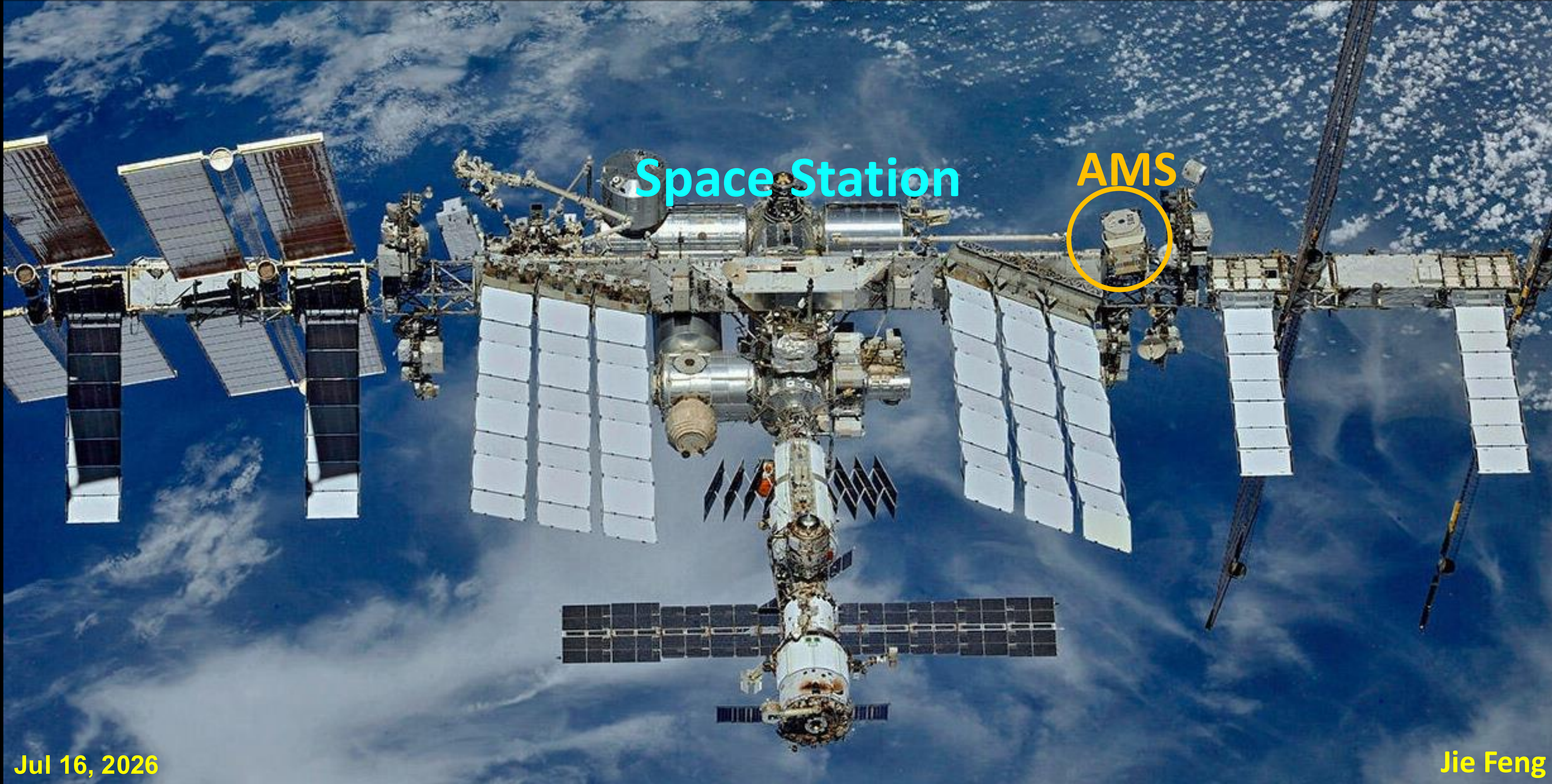
Introduction to cosmic ray physics and AMS experiments

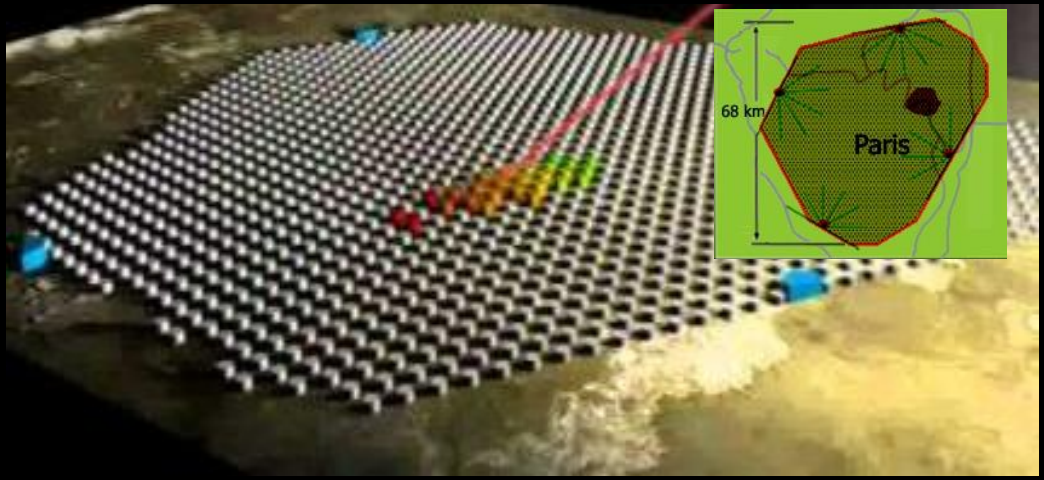


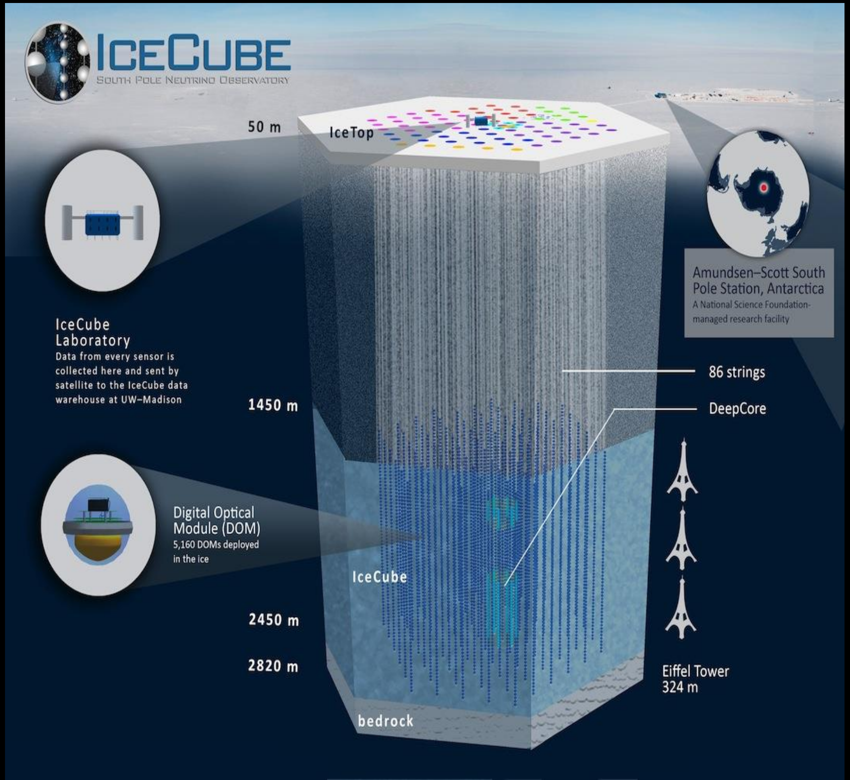
Jul 16, 2026

Jie Feng

Examples of Current Ground-Based Cosmic Ray Experiments

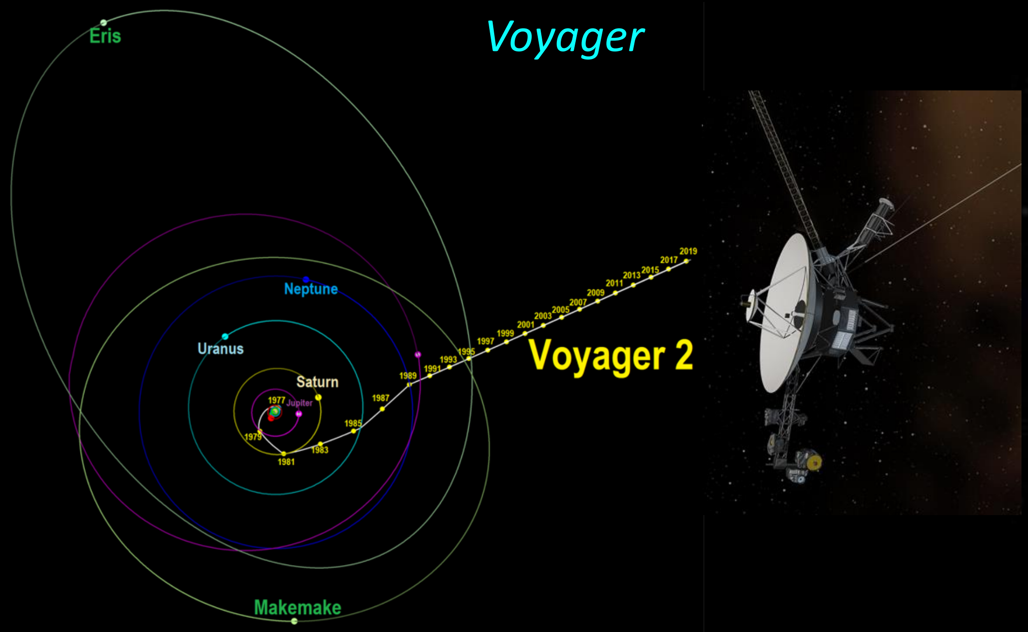
The Pierre Auger Observatory





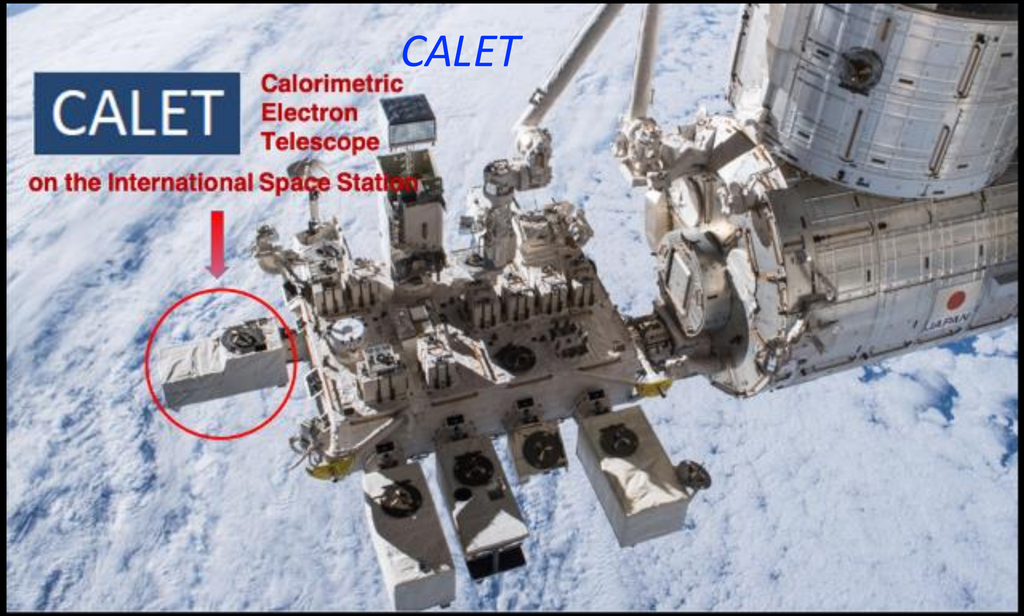
Examples of Current Non-magnetic, Calorimeter Experiments in Space

Voyager

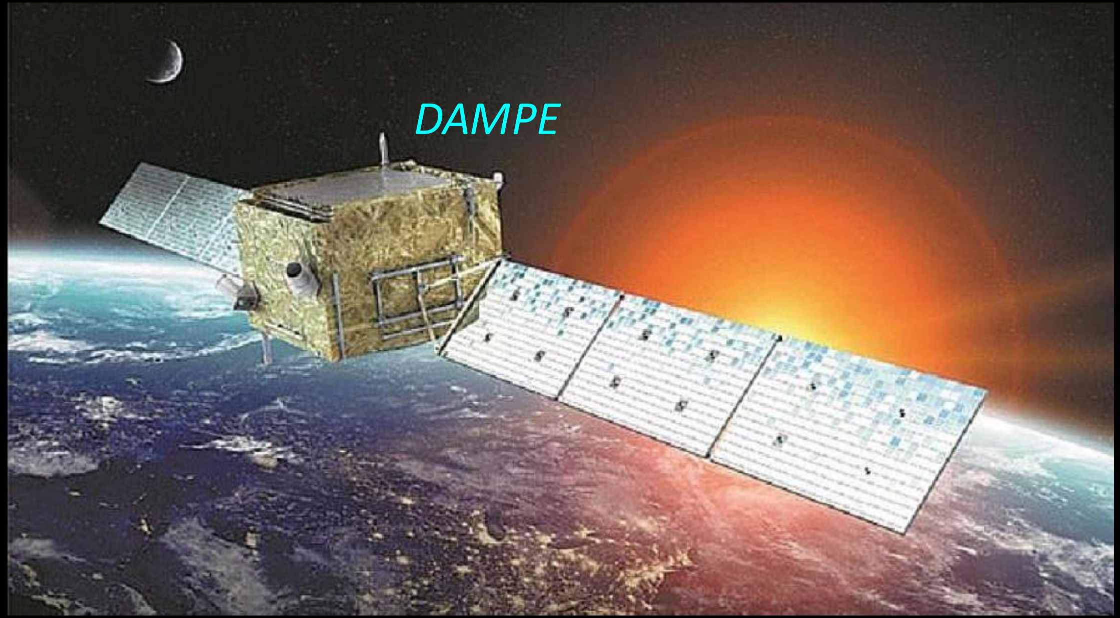


Fermi-LAT

CALET



DAMPE

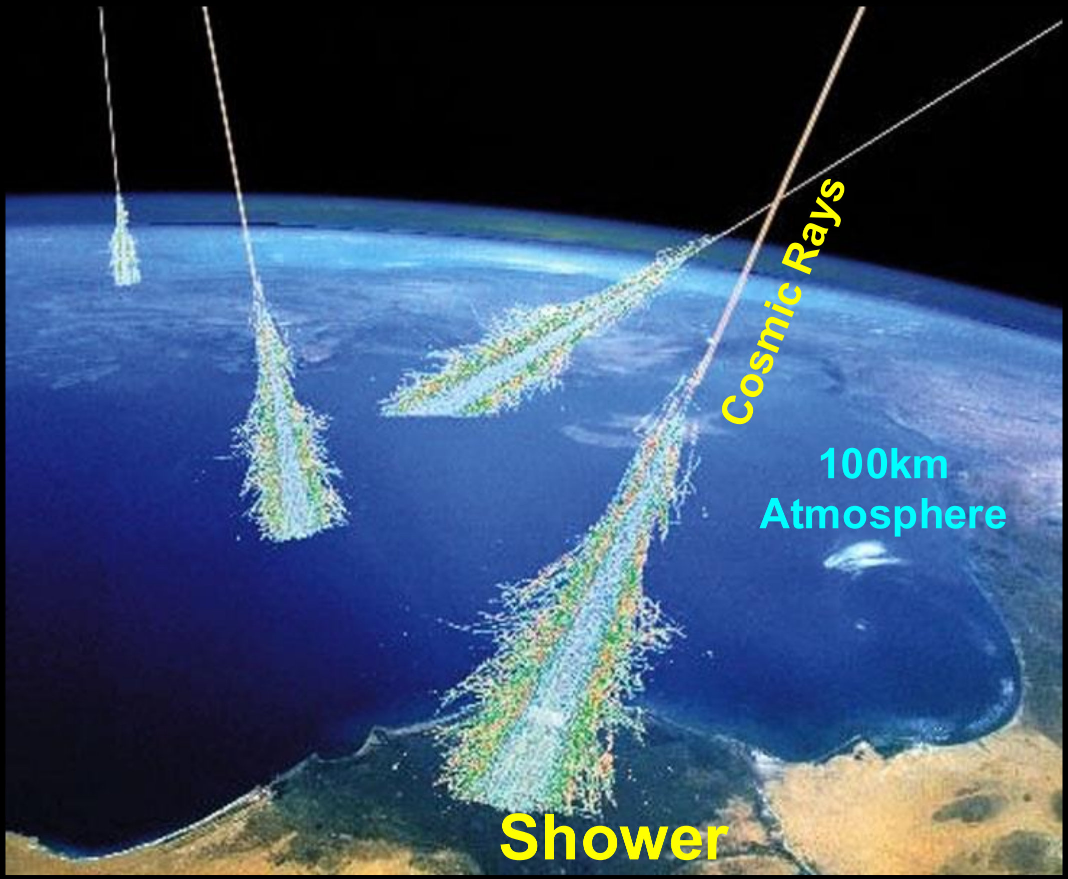


The Alpha Magnetic Spectrometer (AMS) is a unique, precision magnetic spectrometer on the Space Station

Physics of Dark Matter, Antimatter, the Origin of the Cosmos, and new phenomena
can be studied through the precision, long-duration measurement of charged cosmic rays

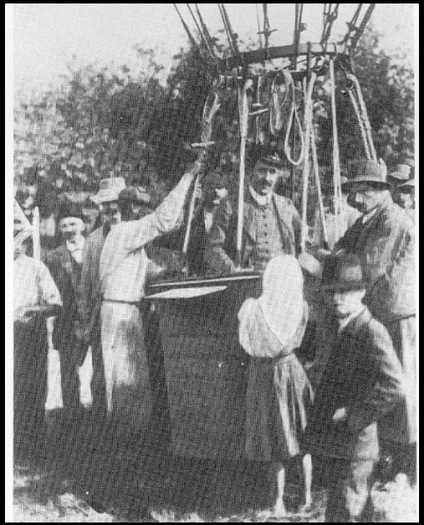
Charged cosmic rays are absorbed by the
100 km of Earth's atmosphere.
Their properties ($\pm Z$, P)
cannot be studied on the ground.

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



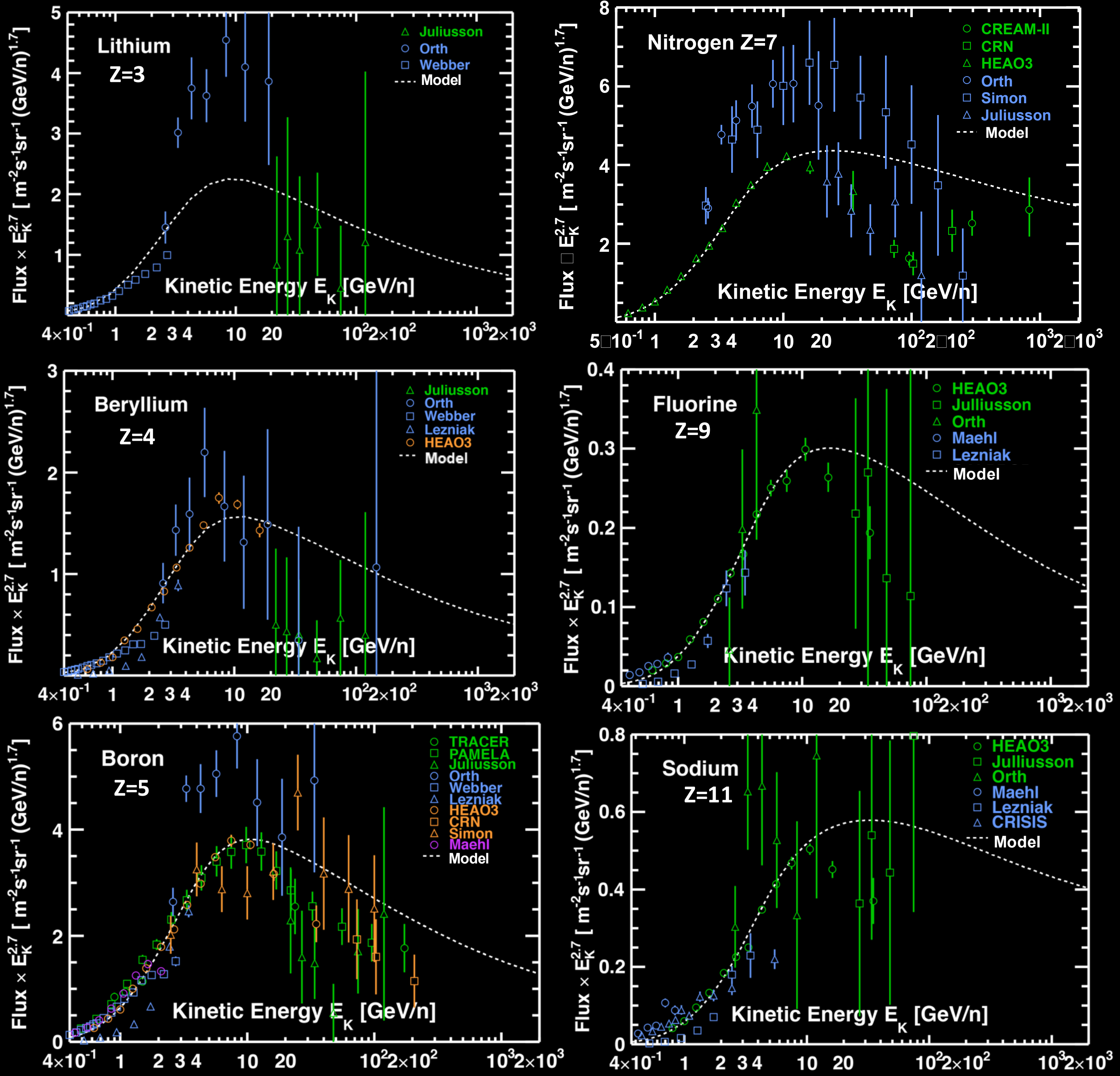
Cosmic Rays in the last 100 years

1912: Discovery of Cosmic Rays



Victor Hess Nobel Prize (1936)

Before AMS: Many theoretical models agree with experimental data

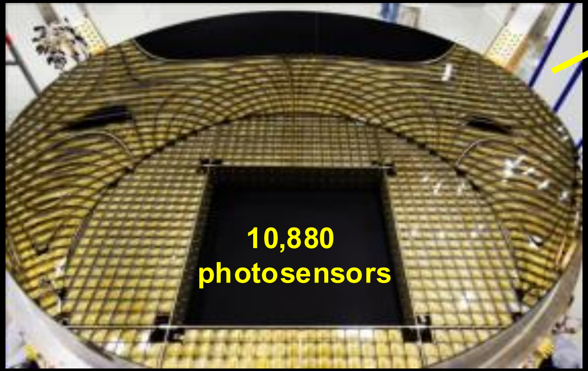


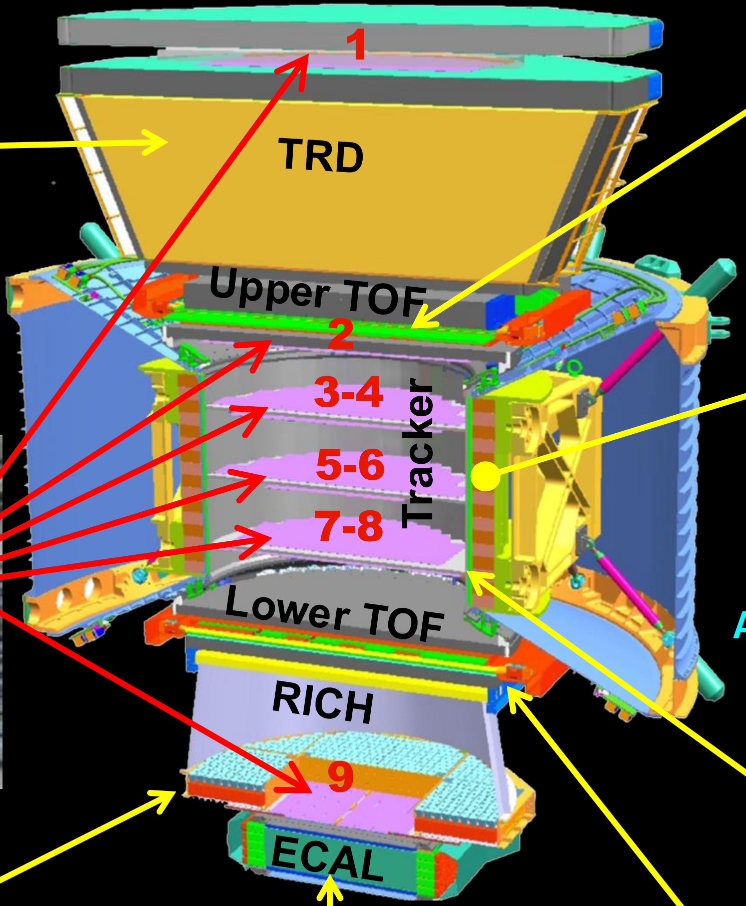
AMS is a space version of a precision detector used in accelerators

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

Silicon Tracker
measure Z, P

Ring Imaging Cerenkov (RICH)
measure Z, E





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

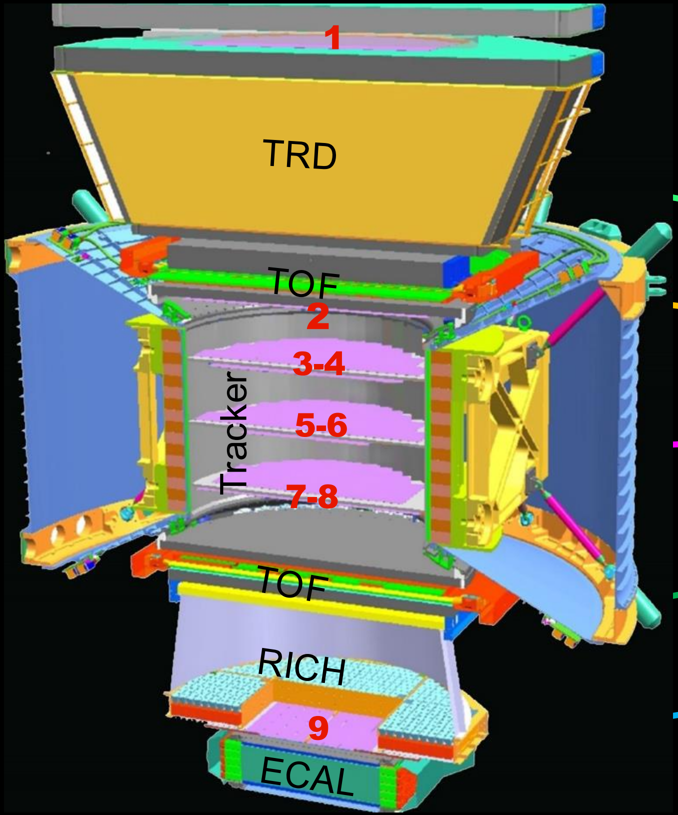
Upper TOF measure Z, E

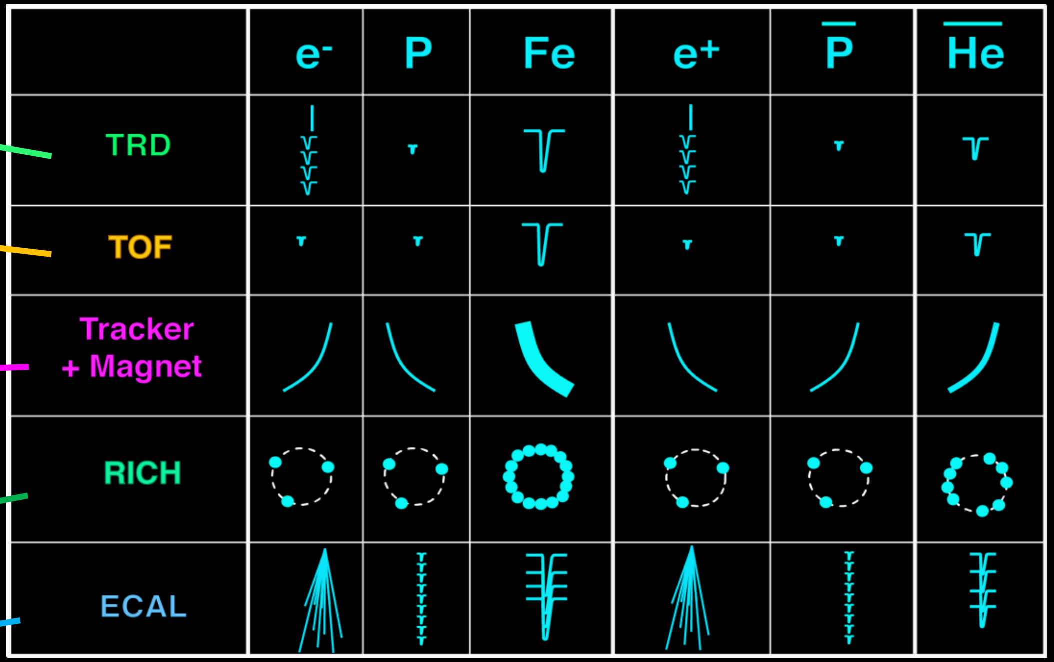
Magnet identify ±Z, P

Anticoincidence Counters (ACC)
reject particles from the side

Lower TOF measure Z, E

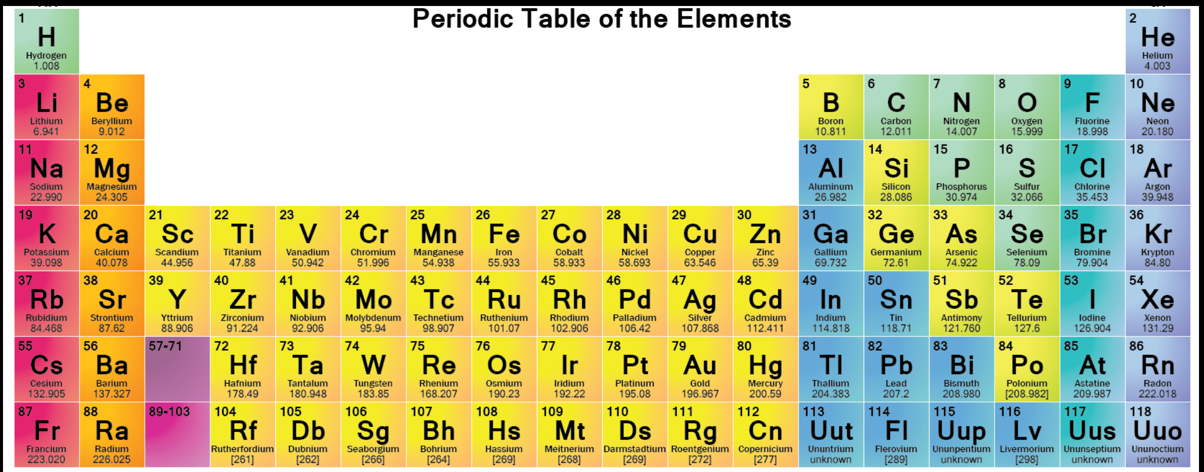
The detectors provide independent information on cosmic rays





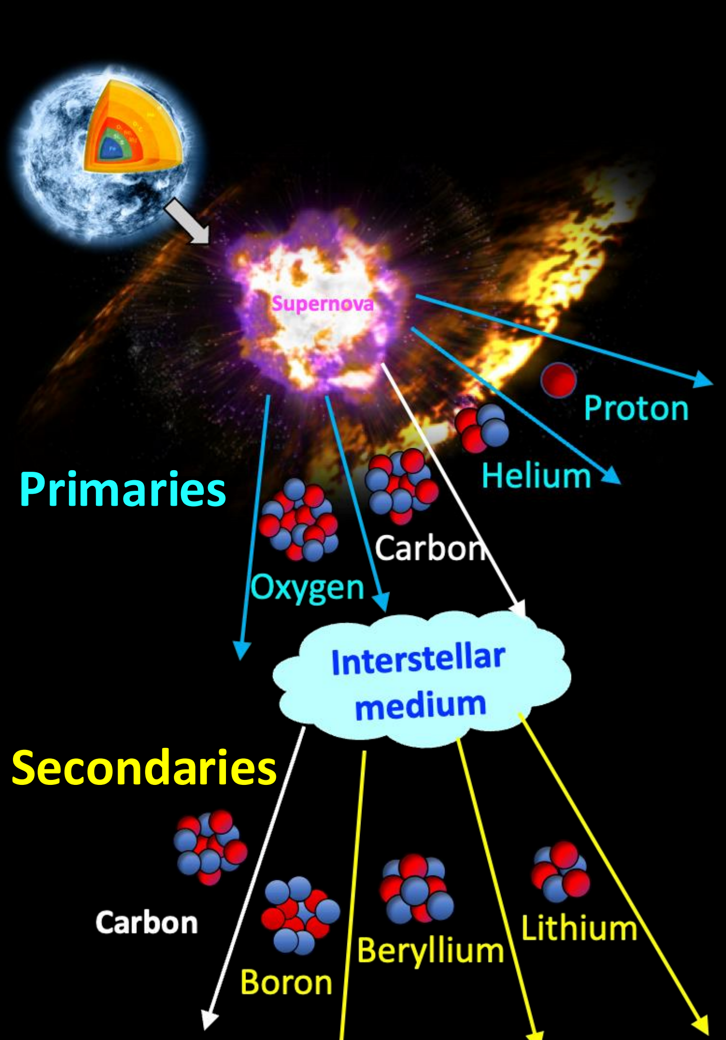
AMS measures:

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

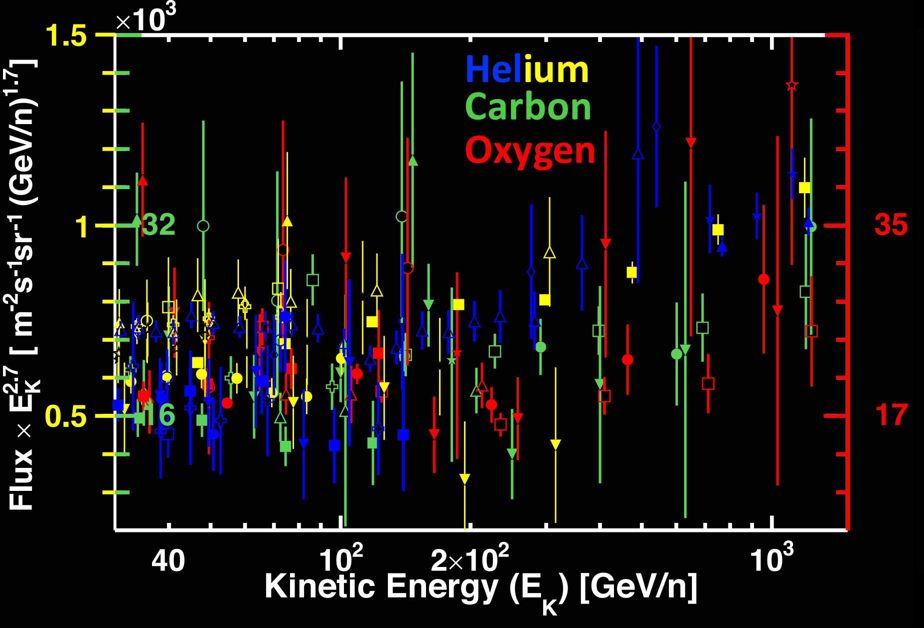


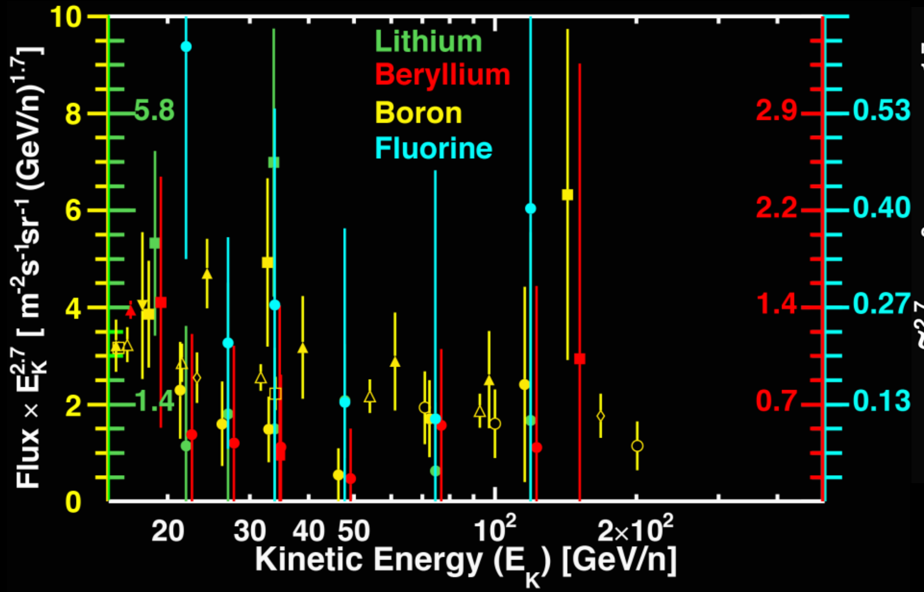
Periodic Table of the Elements

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
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 168.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

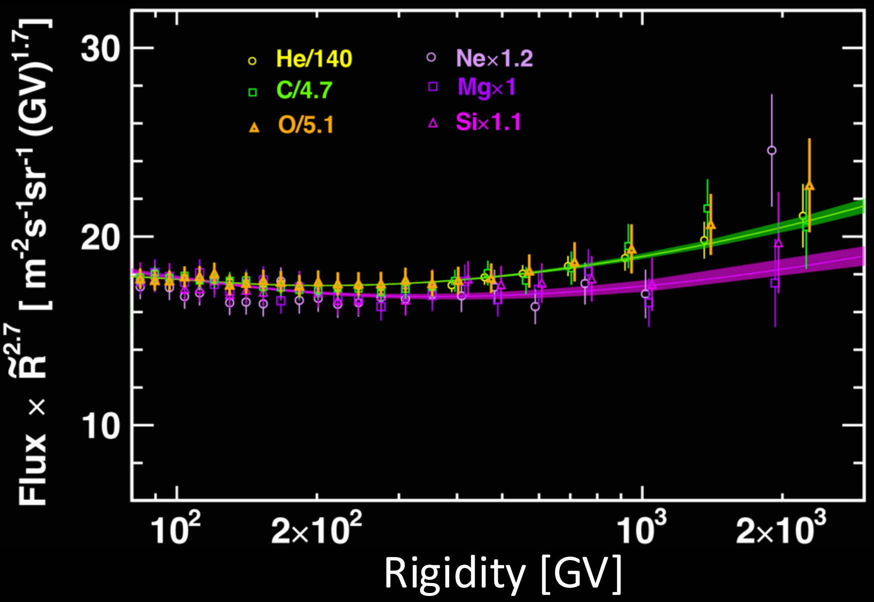


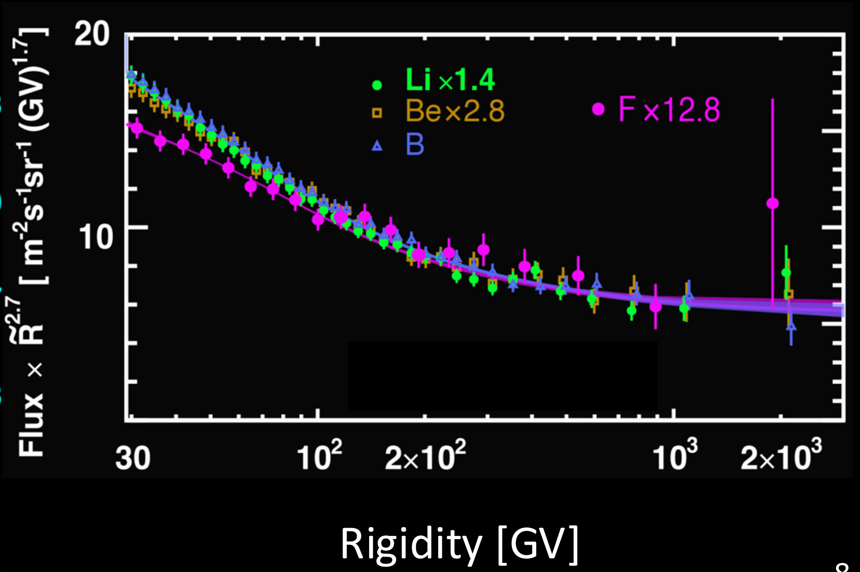
Data before AMS



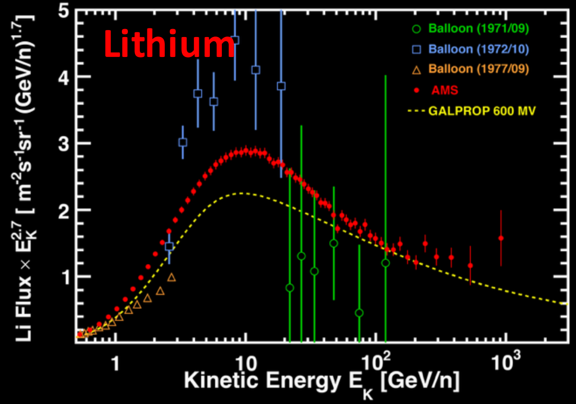


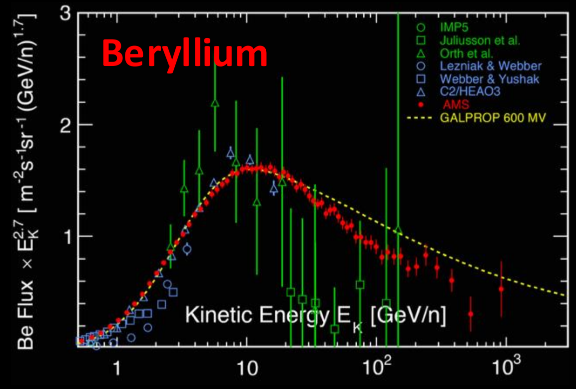
AMS data

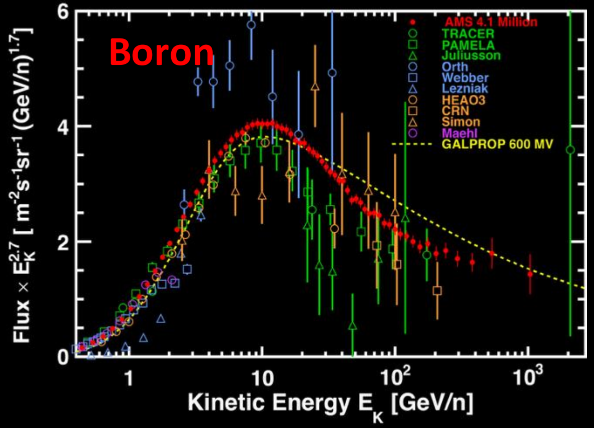


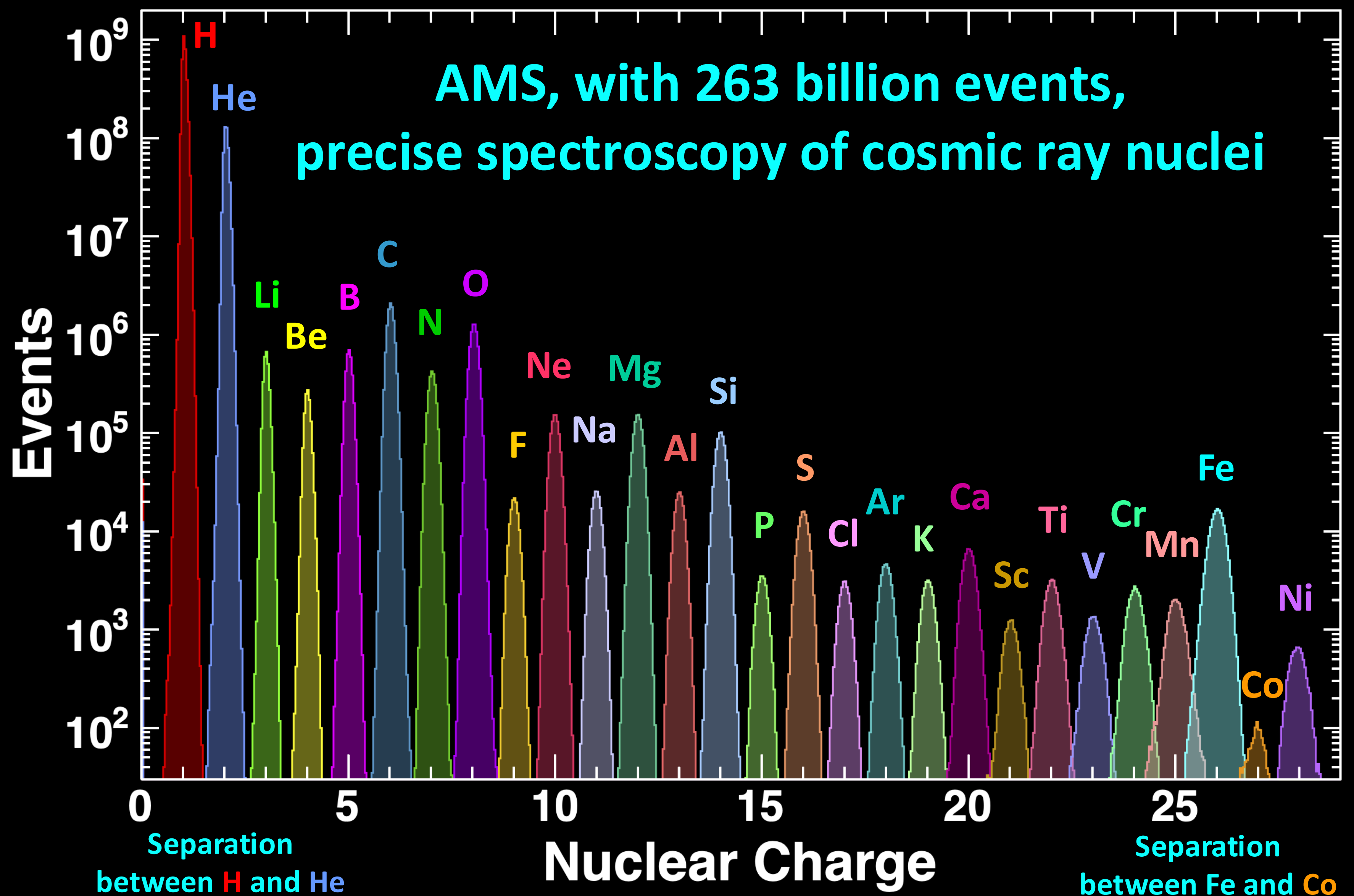


Spectroscopy of cosmic ray nuclei



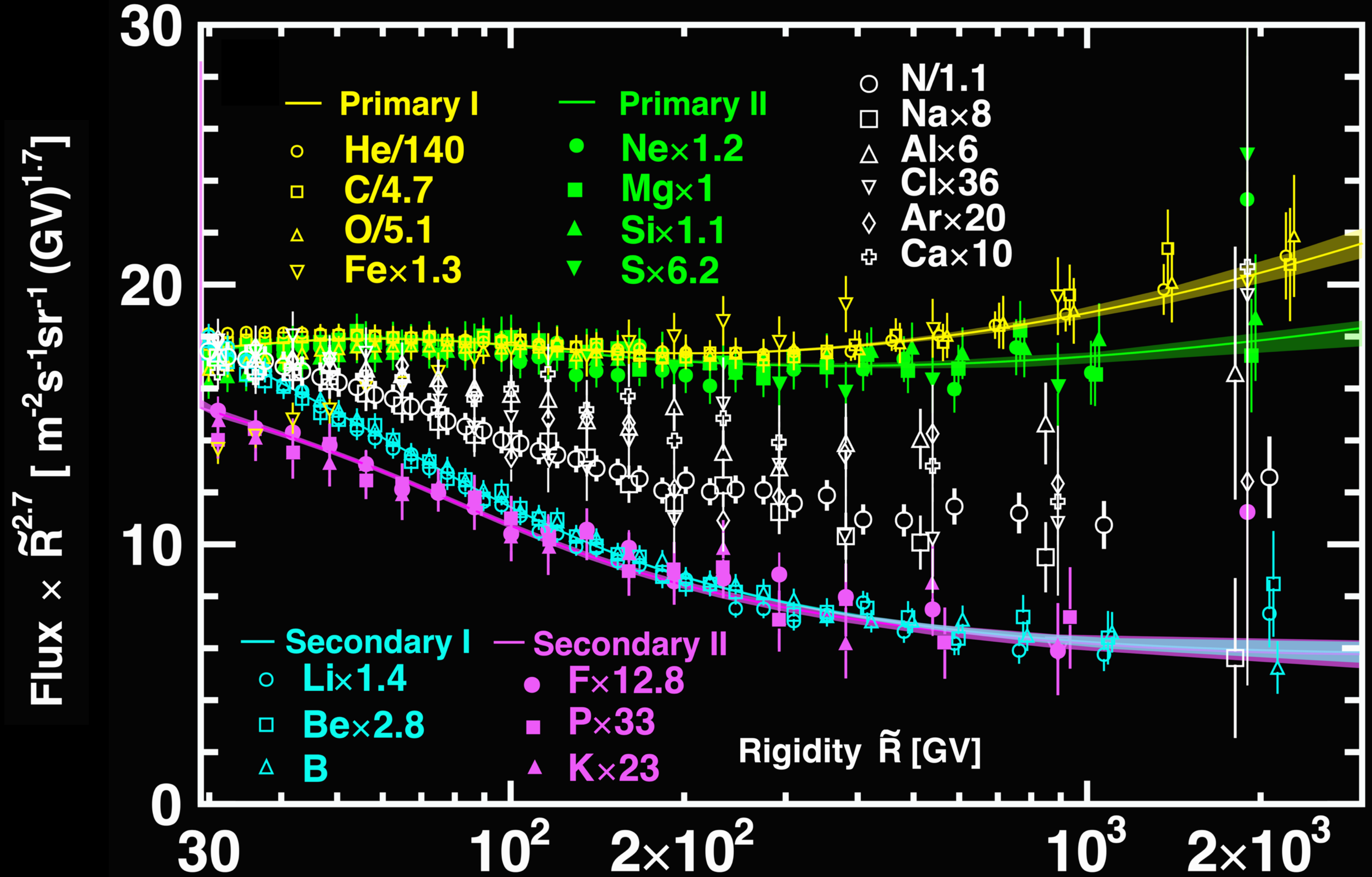




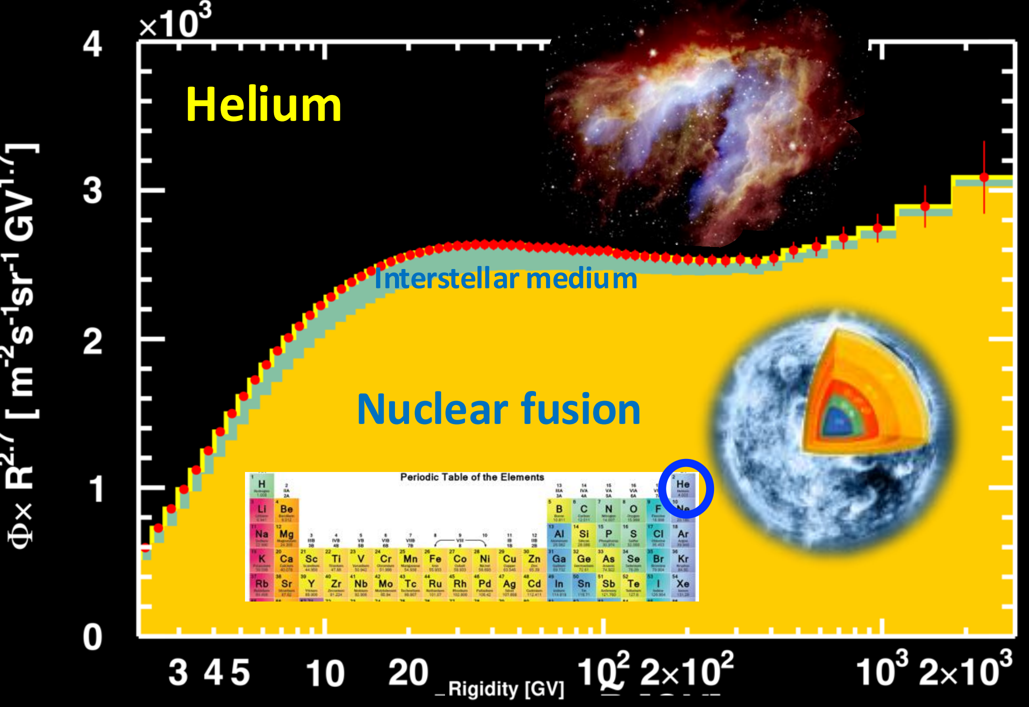


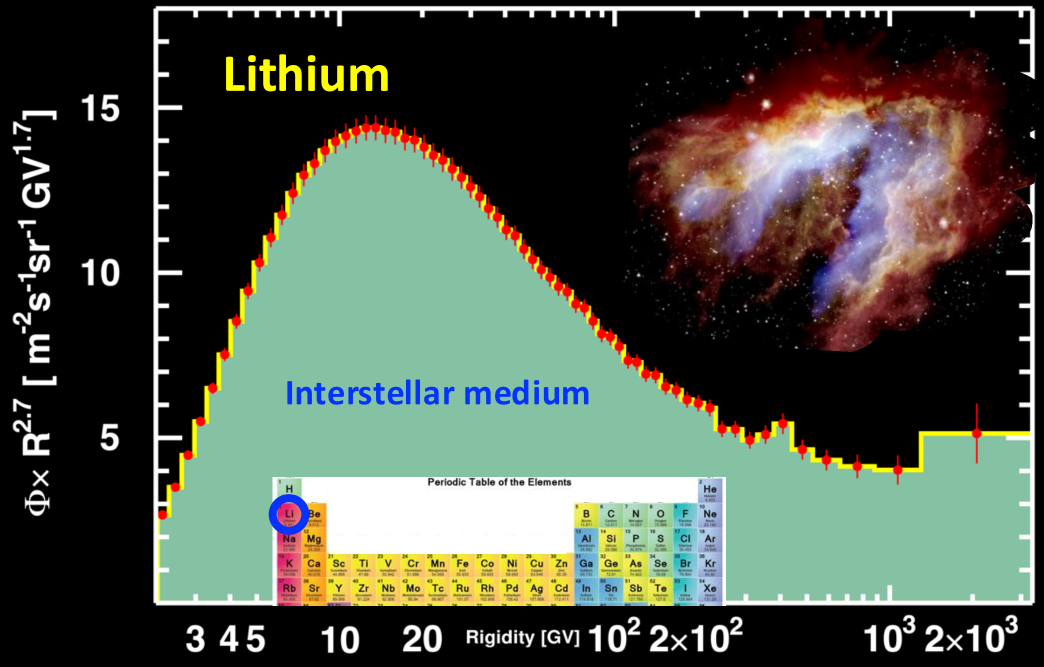
Separation between H and He is better than 1 in 10^9

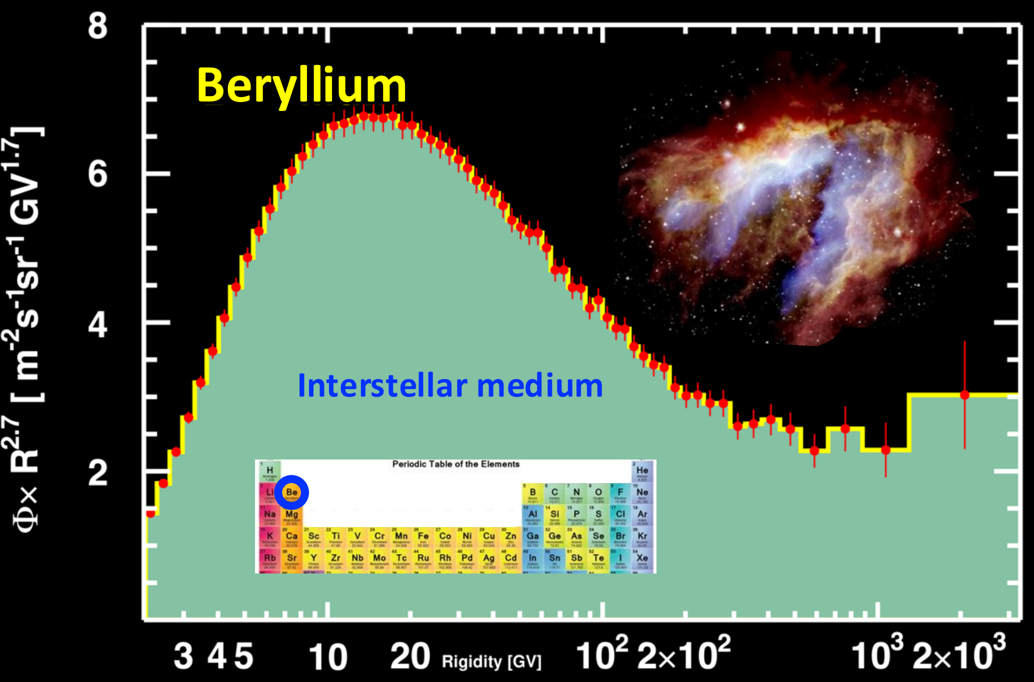
Separation between Fe and Co is better than 1 in 10^2

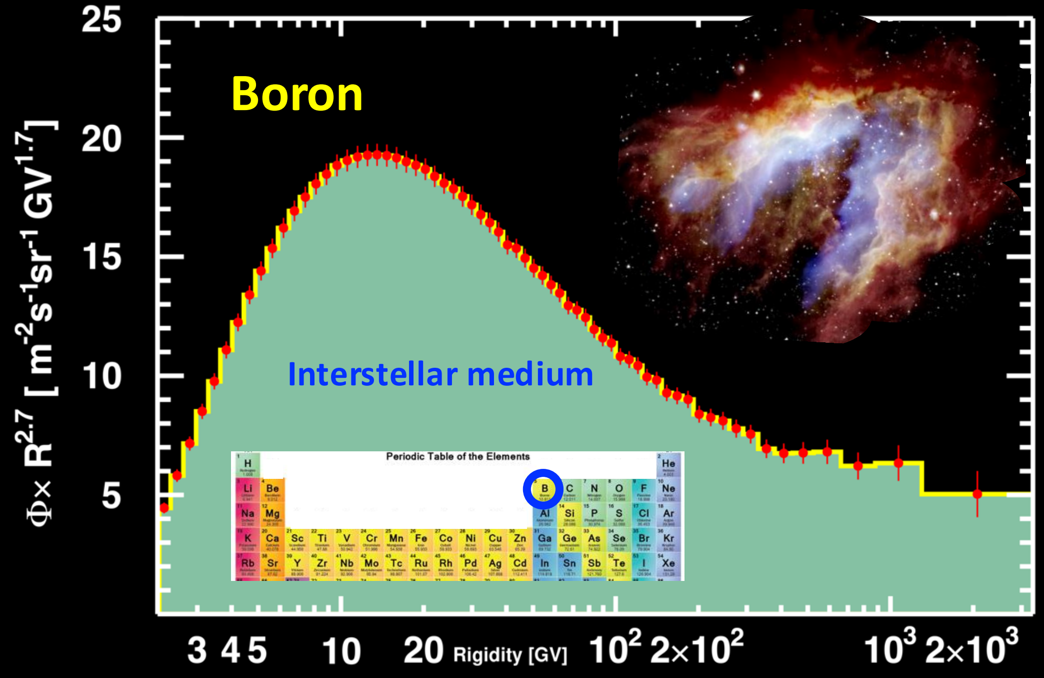


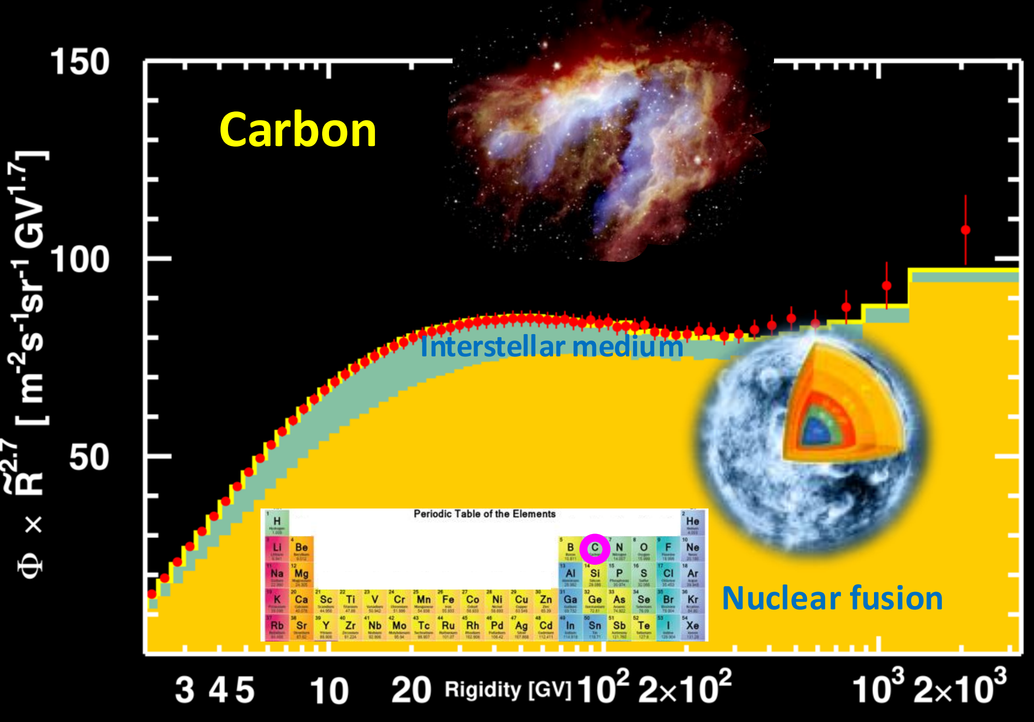
Flux × $\tilde{R}^{2.7}$ [$m^{-2}s^{-1}sr^{-1}$ $(GV)^{1.7}$]
30
20
10
0
Primary I
He/140
C/4.7
O/5.1
Fe×1.3
Primary II
Ne×1.2
Mg×1
Si×1.1
S×6.2
N/1.1
Na×8
Al×6
Cl×36
Ar×20
Ca×10
Secondary I
Li×1.4
Be×2.8
B
Secondary II
F×12.8
P×33
K×23
Rigidity $\tilde{R}$ [GV]
30
10^2
2×10^2
10^3
2×10^3

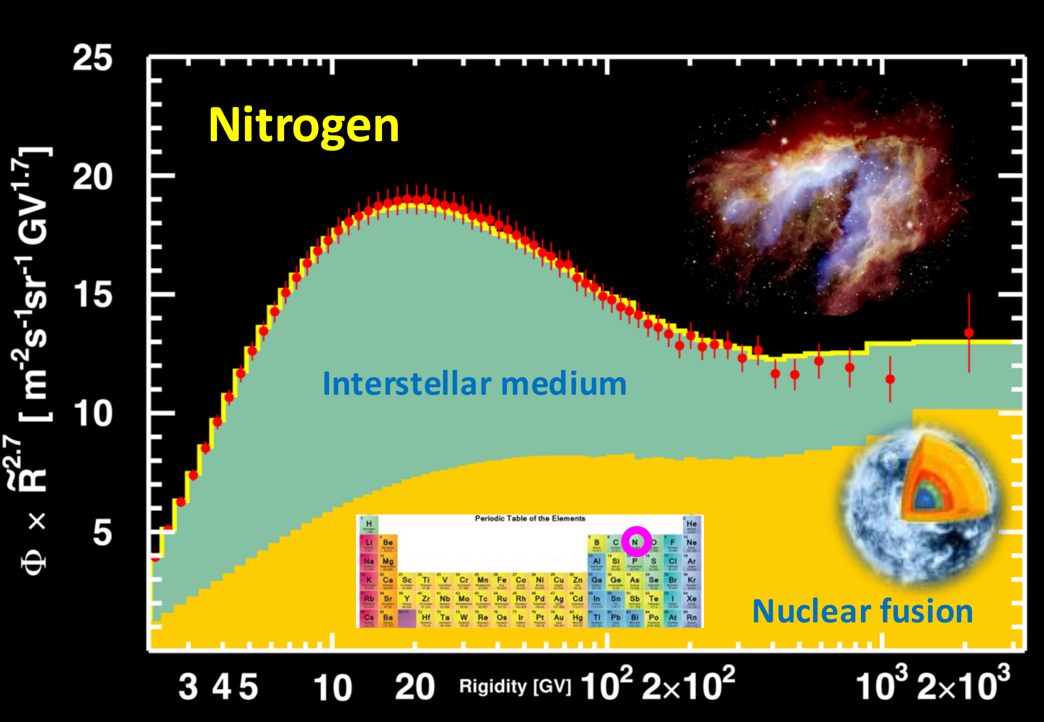

Helium
Interstellar medium
Nuclear fusion
Periodic Table of the Elements
$\Phi \times R^{2.7}$ [$m^{-2}s^{-1}sr^{-1}GV^{1.7}$]
$\times 10^3$
Rigidity [GV]

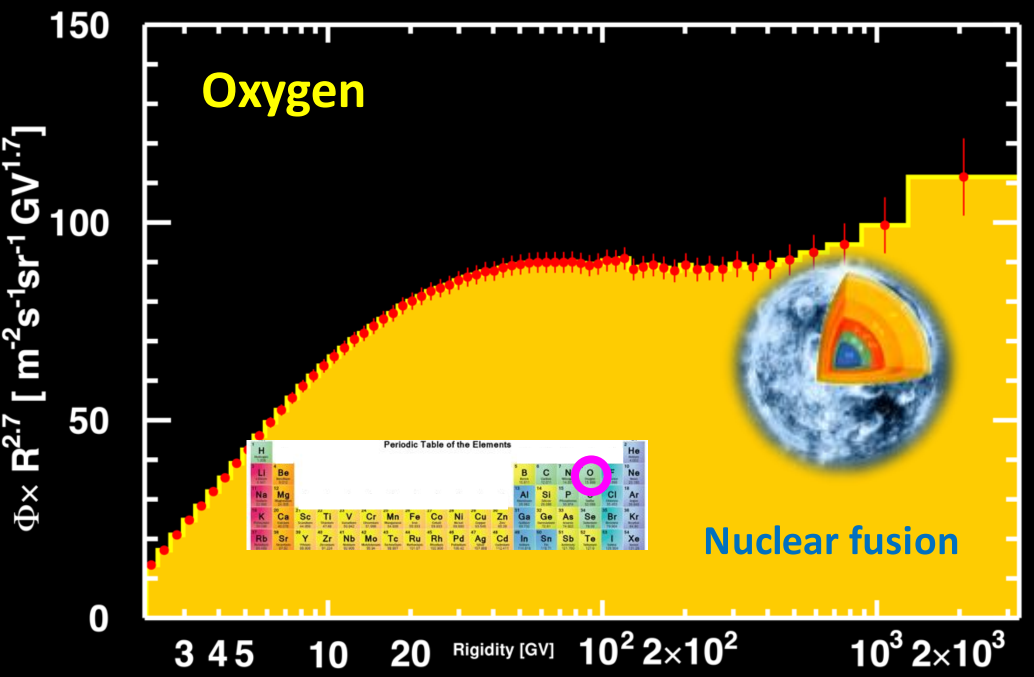

Lithium
Interstellar medium
Periodic Table of the Elements
$\Phi \times R^{2.7}$ [$m^{-2}s^{-1}sr^{-1}GV^{1.7}$]
Rigidity [GV]

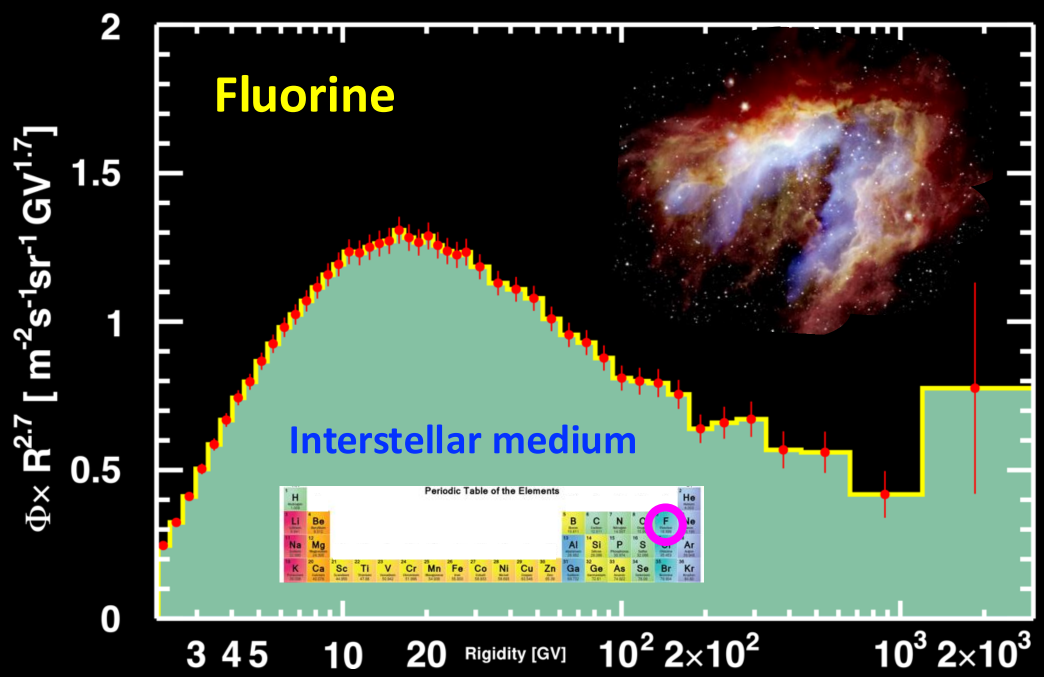

Beryllium
Interstellar medium
Periodic Table of the Elements
$\Phi \times R^{2.7}$ [$m^{-2}s^{-1}sr^{-1}GV^{1.7}$]
Rigidity [GV]

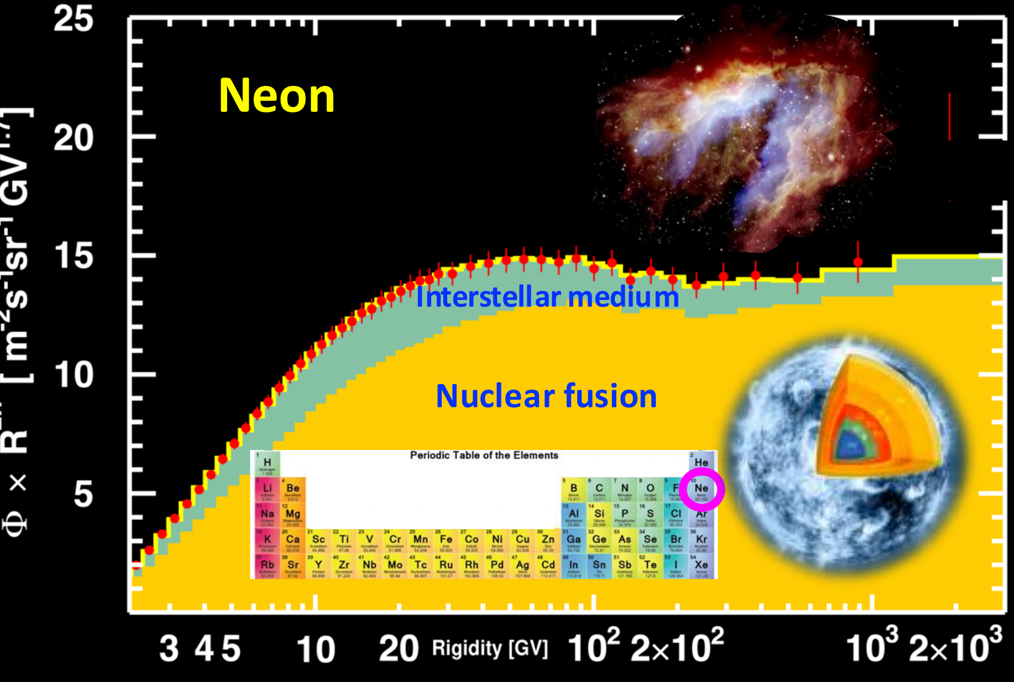

Boron
Interstellar medium
Periodic Table of the Elements
$\Phi \times R^{2.7}$ [$m^{-2}s^{-1}sr^{-1}GV^{1.7}$]
Rigidity [GV]

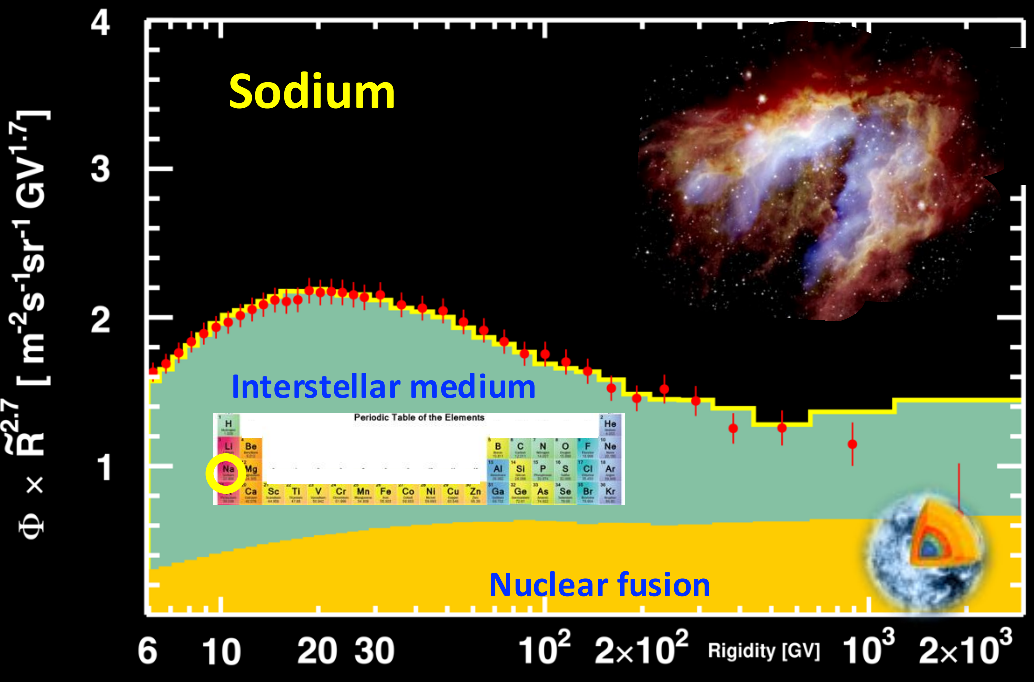

Carbon
Interstellar medium
Nuclear fusion
Φ × R̃^2.7 [m^-2 s^-1 sr^-1 GV^1.7]
Rigidity [GV]

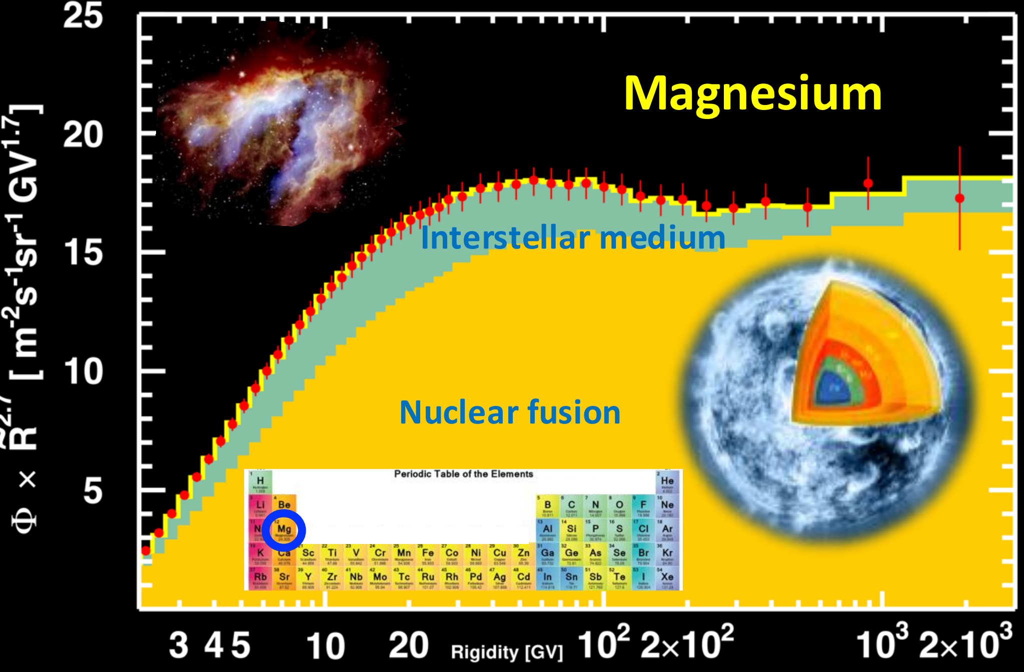

Nitrogen
Interstellar medium
Nuclear fusion
Φ × R̃^2.7 [m^-2 s^-1 sr^-1 GV^1.7]
Rigidity [GV]

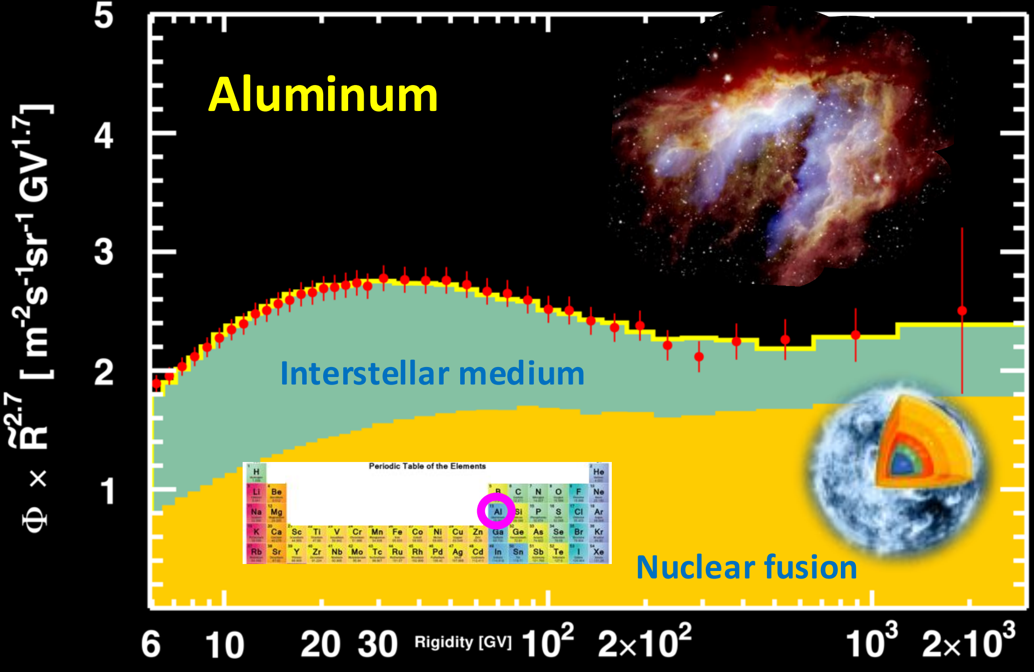

Oxygen
Nuclear fusion
Φ× R^2.7 [m^-2 s^-1 sr^-1 GV^1.7]
Rigidity [GV]

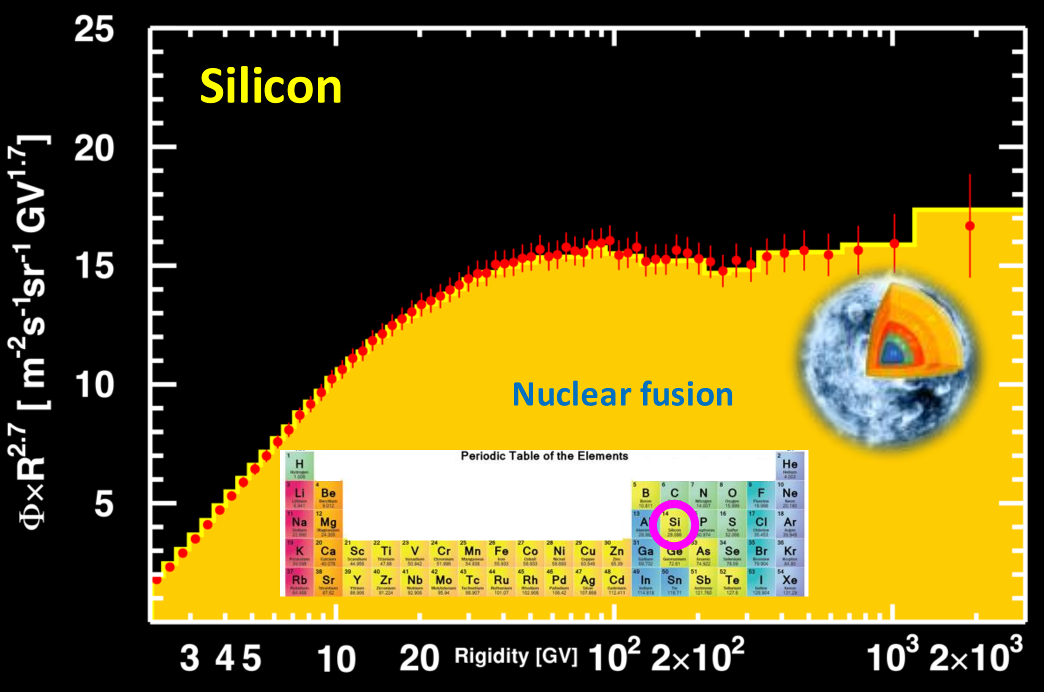

Fluorine
Interstellar medium
Φ× R^2.7 [m^-2 s^-1 sr^-1 GV^1.7]
Rigidity [GV]

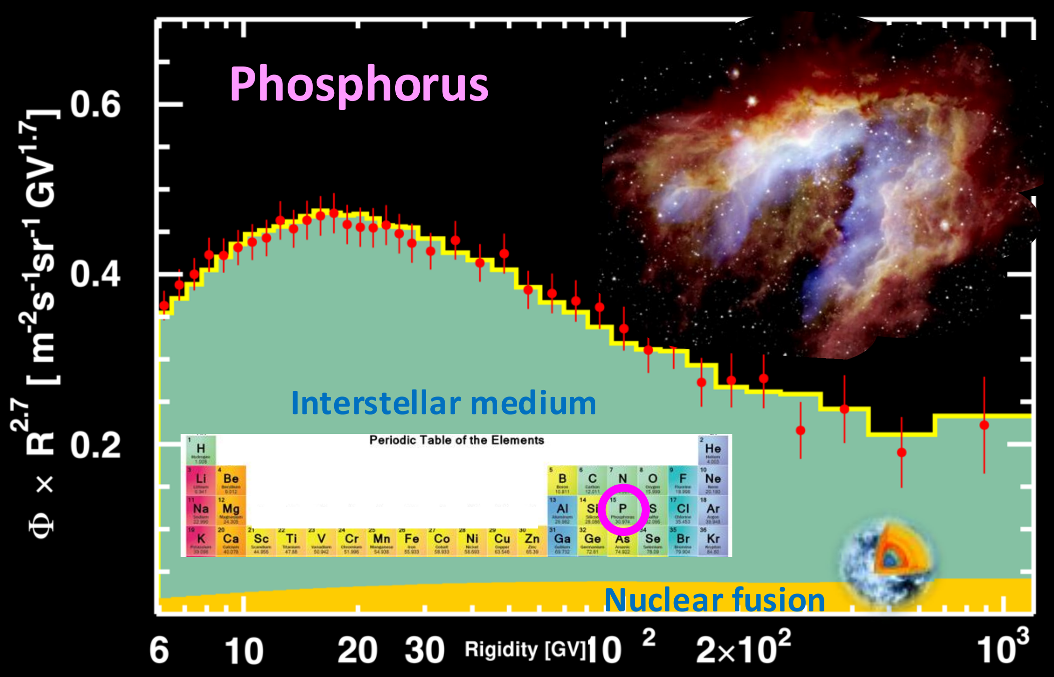

Neon
Interstellar medium
Nuclear fusion
Periodic Table of the Elements
$\Phi \times \tilde{R}^{2.7}$ [$m^{-2}s^{-1}sr^{-1}GV^{1.7}$]
Rigidity [GV]
5
10
15
20
25
3 4 5 10 20 10^2 2×10^2 10^3 2×10^3

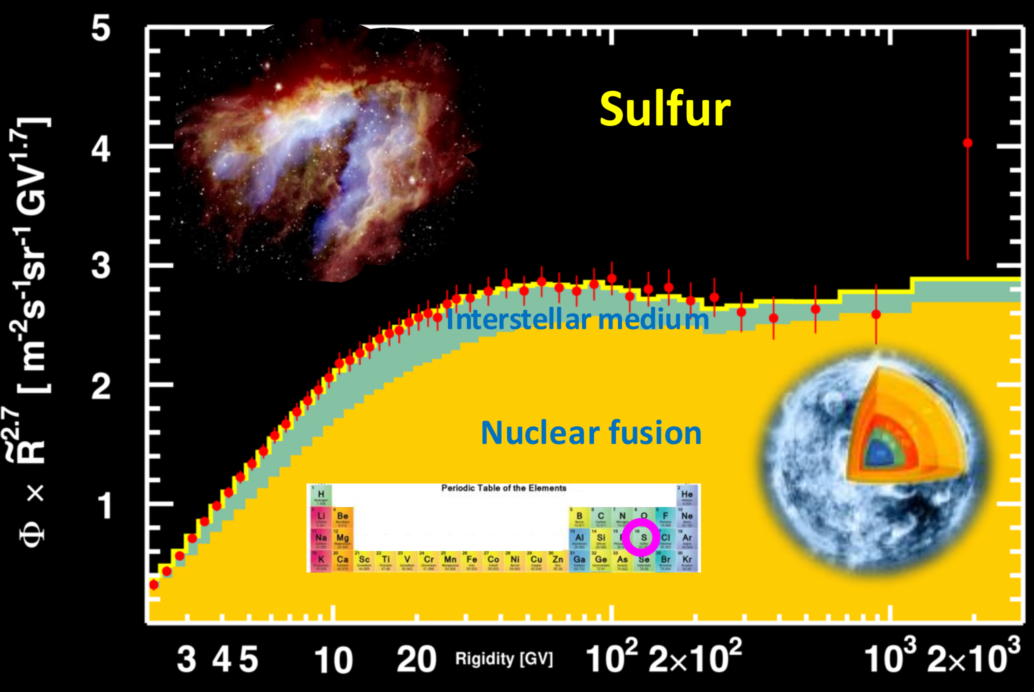

Sodium
Interstellar medium
Nuclear fusion
Periodic Table of the Elements
$\Phi \times \tilde{R}^{2.7}$ [$m^{-2}s^{-1}sr^{-1}GV^{1.7}$]
Rigidity [GV]
1
2
3
4
6 10 20 30 10^2 2×10^2 10^3 2×10^3

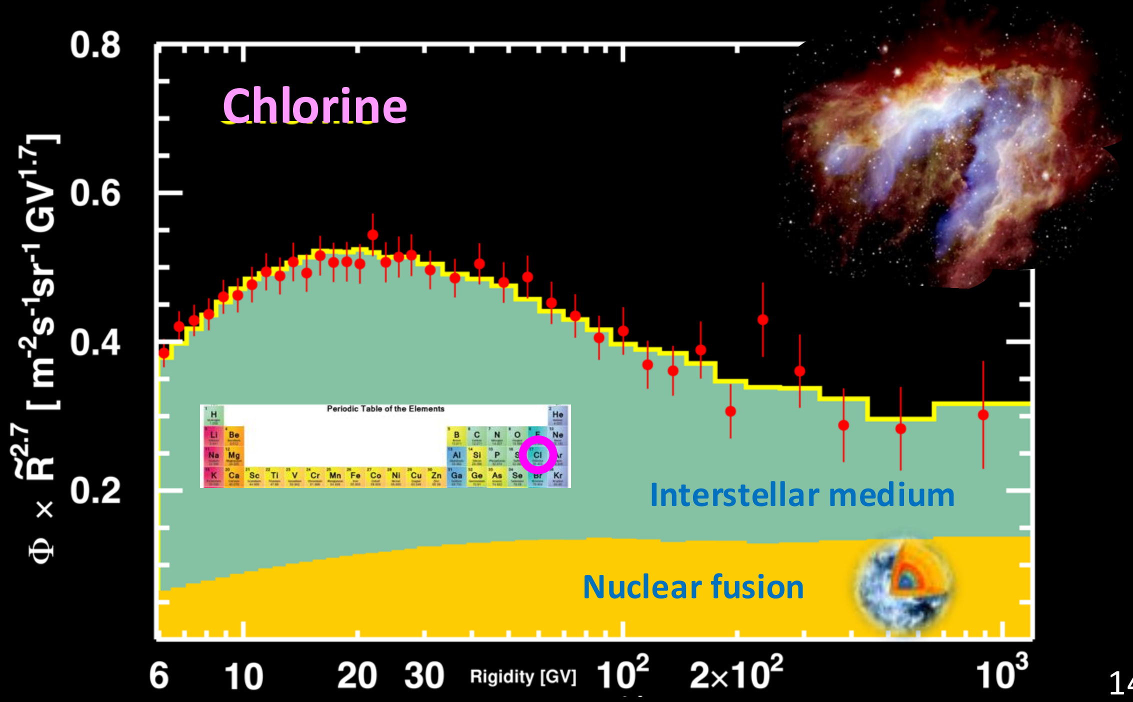

Magnesium
Interstellar medium
Nuclear fusion
Periodic Table of the Elements
$\Phi \times \tilde{R}^{2.7}$ [$m^{-2}s^{-1}sr^{-1}GV^{1.7}$]
Rigidity [GV]
5
10
15
20
25
3 4 5 10 20 10^2 2×10^2 10^3 2×10^3

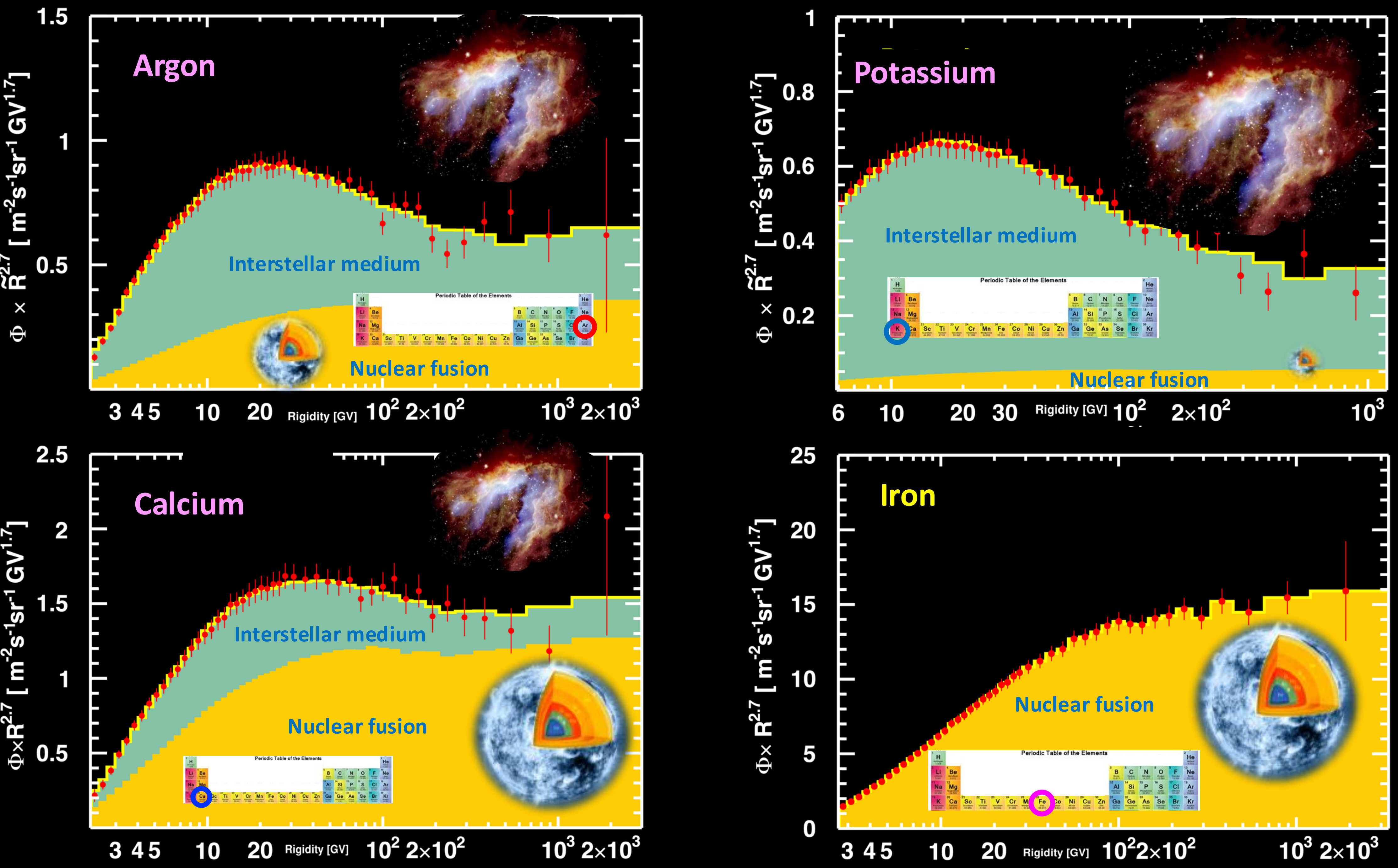

Aluminum
Interstellar medium
Nuclear fusion
Periodic Table of the Elements
$\Phi \times \tilde{R}^{2.7}$ [$m^{-2}s^{-1}sr^{-1}GV^{1.7}$]
Rigidity [GV]
1
2
3
4
5
6 10 20 30 10^2 2×10^2 10^3 2×10^3


Silicon
Nuclear fusion
Periodic Table of the Elements
$\Phi \times R^{2.7}$ [$m^{-2}s^{-1}sr^{-1}$ $GV^{1.7}$]
25
20
15
10
5
3 4 5 10 20 Rigidity [GV] 10^2 2×10^2 10^3 2×10^3

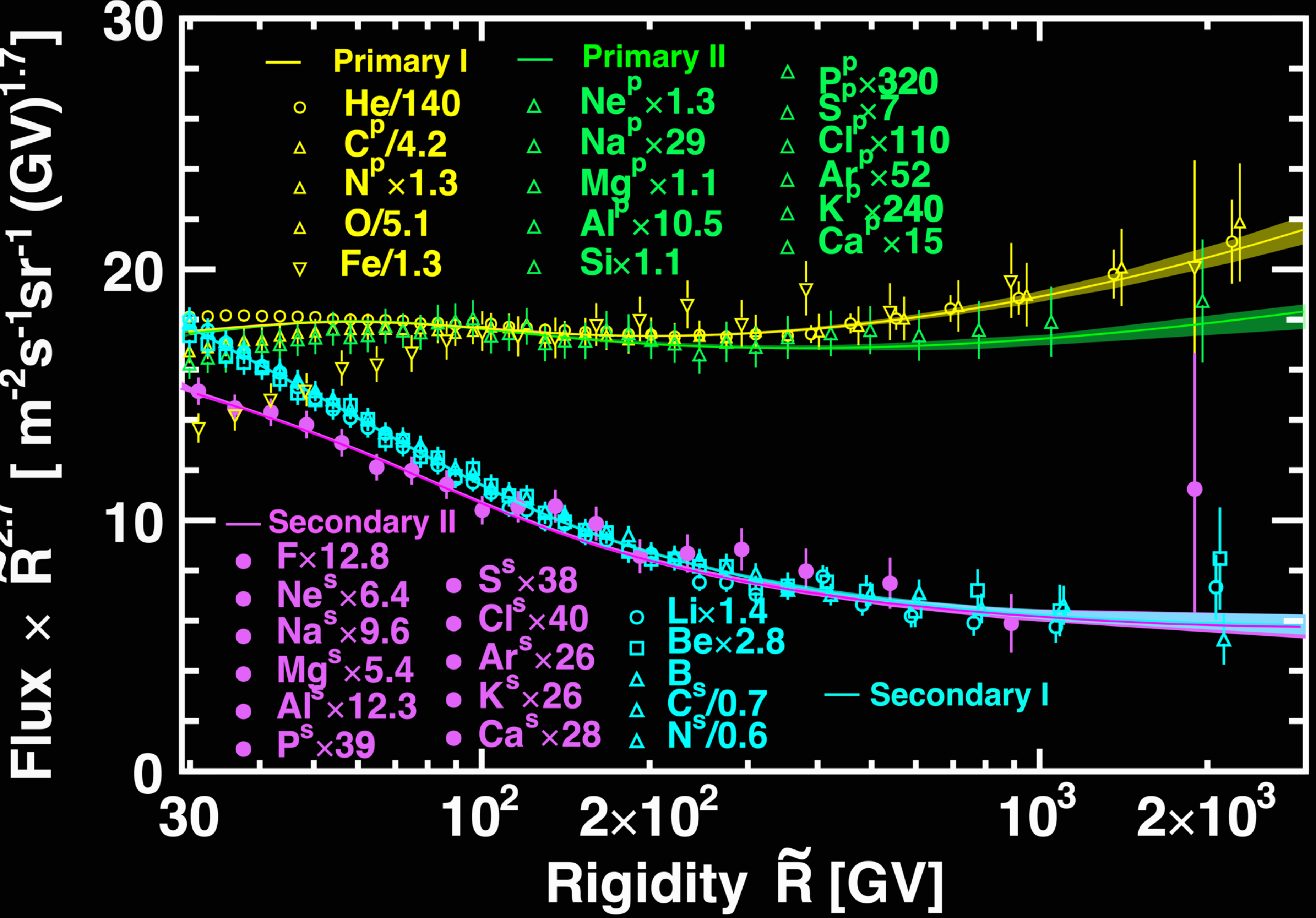

Phosphorus
Interstellar medium
Nuclear fusion
Periodic Table of the Elements
$\Phi \times R^{2.7}$ [$m^{-2}s^{-1}sr^{-1}$ $GV^{1.7}$]
0.6
0.4
0.2
6 10 20 30 Rigidity [GV] 10^2 2×10^2 10^3


Sulfur
Interstellar medium
Nuclear fusion
Periodic Table of the Elements
$\Phi \times \tilde{R}^{2.7}$ [$m^{-2}s^{-1}sr^{-1}$ $GV^{1.7}$]
5
4
3
2
1
3 4 5 10 20 Rigidity [GV] 10^2 2×10^2 10^3 2×10^3


Chlorine
Interstellar medium
Nuclear fusion
Periodic Table of the Elements
$\Phi \times \tilde{R}^{2.7}$ [$m^{-2}s^{-1}sr^{-1}$ $GV^{1.7}$]
0.8
0.6
0.4
0.2
6 10 20 30 Rigidity [GV] 10^2 2×10^2 10^3

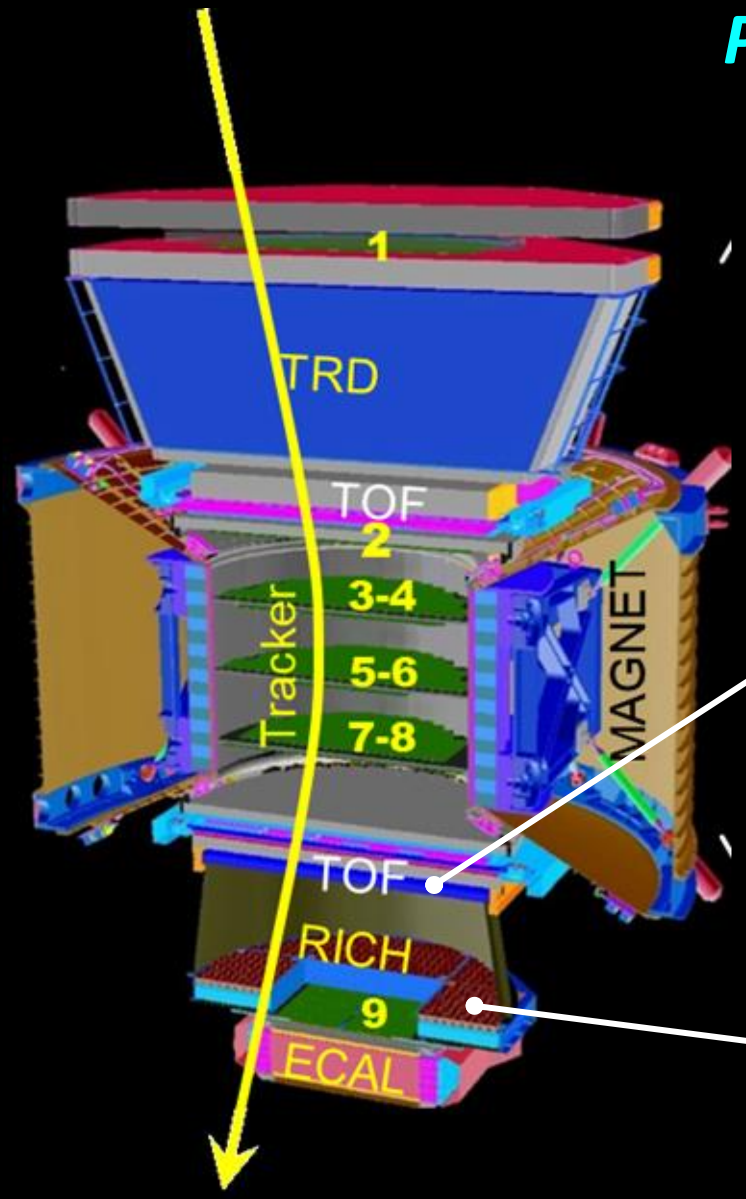

Argon
Interstellar medium
Nuclear fusion
Rigidity [GV]
Potassium
Interstellar medium
Nuclear fusion
Rigidity [GV]
Calcium
Interstellar medium
Nuclear fusion
Rigidity [GV]
Iron
Nuclear fusion
Rigidity [GV]
Periodic Table of the Elements

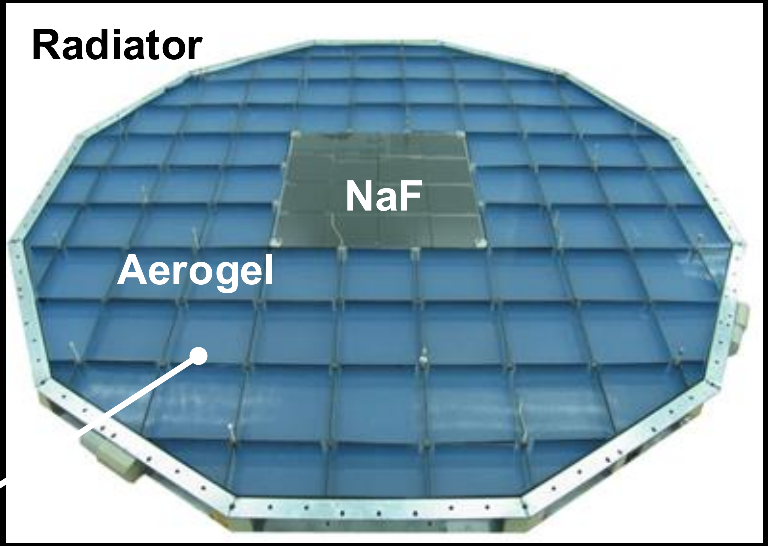
Cosmic elements can be categorized into four classes



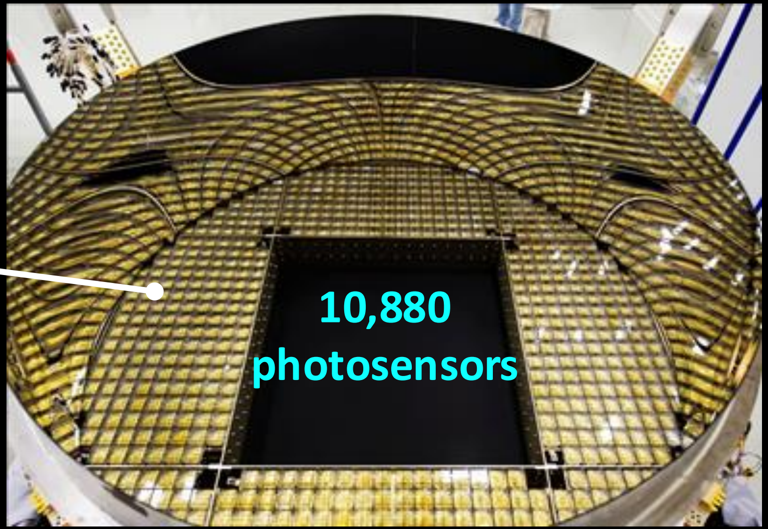
Precision measurement of isotopes

P=mv, isotopes: Same Z, different m

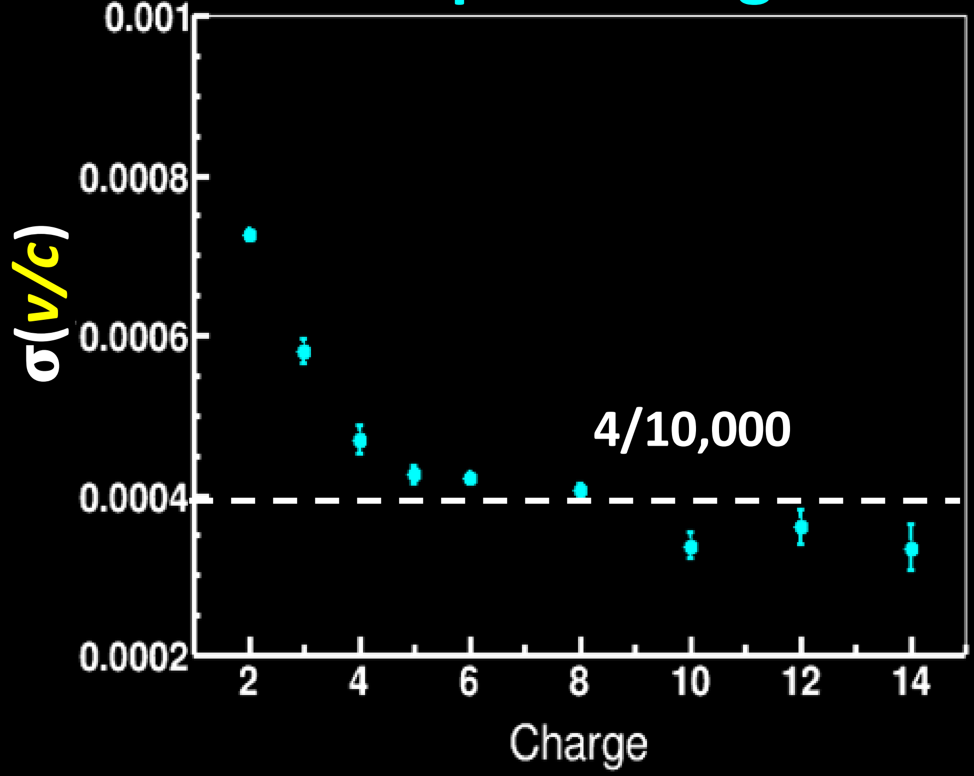




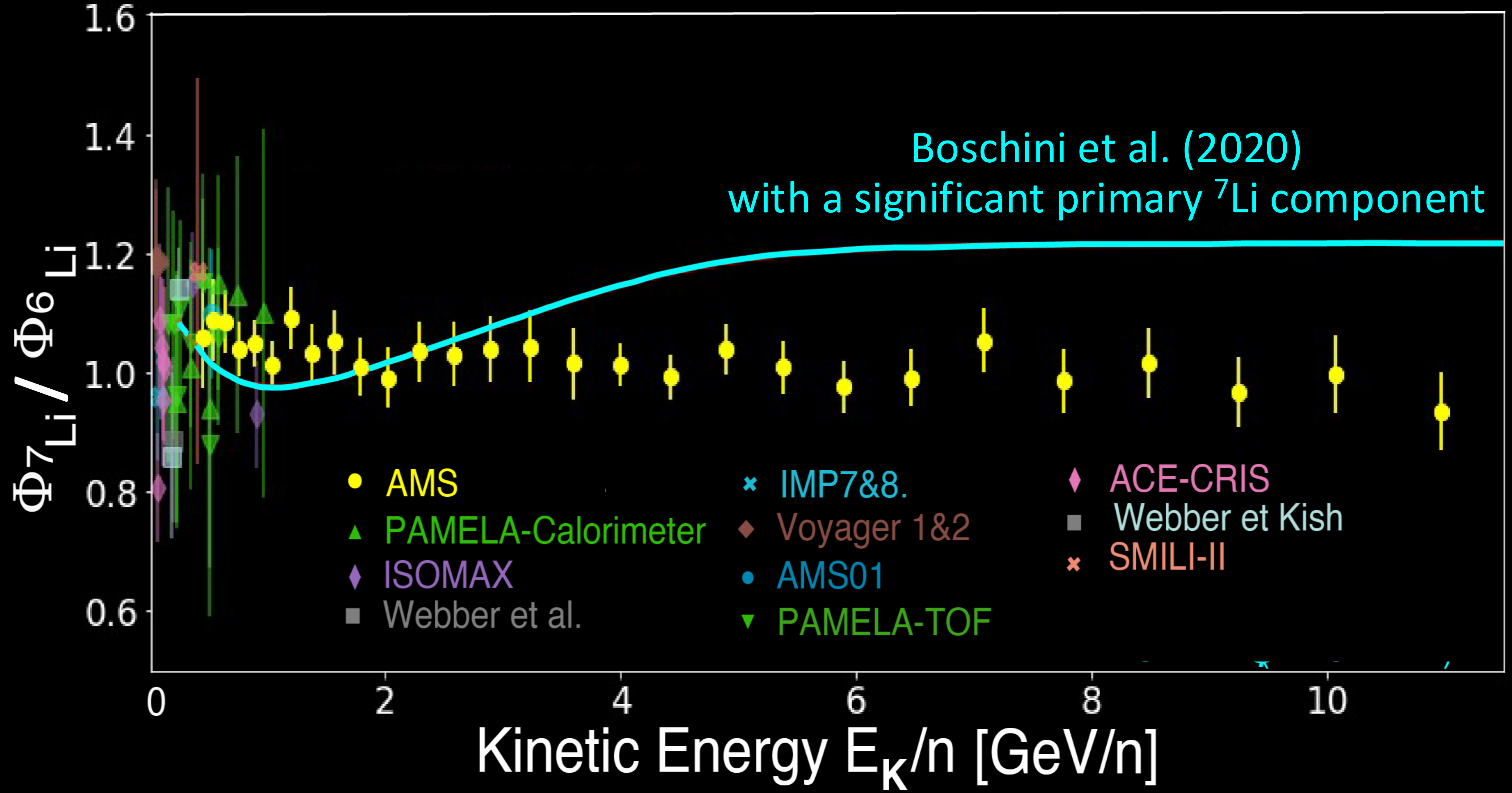
Ring Imaging CHerenkov (RICH)



RICH velocity *v* resolution at the speed of light *c*



Results on Lithium Isotopes (Editors' Suggestion, Viewpoint in *Physics*)
Phys. Rev. Lett. 134, 201001 (20 May 2025)

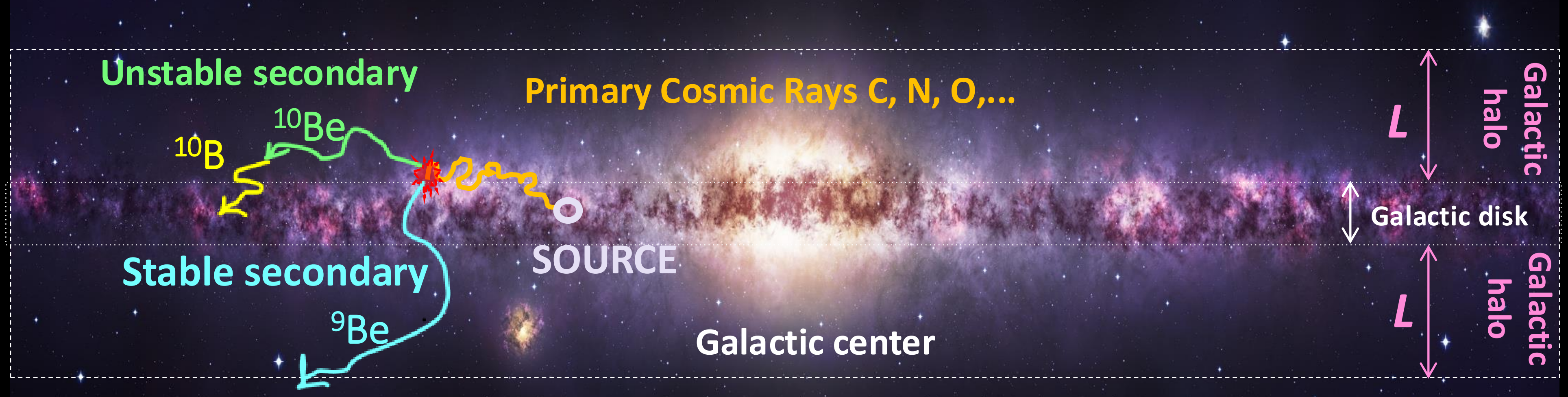


^{7}Li has no primary component

New Results on Beryllium Isotopes

^{7}Be, ^{9}Be, and ^{10}Be

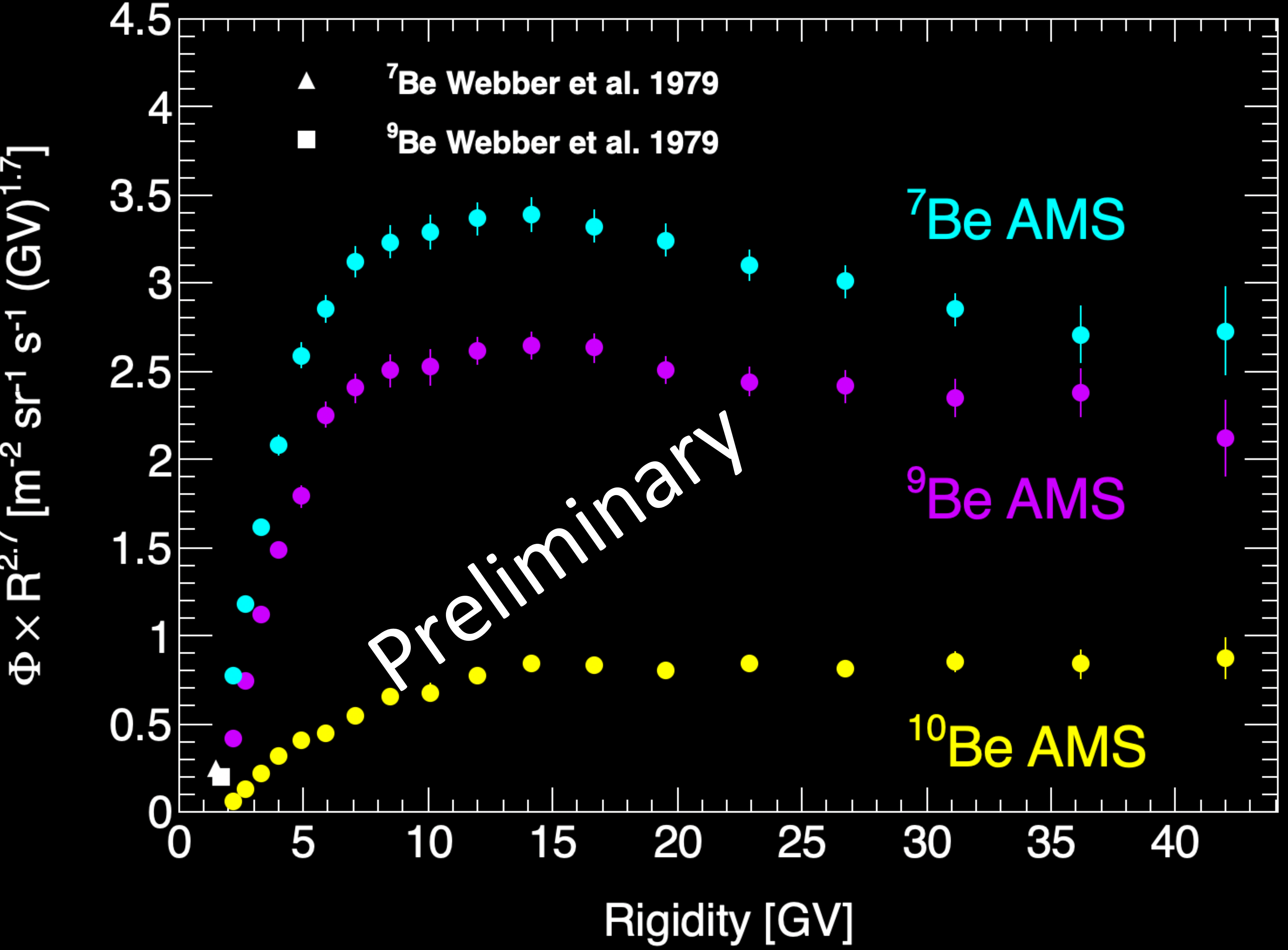
Stable ^{9}Be propagate in the entire galactic halo
while ^{10}Be decay to ^{10}B before reaching the boundary of the Galaxy.



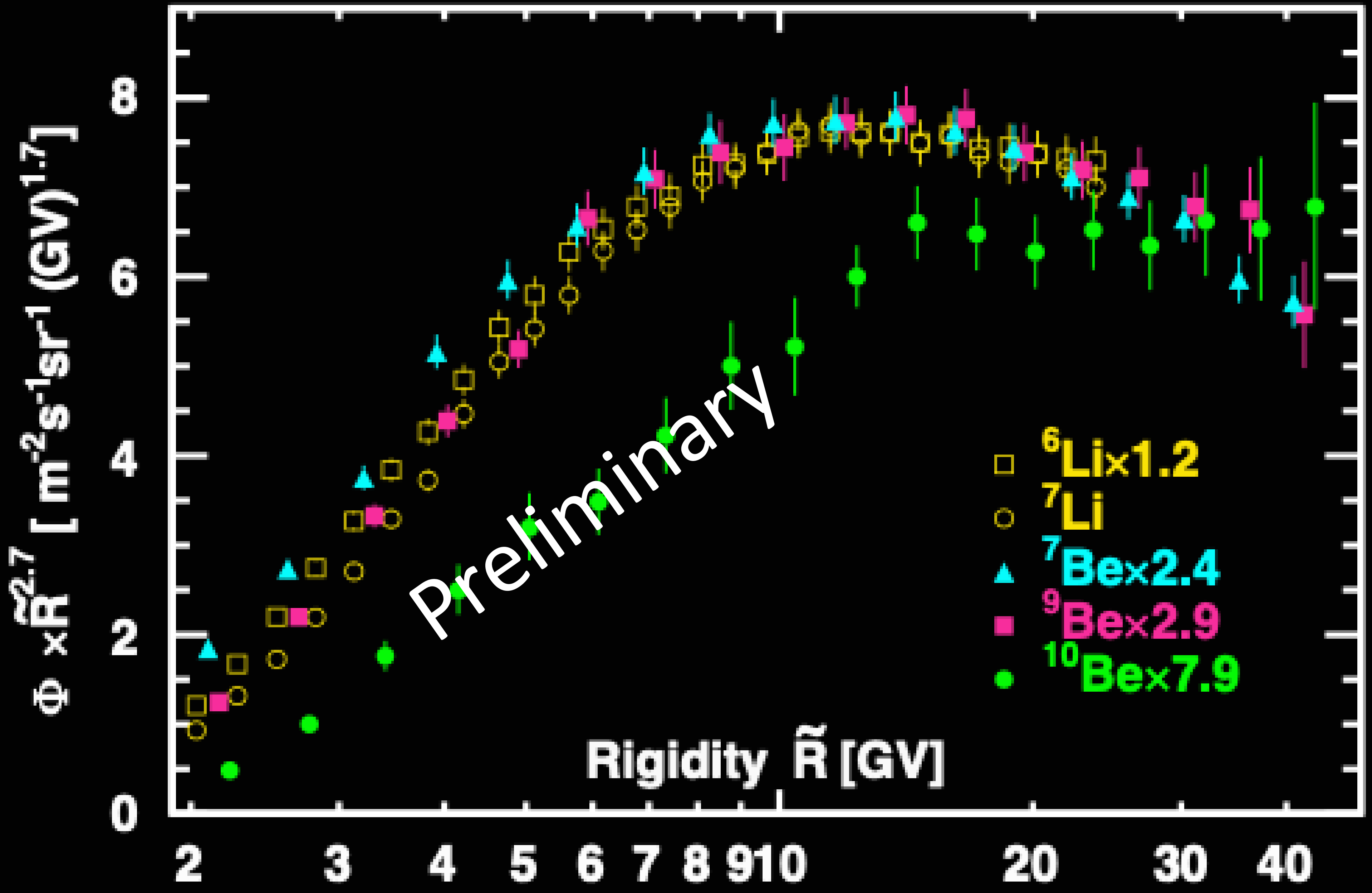
The ratio of unstable-to-stable, $^{10}Be/^{9}Be$, measures the Galactic halo size ***L***

L determines the galactic cosmic ray propagation (or diffusion) volume.

Be isotope fluxes

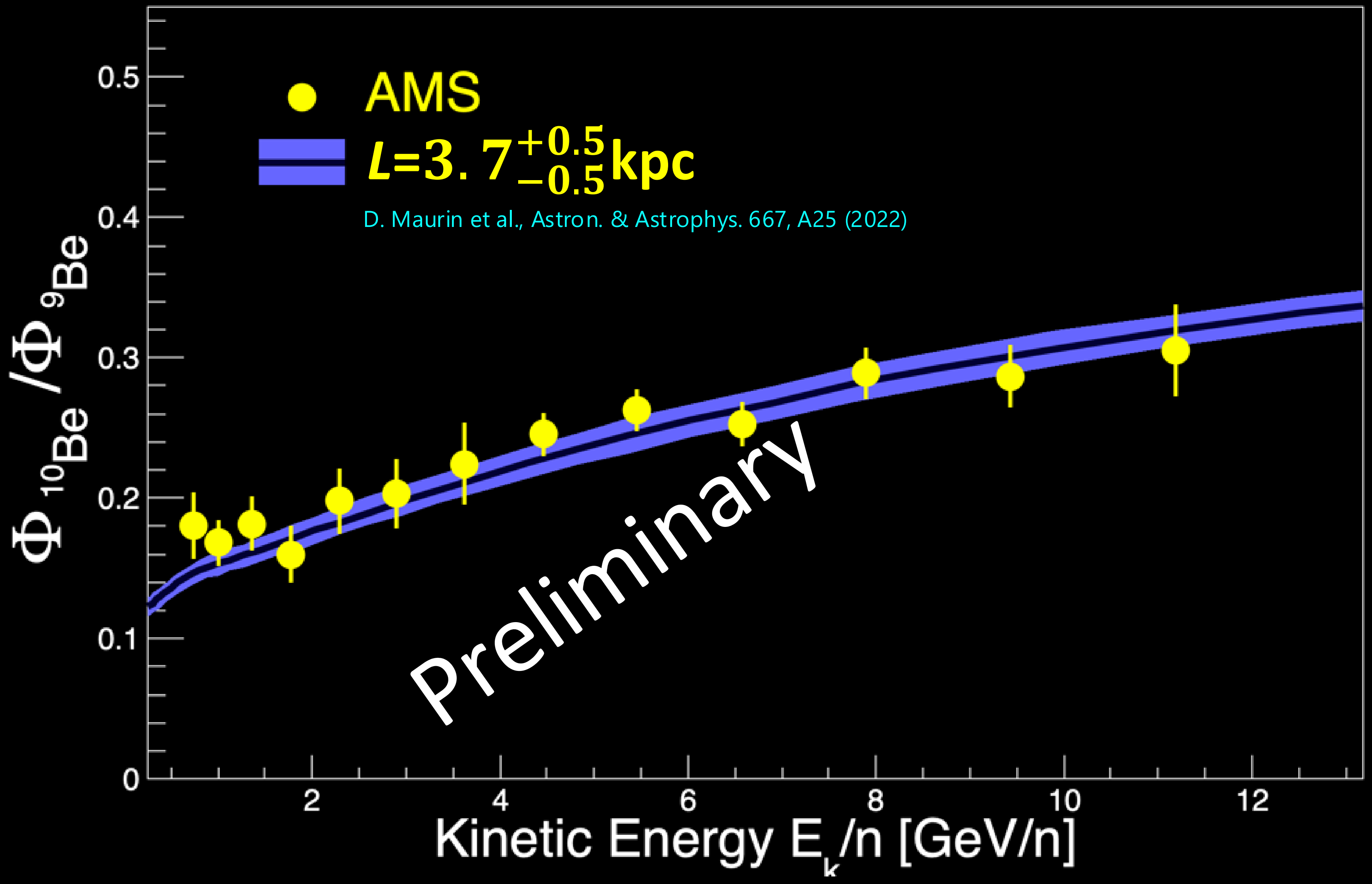


Li+Be



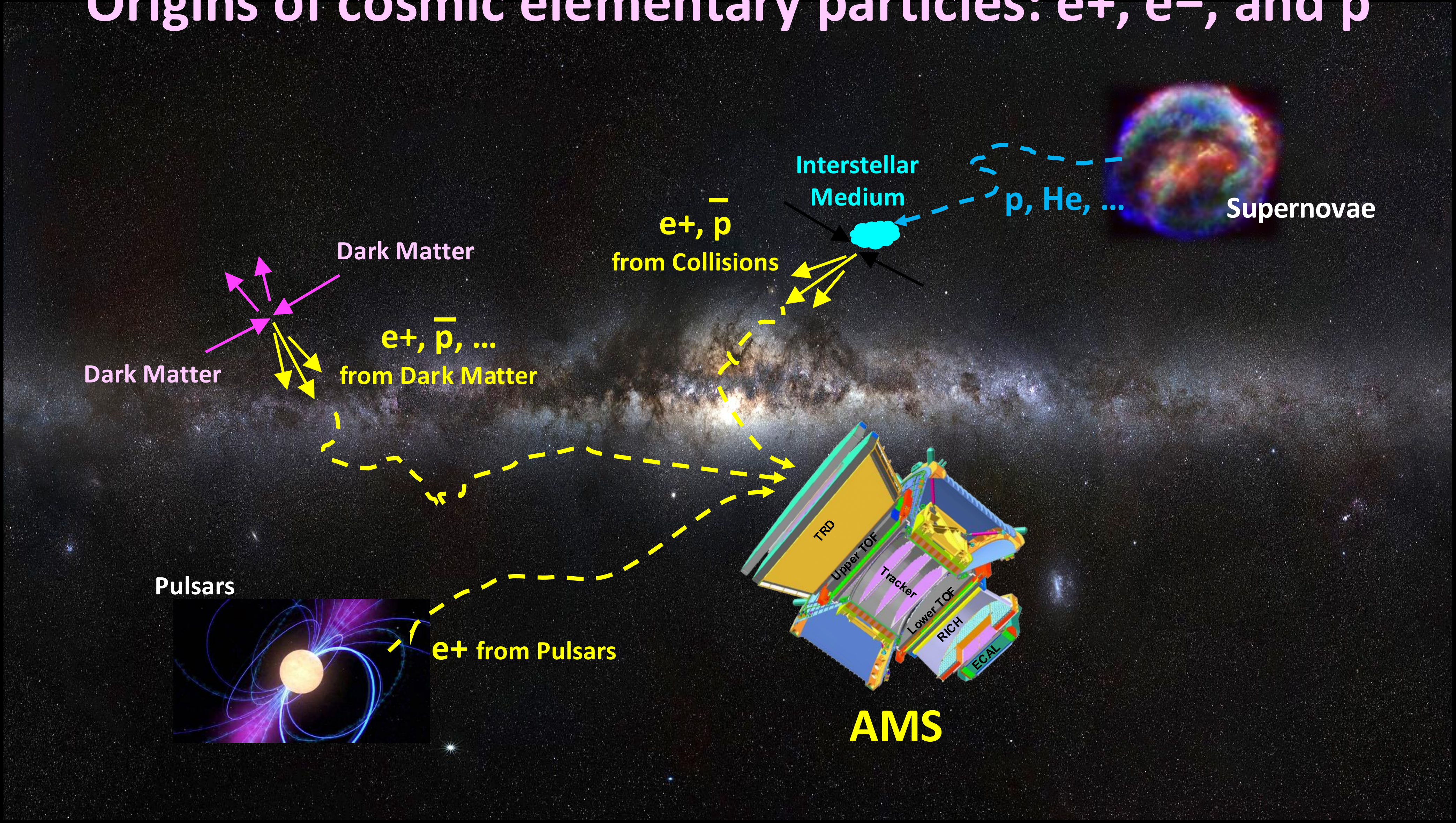
Φ × R̃^2.7 [m^-2s^-1sr^-1 (GV)^1.7]
0
2
4
6
8
Rigidity R̃ [GV]
2
3
4
5
6
7
8
9
10
20
30
40
Preliminary
6Li×1.2
7Li
7Be×2.4
9Be×2.9
10Be×7.9

AMS Measurement of the galactic halo size *L*

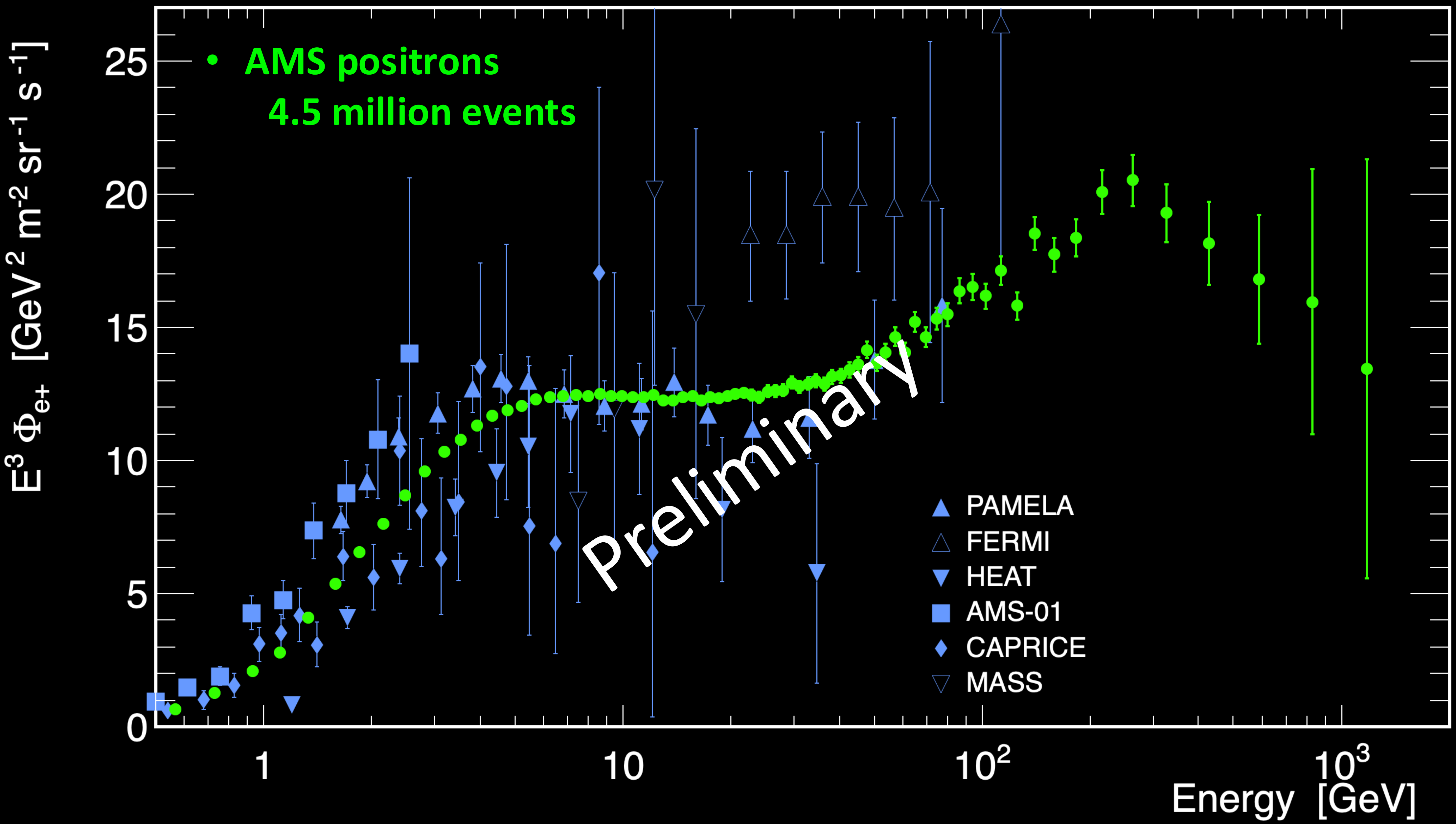


The model that fits the AMS measurement has a halo size ***L*** of $3.7^{+0.5}_{-0.5}$ kiloparsecs

Origins of cosmic elementary particles: e+, e−, and $\bar{p}$



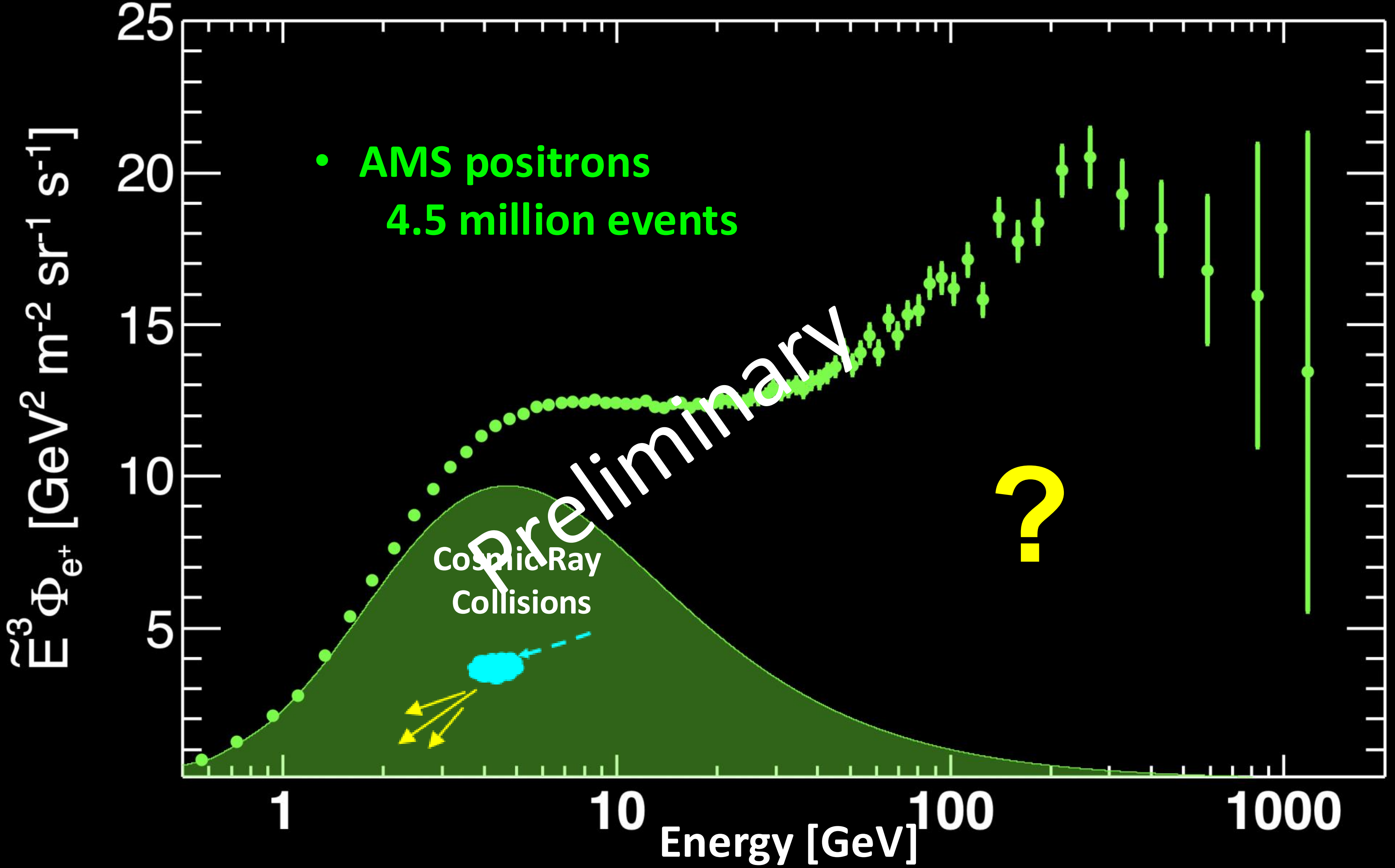
Current Positron Spectra



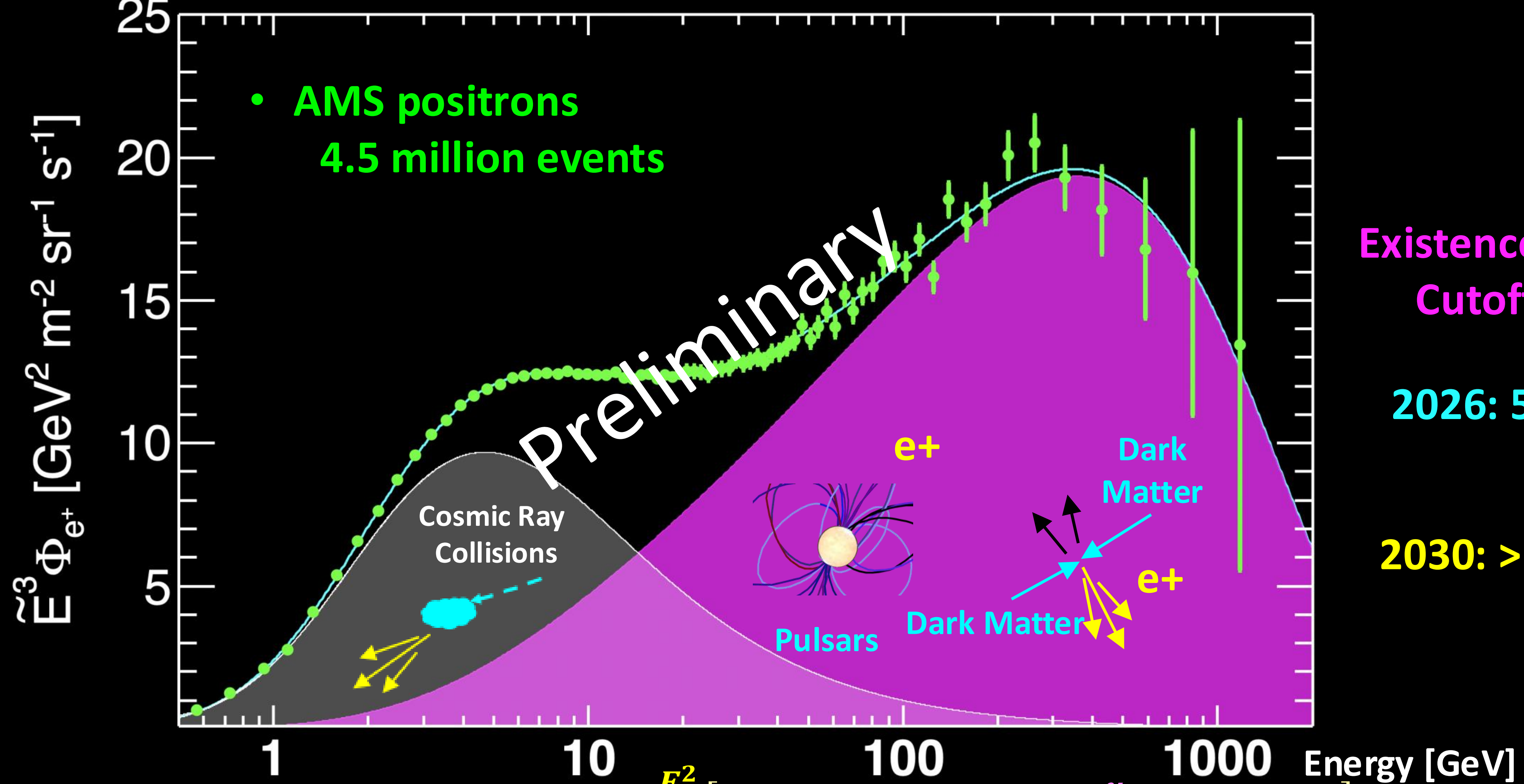
Physics of Dark Matter

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



Existence of Cutoff

2026: 5σ

2030: >6σ

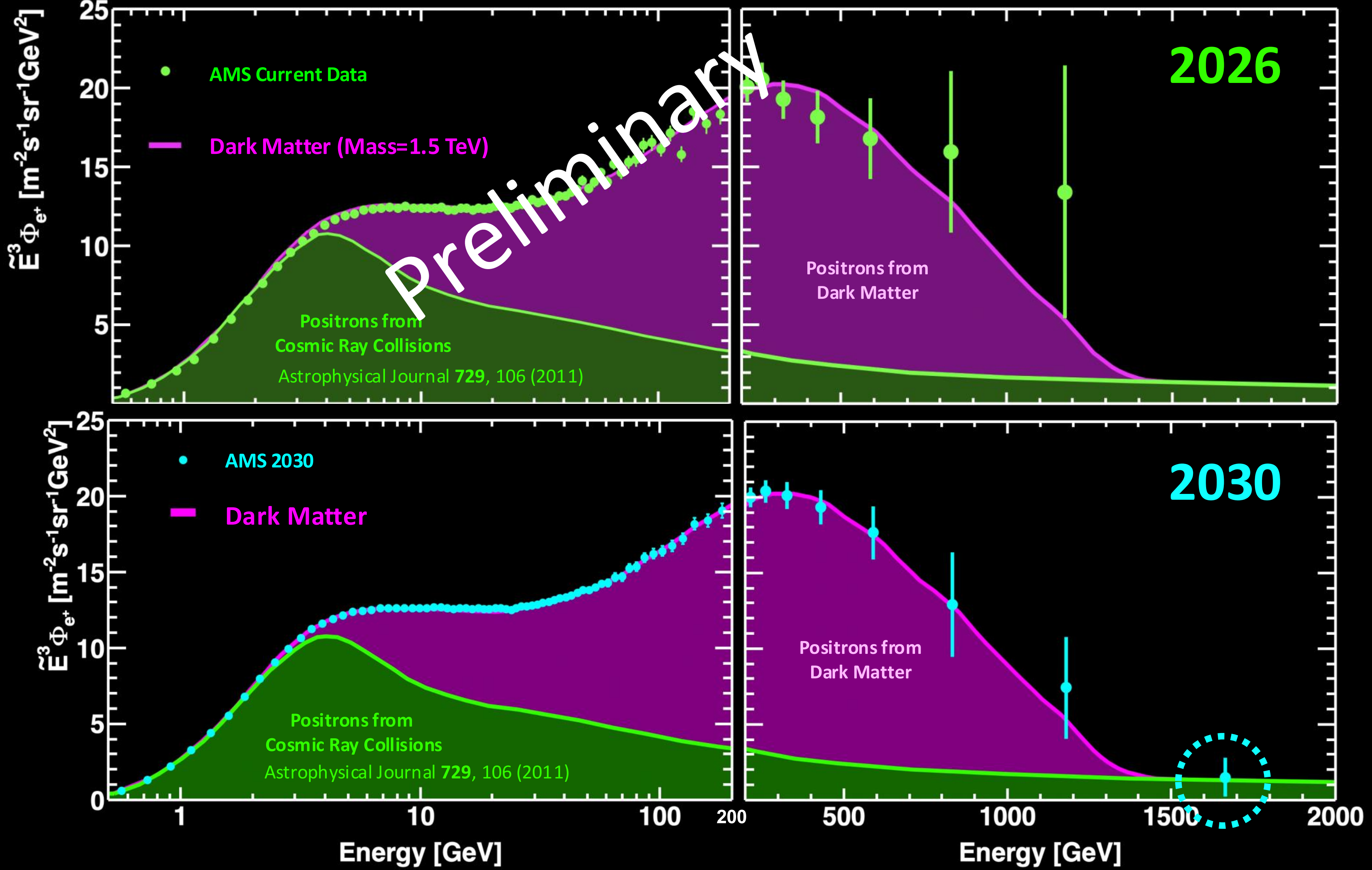
Empirical model:

χ^2/dof = 40/66

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

Solar Collisions Pulsars or Dark Matter

Physics of Dark Matter: AMS Positron Spectrum through 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 in dark matter model

Physics of Dark Matter: AMS Result on the electron spectrum

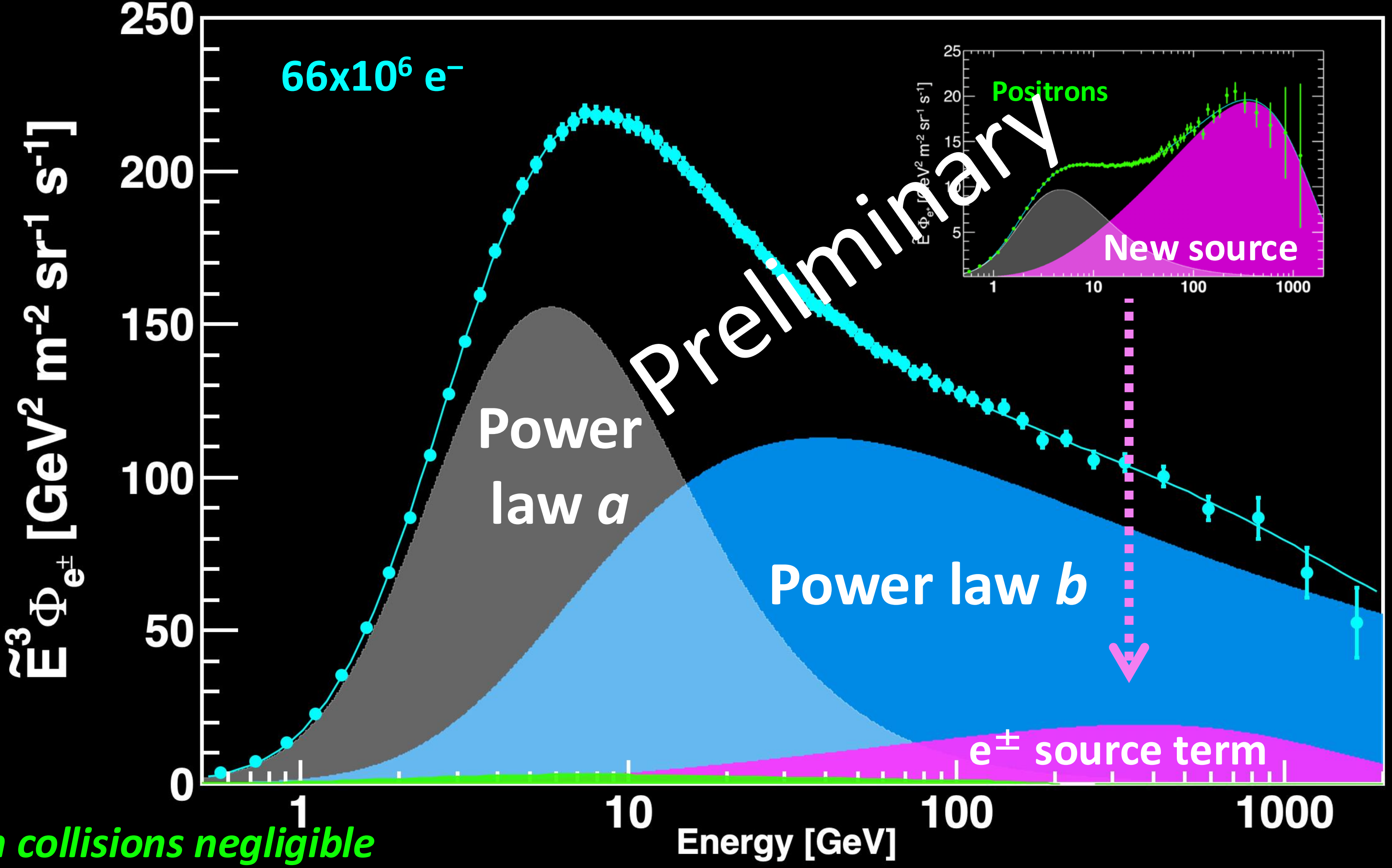
The spectrum fits well with two power laws (*a*, *b*) and the measured positron source term

Empirical model:

χ^2/dof = 25/67

$$\Phi_{e^-}(E) = \frac{E^2}{\widehat{E}^2}\left(C_a \widehat{E}^{\gamma_a} + C_b \widehat{E}^{\gamma_b} + \text{Positron Source Term}\right)$$

Solar Power law *a* Power law *b*



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

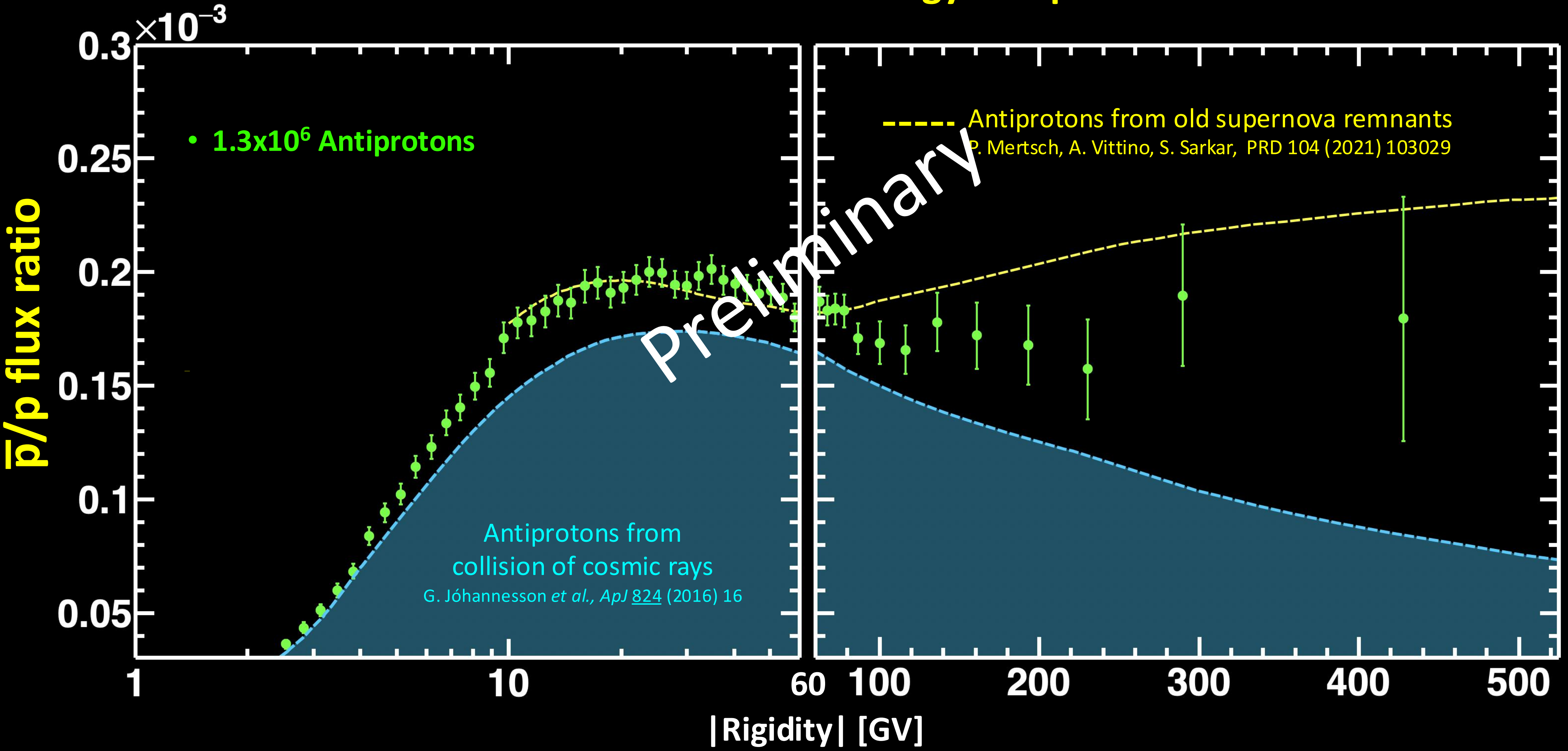
2.6 σ

4 σ in 2030

e⁻ from collisions negligible

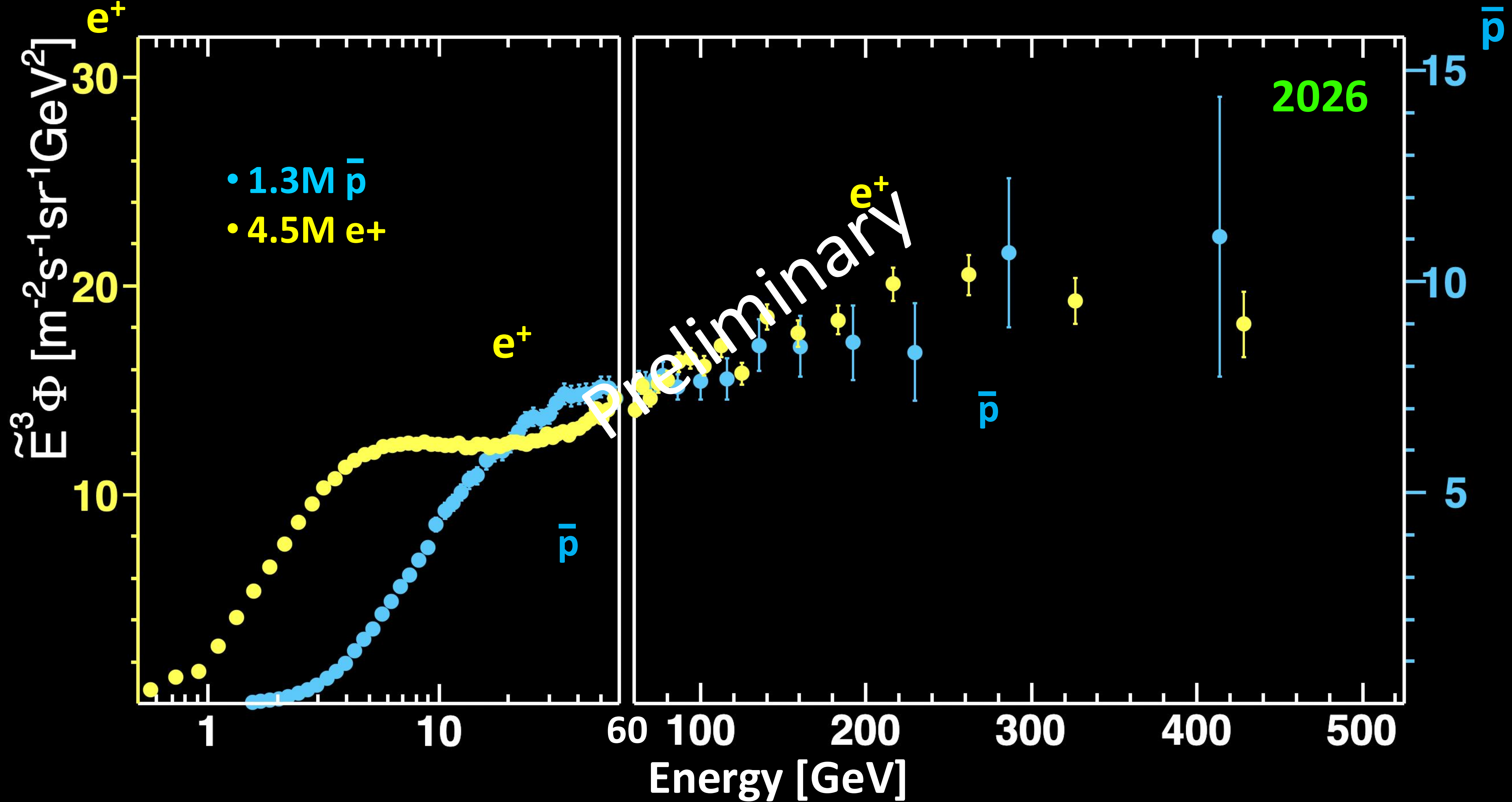
Physics of Dark Matter: Properties of Cosmic Antiprotons

The antiproton-to-proton flux ratio shows that above 60 GV the ratio is energy independent.



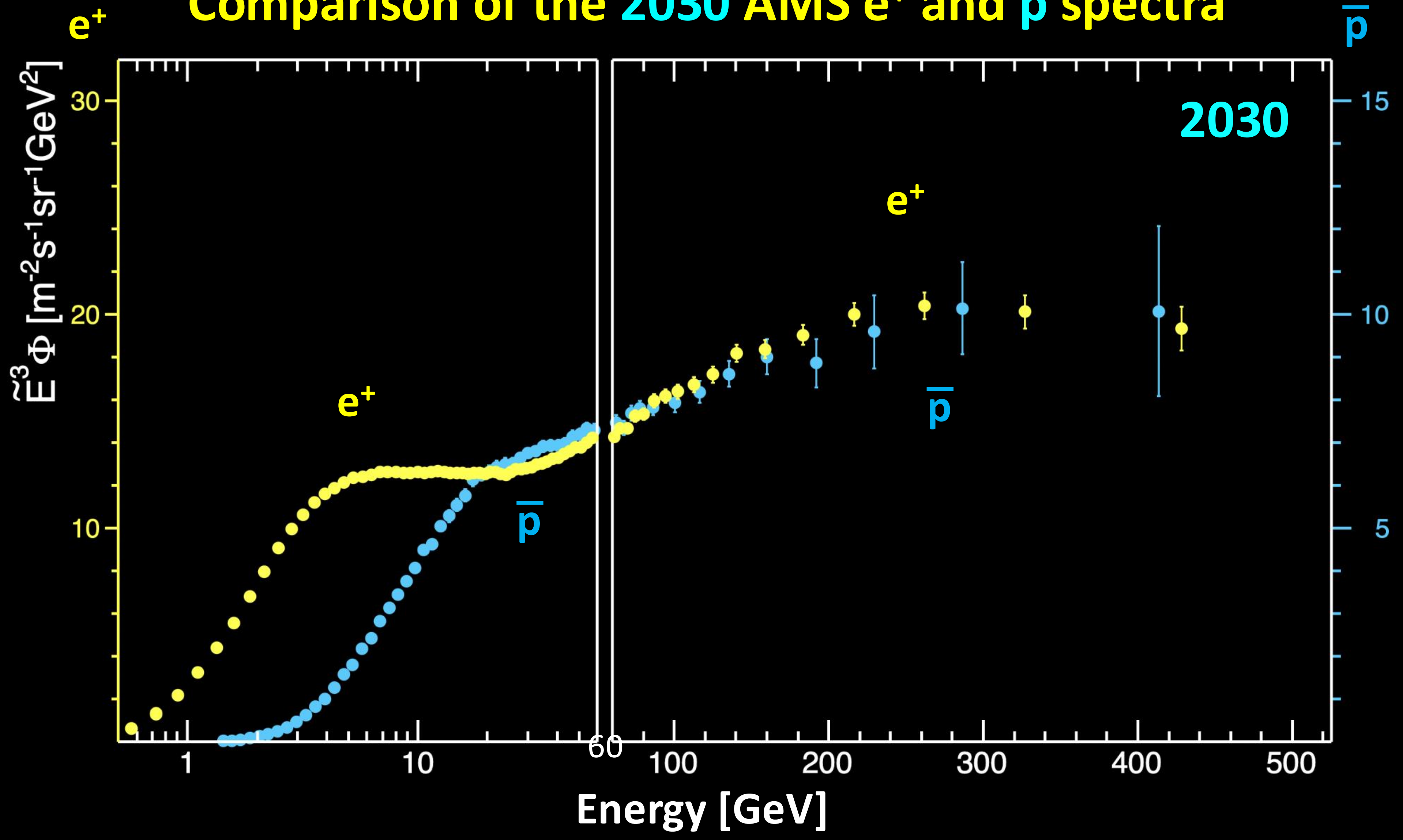
Physics of Dark Matter: Cosmic Antiprotons and Positrons

Above 60 GeV, the p̄ and e^+ fluxes have identical rigidity dependence



Physics of Dark Matter:

Comparison of the 2030 AMS e^+ and $\bar{p}$ spectra



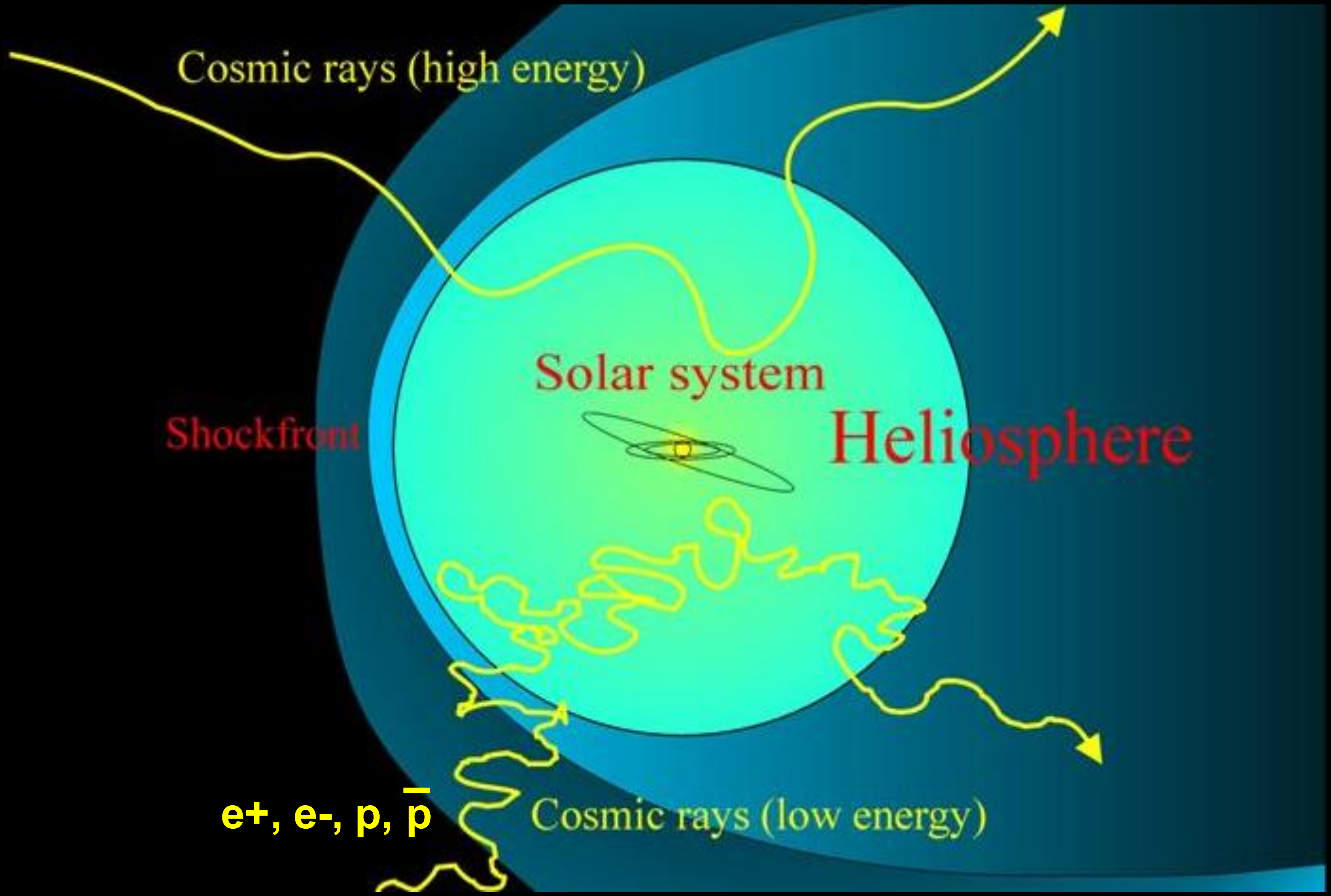
The identical behavior of positrons and antiprotons excludes the pulsar origin of positrons

AMS Publications in *Physical Review Letters*

8821 citations to date

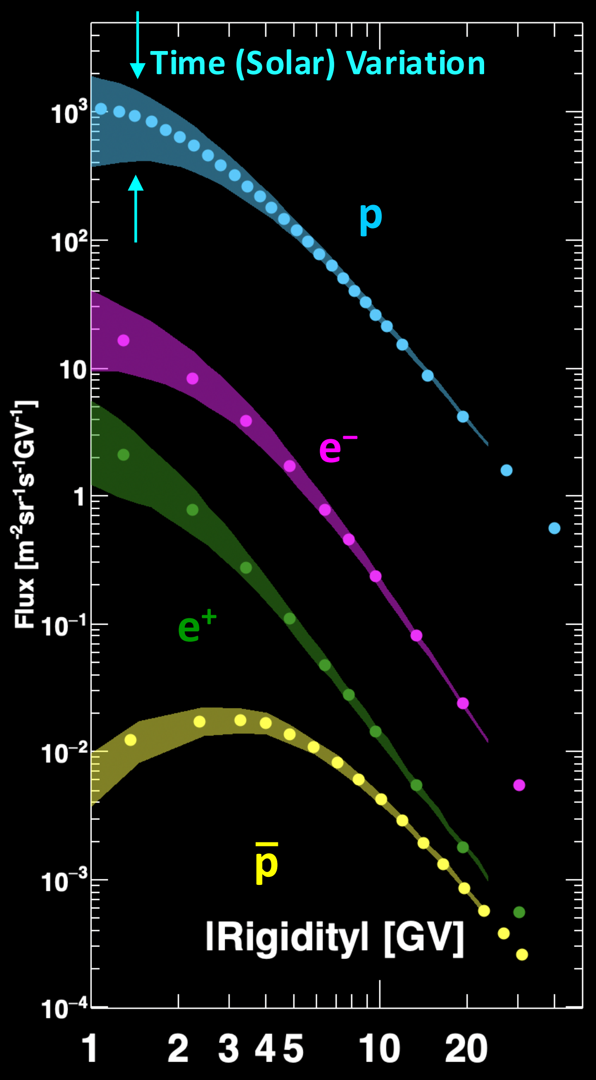
1) Phys. Rev. Lett. 110, 141102 (2013)	Editors' Suggestion.	Viewpoint in *Physics*.
2) Phys. Rev. Lett. 113, 121101 (2014)	Editors' Suggestion	
3) Phys. Rev. Lett. 113, 121102 (2014)	Editors' Suggestion.	Featured in *Physics*.
4) Phys. Rev. Lett. 113, 221102 (2014)		
5) Phys. Rev. Lett. 114, 171103 (2015)	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*.
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) Phys. Rev. Lett. 134, 051002 (2025)	Editors' Suggestion.	Viewpoint in *Physics*.
29) Phys. Rev. Lett. 134, 051001 (2025)		
30) Phys. Rev. Lett. 134, 201001 (2025)	Editors' Suggestion.	Featured in *Physics*.
31) Phys. Rev. Lett. "Cosmic Heavy Nuclei" (2026) - accepted		
32) Phys. Rev. Lett. "Beryllium Isotopes" (2026)		
33) Phys. Rev. Lett. "Boron Isotopes" (2026)		
34) Phys. Rev. Lett. "Nitrogen Isotopes" (2026)		

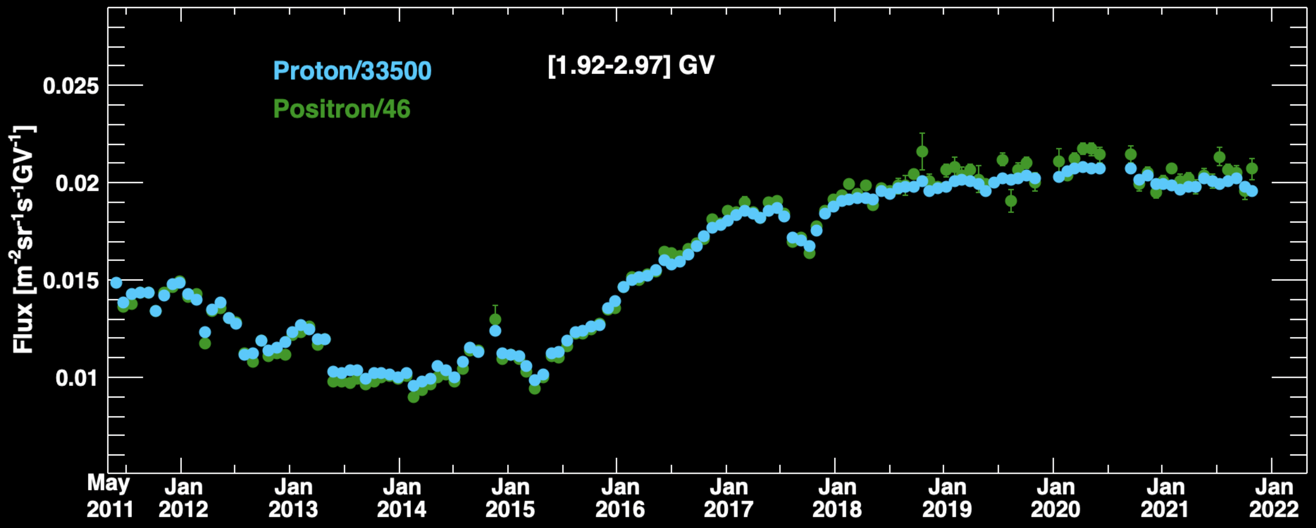
Latest AMS Results on Elementary Particles (e+, e-, p, $\bar{p}$, …) in the Heliosphere over an 11-year Solar Cycle (2011-2022)

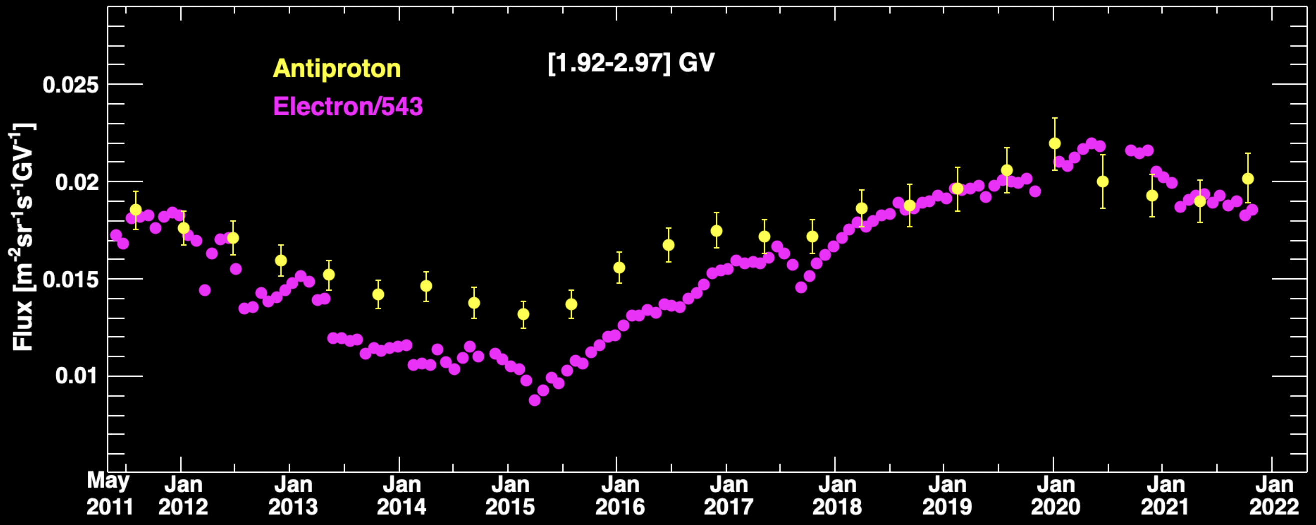


By 2030, AMS will study Heliosphere physics over 22-year Solar Cycle

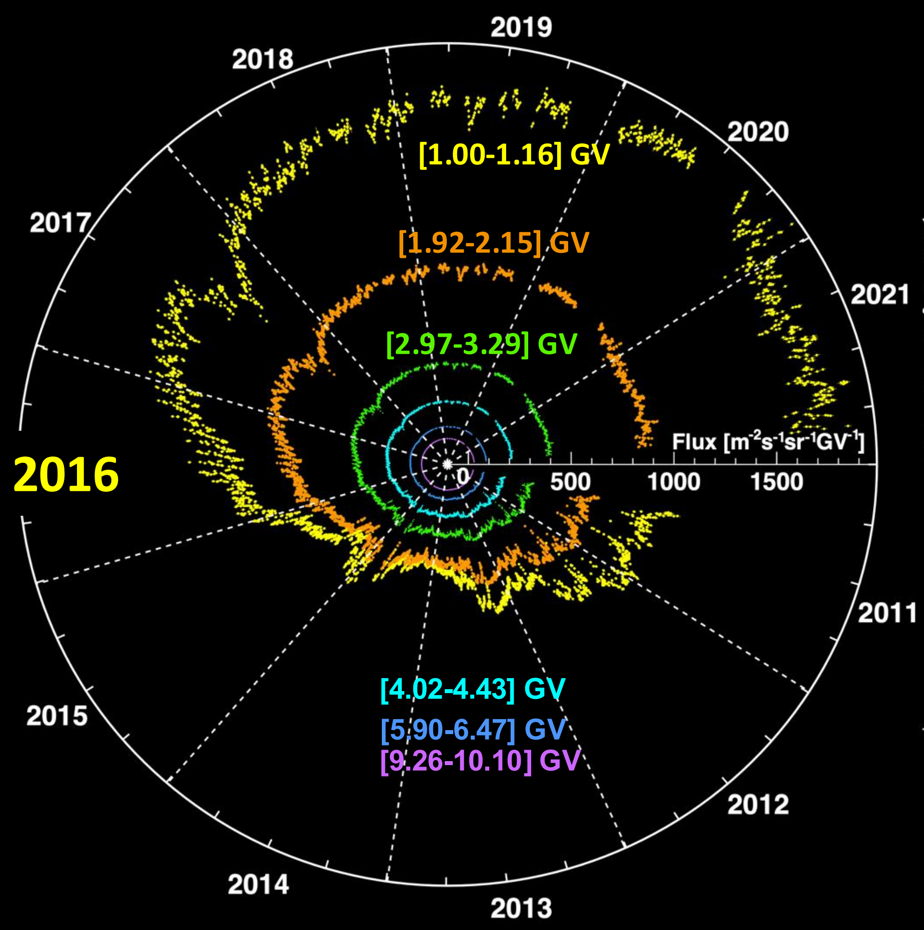
Elementary Particles (e+, e-, p, $\bar{p}$, …)
in the Heliosphere over an 11-year Solar Cycle (2011-2022)





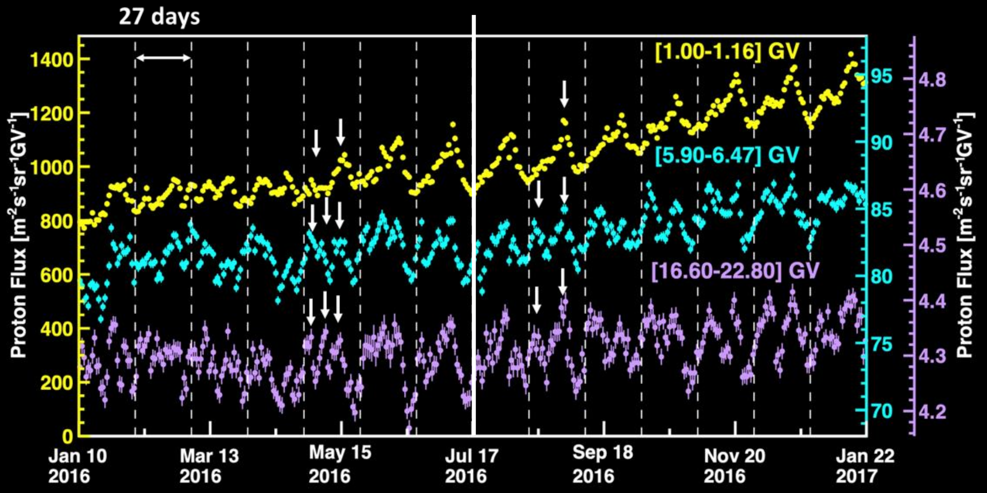


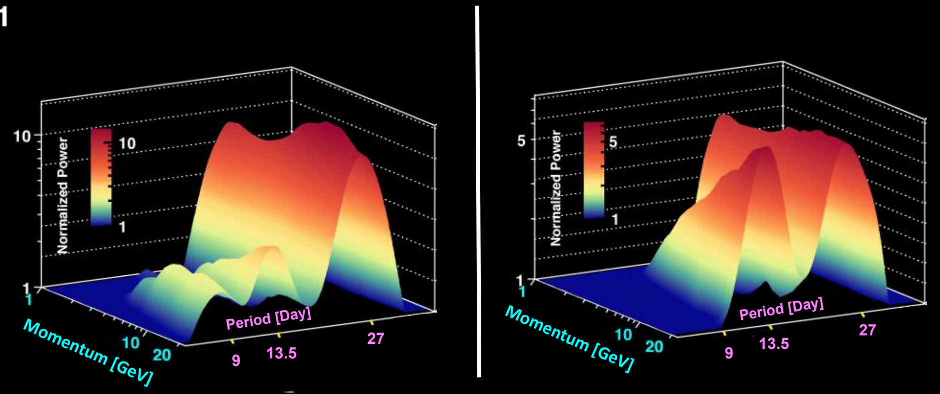
Daily Protons in the Heliosphere



Frequency Analysis of daily fluxes in 2016

Double-peak and triple-peak structures are visible

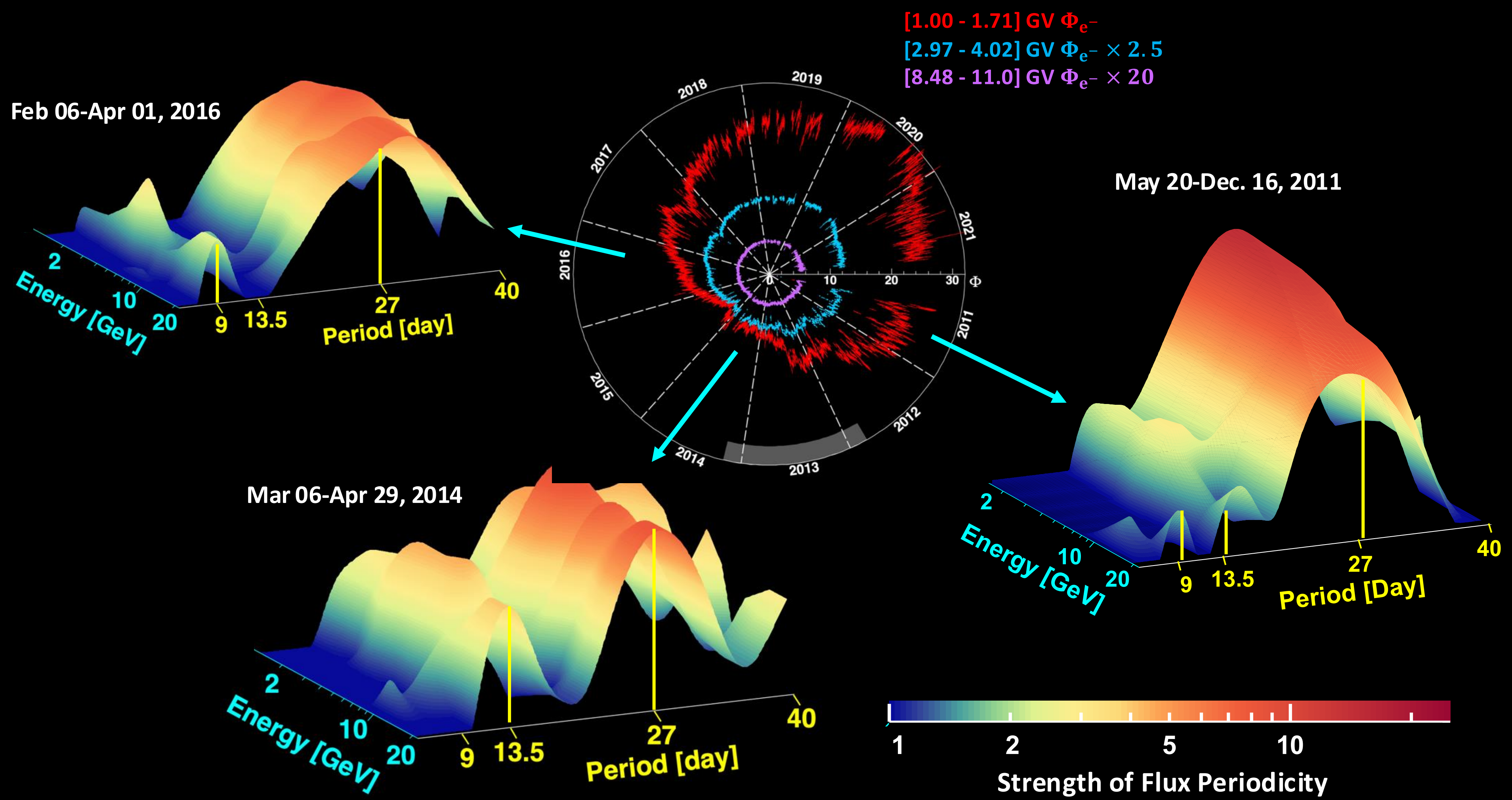




Recurrent variations with periods of 27, 13.5, and 9 days are observed.
Unexpectedly, in 2016, the strength of the 9 and 13.5 periodicity increases with increasing rigidity up to 10 and 20 GeV, respectively.

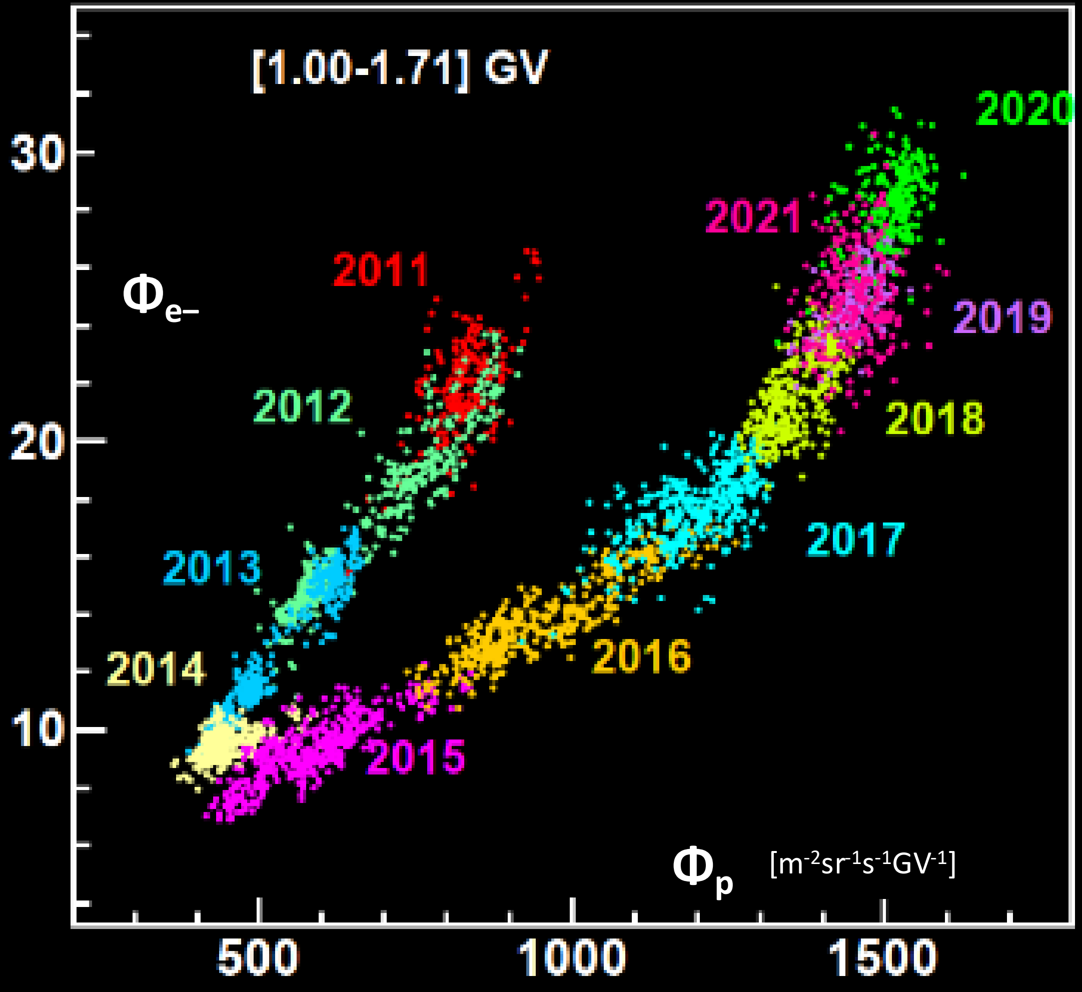
The model expects the strength of the periodicity to decrease with increasing rigidity.

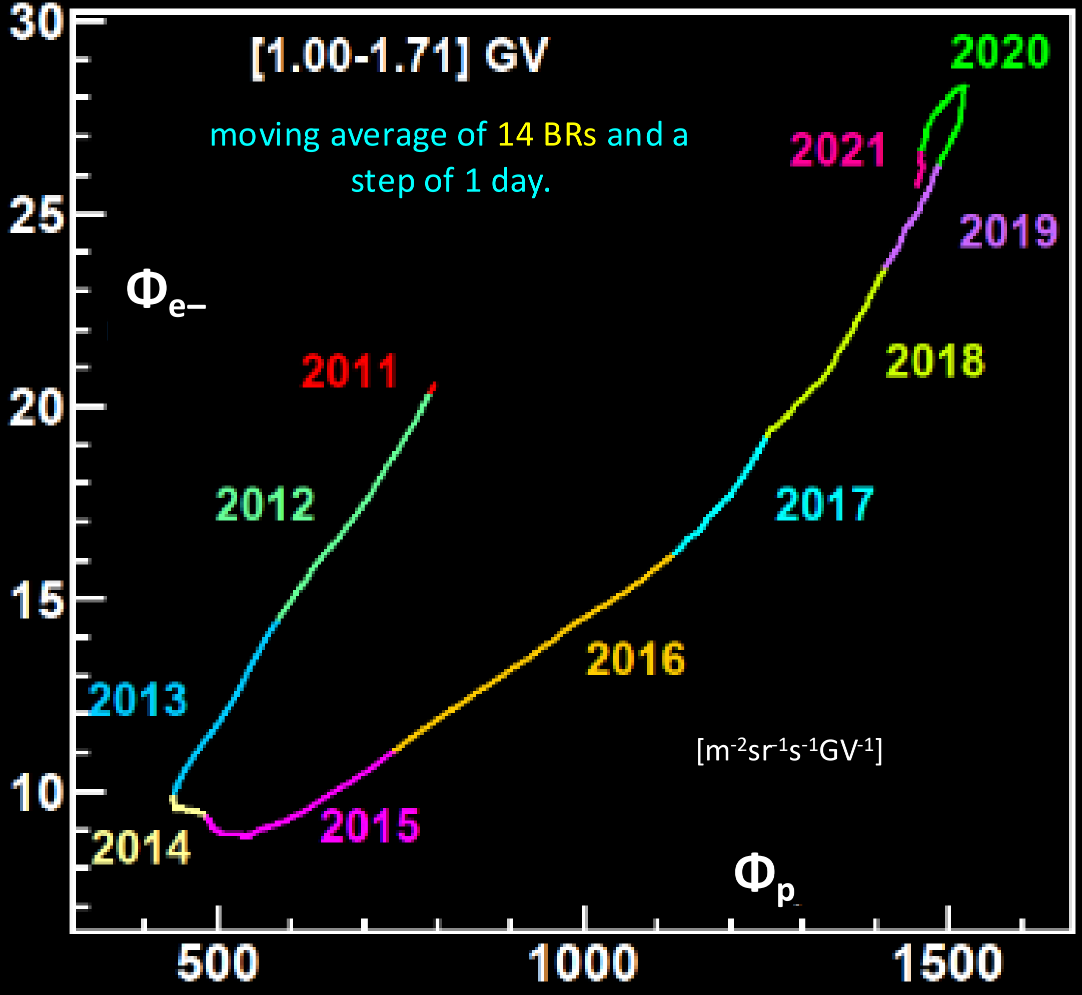
First Observation of Periodicity in the Daily Electron Flux in the Heliosphere



Elementary Particles in the Heliosphere

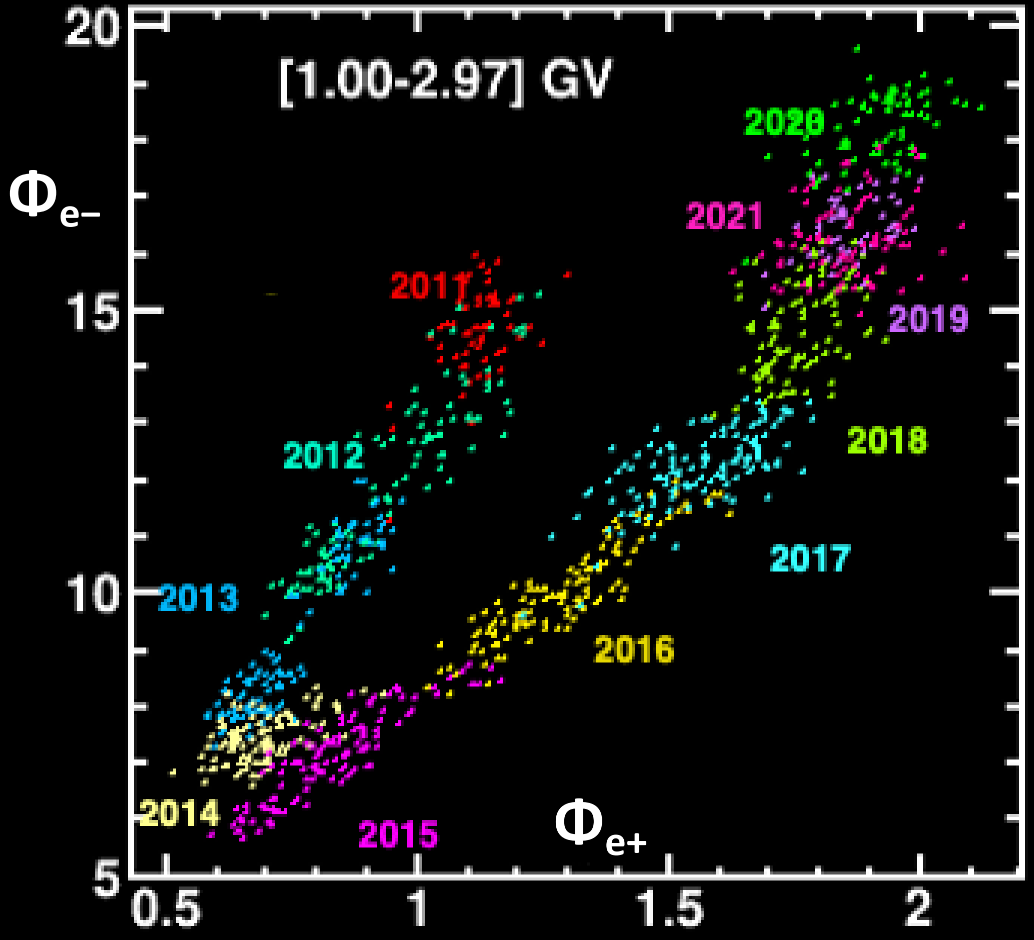
Observation of a hysteresis between daily electron flux Φ_{e-} and daily proton flux Φ_p



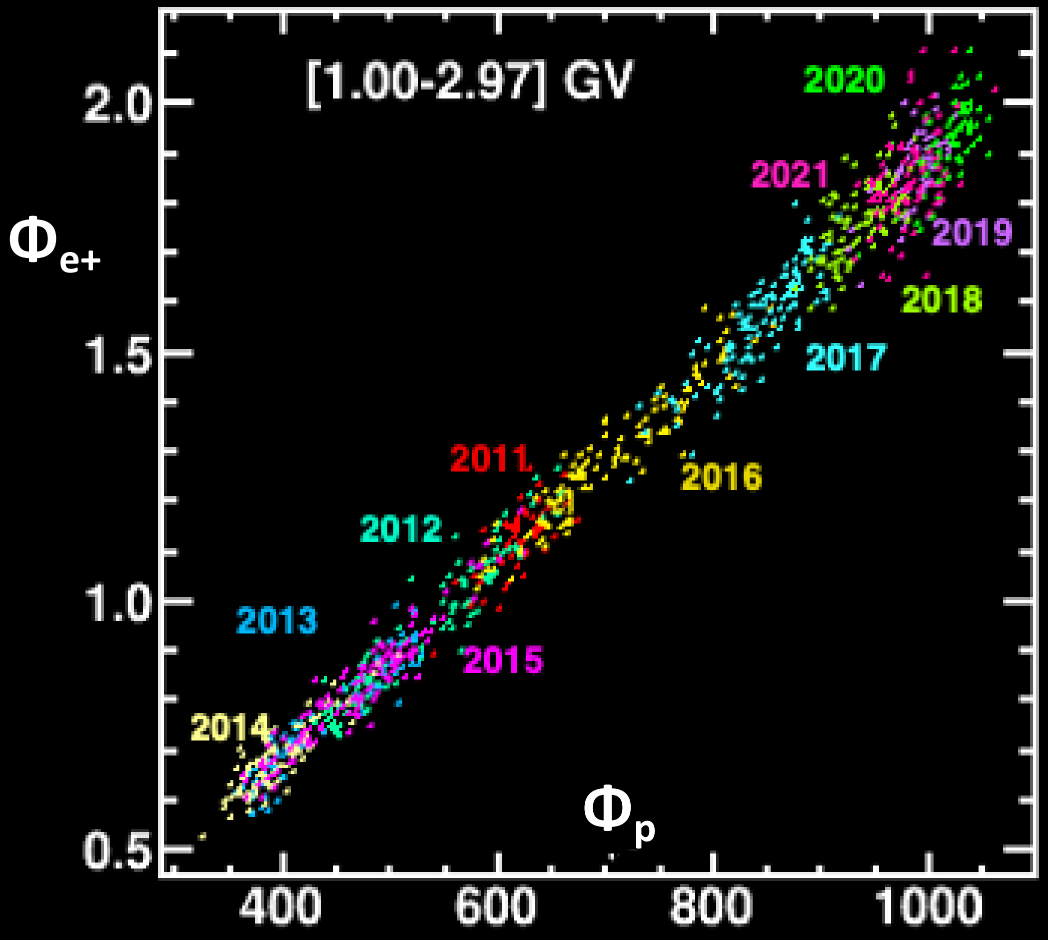


Relationship between charge and mass

Equal mass, Opposite charge



Equal charge, different mass



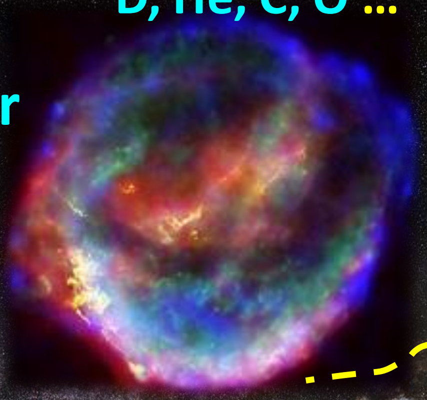
Latest AMS Results on Heavy Antimatter

Matter is defined by its mass *M* and charge *Z*.

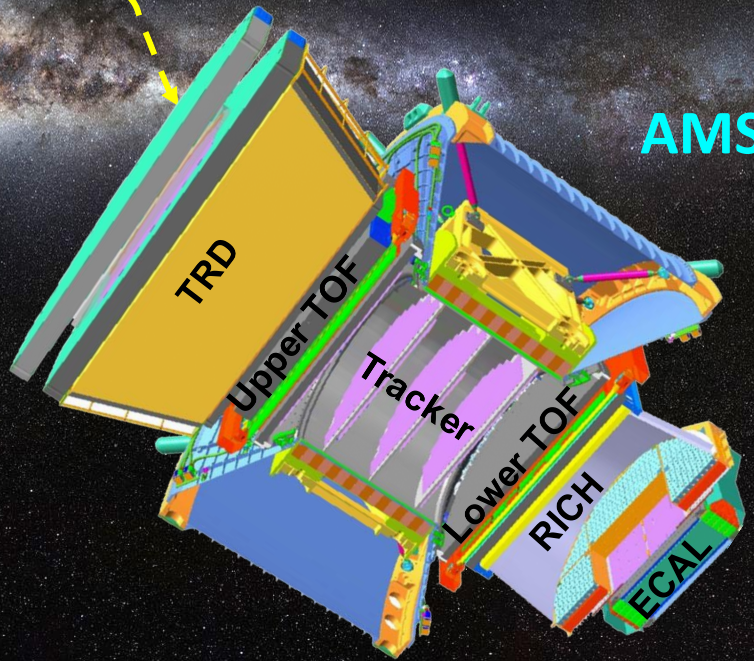
Antimatter has the same mass *M* but opposite charge –*Z*.

$\overline{D}$, $\overline{He}$, $\overline{C}$, $\overline{O}$ ...

Antimatter Star

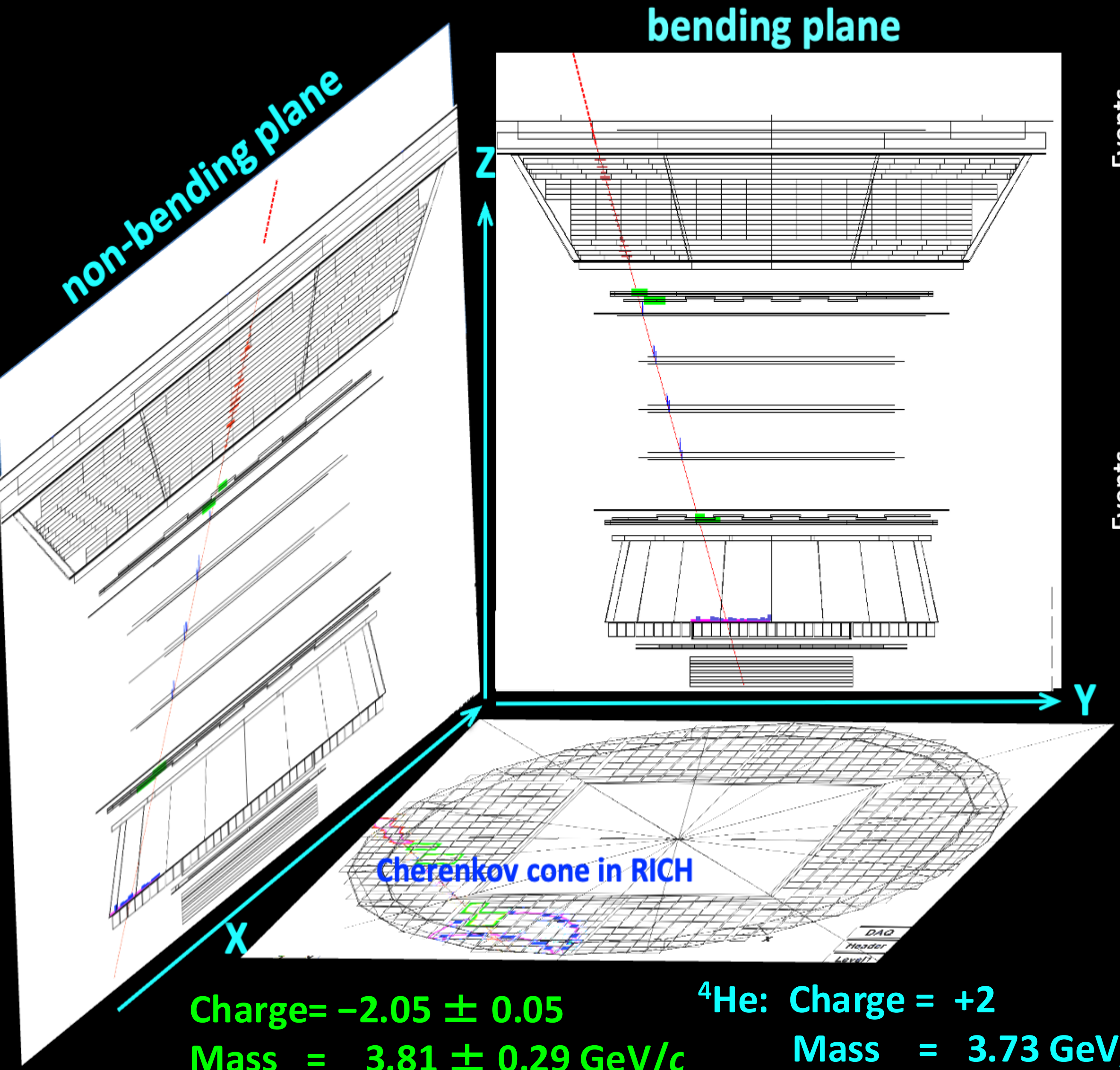


AMS on ISS



AMS is a unique antimatter spectrometer in space

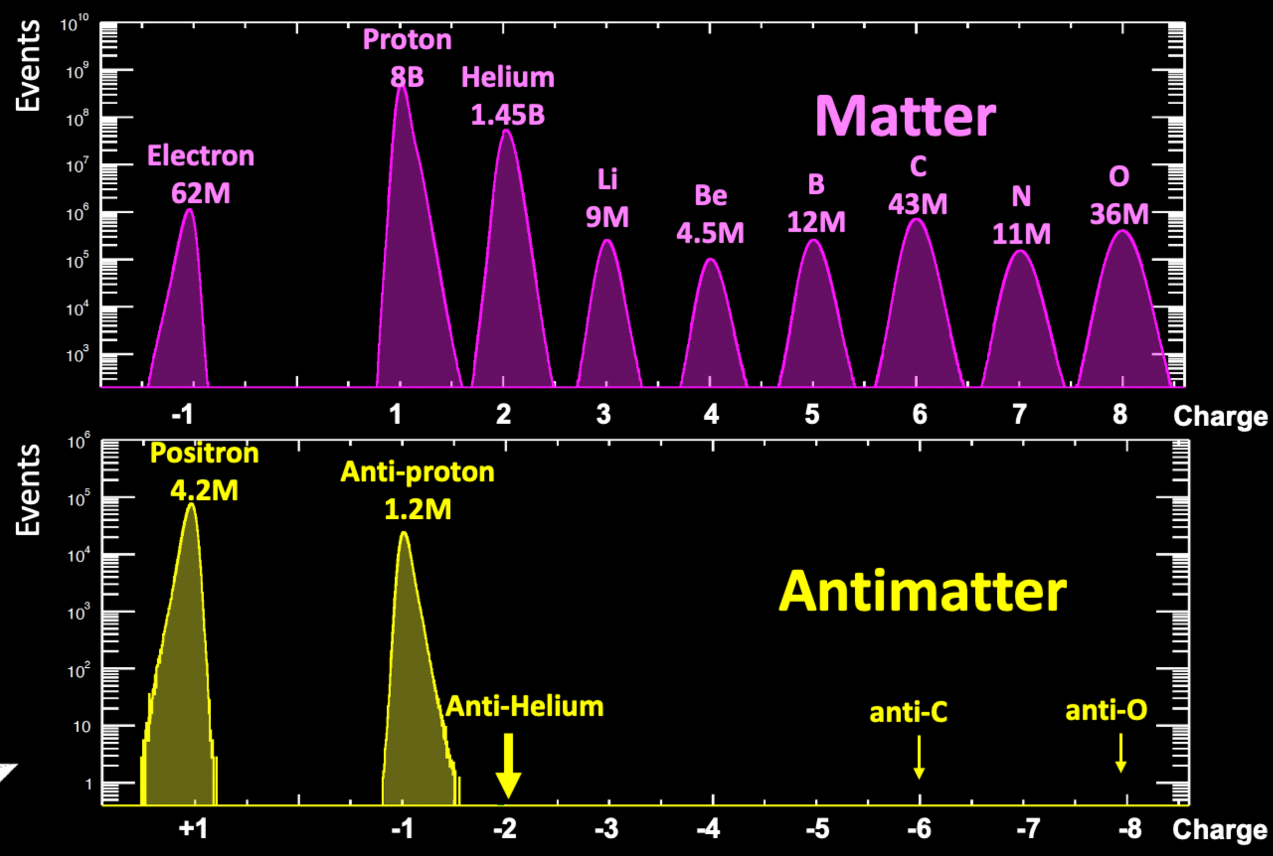
Anti-^{4}Helium Candidate



Charge= −2.05 ± 0.05
Mass = 3.81 ± 0.29 GeV/*c*

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

Current Matter and Antimatter

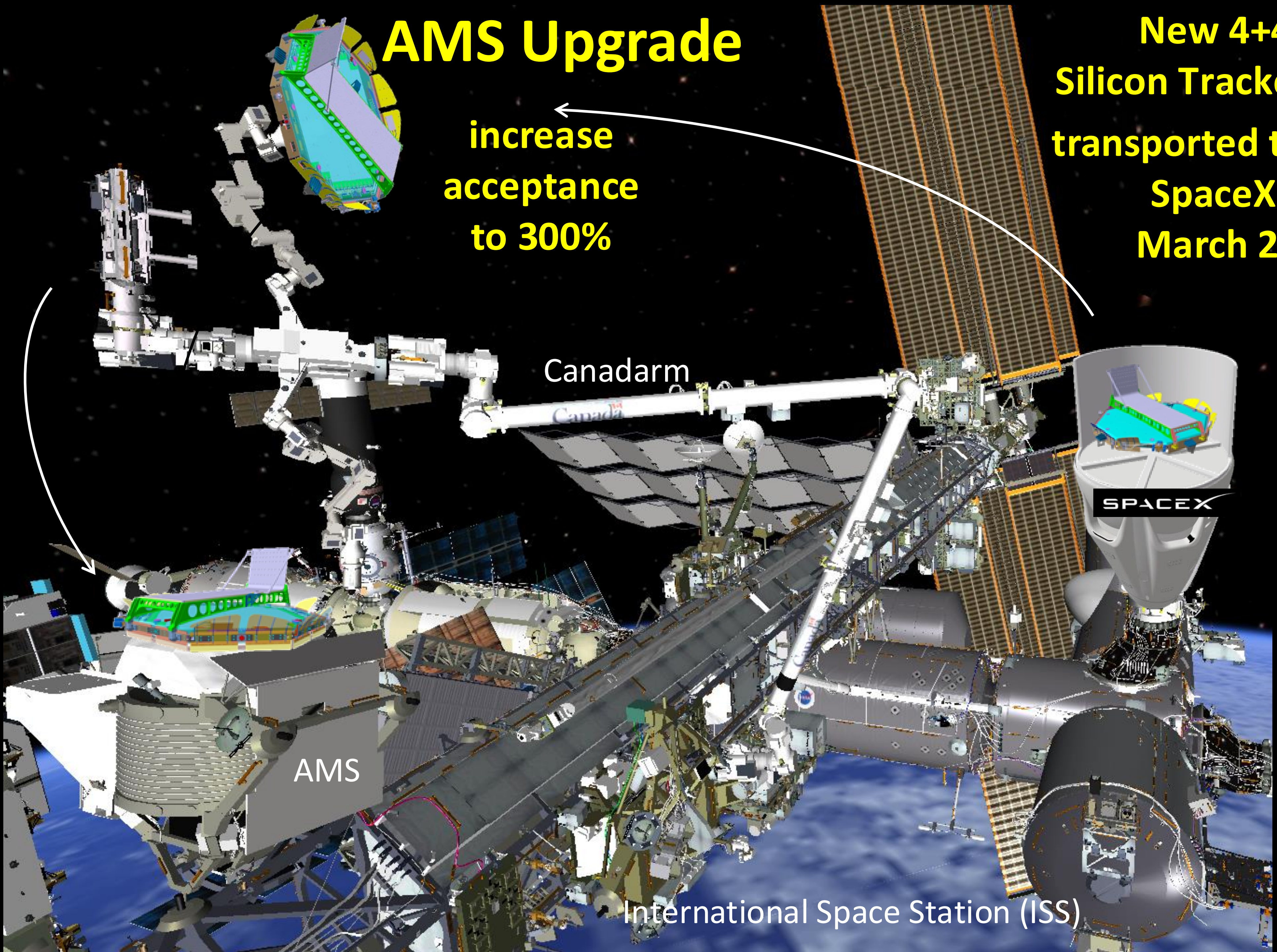


By 2030, AMS will have additional measurements in the study of antimatter: anti-deuterons, anti-helium, anti-carbon, and anti-oxygen.

AMS Upgrade

New 4+4m^2
Silicon Tracker Planes
transported to ISS via
SpaceX 36
March 2027

increase
acceptance
to 300%



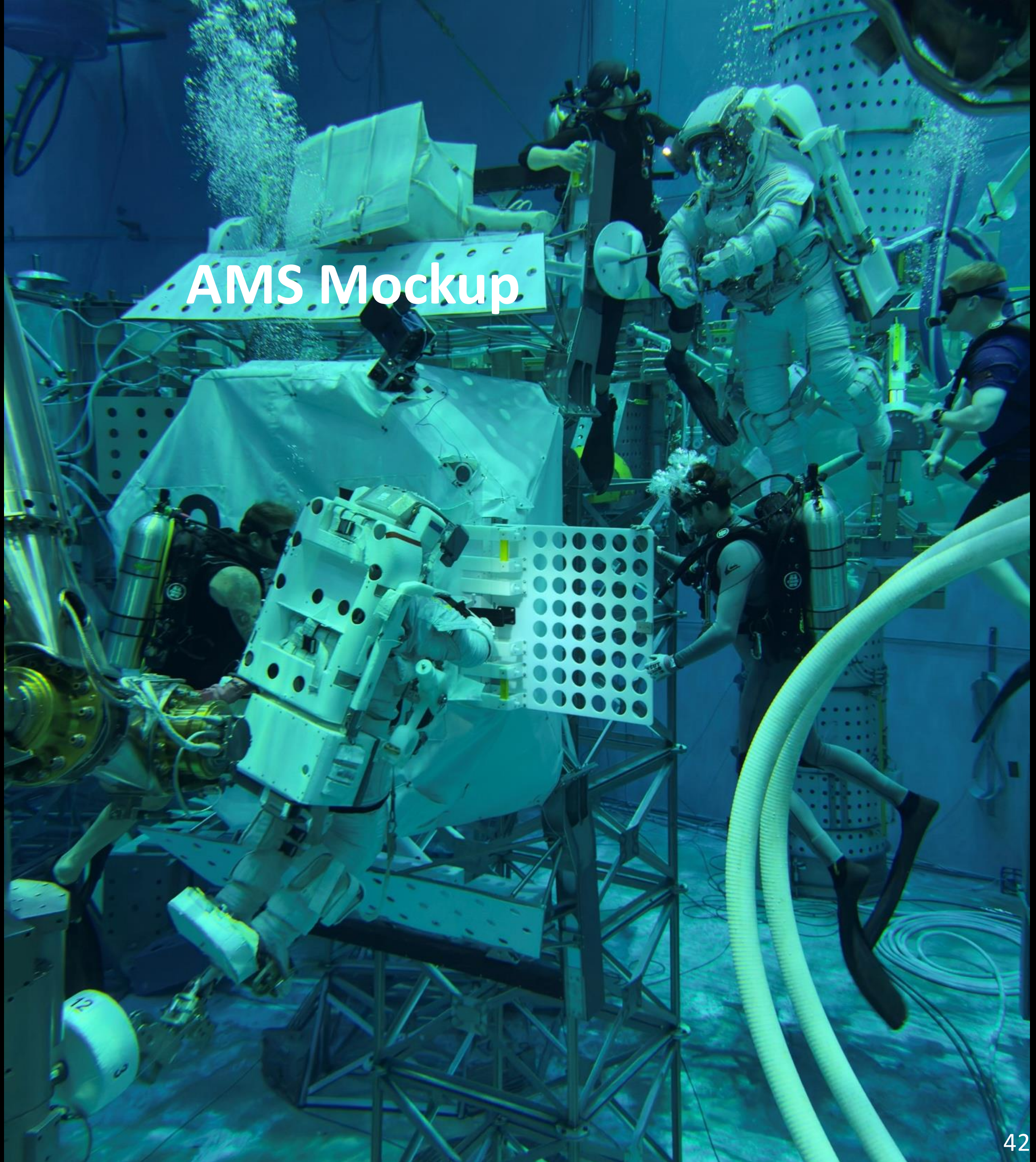
+74K
channels

final
installation
by
astronauts

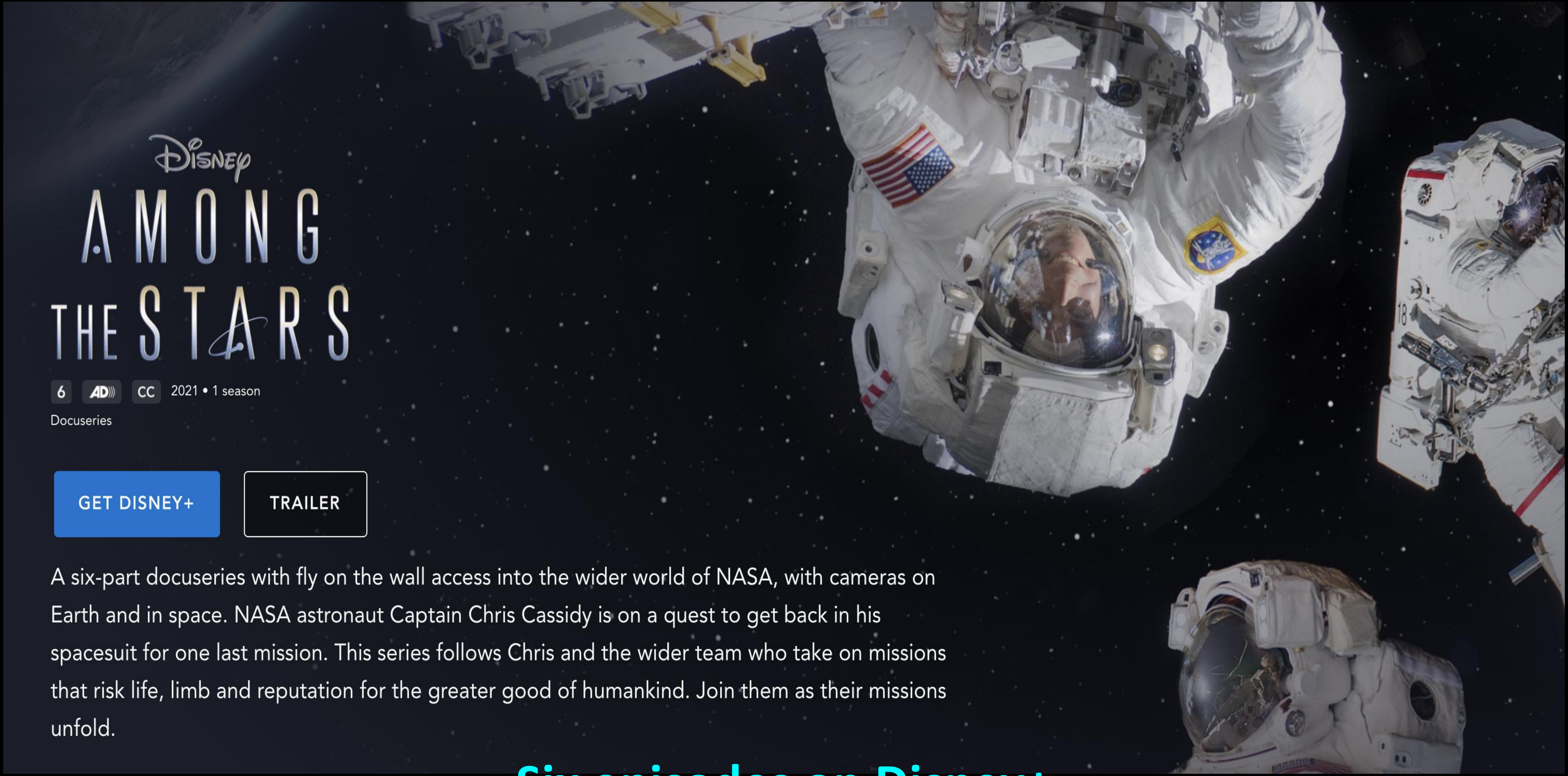
Extensive Training of Astronauts in the Neutral Buoyancy Lab at Johnson Space Center, Houston

Each EVA (Space Walk) requires 2 astronauts working for 6 hours on the Upgrade

It will take 4 EVAs to complete the AMS Upgrade



Description of the 1st AMS Upgrade to replace the tracker cooling system

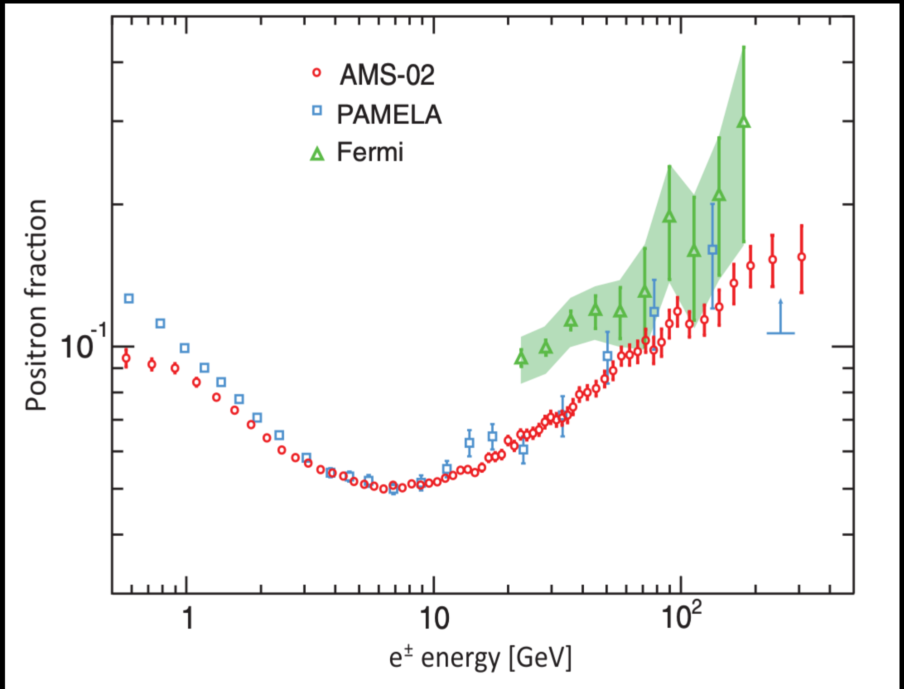


Six episodes on Disney+

Important Results

Result from the Alpha Magnetic Spectrometer on the International Space Station: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5–350 GeV

A precision measurement by the Alpha Magnetic Spectrometer on the International Space Station of the positron fraction in primary cosmic rays in the energy range from 0.5 to 350 GeV based on 6.8×10^6 positron and electron events is presented. The very accurate data show that the positron fraction is steadily increasing from 10 to ~250 GeV, but, from 20 to 250 GeV, the slope decreases by an order of magnitude. The positron fraction spectrum shows no fine structure, and the positron to electron ratio shows no observable anisotropy. Together, these features show the existence of new physical phenomena.



Phys. Rev. Lett. 110, 141102 (2013)

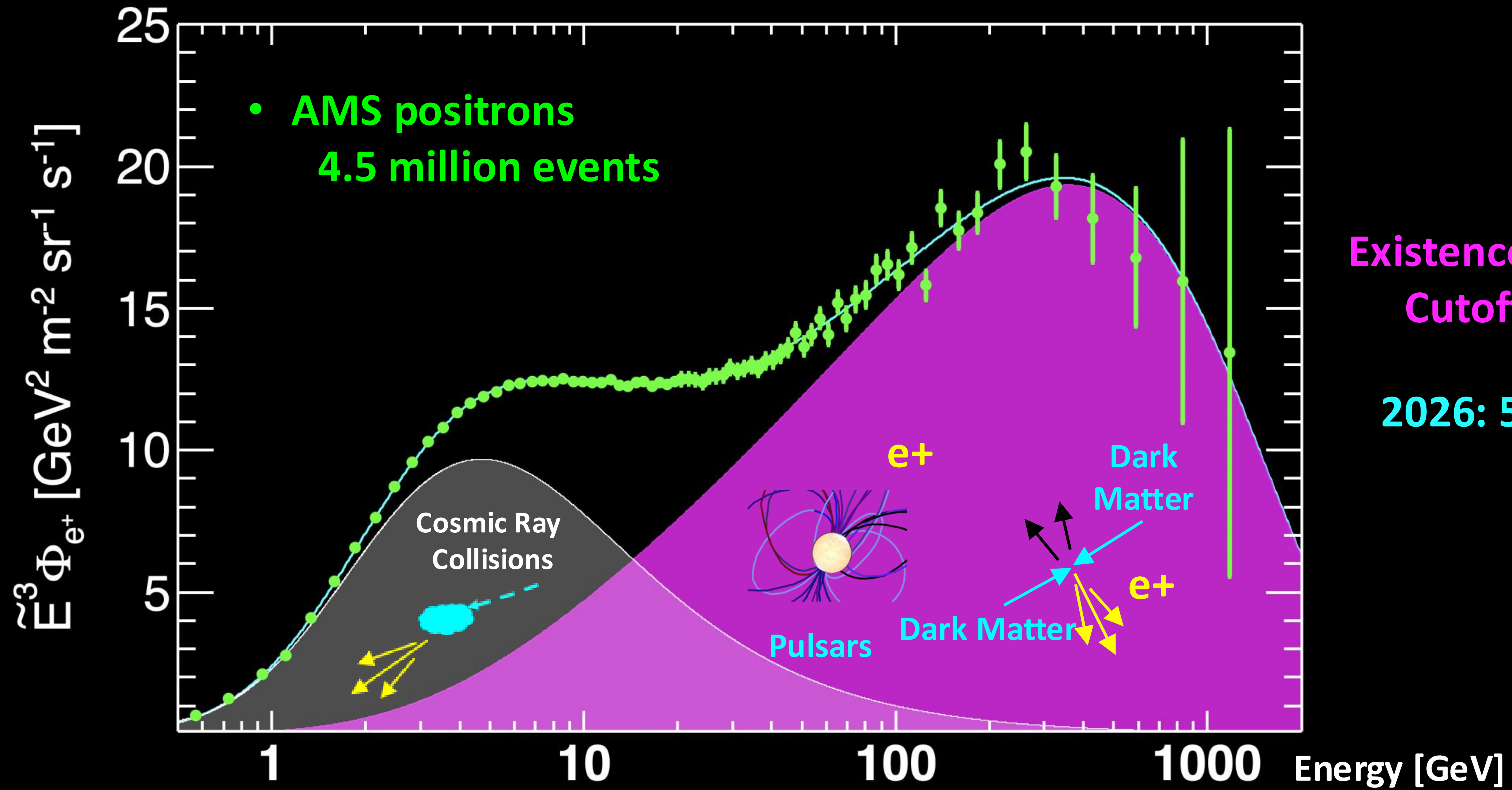
From: "garisto@aps.org" <garisto@aps.org>

Subject: First AMS paper chosen for a ten year retrospective of PRL Editors' Suggestions
Date: April 20, 2017 at 4:49:57 PM GMT+2

… Other papers we have already commemorated in this way include the discovery of element 117, and the observation of gravitational waves by LIGO.

Cheers,
Robert

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



Existence of Cutoff

2026: 5σ