GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Recent Results from the AMS Experiment

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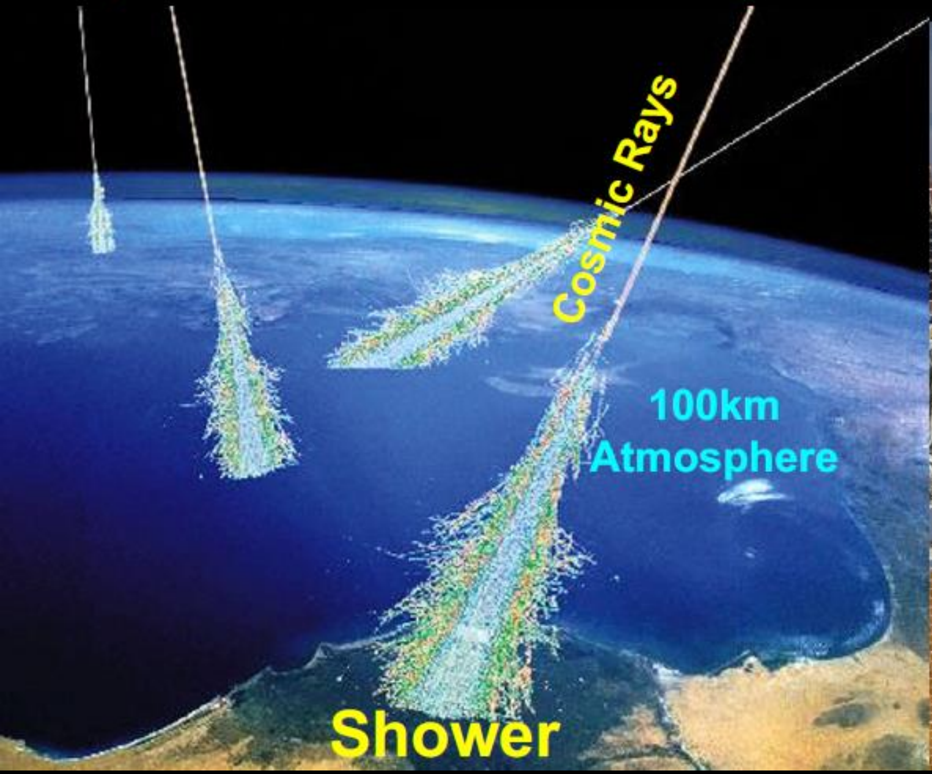
AMS on the Space Station:

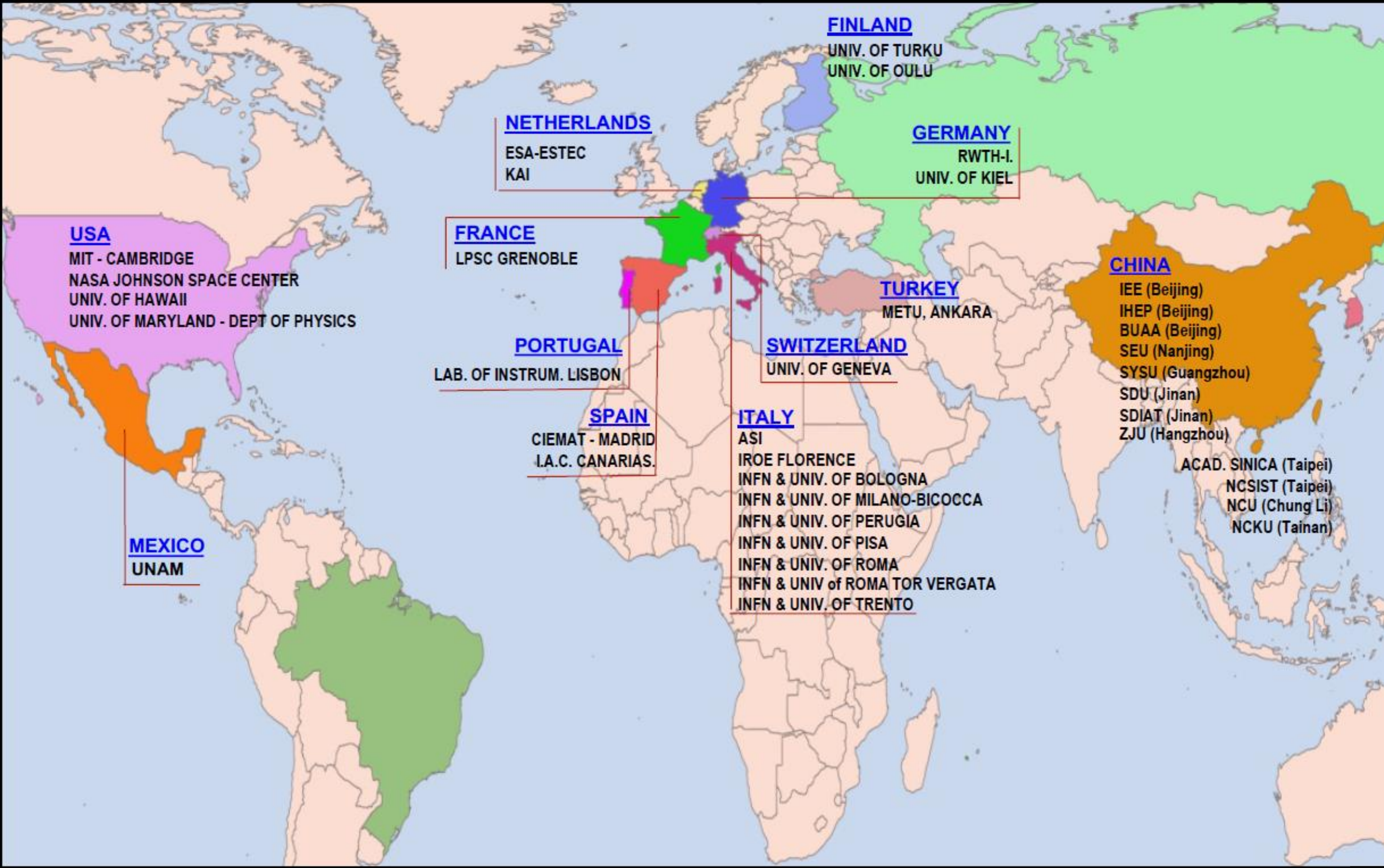
Physics of Dark Matter, Antimatter, the Origin of the Cosmos, and new phenomena through the precision, long-duration measurement of charged cosmic rays

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

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

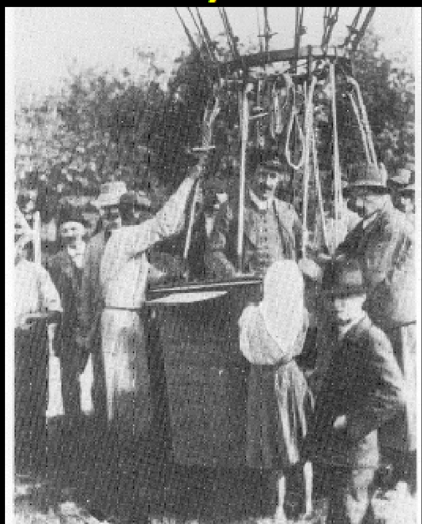


Alpha Magnetic Spectrometer experiment (AMS) on the Space Station



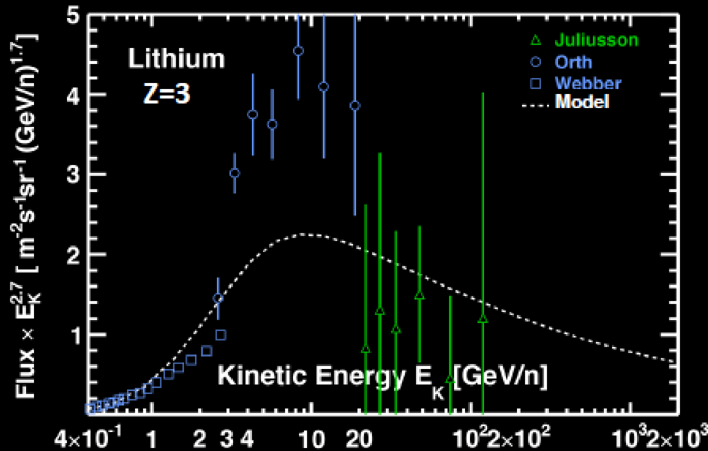
Cosmic Rays in the last 100 years

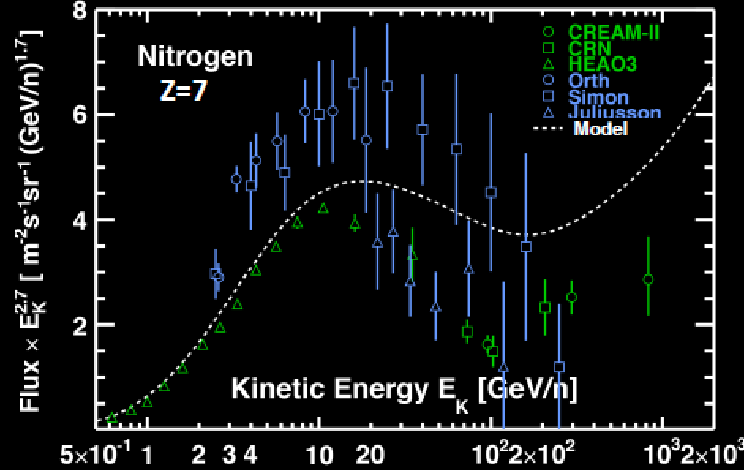
1912: Discovery of Cosmic Rays

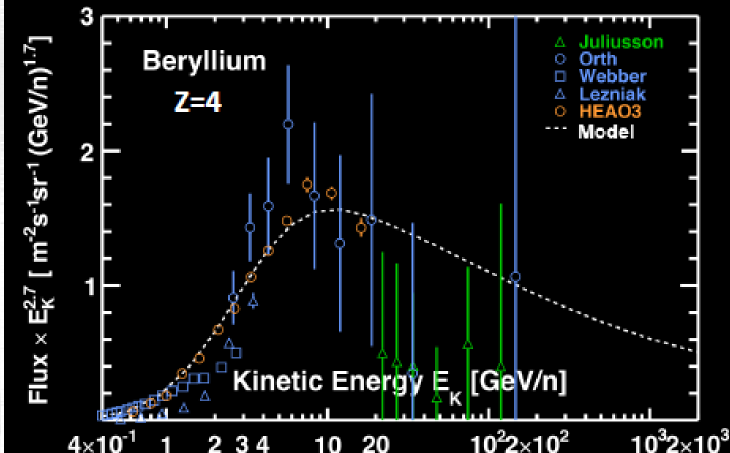


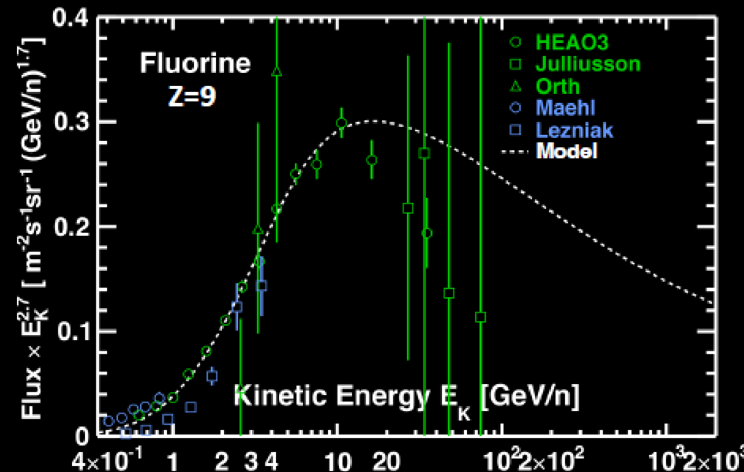
Victor Hess Nobel Prize (1936)

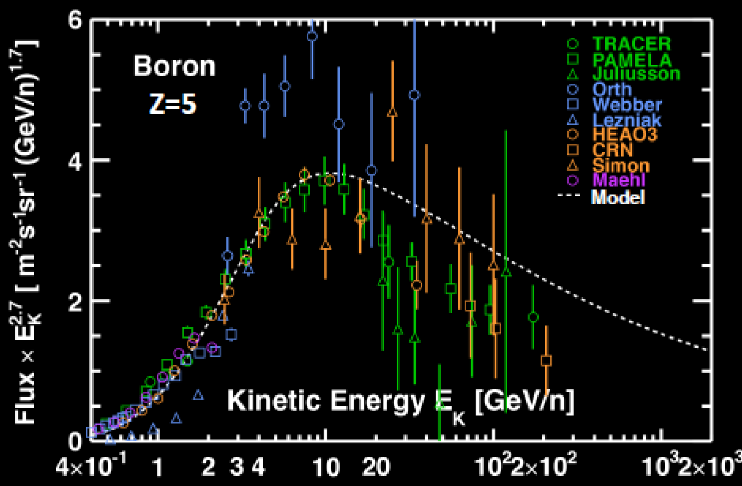
Before AMS: Theoretical models agree with experimental data (large errors)

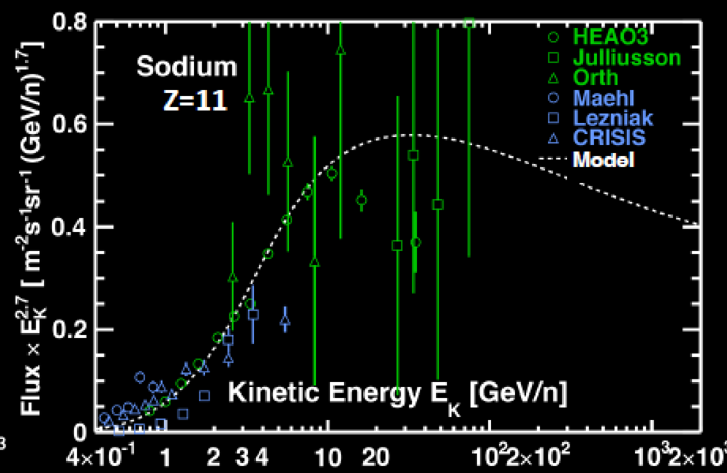






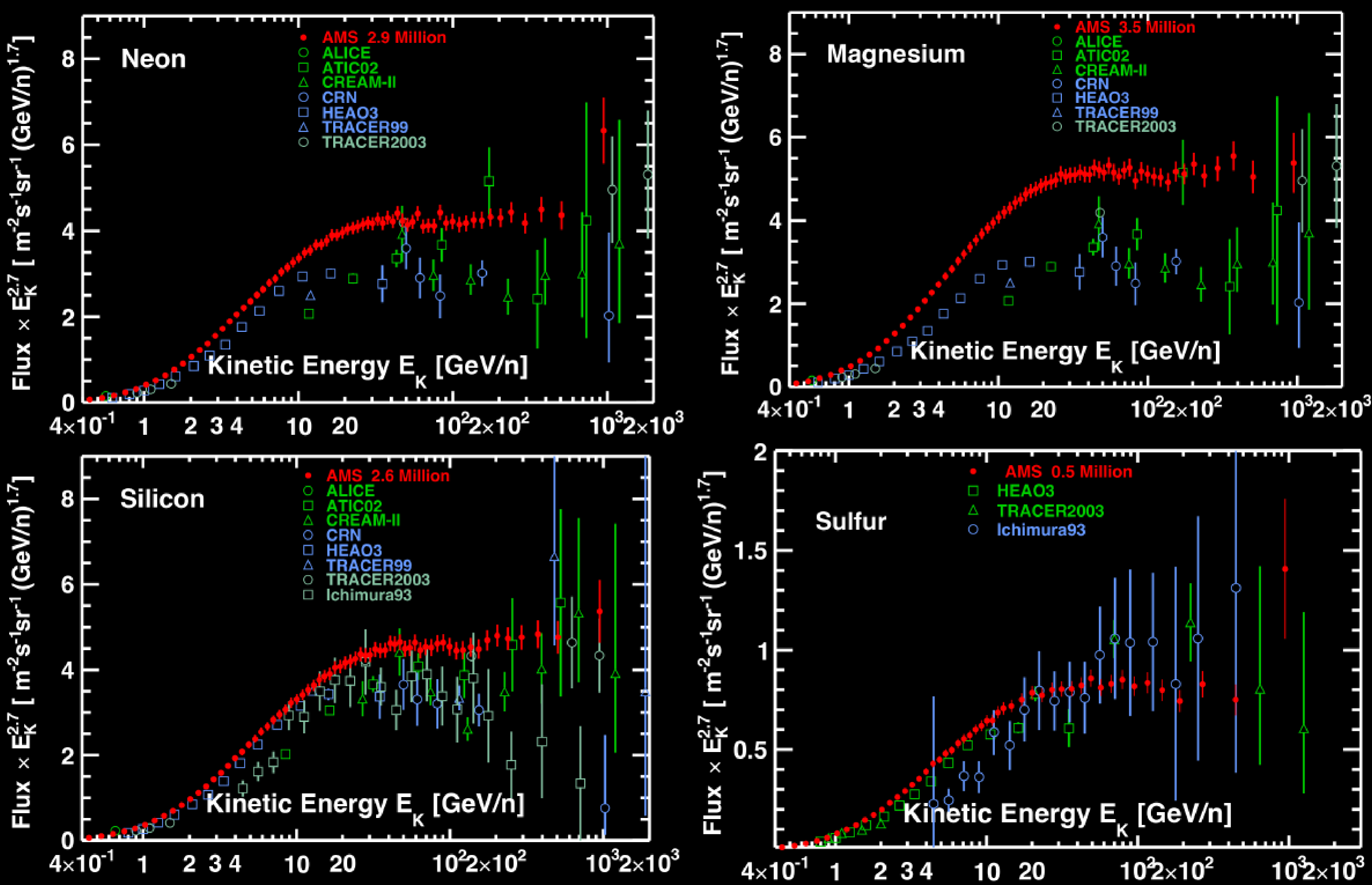




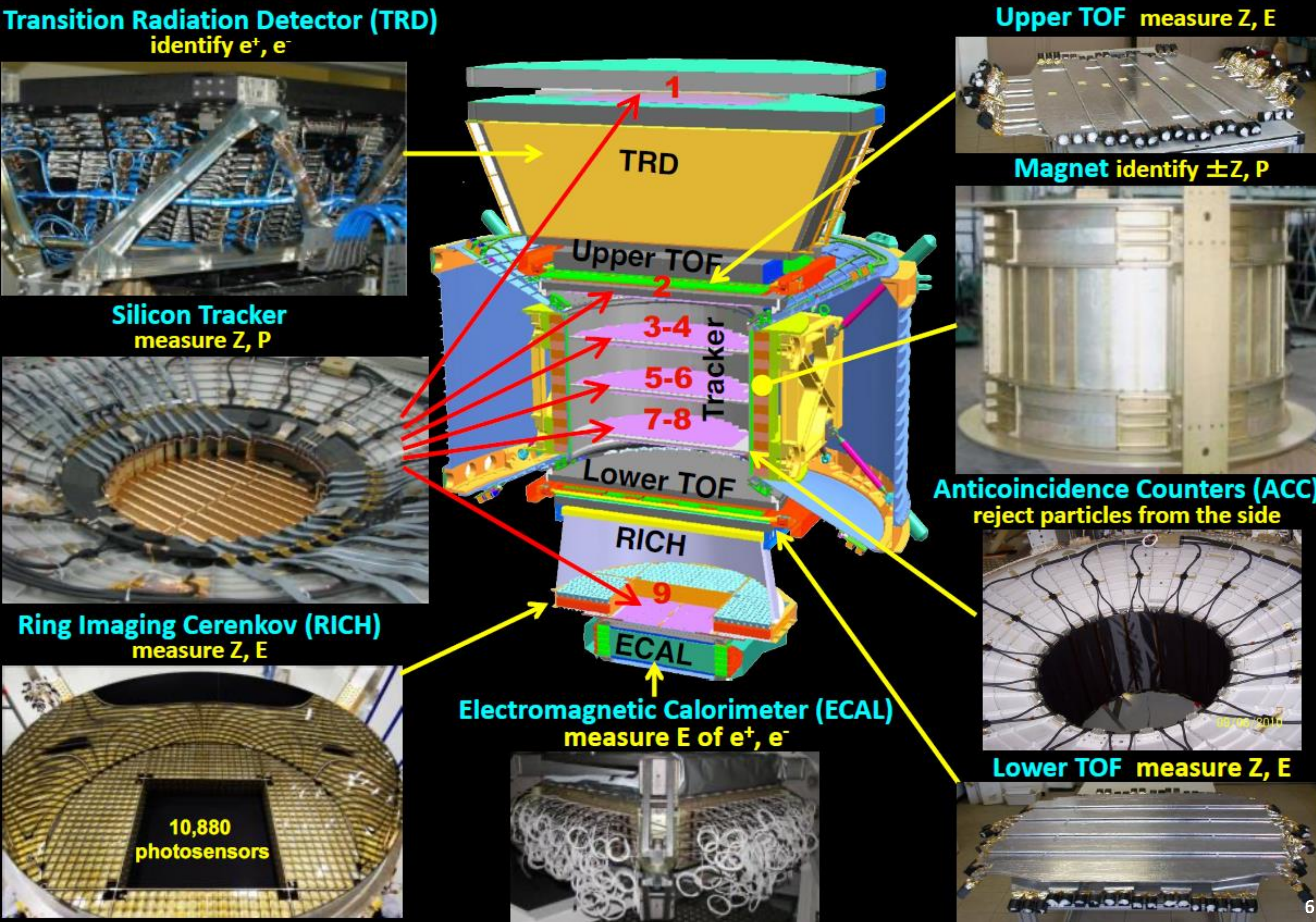


Examples of AMS Results compared with earlier measurements

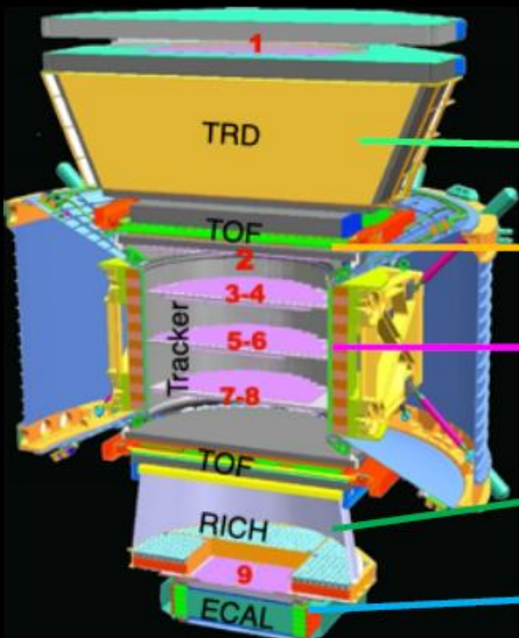
The precision AMS results cannot be explained by current models.

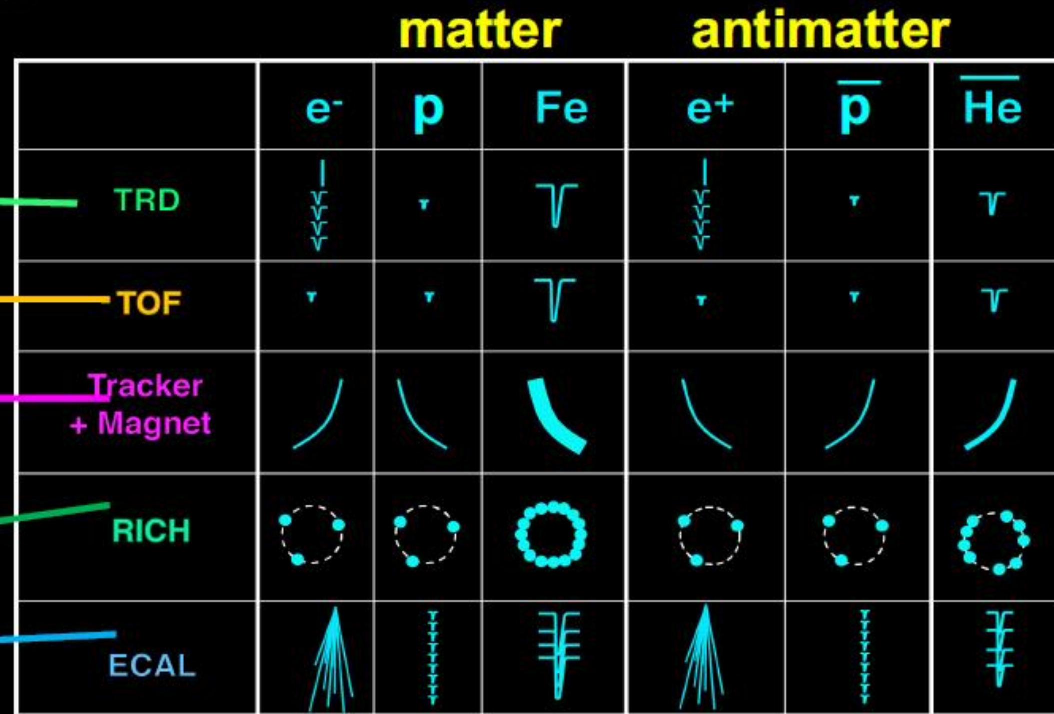


AMS is a space version of a precision detector used in accelerators



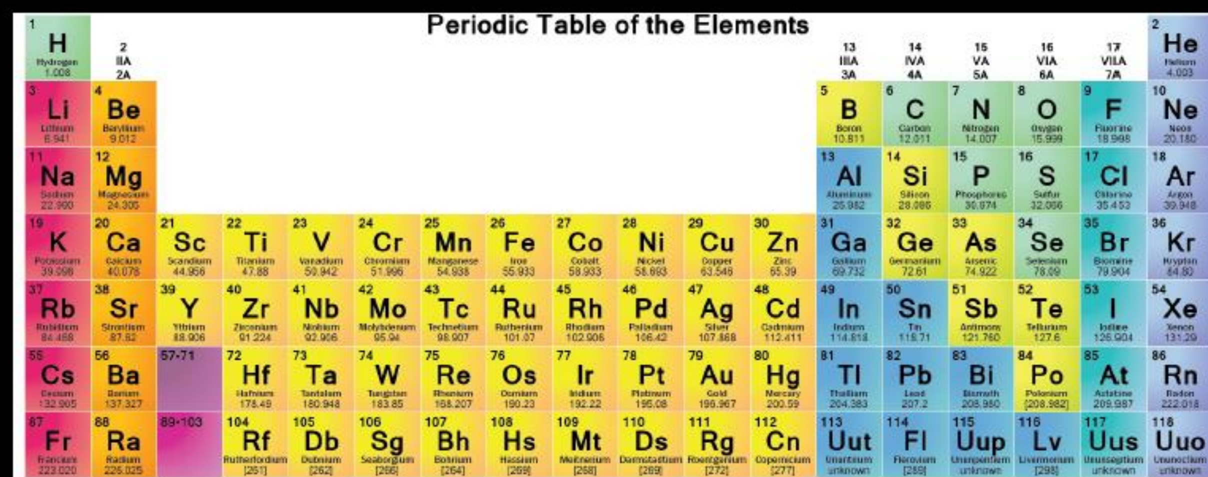
The detectors provide independent information of cosmic rays





Redundant measurements of:

- **Momentum (P, GeV/c)**
- **Charge (Z)**
- **Rigidity (R=P/Z, GV)**
- **Energy (E, GeV/A)**
- **Flux (particles/(s sr m² GeV)**



Periodic Table of the Elements

1 H Hydrogen 1.008	2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	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 186.207	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

AMS on the ISS

AMS 2011-2025
Continuous data taking

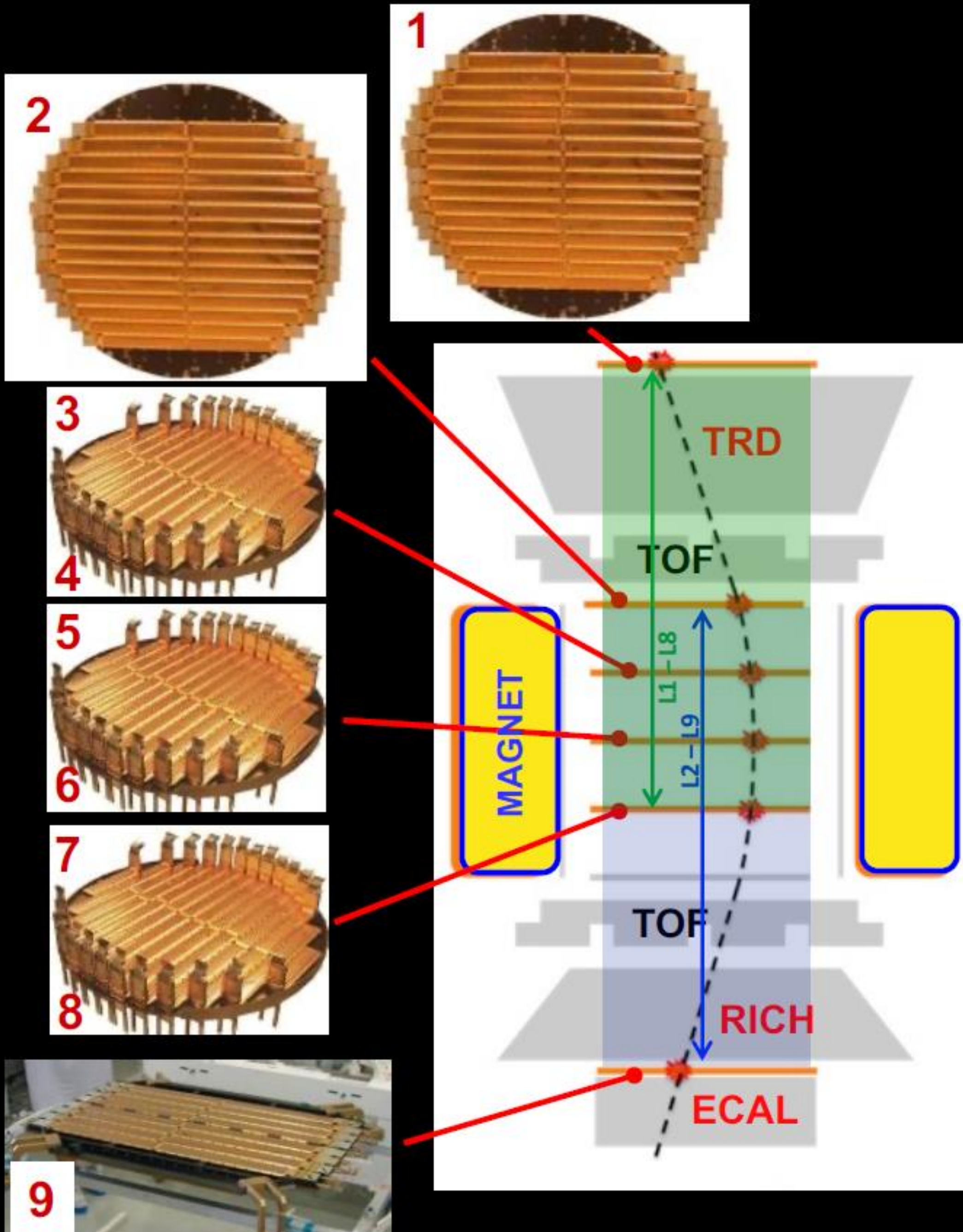
Latest results 2011 - 2022: 220 billion cosmic rays

AMS 2025-2030
Acceptance increased to 300%

new $8m^2$ tracker L0

and projections

Operation of AMS on the ISS: Continuous Calibration

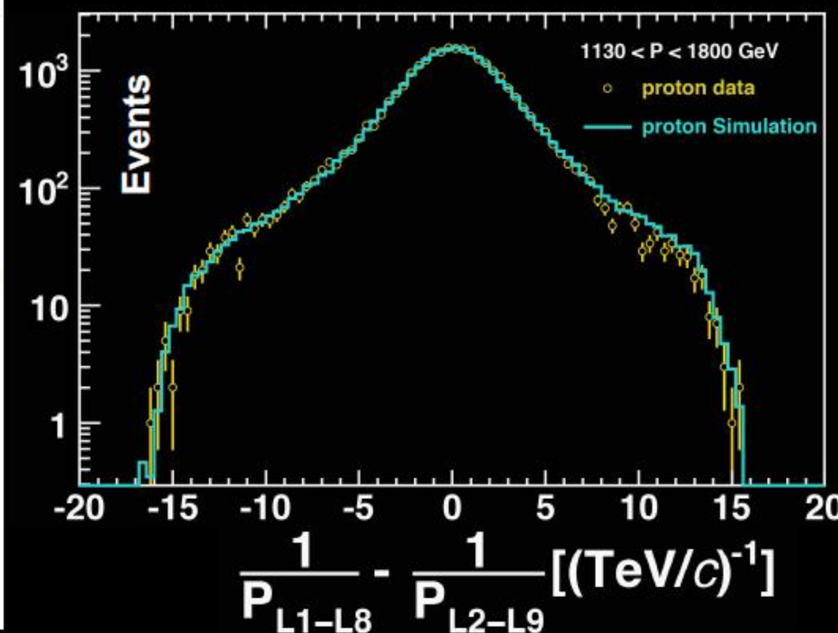


By comparing proton data and simulation from

the upper spectrometer (L1 to L8)

and

the lower spectrometer (L2 to L9)

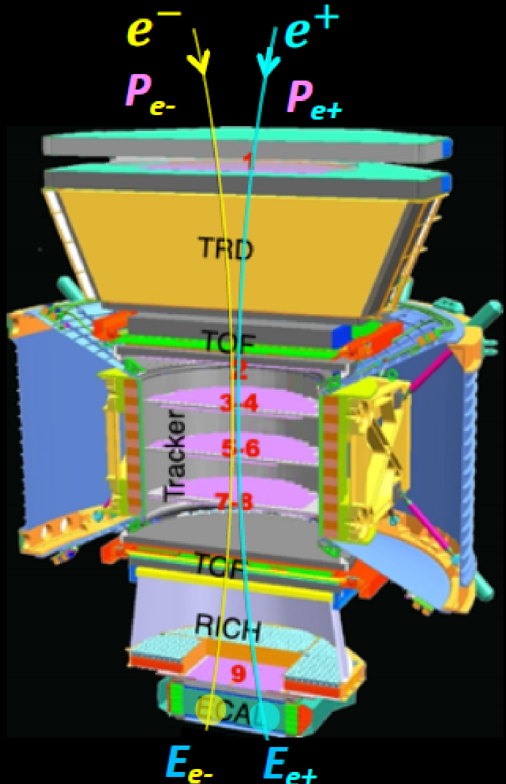


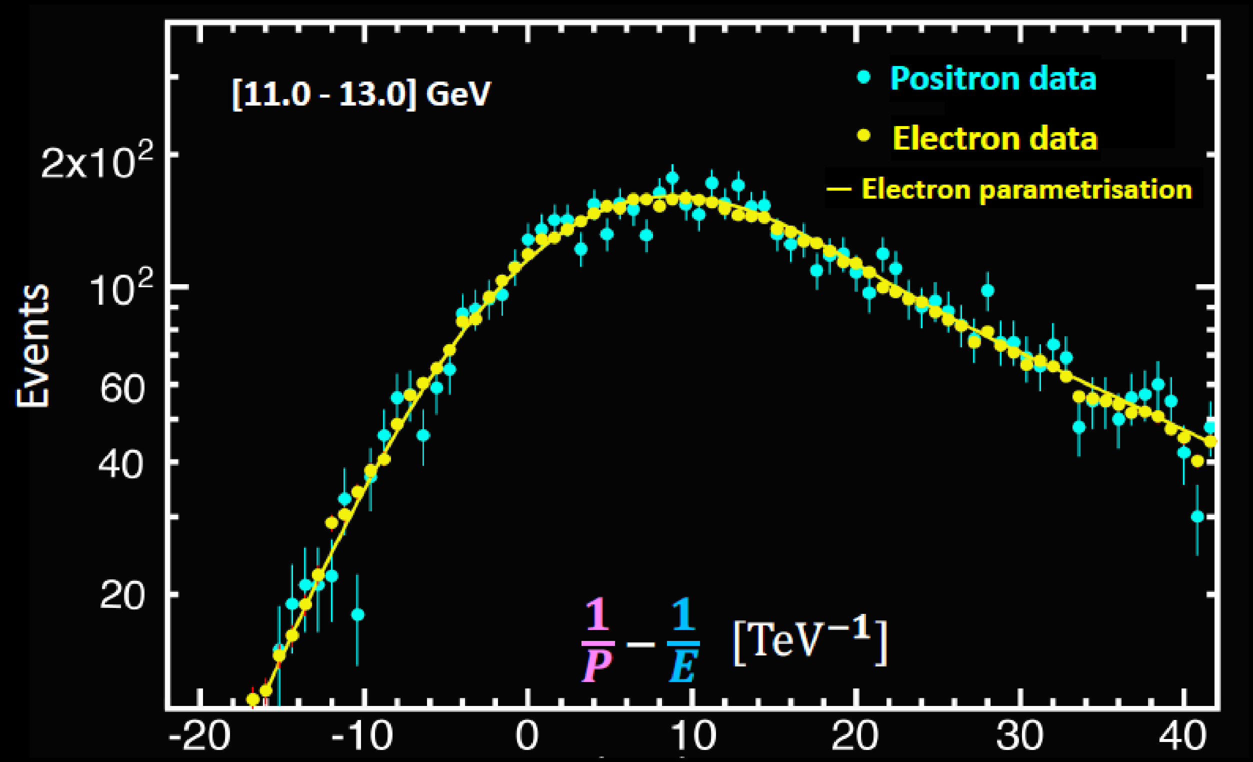
Continuous Momentum Scale Verification

(Unique Advantage of a Magnetic Spectrometer)

In AMS, the largest systematic error in the determination of the fluxes at the highest energies is due to the uncertainty in the absolute momentum scale.

A shift in the central tracker planes of 0.5 microns is sufficient to create a momentum shift of 10% at 1 TeV

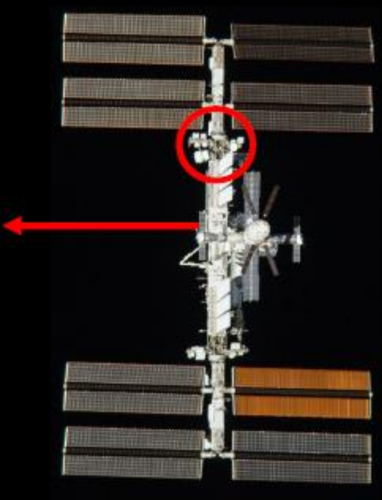


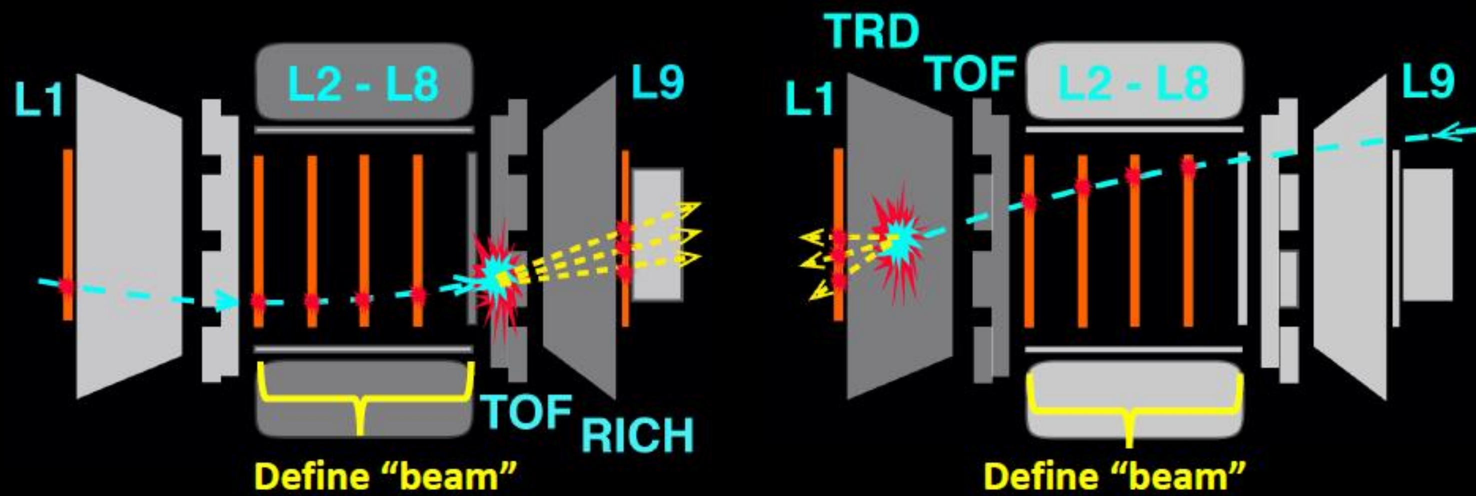


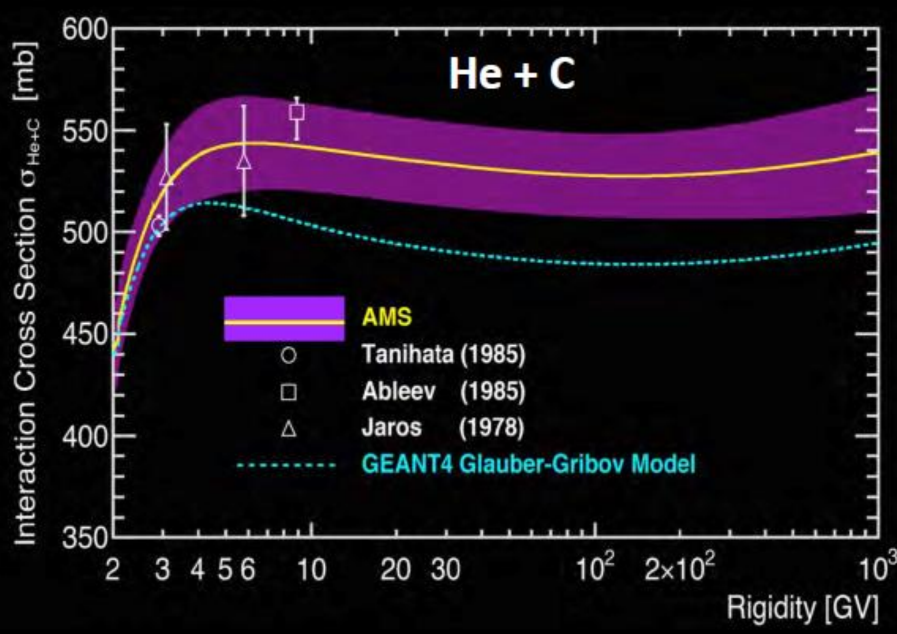
By matching the momentum P and Energy E for both e^+ and e^-,
The accuracy of the momentum is determined to be 1/(34 TeV);
i.e., at 1 TeV the uncertainty is 3%

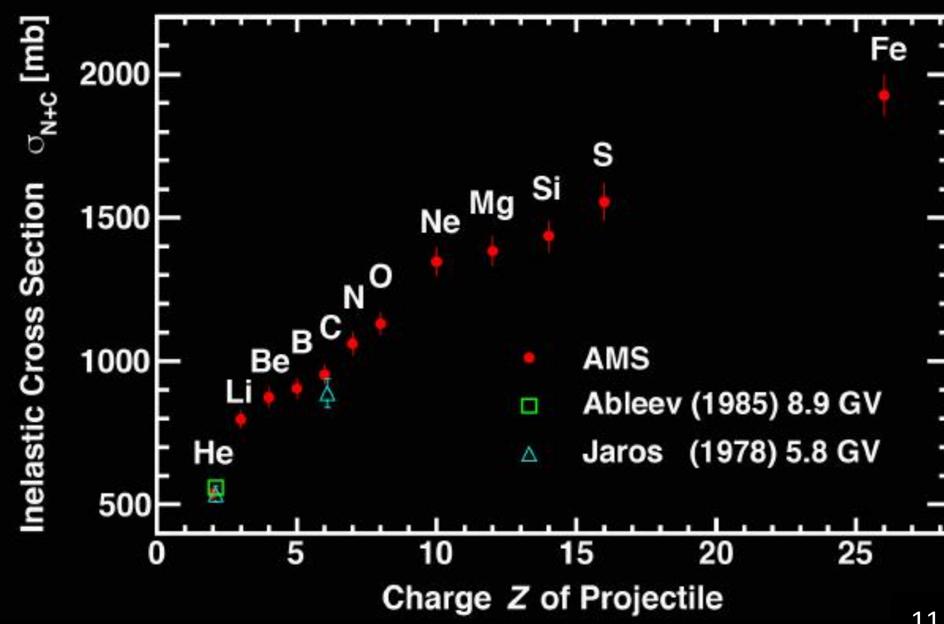
Precision measurements of nuclear inelastic cross sections

"Fix target" experiment in space

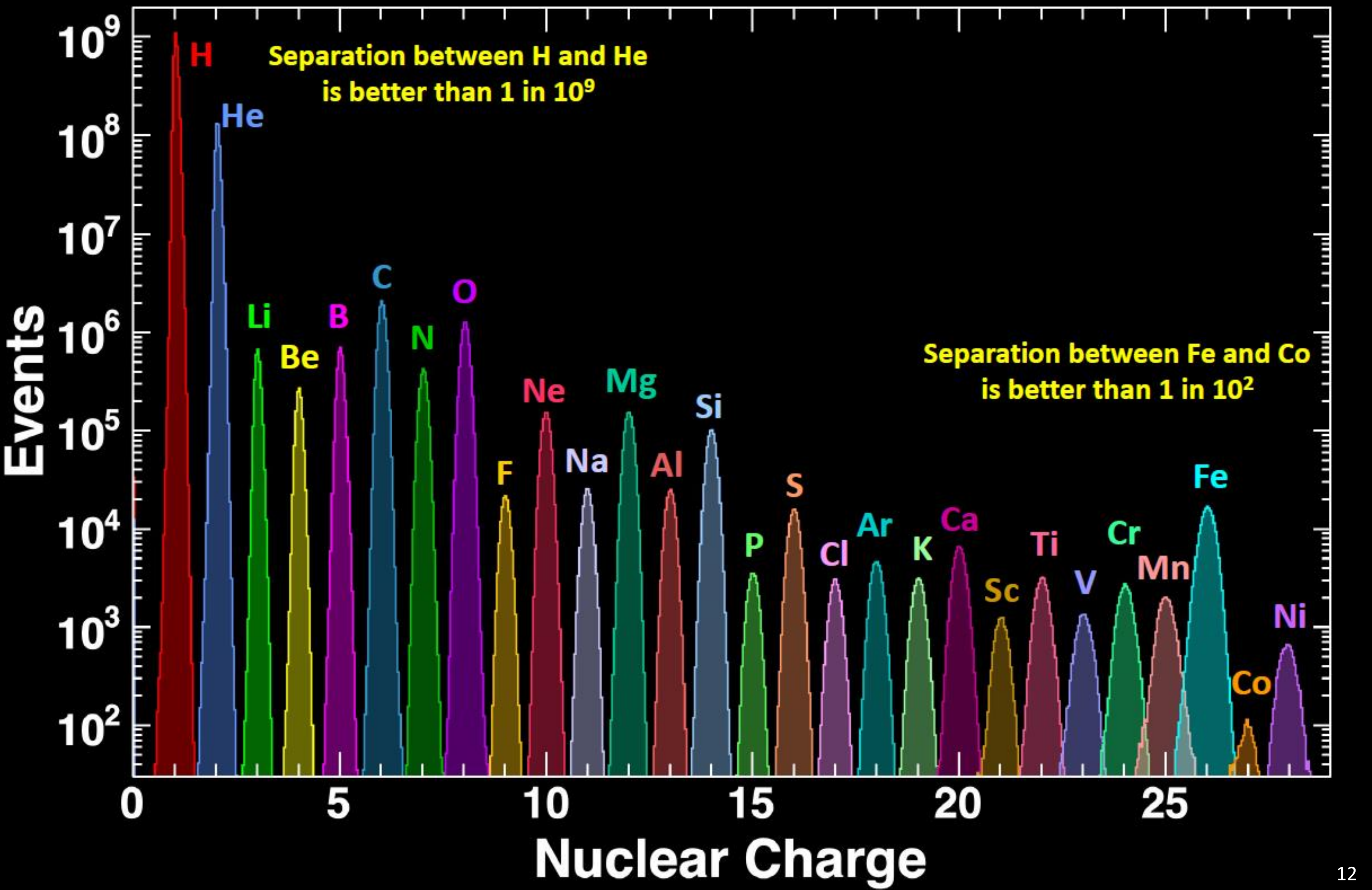




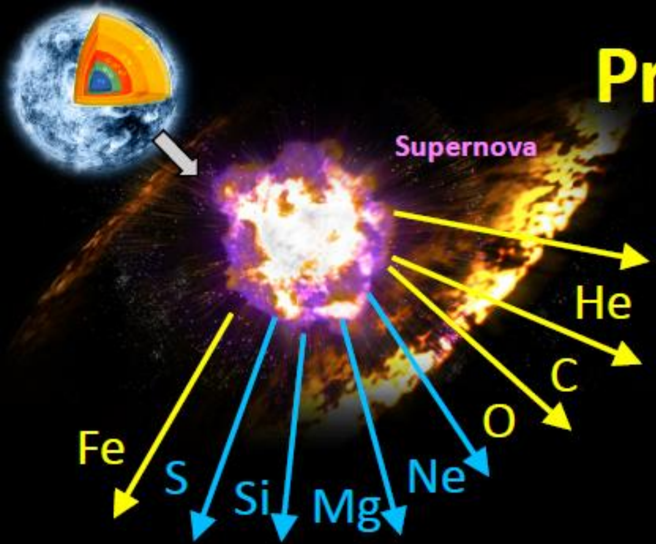




Precision Measurements of Cosmic Nuclei by AMS

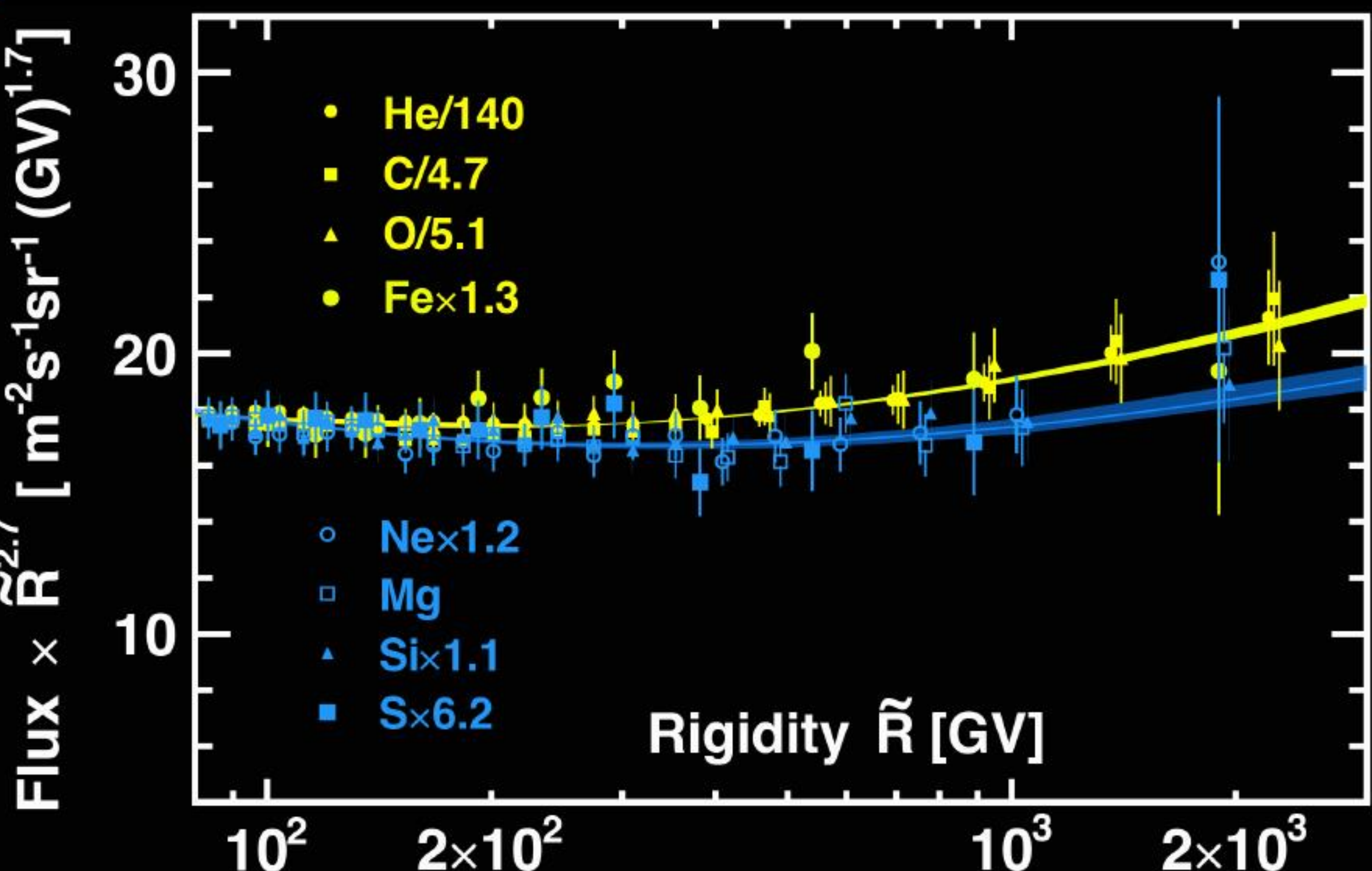


Primary Cosmic Rays

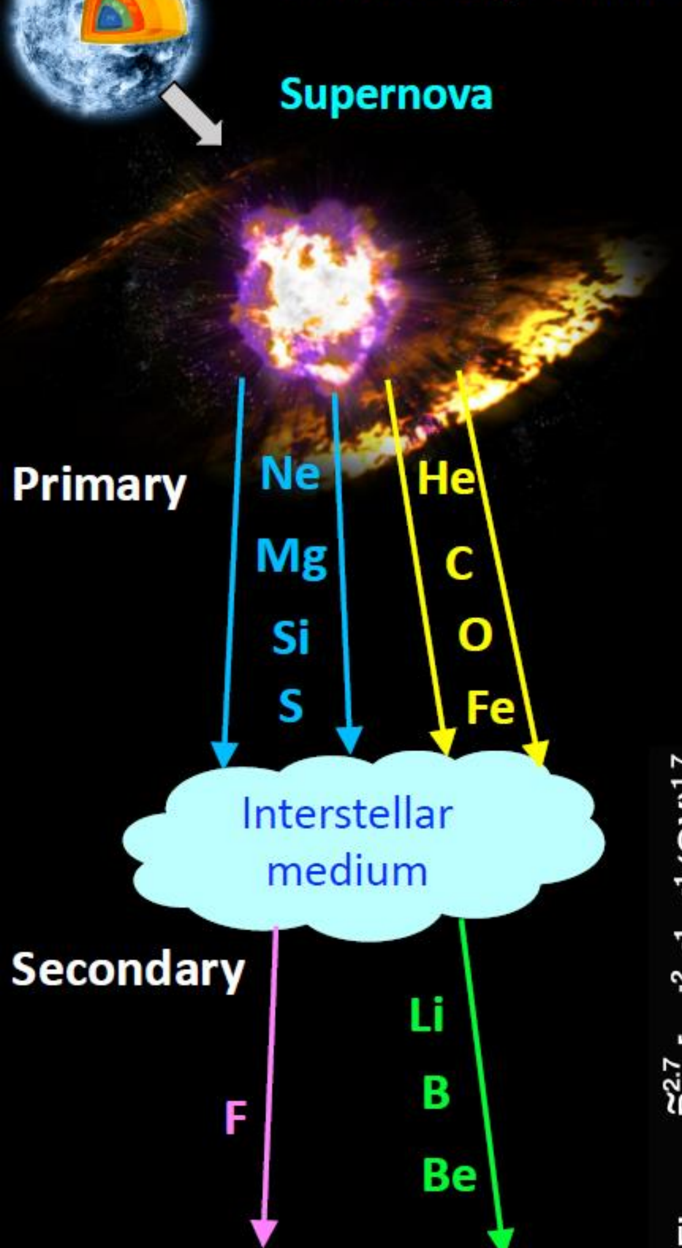


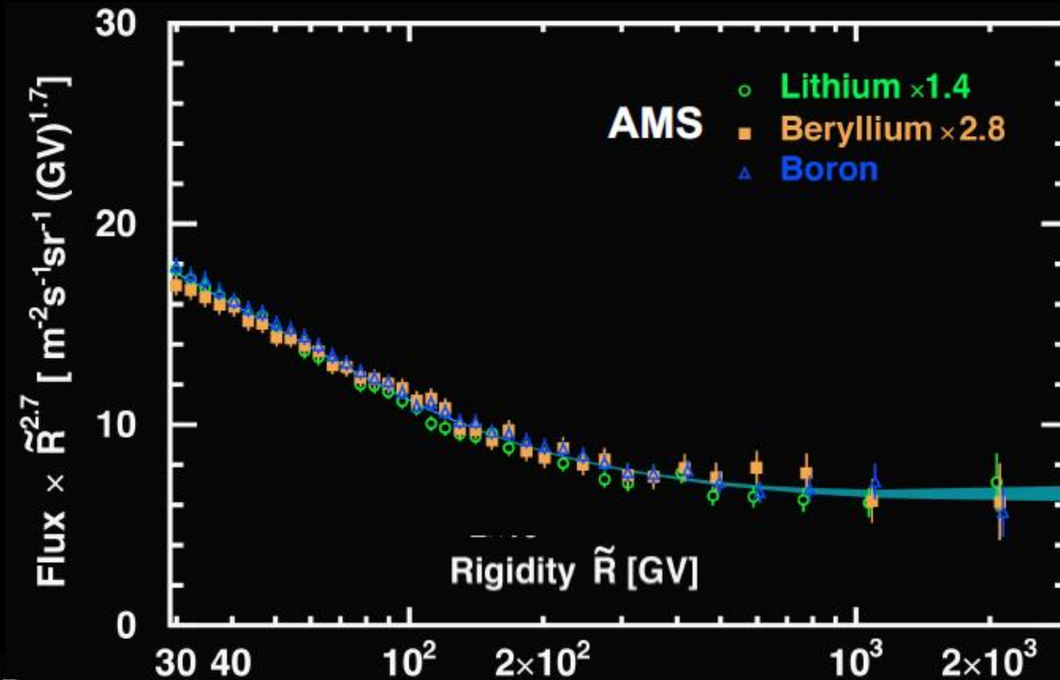
Primary elements (He, C, ..., Fe) are produced during the lifetime of stars.
They are accelerated by the explosion of stars (supernovae).

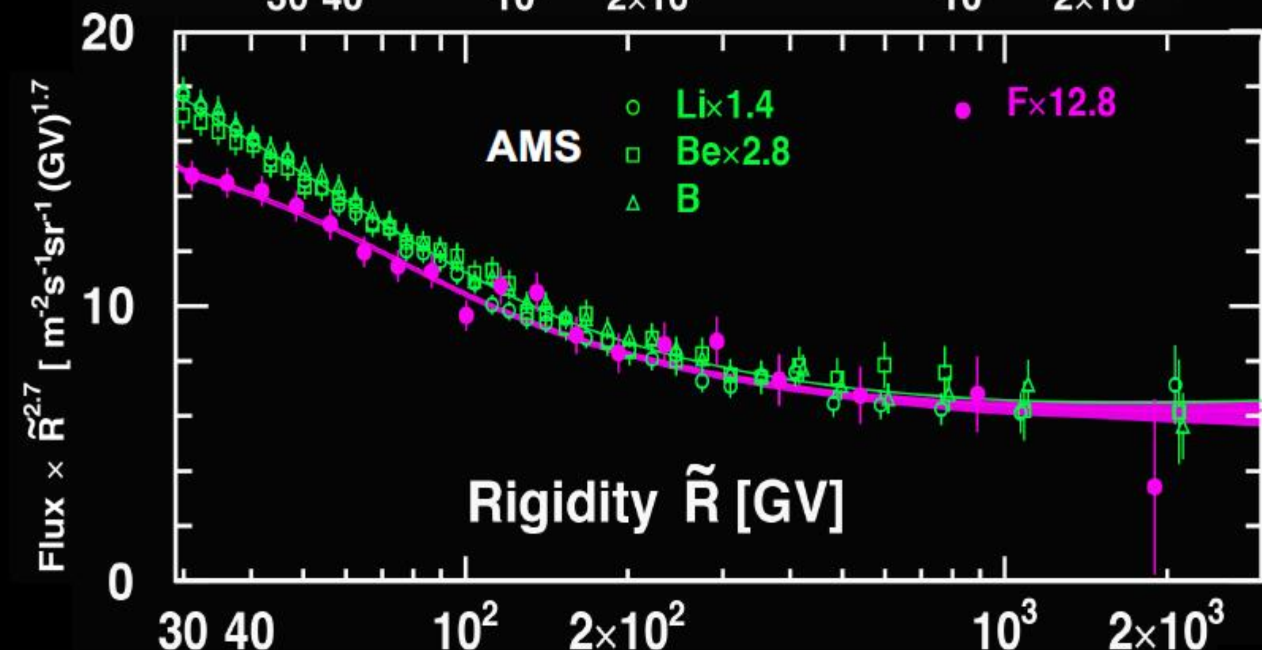
Primary cosmic rays have at least two classes.



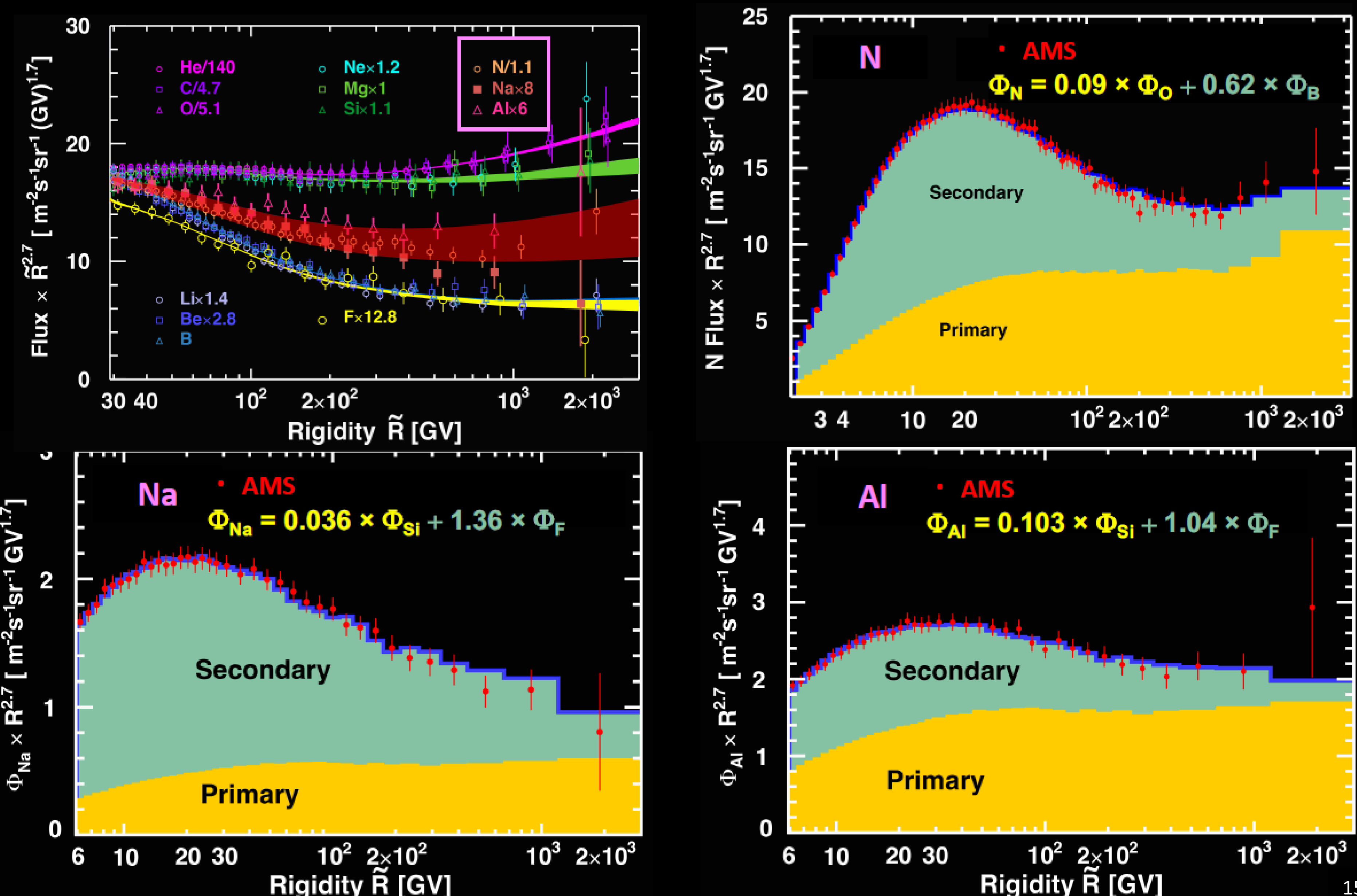
Secondary cosmic rays also have two classes of rigidity dependence



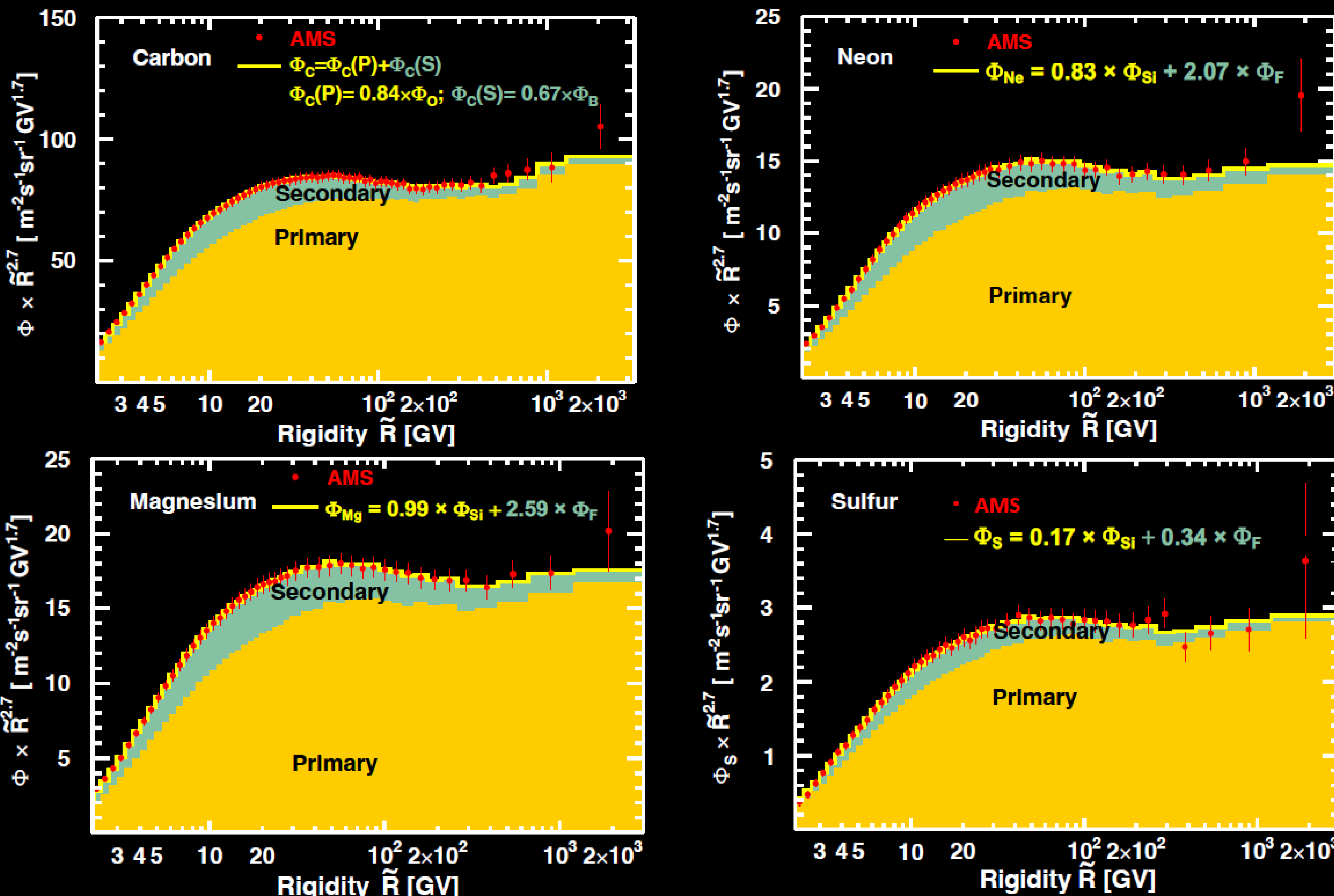




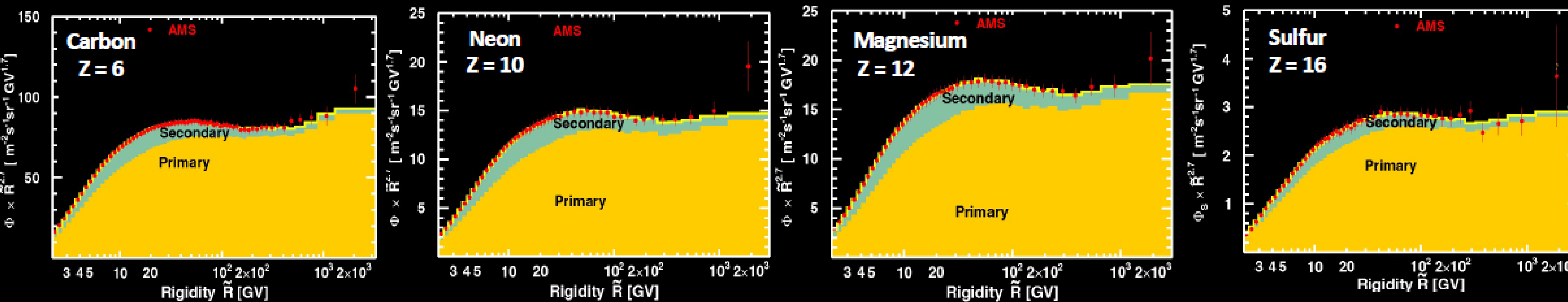
A third group of cosmic rays N-Na-Al partially primary, partially secondary



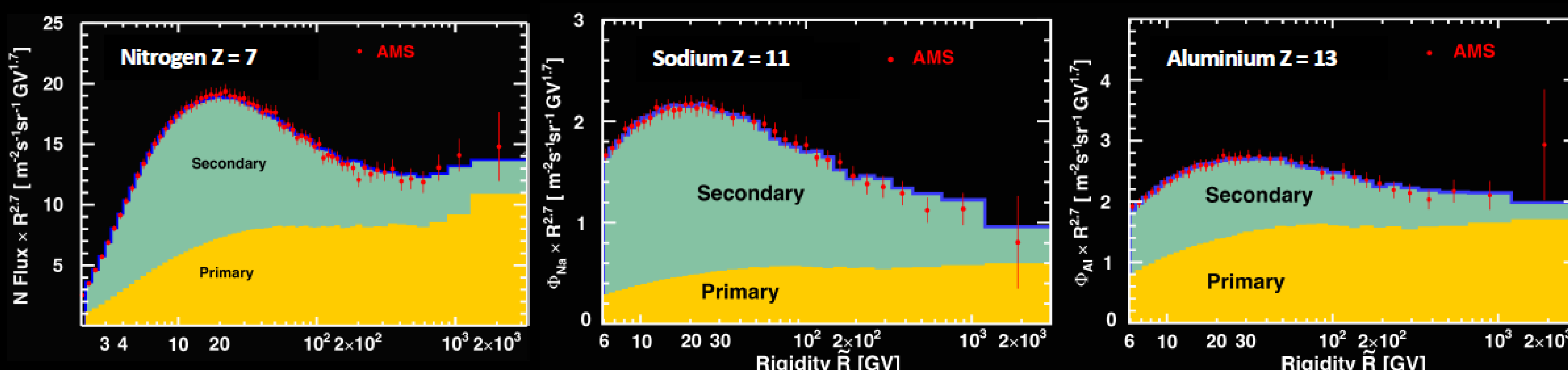
New, unexpected observation :
Traditional primary cosmic rays C, Ne, Mg, and S fluxes are not pure primary; they all have a significant secondary component



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



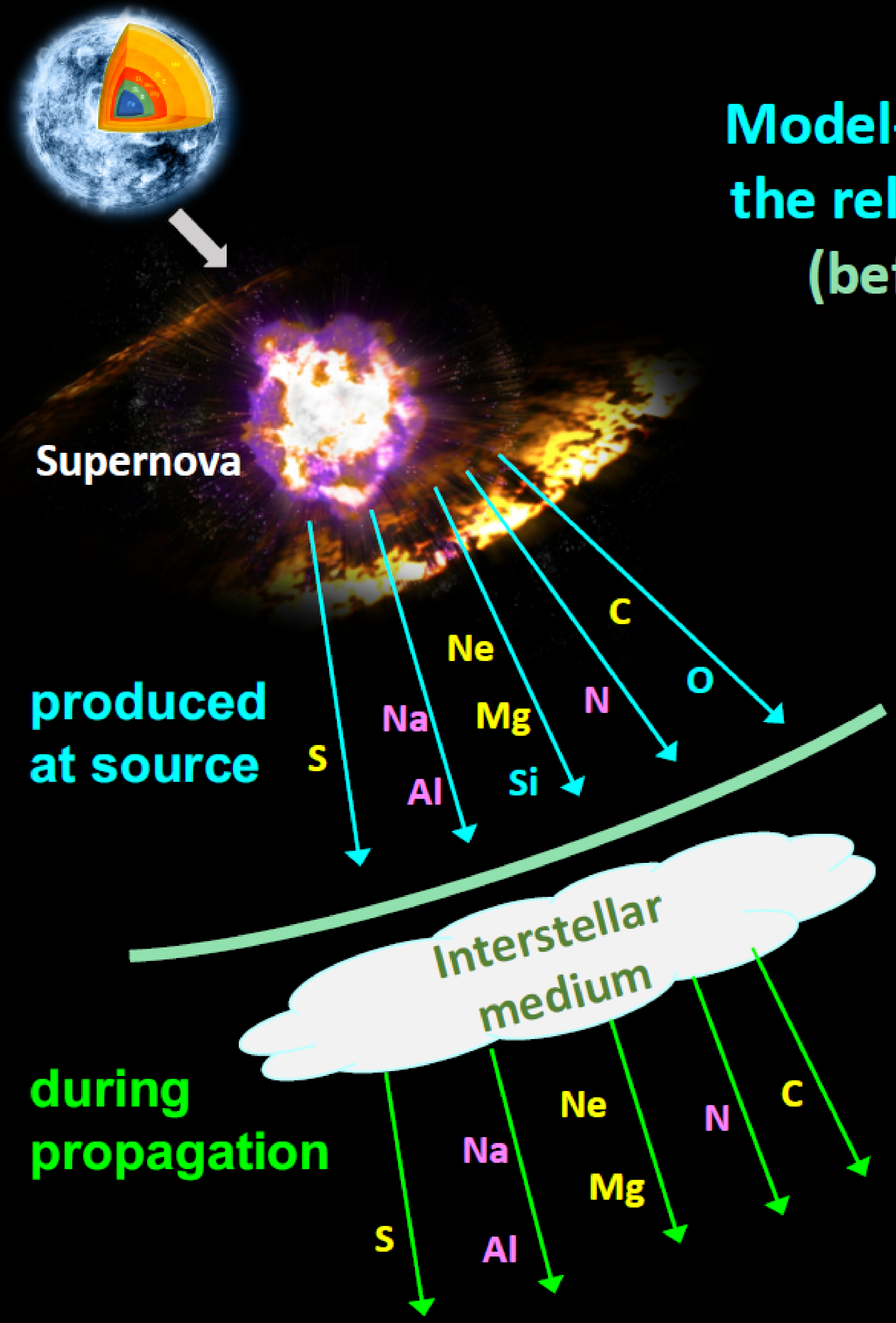
Even-Z nuclei are dominated by primaries



Odd-Z nuclei have more secondaries than even-Z

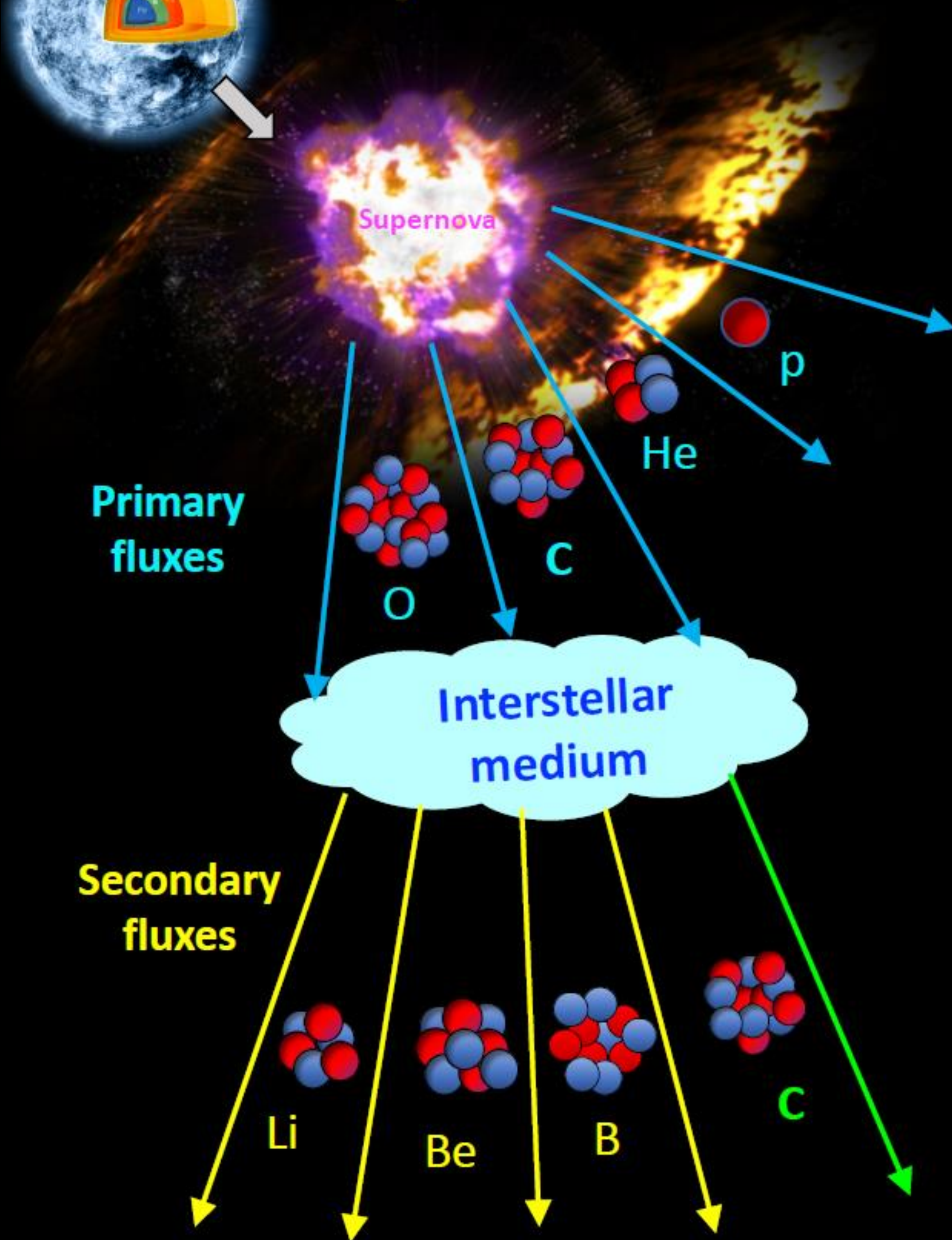
New AMS Result:

Model-independent measurements of the relative abundances at the source (before cosmic ray propagation)

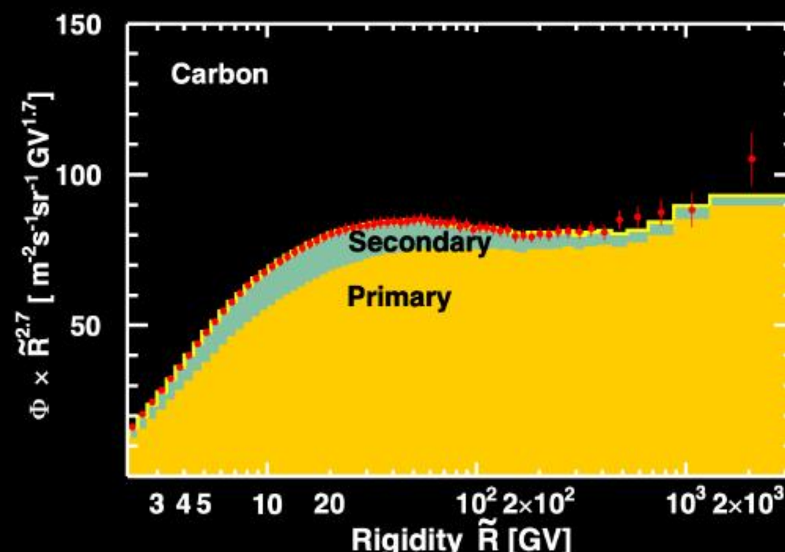


Abundance Ratio	Value at the Source
C/O	0.836 ± 0.025
Ne/Si	0.833 ± 0.025
Mg/Si	0.994 ± 0.029
S/Si	0.167 ± 0.006
N/O	0.092 ± 0.002
Na/Si	0.036 ± 0.003
Al/Si	0.103 ± 0.004

Important New Result and its Implications



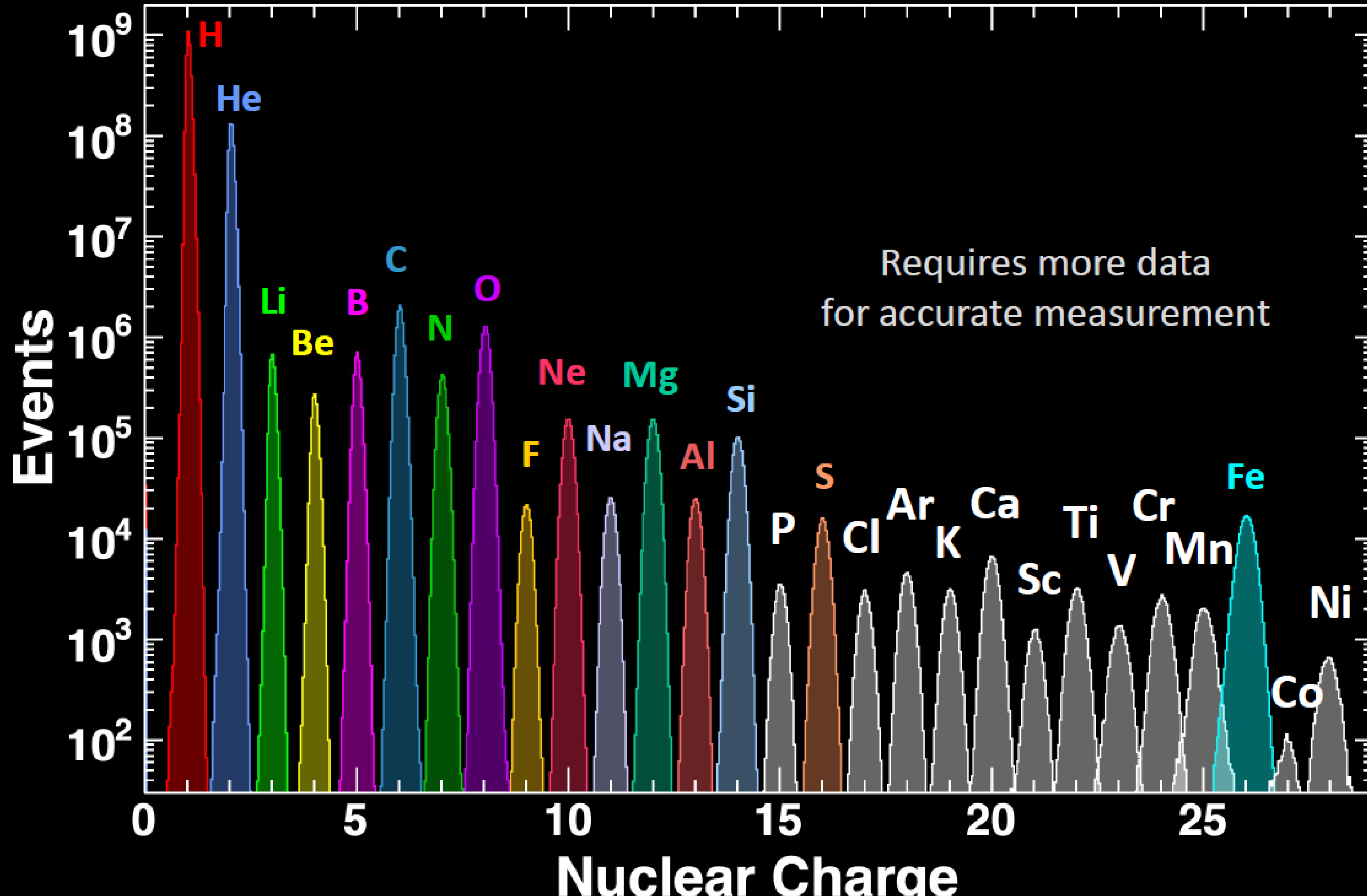
Before AMS, taking into account
the long-standing idea that
C is pure primary
and B is pure secondary,
the (B/C) ratio
has been used in all the theories



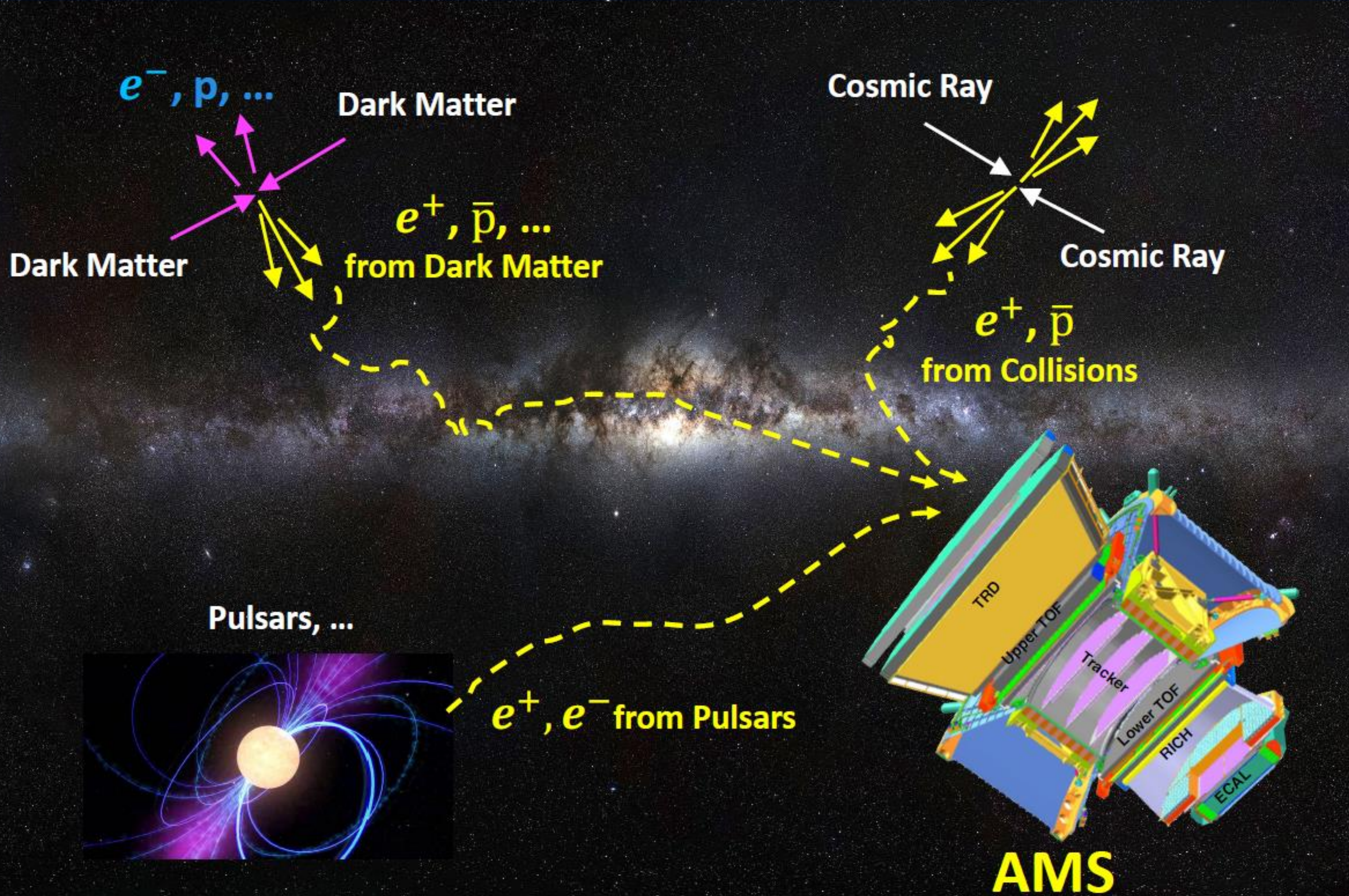
But C is NOT pure primary.
Question: how to use (B/C)
in cosmic ray models?

Cosmic Ray Nuclei by 2030

AMS will provide complete and accurate spectra for the 29 elements and provide the foundation for a comprehensive theory of cosmic rays.



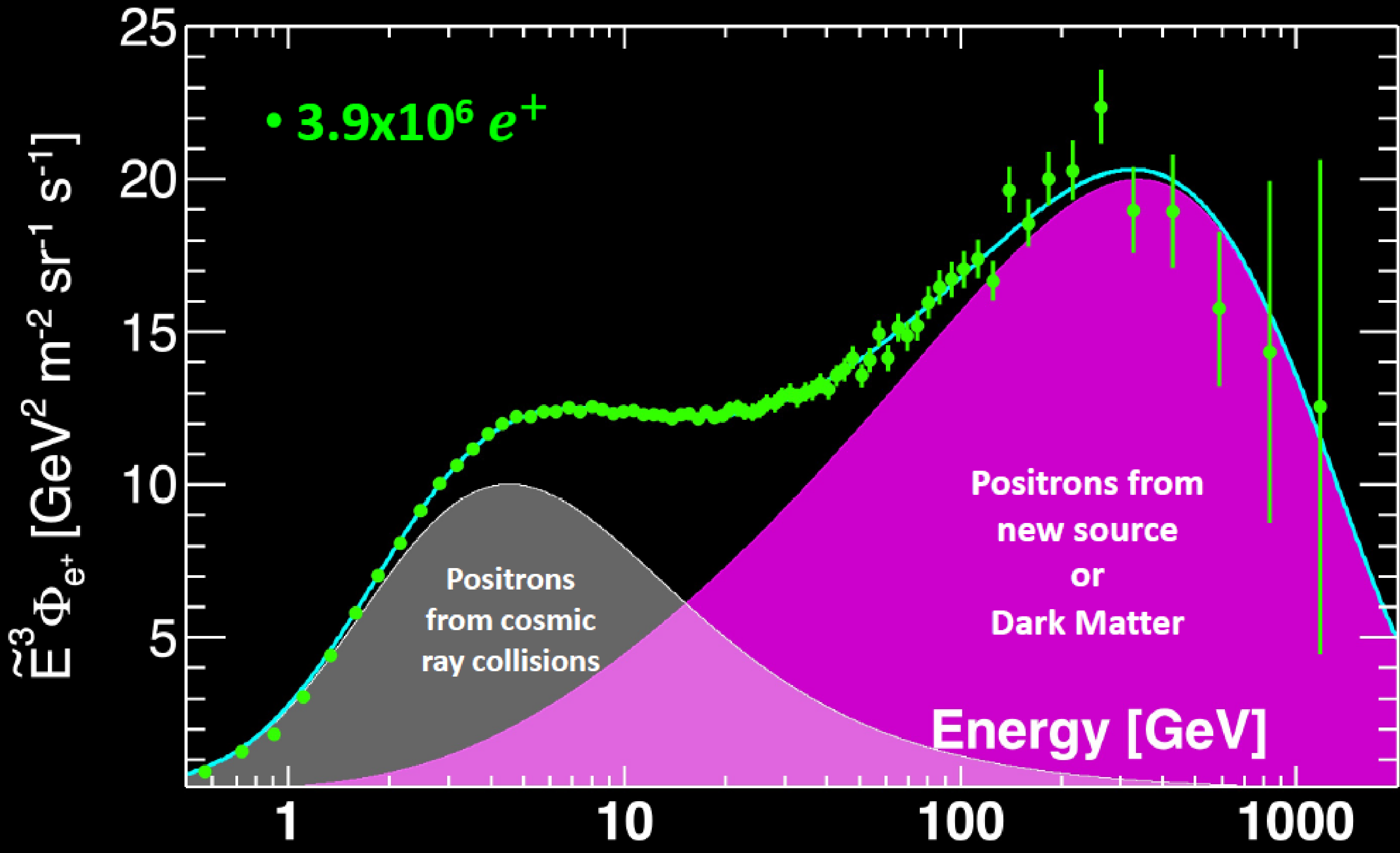
Latest Results on positrons e^+, electrons e^-, antiprotons $\bar{p}$



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

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

Solar Collisions Pulsars or Dark Matter

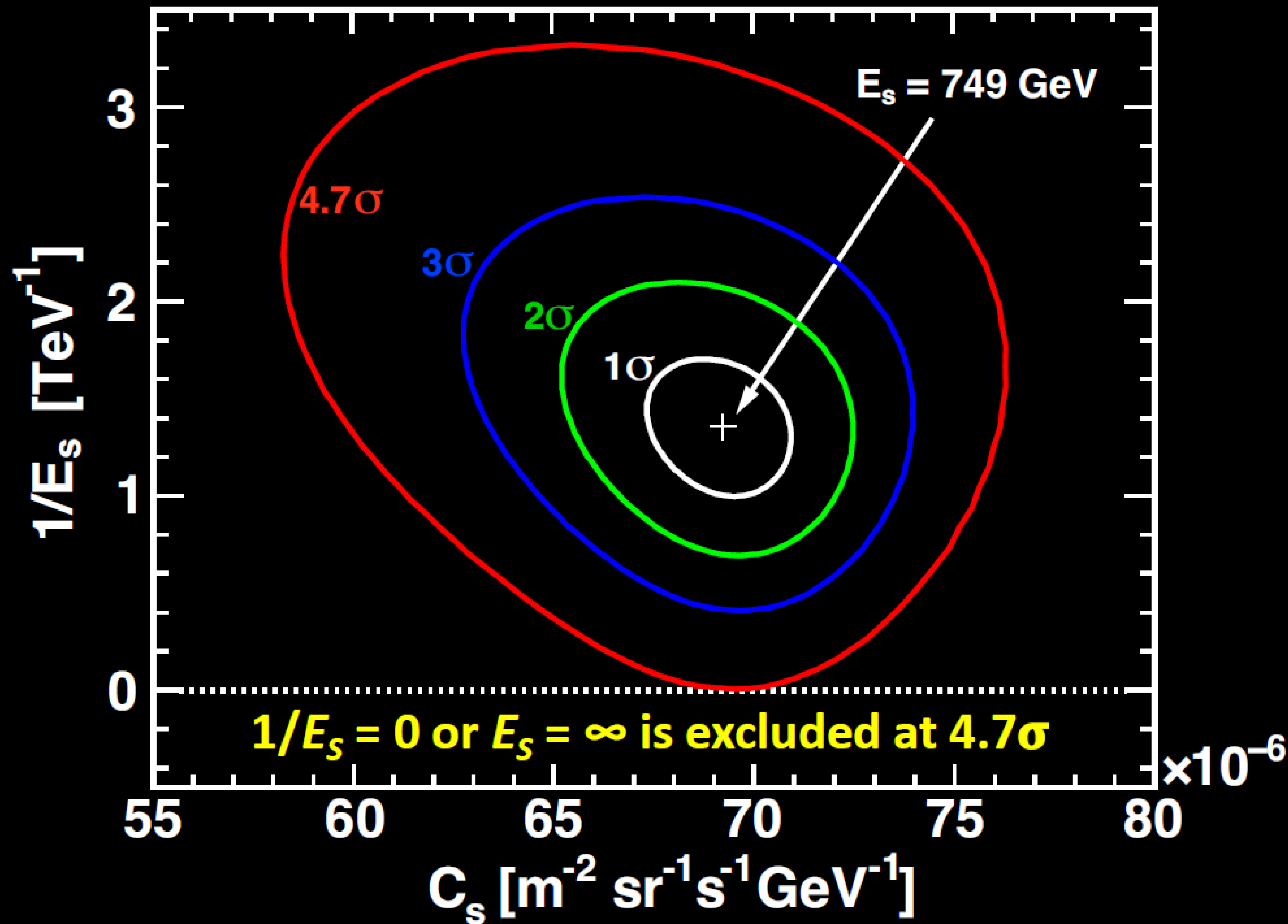


The existence of the finite cutoff energy (4.7σ) is a new and unexpected observation

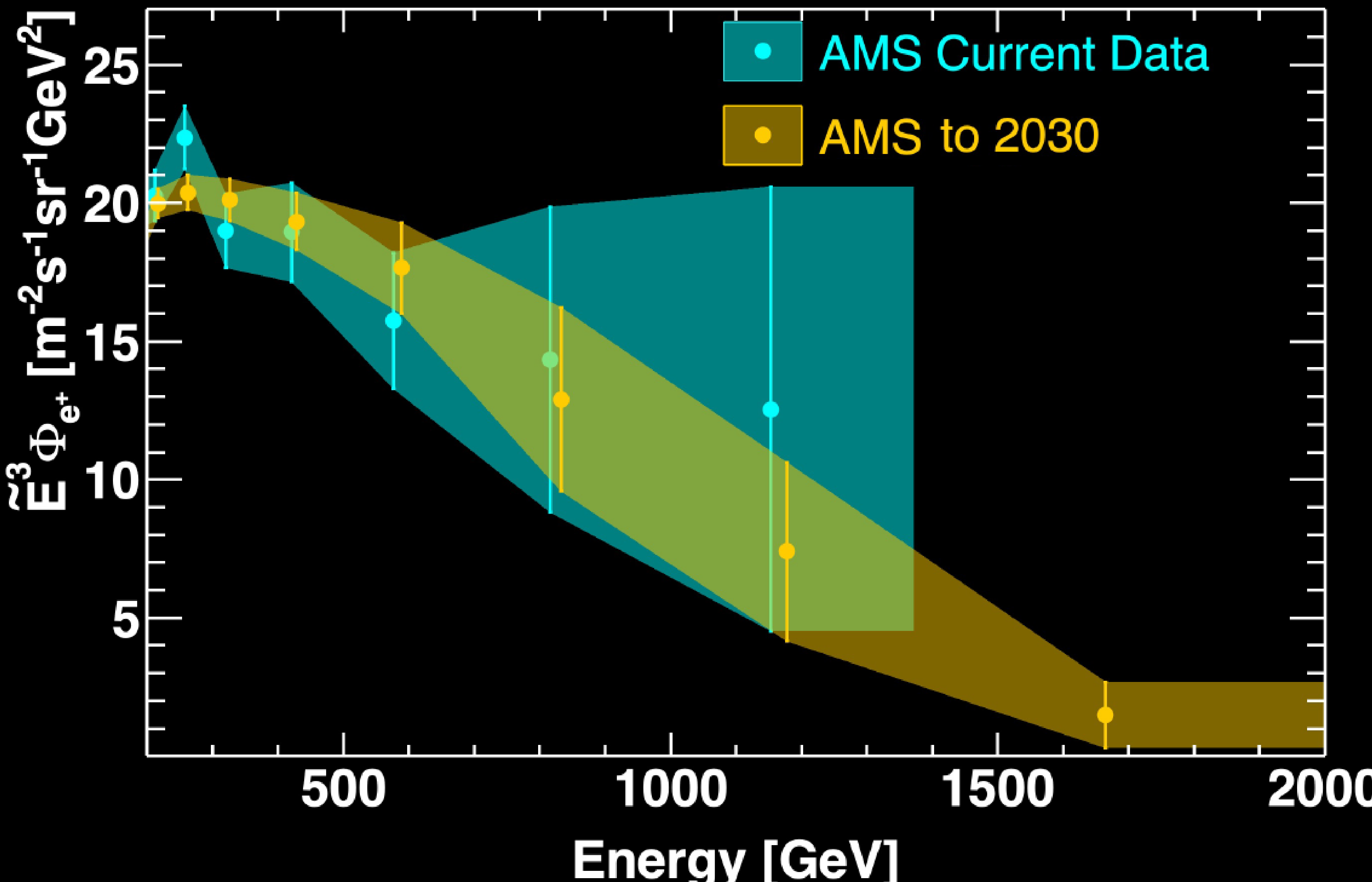
Determination of the cutoff energy E_s

Collisions — New Source or Dark Matter

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

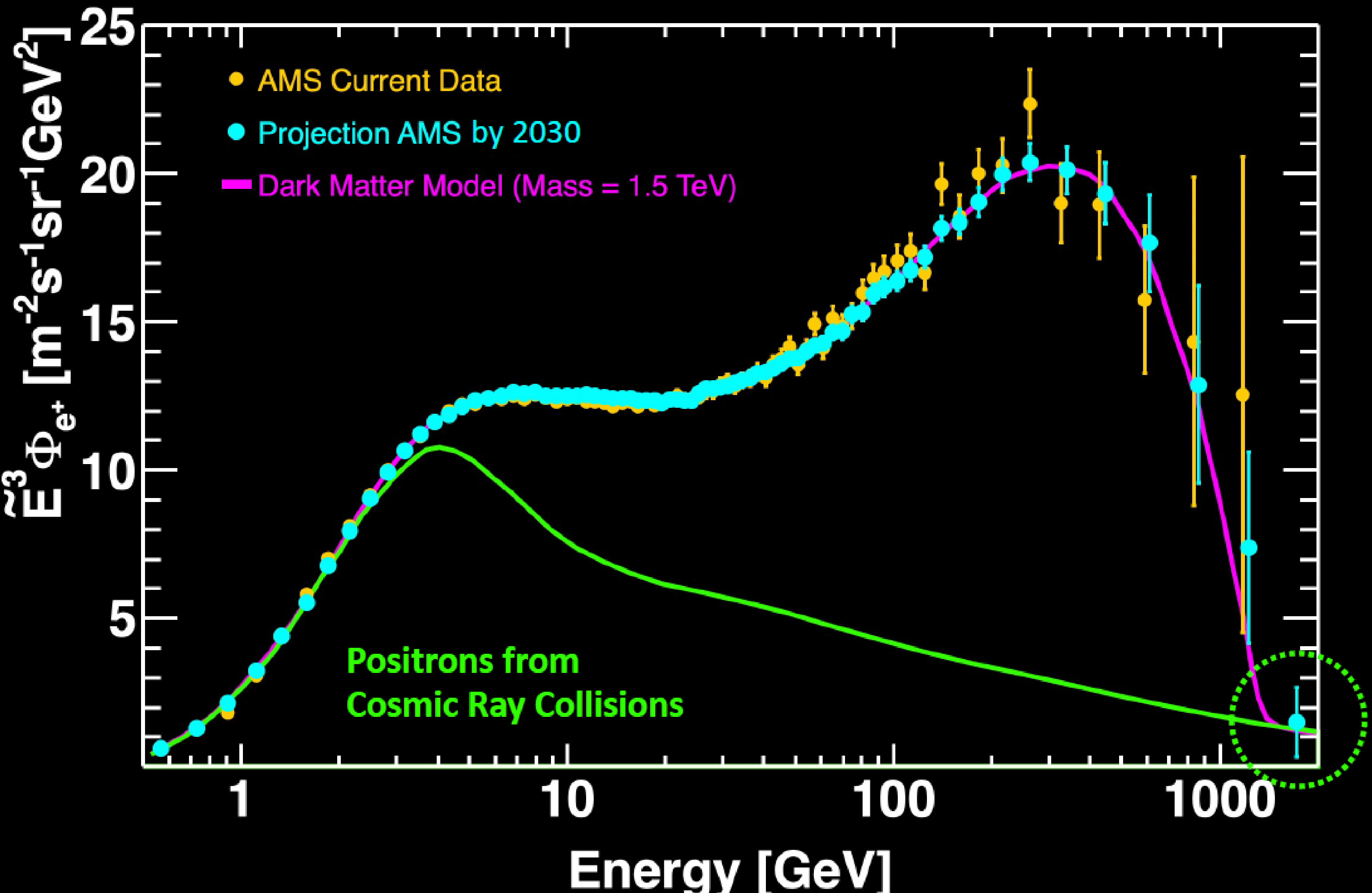


By 2030, AMS will extend the energy range of the positron flux measurement from 1.4 to 2 TeV and reduce the error by a factor of two compared to current data



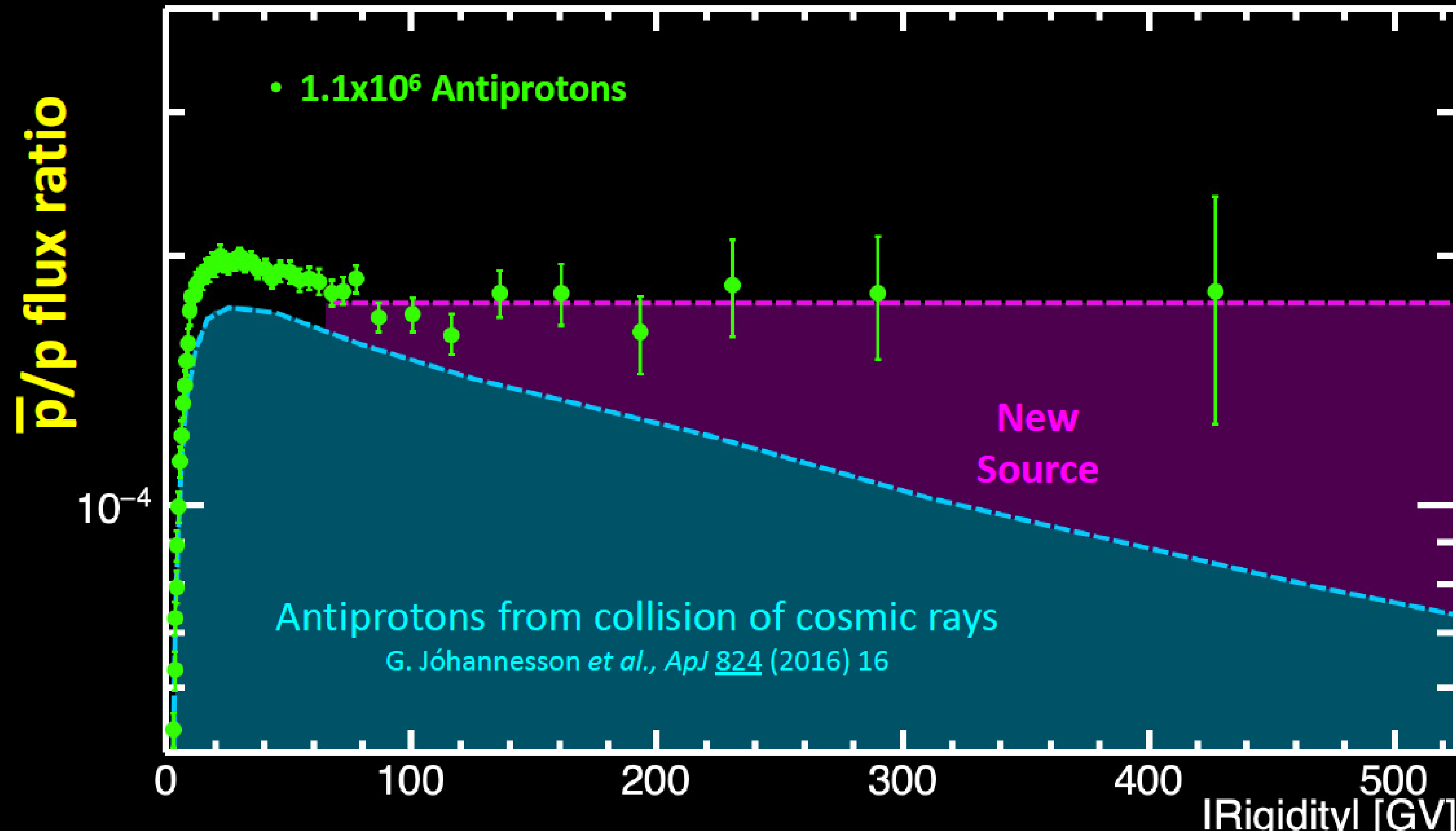
Determination of the Origin of Cosmic Positrons by 2030

AMS will ensure that the measured high energy positron spectrum indeed drops off quickly and, at the highest energies, the positrons only come from cosmic ray collisions as predicted by dark matter models



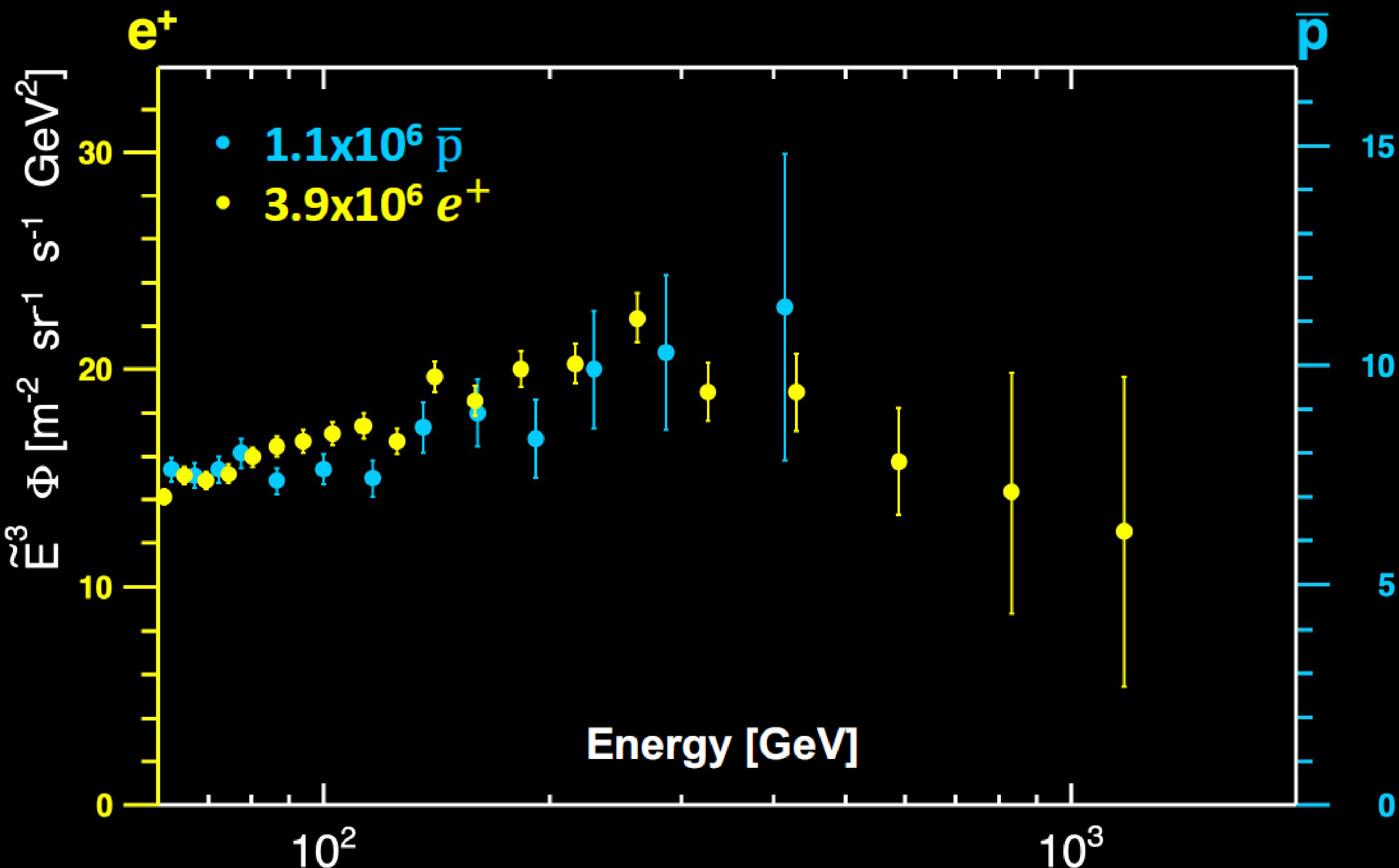
Properties of Cosmic Antiprotons

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



Properties of Cosmic Antiprotons

The $\bar{p}$ and e^+ fluxes have identical rigidity dependence.

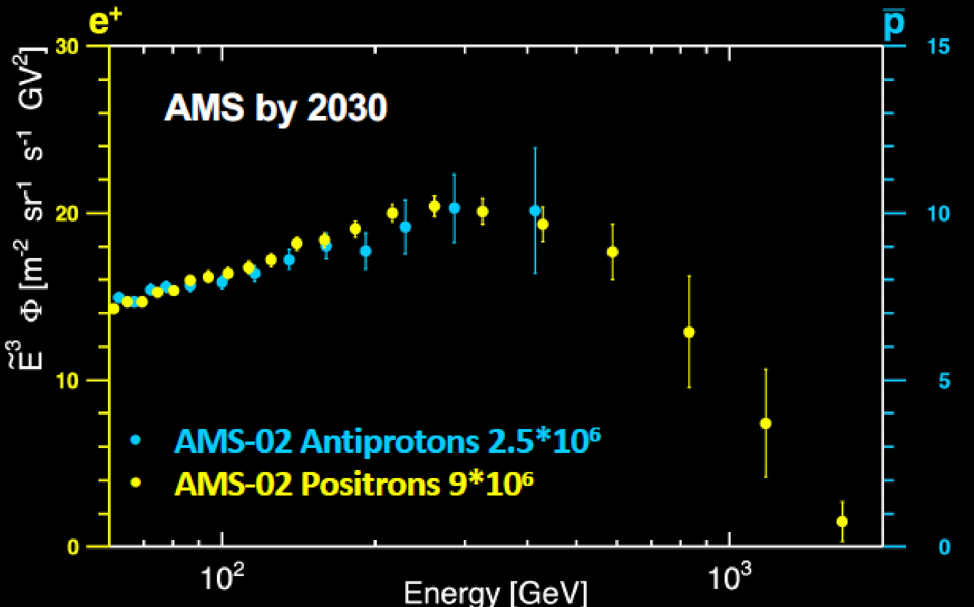


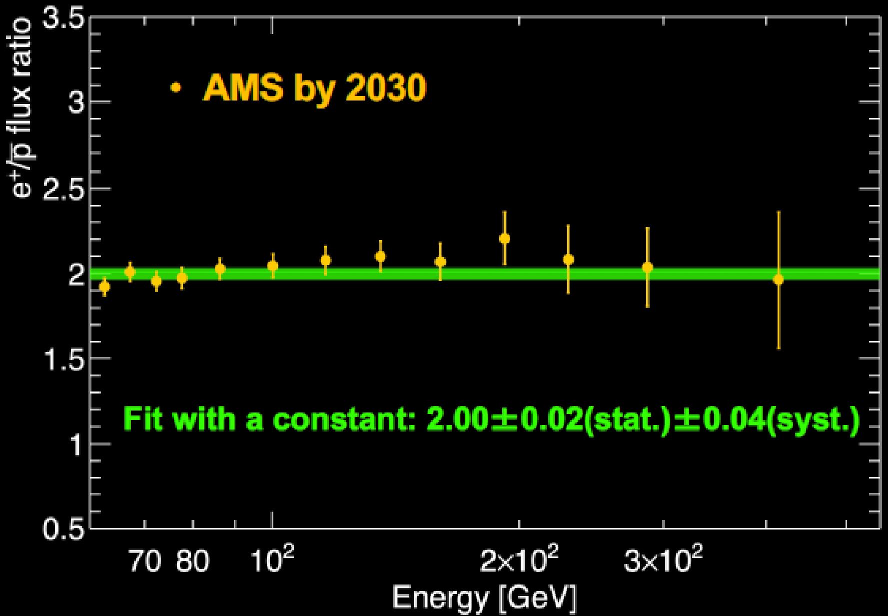
$\bar{p}$ are not produced by pulsars.

By 2030, AMS will greatly improve the accuracy of the antiproton spectra.

The identical behaviour of positrons and antiprotons

excludes the pulsar origin of positrons.



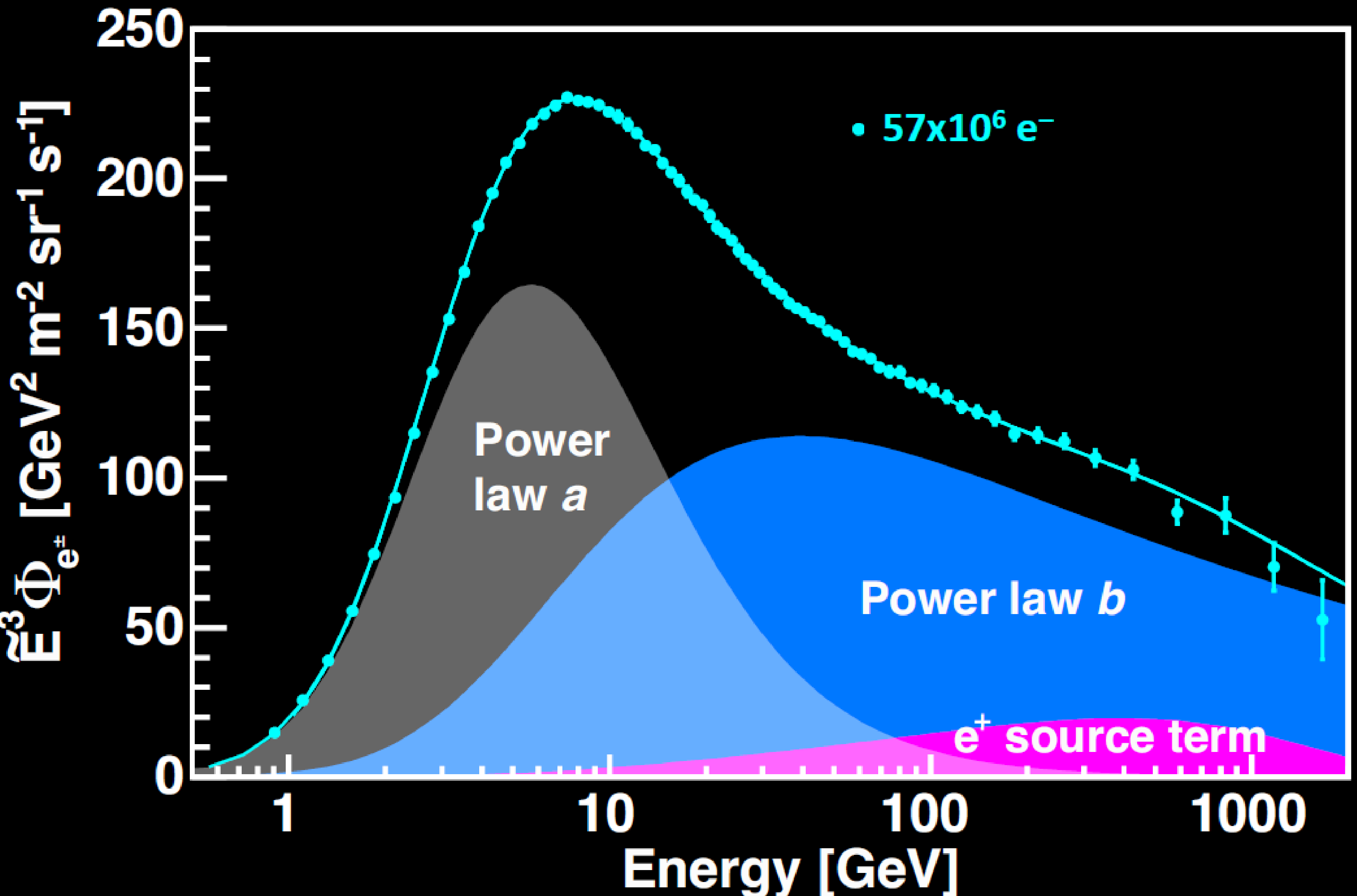


AMS Result on the electron spectrum

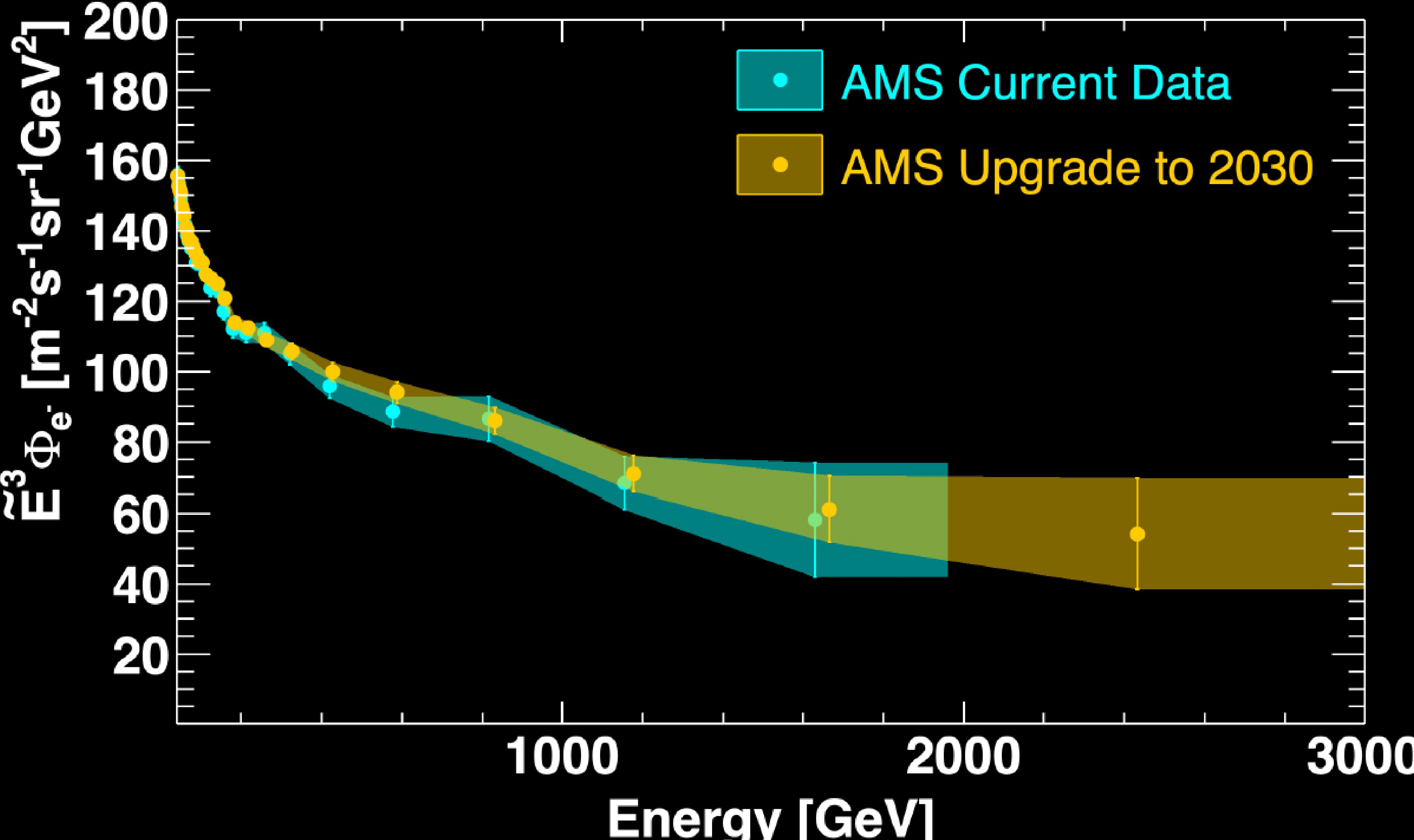
The spectrum fits well with two power laws (*a*, *b*) and a source term like positrons

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

Solar Power law *a* Power law *b*

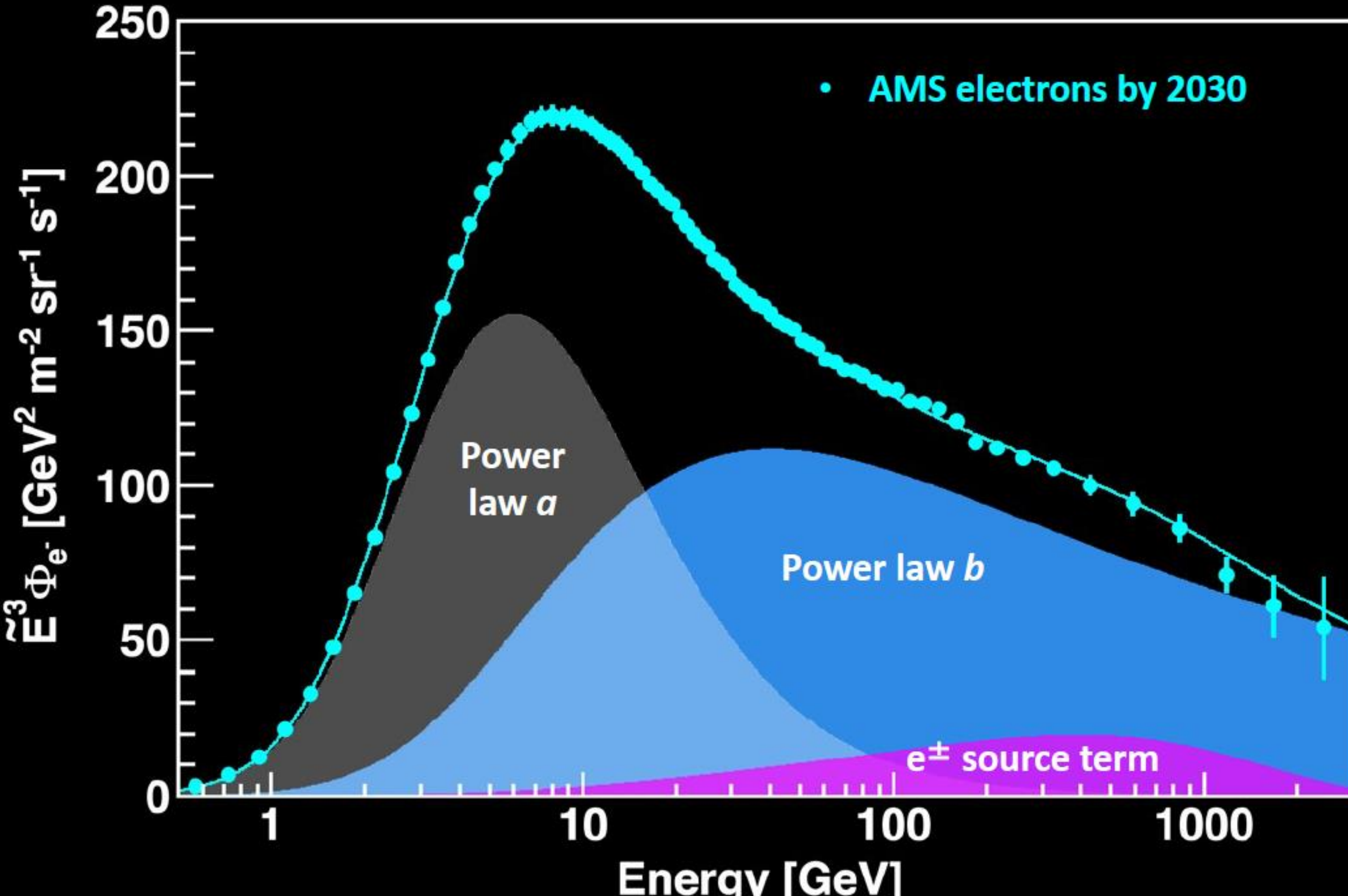


By 2030, AMS will extend the energy range to 3 TeV and reduce the error by a factor of two.

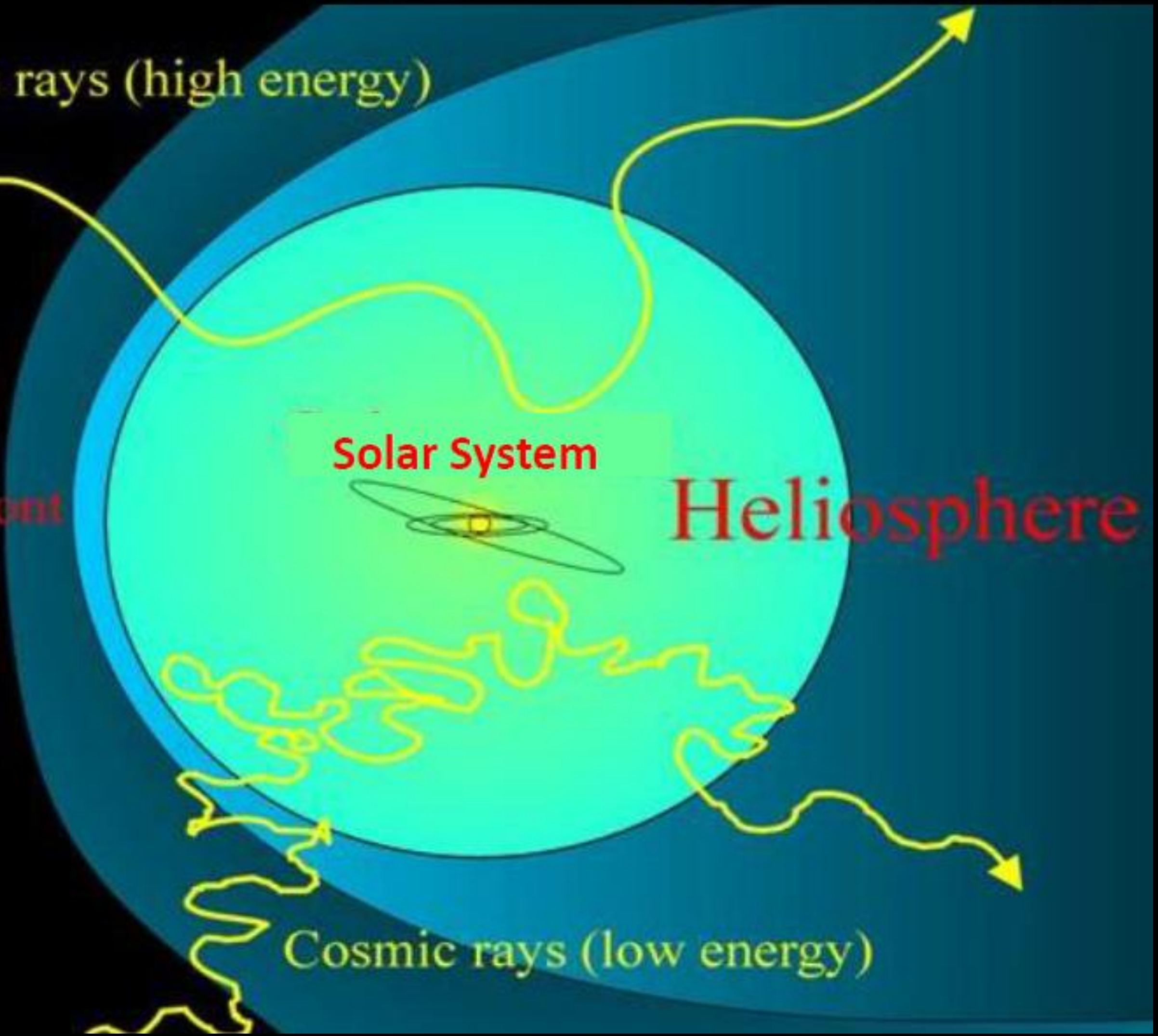


New sources, like Dark Matter or Pulsars, produce equal amounts of e^+ and e^-

By 2030, the charge-symmetric nature of the high energy source will be established at the 4σ level

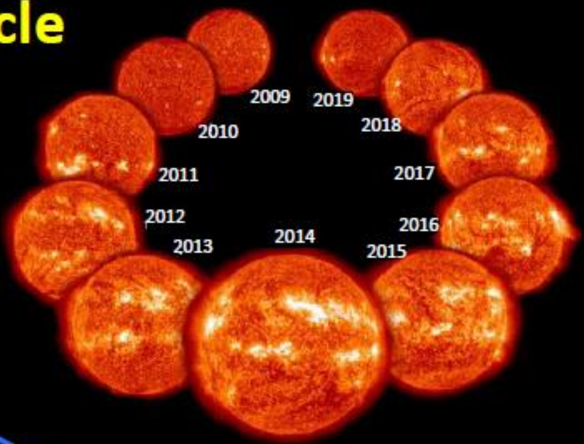


Solar Modulation of Cosmic Rays



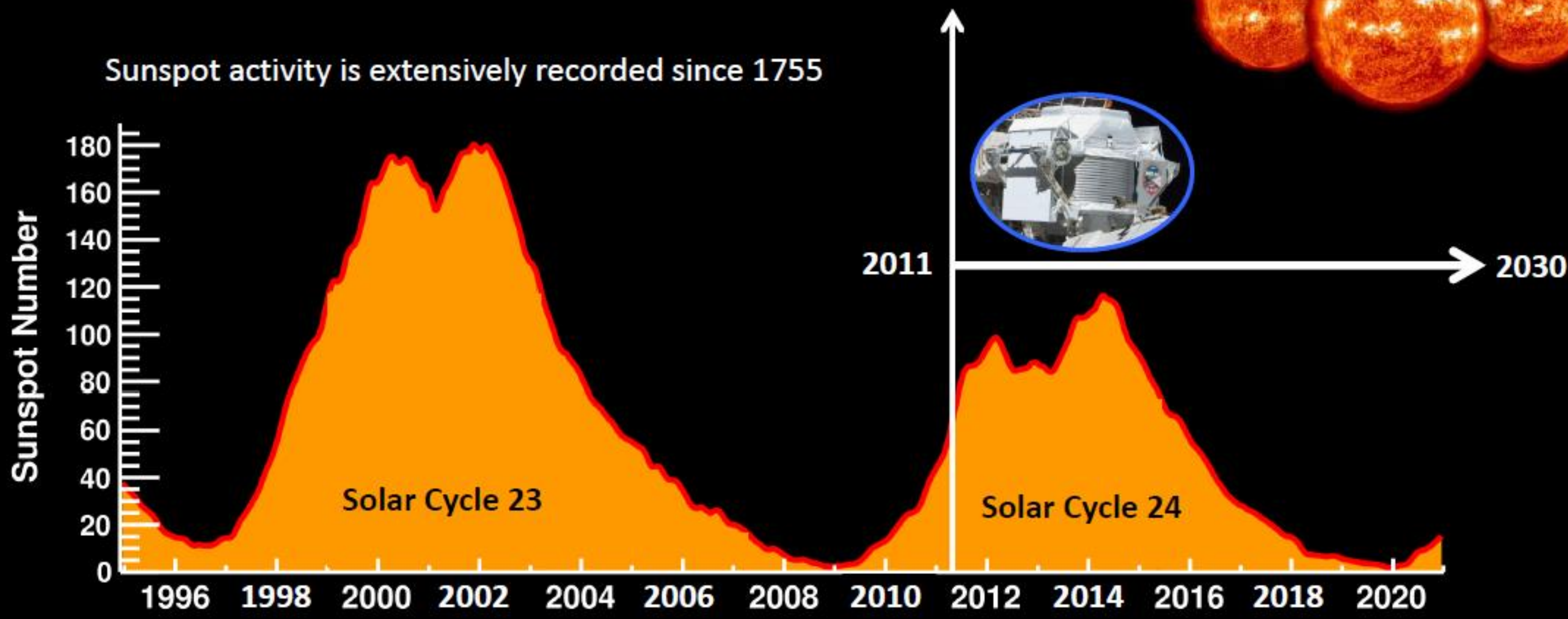
Cosmic ray intensity at low energies is modulated by the Sun through the influence of magnetic field and solar wind.

Long Term Variation: Solar Cycle



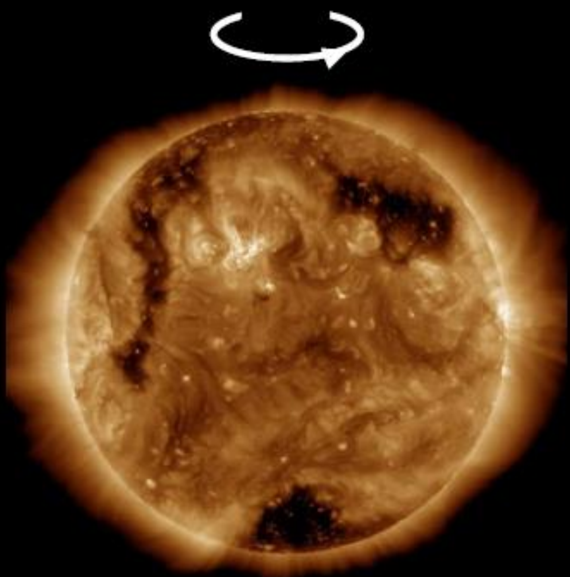
The most significant long-term scale variation of cosmic rays is related to the 11-year solar cycle.

Sunspot activity is extensively recorded since 1755

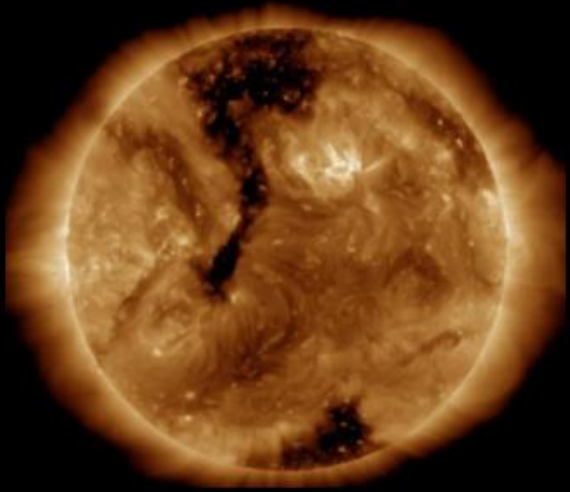


Cosmic Ray Recurrent Variation in Short Scale

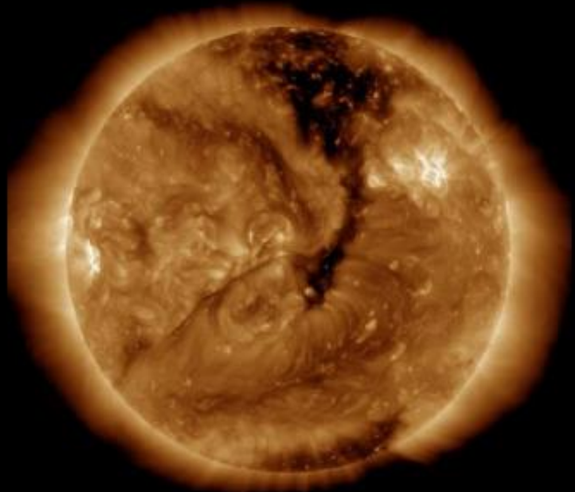
Short scale variation of cosmic rays are related to Sun's rotation (Bartels' rotation: 27 days).



2016-03-22



2016-03-24



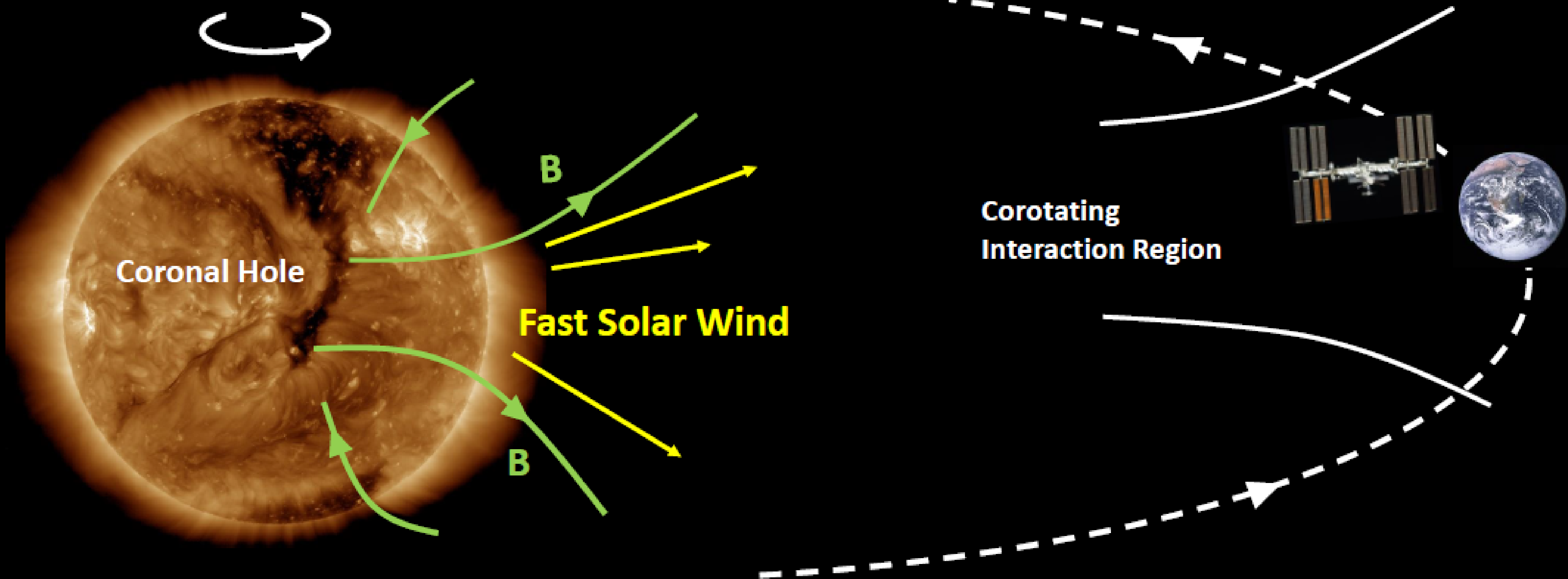
2016-03-26

Image taken by Dynamics Observatory (SDO), NASA

Coronal holes are regions where plasma density and temperature are lower, so they appear darker in images.

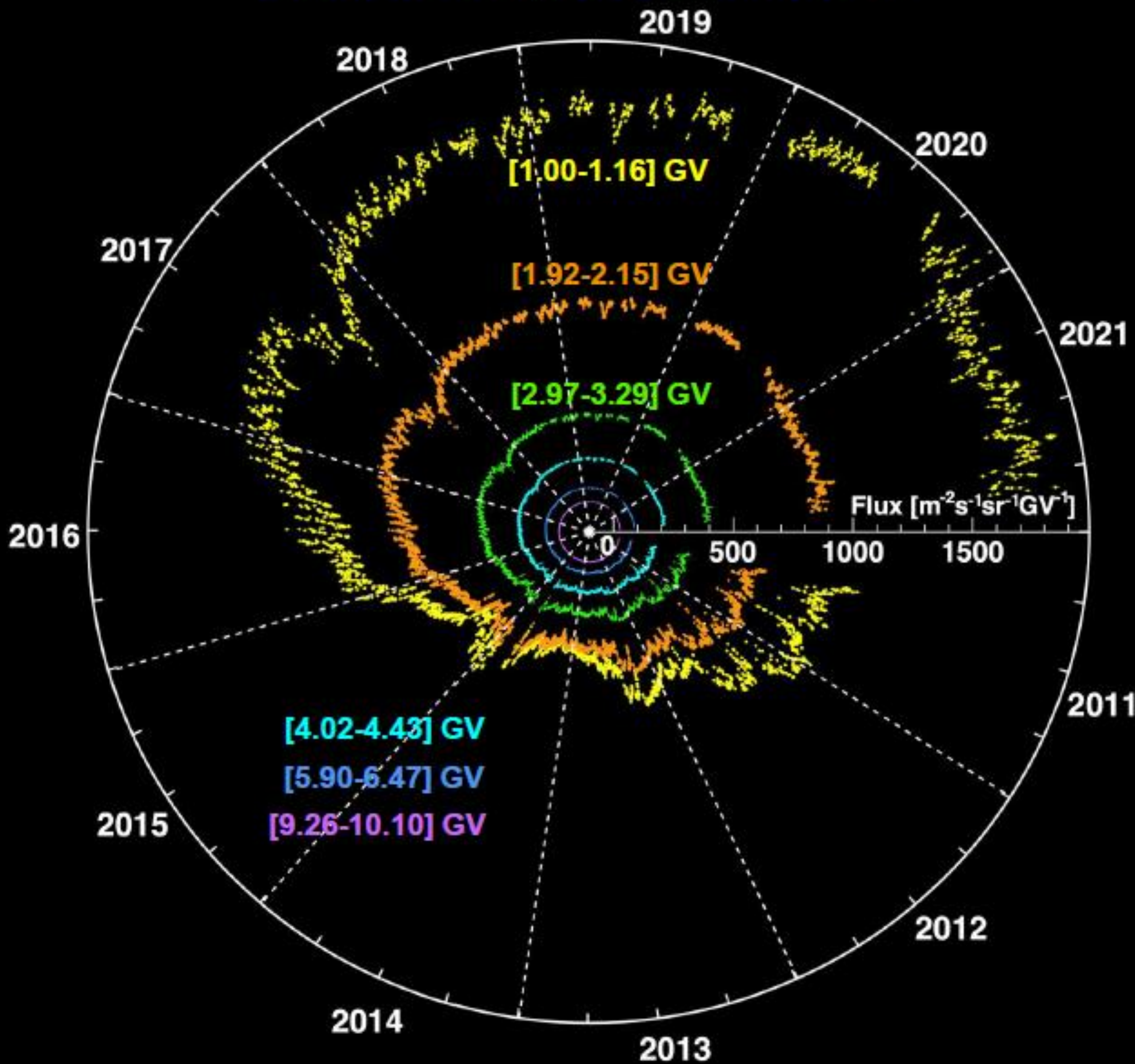
Cosmic Ray Recurrent Variation in Short Scale

Coronal Holes are sources of high speed solar wind affecting Earth.



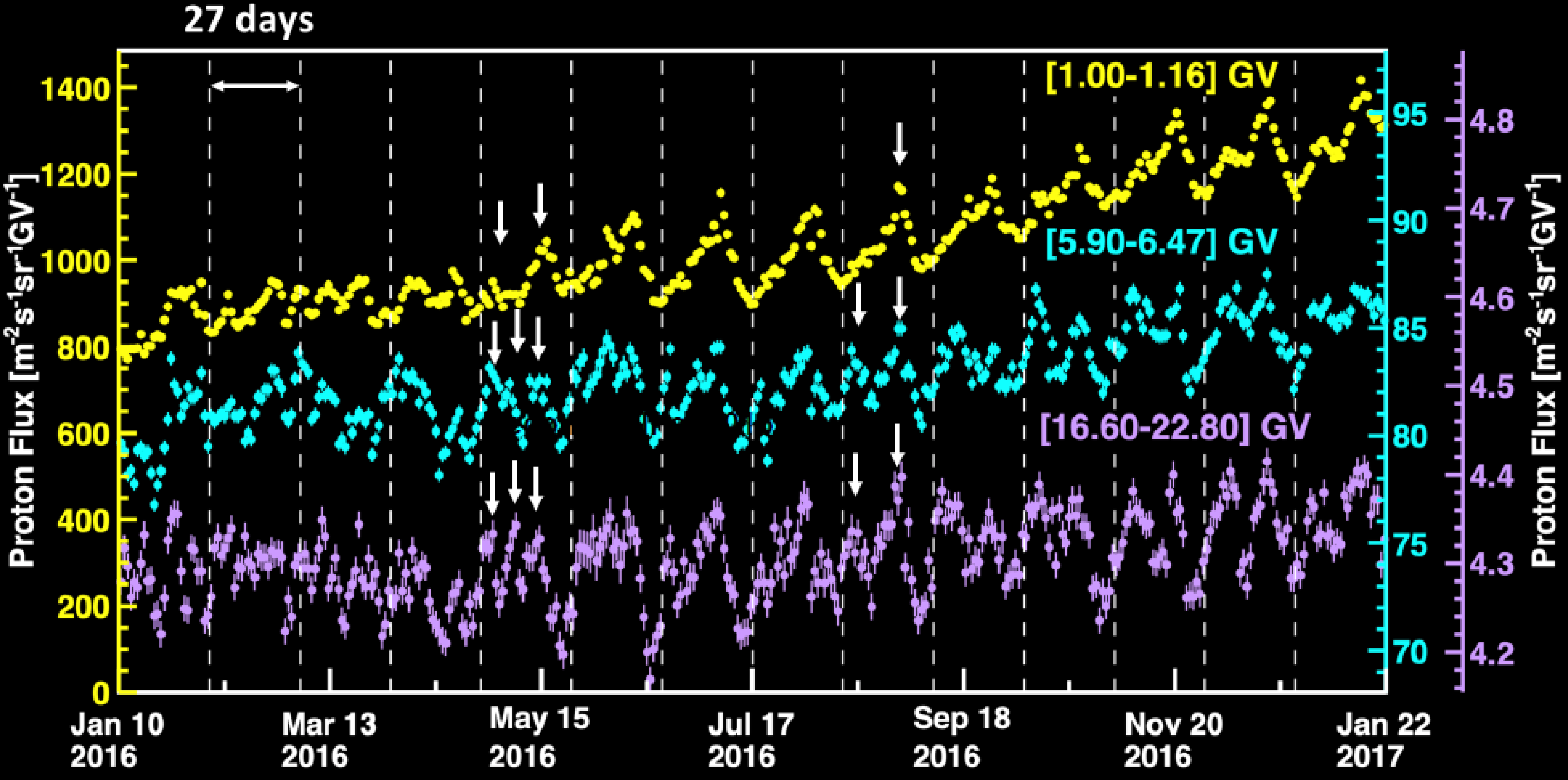
Precision measurements of the individual species of cosmic rays in a solar cycle provide unique inputs for the understanding of cosmic rays in the heliosphere.

AMS Daily Proton Flux

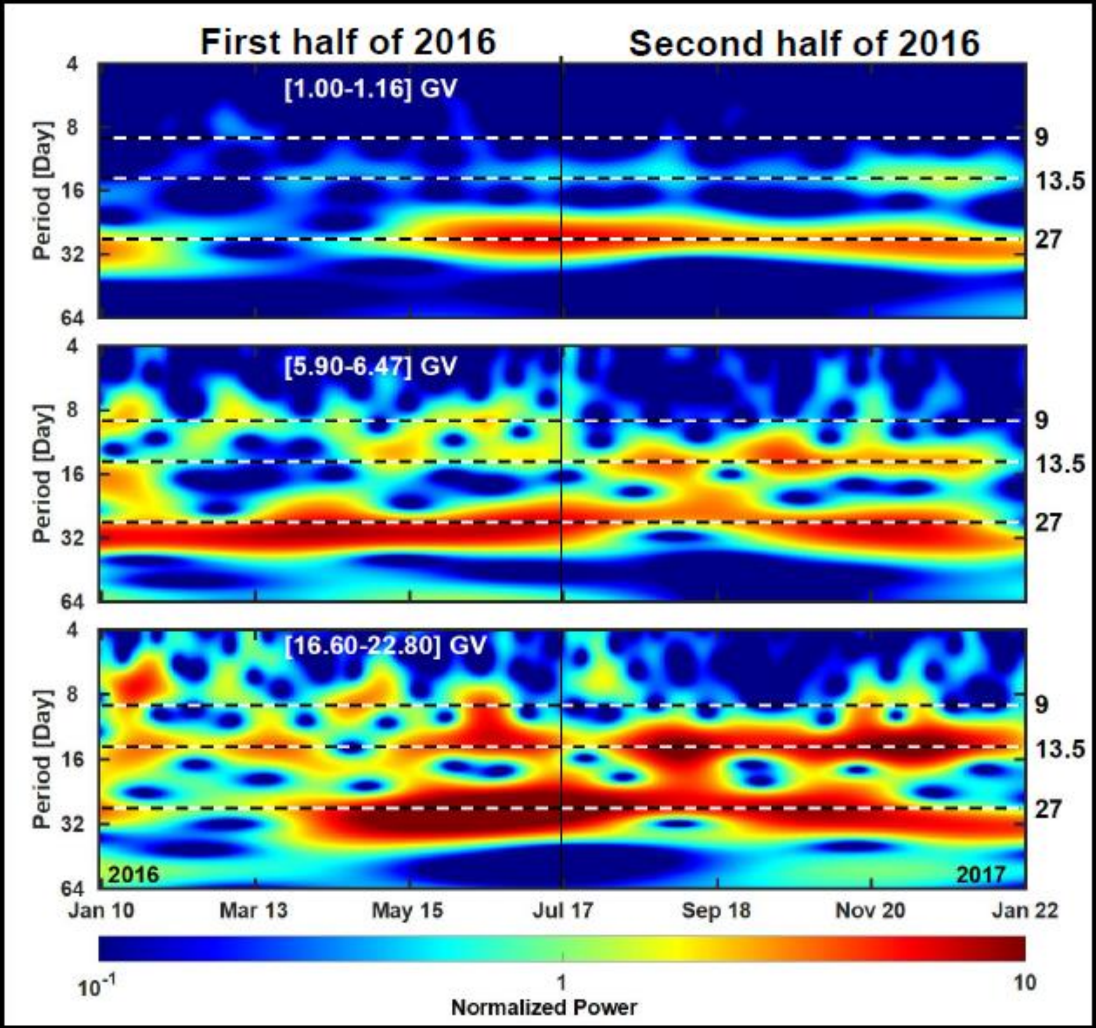


Recurrent Proton Flux Variation in 2016

Double-peak and triple-peak structures are visible in different Bartels rotations



Wavelet Analysis of Proton Fluxes in 2016



To study the recurrent time variations in the daily proton fluxes, a **wavelet time-frequency** technique was used.

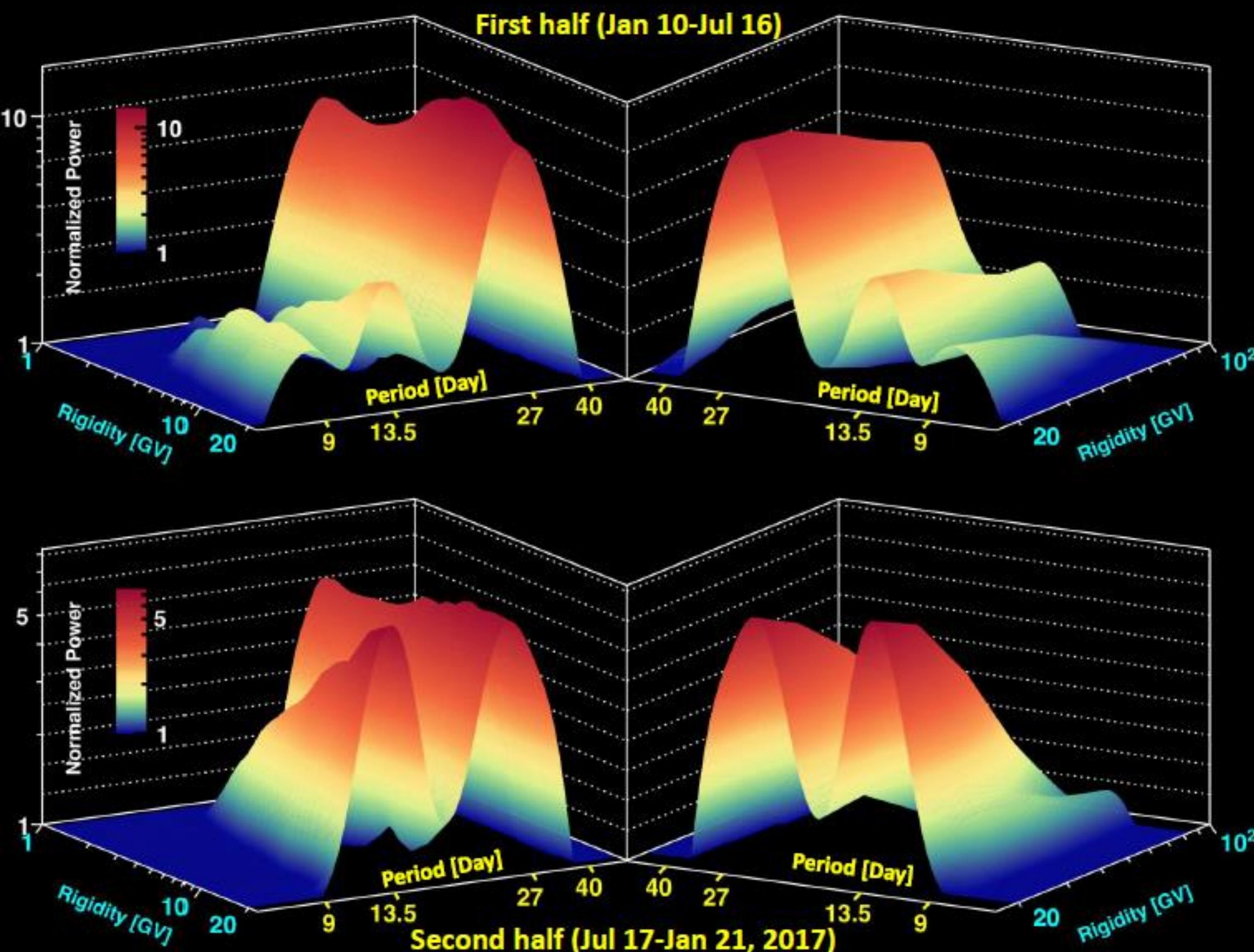
To show the strength of the periodicity, **the normalized power** is defined by the power divided by **the variance** of the time series.

Periods of 9, 13.5, and 27 days are observed in 2016.

The strength of all three periodicities changes with time and rigidity.

In particular, shorter periods of 9 and 13.5 days, when present, are more visible at 6 GV and 20 GV compared to 1 GV.

Periodicities of Daily Proton Fluxes in 2016



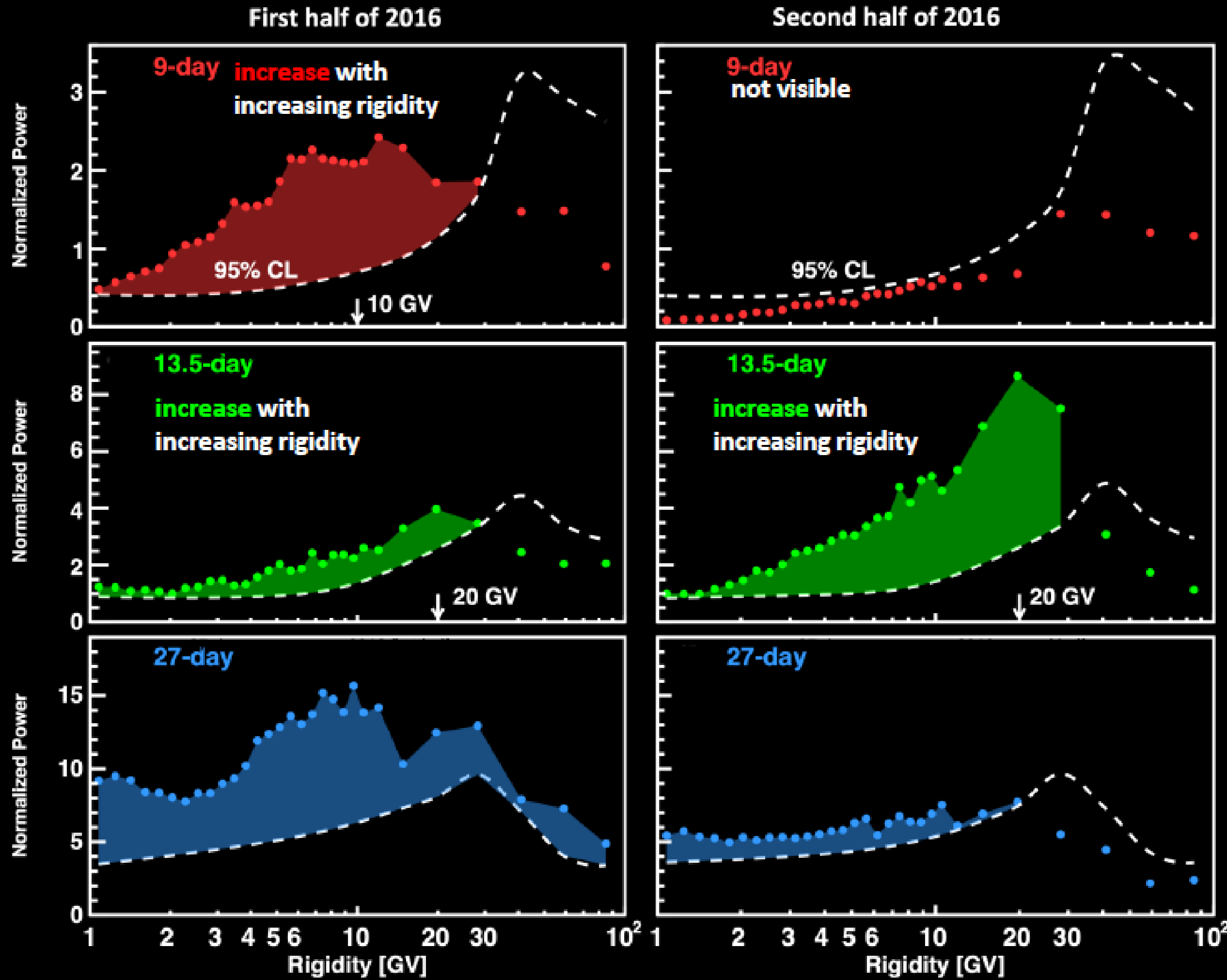
Highlight #1

Unexpectedly, the strength of **9-day and 13.5-day periodicities** increases with increasing rigidity up to **~10 GV** and **~20 GV,** respectively. Then the strength decreases with increasing rigidity up to **100 GV.**

Thus, the AMS results do not support the general conclusion that the strength of the periodicities always decreases with increasing rigidity

Phys. Rev. Lett. 127, 271102 (2021)

Rigidity Dependence of 9-day, 13.5-day, and 27-day periods of protons

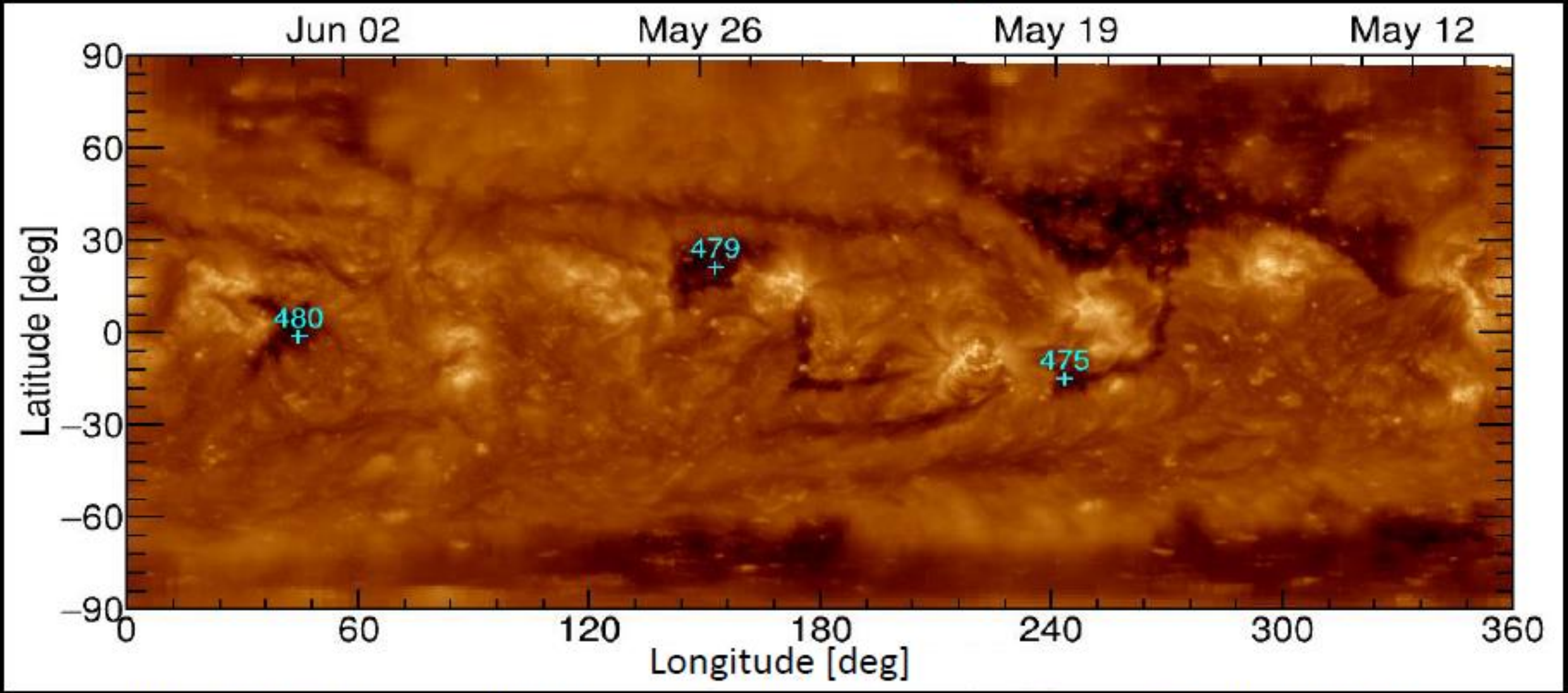


Shaded areas are the rigidity intervals where the periodicity is prominent

Cosmic Ray Periodicities and the Rotation of the Sun

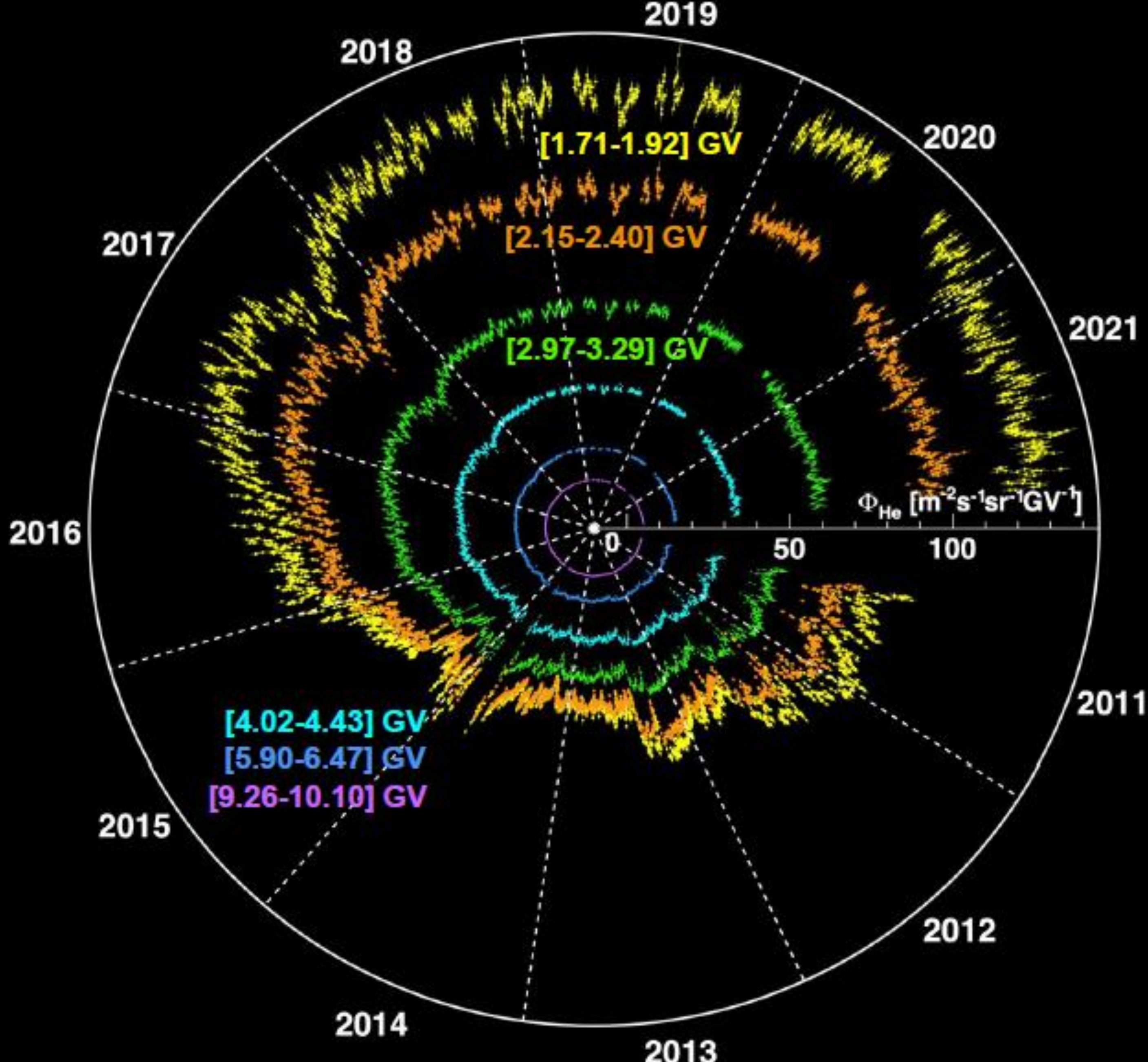
Coronal Holes are sources of high speed solar wind affecting Earth. The rotation of the Sun causes multiple periods in the flux:

0 coronal hole:	⟶	No apparent periods
1 coronal hole	⟶	27-day period (a Bartels rotation)
2 coronal holes separated by 180°	⟶	13.5-day period
3 coronal holes separated by 120°	⟶	9-day period

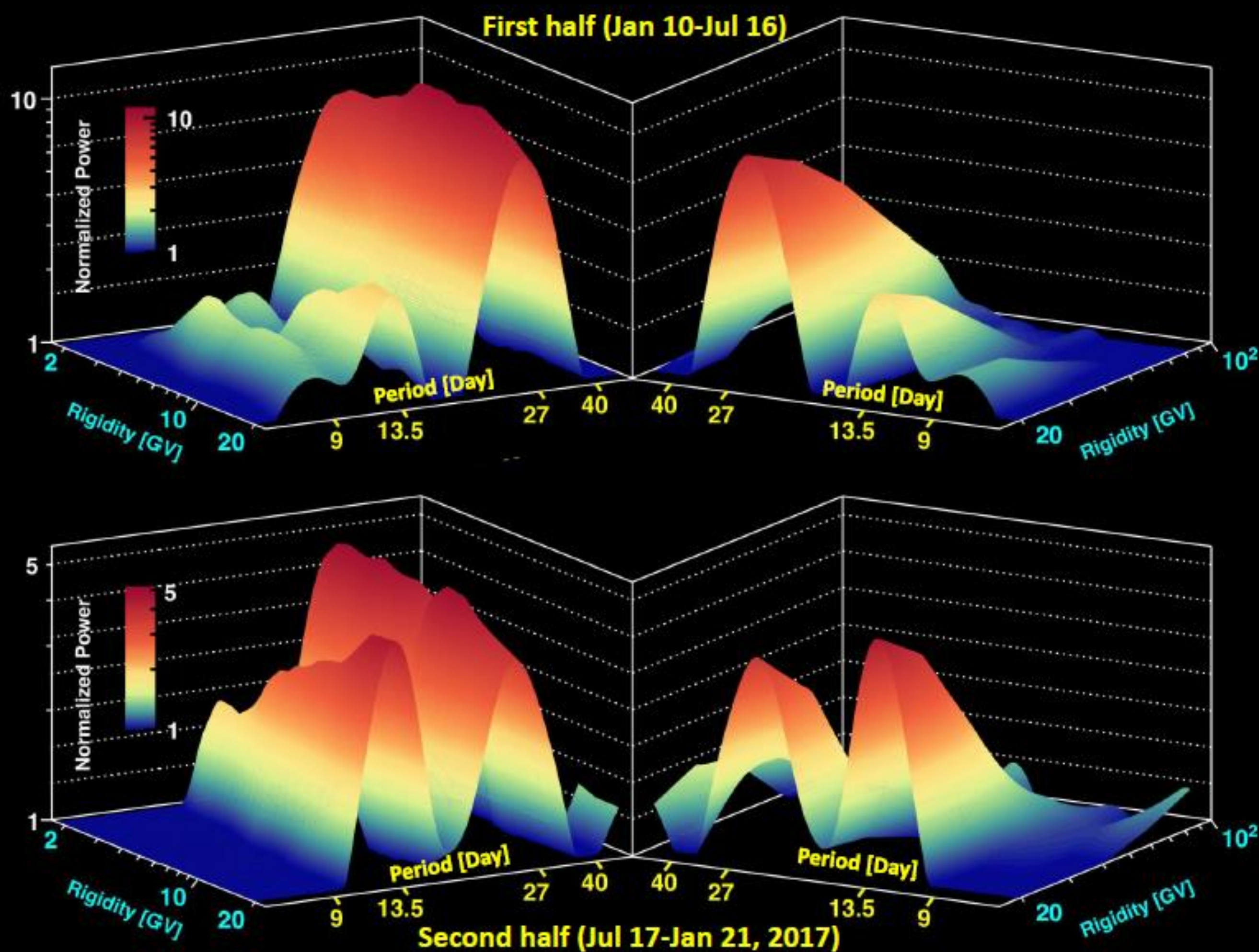


(May 10, 2016-Jun 06, 2016) Image taken by Solar Dynamics Observatory (SDO), NASA

AMS Daily Helium Flux



Periodicities of Daily Helium Fluxes in 2016



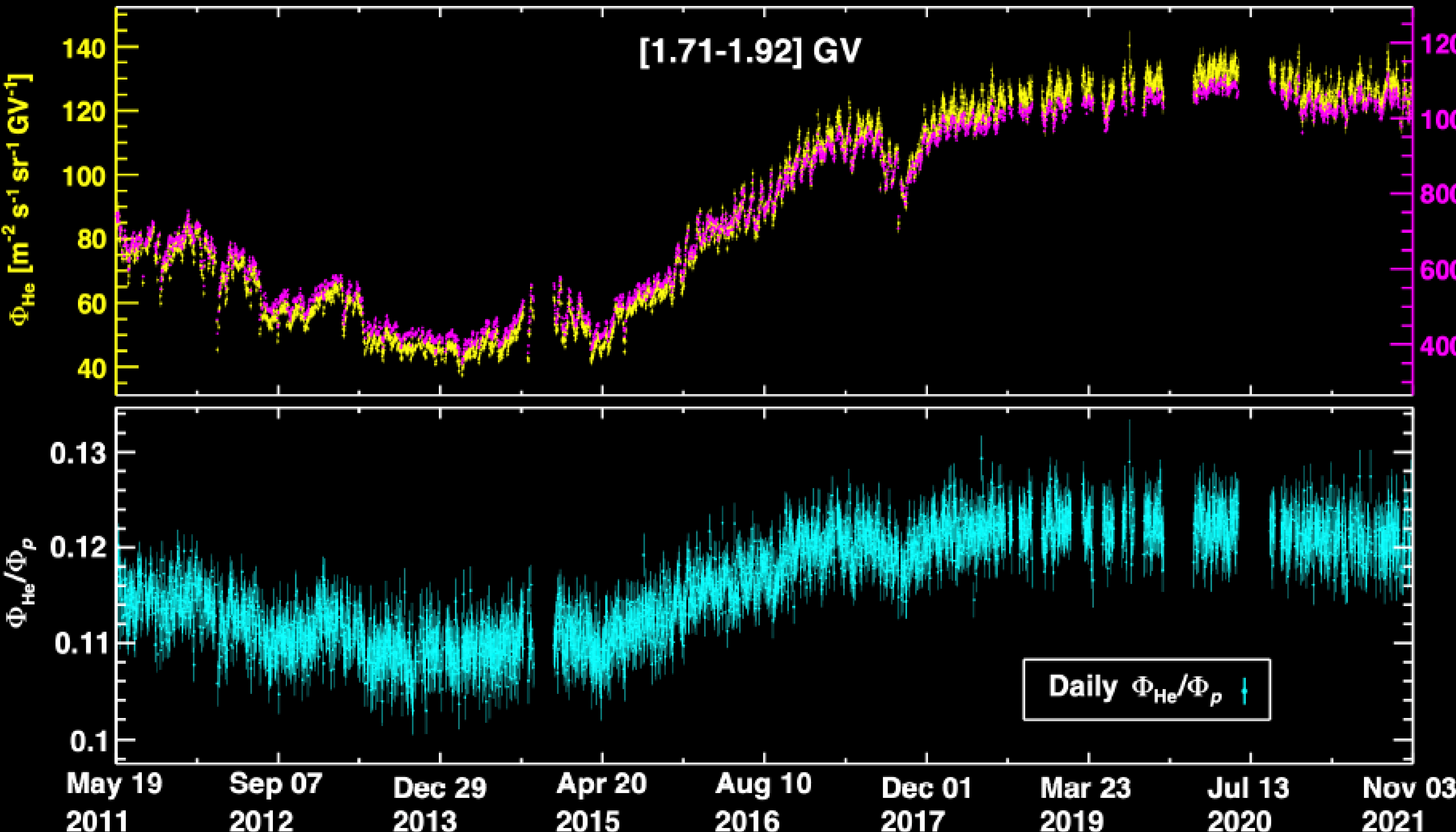
Similar periodic structures are observed for helium.

The AMS results do not support the general conclusion that the strength of the periodicities always decreases with increasing rigidity

Phys. Rev. Lett. 128, 231102 (2022)

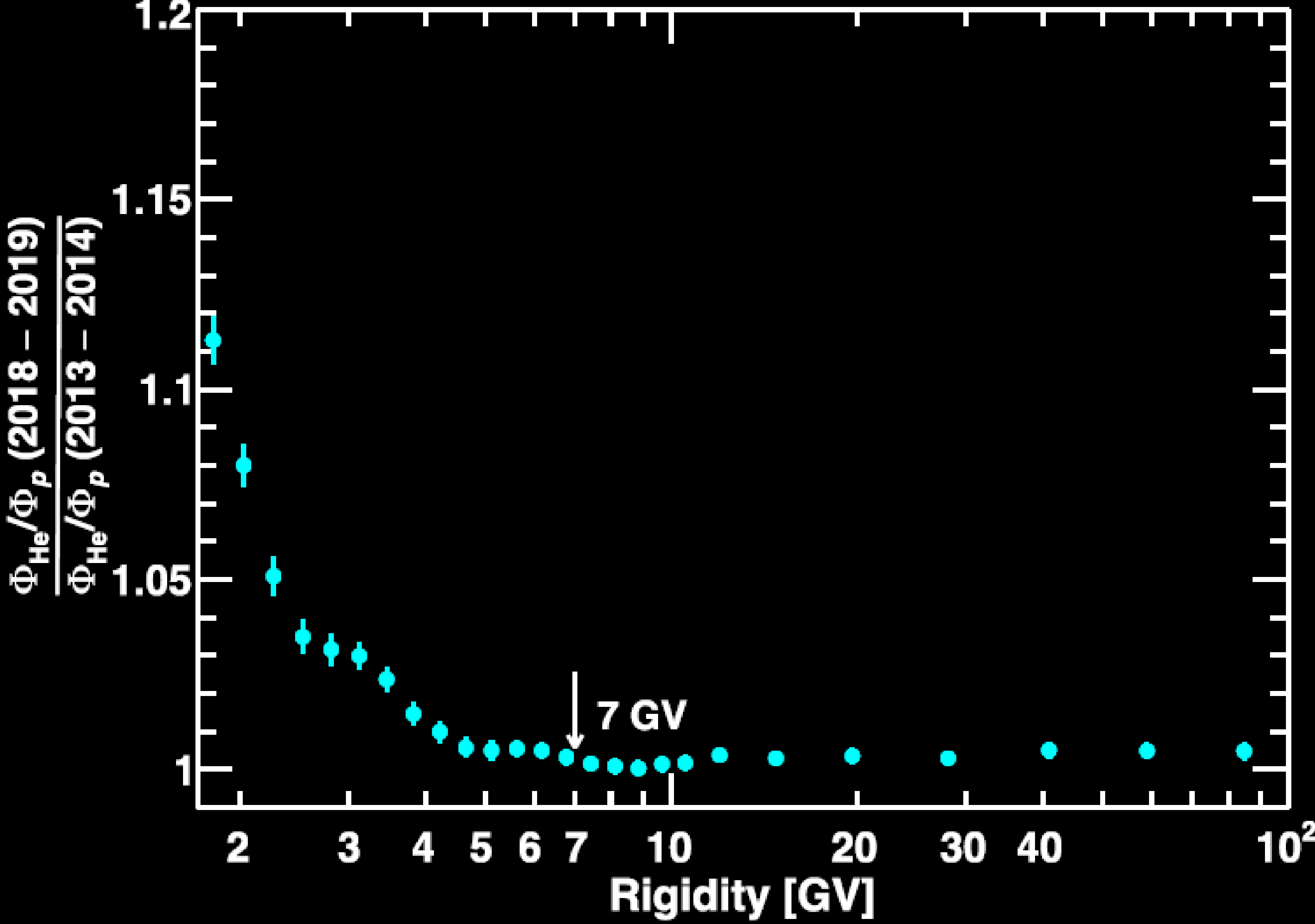
Daily Φ_{He}, Φ_p and Φ_{He}/Φ_p

Φ_{He}/Φ_p exhibits variations on multiple timescales



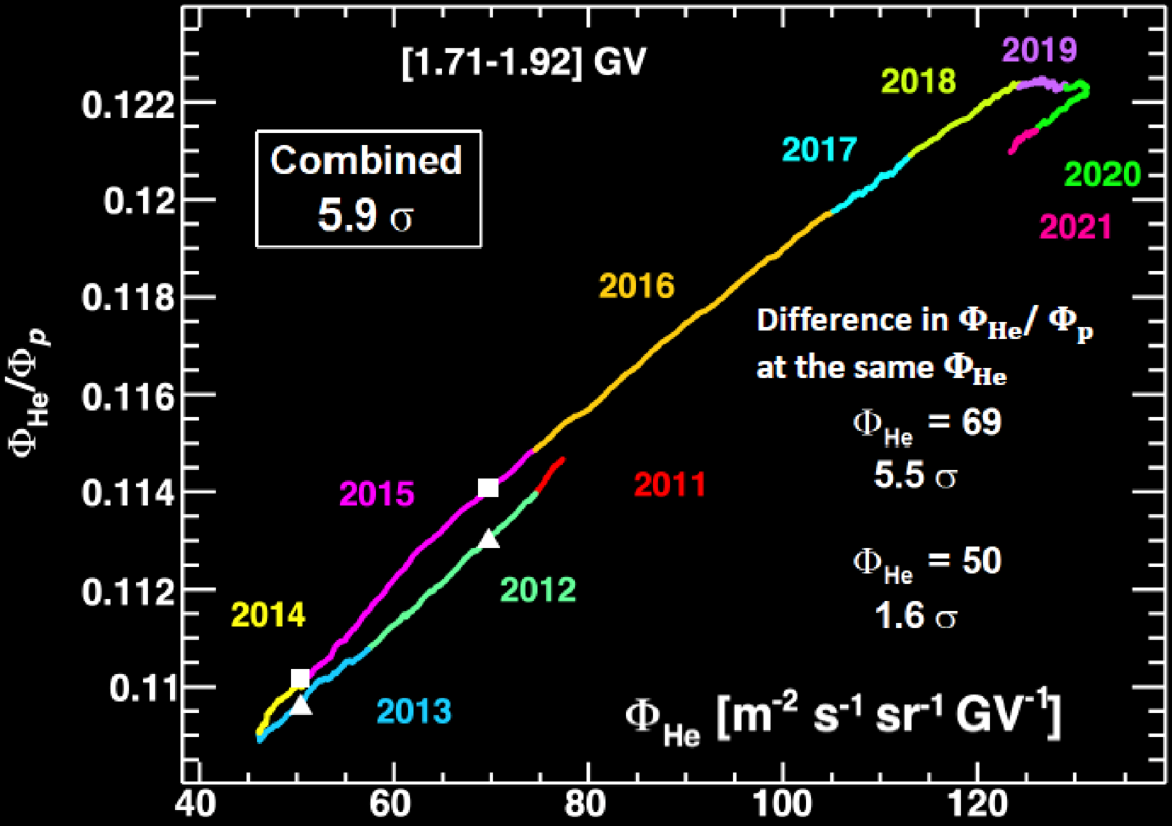
Daily Φ_{He}, Φ_p and Φ_{He}/Φ_p

Below ~7 GV, Φ_{He} exhibits larger time variations than Φ_p



A hysteresis between Φ_{He}/Φ_p and Φ_{He}

At low rigidity the modulation of the helium to proton flux ratio is different before and after the solar maximum in 2014



We study the significance of the difference of Φ_{He}/Φ_p at the same Φ_{He} but different solar conditions:

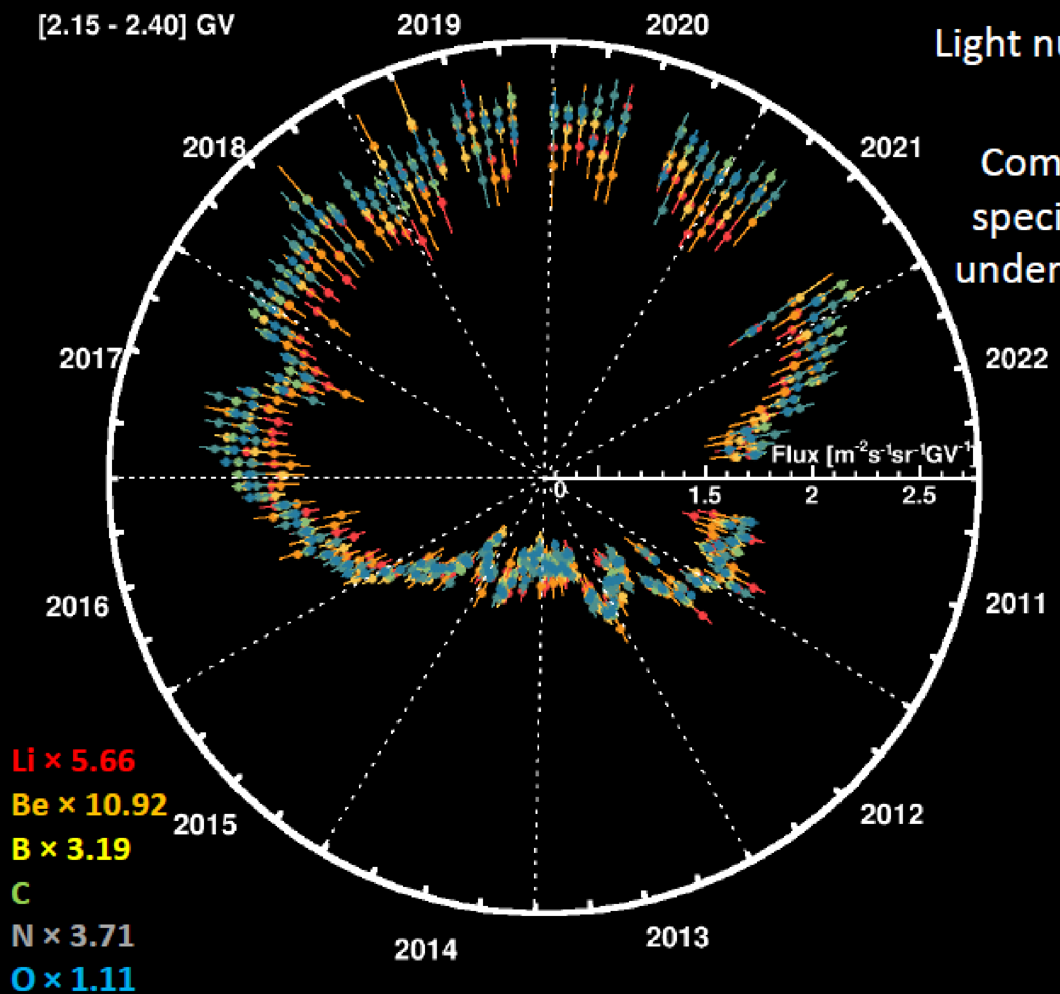
- ▲ : Φ_{He}/Φ_p before the solar maximum 2014
- ■ : Φ_{He}/Φ_p after the solar maximum 2014

Highlight #2

The hysteresis is observed with an overall significance >7σ below 2.4 GV

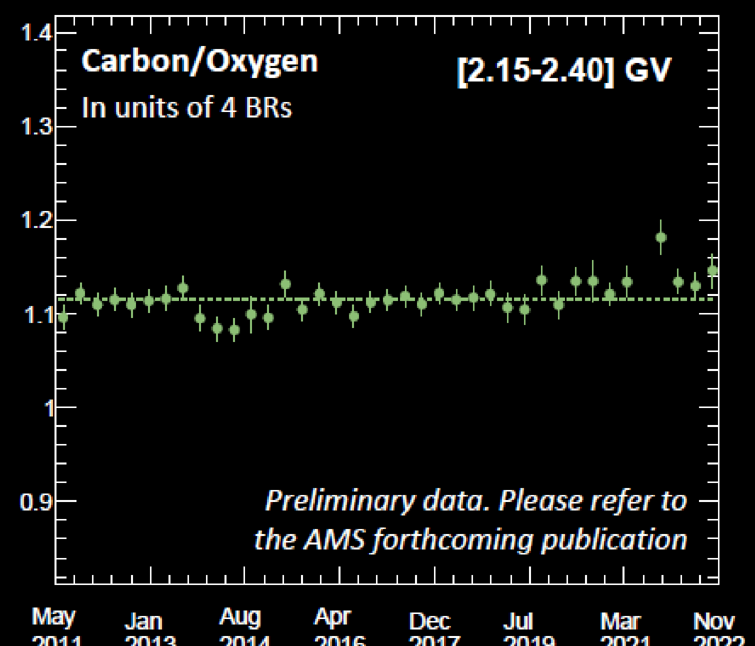
Phys. Rev. Lett. 128, 231102 (2022)

Time Variation of Cosmic Ray Light Nuclei



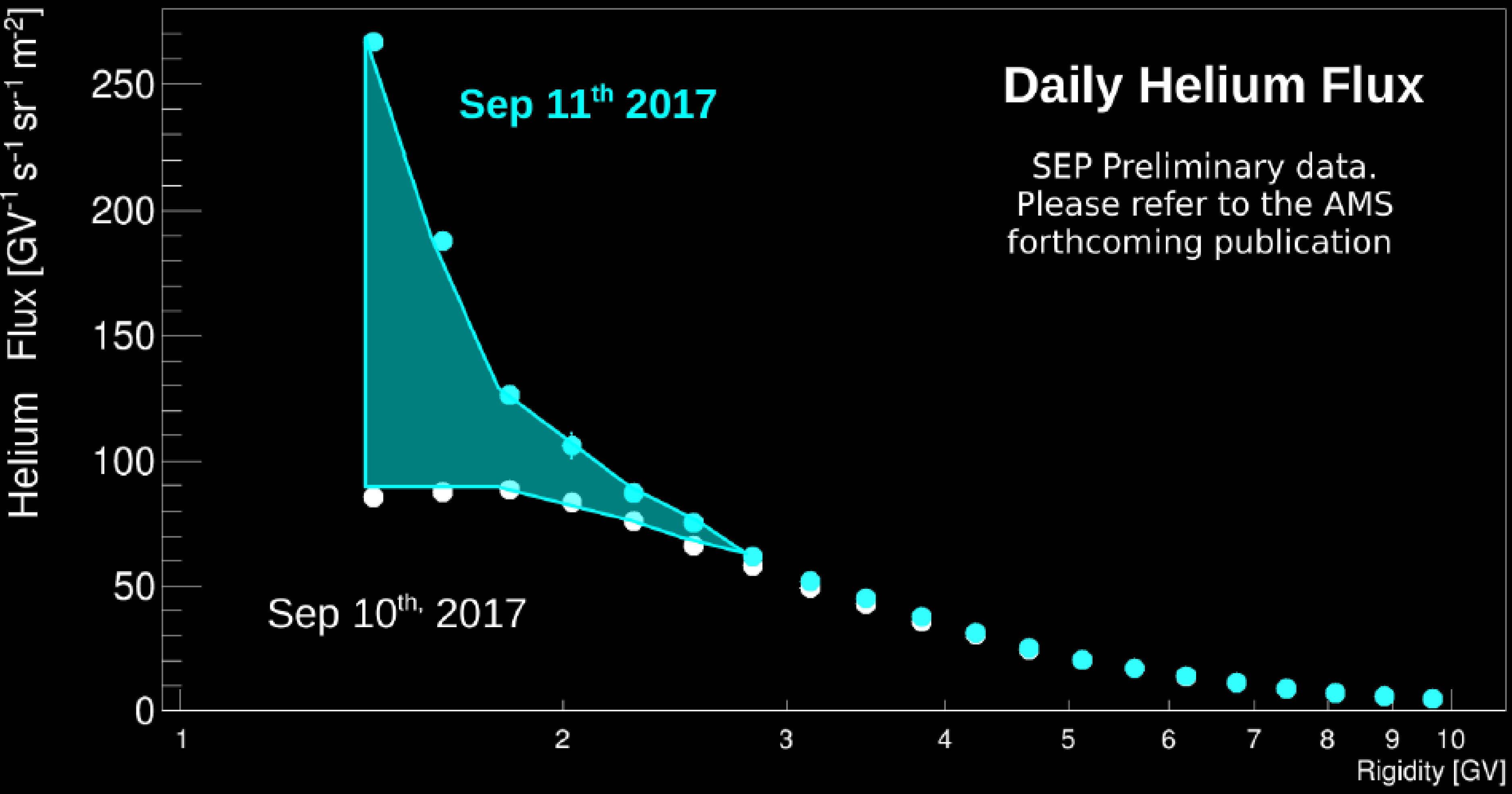
Light nuclei fluxes (Li, Be, B, C, N, O) exhibit **long-term and short-term variation**

Comparison of the time variation of the different species provides information for a comprehensive understanding of the **cosmic ray propagation in the Heliosphere**

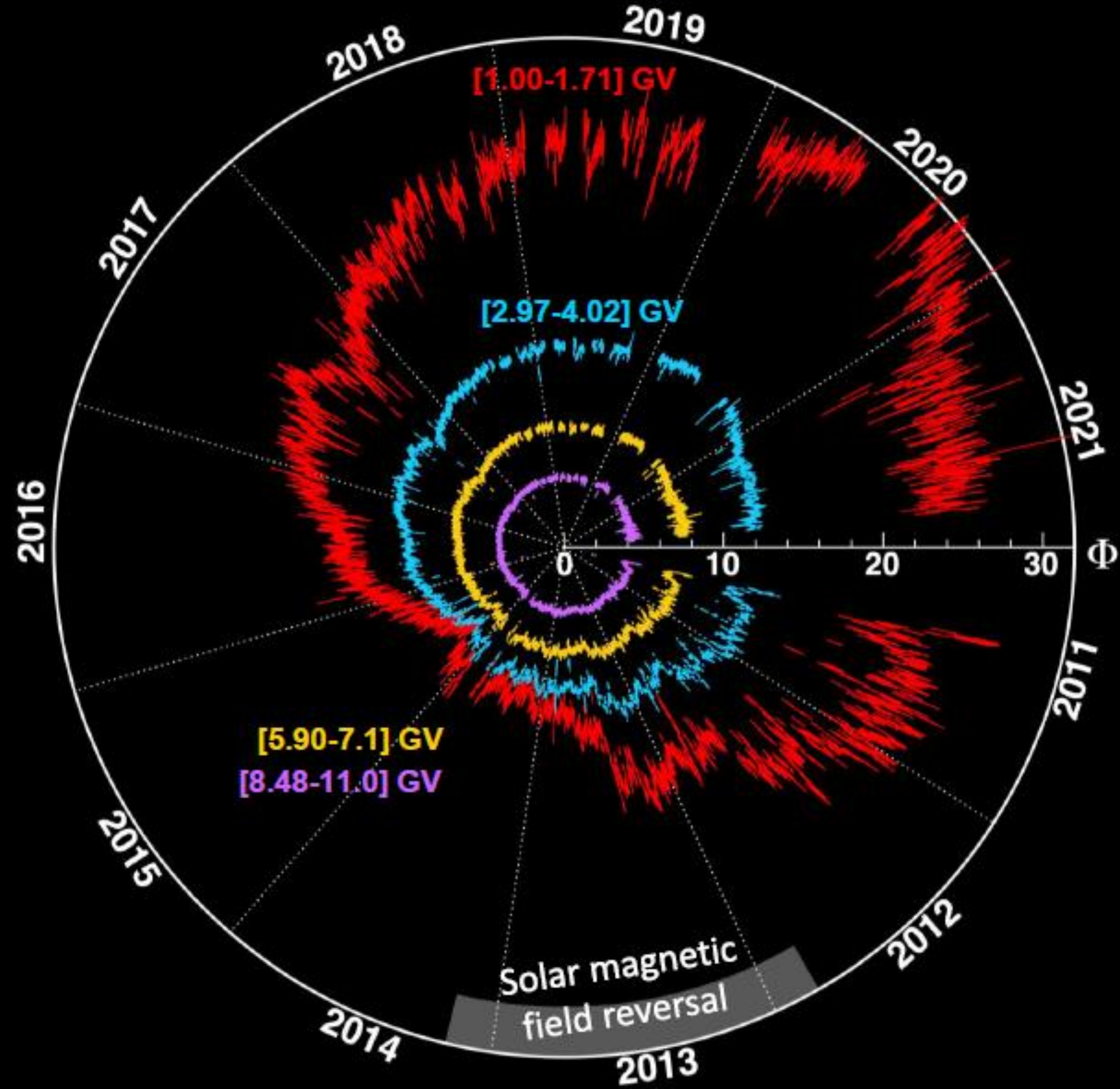


Solar Energetic Particles

AMS has detected 28 Solar Energetic Particle events

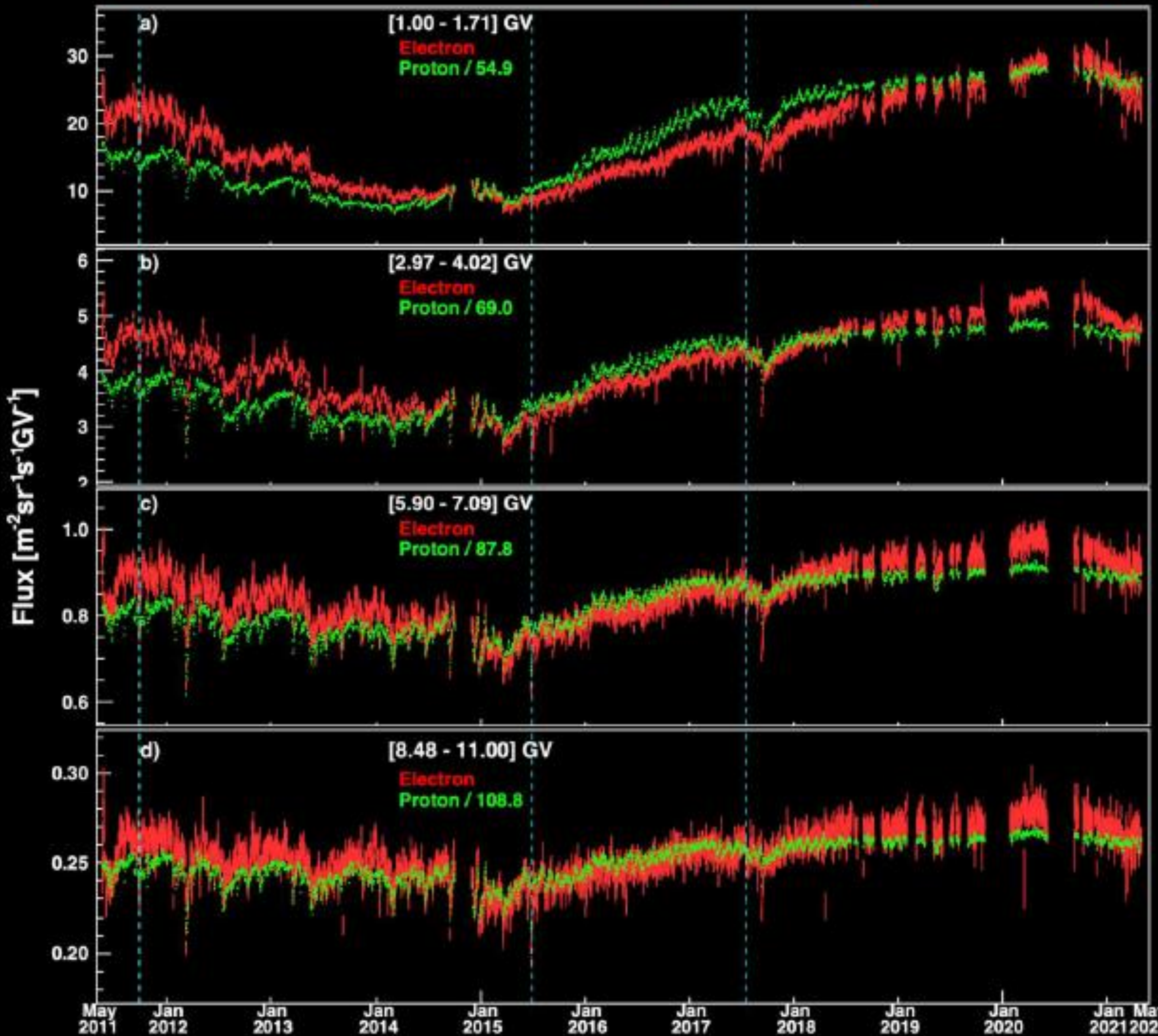


AMS Daily Electron Flux

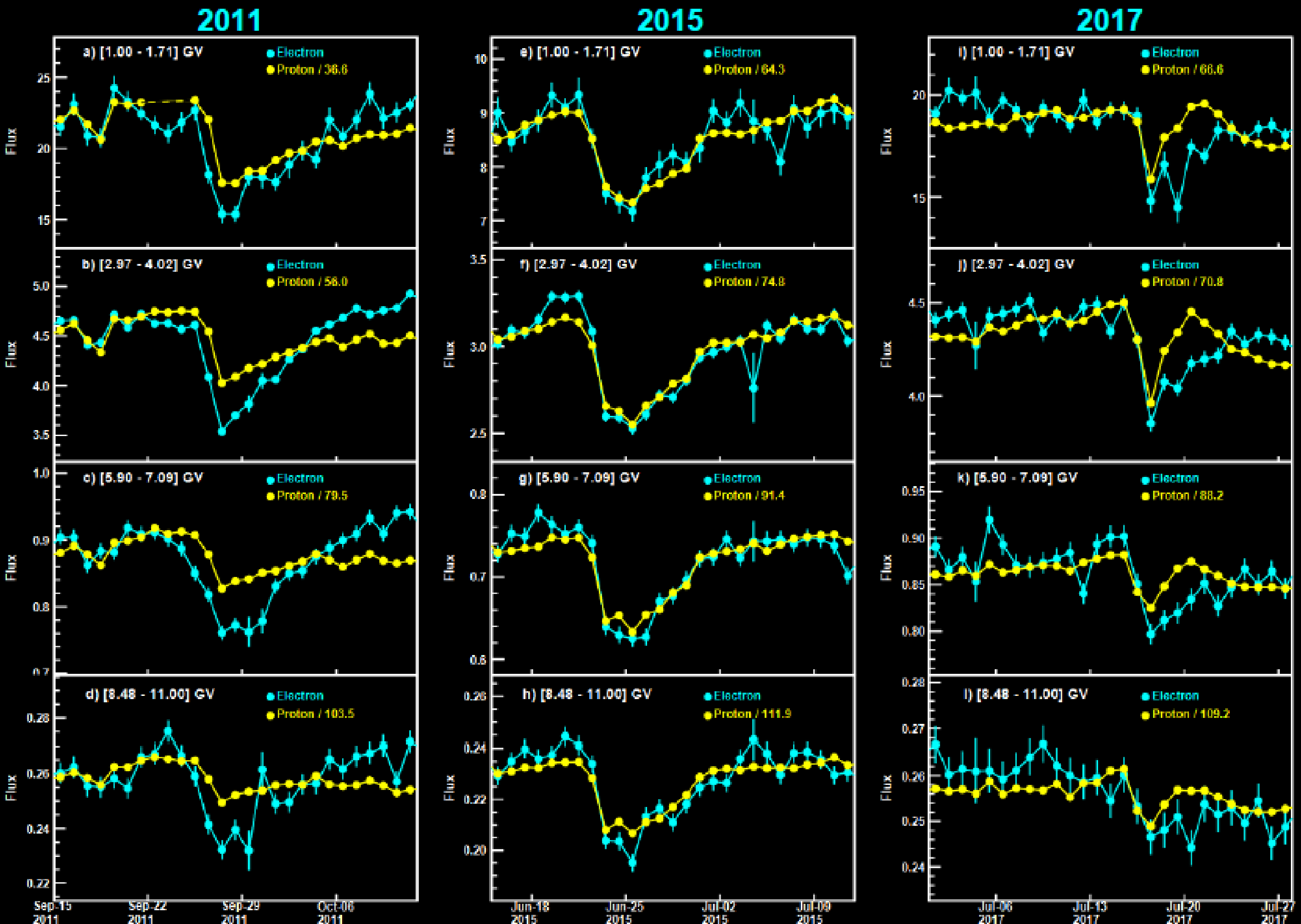


AMS Daily Electron and Proton Fluxes

The time-dependent behavior of the Φ_{e^-} and Φ_p is distinctly different



Non recurrent variations of Electron and Proton Fluxes

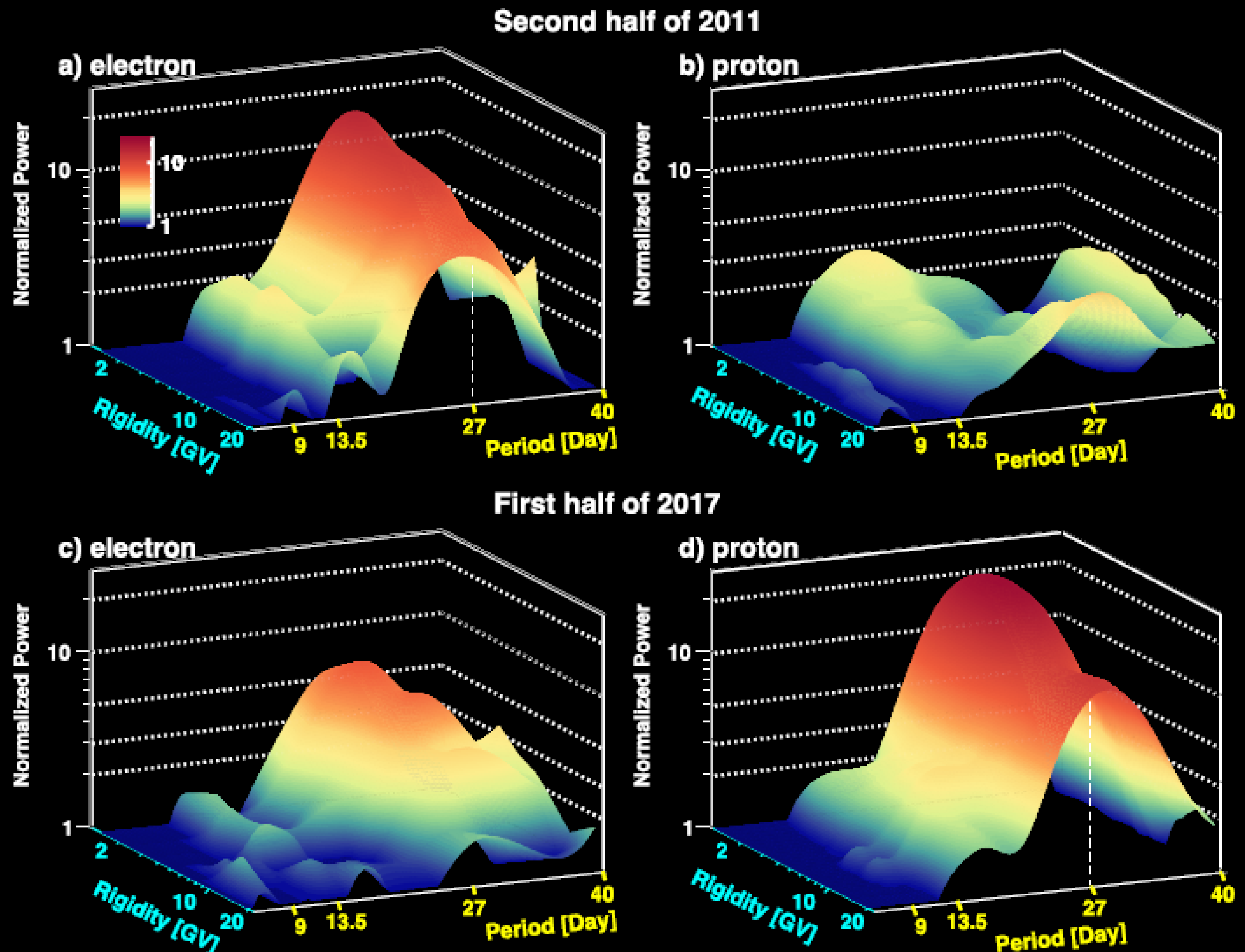


During **lower solar activity** in 2011 and 2017, a **difference between the short-term evolution of electrons and protons** is observed, while during the **solar maximum** in 2015 the **difference vanishes**.

These observations indicate a charge-sign dependence in nonrecurrent solar modulation.

Periodicities of Daily Electron Fluxes

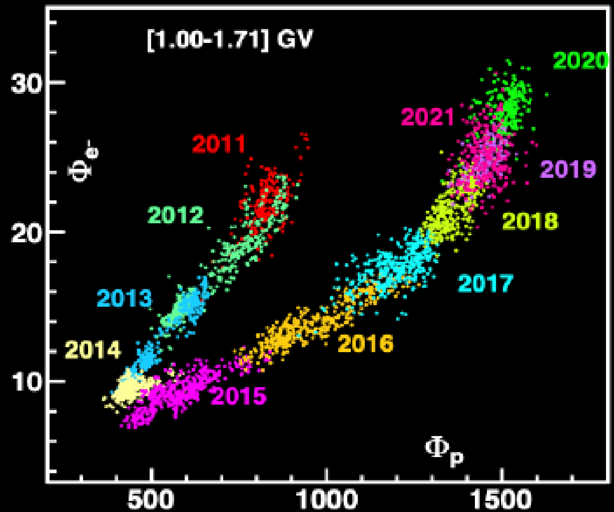
The rigidity dependence of the electron periodicities is different from that of protons

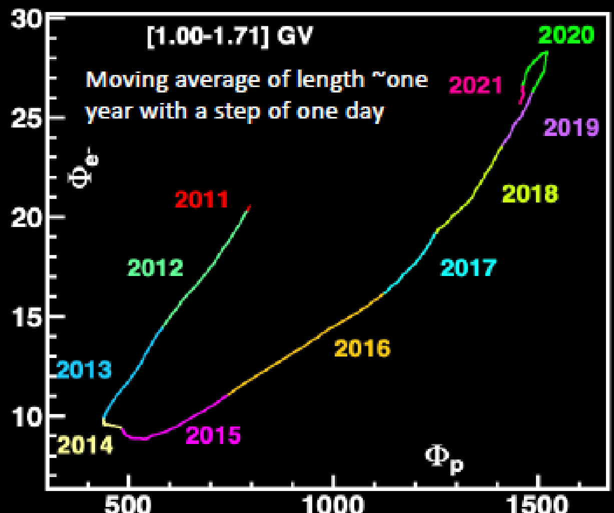


In the second half of 2011 the strength of the 27-day period of electrons is **greater** than that of protons.

In the first half of 2017 the strength of the 27-day period of electrons is **less** than that of protons.

A Hysteresis between Φ_{e^-} and Φ_p



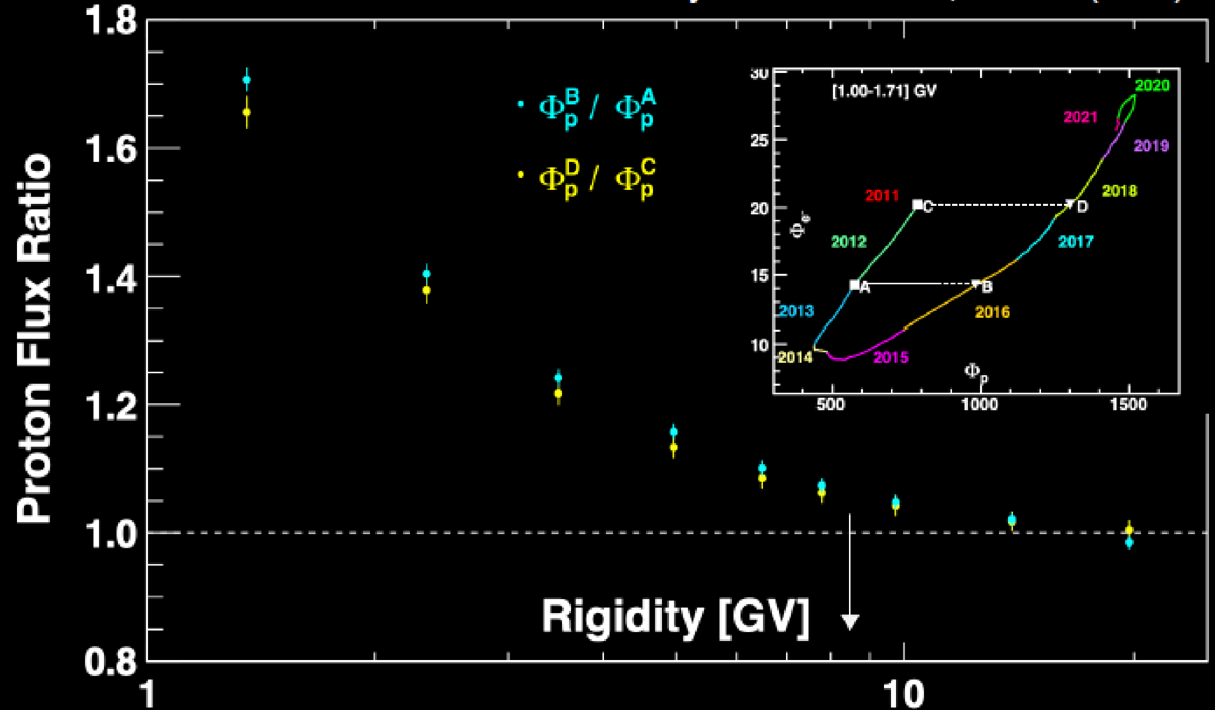


To assess the significance of the hysteresis we study, at different solar conditions, the values of Φ_p at the same Φ_{e^-}

Highlight #3

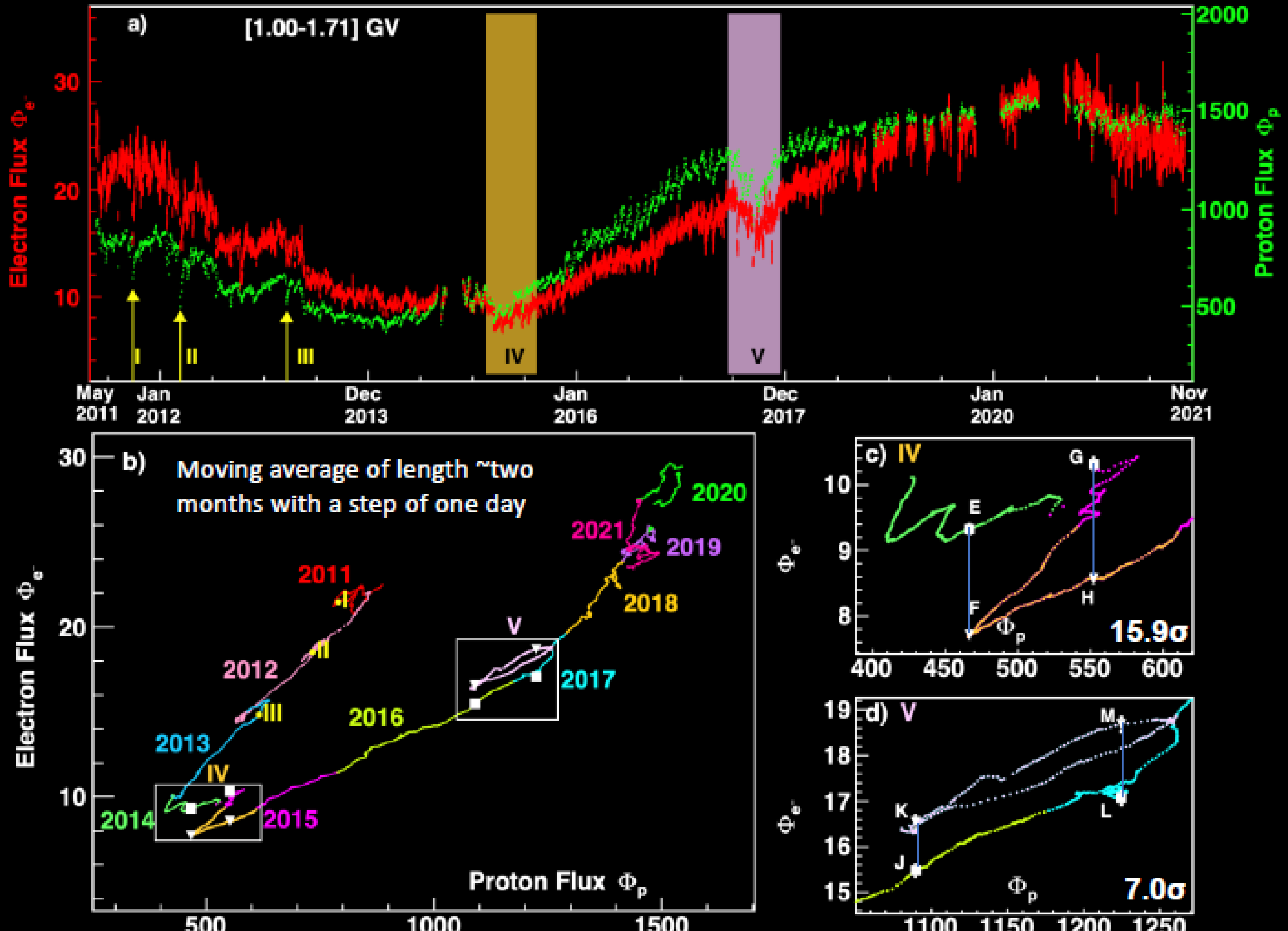
The hysteresis is observed with a significance > 6σ at rigidities below 8.5 GV

Phys. Rev. Lett. 130, 161001 (2023)

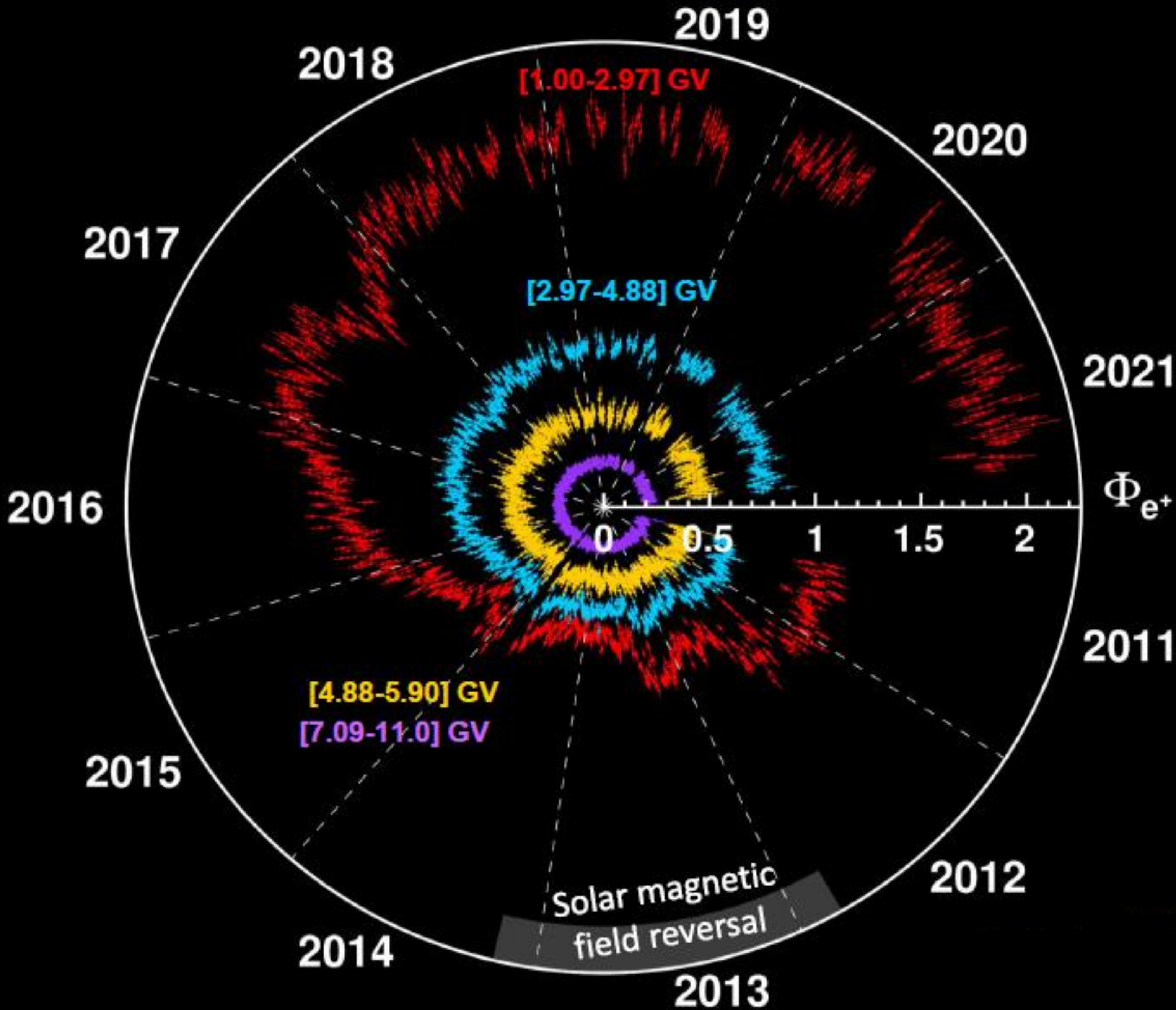


Structures in the Electron-Proton Hysteresis

Significant structures in the electron-proton hysteresis are observed corresponding to sharp variations in the fluxes

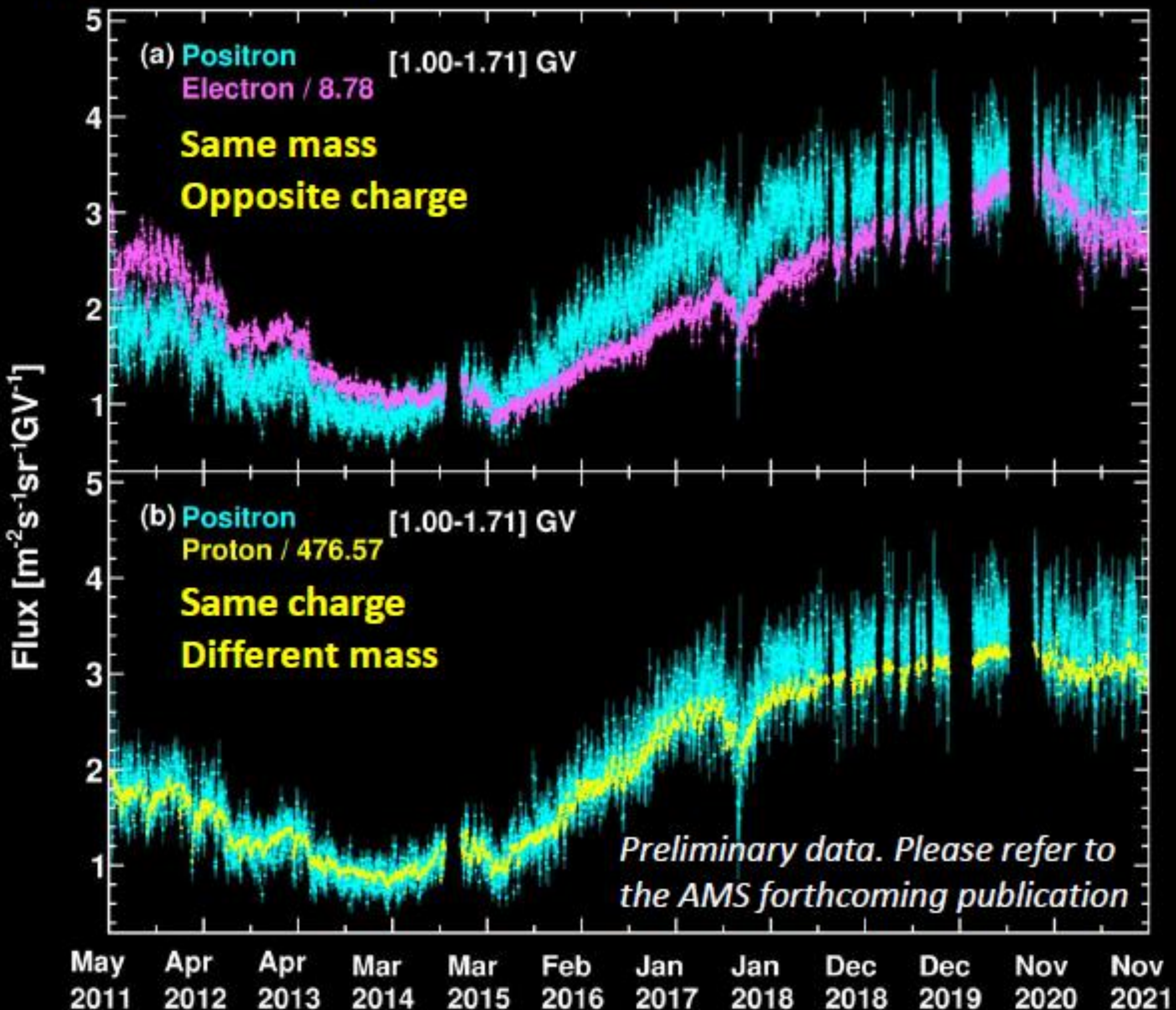


AMS Daily Positron Flux



AMS Daily Positron, Electron and Proton Fluxes

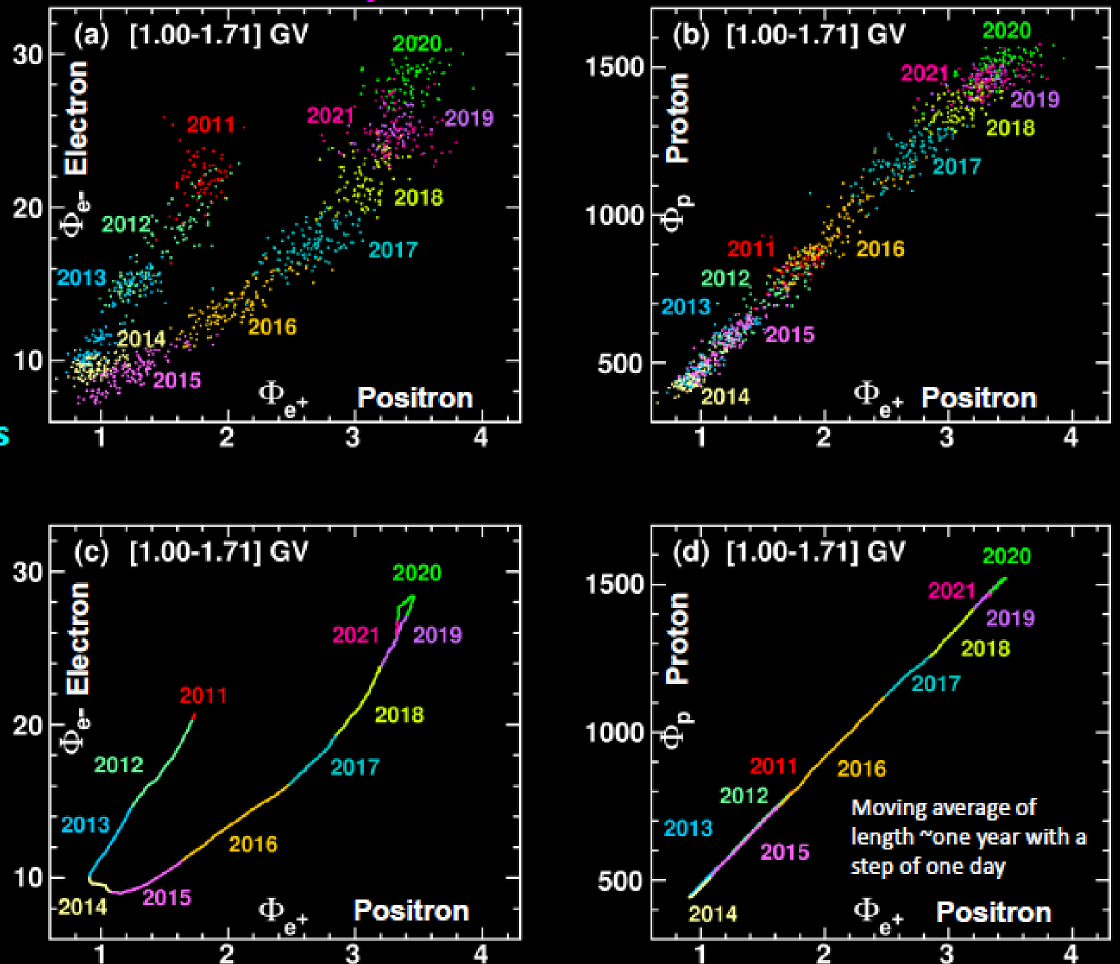
The long-term evolution of **positron** and **electron** fluxes is clearly **different**.
On the contrary, **positron** and **proton** fluxes present a **similar** behavior over time.



Relation between Positron, Electron and Proton Fluxes

Electron-Positron: hysteresis

Proton-Positron: linear relation



Electrons vs Positrons

Same mass

Opposite charge

Protons vs Positrons

Different mass

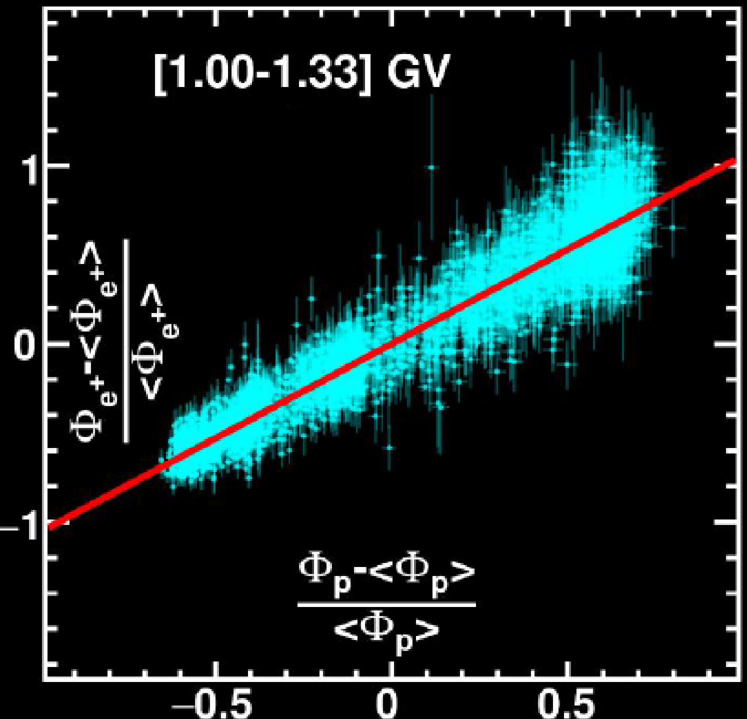
Same charge

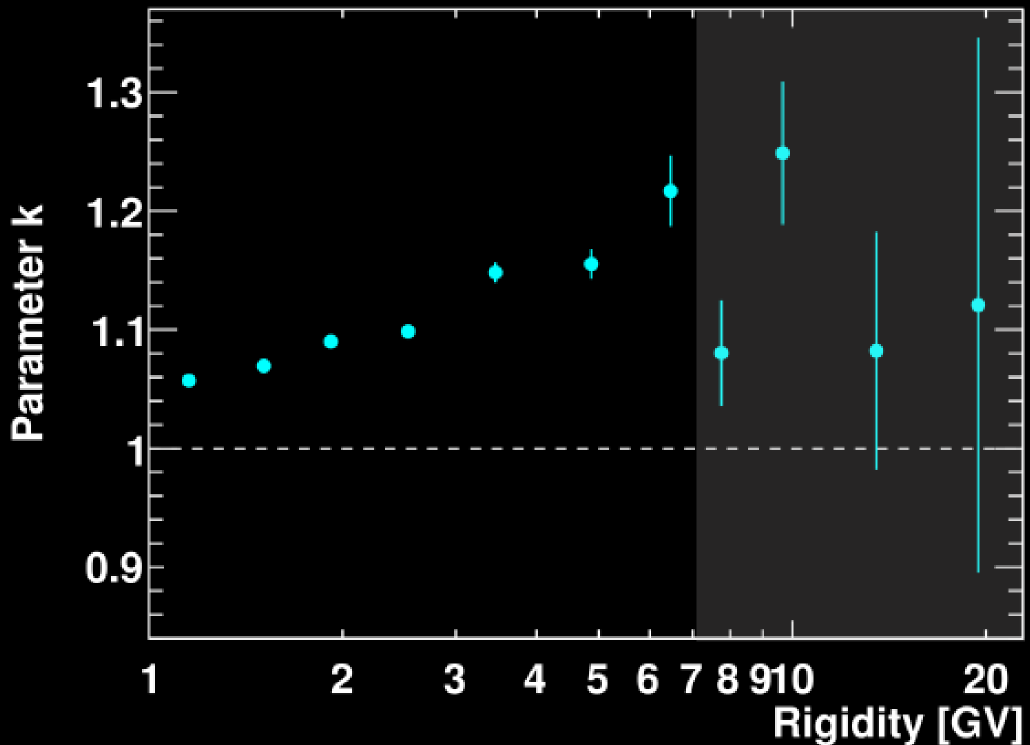
Linear relation between Φ_{e^+} and Φ_p

To compare the long-term variations of the **proton** and **positron** fluxes a linear relation between the relative variations of the fluxes is studied: $\frac{\Phi_{e^+}-\langle\Phi_{e^+}\rangle}{\langle\Phi_{e^+}\rangle} = k\,\frac{\Phi_p-\langle\Phi_p\rangle}{\langle\Phi_p\rangle}$

Highlight #4

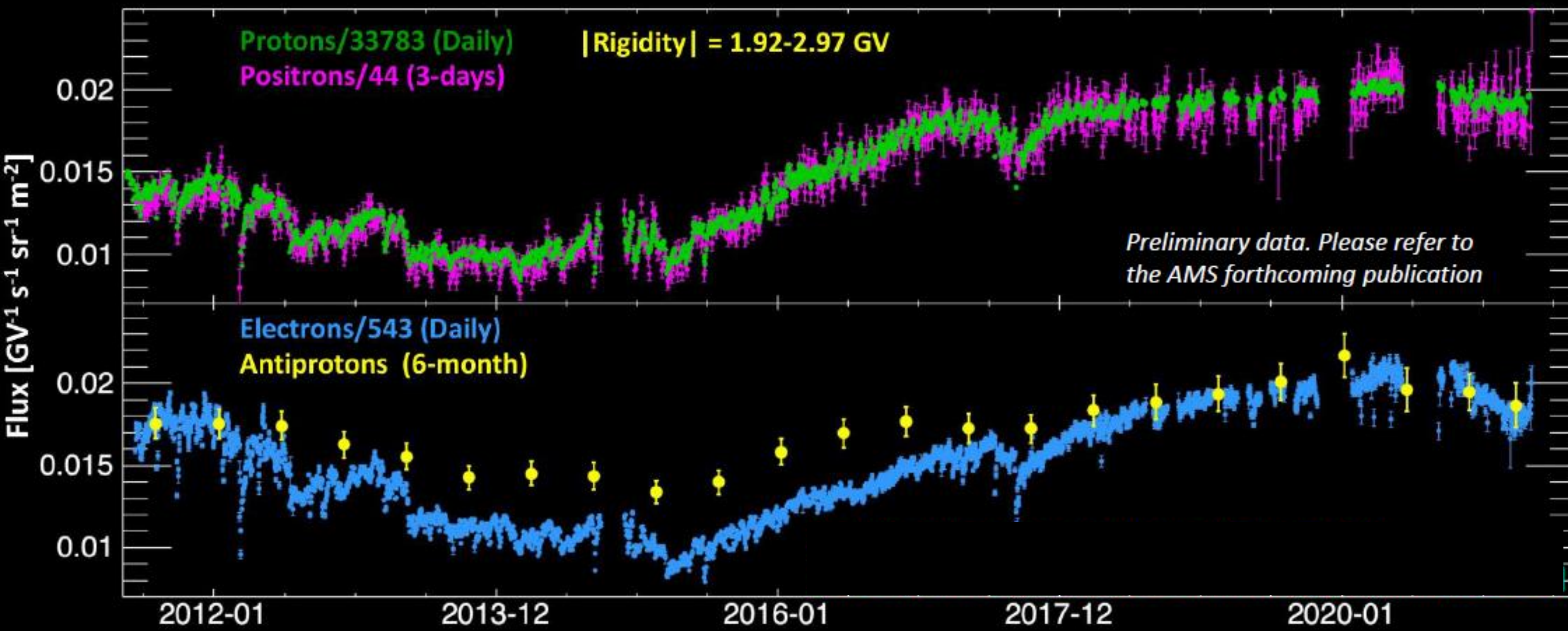
Below 7 GV, the positron flux is more modulated than the proton flux





Time Variation of Cosmic Ray Antiprotons

AMS is a unique experiment to measure simultaneously positive charge and negative charge particles fluxes across the entire solar cycle



AMS Publications in *Physical Review Letters*

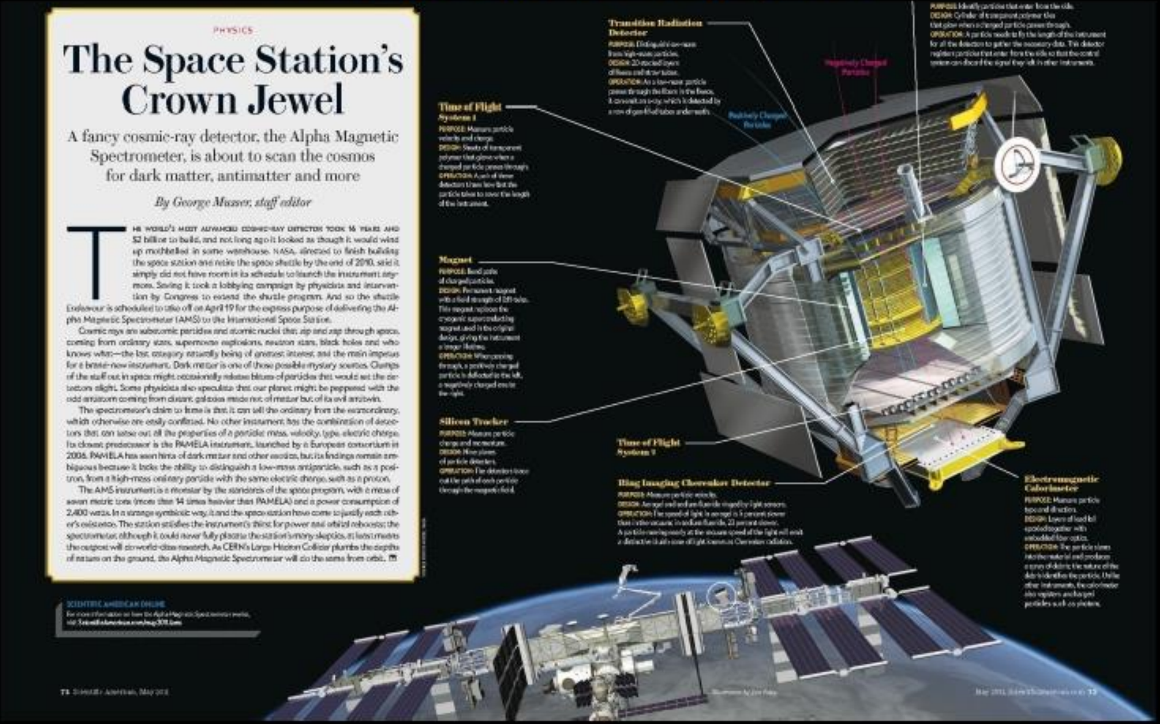
>6500 citations to date

1) Phys. Rev. Lett. 110, 141102 (2013). Editors' Suggestion. Viewpoint in *Physics*. Highlight of 2013. Ten-Year Editors' Suggestion retrospective
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).
26) "Cosmic Positrons", *submitted to* Phys. Rev. Lett.
27) "Cosmic Antiprotons", *to be submitted,* Phys. Rev. Lett.
28) "Cosmic Isotopes", *to be submitted,* Phys. Rev. Lett.

In Conclusion

AMS is in a unique position to provide data to create a definitive theory of cosmic rays.

Scientific American, May 2011



In the first 12 years, none of the AMS results were expected.

Based on the first 12 years of AMS results, with the upgrade, we can anticipate new surprises.