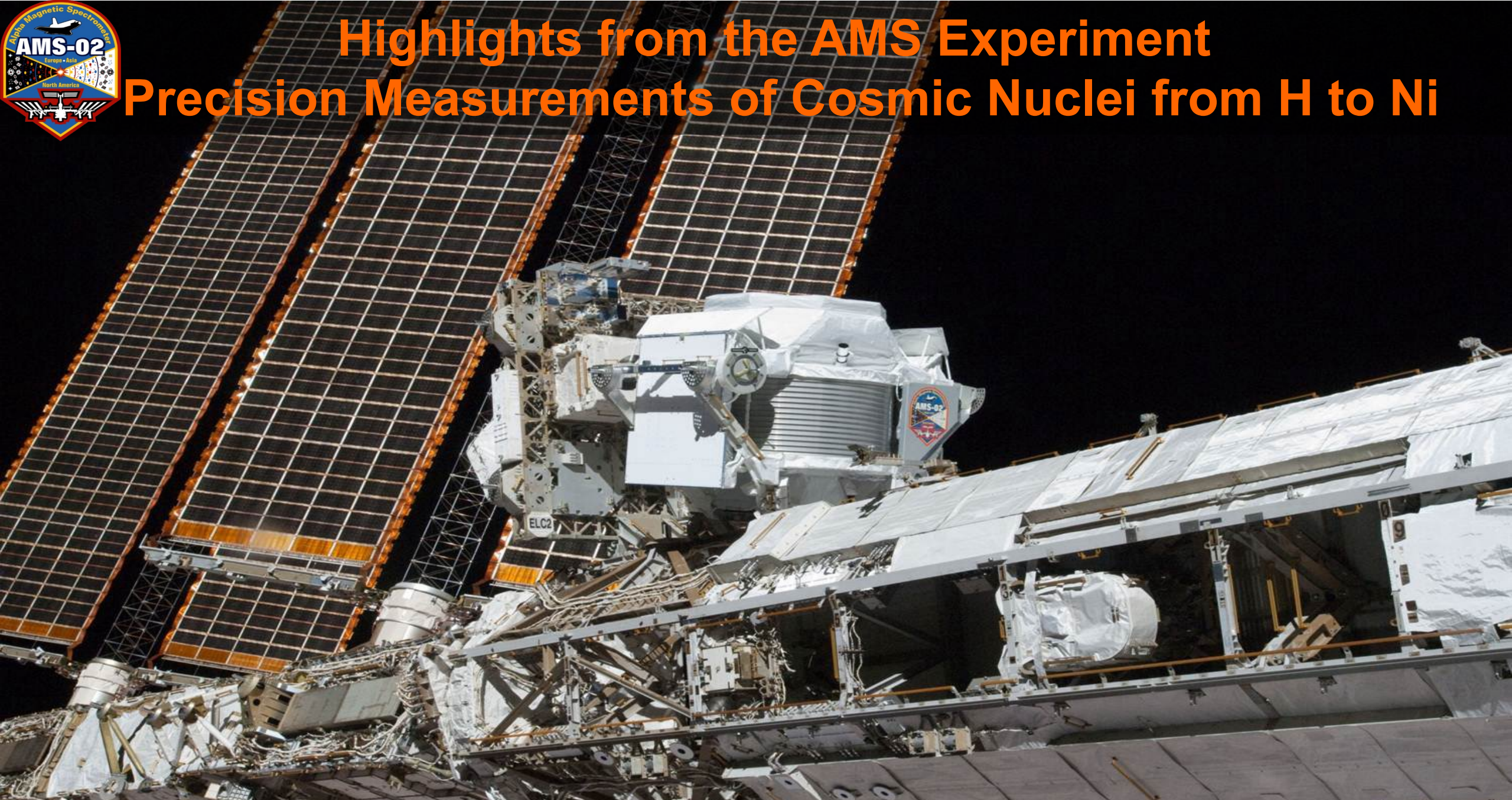




Highlights from the AMS Experiment

Precision Measurements of Cosmic Nuclei from H to Ni



September 3rd, 2026

TeVPA 2026 Tendo, JAPAN

V. CHOUTKO/ M.I.T.

AMS Launch May 2011

Space Shuttle Endeavour

Mission STS-134



To-date 268 billion cosmic. rays have been measured by AMS: e^+ , e^- , p , $\bar{p}$, nuclei, γ ,...

350 billion events expected to 2030

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

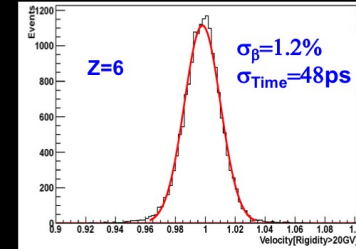
AMS-02: A TeV precision magnetic spectrometer in space

Transition Radiation Detector

Identifies e^+ , e^-

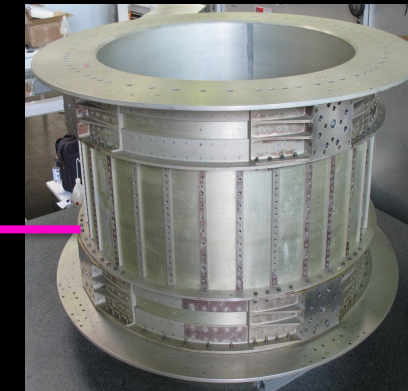
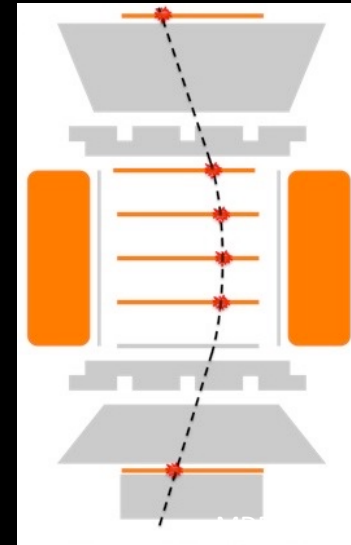
Time Of Flight

Z, β



Magnet

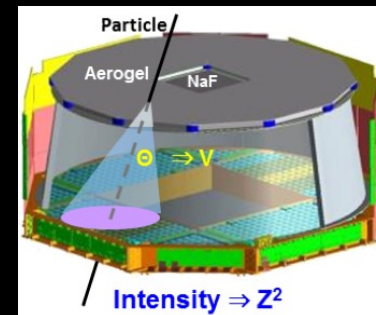
$\pm Z$



Ring Imaging Cherenkov

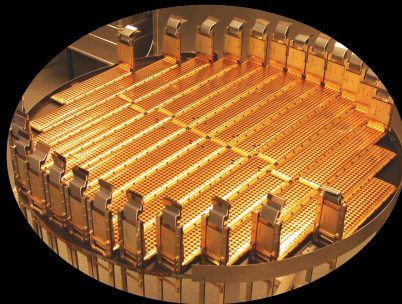
Z, β

Isotopic composition



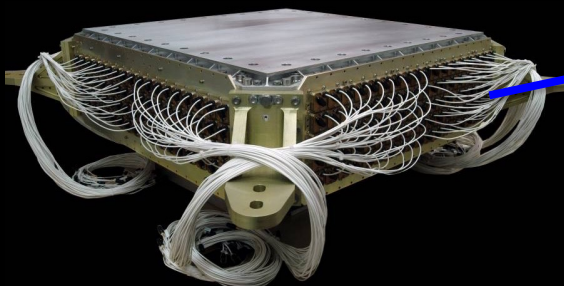
Silicon Tracker

$Z, \text{Rigidity} = p/Zc$



Electromagnetic Calorimeter

Energy of e^+ , e^-



TRD

TOF

2

3-4

Tracker

5-6

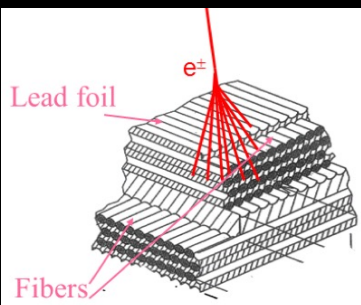
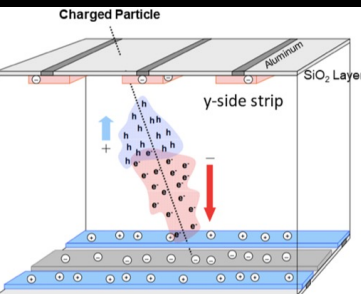
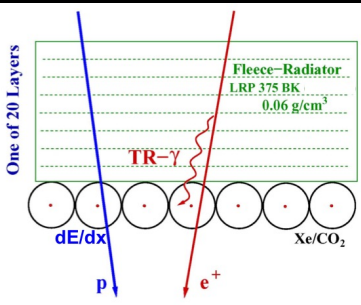
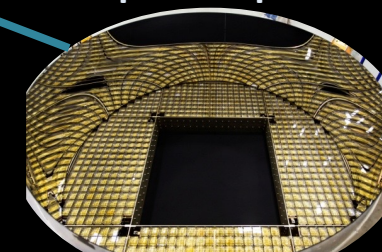
7-8

TOF

RICH

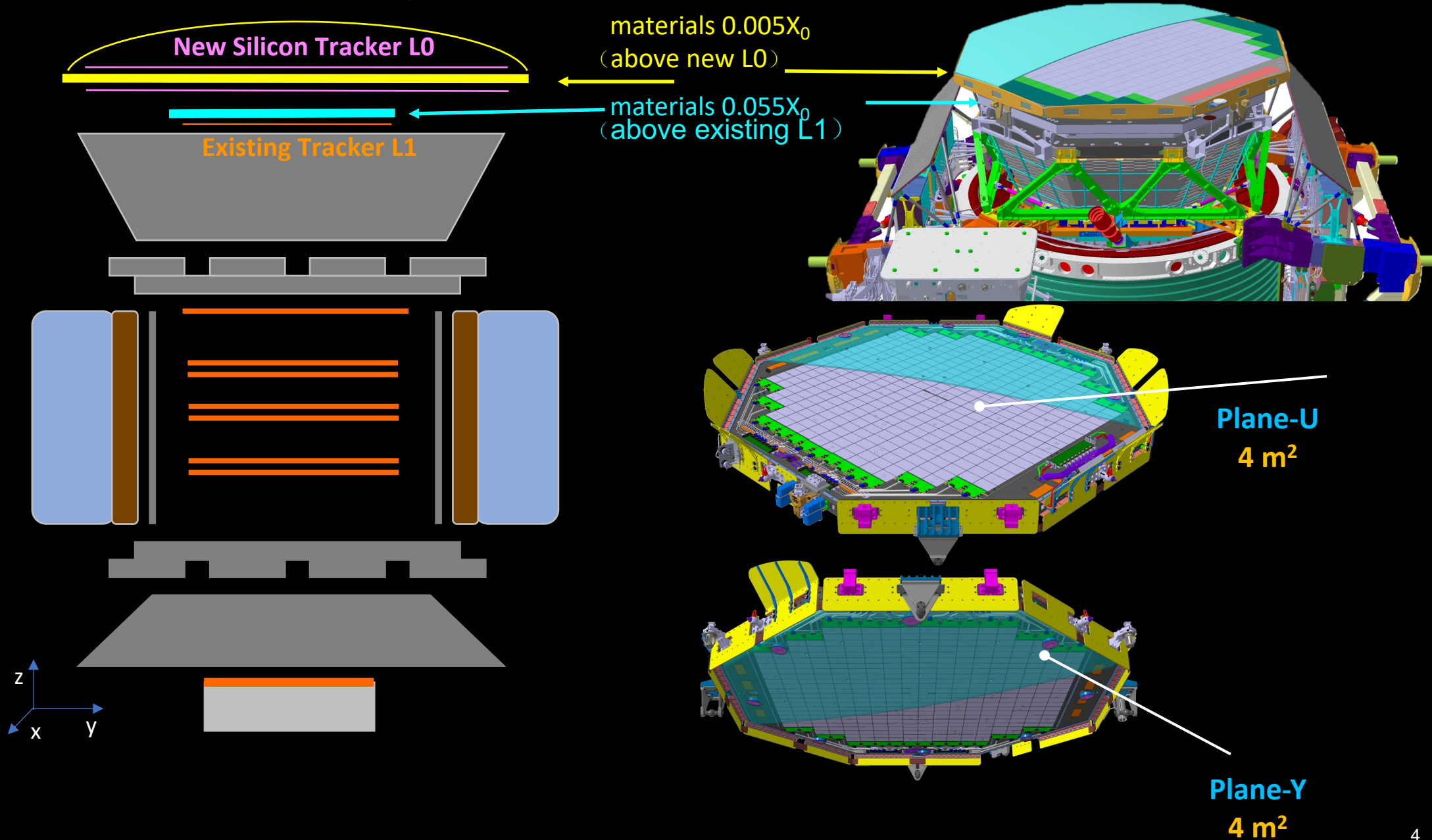
9

ECAL



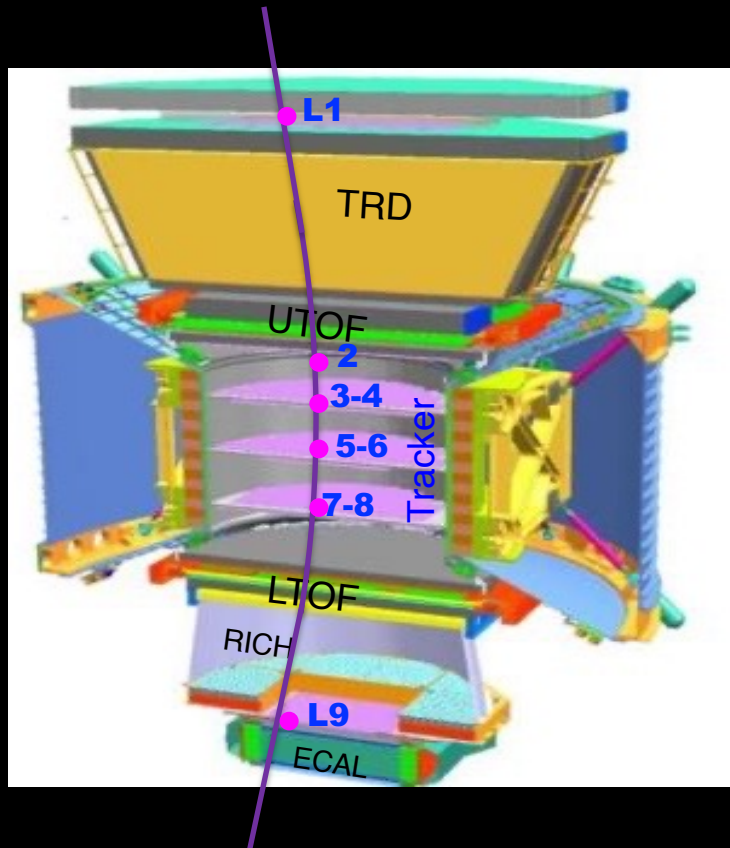
AMS on ISS: 2027-2030+

With Completion of L0 Upgrade AMS Acceptance will be Increased by 300% with Minimal Materials Above



AMS Nuclei Flux Measurements

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



Coordinate Resolution

MDR

$Z=1$

$10 \mu\text{m}$

2 TV

$Z \geq 2$

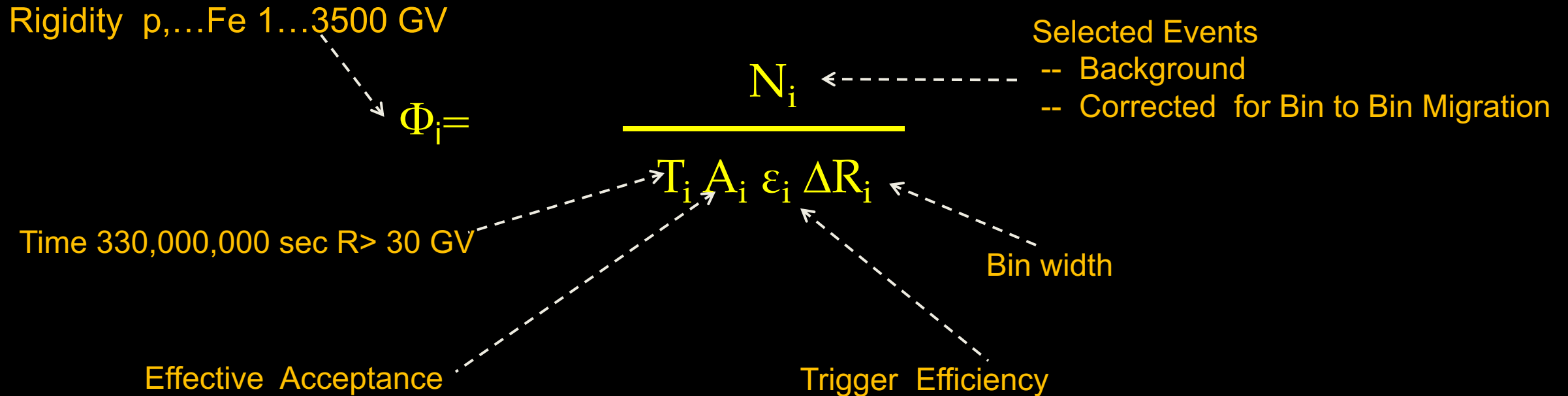
$5-8 \mu\text{m}$

3.0-3.7 TV

ToF (4 Layers): Velocity and Direction
 $\Delta\beta/\beta^2 \approx 1-2\%$ ($Z \geq 2$), 4% ($Z=1$)

L1, UTOF, Inner Tracker (L2-L8), LTOF and L9
Consistent Charge Along Particle Trajectory
Inner Tracker Charge Resolution:
 $\Delta Z = 0.05 - 0.35$ ($1 \leq Z \leq 28$)

AMS Nuclei Flux Measurements

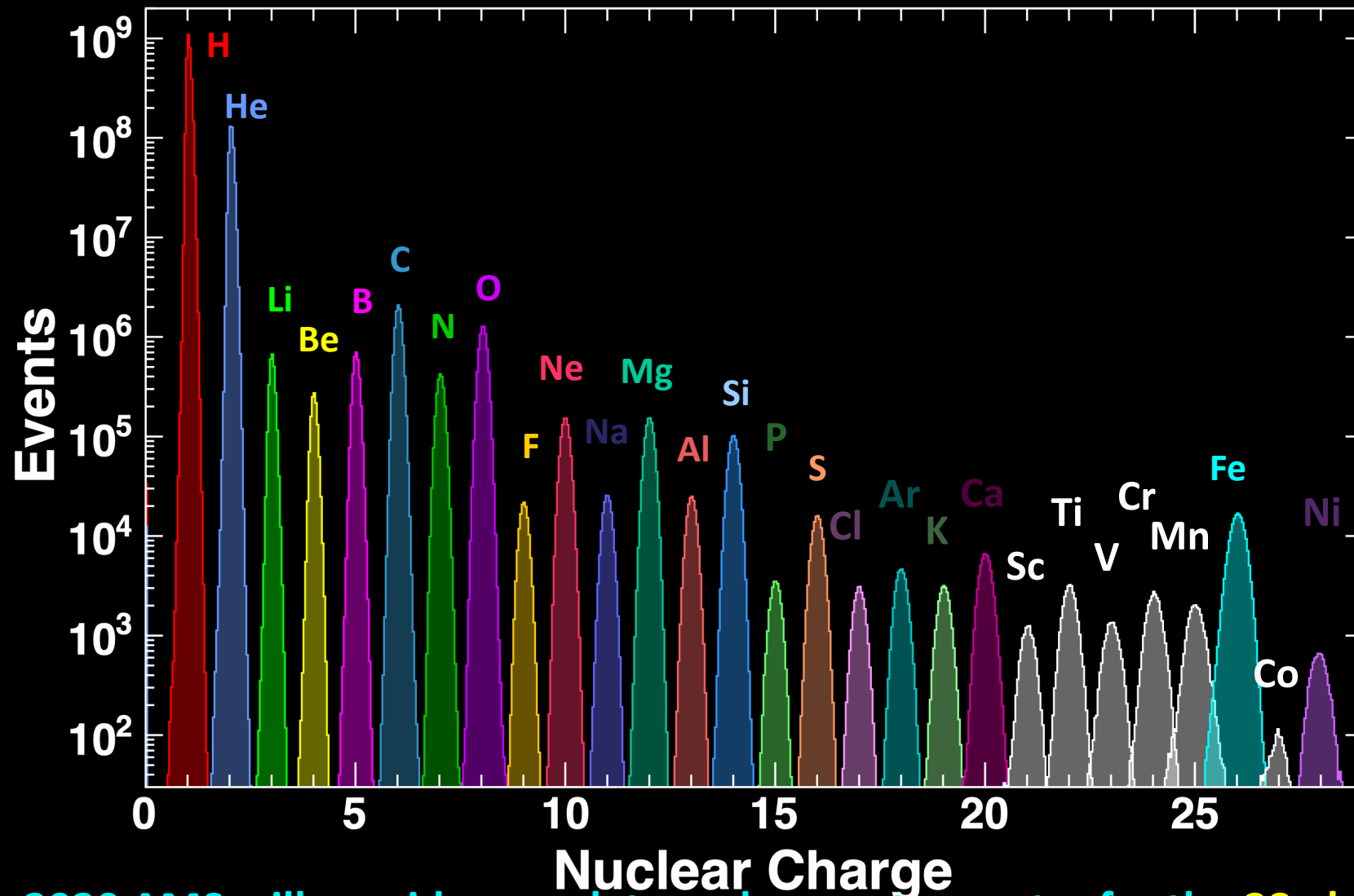


Measurements require knowledge of detector performance details, resolution functions, acceptance ... obtained by AMS Monte Carlo Simulations

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 $N_i, A_i, \varepsilon_i, T_i$ for each flux

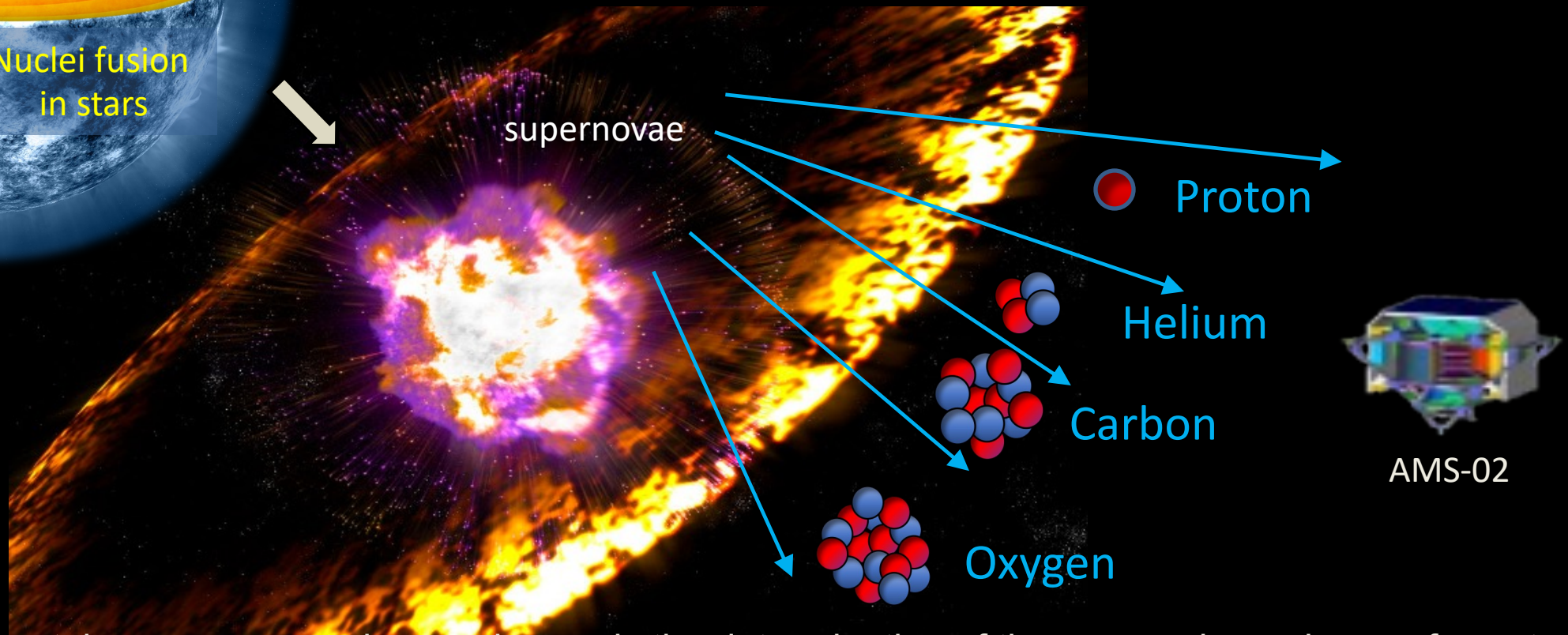
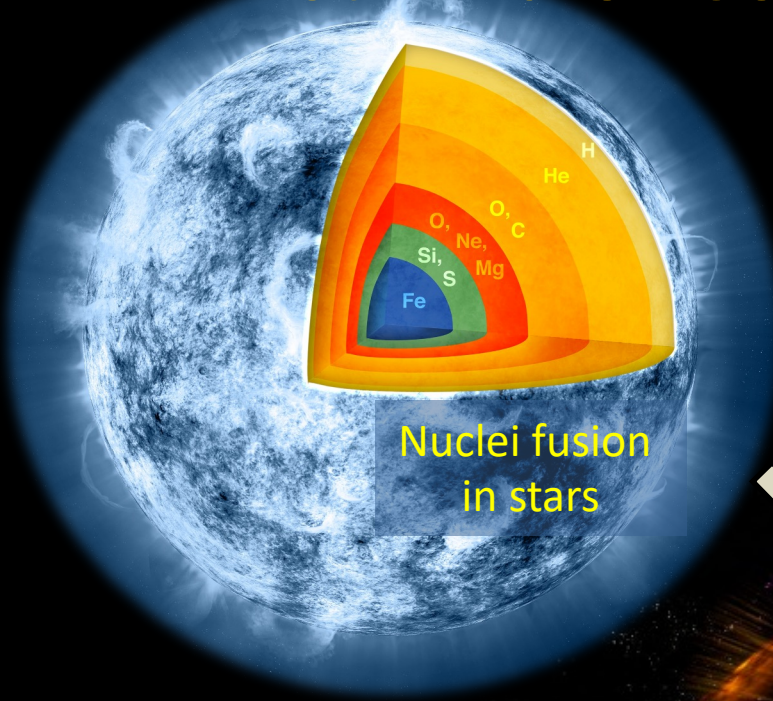
AMS Study of Cosmic Nuclei



By 2030 AMS will provide complete and accurate spectra for the 28 elements

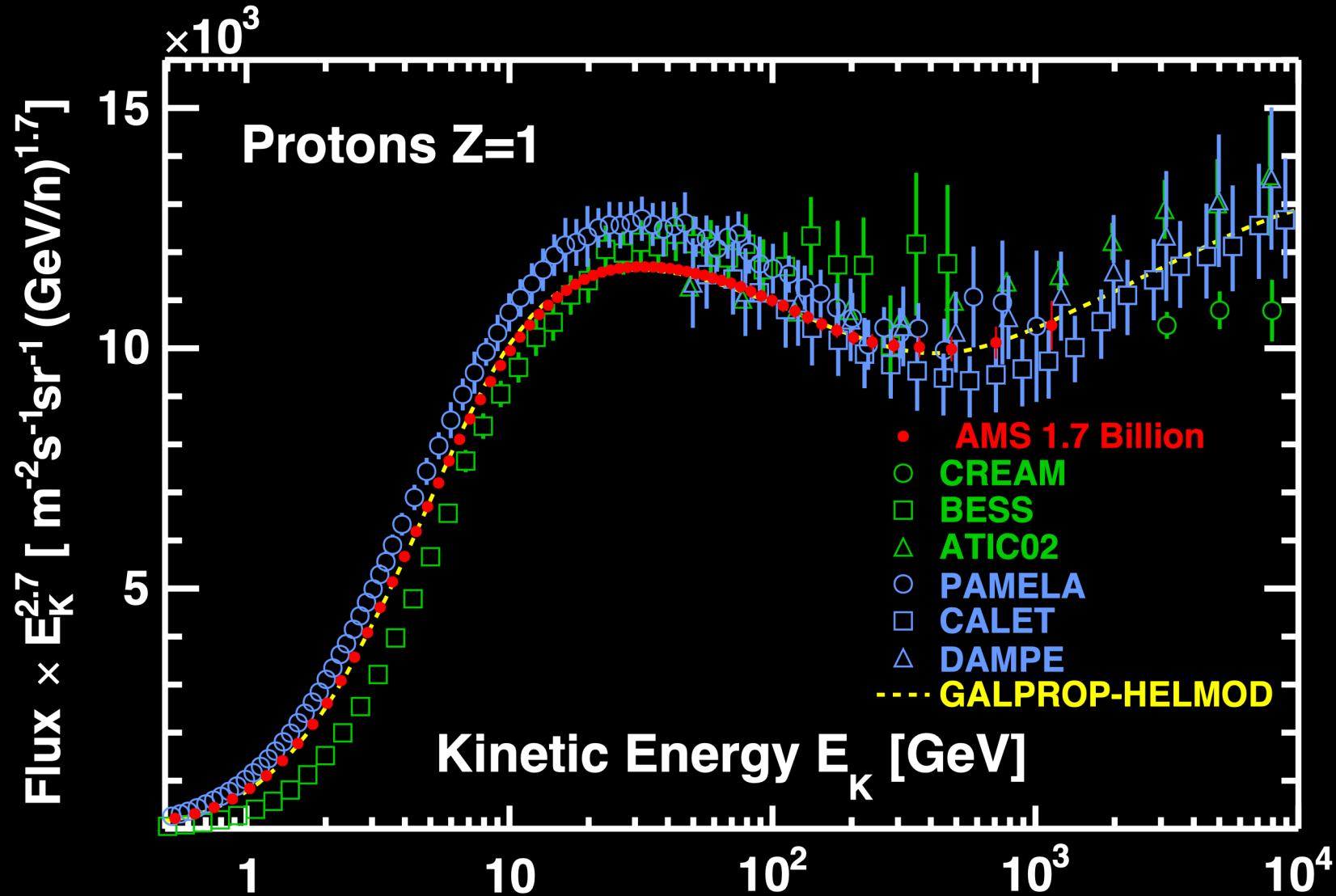
First kind of Cosmic Ray Nuclei: Primary Cosmic Rays

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.



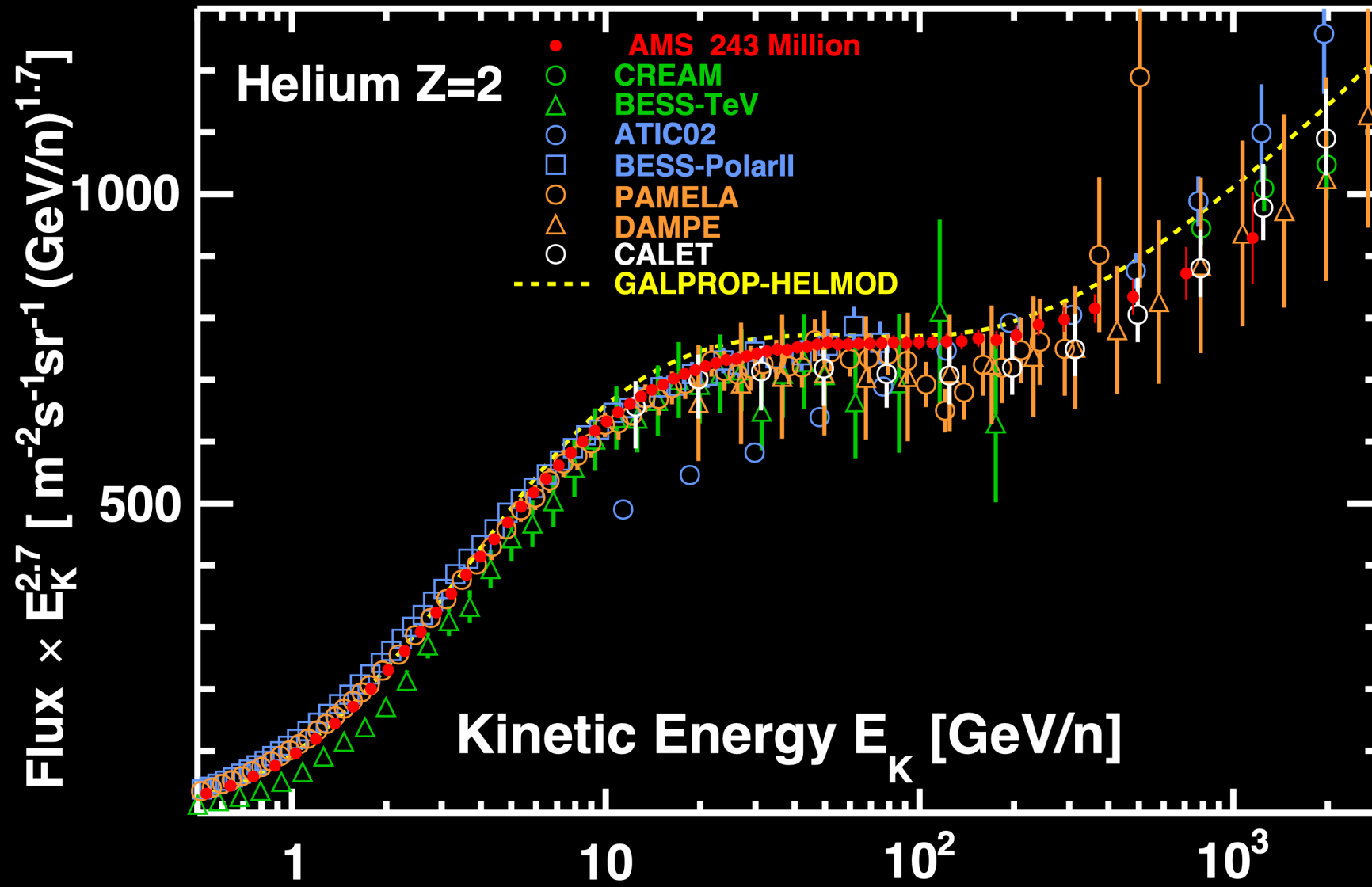
One of the fundamental measurements in cosmic rays is the determination of the energy dependence of spectra of cosmic ray nuclei from protons to Fe and beyond. Their spectra (fluxes) carry the information about cosmic rays production and acceleration in the astrophysical sources and their propagation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

Latest AMS proton flux measurement



AMS provides the most accurate p measurement in the energy range 1 GeV to 1.8 TeV

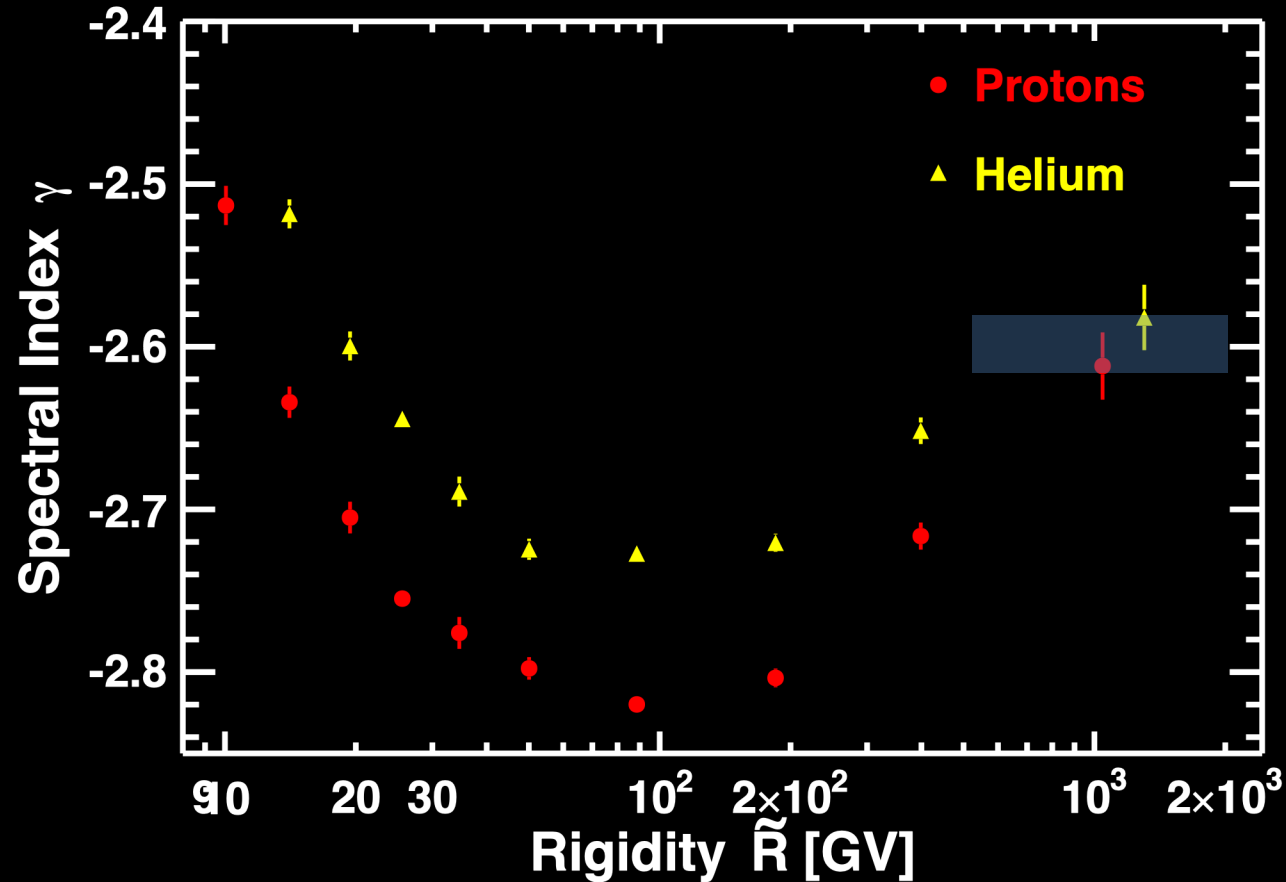
Latest AMS Helium flux measurement



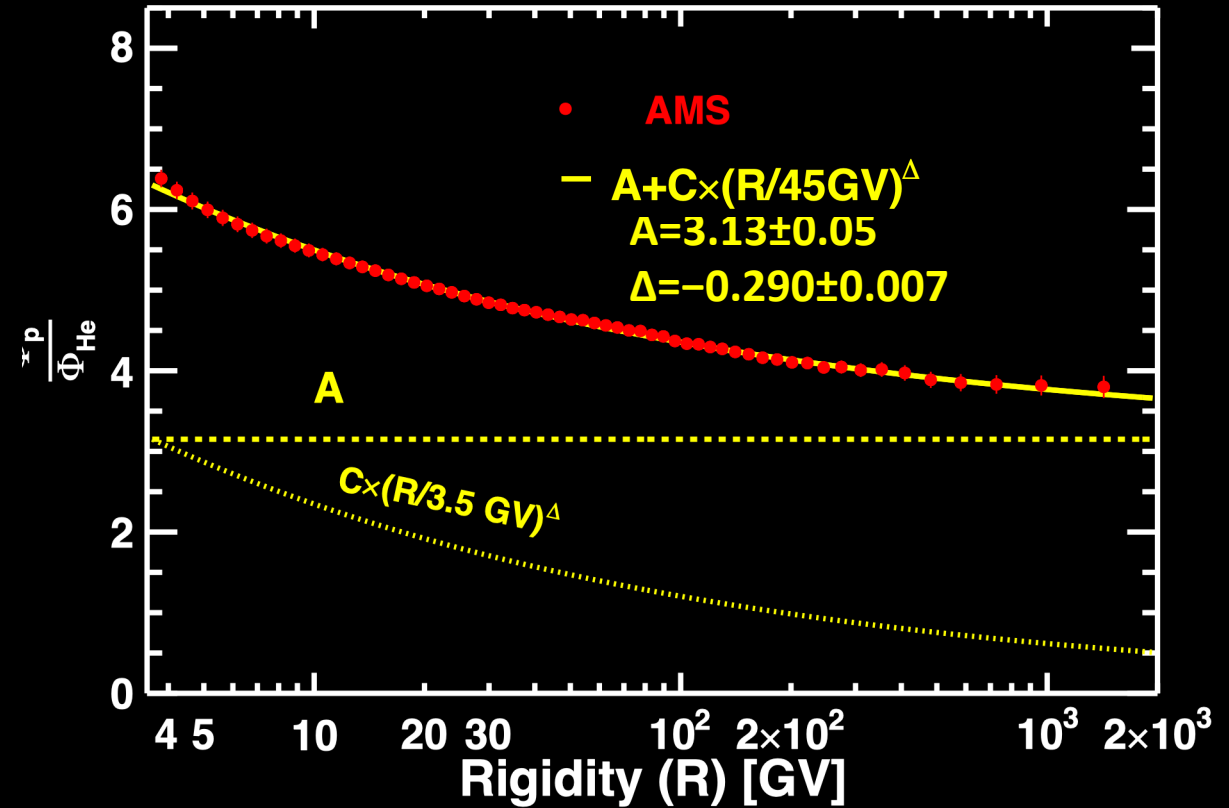
AMS provides the most accurate He measurement in the energy range 1 GeV to 6 TeV

Proton/Helium Flux Ratio

$$\gamma = d\log\Phi / d\log R$$

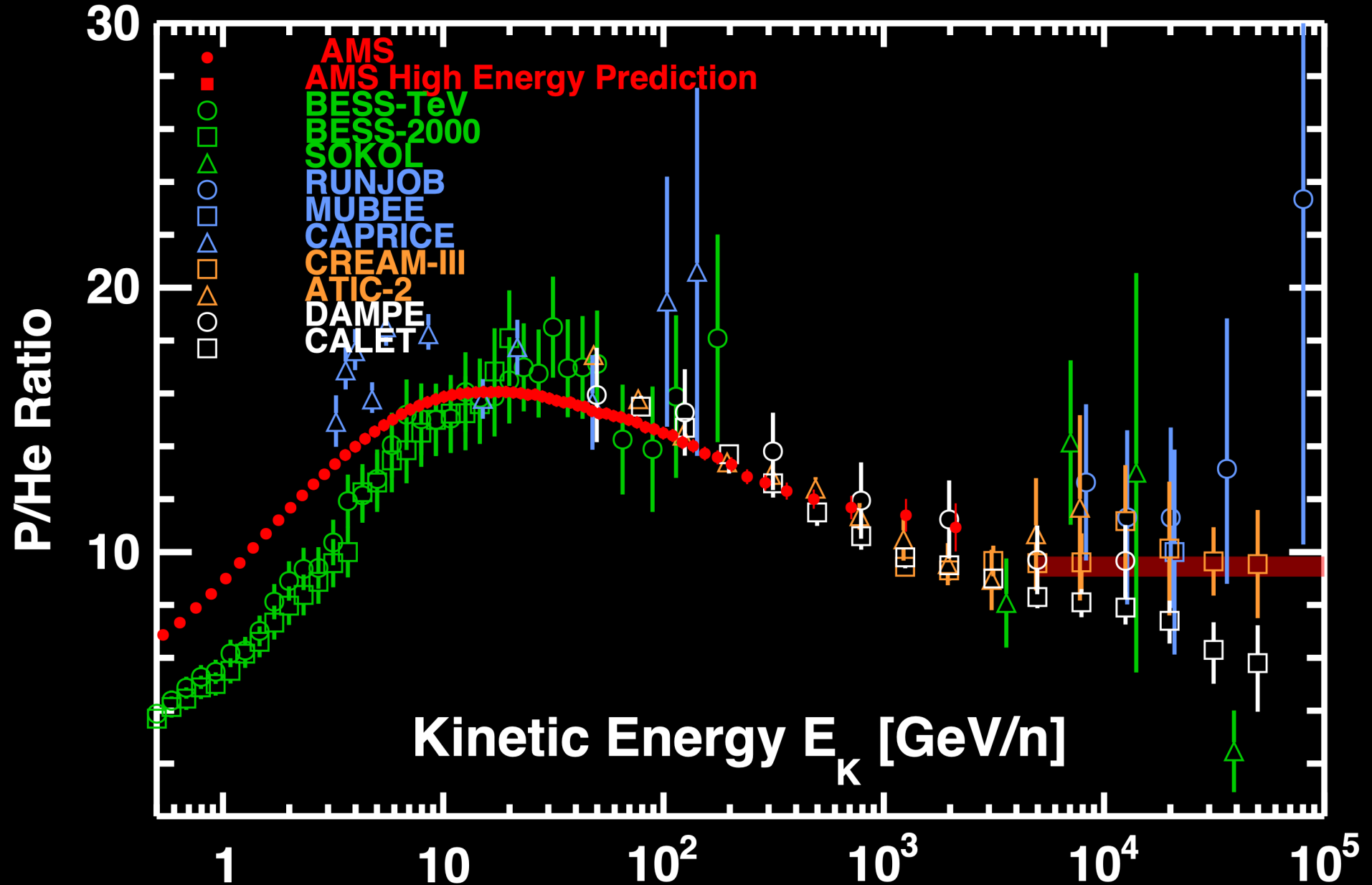


P and He may have same spectral index at highest rigidities



AMS found that proton flux have two components, one is like Helium and another is unique to proton flux. 11

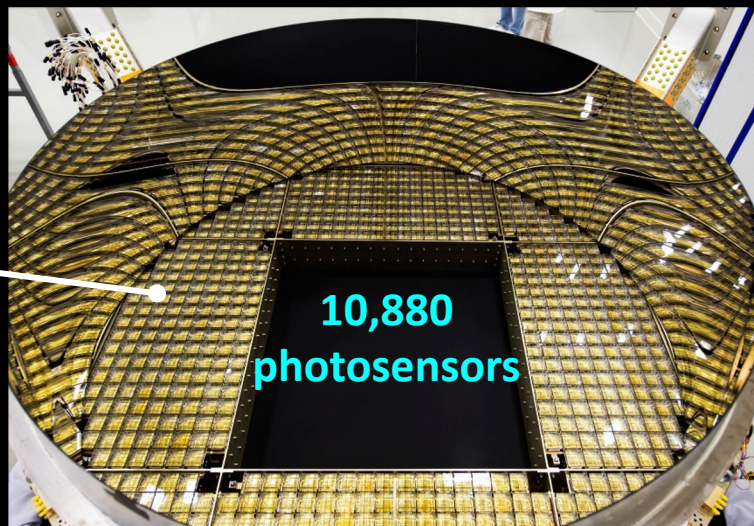
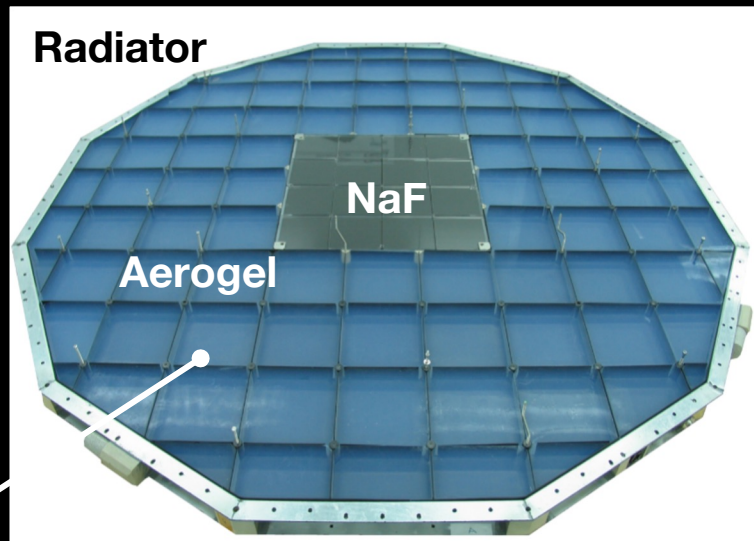
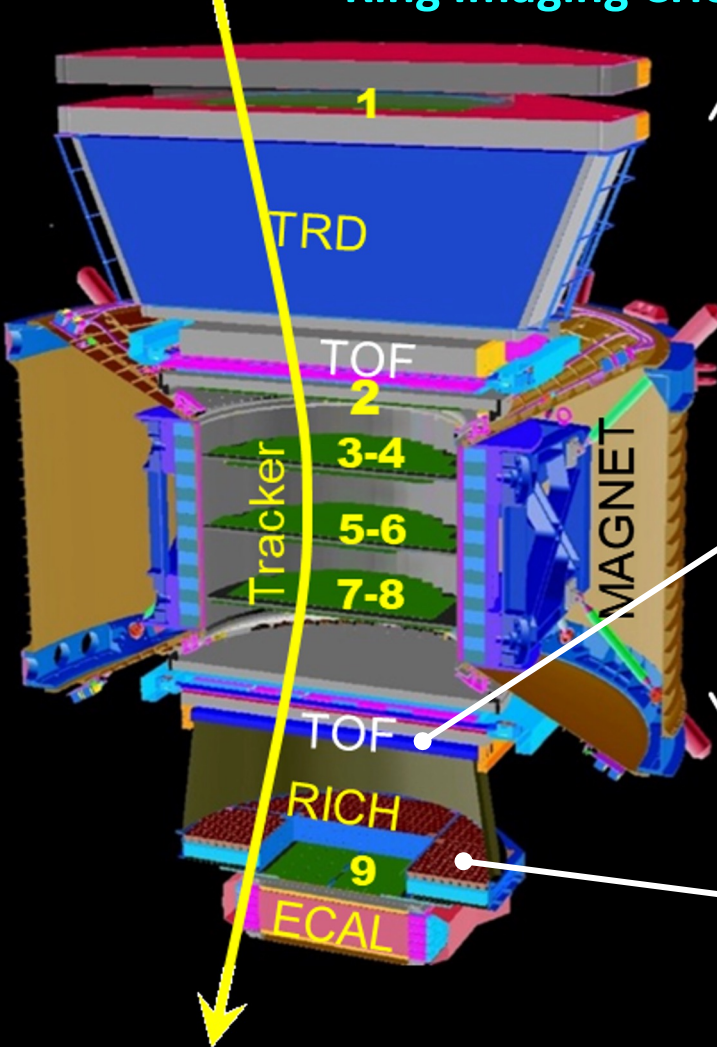
Proton/Helium Flux Ratio



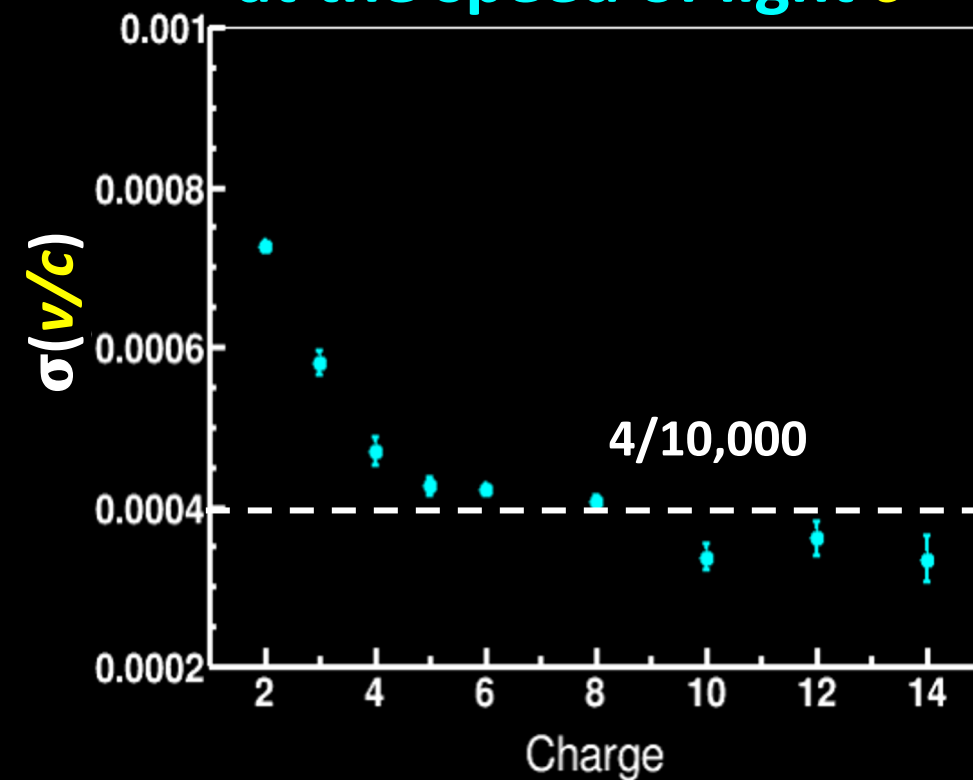
Precision measurement of isotopes

Isotopes: Same Z , different m

Ring Imaging CHerenkov (RICH)



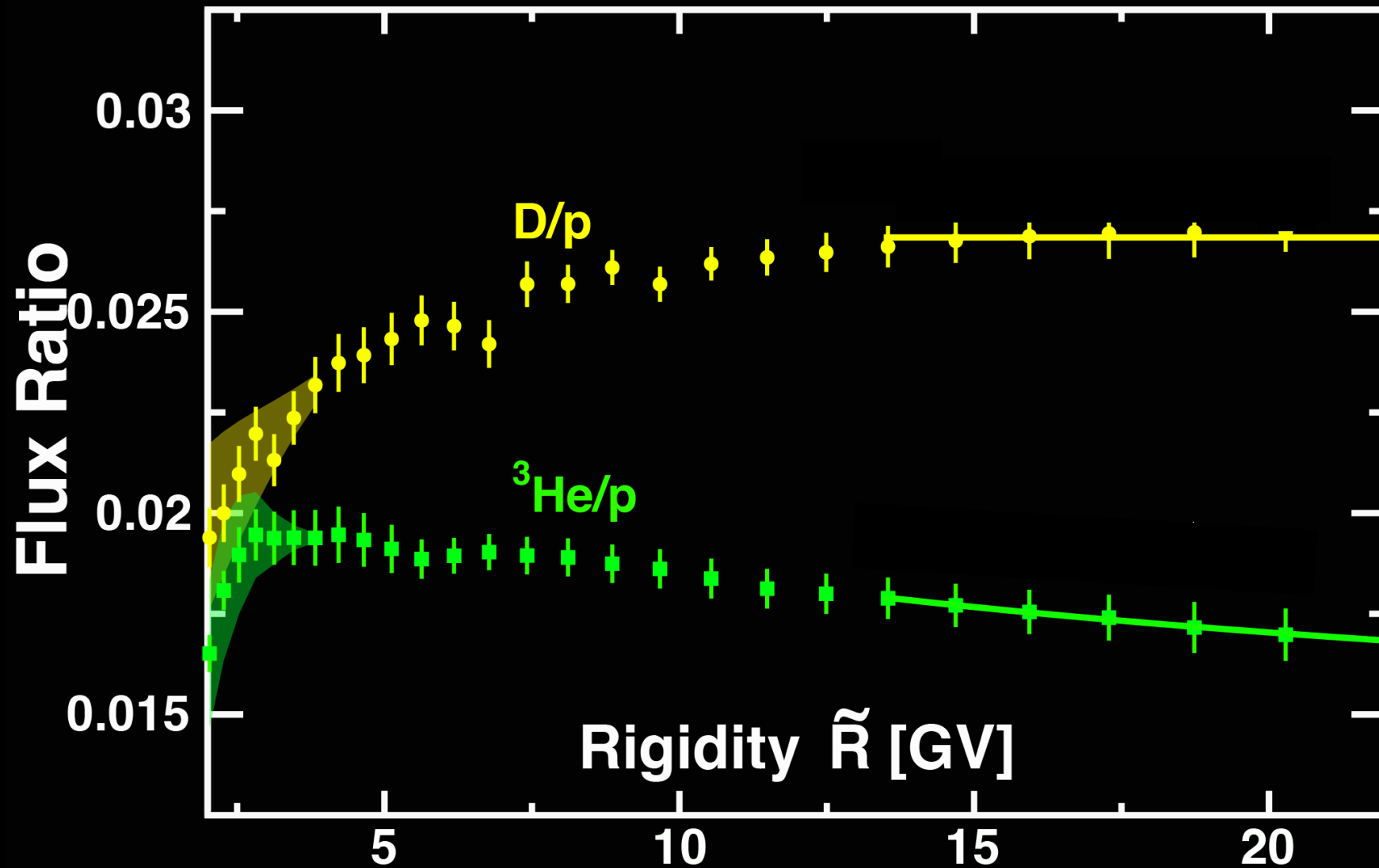
**RICH velocity v resolution
at the speed of light c**



Origin of Cosmic Deuterons D

He, C, O, ... + Interstellar Media $\rightarrow$ (D, ^3He) + X

D and ^3He are both known to be secondary cosmic rays



The flux ratio of $^3\text{He}/p$ decreases with rigidity above 4 GV.

If D is pure secondary, the flux ratio of D/p must also decrease with rigidity above ~ 4 GV

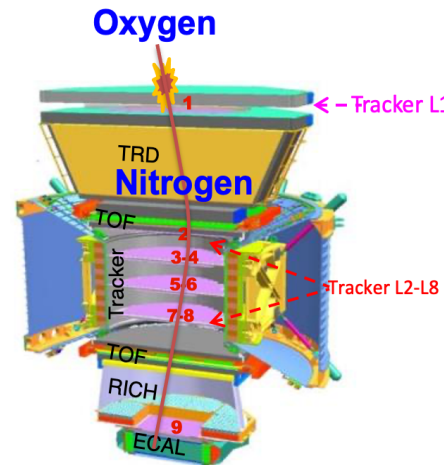
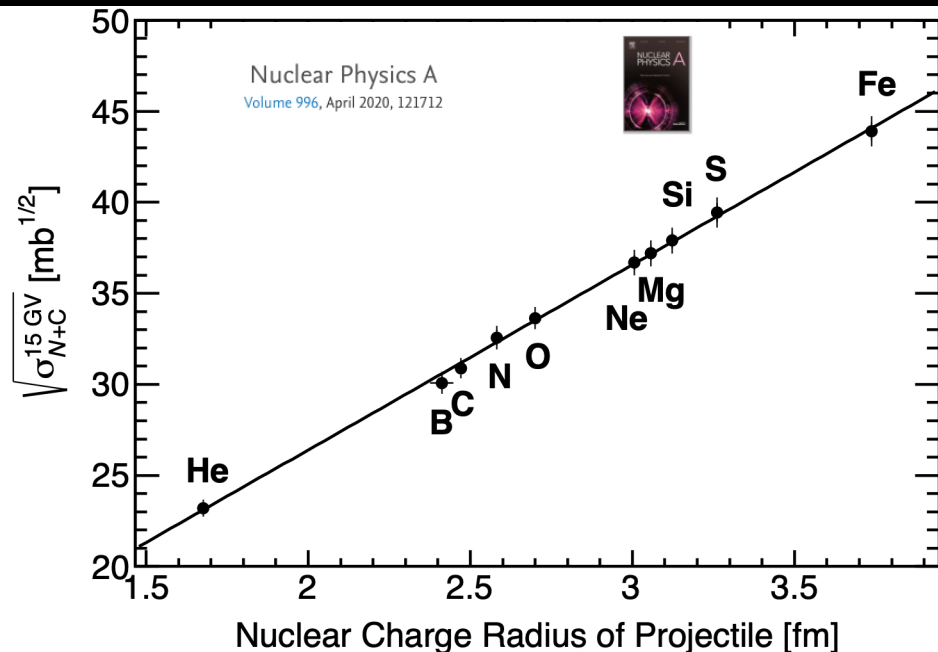
The flux ratio of D/p increases with rigidity and is about to be constant above 13 GV.

D must have an additional primary source

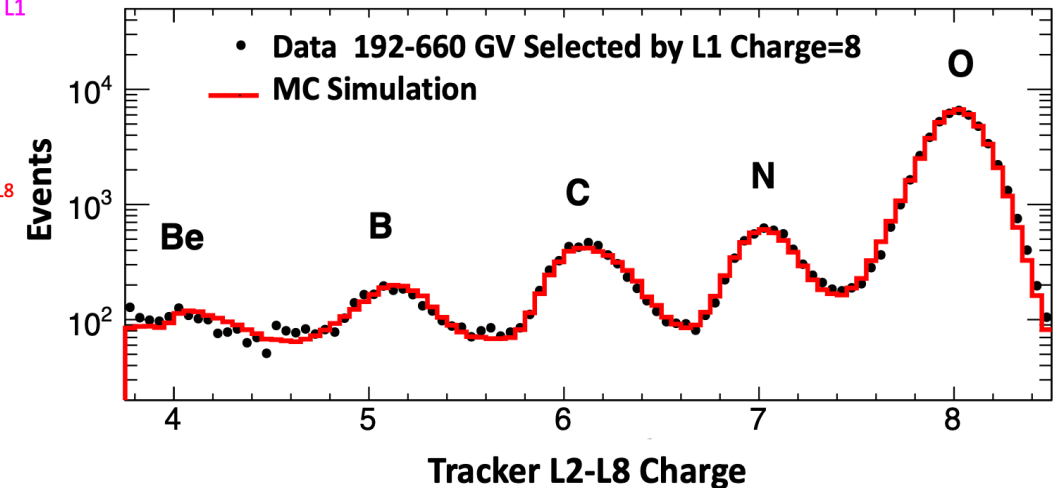
AMS Heavy Nuclei Interactions

- Nuclei Interactions Simulation

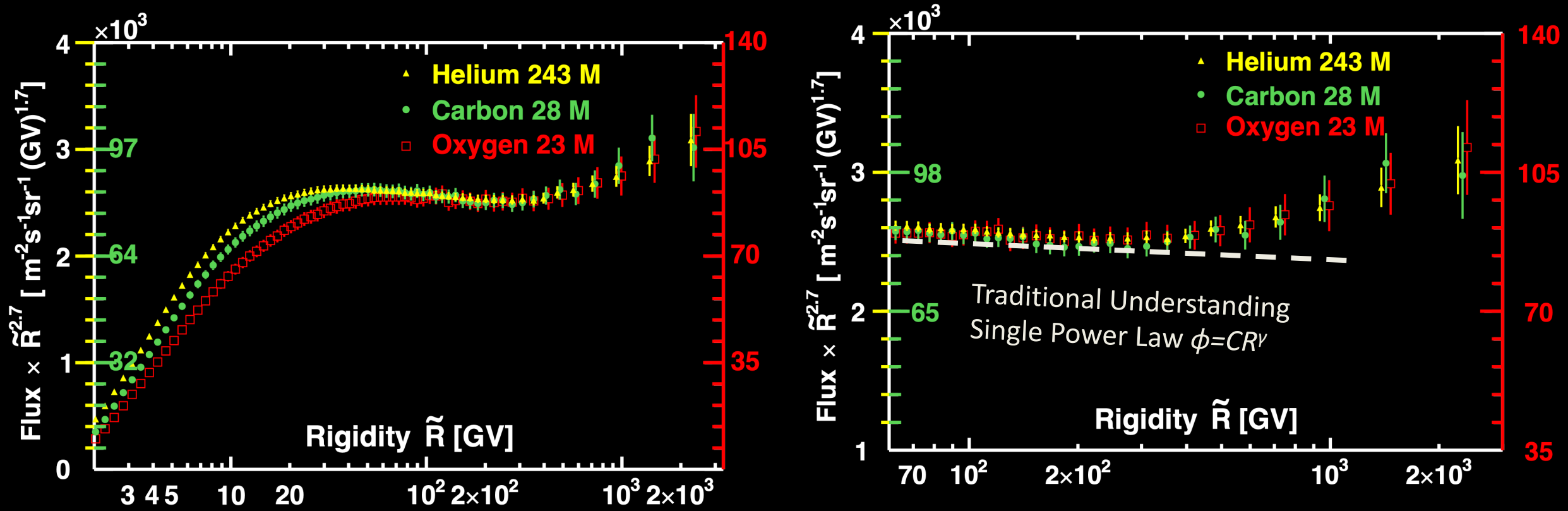
- cross section data set (AMS), elastic and quasy-elastic scattering (AMS), low energy inelastic interactions, fission, nuclei deexcitation (GEANT4-10)
- Most up to date model for nuclei interactions at high energies (DPMJET3)
 - designed to simulate all nucleus and hadron ($1 \leq A_p \leq 208$) inelastic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



MC simulation interactions $\text{O} \rightarrow \text{N, C, B, Be} \dots$



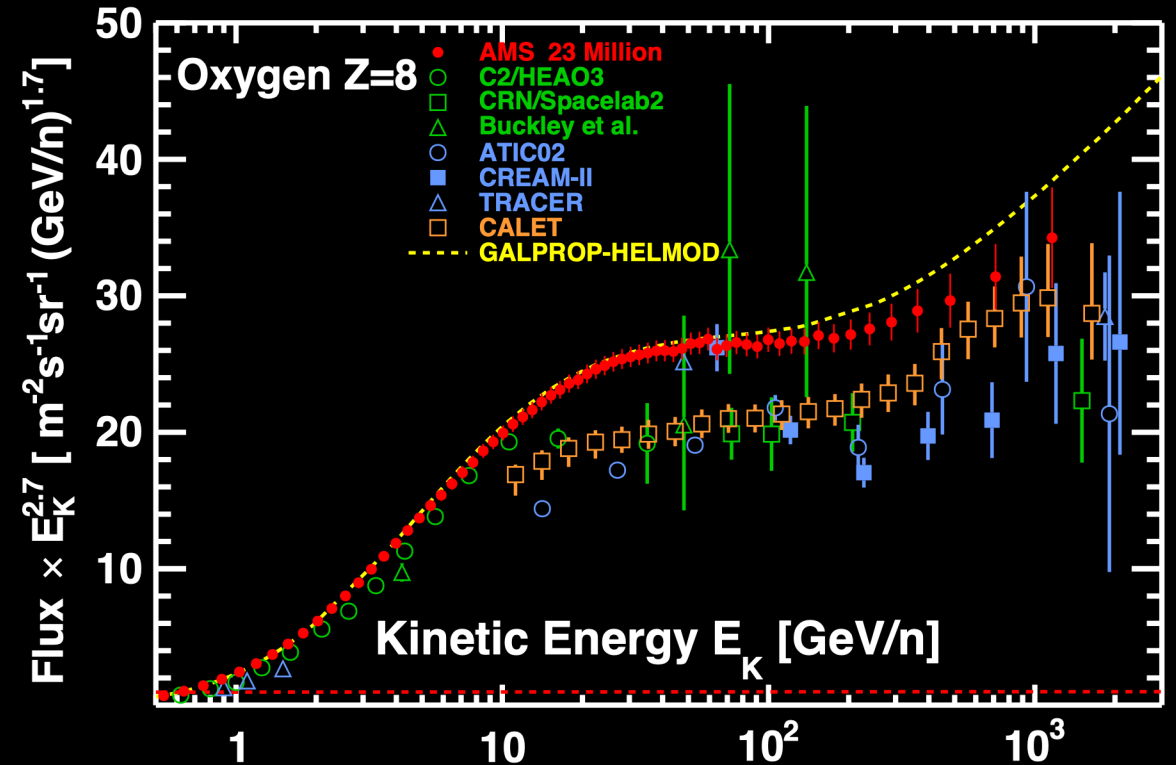
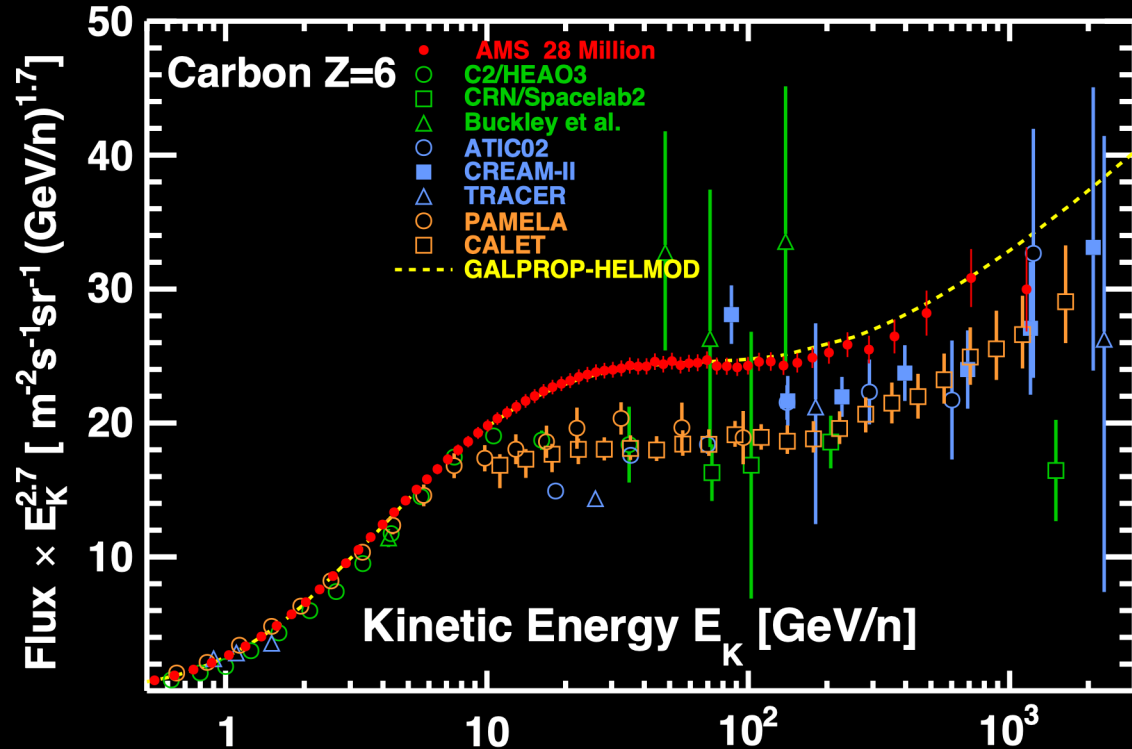
Latest AMS Measurements of He, C and O spectra



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

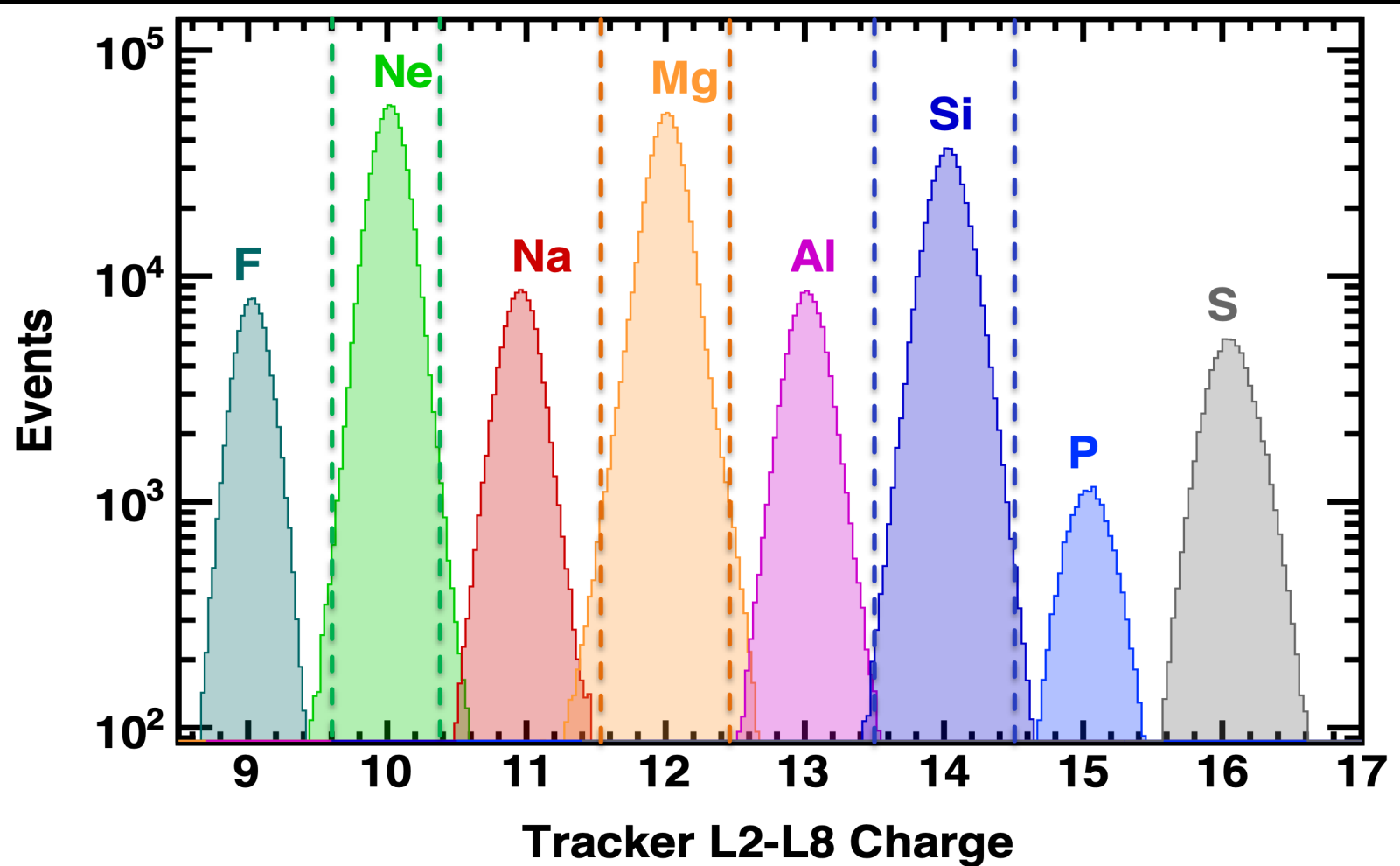
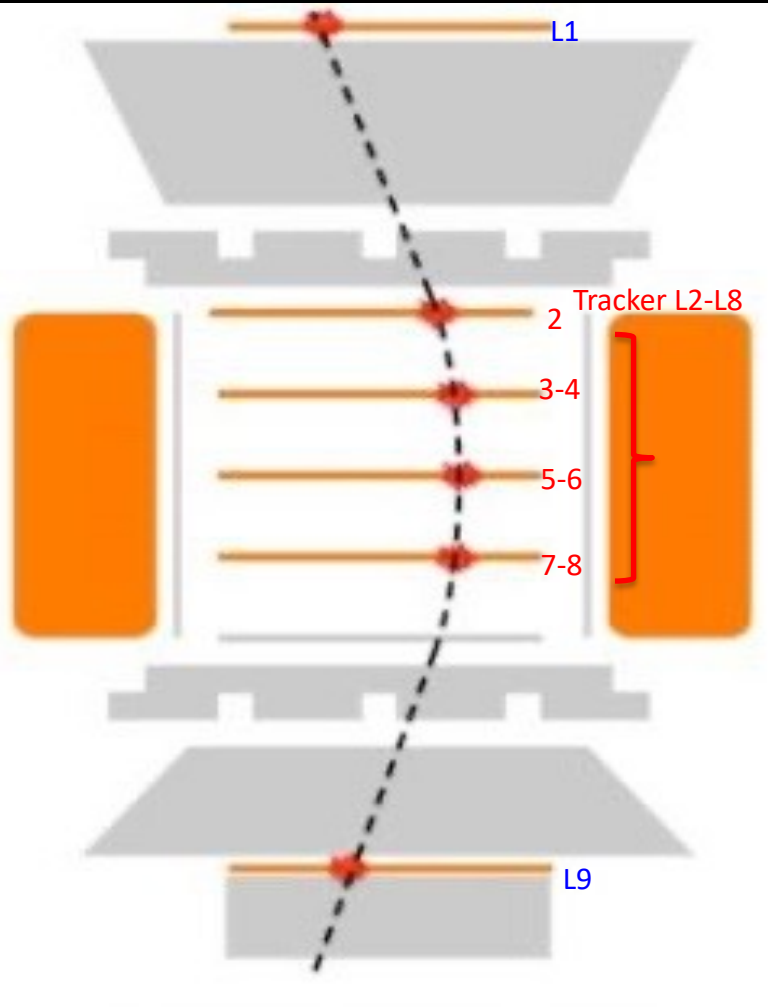
AMS C and O Nuclei Flux Measurements:

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 $< 0.1\%$

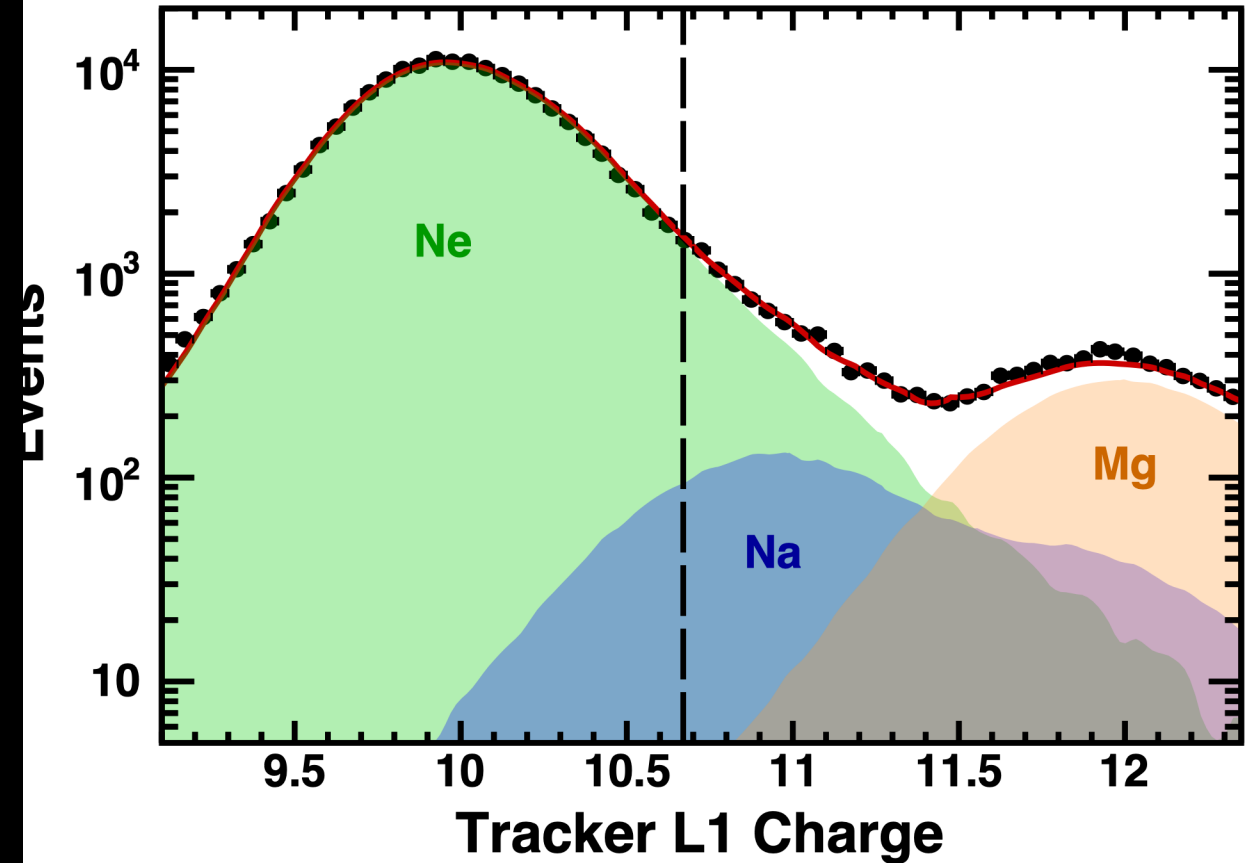
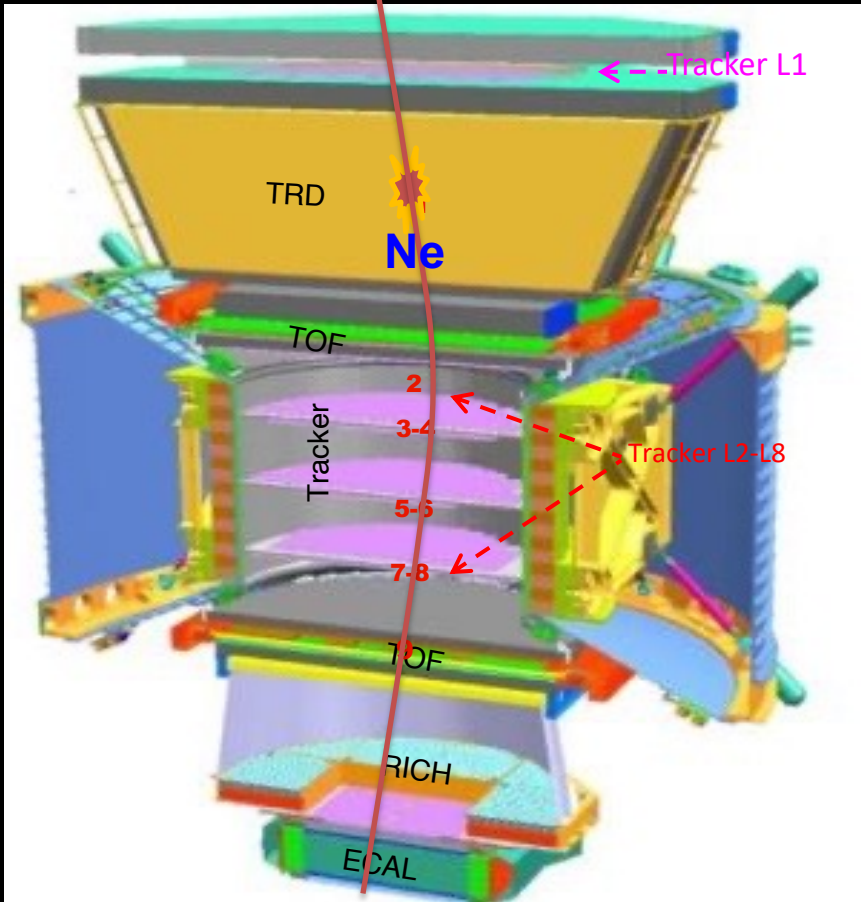


For the events $R > 4$ GV selected by Tracker L1, UpperTOF and LowerTOF.

Background from Nuclei Interactions

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

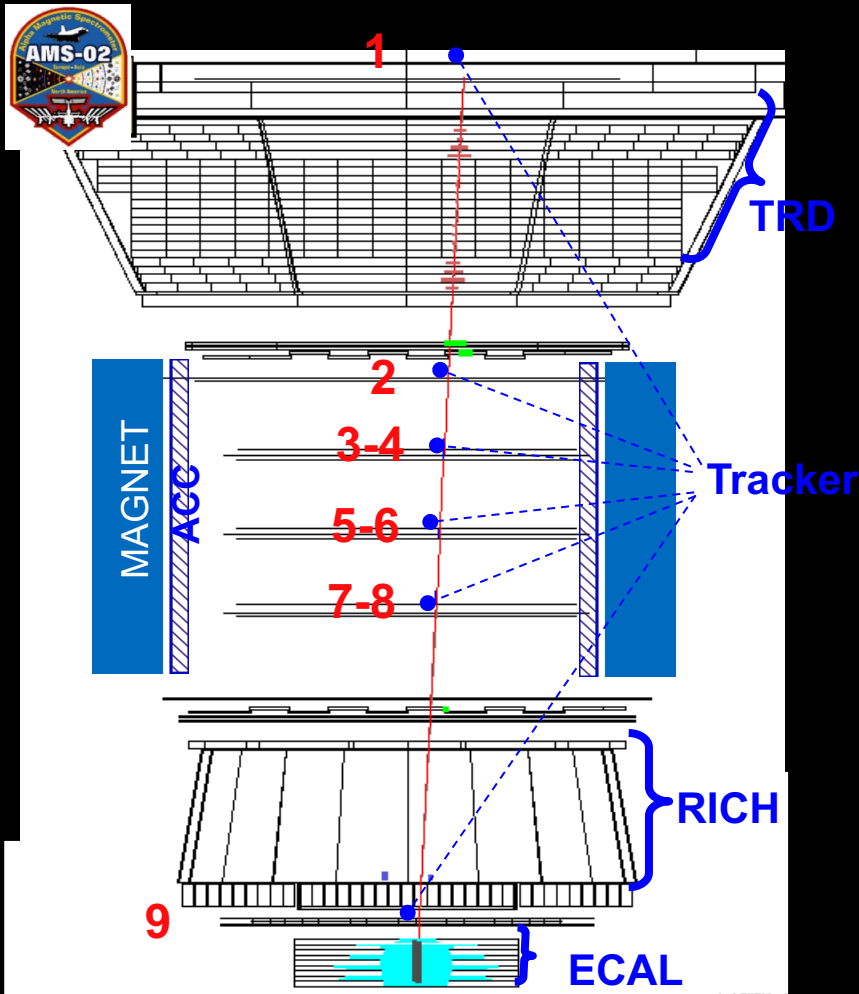
Na, Mg, ...



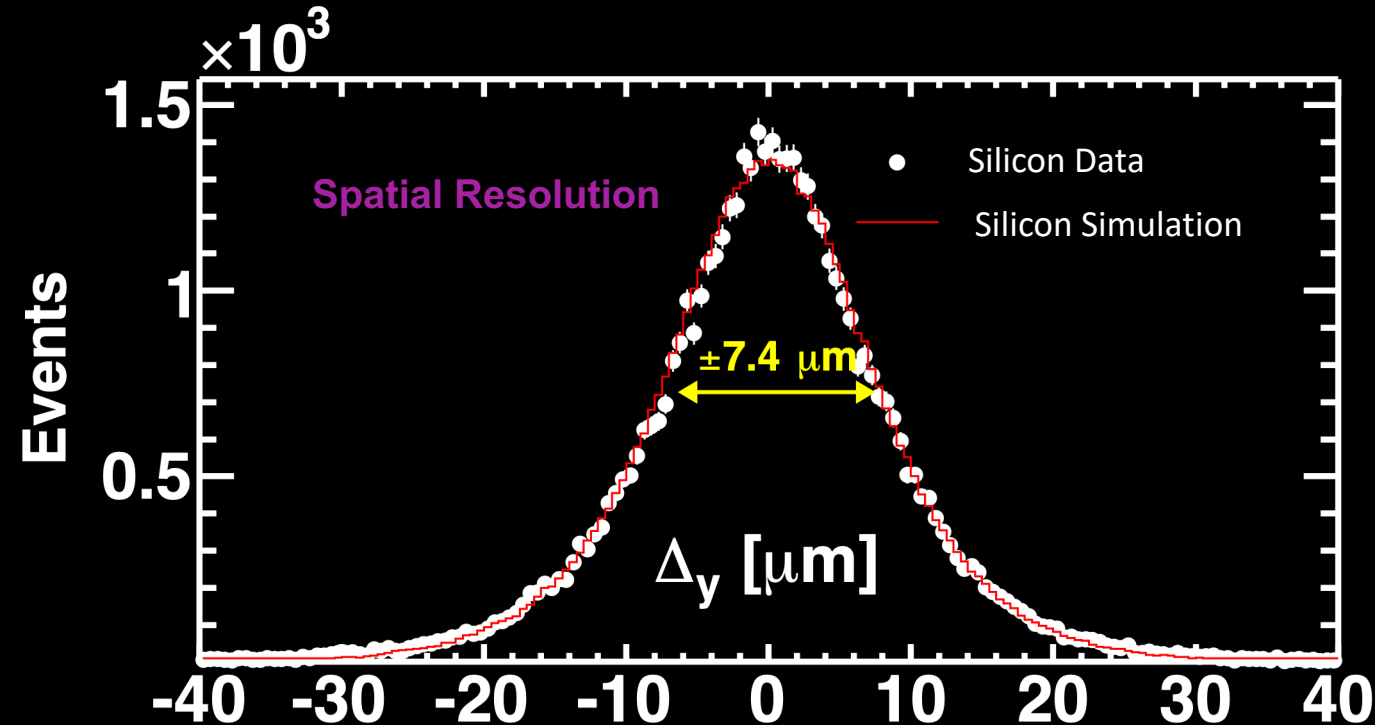
For the events $18 < R < 22$ GV selected by Tracker L2-L8.

Ne-Mg-Si Rigidity Resolution

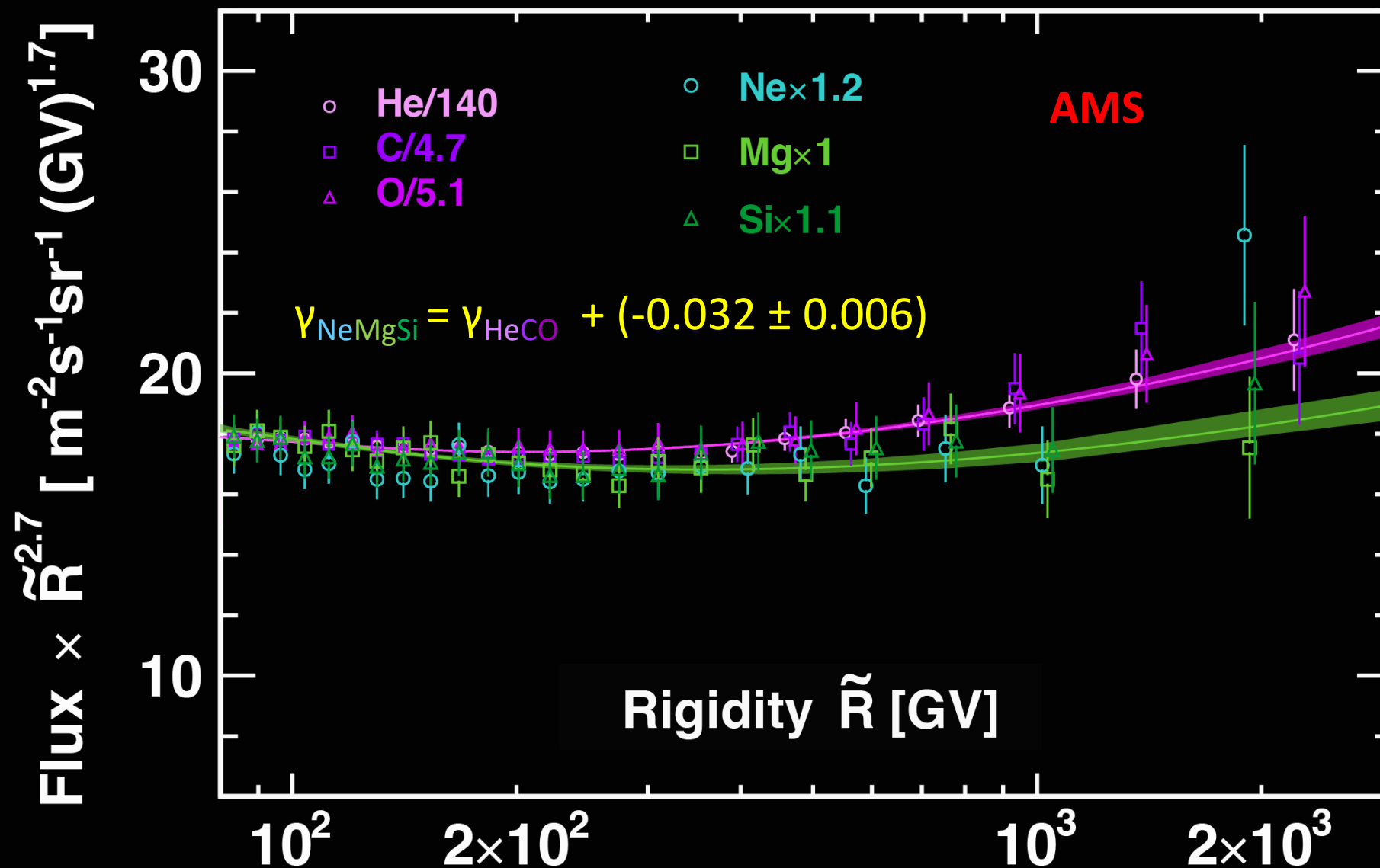
The tracker spatial resolution is 6.7 μm for Ne, 7.1 μm for Mg, and 7.4 μm for Si.



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

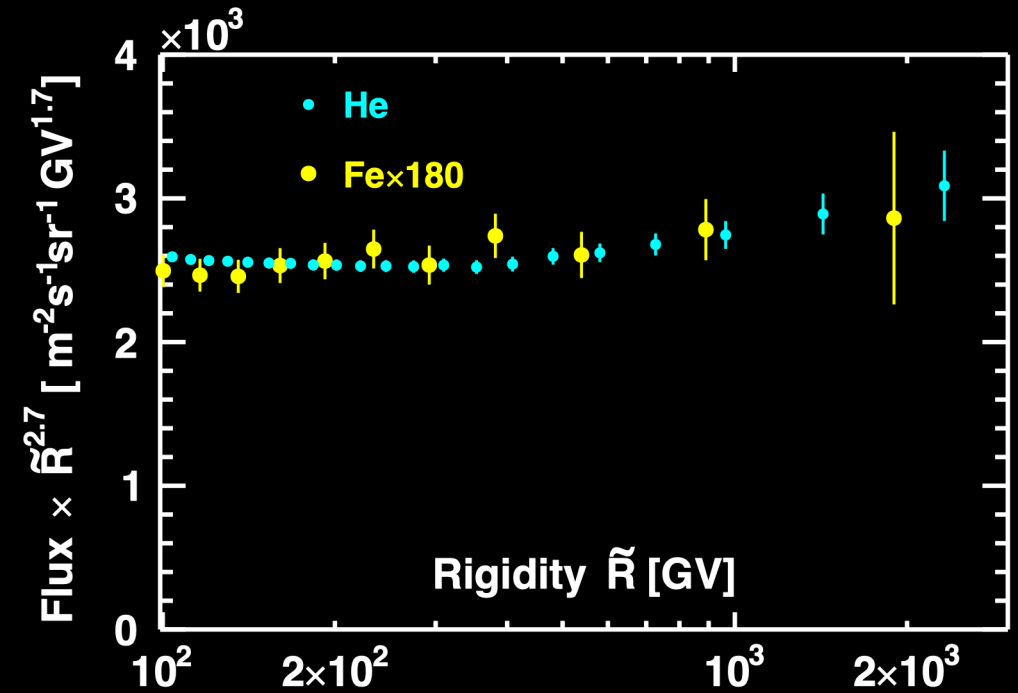
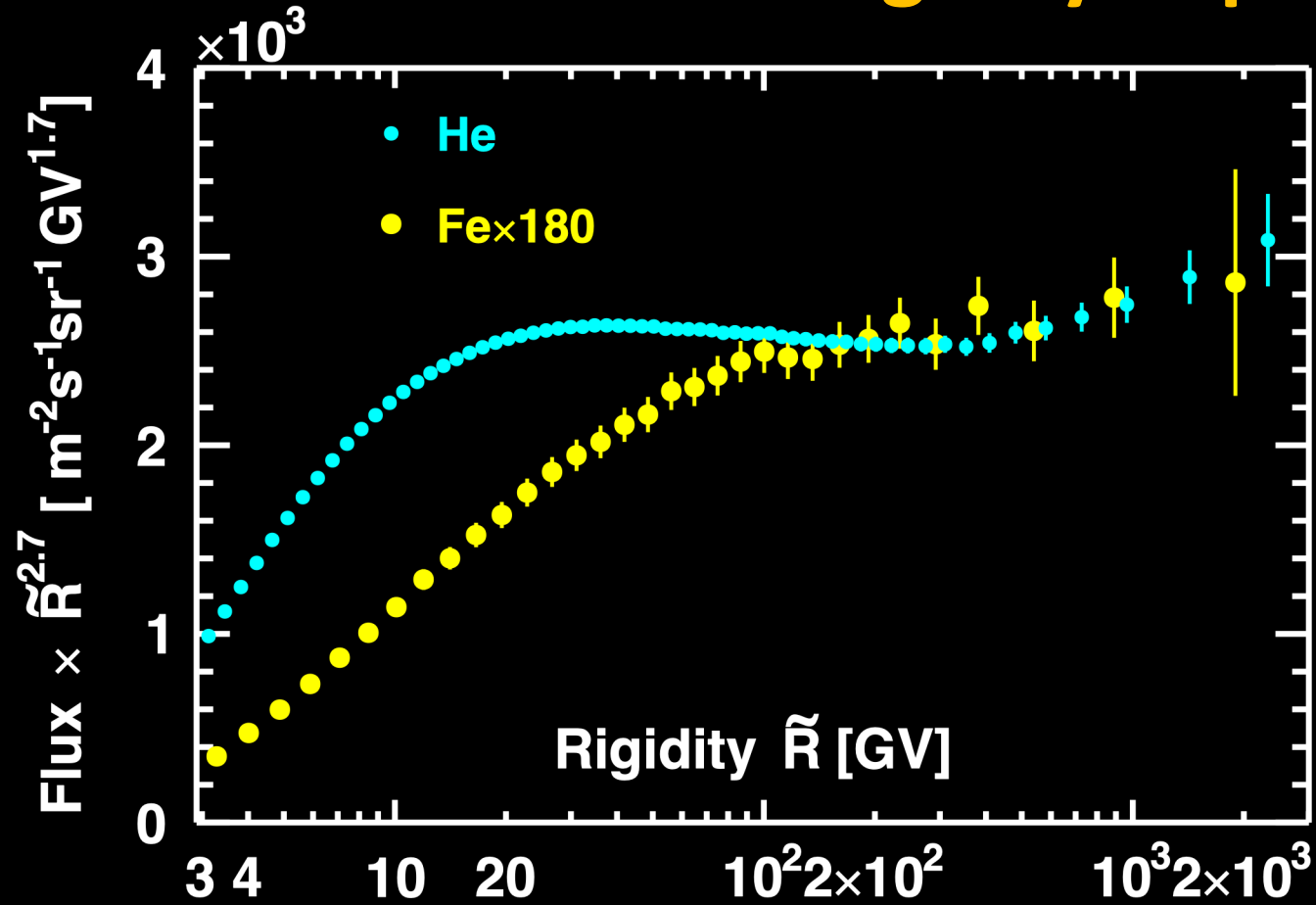


AMS previously observed that light primary cosmic rays He, C, and O have identical rigidity dependence above 60 GV and deviate from a single power law above 200 GV. Surprisingly, heavy primary cosmic rays Ne, Mg, and Si also have identical rigidity dependence above 86 GV, but it is distinctly different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

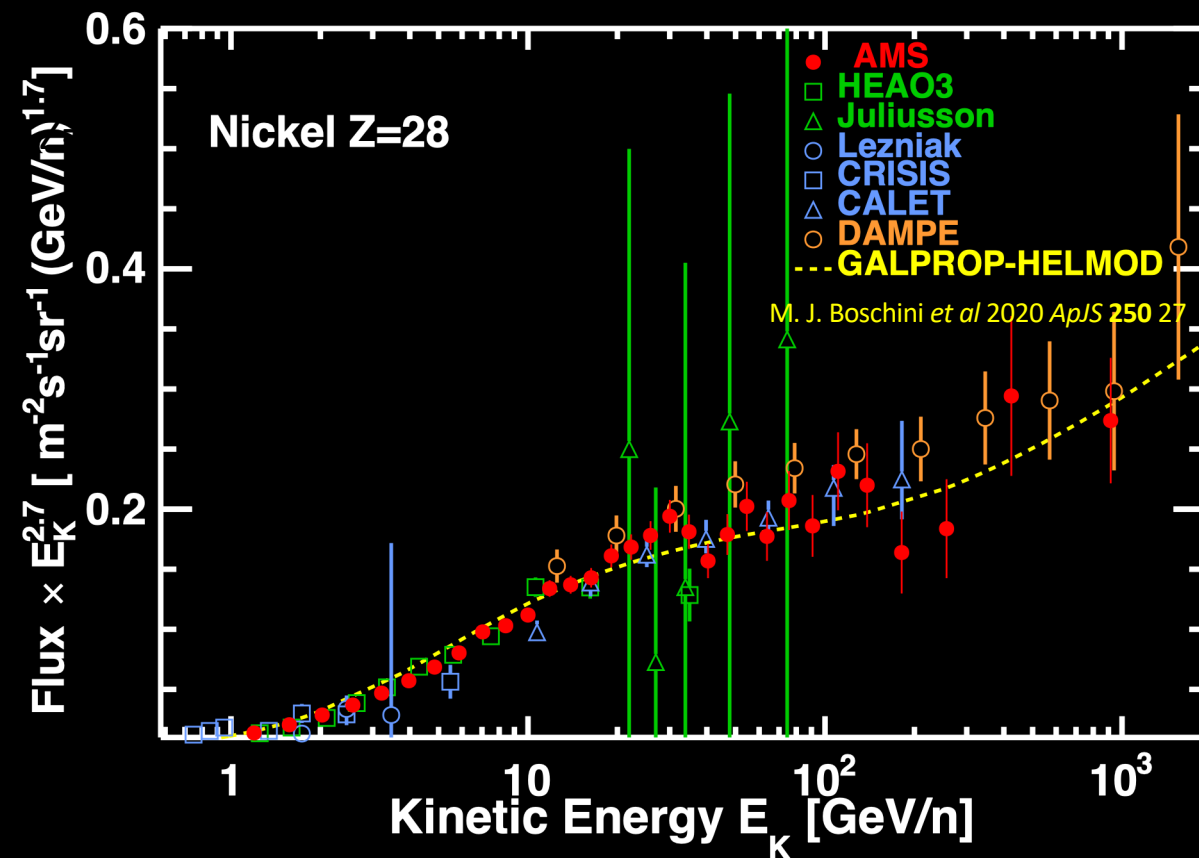
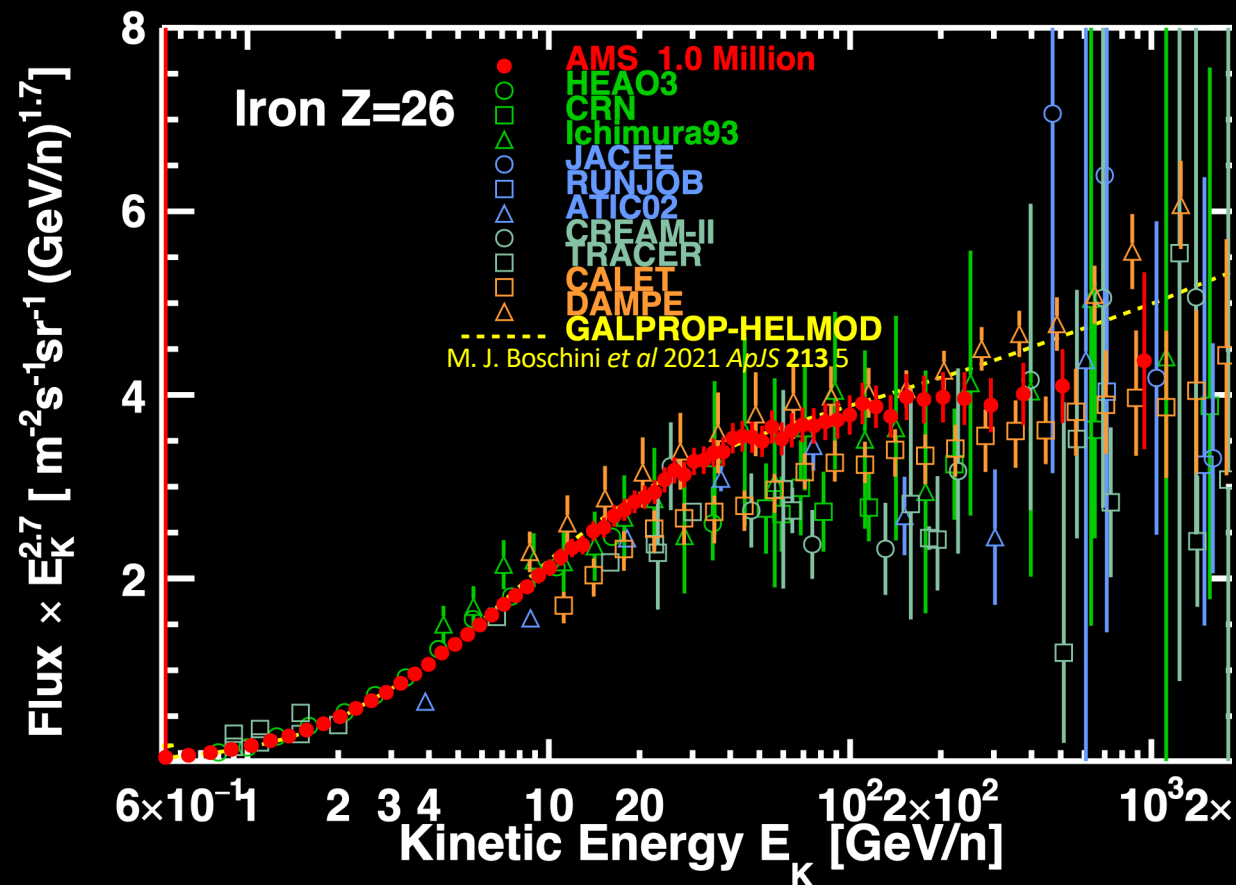
This shows that primary cosmic rays have at least two distinct classes of rigidity dependence.

Iron and Helium

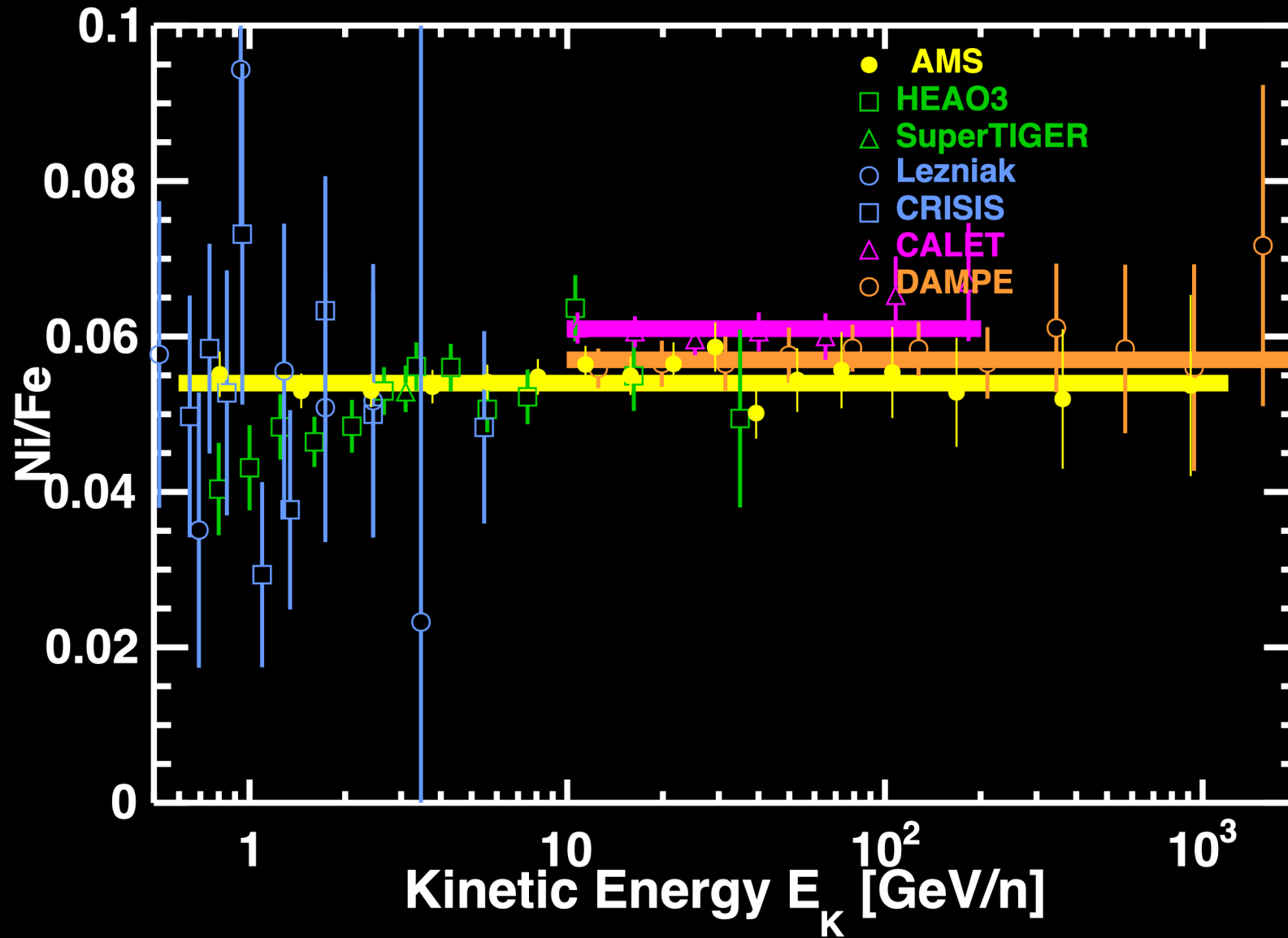
have identical rigidity dependence at high rigidities



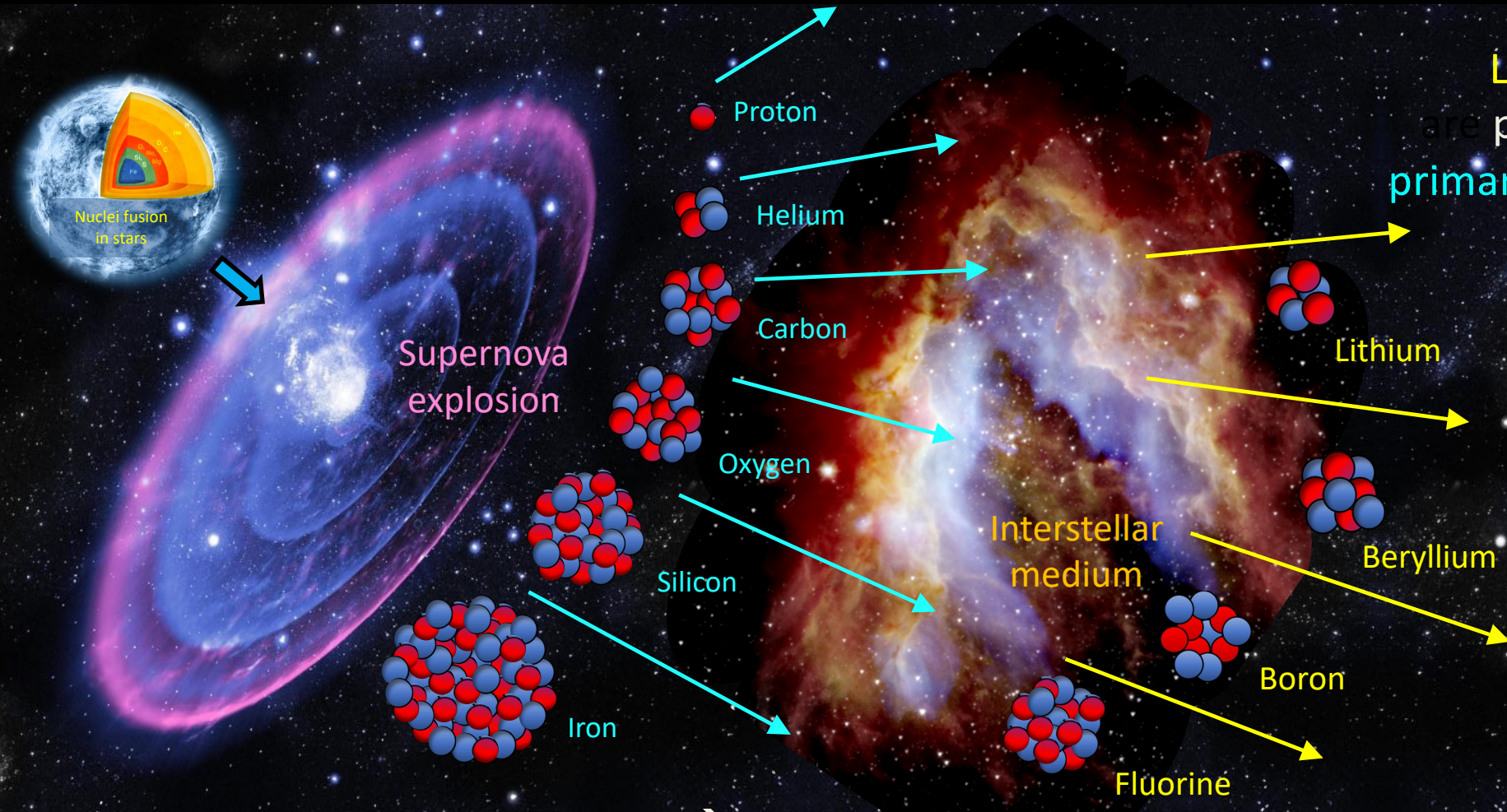
Heavy Primary cosmic rays: Iron and Nickel Fluxes



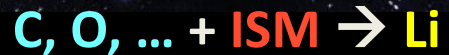
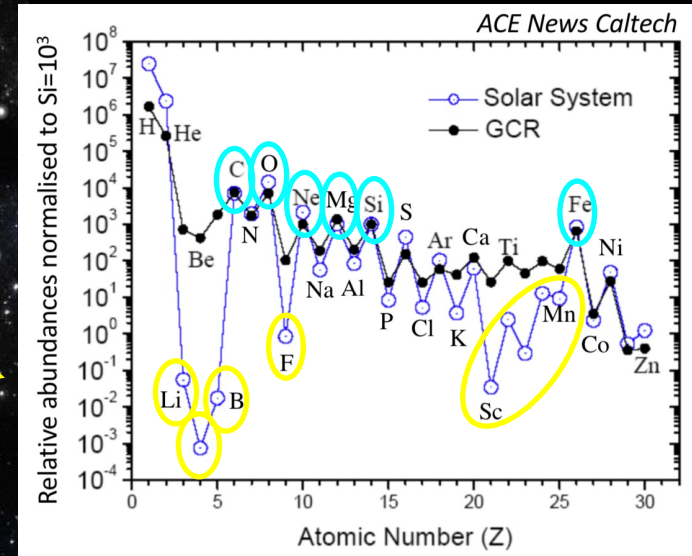
Ni/Fe Ratio



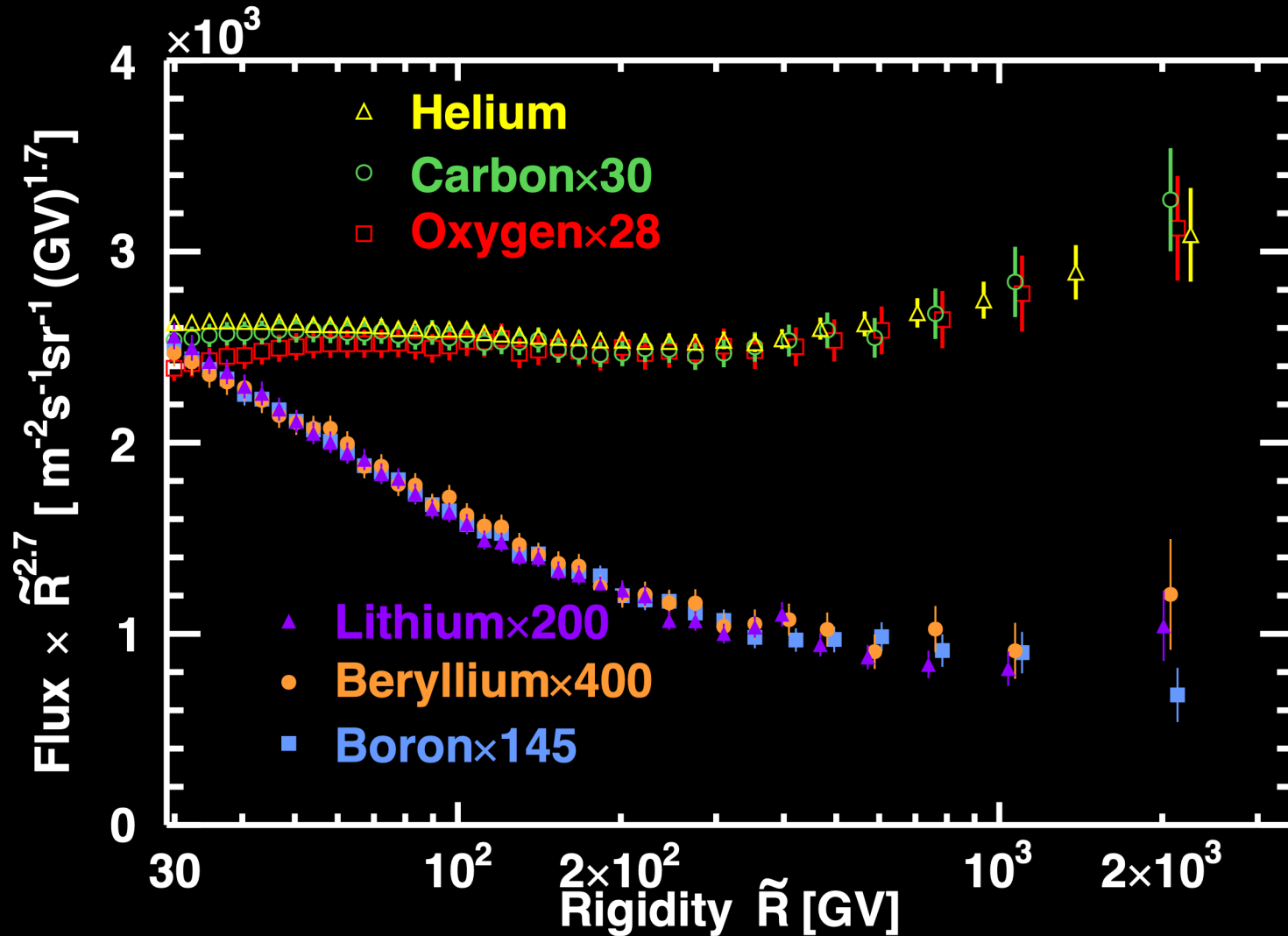
Secondary Cosmic Rays



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



Light Secondary Cosmic Rays Li, Be and B fluxes



Secondary and primary Cosmic rays have distinctly different spectral shapes

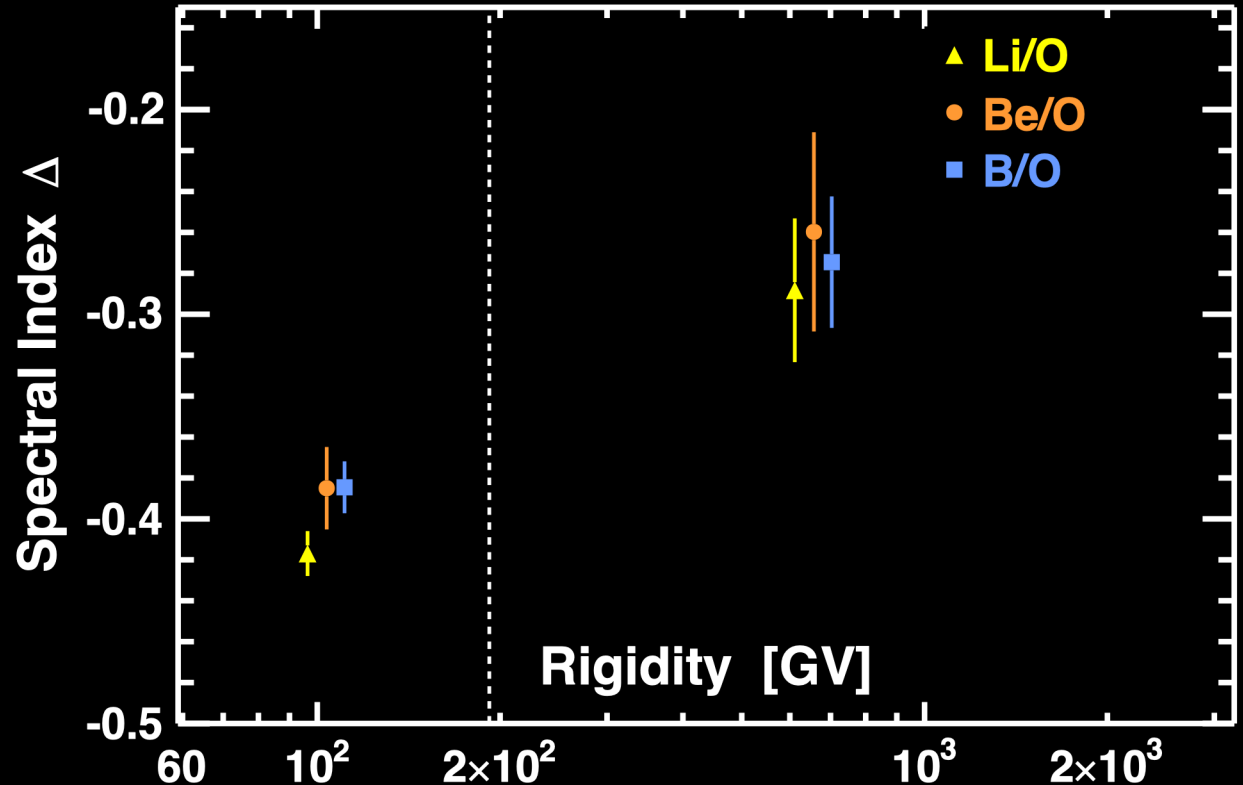
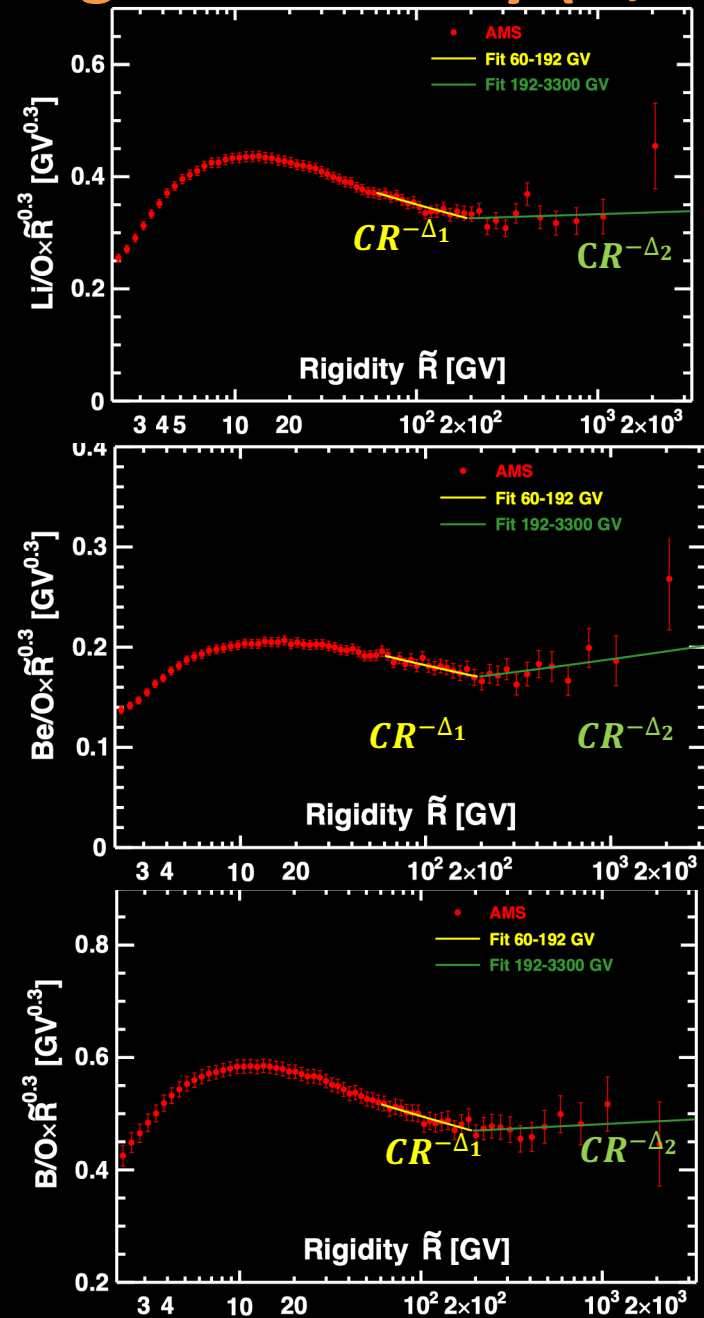
The propagation of cosmic rays through the ISM is modeled as diffusion of charged particles in a turbulent magnetized medium.

Diffusion models based on different assumptions predict a Secondary/Primary flux ratio asymptotically proportional to $\tilde{R}^{-\delta \sim 0.3}$

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

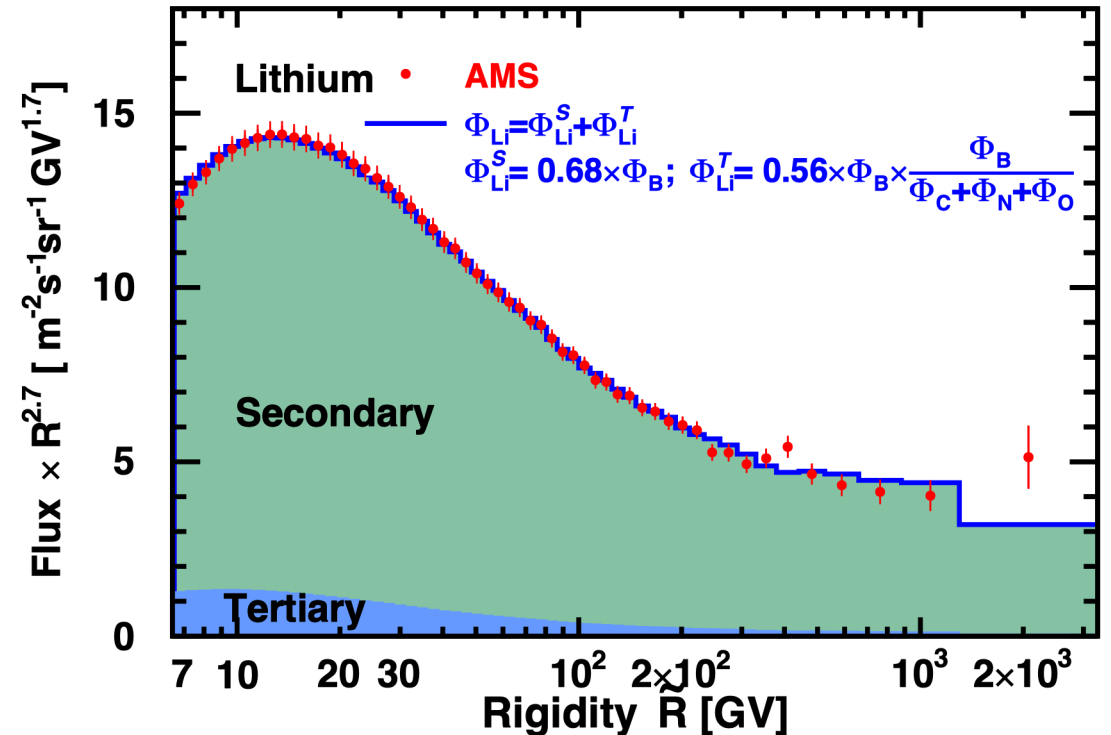
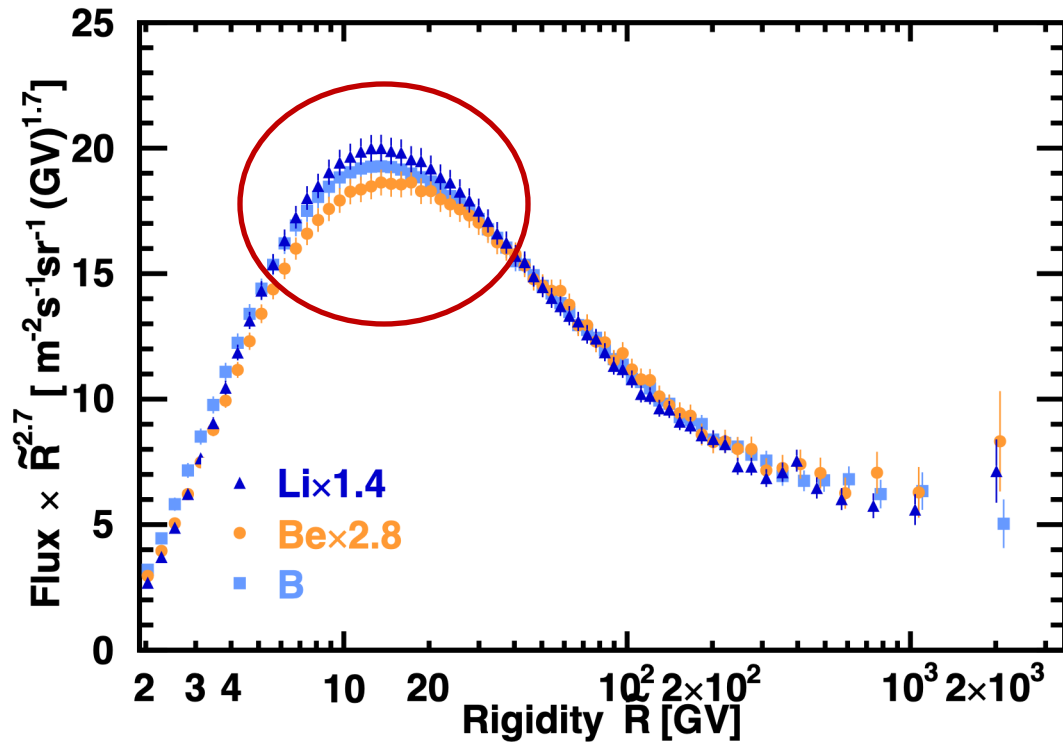
Above 192 GV all 3 secondary-to-primary flux ratios harden.

Average **hardening** $\Delta = \Delta_2 - \Delta_1 = 0.12 \pm 0.02$, significance: **6σ**

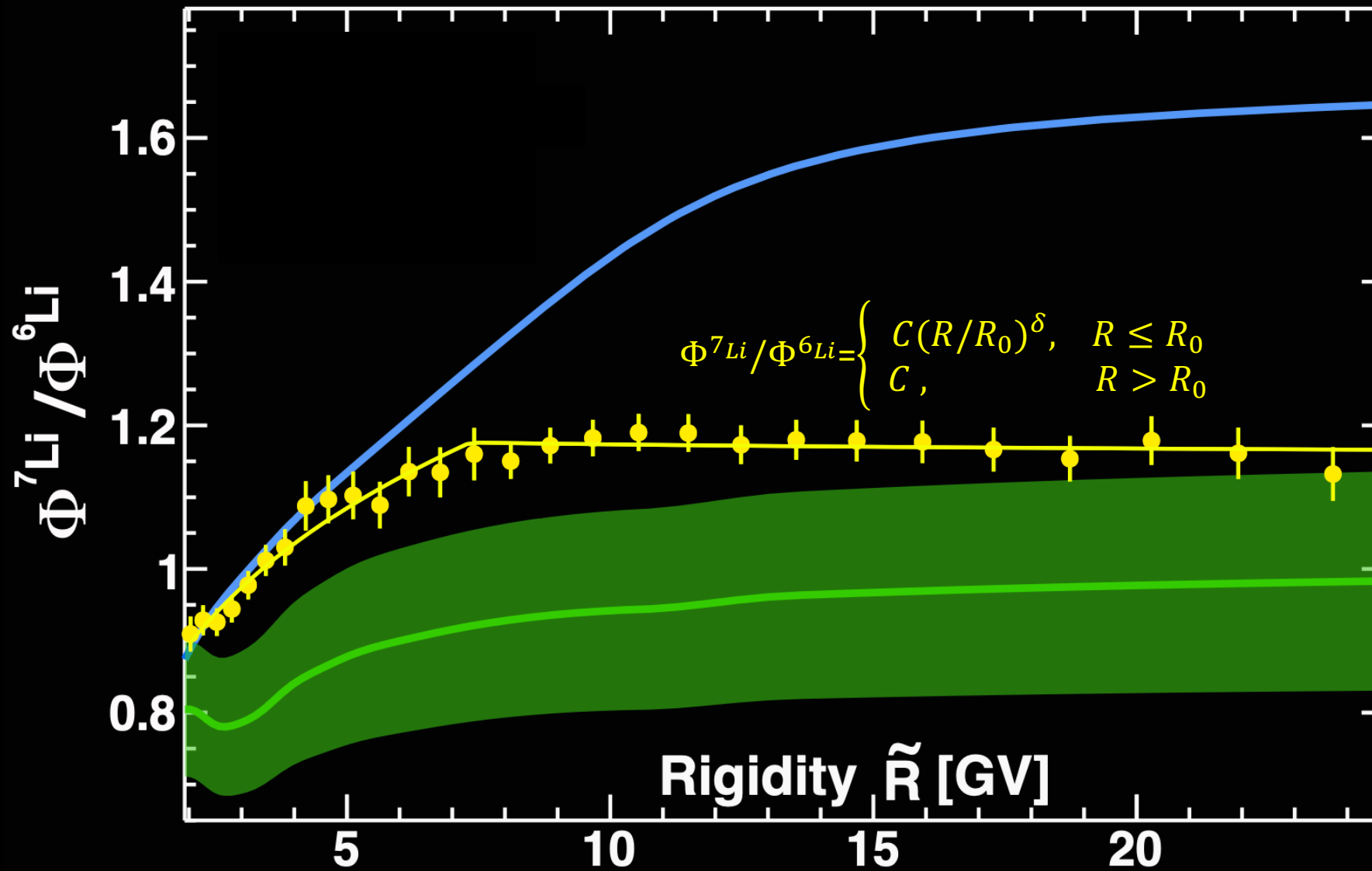


This new observation strongly favors the hypothesis that the observed **spectral hardening** is due to a **propagation effect**

With more statistics we can study the differences between Li and B fluxes rigidity dependence at low rigidities. One can expect that some part of Li flux has a tertiary nature, i.e. produced by the interaction of B and Be with interstellar medium. To obtain the secondary and the tertiary components of the Li flux we fit $\Phi_{\text{Li}} = \Phi_{\text{Li}}^{\text{S}} + \Phi_{\text{Li}}^{\text{T}}$ to the weighted sum of a secondary cosmic ray flux, namely boron Φ_{B} , and of a tertiary cosmic ray flux, namely $\Phi_{\text{B}} \times \frac{\Phi_{\text{B}}}{\Phi_{\text{C}} + \Phi_{\text{N}} + \Phi_{\text{O}}}$ above 6 GV.



Results on Lithium Isotopes



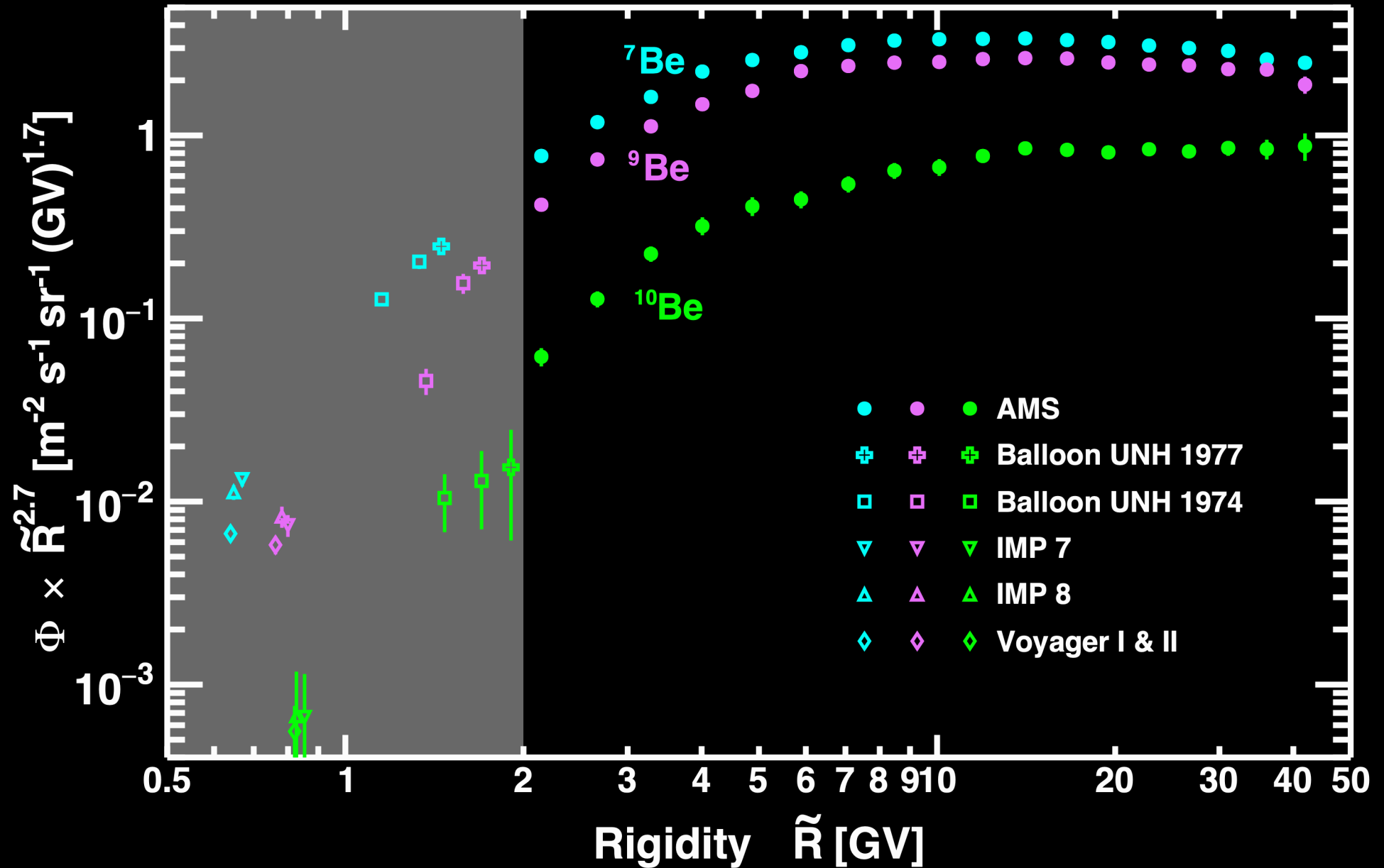
GALPROP Model
assuming a
primary component
in the ^7Li flux

AMS data and fit, $R_0 = 7\text{GV}$

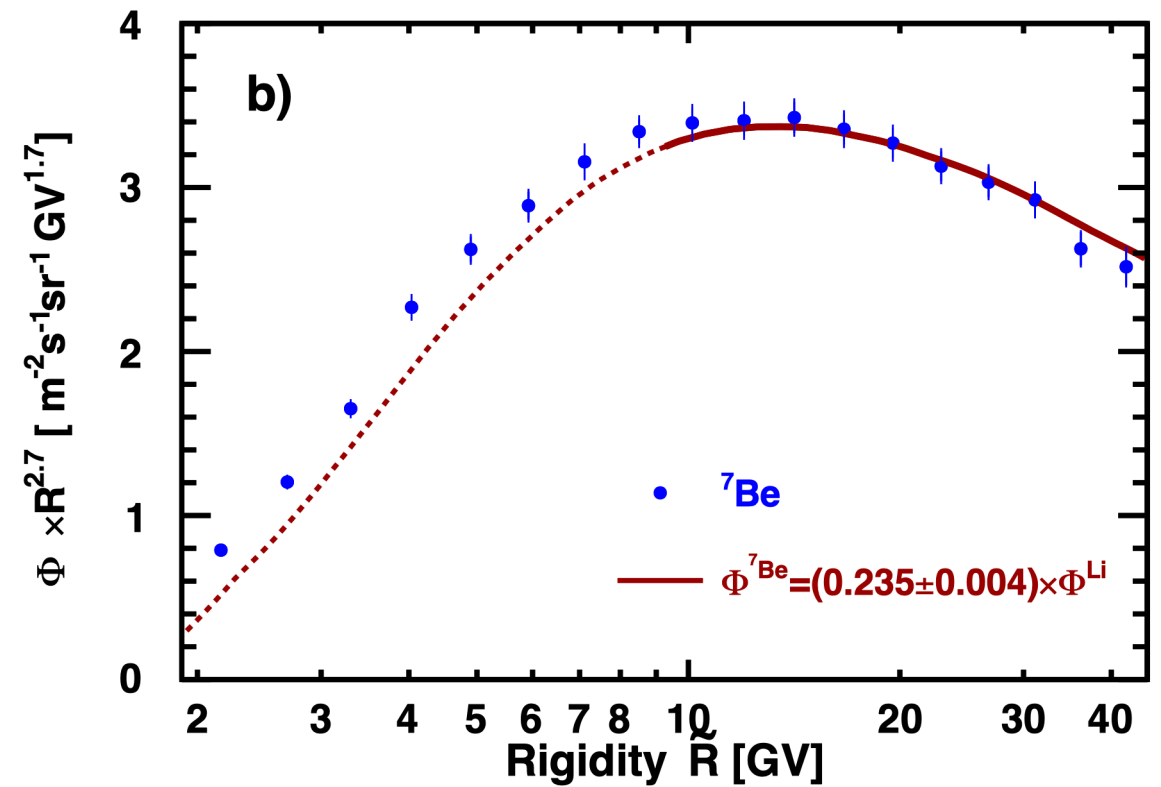
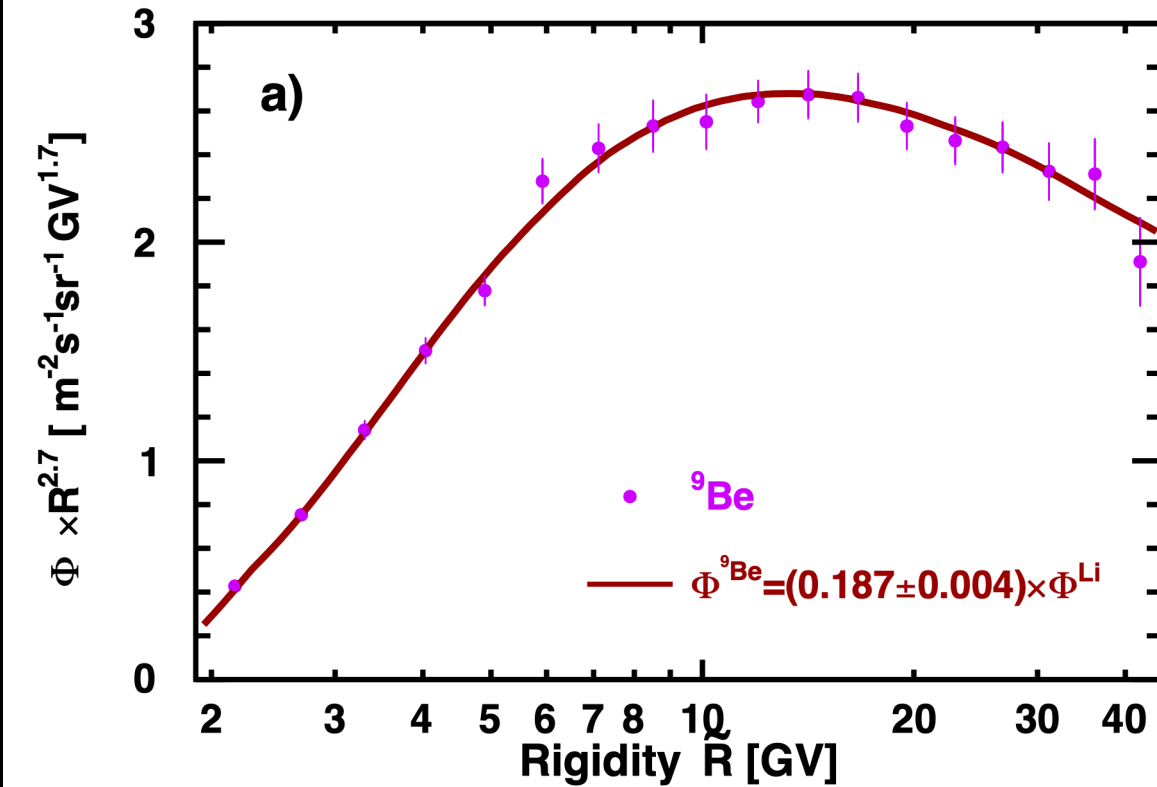
USINE Model
assuming secondary
origin of ^6Li and ^7Li

Above $\sim 7\text{ GV}$, the rigidity dependence of ^6Li and ^7Li fluxes are identical
Excludes the existence of a sizable primary component in the ^7Li flux

Results on Beryllium Isotopes



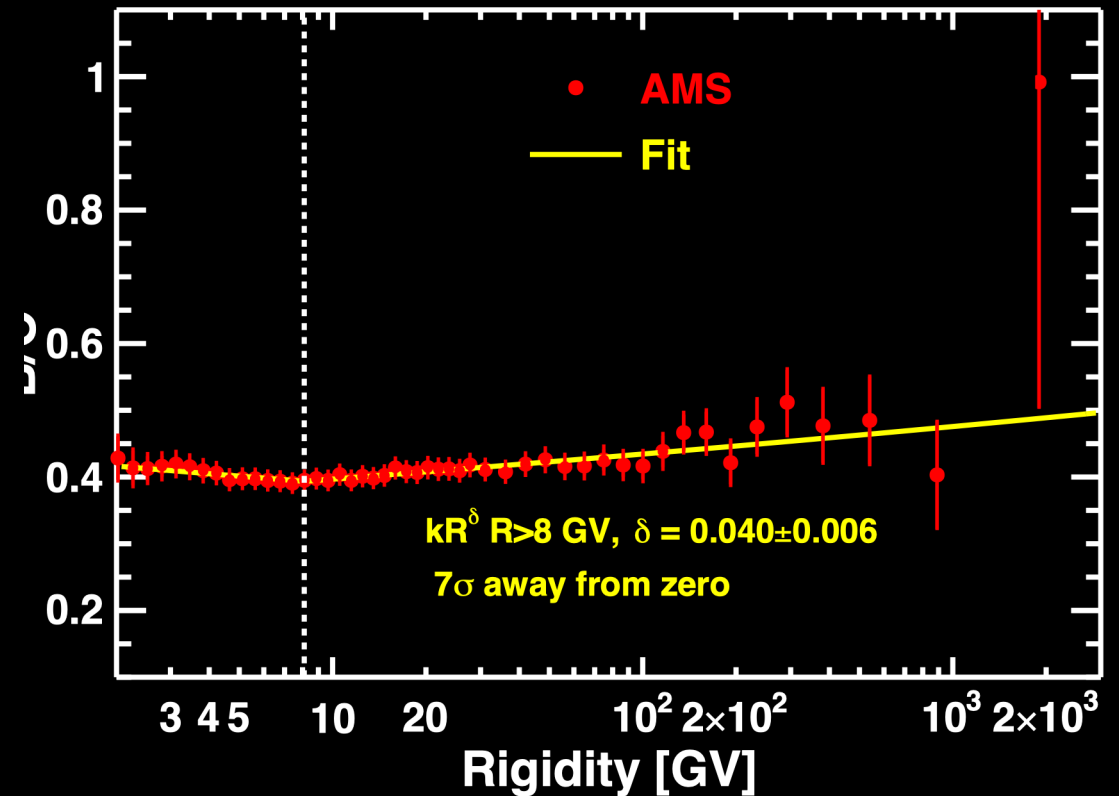
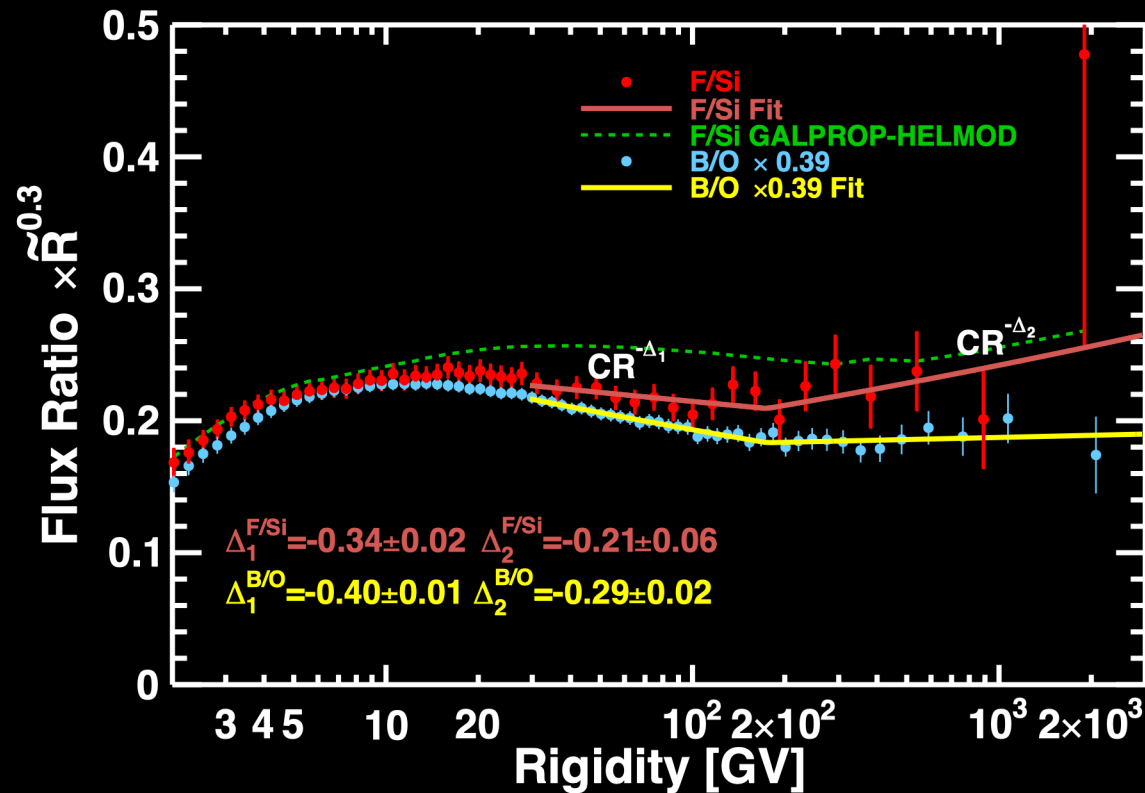
Results on Beryllium Isotopes



**^9Be and Li fluxes have identical rigidity dependence.
Difference between ^7Be and ^9Be is similar to that of ^7Li and ^6Li isotopes.
 ^{10}Be flux is different from both ^9Be and ^7Be due to ^{10}Be β decay**

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.



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

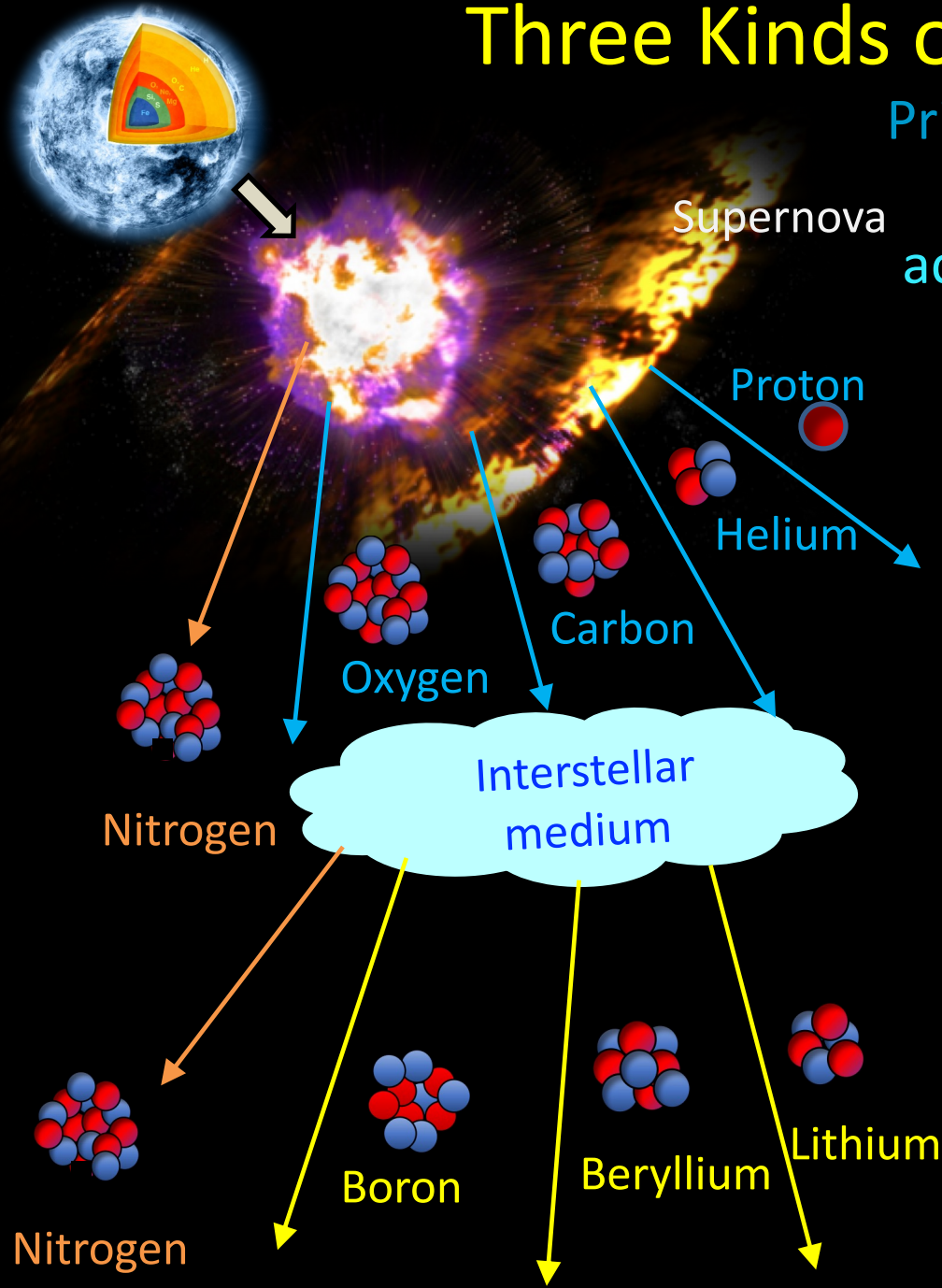
Three Kinds of Charged Cosmic Rays

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.

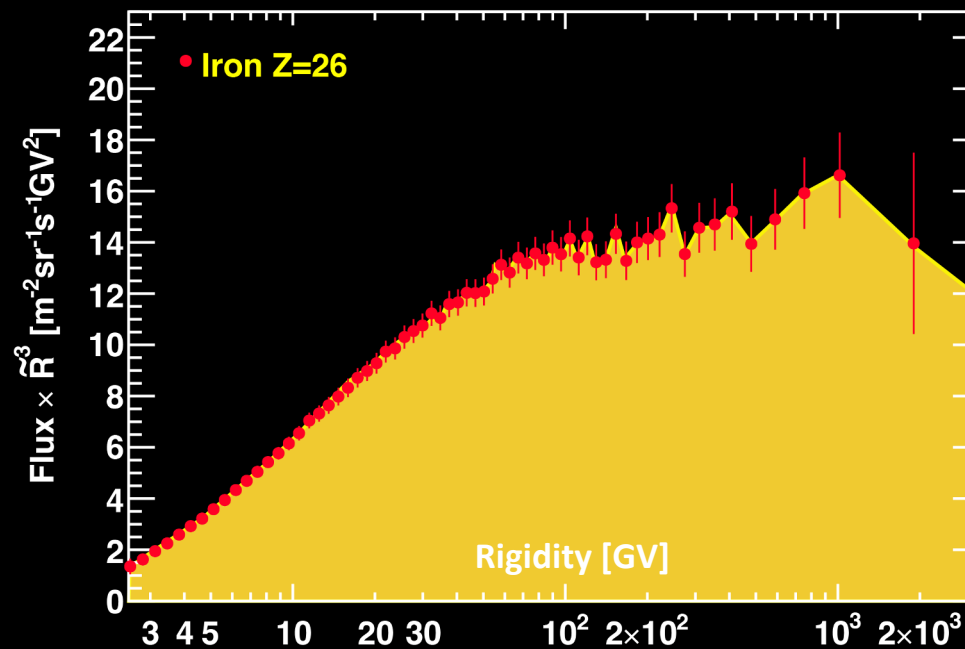
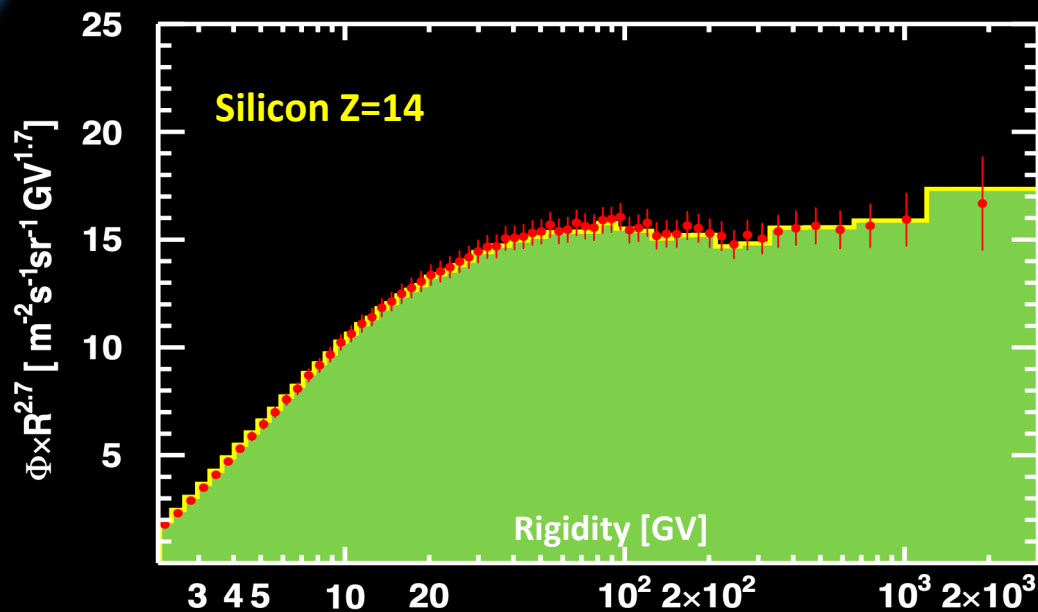
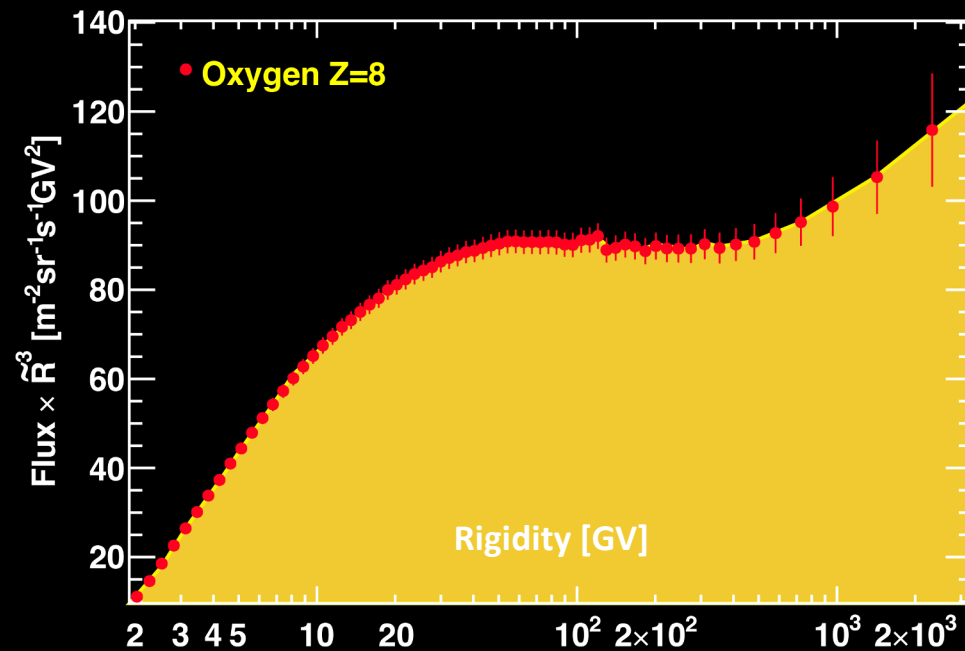
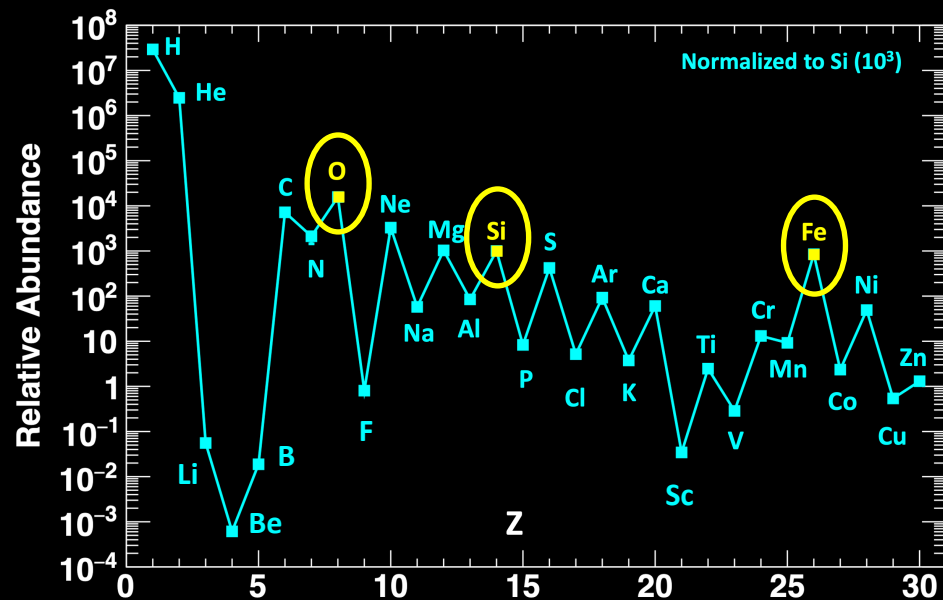
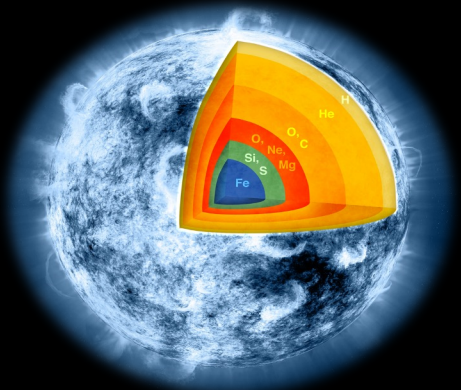
Secondary cosmic nuclei (Li, Be, B, F, ...) are produced by the collisions of primary cosmic rays and interstellar medium.

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

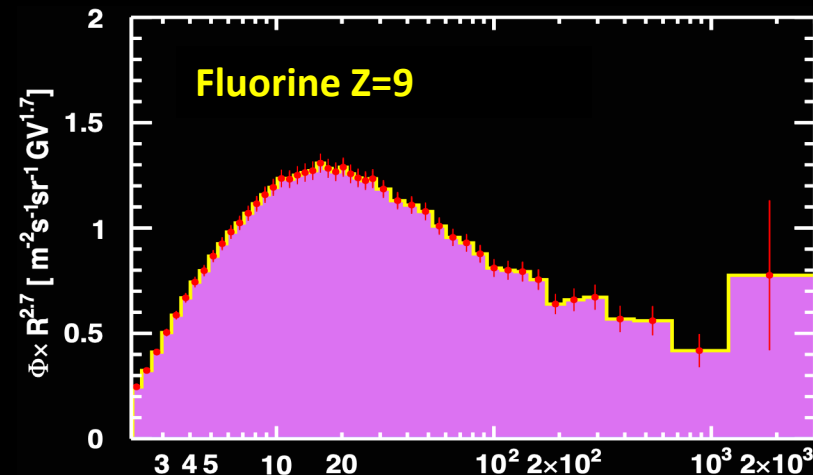
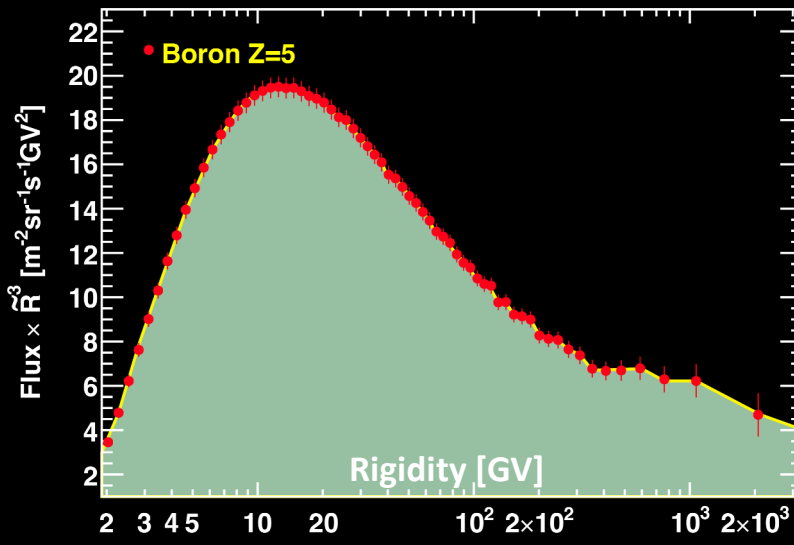
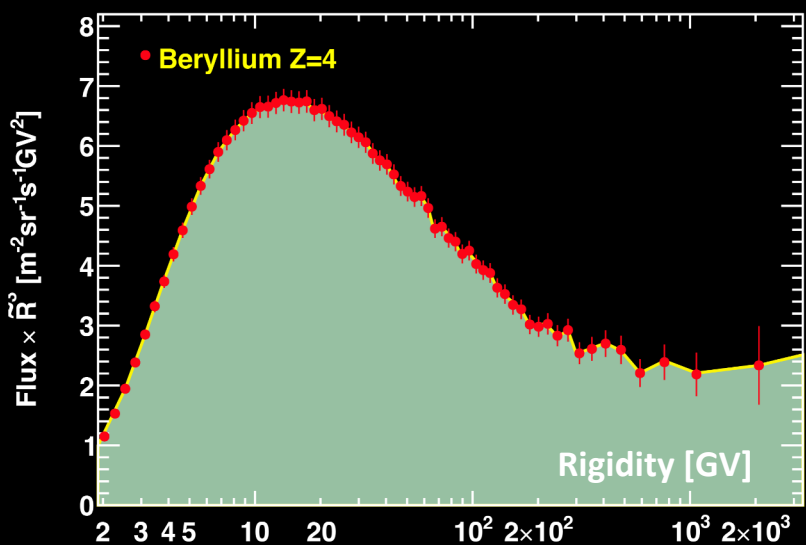
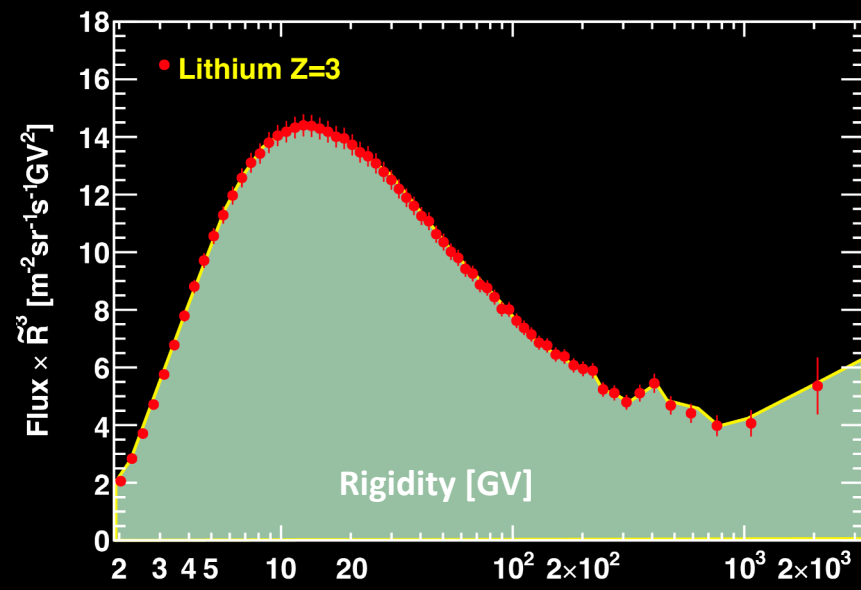
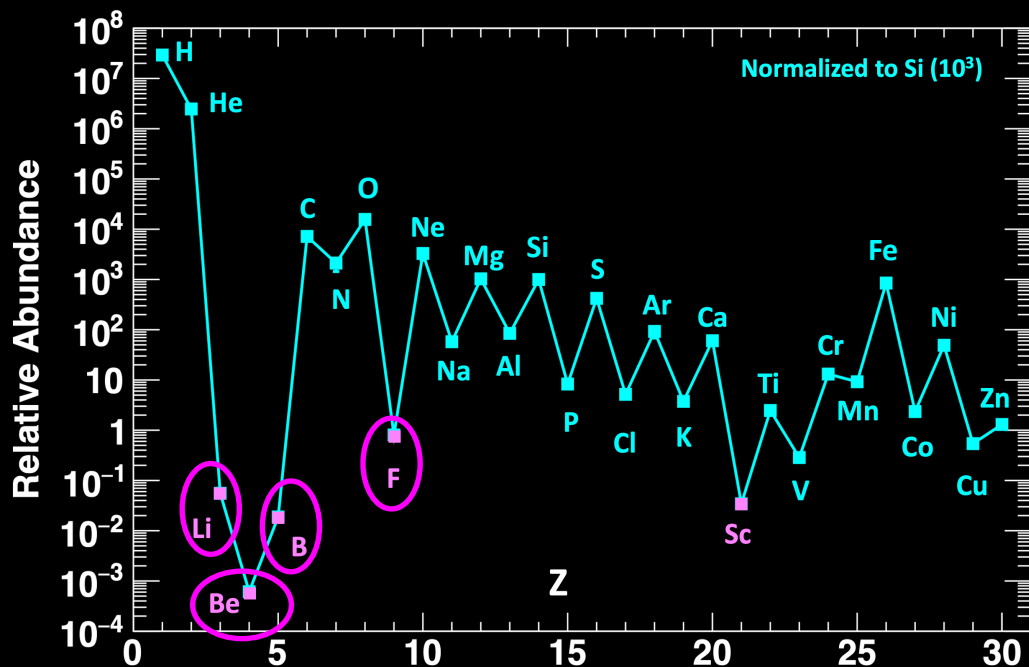
AMS found that all such fluxes can be presented as a weighted sums of the characteristic primary flux (O, Si) and a characteristic secondary flux (B, F)



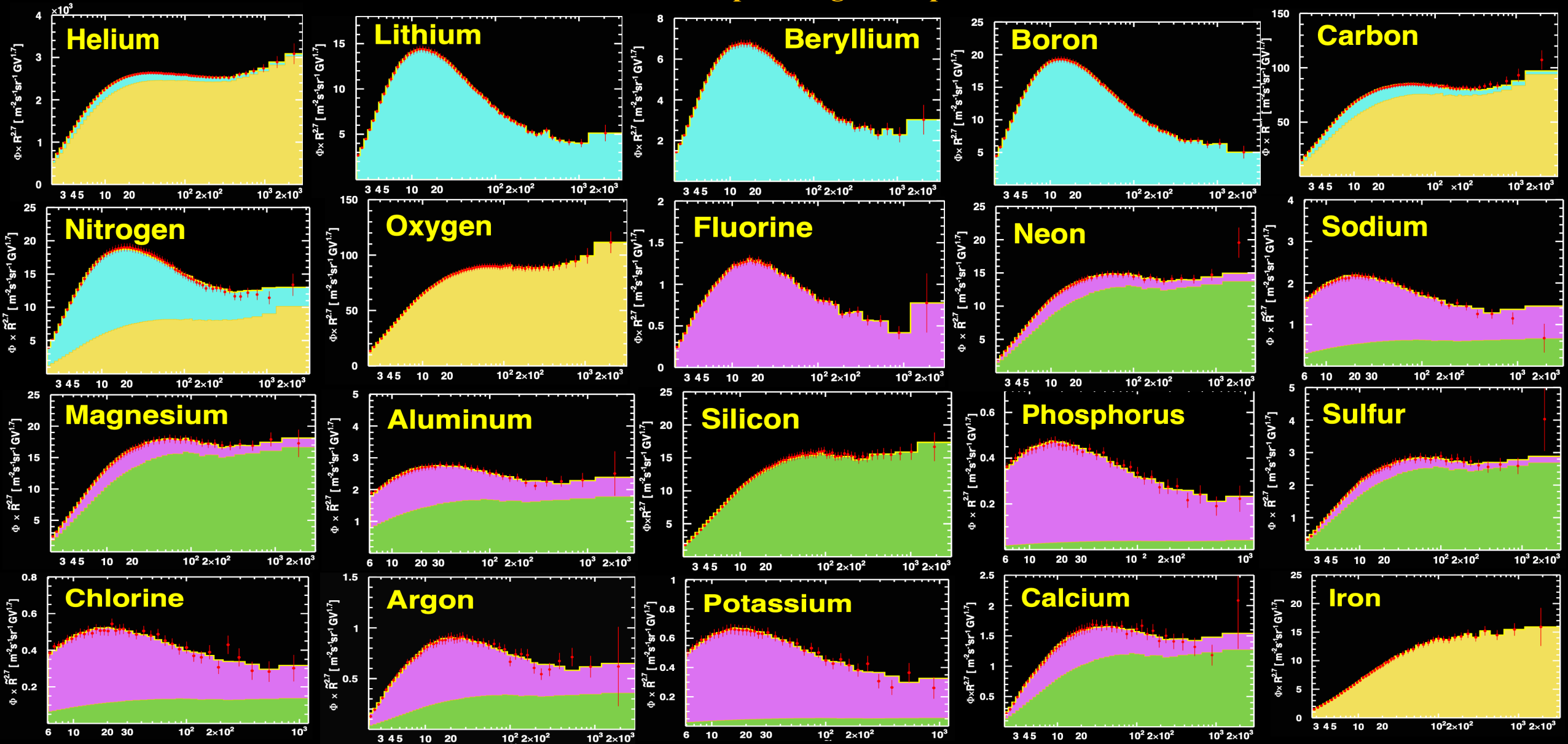
Characteristic primary cosmic rays: O, Si, and Fe



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



Properties of Heavy Cosmic Nuclei Helium (H), Lithium(Li), Beryllium (Be), Boron (B), Carbon (C), Nitrogen (N), Oxygen (O), Fluorine (F), Neon (Ne), Sodium(Na), Magnesium (Mg), Aluminum (Al), Silicon (Si), Phosphorus (P), Sulfur (S), Chlorine (Cl), Argon (Ar), Potassium (K), and Calcium (Ca), Iron (Fe) :
Results from the Alpha Magnetic Spectrometer



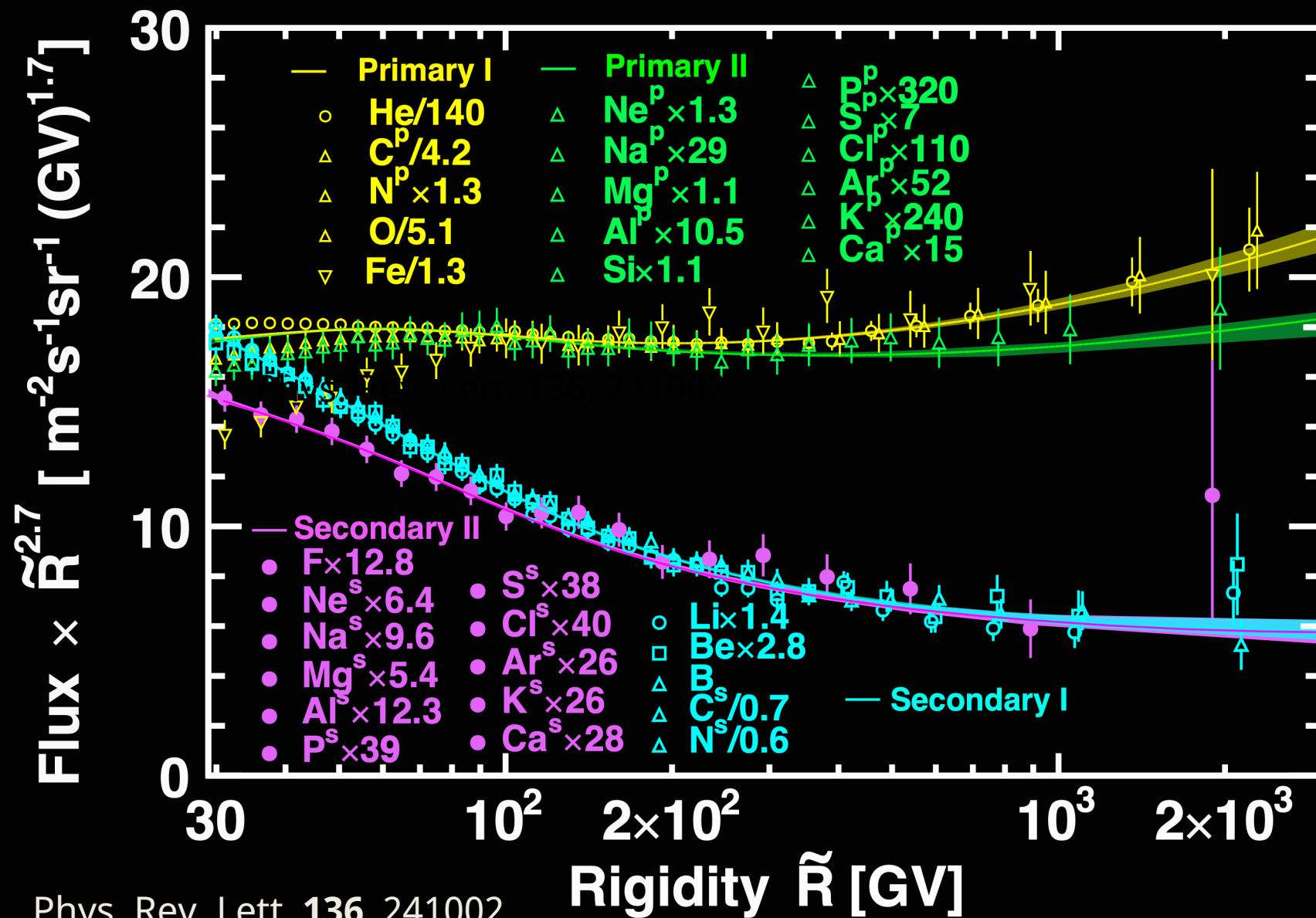
Summary Primary and Secondary Components

Nuclei Flux	Primary	Secondary	Primary Fraction, %			$\chi^2/\text{d.o.f.}$
			10 GV	100 GV	1 TV	
Φ_{C}	$(0.840 \pm 0.025) \times \Phi_{\text{O}}$	$(0.70 \pm 0.02) \times \Phi_{\text{B}}$	80 ± 1	91 ± 0.5	95 ± 0.5	45/65
Φ_{N}	$(0.091 \pm 0.002) \times \Phi_{\text{O}}$	$(0.61 \pm 0.02) \times \Phi_{\text{B}}$	34 ± 1	55 ± 1	70 ± 1	37/64
Φ_{Ne}	$(0.823 \pm 0.025) \times \Phi_{\text{Si}}$	$(1.97 \pm 0.13) \times \Phi_{\text{F}}$	78 ± 1.5	89 ± 1	92 ± 0.6	19/47
Φ_{Na}	$(0.039 \pm 0.003) \times \Phi_{\text{Si}}$	$(1.31 \pm 0.04) \times \Phi_{\text{F}}$	20 ± 1	36 ± 2	46 ± 3	19/36
Φ_{Mg}	$(0.996 \pm 0.029) \times \Phi_{\text{Si}}$	$(2.45 \pm 0.17) \times \Phi_{\text{F}}$	78 ± 1.5	89 ± 1	92 ± 0.5	14/47
Φ_{Al}	$(0.108 \pm 0.004) \times \Phi_{\text{Si}}$	$(1.01 \pm 0.04) \times \Phi_{\text{F}}$	48 ± 1	67 ± 1	75 ± 2	9/36
Φ_{P}	$(0.0034 \pm 0.0014) \times \Phi_{\text{Si}}$	$(0.33 \pm 0.01) \times \Phi_{\text{F}}$	8 ± 3	17 ± 5	24 ± 7	9/29
Φ_{S}	$(0.161 \pm 0.005) \times \Phi_{\text{Si}}$	$(0.33 \pm 0.04) \times \Phi_{\text{F}}$	81 ± 2	90 ± 1	93 ± 1	11/46
Φ_{Cl}	$(0.0097 \pm 0.0015) \times \Phi_{\text{Si}}$	$(0.30 \pm 0.02) \times \Phi_{\text{F}}$	21 ± 3	38 ± 5	43 ± 7	12/29
Φ_{Ar}	$(0.022 \pm 0.002) \times \Phi_{\text{Si}}$	$(0.48 \pm 0.02) \times \Phi_{\text{F}}$	28 ± 2	47 ± 3	57 ± 3	24/46
Φ_{K}	$(0.0046 \pm 0.0016) \times \Phi_{\text{Si}}$	$(0.47 \pm 0.02) \times \Phi_{\text{F}}$	8 ± 3	16 ± 5	22 ± 7	10/29
Φ_{Ca}	$(0.077 \pm 0.003) \times \Phi_{\text{Si}}$	$(0.45 \pm 0.03) \times \Phi_{\text{F}}$	59 ± 2	77 ± 2	83 ± 2	13/46

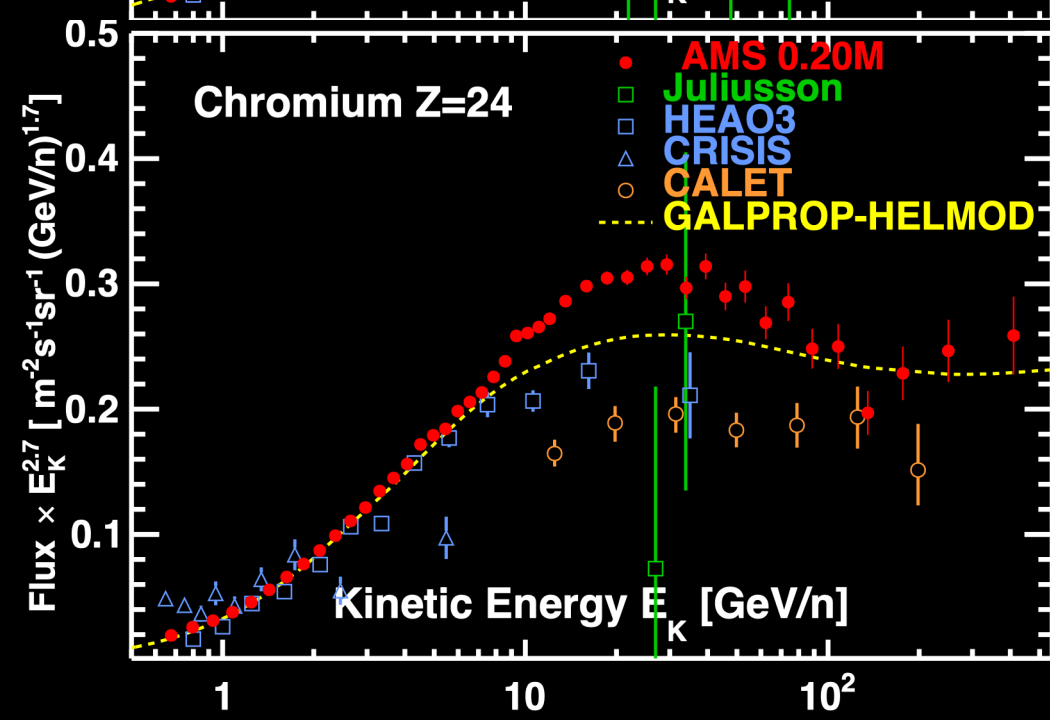
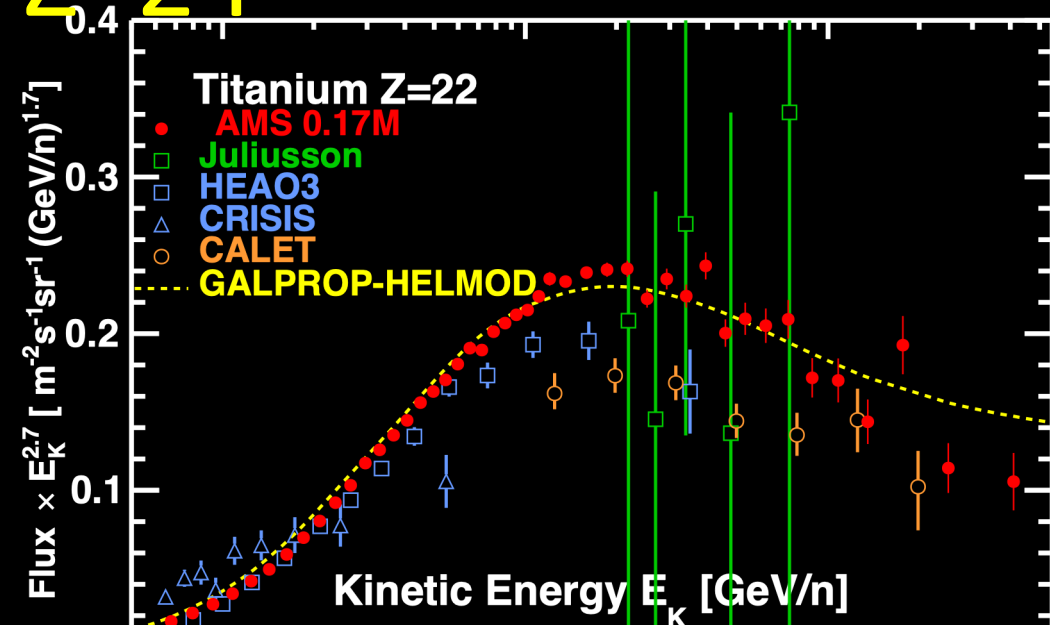
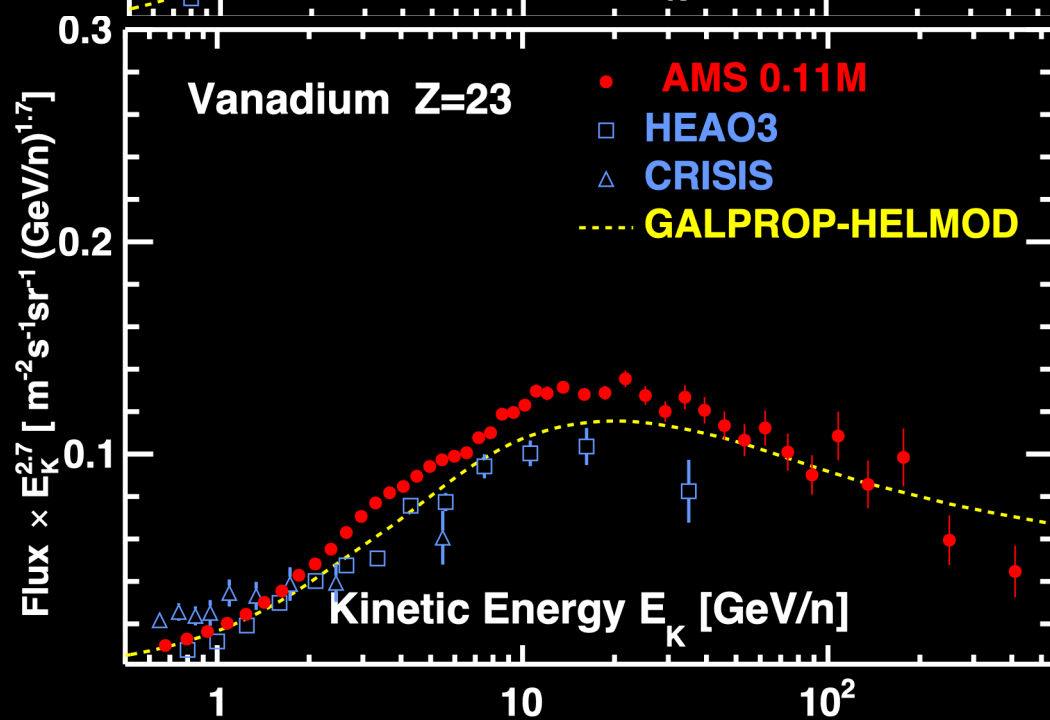
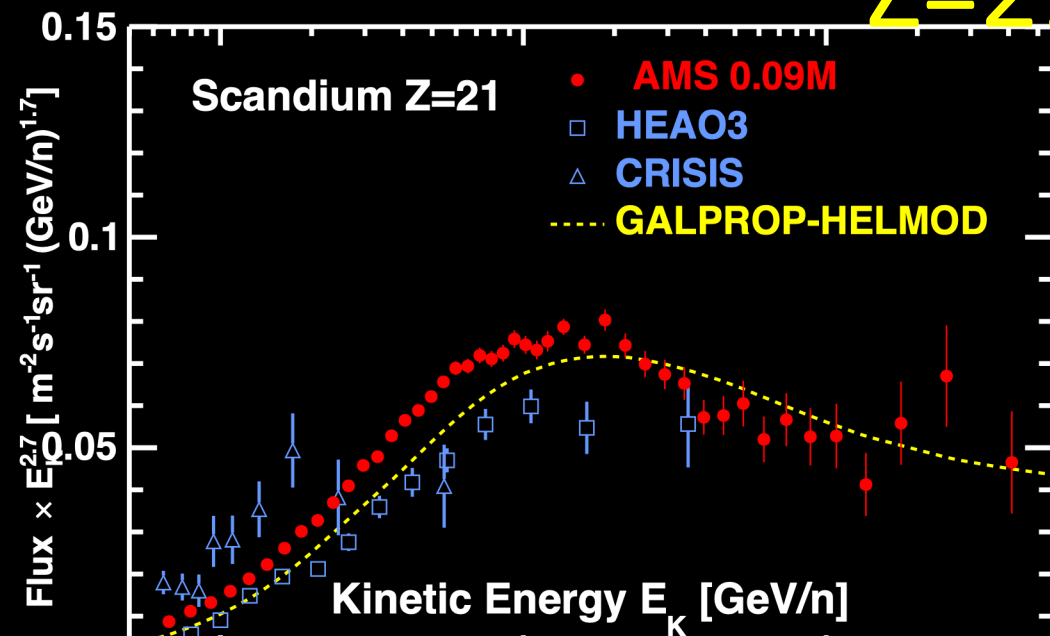
The C (Z=6) to Ca (Z=20) cosmic ray nuclei primary and secondary components derived as fractions of O(Si) and B(F) fluxes, respectively, and their secondary fractions at 6 GV and 2 TV.

This allows to measure relative cosmic ray abundances of C/O, N/O, Ne/Si, Na/Si, Mg/Si, Al/Si, S/Si, Cl/Si, Ar/Si, K/Si, and Ca/Si at the source independently of cosmic ray propagation.

Cosmic elements can be simply described
by **two** Primary classes and **two** Secondary classes

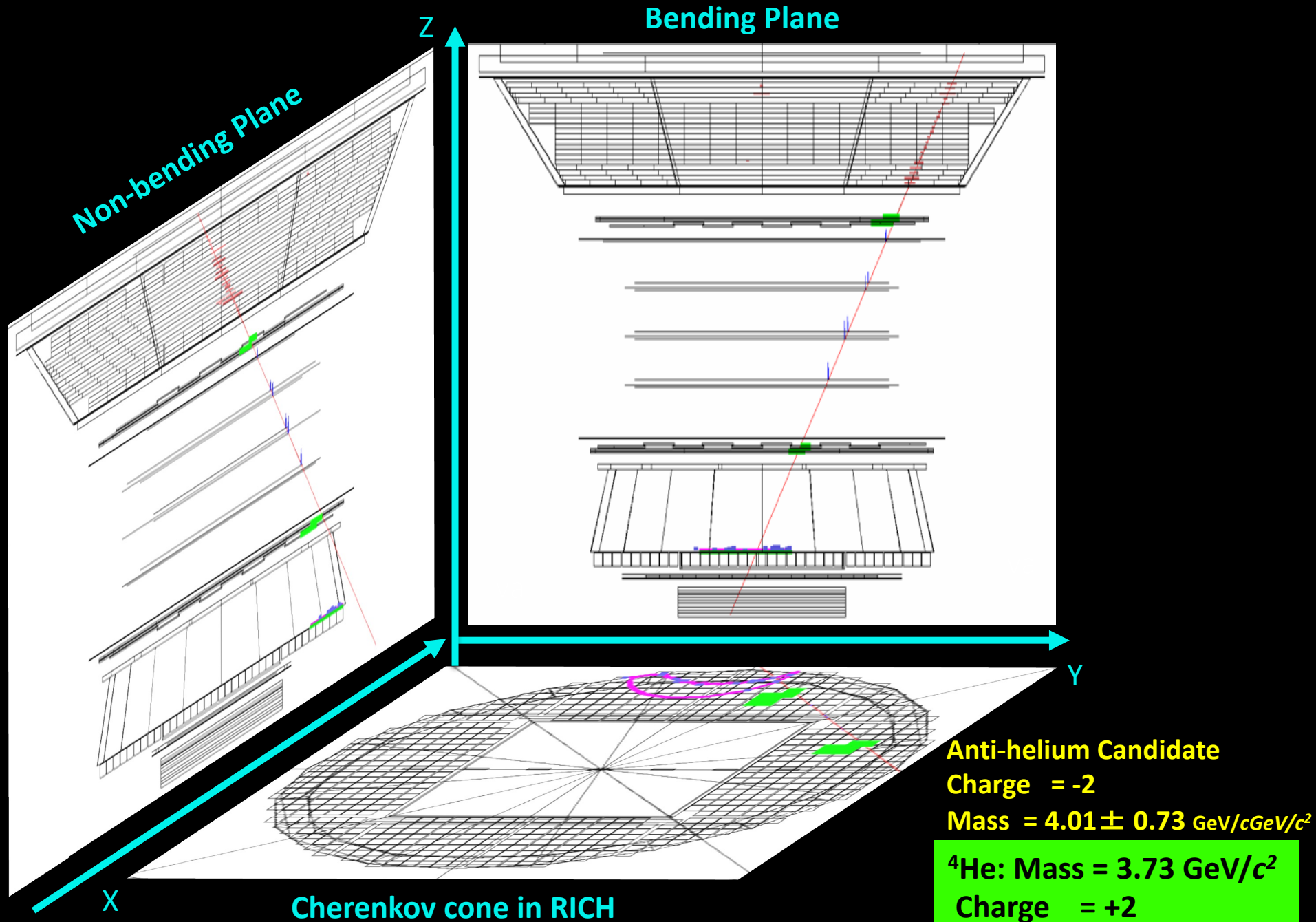


Z=21 to Z=24



Cosmic Heavy Antimatter

- To date, we have observed few events in the mass region from 1 to 10 GeV/c² with Z= −2 with rigidity <50 GV.
- All events masses are in the ³He or ⁴He mass region.



**AMS is the only magnetic spectrometer in space.
AMS will continue to take data for the ISS life time,
exploring properties of cosmic ray up to Zn and beyond.**

