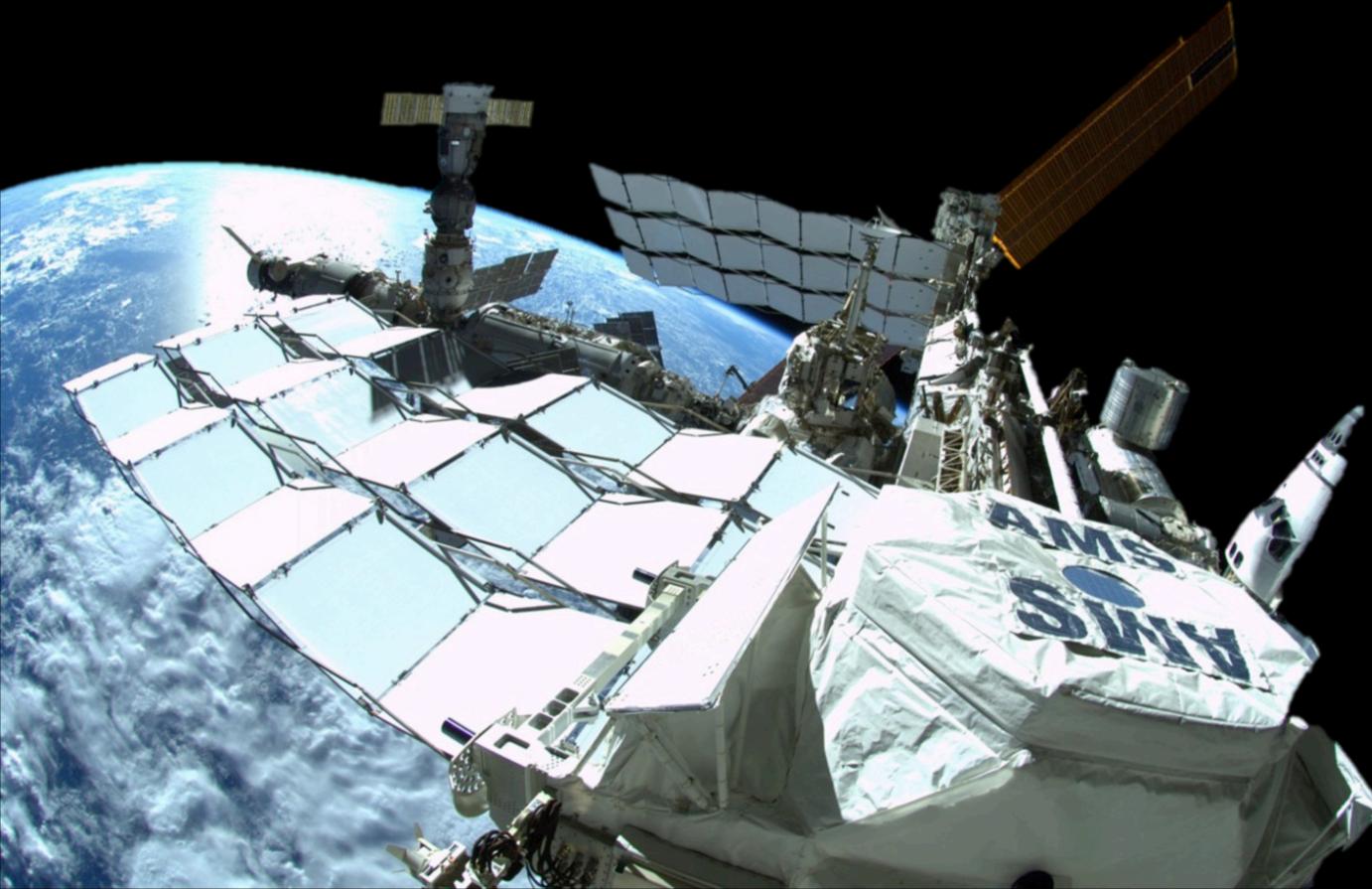


Observations of cosmic-rays and search for anti-nuclei with AMS-02

A. Oliva on behalf of the AMS-02 Collaboration.*

**Istituto Nazionale di Fisica Nucleare, Bologna, Italy.*



*LAN 2019,
14/10/2019,
Leiden, Holland*

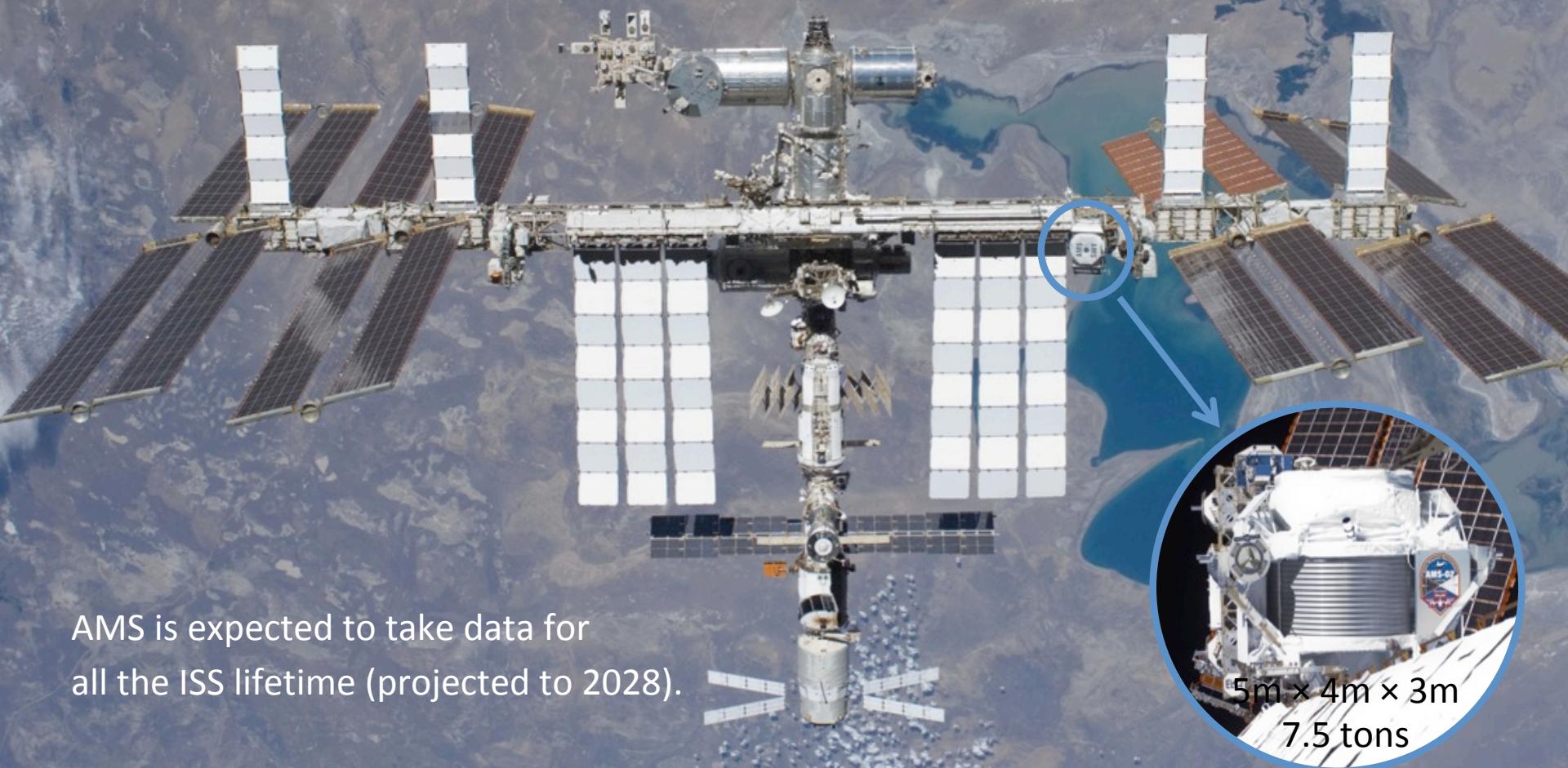


AMS-02 On Orbit

From May 19th 2011 active on ISS, operating continuously since then.

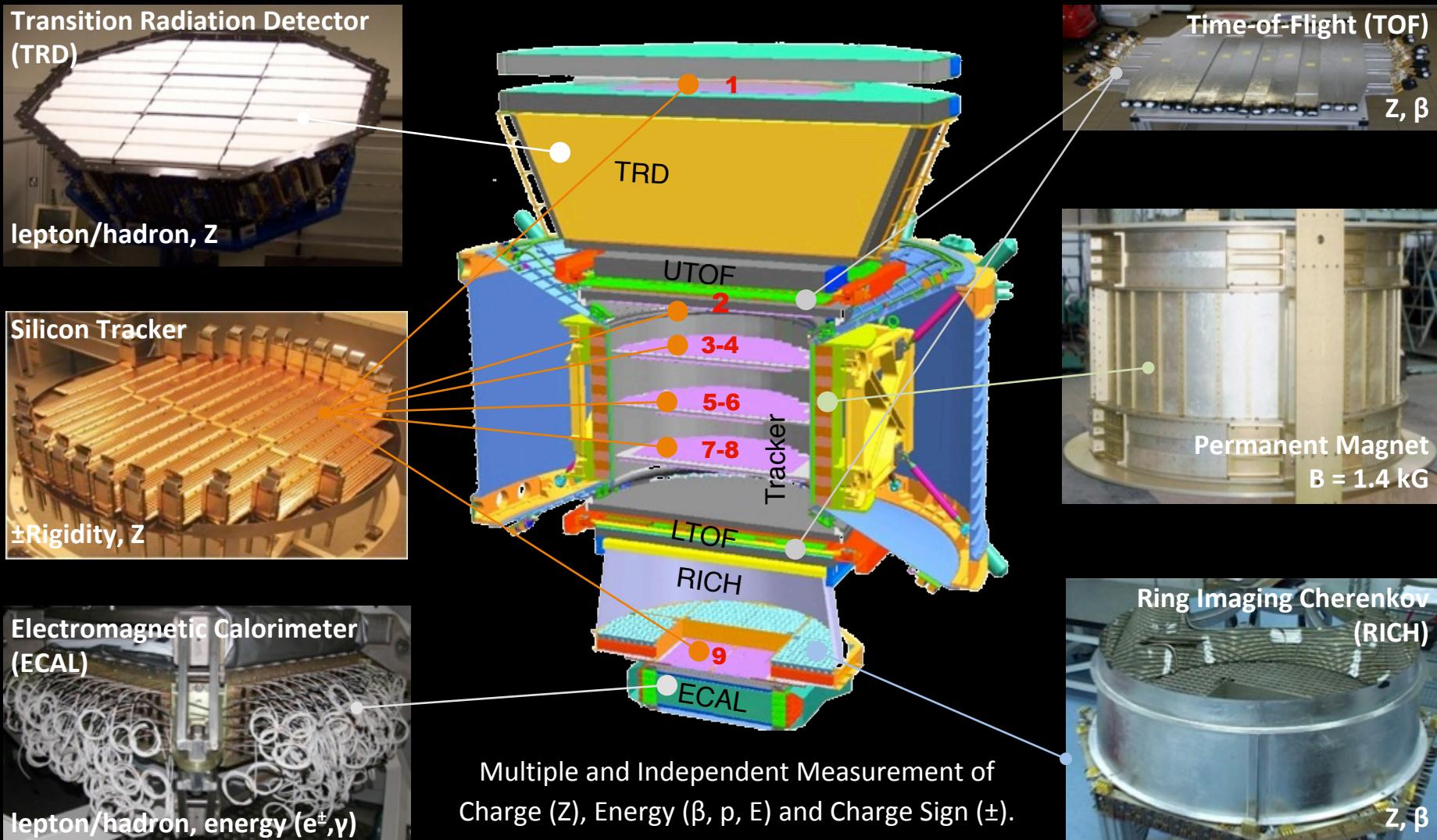
AMS has collected > 146 billion cosmic rays up to today.

With such a statistics the most rare components of the cosmic rays are visible.



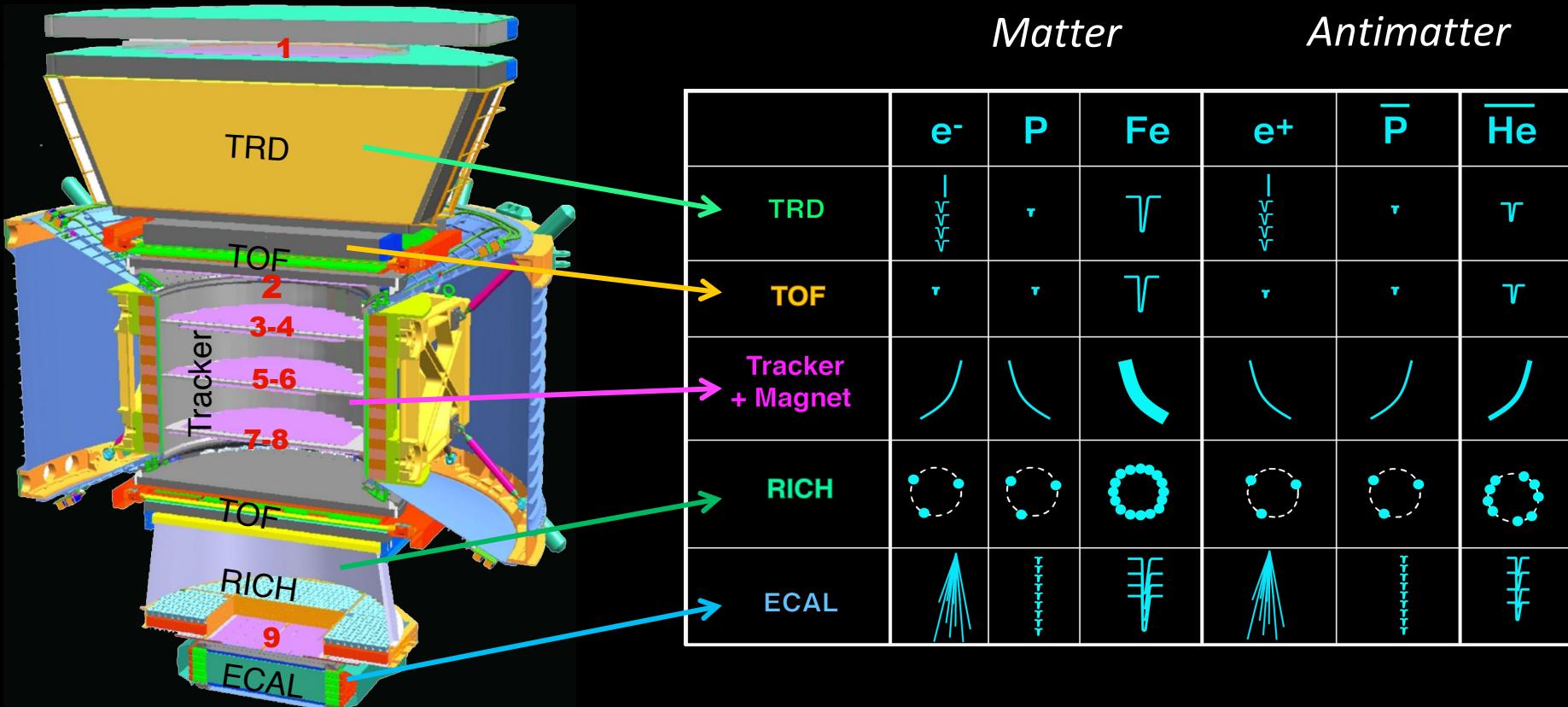
AMS-02: A TeV Multi-Purpose Spectrometer

AMS-2 separates hadrons from leptons, matter from anti-matter, chemical and isotopic composition from fraction of GeV to multi-TeV.



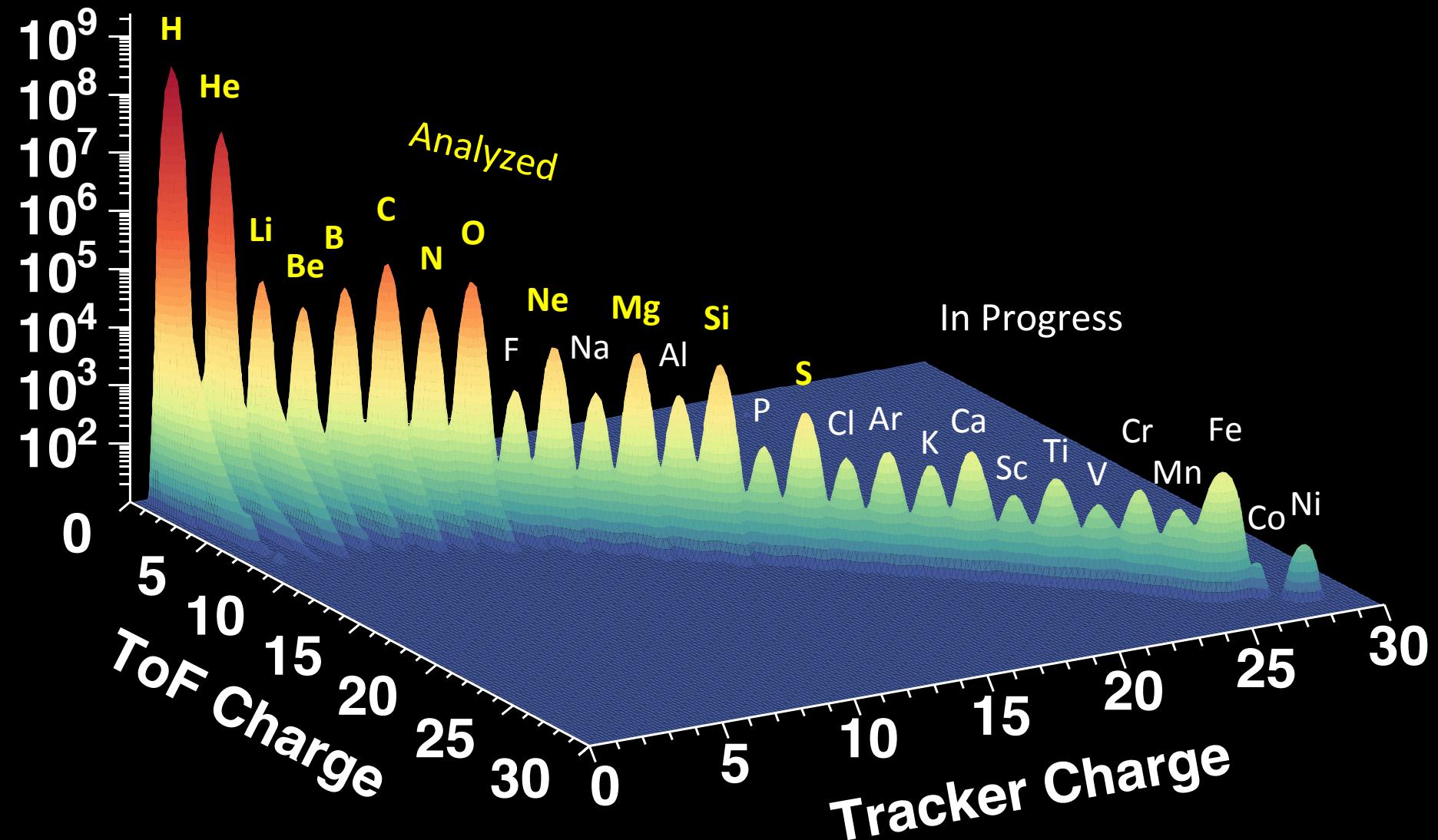
AMS-02: A TeV Multi-Purpose Spectrometer

AMS-02 separates hadrons from leptons, matter from anti-matter, chemical and isotopic composition from fraction of GeV to multi-TeV.



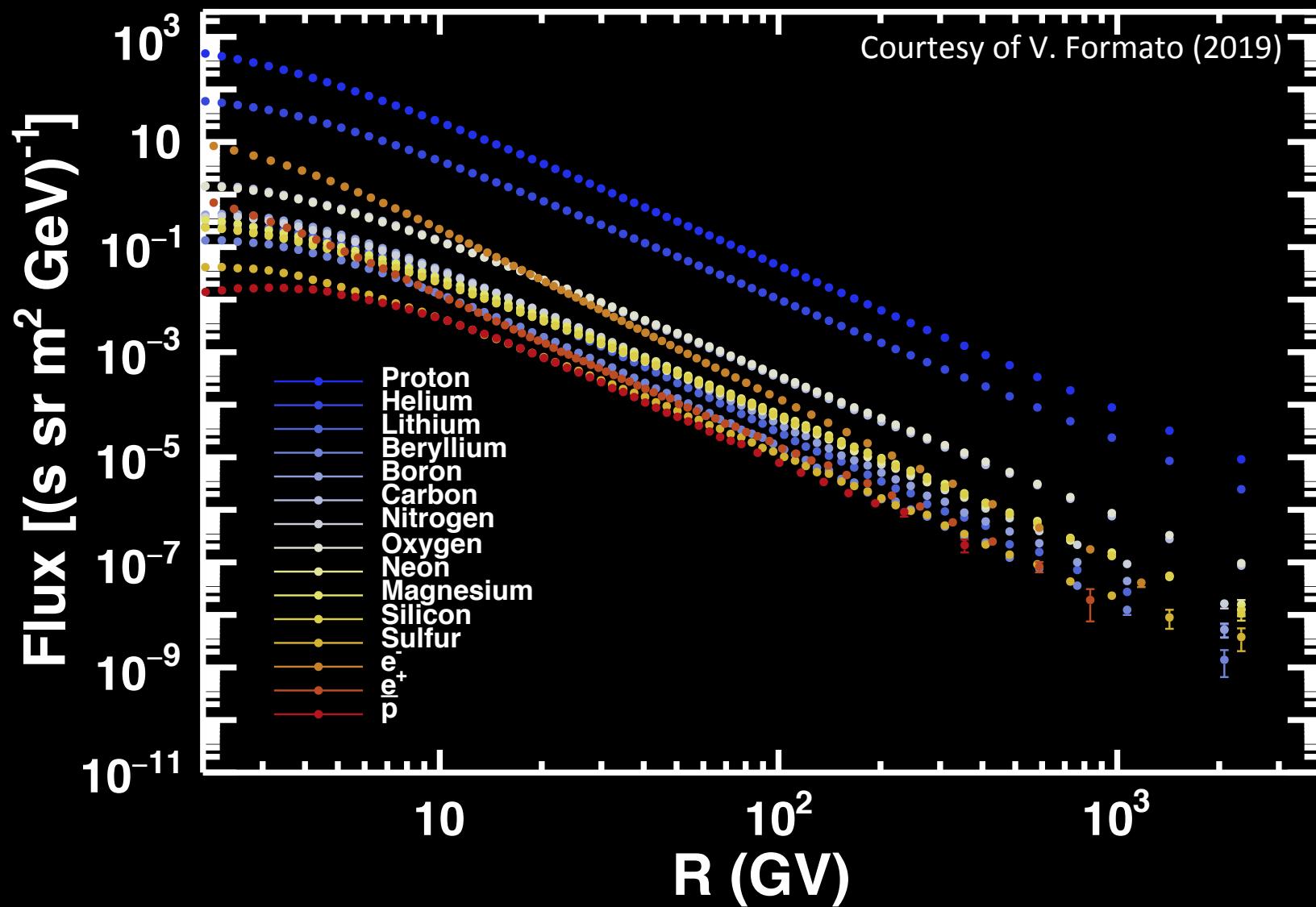
AMS is able to identify 1 positron from 10^6 protons,
unambiguously separate positrons from electrons up to a TeV,
and accurately measure all cosmic rays to TeV.

Chemical Composition with AMS-02



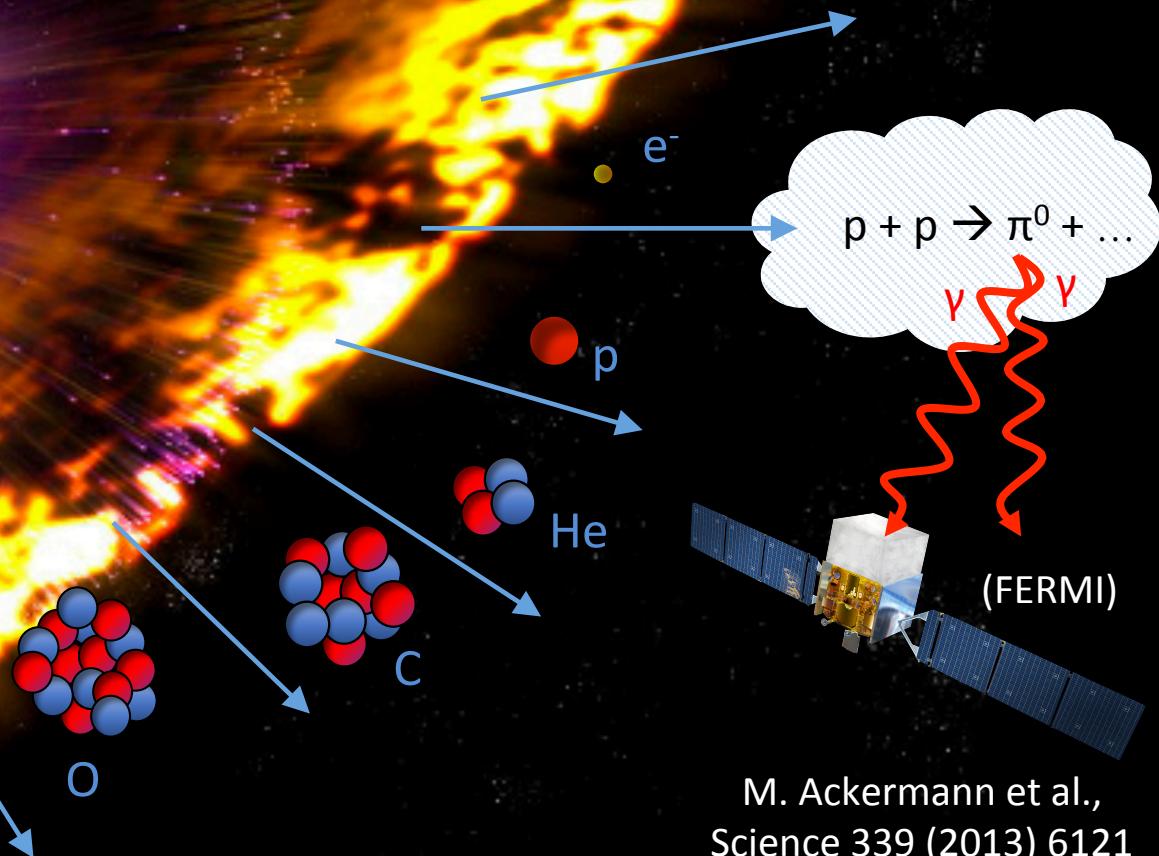
AMS-02: A TeV Multi-Purpose Spectrometer

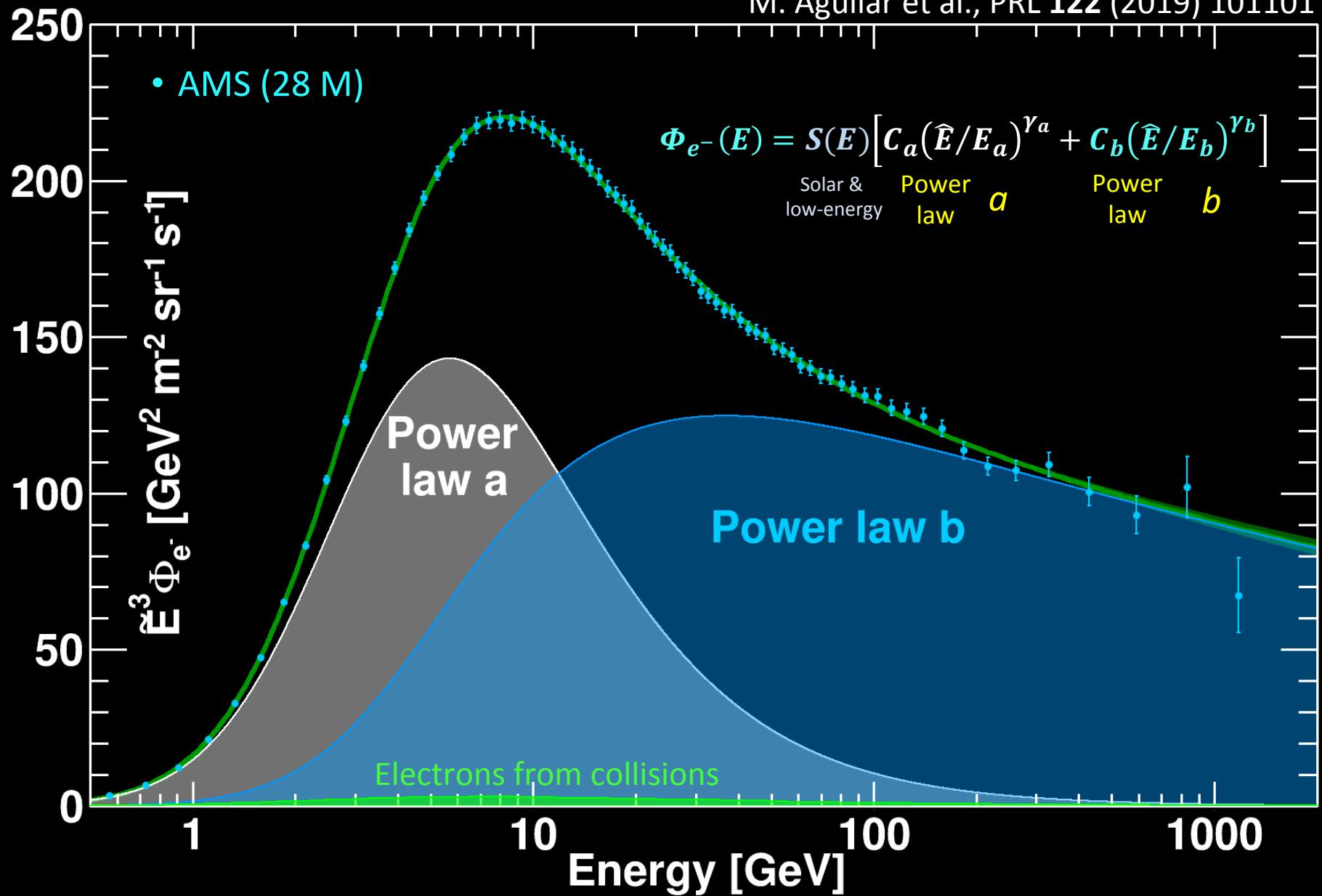
A Physics Report: *The Alpha Magnetic Spectrometer (AMS) on the International Space Station: Part II - Results from the First Seven Years*, is under development.



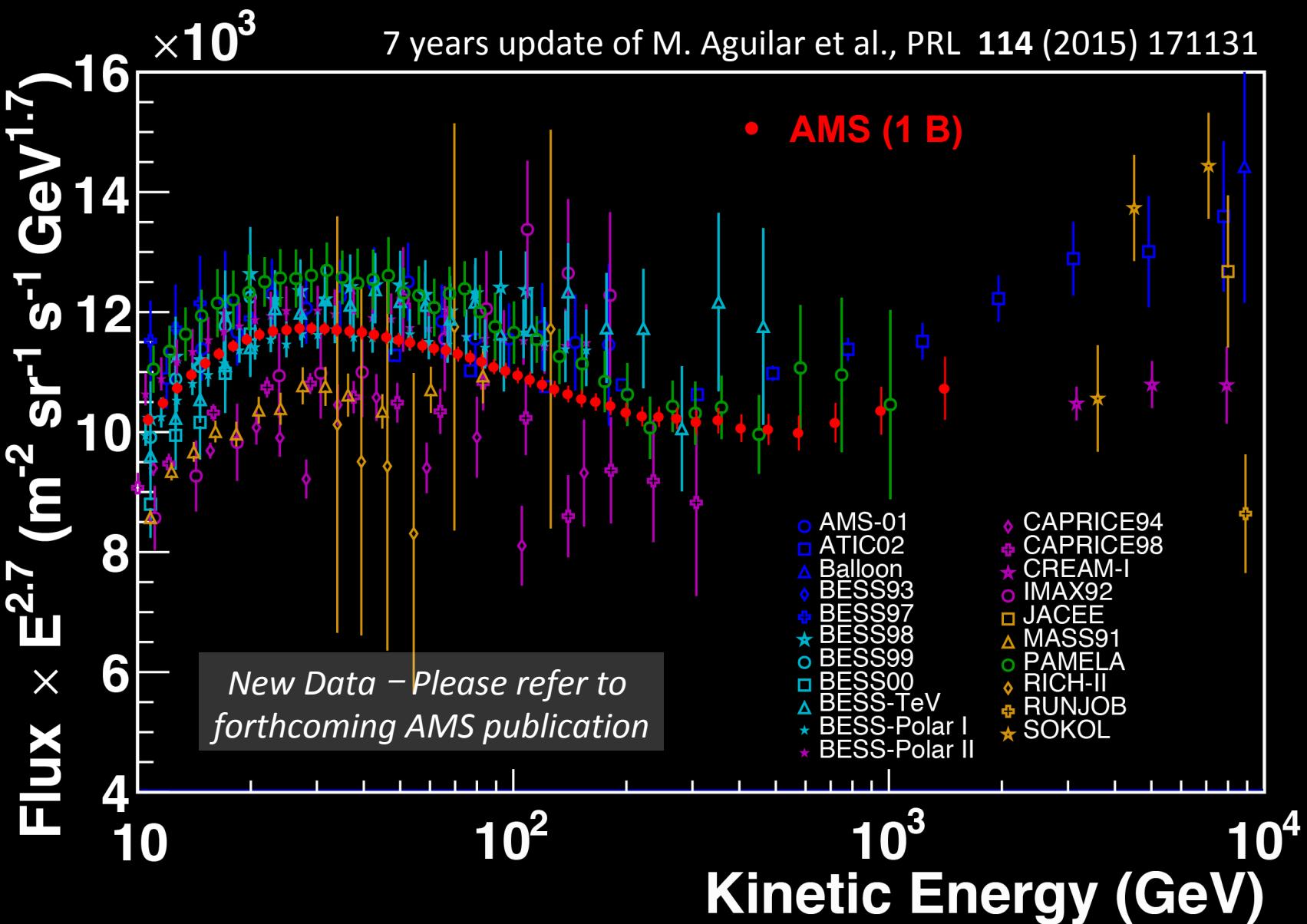
Primary Cosmic Rays

Matter created in nucleosynthesis processes
(big bang, stellar, explosive, neutron star collision, ...) is accelerated by the supernova shockwaves by the diffusive shock acceleration
(other scenarios are also possible ...)



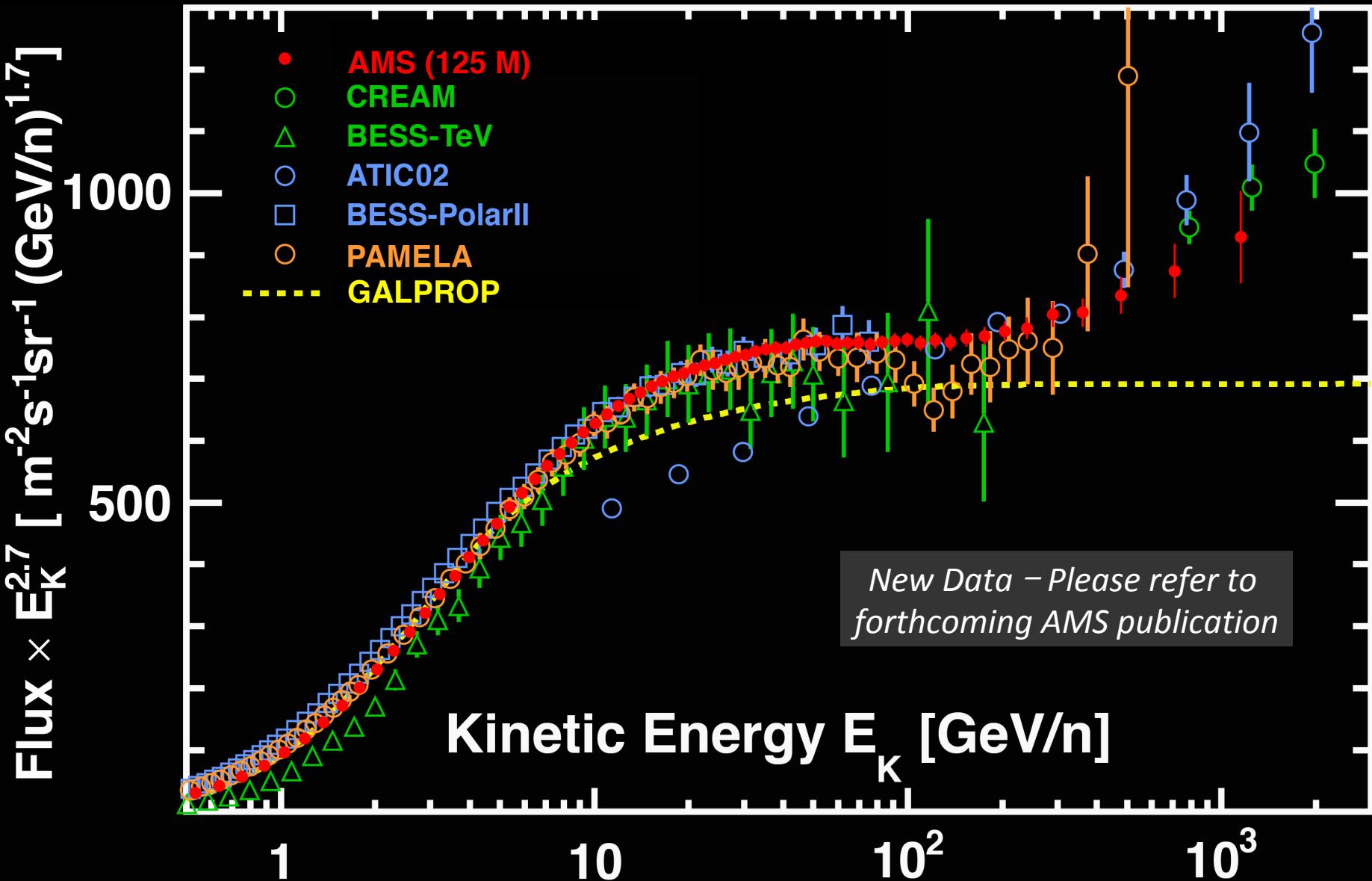
*AMS Electron Flux*M. Aguilar et al., PRL **122** (2019) 101101

AMS Proton Flux



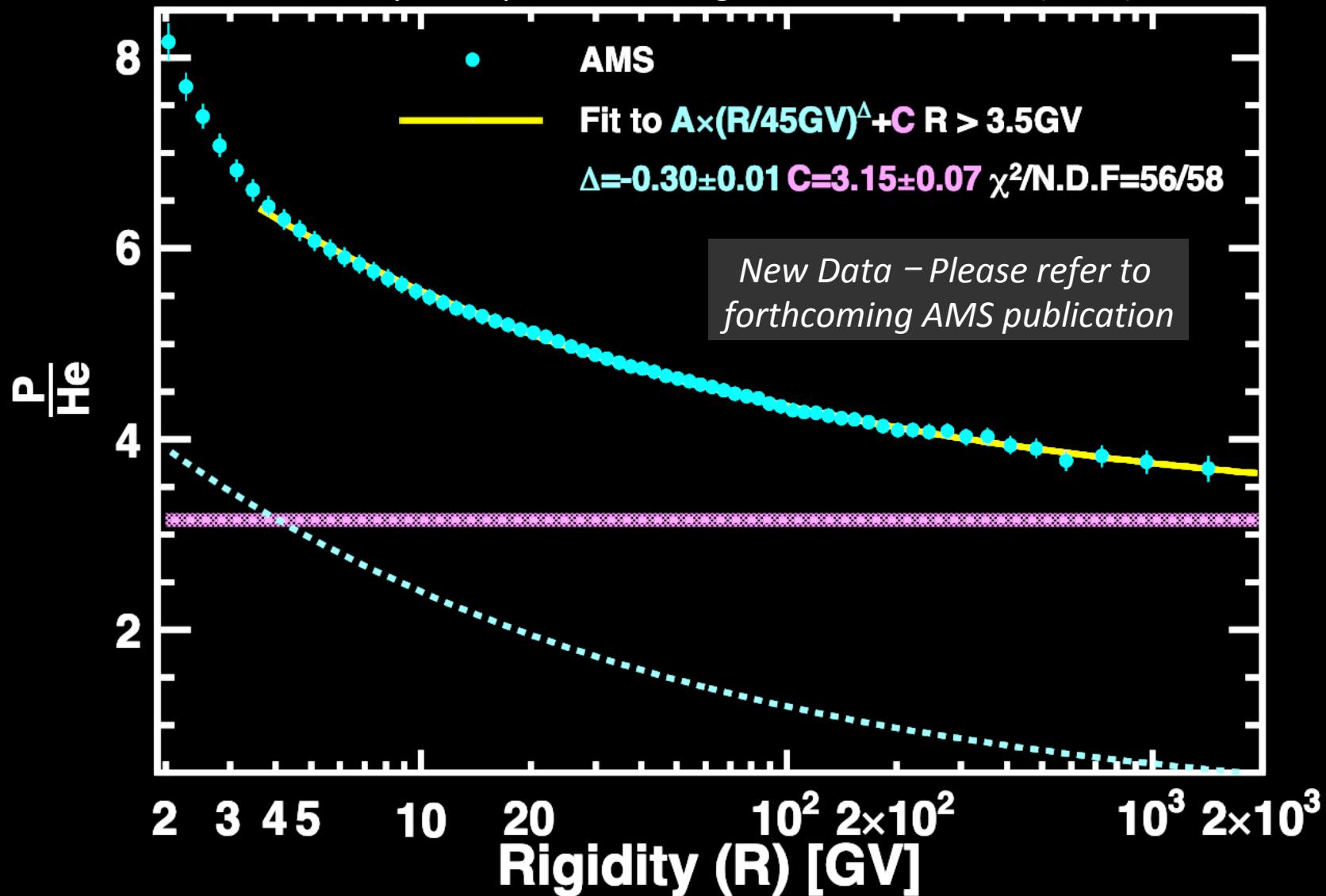
AMS Helium Flux

7 years update of M. Aguilar et al., PRL 115 (2015) 211101



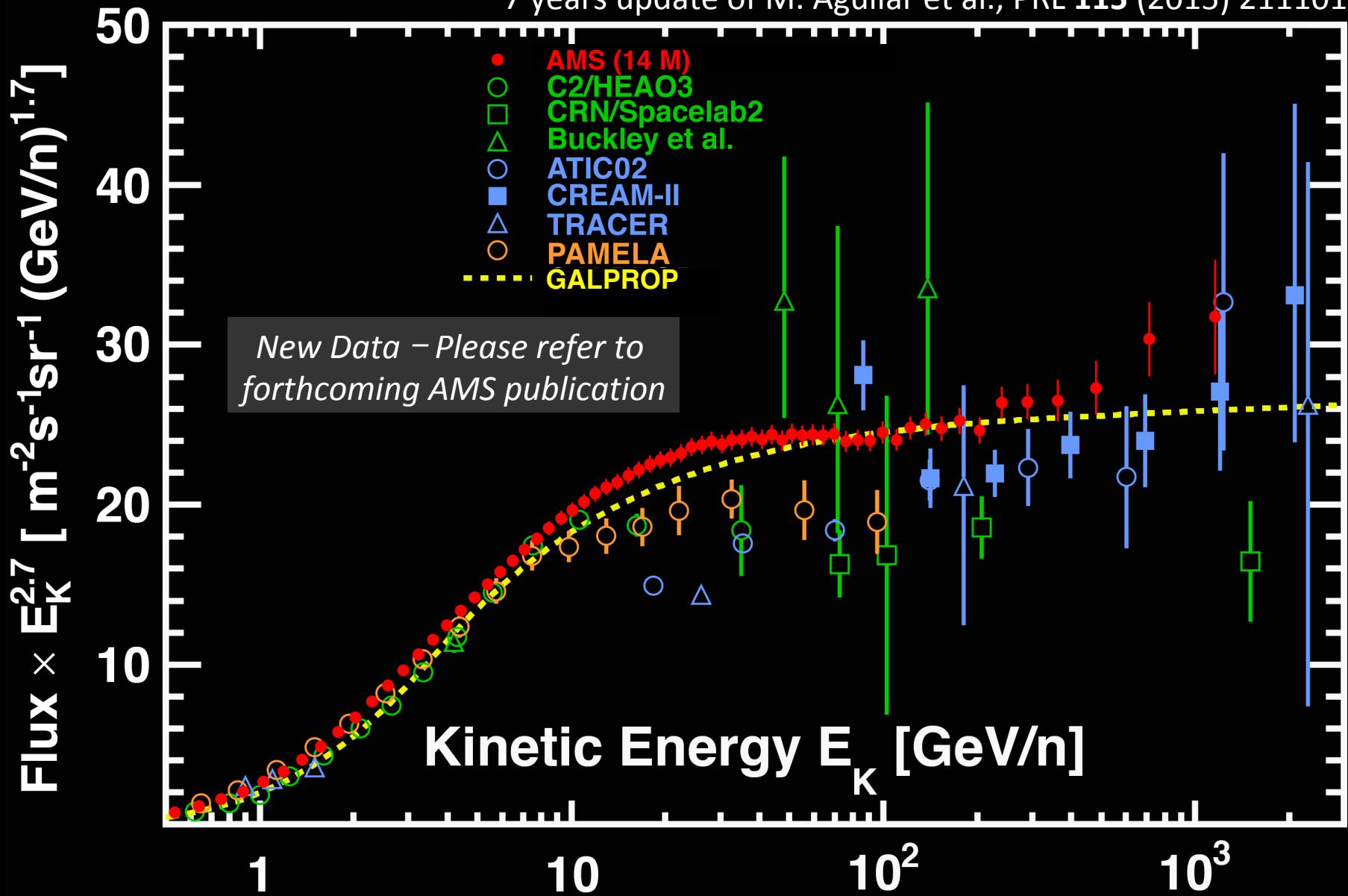
AMS p/He Flux Ratio

7 years update of M. Aguilar et al., PRL 115 (2015) 211101



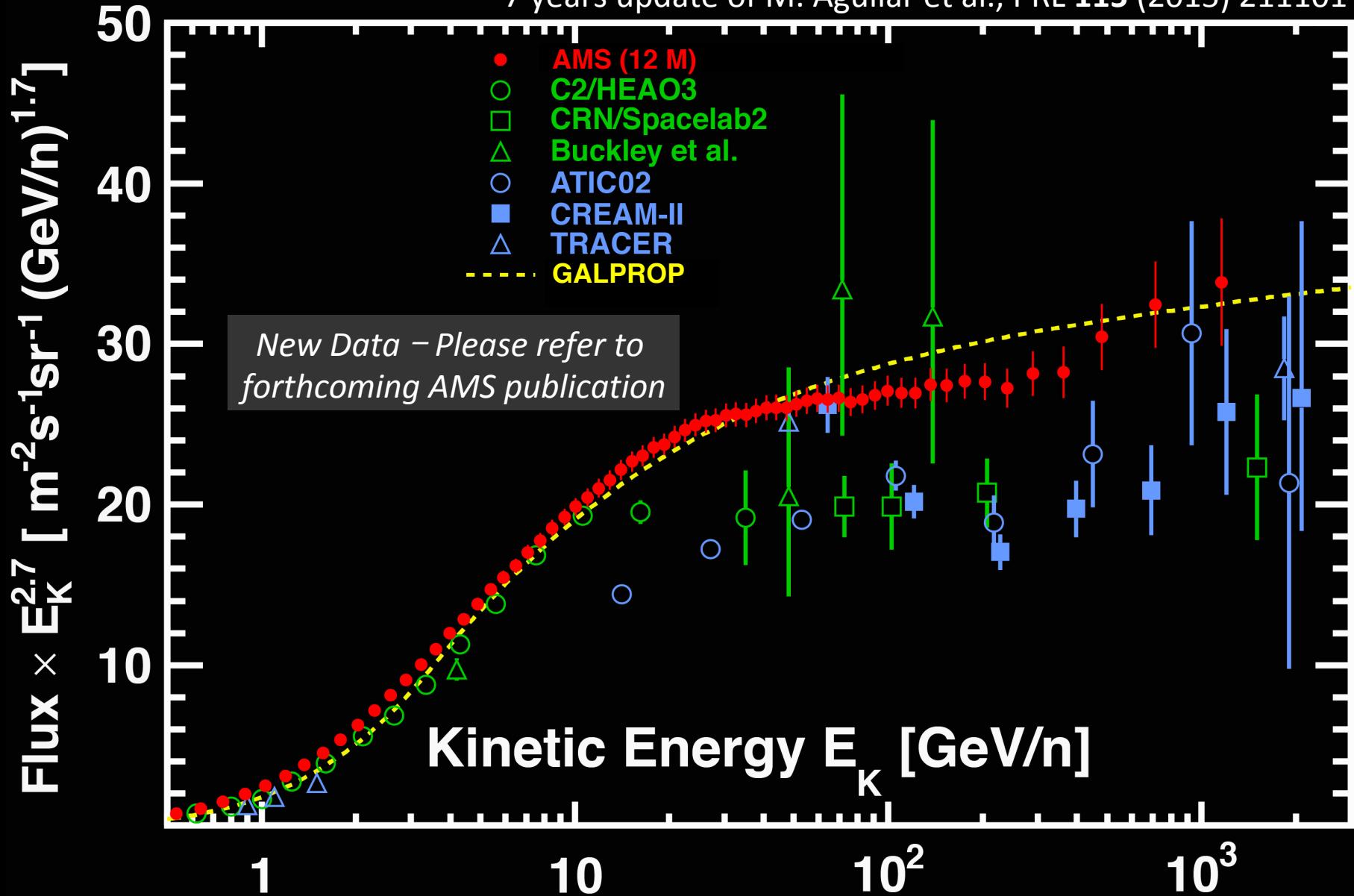
AMS Carbon Flux

7 years update of M. Aguilar et al., PRL 115 (2015) 211101



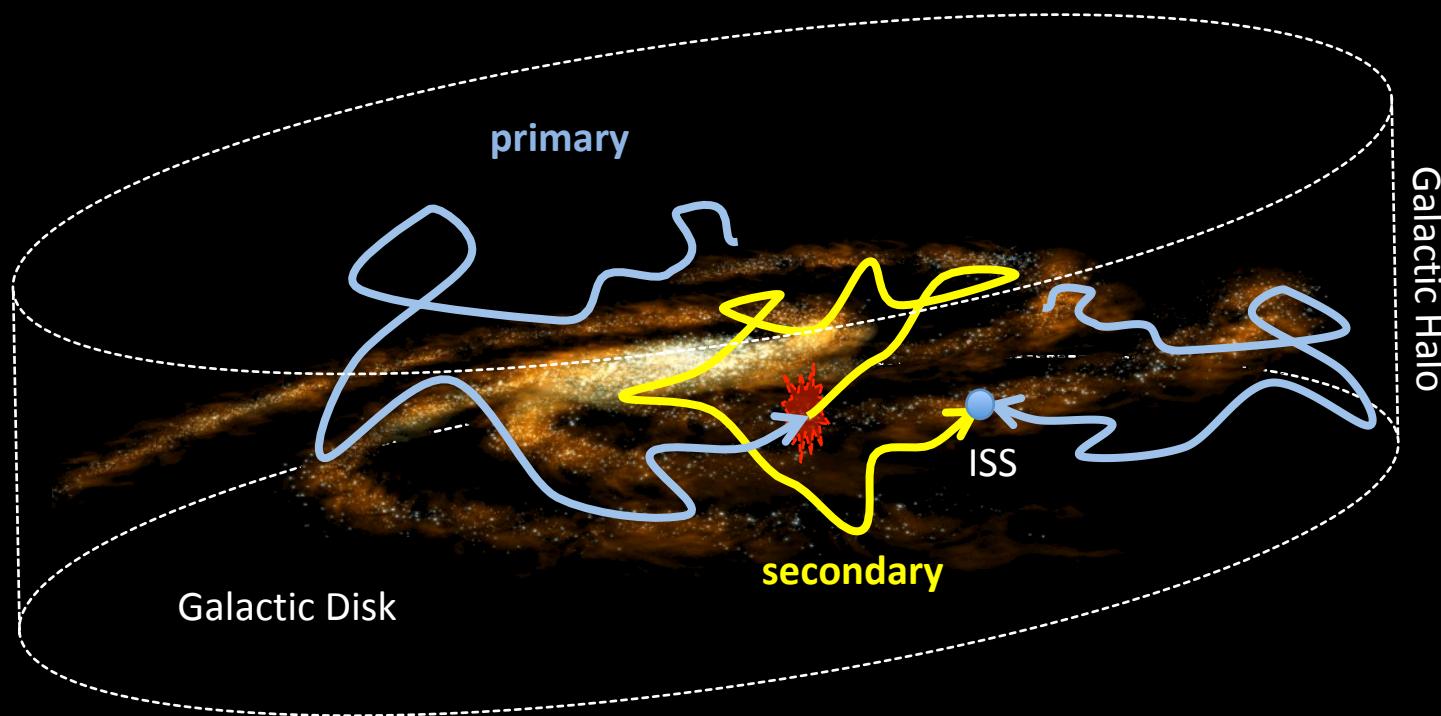
AMS Oxygen Flux

7 years update of M. Aguilar et al., PRL 115 (2015) 211101



Secondary Cosmic Rays

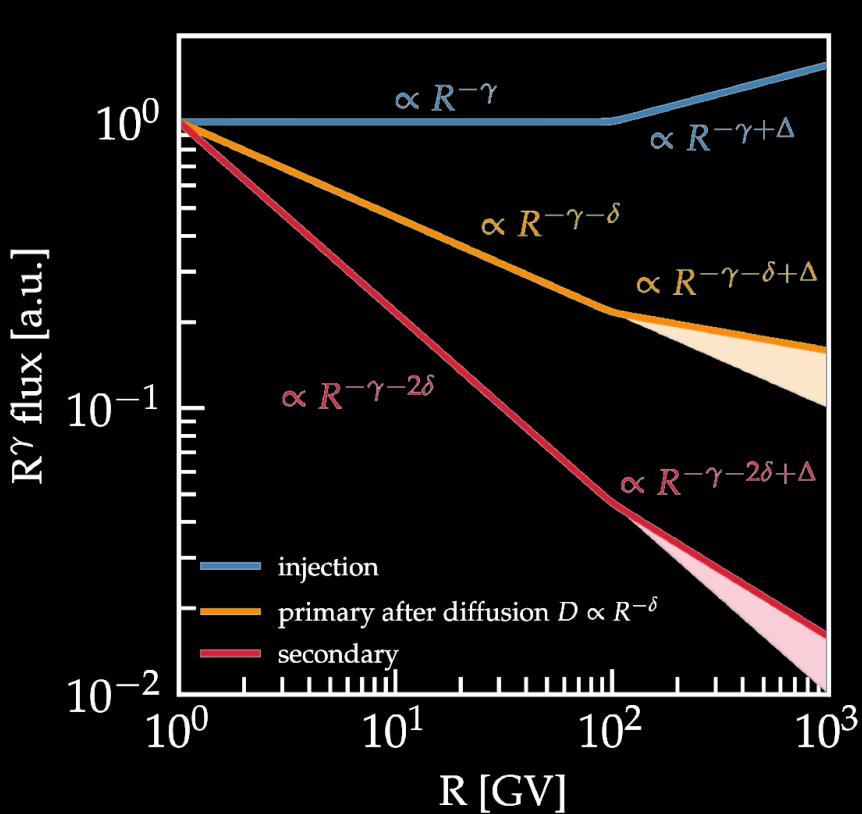
Cosmic rays **primaries** are mostly produced at astrophysical sources (ex. e^- , p, He, C, O, ...), **secondaries** (ex. Li, Be, B, ...) are mostly produced by the collision of cosmic rays with the ISM.



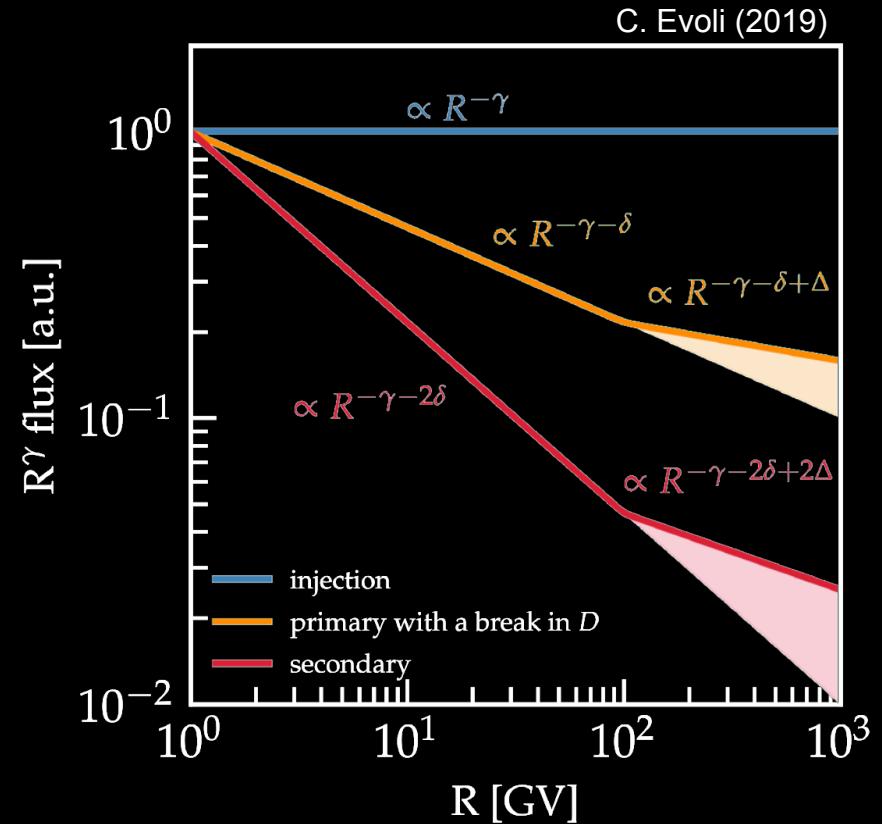
The understanding of primary and secondary cosmic rays nuclei reveal details of sources and propagation of all CRs species, specially for the secondary production of e^+ , \bar{p} , \bar{D} , ...

- The cosmic ray fluxes of their “parents” (p, He)
- Behaviour of their propagation in the Milky Way (B/C, Be/B, ...)

Cosmic Ray Propagation

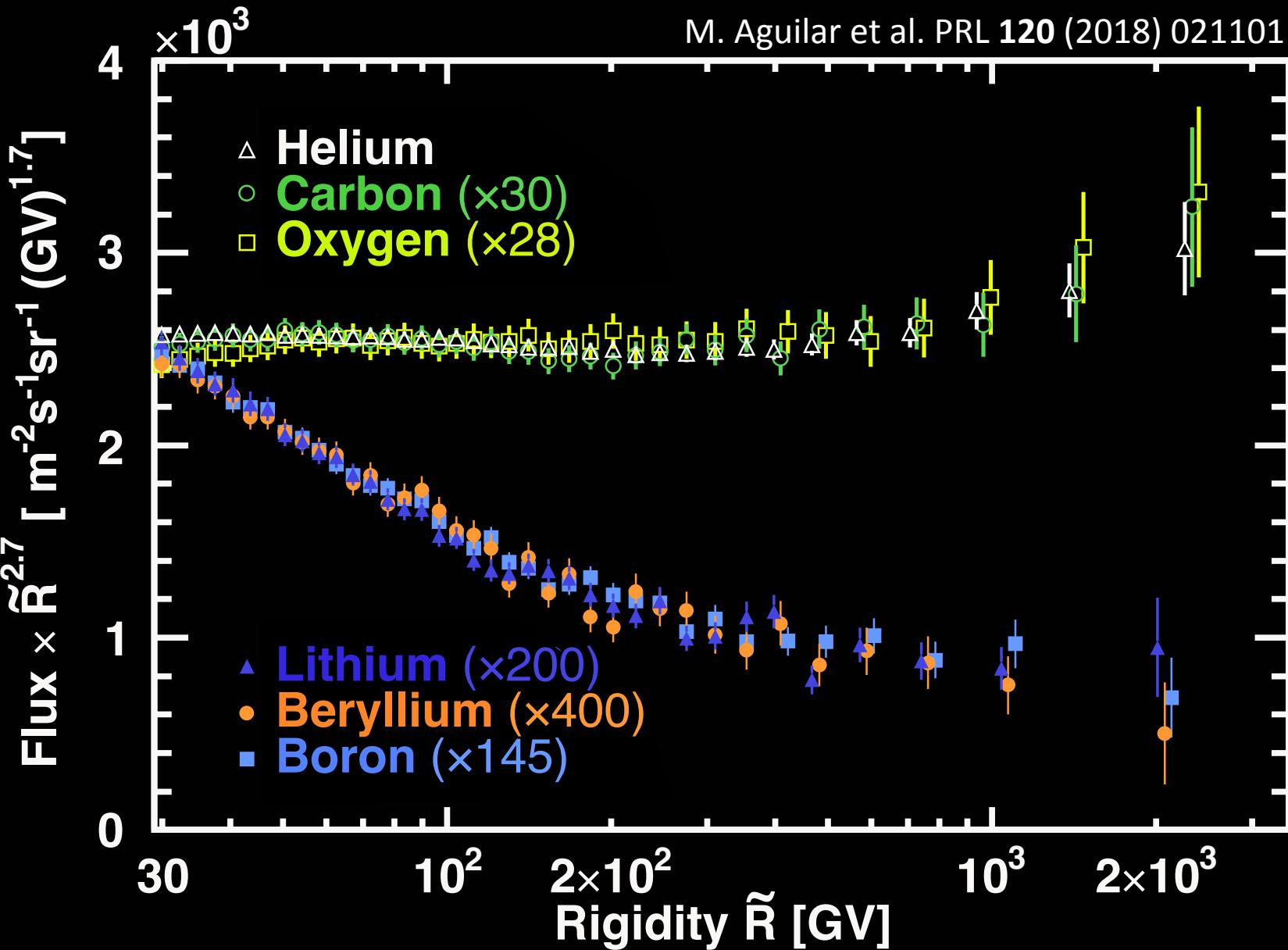


If the hardening in CRs is related to the **injected spectra** at their source, then **similar hardening** is expected both for **secondary** and **primary** cosmic rays.



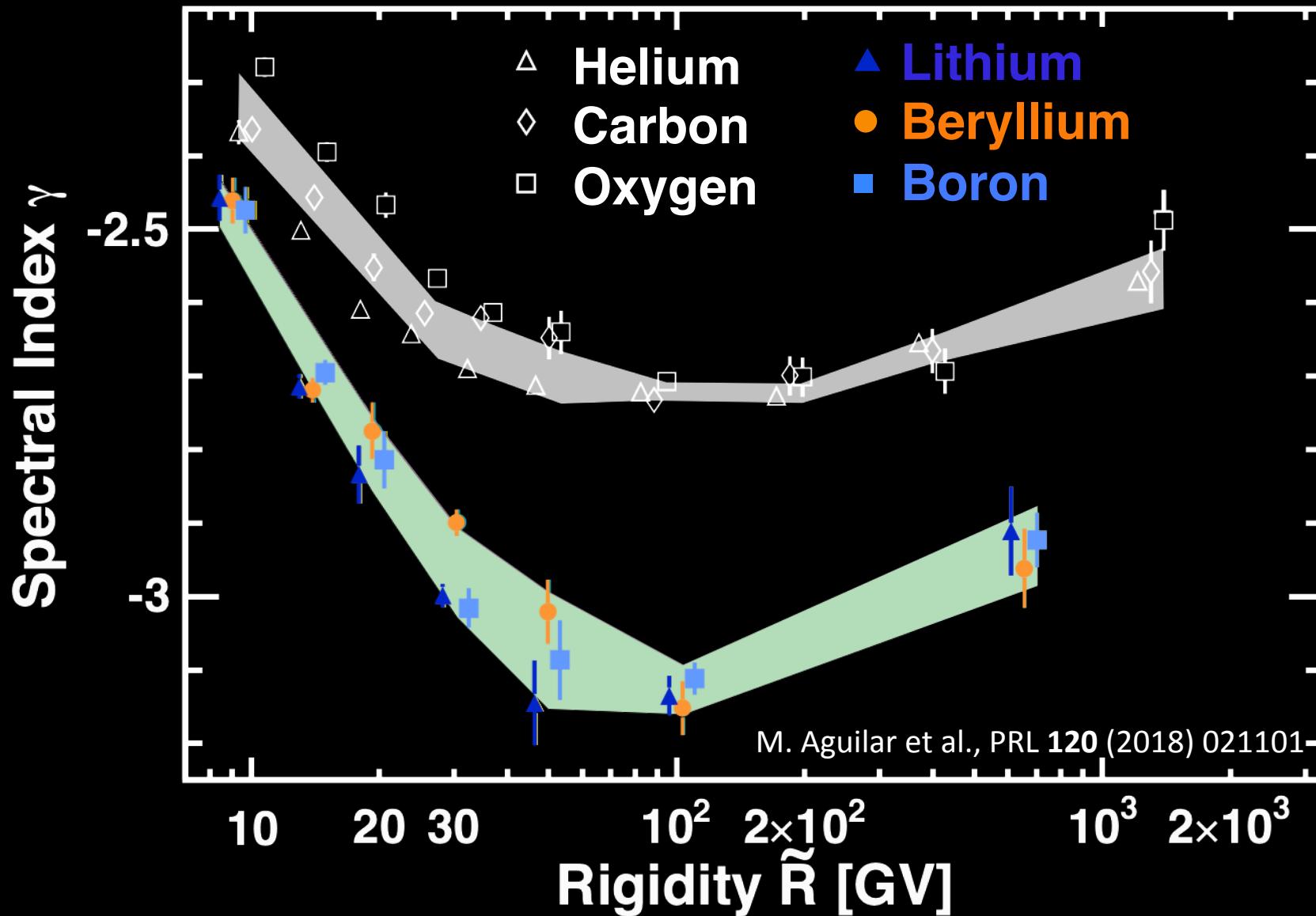
If the hardening is related to **propagation properties** in the Galaxy then a **stronger hardening** is expected for the **secondary** with respect to the **primary** cosmic rays.

C. Evoli (2019)

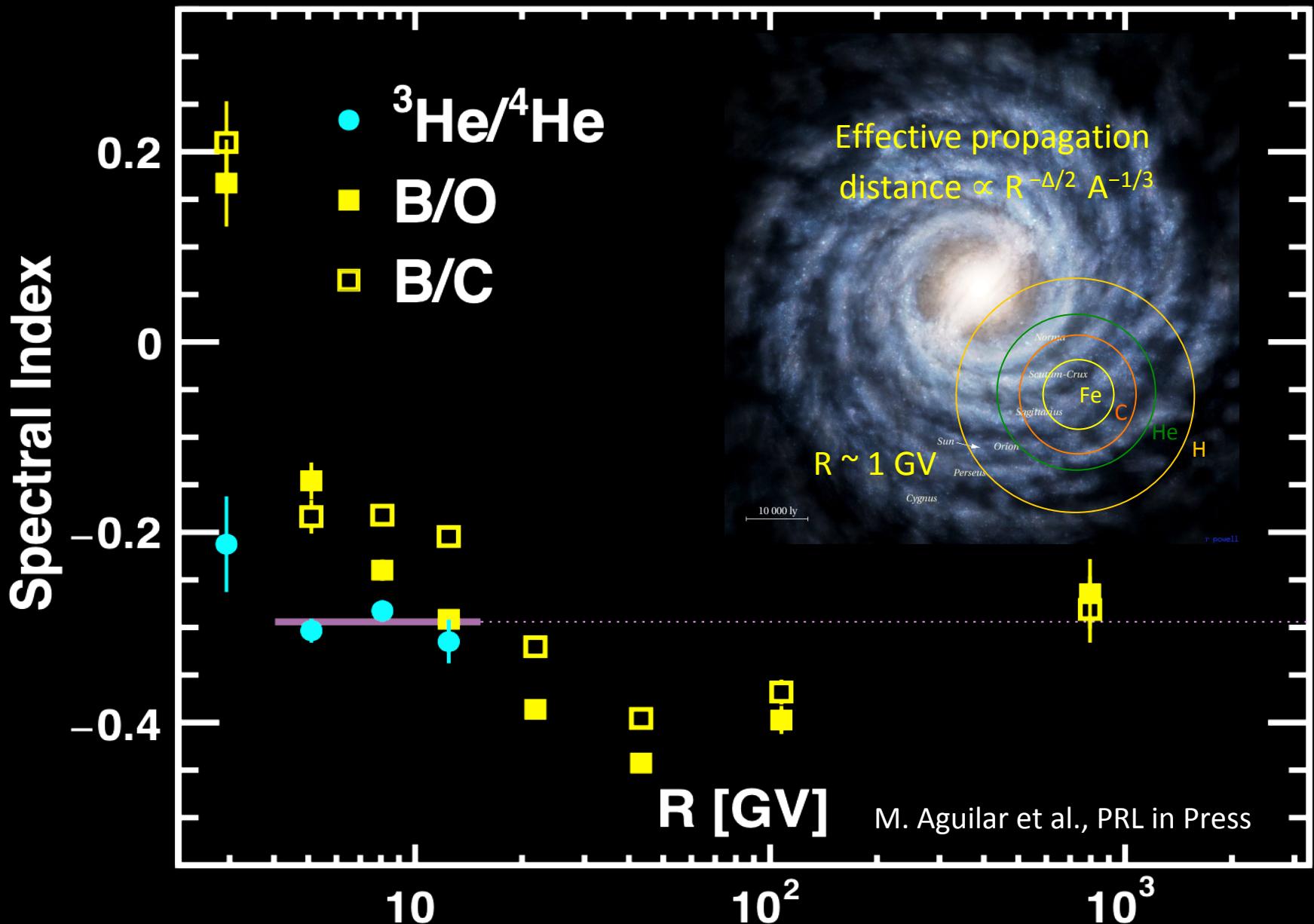
AMS Primary and Secondary Nuclei Fluxes

AMS Primary and Secondary Nuclei Spectral Indices

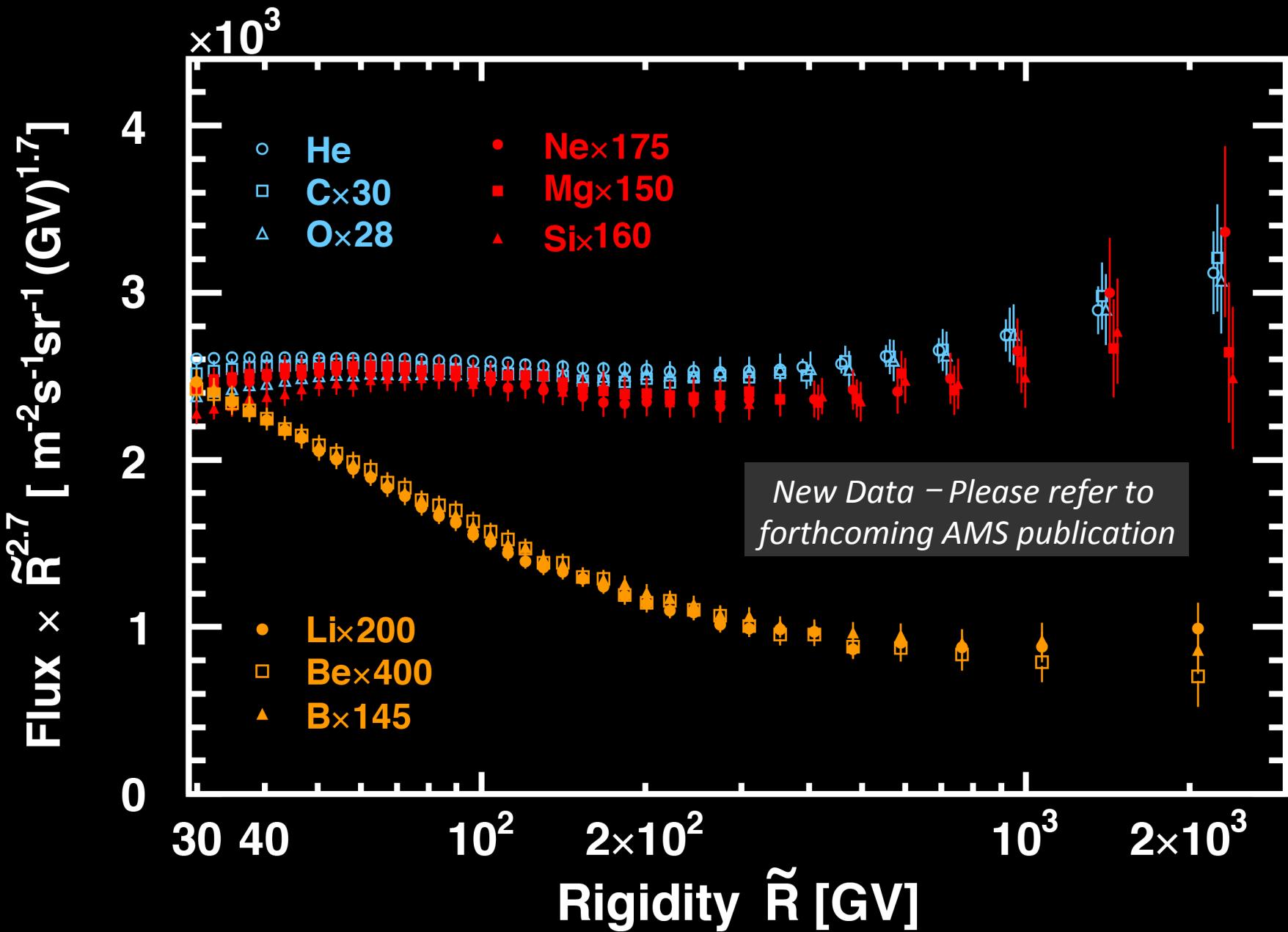
Deviate from single power law above 200 GV. Secondary hardening is stronger
 AMS favors the hypothesis that the flux hardening is an **universal propagation effect**.



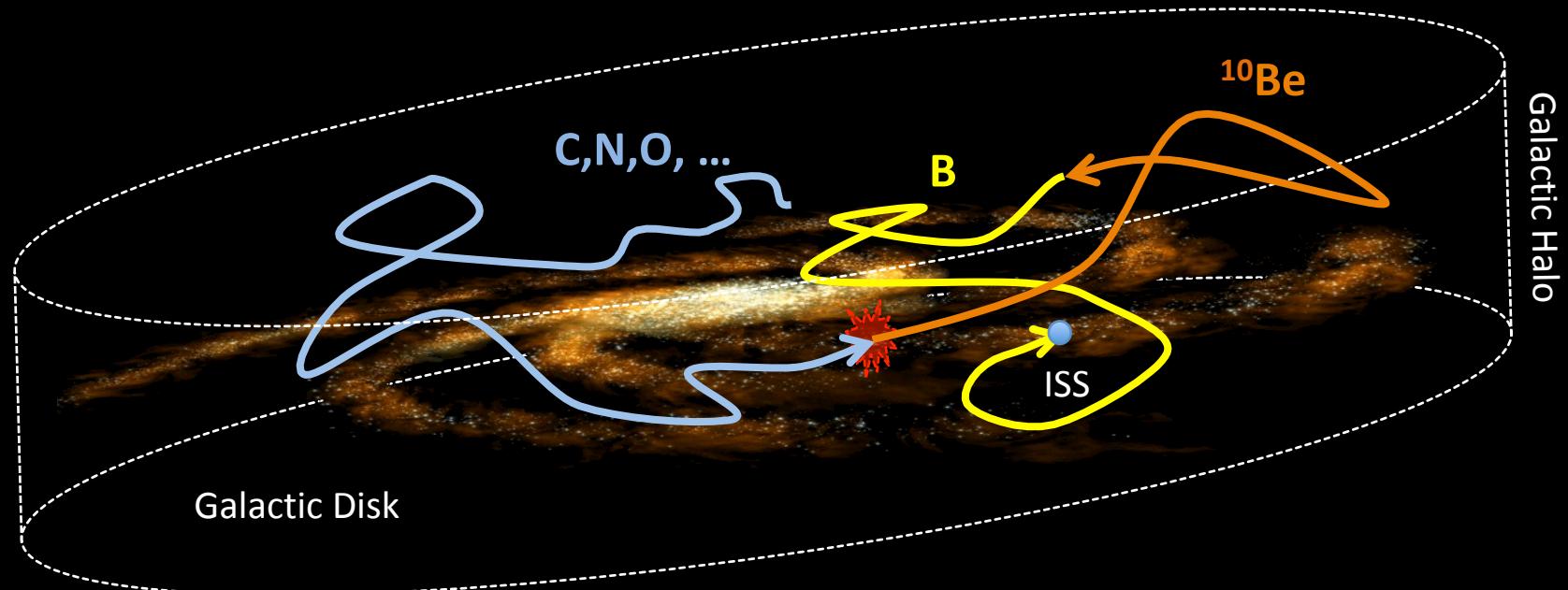
Probing Non-Homogeneous Diffusion: AMS ${}^3\text{He}/{}^4\text{He}$ Ratio¹⁸



Extending AMS Nuclei Fluxes Towards High-Z

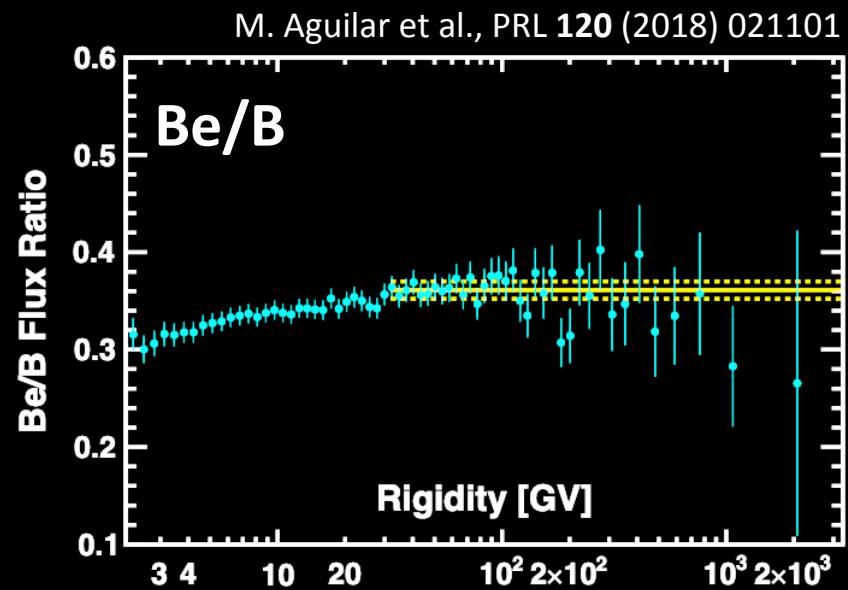


Cosmic Ray Clock: AMS Be/B Flux Ratio



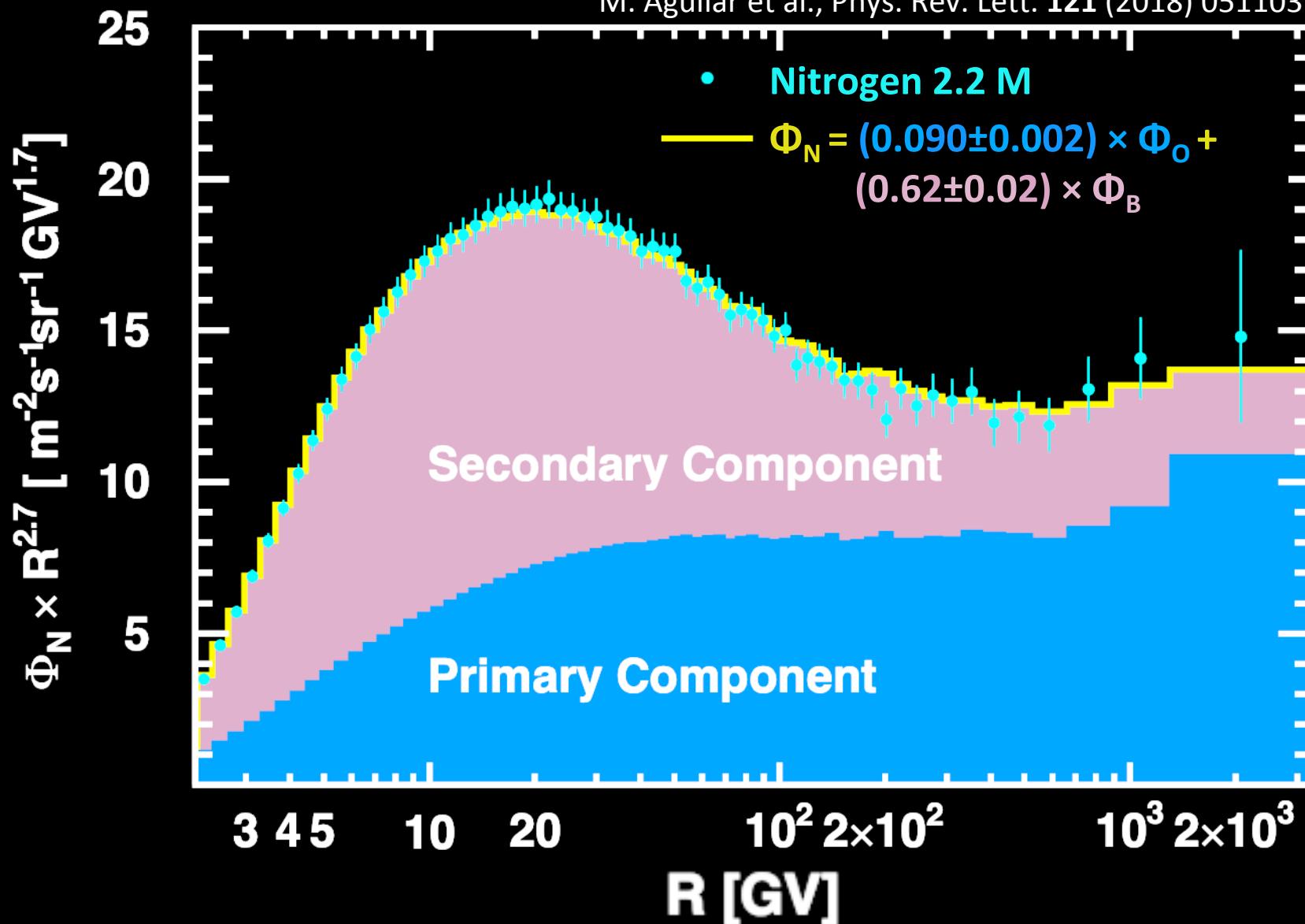
The secondary ^{10}Be beta-decays with $t_{1/2} = 1.4 \text{ My}$ through $^{10}\text{Be} \rightarrow ^{10}\text{B} + e^- + \bar{\nu}$.

The Be/B ratio rigidity dependence is related to the **cosmic rays confinement time** (or the galactic halo size in diffusion models).

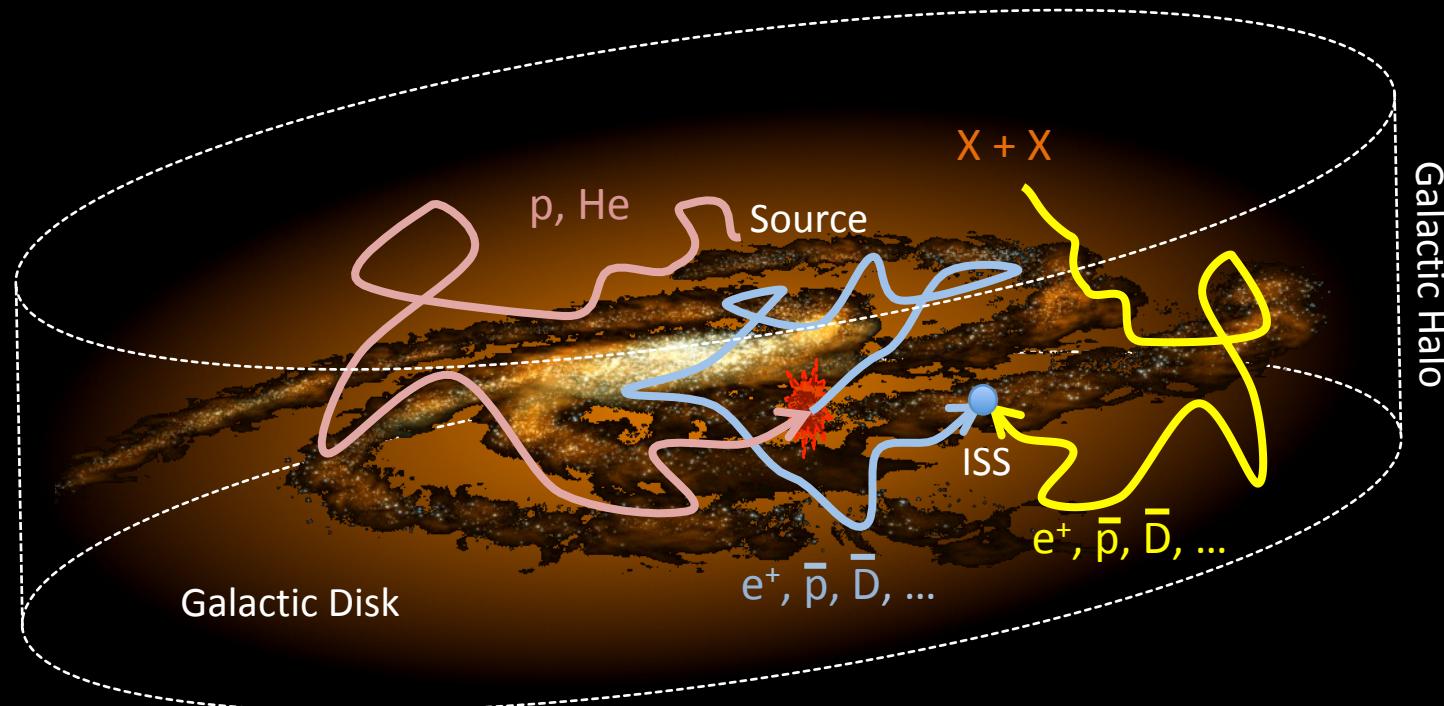


Abundances at Source: AMS Nitrogen Flux

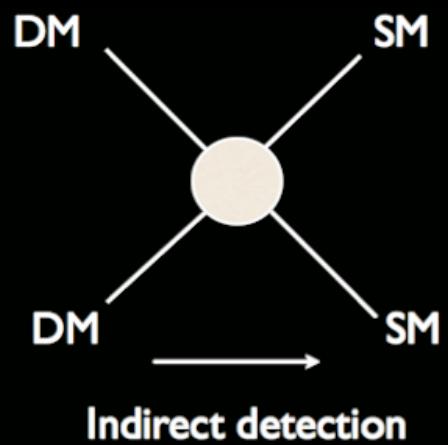
M. Aguilar et al., Phys. Rev. Lett. **121** (2018) 051103



Indirect Search of Dark Matter with CR Anti-Matter

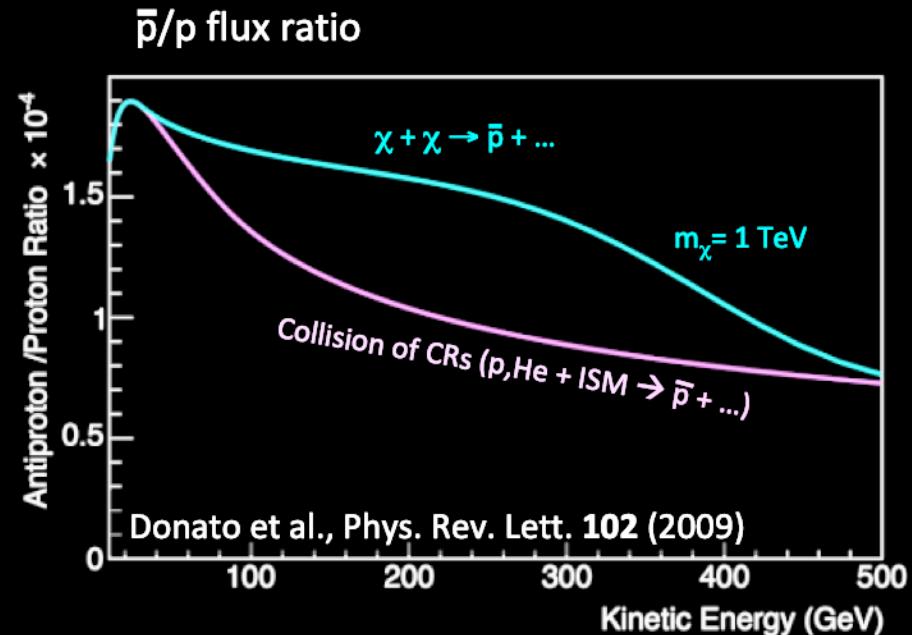
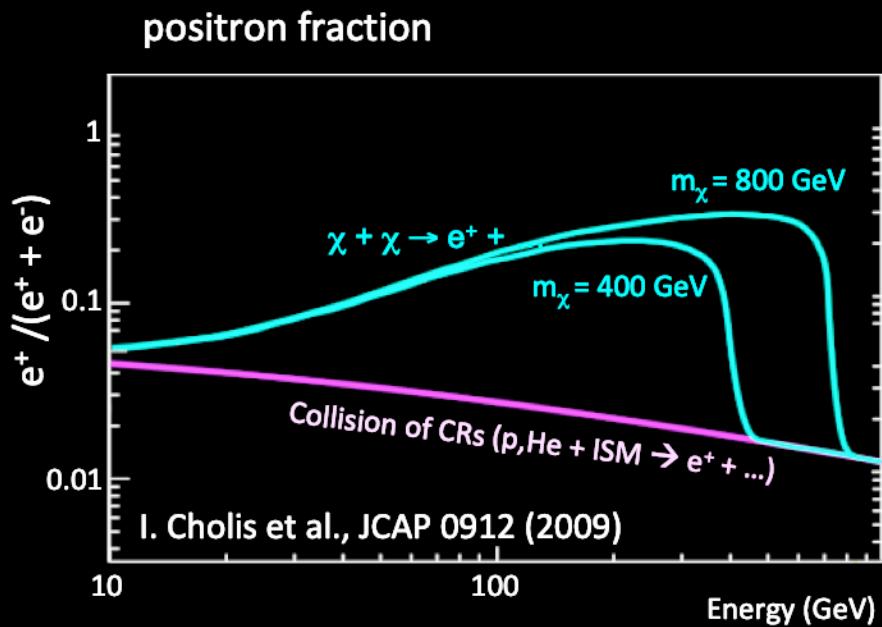


Collisions of dark matter particles (ex. neutralinos)
may produce a signal of $e^+, \bar{p}, \bar{D}, \dots$ that
can be detected above the background from the
collisions of primary CRs on interstellar medium



Indirect Search of Dark Matter with CR Anti-Matter

Collisions of Dark Matter particles (ex. neutralinos) may produce a signal of e^+ , \bar{p} , \bar{D} ... detected above the background from the collisions of CRs on interstellar medium (ISM)

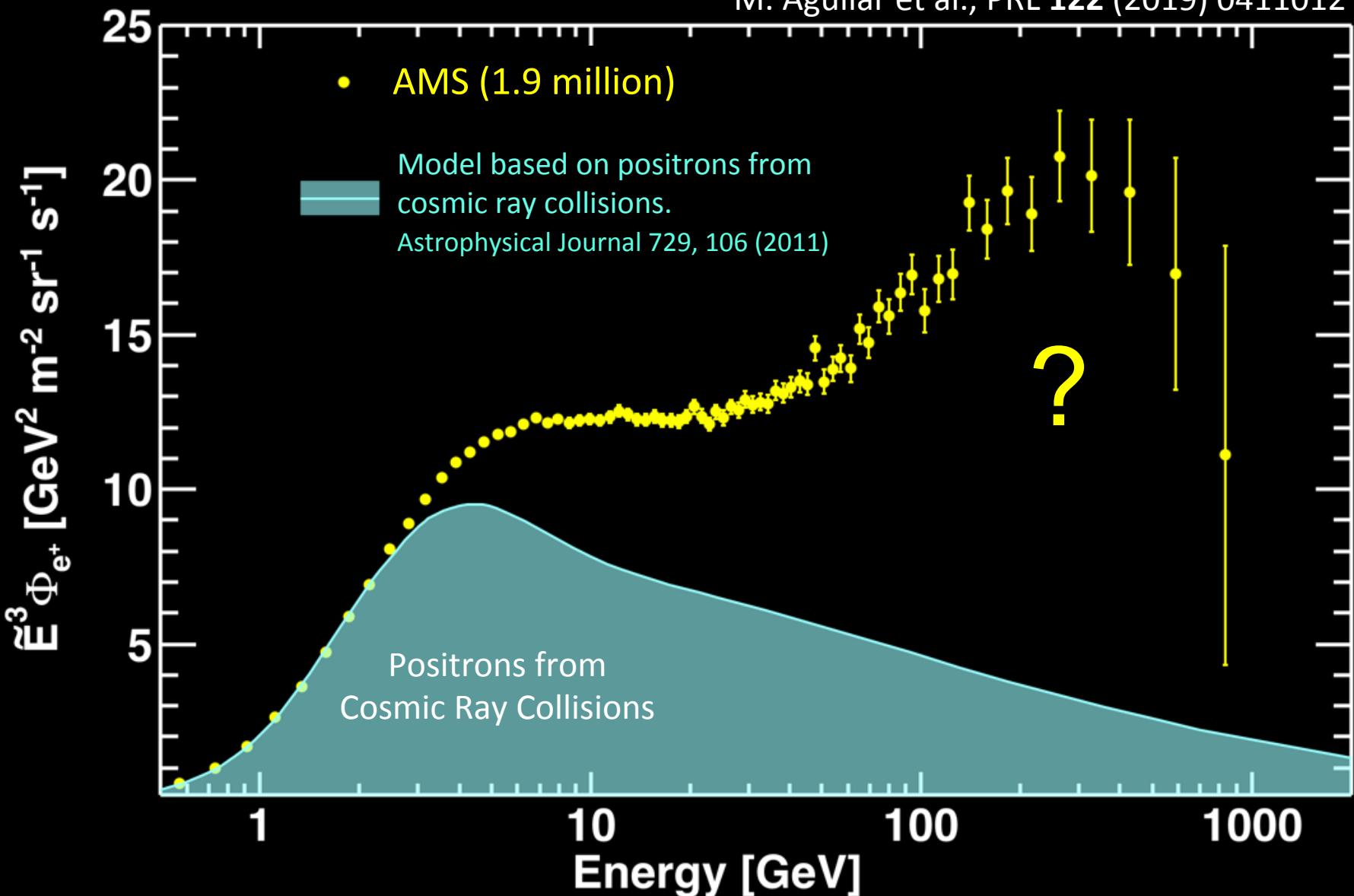


To calculate the secondary production of e^+ and \bar{p} -bar we need

- The cosmic ray fluxes of their “parents” (p , He)
- Production cross-section ($p \rightarrow p + p + p + \dots$)
- Behaviour of their propagation in the Milky Way (B/C, Be/B, ...)

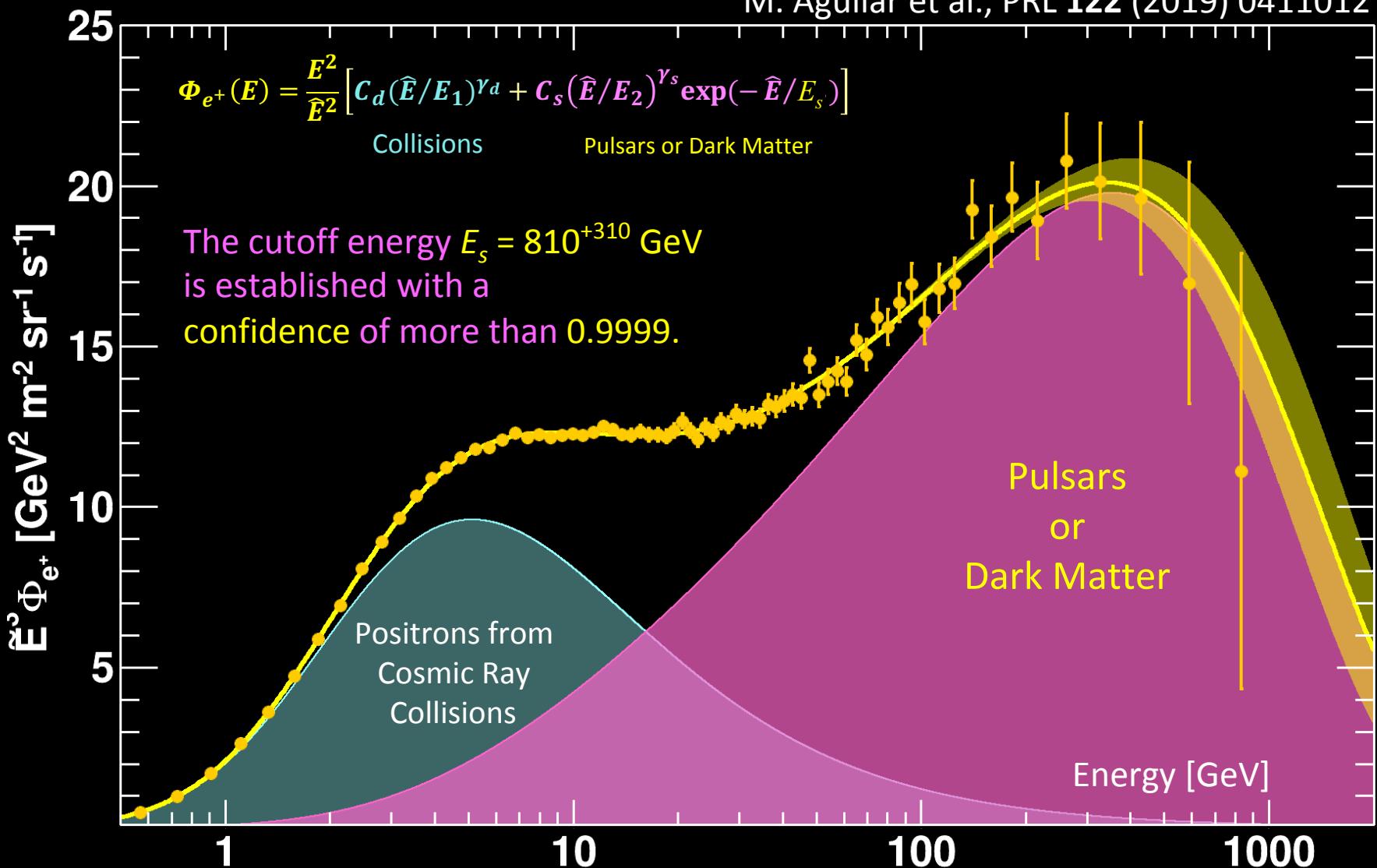
AMS Positron Flux

M. Aguilar et al., PRL 122 (2019) 0411012



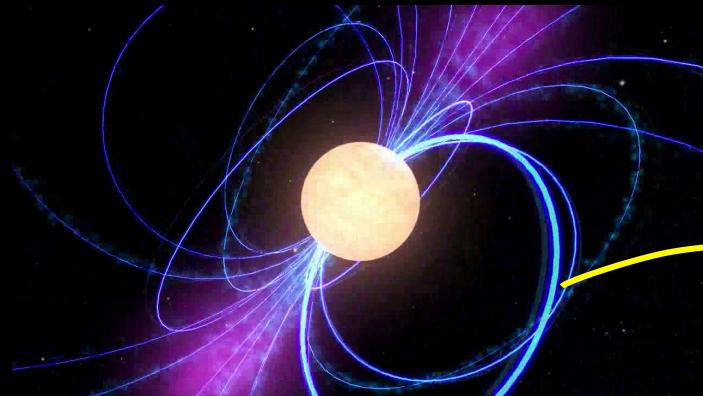
AMS Positron Flux

M. Aguilar et al., PRL **122** (2019) 0411012

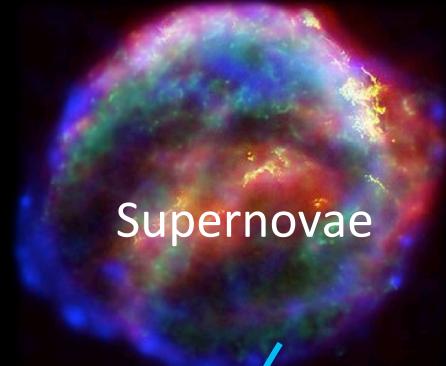


Origin of Positrons

New Astrophysical Sources: Pulsars, ...



Positrons
from Pulsars



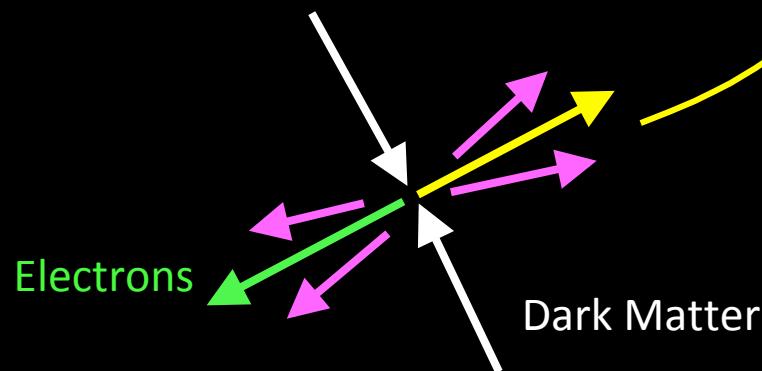
Supernovae

Protons,
Helium, ...

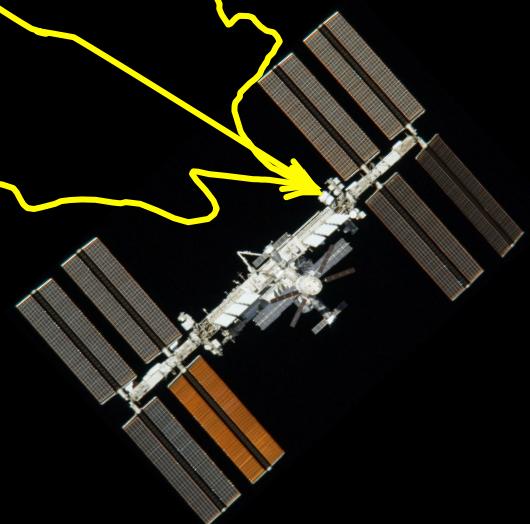
Interstellar
Medium

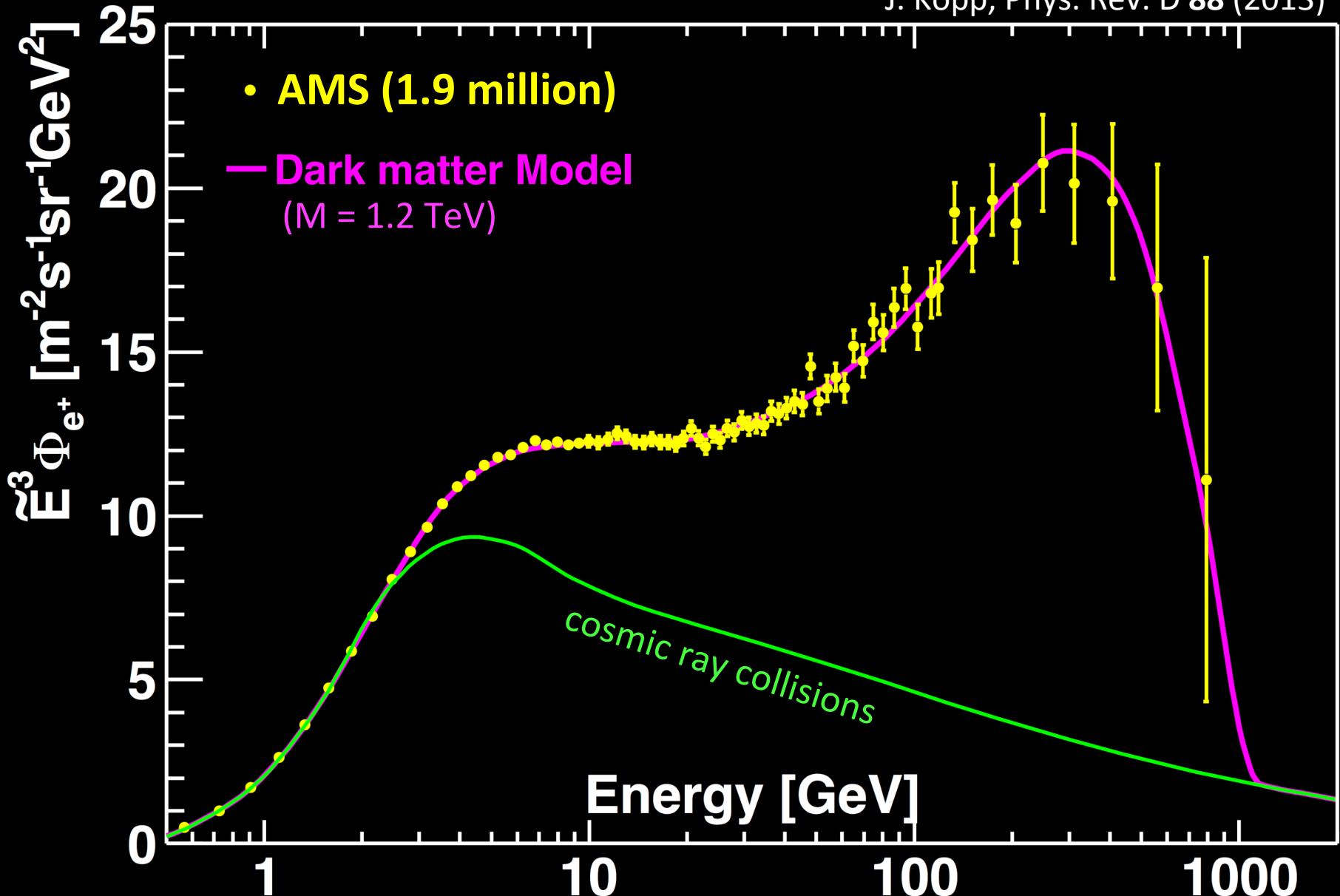
Positrons
from Collisions

Dark Matter



Positrons
from Dark Matter

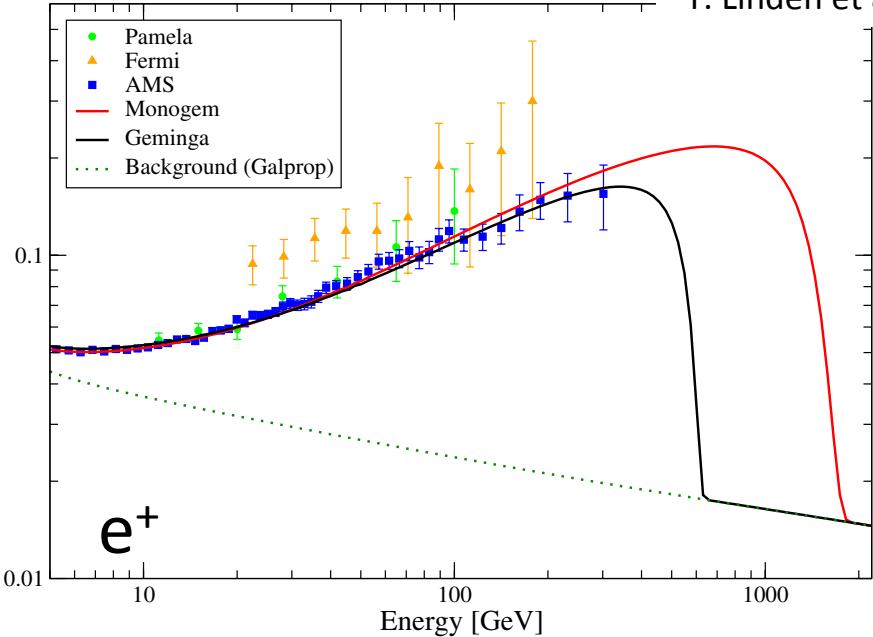


*Positron Excess as Dark Matter Annihilation*J. Kopp, Phys. Rev. D **88** (2013)

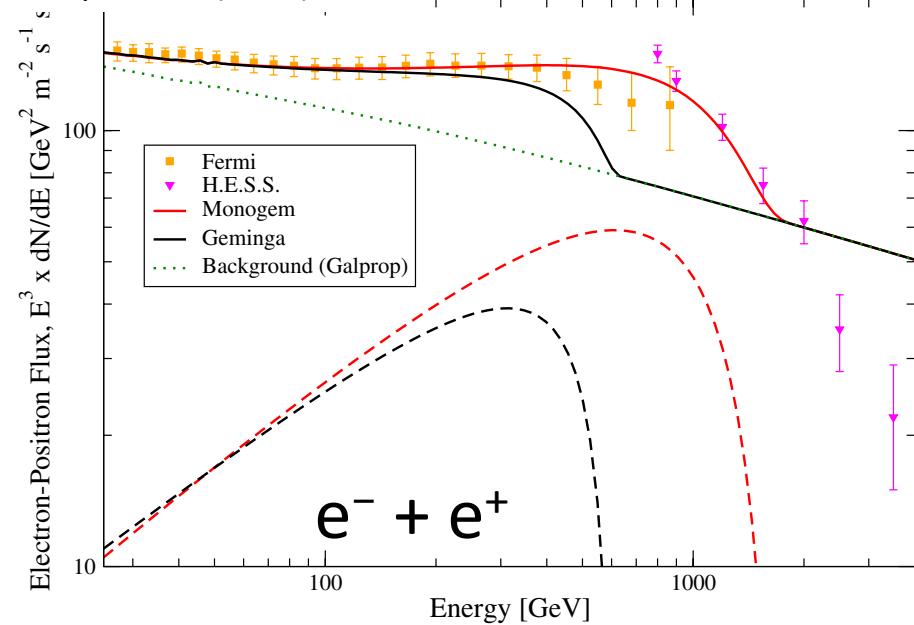
Positron Excess from Pulsar

T. Linden et al., Astrop. J. **772** (2013)

Positron Fraction

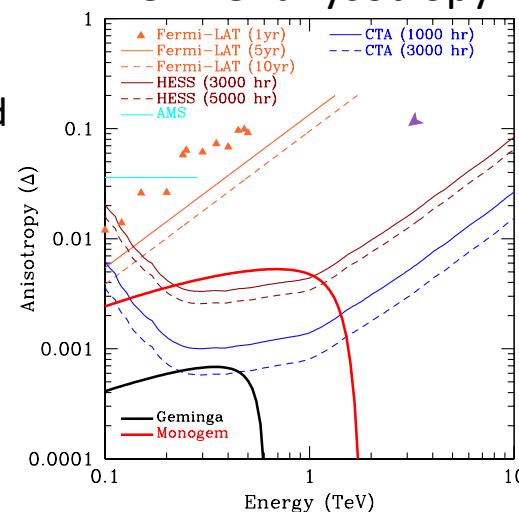


e^+



$e^- + e^+$

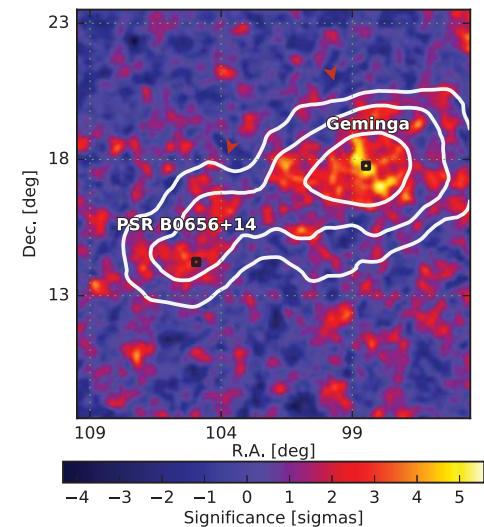
$e^- + e^+$ anisotropy



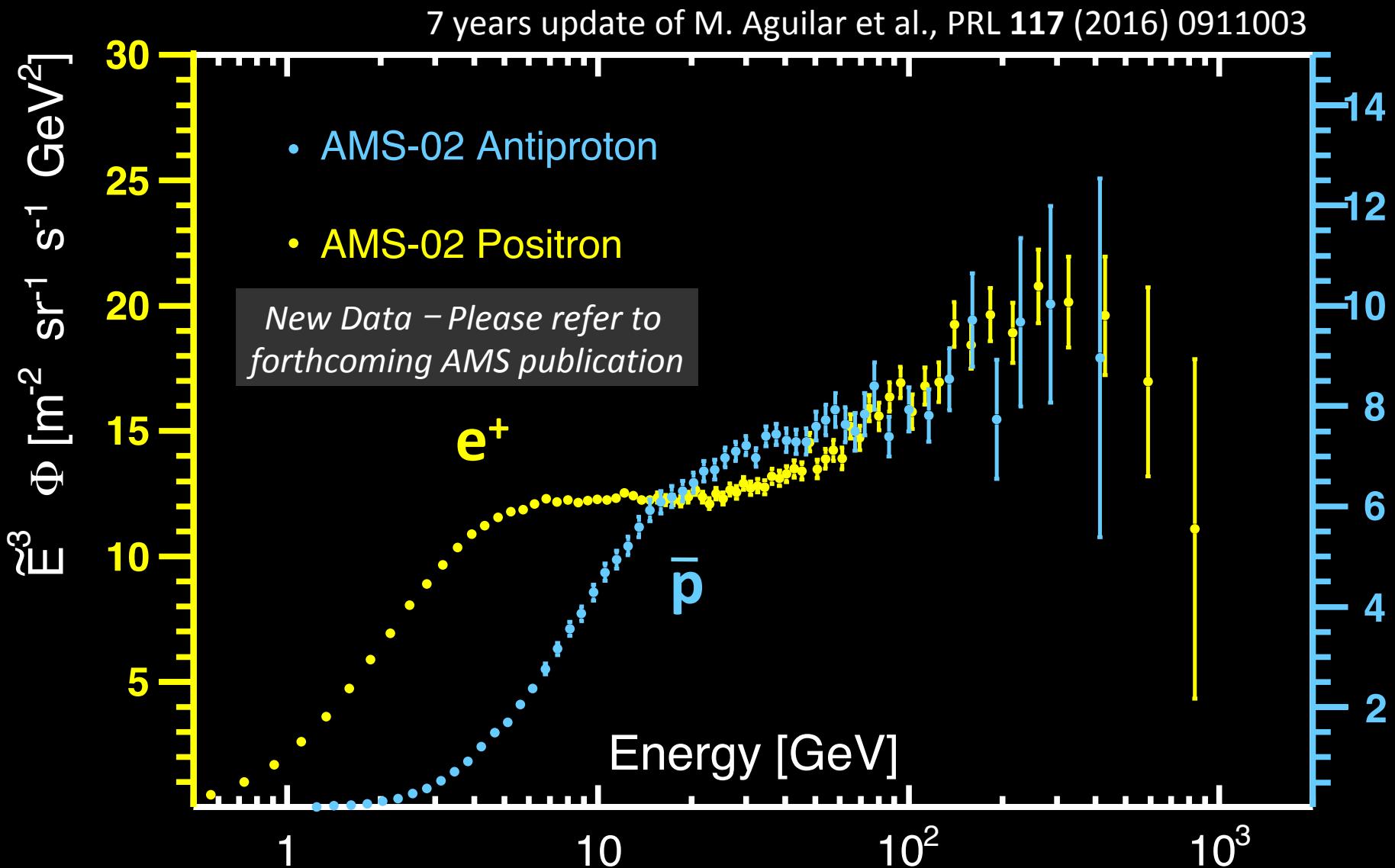
Pulsars spinning produce EM radiation and cosmic rays (pair production).

To distinguish from DM models:

- **spectral features** of e^+ and of $(e^+ + e^-)$
- **anisotropy** of e^+ and of $(e^+ + e^-)$
- **no anti-proton production**



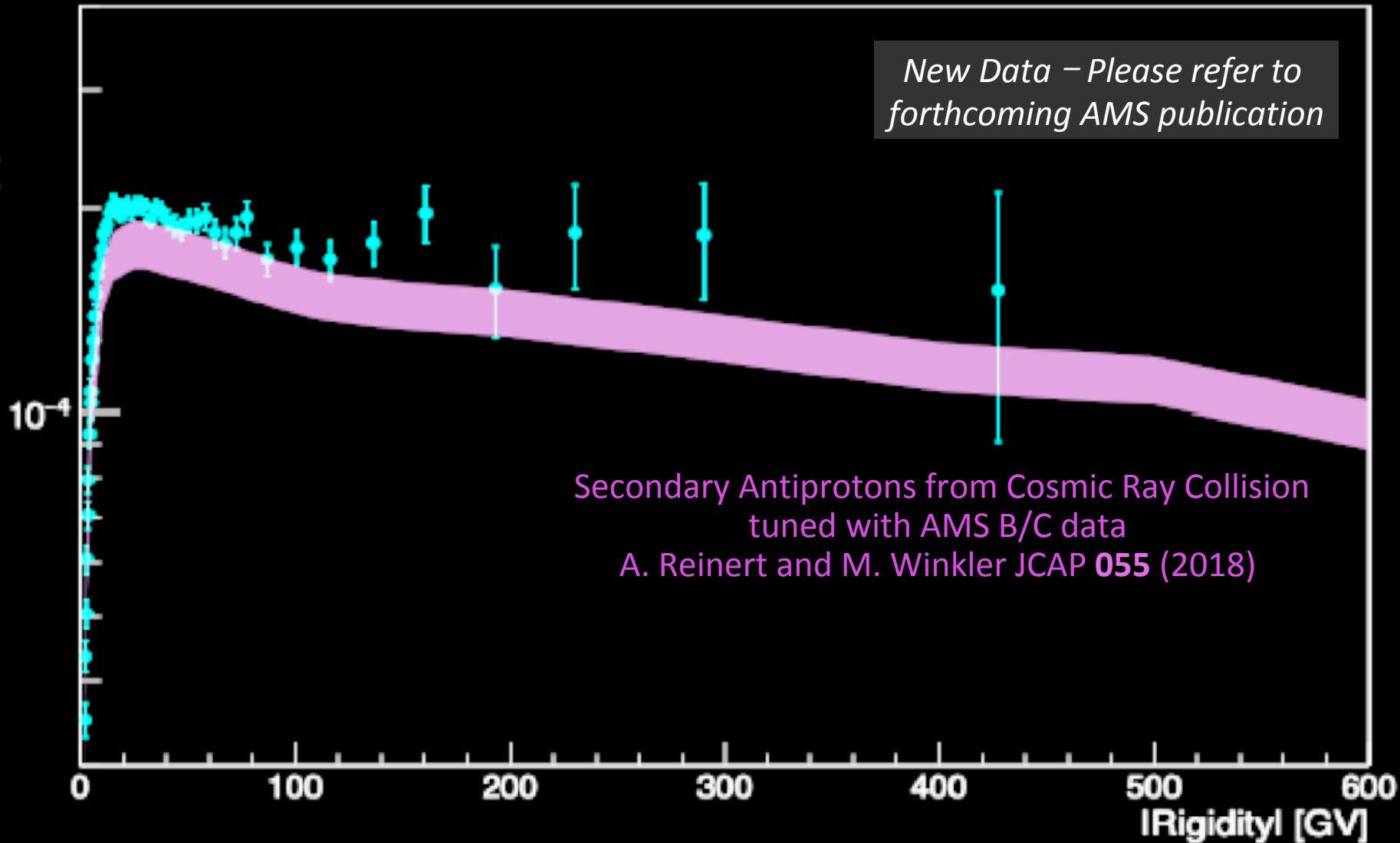
AMS Anti-Proton Flux



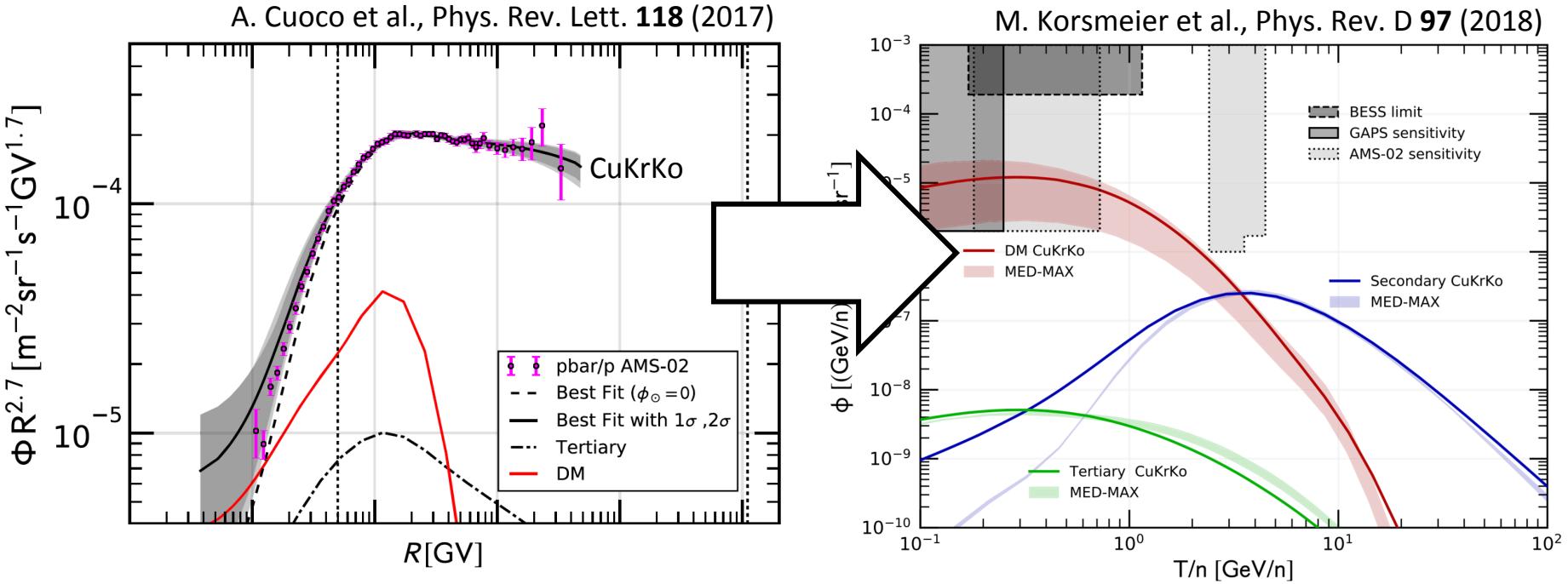
AMS Anti-Proton Flux

7 years update of M. Aguilar et al., PRL **117** (2016) 0911003

New Data – Please refer to
forthcoming AMS publication

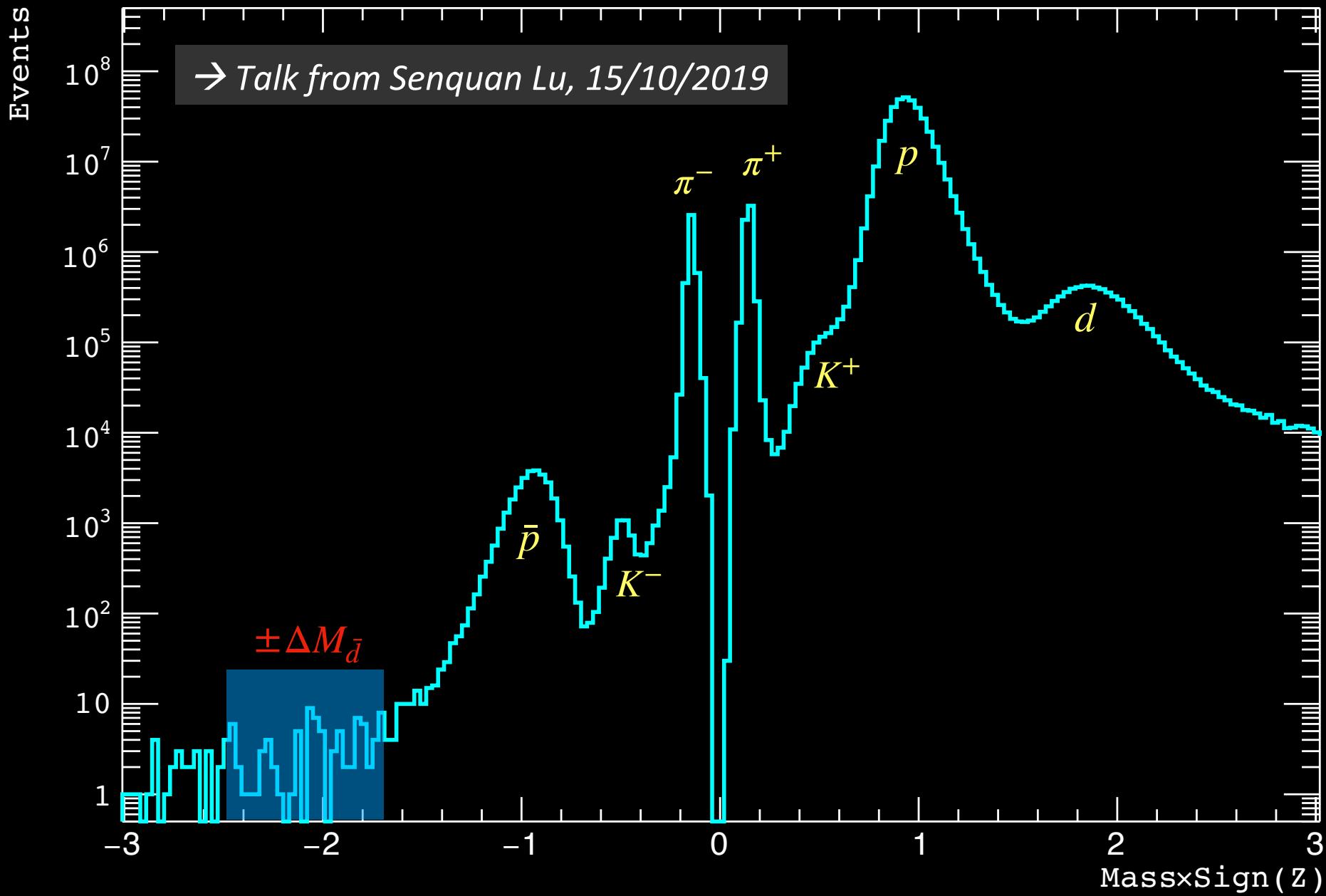


The Anti-Proton/Anti-Deuteron Connection



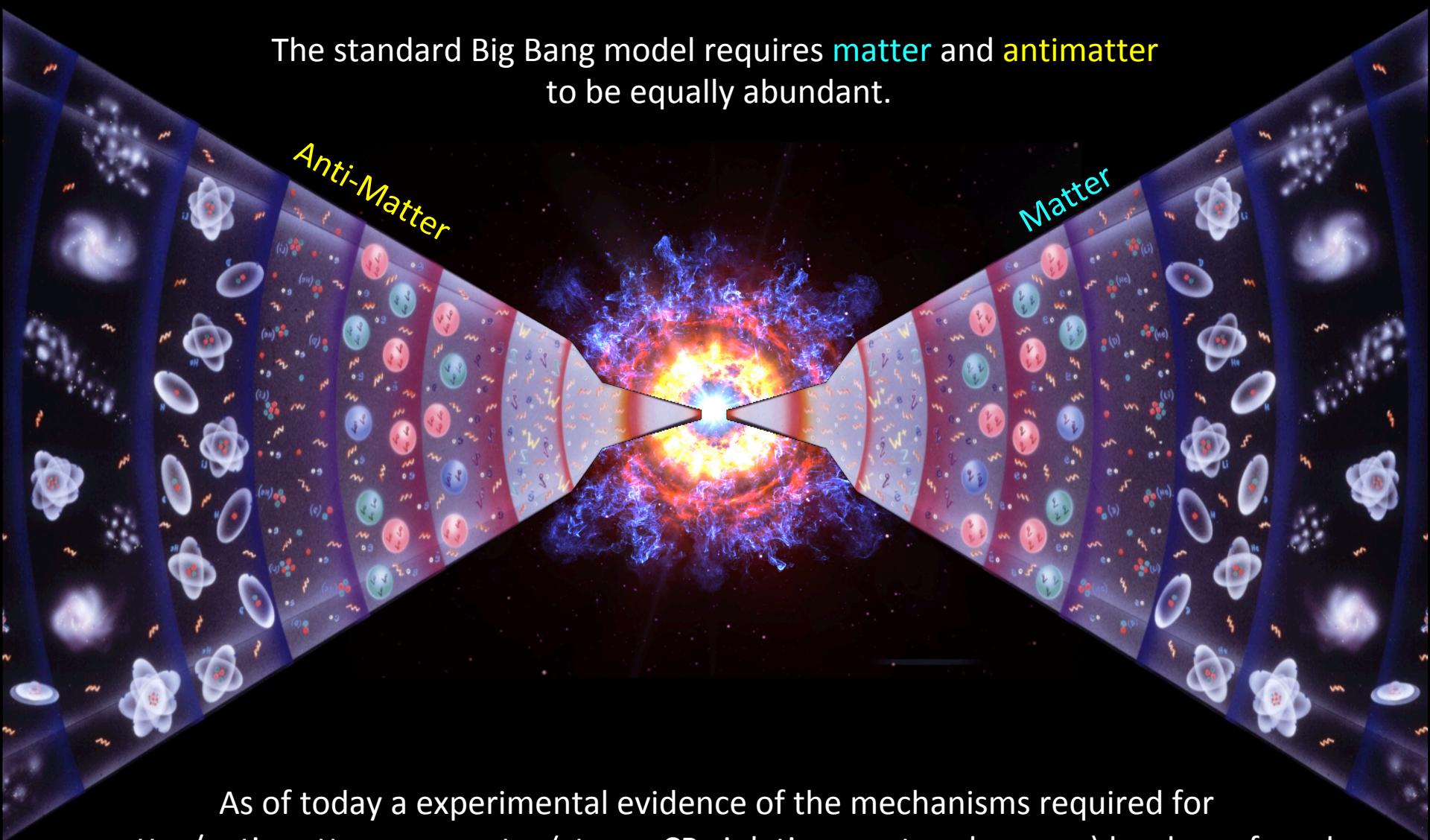
Several authors reported an allowed **anti-proton** excess at low energy, with different significances, at 10 GV that can be explained a dark matter signal. This signal can give a detectable **anti-deuteron** signal.

Status of Search for Anti-Deuteron



Heavy Anti-Matter Search

The standard Big Bang model requires matter and antimatter to be equally abundant.

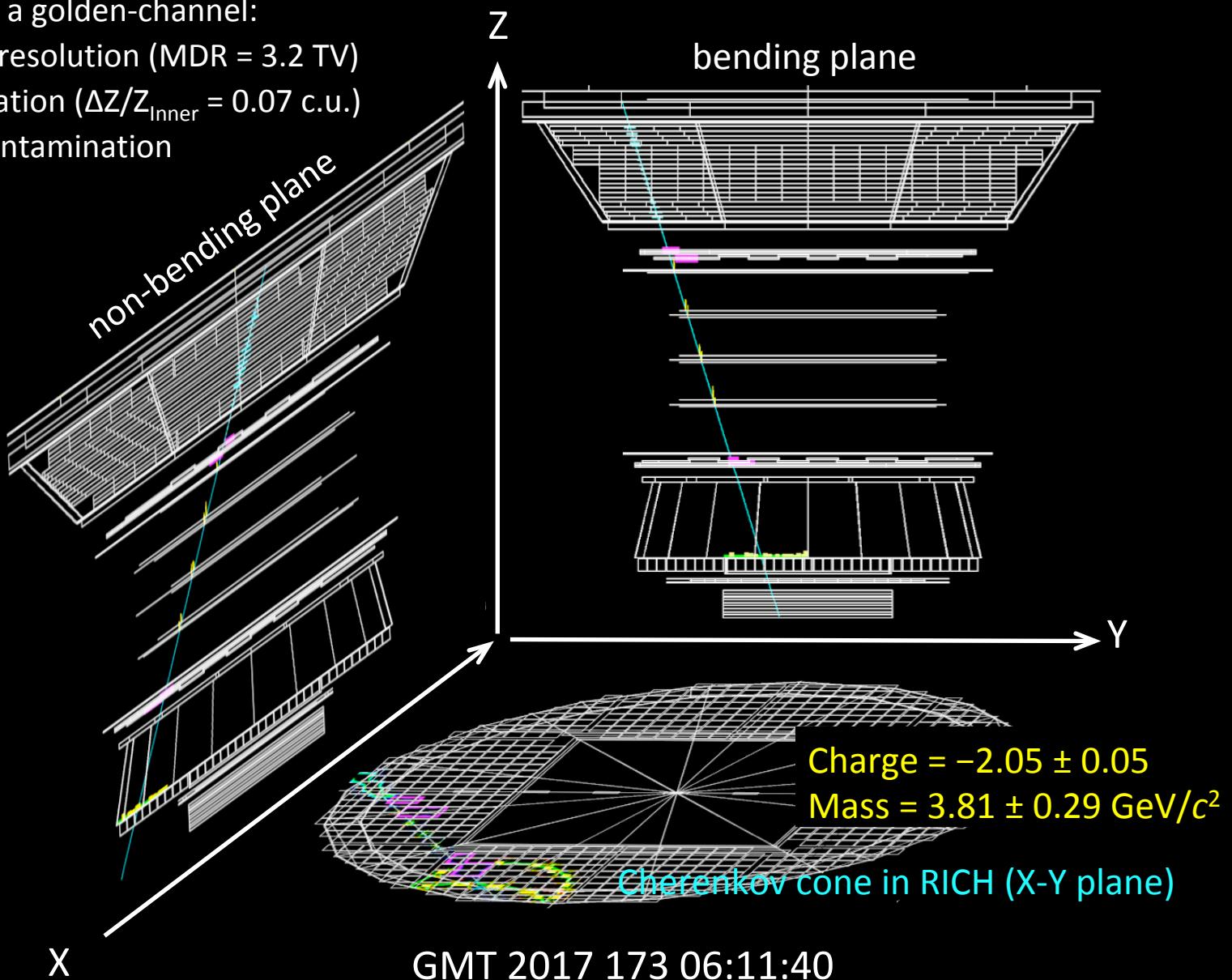


As of today a experimental evidence of the mechanisms required for matter/anti-matter asymmetry (strong CP violation, proton decay, ...) has been found.
Neither has a single anti-nucleus been seen in cosmic rays.

An Anti-Helium Candidate

Anti-helium is a golden-channel:

- Best rigidity resolution ($MDR = 3.2 \text{ TV}$)
- Best Z separation ($\Delta Z/Z_{\text{inner}} = 0.07 \text{ c.u.}$)
- No p, K, π contamination

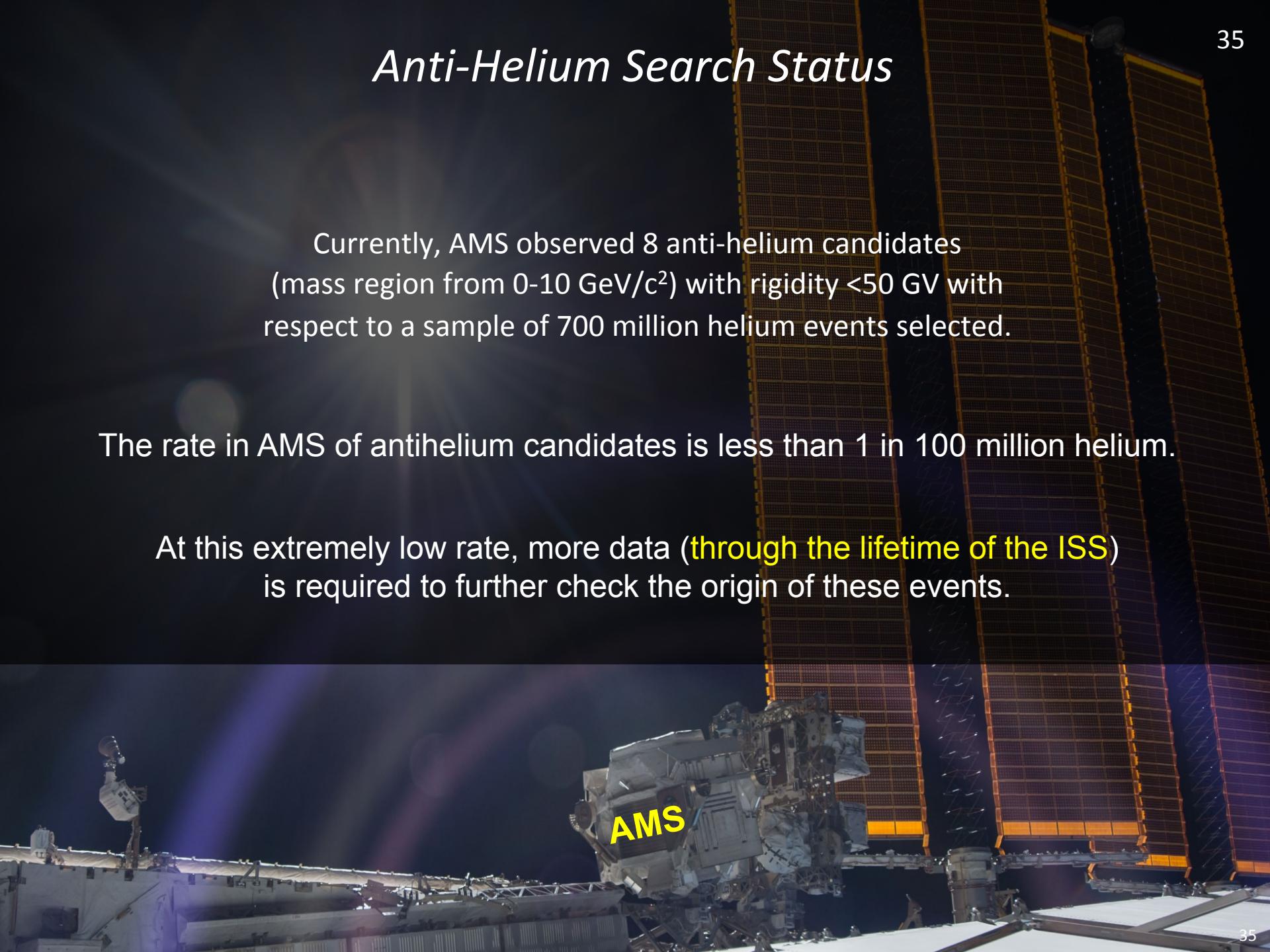


Anti-Helium Search Status

Currently, AMS observed 8 anti-helium candidates (mass region from 0-10 GeV/c²) with rigidity <50 GV with respect to a sample of 700 million helium events selected.

The rate in AMS of antihelium candidates is less than 1 in 100 million helium.

At this extremely low rate, more data (**through the lifetime of the ISS**) is required to further check the origin of these events.





AMS has been operating in the Space Station since May 2011 performing precision measurements of cosmic rays and revealing new details about origin and propagation of all CRs species.

With its unprecedented statistics and accuracy, AMS has an unique capability to detect antimatter in cosmic rays and study their properties.

AMS is the only operating spectrometer in space, and will continue to collect and analyze data for the lifetime of the Space Station.