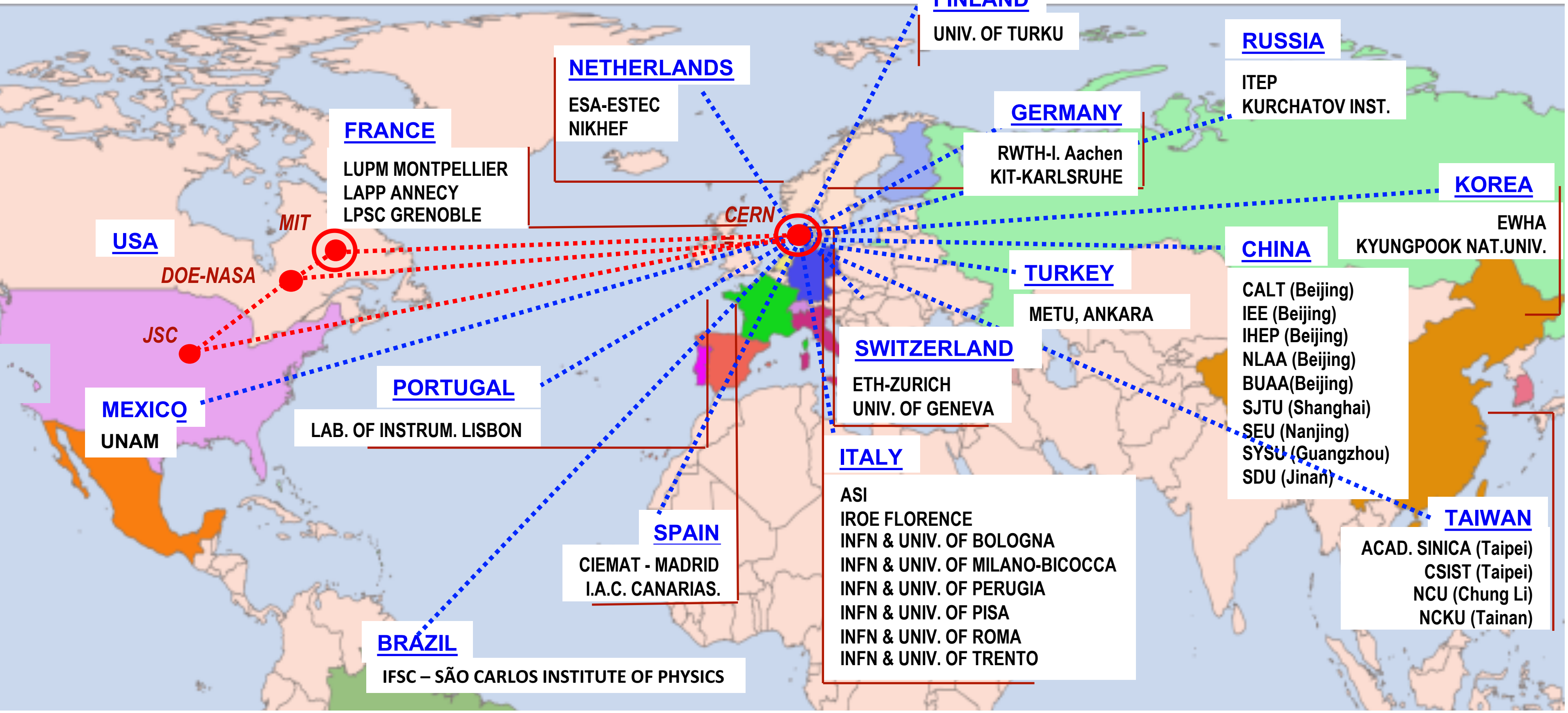
Antimatter in space: results the first 5 years of the Alpha Magnetic Spectrometer on the ISS

R. Battiston

Trento University
INFN-TIFPA
ASI

Orsay , January 17, 2017

AMS is an international collaboration based at CERN



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LAPP ANNECY
LPSC GRENOBLE

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NLAA (Beijing)
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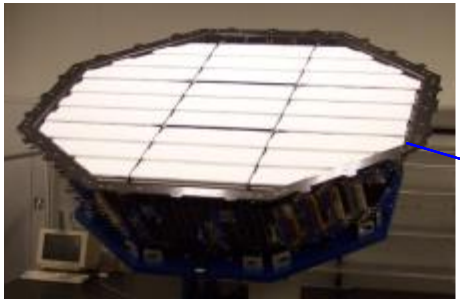
SEU (Nanjing)
SYSU (Guangzhou)
SDU (Jinan)

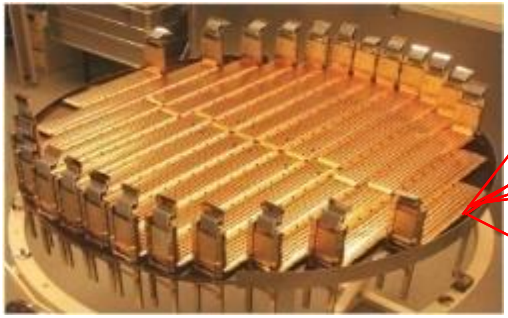
TAIWAN
ACAD. SINICA (Taipei)
CSIST (Taipei)
NCU (Chung Li)
NCKU (Tainan)

AMS: A TeV precision, multipurpose, magnetic spectrometer

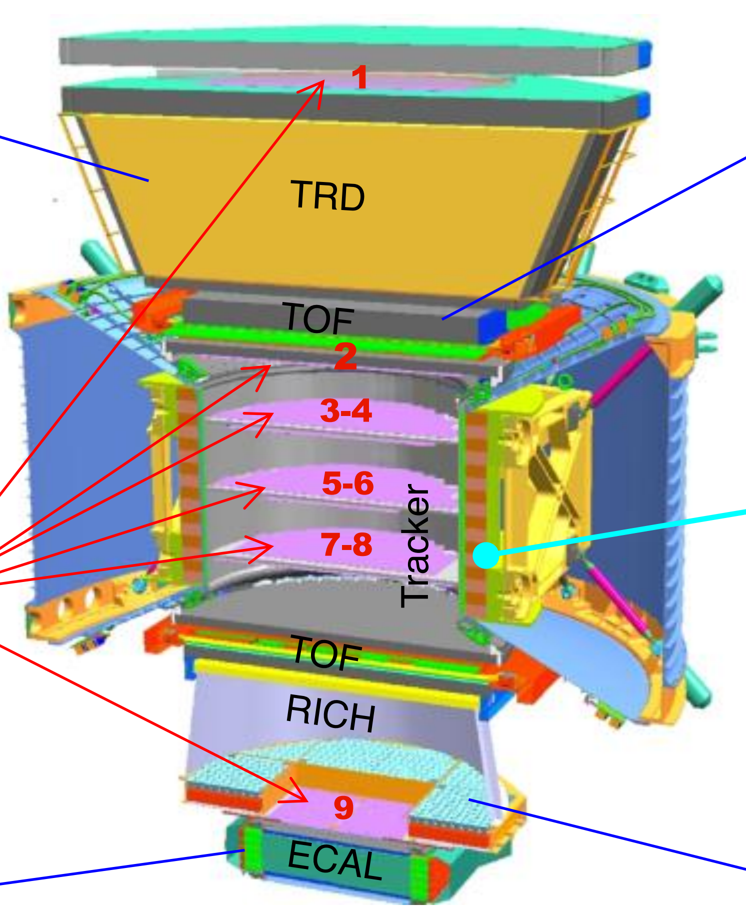
Transition Radiation Detector (TRD)
Identify e$^+$, e$^-$



Silicon Tracker
Z, P or R=P/Z



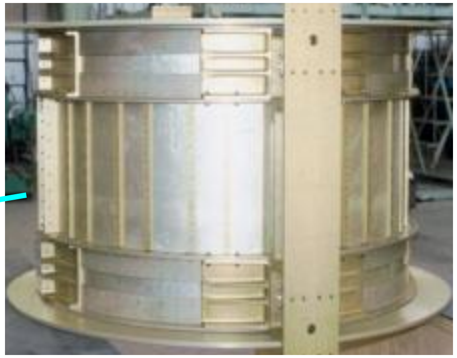
Electromagnetic Calorimeter (ECAL)
E of e$^+$, e$^-$



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

Time of Flight (TOF)
Z, E

Magnet
±Z

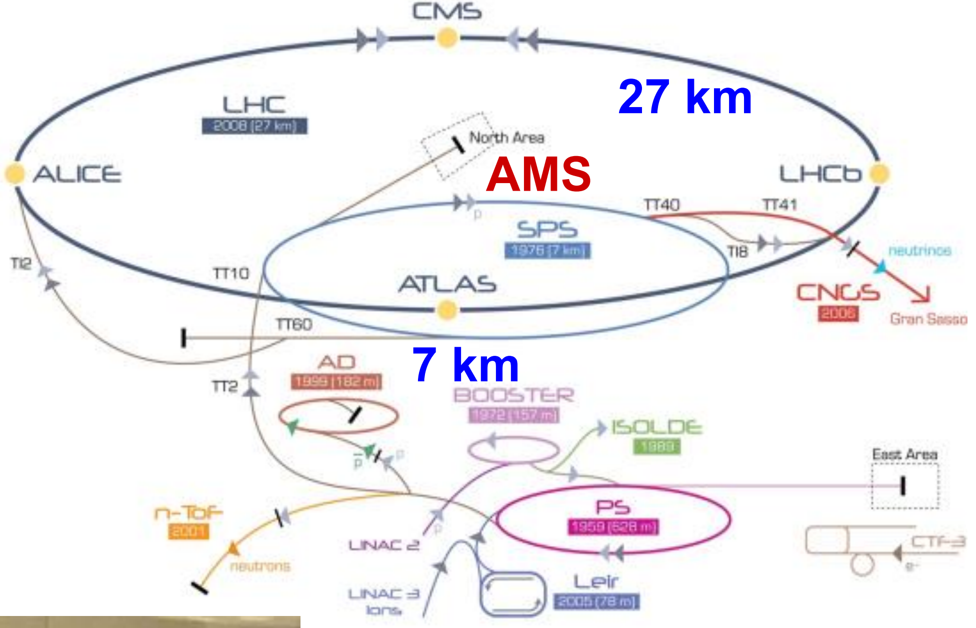


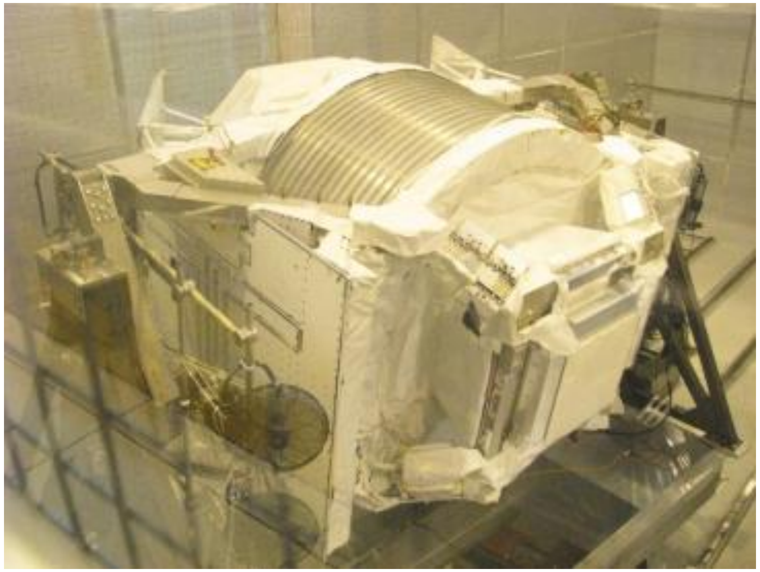
Ring Imaging Cherenkov (RICH)
Z, E

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

New Physics Results

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



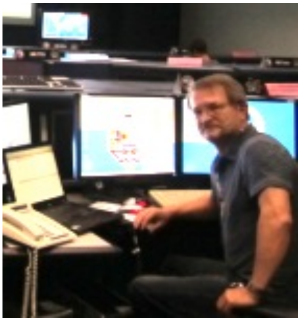


Particle	Momentum (GeV/c)	Positions
Protons	180, 400	1,650
Electrons	100, 120, 180, 290	7 each
Positrons	10, 20, 60, 80, 120, 180	7 each
Pions	20, 60, 80, 100, 120, 180	7 each

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

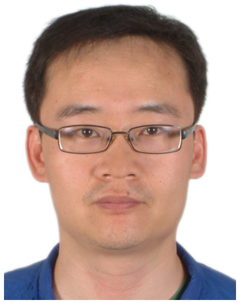
I. Gebauer

J. Casaus

L. Derome

C. Delgado

D. Grandi

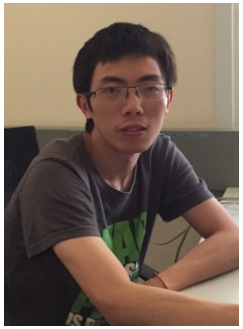


Z. Li

S. Haino, A. Oliva

W. Xu

P. Zuccon

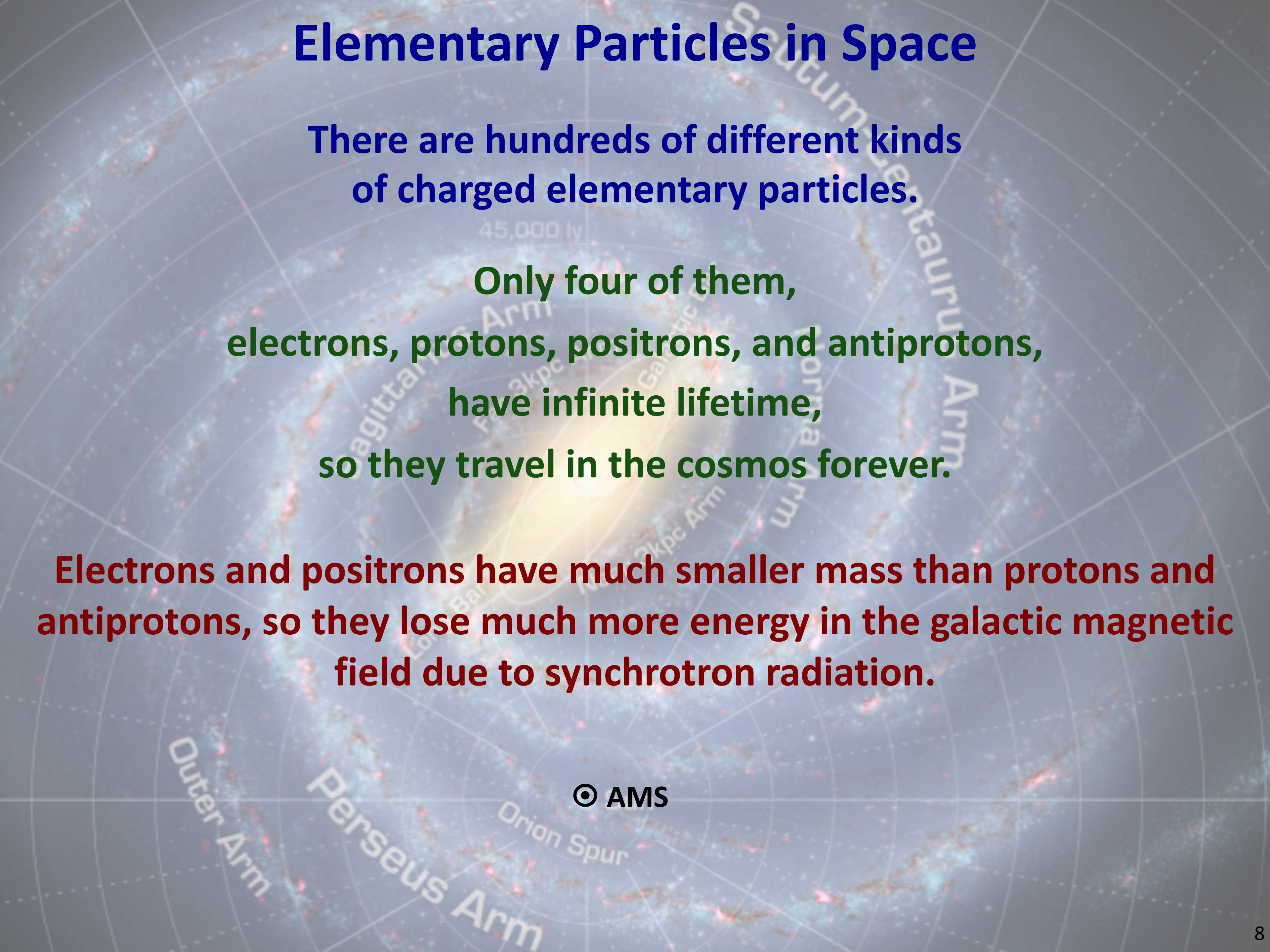


Q. Yan

Z. Weng

N. Tomassetti

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,

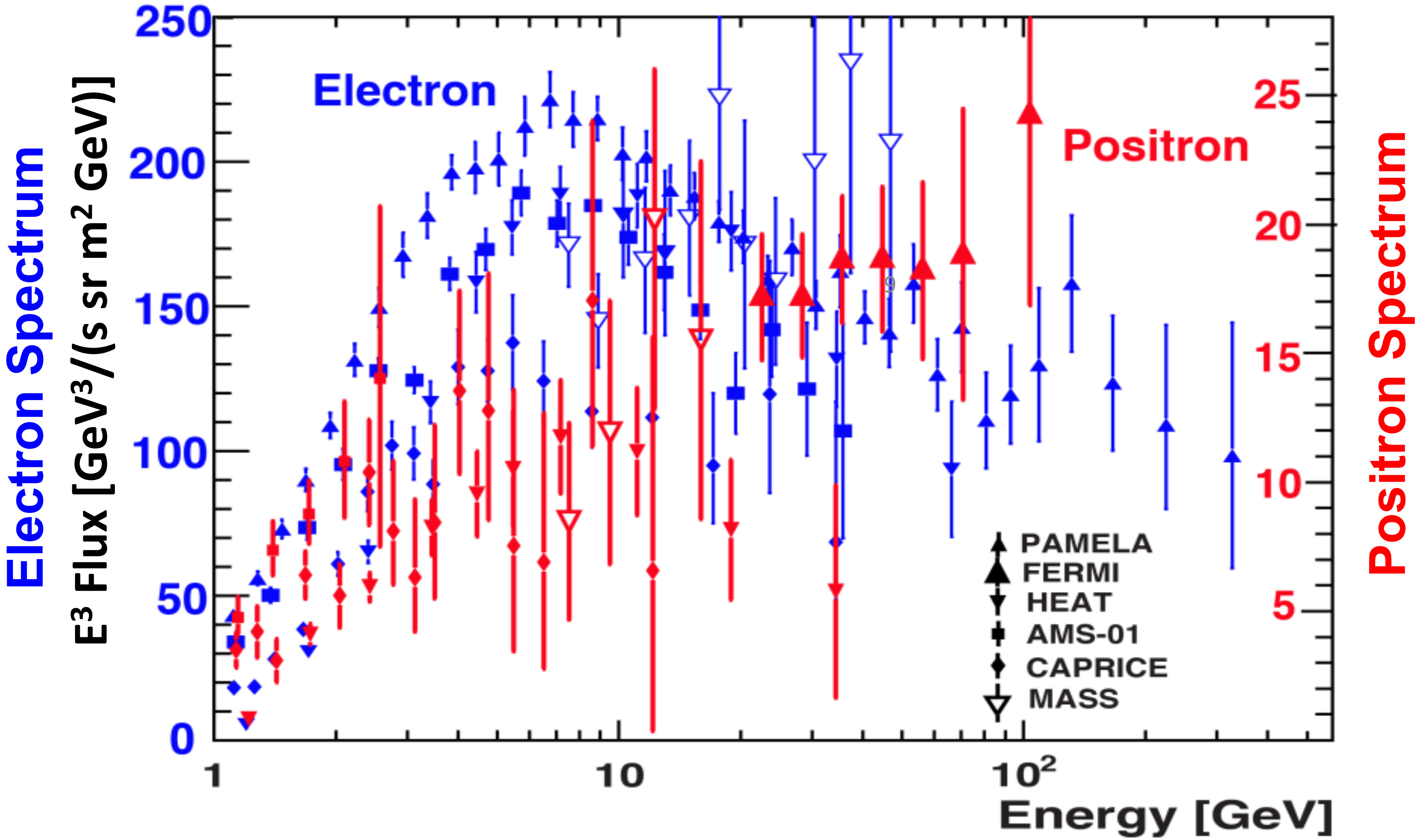
so they travel in the cosmos forever.

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

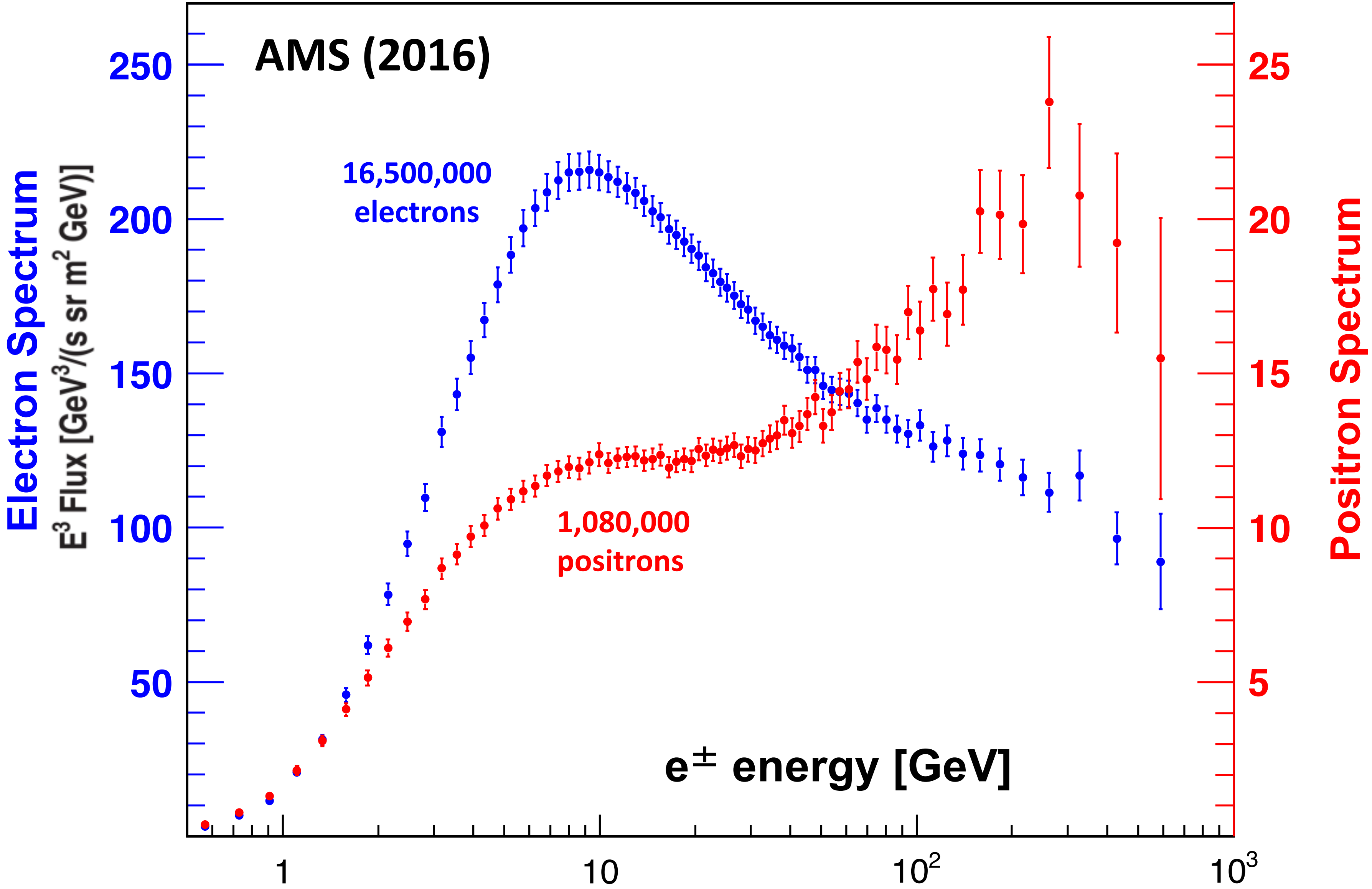
Electron and Positron spectra before AMS

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

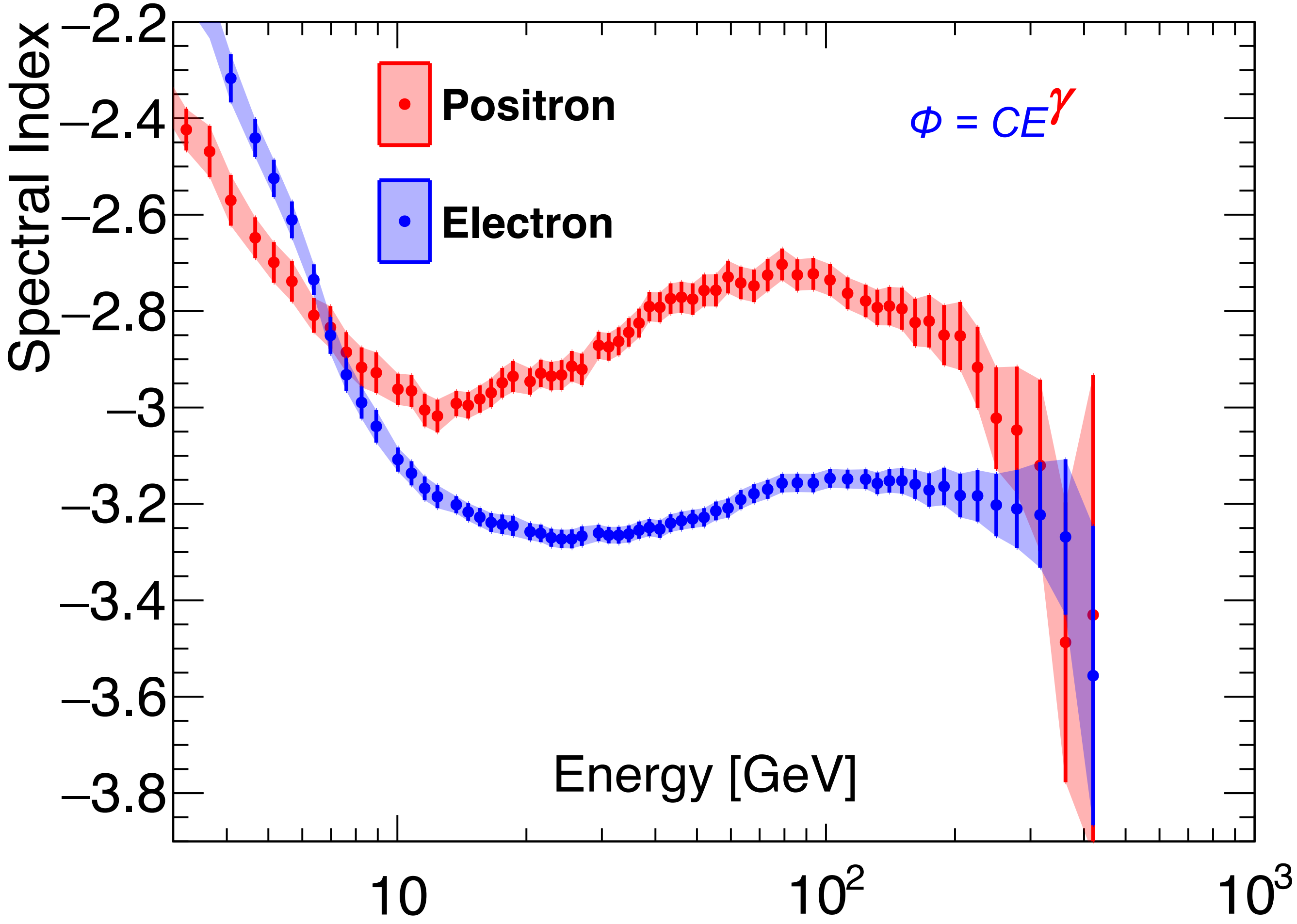
The electron flux and the positron flux are different in their magnitude and energy dependence



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 γ is the spectral index and E is the energy.

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



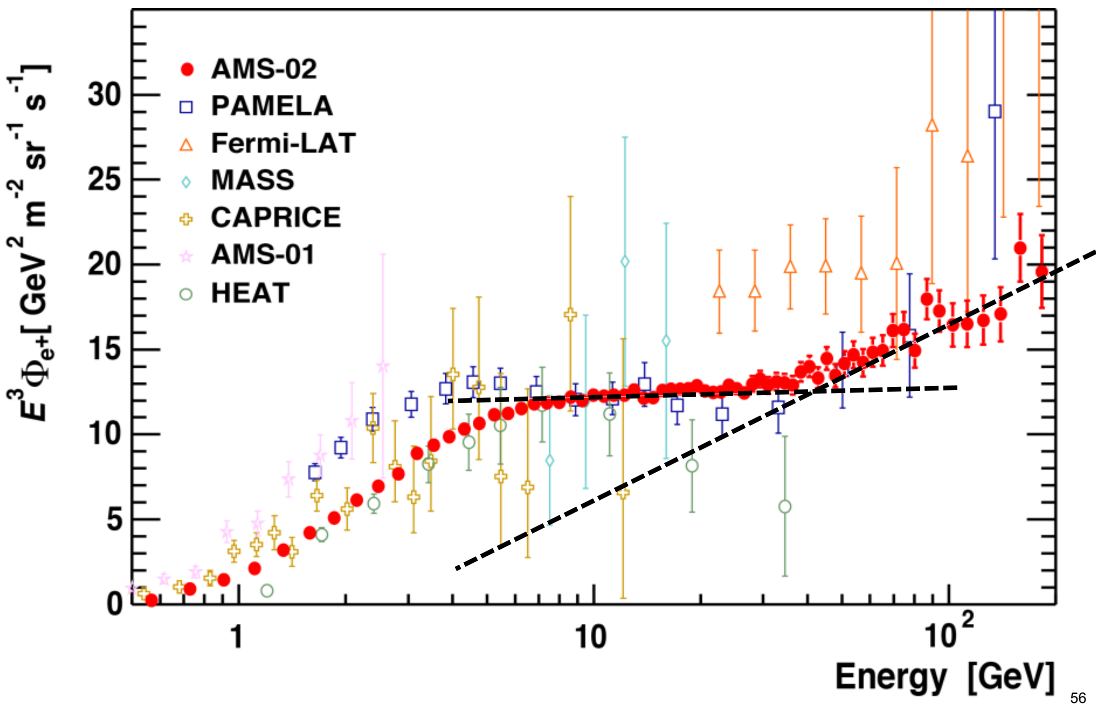
The electron and positron spectral indices are not constant.

They are different in their magnitude and energy dependence

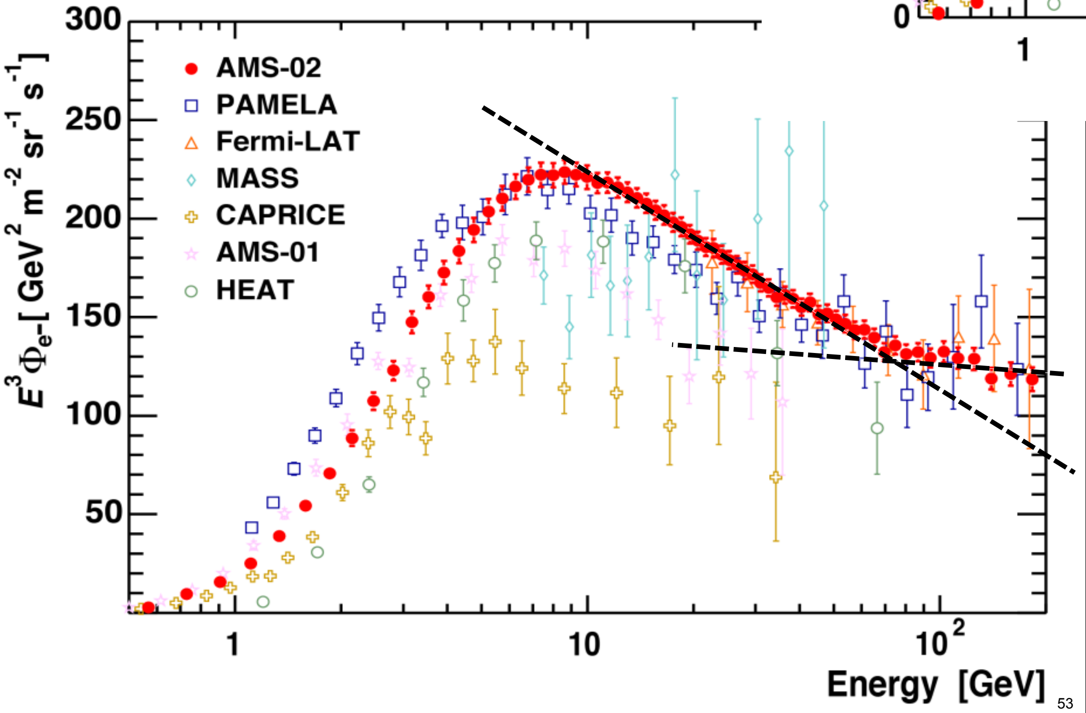
AMS-02 e^+ & e^-

- ✧ One should look at the fluxes of e^+ & e^-, not the positron fraction

Positron Flux

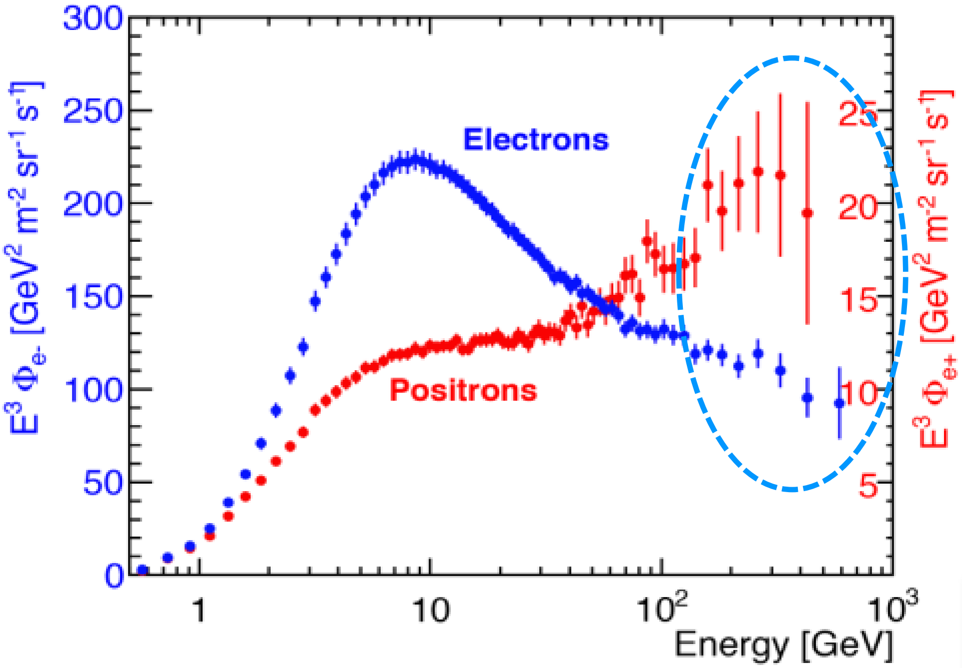


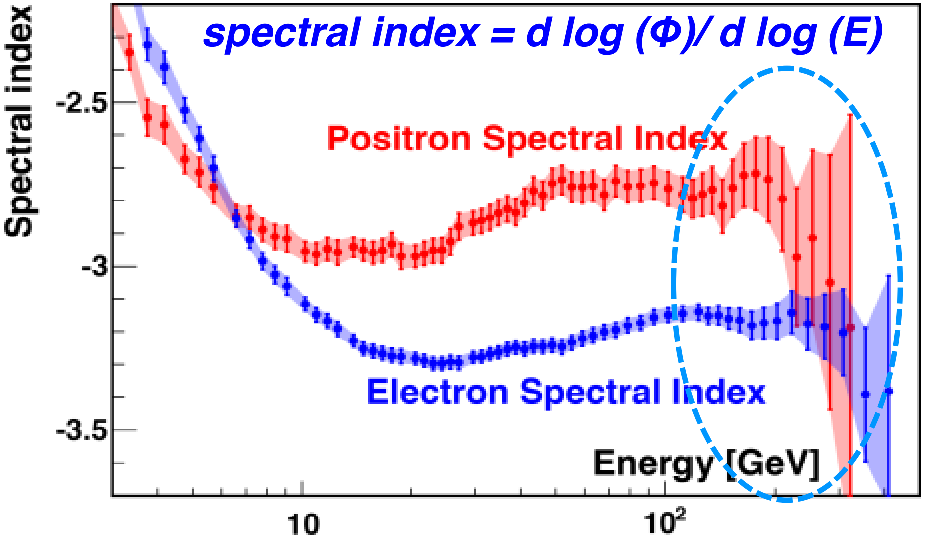
Electron Flux



- ✧ Noticeable is a concave shape in both cases, a clear indication of an additional component >30 GeV

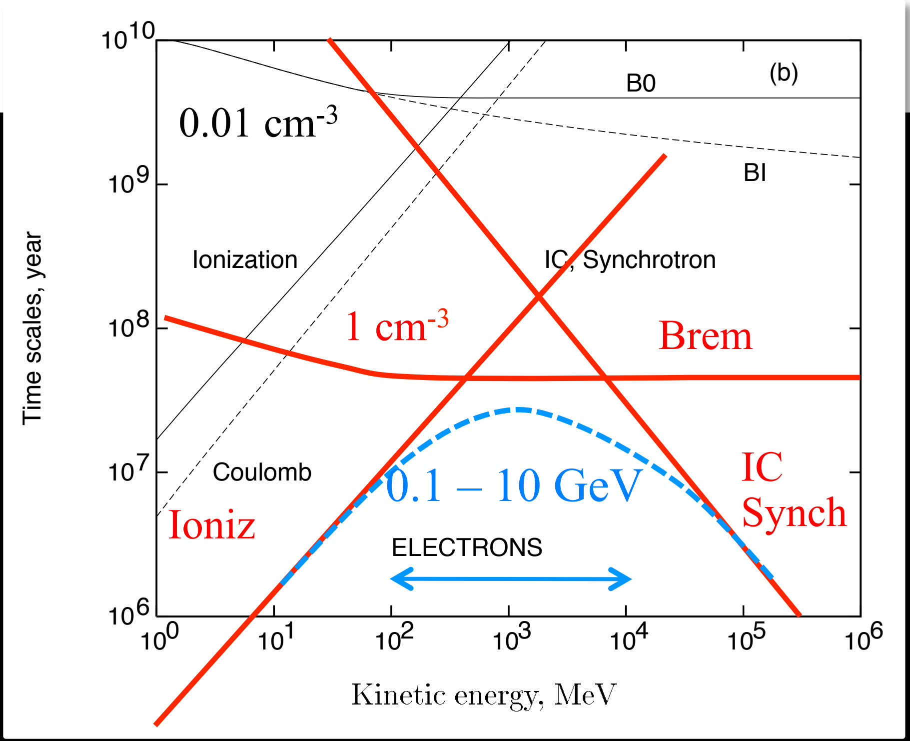
The Electron Flux and the Positron Flux





Energy losses of electrons

- ✧ The ionization and Coulomb losses are calculated for the gas number density 0.01 cm^{-3} & 1 cm^{-3}
- ✧ Min losses are between 0.1 – 10 GeV (τ ~ 10 Myr) and increase fast toward LE and HE
- ✧ Cutoff shape in $e-$ and $e+$ spectra at HE will tell about the distance to the sources

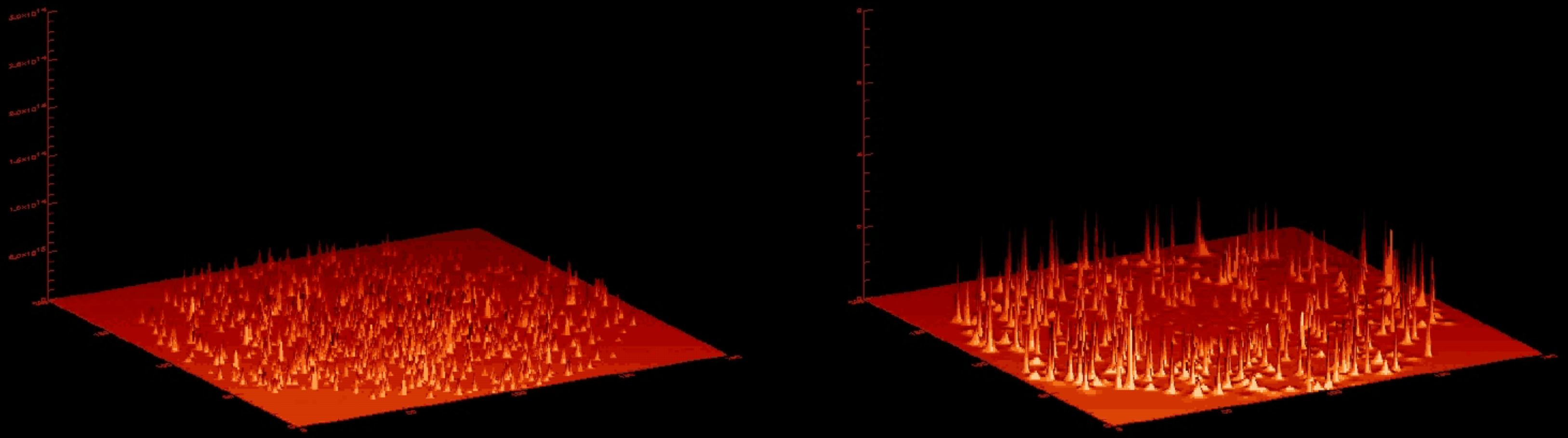


Electron Fluctuations/SNR Stochastic Events

GeV electrons

GALPROP/Credit S.Swordy

100 TeV electrons



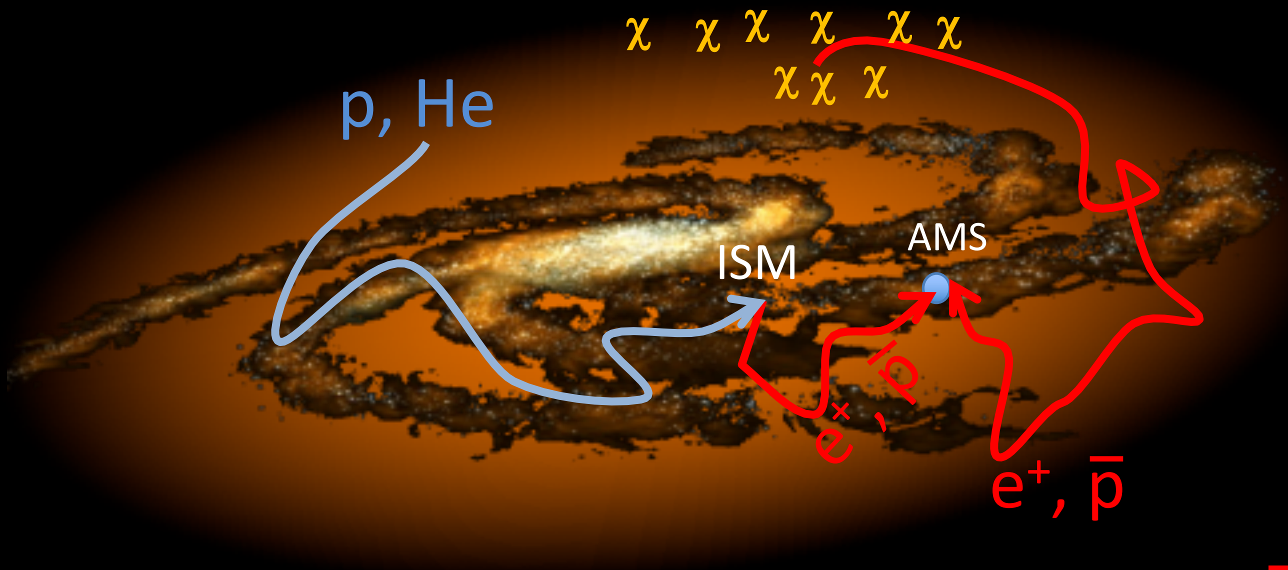
Electron energy loss timescale:
1 TeV: ~300 kyr
100 TeV: ~3 kyr

Compare with CR lifetime ~10 Myr

Dark Matter: χ

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

p, He + ISM → e^+, $\bar{p}$ + …



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

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

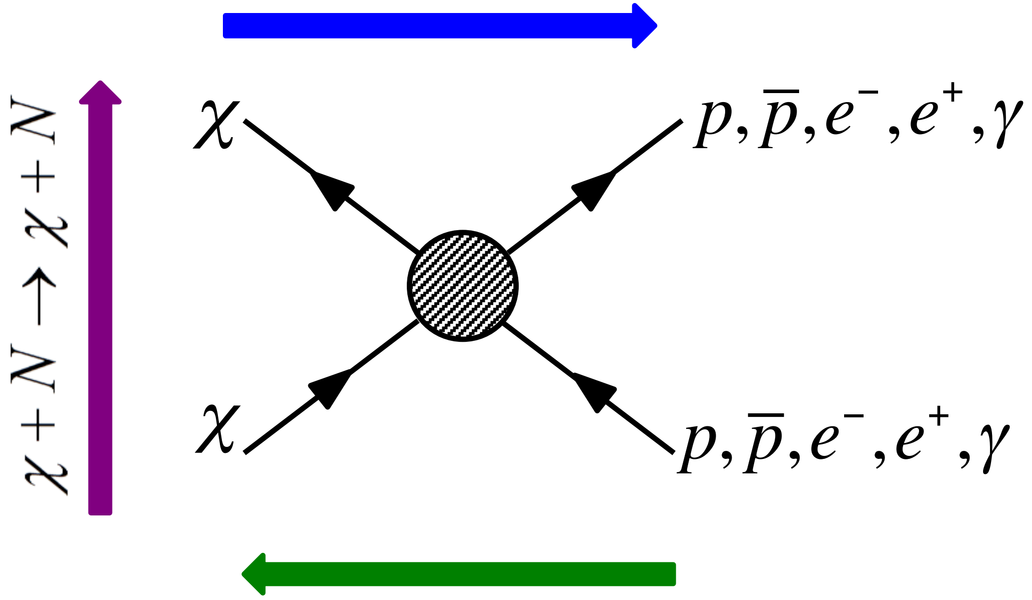
M. Turner and F. Wilczek, Phys. Rev. D42 (1990) 1001; J. Ellis 26th ICRC (1999)

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
…

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

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

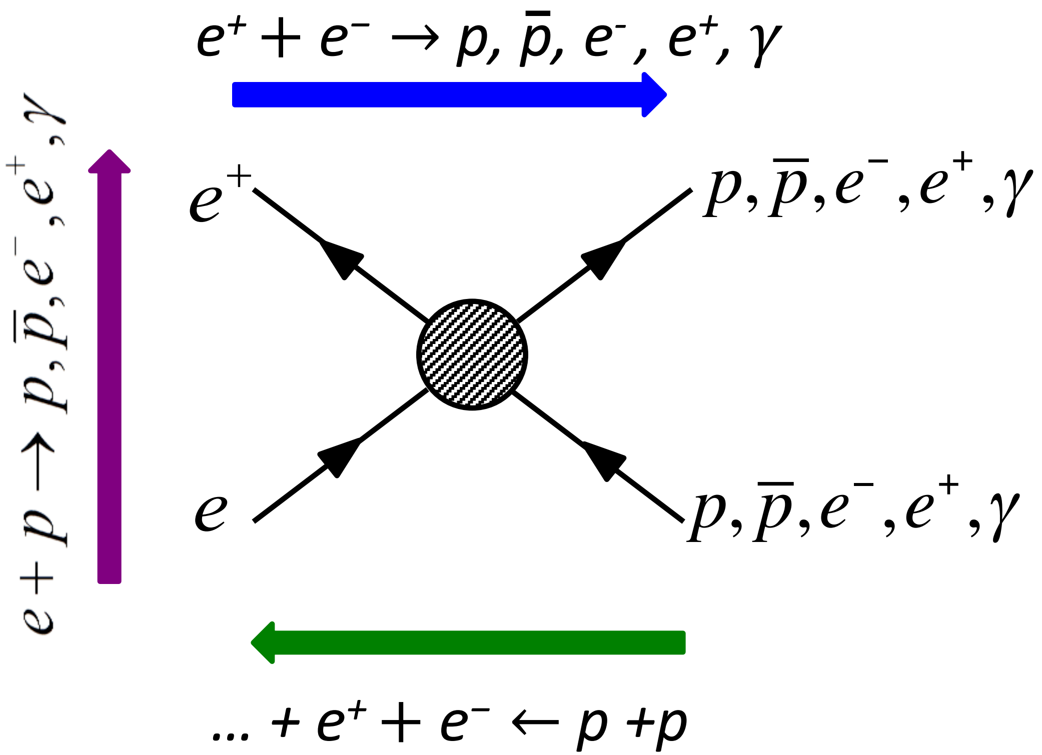
LHC

Production

Physics of electrons and protons

Annihilation

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



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

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

$\ldots + e^+ + e^- \leftarrow p + p$

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

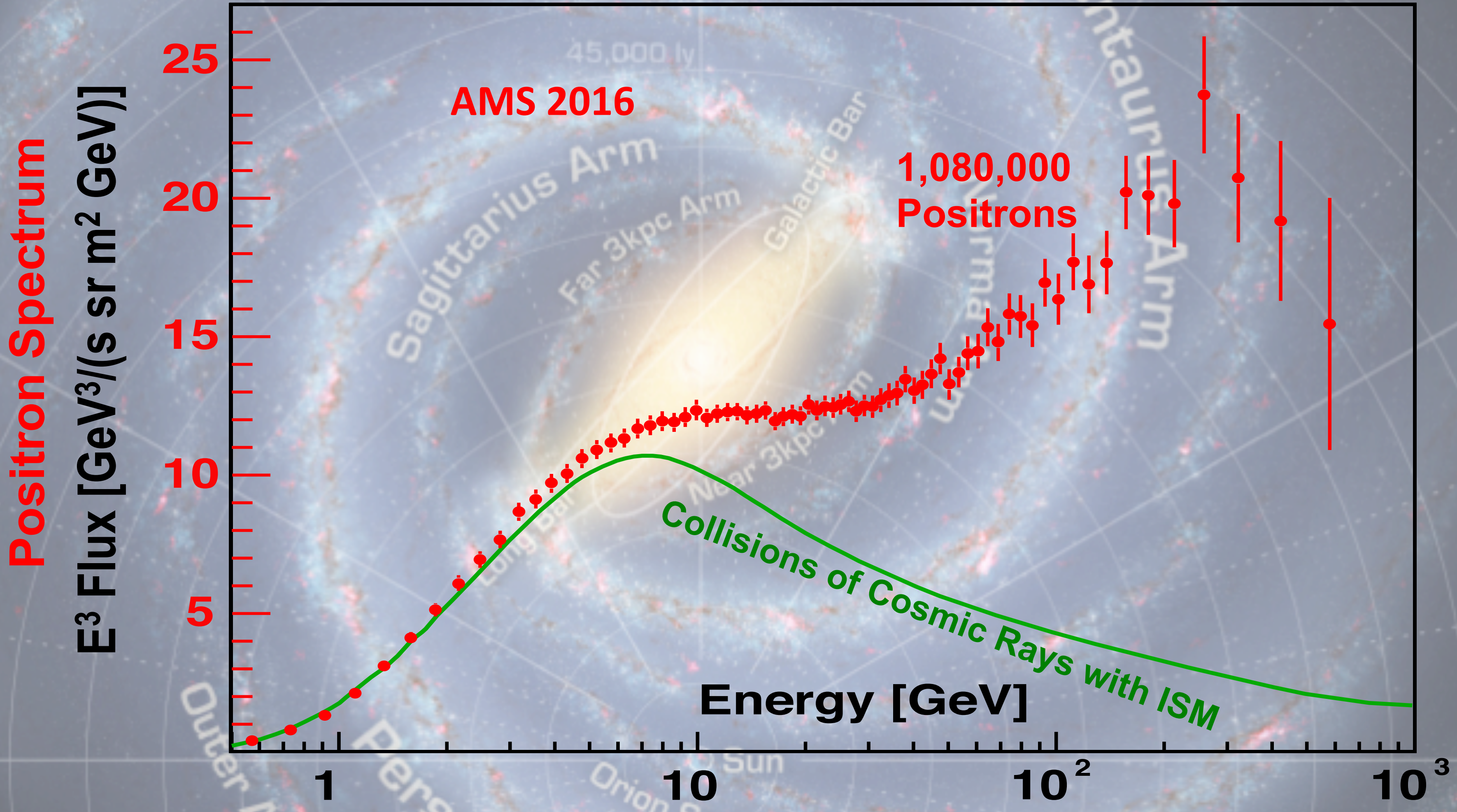
1) T. Linden and S. Profumo, Astrophys.J. 772 (2013) 18
2) P. Mertsch and S. Sarkar, Phys.Rev. D 90 (2014) 061301
3) I. Cholis and D. Hooper, Phys.Rev. D88 (2013) 023013
4) A. Erlykin and A.W. Wolfendale, Astropart.Phys. 49 (2013) 23
5) P.F. Yin, Z.H. Yu, Q. Yuan and X.J. Bi, Phys.Rev. D88 (2013) 2,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

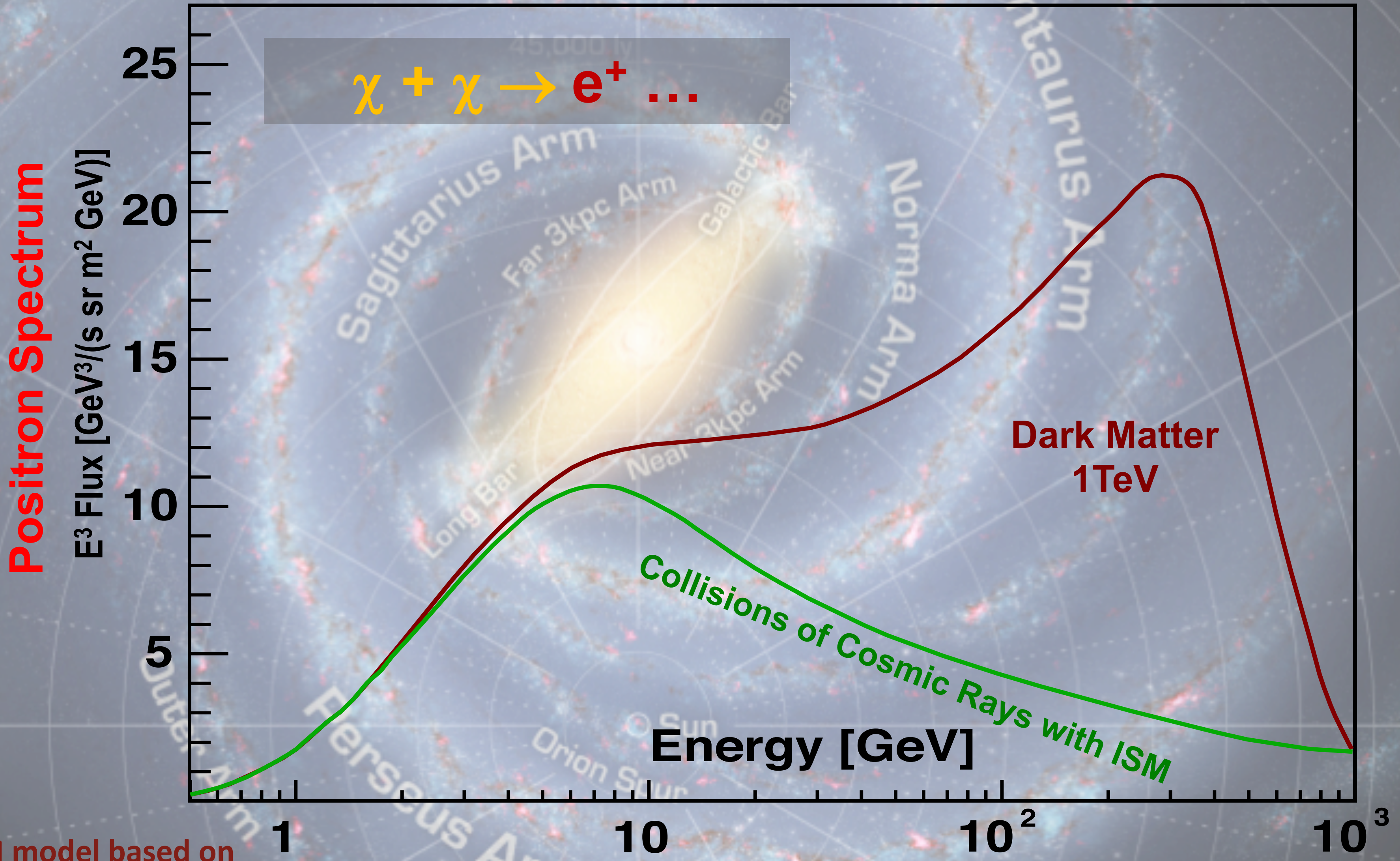
Collision of Cosmic Rays with the Interstellar Media produce e^+
… and this is indeed true at low energies.



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.

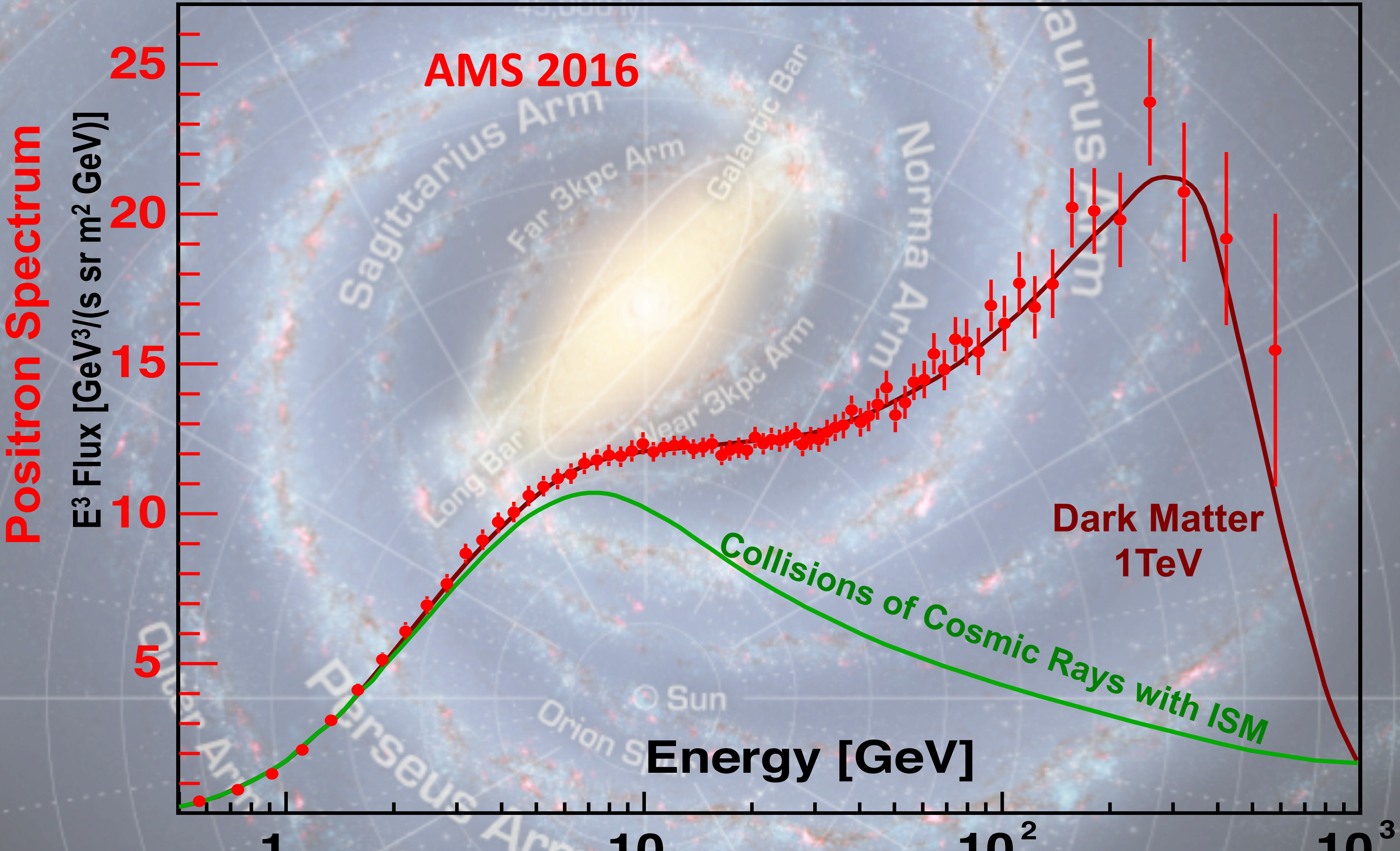


$\chi + \chi \rightarrow e^+ \ldots$

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

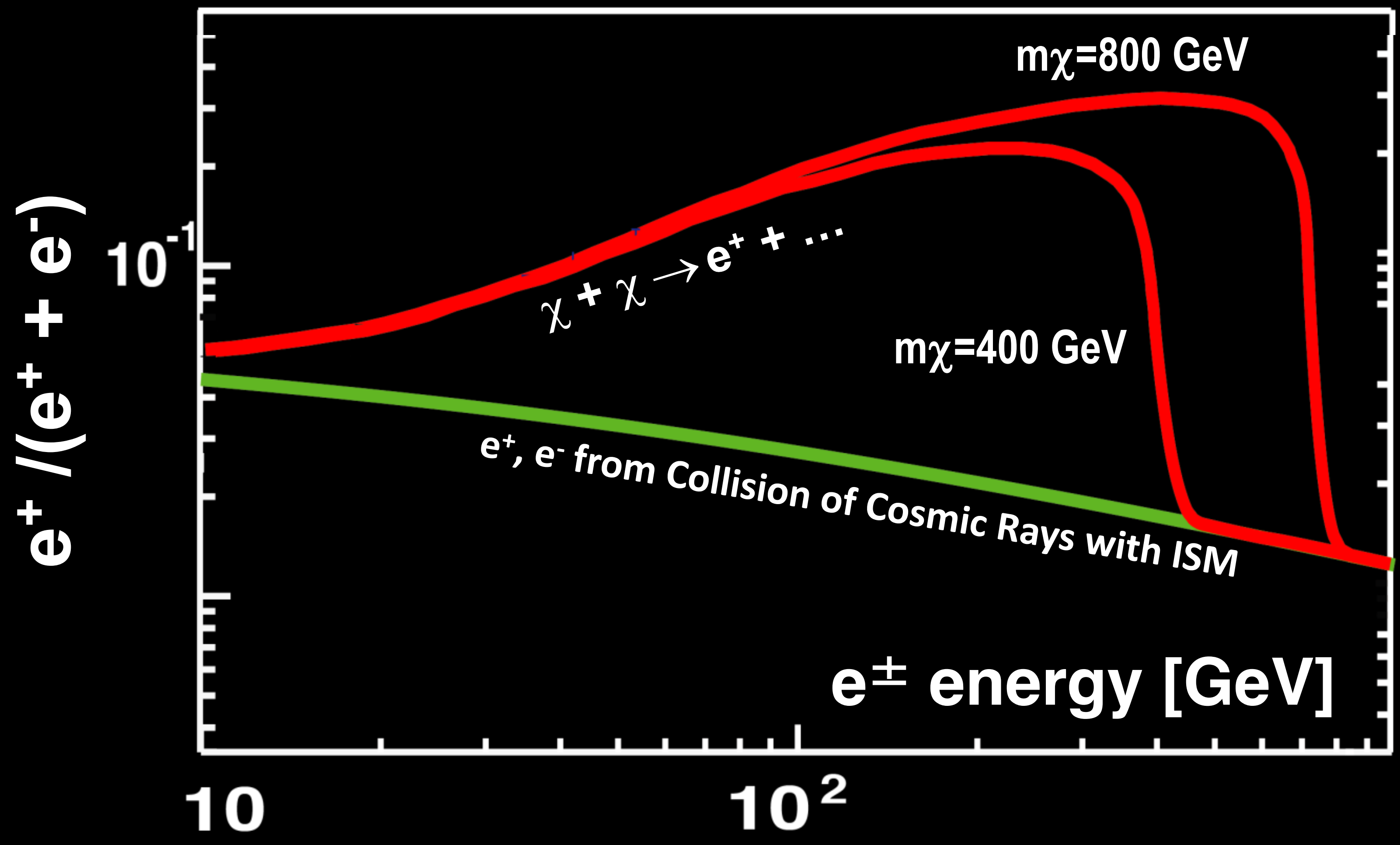
Physics Result 2: The origin of the AMS positron spectrum

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



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

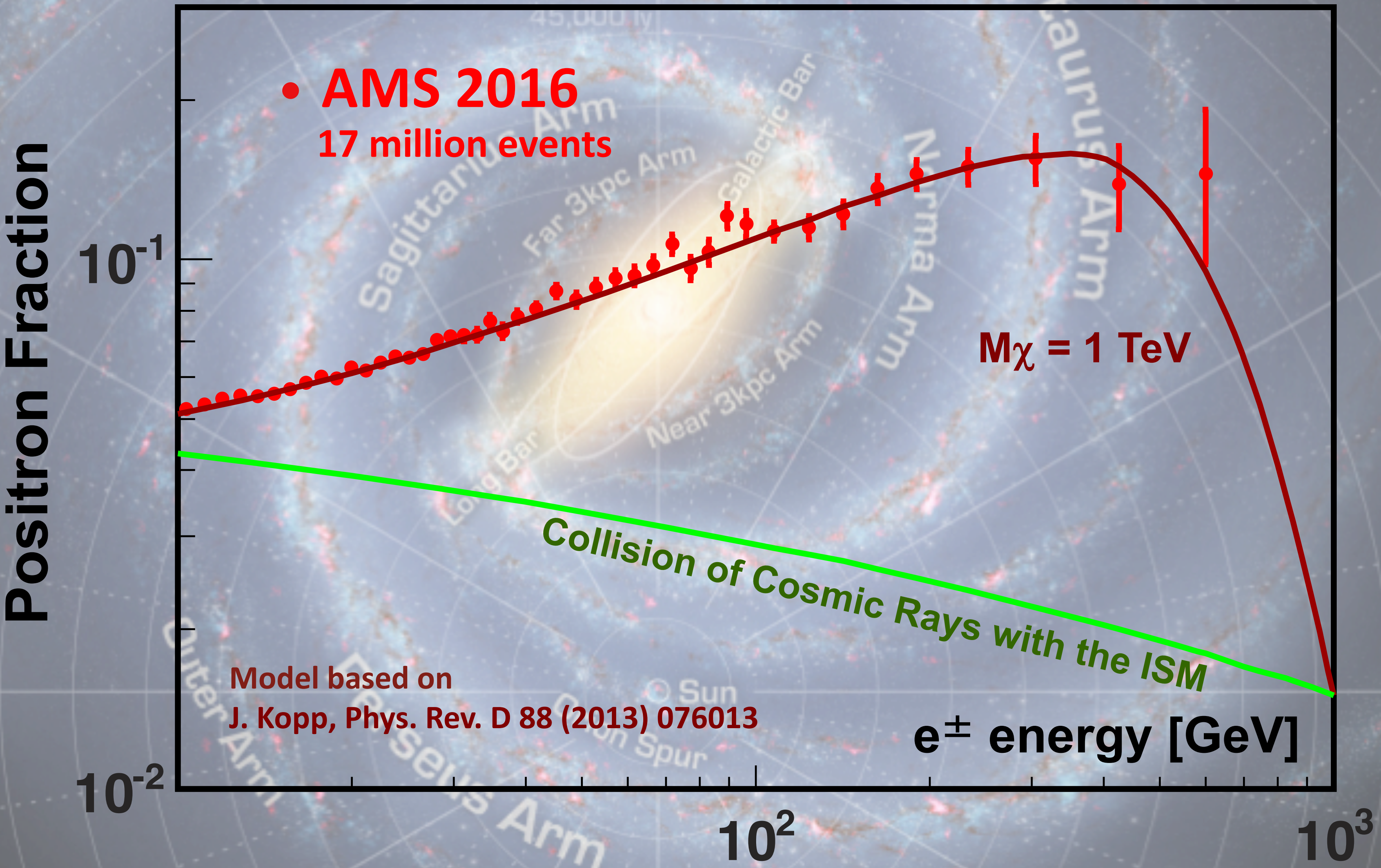
This is an alternative way to search for the signature of Dark Matter but the positron fraction and positron spectrum have different errors.



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

Physics Result 3: The origin of the Positron Fraction

Comparison of the positron fraction measurement with a Dark Matter model



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

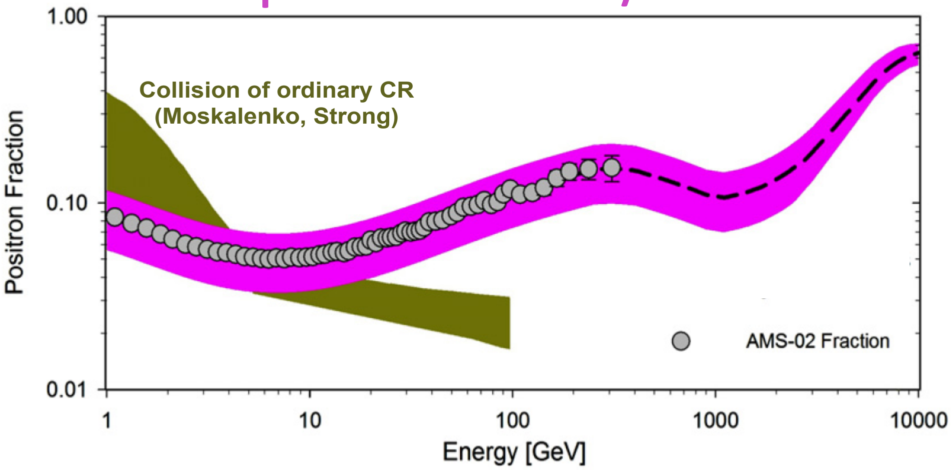
Alternative Models to explain the AMS Positron Flux and Positron Fraction Measurements

- Modified Propagation of Cosmic Rays
- Supernova Remnants
- Pulsars

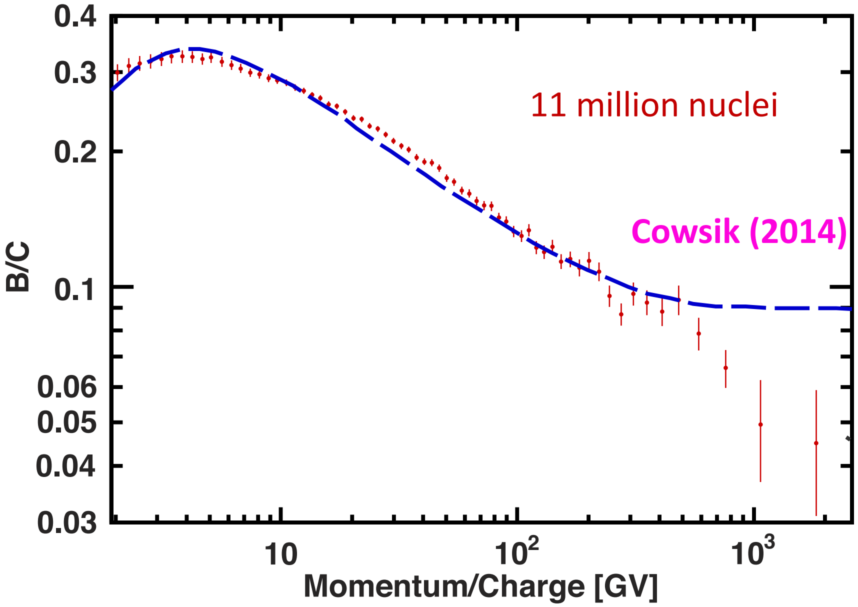
Examples:

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

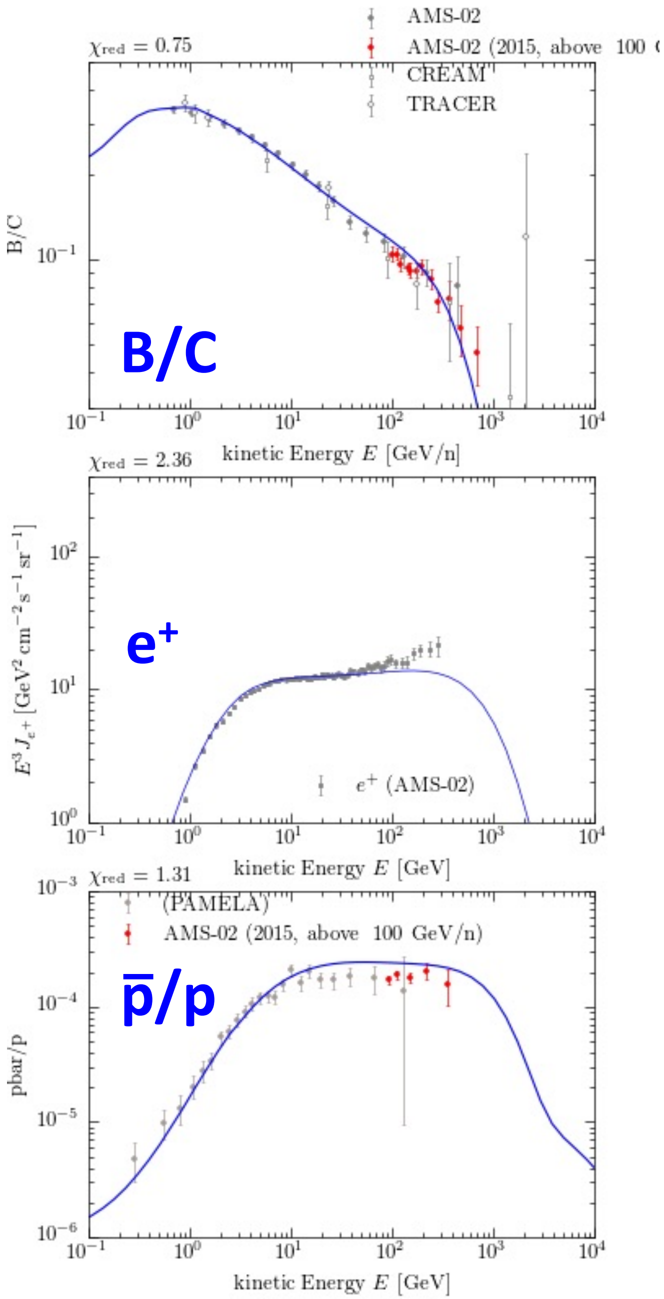


The AMS Boron-to-Carbon (B/C) flux ratio



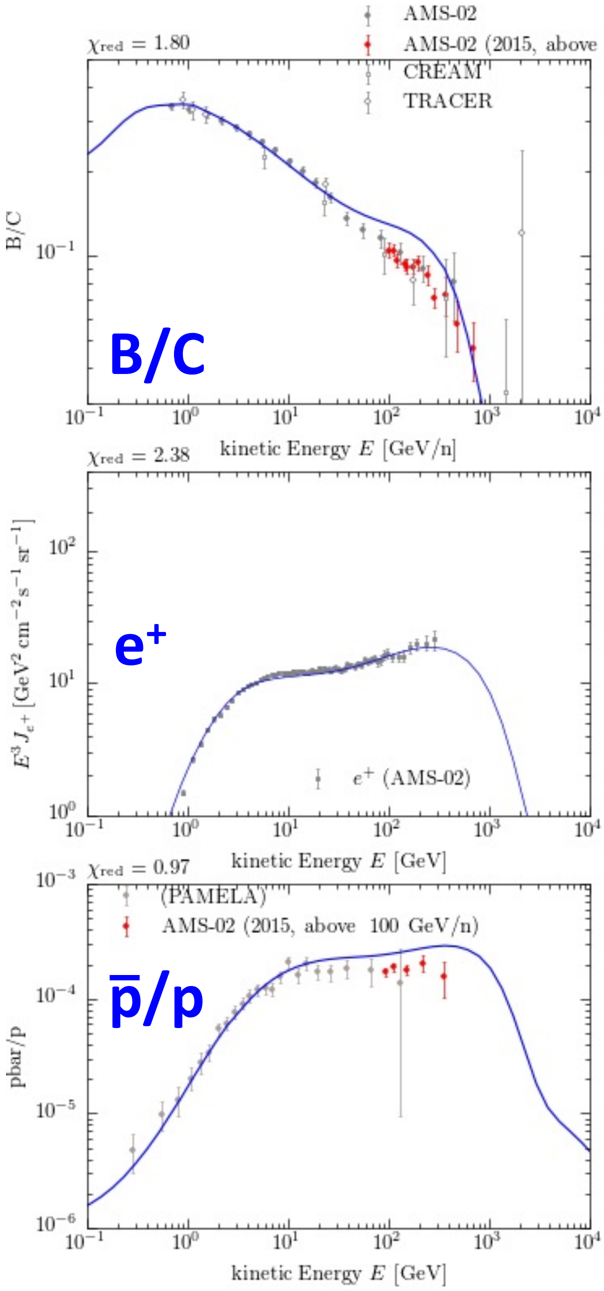
Example: Supernova Remnants

Subir Sarkar: AMS Days@CERN, April 2015



We have been trying 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!

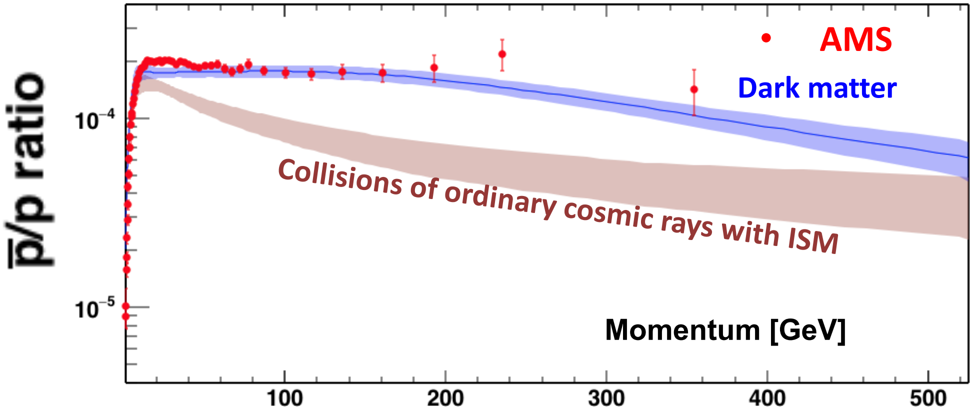


Alternative Models to explain the AMS Positron Flux and Positron Fraction Measurements

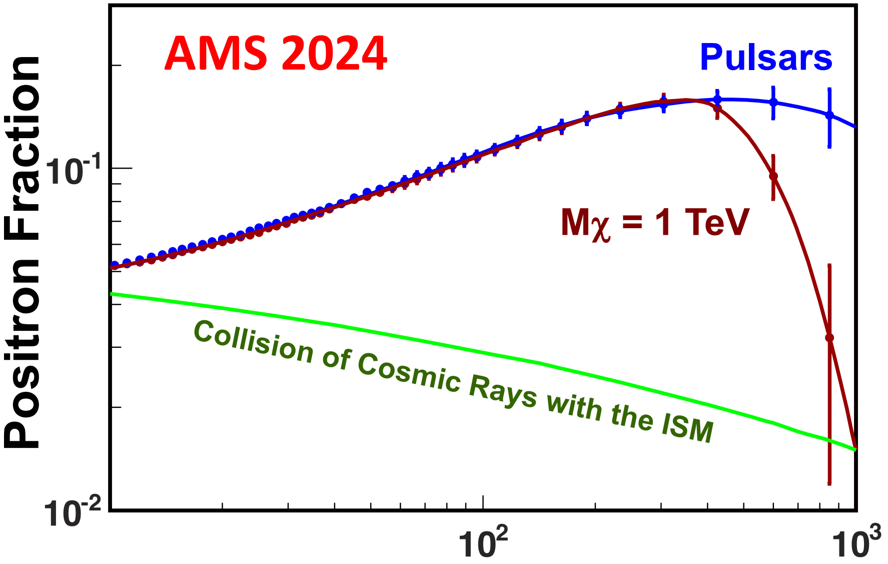
- Modified Propagation of Cosmic Rays
- Supernova Remnants
- Pulsars

Examples:

The AMS Antiproton-to-Proton ratio



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

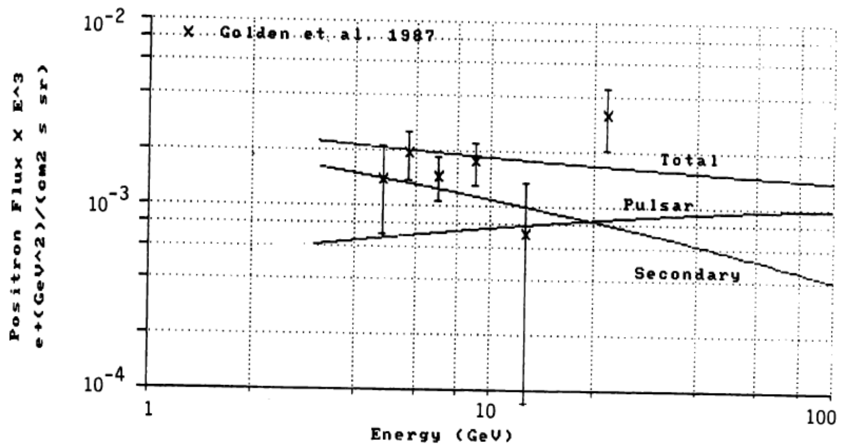


Increasing statistics AMS would improve the capability Dark Matter vs Pulsars

Old friends – pulsars

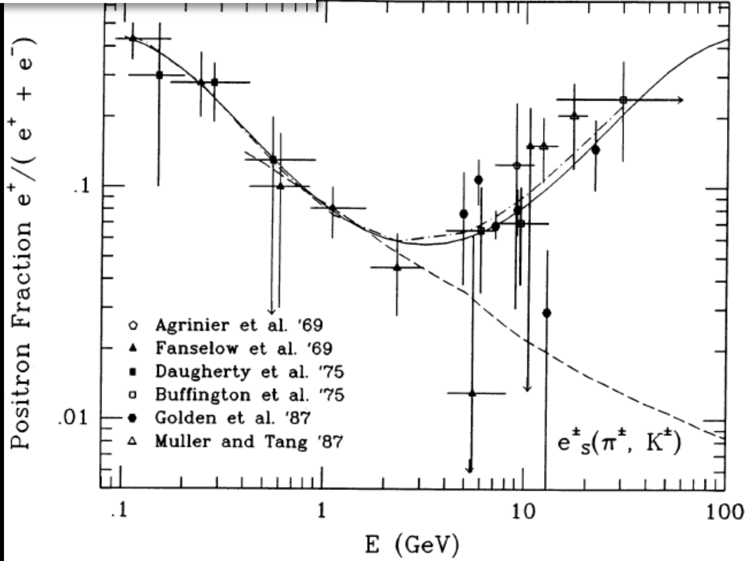
- Arons 1981 “Particle acceleration by pulsars”
- Harding & Ramaty 1987 “The pulsar contribution to Galactic cosmic ray positrons”
- Boulares 1989 “The nature of the cosmic-ray electron spectrum, and supernova remnant contributions”

“Therefore, the only role observed pulsars might play as direct cosmic ray sources is in providing positrons and electrons…”



3 components:

- Secondary $e^{+/-}$
- Primary e^- from SNR
- Primary $e^{+/-}$ from pulsars

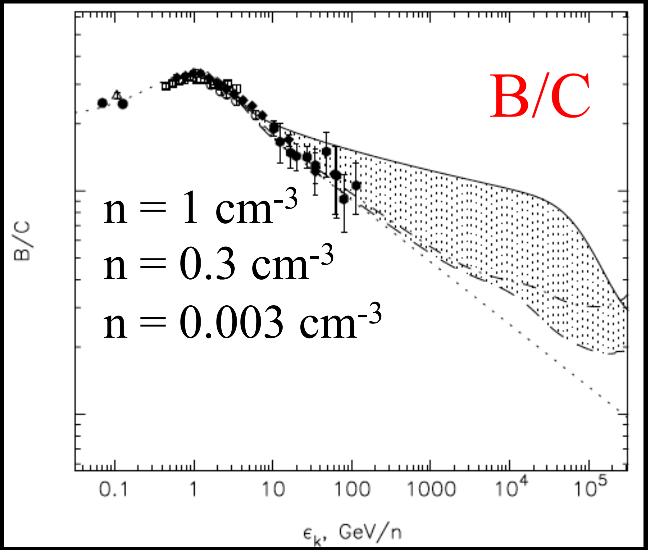


Reinvention of the Nested Leaky-Box – SNRs

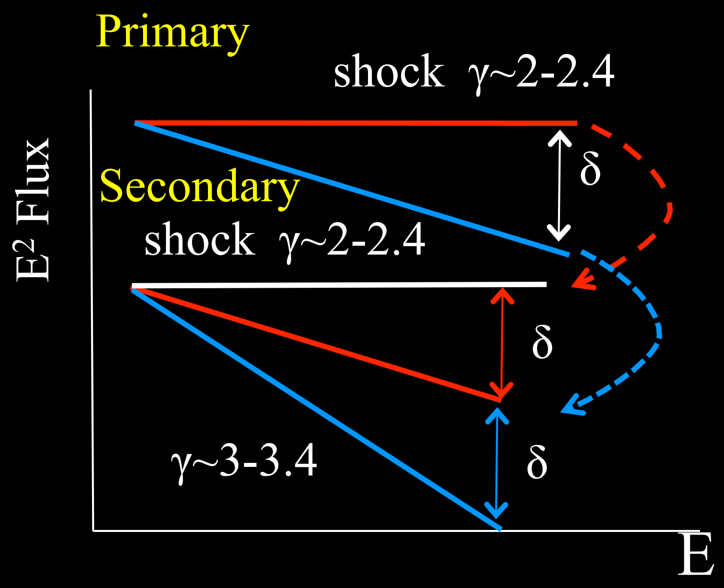
- Cowsik & Wilson 1974 “The nested Leaky-Box model for Galactic cosmic rays”
- Berezkho+2003 “Cosmic ray production in supernova remnants including reacceleration: The secondary to primary ratio”

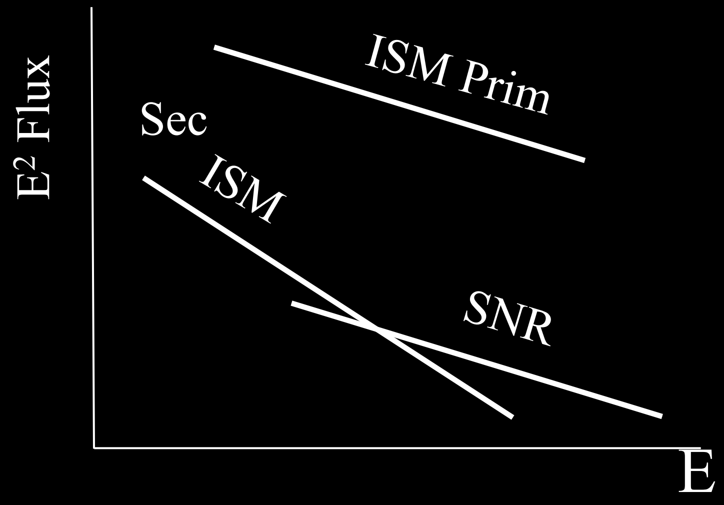
“The ‘inner box’ of cosmic ray confinement, corresponding to the region immediately surrounding the source, is assumed to have energy-dependent life time...”

“In this paper we shall in addition take the effect of nuclear spallation inside the sources into account. The energy spectrum of these source secondaries is harder than that of reaccelerated secondaries. Therefore it plays a dominant role at high energies for a high-density ISM...”



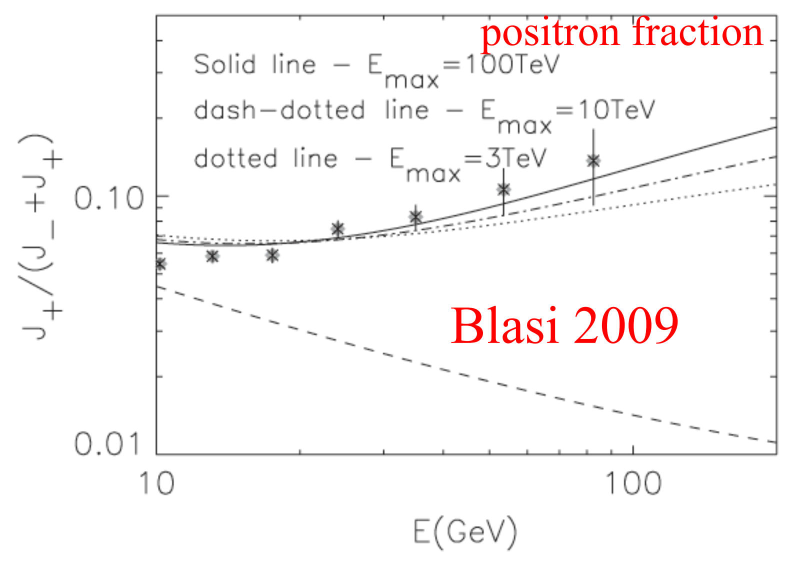
Secondary production in SNR shock





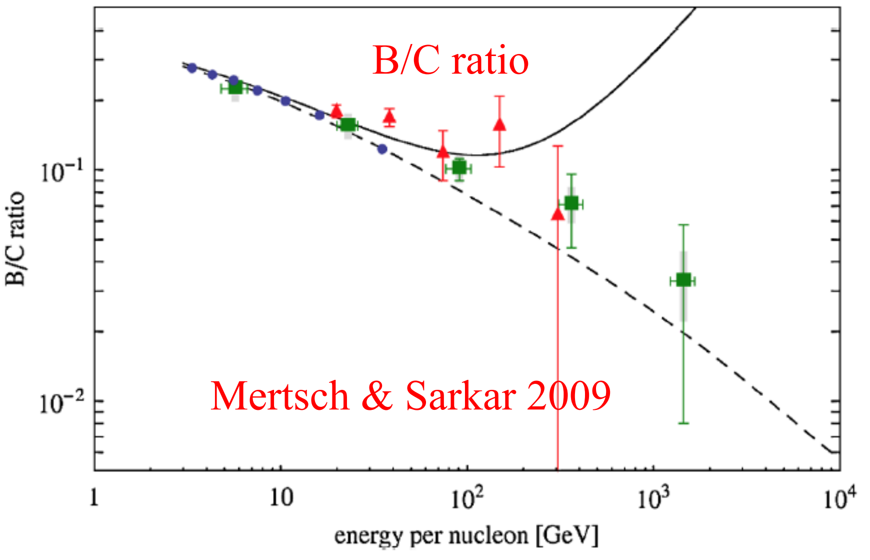
- ✧ Gas in the shock – target for p, A
- ✧ Flatter spectrum of p, A – flatter spectrum of secondaries
- ✧ Assume no energy losses
- ✧ δ~0.3-0.7 – effect of IS propagation (no losses)
- ✧ Same effect should be observed for *any* secondaries (pbars, B, $e^{+/-}$)
- ✧ Energy losses will modify the spectra of $e^{+/-}$ at low and high energies - depend on the environment

Secondary production in a SNR shock



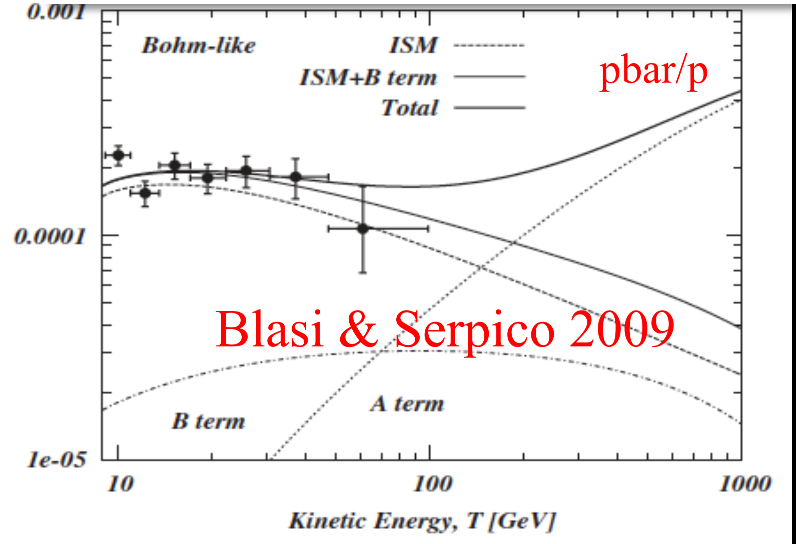
positron fraction

Blasi 2009



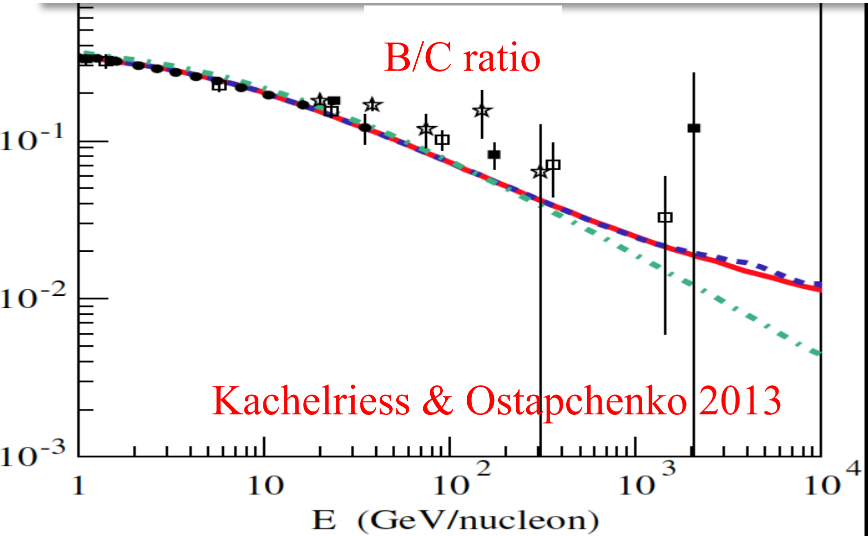
B/C ratio

Mertsch & Sarkar 2009



pbar/p

Blasi & Serpico 2009



B/C ratio

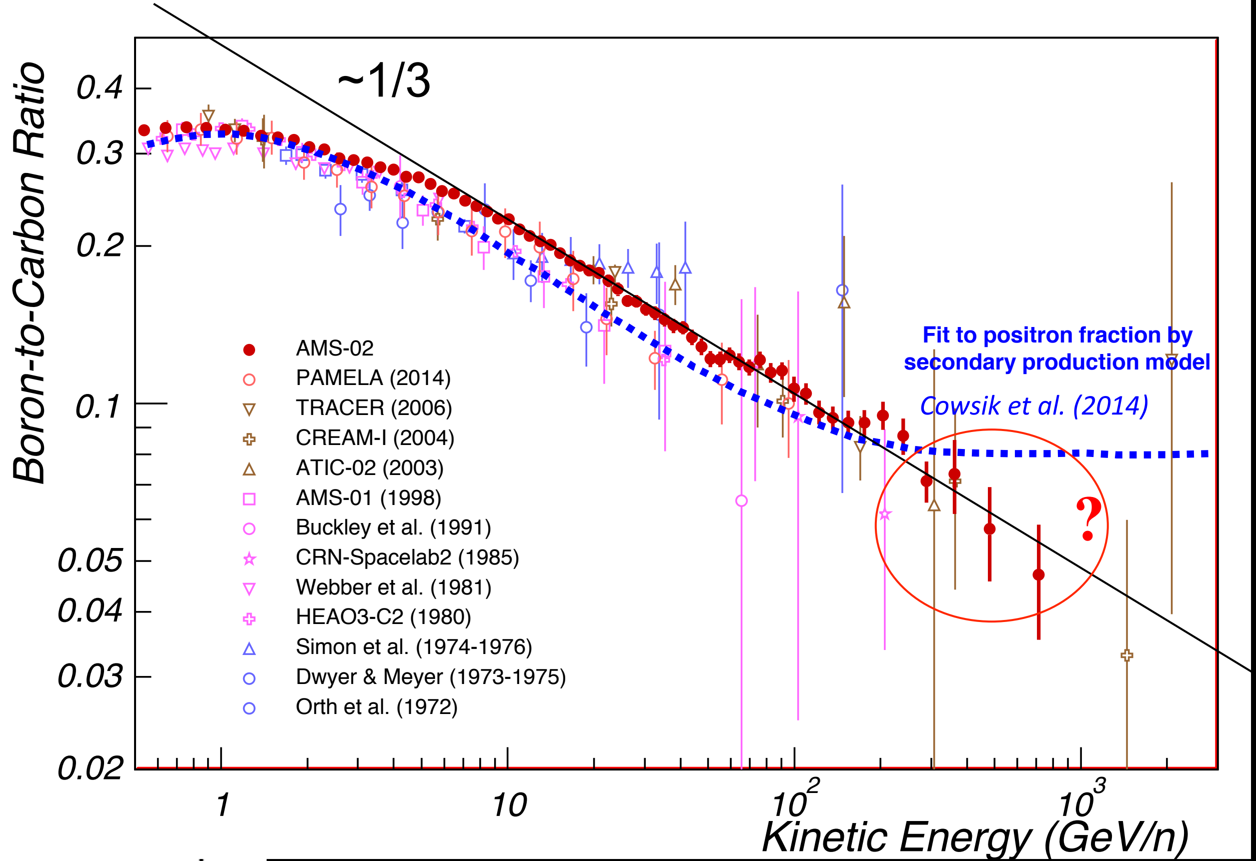
Kachelriess & Ostapchenko 2013

✧ The model assumptions are somewhat different, but all models predict a rise in the secondary products

AMS B/C ratio

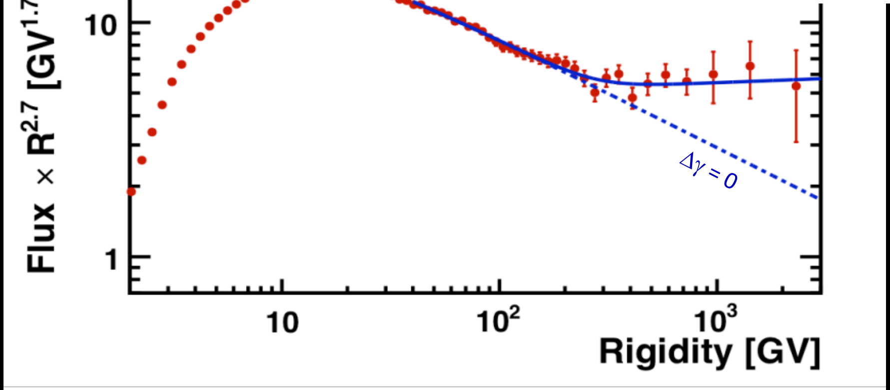
- ✧ No significant change in the slope of the B/C ratio
- ✧ Rules out Cowsik+ model
- ✧ The slope >7 GeV/n is ~1/3 – clearly supports Kolmogorov reacceleration model

B/C Ratio converted in Kinetic Energy



Lithium flux with two pow

$\Phi = C\left(\frac{R}{45\,\mathrm{GV}}\right)^{\gamma}\Big[1$

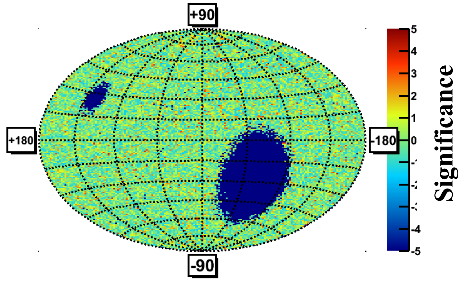


Slope changes at about the same rigidity as for protons and helium

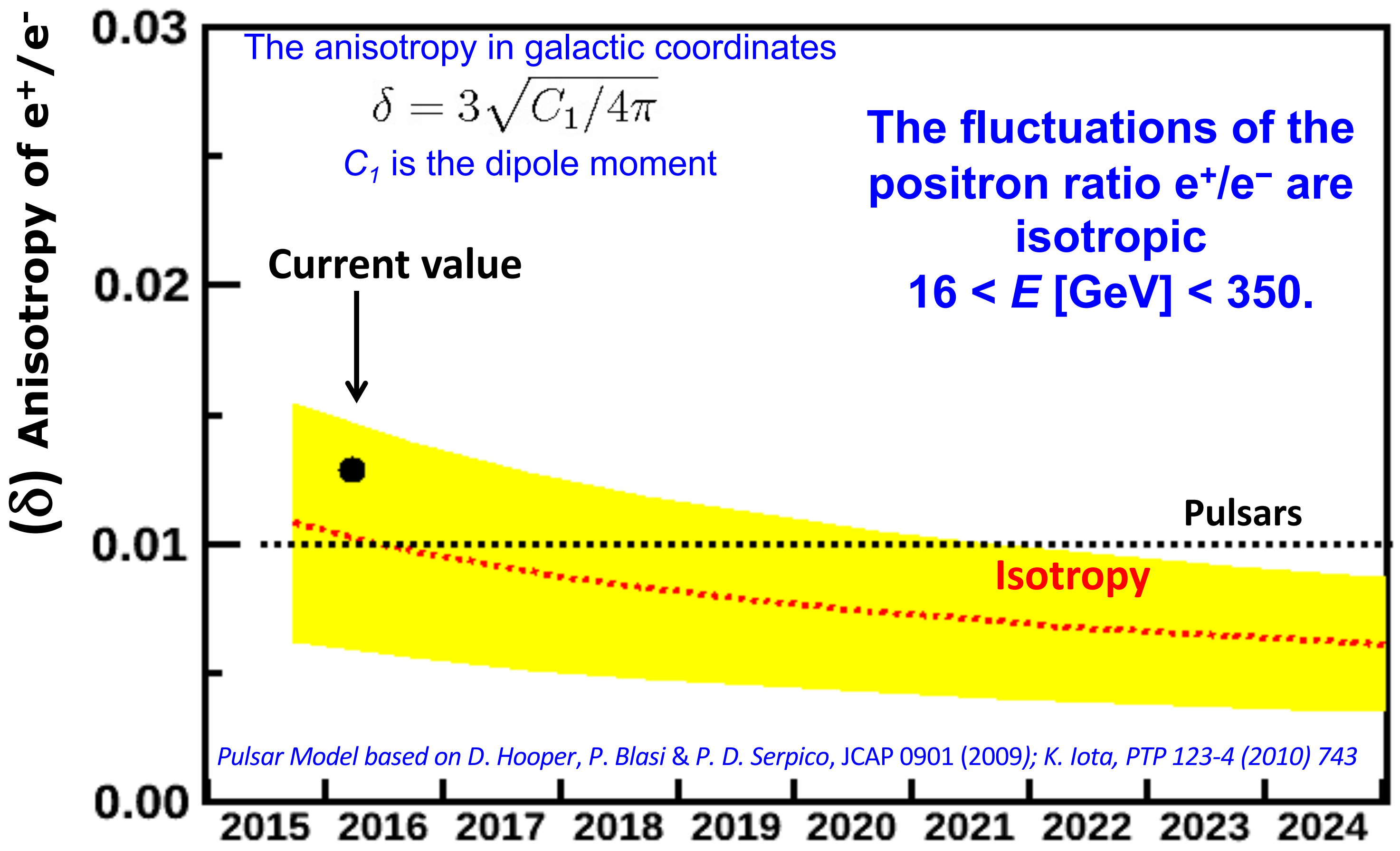
- ✧ Interestingly, a break in the Li spectrum is found – similar to p & He
- ✧ No break in Carbon spectrum?

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)



The anisotropy in galactic coordinates

$$\delta = 3\sqrt{C_1/4\pi}$$

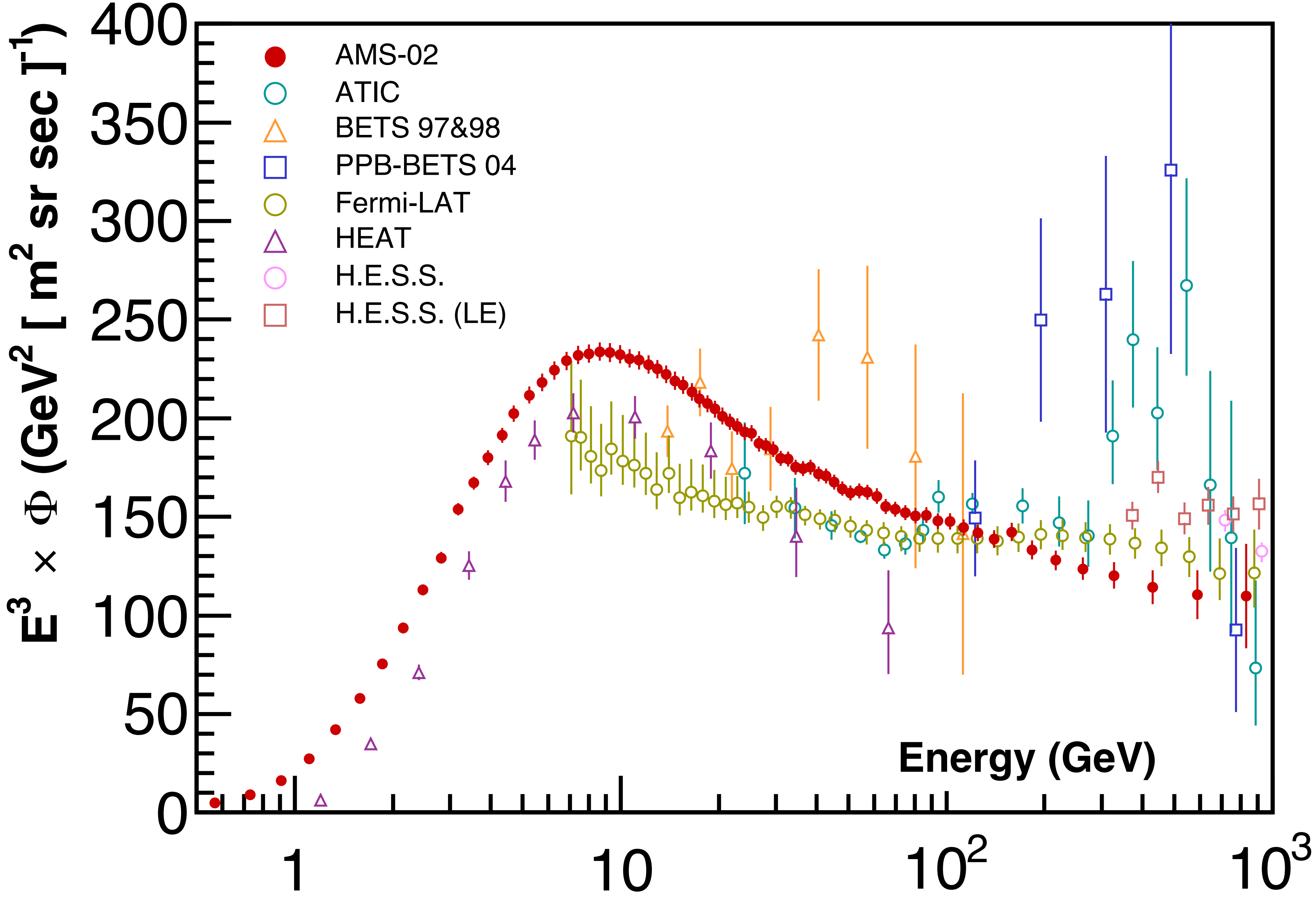
C_1 is the dipole moment

The fluctuations of the positron ratio e^+/e^- are isotropic
$16 < E$ [GeV] < 350.

Pulsar Model based on D. Hooper, P. Blasi & P. D. Serpico, JCAP 0901 (2009); K. Iota, PTP 123-4 (2010) 743

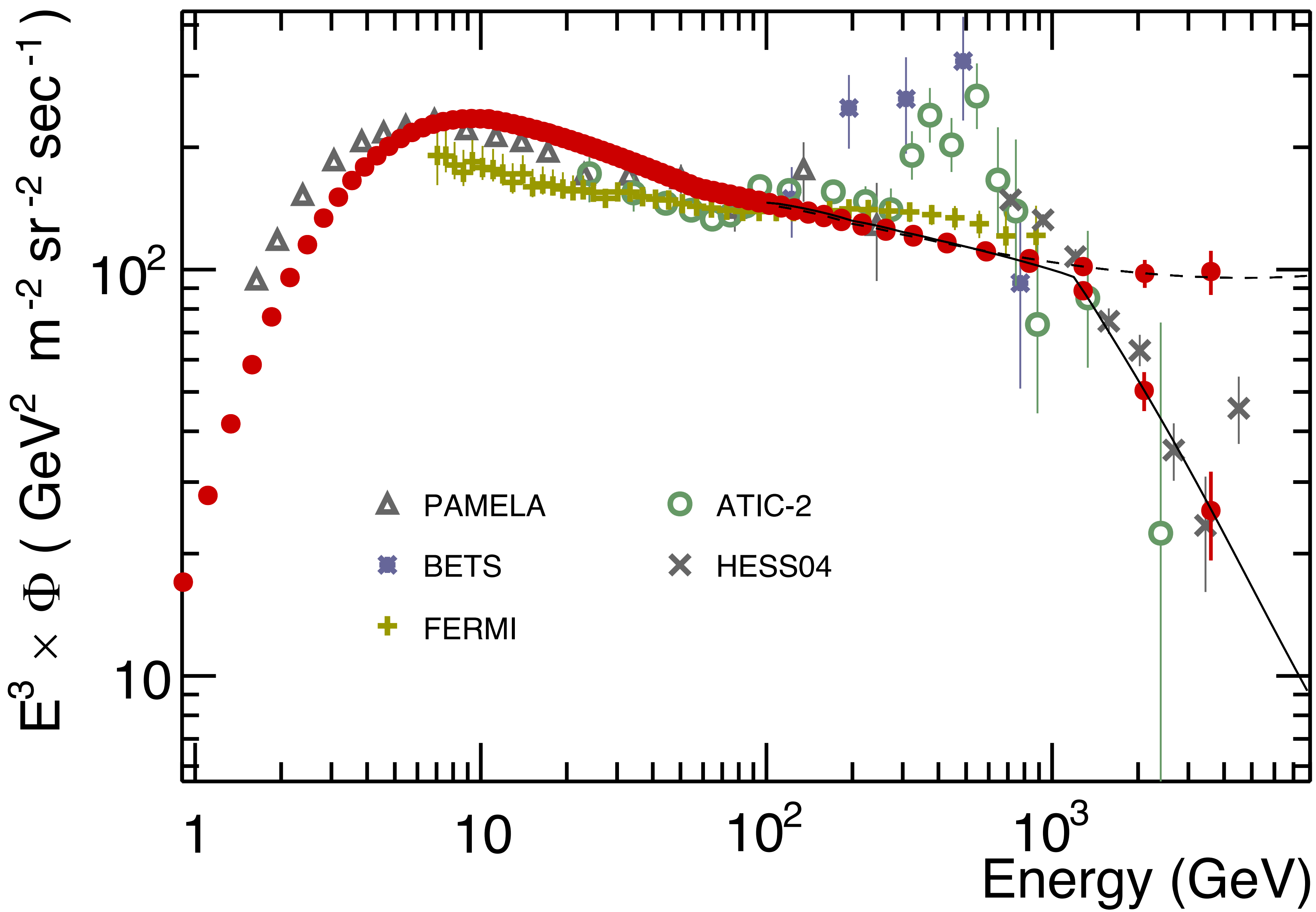
Data taking to 2024 will allow to explore anisotropies of 1%

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

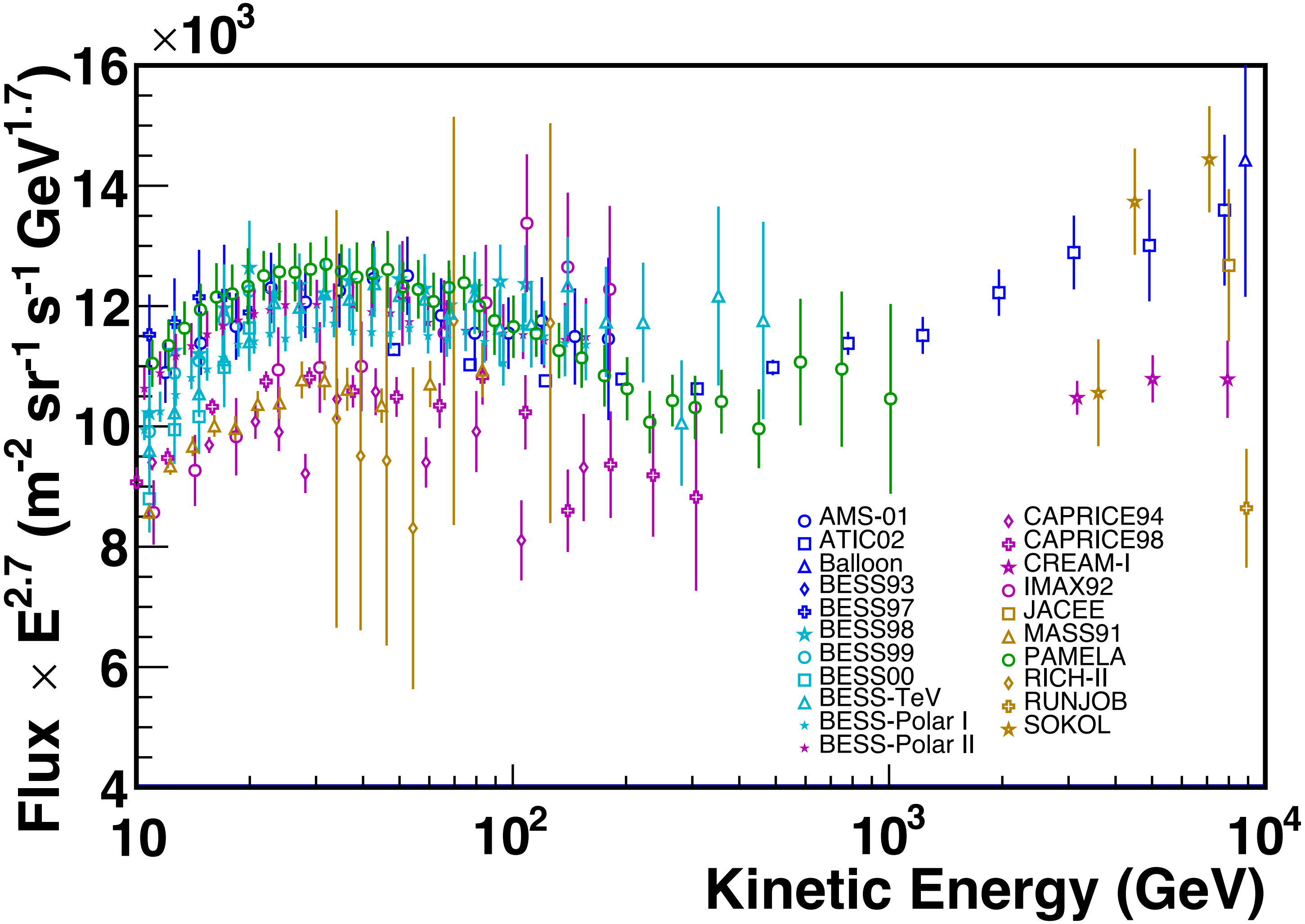


AMS will be able to distinguish the ($e^+ + e^-$) flux behavior above 1 TeV

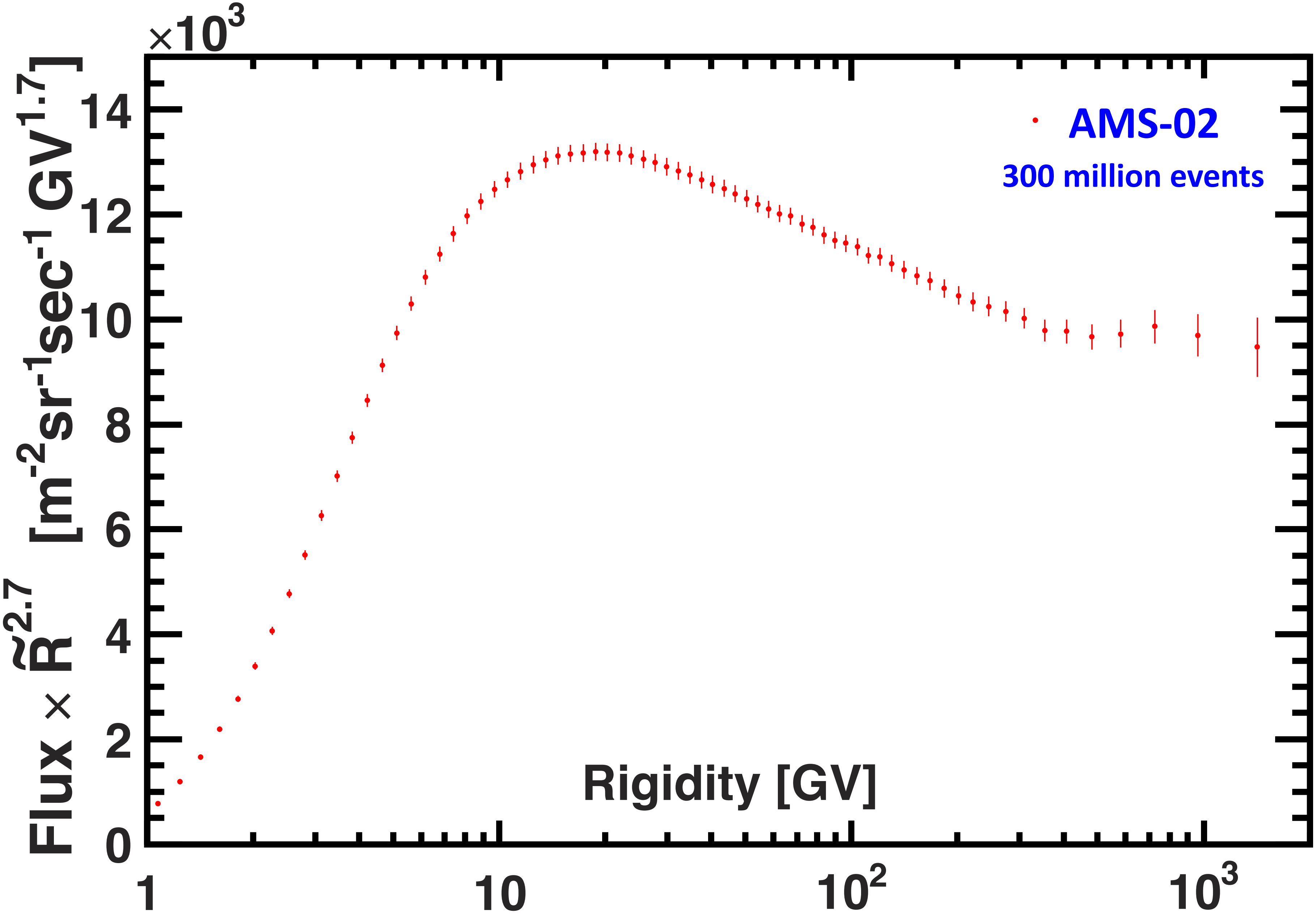
Cosmic Protons

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 γ = -2.7**

Proton Spectrum



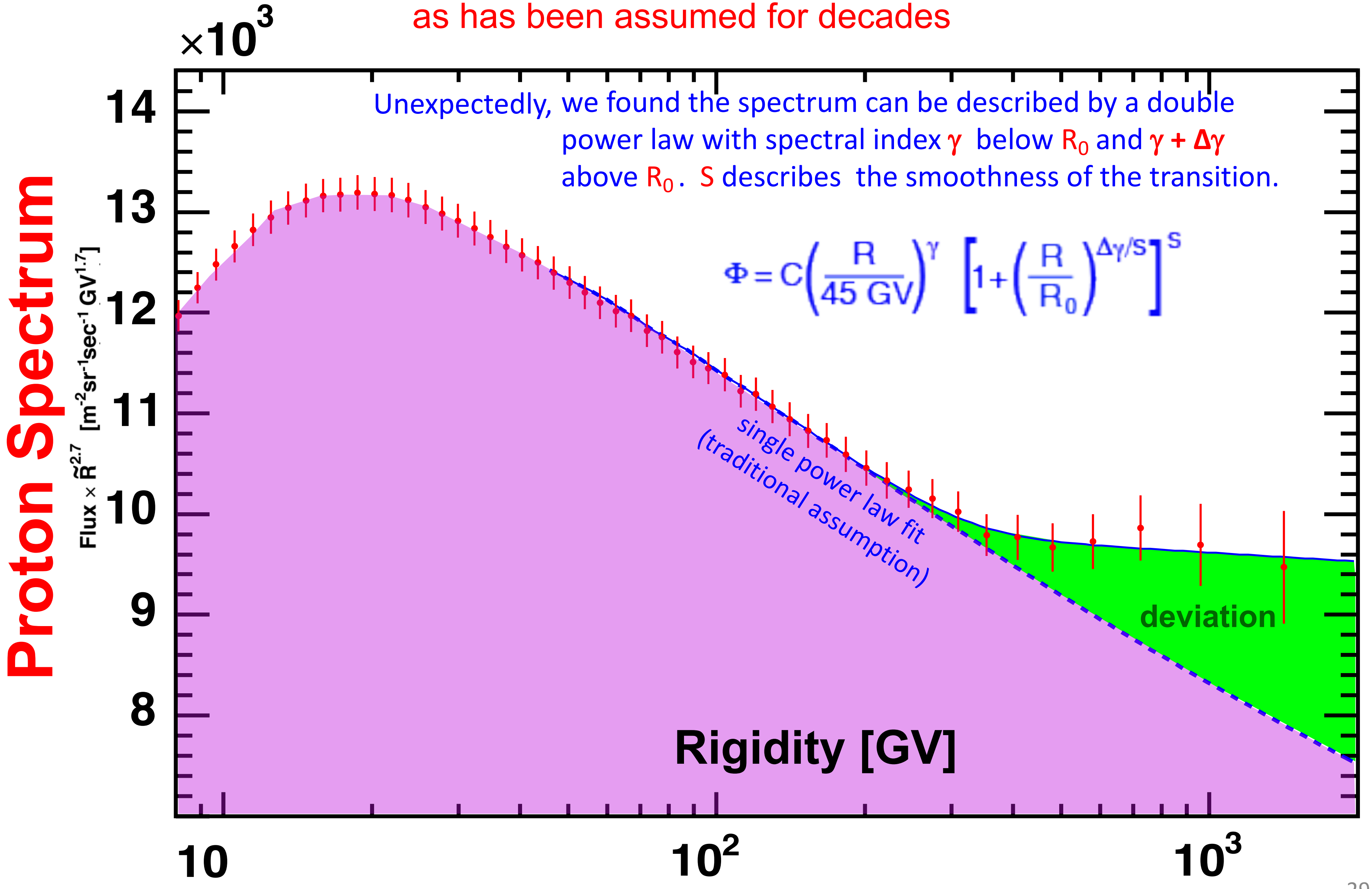
AMS Physics Result 6: Precision measurement of the proton flux to an accuracy of 1%



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^{γ}, as has been assumed for decades

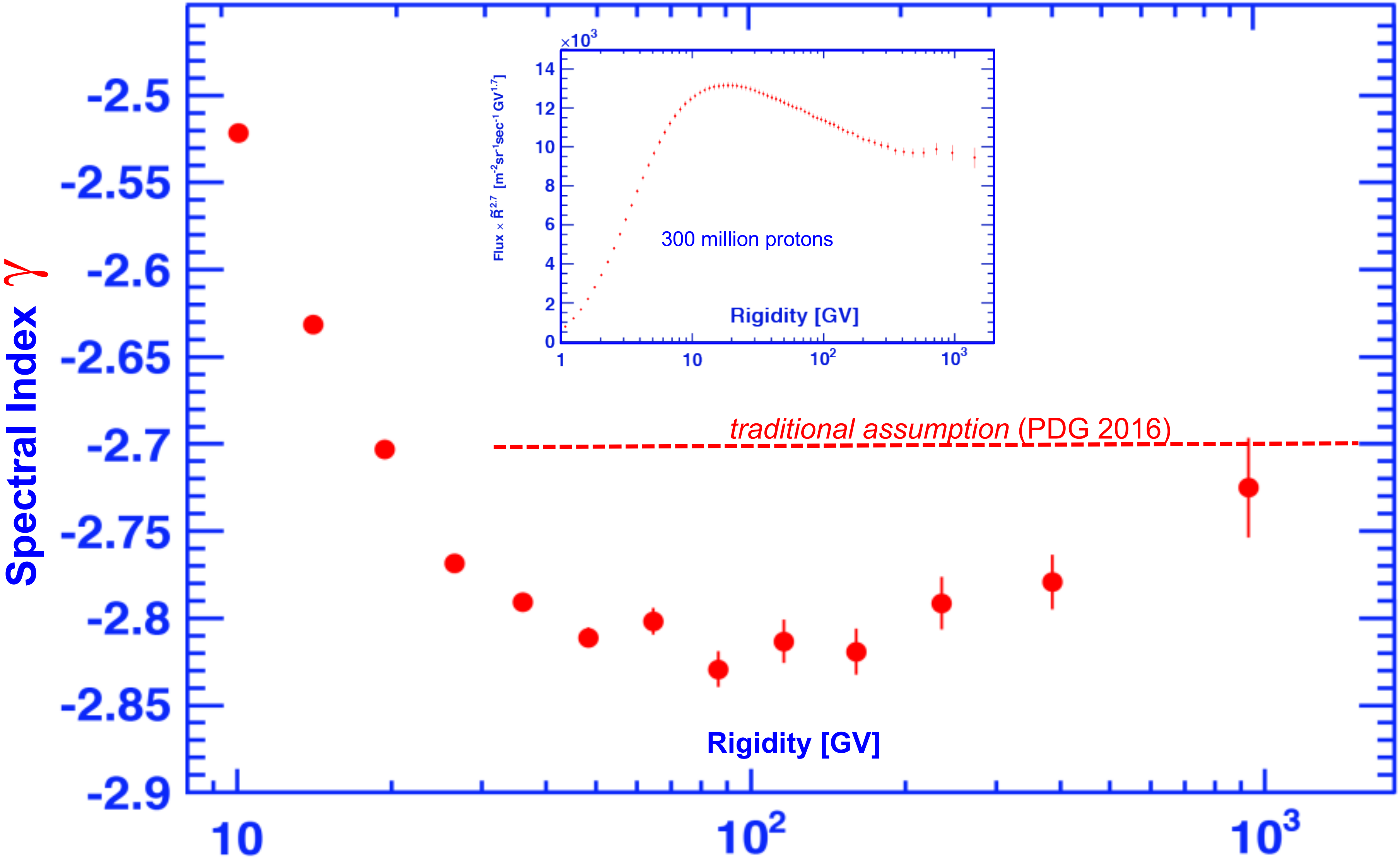


Unexpectedly, we found the spectrum can be described by a double power law with spectral index γ below R_0 and $\gamma + \Delta\gamma$ above R_0. S describes the smoothness of the transition.

$$\Phi = C\left(\frac{R}{45\ \mathrm{GV}}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/S}\right]^{S}$$

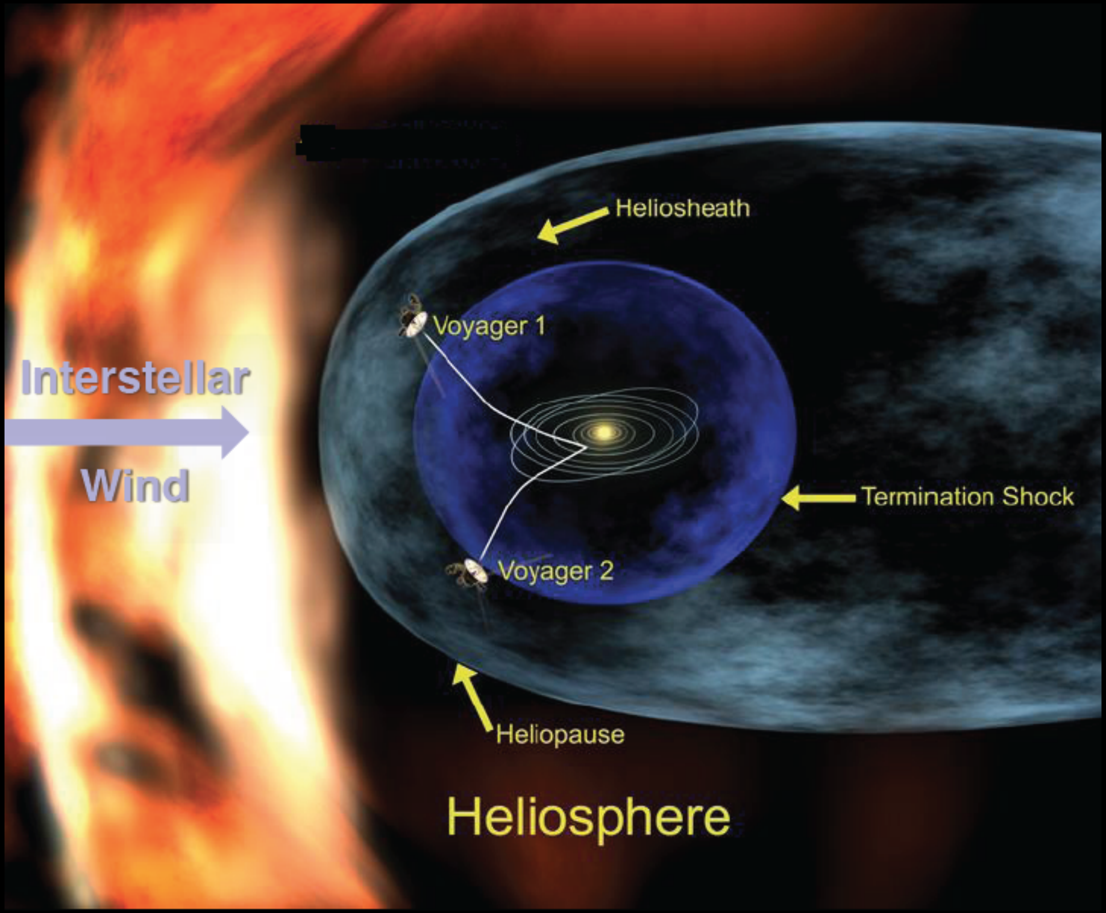
New information: The proton spectral index changes with momentum.

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



γ is not a constant -2.7

Voyager 1 in the interstellar space



Voyager 1 131.0 AU

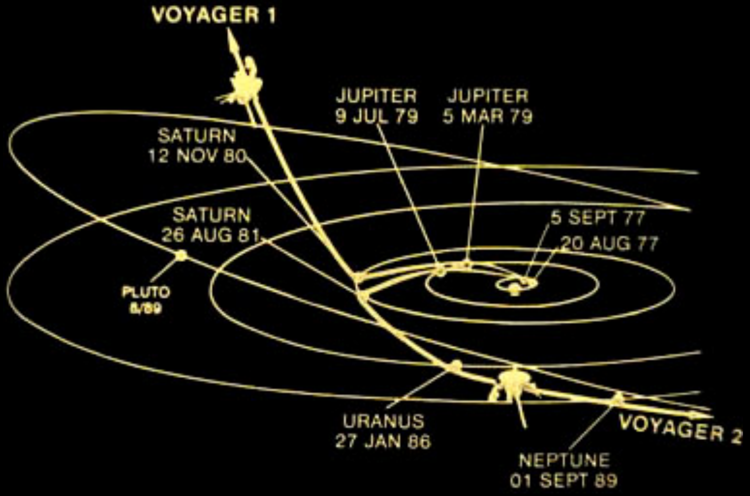
19.7 billion km

Voyager 2   107.7 AU

16.2 billion km

~2 years to interstellar space?

Launched in 1977!

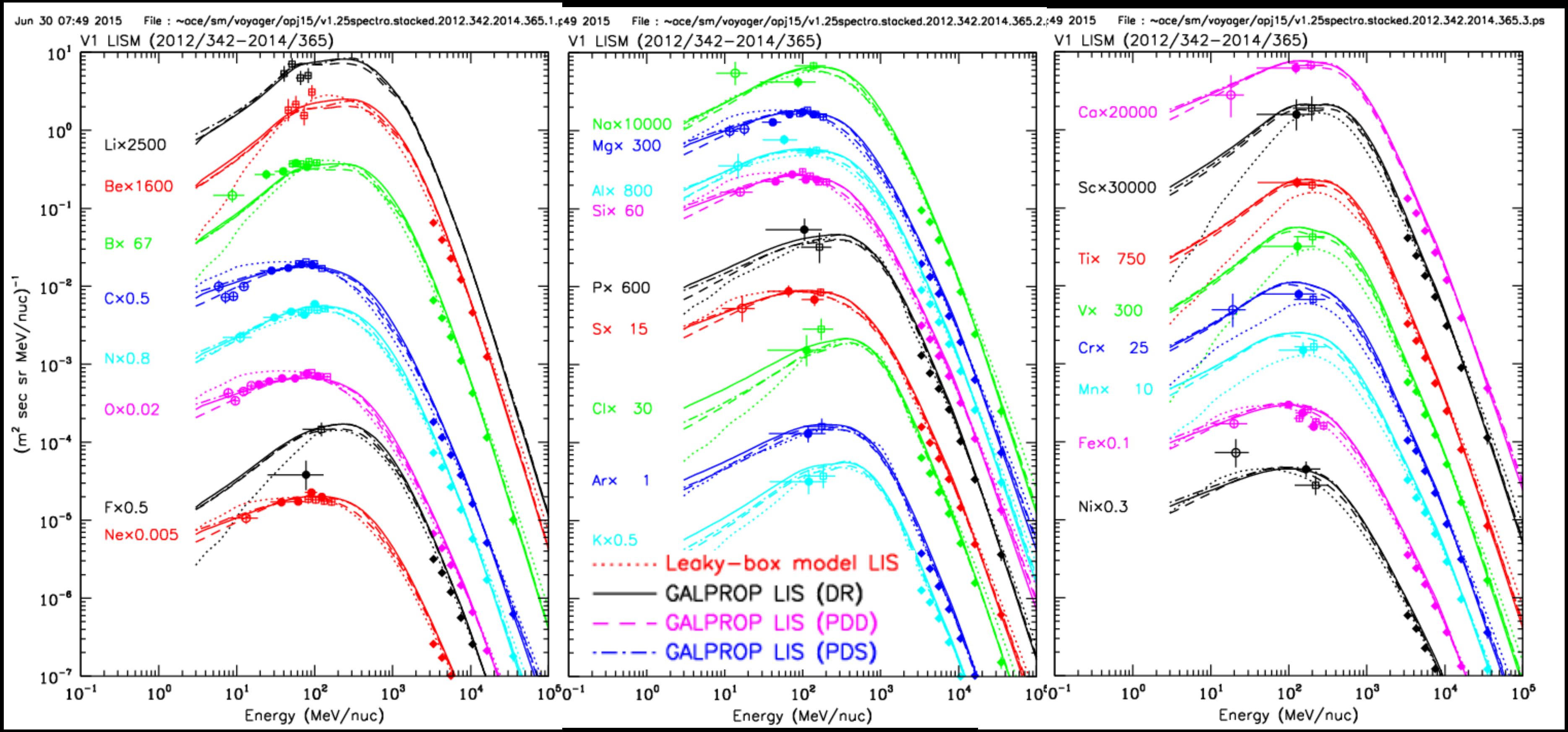


First interstellar probe!

Will operate until 2026

E. Stone 2015

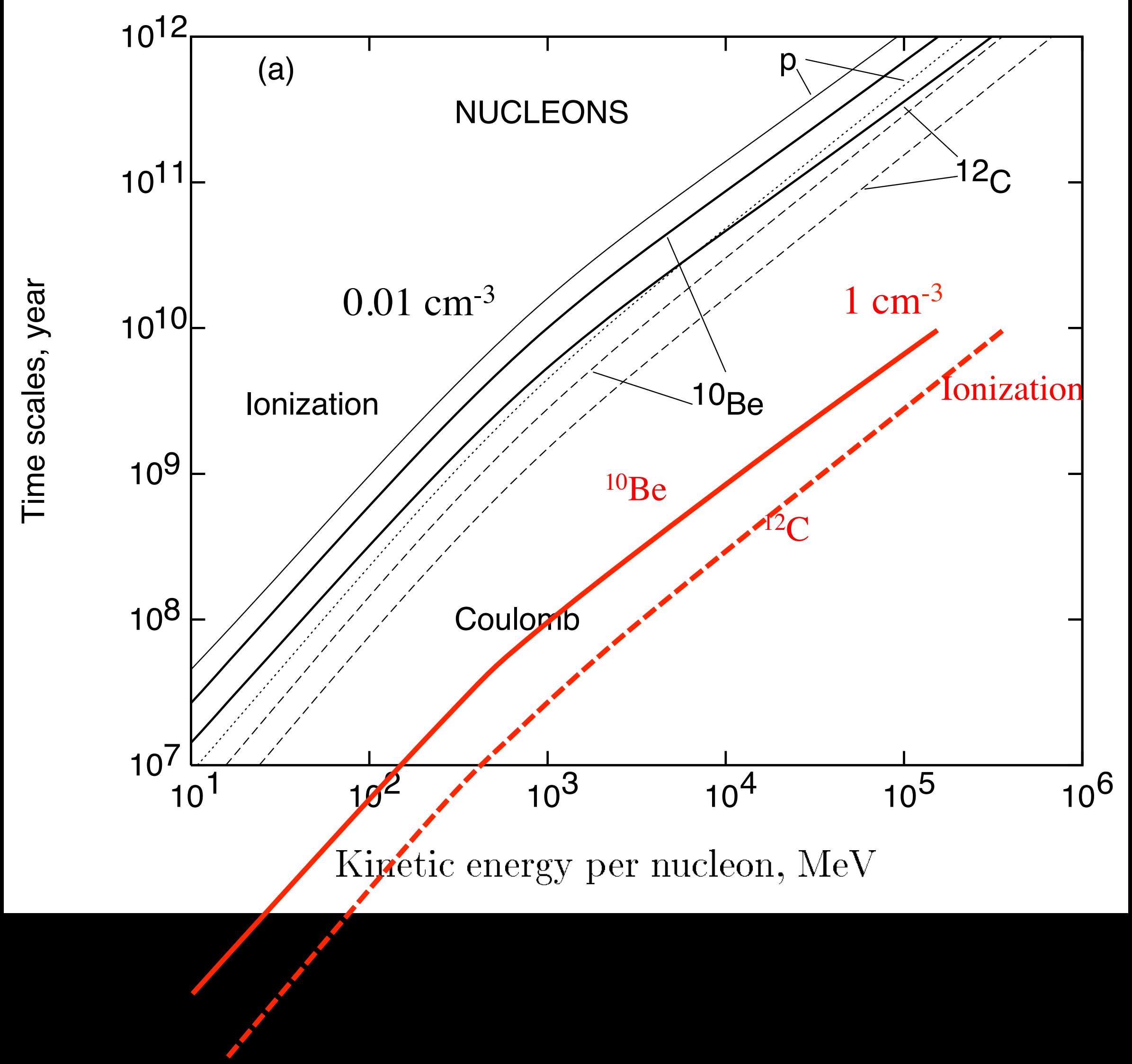
Voyager 1 spectra for 2012/342-2014/365



Li – Ni : V1 spectra together with HEAO-3-C2 data (≥3.35 GeV/nuc)

ApJ Paper – in progress

Energy losses of nucleons



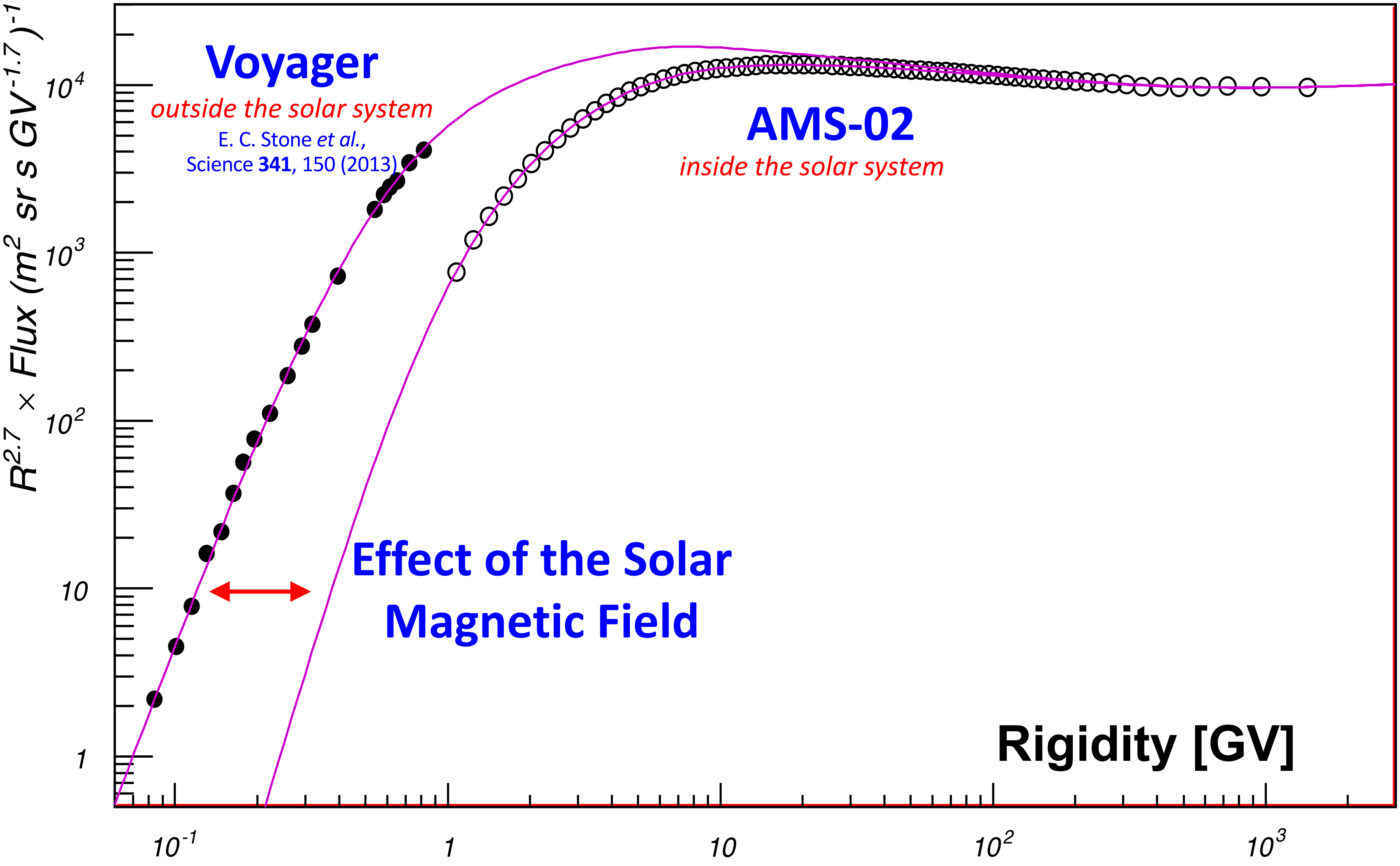
- ✧ The ionization and Coulomb losses are calculated for the gas number density 0.01 cm^{-3} & 1 cm^{-3}

  Carbon at 10 MeV/n (nH ~1 cm^{-3}):

  τ ~ 30 kyr
- ✧ The energy losses by nucleons can be neglected above ~1 GeV
- ✧ Nuclear interactions are more important

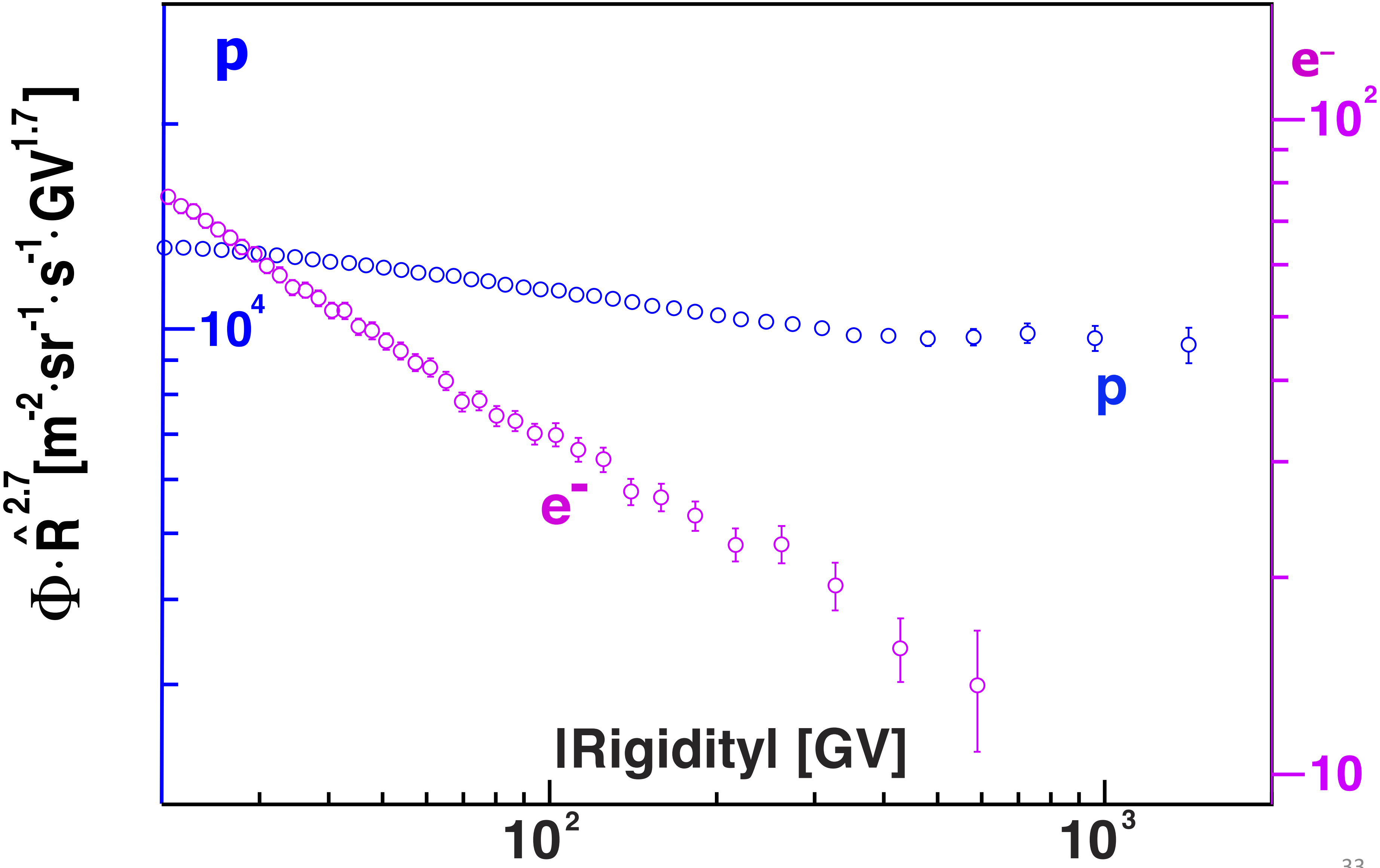
Understanding of the Solar Magnetic Field:

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.



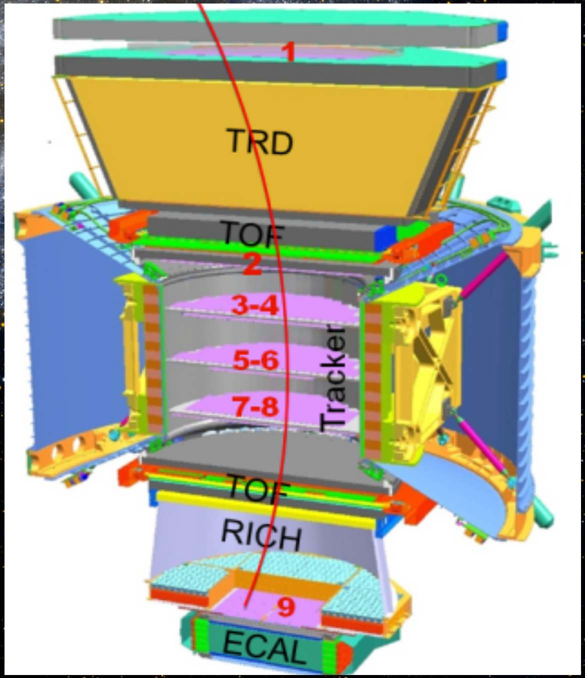
M. Aguilar *et al*., Phys. Rev. Lett. **117,** 091103 (2016)

Antiprotons

$$\text{Cosmic ray} + \text{ISM} \to \bar{p} + \ldots$$

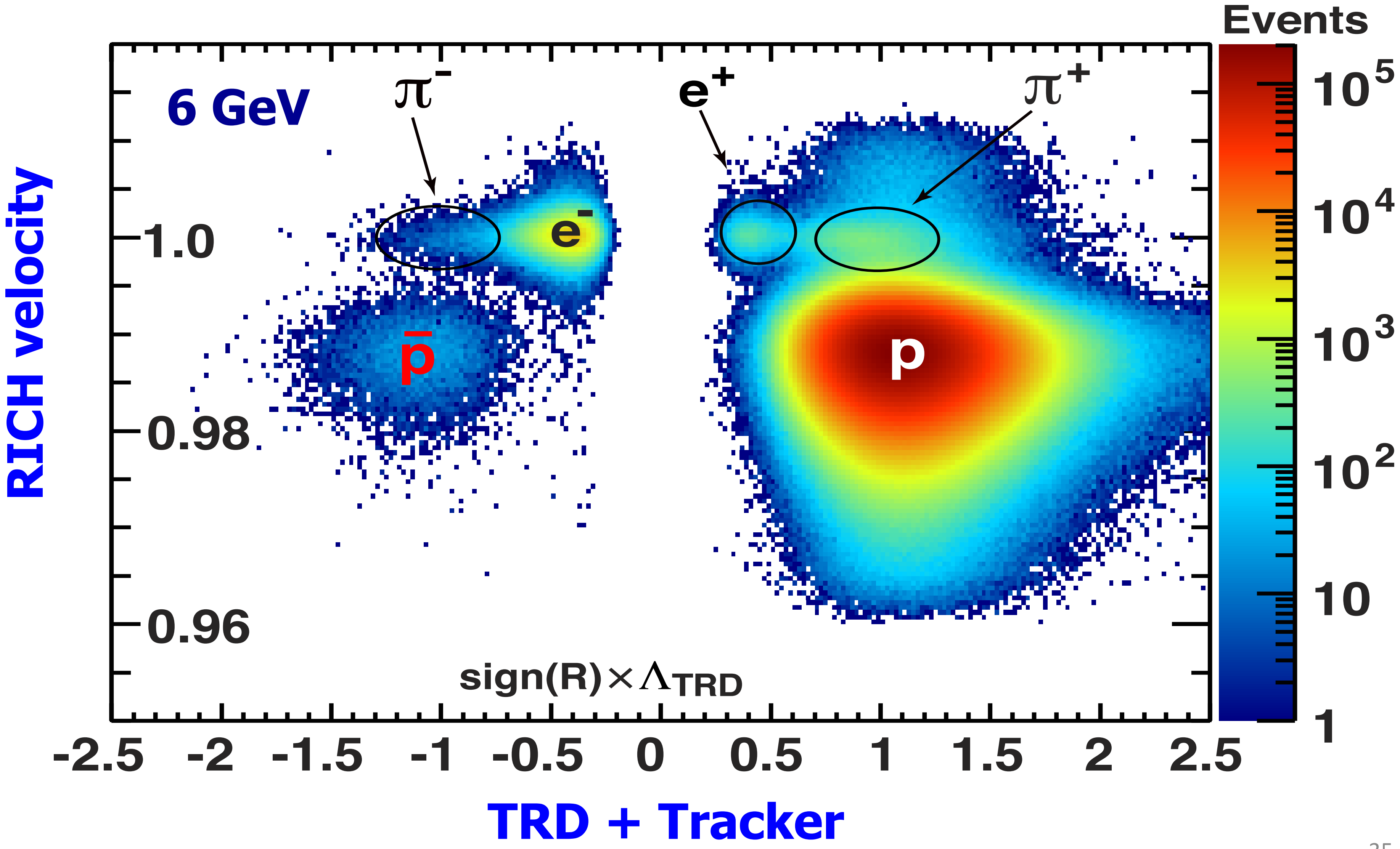
$$\chi + \chi \to \bar{p} + \ldots$$

There is only 1 Antiproton for 10,000 Protons.



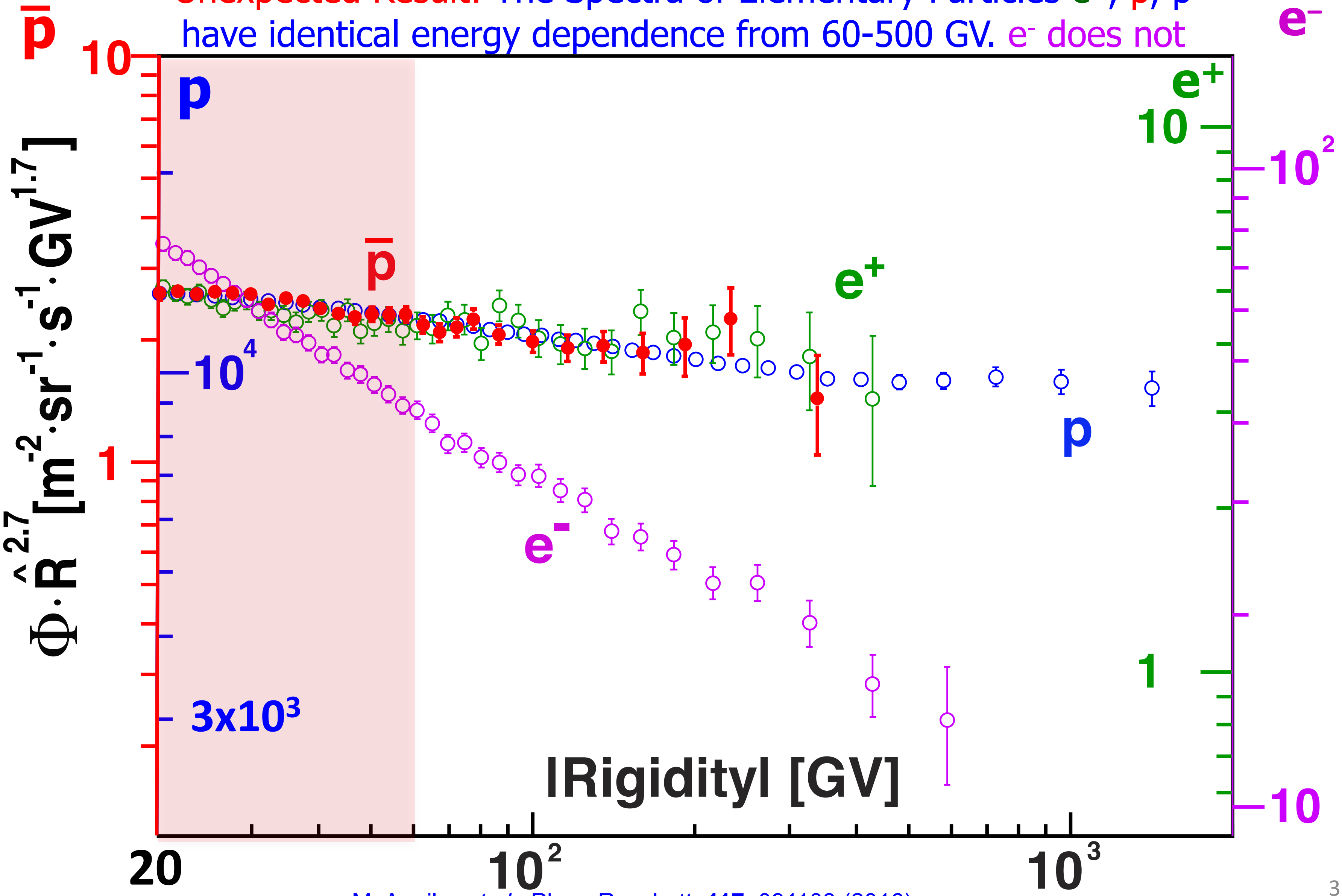
A percent precision experiment requires background rejection close to 1 in a million.

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



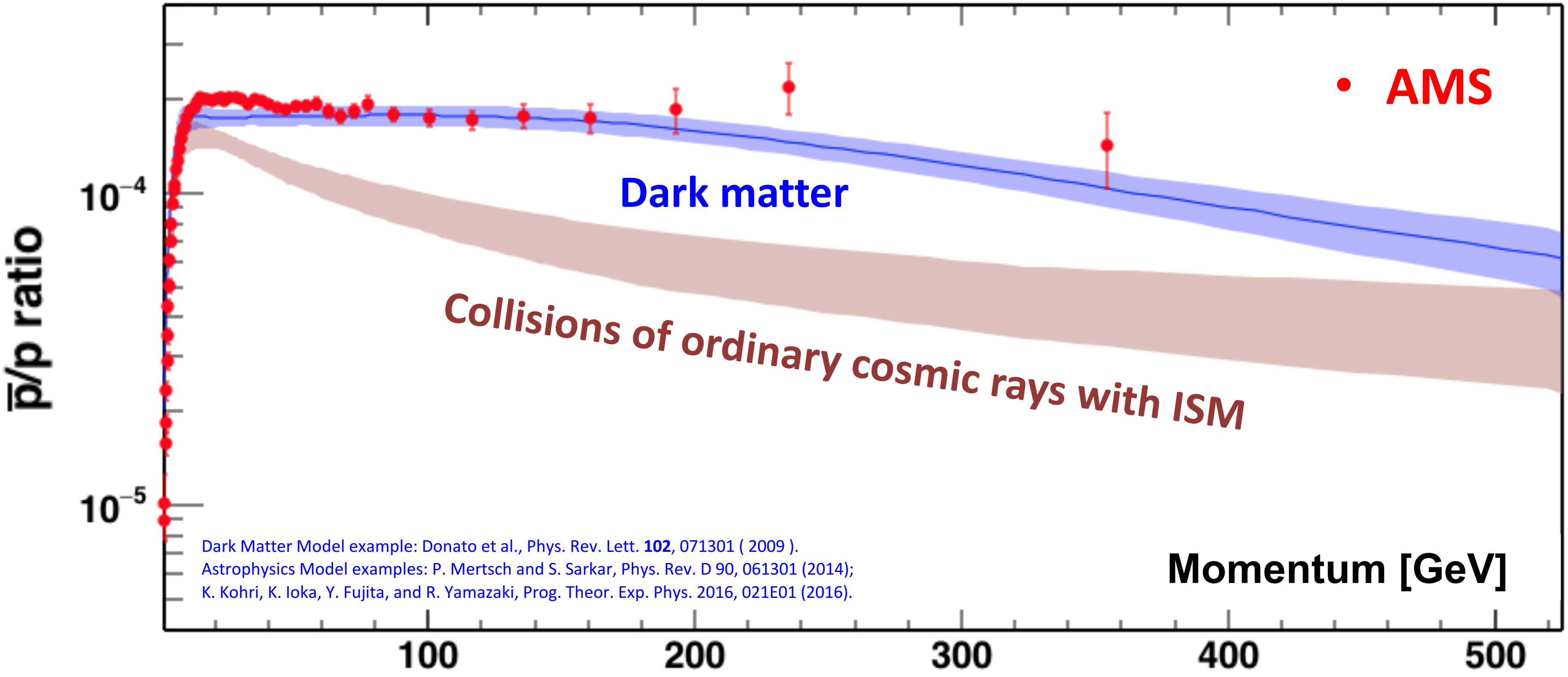
Physics Result 7: The antiproton flux and properties of elementary particle fluxes

Unexpected Result: The Spectra of Elementary Particles e^+, $\bar{p}$, p have identical energy dependence from 60-500 GV. e^- does not



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

Antiproton-to-proton ratio



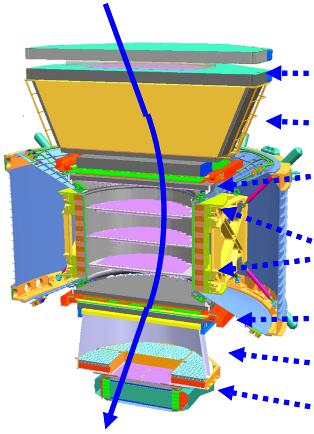
Dark Matter Model example: Donato et al., Phys. Rev. Lett. **102**, 071301 (2009).
Astrophysics Model examples: P. Mertsch and S. Sarkar, Phys. Rev. D 90, 061301 (2014);
K. Kohri, K. Ioka, Y. Fujita, and R. Yamazaki, Prog. Theor. Exp. Phys. 2016, 021E01 (2016).

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

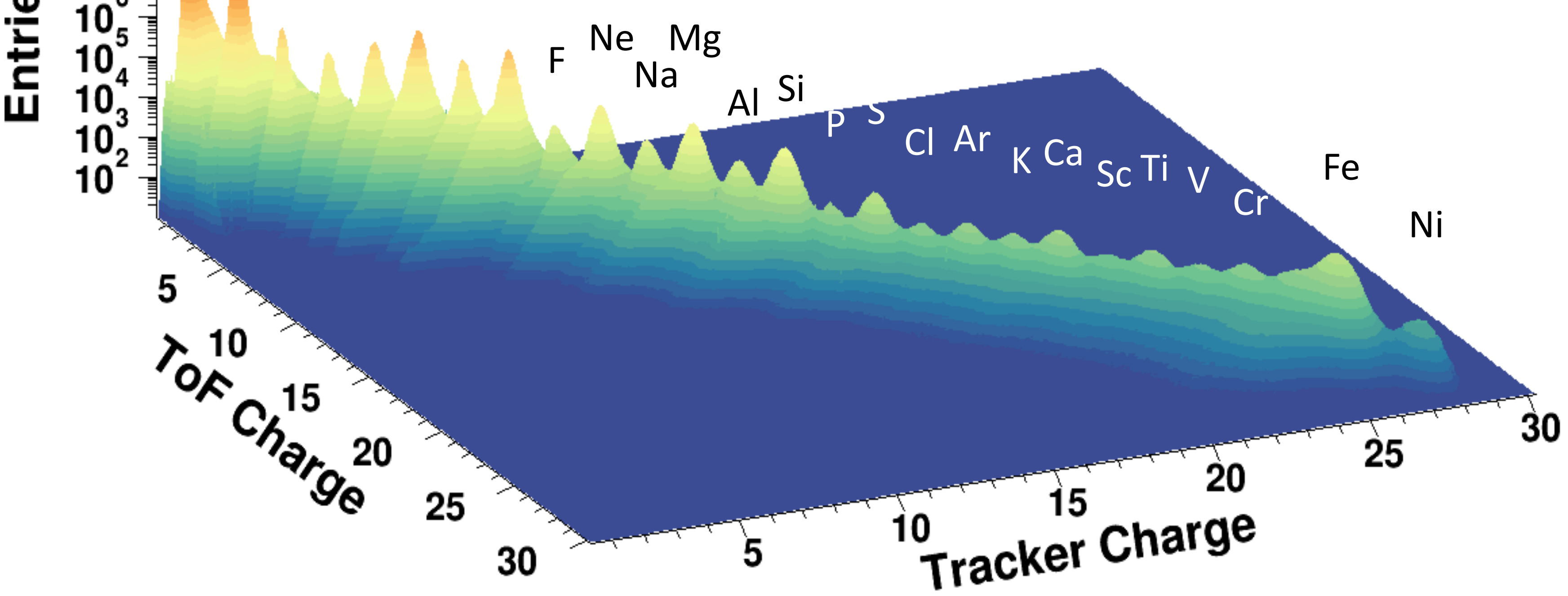
It can be explained by Dark Matter collisions or by new astrophysics phenomena

Cosmic Nuclei

AMS has seven instruments which independently identify different elements

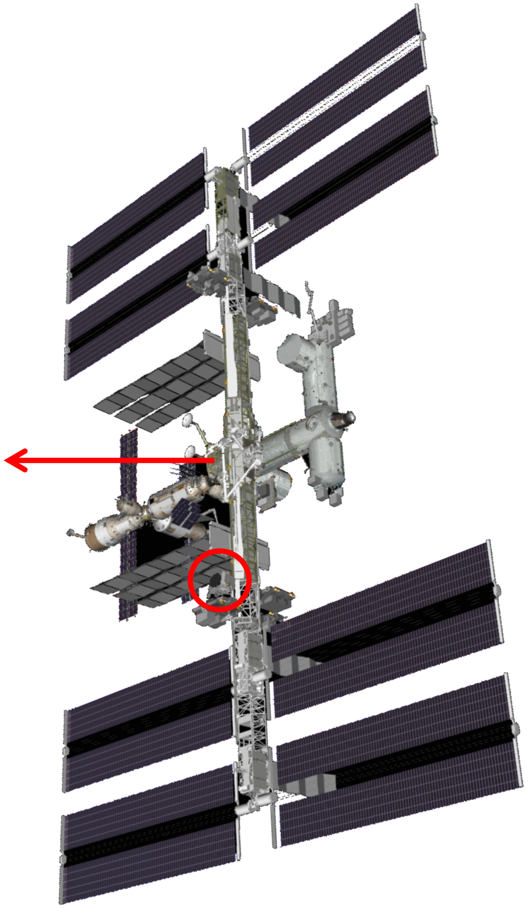


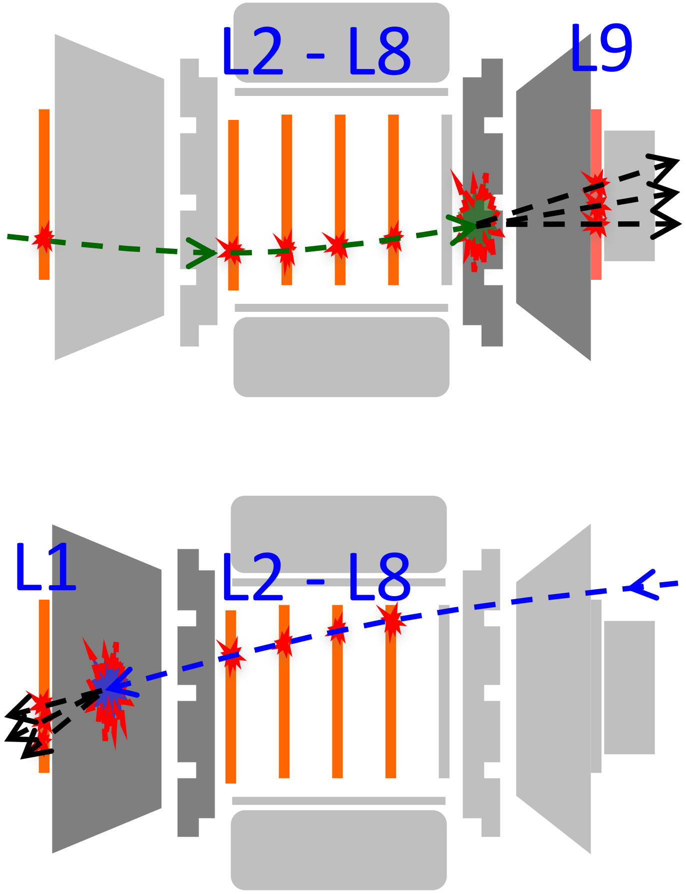
	Charge Resolution Z=6
Tracker Plane 1	0.30
TRD	0.33
Upper TOF	0.16
Tracker Plane 2-8	0.12
Lower TOF	0.16
RICH	0.32
Tracker Plane 9	0.30



Measuring the interactions of nuclei within AMS

AMS horizontal



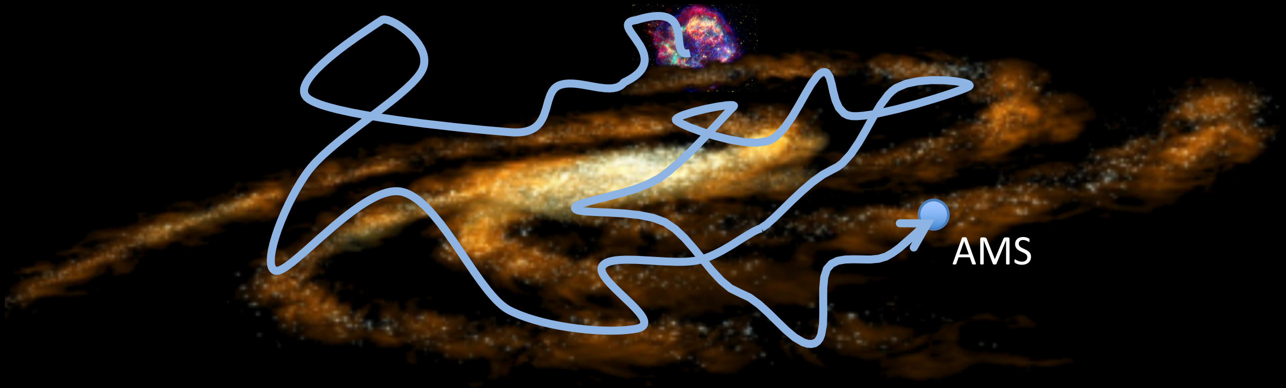


First, we use the seven inner tracker layers, L2-L8, to define beams of nuclei: Li, Be, B, …

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.

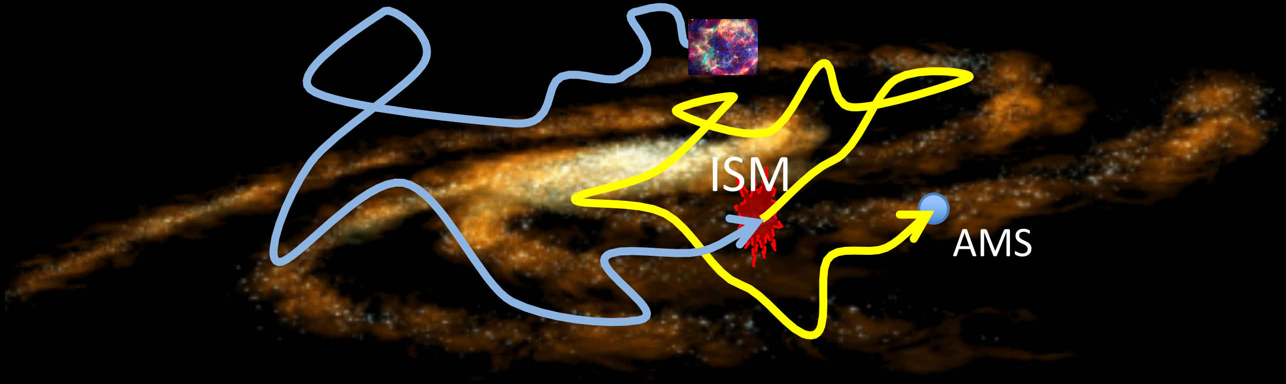
Primary Cosmic Rays (p, He, C, O, …)



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

Secondary Cosmic Rays (Li, Be, B, …)

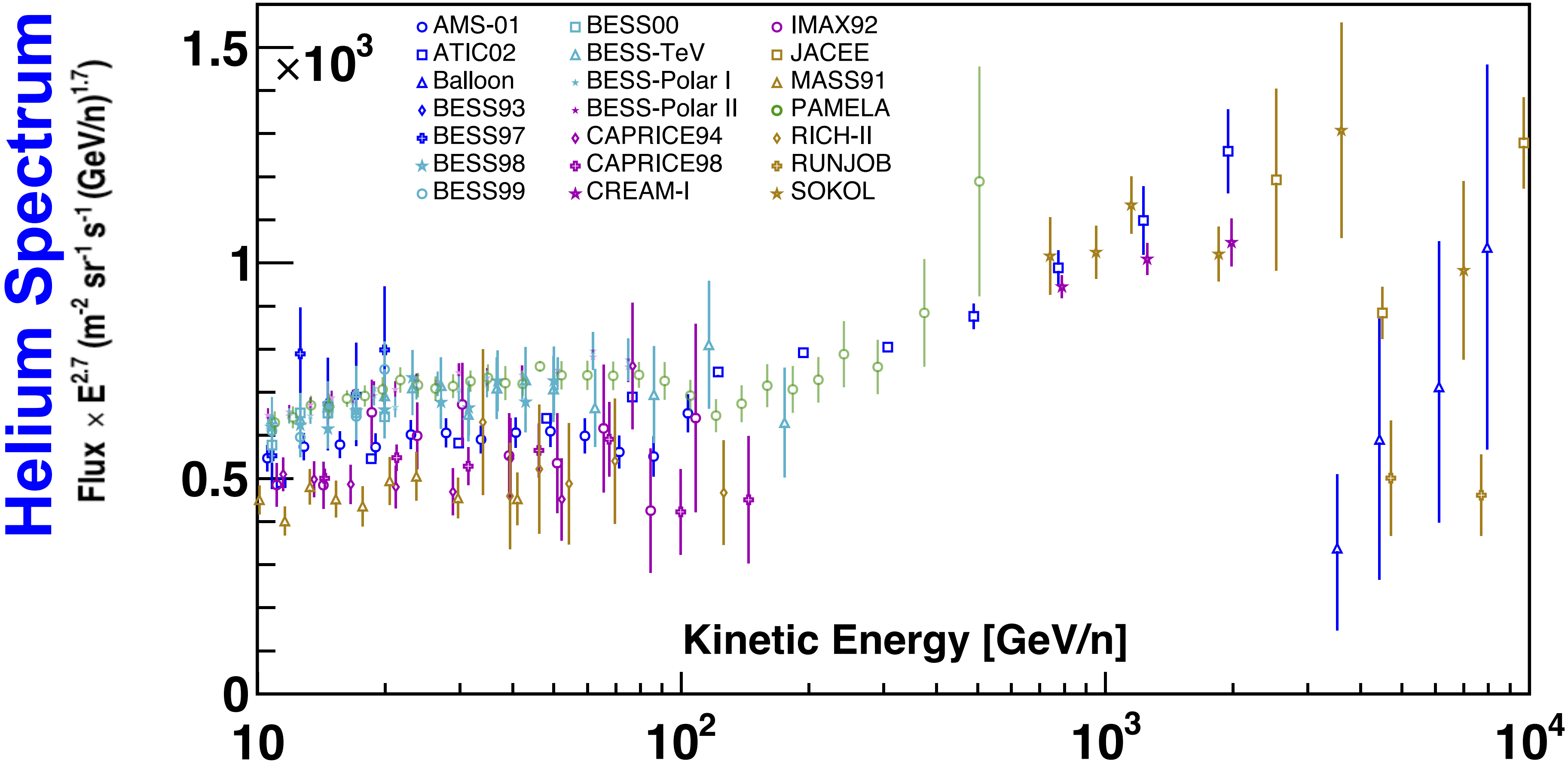
C, O, …, Fe + ISM → Li, Be, B + X



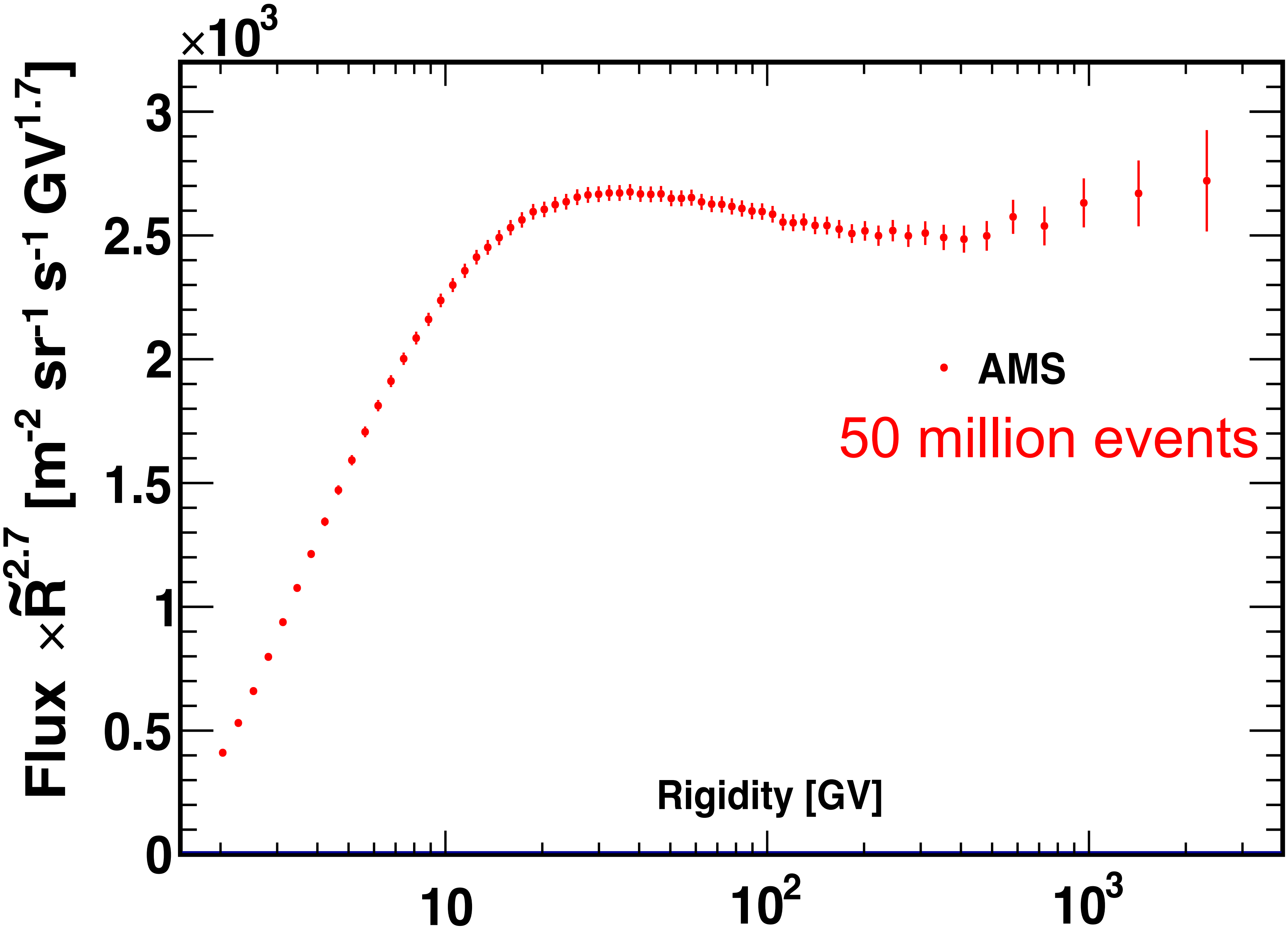
Secondary cosmic rays carry information about propagation of primaries, secondaries and the ISM.

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 γ = -2.7 (as for protons).



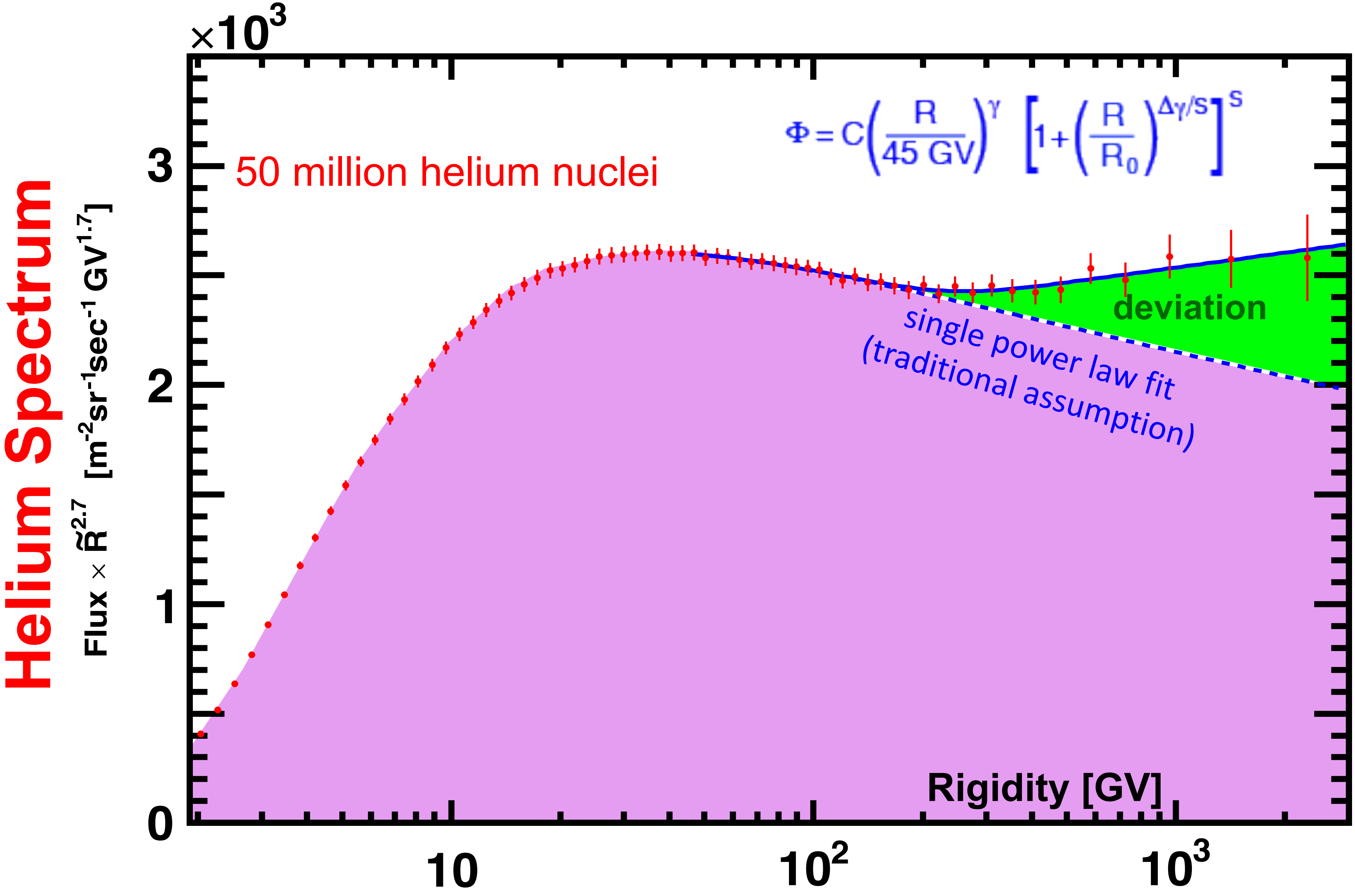
AMS Physics Result 8: Precision measurements of the helium flux



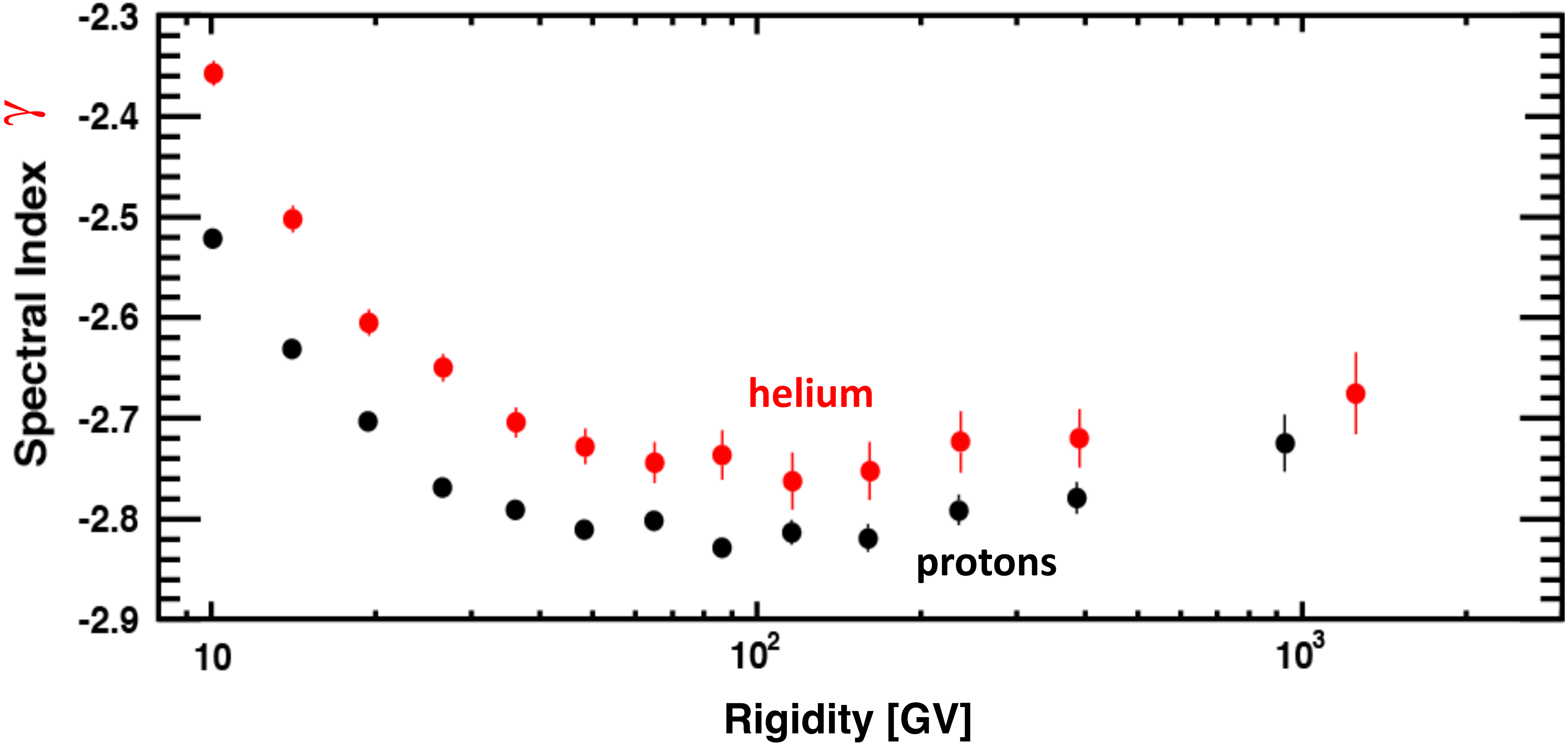
M. Aguilar *et al.*, Phys. Rev. Lett. **115,** 211101 (2015)

AMS Helium Flux

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

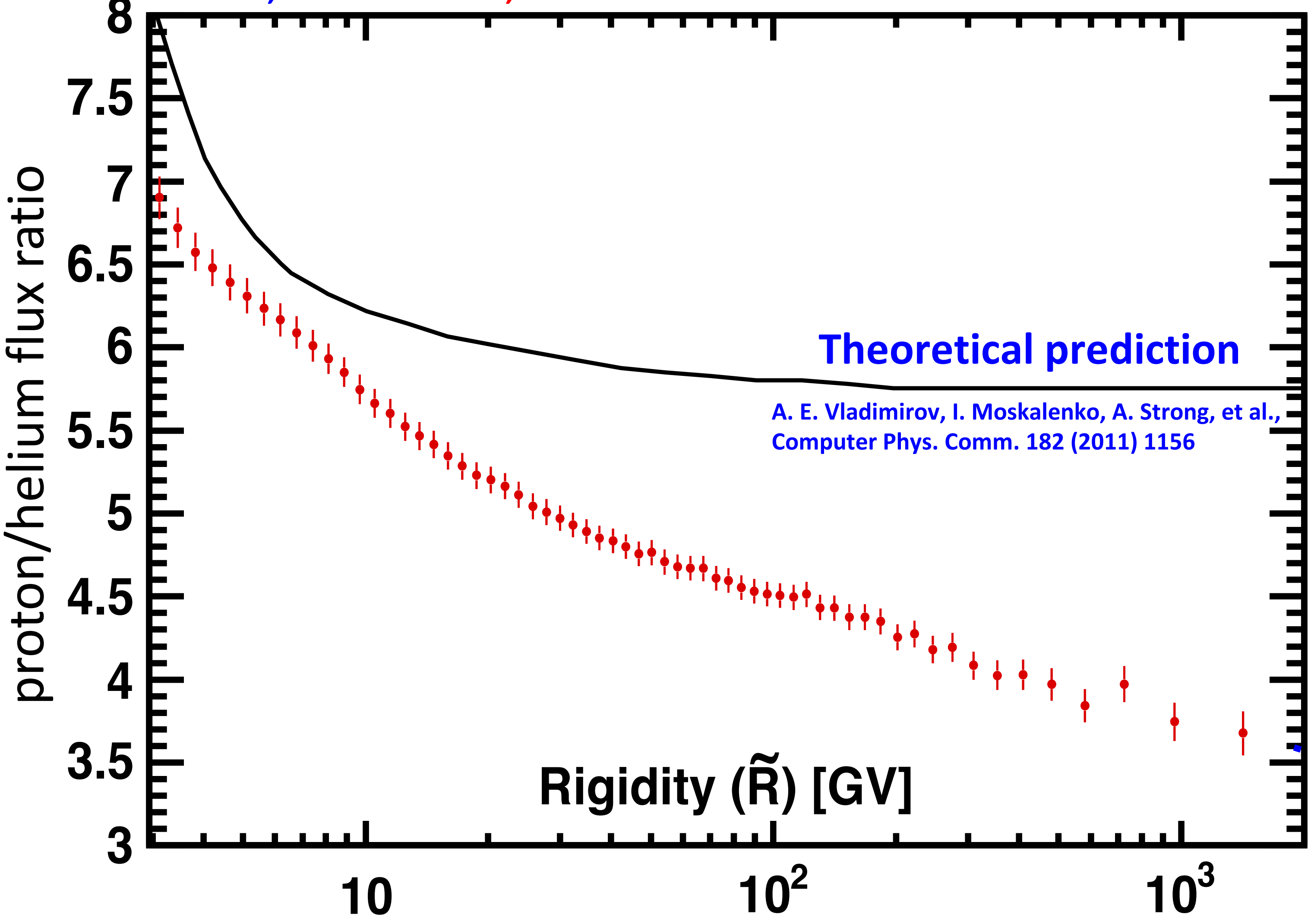


New information: The helium spectral index changes with rigidity in a similar way to that of the proton spectral index but the values are different



Physics Result 9: The AMS proton/helium flux ratio

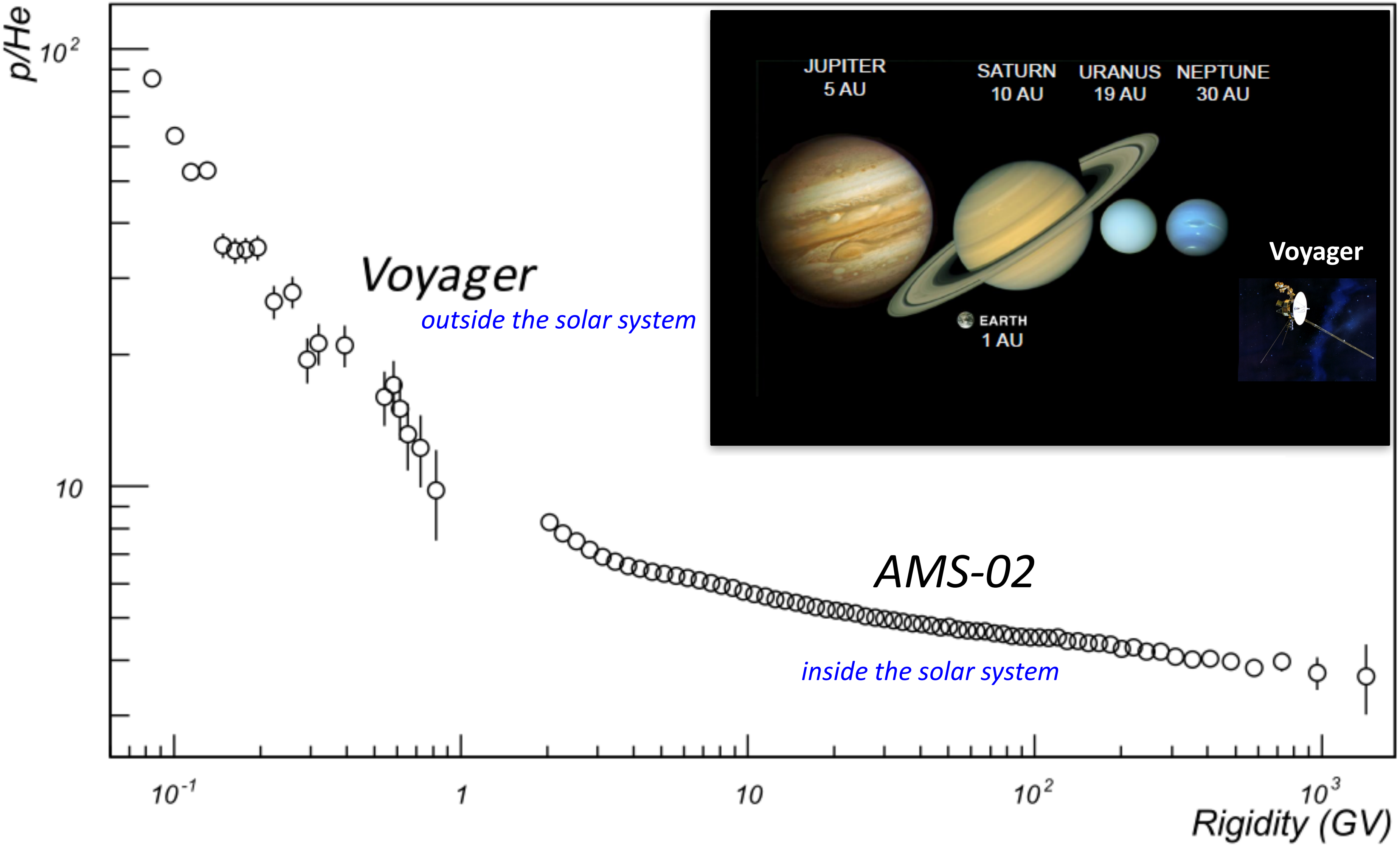
Protons and helium are both “primary” cosmic rays.
Traditionally, they are assumed to be produced in the same sources
and, therefore, their flux ratio should be flat.



A. E. Vladimirov, I. Moskalenko, A. Strong, et al.,
Computer Phys. Comm. 182 (2011) 1156

AMS result: this ratio is not flat.

Proton to Helium Flux Ratio

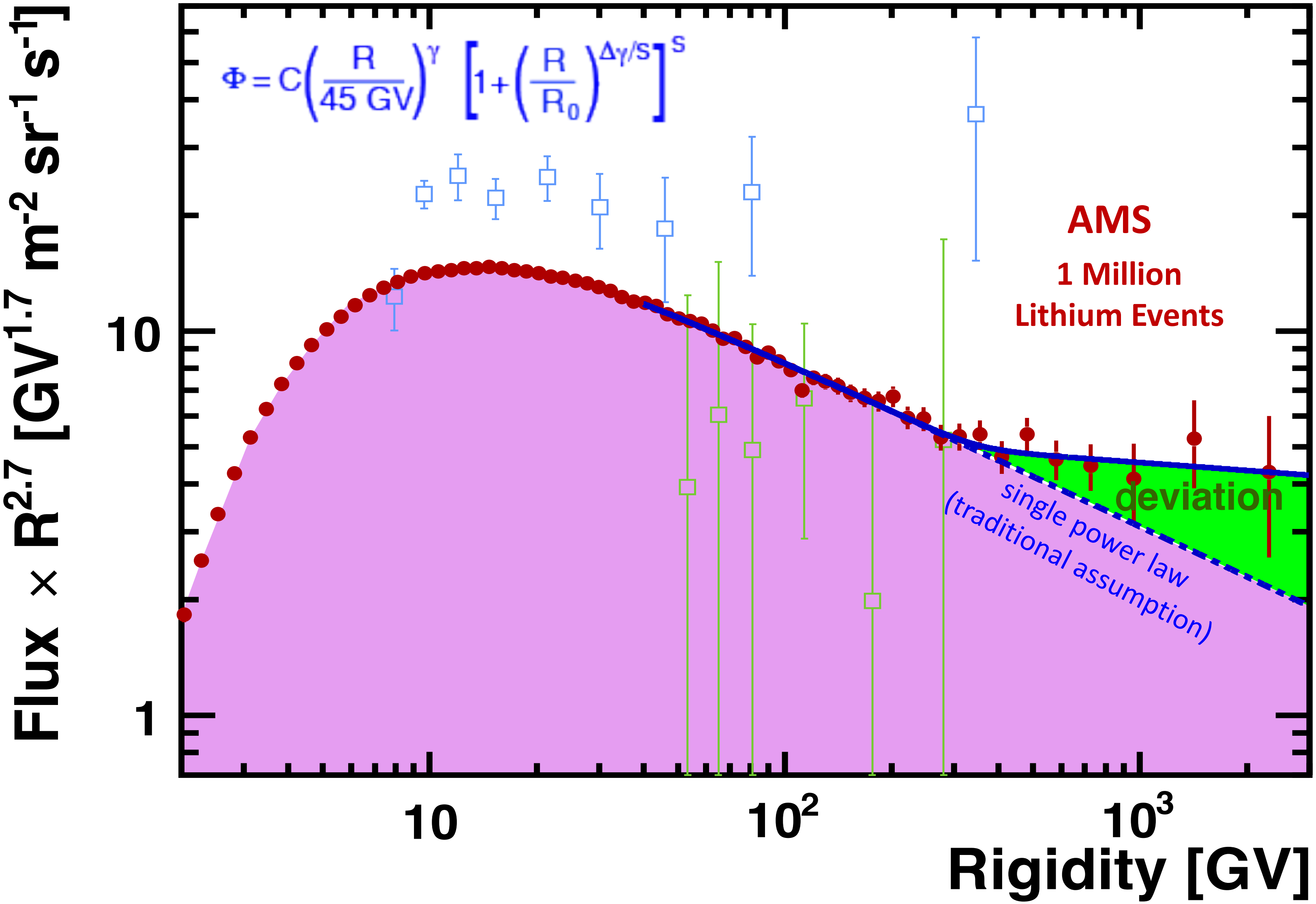


The p/He ratio is independent of solar activity

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.



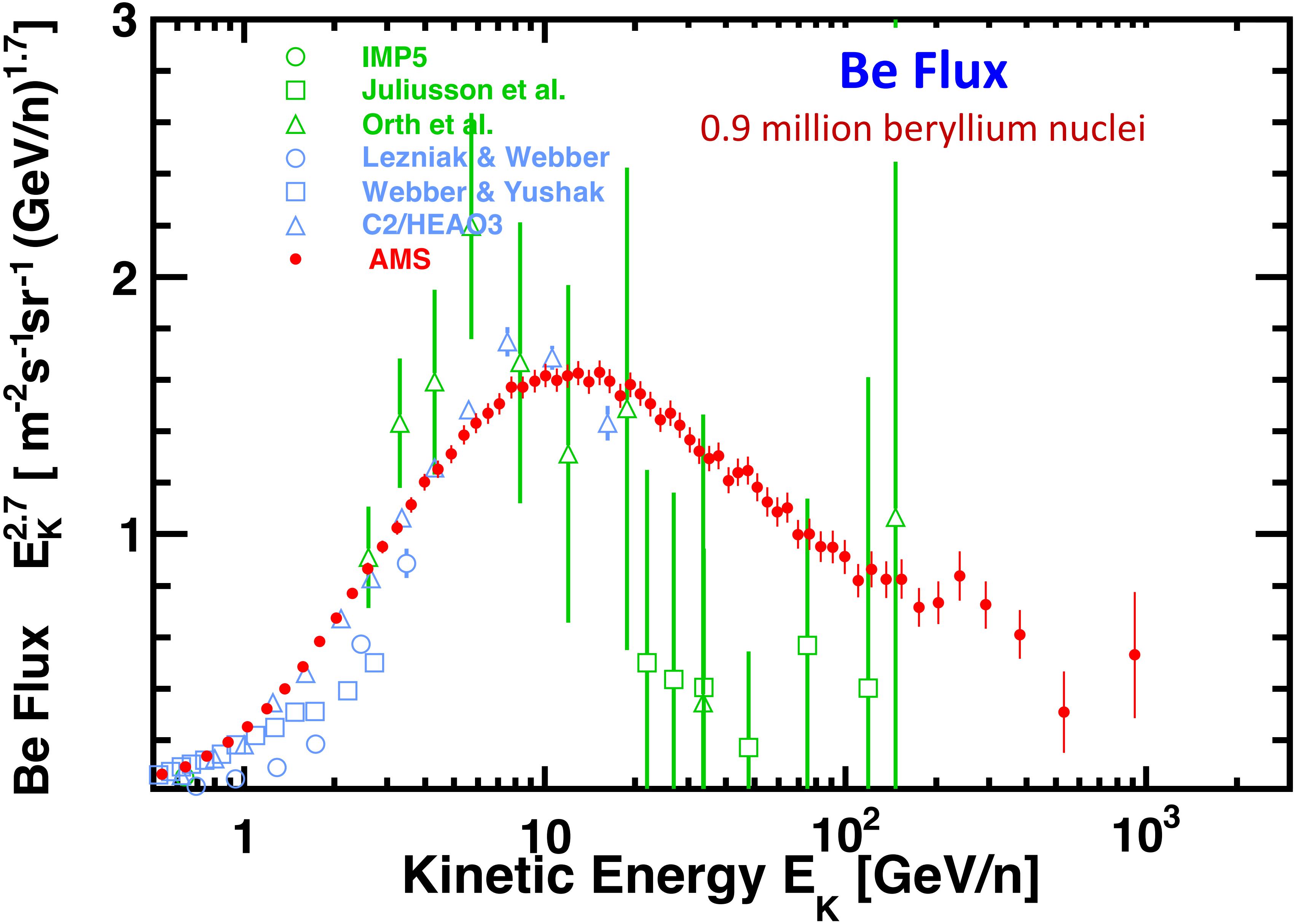
$$\Phi = C\left(\frac{R}{45\ \mathrm{GV}}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/s}\right]^{s}$$

AMS

1 Million Lithium Events

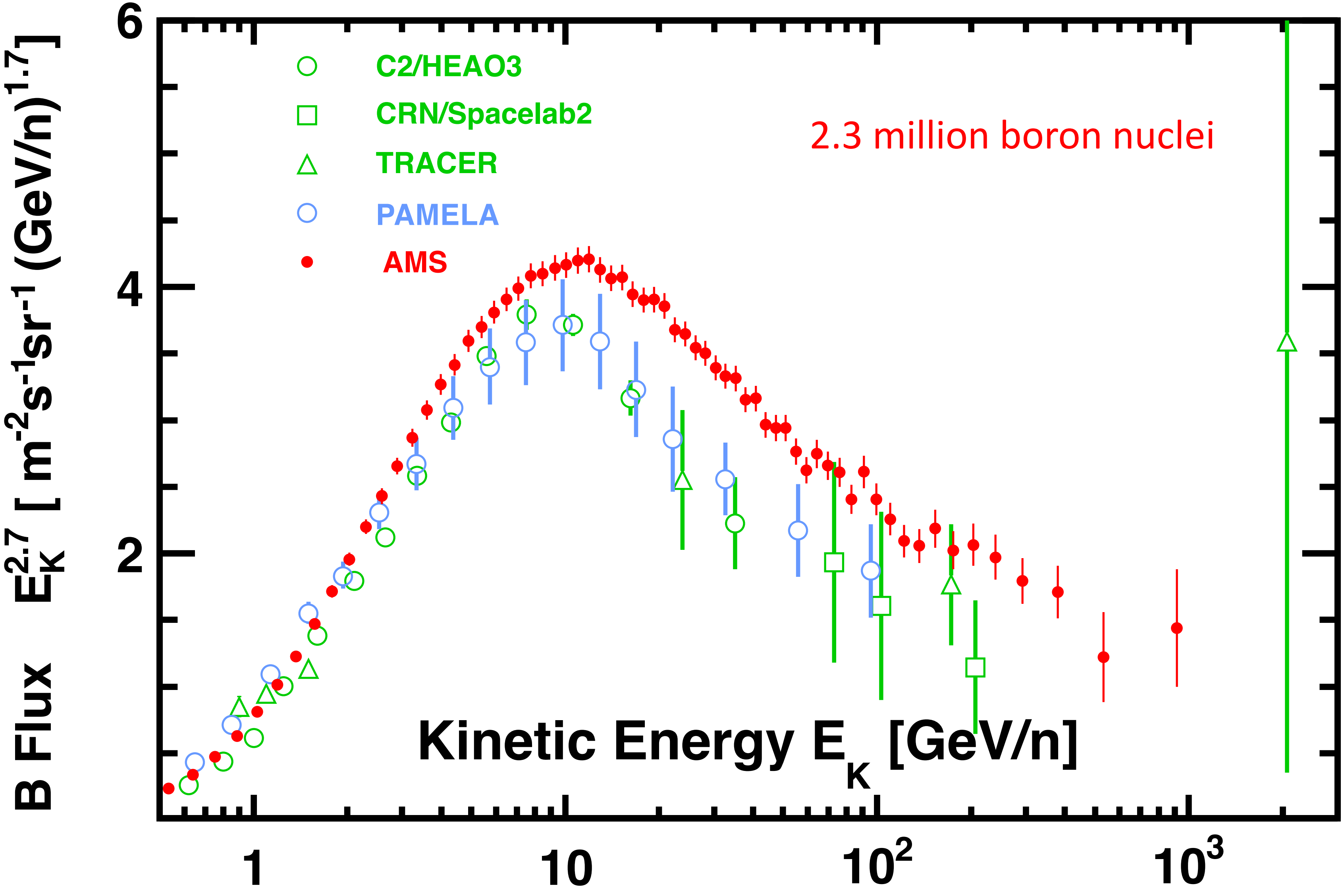
Physics Result 11: The Beryllium flux

New AMS results on Secondary Cosmic Rays (Beryllium)

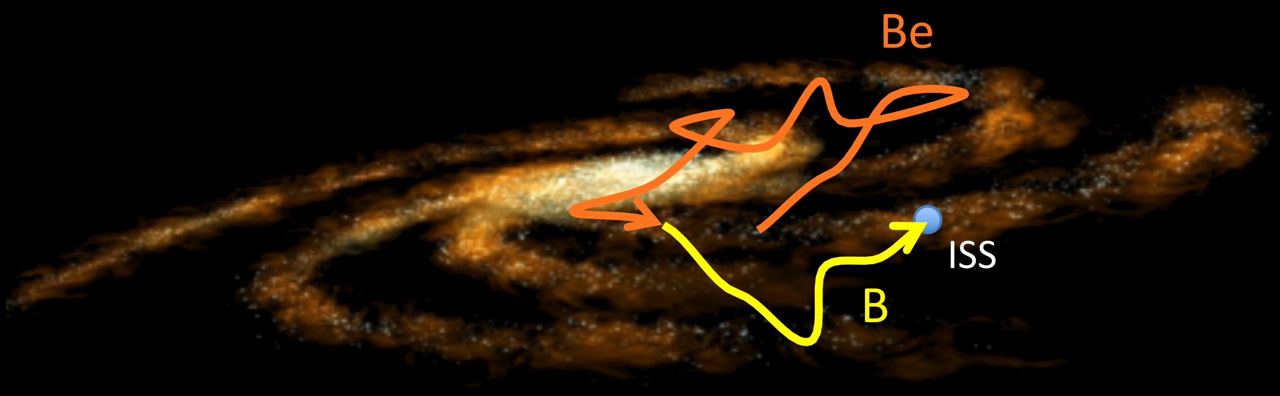


Physics Result 12: The Boron flux

New AMS results on Secondary Cosmic Rays (Boron)



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

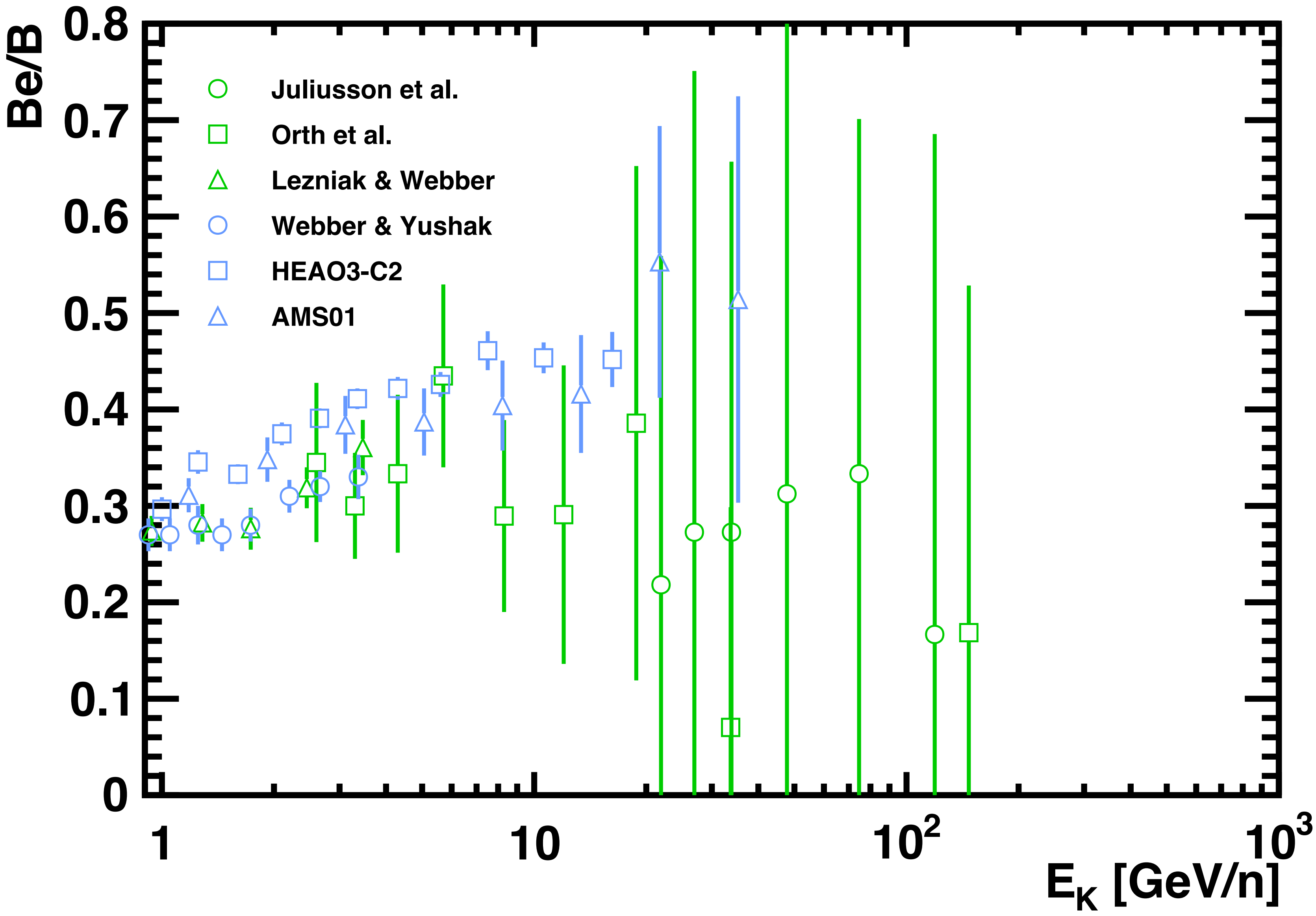


$$^{10}\mathrm{Be} \rightarrow {}^{10}\mathrm{B} + e^{-} + \bar{\nu}_e$$

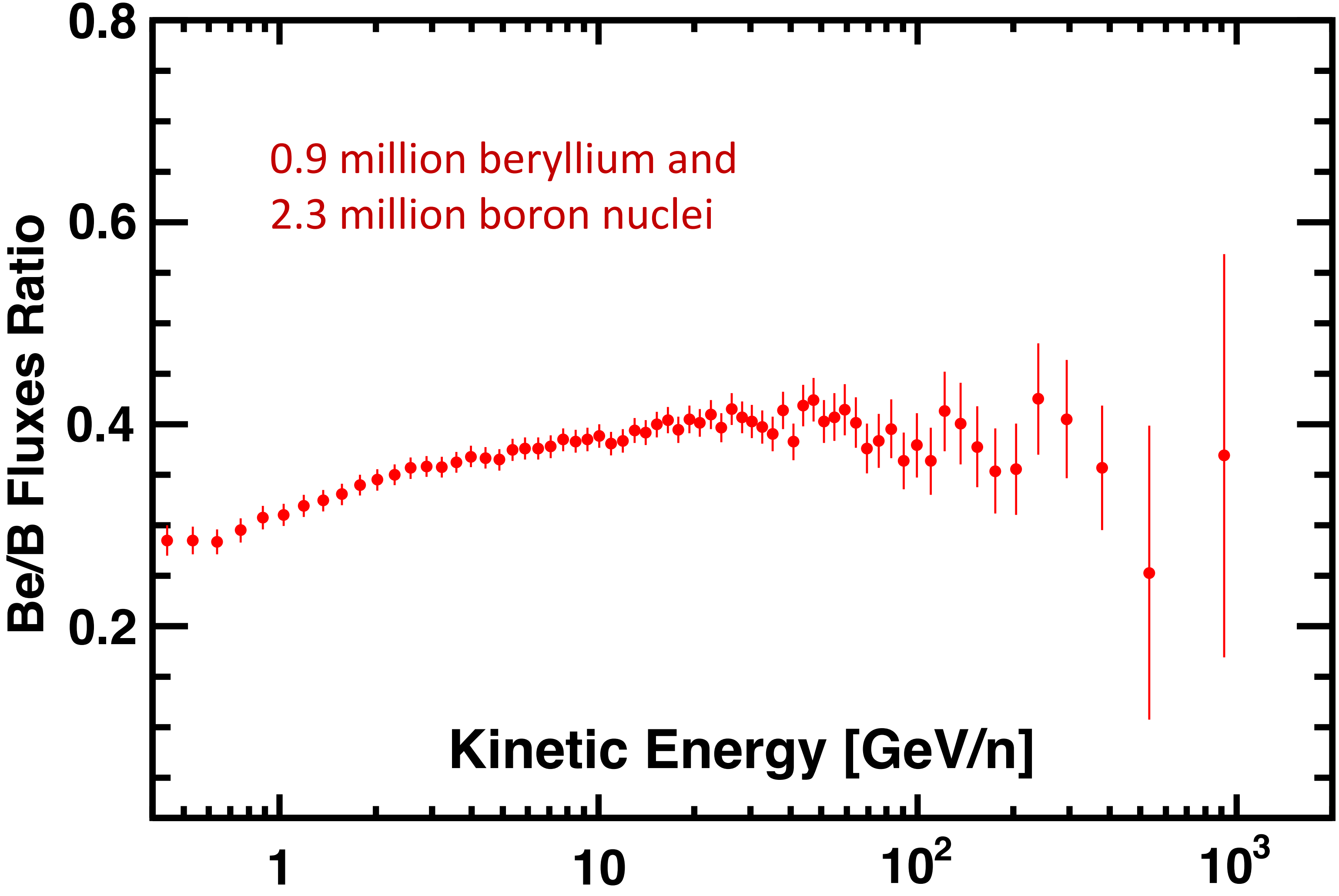
The ^{10}Be half-life is 1.5×10^{6} years.

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.

Beryllium to Boron flux ratio before AMS

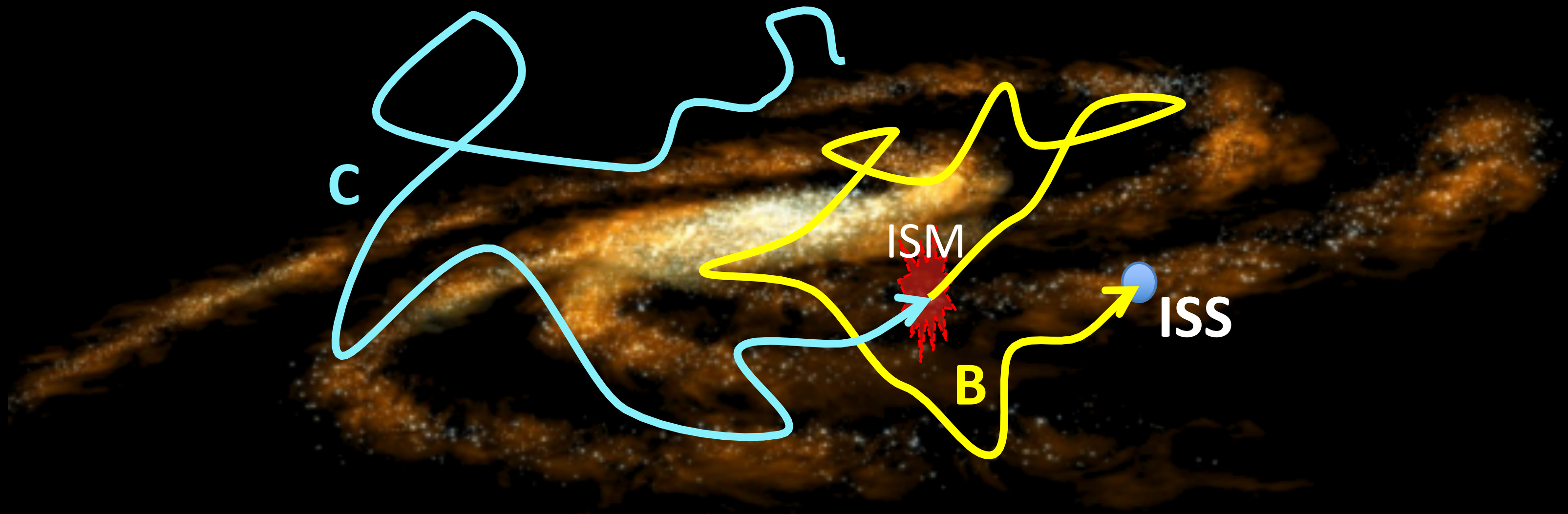


Physics Result 13: The Beryllium-to-Boron flux ratio



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

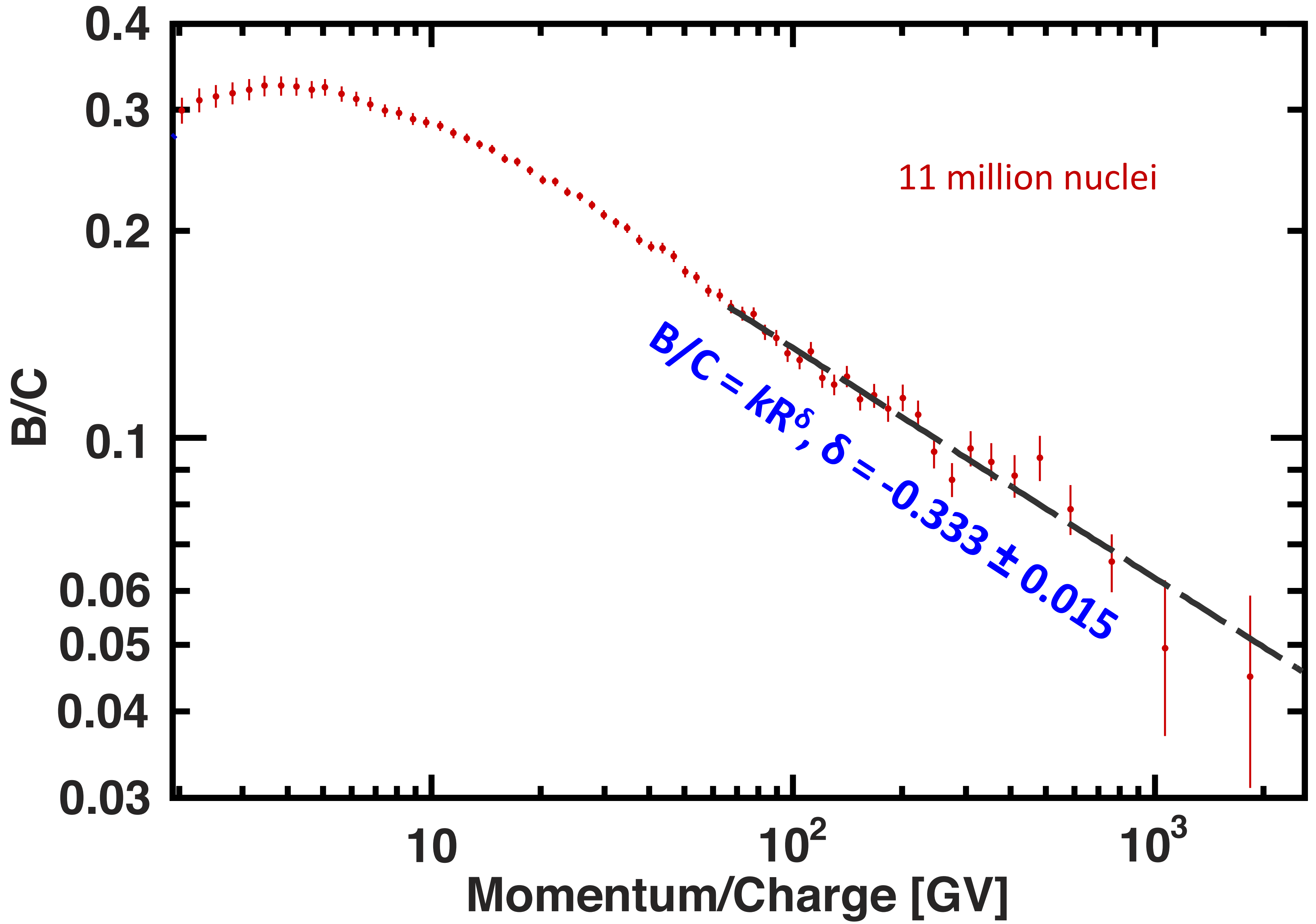


Cosmic ray propagation is commonly modeled as a fast moving gas diffusing through a magnetized plasma.

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

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)

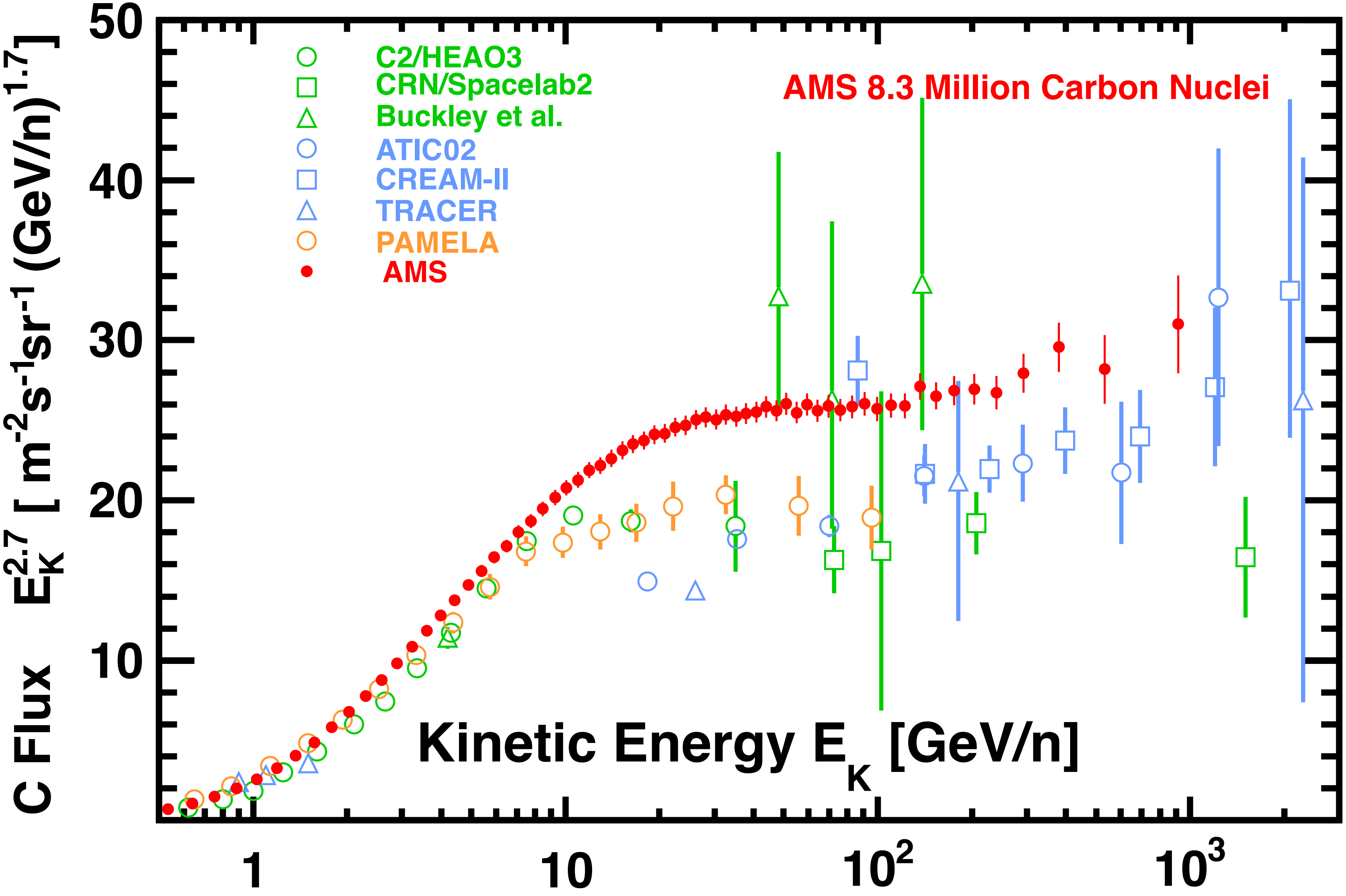
AMS B/C results

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

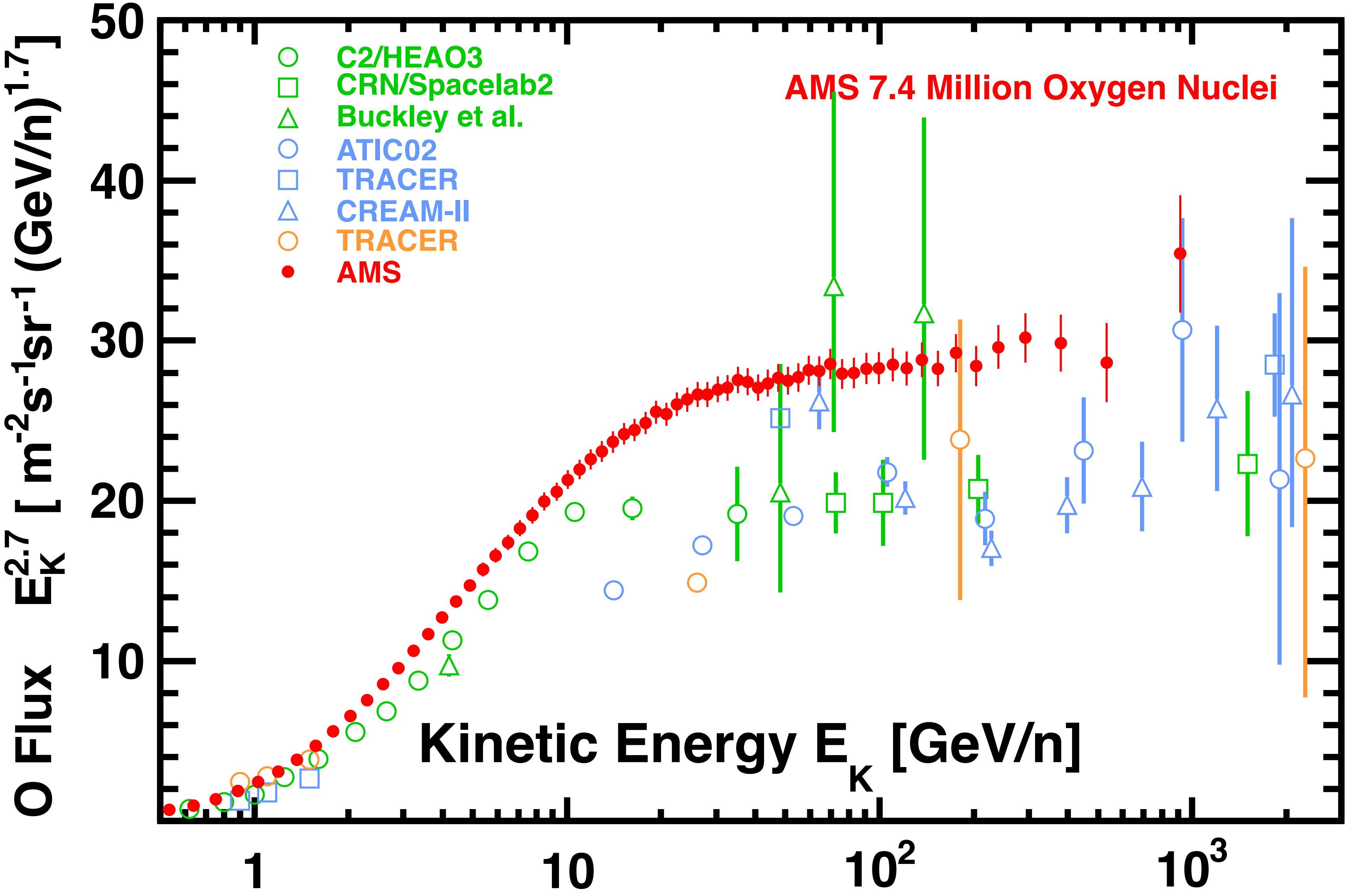
Remarkably, above 65 GV, the B/C ratio is well described by a single power law
$B/C = k R^{\delta}$ with **$\delta = -0.333 \pm 0.015$.**

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

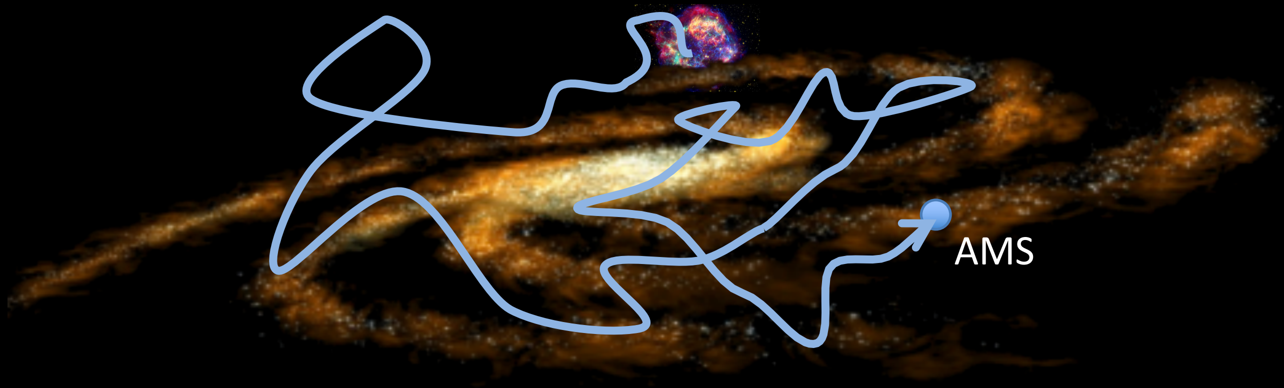
Physics Result 15: The Carbon flux



Physics Result 16: The Oxygen flux



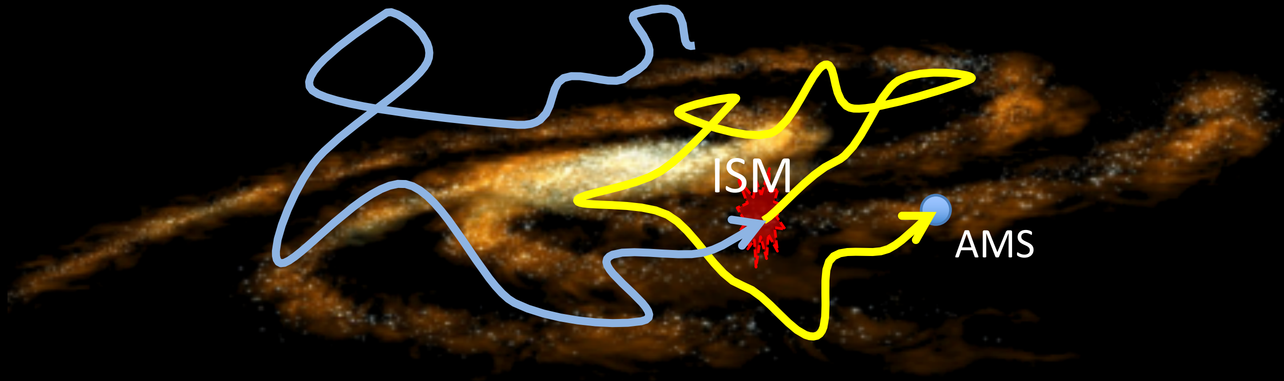
Primary Cosmic Rays (p, He, C, O, …)



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

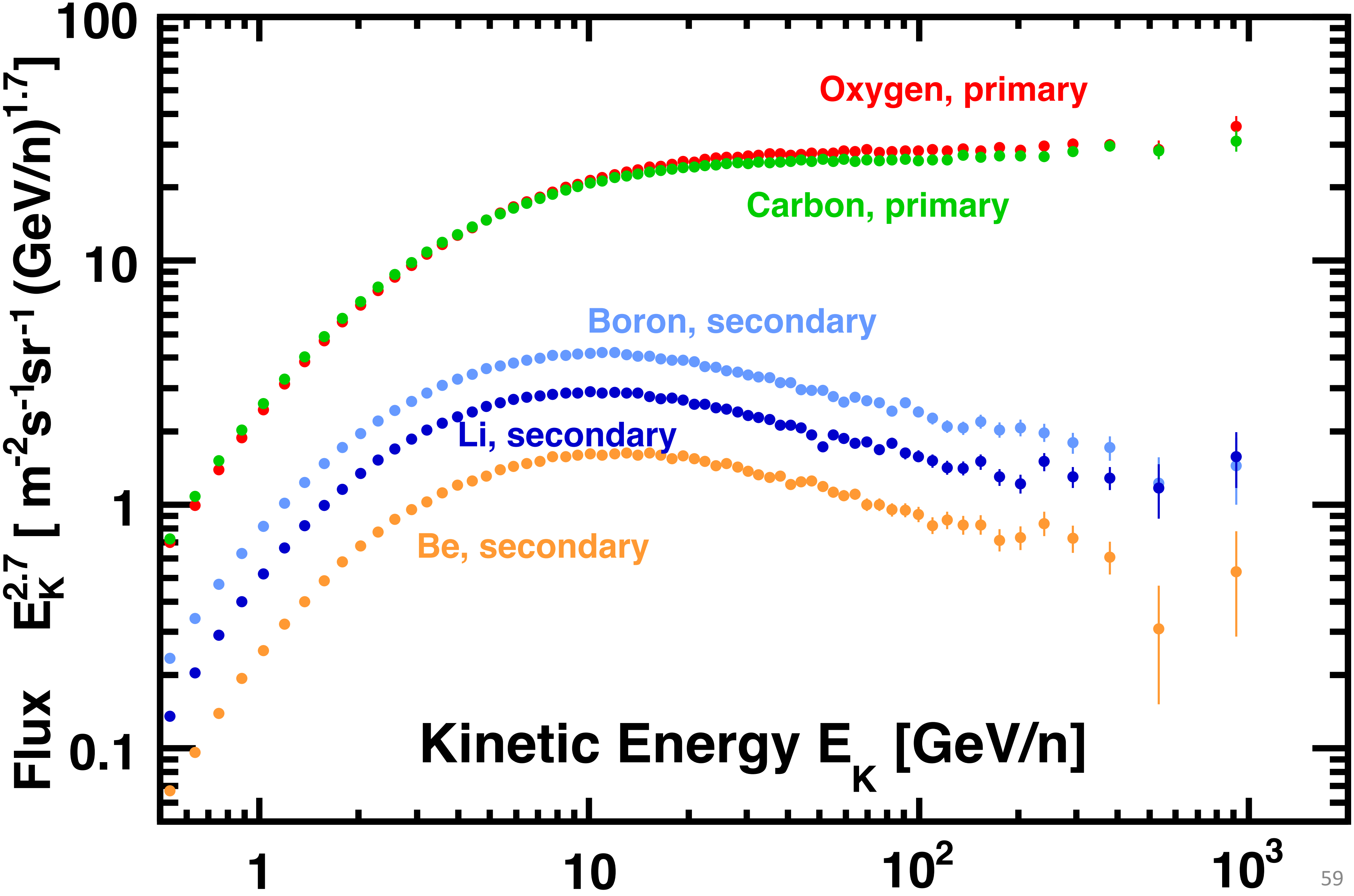
Secondary Cosmic Rays (Li, Be, B, …)

C, O, …, Fe + ISM → Li, Be, B + X

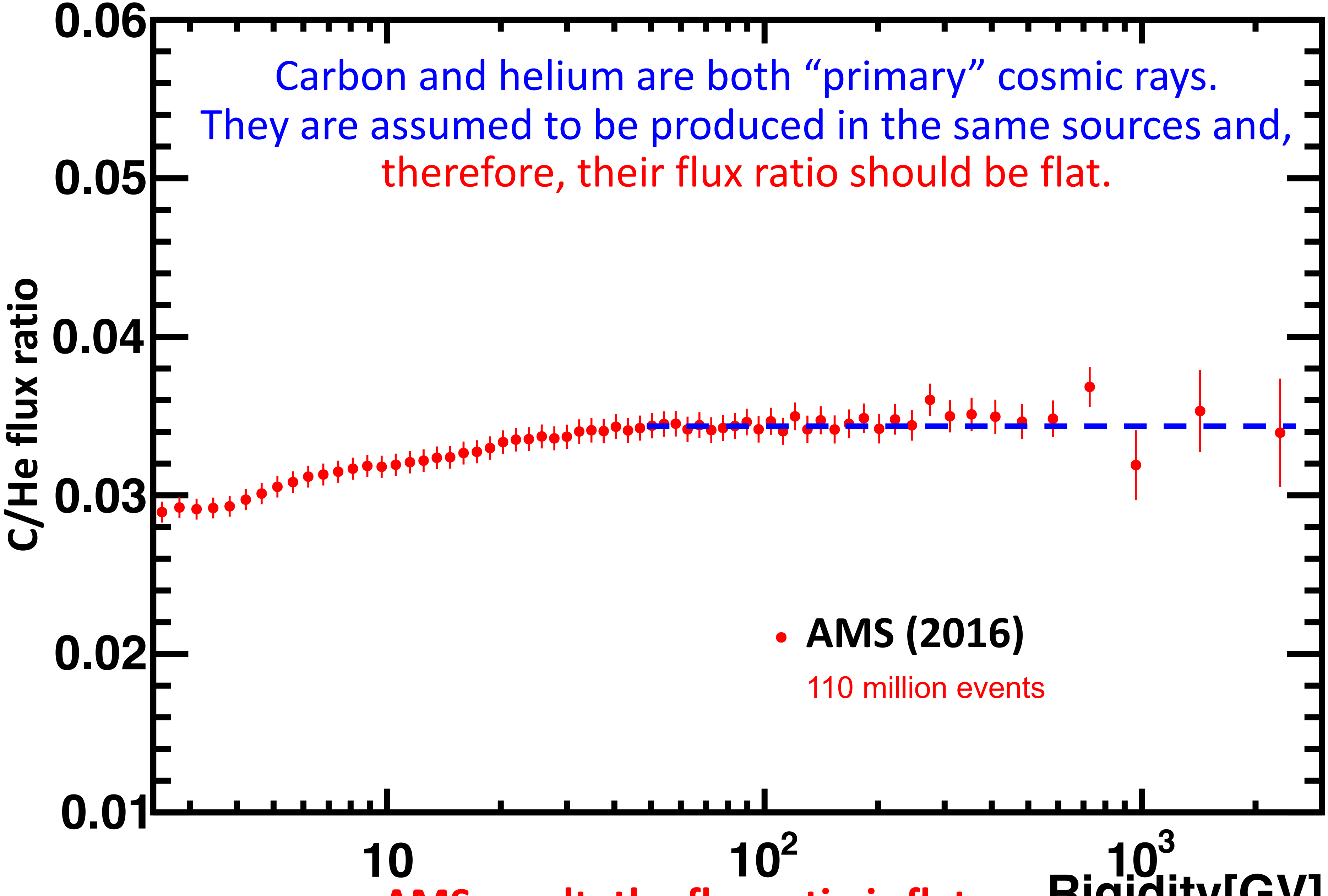


Secondary cosmic rays carry information about propagation of primaries, secondaries and the ISM.

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



Physics Result 18: The AMS carbon/helium flux ratio

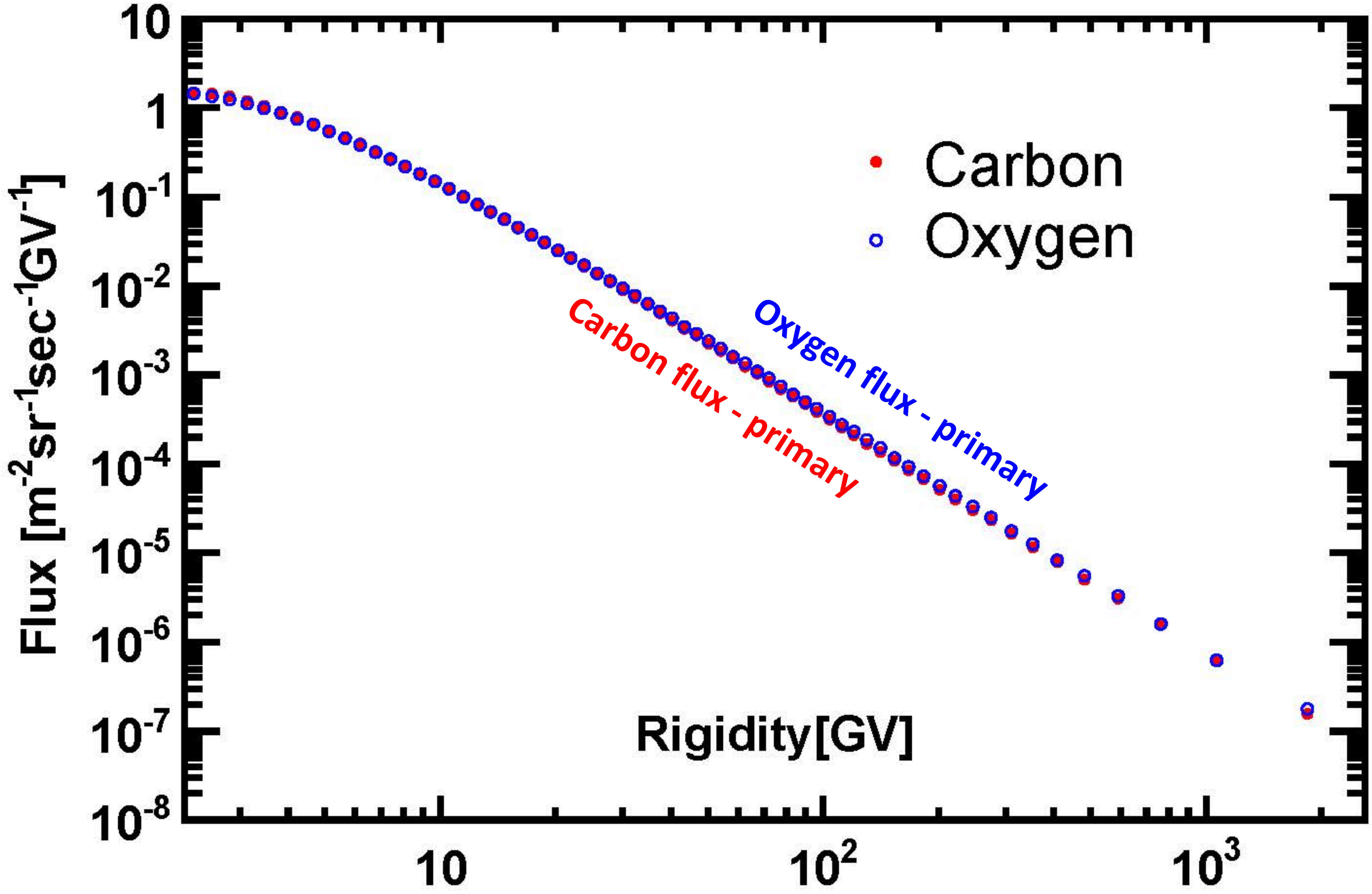


Carbon and helium are both “primary” cosmic rays.
They are assumed to be produced in the same sources and,
therefore, their flux ratio should be flat.

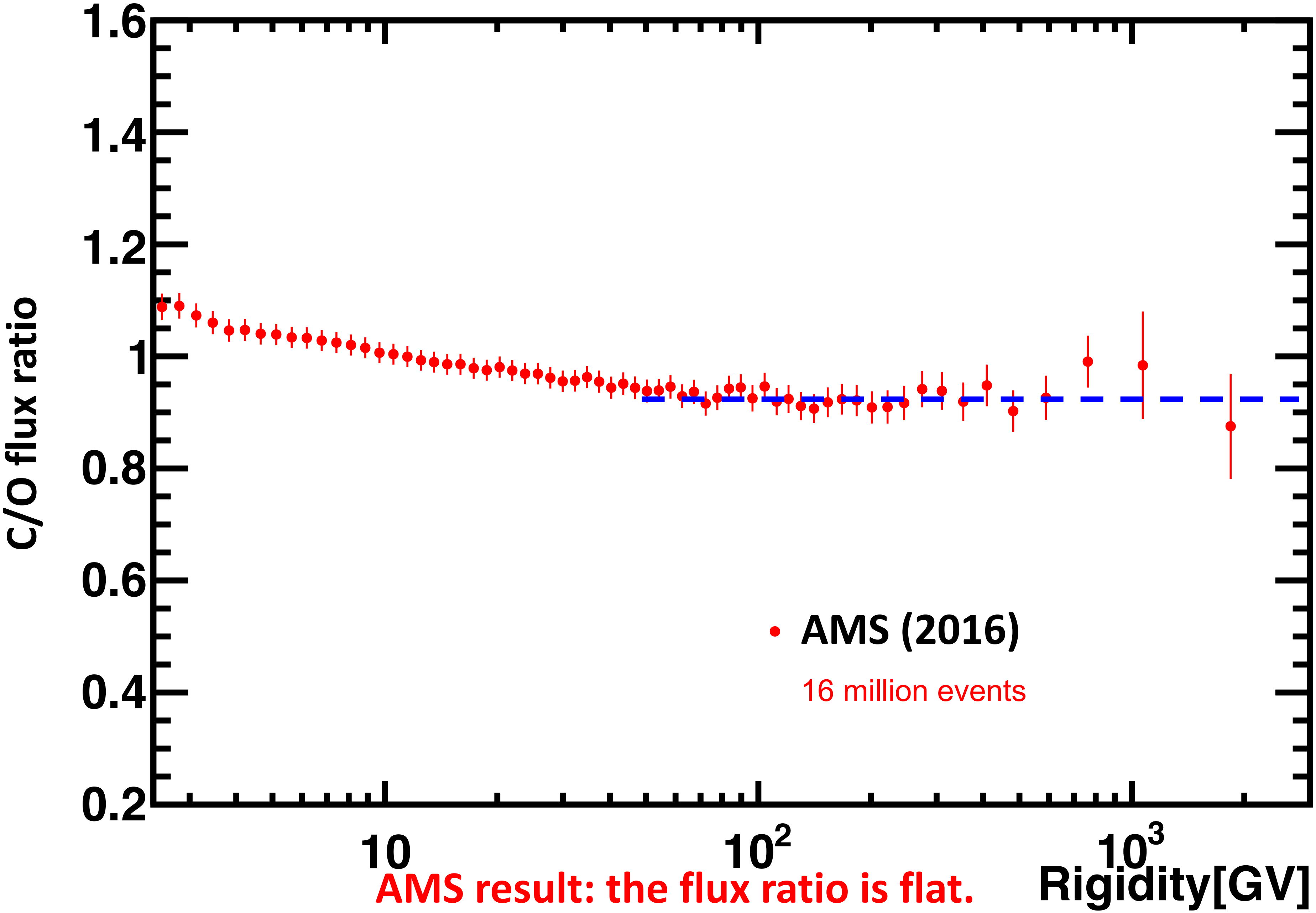
110 million events

AMS result: the flux ratio is flat.

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

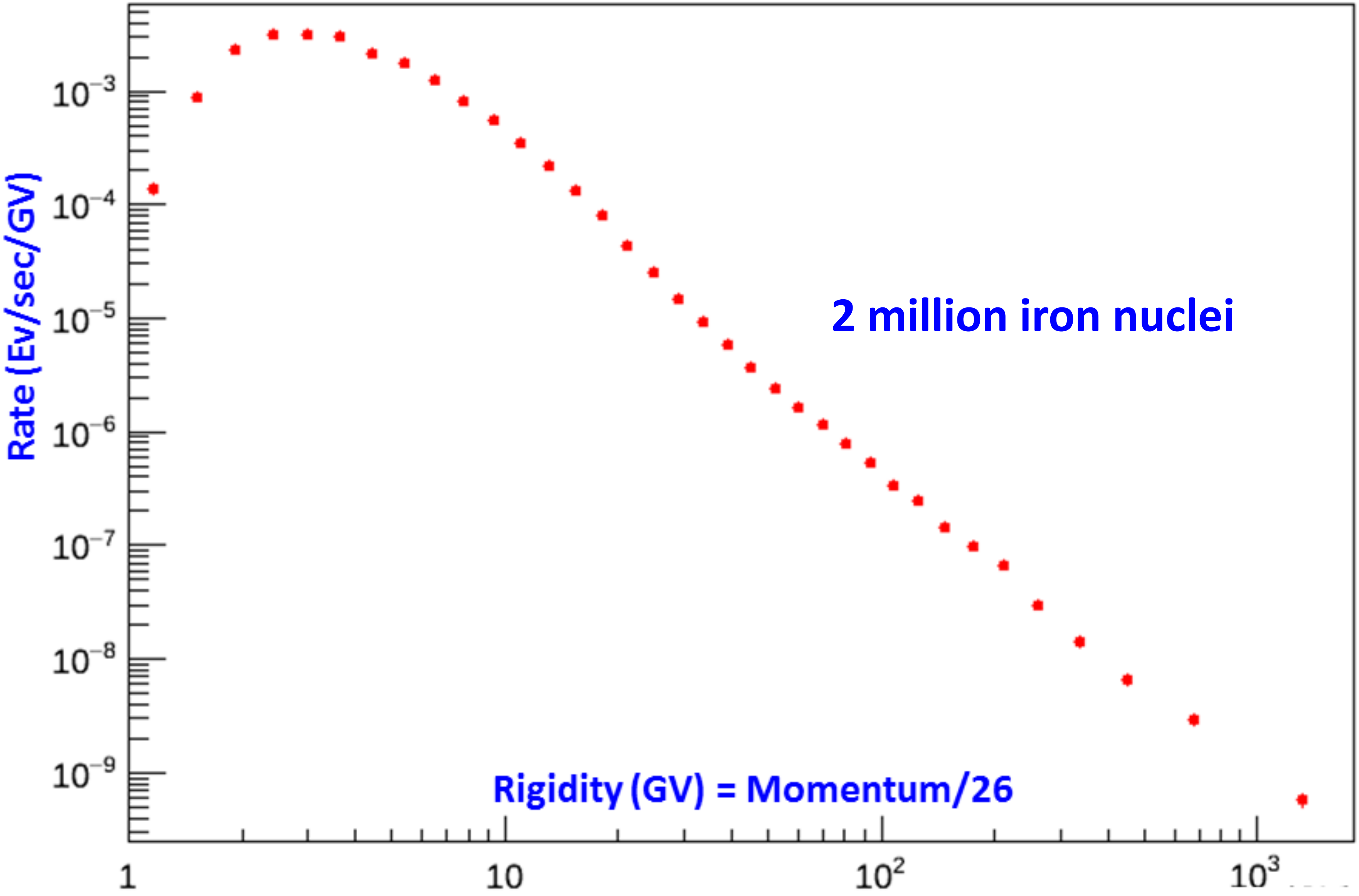


The AMS carbon/oxygen flux ratio



AMS result: the flux ratio is flat.

Physics Result 20: Iron rate

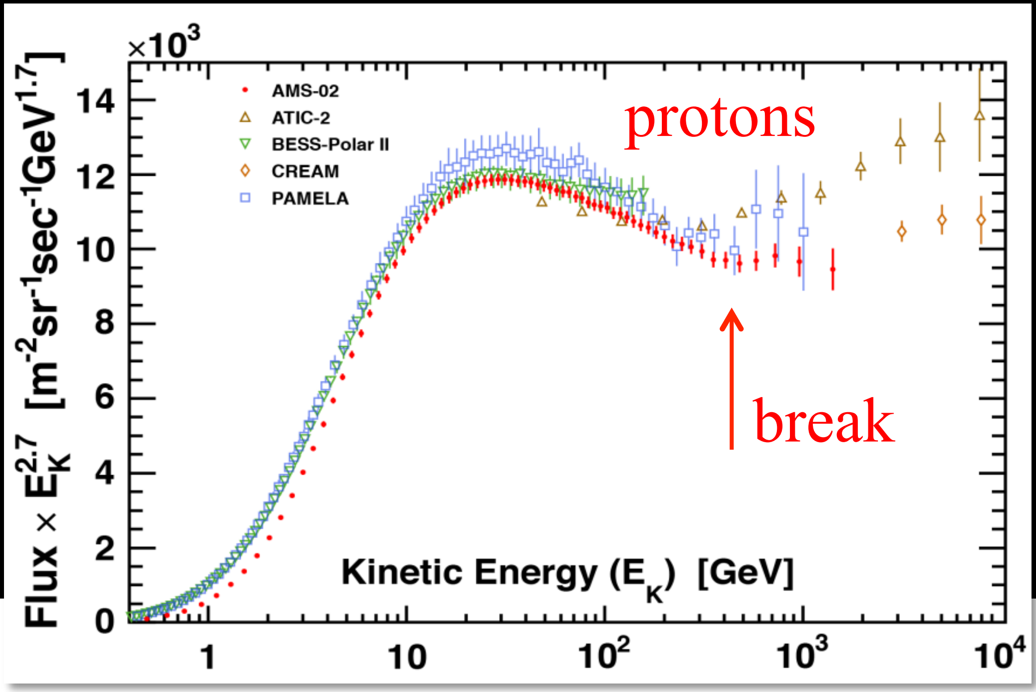


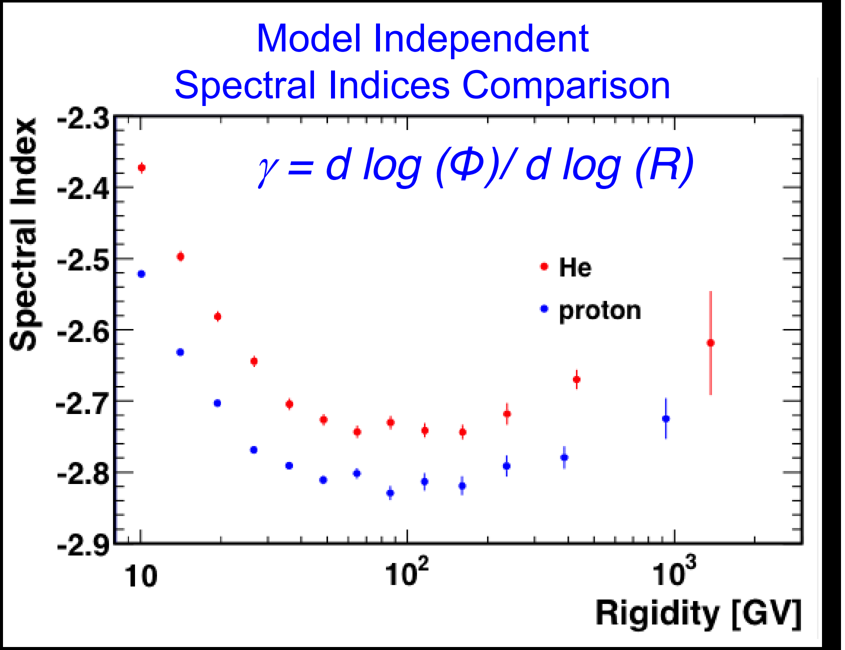
2 million iron nuclei

Rigidity (GV) = Momentum/26

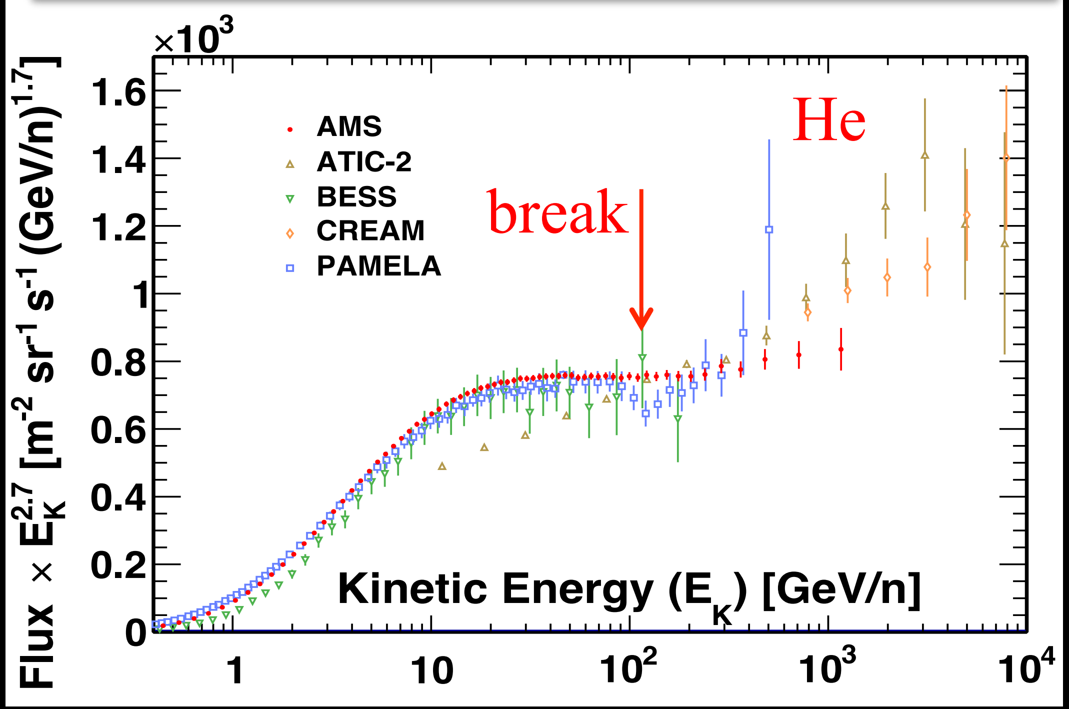
AMS-02 p & He

- The indices of p and He spectra differ by ~0.1 in a wide energy range
- Expansion of the SNR into the stellar wind enriched with heavy elements?



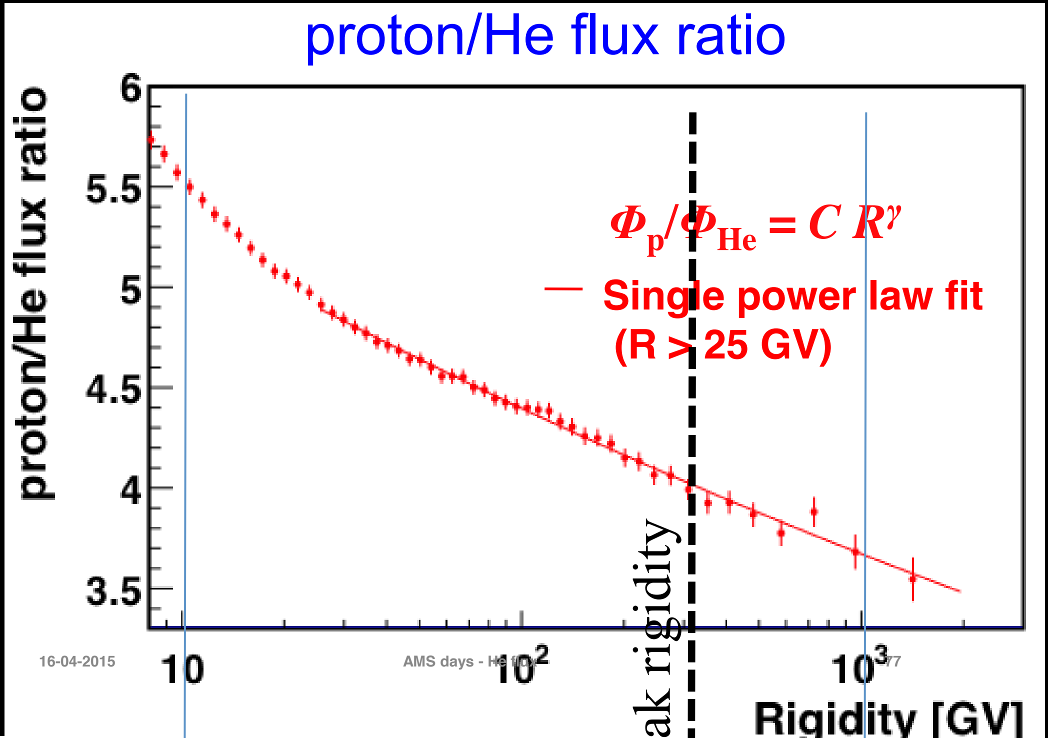


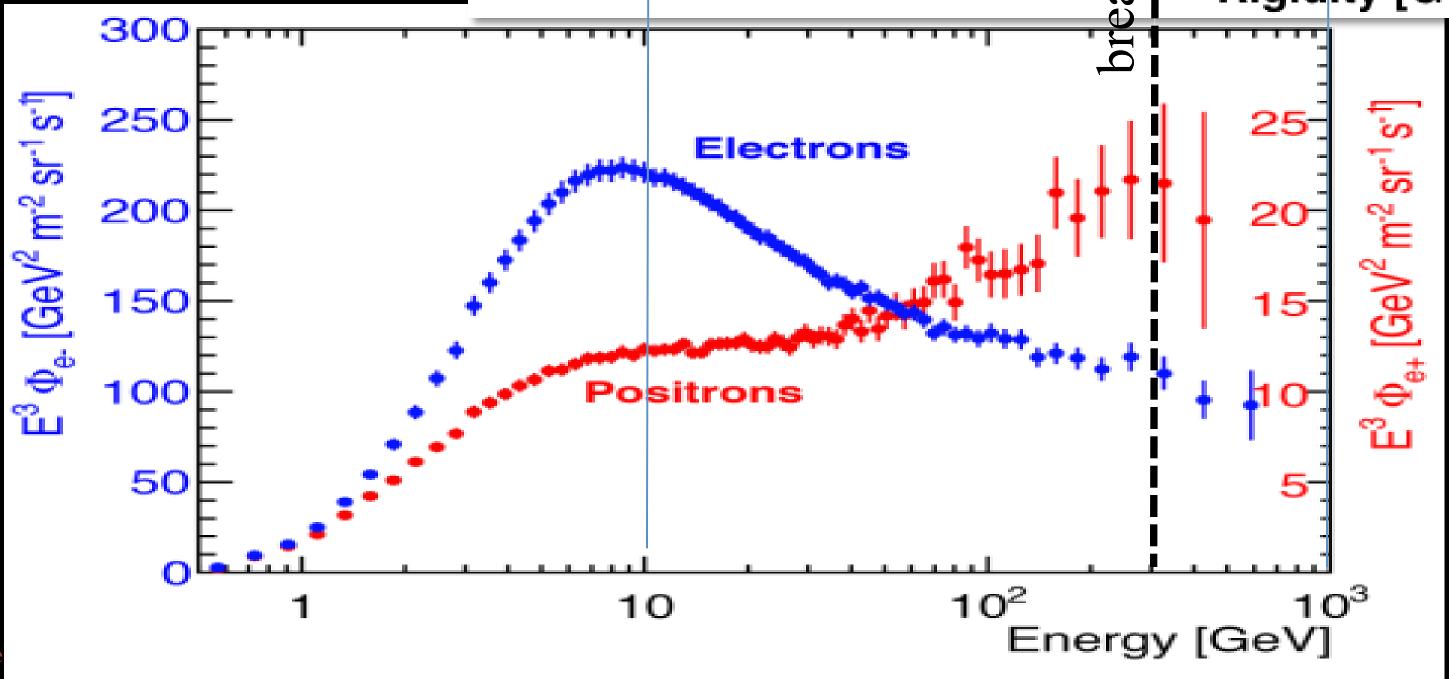
Model Independent Spectral Indices Comparison



AMS p/He ratio

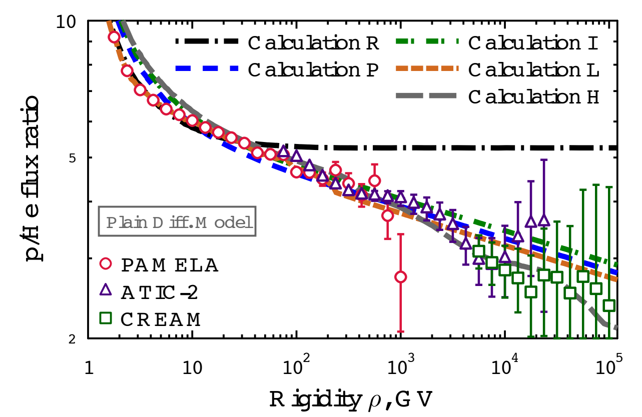
- ✧ The ratio is featureless
- ✧ Indicates that the same (unknown) mechanism works for p, He, and possibly heavier elements
- ✧ What’s about electrons and/or positrons
- ✧ More statistics is necessary

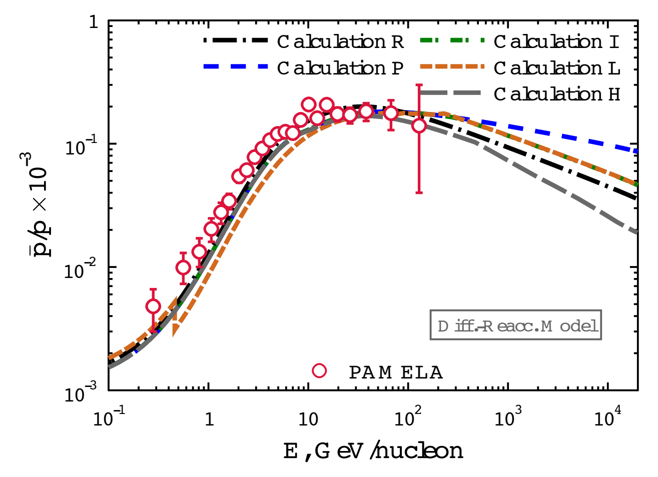


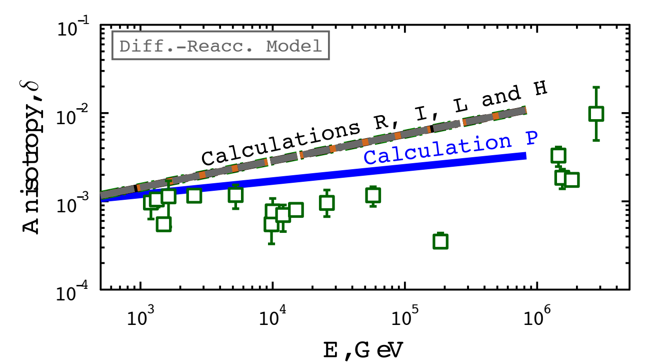


Possible scenarios

- P/He ratio is tuned in all scenarios except Reference scenario
  - Propagation (P)
  - Injection spectrum (I)
  - Local source at LE or HE
- Predicted antiproton/proton ratio agrees with the existing data, but exhibits different behavior at >100 GeV
- Only scenario P agrees with the data on CR anisotropy
- Only scenario L can explain the sharp break in the p, He spectra
- Await for more accurate data



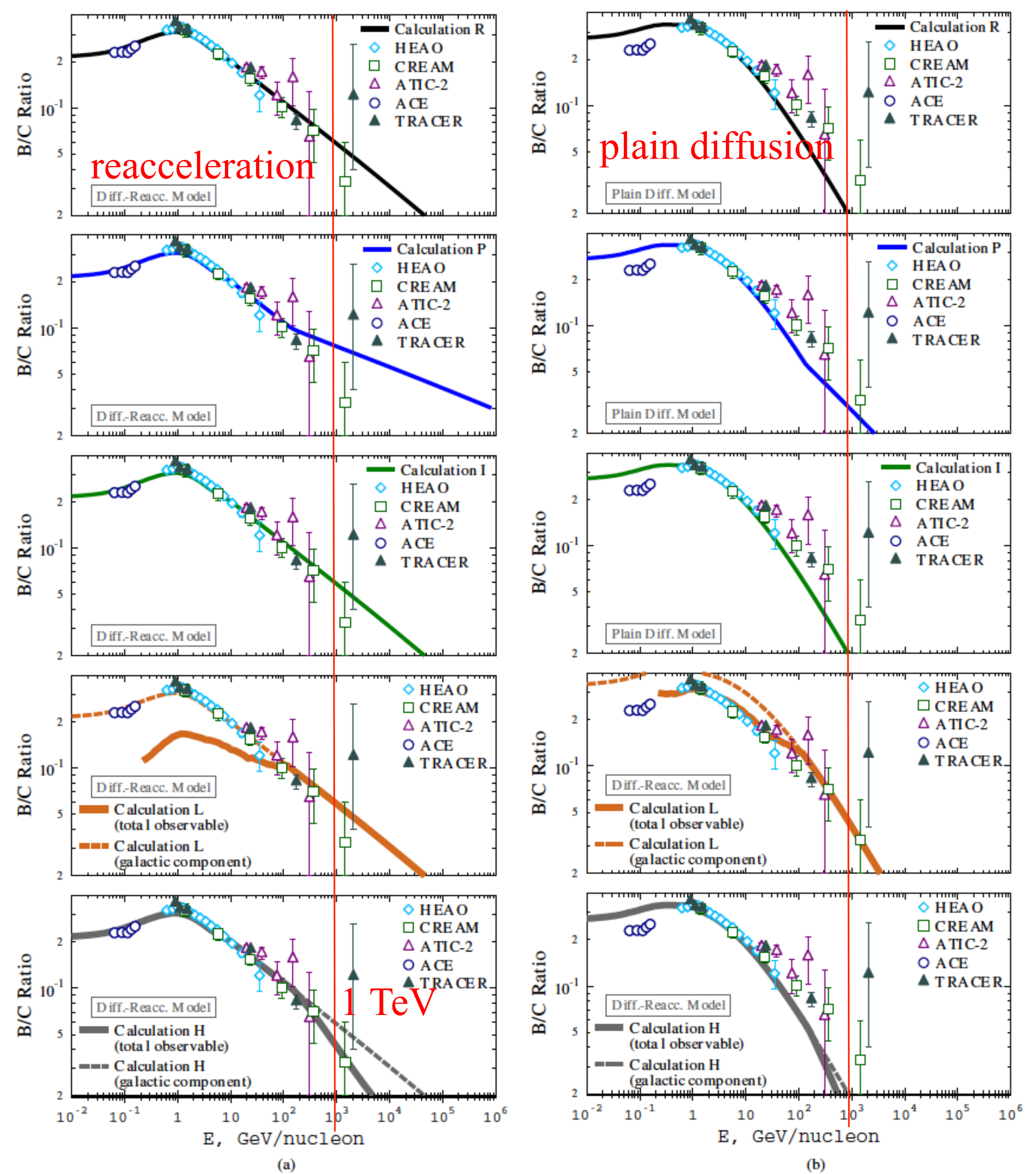




Vladimirov+'2012, ApJ 752, 68

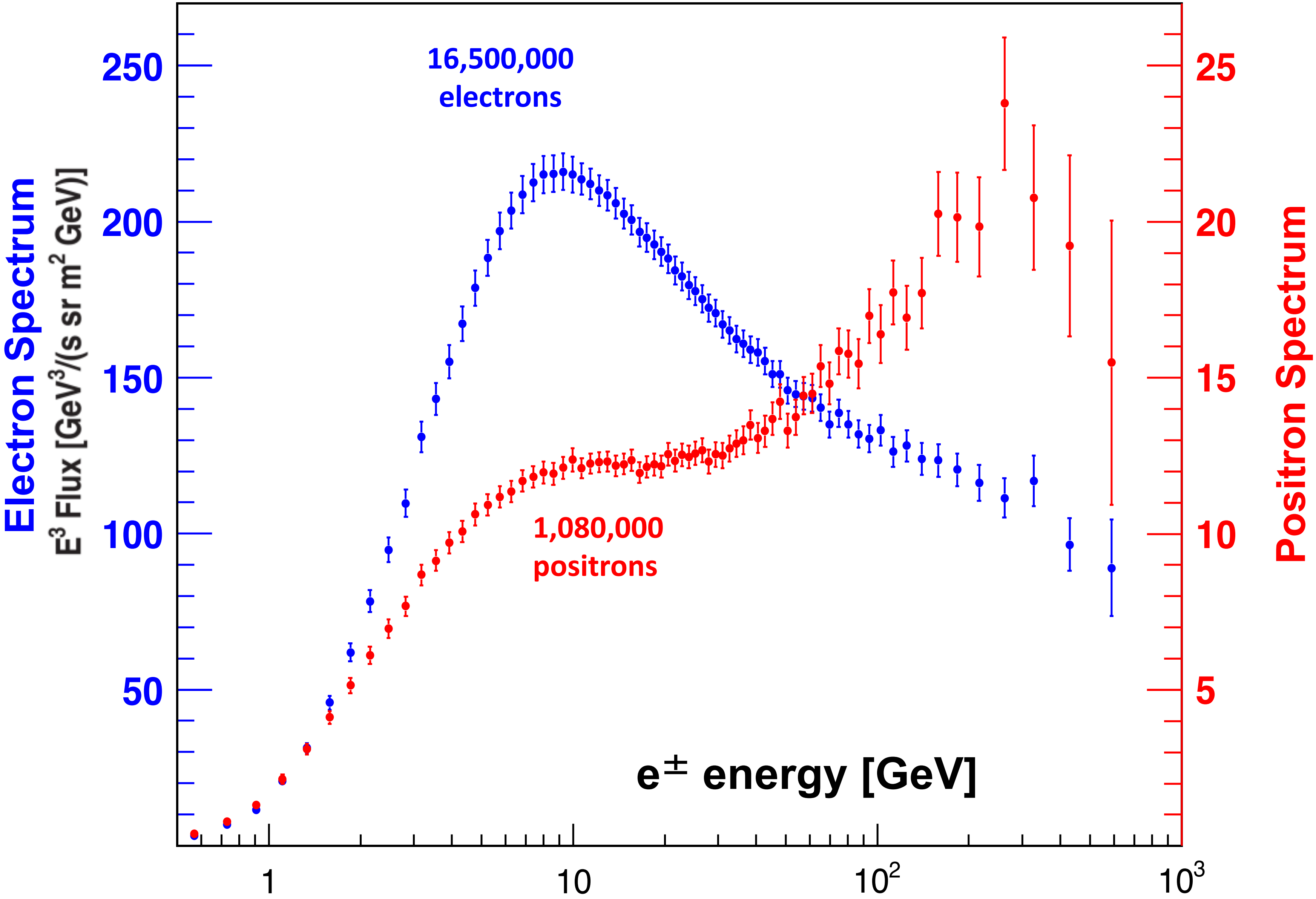
B/C ratio

- Reacceleration and plain diffusion models
- P-scenario is predicting an upturn in the B/C ratio at ~100 GeV/n (~200 GV)



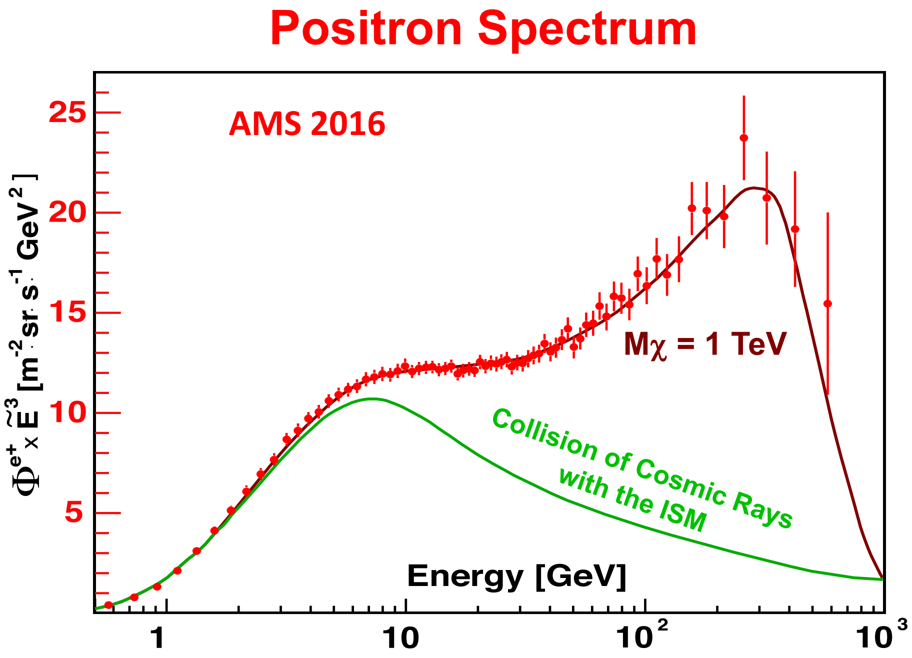
Summary (on elementary particles)

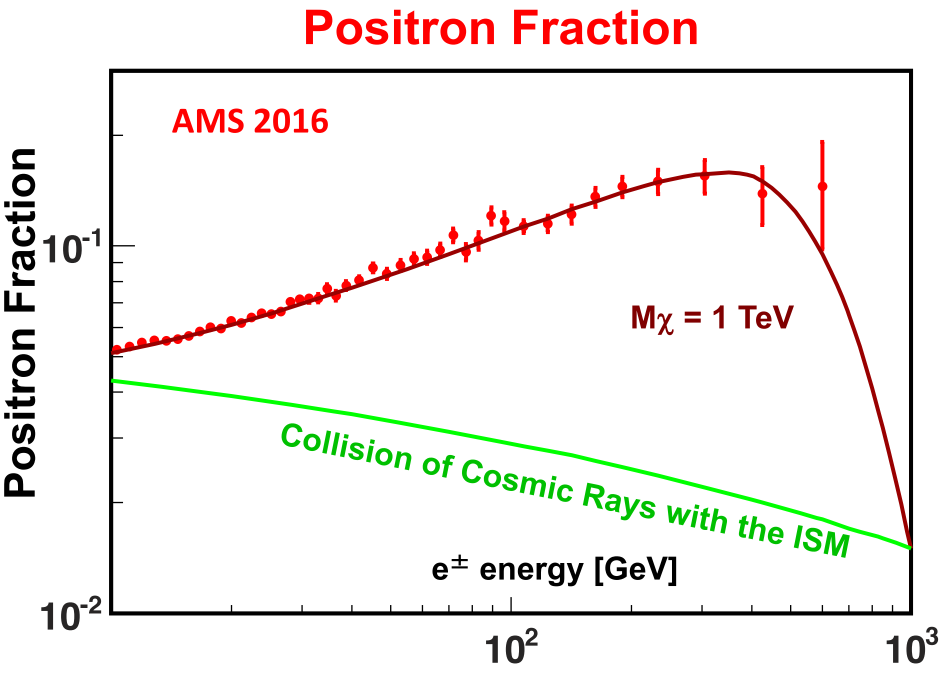
The electron flux and the positron flux are different in their magnitude and energy dependence.



Summary (on elementary particles)

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



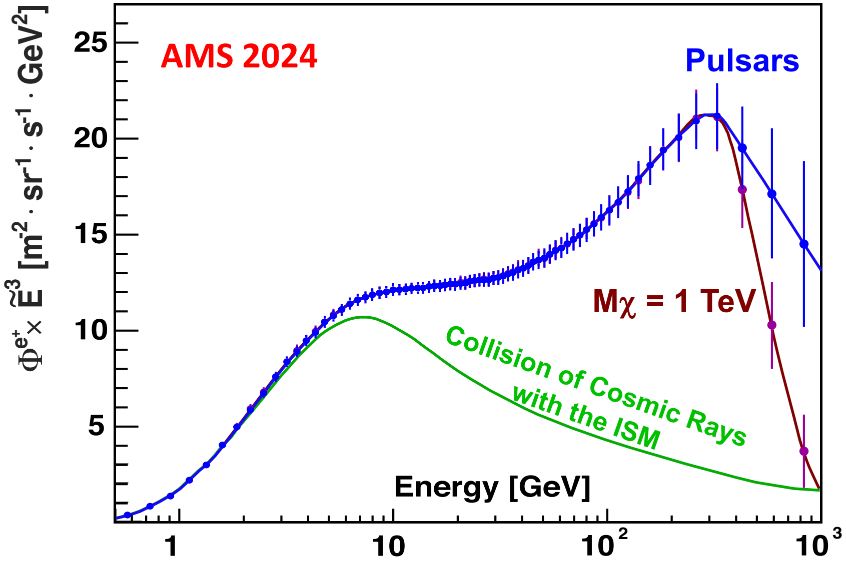


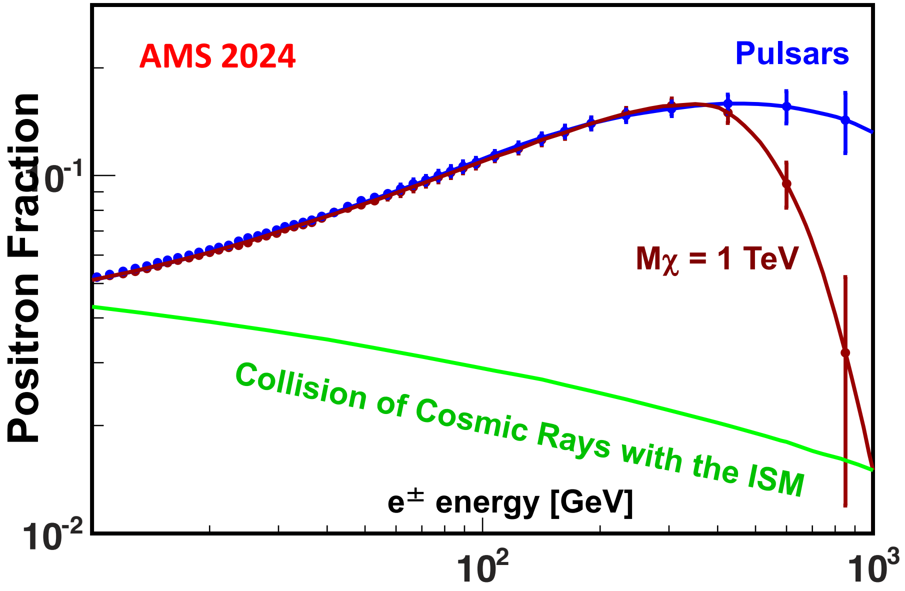
Summary (on elementary particles)

Positron Spectrum

Positron Fraction

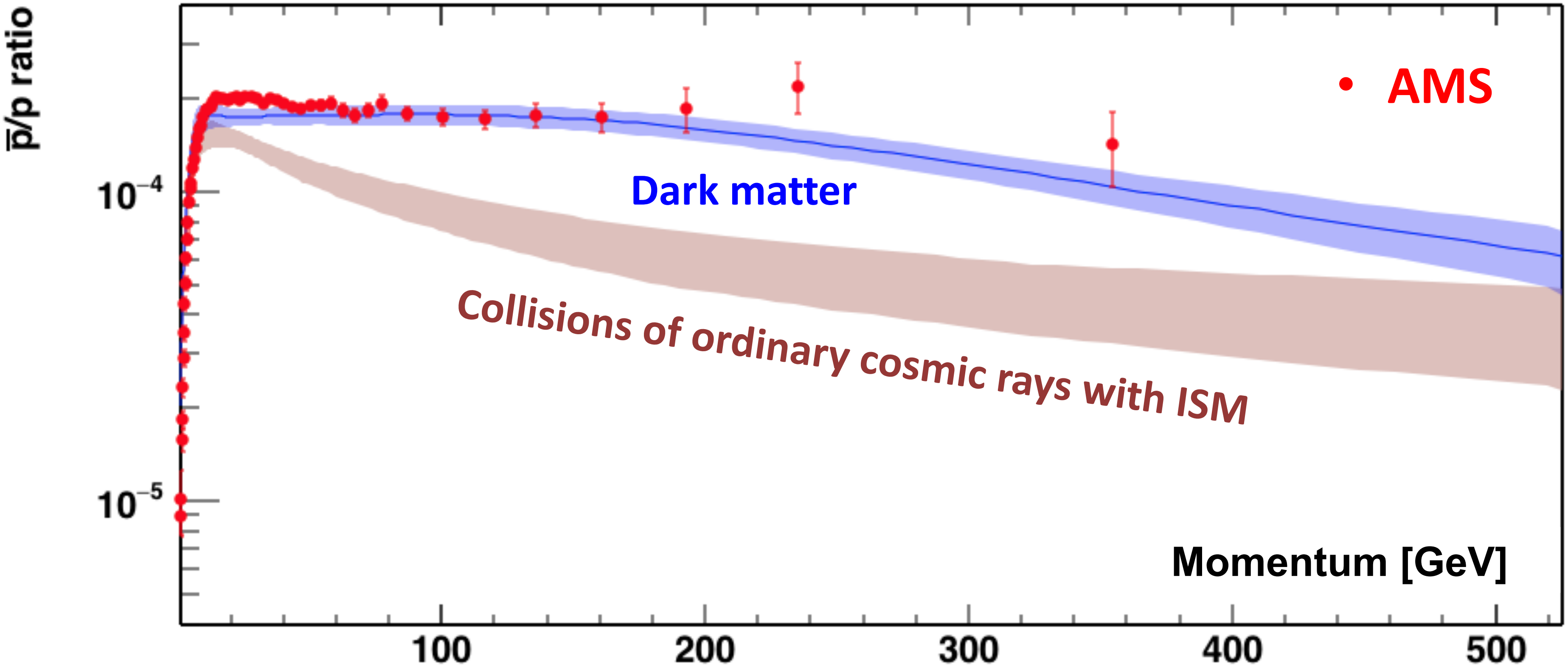
By 2024 we will should be able understand the origin of this unexpected data.





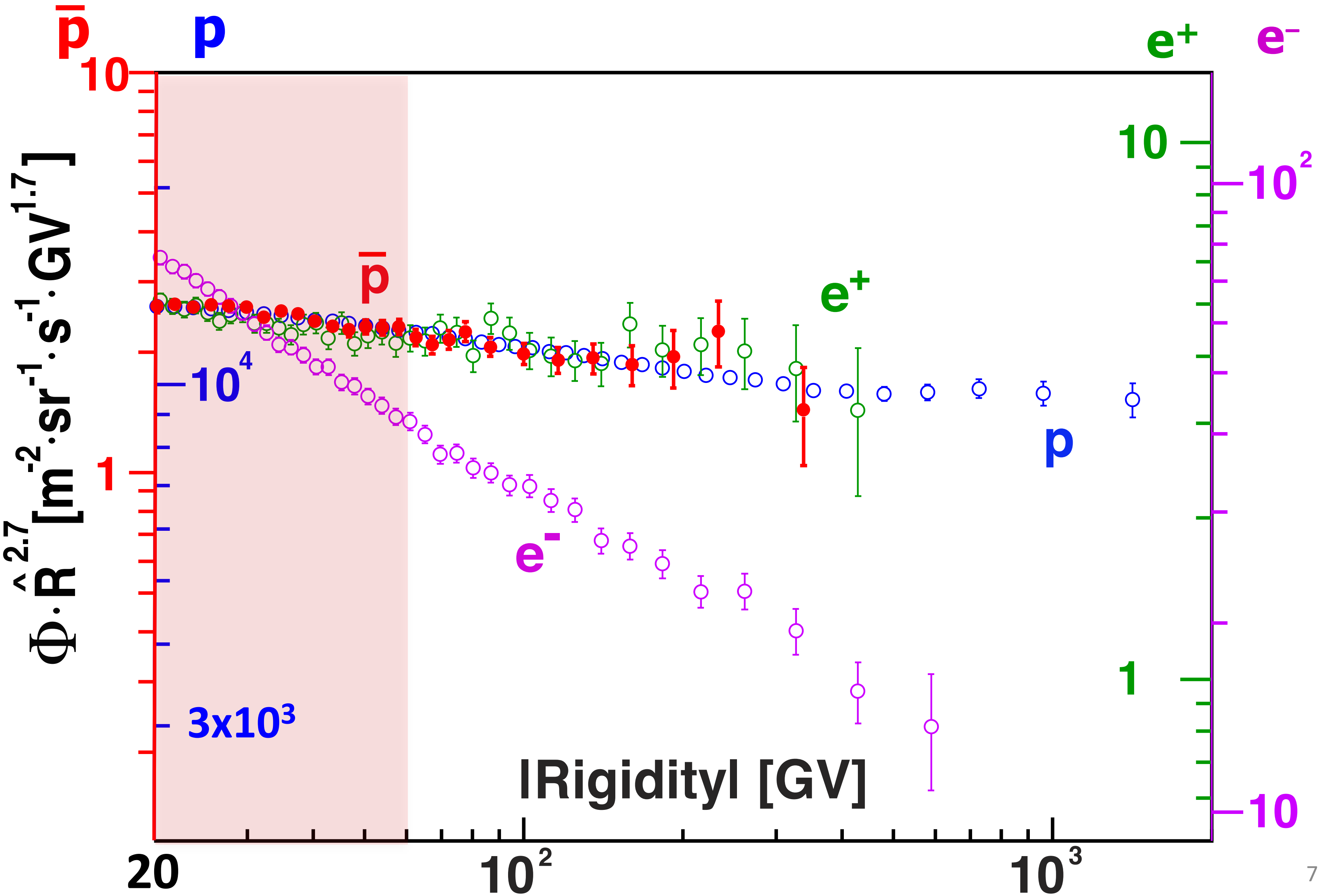
Summary (on elementary particles)

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



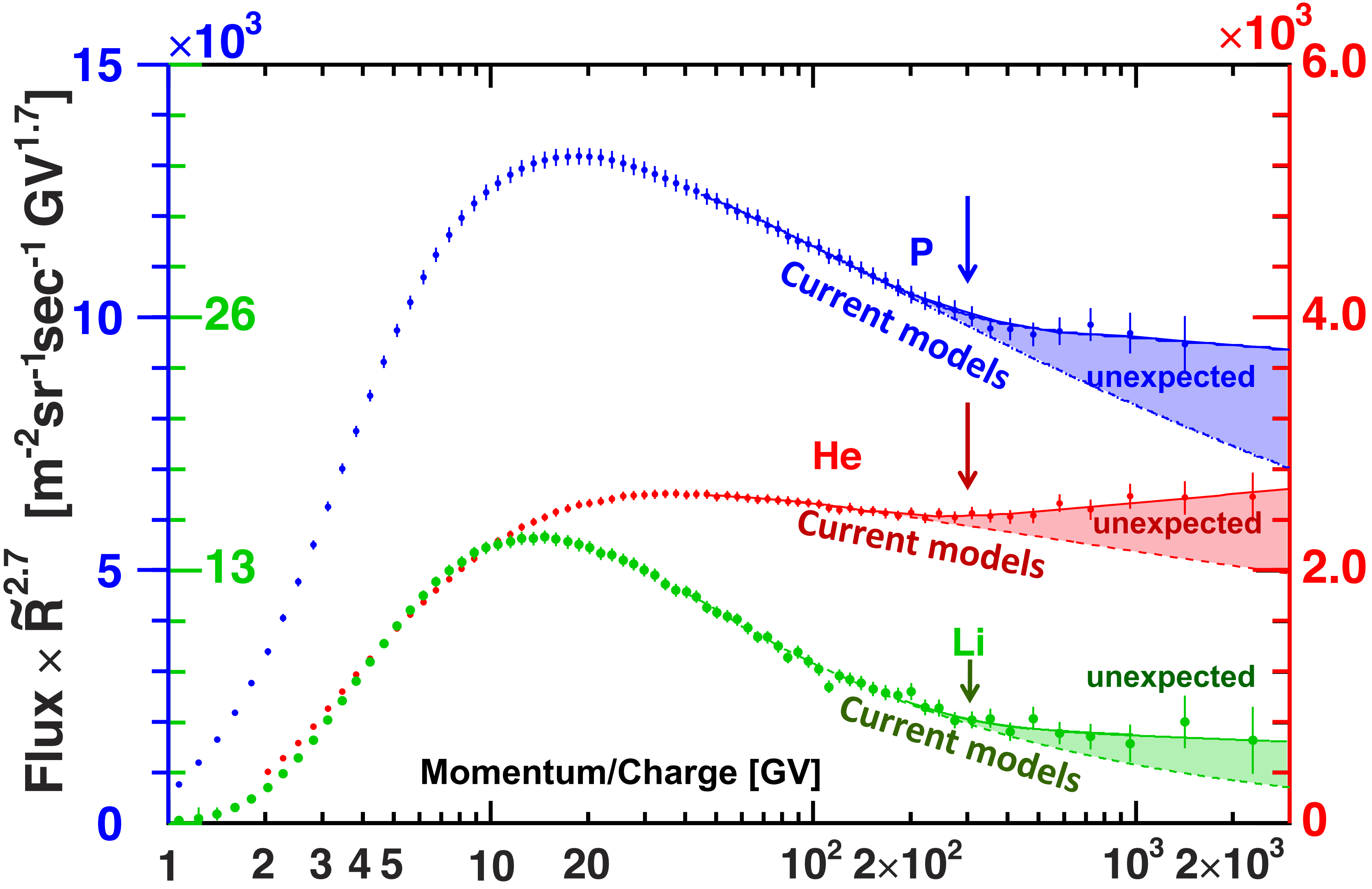
Summary (on elementary particles)

The e+, $\bar{p}$, p spectra have identical energy dependence from 60-500 GV, e- does not.



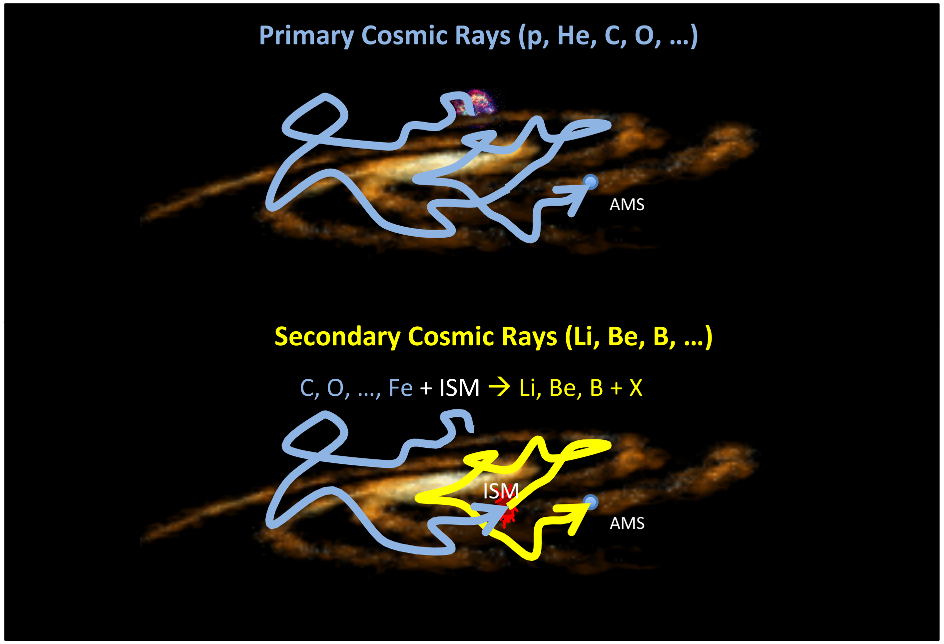
Summary (on nuclei)

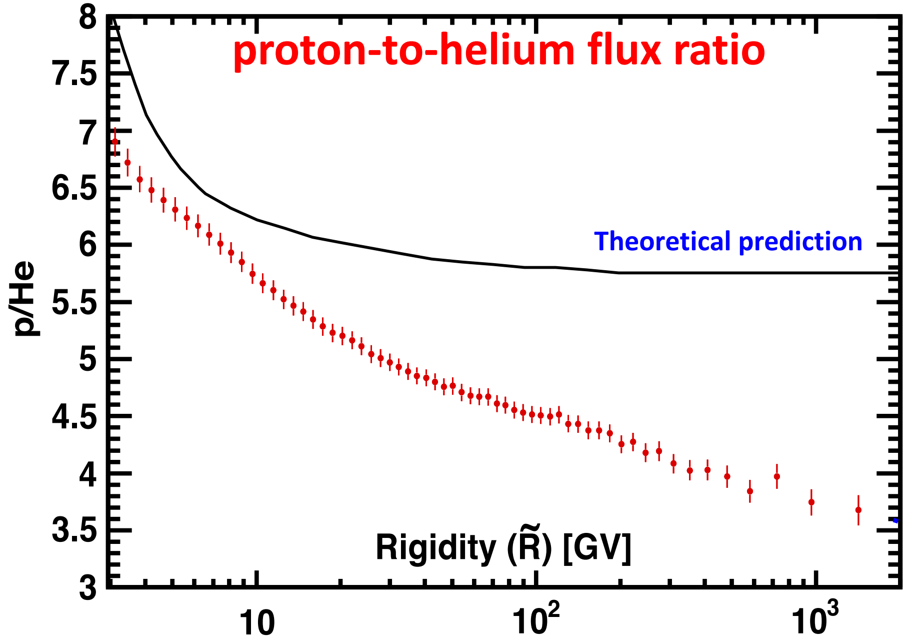
The spectra of protons, helium and lithium do not follow the traditional single power law. They all change their behavior at the same energy.

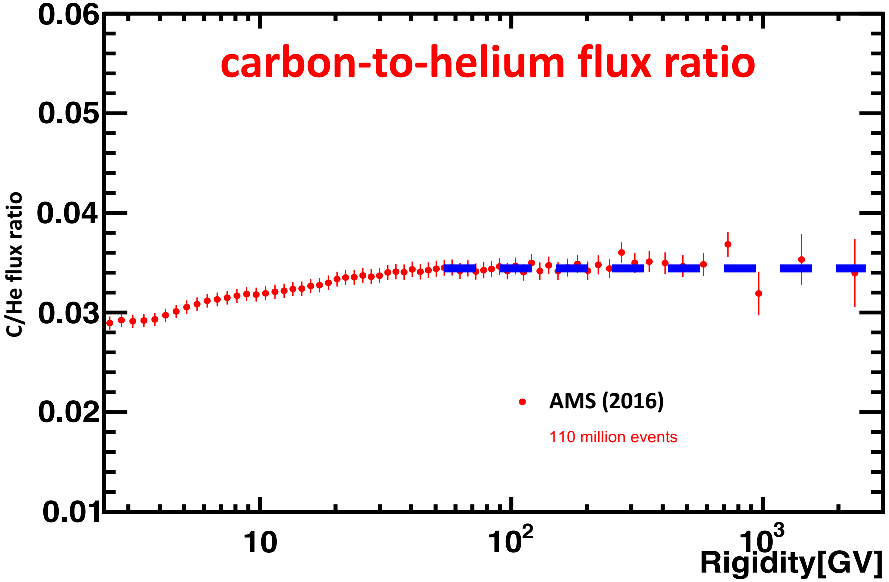


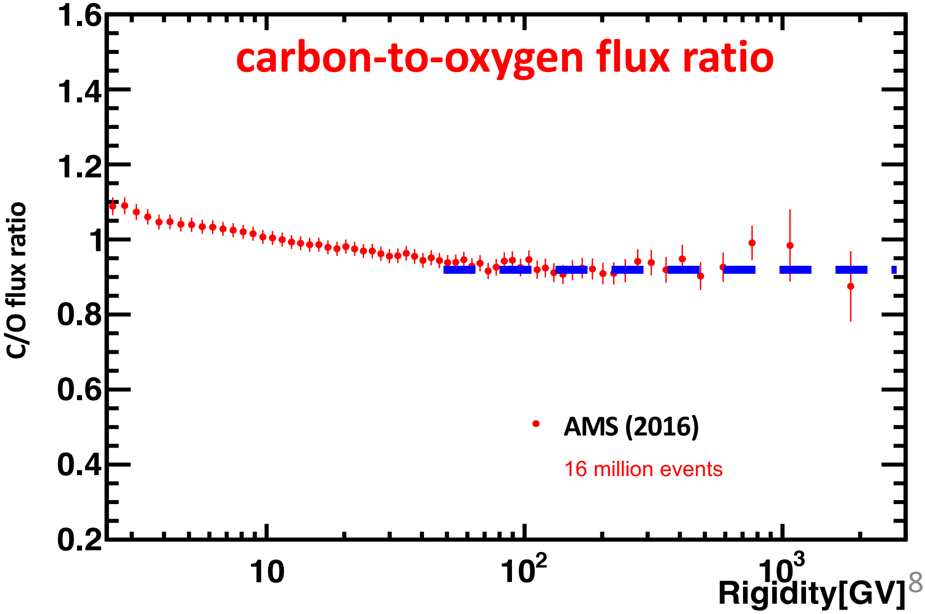
Summary (on nuclei)

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



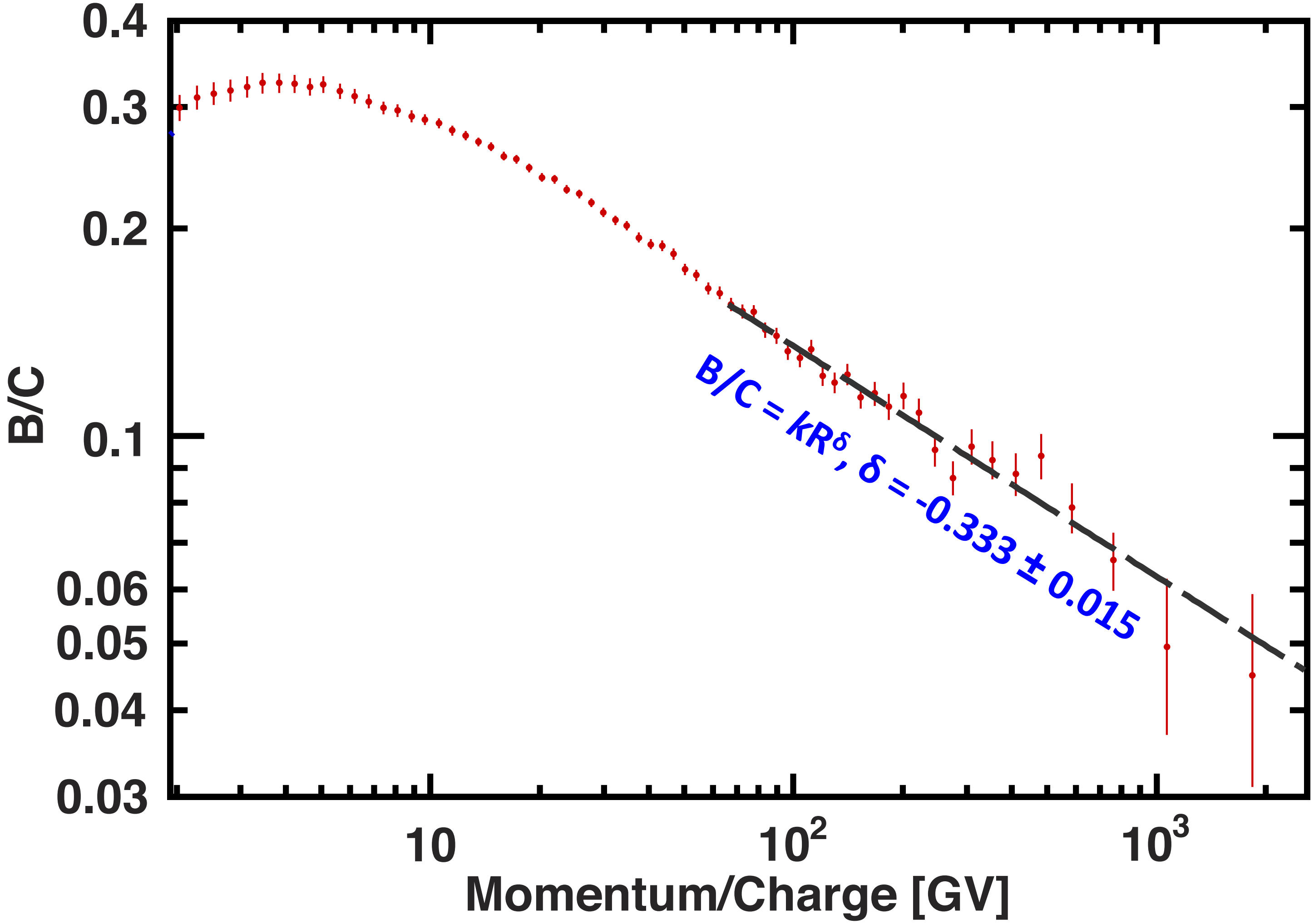






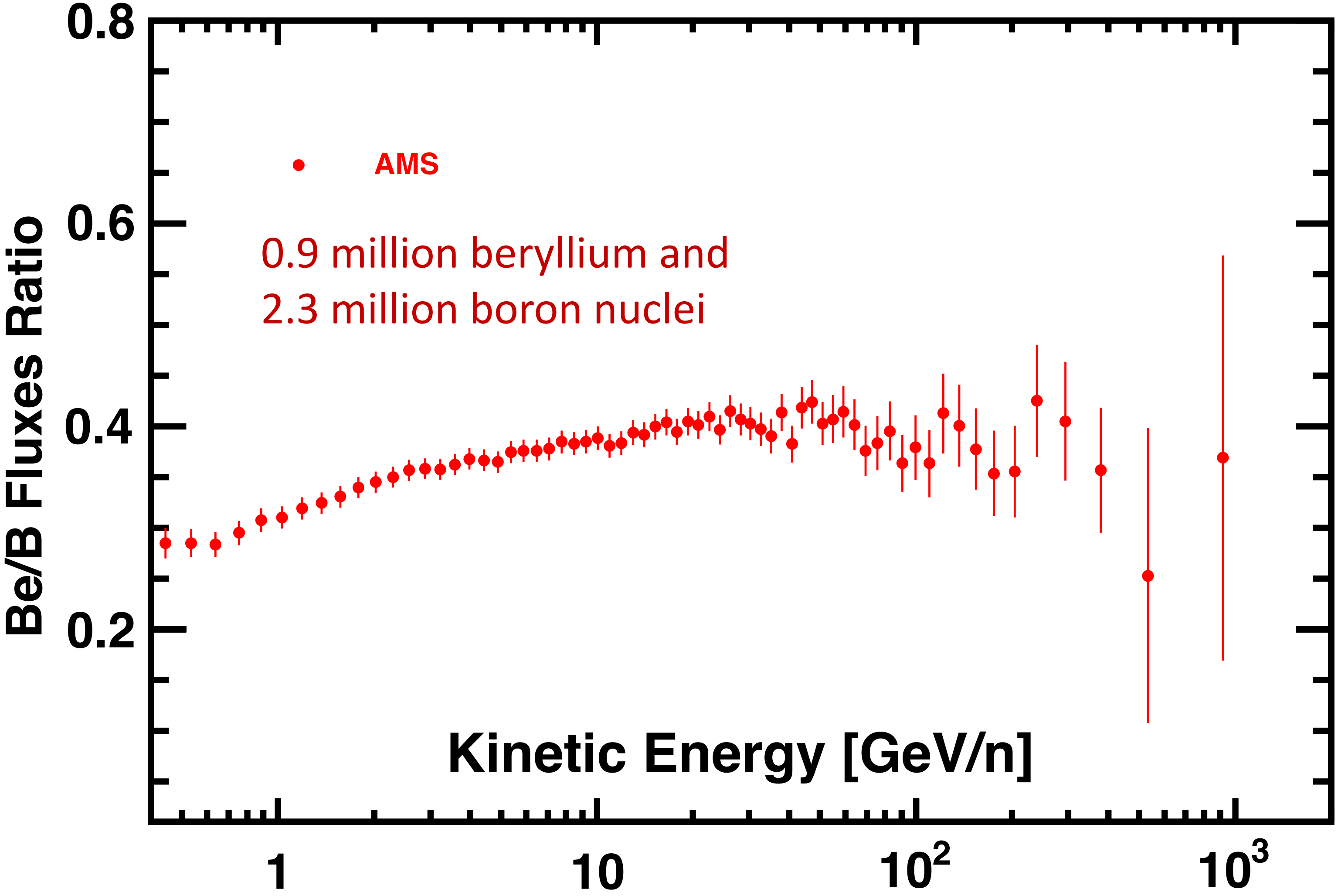
Summary (on nuclei)

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^{δ} with $\delta = -0.333 \pm 0.015$. This is in agreement with the Kolmogorov turbulence model of magnetized plasma of $\delta = -1/3$ asymptotically.



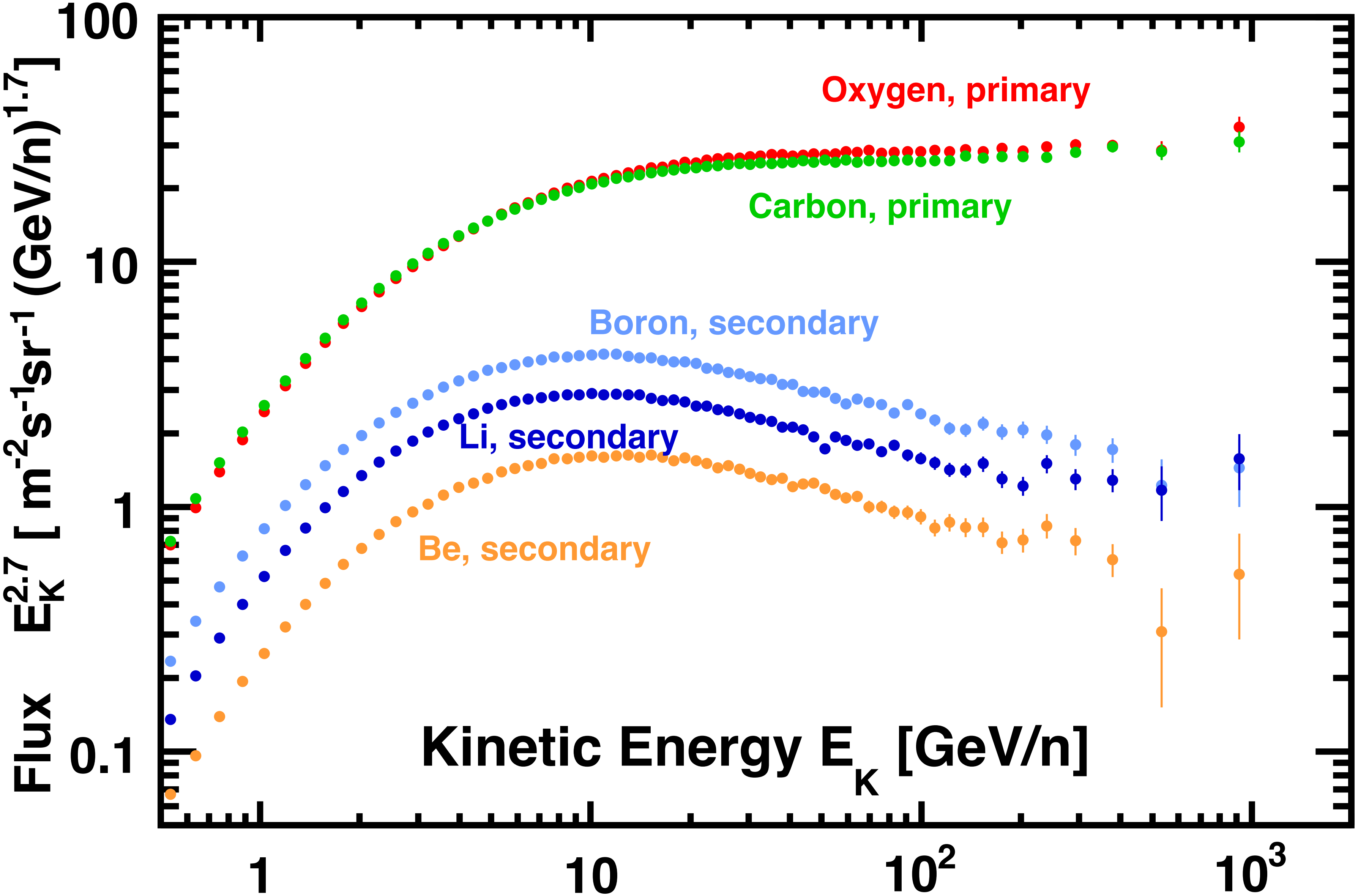
Summary (on nuclei)

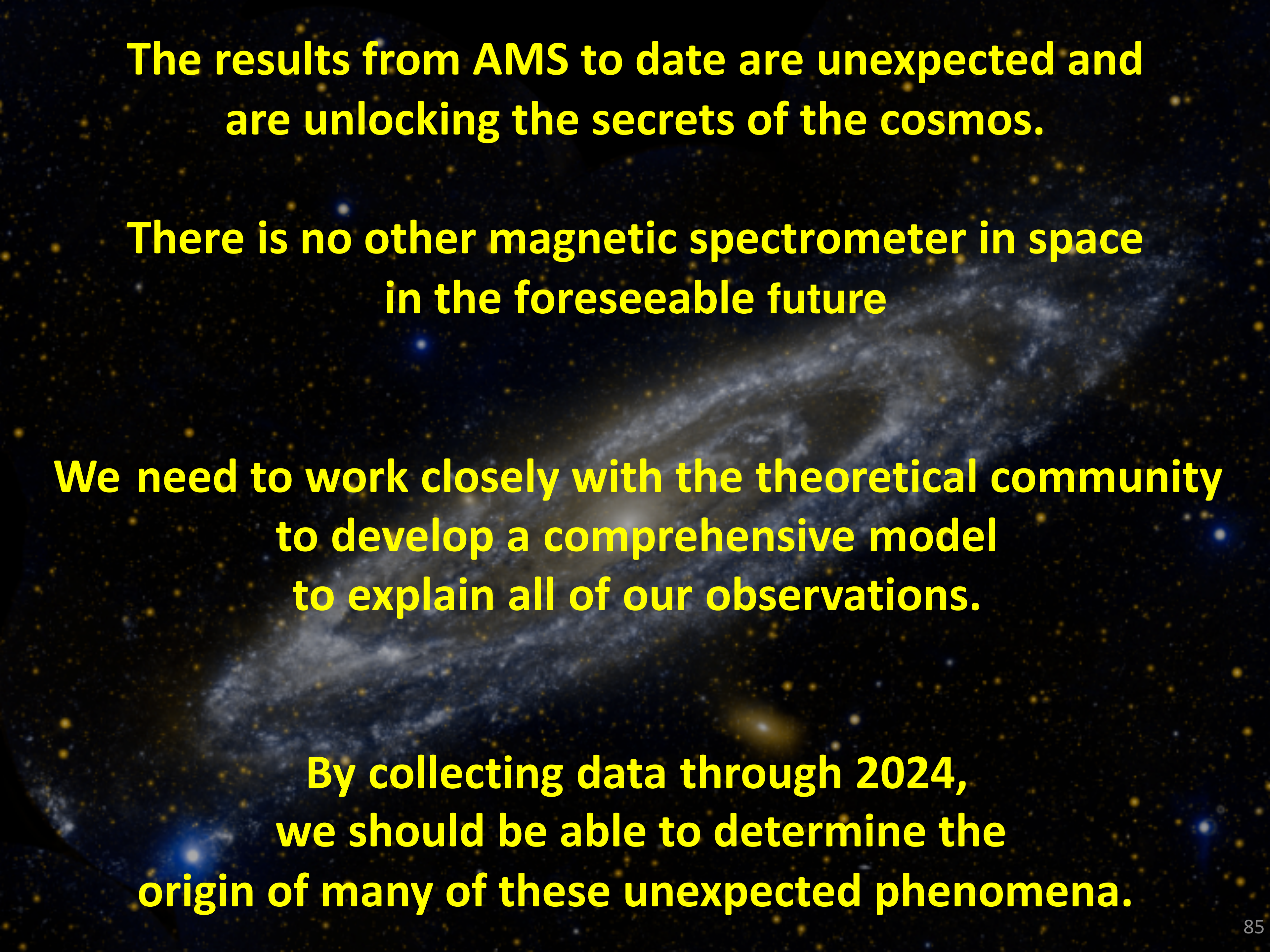
The beryllium-to-boron (Be/B) flux ratio increases with energy due to time dilation of the decaying Be. The age of cosmic rays in the galaxy is ~12 million years.



Summary (on nuclei)

Primary and secondary cosmic rays have characteristically different rigidity dependence.





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 future

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.