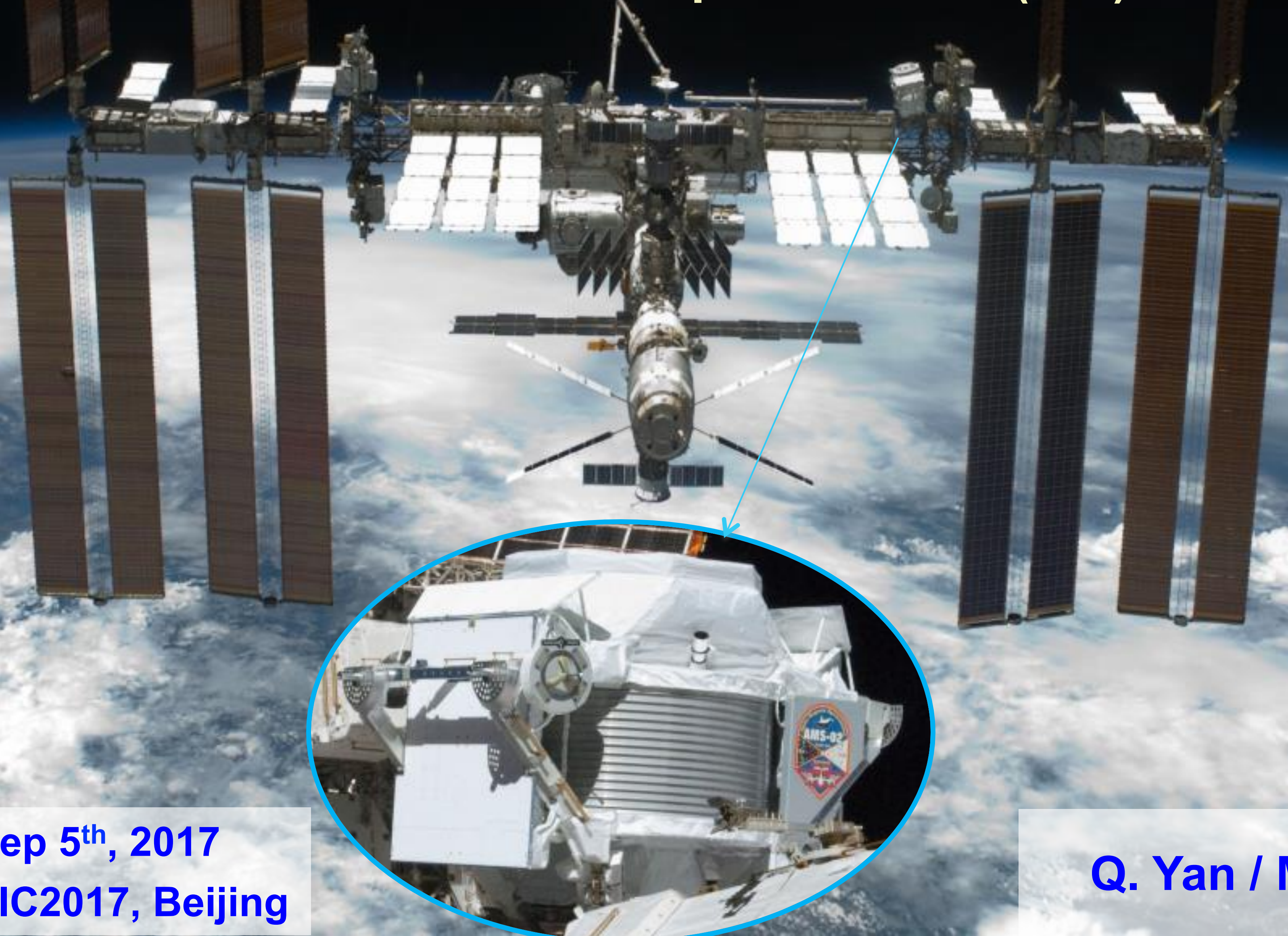
Elementary particles and nuclei measurements with the Alpha Magnetic Spectrometer Experiment on the International Space Station (ISS)



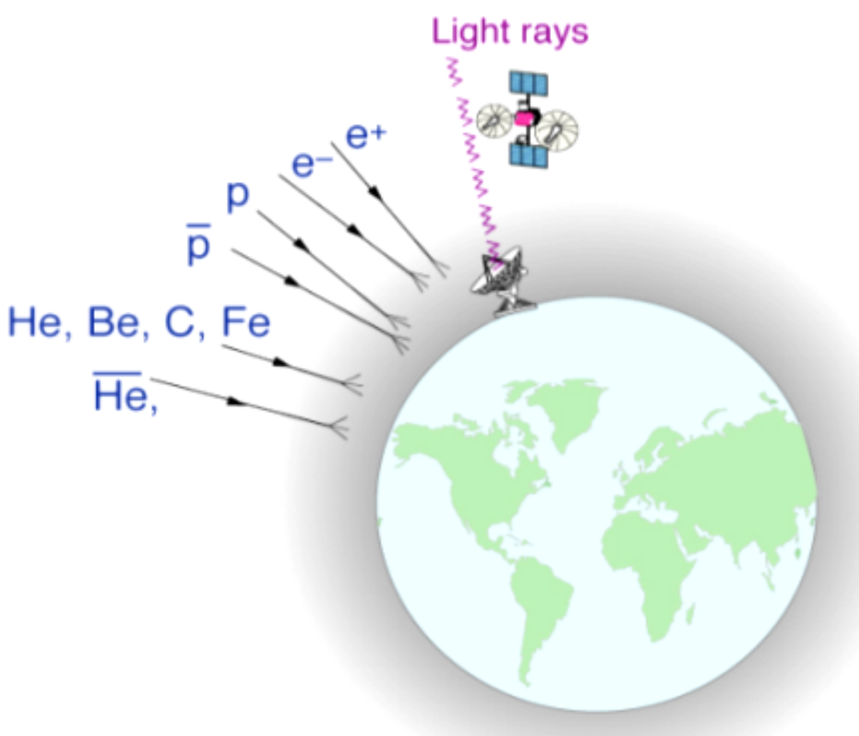
Sep 5th, 2017
PANIC2017, Beijing

Q. Yan / MIT

There are two kinds of cosmic rays traveling through space

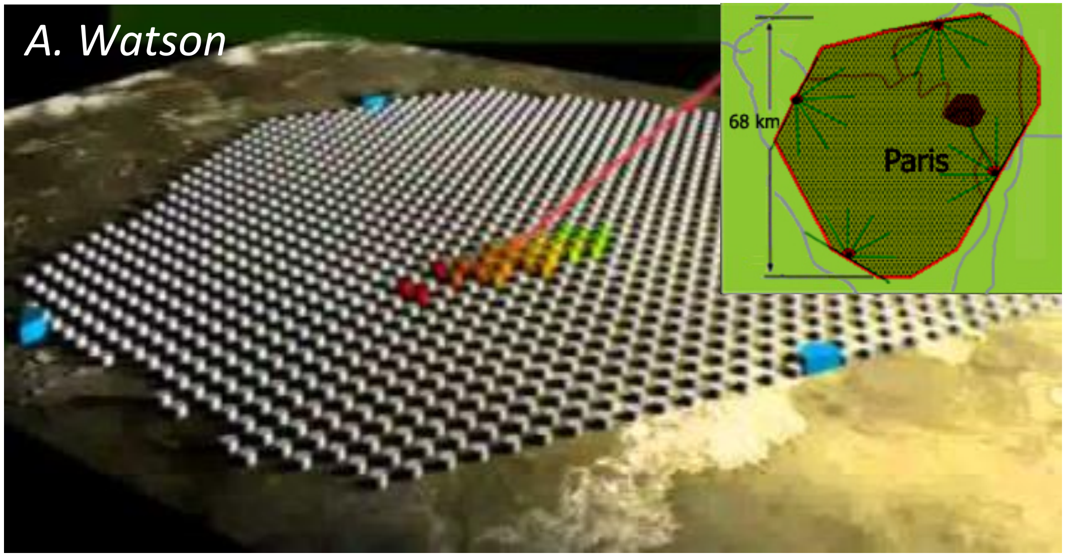
A. <u>Neutral cosmic rays</u> (light rays and neutrinos) can be measured with satellites and large ground-based and underground detectors

B. <u>Charged cosmic rays</u>: The Earth's atmosphere is equivalent to 10 meters of water. The properties of charged cosmic rays is difficult to be measured on the ground. AMS, on the Space Station, is a large-acceptance, long duration magnetic spectrometer directly measuring the original properties of charged cosmic rays.



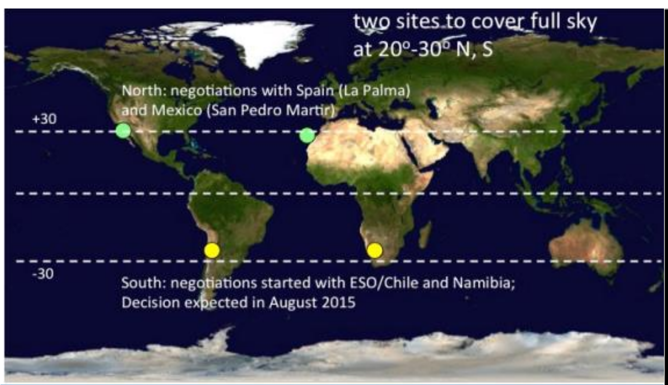
Complementary Cosmic Ray Experiments

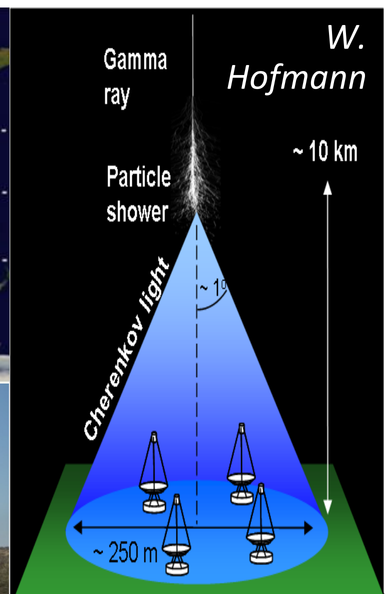
The Pierre Auger Observatory

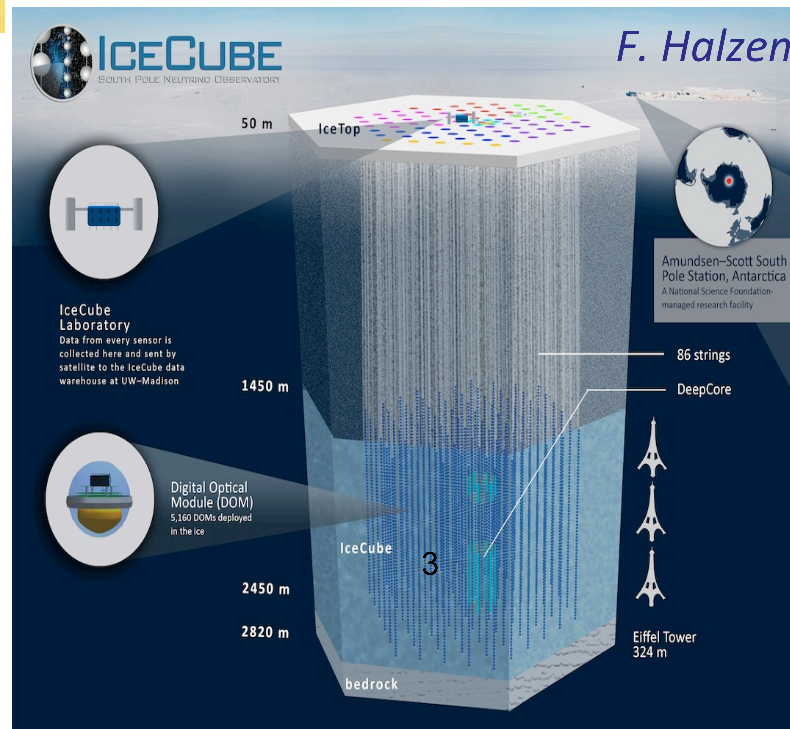


Telescope Array

HESS, CTA

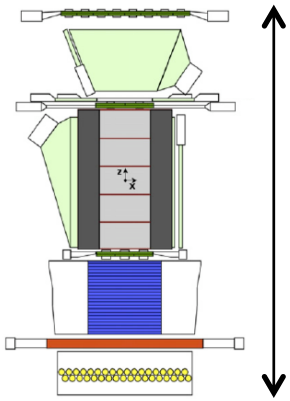






3

PAMELA



ECAL

<u>Acceptance</u>

21.5 cm^{2}sr

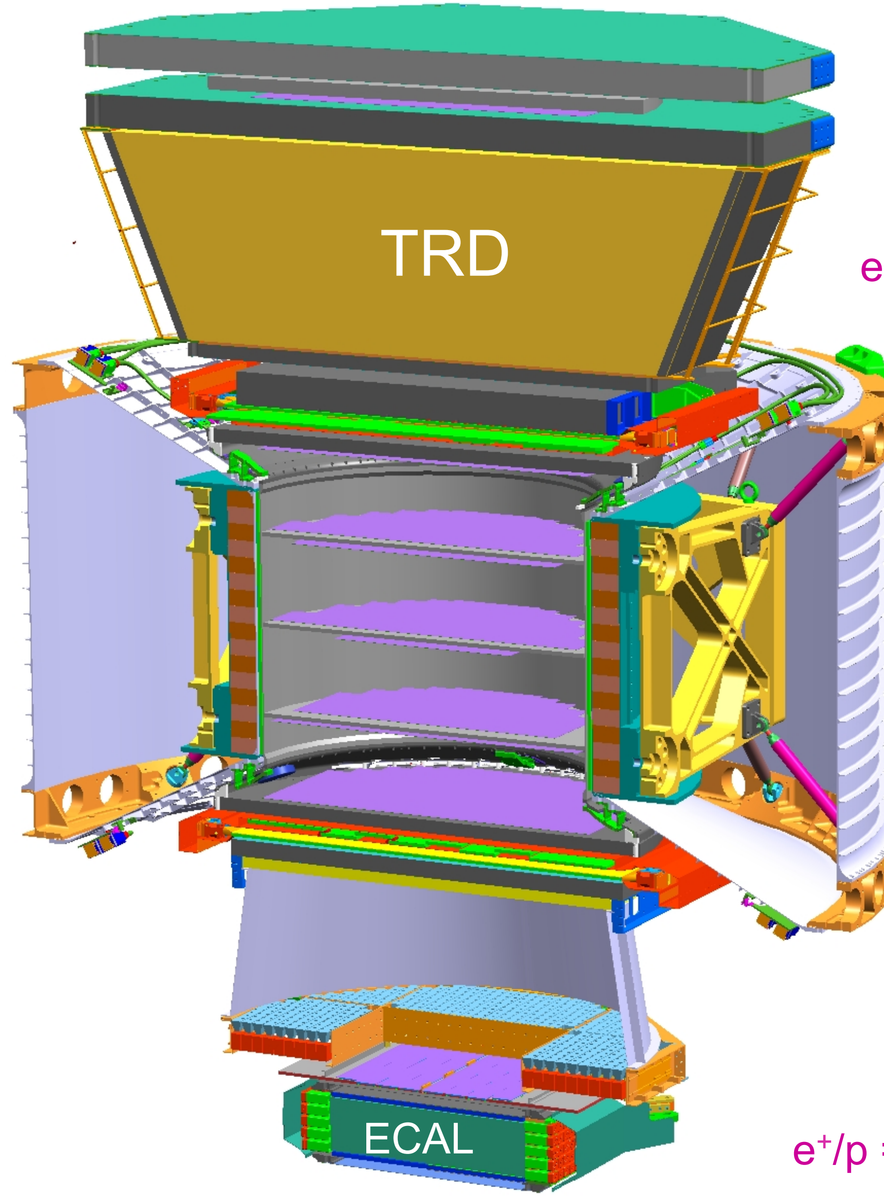
Astroparticle Physics
27 (2007) 296–315

Published e^+ data up to ~ 100 GeV

Professor Roberto Battiston, President ASI

Presented at the DOE HEPAP meeting
Washington, DC, 4 June 2010

AMS-02



$e^+/p = 10^{-2}$

Magnet

$e^+/p = 10^{-4}$

Measured rejection at 0.4 TeV
$e^+/p = 10^{-6}$

<u>Acceptance</u>

e^+ 950 cm^{2}sr

$\bar{p}$, *He*, $\overline{He}$, … 4,500 cm^{2}sr

<u>Exposure (10 to 18 yrs)</u>

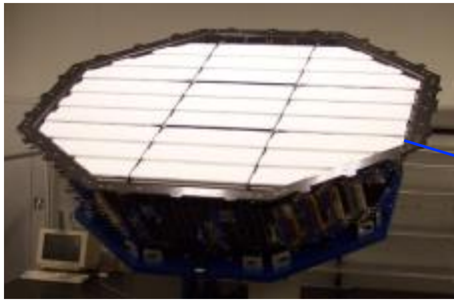
e^+ energy > 1 TeV


AMS
5m x 4m x 3m
7.5 tons

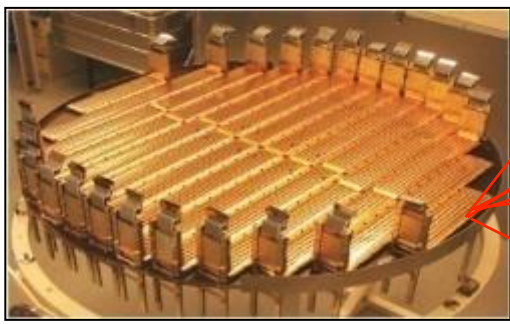
AMS: A TeV precision, magnetic spectrometer

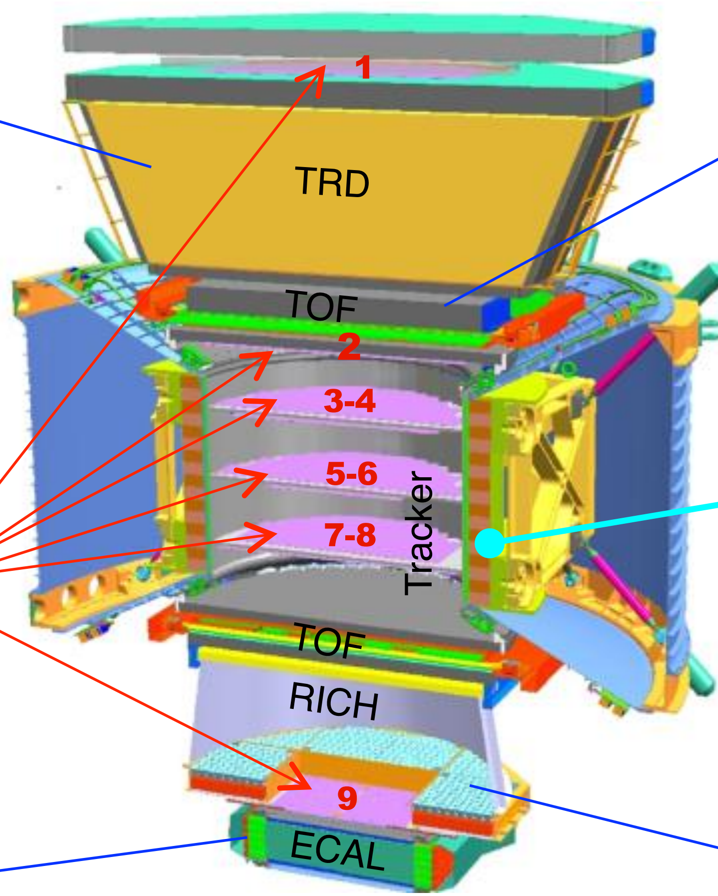
Particles and nuclei are defined by their charge (Z) and energy (E) or rigidity (R=p/Z)

Transition Radiation Detector
Identify e^{+}, e^{-}



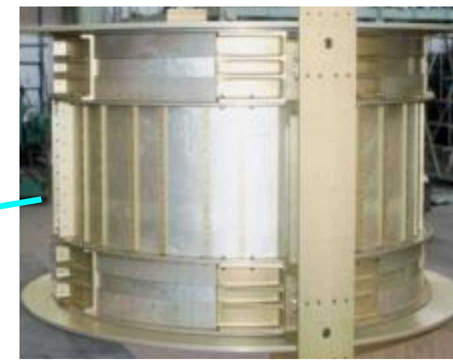
Silicon Tracker
Z, R



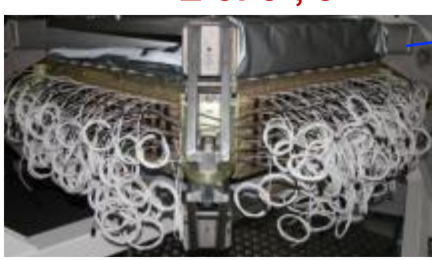


Time of Flight
Z, E

Magnet
±Z, R



Electromagnetic Calorimeter
E of e^{+}, e^{-}

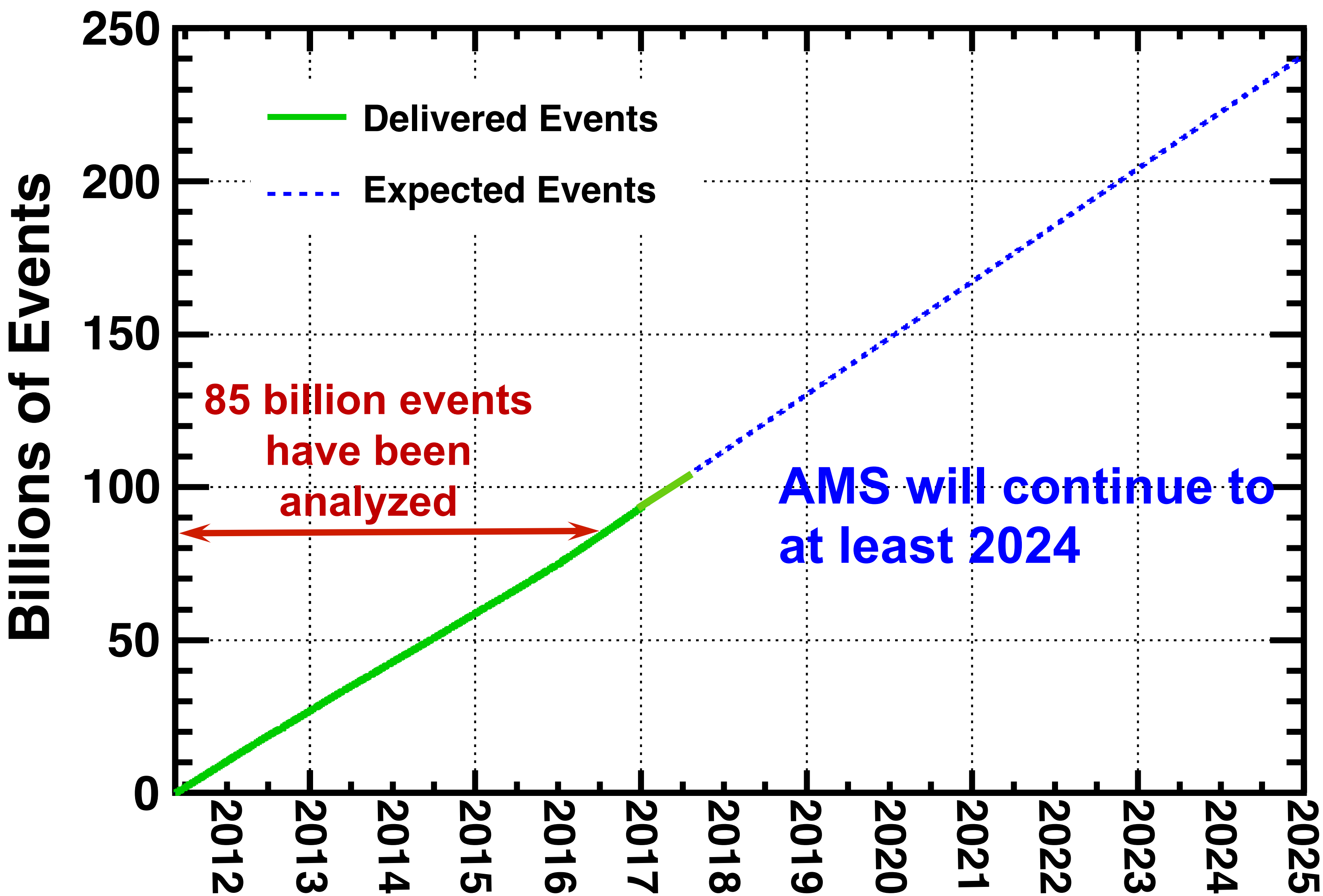


Ring Imaging Cherenkov
Z, E

The Charge and Energy are measured independently by many detectors

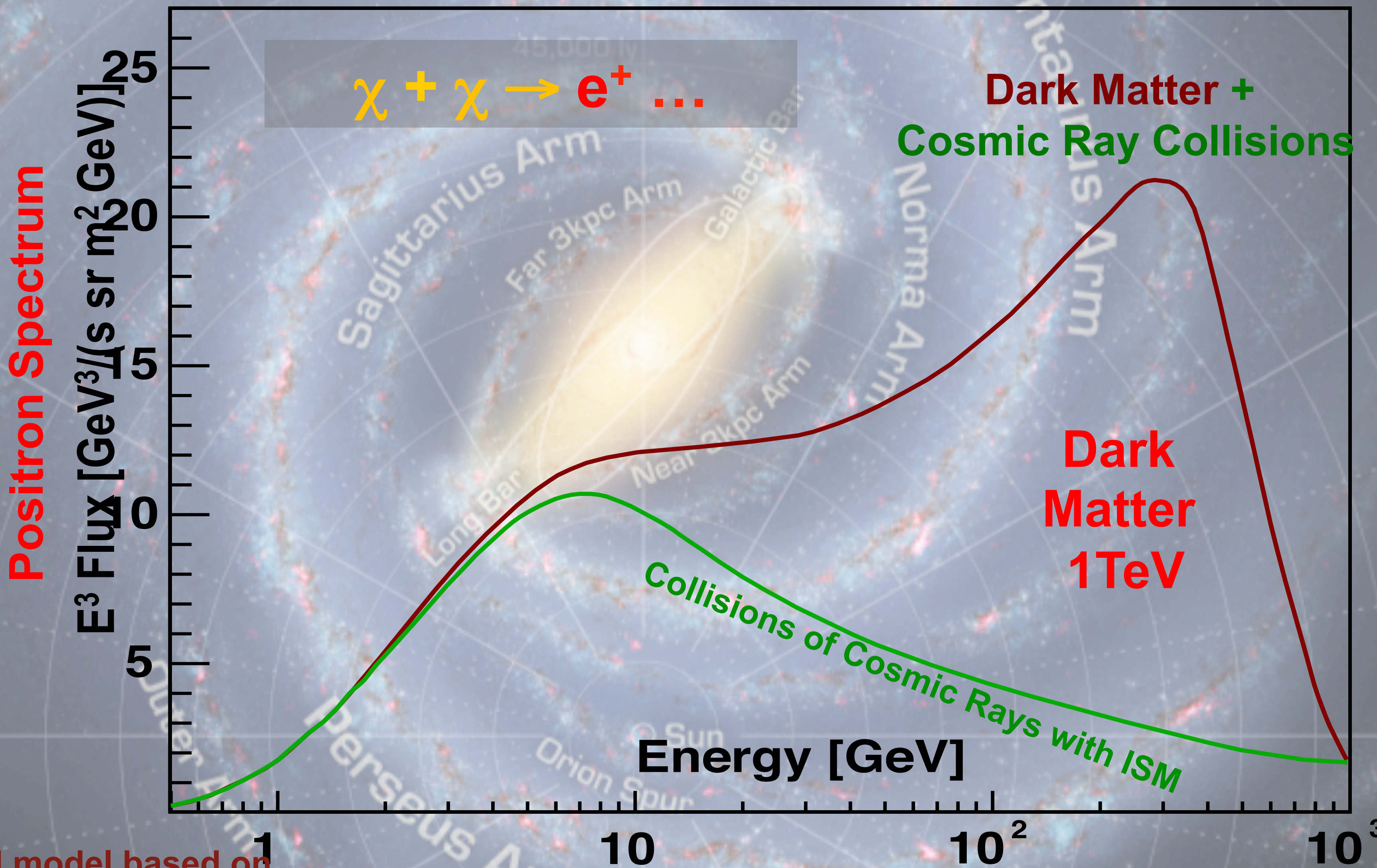
AMS installed on the ISS at 5:15 CDT May 19, 2011

>100 billion events has been collected by AMS during its first 6 years operation



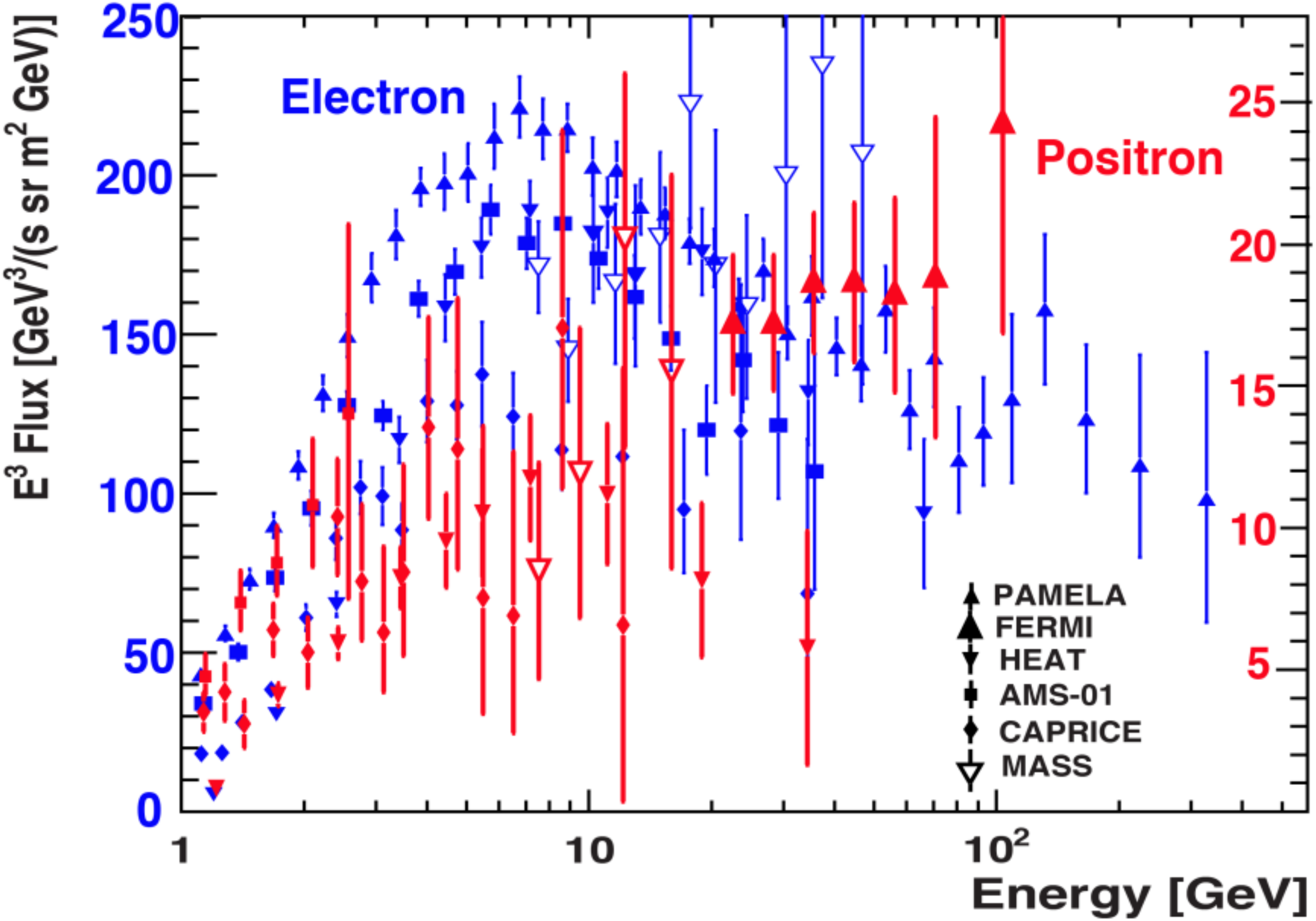
Dark Matter

Annihilation of Dark Matter produces additional e^+ which are characterized by a sharp drop off at the mass of dark matter.



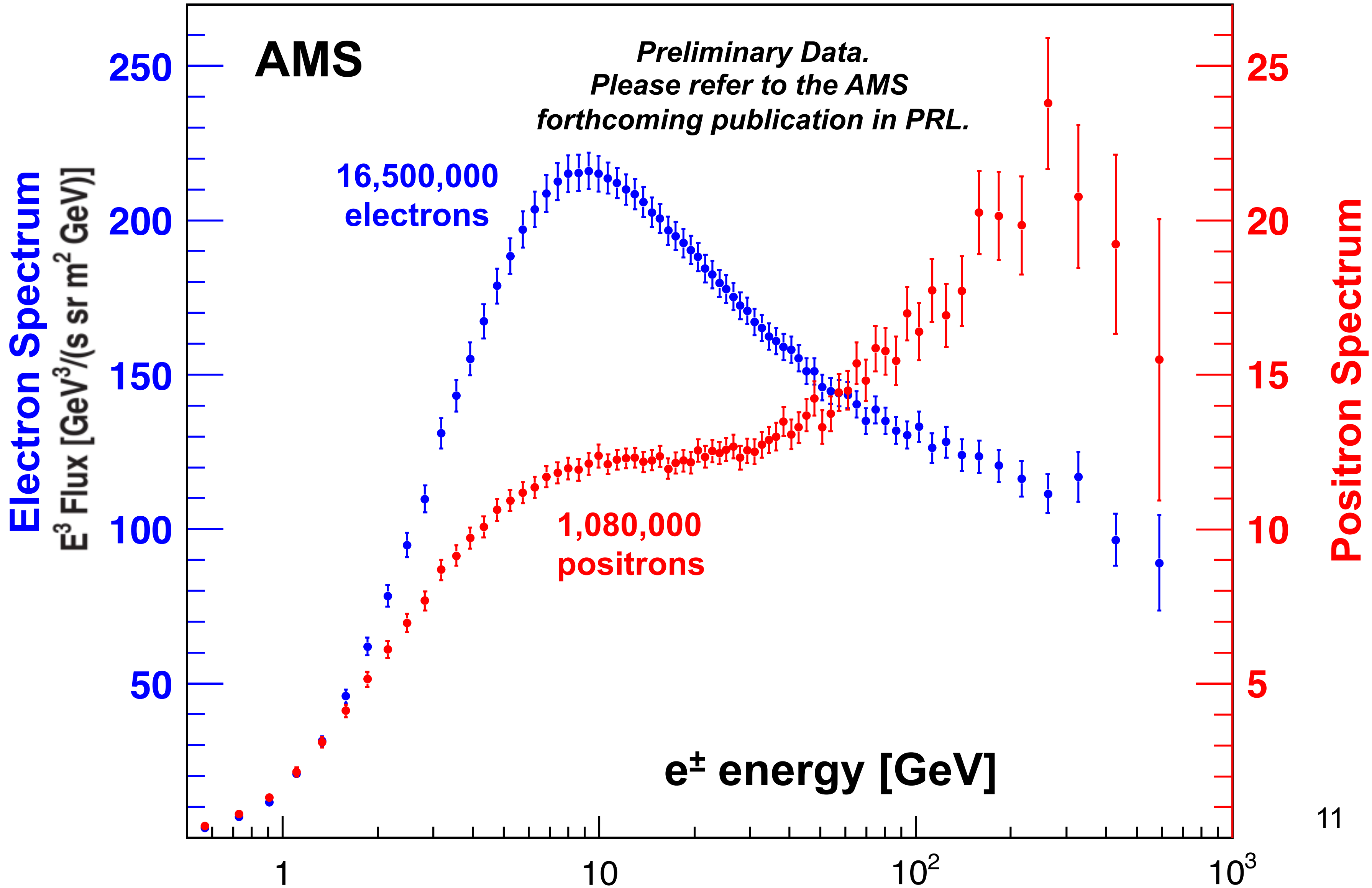
DM model based on
J. Kopp, Phys. Rev. D 88 (2013) 076013

Electron and Positron flux
(before AMS)



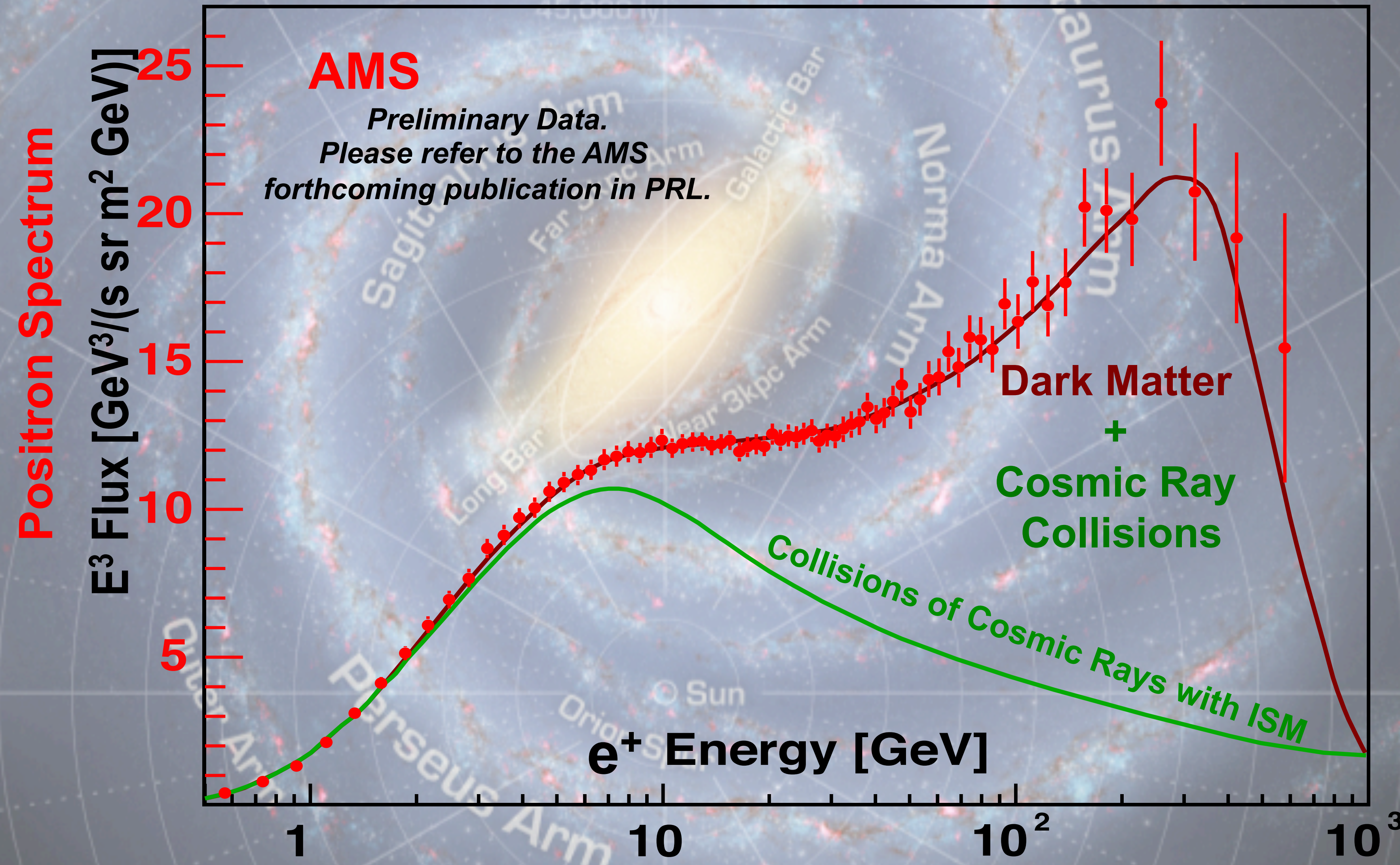
AMS Results on the Electron and Positron fluxes

The electron flux and the positron flux are different in their magnitude and energy dependence



The origin of the positron spectrum

The AMS results are in excellent agreement with a Dark Matter Model



Examples of Theoretical Models for positrons and antiprotons

From Dark Matter

1) J. Kopp, Phys. Rev. D 88, 076013 (2013);
2) L. Feng, R.Z. Yang, H.N. He, T.K. Dong, Y.Z. Fan and J. Chang Phys.Lett. B728 (2014) 250
3) M. Cirelli, M. Kadastik, M. Raidal and A. Strumia ,Nucl.Phys. B873 (2013) 530
4) M. Ibe, S. Iwamoto, T. Moroi and N. Yokozaki, JHEP 1308 (2013) 029
5) Y. Kajiyama and H. Okada, Eur.Phys.J. C74 (2014) 2722
6) K.R. Dienes and J. Kumar, Phys.Rev. D88 (2013) 10, 103509
7) L. Bergstrom, T. Bringmann, I. Cholis, D. Hooper and C. Weniger, PRL 111 (2013) 171101
8) K. Kohri and N. Sahu, Phys.Rev. D88 (2013) 10, 103001
9) P. S. Bhupal Dev, D. Kumar Ghosh, N. Okada and I. Saha, Phys.Rev. D89 (2014) 095001
10) A. Ibarra, A.S. Lamperstorfer and J. Silk, Phys.Rev. D89 (2014) 063539
11) Y. Zhao and K.M. Zurek, JHEP 1407 (2014) 017
12) C. H. Chen, C. W. Chiang, and T. Nomura, Phys. Lett. B 747, 495 (2015)
13) H. B. Jin, Y. L. Wu, and Y.-F. Zhou, Phys.Rev. D92, 055027 (2015)
14) M-Y. Cui, Q. Yuan, Y-L.S. Tsai and Y-Z. Fan, arXiv:1610.03840 (2016)
15) A. Cuoco, M. Krämer and M. Korsmeier, arXiv:1610.03071 (2016)

and many other excellent papers ...

From Astrophysical Sources

1) T. Linden and S. Profumo, Astrophys.J. 772 (2013) 18
2) P. Mertsch and S. Sarkar, Phys.Rev. D 90 (2014) 061301
3) I. Cholis and D. Hooper, Phys.Rev. D88 (2013) 023013
4) A. Erlykin and A.W. Wolfendale, Astropart.Phys. 49 (2013) 23
5) P.F. Yin, Z.H. Yu, Q. Yuan and X.J. Bi, Phys.Rev. D88 (2013) 2, 023001
6) A.D. Erlykin and A.W. Wolfendale, Astropart.Phys. 50-52 (2013) 47
7) E. Amato, Int.J.Mod.Phys.Conf.Ser. 28 (2014) 1460160
8) P. Blasi, Braz.J.Phys. 44 (2014) 426
9) D. Gaggero, D. Grasso, L. Maccione, G. DiBernardo and C Evoli, Phys.Rev. D89 (2014) 083007
10) M. DiMauro, F. Donato, N. Fornengo, R. Lineros and A. Vittino, JCAP 1404 (2014) 006
11) K. Kohri, K. Ioka, Y. Fujita, and R. Yamazaki, Prog. Theor. Exp. Phys. 2016, 021E01 (2016)

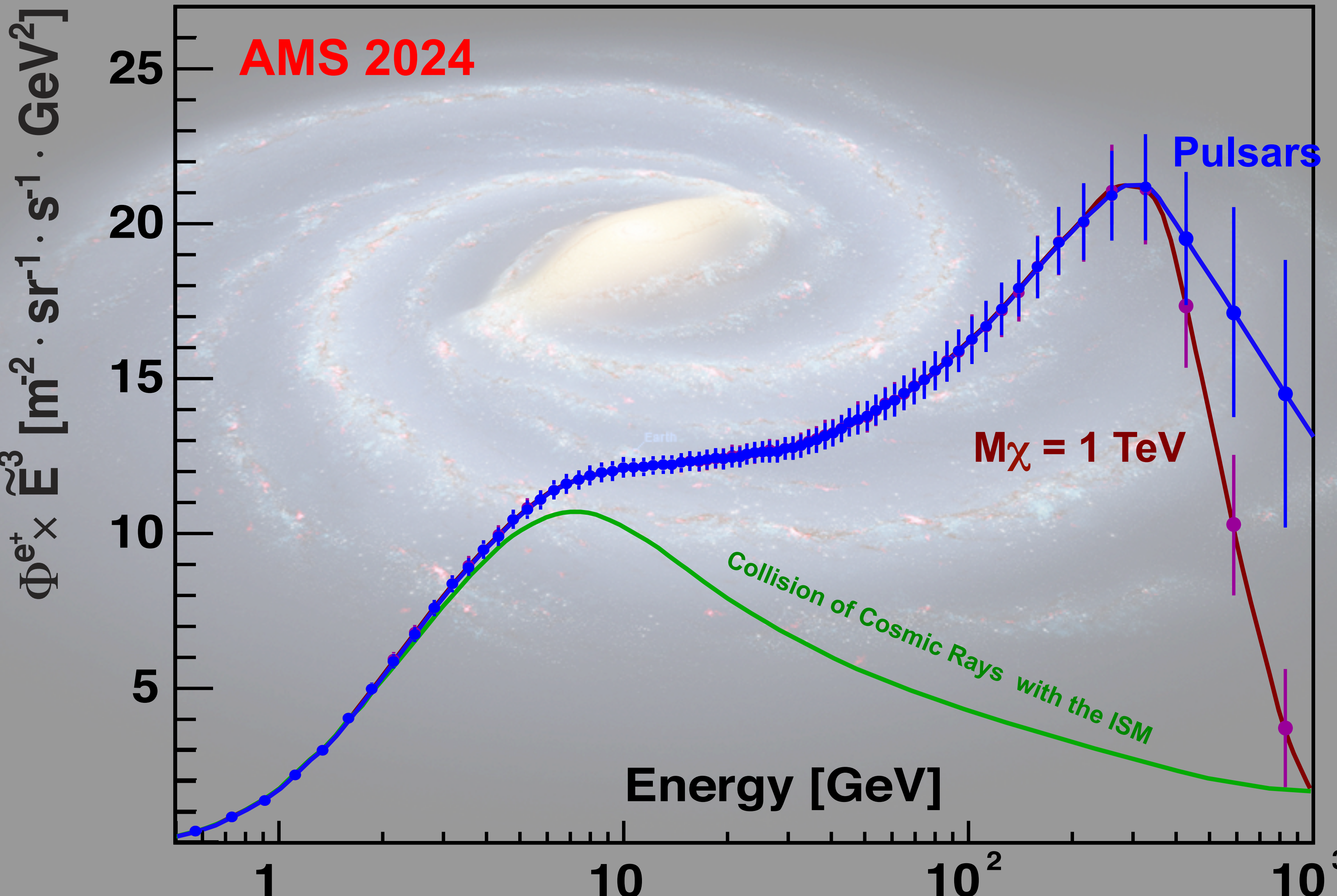
and many other excellent papers ...

From Secondary Production

1) R.Cowsik, B.Burch, and T.Madziwa-Nussinov, Ap.J. 786 (2014) 124
2) K. Blum, B. Katz and E. Waxman, Phys.Rev.Lett. 111 (2013) 211101
3) R. Kappl and M. W. Winkler, J. Cosmol. Astropart. Phys. 09 (2014) 051
4) G.Giesen, M.Boudaud, Y.Gènolini, V.Poulin, M.Cirelli, P.Salati and P.D.Serpico, JCAP09 (2015) 023;
5) C.Evoli, D.Gaggero and D.Grasso, JCAP 12 (2015) 039.
6) R.Kappl, A.Reinertand, and M.W.Winkler, arXiv:1506.04145 (2015)

and many other excellent papers ...

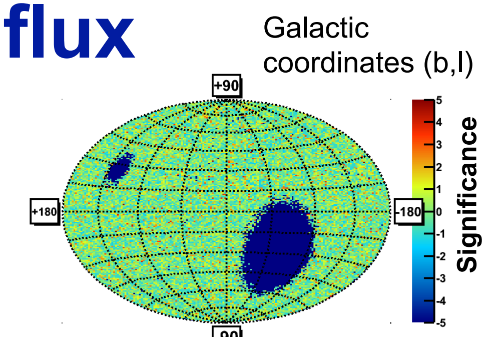
2024: Extend measurement to 1 TeV

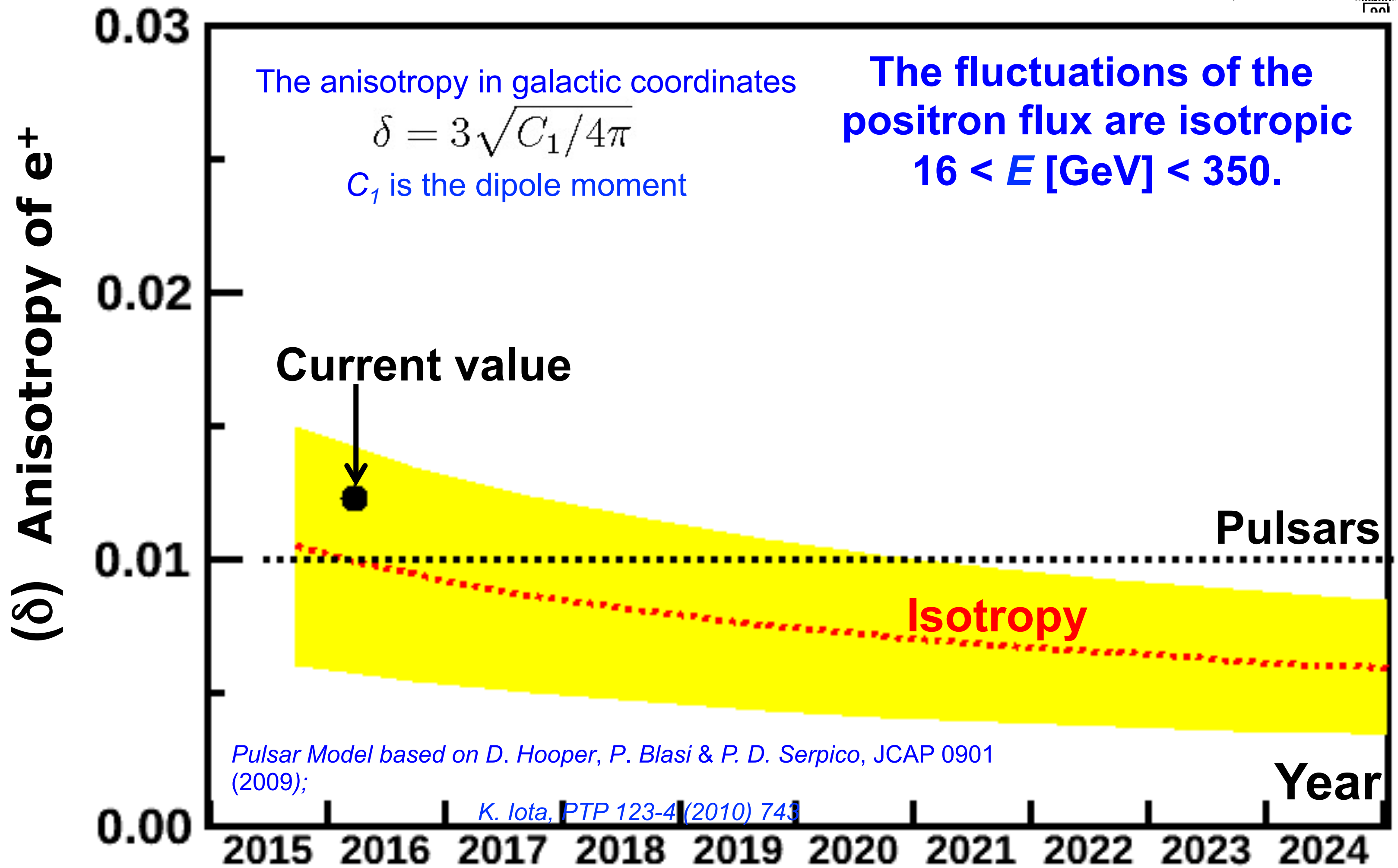


By 2024 we will be able to understand the origin of this unexpected data.

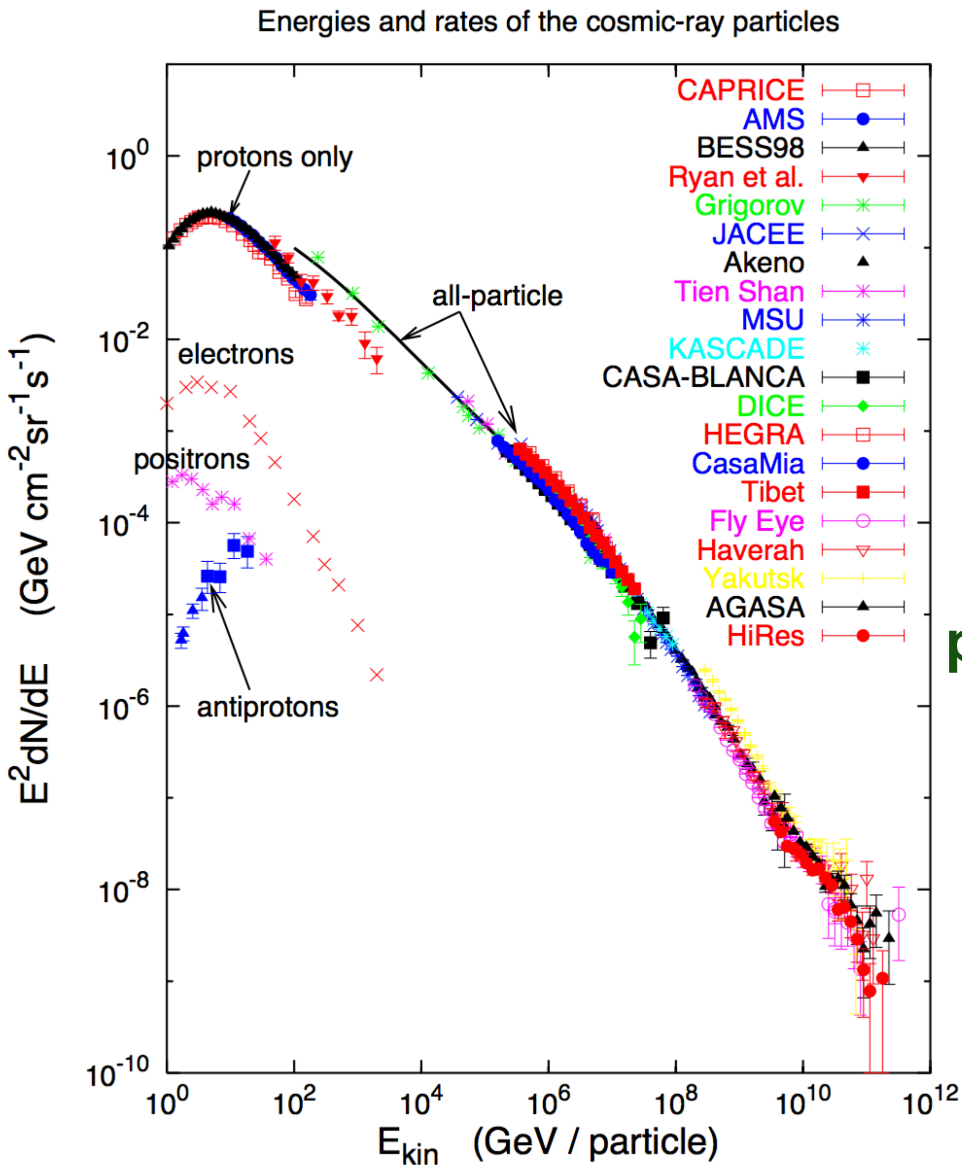
The anisotropy of the positron flux

Astrophysical point sources like pulsars will imprint a higher level of anisotropy on the arrival directions of energetic positrons than dark matter.





Elementary Particles in Space



There are hundreds of different kinds (μ, π, K, Λ,…) of charged elementary particles.

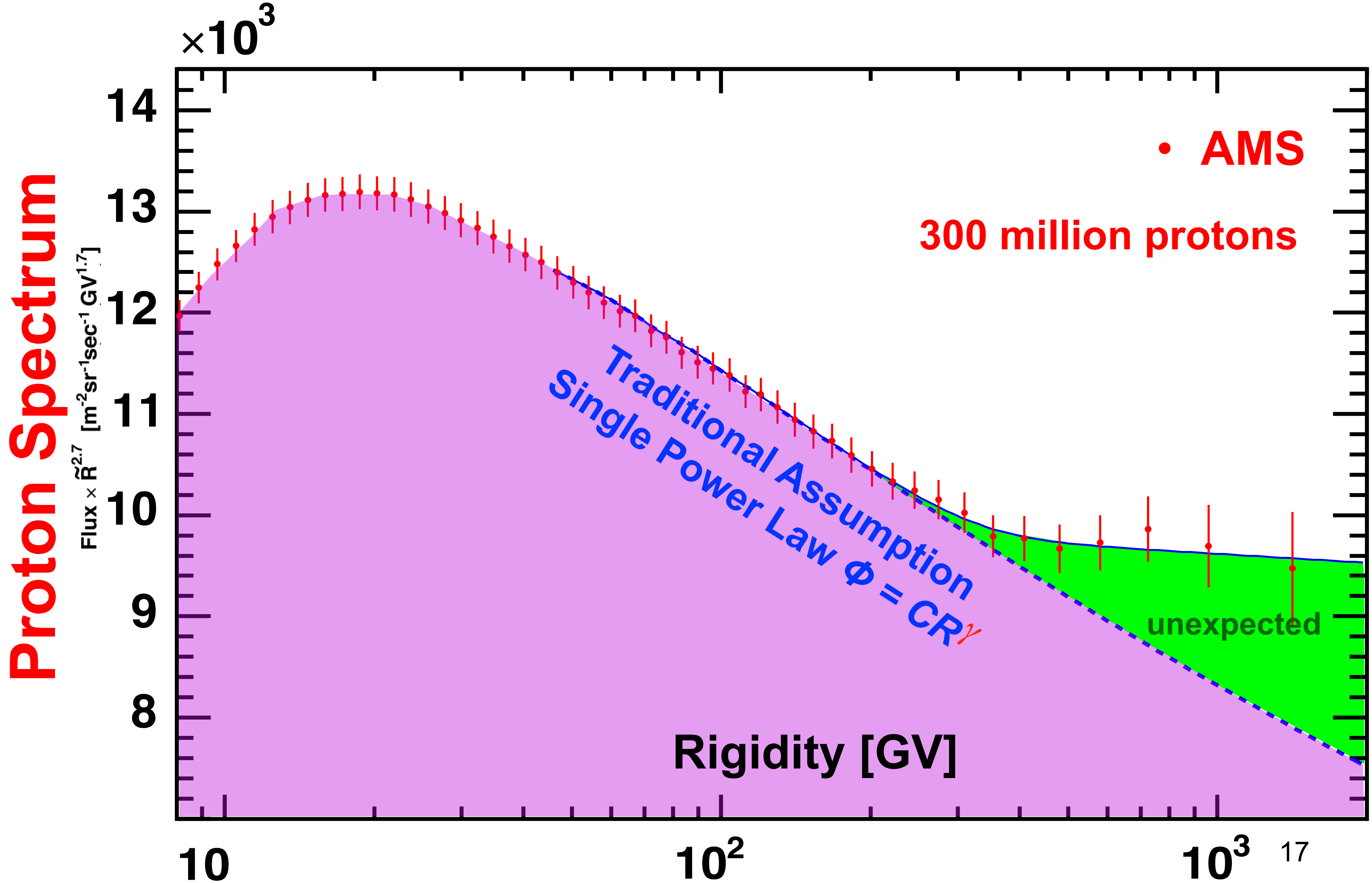
Only four of them,

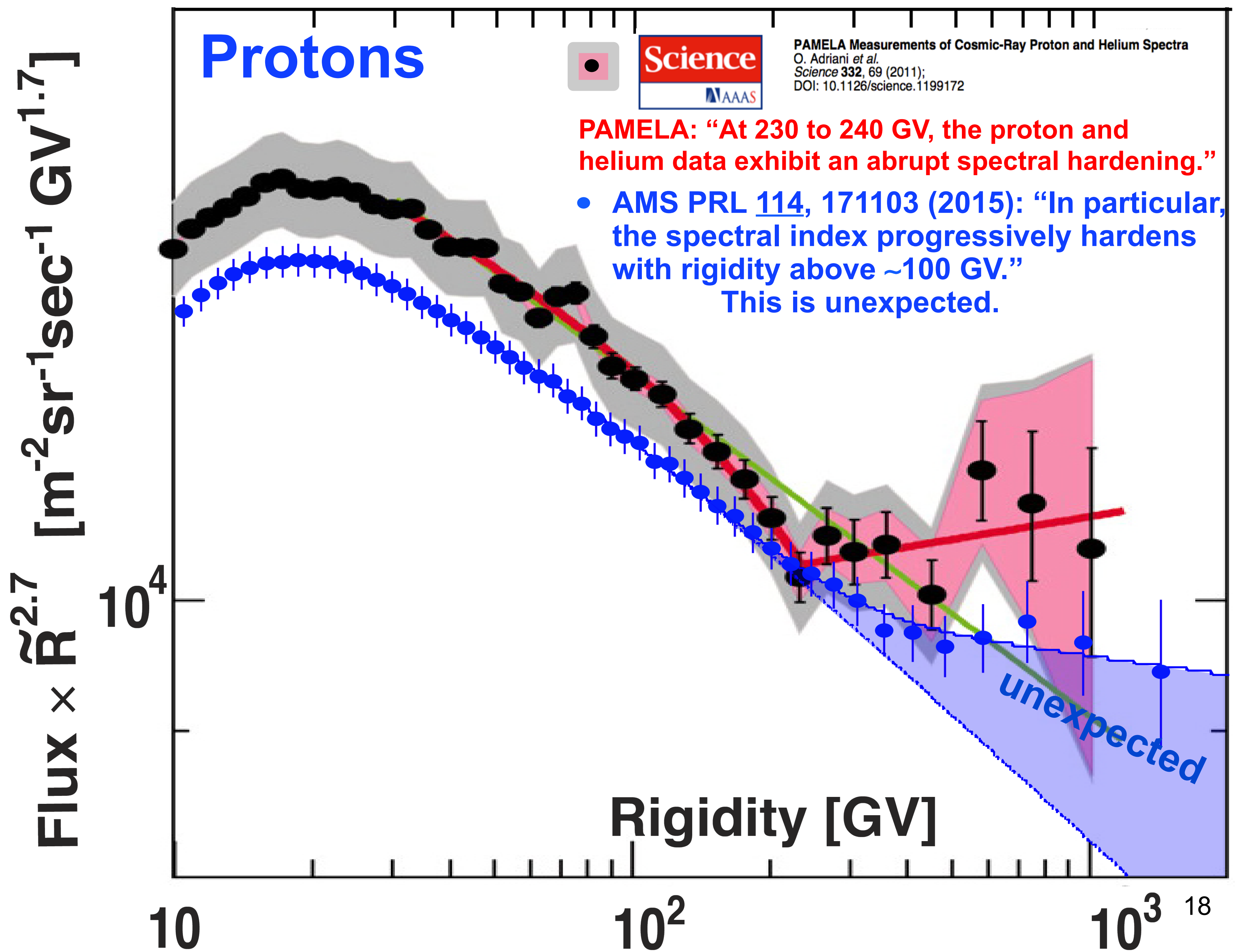
electrons (e-), protons (p), positrons (e+), and antiprotons ($\bar{p}$),

have infinite lifetime,

so they travel in the cosmos forever.

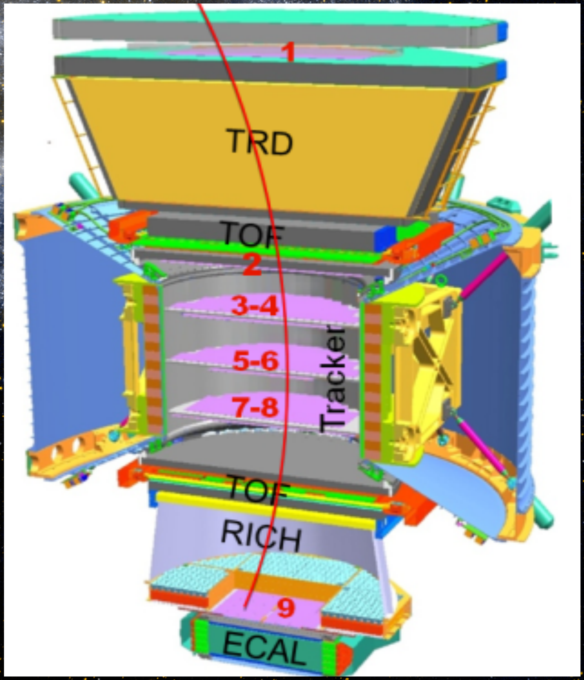
AMS Result on the Proton flux




Protons
PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra
O. Adriani et al.
Science 332, 69 (2011);
DOI: 10.1126/science.1199172
Science
AAAS
PAMELA: “At 230 to 240 GV, the proton and helium data exhibit an abrupt spectral hardening.”
• AMS PRL 114, 171103 (2015): “In particular, the spectral index progressively hardens with rigidity above ~100 GV.”
This is unexpected.
unexpected
Flux × $\tilde{R}^{2.7}$ [m^{-2}sr^{-1}sec^{-1} GV$^{1.7}$]
10^4
Rigidity [GV]
10
10^2
10^3

Antiprotons

There is only 1 Antiproton for 10,000 Protons.



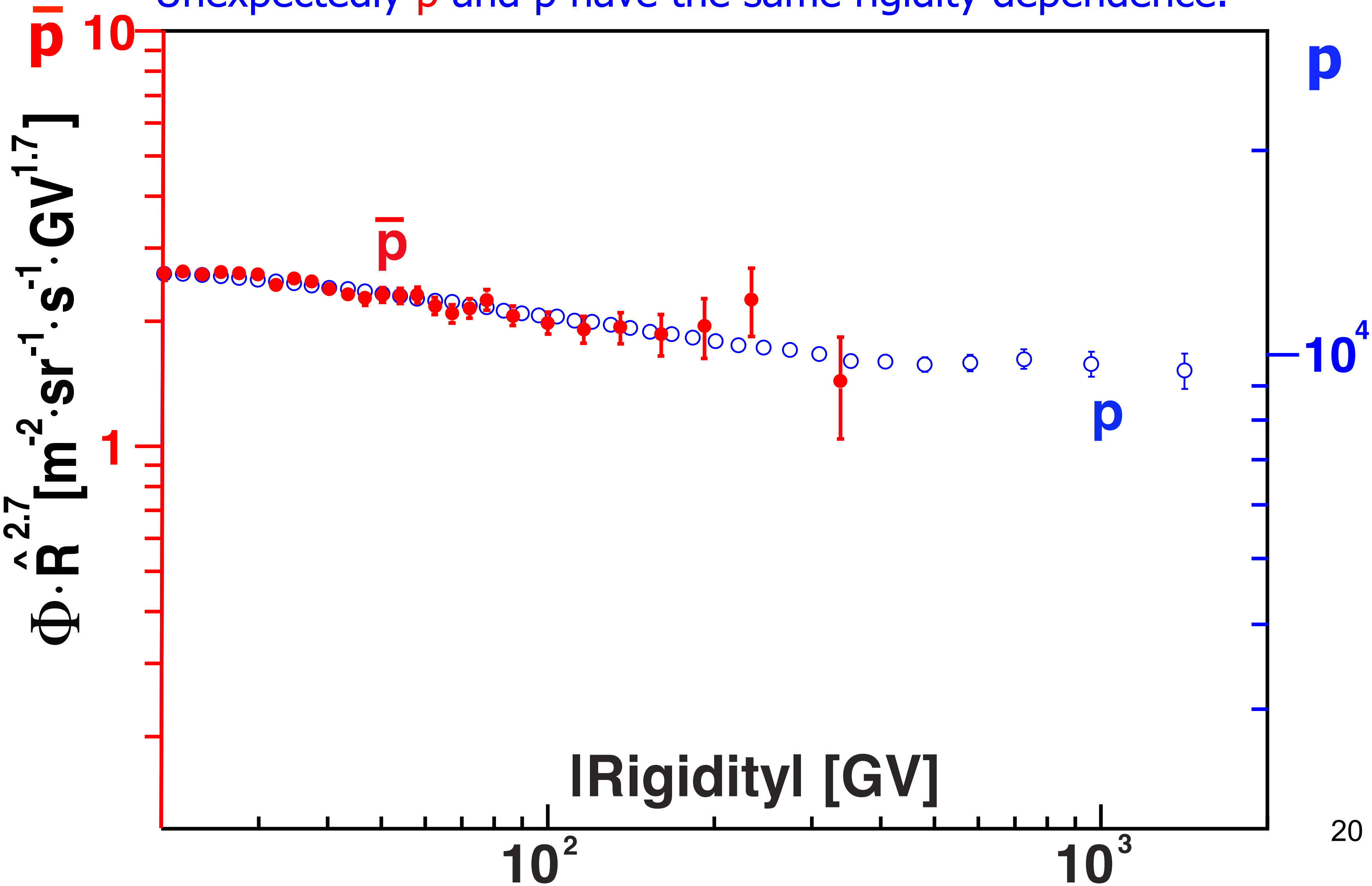
A percent precision experiment requires background rejection close to 1 in a million.

The Spectra of Protons and Antiprotons:

If $\bar{p}$ are secondaries, their rigidity dependence should be different than p:

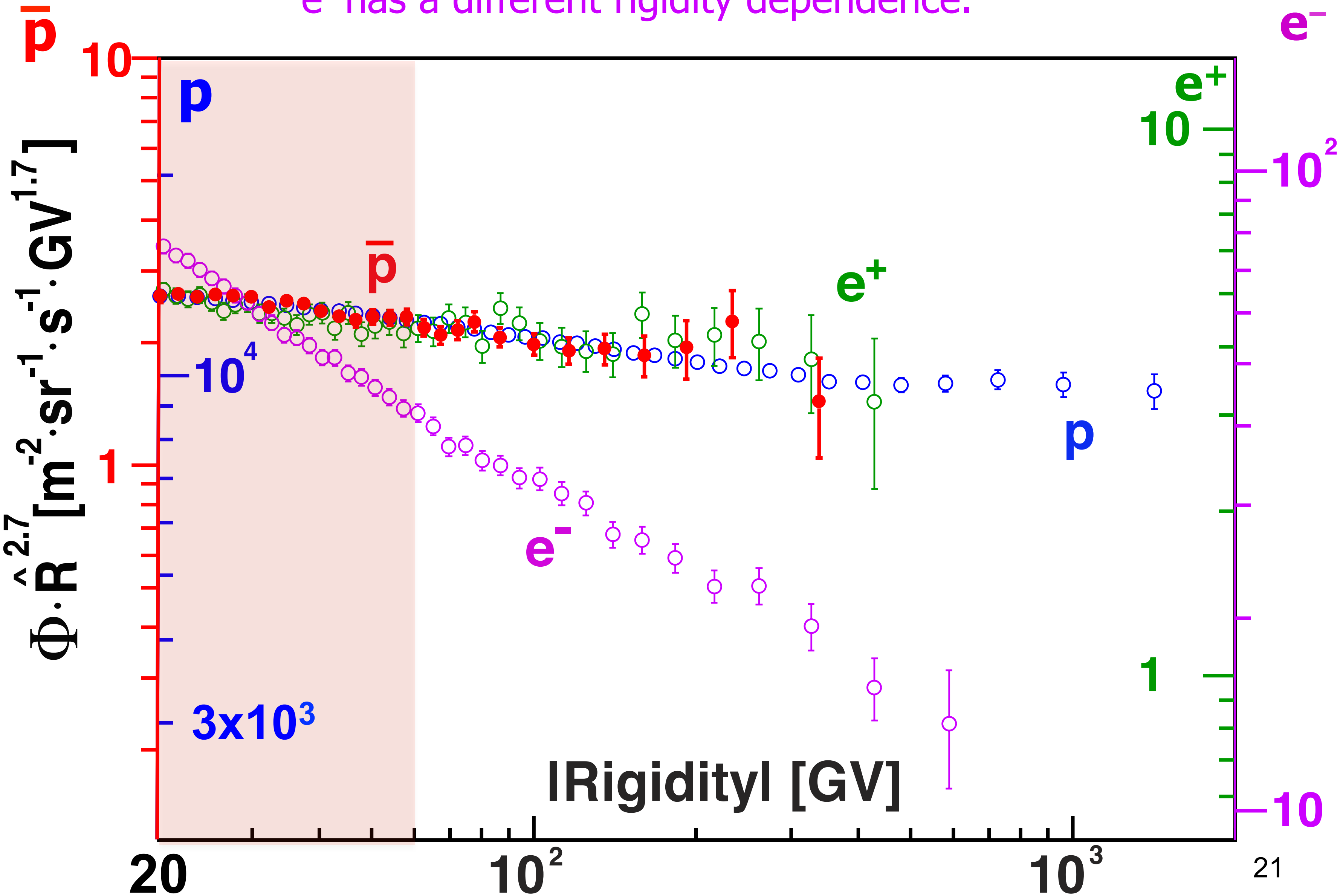
$$p + \mathrm{ISM} \rightarrow \bar{p} + \ldots$$

Unexpectedly $\bar{p}$ and p have the same rigidity dependence.



Unexpected Result: The Rigidity Dependence of Elementary Particles e^+, $\bar{p}$, p are identical from 60-500 GV.

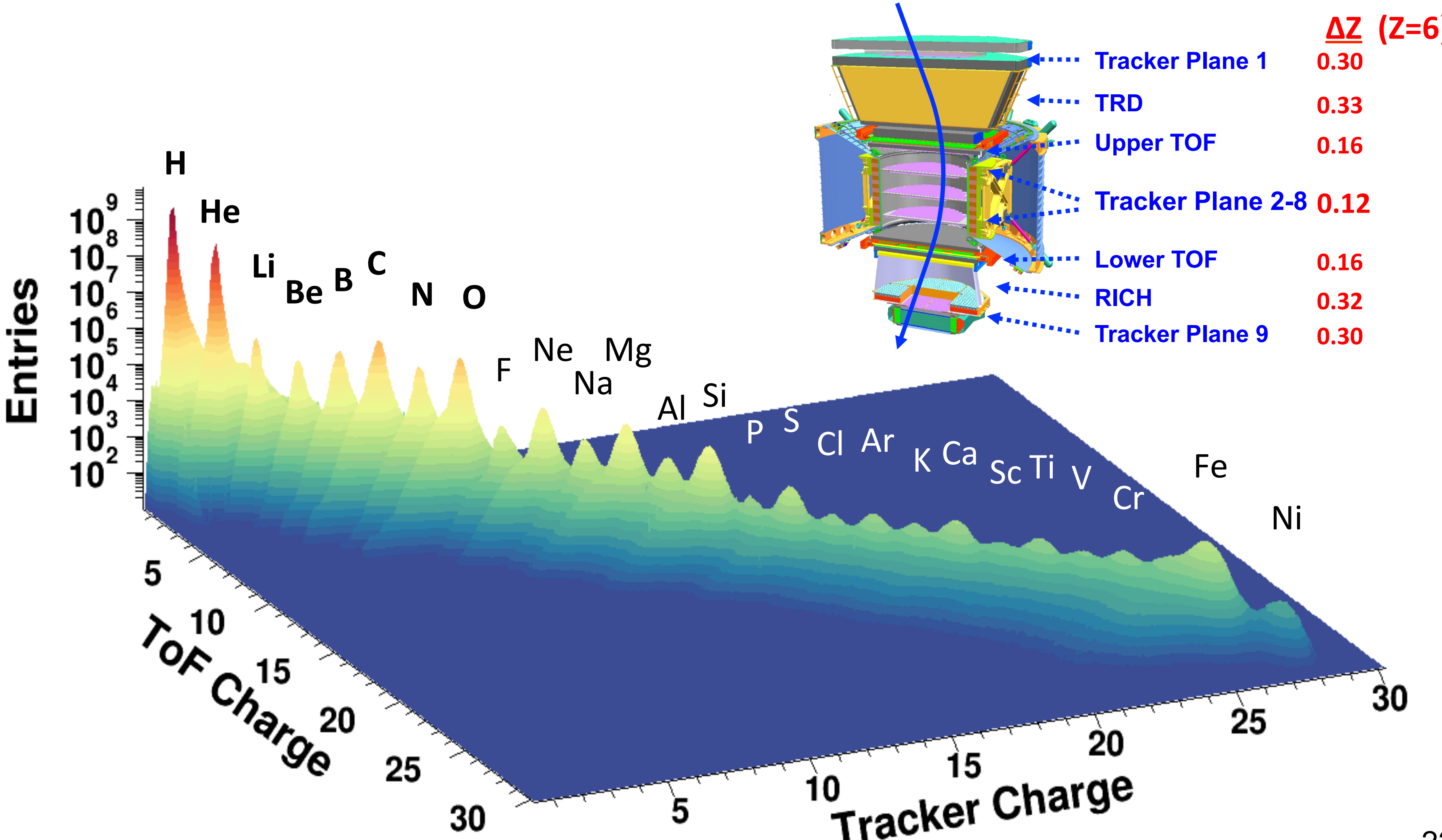
e^- has a different rigidity dependence.



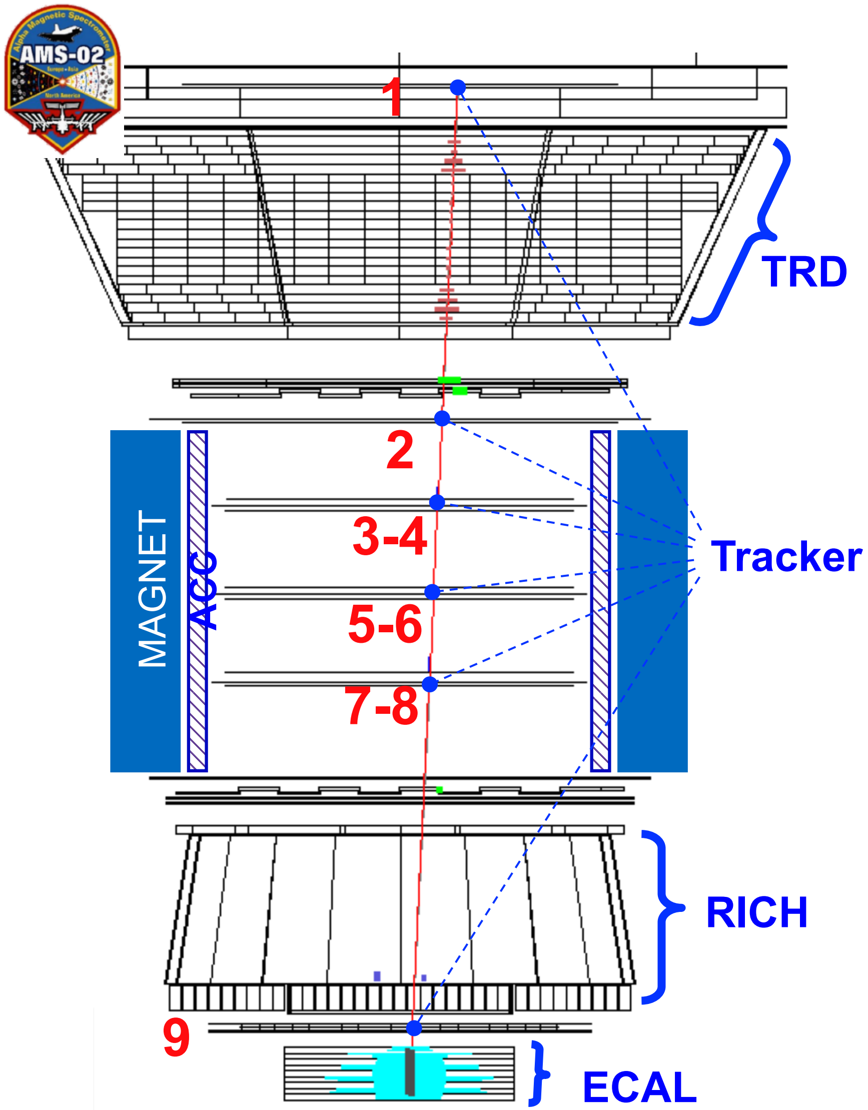
M. Aguilar *et al.*, Phys. Rev. Lett. **117,** 091103 (2016)

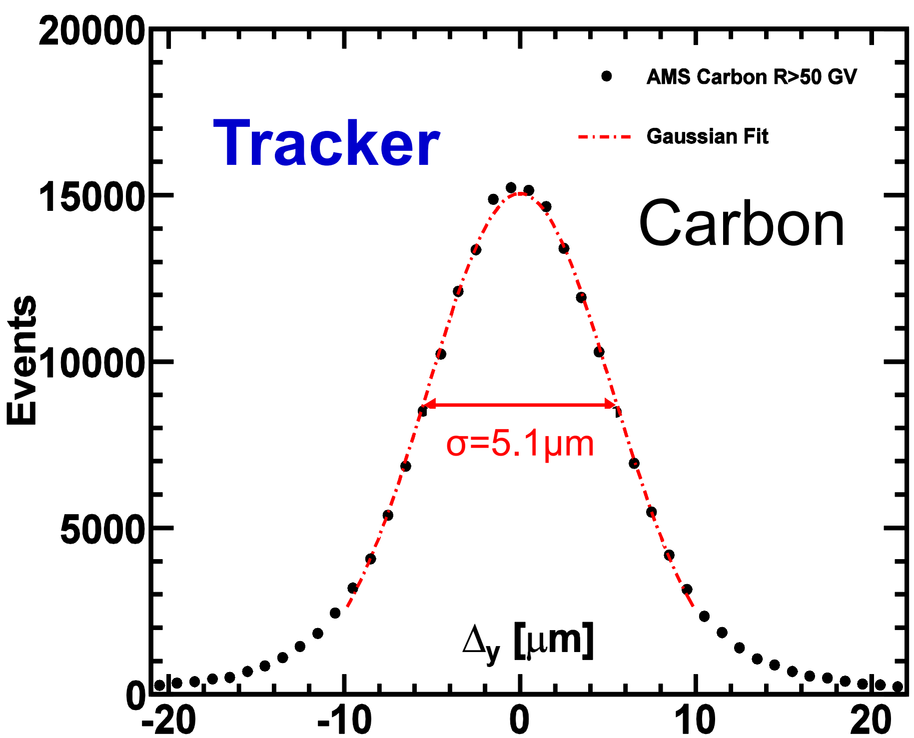
Cosmic Nuclei

AMS has seven instruments which independently identify cosmic nuclei



TV, precision magnetic spectrometer for CR Nuclei measurement

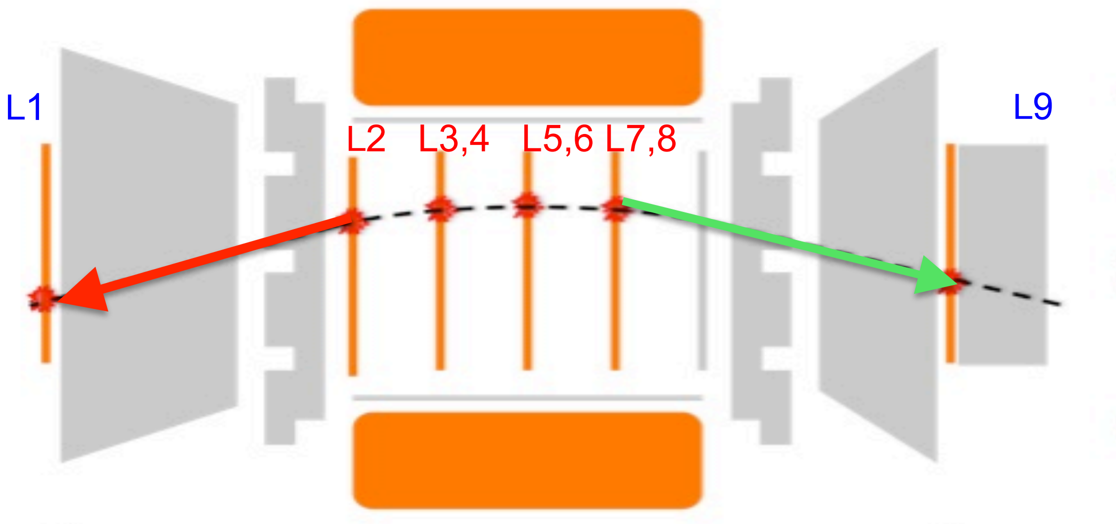


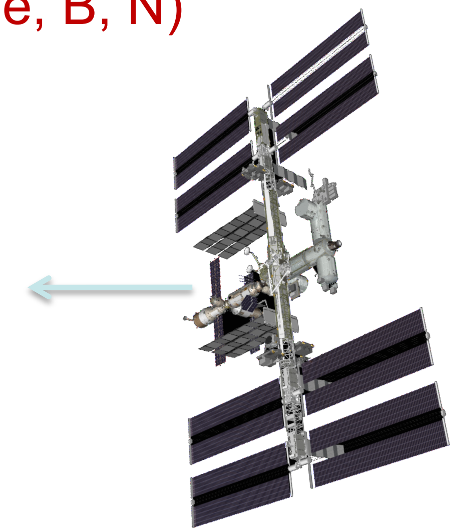


maximum detectable rigidity ≈ 3.7 TV

Measurement of nuclei cross sections by AMS

The detector components are mostly made of Carbon (C) and Aluminum (Al).
The inelastic cross sections of N+ C, N+ Al are only measured below few GV (He, C, O) or not measured (Li, Be, B, N)

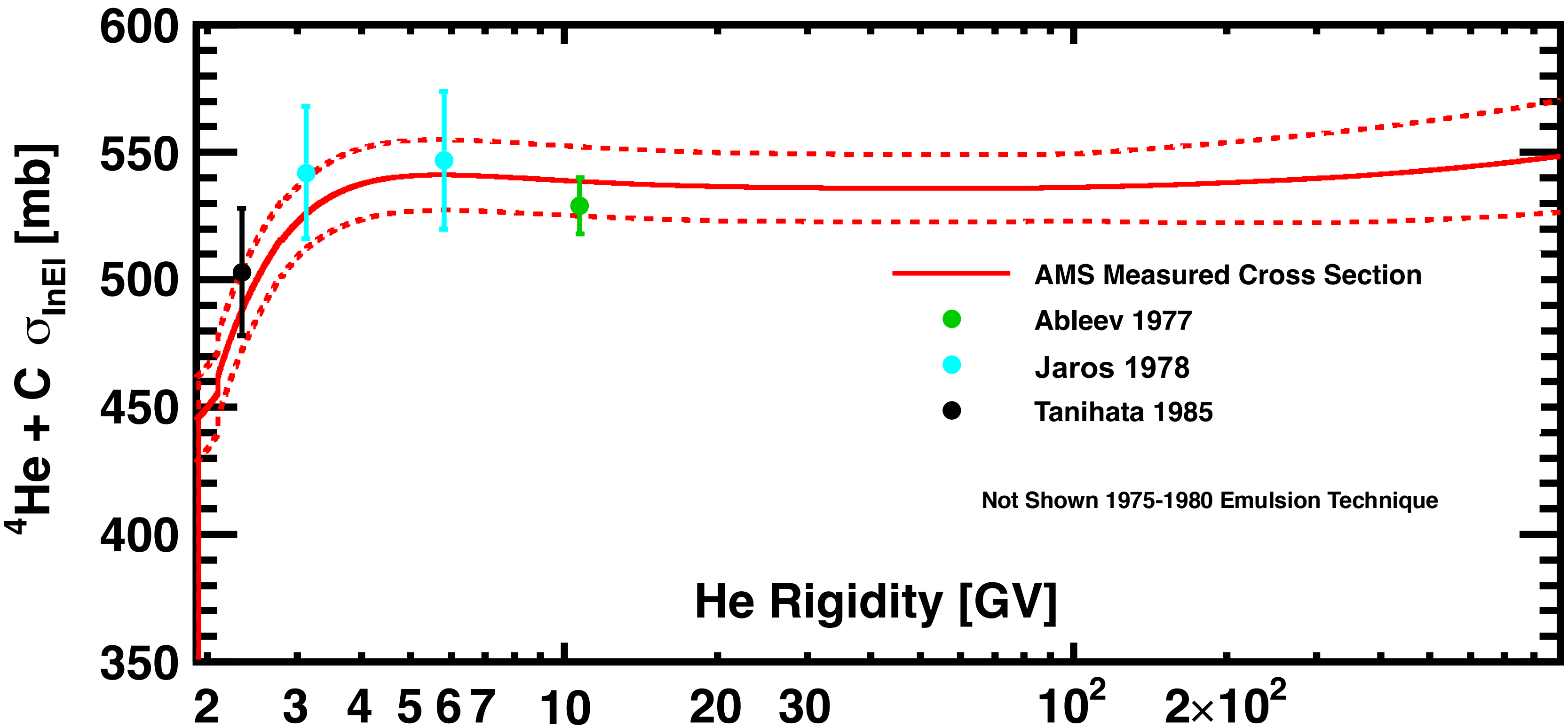




AMS measured the Survival Probabilities during “Horizontal” runs [~10^5 sec exposure] in which CRs can enter AMS both right to the left and left to the right.

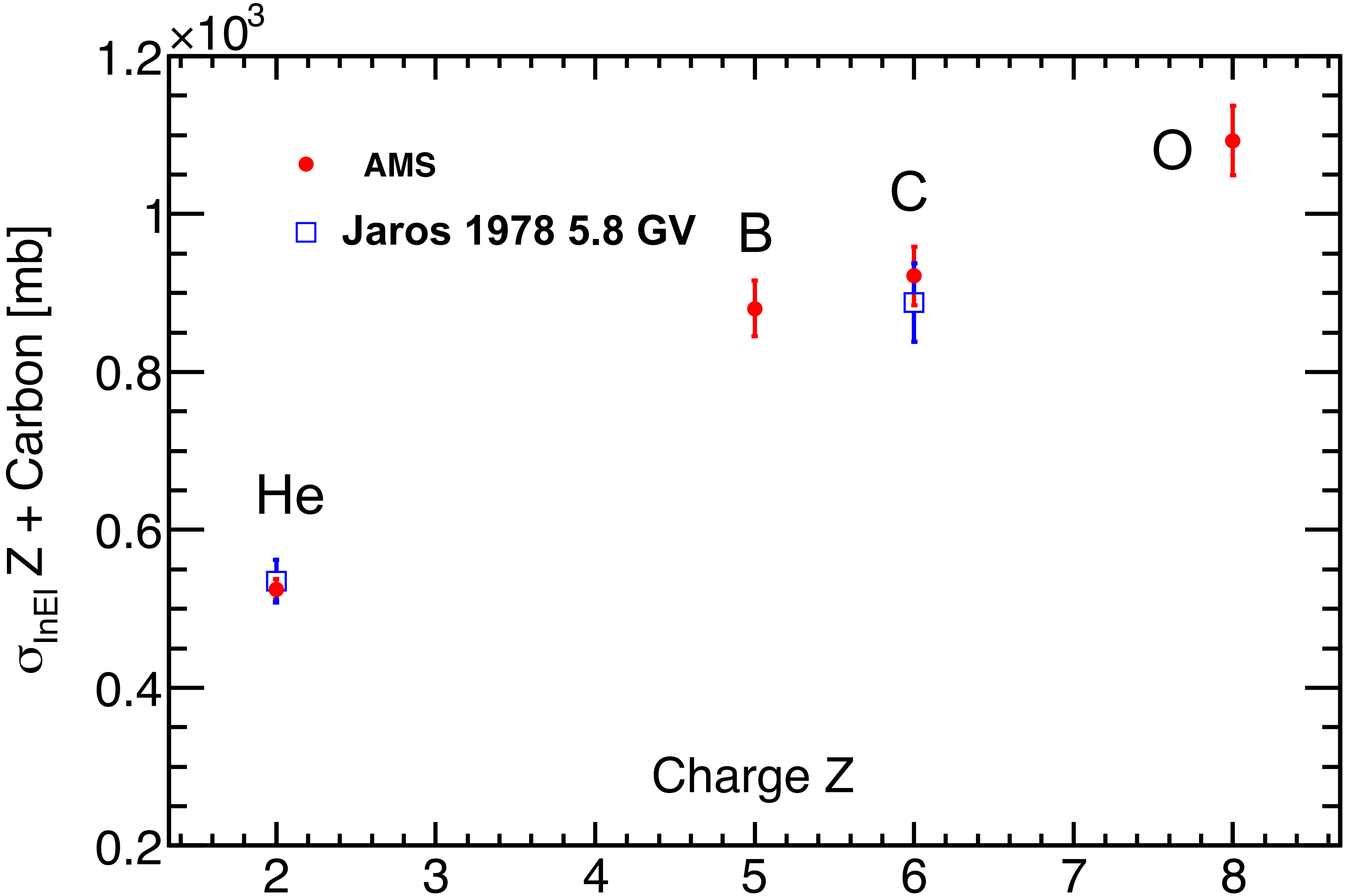
Most importantly, by flying horizontally, AMS was able to make Interaction cross sections measurements which were not available from accelerators.

AMS measured He + C inelastic cross section

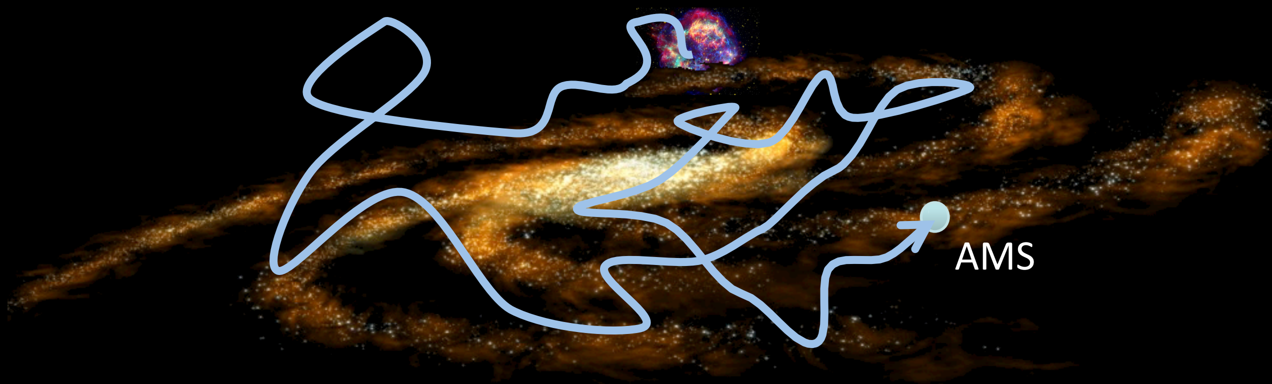


The AMS measured He+C inelastic cross section in comparison with experimental results. The dashed curve indicates the corresponding systematic errors. The cross section rise on R>100 GV follows the Glauber Gribov model.

AMS Nuclei + C Inelastic Cross Section measurements average in 5-100 GV



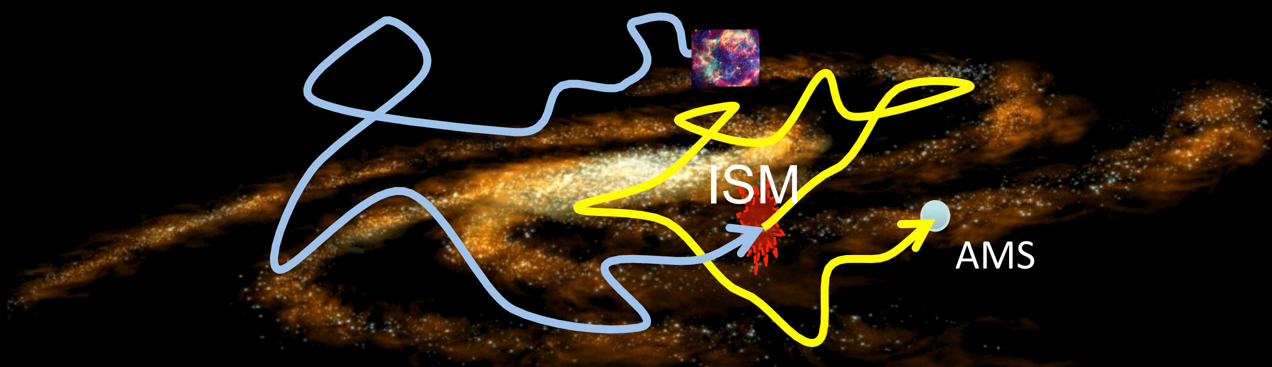
Primary Cosmic Rays (p, He, C, O, …)



Primary cosmic rays carry information about their original spectra and propagation.

Secondary Cosmic Rays (Li, Be, B, …)

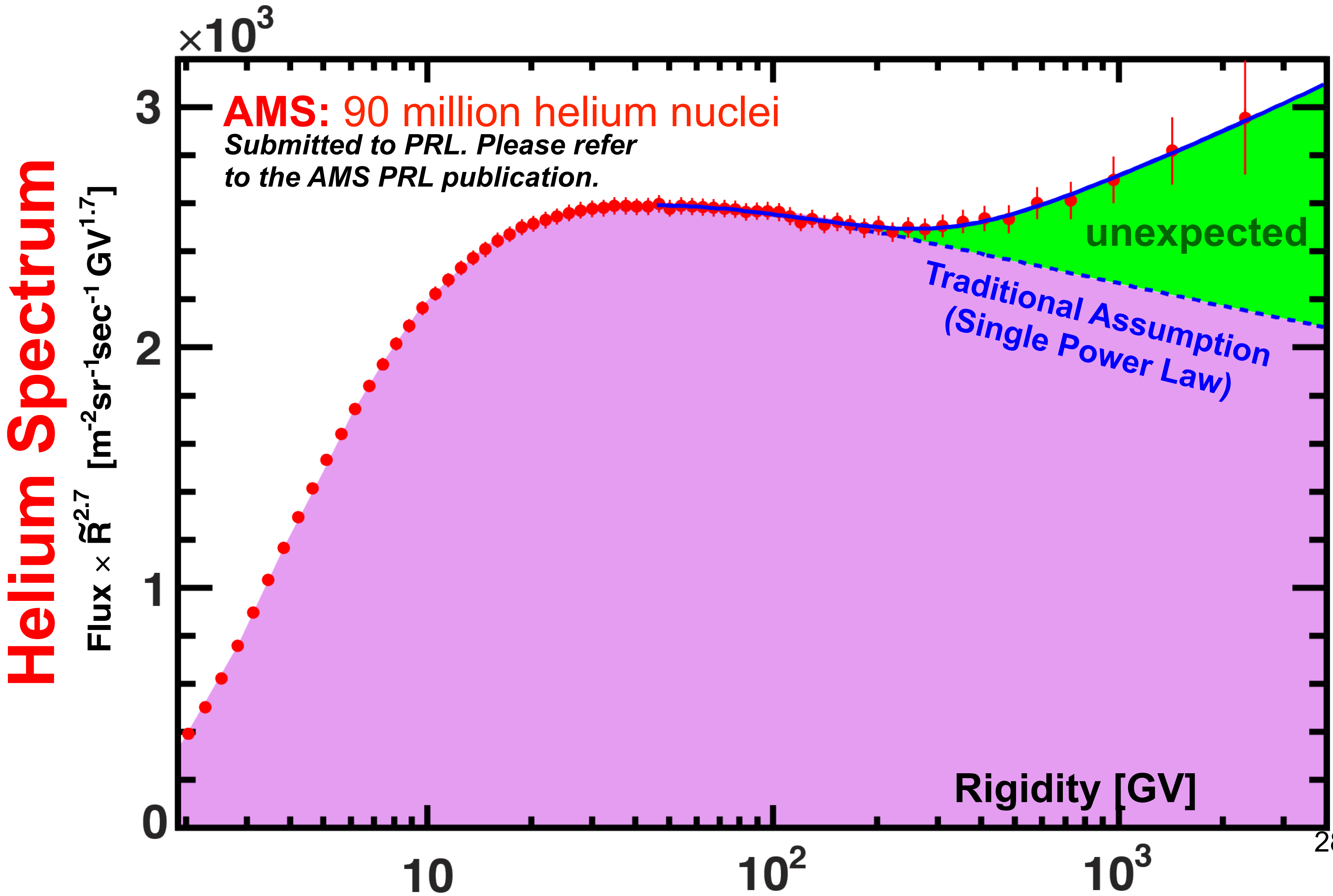
C, O, …, Fe + ISM → Li, Be, B + X

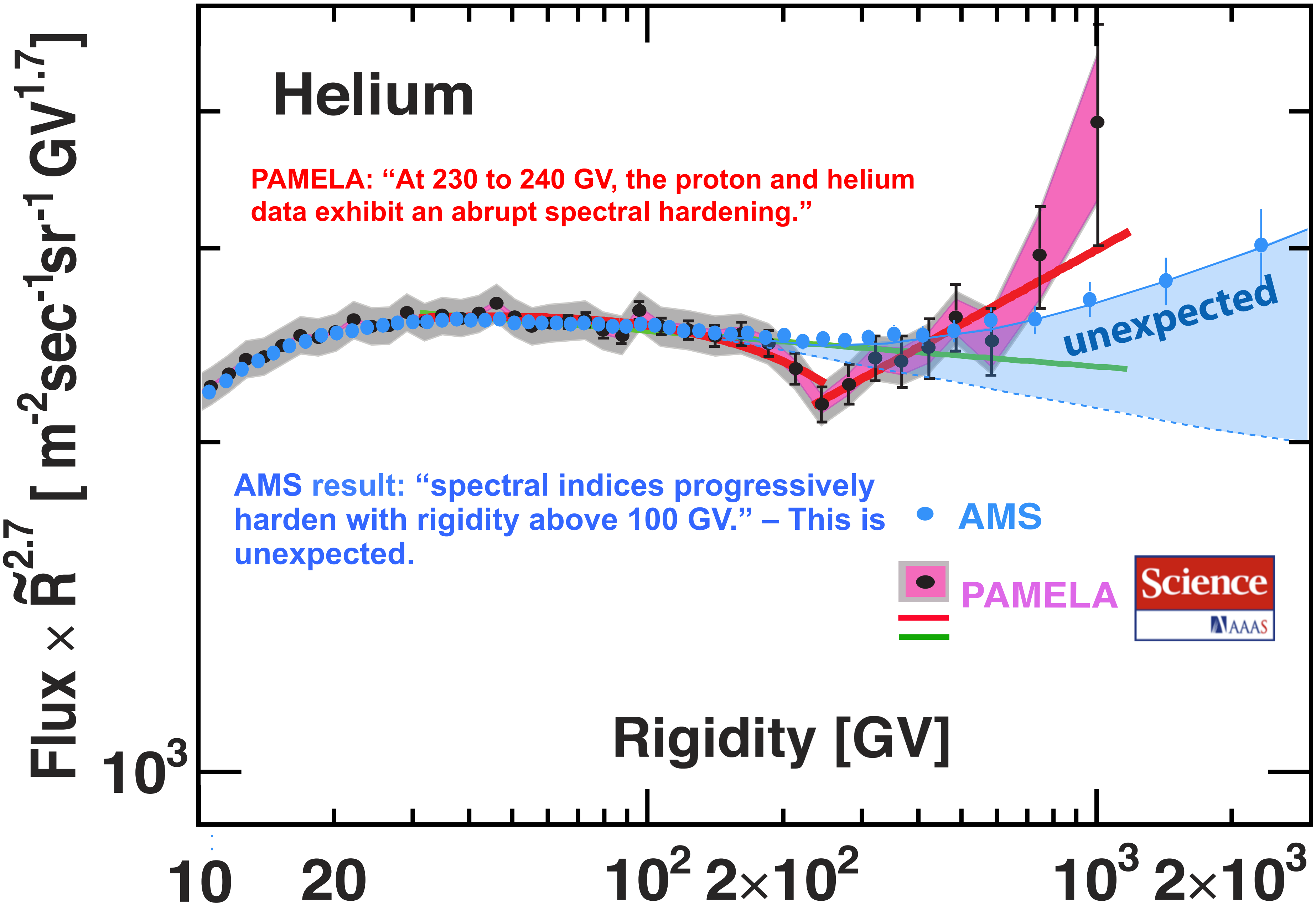


Secondary cosmic rays carry information about propagation of primaries, secondaries and the ISM.

The AMS Result on the Helium Flux

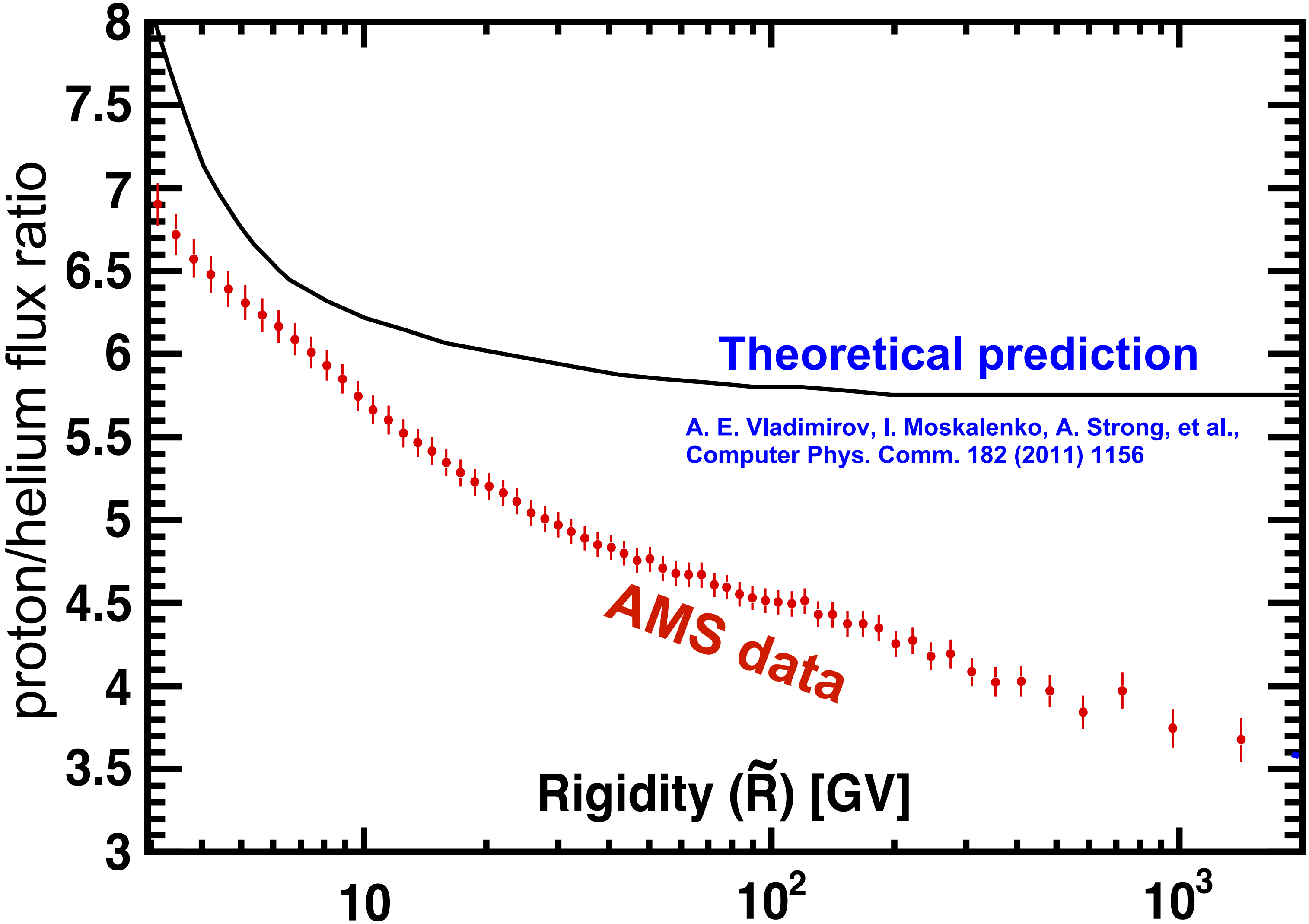
The Helium flux cannot be described by a single power law.




Helium
PAMELA: "At 230 to 240 GV, the proton and helium data exhibit an abrupt spectral hardening."
AMS result: "spectral indices progressively harden with rigidity above 100 GV." – This is unexpected.
unexpected
AMS
PAMELA
Science
AAAS
Flux × $\tilde{R}^{2.7}$ [$m^{-2}sec^{-1}sr^{-1}GV^{1.7}$]
10^3
Rigidity [GV]
10
20
10^2
2×10^2
10^3
2×10^3

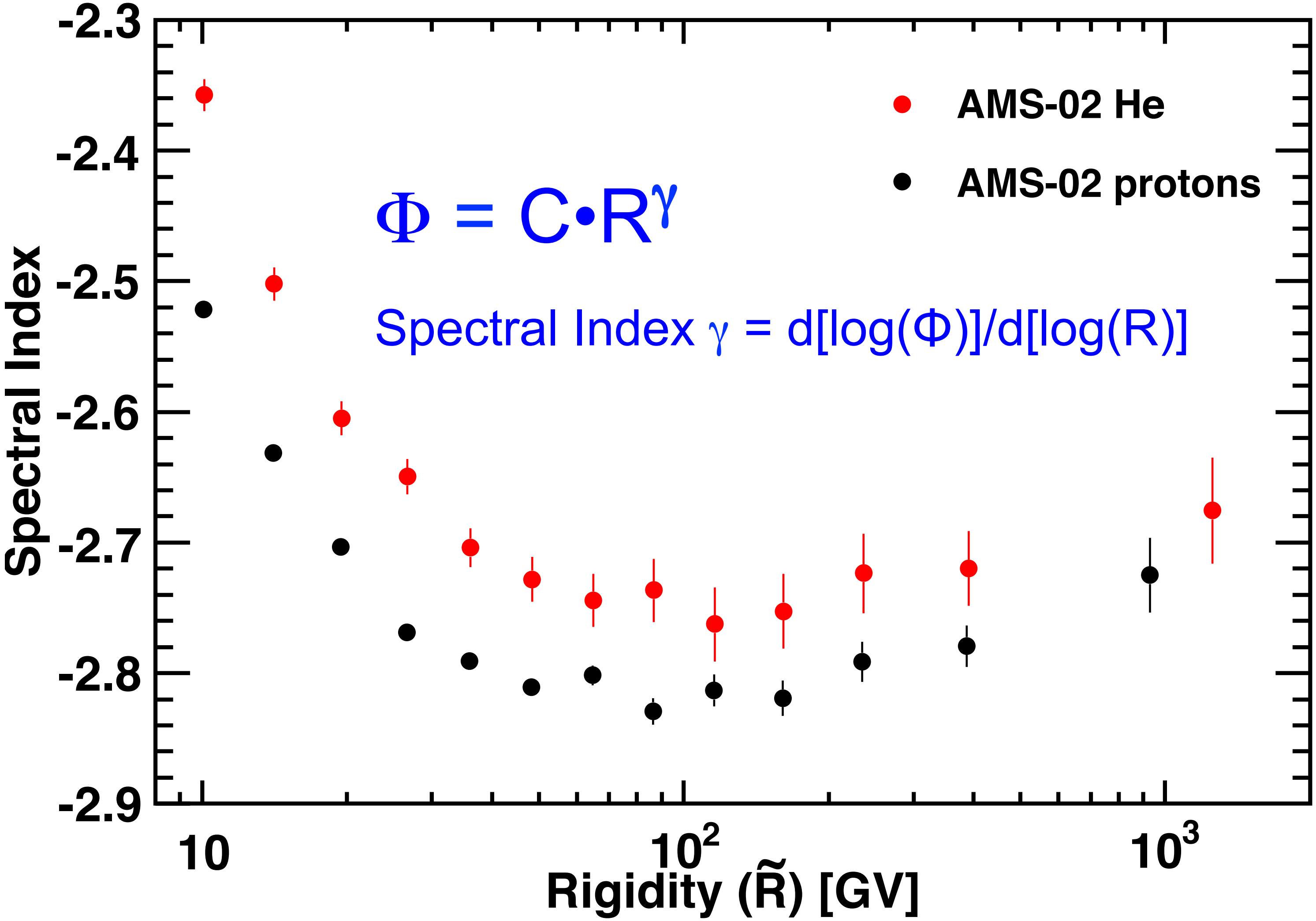
The AMS Result on the Proton/Helium Flux Ratio

Protons and helium are both "primary" cosmic rays.
Traditionally, they are assumed to be produced in the same sources and, therefore, their flux ratio should be rigidity independent.

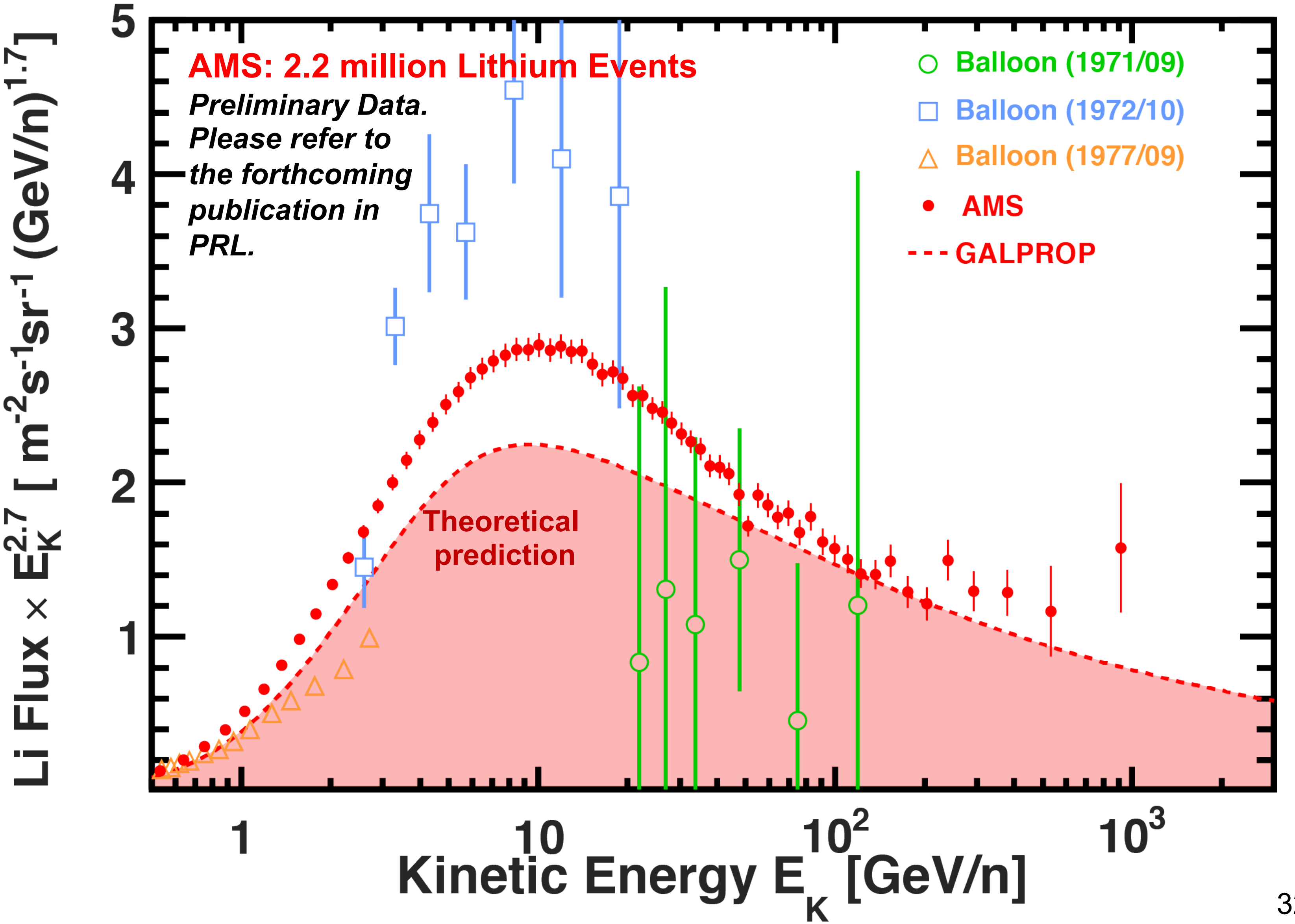


Spectral Index Rigidity Dependence Proton and Helium

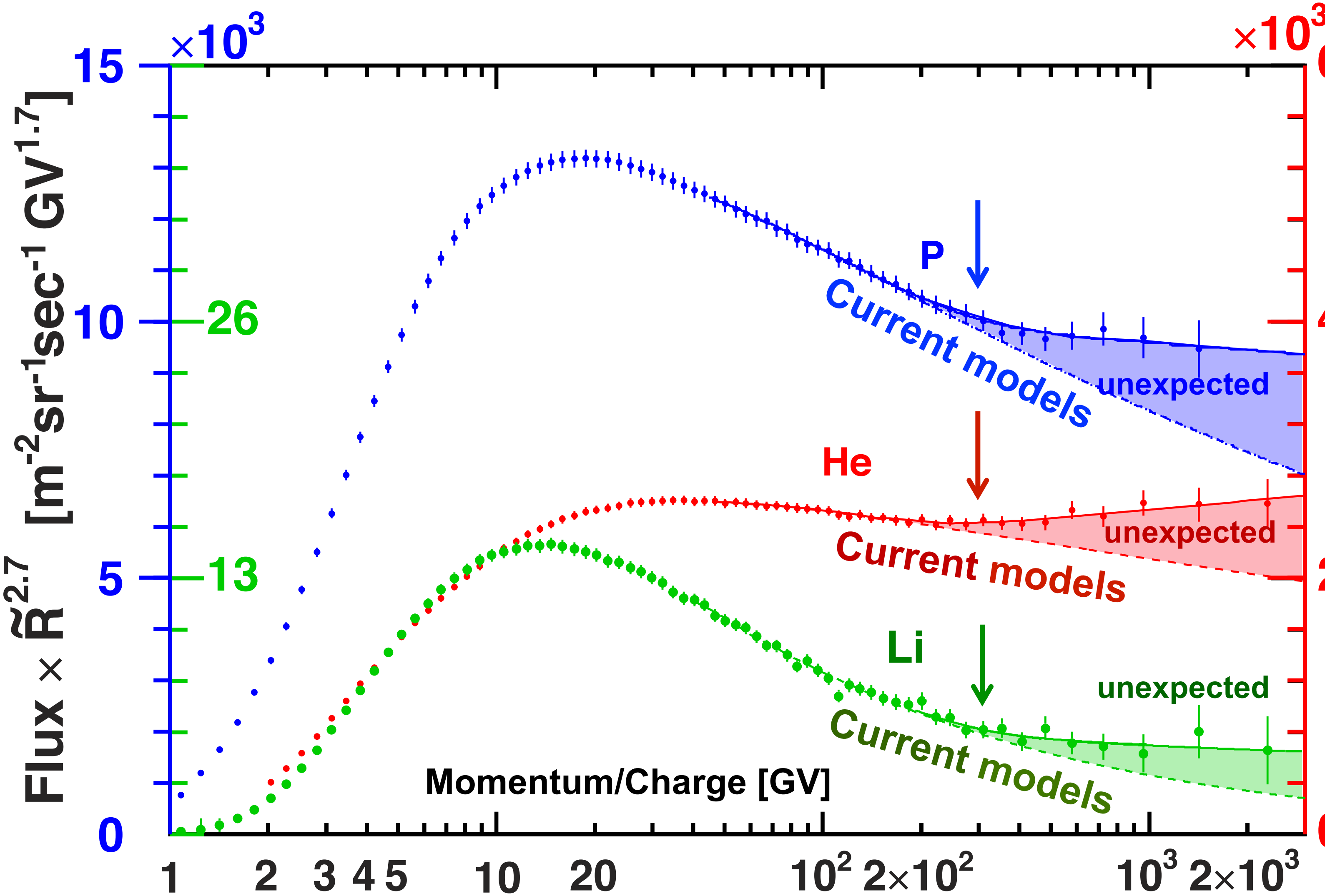
The spectral index varies with rigidity. In particular, the spectral index is progressively hardening with rigidity above ~100 GV.



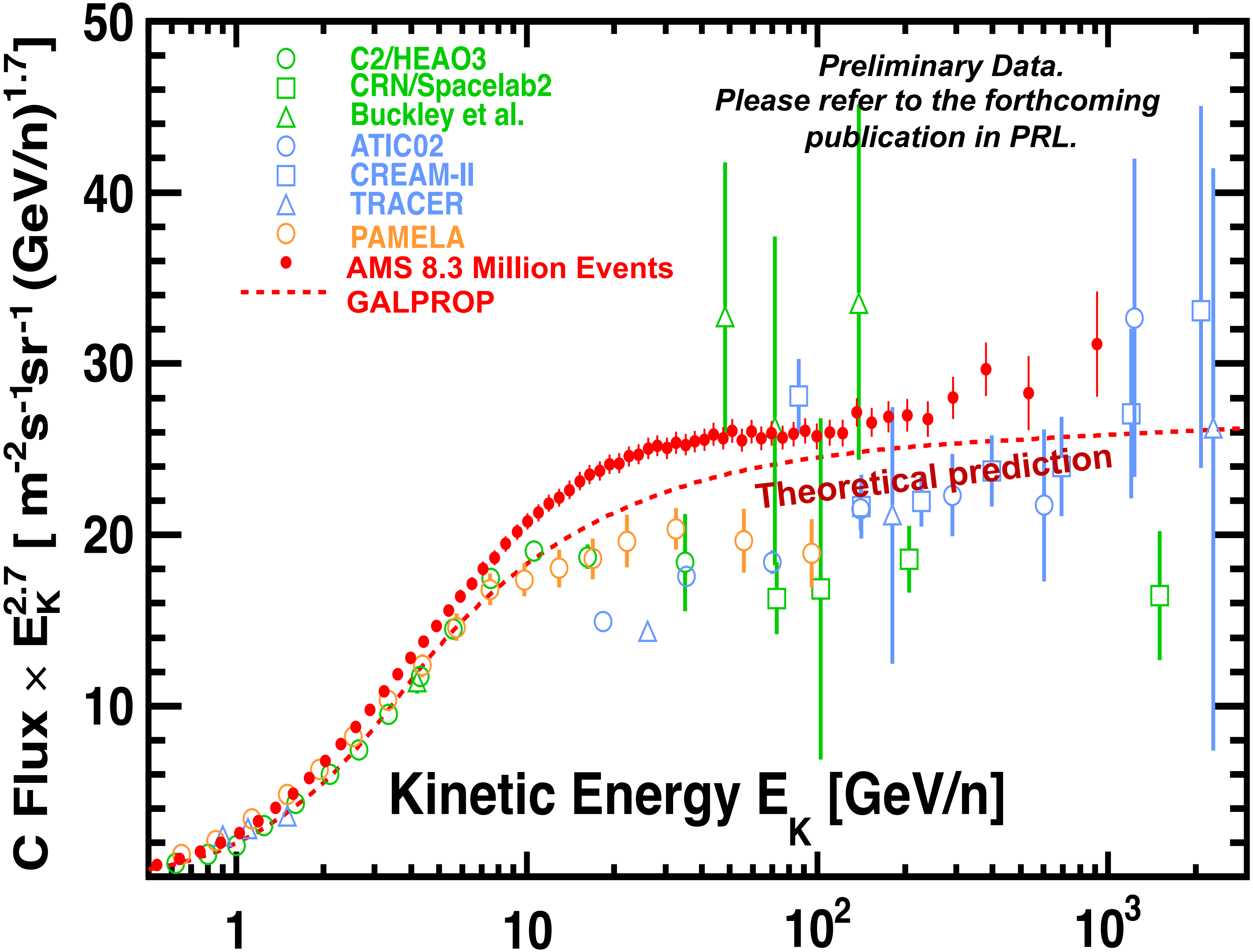
The AMS Result on the Lithium Flux



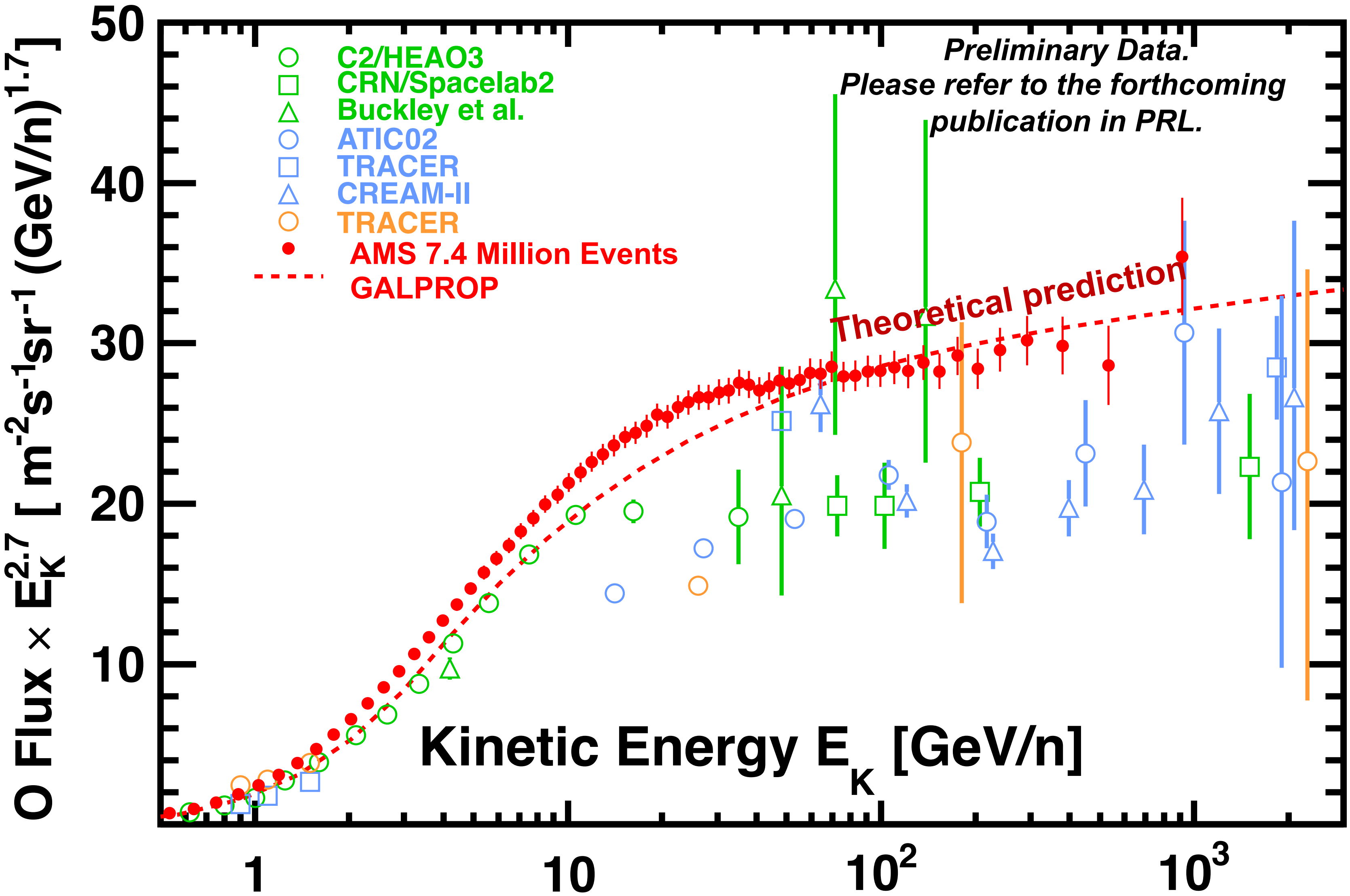
The spectra of Protons, Helium and Lithium do not follow the traditional single power law.



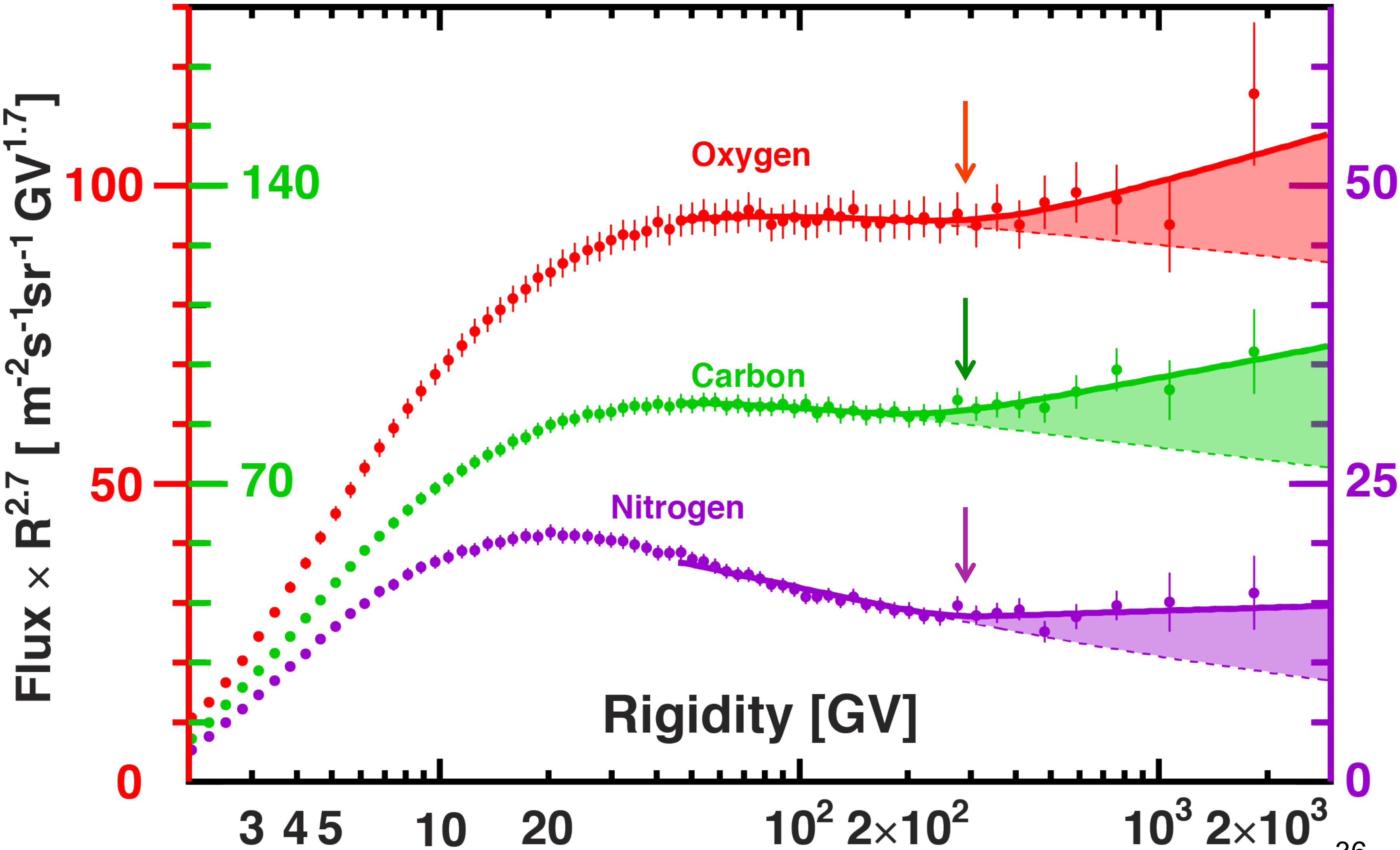
The AMS Result on the Carbon Flux



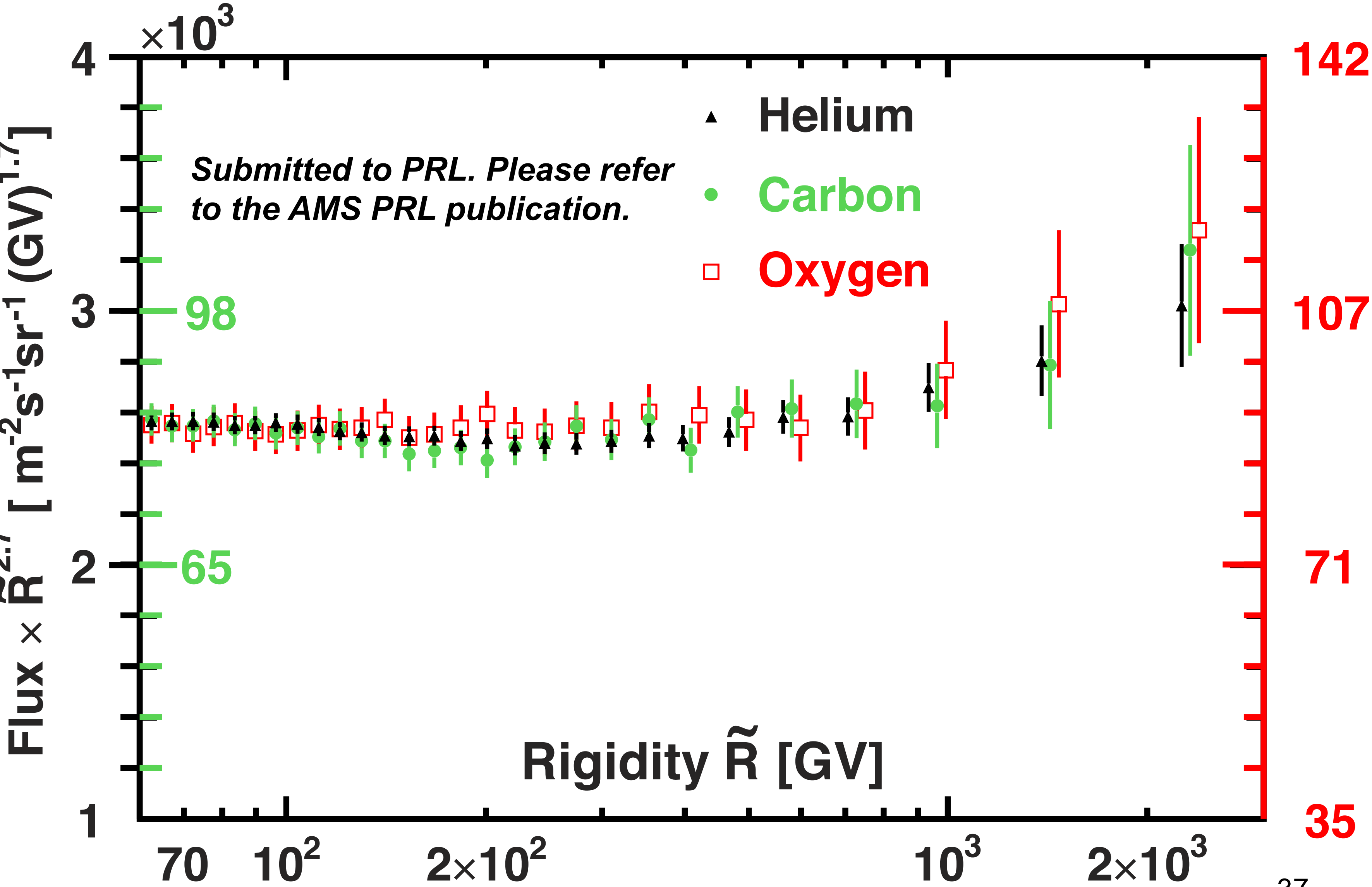
The AMS Result on the Oxygen Flux



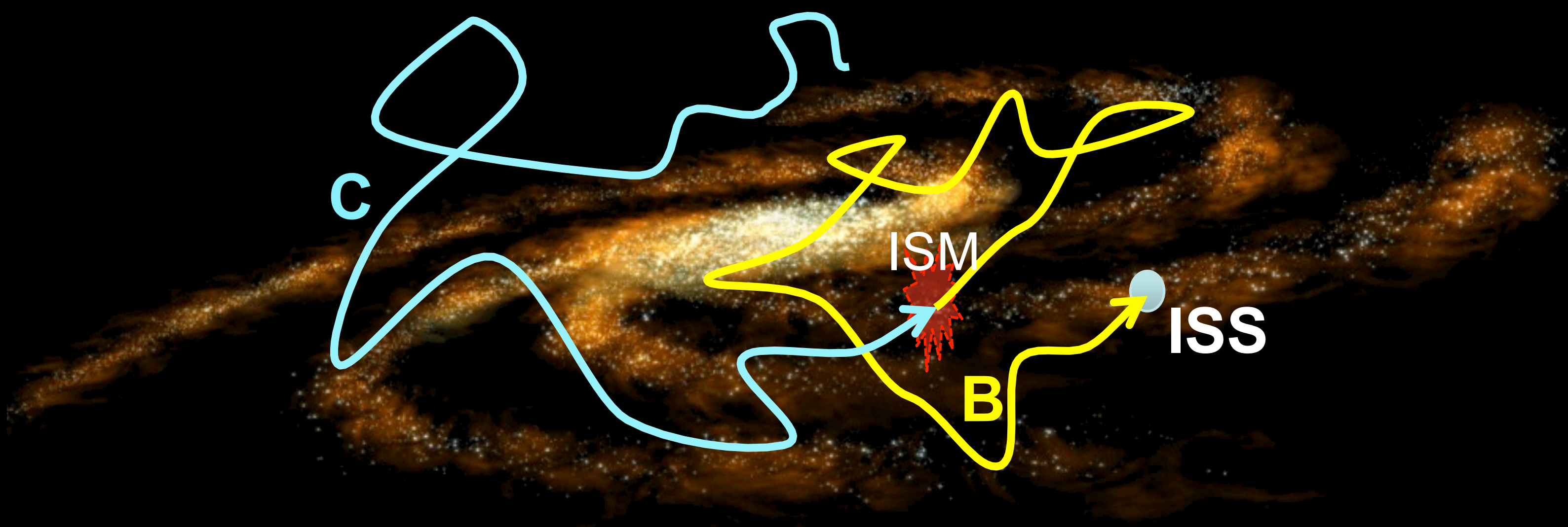
The spectra of Oxygen, Carbon and Nitrogen do not follow the traditional single power law.



Extraordinary Properties of Primary Cosmic Rays: above 60GV, the spectra of Helium, Carbon, and Oxygen have identical rigidity dependence



The flux ratio between primaries (C) and secondaries (B) provides information on propagation and the ISM

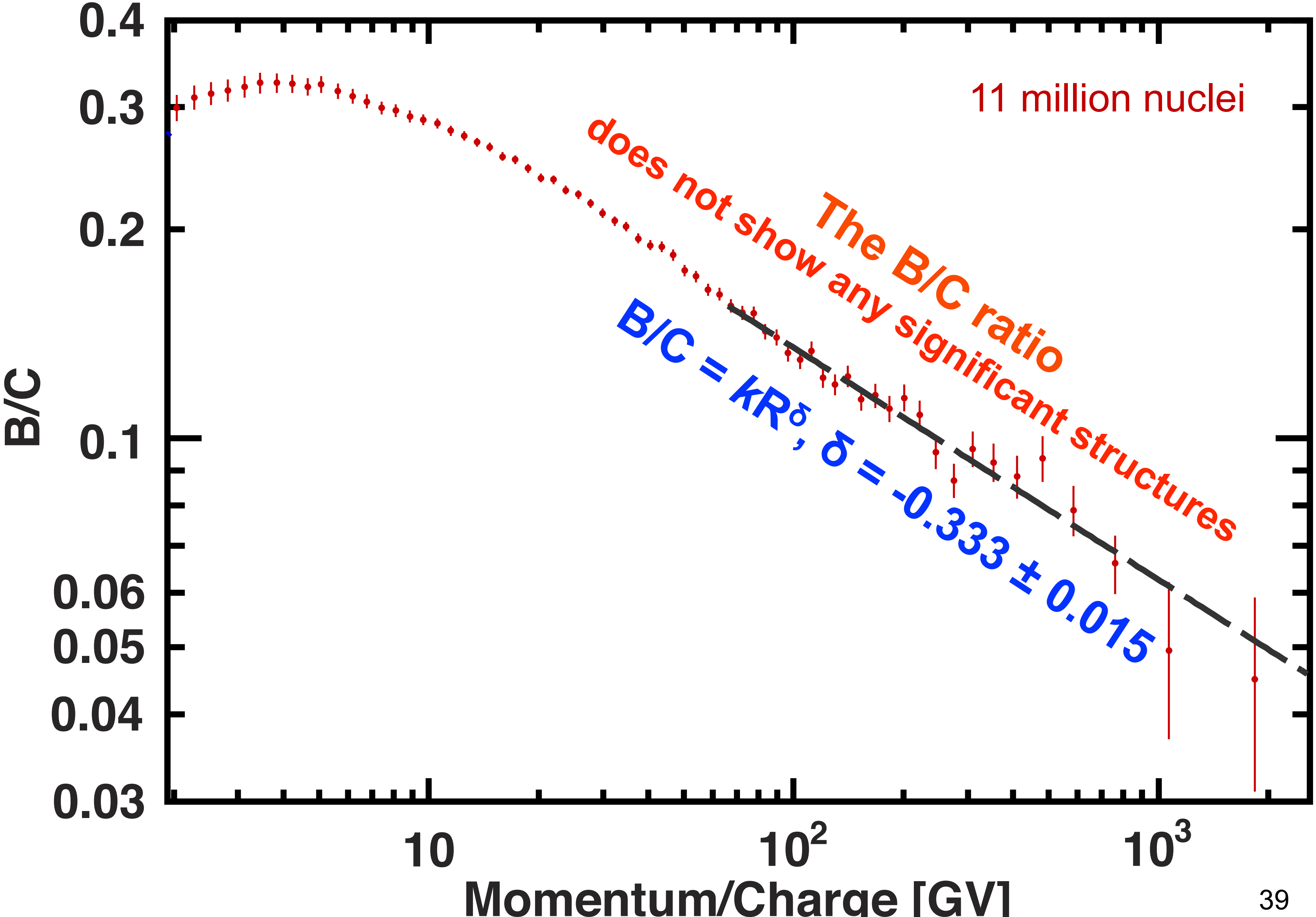


Cosmic ray propagation is commonly modeled as a fast moving gas diffusing through a magnetized plasma.

At high rigidities, models of the magnetized plasma predict different behavior for B/C = kR^{δ}.

With the Kolmogorov turbulence model $\delta = -1/3$ while the Kraichnan theory leads to $\delta = -1/2$.

The AMS Result on the Boron-to-Carbon (B/C) flux ratio

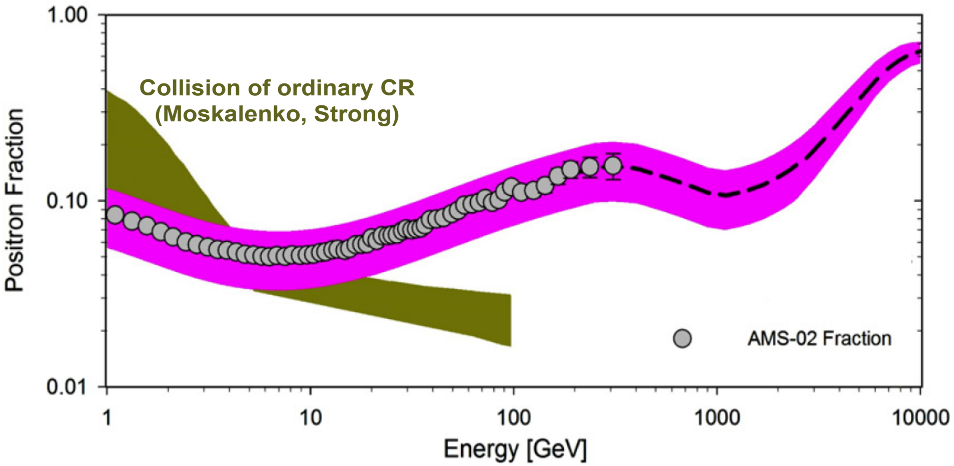


M. Aguilar *et al.*, Phys. Rev. Lett. **117**, 231101 (2016)

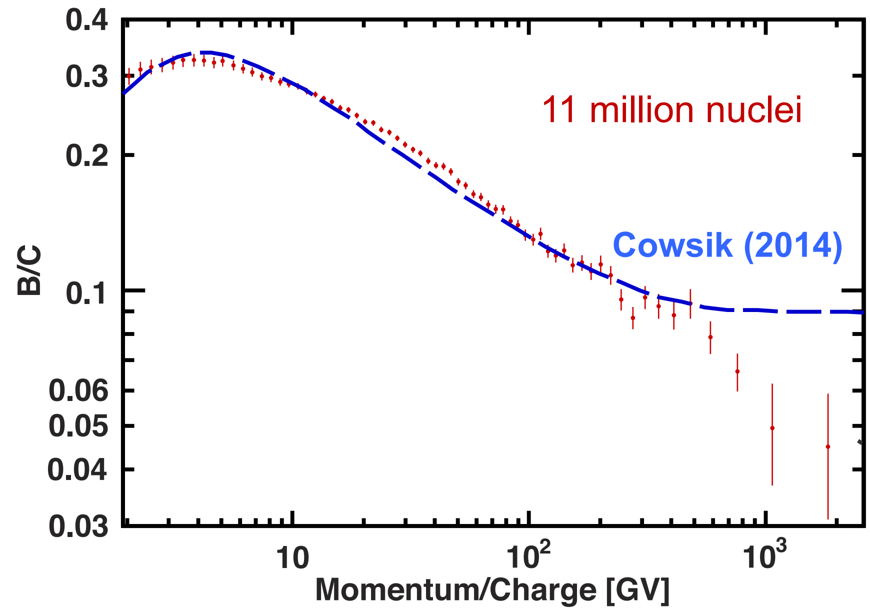
Propagation Models to explain the AMS Positron Flux and Positron Fraction Measurements

R. Cowsik *et al.*, Ap. J. 786 (2014) 124, (pink band) explaining that the AMS positron fraction (gray circles) above 10 GV is due to propagation effects.

However, this requires a specific energy dependence of the B/C ratio

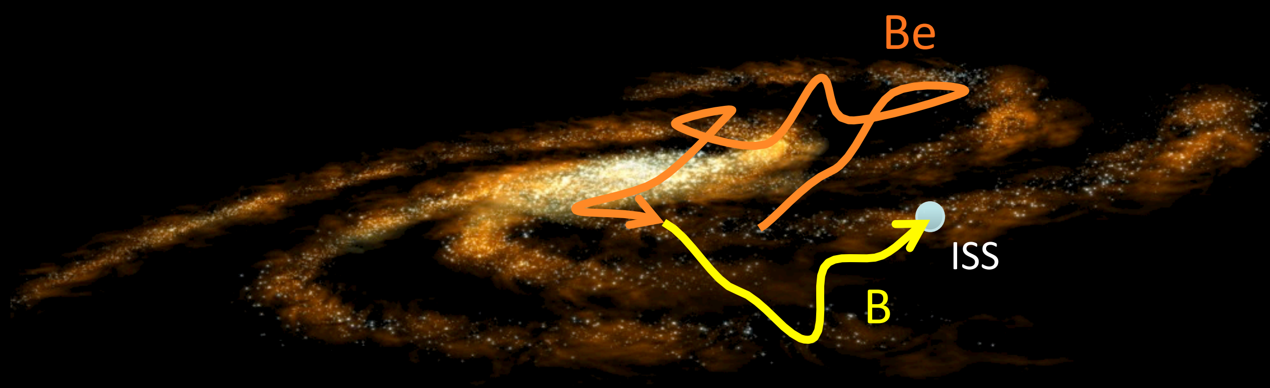


The AMS B/C flux ratio



Precision measurements of B/C put strong constraints on the CR models

Flux Ratios: Beryllium-to-Boron and age of cosmic rays

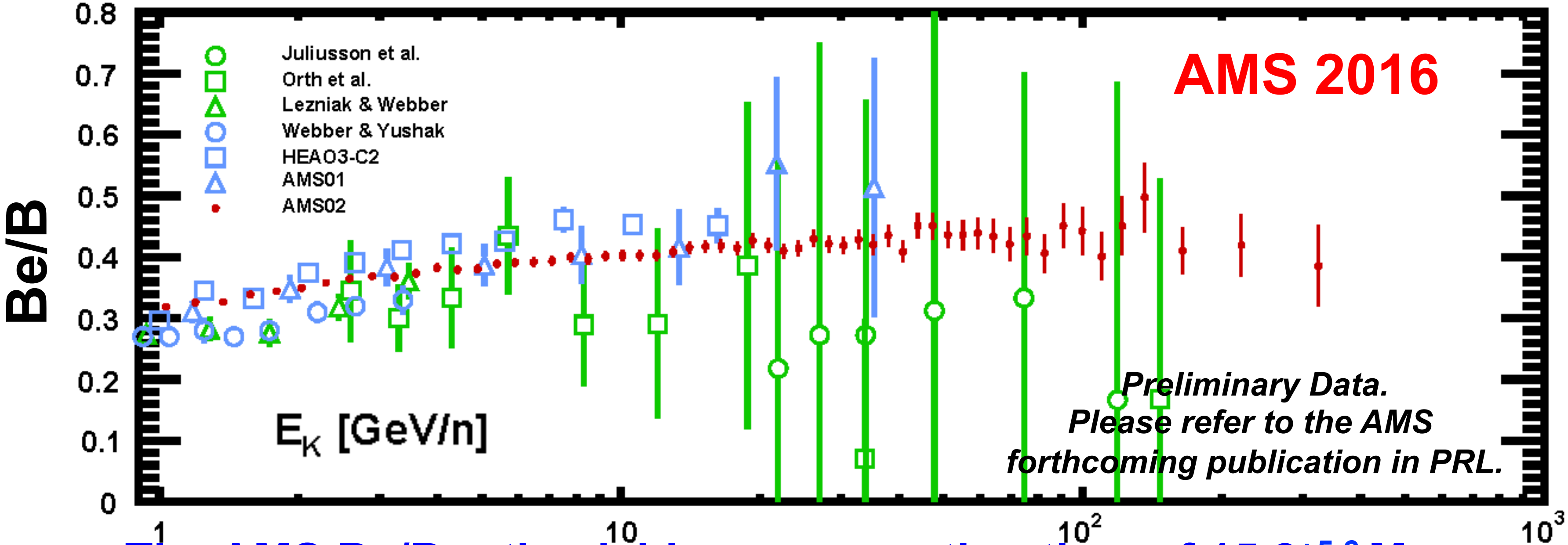


$$^{10}\mathrm{Be} \rightarrow {}^{10}\mathrm{B} + e^{-} + \bar{\nu}_e$$

The ^{10}Be half-life is 1.4×10^{6} years.

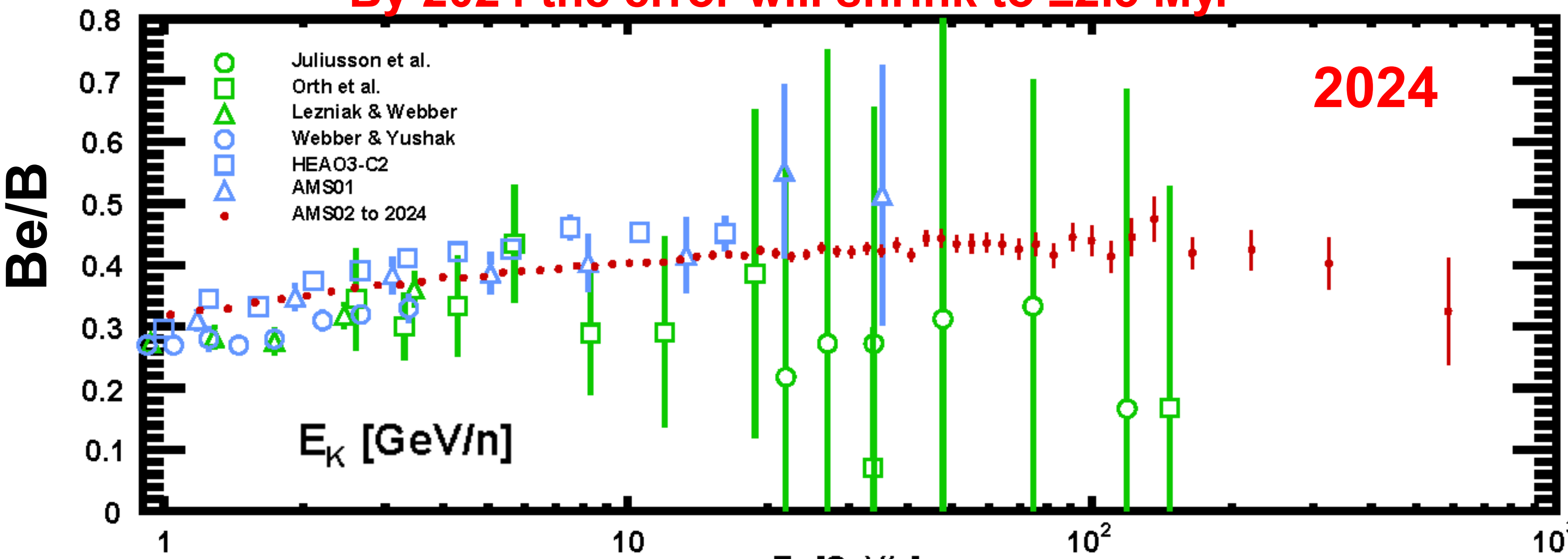
The Be/B ratio rises with energy due to relativistic time dilation. Be/B provides information on the age of cosmic rays in the Galaxy.

The AMS Result on the Beryllium-to-Boron flux ratio

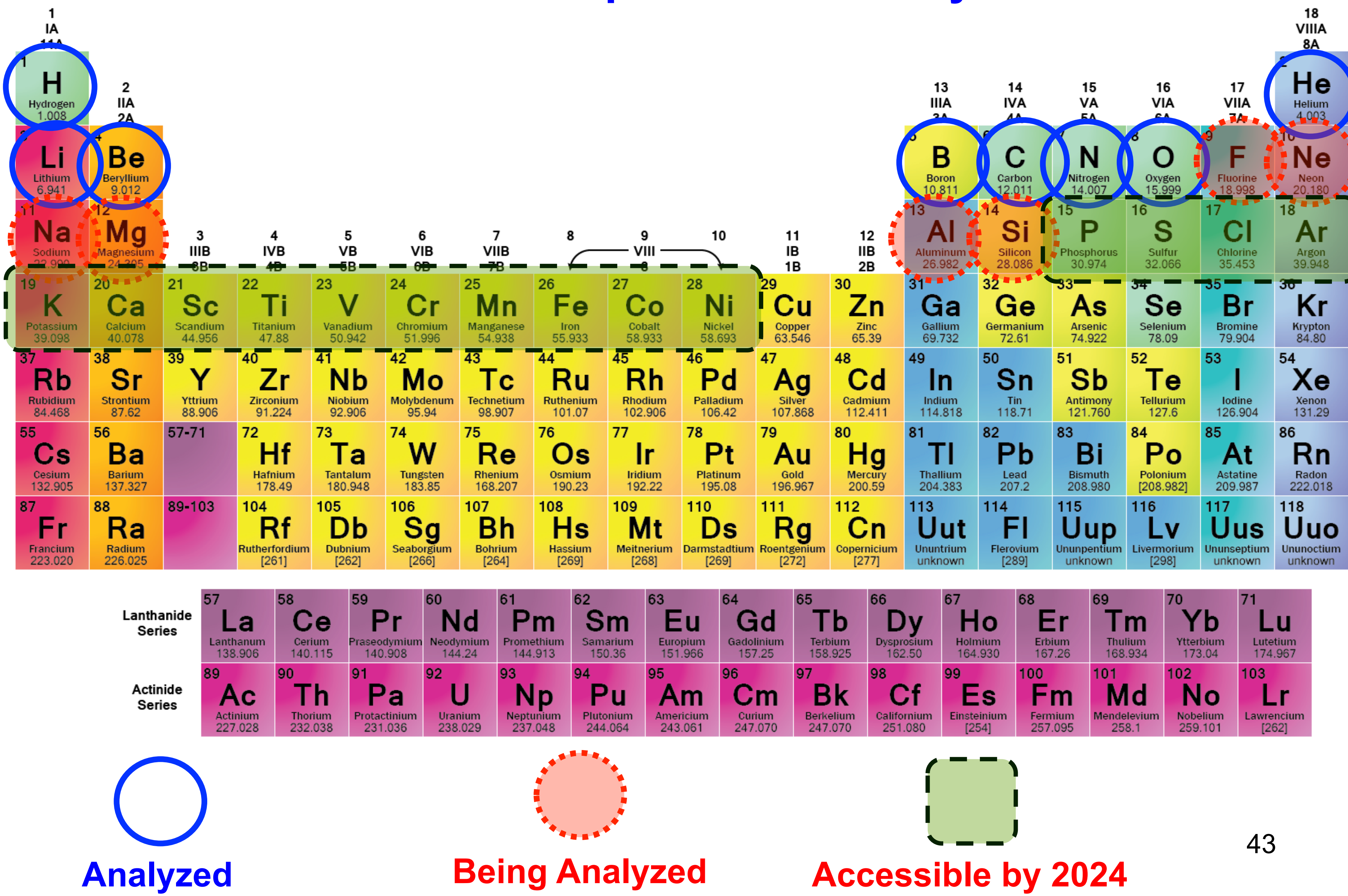


The AMS Be/B ratio yields a propagation time of $15.2^{+5.6}_{-4.5}$ My.

By 2024 the error will shrink to ±2.3 My.

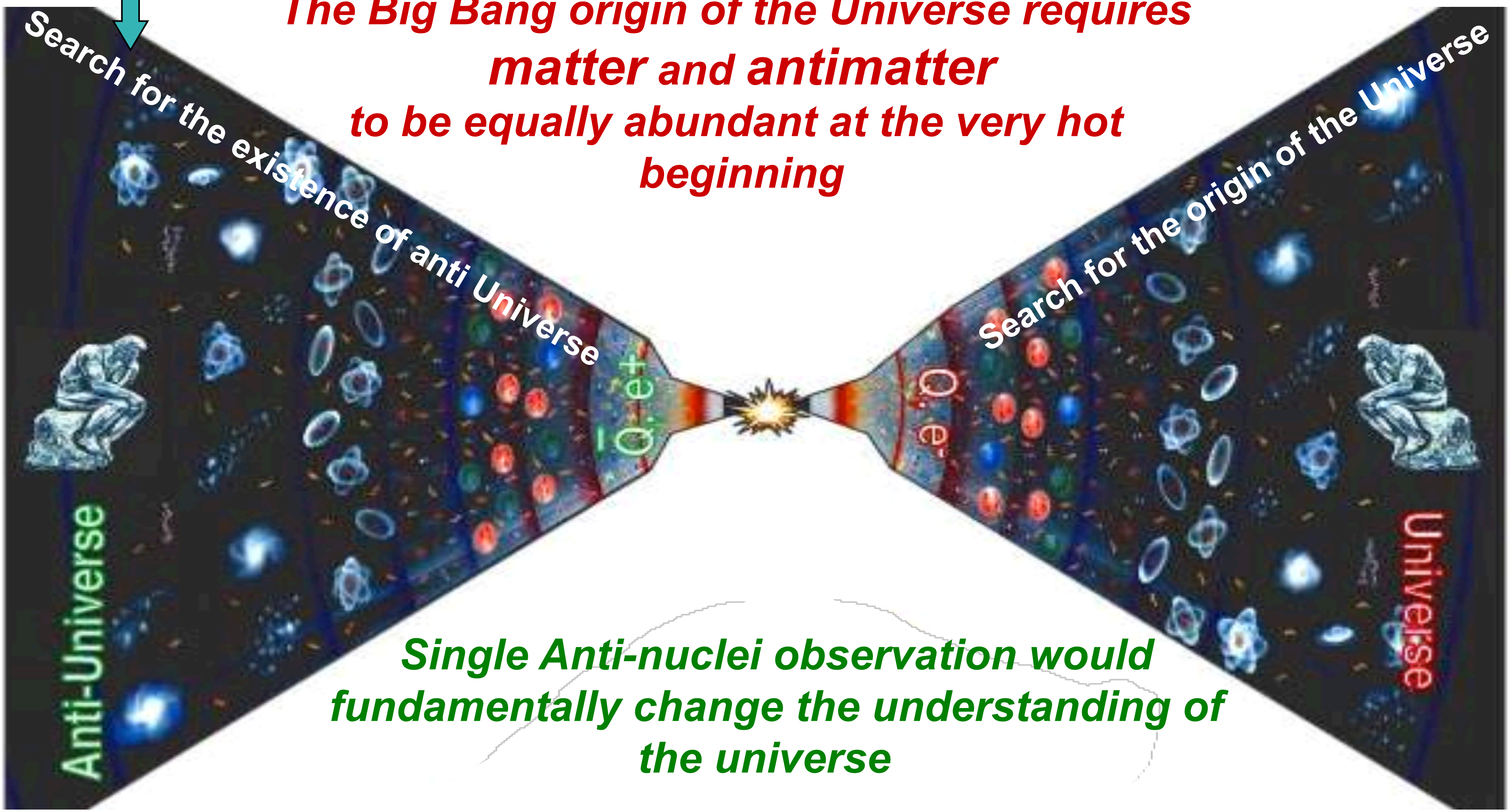


With increasing statistics through 2024, we will measure the elements up to iron and beyond.



Antimatter in Cosmic Rays

AMS in Space



The Big Bang origin of the Universe requires
matter and antimatter
to be equally abundant at the very hot beginning

Single Anti-nuclei observation would fundamentally change the understanding of the universe

?

AMS Anti-nuclei indepth search is on going!

Conclusions and Perspectives

1. The AMS measurements of the fluxes of electrons, positrons, protons, antiprotons, helium, and nuclei is providing new, precise, and unexpected information.

2. The accuracy and characteristics of the data, simultaneously from many different types of cosmic rays, will soon determine the true nature of the new phenomena we observe.

3. AMS physics for the lifetime of the Space Station

   Accurate measurement of Cosmic Rays including:

   a. Continue the study of Dark Matter
   b. Search the Existence of Antimatter
   c. Search for New Phenomena, …