# Cosmic-ray detection in space: Latest Results from the The Alpha Magnetic Spectrometer (AMS) on the International Space Station (ISS)

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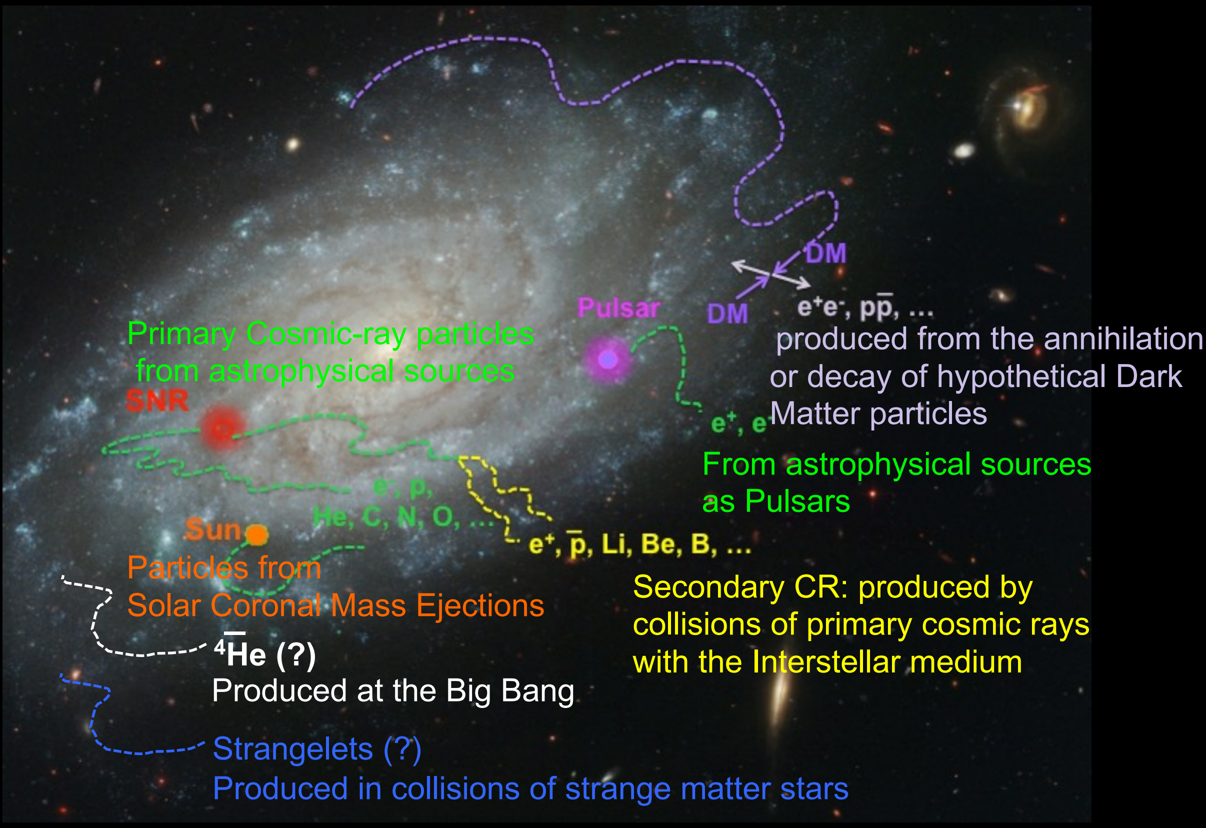
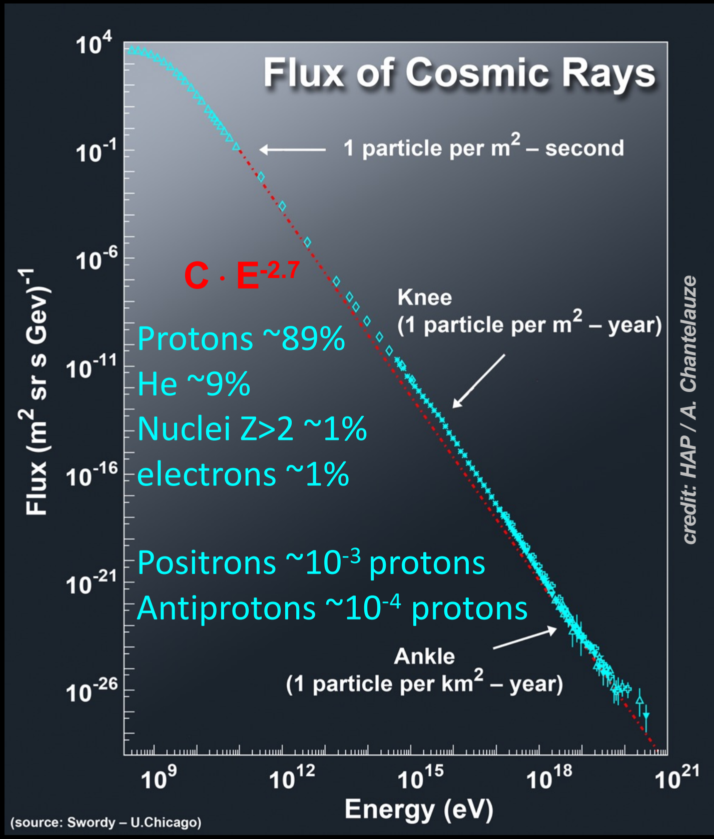
La Thuile 2022
Les Rencontres de Physique de la Vallée d'Aoste

March 8, 2022

# The physics of AMS on the Space Station: Search for Dark Matter, Antimatter, the Origin of the Universe and new physics phenomena through the study of charged cosmic rays

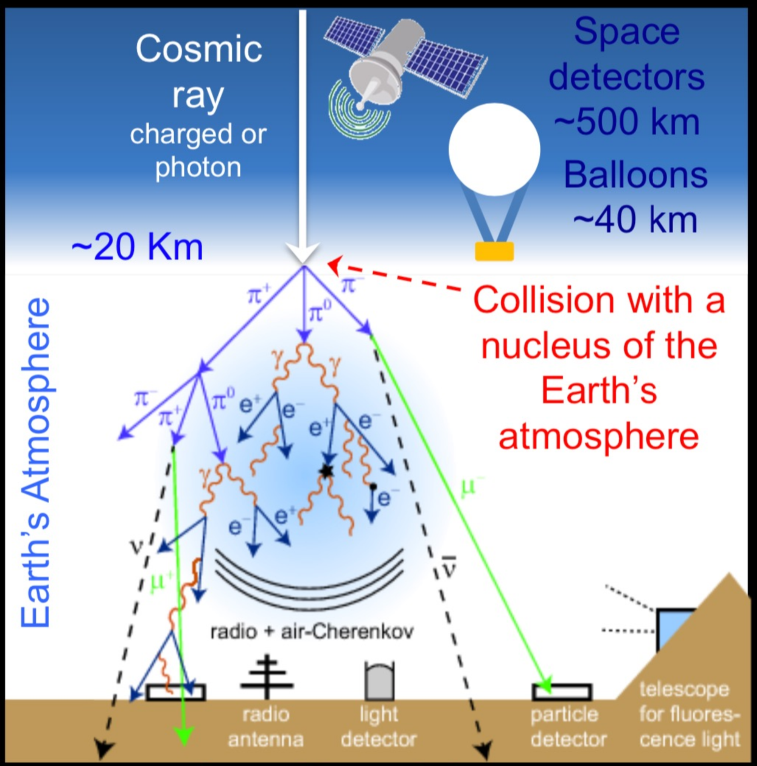


# Detection of charged cosmic rays

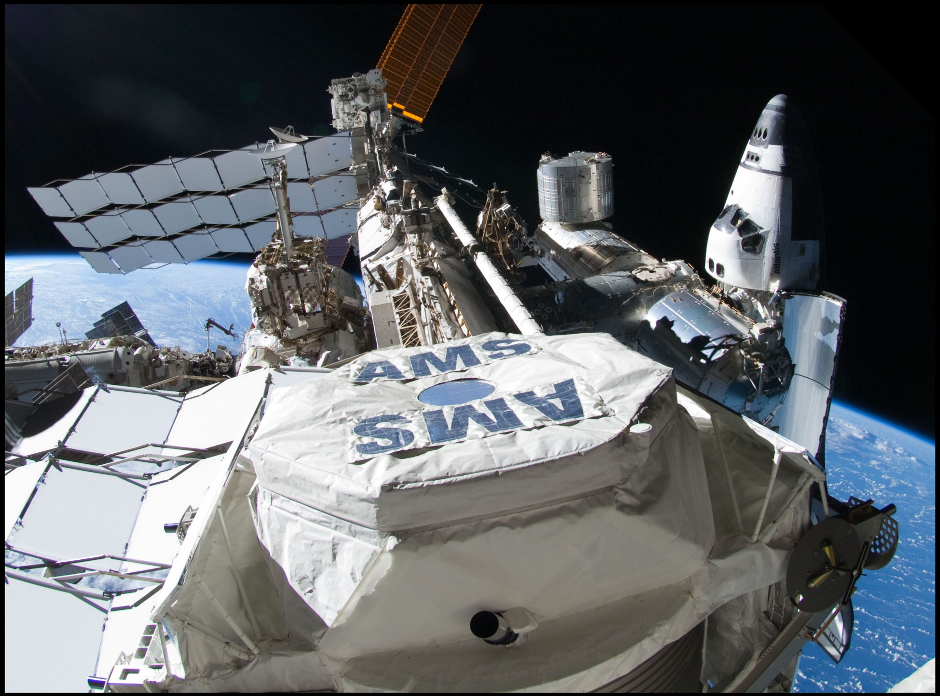
## Accurate measurements of individual spectra can only be achieved with direct detection in space

Charged cosmic rays have mass.
They are absorbed by the
100 km of Earth's atmosphere
(10 m of water)



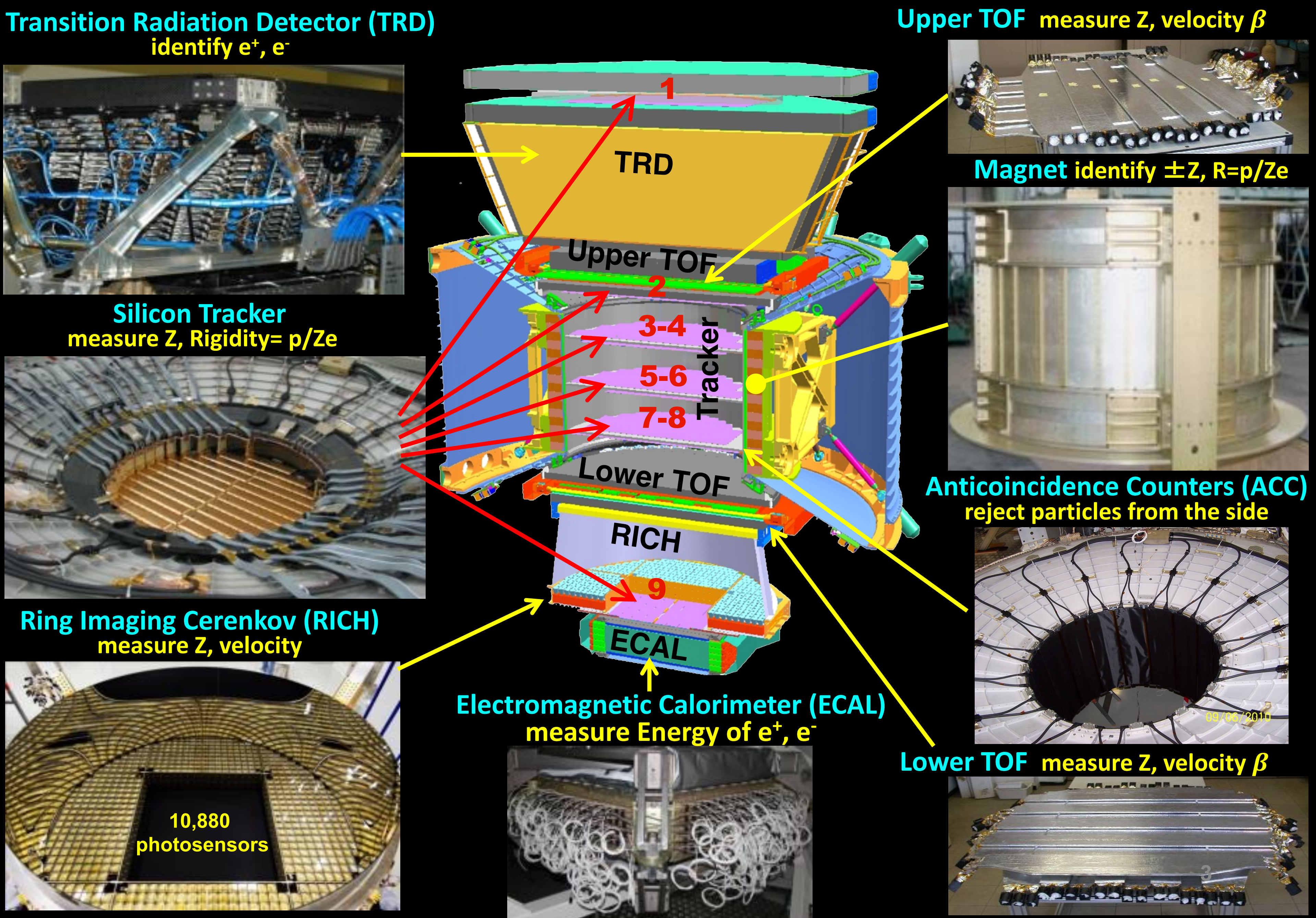

Ground-based detectors

To measure their charge (including sign)
and momentum requires
a magnetic spectrometer in space

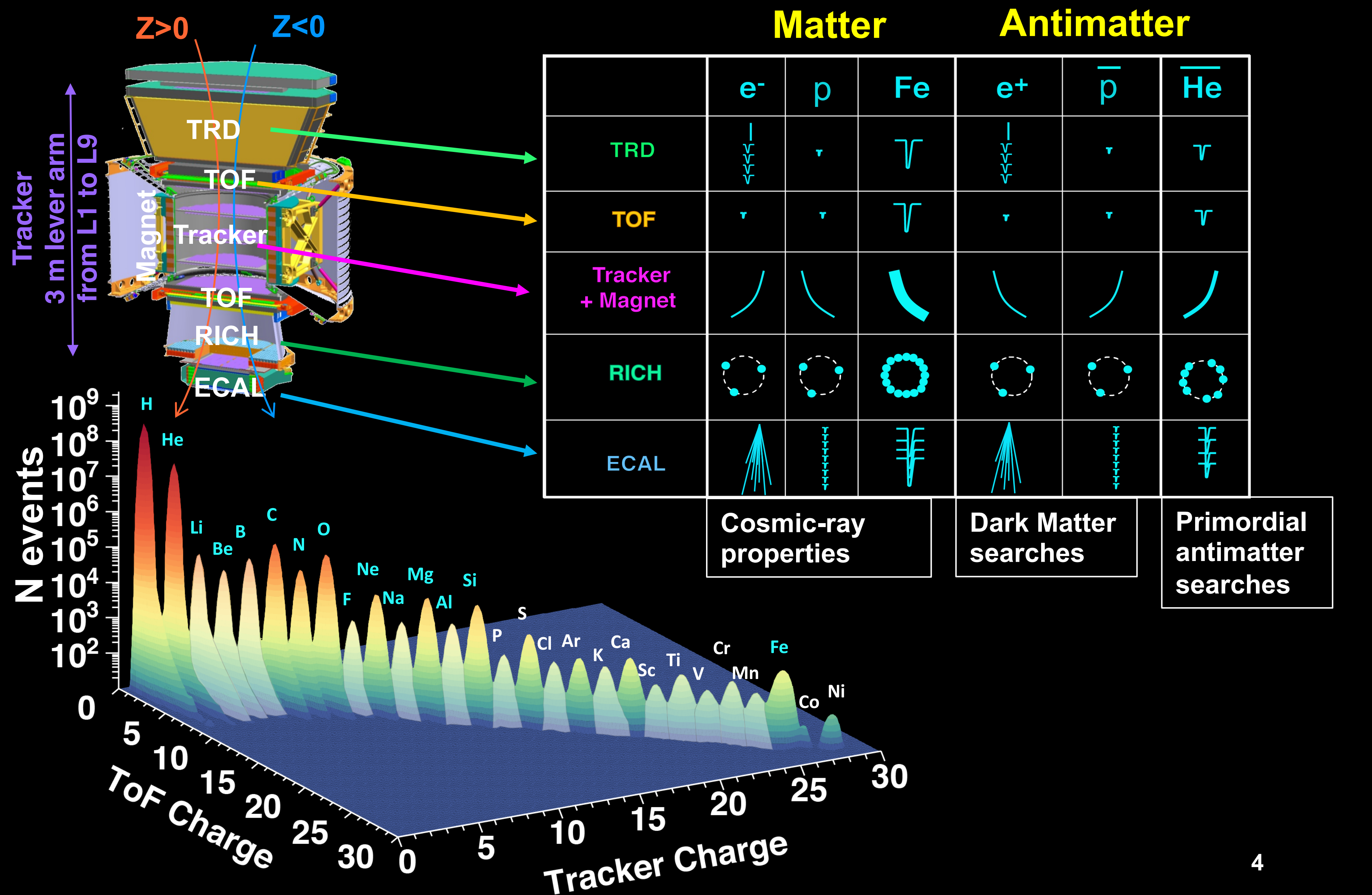



**AMS-02 installation on the ISS: May 2011**
**Operation for the entire ISS lifetime: 2030**

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



# The detectors provide independent and redundant measurements of cosmic-ray particles charge and energy in the GeV to few TeV range

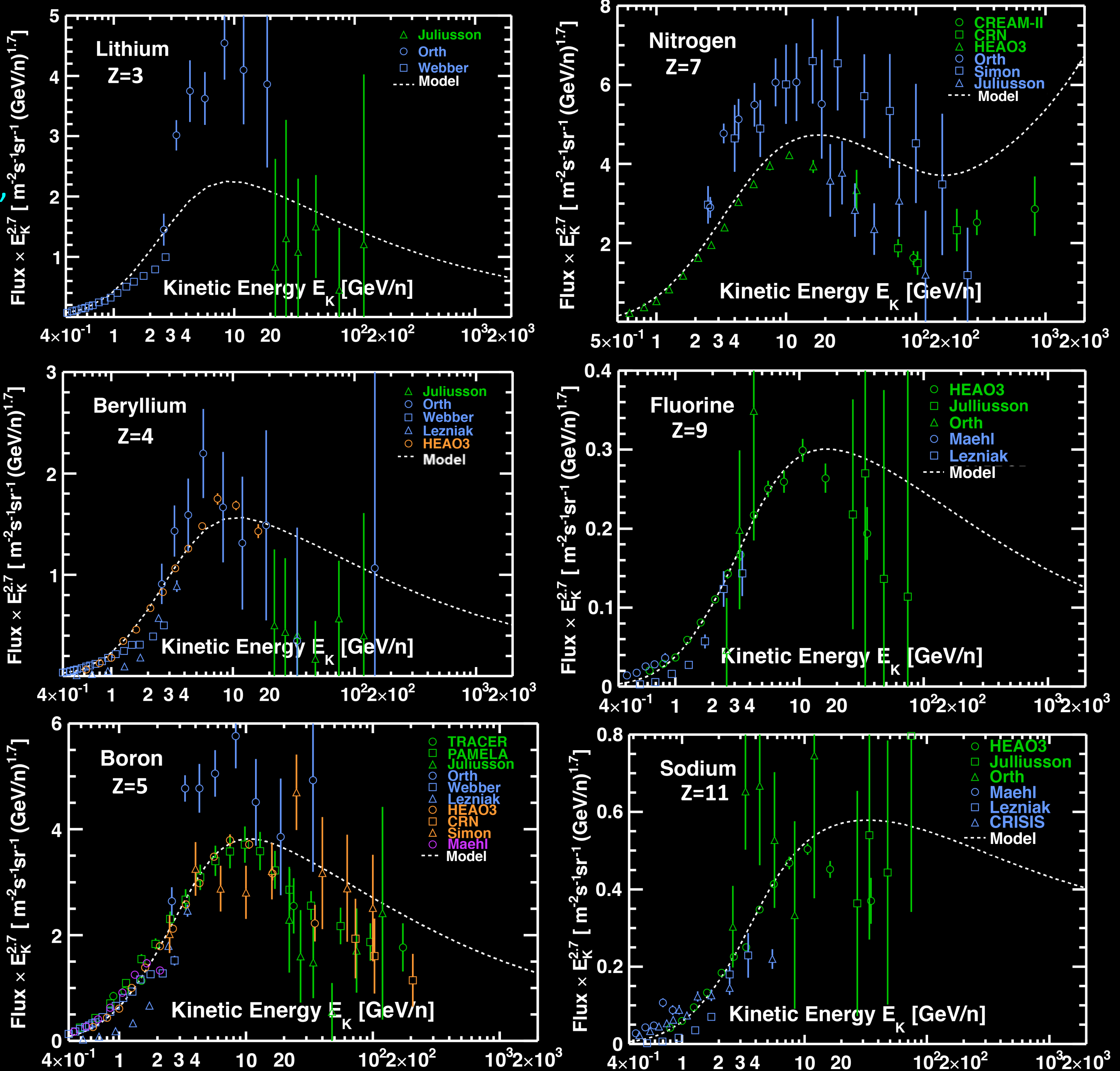


**1912: Discovery of Cosmic Rays**

In the past 100 years, measurements of charged cosmic rays by balloons and satellites have typically had 30% to 50% accuracy.

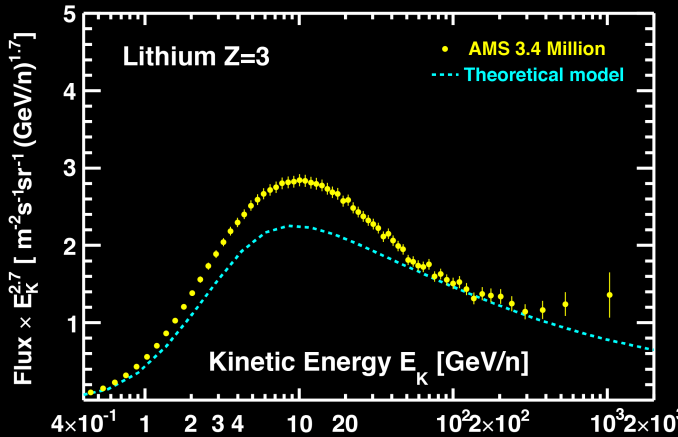
Theoretical models assumed universal energy spectrum $E^{-2.7}$ up to the PeV as for the all-particle spectrum.

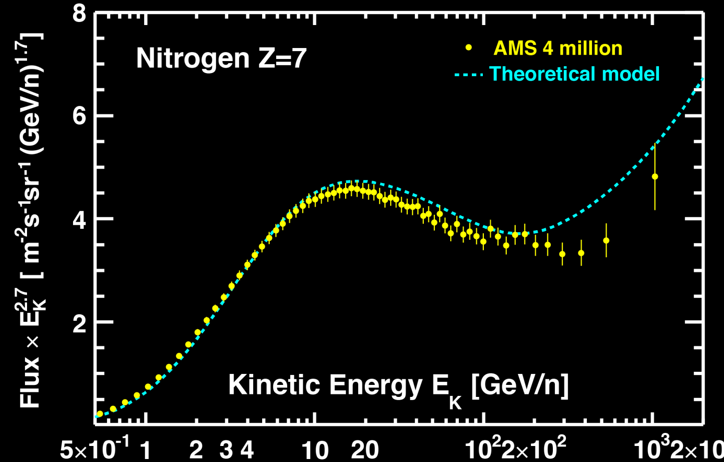
Cosmic-ray spectra are displayed multiplied by $E^{2.7}$

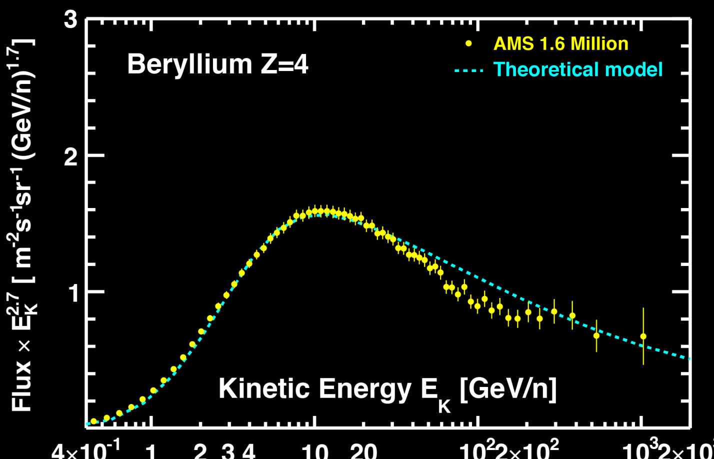


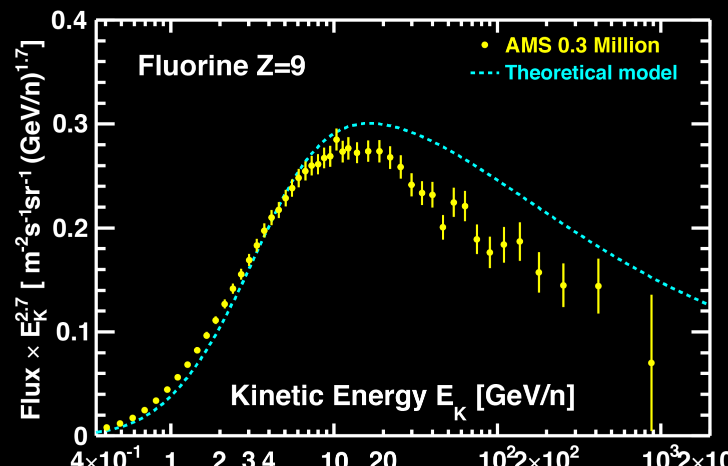
AMS is providing measurements of cosmic ray spectra with ~1% accuracy

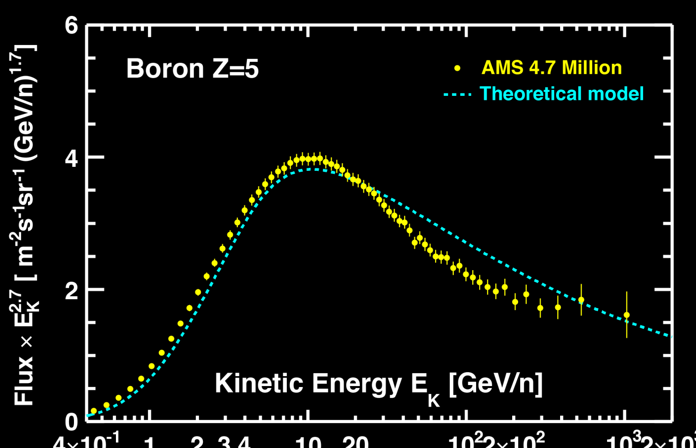

The improvement in accuracy is providing new insights about the cosmos.

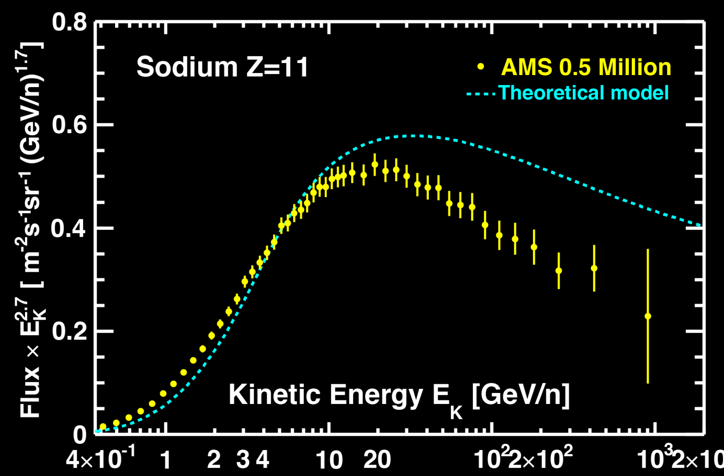


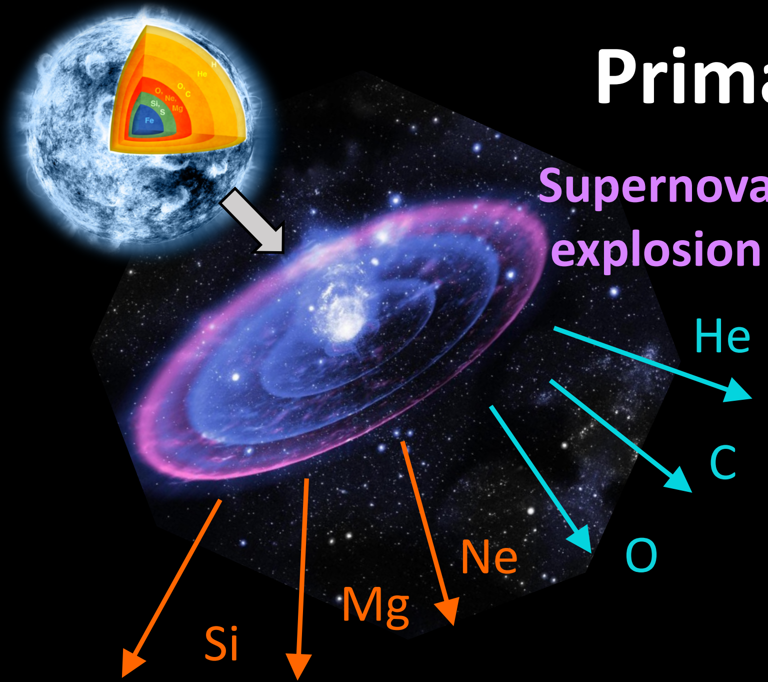



# AMS Publications

1) Phys. Rev. Lett. 110, 141102 (2013). Editors' Suggestion. Viewpoint in *Physics*. Highlight of 2013. Ten-Year retrospective. Positron fraction : $e^+/(e^++e^-)$
2) Phys. Rev. Lett. 113, 121101 (2014). Editors' Suggestion
3) Phys. Rev. Lett. 113, 121102 (2014). Editors' Suggestion. Featured in *Physics* Positron flux: $e^+$ Electron flux: $e^-$
4) Phys. Rev. Lett. 113, 221102 (2014). $(e^++e^-)$ flux
5) Phys. Rev. Lett. 114, 171103 (2015). Editors' Suggestion Proton flux: H nuclei from 1 GV to 1.8 TV
6) Phys. Rev. Lett. 115, 211101 (2015). Editors' Suggestion He nuclei flux from 1.9 GV to 3TV
7) Phys. Rev. Lett. 117, 091103 (2016). Antiproton flux from 1 GV to 450 GV
8) Phys. Rev. Lett. 117, 231102 (2016). Editors' Suggestion Boron-to-Carbon flux ratio: secondary-to-primary nuclei
9) Phys. Rev. Lett. 119, 251101 (2017). Light primary cosmic rays: He, C, O nuclei fluxes from 2 GV to 3TV
10) Phys. Rev. Lett. 120, 021101 (2018). Editors' Suggestion. Featured in *Physics*. Light secondary cosmic-ray Li, Be, B nuclei fluxes 2 GV to 3TV
11) Phys. Rev. Lett. 121, 051101 (2018). Monthly proton and He fluxes
12) Phys. Rev. Lett. 121, 051102 (2018). Editors' Suggestion Monthly electron and positrons fluxes
13) Phys. Rev. Lett. 121, 051103 (2018). Cosmic-ray Nitrogen nuclei flux from 2 GV to 3 TV
14) Phys. Rev. Lett. 122, 041102 (2019). Editor's Suggestion Positron flux up to 1 TeV
15) Phys. Rev. Lett, 122, 101101 (2019). Electron flux up to 1.4 TeV
16) Phys. Rev. Lett. 123, 181102 (2019). Editors' Suggestion He isotopes: $^3$He and $^4$He fluxes from 2 to 15-20 GV
17) Phys. Rev. Lett. 124, 211102 (2020). Editors' Suggestion. Featured in *Physics*. Heavy primary cosmic rays: Ne, Mg, Si nuclei fluxes 2 GV-3 TV
18) Physics Reports 894, 1 (2021). Review of 7-year data results
19) Phys. Rev. Lett. 126, 041104 (2021). Featured in *Physics*. Very heavy primary CR : Iron nuclei 3GV-3TV
20) Phys. Rev. Lett. 126, 081102 (2021). Editors' Suggestion Heavy secondary CR: Fluorine nuclei flux from 2 GV to 3TV
21) Phys. Rev. Lett. 127, 021101 (2021). Third group of cosmic-ray nuclei: Sodium and Aluminum
22) Phys. Rev. Lett. 127, 271102 (2021). Daily proton fluxes (Effect of Sun's magnetic field on CR)
23) "Daily helium fluxes", submitted to PRL

# Primary Cosmic Rays



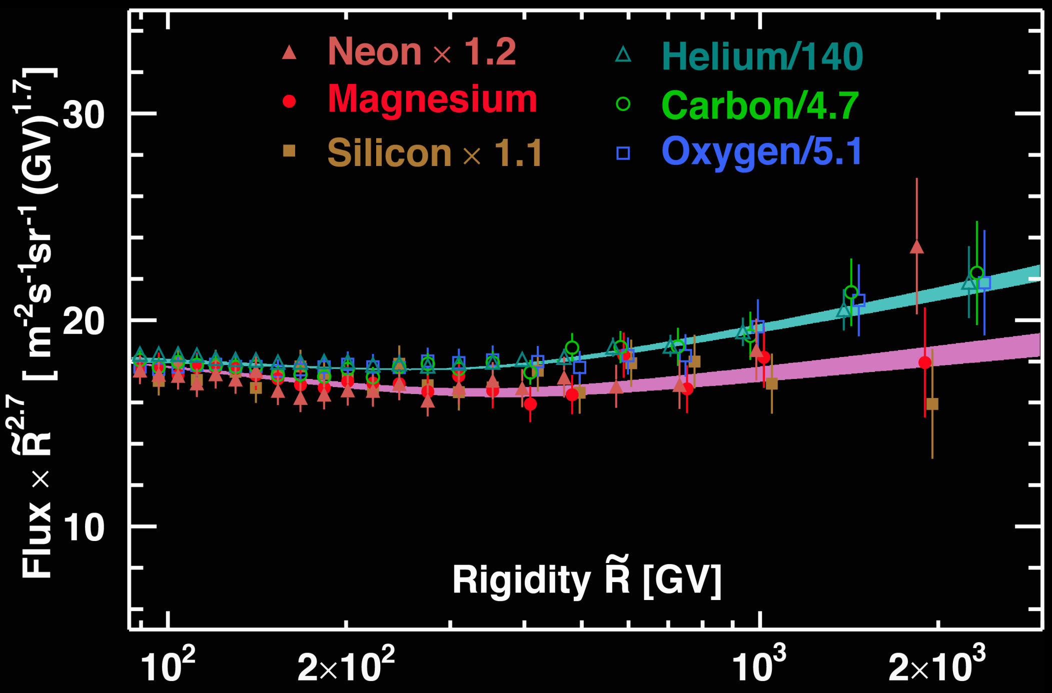

Primary CR nuclei (H, He, C, ..., Fe) are produced during the lifetime of stars.

They are accelerated in supernovae explosions and expelled in the Interstellar Medium where they propagate diffusively.

AMS found that their energy spectra all deviate from the traditional assumed $E^{-2.7}$ spectrum.

Unexpectedly, primary cosmic-ray spectra have at least two classes of rigidity (energy) dependence:

He, C, O have identical spectra.
Heavier primary cosmic rays Ne, Mg, Si have their own identical rigidity different from that of He, C, O.



## American Physical Society announcement May 29, 2020

# New Data Show the Heavy Side of Cosmic Rays

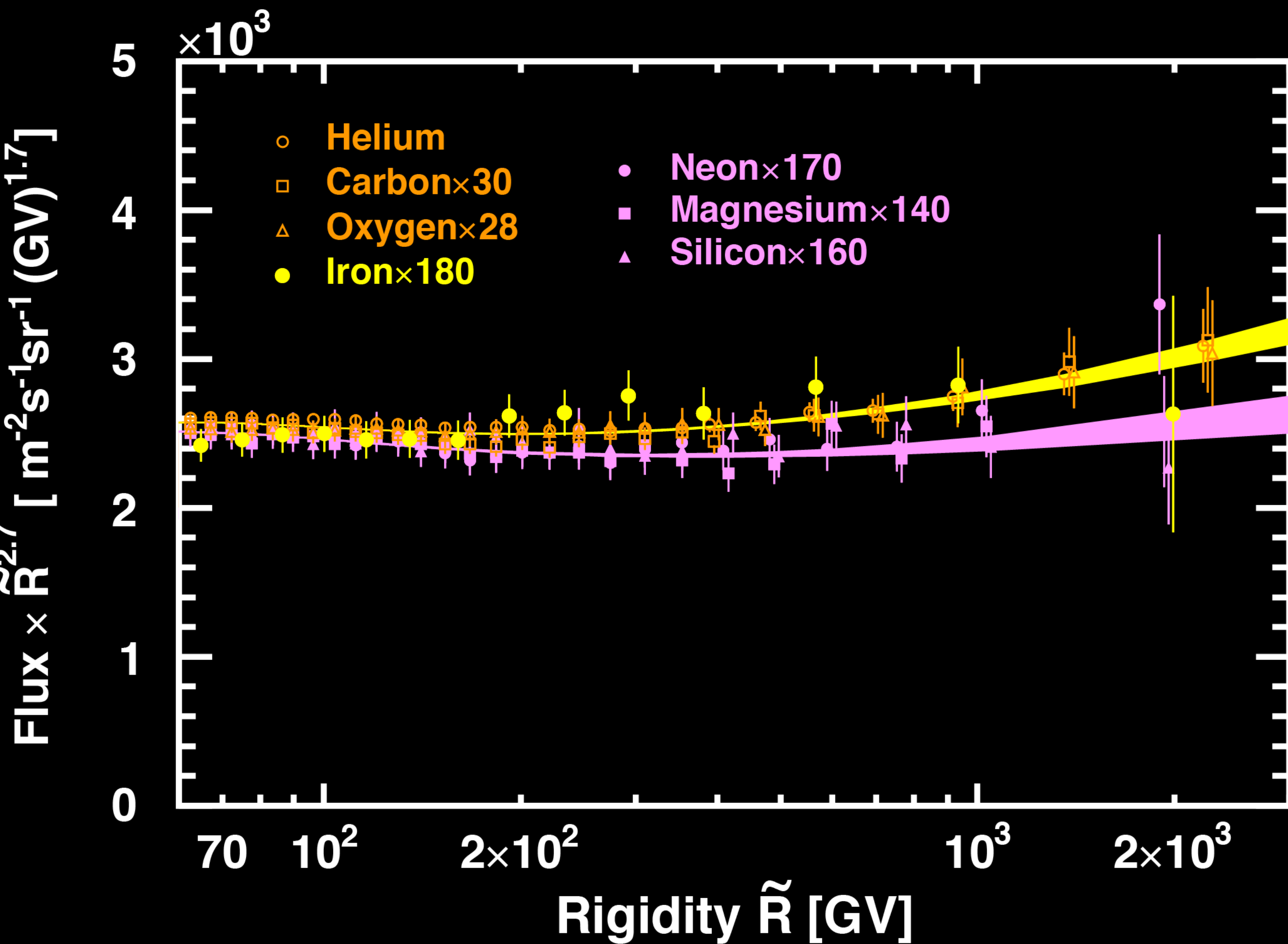
**Clean spectra for heavier cosmic rays measured on the International Space Station provide new opportunities to learn about the particles' origins and about the interstellar medium.**


…

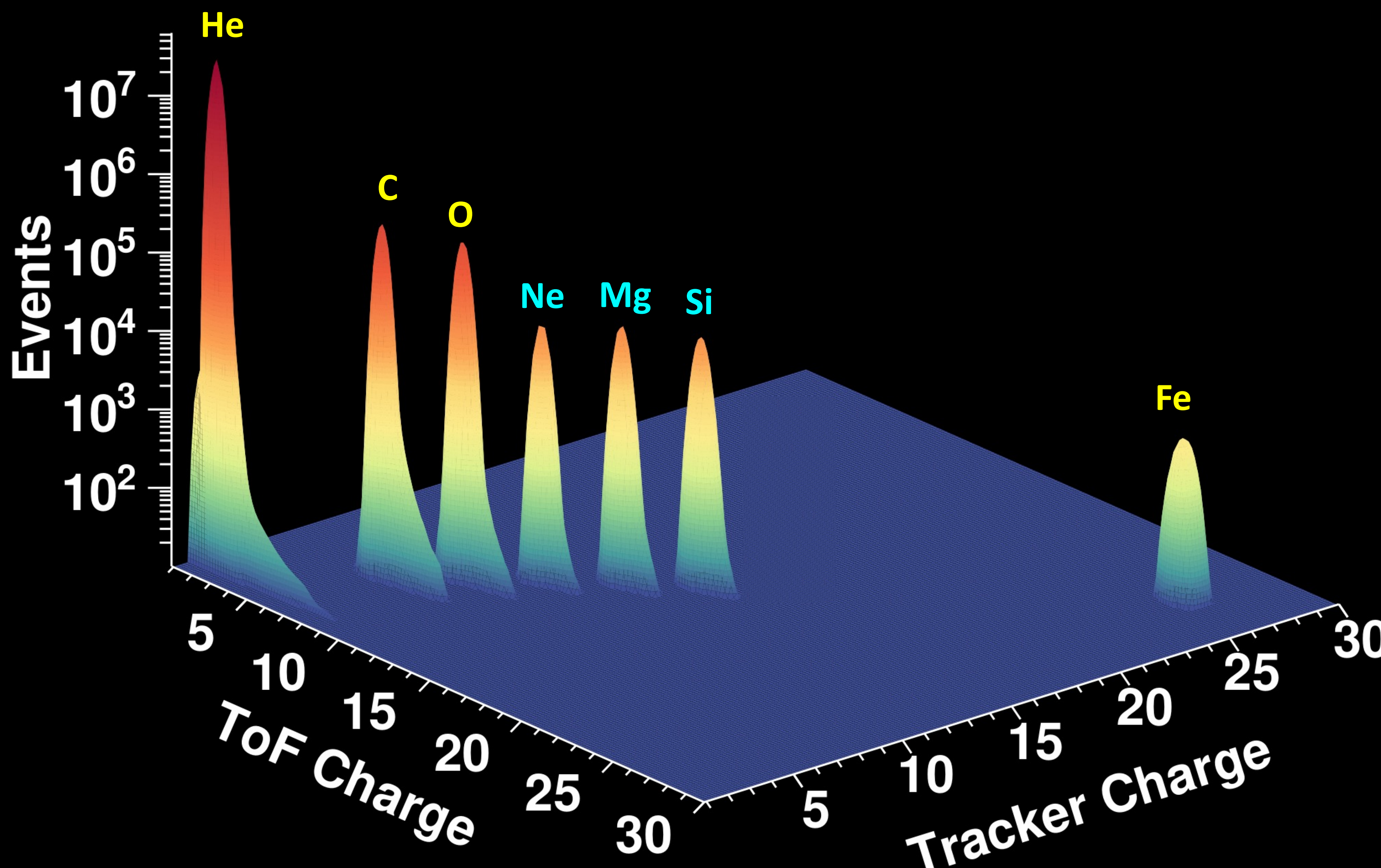
**The results now give theorists a lot of work to do, and they are "opening an entirely new window" on precision cosmic-ray spectroscopy, says Peter Biermann of the Max Planck Institute for Radio Astronomy, Germany. "We can now turn stars into high-energy labs, which the Universe is running for us," he says.**

**This research is published in Physical Review Letters.** ***Matteo Rini, Editor of Physics.***

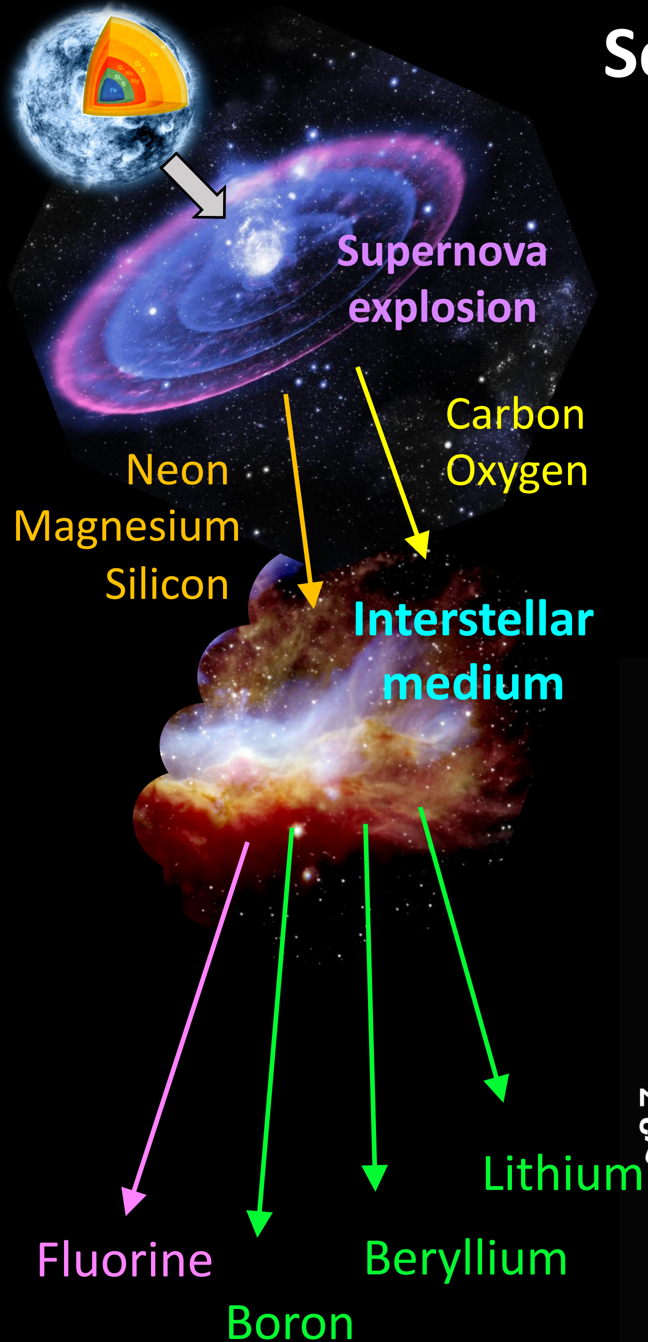
**Unexpected Result:**
**Iron is in the He, C, O primary cosmic ray group instead of the expected Ne, Mg, Si group.**



# Two Classes of Primary Cosmic Rays: He-C-O-Fe and Ne-Mg-Si



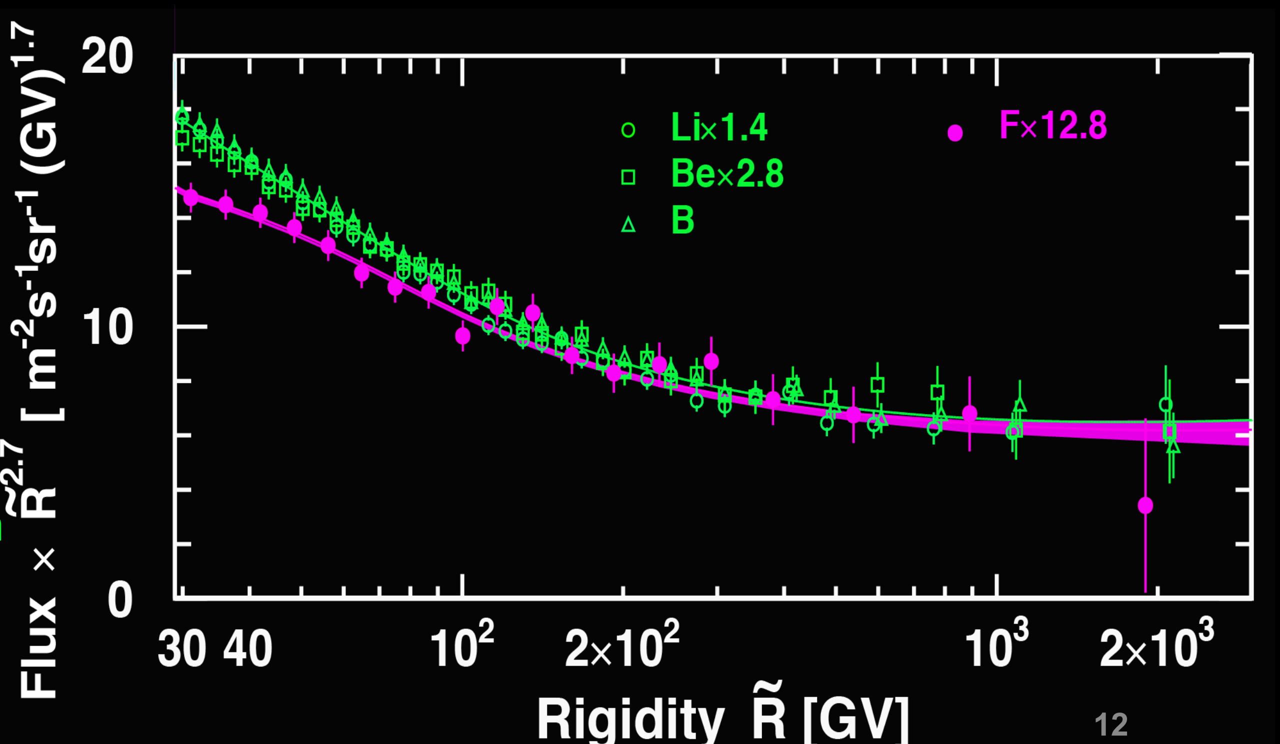
# Secondary Cosmic Rays




Secondary cosmic nuclei (Li, Be, B, F, …)
are produced by the collision of
primary cosmic rays with the interstellar medium

The spectra of secondary CRs are probes of cosmic-ray propagation mechanisms.

AMS found that secondary cosmic rays also have two classes of rigidity dependence

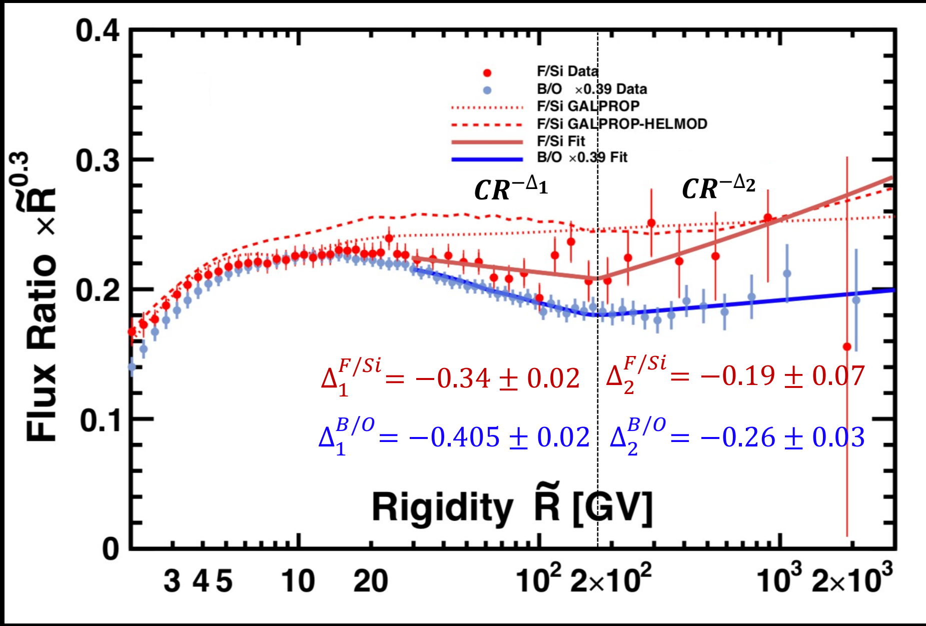


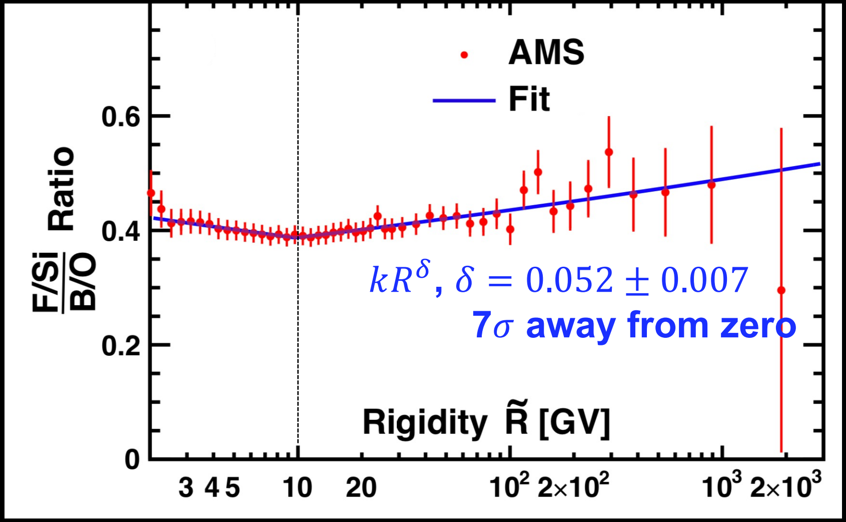
# Propagation properties of heavy nuclei: light vs heavy secondary-to-primary

Traditionally the light secondary-to-primary ratio B/C ( or B/O) is used to describe the propagation properties of all cosmic rays

**AMS found that**

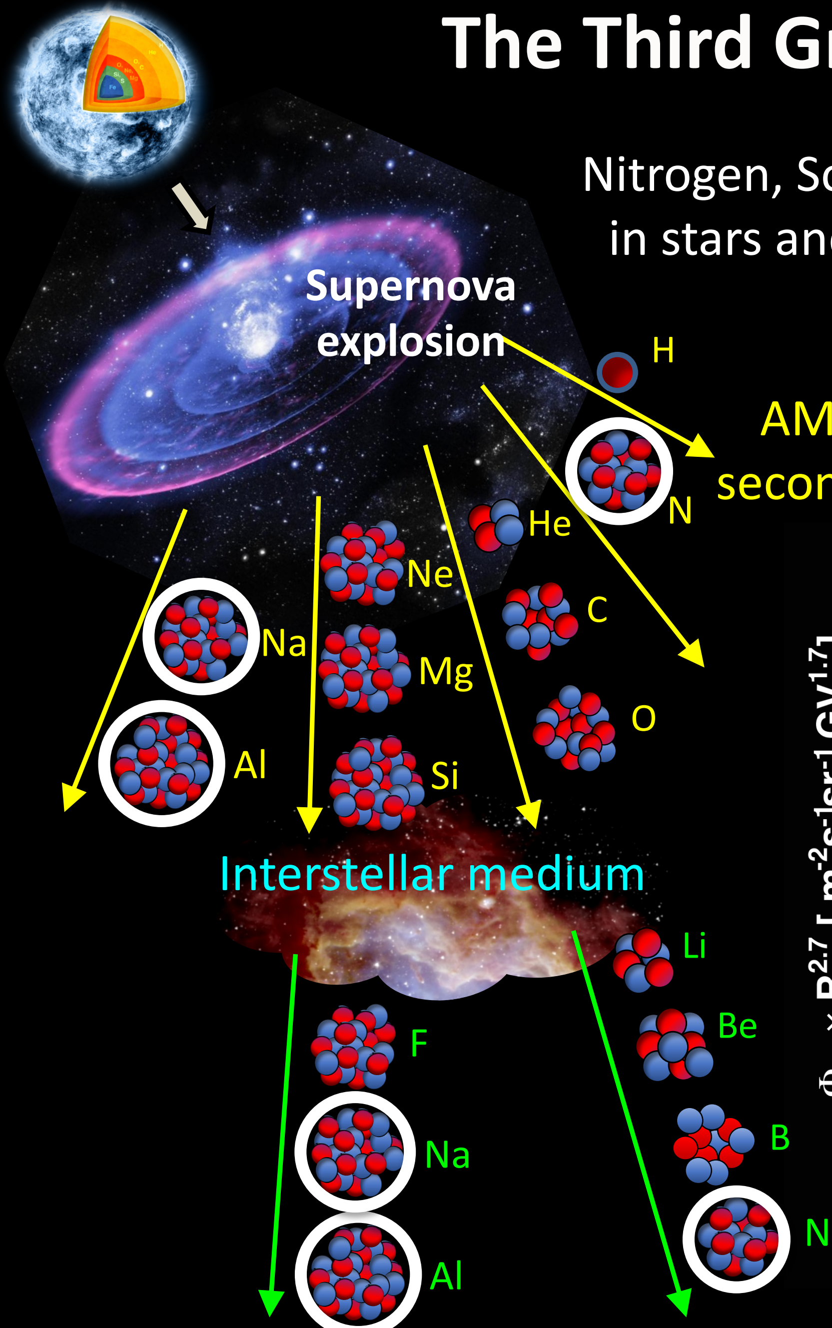
the heavy secondary-to-primary ratio F/Si has a different rigidity dependence from the lighter B/O ratio



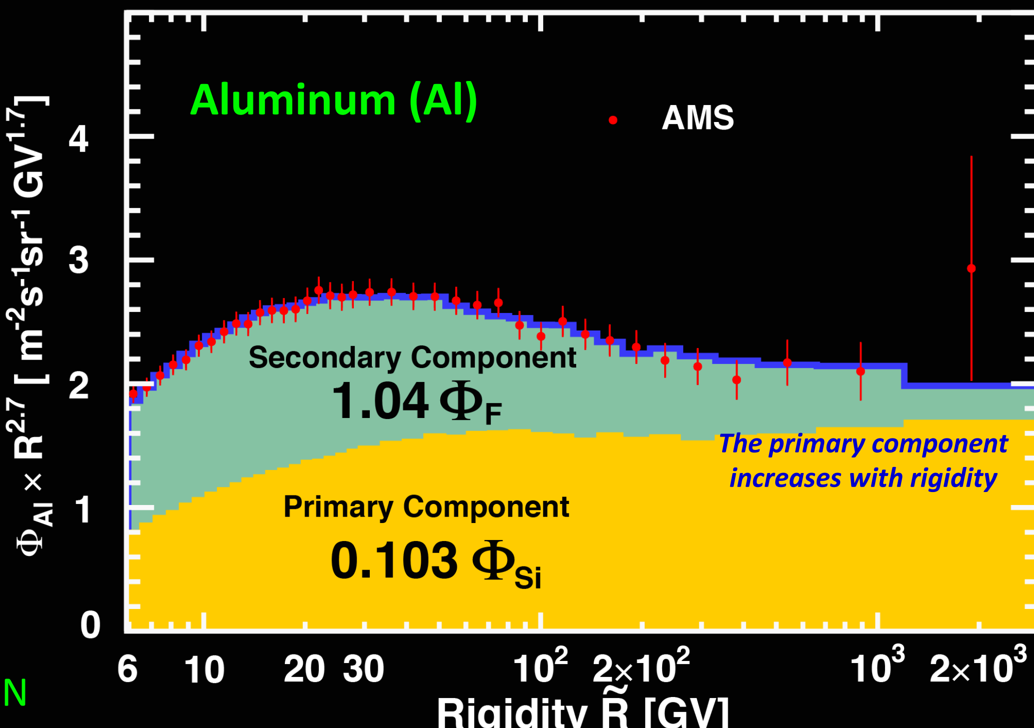

The propagation properties of heavy cosmic rays are different from those of light CRs

# The Third Group of Cosmic Ray

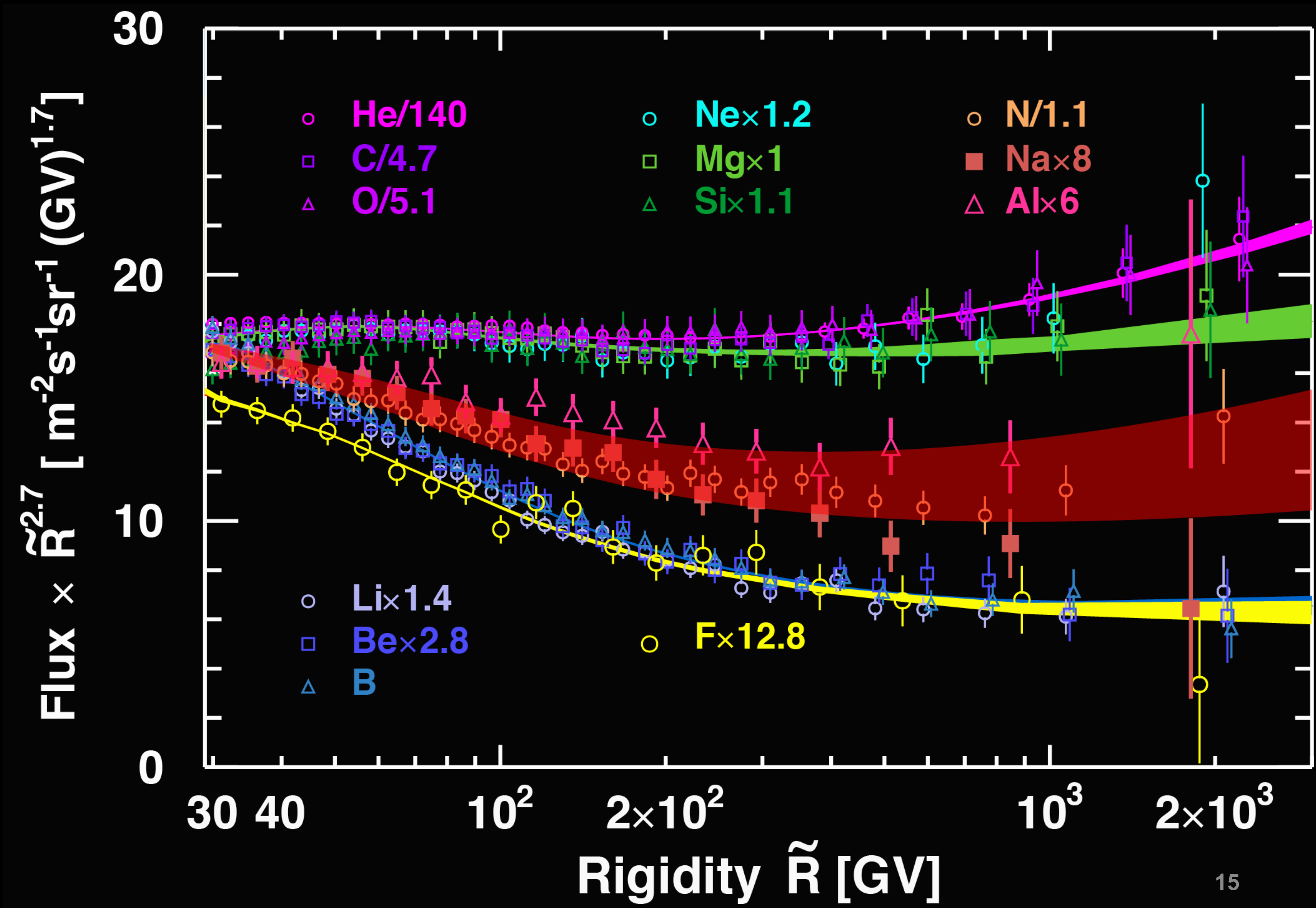



Nitrogen, Sodium and Aluminum nuclei are produced both in stars and by collisions of primary cosmic rays with the interstellar medium.

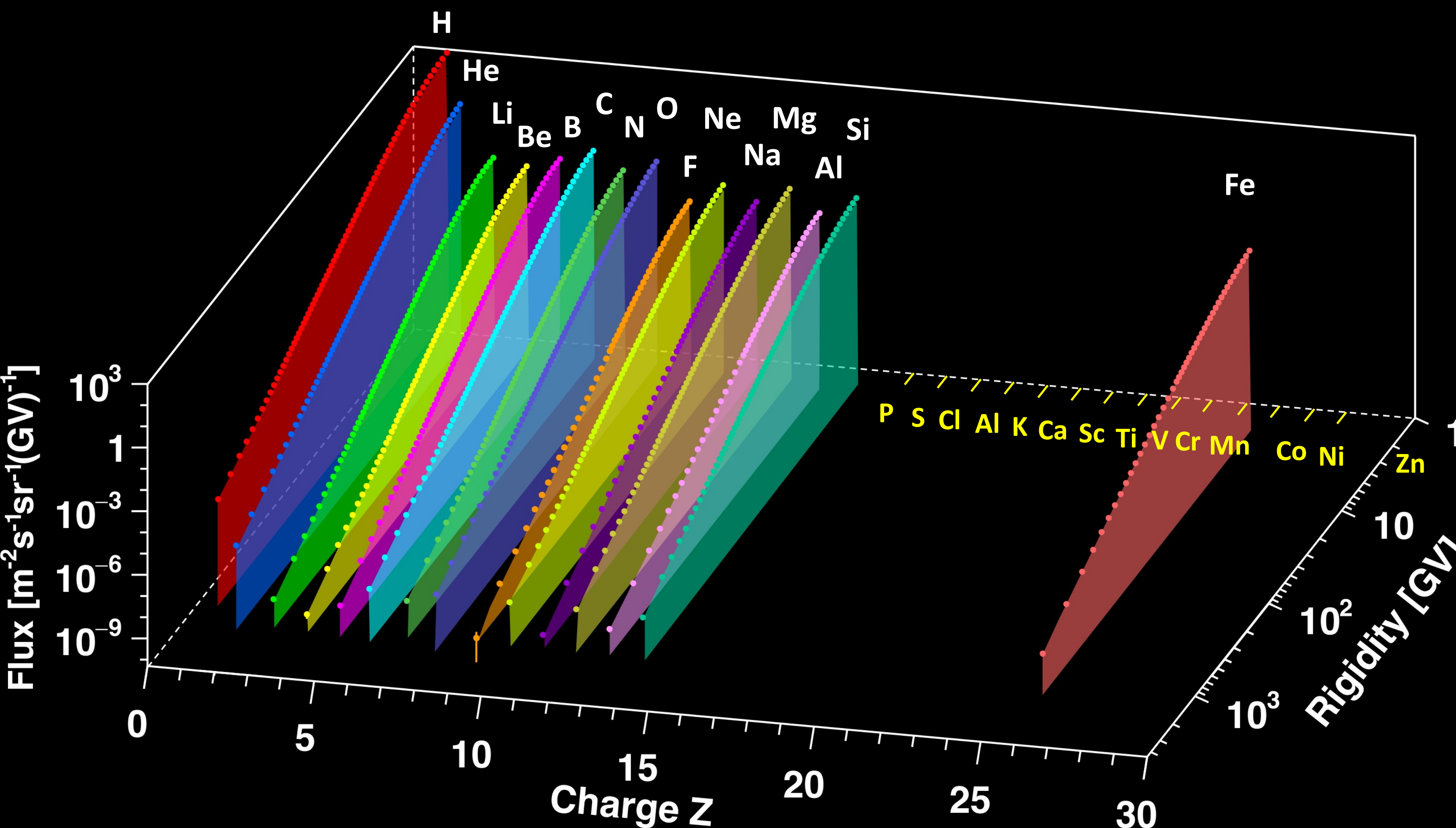
AMS has accurately determined their primary and secondary components as function of rigidity (energy)



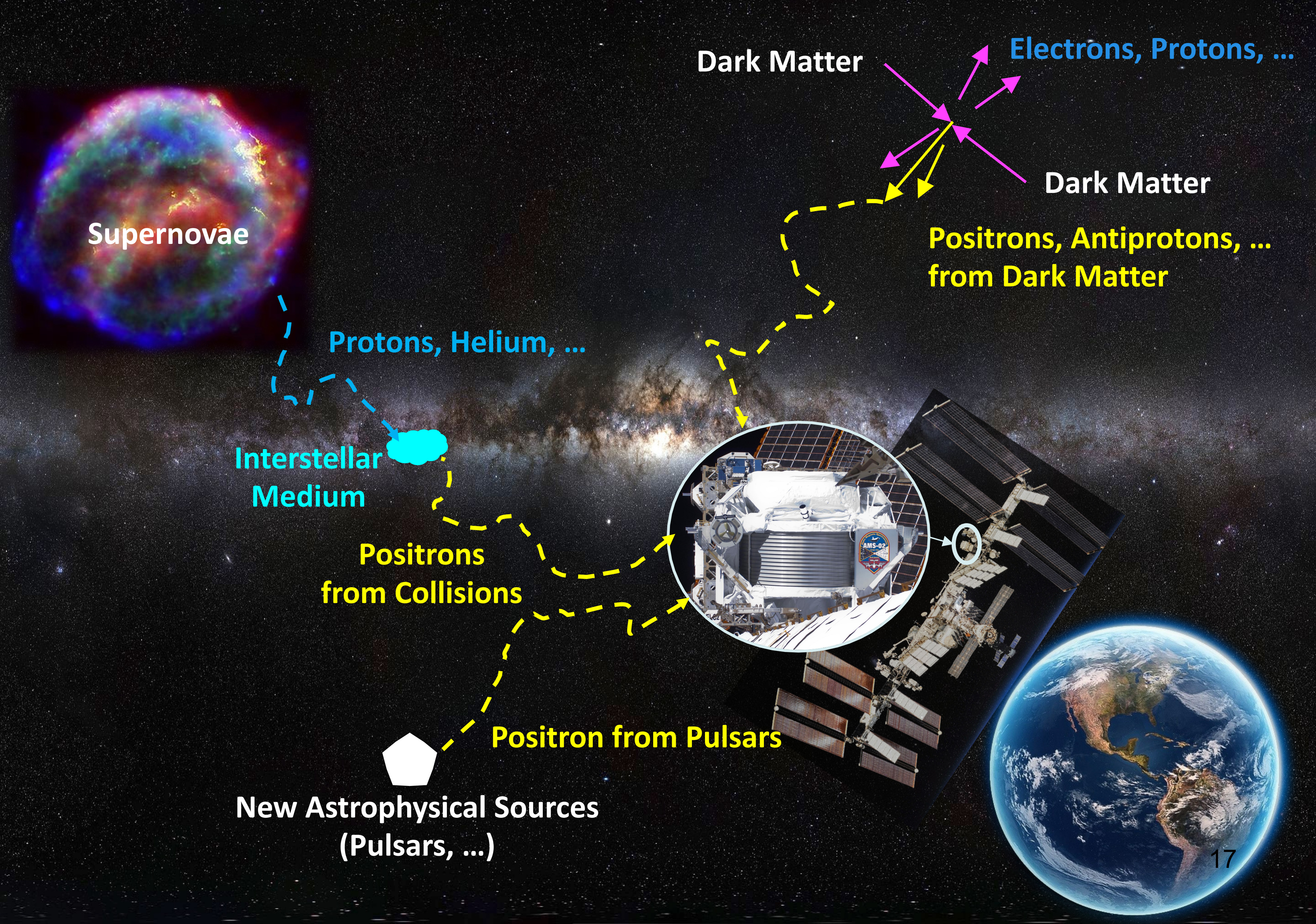
# The Third Group of Cosmic Rays – N, Na, Al



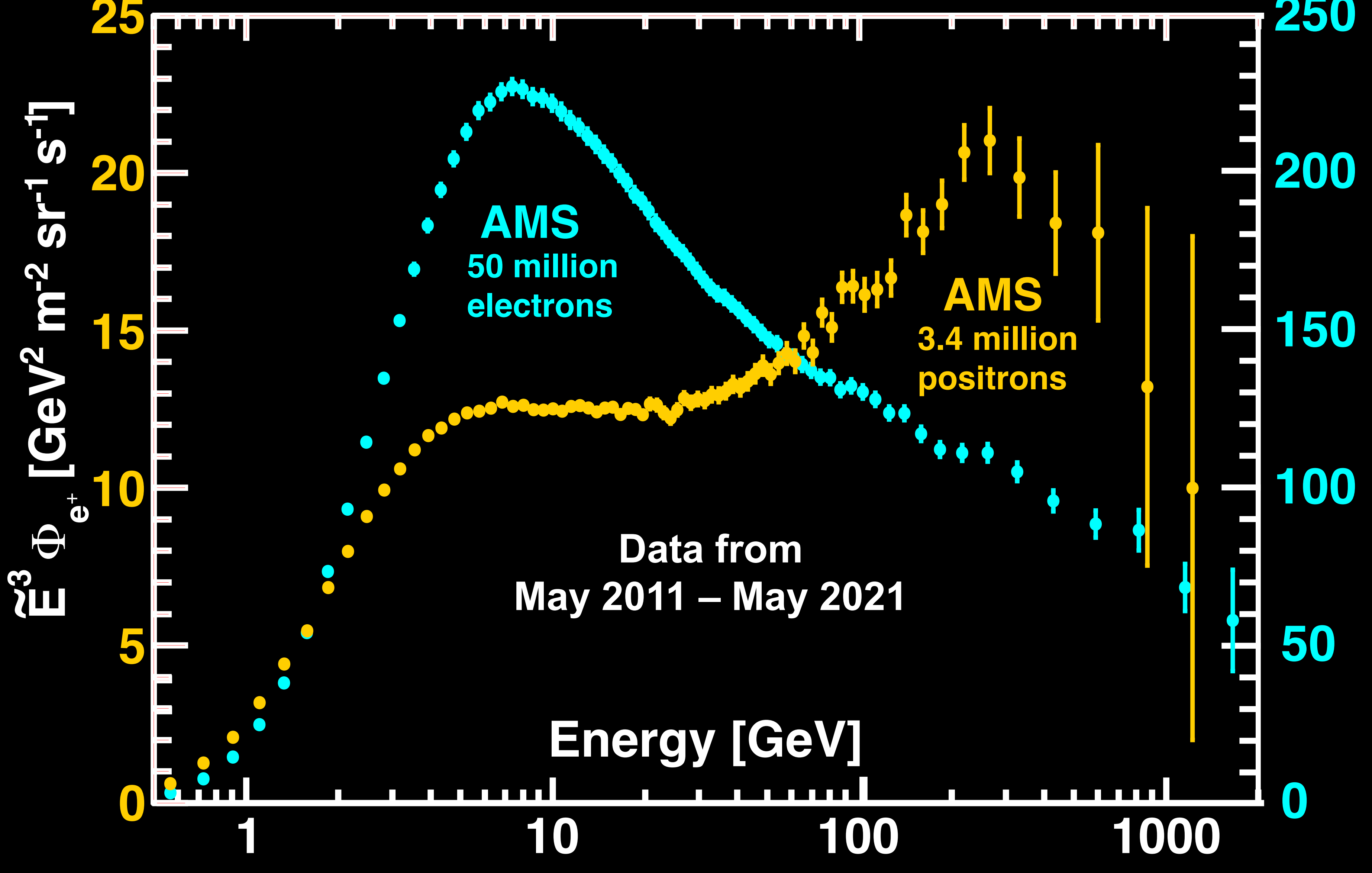
**In ten years we have measured the spectra of 15 elements.**
**In the next ten years we will study the other 14 elements,**
**providing the foundation for a comprehensive theory of cosmic rays.**



# Latest Physics Results from AMS: Study of Positrons & Electrons



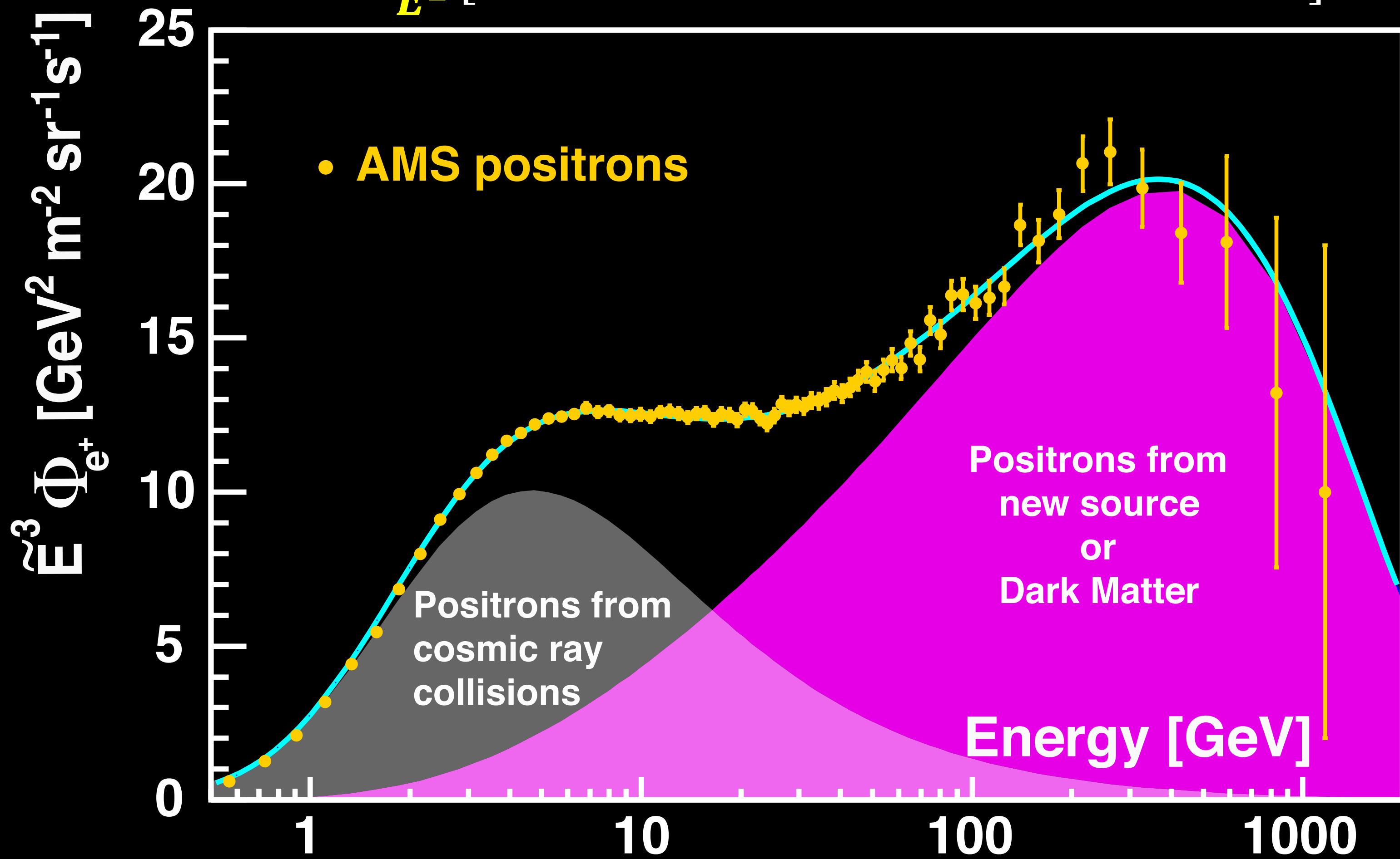
# Latest Physics Results: Precision Study of Positrons & Electrons



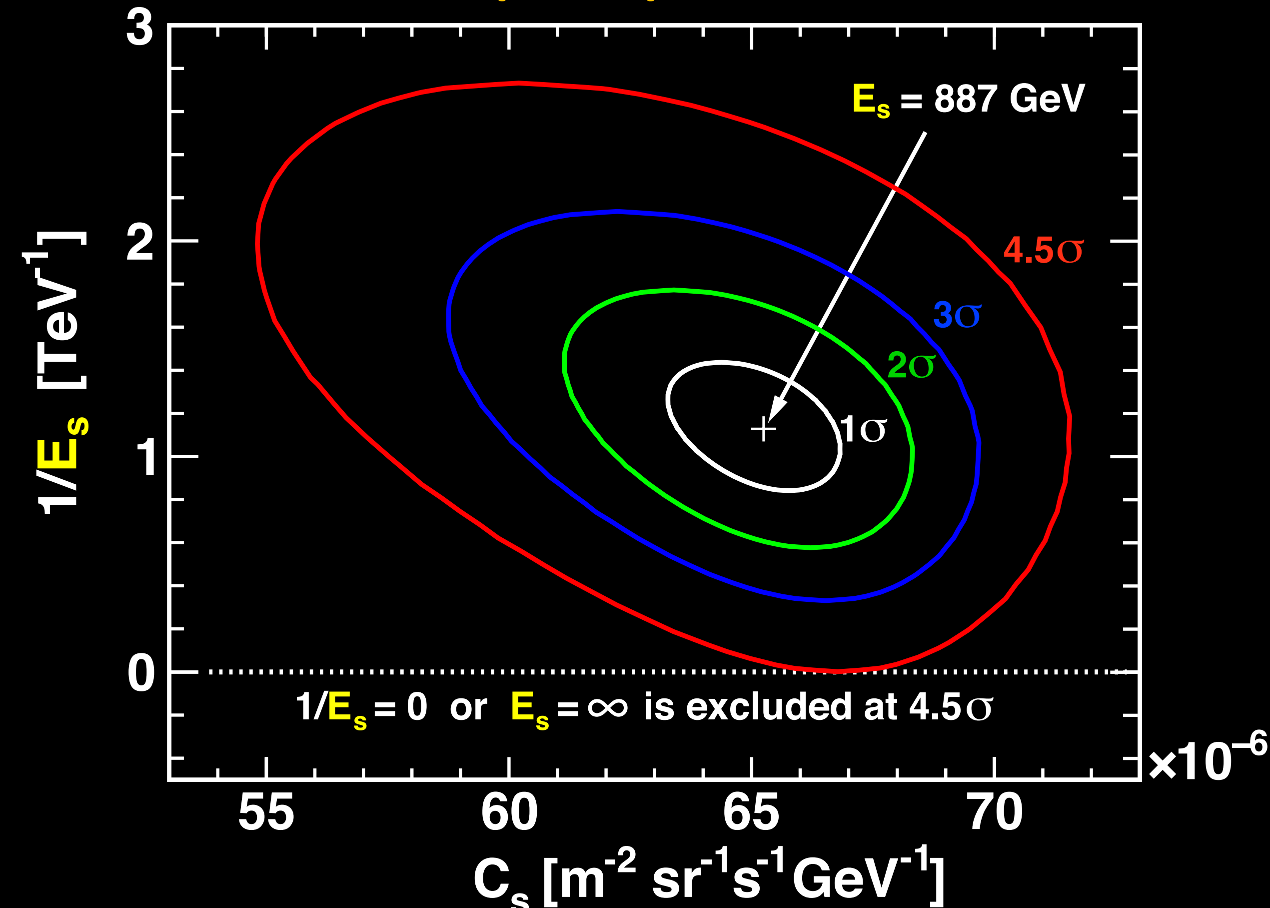
The positron flux is the sum of low-energy part from cosmic ray collisions plus a high-energy part from a new source or dark matter both with a cutoff energy $E_s$.

Collisions New Source or Dark Matter

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



# The finite cutoff energy $E_S$ is established at 99.999 % confidence level (4.5 σ)

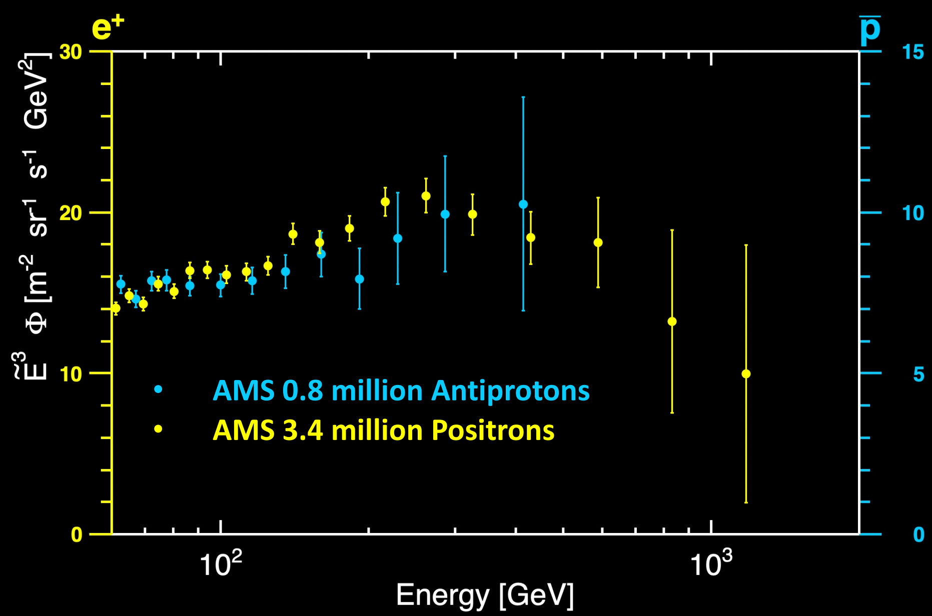


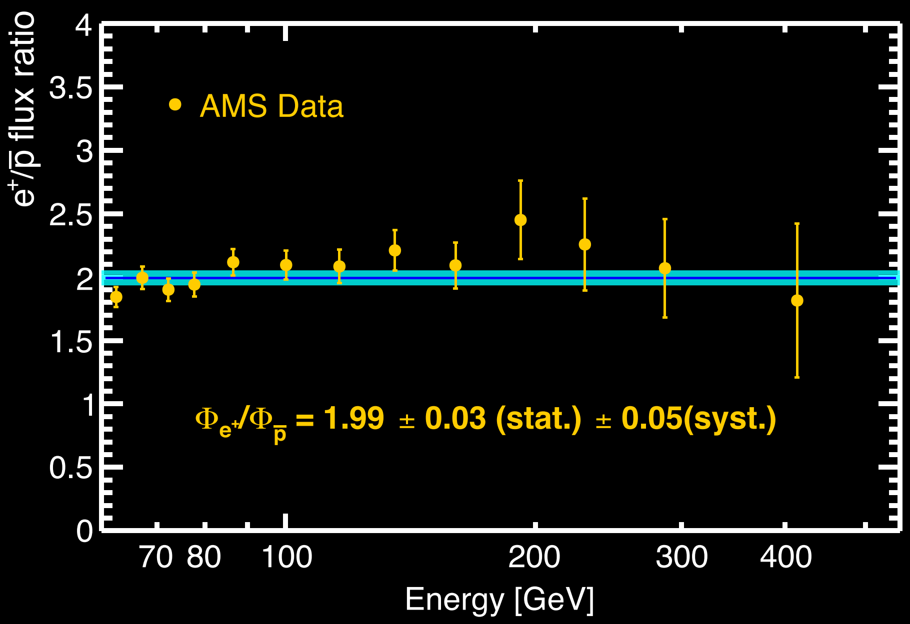

$C_S$ is the magnitude of the flux.

# The positron excess can also be produced by pulsars.

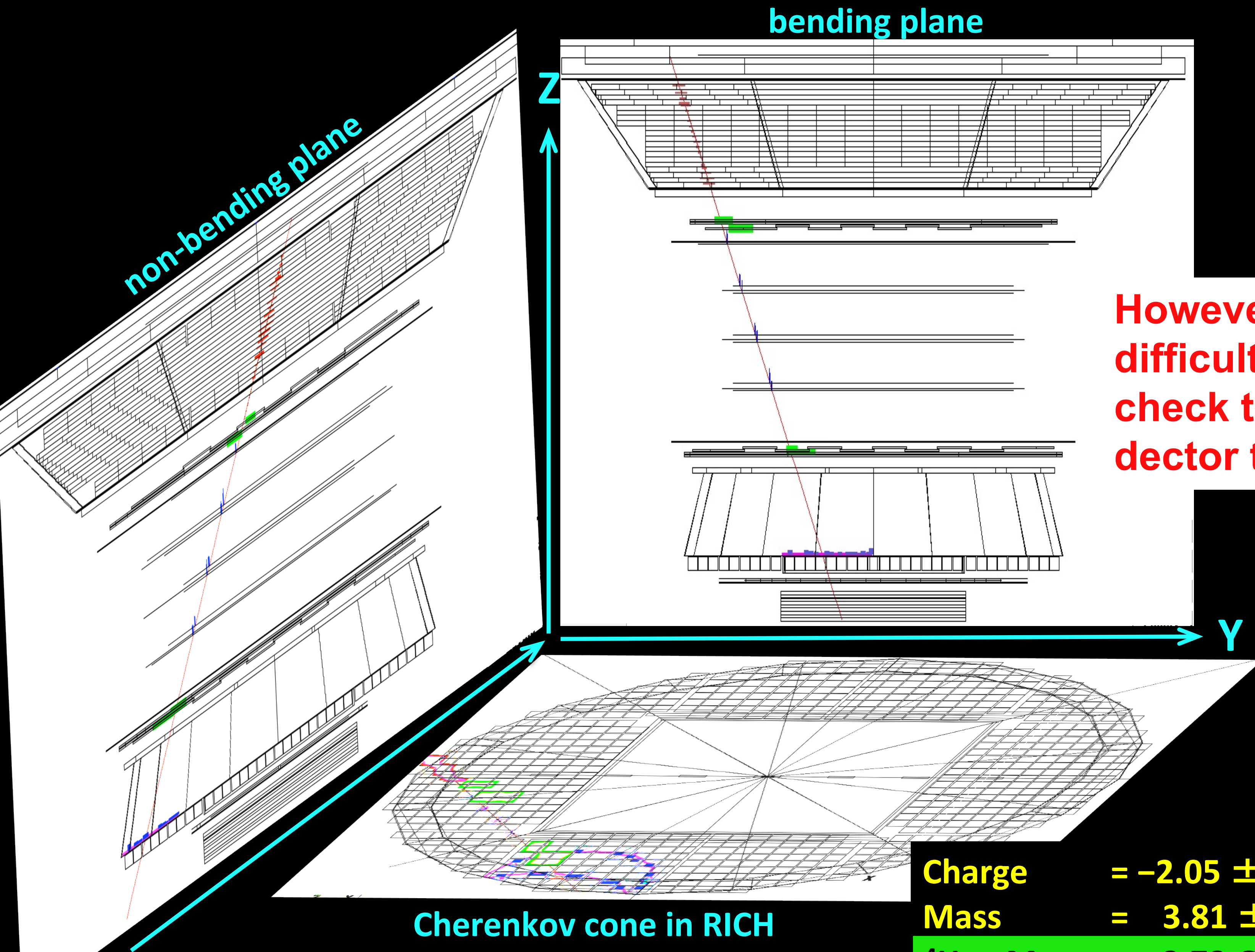
# However, antiprotons show a similar trend as positrons.

# Antiprotons cannot come from pulsars.



# AMS searches for heavy antimatter



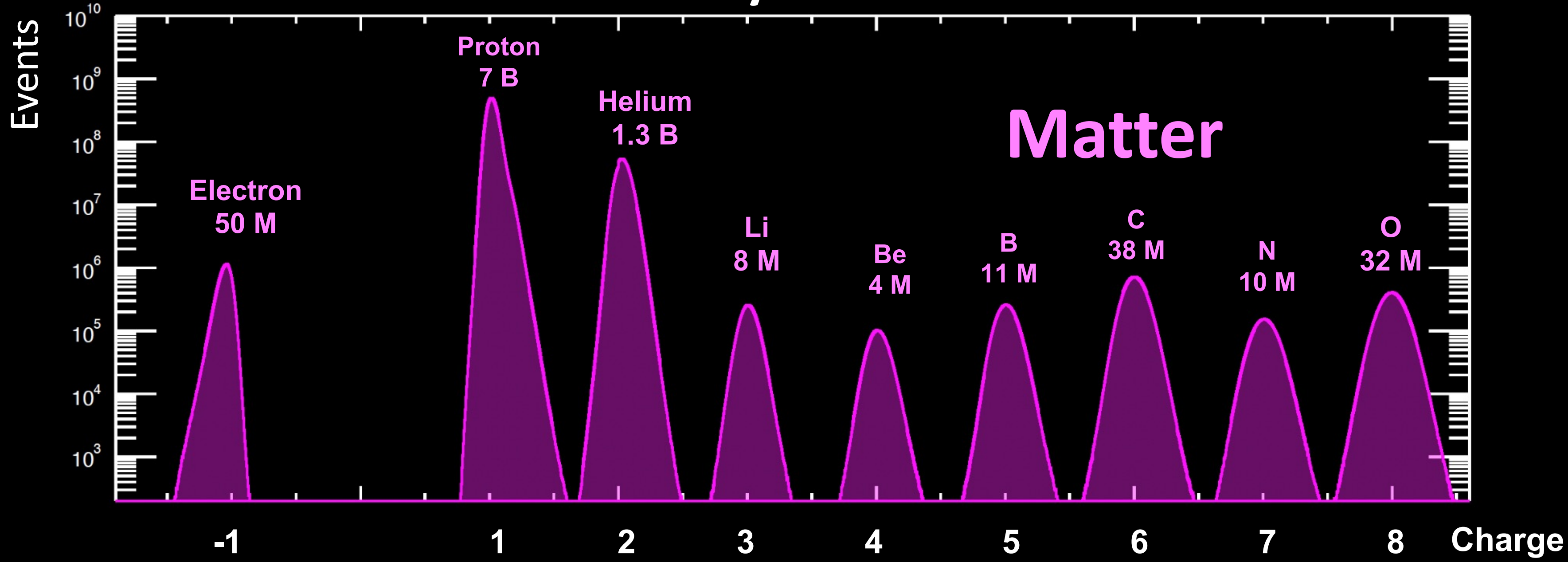

However difficult to check the dector to $1/10^9$

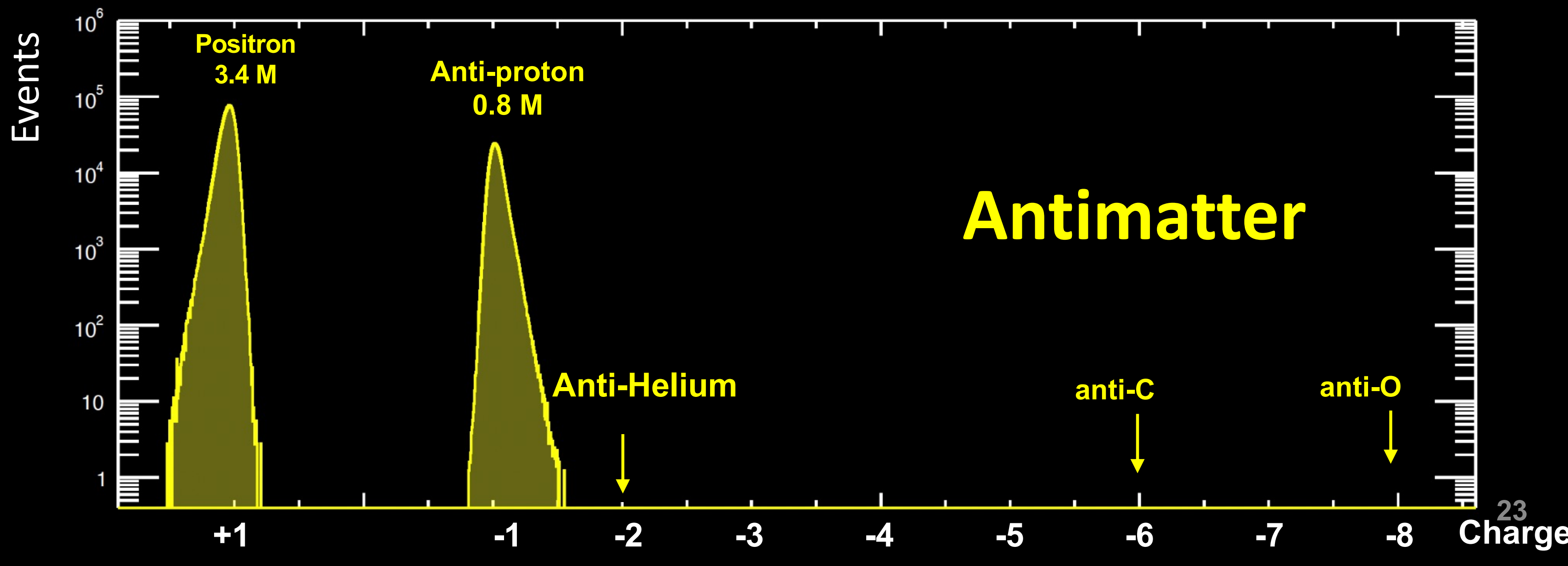
June 22, 2017 06:11:40

| | |
|---|---|
| Charge | $= -2.05 \pm 0.05$ |
| Mass | $= 3.81 \pm 0.29$ GeV/$c^2$ |

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

**AMS searches for antimatter such as anti-deuterons, anti-helium, and beyond.**



**The results from AMS are unexpected.**

**AMS will continue to collect data over the life of the Station**

**This will change our understanding of the universe.**


***The White House announced the lifetime of the Space Station will be extended through 2030.***

## The accurate electron spectrum shows the contribution from cosmic ray collisions is negligible and the existence of a positron-like source term

$$\Phi_{e^-}(E) = S(E)\left[C_a(\hat{E}/E_a)^{\gamma_a} + C_b(\hat{E}/E_b)^{\gamma_b} + f_s C_s^{e^+}(\hat{E}/E_2)^{\gamma_s^{e^+}} \exp(-E/E_s^{e^+})\right]$$

Solar Power law *a* Power law *b* Positron source term