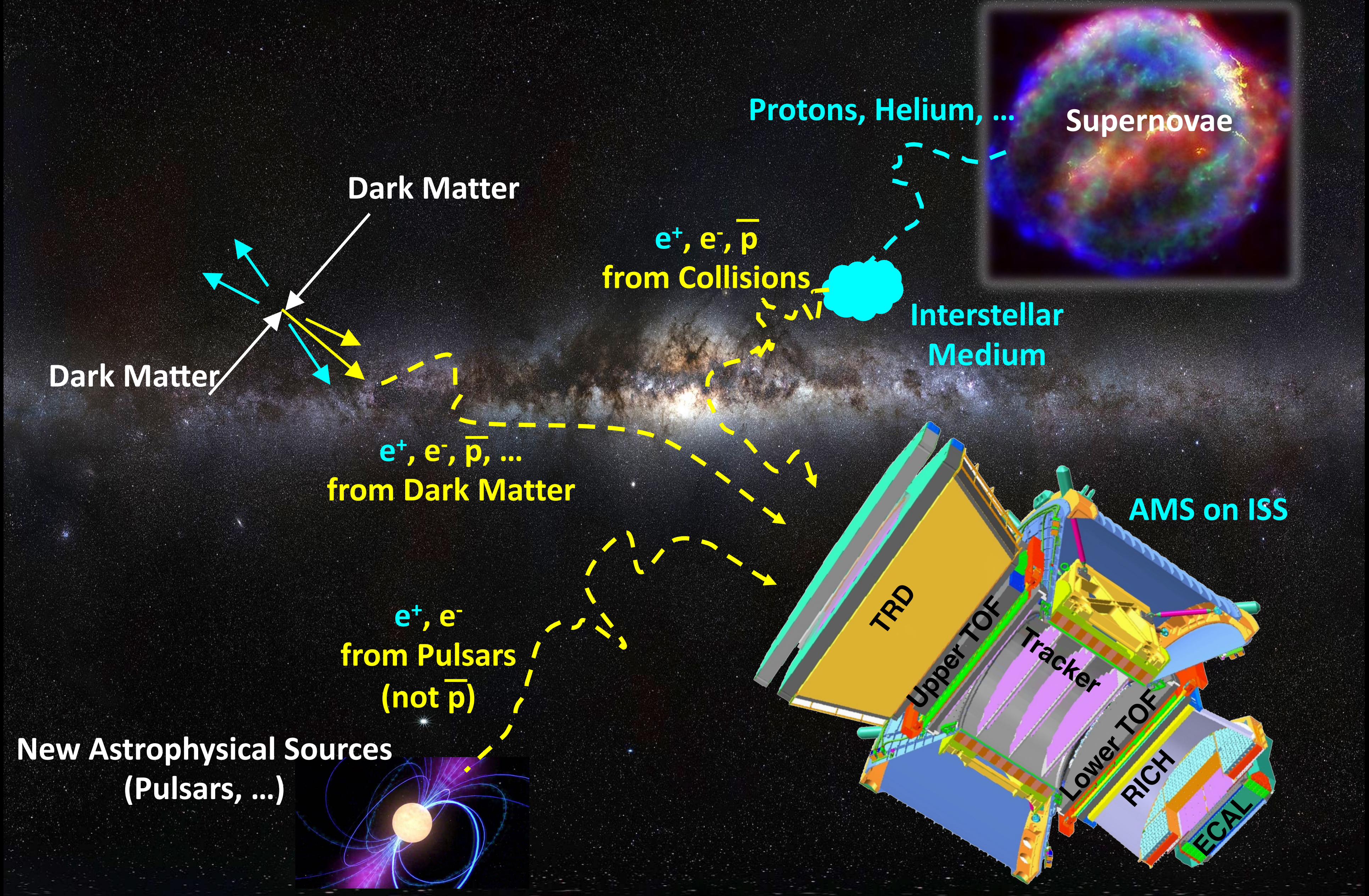


AMS installed on the ISS
Near Earth Orbit:
altitude 400 Km
inclination 52°
period 92 min

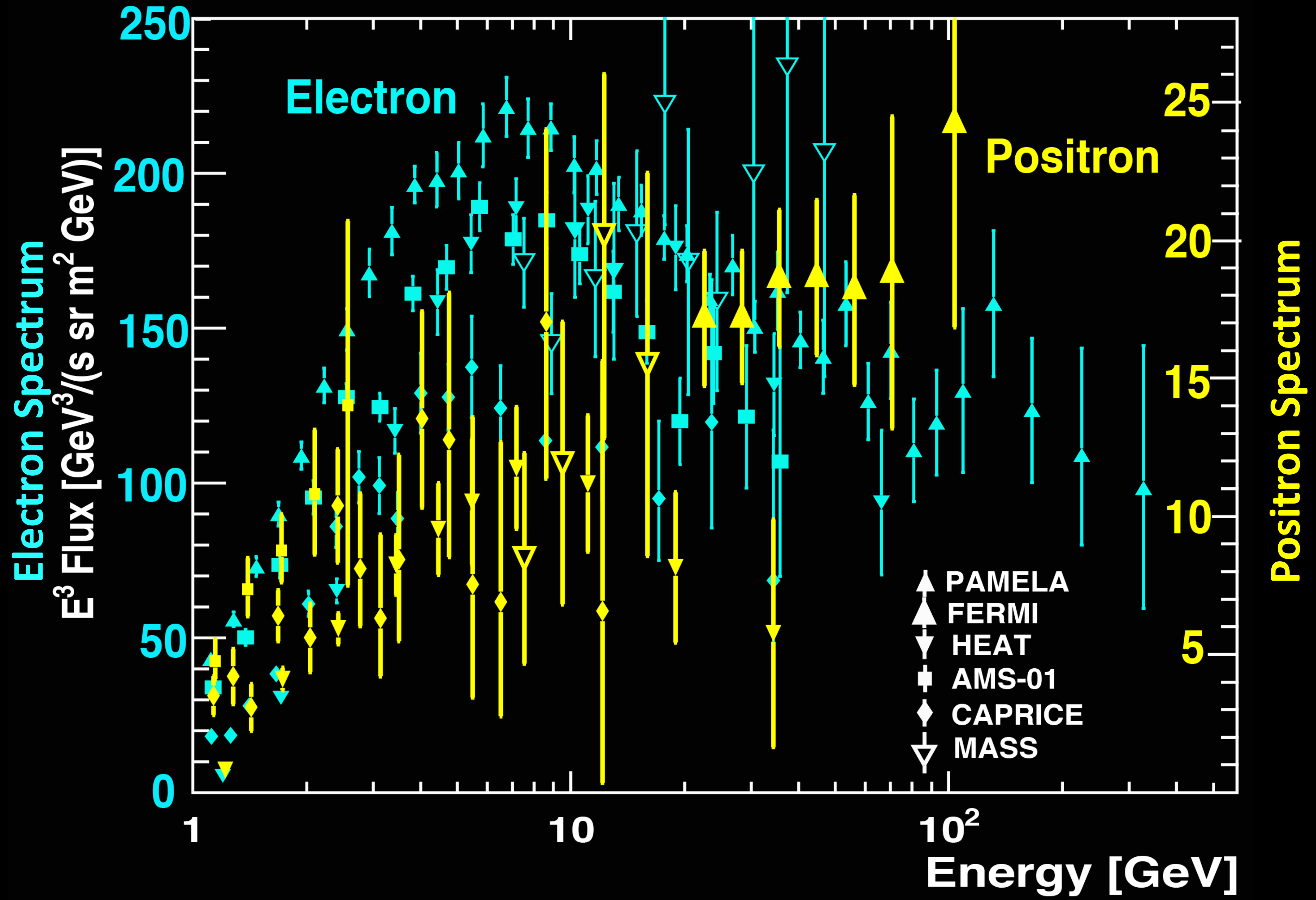
To date, over 200 billion charged particles have been collected by AMS

Origins of Elementary Particles

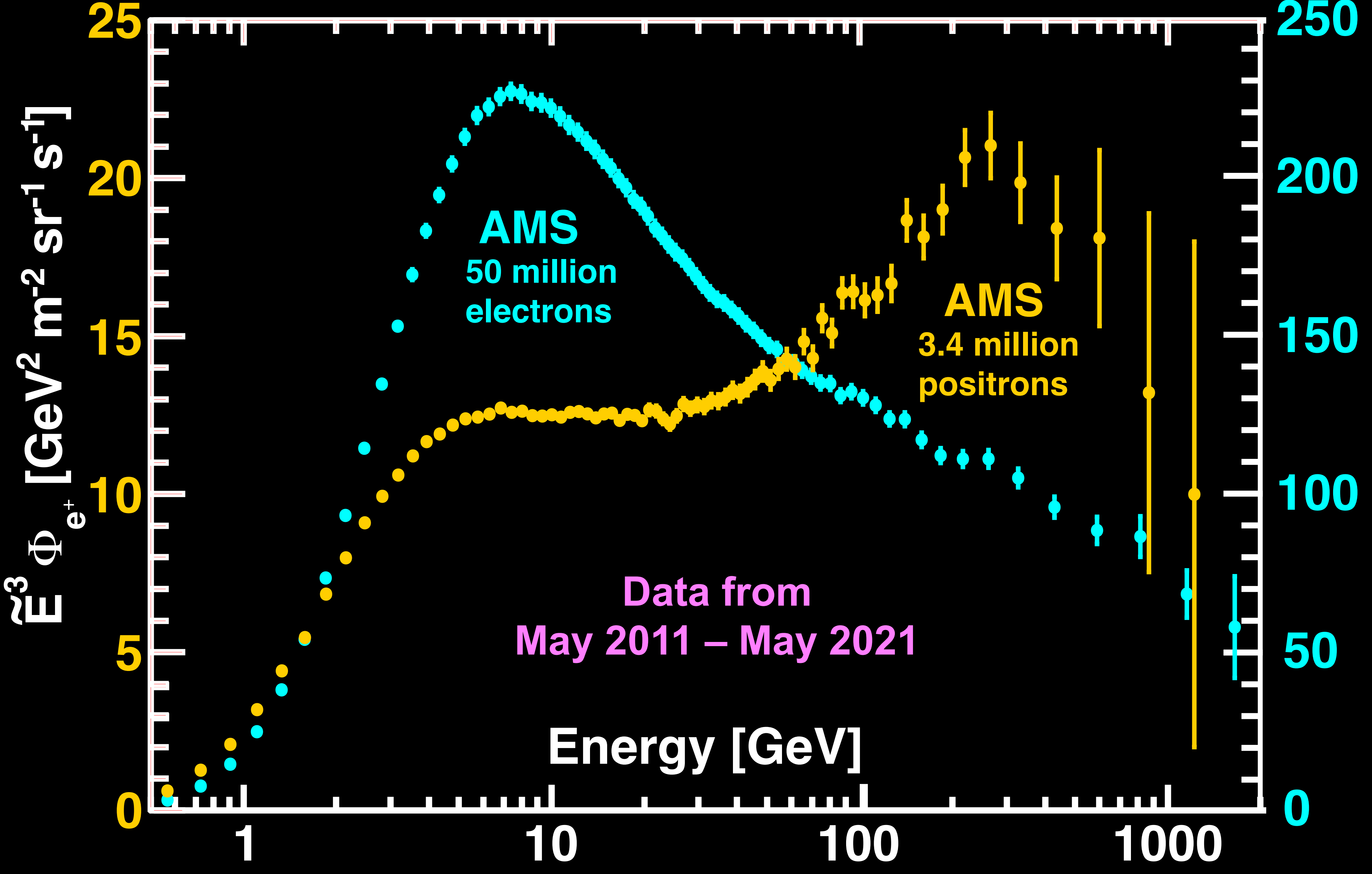
Positrons e^+, Electrons e^-, Antiprotons $\bar{p}$, and Protons p



Cosmic Ray Positron and Electron Spectra before AMS

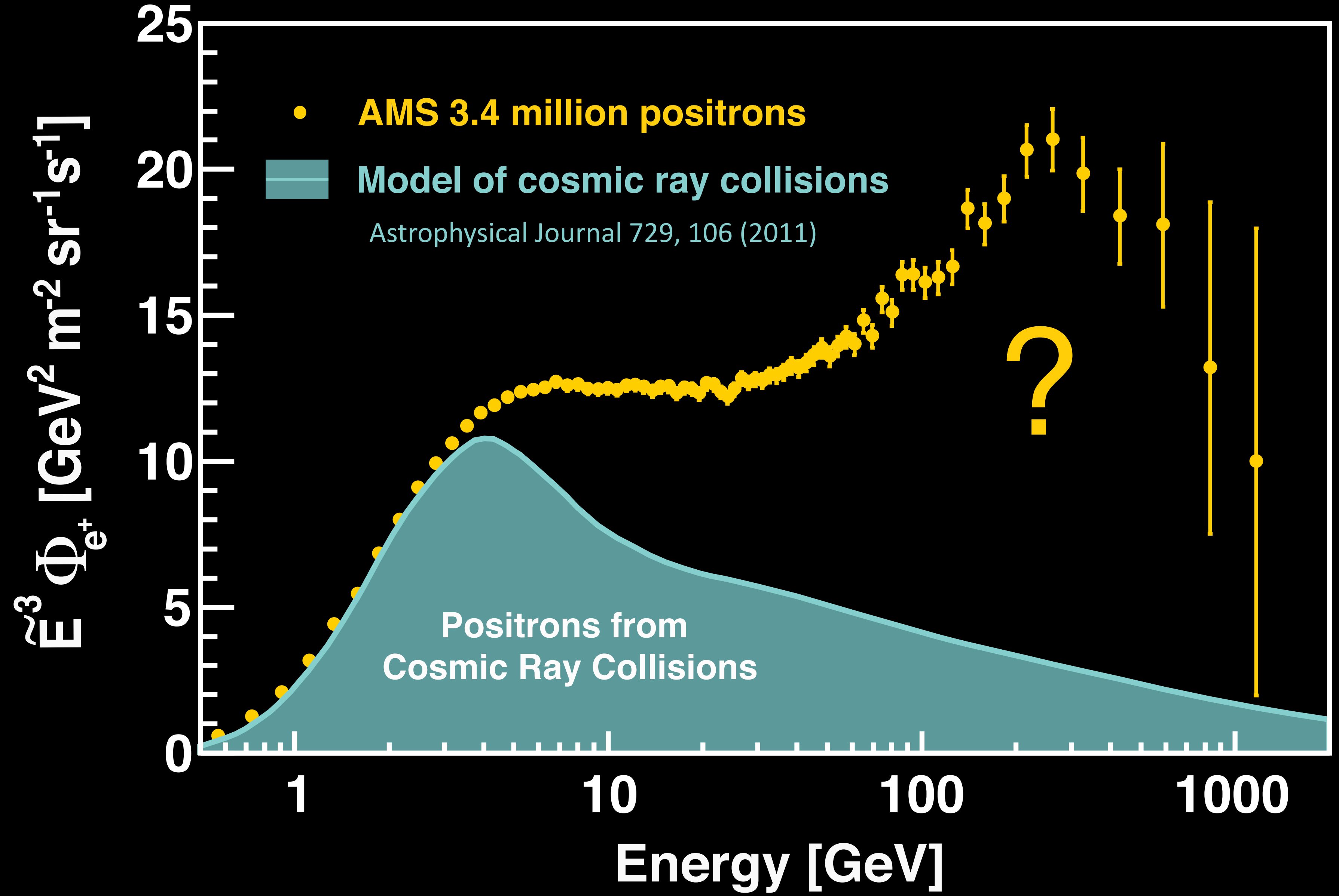


Cosmic Ray Positron and Electron Spectra measured by AMS



The Origin of Positrons

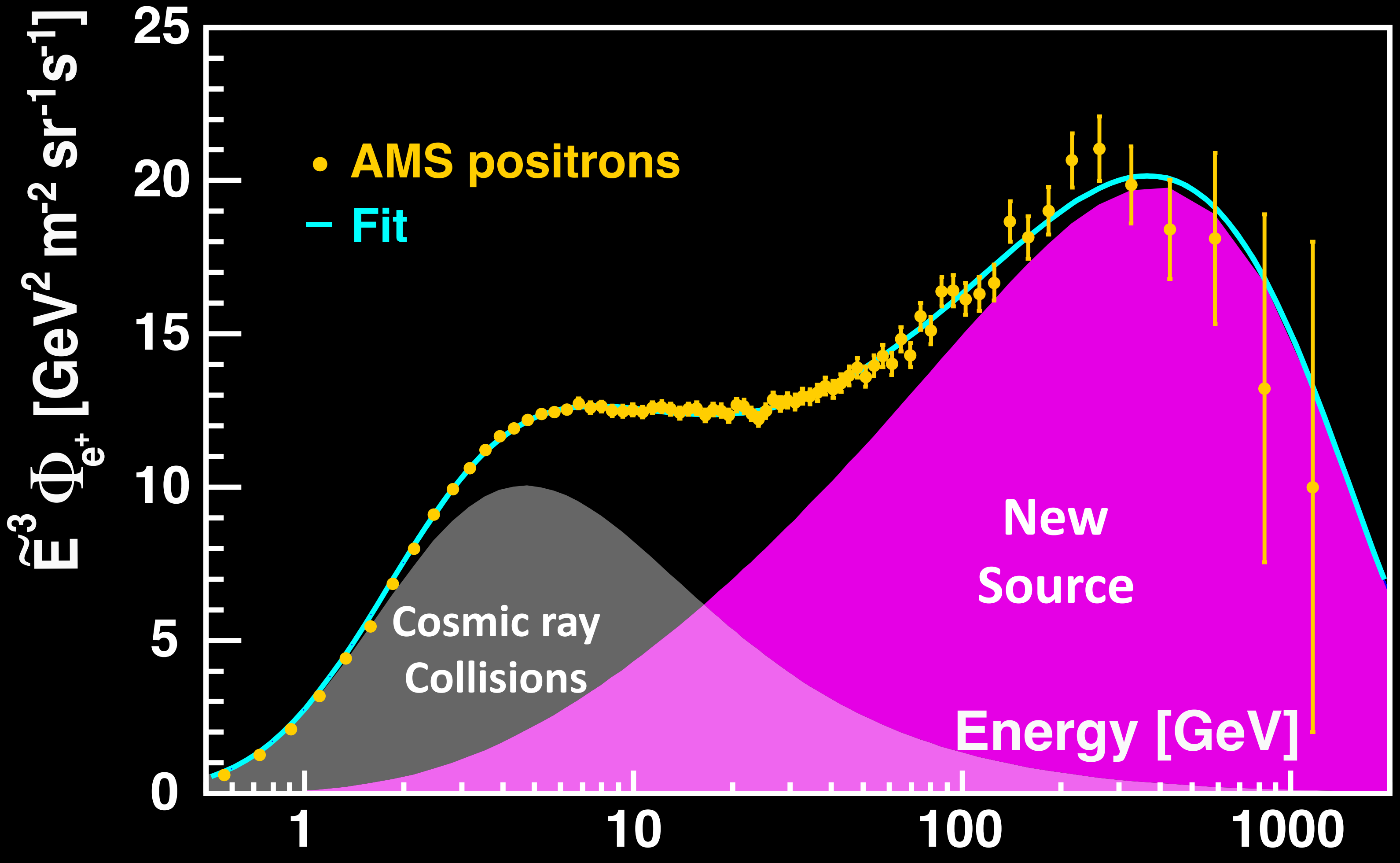
Low energy positrons mostly come from cosmic ray collisions



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

Collisions — New Source

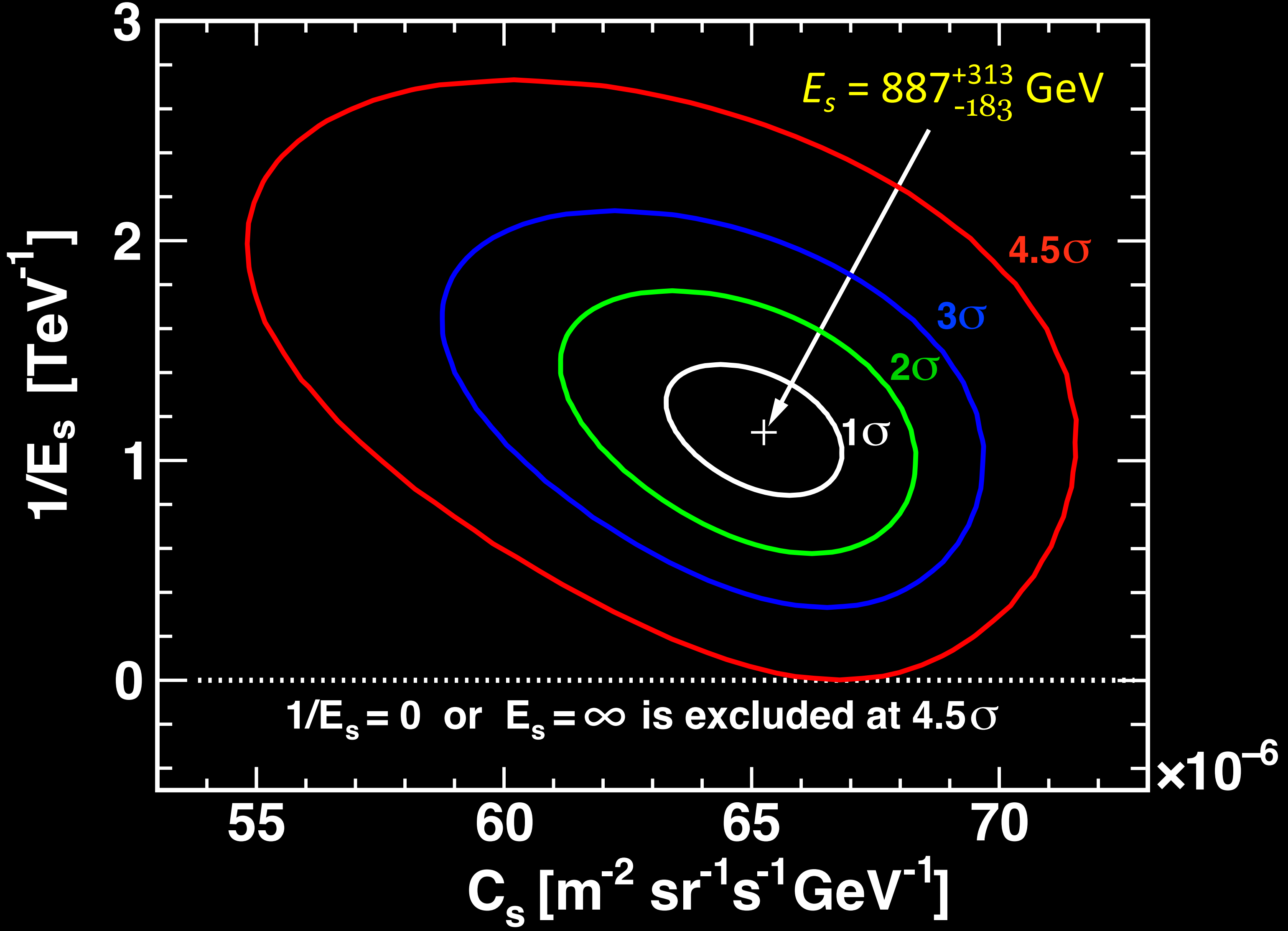
$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$



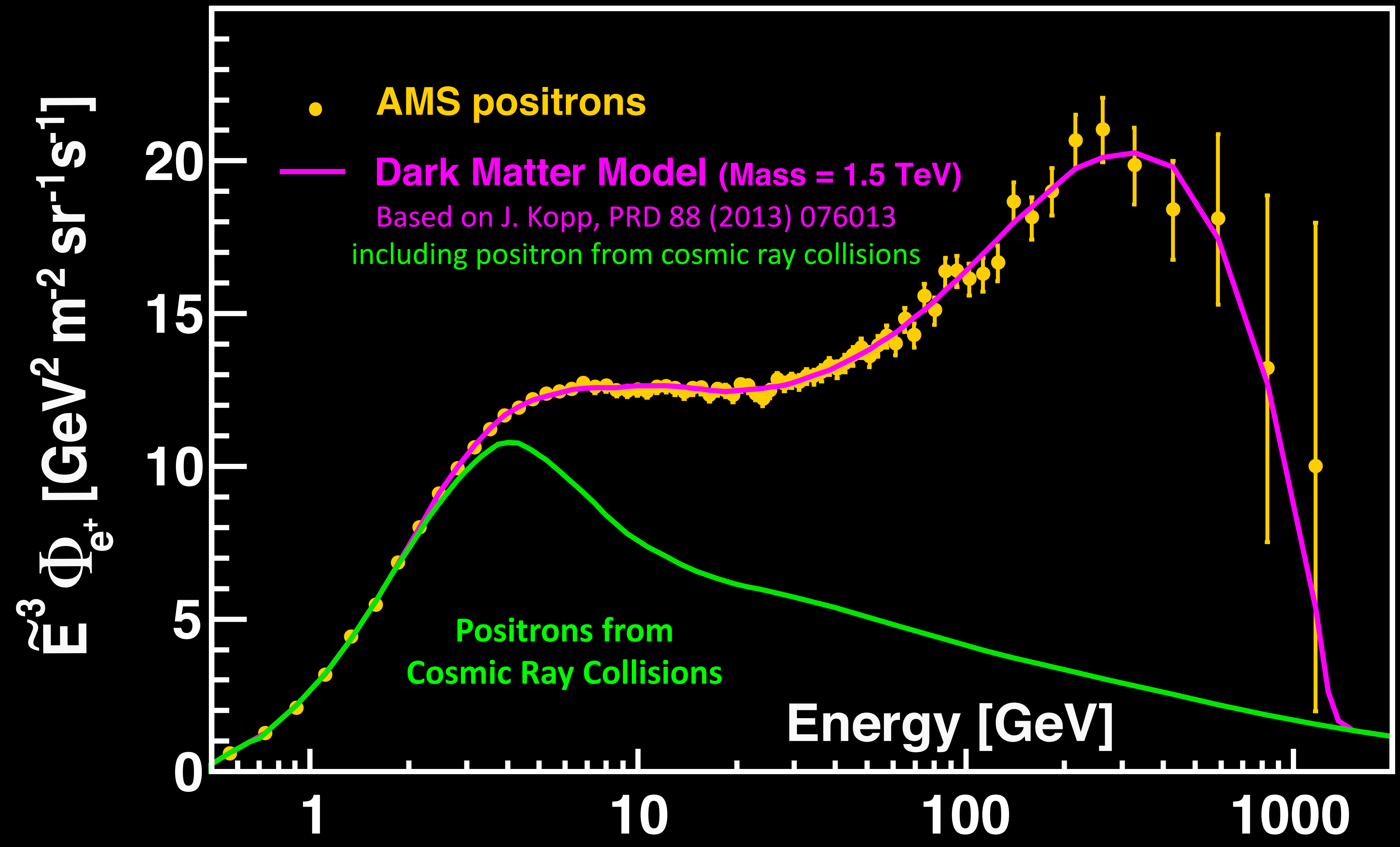
The finite cutoff energy E_s is established at 4.5σ C.L.

Collisions — New Source

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

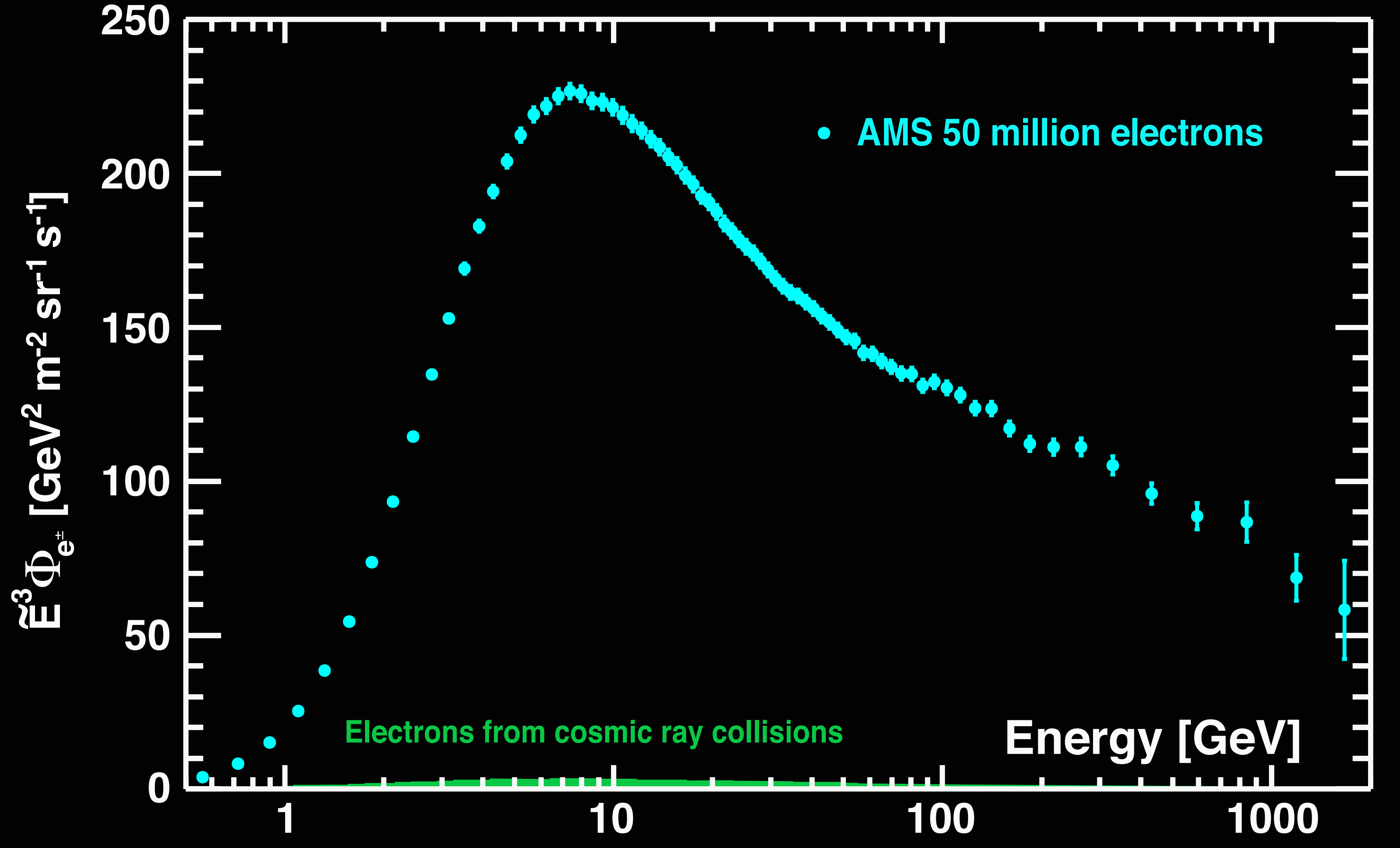


Positron and a Dark Matter Model



Origins of Cosmic Electrons

The contribution from cosmic ray collisions is negligible

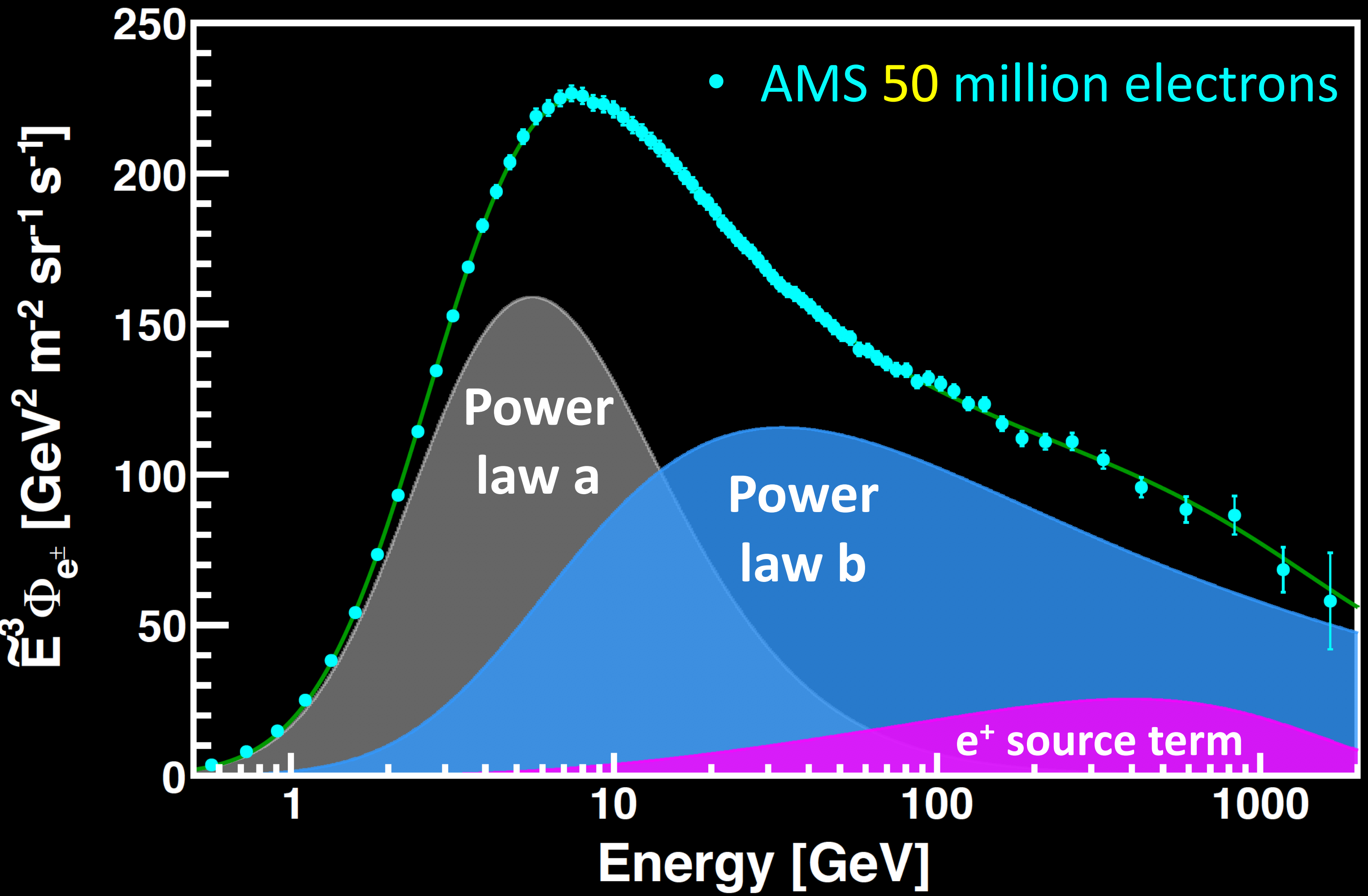


Properties of Cosmic Electrons

$$\Phi_{e^-}(E) = C_a E^{\gamma_a} + C_b E^{\gamma_b} + C_s E^{\gamma_s} \exp(-E/E_s)$$

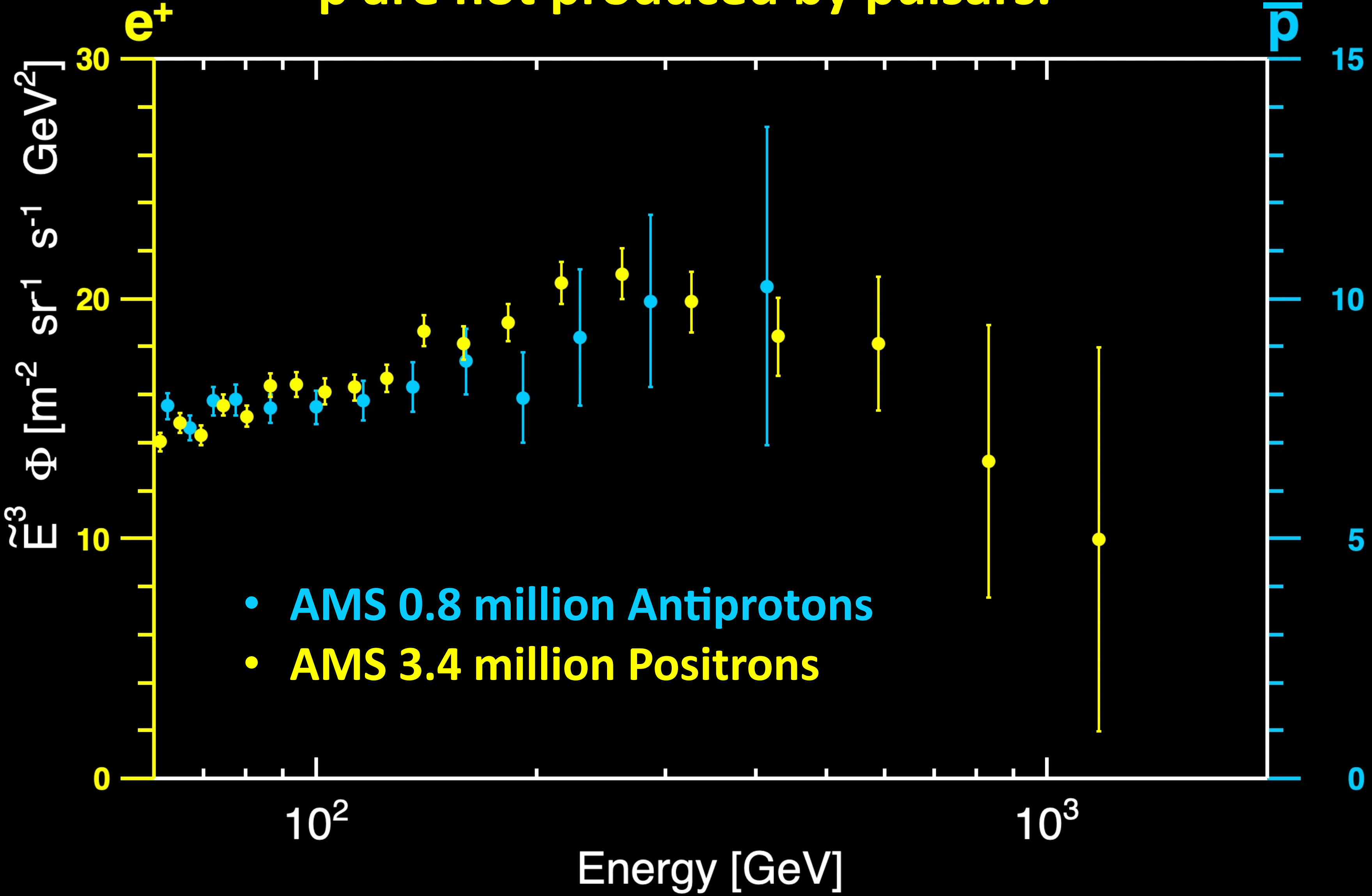
Power law *a* Power law *b* Positron source term

At 95% confidence level, the electron spectrum requires an equal positron source term

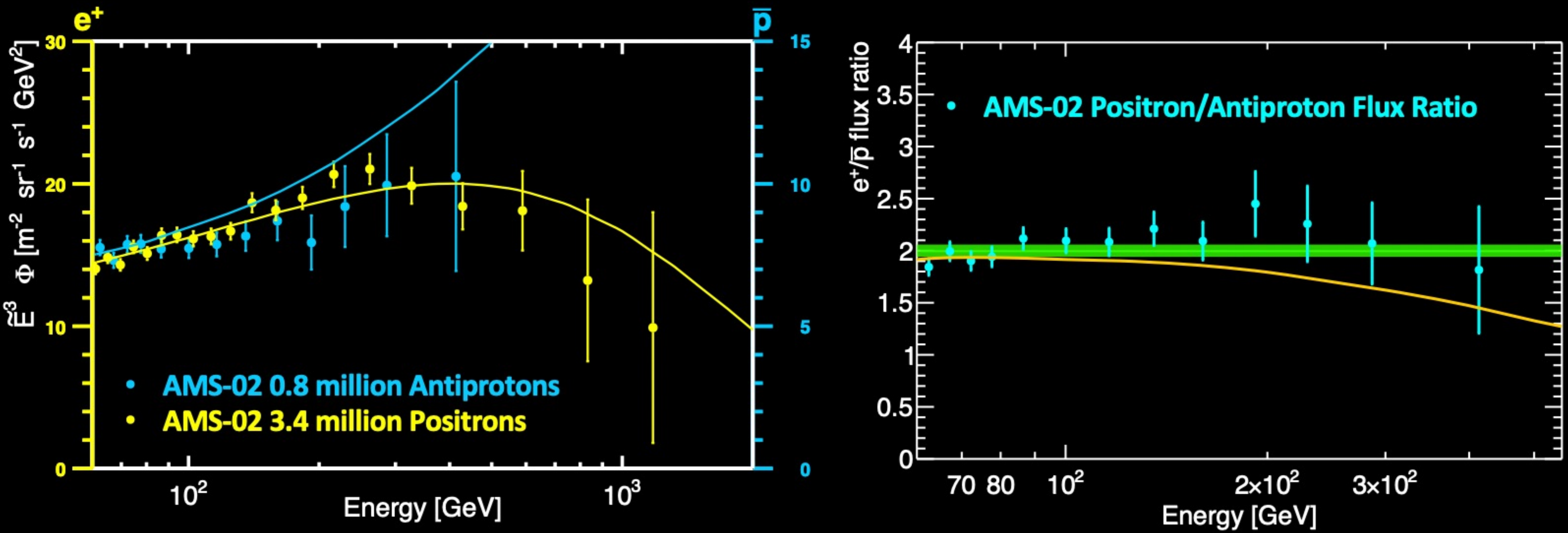


Properties of Cosmic Antiprotons

The $\bar{p}$ and e^+ fluxes have identical rigidity dependence.
$\bar{p}$ are not produced by pulsars.

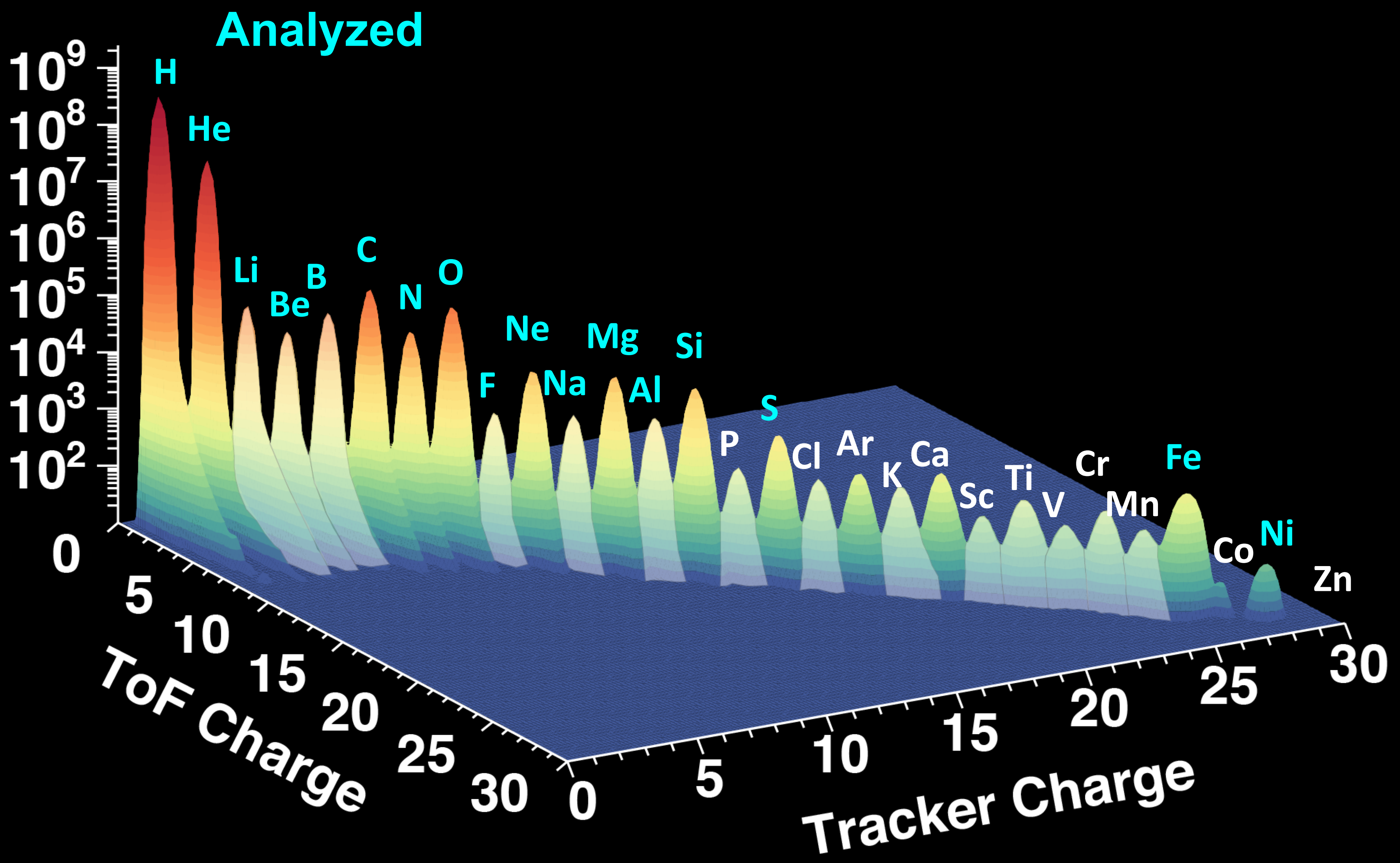


Example: Positron and Antiproton Spectra compared with Recent Models



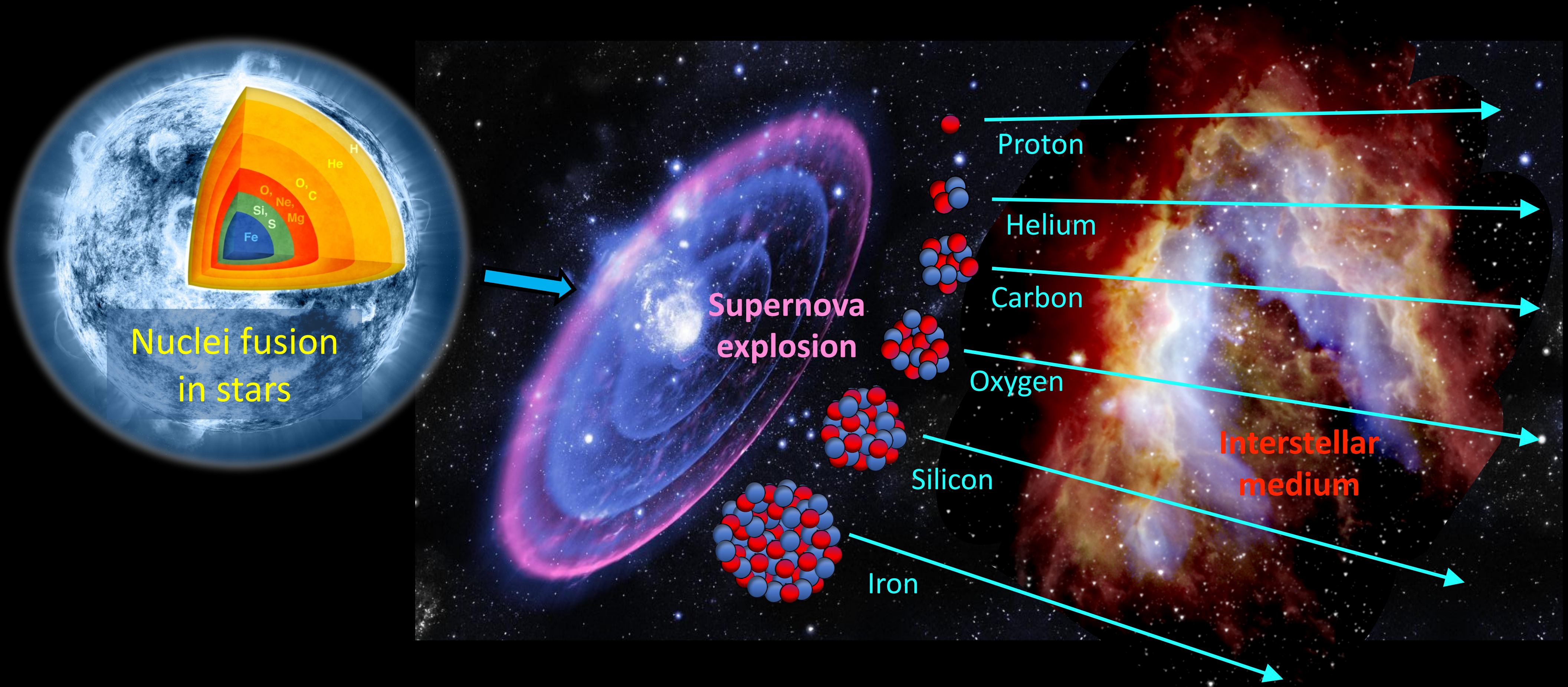
Model Example:
P. Mertsch, A. Vittino, S. Sarkar, PRD 104 (2021) 103029
"Explaining cosmic ray antimatter with secondaries from old supernova remnants"

Precision Measurements of Cosmic Nuclei by AMS



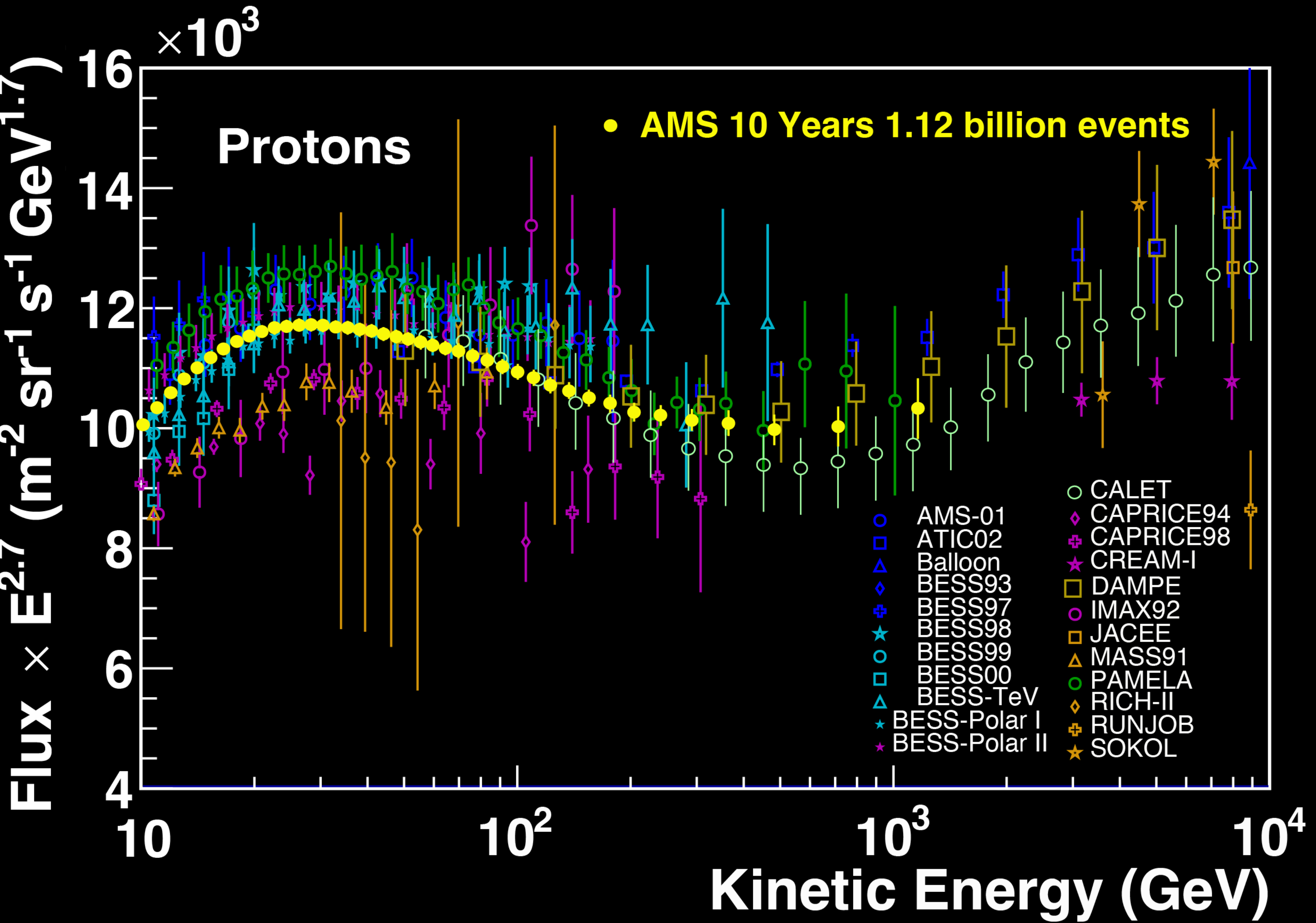
Primary Cosmic Rays

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.

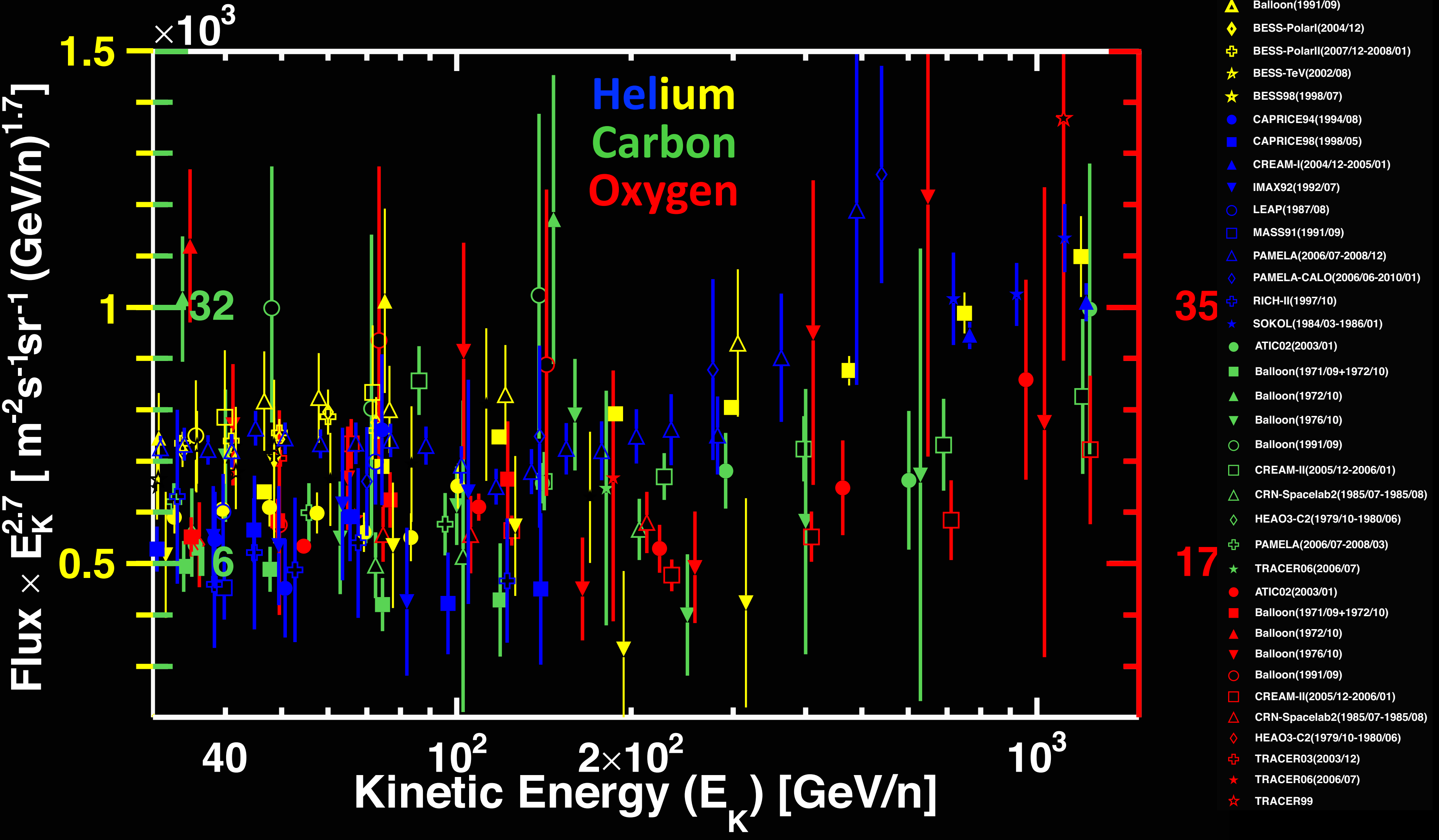
Latest AMS proton flux measurement



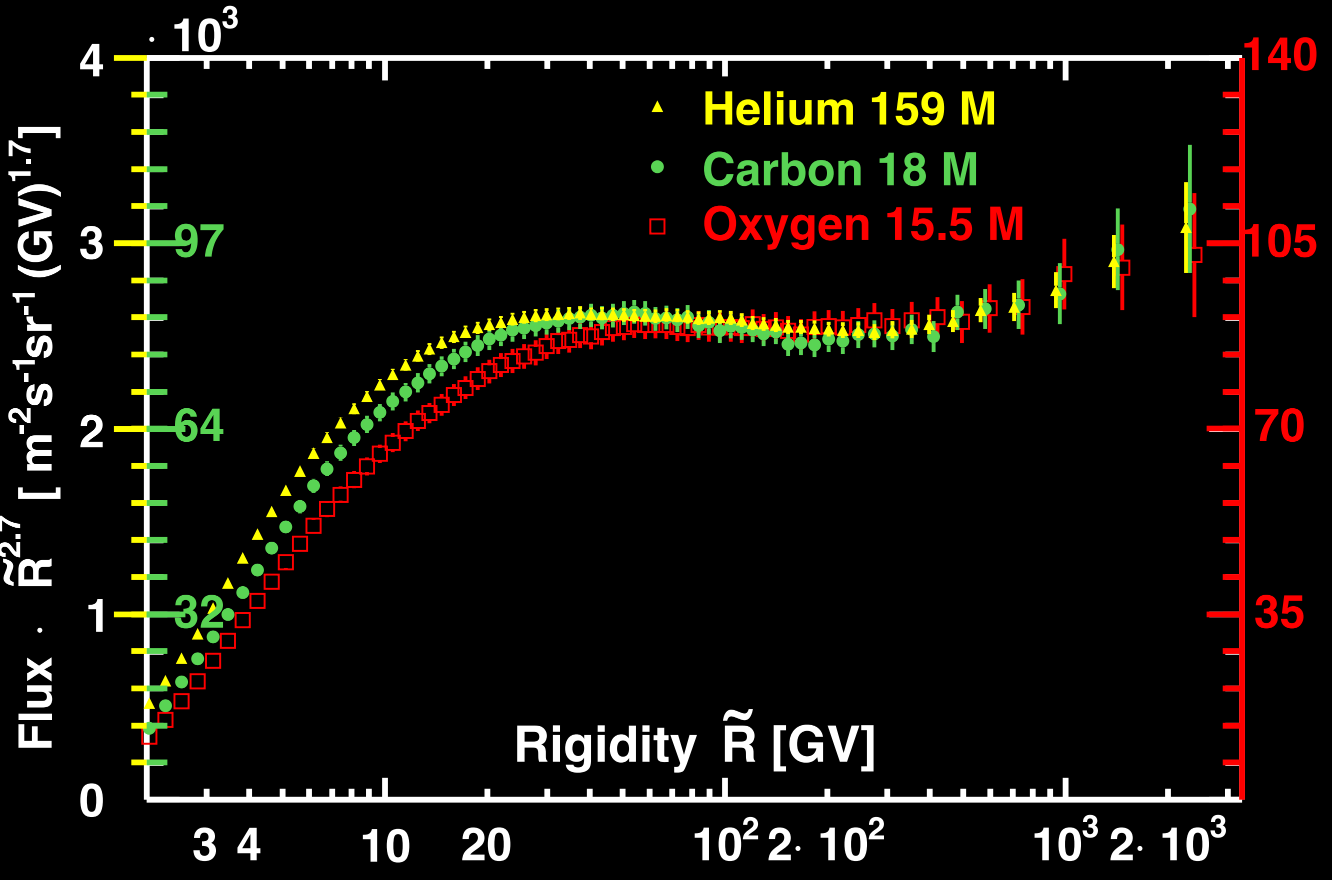
Before AMS there were many results on Light Primary Cosmic Rays

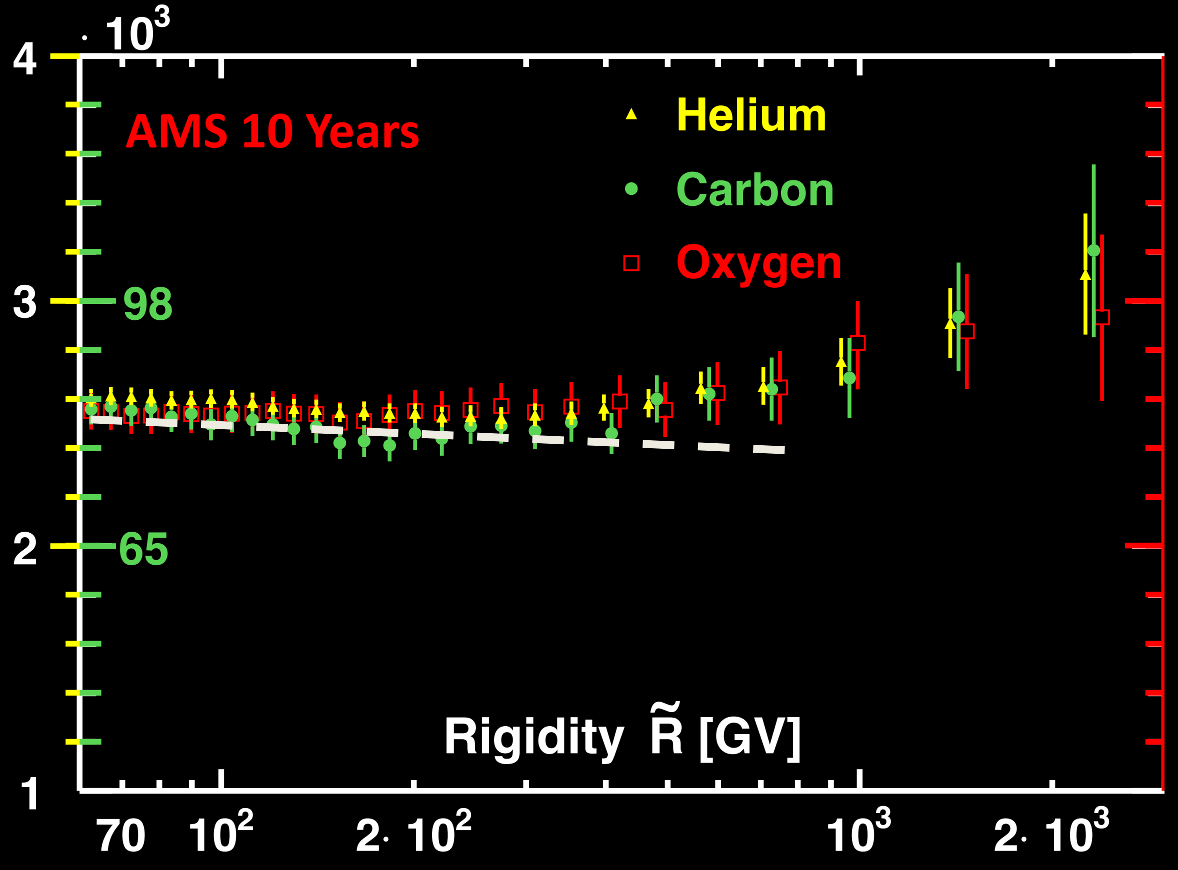
(Helium, Carbon, Oxygen)

from balloon and satellite experiments



Latest AMS Measurements of He, C, and O Fluxes



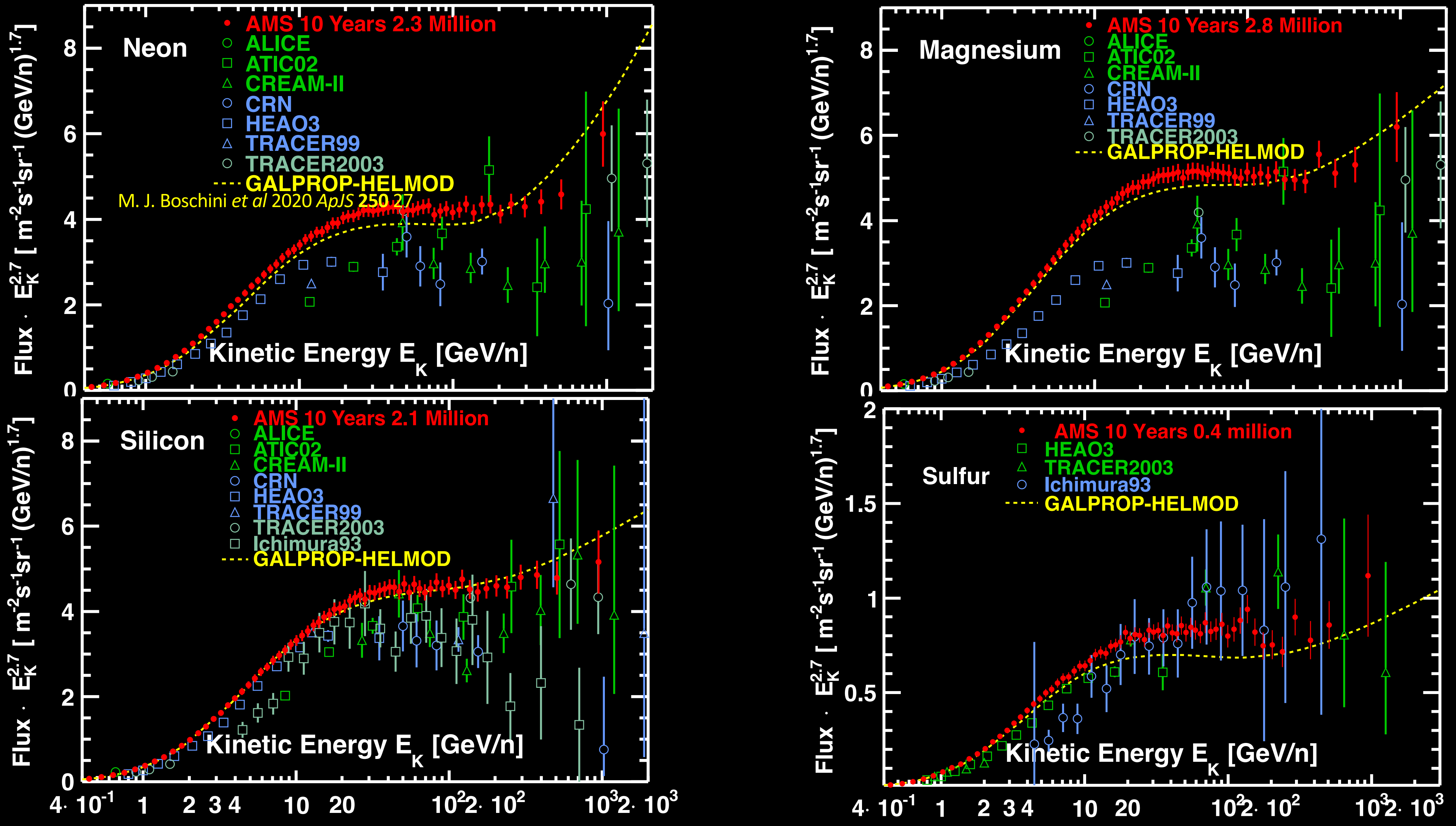


He, C and, O fluxes have an identical rigidity dependence above 60 GV.

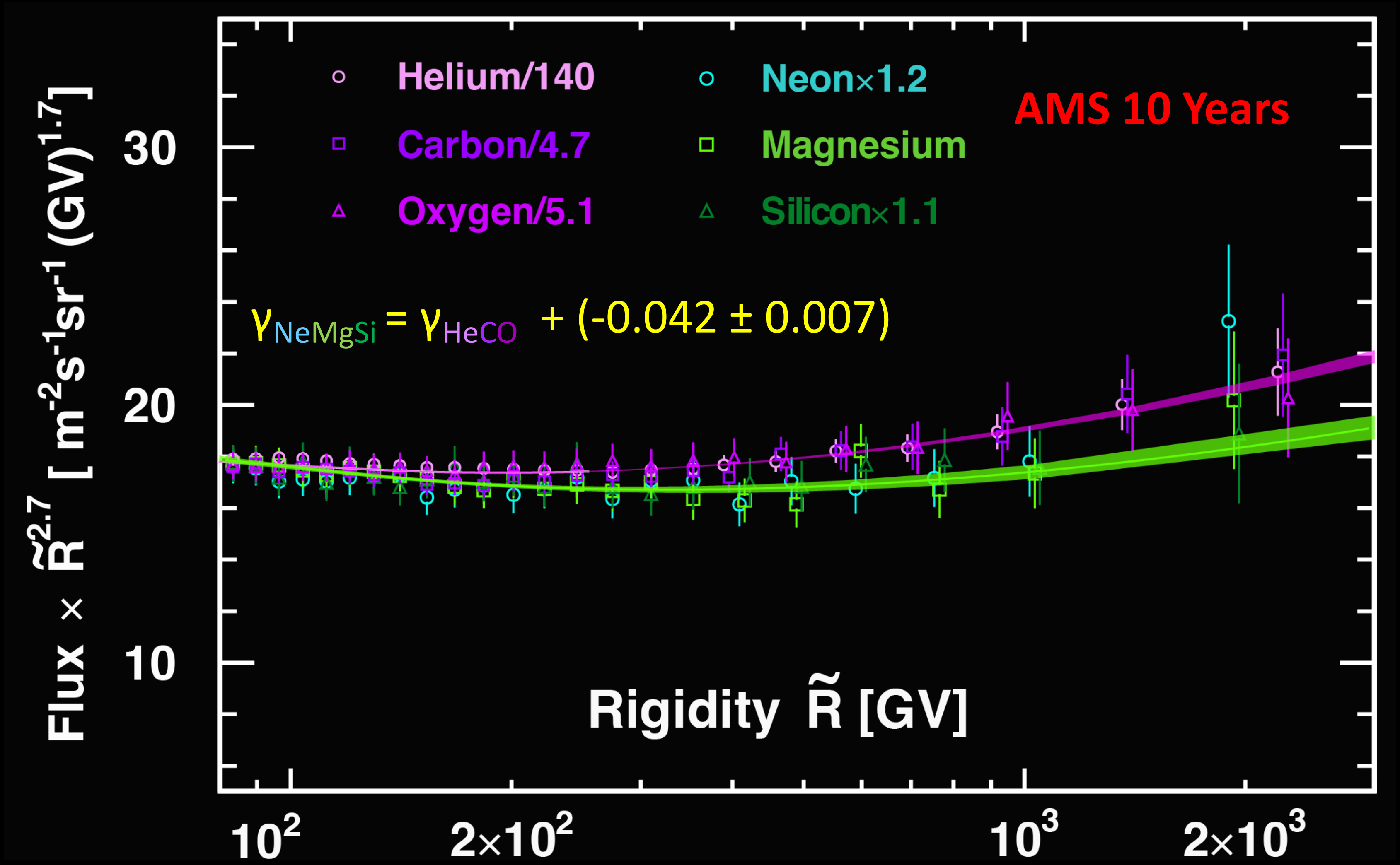
Above 200 GV, they all deviate from a single power law in an identical way.

Latest AMS Measurements of Ne, Mg, Si, and S Fluxes

AMS results are different from previous measurement both in magnitude and the energy dependence.
They are also different from the cosmic ray theory predictions.



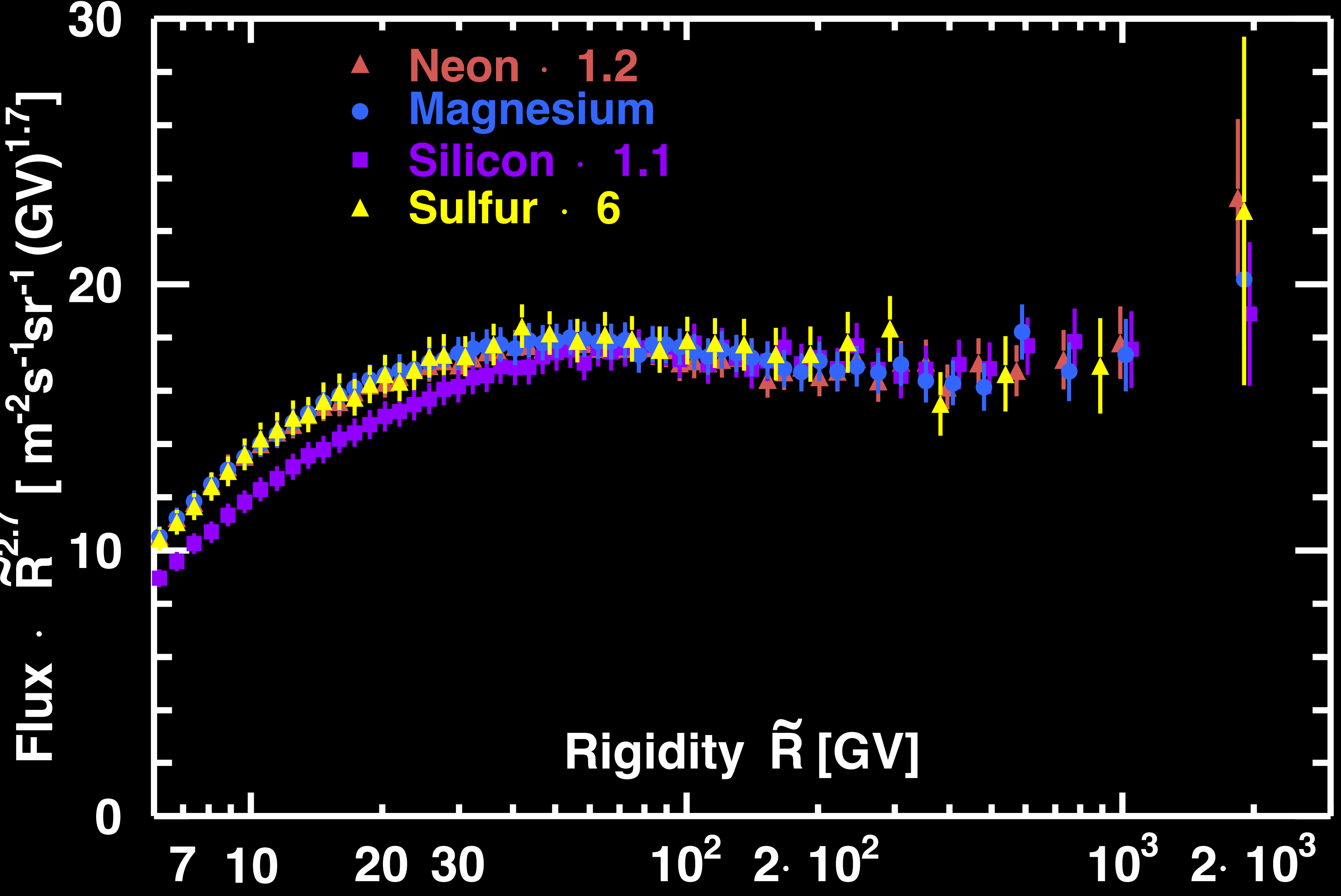
Properties of Heavy Primary Cosmic-Ray Ne, Mg, Si



Suprisingly, heavy primary cosmic rays Ne, Mg, and Si also have identical rigidity dependence above 86 GV, but it is distinctly different from light primary cosmic rays He, C, and O.

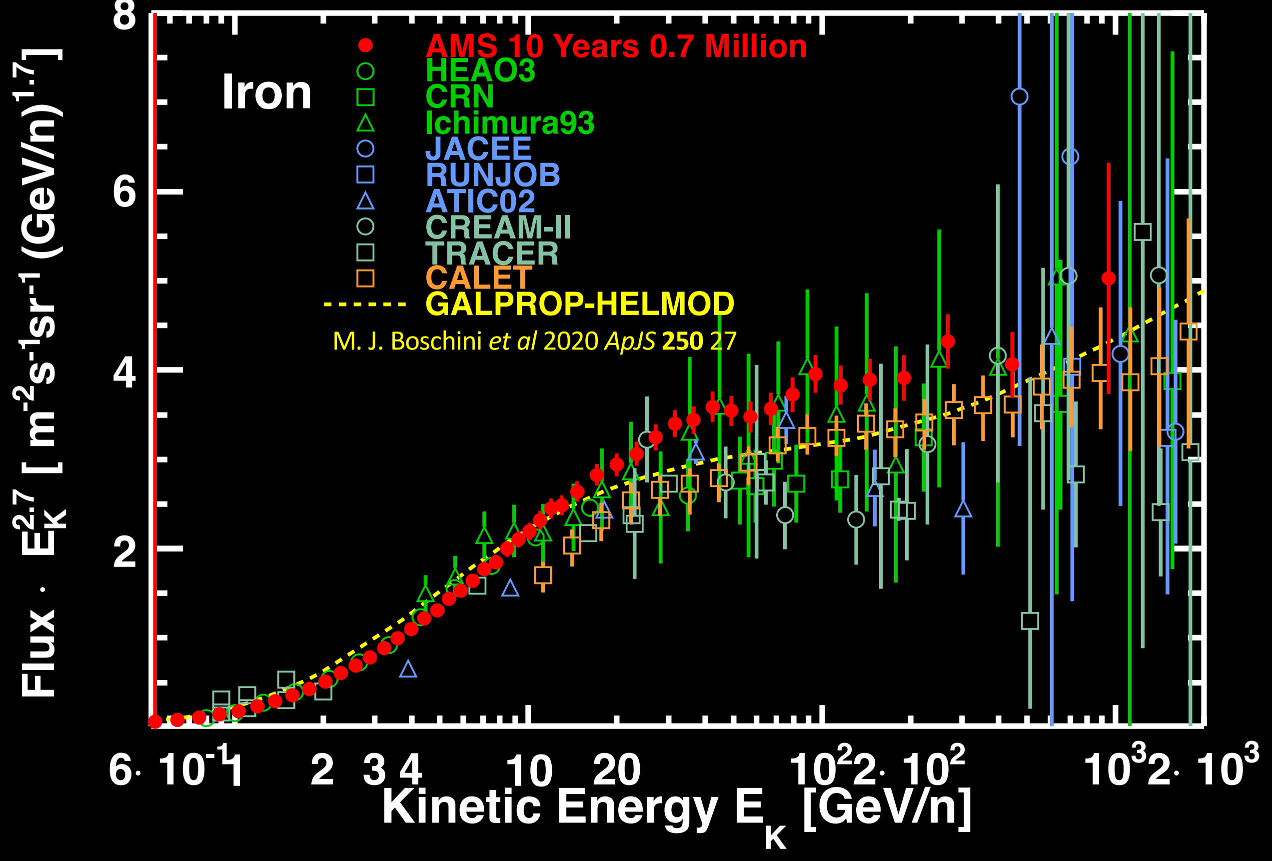
This shows that primary cosmic rays have at least two distinct classes.

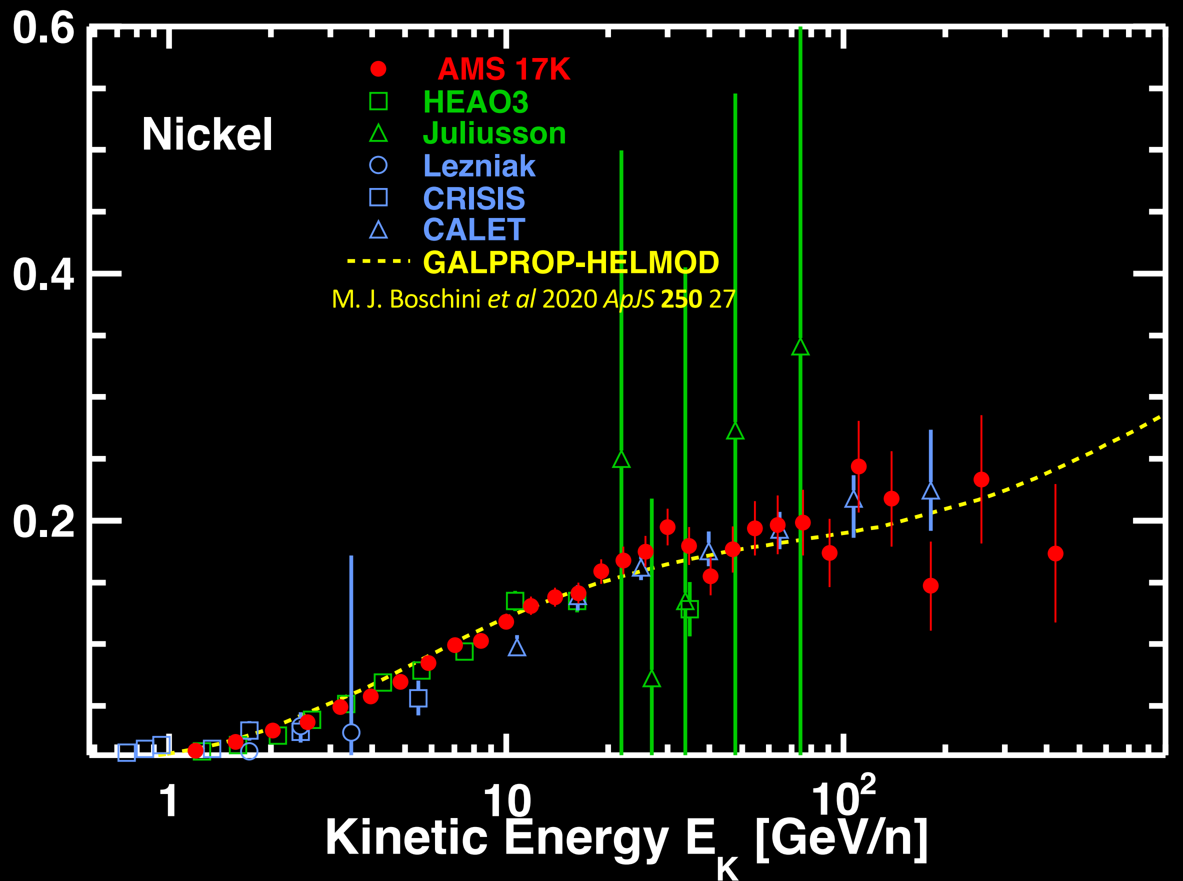
Latest AMS Results: Sulfur Rigidity Dependence



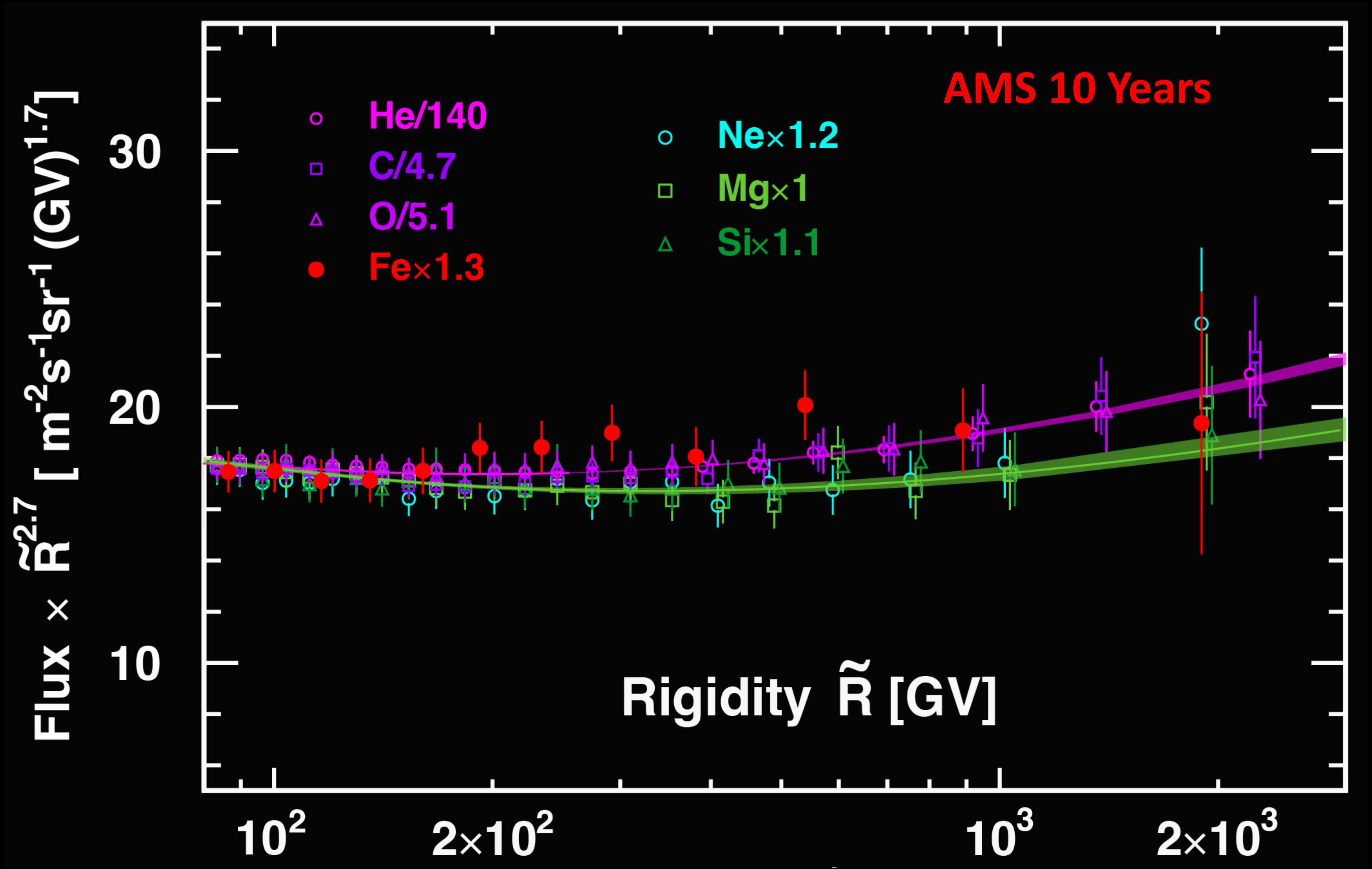
Sulfur belongs to the same class as Ne, Mg, and Si.

Heavy Primary Cosmic Rays: Iron and Nickel Fluxes

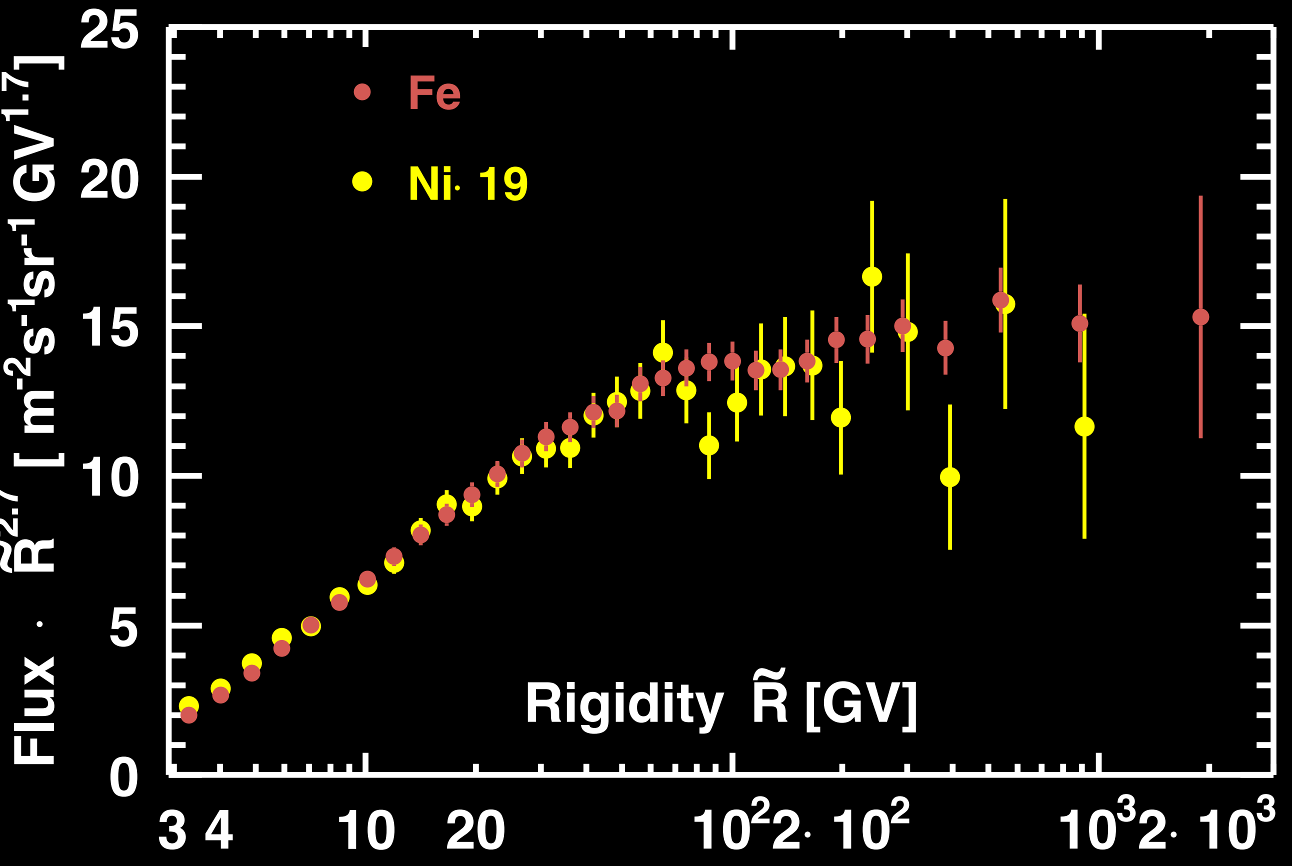


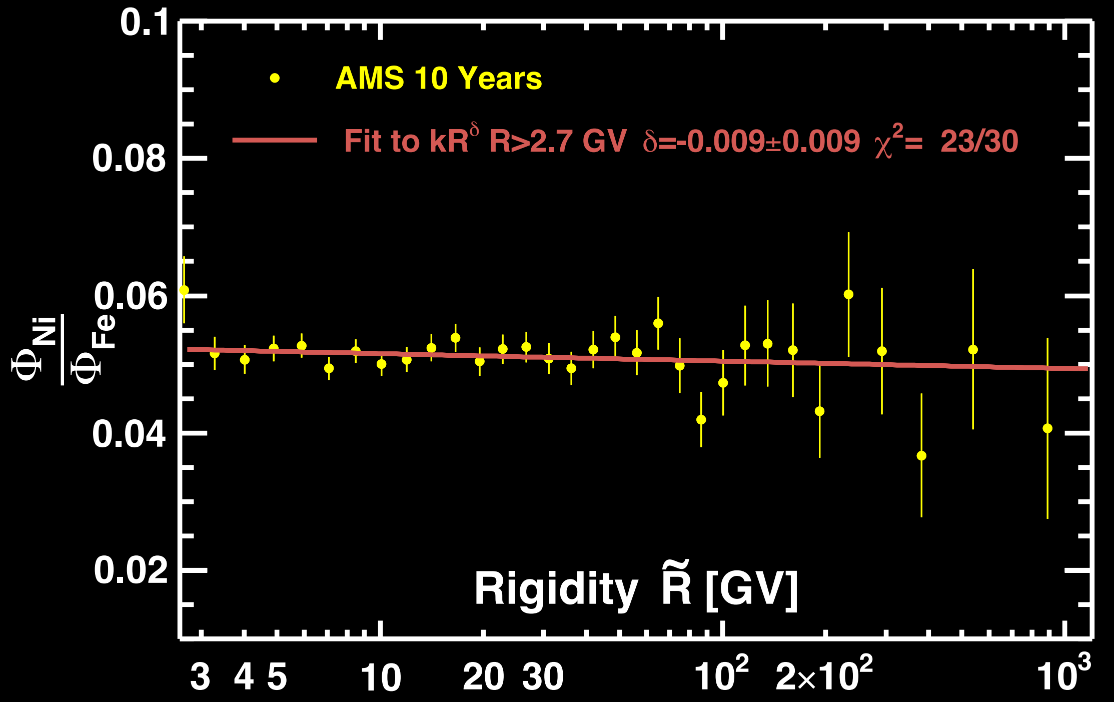


Unexpected Results: Iron is the Same Class as He, C, O instead of the heavier Ne, Mg, Si



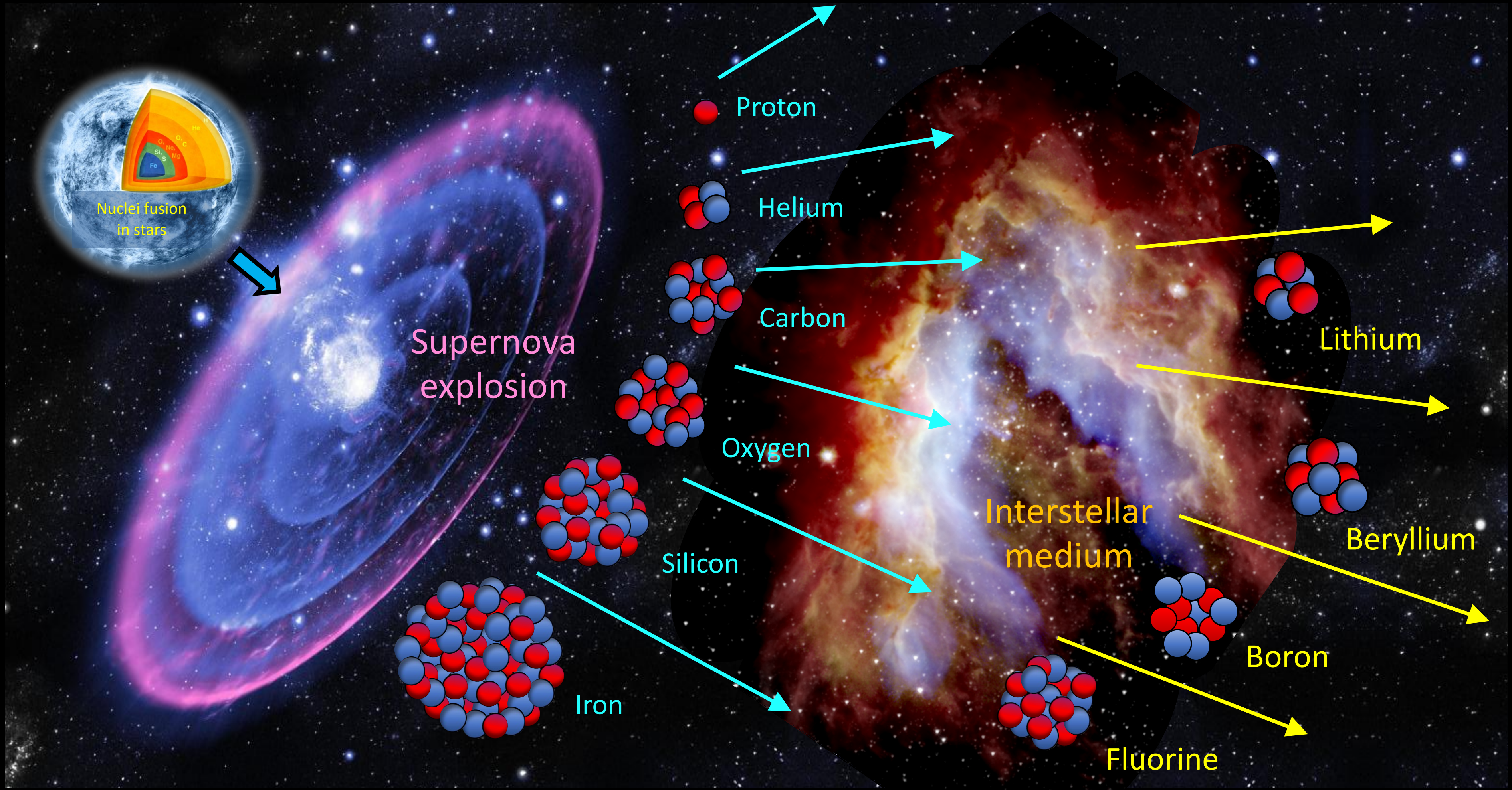
AMS Nickel Flux: rigidity dependence is similar to Fe





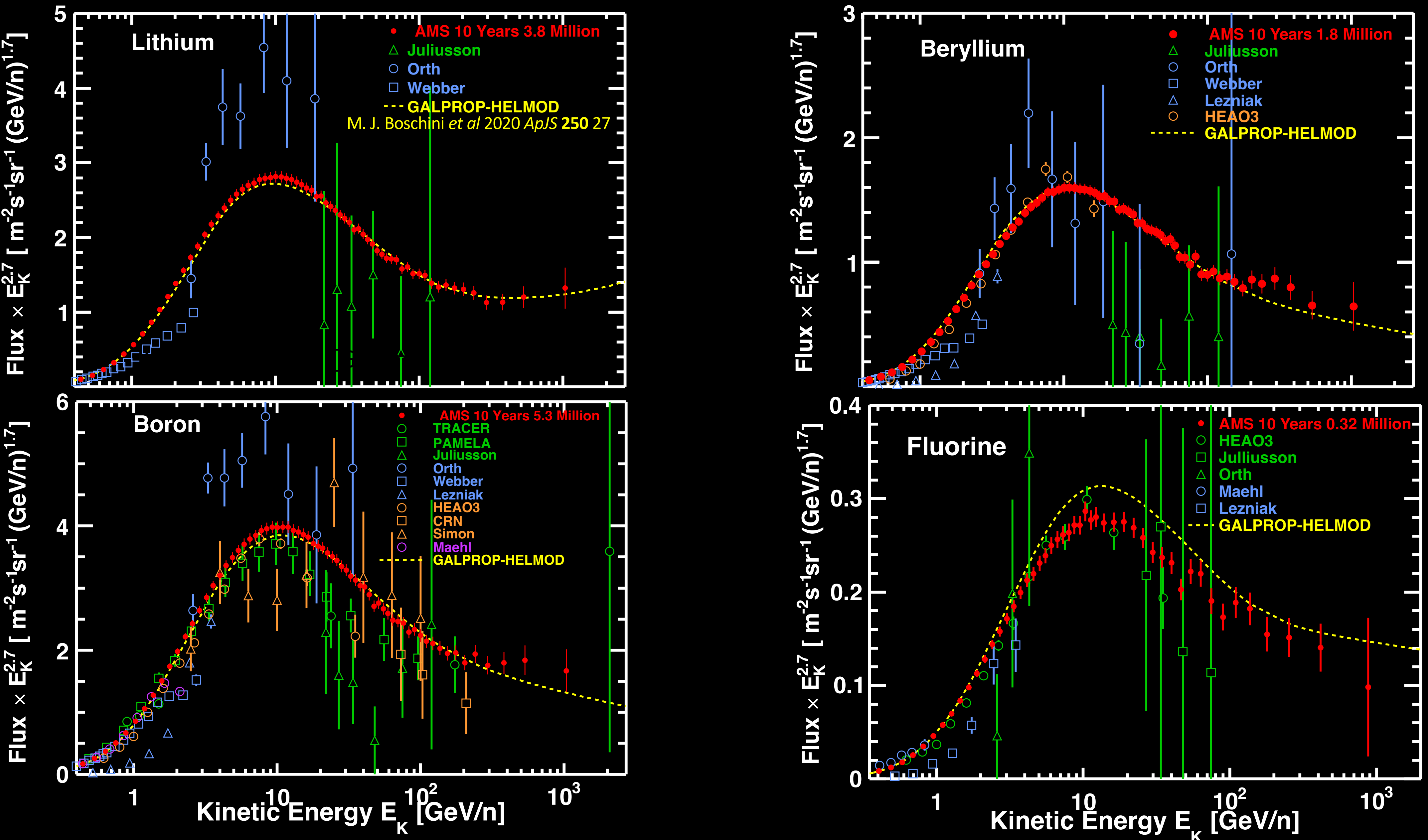
Secondary Cosmic Rays

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.

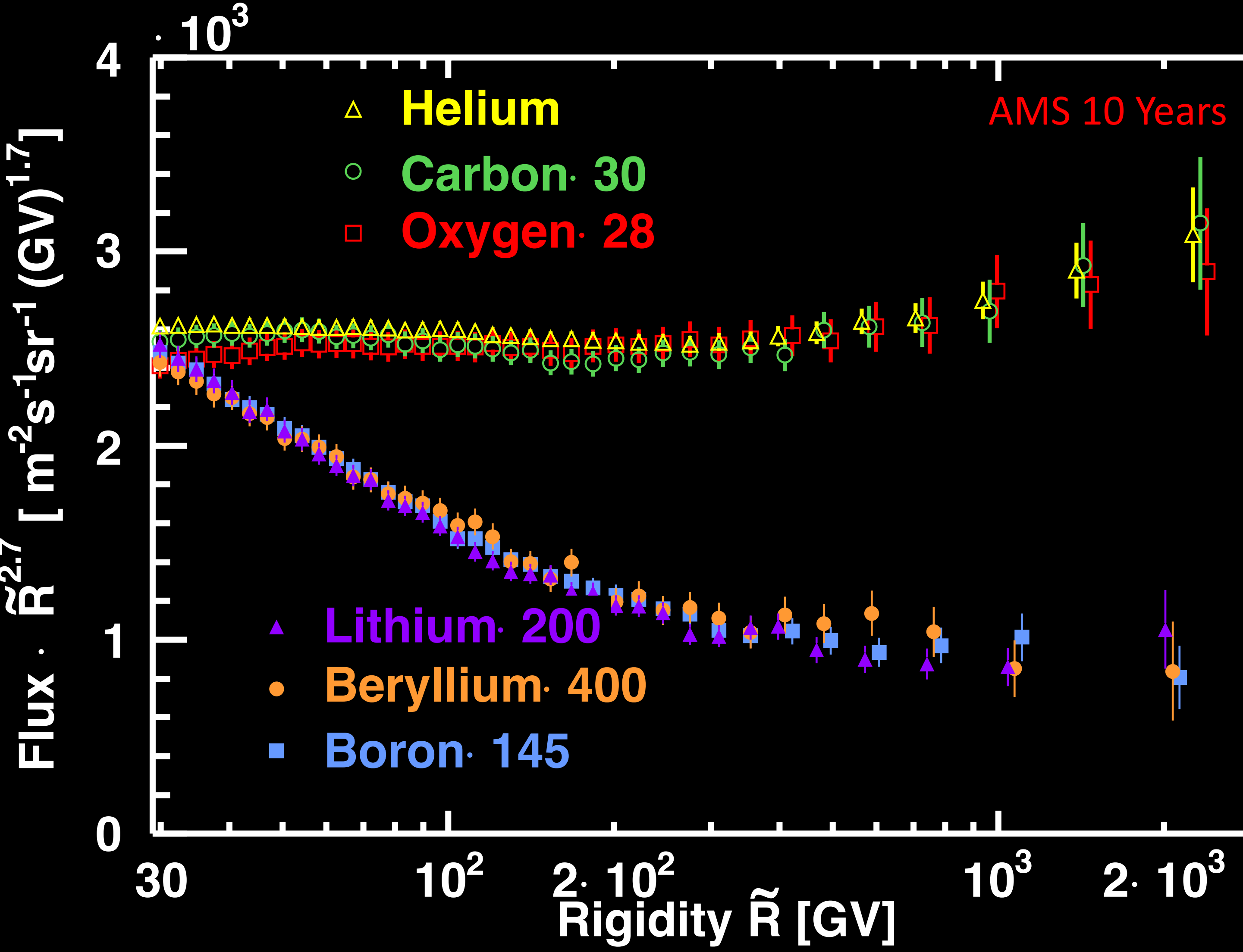


Measurements of the secondary cosmic ray nuclei fluxes are important in understanding the propagation of cosmic rays in the Galaxy.

Latest AMS Measurements of Li, Be, B, and F Fluxes

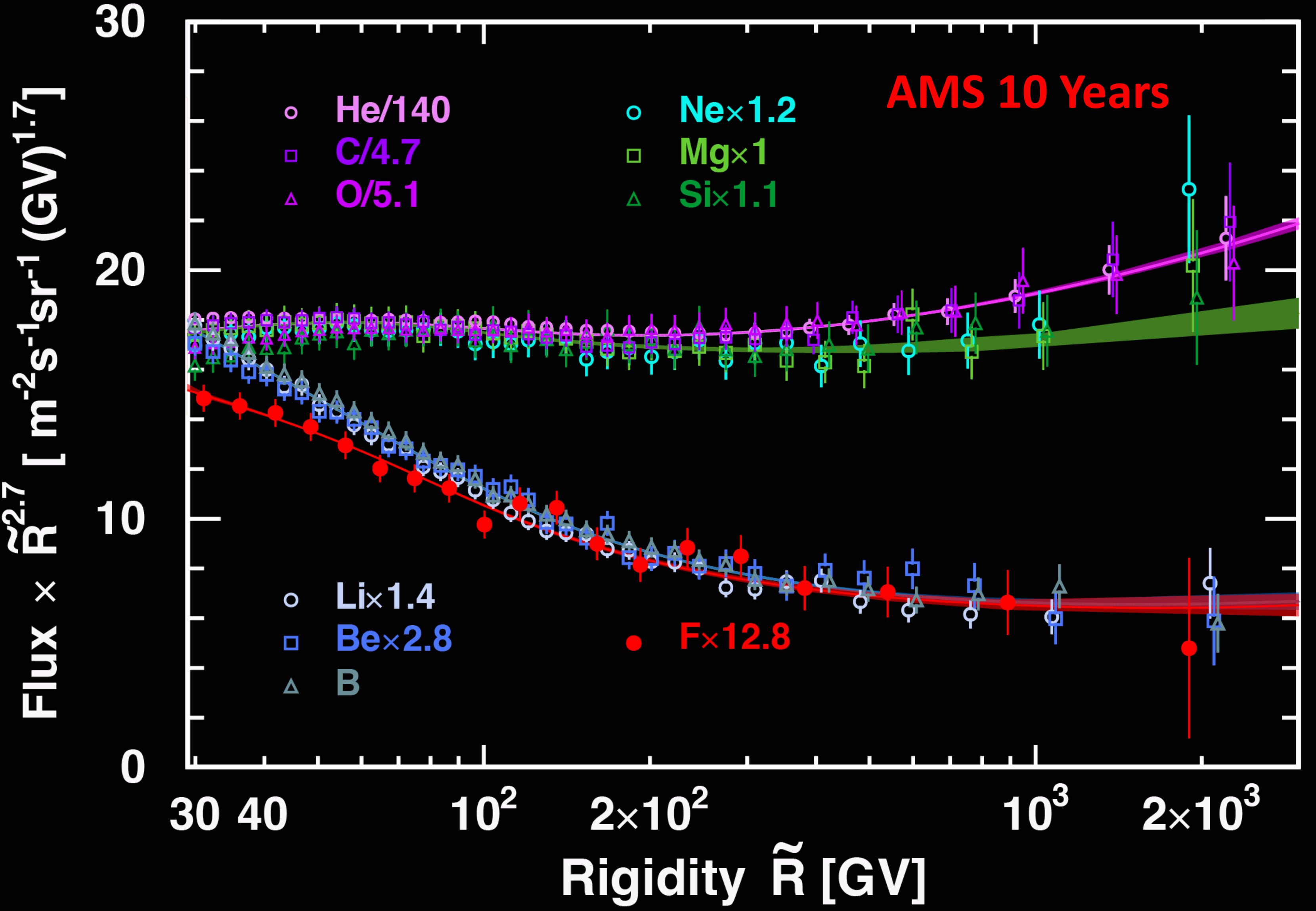


Light Secondary Cosmic Rays Li, Be, and B Fluxes



Li, Be, B also have identical rigidity dependence, but distinctly different from primaries.

Secondary cosmic rays have two classes: Li-Be-B and F

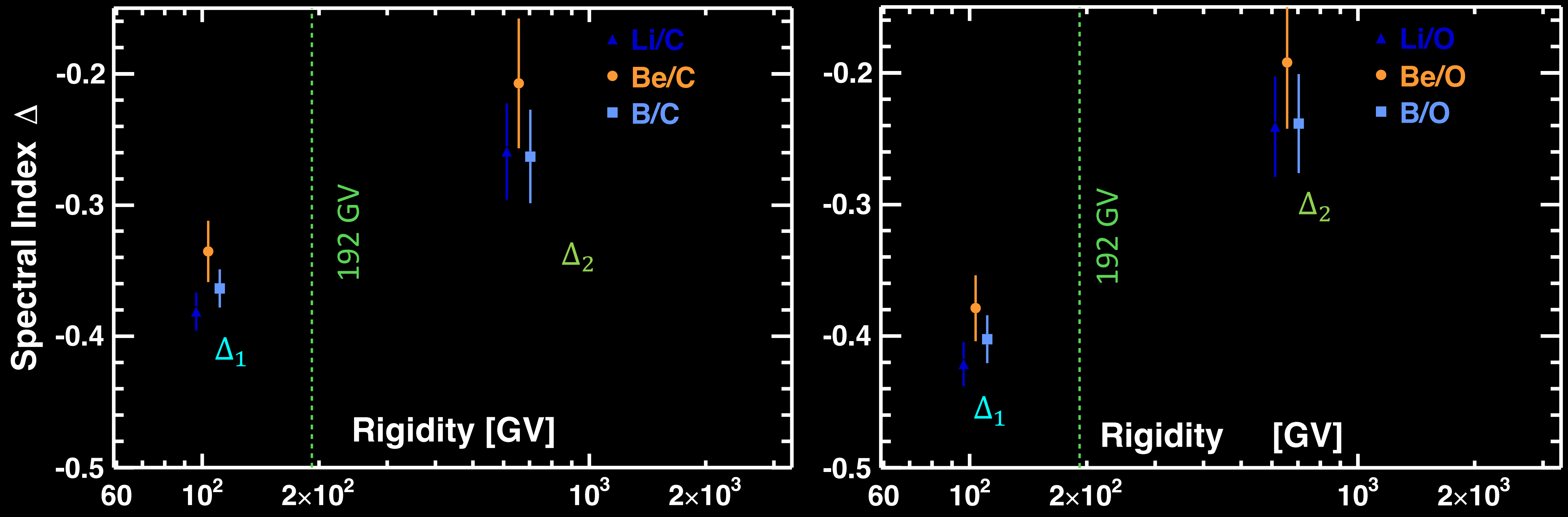


Both classes are different from primaries.

Light Secondary (Li, Be, B) to Primary (C, O) Flux Ratio

The ratio of secondary flux to primary flux directly measures the amount and properties of interstellar medium. Before AMS, the secondary-to-primary ratios (B/C …) were assumed to be **$\propto R^{\Delta}$ with Δ a constant** (independent of R and Z) for R > 60GV.

Above 192 GV all six secondary-to-primary flux ratios harden



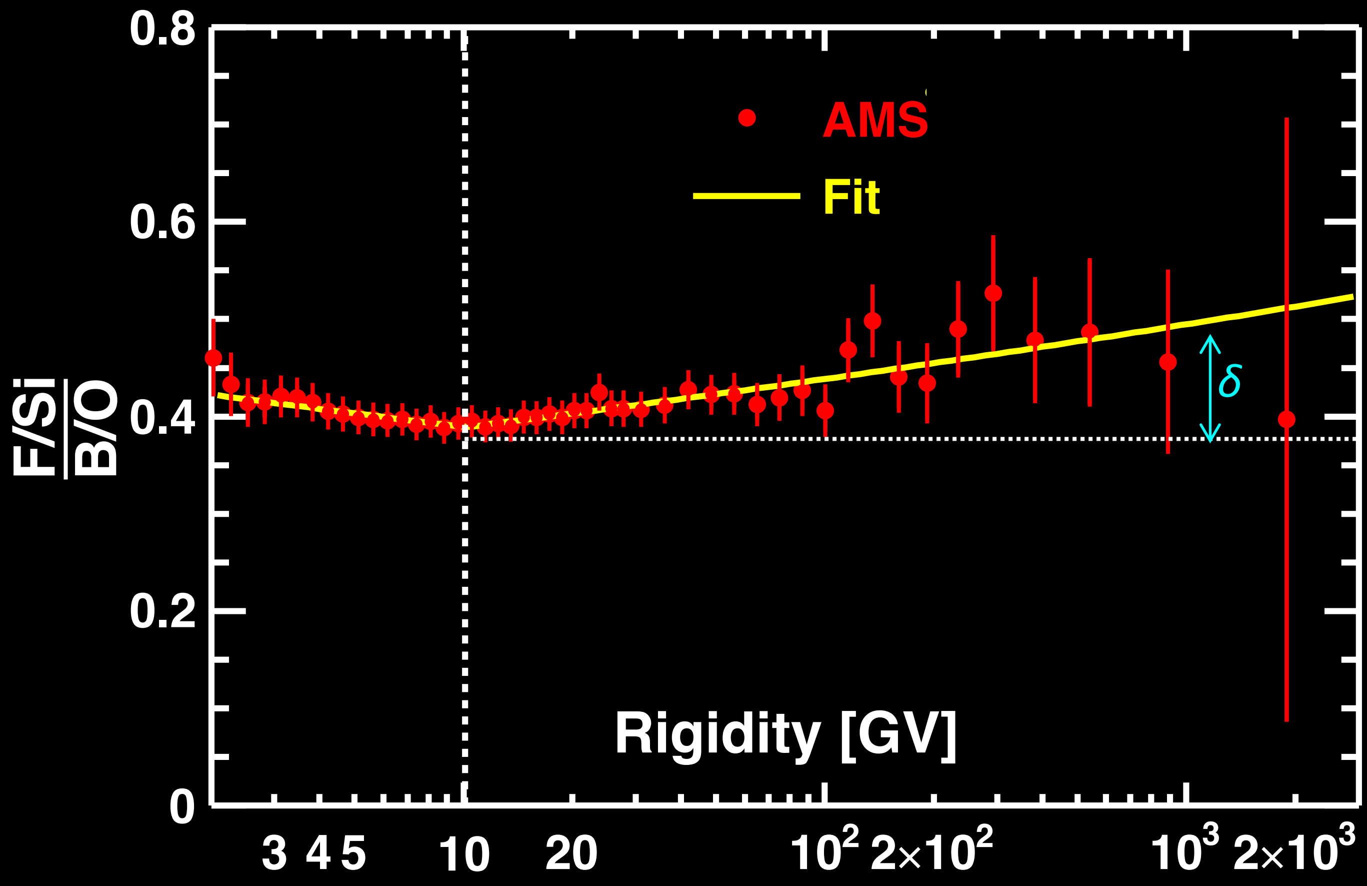
AMS results shows that Δ is a not a constant

Average hardening $\Delta = \Delta_2 - \Delta_1 = 0.145 \pm 0.022$, significance: 6.5σ

AMS 10-year Measurement of (F/Si)/(B/O)

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

AMS results show that the propagation properties of heavy cosmic rays are different from those of light cosmic rays

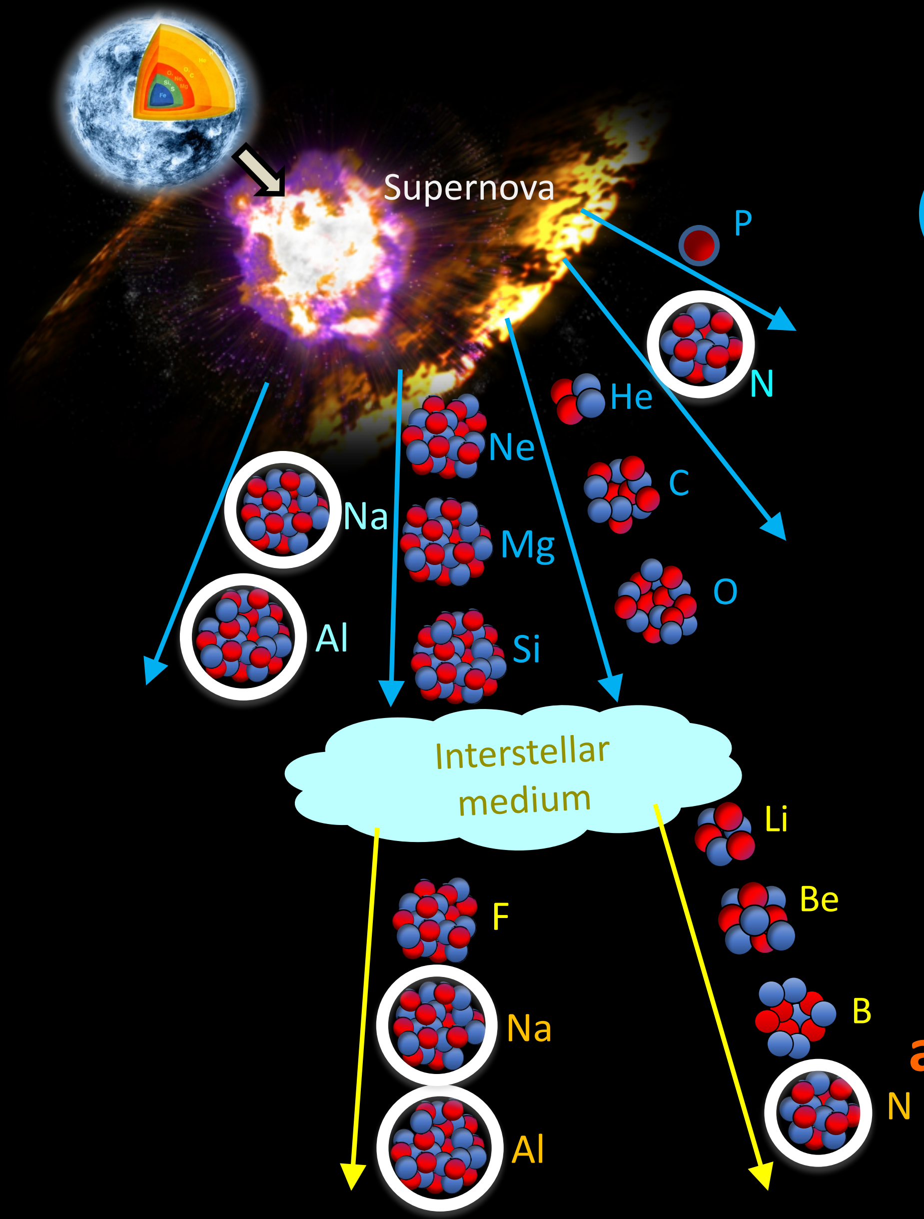


Fit to kR^{δ}

$\delta = 0.053 \pm 0.007$

7σ from zero

The Third Group of Cosmic Rays

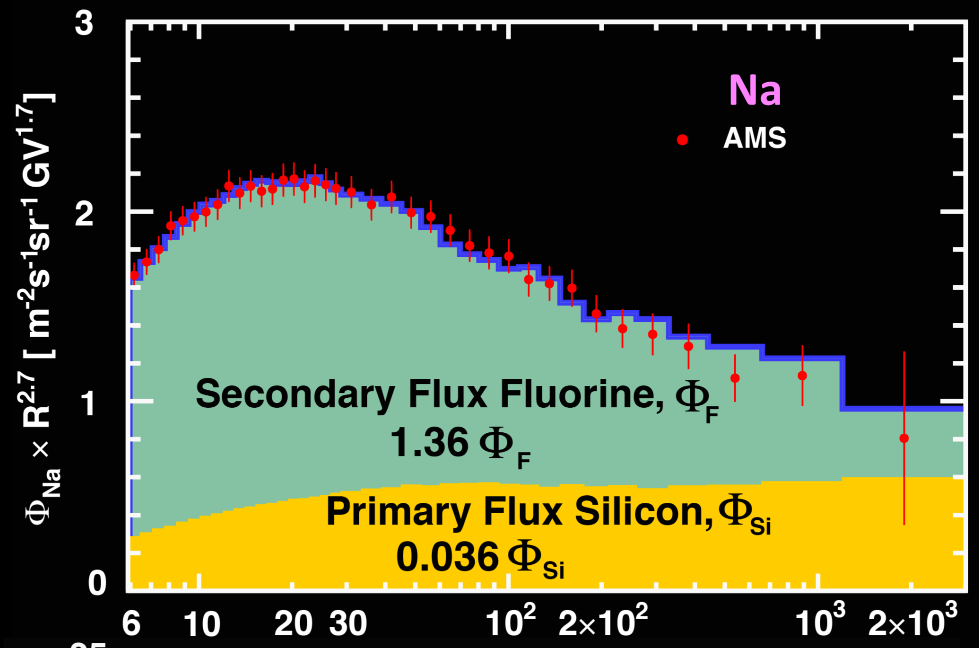


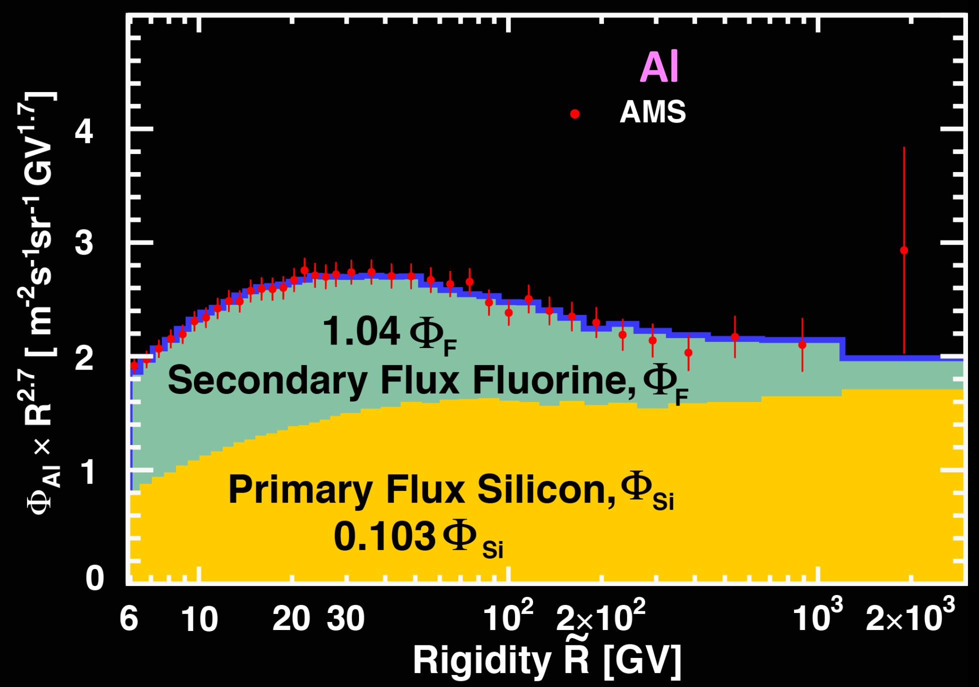
Primary cosmic rays
(p, He, C, O, Ne, Mg, Si ..., Fe)

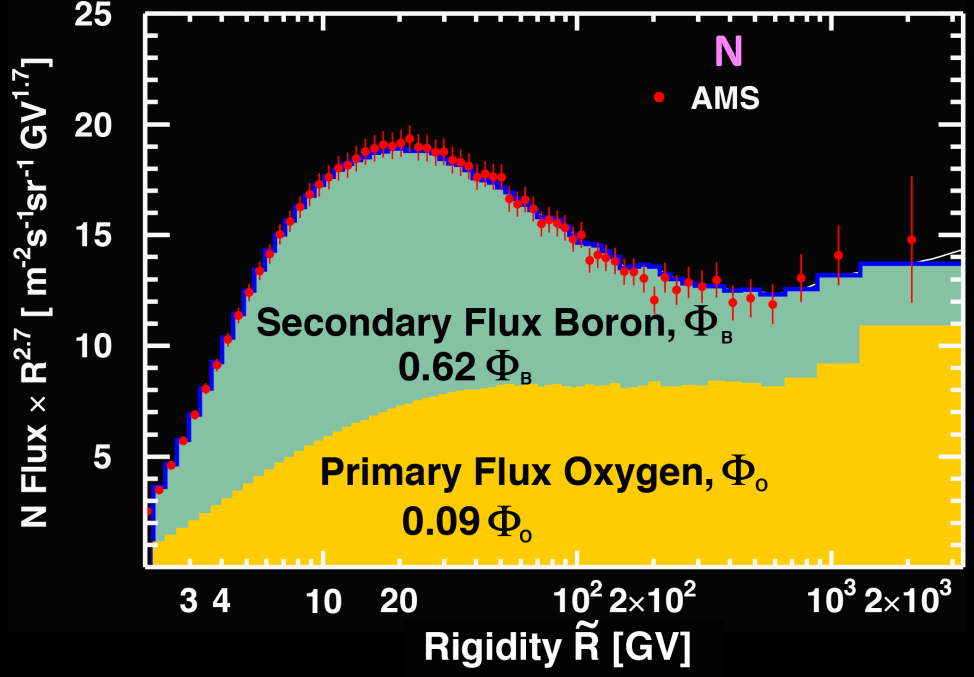
Secondary cosmic nuclei
(Li, Be, B, F, ...)

AMS discovered that
the third group of cosmic rays
(N, Na, Al,...)
are produced both in the stars and
in the interstellar medium

A third group of cosmic rays: N-Na-Al partially primary, partially secondary



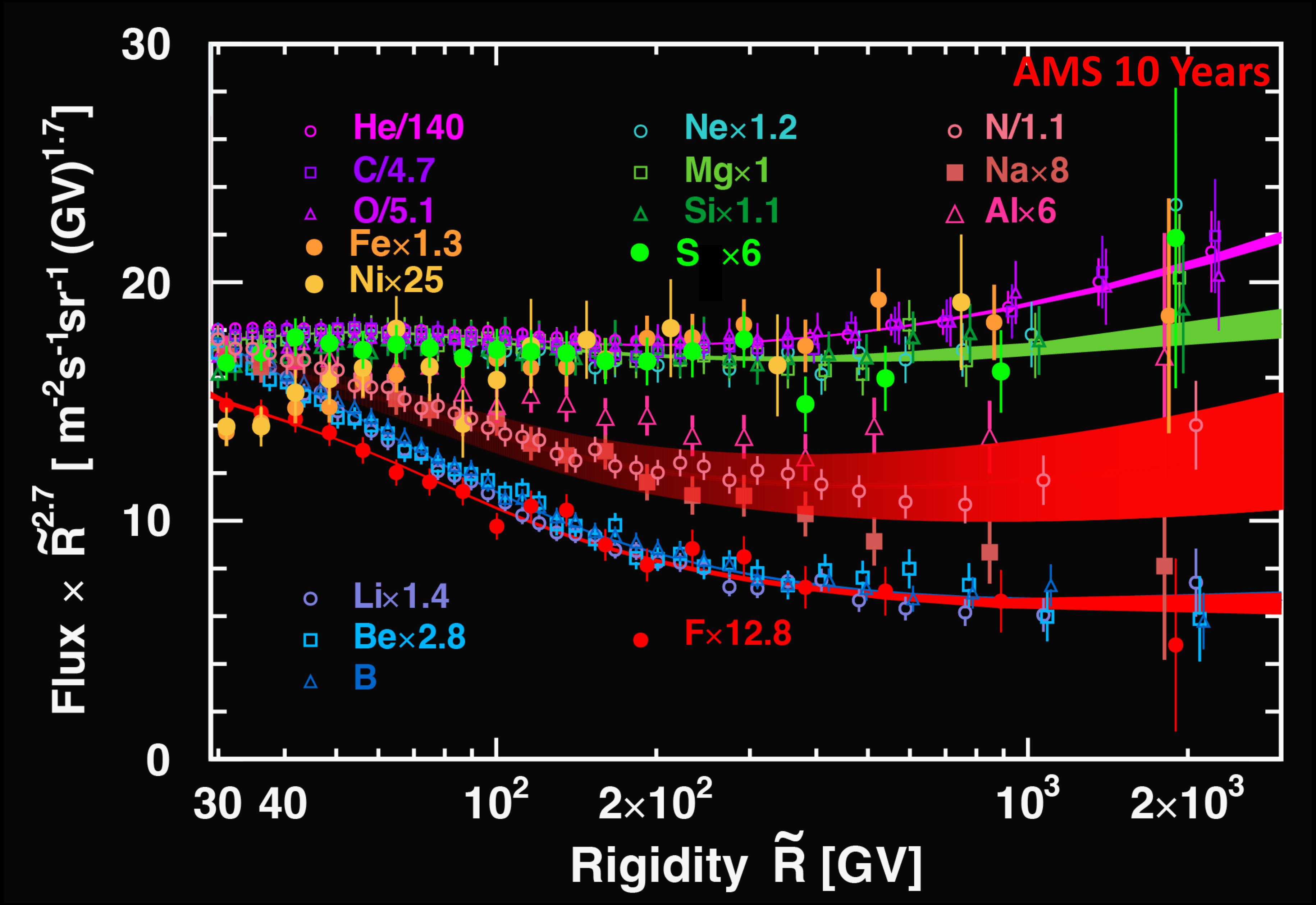




The flux ratios at the source,
Na/Si=0.036±0.003,
Al/Si=0.103±0.004,
and
N/O=0.092±0.002,
are determined
independent of models.

Phys. Rev. Lett. **127**, 021101 (2021)

AMS Results on Cosmic Ray Nuclei



Surprises in Solar Physics

Cosmic radiation from the Milky Way: 90 rem/year

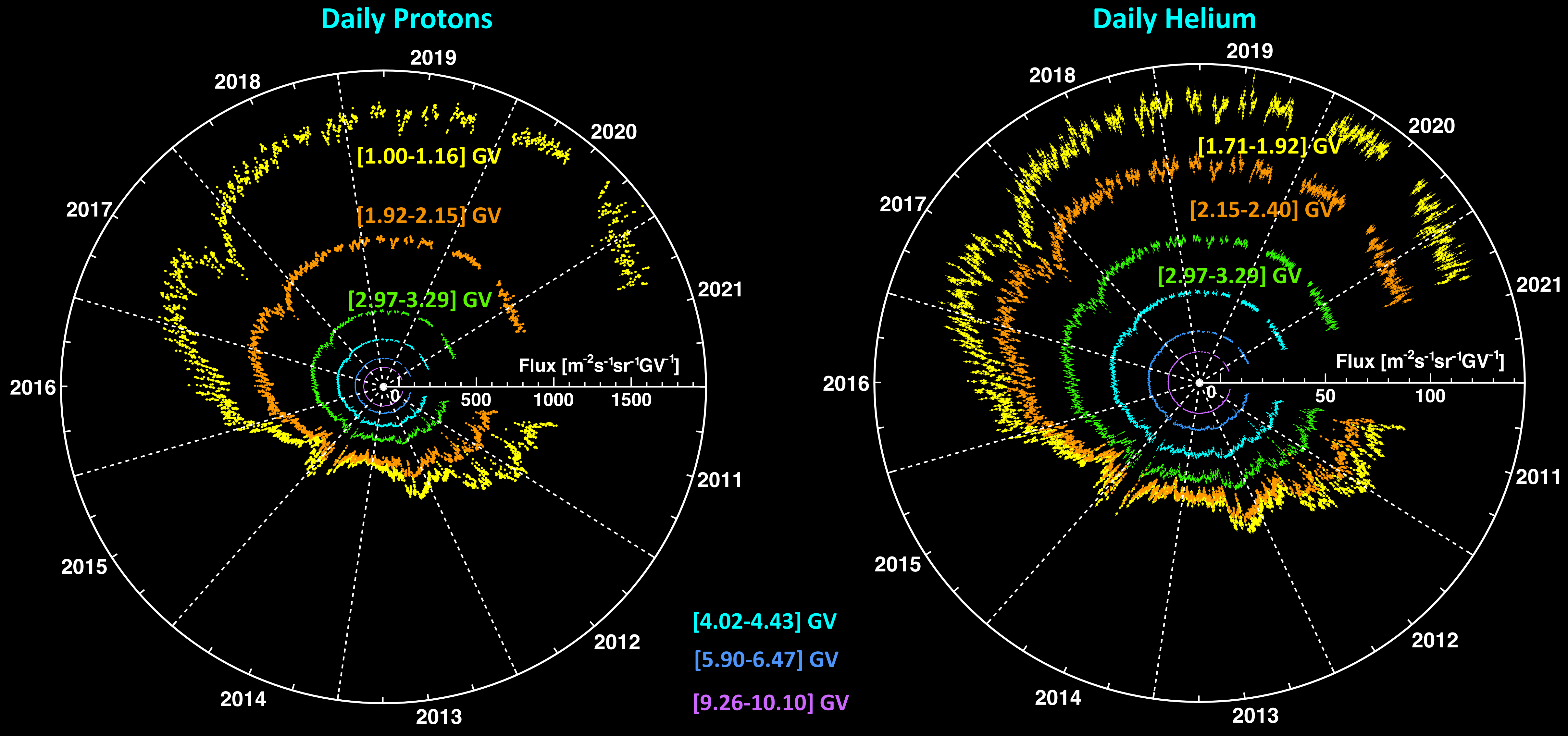
The lethal dose is about 300 rem

long-term base on the Moon or Mars

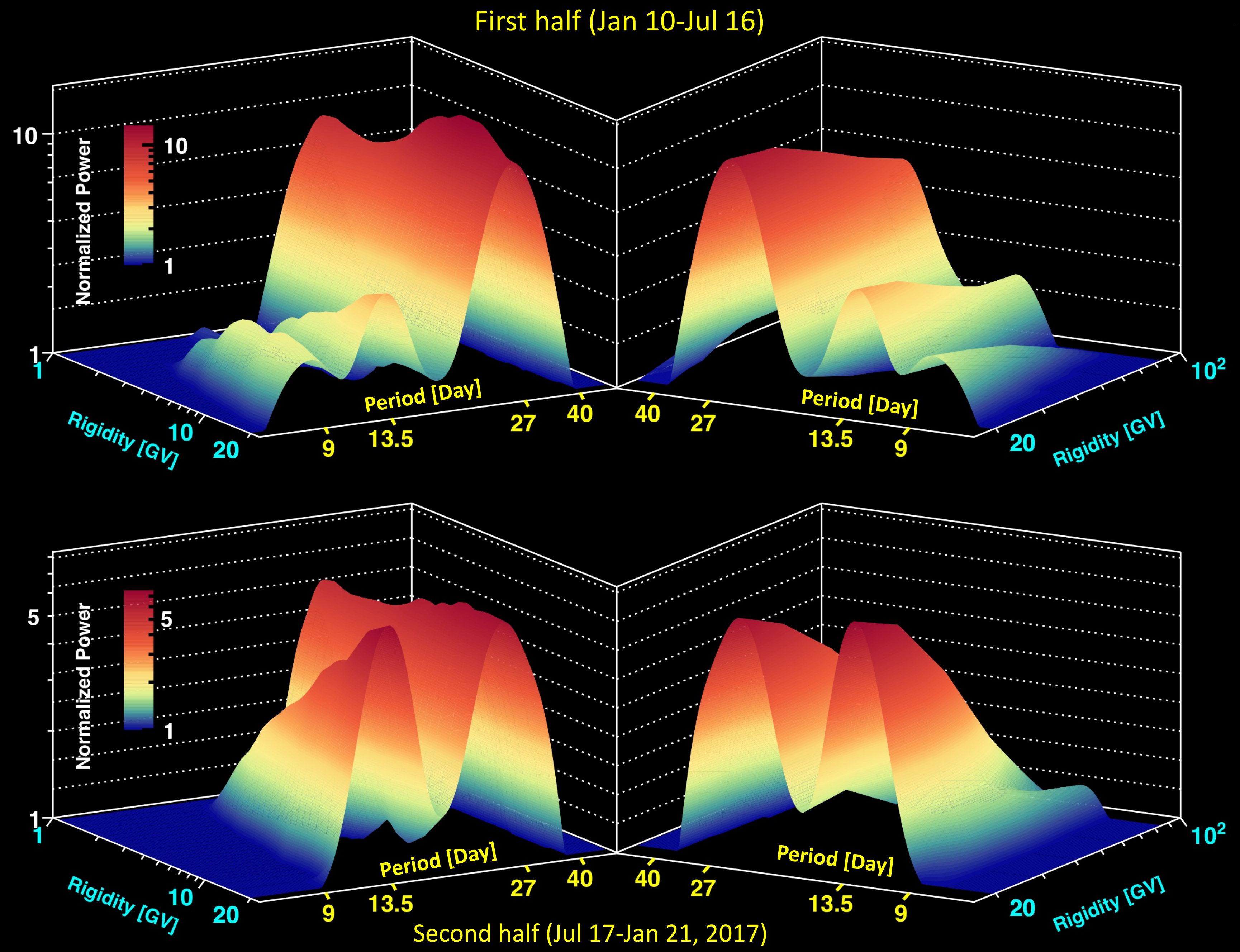
40

AMS Daily Proton and Helium Fluxes

6 billion protons and 850 million helium nuclei collected from **May 20, 2011** to **May 2, 2021**



Periodicities of Daily Proton Fluxes in 2016

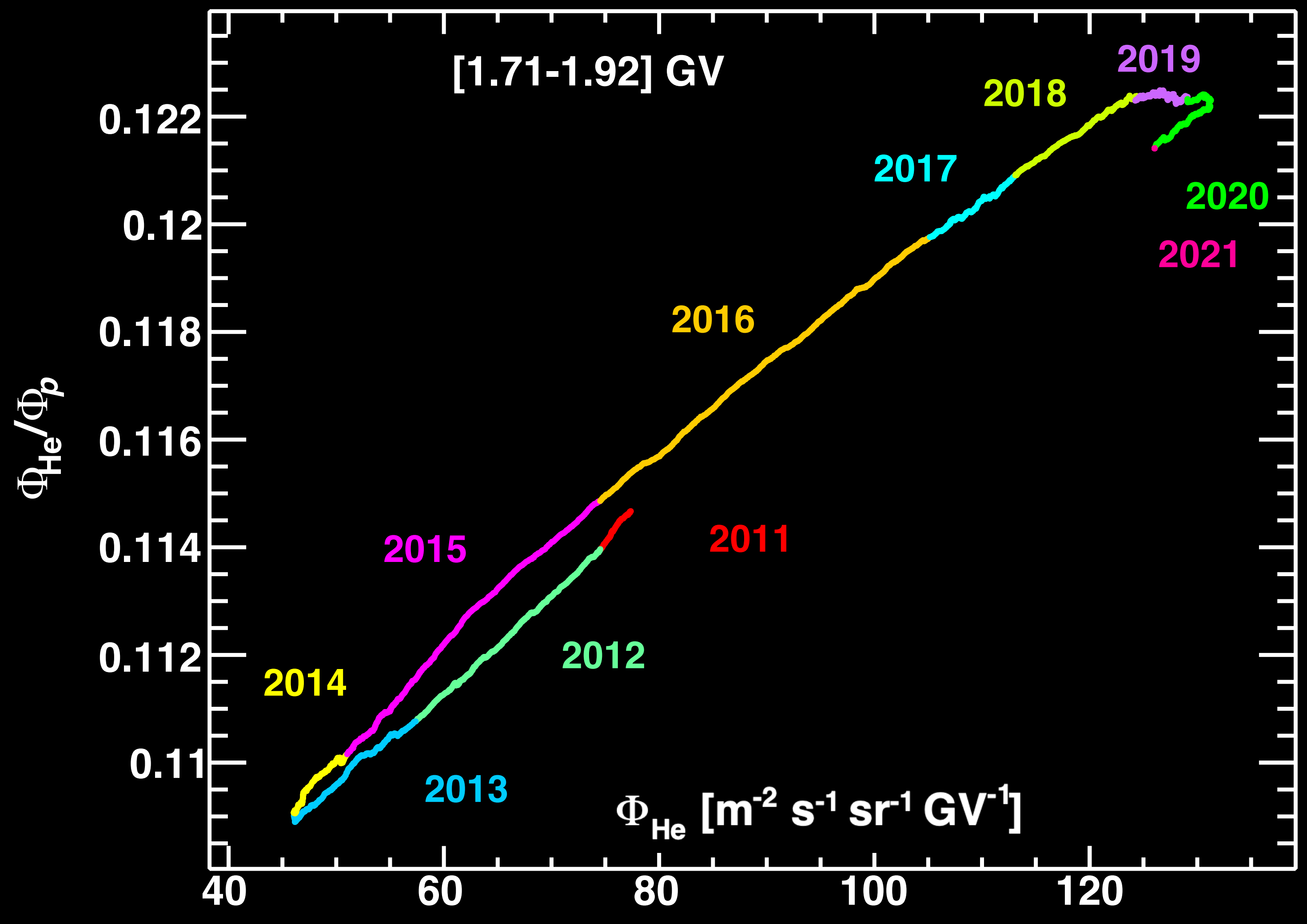


Unexpectedly, the strength of **9-day and 13.5-day periodicities** increases with increasing rigidity up to **~10 GV** and **~20 GV,** respectively. Then the strength decreases with increasing rigidity up to **100 GV.**

Thus, the AMS results do not support the general conclusion that the strength of the periodicities always decreases with increasing rigidity

Phys. Rev. Lett. 127, 271102 (2021)

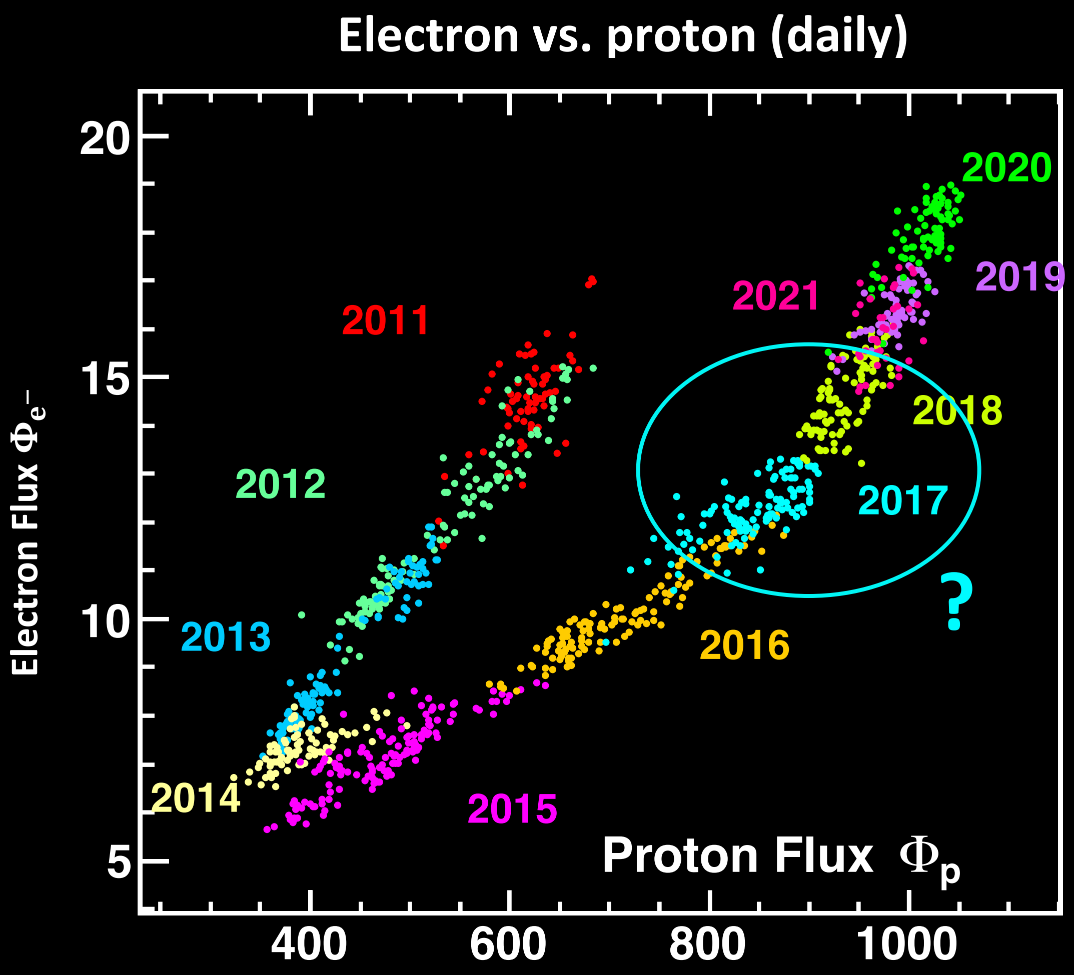
A hysteresis between Φ_{He}/ Φ_p and Φ_{He}



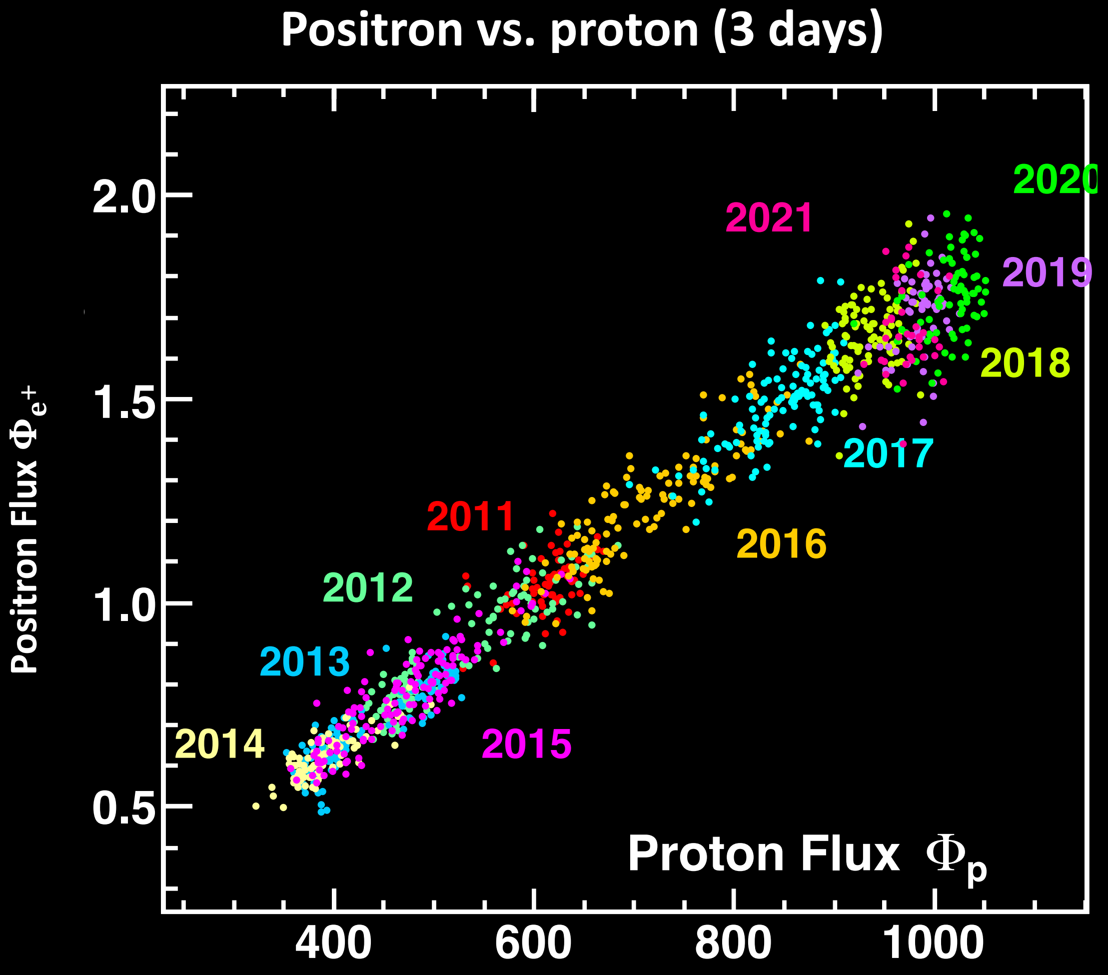
Moving averages of length 14BRs with a step of one day

At low rigidity the modulation of the helium to proton flux ratio is different before and after the solar maximum in 2014

Electron-proton and Positron-proton
1.00 – 2.97 GV

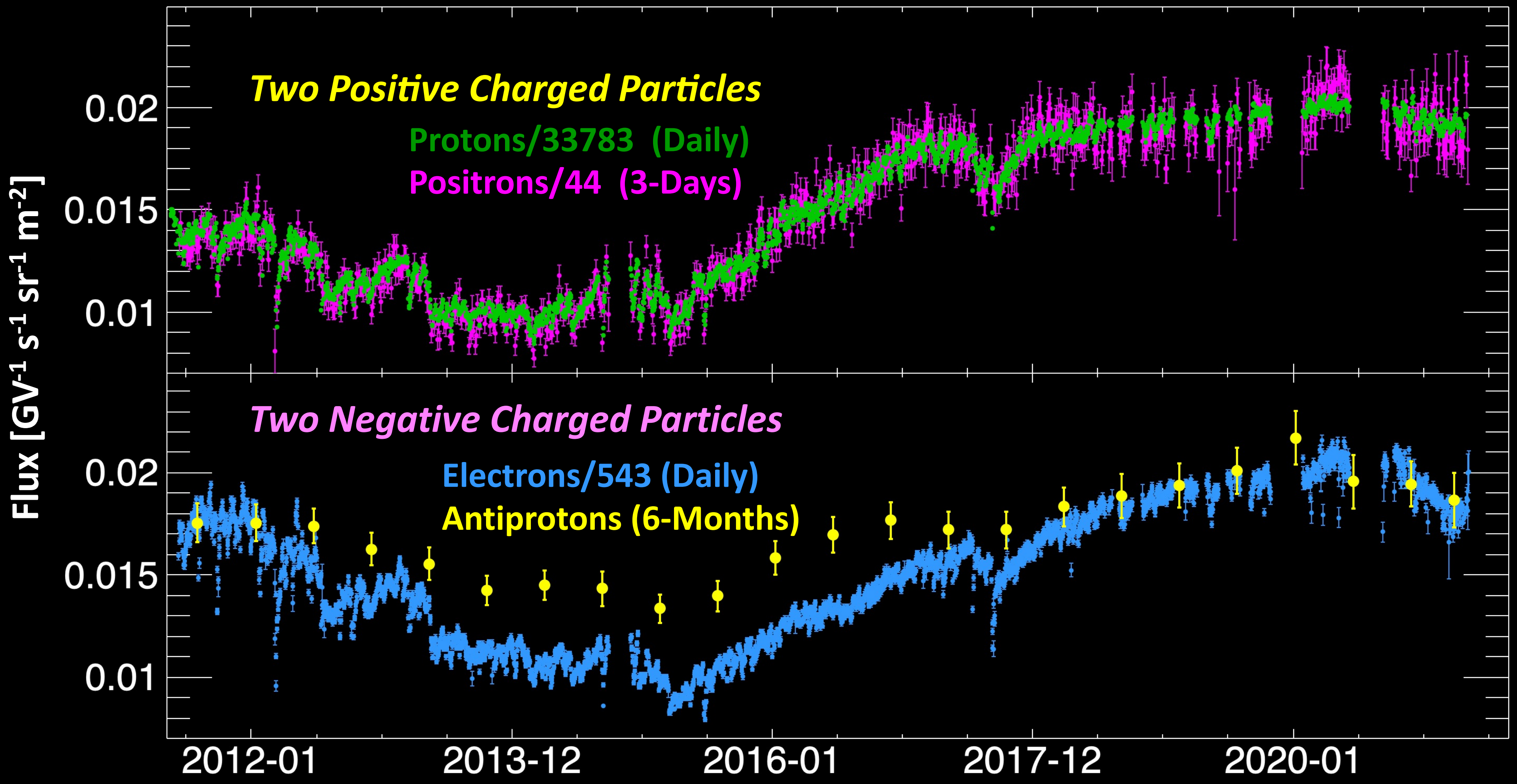


The relation between electrons and protons is a surprise .



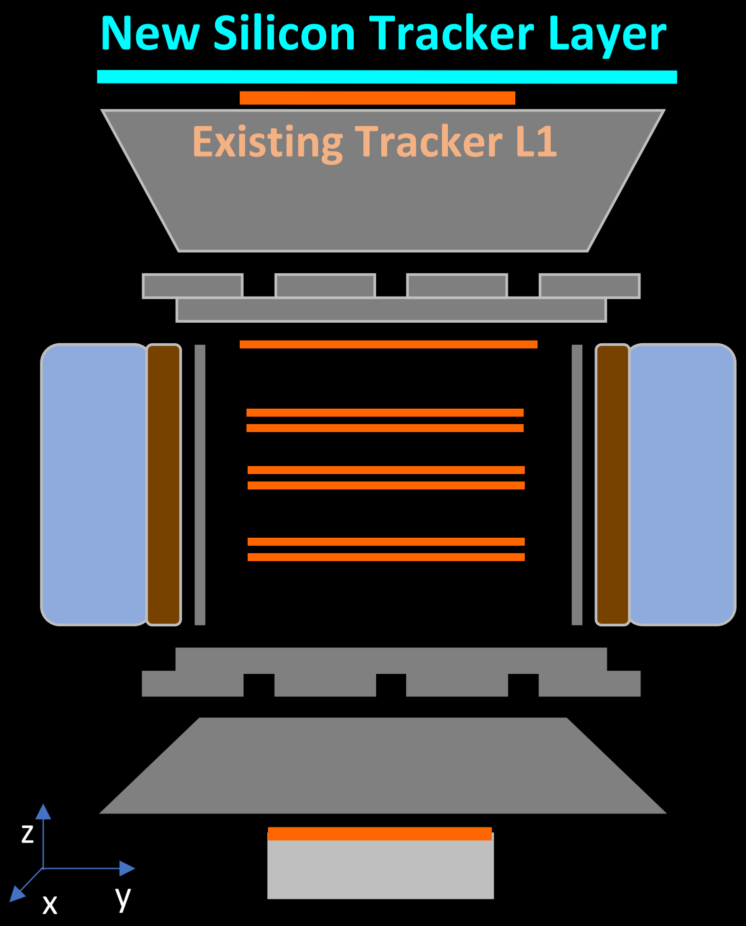
Positrons and protons have a linear relation.

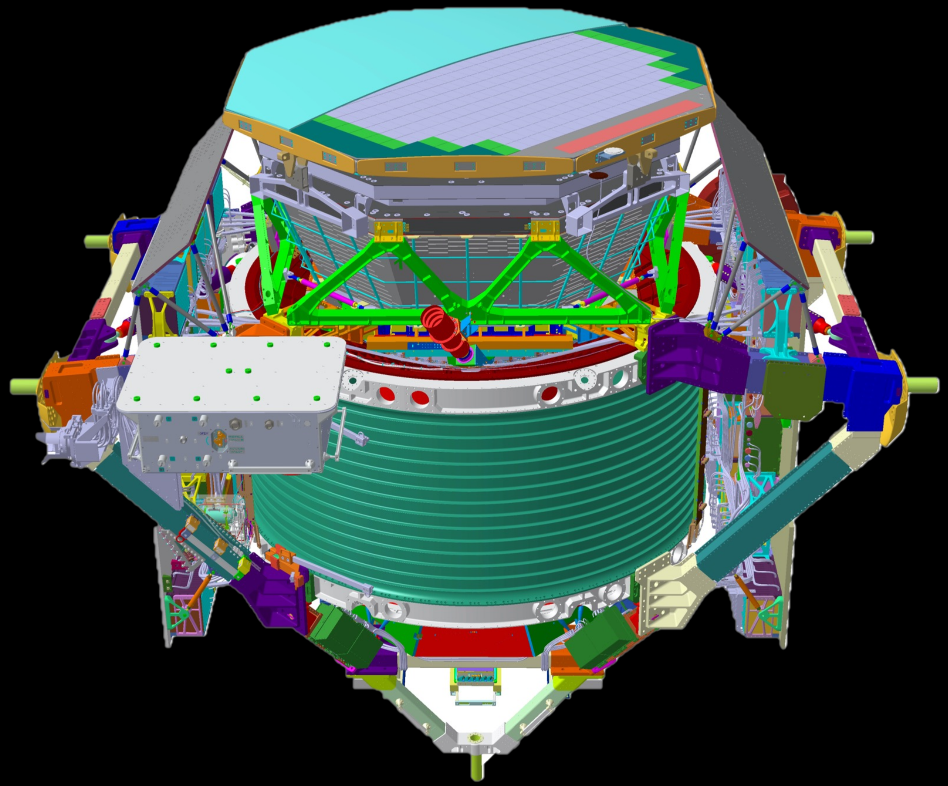
Elementary Particles in the Heliosphere
(Protons, positrons, electrons, and antiprotons)



|Rigidity| = 1.92-2.97 GV

AMS for the next ten years:
Upgrade with new Silicon Tracker Layer
Acceptance increased to 300%





Conclusion

AMS is the only magnetic spectrometer in space.

The latest ten-year AMS results on charged cosmic rays were presented. These new measurements are challenging our understanding of cosmic ray physics.

AMS will continue taking data for the lifetime of the International Space Station.