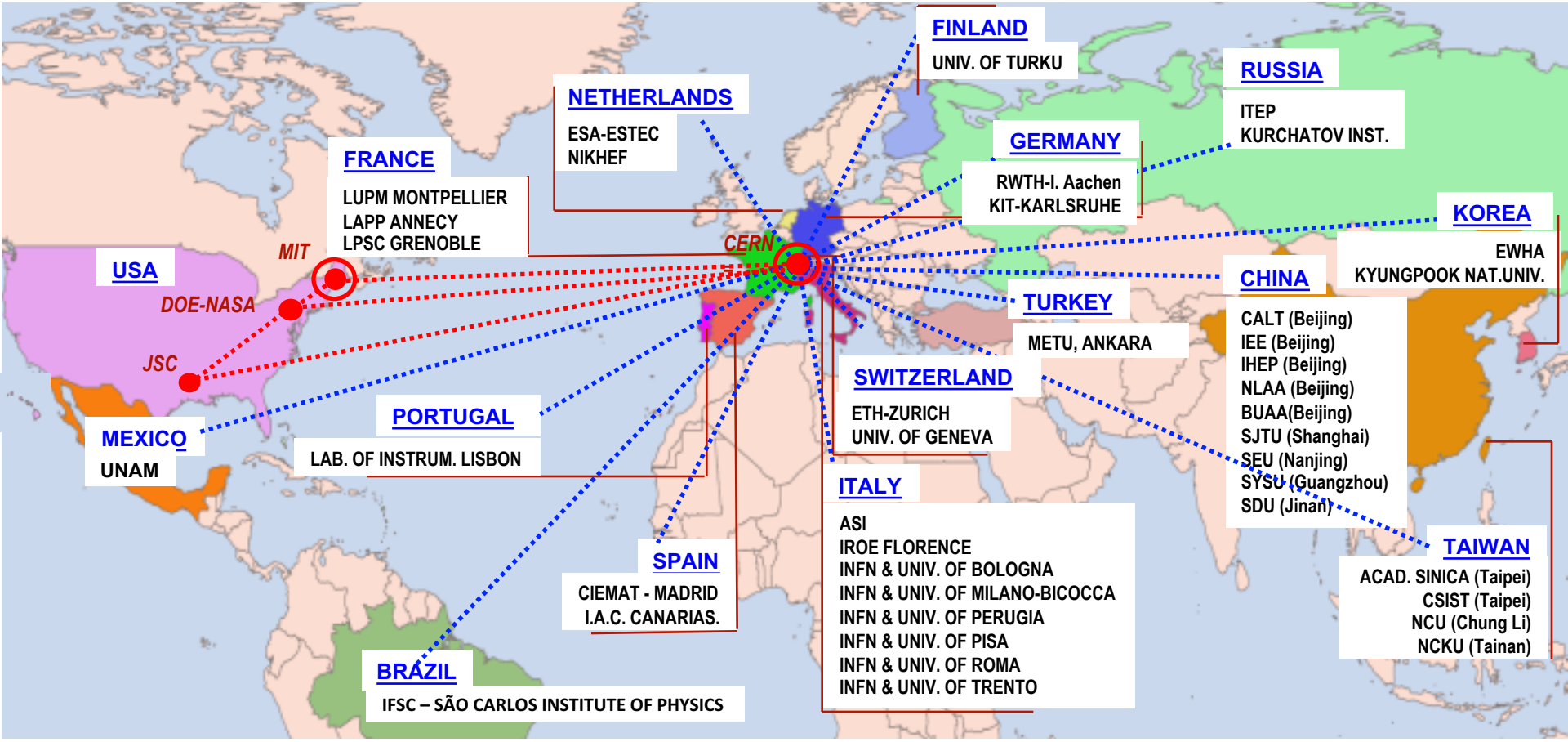
# The First Five Years of the Alpha Magnetic Spectrometer on the International Space Station:

# Unlocking the Secrets of the Cosmos

December 8, 2016

S. Ting

# AMS is an international collaboration based at CERN

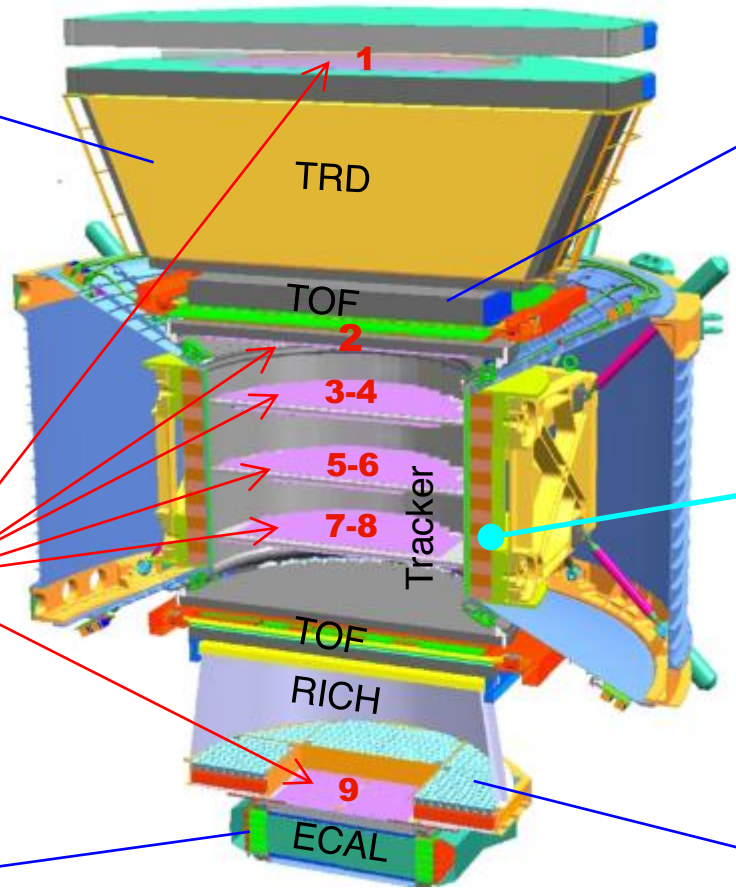



**We thank CERN, F. Gianotti, R. Heuer, R. Aymar, L. Maiani …; from the U.S., W. Gerstenmaier of NASA, J. Siegrist of DOE; from Italy, ASI and INFN; Germany, DLR, RWTH-Aachen, Julich, and KIT; France, CNES and CNRS/IN2P3; Spain, CDTI; Taiwan, Academia Sinica; China, CAST and CAS; Switzerland, SNSF and UniGe; Korea; and ESA; for their strong support.**

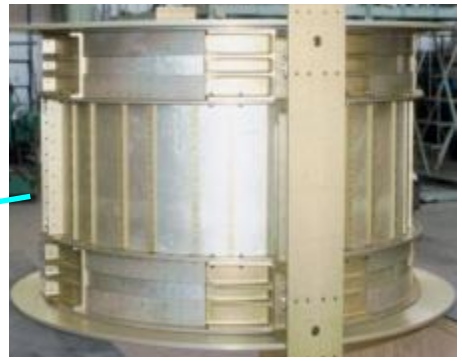
# AMS: A TeV precision, multipurpose, magnetic spectrometer

**Transition Radiation Detector (TRD)**
**Identify $e^+$, $e^-$**

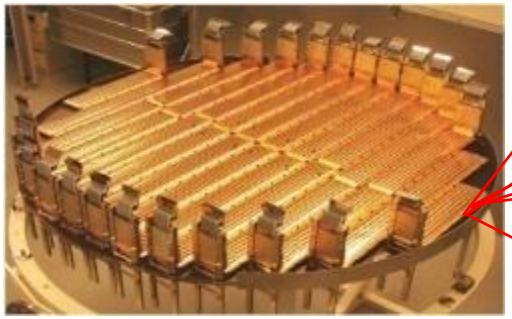
**Time of Flight (TOF)**
**Z, E**




**Magnet**
**±Z**



**Silicon Tracker**
**Z, P or R=P/Z**



**Ring Imaging Cherenkov (RICH)**
**Z, E**

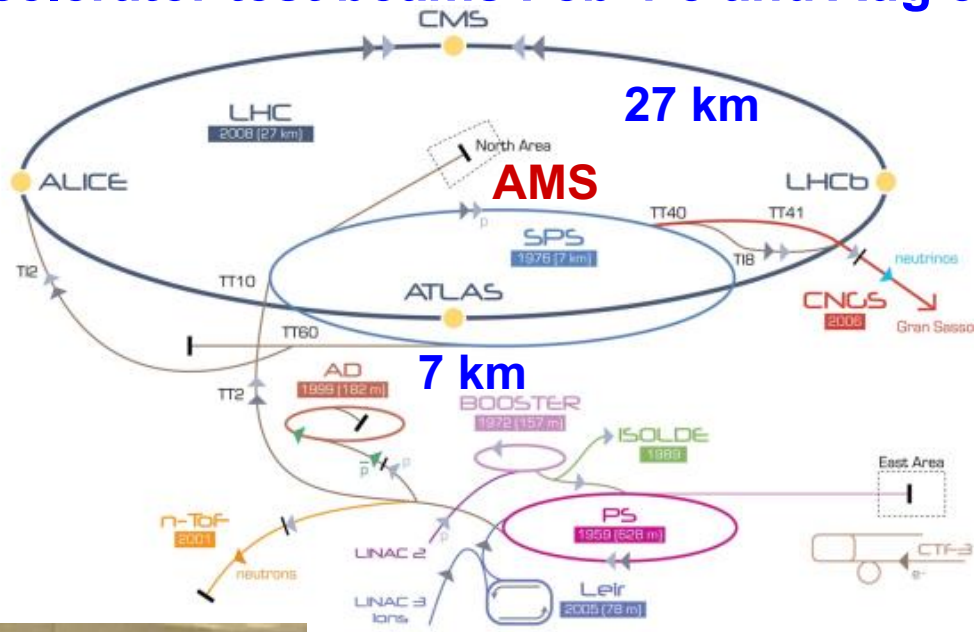
**Electromagnetic Calorimeter (ECAL)**
**E of $e^+$, $e^-$**

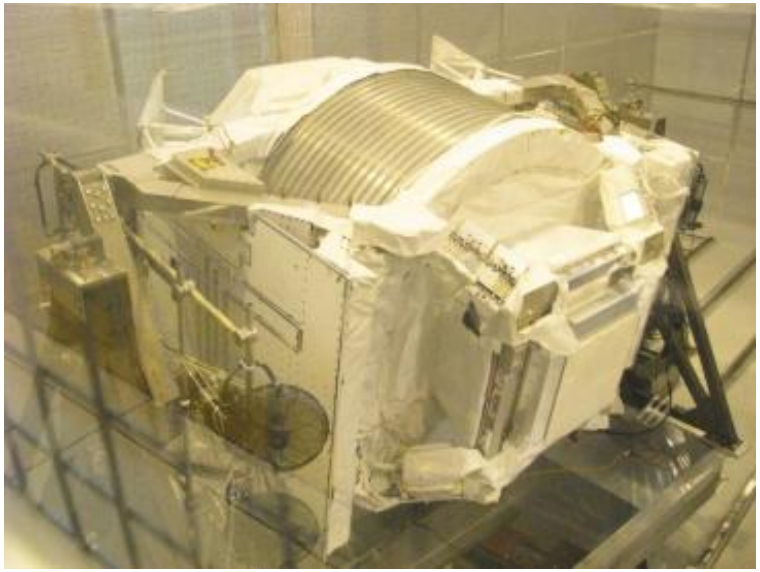
**Z and P, E or R are measured independently by Tracker, ECAL, TOF and RICH**

# In five years of operation on the ISS AMS has collected more than 90 billion charged cosmic rays.

# New Physics Results

# Support from CERN
# AMS in accelerator test beams Feb 4-8 and Aug 8-20, 2010

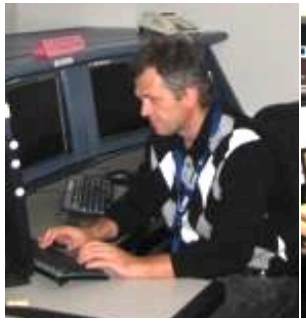


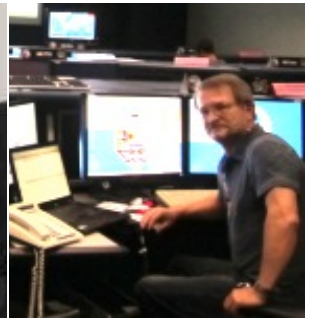



| Particle | Momentum (GeV/c) | Positions |
|---|---|---|
| Protons | 180, 400 | 1,650 |
| Electrons | 100, 120, 180, 290 | 7 each |
| Positrons | 10, 20, 60, 80, 120, 180 | 7 each |
| Pions | 20, 60, 80, 100, 120, 180 | 7 each |

**CERN IT has continuously provided strong support for AMS analysis**

# A few of the physicists active in AMS analysis


V. Choutko


A. Kounine


J. Berdugo


B. Bertucci

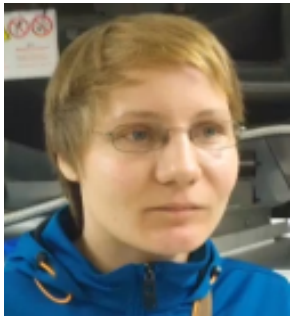

S. Schael


V. Bindi


M. Incagli


M. Duranti


H. Gast

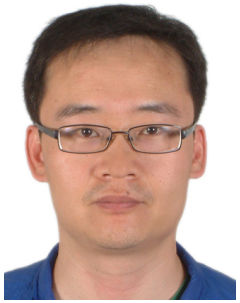

I. Gebauer


J. Casaus


L. Derome


C. Delgado

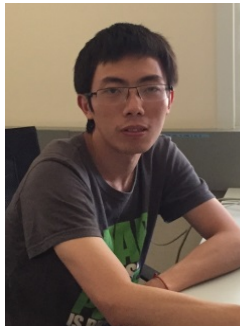

D. Grandi


Z. Li

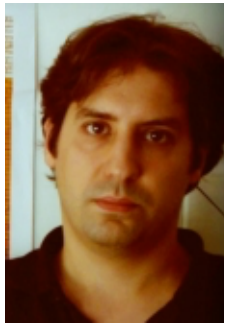

S. Haino, A. Oliva


W. Xu


P. Zuccon


Q. Yan


Z. Weng


N. Tomassetti

# Acknowledgements

**In five years we have benefited enormously from discussions with**

**K. Blum**

**I. Cholis**

**F. Donato**

**J. Ellis**

**J. Feng**

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**J. Kopp**

**I. Moskalenko**

**M. Salamon**

**S. Sarkar**

**G. Smoot**

**M. Turner**

**S. Weinberg**

**A. Wolfendale**

**Y. L. Wu**

# Elementary Particles in Space

**There are hundreds of different kinds of charged elementary particles.**

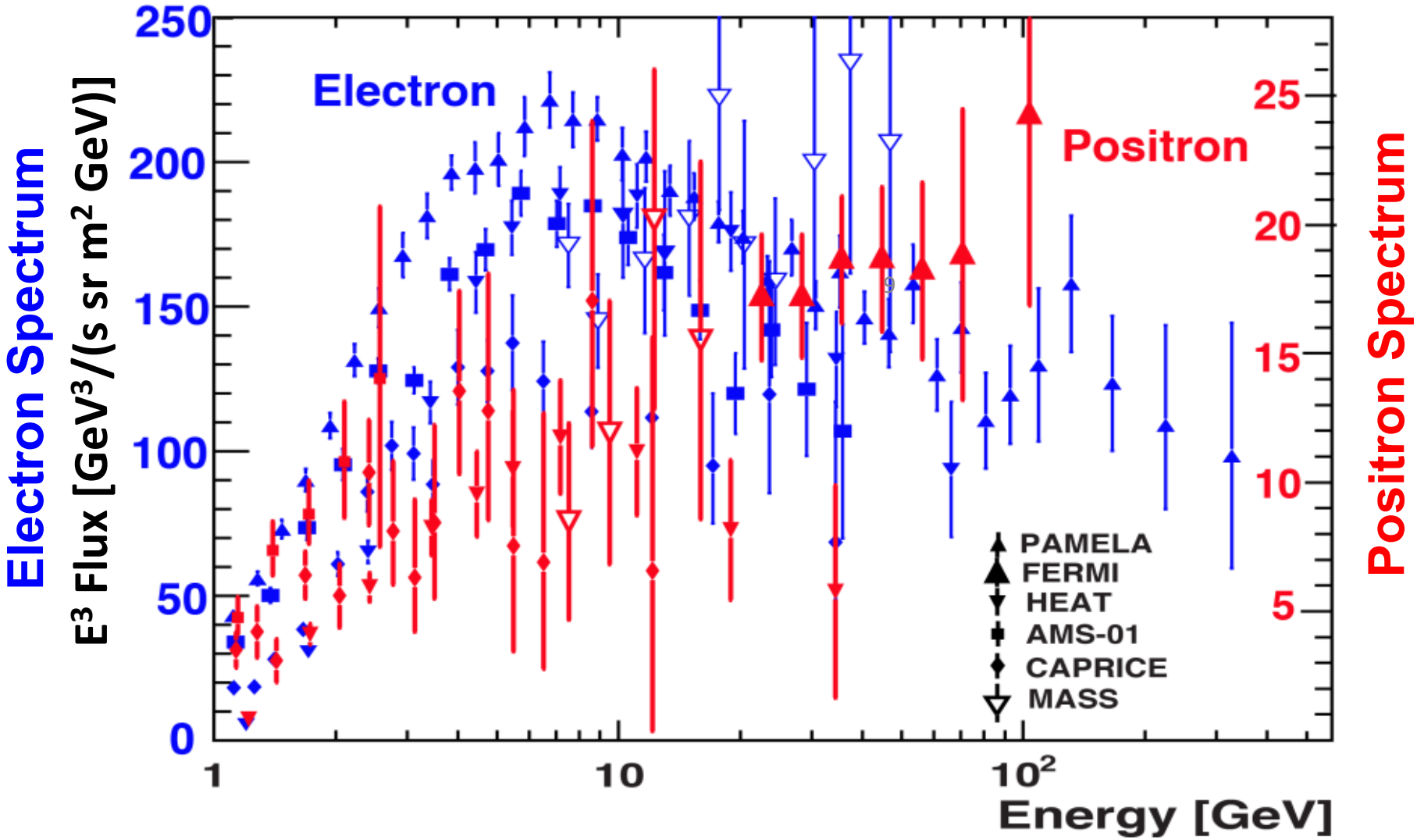
**Only four of them,**
**electrons, protons, positrons, and antiprotons,**
**have infinite lifetime,**
**so they travel in the cosmos forever.**

**Electrons and positrons have much smaller mass than protons and antiprotons, so they lose much more energy in the galactic magnetic field due to synchrotron radiation.**

⊙ **AMS**

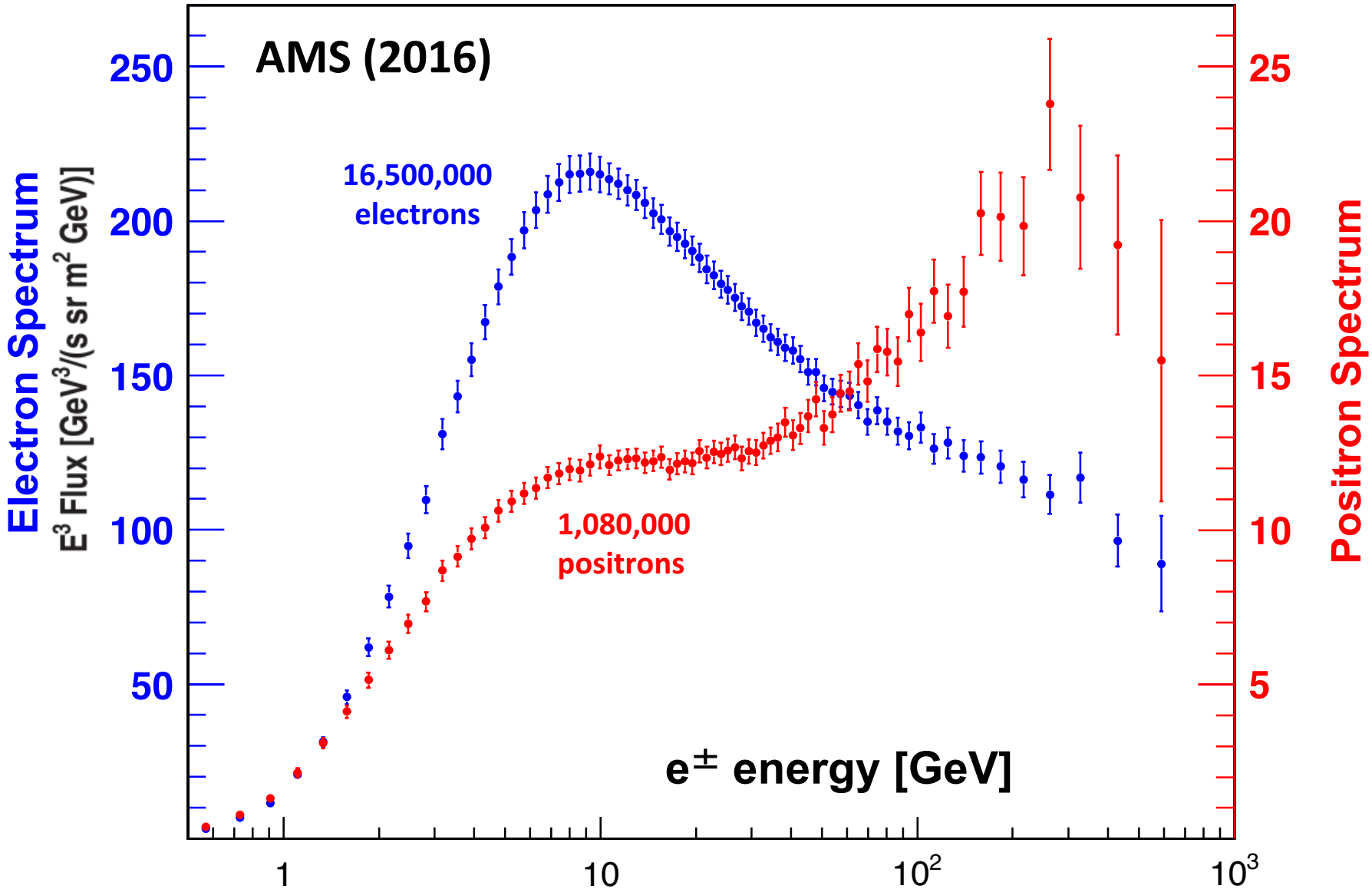
# Electron and Positron spectra before AMS

1. These were the best data.
2. Nonetheless, the data have large errors and are inconsistent.
3. The data has created many theoretical speculations.



# **Physics Result 1:** The Electron and Positron fluxes

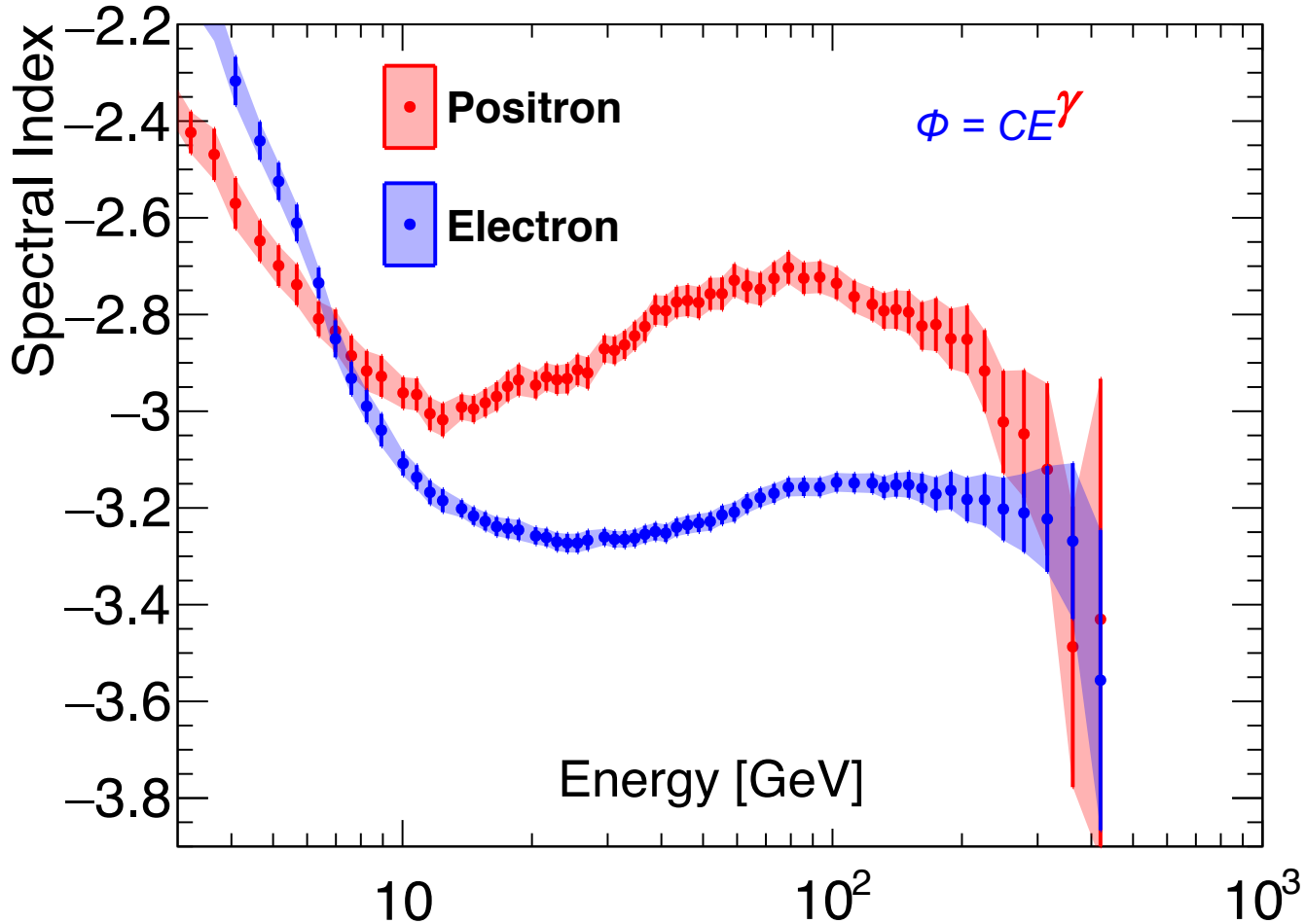
## The electron flux and the positron flux are different in their magnitude and energy dependence



# **Physics Result 1:** The Electron and Positron spectral indices

Traditionally, the spectrum of cosmic rays is characterized by a single power law function $\Phi = CE^{\gamma}$ where $\gamma$ is the spectral index and $E$ is the energy.

Before AMS, $\gamma$ was assumed to be **constant** for the electron and positron spectra.



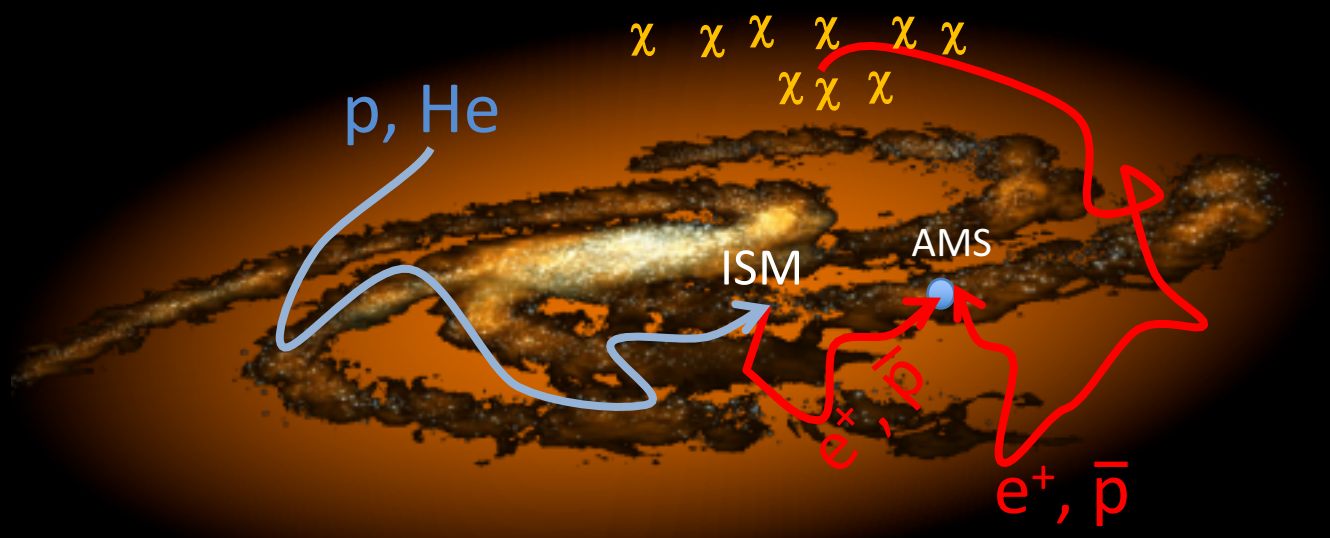

**The electron and positron spectral indices are not constant.**

**They are different in their magnitude and energy dependence**

# Dark Matter: $\chi$

**Collision of Cosmic Rays with the Interstellar Media will produce $e^+$, $\bar{p}$…**

p, He + ISM → $e^+$, $\bar{p}$ + …




**Dark Matter ($\chi$) annihilations** $\chi + \chi \rightarrow e^+, \bar{p} + \ldots$

**The excess of $e^+$, $\bar{p}$ from Dark Matter ($\chi$) annihilations can be measured by AMS**

**M. Turner and F. Wilczek, Phys. Rev. D42 (1990) 1001; J. Ellis 26th ICRC (1999)**

# Three independent methods to search for Dark Matter

**Annihilation**

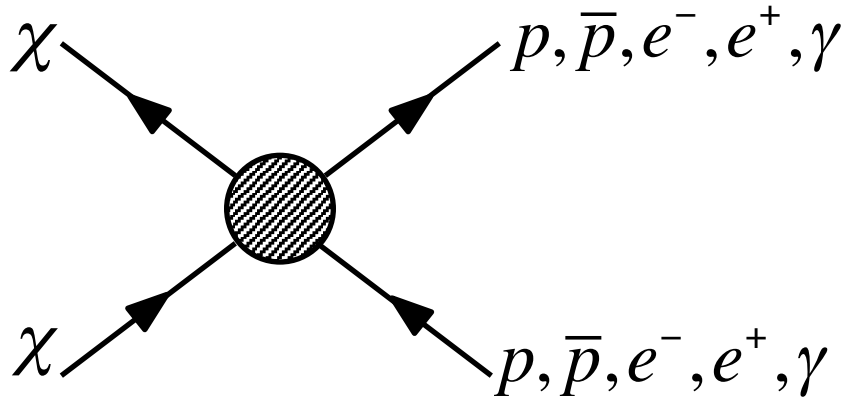
AMS

$\chi + \chi \rightarrow e^+, \bar{p}, \gamma, \ldots$

**Scattering**

LUX
DARKSIDE
XENON 100
CDMS II
…

$\chi + N \rightarrow \chi + N$




$\ldots + \chi + \chi \leftarrow p + p$

LHC

**Production**

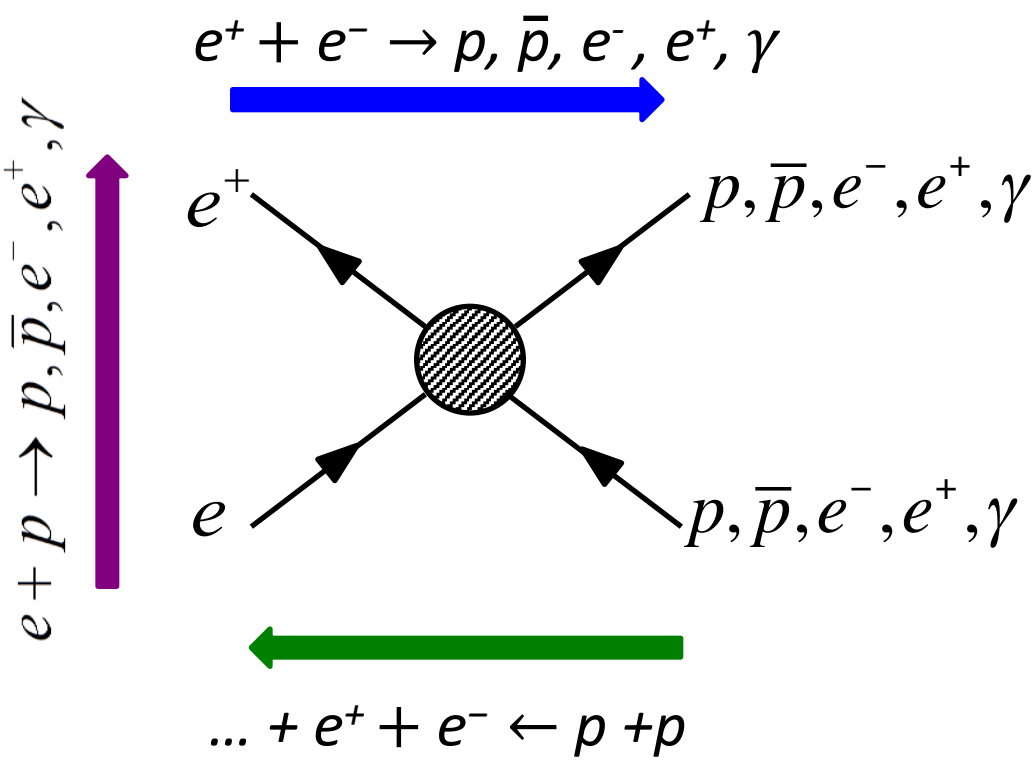
# Physics of electrons and protons

**Annihilation**

SPEAR, DORIS, PEP, PETRA, LEP, … *Ψ, τ*

**Scattering**

SLAC … *partons, electroweak*




BNL, FNAL, LHC …*J, Y, t, Z, W, $h^0$*

**Production**

# 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)

**From Astrophysical Sources**

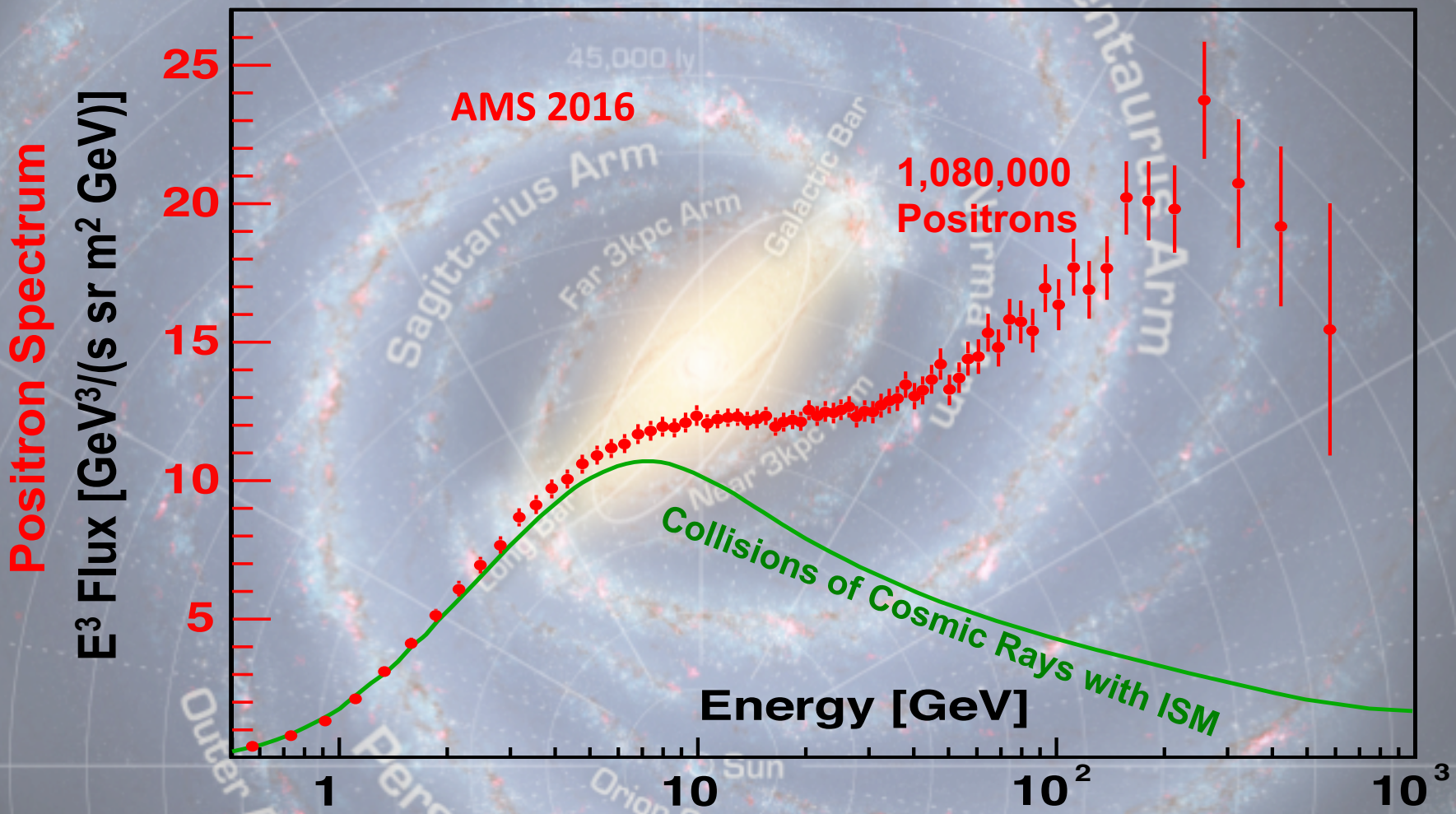
1) T. Linden and S. Profumo, Astrophys.J. 772 (2013) 18
2) P. Mertsch and S. Sarkar, Phys.Rev. D 90 (2014) 061301
3) I. Cholis and D. Hooper, Phys.Rev. D88 (2013) 023013
4) A. Erlykin and A.W. Wolfendale, Astropart.Phys. 49 (2013) 23
5) P.F. Yin, Z.H. Yu, Q. Yuan and X.J. Bi, Phys.Rev. D88 (2013) 2, 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)

**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)

# Positrons in the Galaxy

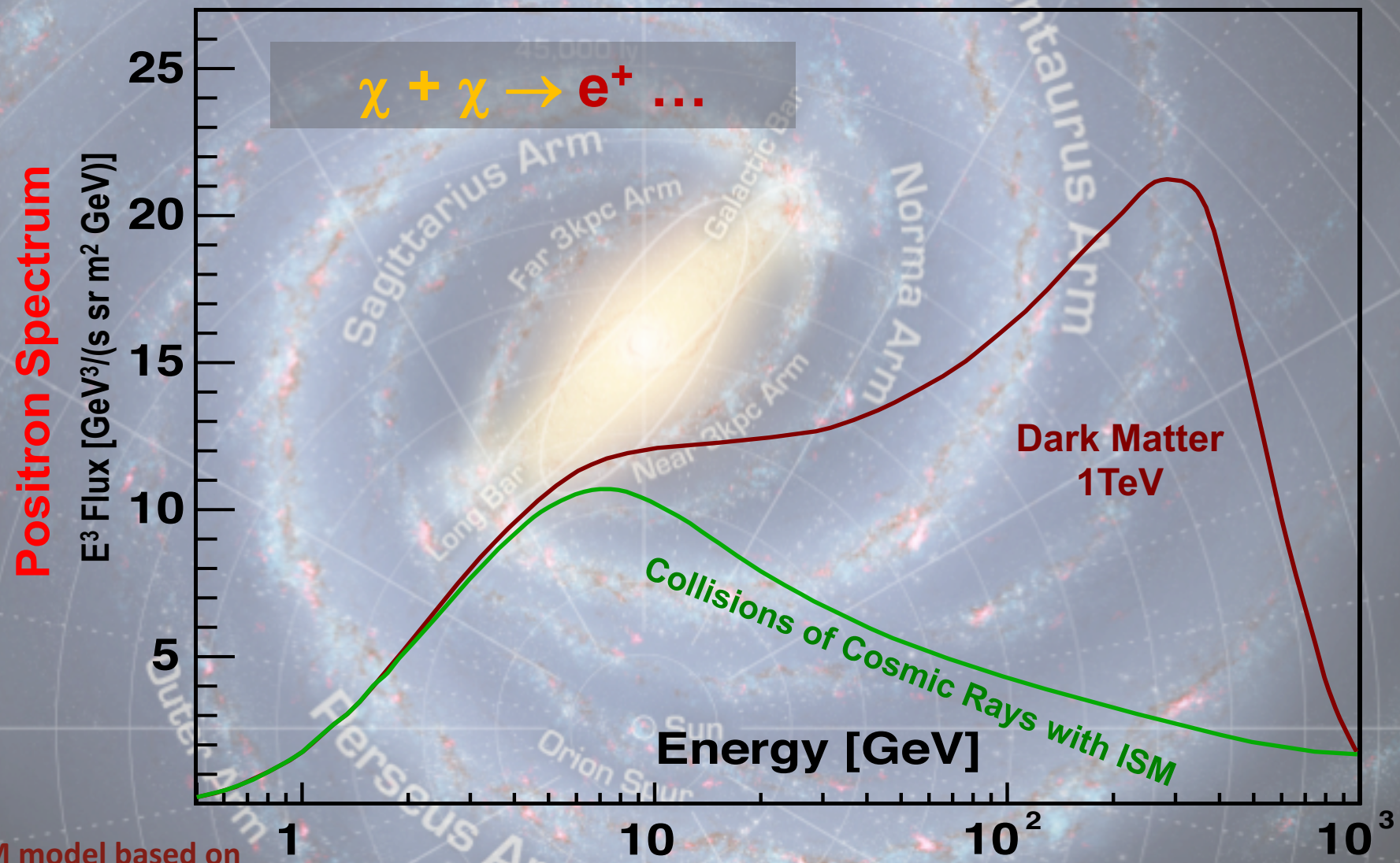
**Collision of Cosmic Rays with the Interstellar Media produce $e^+$**
**… and this is indeed true at low energies.**




**Unexpectedly, starting from ~8GeV, the AMS $e^+$ data show an excess above ordinary Cosmic Ray collisions.**

# Dark Matter

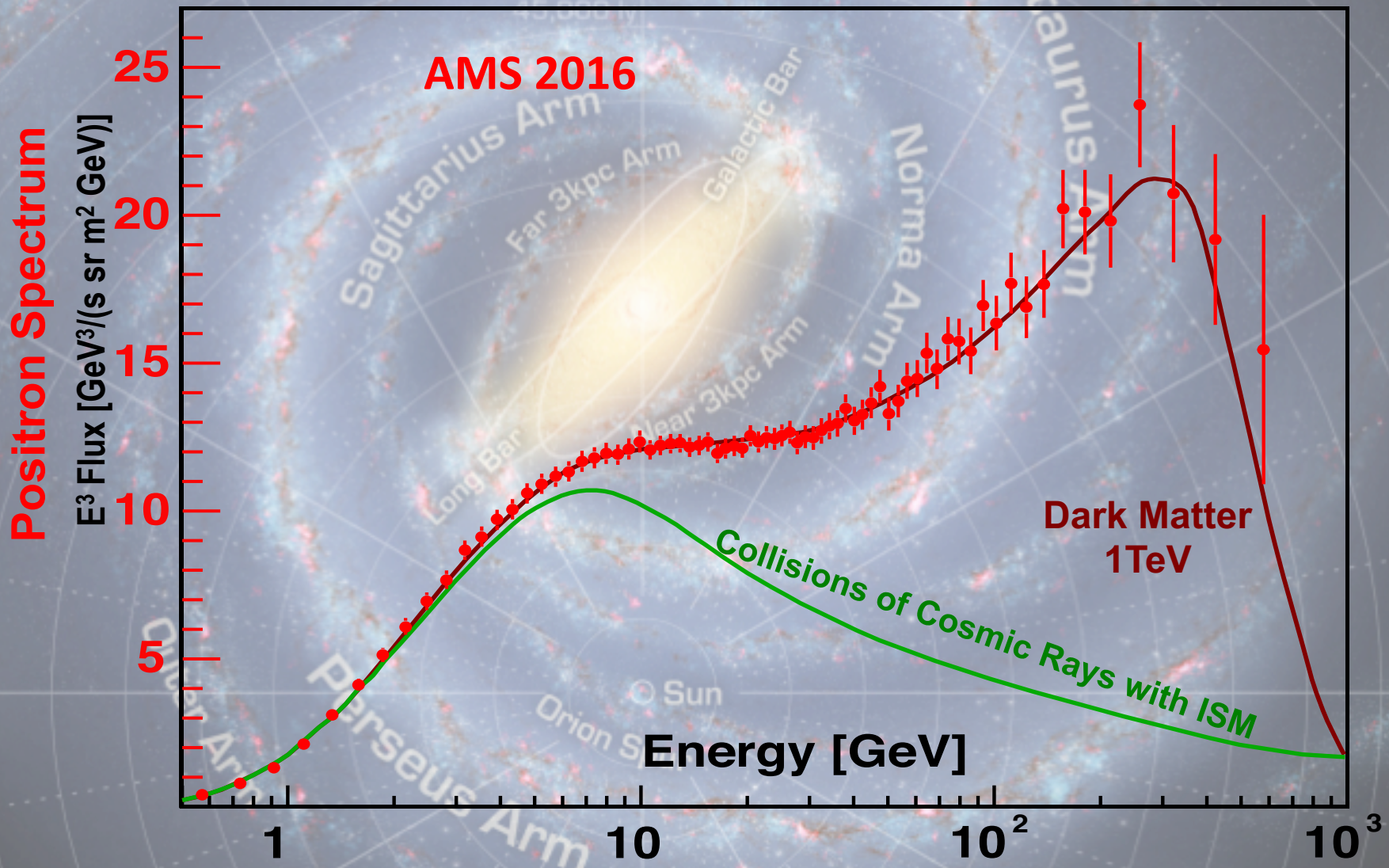
**Annihilation of Dark Matter produces additional $e^+$ which are characterized by a sharp drop off at the mass of dark matter.**




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

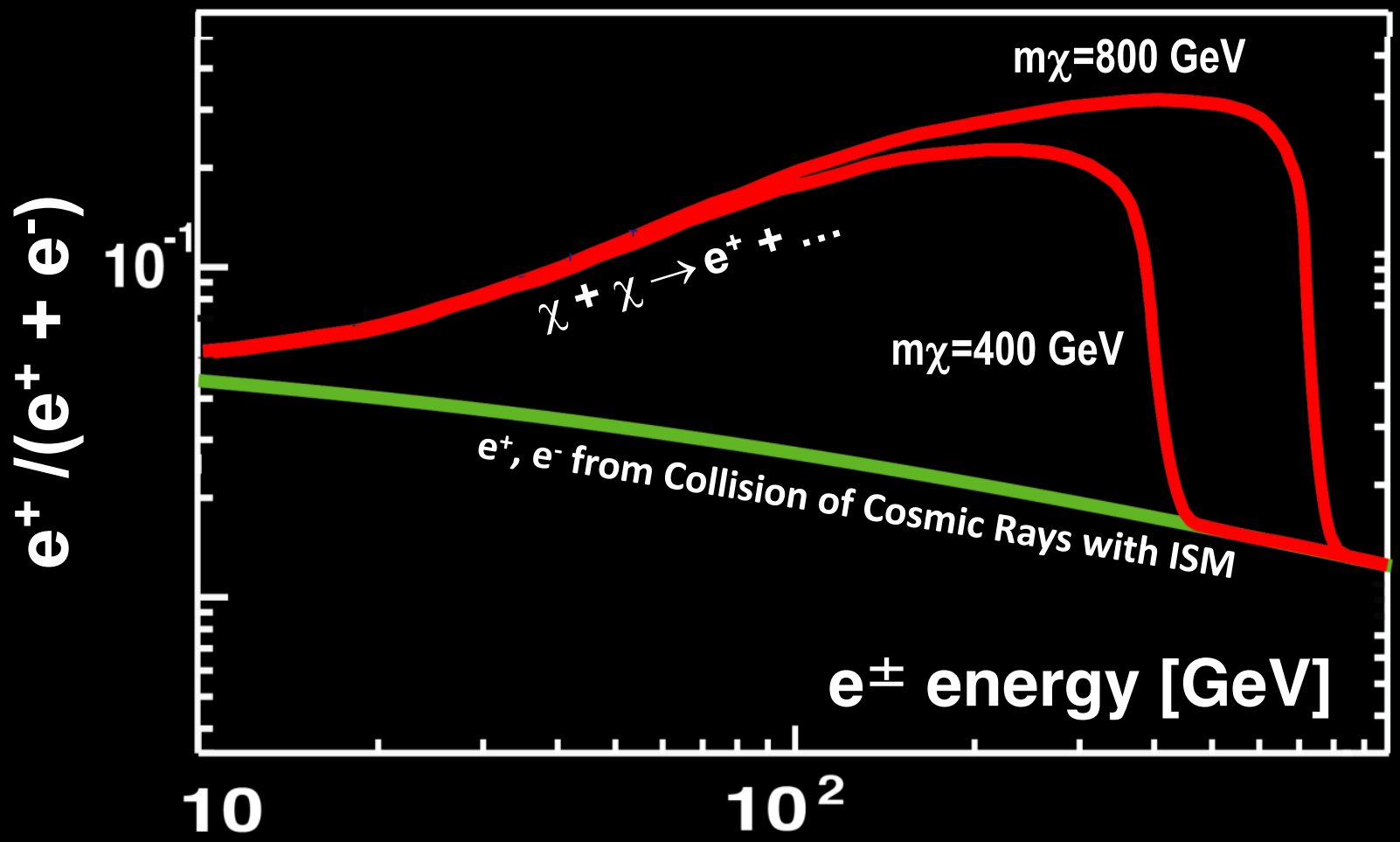
# **Physics Result 2:** The origin of the AMS positron spectrum

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



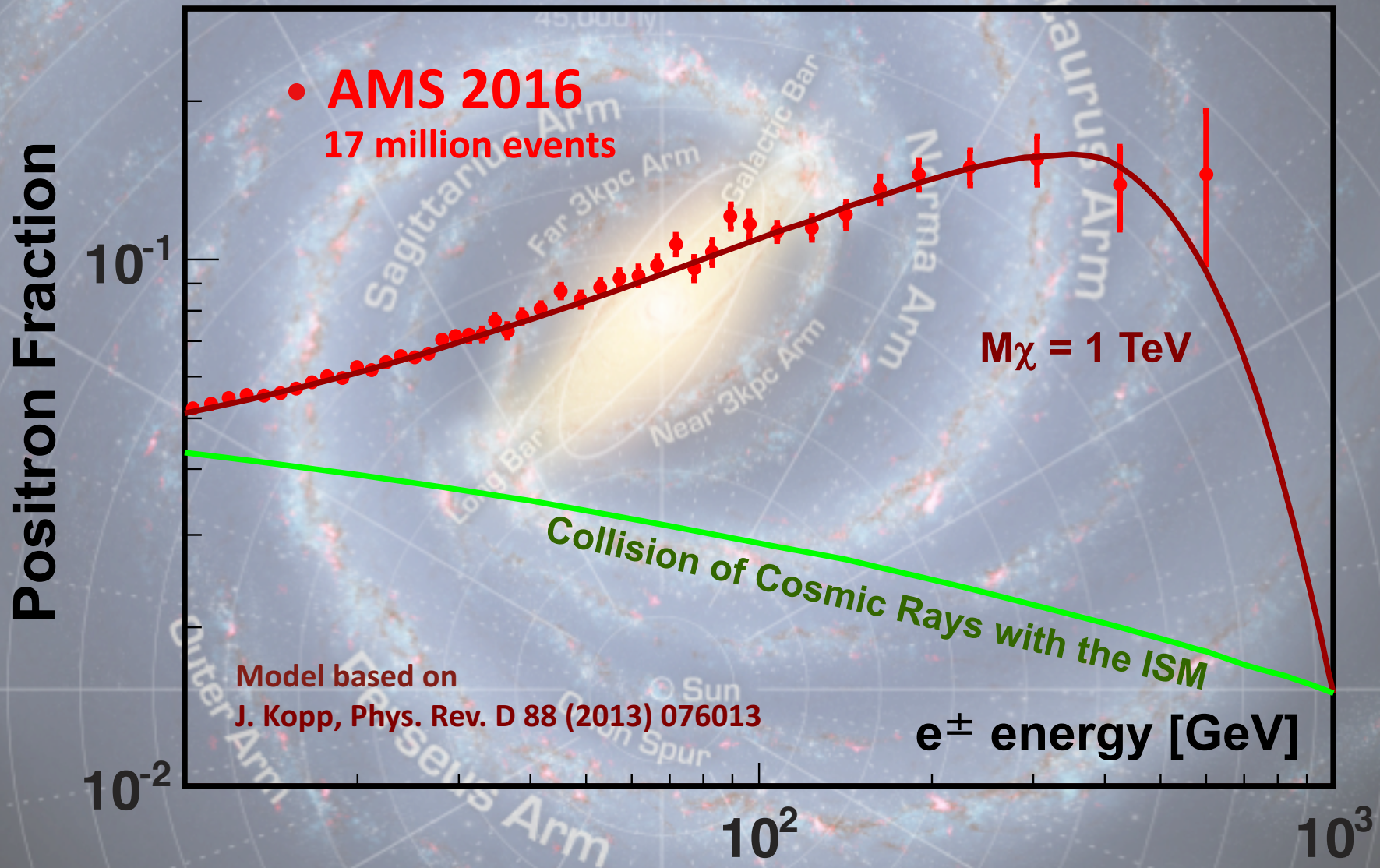
**The excess of positrons can also be measured by the positron fraction: $e^+/(e^+ + e^-)$.**

**This is an alternative way to search for the signature of Dark Matter but the positron fraction and positron spectrum have different errors.**




Dark Matter model based on I. Cholis et al., JCAP 12 (2009) 007.

# Comparison of the positron fraction measurement with a Dark Matter model



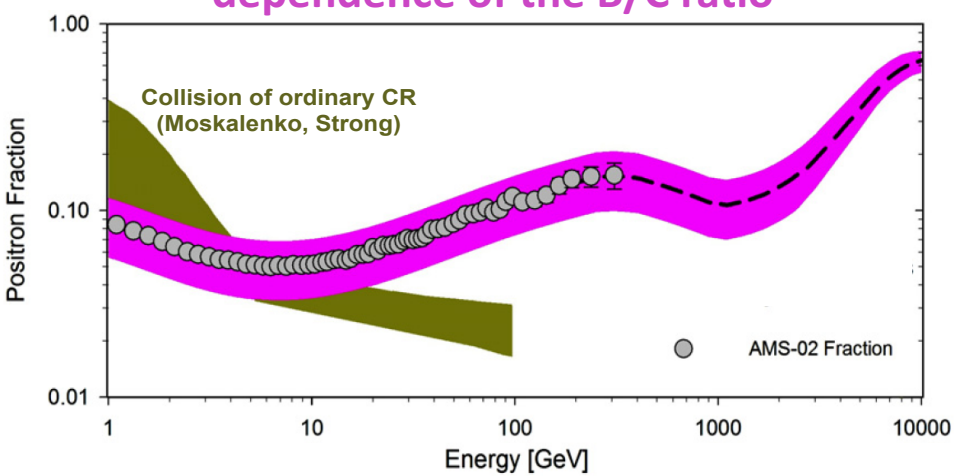
# Alternative Models to explain the AMS Positron Flux and Positron Fraction Measurements

- Modified Propagation of Cosmic Rays
- Supernova Remnants
- Pulsars

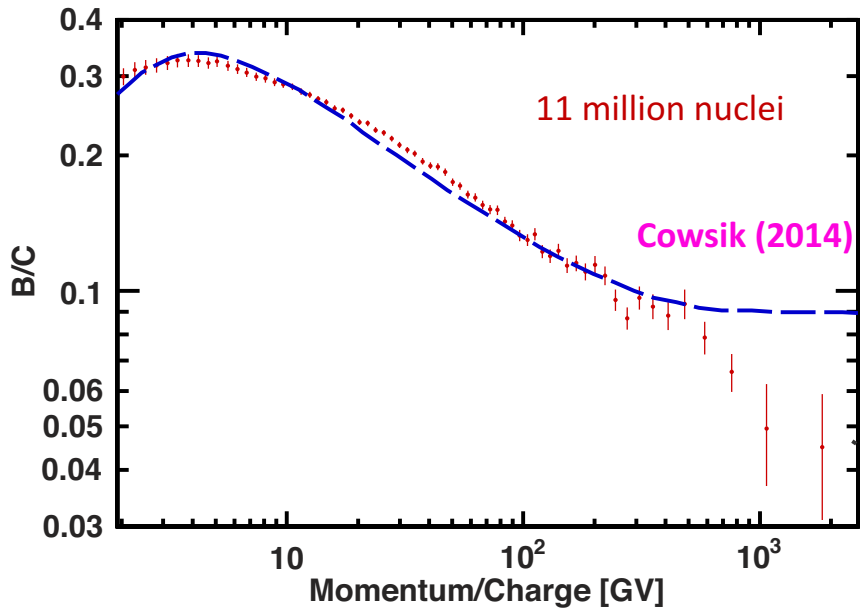
## Examples:

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

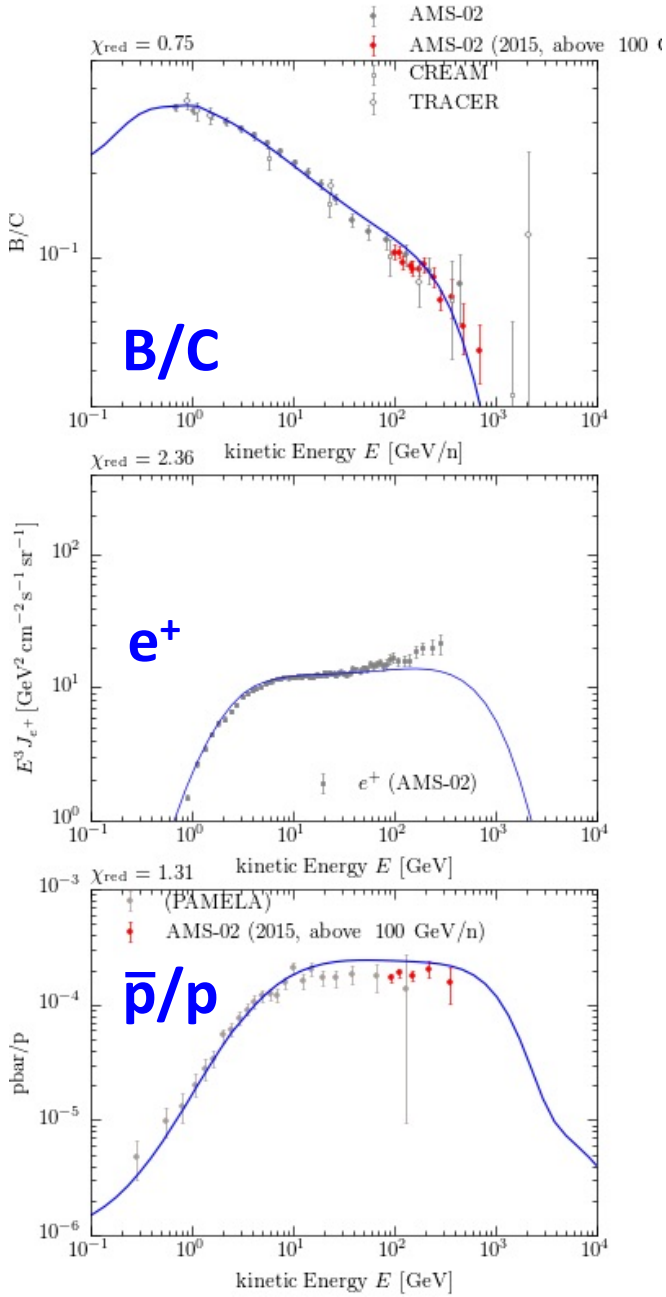



The AMS Boron-to-Carbon (B/C) flux ratio



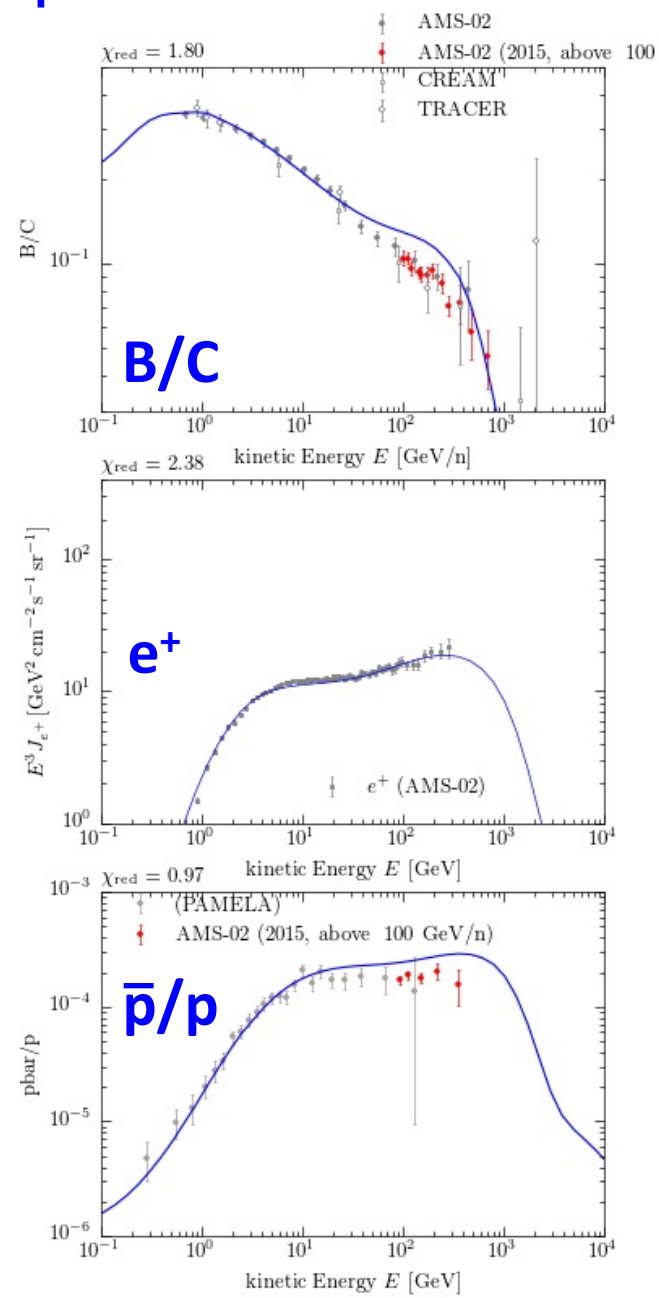
# Example: Supernova Remnants

## Subir Sarkar: AMS Days@CERN, April 2015




We have been trying (late last night!) to get better fits to the new data but it is not easy … perhaps our model is *too* simple and some further refinements are necessary.

This is justified now that we have *precision* data from AMS!

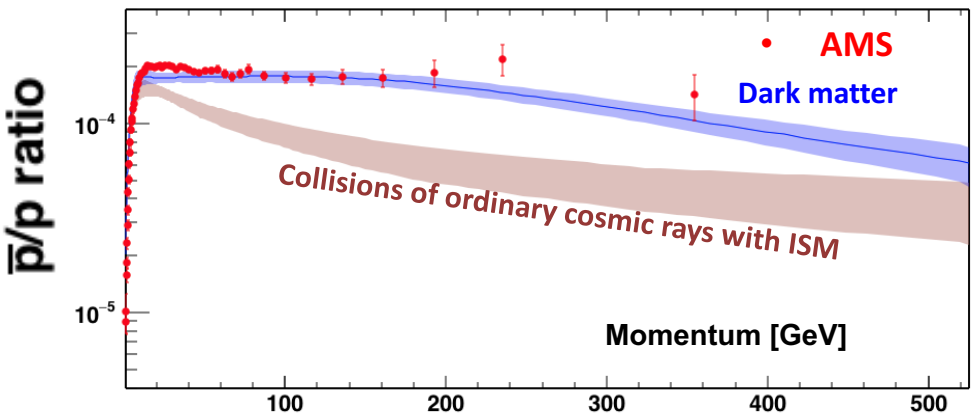


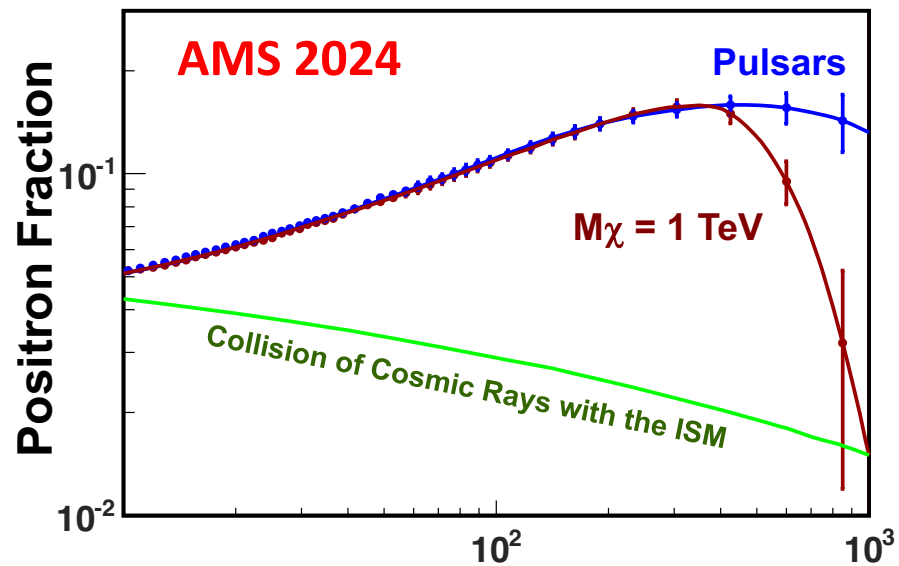
# Alternative Models to explain the AMS Positron Flux and Positron Fraction Measurements

- Modified Propagation of Cosmic Rays
- Supernova Remnants
- Pulsars

## Examples:

### The AMS Antiproton-to-Proton ratio



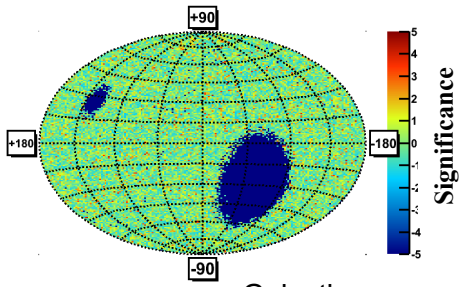




**The excess of antiprotons observed by AMS cannot come from pulsars.**

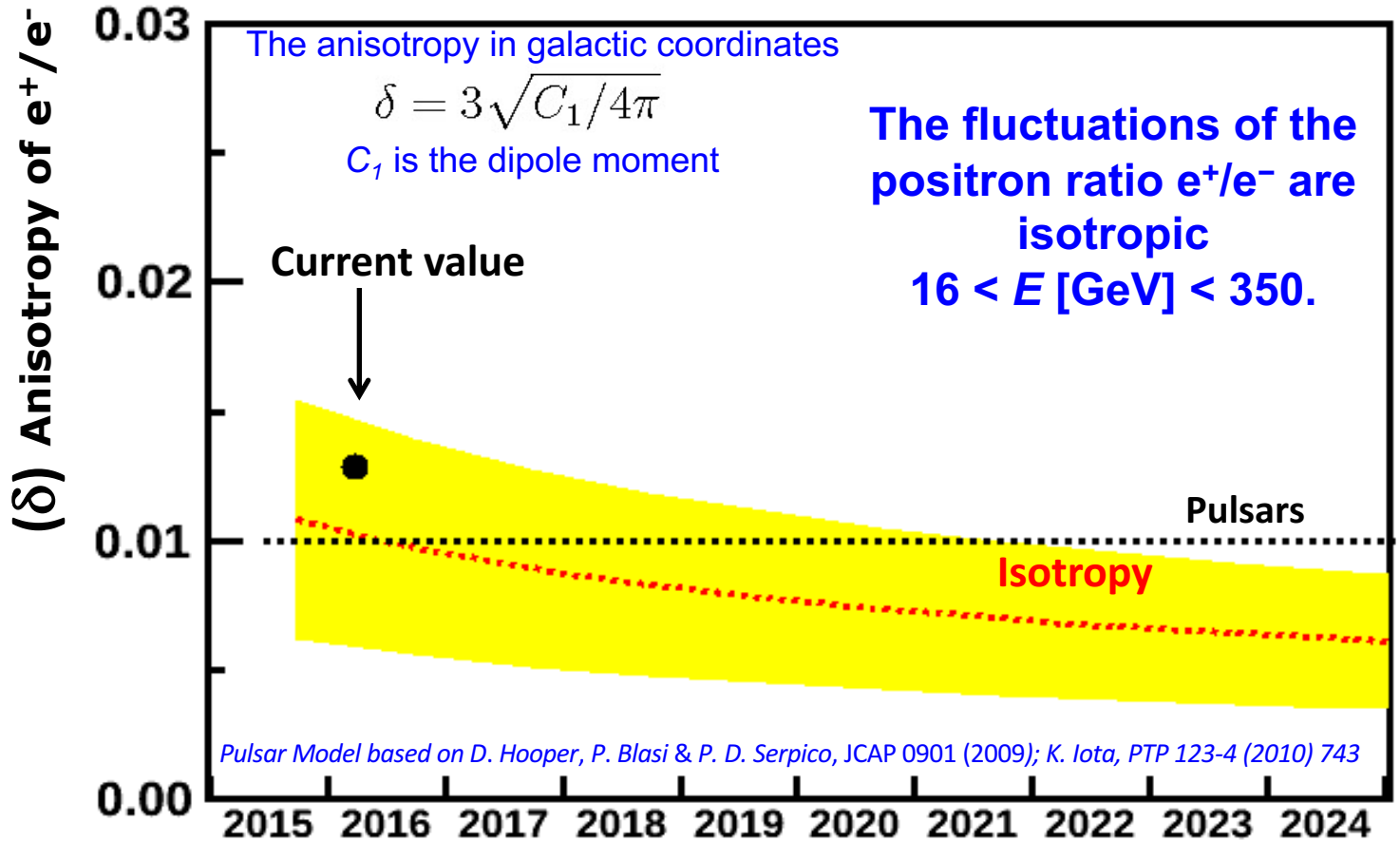
**By 2024, AMS will distinguish Dark Matter from Pulsars**

# **Physics Result 4:** Measurement of anisotropy

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

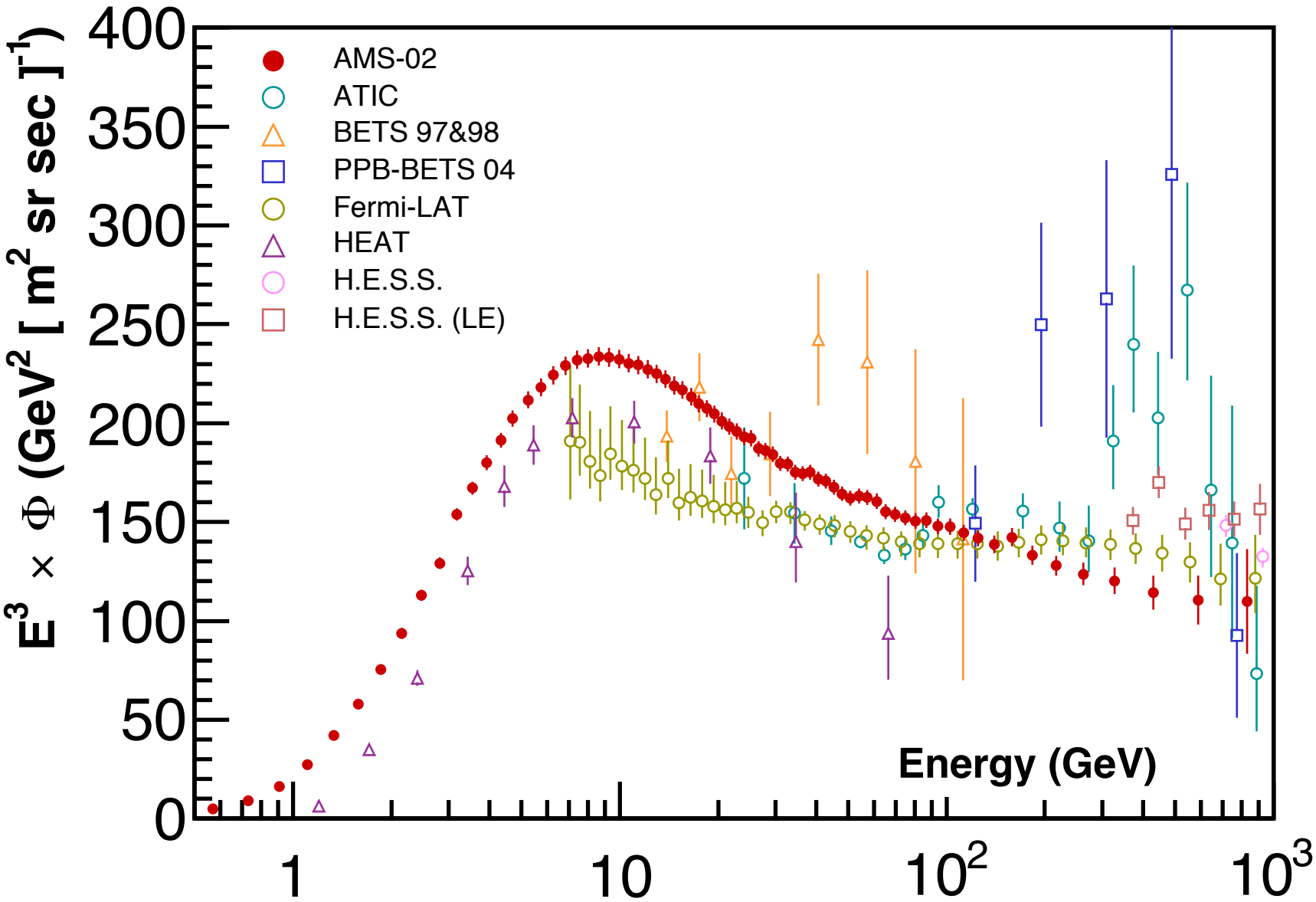



Galactic coordinates (b,l)



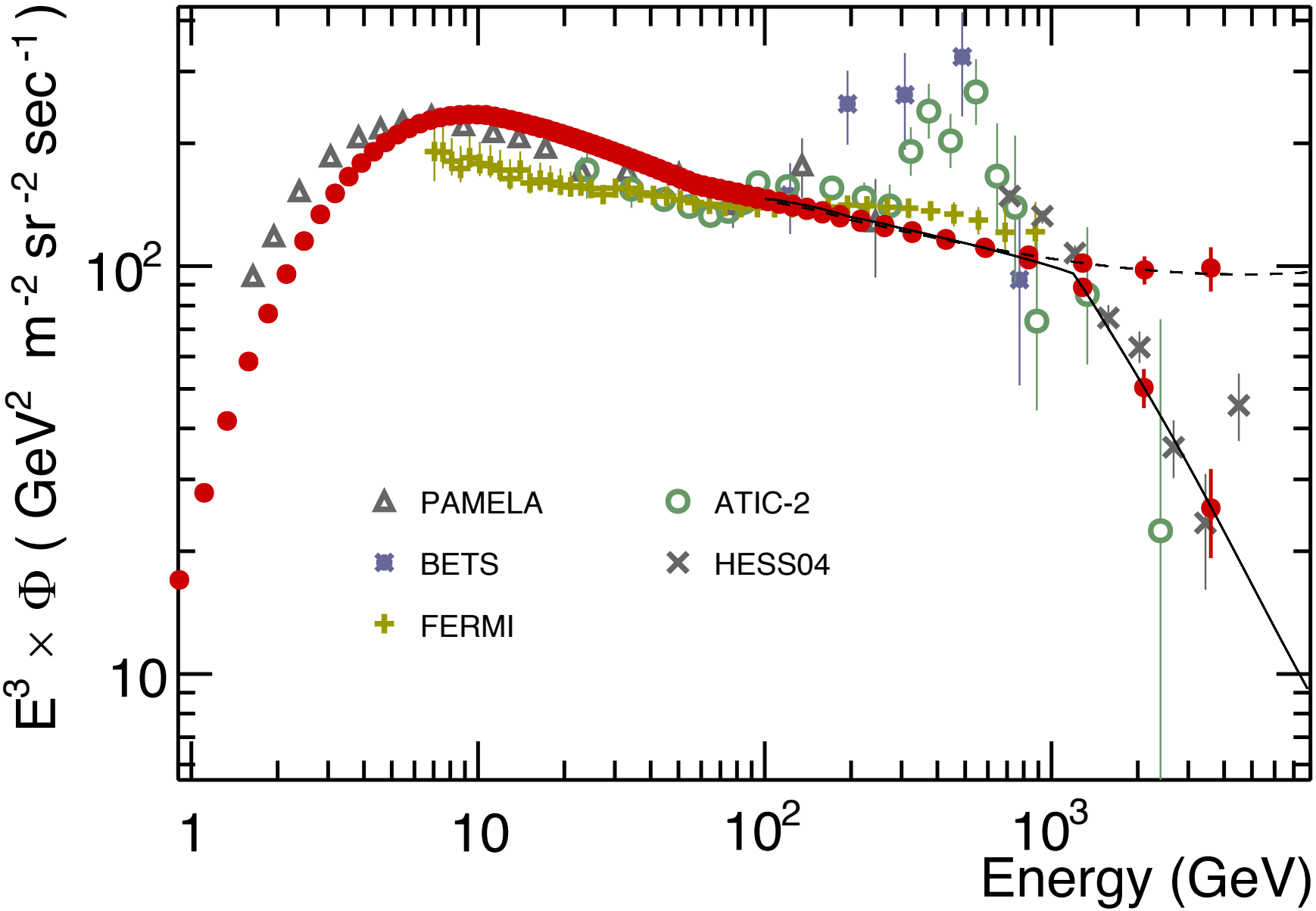

**Data taking to 2024 will allow to explore anisotropies of 1%**

# **Physics Result 5:** The ($e^+ + e^-$) flux




**The precision AMS measurement of the ($e^+ + e^-$) flux contradicts all previous measurements and previous speculations**

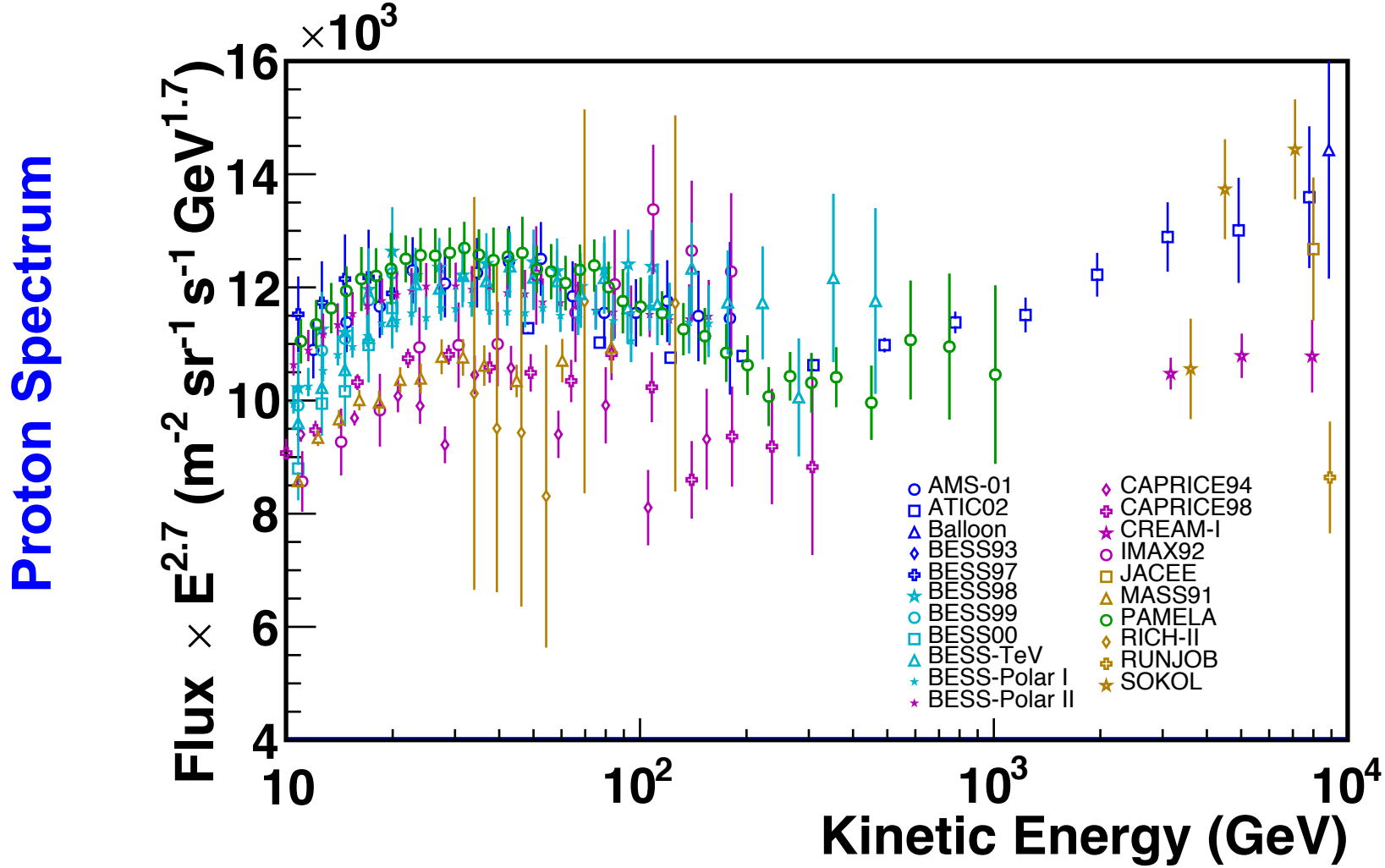
# The AMS ($e^+ + e^-$) flux in 2024



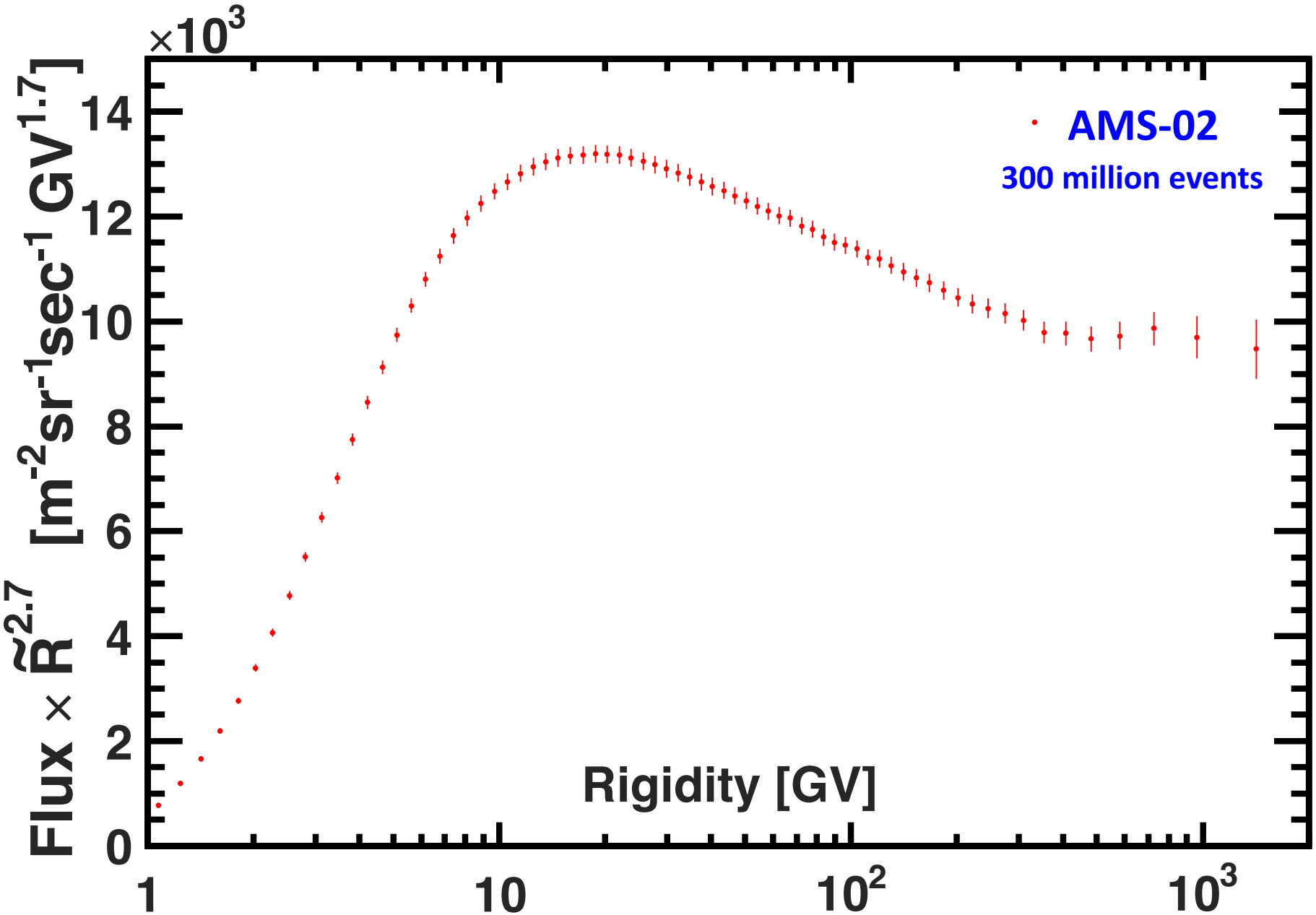

**AMS will be able to distinguish the ($e^+ + e^-$) flux behavior above 1 TeV**

# Cosmic Protons

1. **Protons are the most abundant cosmic rays.**
2. **Before AMS there have been many measurements of the proton spectrum.**
3. **In cosmic rays models, the proton spectral function was assumed to be a single power law $\Phi = CE^{\gamma}$ with $\gamma$ = -2.7**



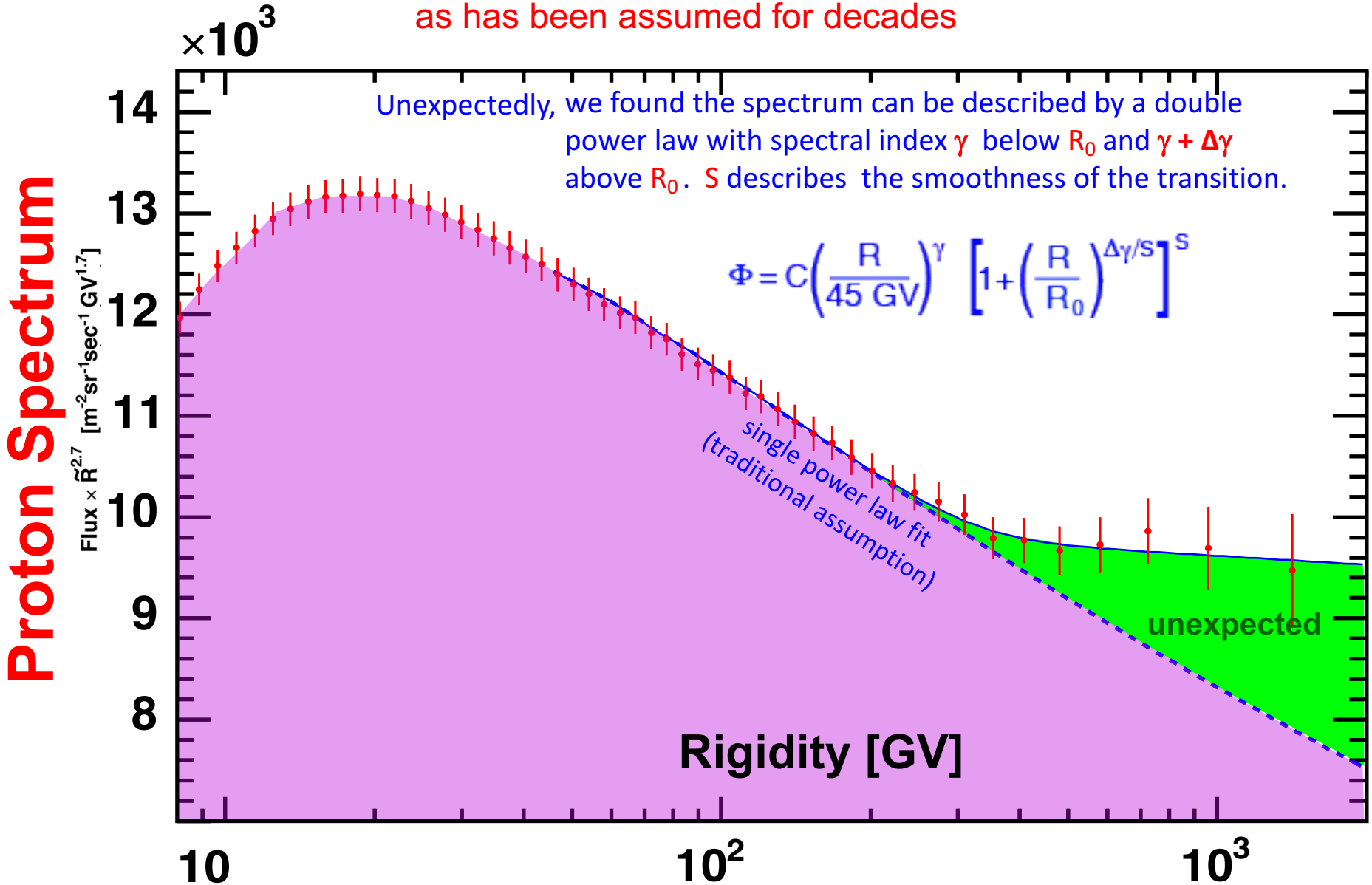
**AMS Physics Result 6:** Precision measurement of the proton flux to an accuracy of 1%




M. Aguilar *et al.*, Phys. Rev. Lett. **114,** 171103 (2015)

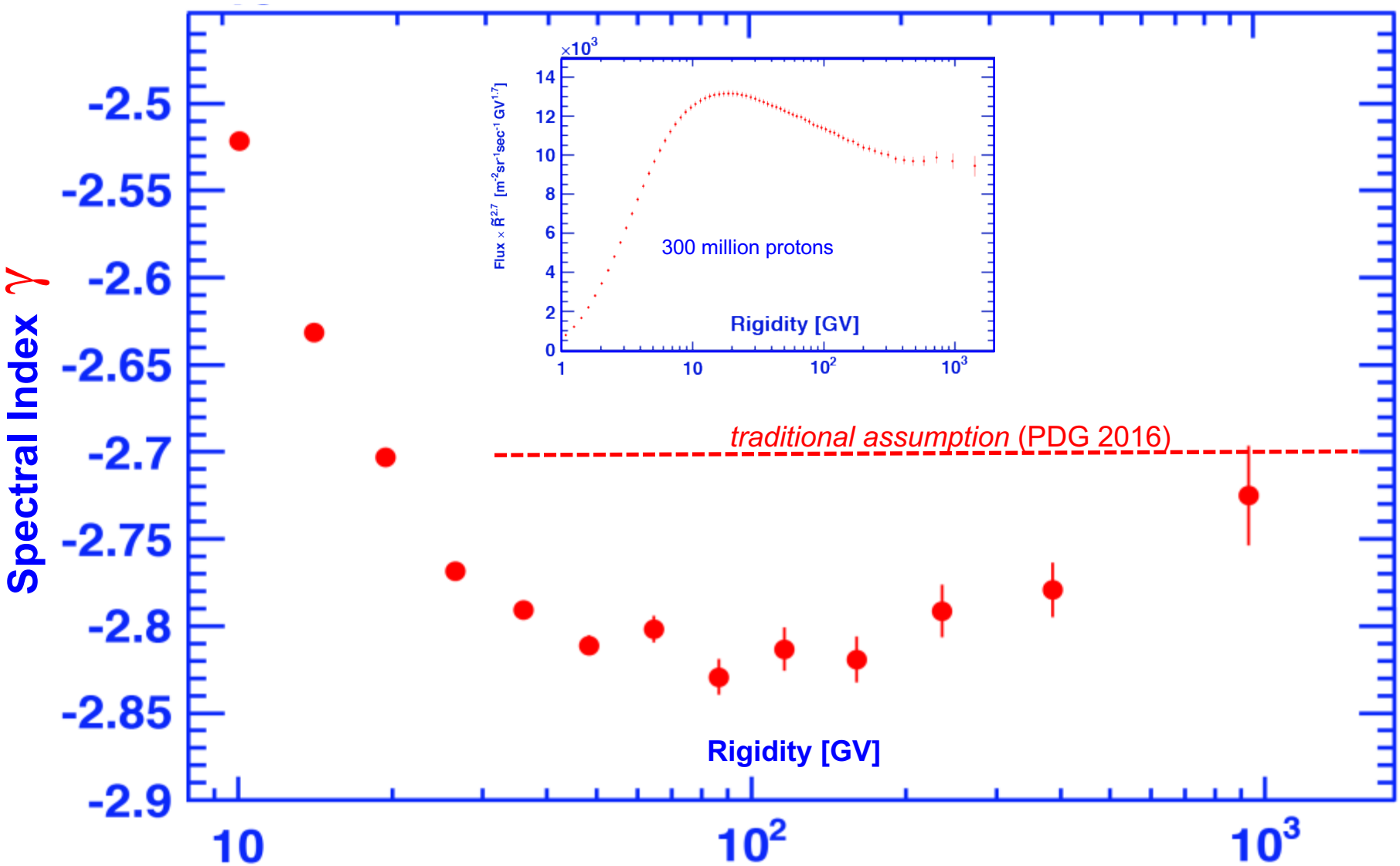
# AMS proton flux

New information: The proton flux cannot be described by a single power law = $CR^{\gamma}$, as has been assumed for decades

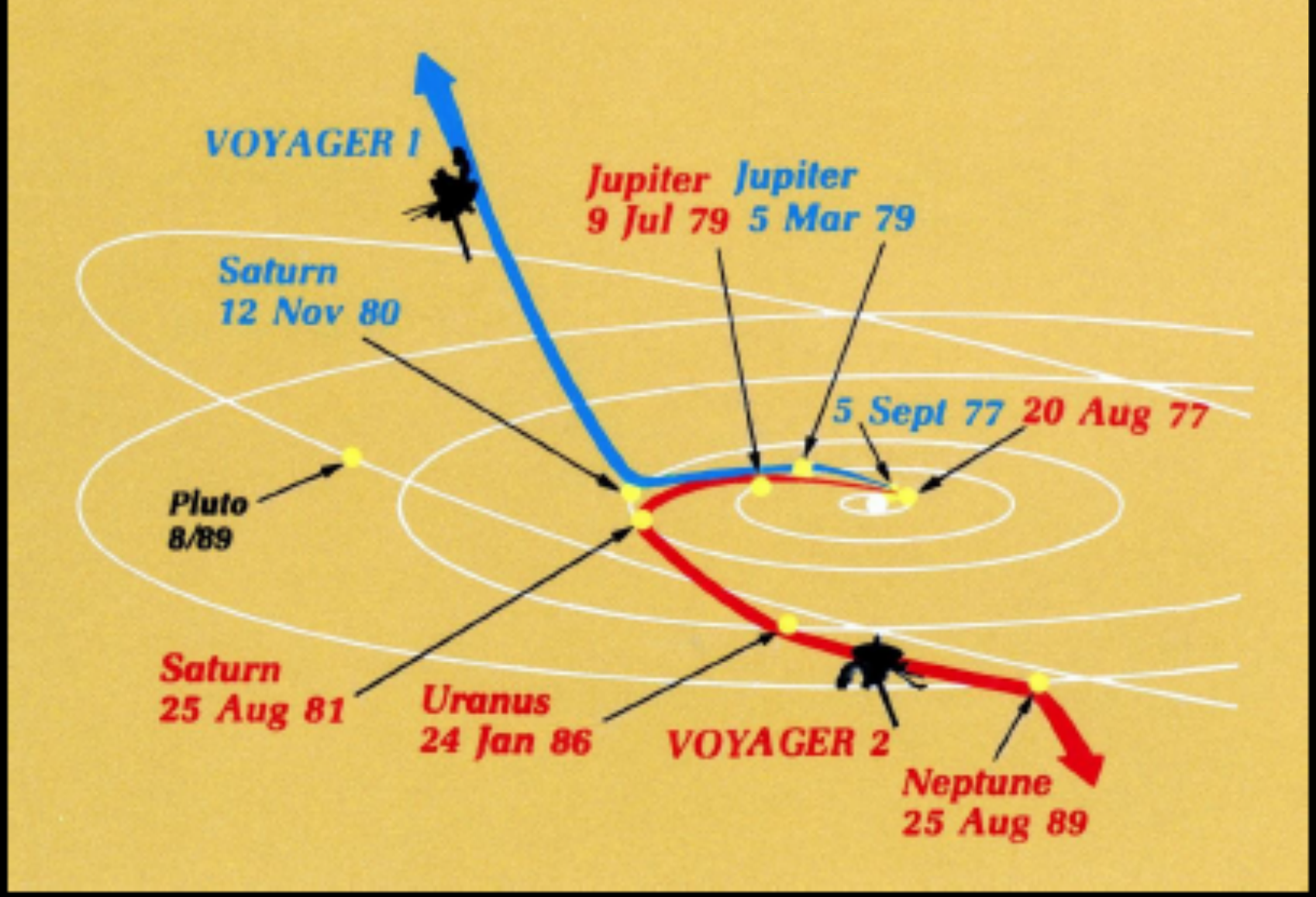


# New information: The proton spectral index changes with momentum.

$\gamma = d[\log(\Phi)] / d[\log(R)]$



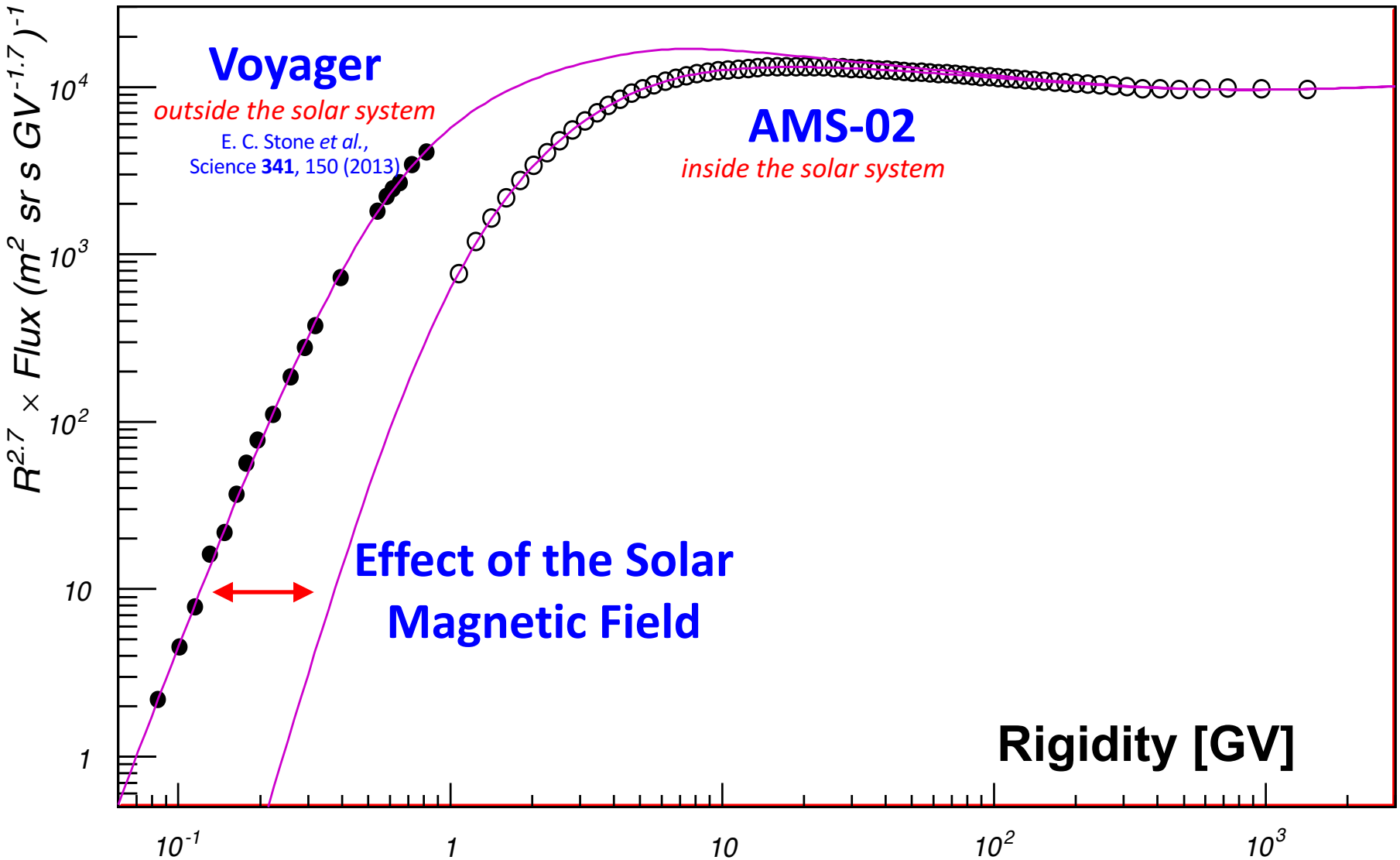

**γ is not a constant -2.7**




Once every 176 years the giant planets are lined up for a Grand Tour, and in 1977 the Voyagers were launched on humankind's longest journey

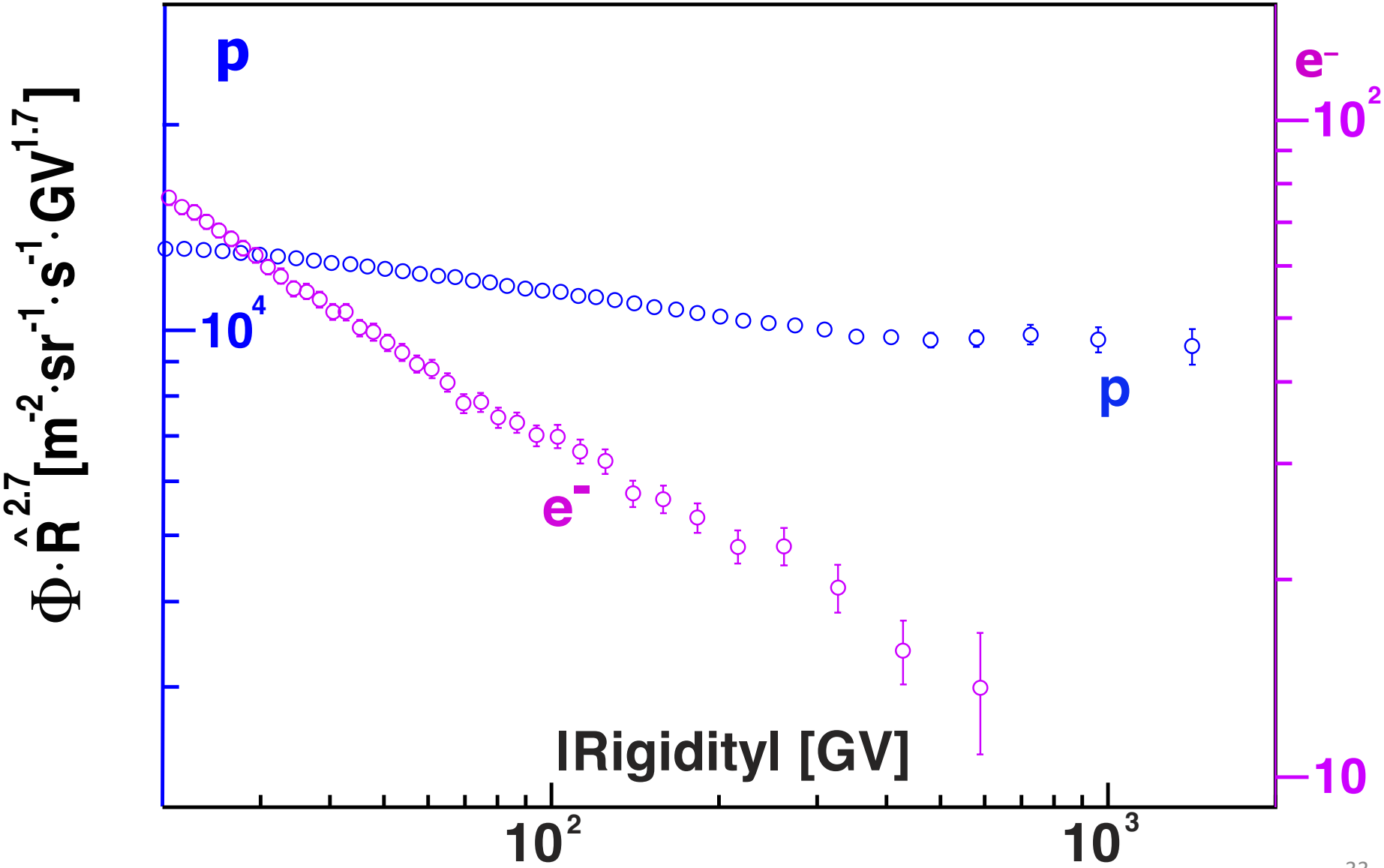
# Understanding of the Solar Magnetic Field:

## The proton flux and the effect of the solar magnetic field




C. Corti *et al.*, ApJ **829**, 8 (2016)

# The Spectra of Elementary Particles: $e^-$ and $e^+$ have much smaller mass than p and $\bar{p}$, so they lose much more energy in the galactic magnetic field due to synchrotron radiation.



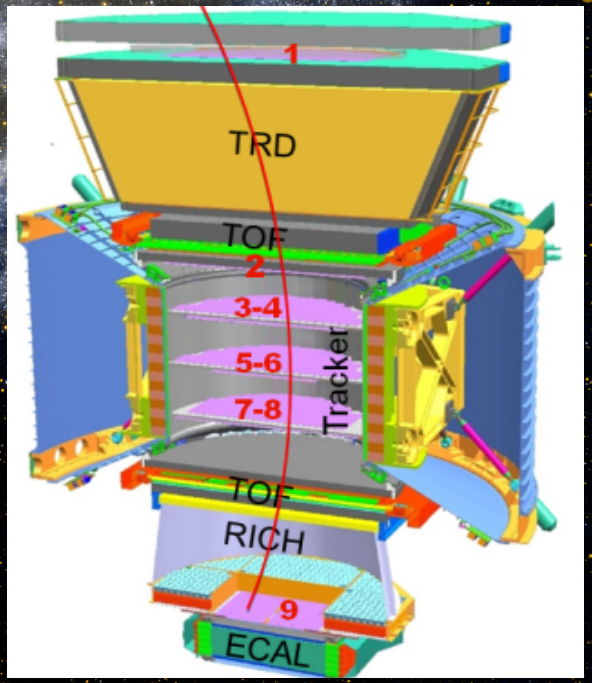

M. Aguilar *et al.*, Phys. Rev. Lett. **117,** 091103 (2016)

# Antiprotons

Cosmic ray + ISM $\rightarrow \bar{p}$ + …

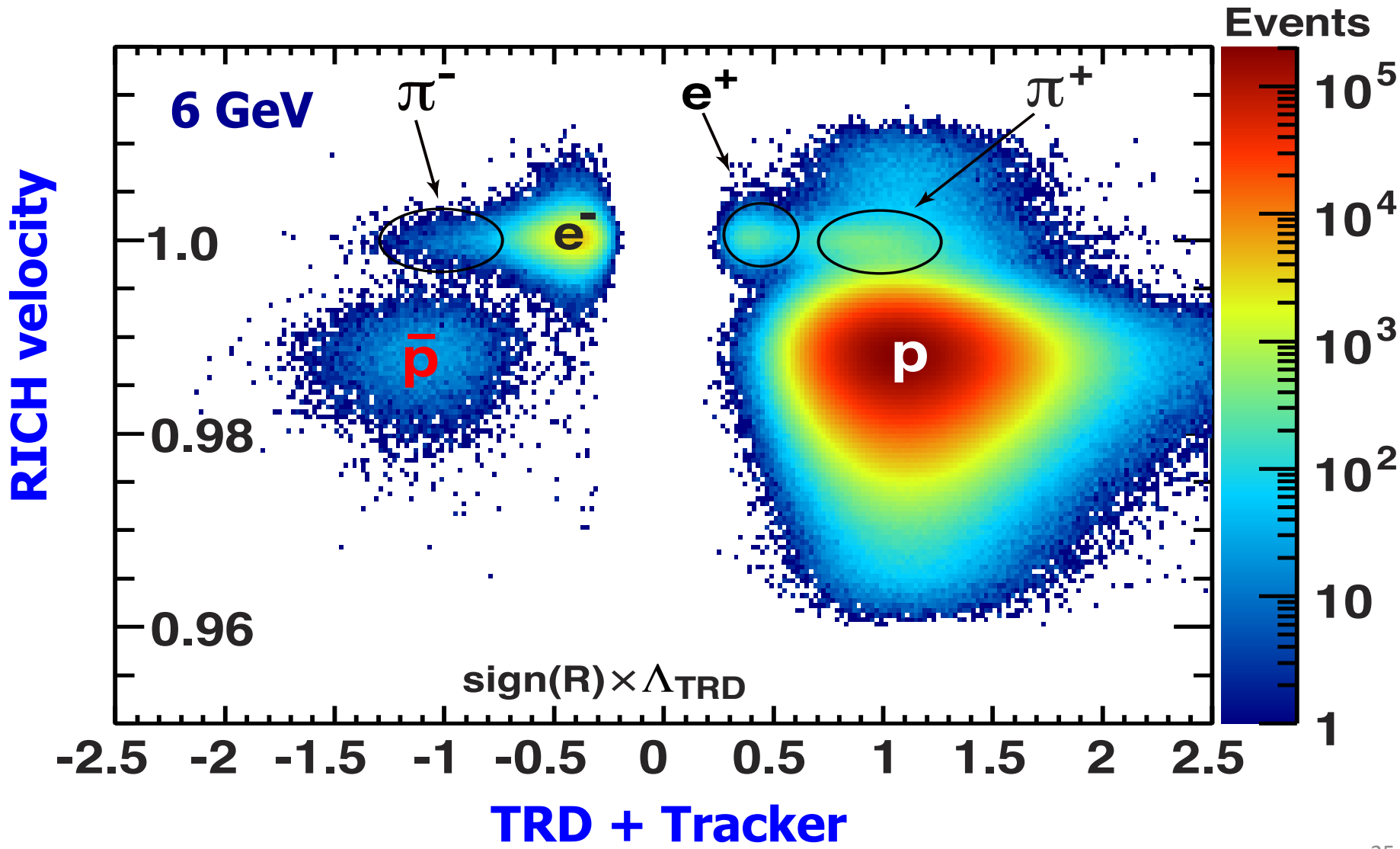
$\chi + \chi \rightarrow \bar{p}$ + …

**There is only 1 Antiproton for 10,000 Protons.**

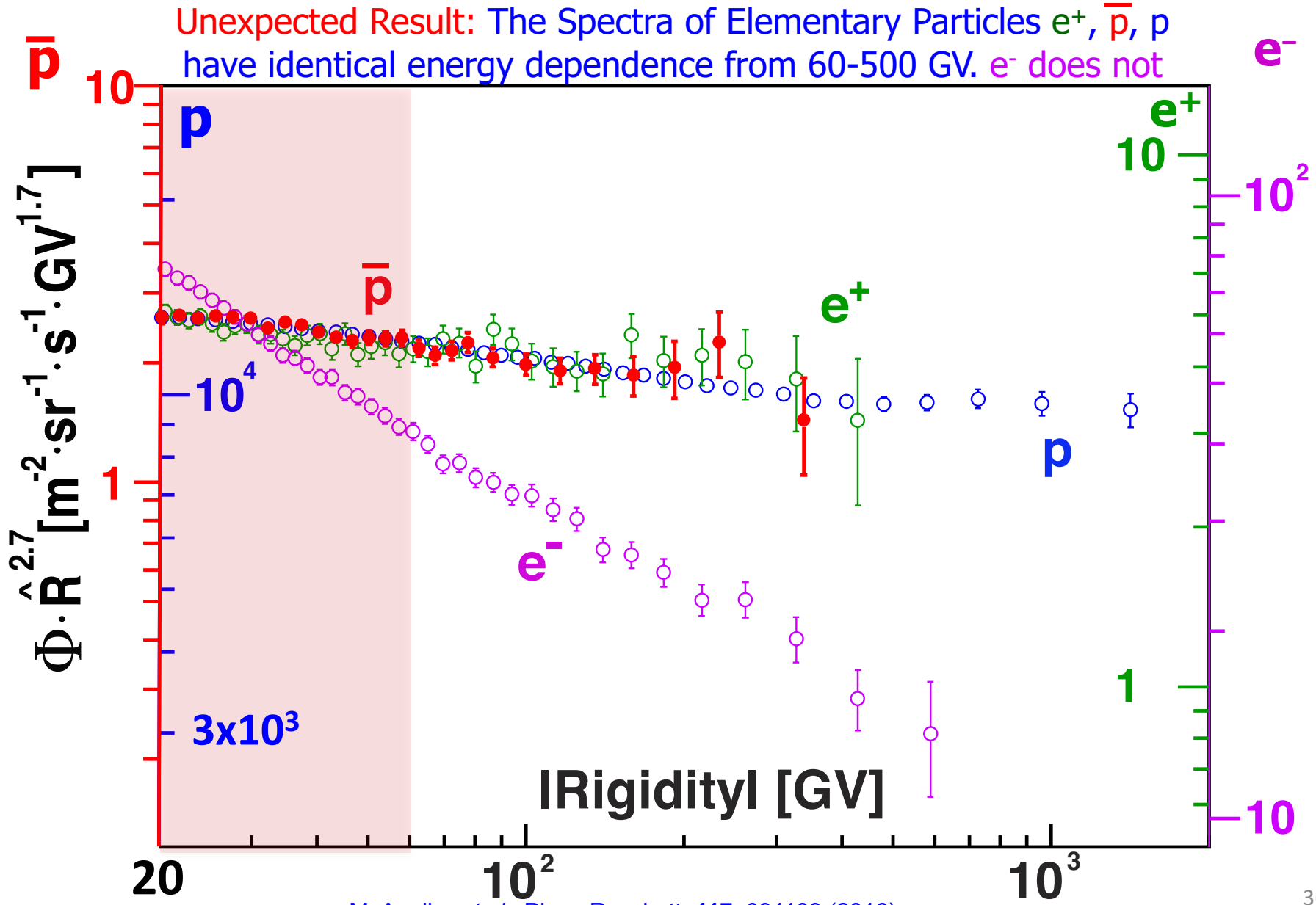



**A percent precision experiment requires background rejection close to 1 in a million.**

# Selection of the signal:
# The $\bar{p}$ signal is well separated from the backgrounds.

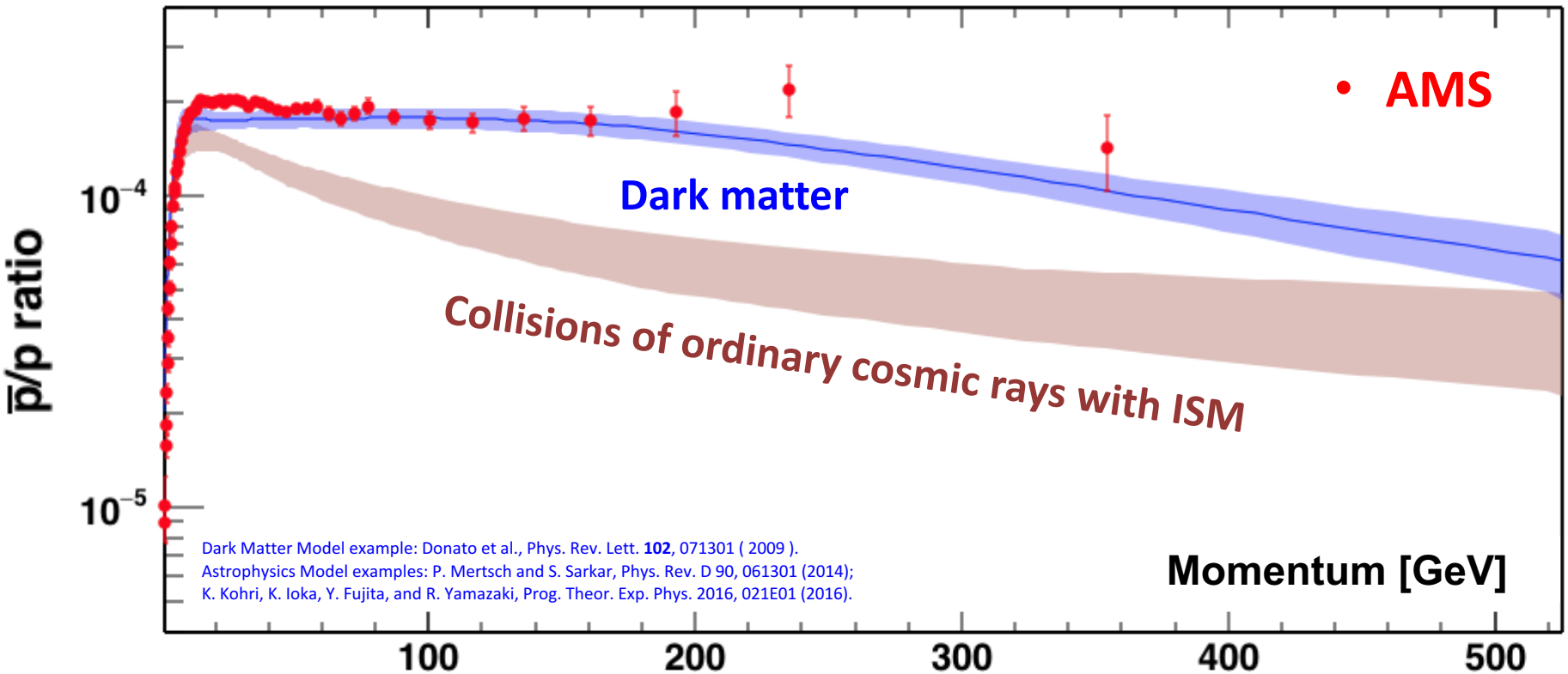


# **Physics Result 7:** The antiproton flux and properties of elementary particle fluxes




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

# Antiproton-to-proton ratio

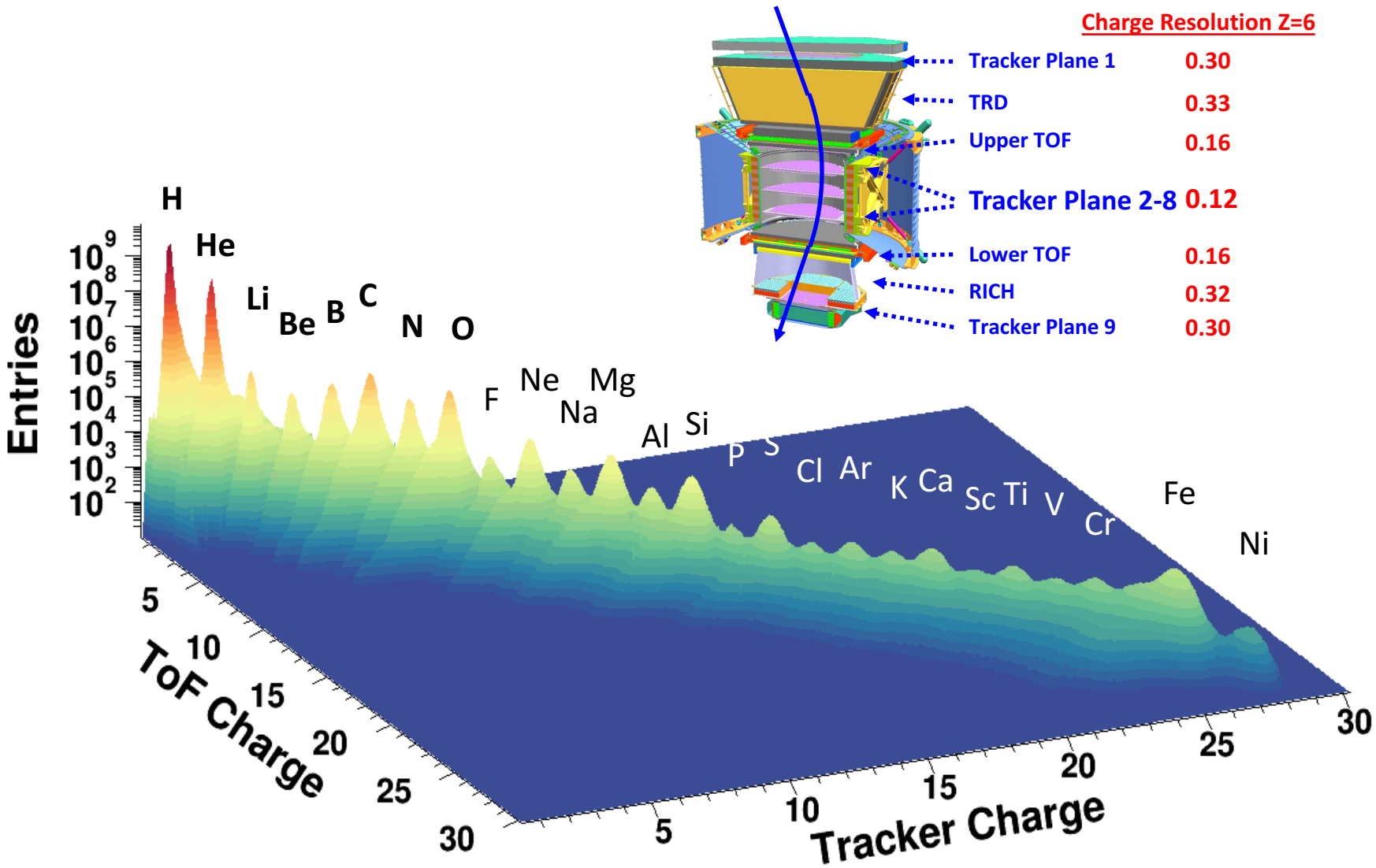



**The excess of antiprotons observed by AMS cannot come from pulsars.**

**It can be explained by Dark Matter collisions or by new astrophysics phenomena**

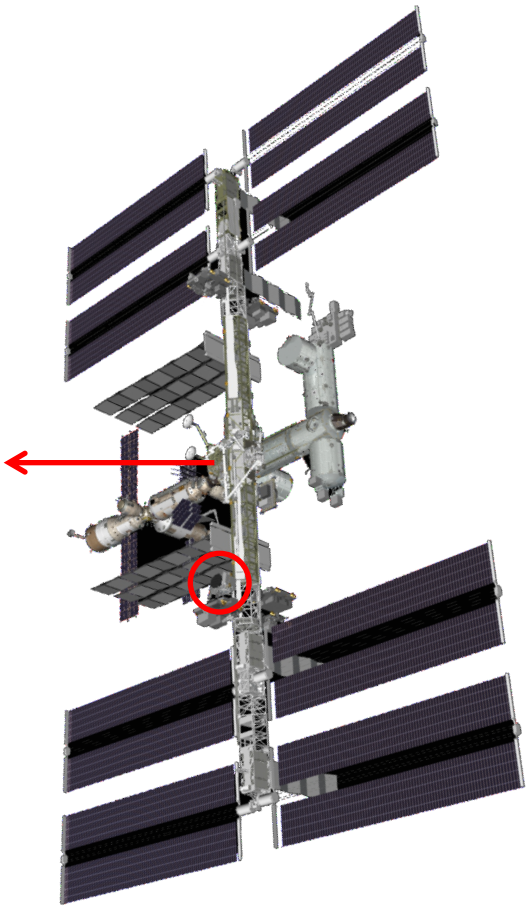
# Cosmic Nuclei

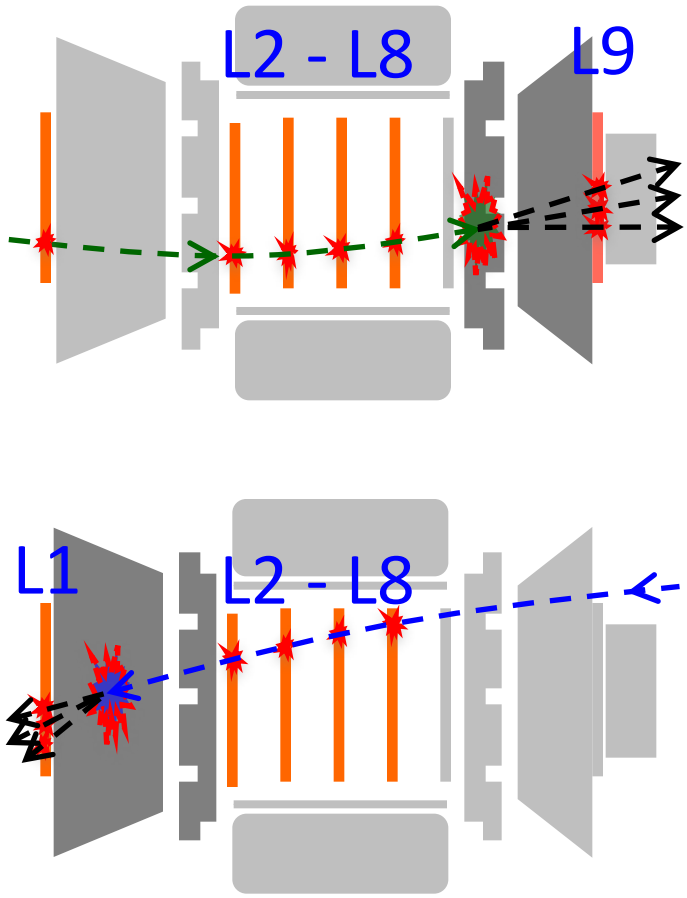
## AMS has seven instruments which independently identify different elements



# Measuring the interactions of nuclei within AMS

## AMS horizontal



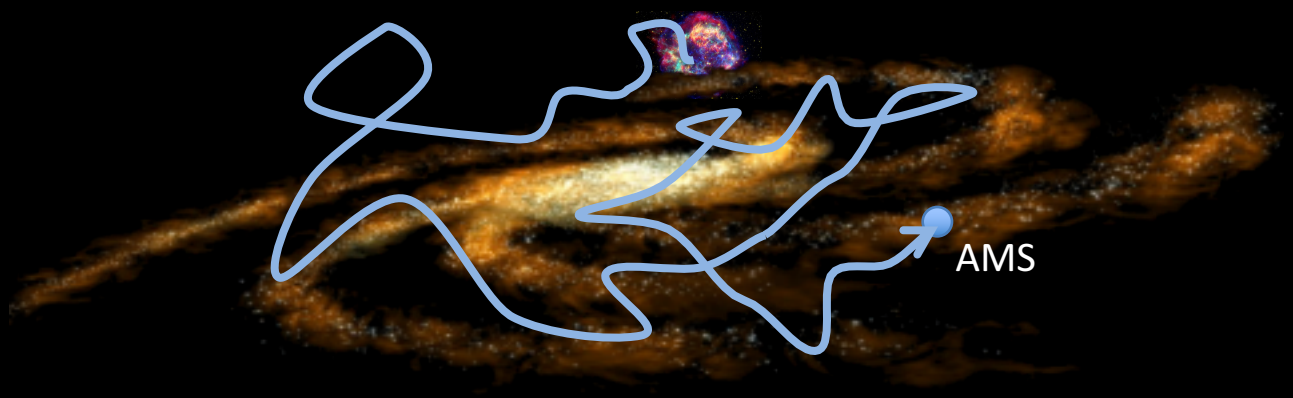



First, we use the seven inner tracker layers, L2-L8, to define beams of nuclei: Li, Be, B, …

Second, we use left-to-right particles to measure the nuclear interactions in the lower part of the detector.

Third, we use right-to-left particles to measure the nuclear interactions in the upper part of detector.

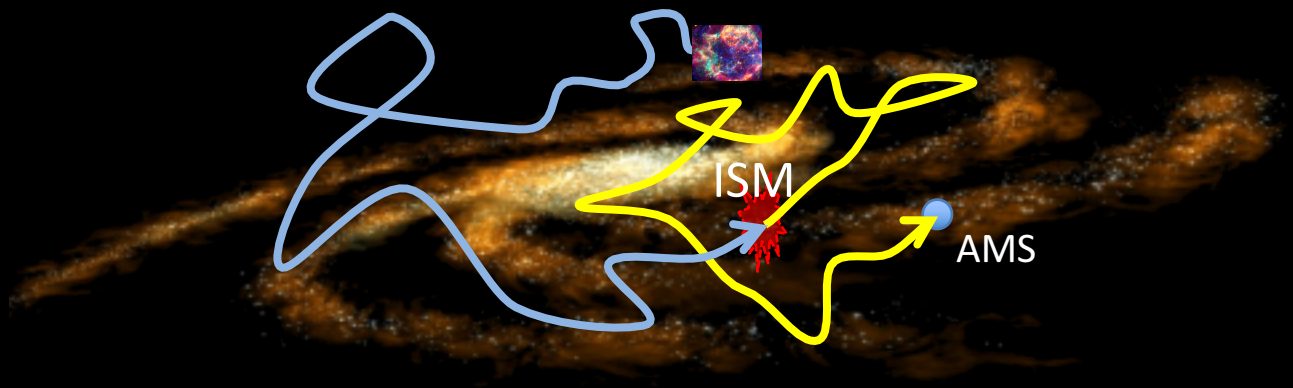
# Primary Cosmic Rays (p, He, C, O, …)




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

# Secondary Cosmic Rays (Li, Be, B, …)

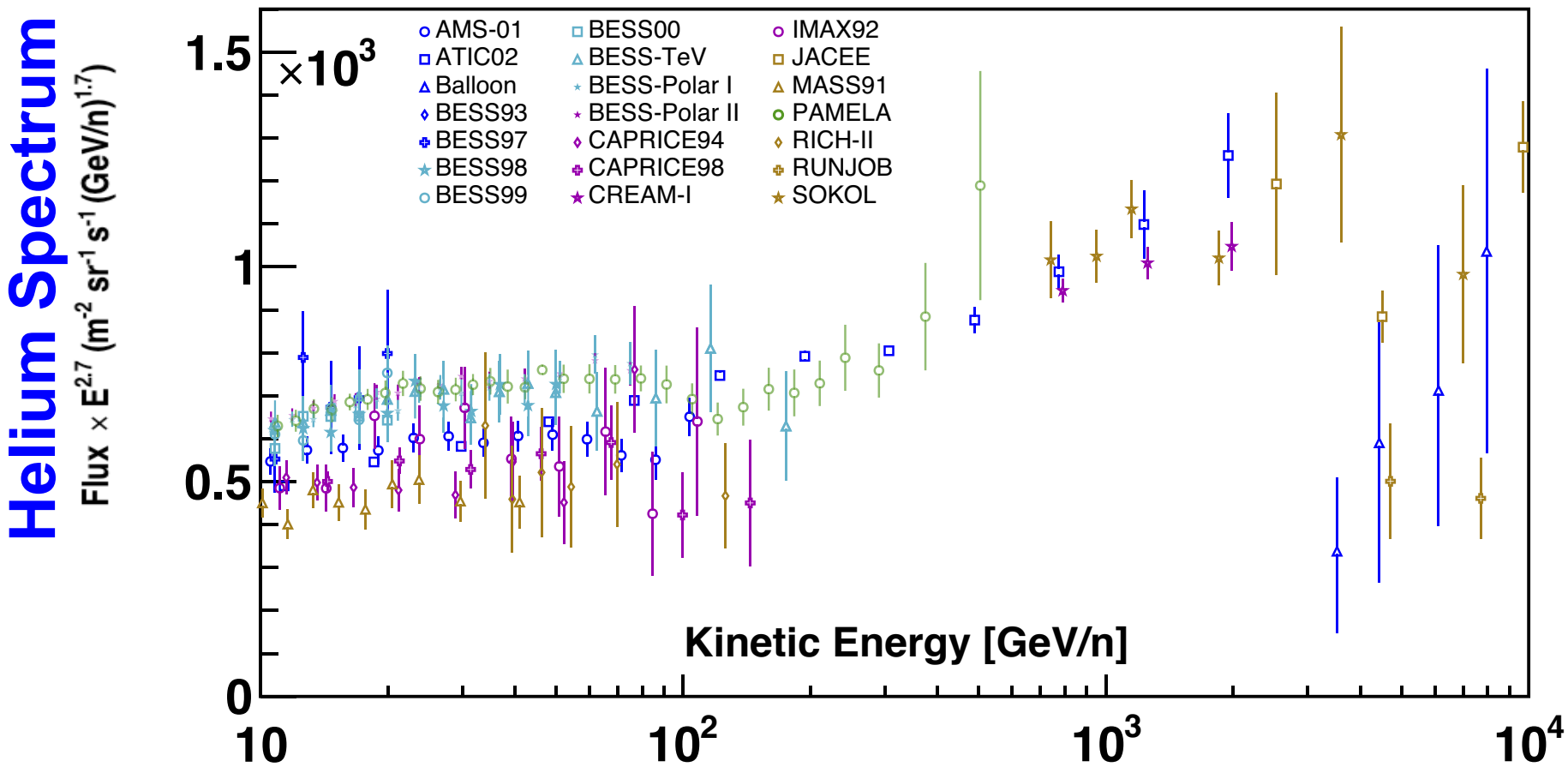
C, O, …, Fe + ISM → Li, Be, B + X



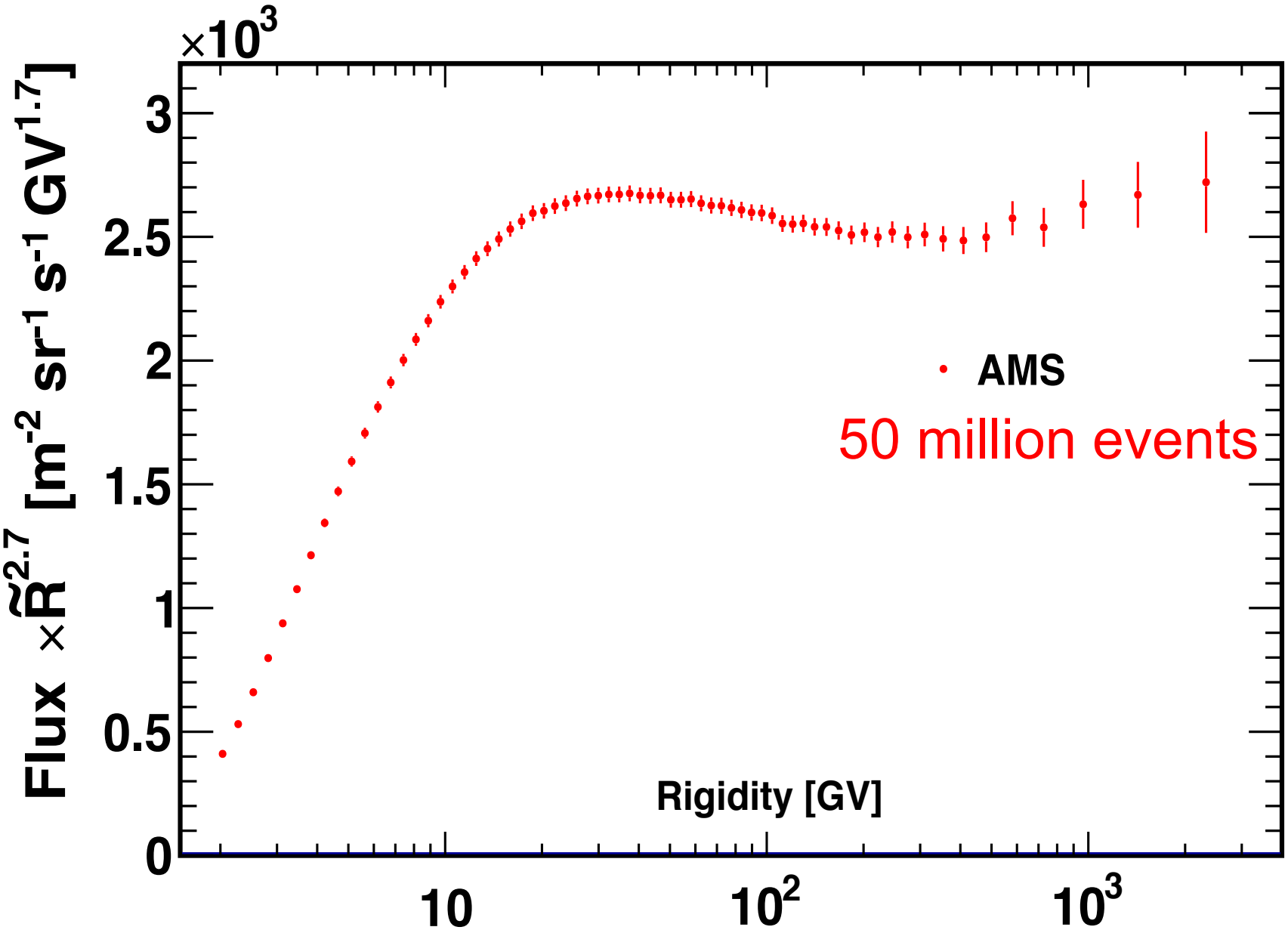

**Secondary cosmic rays carry information about propagation of primaries, secondaries and the ISM.**

# Measurements of the Helium Flux

1. Helium is produced in supernovas and is the 2nd most abundant cosmic ray.
2. It has been studied extensively.
3. In cosmic rays models, the helium spectral function was assumed to be a single power law with $\gamma$ = -2.7 (as for protons).



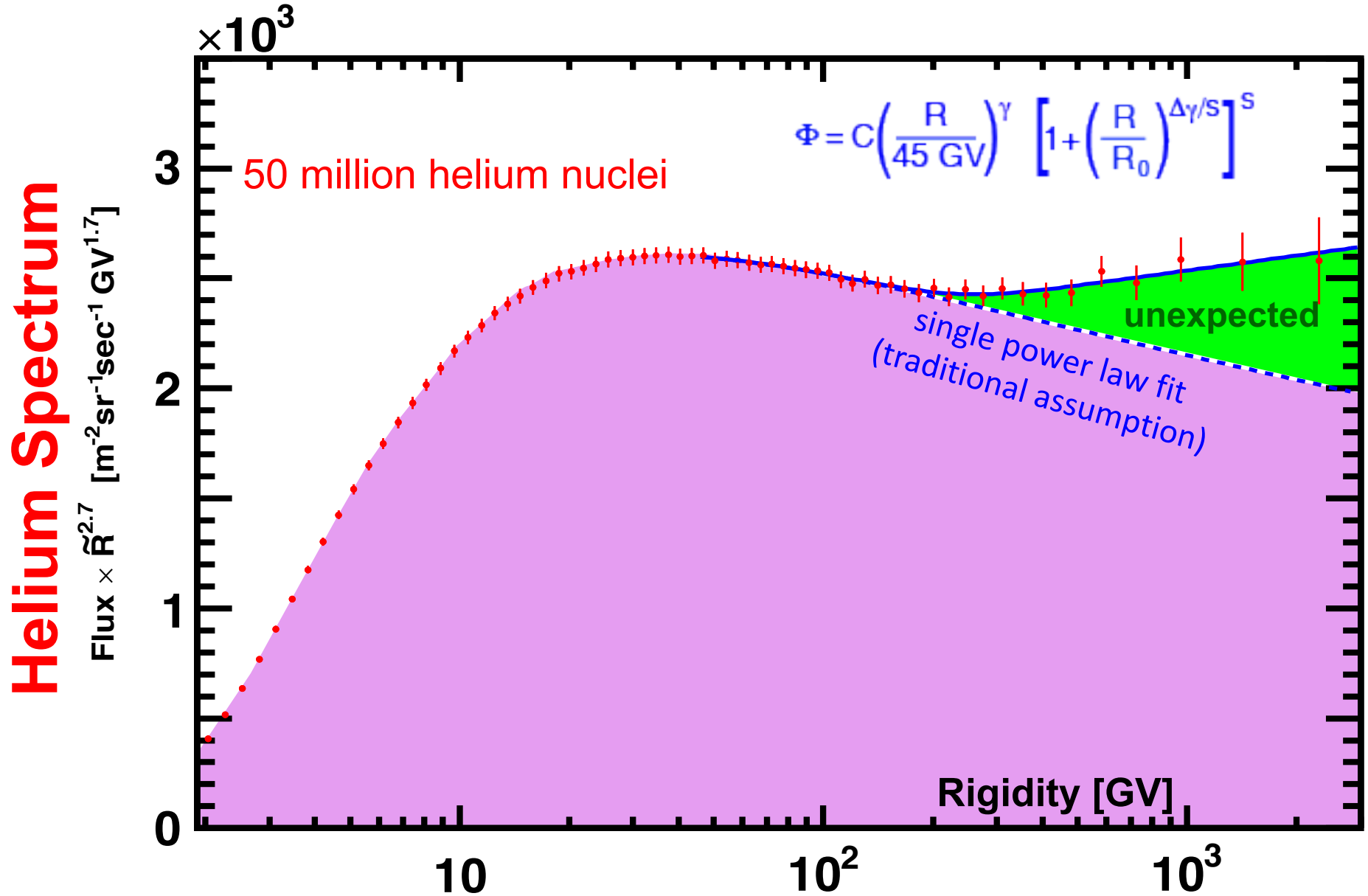
# **AMS Physics Result 8:** Precision measurements of the helium flux



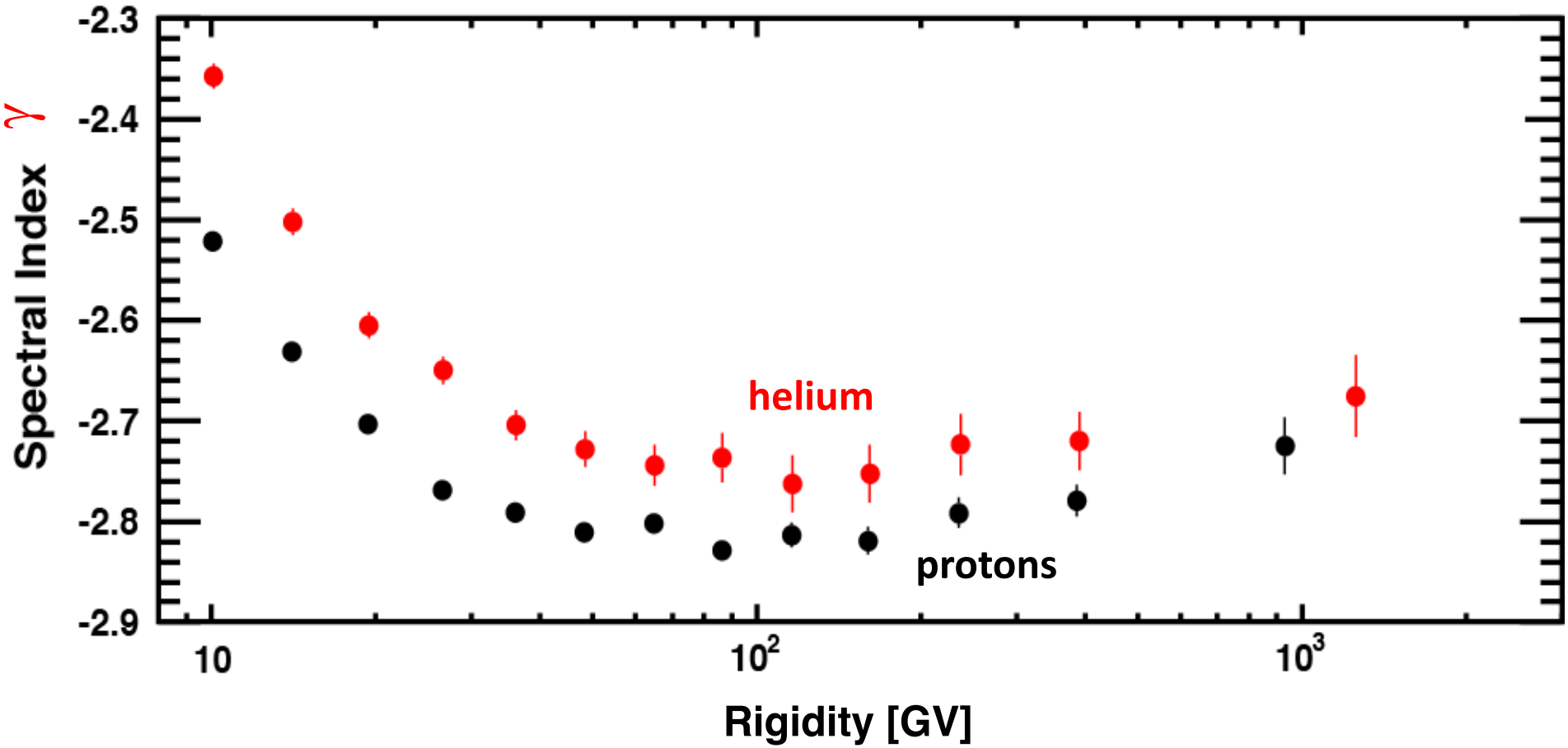

M. Aguilar *et al.*, Phys. Rev. Lett. **115,** 211101 (2015)

# AMS Helium Flux

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

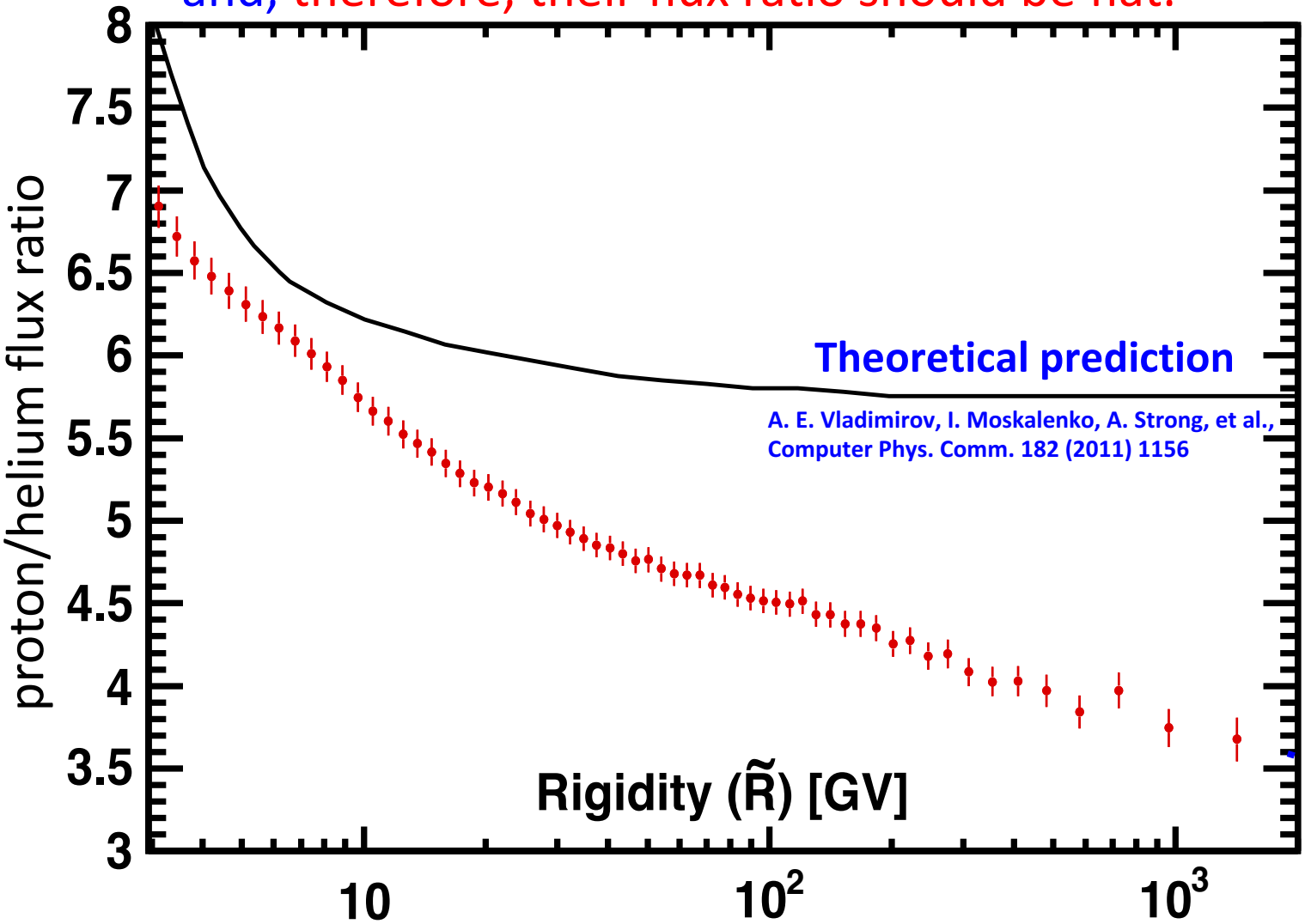


# New information: The helium spectral index changes with rigidity in a similar way to that of the proton spectral index but the values are different



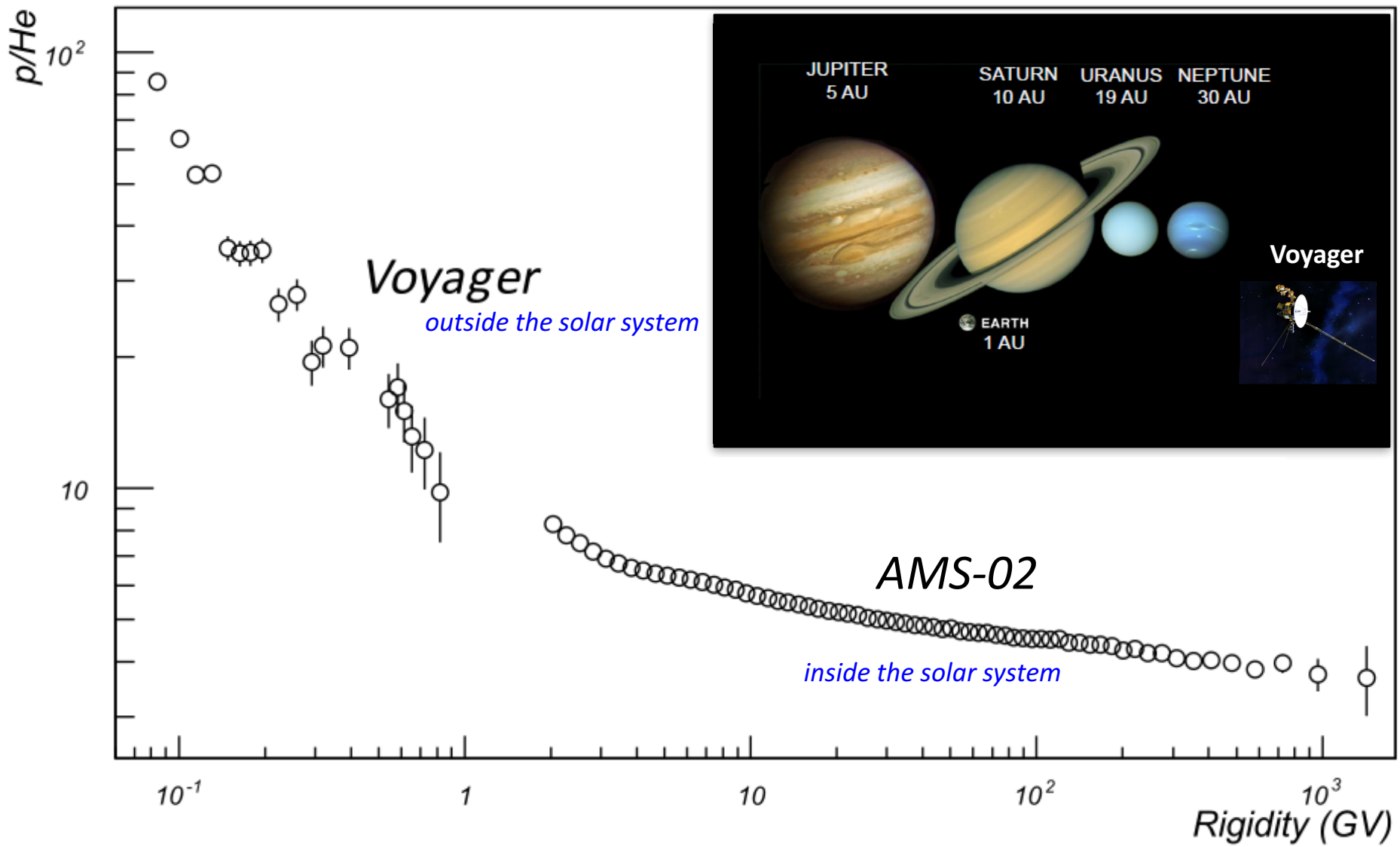
# **Physics Result 9:** The AMS proton/helium flux ratio

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 flat.




**AMS result: this ratio is not flat.**

# Proton to Helium Flux Ratio

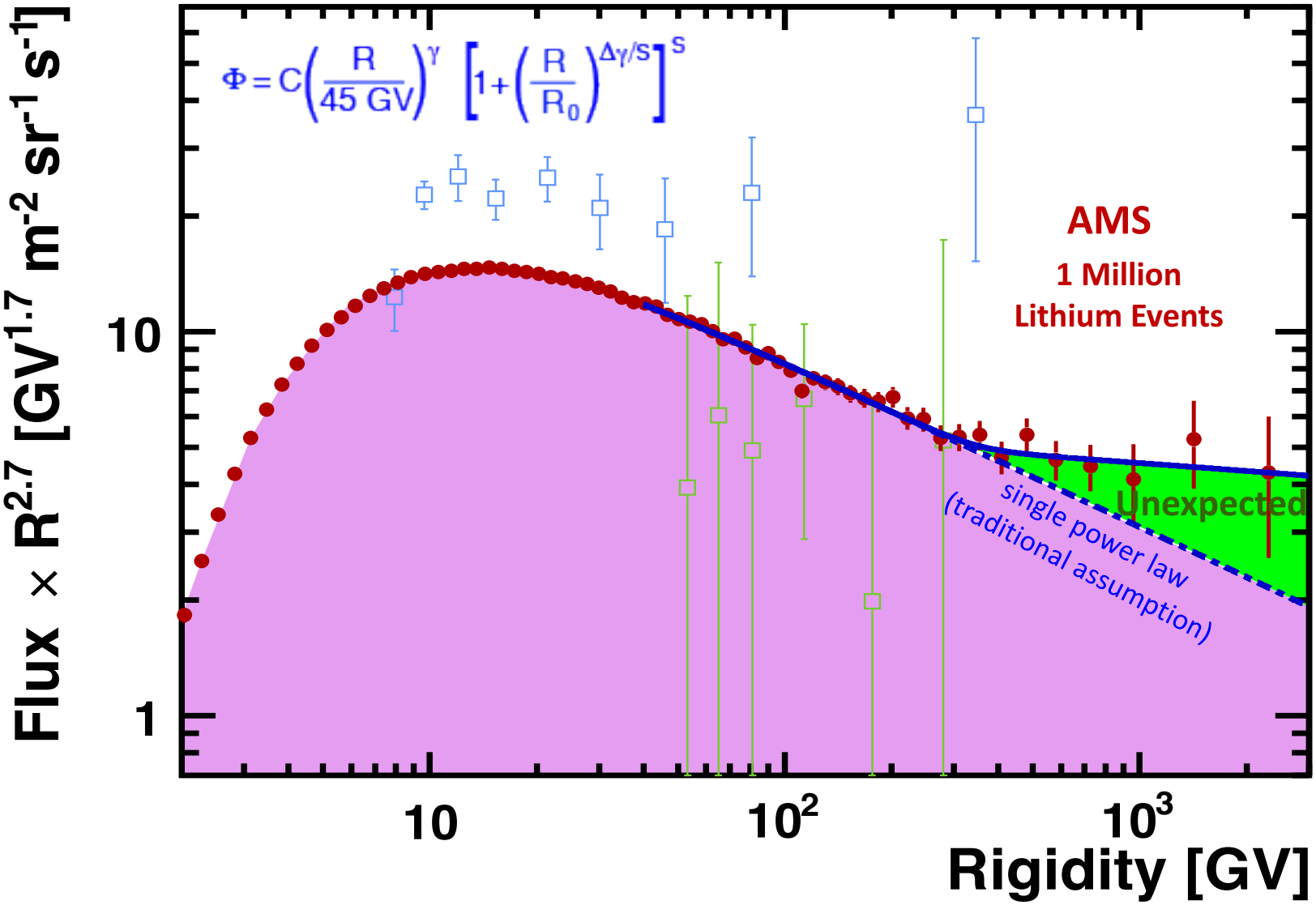



**The p/He ratio is independent of solar activity**

# **Physics Result 10:** The Lithium flux

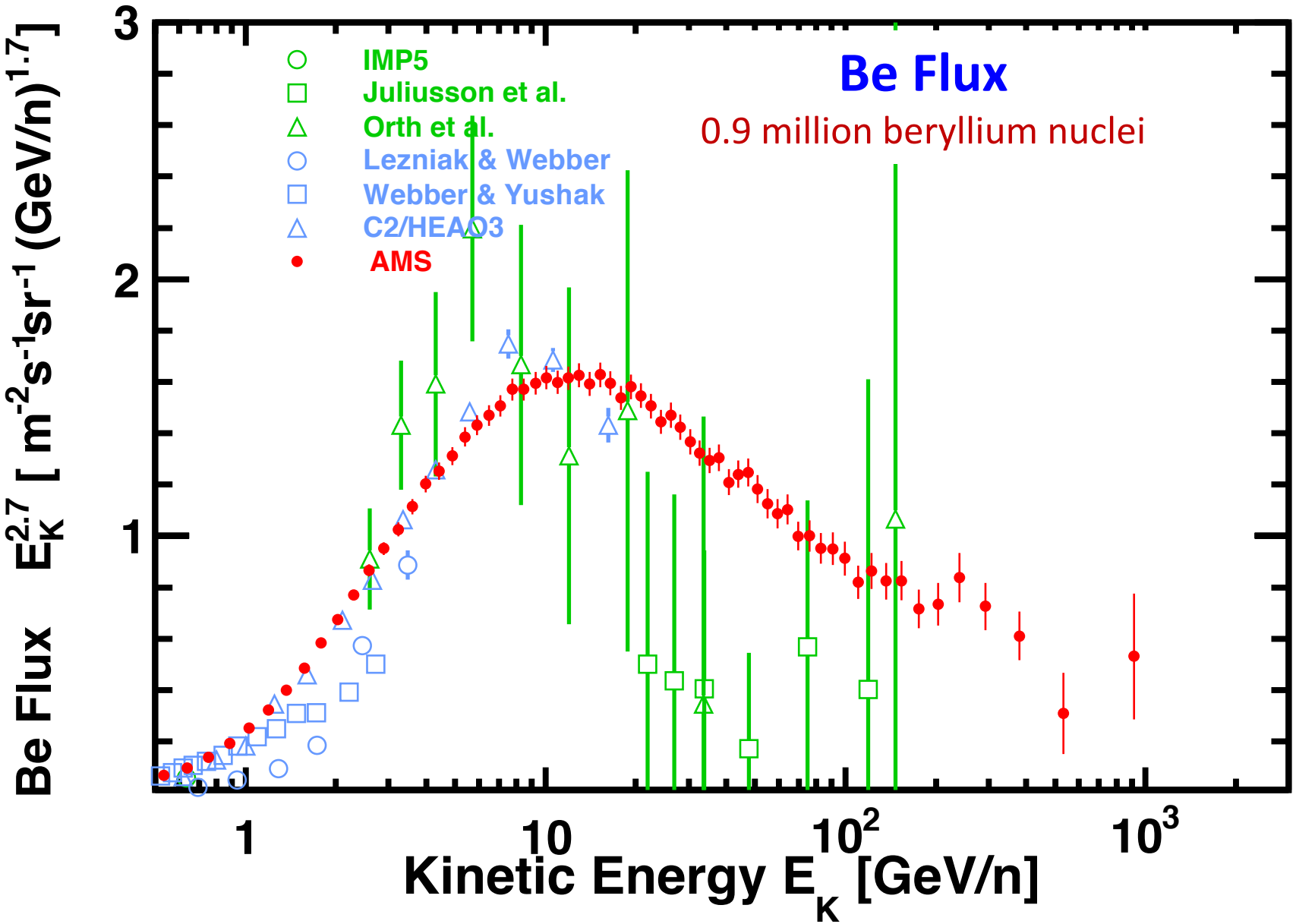
## New AMS results on Secondary Cosmic Rays (Lithium)

New information: The Lithium spectrum behaves similar to protons and Helium and the Lithium flux cannot be described by a single power law.



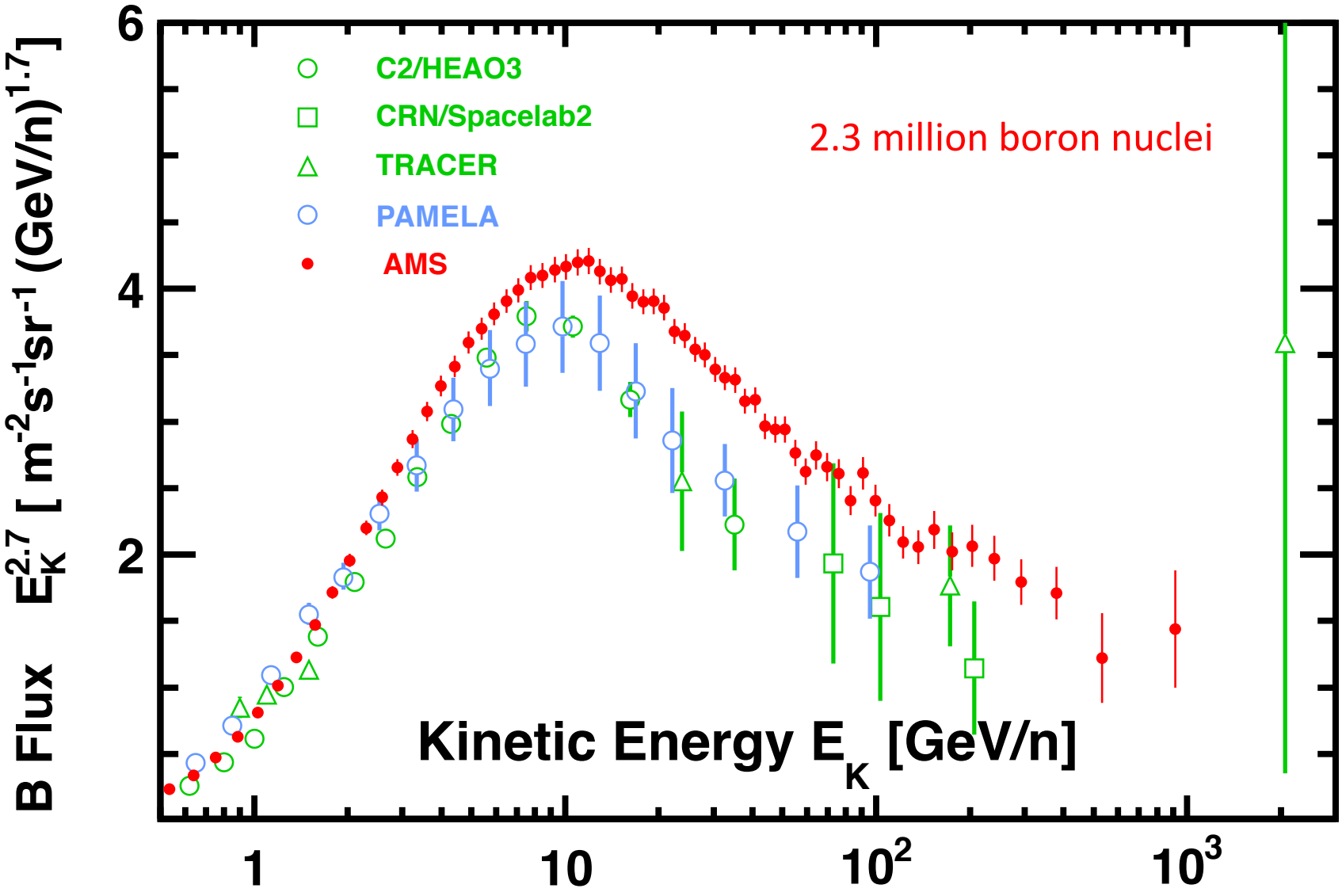
# Physics Result 11: The Beryllium flux

## New AMS results on Secondary Cosmic Rays (Beryllium)

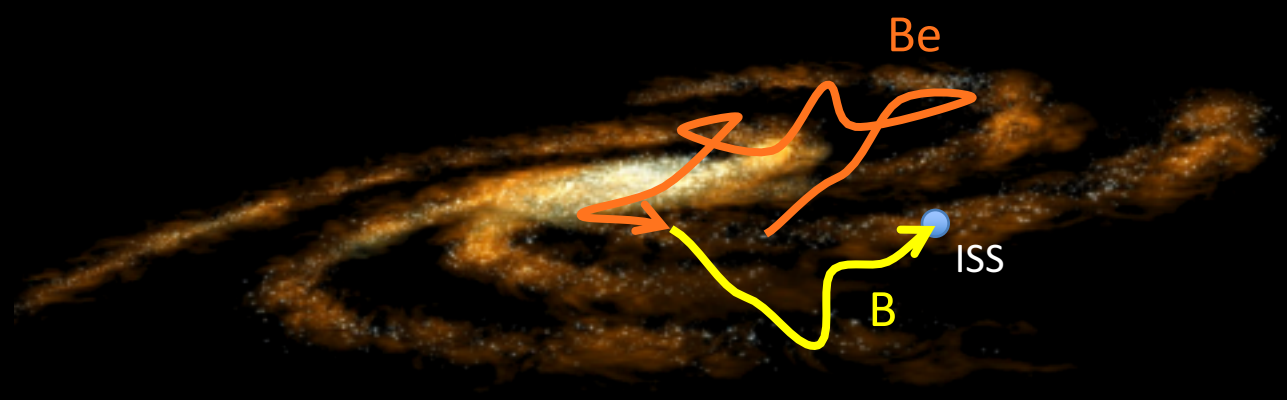


# **Physics Result 12:** The Boron flux

## New AMS results on Secondary Cosmic Rays (Boron)



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

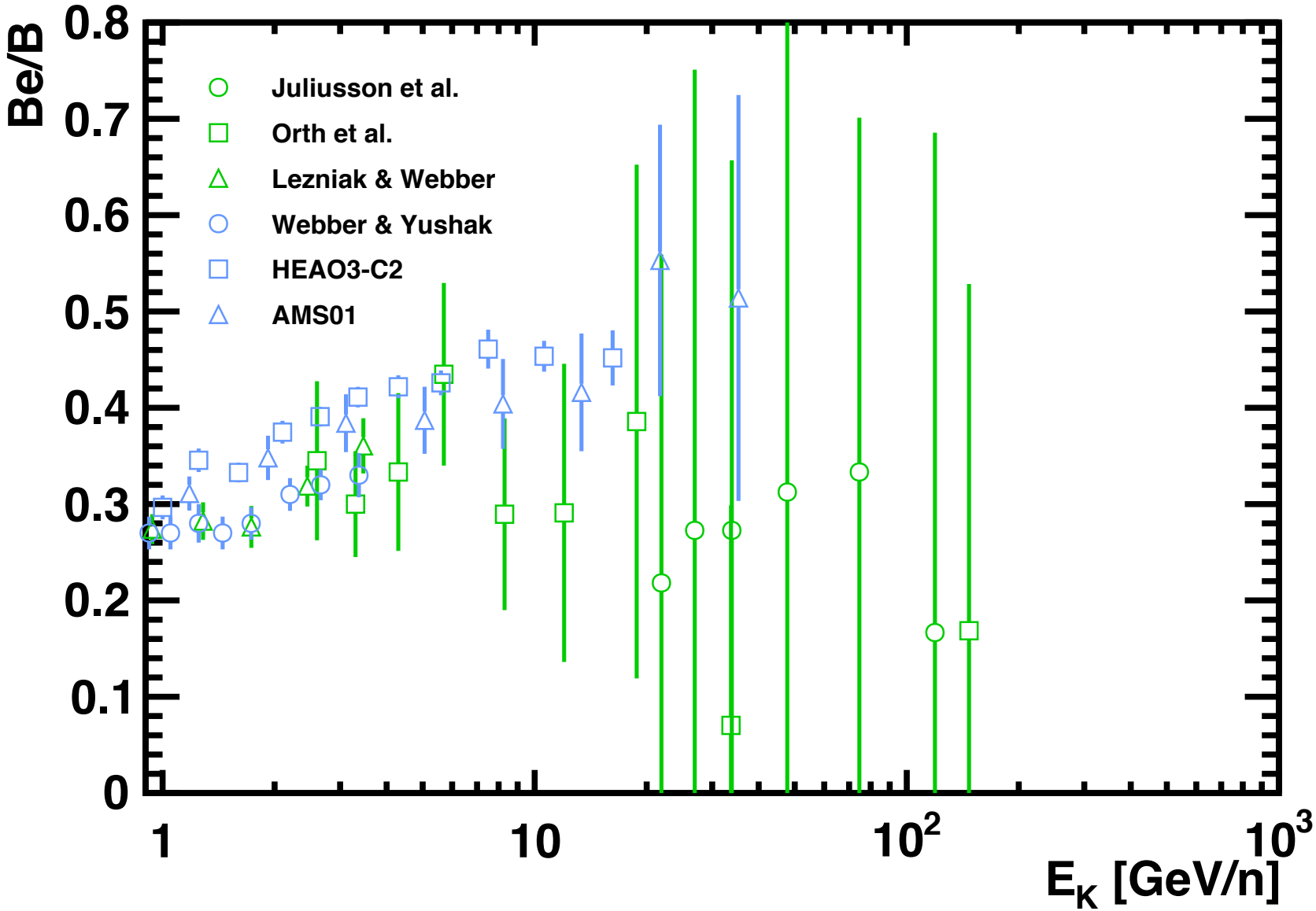



$$^{10}\mathrm{Be} \rightarrow {}^{10}\mathrm{B} + e^{-} + \bar{\nu}_e$$

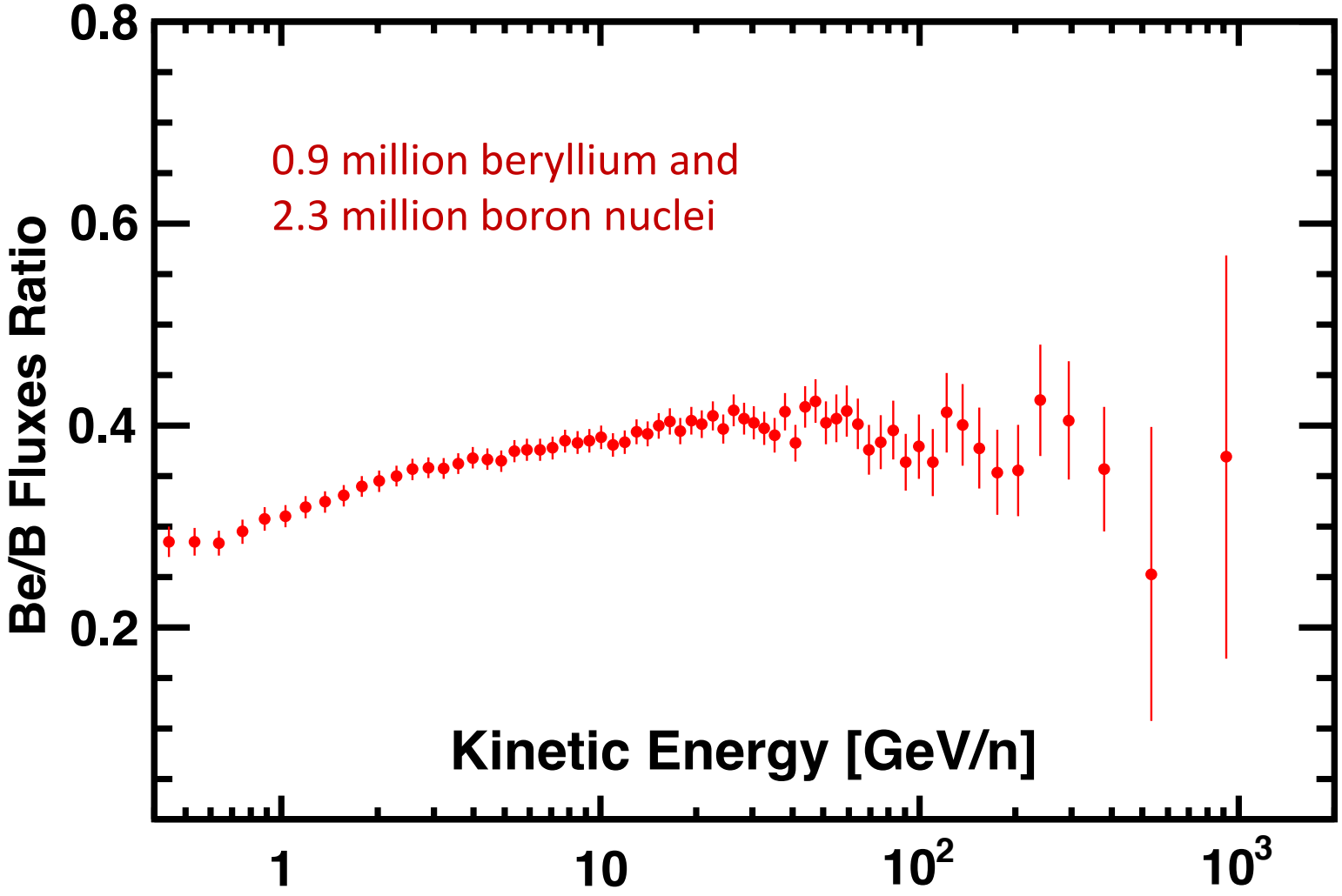
**The $^{10}$Be half-life is $1.5\times10^{6}$ years.**

**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.**

# Beryllium to Boron flux ratio before AMS

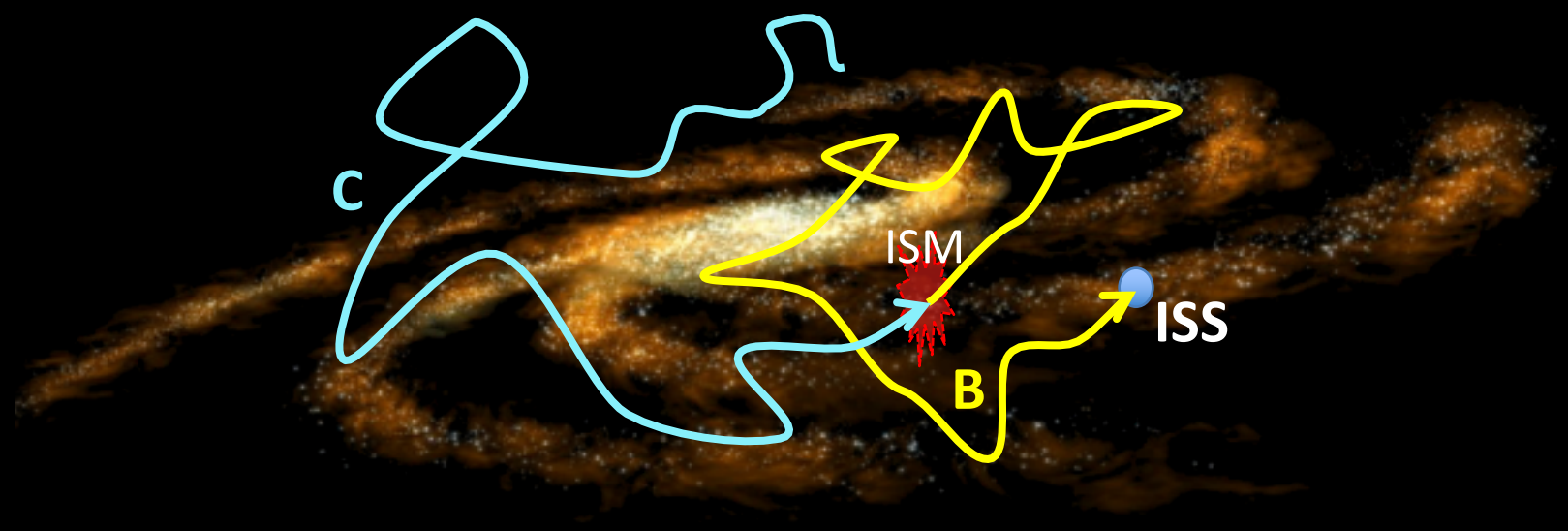


# **Physics Result 13:** The Beryllium-to-Boron flux ratio




**AMS: The age of cosmic rays in the galaxy is ~12 million years.**

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

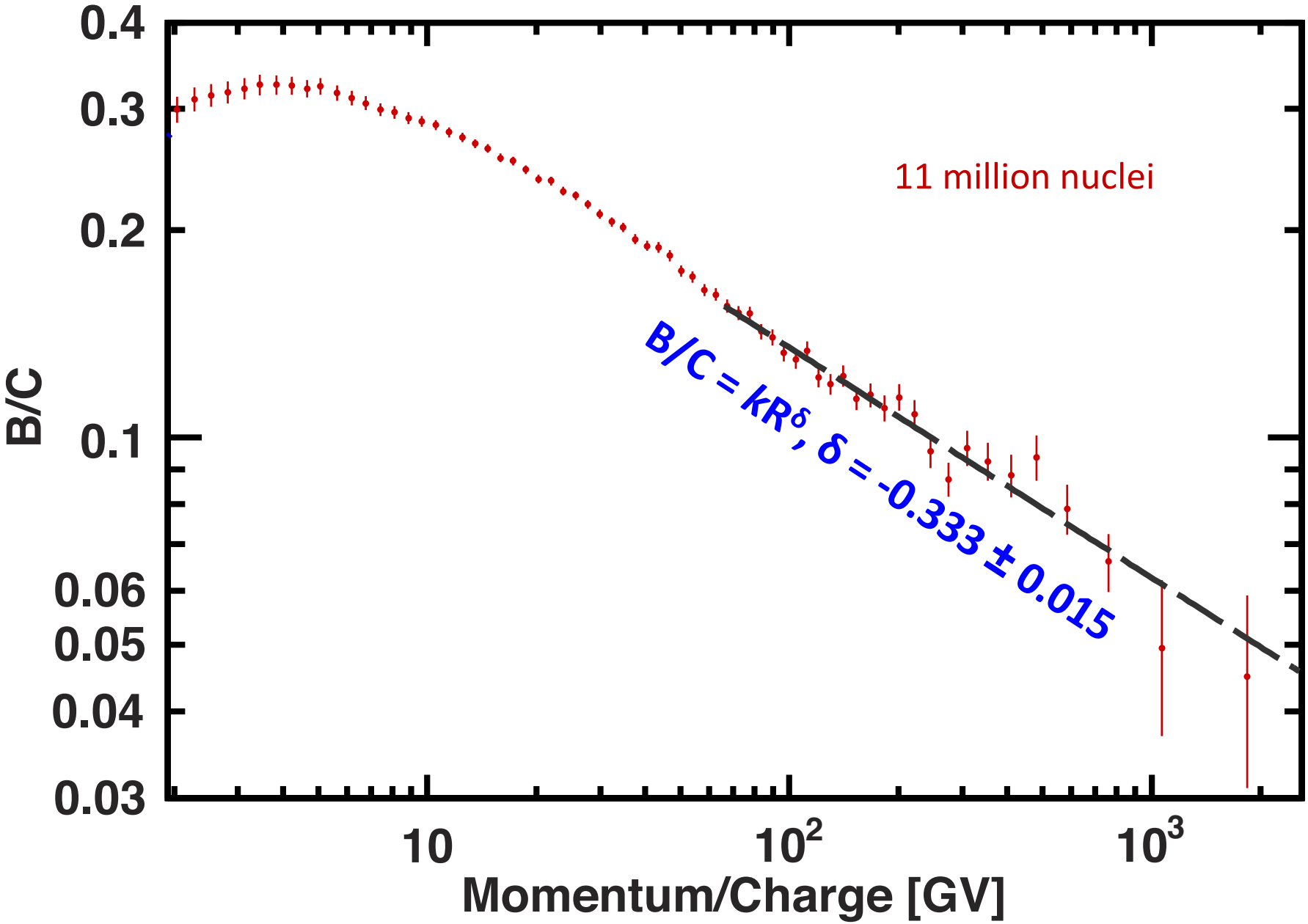



**Cosmic ray propagation is commonly modeled as a fast moving gas diffusing through a magnetized plasma.**

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

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

# **Physics Result 14:** The Boron-to-Carbon (B/C) flux ratio




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

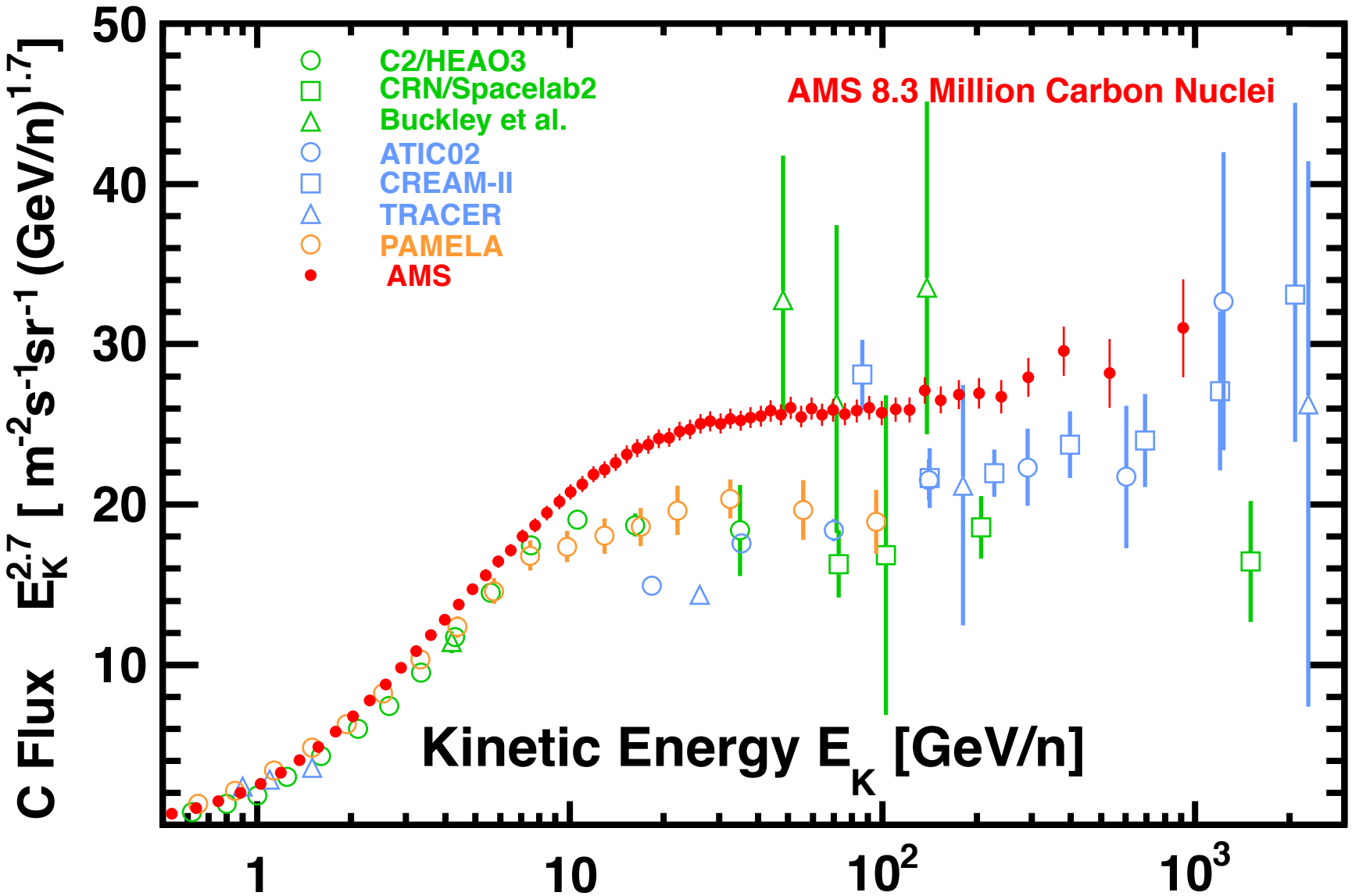
# AMS B/C results

The B/C ratio does not show any significant structures in contrast to many cosmic ray models that require such structures at high rigidities.

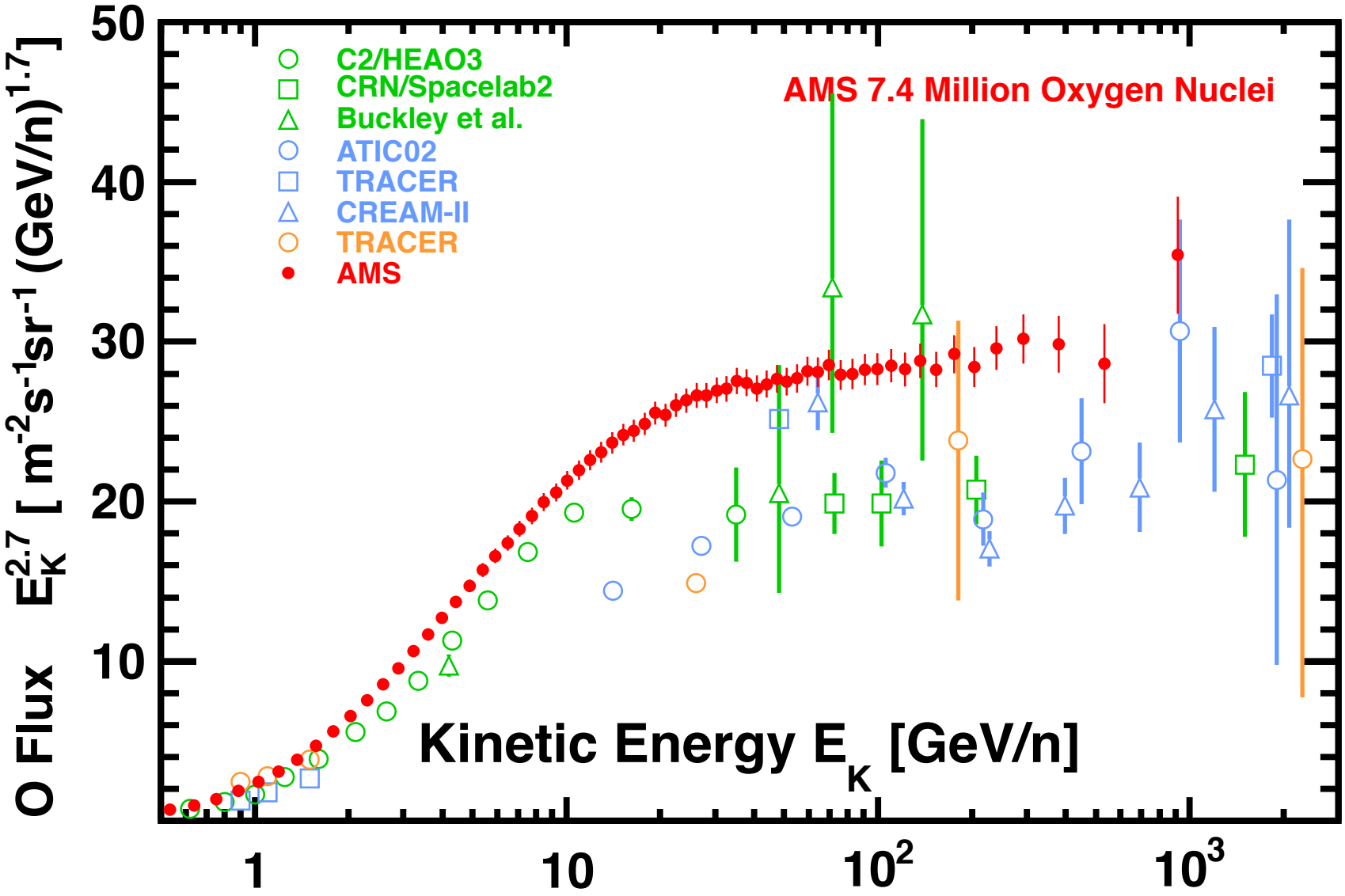
Remarkably, above 65 GV, the B/C ratio is well described by a single power law
**$B/C = k\,R^{\delta}$** with **$\delta = -0.333 \pm 0.015$.**

This is in agreement with
the Kolmogorov turbulence model
of magnetized plasma of
**$\delta = -1/3$** asymptotically.

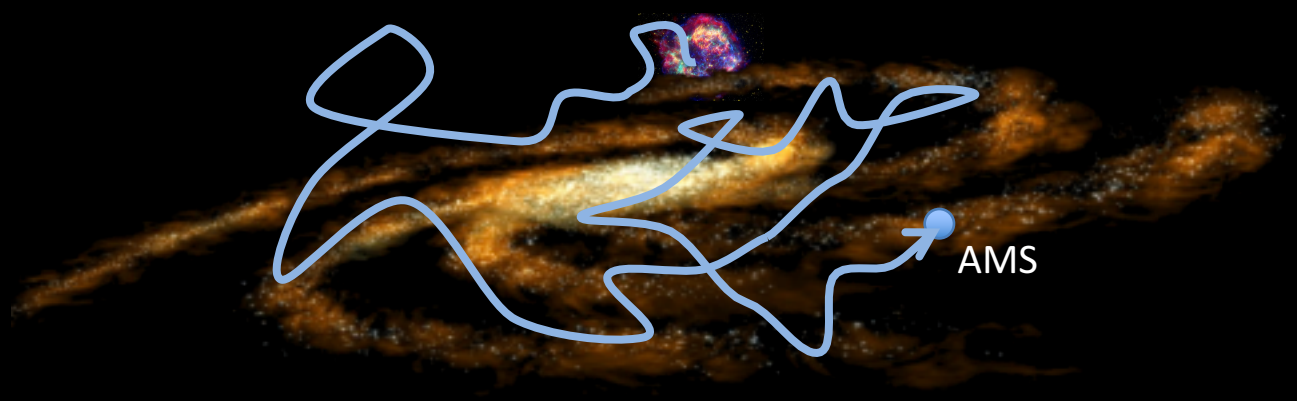
# **Physics Result 15:** The Carbon flux



# **Physics Result 16:** The Oxygen flux



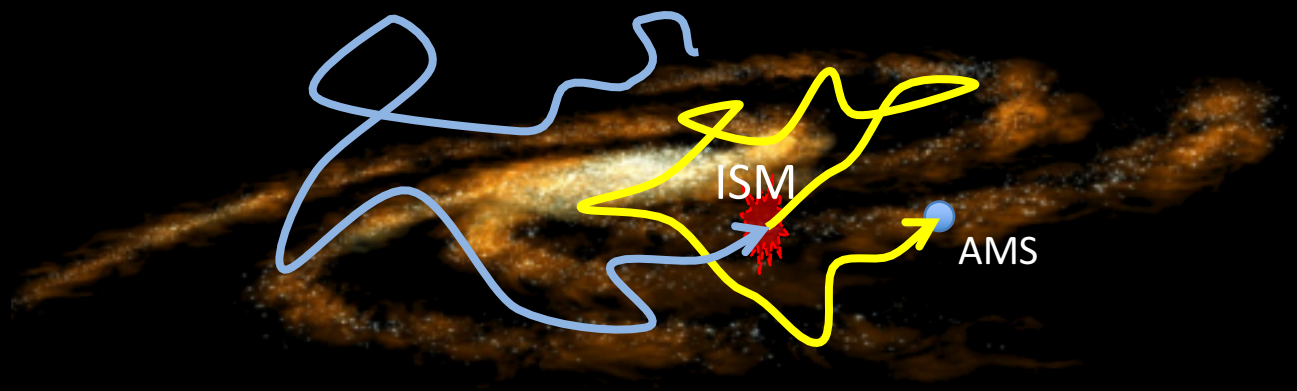
# Primary Cosmic Rays (p, He, C, O, …)




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

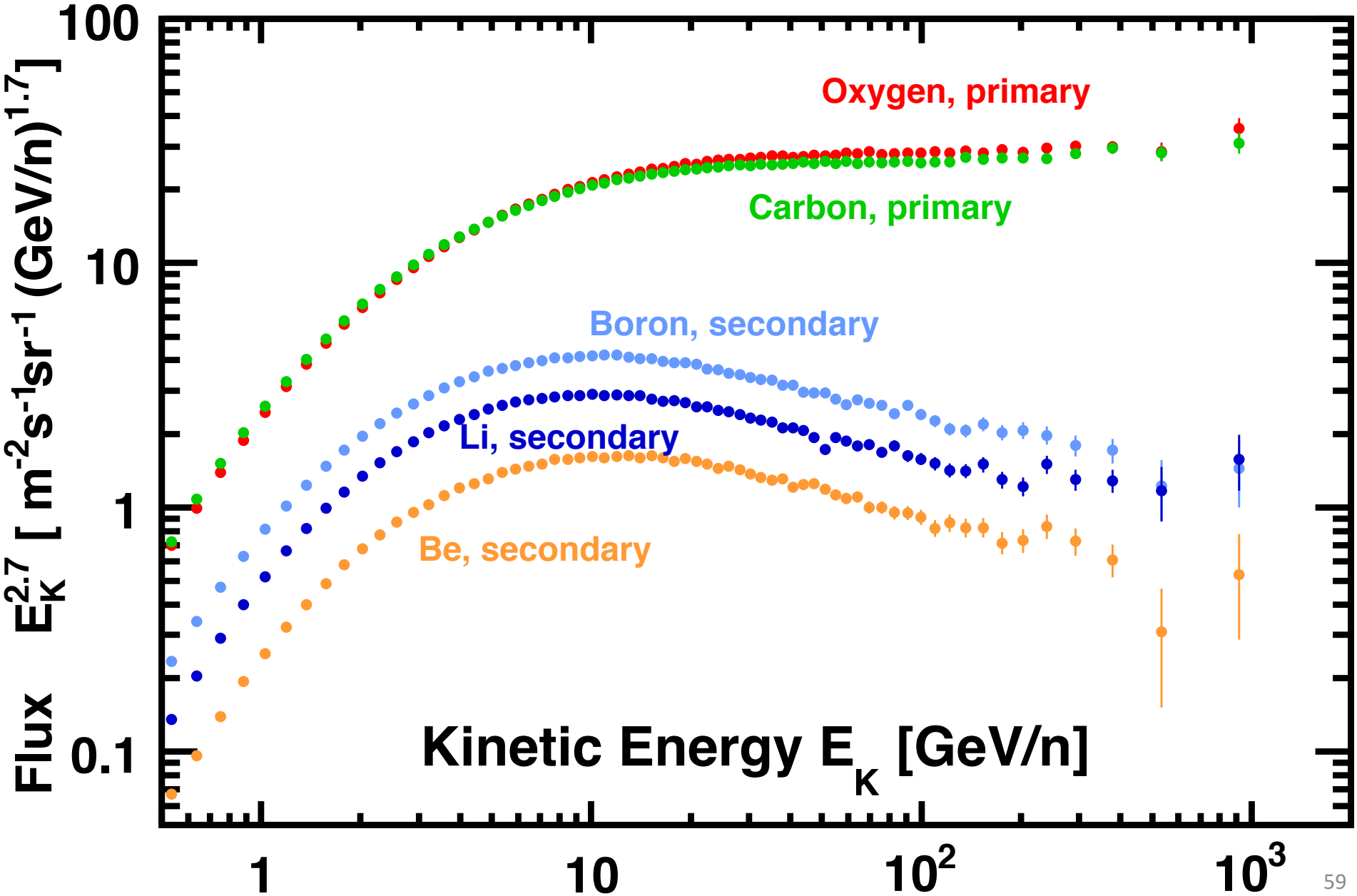
# Secondary Cosmic Rays (Li, Be, B, …)

C, O, …, Fe + ISM → Li, Be, B + X

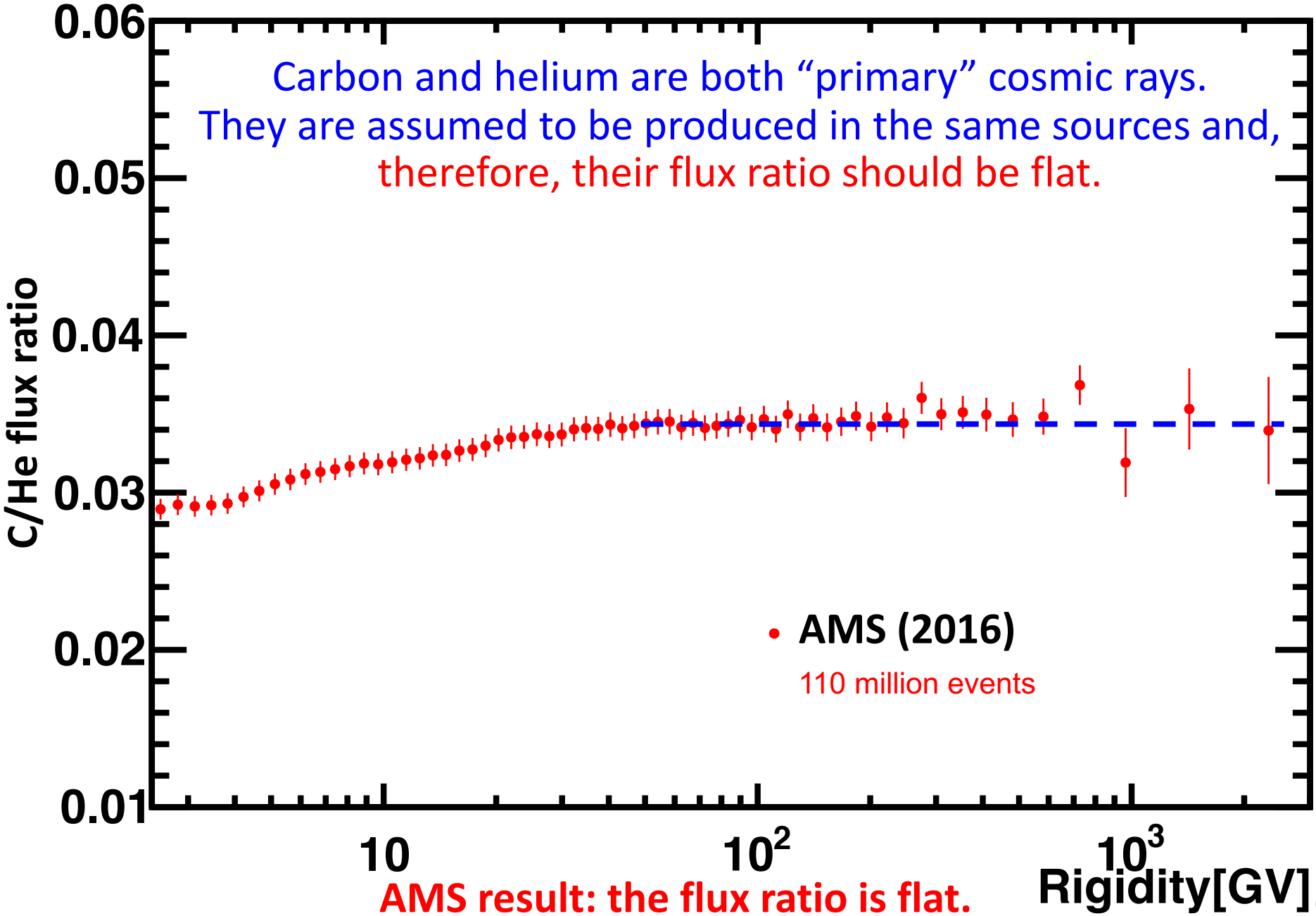



**Secondary cosmic rays carry information about propagation of primaries, secondaries and the ISM.**

# Physics Result 17: Primary and secondary Cosmic Rays have very different momentum dependence

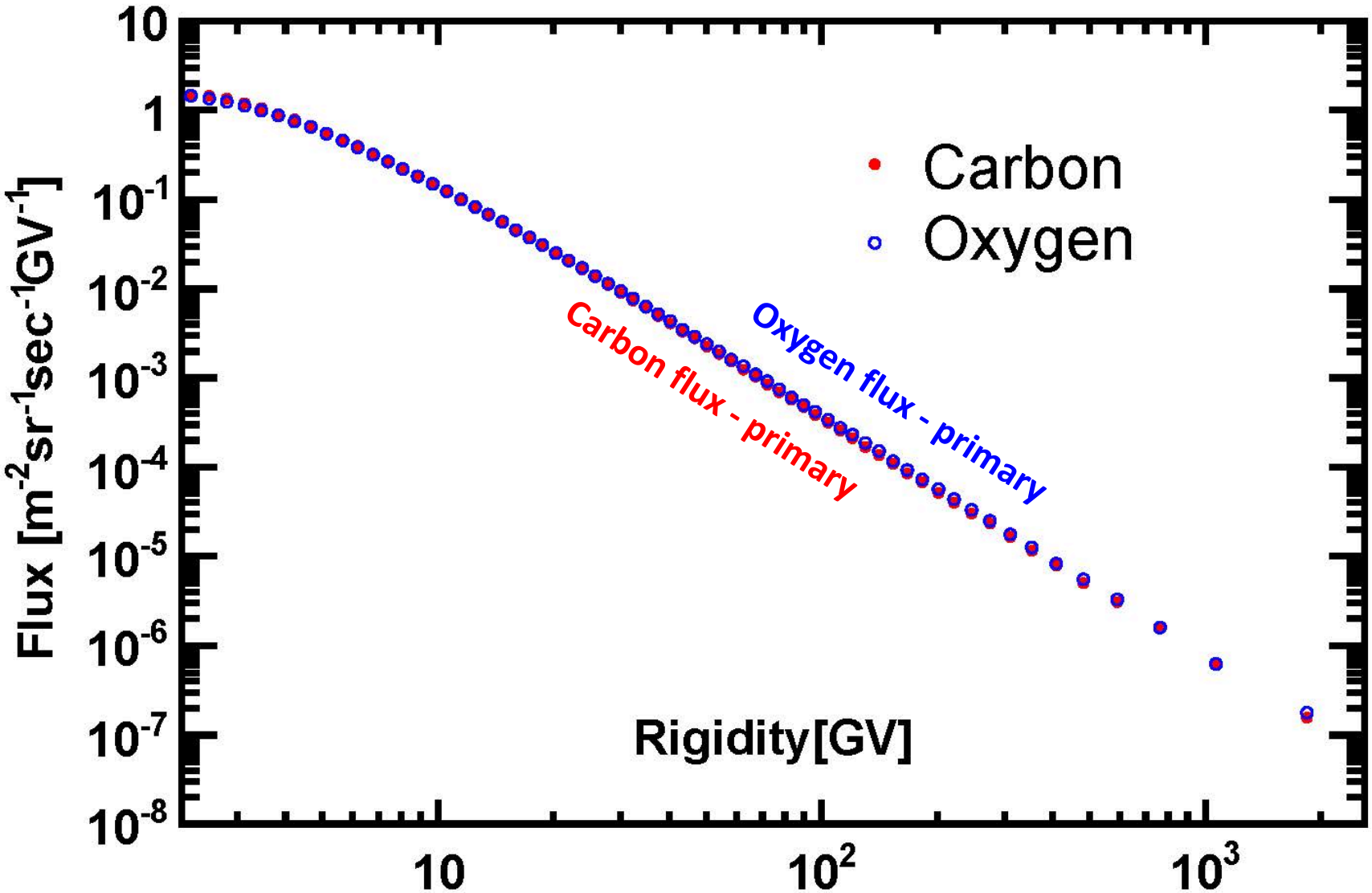


# **Physics Result 18:** The AMS carbon/helium flux ratio

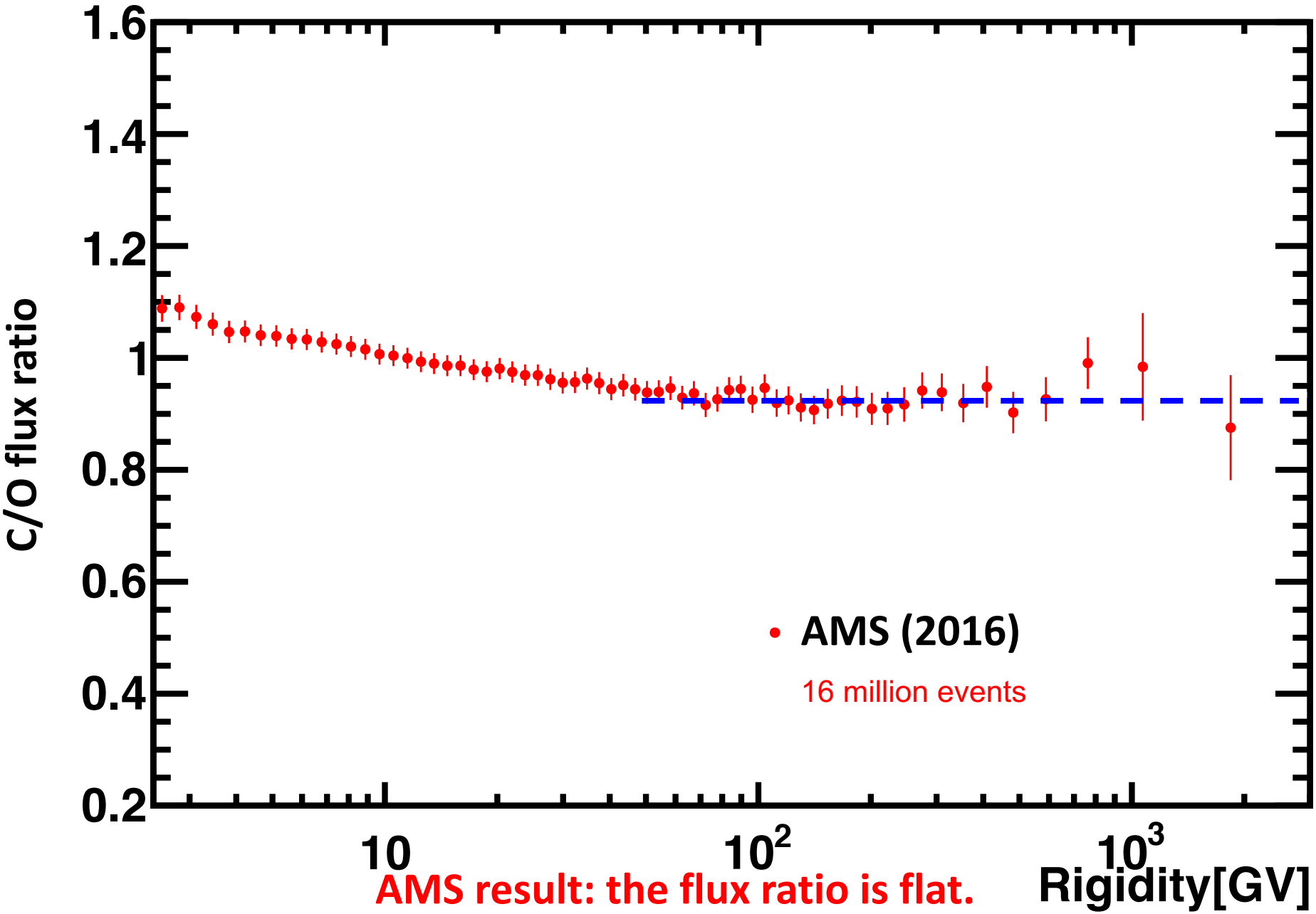



**AMS result: the flux ratio is flat.**

# Physics Result 19: Primary Cosmic Rays Carbon and Oxygen have identical momentum dependence.

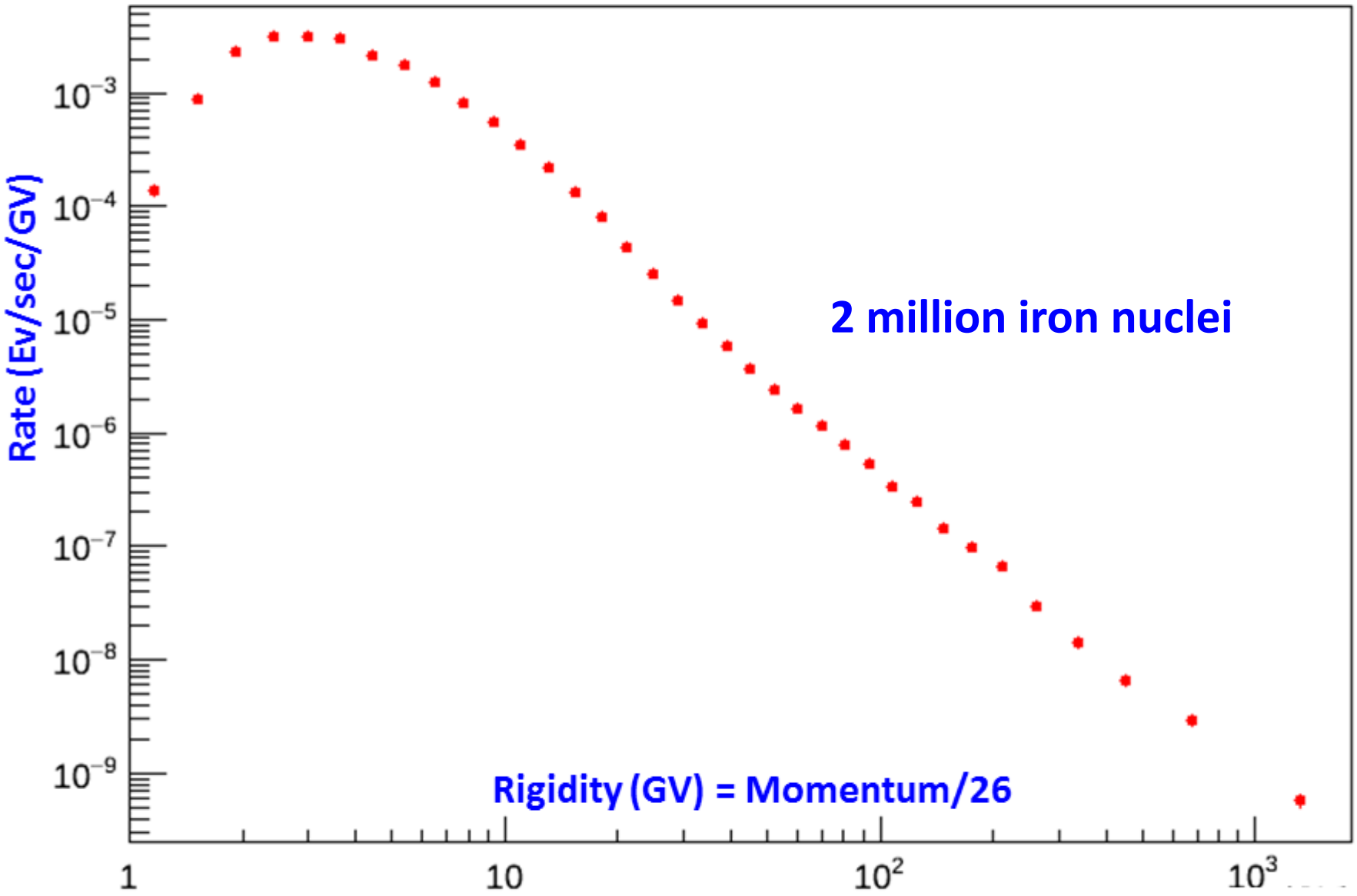


# The AMS carbon/oxygen flux ratio




AMS result: the flux ratio is flat.

# **Physics Result 20:** Iron rate

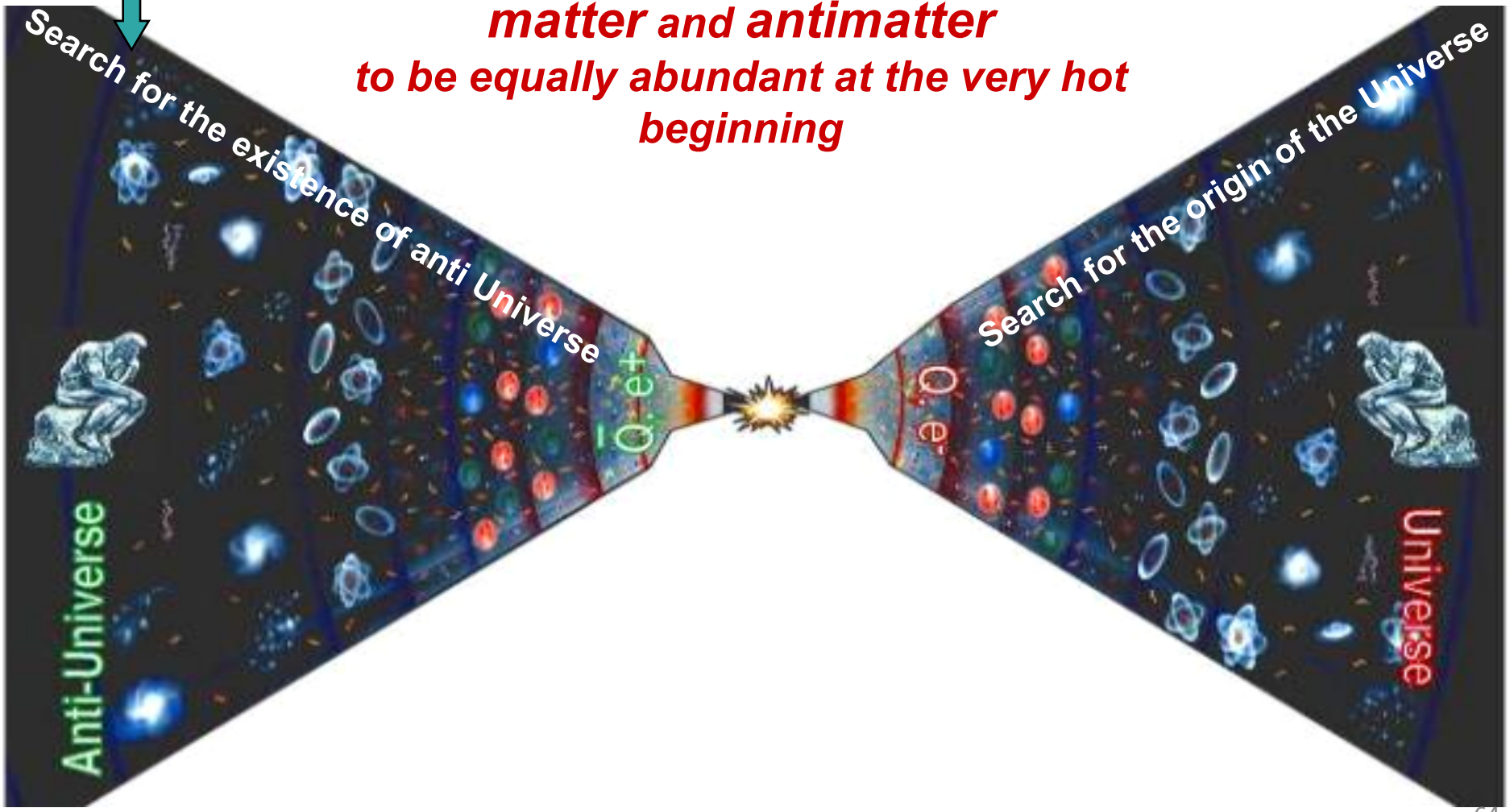


# **Physics Result 21:** Complex Antimatter in cosmic rays

## A Status Report

**AMS in Space**

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



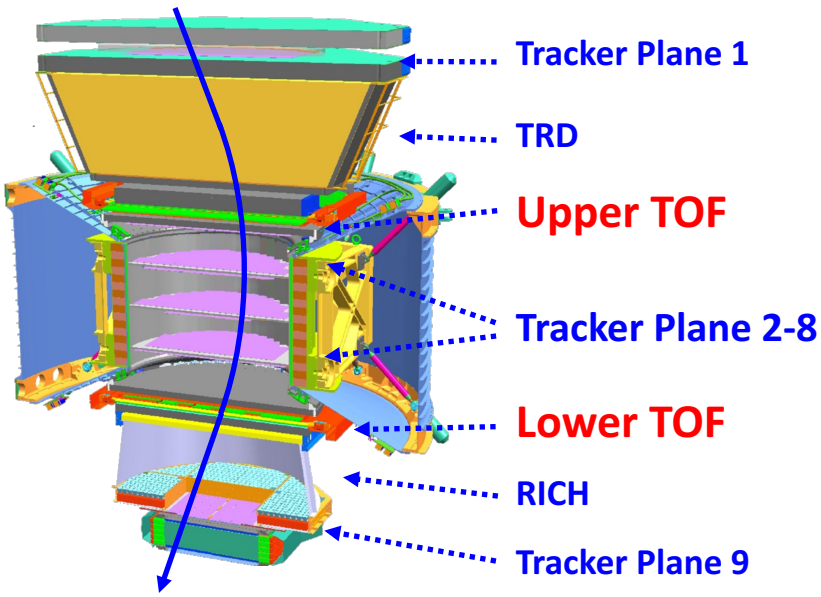
# Search for the explanation of the absence of antimatter in a complex form, that is, the search for Baryogenesis

## Baryogenesis requires:

| Strong Symmetry Breaking | Proton has a finite lifetime |
| --- | --- |
| BELLE, BaBar | underground experiments |
| FNAL: KTeV, CDF, D0, NOvA | Super Kamiokande |
| CERN NA-48<br>T2K,<br>LHC: LHC-b, ATLAS,CMS | |

**Despite the outstanding experimental efforts over the last half a century, no evidence for strong symmetry breaking nor proton decay have been found**

**In five years, 3.7 billion helium events have been collected by AMS when both the Upper and Lower TOF measure |Z| = 2 with an accuracy of 0.08**



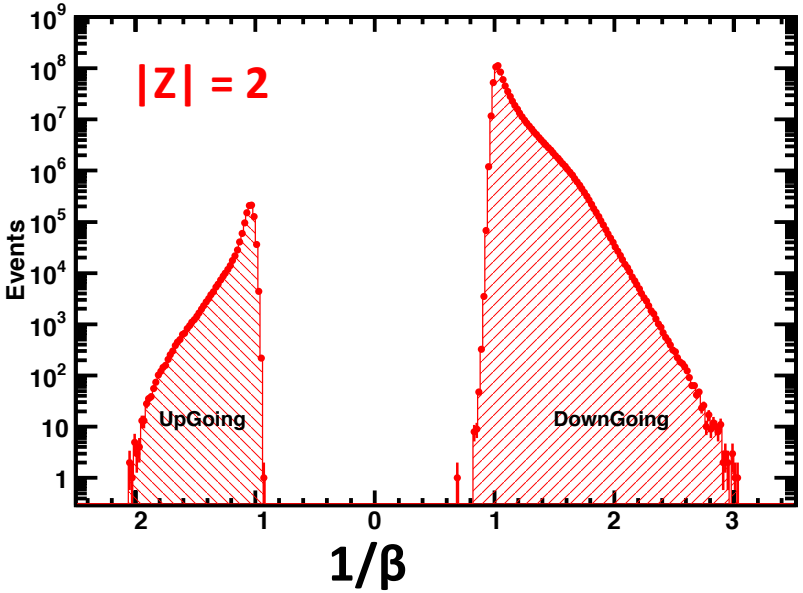

**Of these, 100 million passed through the full lever arm (L1 to L9) and are used in the analysis of the helium spectrum.**

**In our helium publication we used the first 2.5 years of data (50 million events).**

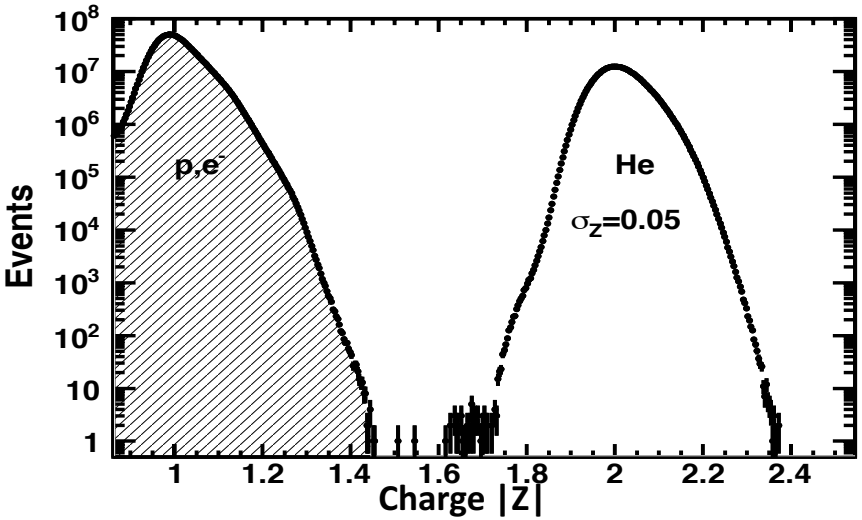
**In searching for antihelium we use a larger acceptance (L2 to L8) with 700 million helium events to date.**

# Identification of antihelium

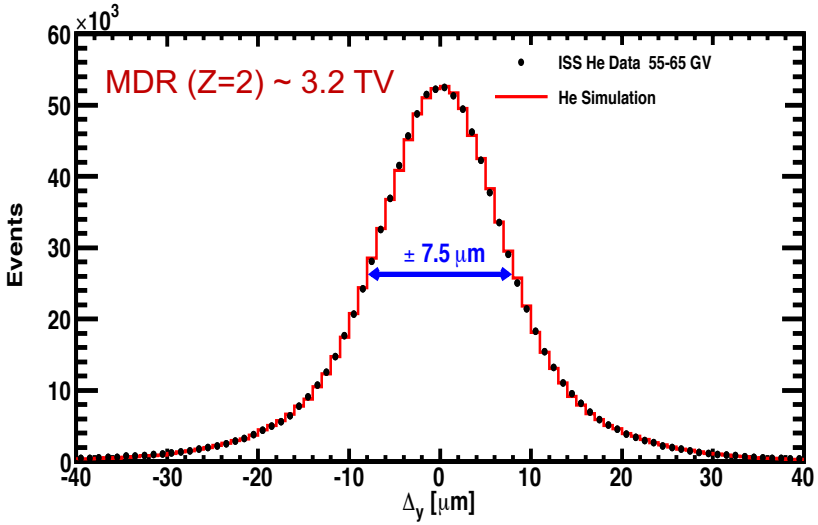
1. Determine direction with TOF.



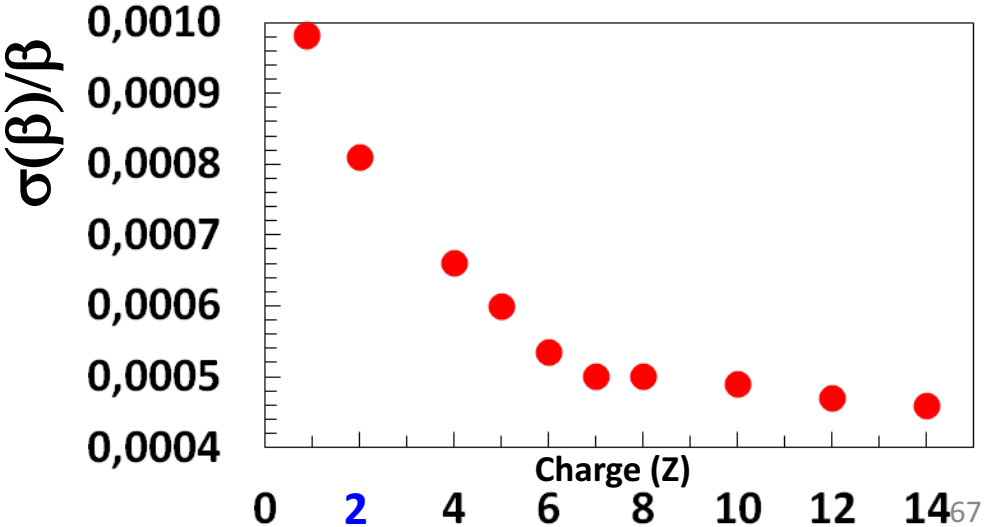

2. To measure |Z|, use the TOF+Tracker+RICH to separate p,e$^{\pm}$ from He




3. To measure momentum and sign of the charge, use Tracker




4. To determine mass, use the RICH to measure the velocity.



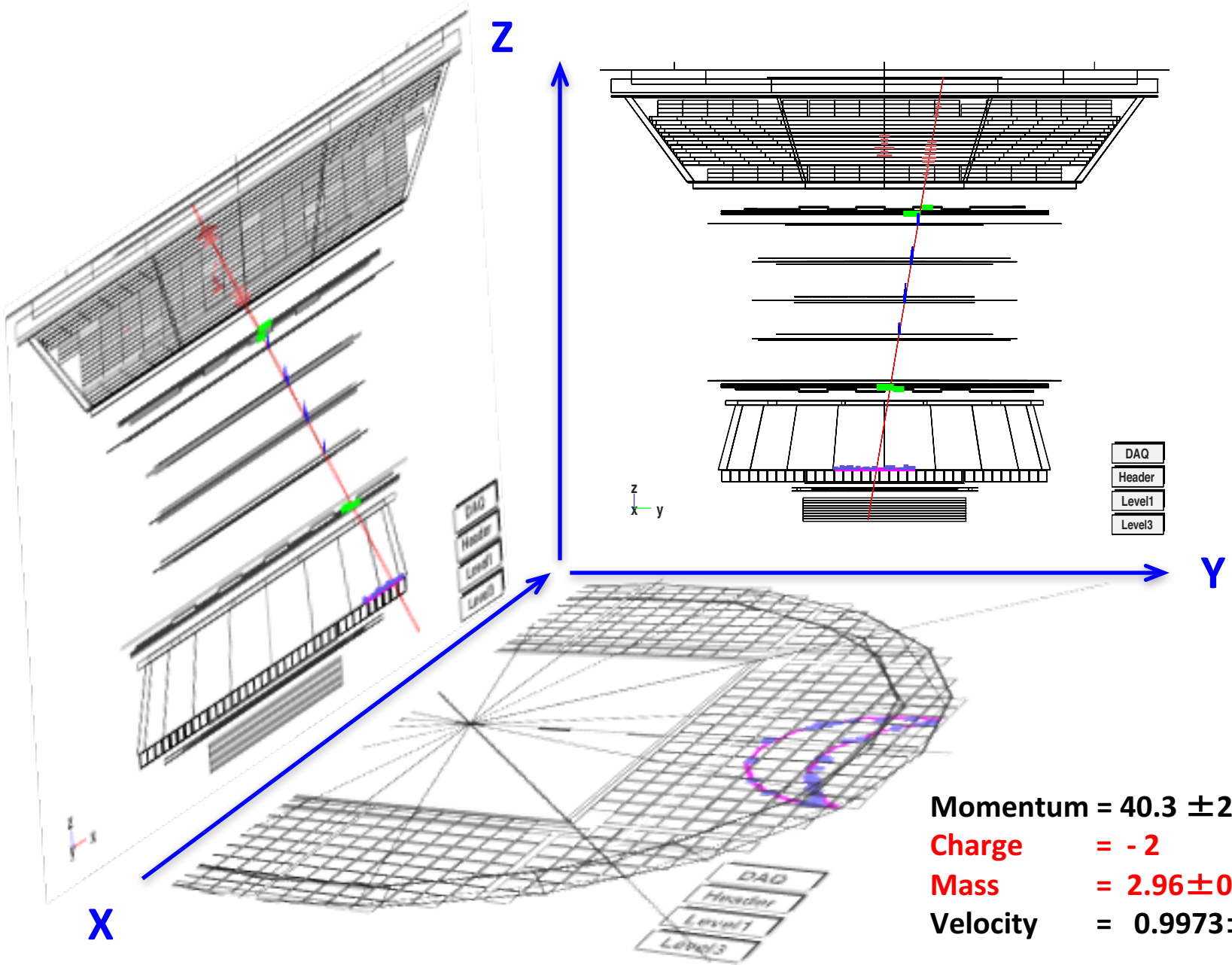
**To date we have observed**

**a few events**

**with Z = -2 and**

**with mass around $^{3}$He.**

# An anti-Helium candidate:




Momentum = 40.3 ±2.9 GeV/$c$

Charge = - 2

Mass = 2.96±0.33 GeV/$c^2$

Velocity = 0.9973±0.0005 $c$

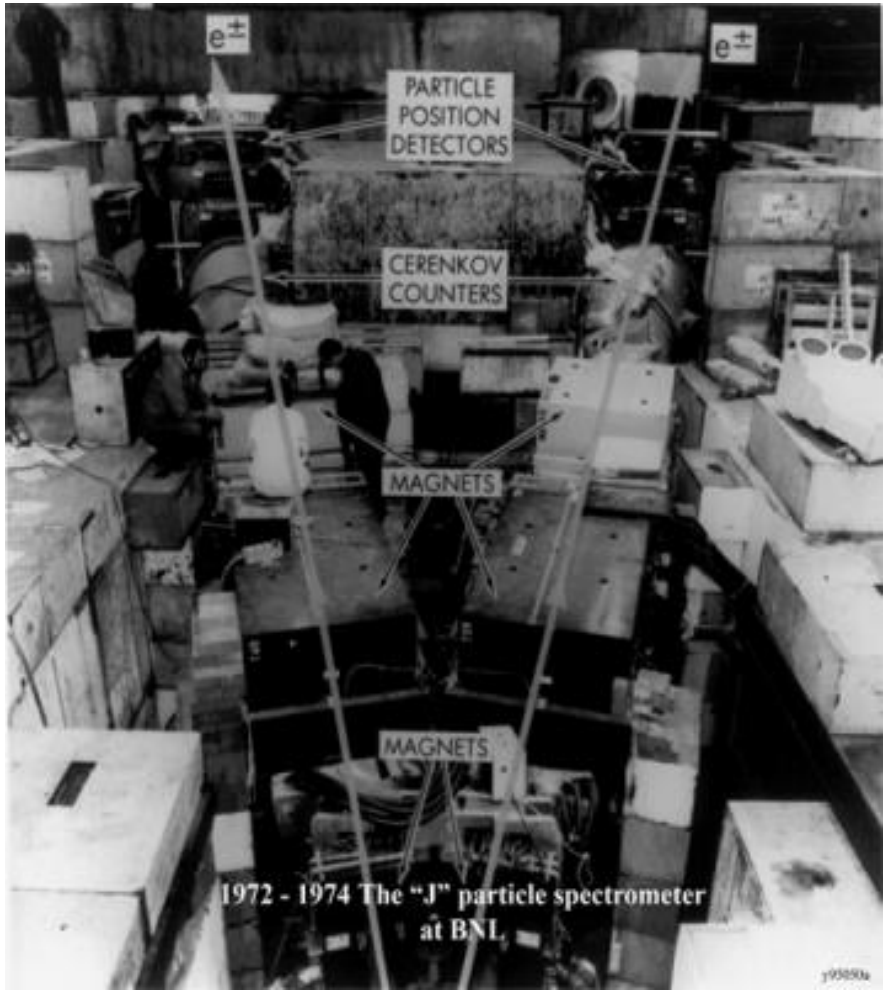
# Antihelium and AMS

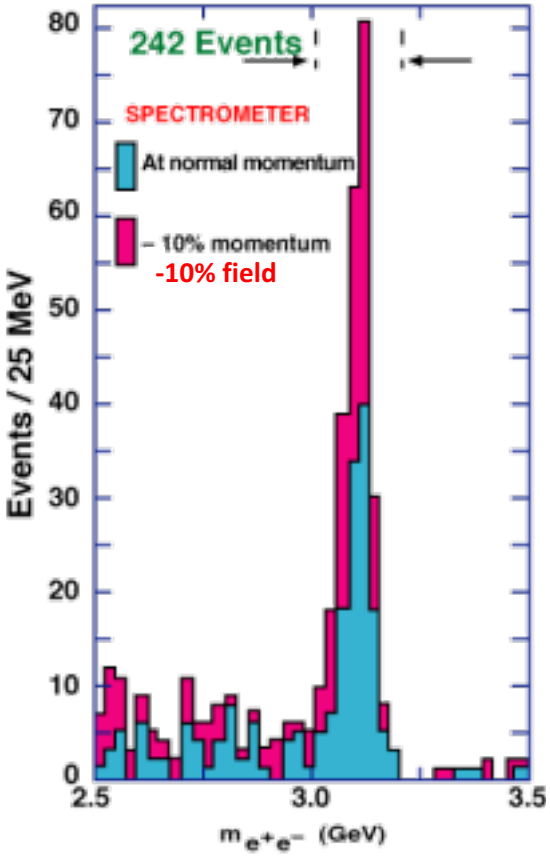
**At a signal to background ratio of 1/$10^9$, detailed understanding of the instrument is required.**

**Example A:** Discovery of the J particle requires $\frac{\text{Background}}{\text{Signal}} = \frac{\pi\ \pi}{e\ e} > 10^{10}$

**Detector Verification: Collecting data at 2 magnetic fields**

$P + Be \rightarrow e^+ + e^- + \ldots$



**Example B:**

THE NEW YORK TIMES, MONDAY, JUNE 14, 1965.

AY PRESSES TO LIBERALS

alks With Dubinsky
ıse and Is Reported
ıraged by Results

ndsay-for-Mayor forces

*Physicists Produce Antimatter Particles In a Complex Form*

By HAROLD M. SCHMECK Jr.

Are there somewhere anti-worlds, populated, perhaps, by antipeople?

The question seems like fantasy, but the answer could conceivably be yes in the light of research just reported from

HOUSE WILL VOTE ON CABINET POST

Johnson Faces Major Test This Week on New Urban and Housing Agency

By MARJORIE HUNTER

*Moscow Uncertain Whether to Speed Economic Reform*

By THEODORE SHABAD

Special to The New York Times

MOSCOW, June 13—A year ago the Soviet Union embarked on an experiment in economic reform. The implications were immense, for the whole notion of rigid central control, the

as "tantamount to capitalism."

The letter emphas Chinese Communist more militaristic idec asserted that there was torical precedent for a transition" of any co Socialism.

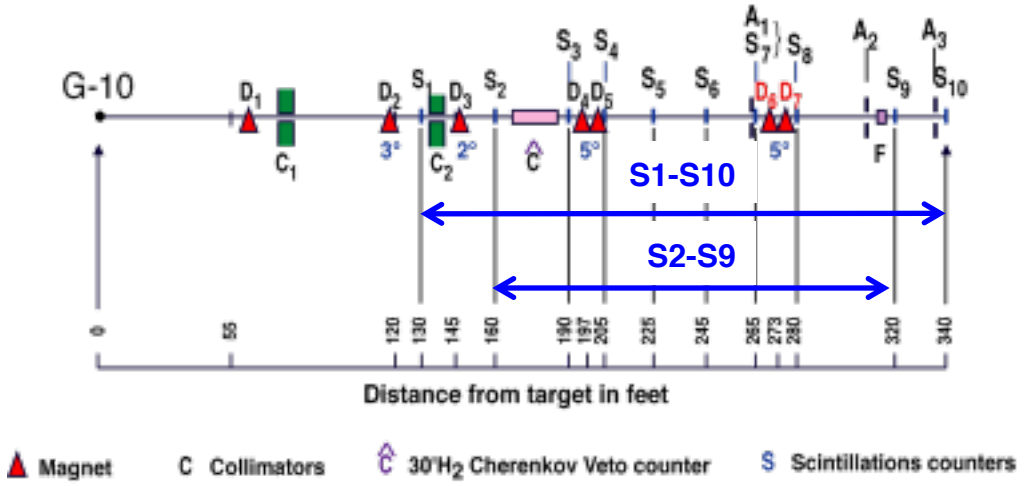
Collusion Charge

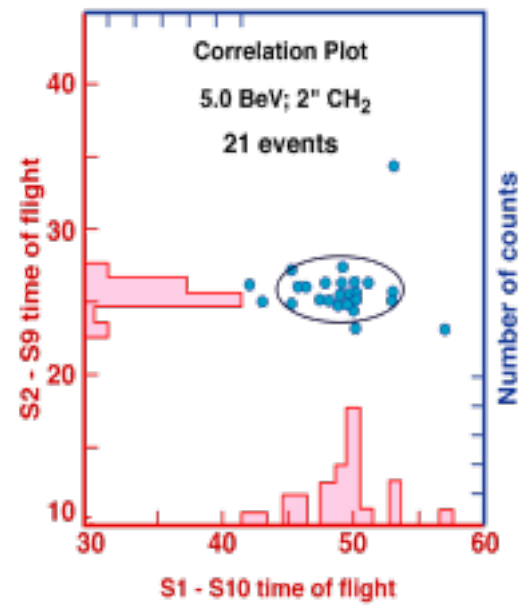
The current article Soviet policy on Viet charged that while Mos made "some gestures in Vietnam, it had disc

y97153

## Anti Deuterons (1965)

D.E. Dorfan, J. Eades, L.M. Lederman, W. Lee, and S.C.C. Ting
Phys. Rev. Letters 14, 1003 (1965)



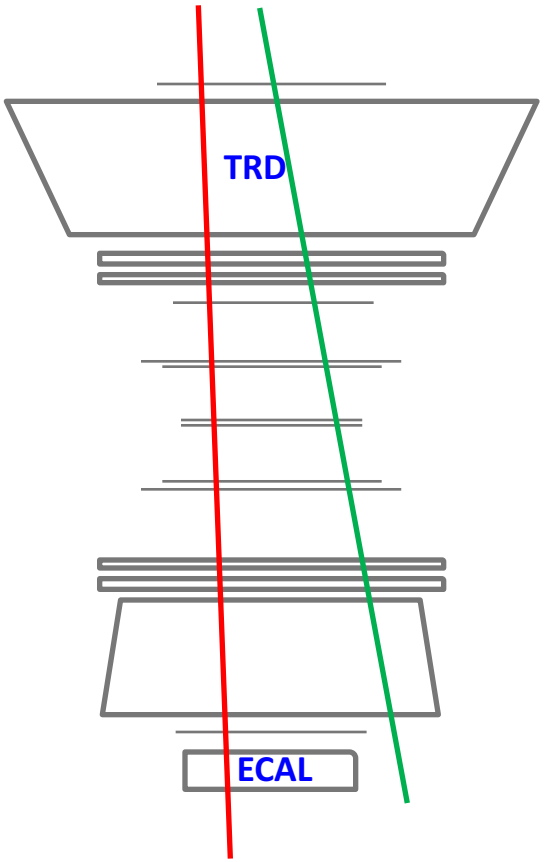



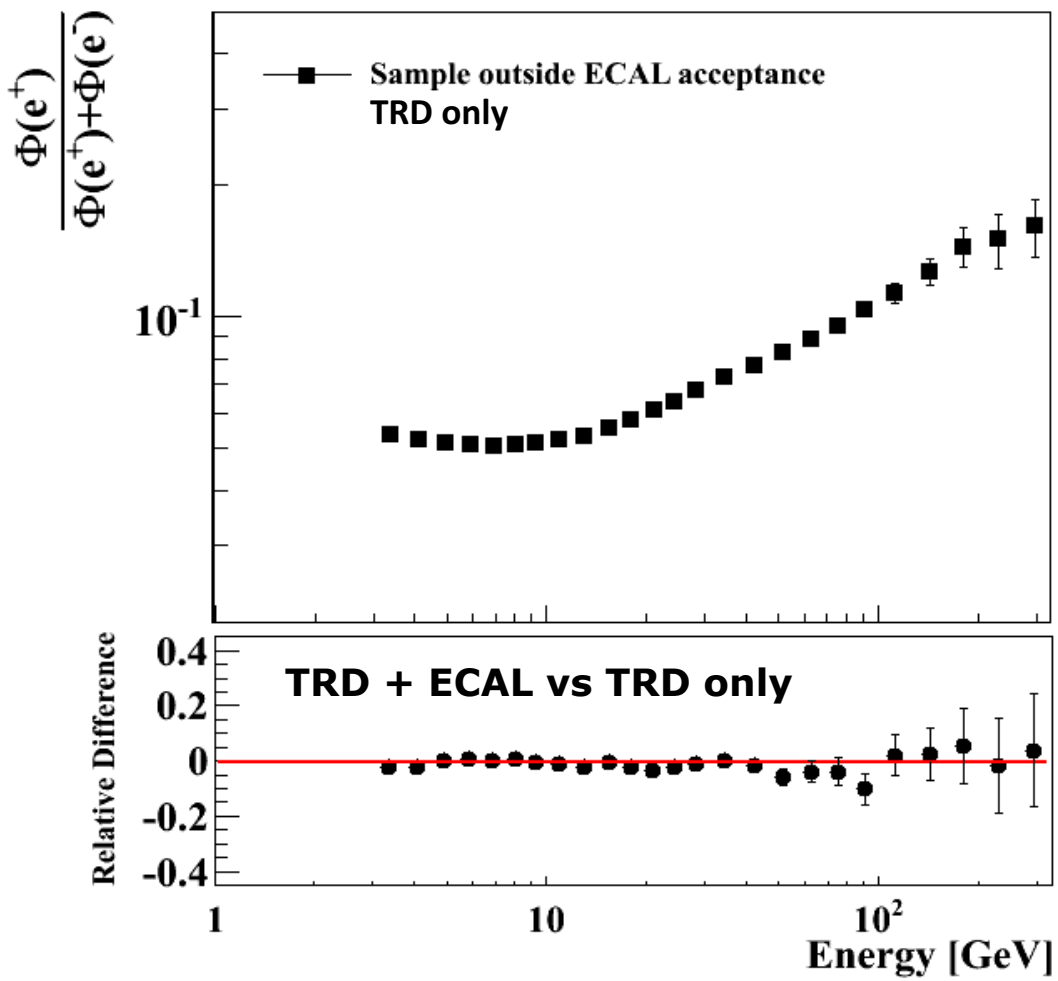

**S1 and S2 separated by strong bending magnet D3**

Example C:

## Precision measurement of Positron Fraction requires e and p separation of $1/10^6$

## Positron fraction analysis with TRD+ECAL compared with TRD Only



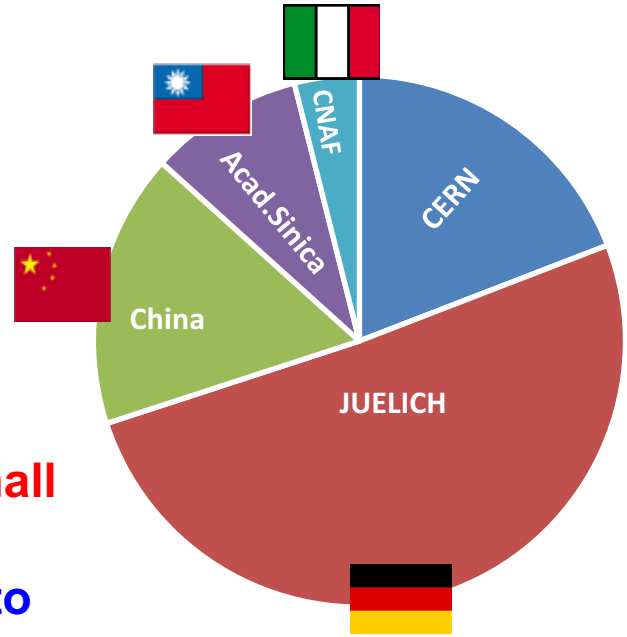

**Good agreement between two independent samples**

# Antihelium and AMS

**At a signal to background ratio of one in one billion, detailed understanding of the instrument is required.**

**Detector verification is difficult.**

1. **The magnetic field cannot be changed.**
2. **The rate is ~1 per year.**
3. **Simulation studies:**




**Helium simulation to date:**
**2.2 million CPU-Days =**
**35 billion simulated helium events:**
**Monte Carlo study shows the background is small**

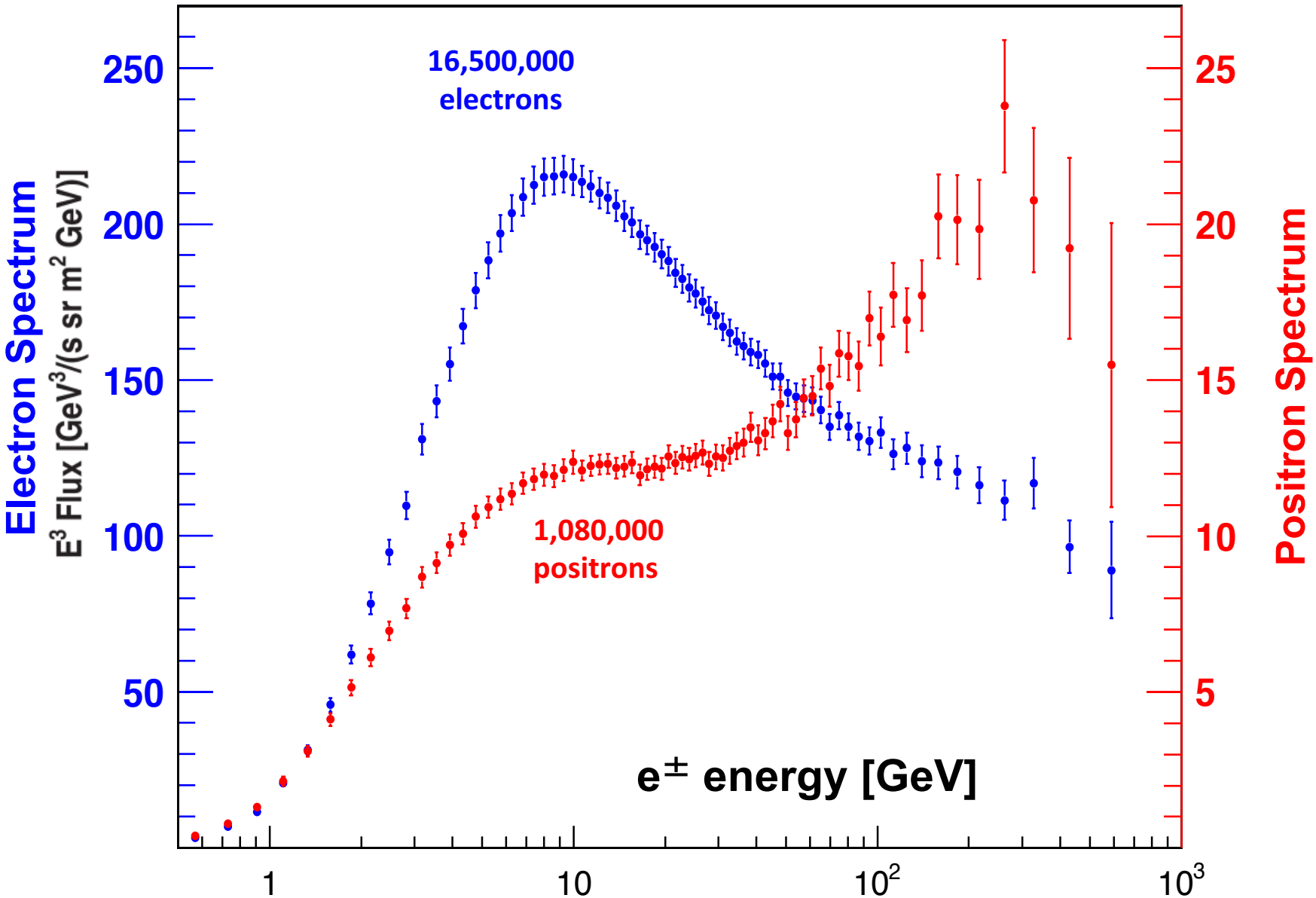
**How to ensure that the simulation is accurate to one in one billion?**

**The few candidates have mass 2.8 GeV and charge -2 like $^{3}\overline{He}$.**

**It will take a few more years of detector verification and to collect more data to ascertain the origin of these events.**

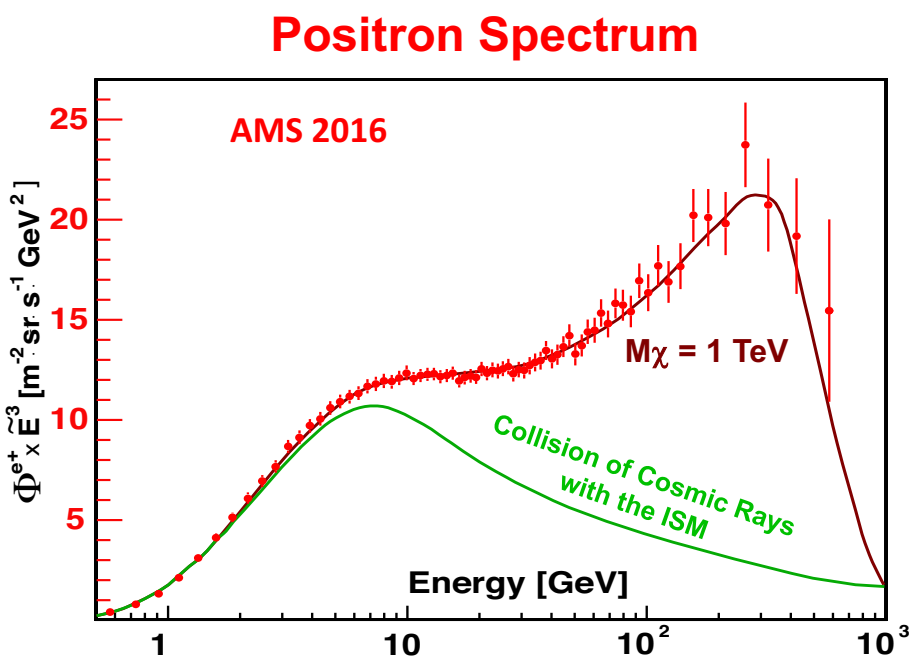
# Summary (on elementary particles)

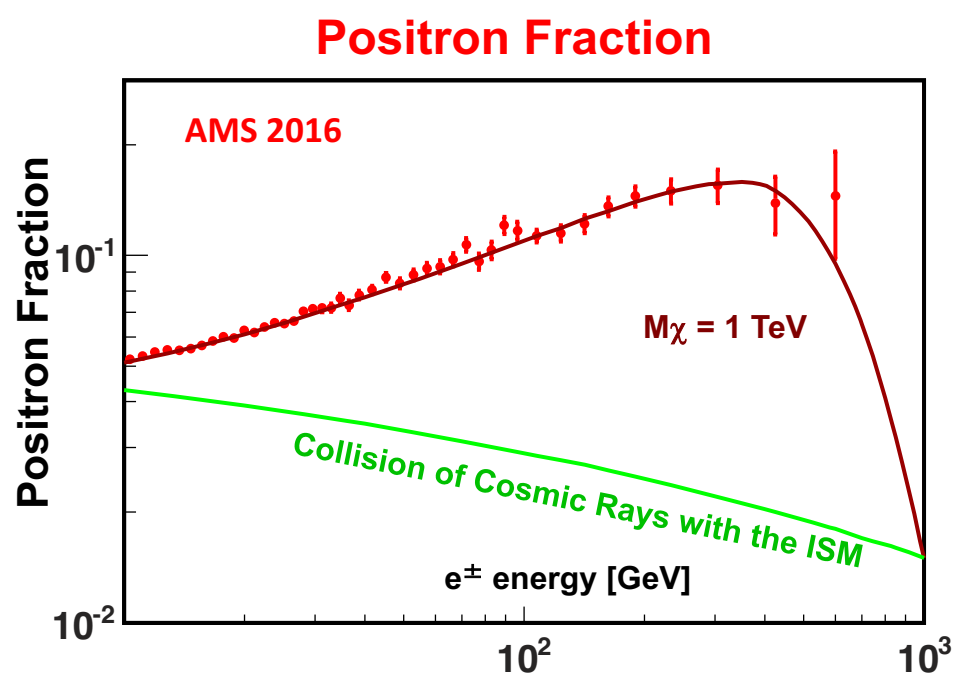
**The electron flux and the positron flux are different in their magnitude and energy dependence.**



# Summary (on elementary particles)

## The positron flux and the positron fraction data require new physics.

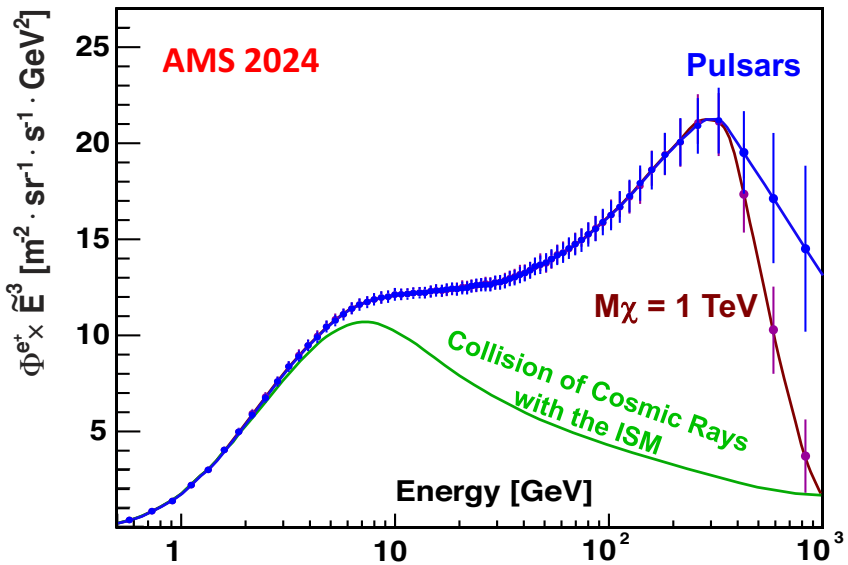


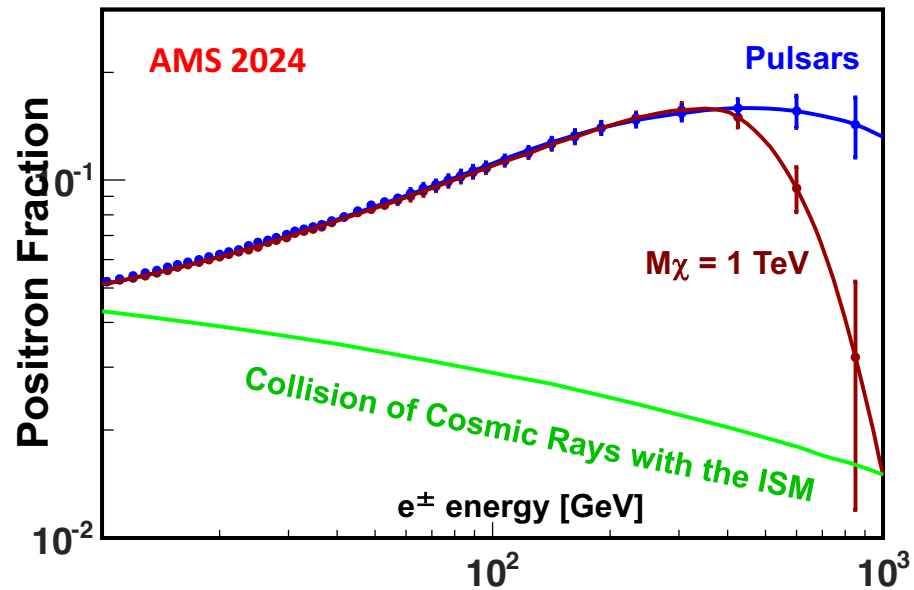



# Summary (on elementary particles)

**Positron Spectrum** **Positron Fraction**

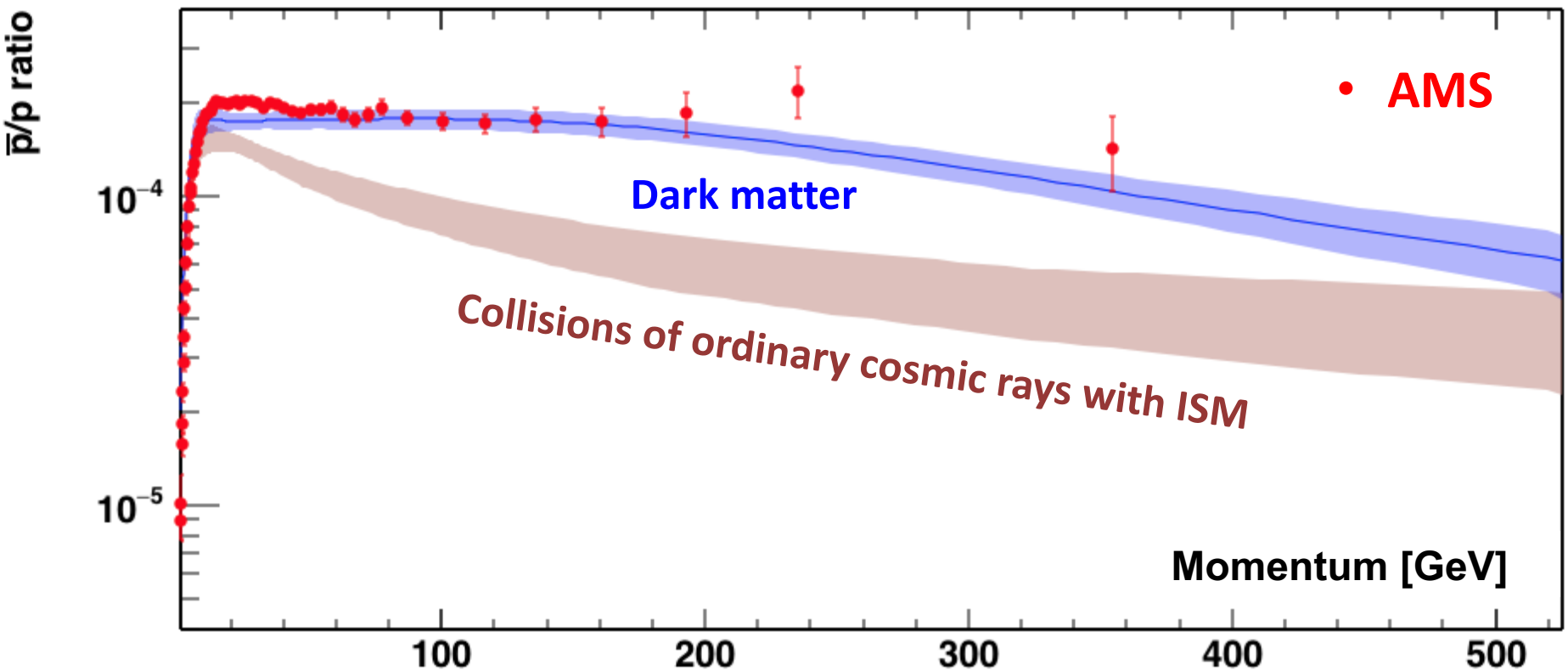
**By 2024 we will should be able understand the origin of this unexpected data.**



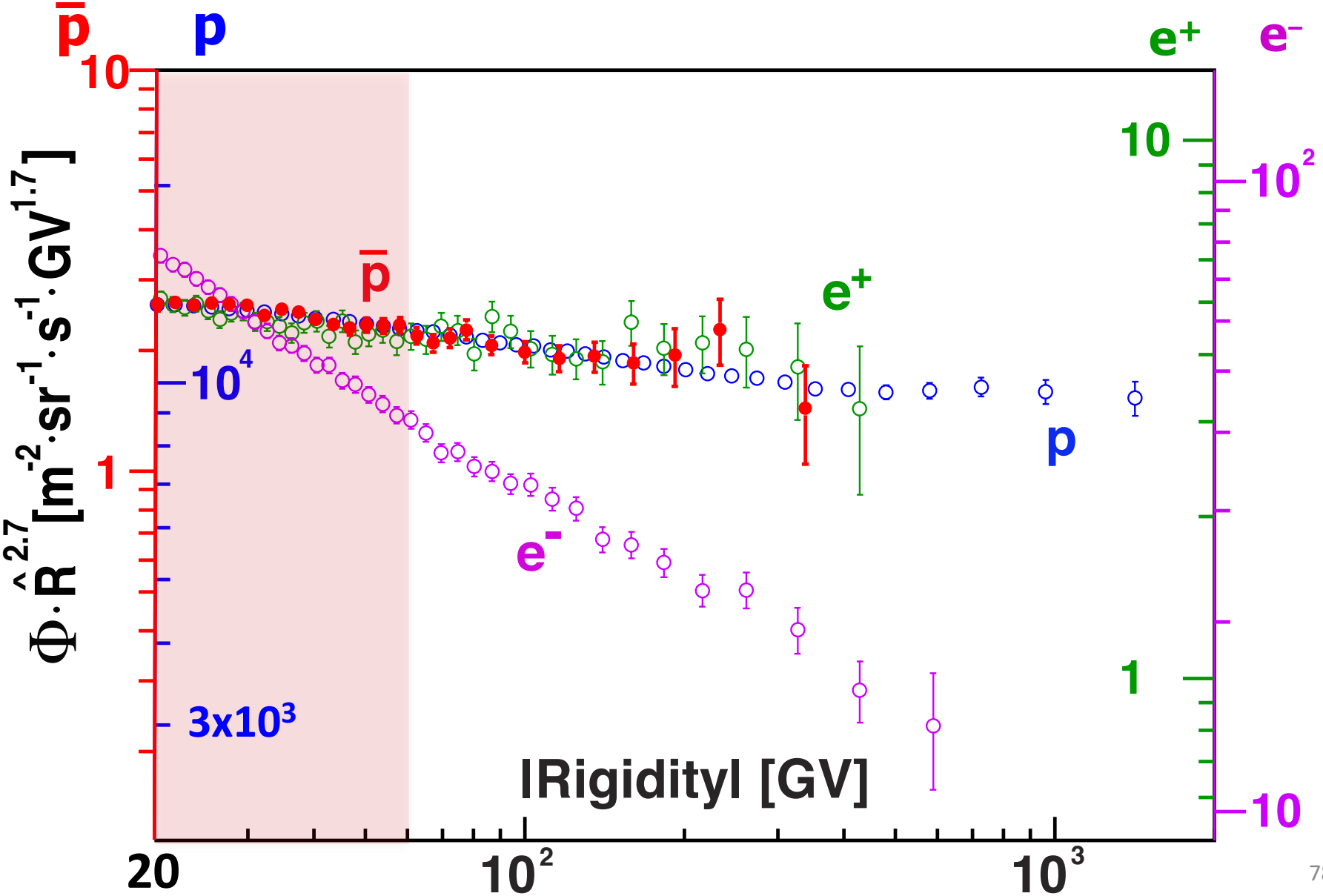
# Summary (on elementary particles)

**The excess of antiprotons observed by AMS cannot come from pulsars.**
**It can be explained by Dark Matter collisions or by new astrophysics phenomena.**



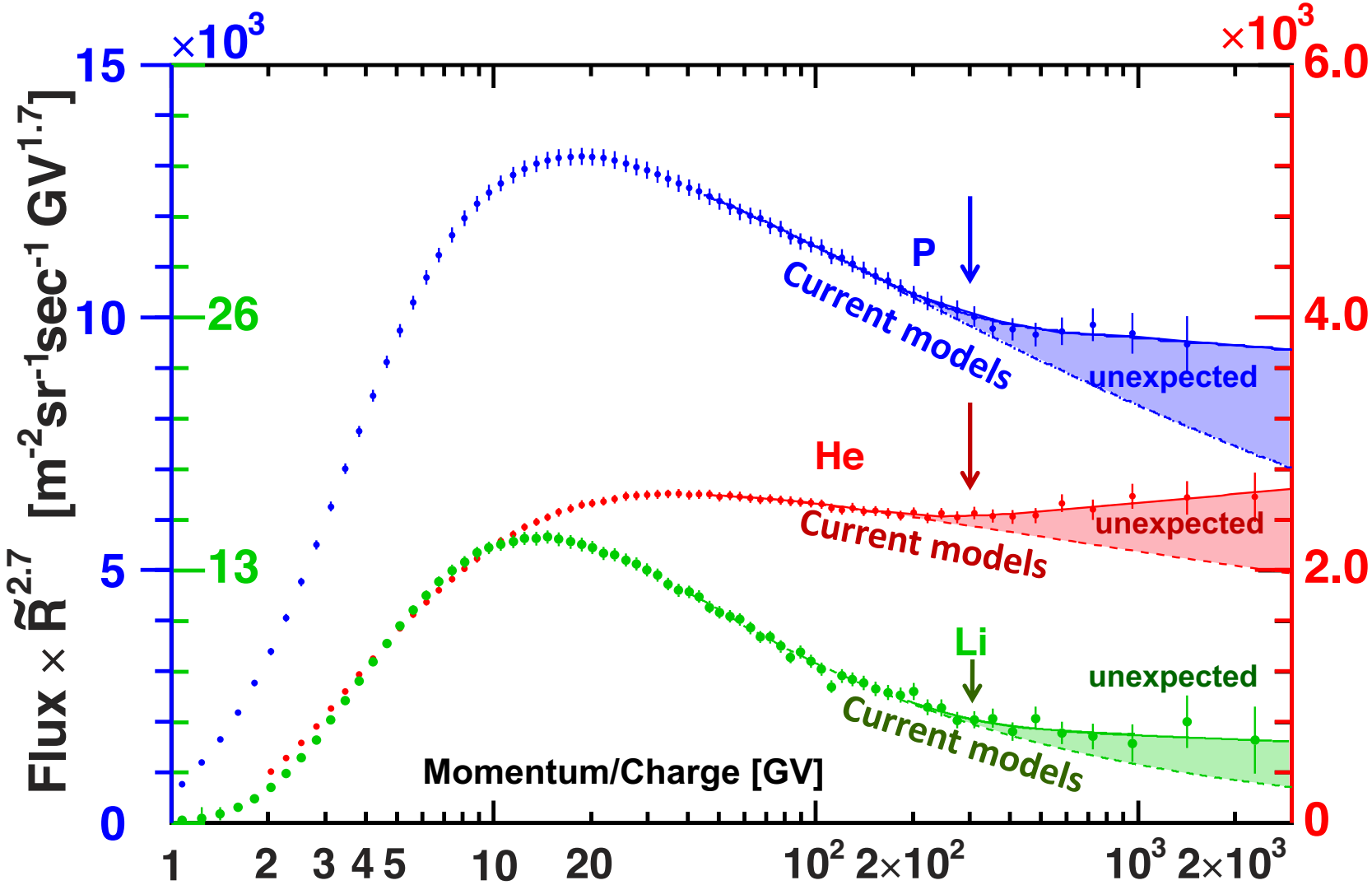
# Summary (on elementary particles)

**The e+, p̄, p spectra have identical energy dependence from 60-500 GV, e- does not.**



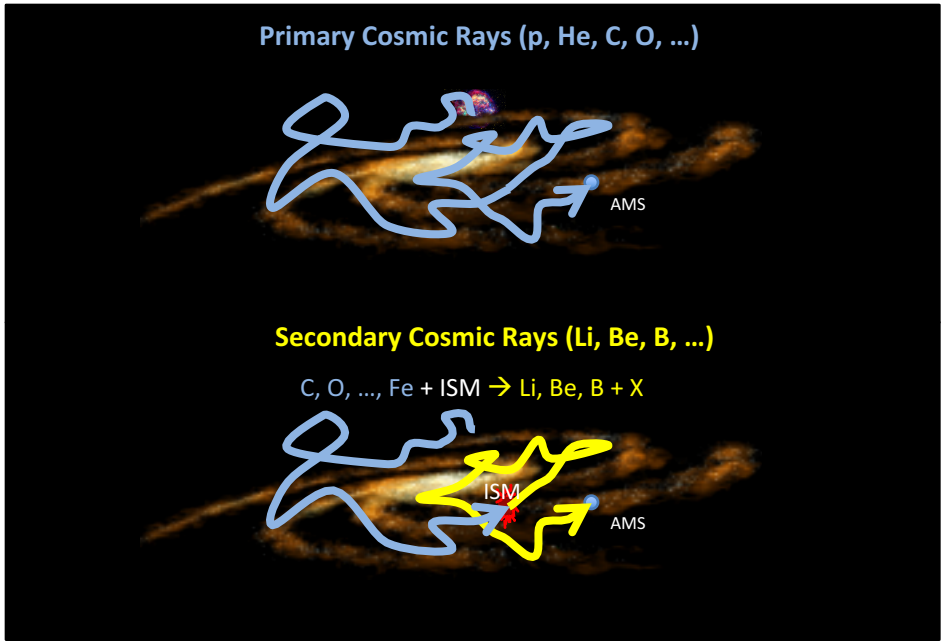
# Summary (on nuclei)

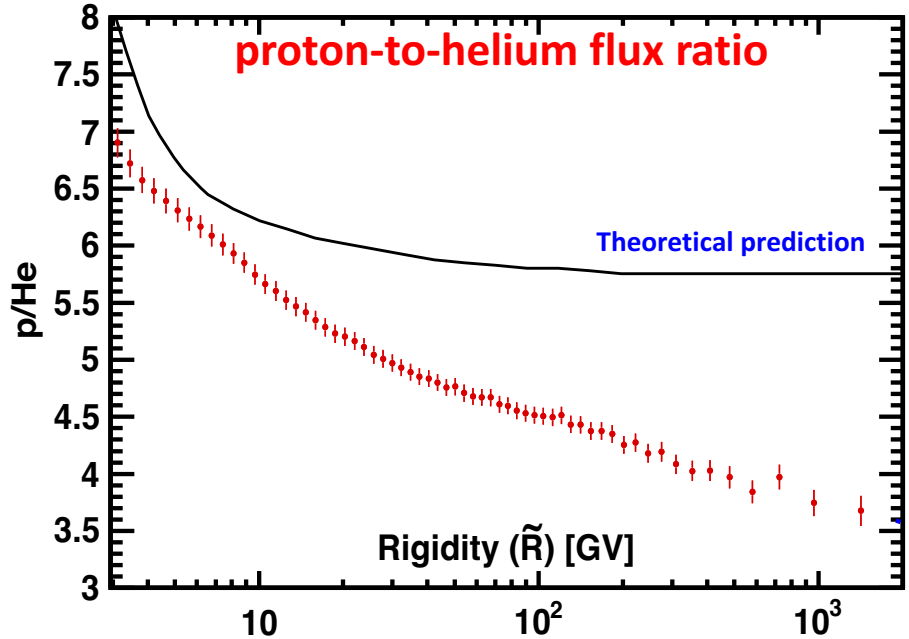
**The spectra of protons, helium and lithium do not follow the traditional single power law. They all change their behavior at the same energy.**

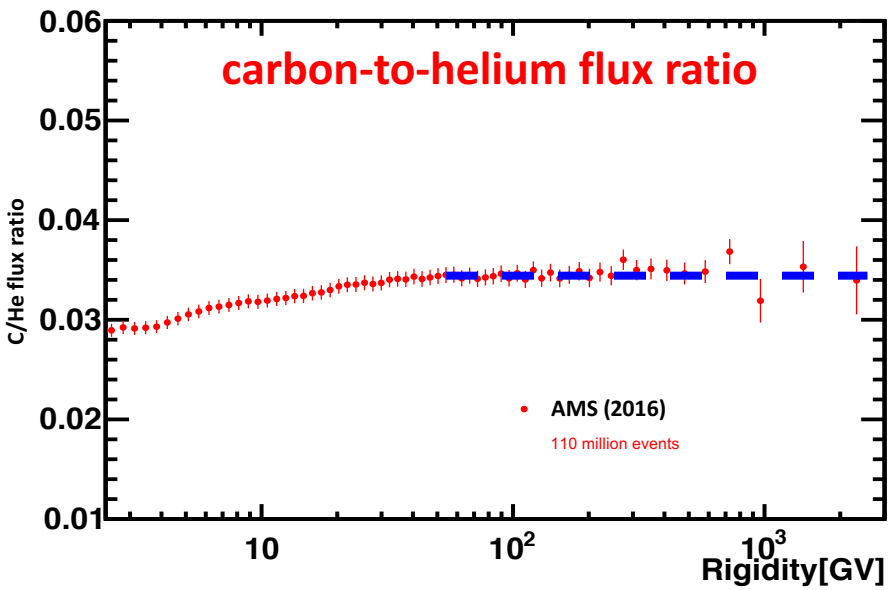


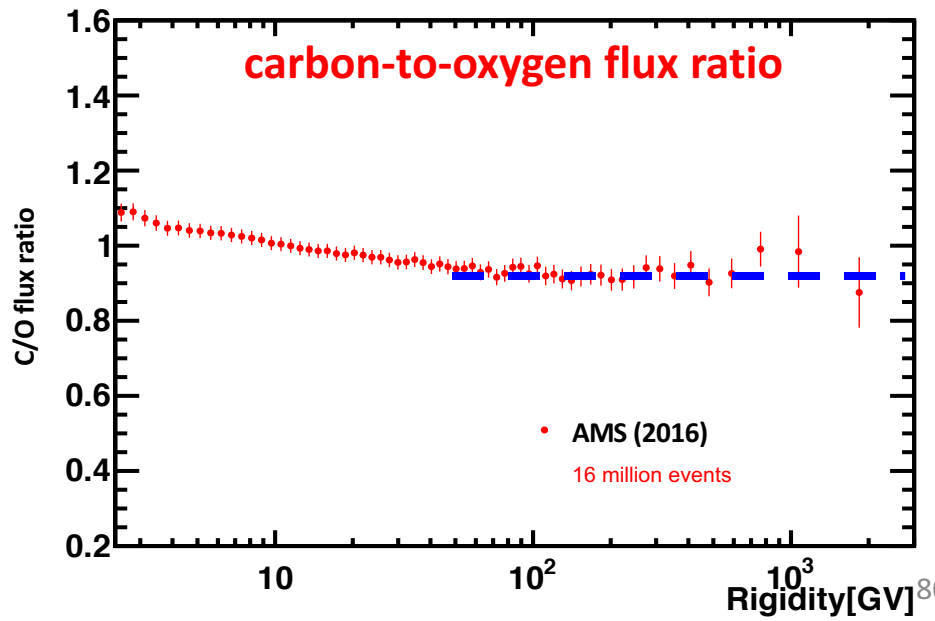
# Summary (on nuclei)

## The flux ratios of primary cosmic rays are energy independent except p/He.



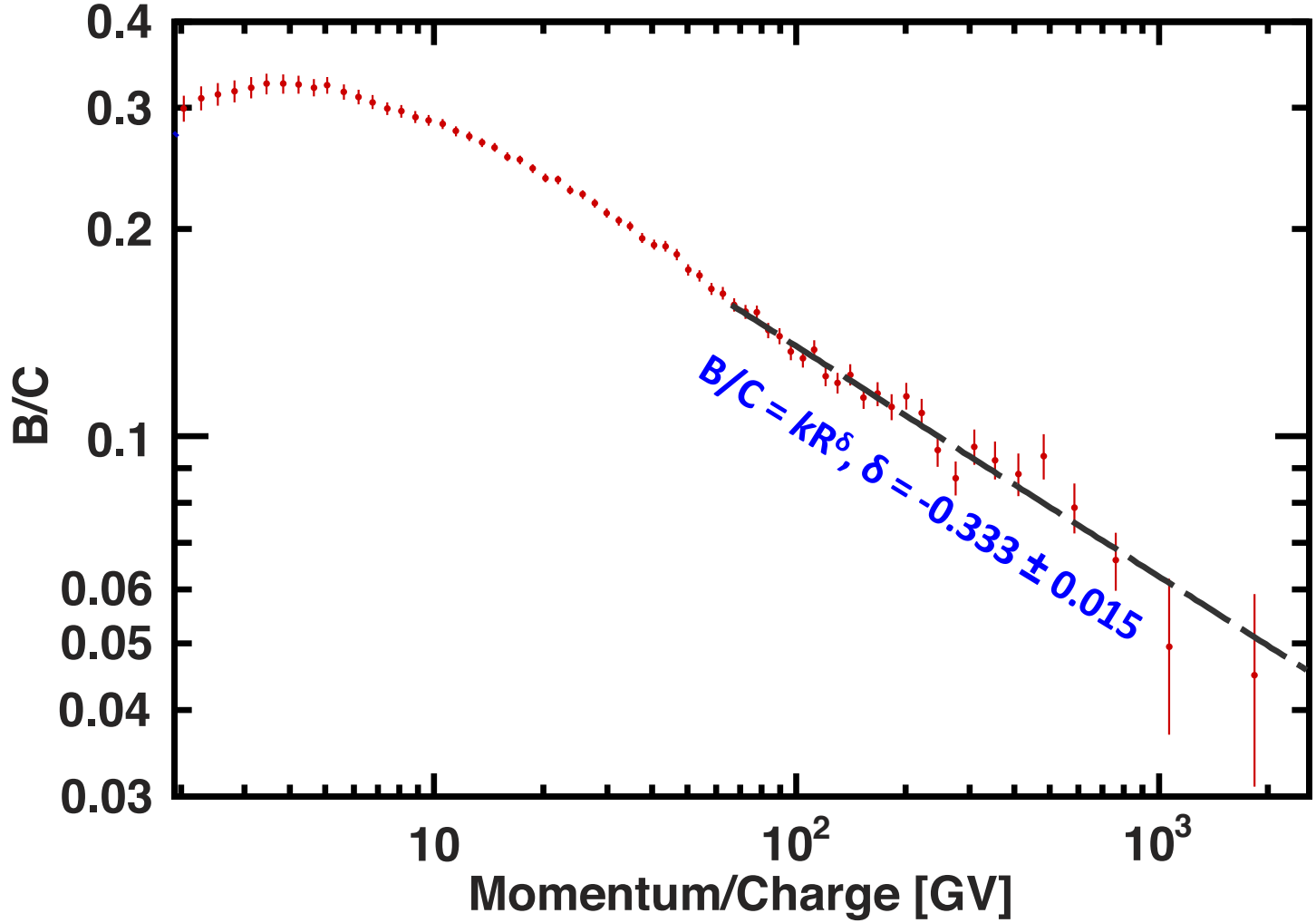



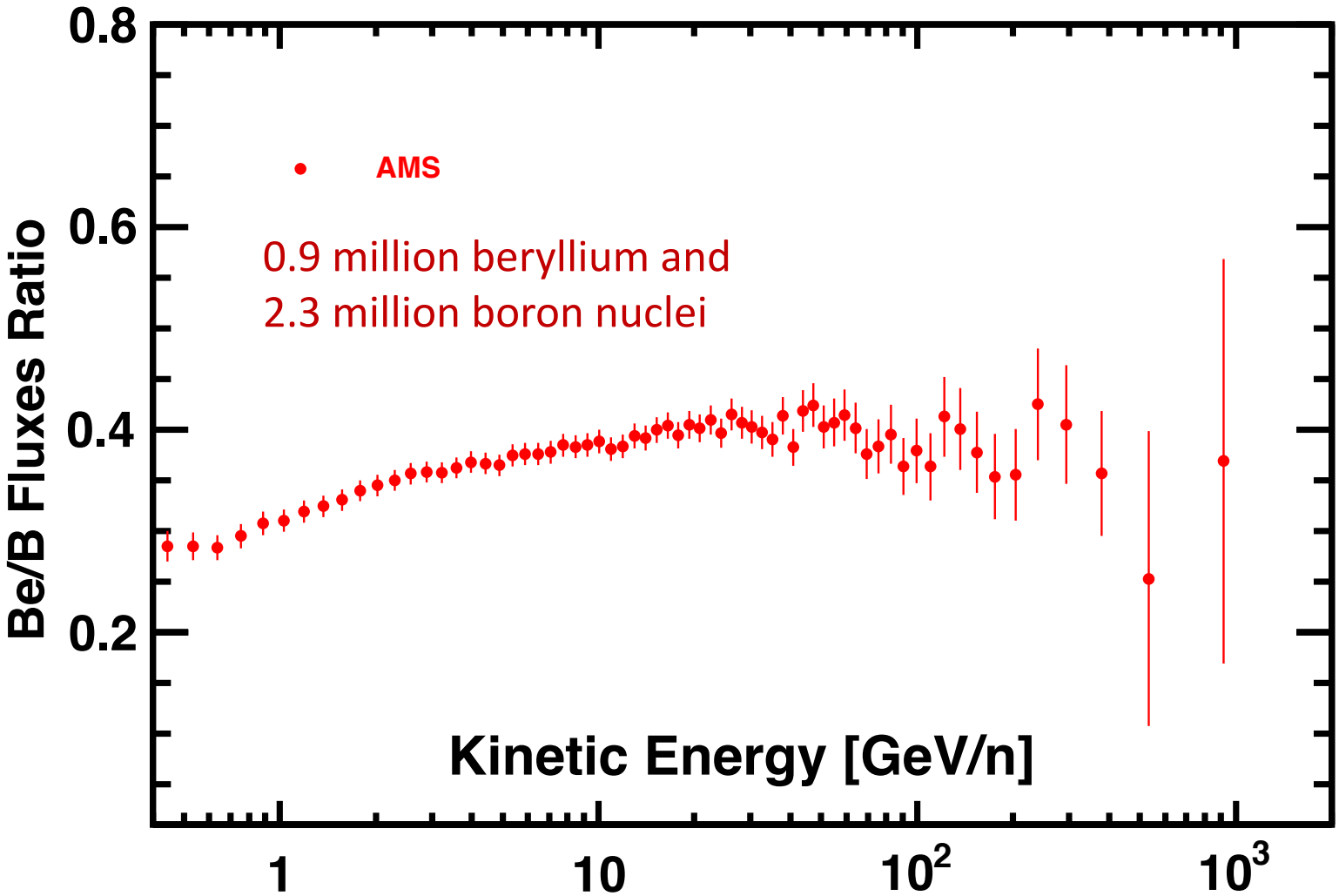
# Summary (on nuclei)

The B/C ratio does not show any significant structures in contrast to many cosmic ray models that require such structures at high rigidities. Remarkably, above 65 GV, the B/C ratio is well described by a single power law $B/C = k\,R^{\delta}$ with $\delta = -0.333 \pm 0.015$. This is in agreement with the Kolmogorov turbulence model of magnetized plasma of $\delta = -1/3$ asymptotically.



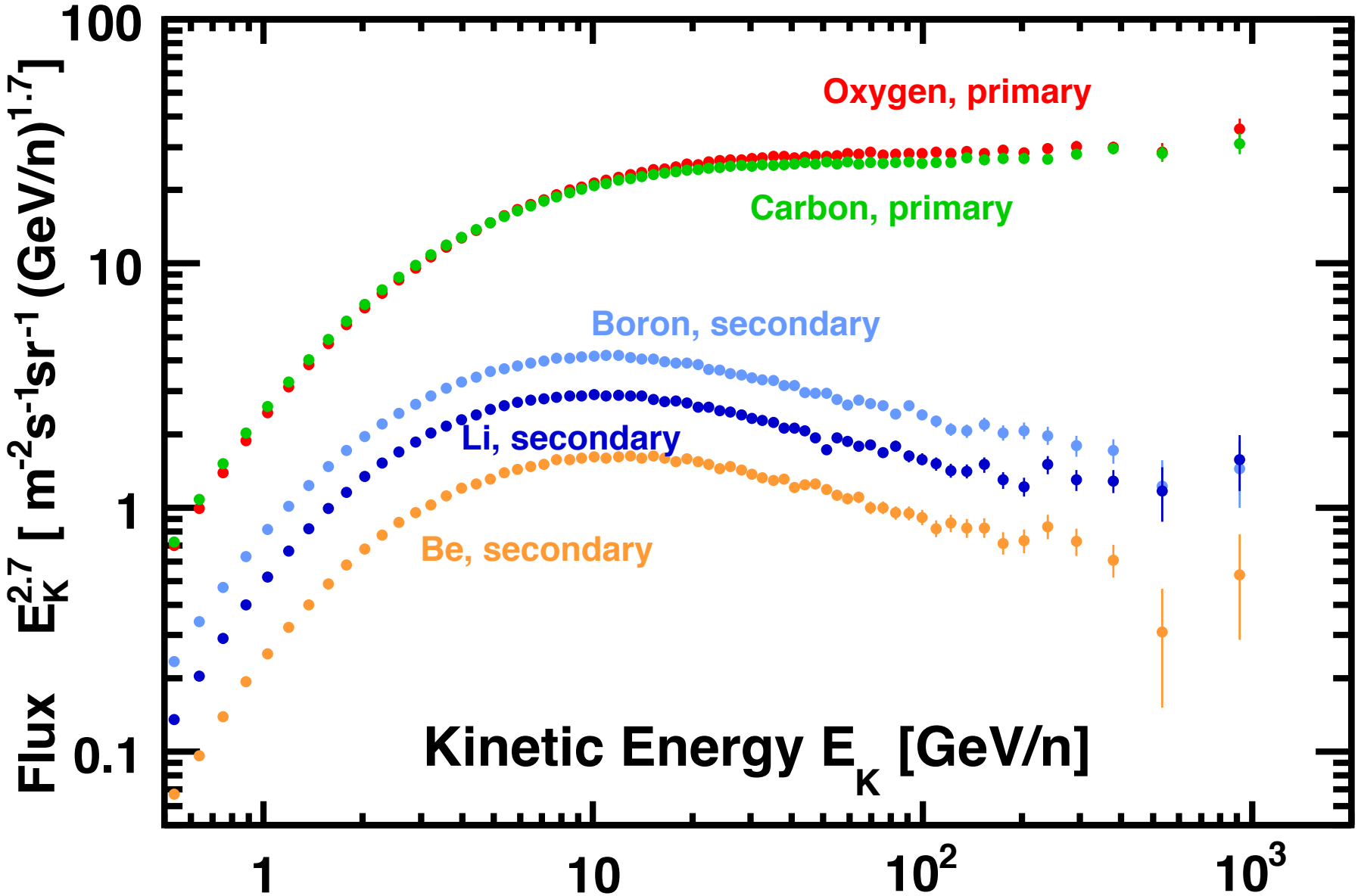
# Summary (on nuclei)

**The beryllium-to-boron (Be/B) flux ratio increases with energy due to time dilation of the decaying Be. The age of cosmic rays in the galaxy is ~12 million years.**



# Summary (on nuclei)

**Primary and secondary cosmic rays have characteristically different rigidity dependence.**



# Summary (on antinuclei)

**To date we have observed a few Z = -2 events with mass around $^{3}$He.**

**At a signal to background ratio of one in one billion, detailed understanding of the instrument is required.**

**It will take a few more years of detector verification and to collect more data to ascertain the origin of these events.**

**The results from AMS to date are unexpected and are unlocking the secrets of the cosmos.**

**There is no other magnetic spectrometer in space in the foreseeable decades.**

**We need to work closely with the theoretical community to develop a comprehensive model to explain all of our observations.**

**By collecting data through 2024, we should be able to determine the origin of many of these unexpected phenomena.**