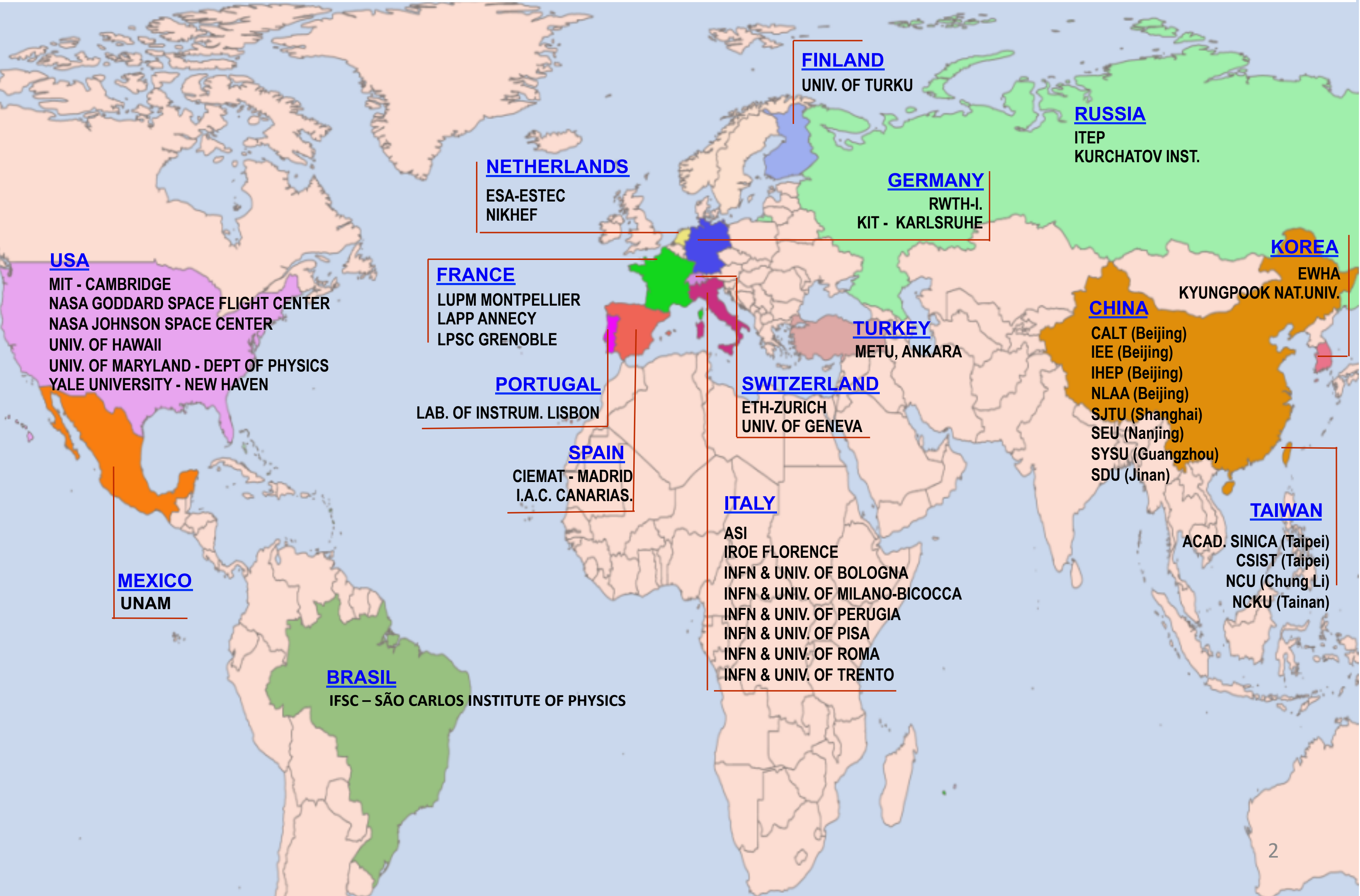
Latest Results from AMS on the Space Station

M. Heil, MIT
On behalf of the AMS collaboration

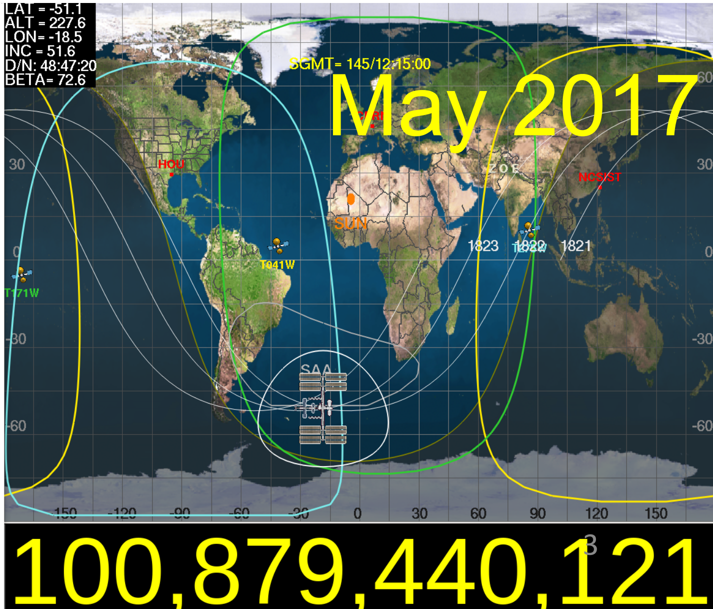
TeVPA17, Columbus,
7th August 2017

AMS is an International Collaboration
15 Countries, 46 Institutes



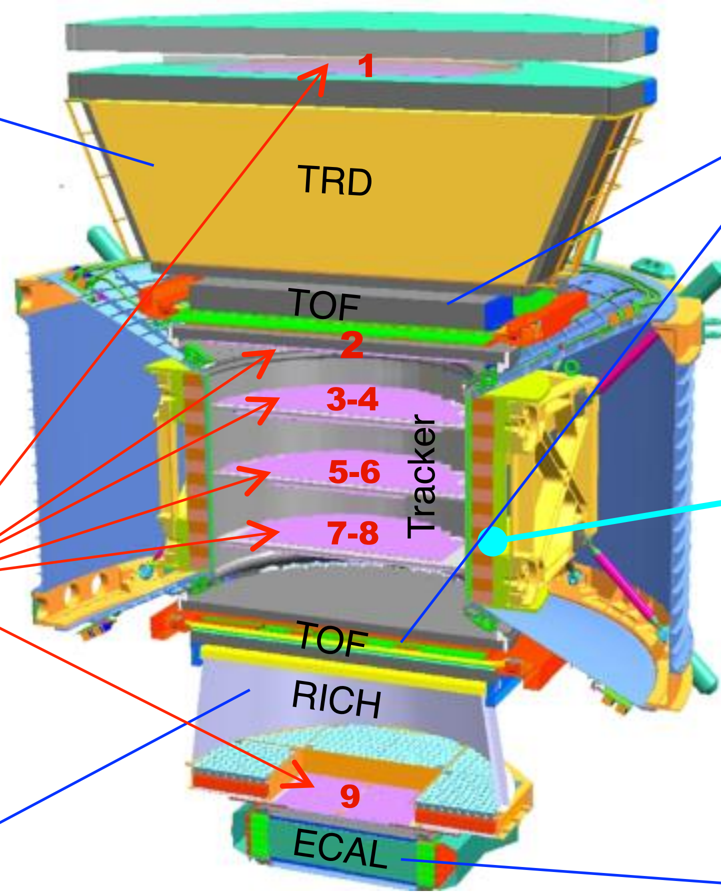
May 19, 2011: AMS is installed on the ISS and data taking started

May 25, 2017: AMS collected its 100 billionth cosmic ray event

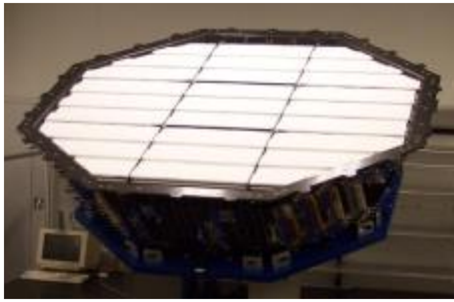


AMS: A TeV precision, multipurpose magnetic spectrometer

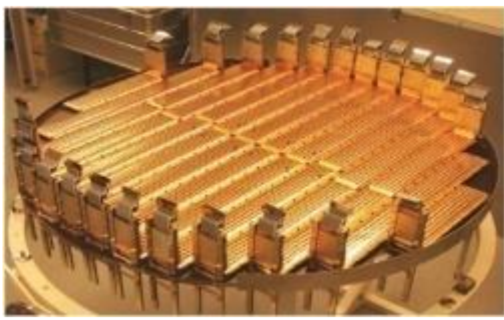
Particles and nuclei are defined by their charge (Z) and energy (E) or (R=p/Z)



Transition Radiation Detector
Identify e^+, e^-



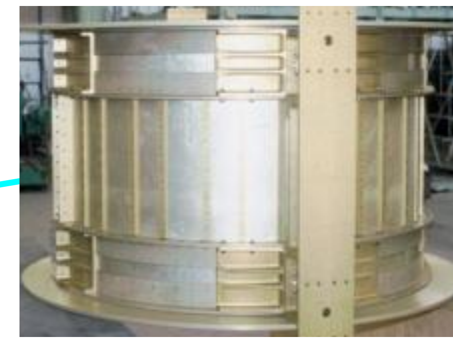
Silicon Tracker
Z, R



Ring Imaging Cherenkov
Z, E

Time of Flight
Z, E

Magnet
±Z, R

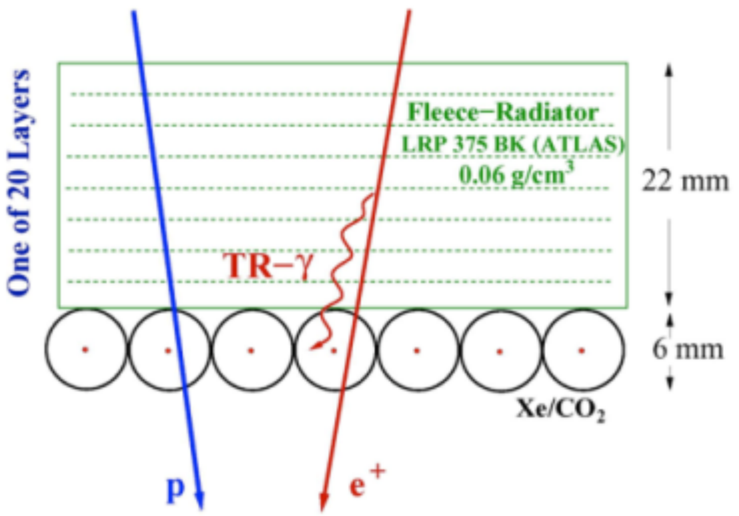


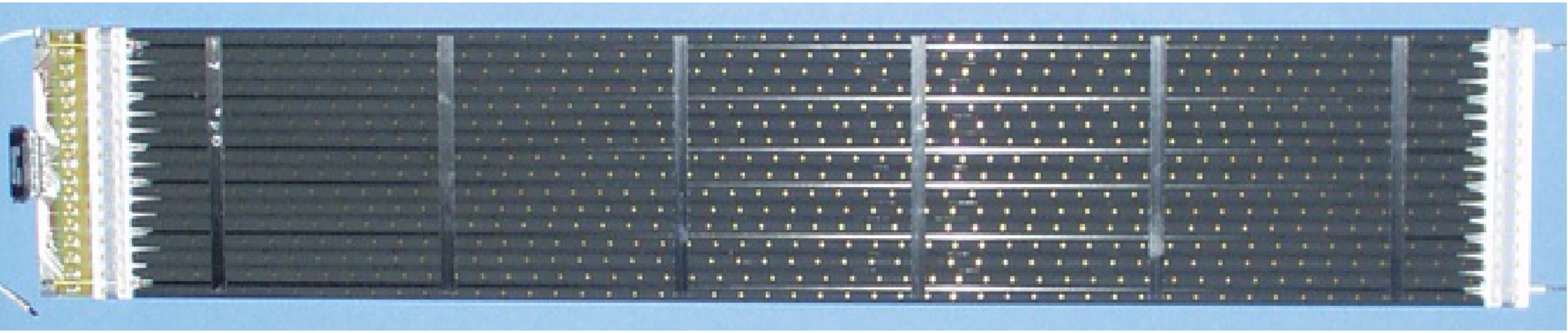
Electromagnetic Calorimeter
E of e^+, e^-

The Charge and Energy are measured independently by many subdetectors

Transition Radiation Detector (TRD)

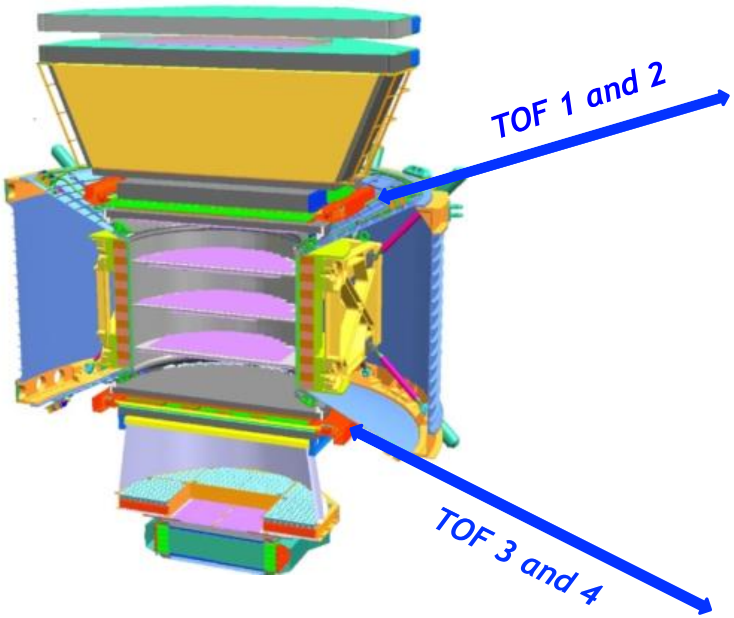
Identifies $e^{\pm}$ by transition radiation and Nuclei by dE/dX

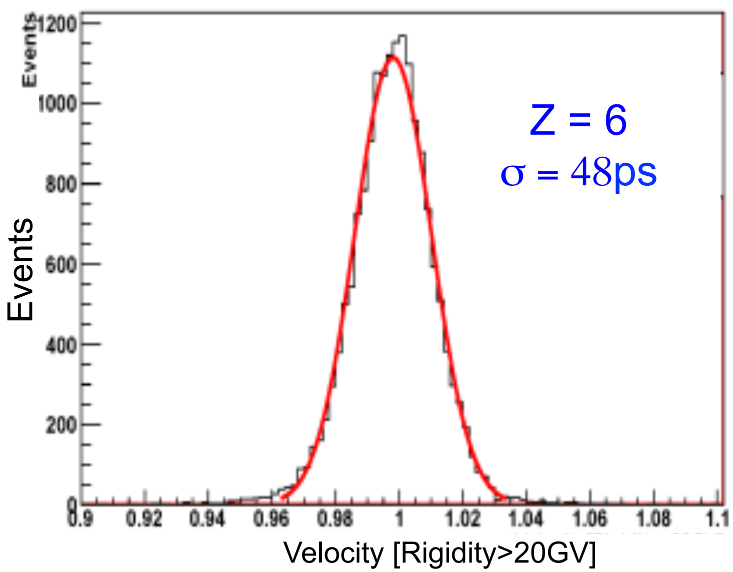




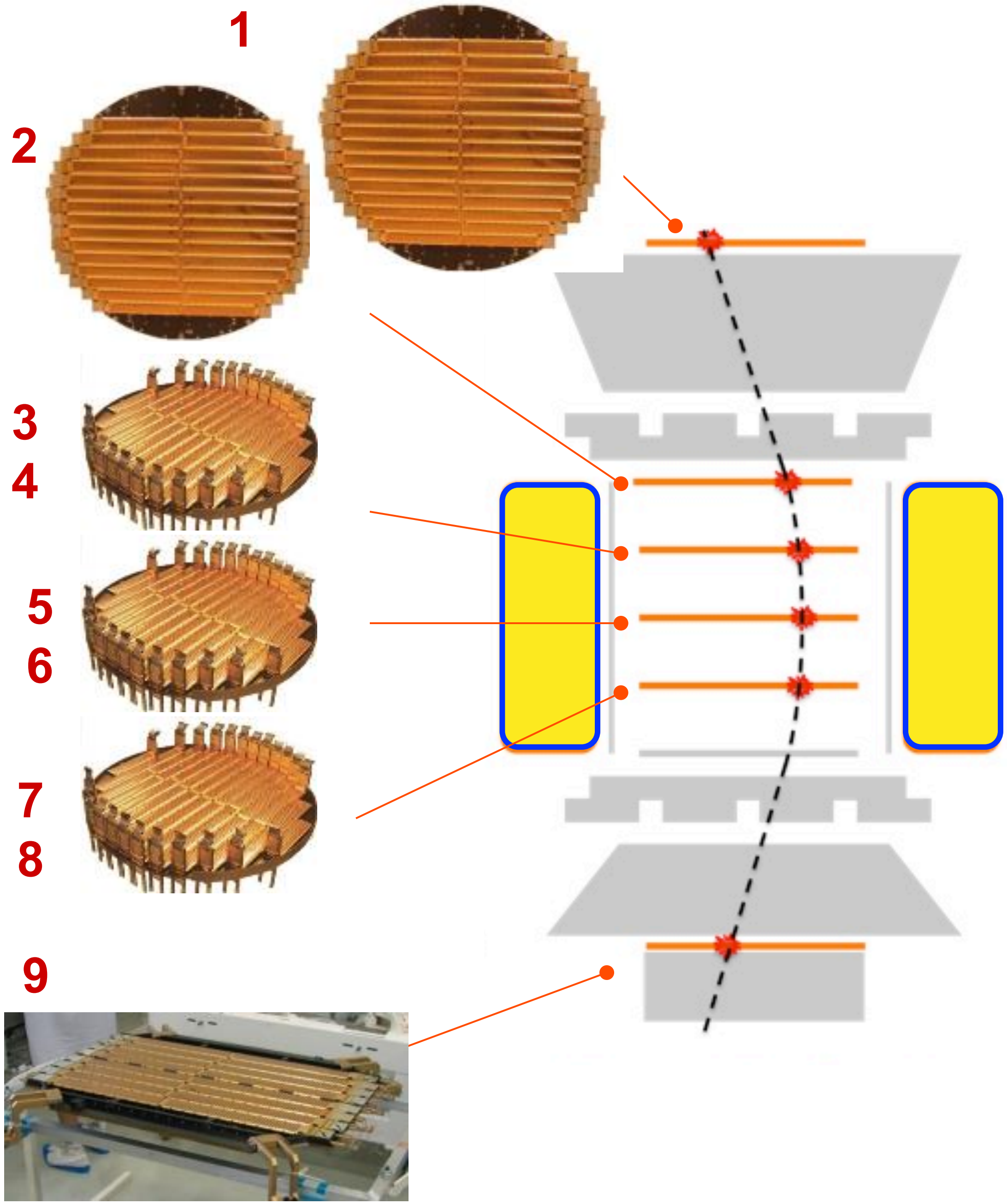
Time of Flight System (TOF)

Measures Velocity and Charge of particles

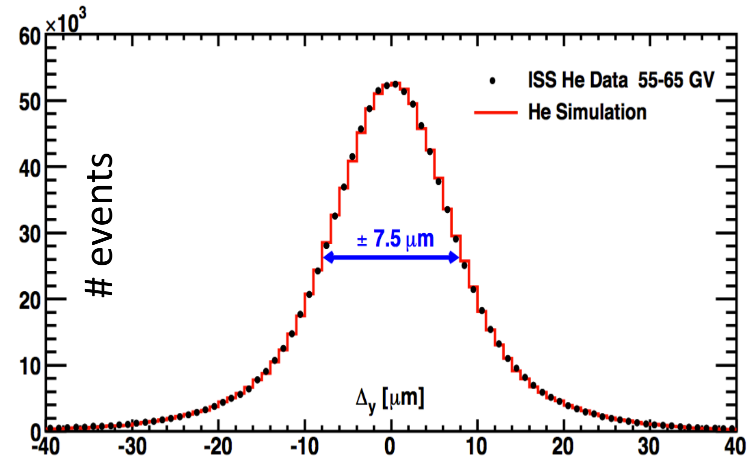




Silicon Tracker



9 planes reconstructing the particle trajectory with 5-10 micron coordinate resolution



This provides a maximum detectable rigidity (momentum/charge) :

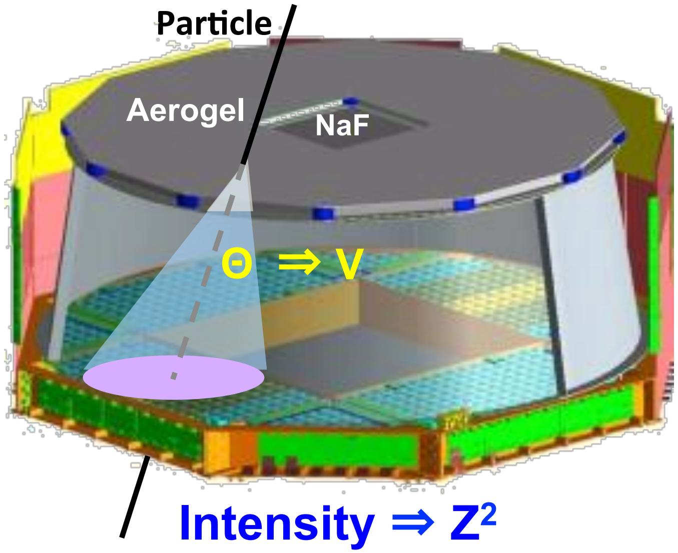
2 TV for |Z|=1 particles

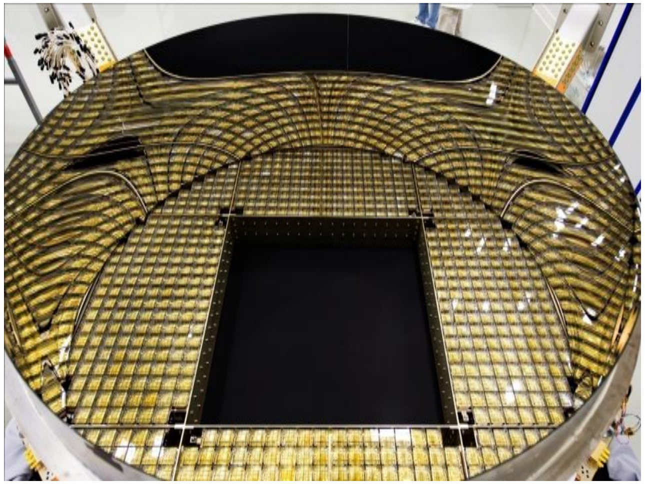
and

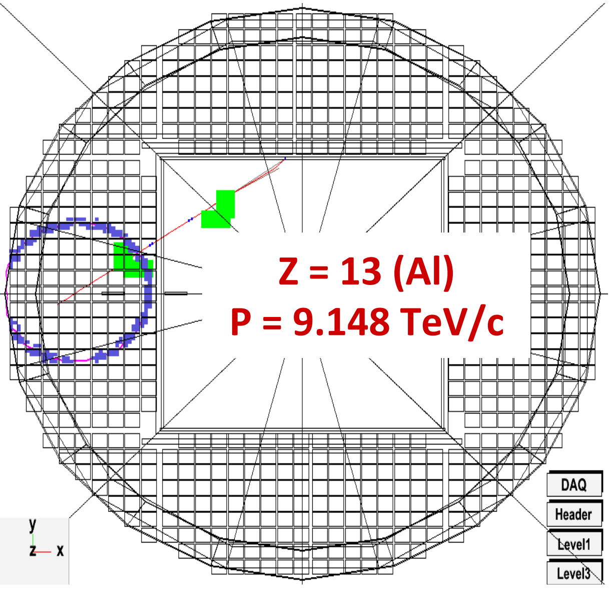
3.4 – 4.0 TV for |Z|=2-8 nuclei

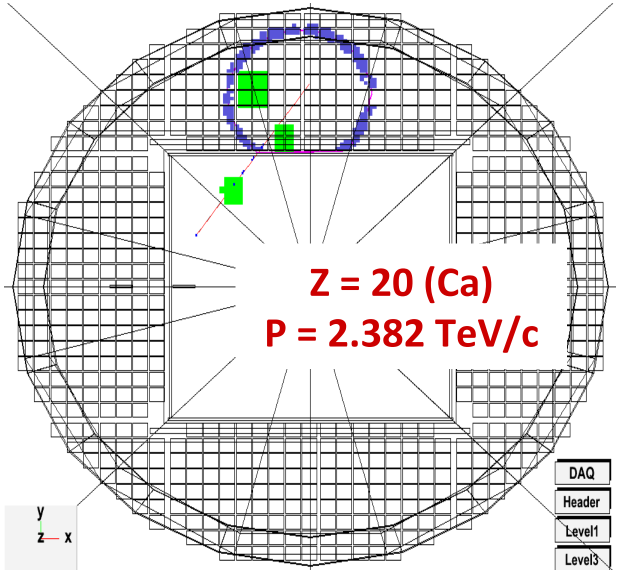
AMS Ring Imaging CHerenkov (RICH)

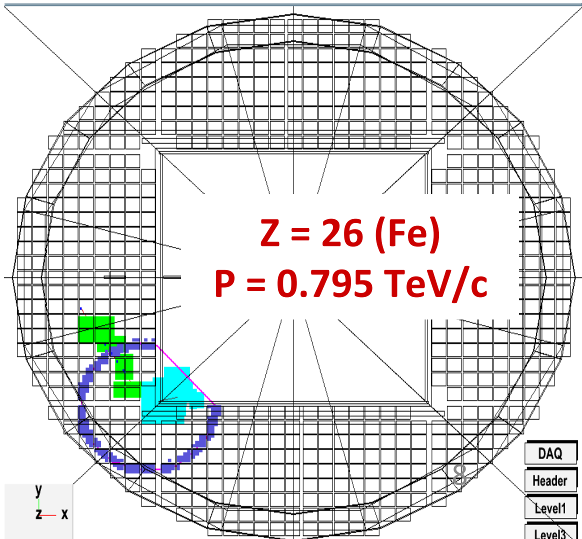
Measurement of Nuclear Charge (Z^2) and Velocity to 1/1000



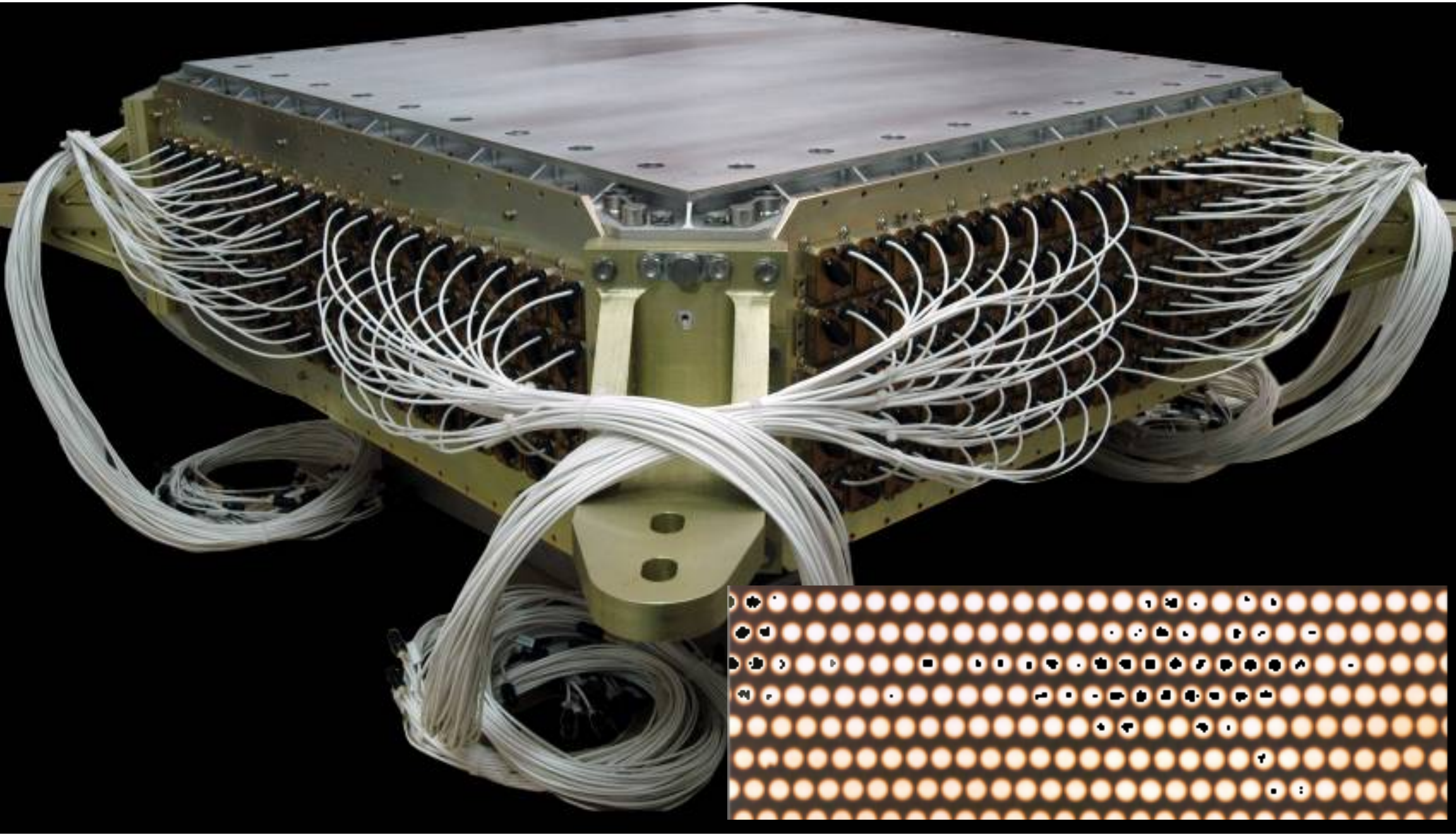








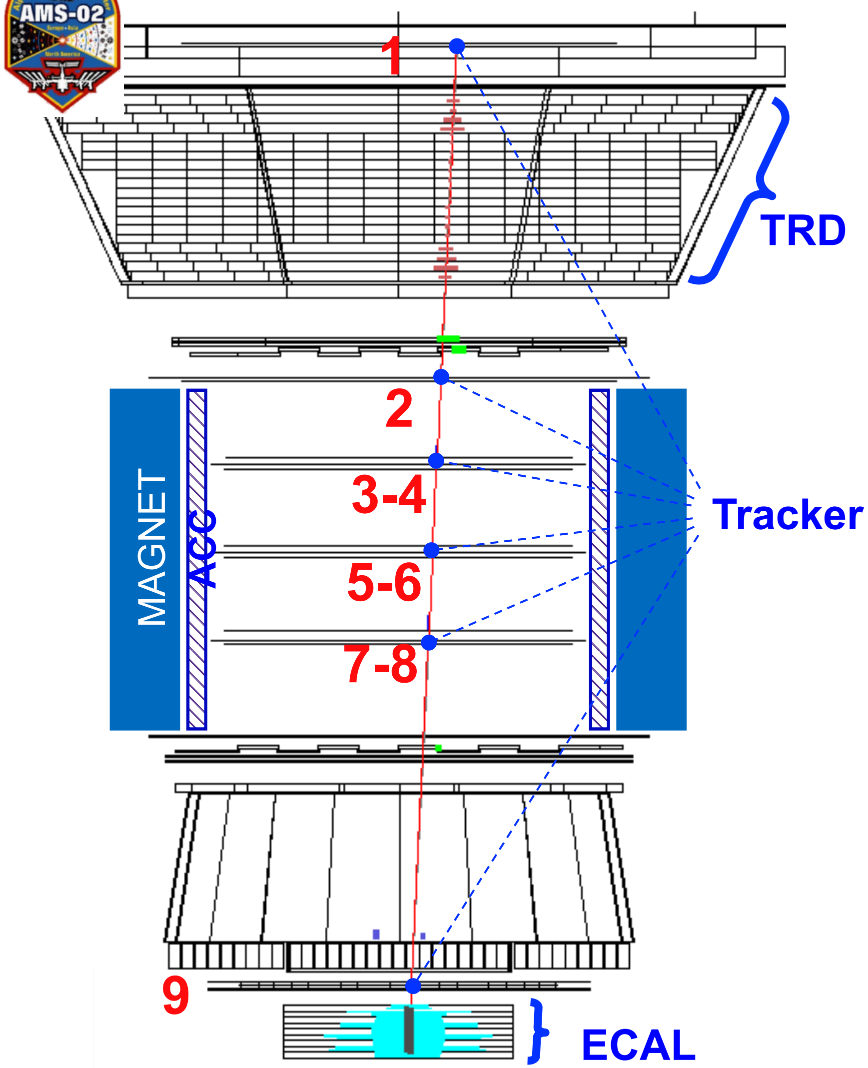
Calorimeter (ECAL)



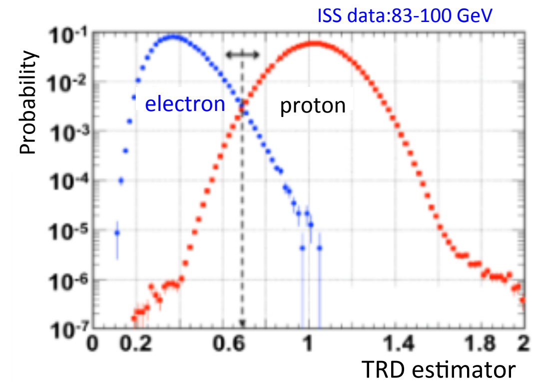
50,000 fibers, $\phi = 1$mm, distributed uniformly inside 600 kg of lead which provides a precision, 3-D, $17X_0$ measurement of the directions and energies of $e^{\pm}$ to TeV

Electron/positron identification

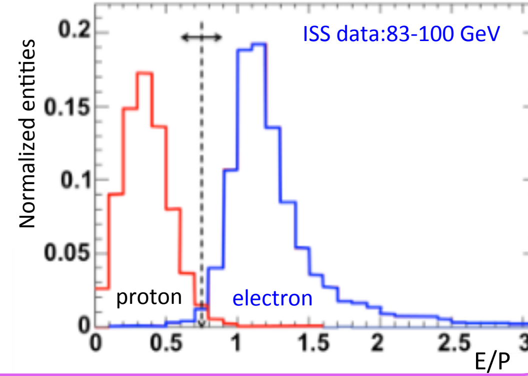
424 GeV positron



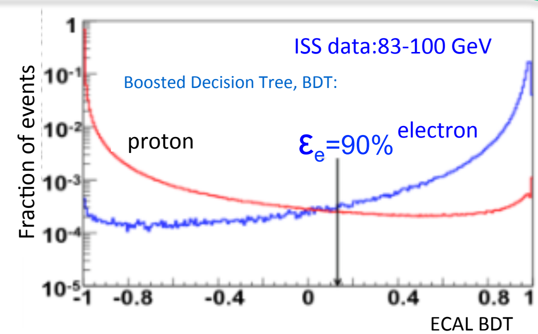
TRD
identifies $e^{\pm}$



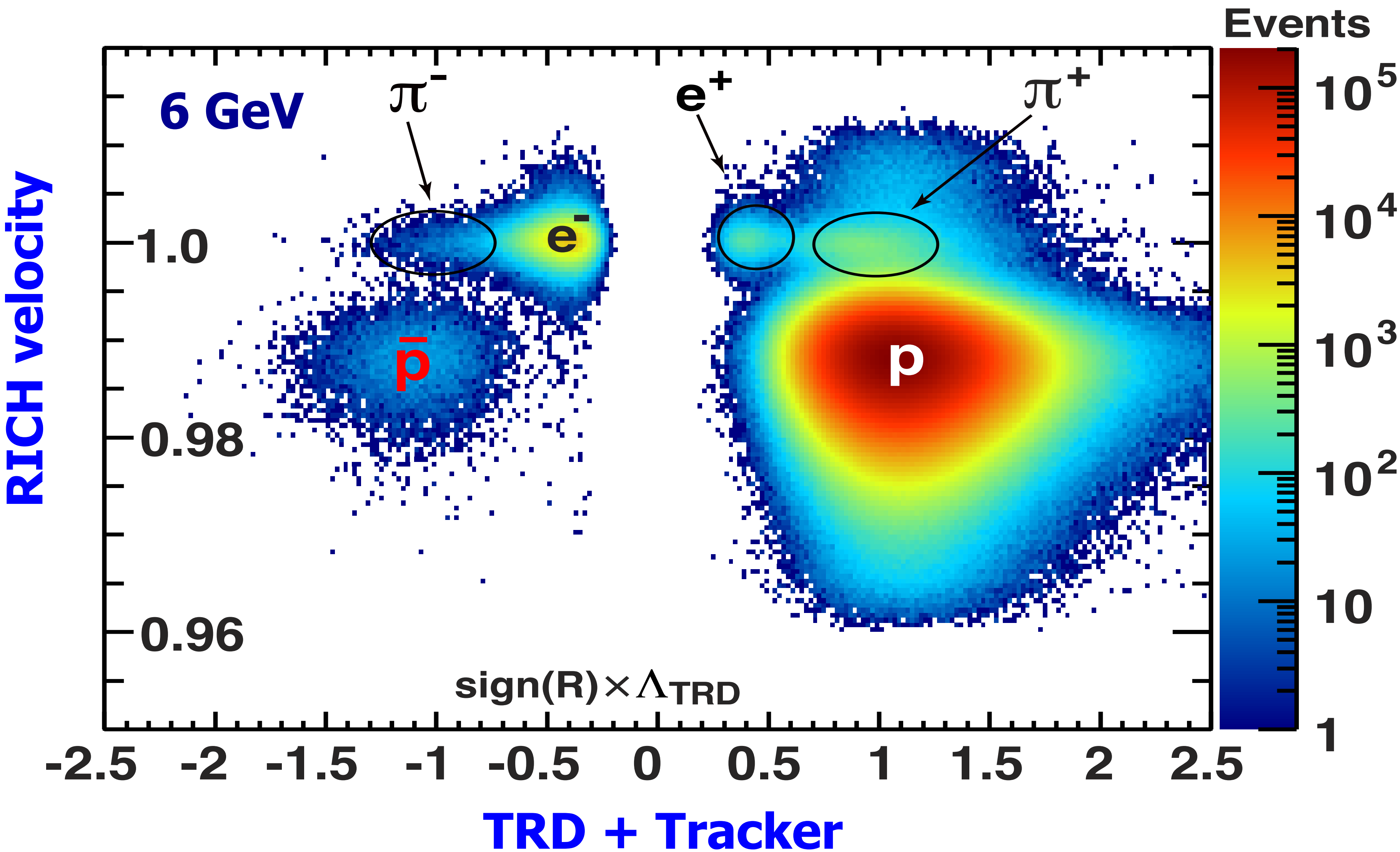
TRACKER
measures P
ECAL measures E
$e^{\pm}$: E=P
proton: E<P



ECAL
measures
shower shape
to separate $e^{\pm}$
from protons

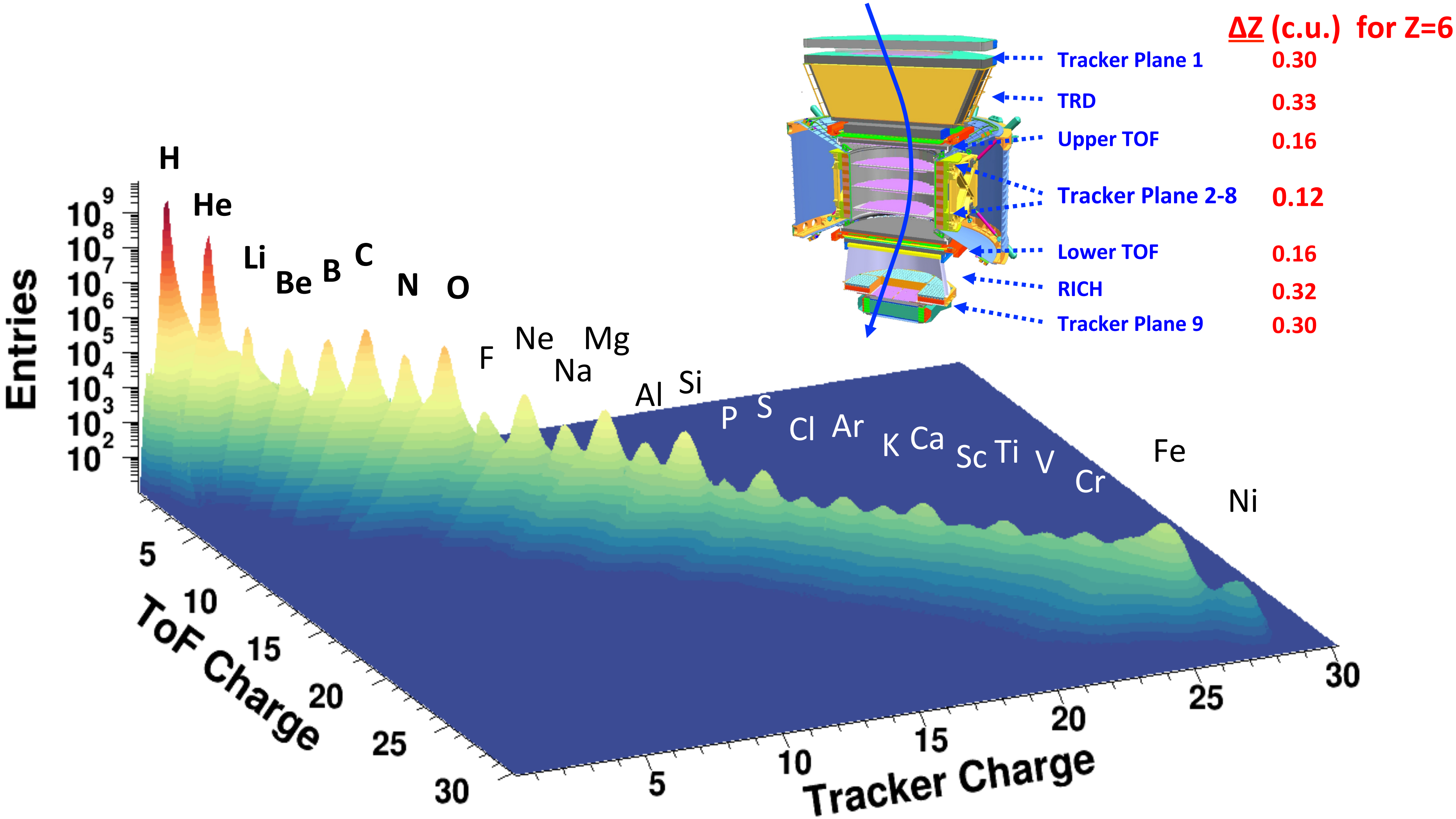


Selection of the signal:
The $\bar{p}$ signal is well separated from the backgrounds.

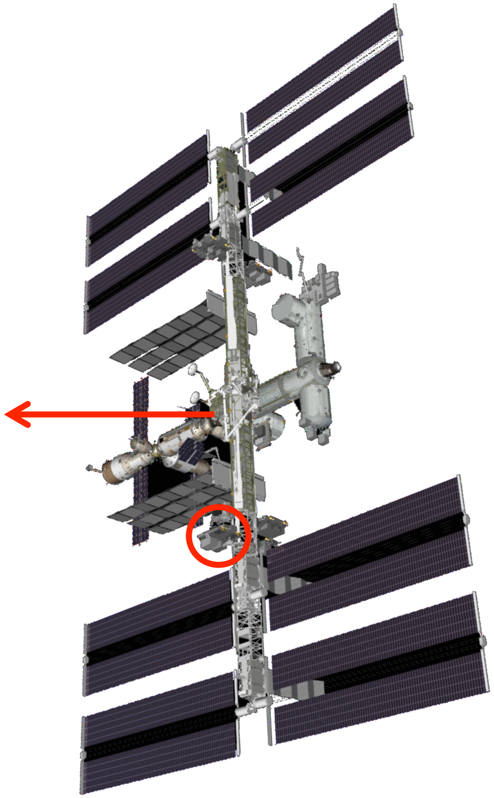


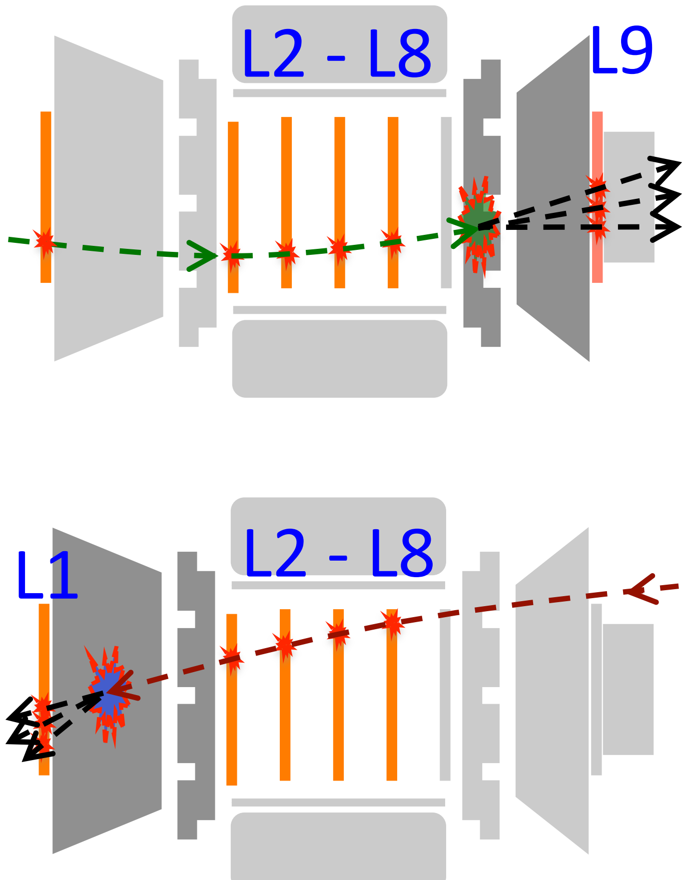
Cosmic Nuclei

AMS has seven instruments which independently identify different elements



Measuring the interactions of nuclei within AMS with AMS horizontal





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

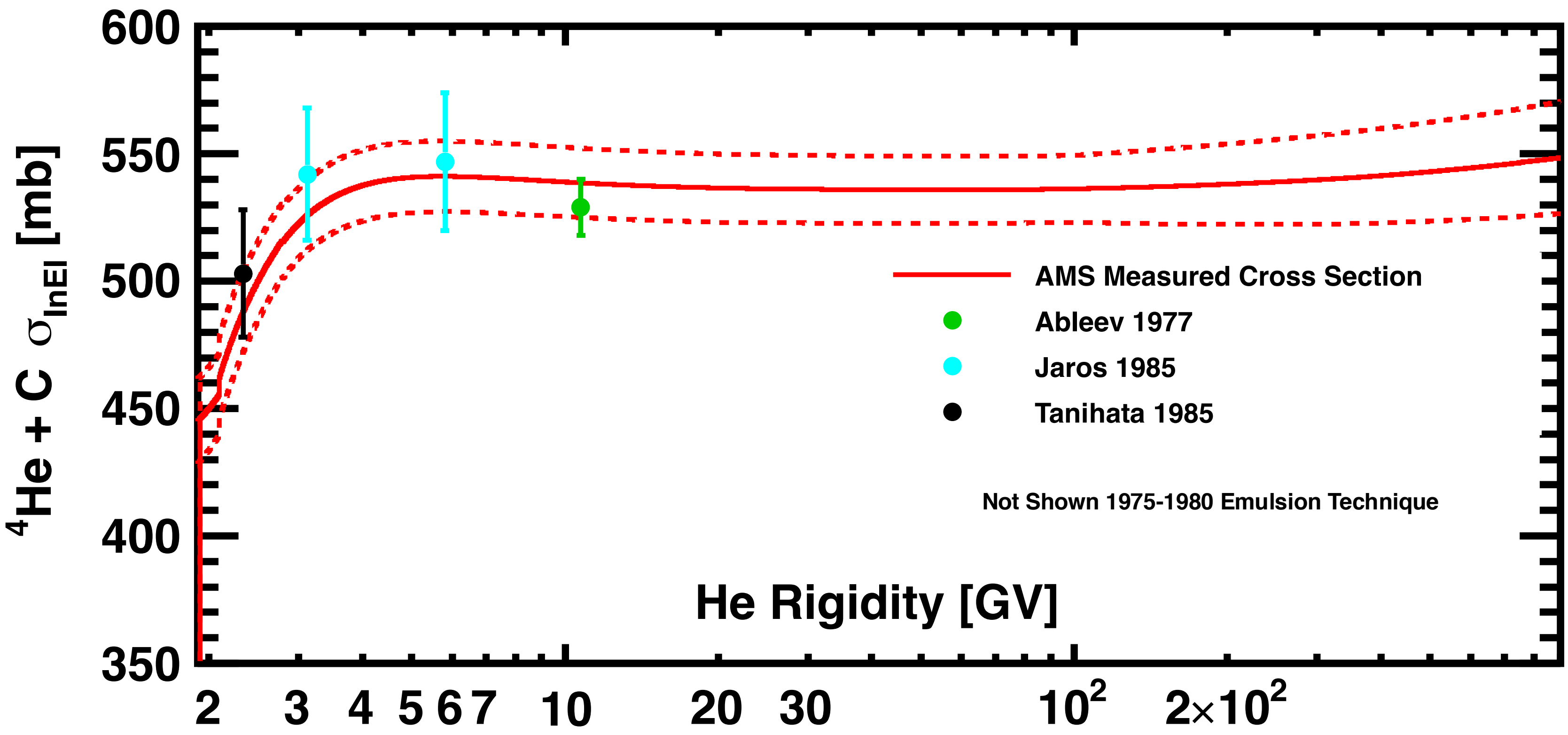
Second, we use left-to-right particles to measure the nuclear interactions in the lower part of the detector

(also during normal ISS orientation with higher statistics)

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

When ISS flies with AMS horizontal it is a unique high energy (> TeV) accelerator for particles and nuclei

AMS Measurement of He+C Cross Section



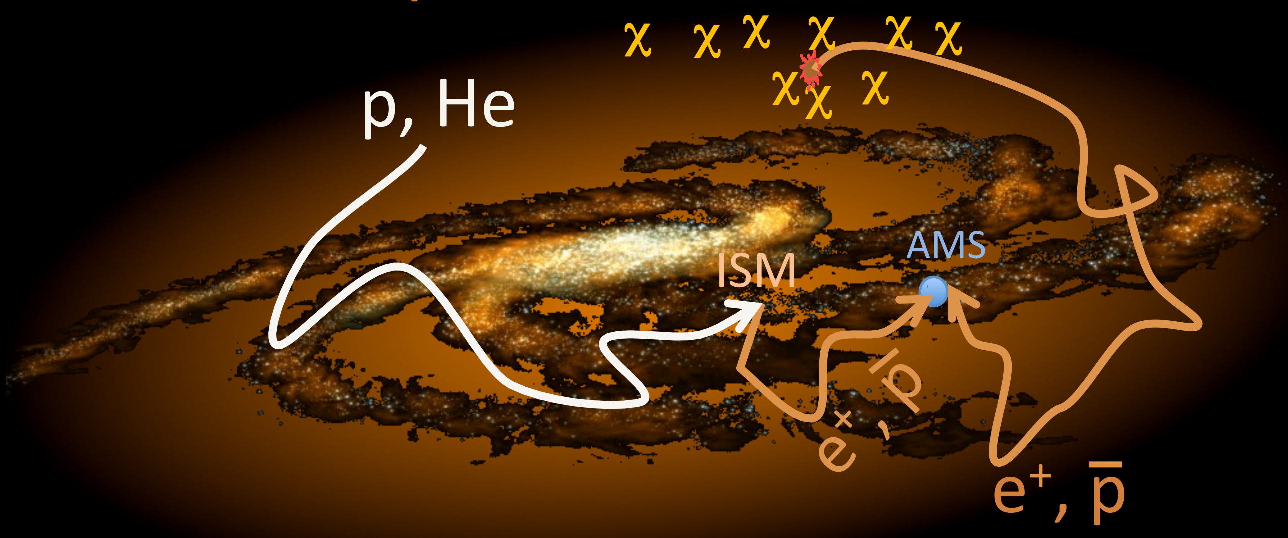
Accuracy mostly limited by exposure time in horizontal orientation (~2 days)

Similarly, the tracker allows us to check individual fragmentation channels, like Carbon -> Boron, further reducing the systematic errors from nuclei interactions

Dark Matter: χ

p, He + ISM $\rightarrow$ e^+, $\bar{p}$ + …

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

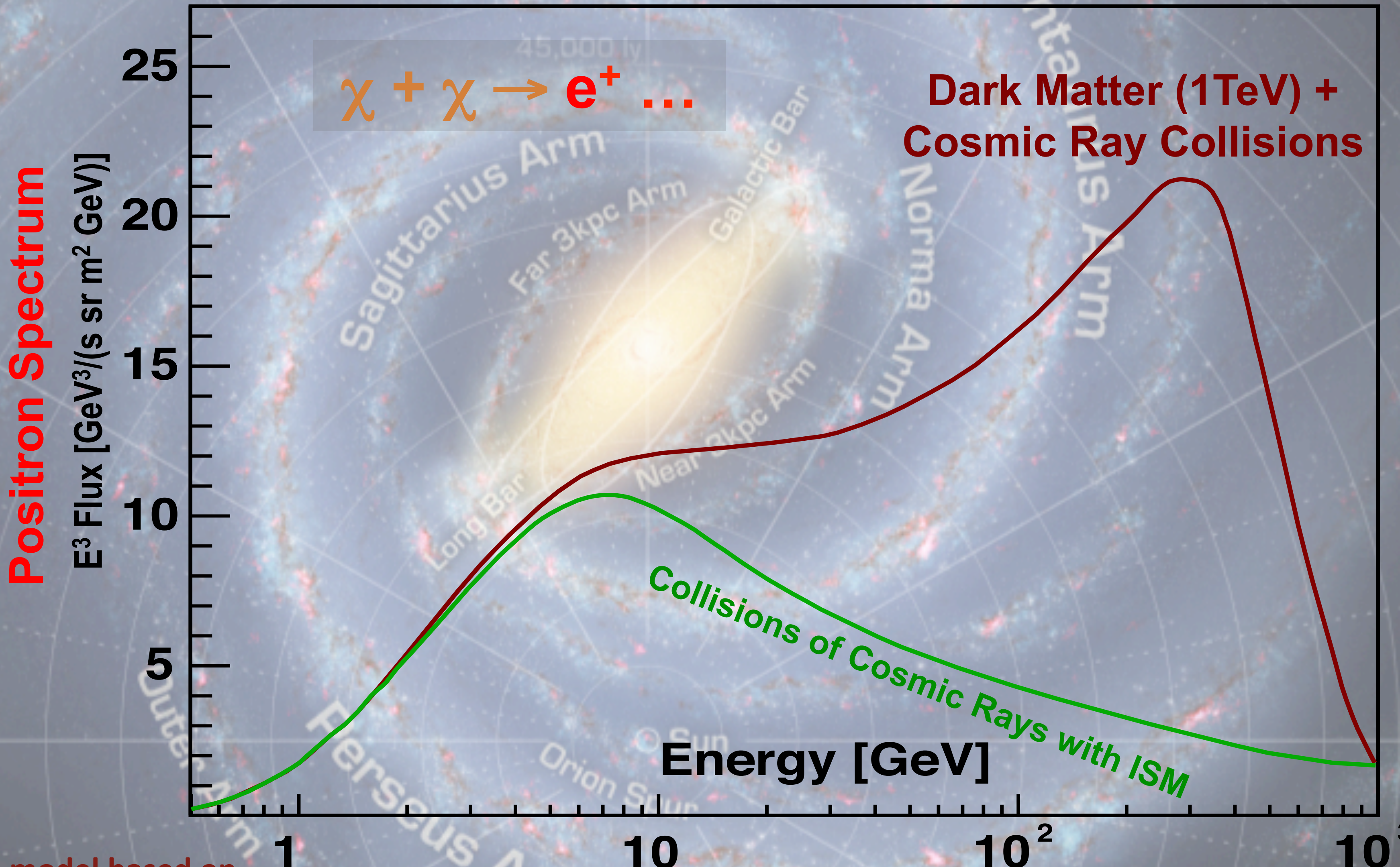


The excess of e^+, $\bar{p}$ from Dark Matter (χ) annihilations can be measured by AMS

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

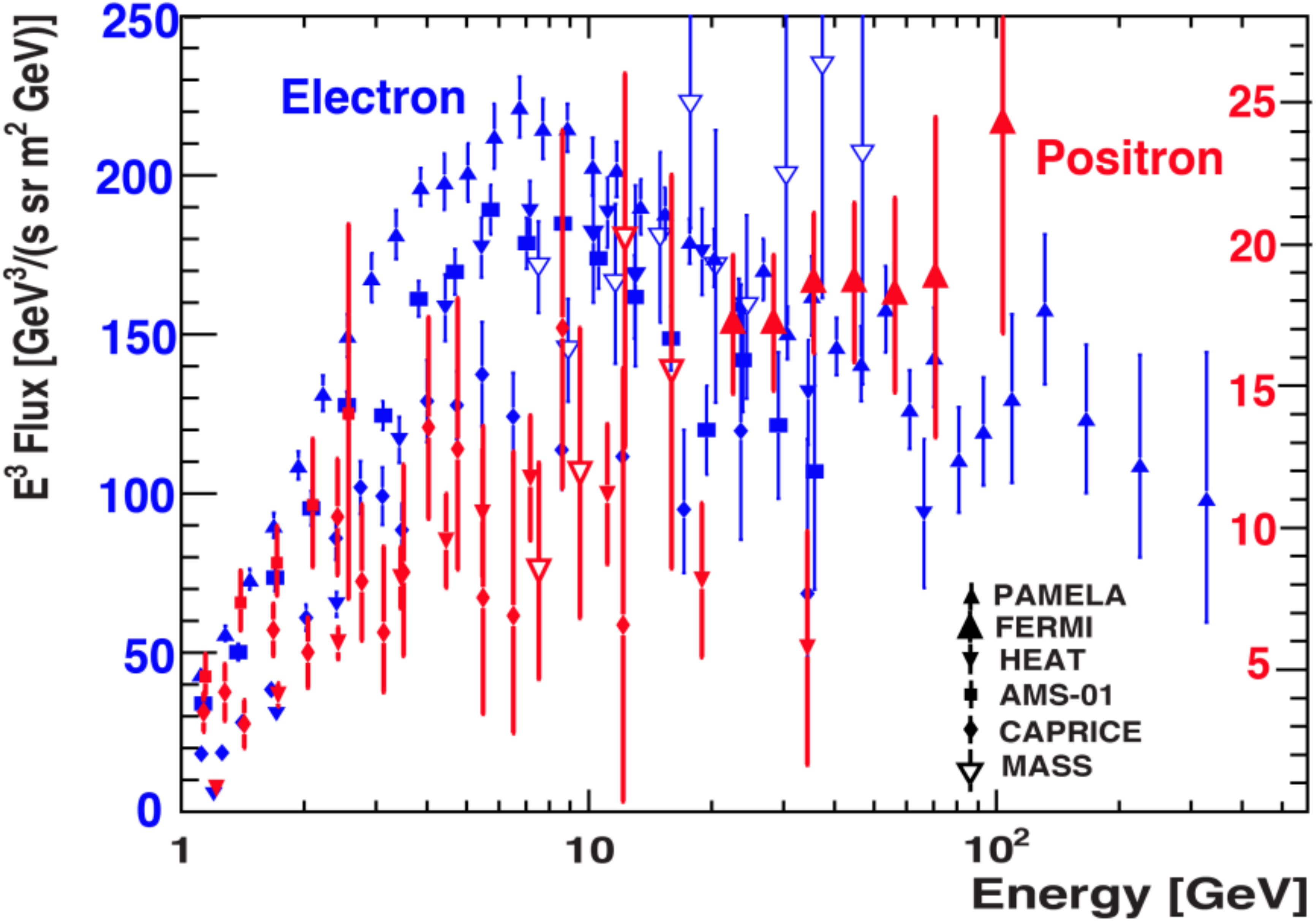
Dark Matter

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

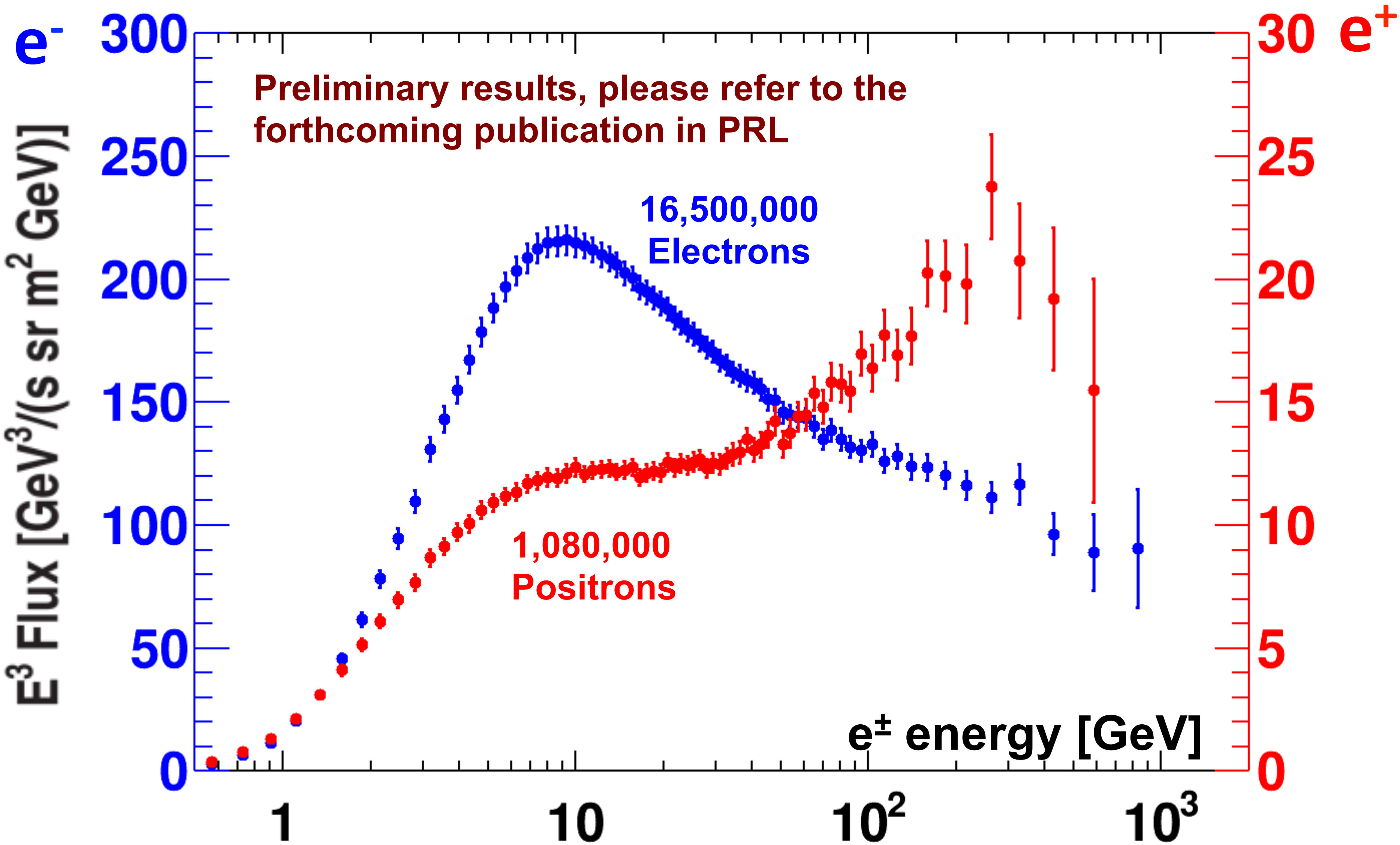


DM model based on
J. Kopp, Phys. Rev. D 88 (2013) 076013

Electron and Positron flux (before AMS)



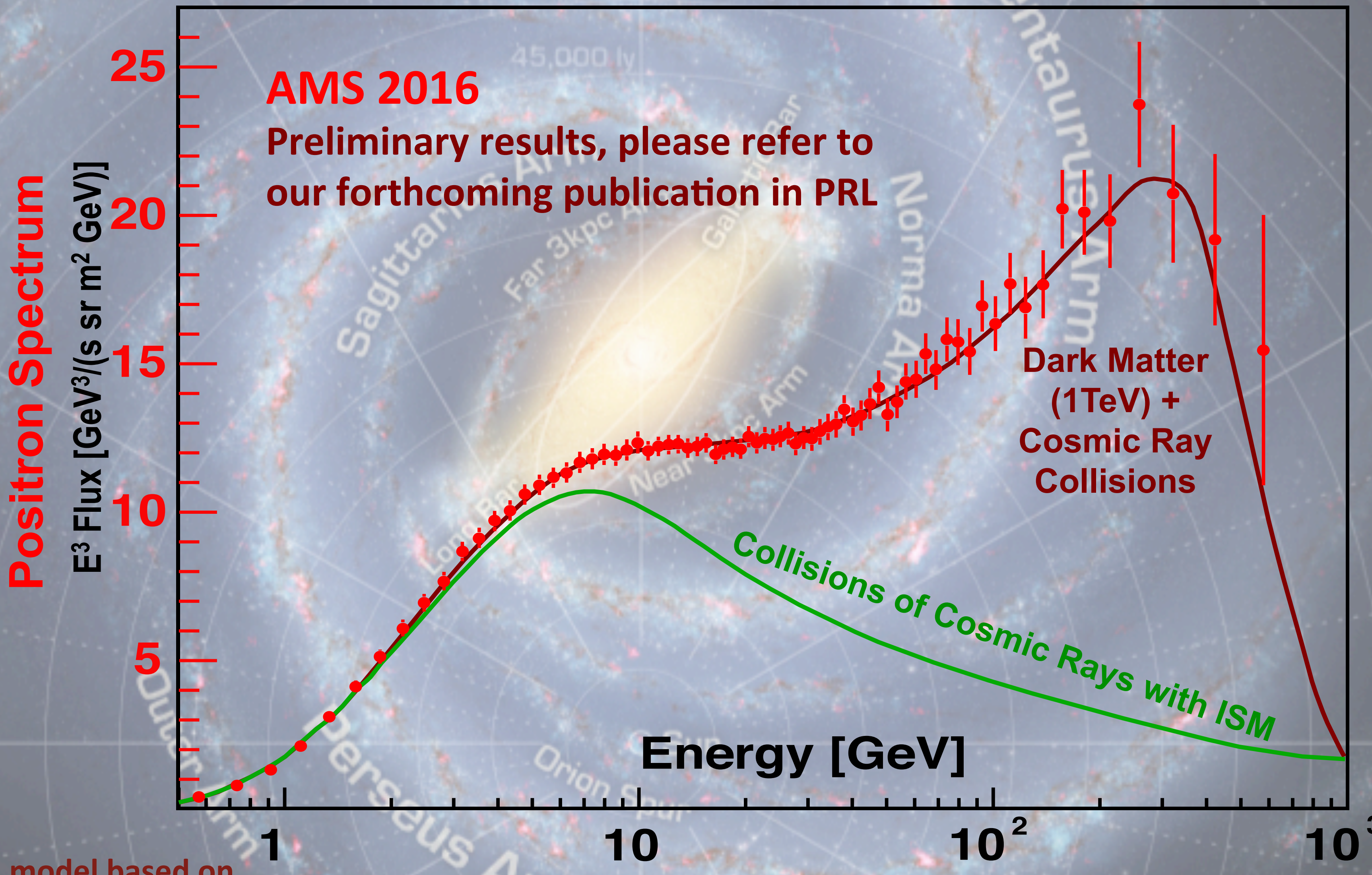
Physics Result: AMS 5 years positron and electron spectrum



Presented by **Matteo Duranti**

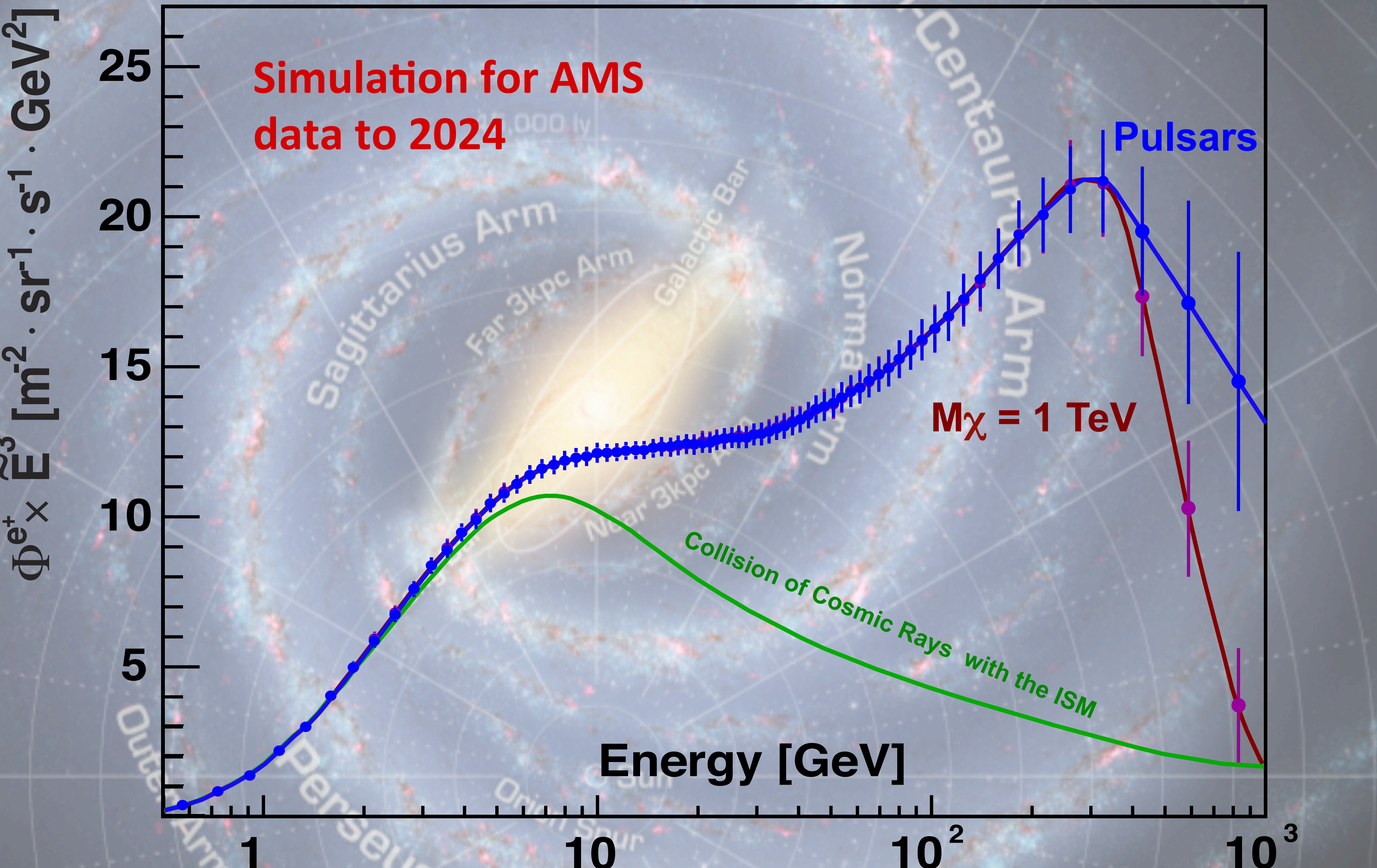
Physics Result: The origin of the AMS positron spectrum

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



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

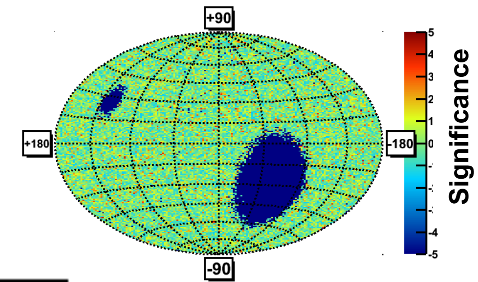
2024: Extend measurement to 1 TeV



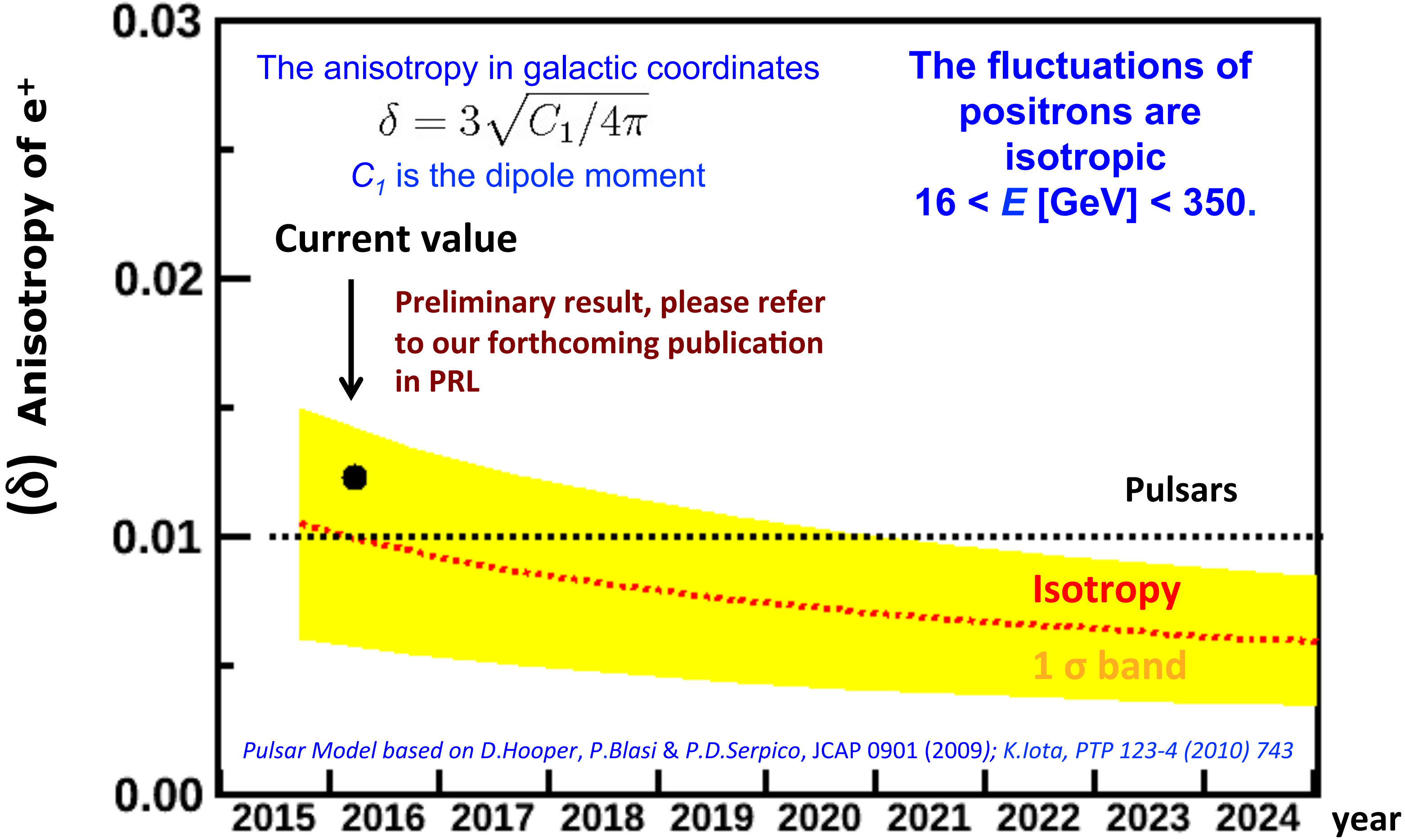
By 2024 we will be able to understand the origin of this unexpected data.

Physics Result: Measurement of e^+ 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.



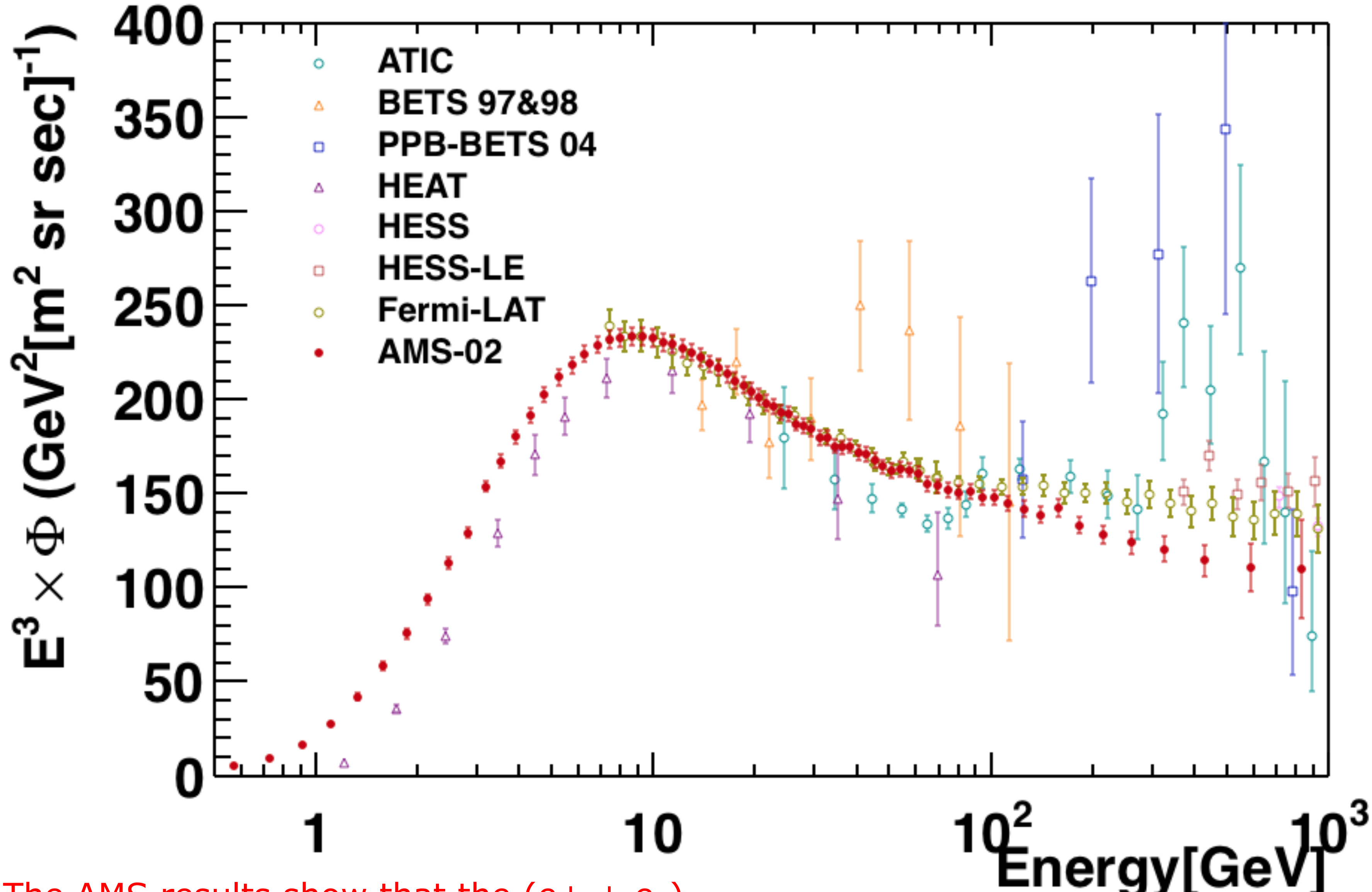
Galactic coordinates (b,l)



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

***Presented by* Jorge Casaus**

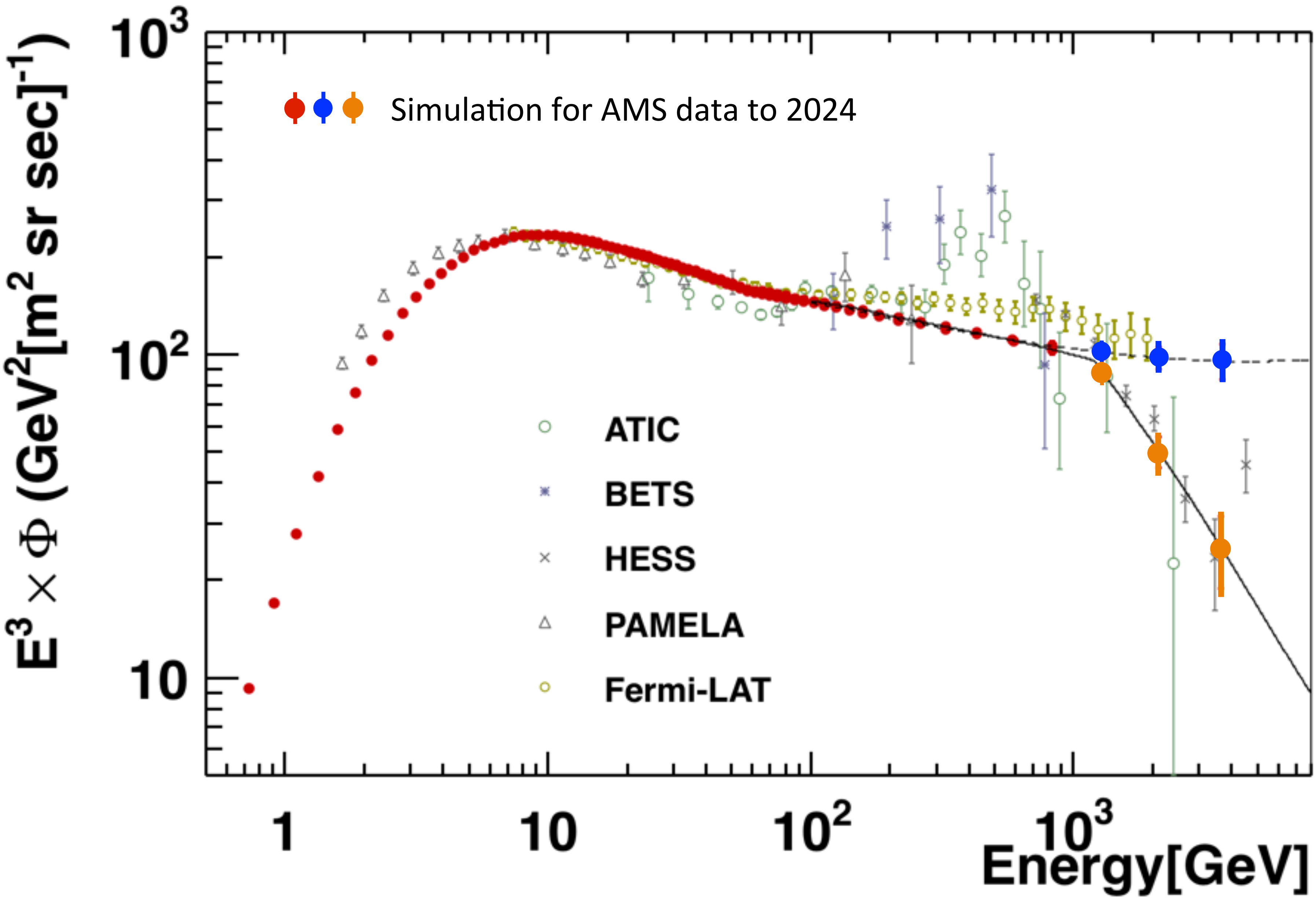
Physics Result: ($e^+ + e^-$) flux



The AMS results show that the (e+ + e-) spectrum has no structure and no hints of new particles.

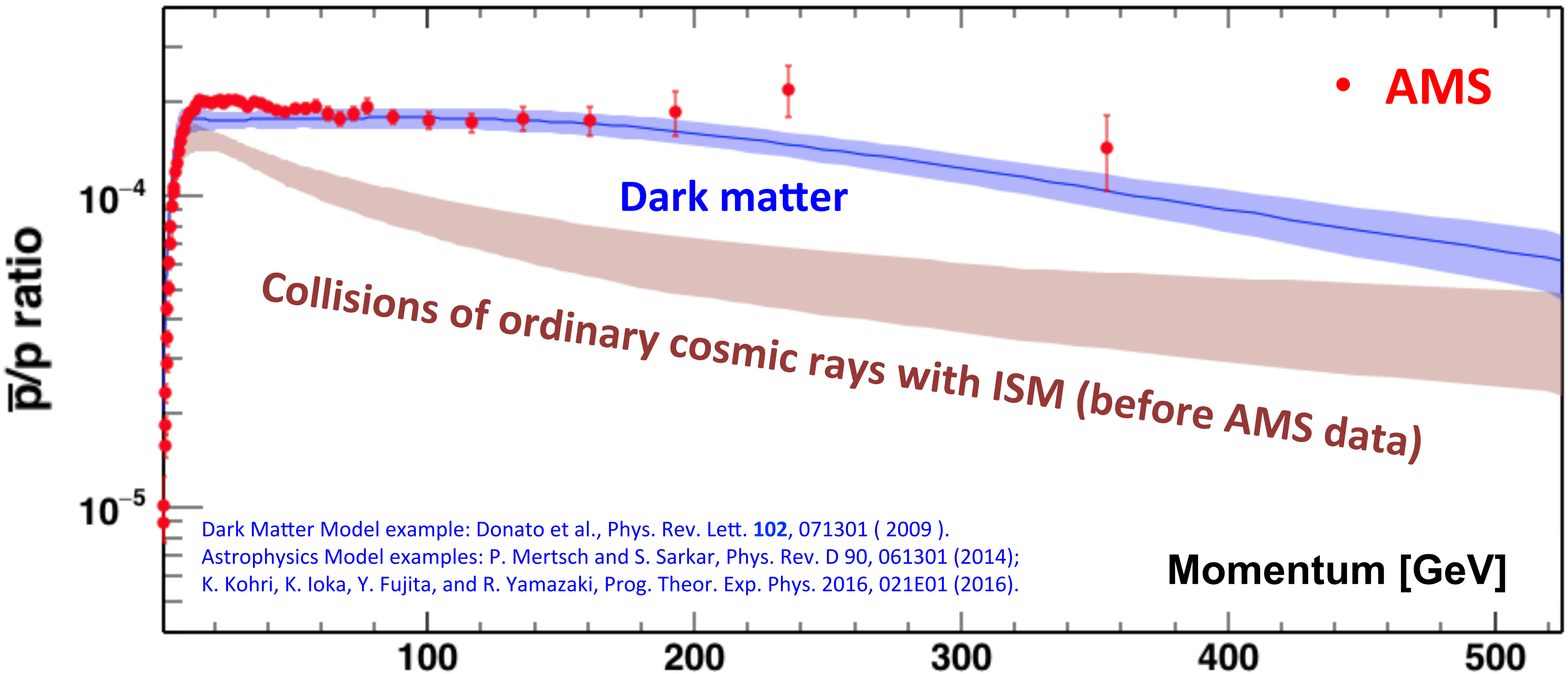
M. Aguilar *et al*., Phys. Rev. Lett. **113**, 221102 (2014)

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



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

Physics result: The AMS $\bar{p}/p$ measurement



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

***Presented by* Andreas Bachlechner**

Elementary Particles in Space

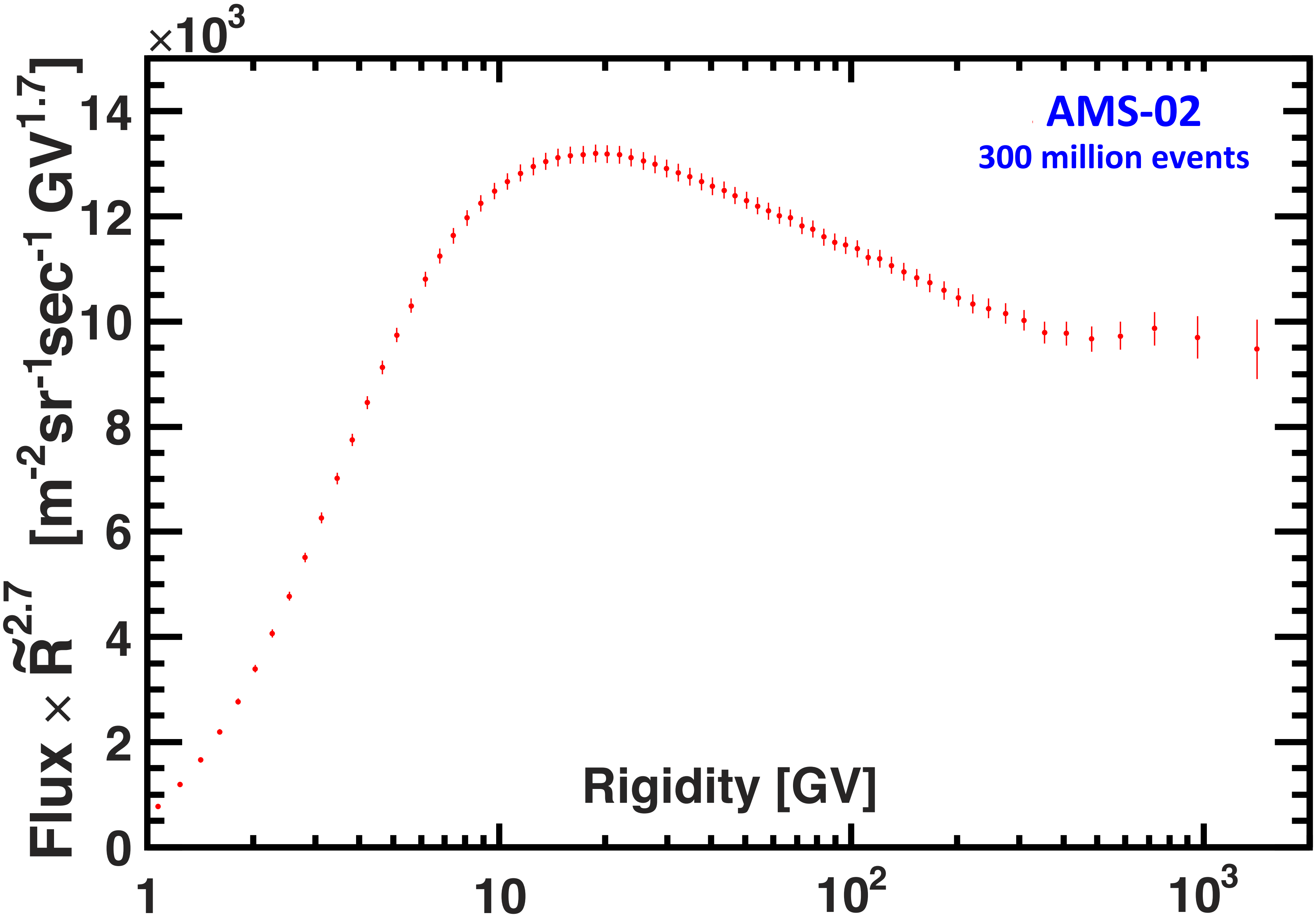
There are hundreds of different kinds (μ, π, K, Λ,…)
of charged elementary particles.

Only four of them,
electrons (e-), protons (p), positrons (e+), and antiprotons ($\bar{p}$),
have infinite lifetime,
so they travel in the cosmos forever.

Electrons and positrons have much smaller mass (0.5 MeV)
than protons and antiprotons (941 MeV)
so they lose much more energy in the galactic magnetic field.

⊙ AMS

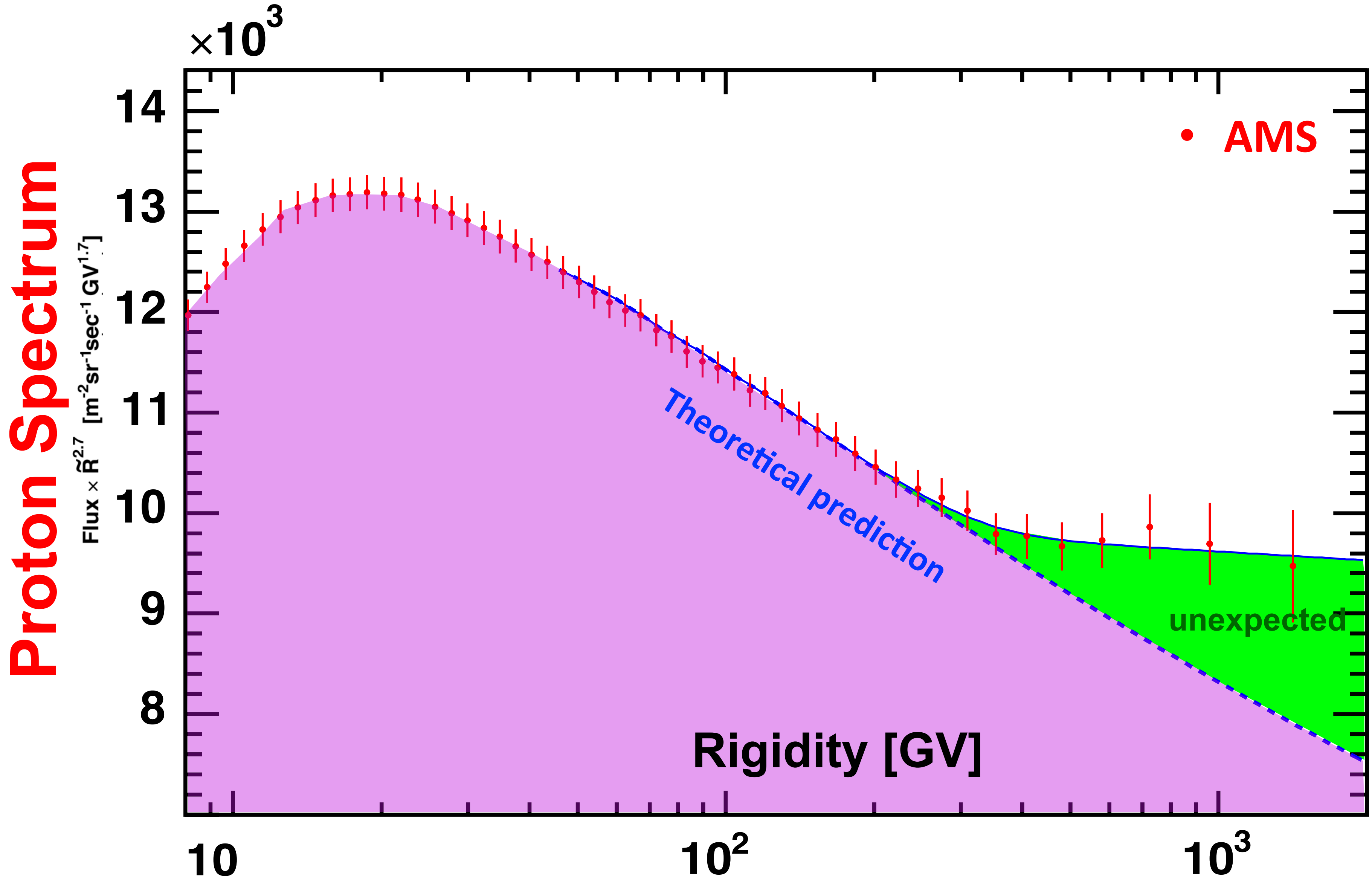
Physics Result: Measurement of the proton flux to an accuracy of 1%

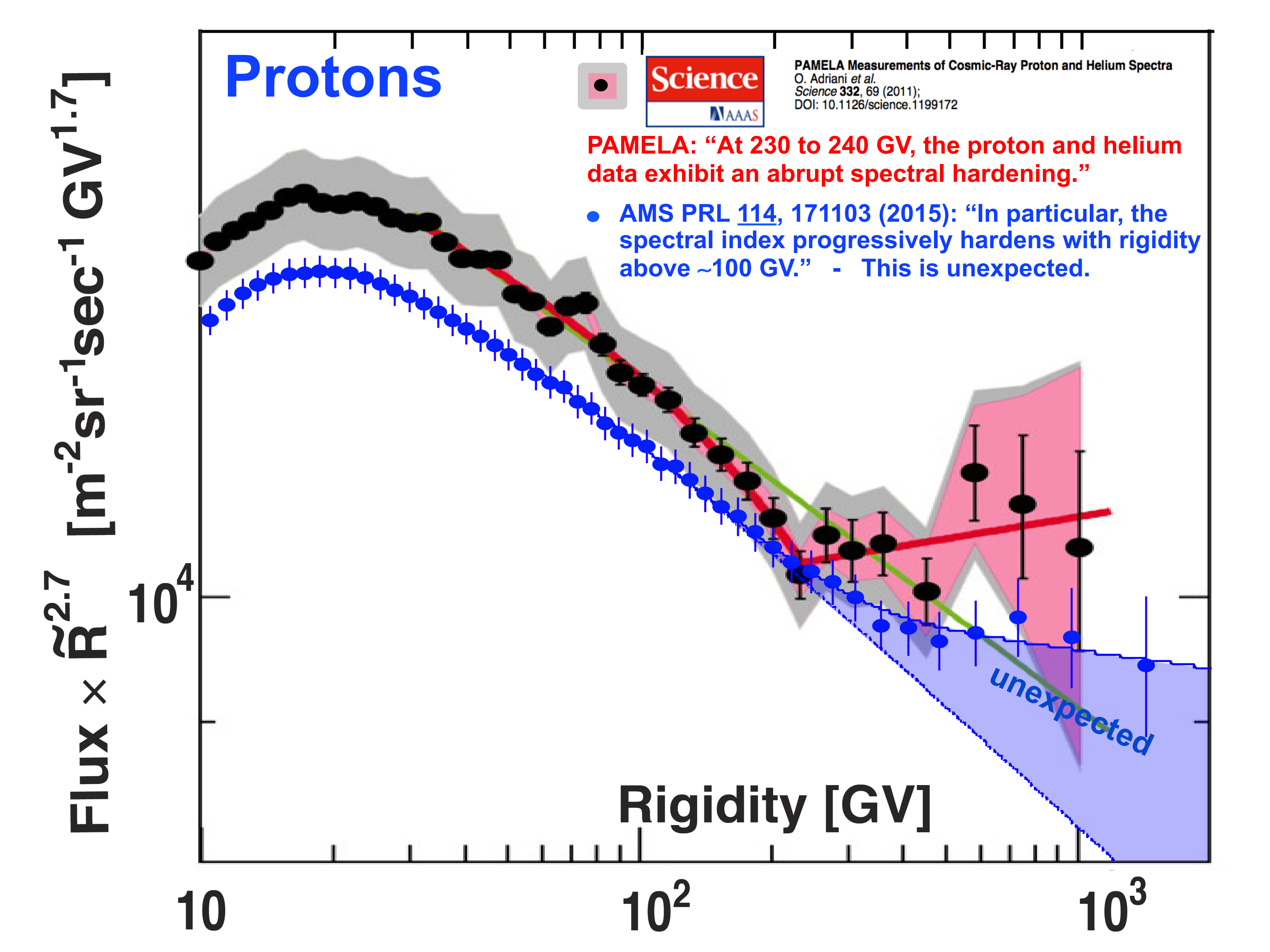


M. Aguilar *et al.*, Phys. Rev. Lett. **114**, 171103 (2015)

AMS proton flux

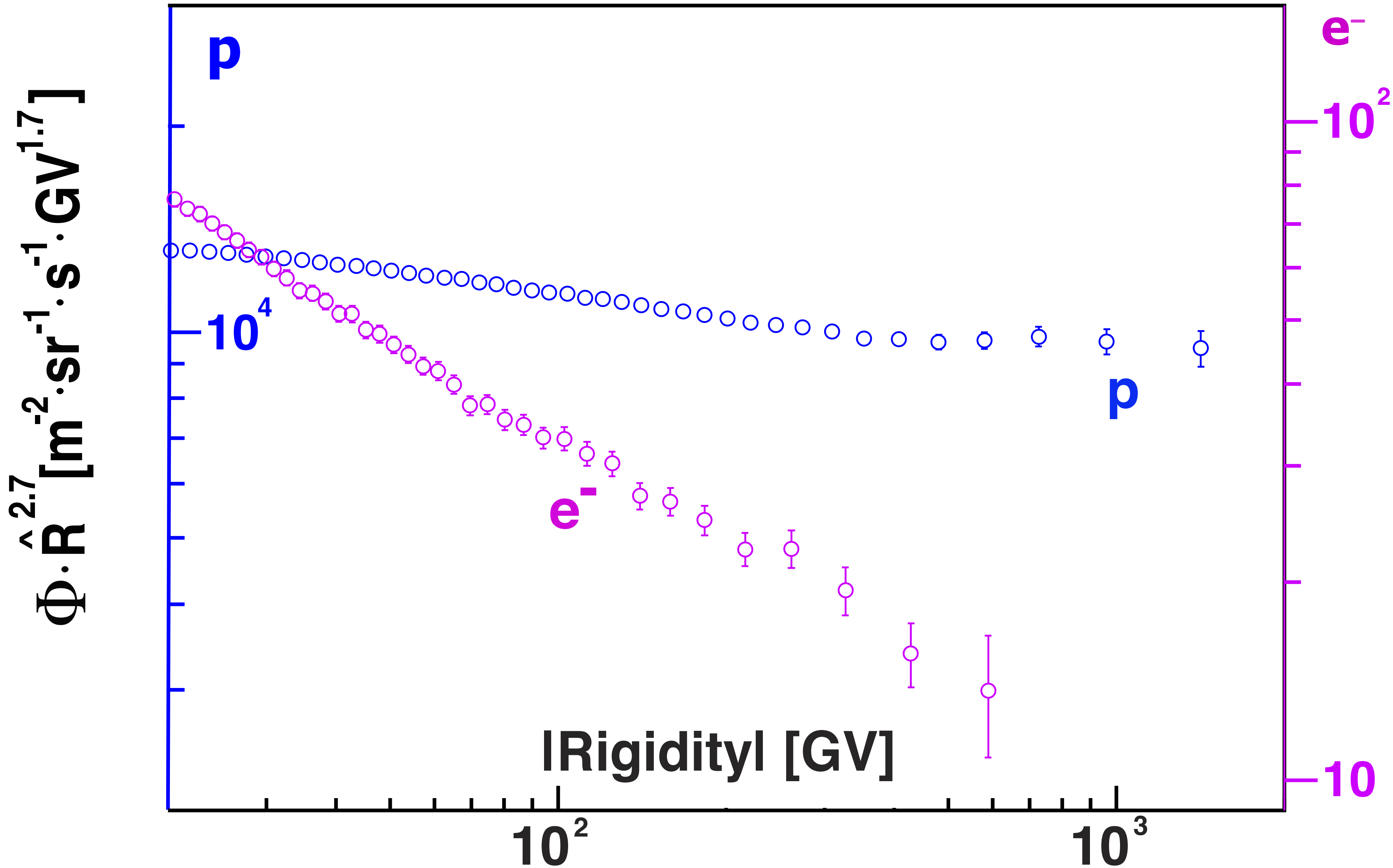
The Flux cannot be described by a single power law as has traditionally been assumed




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

The Spectra of Protons and Electrons:

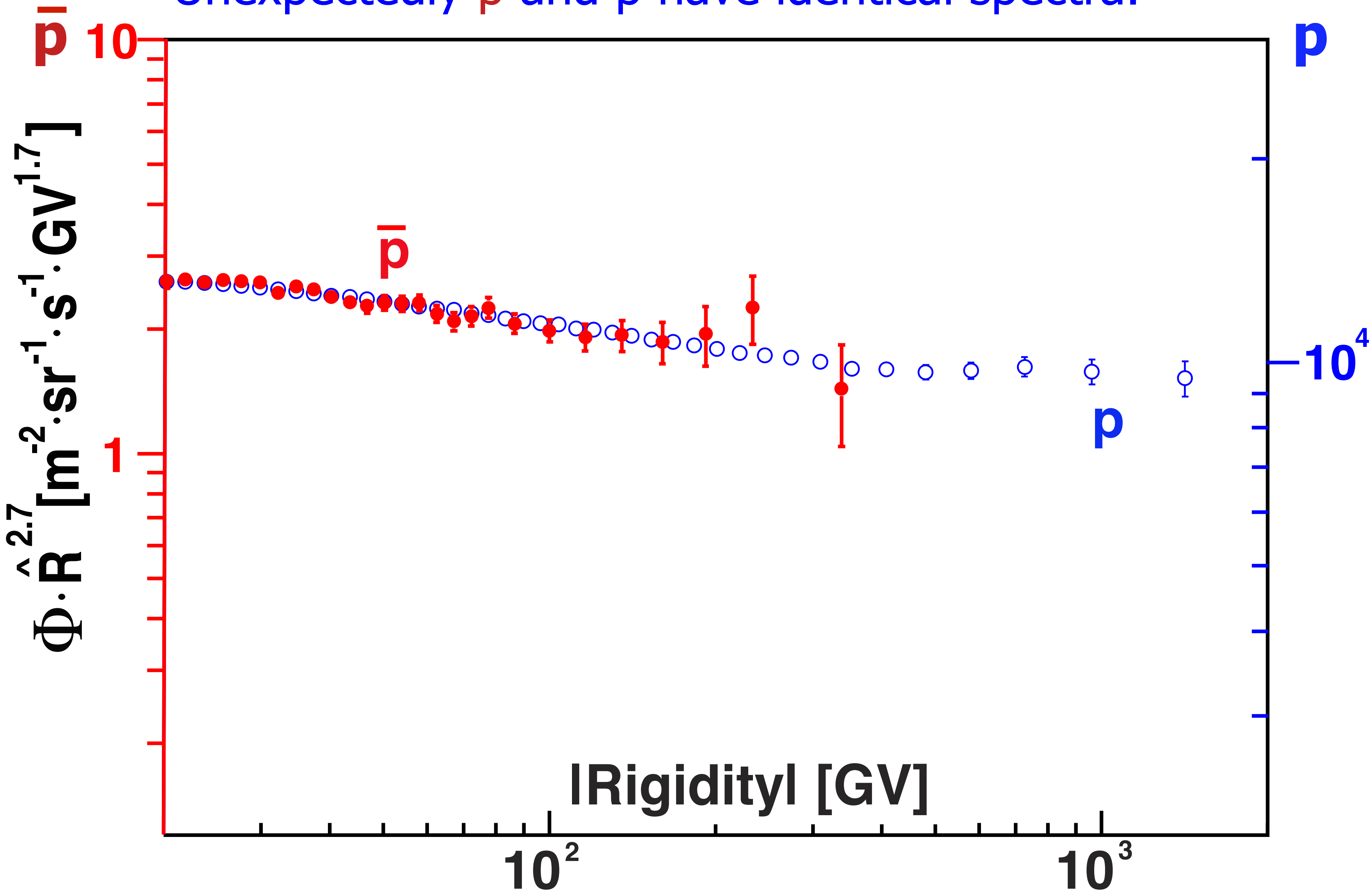
e⁻ and p are different, as expected



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

The Spectra of Protons and Antiprotons:

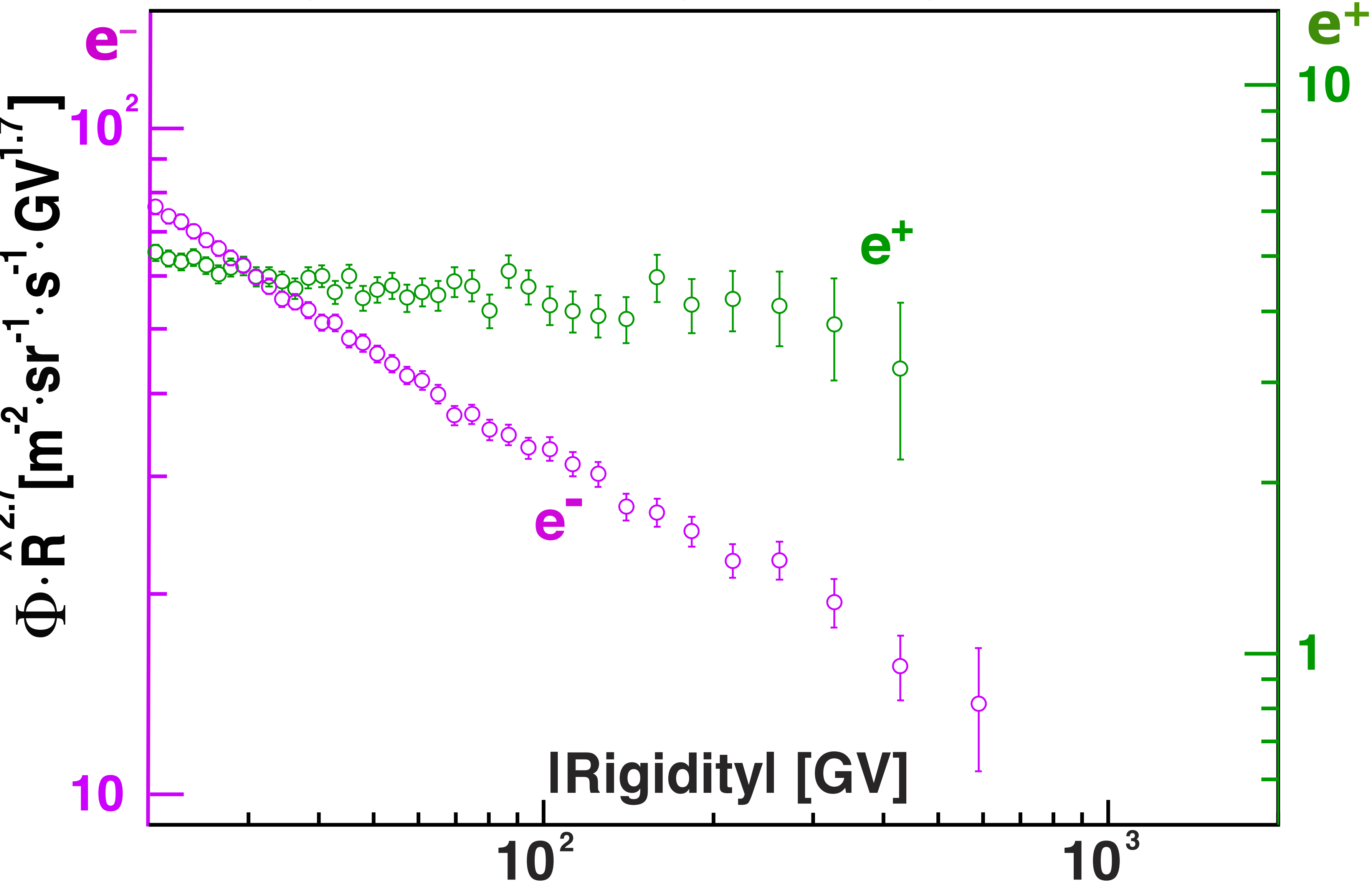
If $\bar{p}$ are secondaries, their spectrum should be different than p.
Unexpectedly $\bar{p}$ and p have identical spectra.



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

The Spectra of Electrons and Positrons:

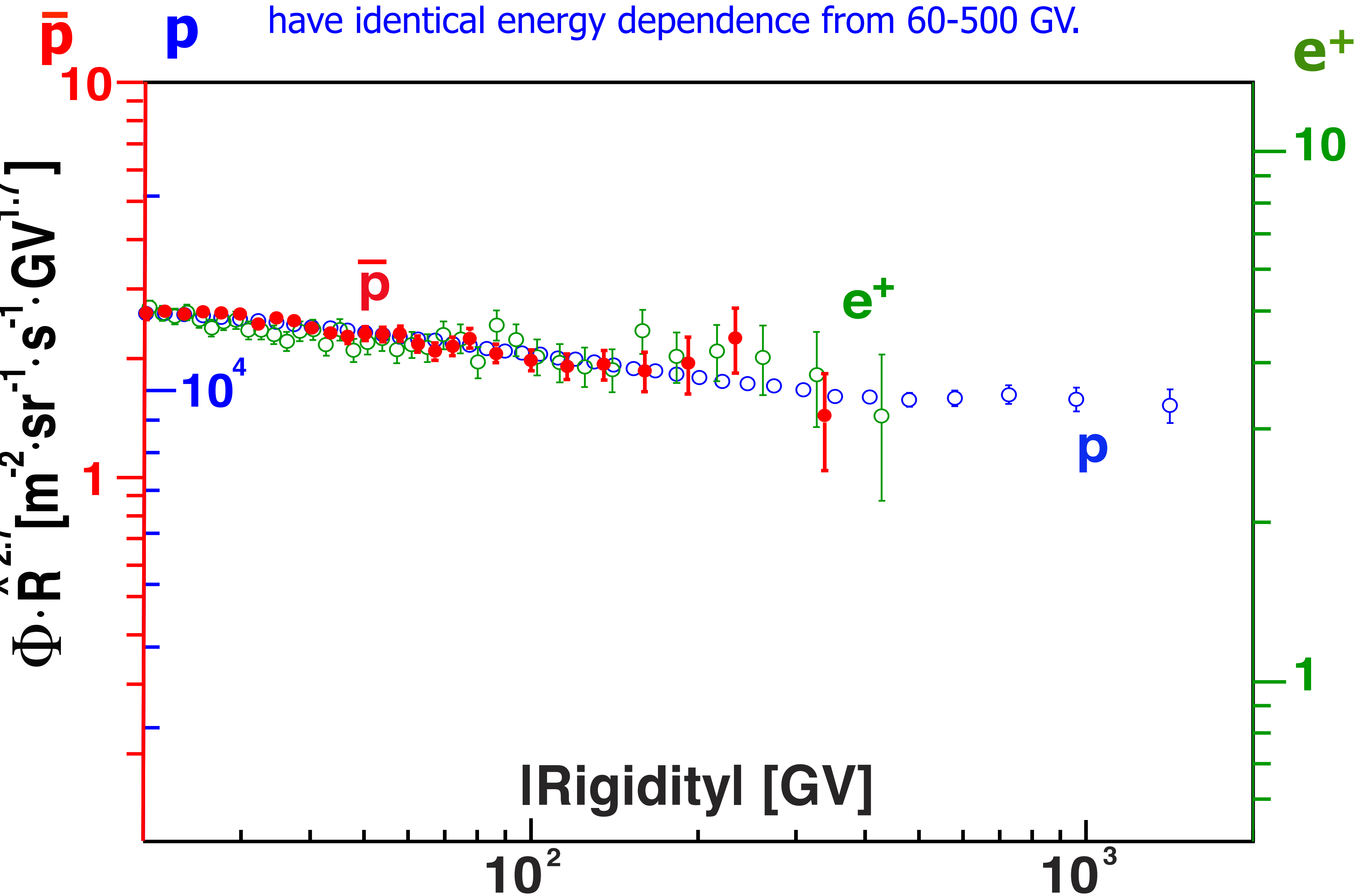
e^- and e^+ have very different spectra, despite the fact that they lose energy equally in the galactic magnetic field.



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

The Spectra of Protons, Antiprotons and Positrons:

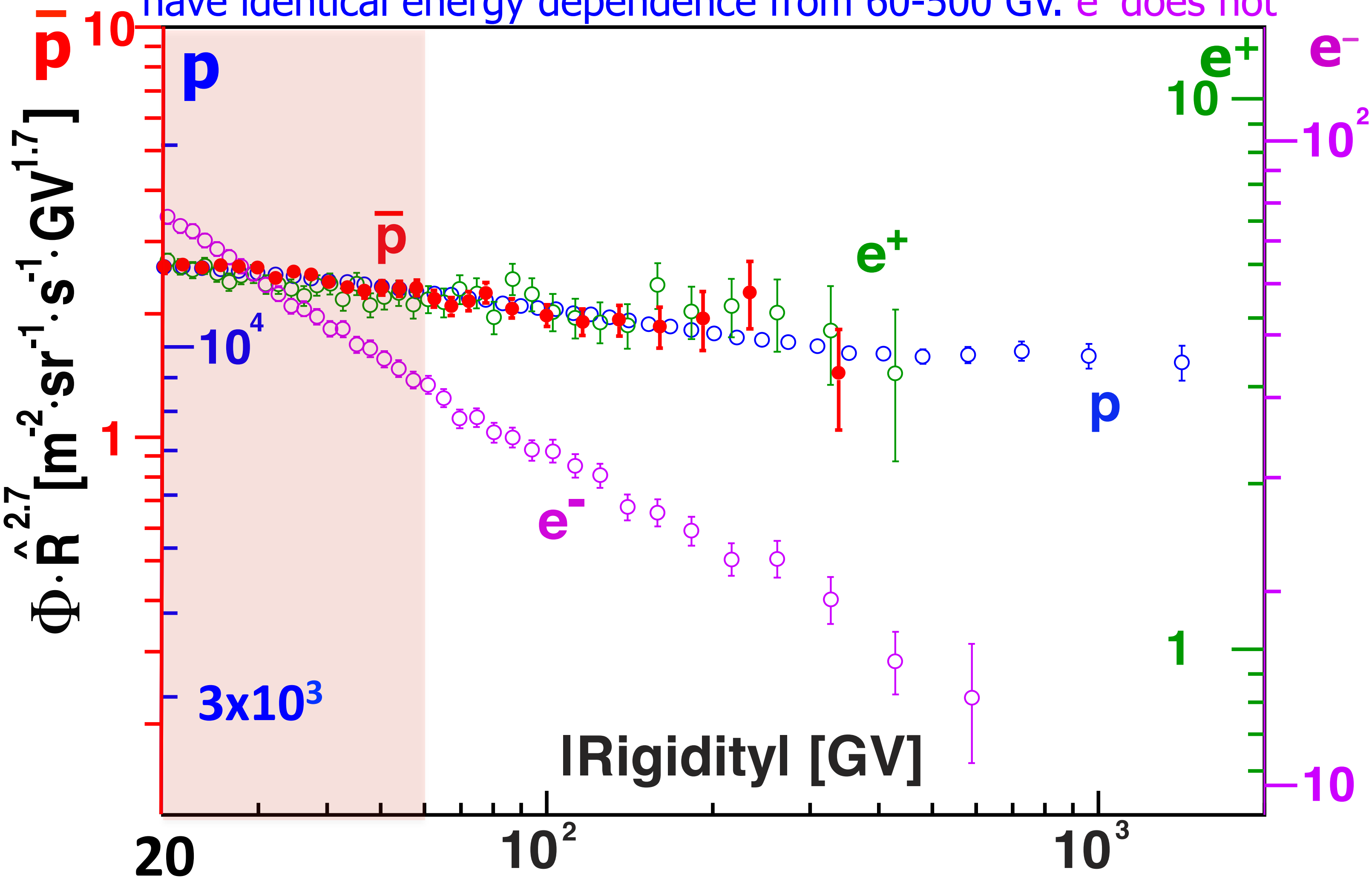
Unexpectedly, the Spectra of Elementary Particles e^+, $\bar{p}$, p have identical energy dependence from 60-500 GV.



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

Physics Result: 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



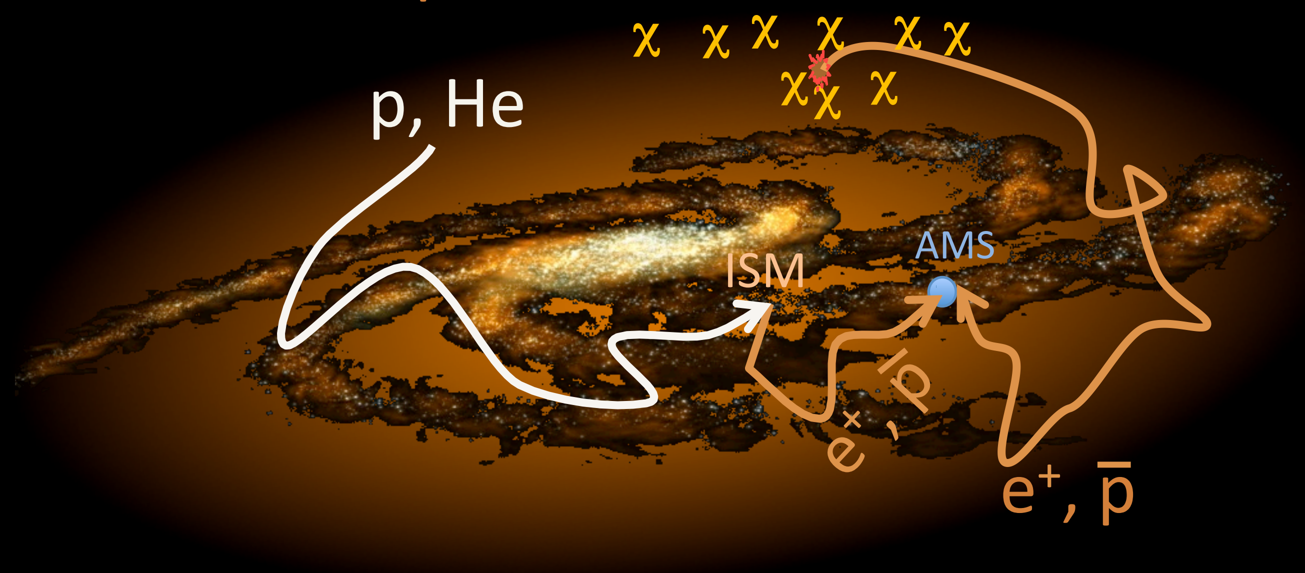
M. Aguilar *et al*., Phys. Rev. Lett. **117,** 091103 (2016)

Presented by **Yuan-Hann Chang**

Dark Matter: χ

p, He + ISM $\rightarrow e^{+}, \bar{p} + \ldots$

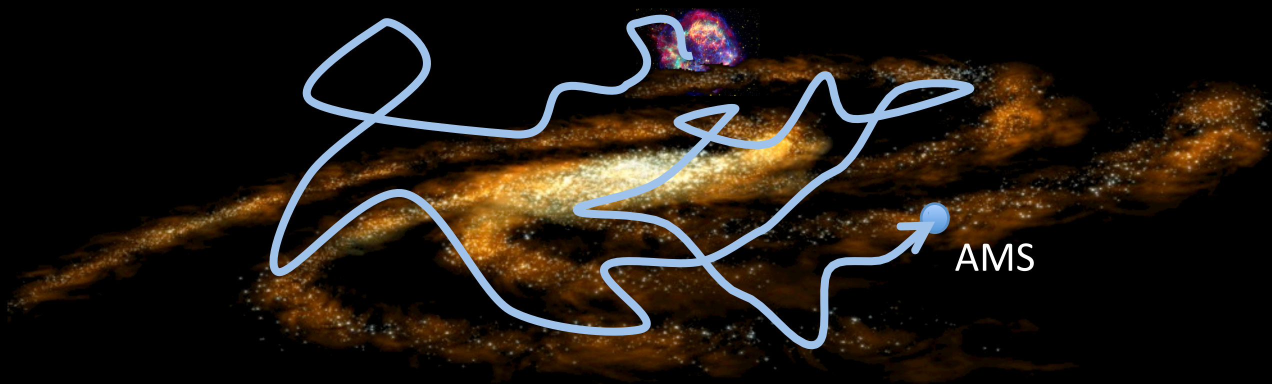
$\chi + \chi \rightarrow e^{+}, \bar{p} + \ldots$



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)

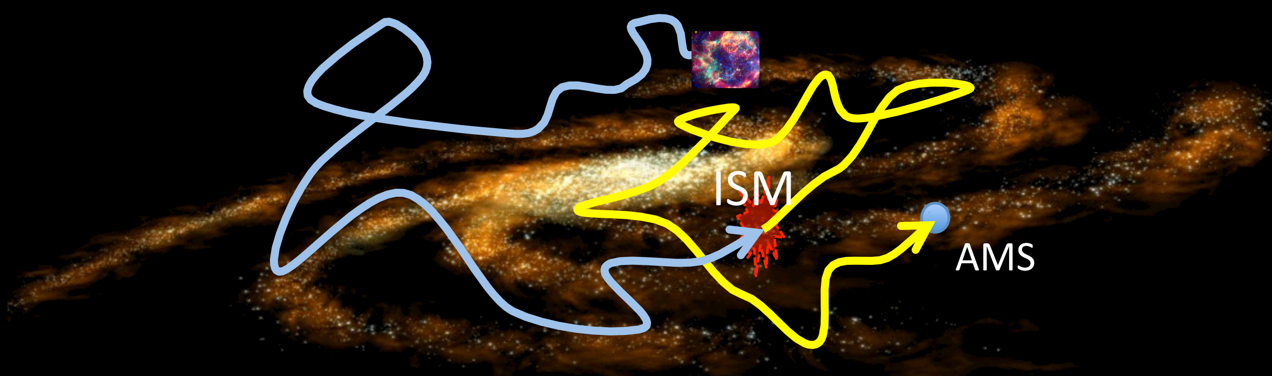
Primary Cosmic Rays (p, He, C, O, …)



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

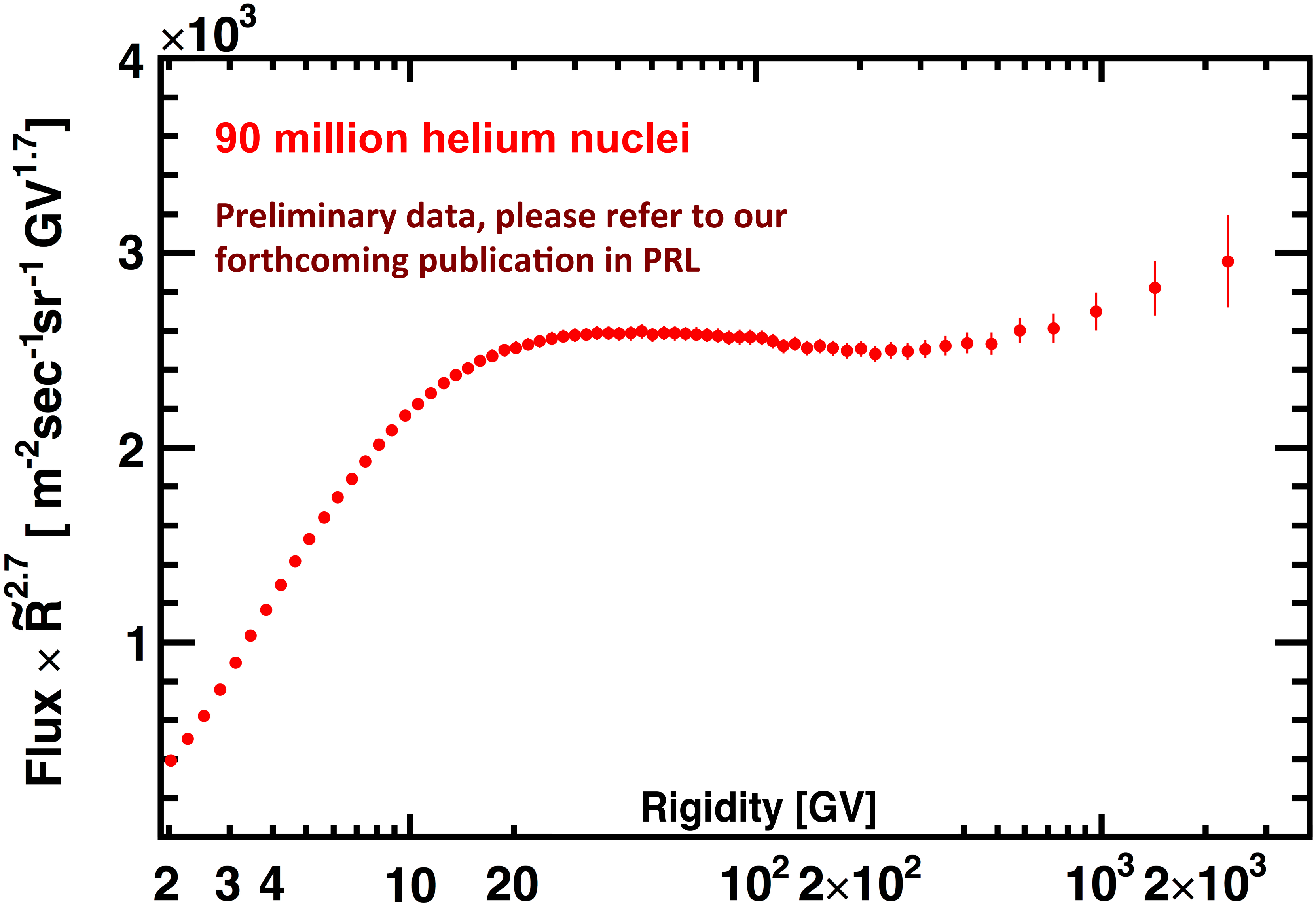
Secondary Cosmic Rays (Li, Be, B, …)

C, O, …, Fe + ISM → Li, Be, B + X



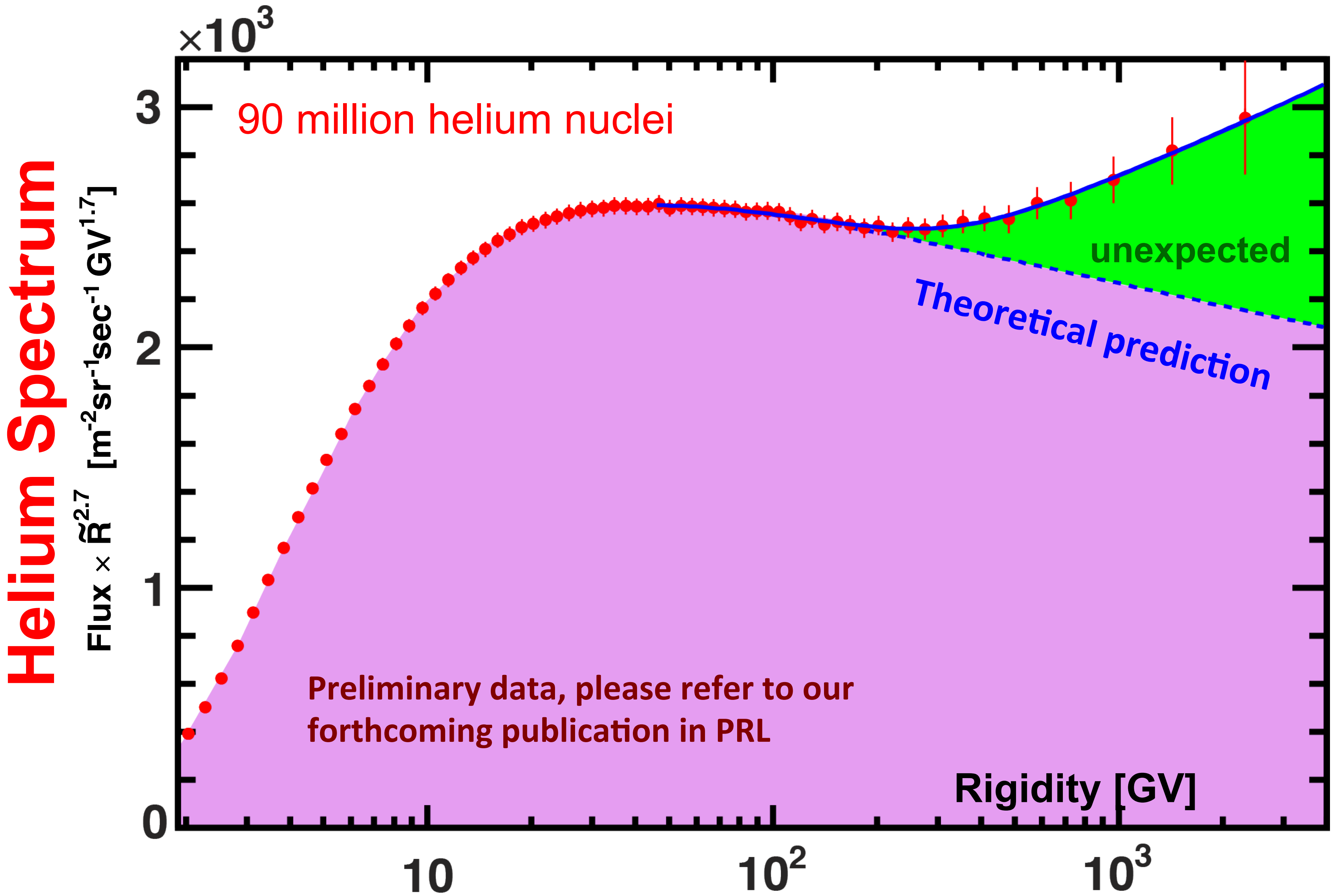
Secondary cosmic rays carry information about propagation of primaries, secondaries and the ISM.

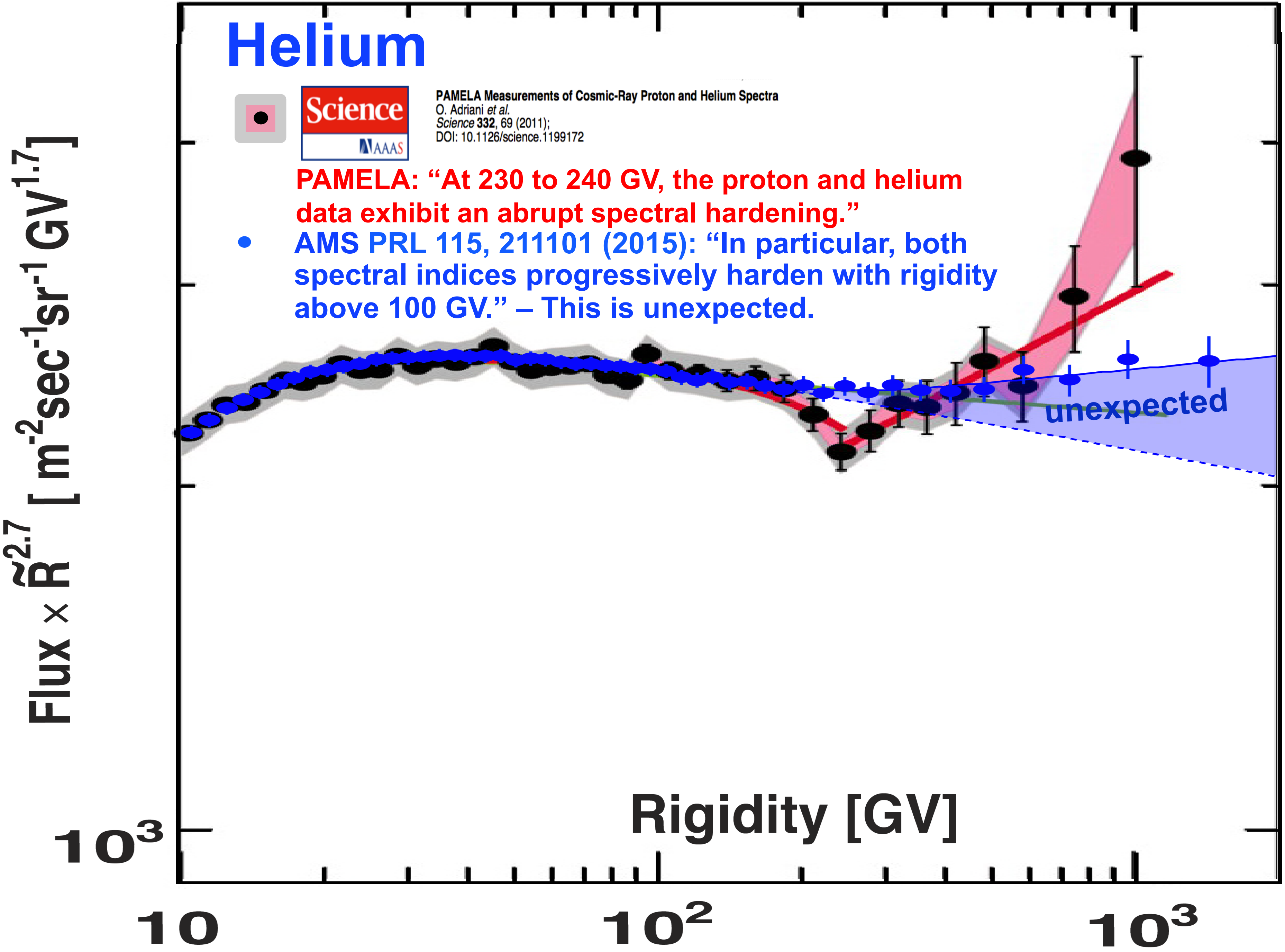
New Physics Result: 5 year measurement of the Helium flux



AMS helium flux

The Flux cannot be described by a single power law as has traditionally been assumed





Helium
Science
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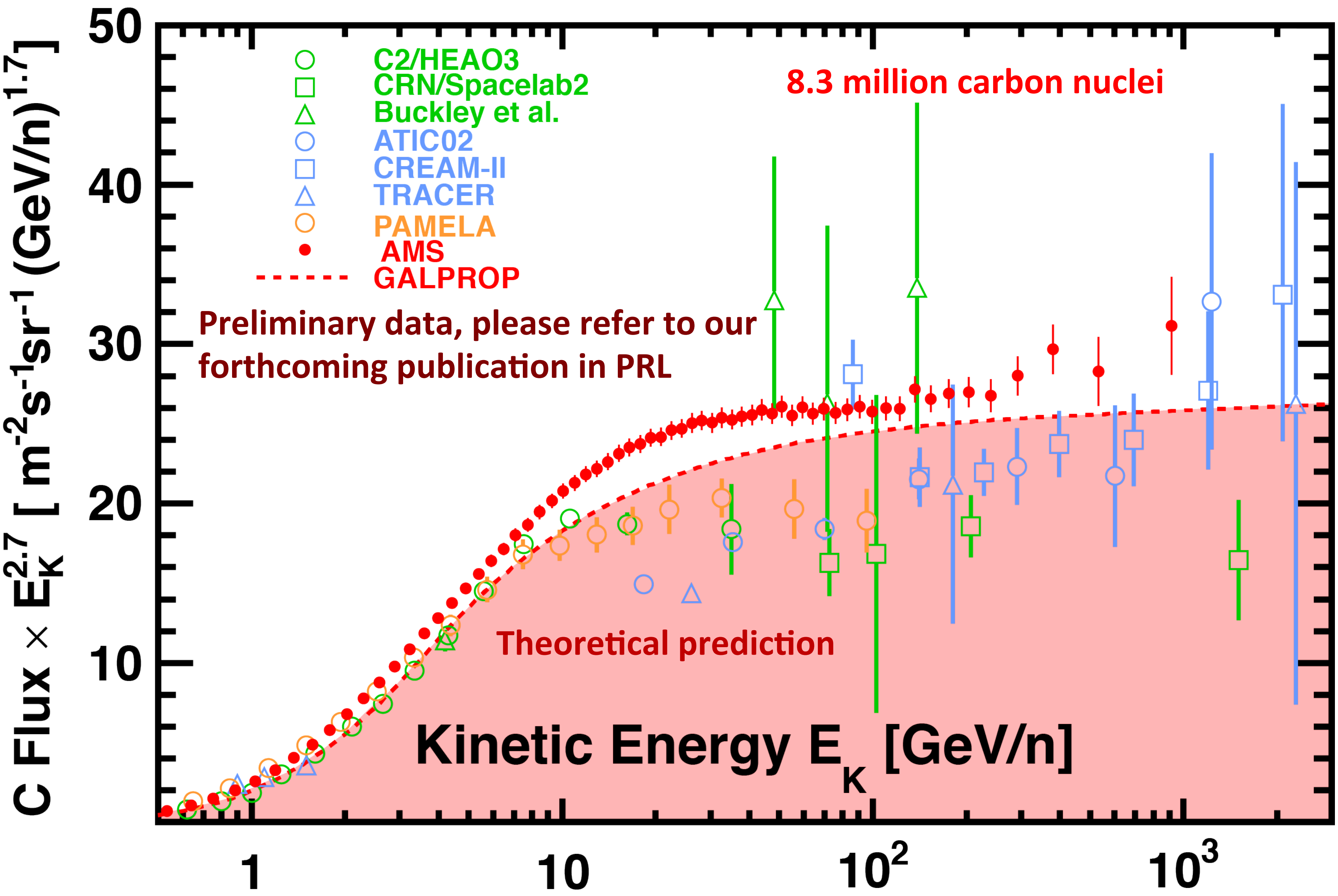
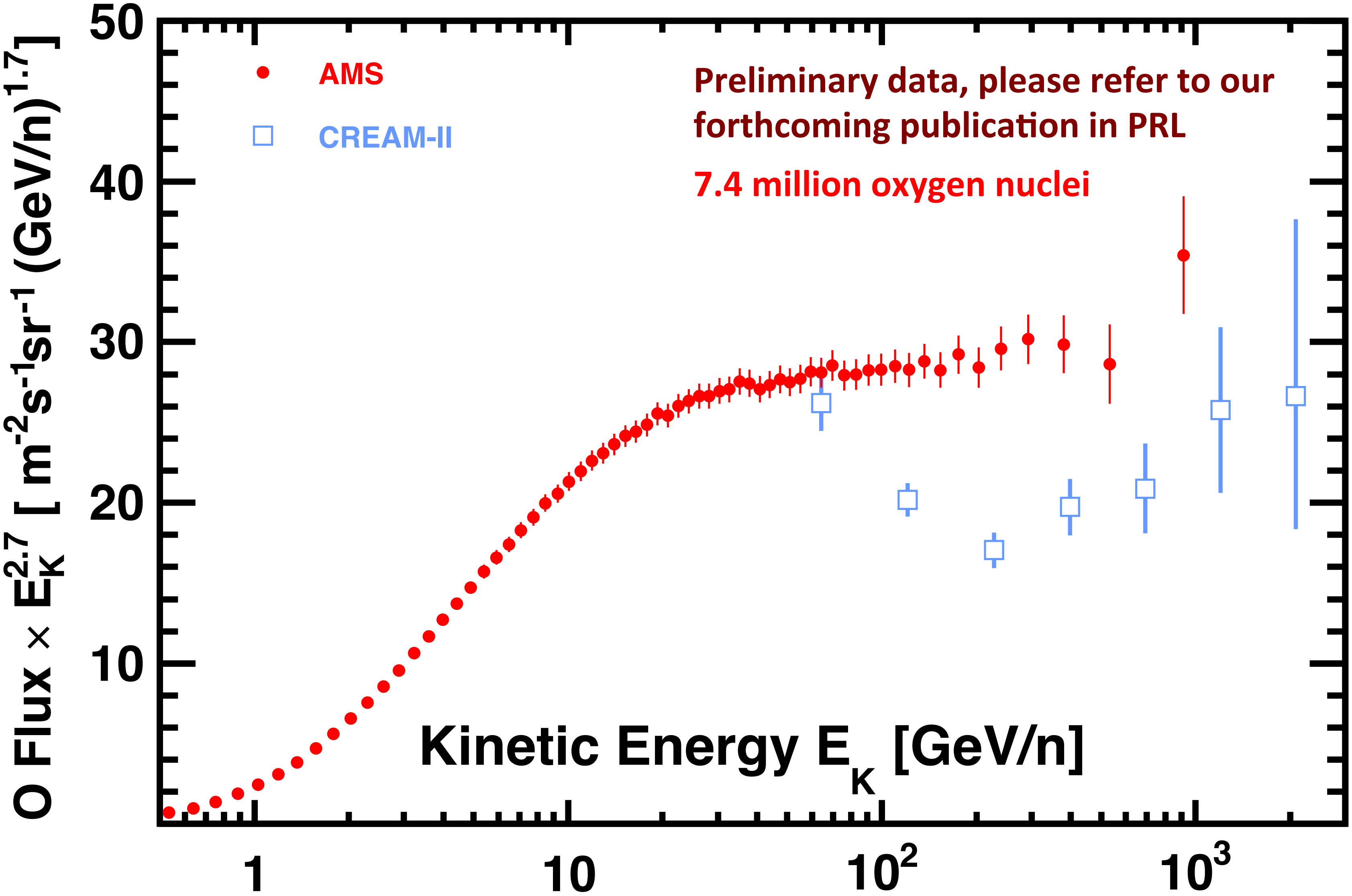
unexpected
Flux × R̃^2.7 [m^-2 sec^-1 sr^-1 GV^1.7]
10^3
Rigidity [GV]
10
10^2
10^3

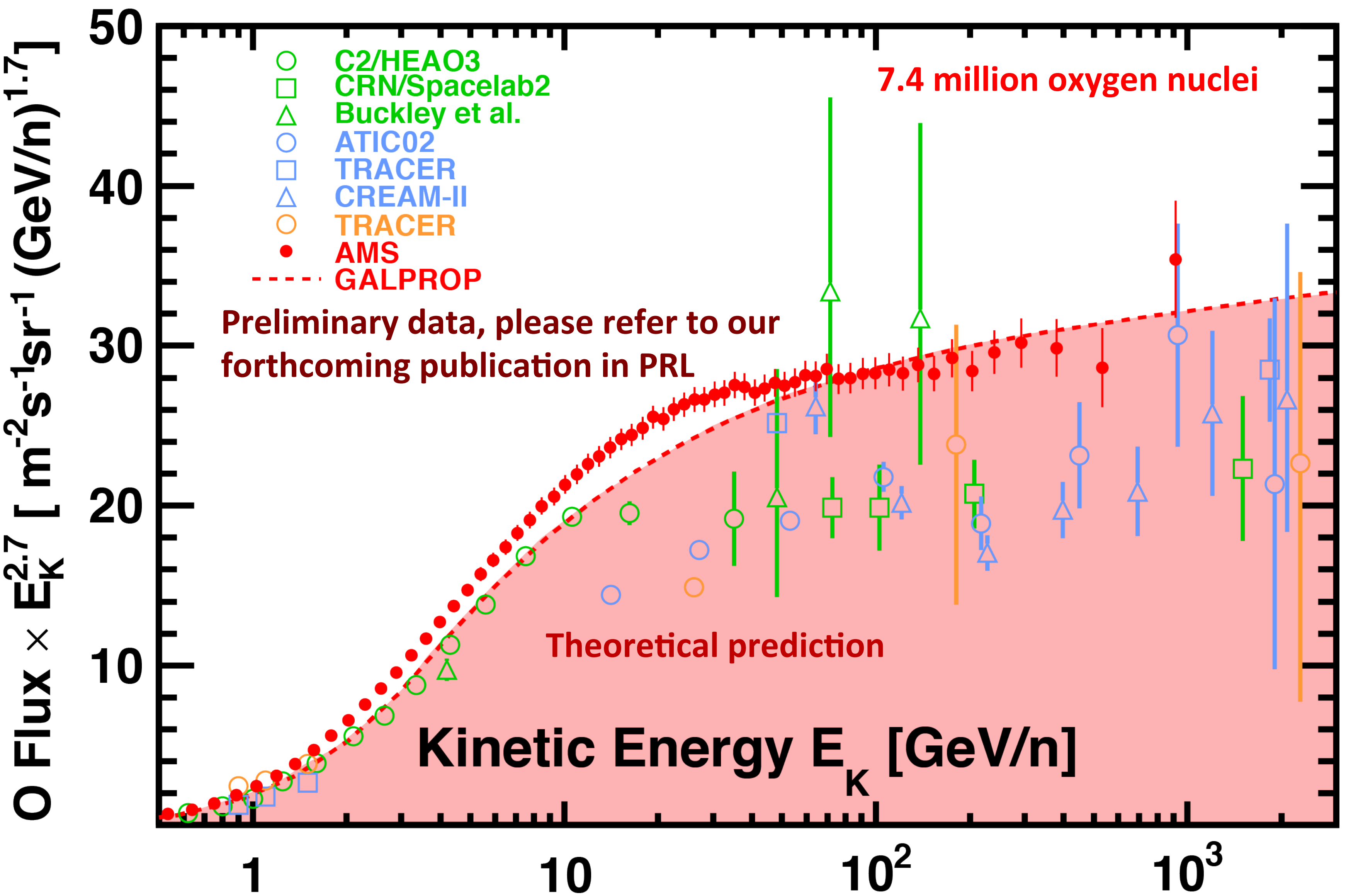
New Physics Result:
5 year measurement of the Carbon flux



New Physics Result:
5 year measurement of the Oxygen flux

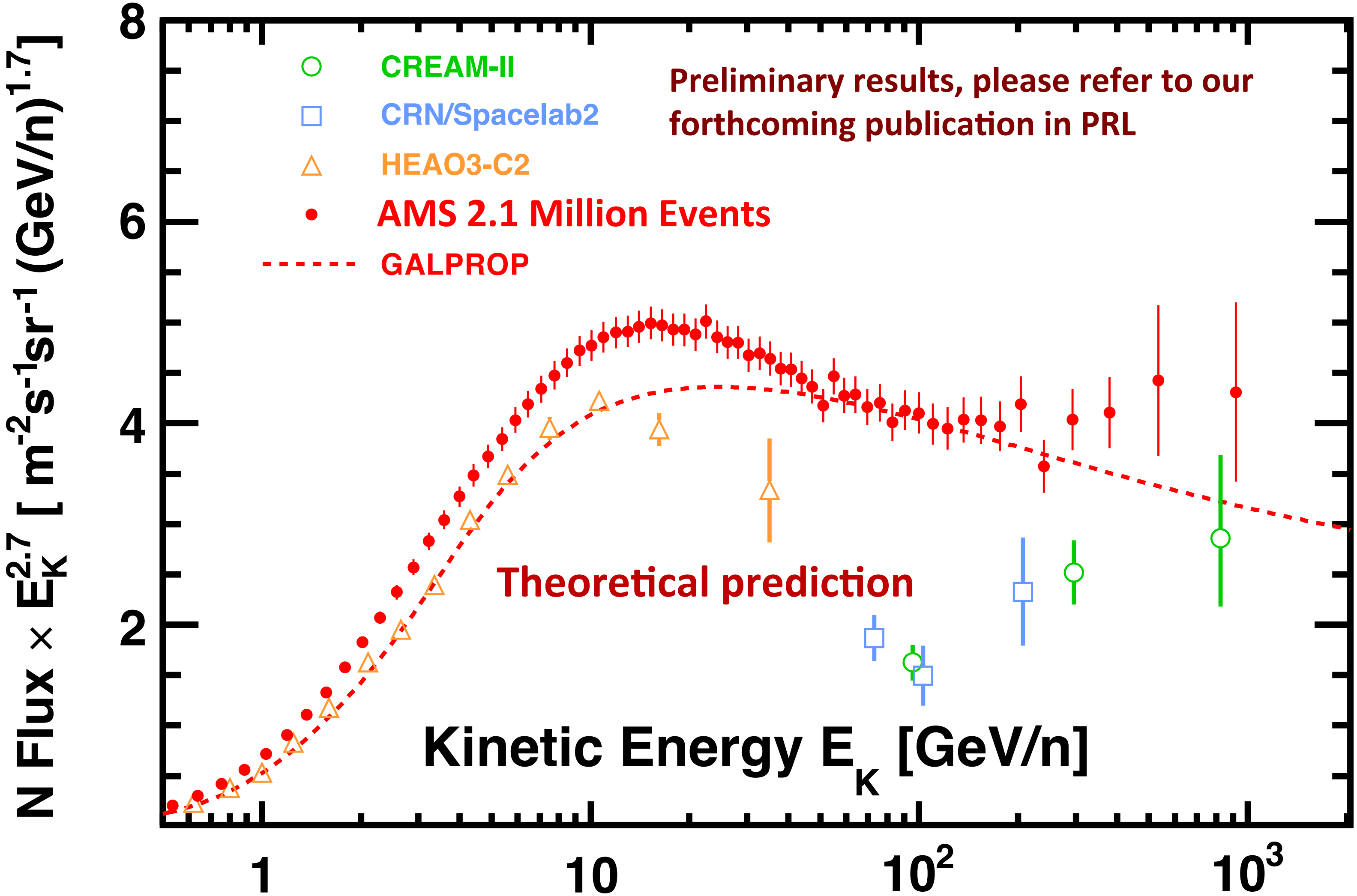


New Physics Result:
5 year measurement of the Oxygen flux



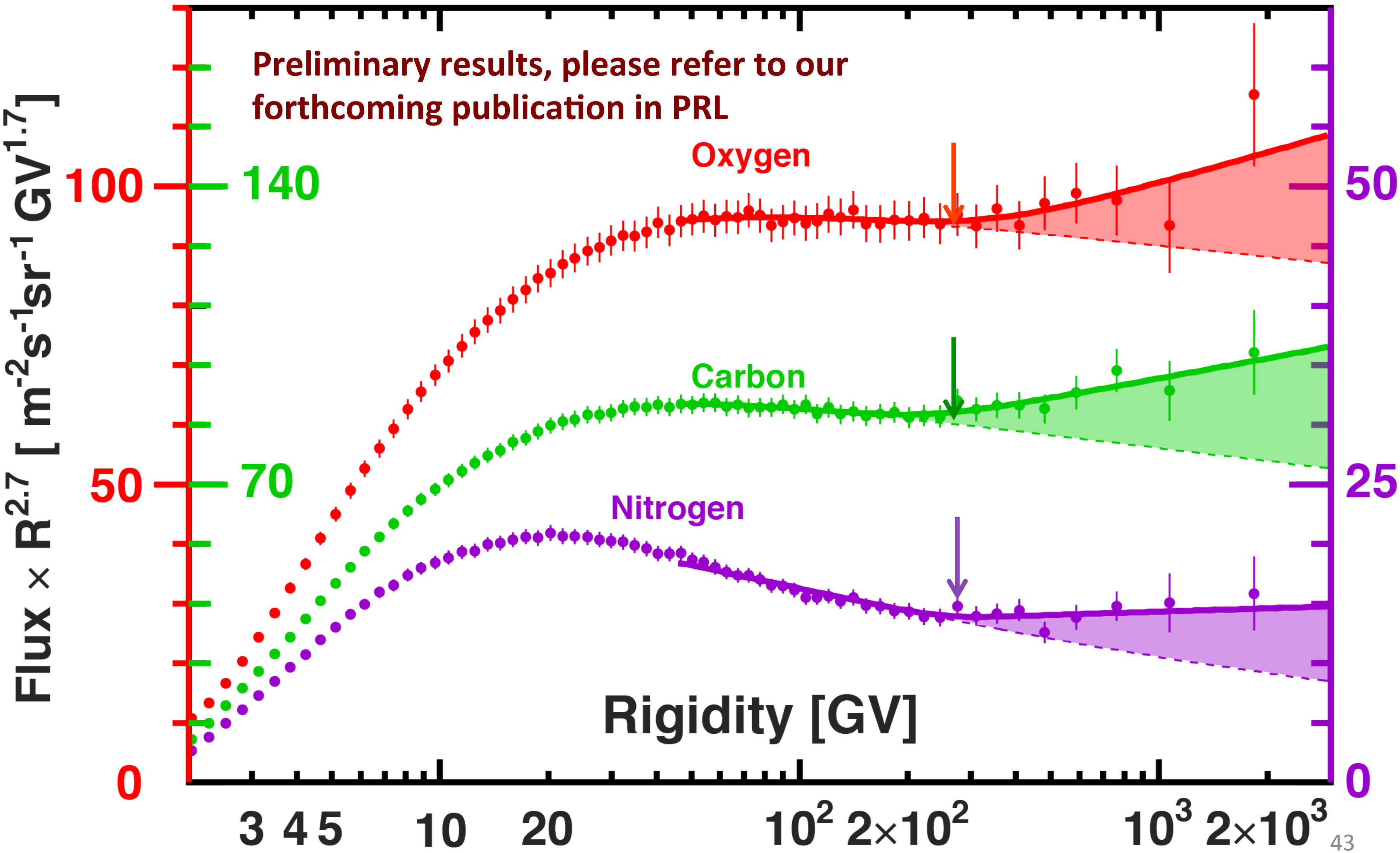
New Physics Result:
5 year measurement of the Nitrogen flux

Partially Primary and partially Secondary

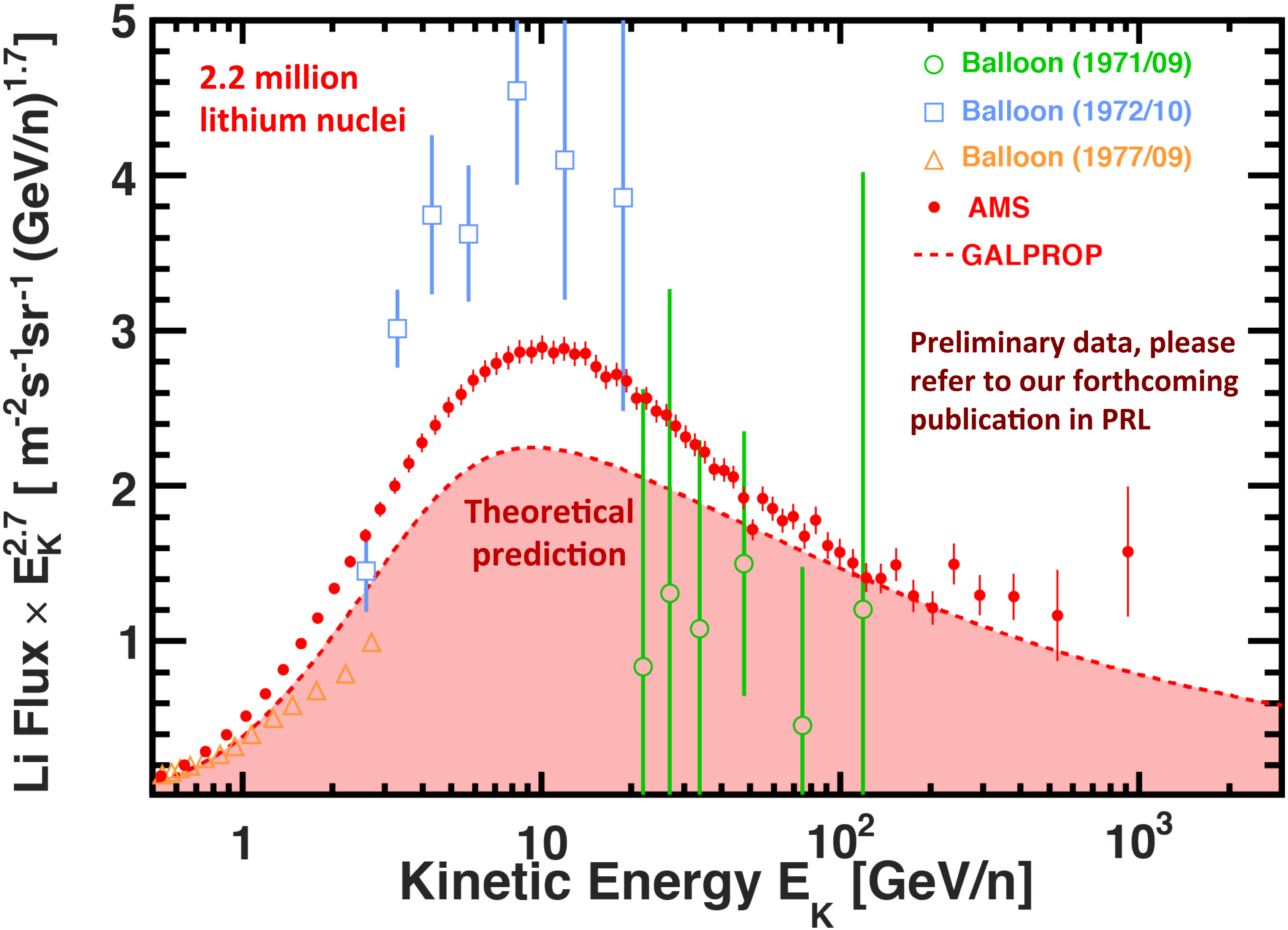


New Physics Result: Carbon, Nitrogen, Oxygen

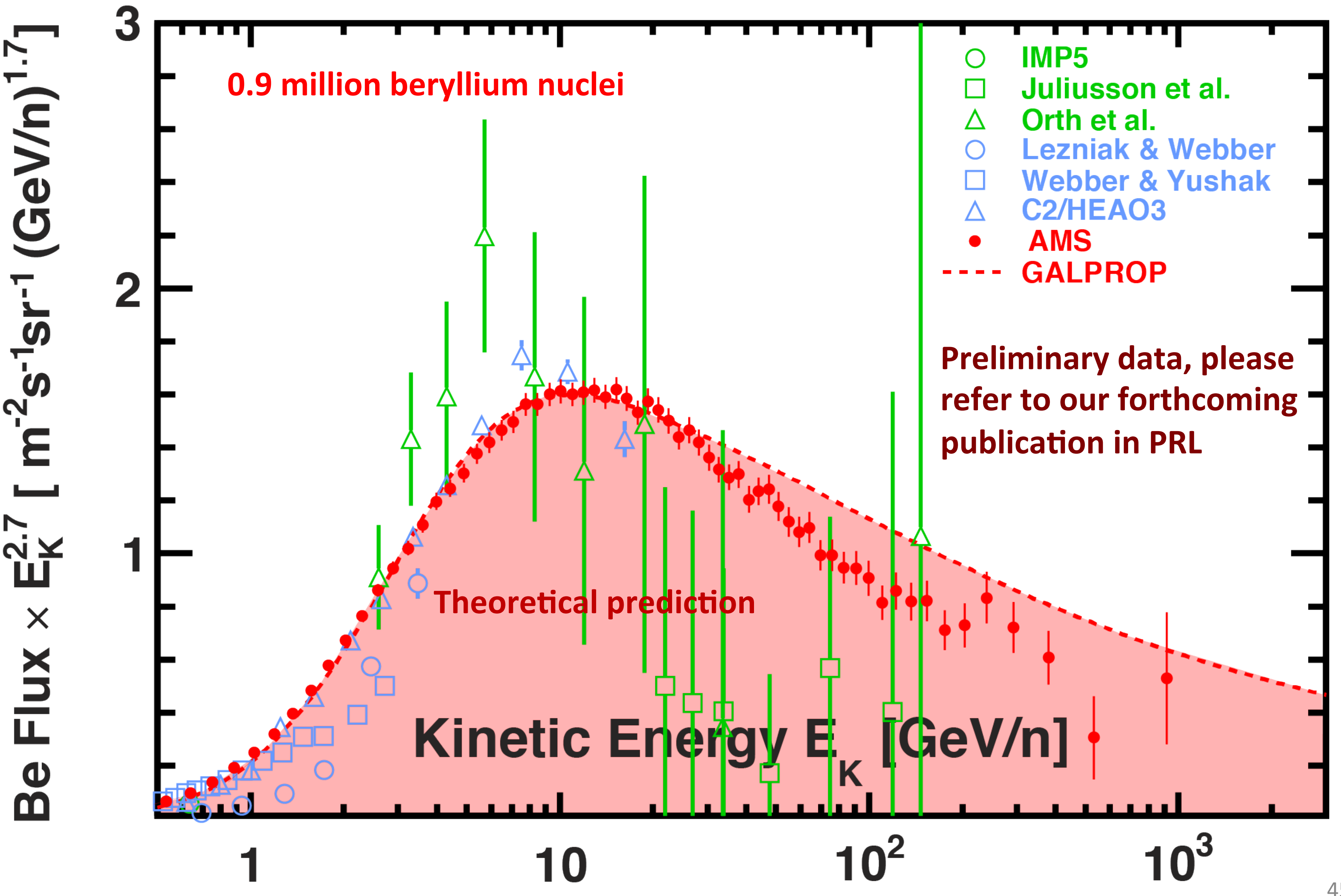
The spectra of carbon, nitrogen and oxygen do not follow the traditional single power law.



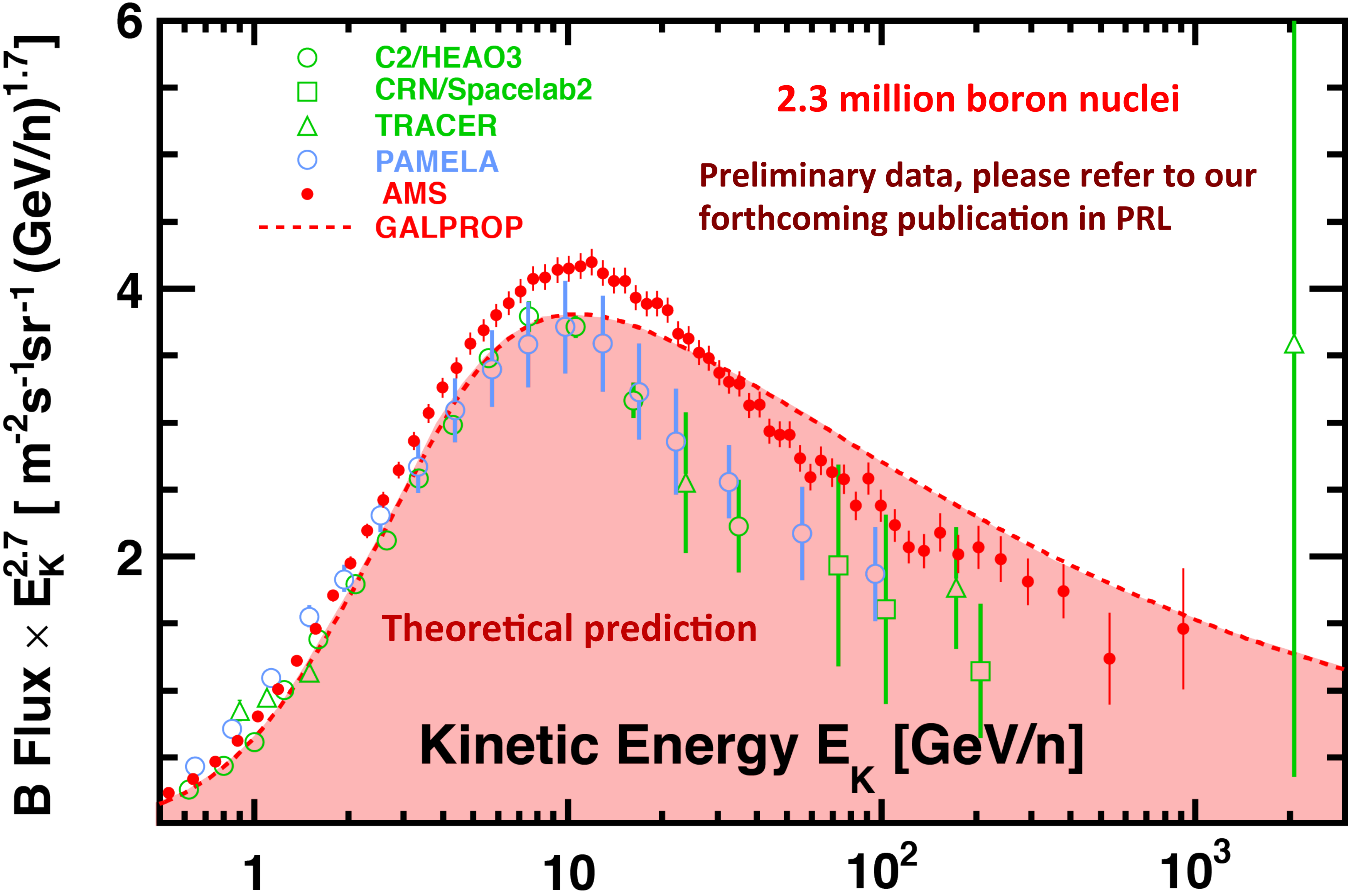
New Physics Result:
5 year measurement of the Lithium flux



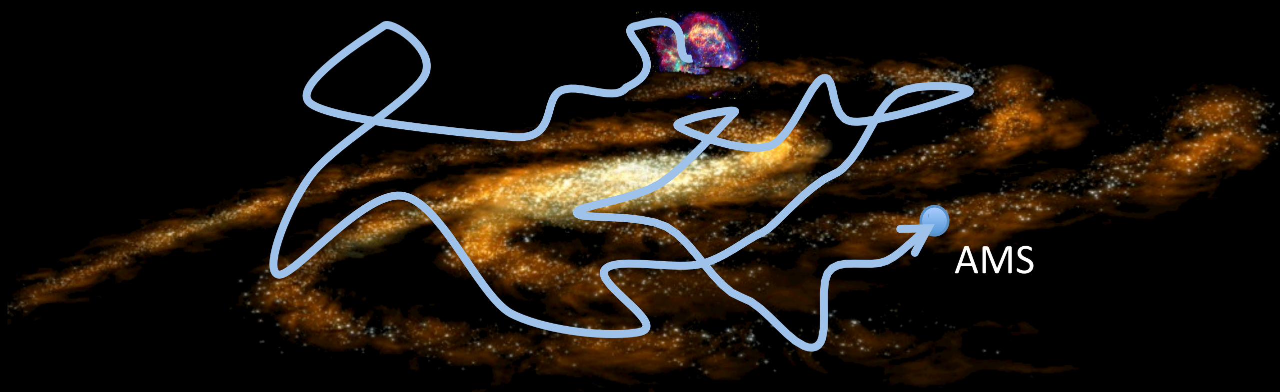
New Physics Result:
5 year measurement of the Beryllium flux



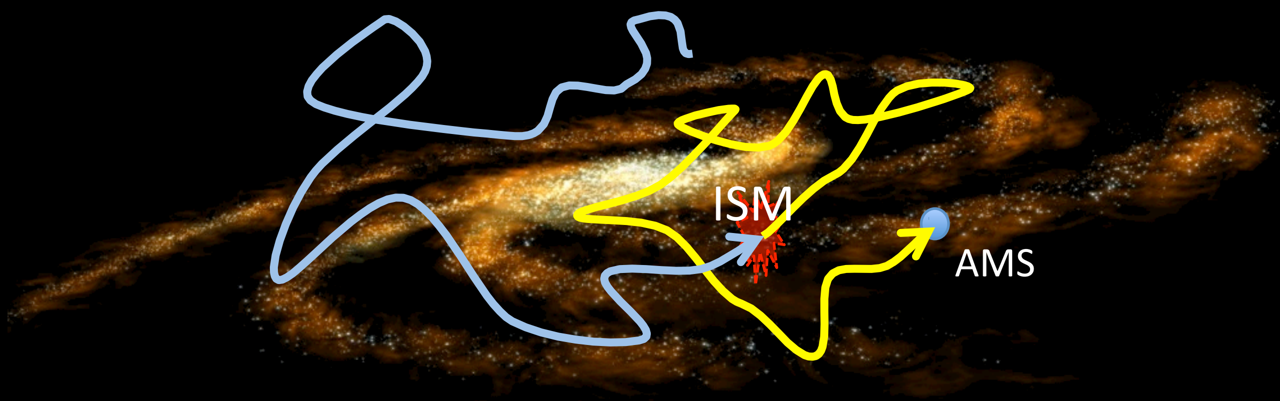
New Physics Result:
5 year measurement of the Boron flux



Primary Cosmic Rays (p, He, C, O, …)

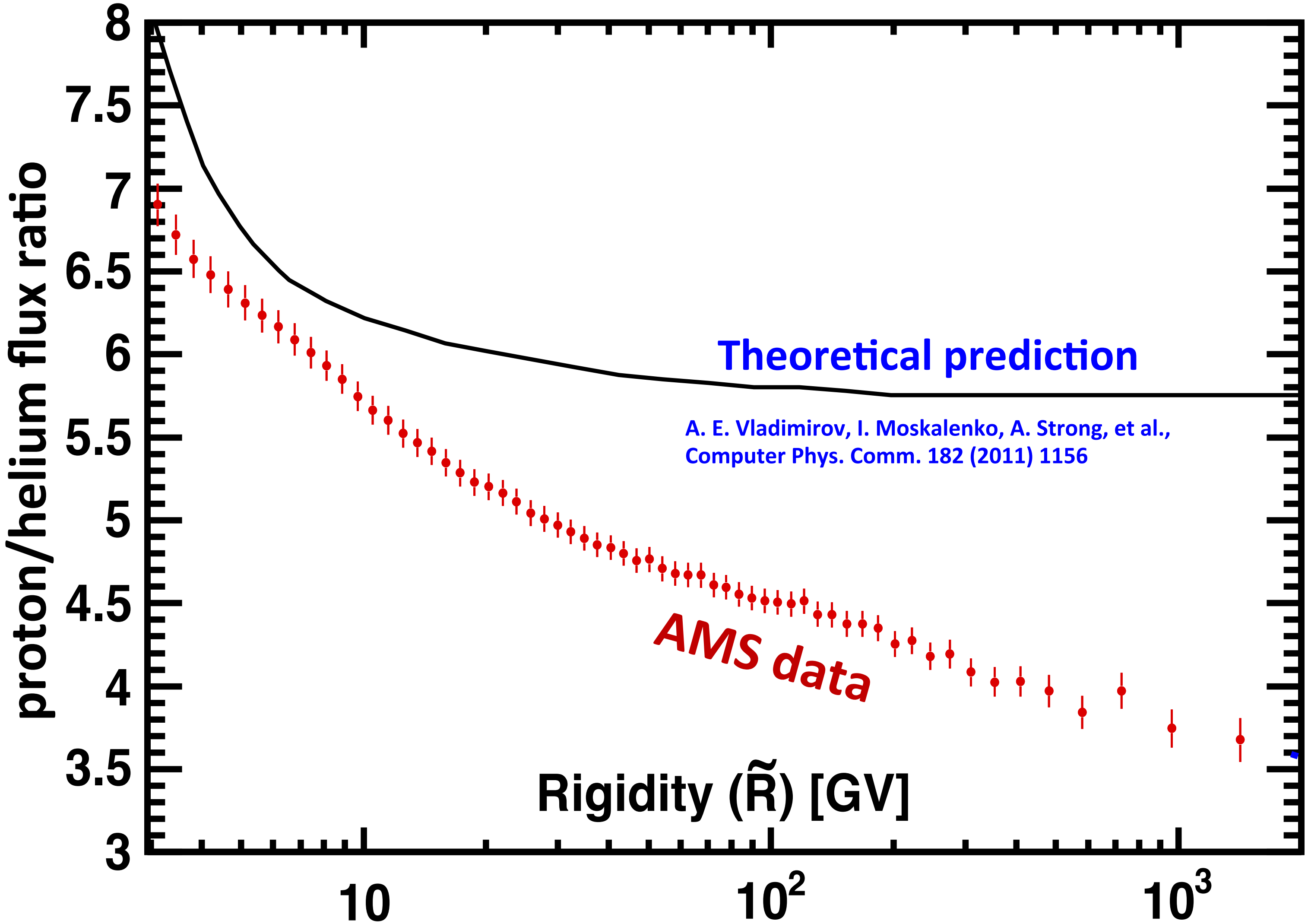


Secondary Cosmic Rays (Li, Be, B, …)

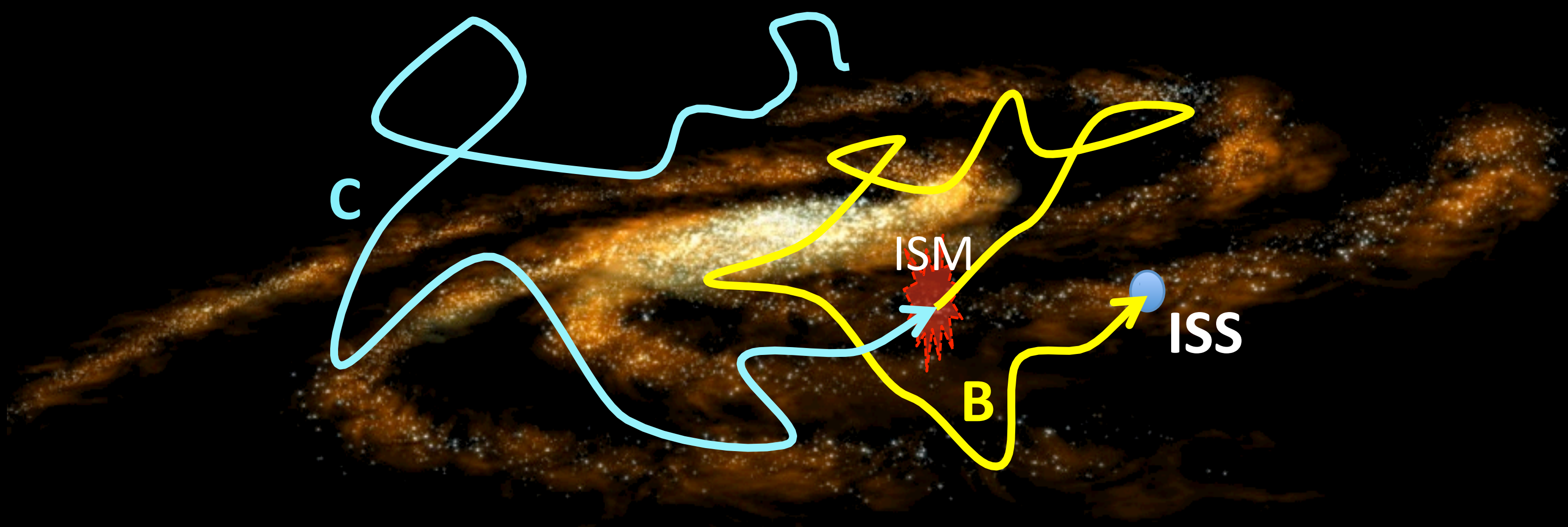


Physics Result: The AMS proton/helium flux ratio

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 rigidity independent.



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

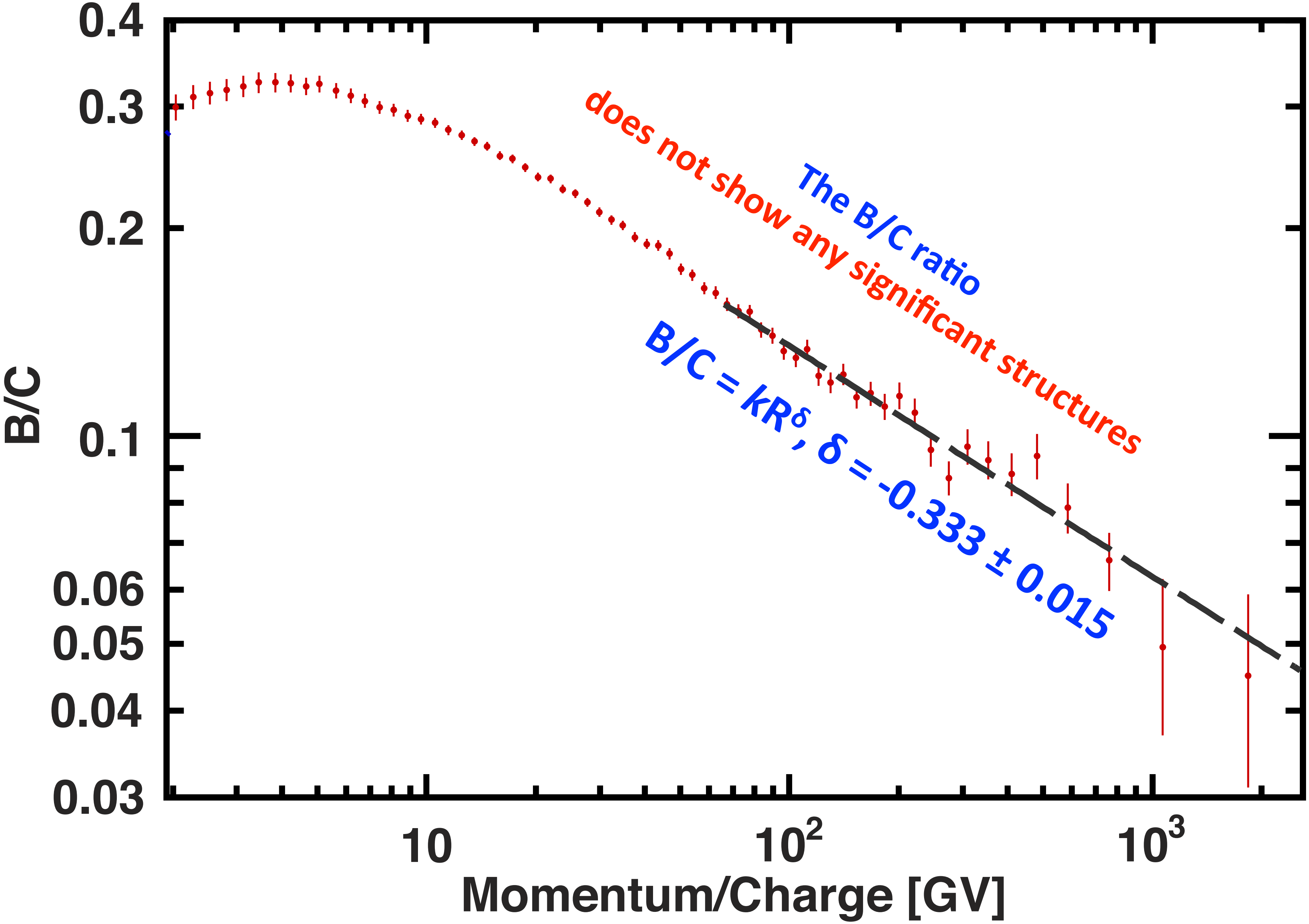


Cosmic ray propagation is commonly modeled as a fast moving gas diffusing through a magnetized plasma.

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

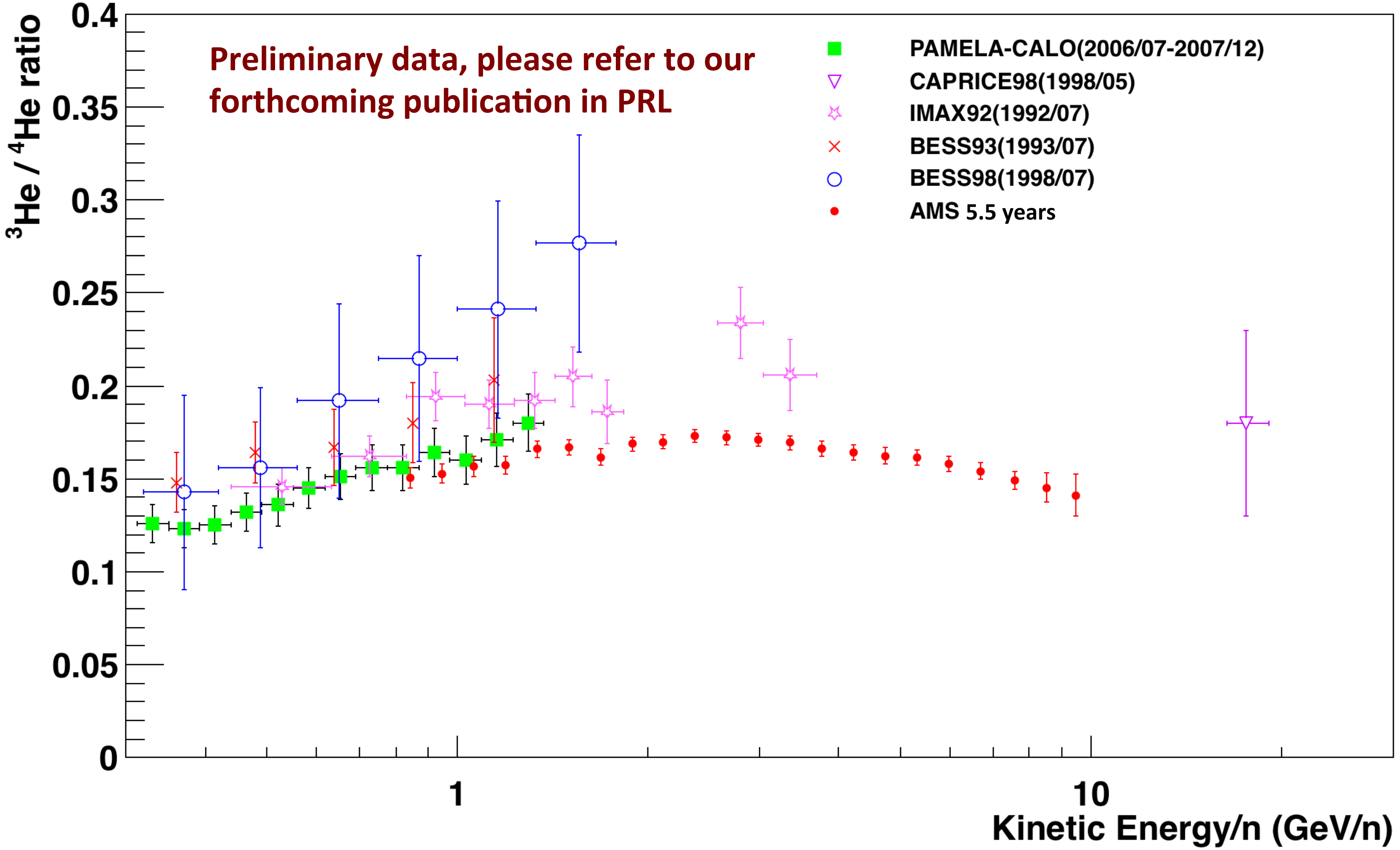
With the Kolmogorov turbulence model $\delta = -1/3$ while the Kraichnan theory leads to $\delta = -1/2$.

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



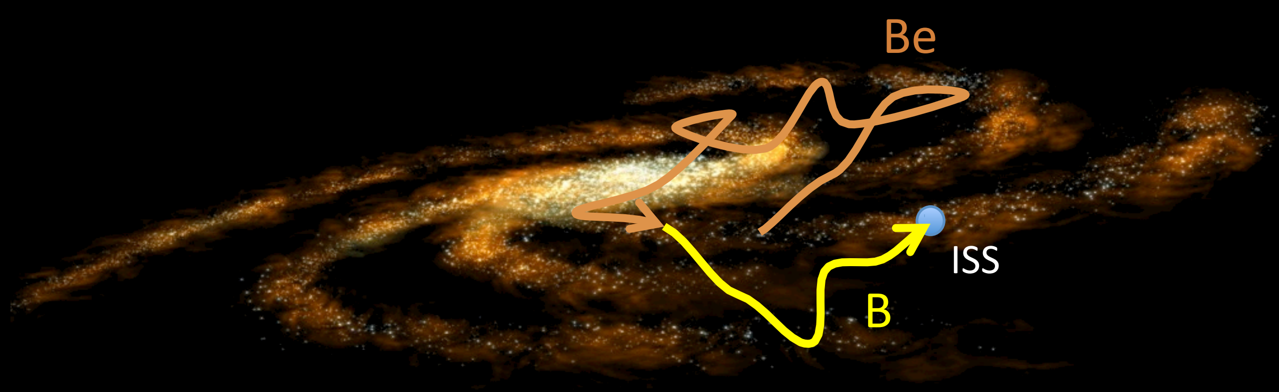
M. Aguilar *et al*., Phys. Rev. Lett. **117**, 231101 (2016)

New Physics Result: The isotopic composition of helium $^3He/^4He$



Presented by **Francesca Giovacchini**

Beryllium-to-Boron and the age of cosmic rays

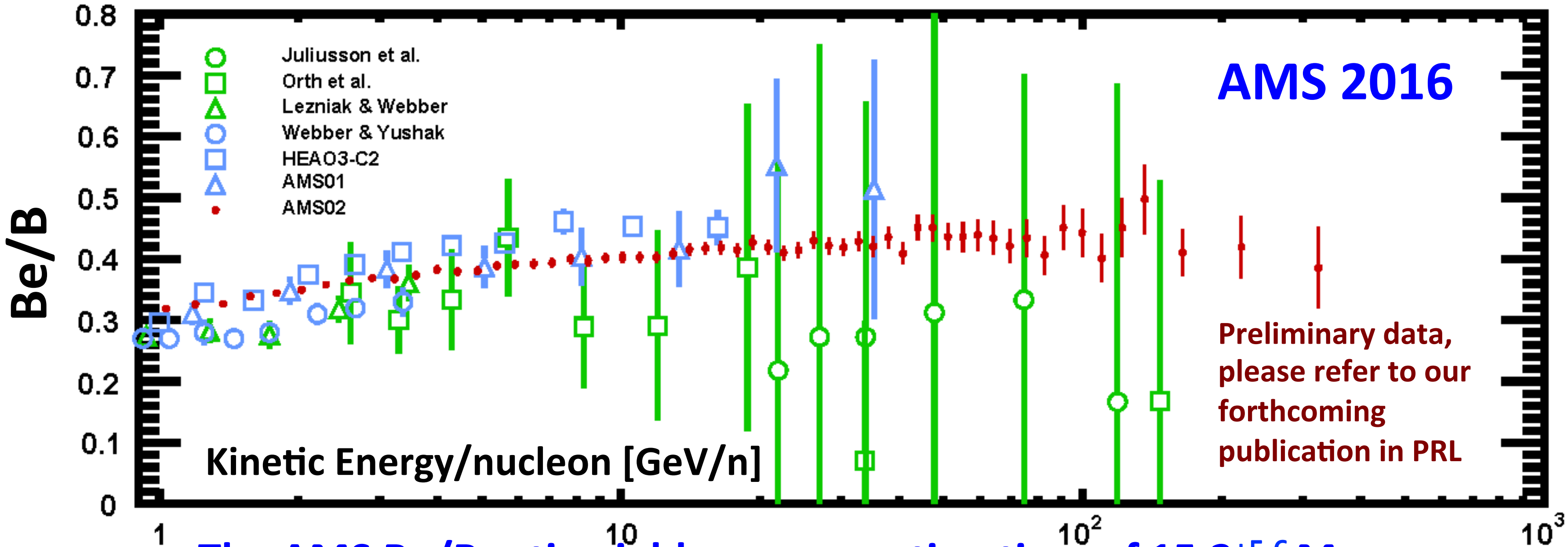


$$^{10}Be \rightarrow {}^{10}B + e^{-} + \bar{\nu}_e$$

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

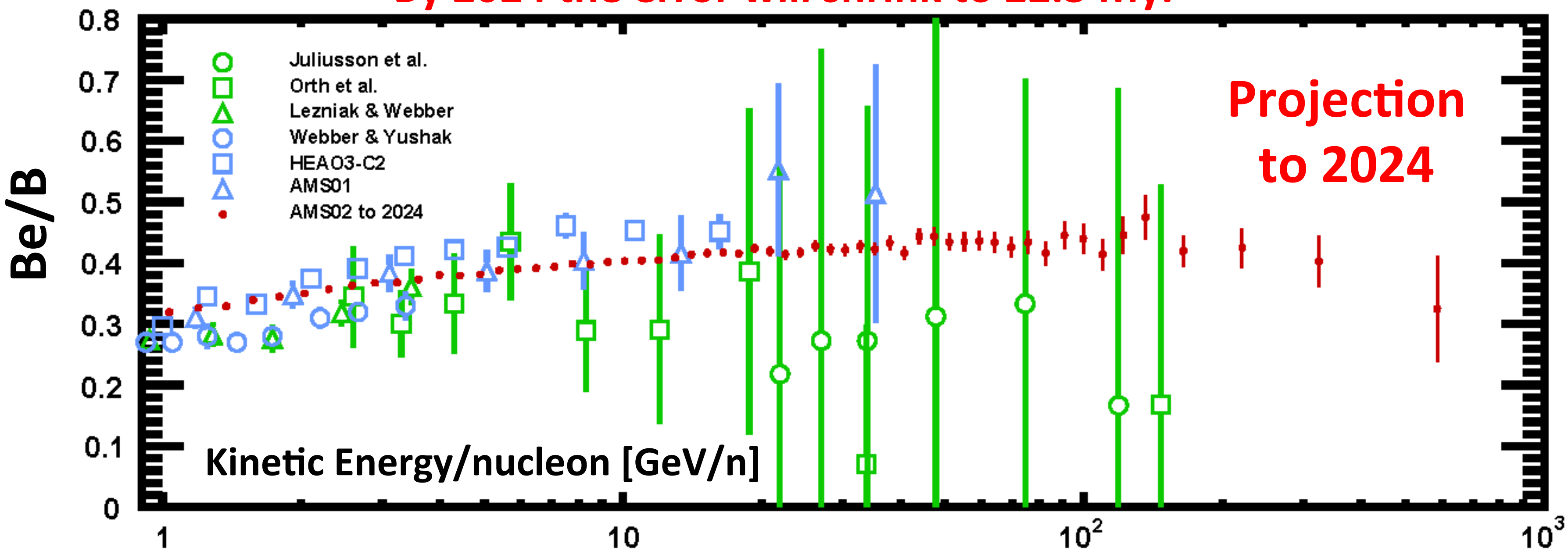
The Be/B ratio rises with energy due to relativistic time dilation. Be/B provides information on the age of cosmic rays in the Galaxy.

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

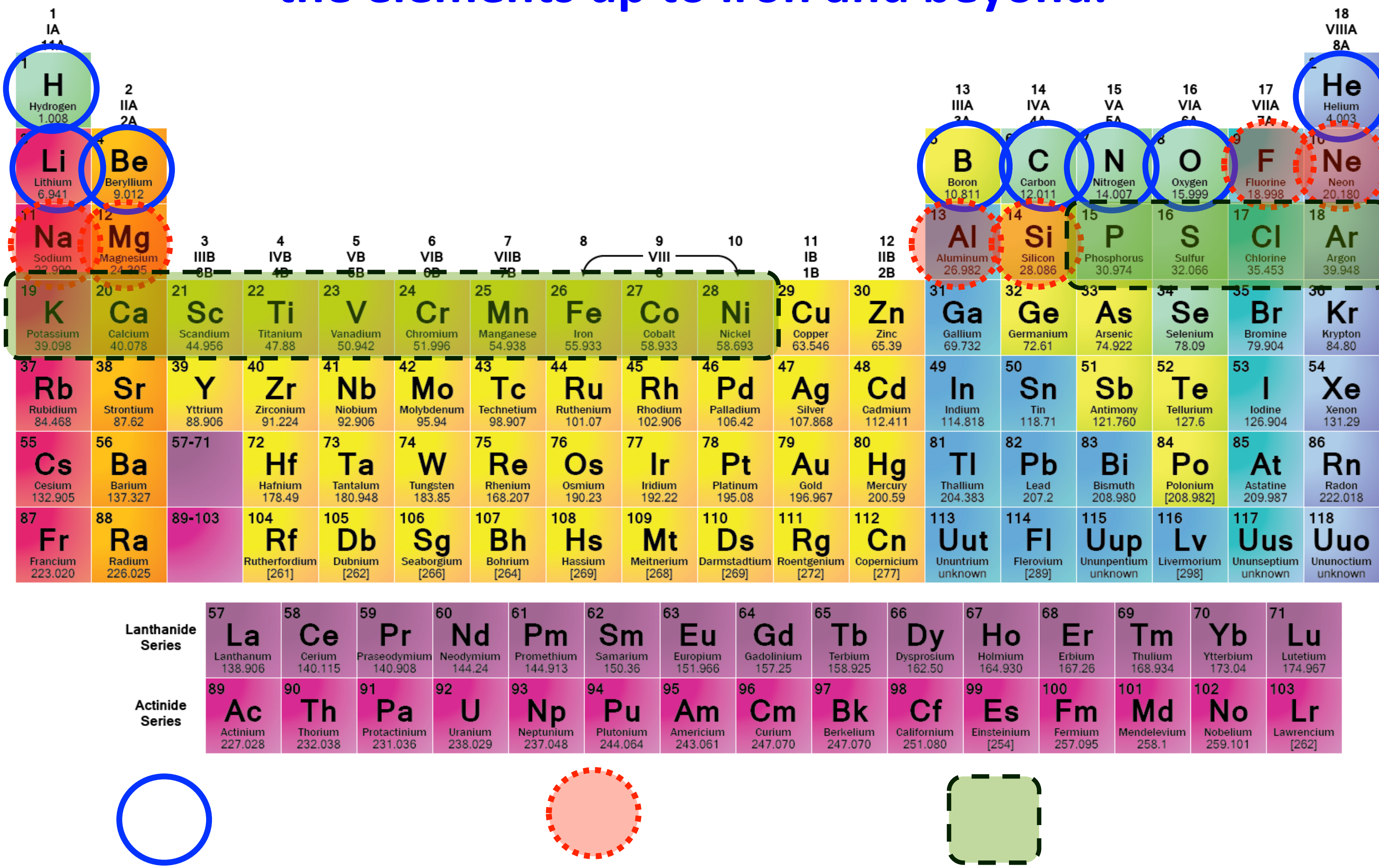


The AMS Be/B ratio yields a propagation time of $15.2^{+5.6}_{-4.5}$ My.

By 2024 the error will shrink to ±2.3 My.



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

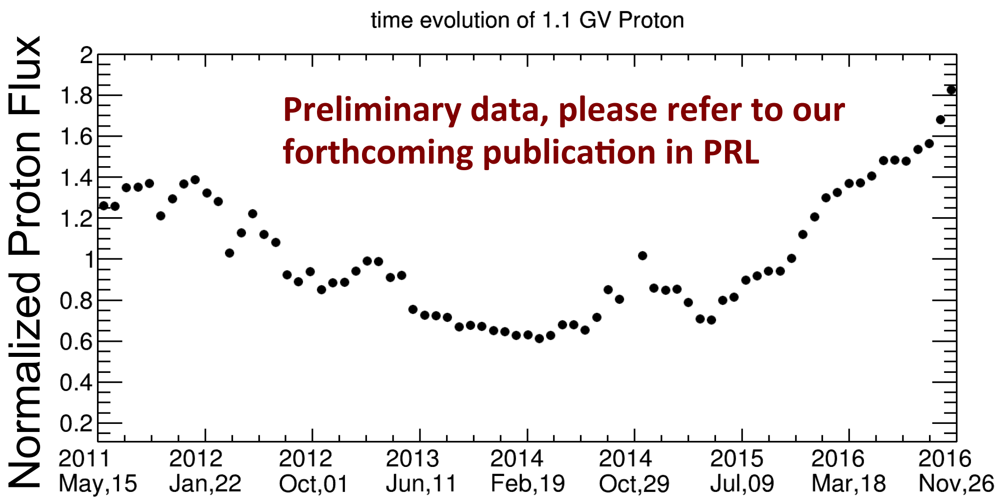


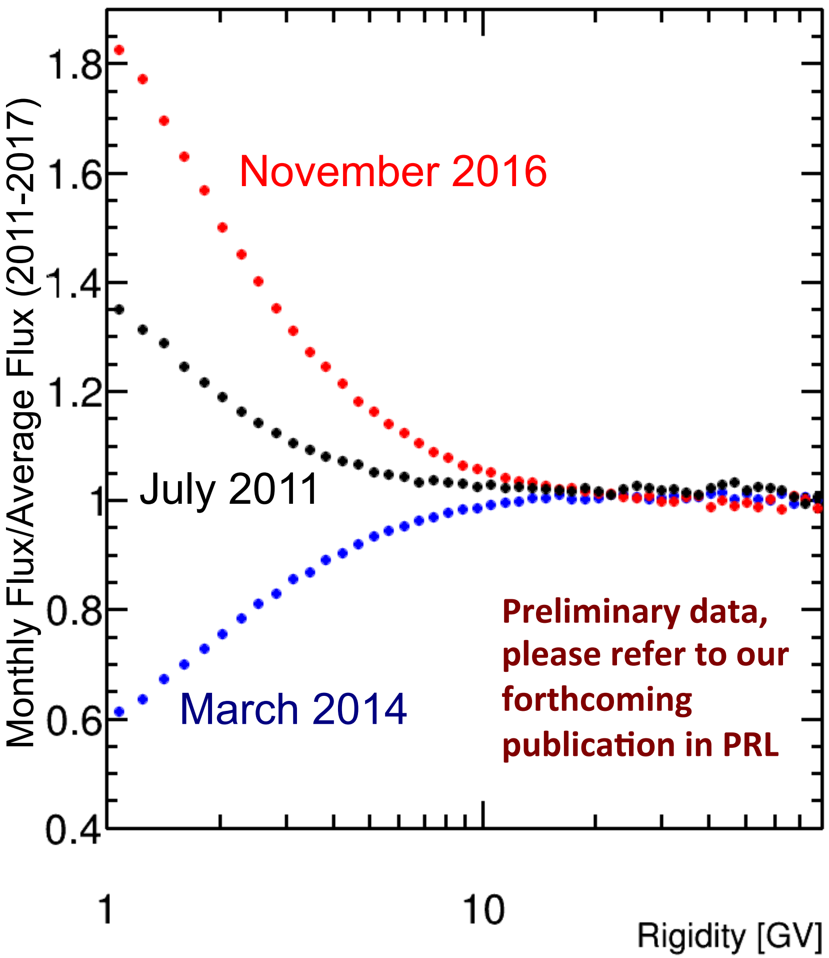
Analyzed **Being Analyzed** **Will be analyzed by 2024**

Long term Solar modulation of Galactic Cosmic Ray protons

The time variation of the Proton flux is continuously monitored by AMS

The proton flux is currently rapidly increasing

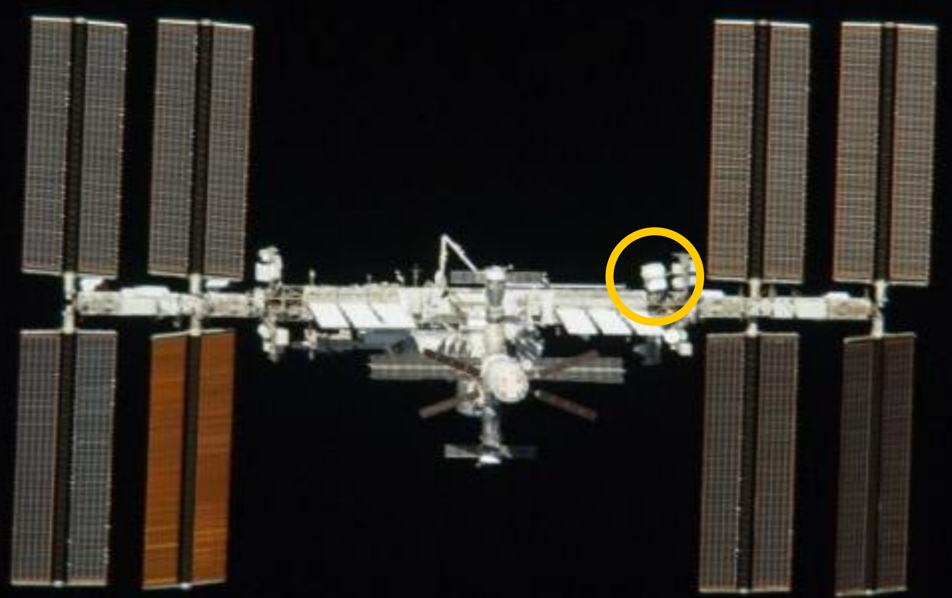




***Presented by* Veronica Bindi**

The latest AMS measurements of electrons, positrons, protons, antiprotons, helium, and Z>2 nuclei are providing new, precise, and unexpected information.

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



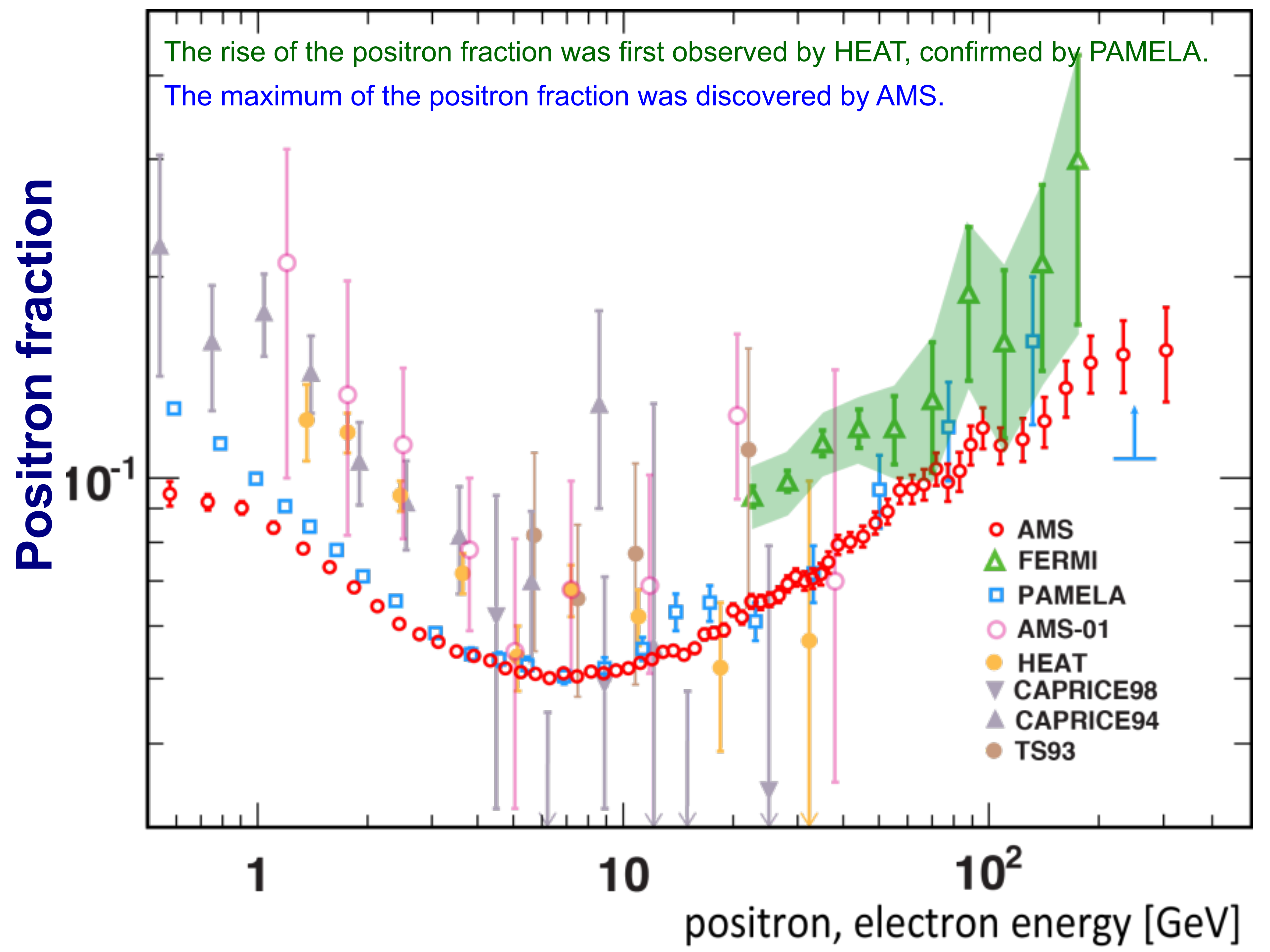
AMS physics for the lifetime of the Space Station

Accurate measurement (~1%) of Cosmic Rays to higher energies including:

a. Continue the study of Dark Matter

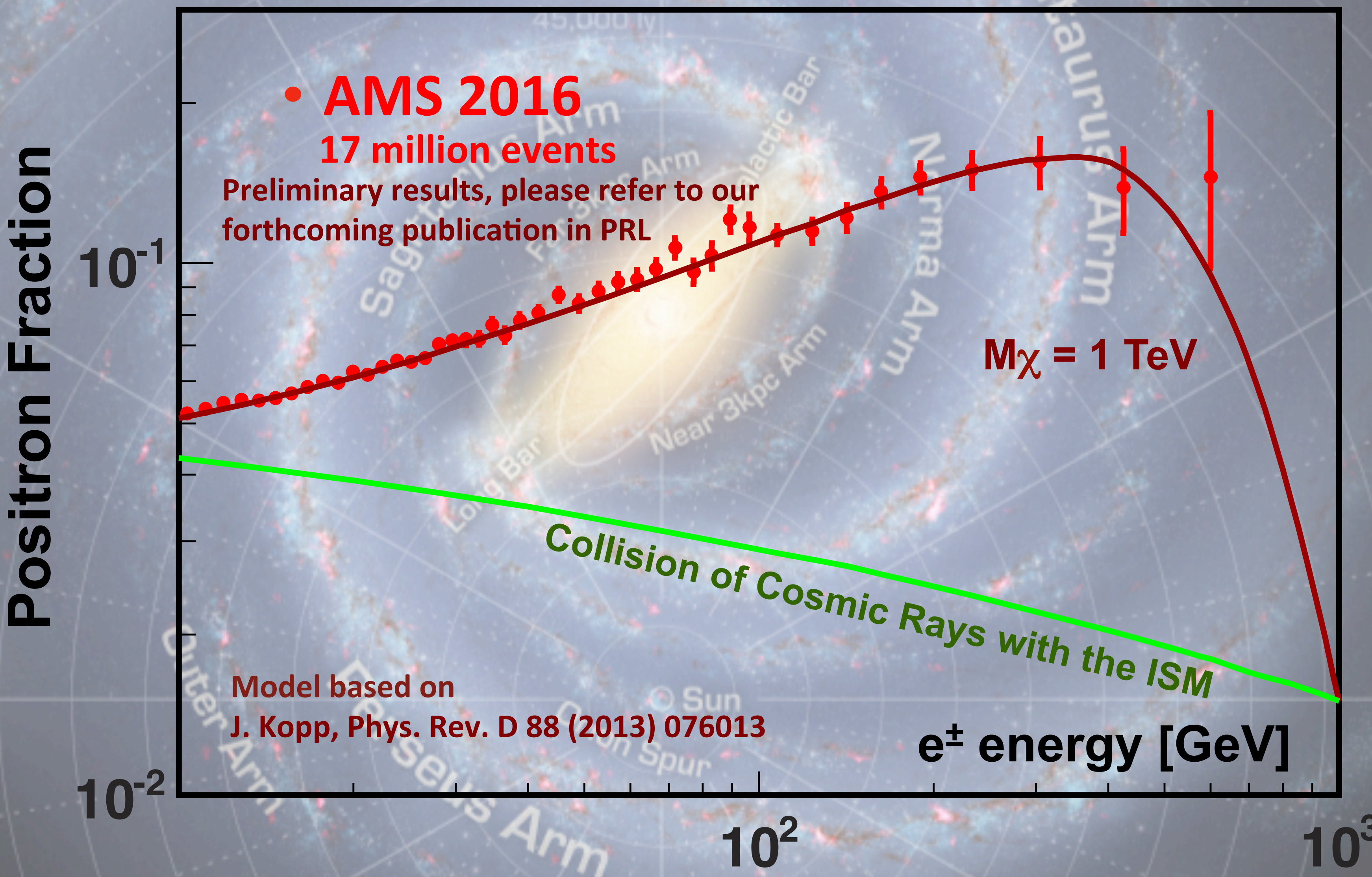
b. Search for the Existence of Antimatter

c. Search for New Phenomena, …



The rise of the positron fraction was first observed by HEAT, confirmed by PAMELA.
The maximum of the positron fraction was discovered by AMS.
Positron fraction
10^{-1}
1
10
10^2
positron, electron energy [GeV]
AMS
FERMI
PAMELA
AMS-01
HEAT
CAPRICE98
CAPRICE94
TS93

Comparison of the positron fraction measurement with a Dark Matter model



GALPROP is a numerical code for calculating the propagation of relativistic charged cosmic rays in the Galaxy and the diffuse emissions produced during their propagation.

We used GALPROP.v54 with the parameterisation from R. Trotta *et al.*, Astrophys. J. 729, 2 (2011).

We thank Dr. I. Moskalenko for useful discussions.

AMS Proton Flux

The isotropic proton flux Φ_i for the i th rigidity bin (R_i , $R_i + \Delta R_i$) is $\Phi_i = \frac{N_i}{A_i \varepsilon_i T_i \Delta R_i}$

N_i is the number of events; A_i is the effective acceptance;
ε_i is the trigger efficiency; T_i is the collection time (which depends on the geomagnetic cutoff).

To match the statistics of 300 million events, extensive systematic errors studies have been made.

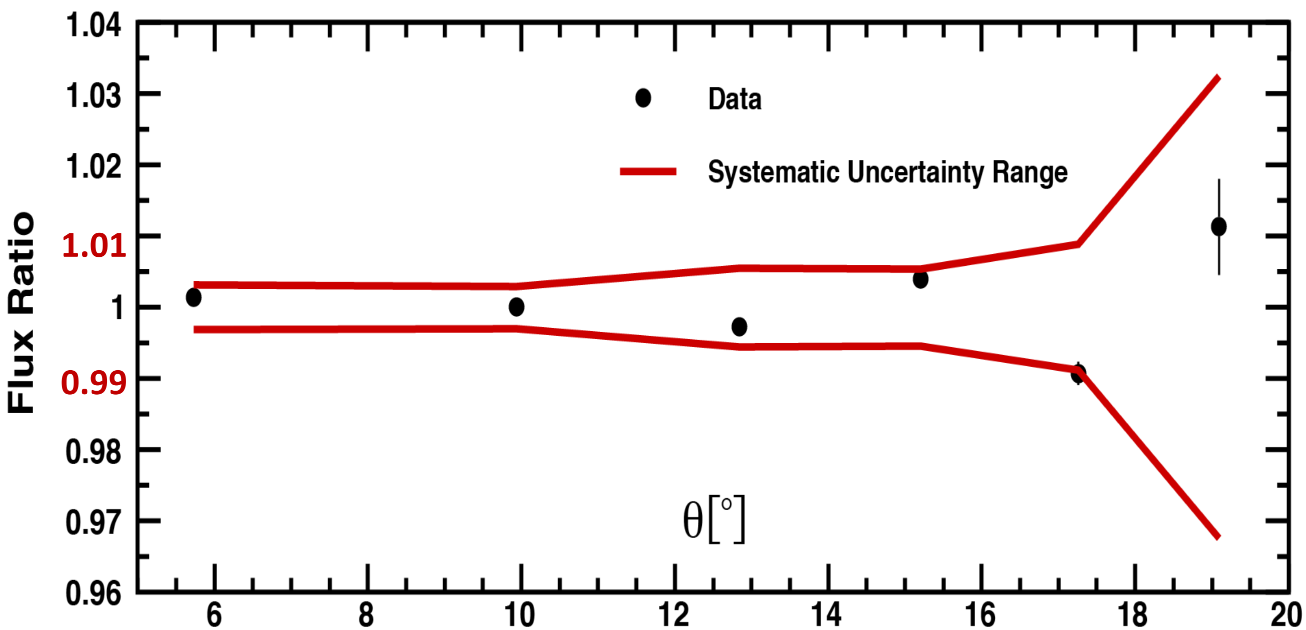
Breakdown of Systematic Errors

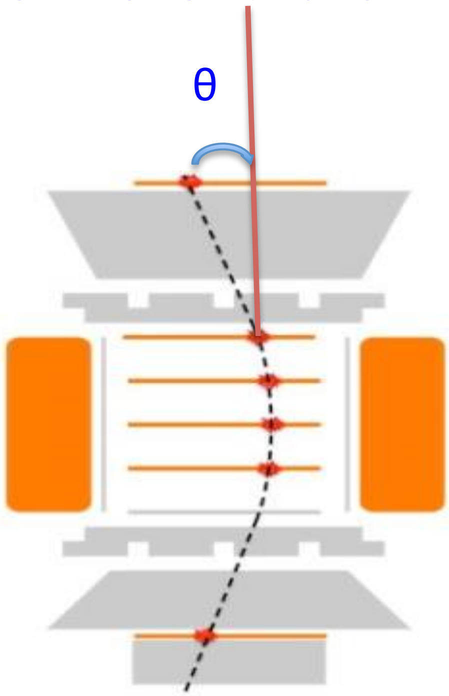
Source	Error (%) at 200 GV
Trigger	0.2
Acceptance	1.1
Unfolding & Rigidity Resolution	0.95
Rigidity Scale	0.7

AMS Proton Flux

1) Independent verification of the systematic errors.

Study the dependence of the integral of the proton flux above 30 GV on the angle ϑ between the incoming proton direction and the AMS zenith axis.



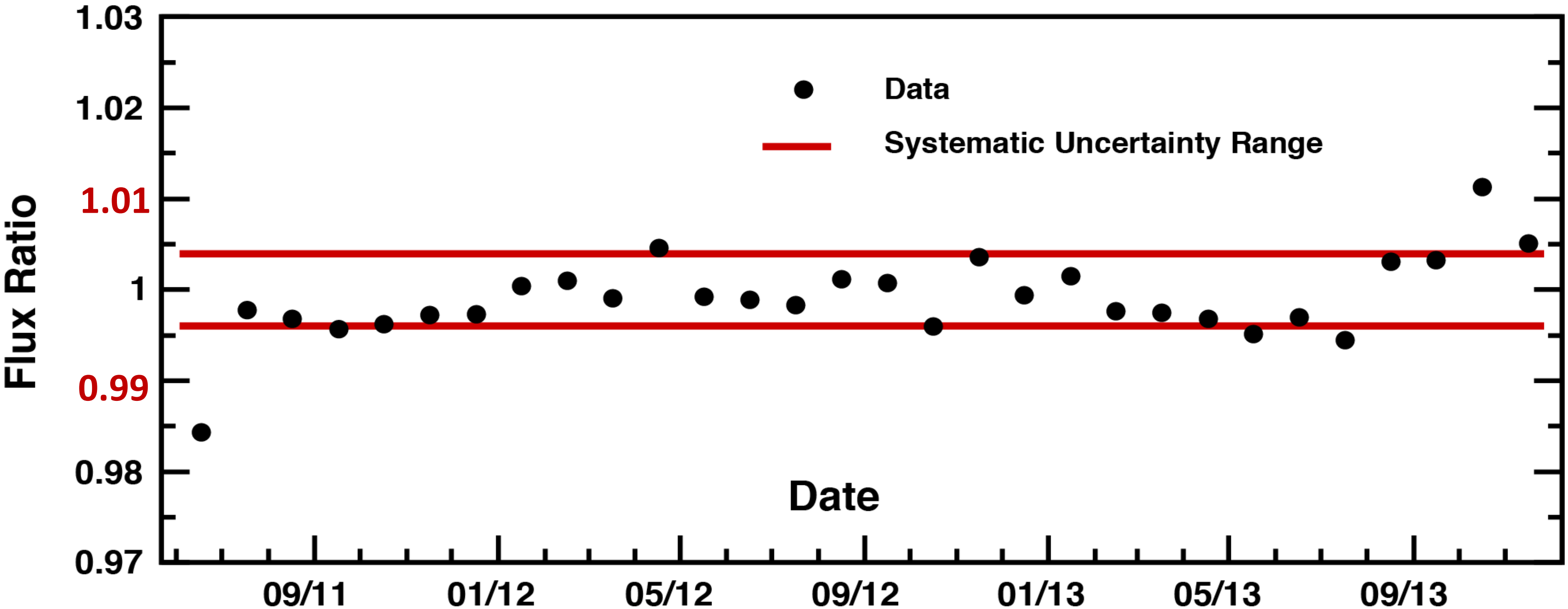


This verifies the systematic error assigned to the acceptance.

AMS Proton Flux

2) Independent verification of the systematic errors.

The monthly integral flux above 45GV is within the systematic error of 0.4%.

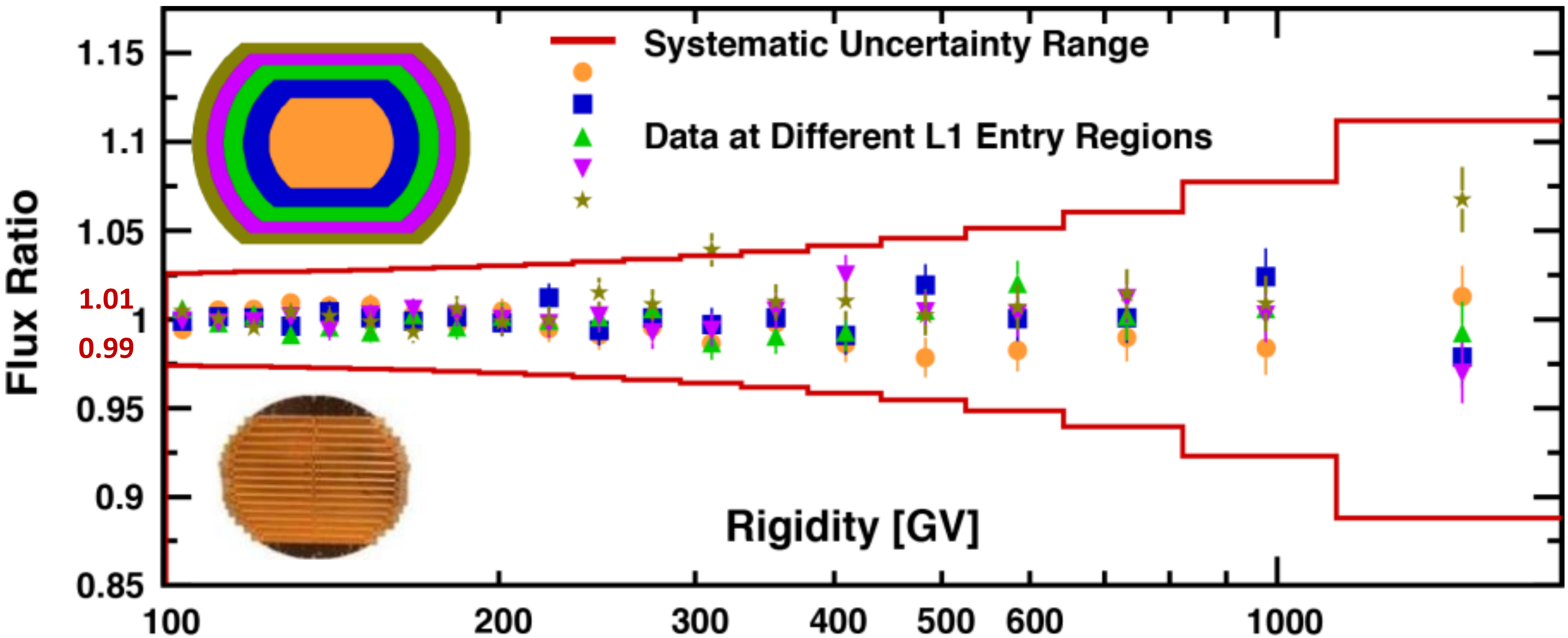


This verifies that the flux above 45GV shows no observable effect from solar modulation fluctuations and that the detector performance is stable.

AMS Proton Flux

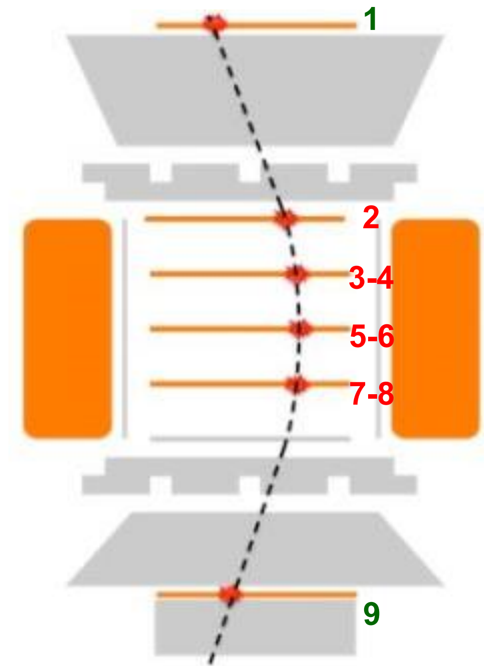
3) Independent verification of the systematic errors.

The ratios of fluxes obtained using events which pass through different sections of L1 to the average flux is in good agreement and within the assigned systematic errors.



This verifies the errors assigned to the tracker alignment.

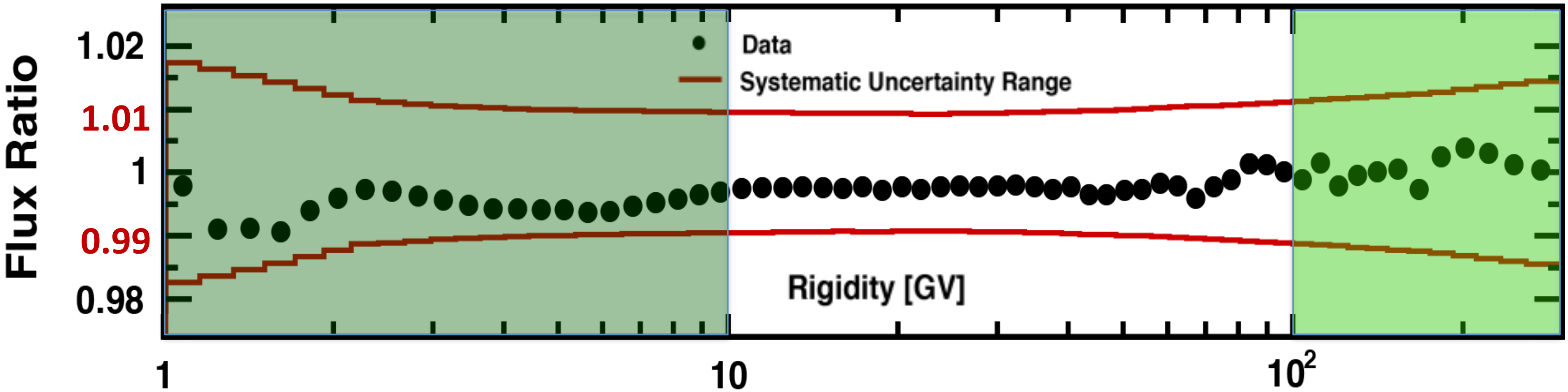
AMS Proton Flux



4) Independent verification of the systematic errors
Understanding resolution (unfolding effects).

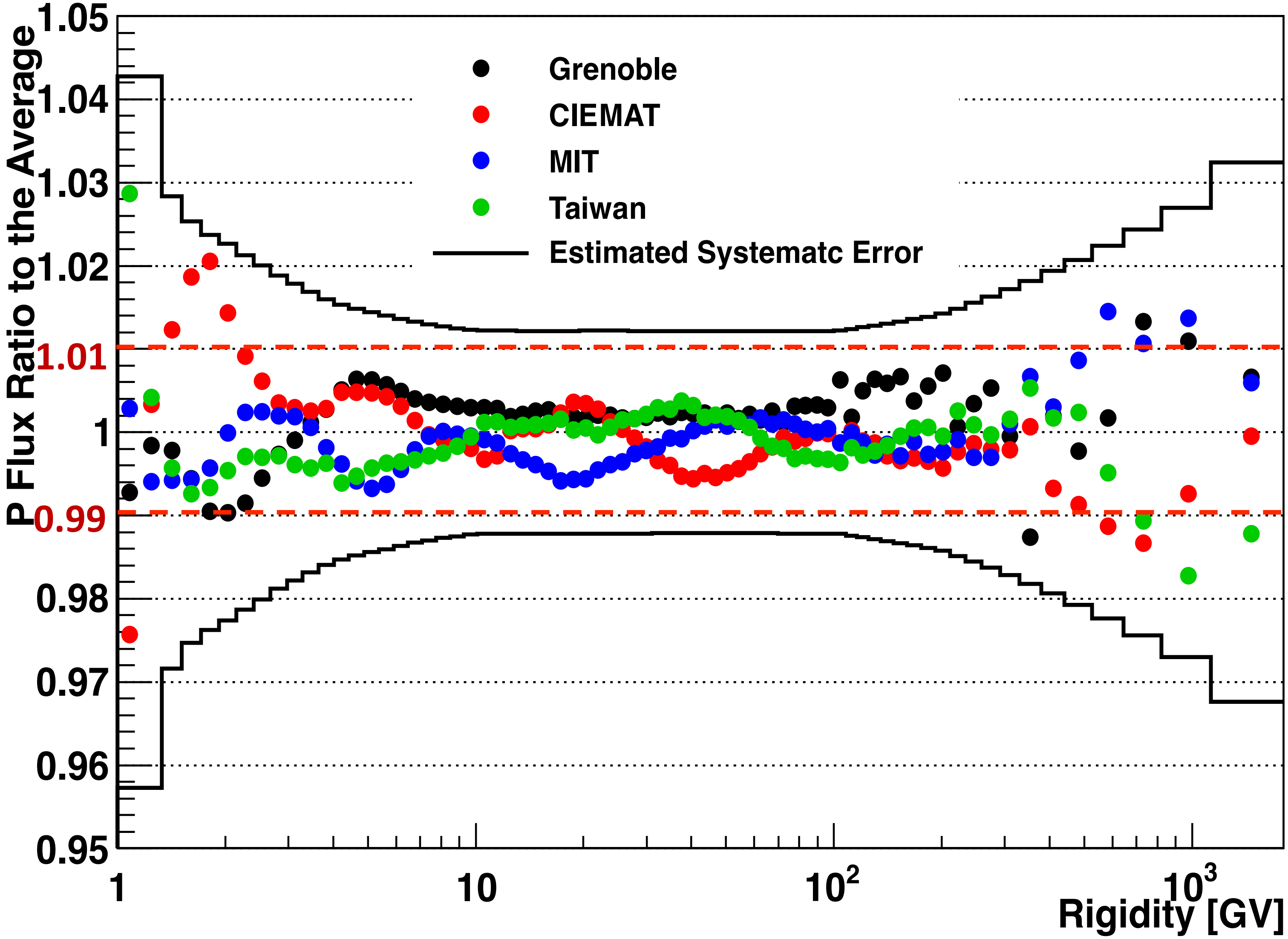
The inner tracker (2-8) measures rigidity up to 300 GV but has less material with respect to the full level arm tracker.

Full level arm tracker measures rigidity up to 2 TV.

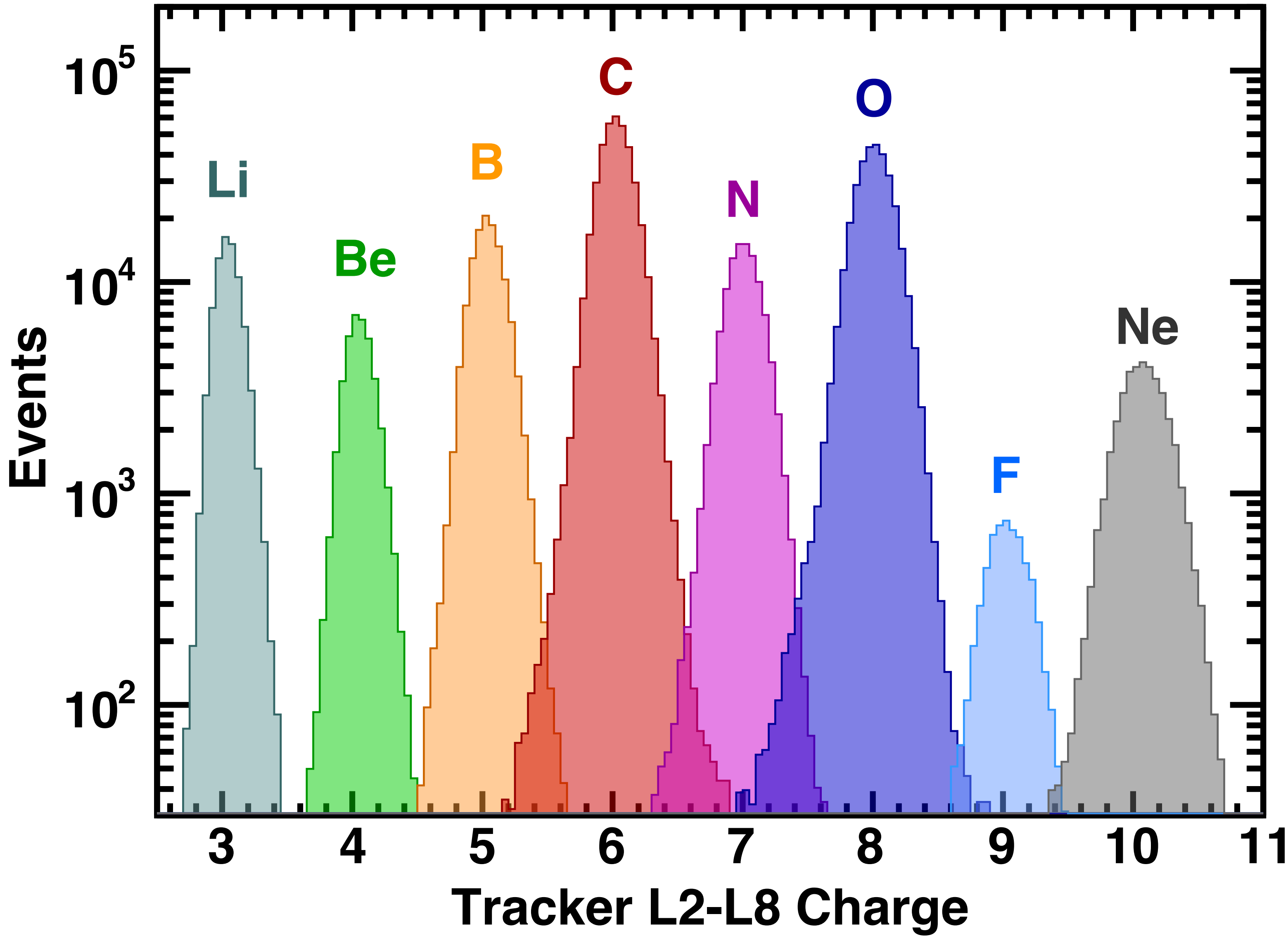


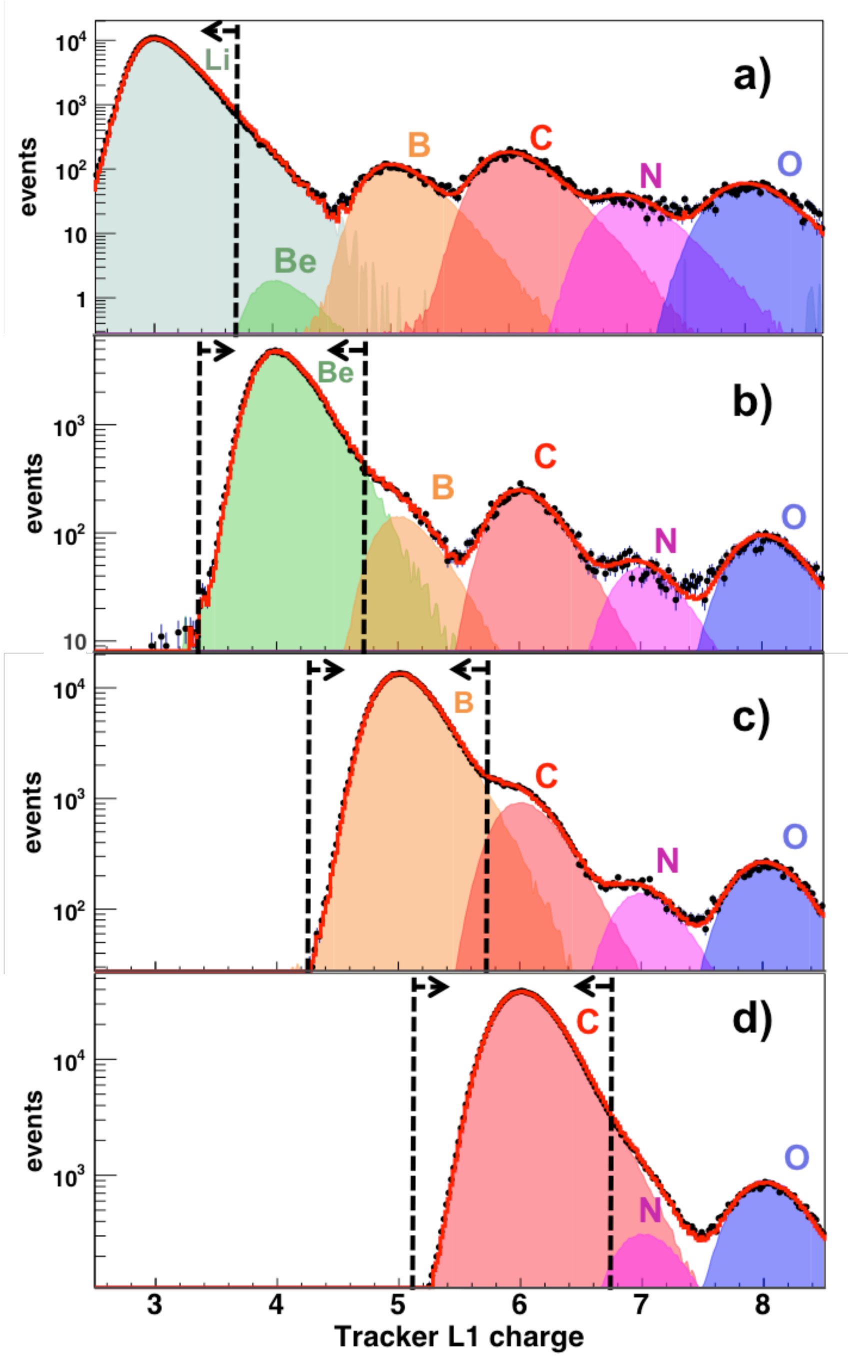
The flux measured by only the inner tracker (2-8) is in good agreement (1%) with the flux measured using the full lever arm (1-9).
This means we understand resolution effects on the % level.

There are no plans to put another magnetic spectrometer in space.
The AMS proton, helium, … fluxes are unique.
These fluxes are analyzed by 4 independent AMS groups.



Tracker Charge resolution for Z=2-10





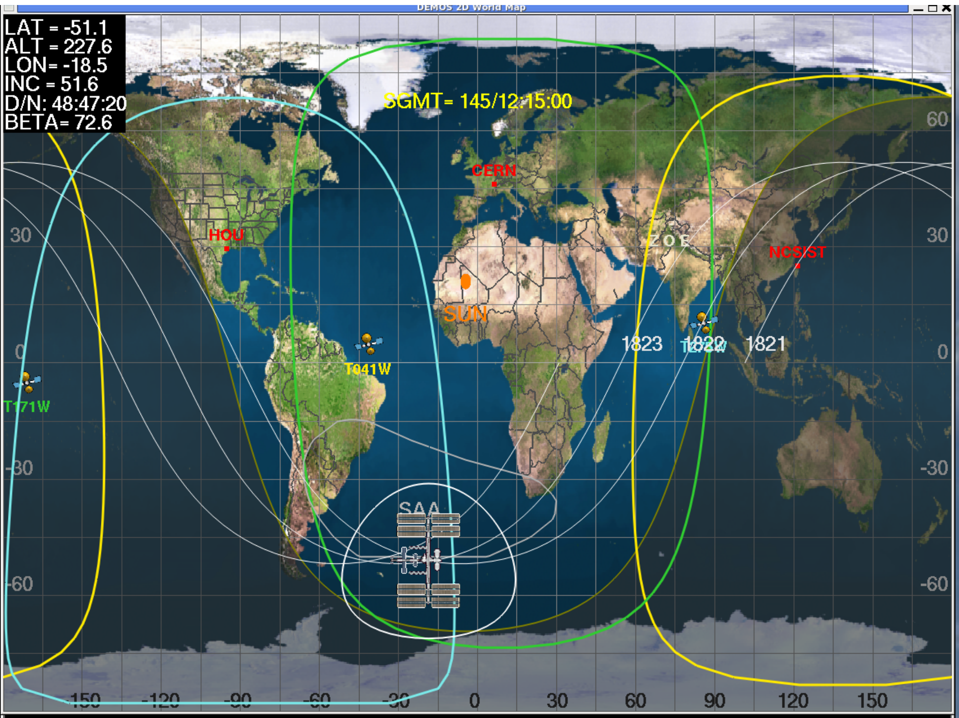
Top-of-Instrument correction for nuclei with AMS

May 2011

May 19, 2011: AMS installation completed at 5:15 AM.
Data taking started at 9:35 AM

AMS Main Display

Cosmic rays measured as of 25 May 2017 14:15 CEDT



100,879,440,121