GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA, INDUSTRIA Y COMPETITIVIDAD

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

EXCELENCIA MARÍA DE MAEZTU

cfp CIEMAT física de partículas

AMS-02

RECENT RESULTS OF THE AMS-02 EXPERIMENT ON THE ISS

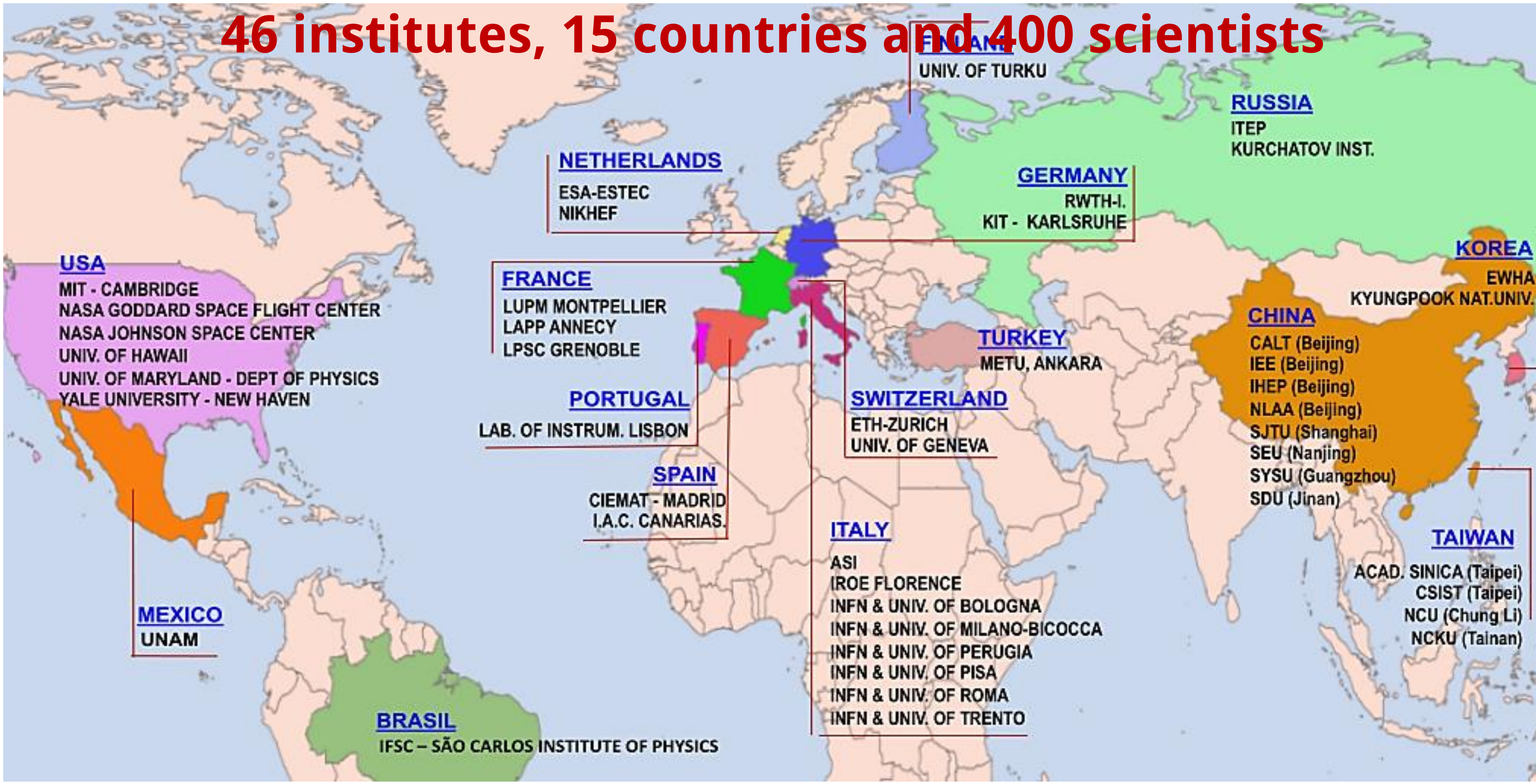
M. A. Velasco
(CIEMAT, Madrid, Spain)
MiguelAngel.Velasco@Ciemat.es

on behalf of the AMS Collaboration

CRA2017
4th Cosmic Ray Anisotropy Workshop
10 - 13 October, 2017
Guadalajara, Jalisco, México

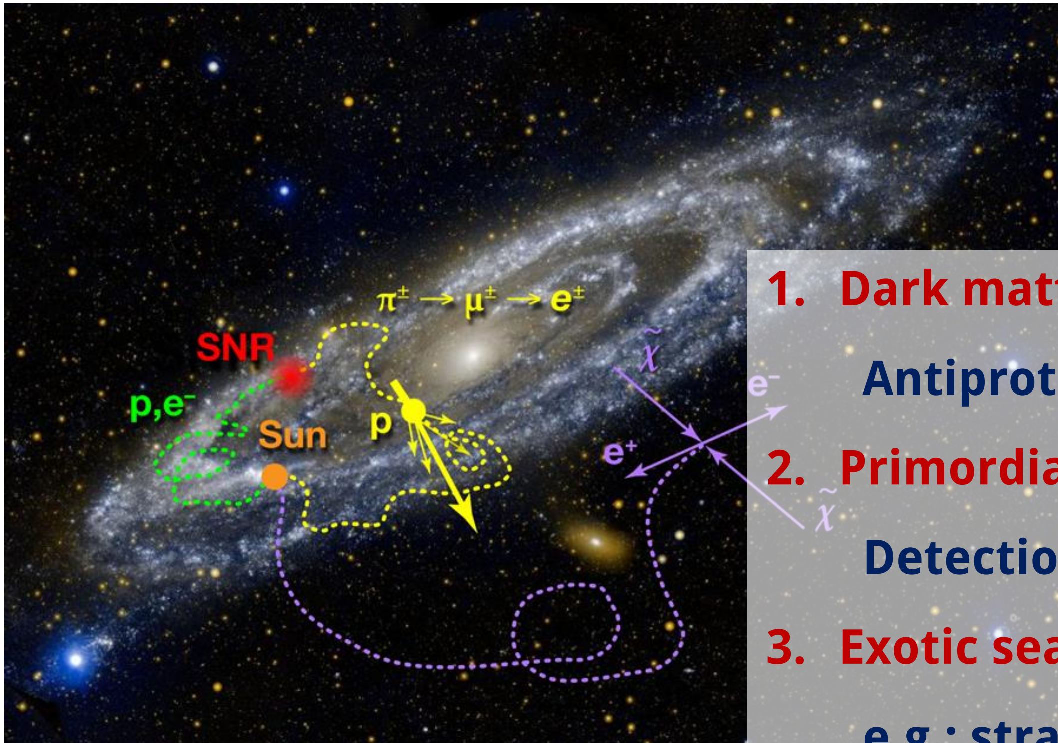
AMS Collaboration

AMS is an international collaboration
46 institutes, 15 countries and 400 scientists



AMS-02 Experiment

Scientific goals



1. **Dark matter indirect search**

   Antiprotons, positrons, antideuterons…
2. **Primordial antimatter search**

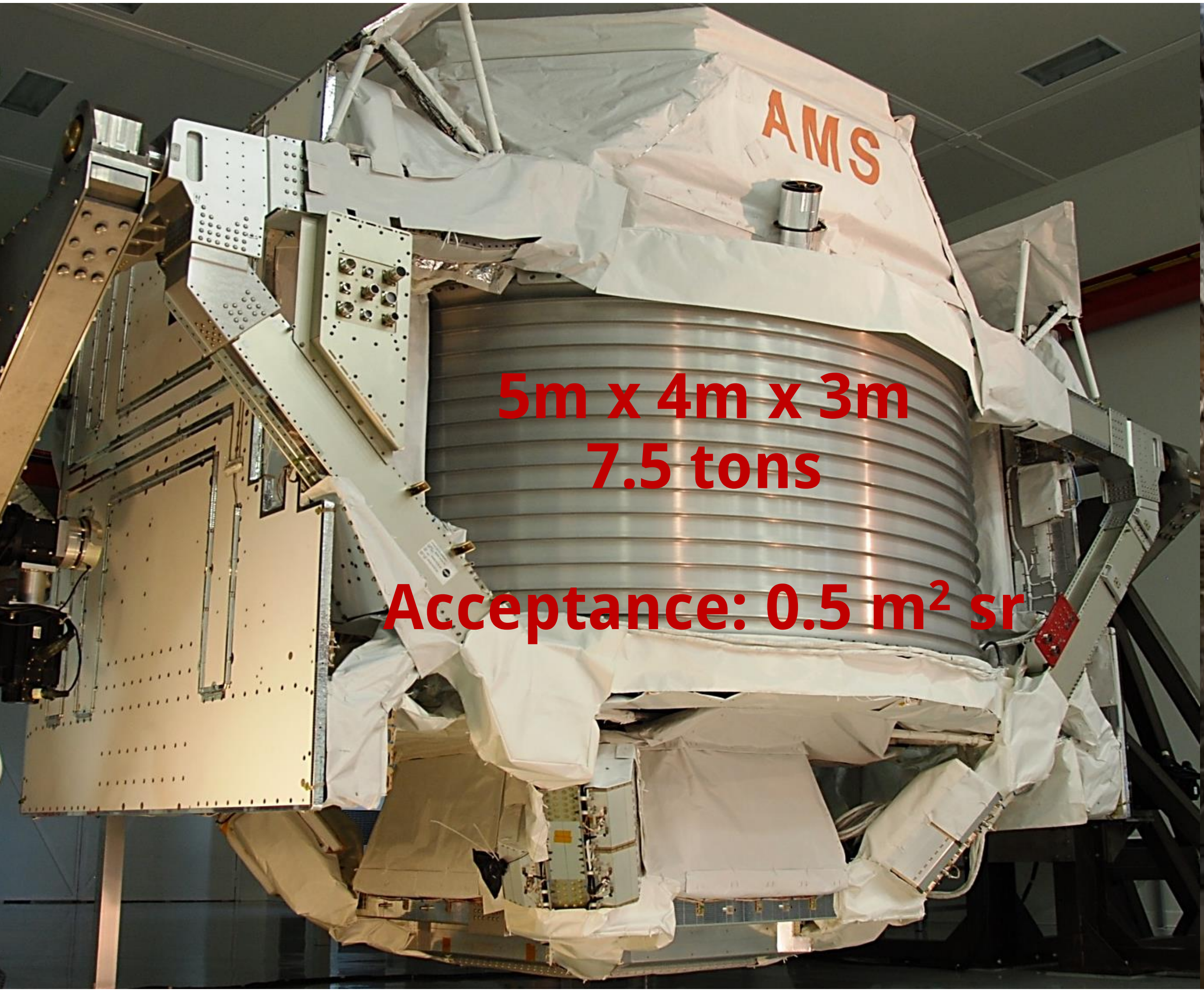
   Detection of anti-nuclei, $|Z|\geq 1$
3. **Exotic searches**

   e.g.: strangelets…
4. **Cosmic ray propagation models**

   Composition and flux
5. **Solar activity and modulation**

   CR spectra over 11 year solar cycle & SEPs

AMS-02 Experiment
A TeV precision, multipurpose spectrometer in space



AMS-02 Experiment

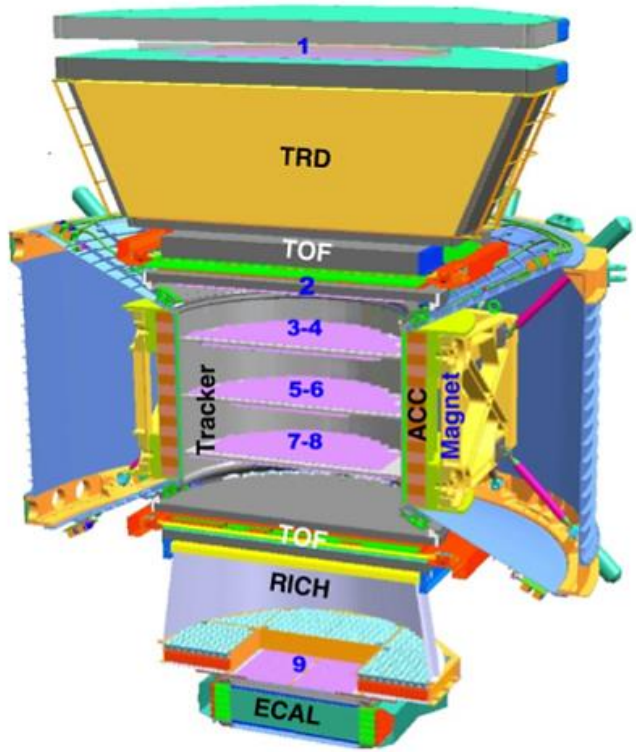
A TeV precision, multipurpose spectrometer in space

May 19, 2011: AMS installation completed.
In ~6 years we have collected more than 100 billion events.

AMS-02 Experiment

A TeV precision, multipurpose spectrometer in space

Particles and nuclei are defined
by their charge (Z)
and energy (E~P)

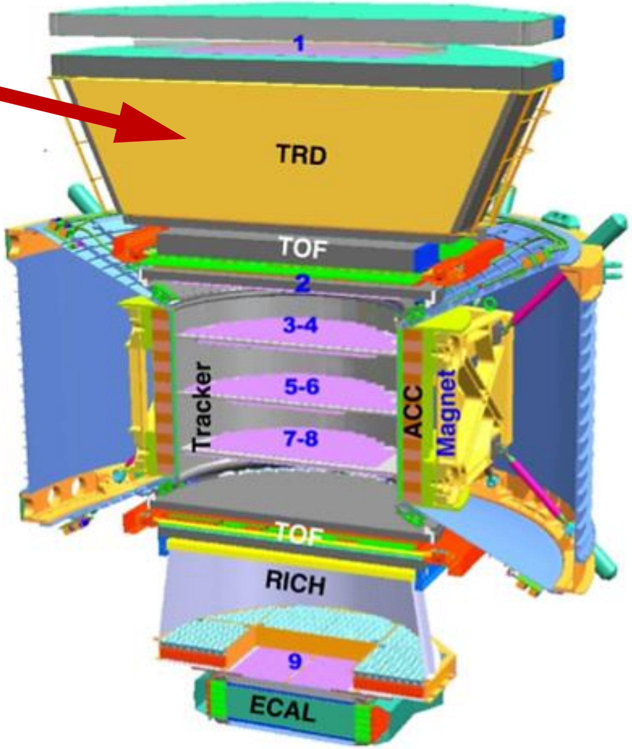


AMS-02 Experiment

A TeV precision, multipurpose spectrometer in space

TRD: Identify e^+, e^-

Particles and nuclei are defined by their charge (Z) and energy (E~P)



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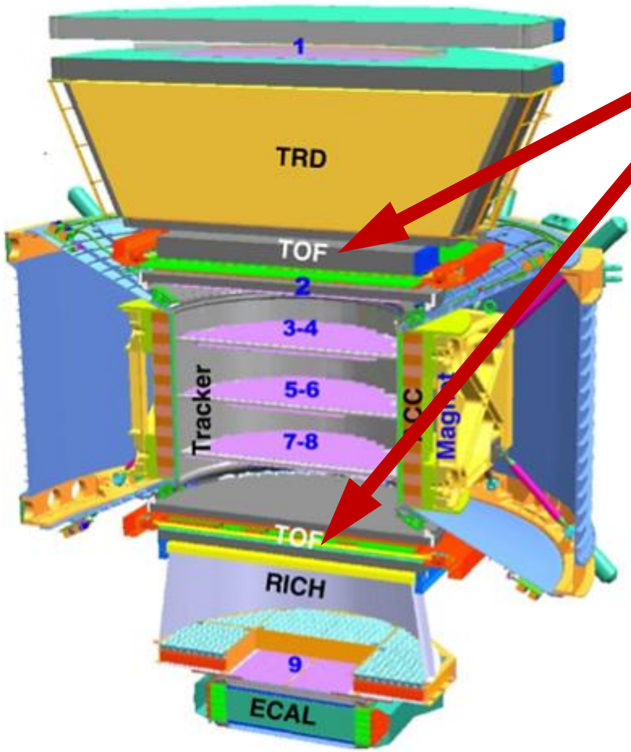
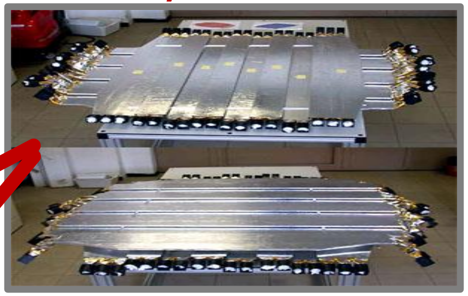


TOF: Z, E

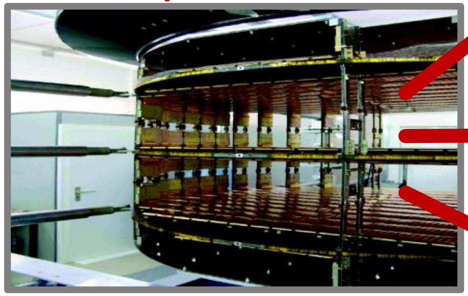


AMS-02 Experiment

A TeV precision, multipurpose spectrometer in space

TRD: Identify e^+, e^-

STD: Z, P



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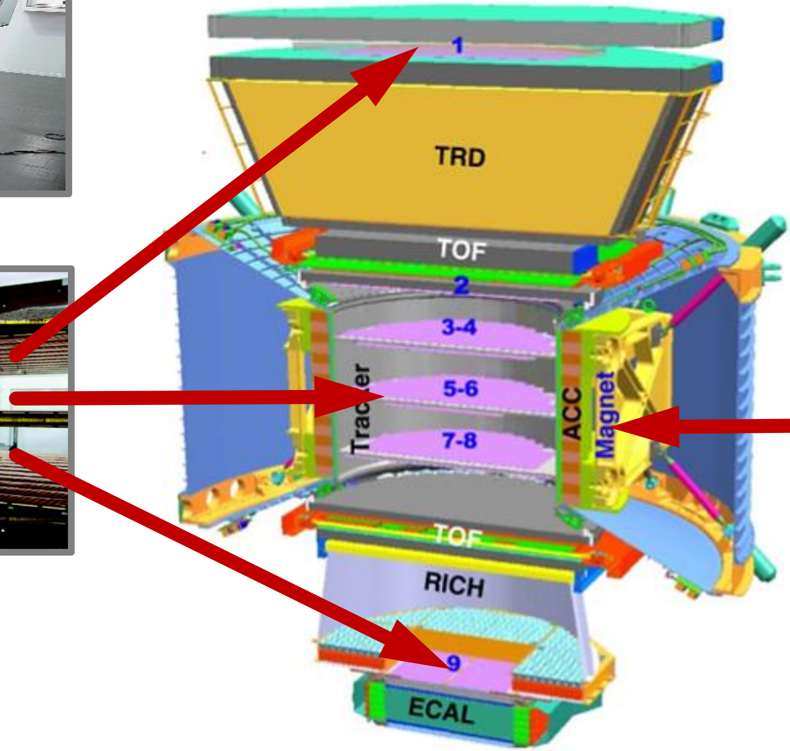
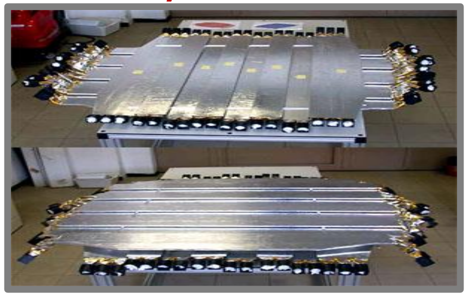
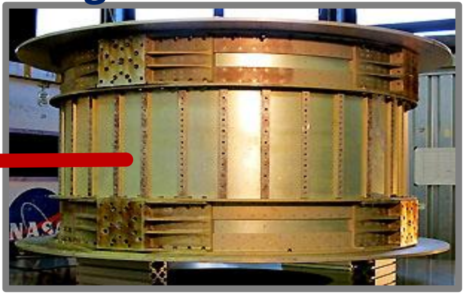


TOF: Z, E



Magnet: ± Z



AMS-02 Experiment

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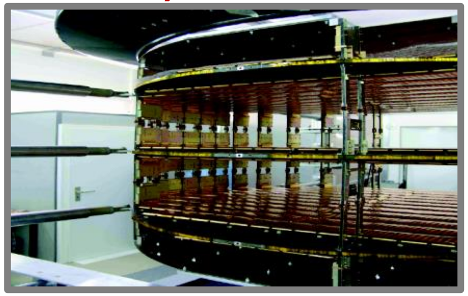
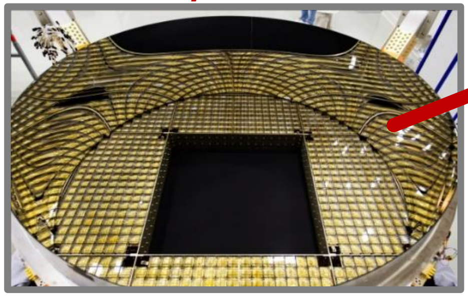


RICH: Z, E



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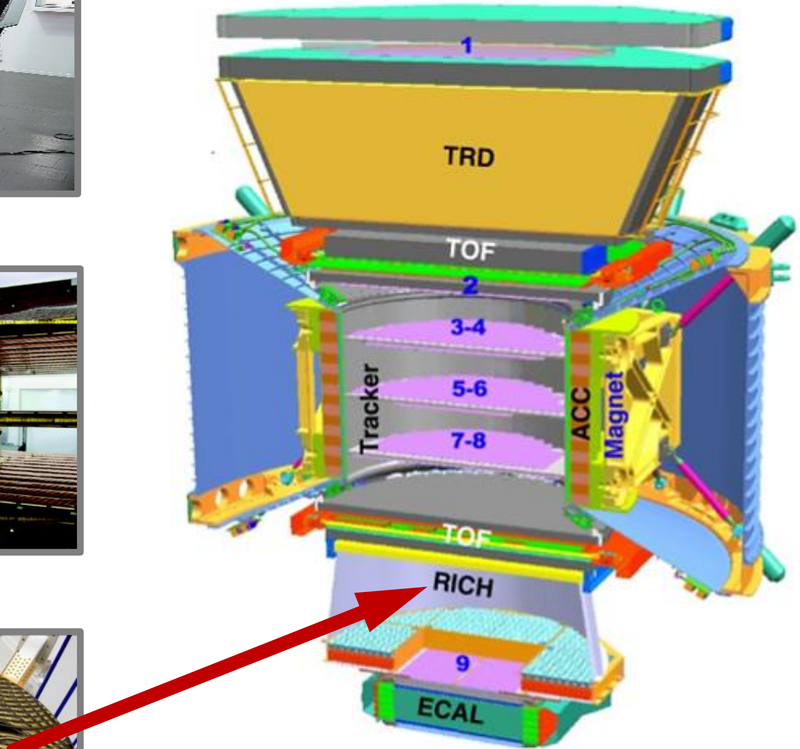
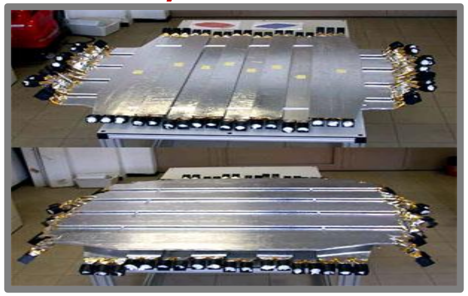


TOF: Z, E



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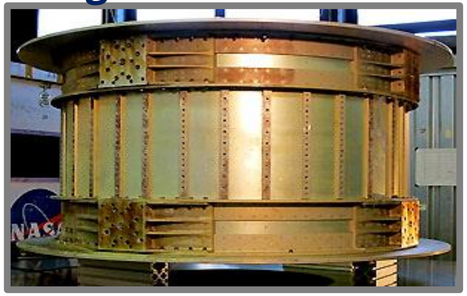

AMS-02 Experiment

A TeV precision, multipurpose spectrometer in space

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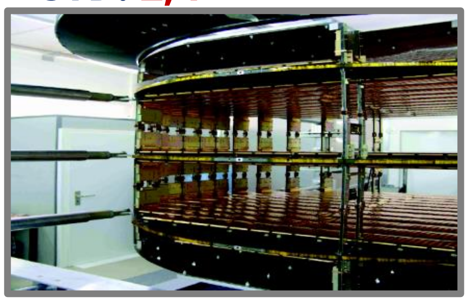
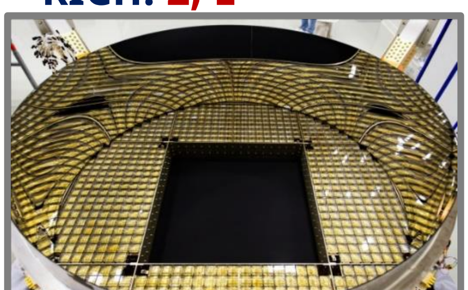
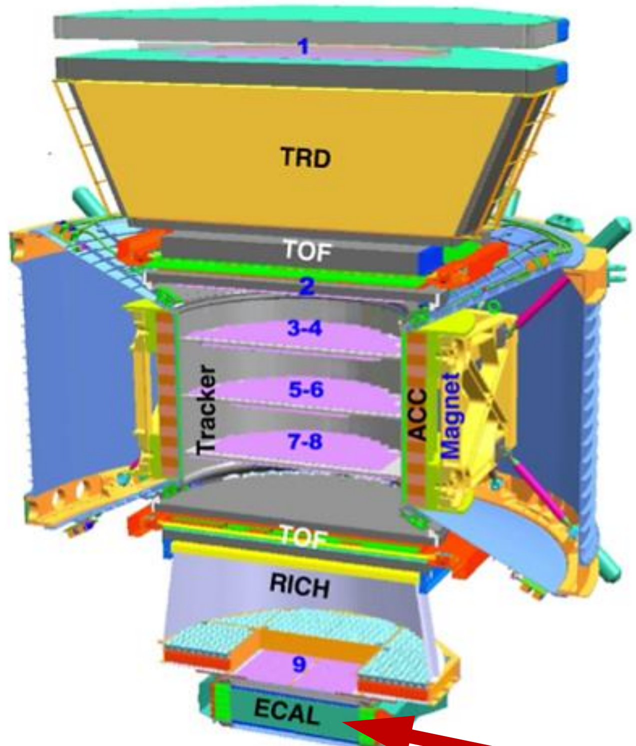
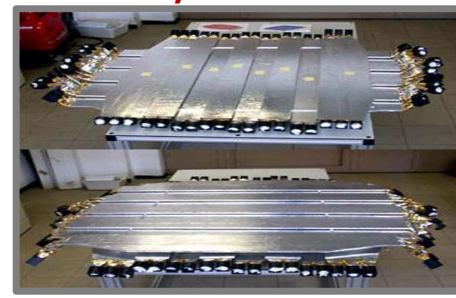


RICH: Z, E

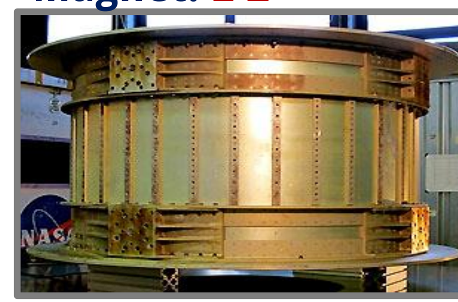




TOF: Z, E



Magnet: ± Z



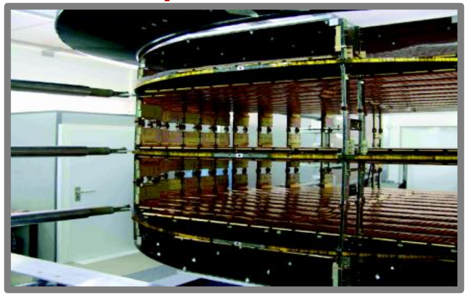
ECAL: E of e^+, e^-, γ

AMS-02 Experiment

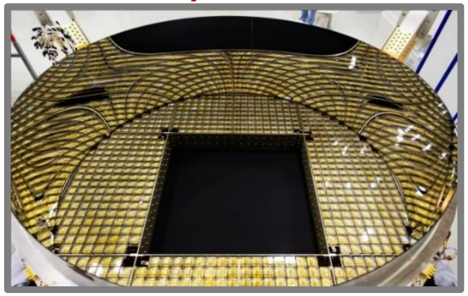
A TeV precision, multipurpose spectrometer in space

TRD: Identify e^+, e^-

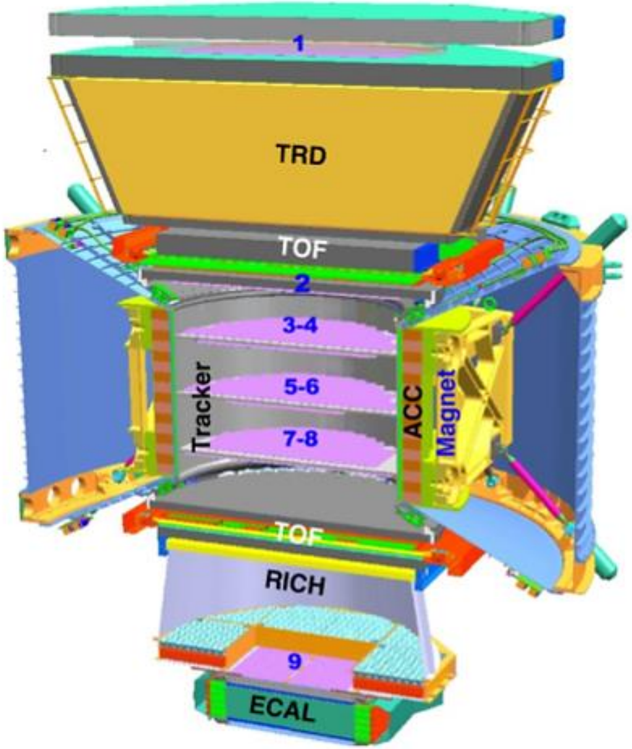
STD: Z, P



RICH: Z, E

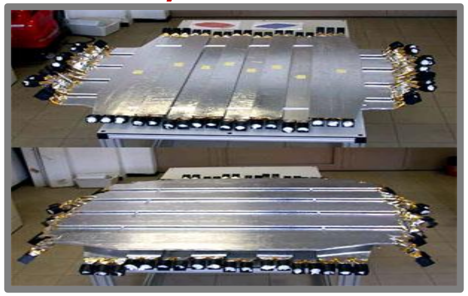


Particles and nuclei are defined by their charge (Z) and energy (E~P)

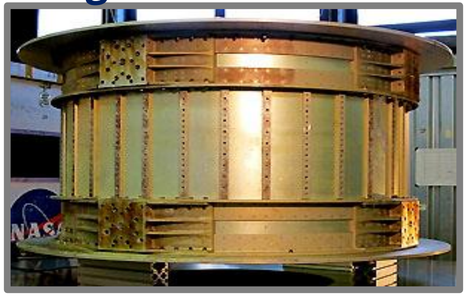


Z, P are measured independently by the Tracker, RICH, TOF and ECAL

TOF: Z, E



Magnet: ± Z

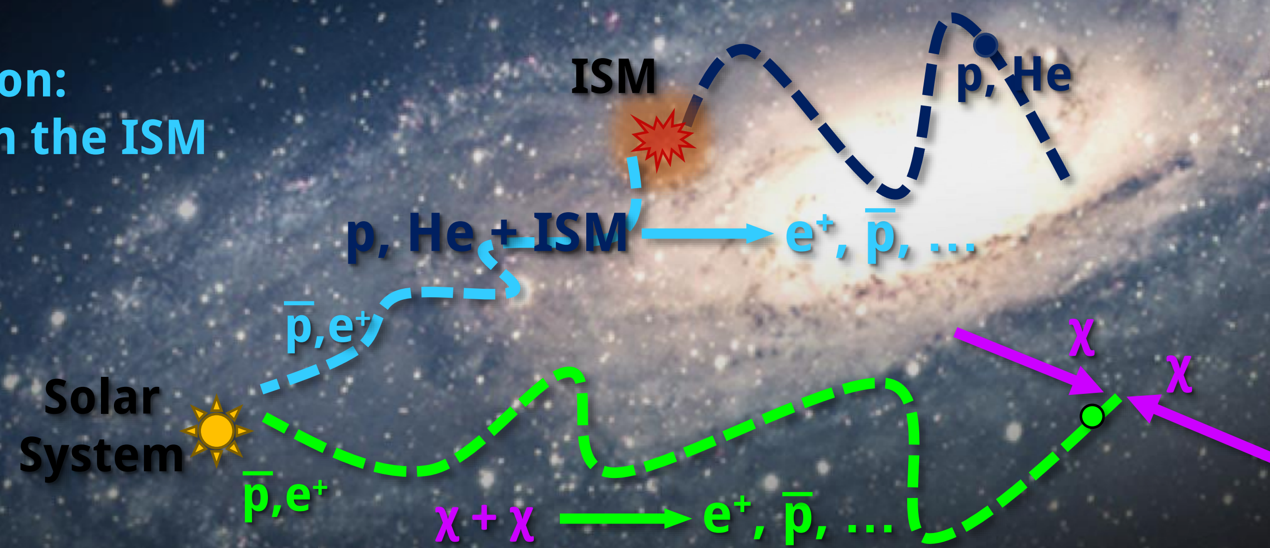


ECAL: E of e^+, e^-, γ

The quest for Dark Matter

In ordinary cosmic ray models, protons and electrons are considered mainly primaries, while antiprotons and positrons are secondaries

Secondary production:
Collision of CRs with the ISM

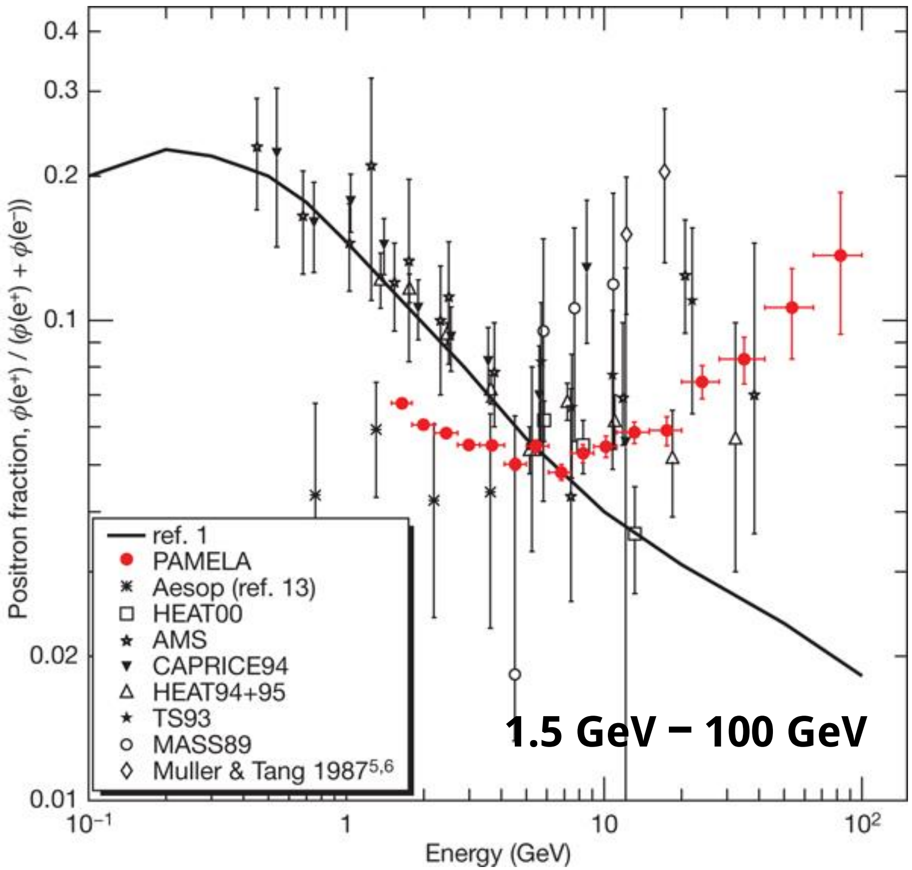


Dark Matter annihilations may produce additional particles of antimatter

Simultaneous high precision measurement of p, $\bar{p}$, e^+, e^- … with the same detector, for the same period of time, provide unbiased comparisons which are critical for the cosmic rays and fundamental physics

The positron fraction

O. Adriani *et al*, Nature, **458**, 607-609 (2009)]



Several experiments in the last decades, and more recently FERMI-LAT and PAMELA, reported an increase in the positron fraction above ~10 GeV

$$\frac{\phi_{e^+}}{\phi_{e^+} + \phi_{e^-}}$$

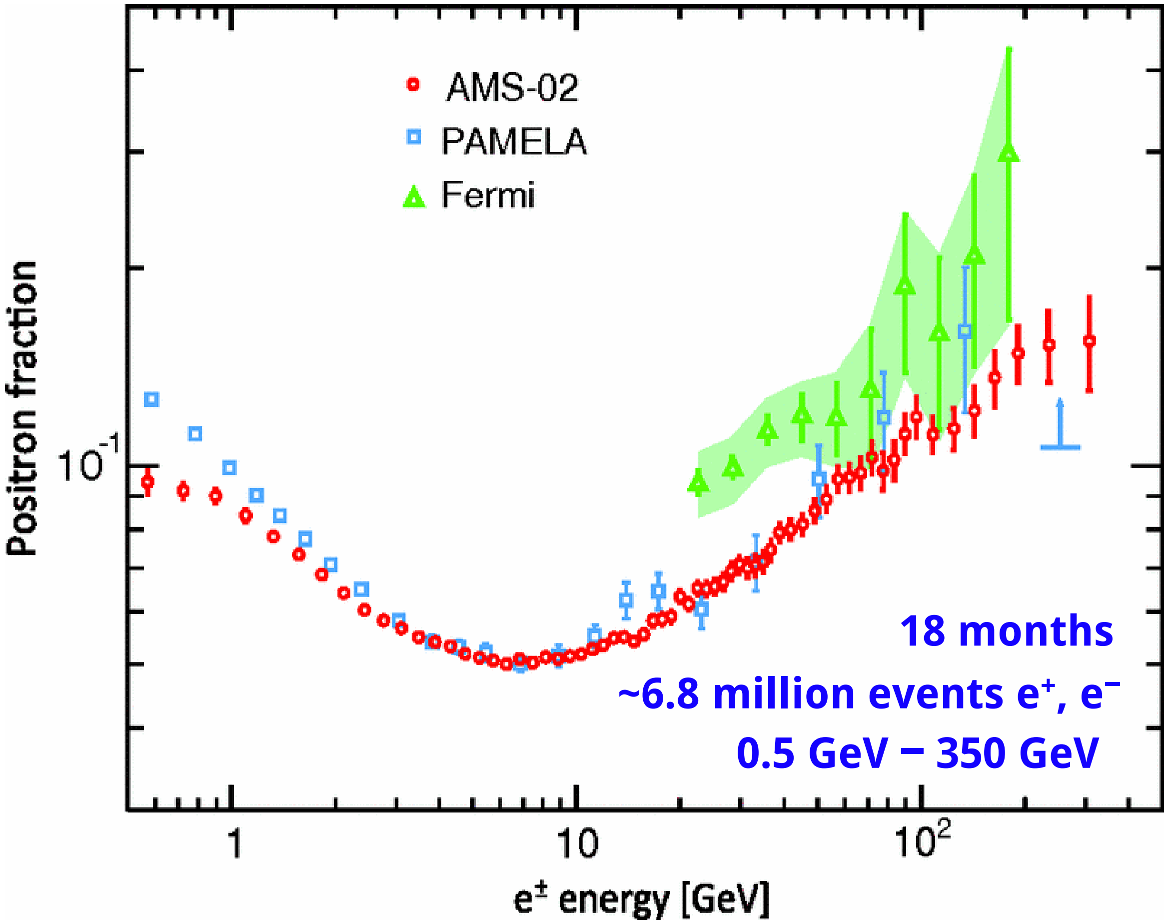
This rise was not compatible with only the ordinary secondary production of positrons and was a hint of Dark Matter

Increase statistics and energy range of the measurment

The AMS-02 positron fraction

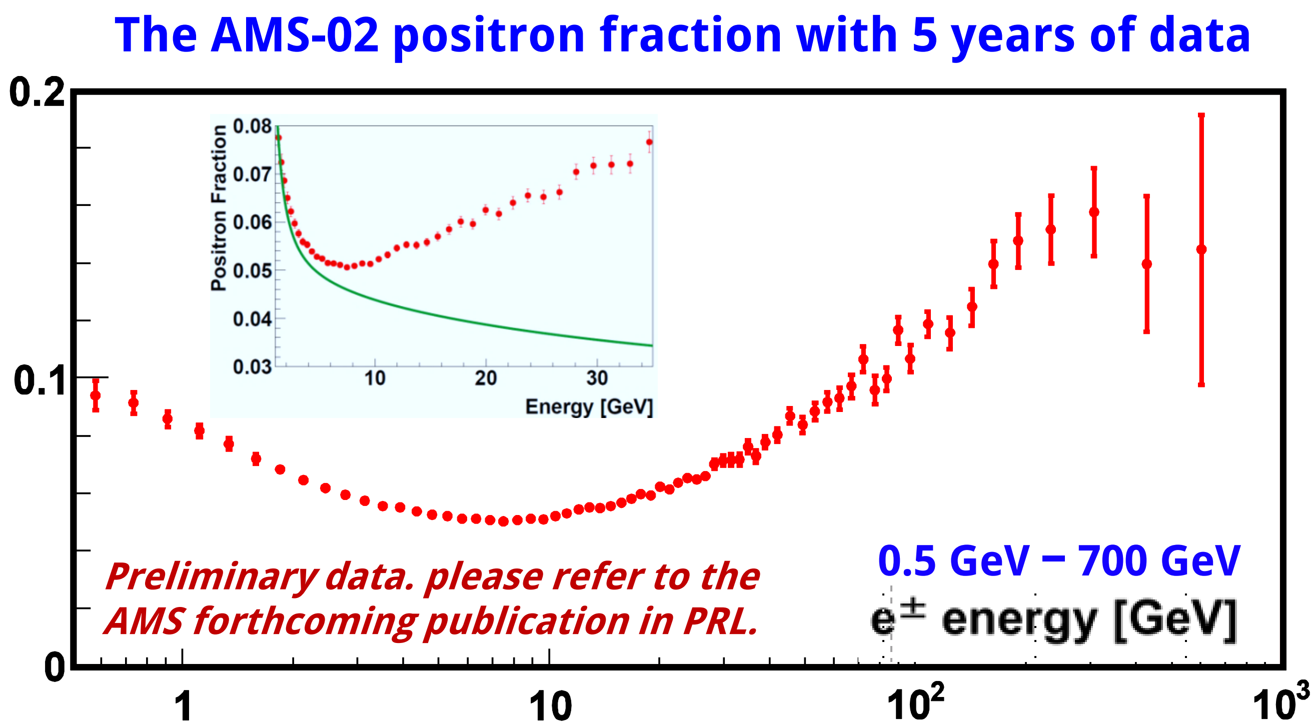
First result from AMS-02

[M. Aguilar *et al.*, Phys. Rev. Lett. **110**, 141102 (2013)]



… later extended to 500 GeV

The AMS-02 positron fraction

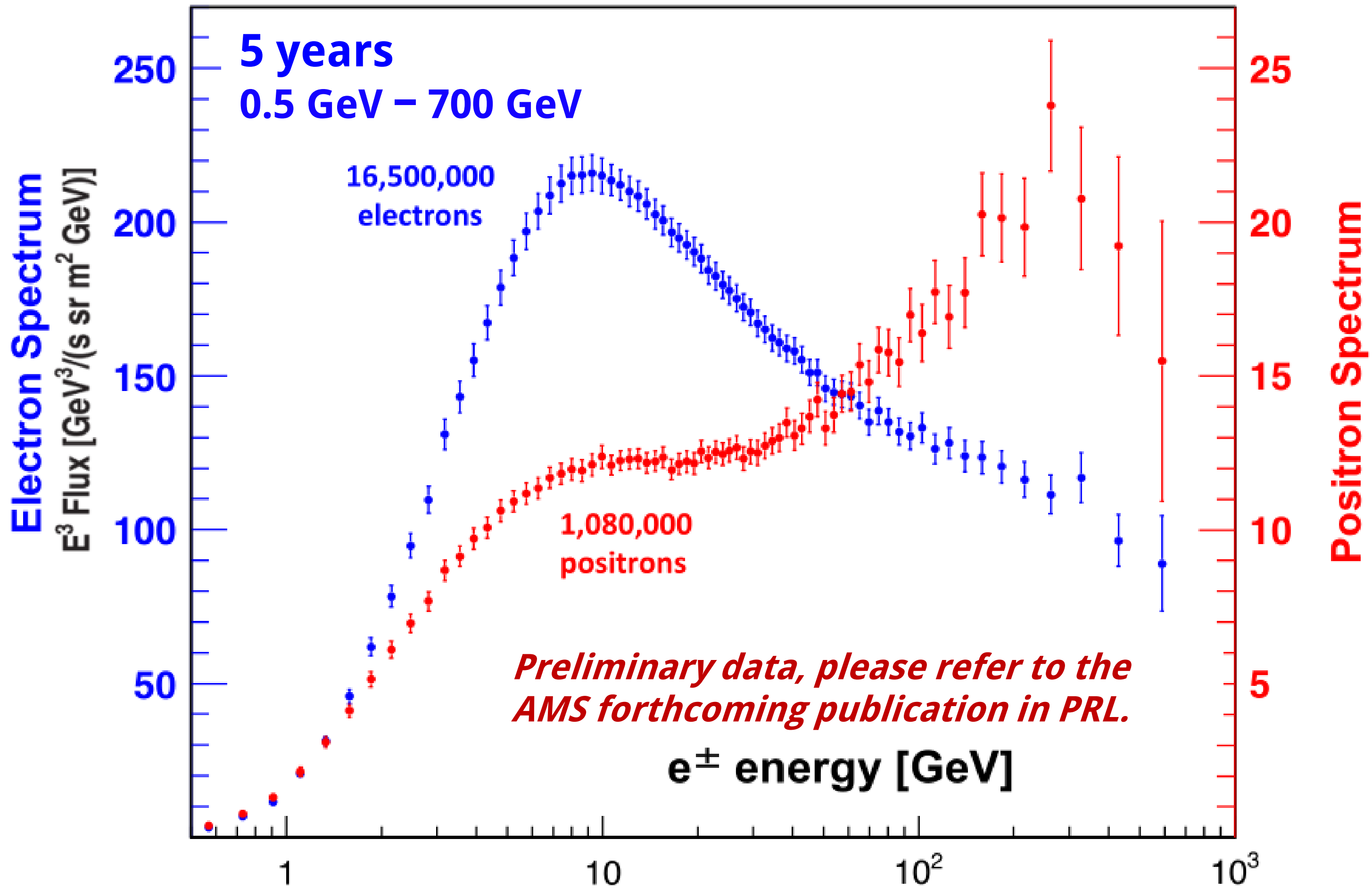


Precise measurement by AMS-02 allows to characterize the behavior of the PF:

- At the lowest energies, the positron fraction decreases rapidly.
- Above ~8 GeV it increases steadily with energy
- No existence of sharp structures
- Above ~200 GeV the positron fraction is no longer increasing with energy

The AMS-02 e⁻ and e⁺ fluxes

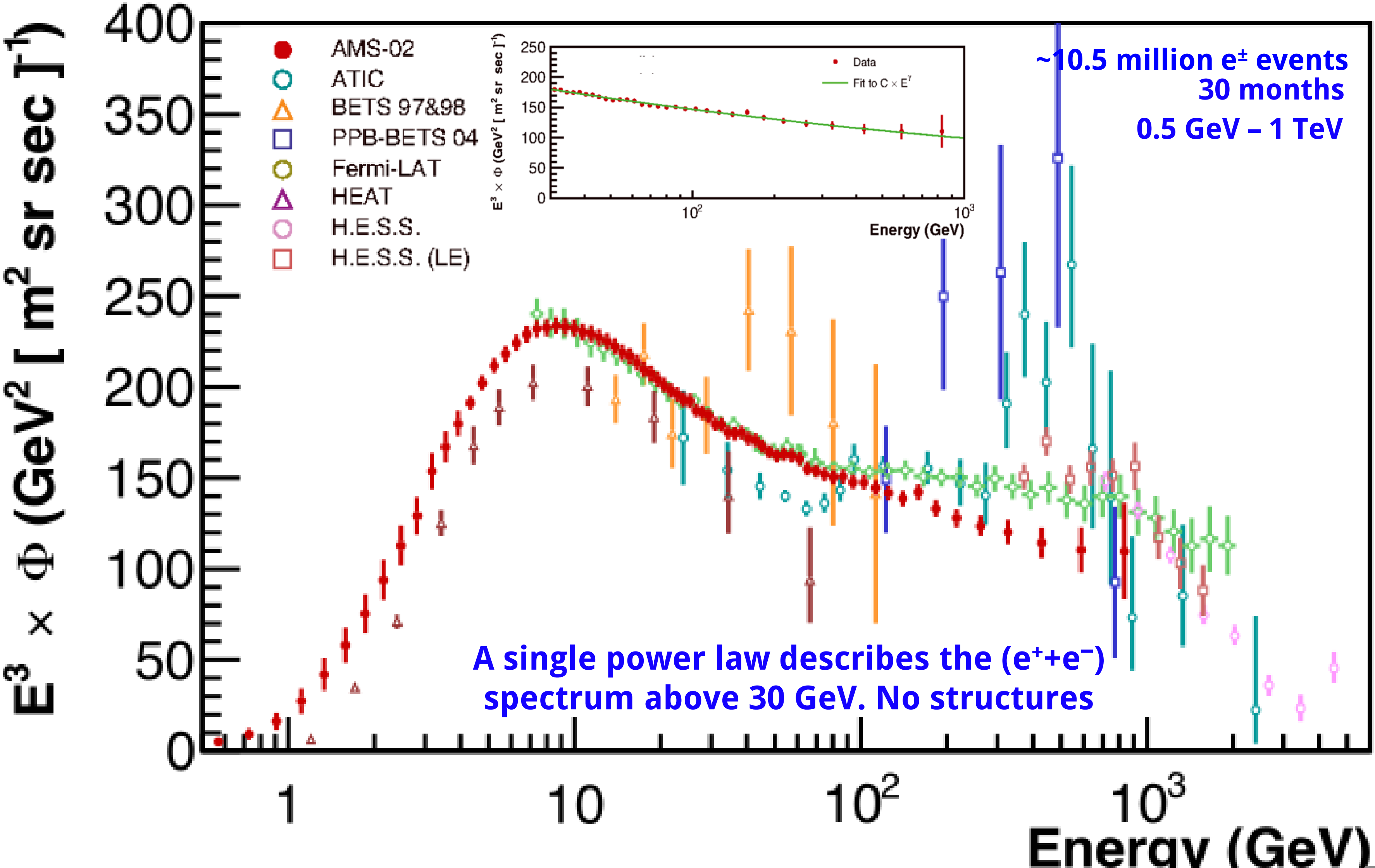
Precise measurement of Electron and Positron spectra is studied separately



The rise in the positron fraction from 20 GeV is due to an excess of positrons, not to the loss of electrons (the positron flux is harder)

The AMS-02 (e^- + e^+) flux

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

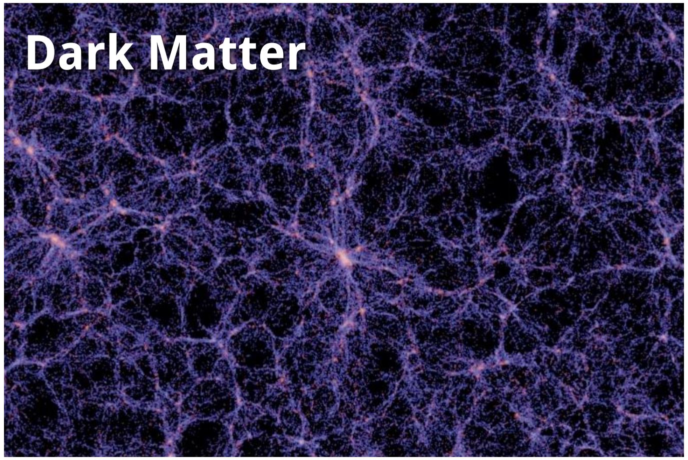


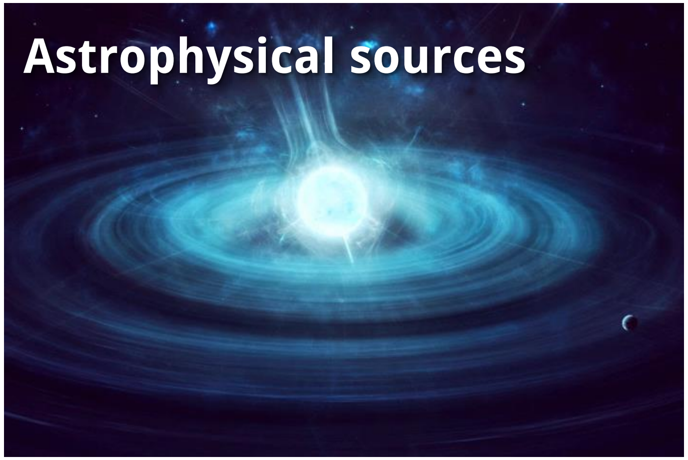
Interpretations of the 'excess'

Modified propagation of cosmic rays

It needs to explain not only the positron fraction but also the observation in many other channels

Primary sources of positrons

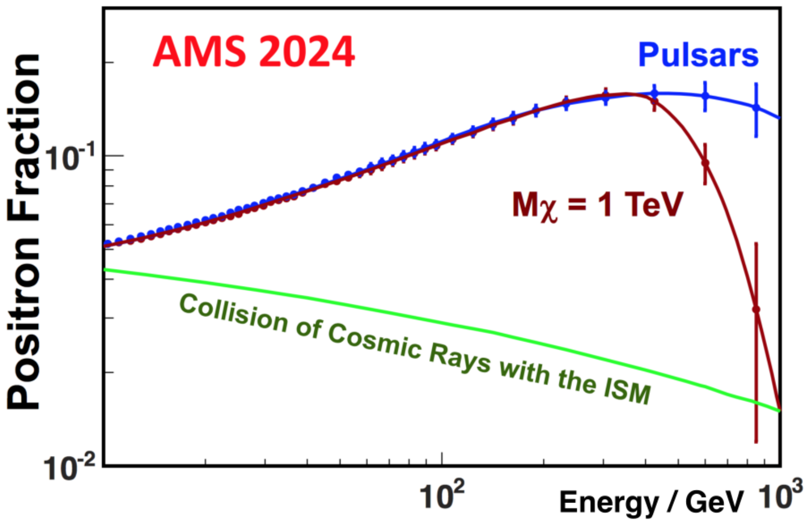


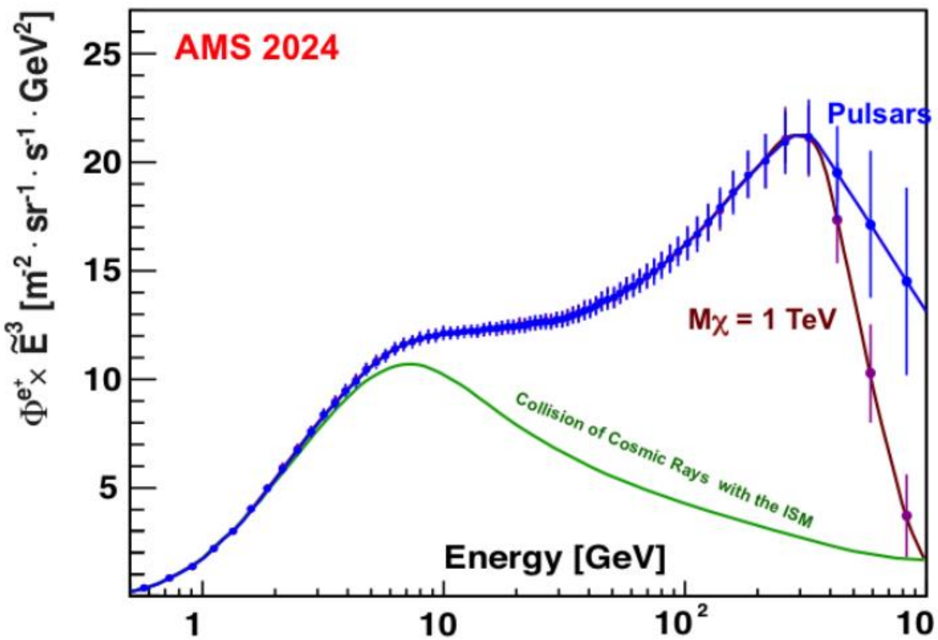


- **Increase statistics and energy range**
- **Study of other anti-particle channels**
- **Better understanding of astrophysical processes from other measurements (nuclei, secondary/primary…)**

Interpretations of the 'excess'

The rate at which it falls beyond the turning point may give information about the mechanism that originates the increase in the positron fraction



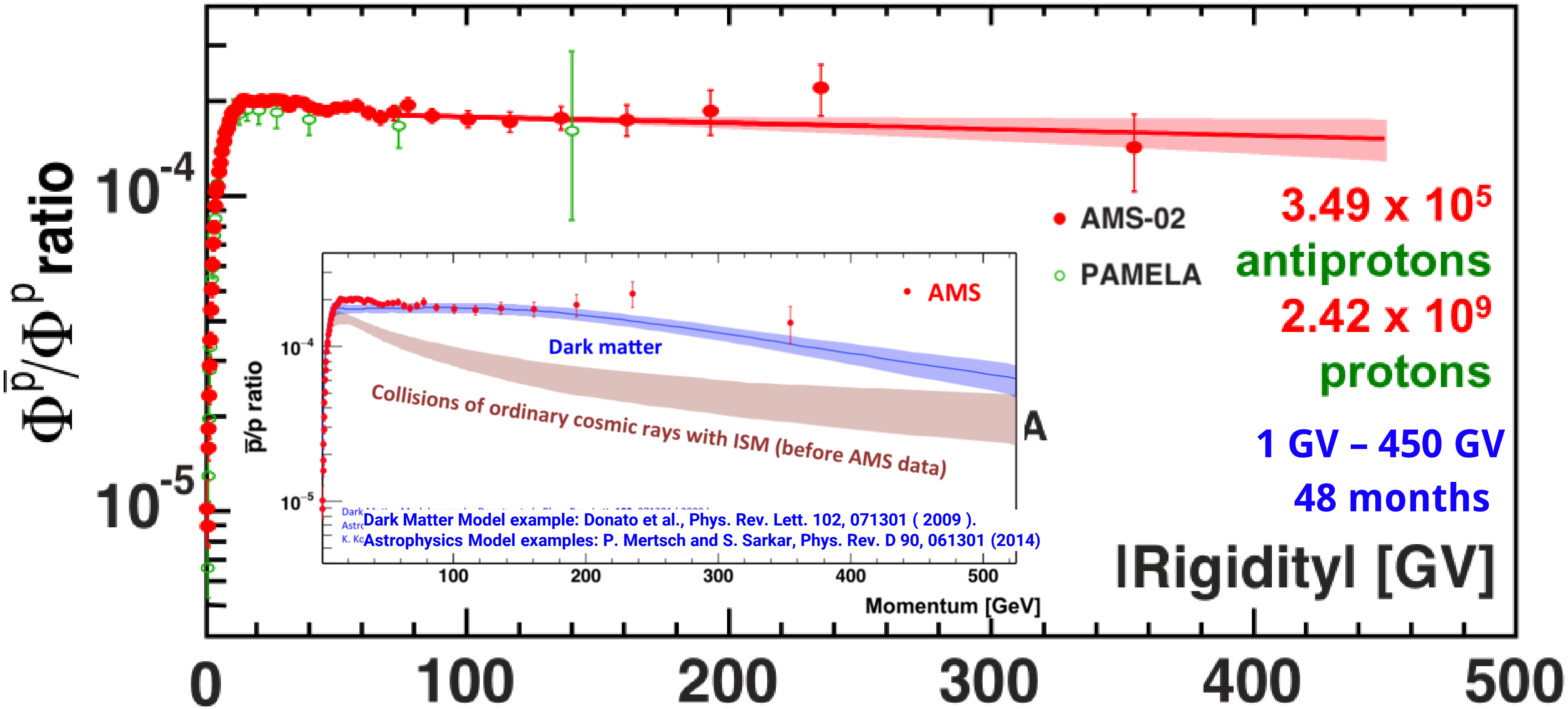


Astrophysical point sources like nearby pulsars may imprint a higher level of anisotropy on the arrival directions of energetic positrons than a smooth dark matter halo

The AMS-02 $\bar{p}/p$ flux ratio

[M. Aguilar *et al.*, Phys. Rev. Lett. **117**, 091103 (2015)]

Antiproton to proton flux ratio is rigidity independent above 60 GV

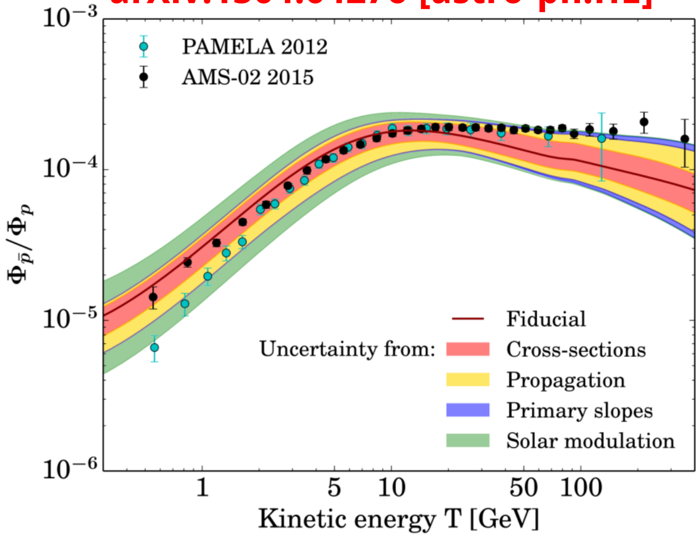


An excess in the antiproton to proton ratio with respect to expectations from secondary production cannot come from pulsars.

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

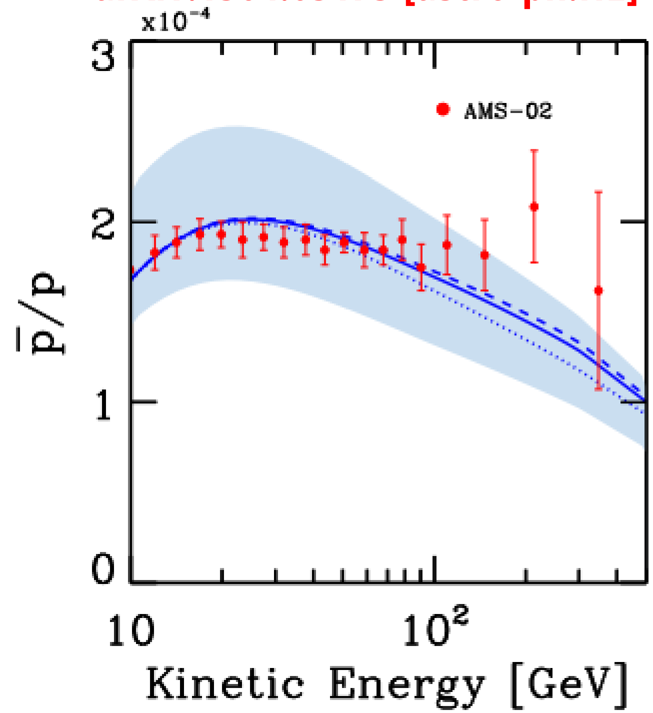
Phenomenological models of the $\bar{p}/p$

arXiv:1504.04276 [astro-ph.HE]

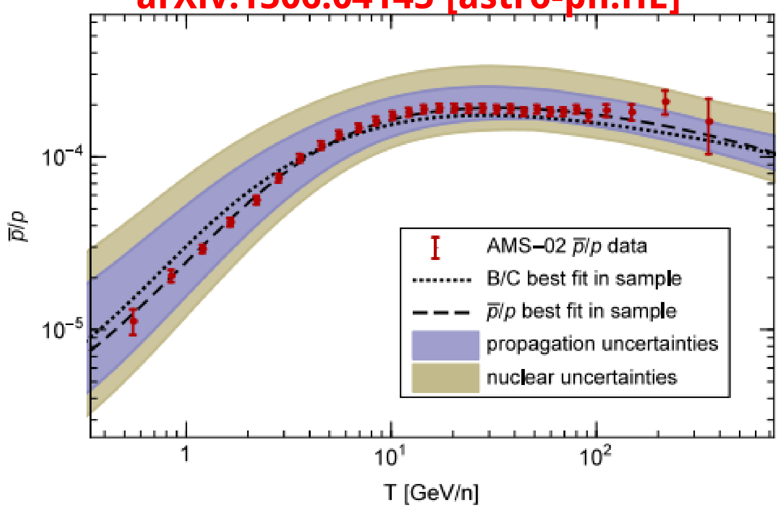


The accuracy of the AMS measurements challenges the current knowledge of cosmic background

arXiv:1504.05175 [astro-ph.HE]



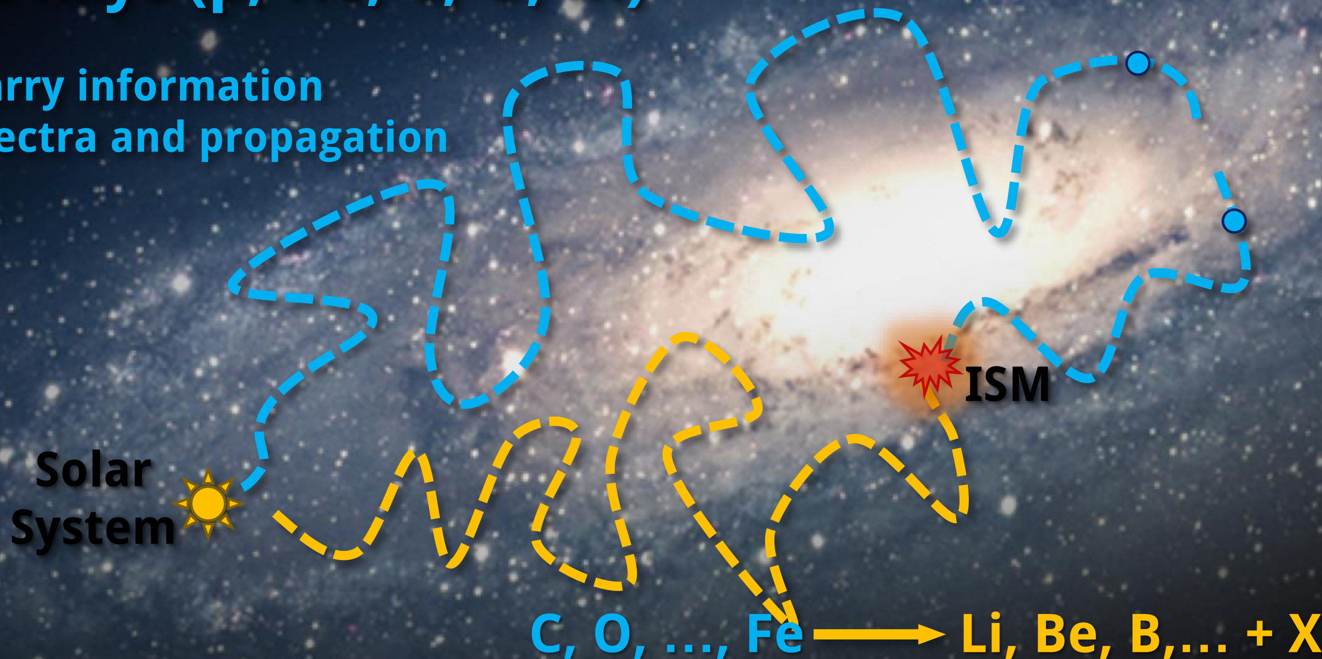
arXiv:1506.04145 [astro-ph.HE]



Primary and secondary CRs

Primary Cosmic Rays (p, He, C, O, ...)

Primary cosmic rays carry information
about their original spectra and propagation

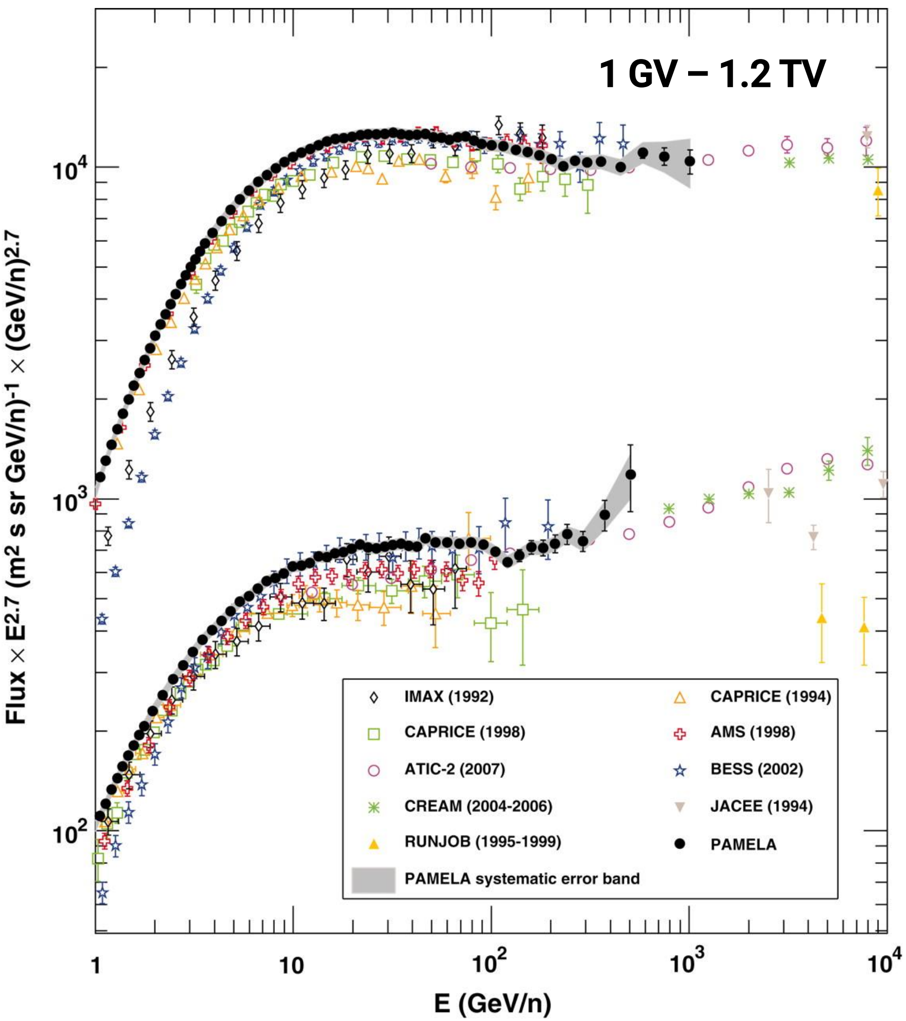


Secondary Cosmic Rays (Li, Be, B, ...)

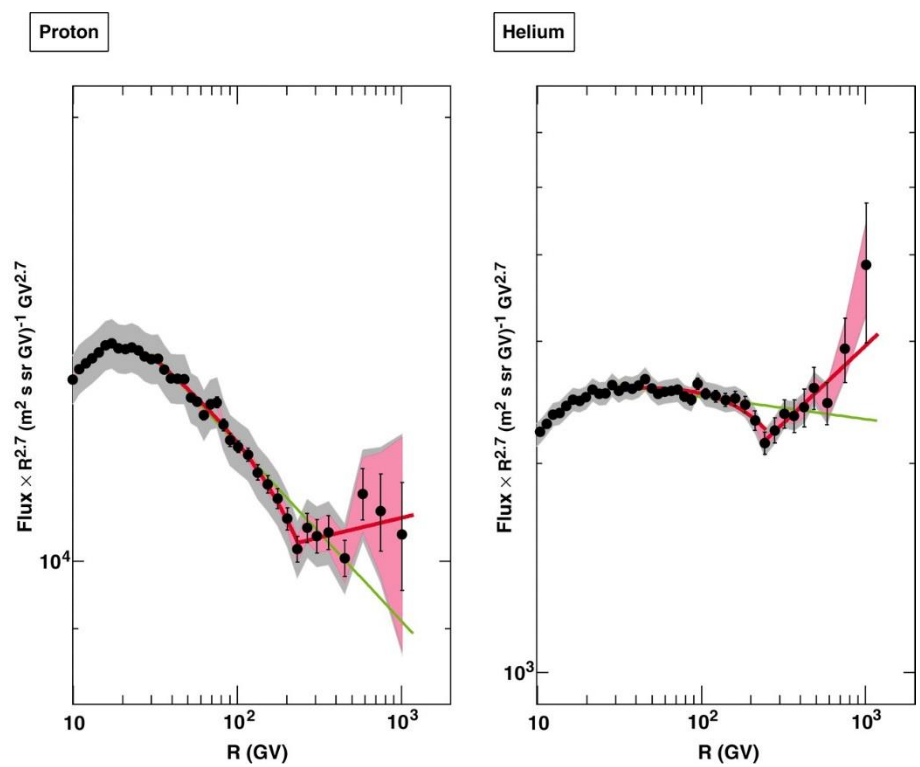
Secondary cosmic rays carry information about propagation
of primaries, secondaries and interactions in the ISM

The hint of a break in the spectrum

PAMELA: “At 230 to 240 GV, the proton and helium data exhibit an abrupt spectral hardening.”



PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra
O. Adriani *et al. Science*, **332**, 69-72
DOI: 10.1126/science.1199172 (2011)

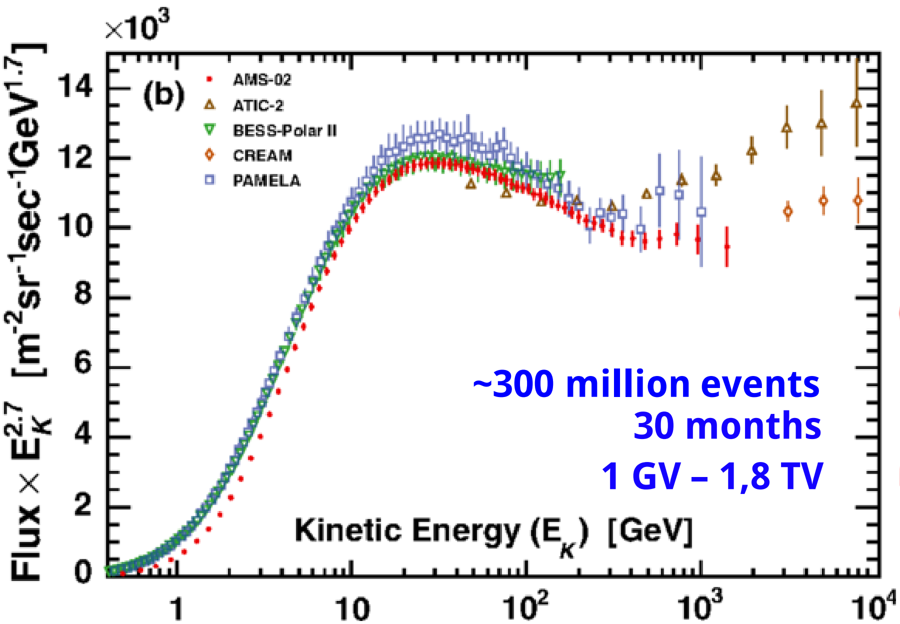


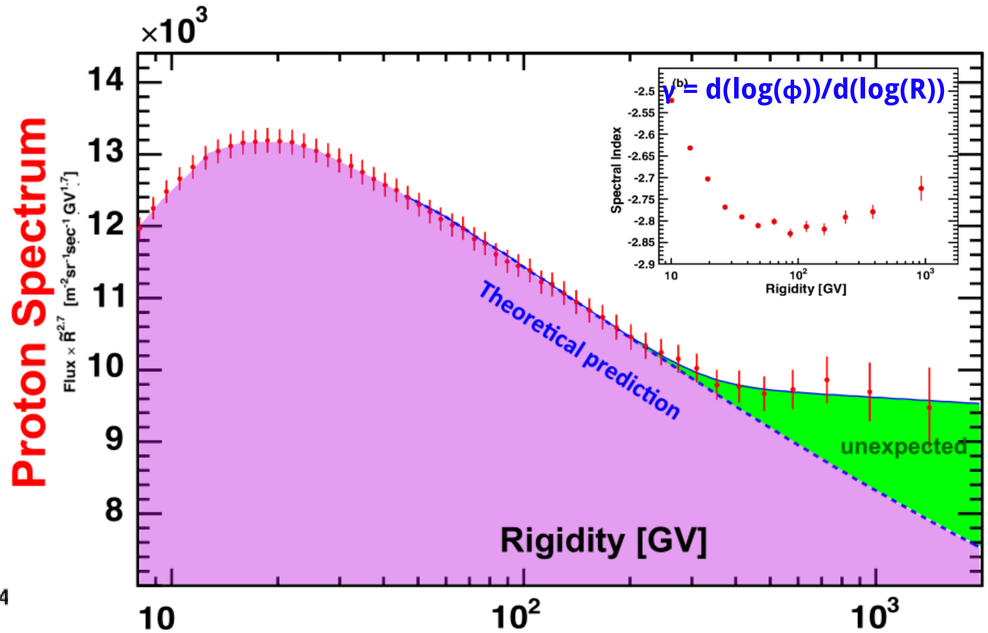
The AMS-02 proton flux

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

Proton flux cannot be described by a single power law

The spectral index progressively hardens at rigidities larger than 100 GV





Possible explanations for the spectral hardening:

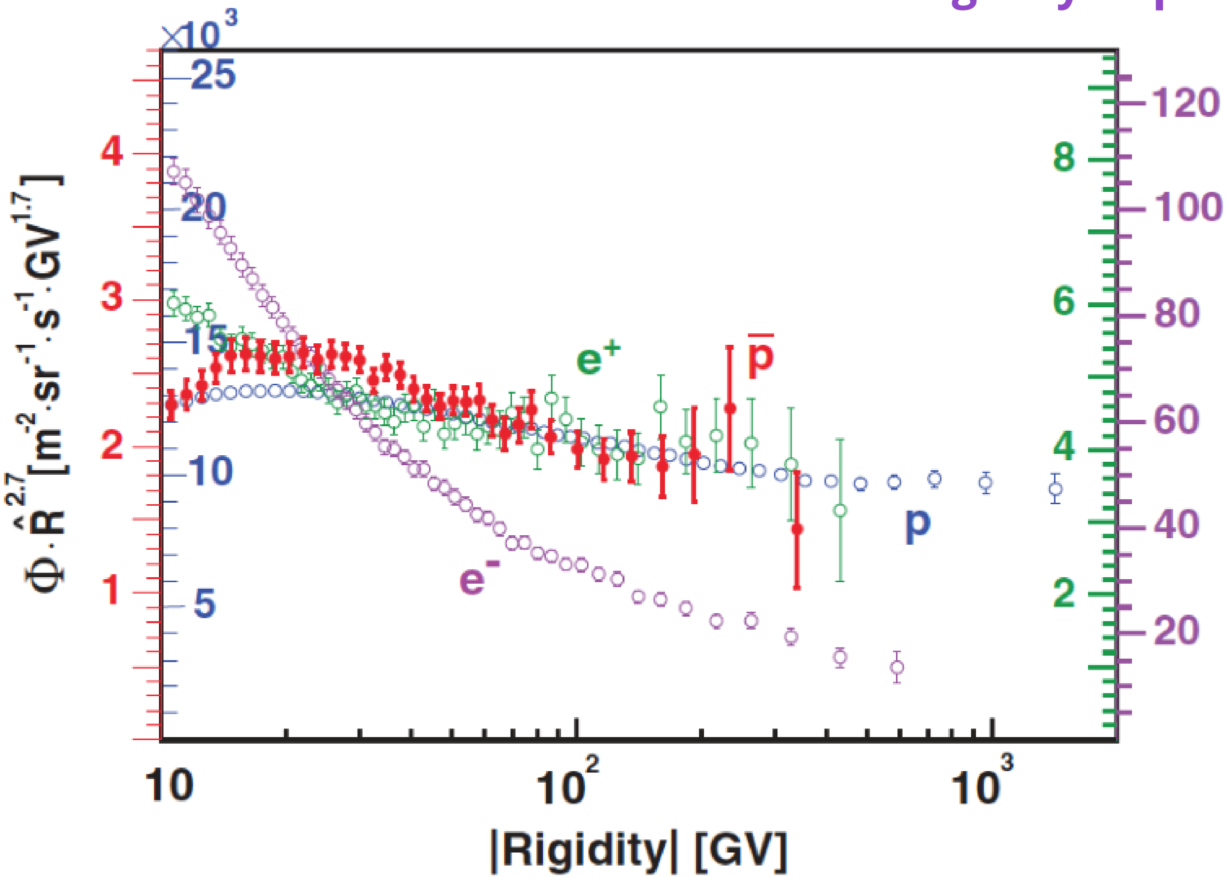
- Local CR sources
- Different acceleration mechanisms at source
- Propagation effects: local structures in the GMF…

Studies in the directionality of the high rigidity sample may favor some of these explanations

Rigidity dependence of e^-, e^+, p, $\bar{p}$

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

The rigidity dependences of elementary particles e^+, $\bar{p}$, p
are identical from 60-500 GV. e^- has a different rigidity dependence

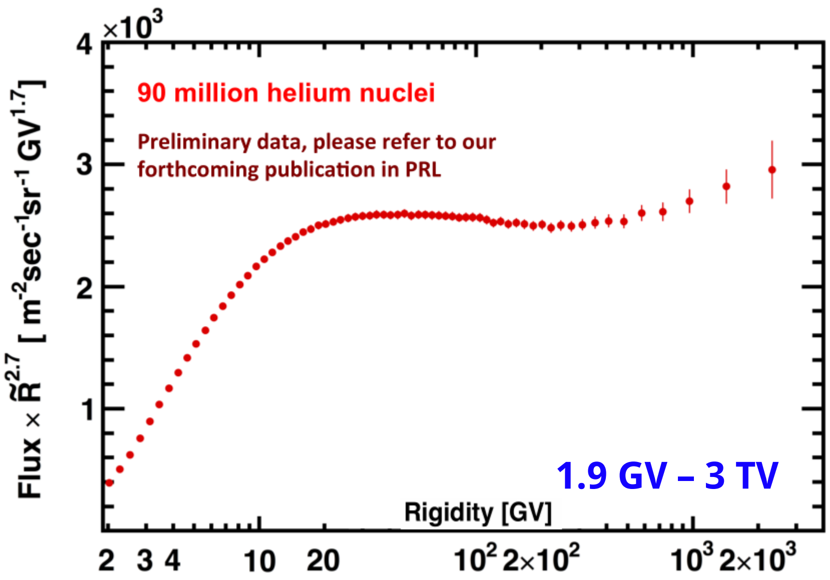


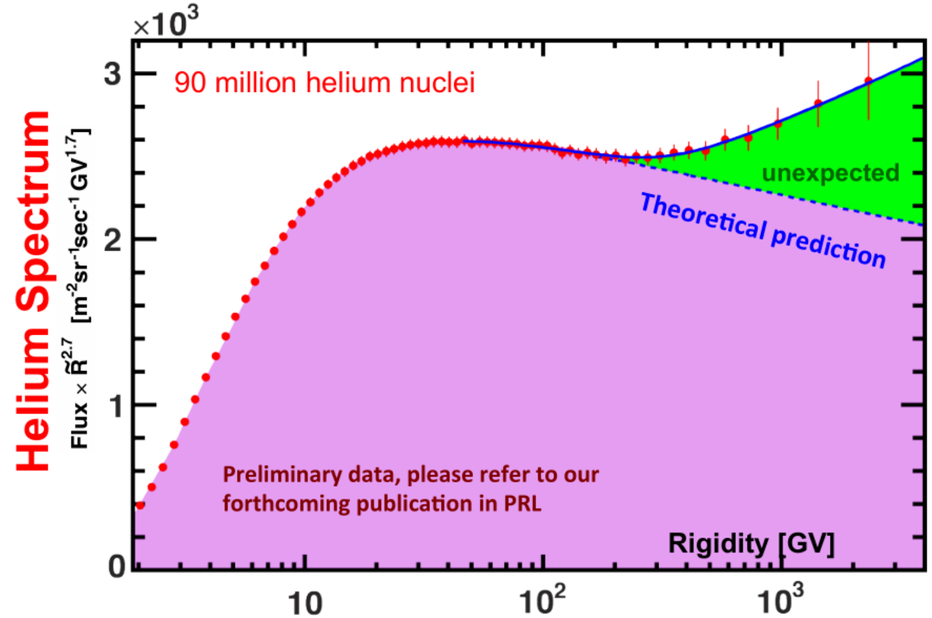
It is very challenging for any model to describe simultaneously all four spectra

The AMS-02 helium flux

Helium flux cannot be described by a single power law

5 year measurement of the Helium flux

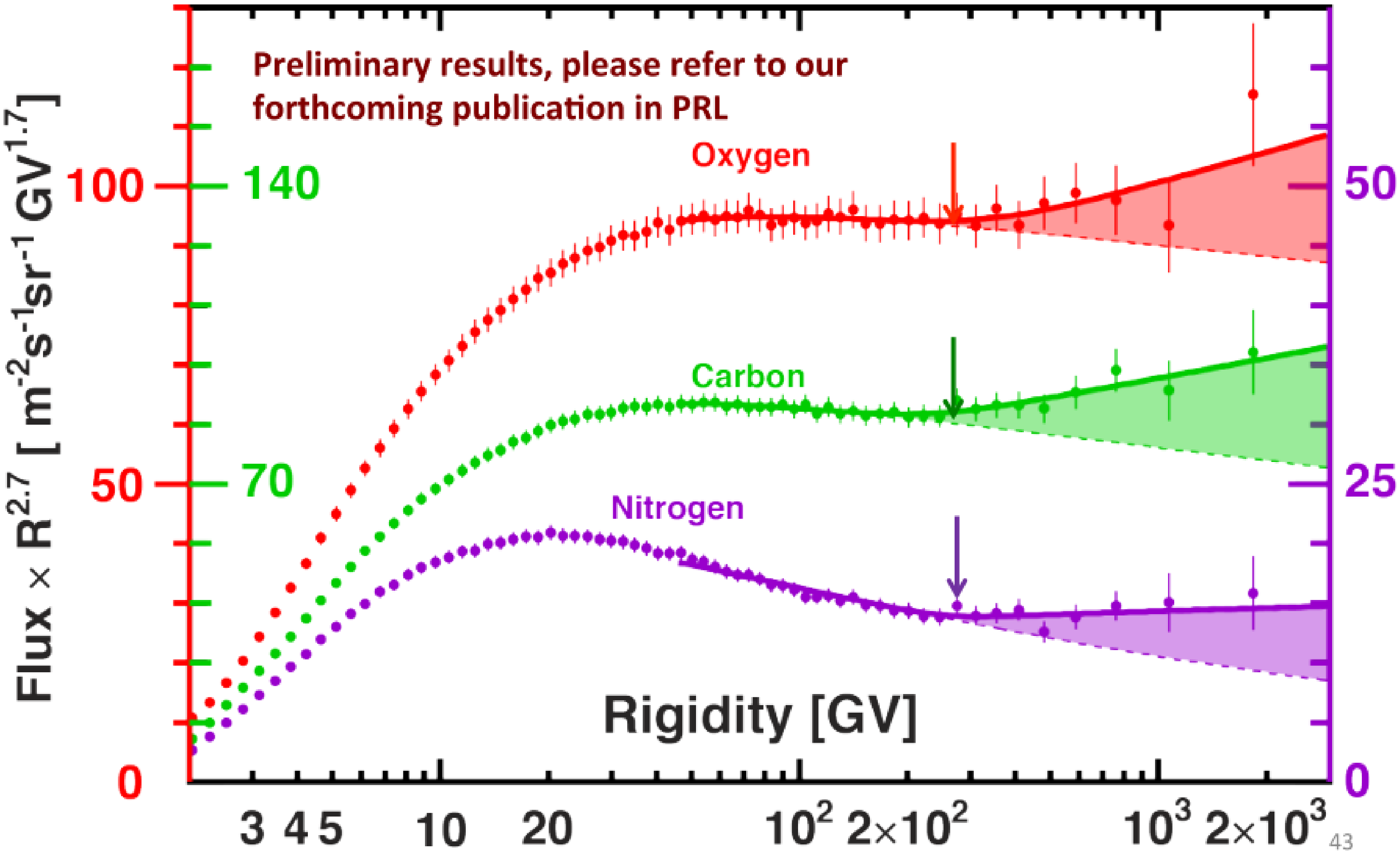




The AMS-02 C, N and O fluxes

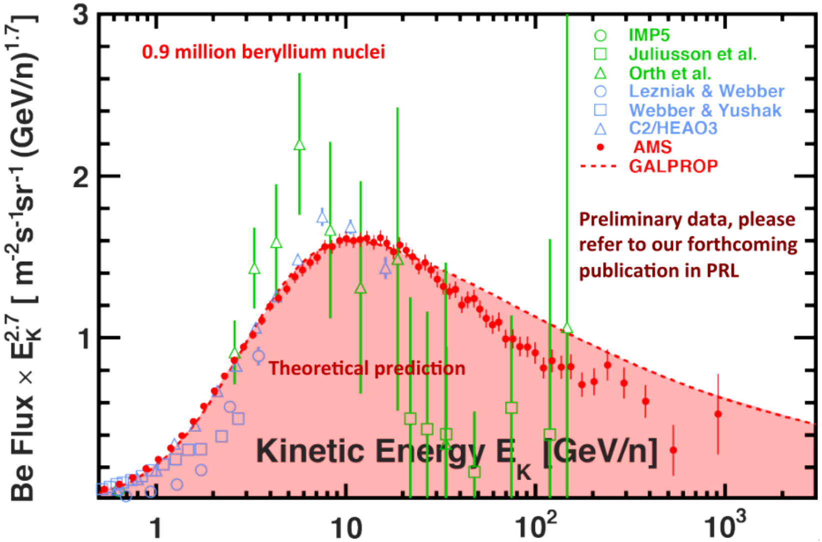
The spectra of Carbon, Nitrogen and Oxygen do not follow the traditional single power law

5 year measurement of the Carbon, Nitrogen and Oxygen fluxes

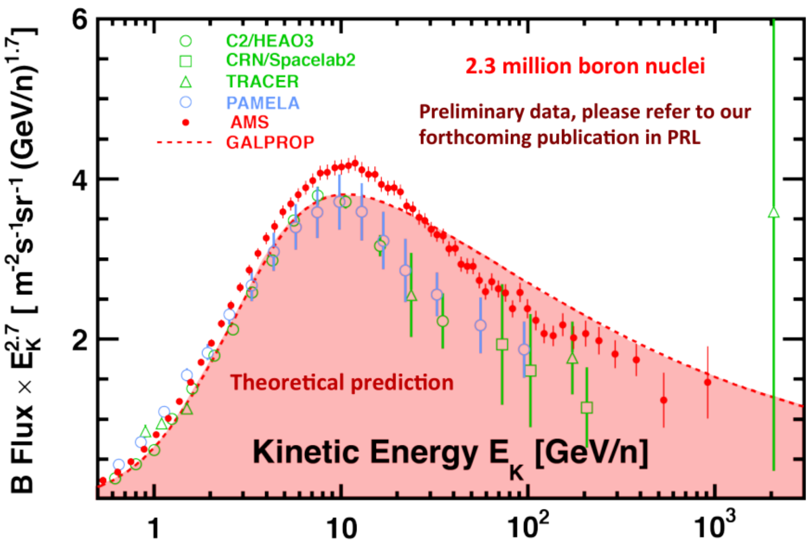


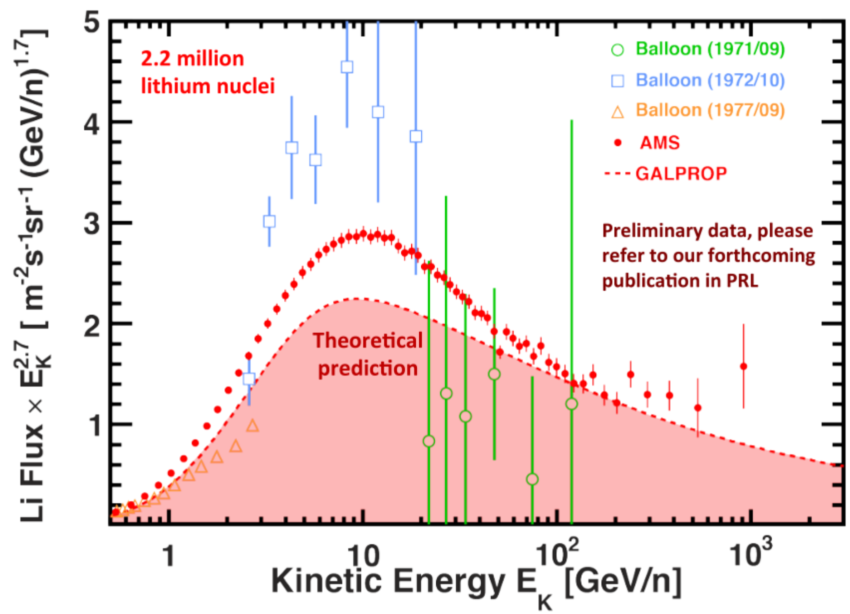
The AMS-02 Li, Be and B fluxes

5 year measurement of the Lithium, Beryllium and Boron fluxes



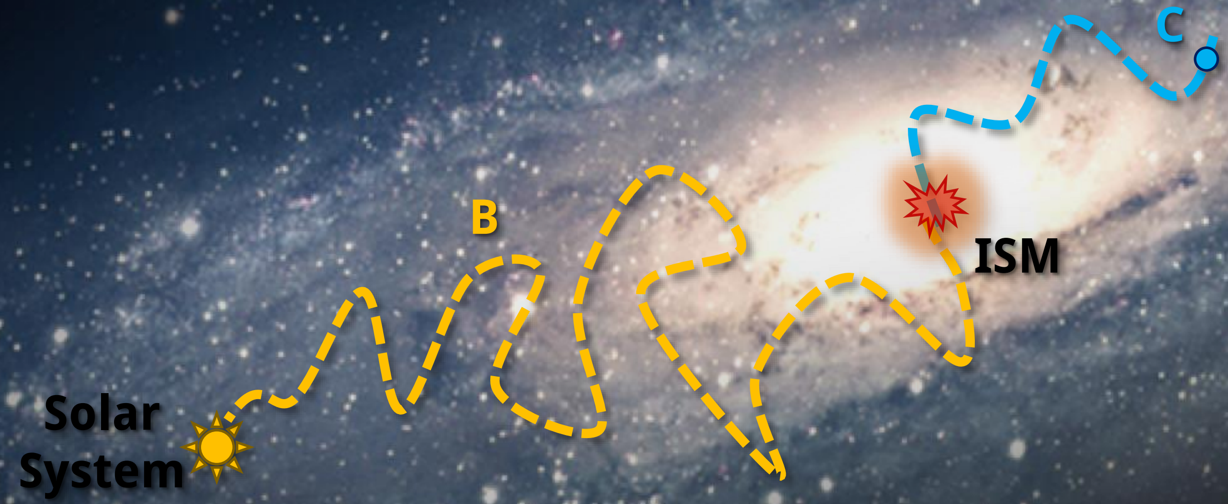
Precise measurements of AMS-02 challenge the current understanding of CRs origin and propagation





Secondary-to-primary flux ratios

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



- **Cosmic ray propagation is commonly modeled as a fast moving gas diffusing through a magnetized plasma, characterized by a diffusion coefficient δ**
- **At high rigidities, models of the magnetized plasma predict different behavior for B/C = kR^δ**
  - **Kolmogorov turbulence model δ = -1/3**
  - **Kraichnan turbulence model δ = -1/2**

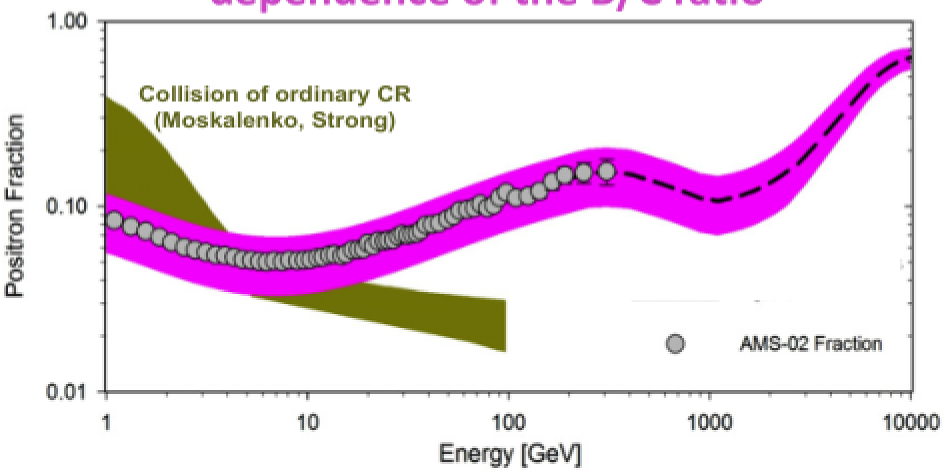
The AMS-02 B/C flux ratio

[M. Aguilar *et al.*, Phys. Rev. Lett. **117**, 231102 (2016)]

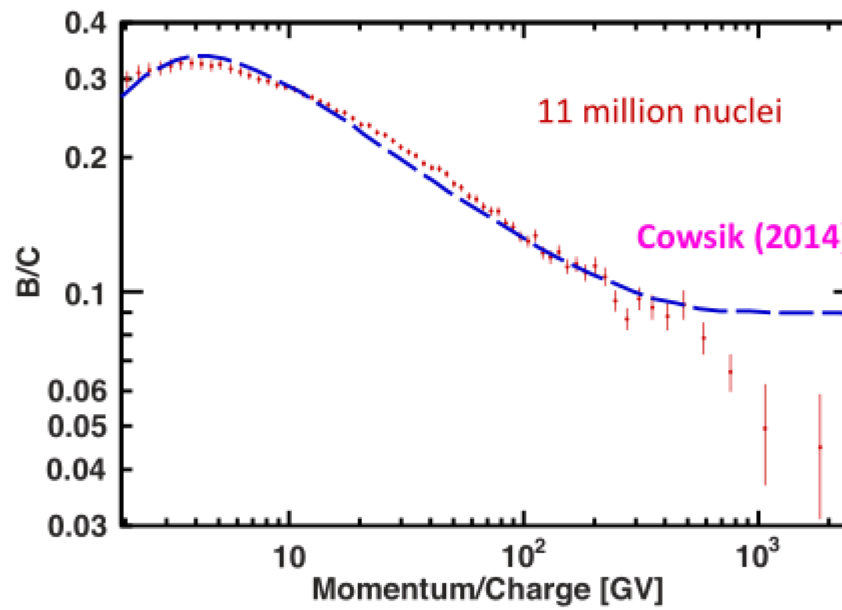
B/C measurement allows to constrain propagation parameters needed to understand the expected background from collisions with the ISM

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

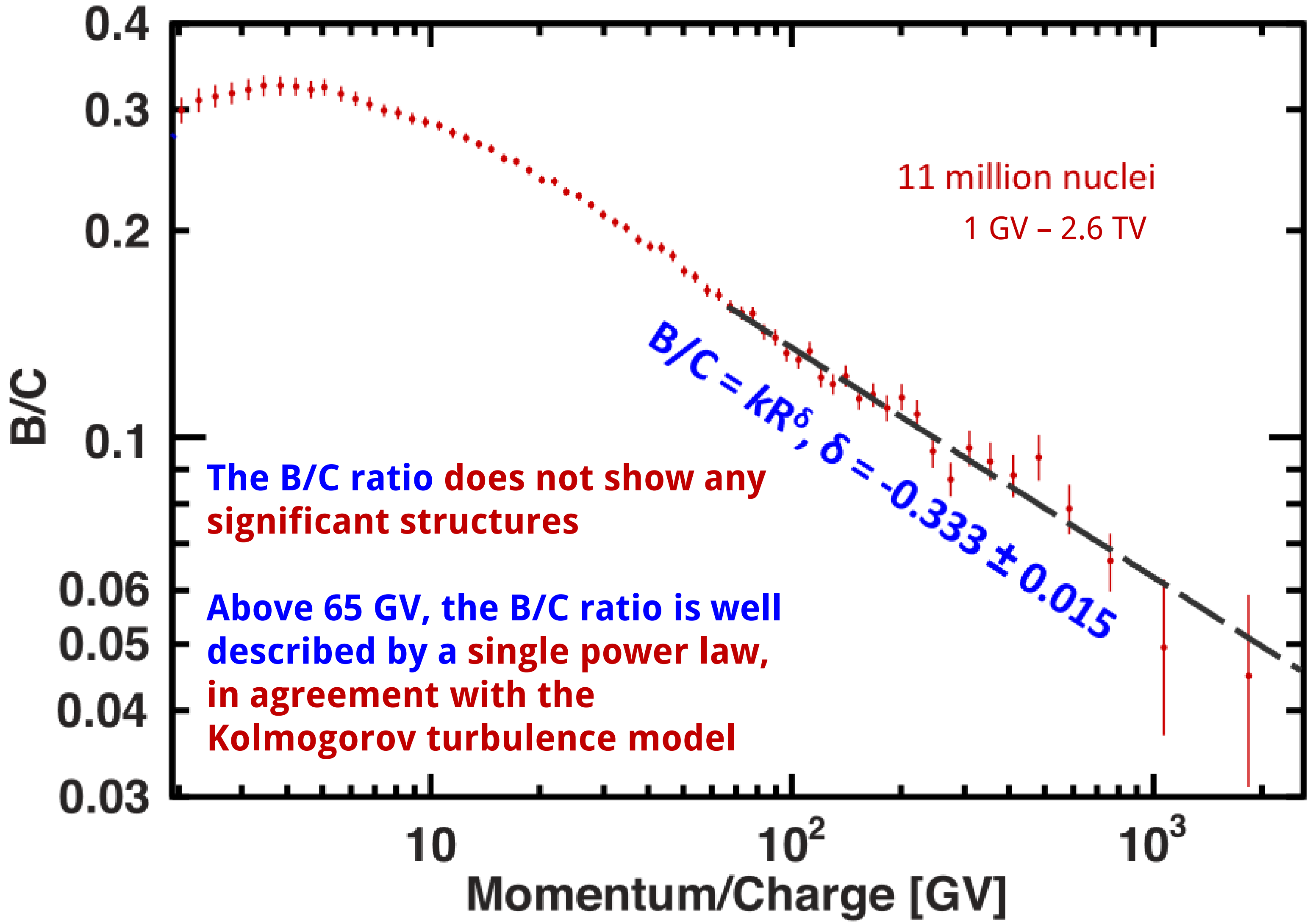


The AMS Boron-to-Carbon (B/C) flux ratio



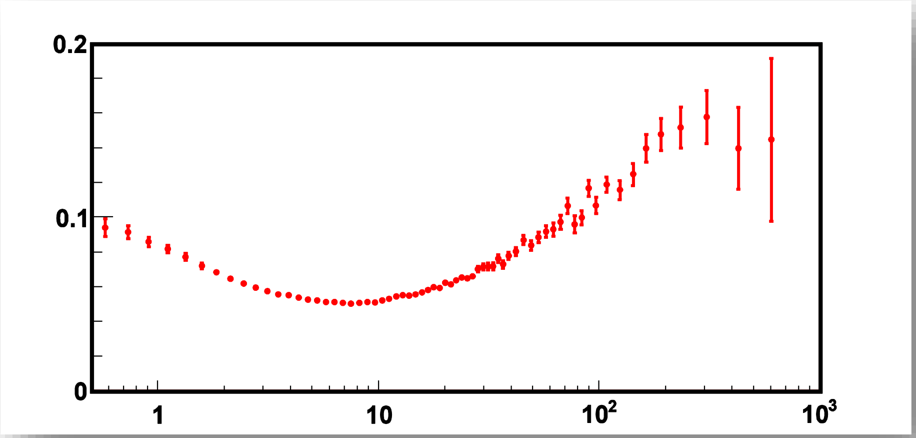
The AMS-02 B/C flux ratio

[M. Aguilar *et al.*, Phys. Rev. Lett. **117**, 231102 (2016)]



Summary

To understand the observation it is needed…



Summary

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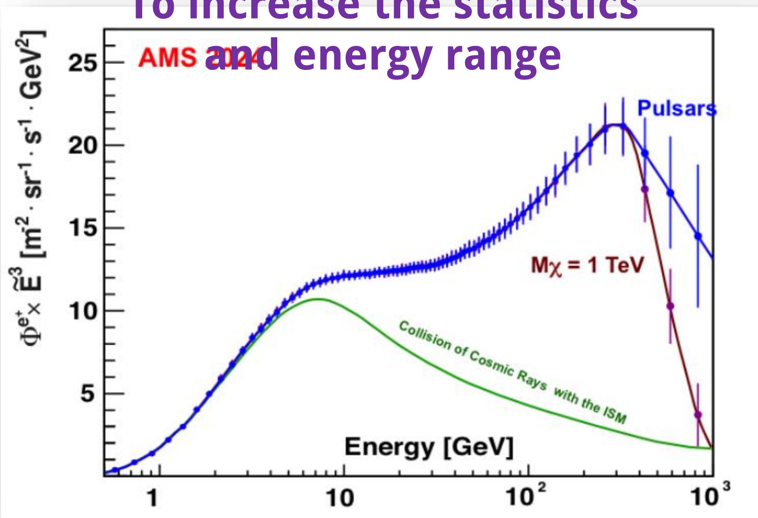
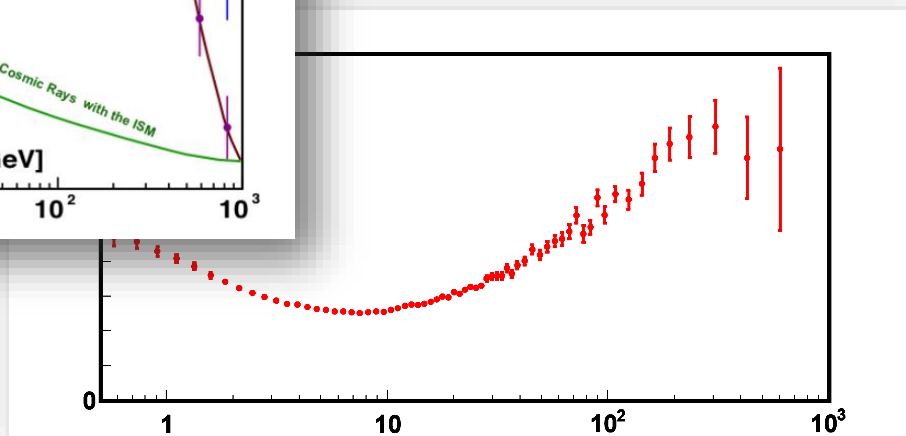
To increase the statistics and energy range





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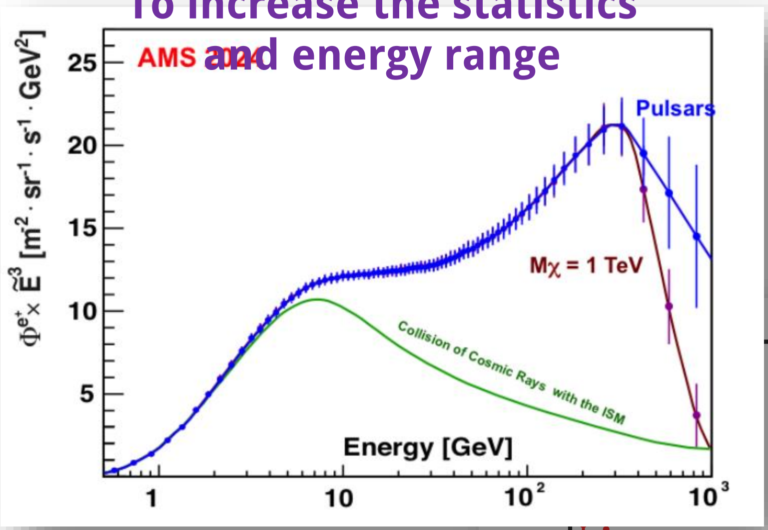
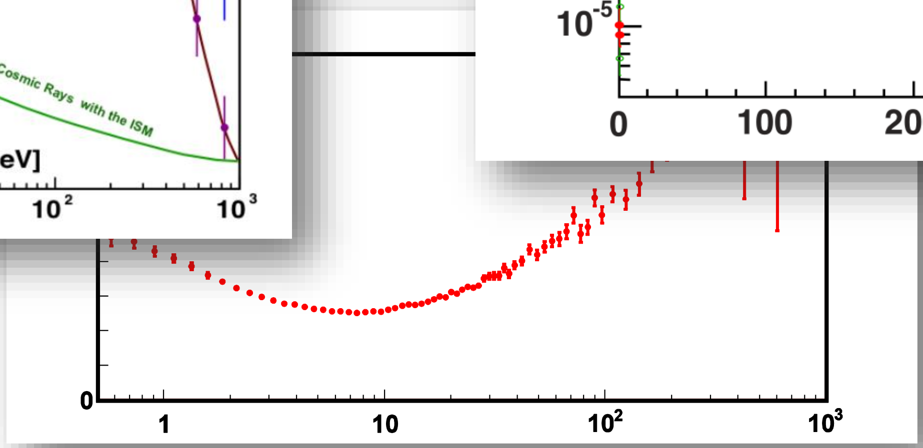
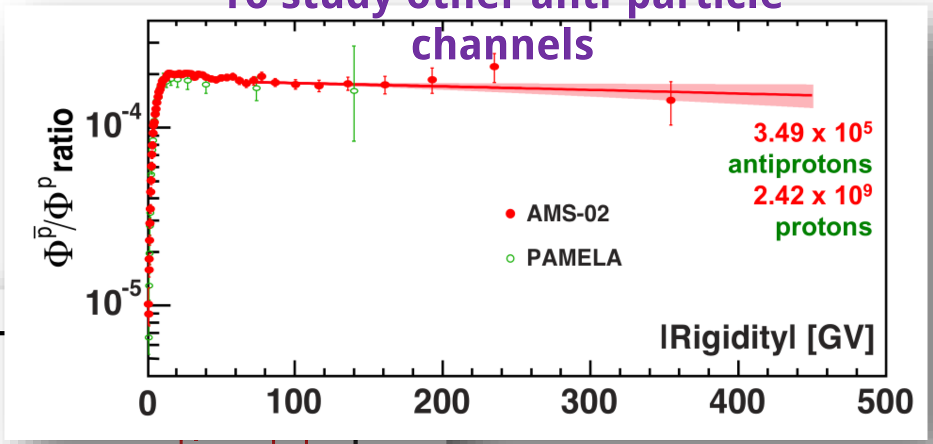




To study other anti-particle channels



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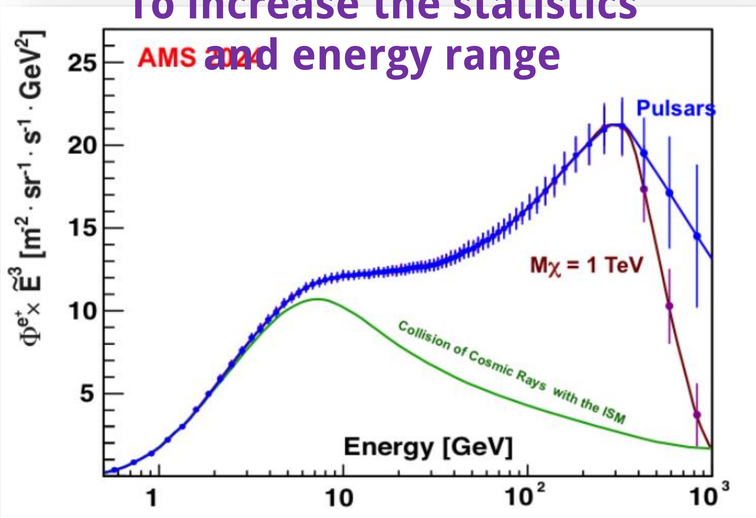

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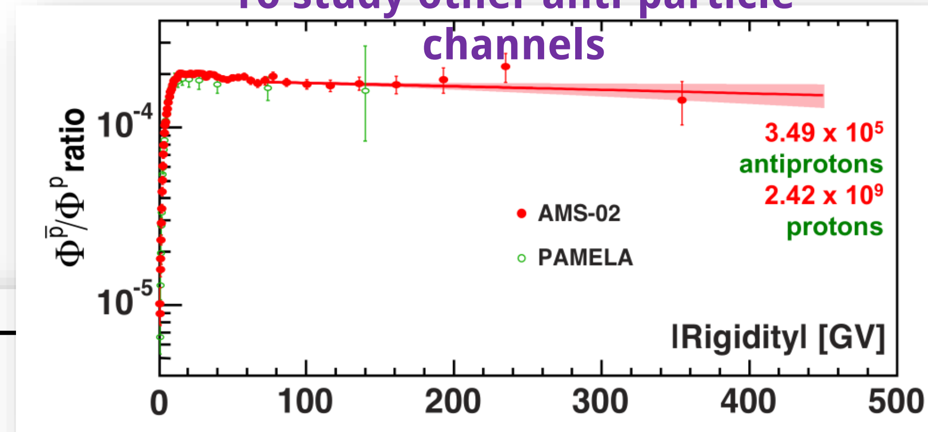
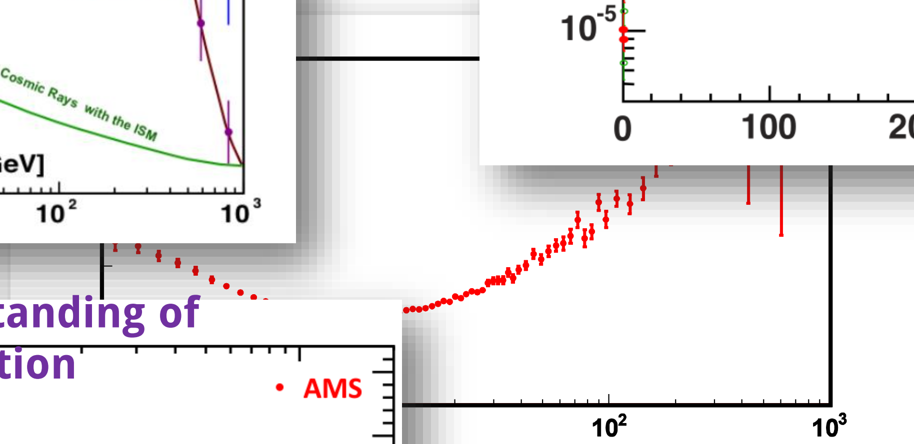
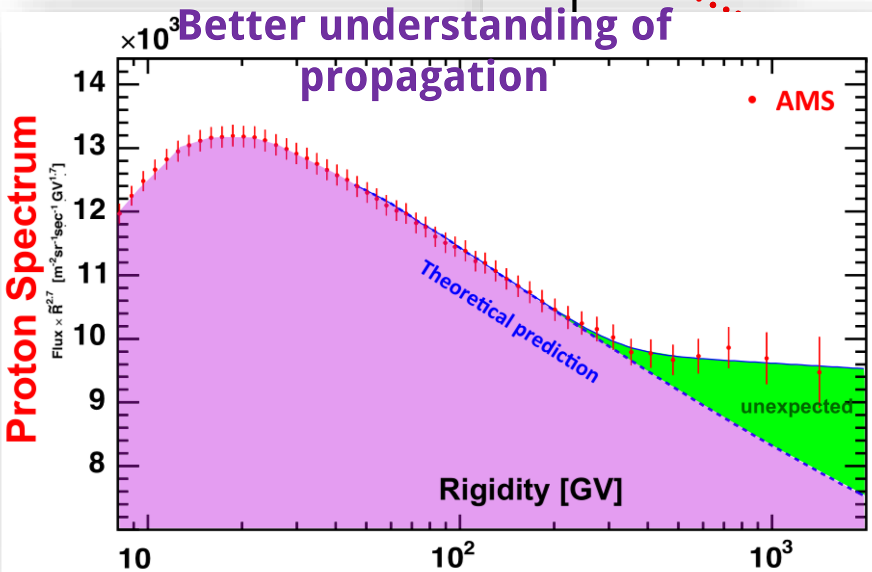




Better understanding of propagation



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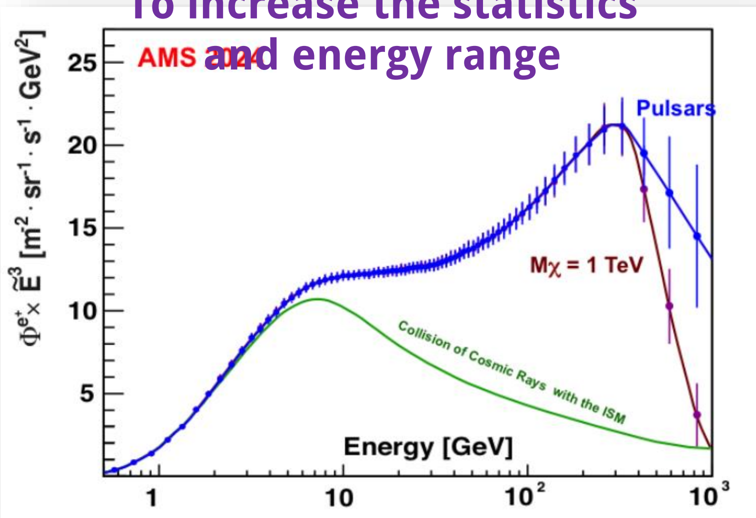

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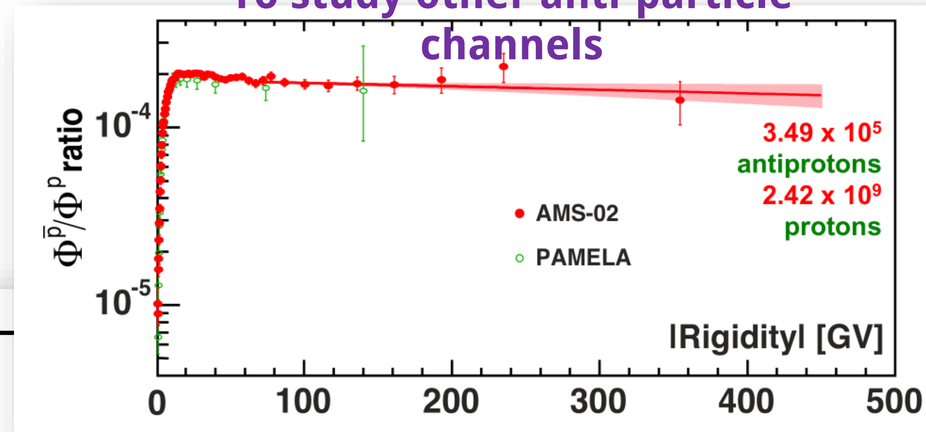

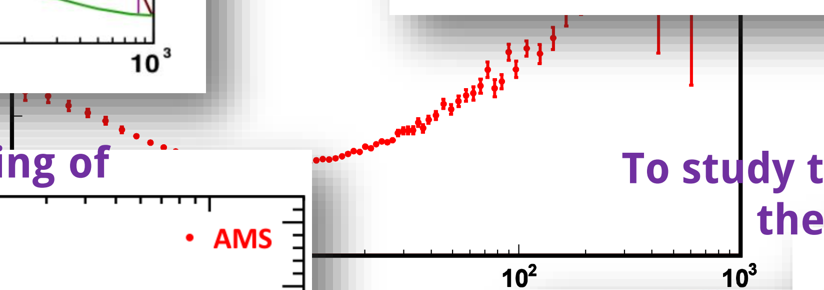

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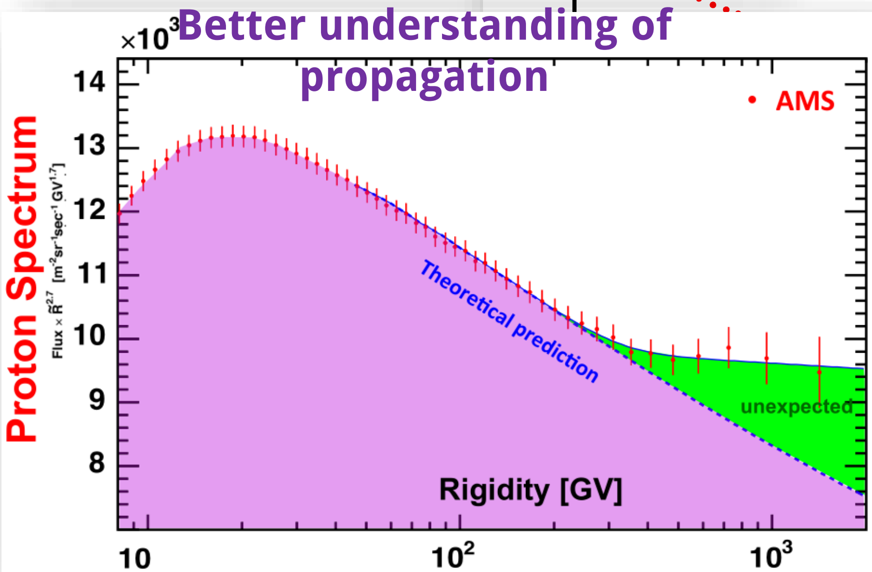
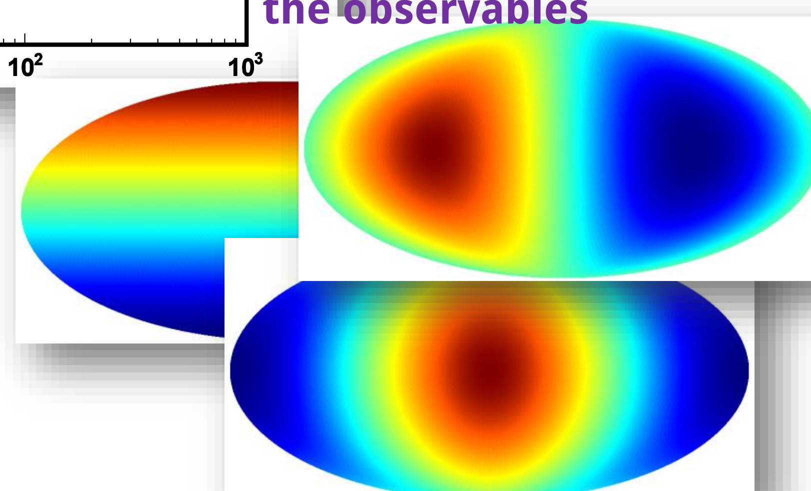


To study the directionality of the observables



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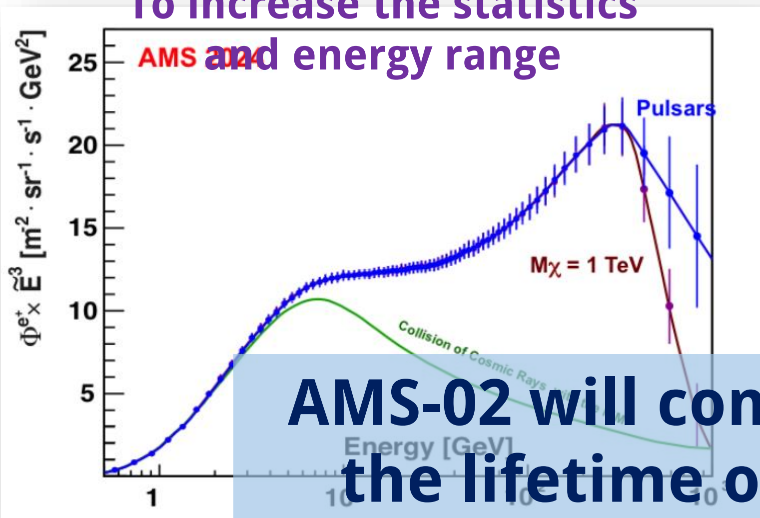

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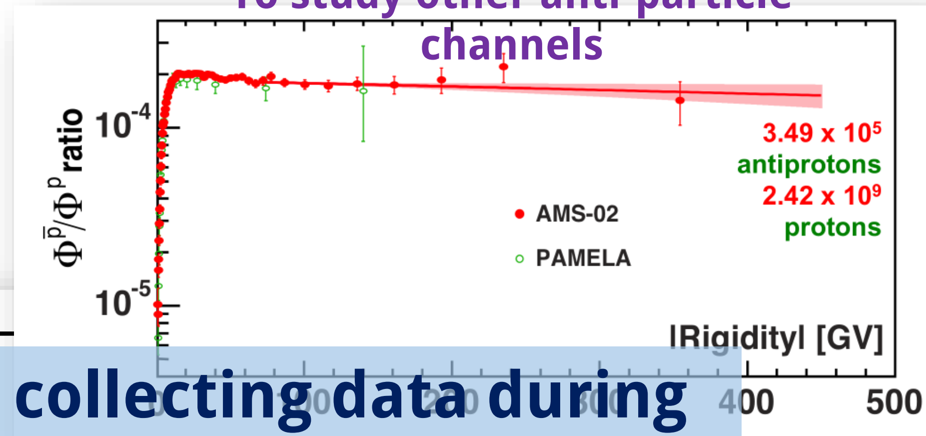
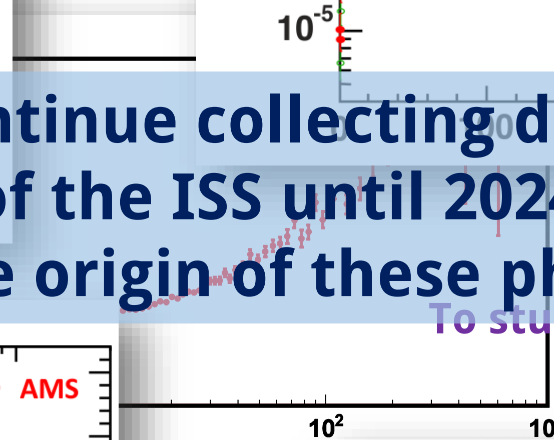
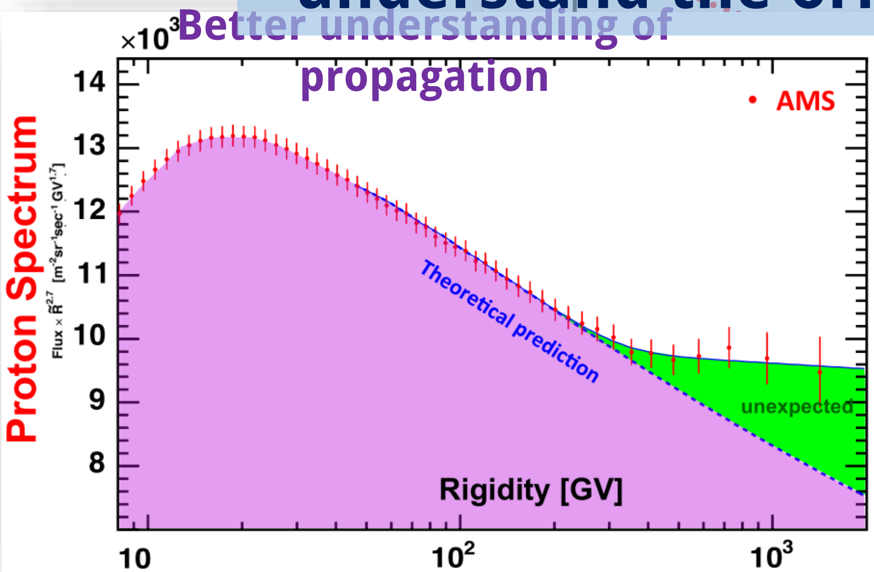




AMS-02 will continue collecting data during the lifetime of the ISS until 2024 to help understand the origin of these phenomena

Better understanding of propagation



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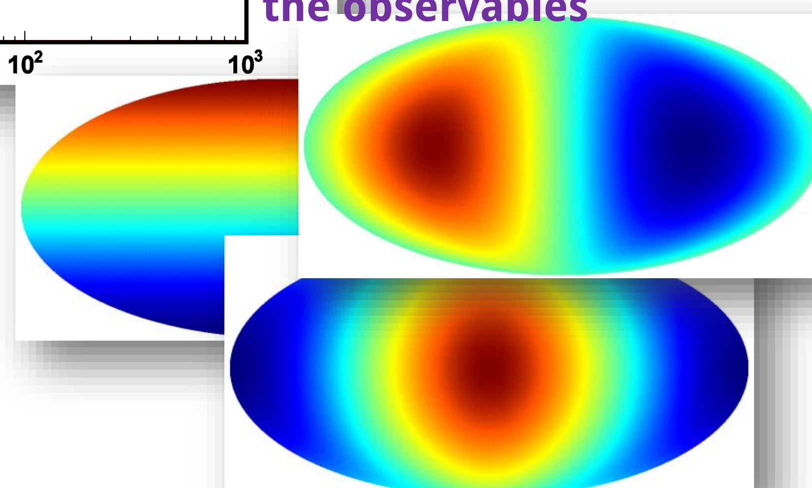


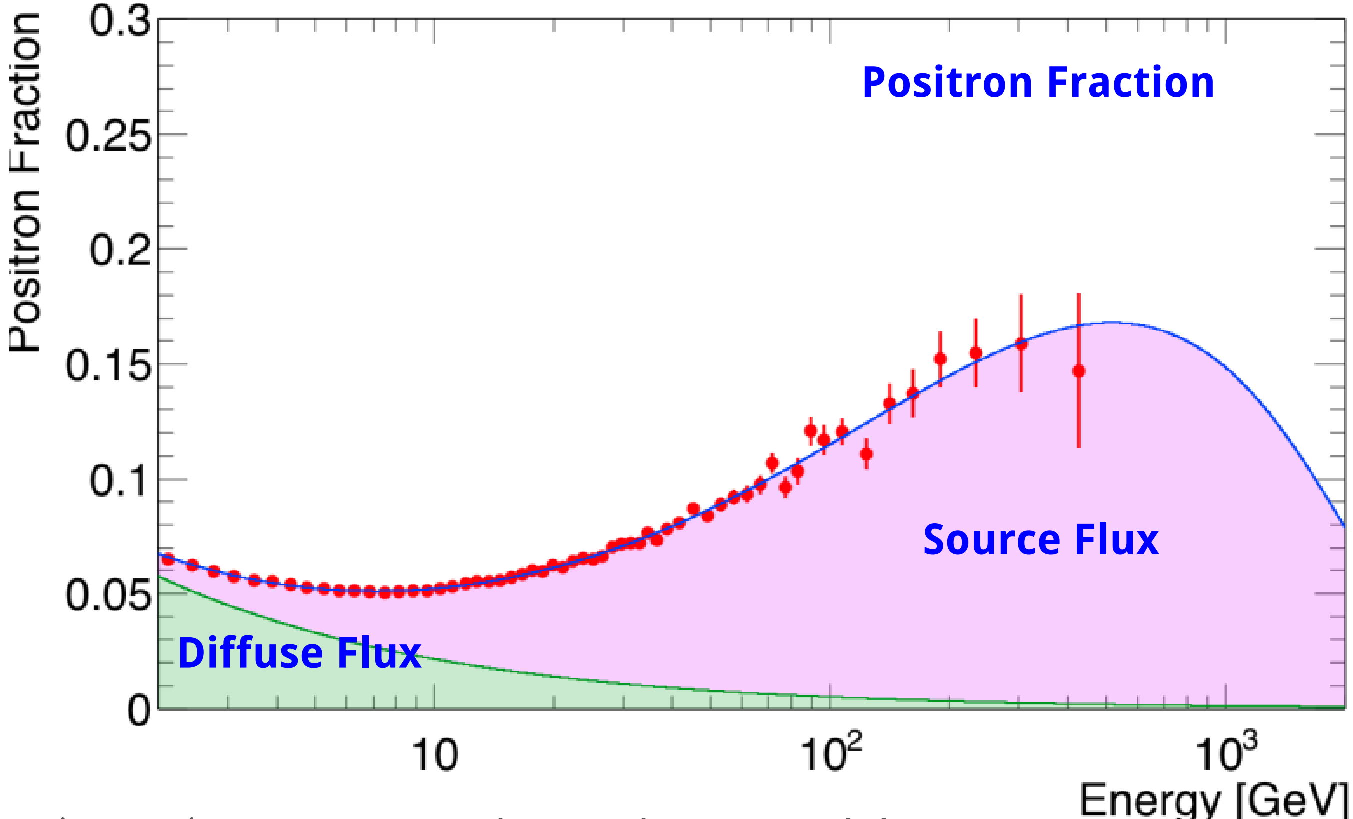
On the origin of excess positron

Minimal model

Diffuse Flux Source Flux

$$\Phi_{e^+} = C_{e^+} E^{-\gamma_{e^+}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

$$\Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_s E^{-\gamma_s} e^{-E/E_s}$$



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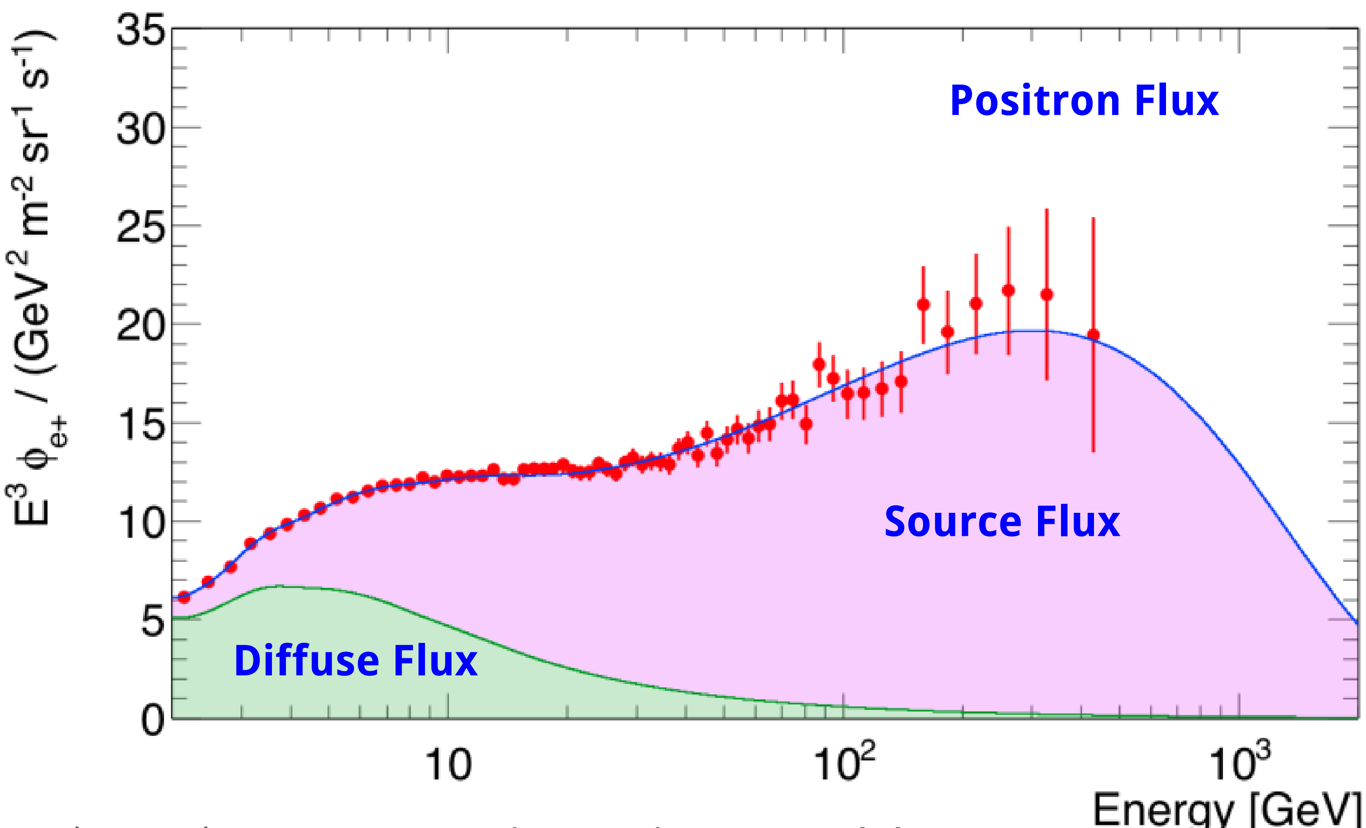
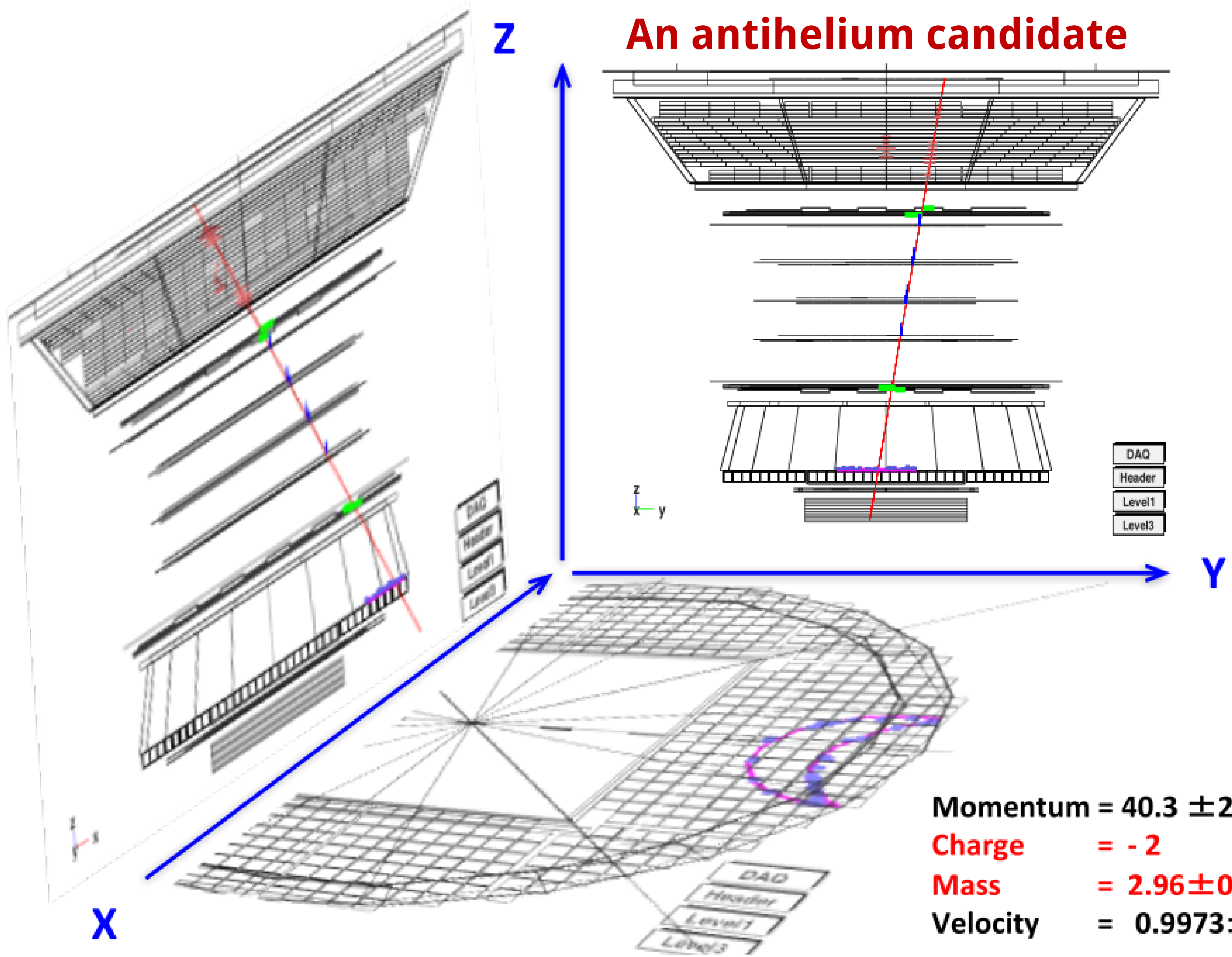


Antihelium and AMS-02

An antihelium 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-02

To date we have observed a few events with Z = -2 and mass around 2.8 GeV, like $^{3}\overline{He}$, at a rate of ~1 per year

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

How to ensure that the simulation is accurate to one in one billion?
2.2 million CPU-Days = 35 billion simulated helium events

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