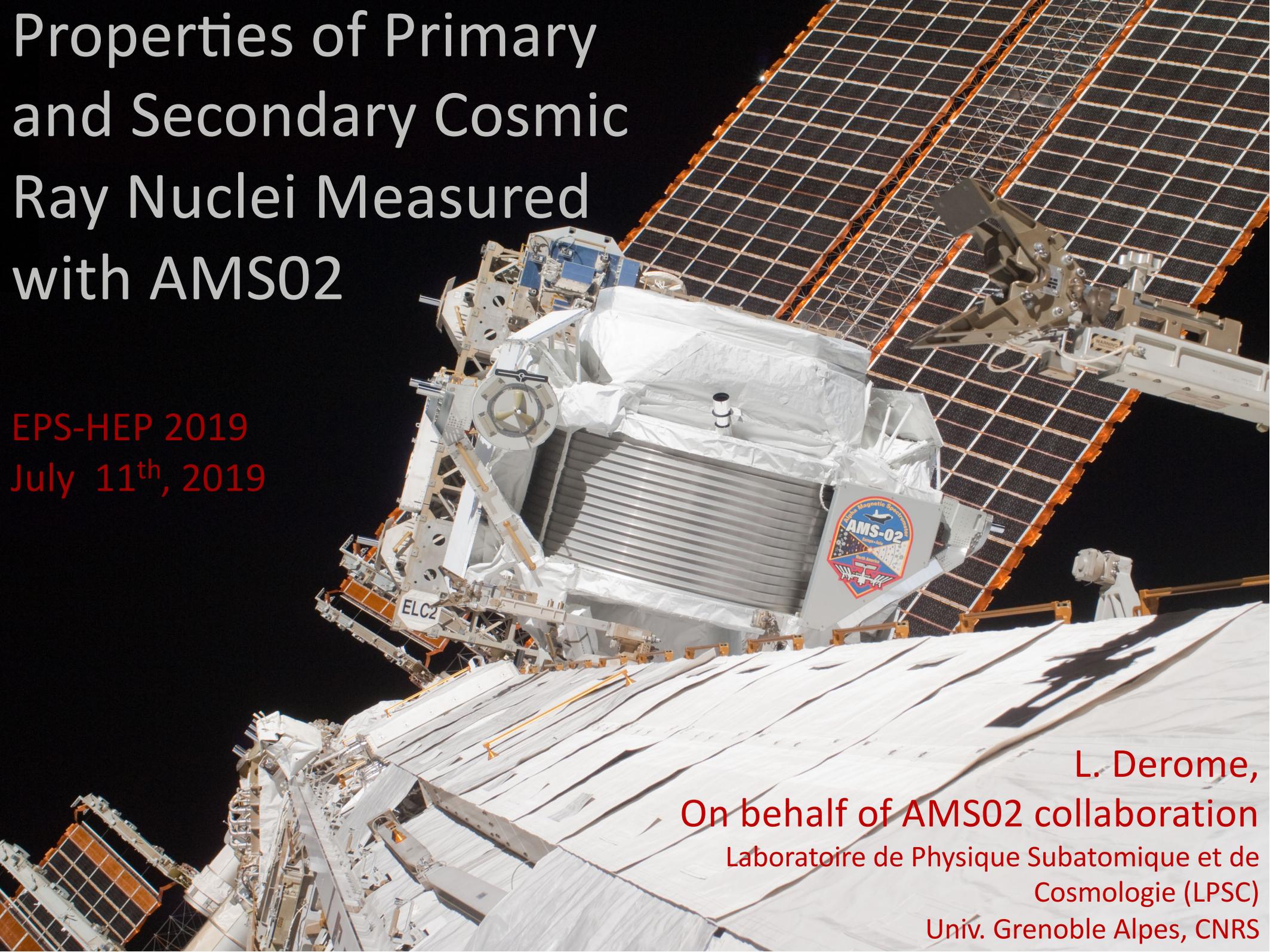


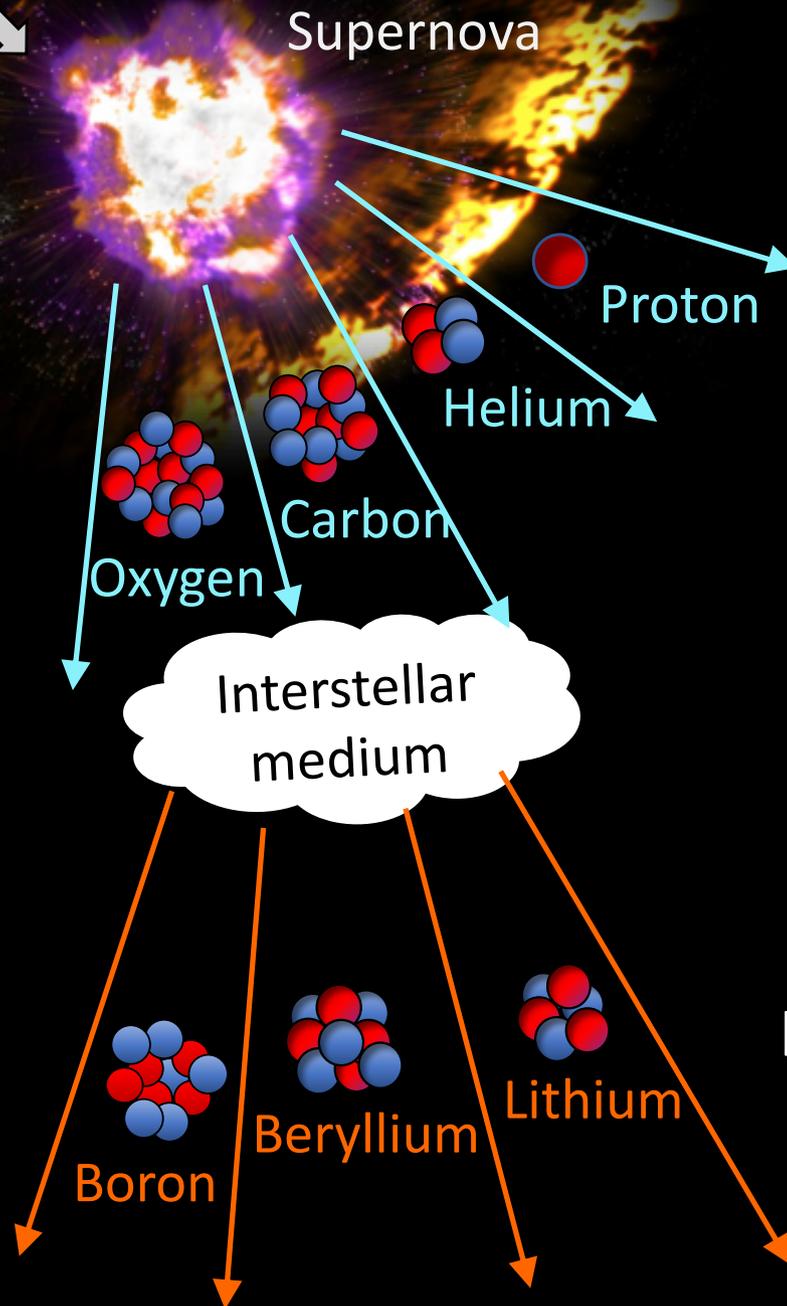
# Properties of Primary and Secondary Cosmic Ray Nuclei Measured with AMS02

EPS-HEP 2019  
July 11<sup>th</sup>, 2019



L. Derome,  
On behalf of AMS02 collaboration  
Laboratoire de Physique Subatomique et de  
Cosmologie (LPSC)  
Univ. Grenoble Alpes, CNRS

# Galactic Cosmic-Ray Nuclei



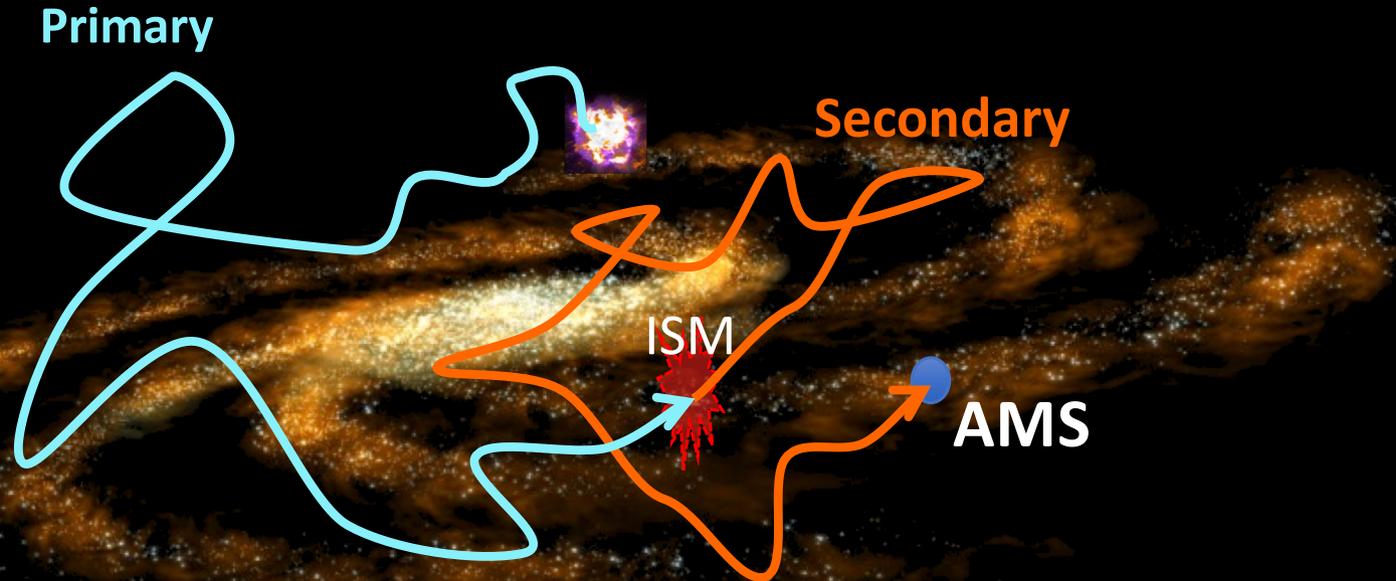
Primary cosmic nuclei (H, He, C, O, Ne ..., Fe) are the most abundant component in CR.

They are produced during the lifetime of stars and accelerated by their explosion (supernovae).

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

are produced by the collision of primary cosmic rays and interstellar medium

# Galactic Cosmic-Ray Nuclei



Cosmic ray propagation is commonly modeled as a diffusion process due to the turbulent magnetic field:

$$\text{Primary} \sim \text{source } (R^{-\alpha}) \times \text{propagation } (R^{-\delta}) \sim R^{-(\alpha+\delta)}$$

$$\text{Secondary} \sim \text{source } (R^{-(\alpha+\delta)}) \times \text{propagation } (R^{-\delta}) \sim R^{-(\alpha+2\delta)}$$

$$\text{Secondary/Primary} \sim R^{-\delta}$$

With the Kolmogorov turbulence model  $\delta = -1/3$

**Precise measurements of primaries and secondaries rigidity dependence provide key information on propagation and source processes**

# Measurement of Cosmic-Ray Nuclei

AMS has seven instruments which independently measure Cosmic Nuclei

Energy (E) or Momentum(P)

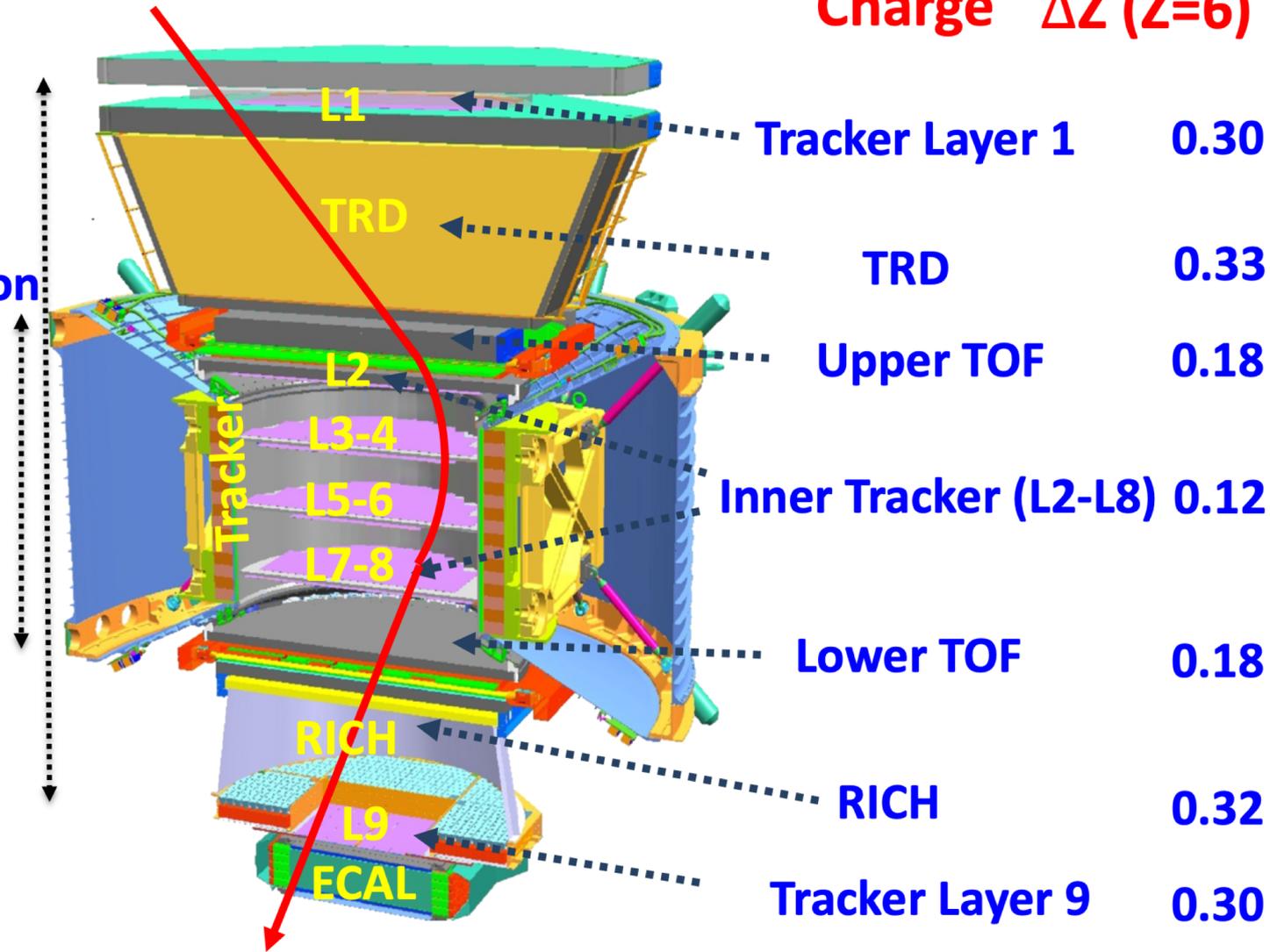
Charge  $\Delta Z$  (Z=6)

Tracker and Magnet:

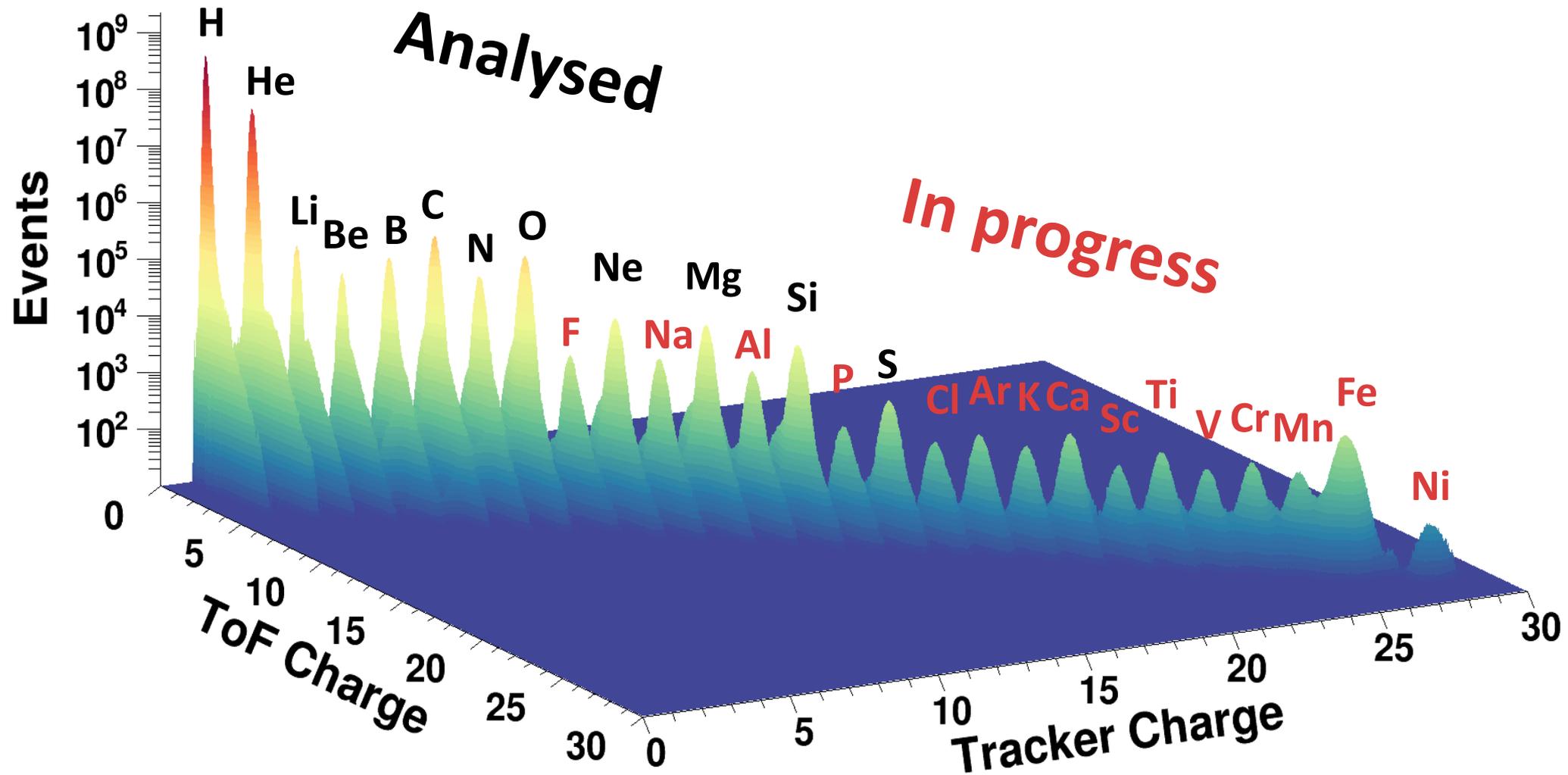
Rigidity  $R = P/Z$

Bending Spatial Resolution (Z=6)  $\approx 5 \mu m$

Maximum Detectable Rigidity (MDR) (Z=6) = 3.7 TV



# AMS Charge Measurement of Cosmic-Ray Nuclei



# Flux Measurement

Isotropic flux in the  $i^{\text{th}}$  rigidity bin  $(R_i, R_i + \Delta R_i)$

Number of selected events  
(subtracted for backgrounds and corrected for bin-to-bin migration)

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

Bin width  
(68 bins between 1.9 GV to 3 TV for Z=6)

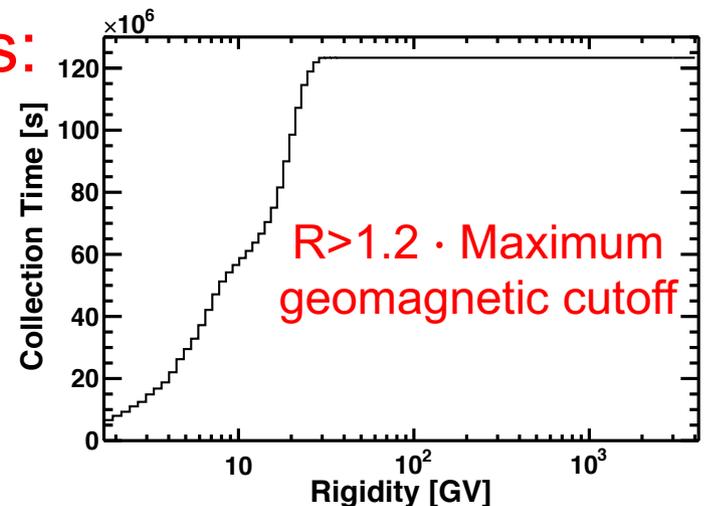
Effective acceptance  
(from MC, verified with data)

Trigger efficiency (5 years,  $1.23 \times 10^8$  s for  $R > 30$  GV)  
( $>97\%$  over entire R range for Z=6)

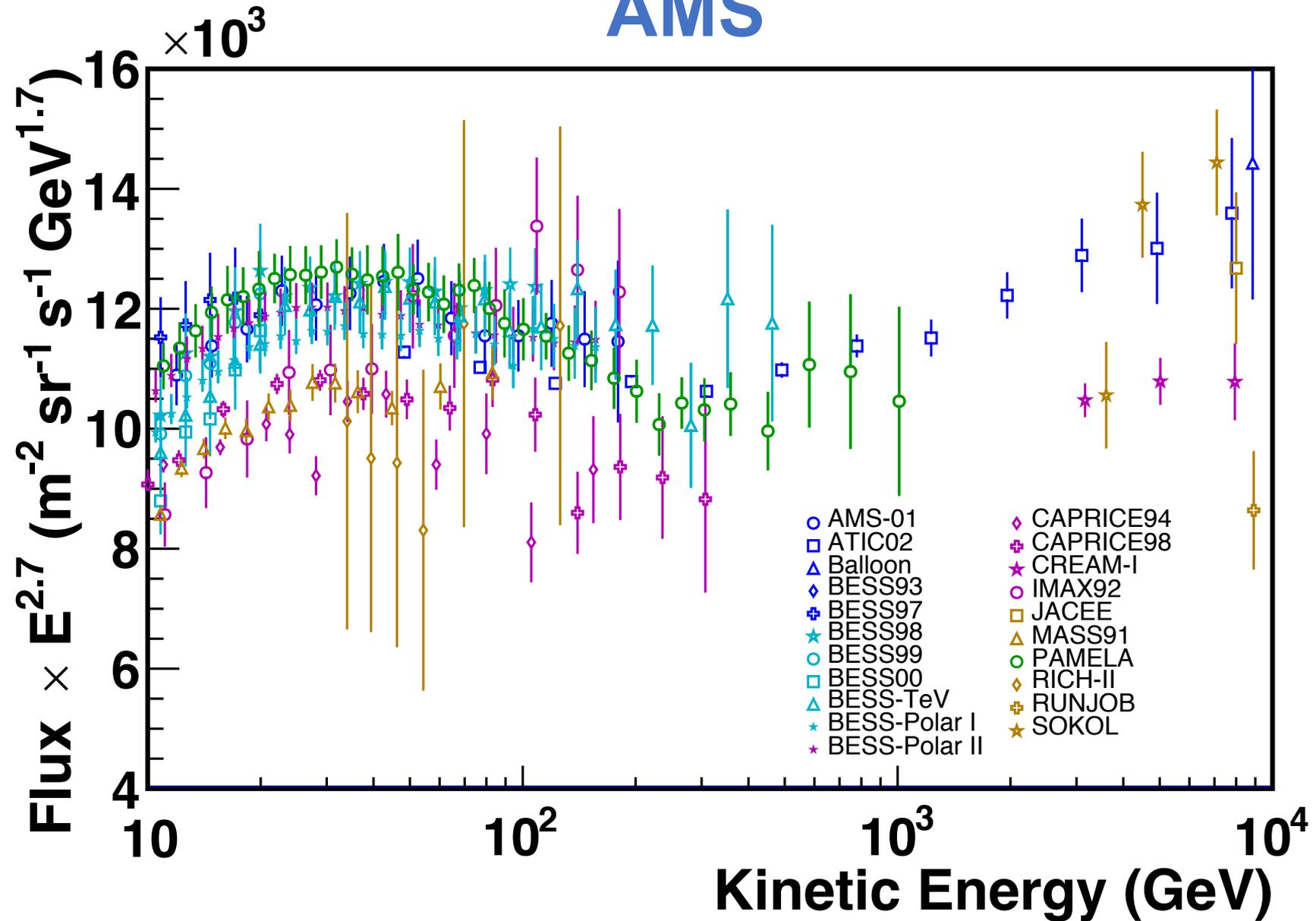
Collection time

## Extensive studies of the systematic errors:

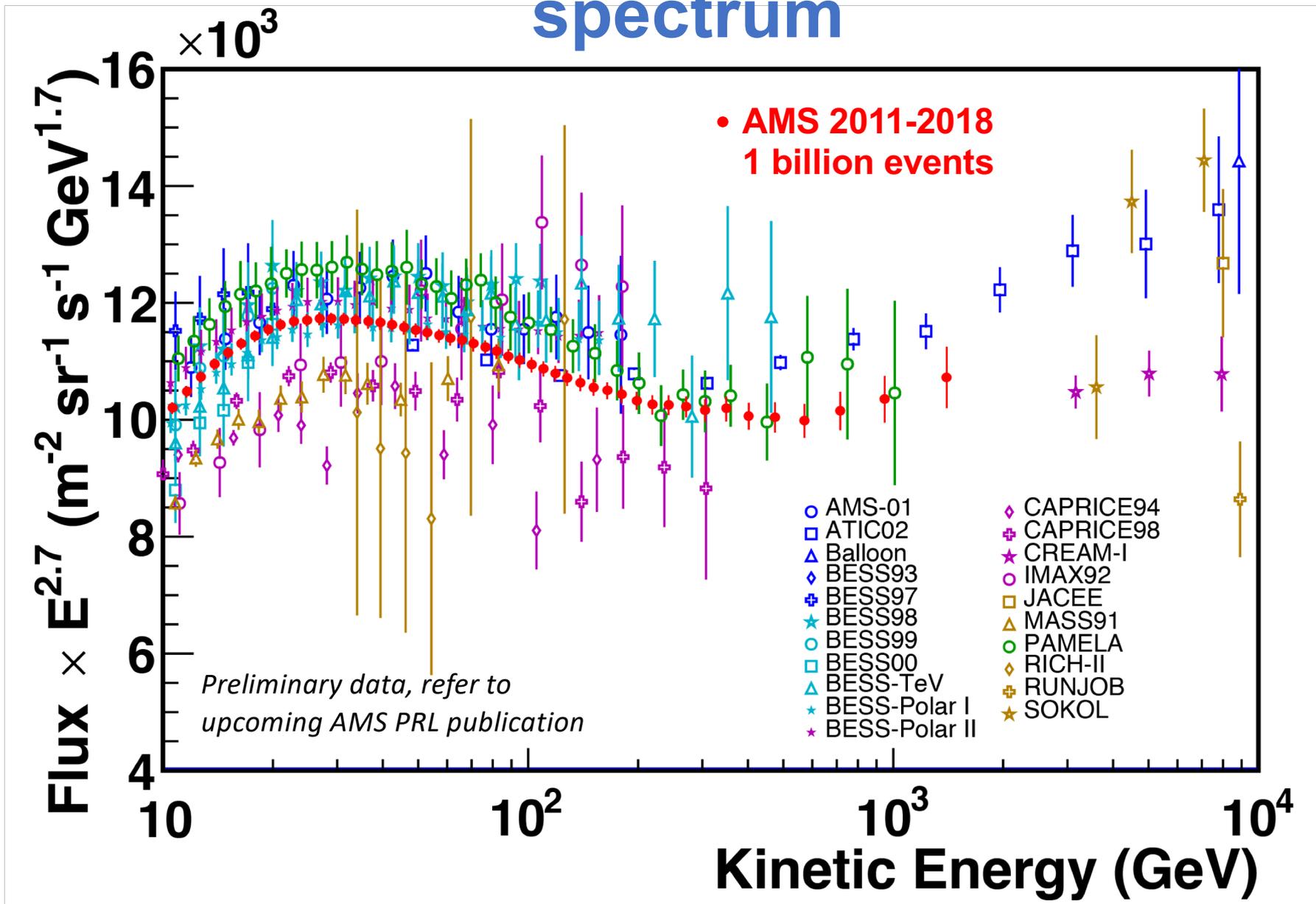
- Background estimations
- Acceptance and Trigger efficiency
- Rigidity resolution function
- Absolute rigidity scale



# Measurements of proton spectrum before AMS



# Latest AMS Measurements of proton spectrum

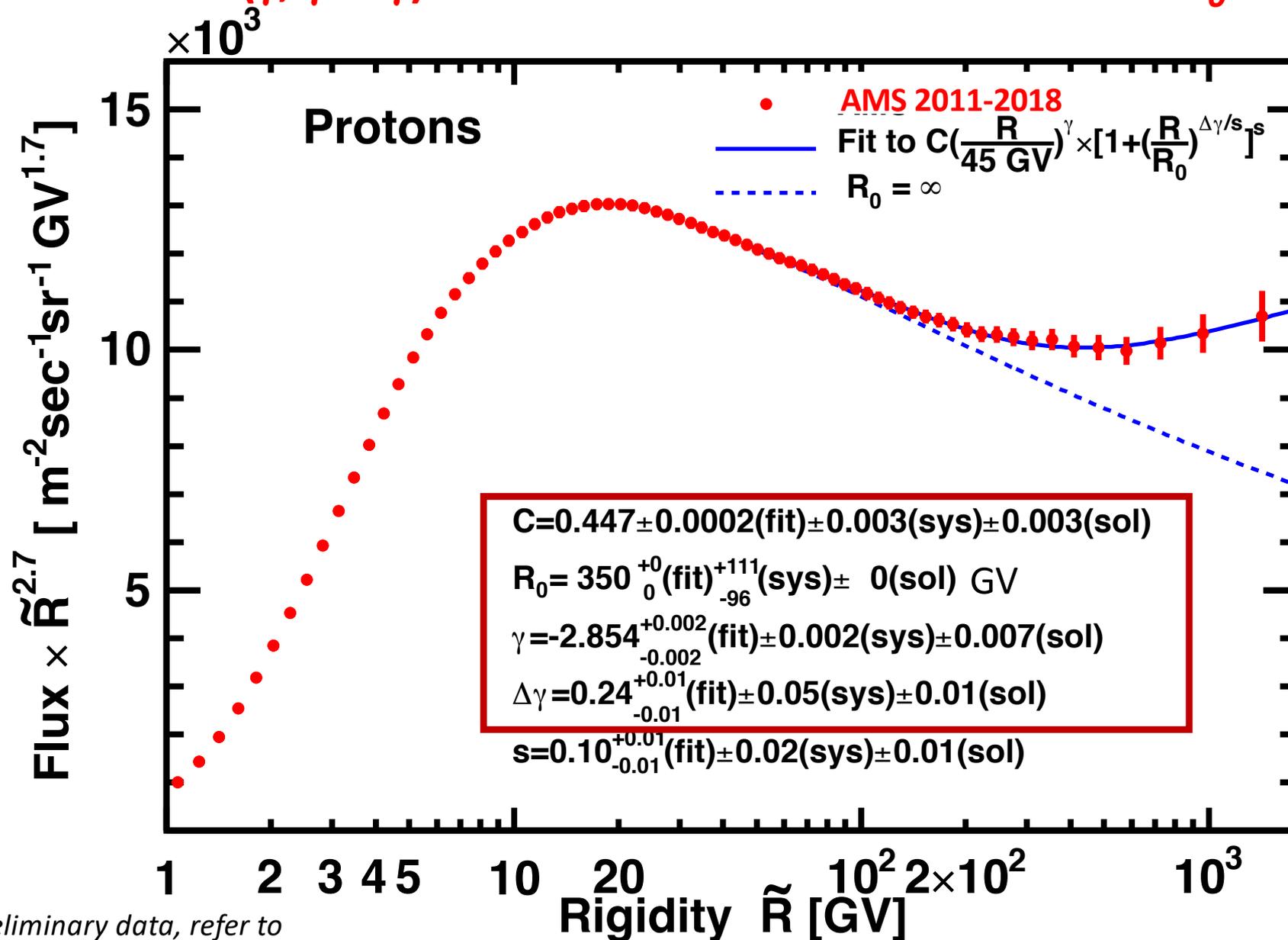


**Proton flux measured by AMS shows a deviation from a single power law above few hundred GV.**

# Origin of structure in the latest proton spectrum

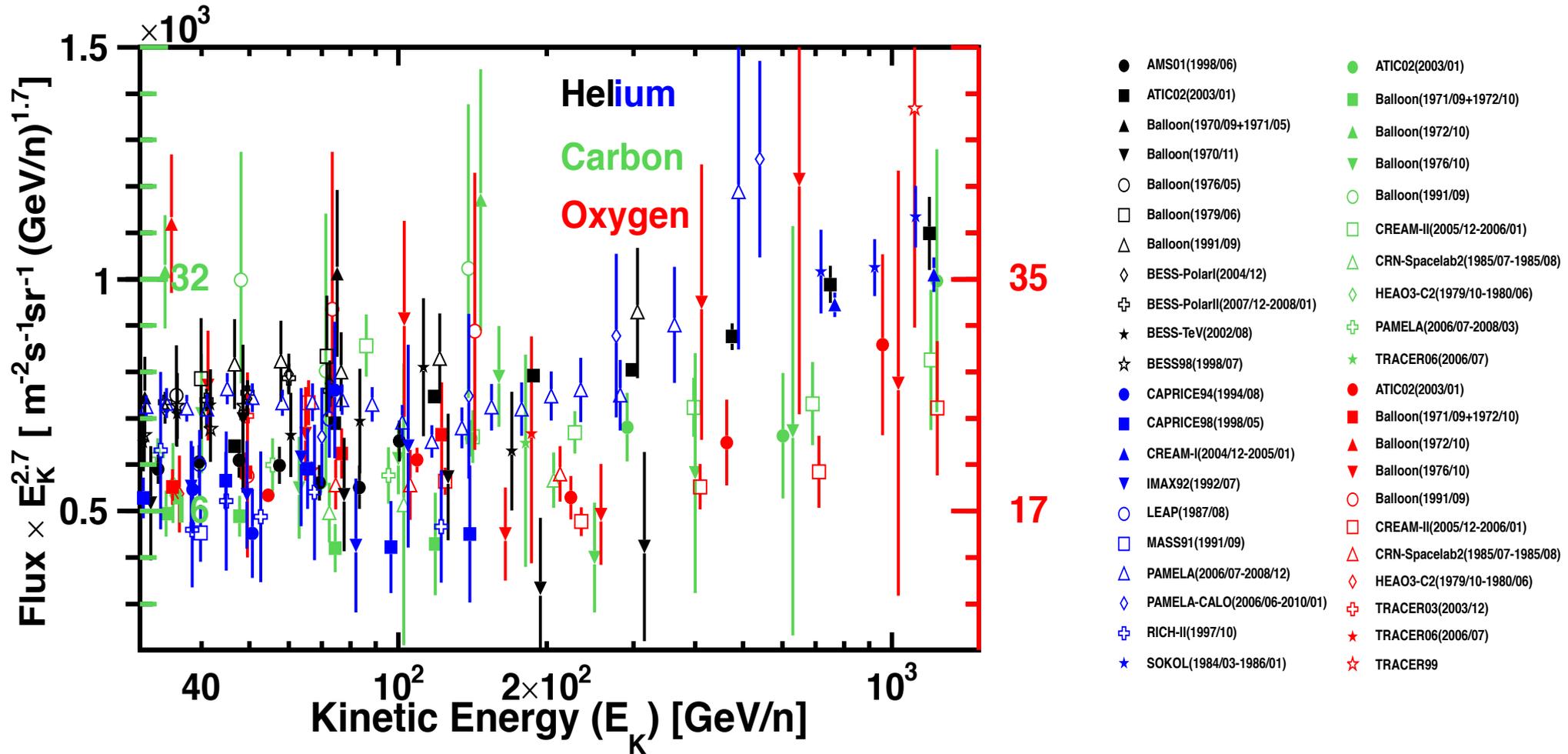
High rigidity deviation can be describe with a double power law model

$(\gamma, \gamma+\Delta\gamma)$  with a smooth transition around  $R_0$

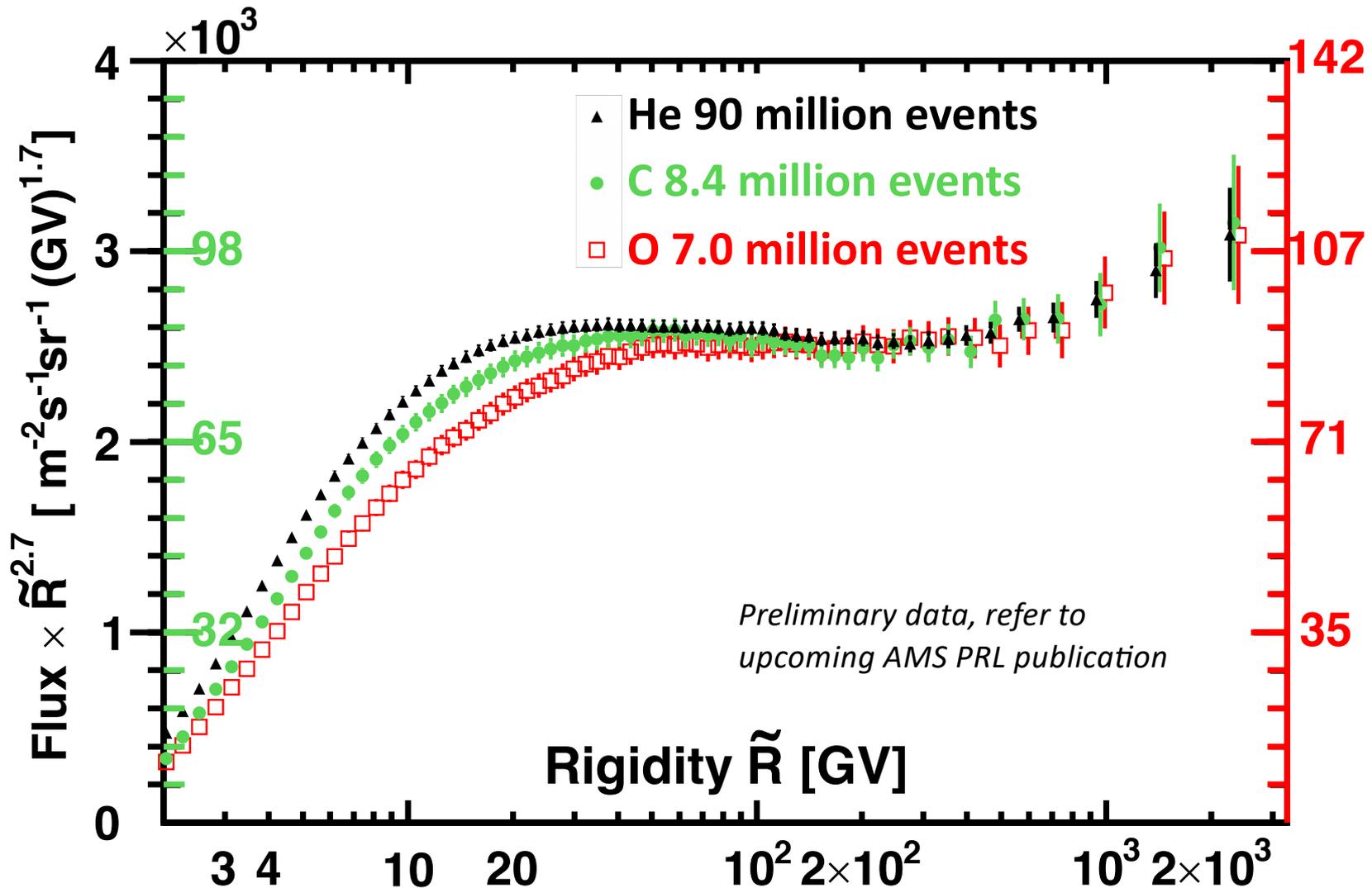


Preliminary data, refer to  
 upcoming AMS PRL publication

# Before AMS: Results on Primary Cosmic Rays (Helium, Carbon, Oxygen) from balloon and satellite experiments



# Latest AMS results (2011-2018) on Primary Cosmic Rays He, C, O



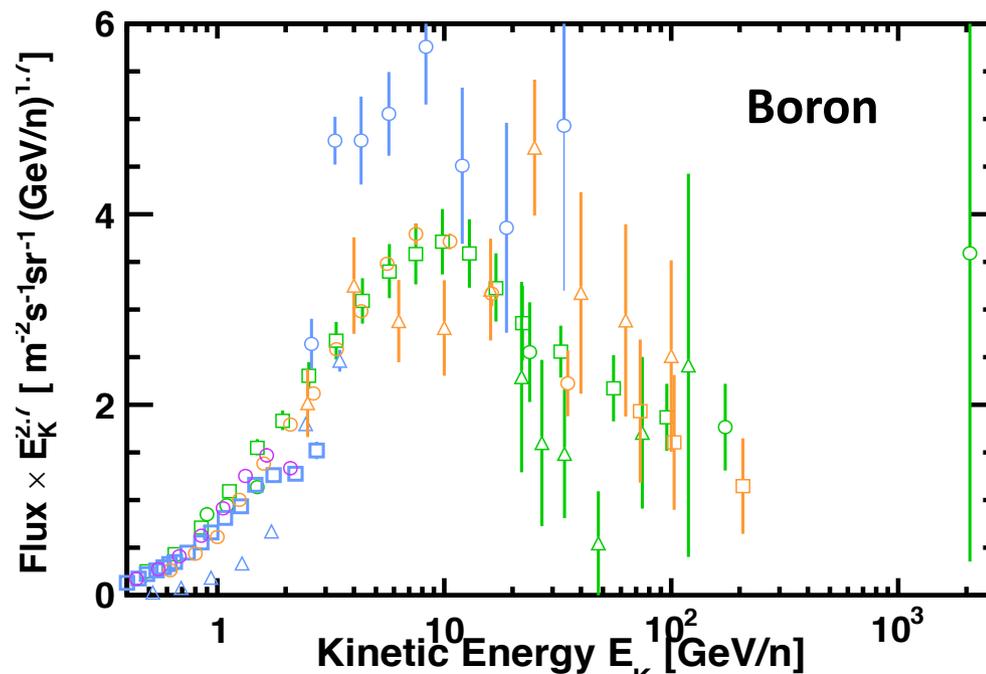
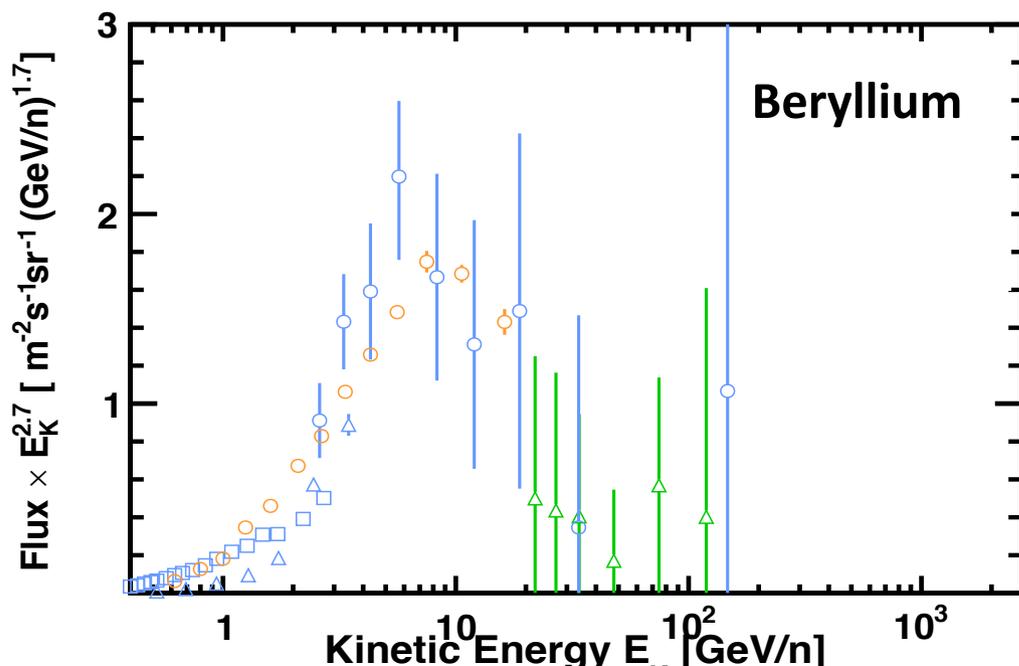
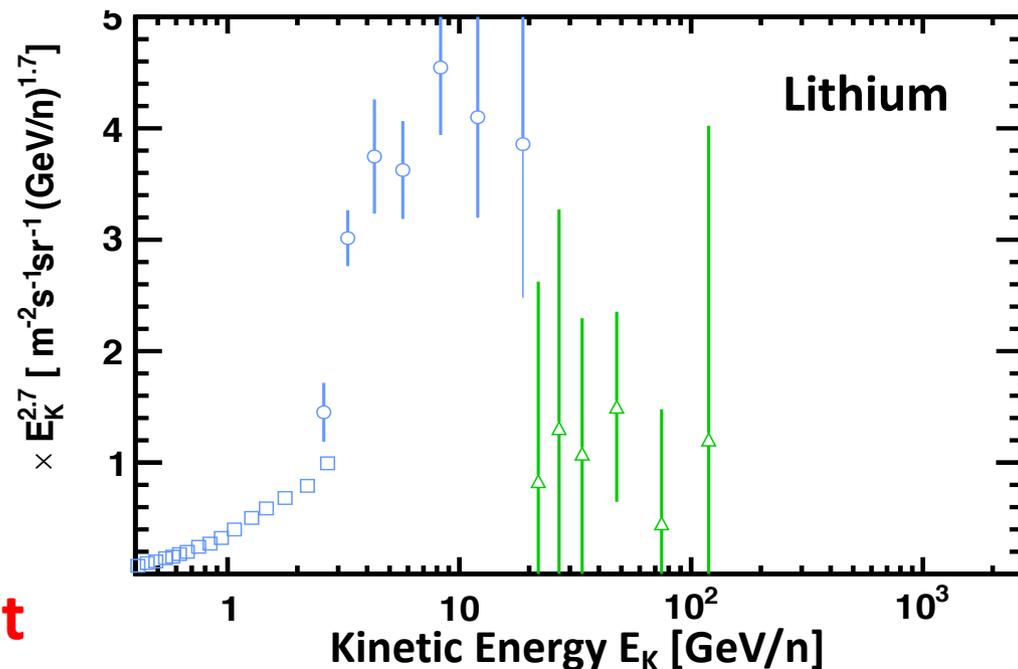
**Above 60 GV, the primary cosmic rays have identical rigidity dependence.**

**Same hardening as proton above 200 GV**

# Before AMS: Results on Secondary Cosmic Rays (Li, Be, B)

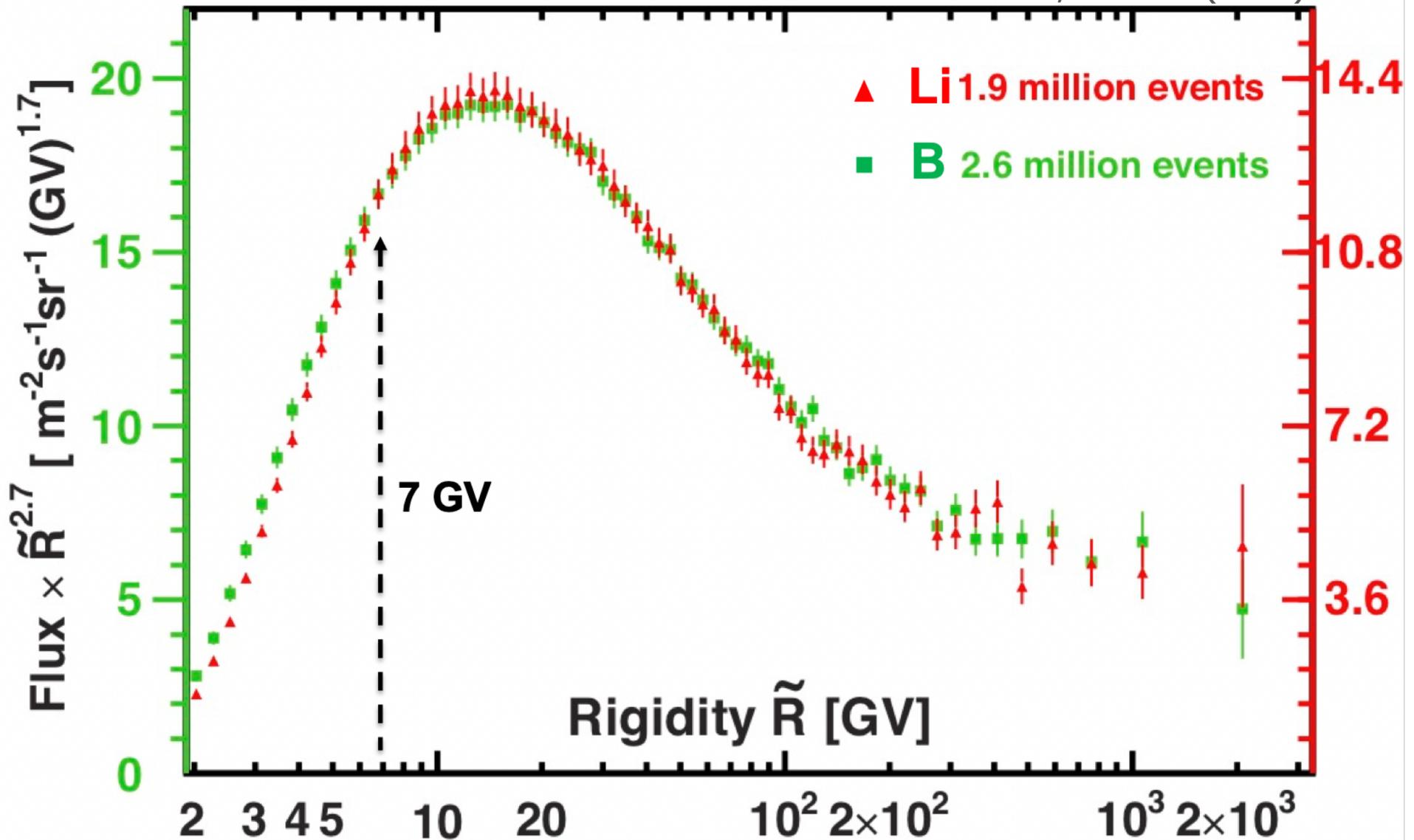
- TRACER
- PAMELA
- △ Juliusson
- Orth
- Webber
- △ Lezniak
- HEAO3
- CRN
- △ Simon
- Maehl

Typically, errors are larger than  
50% above 50 GV for each element



# AMS results on Secondary Cosmic Rays Li, Be, B

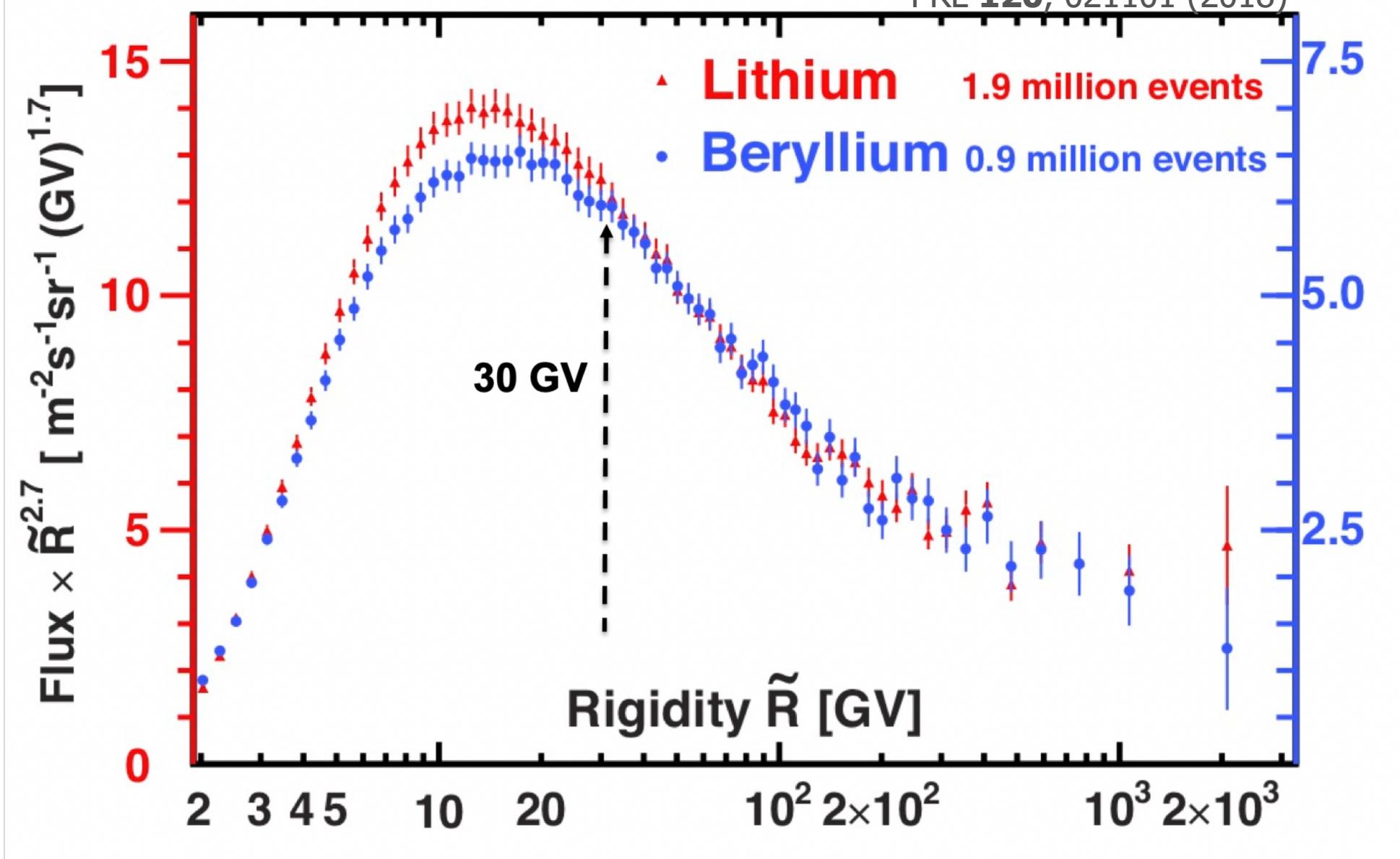
PRL **120**, 021101 (2018)



- Above 7 GV, Li and B have identical rigidity dependence

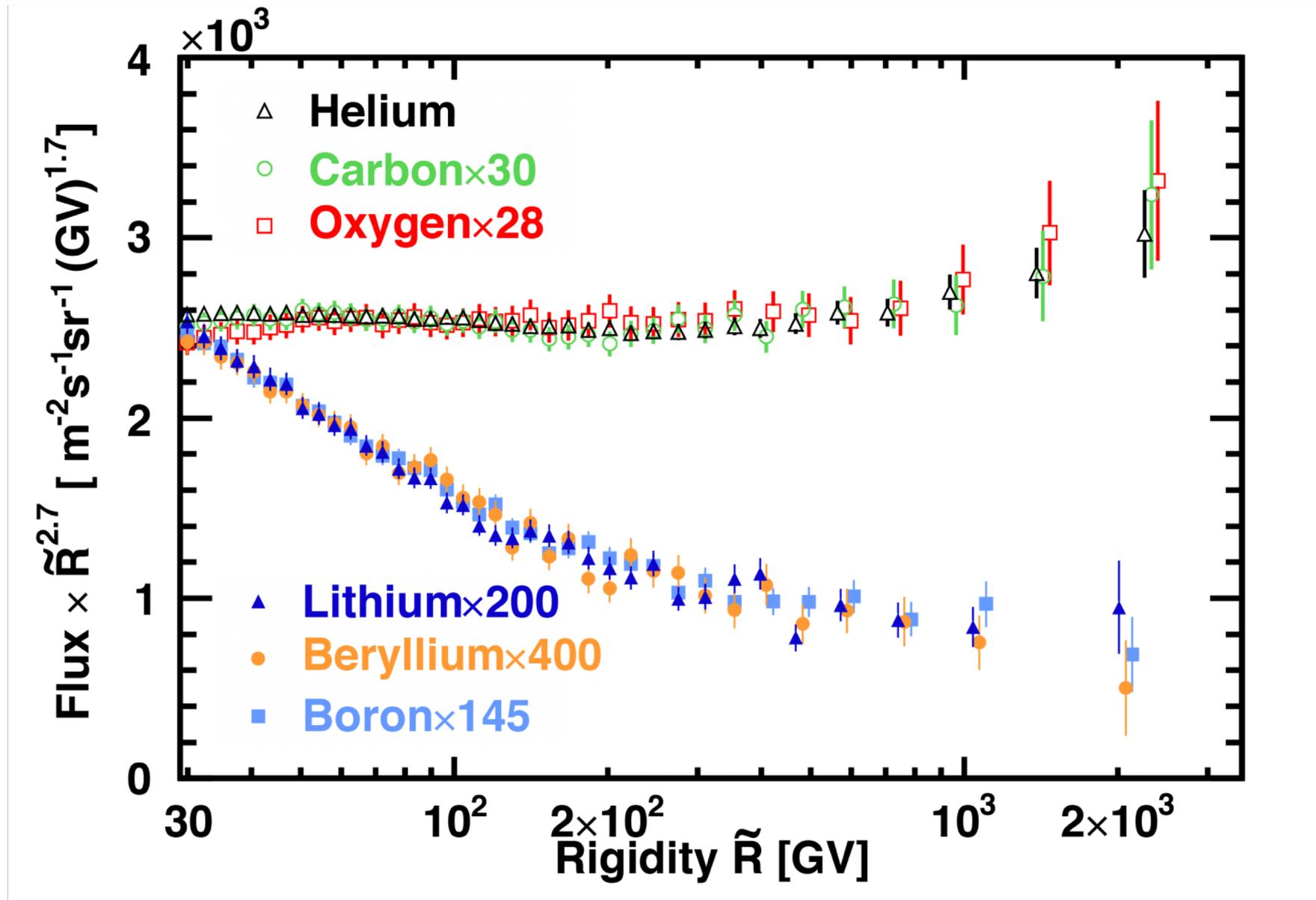
# AMS results on Secondary Cosmic Rays Li, Be, B

PRL **120**, 021101 (2018)



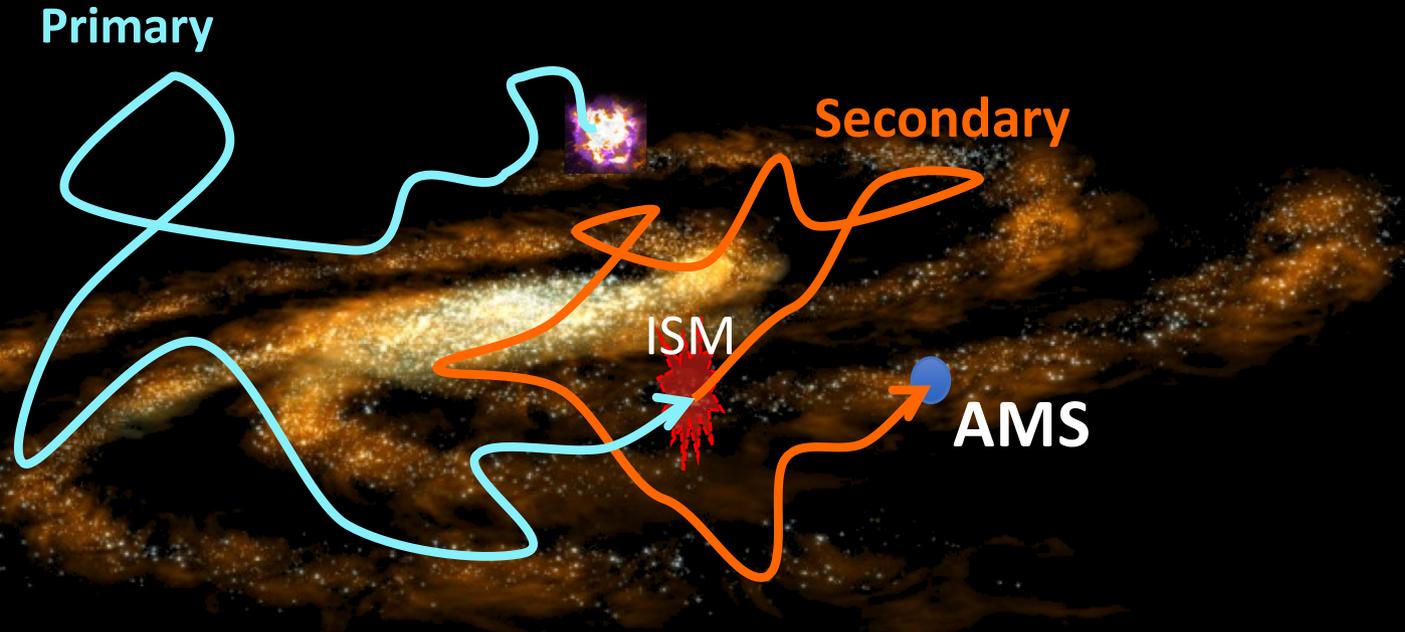
- Above 30 GV, Li and Be have identical rigidity dependence.
- Below 30 GV, difference can be due to the presence of radioactive  $^{10}\text{Be}$  isotope ( $T_{1/2} = 1.4$  My)

# Rigidity dependence of Primary and Secondary Cosmic Rays



- Rigidity dependences are distinctly different for primaries and secondaries.
- Both deviate from a traditional single power law above 200 GeV.

# Galactic Cosmic Rays



*Fundamental questions:*

*What is the propagation history of cosmic rays?  
What is the origin of the break at high rigidity?*

**Primary**  $\sim$  source ( $R^{-\alpha}$ )  $\times$  propagation ( $R^{-\delta}$ )  $\sim R^{-(\alpha+\delta)}$

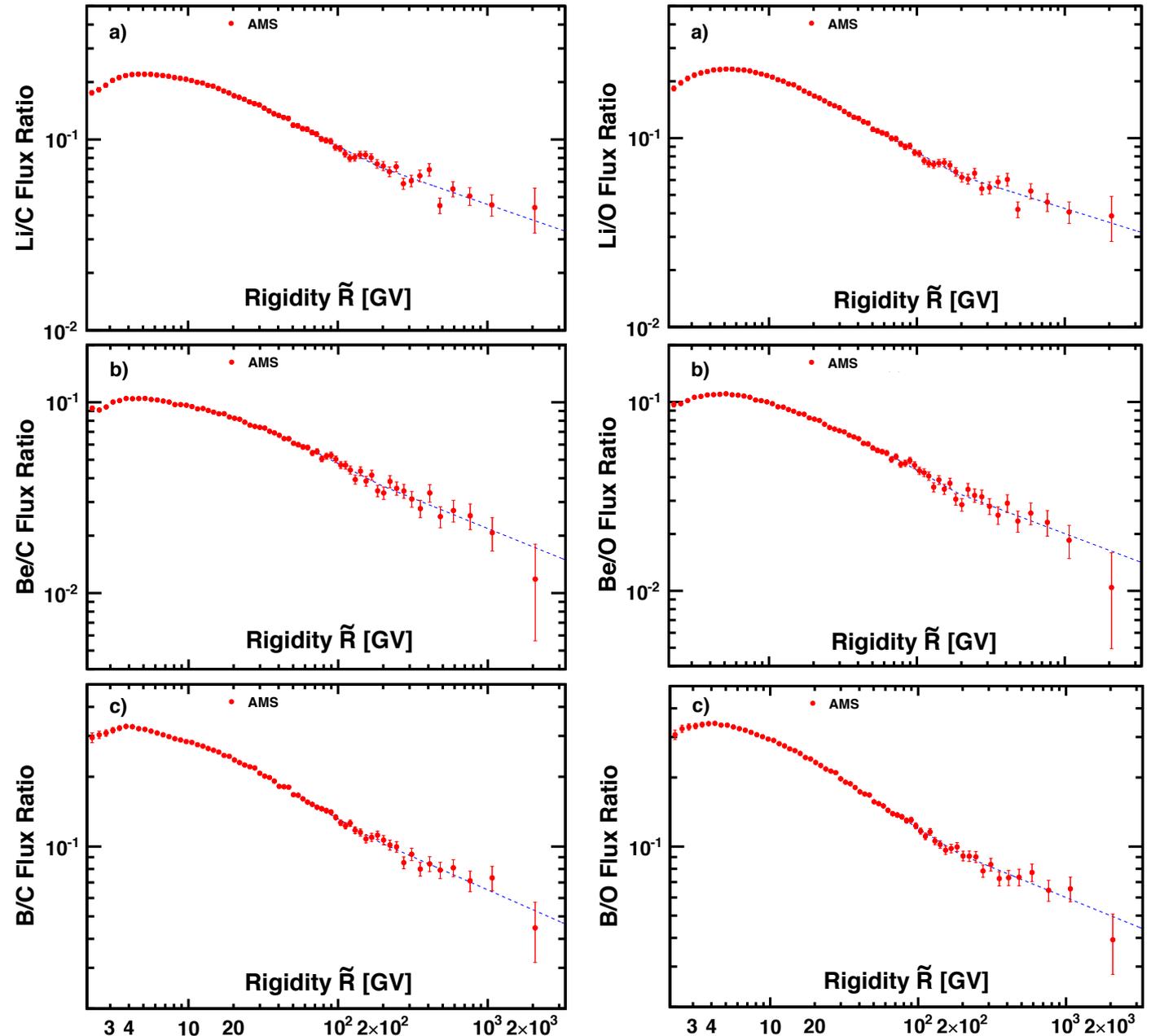
**Secondary**  $\sim$  source ( $R^{-(\alpha+\delta)}$ )  $\times$  propagation ( $R^{-\delta}$ )  $\sim R^{-(\alpha+2\delta)}$

**Secondary/Primary**  $\sim R^{-\delta}$

# Secondary/Primary flux ratios vs rigidity

Li/C, Be/C, B/C  
and  
Li/O, Be/O, B/O  
ratios between 2 GV  
and 3 TV

PRL **120**, 021101 (2018)



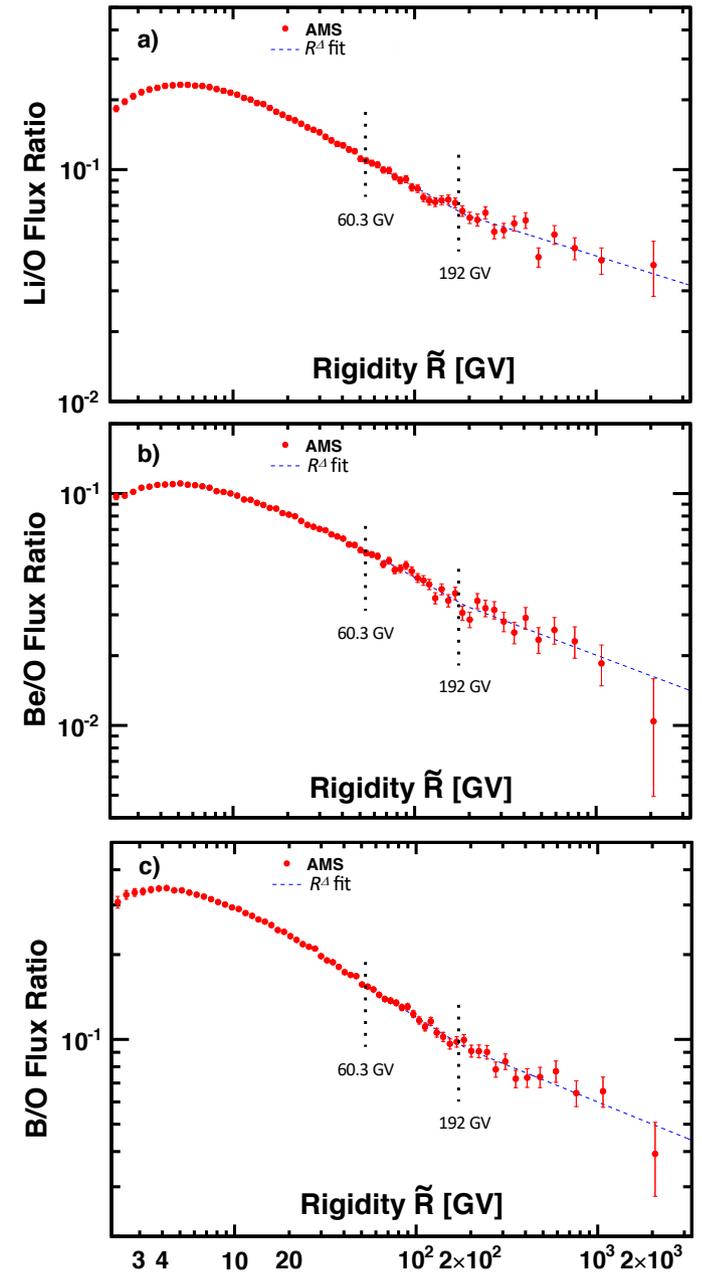
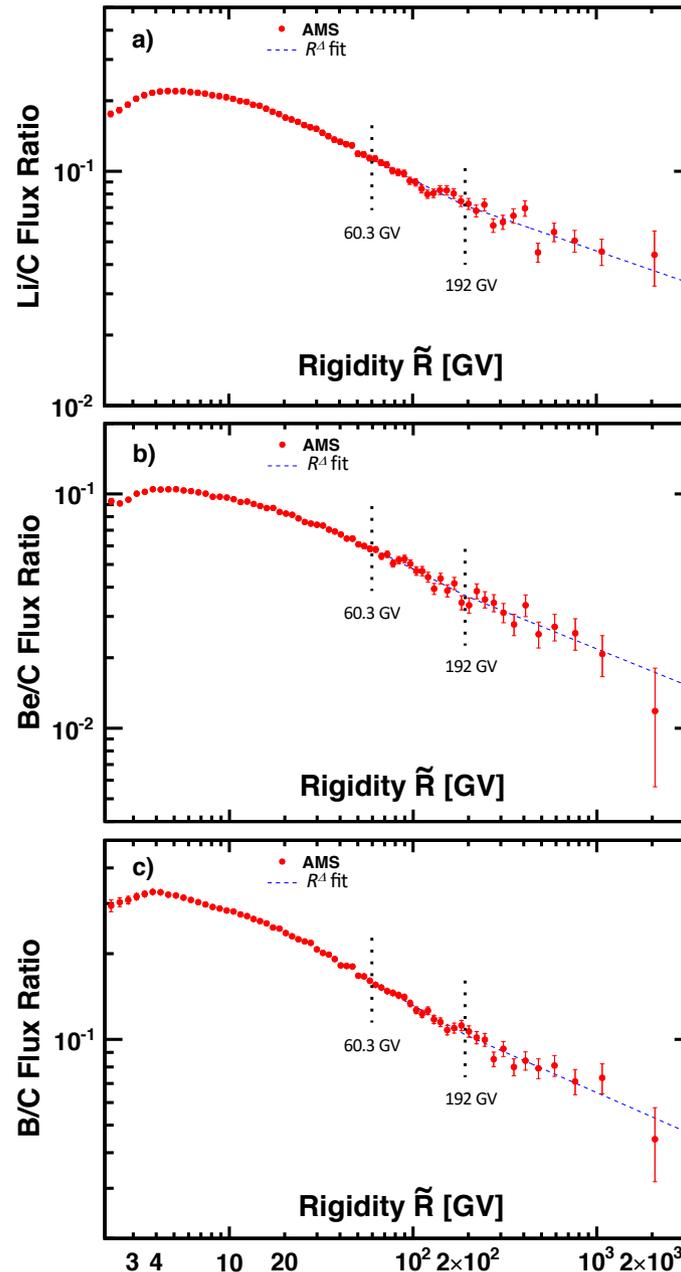
# Secondary/Primary flux ratios vs rigidity

PRL **120**, 021101 (2018)

To investigate the rigidity dependence and the origin of the spectral hardening at high rigidity :

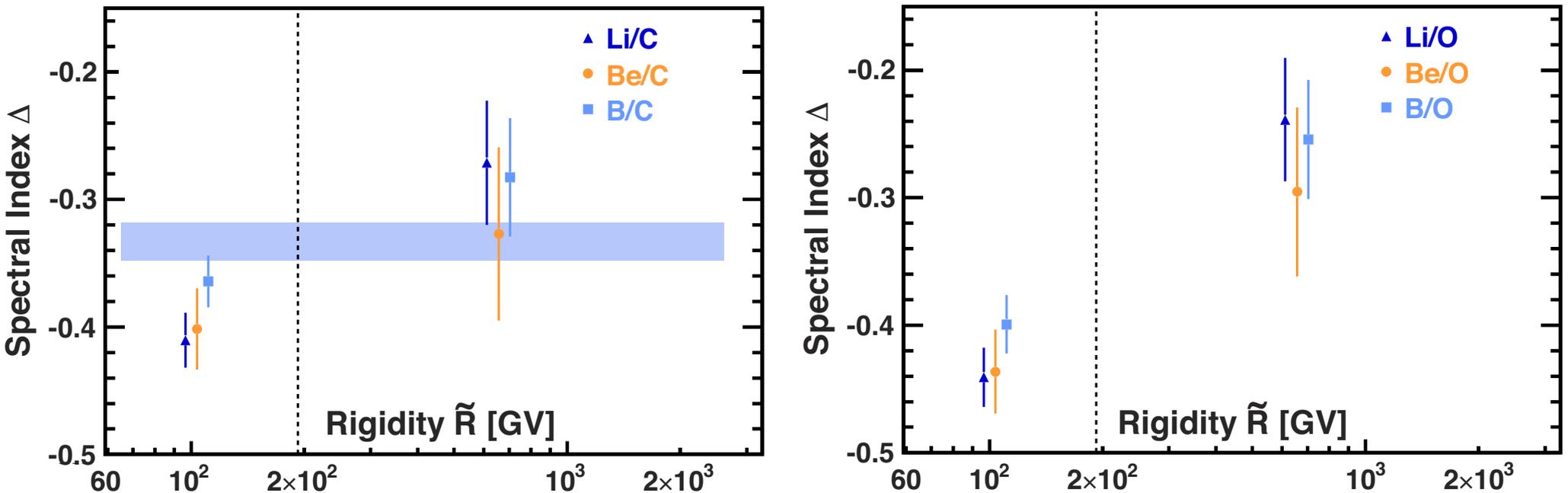
$R^{\Delta}$  fits for two rigidity intervals:

[60.3 GV–192 GV]  
and [192 GV–3300 GV]



# Secondary/Primary flux ratios vs rigidity

$R^{\Delta}$  fits for two rigidity intervals [60.3 GV–192 GV] and [192 GV–3300 GV] of Li/C, Be/C, B/C and Li/O, Be/O, B/O:

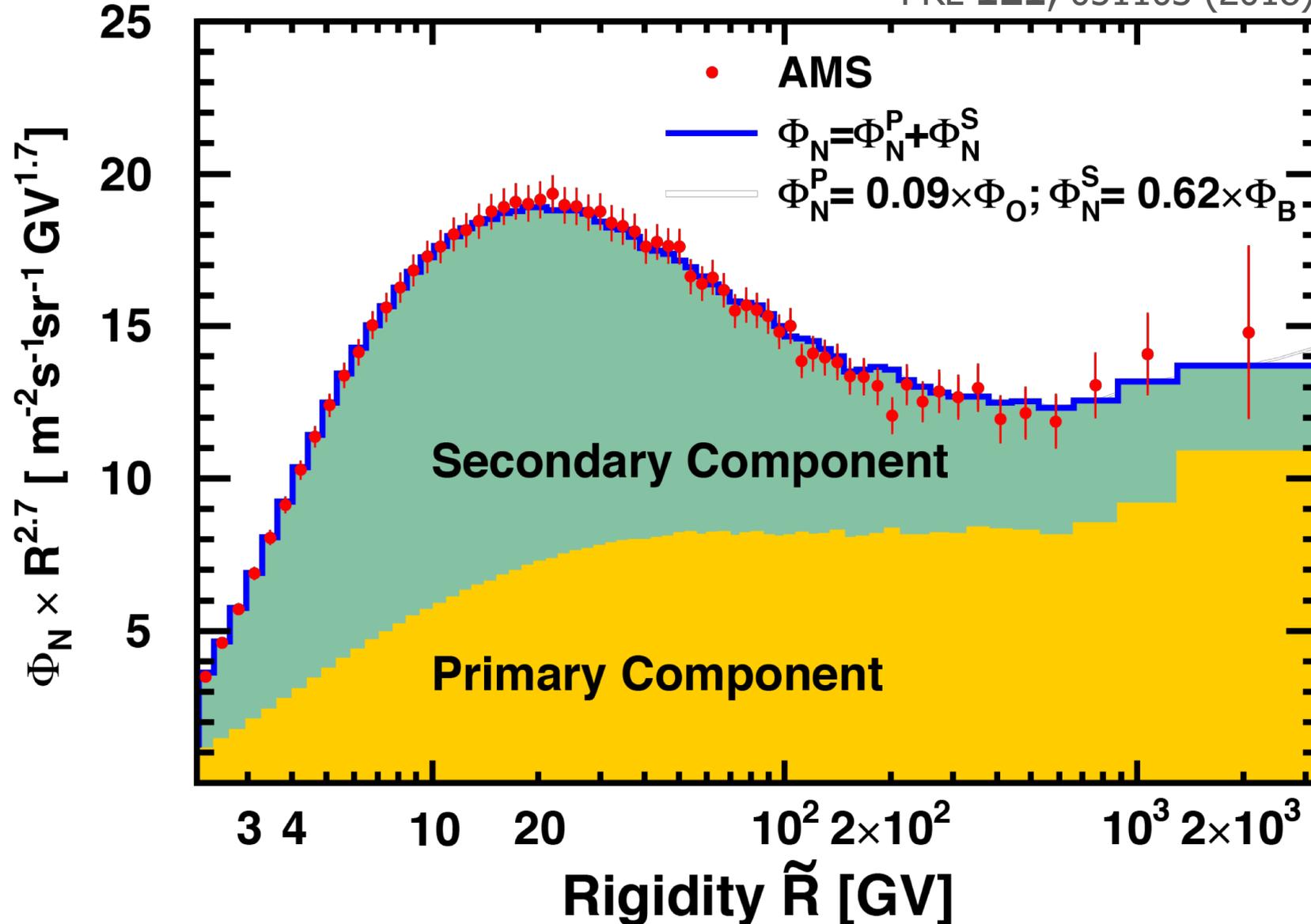


→ Indications for a deviation on the ratio (all data combined:  $0.13 \pm 0.03$ )

→ Support the interpretation of the hardening in terms of a change in the propagation properties in the Galaxy.

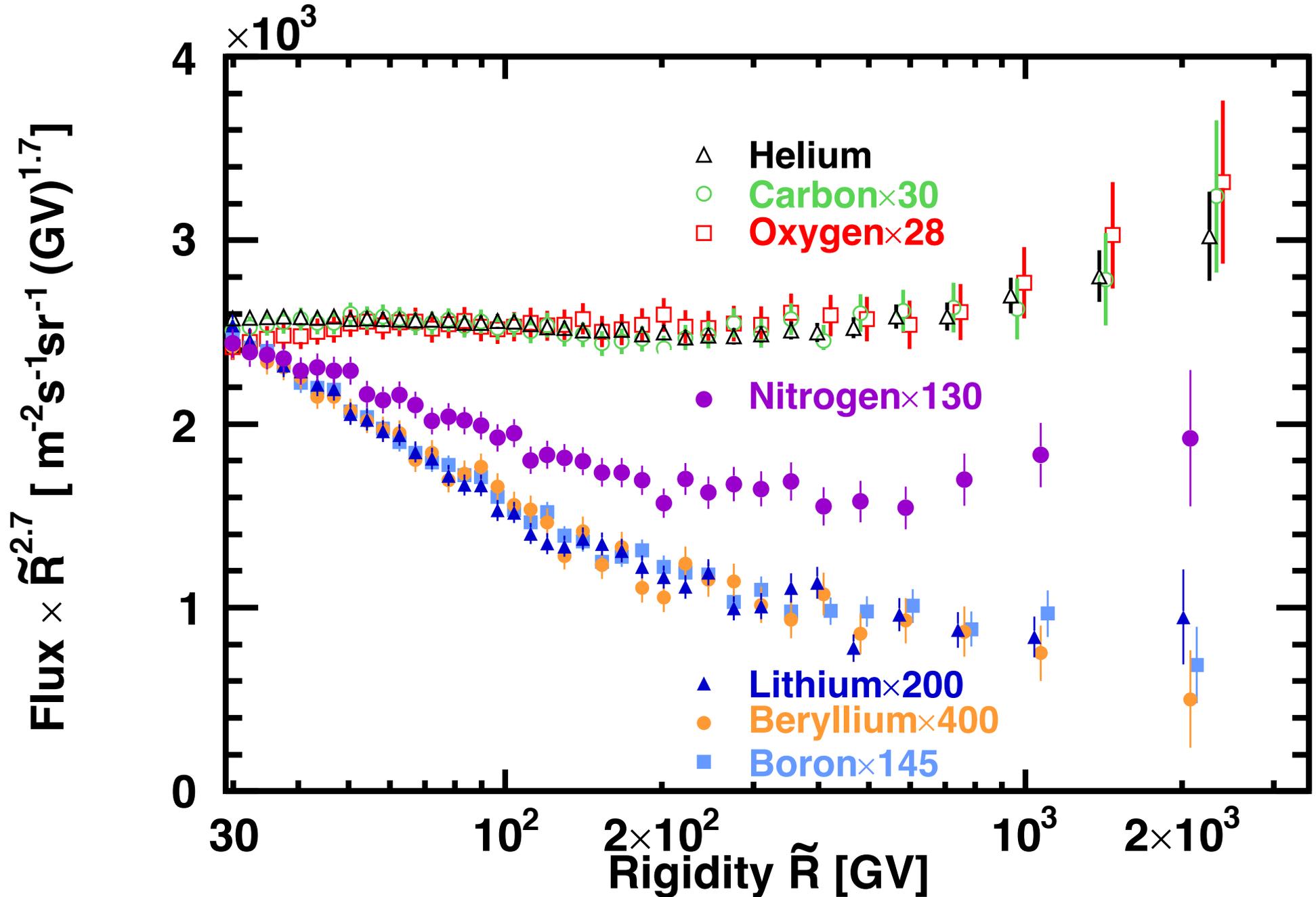
# Nitrogen Flux measurement with AMS02

PRL **121**, 051103 (2018)

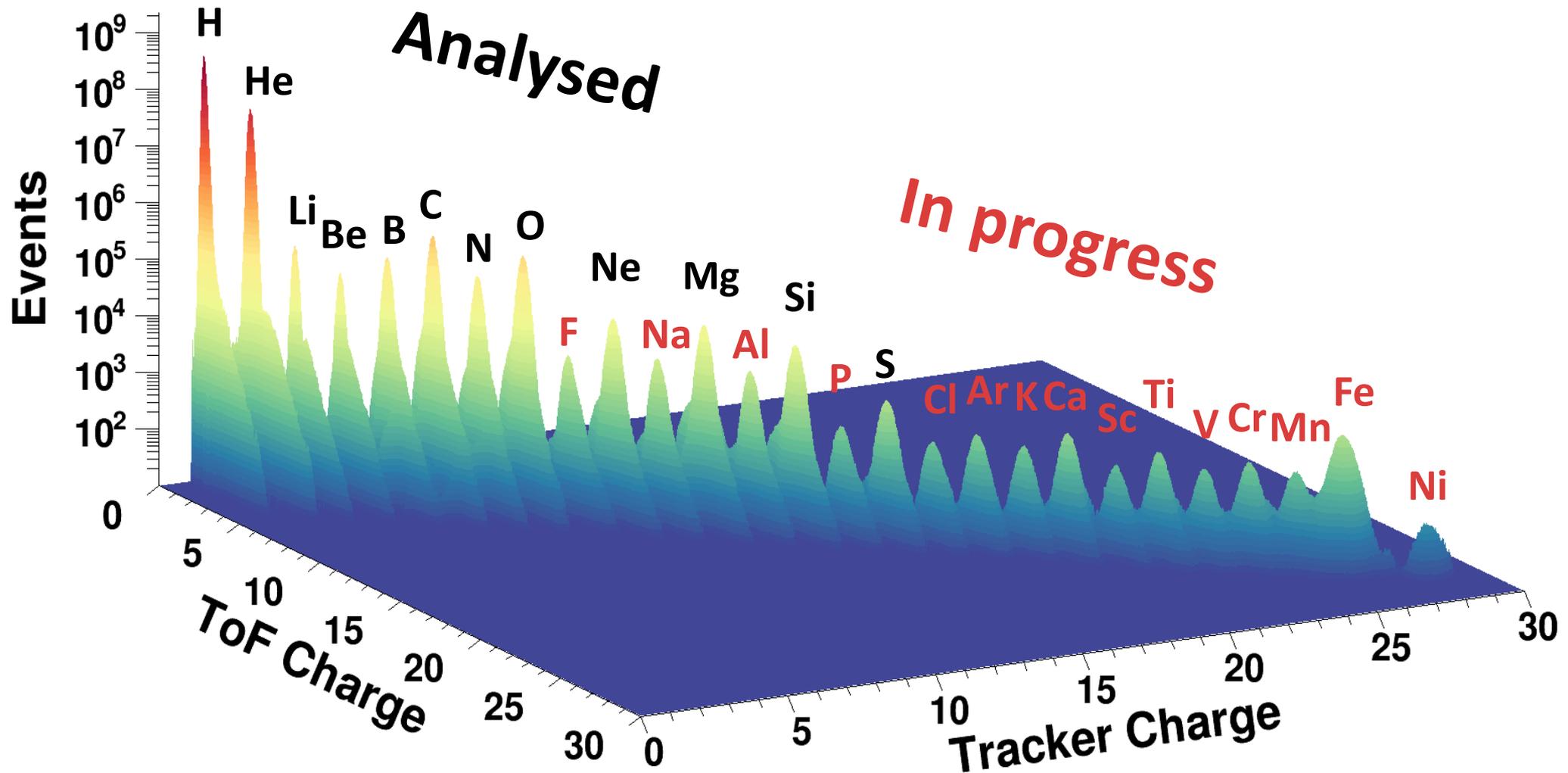


The Nitrogen flux  $\Phi_N$  is composed of a Primary flux  $\Phi_N^P$  and a Secondary flux  $\Phi_N^S$  in the entire rigidity range

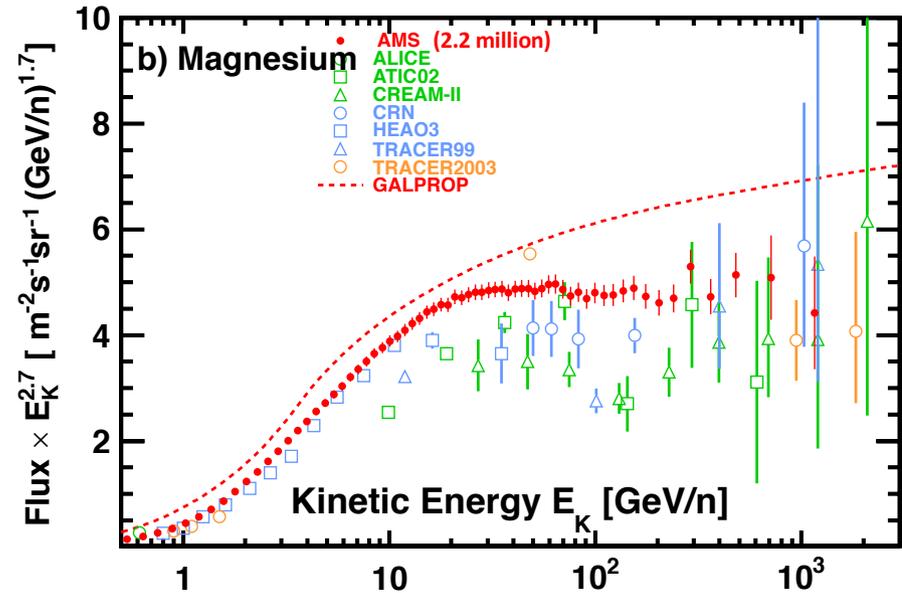
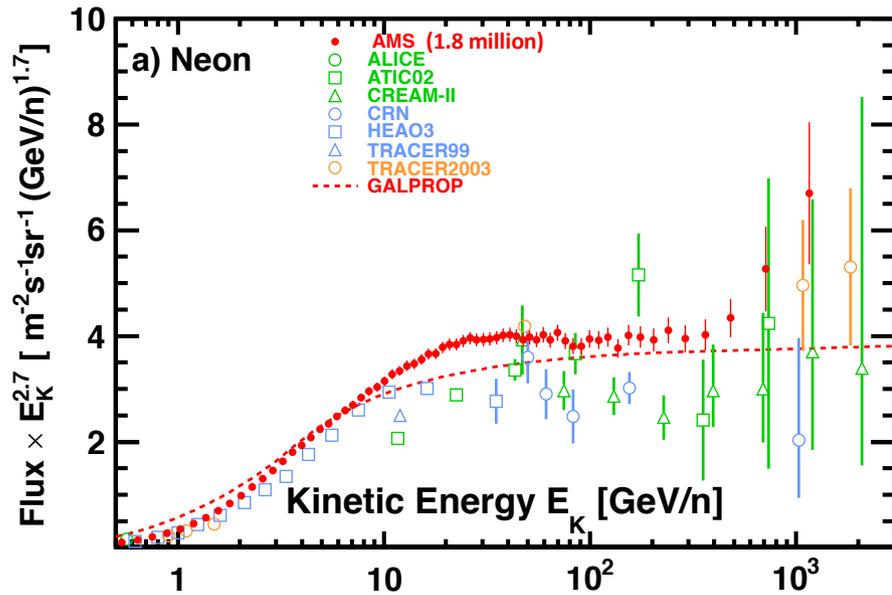
# The AMS measurements of the primary cosmic ray fluxes and the secondary cosmic rays fluxes with the nitrogen flux.



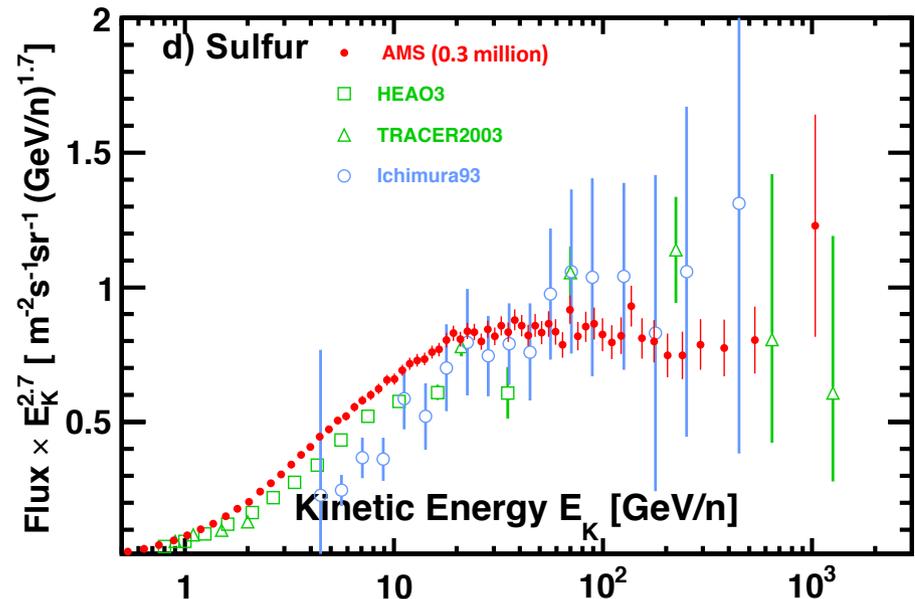
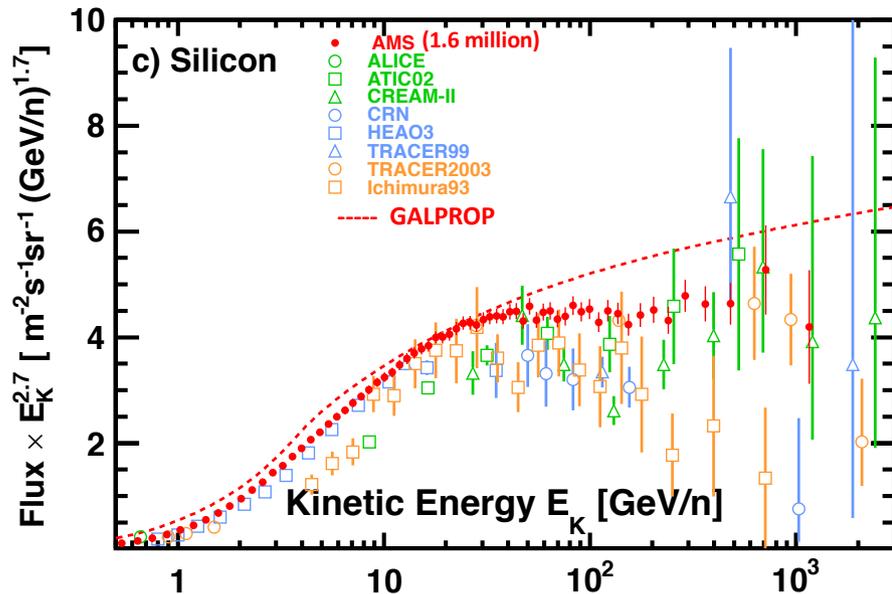
# Precision measurement of Cosmic Rays



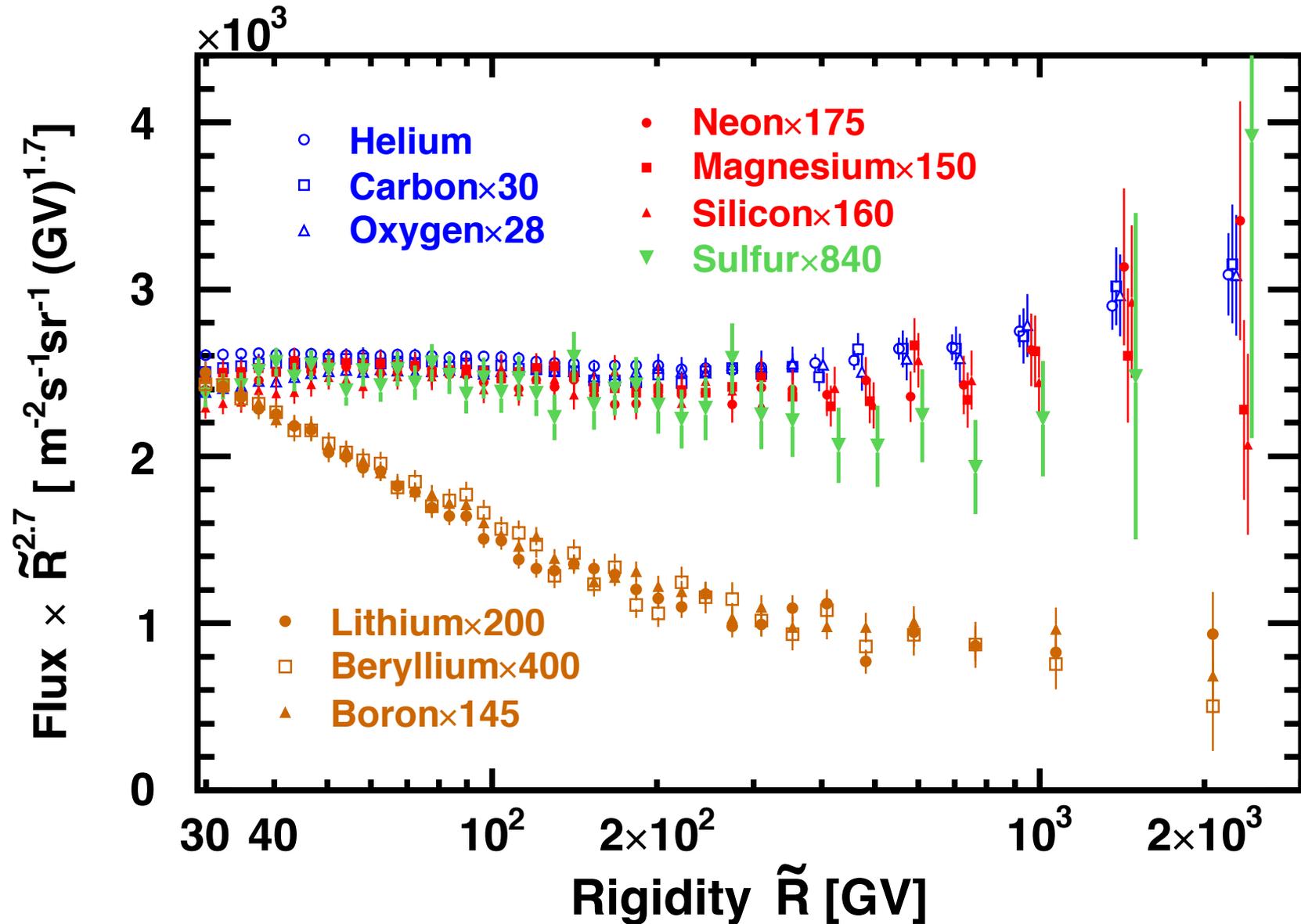
# Latest AMS results (2011-2018) on Primary Cosmic Rays Z=10, 12, 14, 16



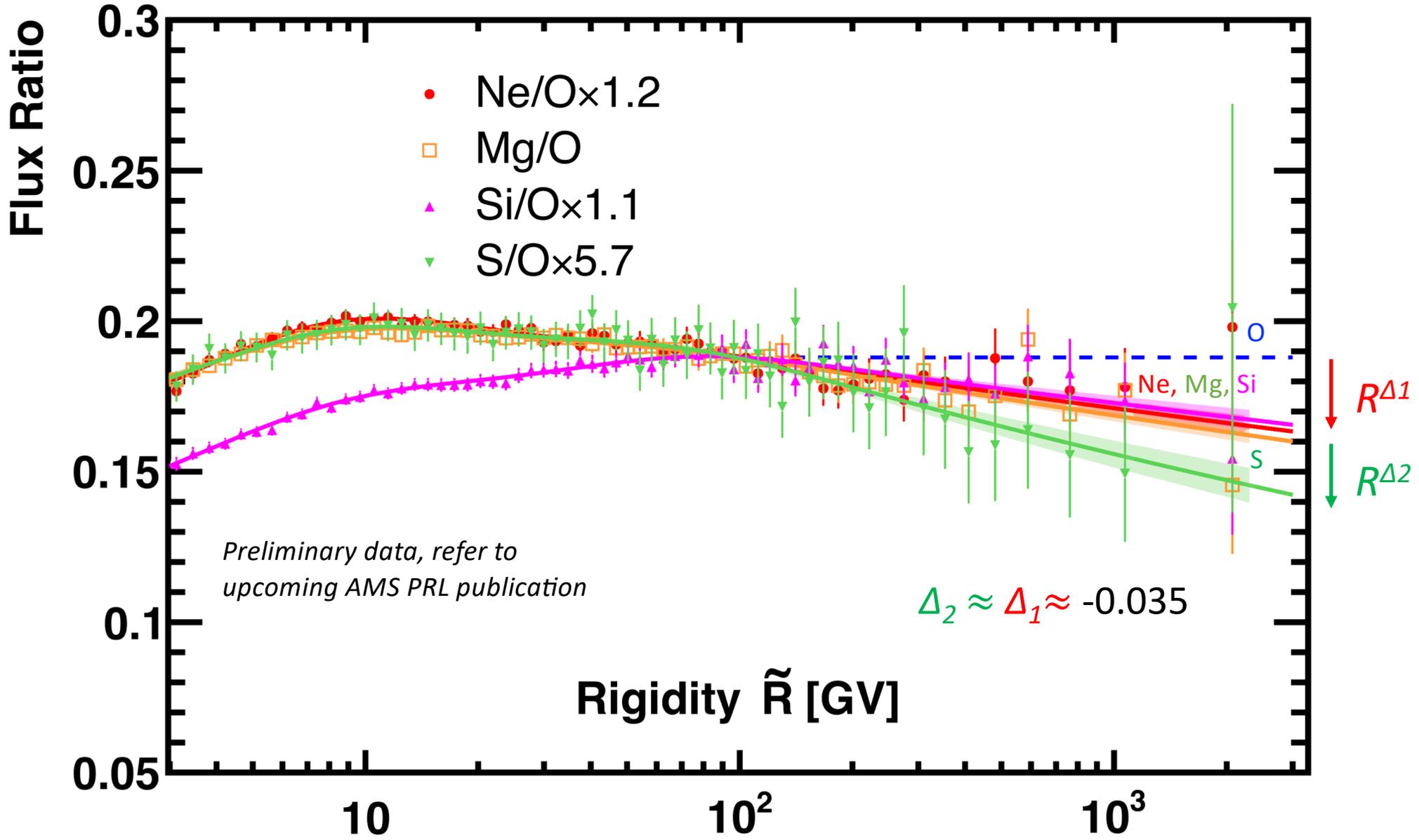
*Preliminary data, refer to upcoming AMS PRL publication*



# Latest AMS results (2011-2018) on Primary Cosmic Rays Z=10, 12, 14, 16



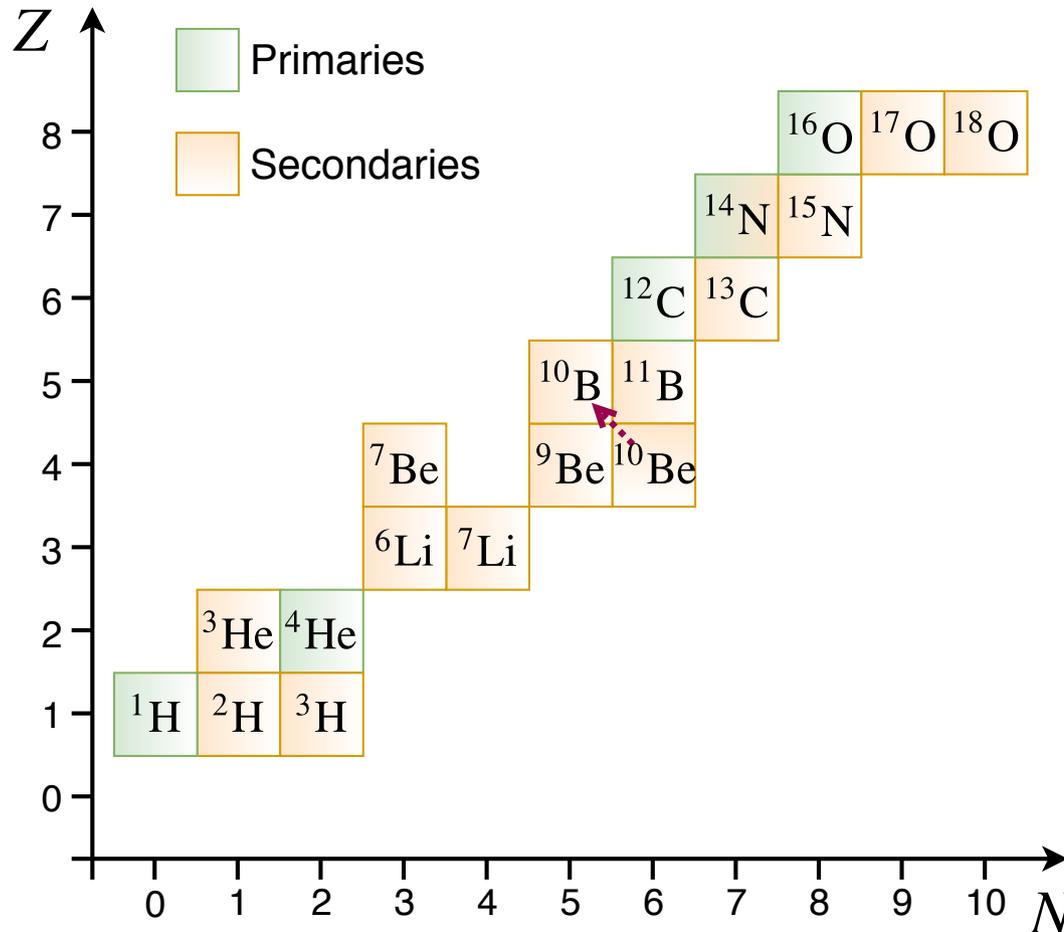
# Flux Ratio to Oxygen (Ne/O, Mg/O, Si/O, and S/O)



Above 100GV Ne,Mg,Si/O  $\propto R^{\Delta_1}$  and S/O  $\propto R^{\Delta_1+\Delta_2}$  where  $\Delta_2 \approx \Delta_1 \approx -0.035$

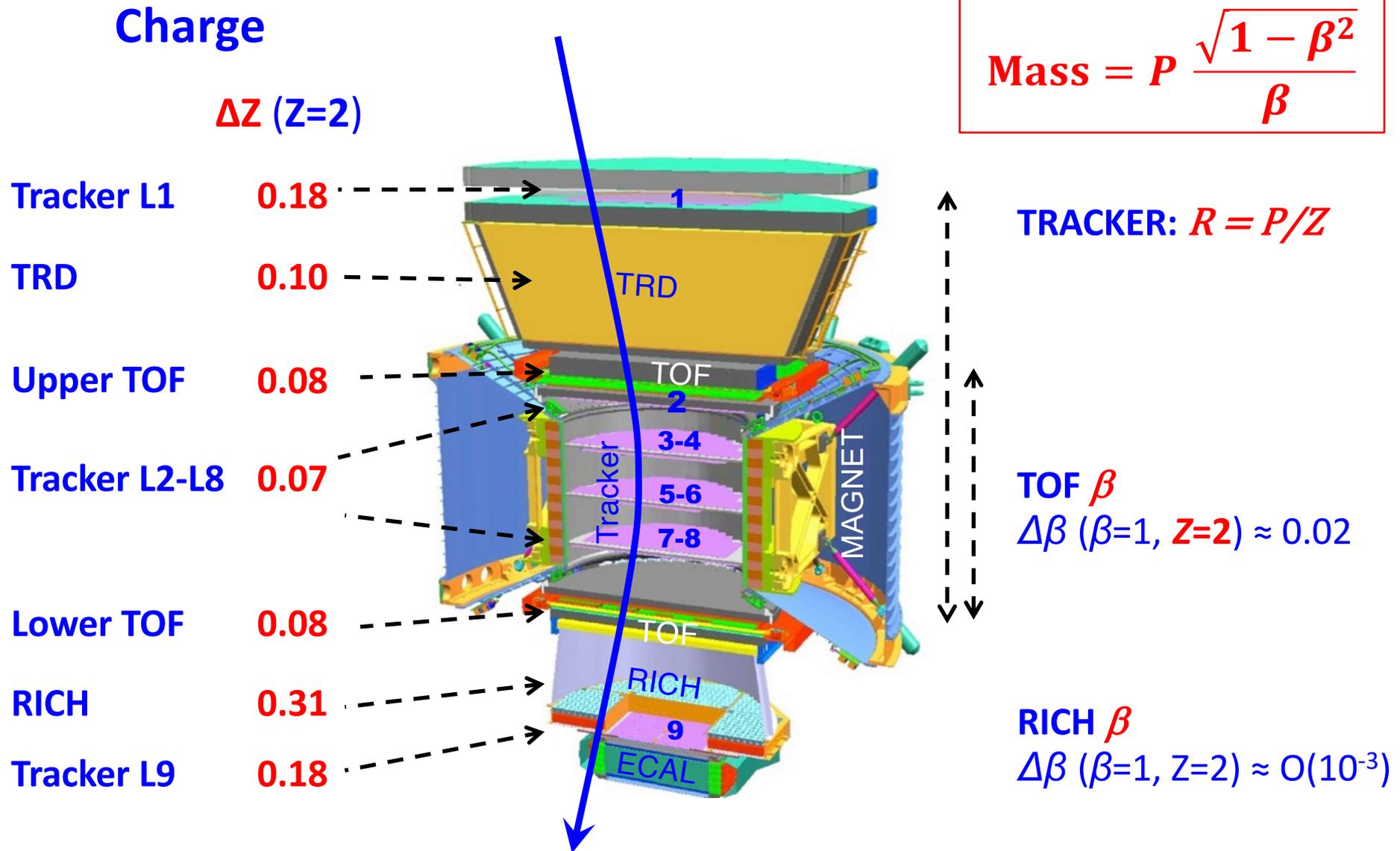
# Light Isotopes in Cosmic Rays

Additional information from isotopic composition of Cosmic Rays:

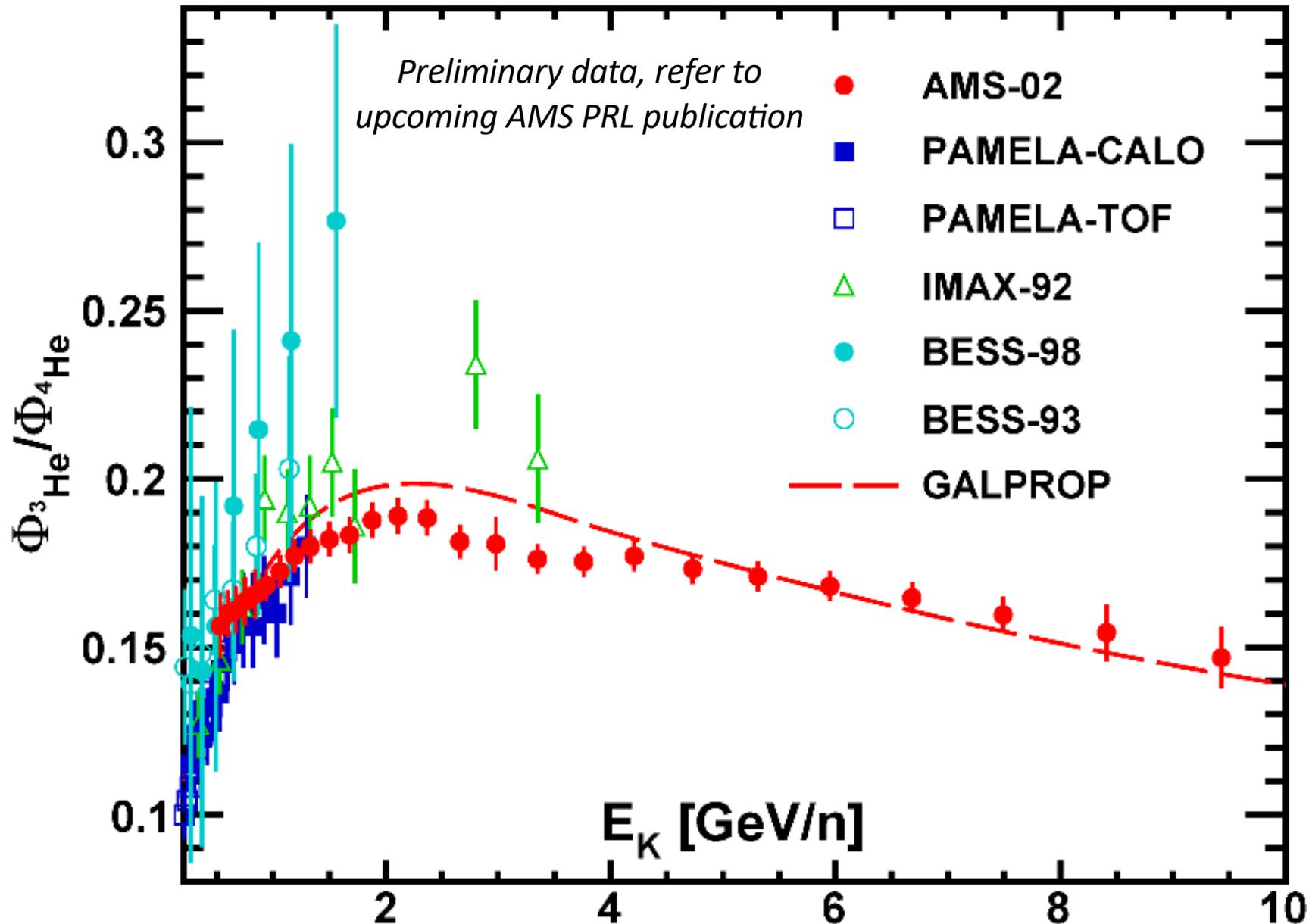


- Different origins (secondary/primary):
  - $^3\text{He}/^4\text{He}$
- Different propagation history:
  - decay of  $^{10}\text{Be}$  ( $t_{1/2} = 1.4 \text{ My}$ )  $\rightarrow$  radioactive clock

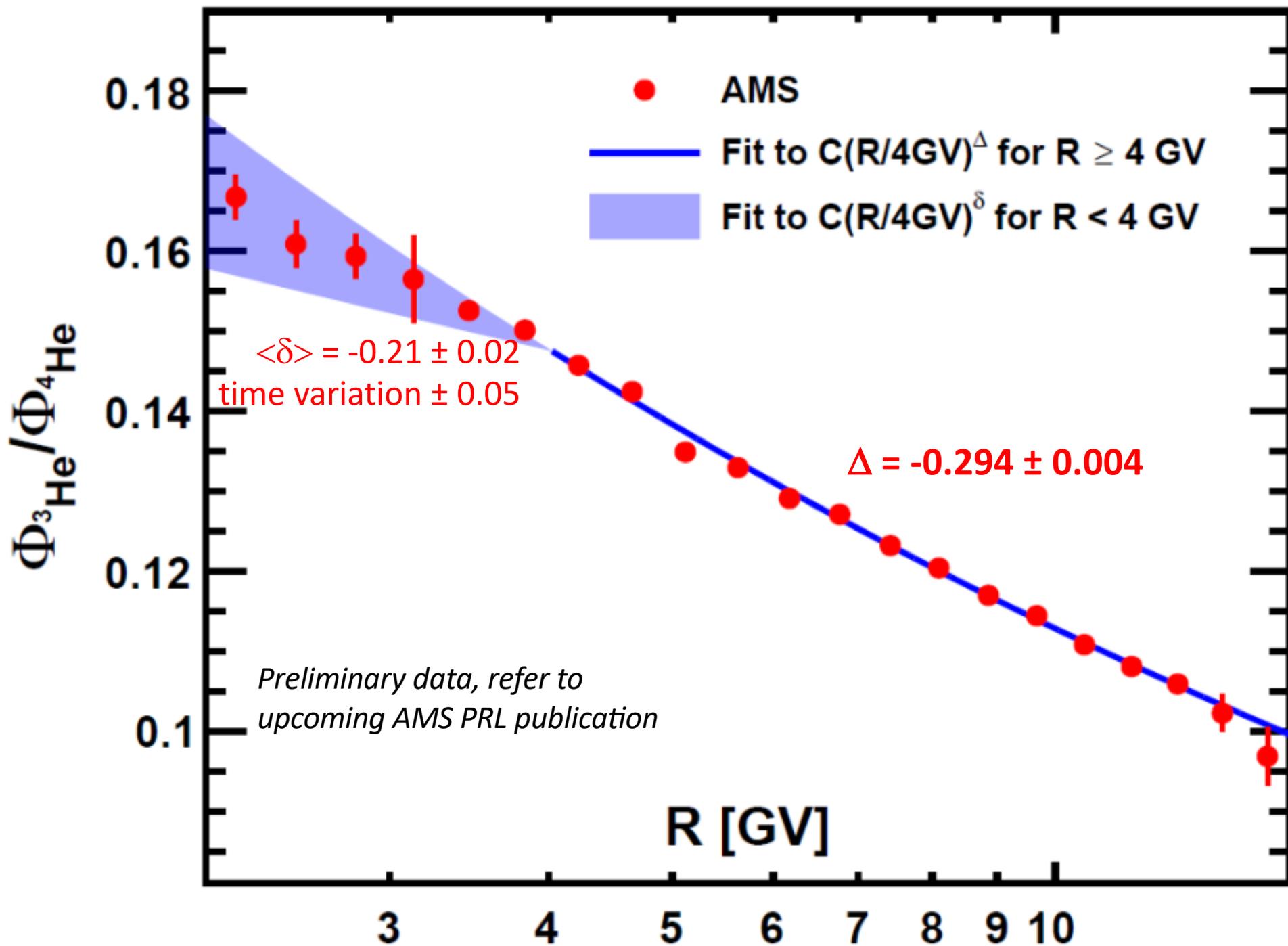
# AMS: Isotopes identification



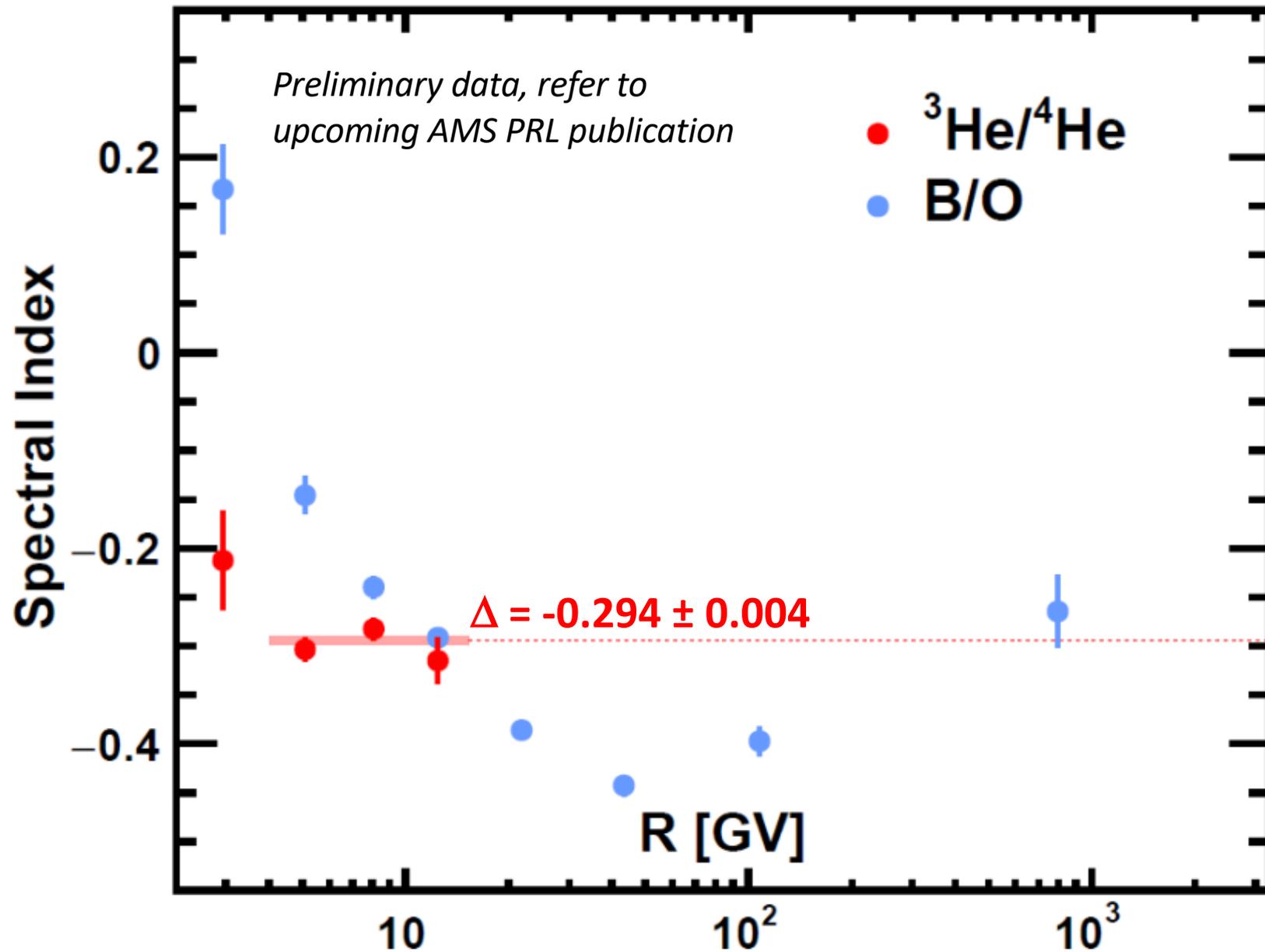
# $^3\text{He}/^4\text{He}$ abundancies compared with earlier measurements



# AMS $^3\text{He}/^4\text{He}$ flux ratio



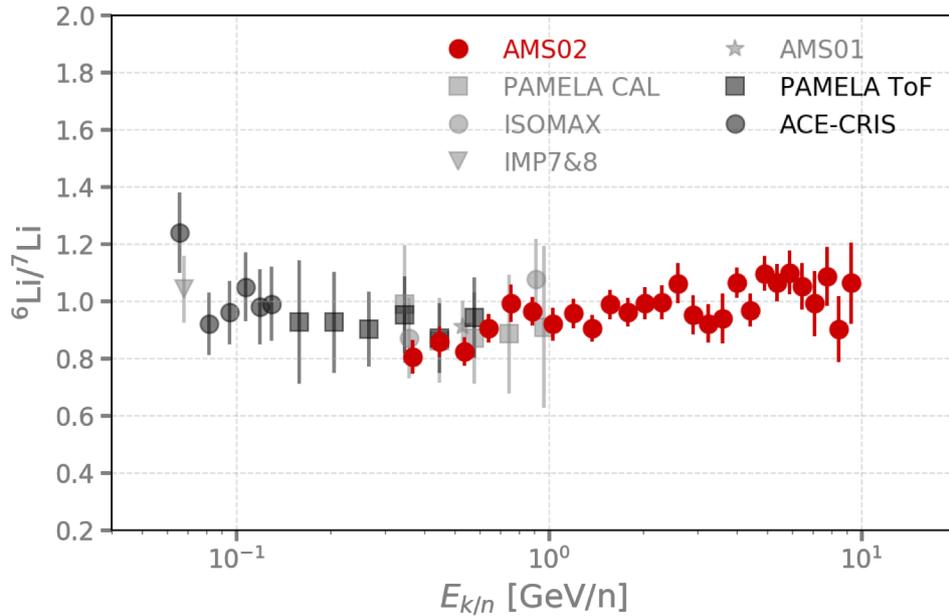
# AMS $^3\text{He}/^4\text{He}$ Spectral Index



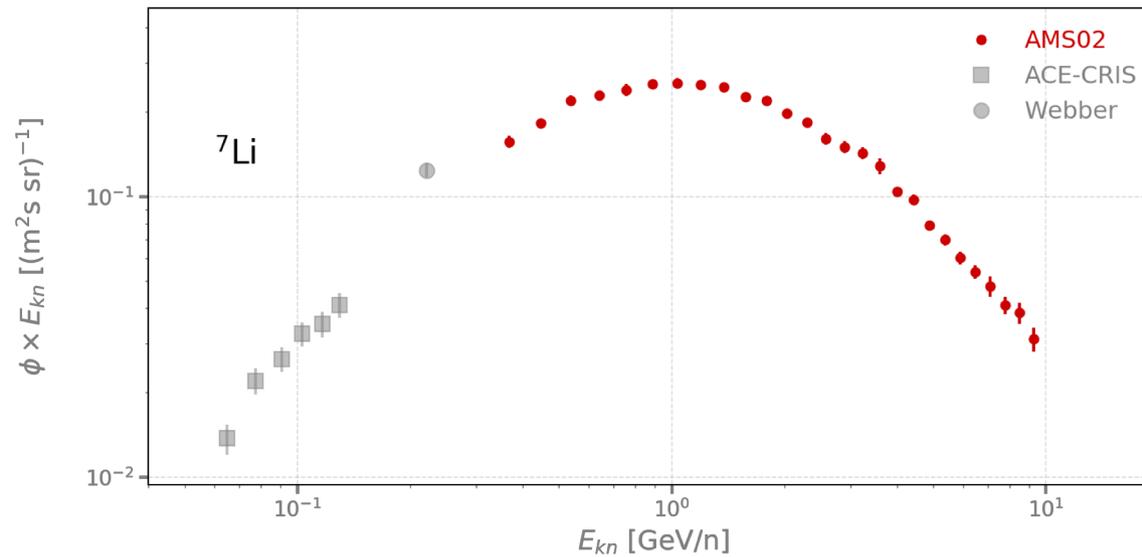
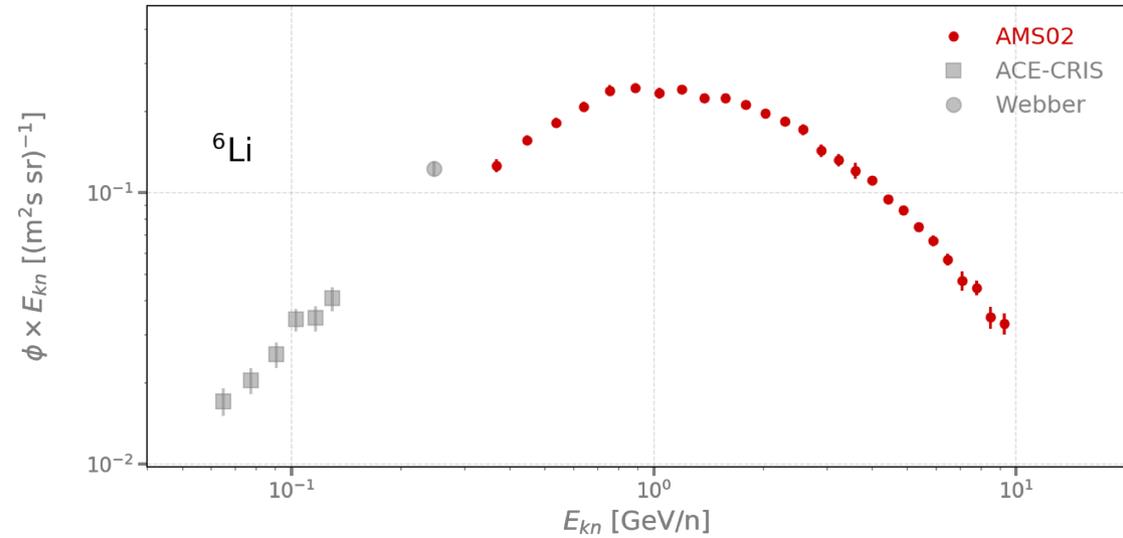
$^3\text{He}/^4\text{He}$  flux ratio power law spectral index is in agreement with the one measures at high rigidity for the B/O ratio.

# Lithium isotopes in cosmic rays

- Both  ${}^6\text{Li}$ ,  ${}^7\text{Li}$  are secondaries
- ${}^6\text{Li}/{}^7\text{Li}$  mainly determined by the production cross sections from C, O fragmentation.



*Preliminary data, refer to  
upcoming AMS PRL publication*



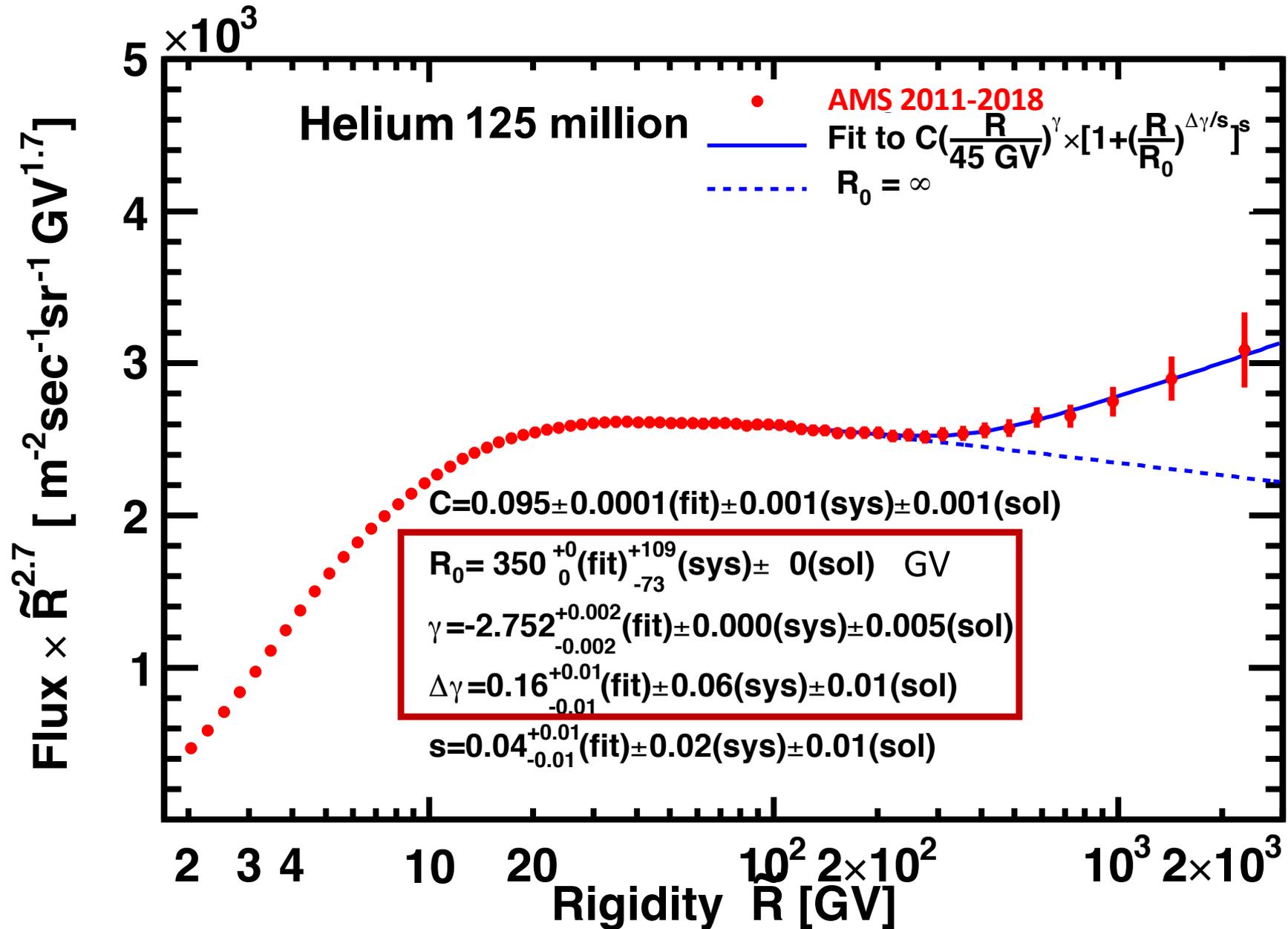
**First measurement of  ${}^6\text{Li}$  and  ${}^7\text{Li}$  fluxes above 0.3 GeV/n.**

# Conclusions

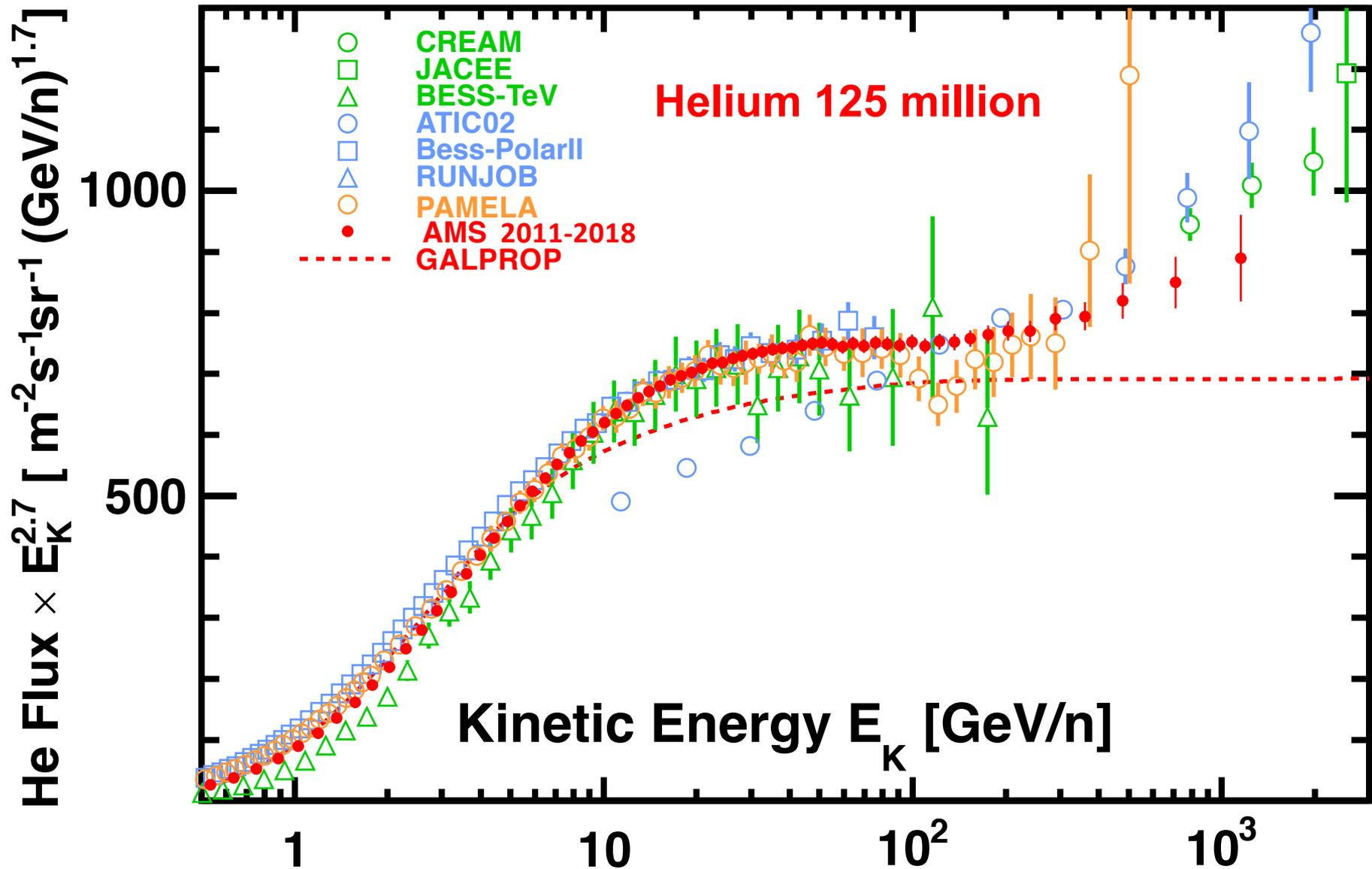
- AMS precision measurements of cosmic ray nuclei up to multi-TeV energies are challenging our understanding of cosmic ray physics.
- The AMS results on cosmic-ray fluxes do not follow a single power law. They all have a break at  $\sim 200$  GV.
- Identical rigidity dependences are observed for both primary cosmic rays (He, C, O) and secondary cosmic rays (Li, Be, B). But they are distinctly different from each other.
- Measurements of heavier species,  $Z > 8$ , enable us to explore a new region in cosmic rays. The flux Rigidity behaviors of Ne, Mg, Si and S deviate from the one of O
- Additional information on cosmic ray physics from isotopic fluxes ( $^3\text{He}/^4\text{He}$ ,  $^6\text{Li}/^7\text{Li}$ ,  $^9\text{Be}/^{10}\text{Be}$ , ...)
- AMS will continue taking data for the lifetime of the International Space Station (beyond 2024, through the lifetime of the ISS).

# BACKUP SLIDES

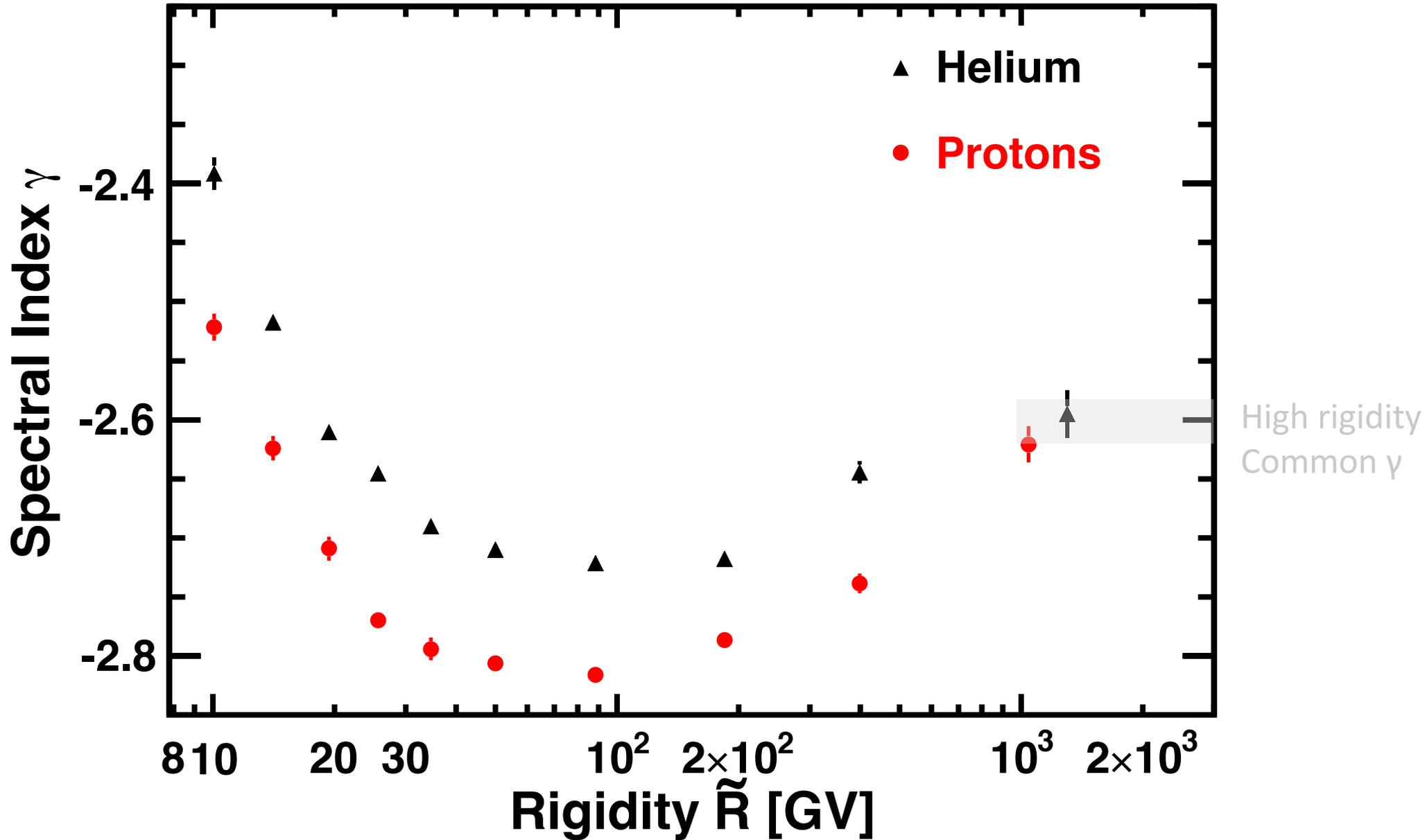
# Structure in the latest helium spectrum



# AMS Measurement of the helium spectrum together with earlier measurements



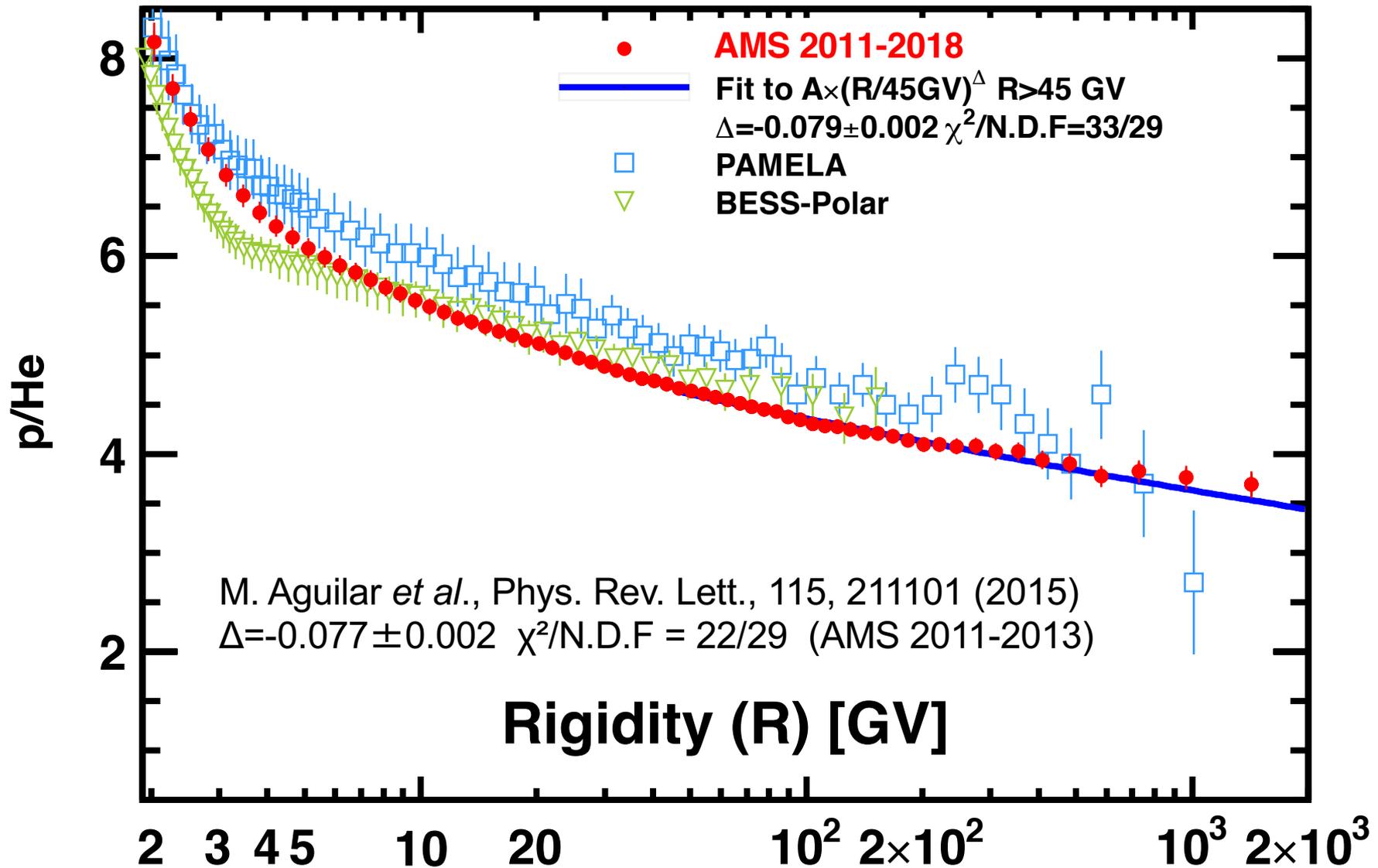
# MS Measurement of P&He Spectral Indices (2011-2018)



# The AMS Result on the Proton/Helium Flux Ratio

Protons and helium are both primary cosmic rays.

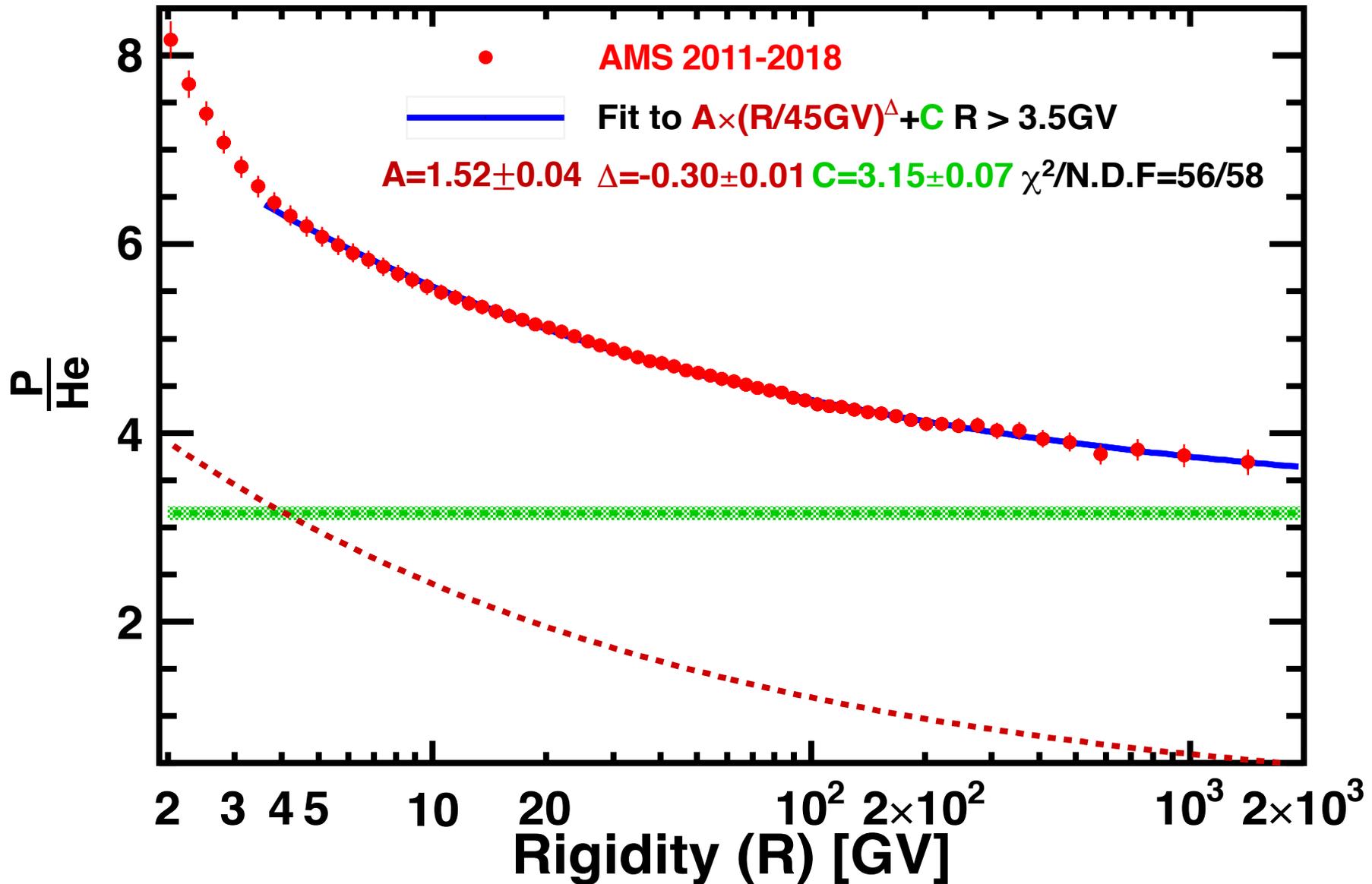
Traditionally, they are assumed to be produced in the same sources so their flux ratio should be asymptotically rigidity independent.



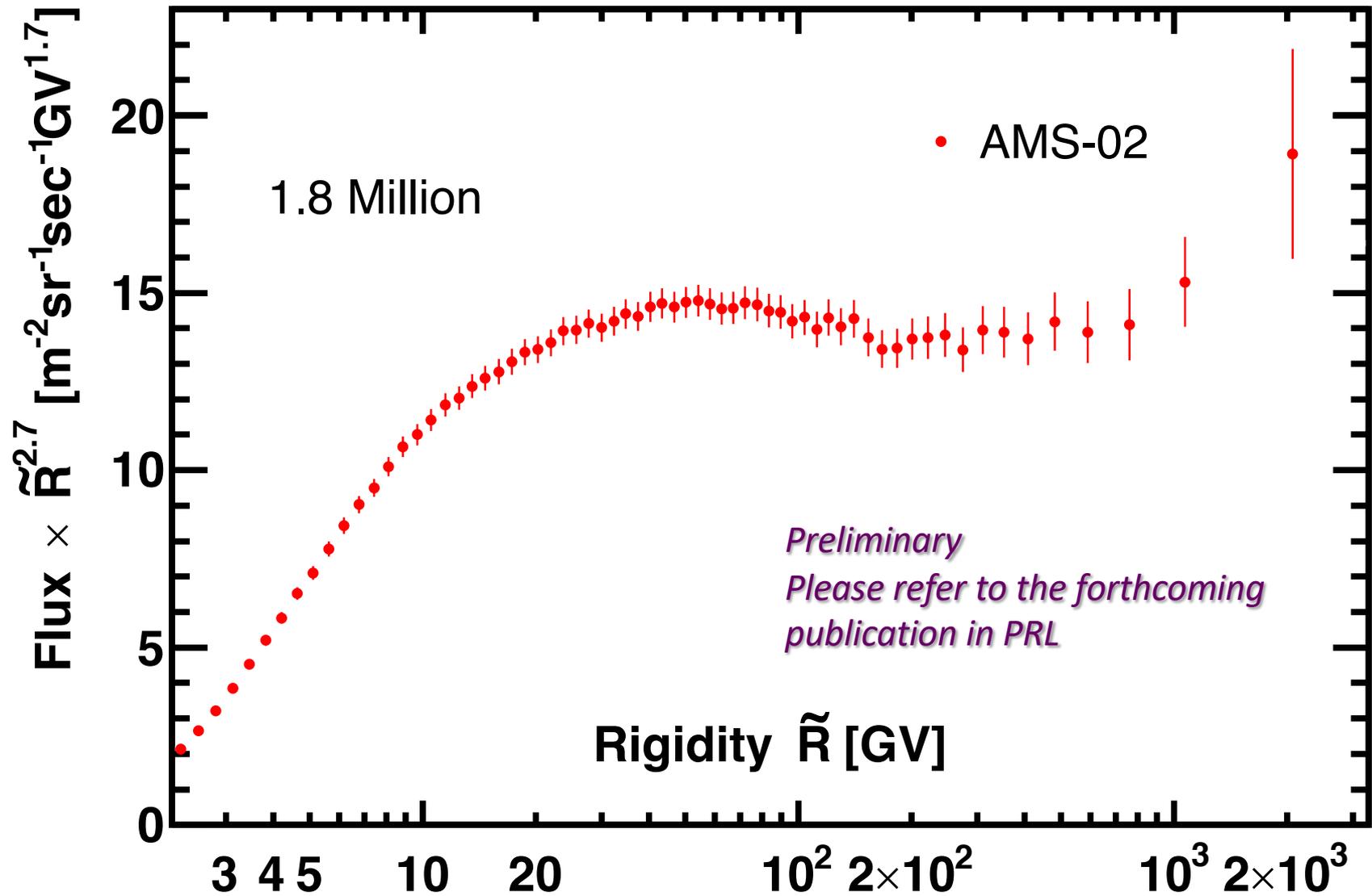
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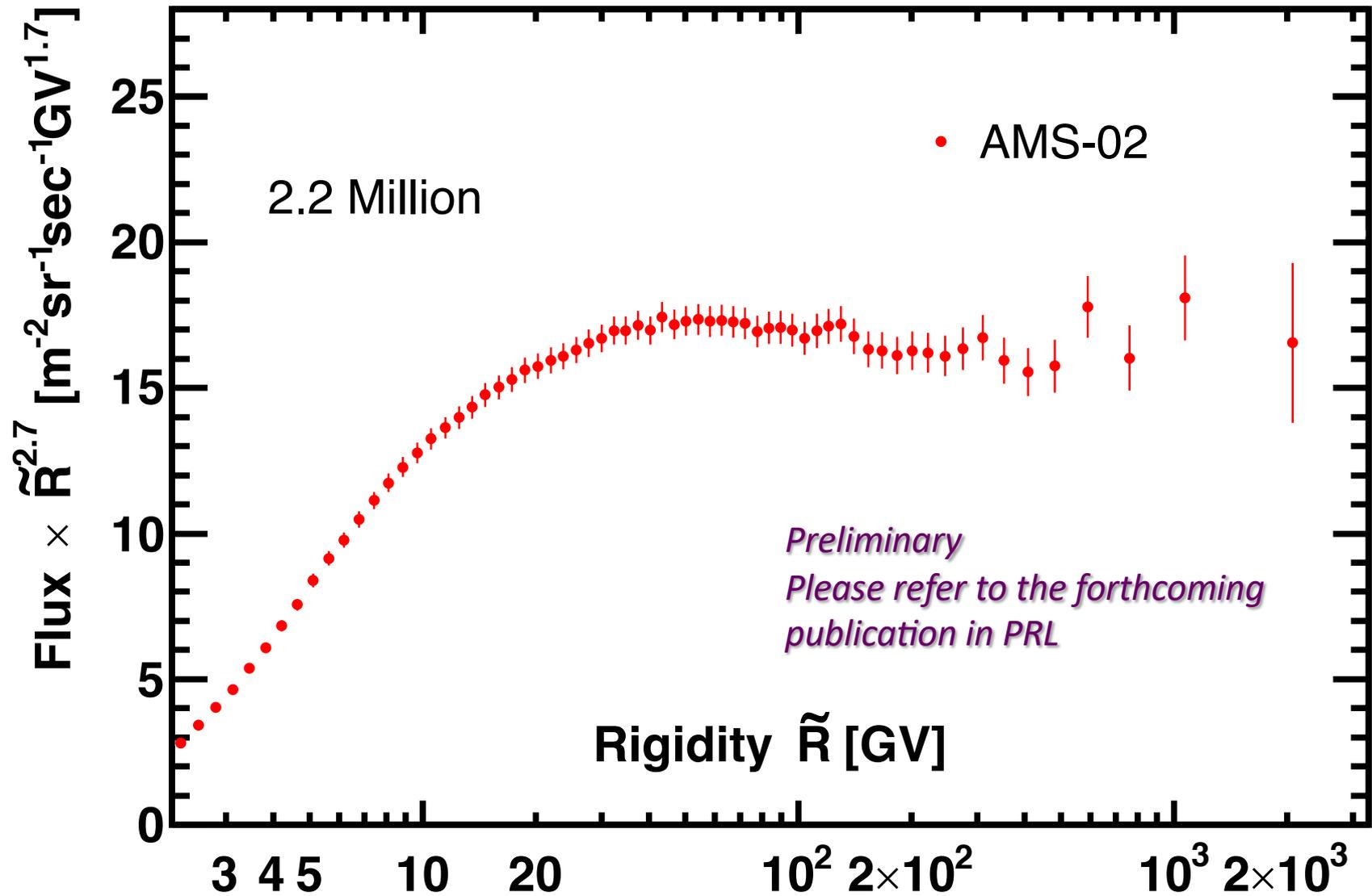
Their flux ratio seems to be rigidity independent at high rigidities.



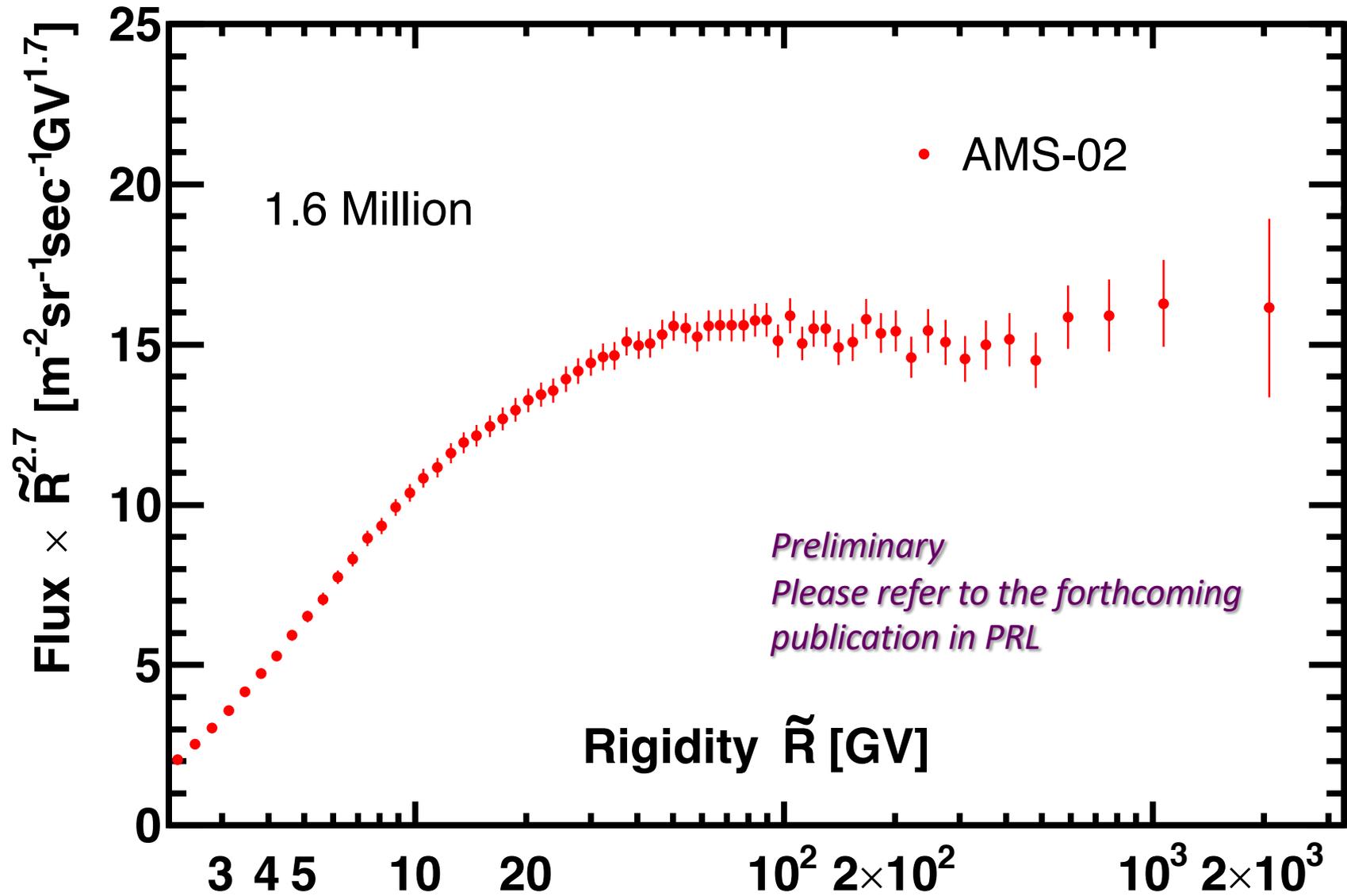
# Neon Flux



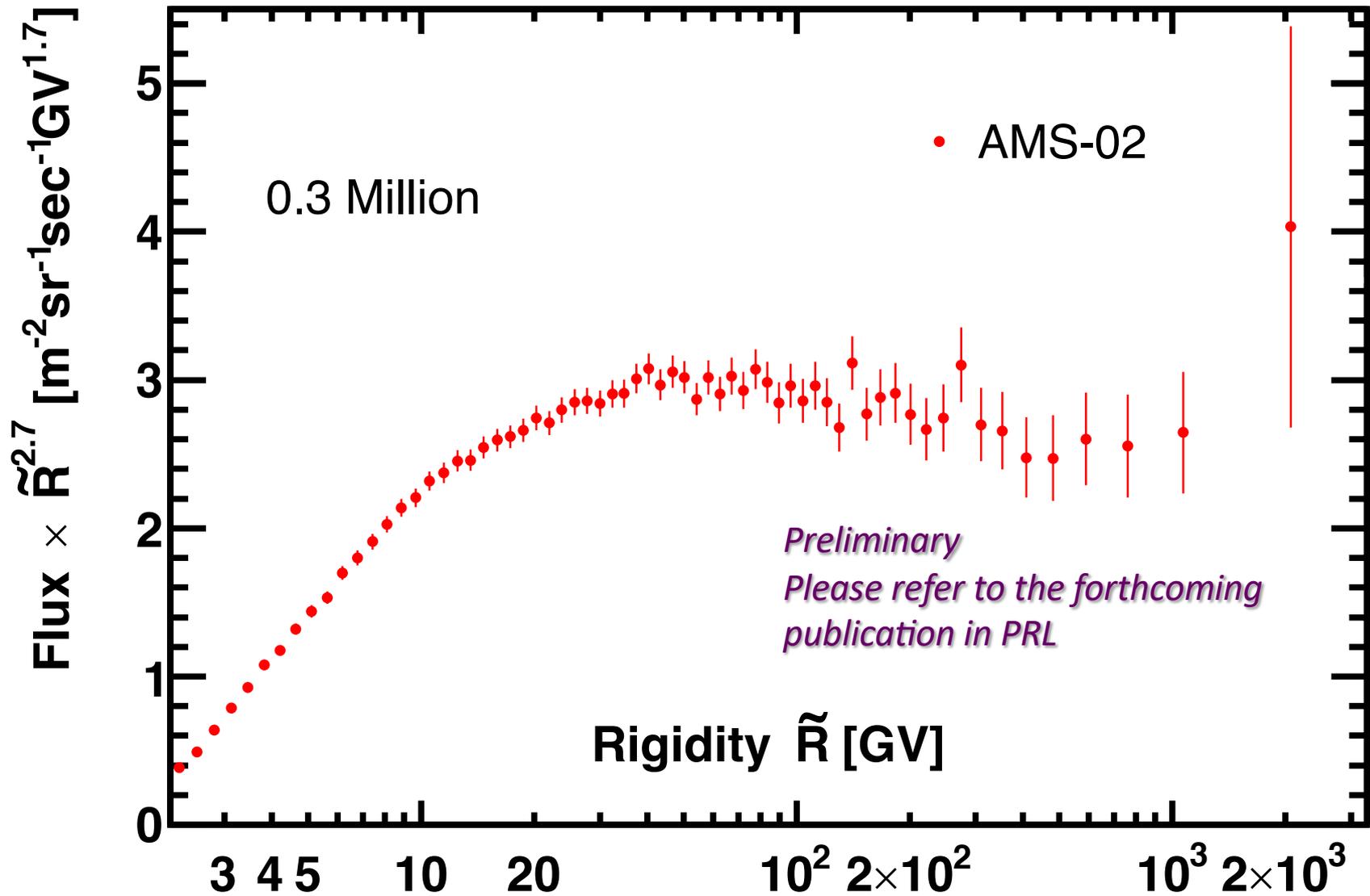
# Magnesium Flux



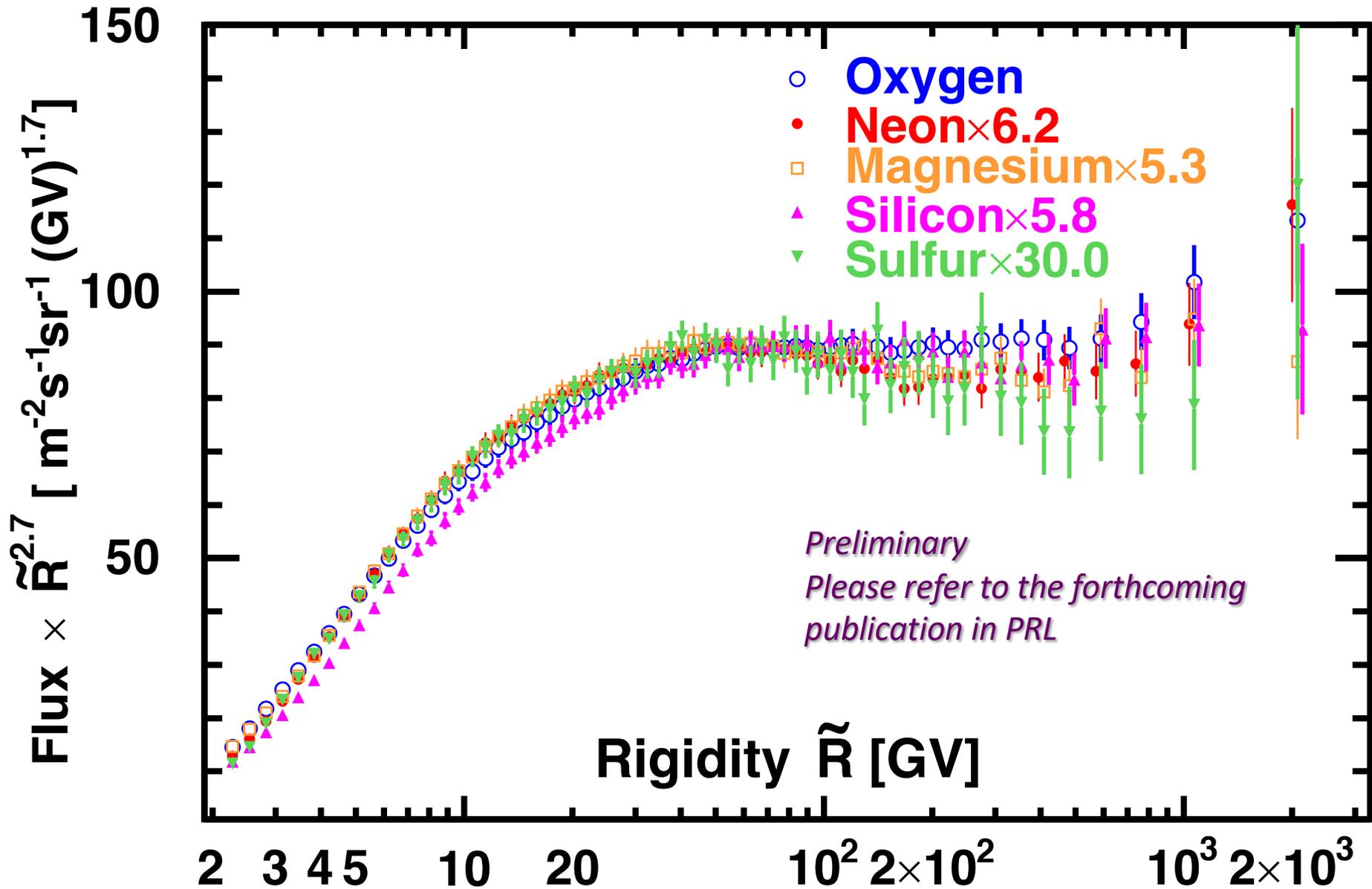
# Silicon Flux



# Sulfur Flux

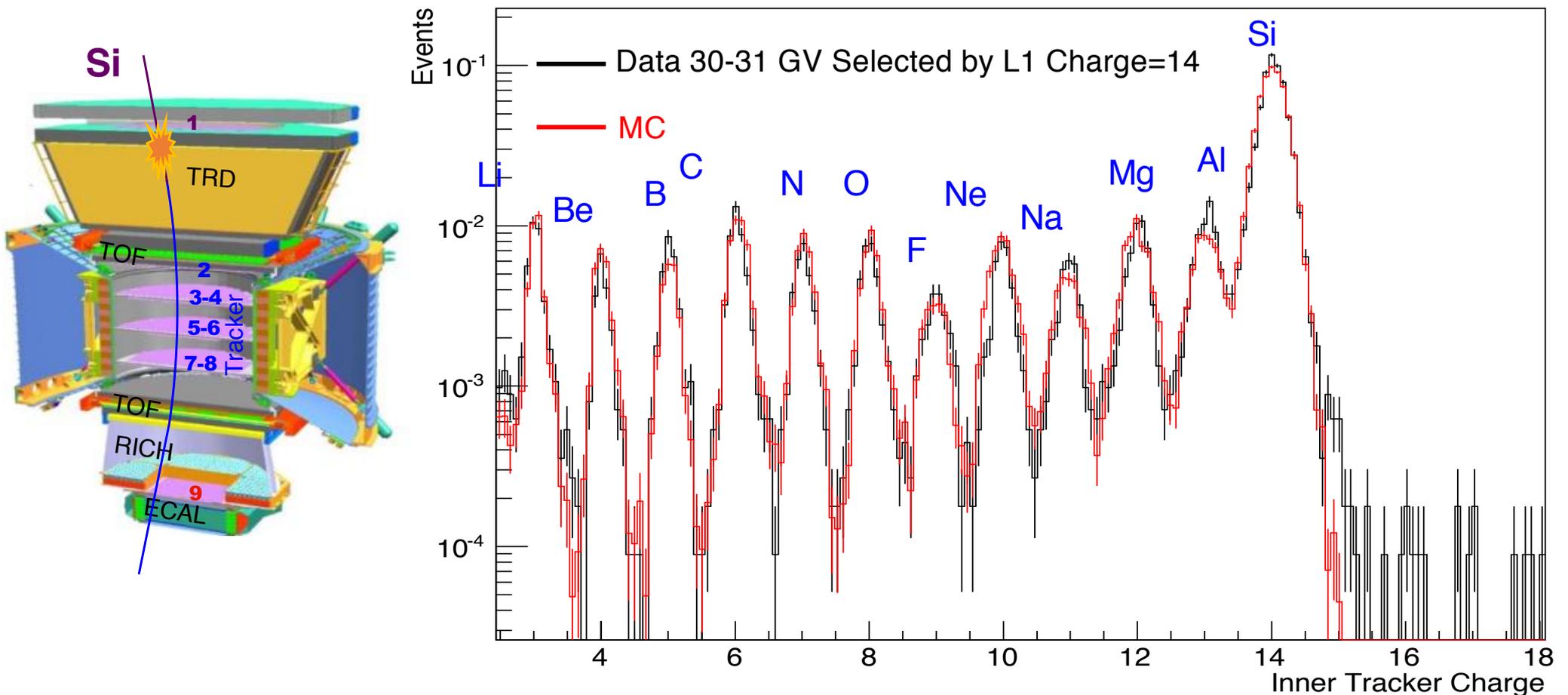


# O, Ne, Mg, Si and S Fluxes



# Survival Probability by Breakup Channels Distribution (Silicon)

- Select primary nuclei by L1 charge
- Obtain survival probability by comparing charge measured with inner tracker



# Nucleus + C Inelastic Cross Section Parameterization

