Latest Results from Alpha Magnetic Spectrometer (AMS) on the International Space Station (ISS)

Oct. 4, 2024

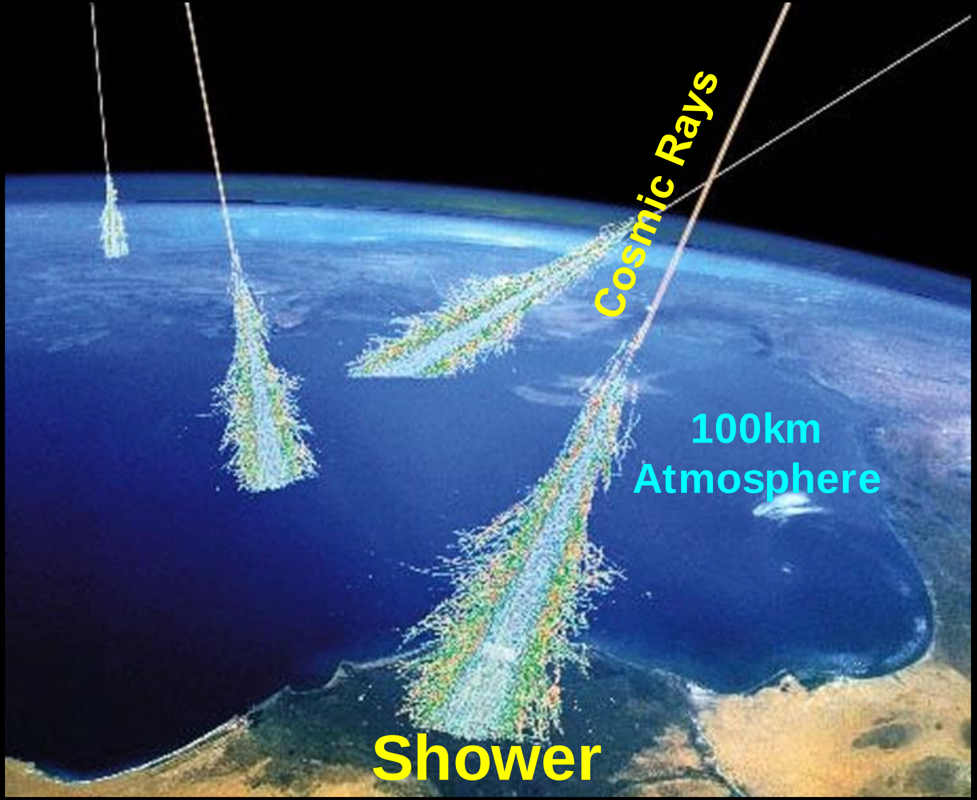
LHC Days in Split

Weiwei Xu / SDU, SDIAT

AMS on the Space Station

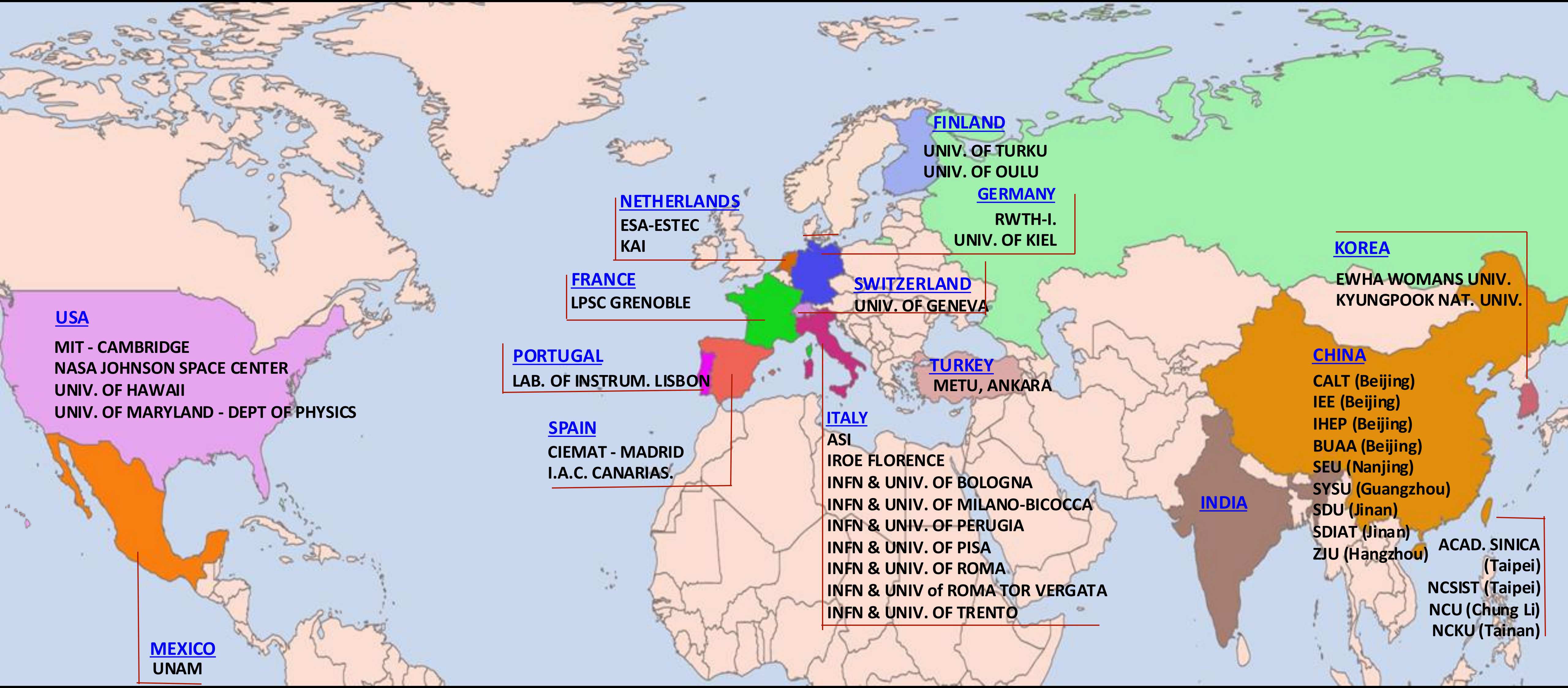
Provides precision, long-duration measurements of charged cosmic rays to study the Origin of the Cosmos, the physics of Dark Matter and Antimatter

Charged cosmic rays have mass.
They are absorbed by the
100 km of Earth's atmosphere (10m of water).
The properties (±Z, P) of charged cosmic rays
cannot be studied on the ground.



To measure cosmic ray charge and momentum
requires a magnetic spectrometer
in space

Alpha Magnetic Spectrometer experiment (AMS) on the Space Station



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BUAA (Beijing)
SEU (Nanjing)
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SDU (Jinan)
SDIAT (Jinan)
ZJU (Hangzhou)

ACAD. SINICA (Taipei)
NCSIST (Taipei)
NCU (Chung Li)
NCKU (Tainan)

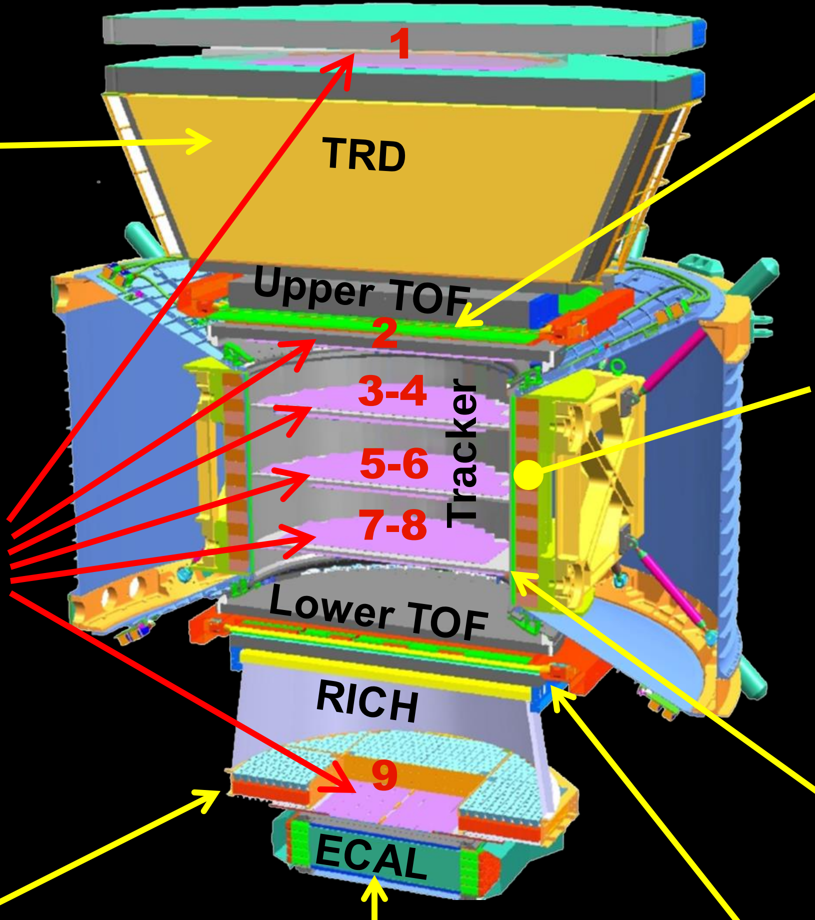
AMS is a space version of a precision detector used in accelerators

Transition Radiation Detector (TRD)
identify e^+, e^-

Upper TOF measure Z, E

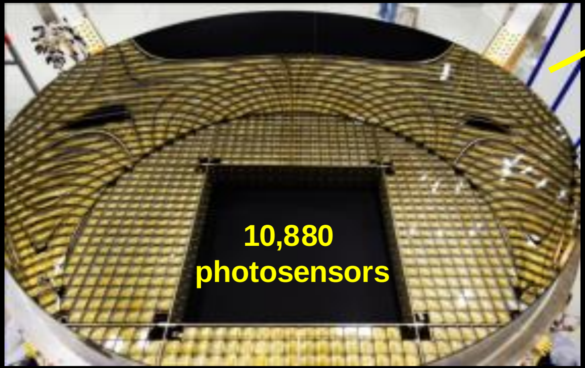
Magnet identify ±Z, P

Silicon Tracker
measure Z, P



Anticoincidence Counters (ACC)
reject particles from the side

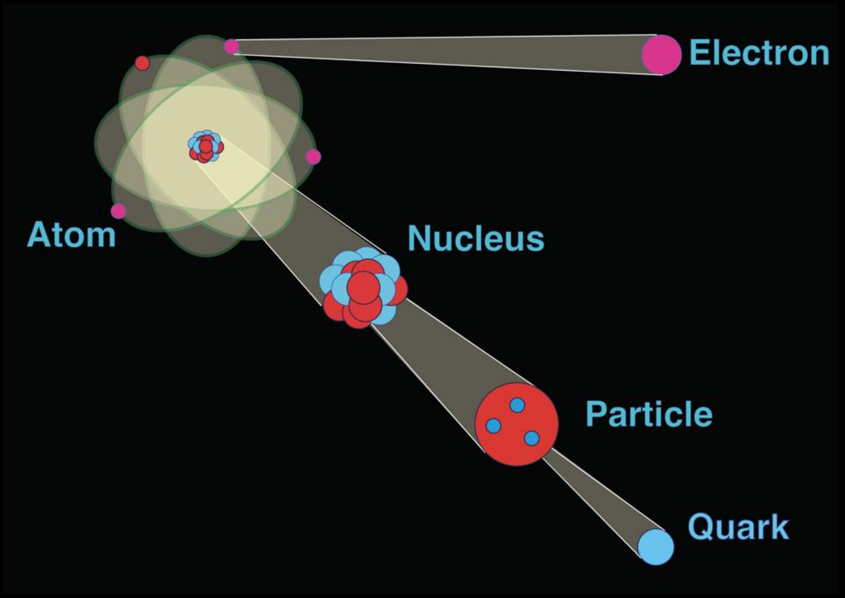
Ring Imaging Cerenkov (RICH)
measure Z, E

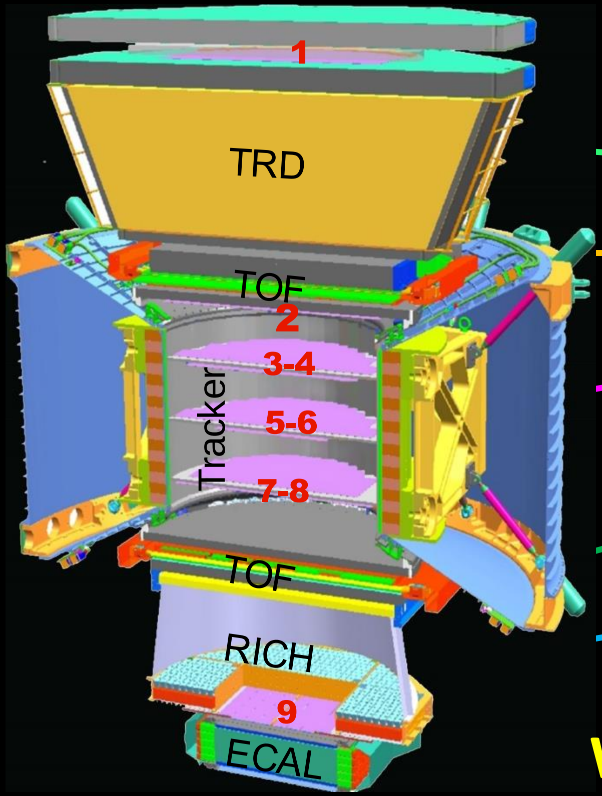


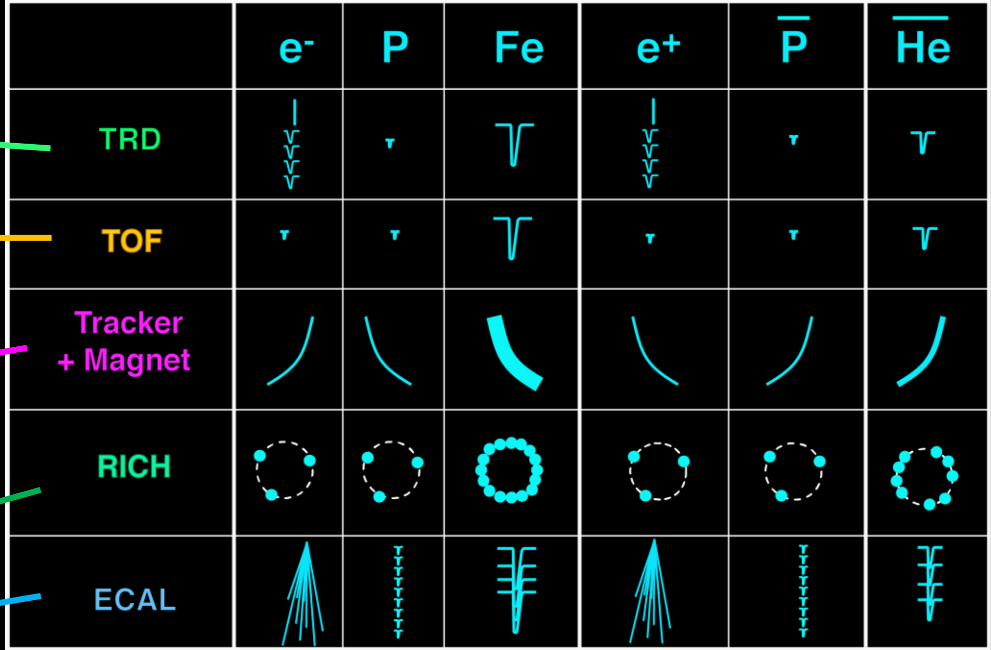
Electromagnetic Calorimeter (ECAL)
measure E of e^+, e^-

Lower TOF measure Z, E

The AMS detectors provide independent information on cosmic rays



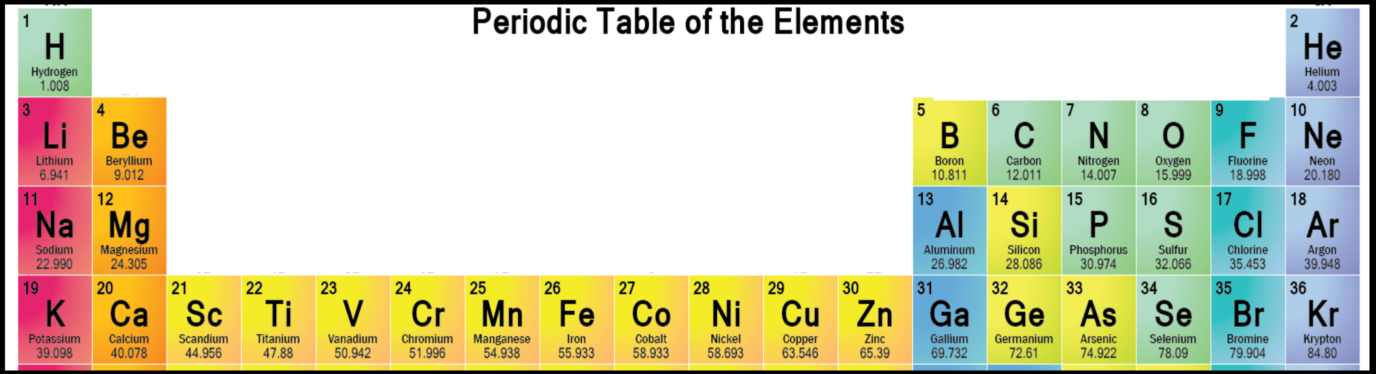




With high accuracy, AMS measures

Momentum (P, GeV/c)
Charge (Z)
Rigidity (R=P/Z, GV)
Energy (E, GeV/A)
Flux (signals/(s sr m^2 GeV))

for all the charged cosmic rays, e+, e−, p, and $\bar{p}$,
and the nuclei in the Periodic Table

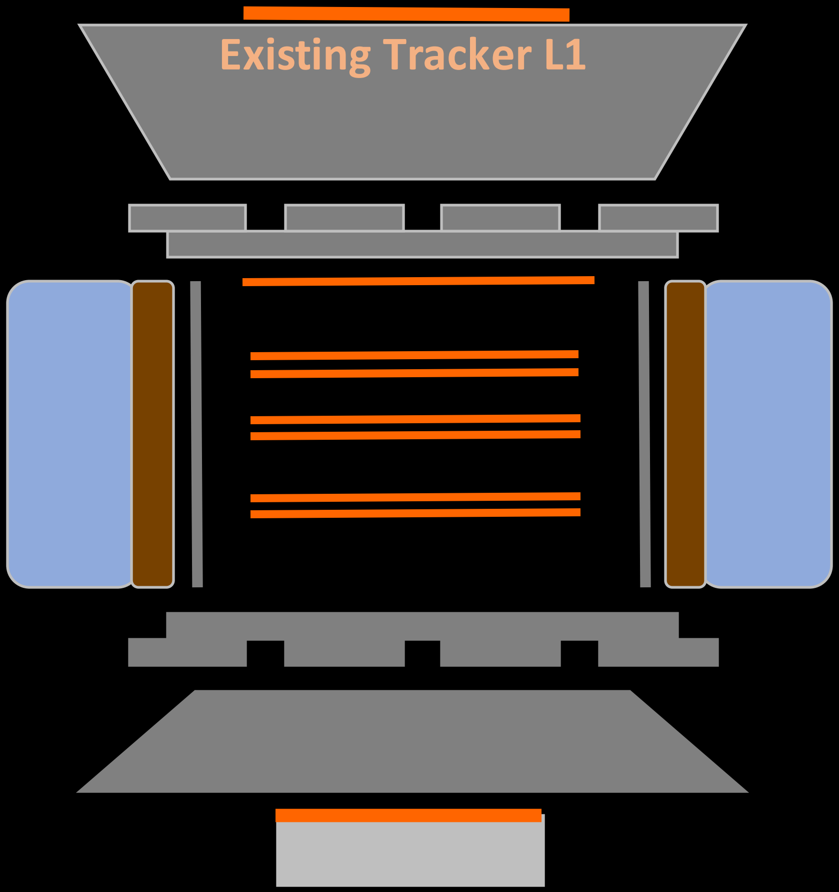


Periodic Table of the Elements

1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.09	35 Br Bromine 79.904	36 Kr Krypton 84.80

AMS 2011-2026

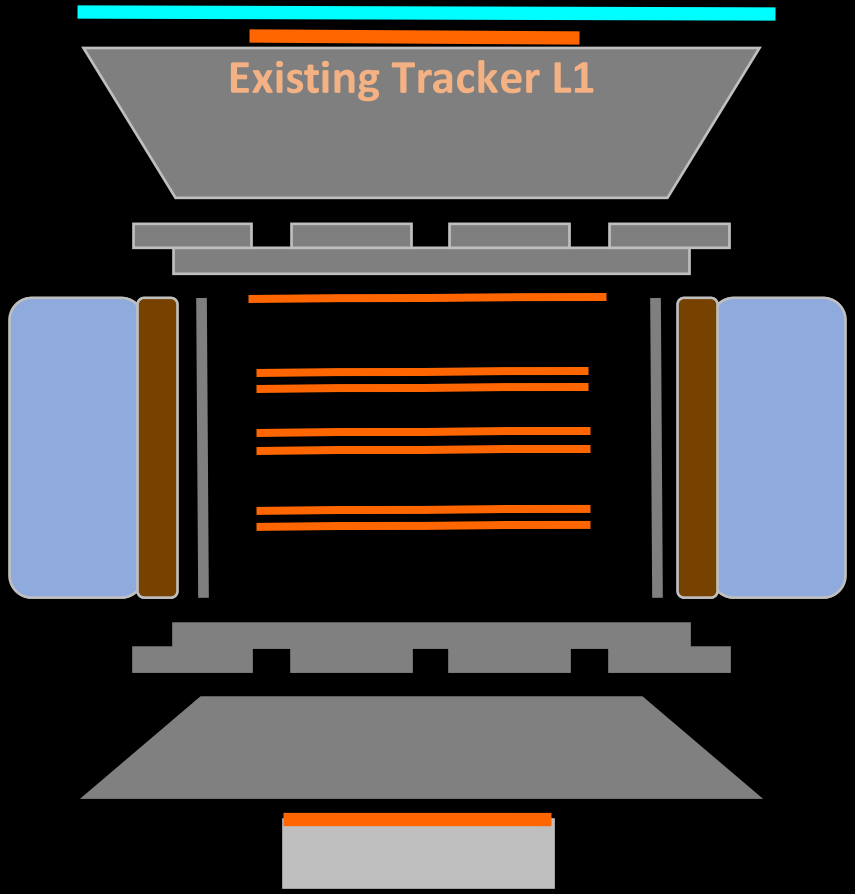
Continuous data-taking



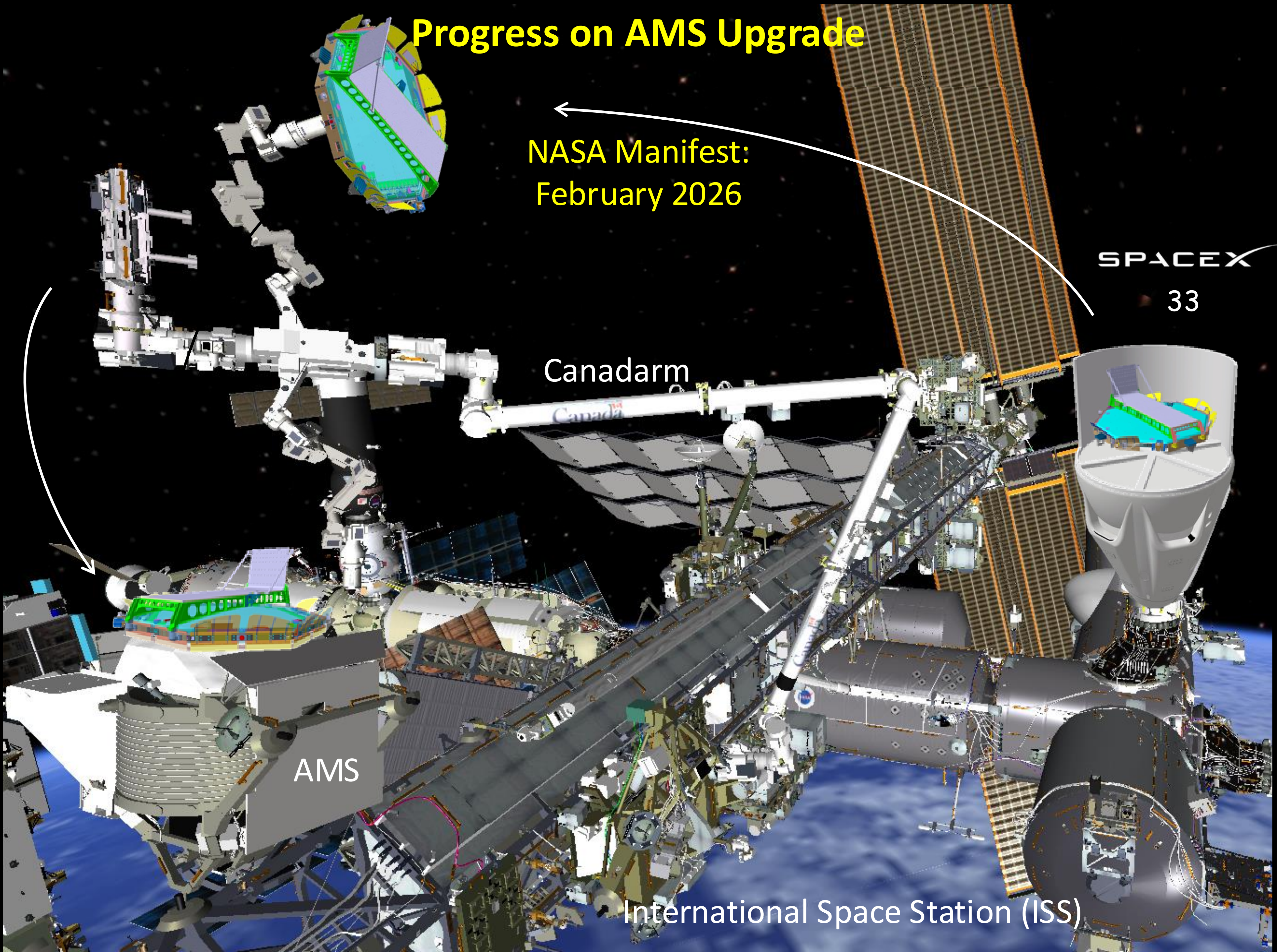
AMS 2026-2030+

New 4+4m^2 Silicon Tracker Planes

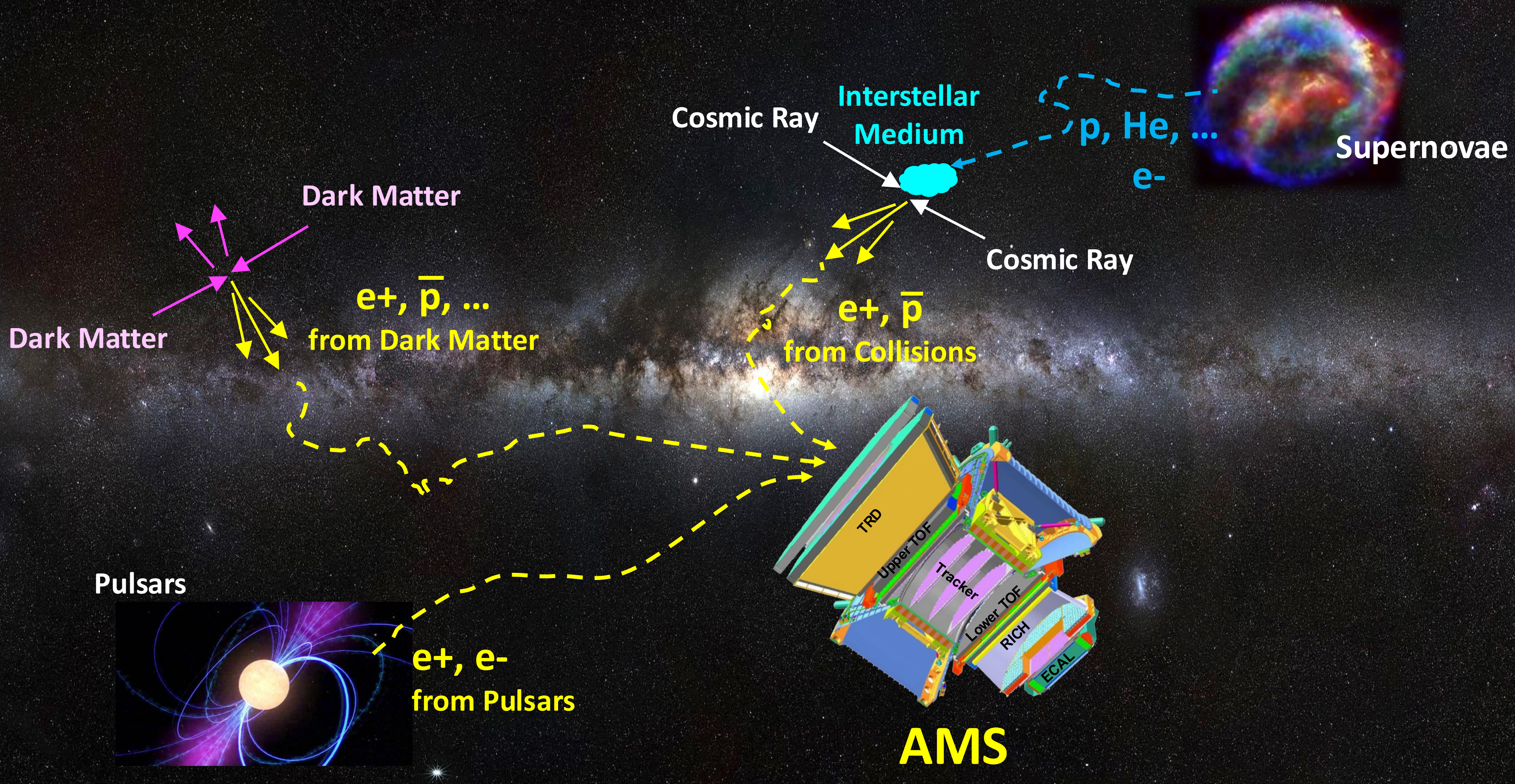
Acceptance increased to 300%



Progress on AMS Upgrade


NASA Manifest:
February 2026

Latest Results on cosmic elementary particles: e+, e−, p, and $\bar{p}$



Interstellar Medium

Cosmic Ray

p, He, …

e-

Supernovae

Cosmic Ray

Dark Matter

Dark Matter

e+, $\bar{p}$, …
from Dark Matter

e+, $\bar{p}$
from Collisions

Pulsars

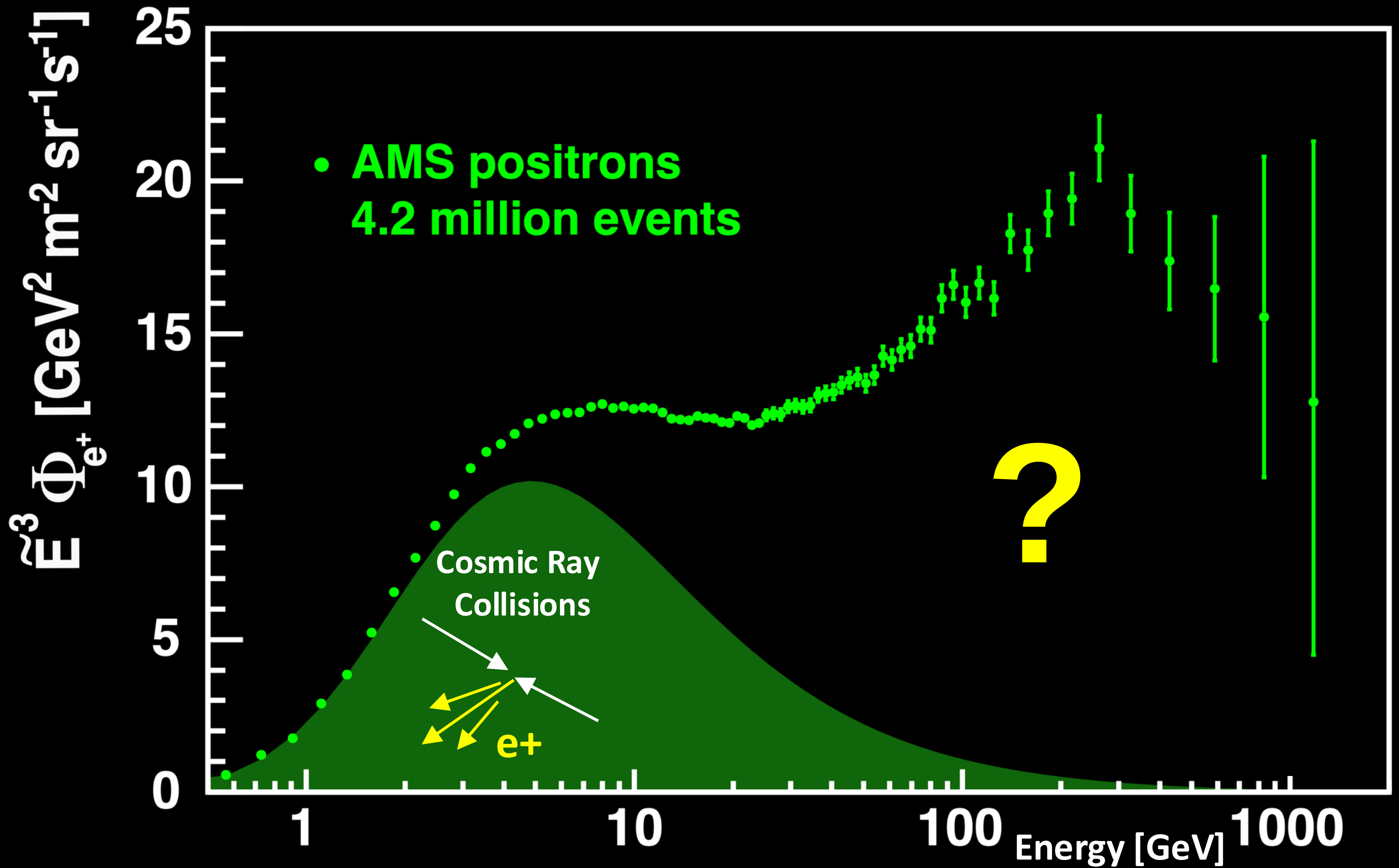
e+, e-
from Pulsars

AMS

AMS positron flux measurement

Low-energy positrons come from cosmic ray collisions

High-energy positrons must come from a new source



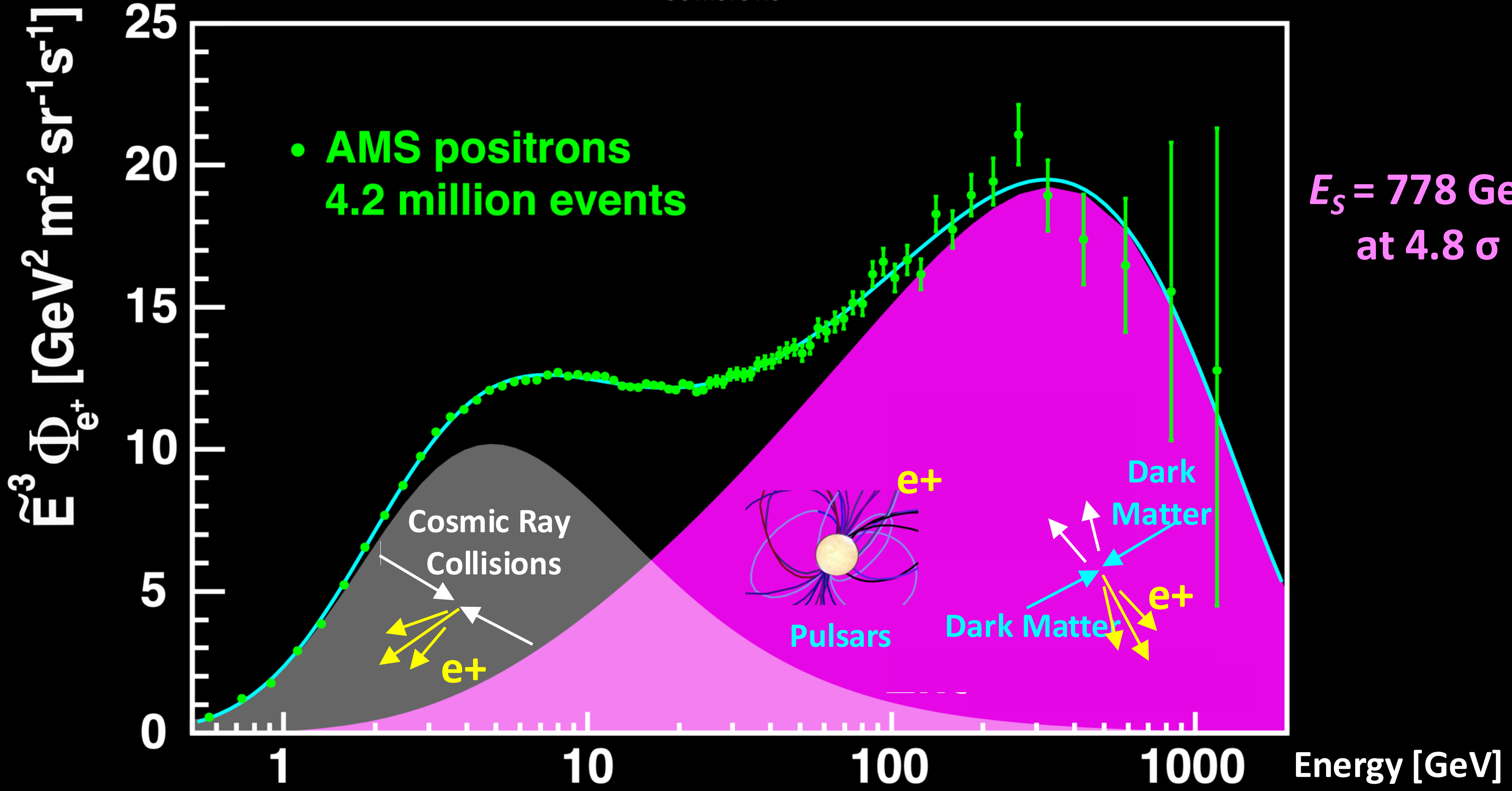
The positron flux is the sum of low-energy part from cosmic ray collisions plus a high-energy part from pulsars or dark matter with a cutoff energy

Empirical model:

$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$

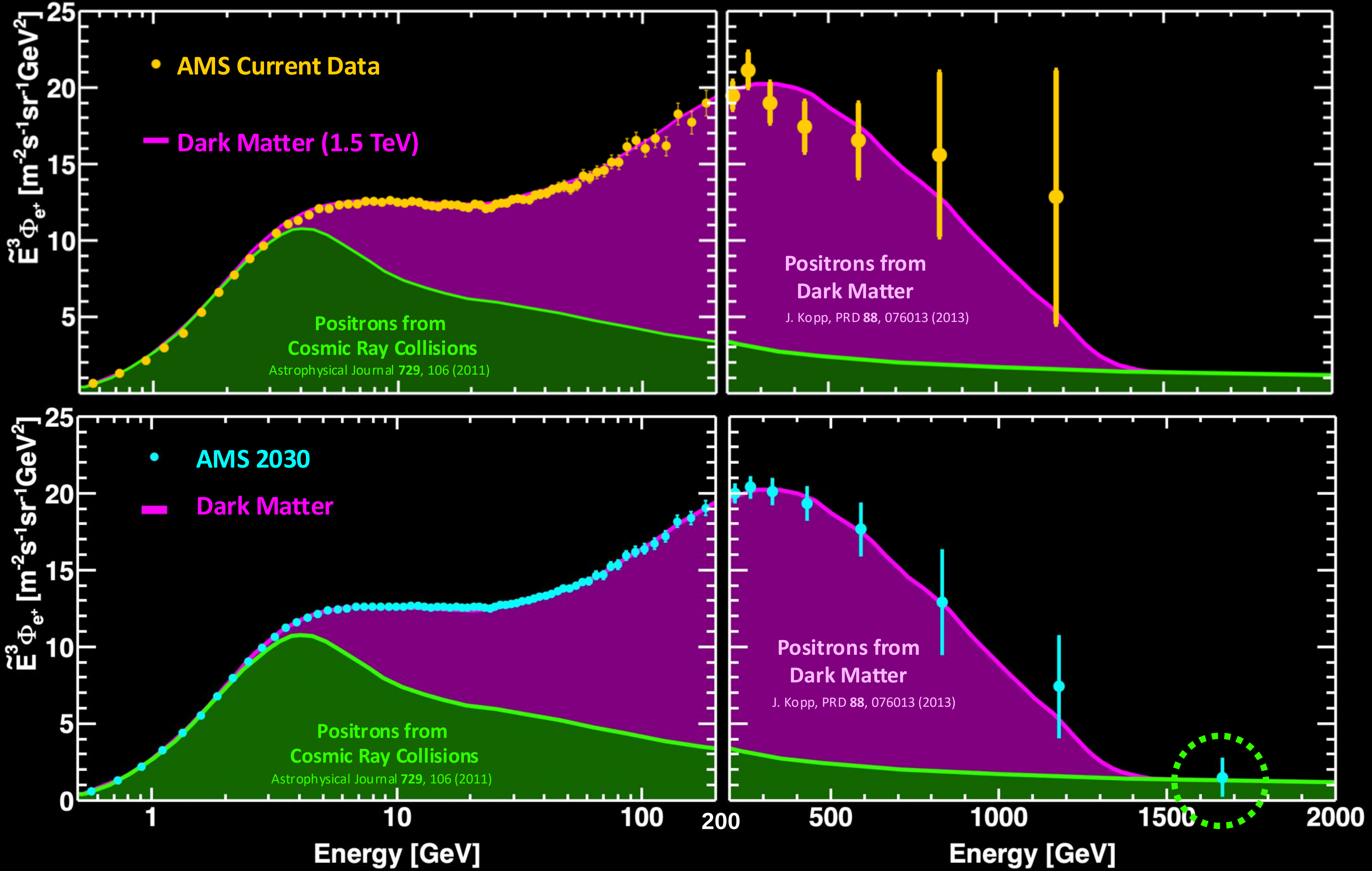
Solar Collisions Pulsars or Dark Matter

$\chi^2/\text{dof} = 63/66$



E_S = 778 GeV at 4.8 σ

Positron spectrum to 2030



By 2030, AMS will ensure that the high energy positron spectrum drops off quickly in the 0.2-2 TeV region and the highest energy positrons only come from cosmic ray collisions as predicted for dark matter collisions

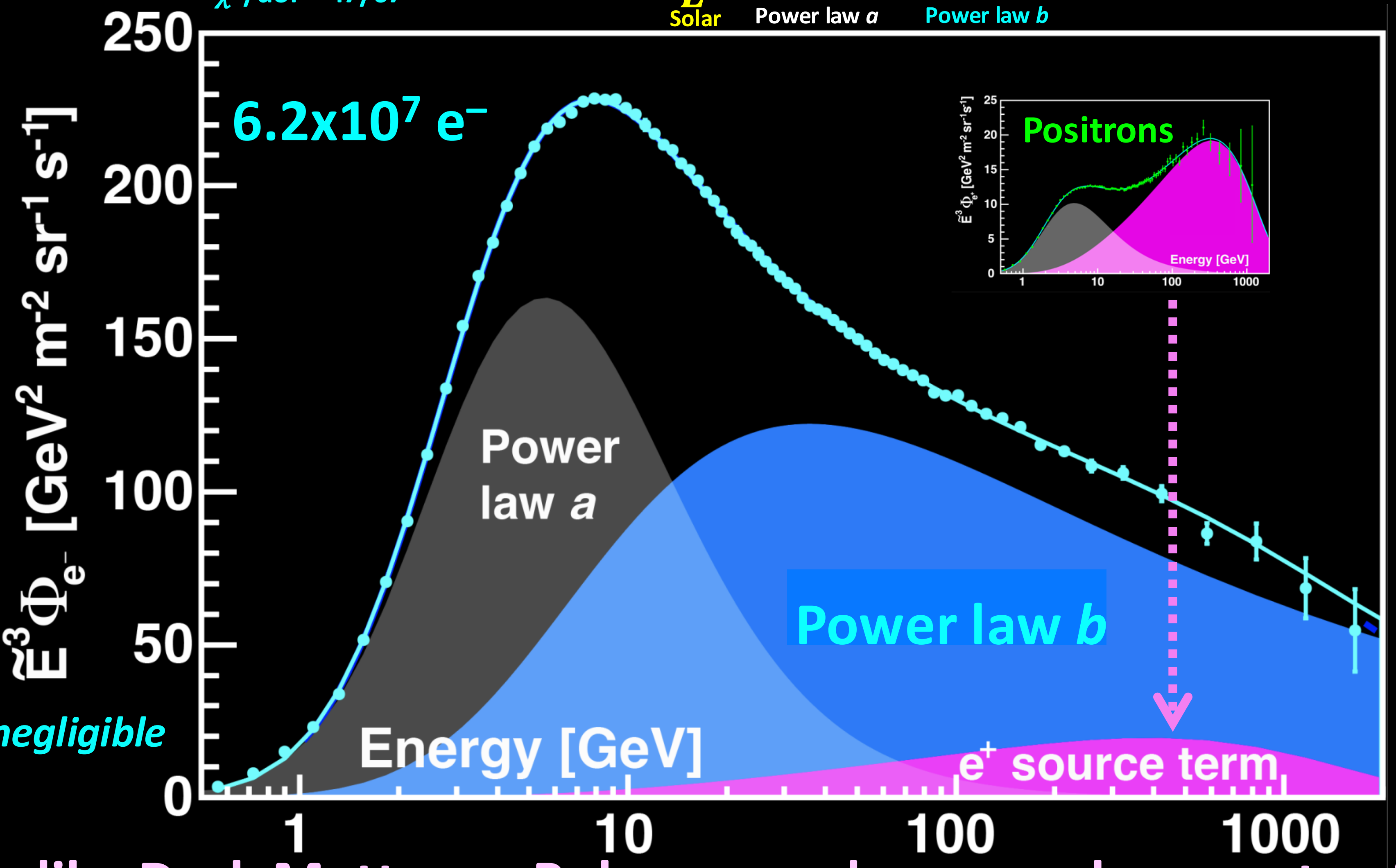
AMS Result on the electron spectrum

The spectrum fits well with two power laws (*a*, *b*) and **a source term like positrons**

Empirical model:

$\chi^2/\text{dof} = 47/67$

$$\Phi_{e^-}(E) = \underbrace{\frac{E^2}{\hat{E}^2}}_{\text{Solar}}\Big(\underbrace{C_a \hat{E}^{\gamma_a}}_{\text{Power law } a} + \underbrace{C_b \hat{E}^{\gamma_b}}_{\text{Power law } b} + \text{Positron Source Term}\Big)$$



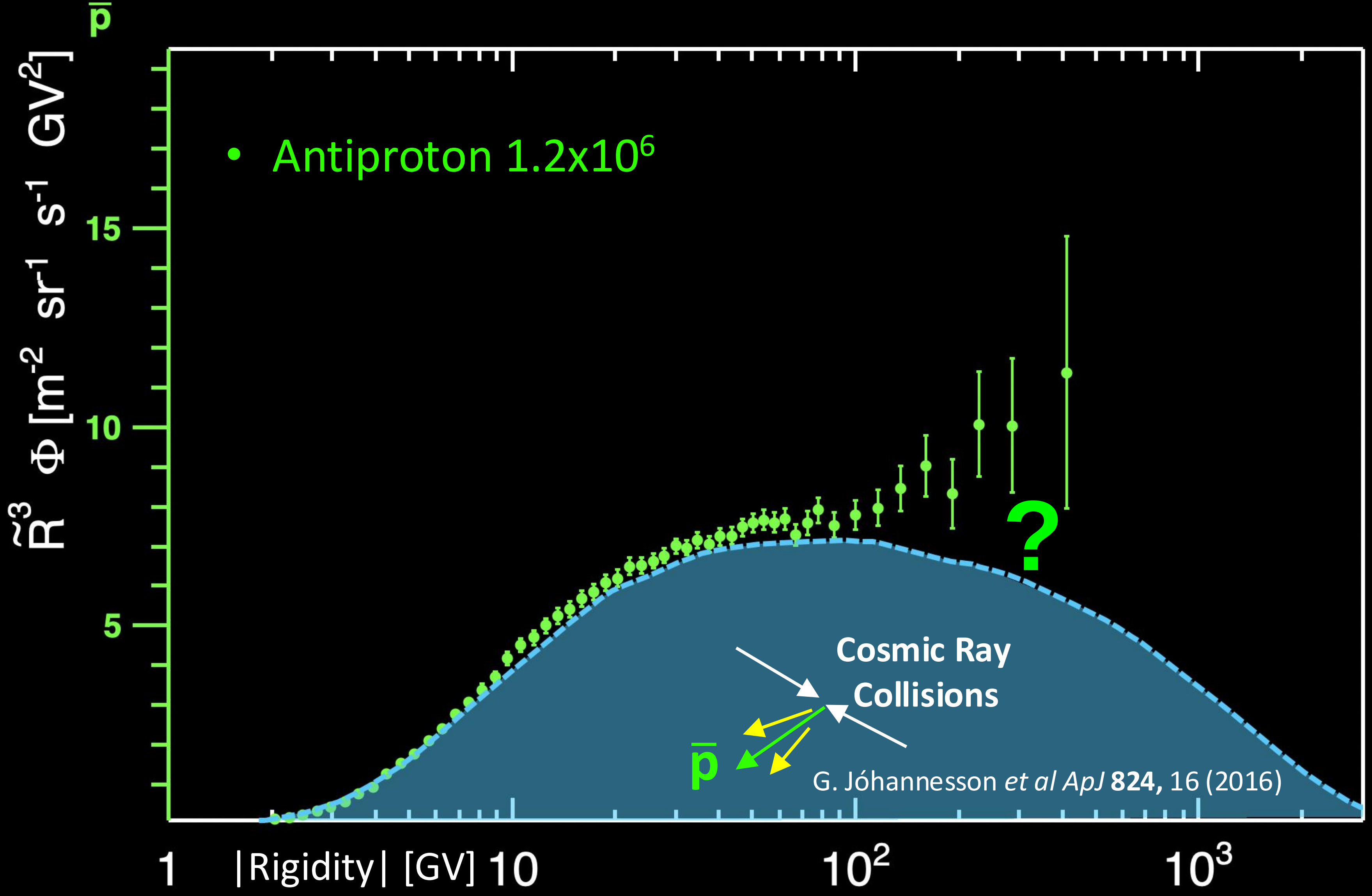
e⁻ from collisions negligible

Current data
98.8% CL

by 2030
99.99% CL

New sources, like Dark Matter or Pulsars, produce equal amounts of e+ and e−

Cosmic Antiprotons

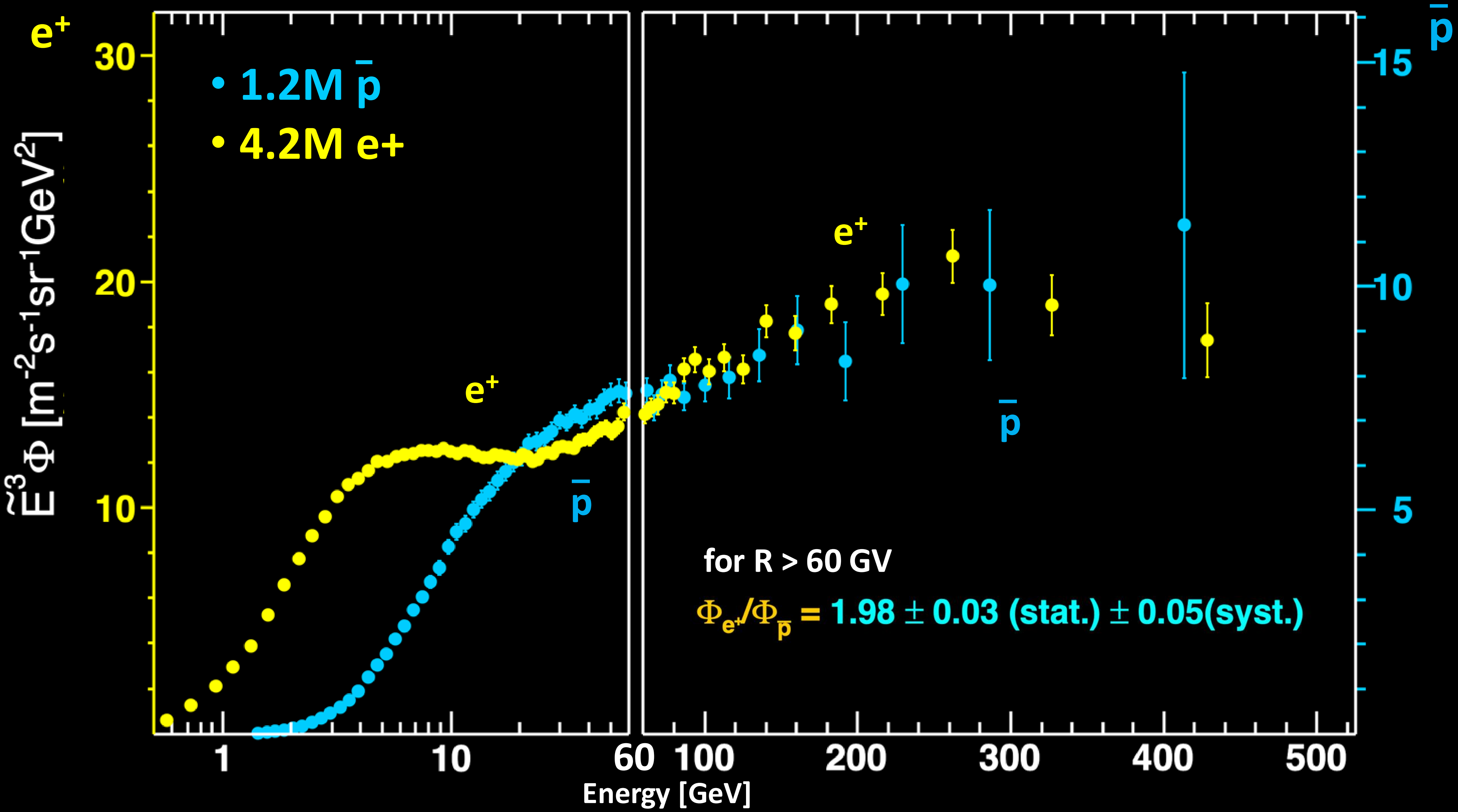


G. Jóhannesson *et al ApJ* **824,** 16 (2016)

p̄ are not produced by pulsars nor by cosmic ray collisions above 60 GV

Cosmic Antiprotons and Positrons

Above 60 GeV, the $\bar{p}$ and e^+ fluxes have identical rigidity dependence

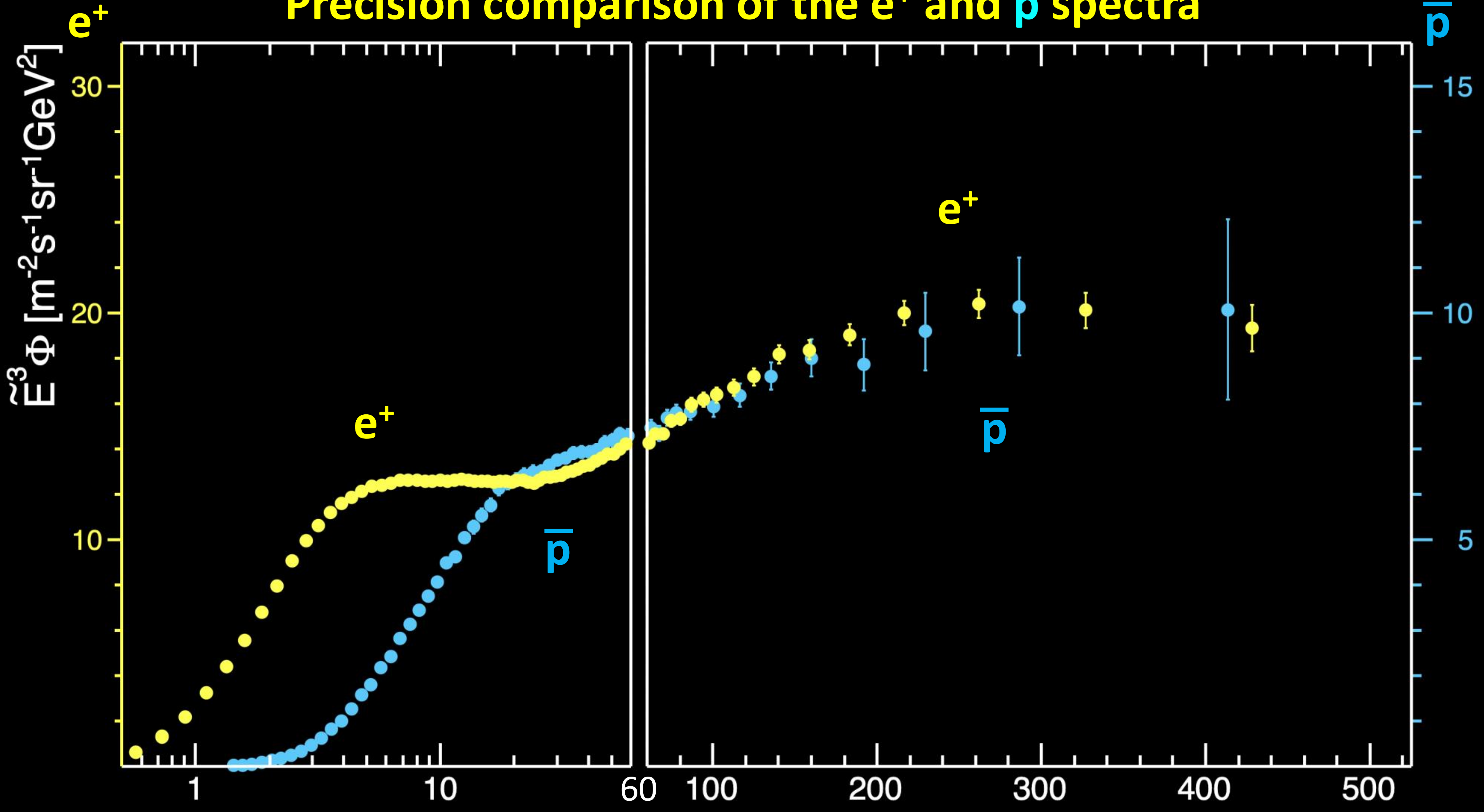


for R > 60 GV

$\Phi_{e^+}/\Phi_{\bar{p}}$ = 1.98 ± 0.03 (stat.) ± 0.05(syst.)

Antiproton to 2030

Precision comparison of the e^+ and $\overline{p}$ spectra

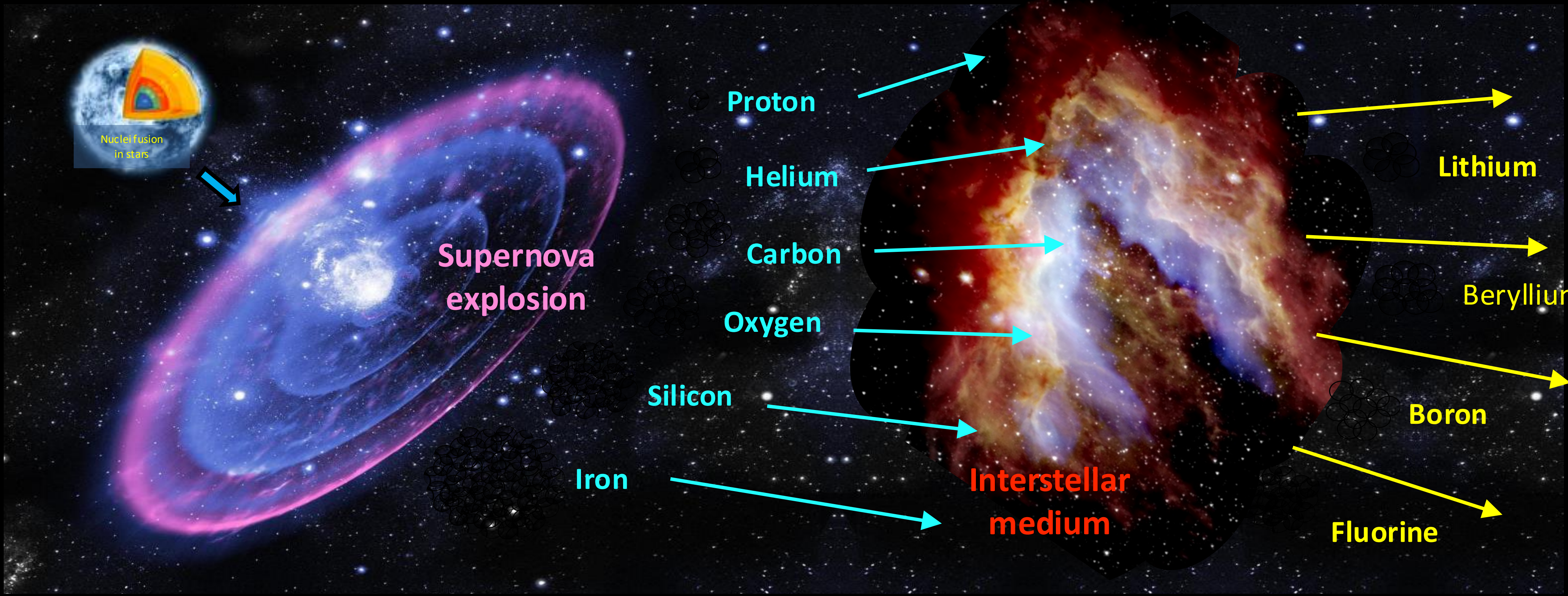


Energy [GeV]

The identical behavior of positrons and antiprotons above 60 GeV

excludes the pulsar origin of positrons

Latest AMS Results on Cosmic Ray Nuclei



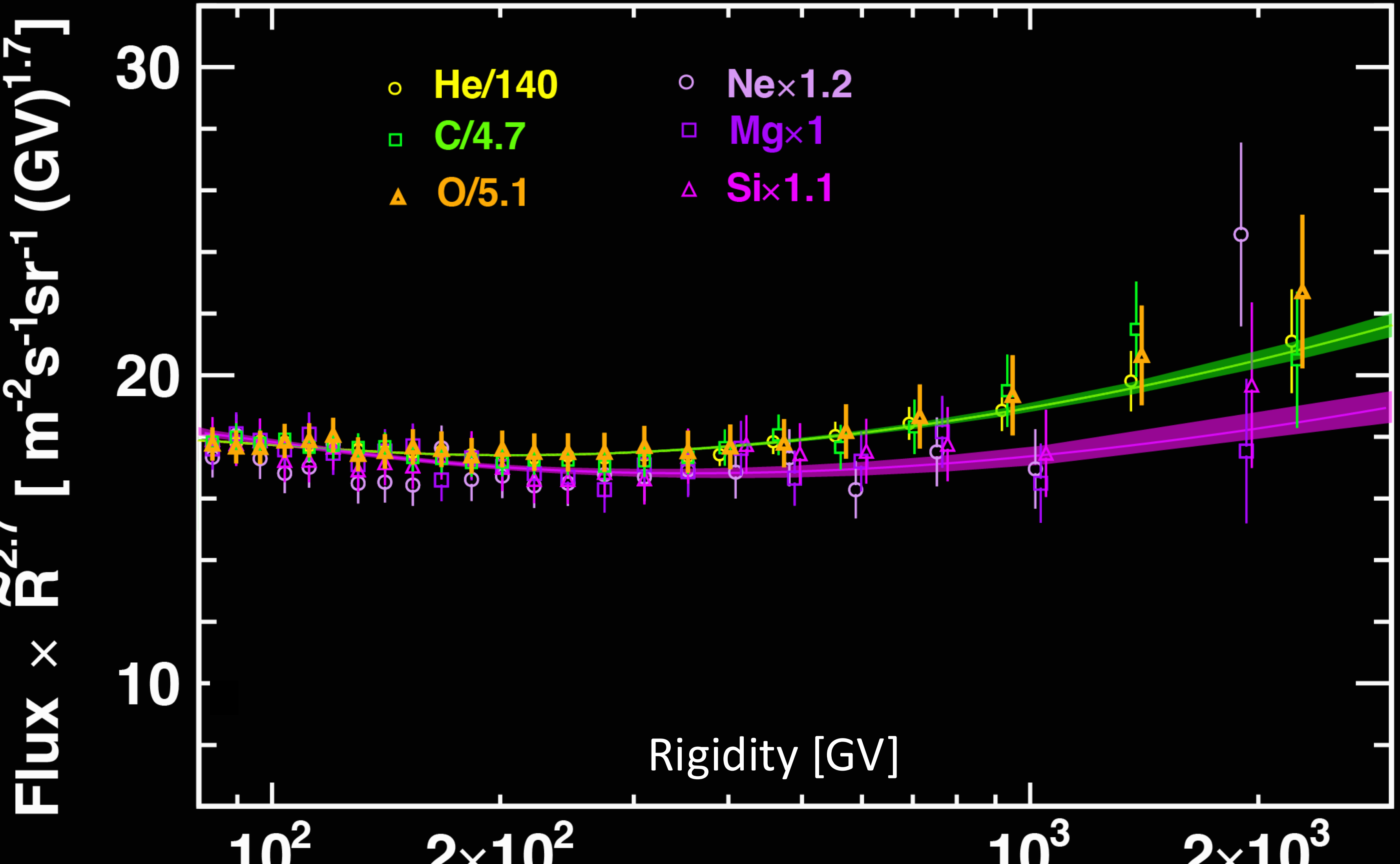
Primary cosmic rays p, He, C, O, ..., Si, ..., Fe are produced during the lifetime of stars and accelerated by supernovae. They propagate through interstellar medium before they reach AMS.

Secondary Li, Be, B, and F nuclei in cosmic rays are produced by the collision of primary cosmic rays C, O, Ne, Mg, Si, ..., Fe with the interstellar medium.

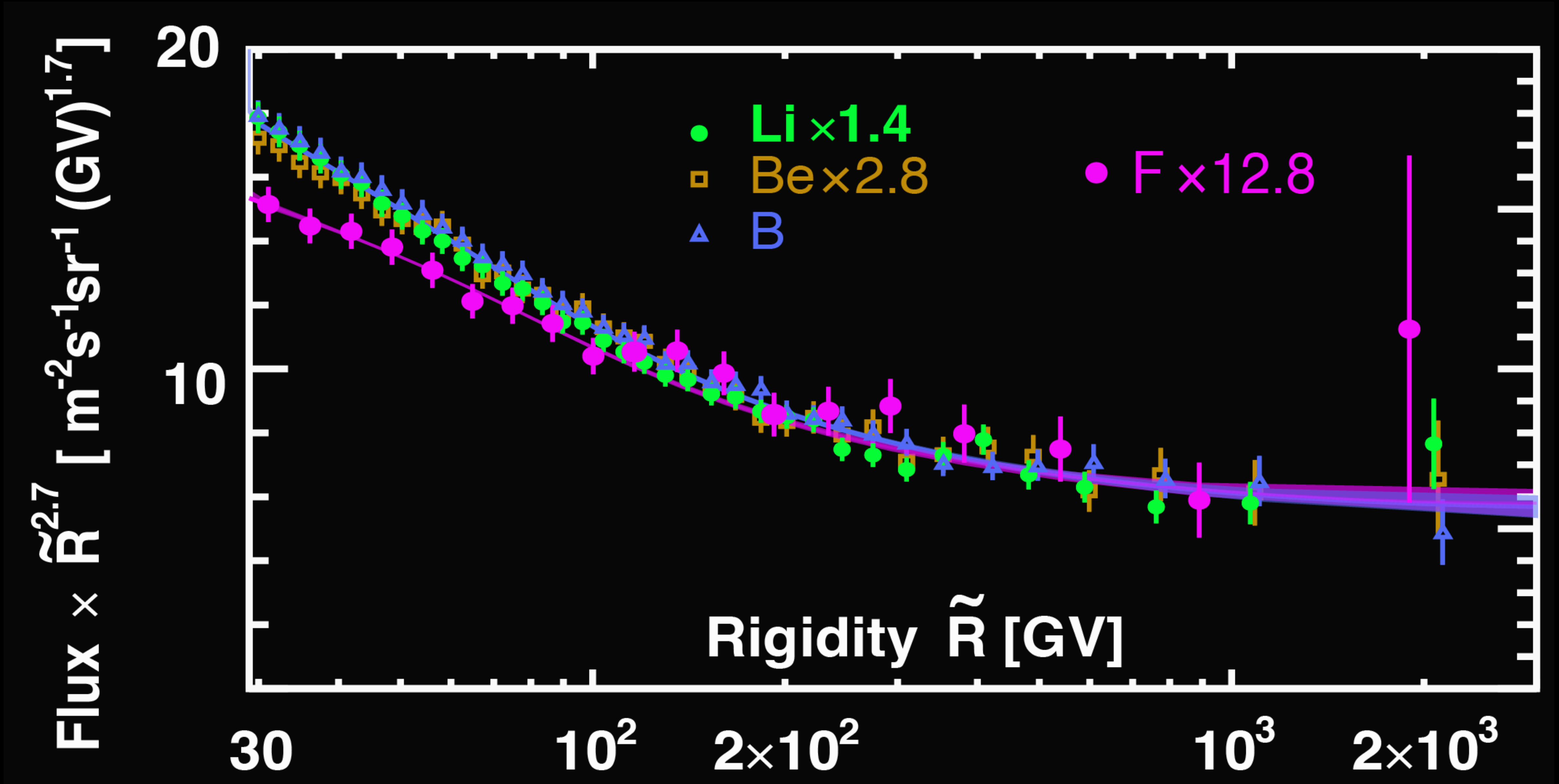
Primary cosmic rays have two classes

Light elements He-C-O and Heavier elements Ne-Mg-Si

each have their own rigidity dependence

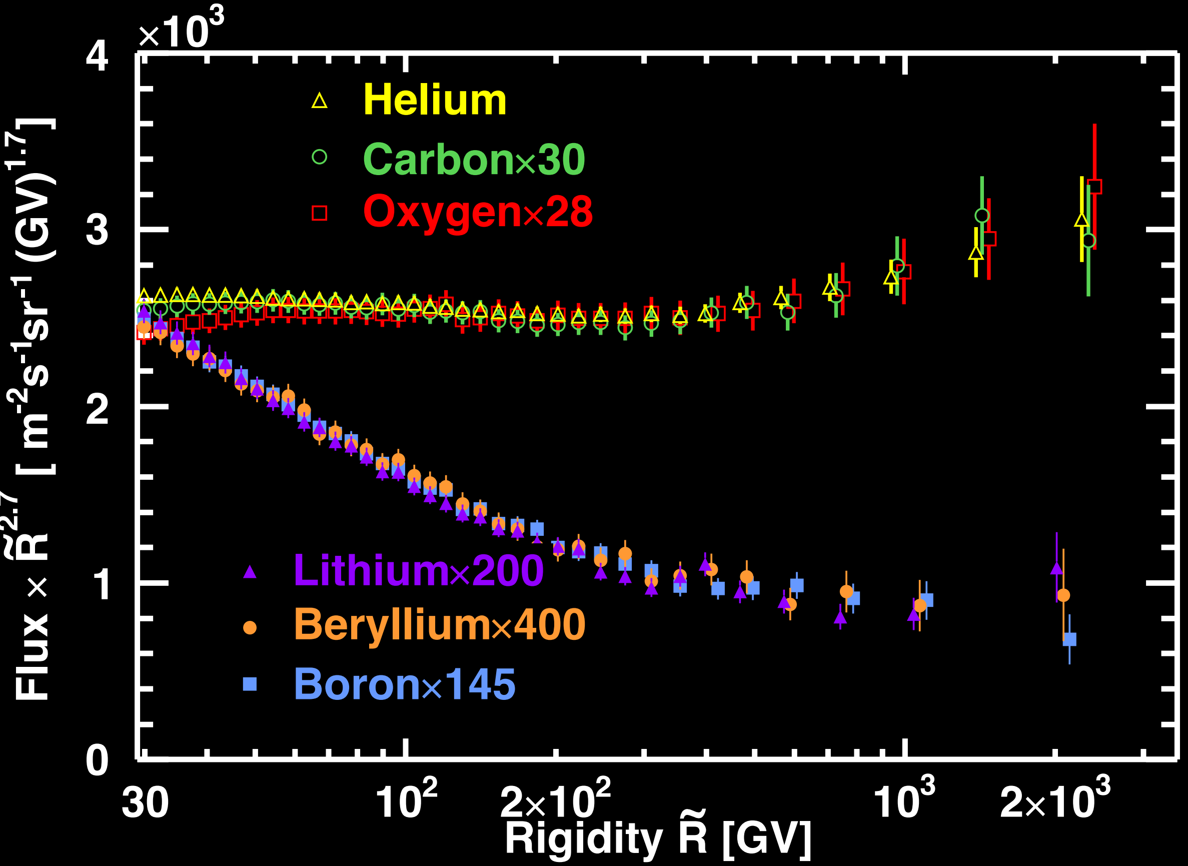


Secondary cosmic rays have two classes of rigidity dependence
Li-Be-B and F



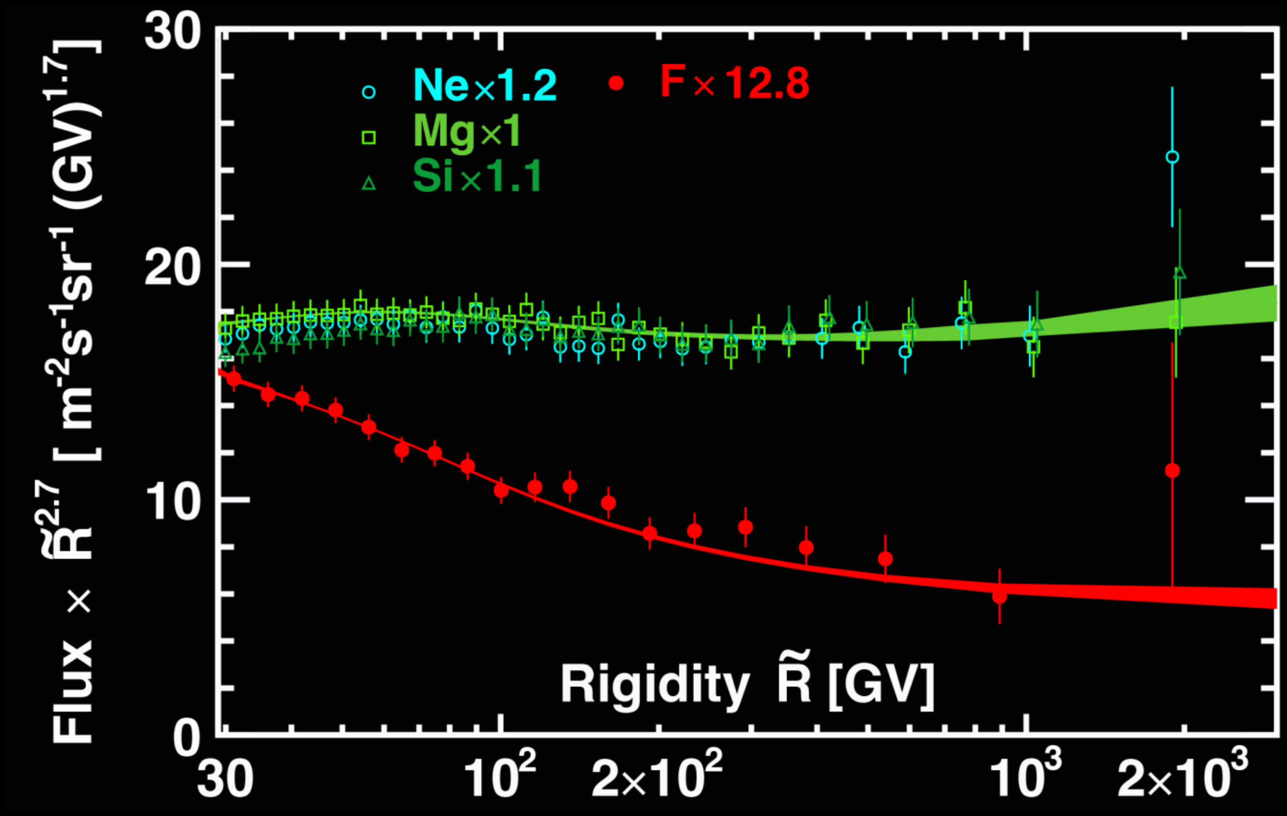
Light Nuclei 2 ≤ Z ≤ 8

He-C-O primaries compared with Li-Be-B secondaries



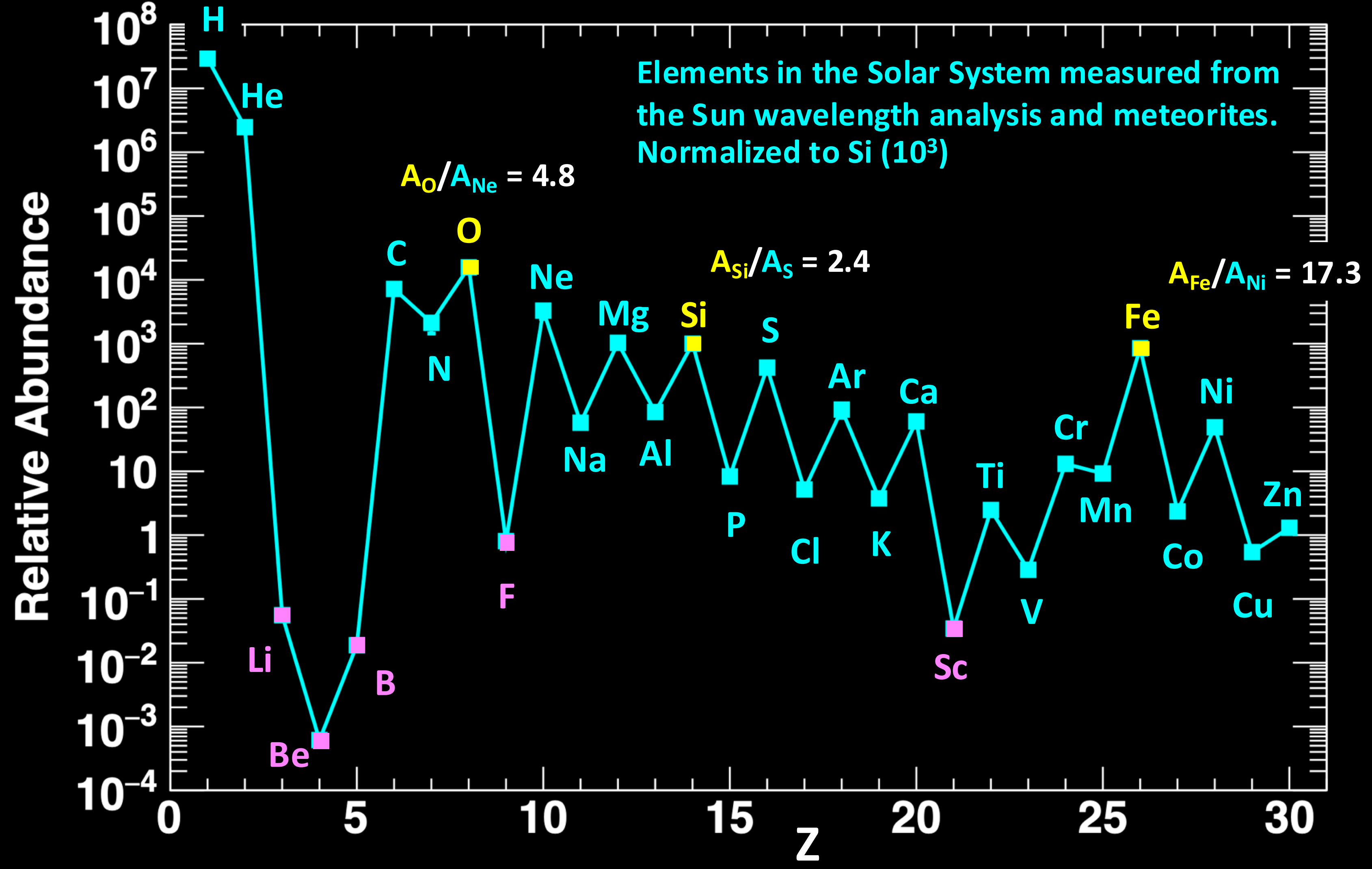
Heavier Nuclei 9 ≤ Z ≤ 14

Ne-Mg-Si primaries compared with F secondaries



Light and heavy nuclei each have two distinct classes

Abundance of elements in the Solar System



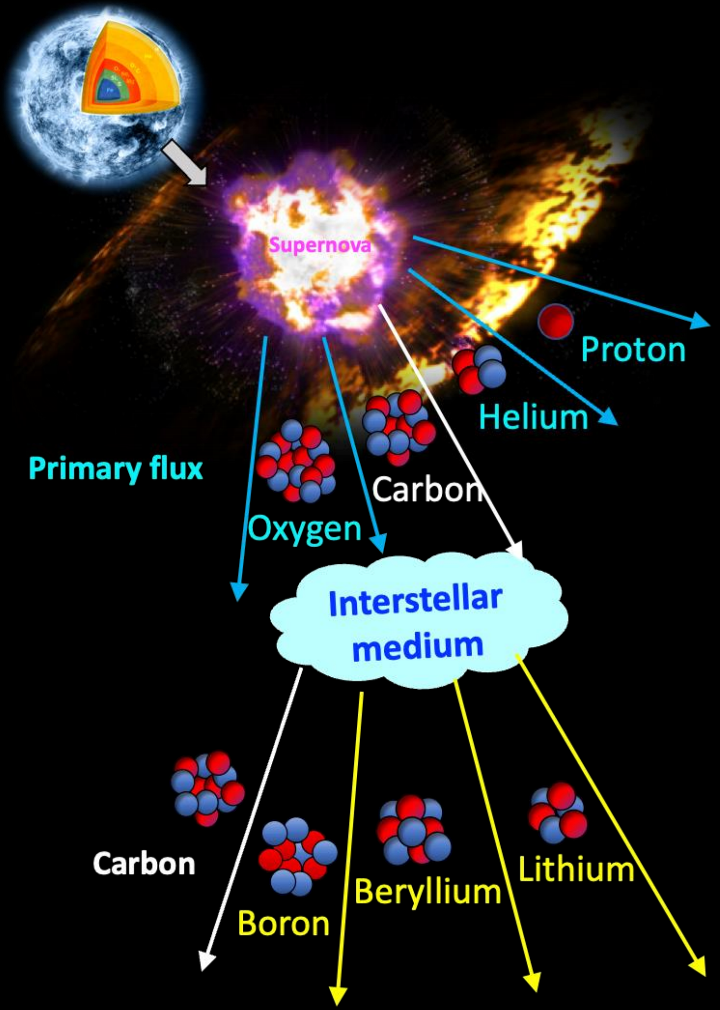
Elements in the Solar System measured from the Sun wavelength analysis and meteorites. Normalized to Si (10^3)

O, Si, and Fe are characteristic primary cosmic rays

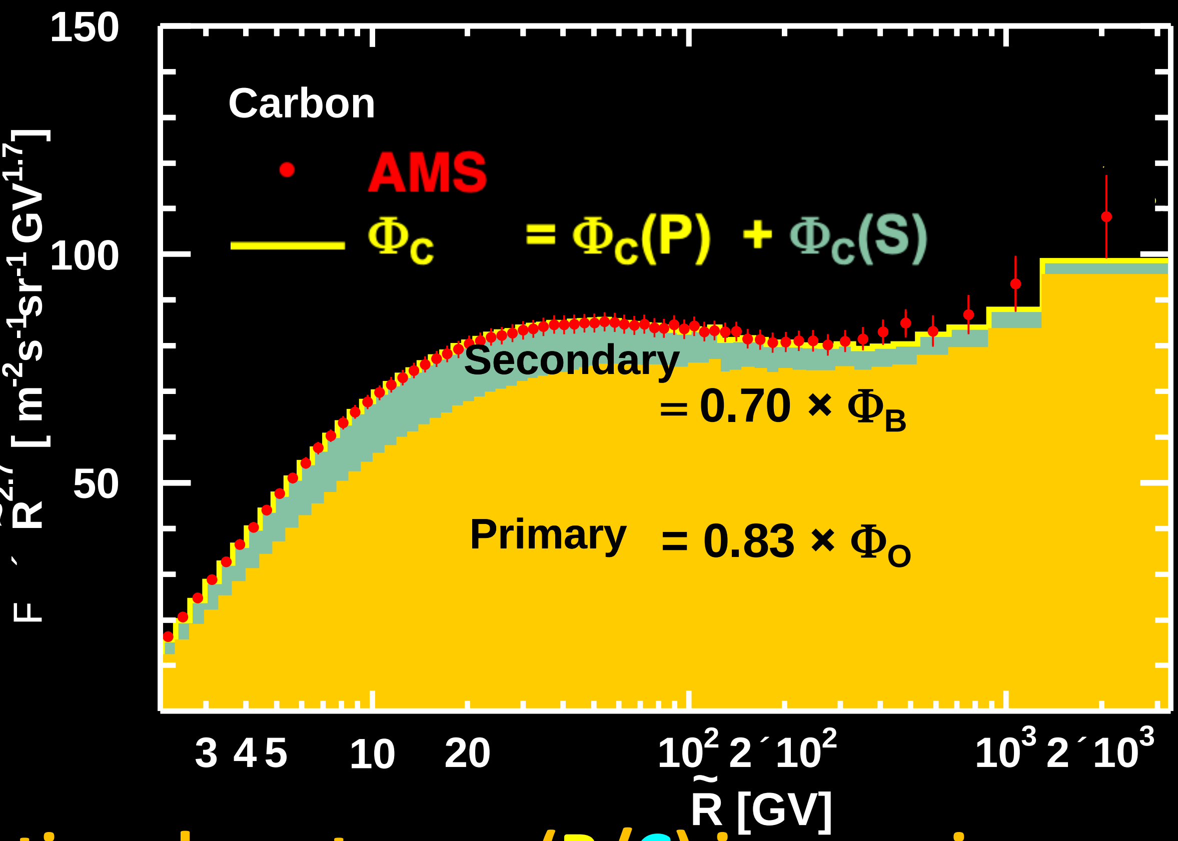
Li, Be, B, F, and Sc are characteristic secondary cosmic rays

Further Surprising Results:

Before AMS, taking into account the long-standing idea that C is pure primary and B is pure secondary, the (B/C) ratio has been used in models to describe cosmic ray propagation

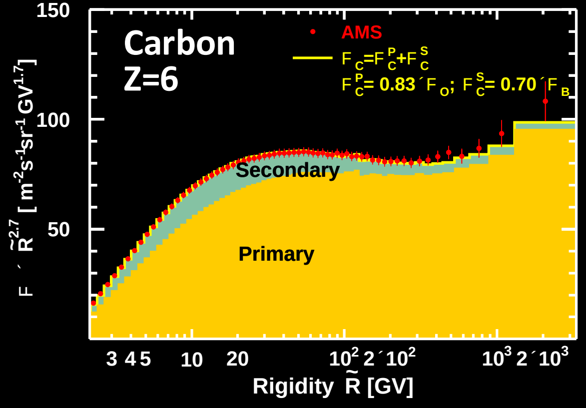


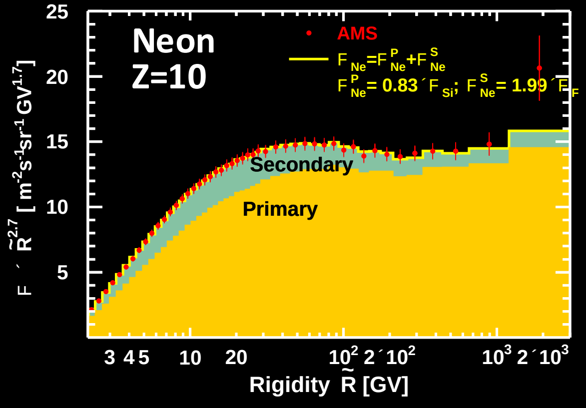
The spectrum of carbon Φ_C is the composition of a primary flux $\Phi_C(P)$ identical to $0.83 \times \Phi_O$ oxygen and a secondary flux $\Phi_C(S)$ identical to $0.70 \times \Phi_B$ boron

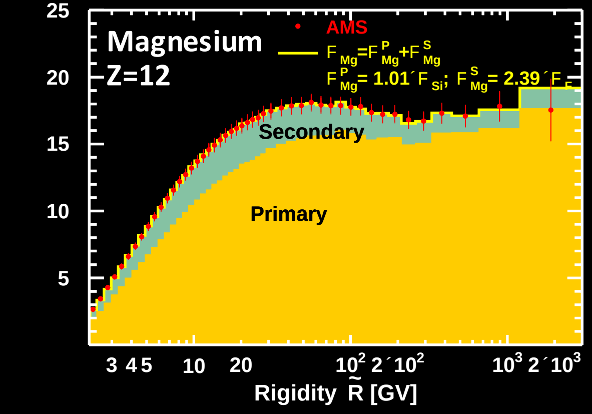


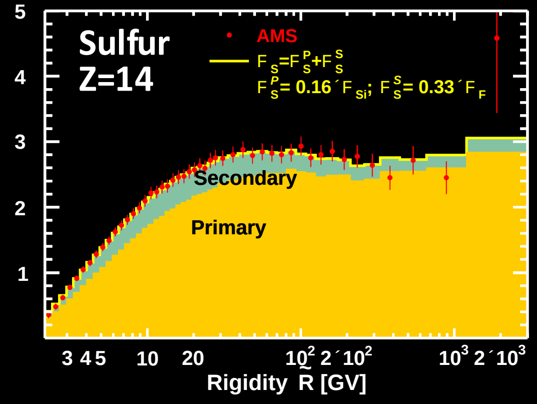
But C is NOT pure primary. Question: how to use (B/C) in cosmic ray models?

Even-Z nuclei and Odd-Z nuclei have distinctly different primary and secondary composition

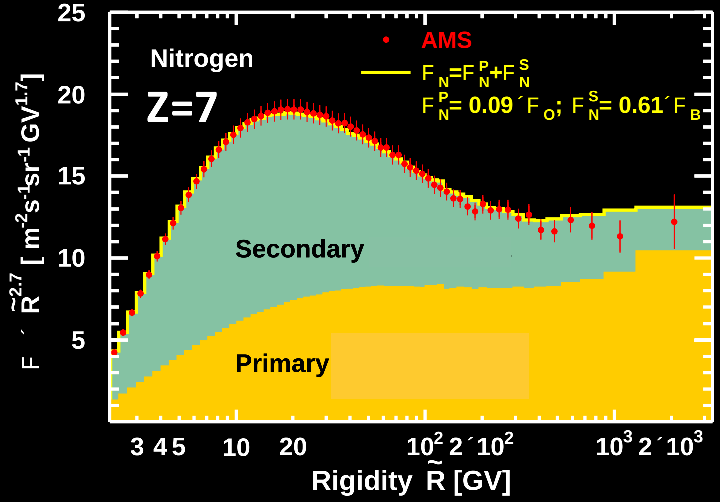


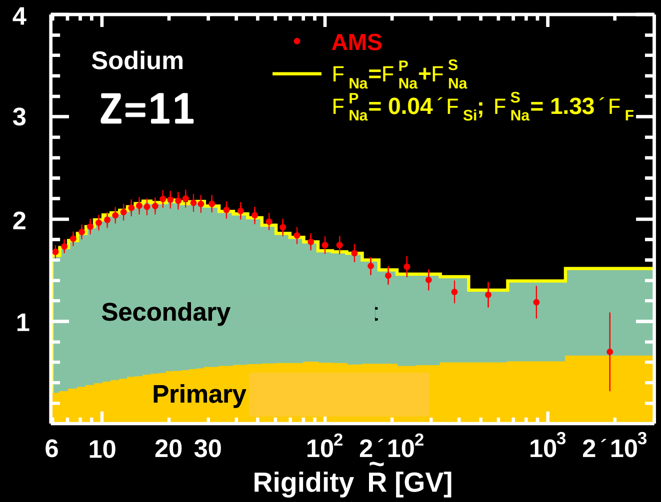


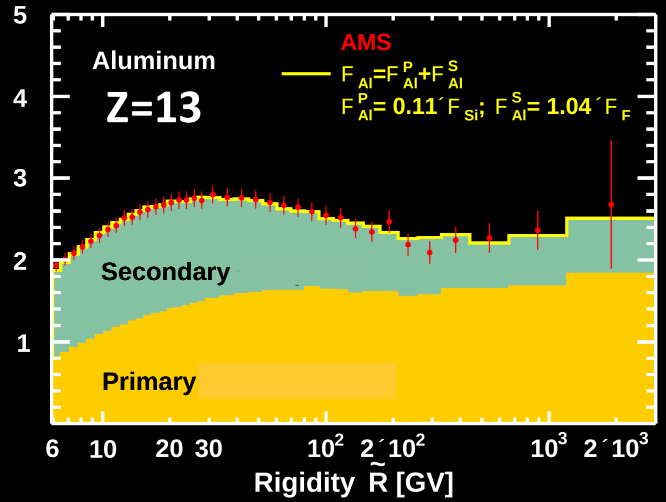




Even-Z nuclei are dominated by primaries

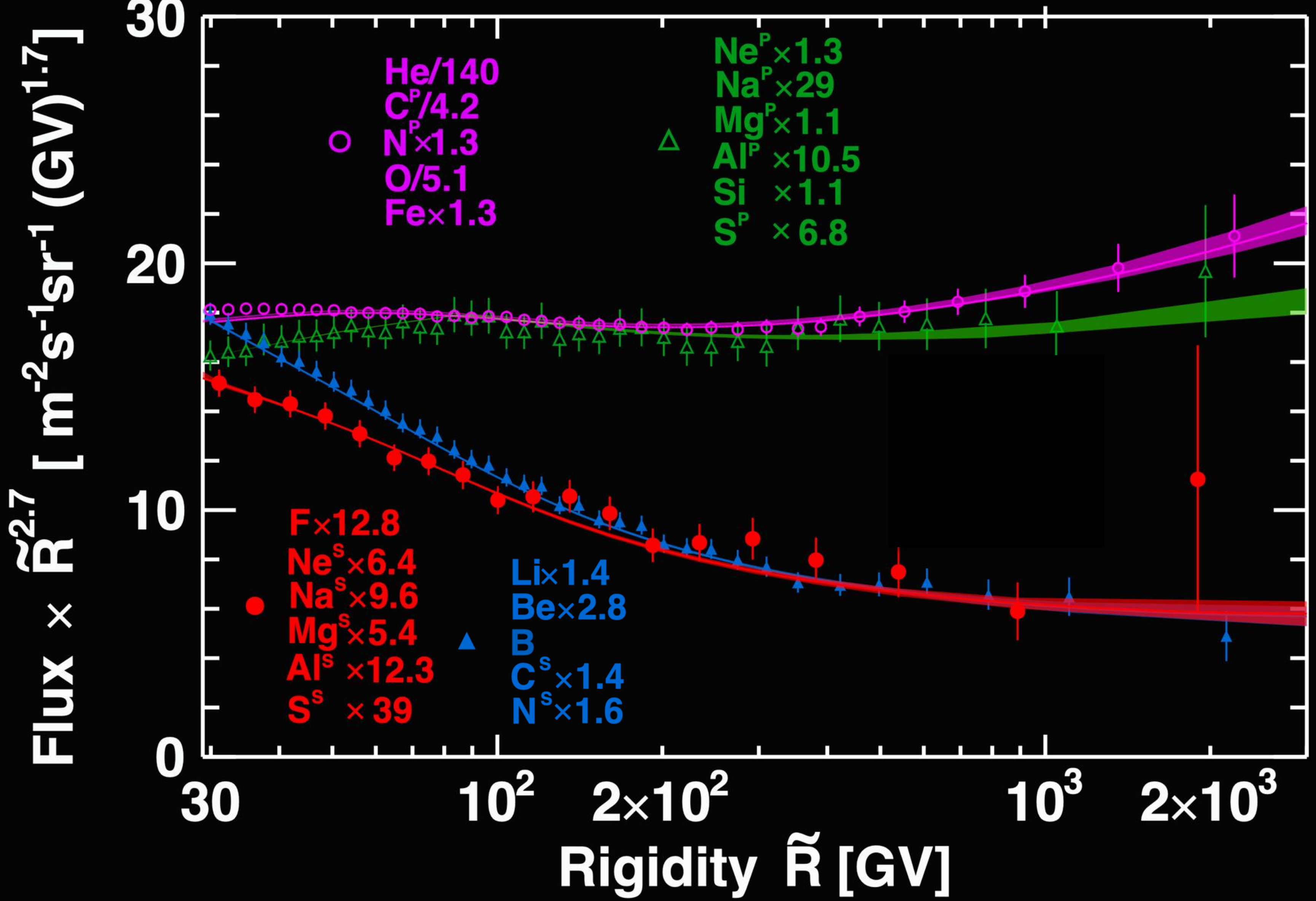






Odd-Z nuclei have more secondaries than even-Z

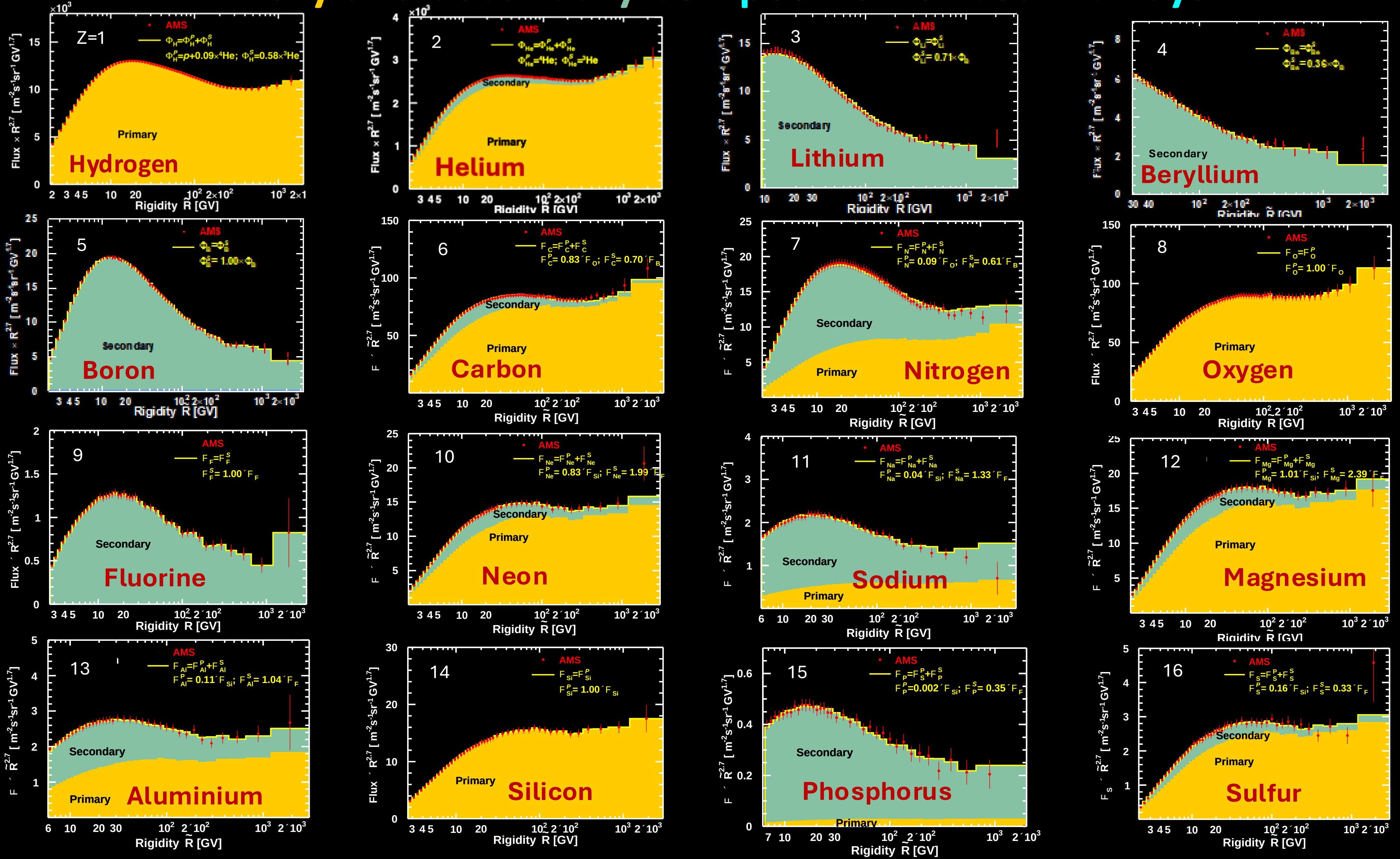
All of the measured cosmic rays can be described by **two** Primary classes and **two** Secondary classes



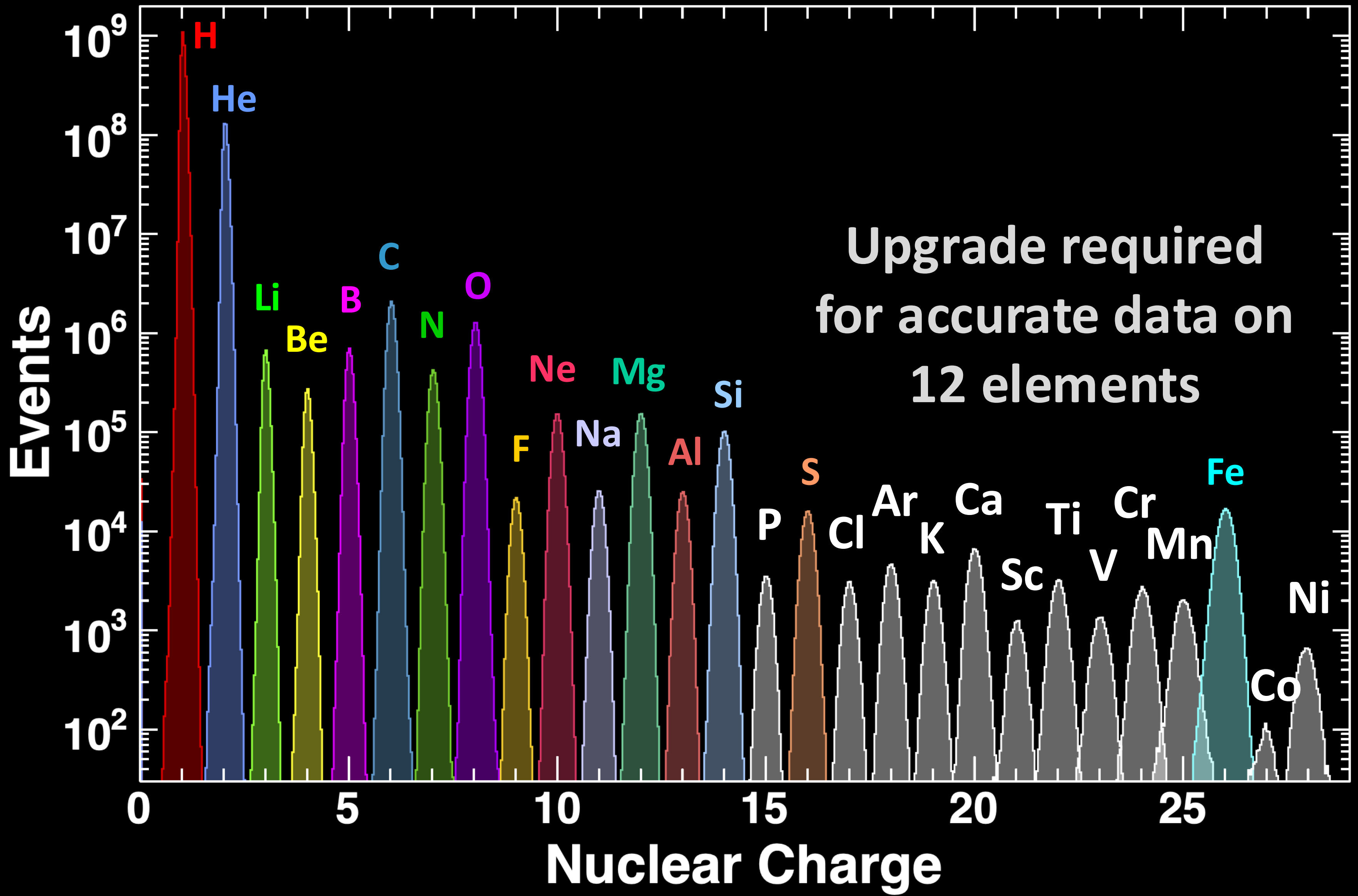
Primary

Secondary

Primary and Secondary Composition of Cosmic Rays



Current AMS Cosmic Ray Data

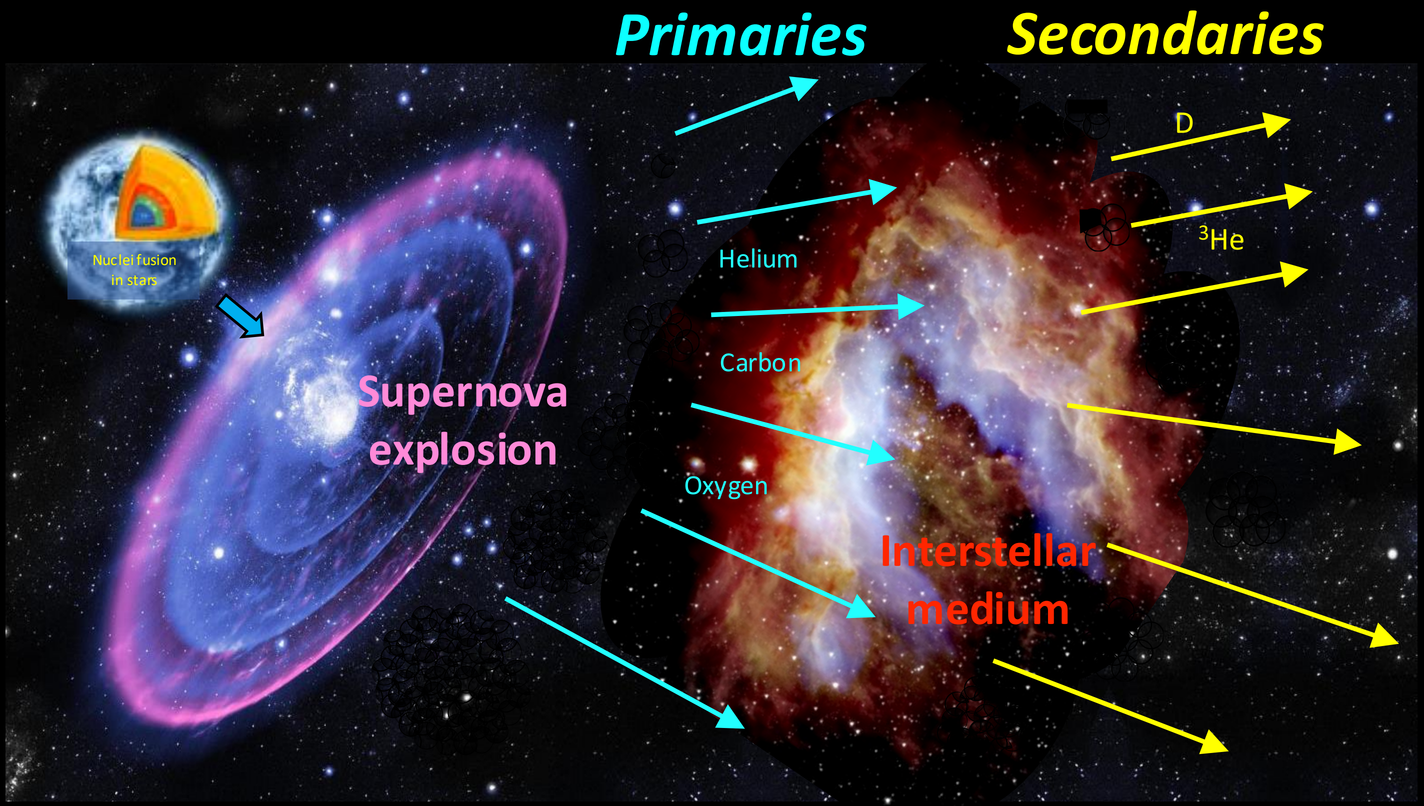


Upgrade required
for accurate data on
12 elements

By 2030 AMS will provide complete and accurate spectra for the 28 elements and will provide the foundation for a comprehensive theory of cosmic rays.

Origin of Cosmic Deuterons

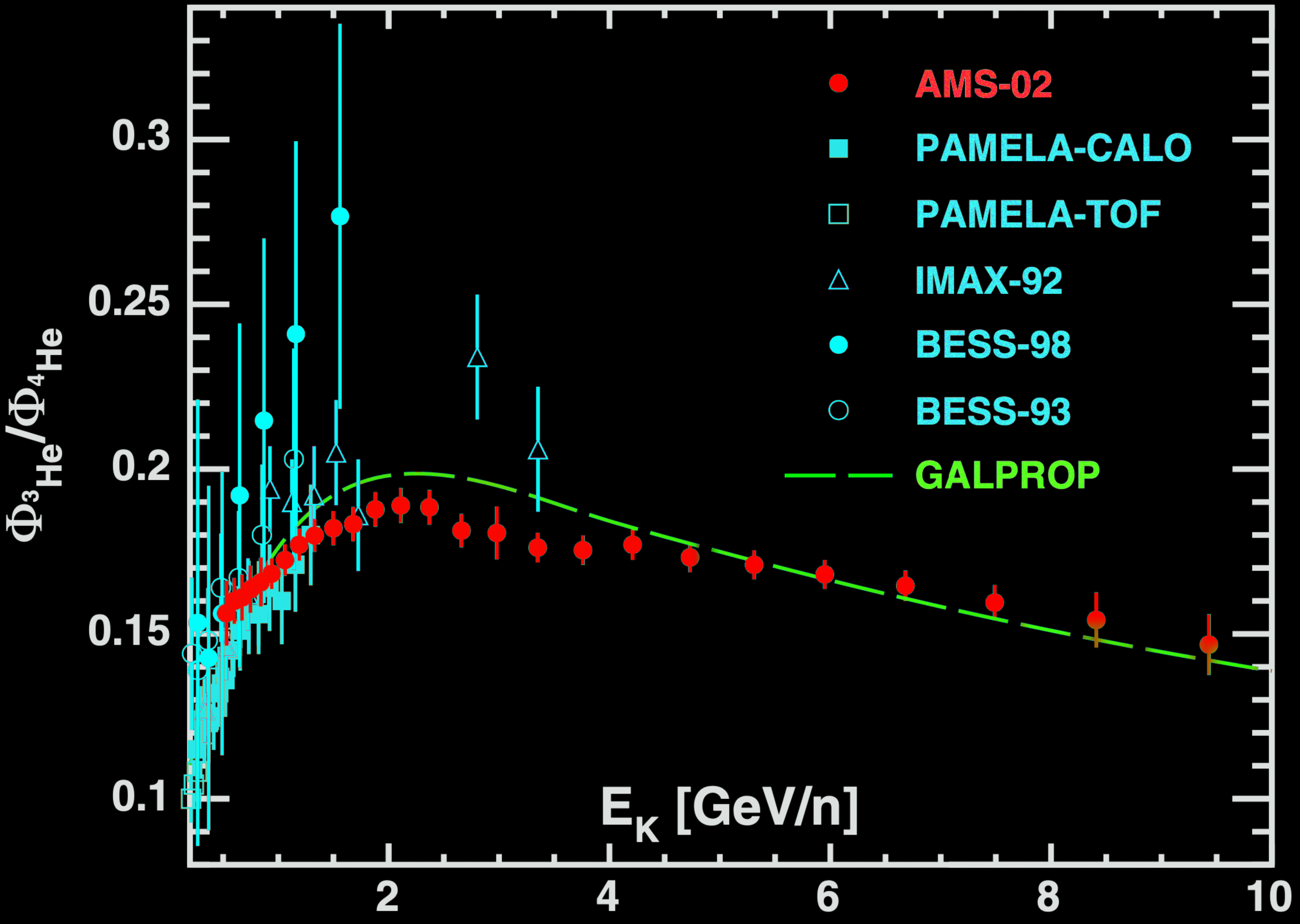
(He, C, O, …) + Interstellar Medium → (D, ^{3}He) + *X*



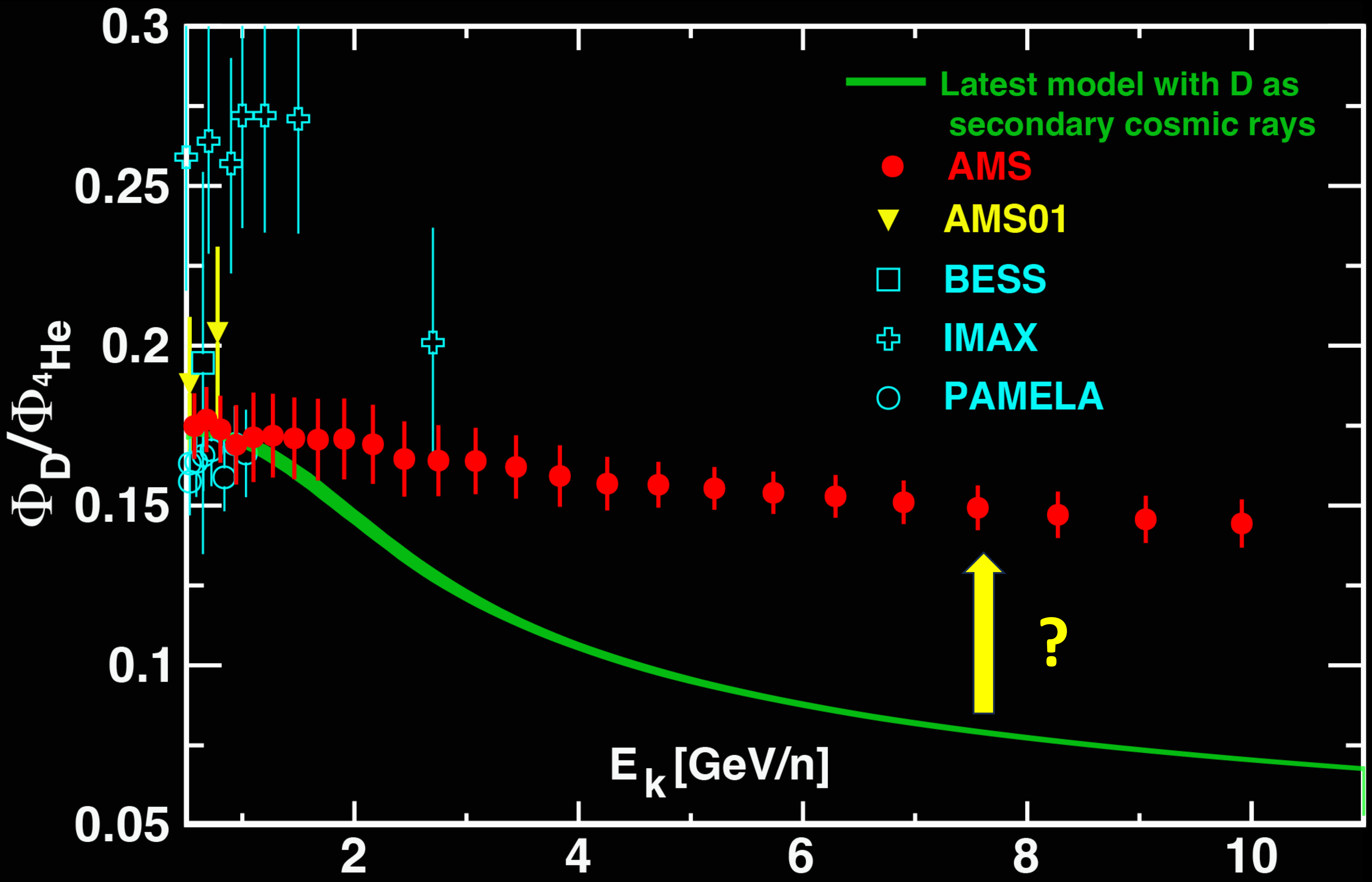
D and ^{3}He are both considered to be secondary cosmic rays

A. W. Strong, I. V. Moskalenko, and V. S. Ptuskin, Annu. Rev. Nucl. Part. Sci. **57**, 285 (2007)
E. G. Adelberger et al., Rev. Mod. Phys. **83**, 195 (2011)
N. Tomassetti, Astroph. Space Sci. **342**, 131 (2012)
B. Coste, L. Derome, D. Maurin, and A. Putze, A&A **539**, A88 (2012)
P. Blasi, Astron. Astrophys. Rev. **21**, 70 (2013)
I. A. Grenier, J. H. Black and A. W. Strong, Annu. Rev. Astron. Astrophys. **53**, 199 (2015)
G. Johannesson et al., Astroph. J. **824**, 16 (2016)

AMS Helium Isotopes: consistent with secondary ^{3}He

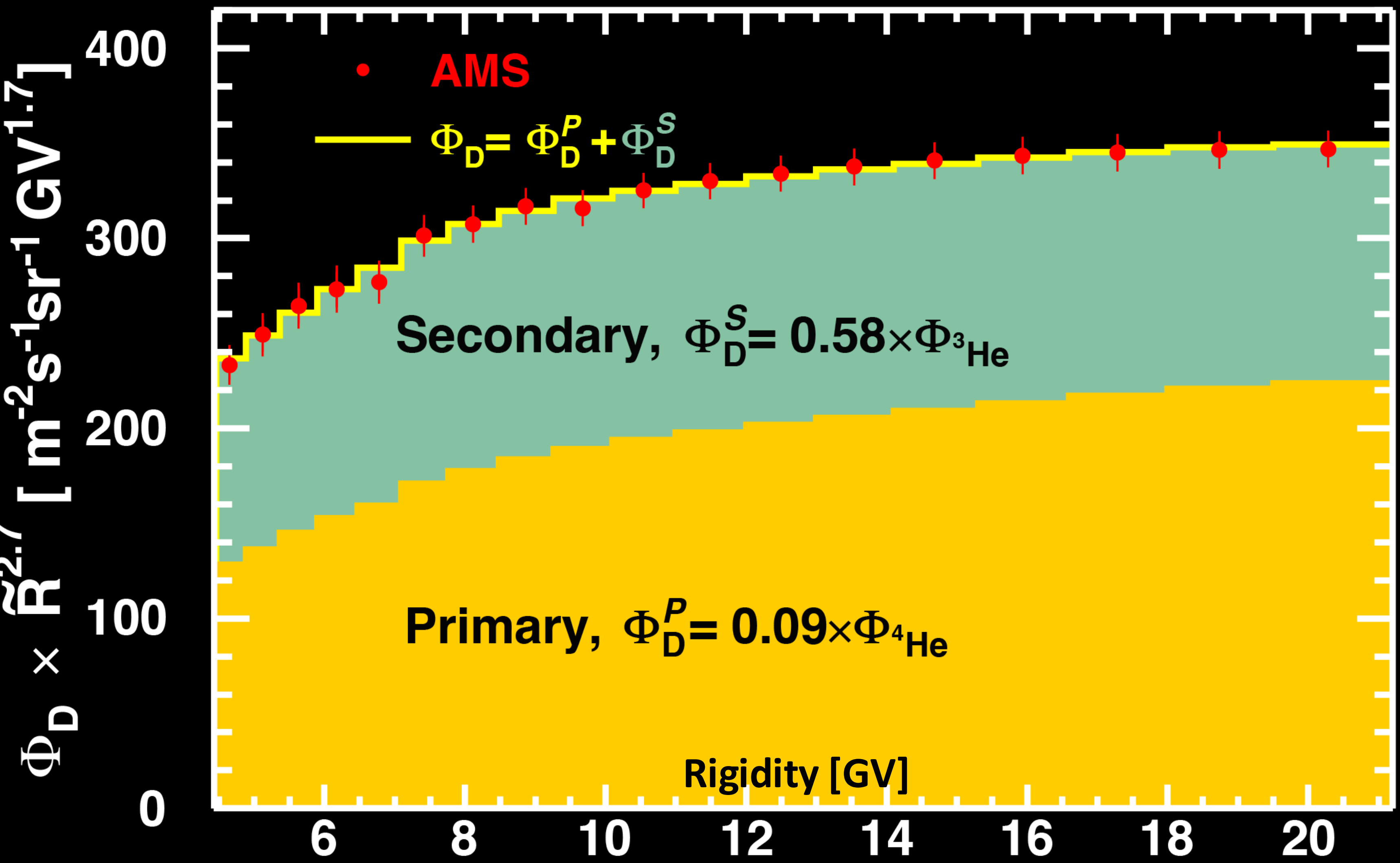


AMS result on Deuterons



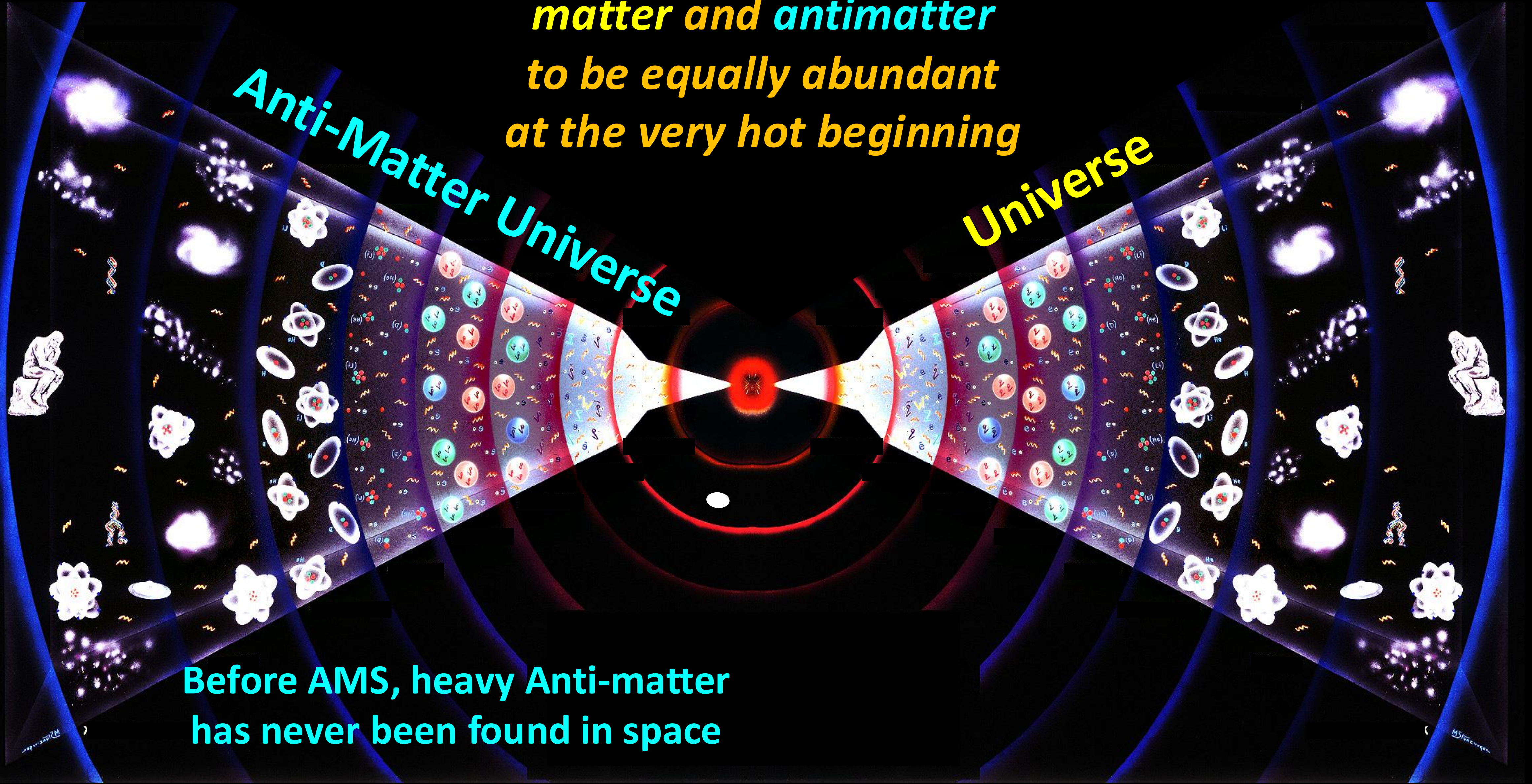
Deuterons have a significant primary component

From 5 to 20 GV, the precision deuteron flux Φ_D is a composition of a primary part Φ_D^P identical to the ^{4}He flux $\Phi_{^4He}$ and a secondary part Φ_D^S , identical to the 3He flux $\Phi_{^3He}$



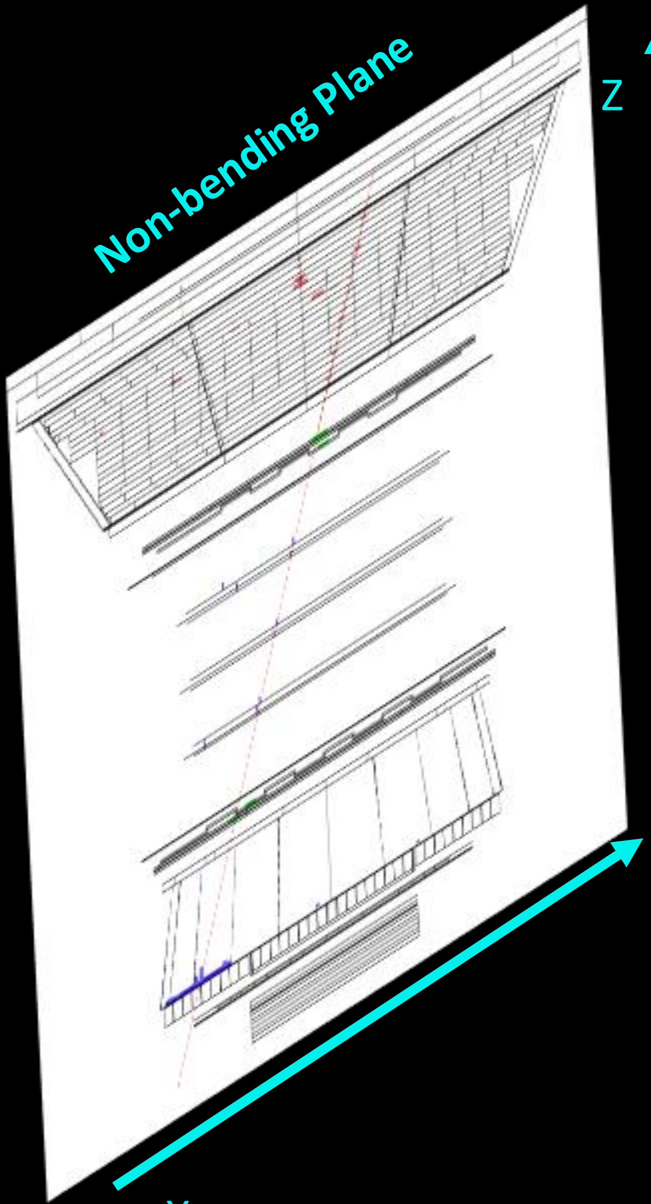
AMS Results on Antimatter

The Big Bang origin of the Universe requires
matter and antimatter
to be equally abundant
at the very hot beginning

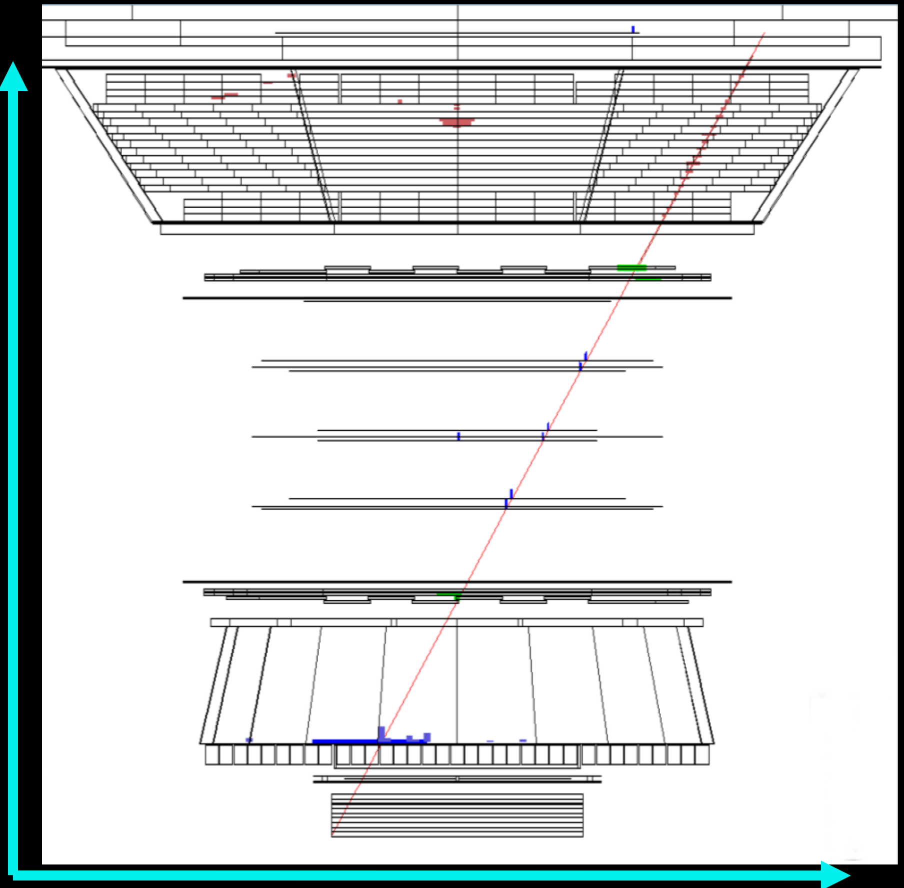


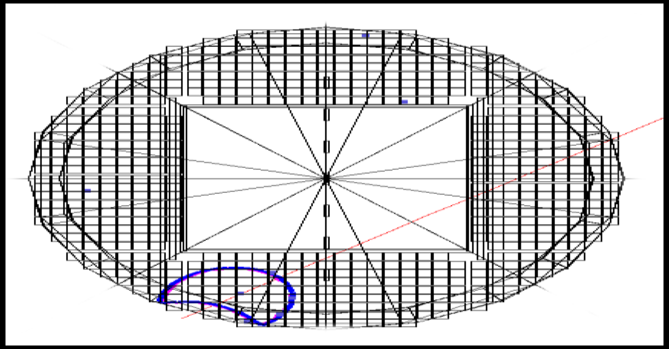
Before AMS, heavy Anti-matter has never been found in space

An Anti-Deuteron Candidate from ~100 million deuterons and ~10 billion protons



Bending Plane





Cherenkov cone in RICH

Anti-deuteron Candidate

Charge = -1.02 ± 0.05

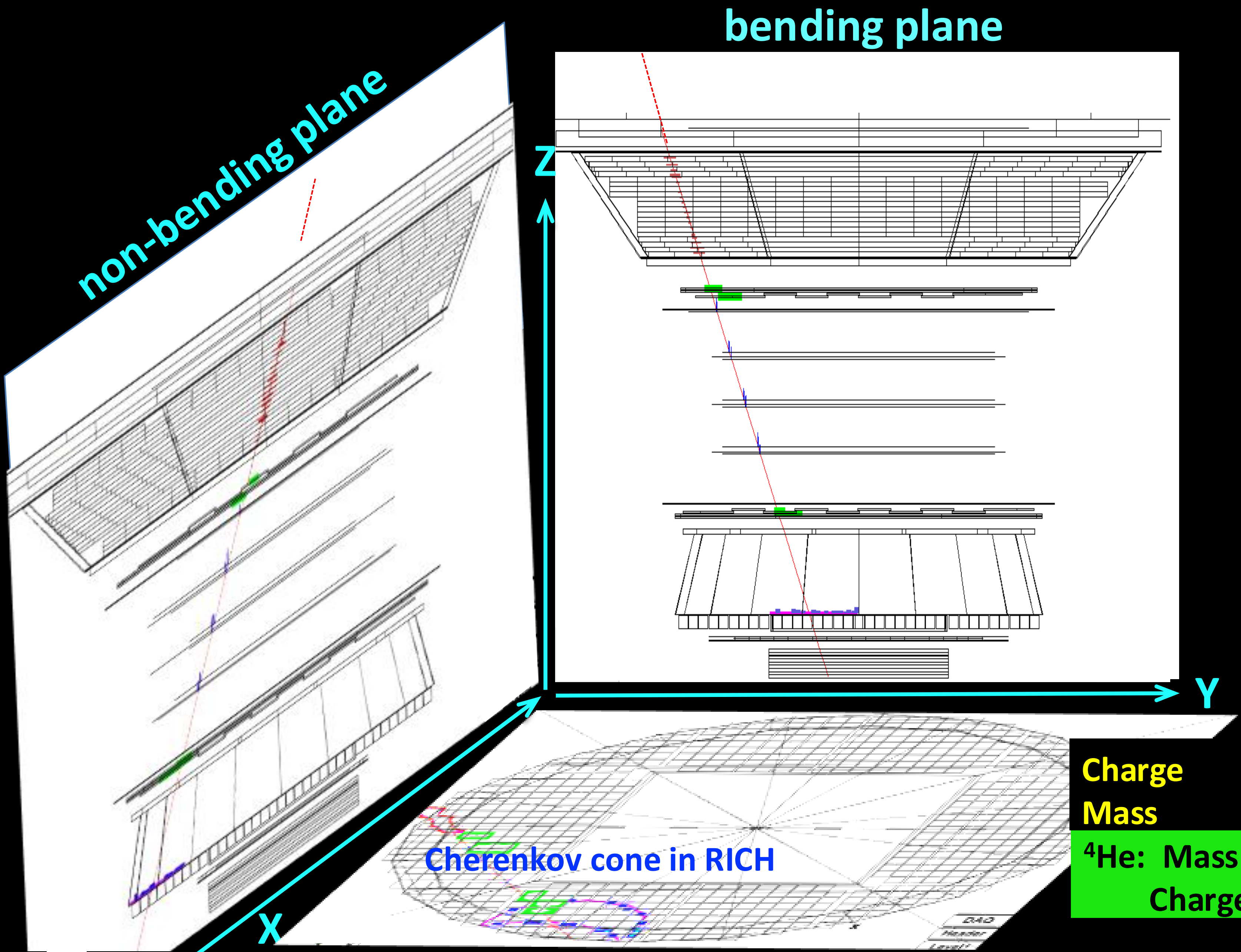
Mass = 1.9 ± 0.1 *GeV/c^2*

Deuteron

Charge = +1

Mass = 1.88 *GeV/c^2*

Anti-^{4}Helium Candidate



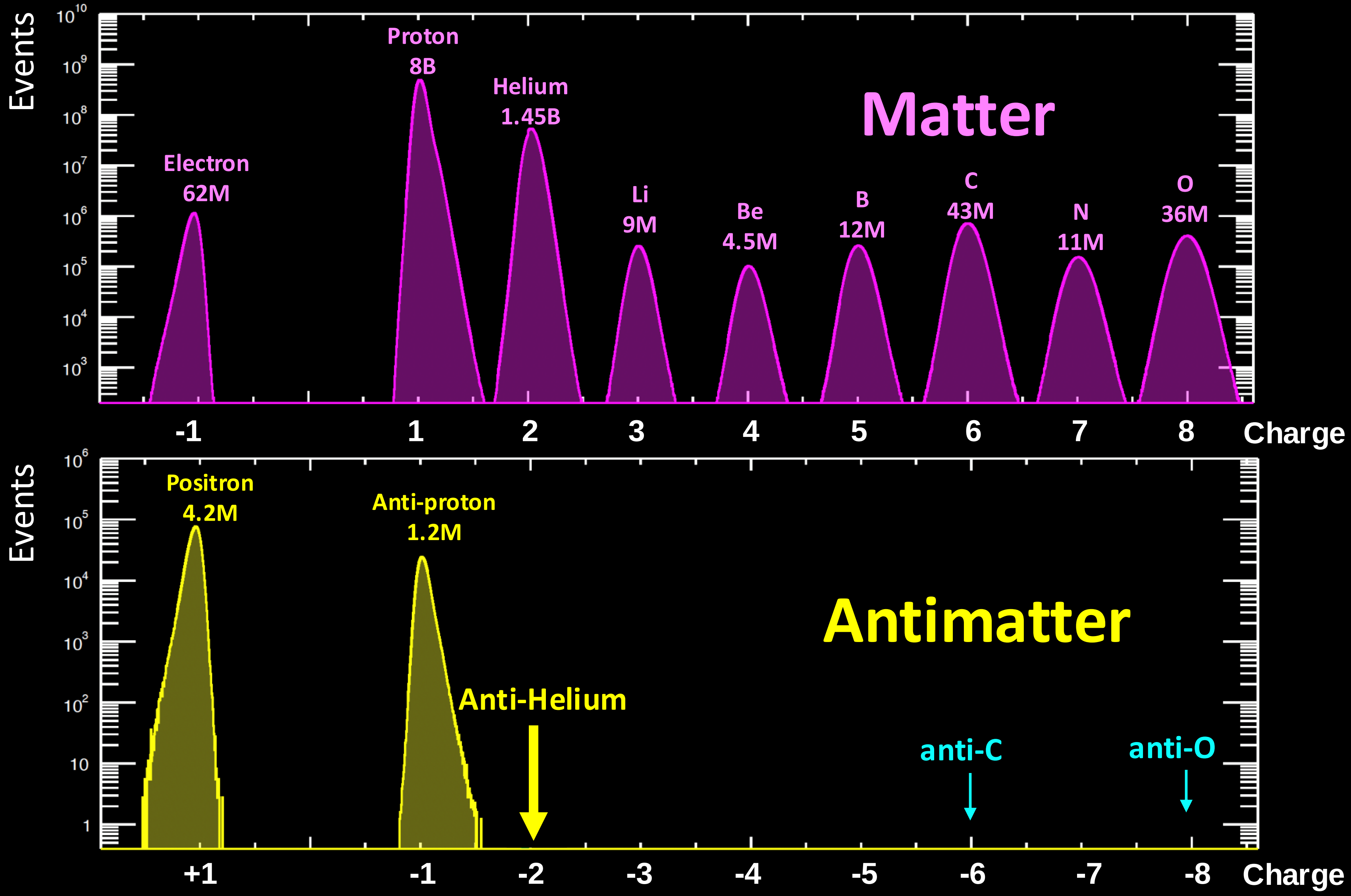
Charge = -2.05 ± 0.05

Mass = 3.81 ± 0.29 GeV/c^2

^{4}He: Mass = 3.73 GeV/c^2

Charge = +2

AMS Matter and Antimatter Results



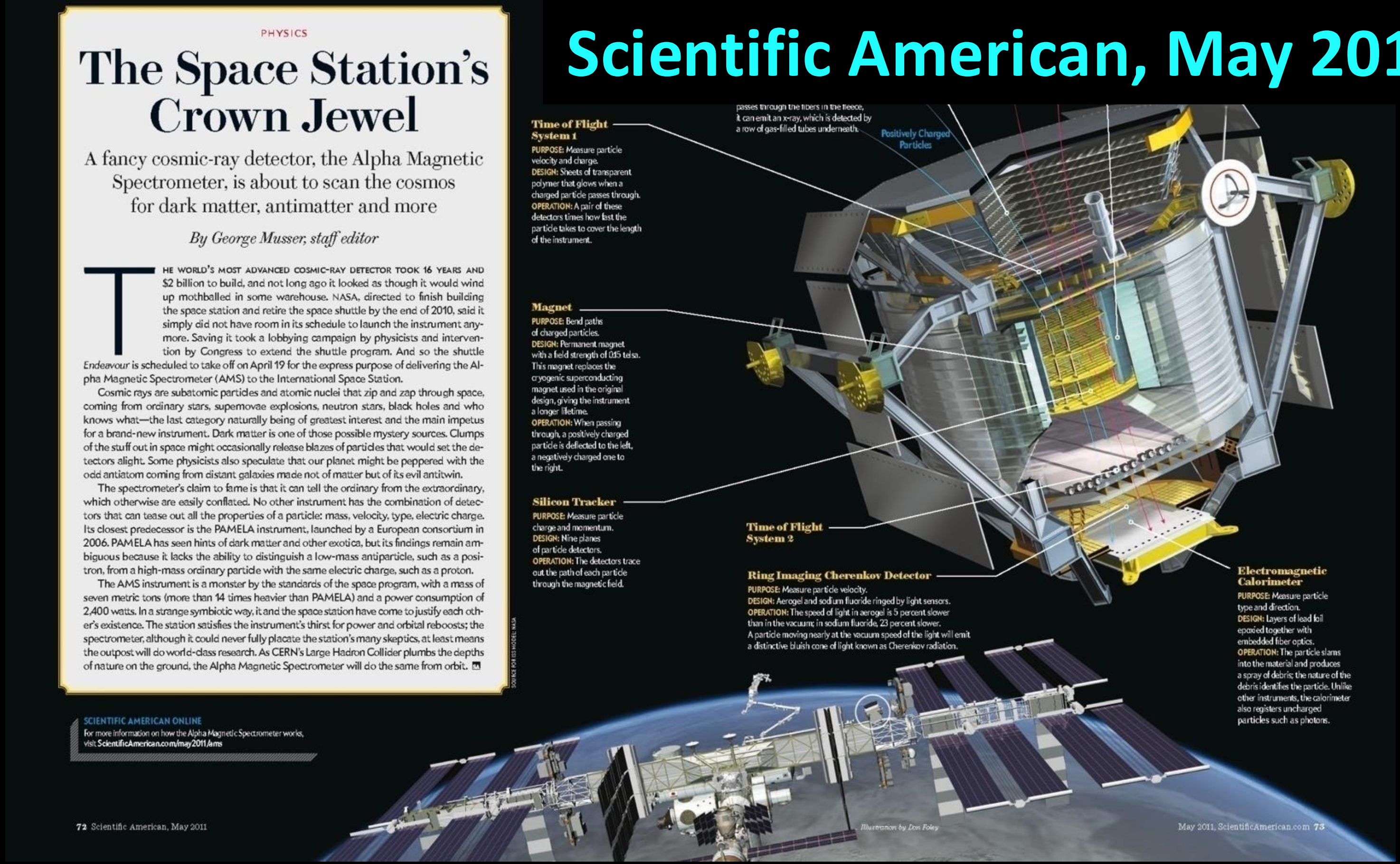
By 2030, AMS will have additional measurement points in the study of antimatter: anti-deuterons, anti-helium, anti-carbon, and anti-oxygen.

AMS Publications in *Physical Review Letters*

7544 citations as of Oct. 3, 2024

1)	Phys. Rev. Lett. 110, 141102 (2013)	Editors’ Suggestion.	Viewpoint in *Physics*. Ten-Year Editors’ Suggestion retrospective	Highlight of 2013.
2)	Phys. Rev. Lett. 113, 121101 (2014)	Editors’ Suggestion		
3)	Phys. Rev. Lett. 113, 121102 (2014)	Editors’ Suggestion.	Featured in *Physics.*	
4)	Phys. Rev. Lett. 113, 221102 (2014)			
5)	Phys. Rev. Lett. 114, 171103 (2015)	Editors’ Suggestion		
6)	Phys. Rev. Lett. 115, 211101 (2015)	Editors’ Suggestion		
7)	Phys. Rev. Lett. 117, 091103 (2016)			
8)	Phys. Rev. Lett. 117, 231102 (2016)	Editors’ Suggestion		
9)	Phys. Rev. Lett. 119, 251101 (2017)			
10)	Phys. Rev. Lett. 120, 021101 (2018)	Editors’ Suggestion.	Featured in *Physics*.	
11)	Phys. Rev. Lett. 121, 051101 (2018)			
12)	Phys. Rev. Lett. 121, 051102 (2018)	Editors’ Suggestion		
13)	Phys. Rev. Lett. 121, 051103 (2018)			
14)	Phys. Rev. Lett. 122, 041102 (2019)	Editor’s Suggestion		
15)	Phys. Rev. Lett, 122, 101101 (2019)			
16)	Phys. Rev. Lett. 123, 181102 (2019)	Editors’ Suggestion		
17)	Phys. Rev. Lett. 124, 211102 (2020)	Editors’ Suggestion.	Featured in *Physics*.	
18)	Physics Reports 894, 1 (2021)			
19)	Phys. Rev. Lett. 126, 041104 (2021)		Featured in *Physics*.	
20)	Phys. Rev. Lett. 126, 081102 (2021)	Editors’ Suggestion		
21)	Phys. Rev. Lett. 127, 021101 (2021)			
22)	Phys. Rev. Lett. 127, 271102 (2021)			
23)	Phys. Rev. Lett. 128, 231102 (2022)			
24)	Phys. Rev. Lett. 130, 161001 (2023)	Editors’ Suggestion.	Viewpoint in *Physics*.	APS Press Announcement
25)	Phys. Rev. Lett. 130, 211002 (2023)		Featured on *Phys.org*	
26)	Phys. Rev. Lett. 131, 151002 (2023)			
27)	Phys. Rev. Lett. 132, 261001 (2024)	Editors’ Suggestion.	Featured in *Physics*.	
28)	“Cosmic Antiprotons”, *submitted to* Phys. Rev. Lett.			
29)	“Temporal Variation of Cosmic Nuclei”, *to be submitted to* Phys. Rev. Lett.			

Scientific American, May 2011



PHYSICS

The Space Station's Crown Jewel

A fancy cosmic-ray detector, the Alpha Magnetic Spectrometer, is about to scan the cosmos for dark matter, antimatter and more

By George Musser, staff editor

THE WORLD'S MOST ADVANCED COSMIC-RAY DETECTOR TOOK 16 YEARS AND $2 billion to build, and not long ago it looked as though it would wind up mothballed in some warehouse. NASA, directed to finish building the space station and retire the space shuttle by the end of 2010, said it simply did not have room in its schedule to launch the instrument anymore. Saving it took a lobbying campaign by physicists and intervention by Congress to extend the shuttle program. And so the shuttle *Endeavour* is scheduled to take off on April 19 for the express purpose of delivering the Alpha Magnetic Spectrometer (AMS) to the International Space Station.

Cosmic rays are subatomic particles and atomic nuclei that zip and zap through space, coming from ordinary stars, supernovae explosions, neutron stars, black holes and who knows what—the last category naturally being of greatest interest and the main impetus for a brand-new instrument. Dark matter is one of those possible mystery sources. Clumps of the stuff out in space might occasionally release blazes of particles that would set the detectors alight. Some physicists also speculate that our planet might be peppered with the odd antiatom coming from distant galaxies made not of matter but of its evil antitwin.

The spectrometer's claim to fame is that it can tell the ordinary from the extraordinary, which otherwise are easily conflated. No other instrument has the combination of detectors that can tease out all the properties of a particle: mass, velocity, type, electric charge. Its closest predecessor is the PAMELA instrument, launched by a European consortium in 2006. PAMELA has seen hints of dark matter and other exotica, but its findings remain ambiguous because it lacks the ability to distinguish a low-mass antiparticle, such as a positron, from a high-mass ordinary particle with the same electric charge, such as a proton.

The AMS instrument is a monster by the standards of the space program, with a mass of seven metric tons (more than 14 times heavier than PAMELA) and a power consumption of 2,400 watts. In a strange symbiotic way, it and the space station have come to justify each other's existence. The station satisfies the instrument's thirst for power and orbital reboosts; the spectrometer, although it could never fully placate the station's many skeptics, at least means the outpost will do world-class research. As CERN's Large Hadron Collider plumbs the depths of nature on the ground, the Alpha Magnetic Spectrometer will do the same from orbit.

SOURCE FOR ISS MODEL: NASA

SCIENTIFIC AMERICAN ONLINE
For more information on how the Alpha Magnetic Spectrometer works, visit ScientificAmerican.com/may2011/ams

passes through the fibers in the fleece, it can emit an x-ray, which is detected by a row of gas-filled tubes underneath.

Time of Flight System 1
PURPOSE: Measure particle velocity and charge.
DESIGN: Sheets of transparent polymer that glows when a charged particle passes through.
OPERATION: A pair of these detectors times how fast the particle takes to cover the length of the instrument.

Magnet
PURPOSE: Bend paths of charged particles.
DESIGN: Permanent magnet with a field strength of 0.15 telsa. This magnet replaces the cryogenic superconducting magnet used in the original design, giving the instrument a longer lifetime.
OPERATION: When passing through, a positively charged particle is deflected to the left, a negatively charged one to the right.

Silicon Tracker
PURPOSE: Measure particle charge and momentum.
DESIGN: Nine planes of particle detectors.
OPERATION: The detectors trace out the path of each particle through the magnetic field.

Time of Flight System 2

Ring Imaging Cherenkov Detector
PURPOSE: Measure particle velocity.
DESIGN: Aerogel and sodium fluoride ringed by light sensors.
OPERATION: The speed of light in aerogel is 5 percent slower than in the vacuum; in sodium fluoride, 23 percent slower. A particle moving nearly at the vacuum speed of the light will emit a distinctive bluish cone of light known as Cherenkov radiation.

Electromagnetic Calorimeter
PURPOSE: Measure particle type and direction.
DESIGN: Layers of lead foil epoxied together with embedded fiber optics.
OPERATION: The particle slams into the material and produces a spray of debris; the nature of the debris identifies the particle. Unlike other instruments, the calorimeter also registers uncharged particles such as photons.

Illustration by Don Foley

72 Scientific American, May 2011

May 2011, ScientificAmerican.com 73

In the past hundred years, measurements of charged cosmic rays by balloons and satellites have typically had ~(30-50)% accuracy.

AMS is providing cosmic ray information with ~1% accuracy.
The improvement in accuracy and energy range is providing new insights.

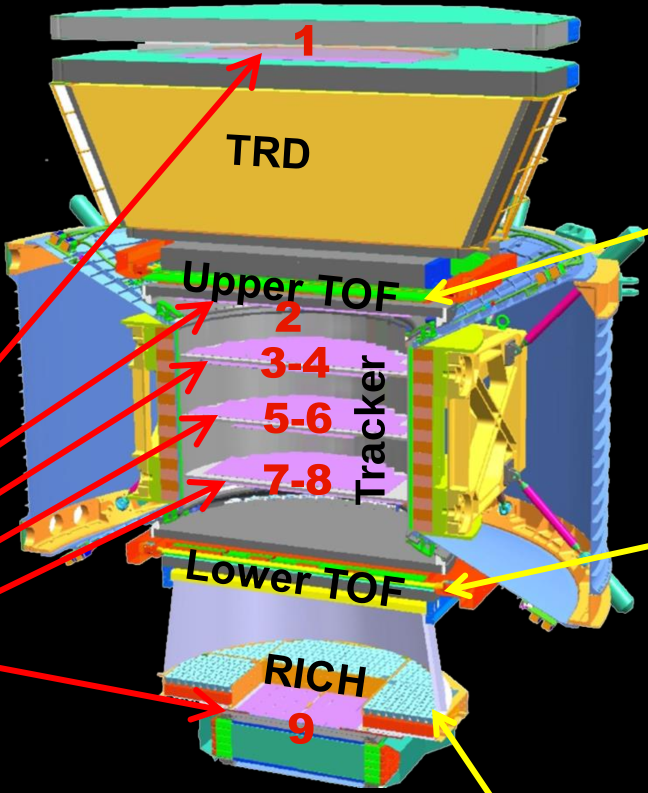
AMS results contradict current cosmic ray theories and
require the development of a new understanding of the universe.

Measurement of Isotopes: Cosmic rays with *same Z, different m*

Silicon Tracker + Magnet
Measurement of P and Z

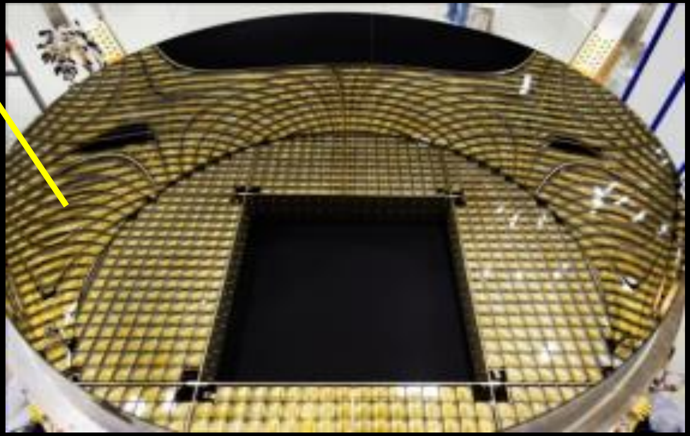
P = mv

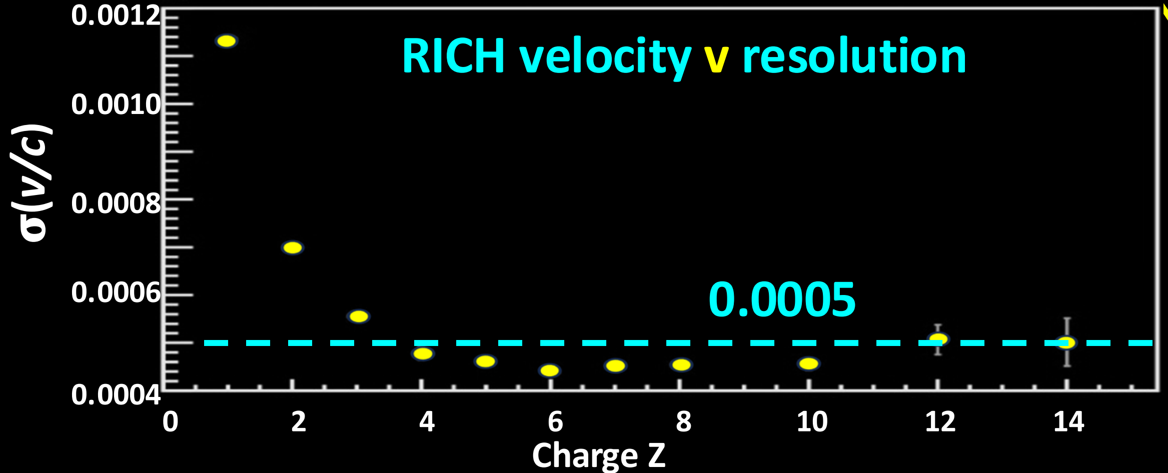
Measurement of P and v
determine the mass m



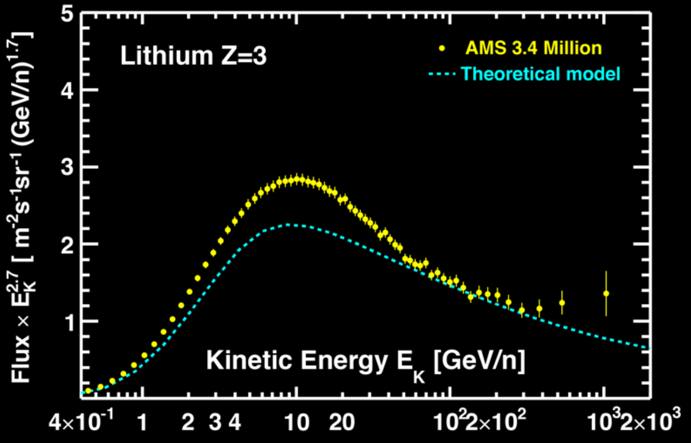
Time-of-Flight
Measurement of
v and Z

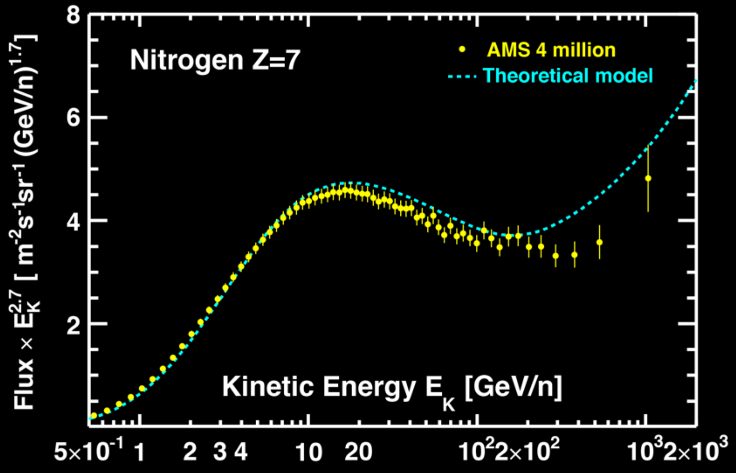
Ring Imaging Cerenkov (RICH)
measurement of v and Z

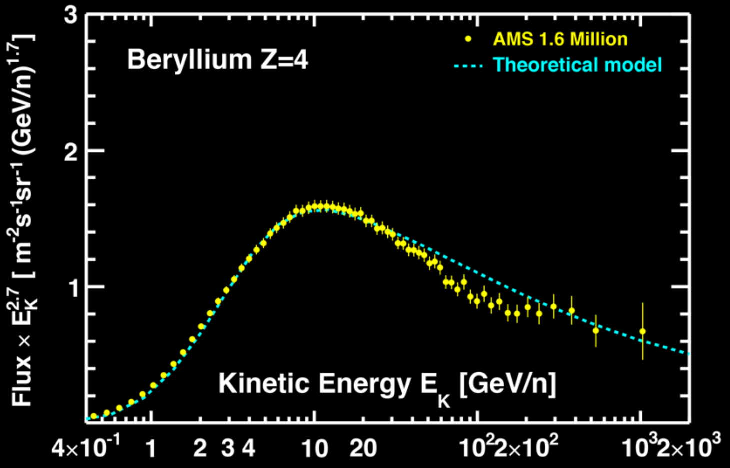


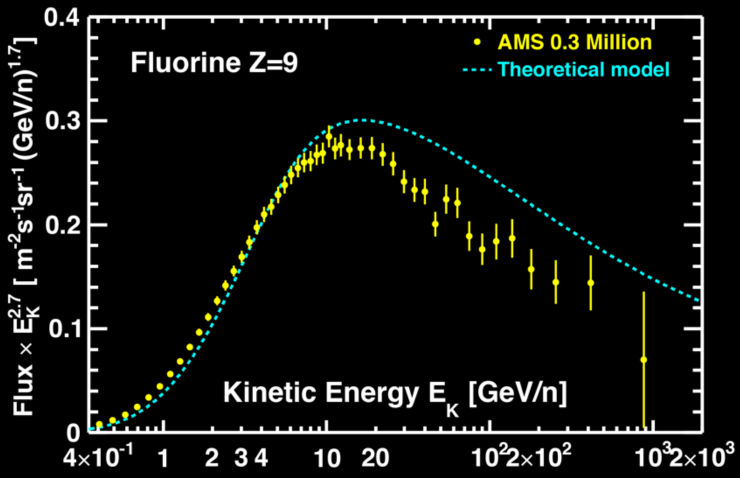


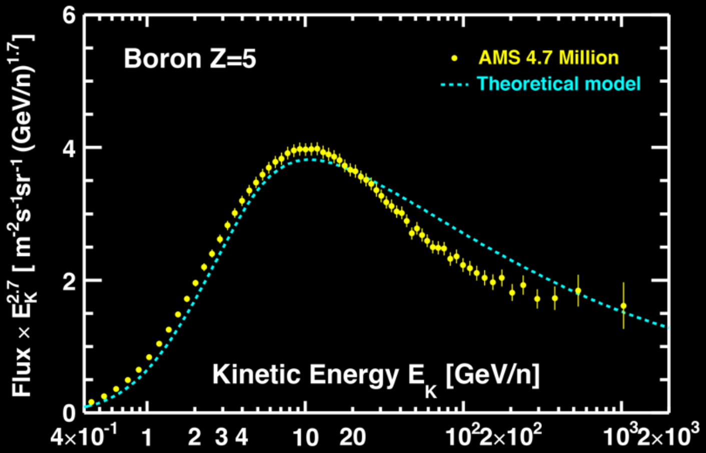
AMS results
(~1% accuracy
to multi-TeV)
contradict current
cosmic ray
theories
and require the
development of a
new
understanding
of the universe.

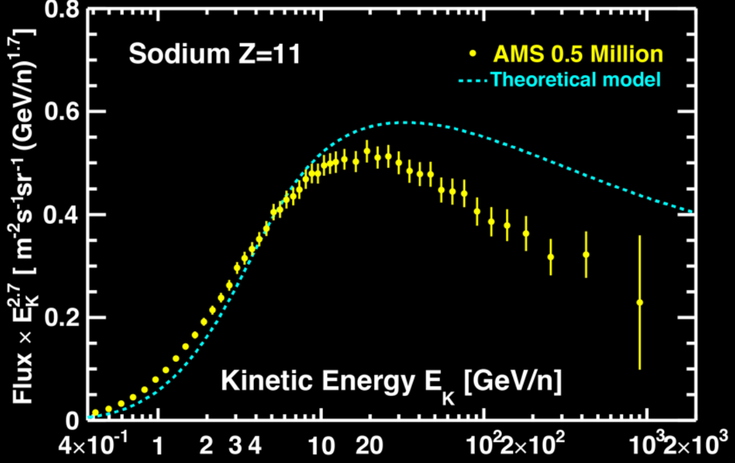




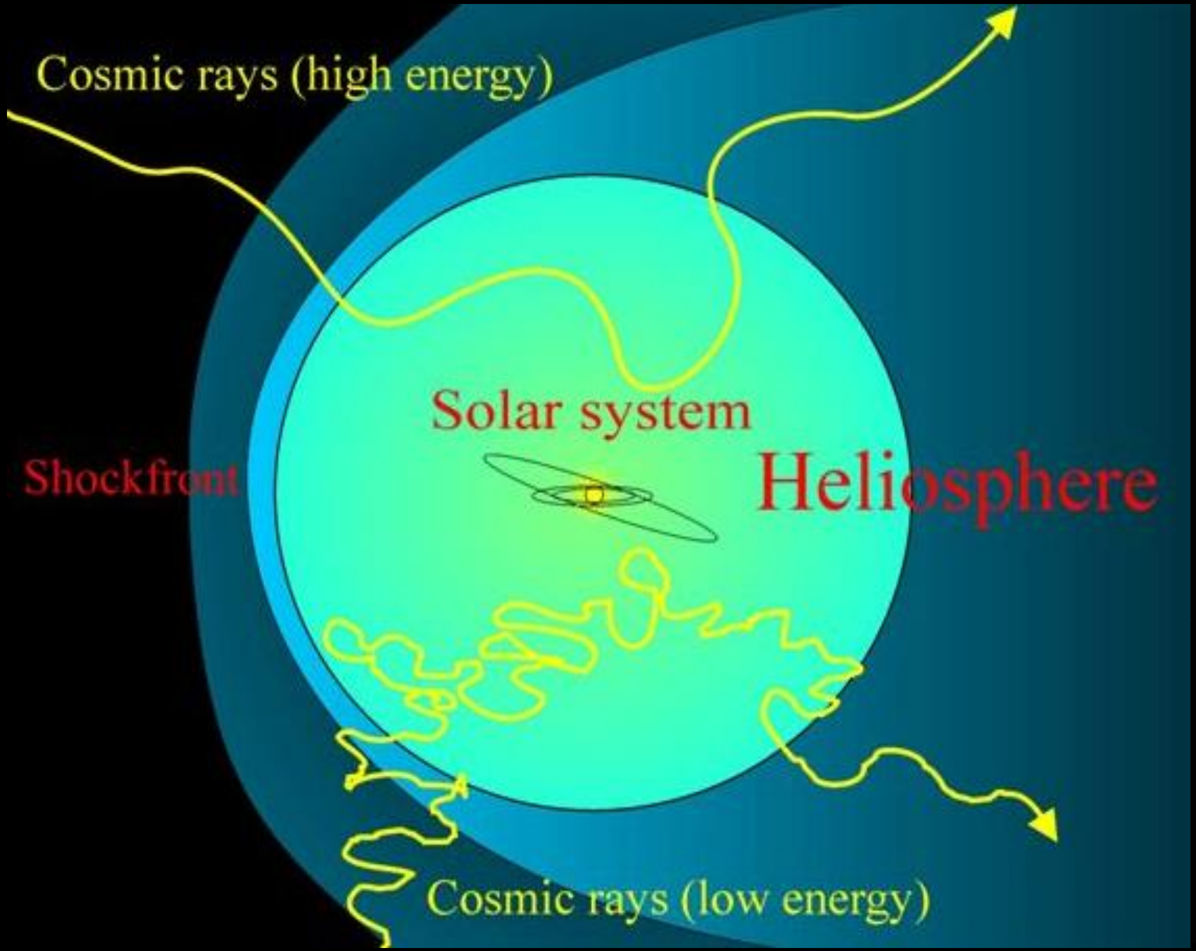


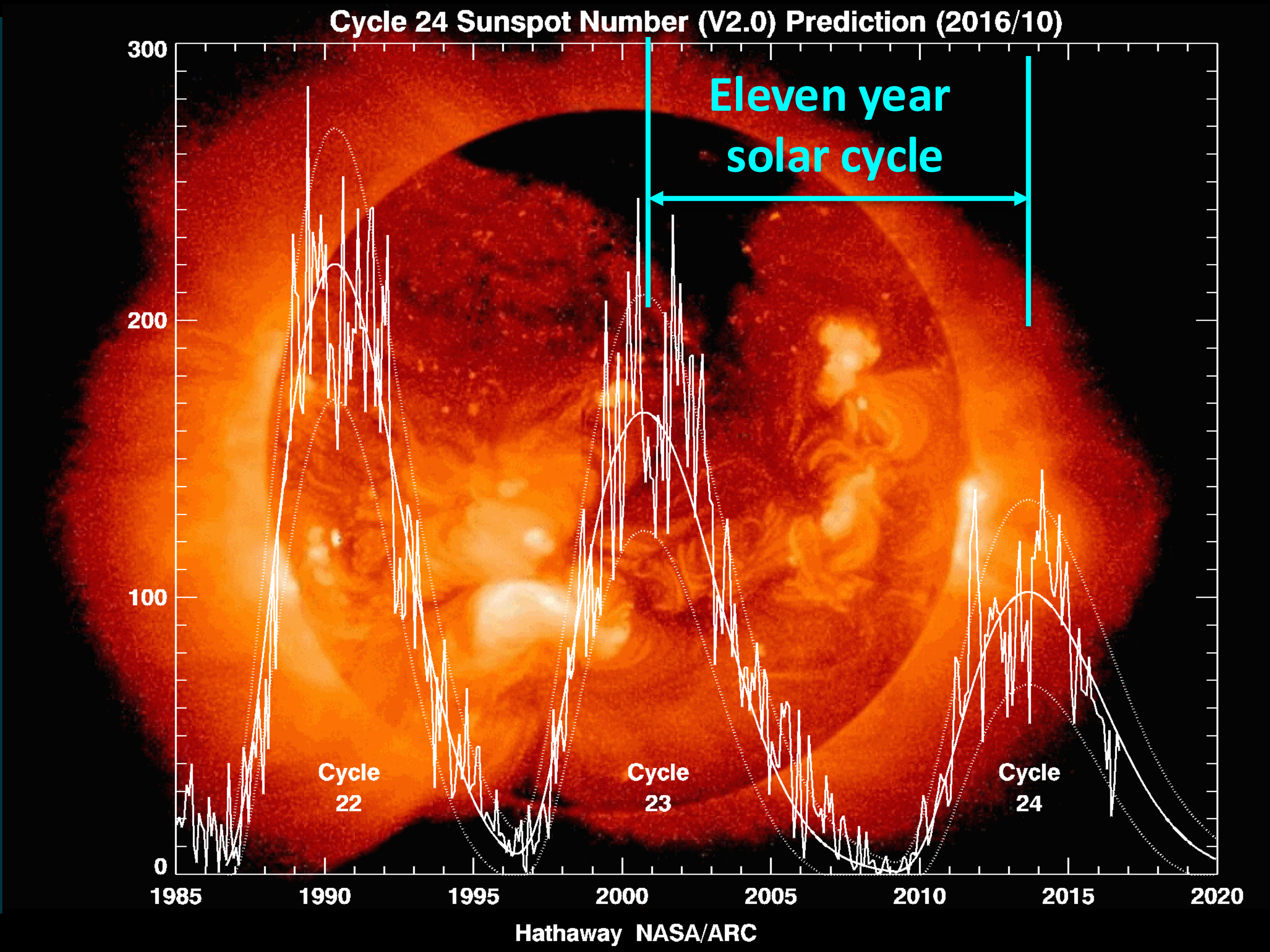






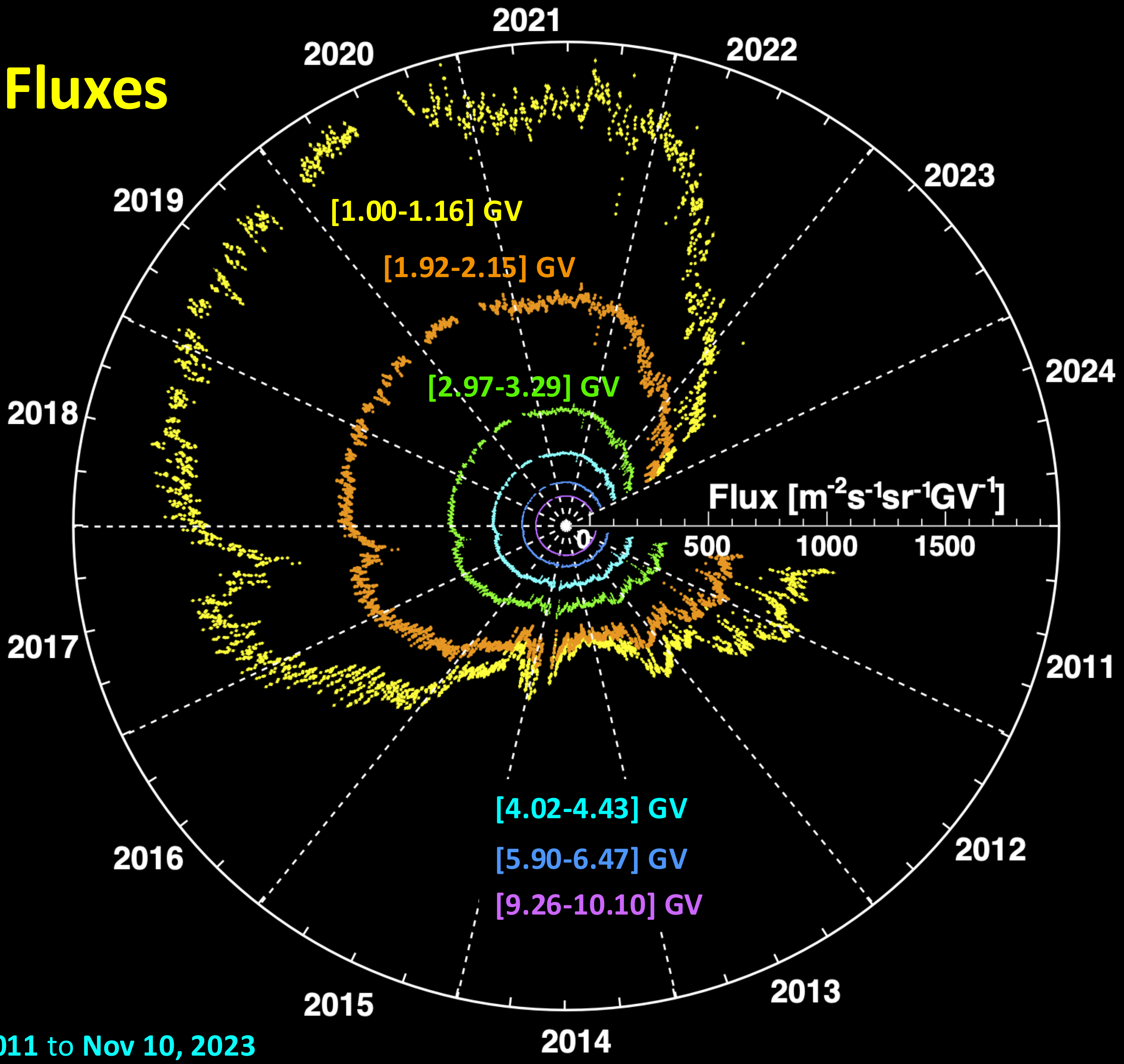
AMS Studies of the cosmic ray propagation in solar system





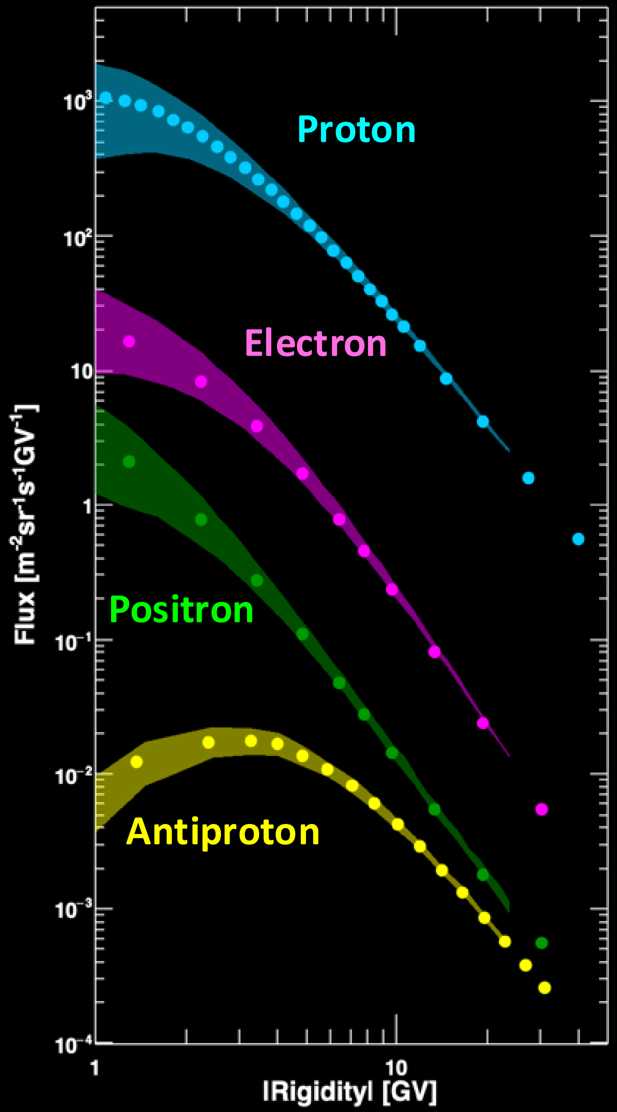
AMS continuously measures cosmic ray fluxes of different species (matter and antimatter), with high precision and time granularity.

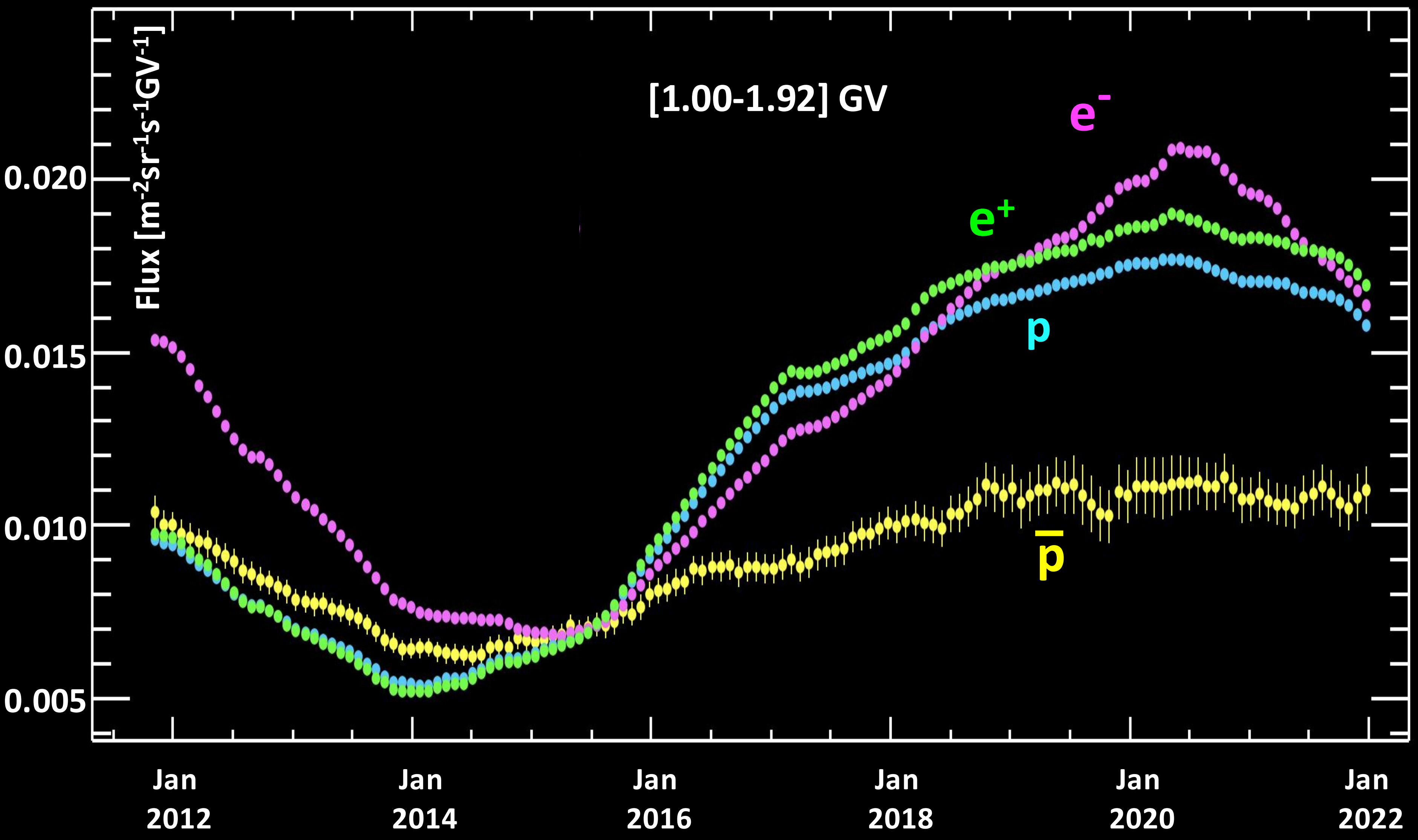
Daily Proton Fluxes



May 20, 2011 to Nov 10, 2023

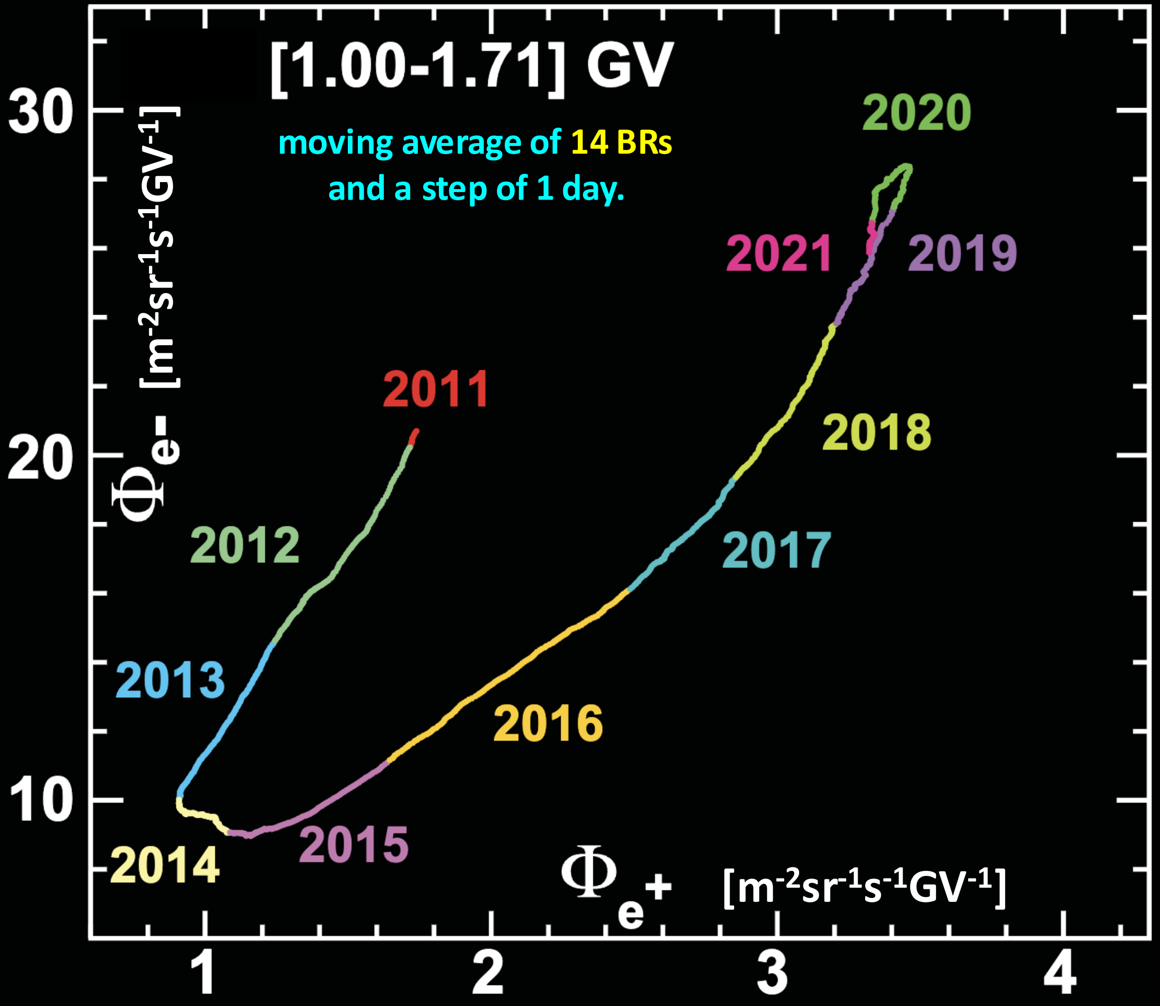
AMS Elementary Particles (e+, e-, p, $\bar{p}$, …) in the Heliosphere over an 11-year Solar Cycle (2011-2022)





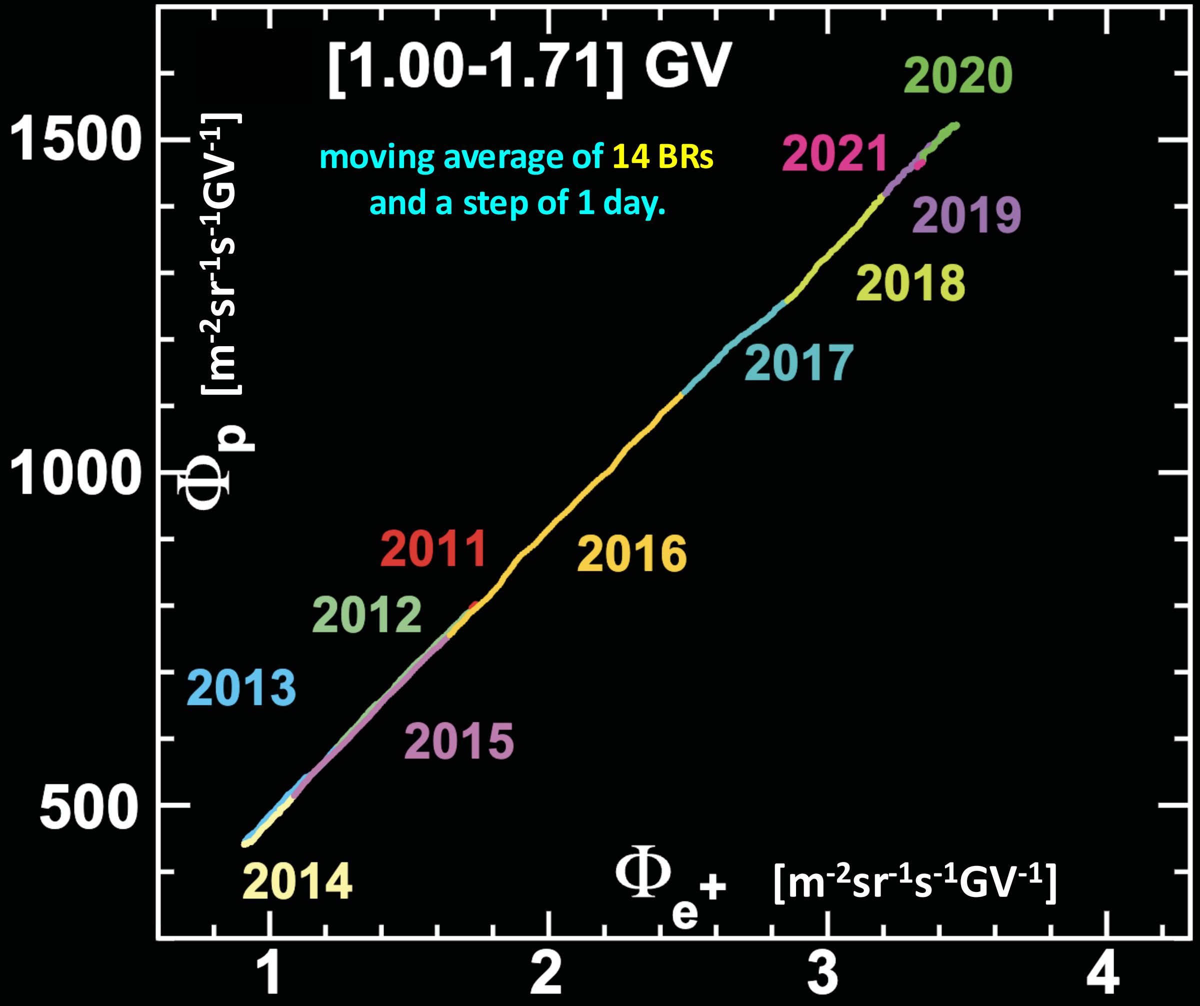
Relation between charge and mass

Equal mass, Opposite charge



Hysteresis Behavior

Equal charge, different mass



Linear Relation

Current AMS Anti-Deuteron Results