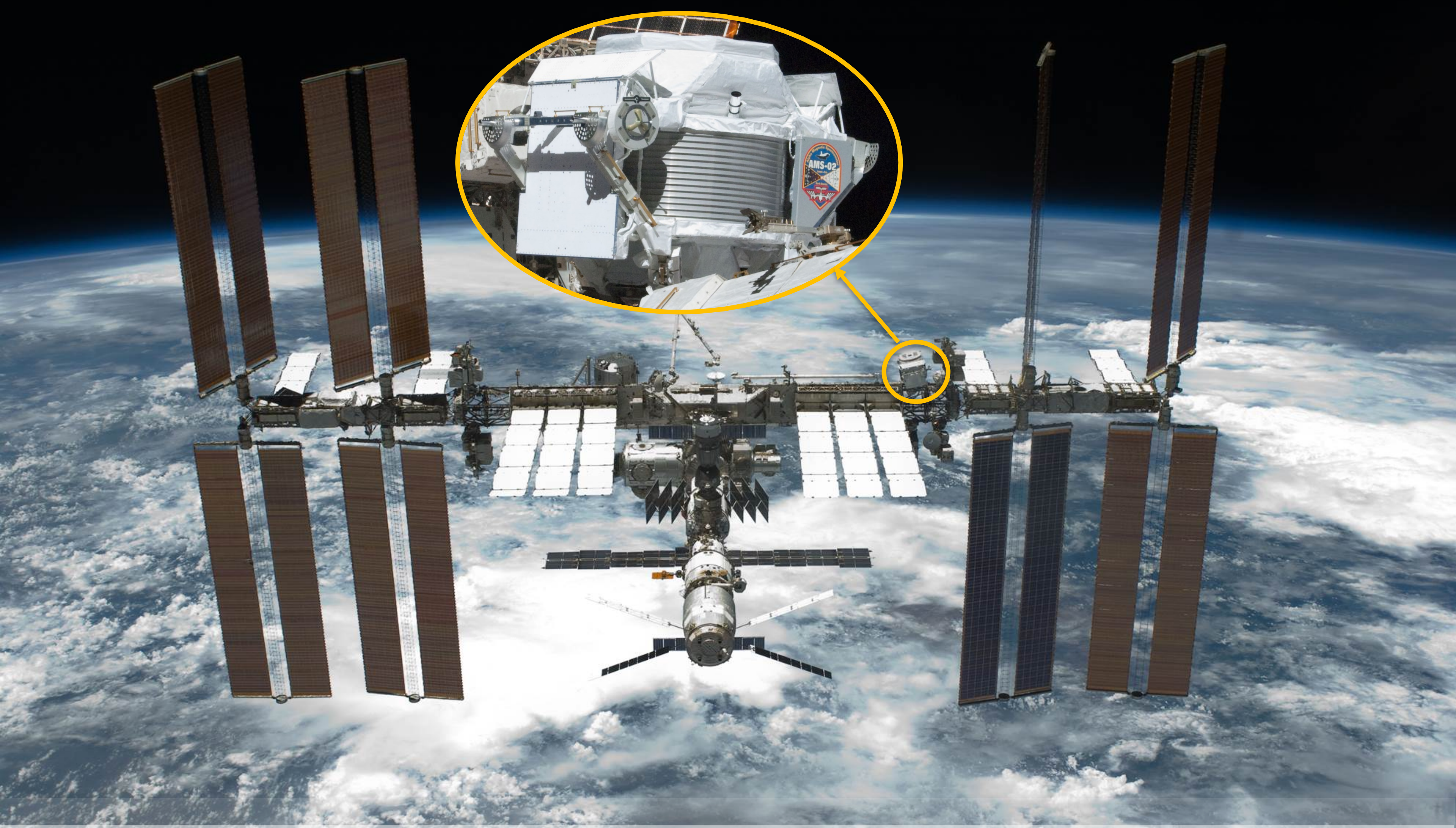
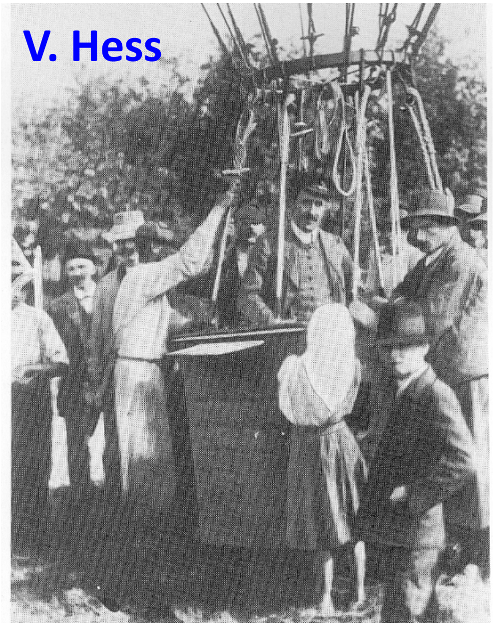
Alpha Magnetic Spectrometer on the International Space Station



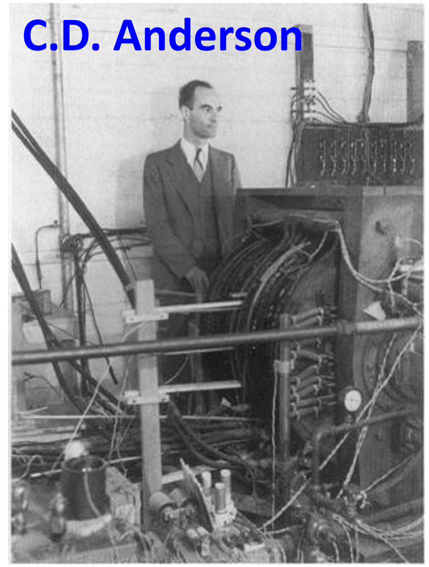
Andrei Kounine / MIT

DESY, January 28, 2020

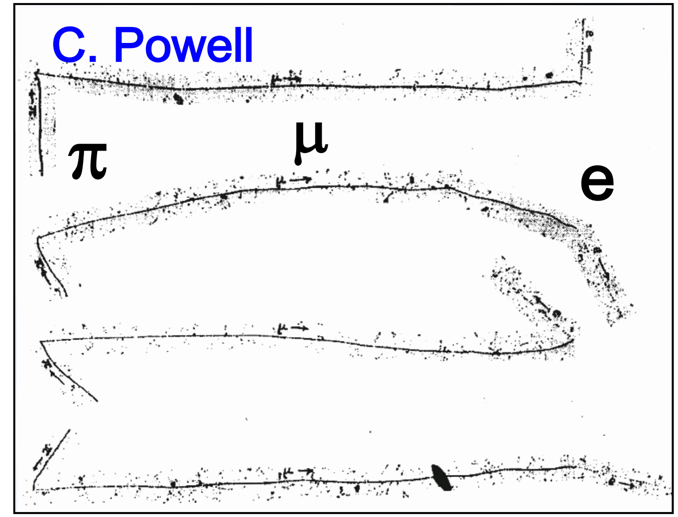
Physics of Charged Cosmic Rays



1912: Discovery of Cosmic Rays



1932: Discovery of positron



1947: Discovery of pions

Discoveries of

- 1936: Muon (μ)
- 1938: 10^{15} eV CR
- 1949: Kaon (K)
- 1949: Lambda (Λ)
- 1952: Xi (Ξ)
- 1953: Sigma (Σ)

Cosmic Rays with energies of 100 Million TeV have been observed.

Question

Universe

He

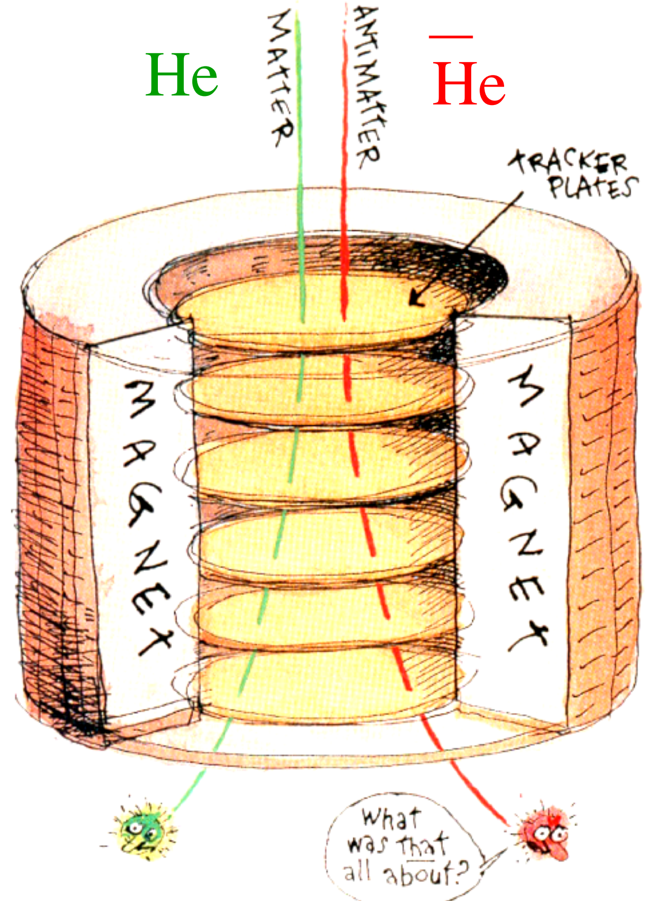
C

Anti universe ?

$\overline{\mathrm{He}}$

$\overline{\mathrm{C}}$

He $\overline{\mathrm{He}}$



Requires a magnetic detector in space.

NATURE VOL. 236 APRIL 14 1972 335

Search for Antimatter in Primary Cosmic Rays

A. BUFFINGTON, L. H. SMITH, G. F. SMOOT & L. W. ALVAREZ

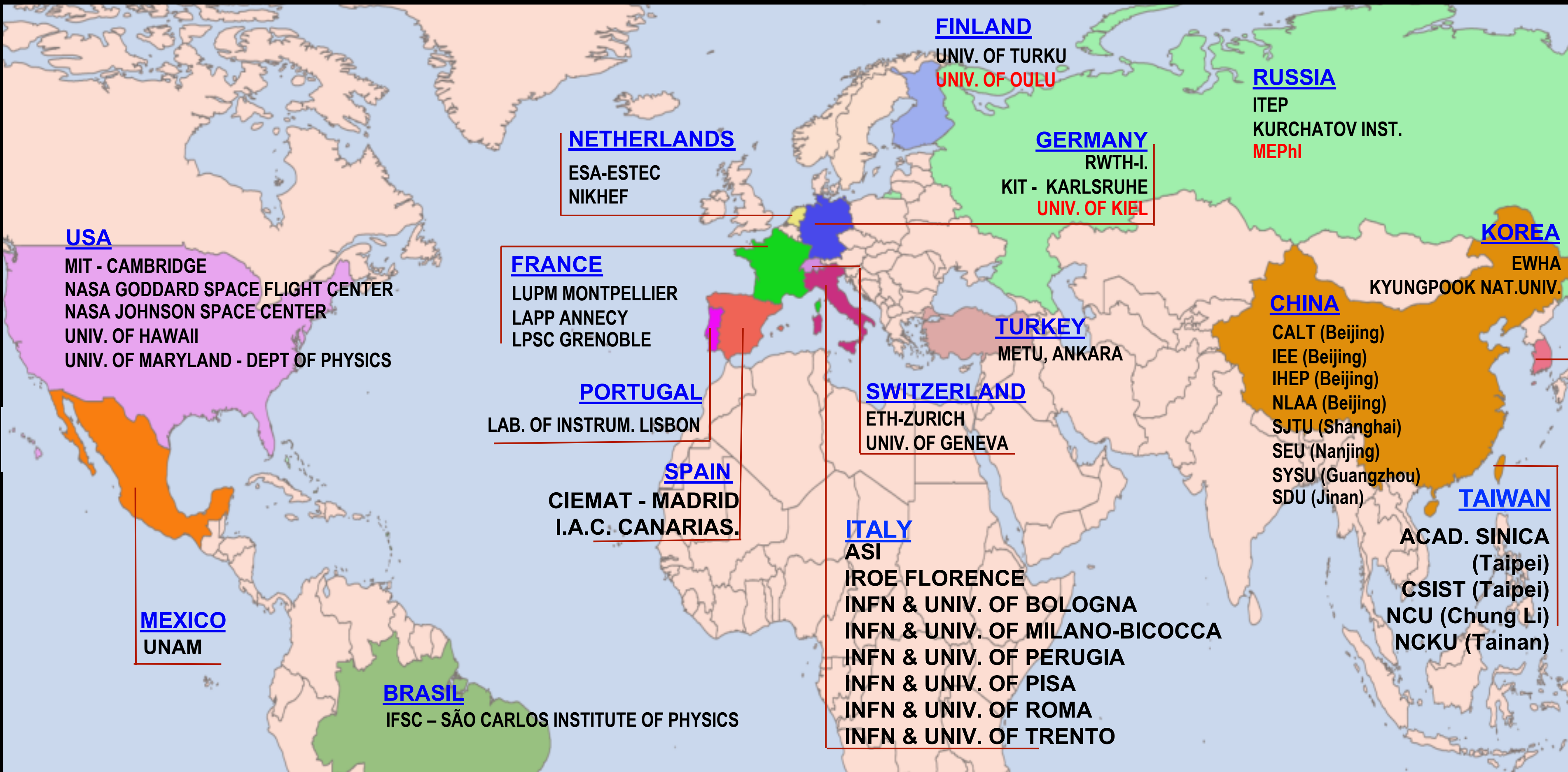
Space Sciences Laboratory, University of California, Berkeley

M. A. WAHLIG

Lawrence Berkeley Laboratory, University of California

AMS is an International Collaboration

It took 650 physicists and engineers 17 years to build AMS

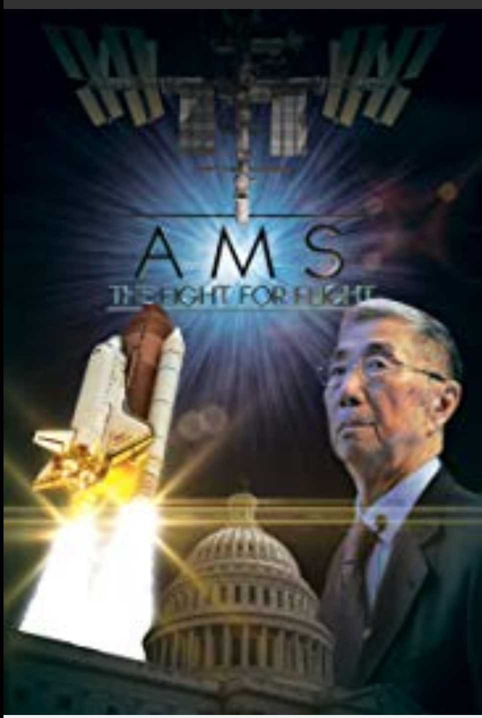


The detectors were constructed in Europe and Asia and assembled at CERN, Geneva

NASA Presents: AMS - The Fight for Flight (2017)

6.9/10
19
Rate This

1h 3min | Documentary | 17 October 2017 (USA)



NASA has produced a documentary about the Alpha Magnetic Spectrometer (AMS), a particle physics experiment on the International Space Station. The film covers the history of this ...

Storyline

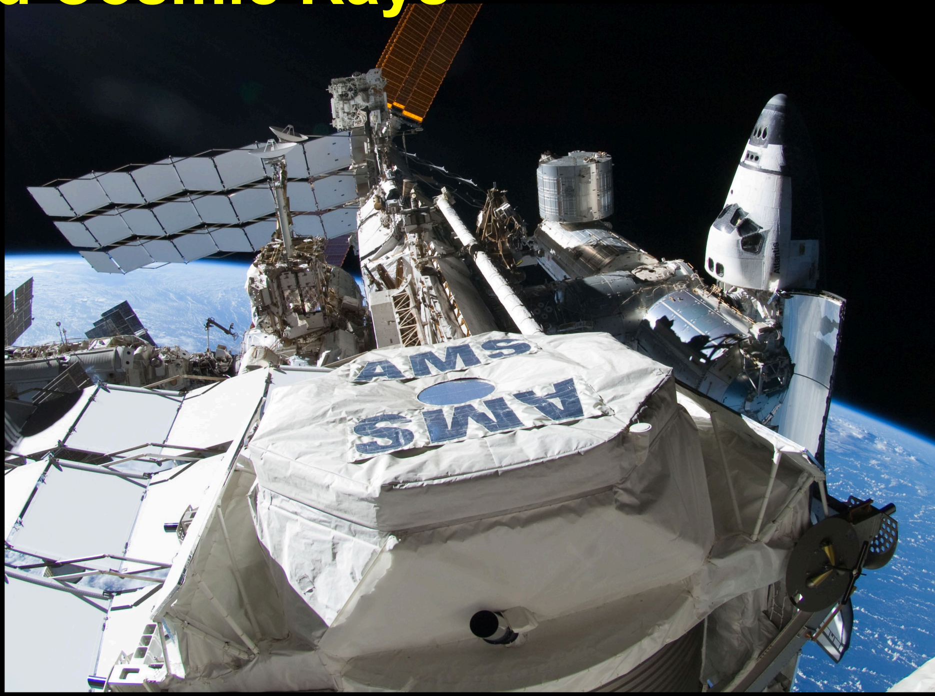
Edit

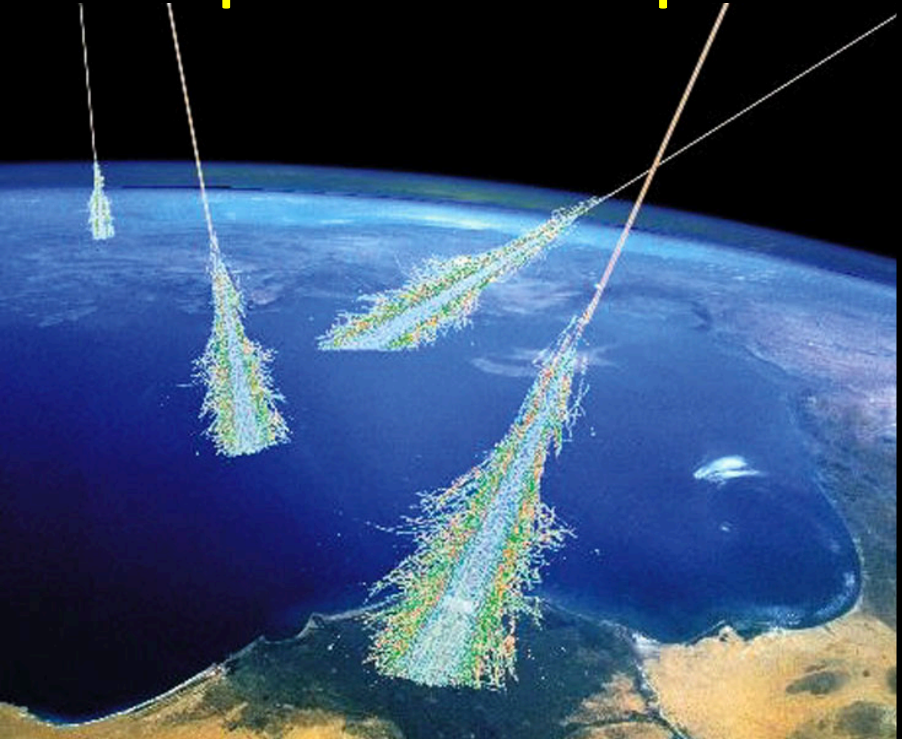
NASA has produced a documentary about the Alpha Magnetic Spectrometer (AMS), a particle physics experiment on the International Space Station. The film covers the history of this revolutionary experiment and the man behind it. Originally proposed in 1994 by Samuel Ting, a Nobel laureate and MIT Professor of Physics, and built by over 600 physicists and engineers all over the world, the Alpha Magnetic Spectrometer is by far the most complex physics experiment ever launched into space. The goal of the instrument is to help researchers unlock the mysteries of antimatter and better understand the structure of our universe. While still under construction, the AMS experiment suffered a major setback because of the Space Shuttle Columbia tragedy in 2003. Soon after, the decision was made to cancel the space shuttle program, and as a result the AMS was removed from the manifest. After ten years and $1.5B spent, there would be no ride to the space station. This film tracks the AMS's 23 year ...
Written by National Aeronautics and Space Administration

The physics of AMS on the Space Station: Study of Charged Cosmic Rays

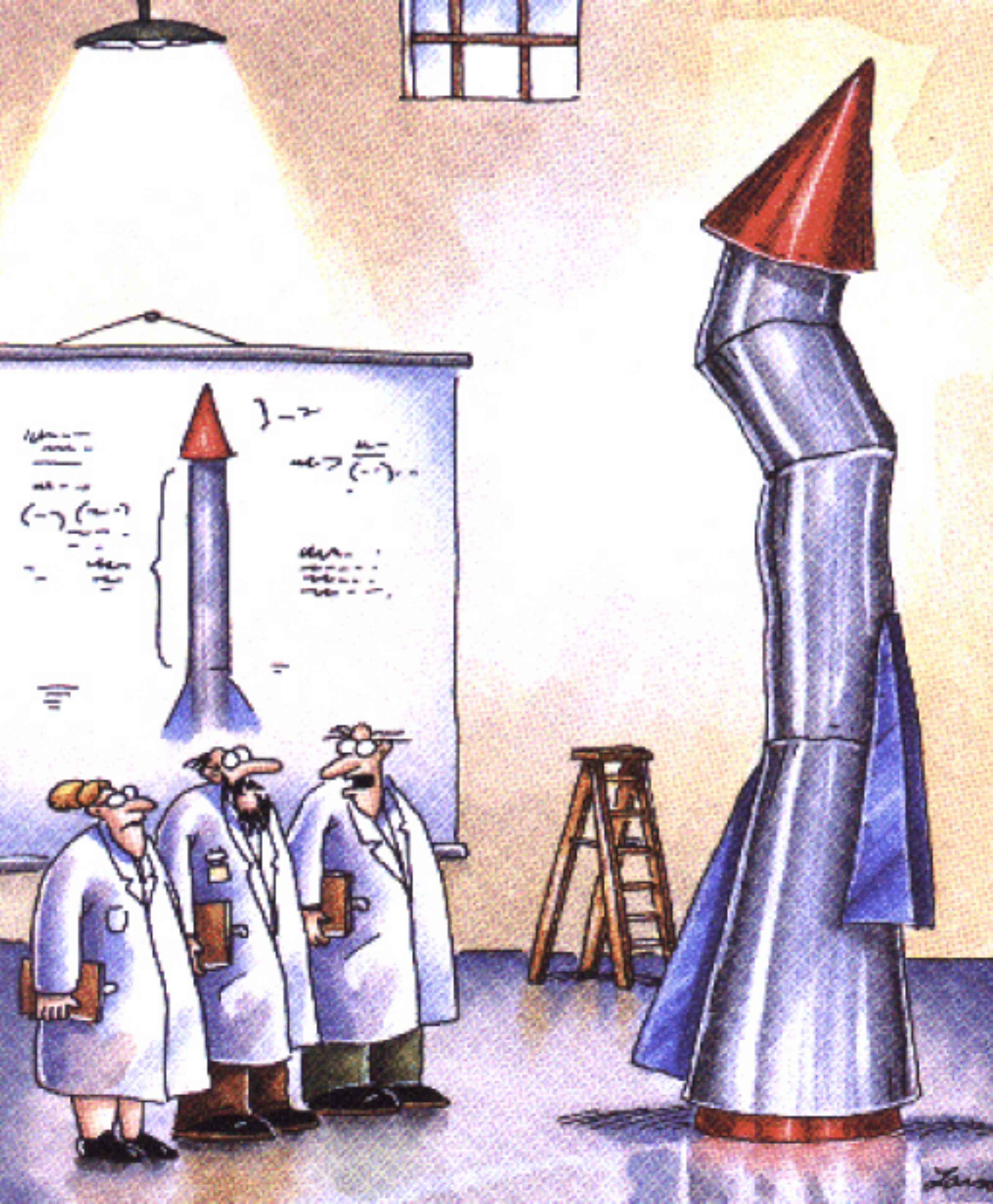
Charged cosmic rays have mass.
They are absorbed by 100 km of Earth's atmosphere (10m of water).

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





AMS on ISS provides long term (20 years) precision measurements of charged cosmic rays.



“Its time we face reality,

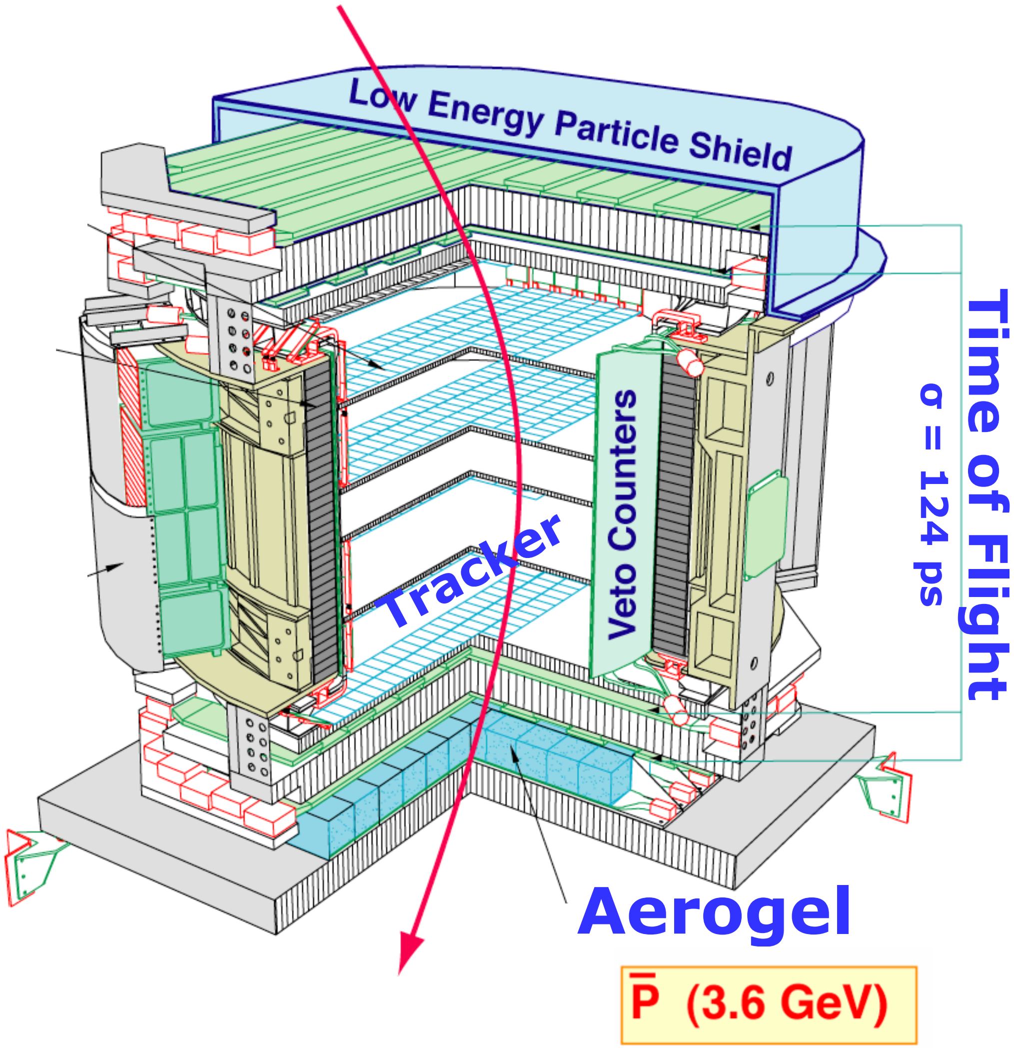
my friends….

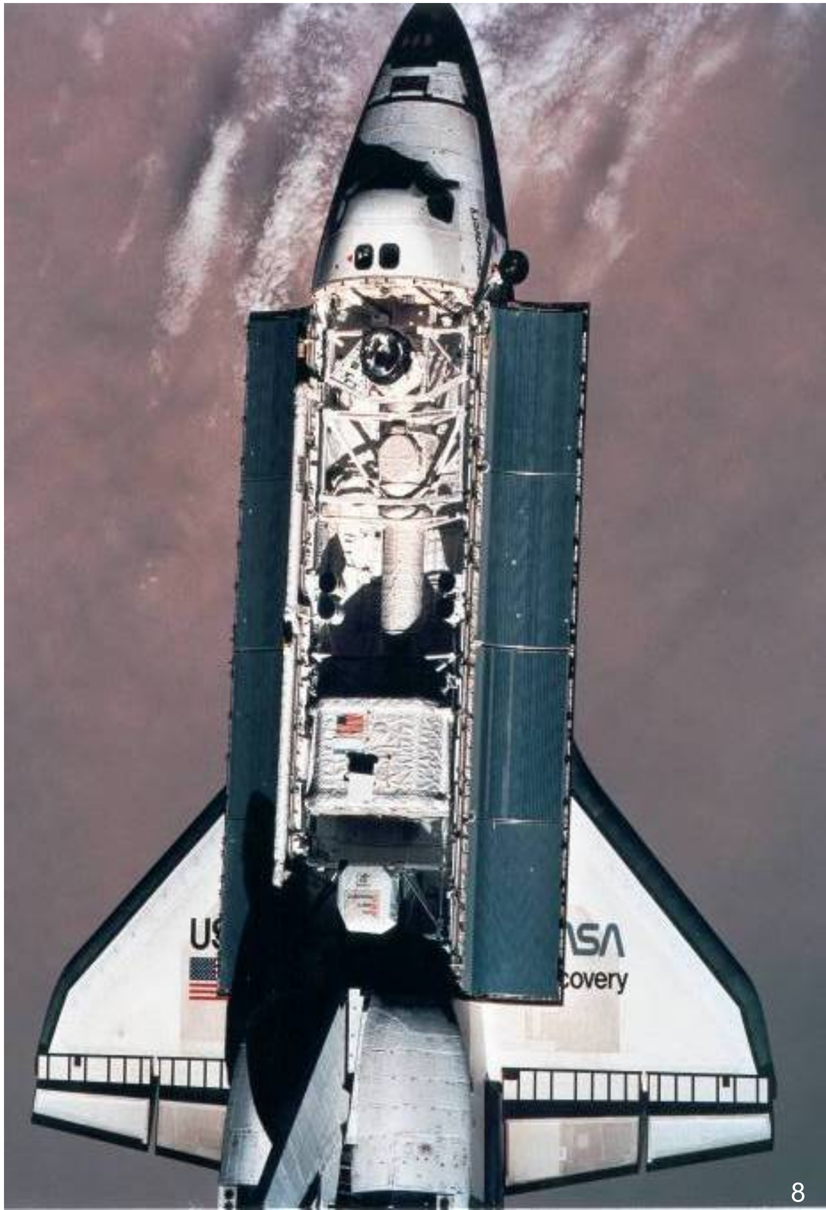
We’re not exactly

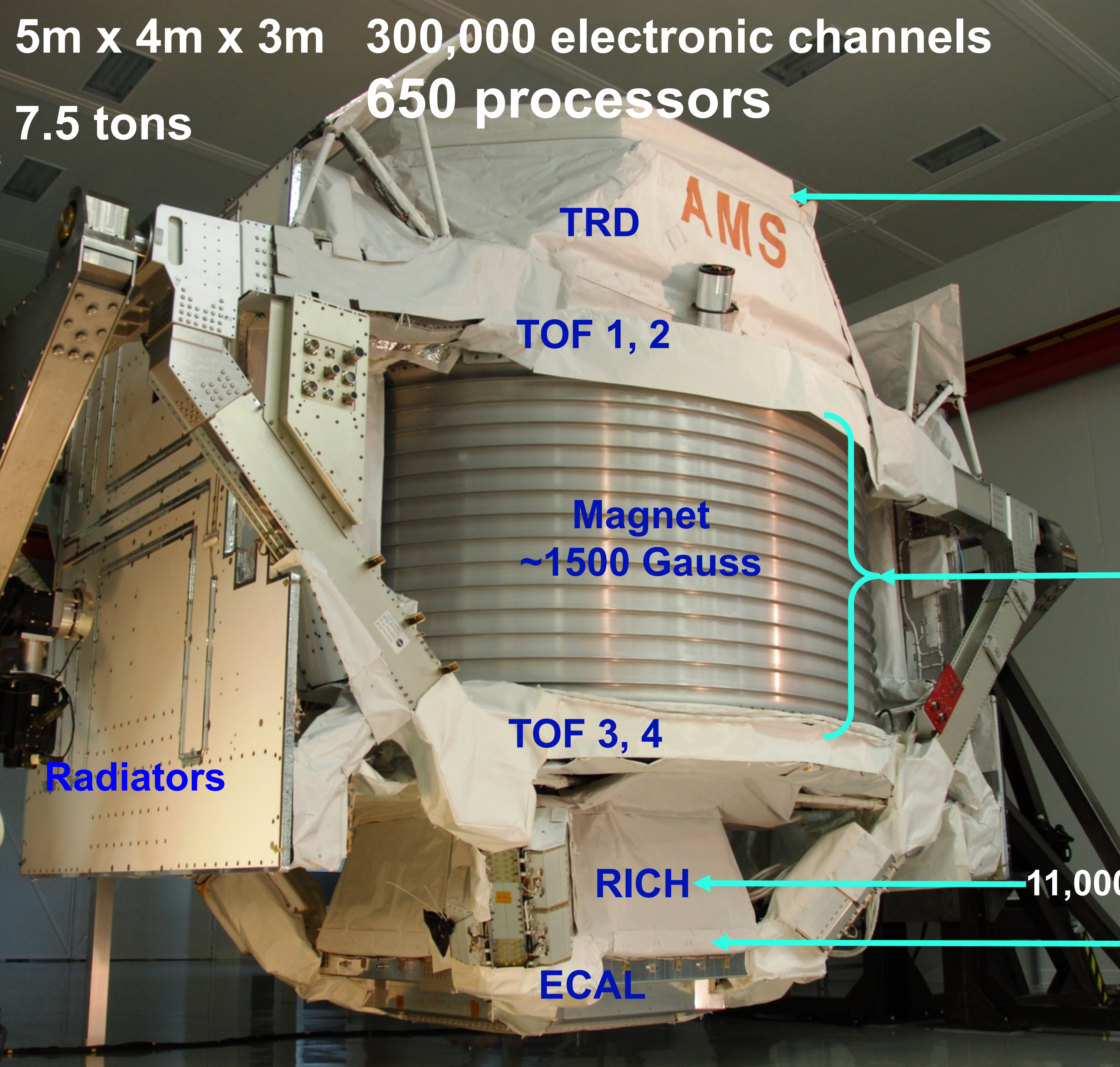
rocket scientists.”

The AMS-01 Detector

Approval: April 1995, Assembly: December 1997, Flight: 10 days in June 1998

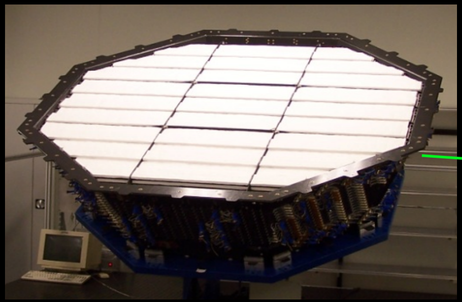




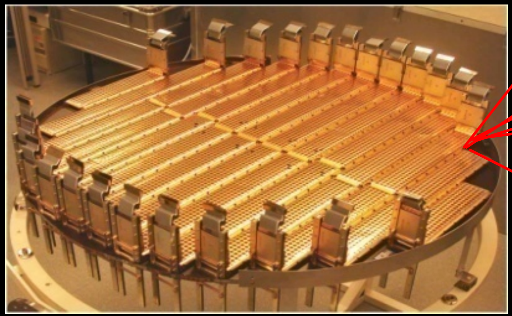

5m x 4m x 3m
7.5 tons
300,000 electronic channels
650 processors
TRD
AMS
TOF 1, 2
Magnet
~1500 Gauss
TOF 3, 4
Radiators
RICH
ECAL
Silicon layer
7 Silicon layers
11,000 Photo Sensors
Silicon layer

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

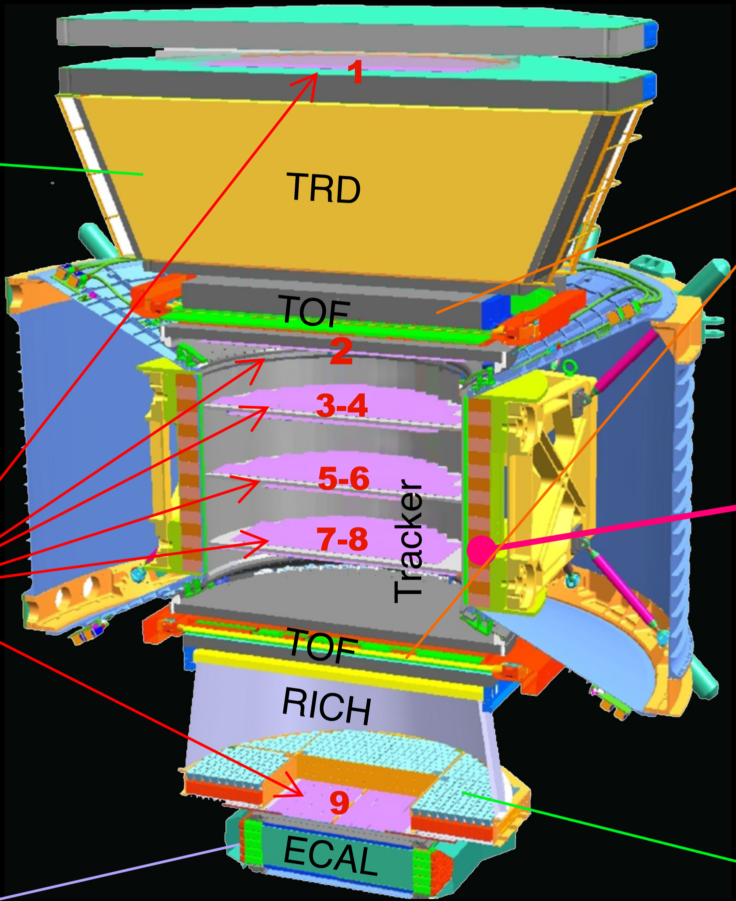
Transition Radiation Detector (TRD)



Silicon Tracker

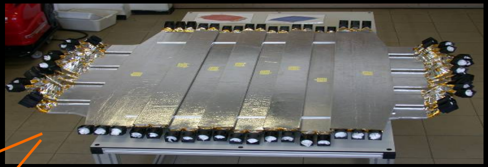


Electromagnetic Calorimeter (ECAL)

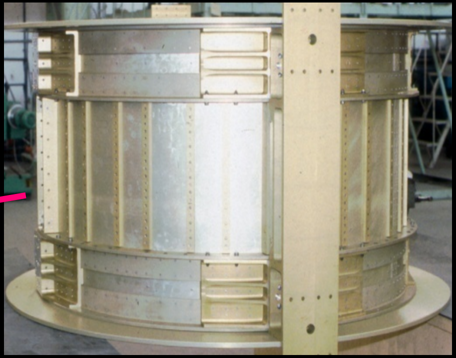


300,000 electronic channels,
650 fast microprocessors
5m x 4m x 3m
7.5 tons

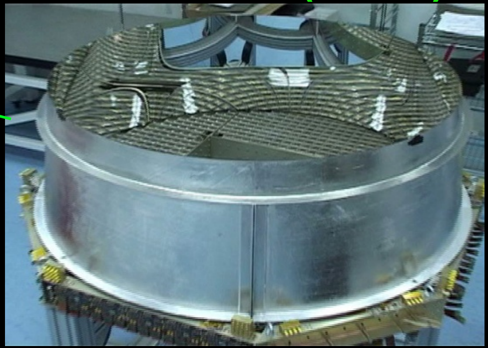
Time of Flight Detector (TOF)



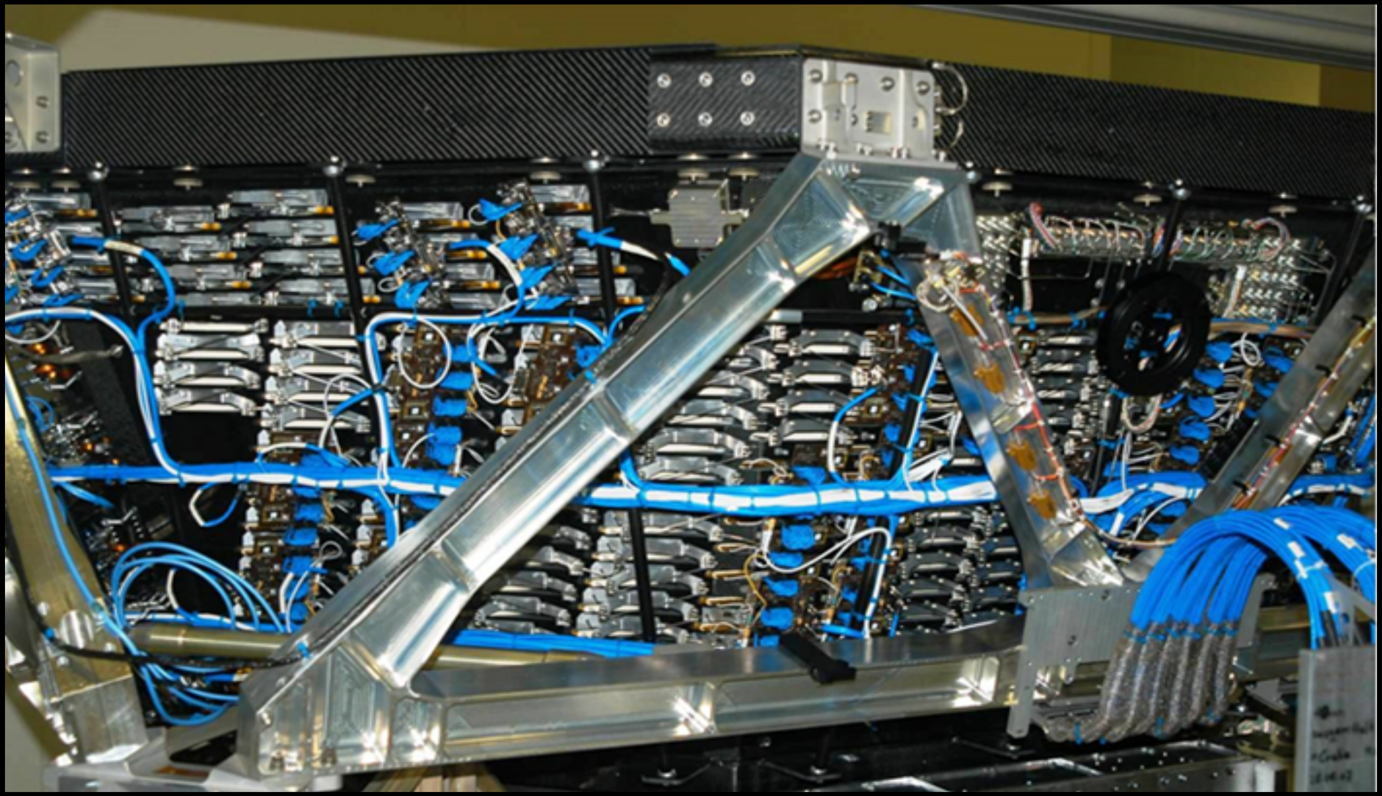
Magnet

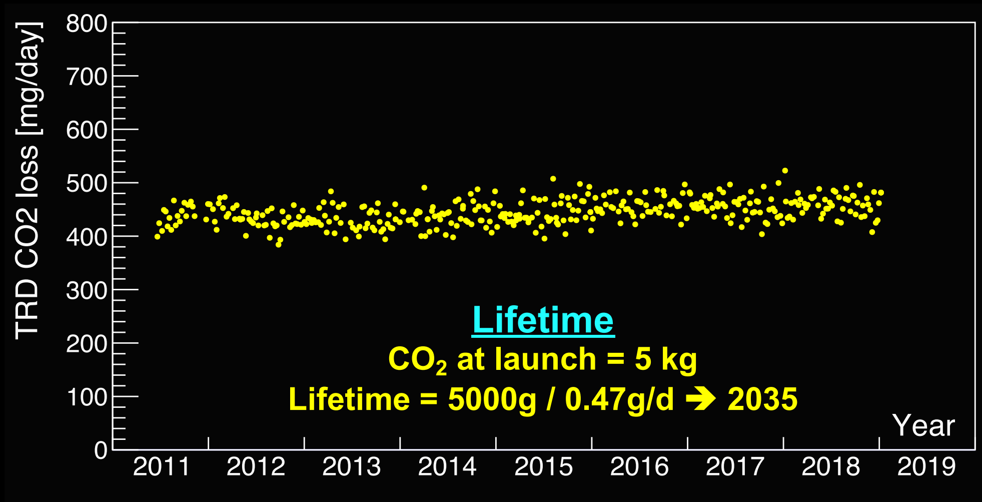


Ring Imaging Cherenkov (RICH)

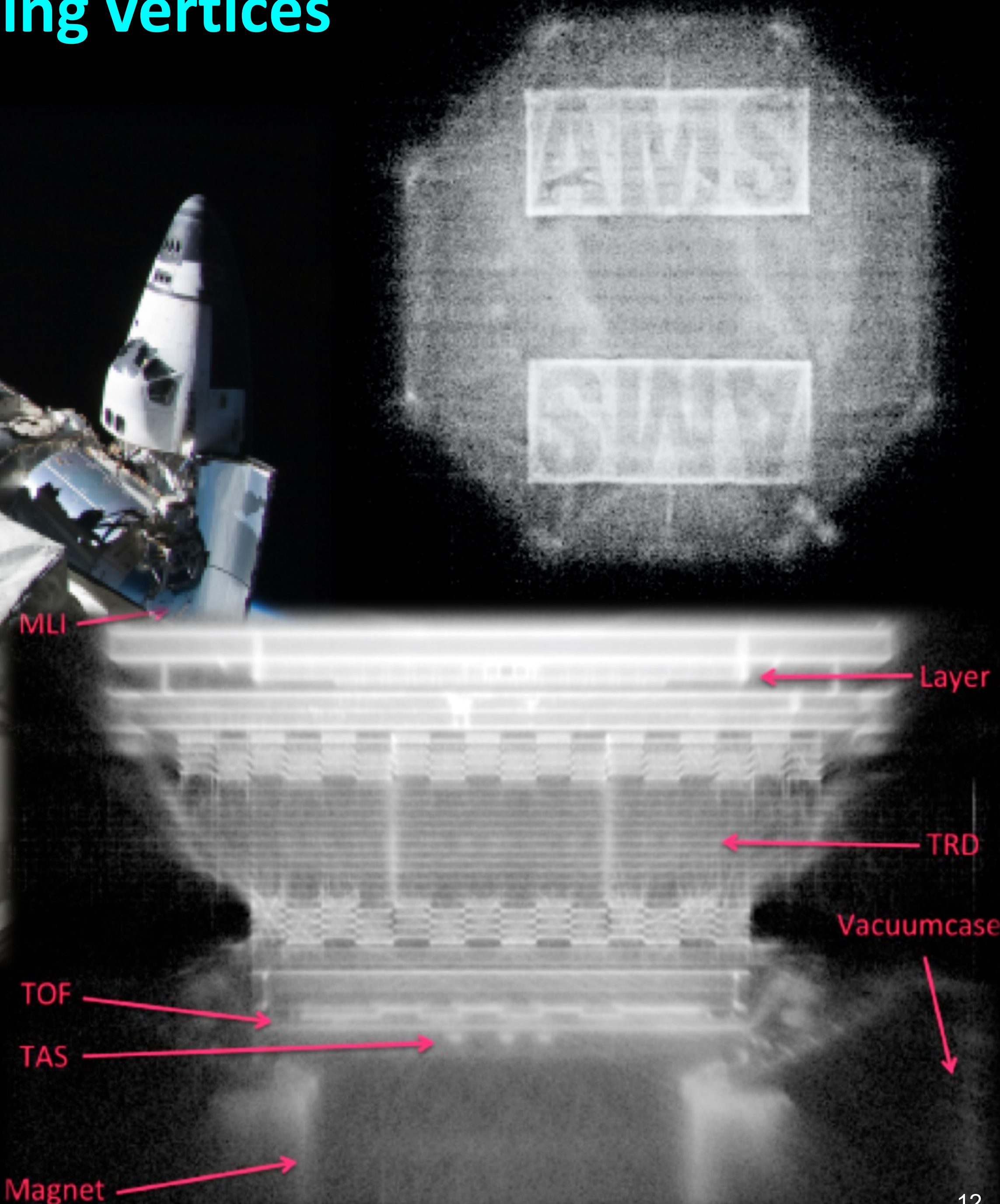


Transition Radiation Detector (TRD) built by RWTH: identifies Positrons and Electrons, rejects protons to <1 in 1000

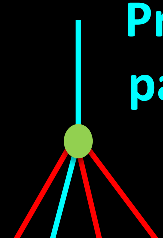




Precision – CAT scan using vertices



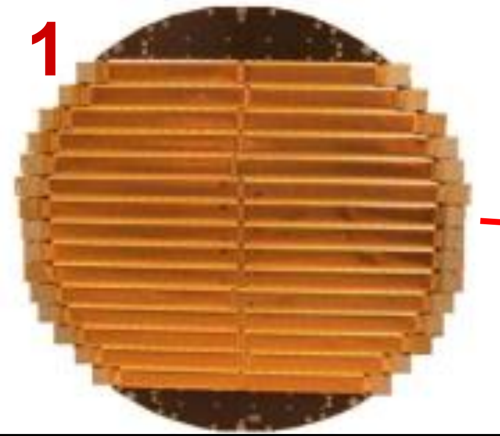
Vertex:

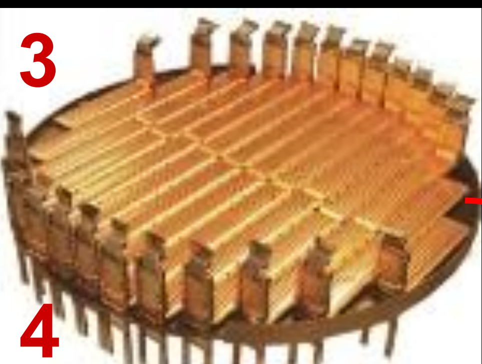


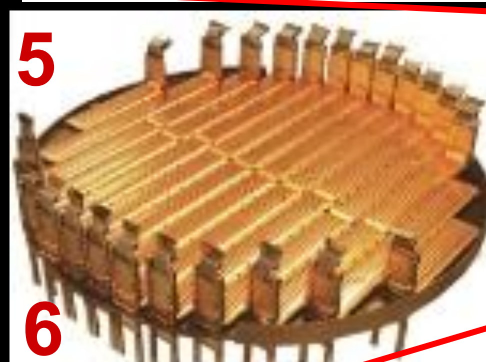
Silicon Tracker

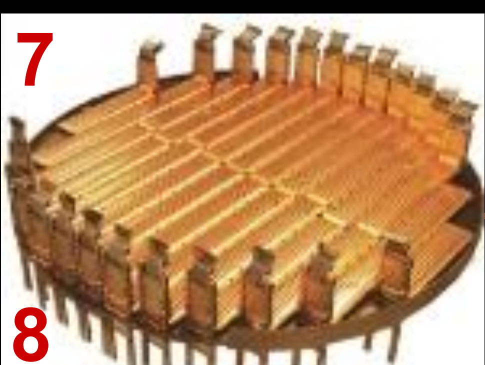
Coordinate resolution 5-10 microns

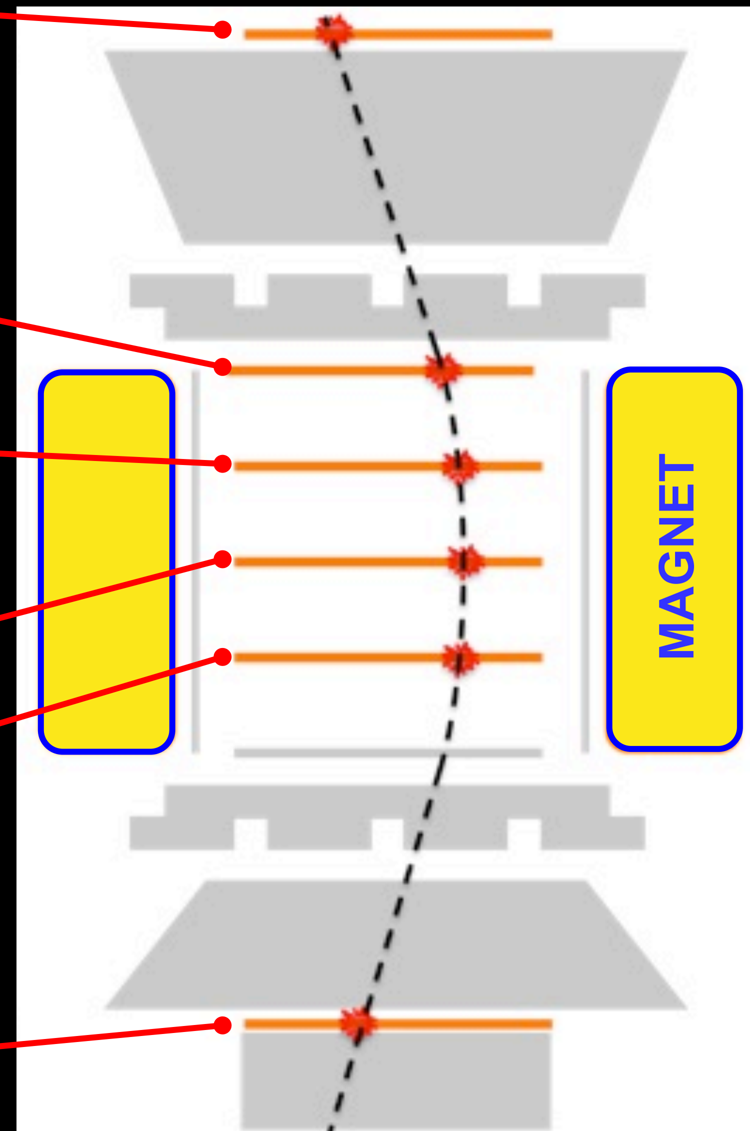
Measure momentum P and nuclear charge Z





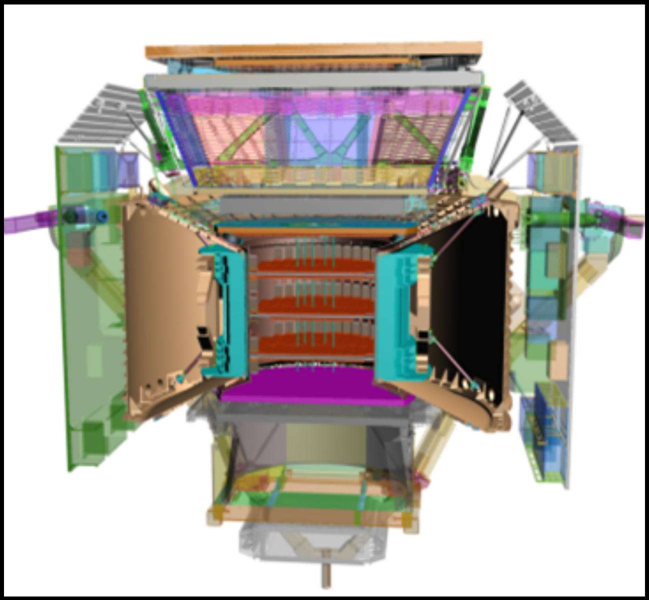




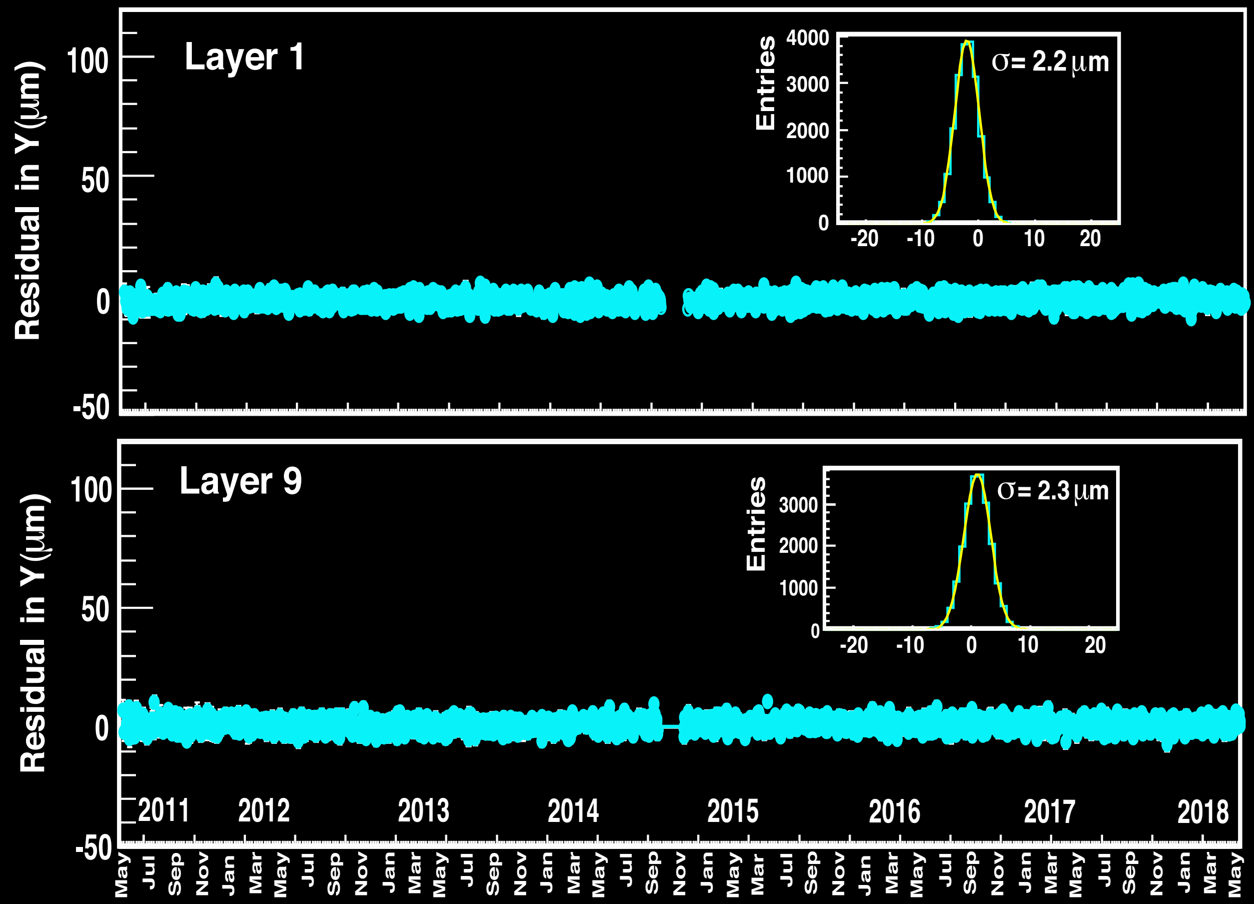


200,000 channels

Tracker stable to 2 microns over eight years



Inner tracker alignment (< 1 micron) monitored with IR lasers

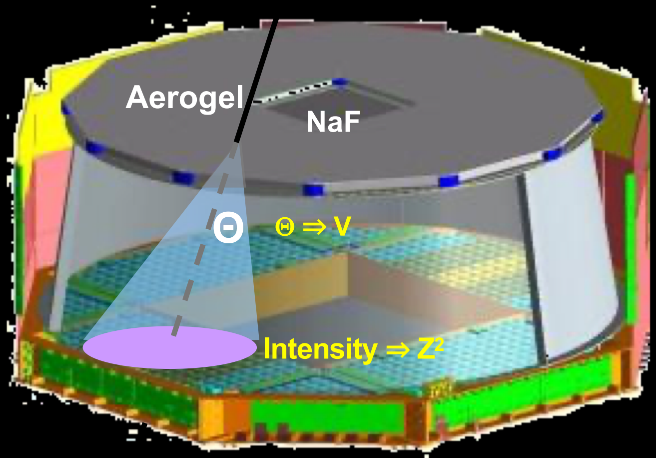


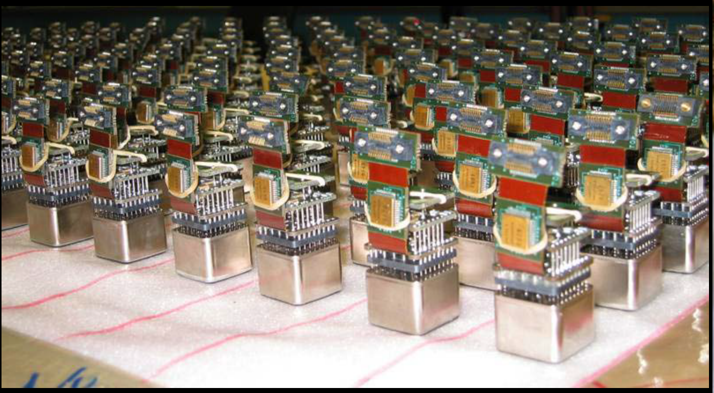
Outer tracker stable to 2 micron over 8 years

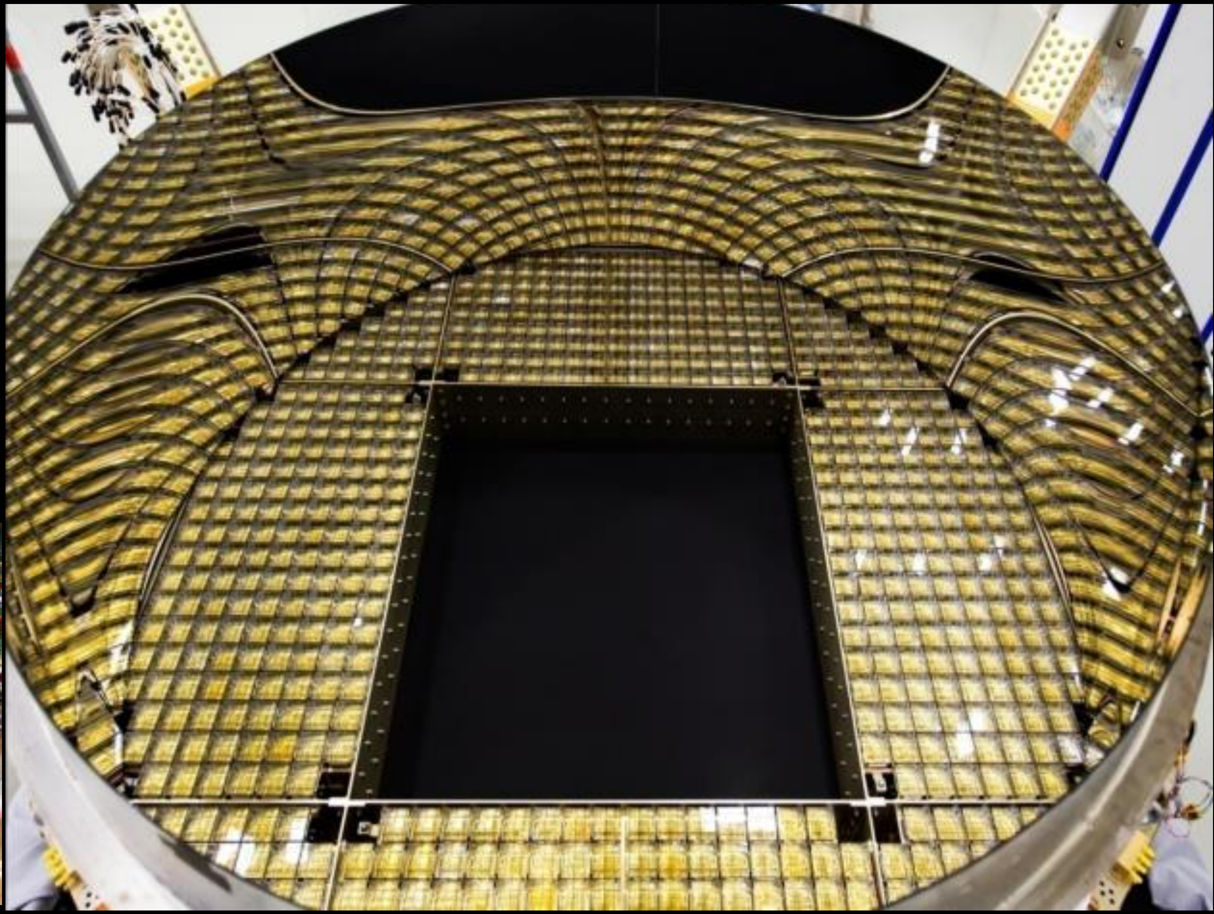
Maximal Detectable Rigidity – 2TV for Z=1 particles

Ring Imaging CHerenkov (RICH)

Measurement of Nuclear Charge and its Velocity to 1/1000

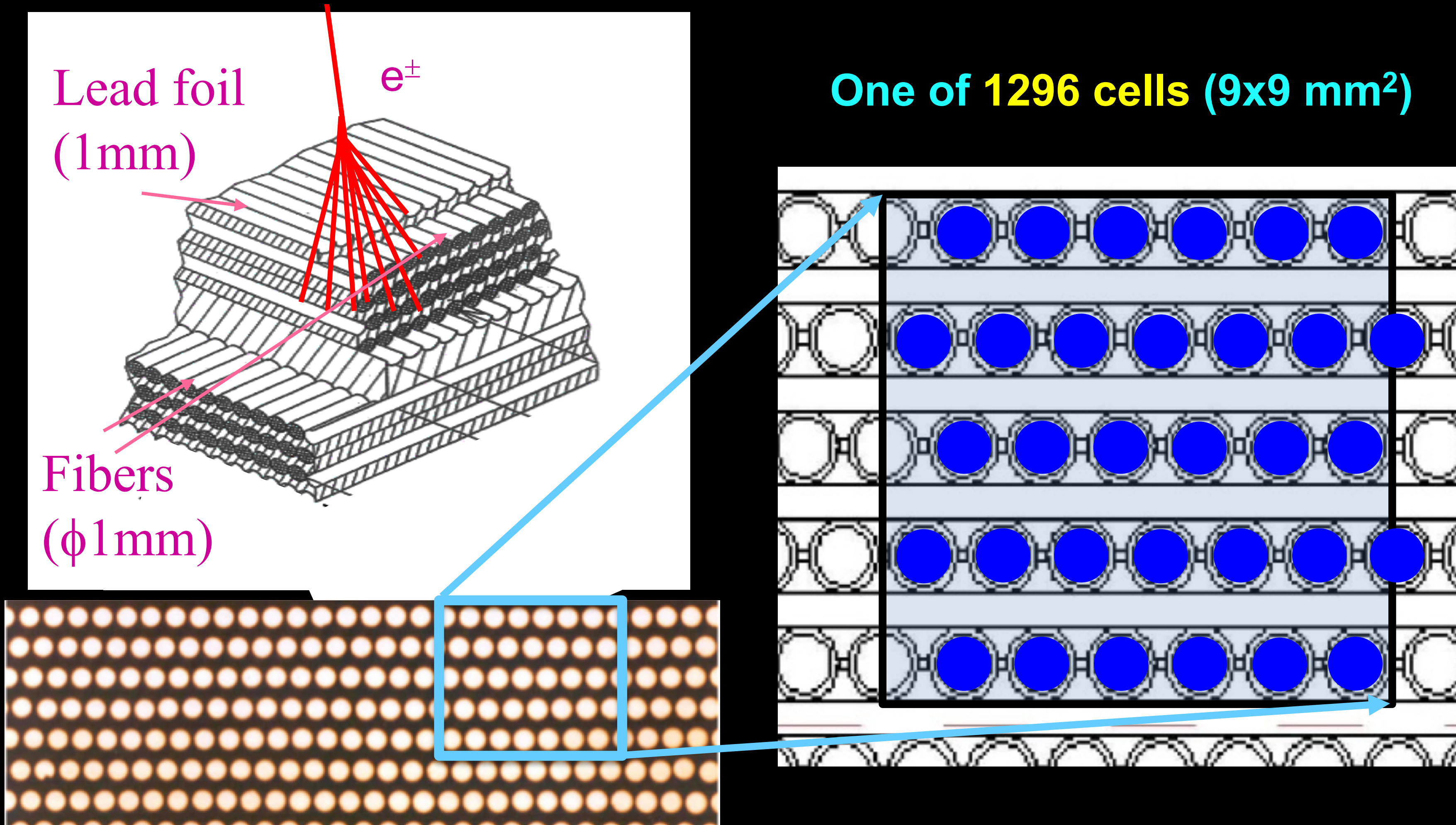






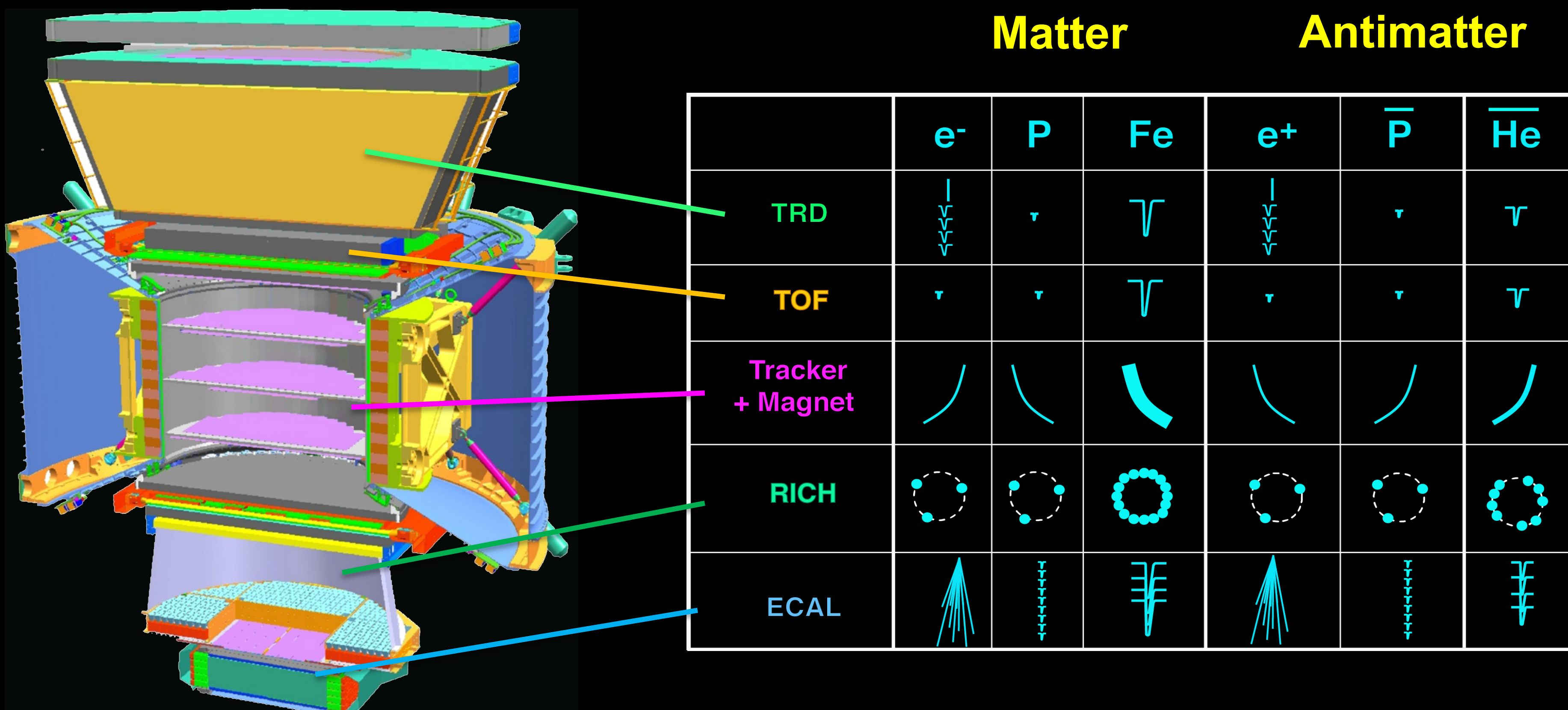
10,880 photosensors

Electromagnetic Calorimeter (ECAL) to measure the highest energy electrons in space with ~2% accuracy



A precision, 17 X_0, TeV, 3-dimensional measurement of the directions and energies of light rays and electrons

AMS is a unique magnetic spectrometer in space

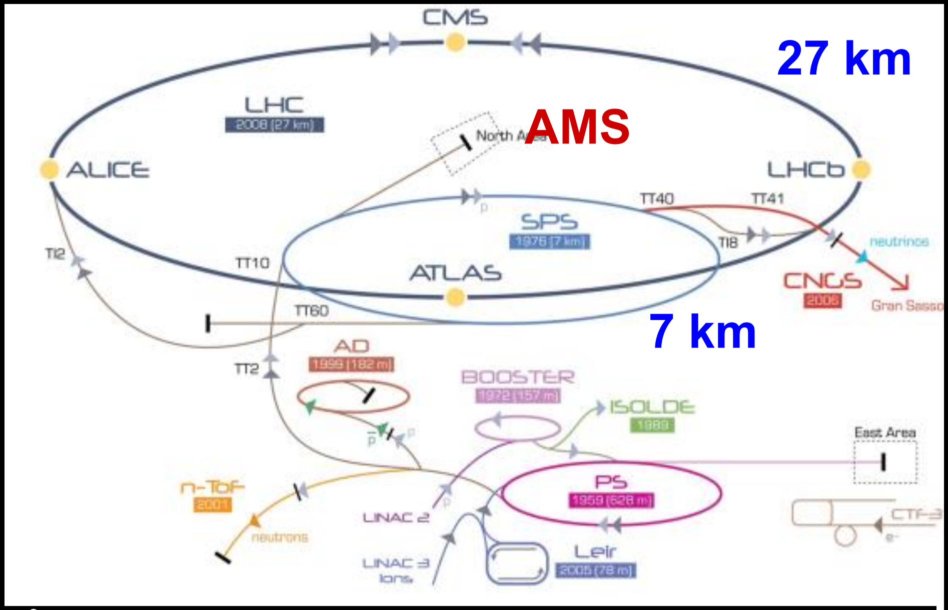


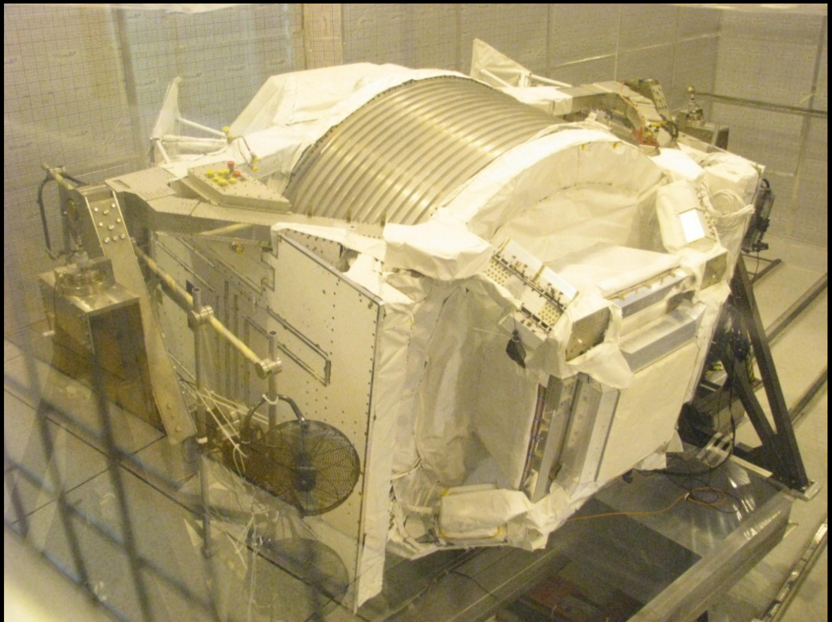
Cosmic rays are defined by:

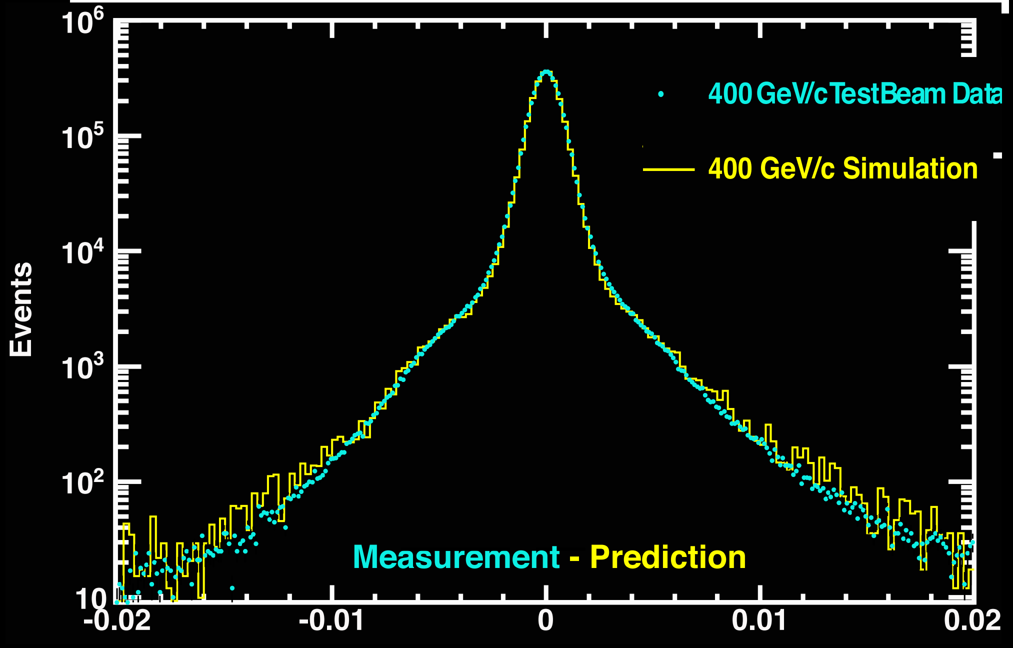
- Energy (E in units of GeV)
- Rigidity (R=p/Z in units of GV)
- Charge (Z - location on the periodic table: H Z=1, He Z=2, …)

Calibration at CERN

with different particles at different energies







May 16, 2011, 08:56 AM

Total weight: 2008 t
AMS weight: 7.5 t

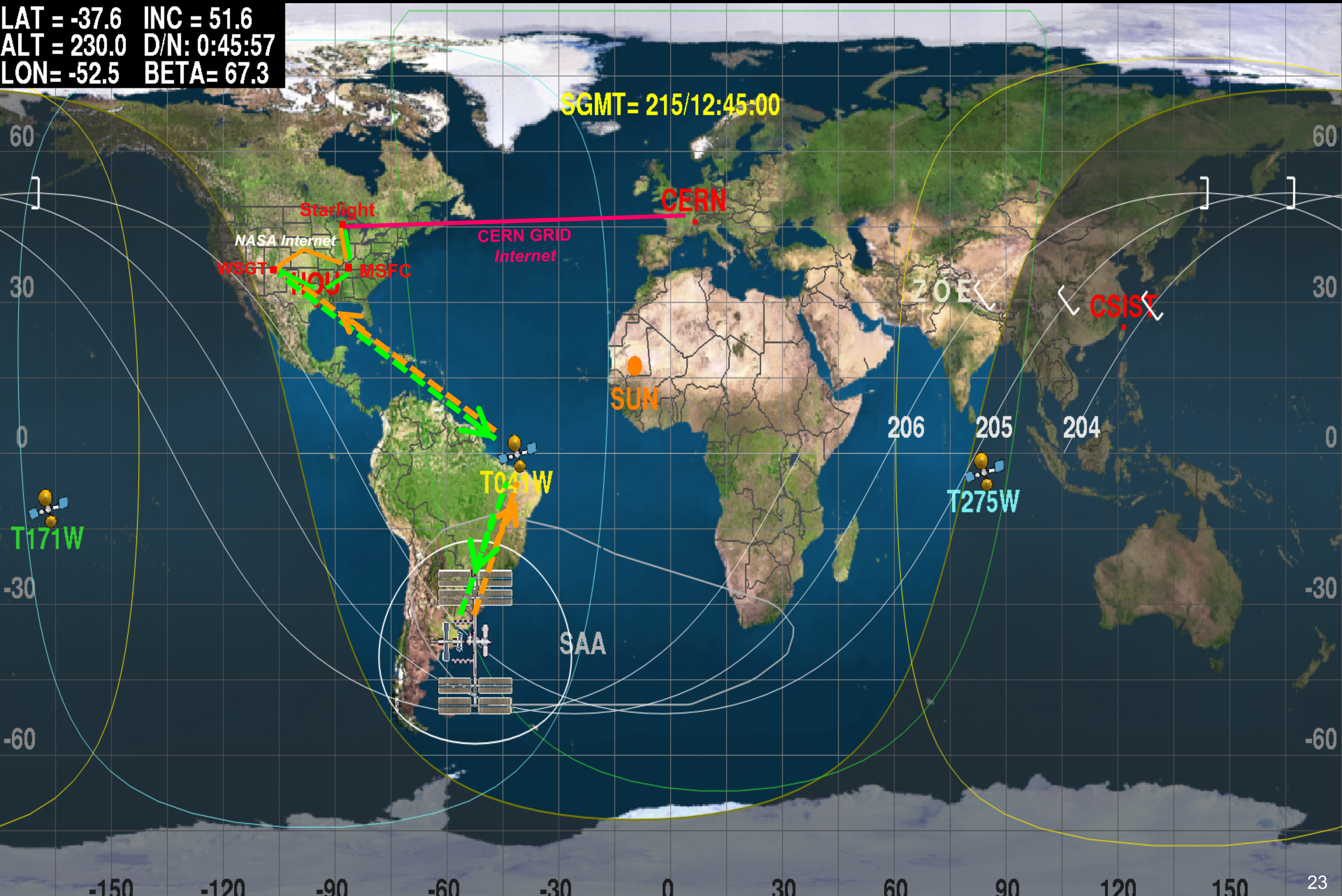
AMS installed on the ISS Truss at 5:15 CDT and taking data since 9:35 CDT May 19, 2011

POCC at CERN in control of AMS since 19 June 2011

Payload Operations and Integration Center, MSFC, Huntsville, AL

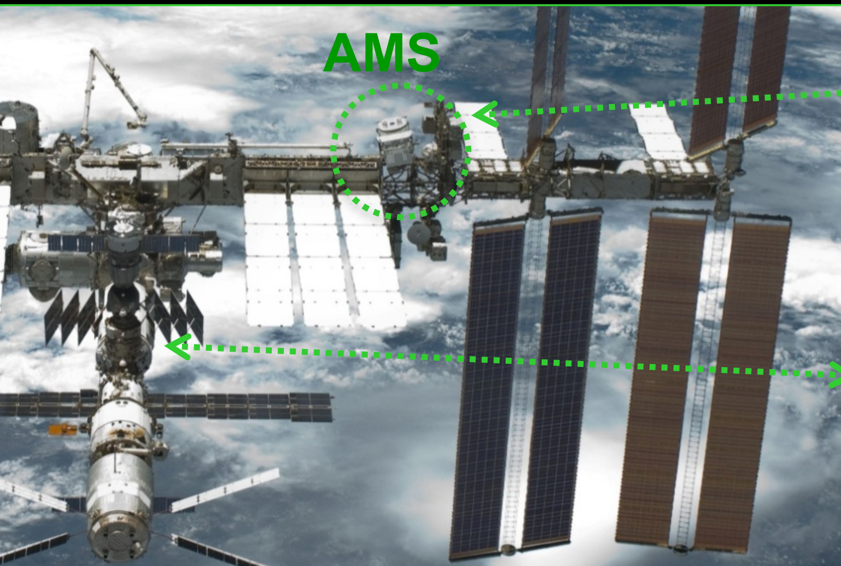
Mission Control Center, JSC, Houston, TX

AMS on ISS



LAT = -37.6 INC = 51.6
ALT = 230.0 D/N: 0:45:57
LON= -52.5 BETA= 67.3
SGMT= 215/12:45:00
CERN
Starlight
NASA Internet
WSGT
MSFC
CERN GRID
Internet
ZOE
CSIST
SUN
206
205
204
T041W
T275W
T171W
SAA
60
30
0
-30
-60
-150
-120
-90
-60
-30
0
30
60
90
120
150

AMS Operations



Flight Operations

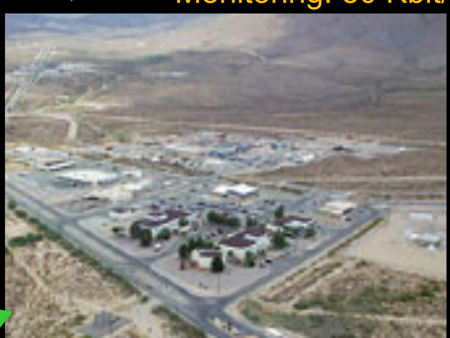
Ku-Band
High Rate (down):
Events <10Mbit/s>

Ground Operations

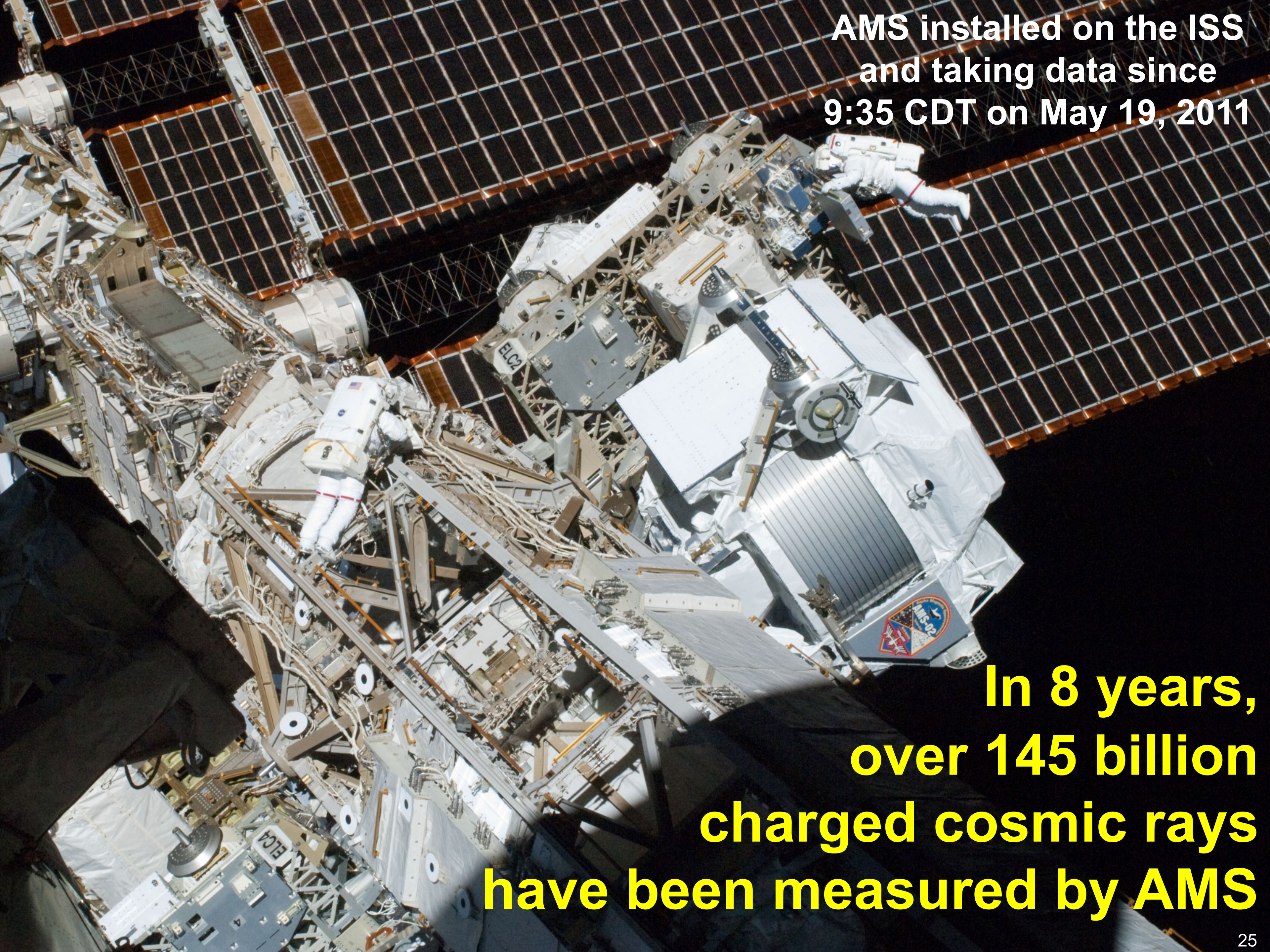
S-Band
Low Rate (up & down):
Commanding: 1 Kbit/s
Monitoring: 30 Kbit/s

AMS Payload Operations Control and Science Operations Centers (POCC, SOC) at CERN

AMS Computers



White Sands Ground Terminal, NM

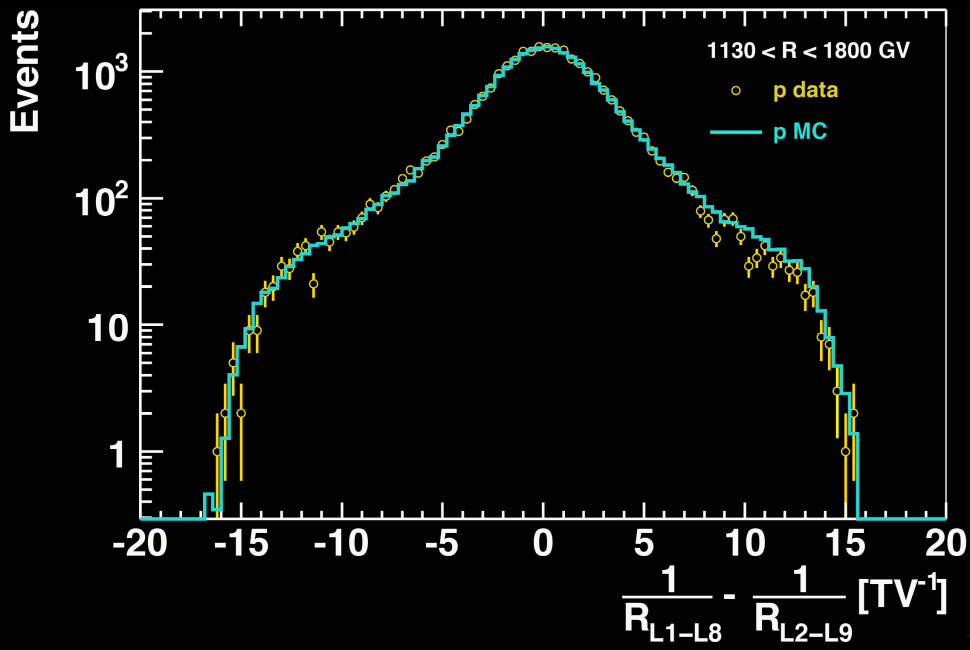


AMS installed on the ISS and taking data since 9:35 CDT on May 19, 2011

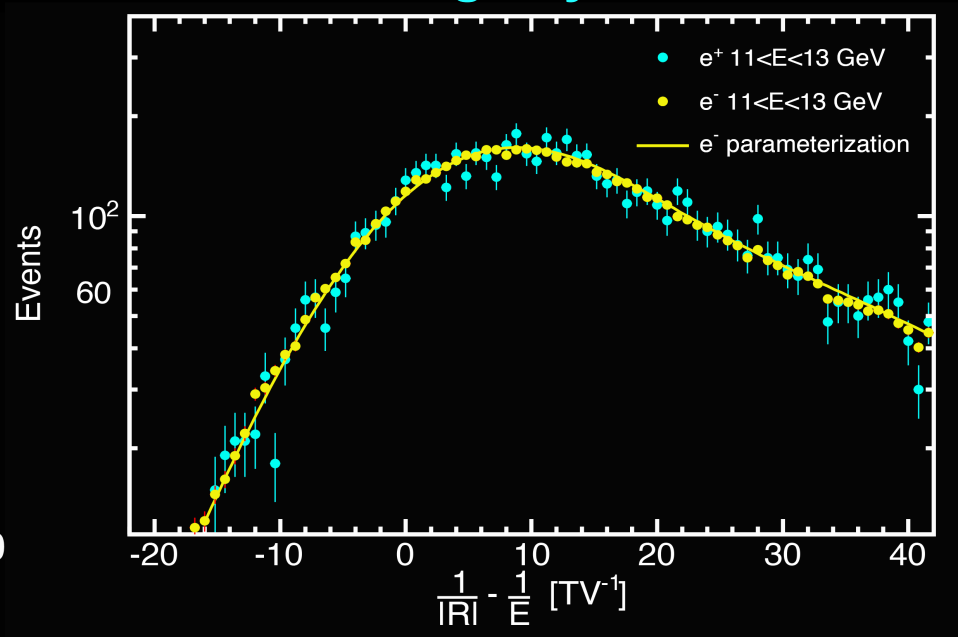
In 8 years, over 145 billion charged cosmic rays have been measured by AMS

Unique properties of AMS:

Measurements above test beam rigidity

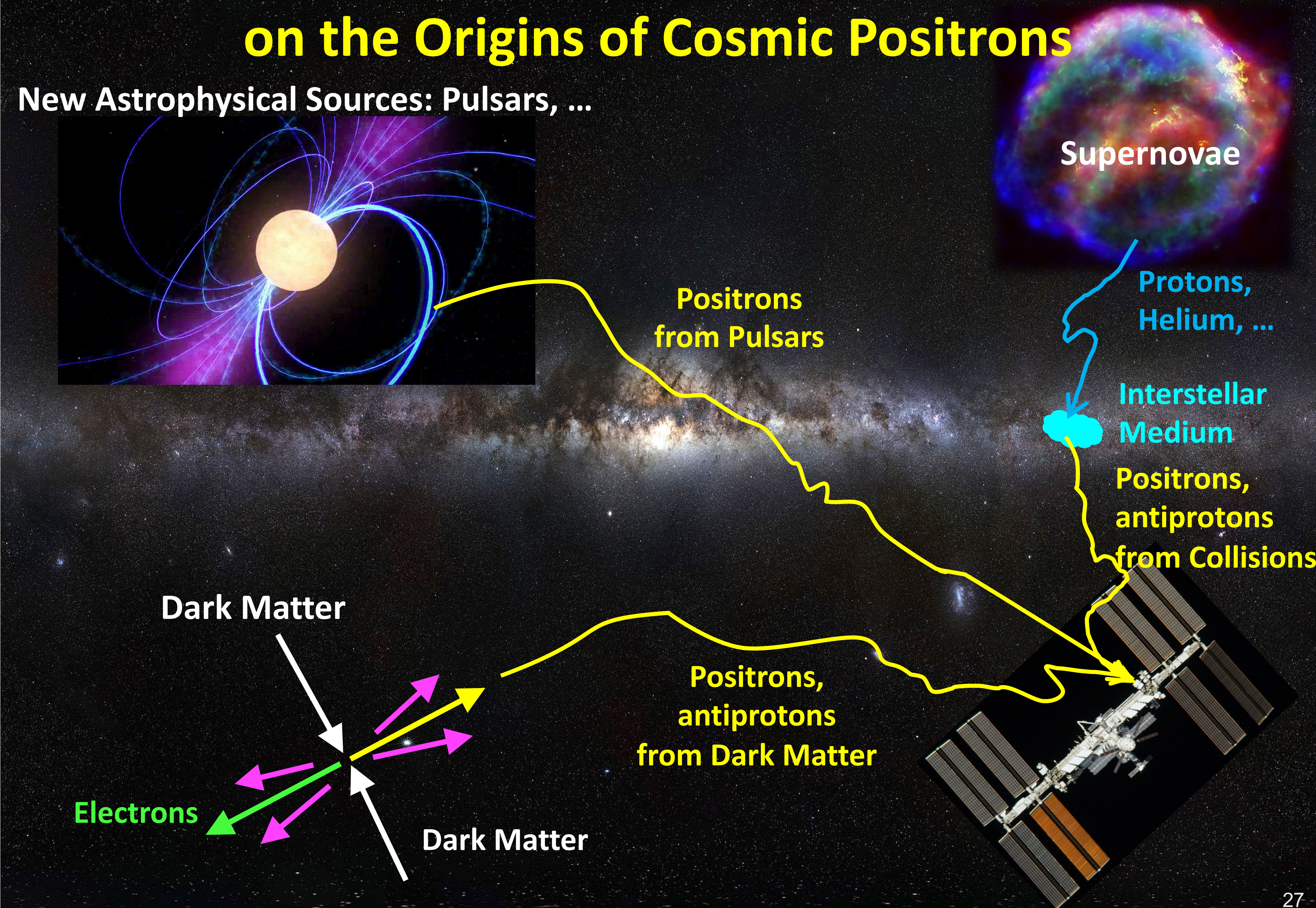


Accuracy of the rigidity scale

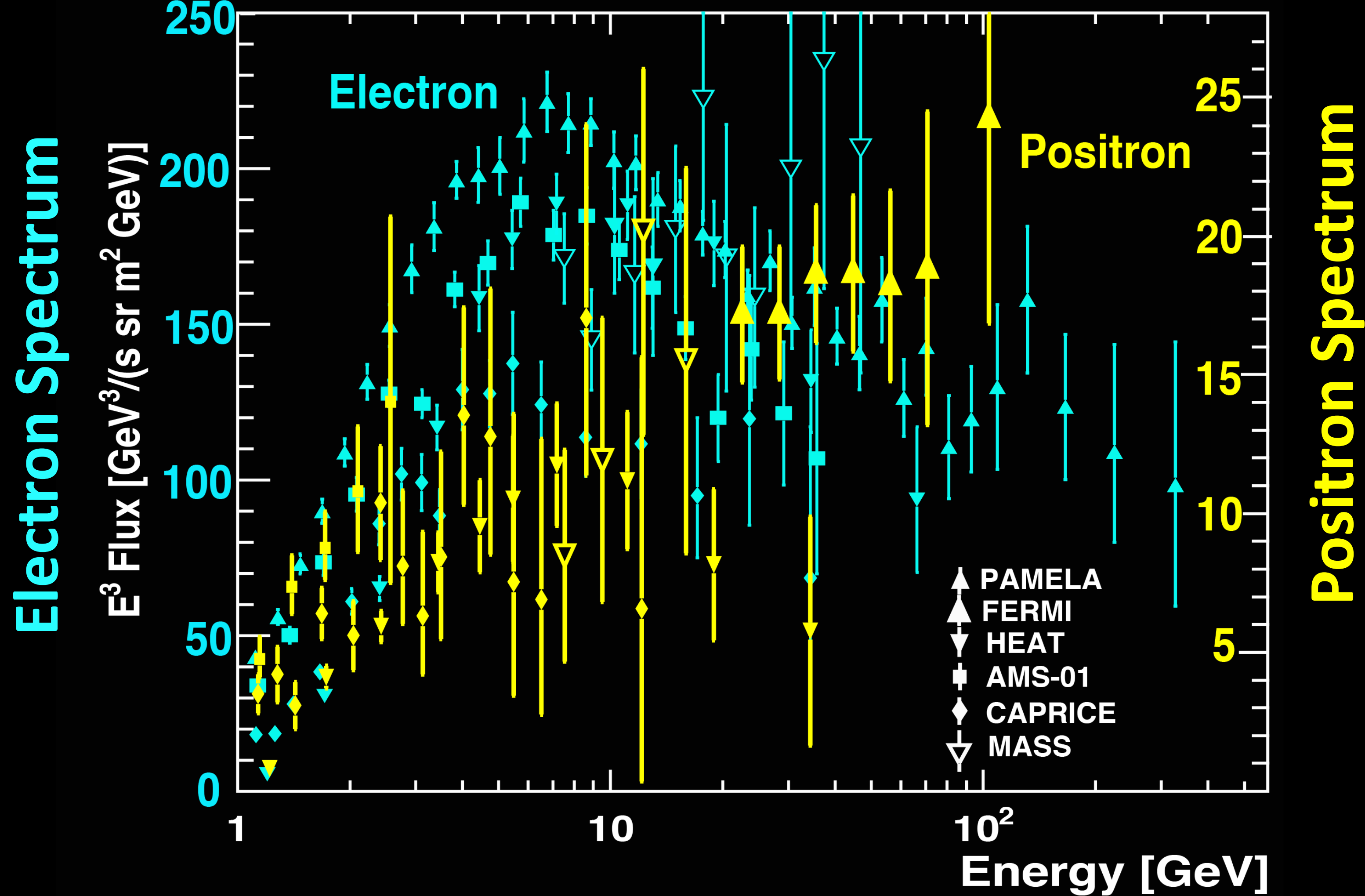


The accuracy of the rigidity scale is found to be 0.033 TV^{-1}, limited mostly by available positron statistics.

AMS Physics Results: on the Origins of Cosmic Positrons



Cosmic Electron and Positron spectra before AMS

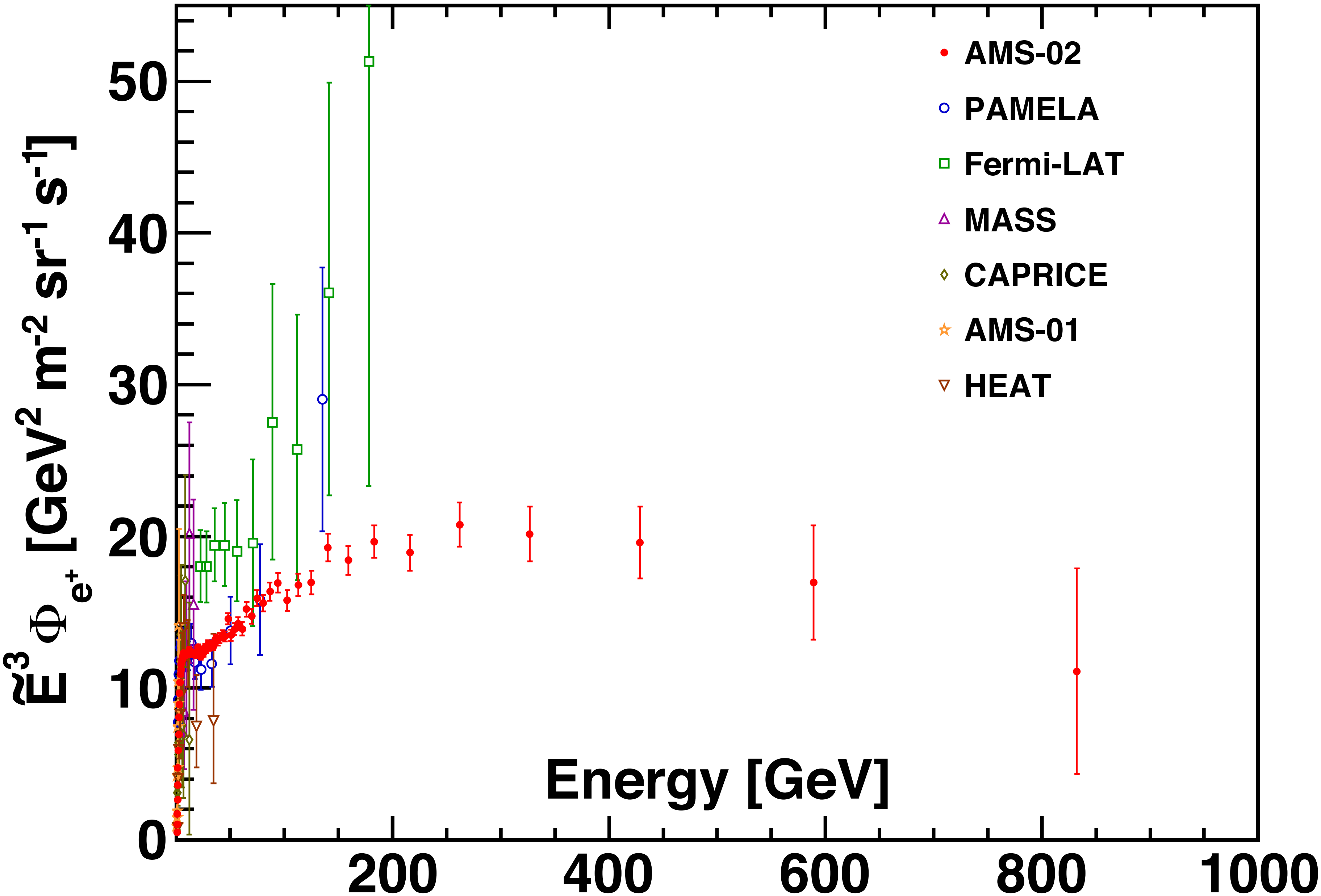


The data have created many theoretical speculations.

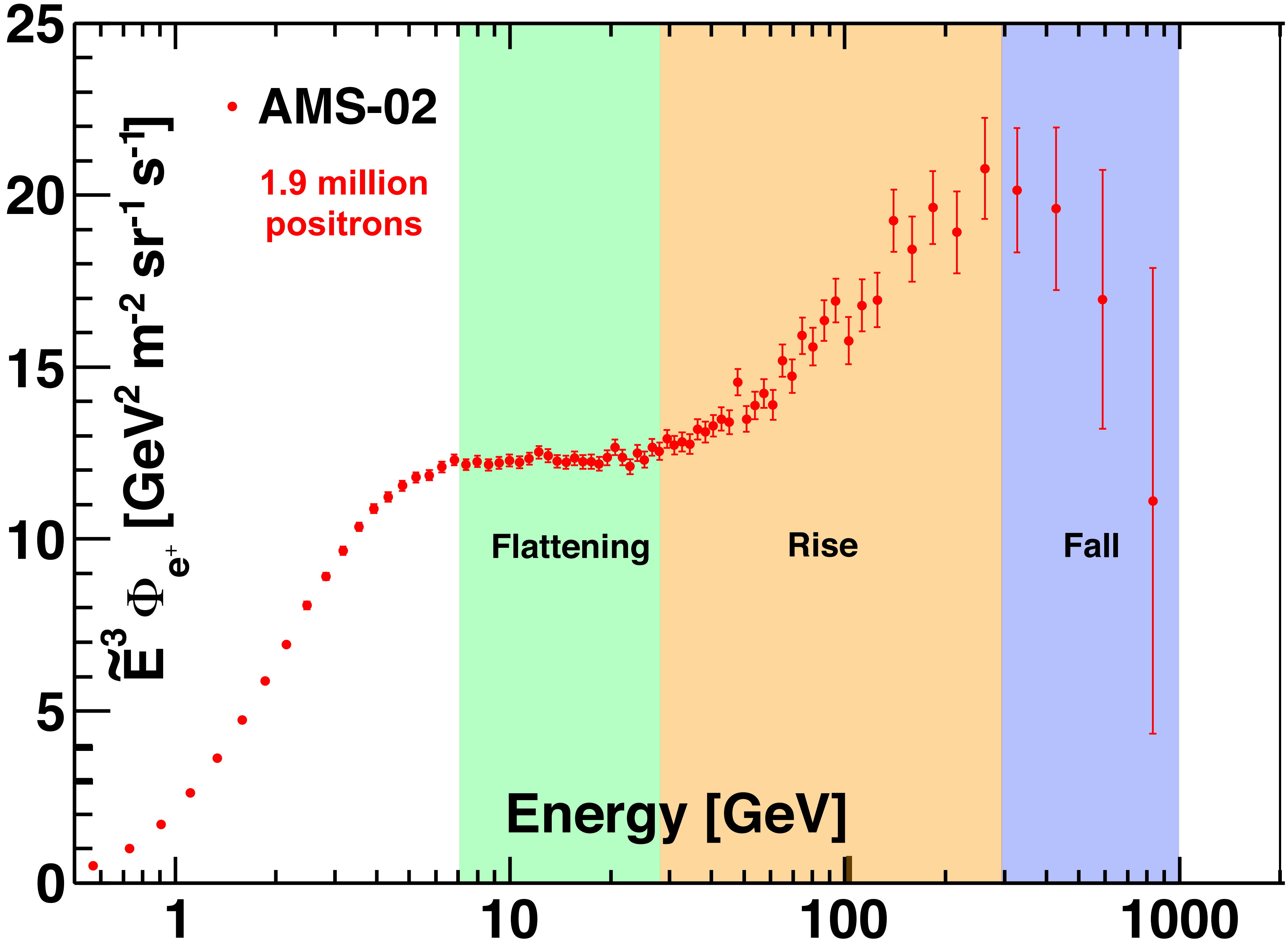
Standard assumption was (PDG):

Flux = C · (Energy)$^\gamma$ γ is the Spectral Index

Comparison with other recent measurements



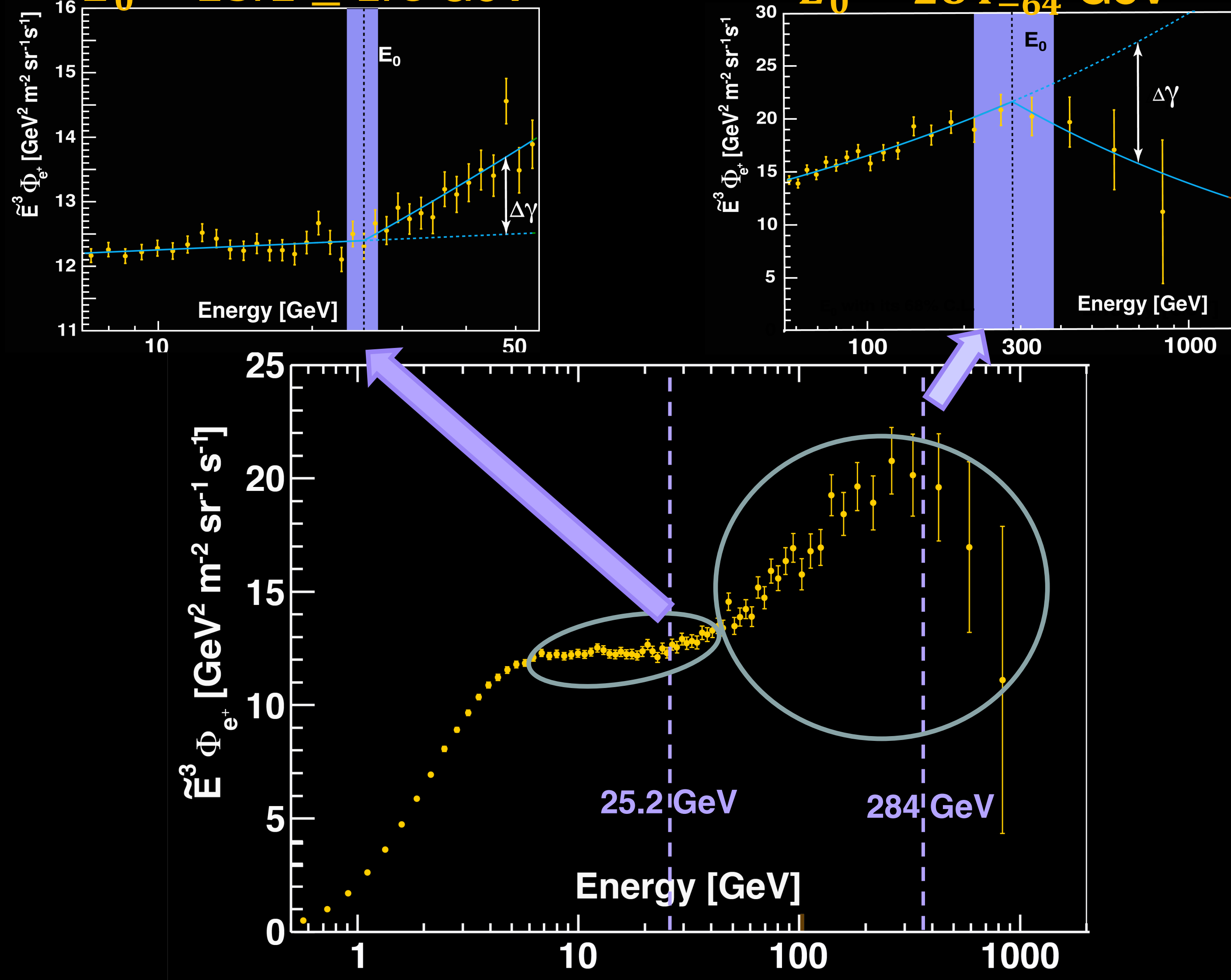
Towards understanding the origin of cosmic ray positrons



Fits of the data to $\Phi_{e^+}(E) = \begin{cases} CE^{\gamma}, & E \le E_0; \\ CE^{\gamma}(E/E_0)^{\Delta\gamma}, & E > E_0. \end{cases}$

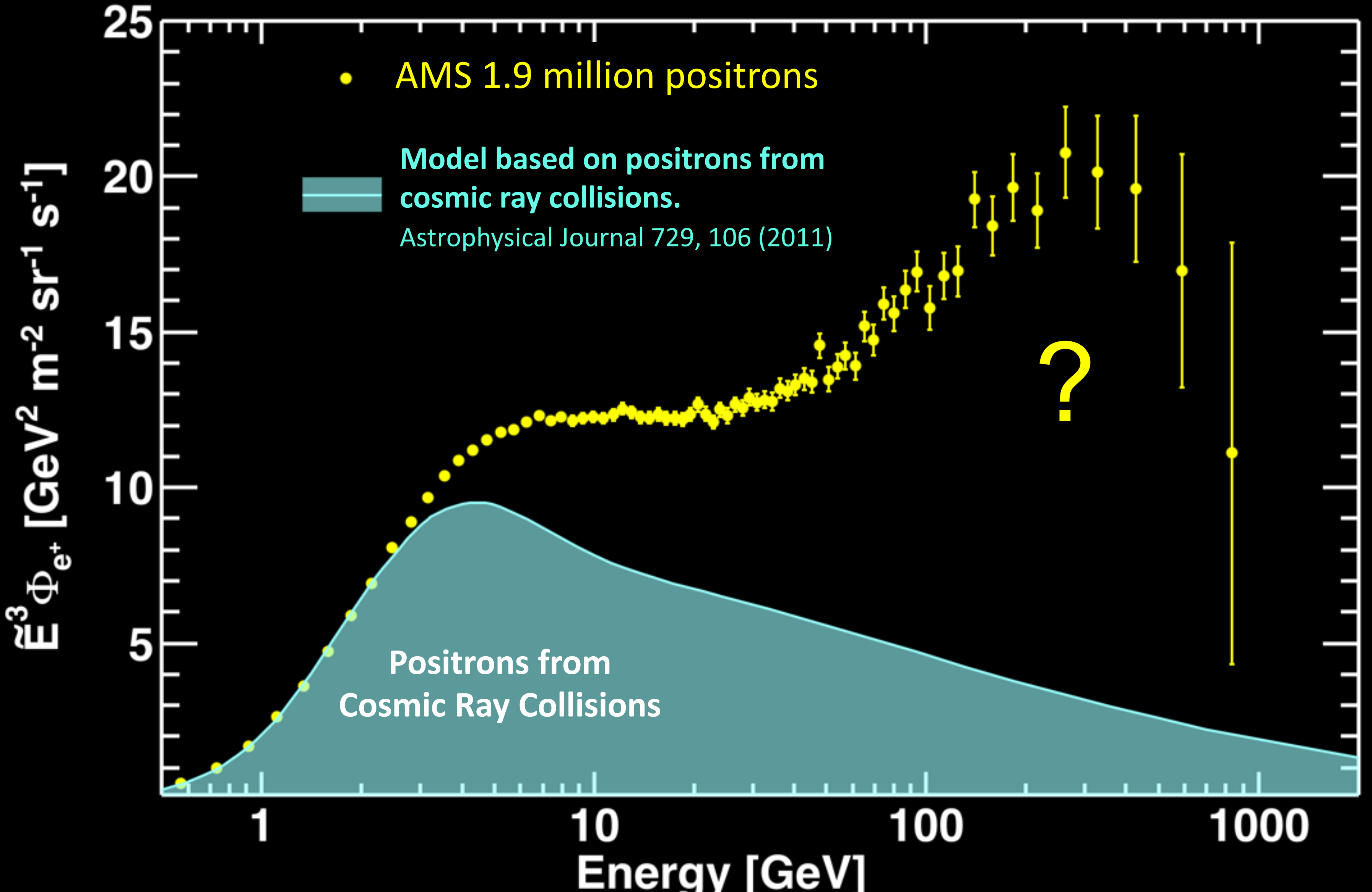
(a) An excess above $E_0 = 25.2 \pm 1.8$ GeV

(b) A sharp drop-off at $E_0 = 284^{+91}_{-64}$ GeV



The Origin of Positrons

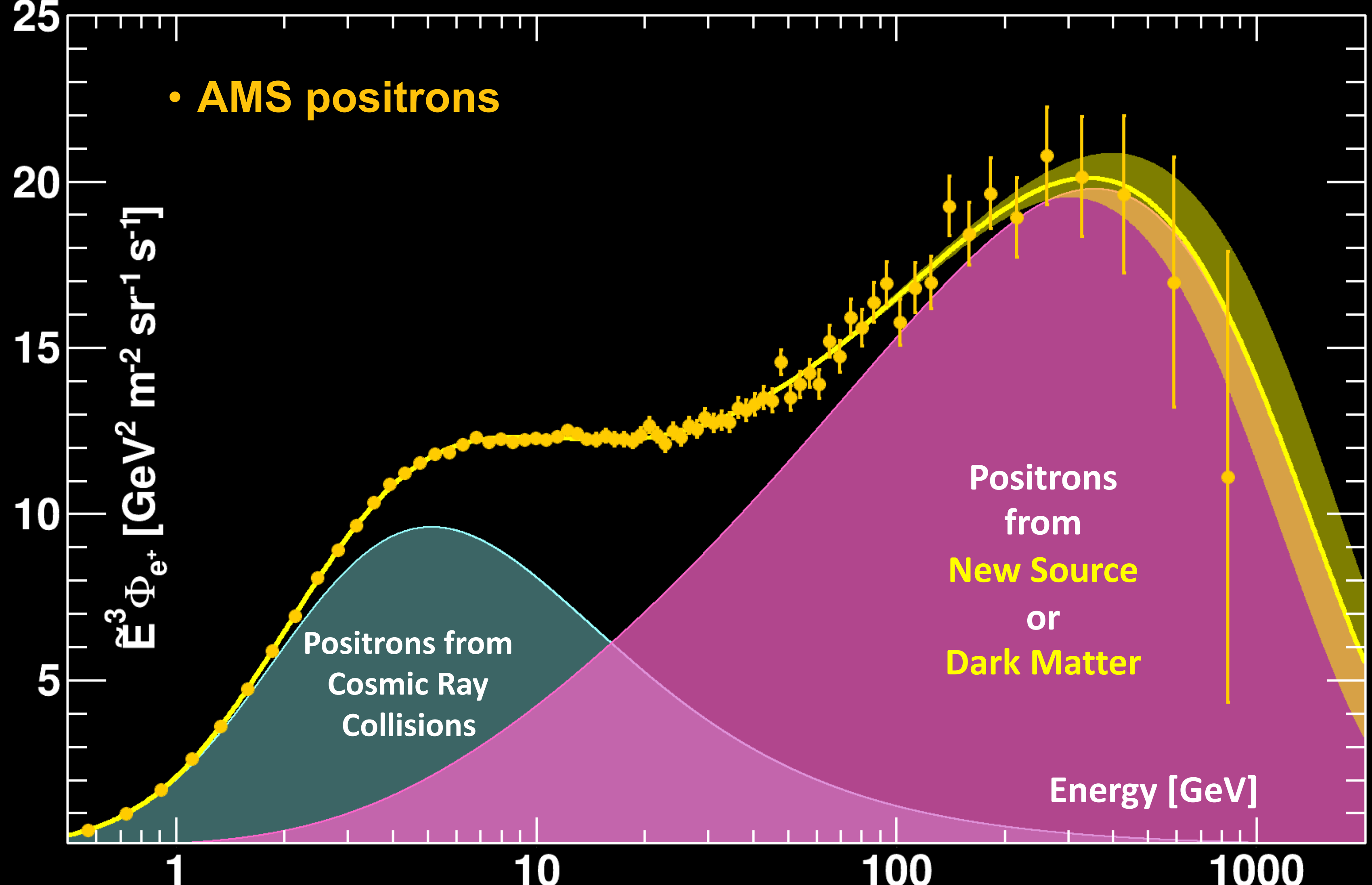
Low energy positrons mostly come from cosmic ray collisions



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.

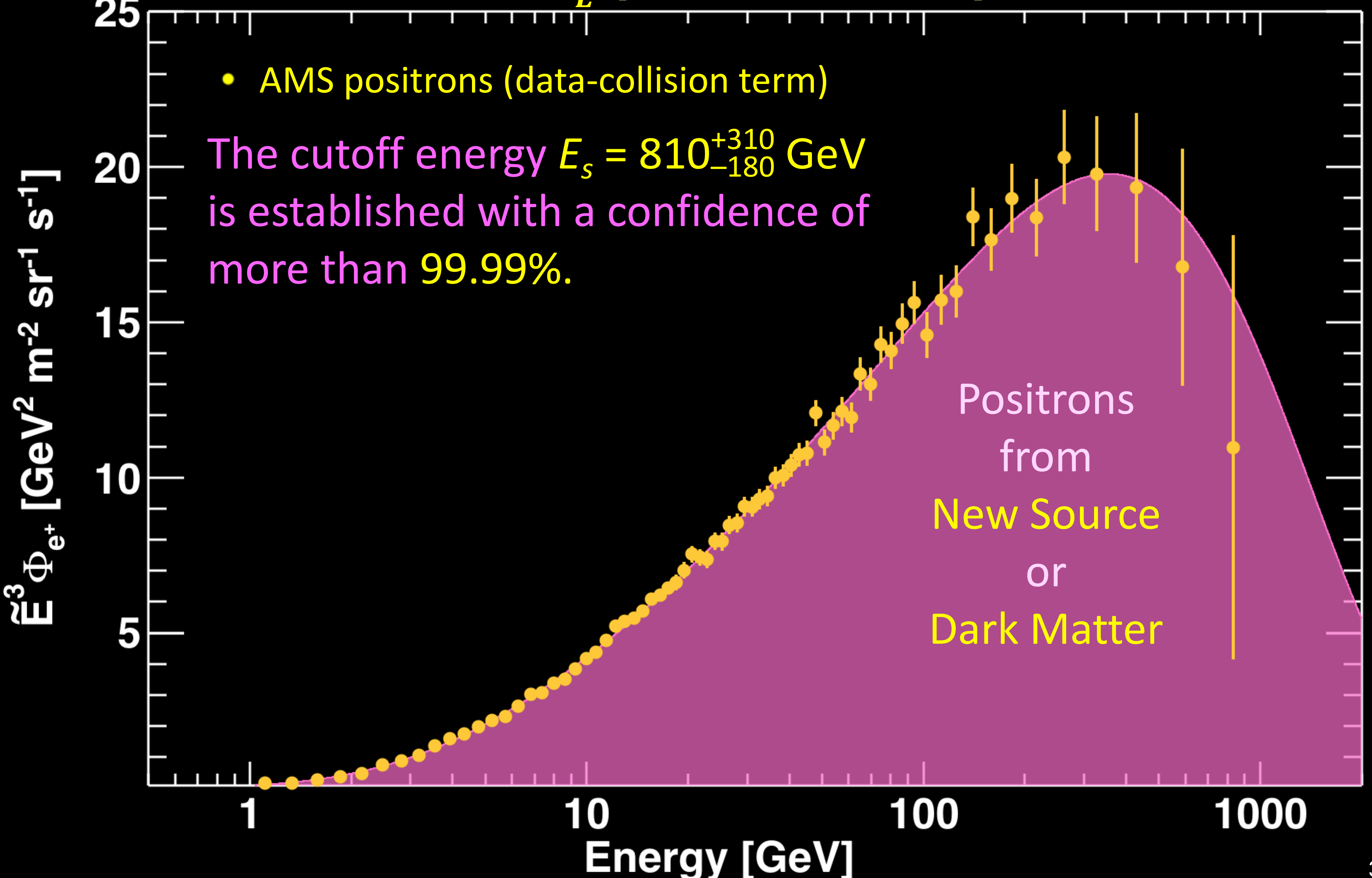
Collisions — New Source or Dark Matter

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



At high energies positrons come from
dark matter or new astrophysical sources with a cutoff energy E_s.

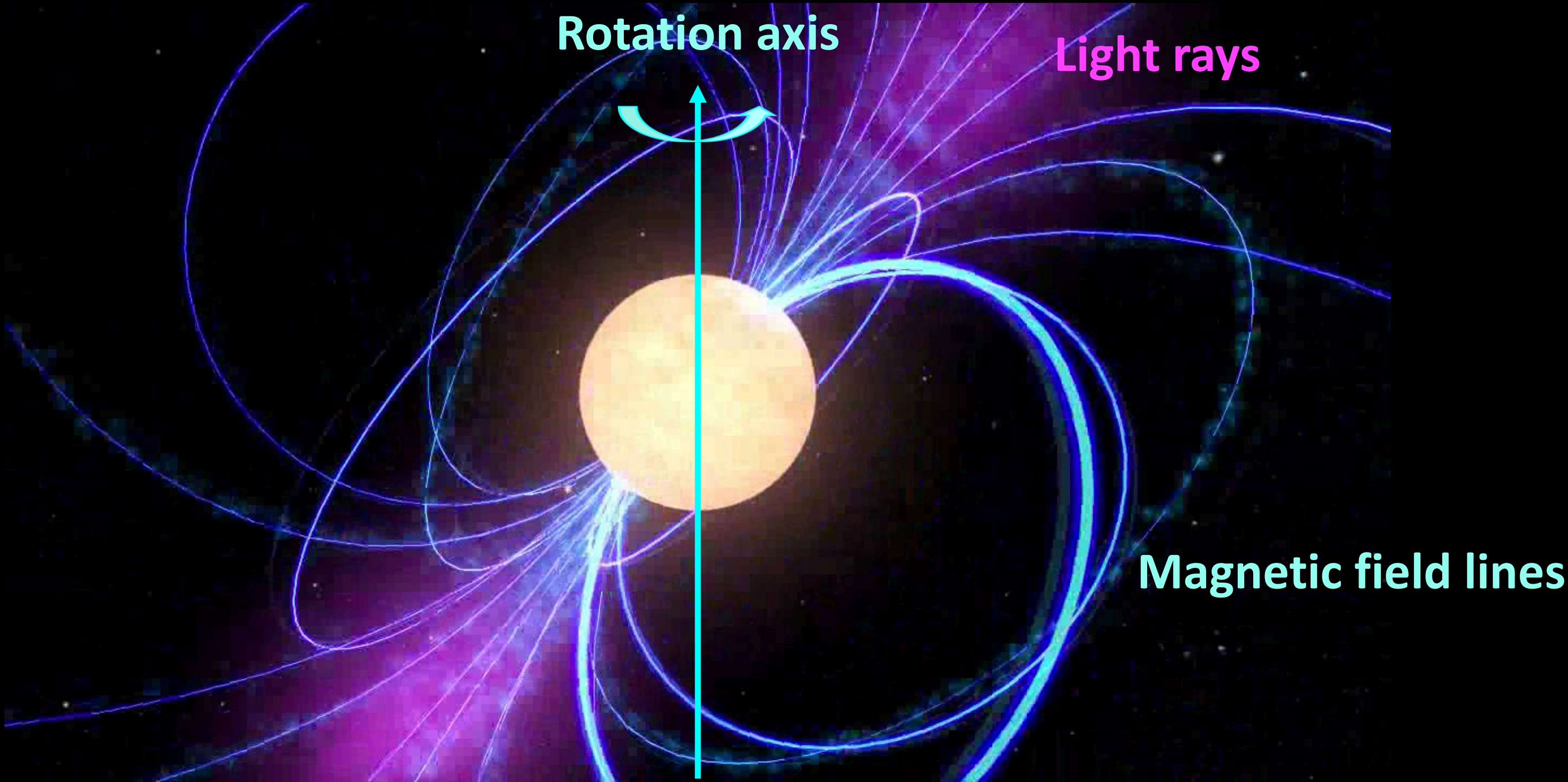
$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_s(\hat{E}/E_2)^{\gamma_s} \exp(-\hat{E}/E_s) \right]$$



Positrons from Pulsars

1. Pulsars produce and accelerate positrons to high energies without a sharp cutoff.

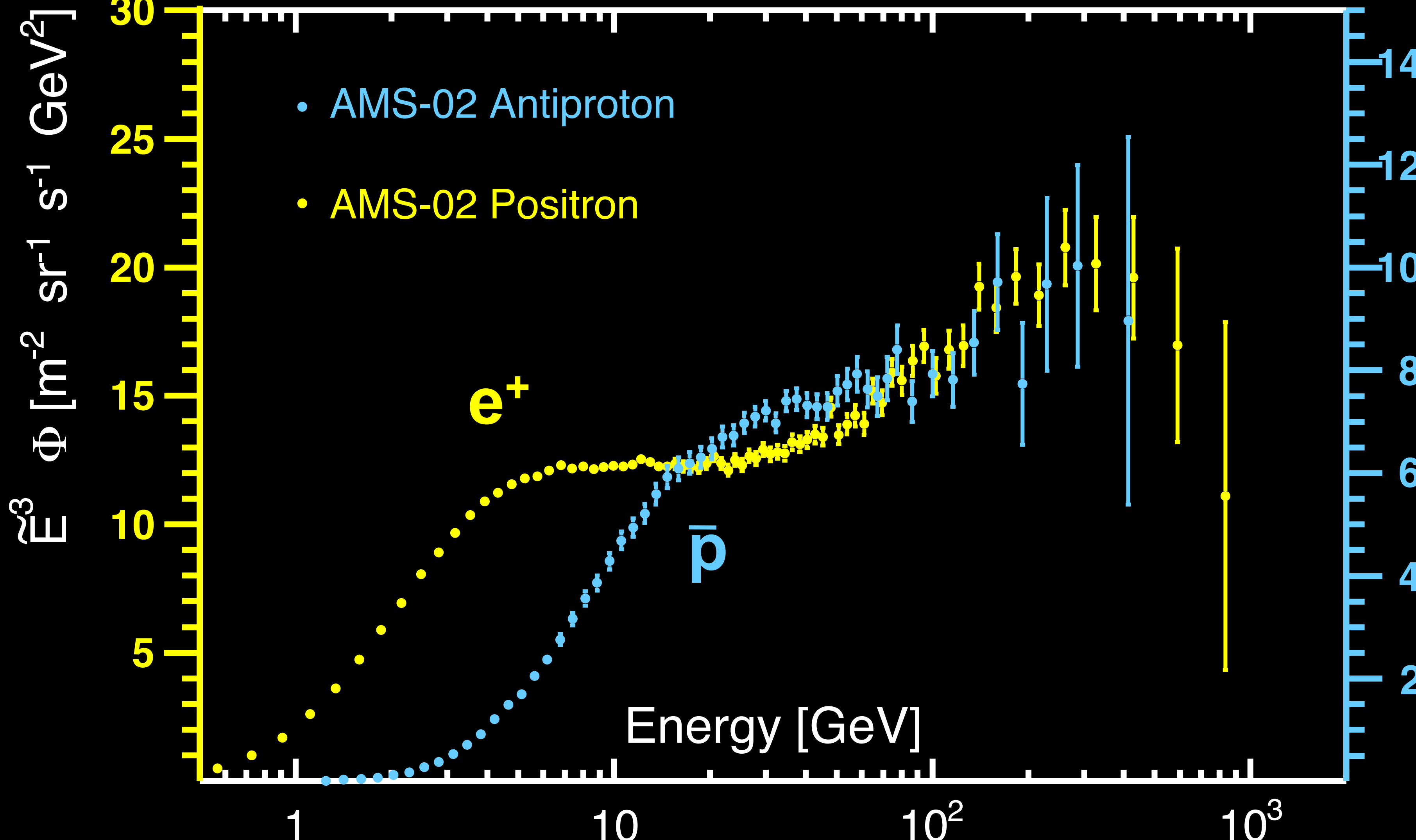
2. Pulsars do not produce antiprotons.



AMS Physics Results:

Antiproton data show a similar trend as positrons.

Antiprotons cannot come from pulsars.

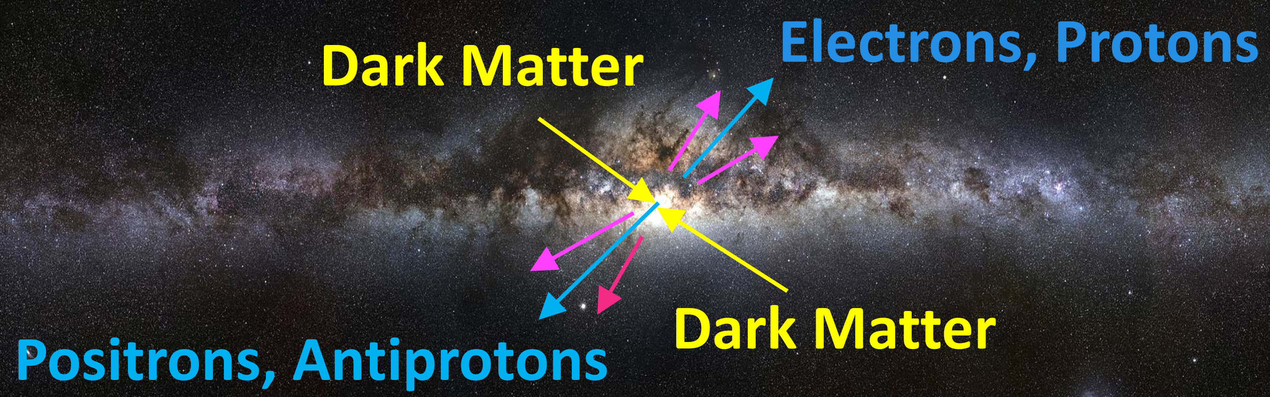


Dark Matter

Collision of Dark Matter produces positrons and antiprotons.

Dark Matter particle have mass *M* and they move slowly.

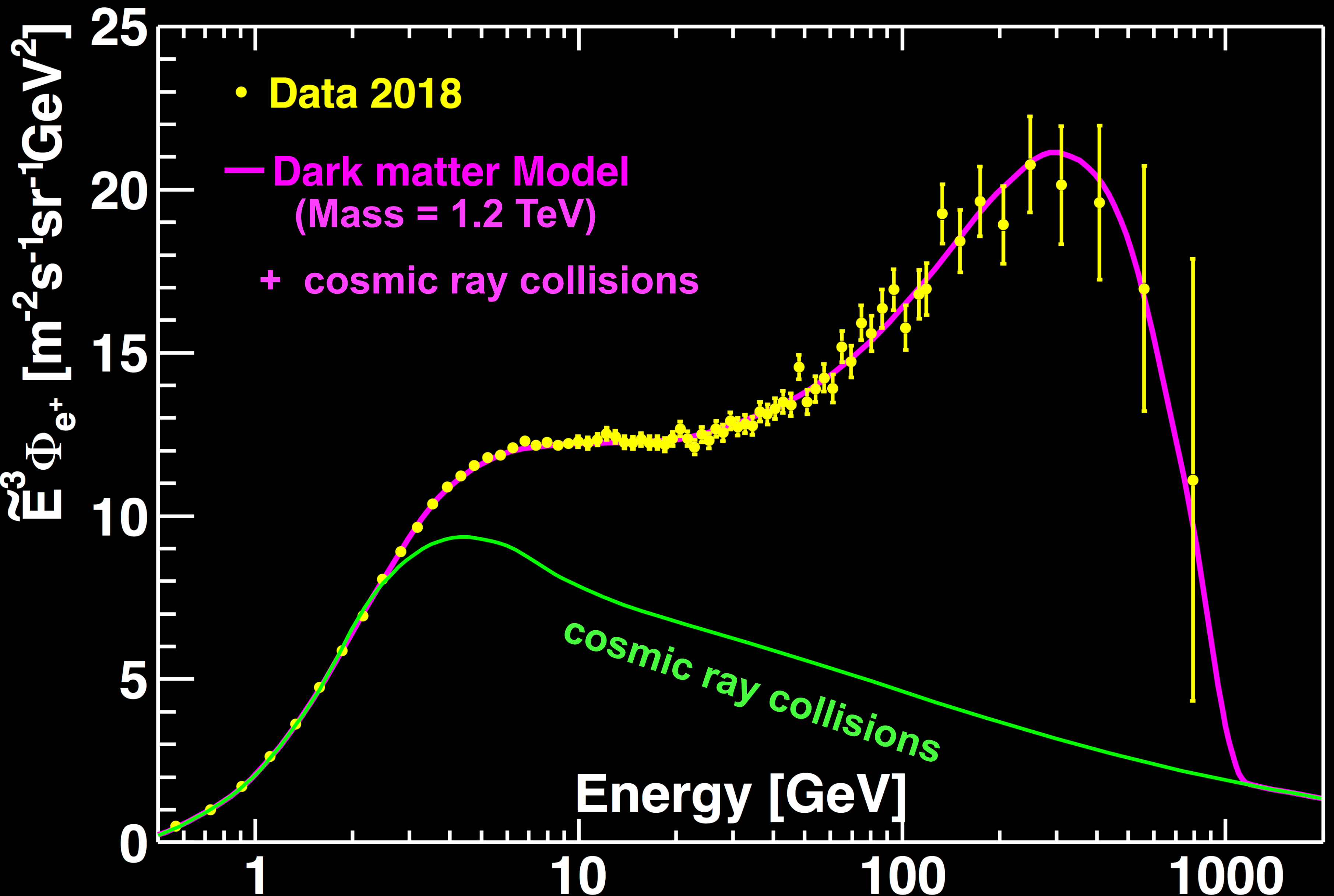
Before collision the total energy ≈ 2*M*.



The conservation of energy and momentum requires that the positron or antiproton energy must be smaller than *M*.

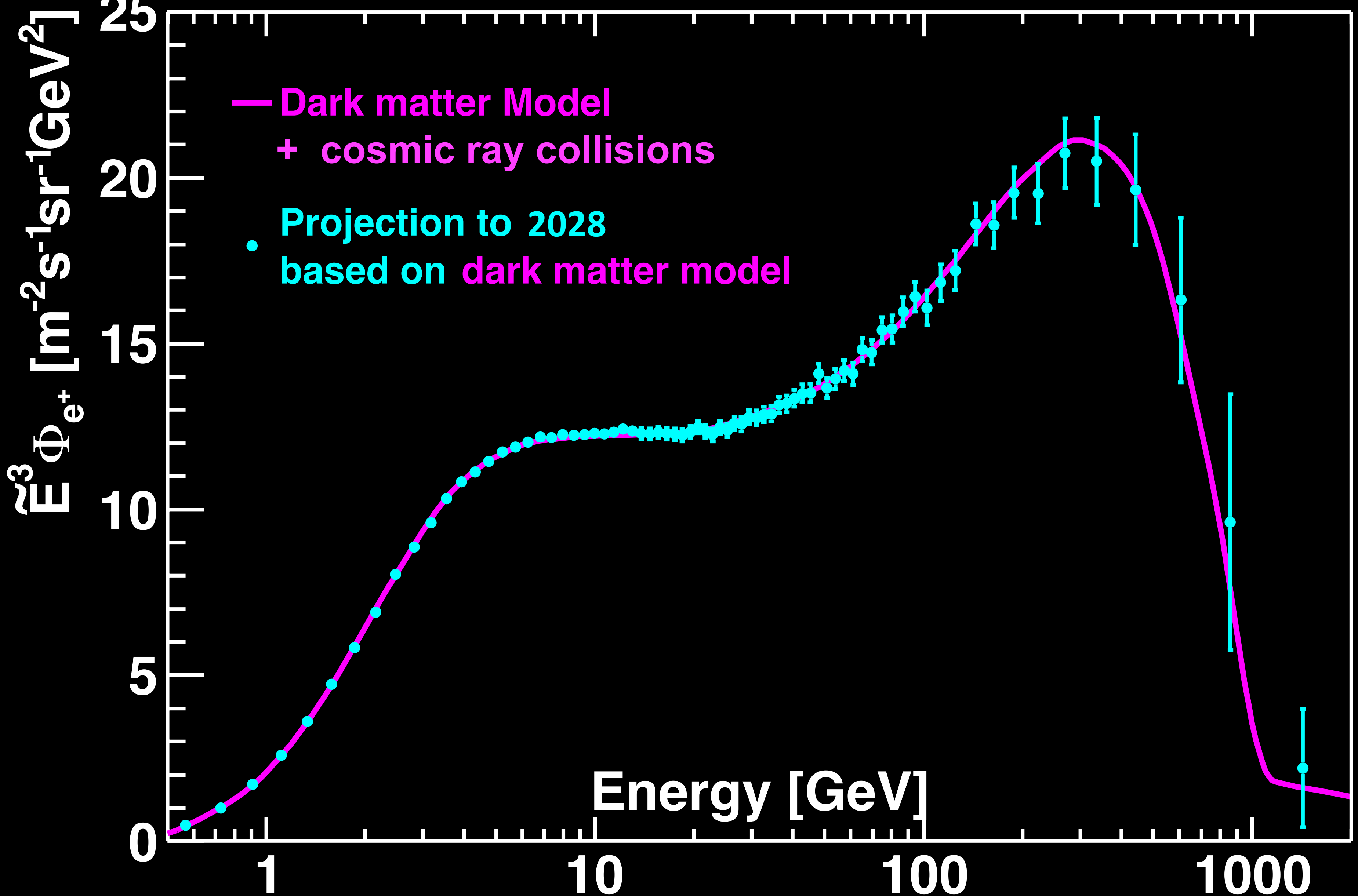
So, there is a sharp cutoff in the spectra at *M*.

Positrons and Dark Matter 2018



Positrons and Dark Matter by 2028

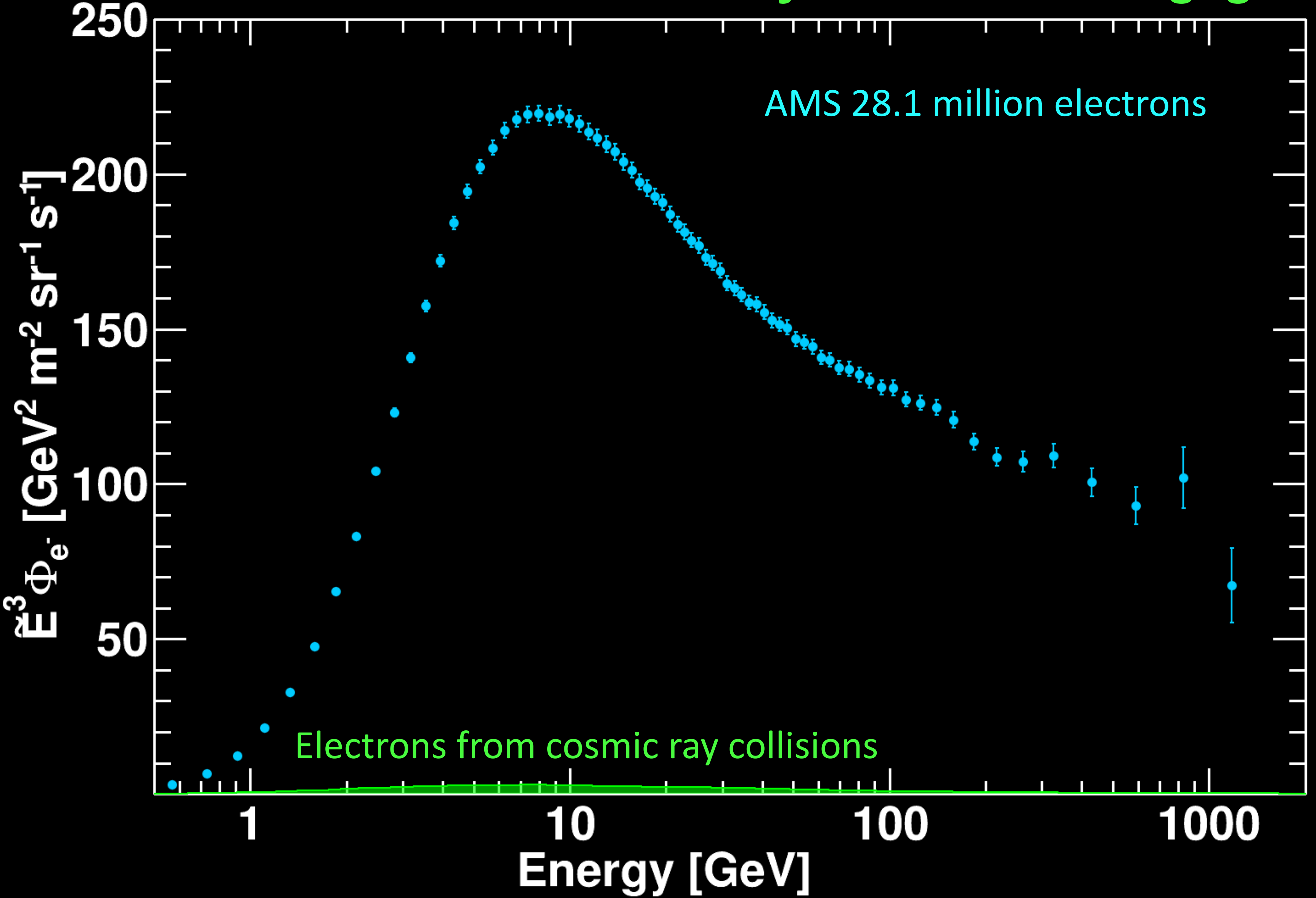
AMS will provide the definitive answer on the nature of dark matter



AMS Physics Results:

The Origins of Cosmic Electrons

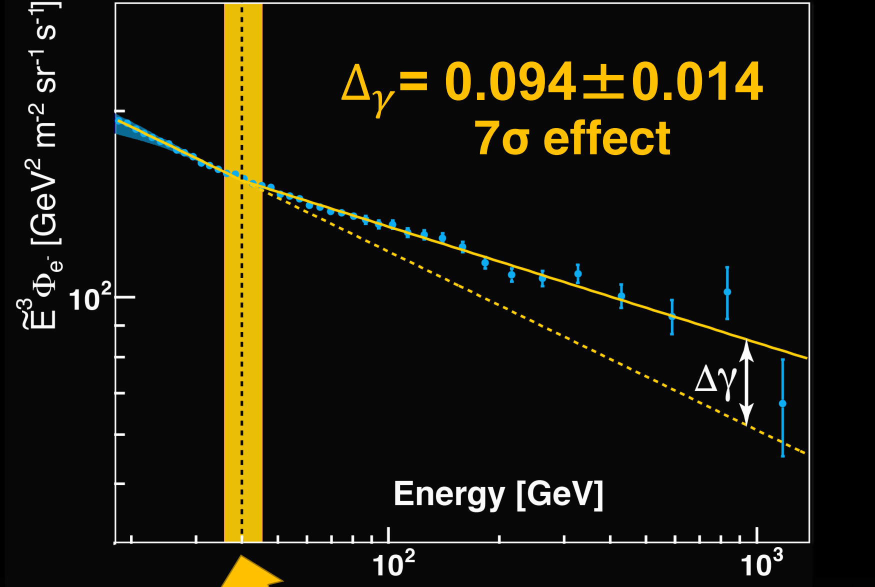
The contribution from cosmic ray collisions is negligible



Origins of Cosmic Electrons

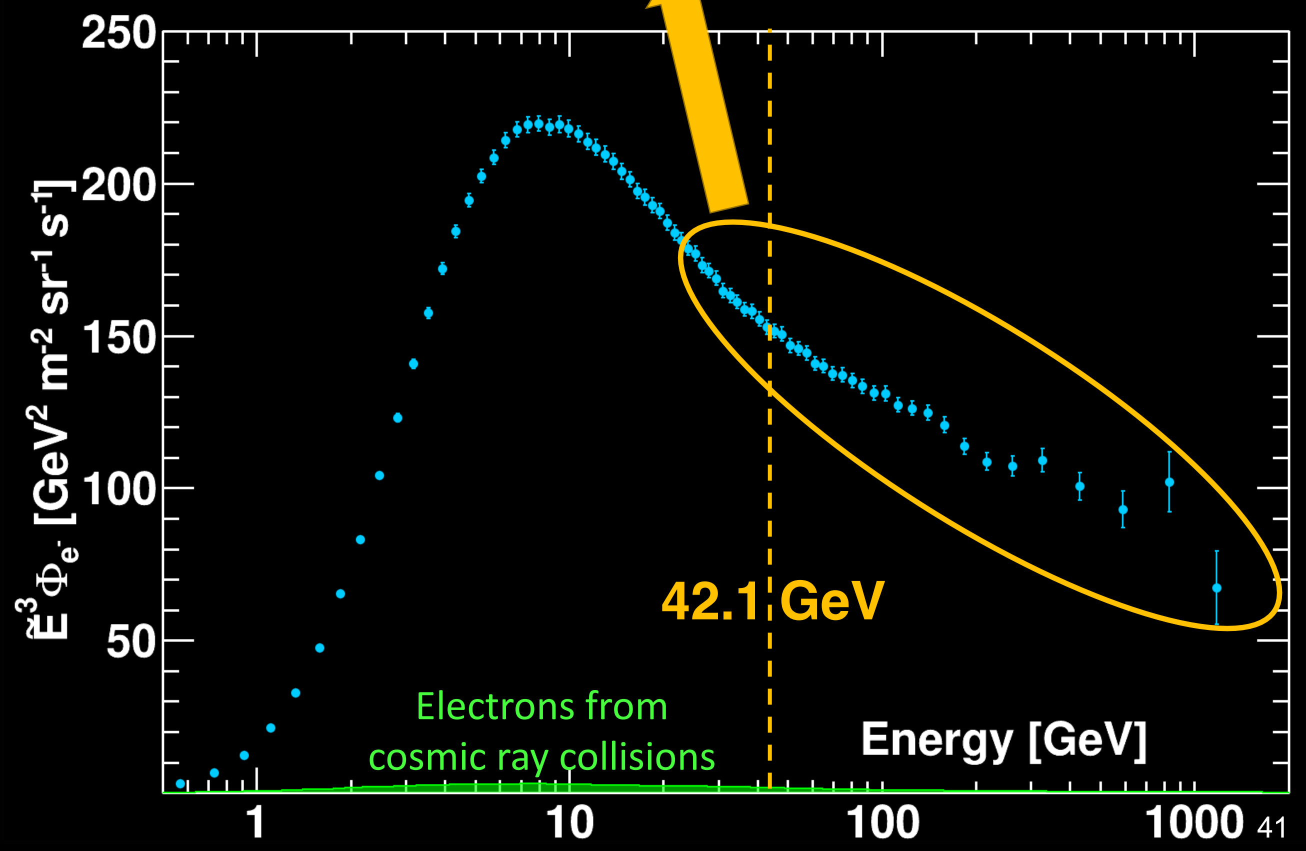
Fit to the data

$$\Phi_{e^+}(E) = \begin{cases} CE^{\gamma}, & E \leq E_0; \\ CE^{\gamma}(E/E_0)^{\Delta_\gamma}, & E > E_0. \end{cases}$$



A significant excess at

$E_0 = 42.1^{+5.4}_{-5.2}$ **GeV**

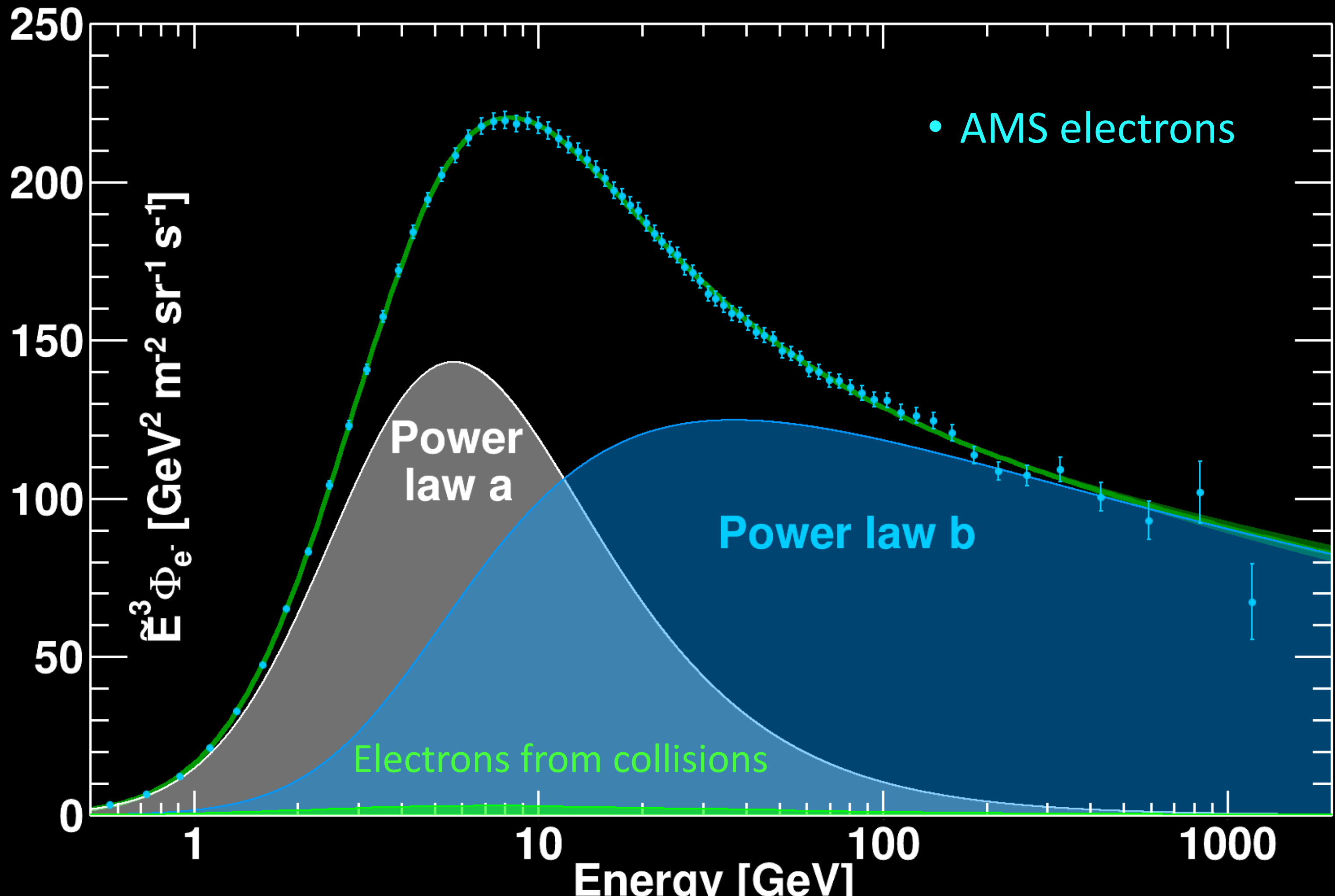


The electron flux can be described by two power law functions:

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

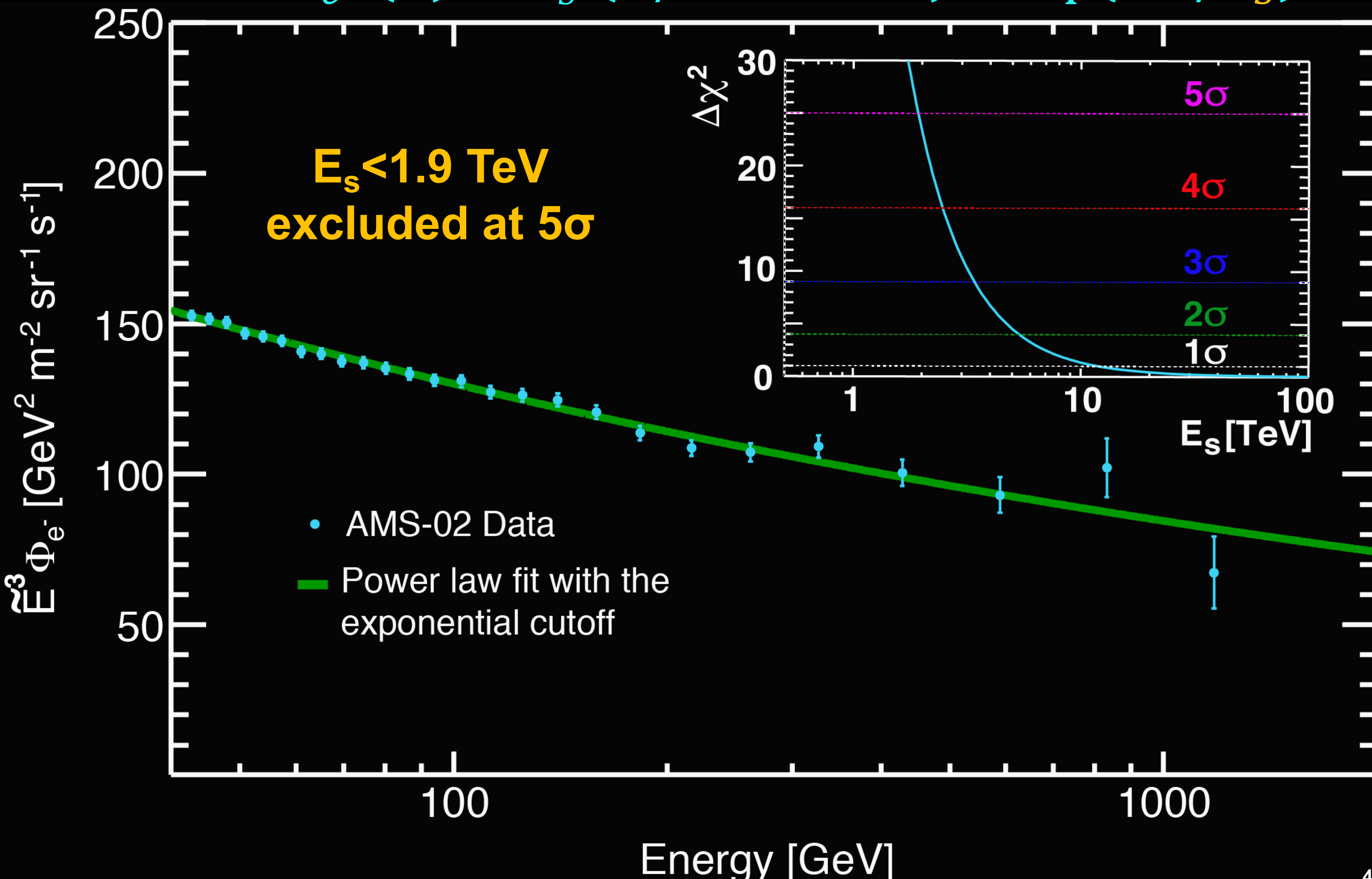
Solar & low-energy — Power law *a* — Power law *b*

What is the origin of power law a and power law b?



No source term in the electron spectrum

$$\Phi_{e^-}(E) = C_S\,(E/41.61\ \text{GeV})^{\gamma_S}\exp(-E/E_S)$$

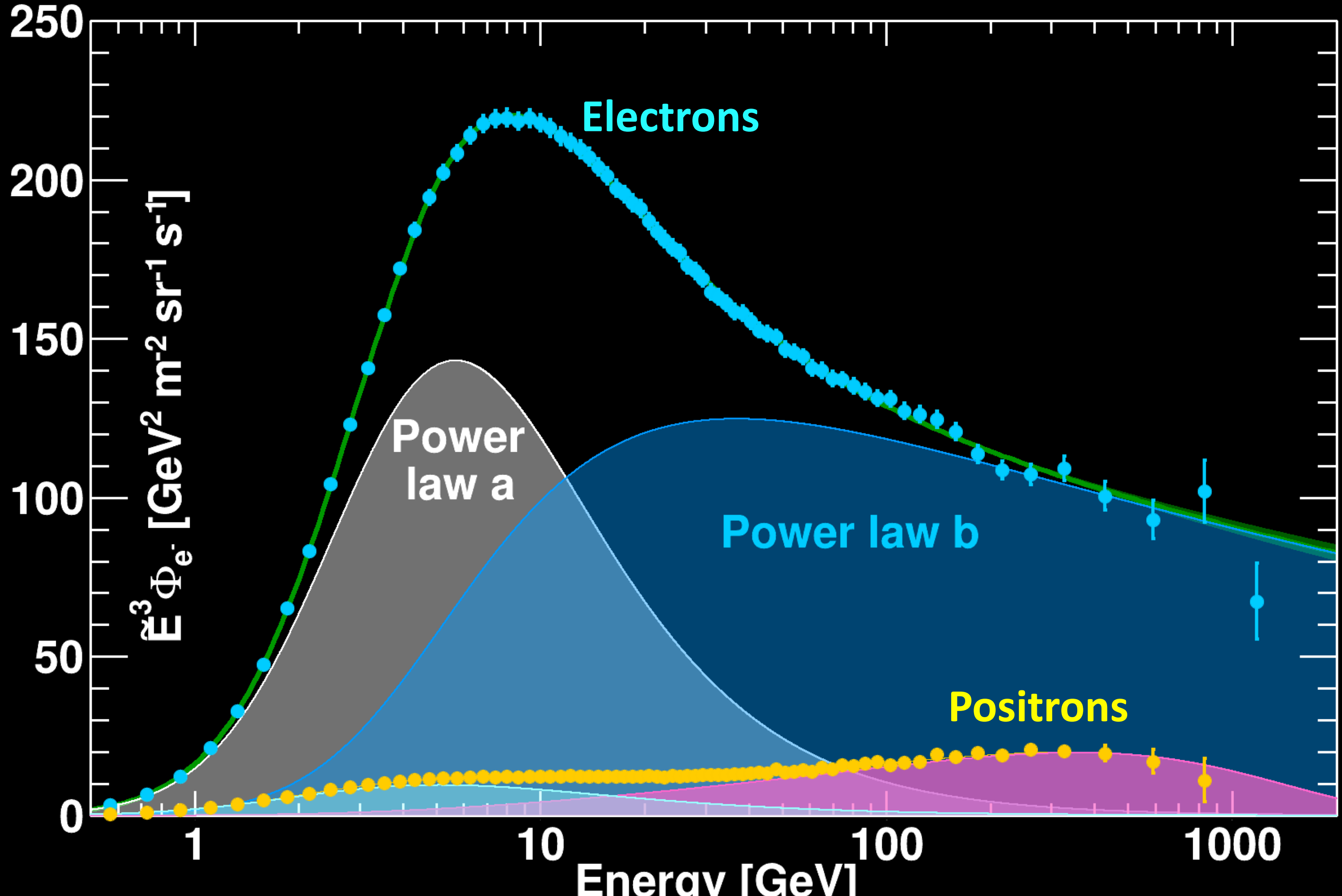


AMS Physics Results:

Electrons originate from different sources than positrons;

the electron spectrum comes from two power law contributions.

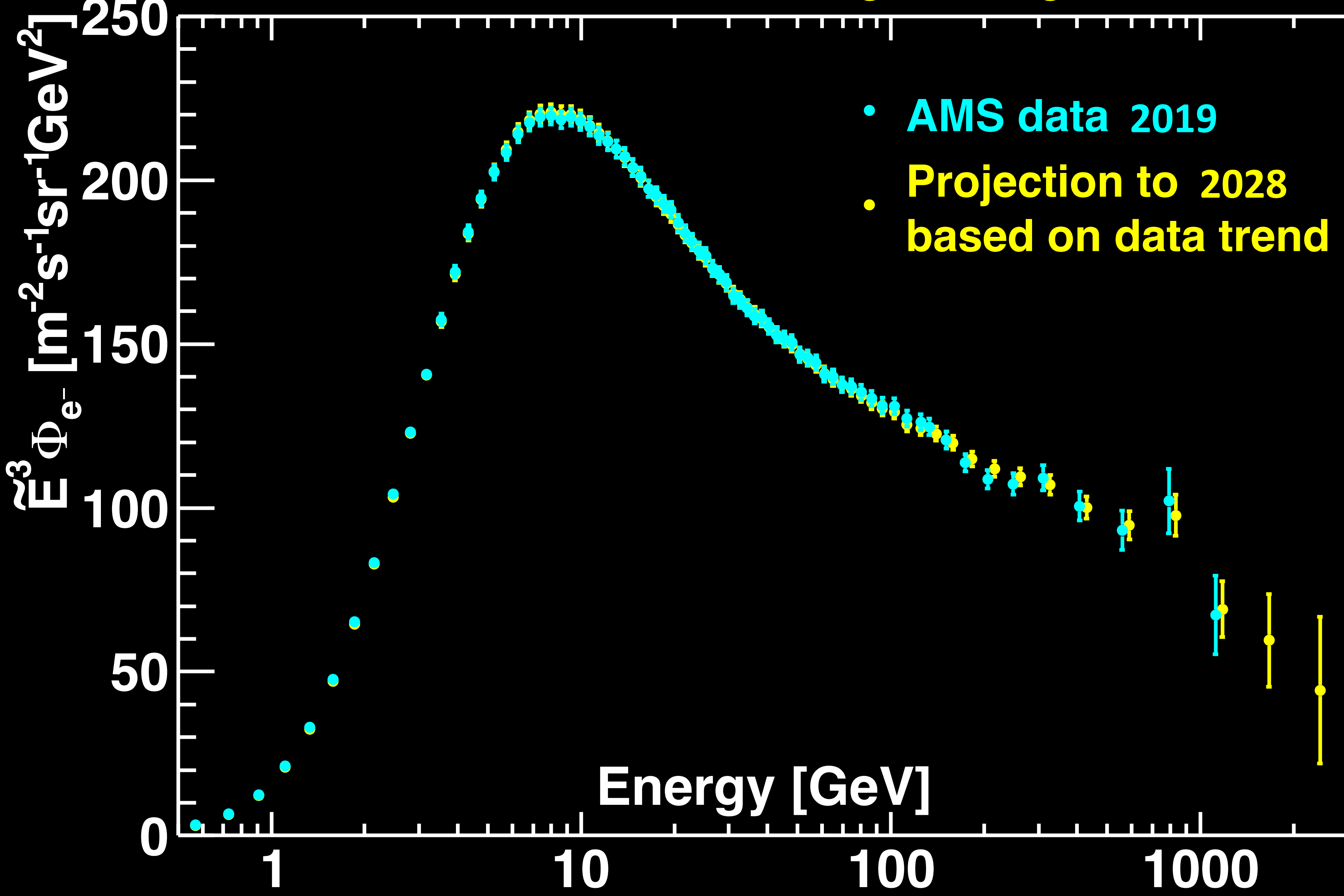
The positron flux is the sum of low-energy part from cosmic ray collisions plus a high-energy part from a new source or dark matter both with a cutoff energy E_S.



Physics of cosmic electrons to 2028

What is the origin of power law a and power law b?

Is there a cutoff for electrons at higher energies?



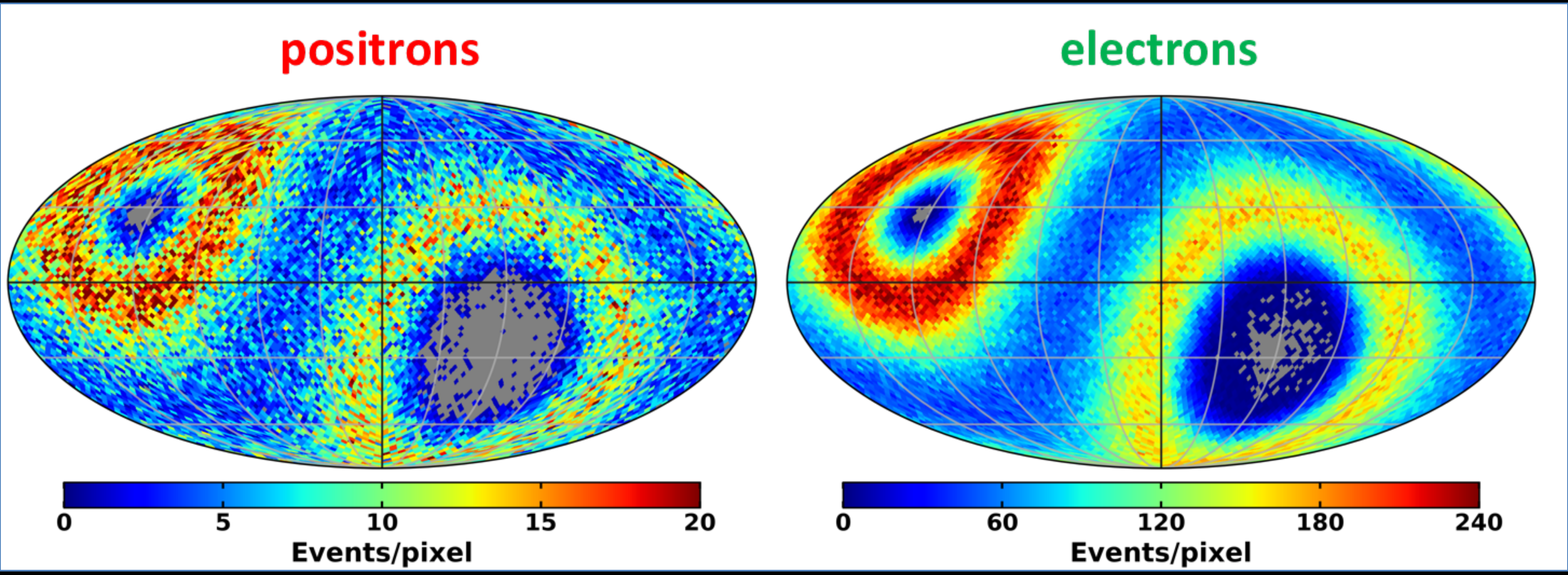
Positron Anisotropy and Dark Matter

Astrophysical point sources like pulsars will imprint a higher anisotropy on the arrival directions of energetic positrons than a smooth dark matter halo.

The anisotropy in galactic coordinates

$$\delta = 3\sqrt{C_1/4\pi}$$

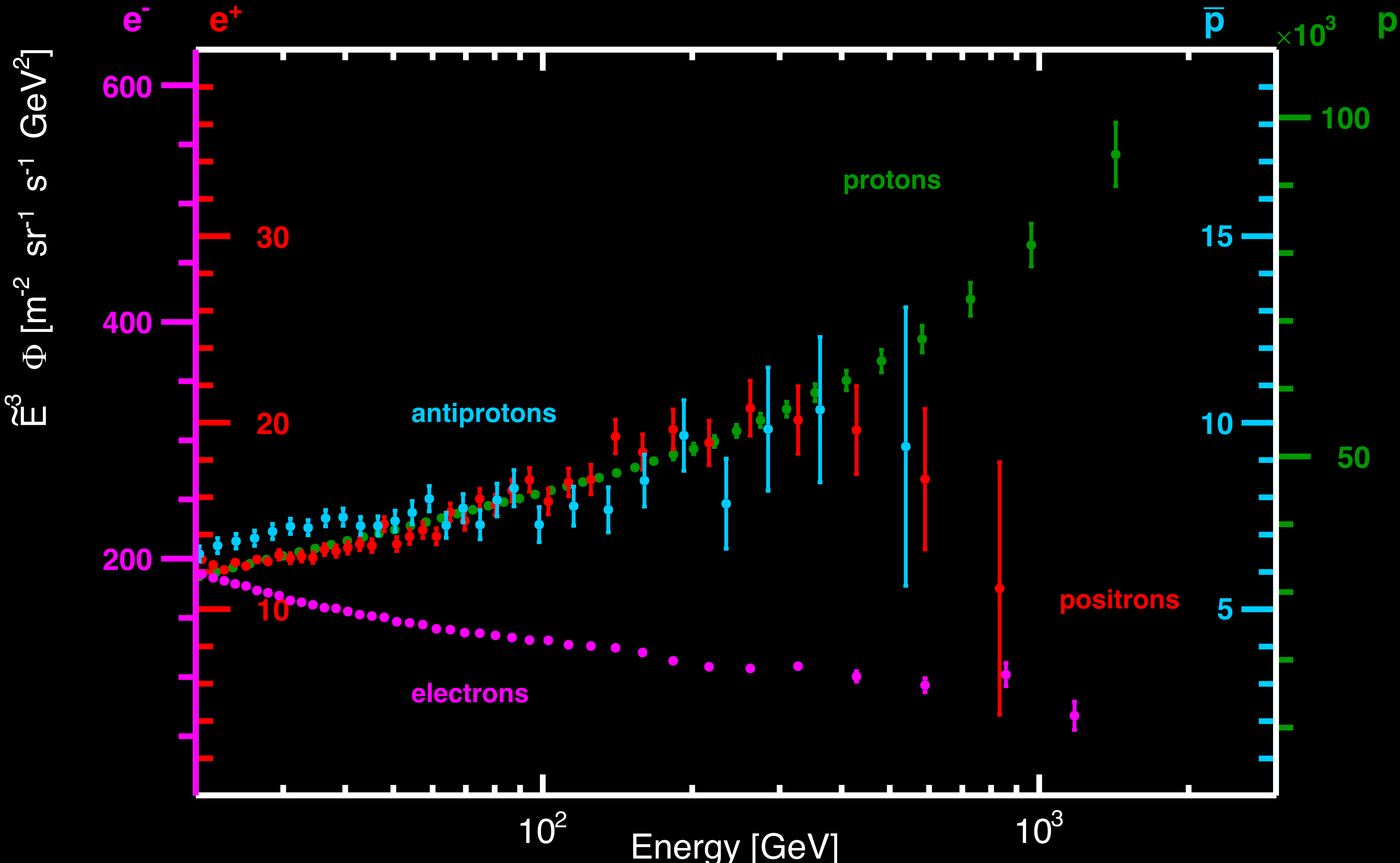
C_1 is the dipole moment



Currently at 95% C.L.: for 16<E<350

positrons: $\delta < 0.019$
electrons: $\delta < 0.005$

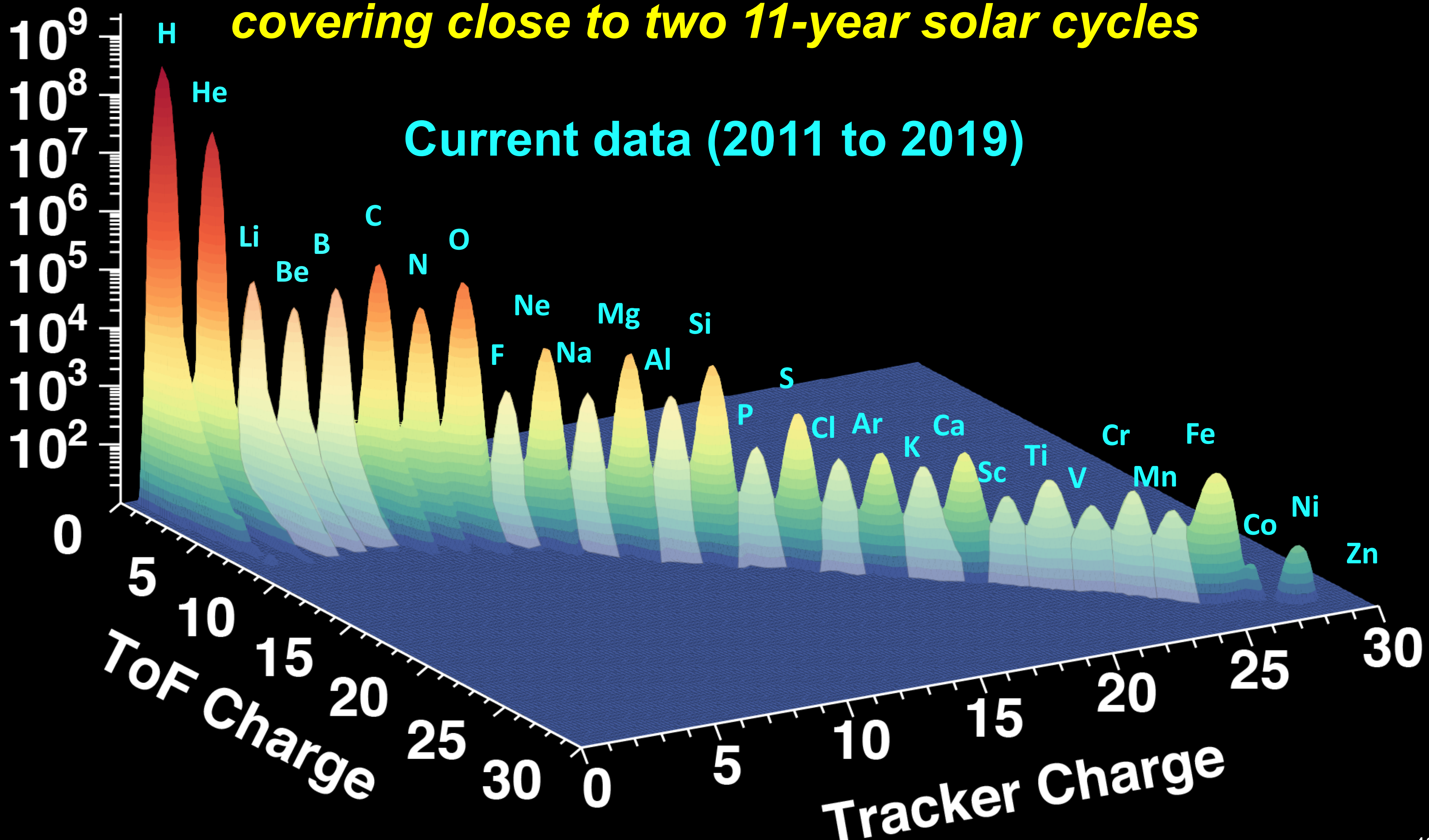
Elementary particle fluxes show three distinct patterns



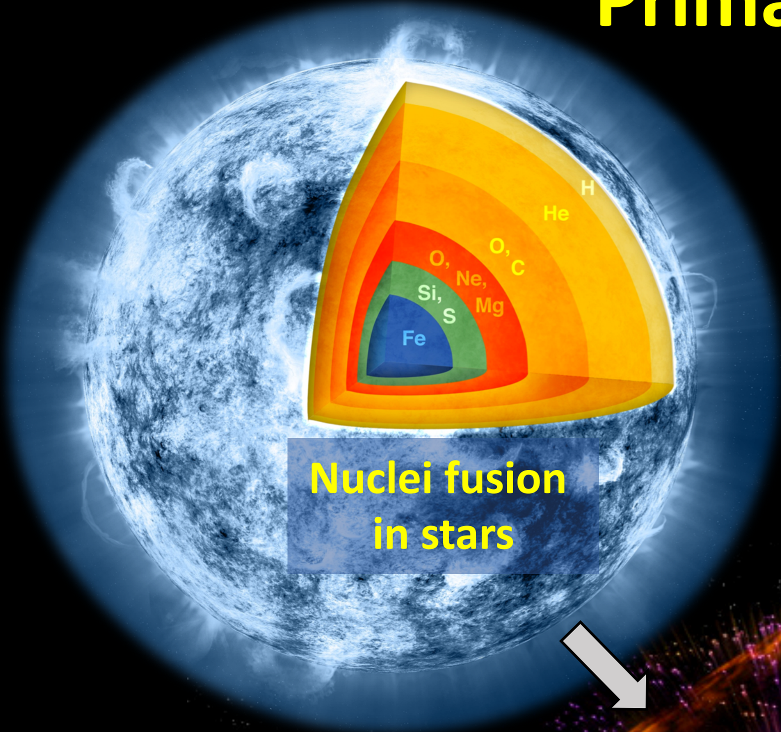
Precision Study of Cosmic Nuclei through the lifetime of ISS

Accuracy of ~ 1%, Energy range 500 to 3,000,000 MeV

Exploring an uncharted region from 2011 to 2028 and beyond covering close to two 11-year solar cycles

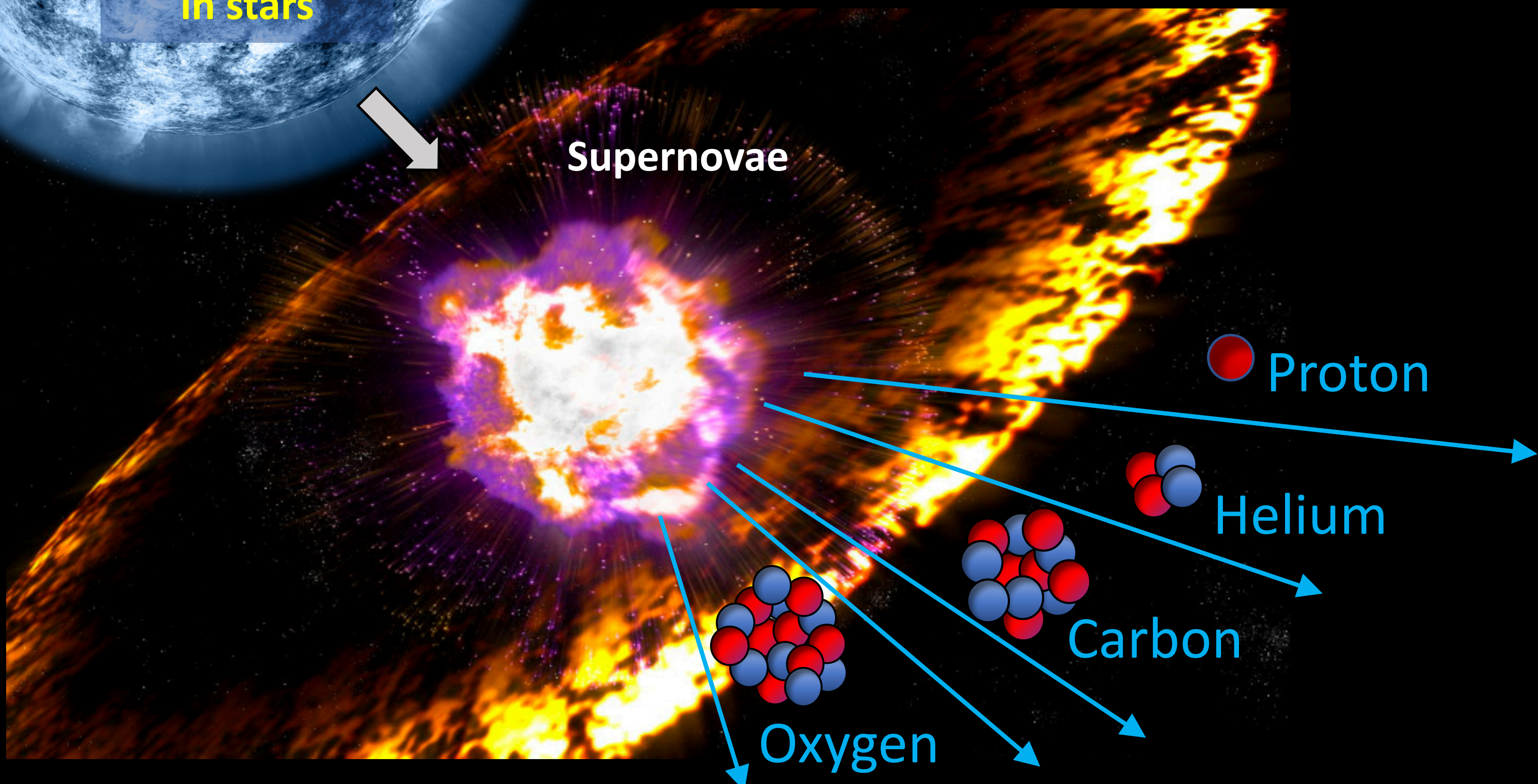


Primary Cosmic Rays



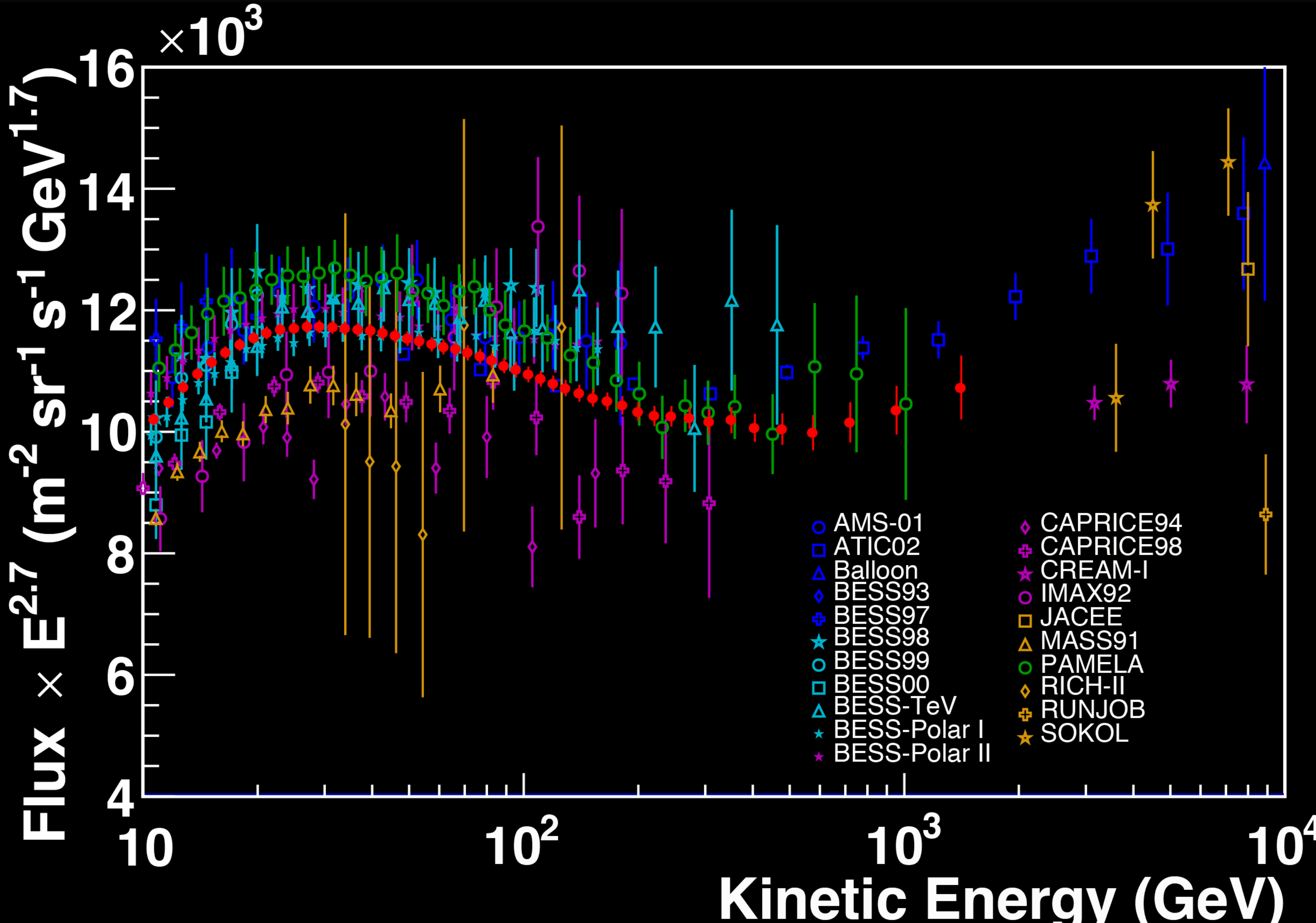
Primary elements (H, He, C, ..., Fe) are produced during the lifetime of stars.

They are accelerated by the explosion of stars (supernovae).

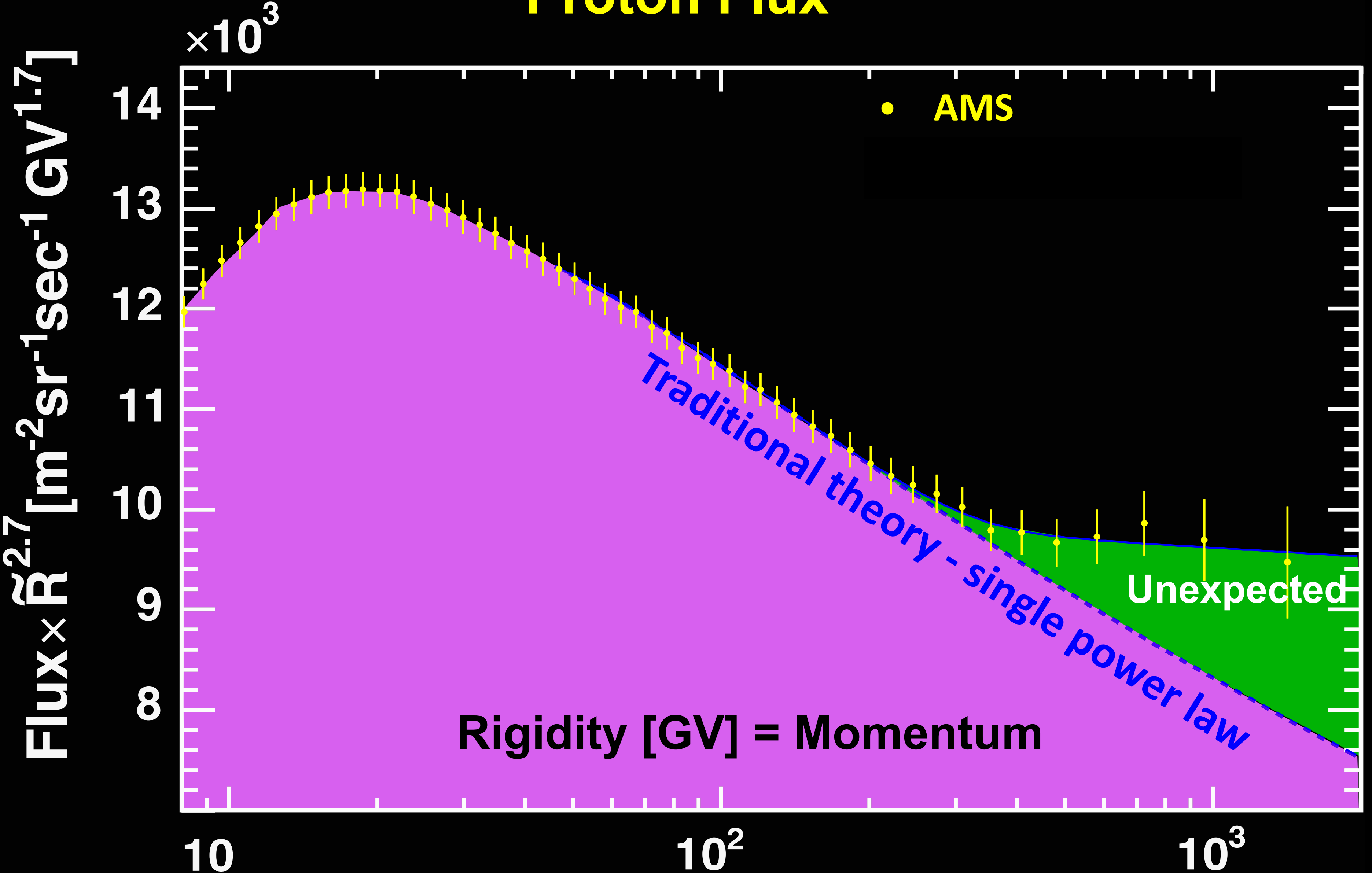


Latest results – 1 billion protons

AMS Measurement of the proton spectrum

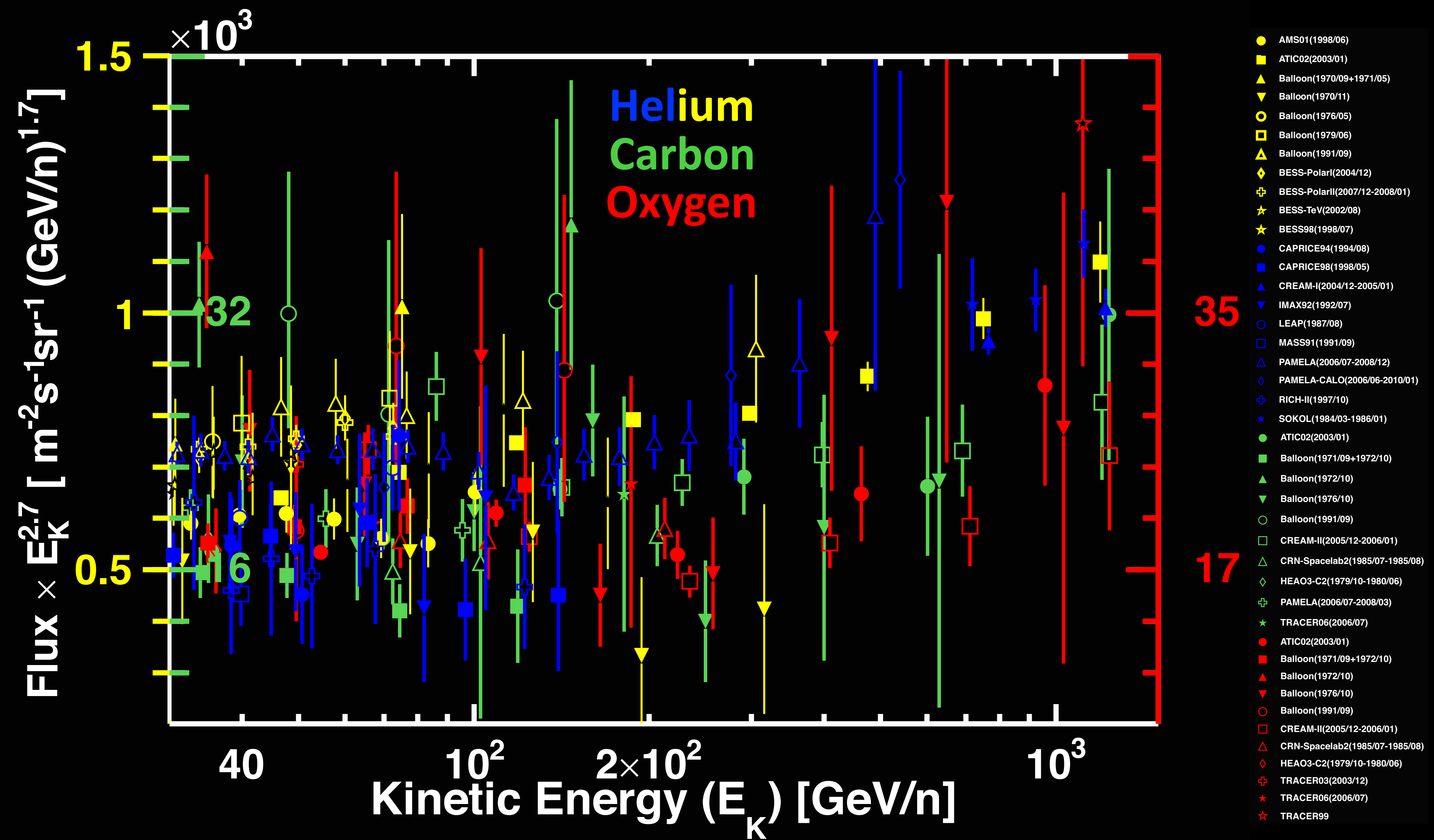


AMS Physics Results:
Proton Flux



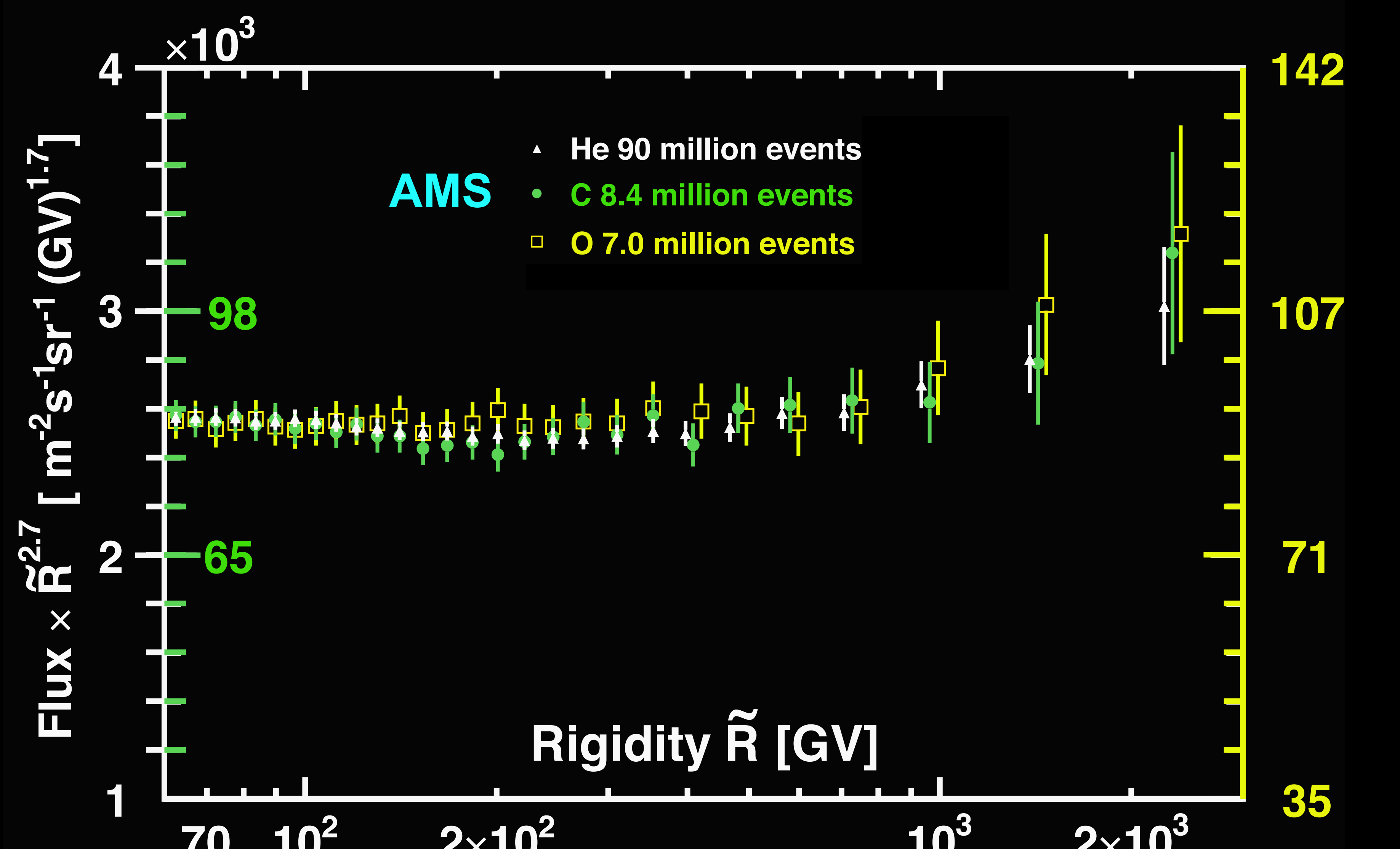
The proton flux cannot be described by the traditional theory

Before AMS there were many results on Primary Cosmic Rays (Helium, Carbon, Oxygen) from balloon and satellite experiments

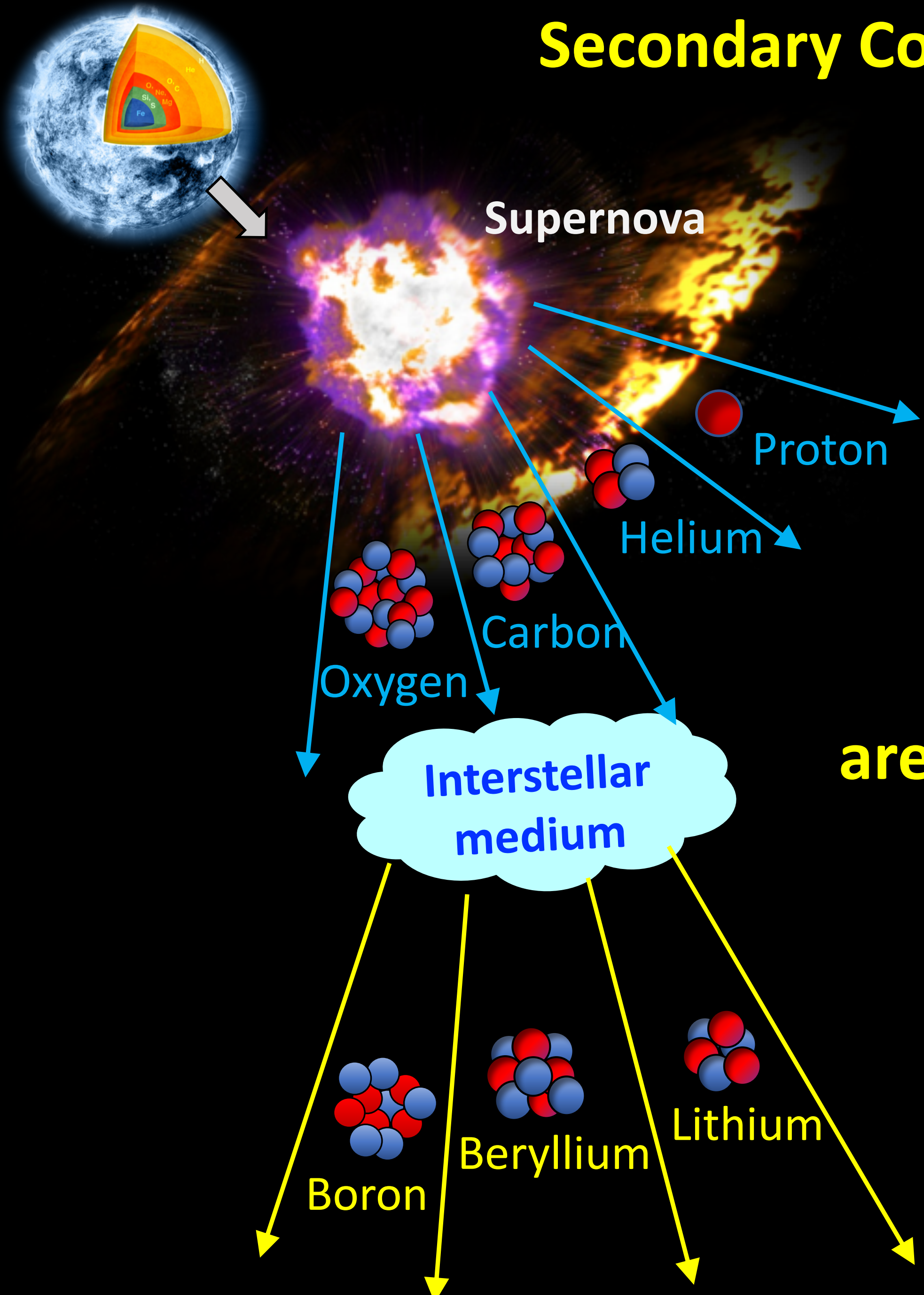


AMS Physics Results:

Surprisingly, above 60 GV, the primary cosmic rays have identical rigidity (P/Z) dependence.



Secondary Cosmic Rays

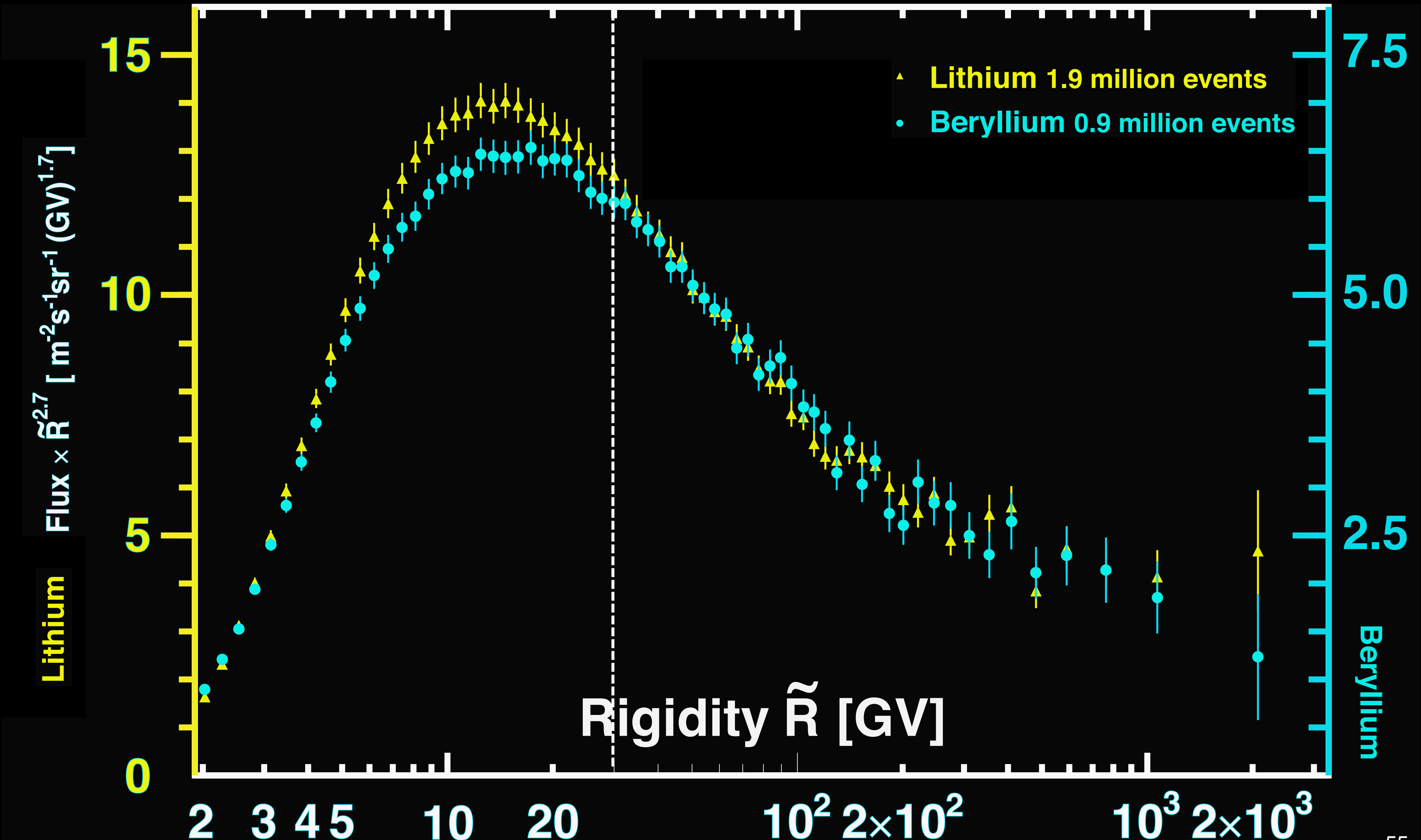


Secondary cosmic nuclei (Li, Be, B, …) are produced by the collision of primary cosmic rays and interstellar medium

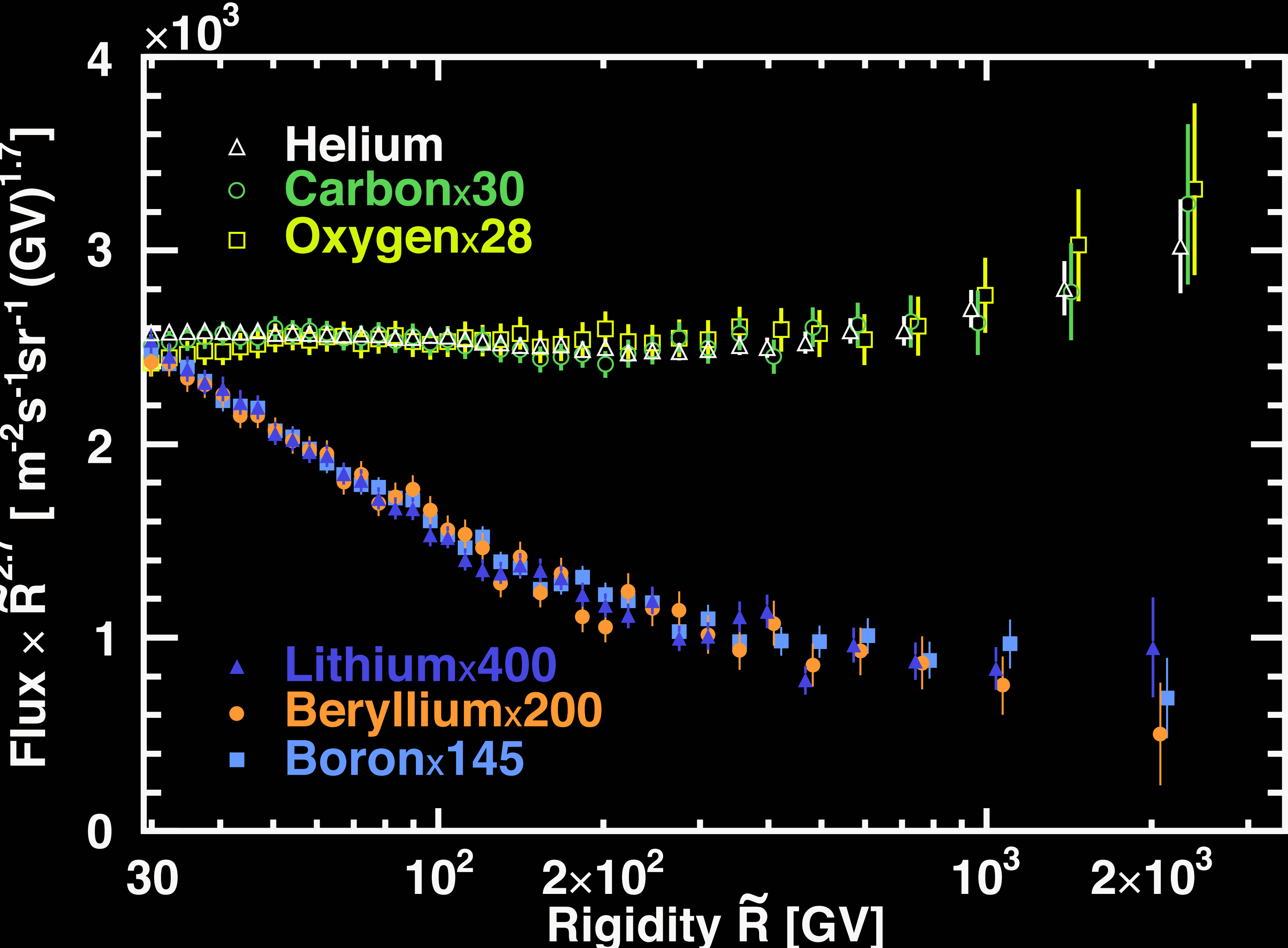
Physics Results on Lithium and Beryllium

The rigidity dependences are identical above 30 GV

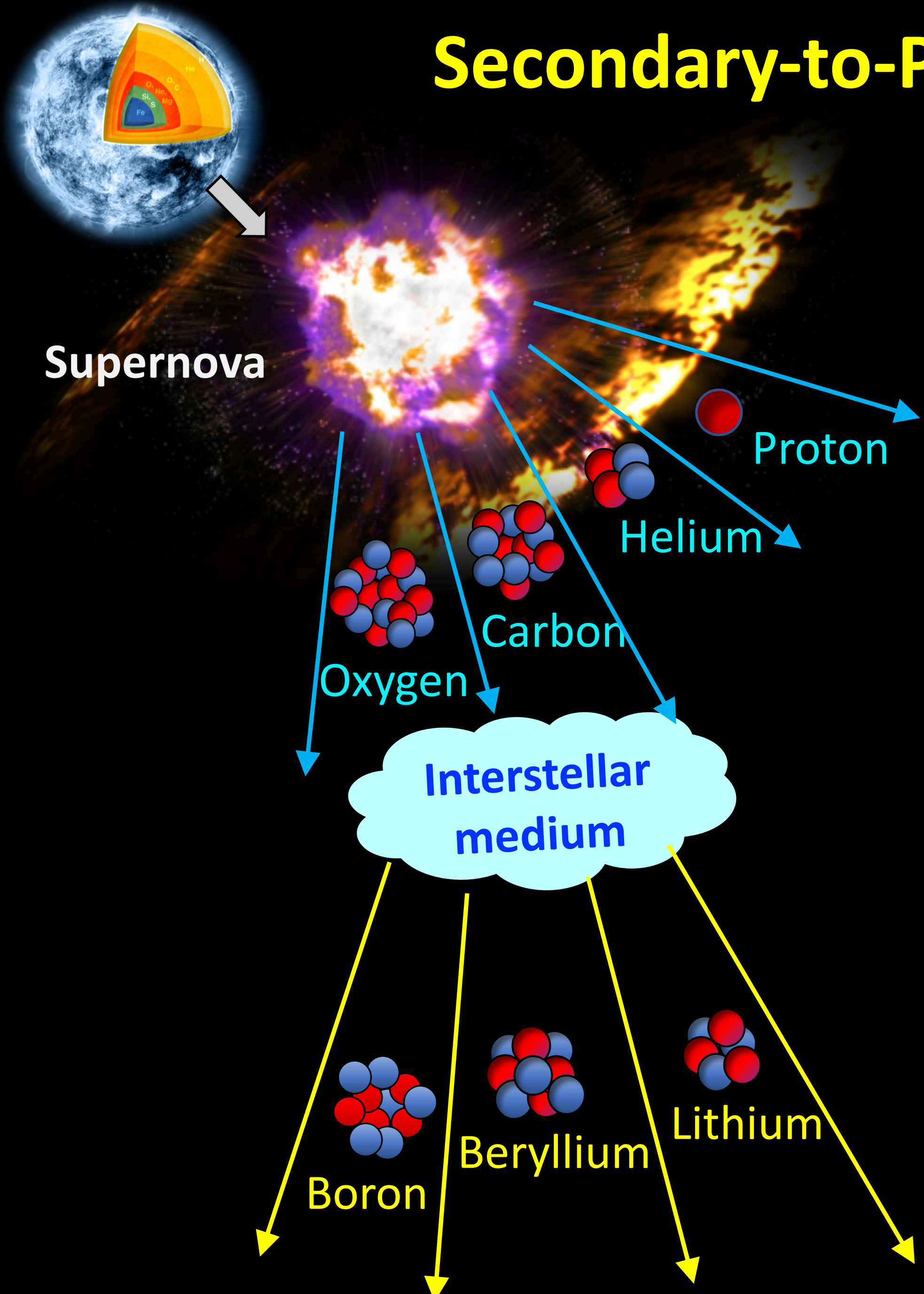
Fluxes are different by a factor of 2.0 ± 0.1



AMS Physics Results:
Secondary cosmic rays Li, Be, and B also have identical rigidity dependence but they are different from primaries



Secondary-to-Primary Ratios



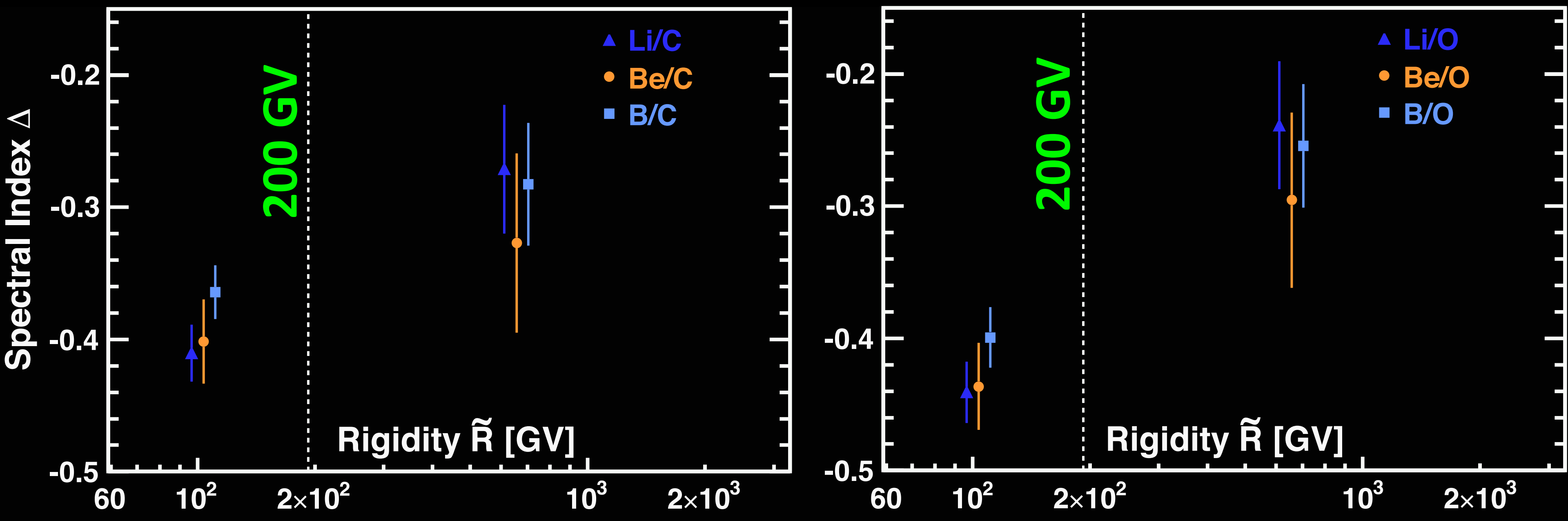
The ratio of secondary flux to primary flux directly measures the amount and properties of interstellar medium.

Before AMS, the B/C ratio was assumed to be $\propto R^{\Delta}$ with Δ a constant for R > 60GV.

AMS Physics Results:

The Secondary/Primary Ratios ≠ kR^{Δ}

Δ is not a constant



$$\Delta_{[200\text{-}3300]\mathrm{GV}} - \Delta_{[60\text{-}200]\mathrm{GV}} = 0.13 \pm 0.03$$

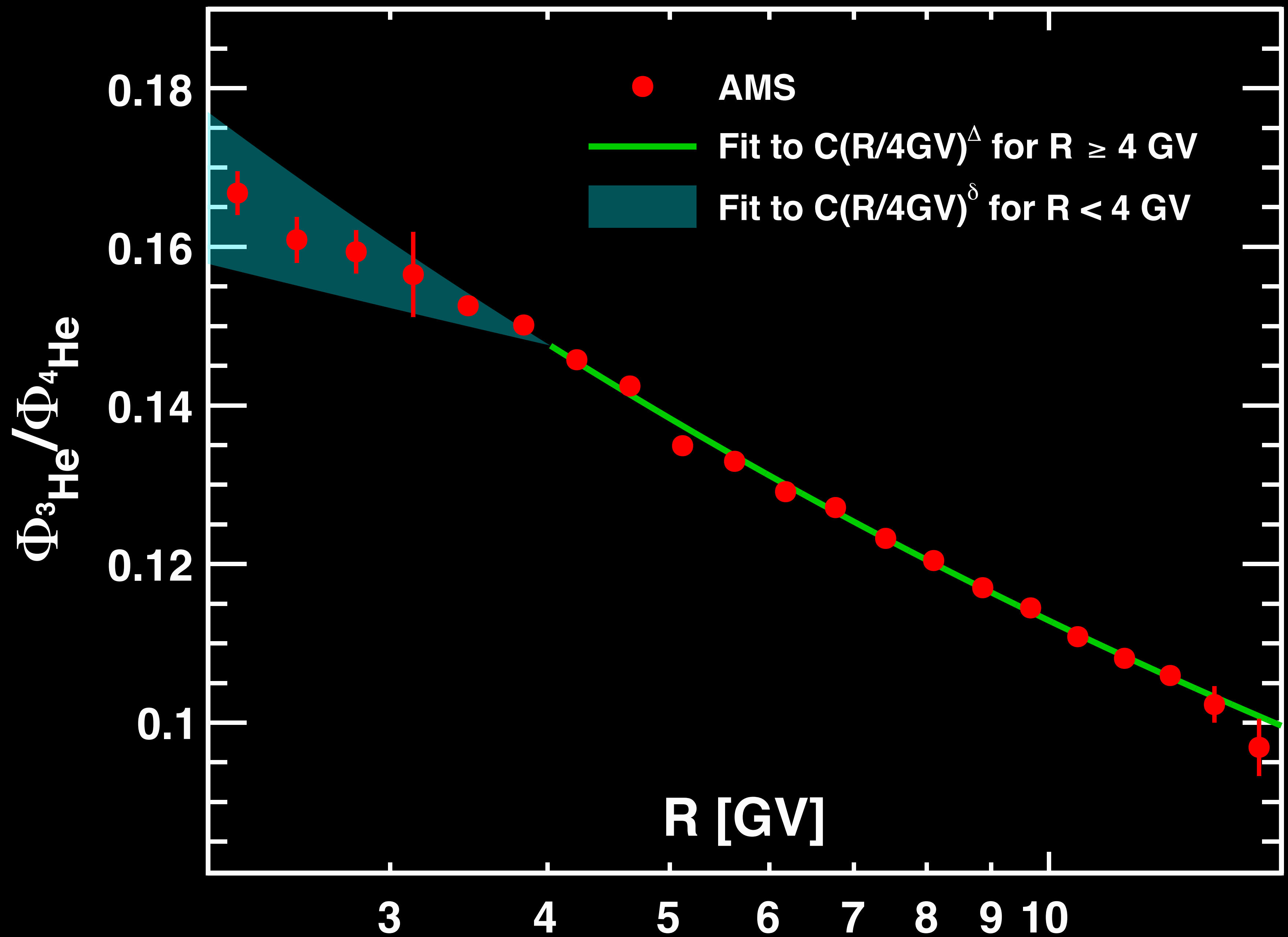
AMS Helium Isotope Ratio

Helium (^{3}He, ^{4}He) interaction cross sections with the interstellar medium (p, He) are significantly smaller than those of heavier nuclei (Li, Be, B, C, N, O, ...).

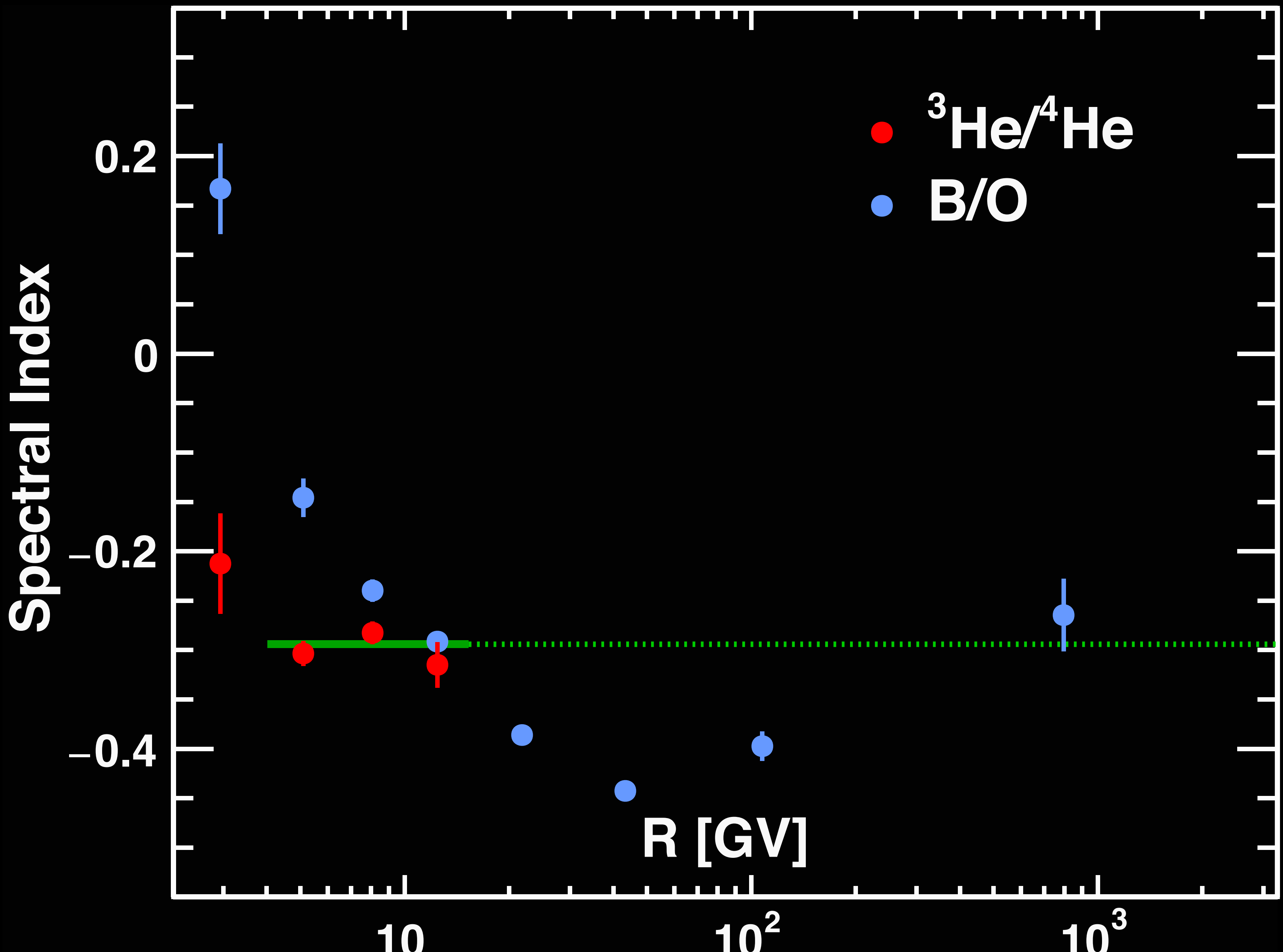
Therefore, helium travels larger distances, probing a larger Galactic volume.

Explicitly, the $^{3}He/^{4}He$ ratio probes the properties of diffusion at larger distances.

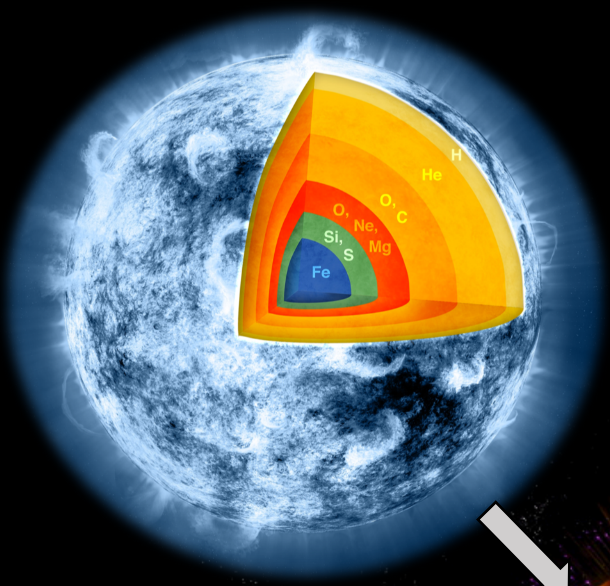
AMS Helium Isotope Ratio



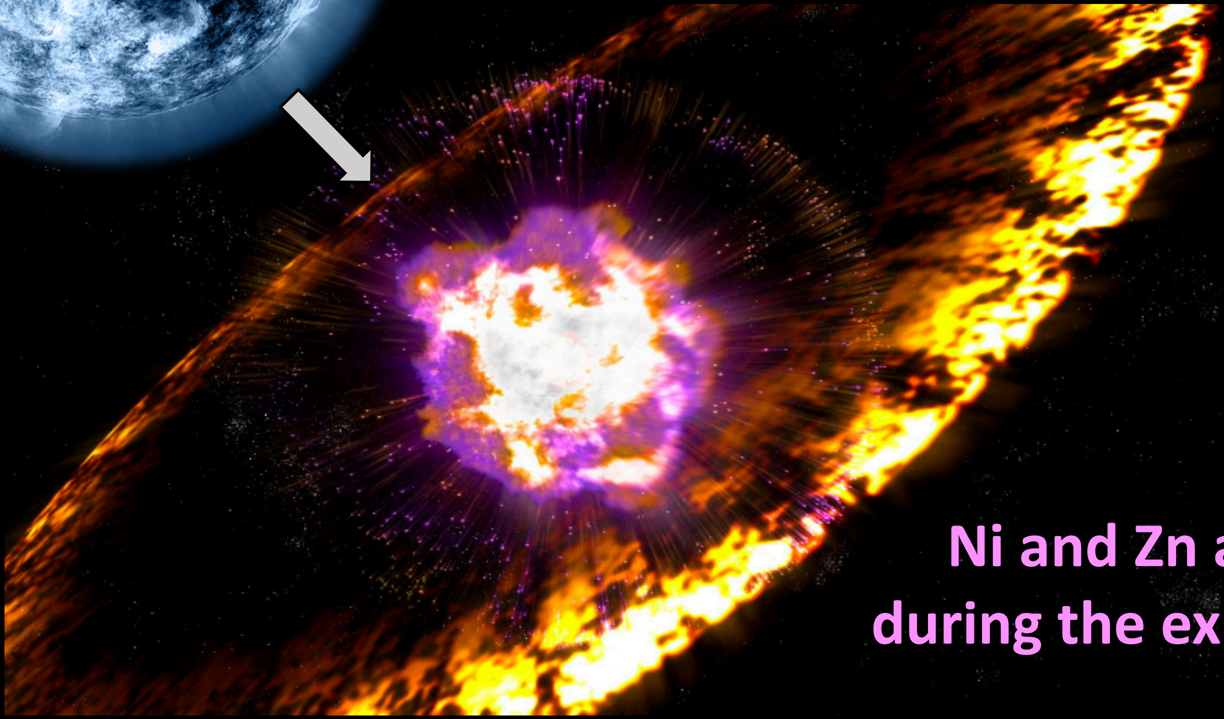
AMS Helium Isotope Ratio – Spectral Index



Are heavier elements Ni and Zn different from He, C, … Fe?

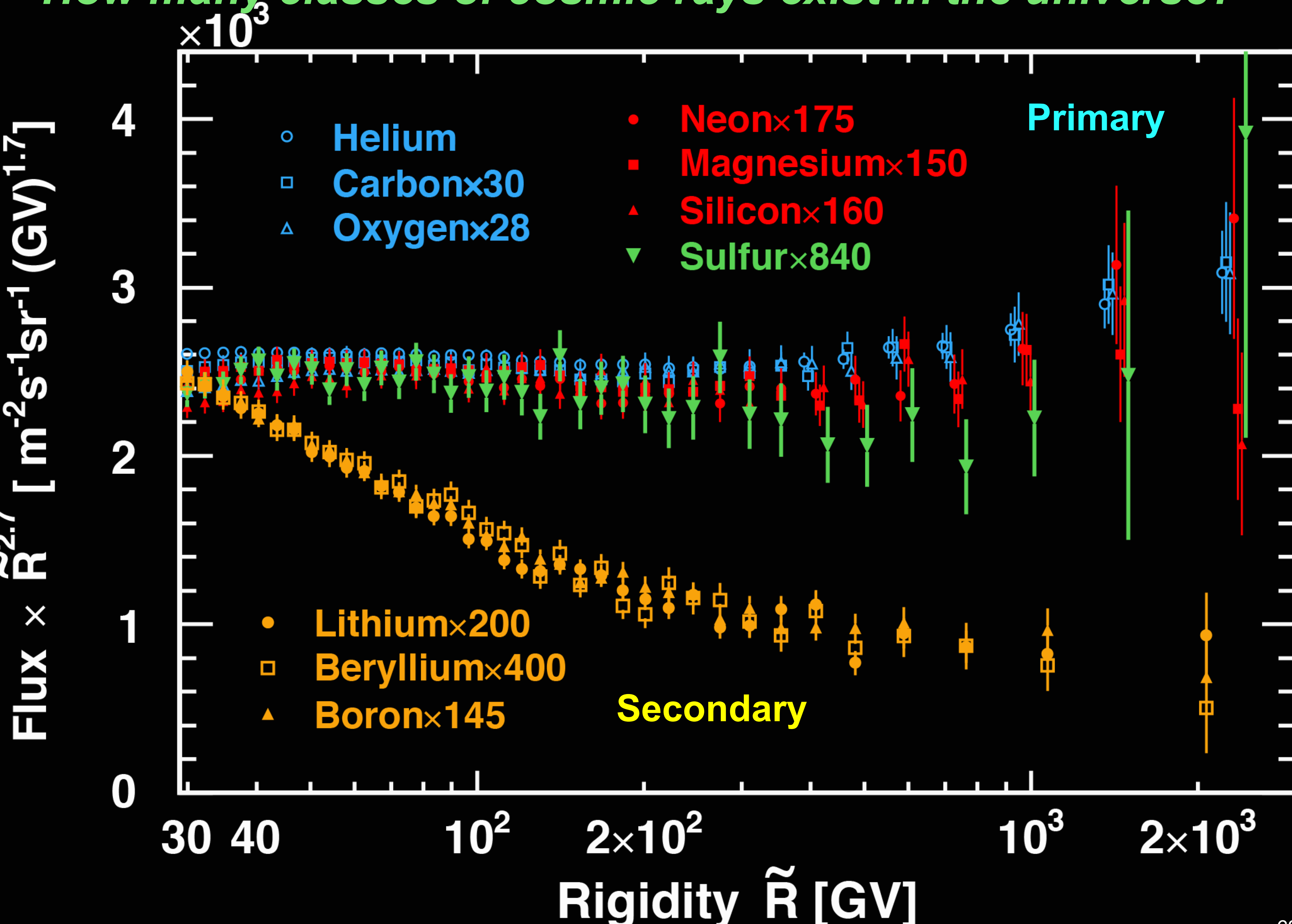


Primary elements (He, C, ..., Fe)
are produced during the lifetime of stars and
then accelerated by
the explosion of stars (supernovae)

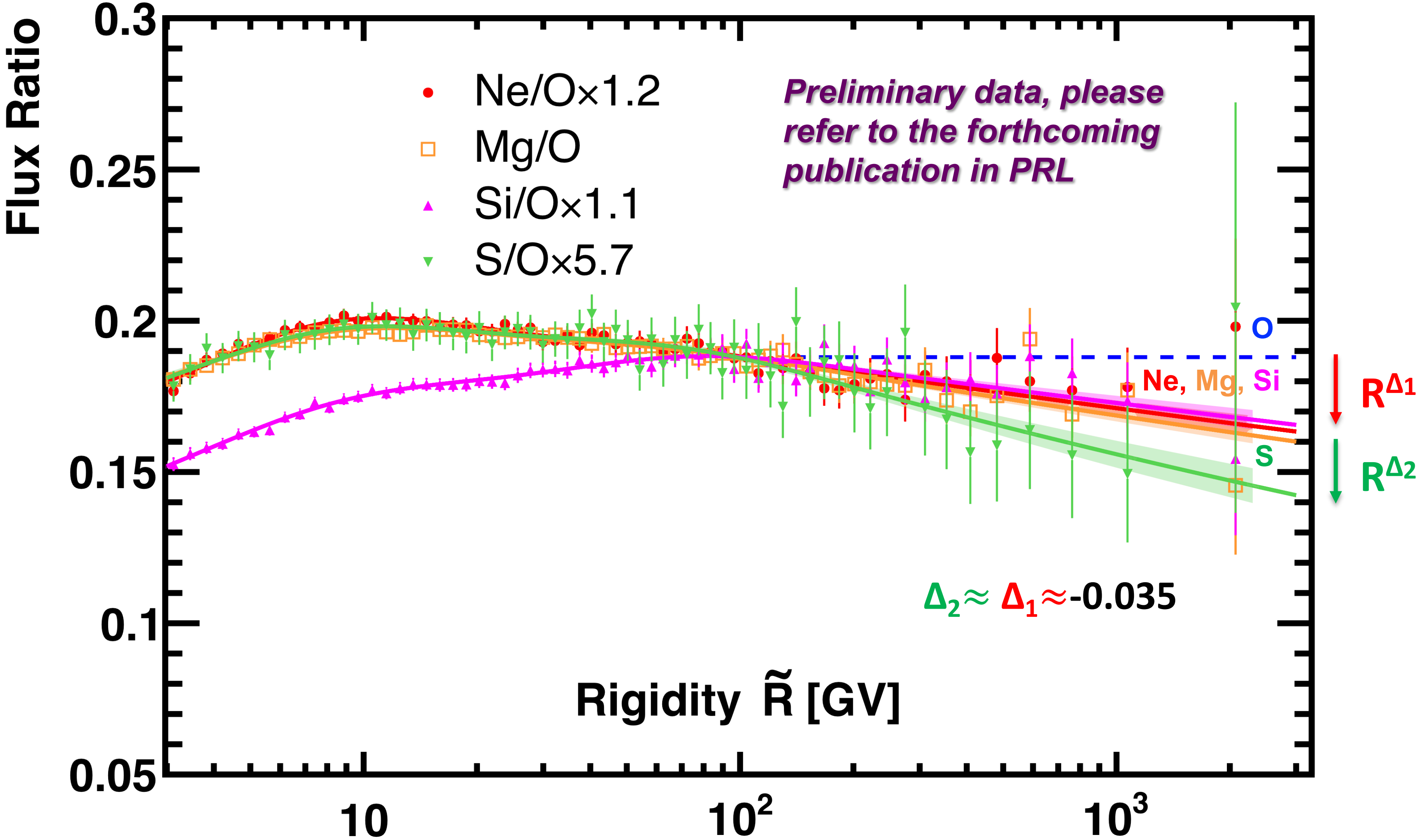


Ni and Zn are produced
during the explosion of stars.

How many classes of cosmic rays exist in the universe?

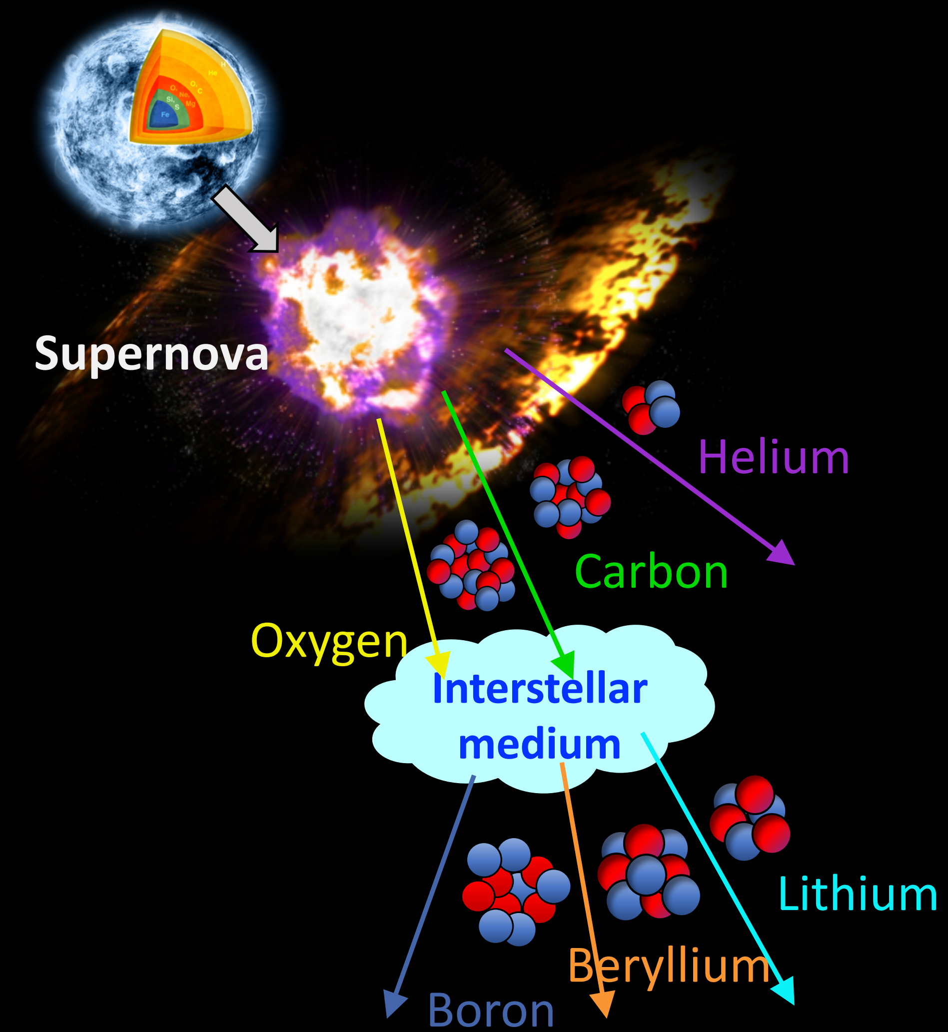


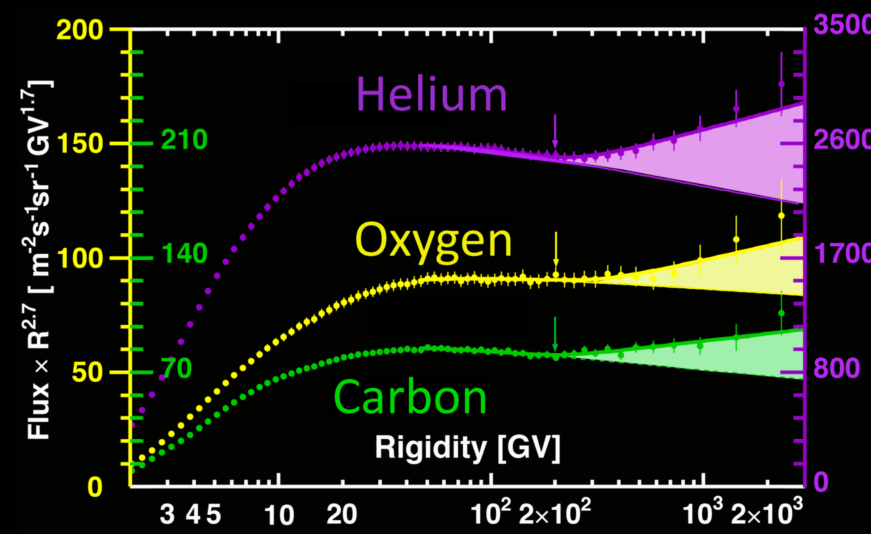
Flux Ratios Ne/O, Mg/O, Si/O, and S/O

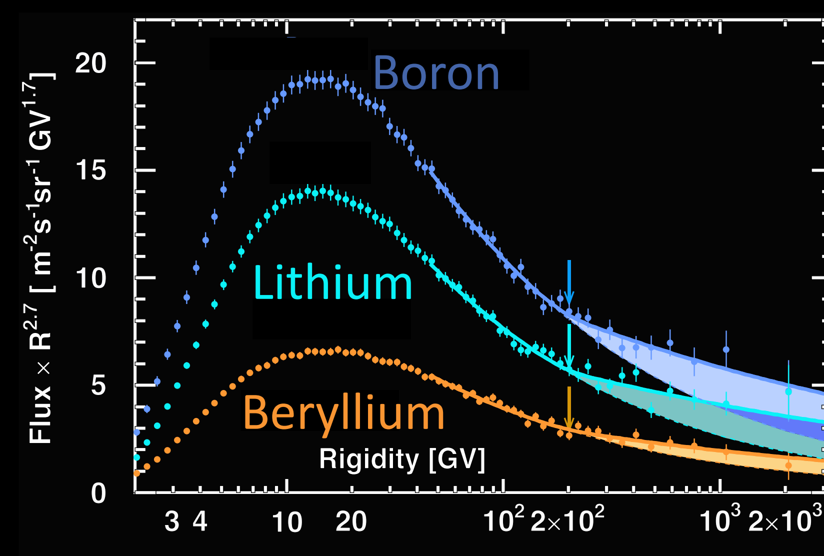


The measured spectra of Cosmic Rays break at ~200 GV.

Is there a break for all the elements? Why?

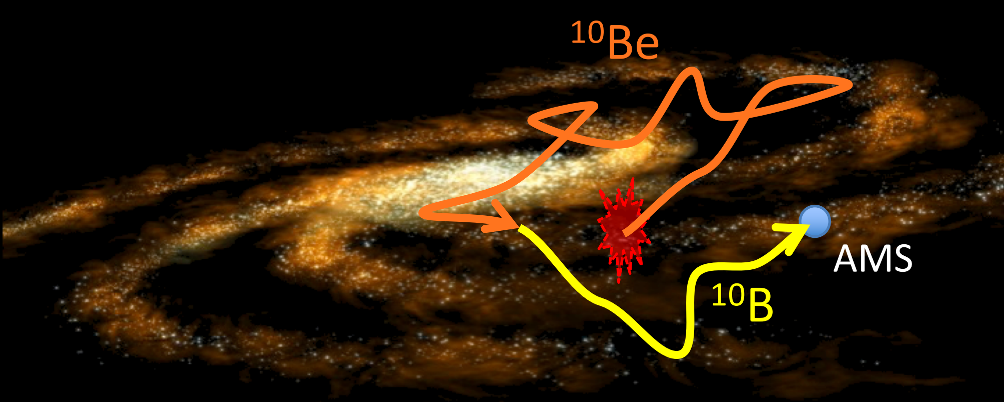


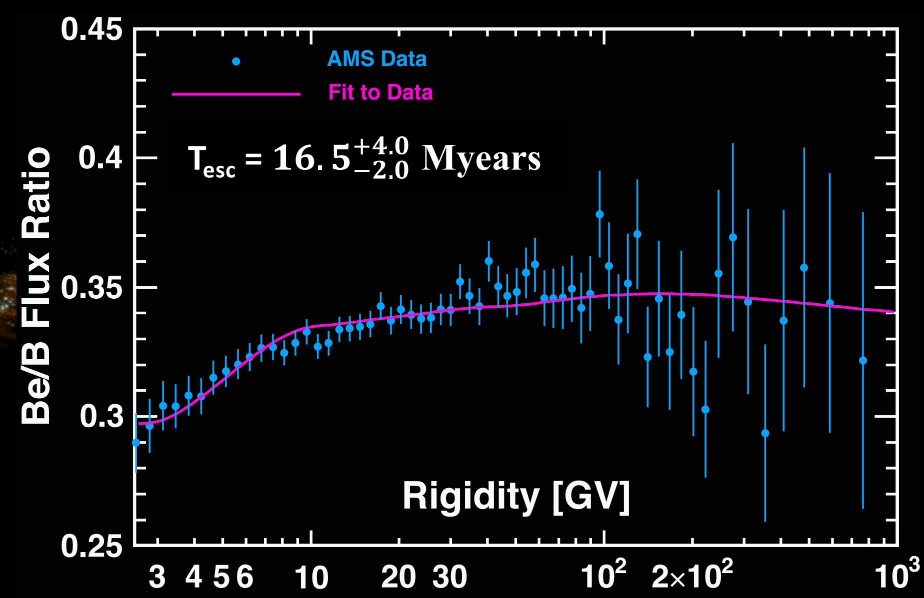




How old are cosmic rays?

^{10}Be (Z=4) decays with a half-life 1.4×10^6 years $^{10}Be \rightarrow {}^{10}B + e^- + \nu_e$.
Precision measurement of the rigidity dependence of Be/B ratio provides information on the age of cosmic rays





The measurements of radioactive Aluminum (Z=13), Chlorine (Z=17), and Manganese (Z=25) spectra will precisely establish the age of cosmic rays as they (like Be) are radioactive clocks.

Complex anti-matter

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

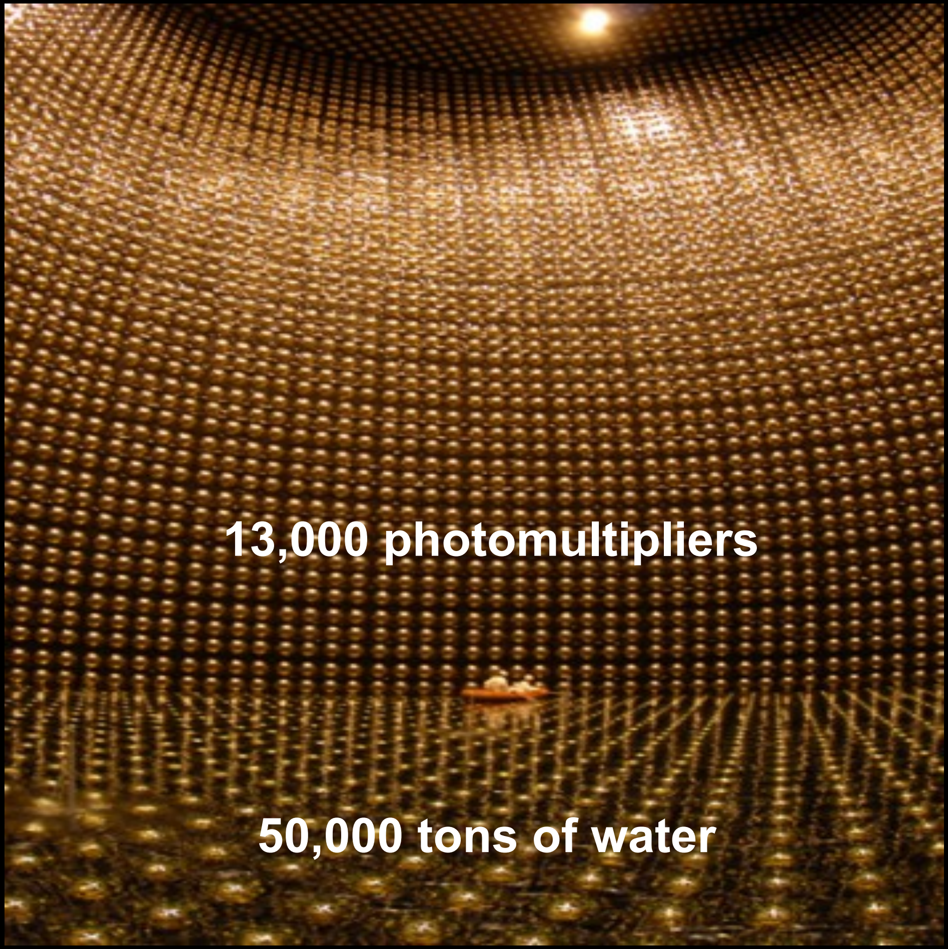
AMS is orders of magnitude more sensitive than previous experiments on balloons and satellites

Search for Baryogenesis

New symmetry breaking

LHC-b, ATLAS,CMS

Proton has finite lifetime

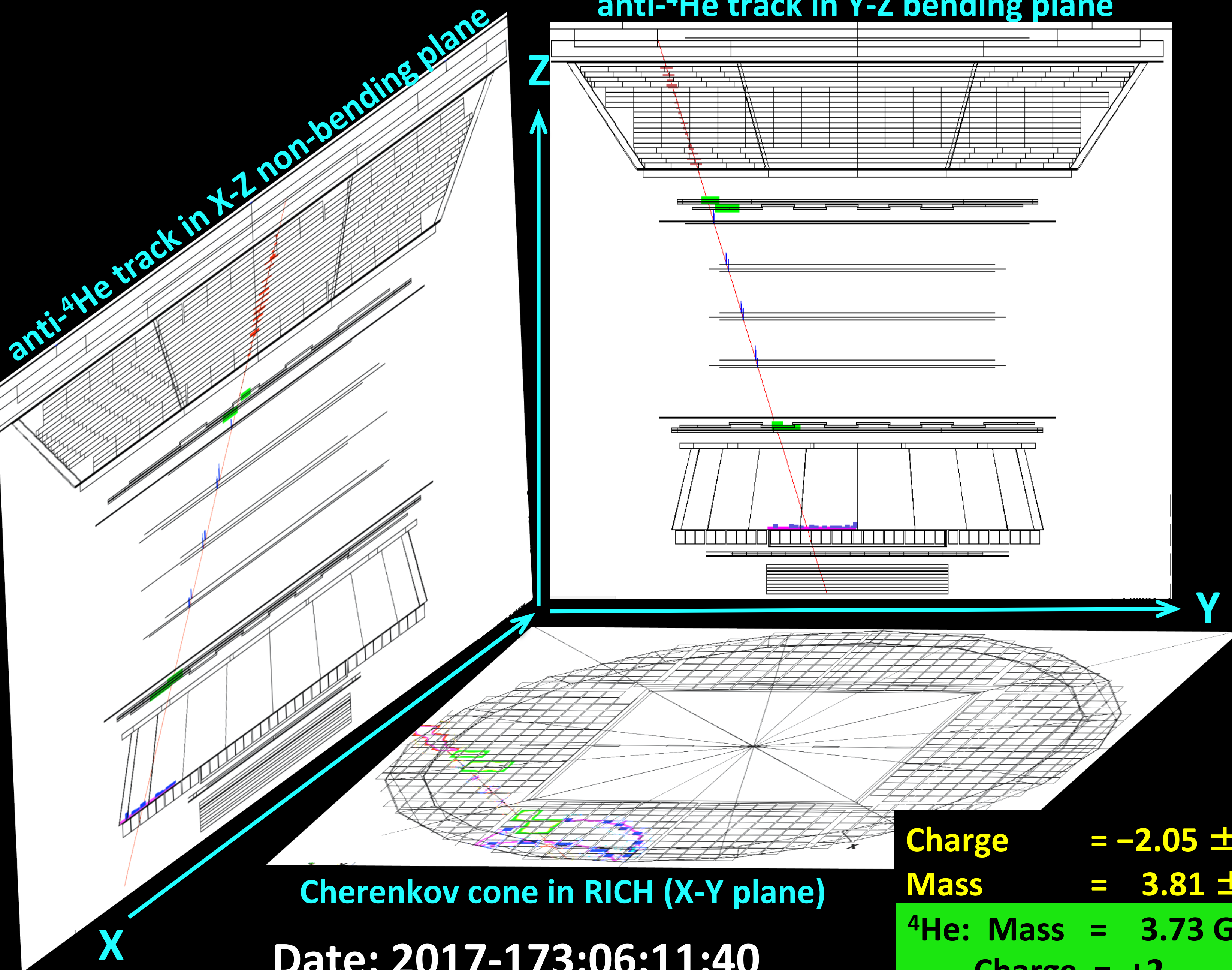


Super Kamiokande

No explanation found for the absence of antimatter.

No reason why antimatter should not exist.

Observation of heavy antimatter



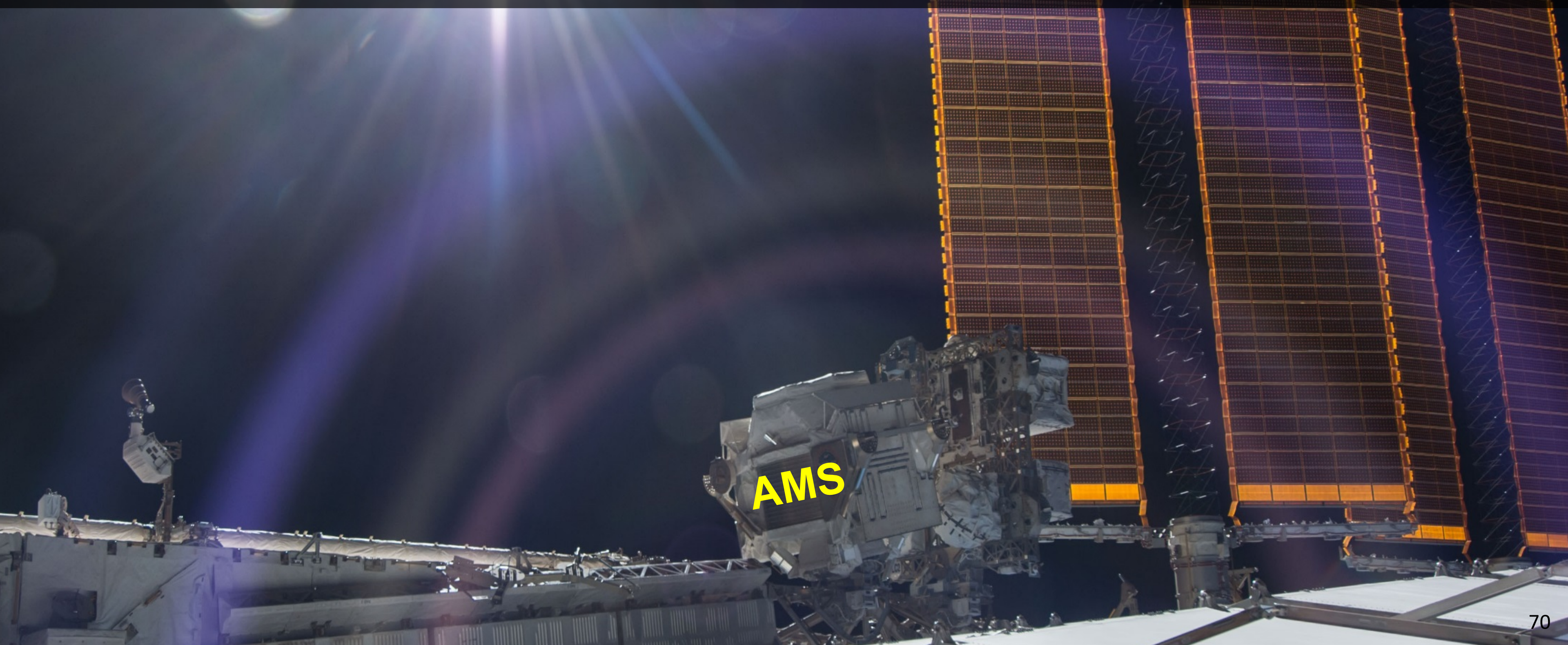
Date: 2017-173:06:11:40

Charge = −2.05 ± 0.05
Mass = 3.81 ± 0.29 GeV/c^2

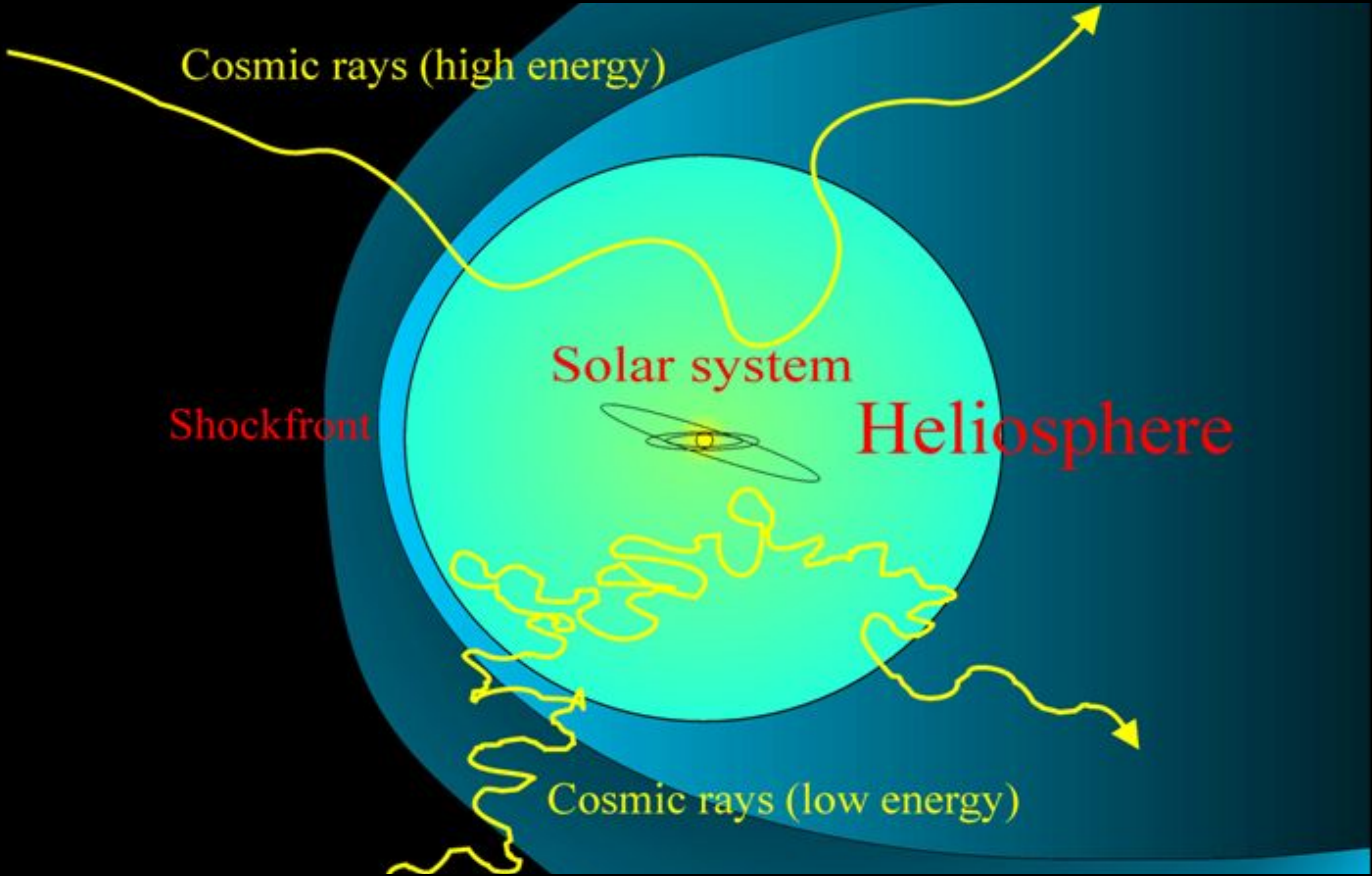
^{4}He: Mass = 3.73 GeV/c^2
Charge = +2

Complex Antimatter

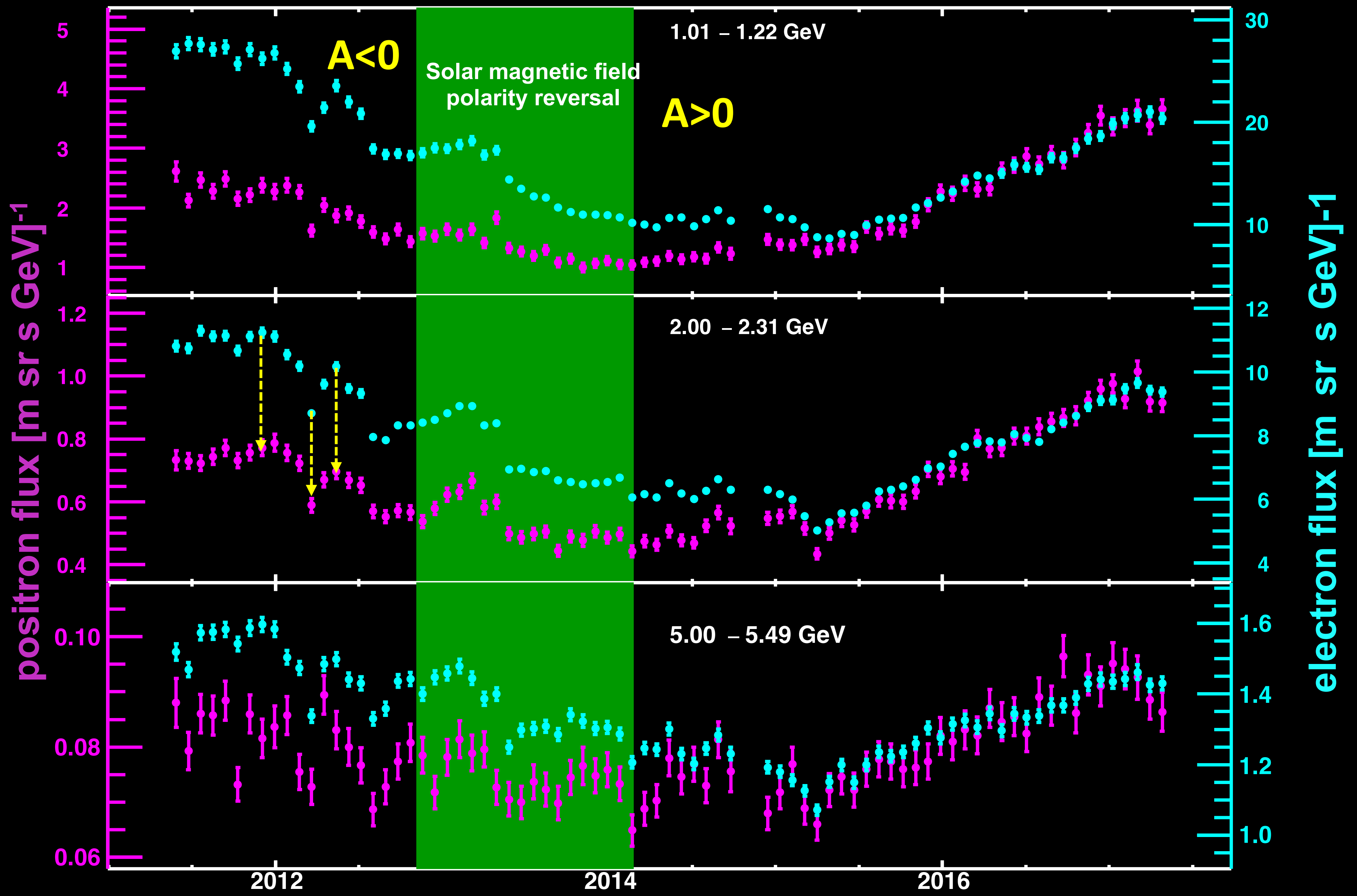
The rate in AMS of antihelium candidates is less than 1 in 100 million helium. At this extremely low rate, more data (through the lifetime of the ISS) is required to further check the origin of these events.



Solar Physics over an 11-year Solar Cycle: 2011 - 2028

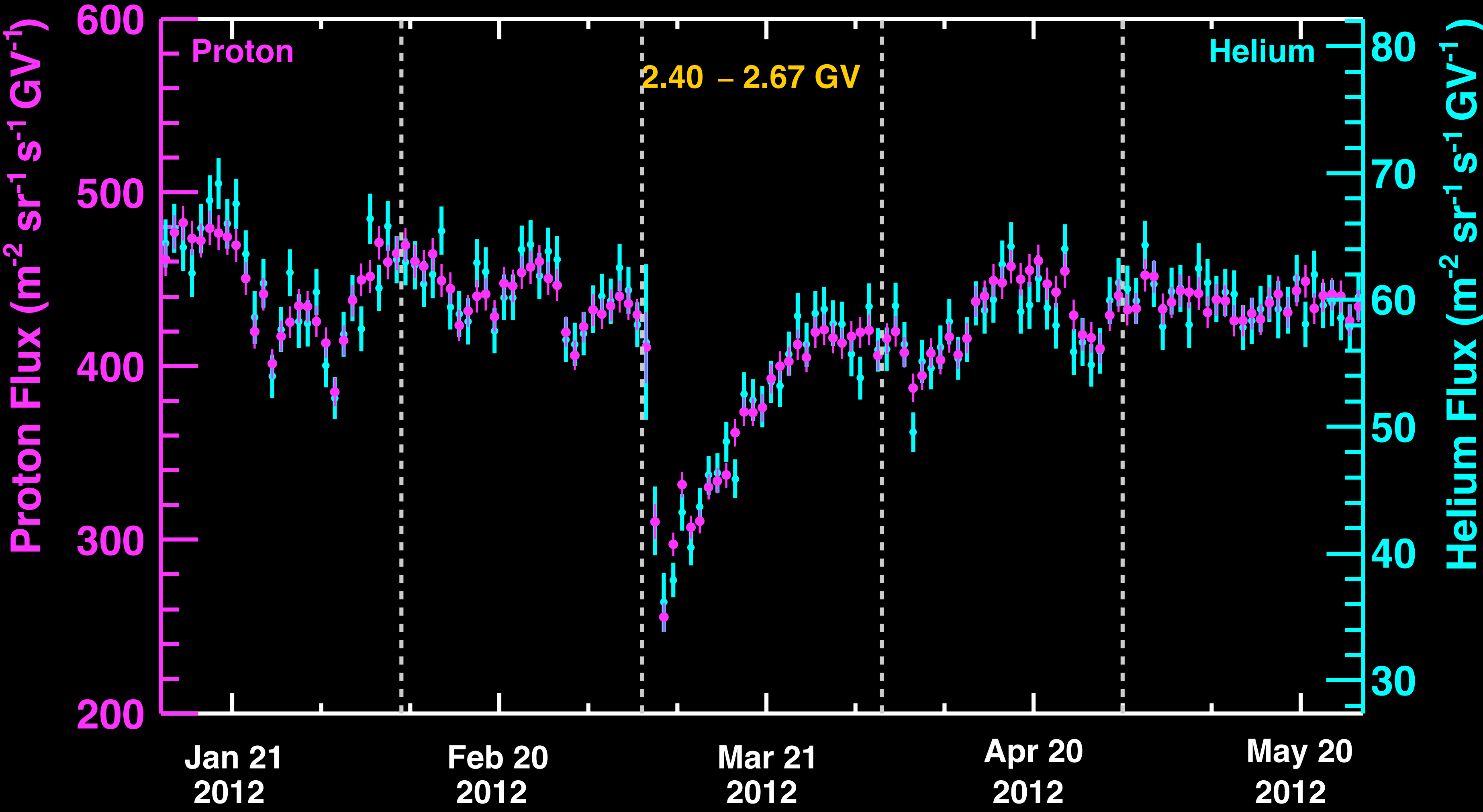


AMS Results on Structures in the positron and electron fluxes in 6 years

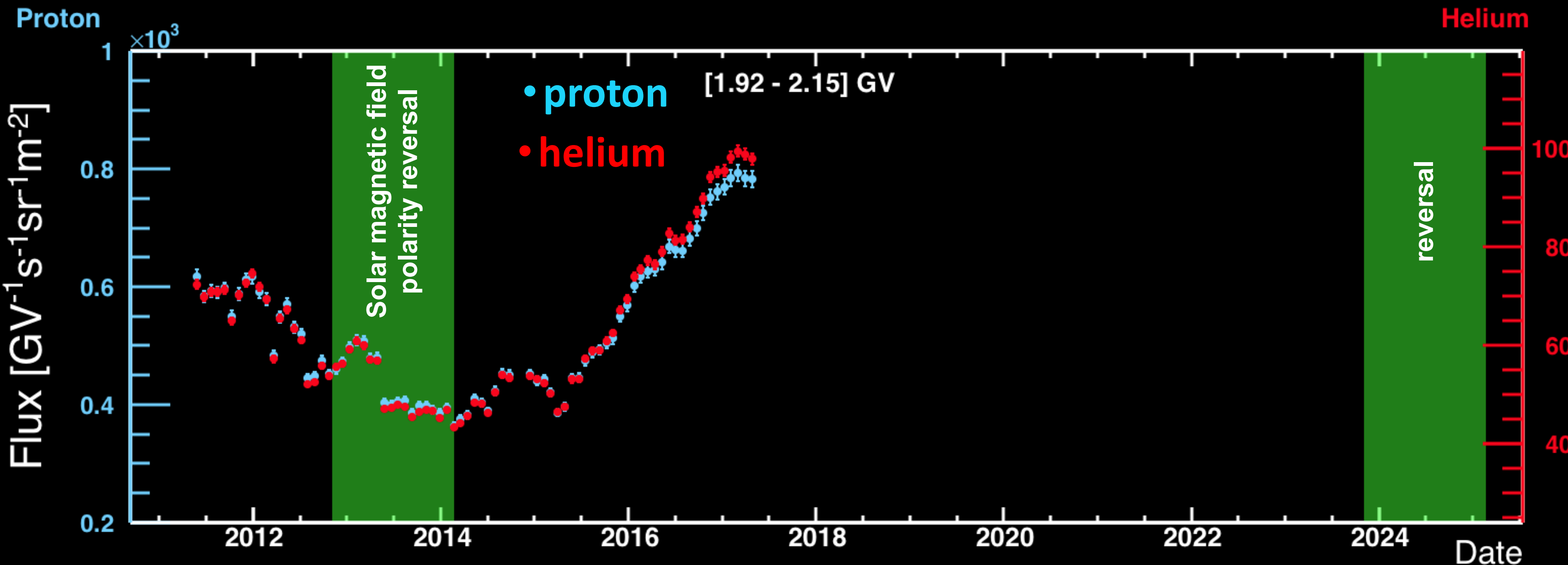


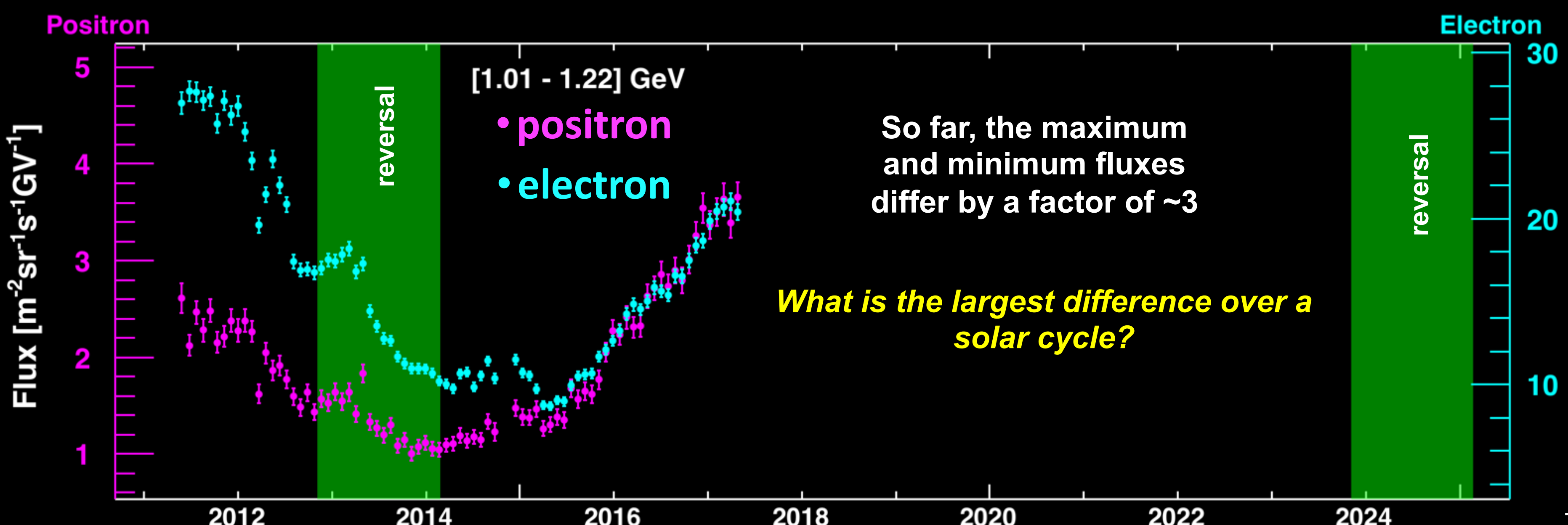
Solar physics

Identical daily time variation of the p, He fluxes



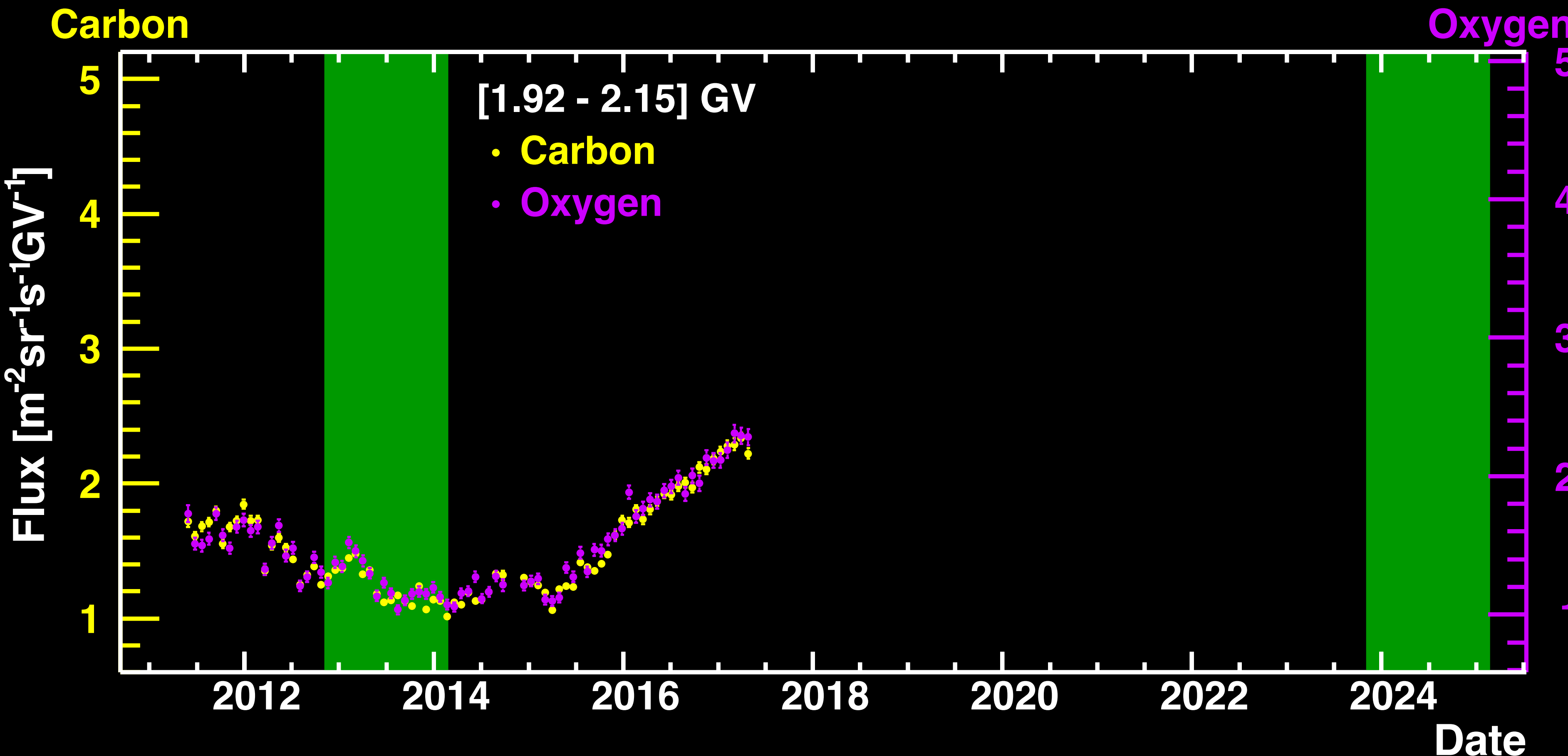
Solar physics over a complete 11-year solar cycle





Solar physics over a complete 11-year solar cycle

Carbon and Oxygen



The maximum and minimum fluxes differ by a factor of ~3

What is the largest difference over a solar cycle?

All AMS Publications in *Physical Review Letters*

These results do not agree with previous measurements.
Explanation of these results require new comprehensive theory.

1) M. Aguilar *et. al*., Phys. Rev. Lett. 110 (2013) 141102. Editor's Suggestion
   Viewpoint in Physics, Highlight of the Year 2013.
2) L. Accardo *et al*., Phys. Rev. Lett. 113 (2014) 121101. Editor's Suggestion
3) M. Aguilar *et. al*., Phys. Rev. Lett. 113 (2014) 121102. Editor's Suggestion
4) M. Aguilar *et. al*., Phys. Rev. Lett. 113 (2014) 221102.
5) M. Aguilar *et. al*., Phys. Rev. Lett. 114 (2015) 171103. Editor's Suggestion
6) M. Aguilar *et. al*., Phys. Rev. Lett. 115 (2015) 211101. Editor's Suggestion
7) M. Aguilar *et. al*., Phys. Rev. Lett. 117 (2016) 091103.
8) M. Aguilar *et. al*., Phys. Rev. Lett. 117 (2016) 231102. Editor's Suggestion
9) M. Aguilar *et. al*., Phys. Rev. Lett. 119 (2017) 251101.
10) M. Aguilar *et. al*., Phys. Rev. Lett. 120 (2018) 021101. Editor's Suggestion
11) M. Aguilar *et. al*., Phys. Rev. Lett. 121 (2018) 051101.
12) M. Aguilar *et. al*., Phys. Rev. Lett. 121 (2018) 051102. Editor's Suggestion
13) M. Aguilar *et. al*., Phys. Rev. Lett. 121 (2018) 051103.
14) M. Aguilar *et. al*., Phys. Rev. Lett. 122 (2019) 041102. Editor's Suggestion
15) M. Aguilar *et. al*., Phys. Rev. Lett. 122 (2019) 101101.
16) M. Aguilar *et. al*., Phys. Rev. Lett. 123 (2019) 181102. Editor's Suggestion

17) M. Aguilar *et. al*., To be submitted to Phys. Rev. Lett.,
    "Rigidity Dependence of Ne, Mg, and Si Cosmic Rays"
18) …

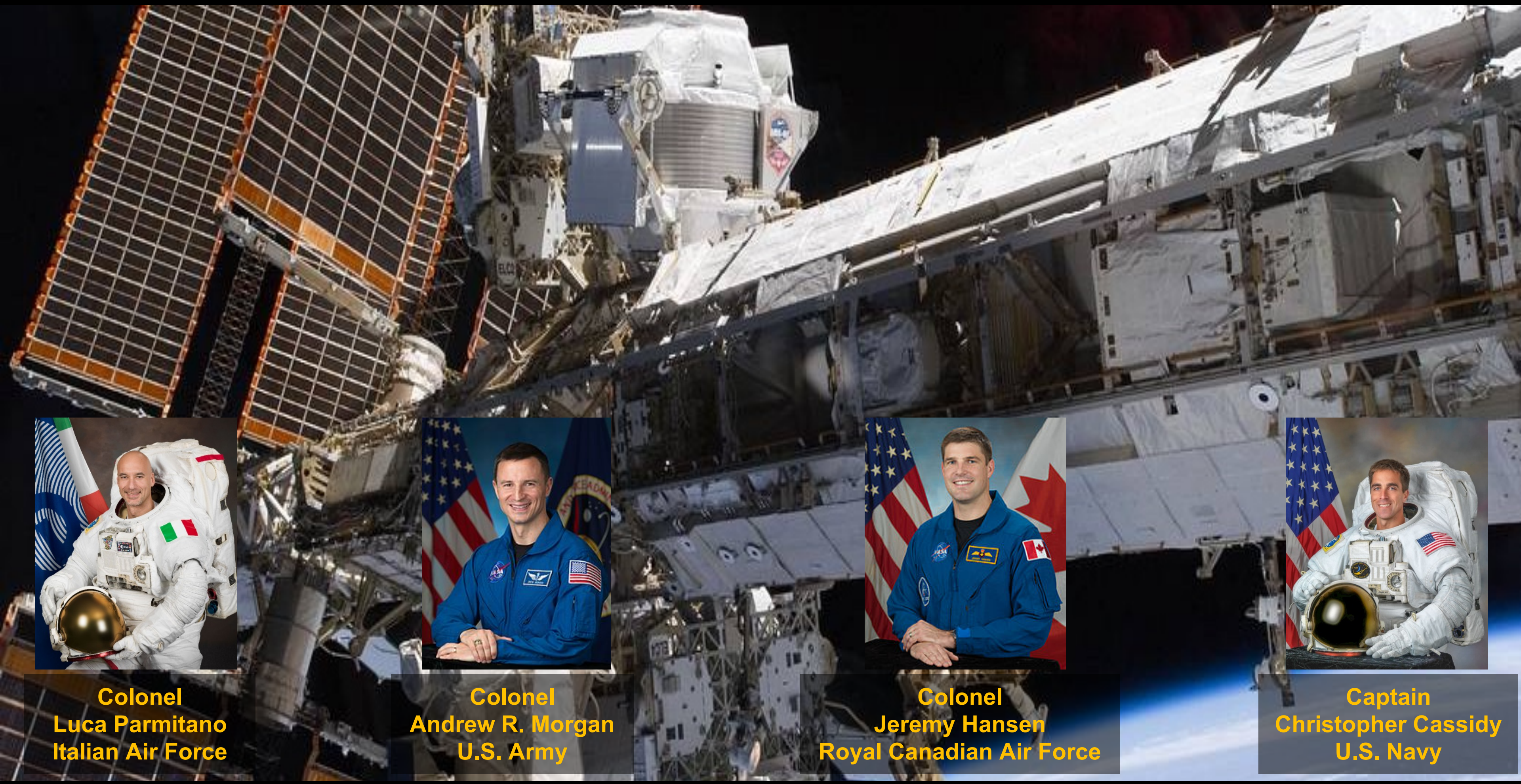
Current state: a nightmare

I. Moskalenko, APS meeting
Washington, Jan. 29, 2017

Aivazovsky: The 9th wave (1850)

After 8 years, the cooling system for the silicon tracker requires an upgrade, known as the UTTPS.

To install it, four EVAs were performed by two astronauts.



Colonel
Luca Parmitano
Italian Air Force

Colonel
Andrew R. Morgan
U.S. Army

Colonel
Jeremy Hansen
Royal Canadian Air Force

Captain
Christopher Cassidy
U.S. Navy

The UTTPS cooling system is made possible through the strong support of NASA, DOE, MIT, DLR, ASI, CSA, and Taiwan

WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the January/February 2020 issue of *CERN Courier*.

On the cover of this issue, NASA astronaut Drew Morgan is photographed 400 km above Earth's surface installing a new coolant system for the Alpha Magnetic Spectrometer (AMS) during a crucial spacewalk on 2 December. Masterminded by charm–quark co-discoverer Sam Ting of MIT, and assembled and overseen by an international team at CERN, AMS has been attached to the International Space Station since 2011. Its various subdetectors, which include a silicon tracker embedded in a 0.15 T magnet, have so far clocked up almost 150 billion charged cosmic rays with energies up to the multi-TeV range and produced results that contradict conventional understanding. The new coolant system (which was delivered by an Antares rocket on 2 November) will extend the lifetime of AMS until the end of the decade, allowing more conclusive statements to be made about the origin of the unexpected observations. A full report on the unprecedented AMS intervention – and a taste of the experiment's latest results – will appear on cerncourier.com following the final extravehicular activity by Drew and his colleagues in mid-January.

Meanwhile, in this issue we investigate an intriguing anomaly in nuclear decay rates seen by the "Atomki" experiment, learn about the wider value of anomalies to phenomenologists, talk to theorist John Ellis about the past, present and future of the field, and explore high-level attempts to solve the flavour puzzle. KATRIN's quest for the neutrino mass, outreach for visually impaired audiences, the latest results from the LHC experiments and careers in visual effects are among other highlights of this first issue of the 2020s.

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EDITOR: MATTHEW CHALMERS, CERN
DIGITAL EDITION CREATED BY IOP PUBLISHING

The accuracy and characteristics of the AMS data on many different types of cosmic rays require the development of a comprehensive model of cosmic rays.

AMS will continue to collect and analyze data for the lifetime of the Space Station because whenever a precision instrument such as AMS is used to explore the unknown, new and exciting discoveries can be expected