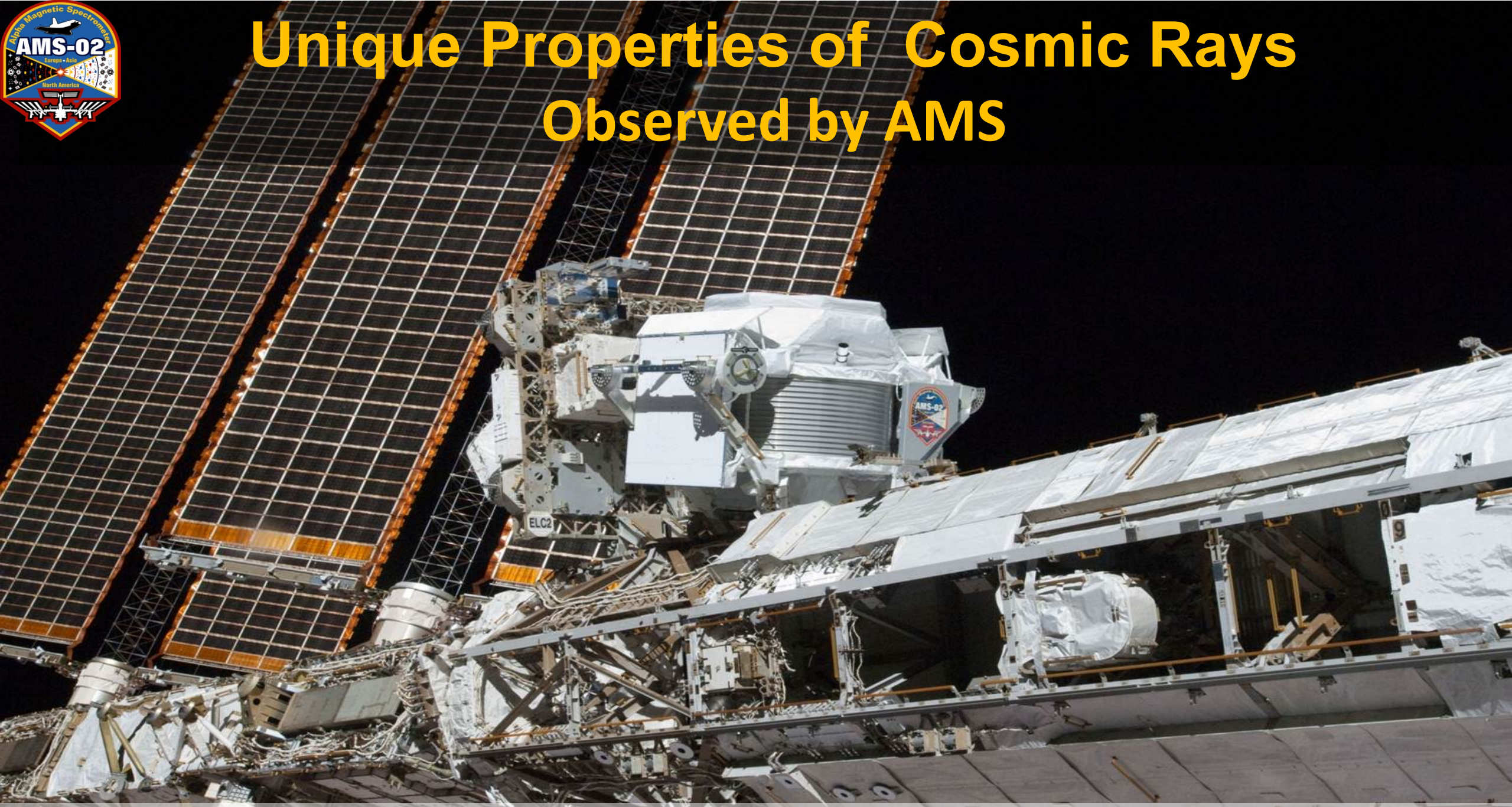
Unique Properties of Cosmic Rays Observed by AMS



July 27th 2022

27th ECRS, Nijmegen

V. CHOUTKO MIT

AMS Launch May 2011
Space Shuttle Endeavour
Mission STS-134

To-date >200 billion cosmic. rays have been measured by AMS: e^+, e^-, p, $\bar{p}$, nuclei, γ,…

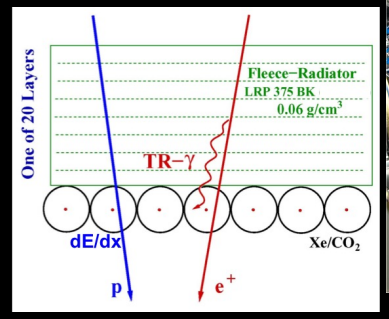
400 billion events expected to 2030

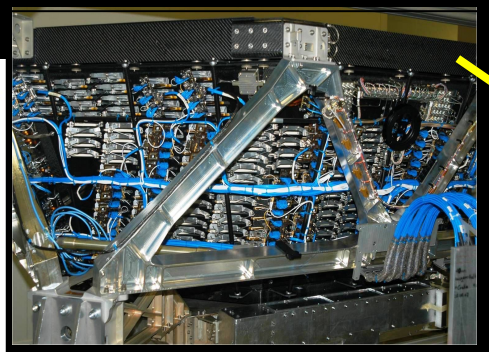
AMS installed on the ISS
Near Earth Orbit:
altitude 400 Km
inclination 52°
period 92 min

AMS-02: A TeV precision magnetic spectrometer in space

Transition Radiation Detector

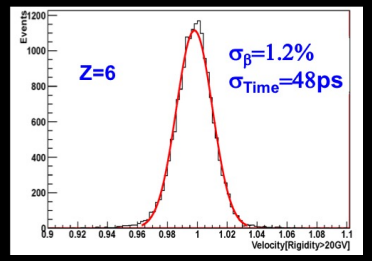
Identifies e^+, e^-

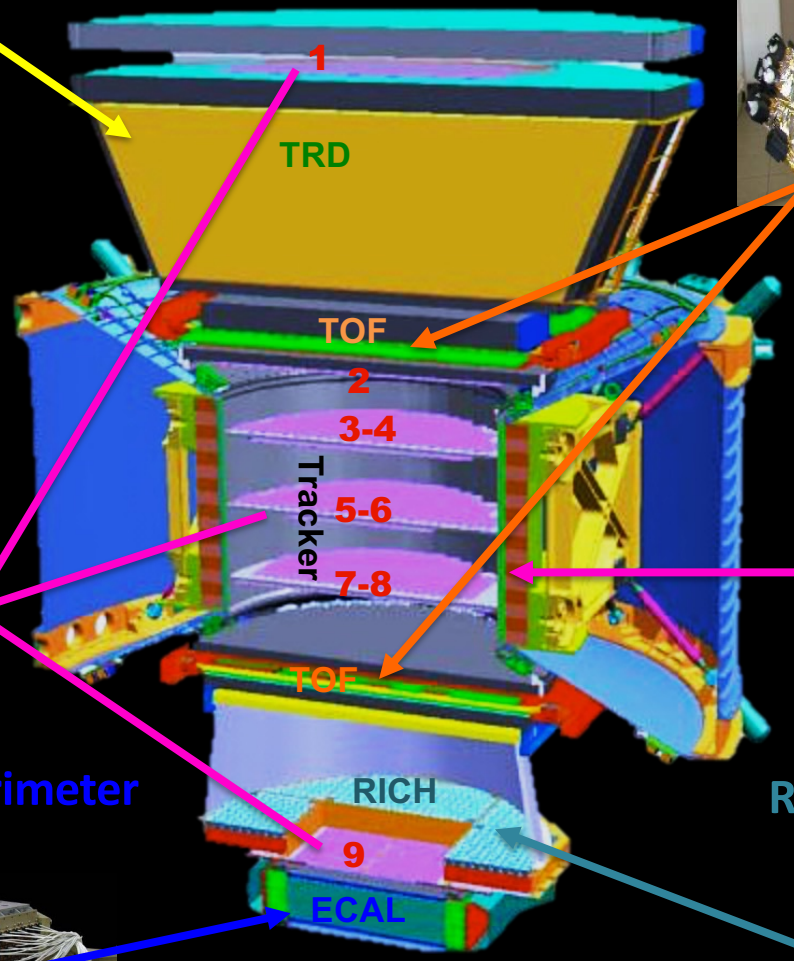




Time Of Flight

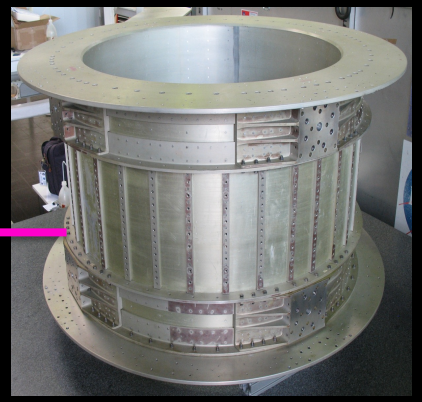
Z, β

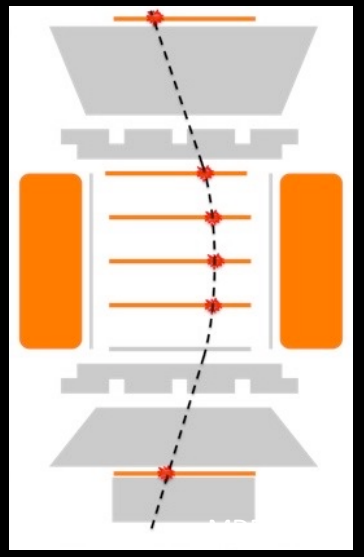




Magnet

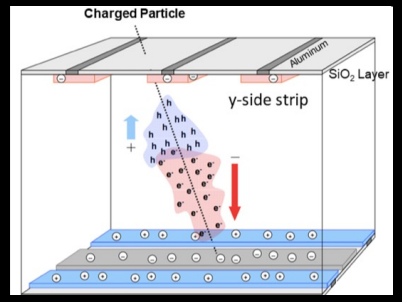
±Z

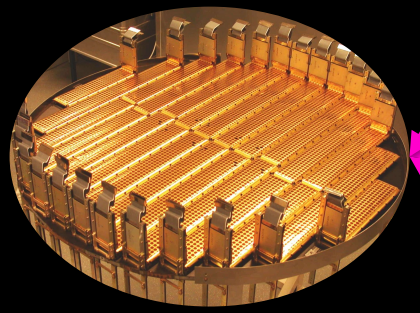




Silicon Tracker

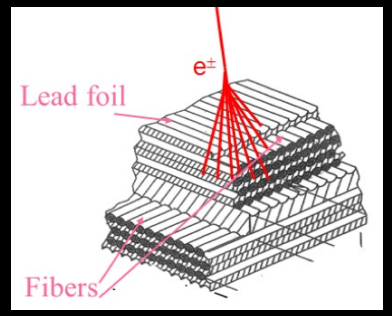
Z, Rigidity=p/Ze





Electromagnetic Calorimeter

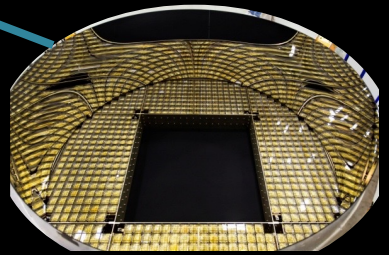
Energy of e^+, e^-

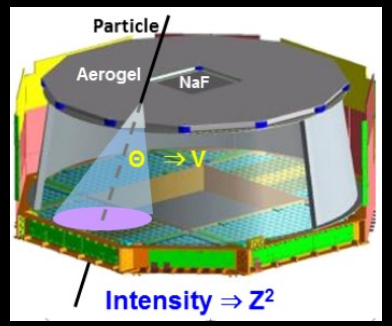


Ring Imaging Cherenkov

Z, β

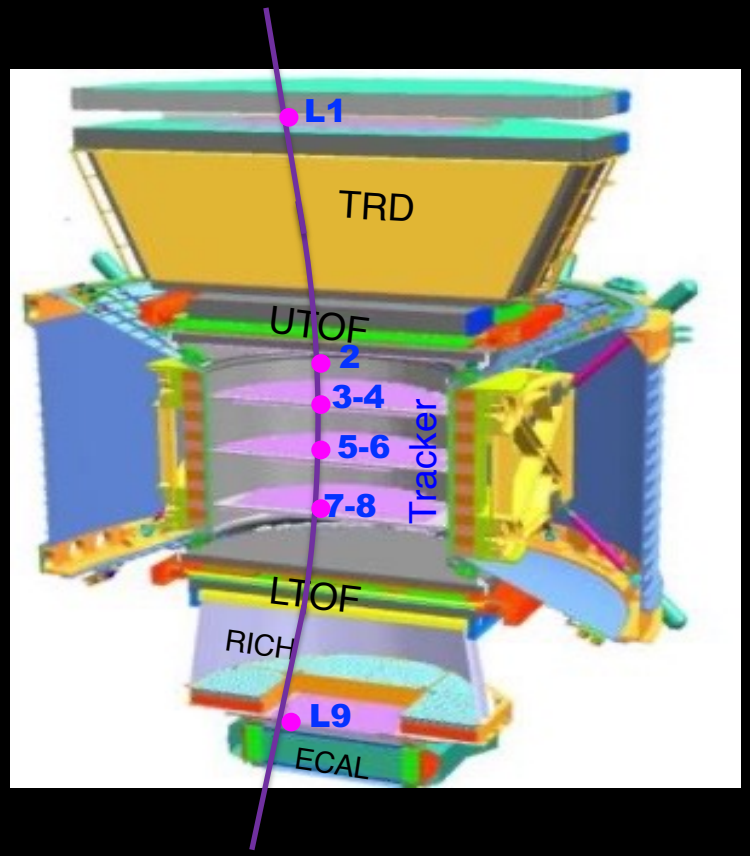
Isotopic composition





AMS Nuclei Flux Measurements

Tracker (9 Layers) + Magnet: Rigidity (Momentum/Charge)
with multi-TV maximal detectable rigidity (MDR)



	Coordinate Resolution	MDR
Z=1	10 μm	2 TV
Z≥2	5-8 μm	3.0-3.7 TV

ToF (4 Layers): Velocity and Direction

$\Delta\beta/\beta^2 \approx$ 1-2% (Z≥2), 4% (Z=1)

L1, UTOF, Inner Tracker (L2-L8), LTOF and L9

Consistent Charge Along Particle Trajectory

Inner Tracker Charge Resolution:

ΔZ = 0.05 - 0.35 ($1 \leq Z \leq 28$)

AMS Nuclei Flux Measurements

Rigidity p,…Fe 1…3500 GV

Selected Events
-- Background
-- Corrected for Bin to Bin Migration

$$\Phi_i = \frac{N_i}{T_i\, A_i\, \varepsilon_i\, \Delta R_i}$$

Time 220,000,000 sec R> 30 GV

Bin width

Effective Acceptance

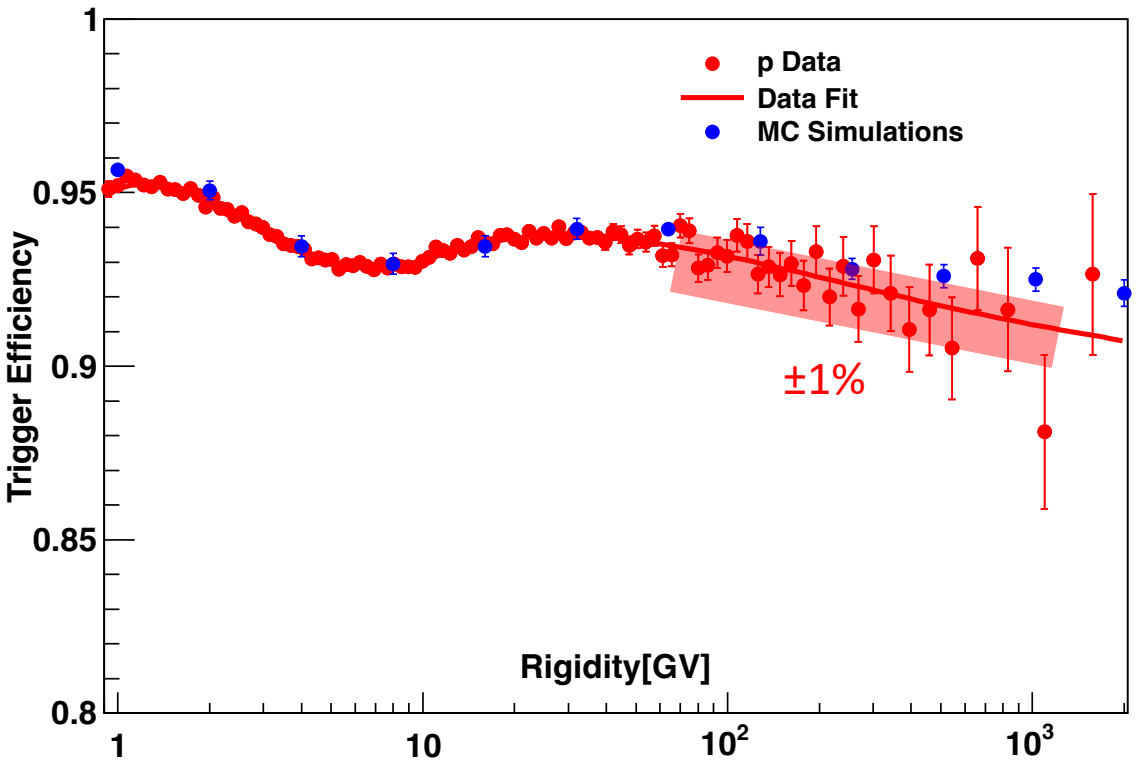
Trigger Efficiency

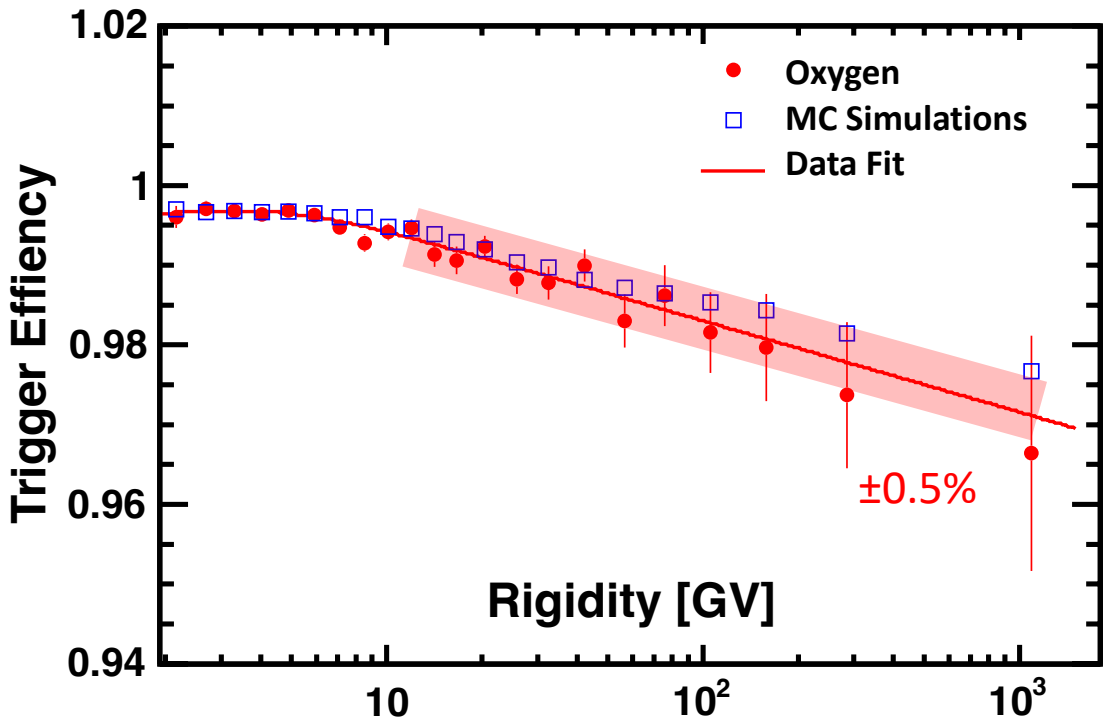
Measurements require knowledge of detector performance details, resolution functions, acceptance … obtained by AMS Monte Carlo Simulations

Fluxes statistical errors are often small so the final accuracy is defined mostly by systematic errors on trigger efficiency, acceptance, and rigidity resolution.

In AMS 2 to 4 independent analysis are done to compute N_i, A_i, ε_i, T_i for each flux

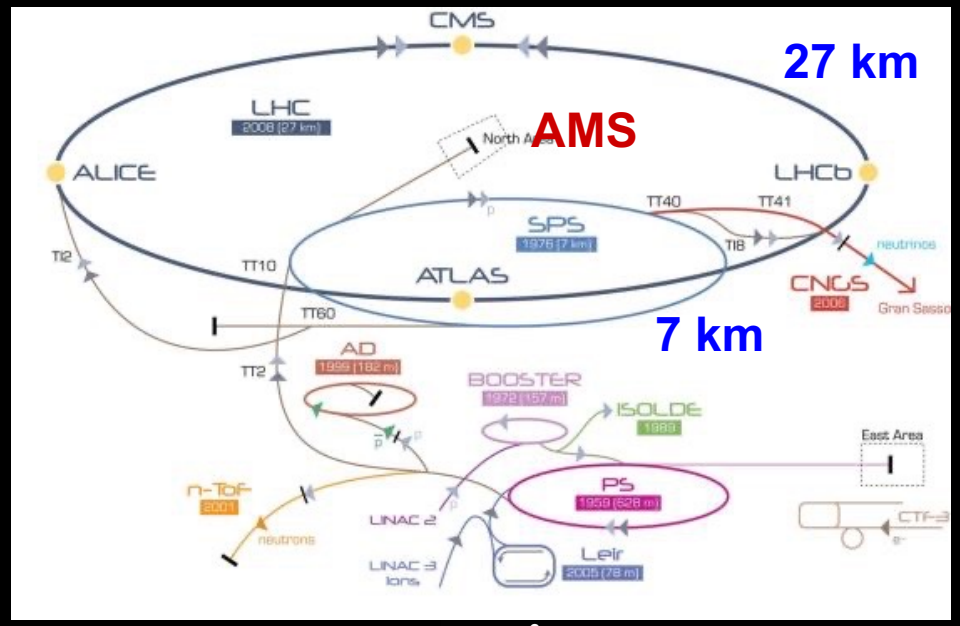
Example of Systematic Errors on Trigger Efficiency

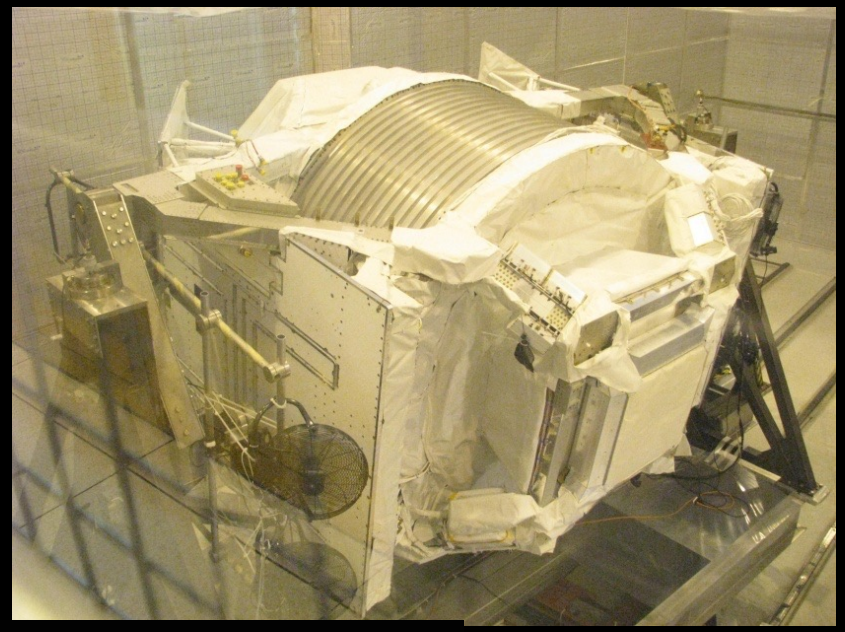


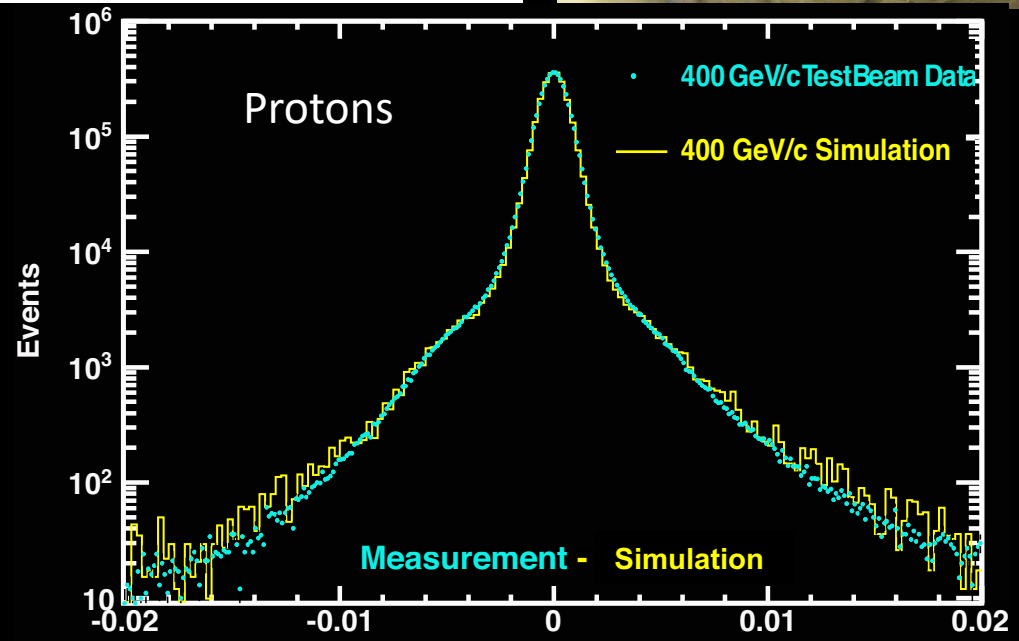


Calibration at CERN

with different particles at different energies



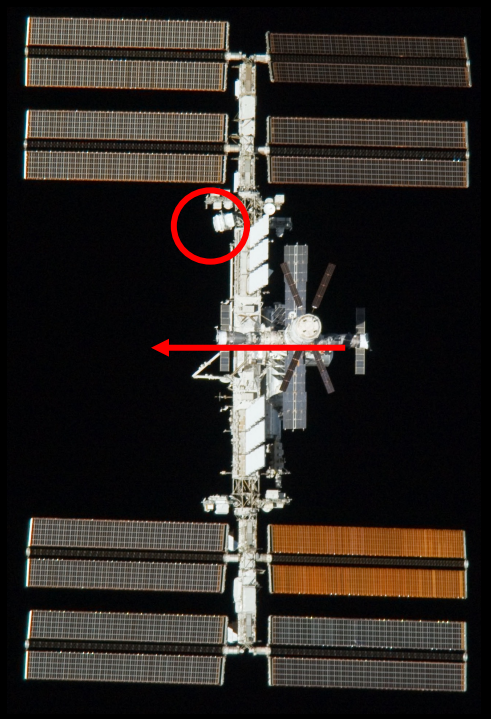


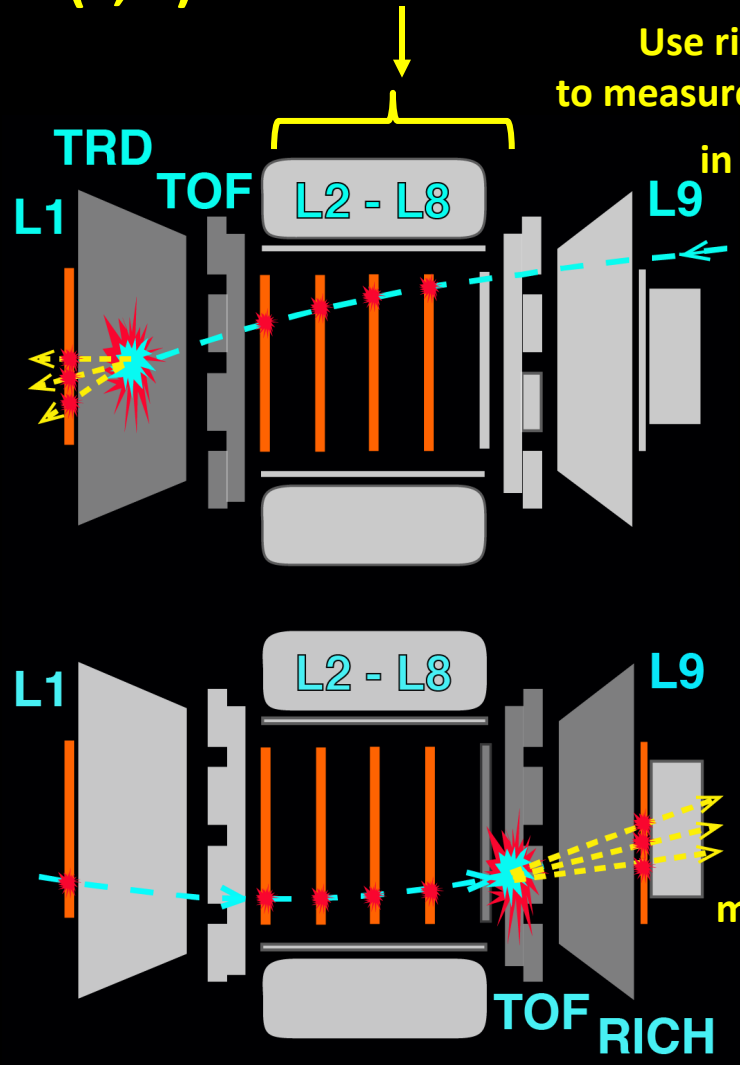


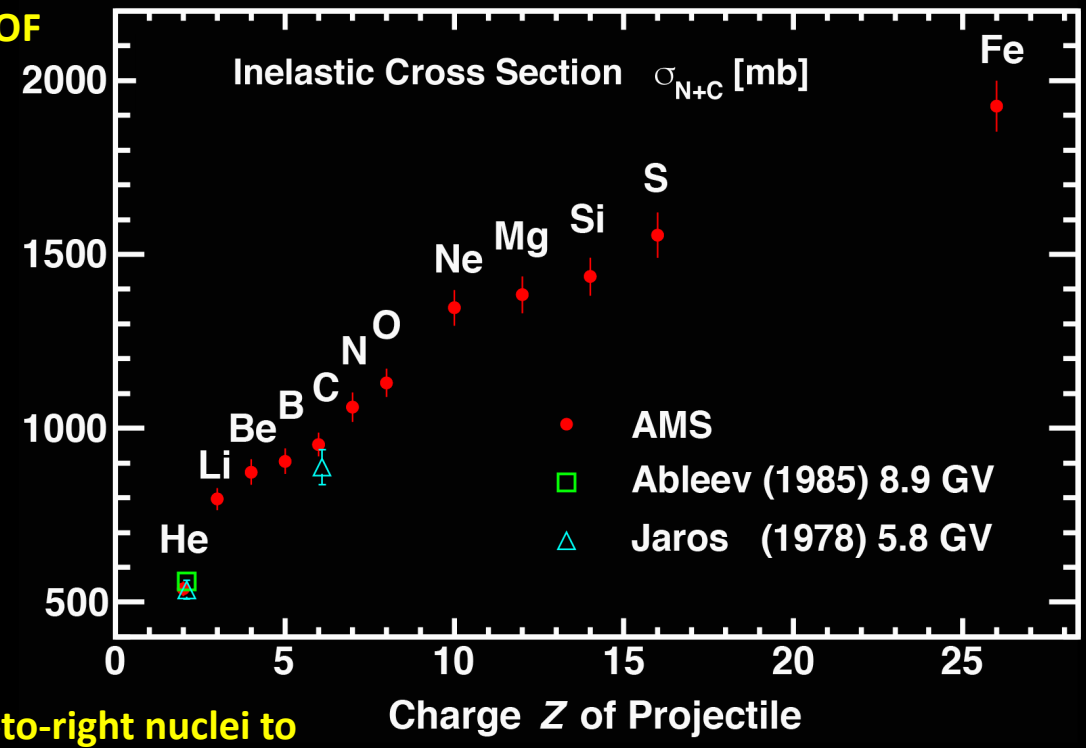
Precision measurement of cosmic-ray spectra requires an determination of nuclear interactions of each element in the detector material

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

ISS horizontal

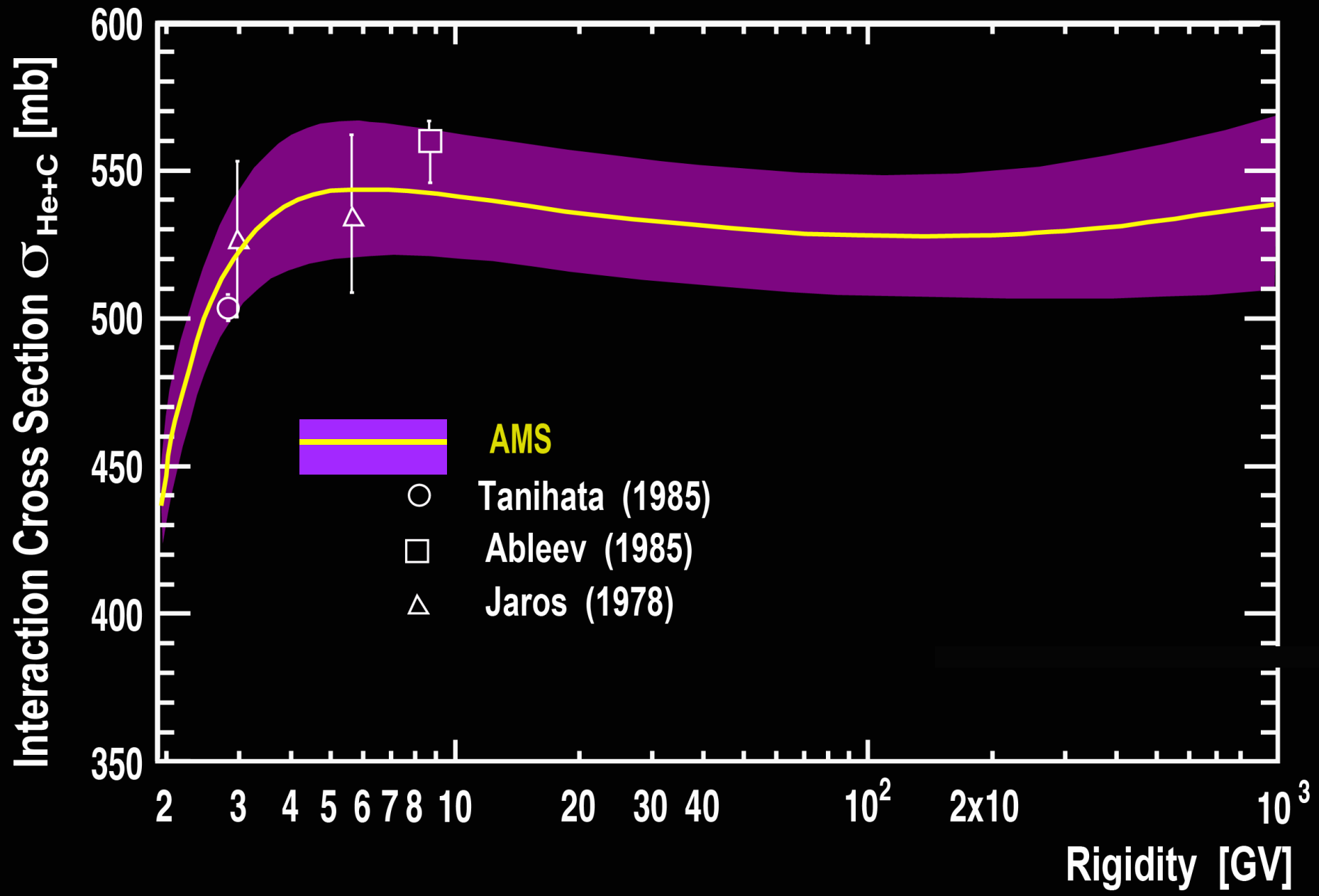




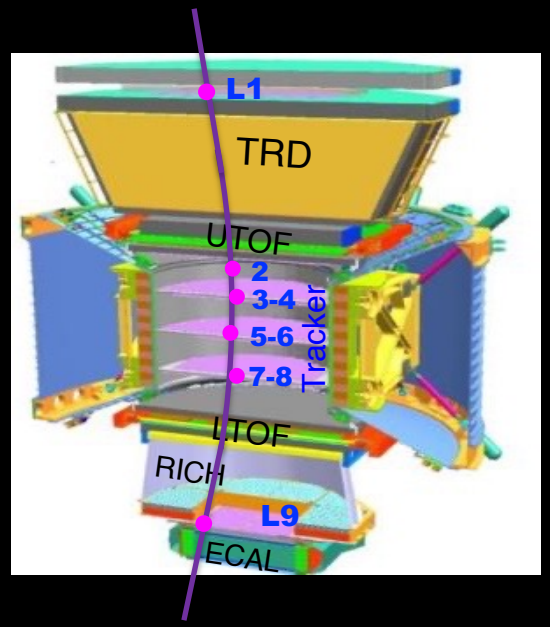


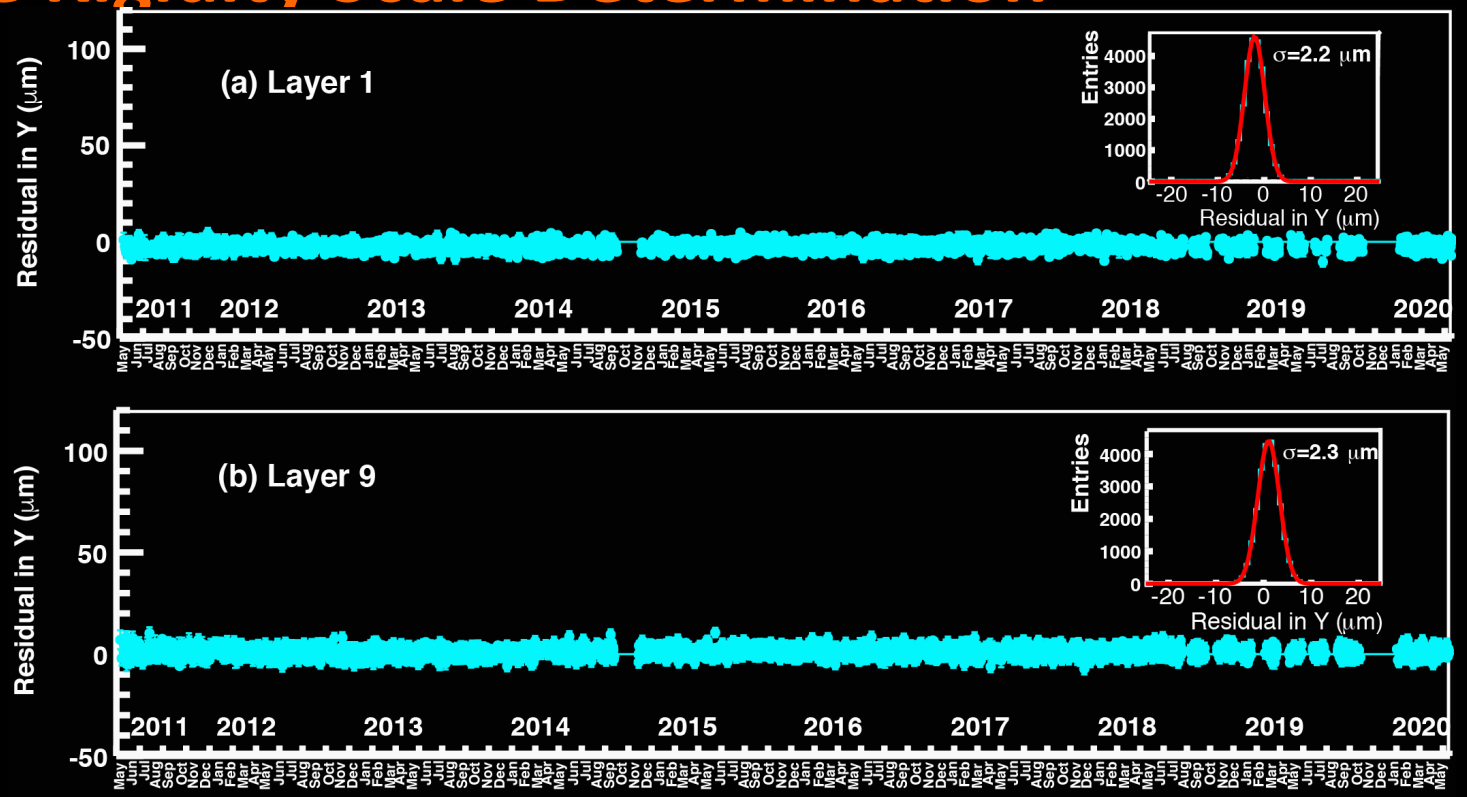
Use left-to-right nuclei to measure the nuclear interactions in the TOF+RICH

He on C Target Cross Section Measurement



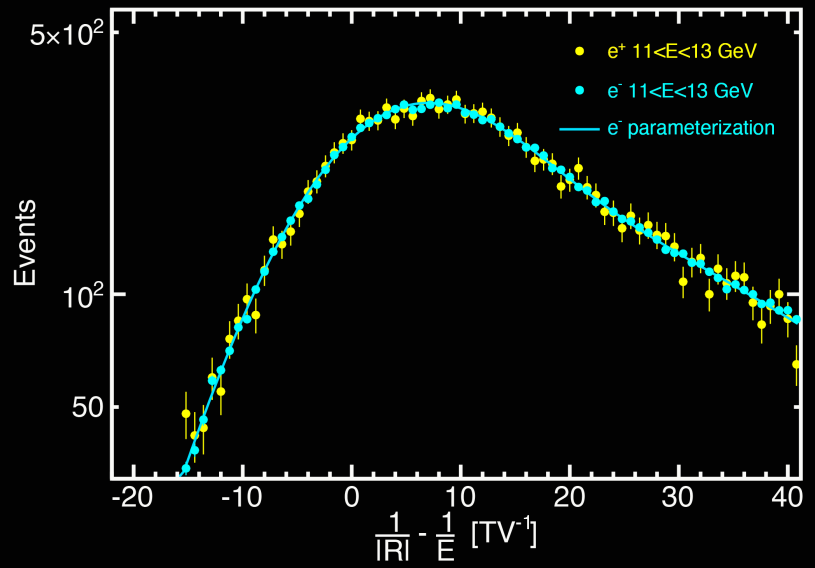
AMS Accurate Rigidity Scale Determination



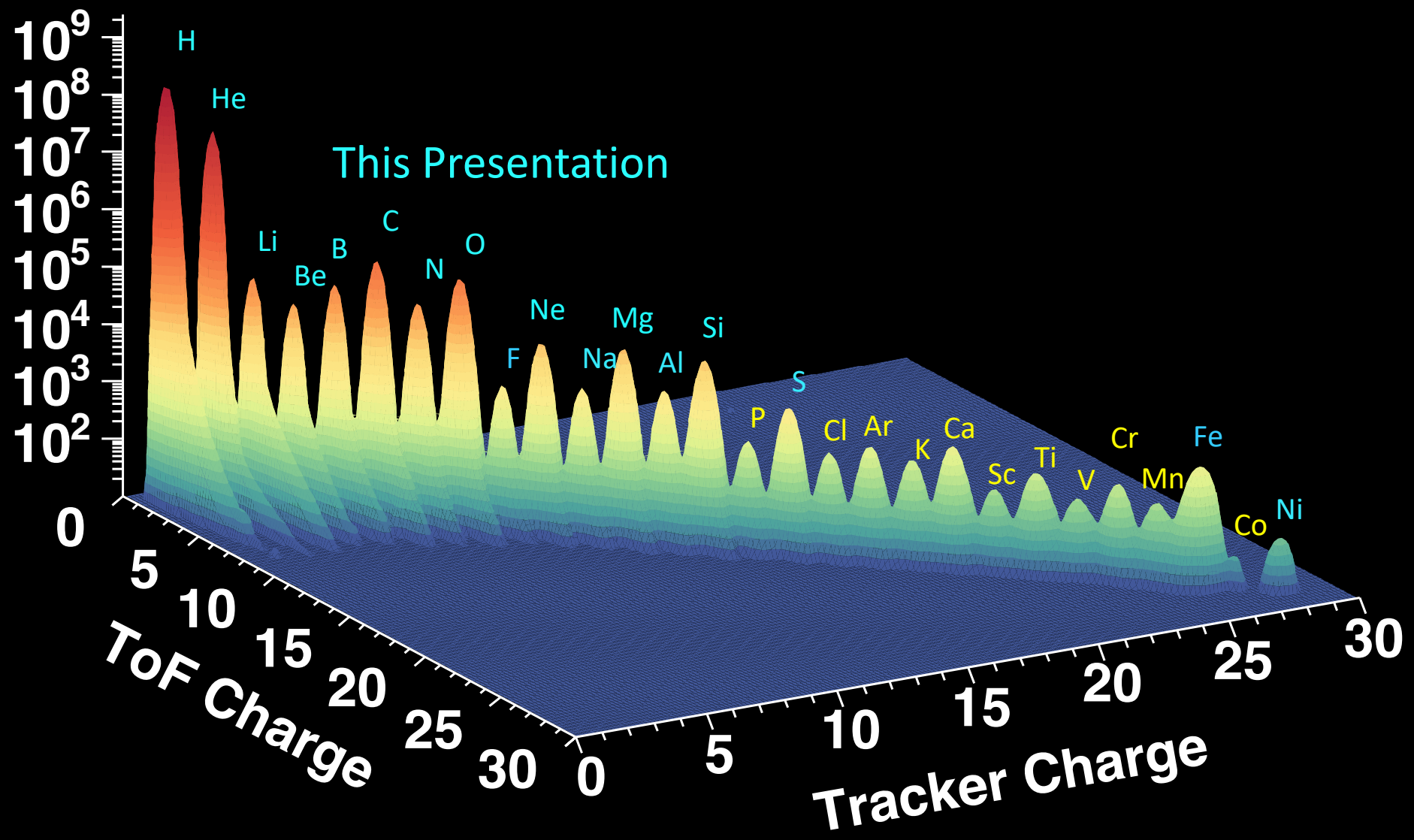


The position of the outer planes L1 and L9 are precisely aligned by using cosmic rays even to a stability of ~2 μm.
The stability of inner tracker layers (L2-L8) is a tenth of micron.

The vibrations and accelerations during the AMS launch into space could change the tracker ladder positions at the submicron level. Such misalignment was corrected in space by analyzing trajectories of opposite charged particles in tracker, namely by comparing of the tracker measured rigidity (R) with electromagnetic calorimeter measured energy (E), for positron and electron events. This allows to measure the coherent displacement of the L2-L8 layers with accuracy better than 0.2 μm, corresponding to the accuracy of the tracker rigidity scale of better than 1/33,000 GV^{-1}.

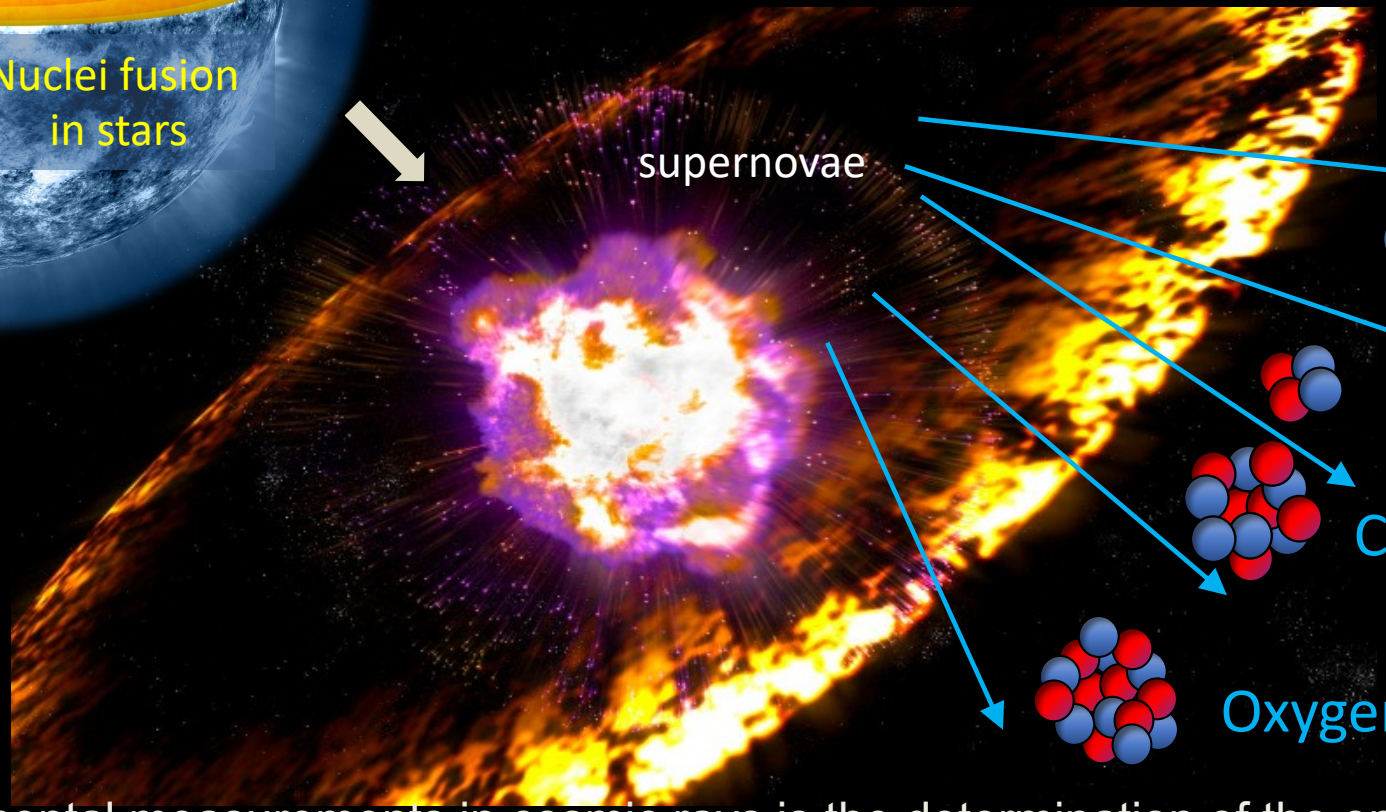


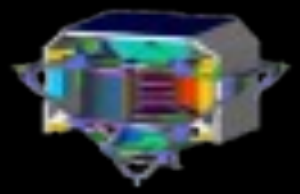
AMS Study of Cosmic Nuclei



First kind of Cosmic Ray Nuclei: Primary Cosmic Rays

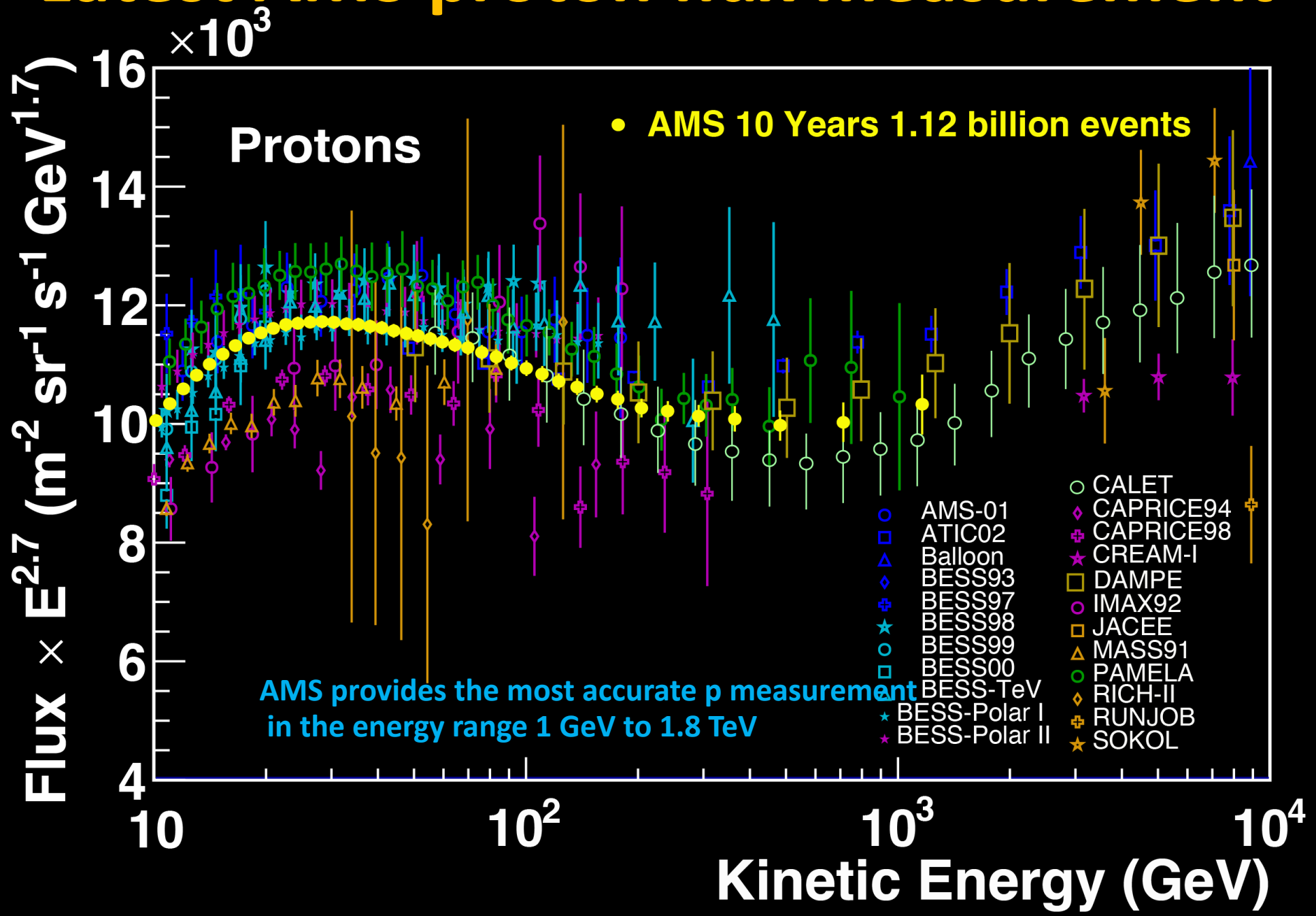
Primary cosmic rays (p, He, C, O, Ne, Mg, Si … Fe … are mostly produced during the lifetime of stars and are accelerated in supernovae shocks, whose explosion rate is about 2-3 per century in our Galaxy.



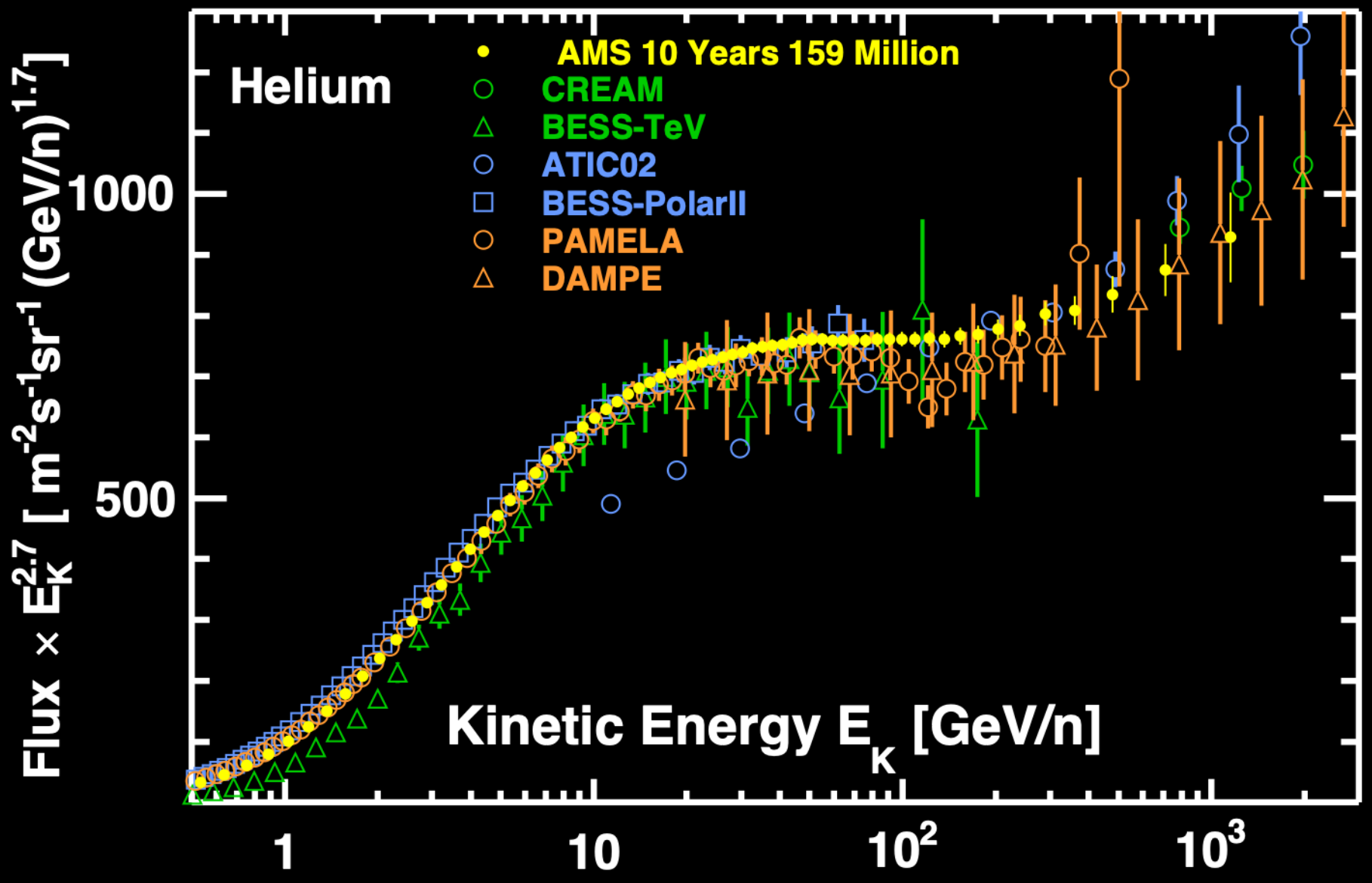


One of the fundamental measurements in cosmic rays is the determination of the energy dependence of spectra of cosmic ray nuclei from protons to Fe and beyond. Their spectra (fluxes) carry the information about cosmic rays production and acceleration in the astrophysical sources and their propagation in the interstellar media.

Latest AMS proton flux measurement

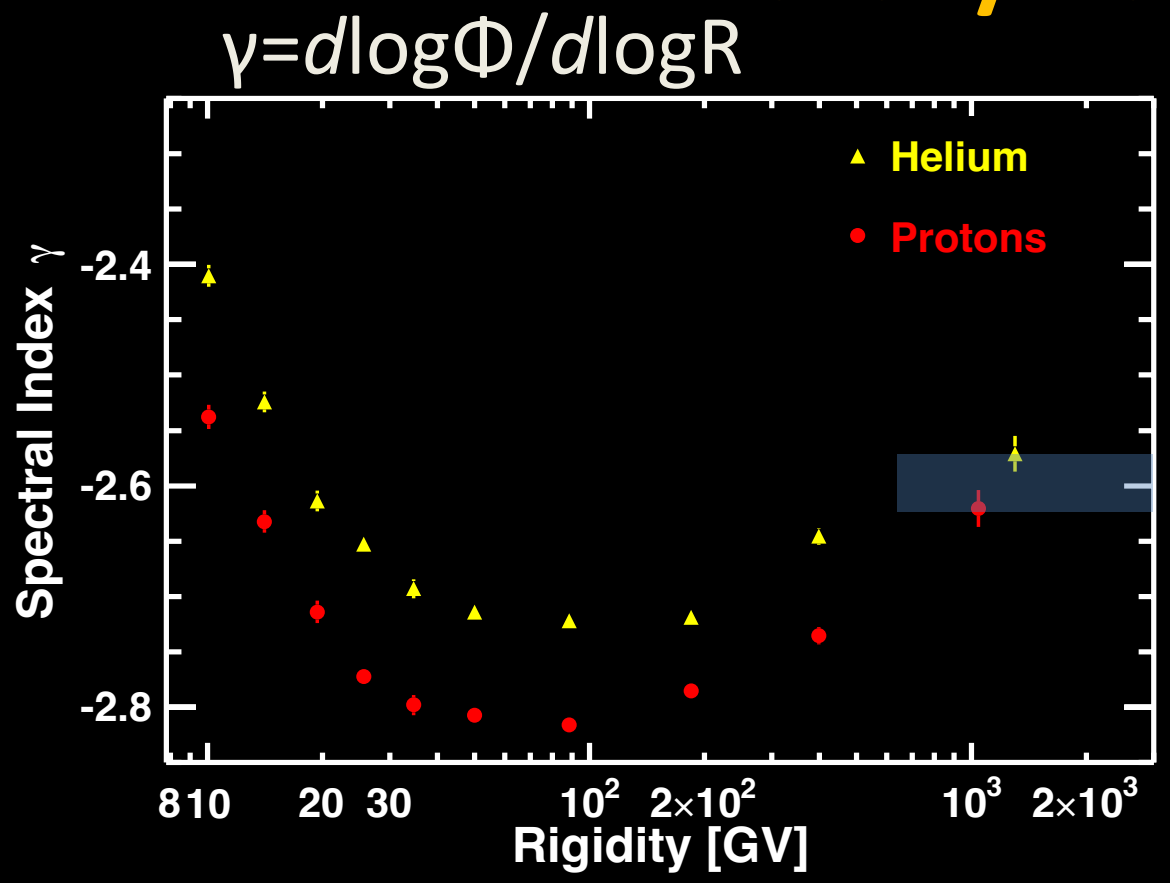


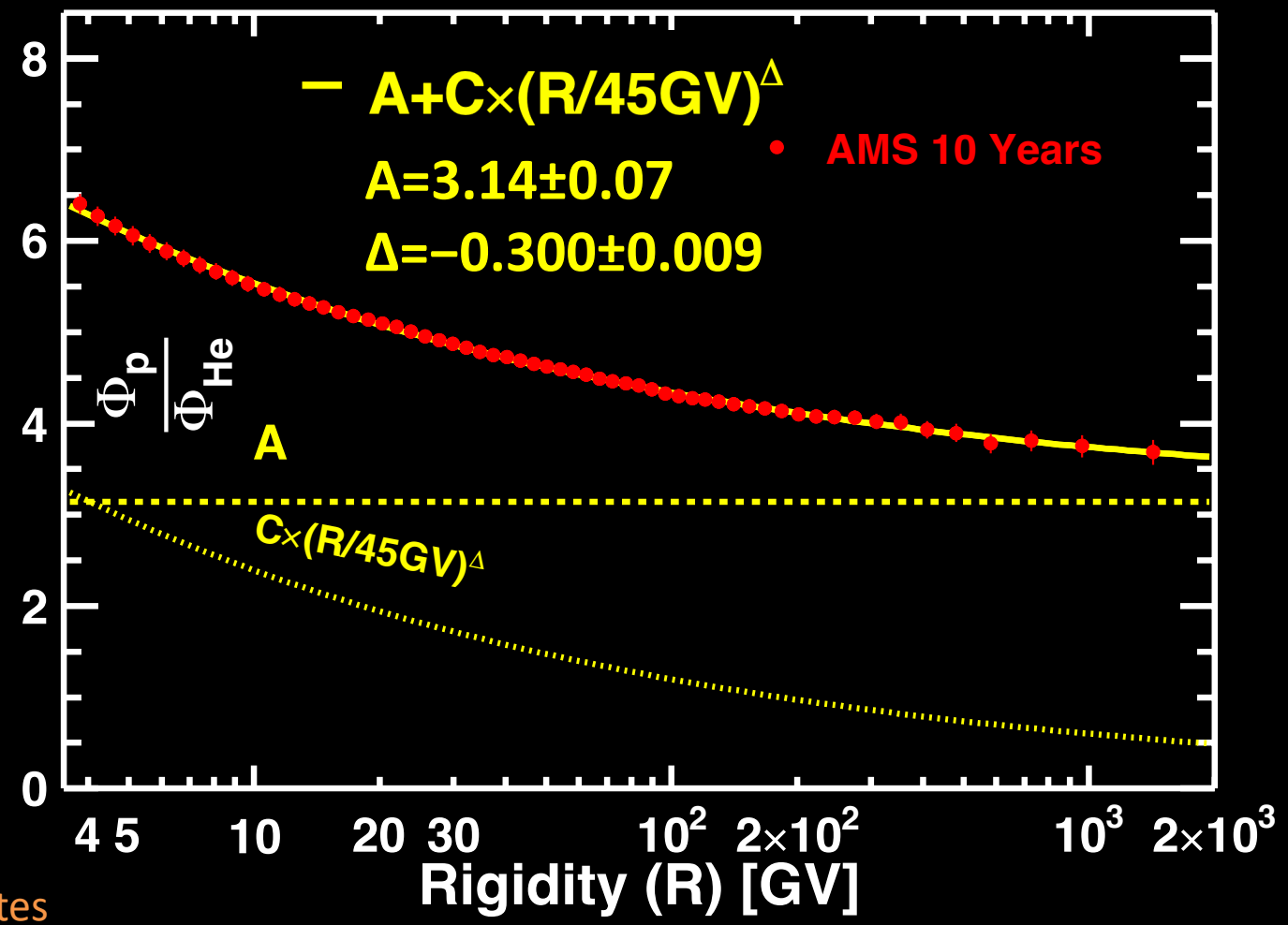
Latest AMS Helium flux measurement



AMS provides the most accurate He measurement in the energy range 1 GeV to 6 TeV

Proton/Helium Flux Ratio

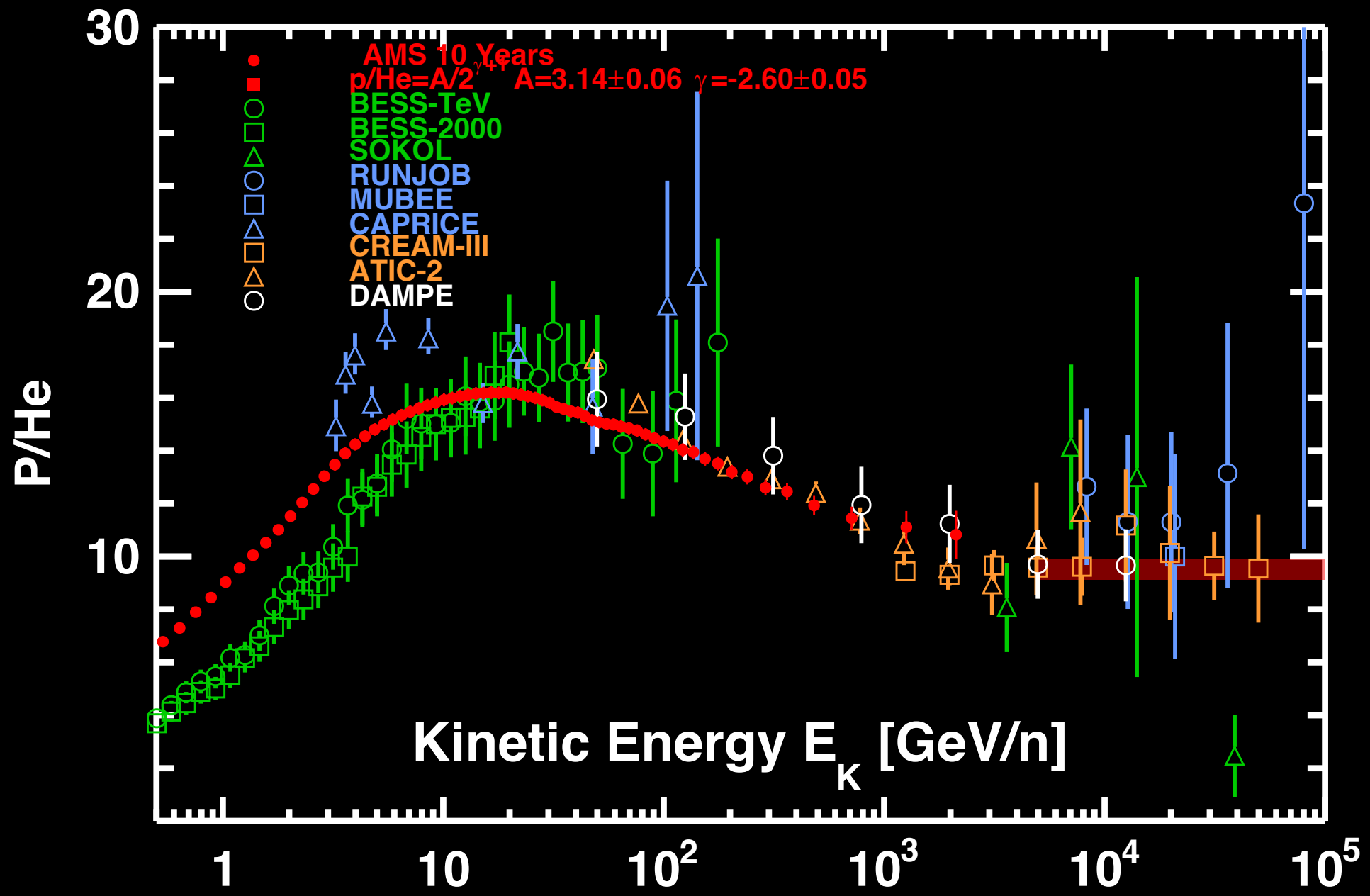




P and He may have same spectral index at highest rigidites

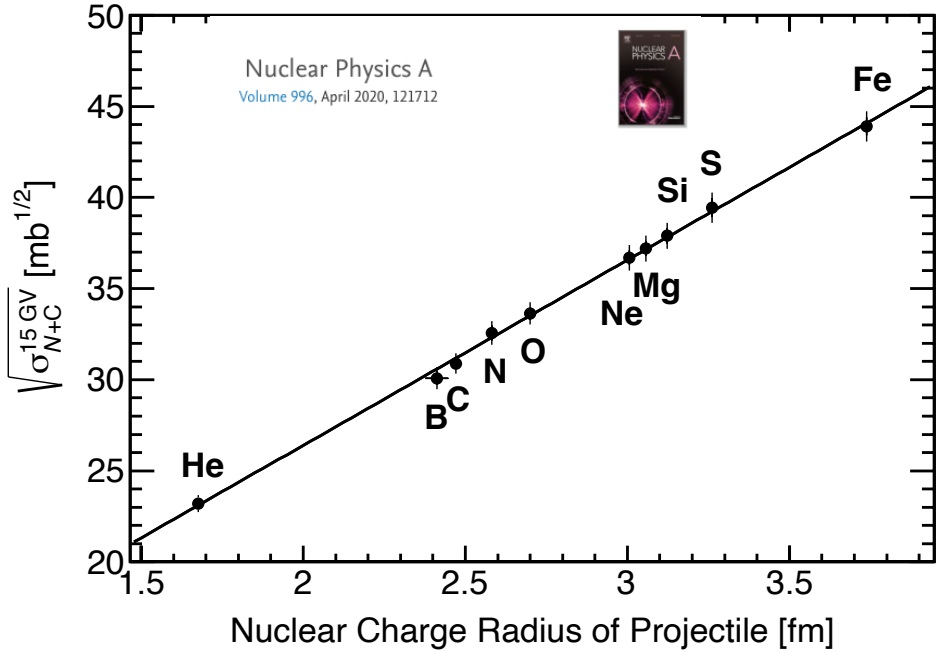
Physics Reports, 894, 1 (2021) :
AMS found that proton flux have two components,
one is like Helium and another is unique to proton flux.

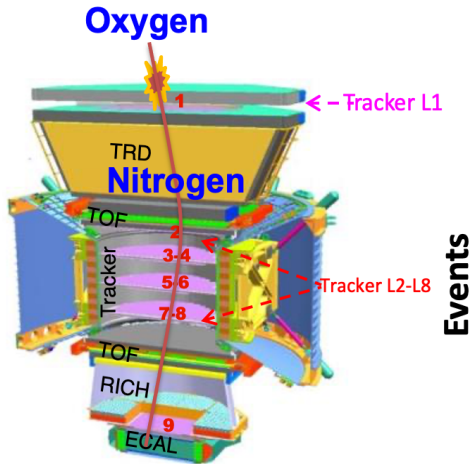
Proton/Helium Flux Ratio



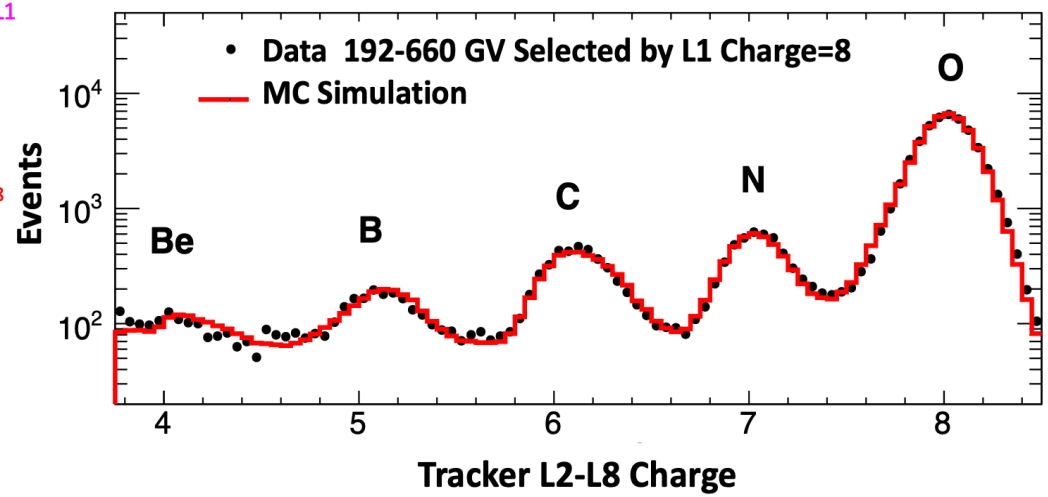
AMS Heavy Nuclei Interactions

- Nuclei Interactions Simulation
  - cross section data set (AMS), elastic and quasy-elastic scattering (AMS) , low energy inelastic interactions, fission, nuclei deexcitation (GEANT4-10)
  - Most up to date model for nuclei interactions at high energies (DPMJET3)
    - designed to simulate all nucleus and hadron ($1 \le A_p \le 208$) inelastic interactions with energy >6GeV/n in all AMS materials.
    - The AMS tuned DPMJET3 well reproduces the partial cross sections and the isotope yields of data: ^{4}He->^{3}He, ^{9}Be->^{7}Be, C->B, O->C, Si->Mg...

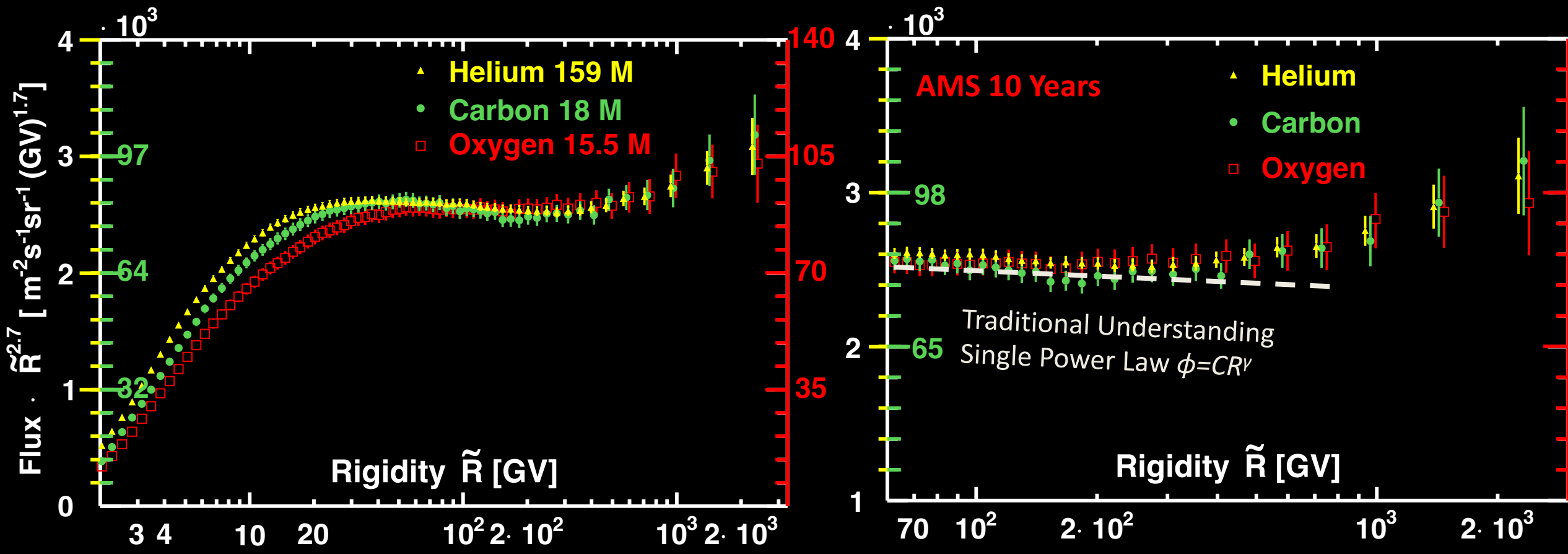




MC simulation interactions O → N, C, B, Be ...



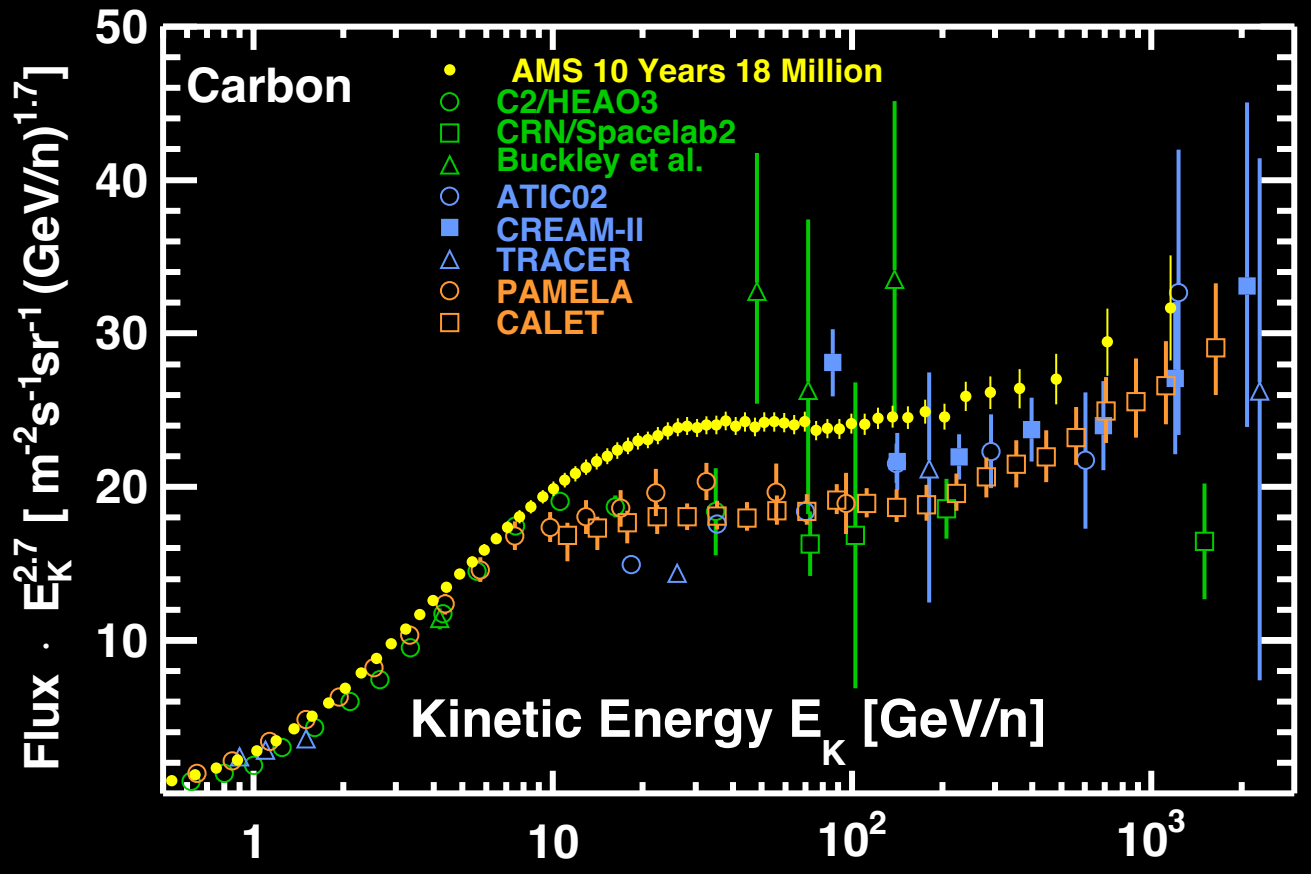
Latest AMS Measurements of He, C and O spectra

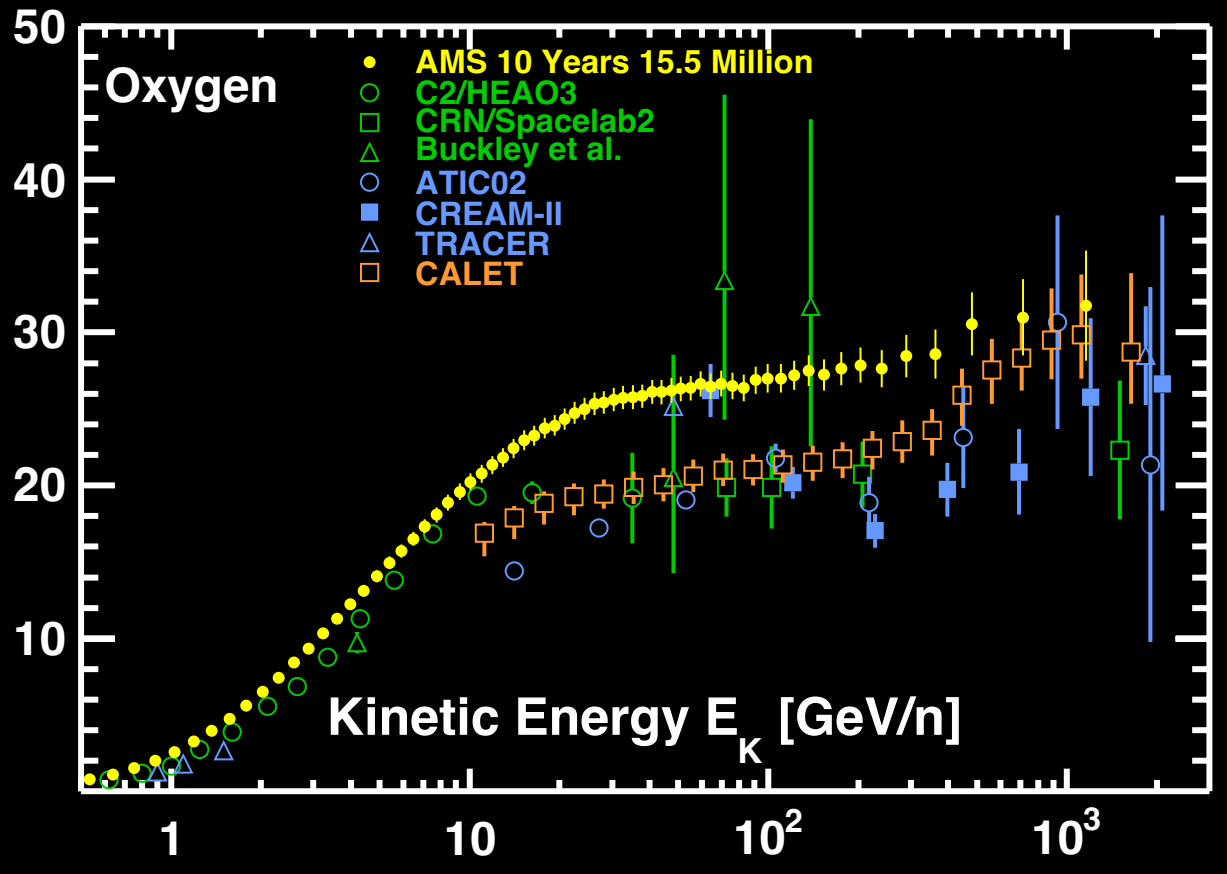


Phys. Rev. Lett. 119, 251101 (2017): AMS found that He, C, O have an identical rigidity dependence above ~60 GV and at higher rigidities they all deviate from a single power in an identical way

AMS C and O Nuclei Flux Measurements:

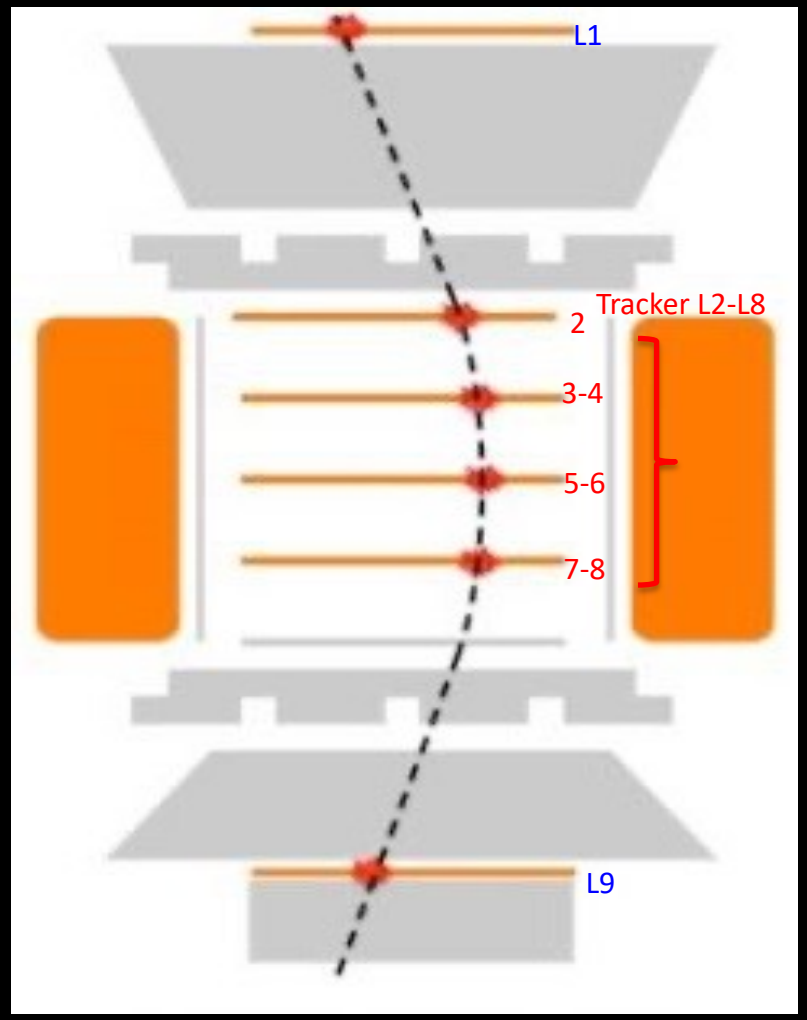
AMS results are different from other measurement both in magnitude and the energy dependence.

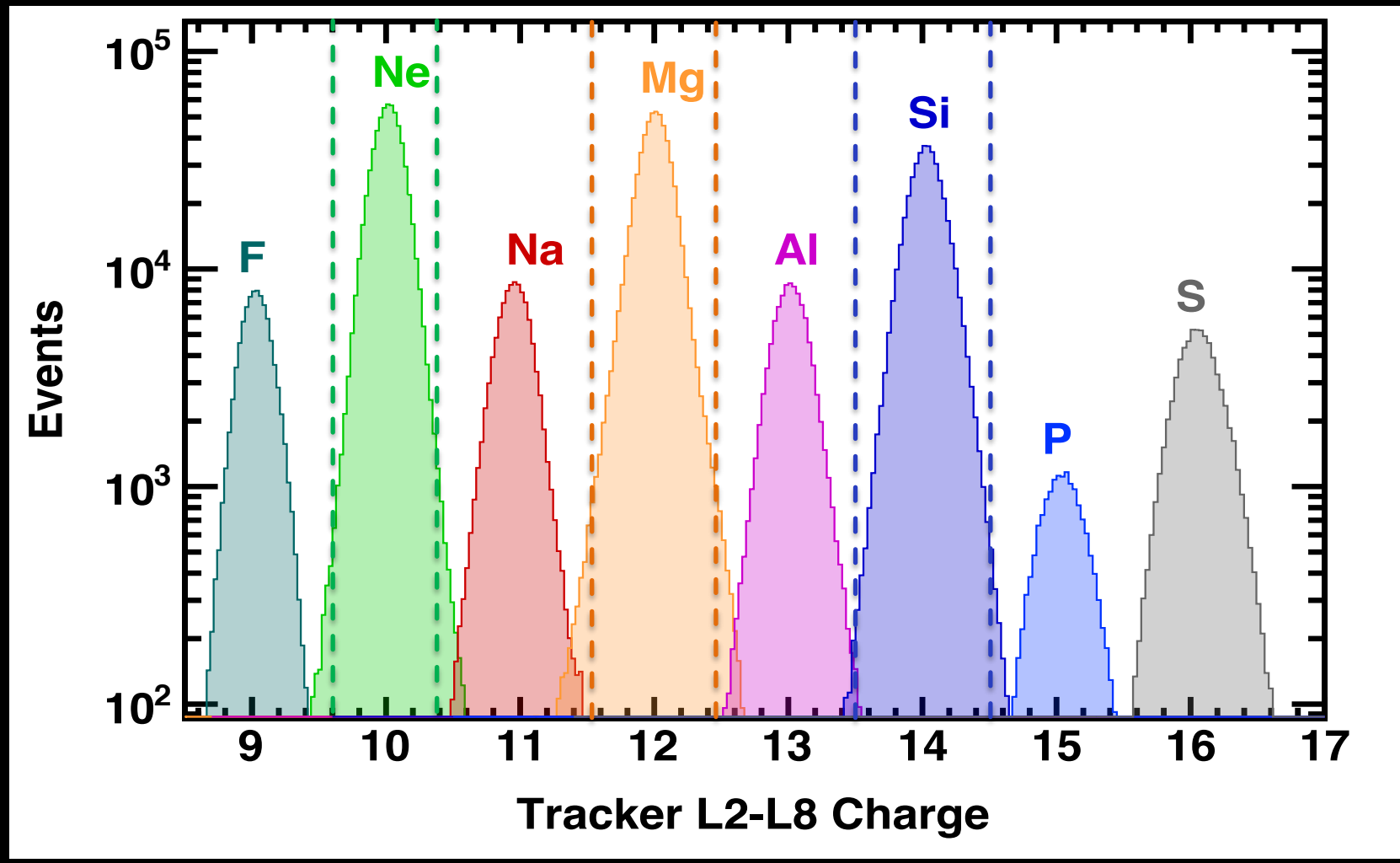




Ne, Mg, and Si : Heavier Primary Cosmic Rays

Charge misidentification from non-interacting nuclei is negligible <0.1%

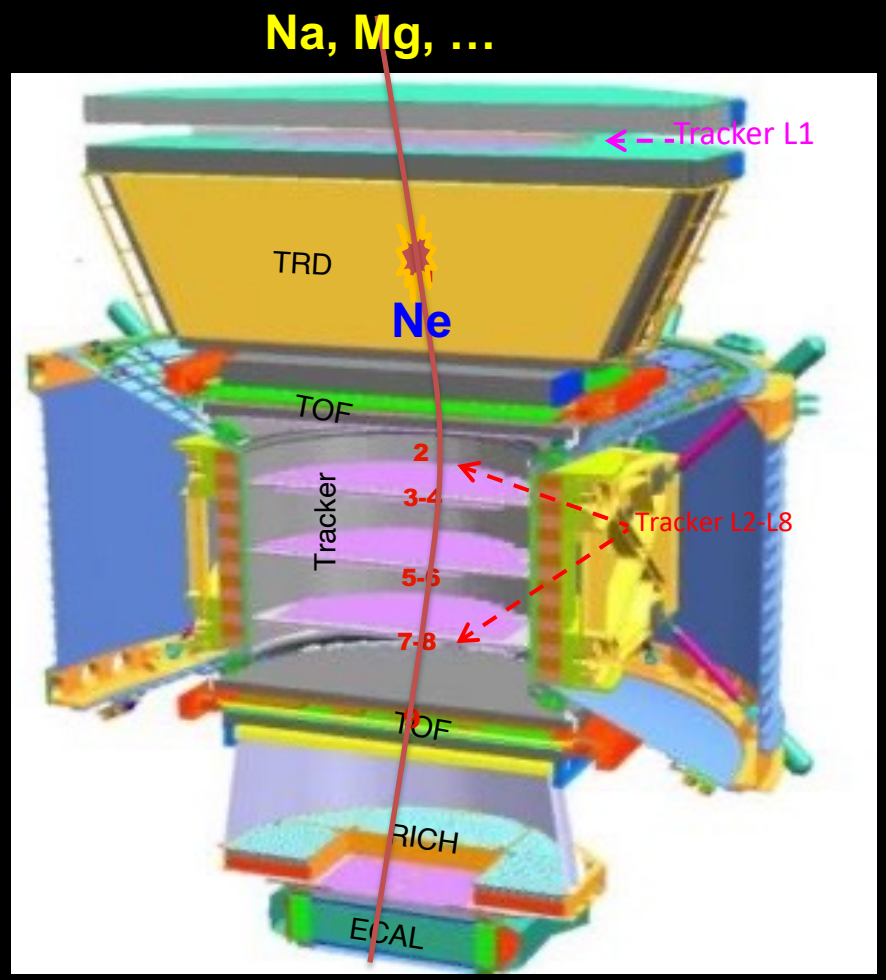


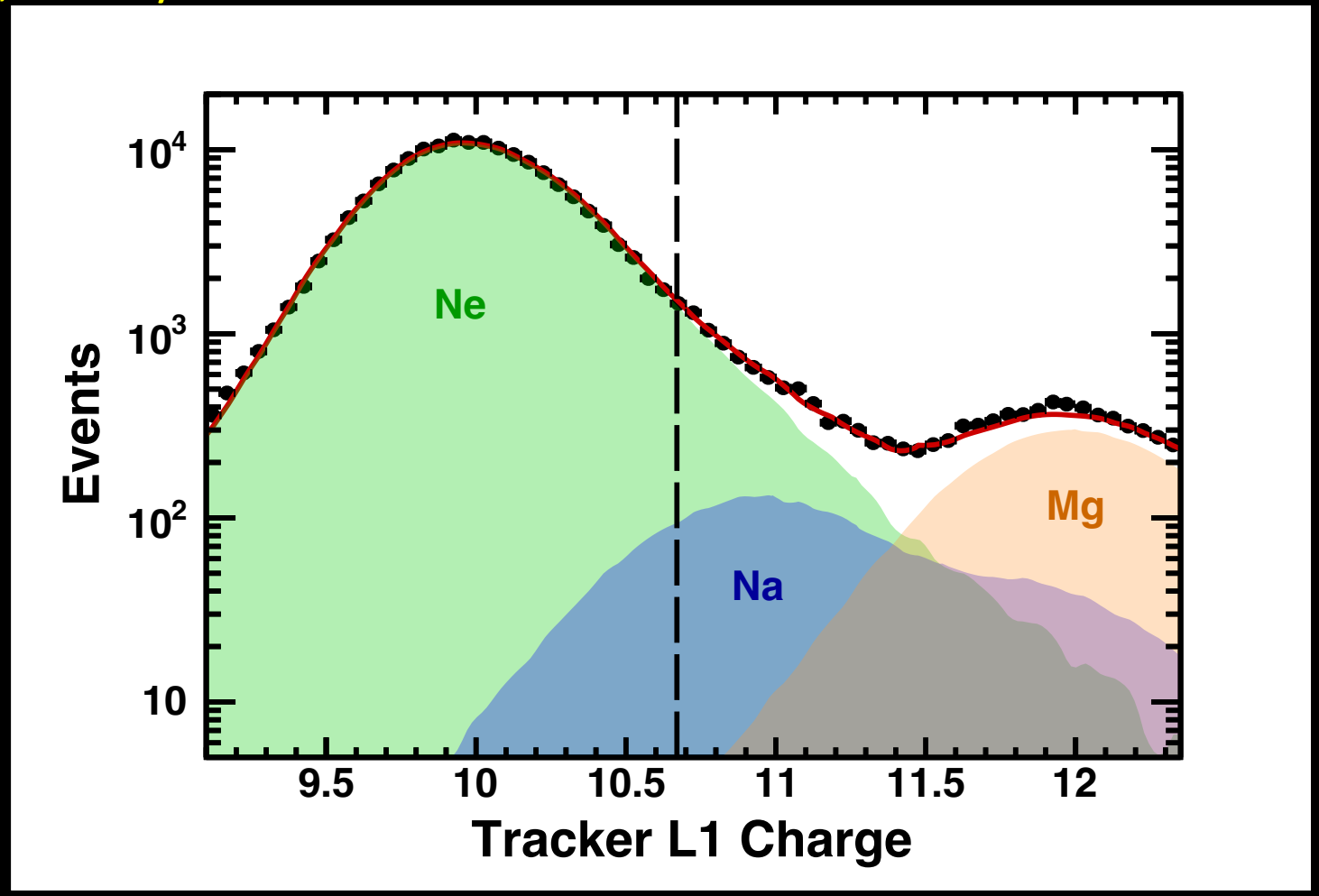


For the events R > 4 GV selected by Tracker L1, UpperTOF and LowerTOF.

Background from Nuclei Interactions

Residual background from heavy nuclei , interacting in AMS materialsbetween L1 and L2 , was found to be 1-2% depending on rigidity, with systematic error on flux measurements <0.5%.

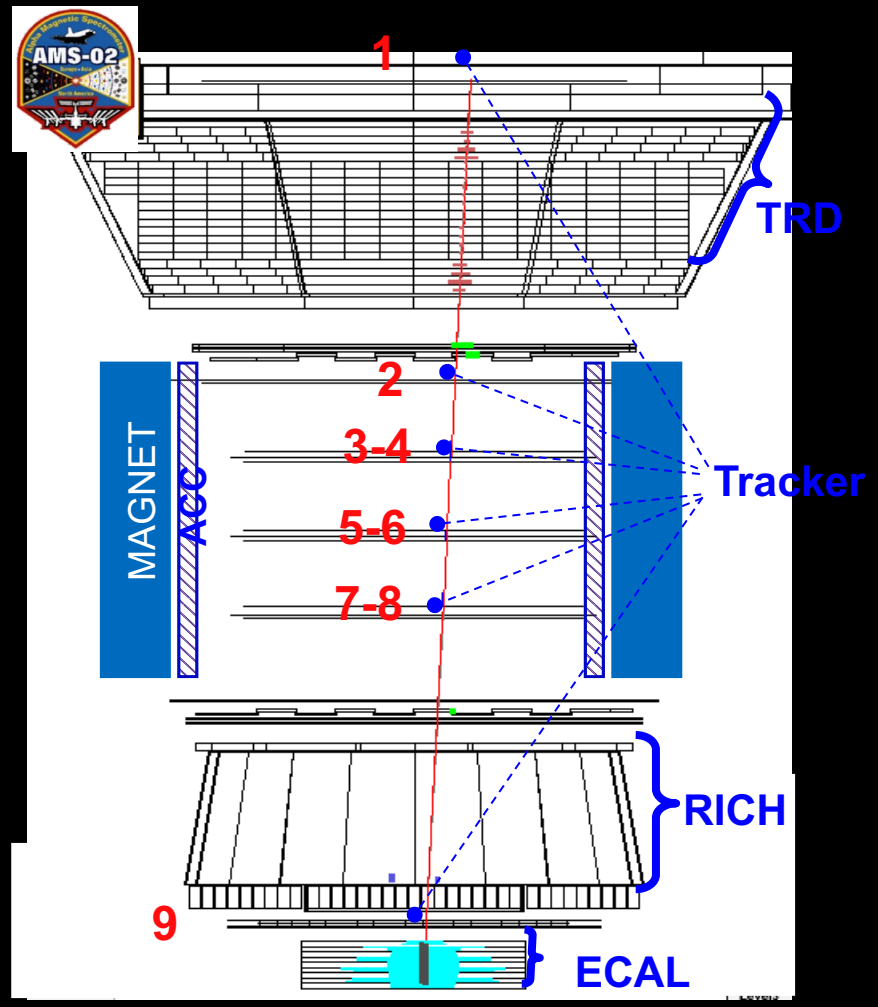




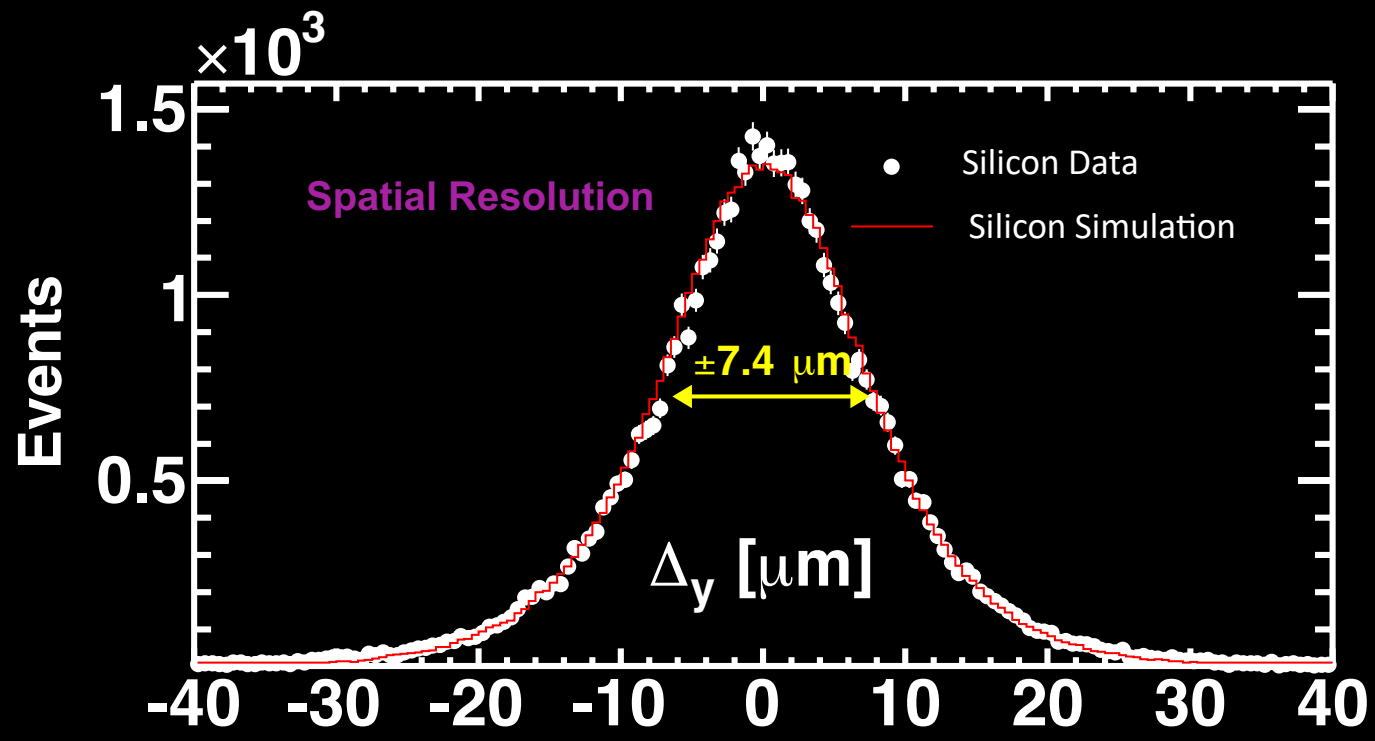
For the events 18<R<22 GV selected by Tracker L2-L8.

Ne-Mg-Si Rigidity Resolution

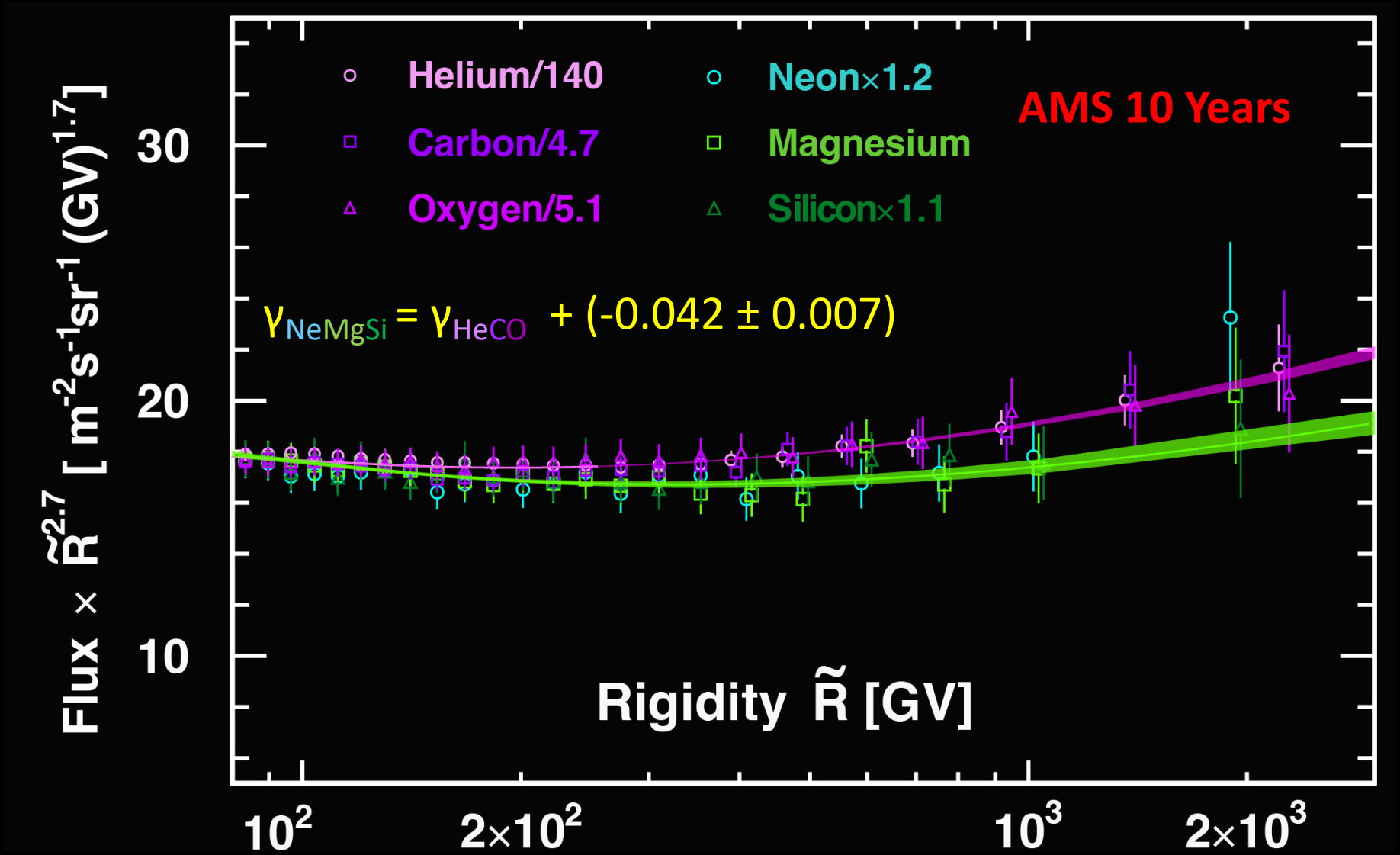
The tracker spatial resolution is 6.7 μm for Ne, 7.1 μm for Mg, and 7.4 μm for Si.



Maximal detectable rigidity ~ 3 TV



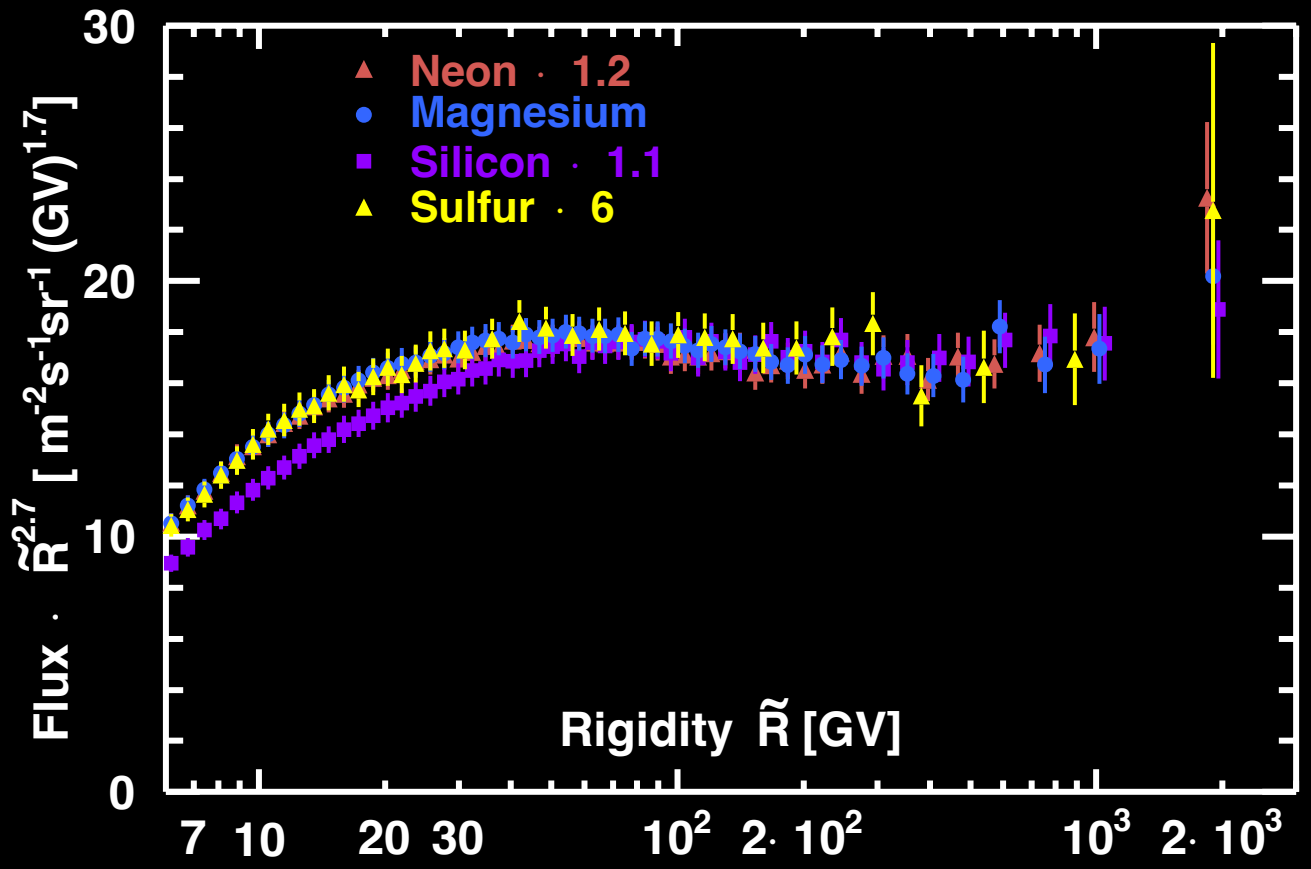
Comparison of the differences of the coordinates measured in L3 or L5 to those obtained from the track fit using the measurements from L1, L2, L4, L6, L7, and L8 between data and simulation

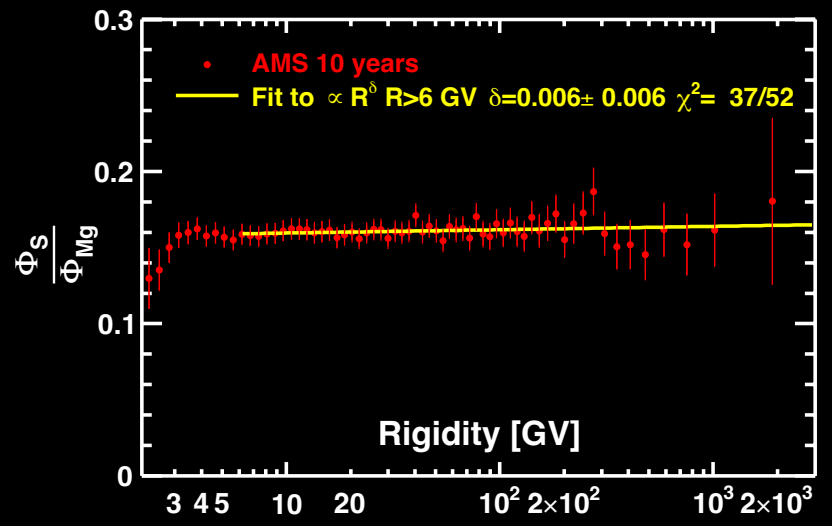


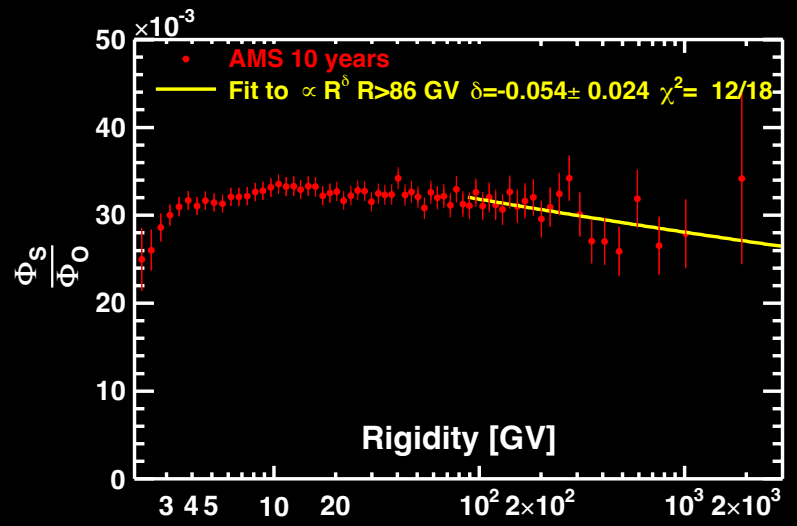
Phys. Rev. Lett. 124, 211102 (2020): AMS previously observed that light primary cosmic rays He, C, and O have identical rigidity dependence above 60 GV and deviate from a single power law above 200 GV. Surprisingly, heavy primary cosmic rays Ne, Mg, and Si also have identical rigidity dependence above 86 GV, but it is distinctly different from light primary cosmic rays.

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

Latest AMS Results: Sulfur Rigidity Dependence



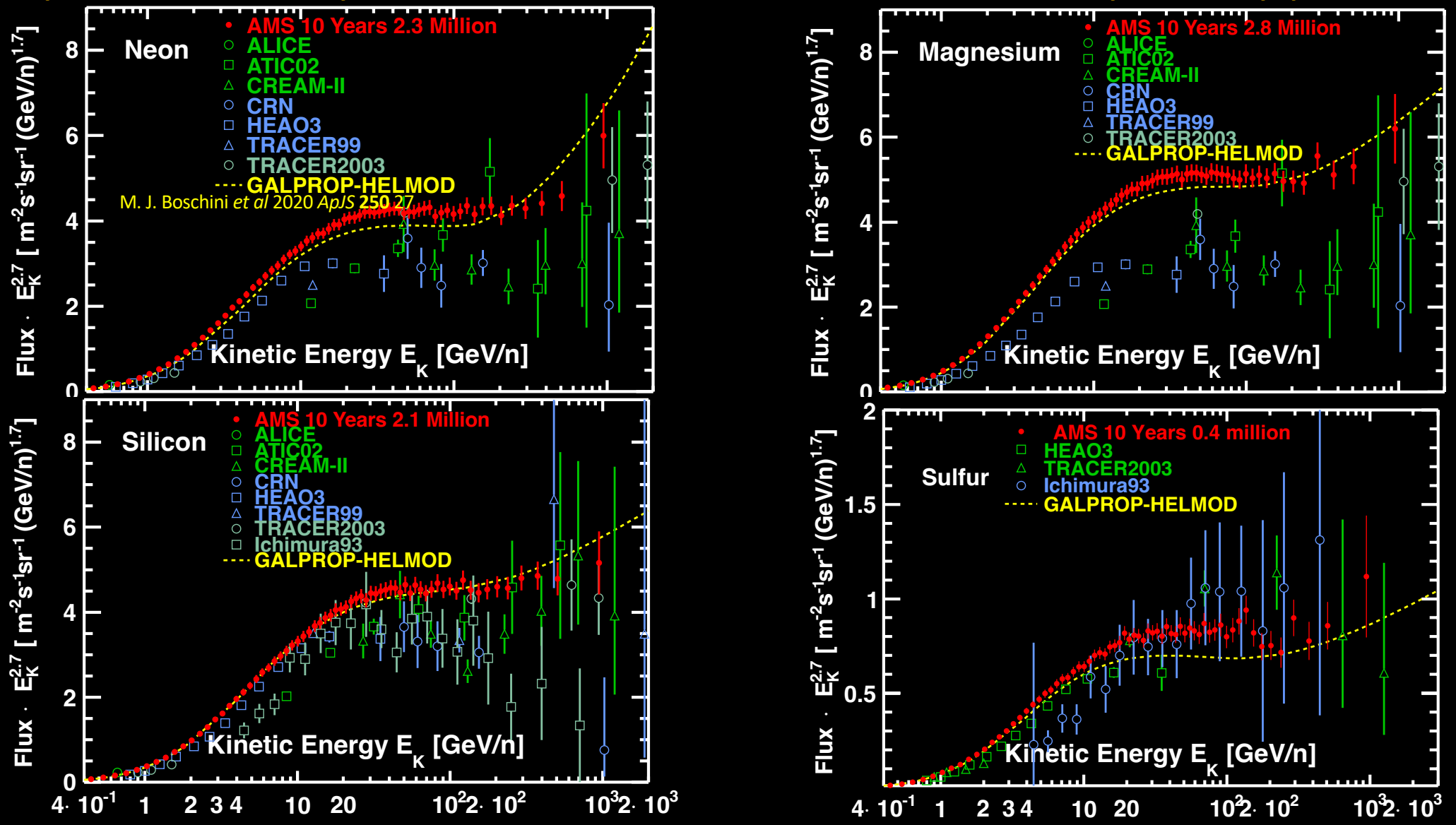




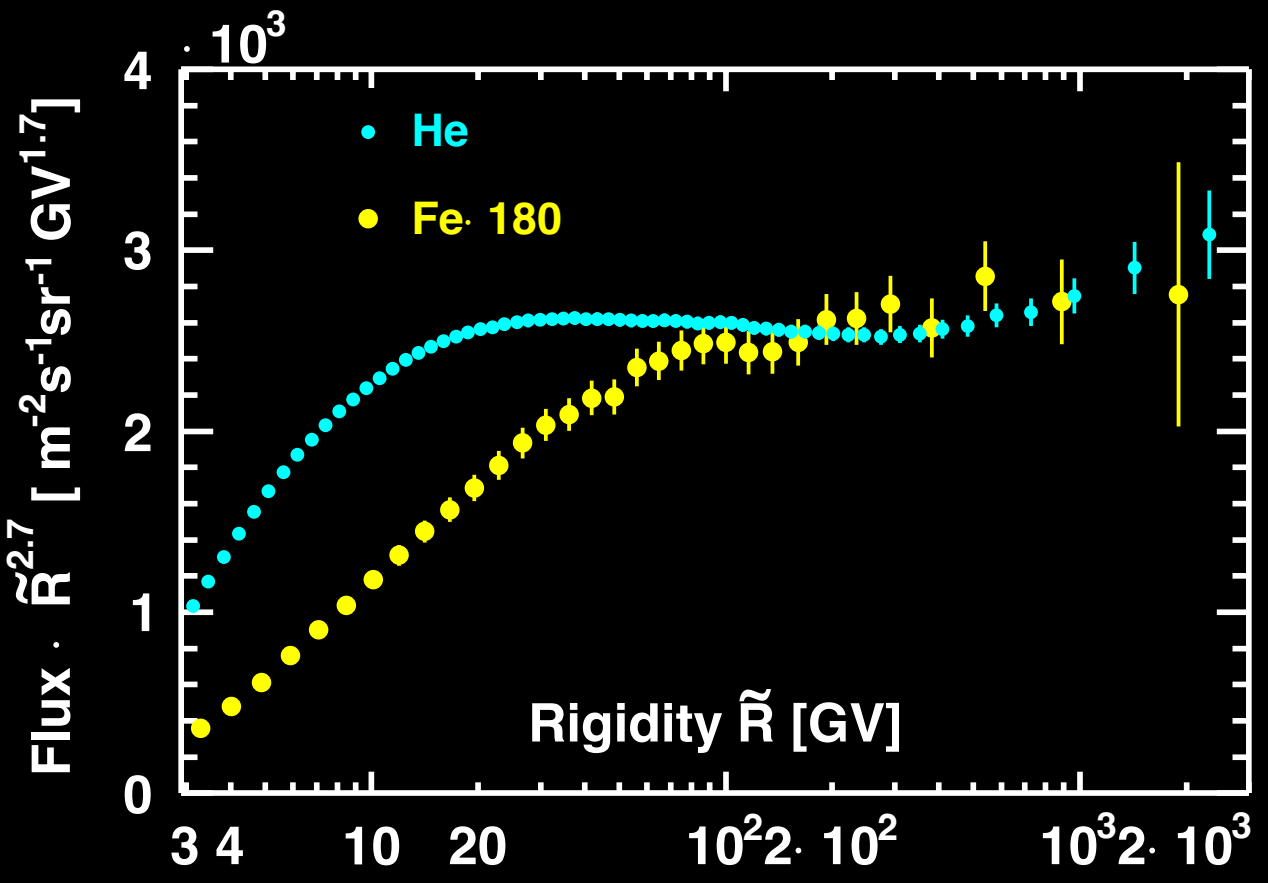
Sulfur belongs to the same class as Ne, Mg, and Si.

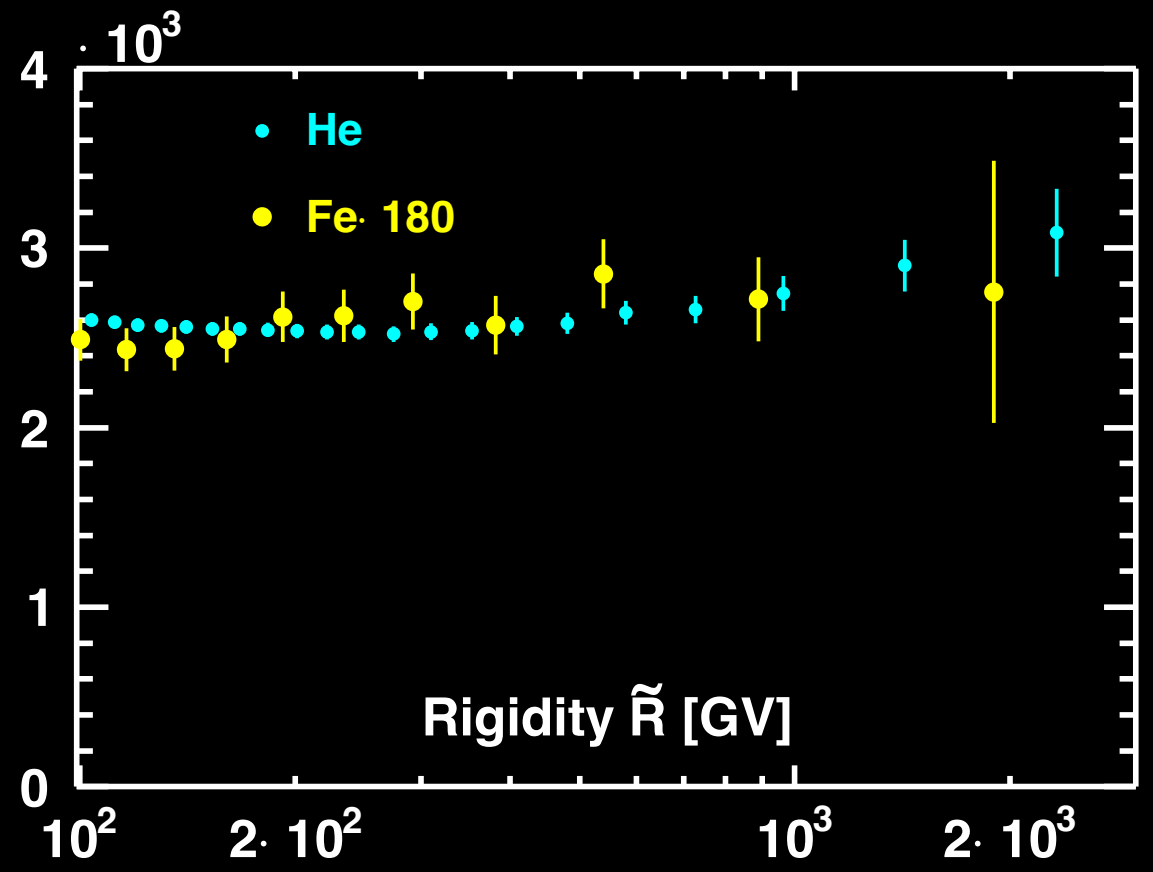
AMS Ne, Mg, Si, and S Nuclei Flux Measurements:

AMS results are different from previous measurement both in magnitude and the energy dependence. They are also different from the Cosmic Ray Theory predictions.

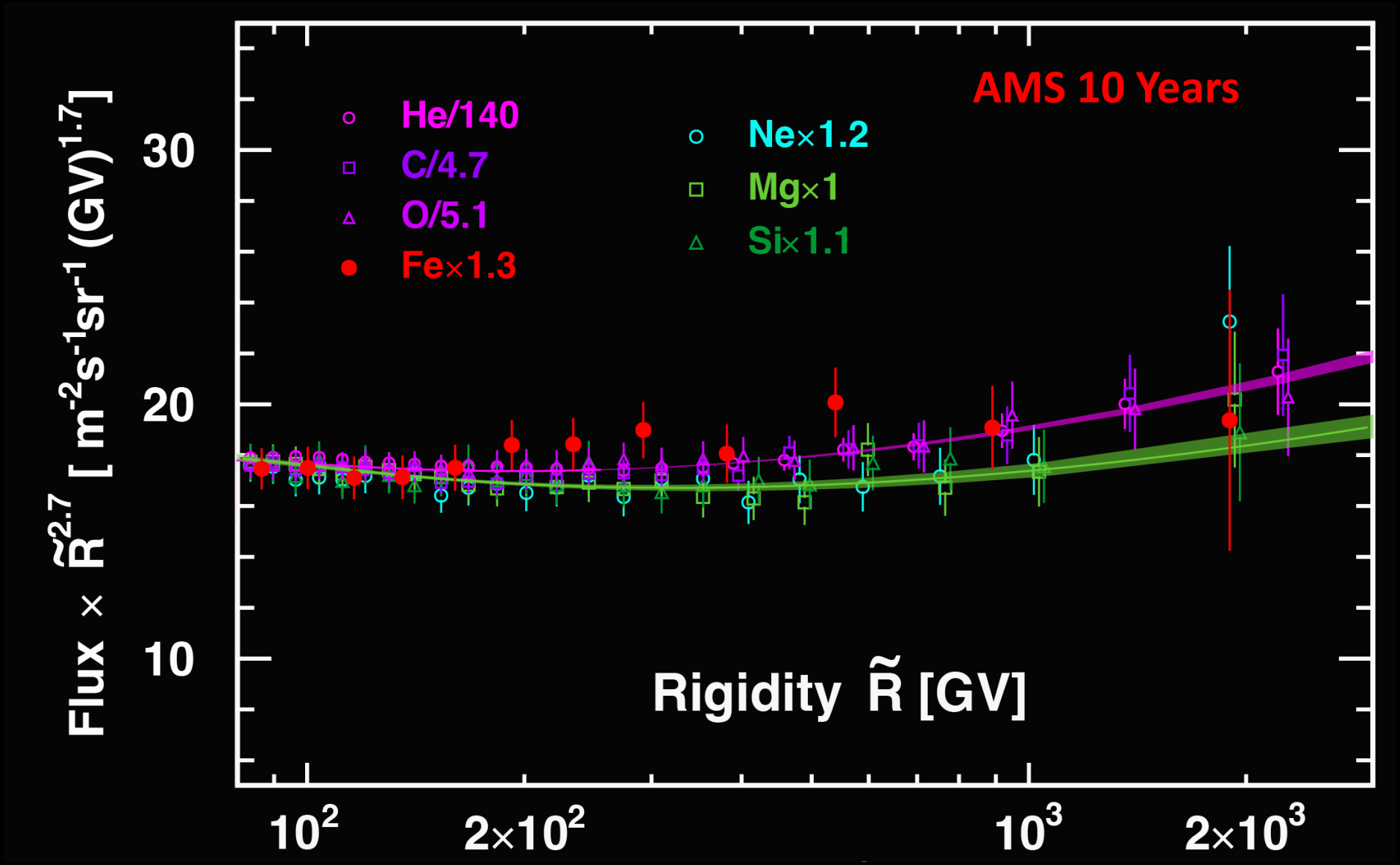


Iron and Helium
have identical rigidity dependence at high rigidities

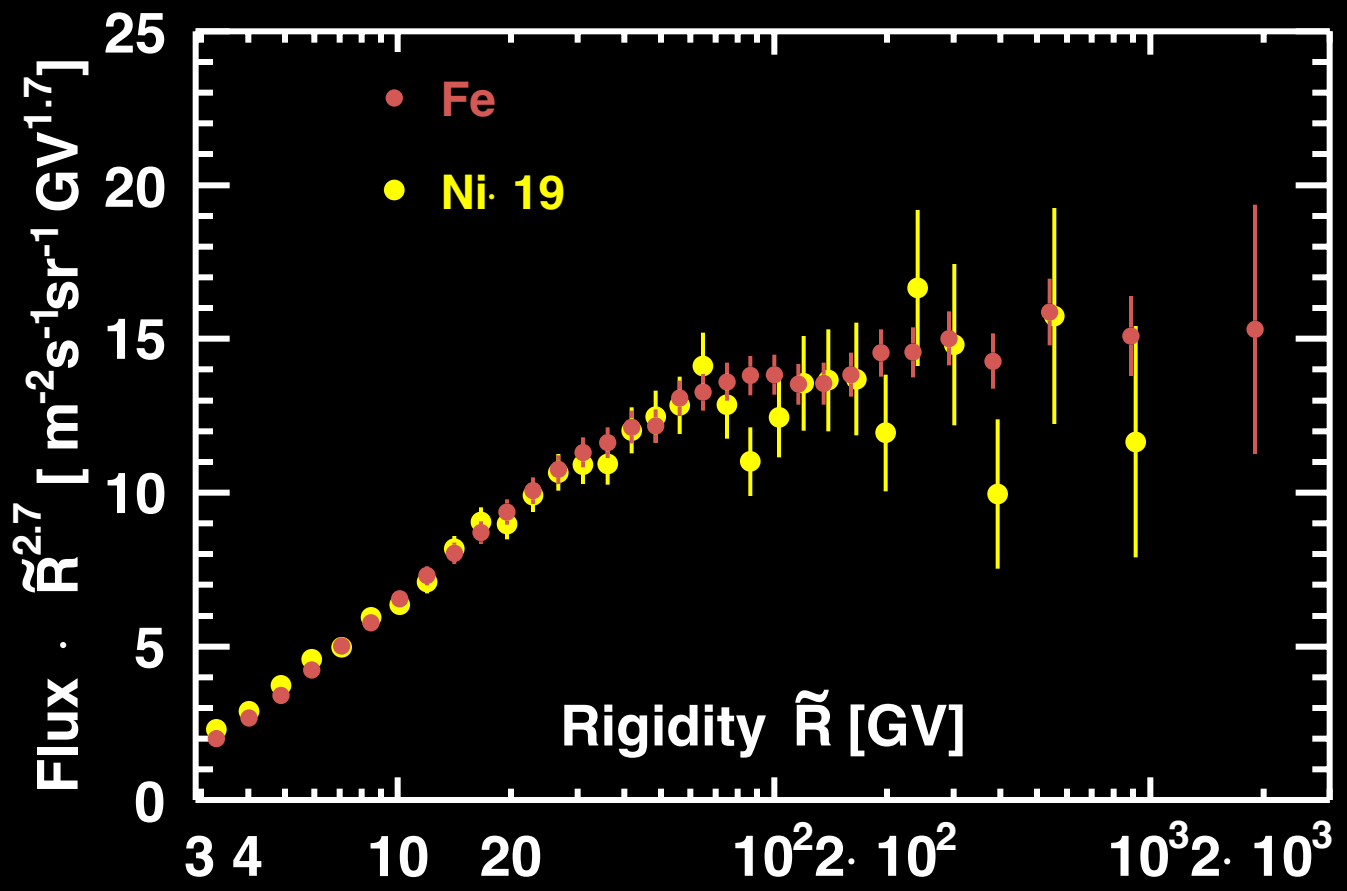


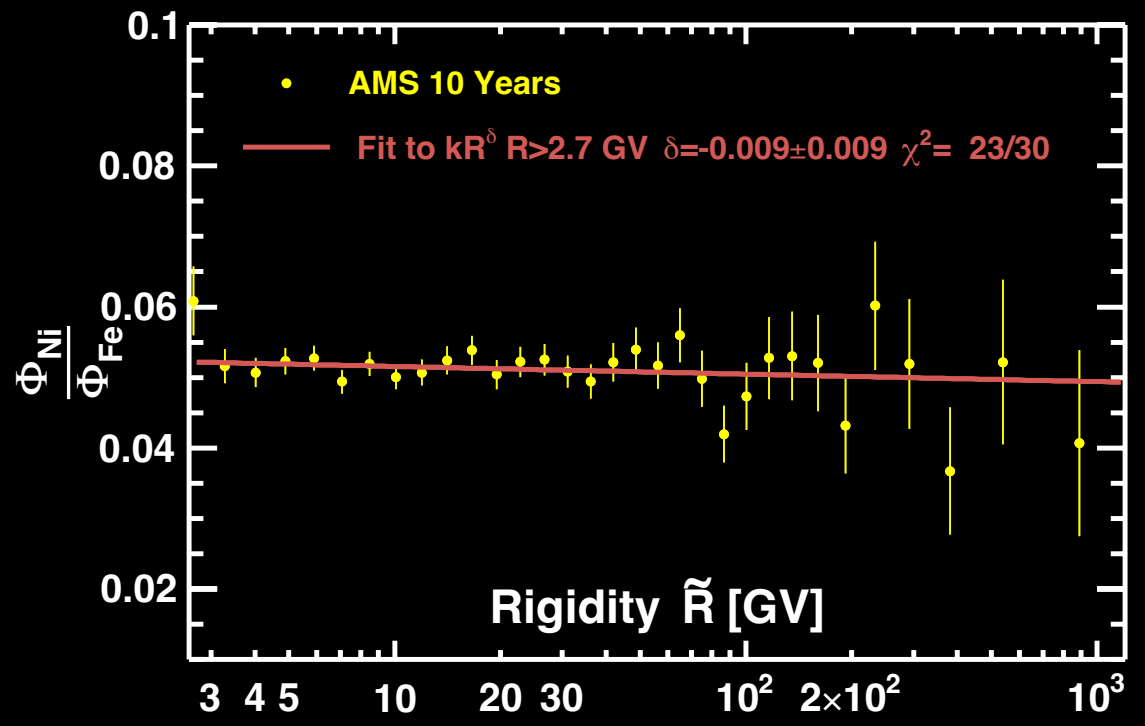


Unexpectedly, Iron is in the He, C, O primary cosmic ray group

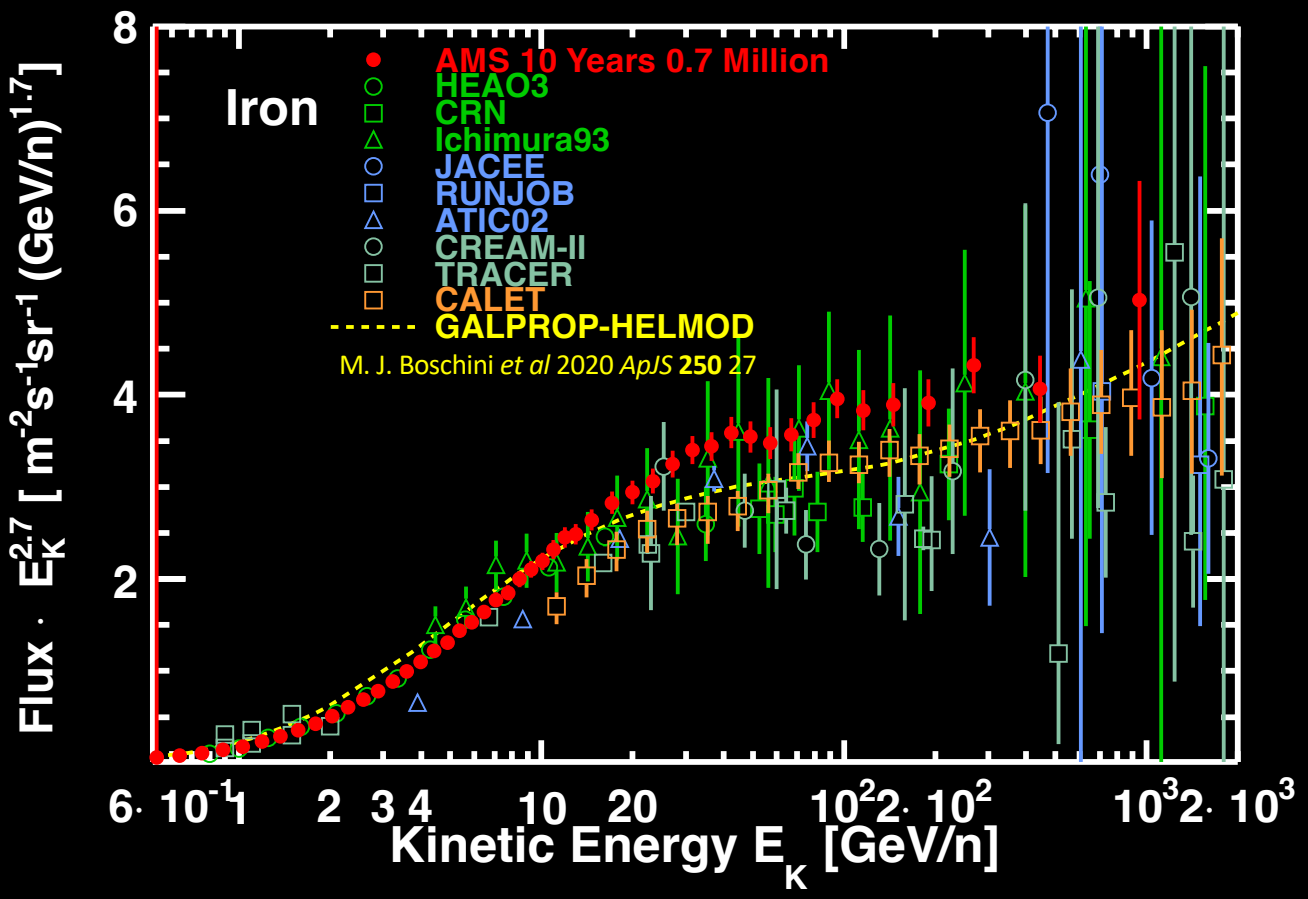


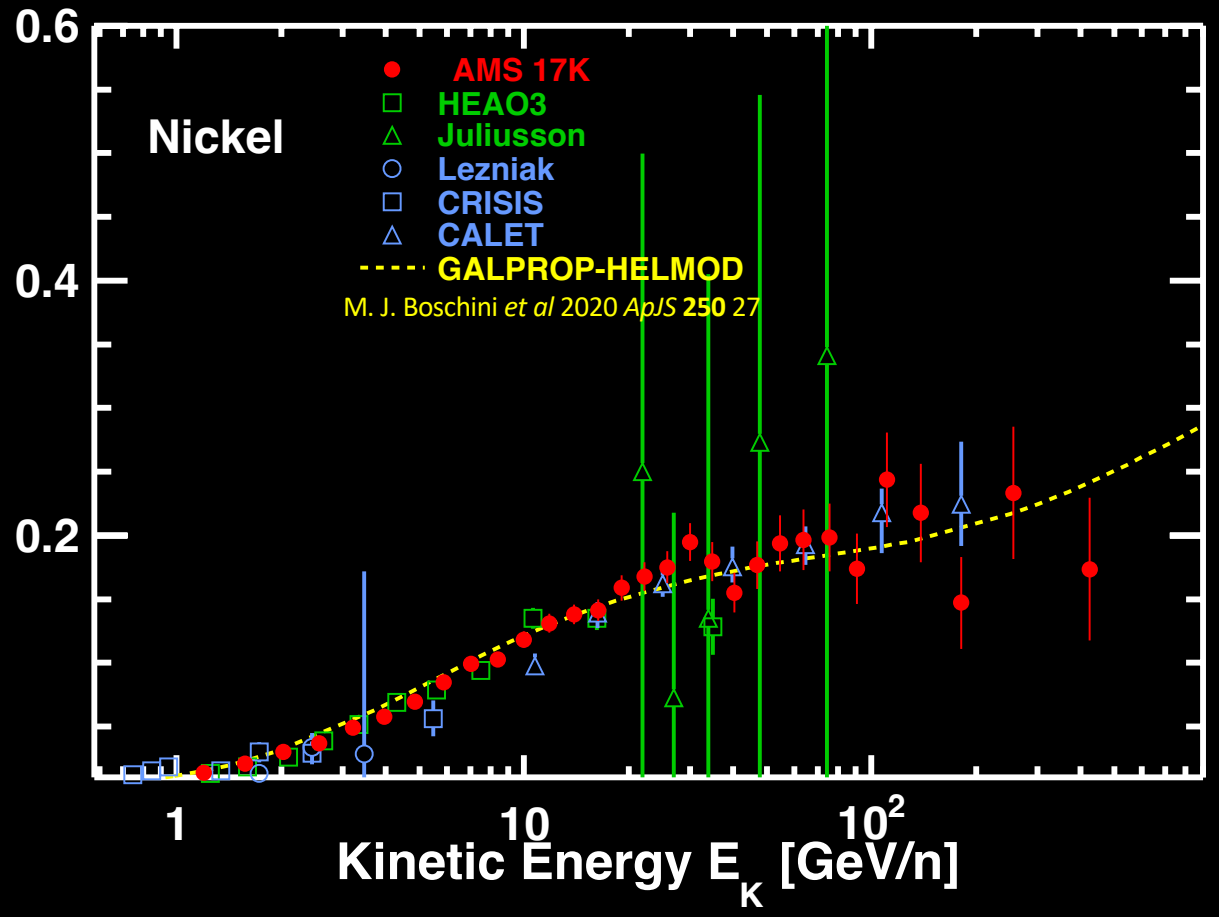
AMS Nickel flux: rigidity dependence is similar to Fe



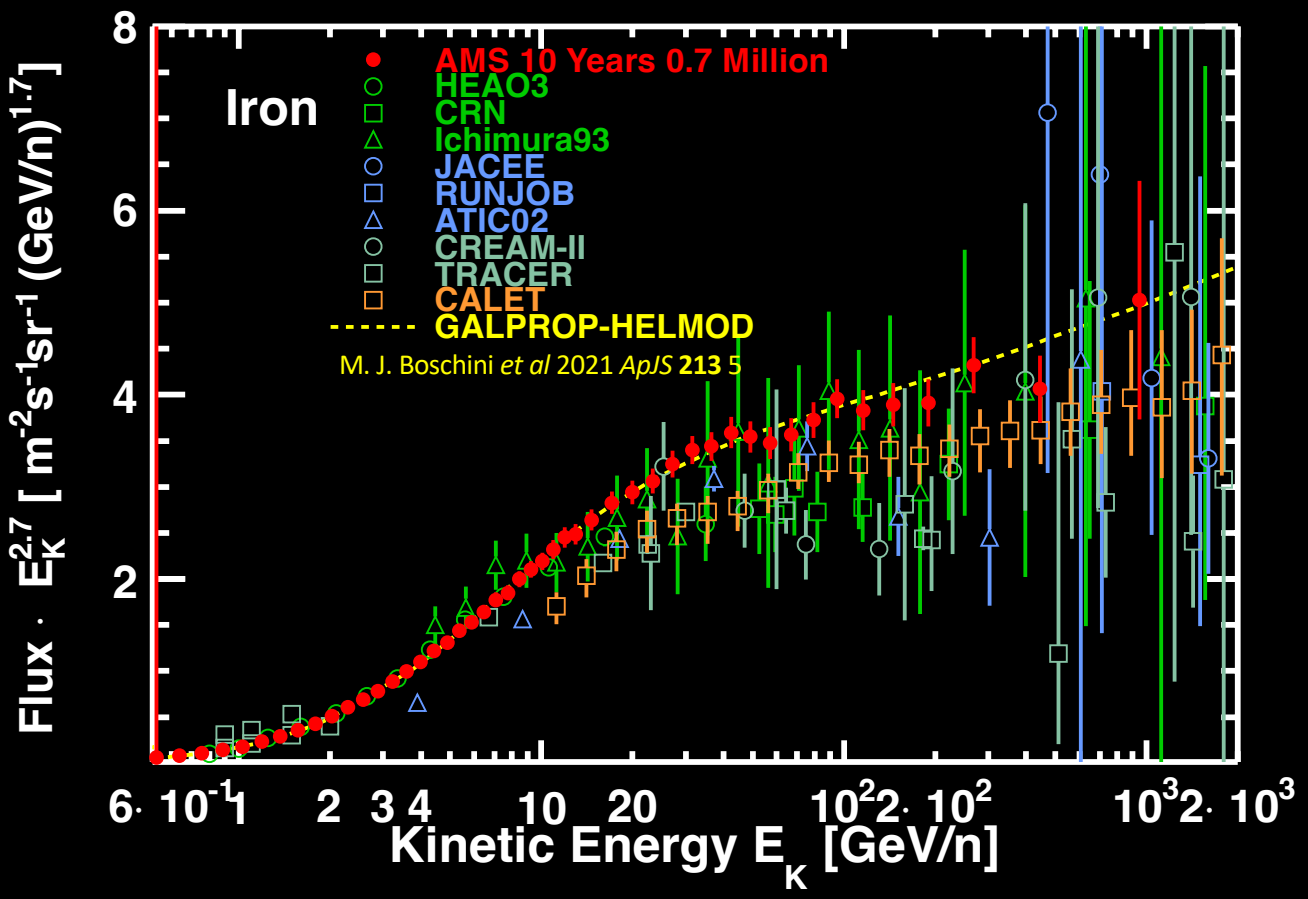


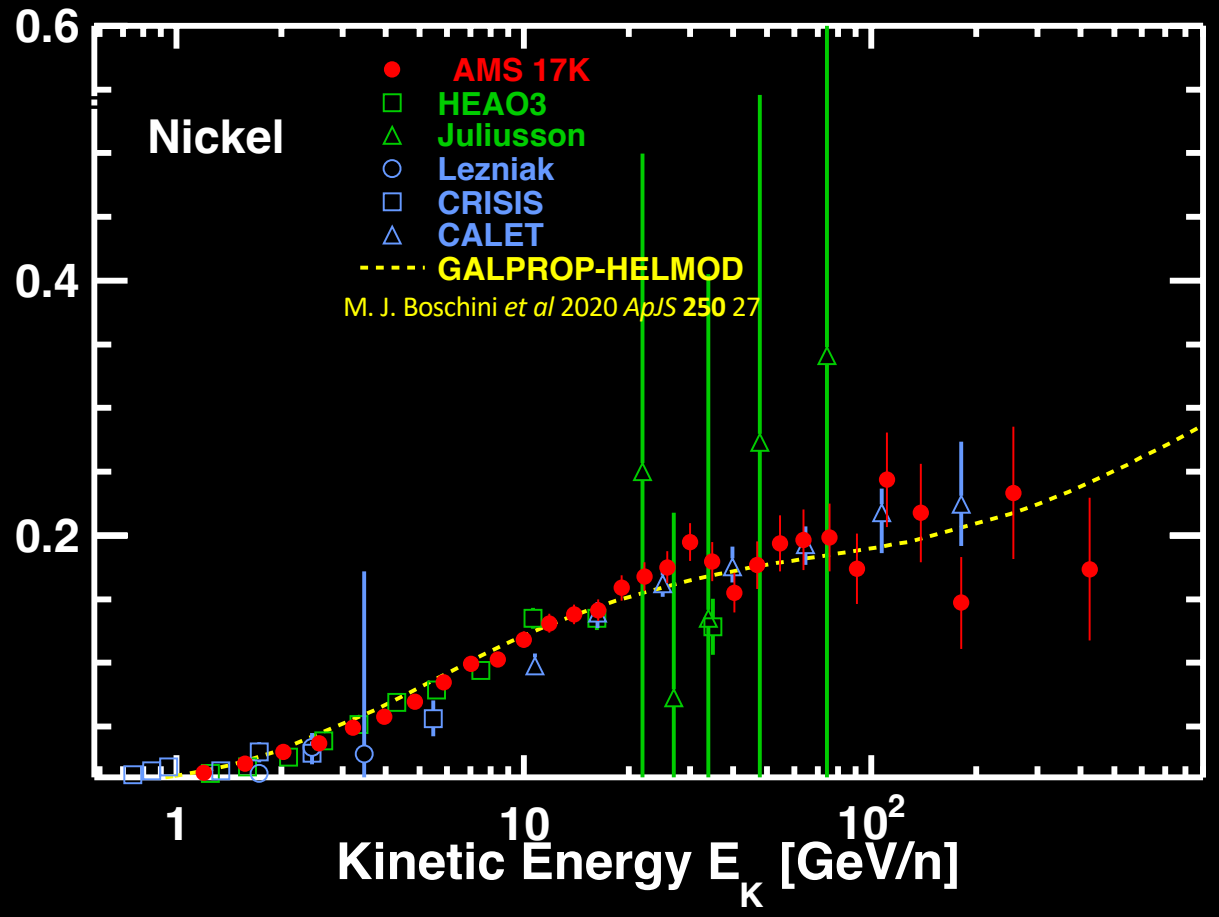
Heavy Primary cosmic rays: Iron and Nickel Fluxes



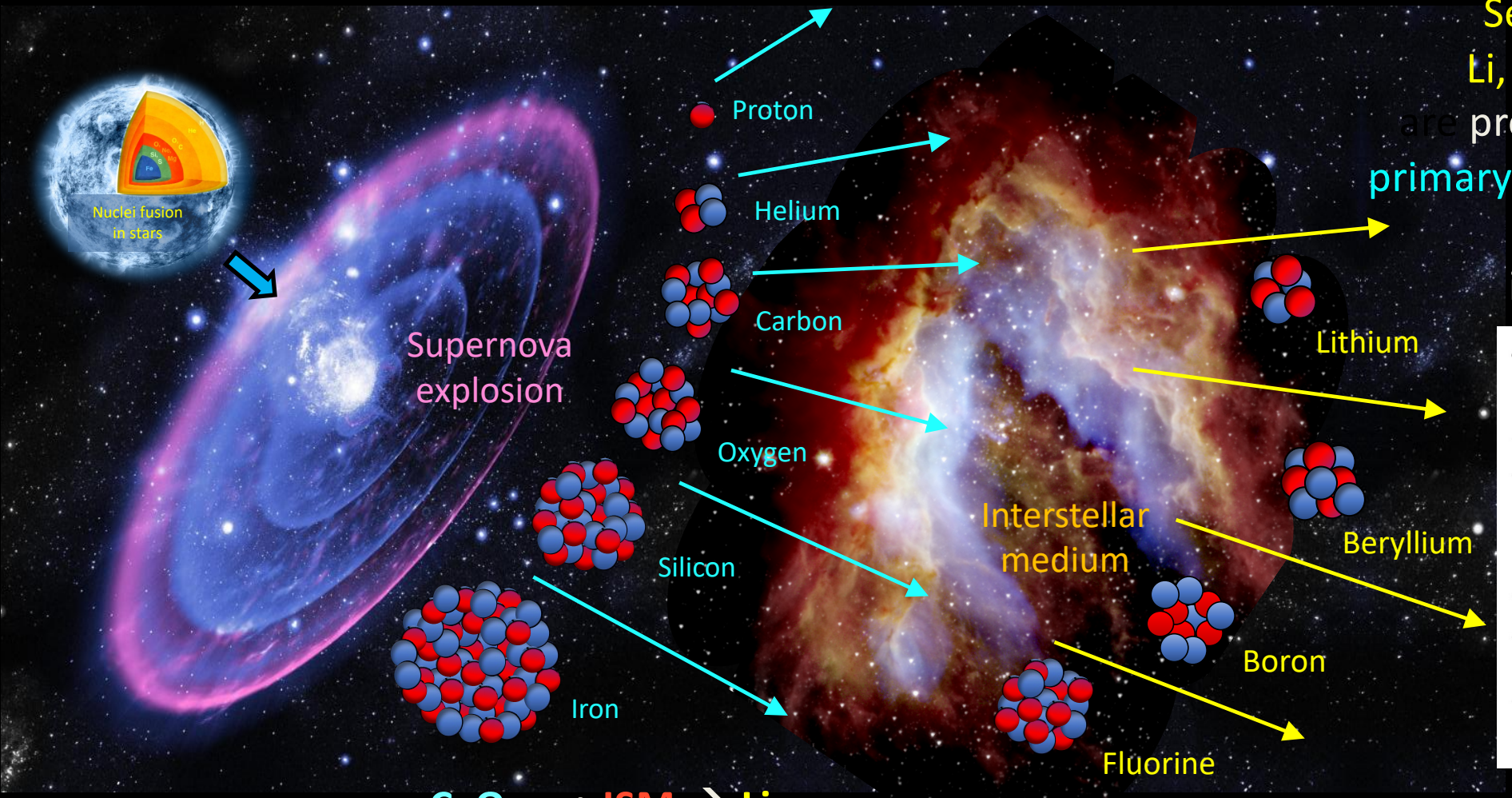


Heavy Primary cosmic rays: Iron and Nickel Fluxes

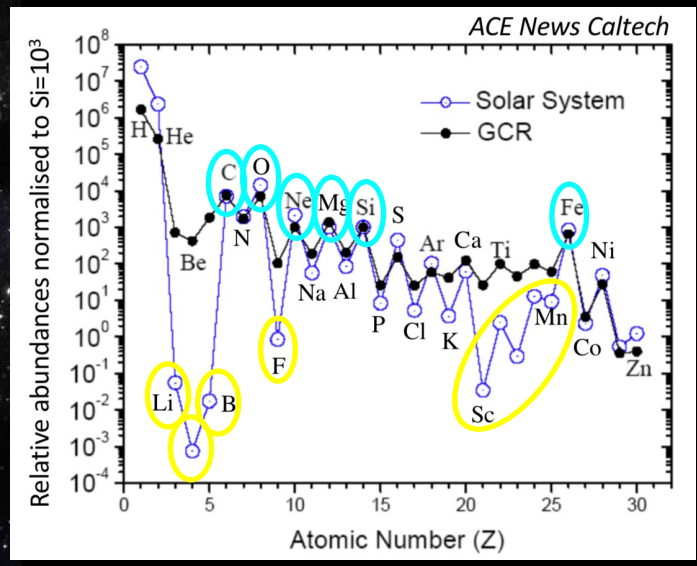




Secondary Cosmic Rays



Secondary
Li, Be, B, F, sub-Fe nuclei
are produced by the collision of
primary cosmic rays C, O, Si, … , Fe
with the
interstellar medium



C, O, … + ISM → Li
C, O, … + ISM → Be
C, O, … + ISM → B

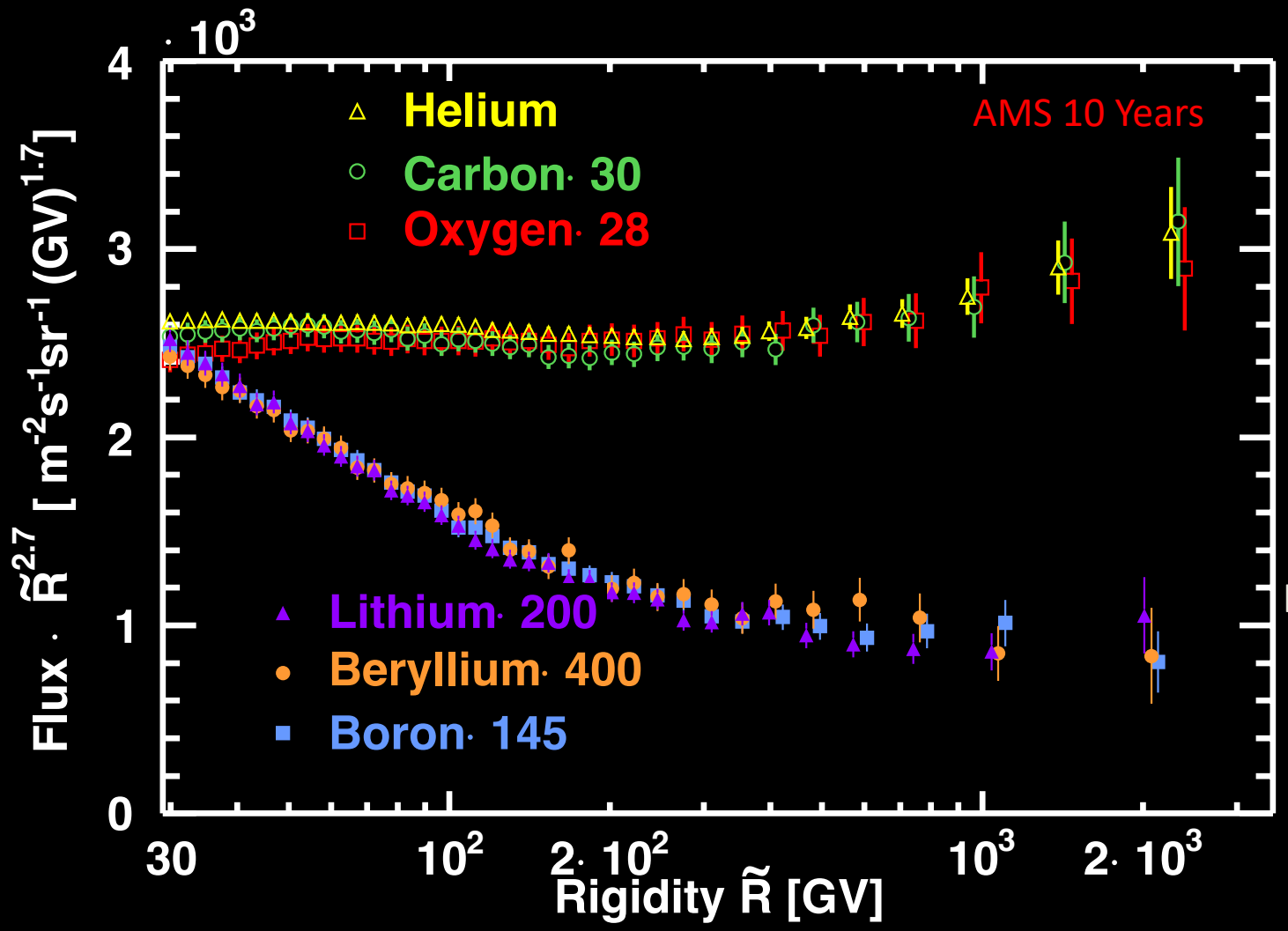
Ne, Mg, Si, … + ISM → F + X

Fe, … + ISM → Sc, … ,Mn

Light Secondary Cosmic Rays Li, Be and B fluxes

Phys. Rev. Lett. 120, 021101 (2018): Above 30 GV, Li, Be and B have identical spectral shape

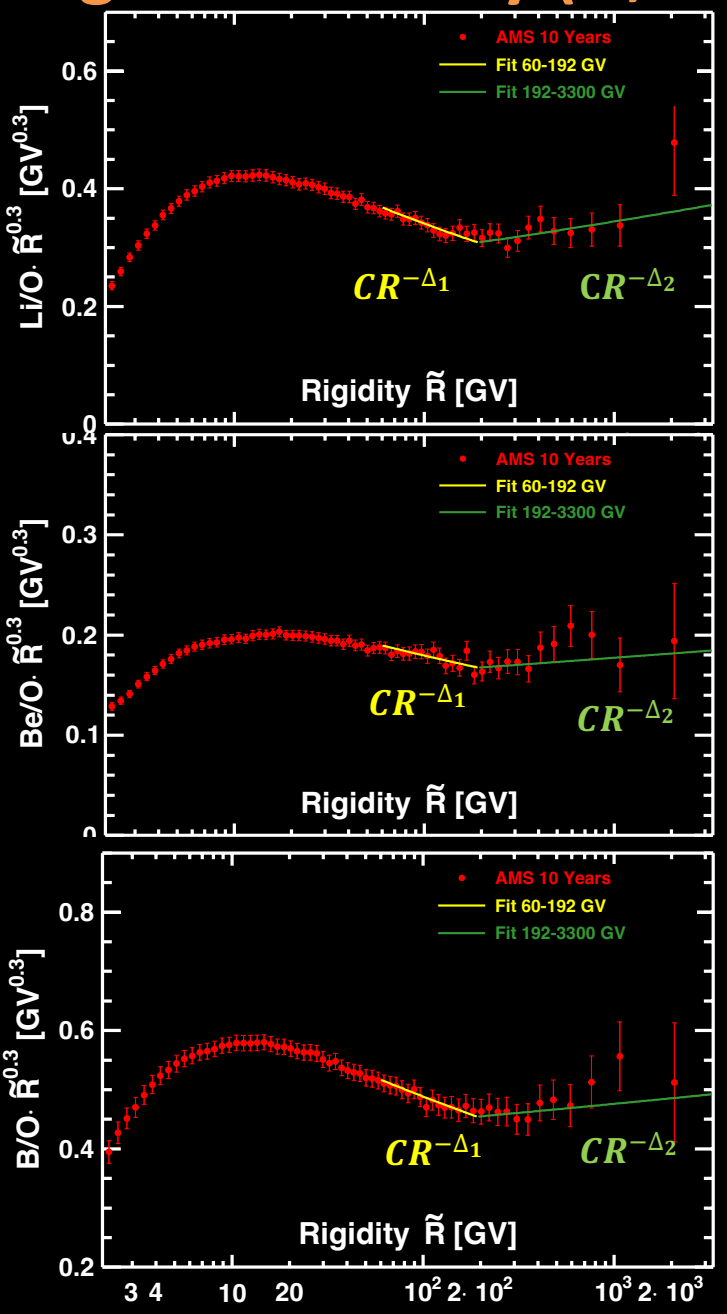
Li, Be and B also exhibit a spectral hardening at 200 GV as do the primary cosmic rays



Secondary and primary Cosmic rays have distinctly different spectral shapes

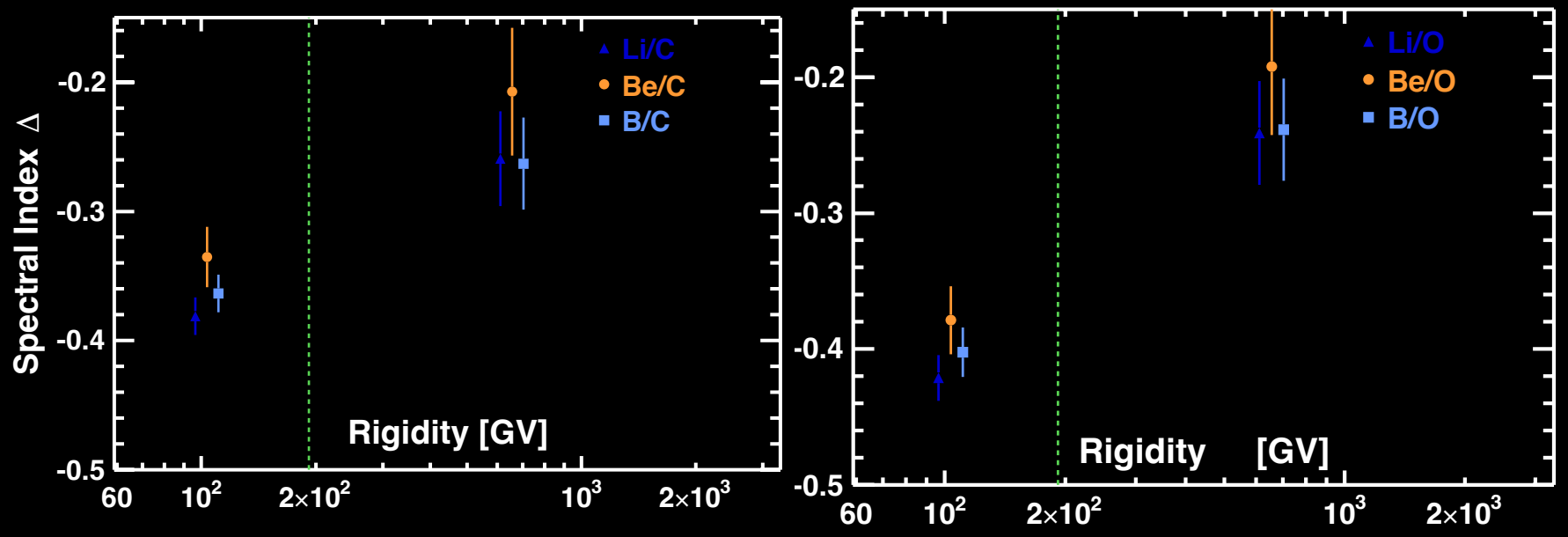
The propagation of cosmic rays through the ISM is modeled as diffusion of charged particles in a turbulent magnetized medium.
Diffusion models based on different assumptions predict a Secondary/Primary flux ratio asymptotically proportional to $R^{-\delta \sim 0.3}$

Light Secondary (Li, Be, B) to Primary (C,O) flux ratios not a single power law



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

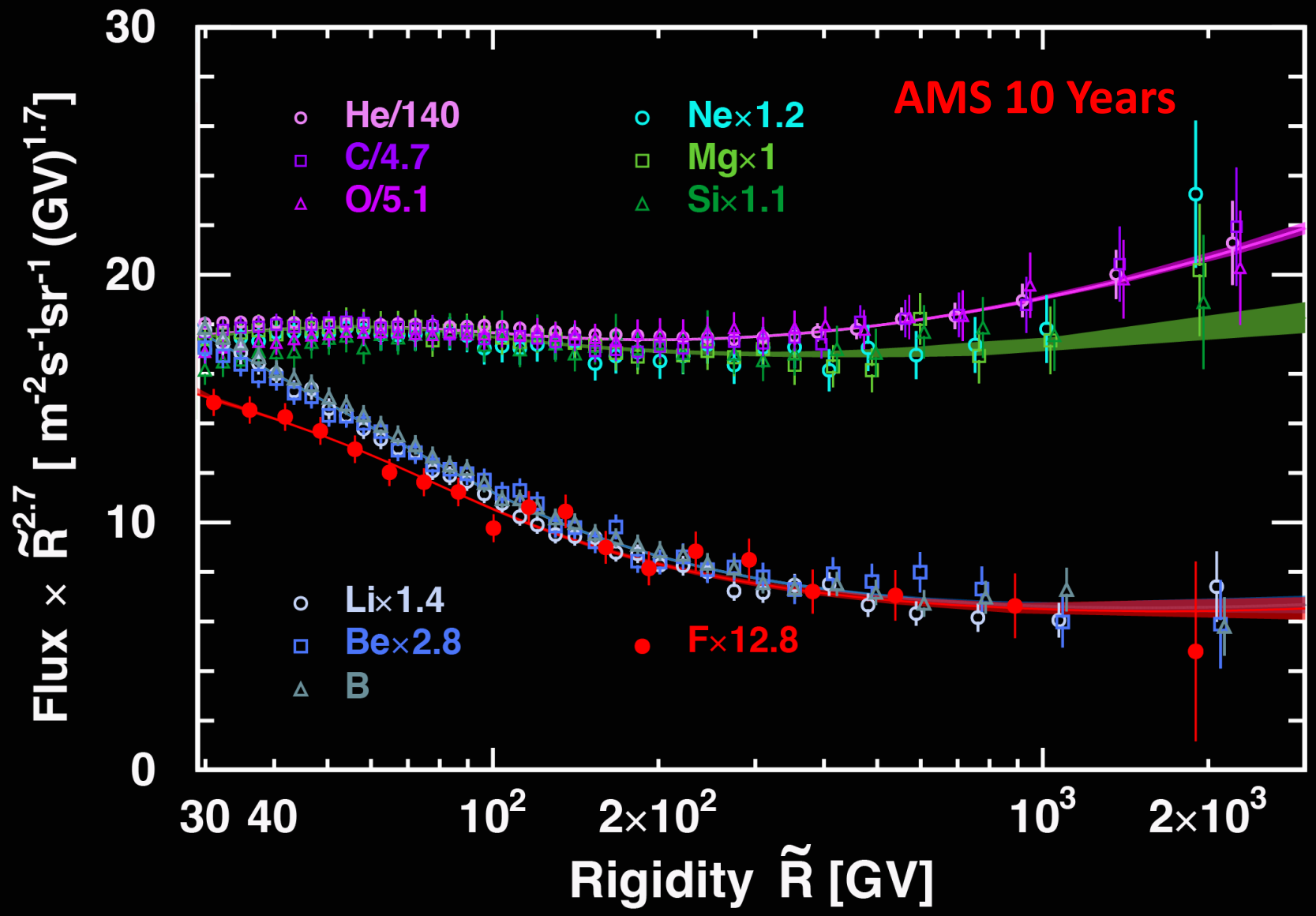
Average **hardening** $\Delta = \Delta_2 - \Delta_1 = 0.145 \pm 0.022$, significance: $\mathbf{6.5\sigma}$



This new observation strongly favors the hypothesis that **the observed spectral hardening** is due to a **propagation effect**

Is the secondary –to-primary ratio rigidity dependence universal? AMS paper about F nuclei in Phys.Rev. Lett. answering this question.

Secondary Cosmic Rays also have two classes above 30 GV

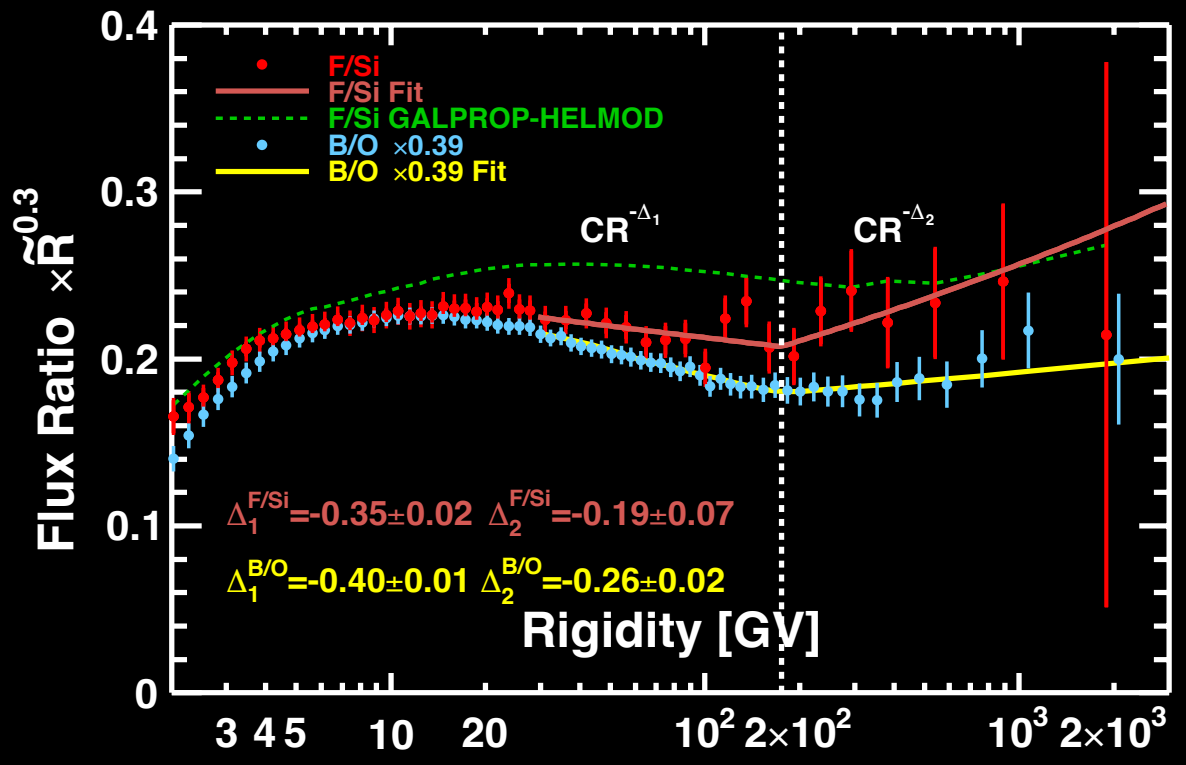


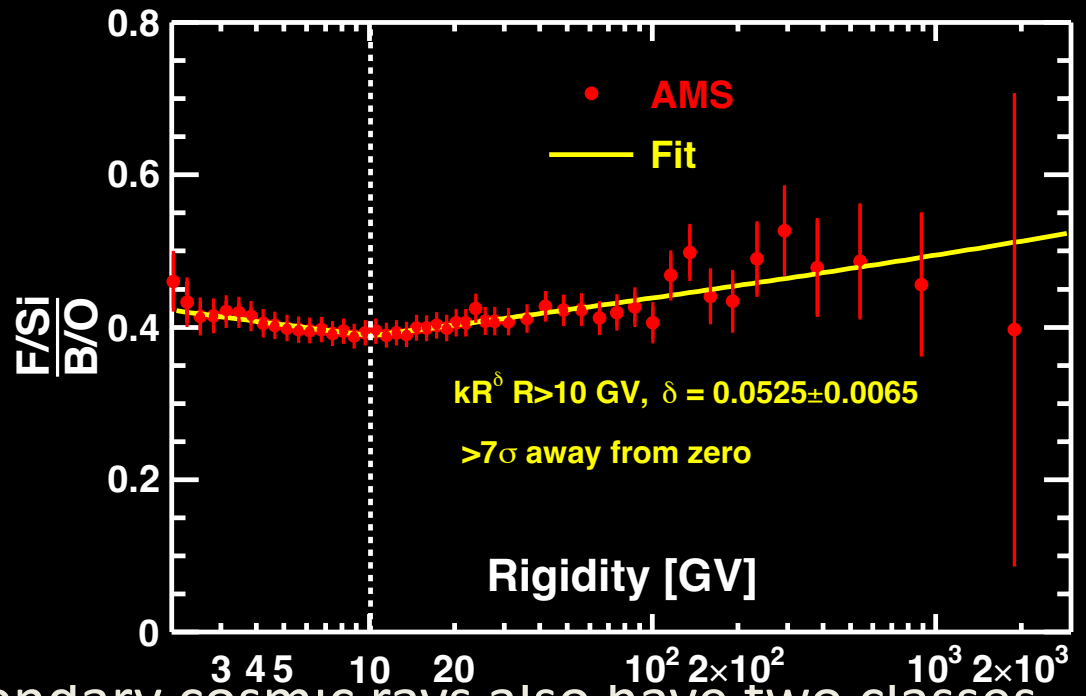
Propagation properties of heavy nuclei: light vs heavy secondary-to-primary

Traditionally the light secondary-to-primary ratio B/O (or B/C) is used to describe the propagation properties of all cosmic rays.

New AMS result:

the heavy secondary-to-primary ratio F/Si has a different rigidity dependence from the lighter B/O ratio

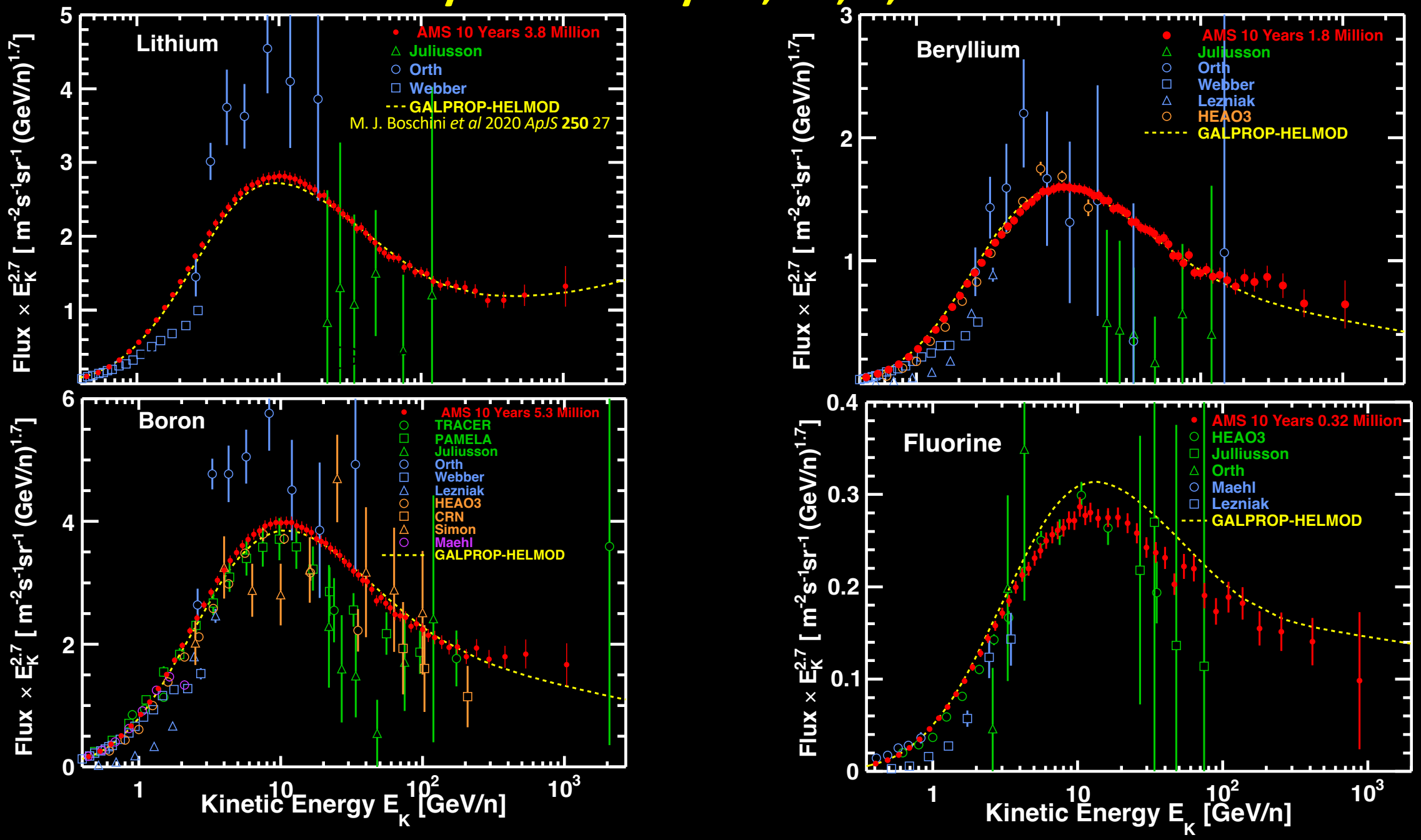




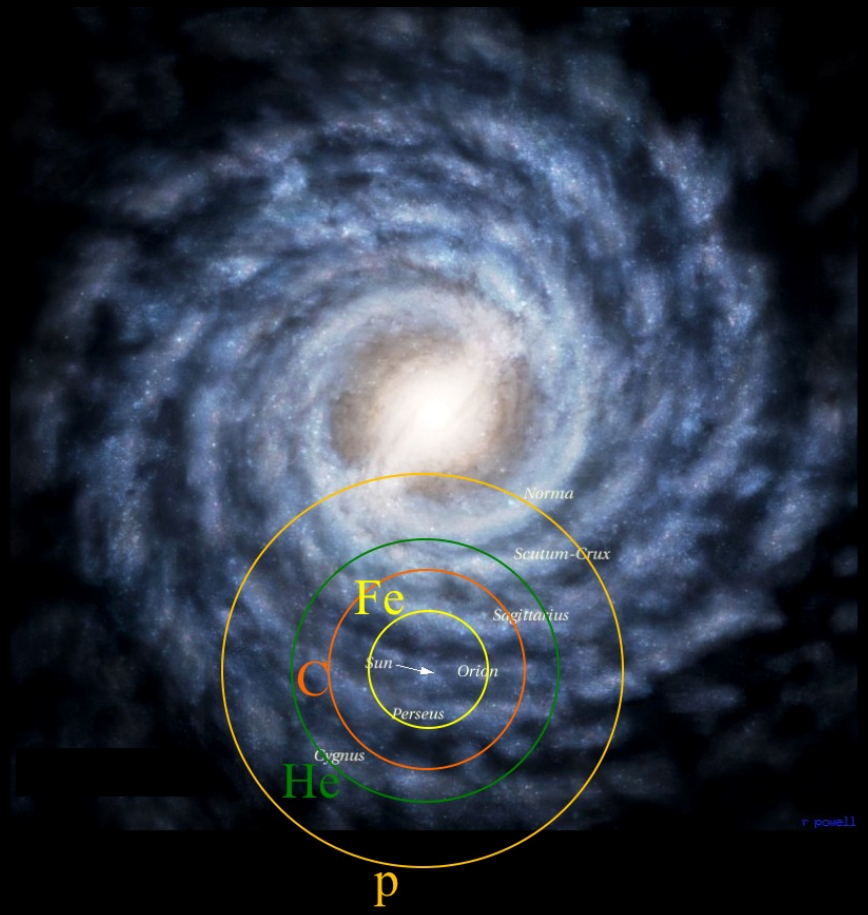
This shows for the first time that the secondary cosmic rays also have two classes

The propagation properties of heavy cosmic rays are different from those of light CRs

Secondary Cosmic Rays Li, Be, B, and F fluxes



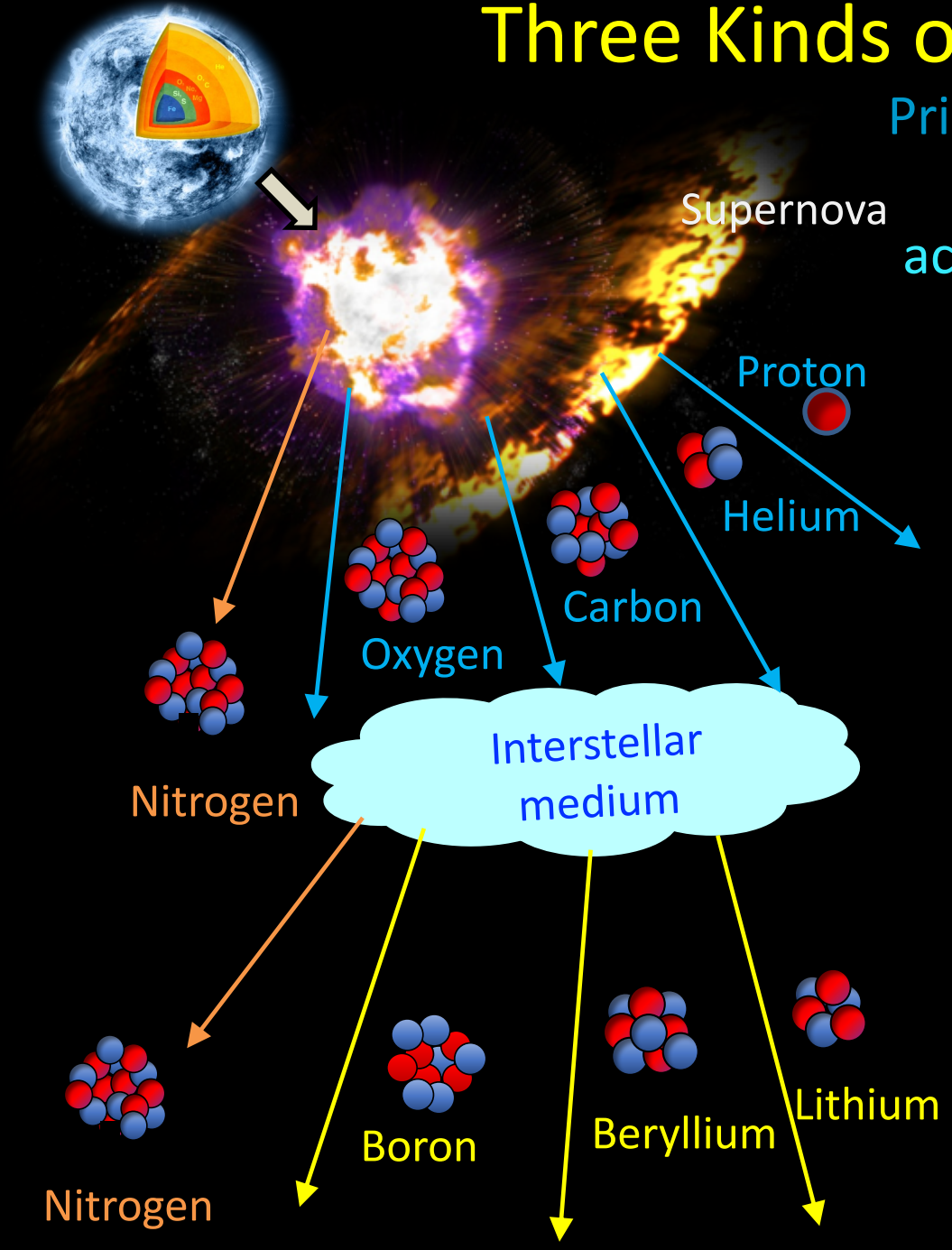
Study of Cosmic Ray Propagation in Heavy Cosmic Rays



The effective propagation distances for p, He, C, and Fe for 1 GV rigidity.

Measurements of the heavy secondary cosmic ray nuclei with Z>14 will allow AMS to study propagation properties in the Galaxy at different distances. The precision
AMS data will provide the most comprehensive information on the cosmic ray propagation model.

Three Kinds of Charged Cosmic Rays



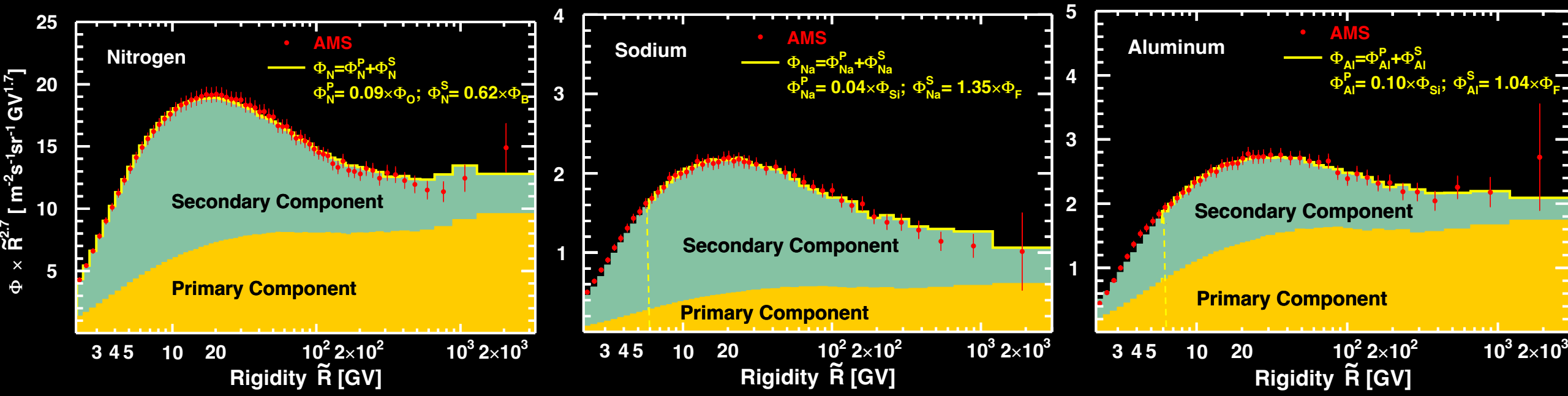
Primary cosmic rays (p, He, C, O, Ne, Mg, S ,Ar, ..., Fe) are mostly produced during the lifetime of stars and are accelerated in supernovae shocks, whose explosion rate is about 2-3 per century in our Galaxy.

Secondary cosmic nuclei (Li, Be, B, F, ...) are produced by the collisions of primary cosmic rays and interstellar medium.

Cosmic nuclei with both Primary and Secondary Components (N, Na, Al, Cl,...) . Many primary cosmic rays C, Ne, Mg, S are also expected have sizeable secondary component.

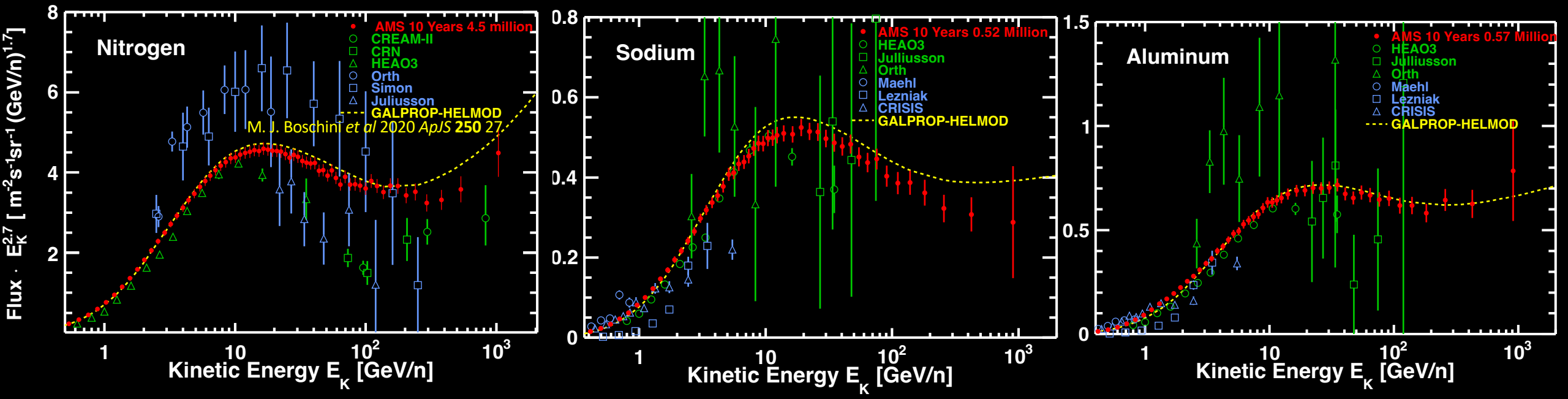
N, Na and Al fluxes can be expressed as a sum of primary (O,Si) and secondary (B,F) fluxes

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

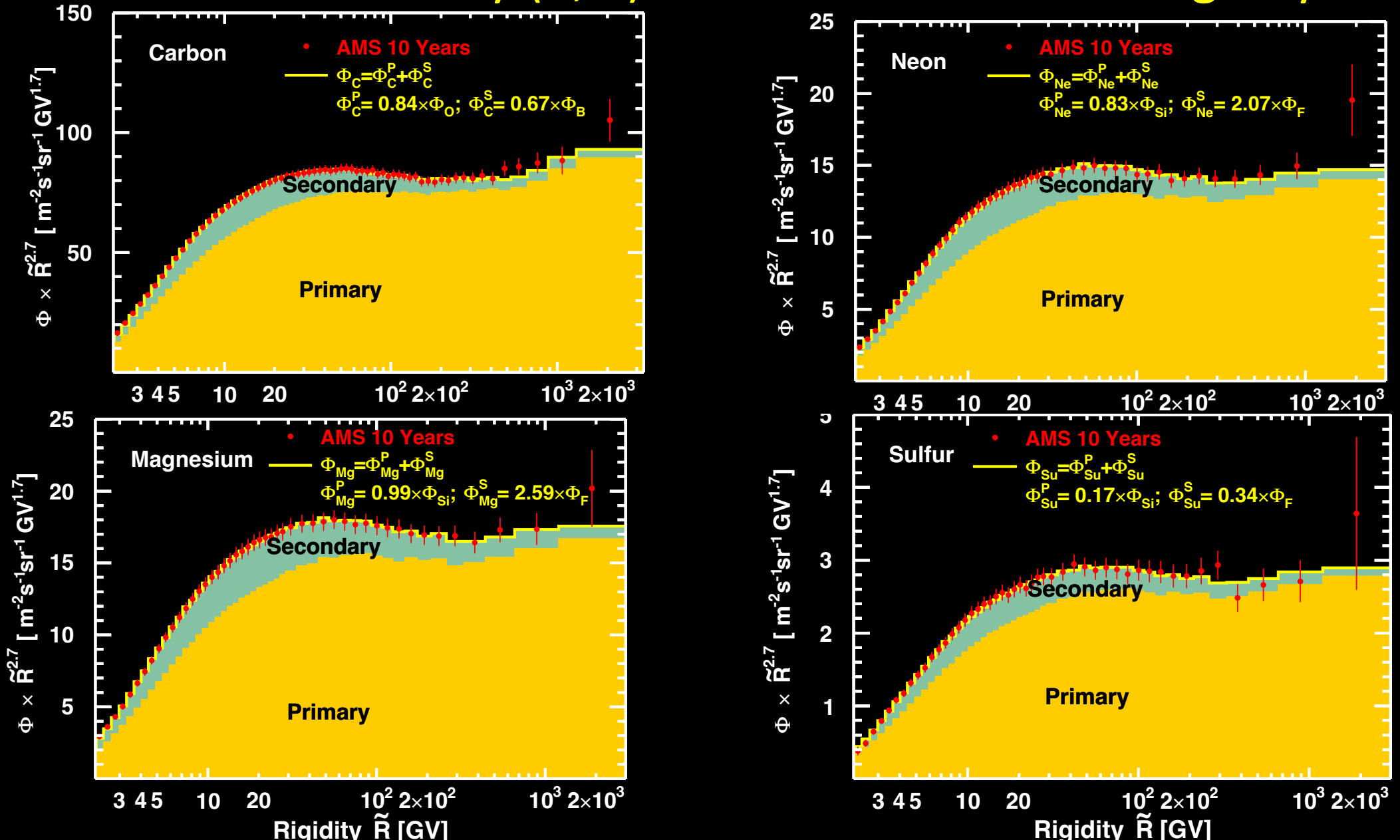


AMS N, Na, and Al Nuclei Fluxes together with earlier measurements and theory predictions.

Note that latest GALPROP-HELMOD model, based largely on AMS published data provides good agreement with AMS Na and Al measurements.



C, Ne, Mg, and S fluxes can also be expressed as a sum of primary (O,Si) and secondary (B,F) fluxes over the entire rigidity range

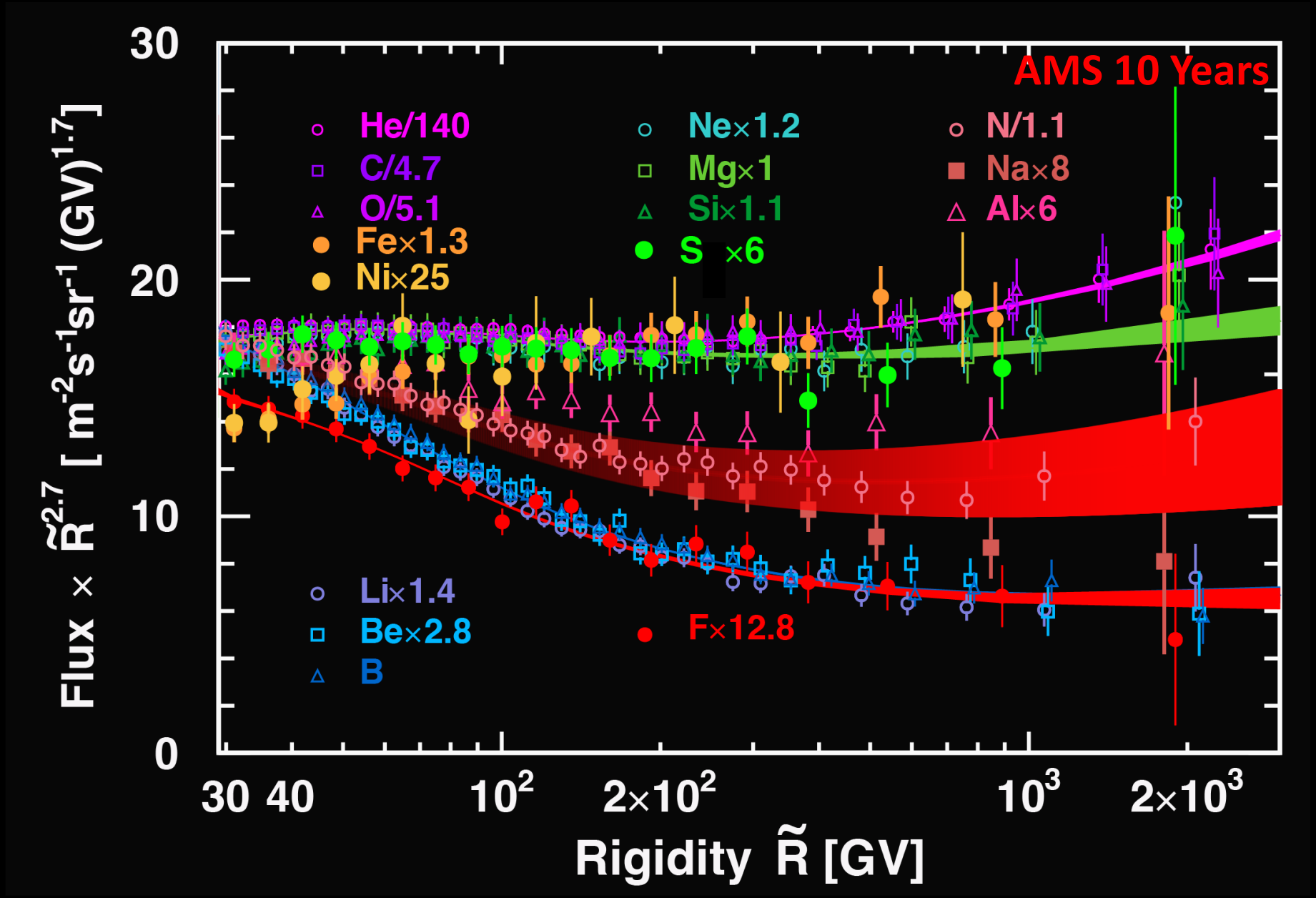


Summary C to S Primary and Secondary Components

Nuclei Flux	Primary	Secondary	Secondary Fraction,% 6 GV	Secondary Fraction,% 2 TV
Φ_C	$(0.84 \pm 0.02) \times \Phi_O$	$(0.67 \pm 0.02) \times \Phi_B$	21±1	4±0.5
Φ_N	$(0.090 \pm 0.002) \times \Phi_O$	$(0.62 \pm 0.02) \times \Phi_B$	69±1	23±2
Φ_{Ne}	$(0.83 \pm 0.02) \times \Phi_{Si}$	$(2.07 \pm 0.1) \times \Phi_F$	24±1	4±0.5
Φ_{Na}	$(0.036 \pm 0.003) \times \Phi_{Si}$	$(1.35 \pm 0.04) \times \Phi_F$	81±2	32±1
Φ_{Mg}	$(0.99 \pm 0.03) \times \Phi_{Si}$	$(2.59 \pm 0.09) \times \Phi_F$	25±1	4±0.5
Φ_{Al}	$(0.104 \pm 0.005) \times \Phi_{Si}$	$(1.04 \pm 0.03) \times \Phi_F$	57±2	14±1
Φ_S	$(0.165 \pm 0.005) \times \Phi_{Si}$	$(0.34 \pm 0.04) \times \Phi_F$	24±1	4±0.5

The C (Z=6) to S (Z=16) cosmic ray nuclei primary and secondary components derived as fractions of O(Si) and B(F) fluxes, respectively, and their secondary fractions at 6 GV and 2 TV.

This allows to measure relative cosmic ray abundances of C, N, Ne, Na, Mg, Al, and S at the source independently of cosmic ray propagation.


AMS 10 Years
He/140
C/4.7
O/5.1
Fe×1.3
Ni×25
Ne×1.2
Mg×1
Si×1.1
S ×6
N/1.1
Na×8
Al×6
Li×1.4
Be×2.8
B
F×12.8
Flux × R̃^2.7 [m^-2 s^-1 sr^-1 (GV)^1.7]
Rigidity R̃ [GV]
30
20
10
0
30 40
10^2
2×10^2
10^3
2×10^3

AMS is the only magnetic spectrometer in space.

The results from AMS are unlocking the secrets of the cosmos.

AMS will continue to take data for the ISS life time,

exploring properties of cosmic ray up to Zn and beyond.