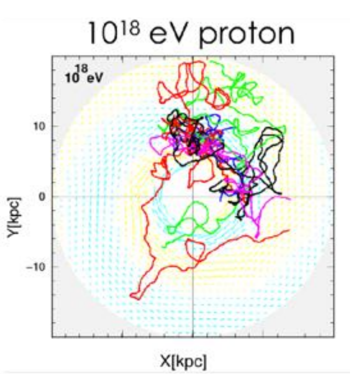
Astroparticle Physics with Alpha Magnetic Spectrometer on-board of the International Space Station

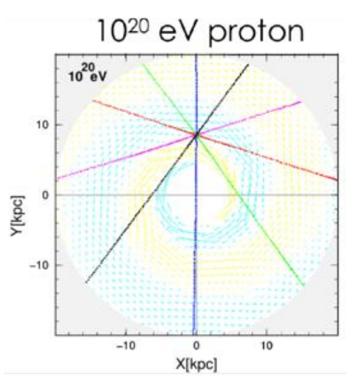
A. Oliva[*] on behalf of the AMS-02 Collaboration.
[*]Istituto Nazionale di Fisica Nucleare, Bologna, Italy.

Joint Astrophysical Colloquium, 14/05/2019

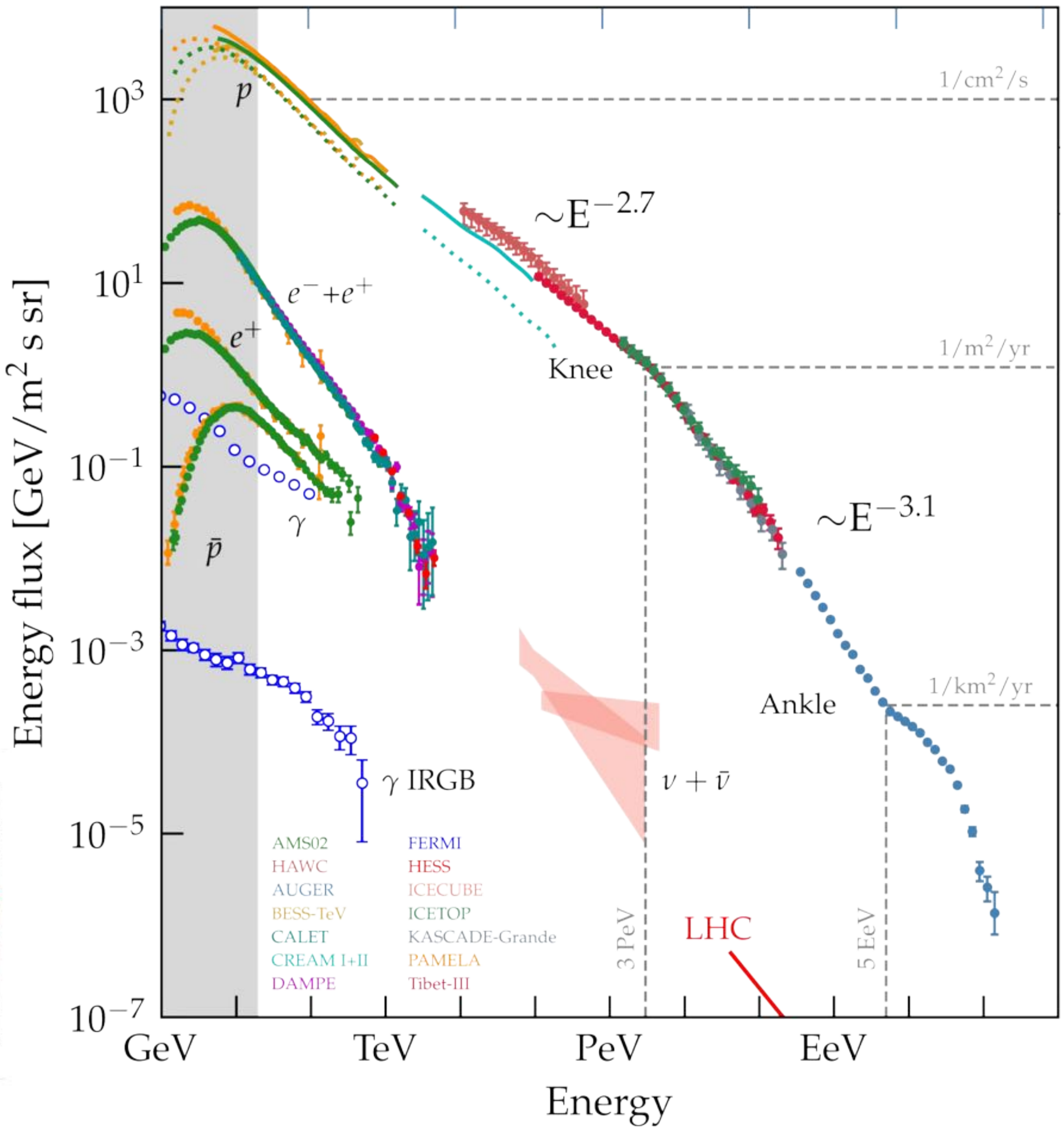
Cosmic Rays

- Energetic particles and completely ionized nuclei from outer space.
- Many orders of magnitude in energy and flux (low-E: *direct detection*, high-E: *Extensive Air Shower*)
- A power law several features (*knee & ankle* → different origin).
- At TeV, charged CRs are confined by the *galactic* magnetic field.

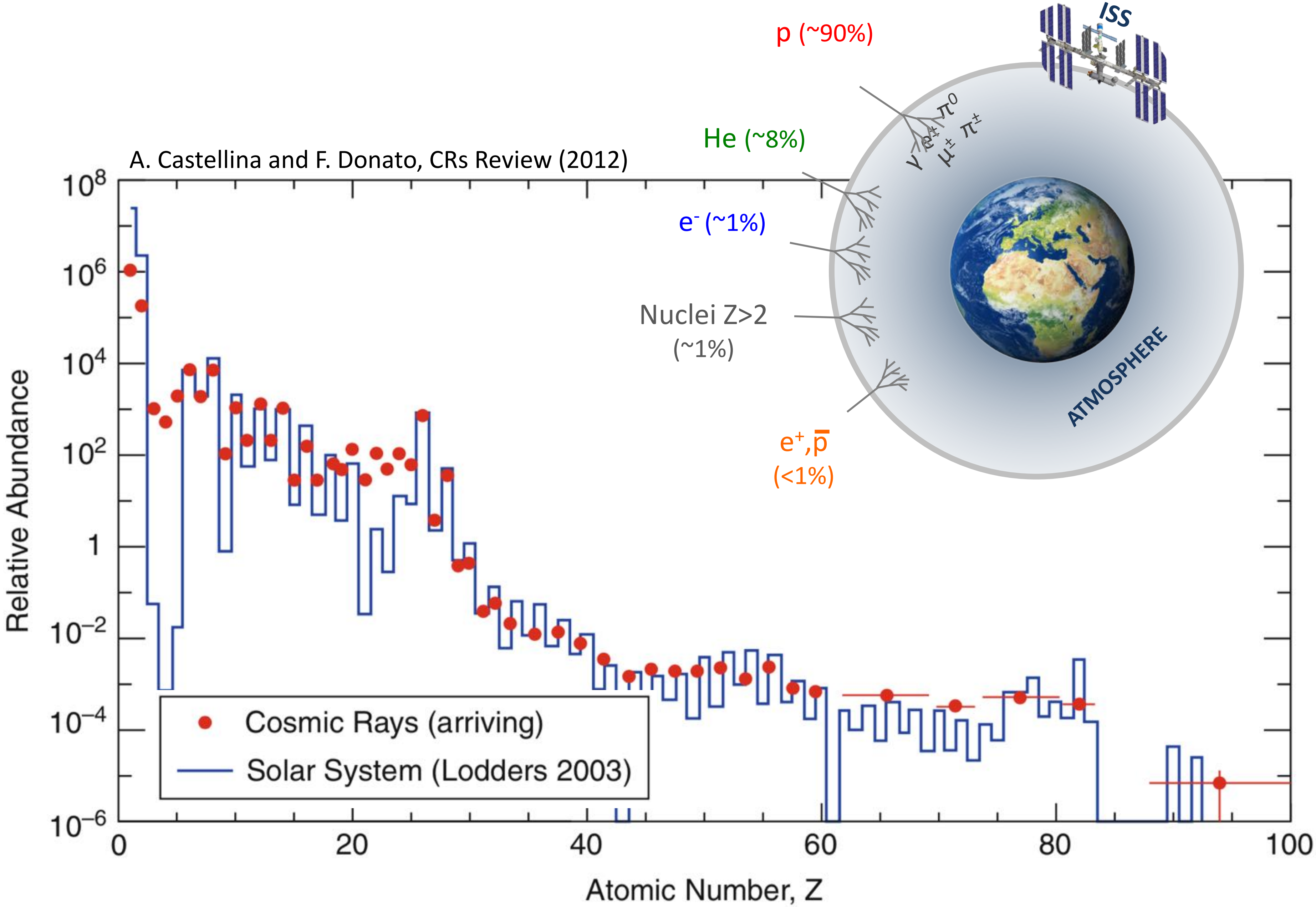




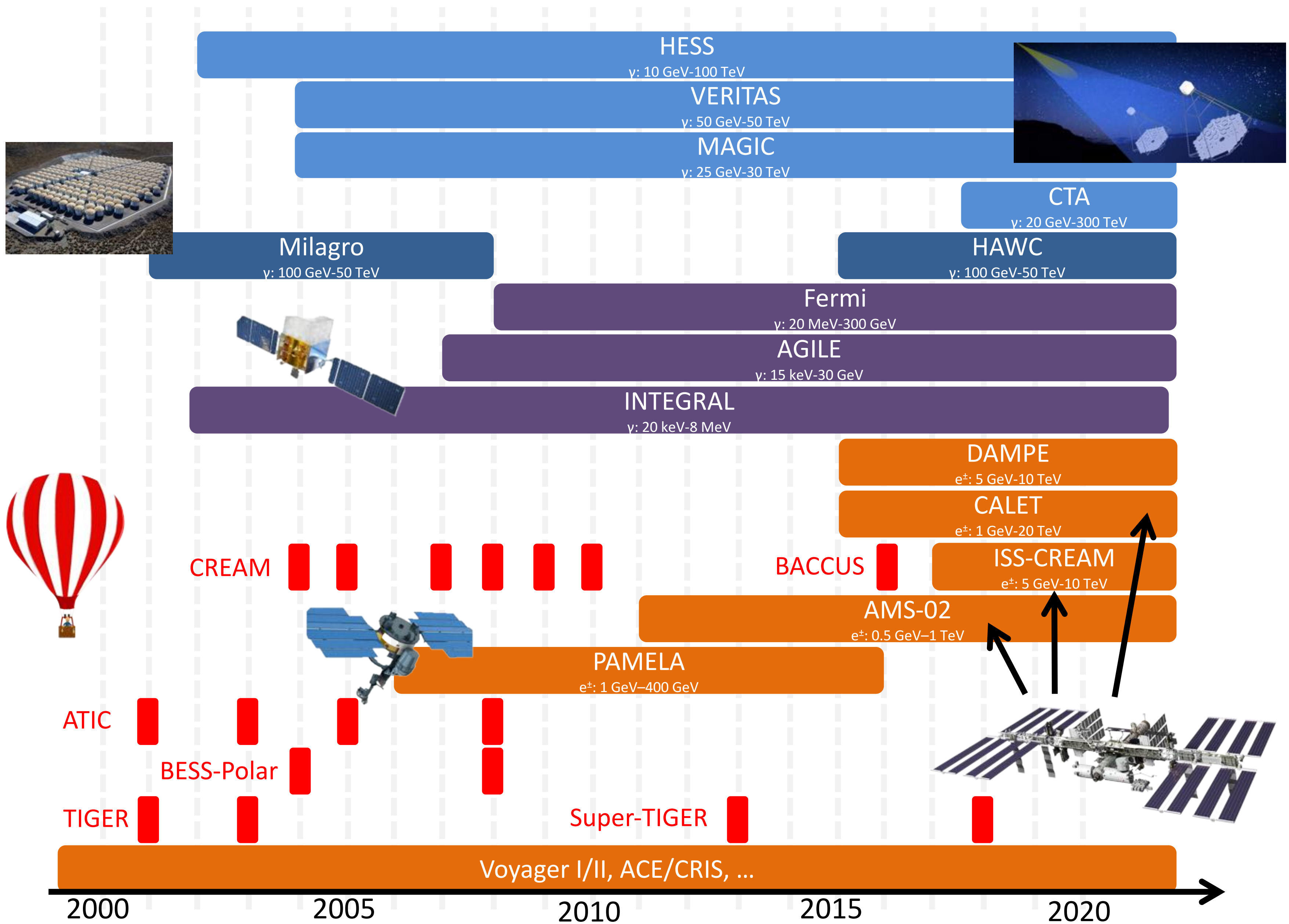
C. Evoli, http://doi.org/10.5281/zenodo.2360277 (2018)



Galactic Charged CRs Composition



Timeline of Recent "TeV" γ-Rays and CRs Experiments



AMS-02 on-board of the International Space Station

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

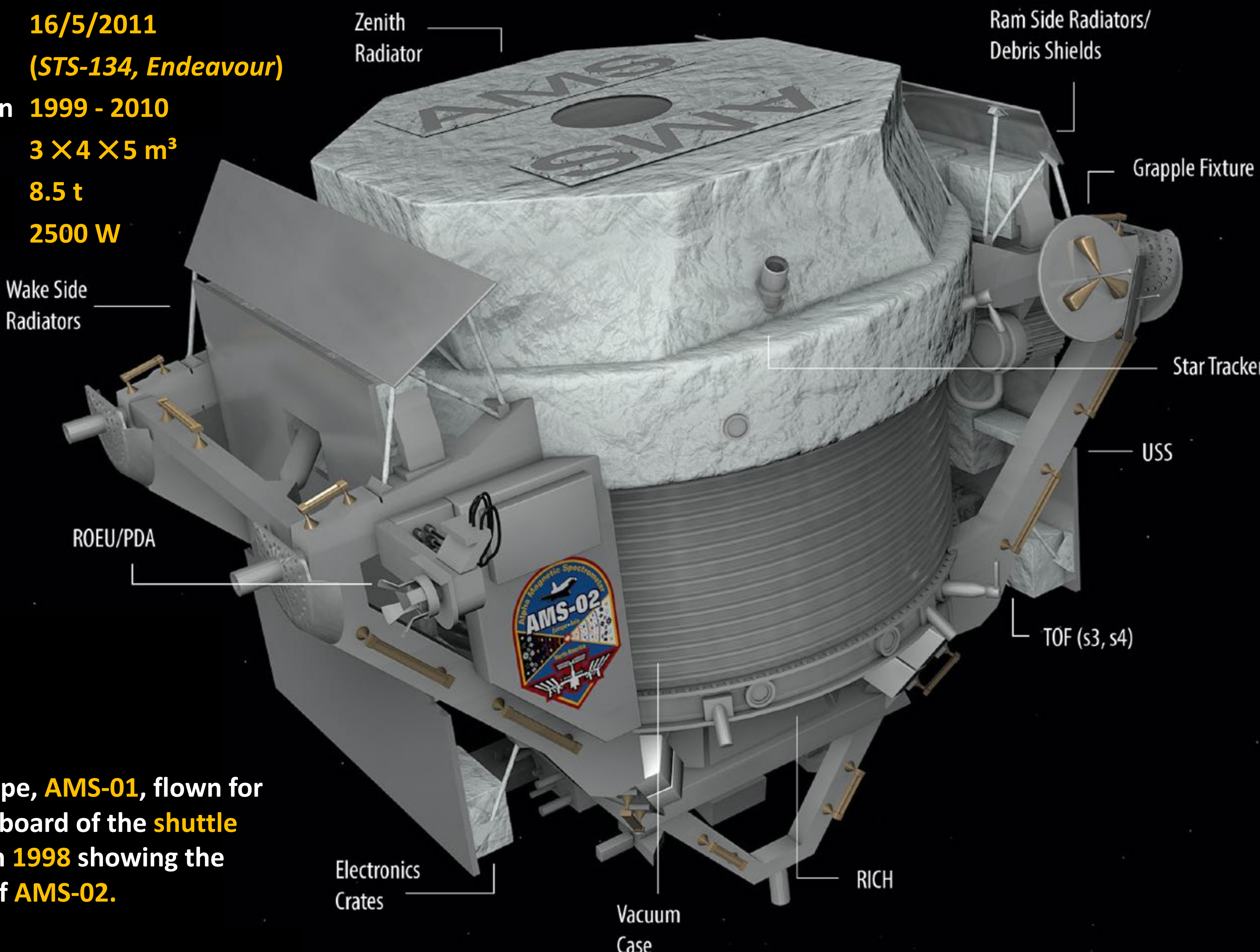
AMS has collected > 150 billion cosmic rays up to today.

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

Altitude	**~ 400 km**
Inclination	**~ 51°**
Period	**~ 93 min**
Construction	**1998 - …**
Dimensions	**73 × 109 m^2**
Weight	**420 t**

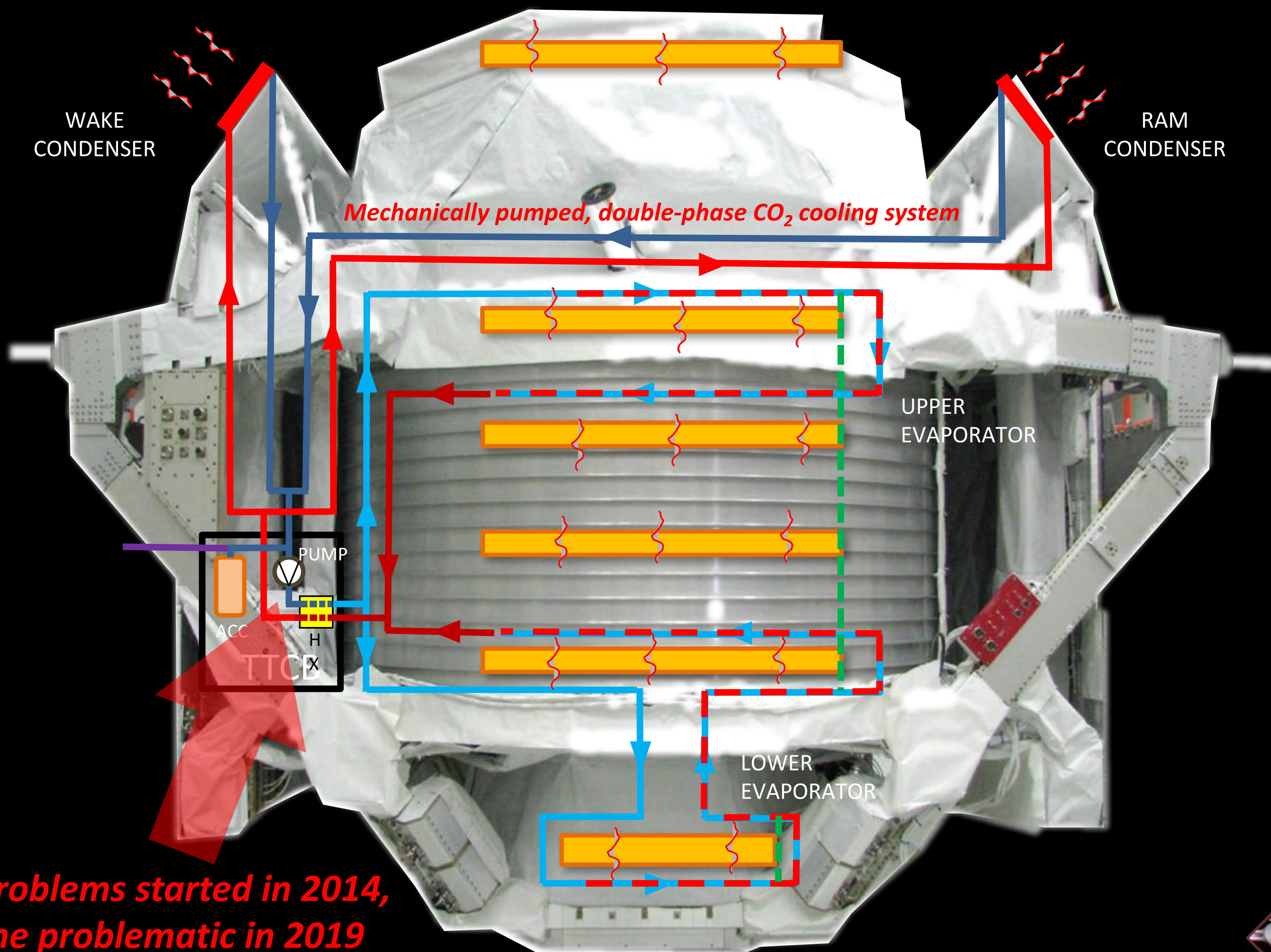
AMS-02: *the Alpha Magnetic Spectrometer*

Launch	**16/5/2011**
	(*STS-134, Endeavour*)
Construction	**1999 - 2010**
Dimensions	**3 × 4 × 5 m³**
Weight	**8.5 t**
Power	**2500 W**



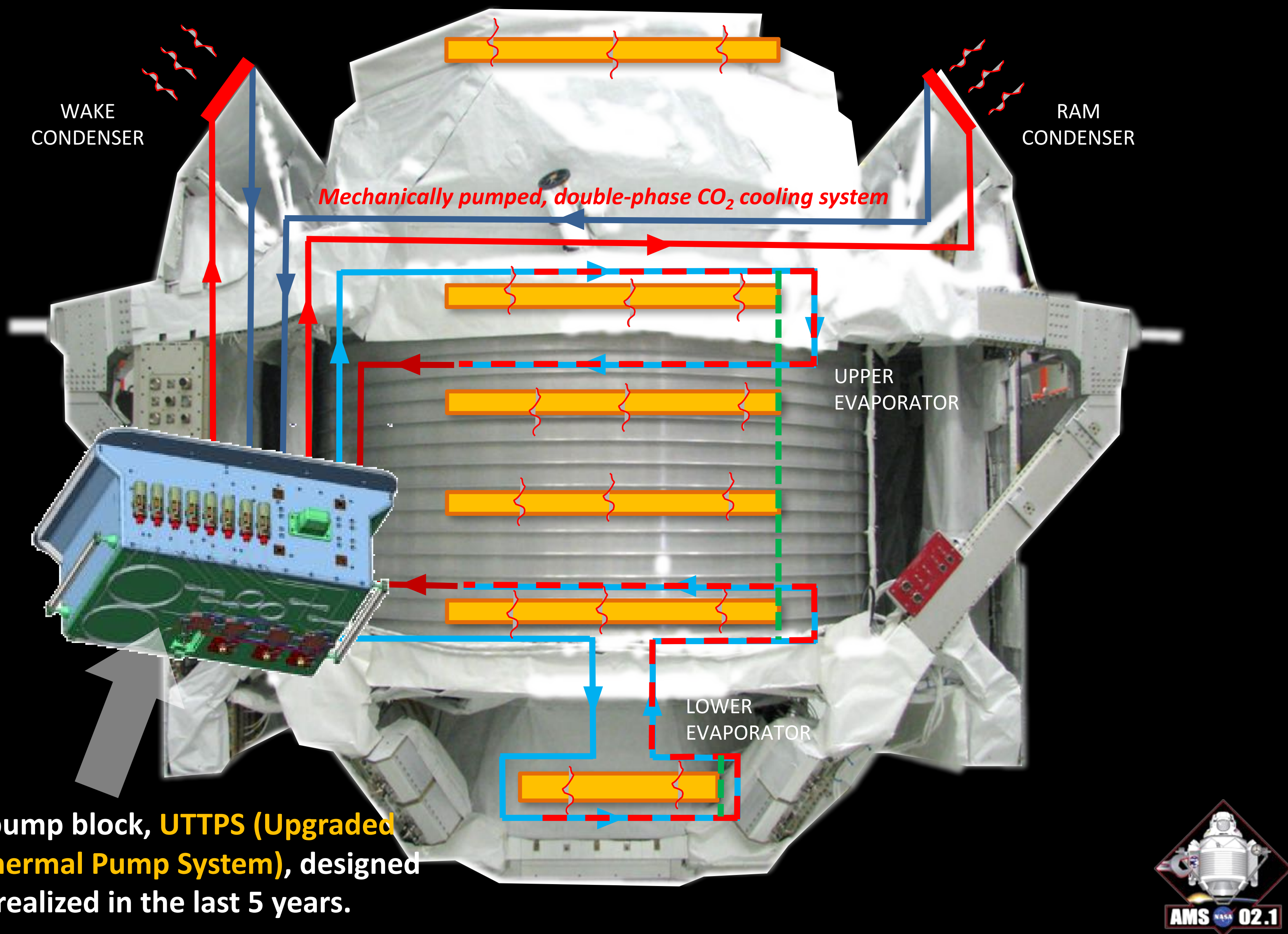
The prototype, AMS-01, flown for 10-days on-board of the shuttle Discovery in 1998 showing the feasibility of AMS-02.

The Tracker Thermal Control System



Some problems started in 2014, became problematic in 2019

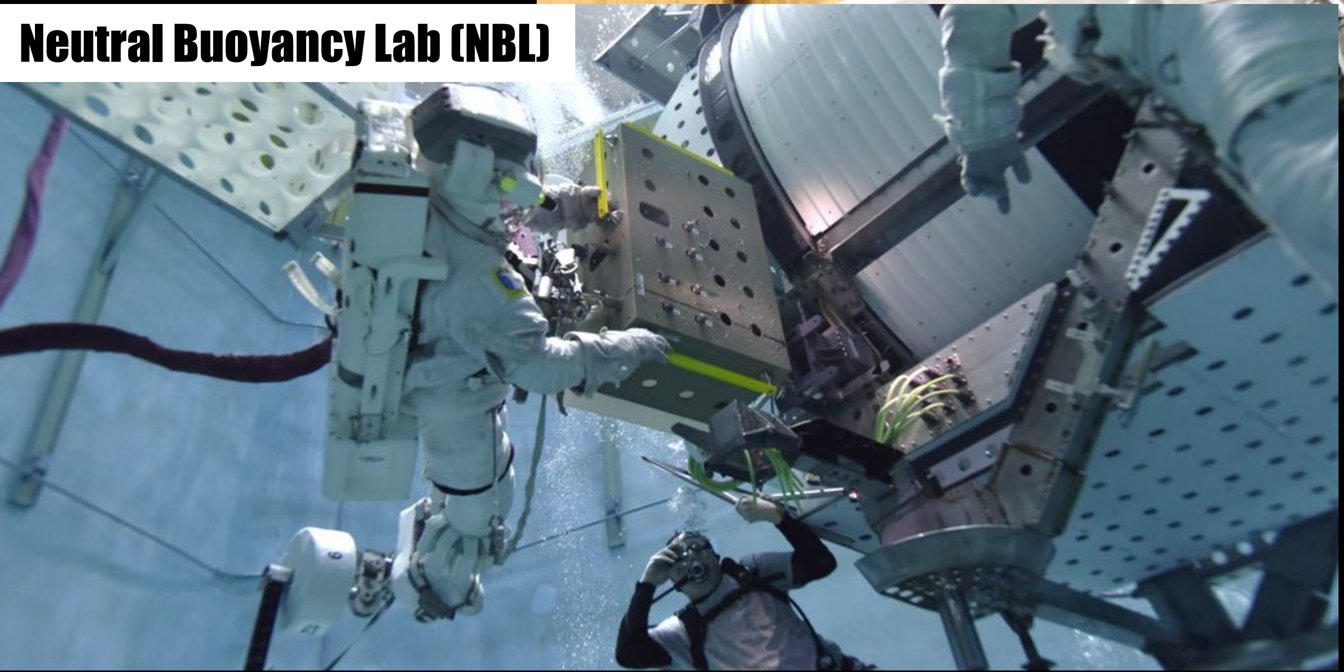
The Upgraded Tracker Thermal Pump System



A new pump block, UTTPS (Upgraded Tracker Thermal Pump System), designed and realized in the last 5 years.

Extending AMS-02 Lifetime: Astronauts Training

Active Response Gravity Offload System (ARGOS)



Neutral Buoyancy Lab (NBL)

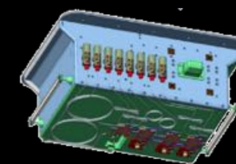
95 simulations (ARGOS + NBL) with 7 astronauts involved.

Extending AMS-02 Lifetime: Shipping

Astronauts:
Luca Parmitano,
Drew Morgan,
Alexander Skvortsov

Instrumentation

UTTPS



Extending AMS-02 Lifetime: UTTPS Installation

L. Parmitano on the robotic arm, transporting the UTTPS

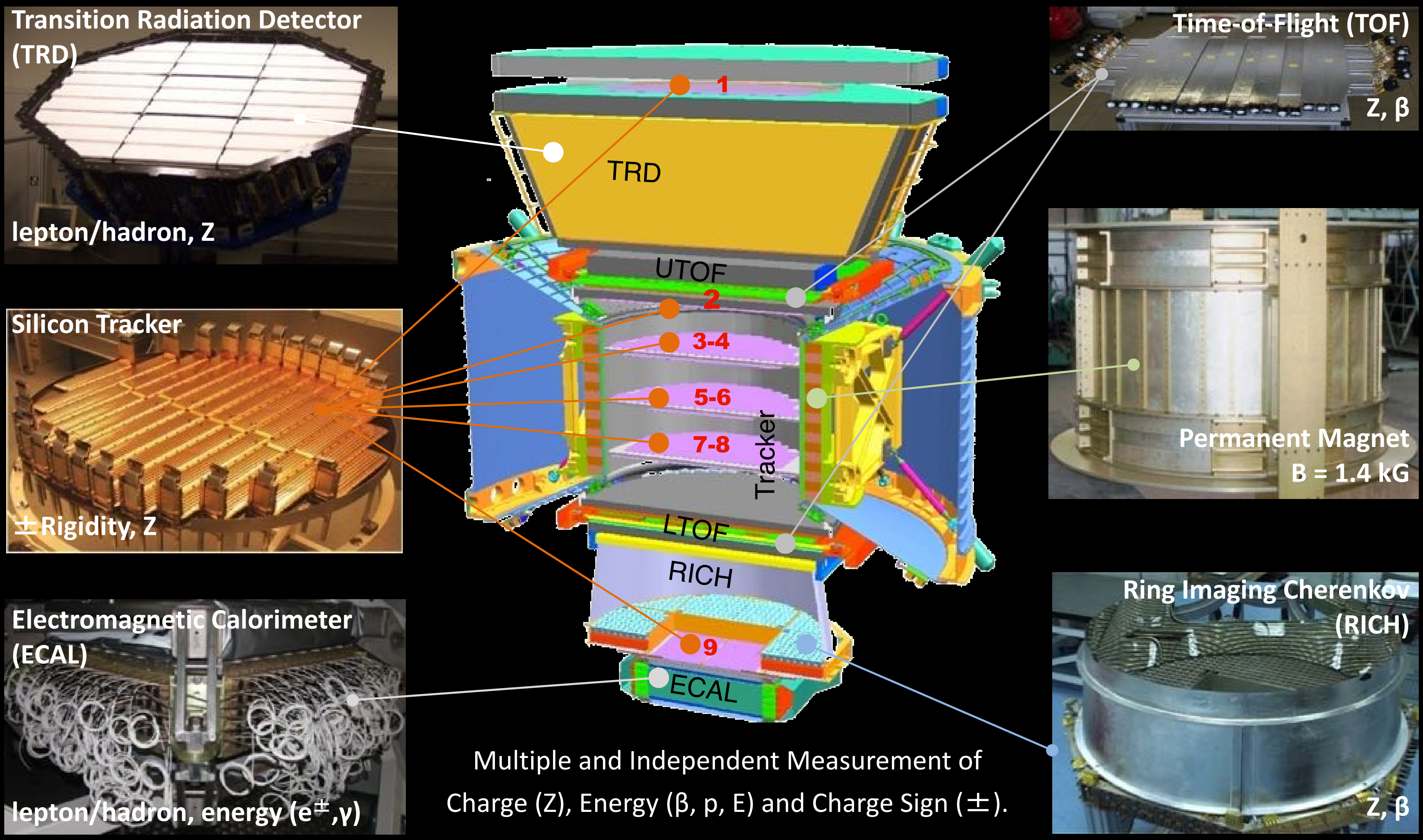
2/12/'19

Extending AMS-02 Lifetime: UTTPS Installation

Luca Parmitano (Commander, ESA 🇮🇹),
Andrew Morgan (NASA 🇺🇸)
EVA #1: 15 Nov. 2019, take access
EVA #2: 22 Nov. 2019, cut the tubes
EVA #3: 2 Dec. 2019, install UTTPS
EVA #4: 25 Jan. 2020, activation

AMS-02: a TeV Multi-Purpose Spectrometer

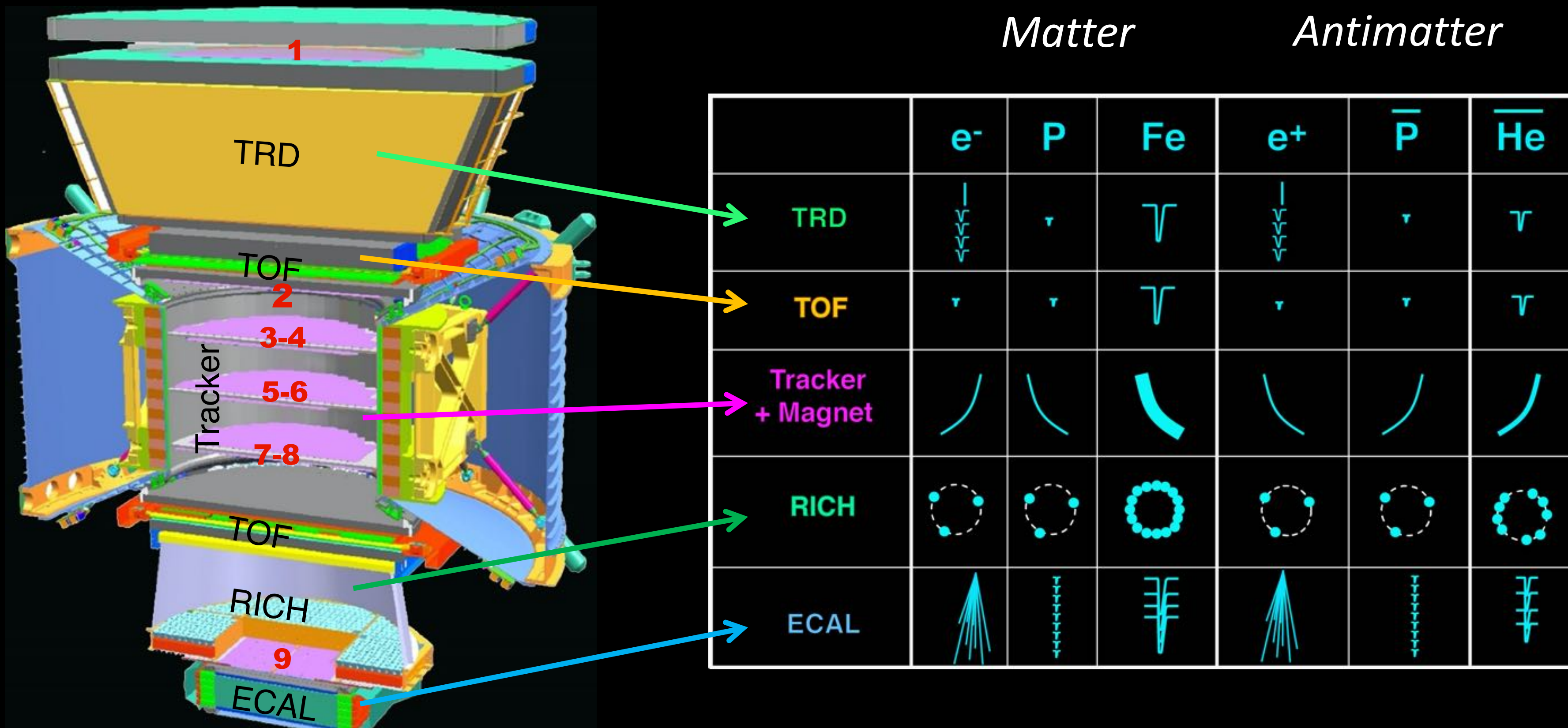
AMS-02 separates hadrons from leptons, matter from anti-matter, chemical and isotopic composition from fraction of GeV to multi-TeV.



Multiple and Independent Measurement of Charge (Z), Energy (β, p, E) and Charge Sign (±).

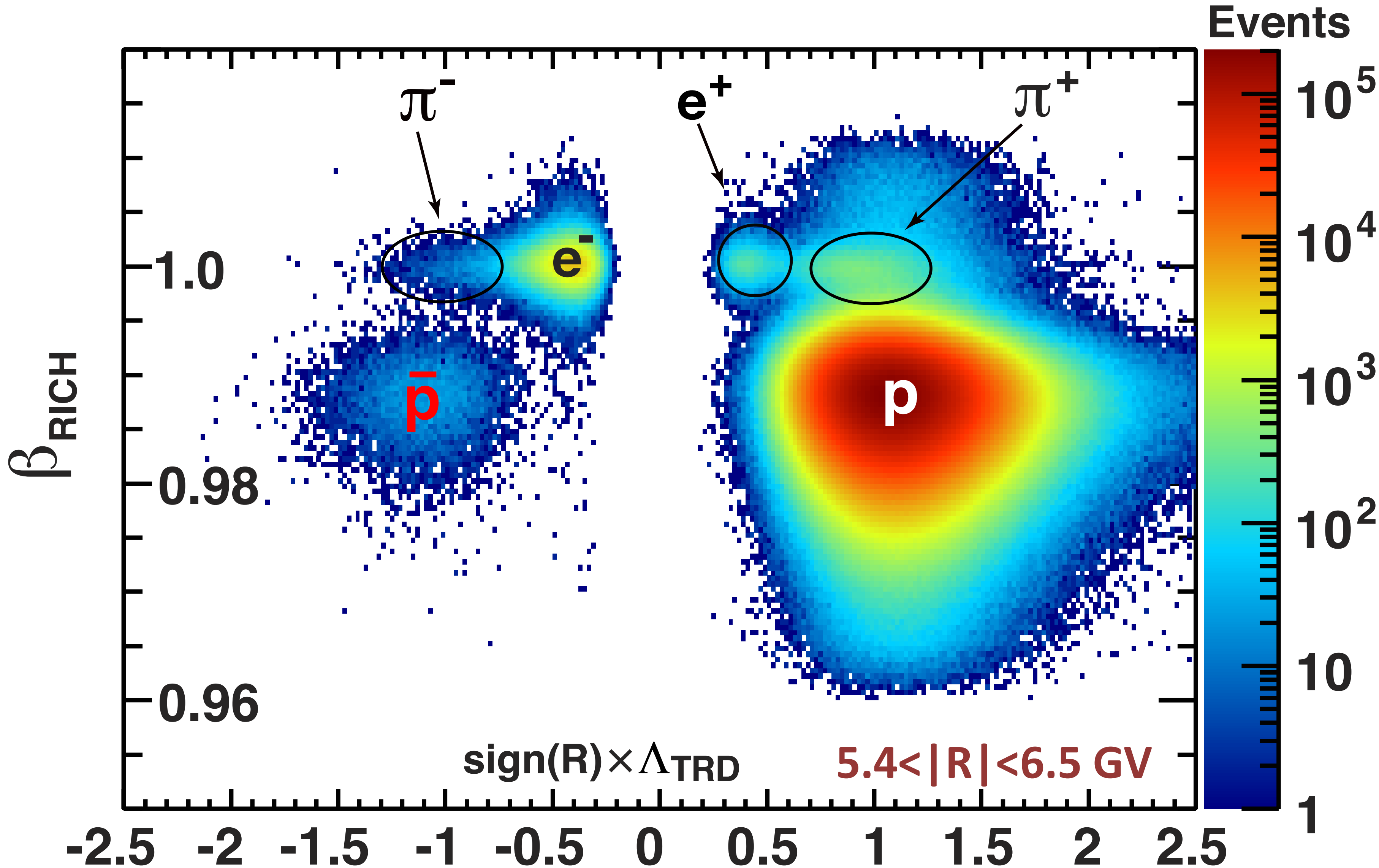
AMS-02: a TeV Multi-Purpose Spectrometer

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

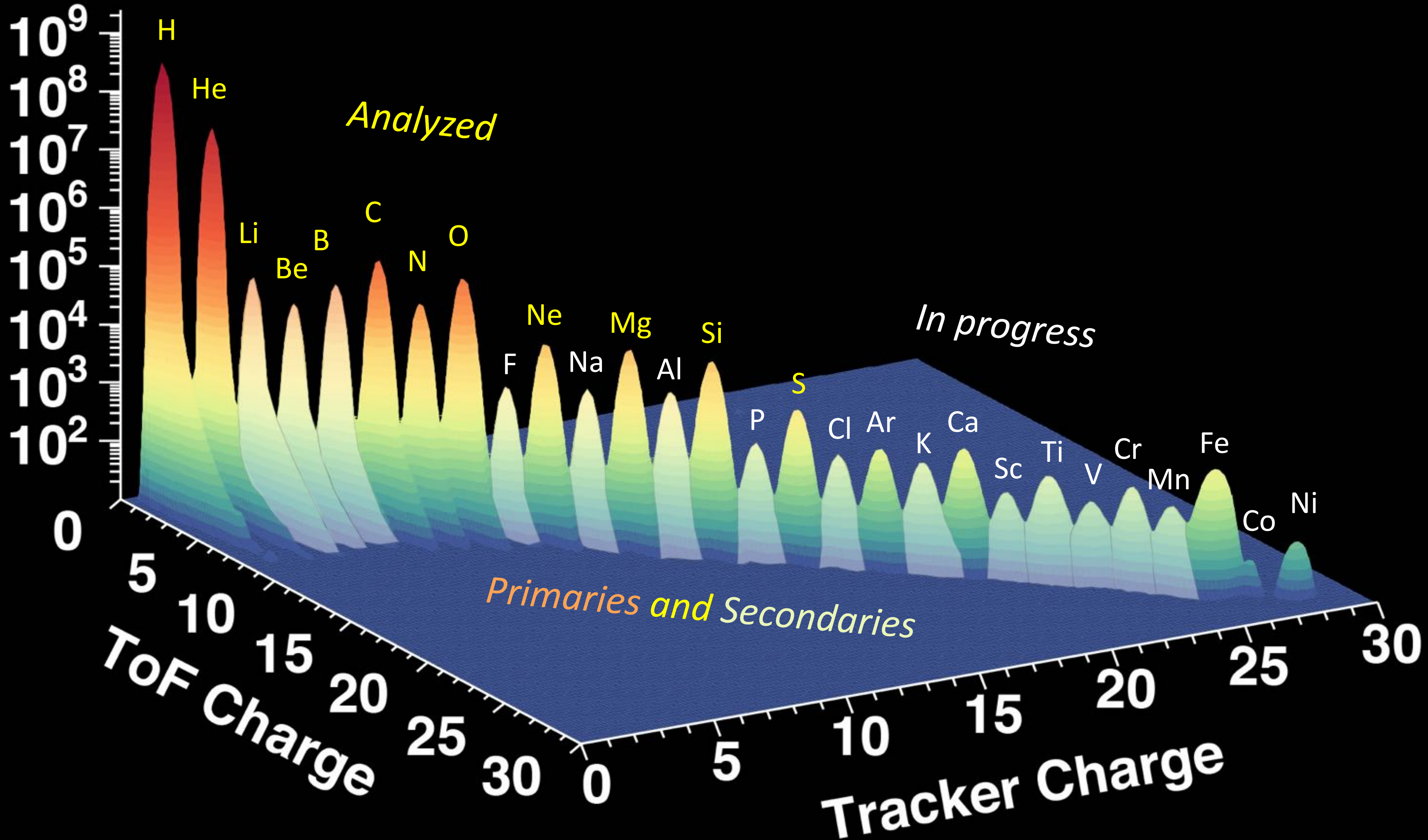


AMS is able to identify 1 positron from 10^6 protons, unambiguously separate positrons from electrons up to a TeV.

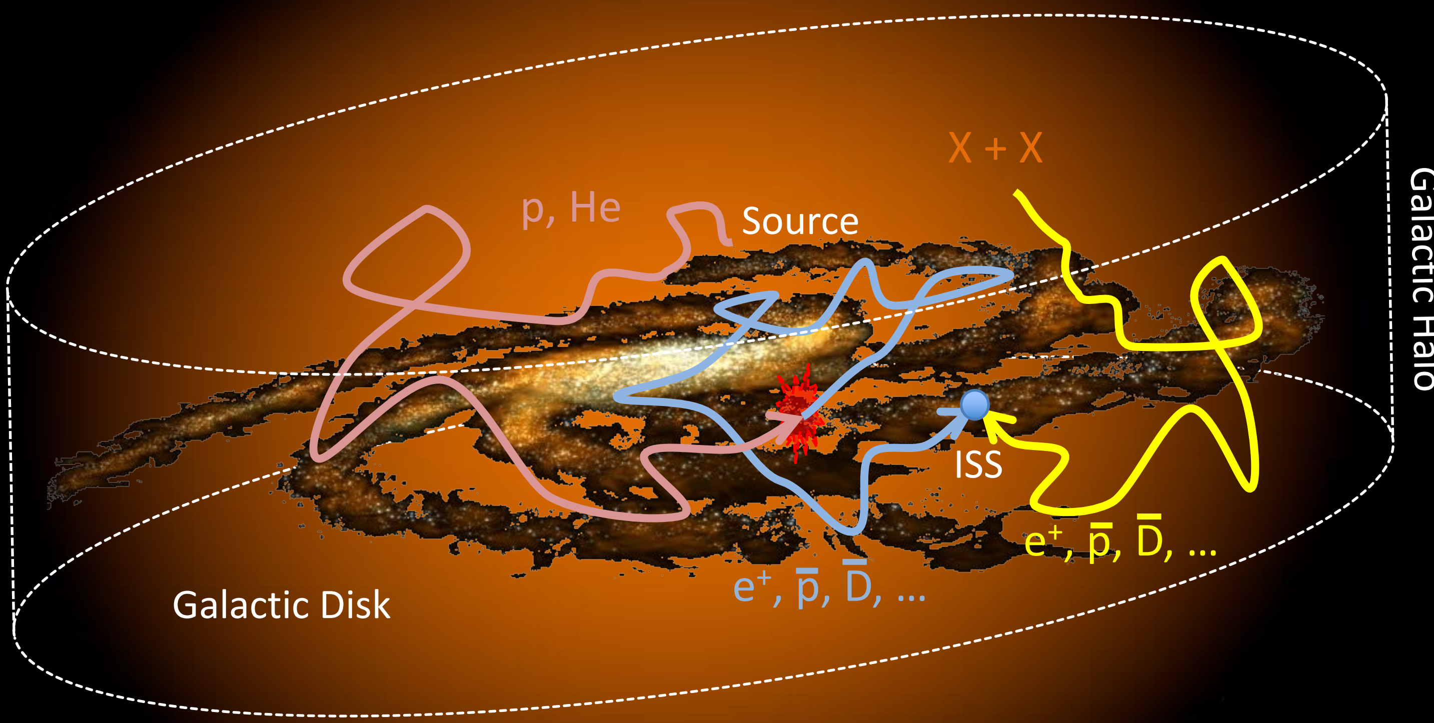
AMS-02 Lepton/Hadron Identification



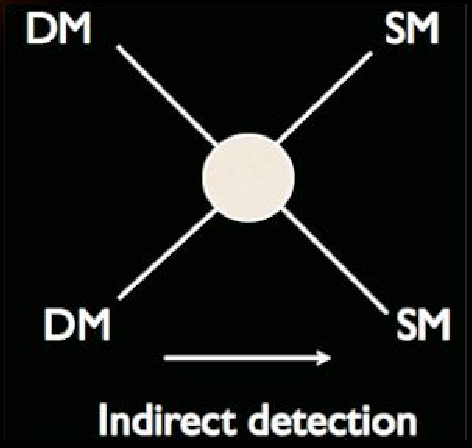
AMS-02 Chemical Composition Measurement



Indirect Search of Dark Matter with CR Anti-Matter

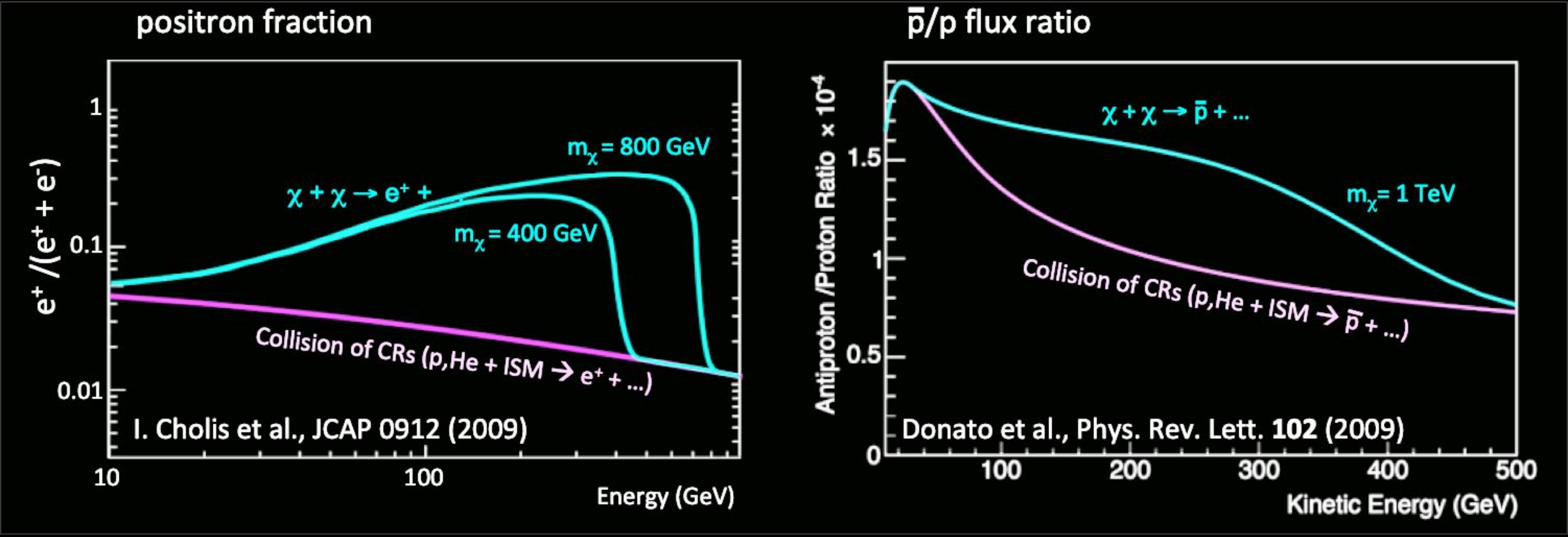


Collisions of dark matter particles (ex. neutralinos)
may produce a signal of e^+, $\bar{p}$, $\bar{D}$, ... that
can be detected above the background from the
collisions of primary CRs on interstellar medium



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)

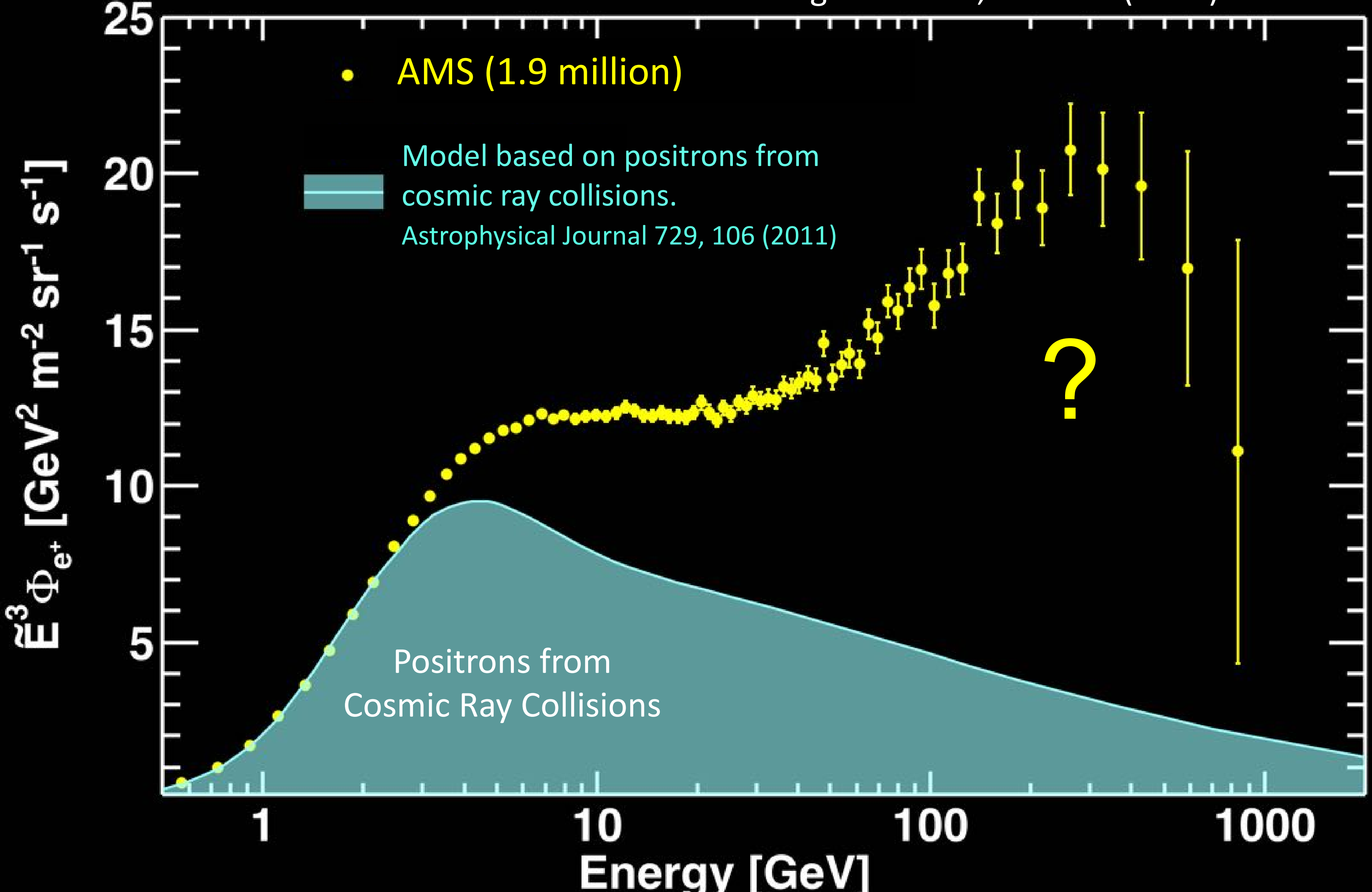


To calculate the secondary production of e^+ and p-bar we need

- The cosmic ray fluxes of their "parents" (p, He)
- Production cross-section
- Behaviour of their propagation in the Milky Way (B/C, B/O, Be/B, …)

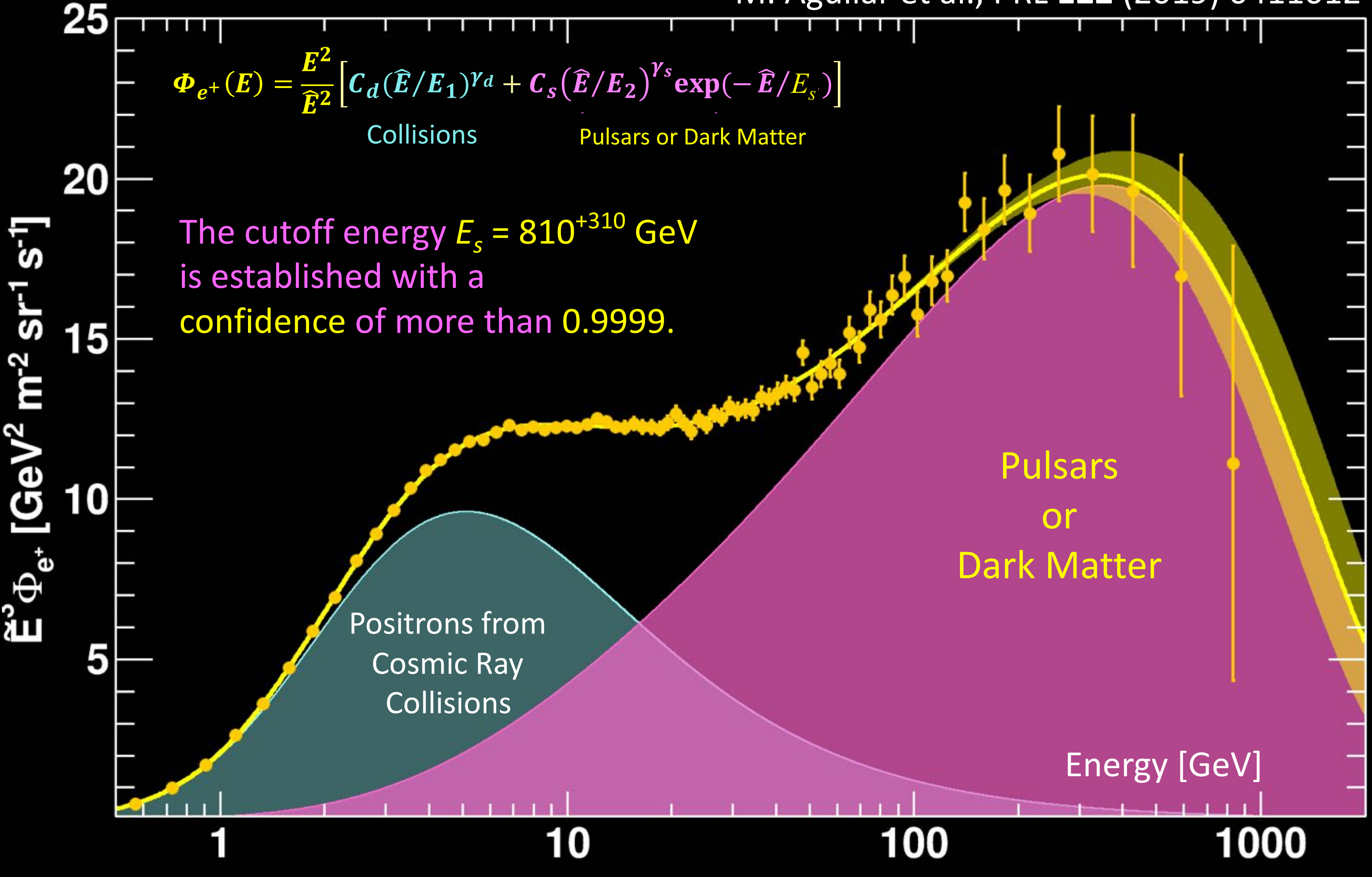
AMS Positron Flux

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



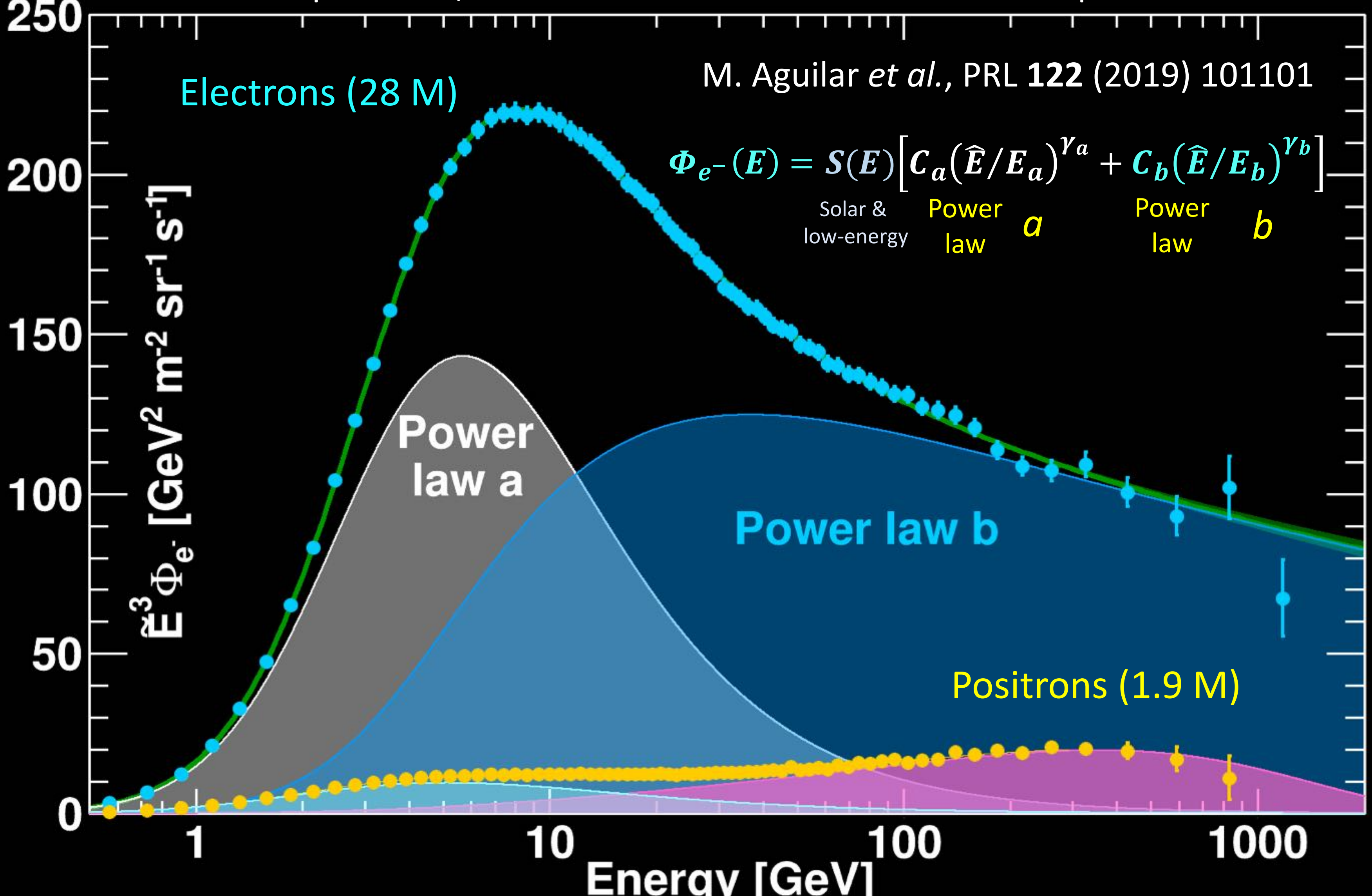
AMS Positron Flux

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

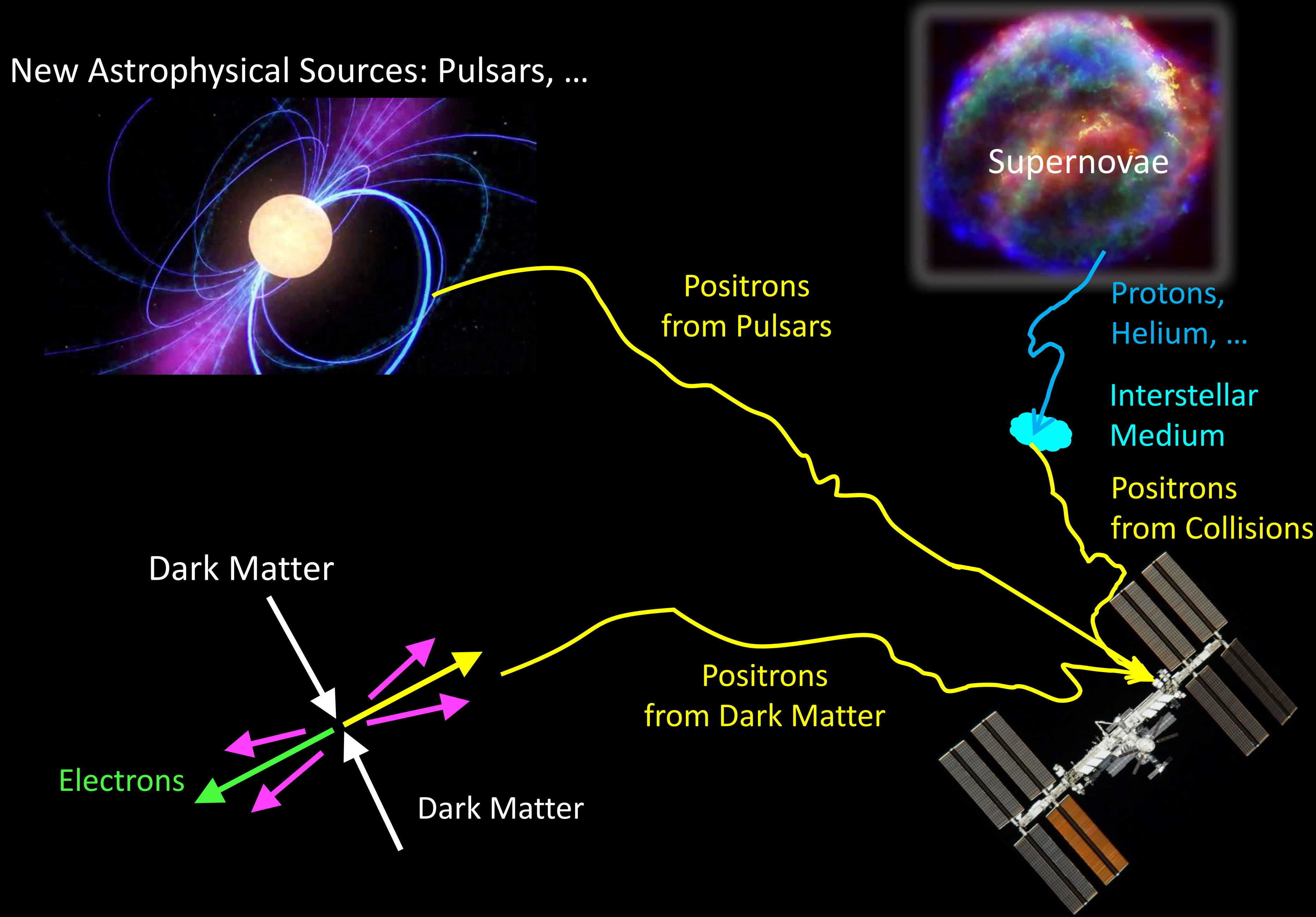


AMS Electron Flux

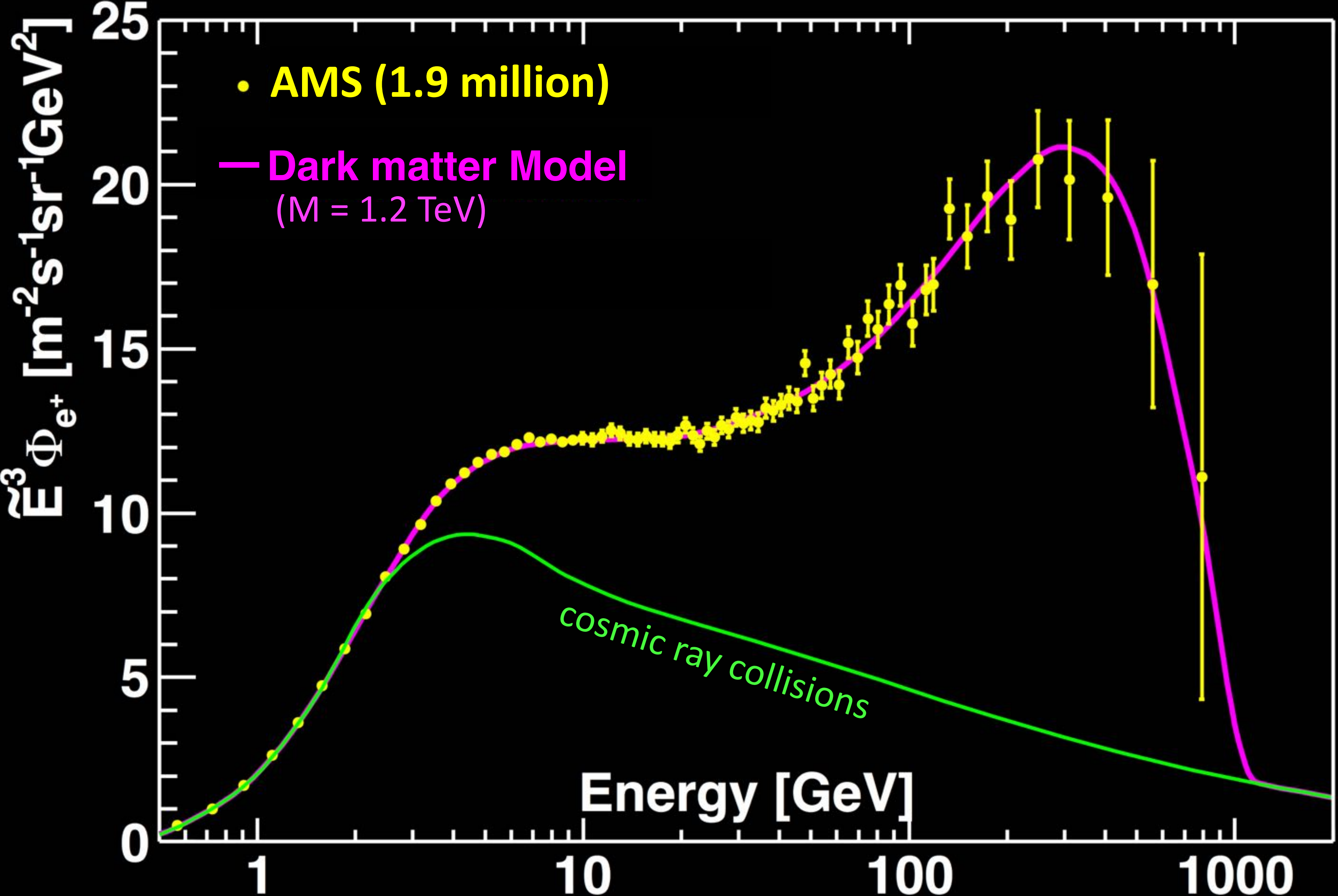
Electrons are primaries, can have some source in common with positrons.



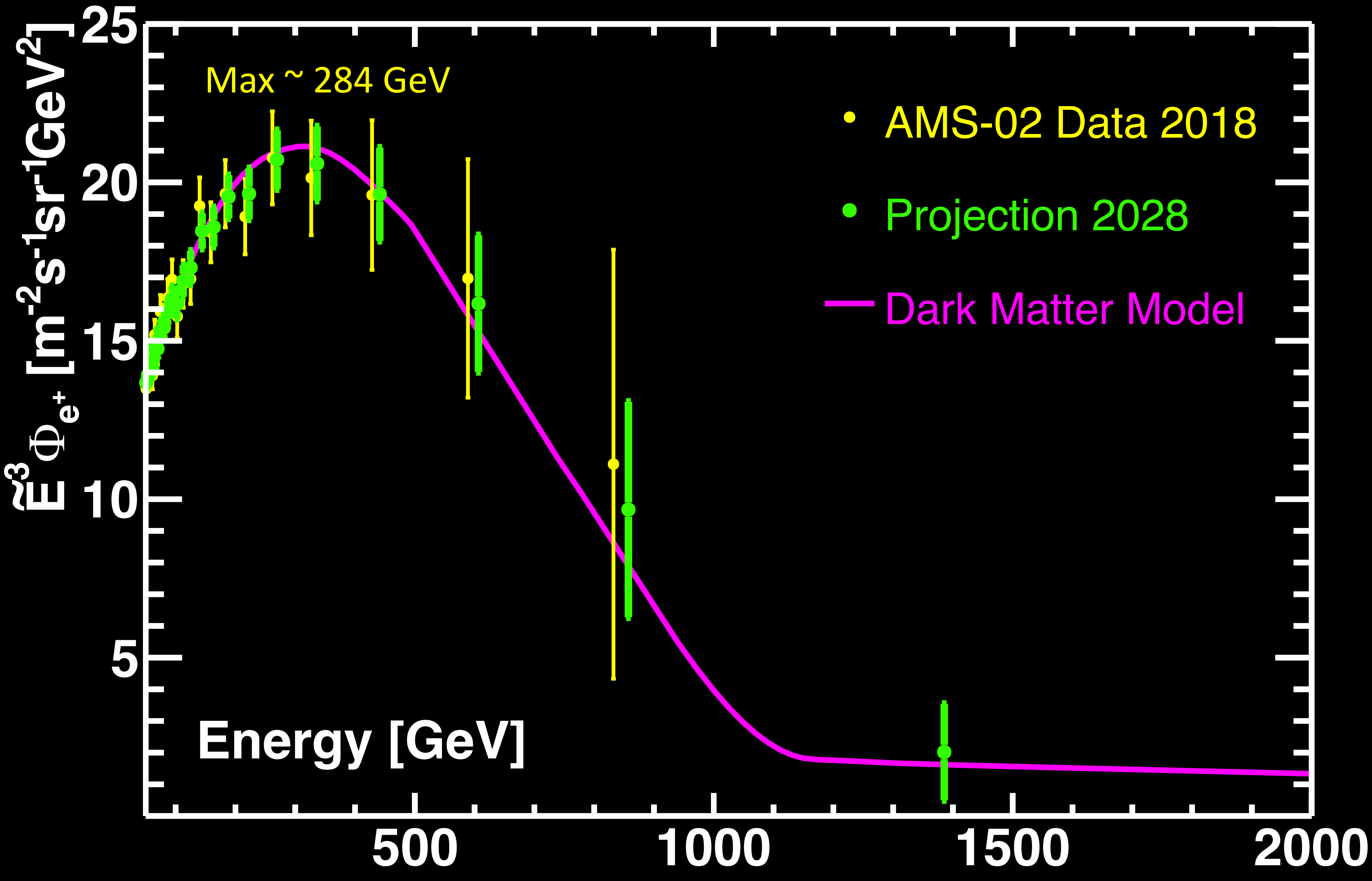
Origin of Positrons



Positron Excess as Dark Matter Annihilation

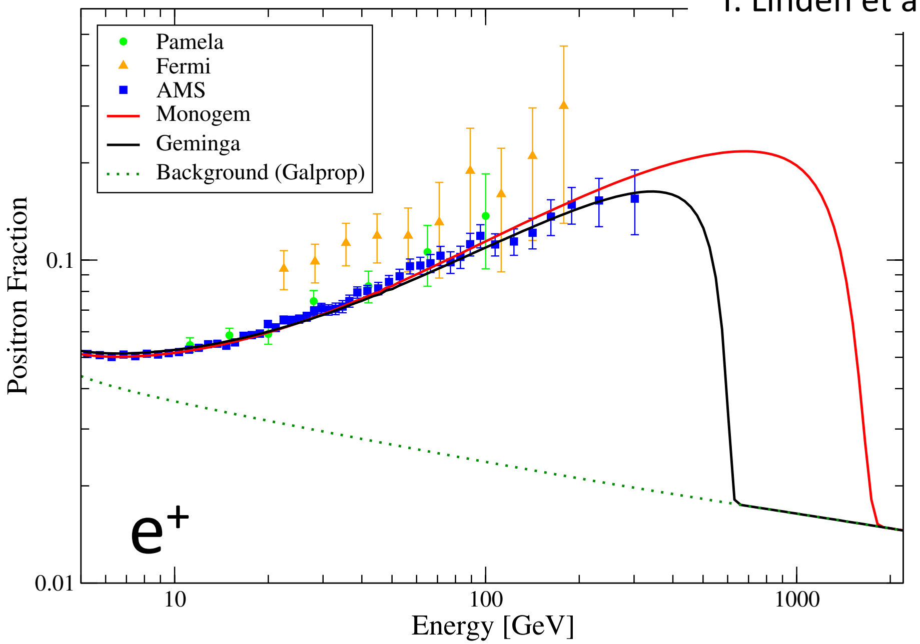


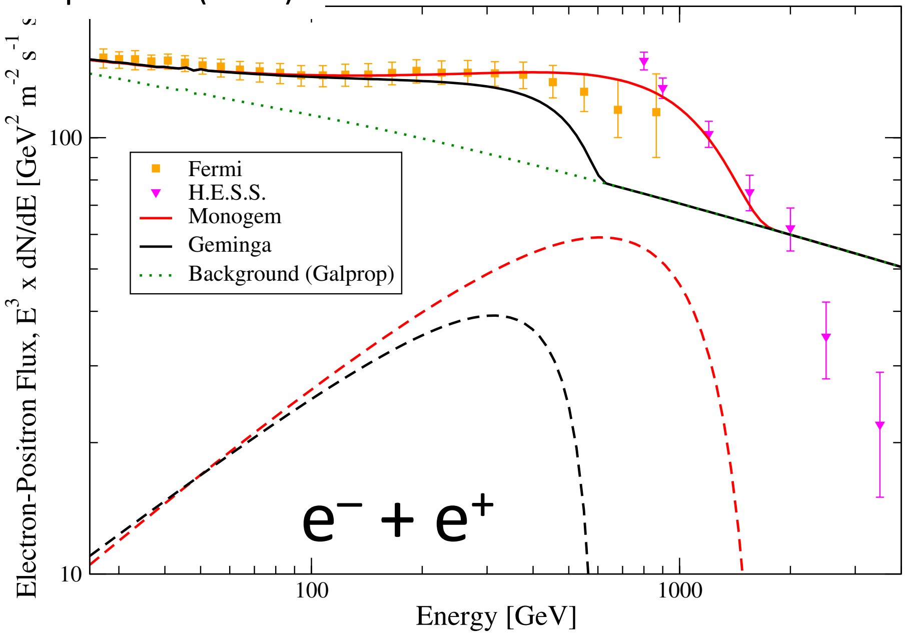
Projection of Positron Excess through 2028



Positron Excess from Pulsar

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

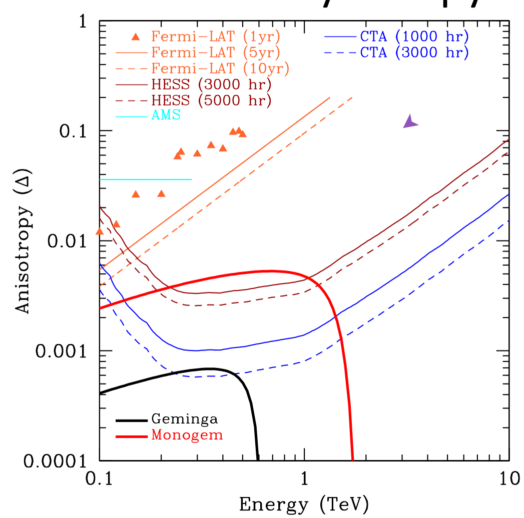


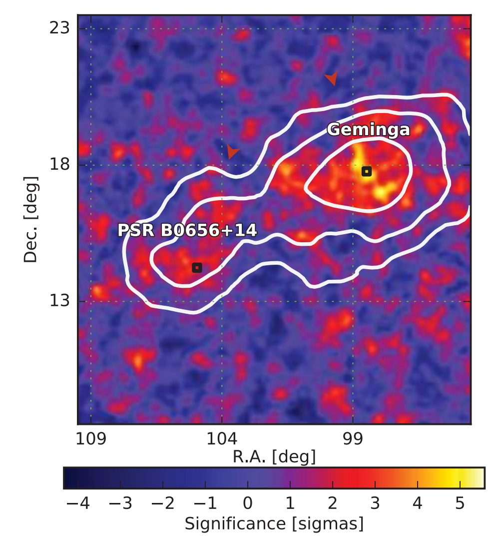


e⁻ + e⁺ anysotropy

Pulsars spinning produce EM radiation and cosmic rays (pair production).
To distinguish from DM models:

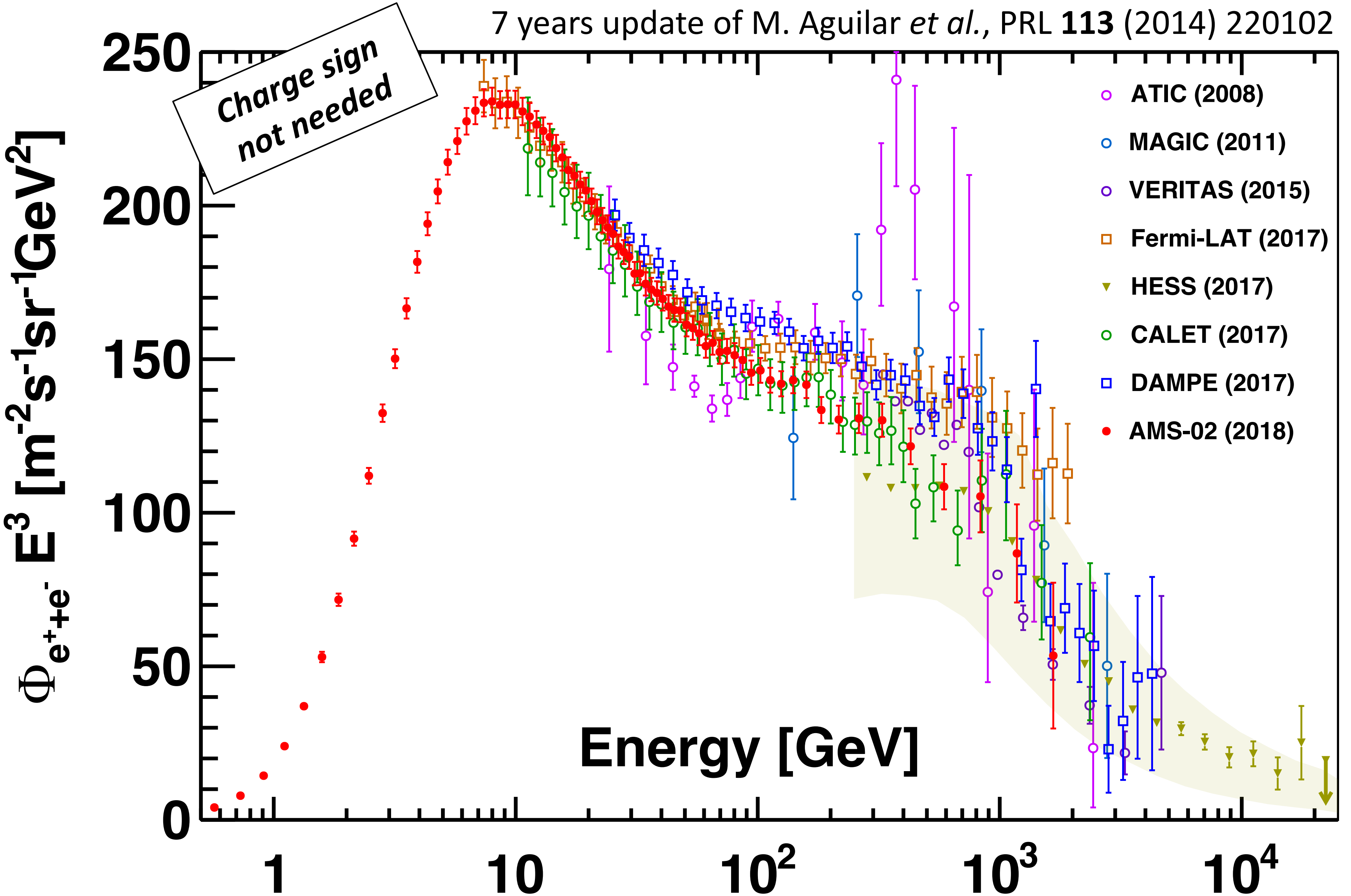
→ **spectral features** of e^+ and of ($e^+ + e^-$)
→ **anisotropy** of e^+ and of ($e^+ + e^-$)
→ **no anti-proton** production





AMS (e^+ + e^-) Flux

7 years update of M. Aguilar *et al.*, PRL **113** (2014) 220102

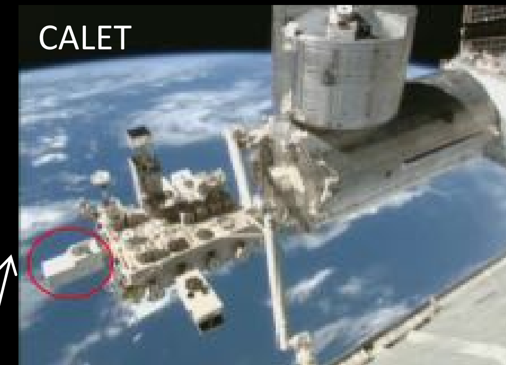


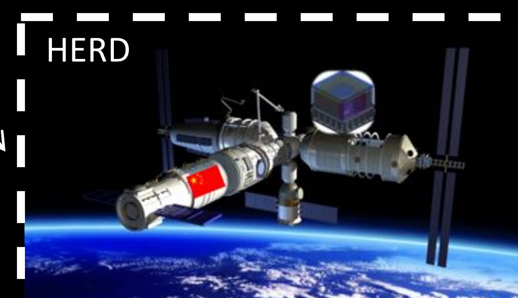
$(e^+ + e^-)$ Flux

Spectrometer
& EM Calorimeter

EM Calorimeter

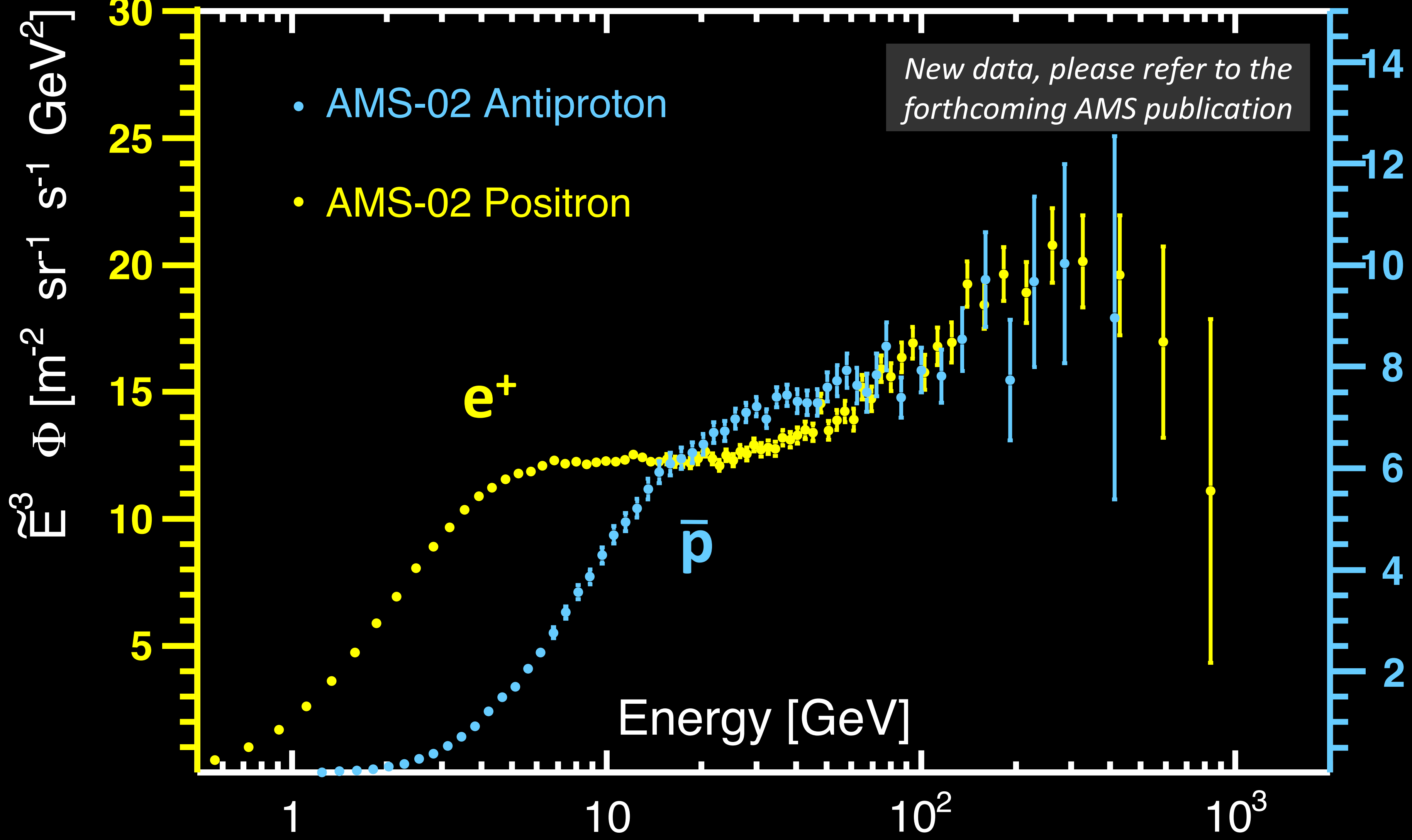
Cherenkov Telescope





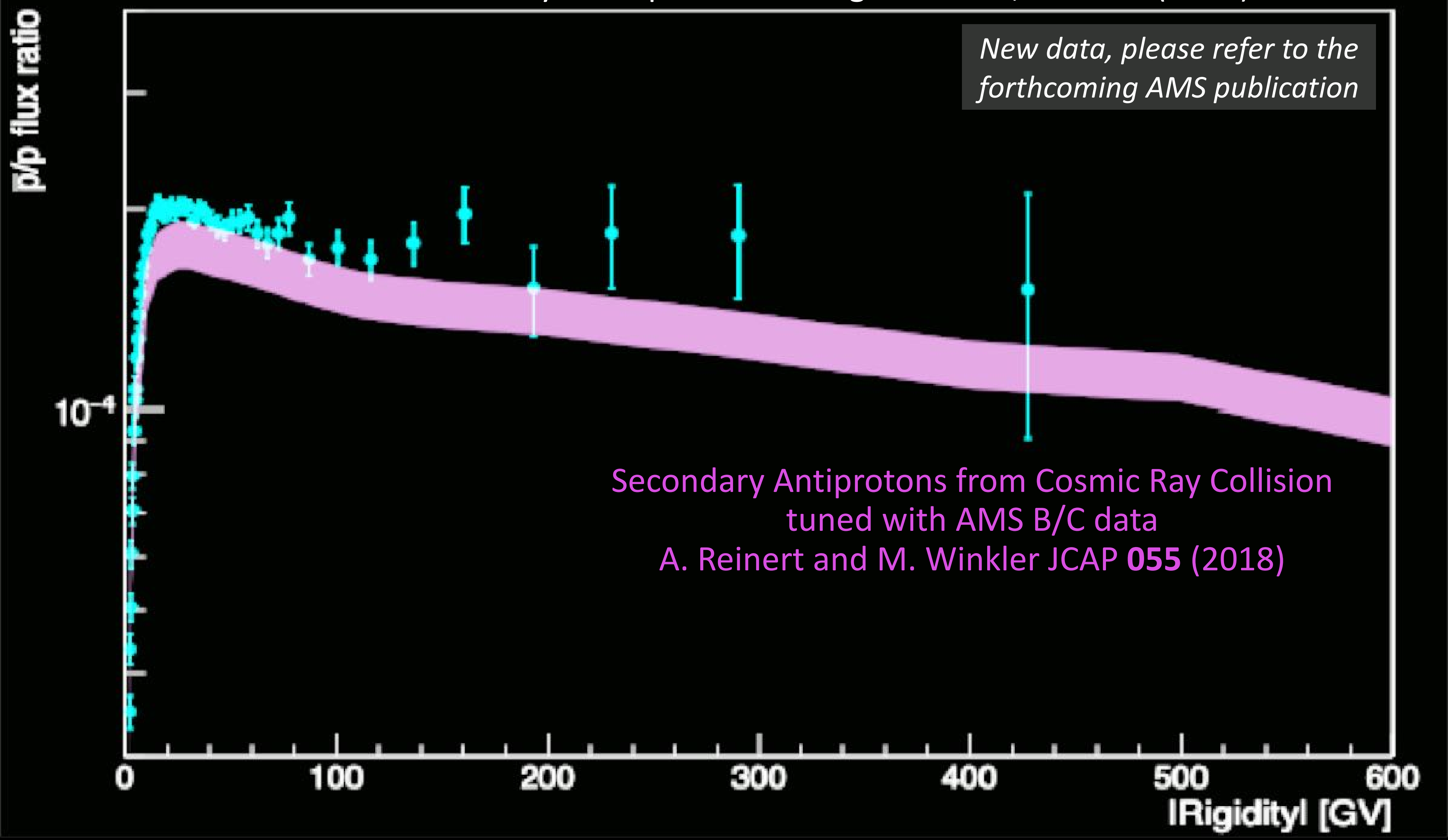
AMS Anti-Proton Flux

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



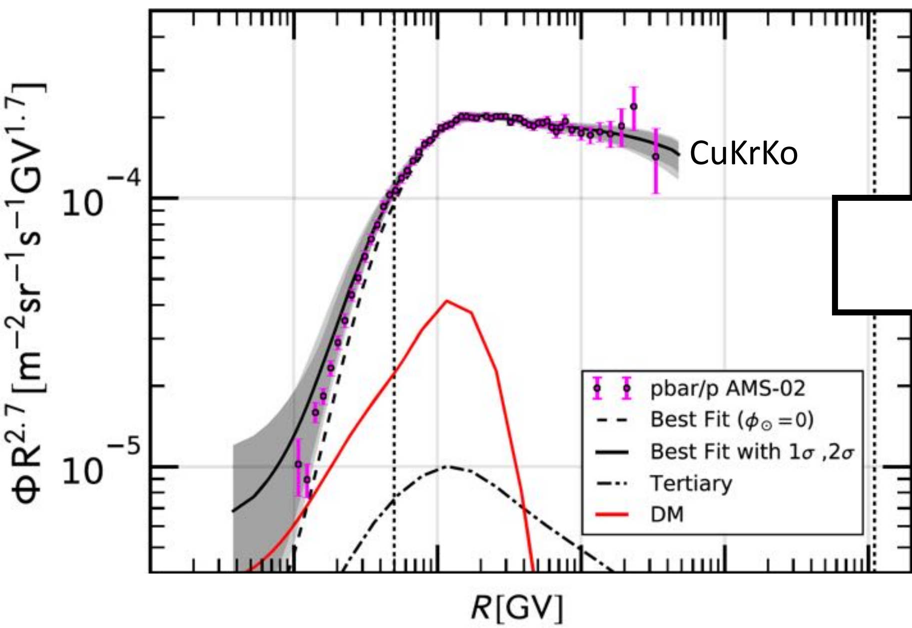
AMS Anti-Proton Flux

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

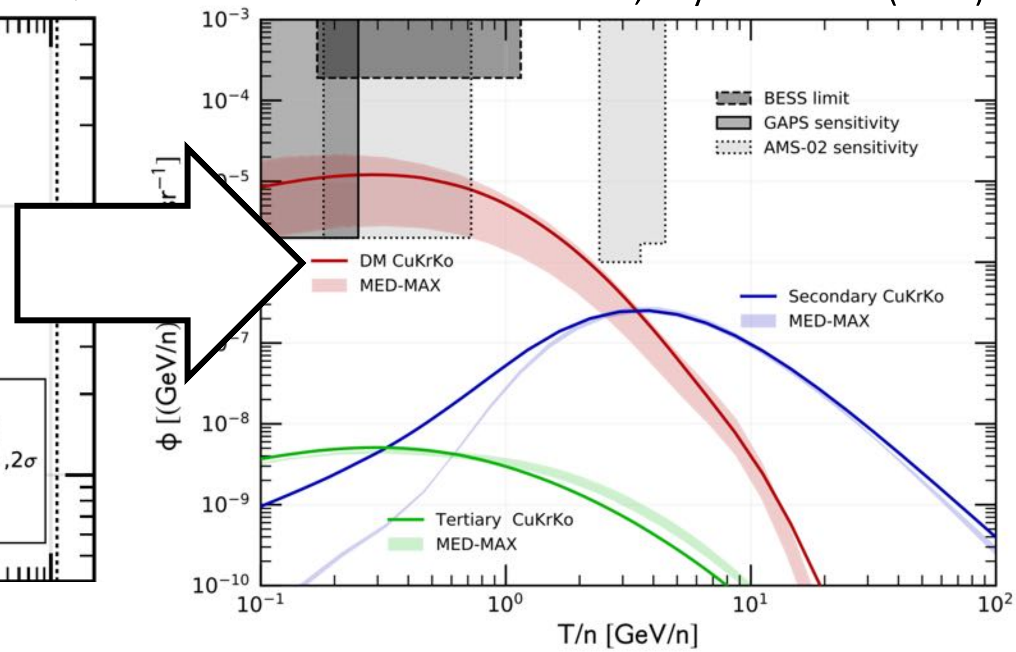


The Anti-Proton/Anti-Deuteron Connection

A. Cuoco et al., Phys. Rev. Lett. **118** (2017)



M. Korsmeier et al., Phys. Rev. D **97** (2018)

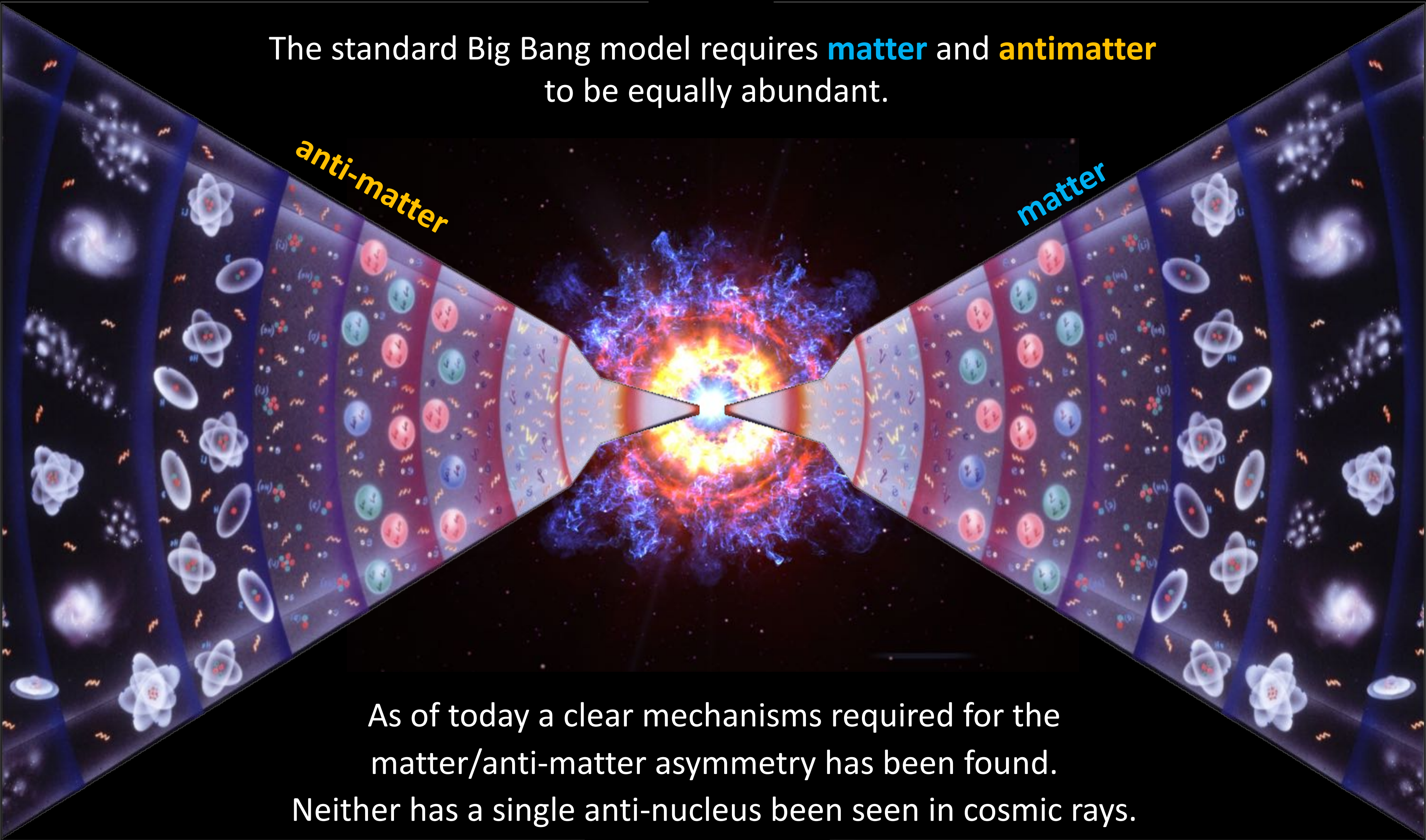


Several authors reported an allowed **anti-proton** excess at low energy, with different significances, that can be explained a dark matter signal.

This signal can give a detectable **anti-deuteron** signal.
Anti-deuteron search with AMS-02 is on-going.

Heavy Anti-Matter Search

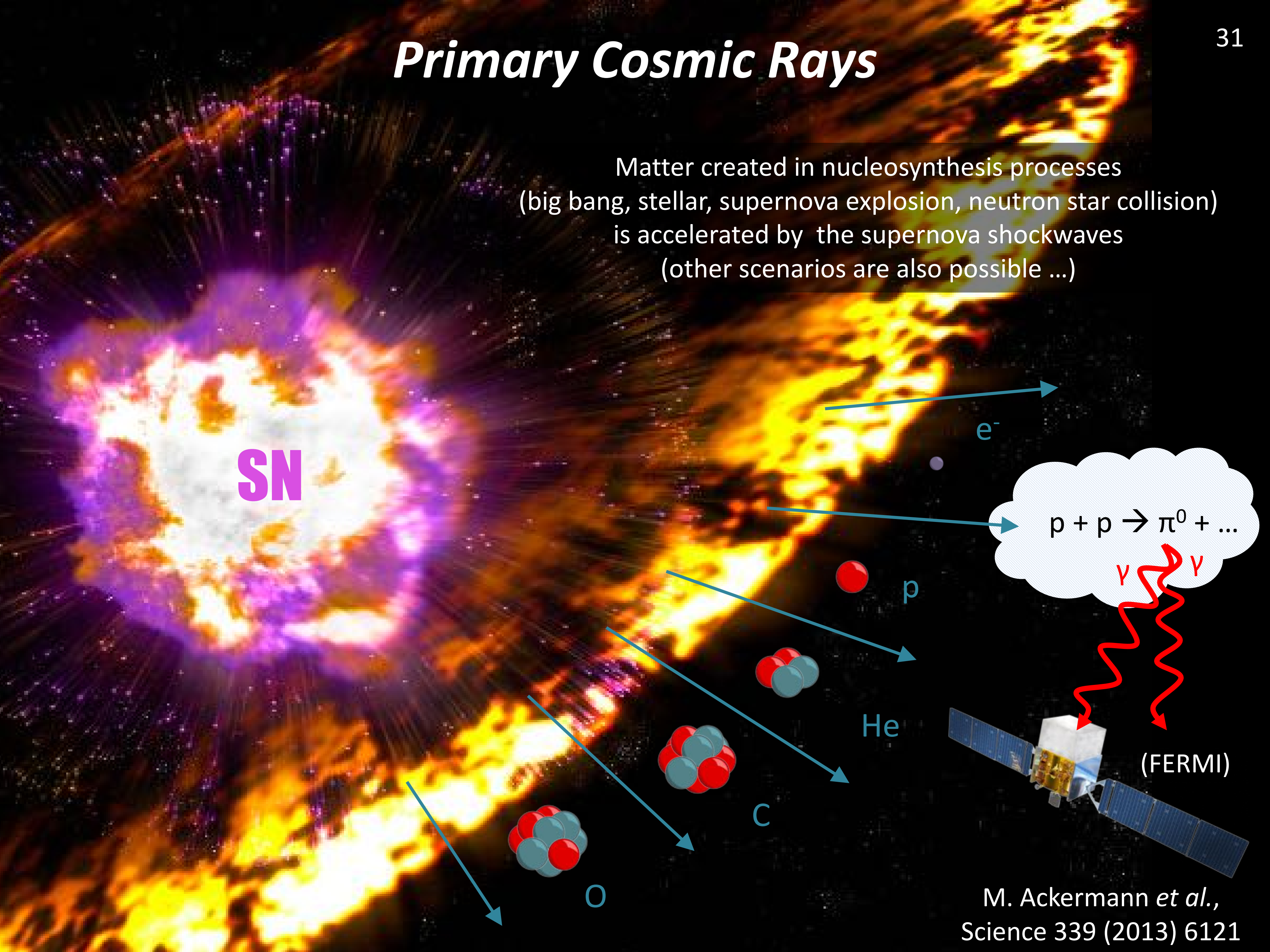
The standard Big Bang model requires **matter** and **antimatter** to be equally abundant.



As of today a clear mechanisms required for the matter/anti-matter asymmetry has been found.
Neither has a single anti-nucleus been seen in cosmic rays.
Anti-helium (and anti-nuclei) search with AMS-02 is on-going.

Primary Cosmic Rays

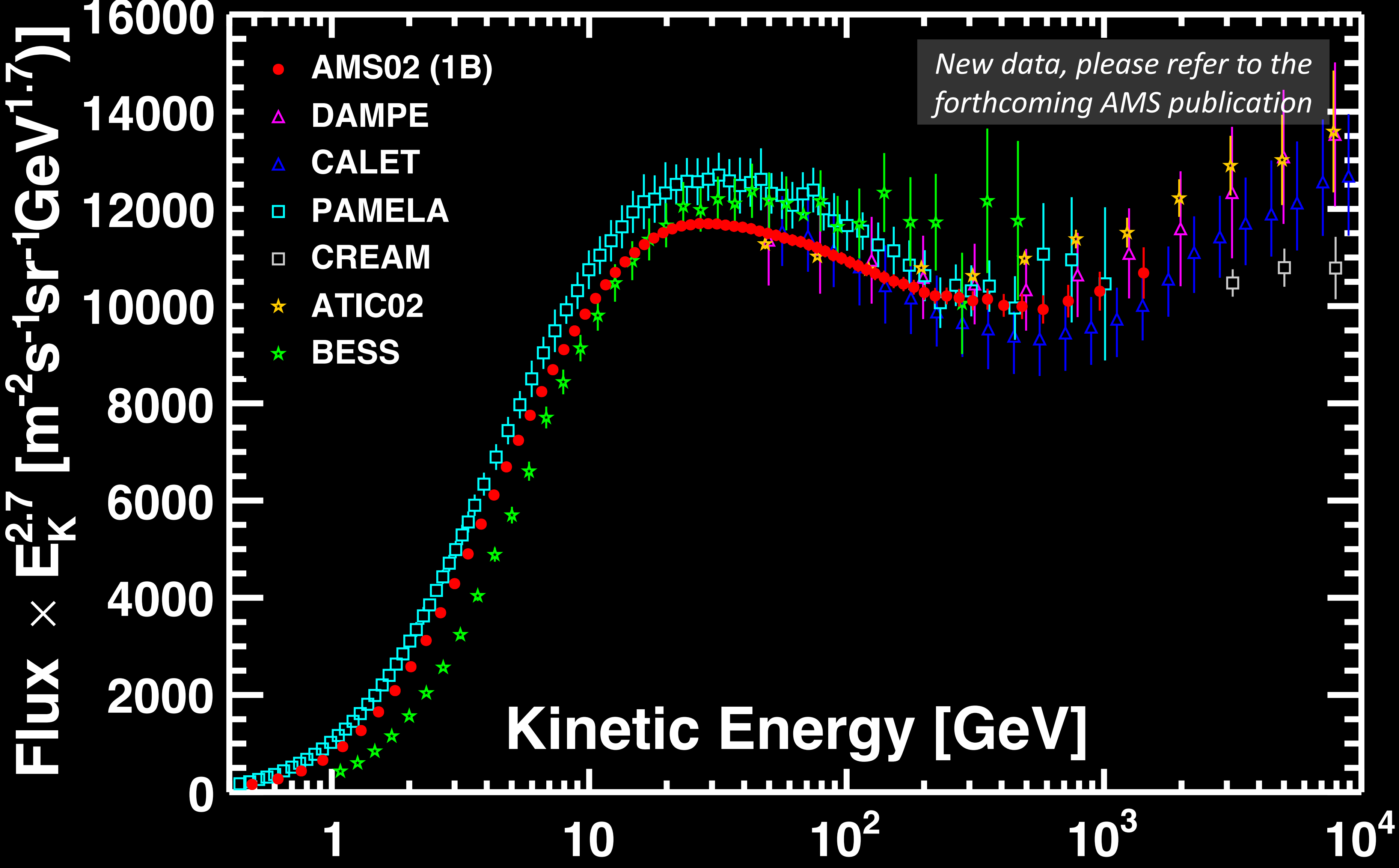
Matter created in nucleosynthesis processes
(big bang, stellar, supernova explosion, neutron star collision)
is accelerated by the supernova shockwaves
(other scenarios are also possible …)



M. Ackermann *et al.*,
Science 339 (2013) 6121

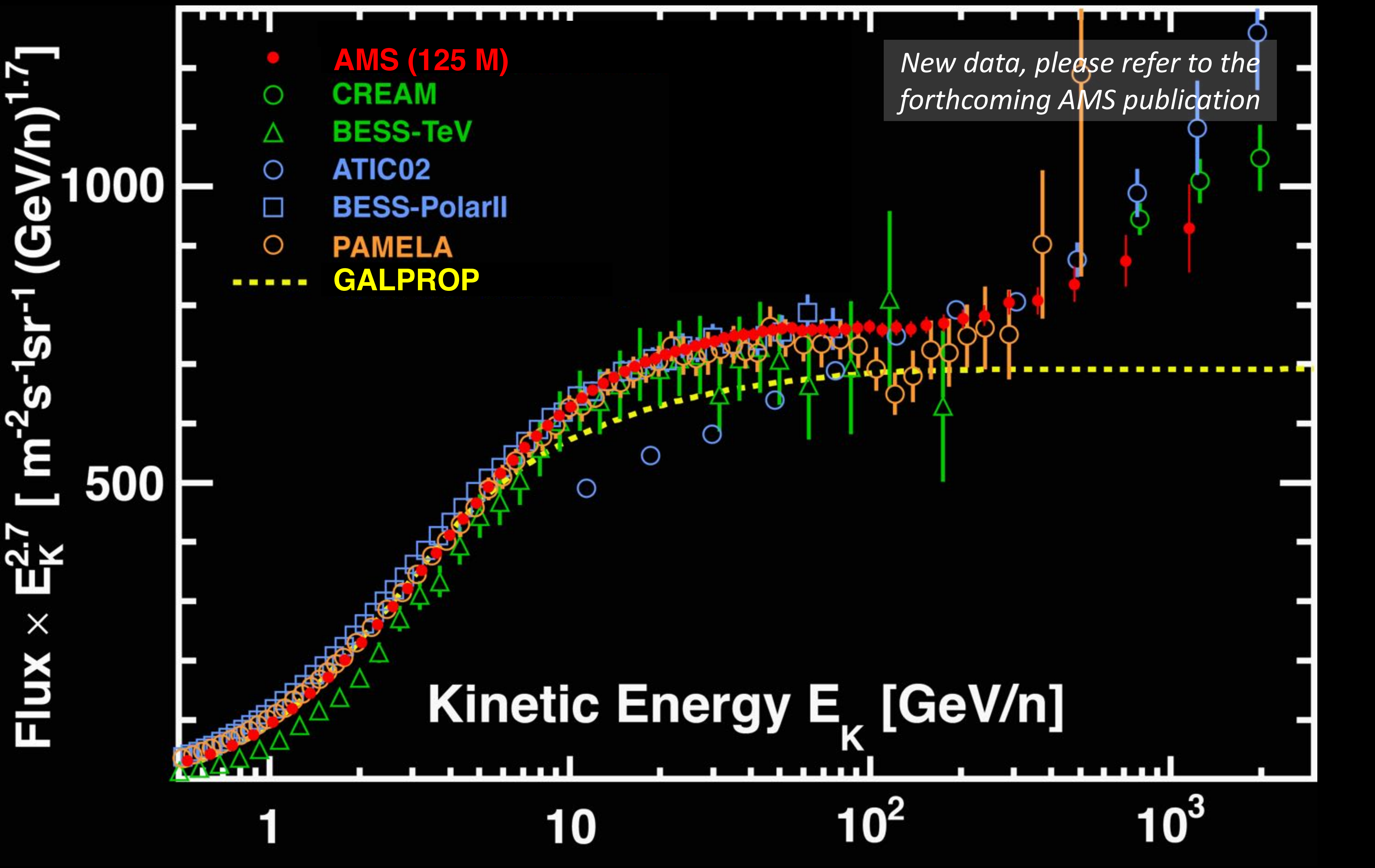
AMS Proton Flux

7 years update of M. Aguilar *et al.*, PRL **114** (2015) 171131



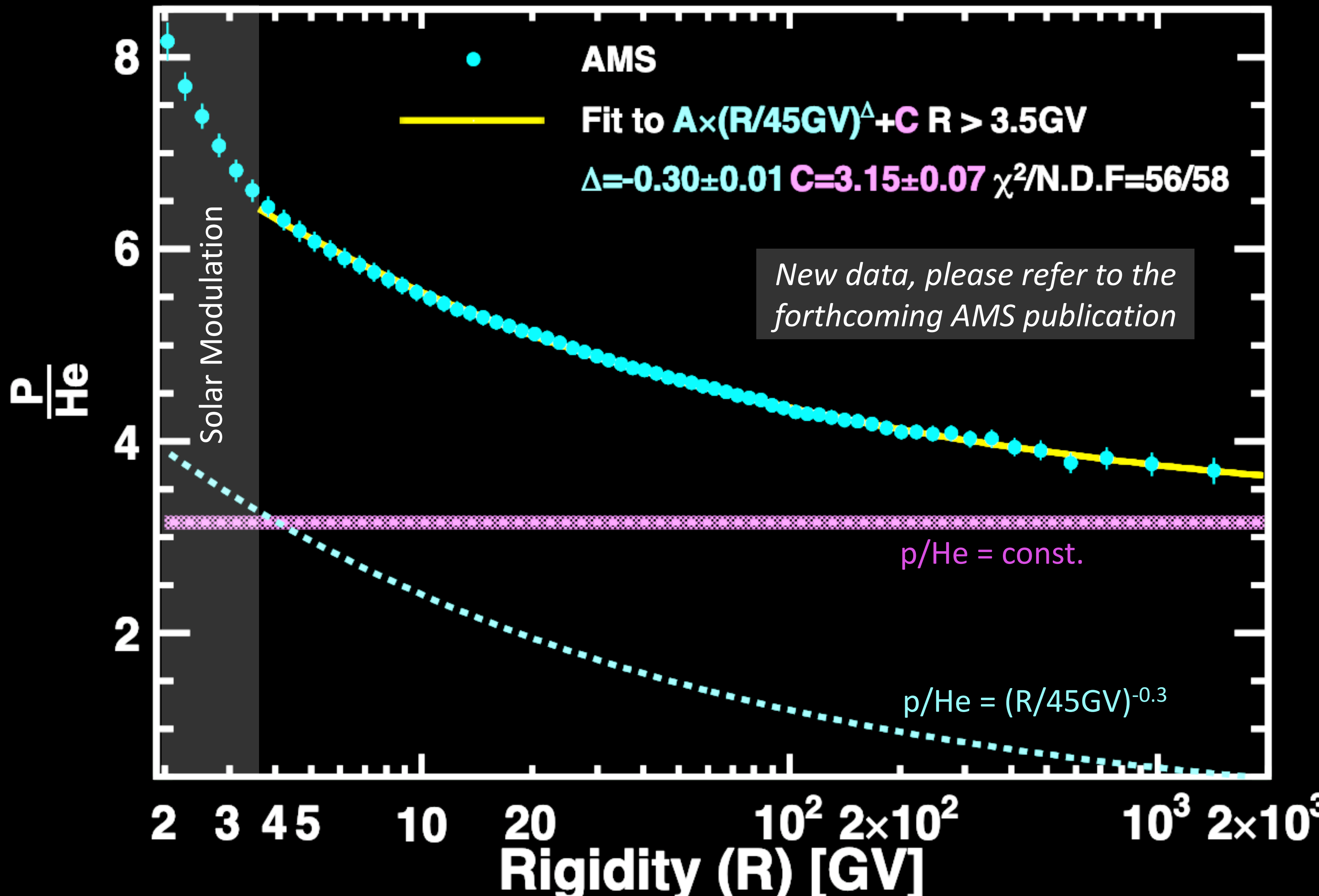
AMS Helium Flux

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



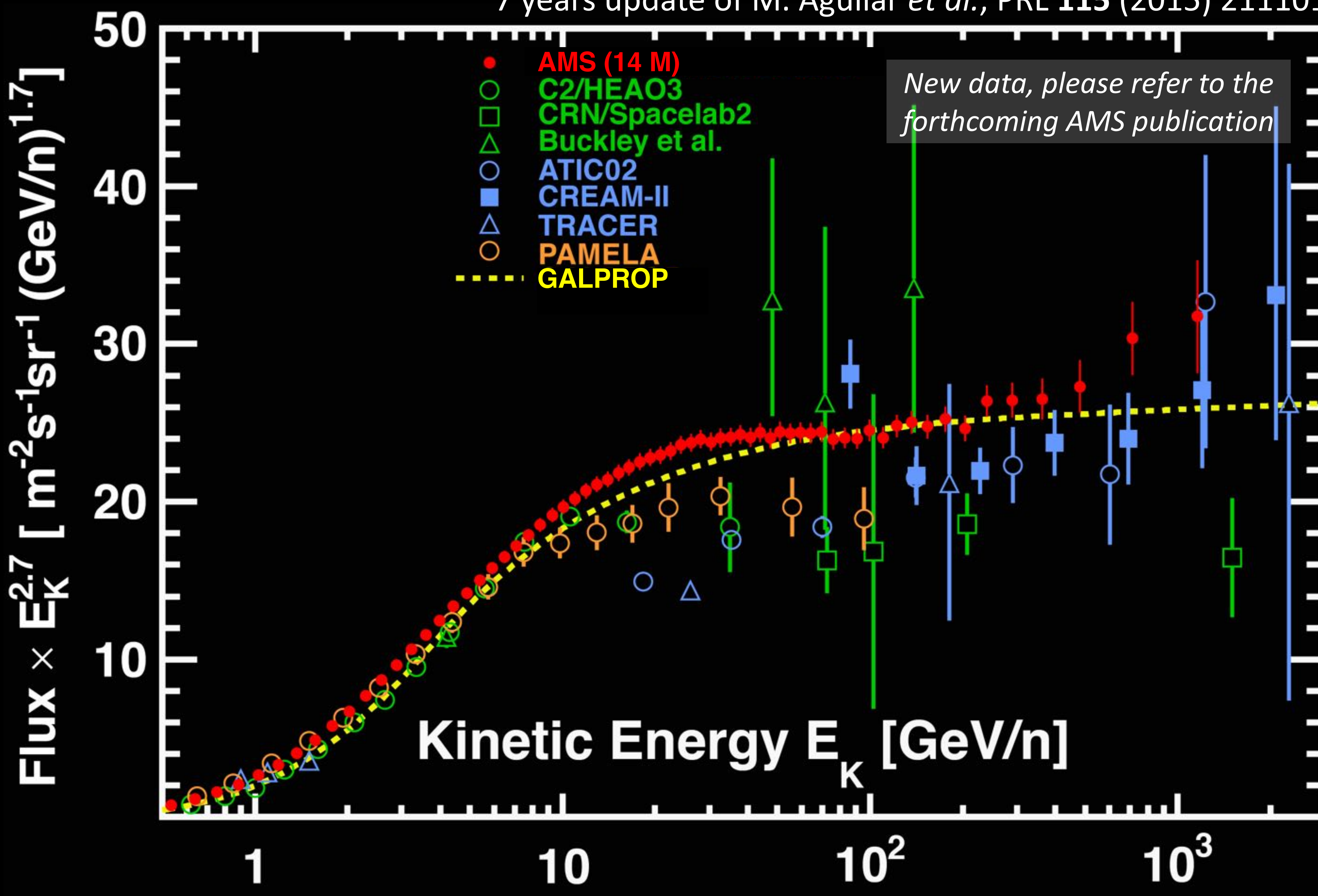
AMS p/He Flux Ratio

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



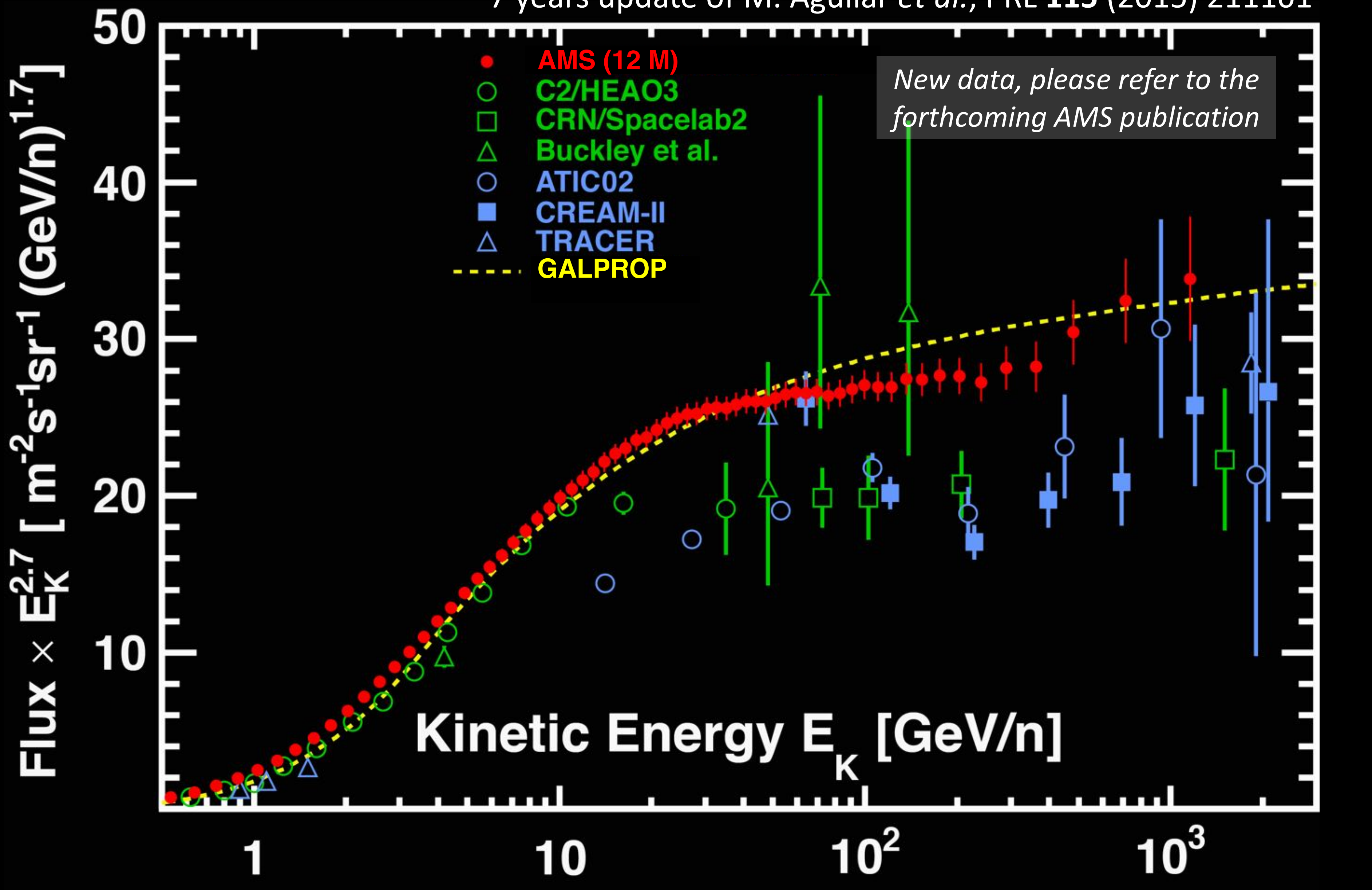
AMS Carbon Flux

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



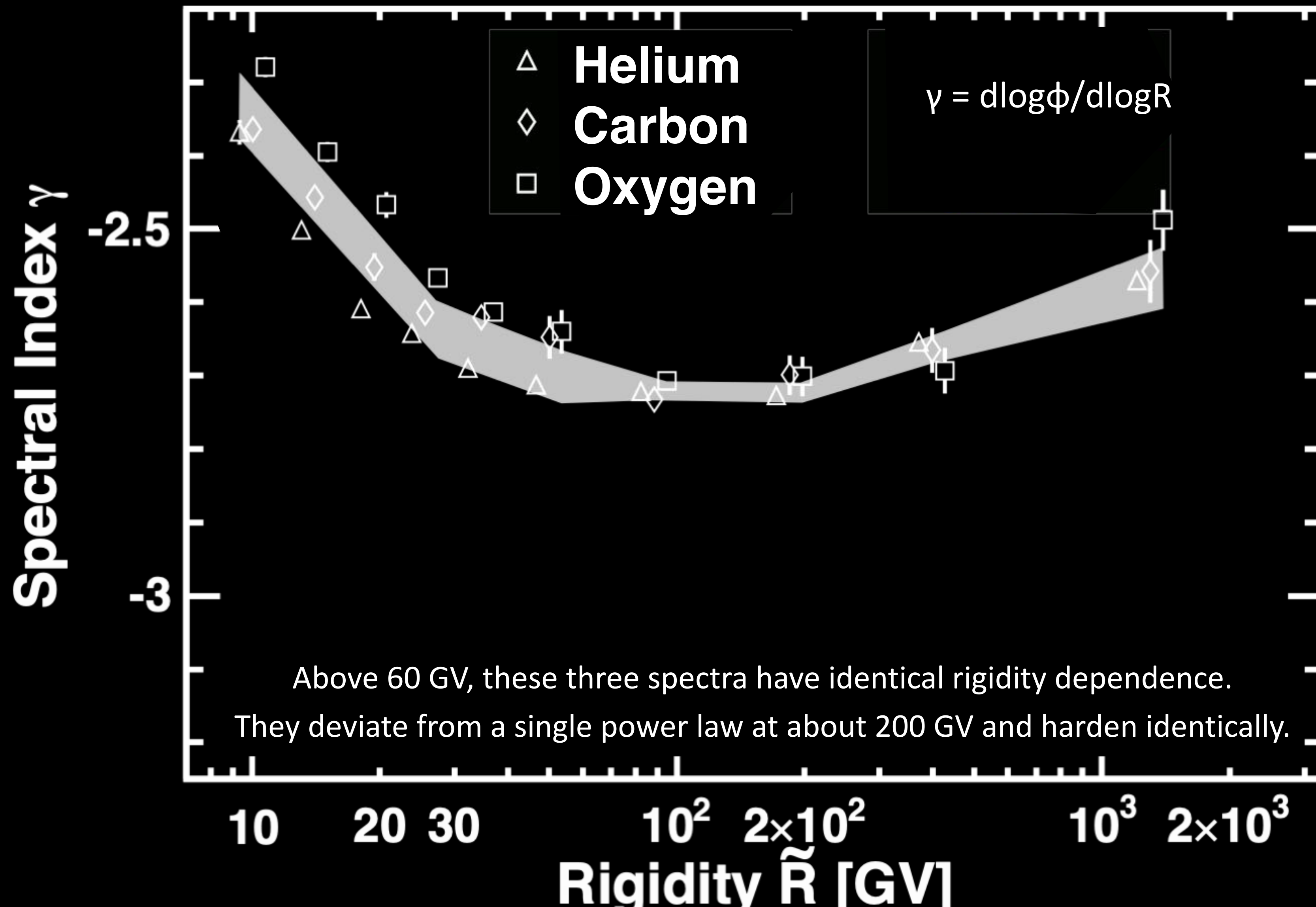
AMS Oxygen Flux

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



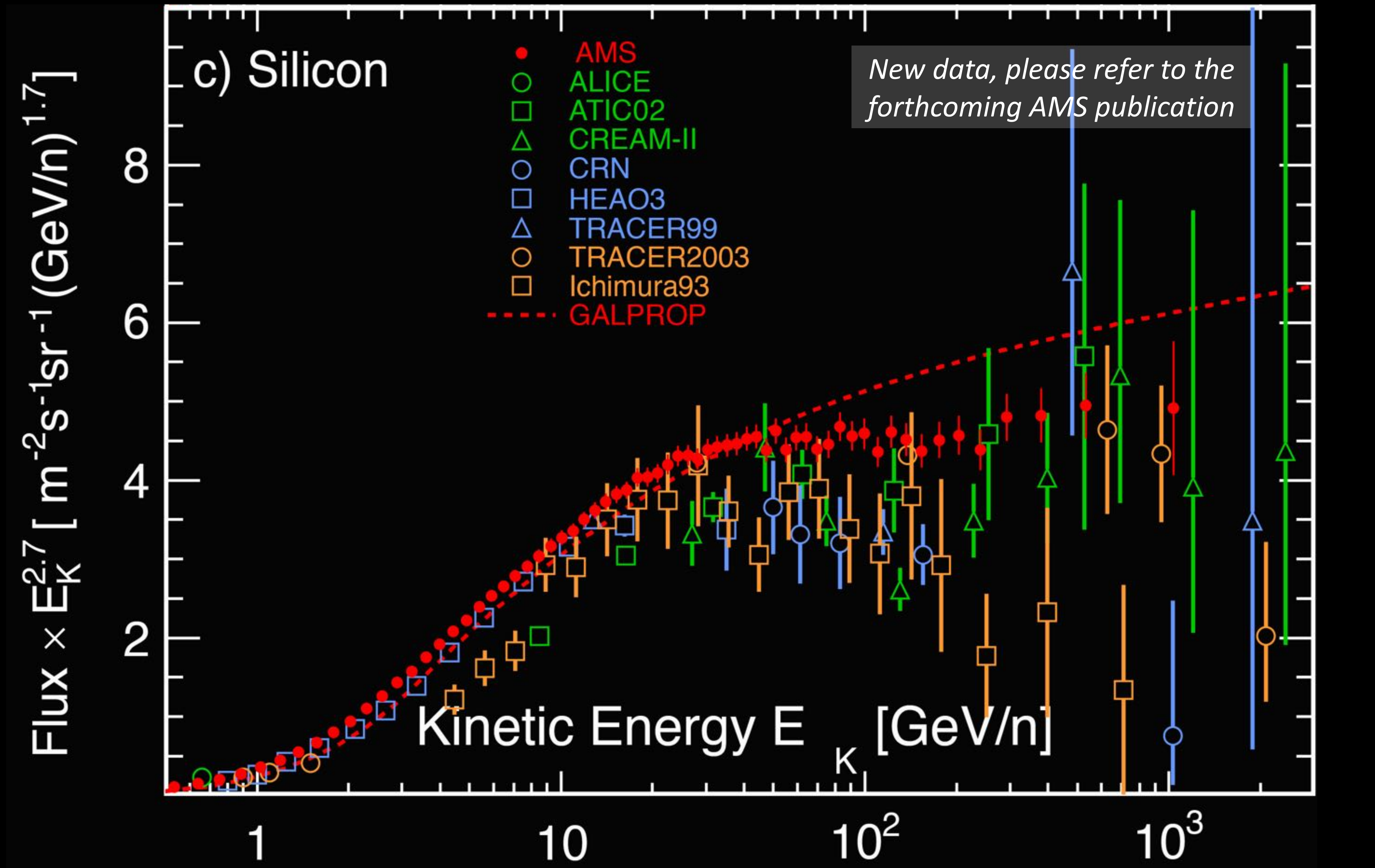
AMS He, C, O Spectral Indices

M. Aguilar *et al.*, PRL **120** (2018) 021101



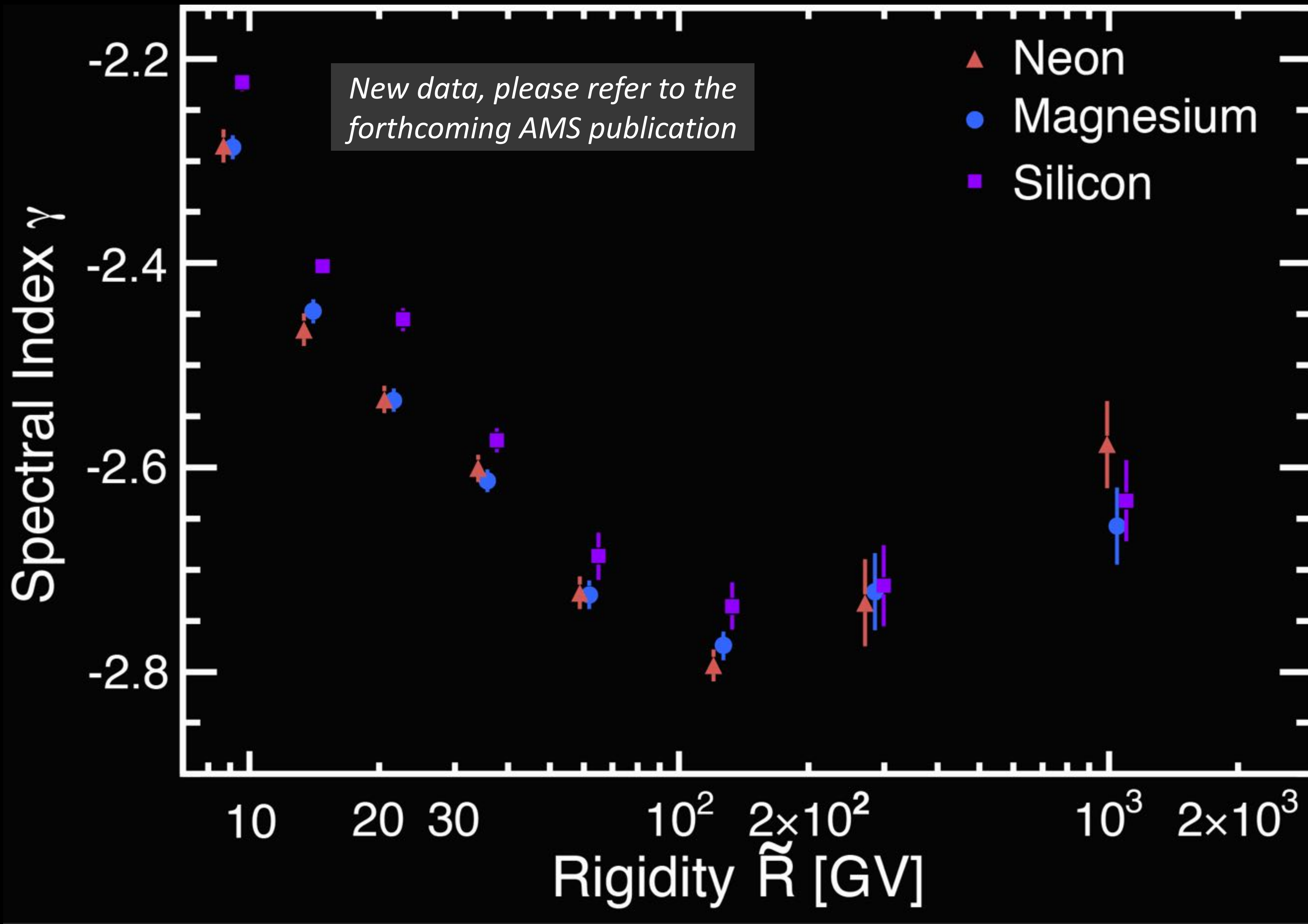
AMS Primary Fluxes at High-Z

M. Aguilar et al, accepted on PRL (2020)



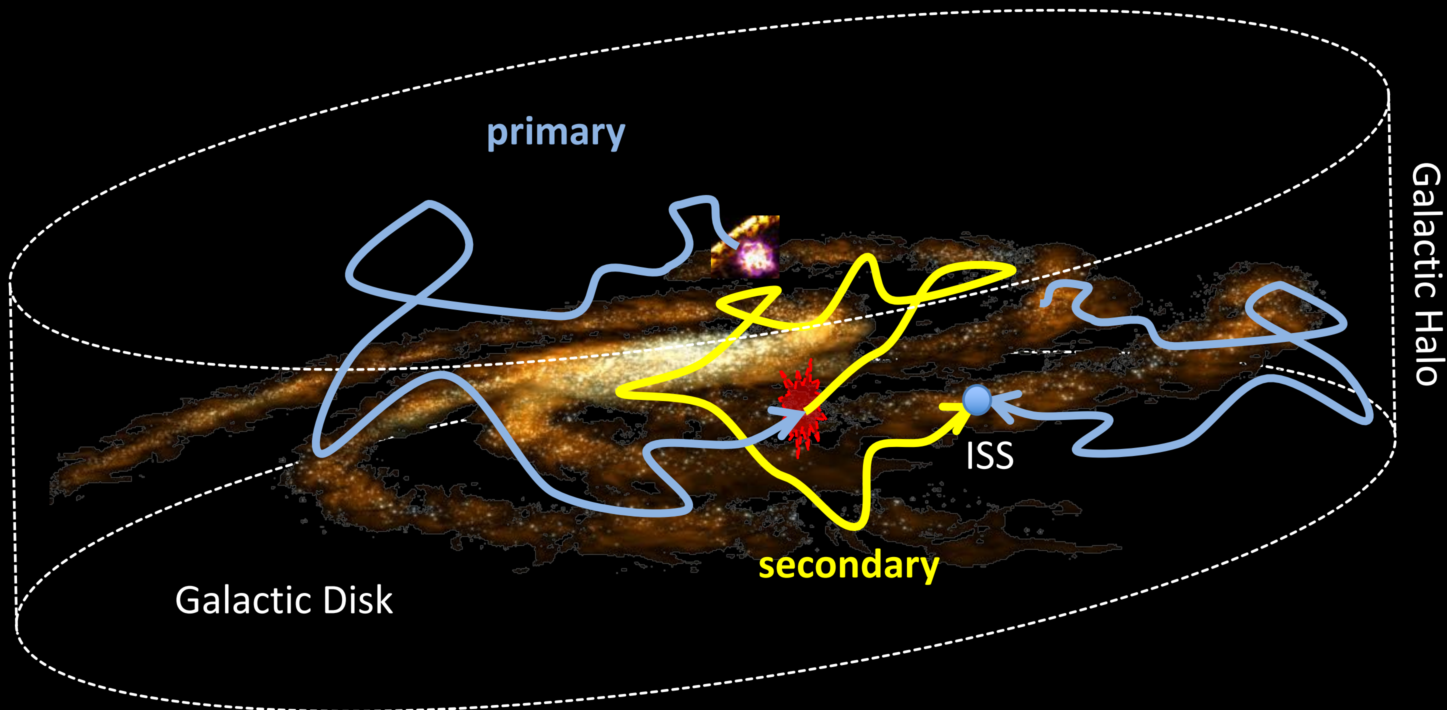
AMS Primary Fluxes at High-Z

M. Aguilar et al, accepted on PRL (2020)



Secondary Cosmic Rays

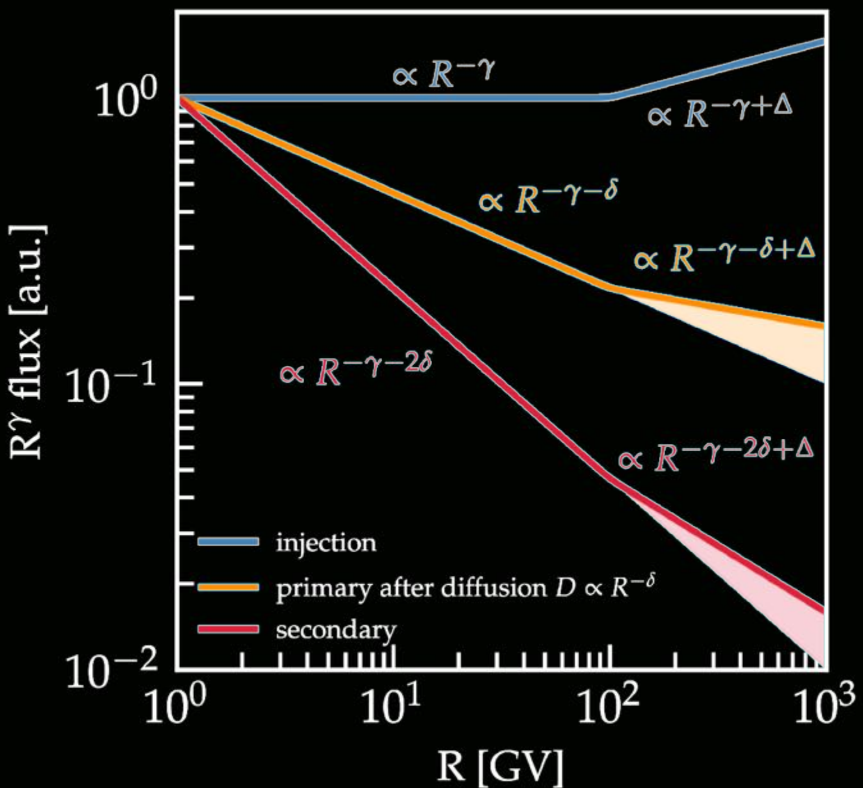
Cosmic rays **primaries** are mostly produced at astrophysical sources (ex. e^-, p, He, C, O, …),
secondaries (ex. Li, Be, B, …) are mostly produced by the collision of cosmic rays with the ISM.

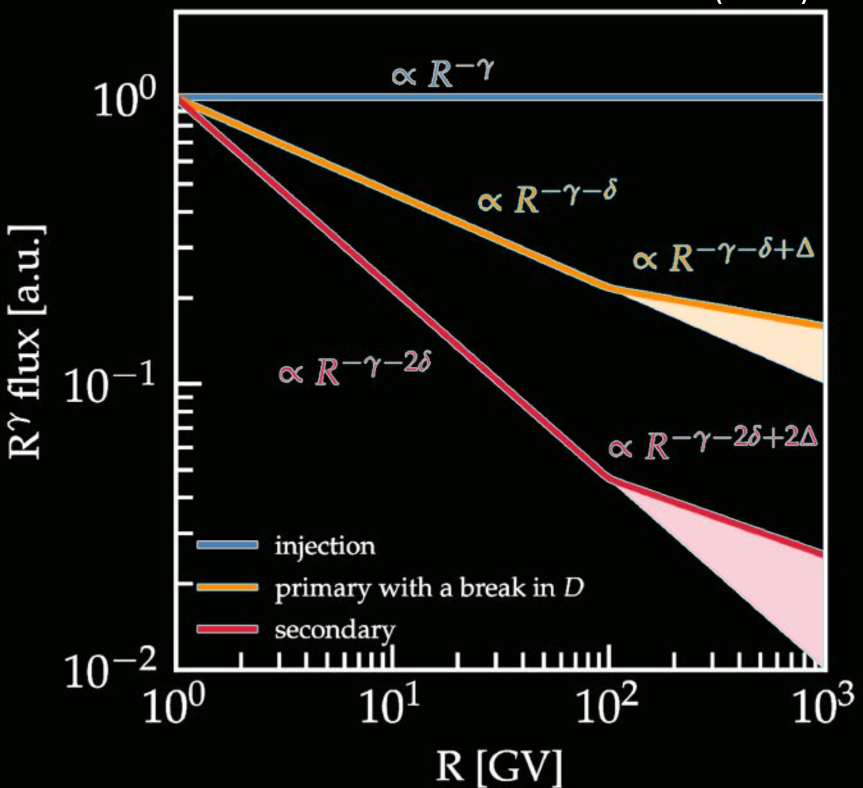


Cosmic rays are commonly modeled as a relativistic gas diffusing into a magnetized plasma.
Diffusion models based on different assumptions predict a Sec/Pri ratio asymptotically proportional to $\mathbf{R^{\delta}}$.
With Kolmogorov turbulence model a $\boldsymbol{\delta = -1/3}$ is expected, while Kraichnan theory leads to $\boldsymbol{\delta = -1/2}$.

Cosmic Ray Propagation

C. Evoli (2019)

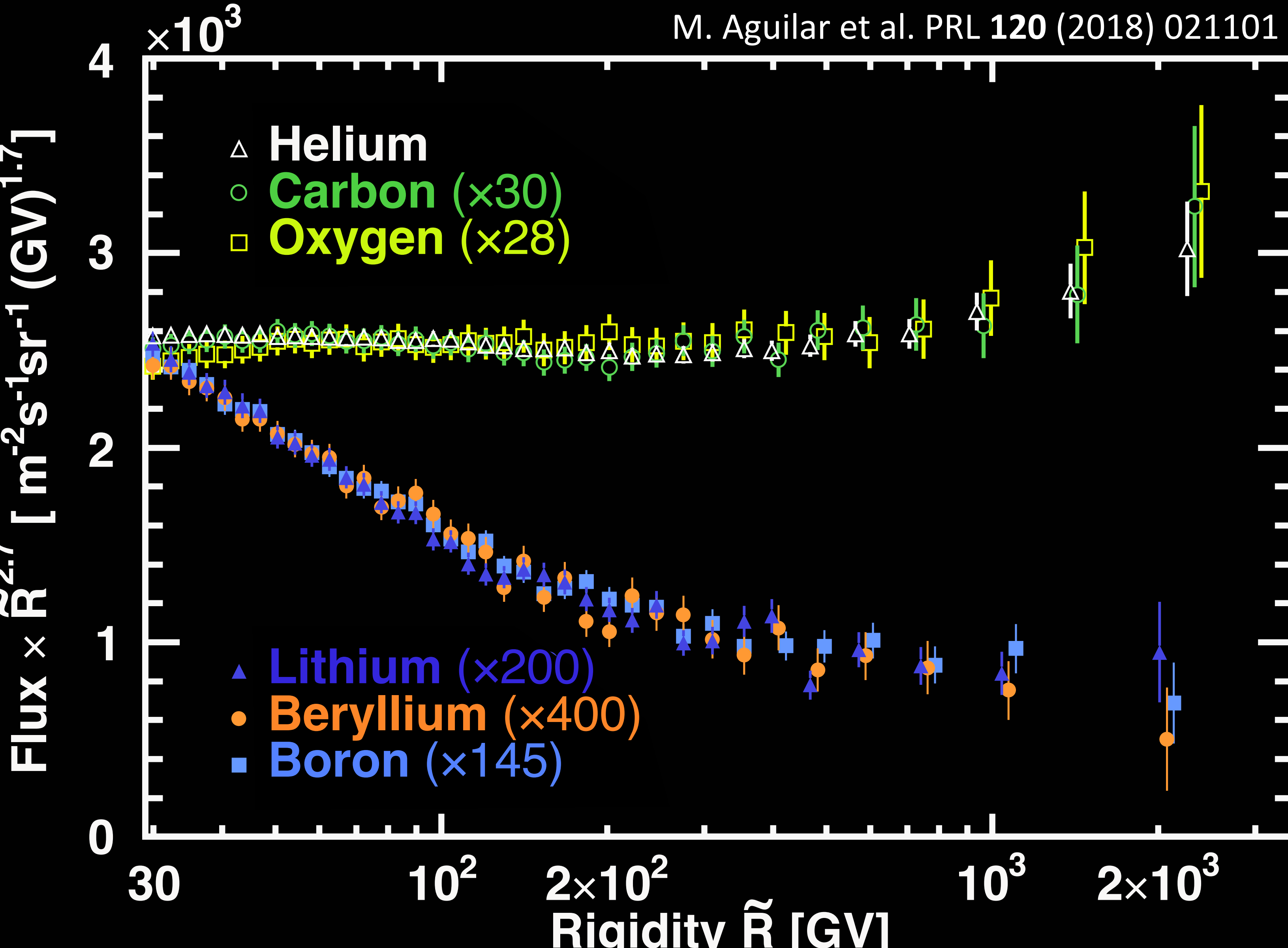




If the hardening in CRs is related to the **injected spectra** at their source, then **similar hardening** is expected both for **secondary** and **primary** cosmic rays.

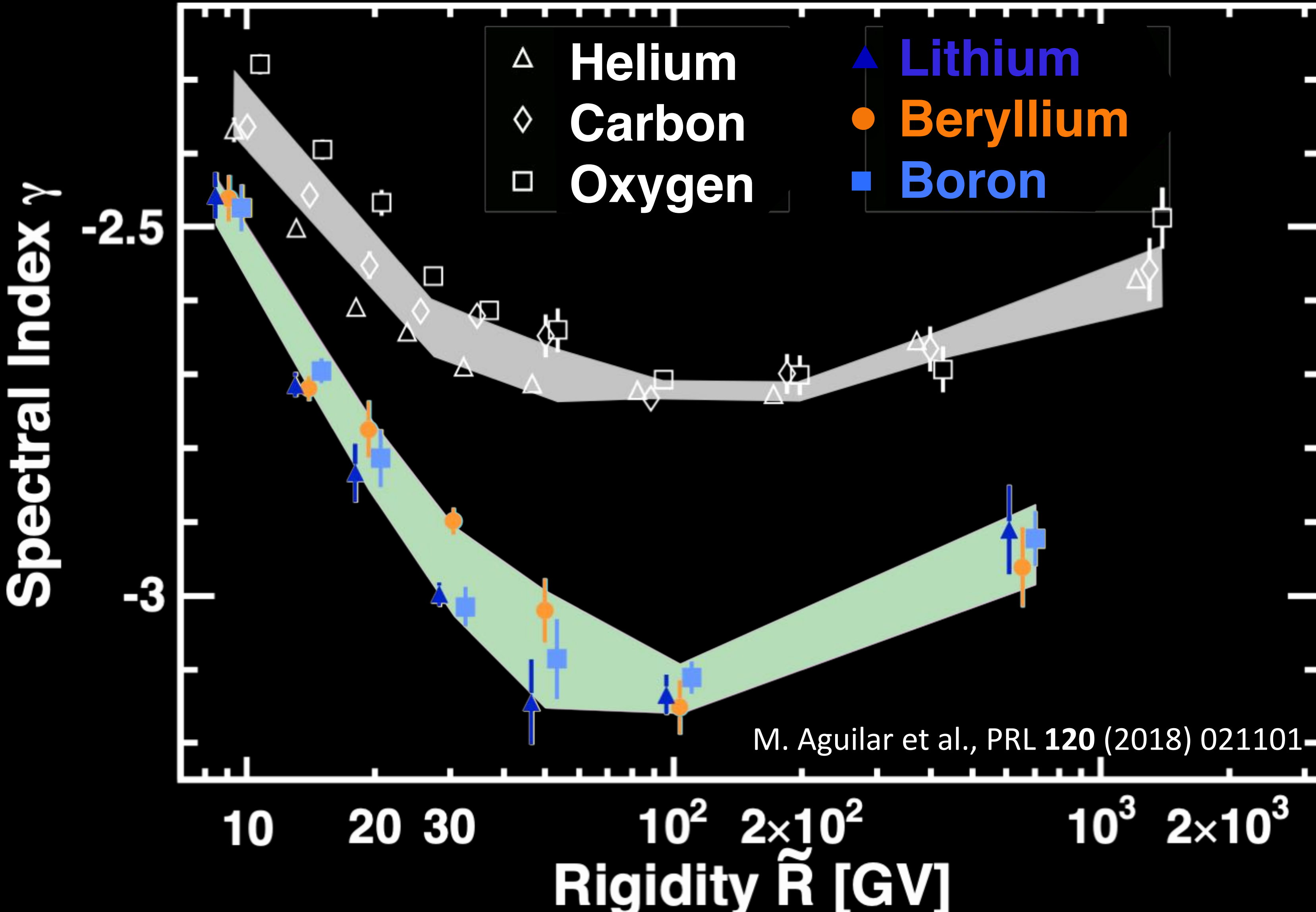
If the hardening is related to **propagation properties** in the Galaxy then a **stronger hardening** is expected for the **secondary** with respect to the **primary** cosmic rays.

AMS Primary and Secondary Nuclei Fluxes

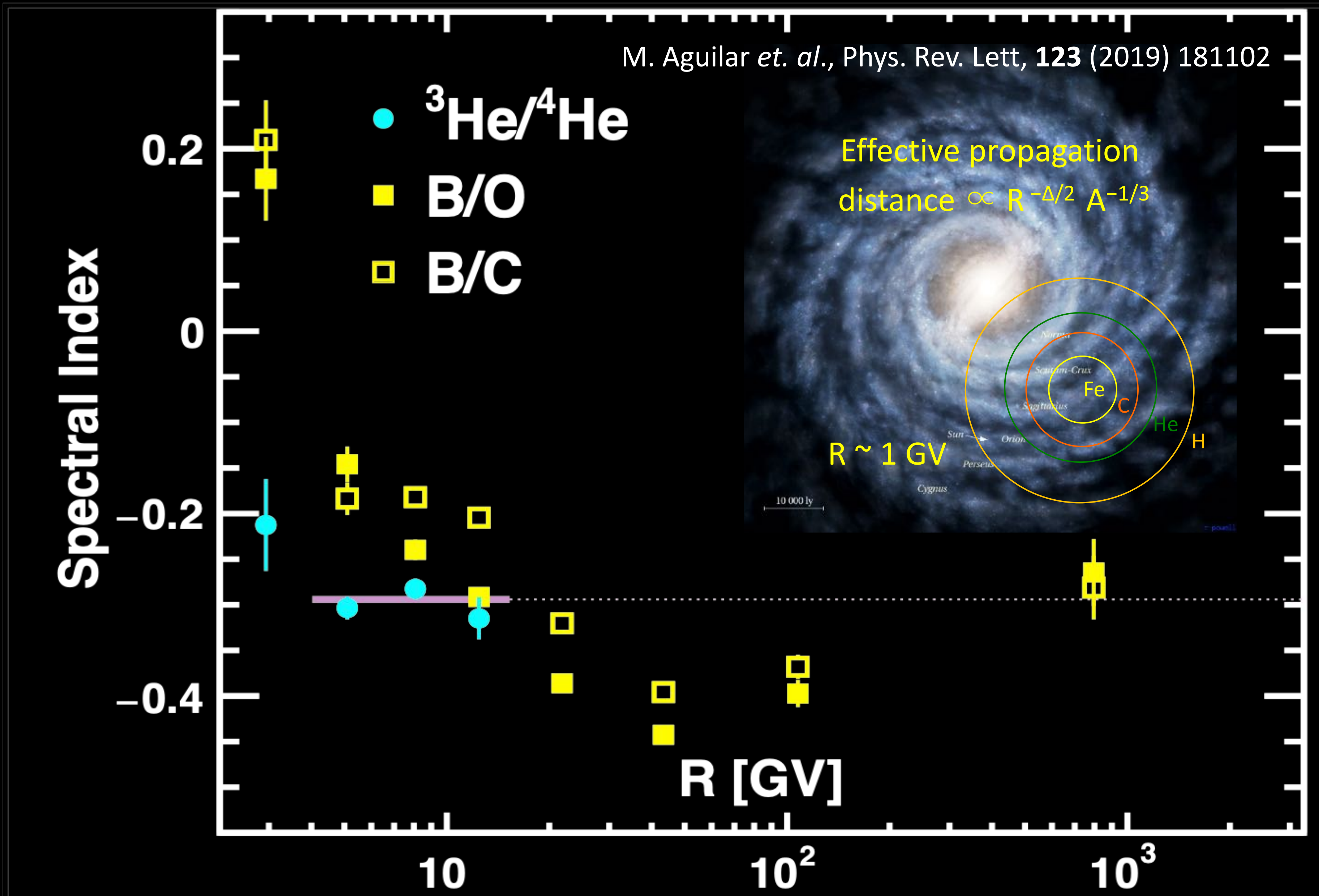


AMS Primary and Secondary Nuclei Spectral Indices

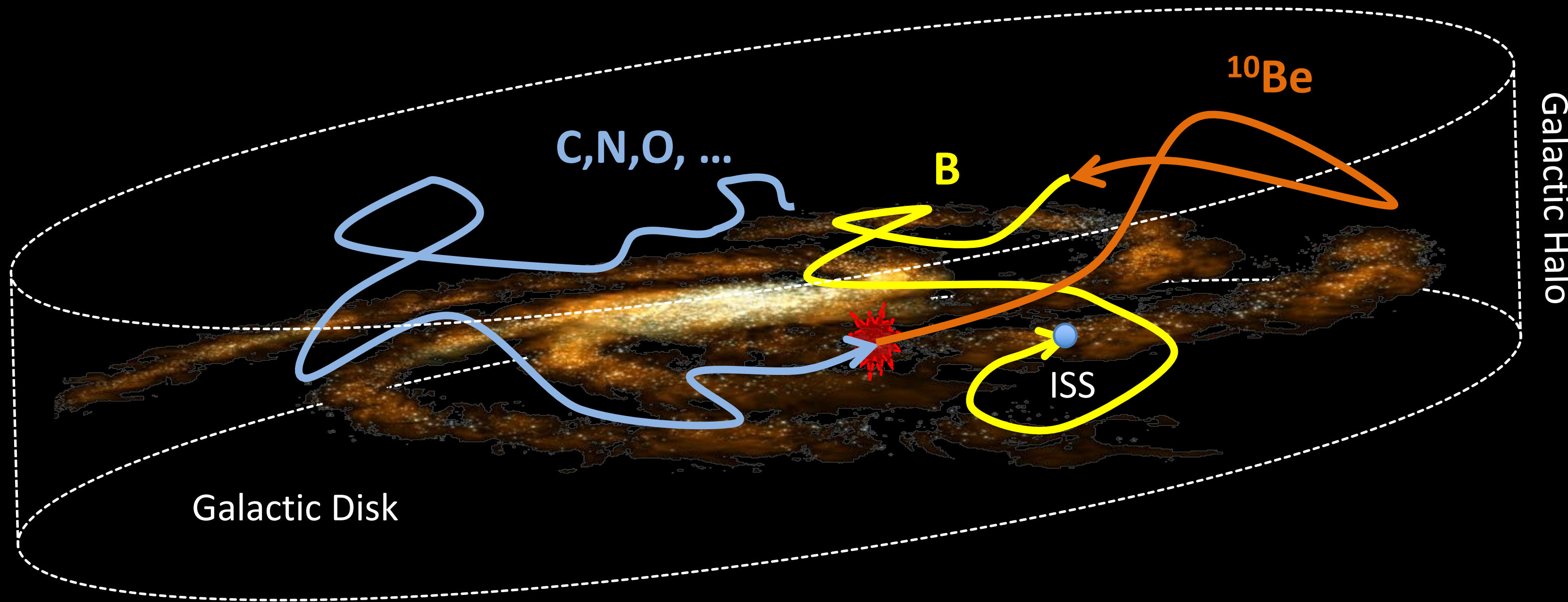
Deviate from single power law above 200 GV. Secondary hardening is stronger
AMS favors the hypothesis that the flux hardening is an **universal propagation effect**.



Probing Non-Homogeneous Diffusion: AMS $^3He/^4He$



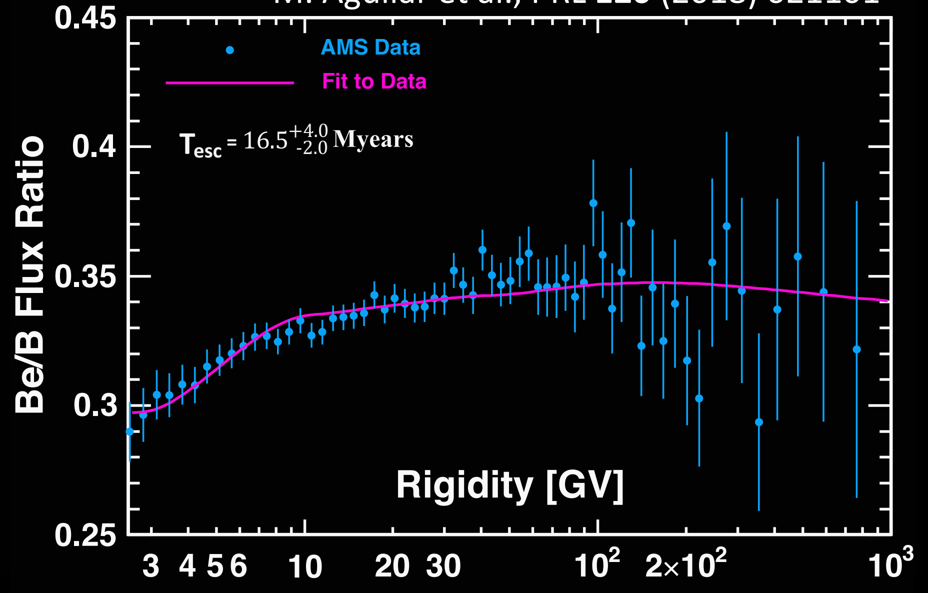
Cosmic Ray Clock: AMS Be/B Flux Ratio



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

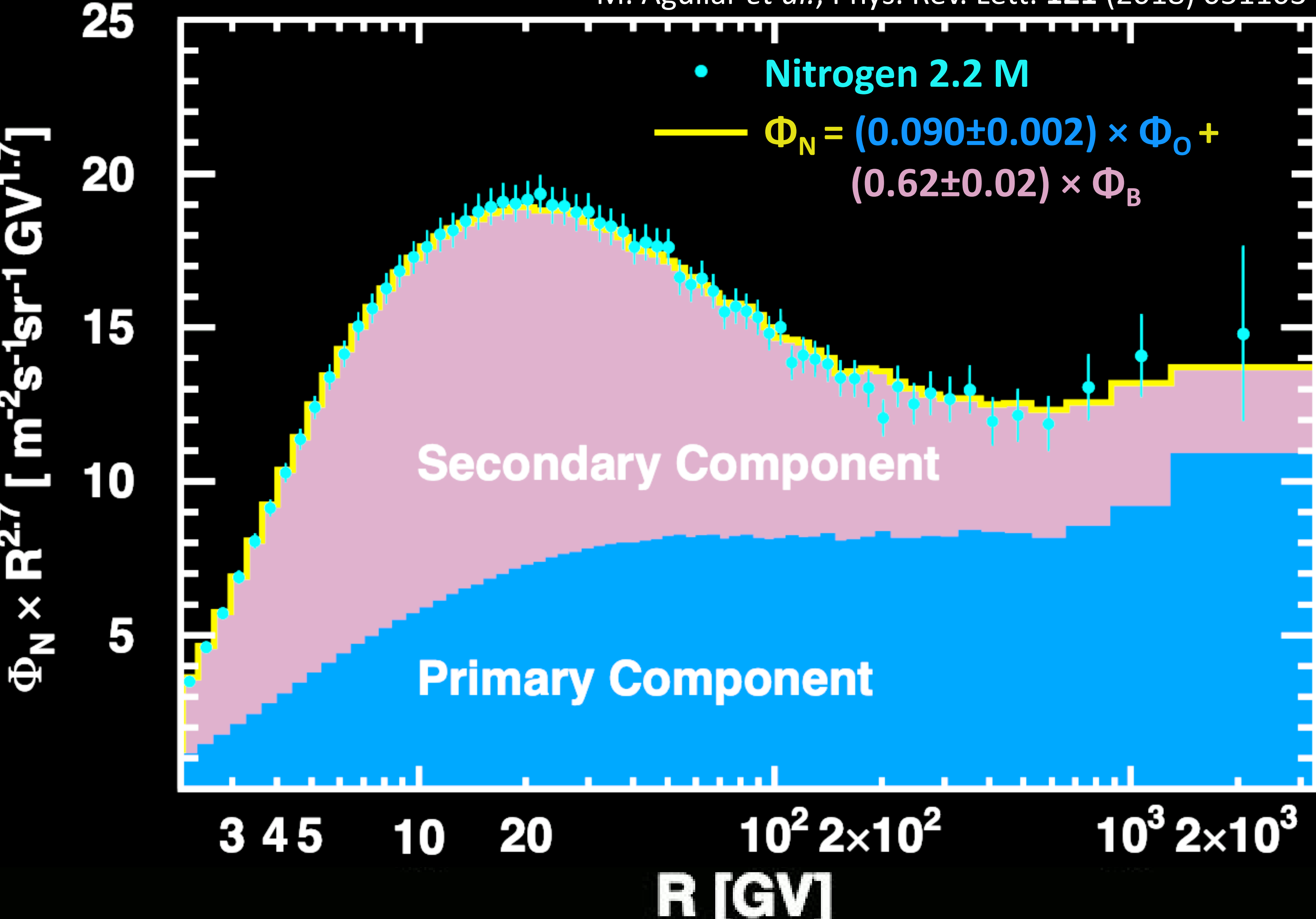
The Be/B ratio rigidity dependence is related to the **cosmic rays confinement time** (or the galactic halo size in diffusion models).

M. Aguilar et al., PRL **120** (2018) 021101



Abundances at Source: AMS Nitrogen Flux

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



Also tested with C flux, revealing a secondary component of about 20% at 4 GV and less than 5% at 2 TV.

Solar Physics and Space Weather with AMS-02

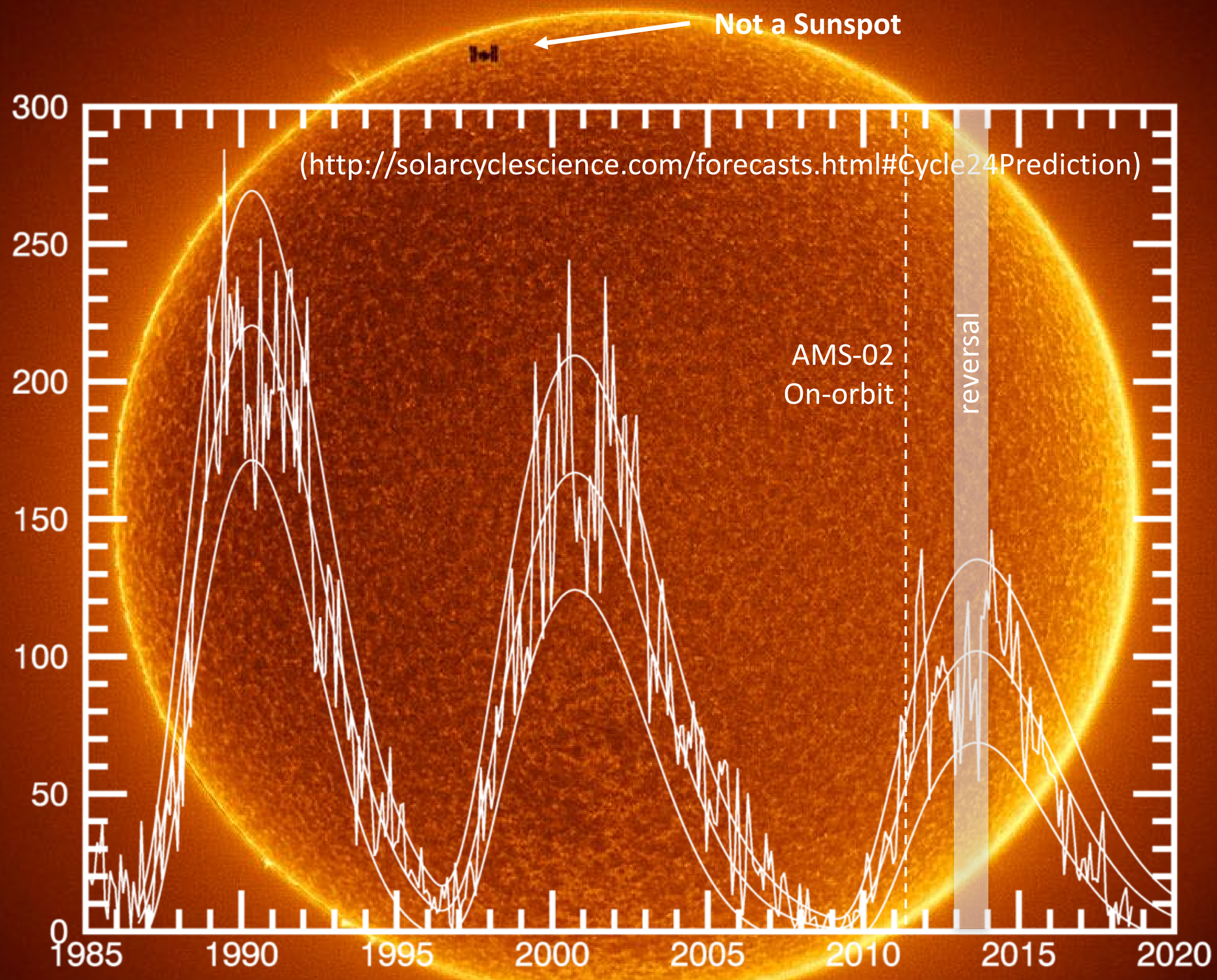
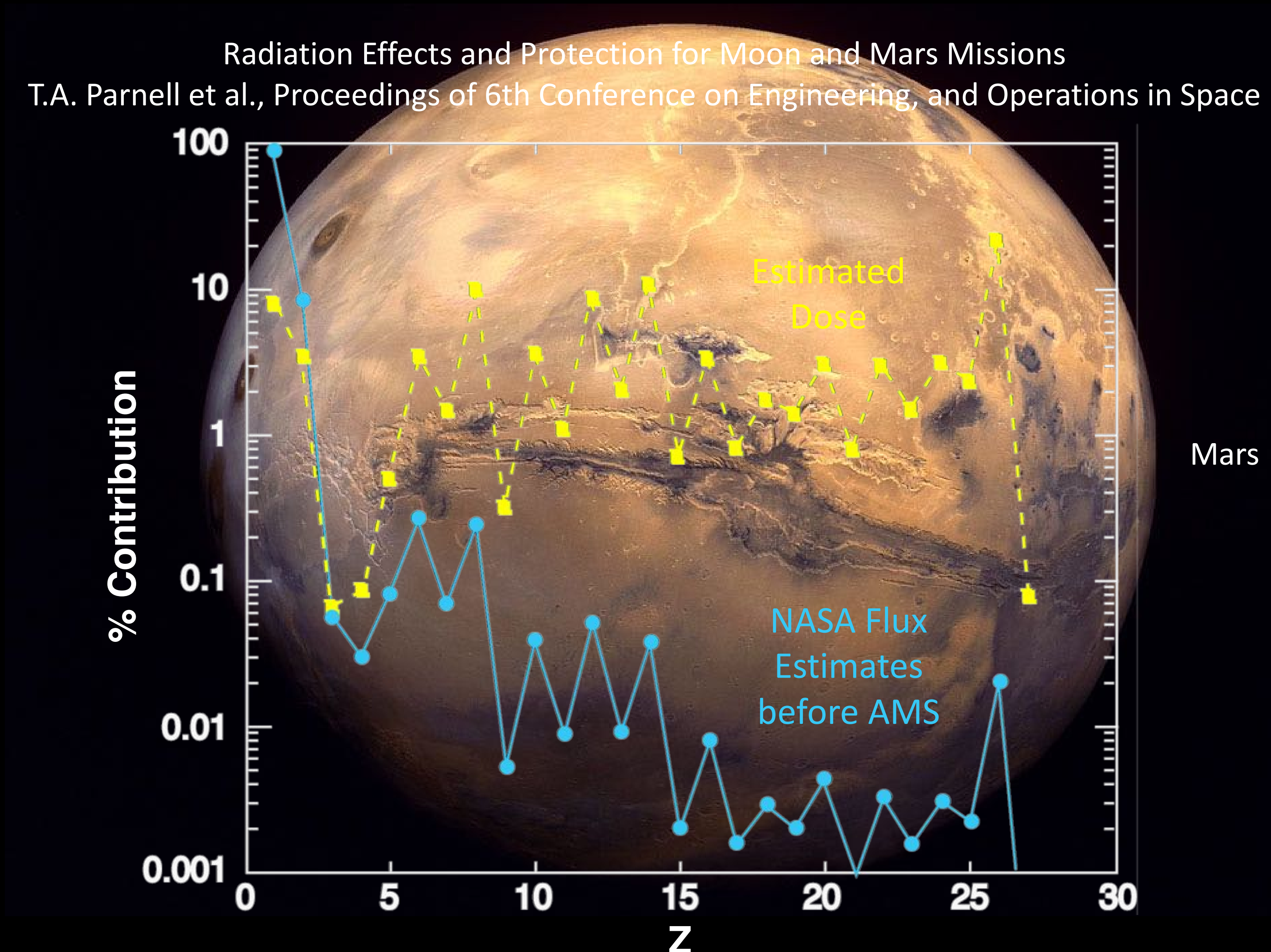


Image Credits: APOD 15 July 2019

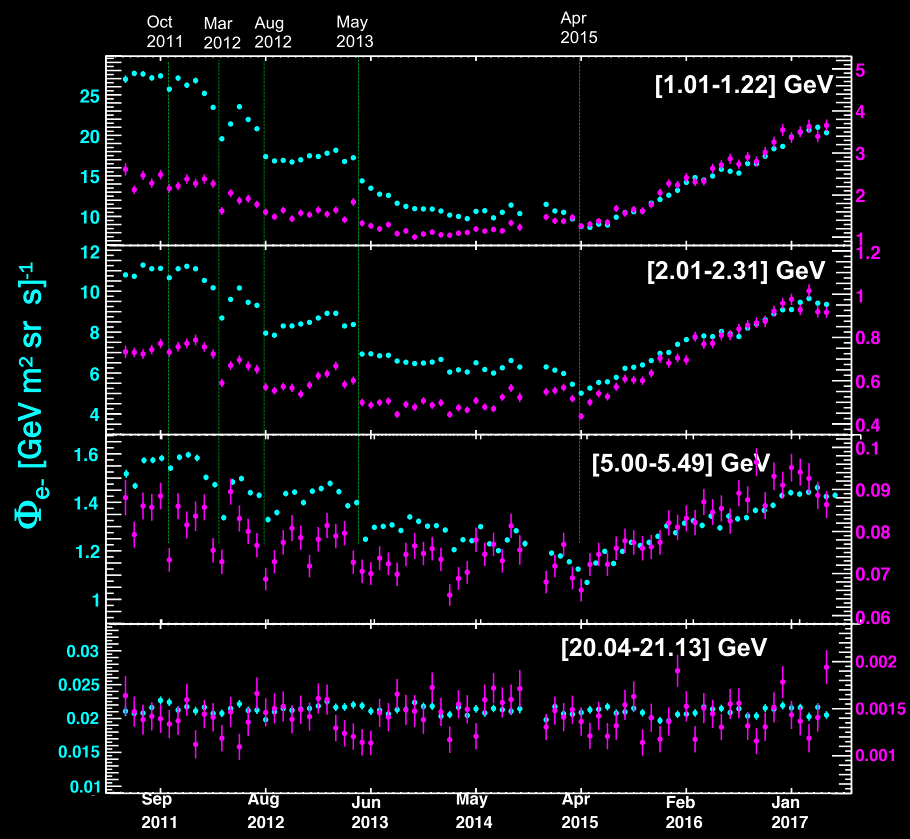
Solar Physics and Space Weather with AMS-02

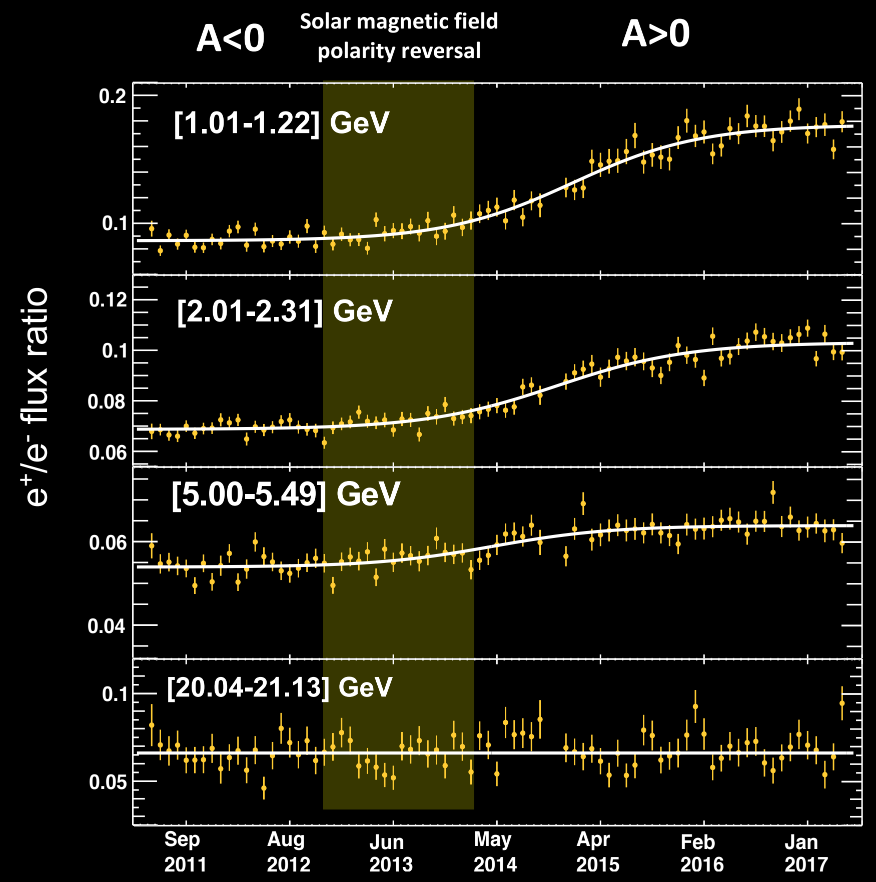


Space travel needs CRs fluxes measurement up-to high-Z, as a function of time and energy.

e^+, e^- and e^+/e^- Dependence with Time

M. Aguilar *et. al.*, Phys. Rev. Lett, **121** (2018) 051102

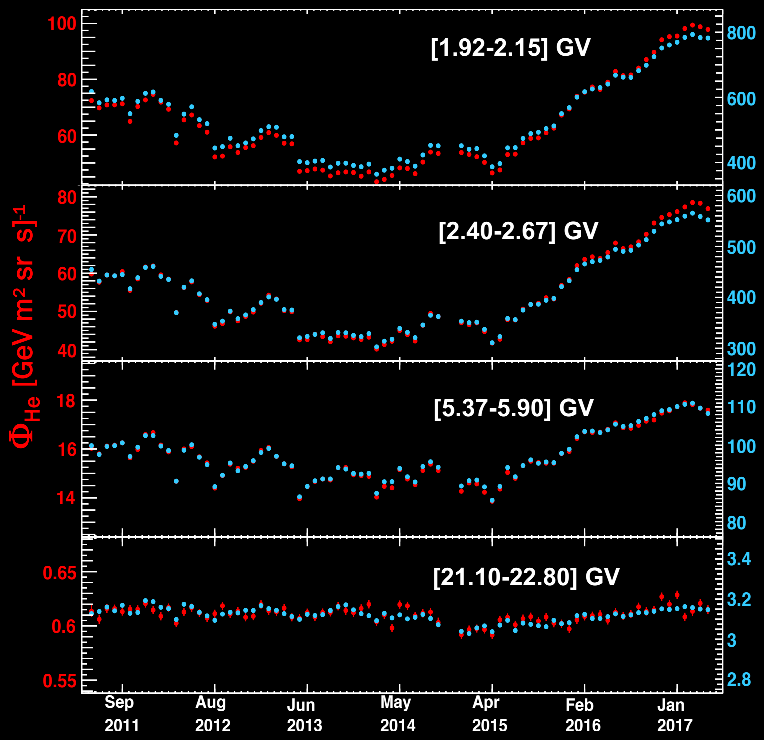


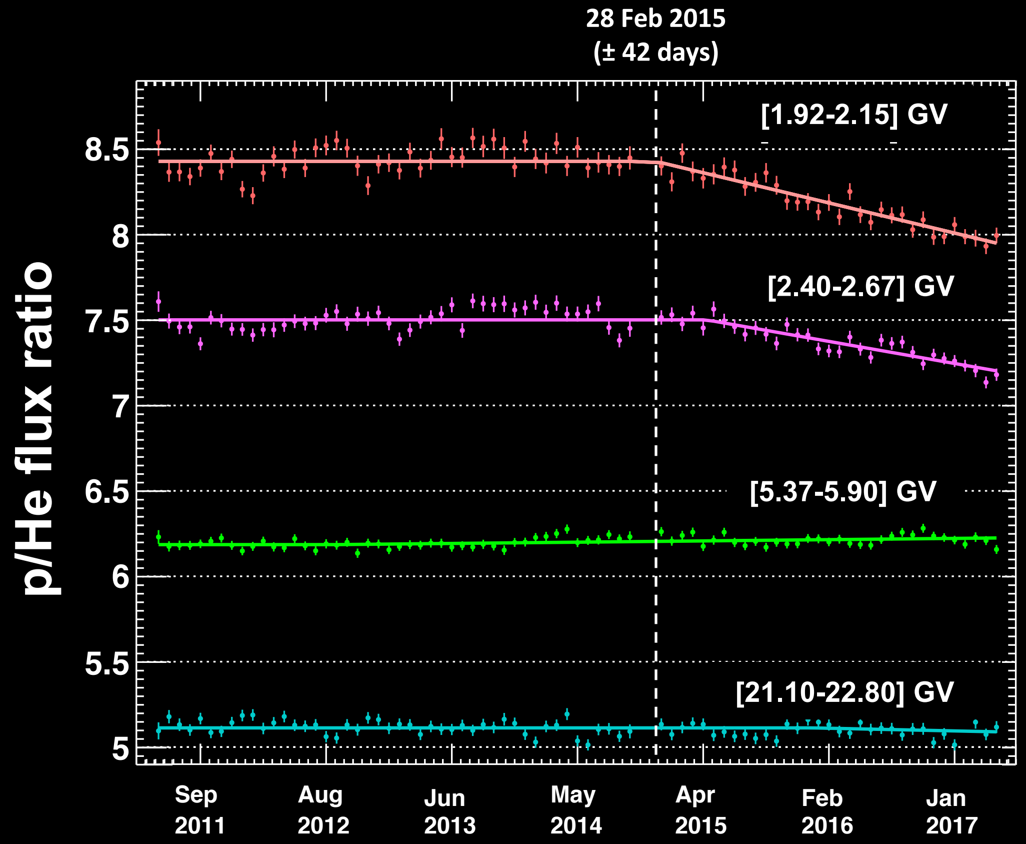


Solar modulation charge sign dependence

p, He and p/He Dependence with Time

M. Aguilar *et. al.*, Phys. Rev. Lett, **121** (2018) 051101

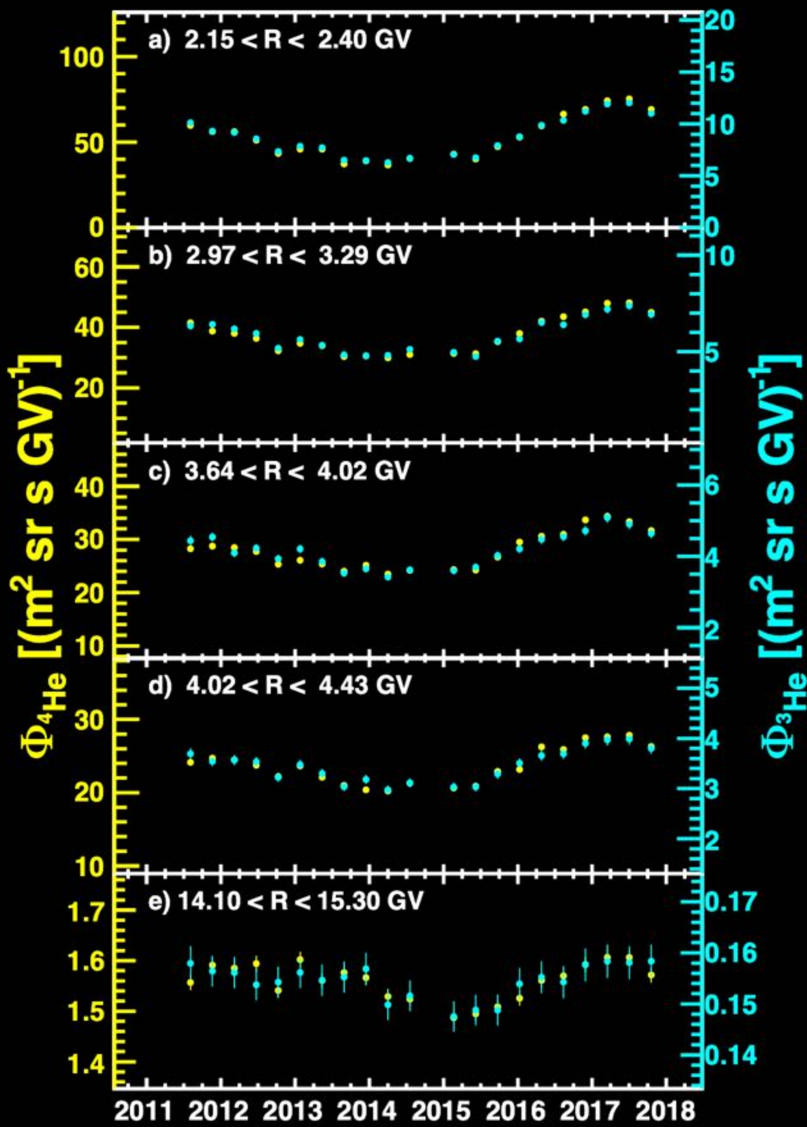


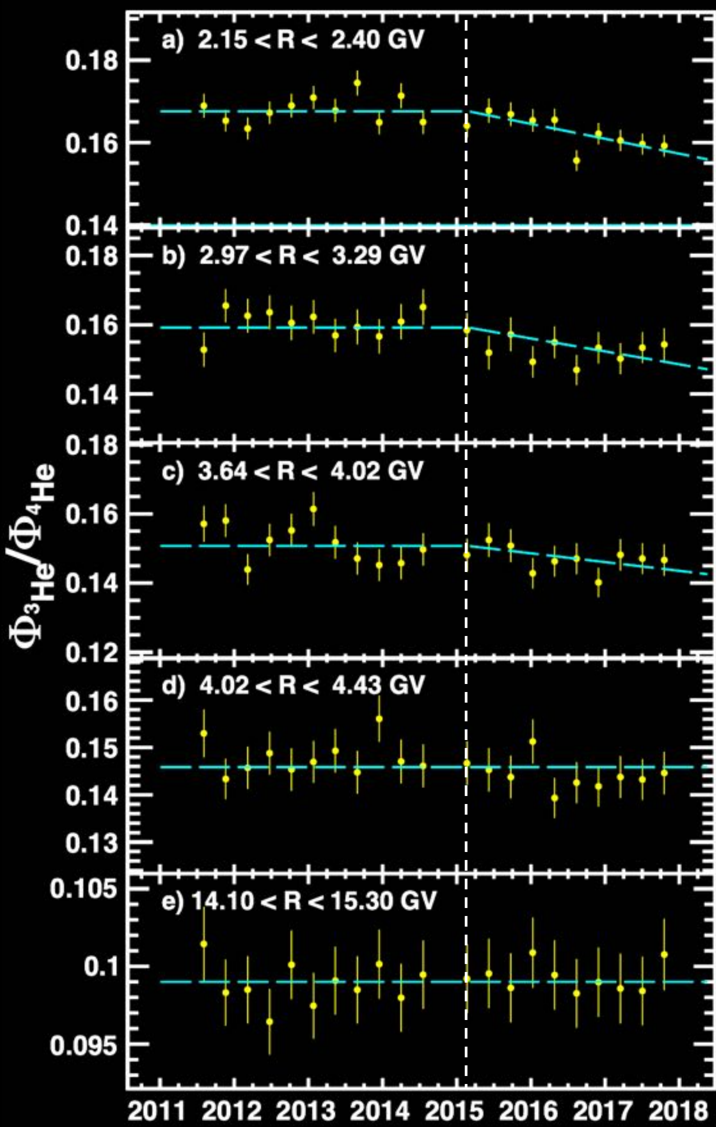


Solar modulation mass and/or absolute charge dependence

^{3}He, ^{4}He and ^{3}He/^{4}He Dependence with Time

M. Aguilar *et. al.*, Phys. Rev. Lett, **123** (2019) 181102





Solar modulation mass dependence

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 its properties.

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

Please visit

https://AMS02.space

For more details about our detector, analysis, and physics results