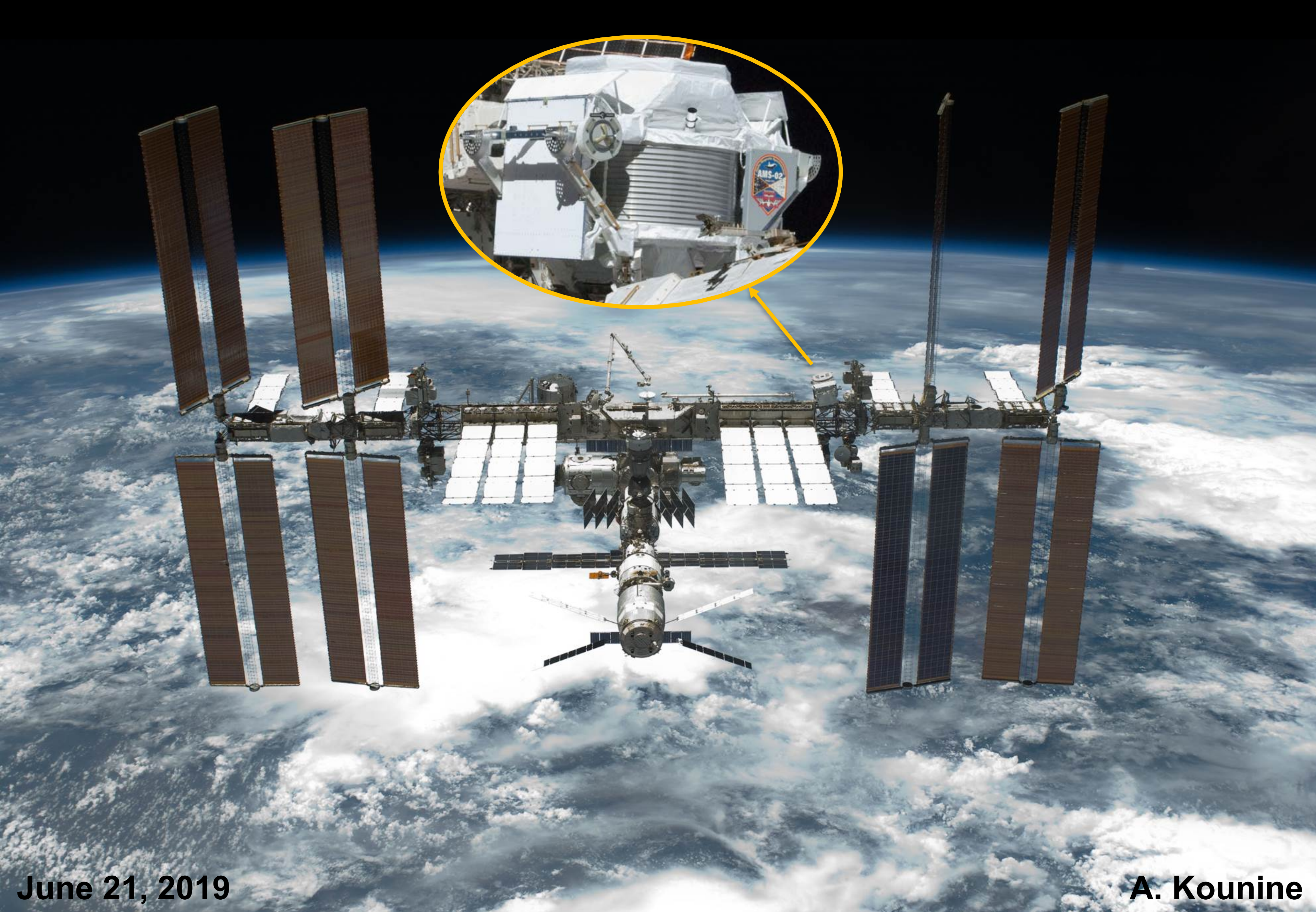
AMS Experiment on the International Space Station



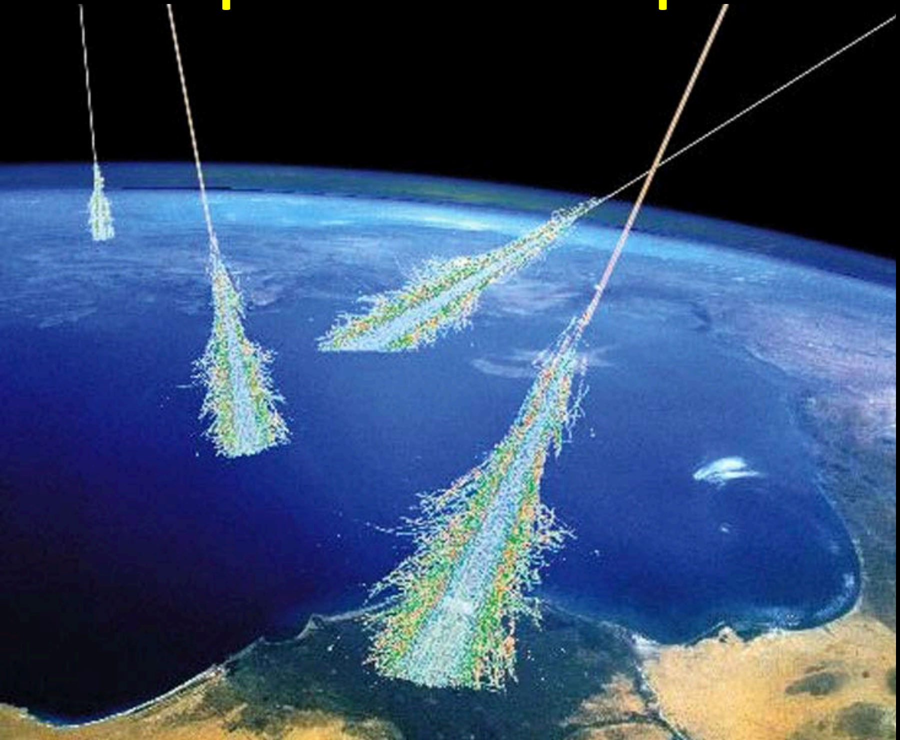
June 21, 2019

A. Kounine

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).

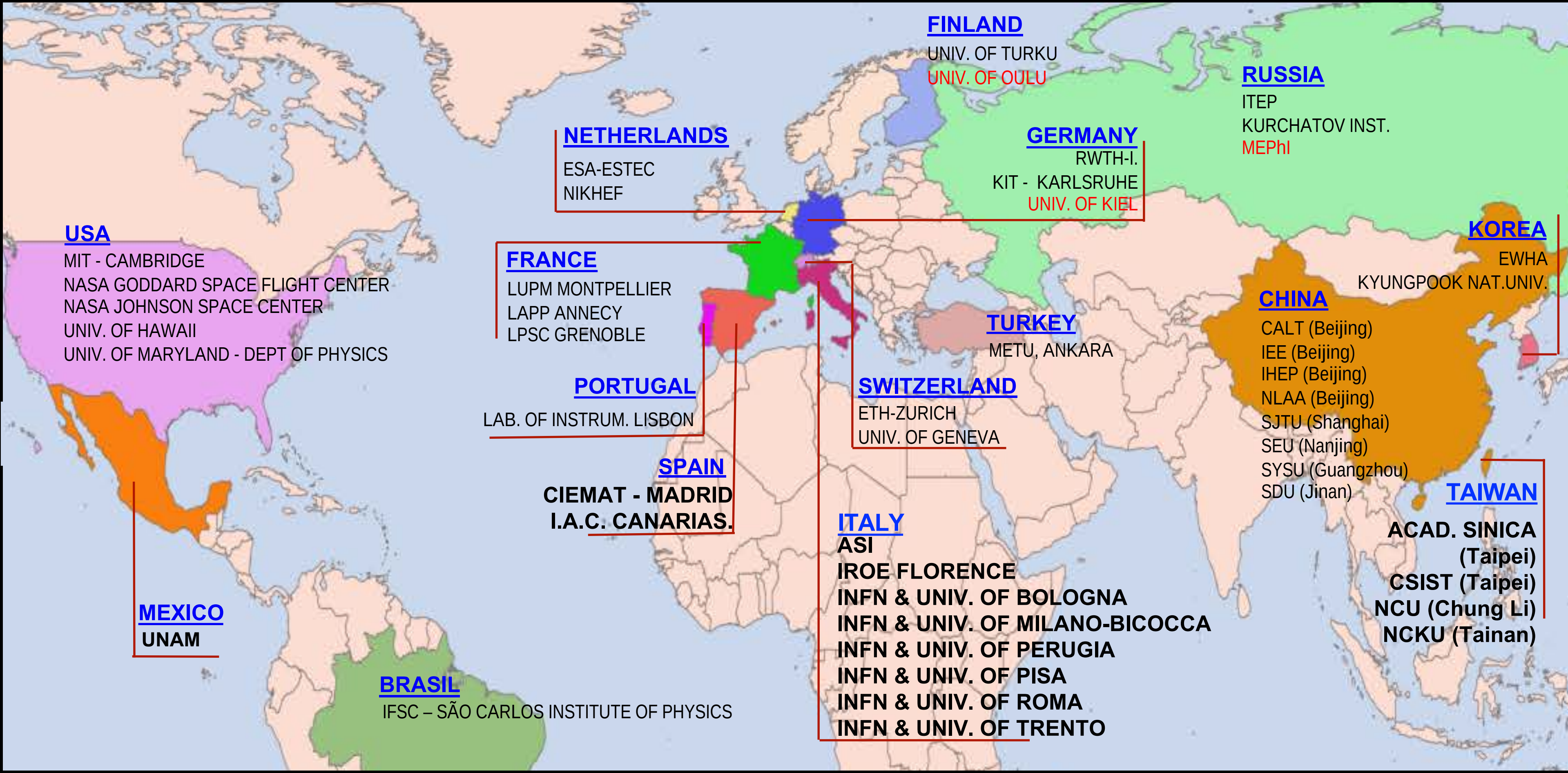
To measure their charge and
momentum requires a magnetic
spectrometer in space.



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

AMS is an International Collaboration

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



FINLAND
UNIV. OF TURKU
UNIV. OF OULU

RUSSIA
ITEP
KURCHATOV INST.
MEPhI

NETHERLANDS
ESA-ESTEC
NIKHEF

GERMANY
RWTH-I.
KIT - KARLSRUHE
UNIV. OF KIEL

USA
MIT - CAMBRIDGE
NASA GODDARD SPACE FLIGHT CENTER
NASA JOHNSON SPACE CENTER
UNIV. OF HAWAII
UNIV. OF MARYLAND - DEPT OF PHYSICS

FRANCE
LUPM MONTPELLIER
LAPP ANNECY
LPSC GRENOBLE

KOREA
EWHA
KYUNGPOOK NAT.UNIV.

CHINA
CALT (Beijing)
IEE (Beijing)
IHEP (Beijing)
NLAA (Beijing)
SJTU (Shanghai)
SEU (Nanjing)
SYSU (Guangzhou)
SDU (Jinan)

TURKEY
METU, ANKARA

PORTUGAL
LAB. OF INSTRUM. LISBON

SWITZERLAND
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TAIWAN
ACAD. SINICA (Taipei)
CSIST (Taipei)
NCU (Chung Li)
NCKU (Tainan)

ITALY
ASI
IROE FLORENCE
INFN & UNIV. OF BOLOGNA
INFN & UNIV. OF MILANO-BICOCCA
INFN & UNIV. OF PERUGIA
INFN & UNIV. OF PISA
INFN & UNIV. OF ROMA
INFN & UNIV. OF TRENTO

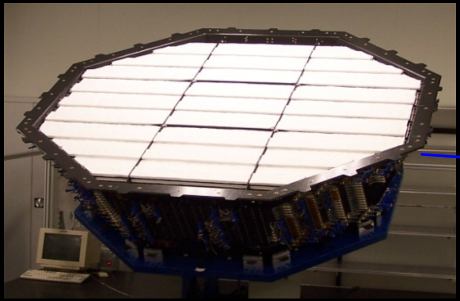
MEXICO
UNAM

BRASIL
IFSC – SÃO CARLOS INSTITUTE OF PHYSICS

It took 650 physicists and engineers 17 years to construct AMS

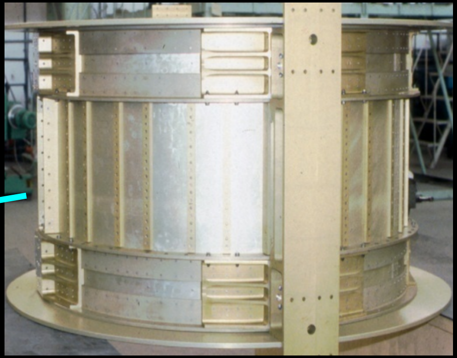
AMS is a space version of a precision detector used in accelerators

Transition Radiation Detector (TRD)

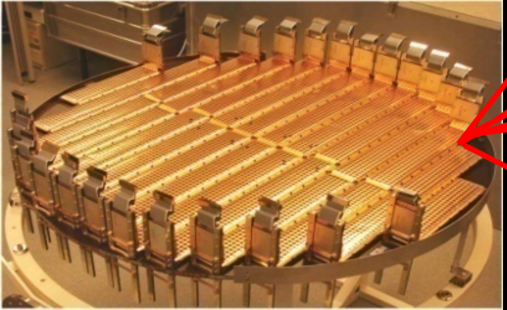


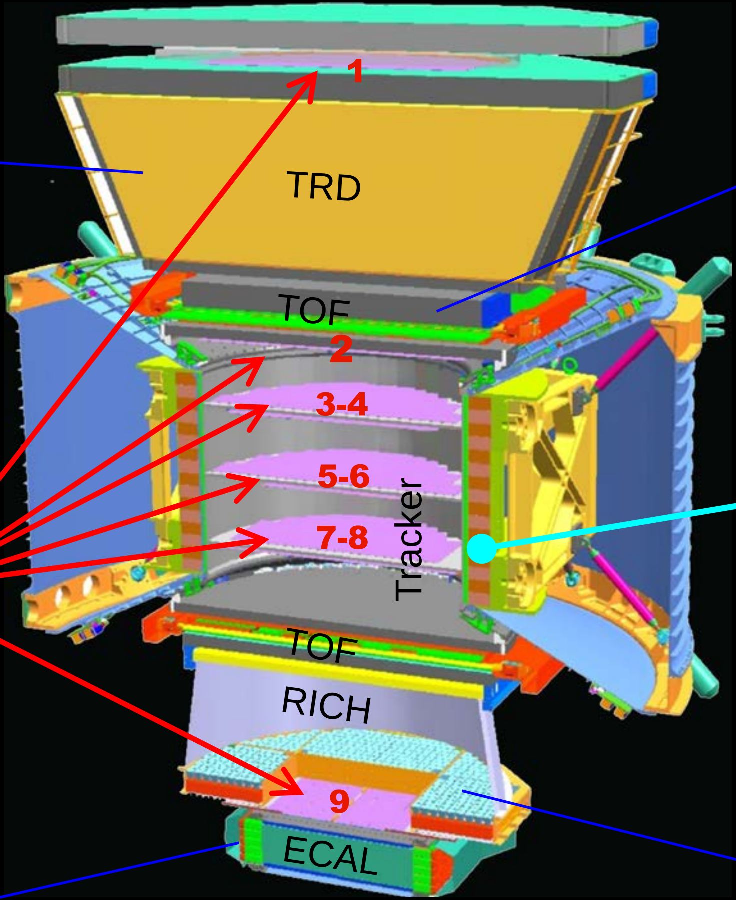
Time of Flight Detector (TOF)

Magnet

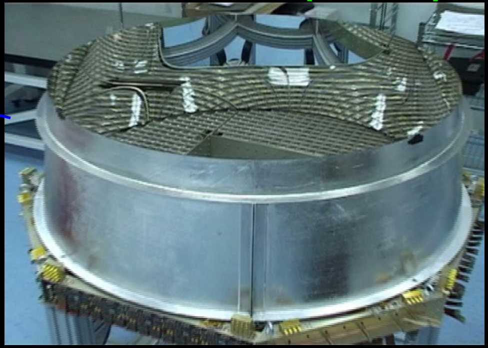


Silicon Tracker





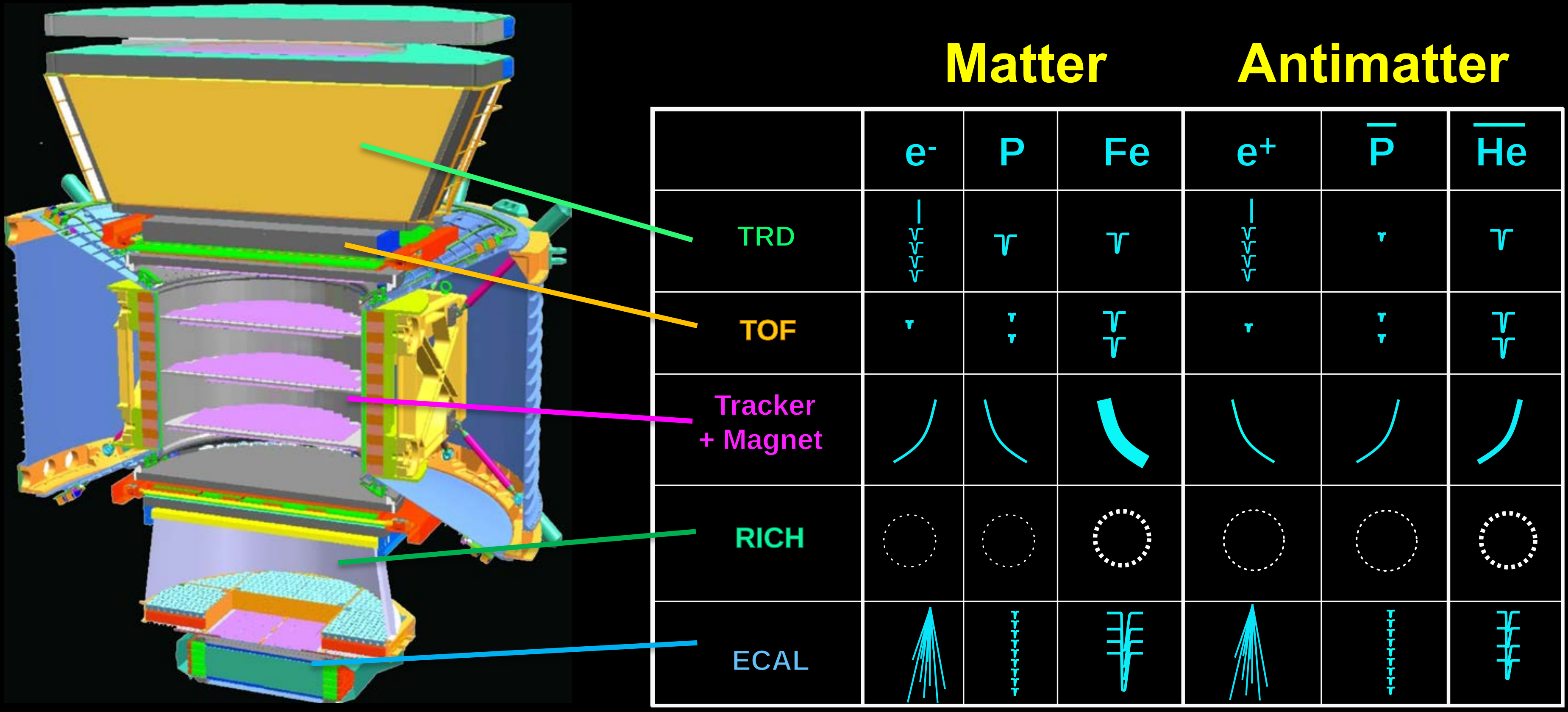
Ring Imaging Cherenkov (RICH)



Electromagnetic Calorimeter (ECAL)

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

AMS is a unique magnetic spectrometer in space

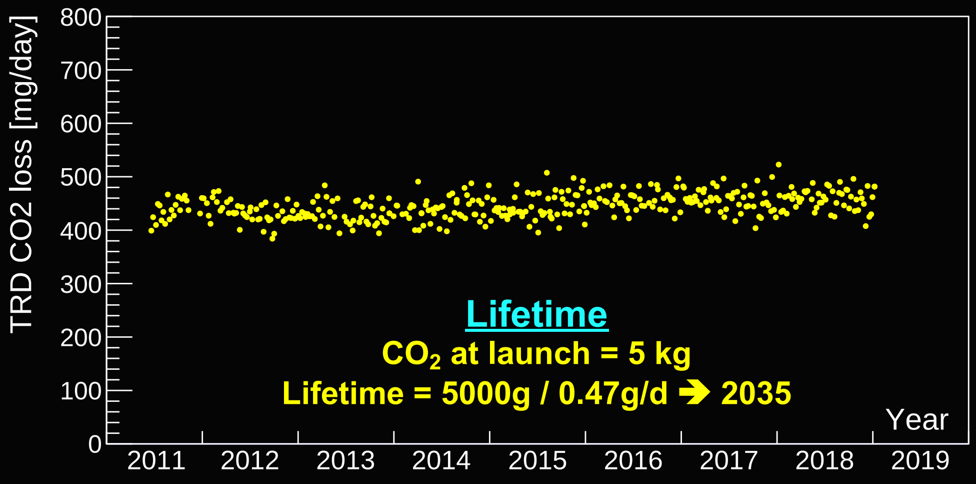


Cosmic rays are defined by:

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

Transition Radiation Detector (TRD) built by RWTH: identifies Positrons and Electrons

5248 tubes



Lifetime

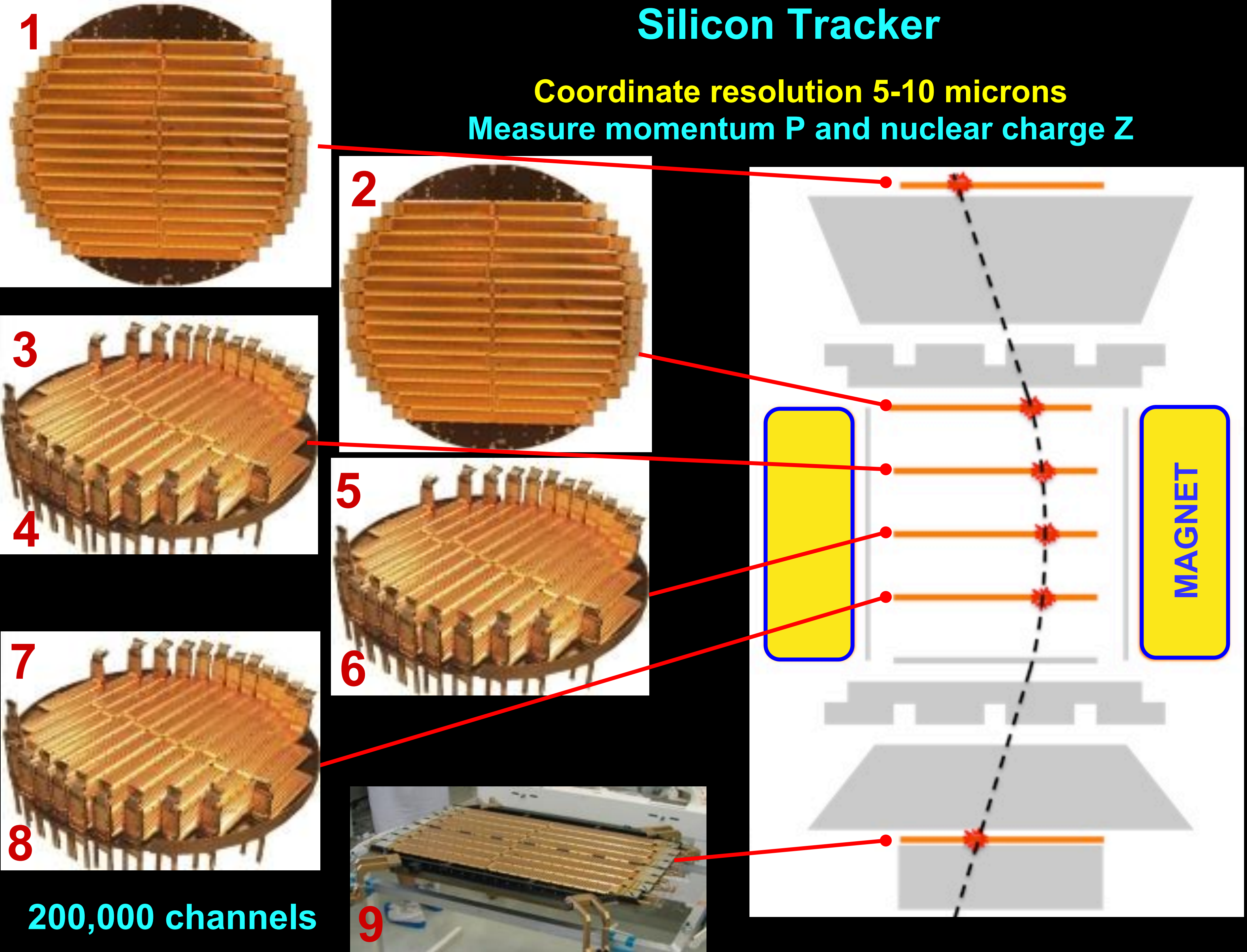
CO_2 at launch = 5 kg

Lifetime = 5000g / 0.47g/d ➔ 2035

Silicon Tracker

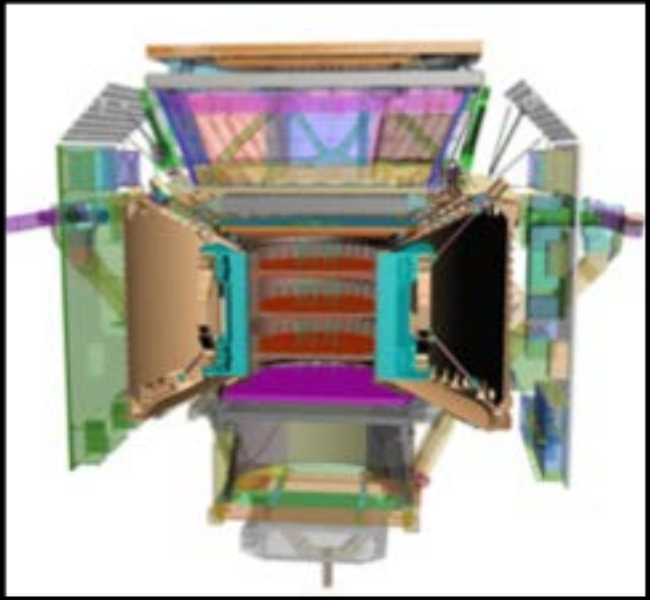
Coordinate resolution 5-10 microns

Measure momentum P and nuclear charge Z

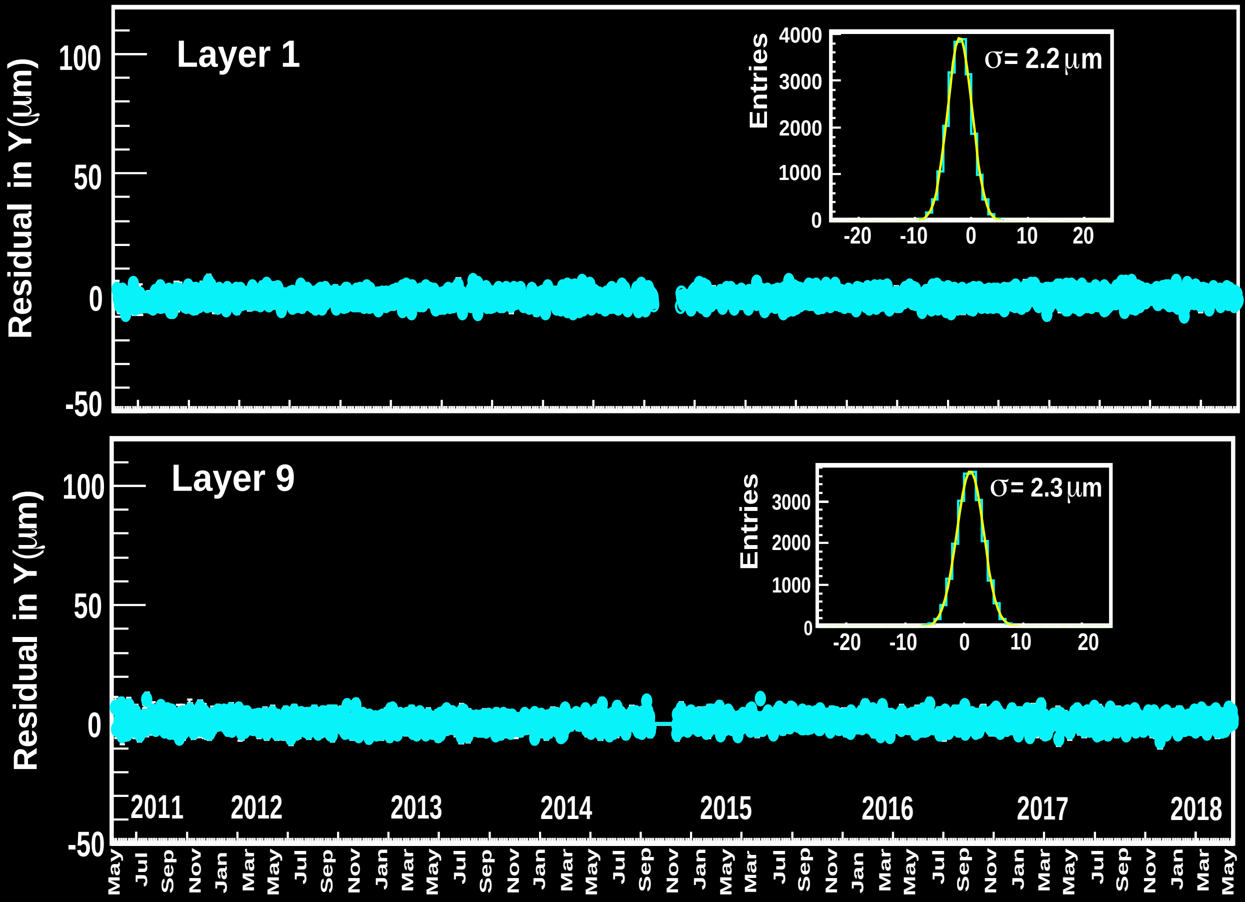


200,000 channels

Tracker stable to 2 microns over eight years



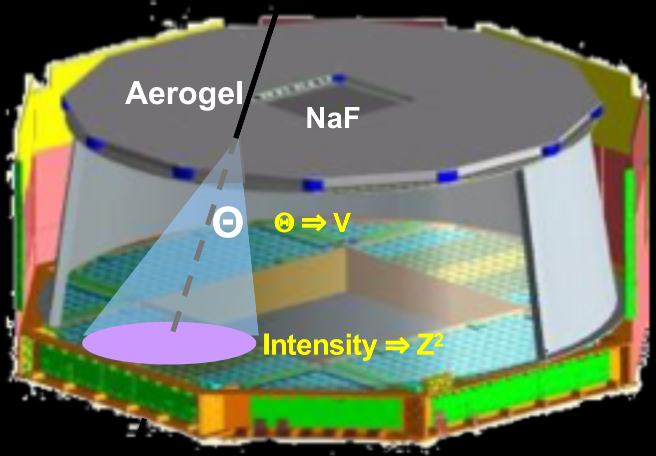
Inner tracker alignment (< 1 micron) monitored with IR lasers (RWTH).

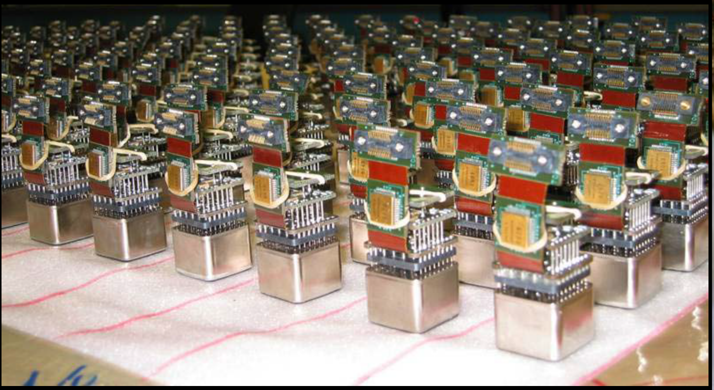


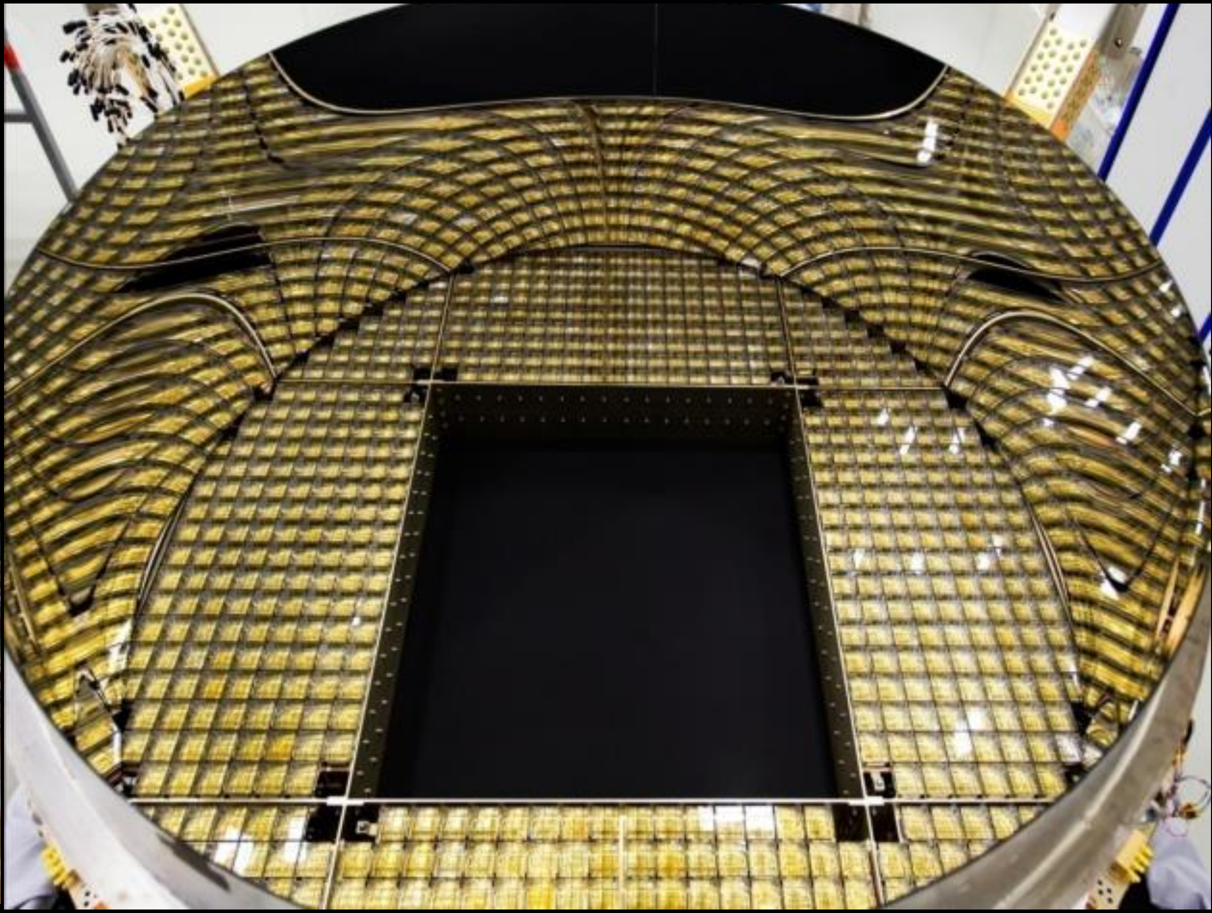
Outer tracker stable to 2 micron over 8 years

Ring Imaging CHerenkov (RICH)

Measurement of Nuclear Charge and its Velocity to 1/1000

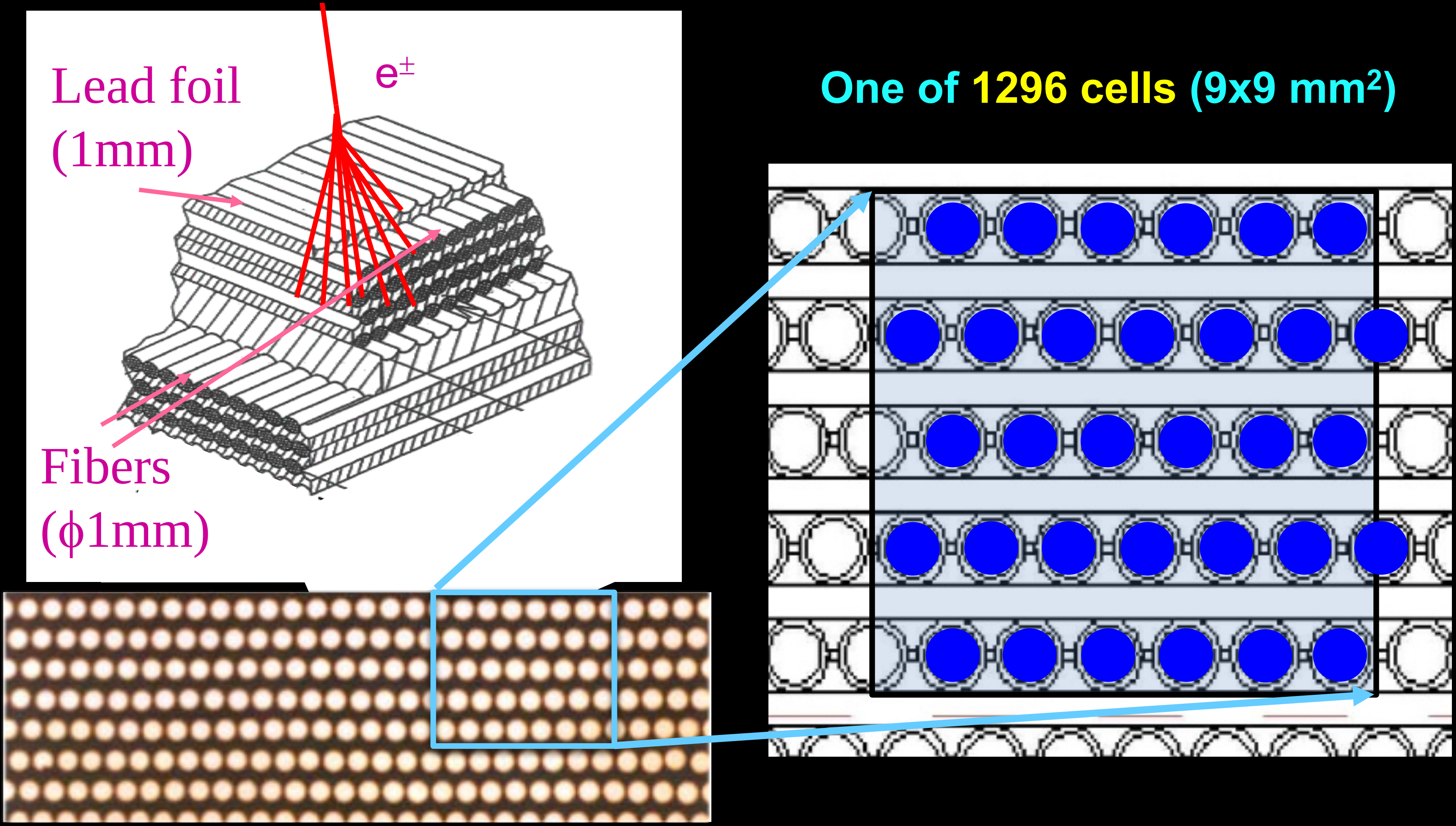






10,880 photosensors

Electromagnetic Calorimeter (ECAL) to measure the highest energy electrons are in space



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

AMS Electronics

464 boards on orbit of 70 different types.

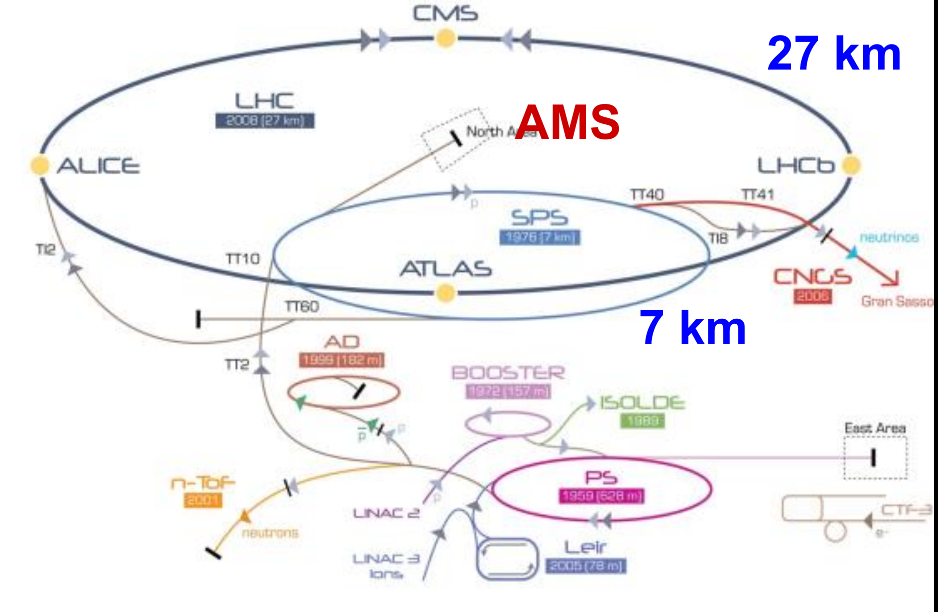
Total of 300,000 channels producing 7 Gbit/s processed by 650 computers to <10 Mbit/s>

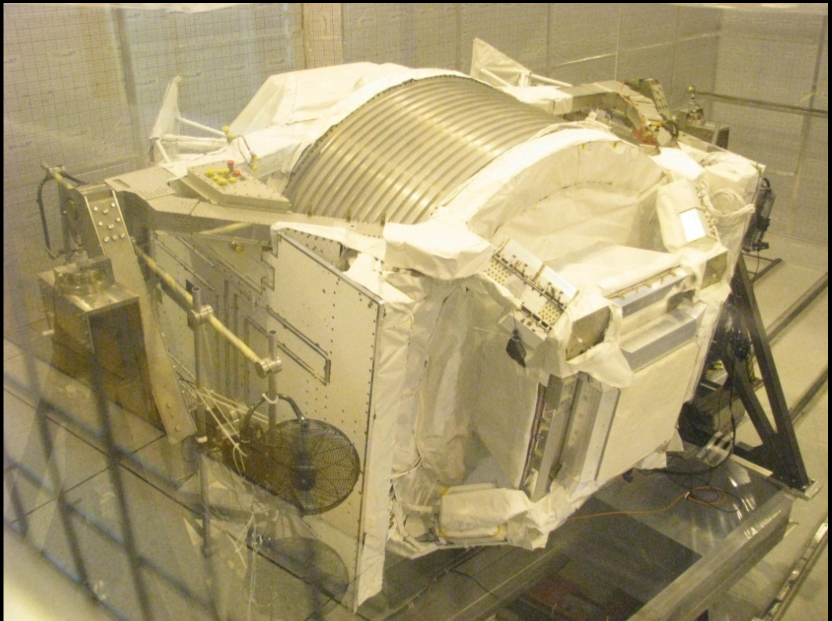
Taiwan provided 70 engineers for 10 years.

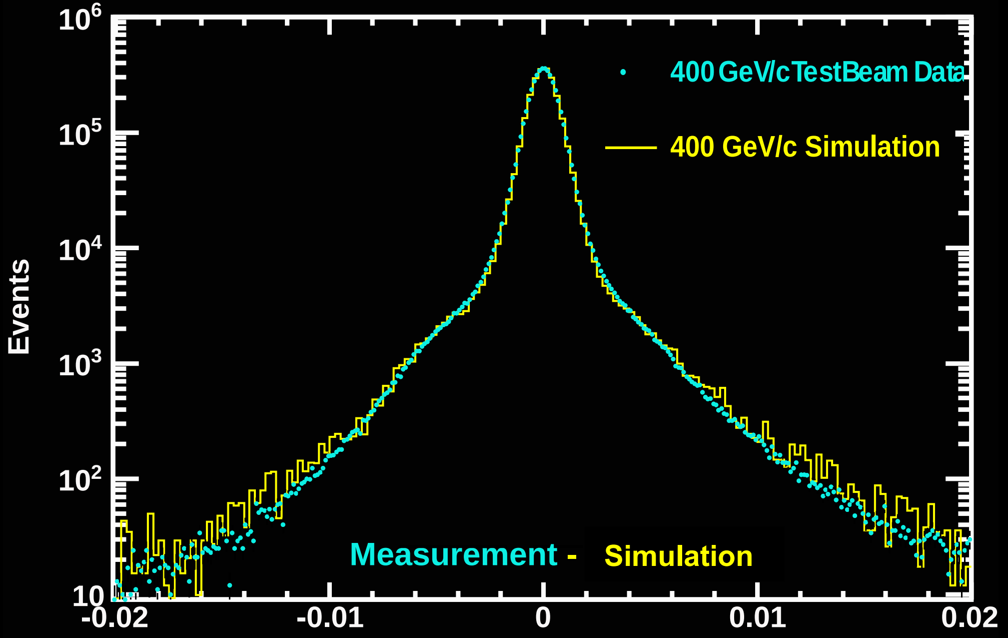
In 8 years on the ISS, the 650 microprocessors are functioning flawlessly

Calibration at CERN

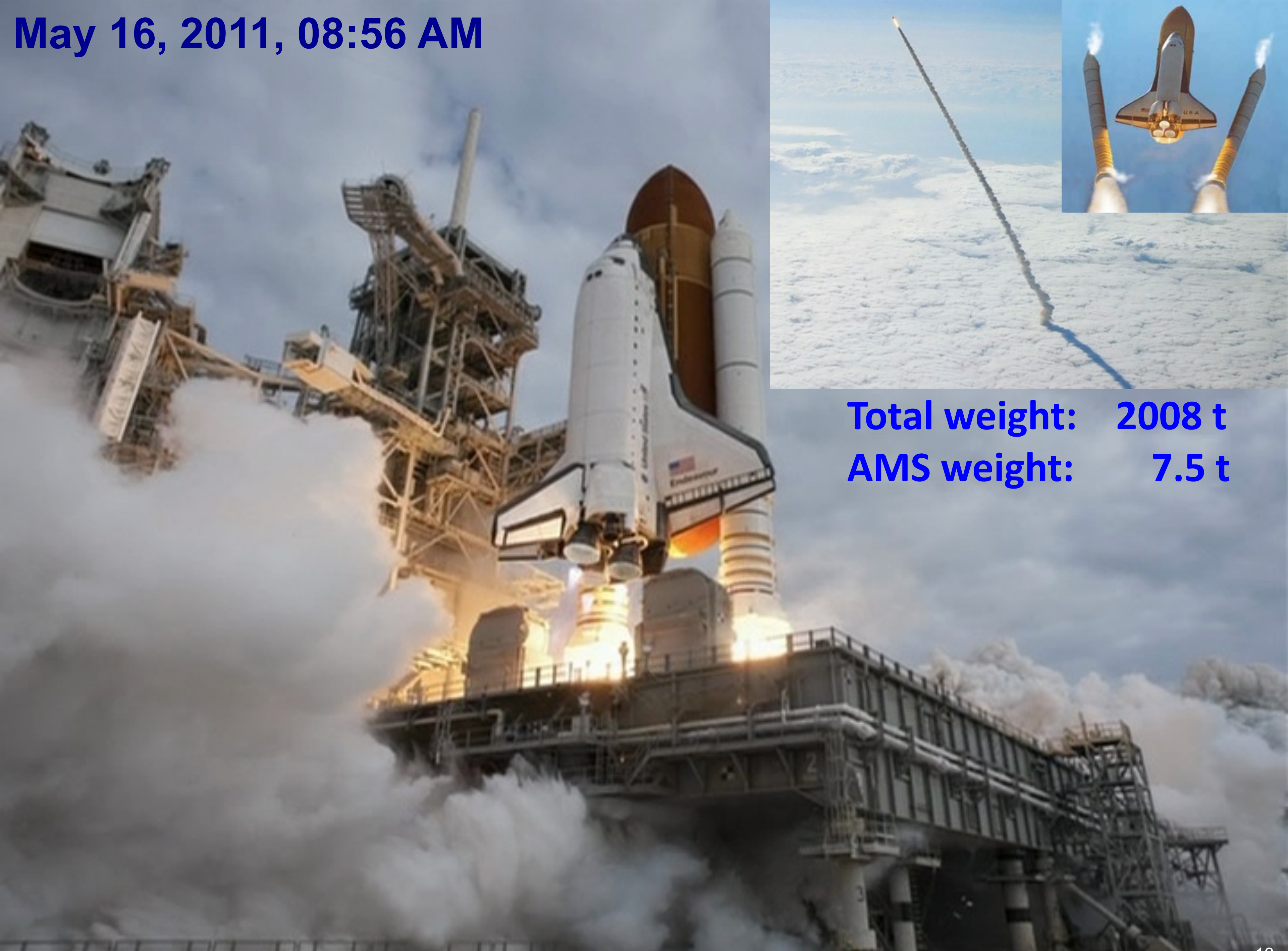
with different particles at different energies





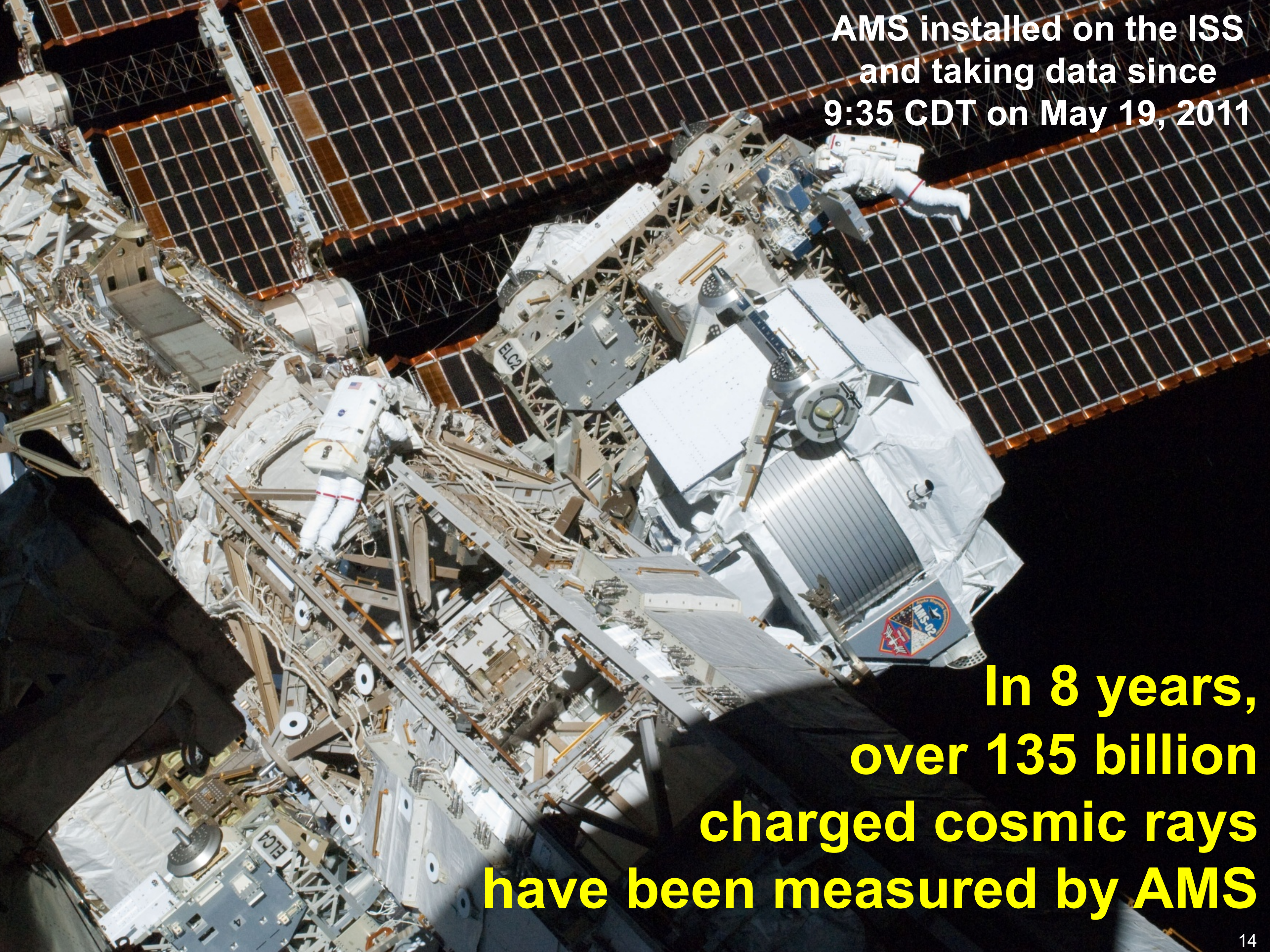


May 16, 2011, 08:56 AM



Total weight: 2008 t

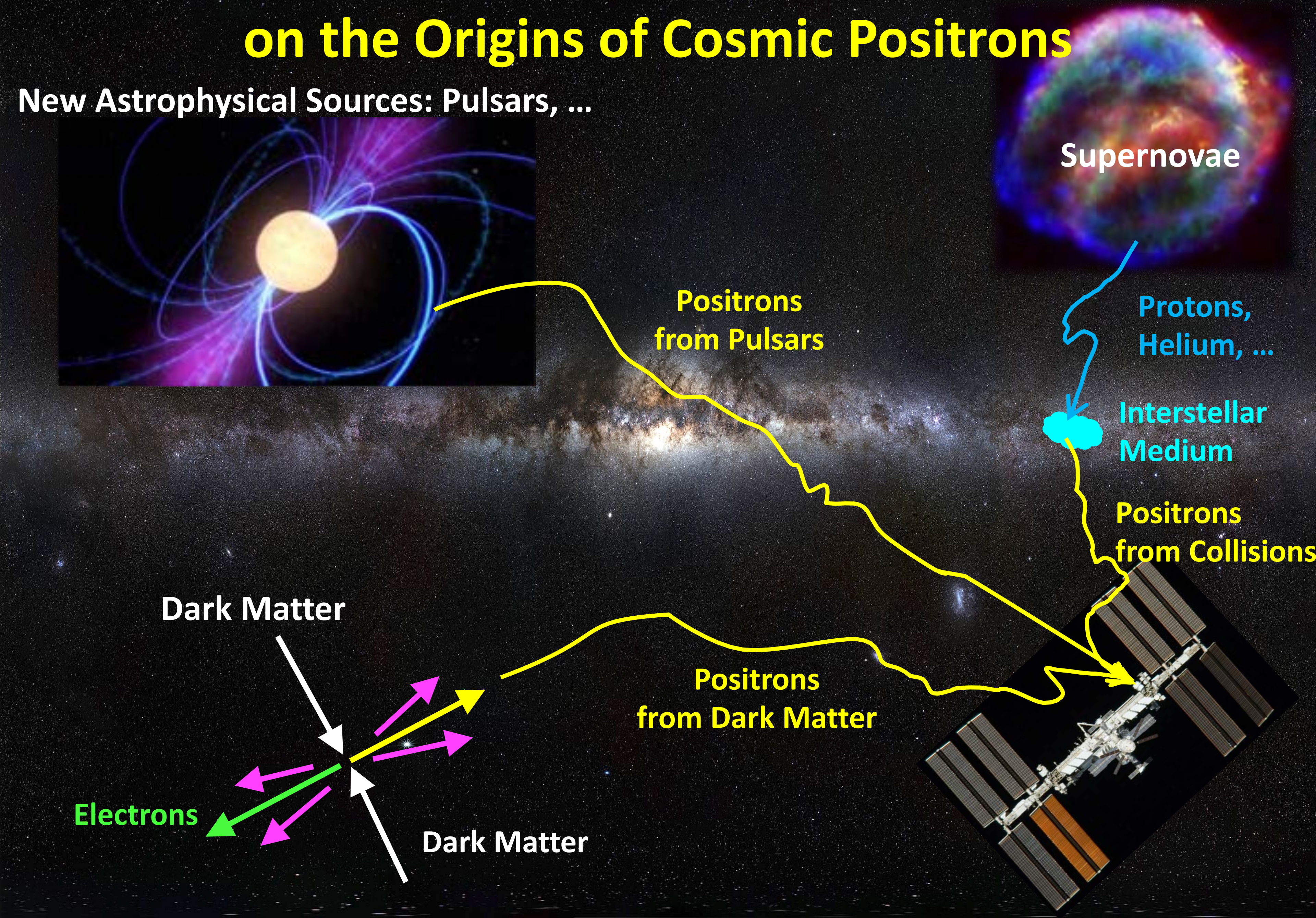
AMS weight: 7.5 t



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

In 8 years,
over 135 billion
charged cosmic rays
have been measured by AMS

AMS Physics Results:
on the Origins of Cosmic Positrons



New Astrophysical Sources: Pulsars, …

Supernovae

Positrons
from Pulsars

Protons,
Helium, …

Interstellar
Medium

Positrons
from Collisions

Dark Matter

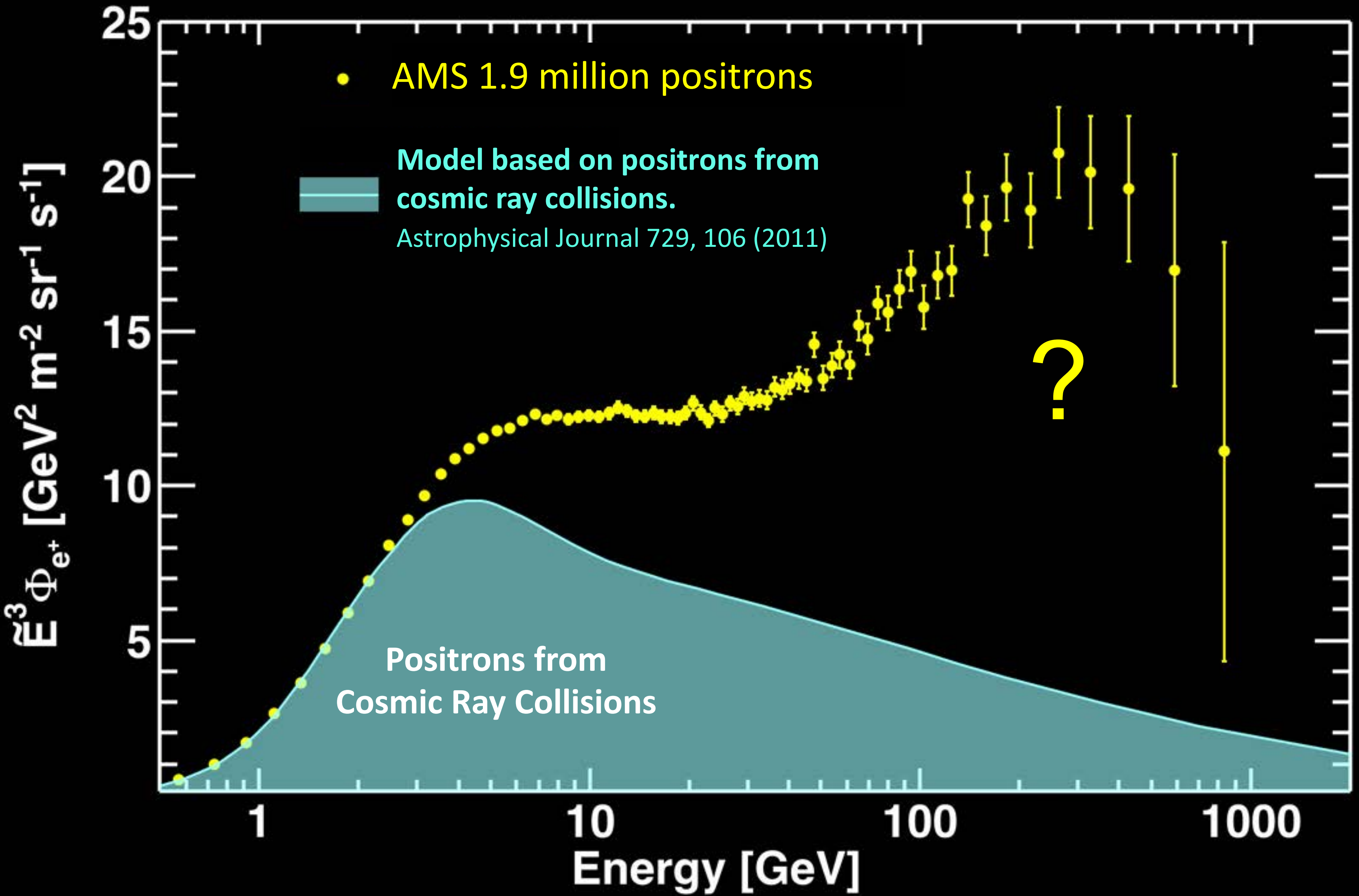
Positrons
from Dark Matter

Electrons

Dark Matter

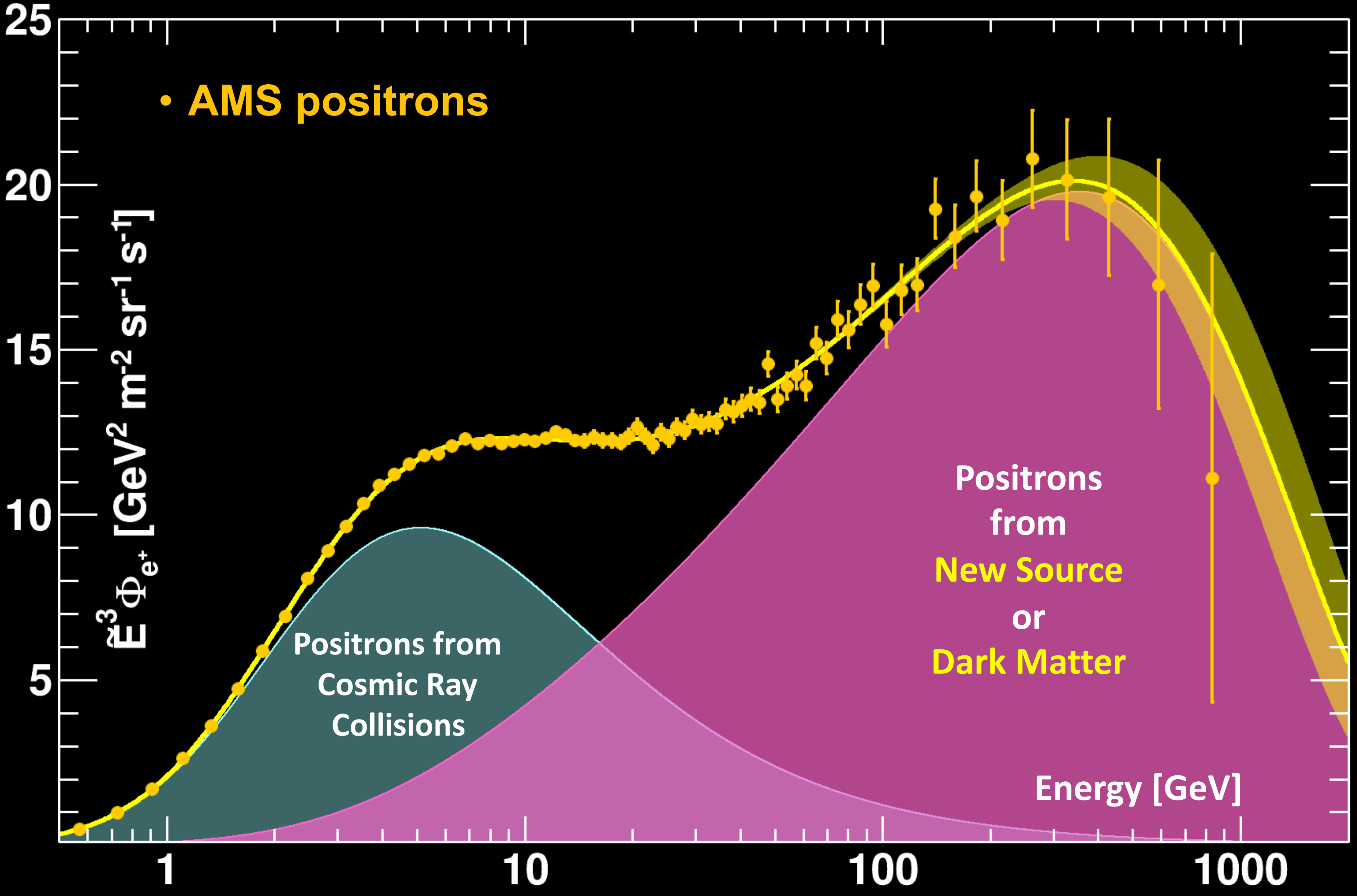
The Origin of Positrons

Low energy positrons mostly come from cosmic ray collisions



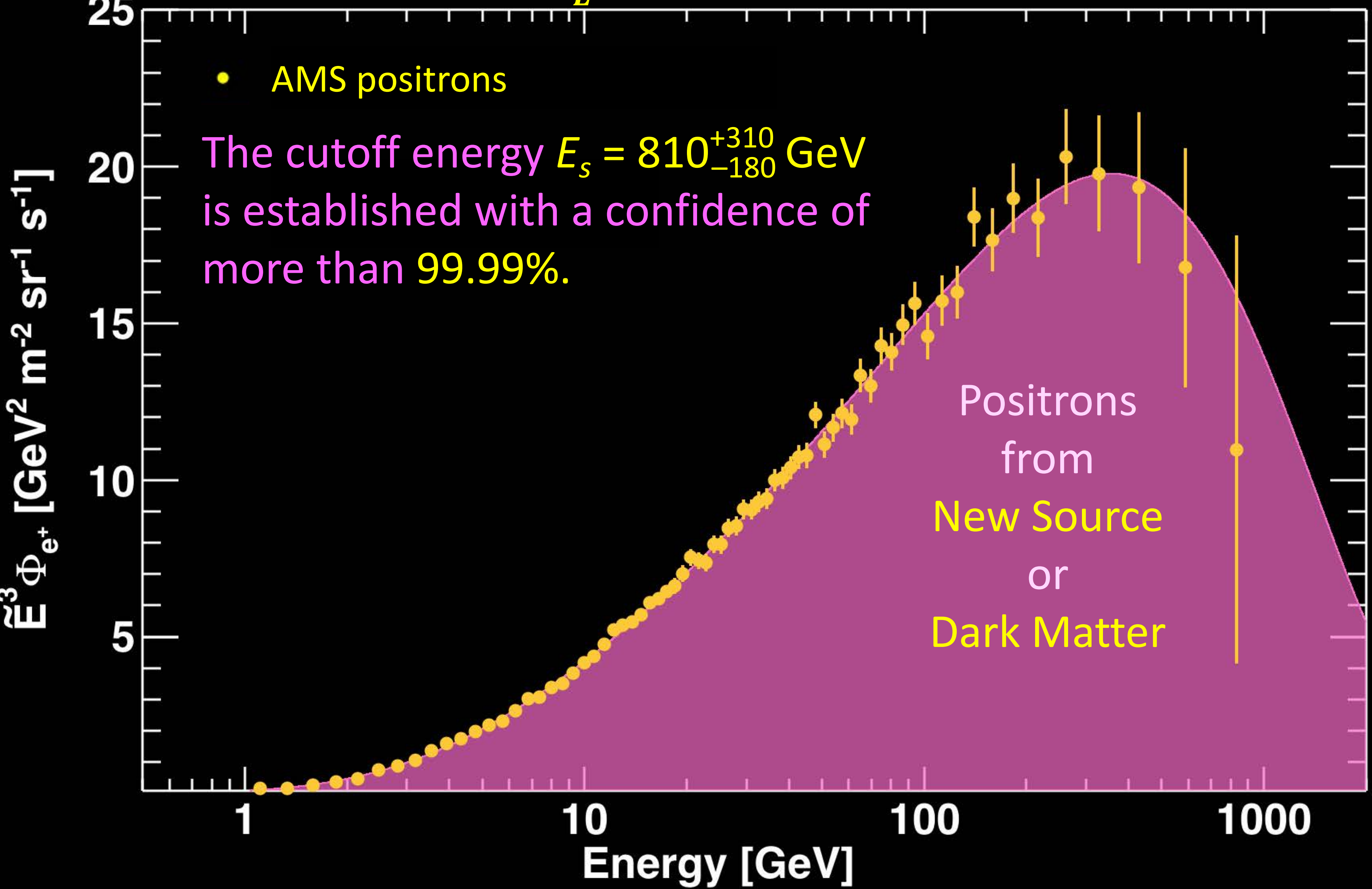
The positron flux is the sum of low-energy part from cosmic ray collisions plus a high-energy part from a new source or dark matter both with a cutoff energy E_S.

$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\Big[\underbrace{C_d(\hat{E}/E_1)^{\gamma_d}}_{\text{Collisions}} + \underbrace{C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)}_{\text{New Source or Dark Matter}}\Big]$$



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

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



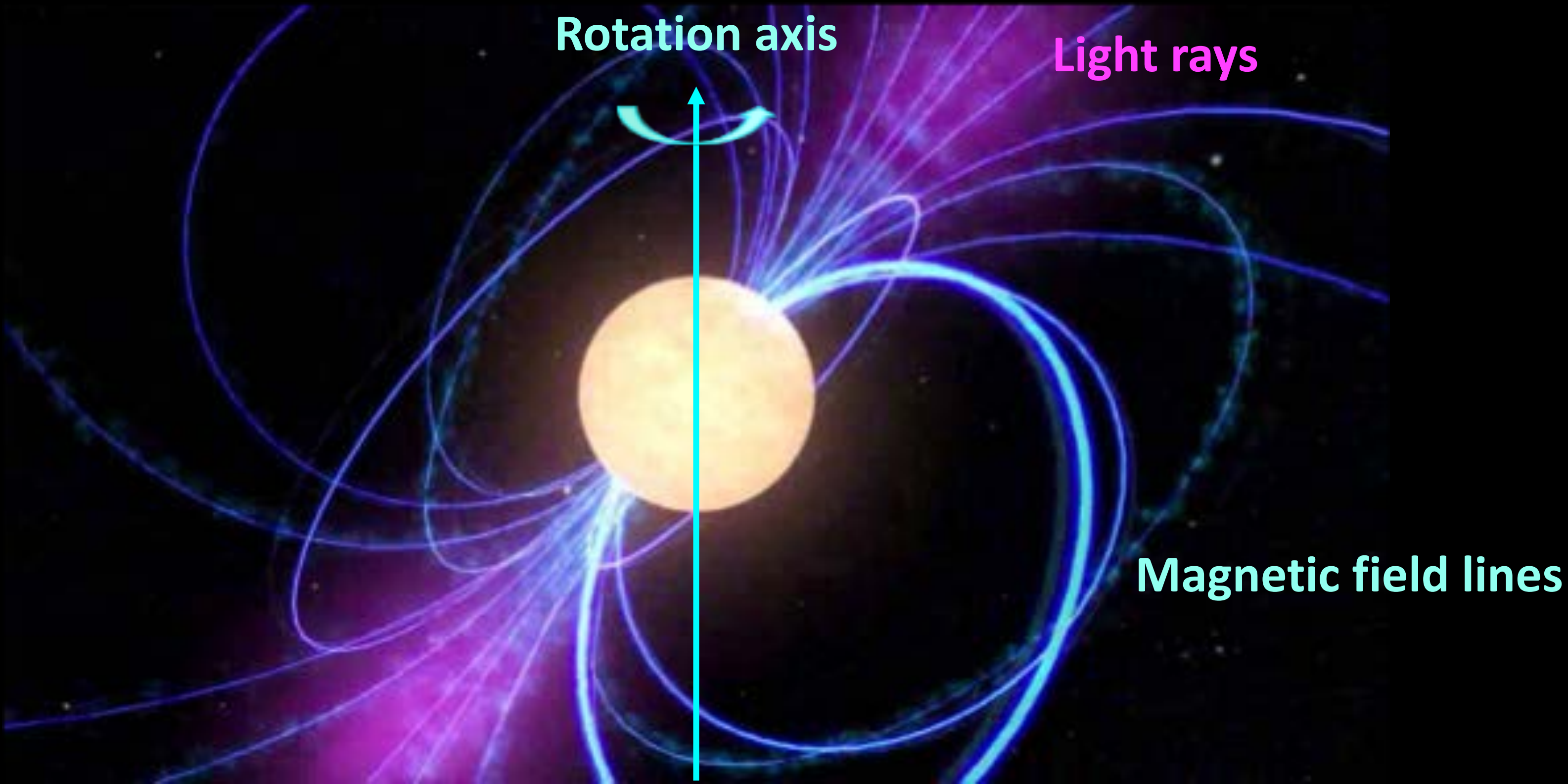
The cutoff energy $E_s = 810^{+310}_{-180}$ GeV is established with a confidence of more than 99.99%.

Positrons from New Source or Dark Matter

Positrons from Pulsars

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

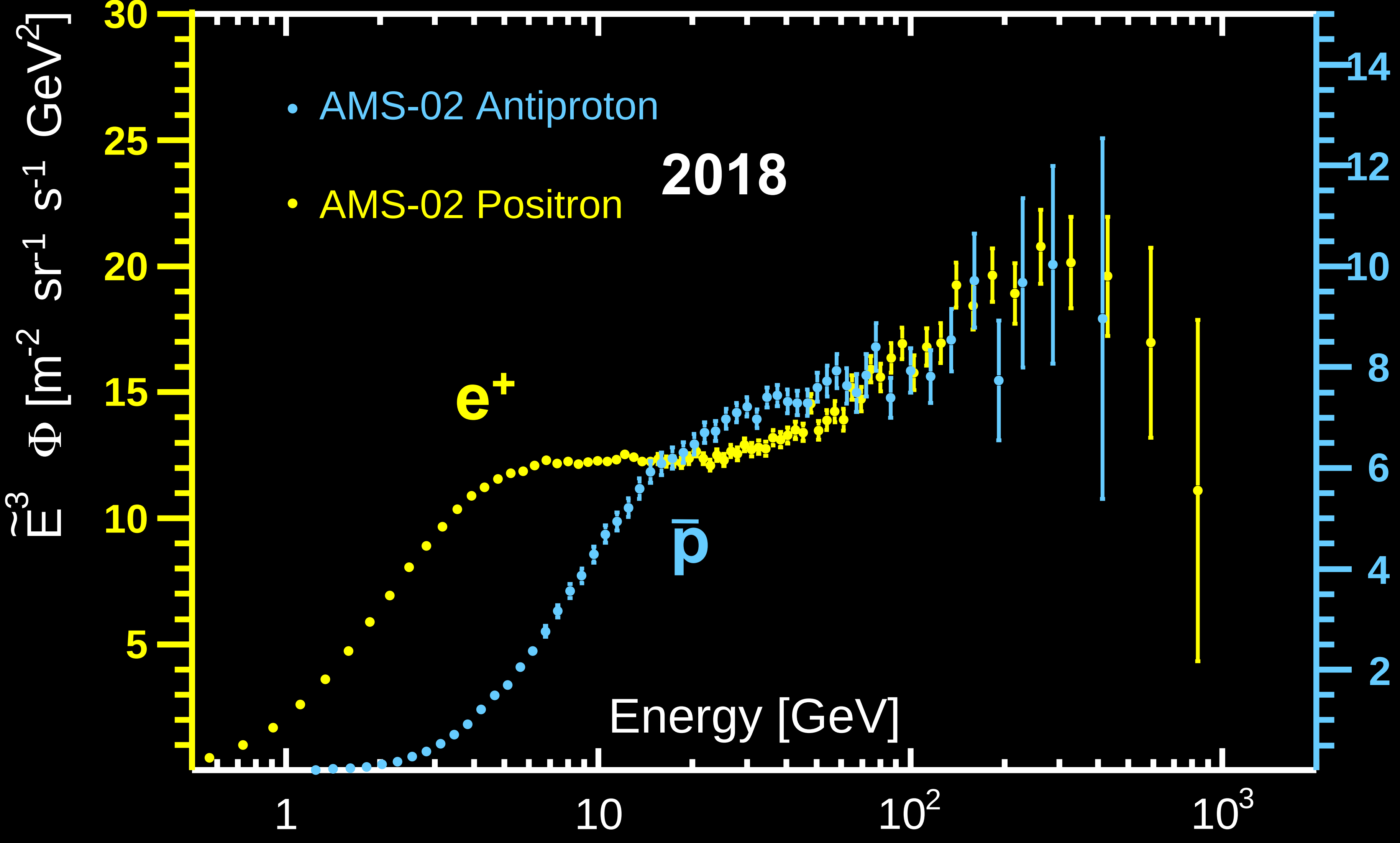
2. Pulsars do not produce antiprotons.



AMS Physics Results:

Antiproton data show a similar trend as positrons.

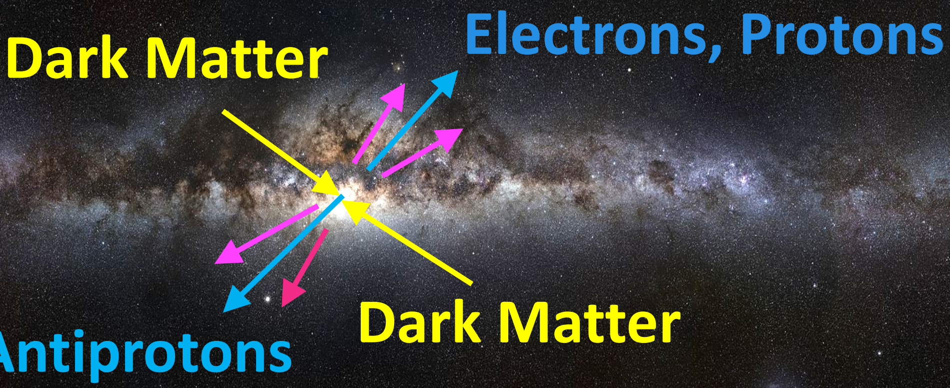
Antiprotons cannot come from pulsars.



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 $\approx 2M$.



Dark Matter

Electrons, Protons

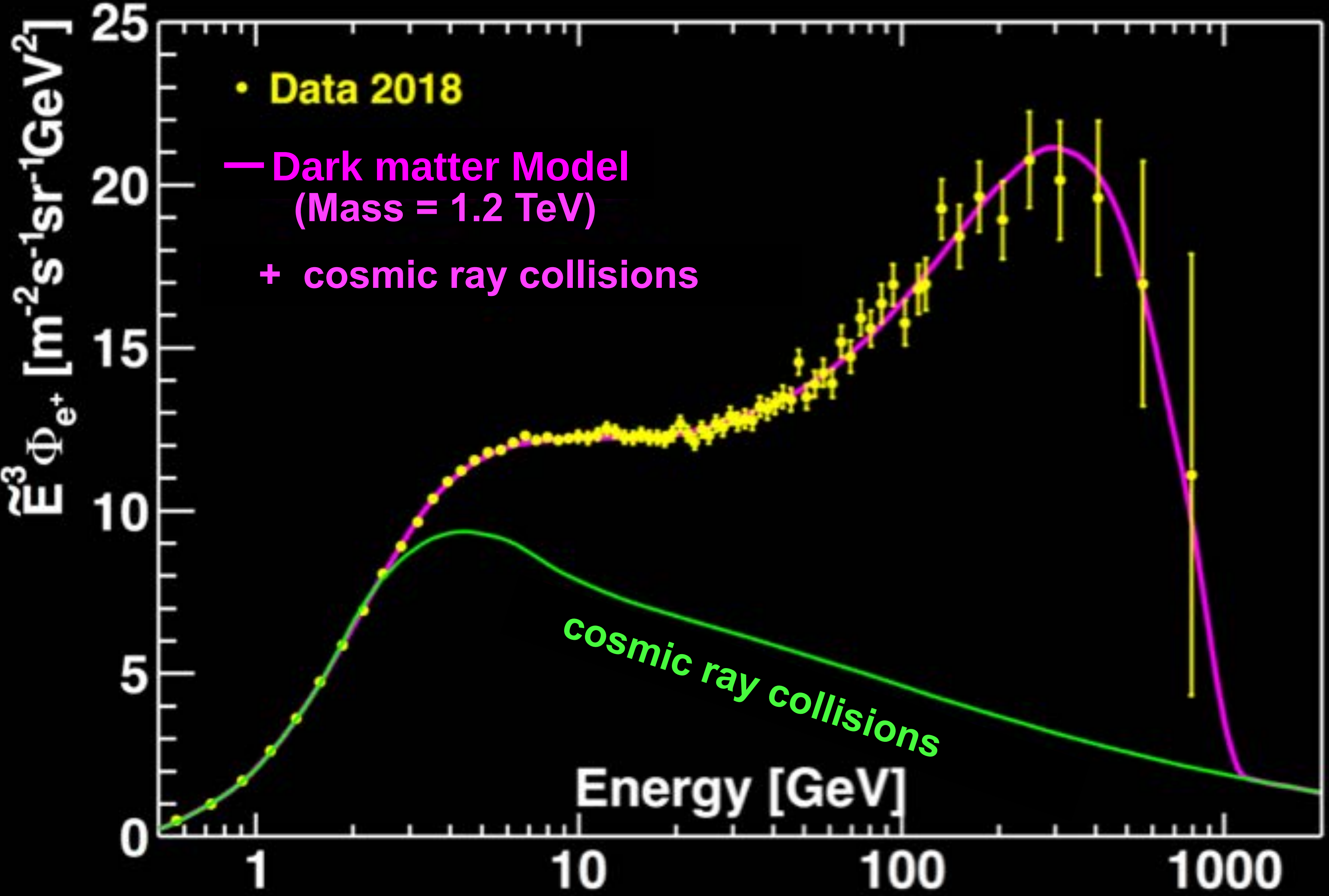
Dark Matter

Positrons, Antiprotons

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

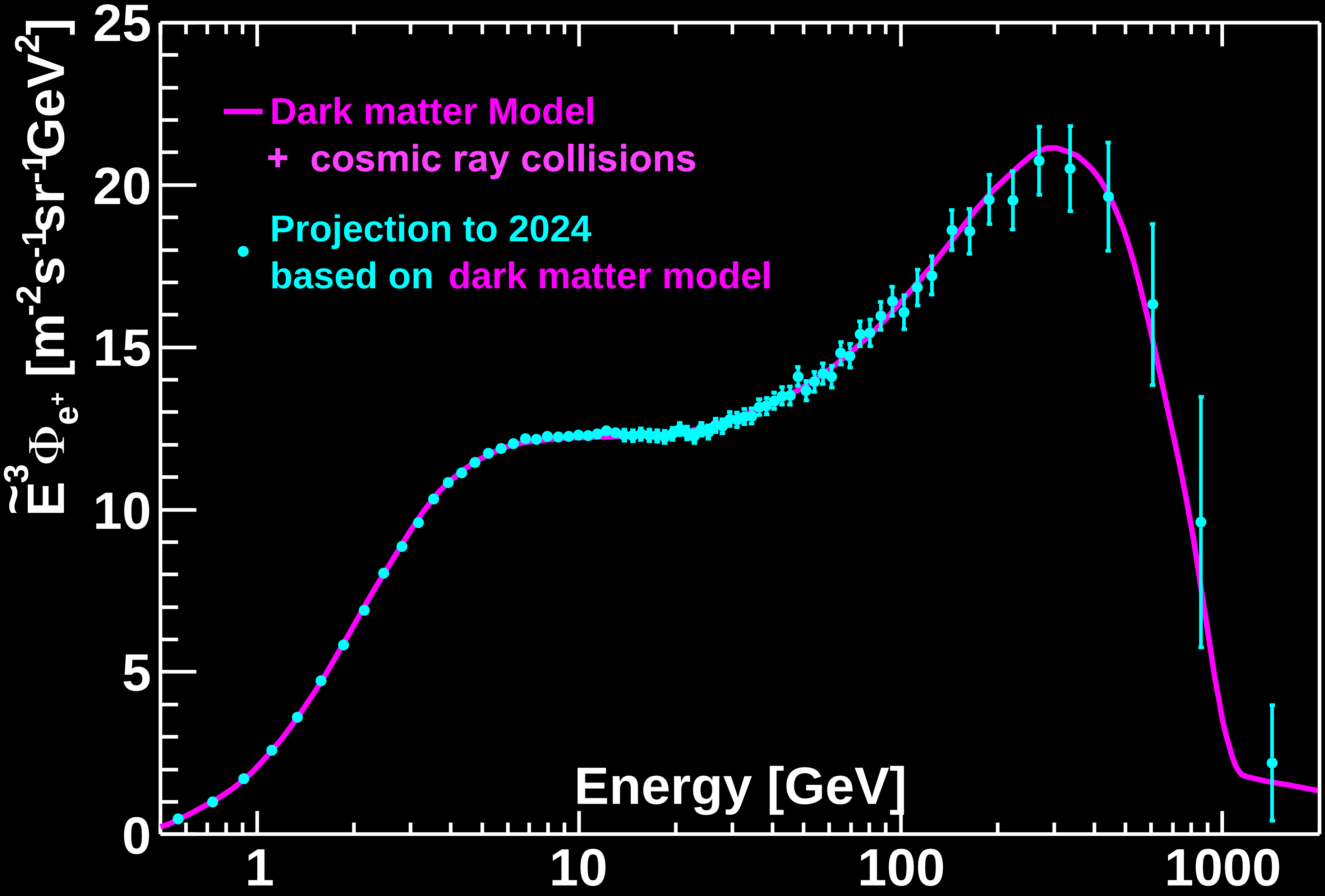
So, there is a sharp cutoff in the spectra at M.

Positrons and Dark Matter 2018



Positrons and Dark Matter by 2024

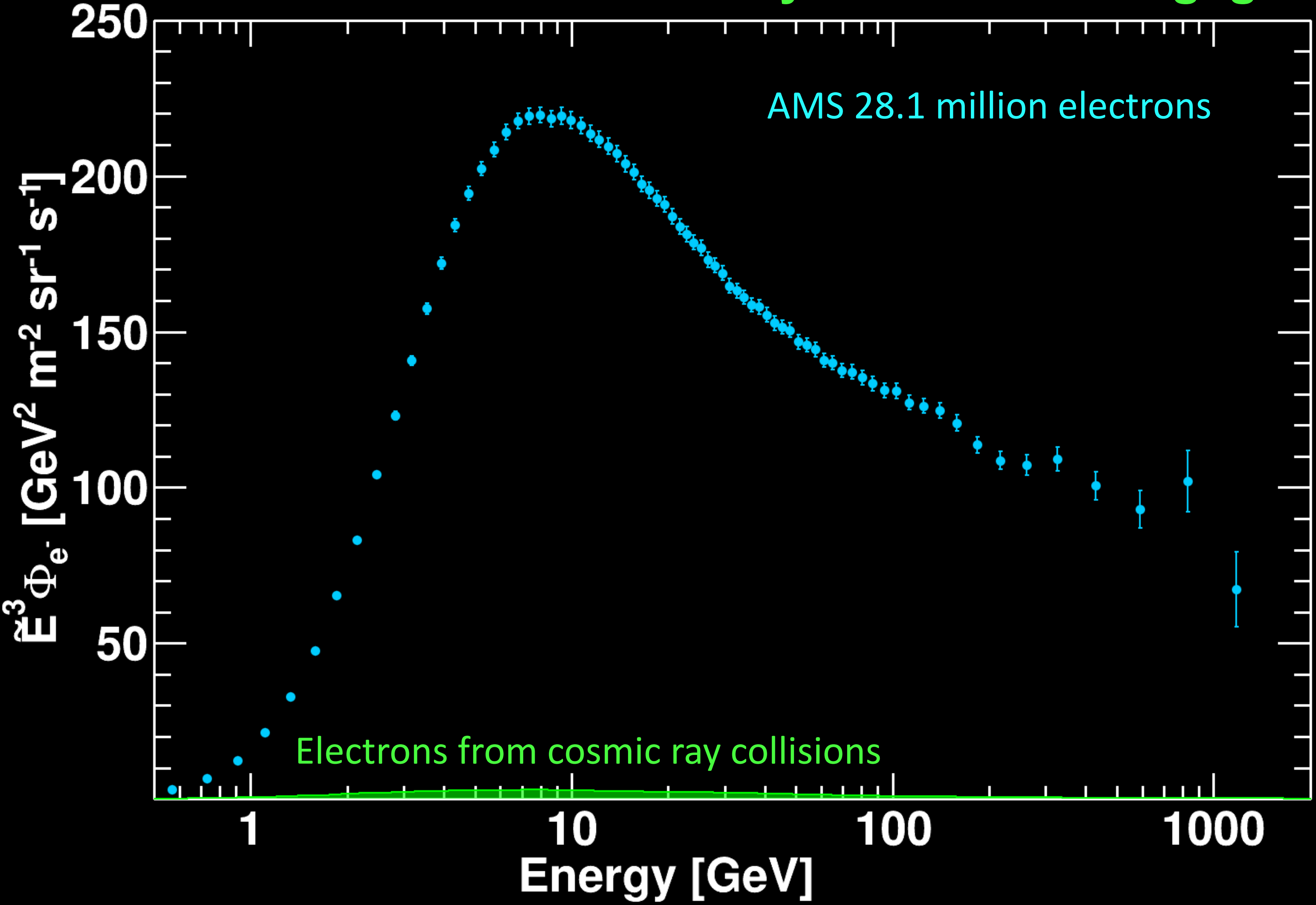
AMS will provide the definitive answer on the nature of dark matter



AMS Physics Results:

The Origins of Cosmic Electrons

The contribution from cosmic ray collisions is negligible



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

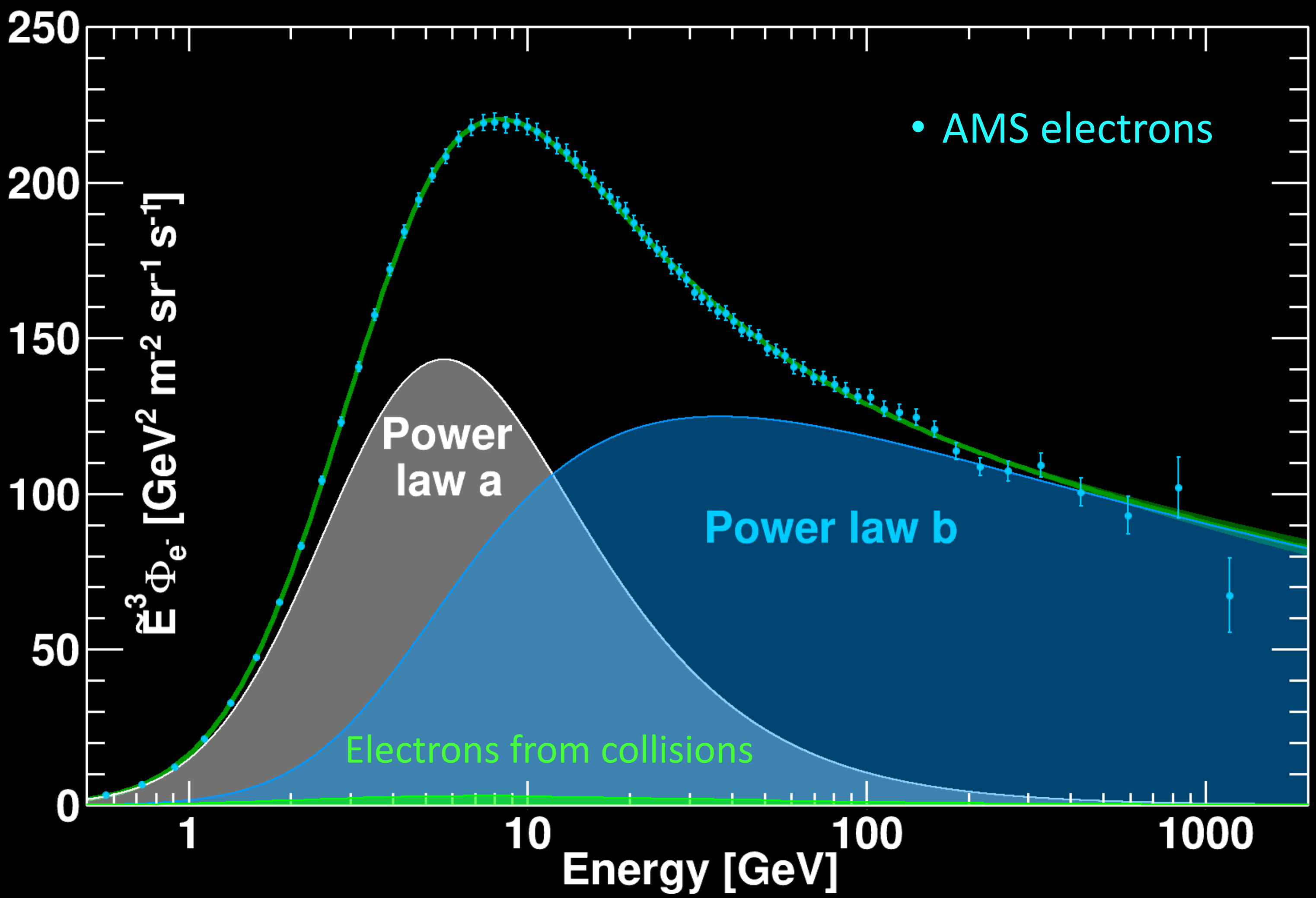
$$\Phi_{e^-}(E) = S(E)\left[C_a\left(\hat{E}/E_a\right)^{\gamma_a} + C_b\left(\hat{E}/E_b\right)^{\gamma_b}\right]$$

Solar & low-energy

Power law *a*

Power law *b*

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



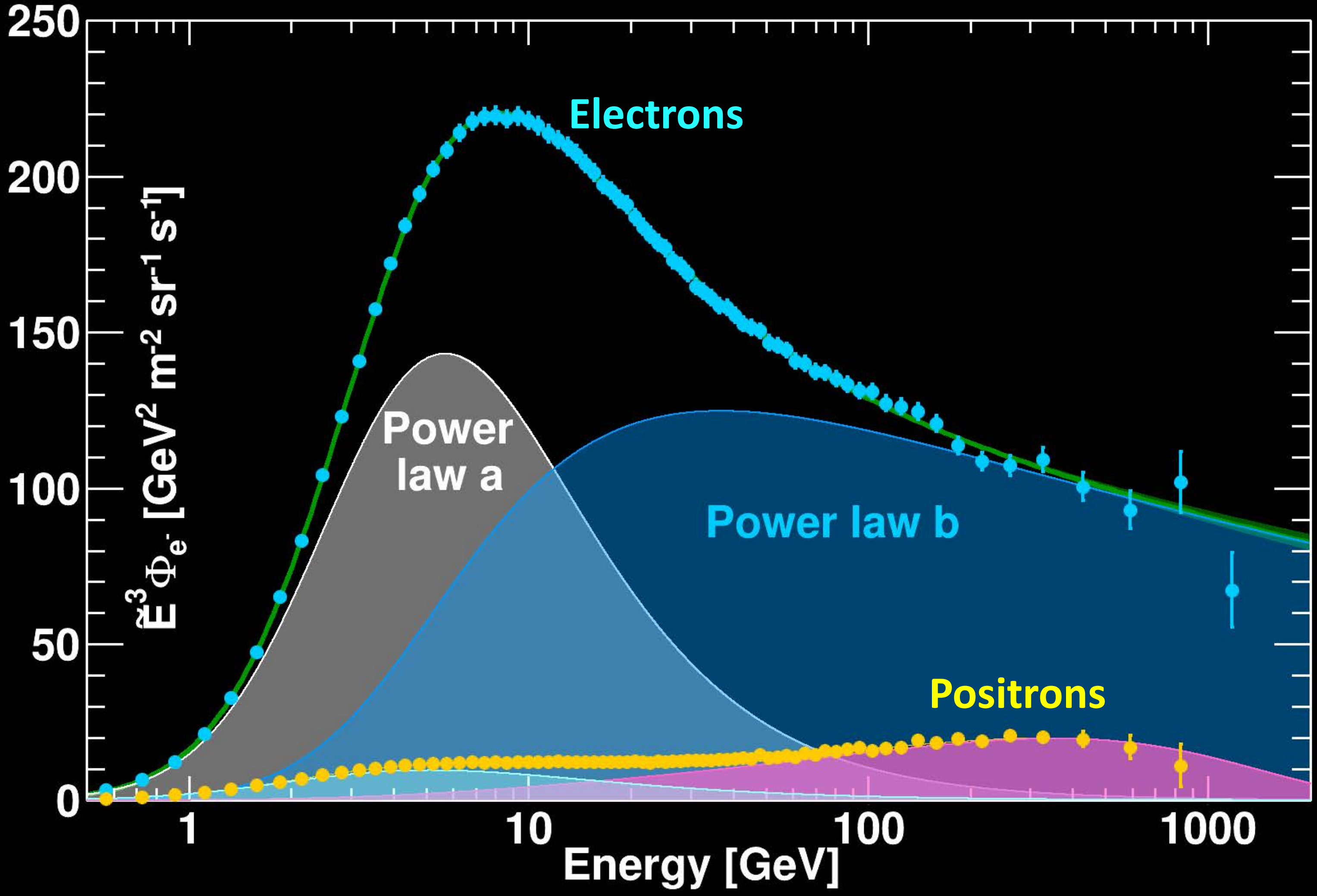
AMS Physics Results:

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

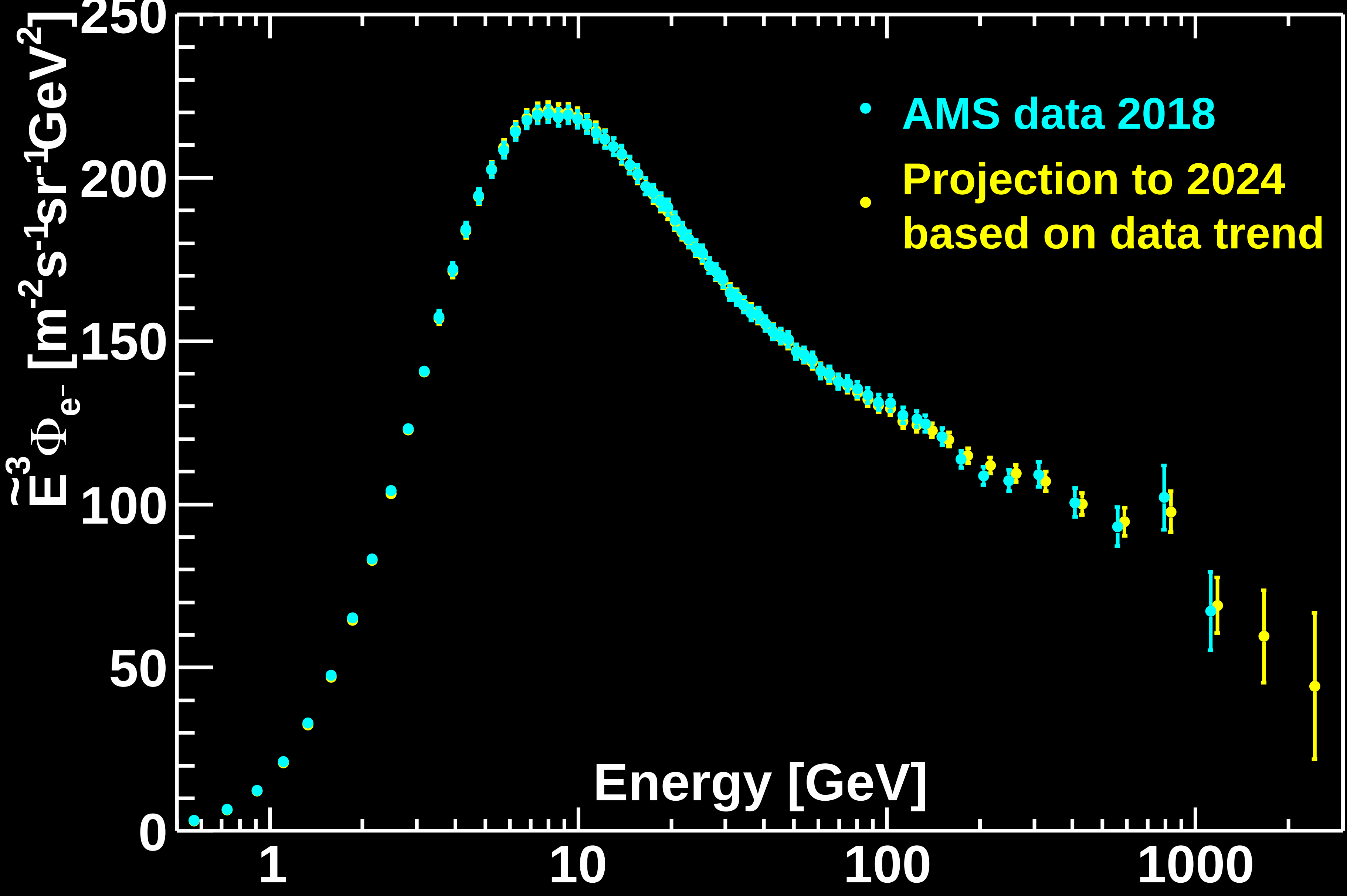
a high-energy part from a new source or dark matter both with a cutoff energy E_S.



Physics of cosmic electrons to 2024

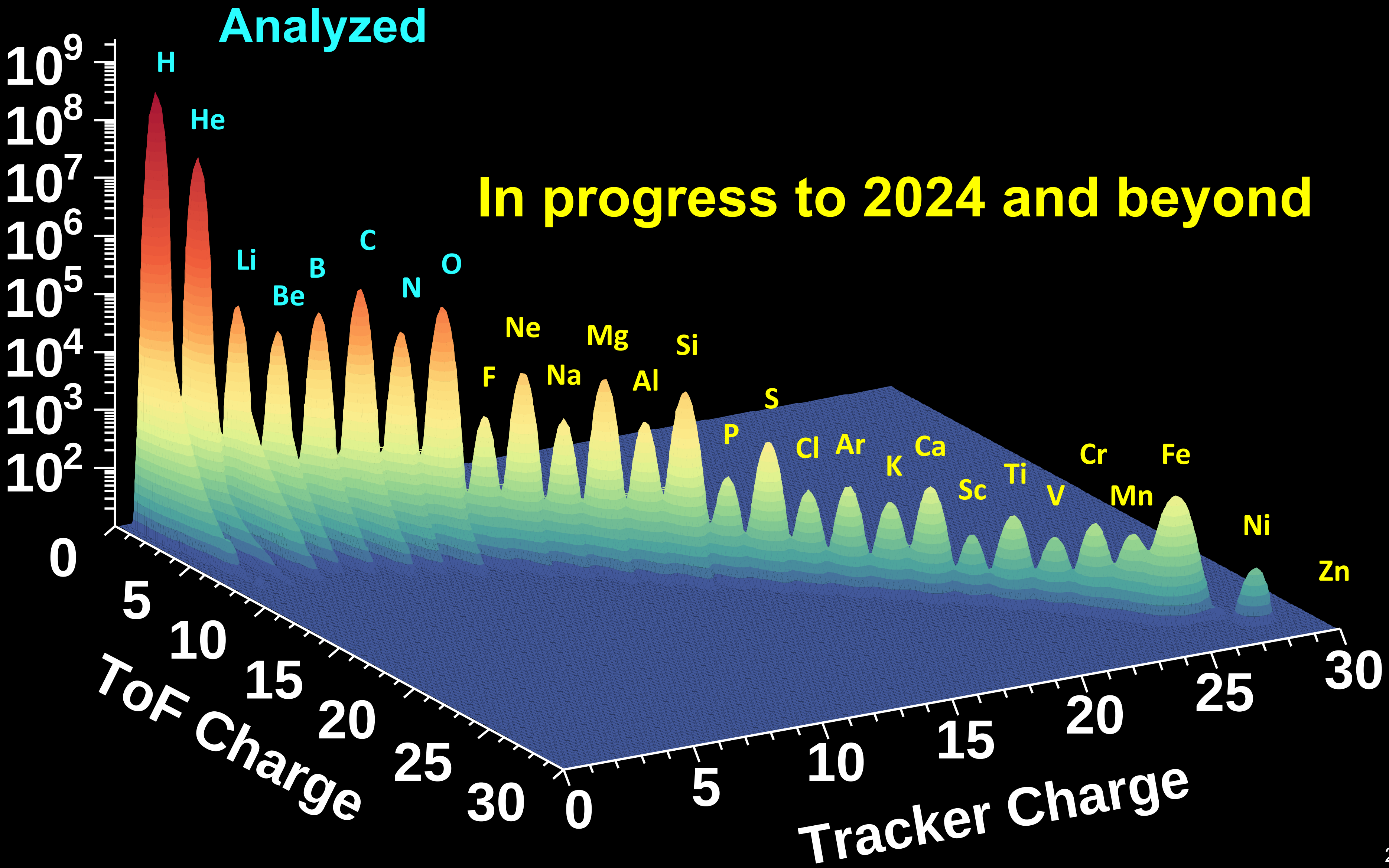
What is the origin of power law a and power law b?

Is there a cutoff for electrons at higher energies?

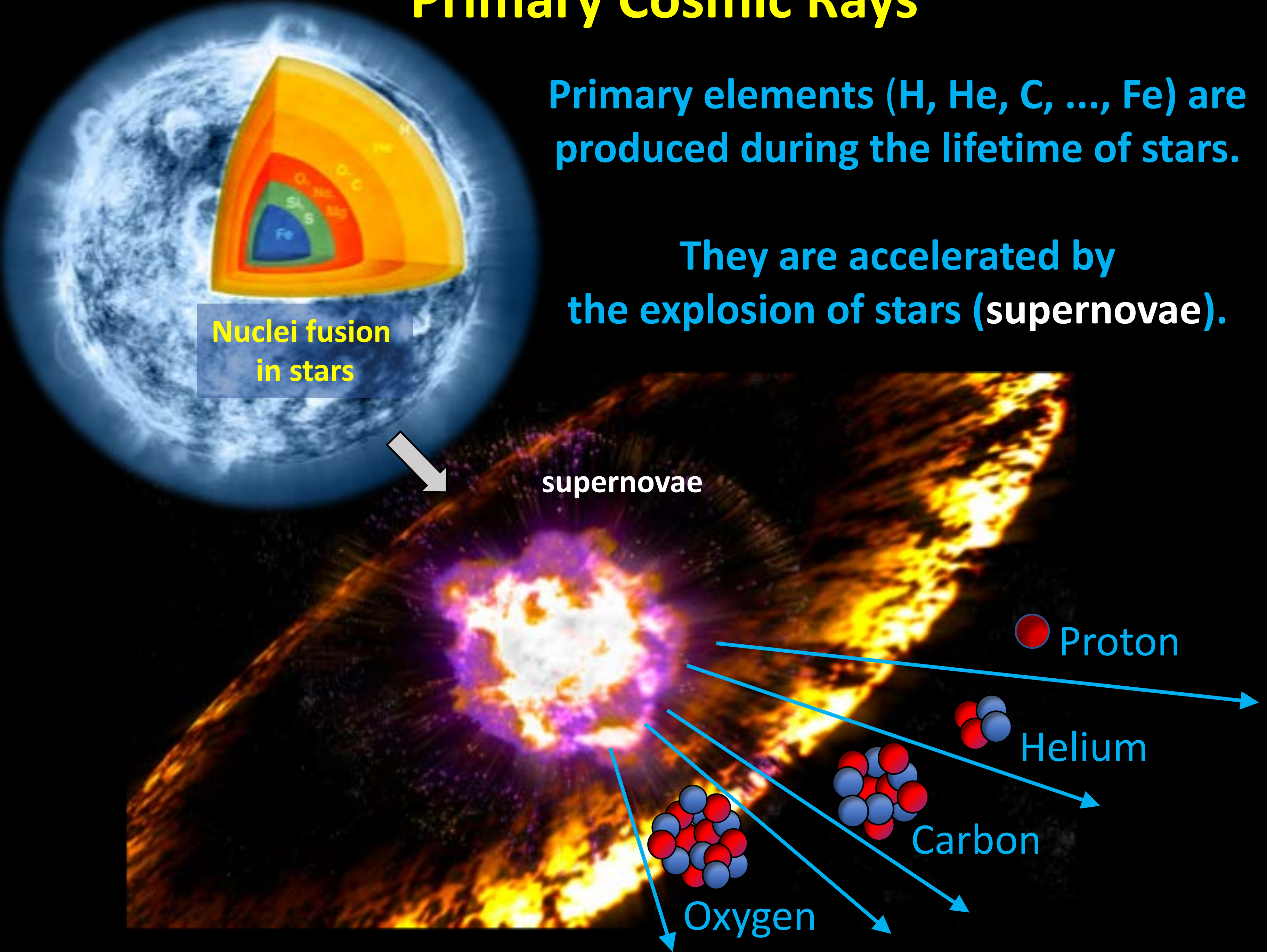


Precision Study of Cosmic Nuclei through the lifetime of ISS

Exploring an uncharted region



Primary Cosmic Rays

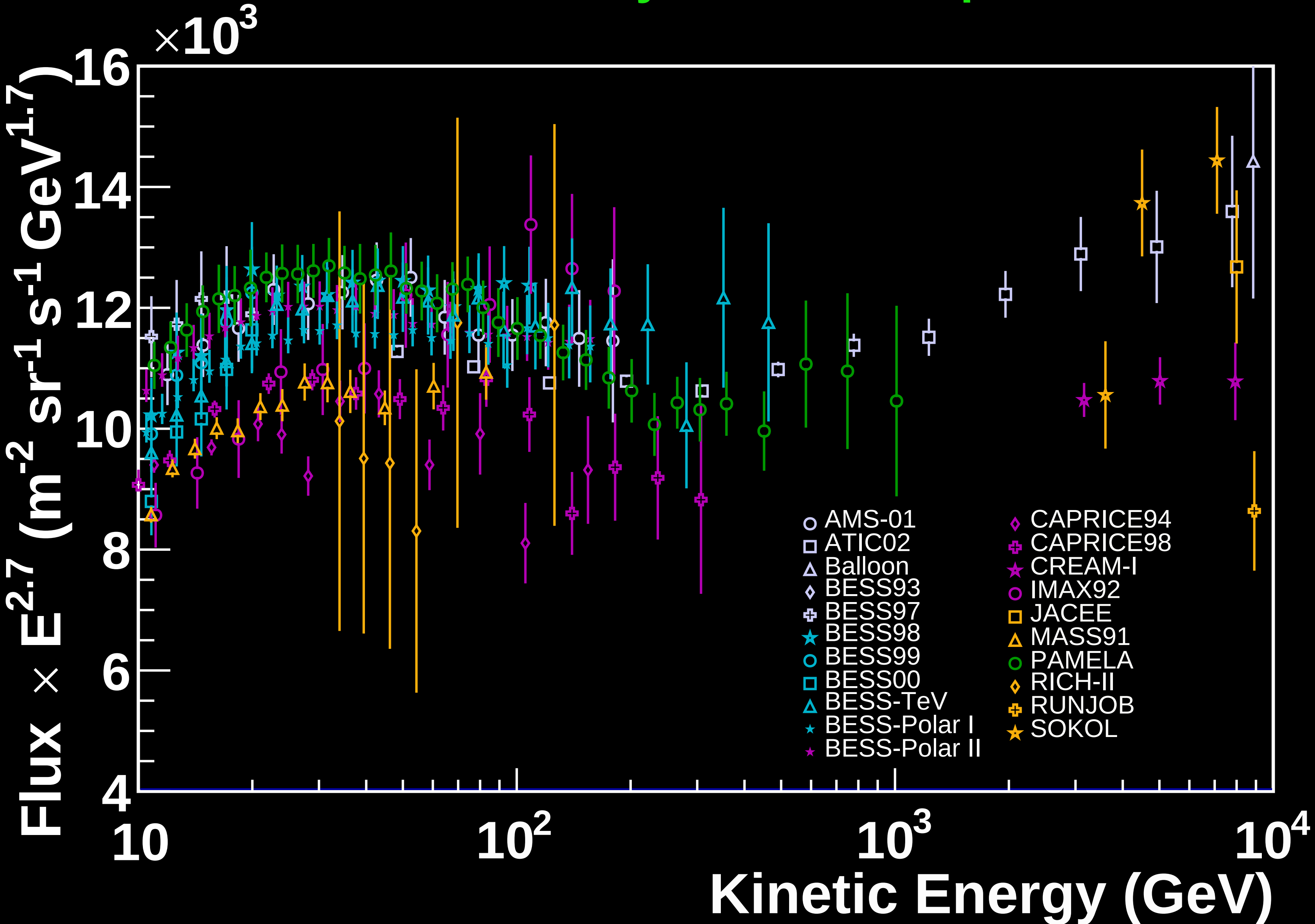


Primary elements (H, He, C, ..., Fe) are produced during the lifetime of stars.

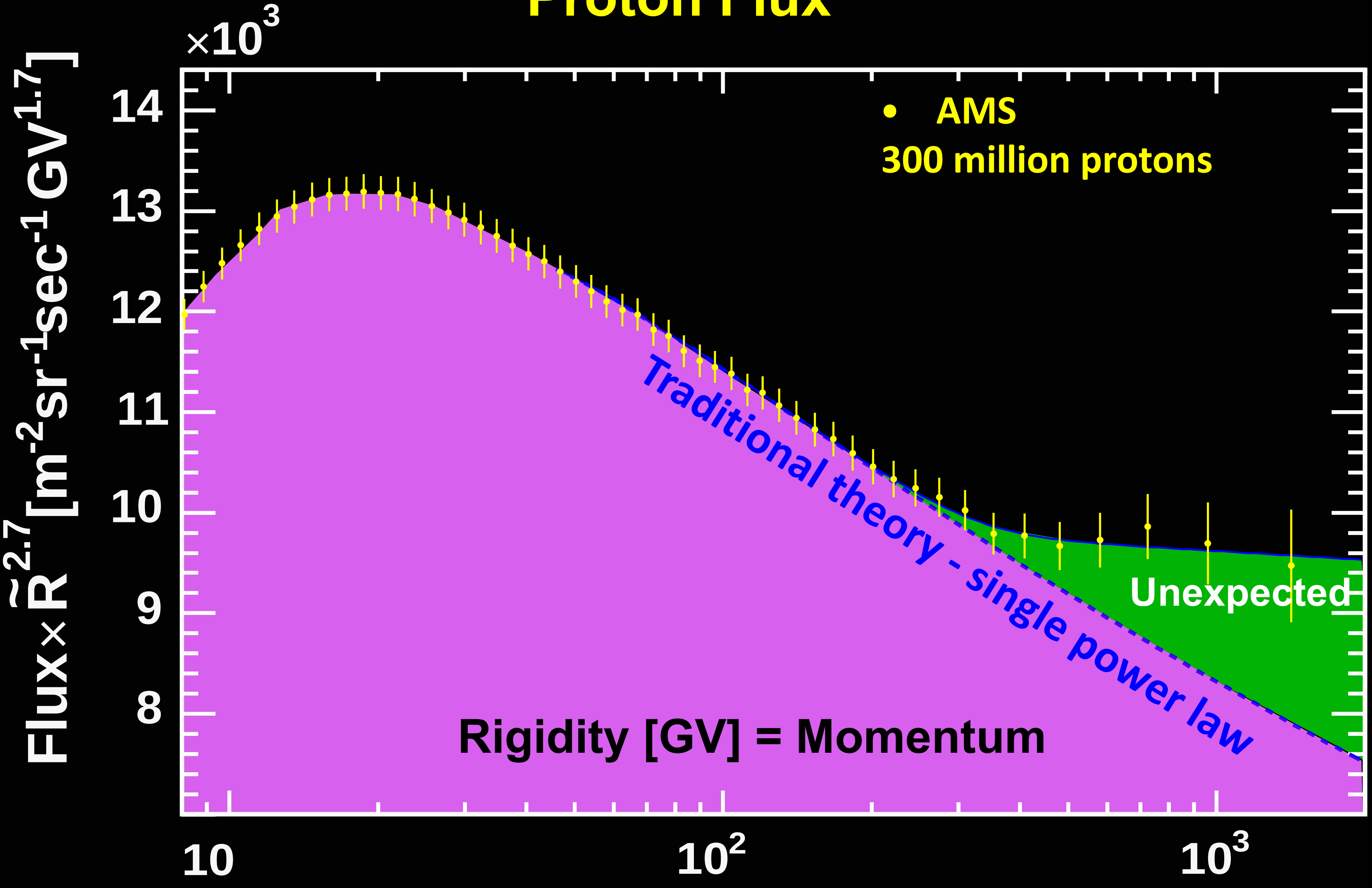
They are accelerated by the explosion of stars (**supernovae**).

Cosmic Protons before AMS

The data have created many theoretical speculations.



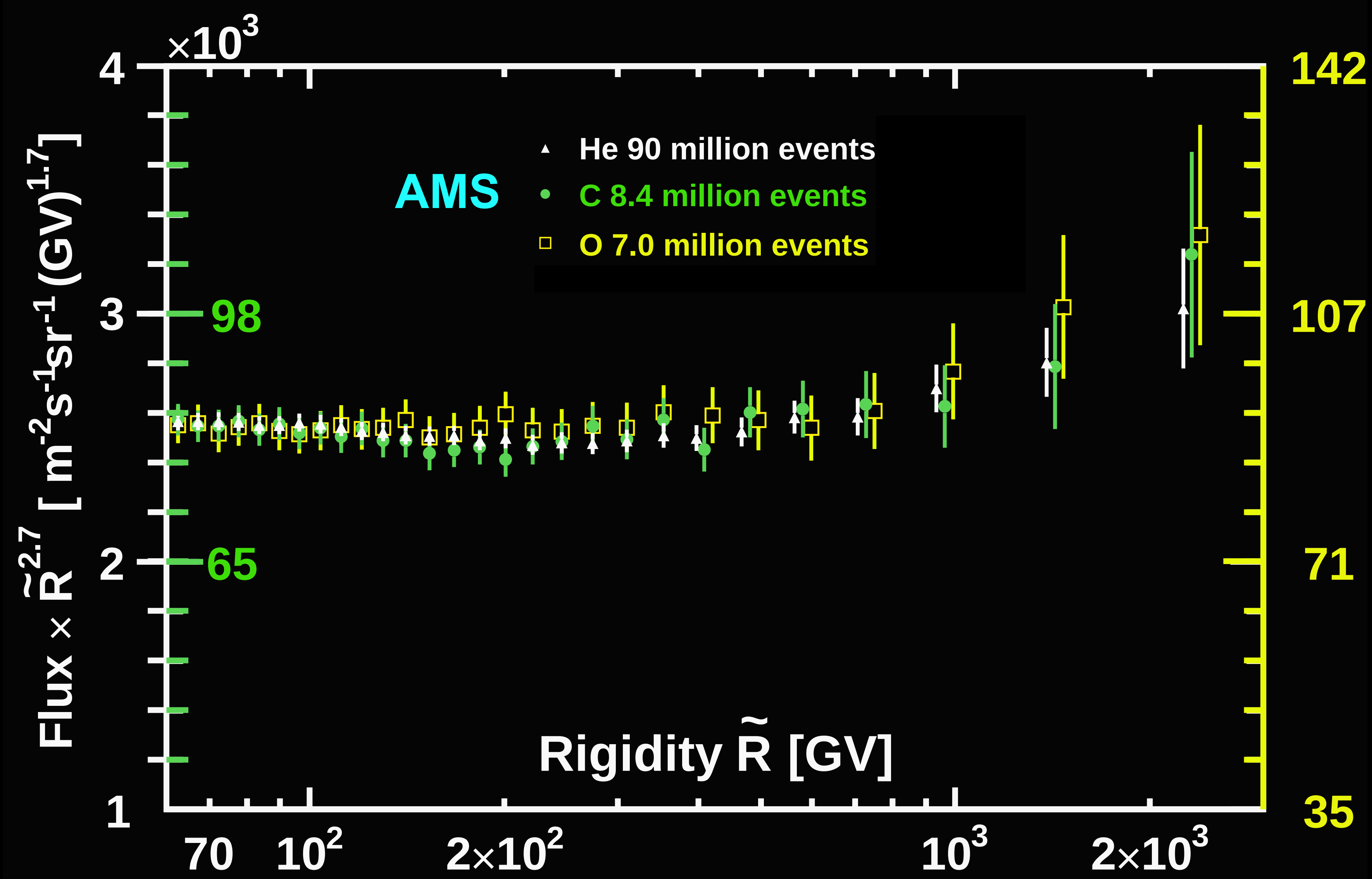
AMS Physics Results:
Proton Flux



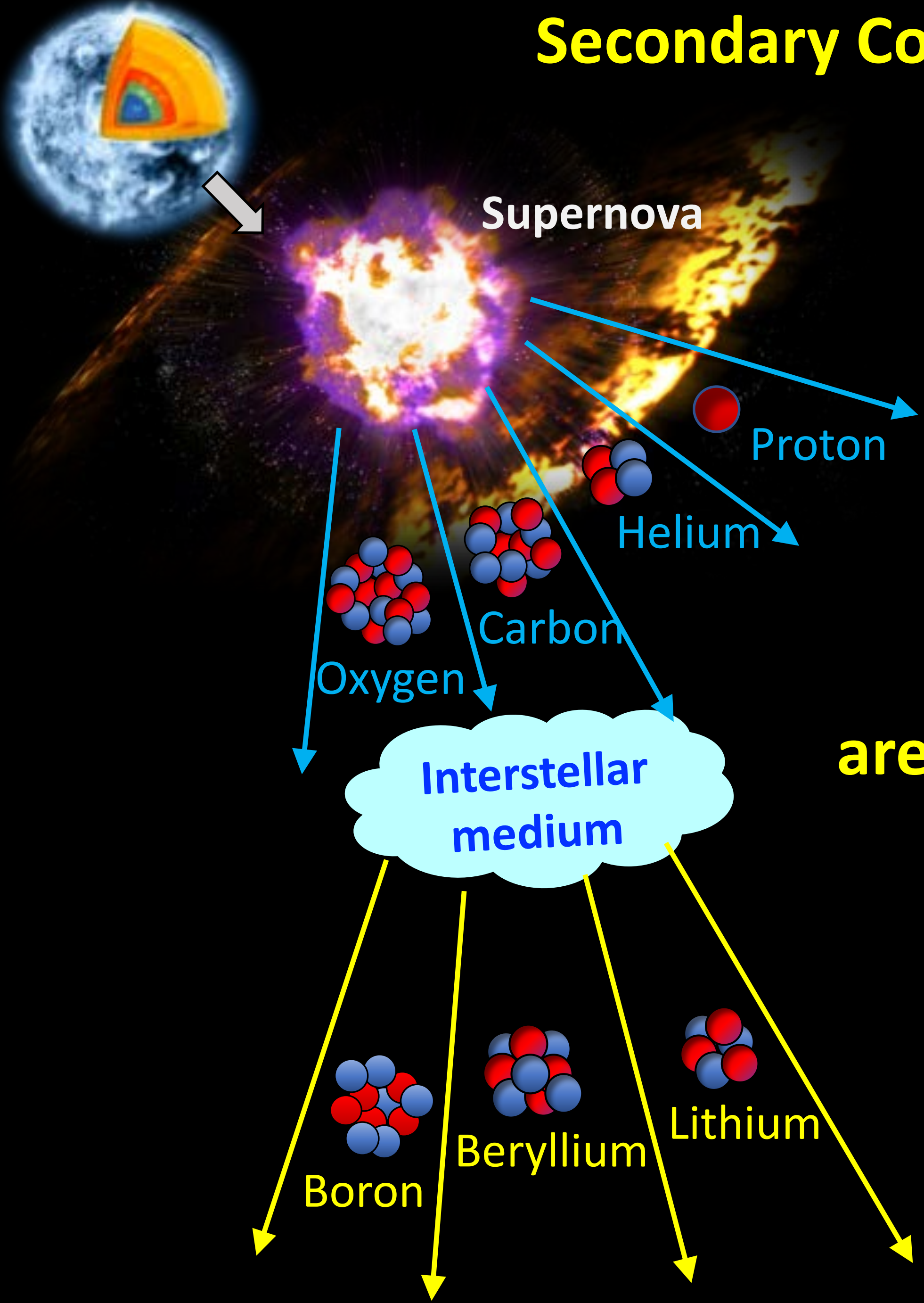
The proton flux cannot be described by the traditional theory

AMS Physics Results:

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



Secondary Cosmic Rays

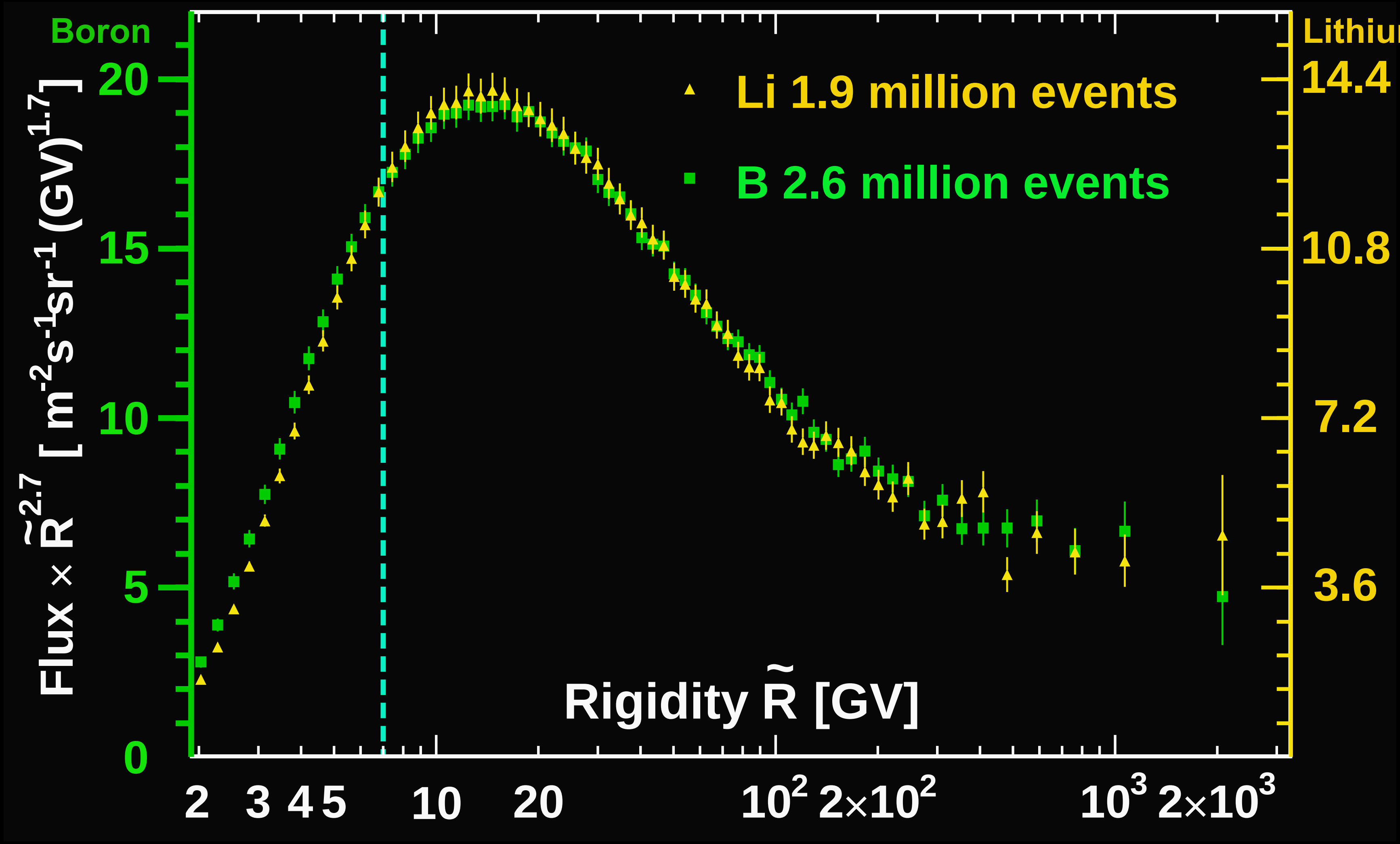


Secondary cosmic nuclei
(Li, Be, B, …)
are produced by the collision of
primary cosmic rays and
interstellar medium

AMS Physics Results:

Lithium and Boron

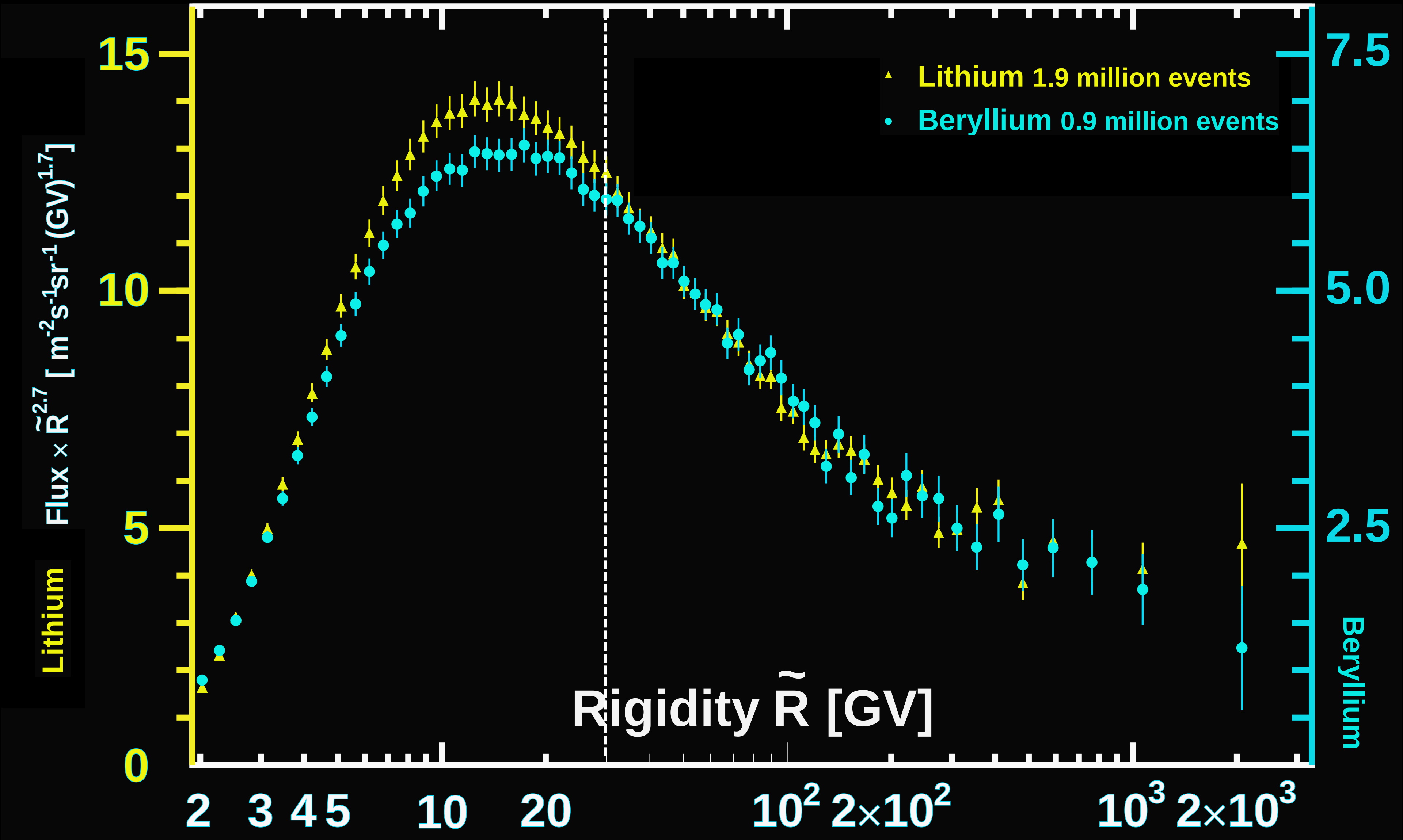
The flux rigidity dependences are identical above 7 GV



Physics Results on Lithium and Beryllium

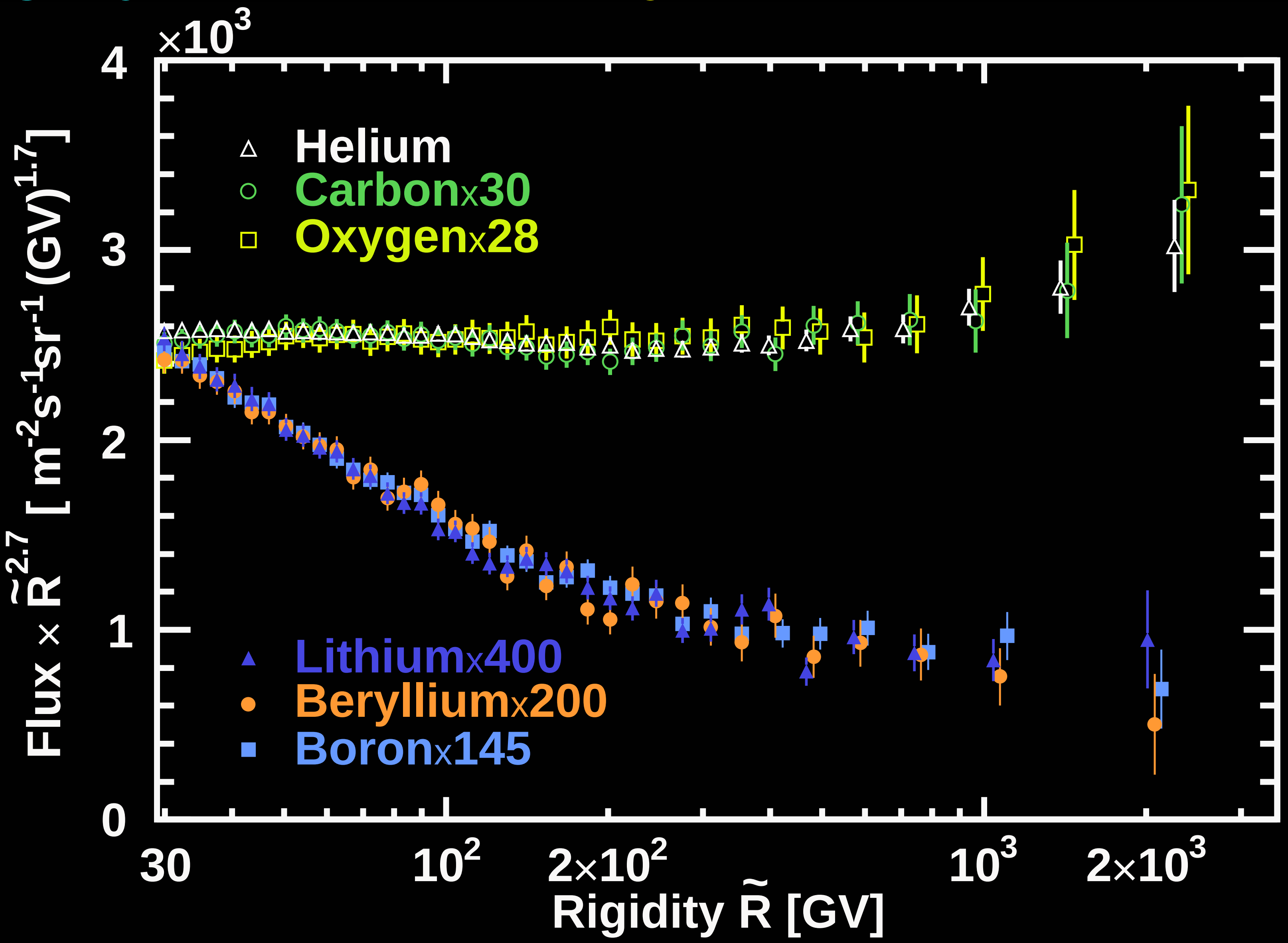
The rigidity dependences are identical above 30 GV

Fluxes are different by a factor of 2.0 ± 0.1

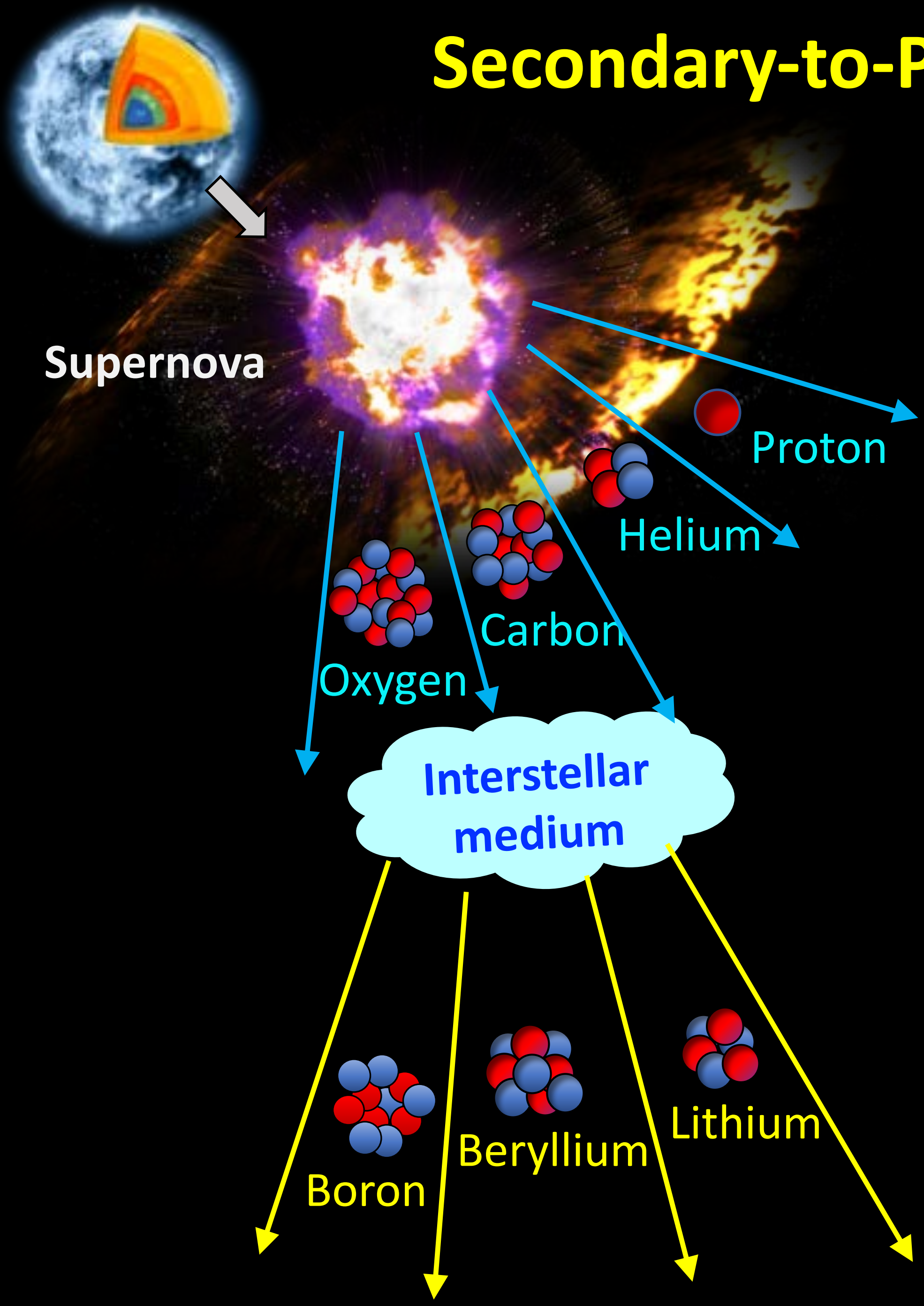


AMS Physics Results:

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



Secondary-to-Primary Ratios



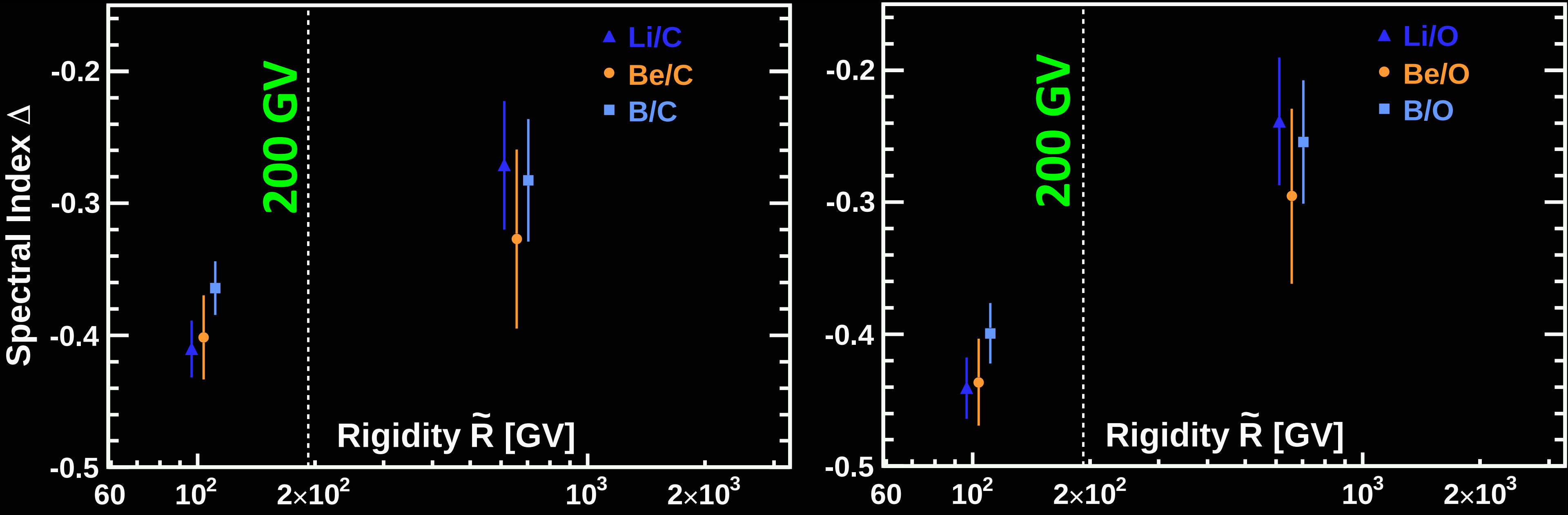
The ratio of secondary flux to **primary flux** directly measures the amount and properties of interstellar medium.

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



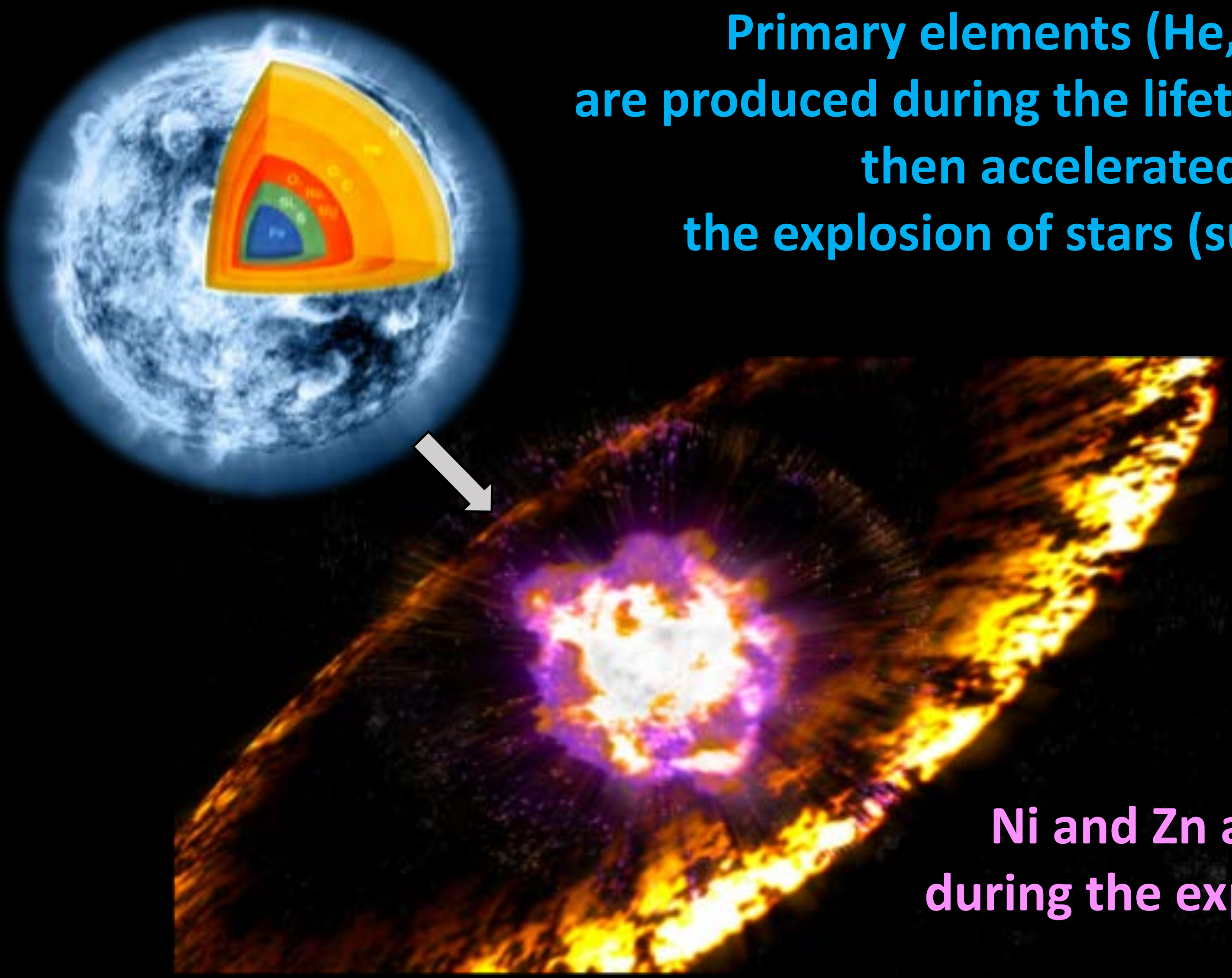
This AMS data provides new and unexpected information on the interstellar medium

All AMS Publications in *Physical Review Letters*

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

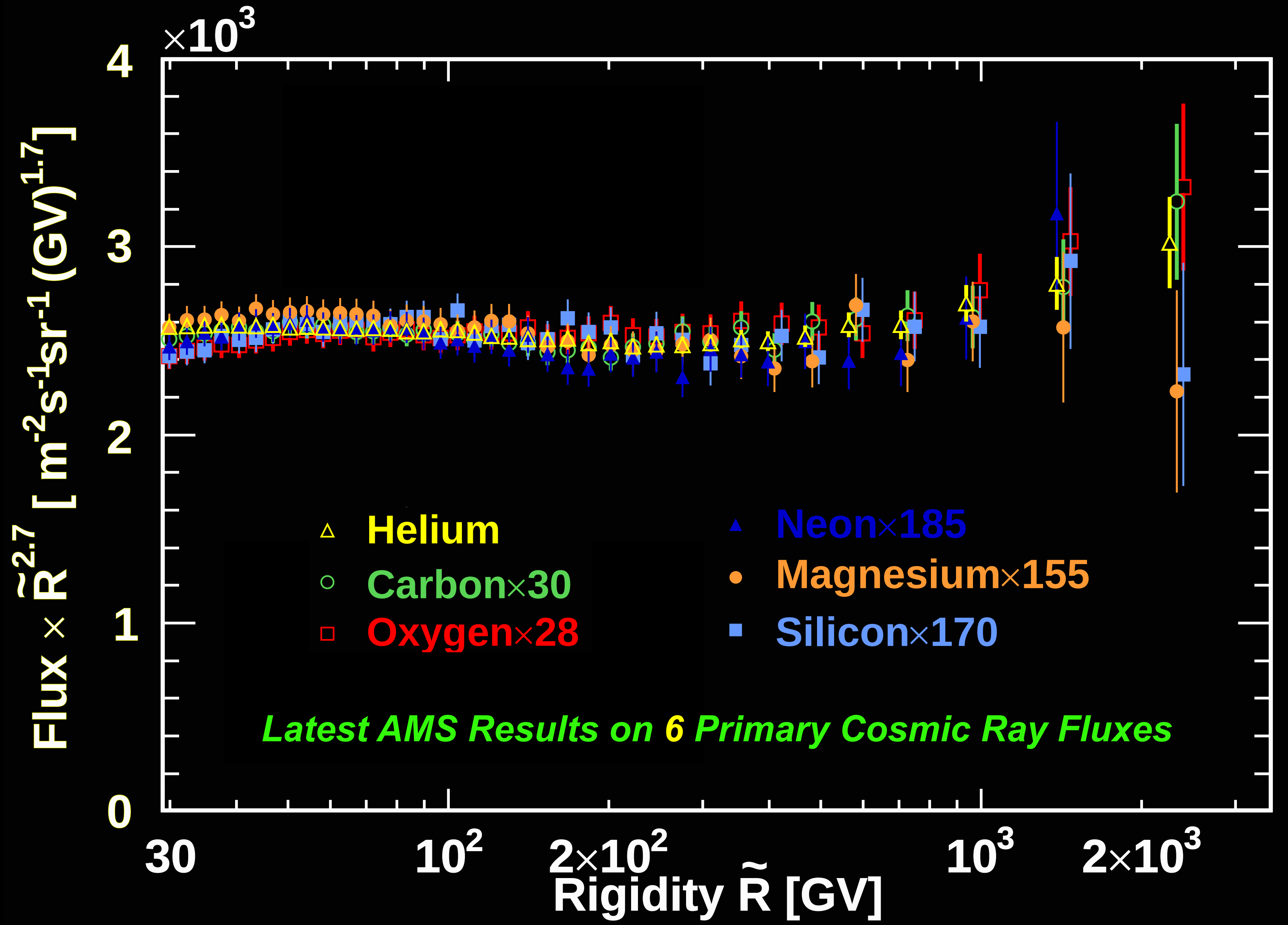
Fundamental Question: are Ni and Zn different from He, C, … Fe?



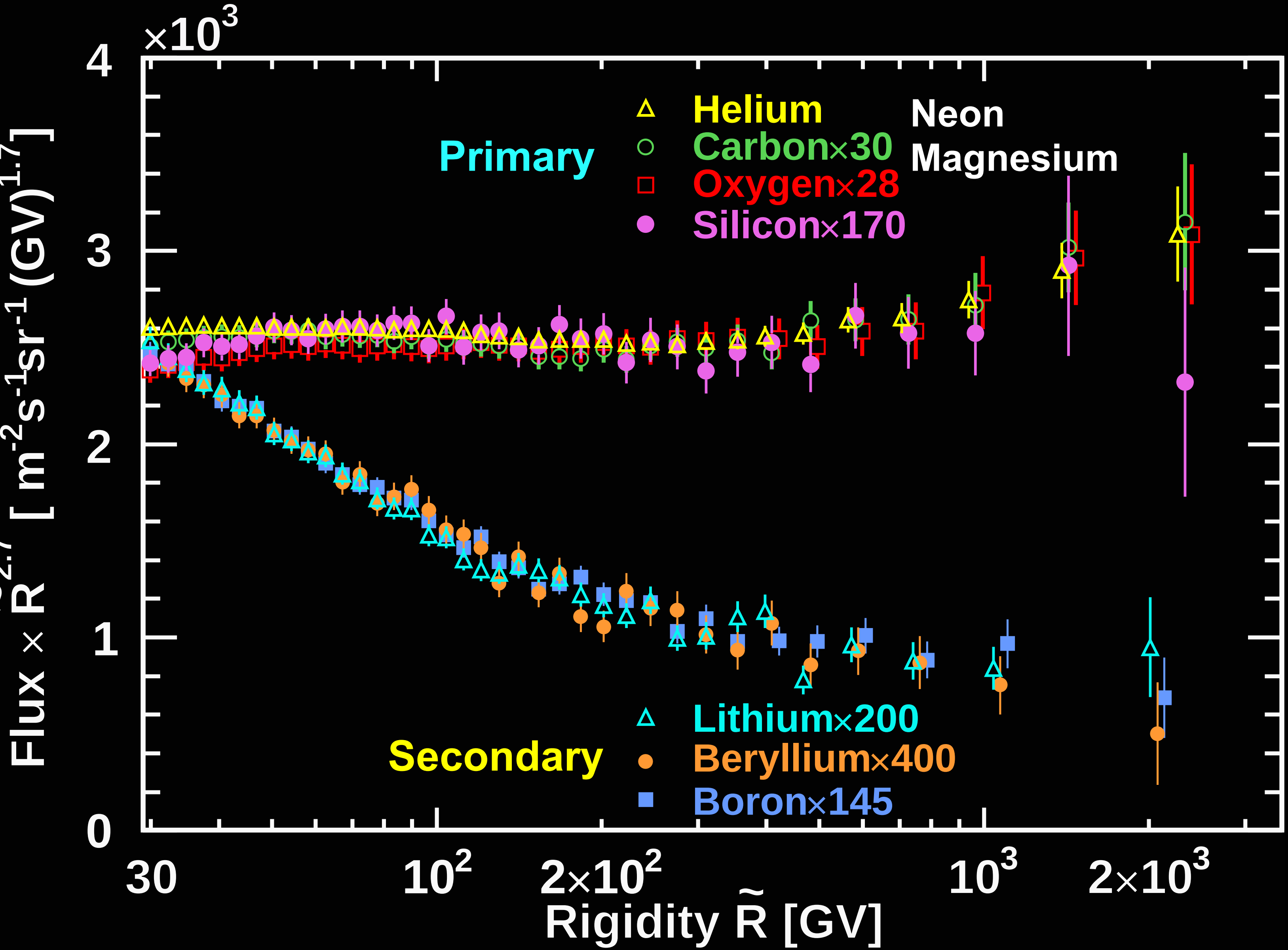
Primary elements (He, C, ..., Fe)
are produced during the lifetime of stars and
then accelerated by
the explosion of stars (supernovae)

Ni and Zn are produced
during the explosion of stars.

Fundamental Question:
Do all the primaries have the same rigidity dependence?

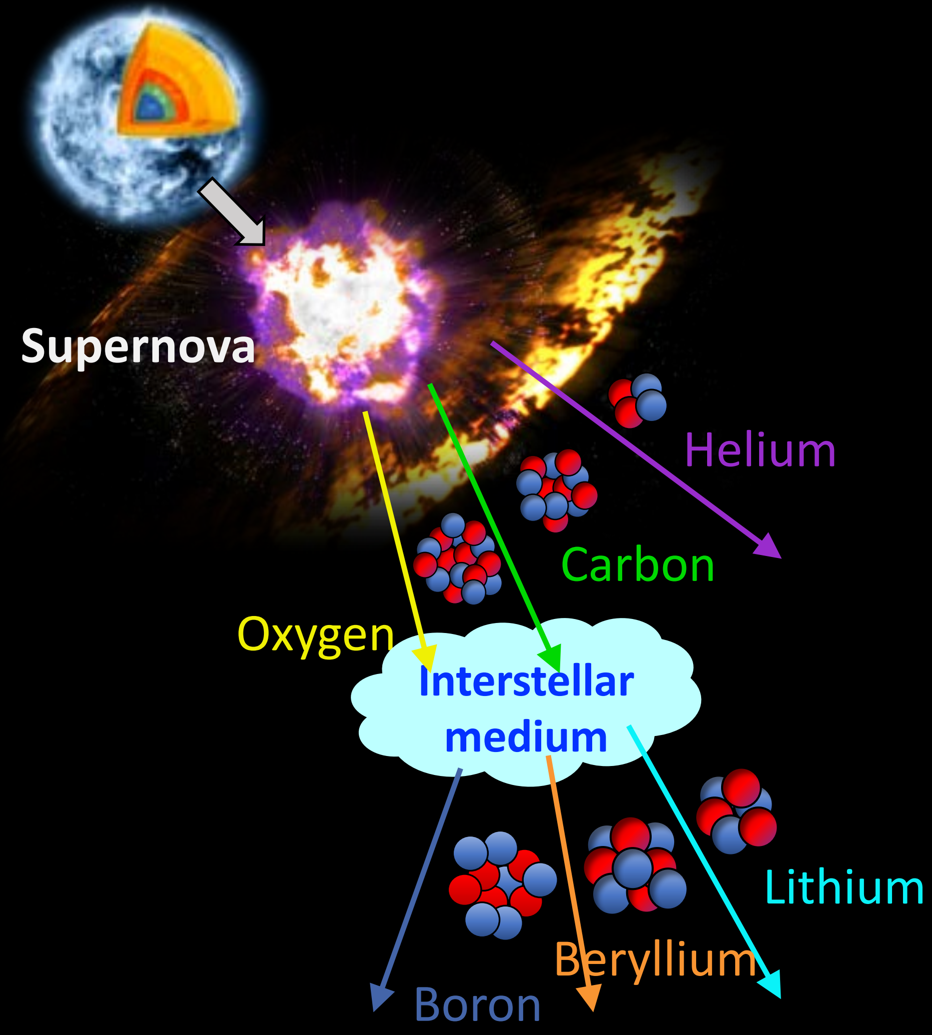


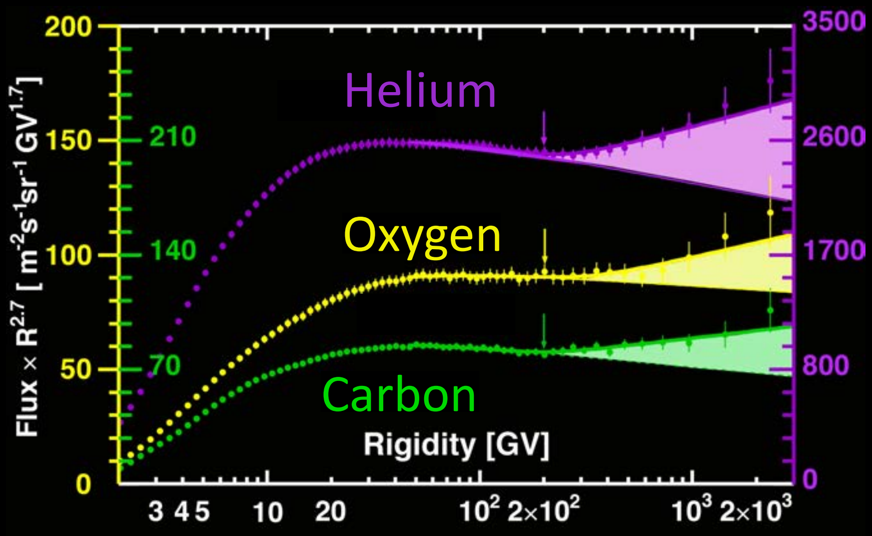
Fundamental question:
How many classes of cosmic rays exist in the universe?

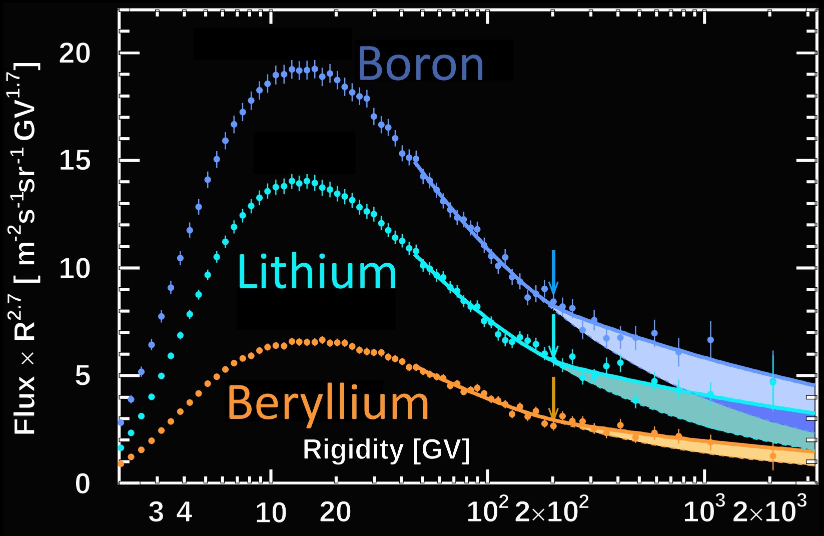


The measured spectra of Cosmic Rays break at ~200 GV.

Is there a break for all the elements? Why?

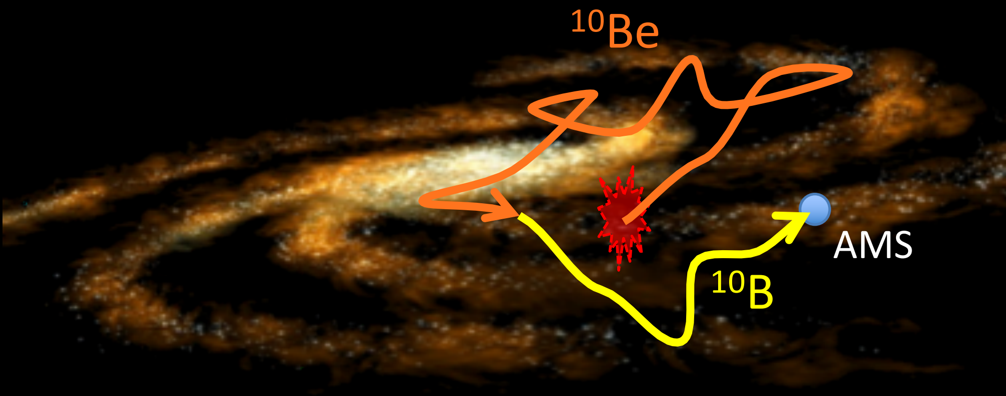


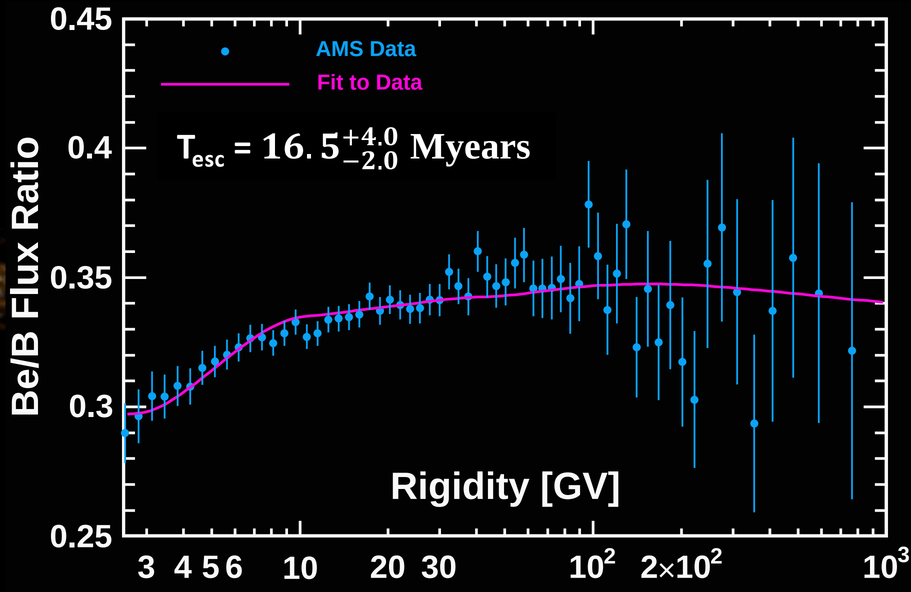




How old are cosmic rays?

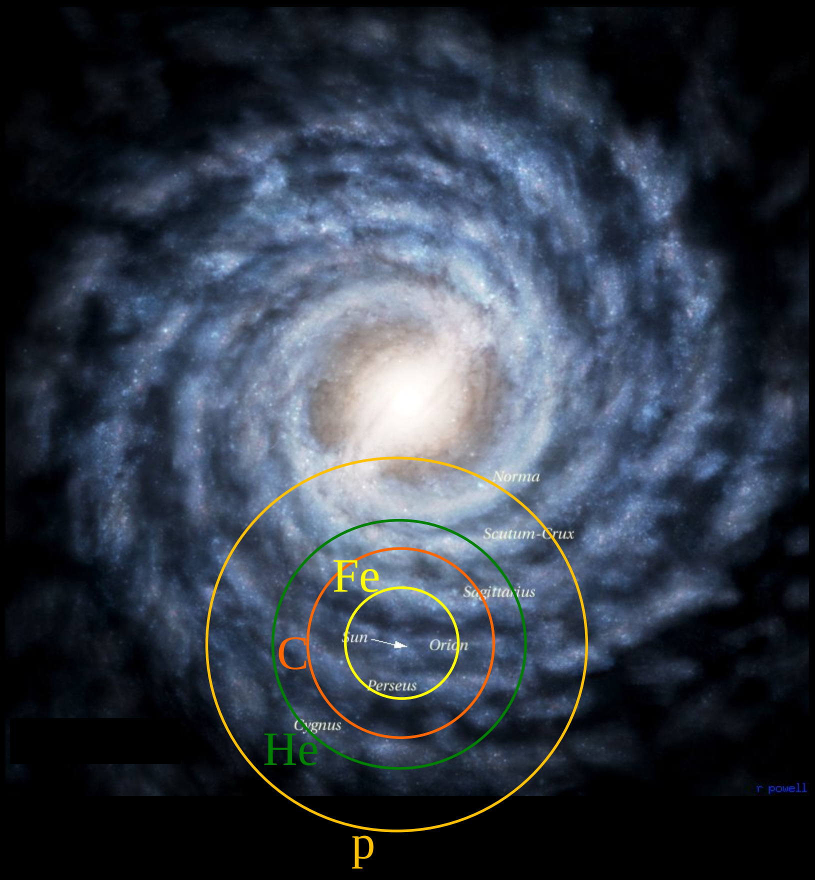
^{10}Be (Z=4) decays with a half-life 1.4×10^{6} years $^{10}\text{Be} \rightarrow {}^{10}\text{B}+e^{-}+\nu_{e}$.
Precision measurement of the rigidity dependence of Be/B ratio provides information on the age of cosmic rays





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.

How do cosmic rays propagate in the Galaxy?



Effective distance is shown for ~1 GV.

Effective propagation distance

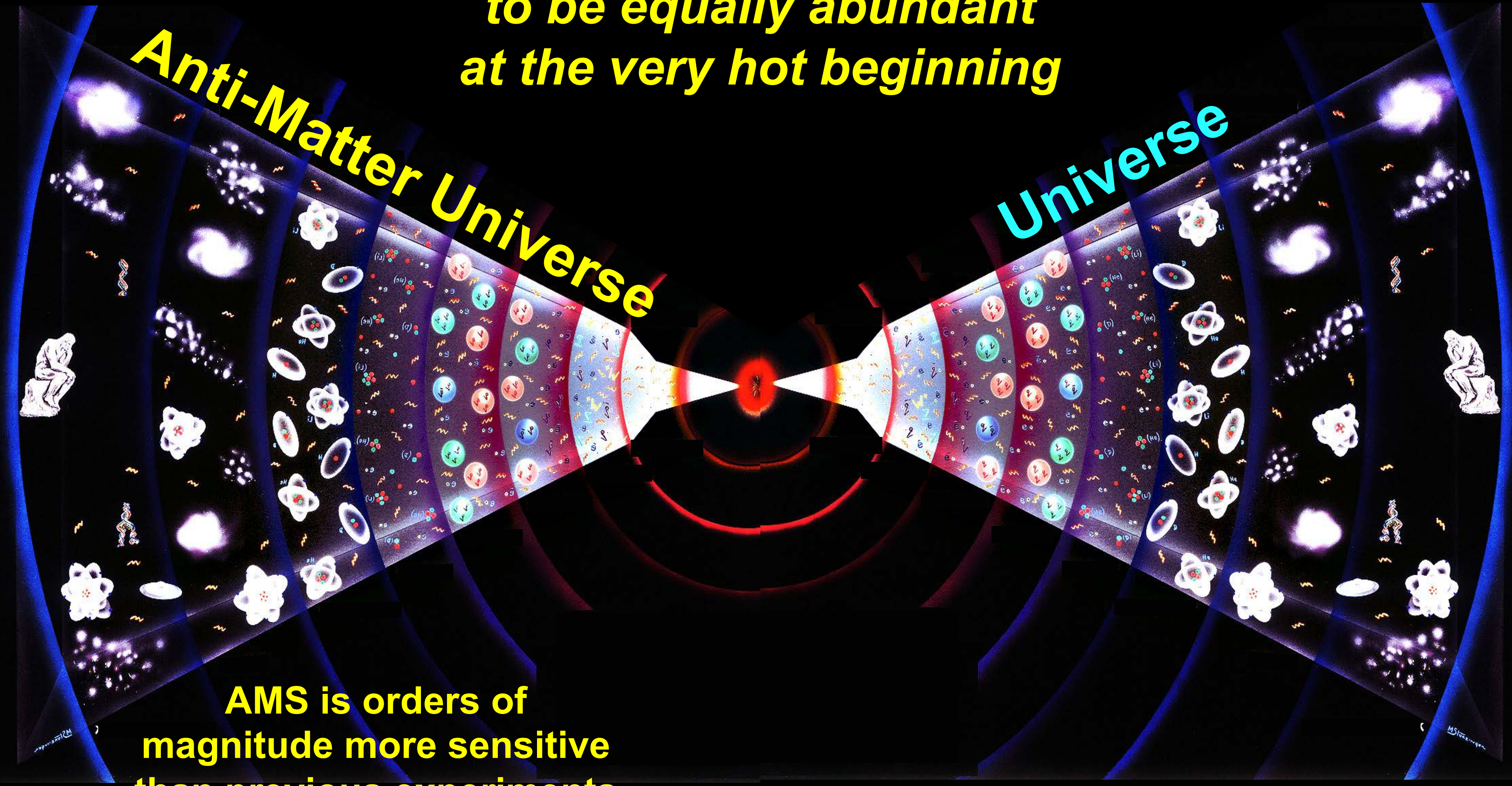
$$\propto R^{1/6}\ A^{-1/3}$$

i. Different nuclei A (1 - 60) probe different distances.

ii. Different rigidities R (1 – 3000 GV) probe different distances

Complex anti-matter

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



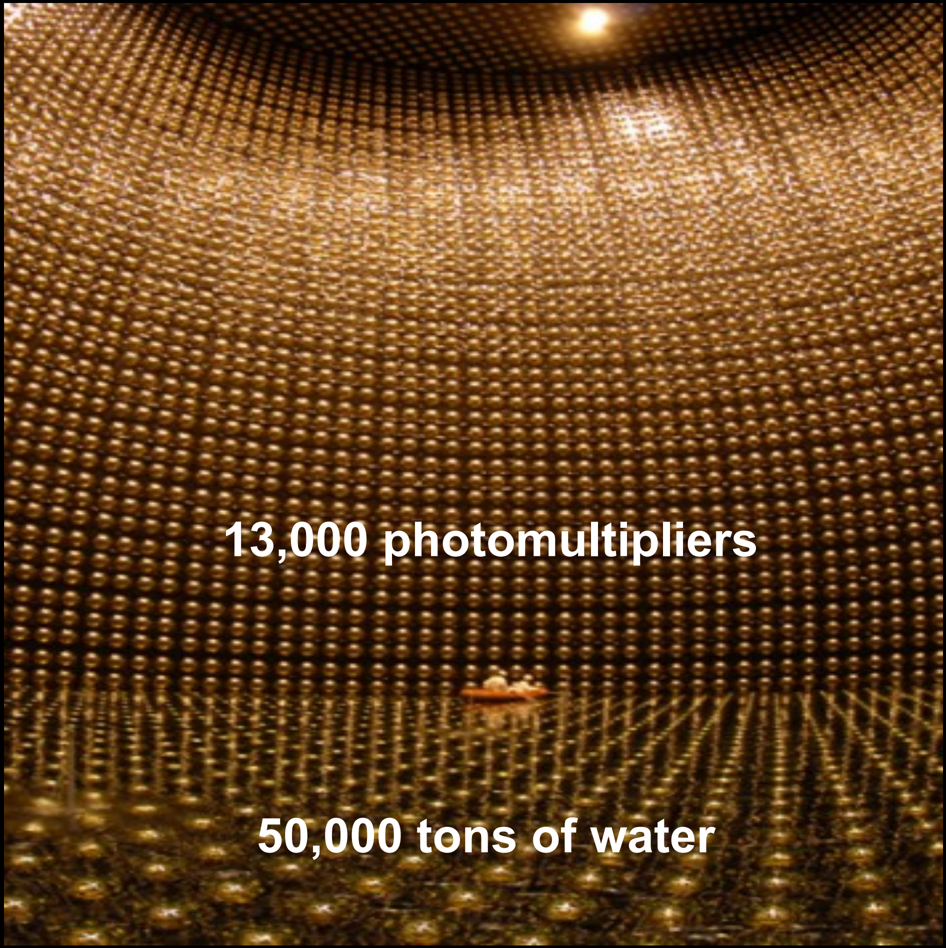
AMS is orders of
magnitude more sensitive
than previous experiments
on balloons and satellites

Search for Baryogenesis

New symmetry breaking

LHC-b, ATLAS,CMS

Proton has finite lifetime



13,000 photomultipliers

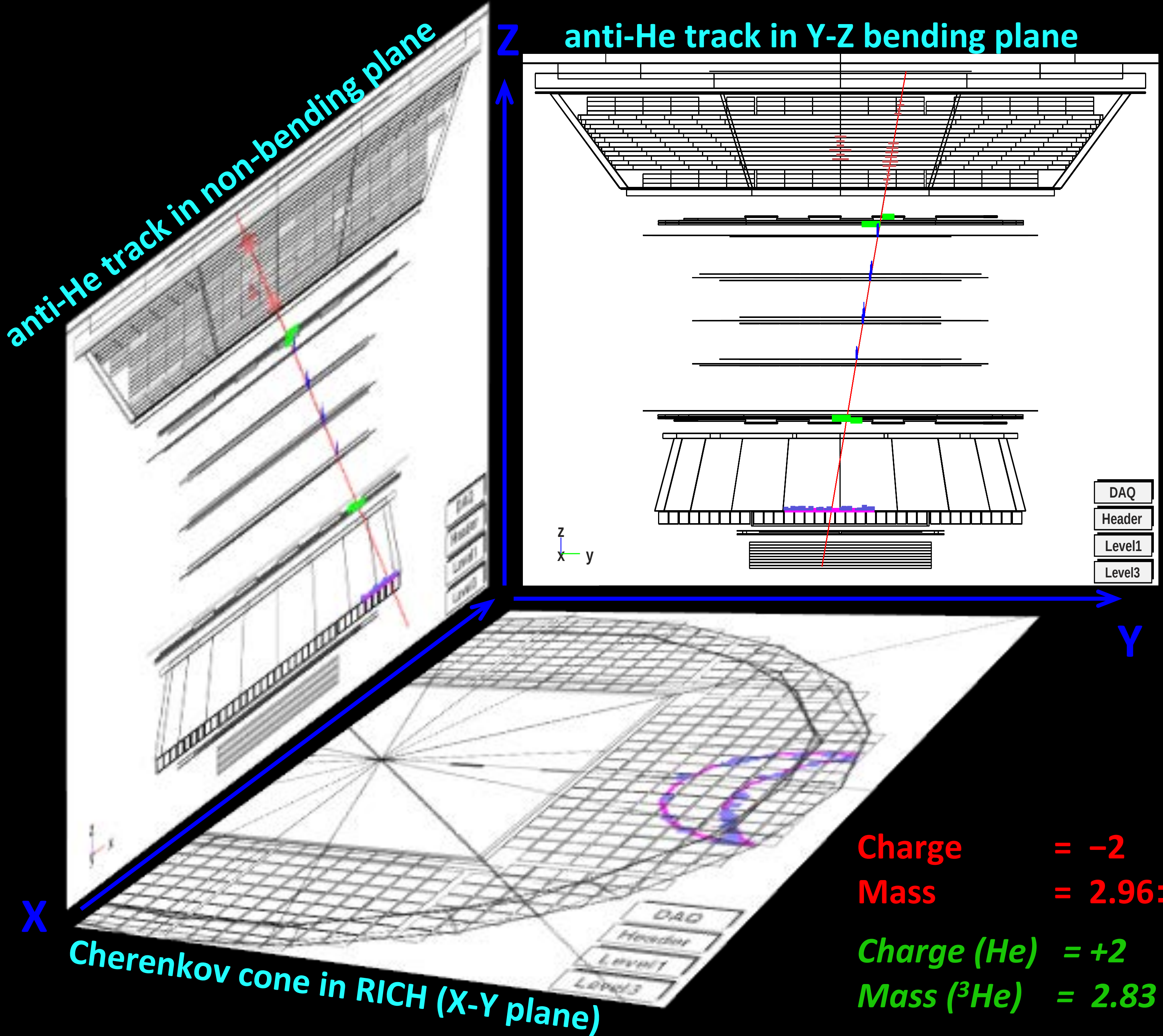
50,000 tons of water

Super Kamiokande

No explanation found for the absence of antimatter.

No reason why antimatter should not exist.

Observation of anti-He events



Charge = -2

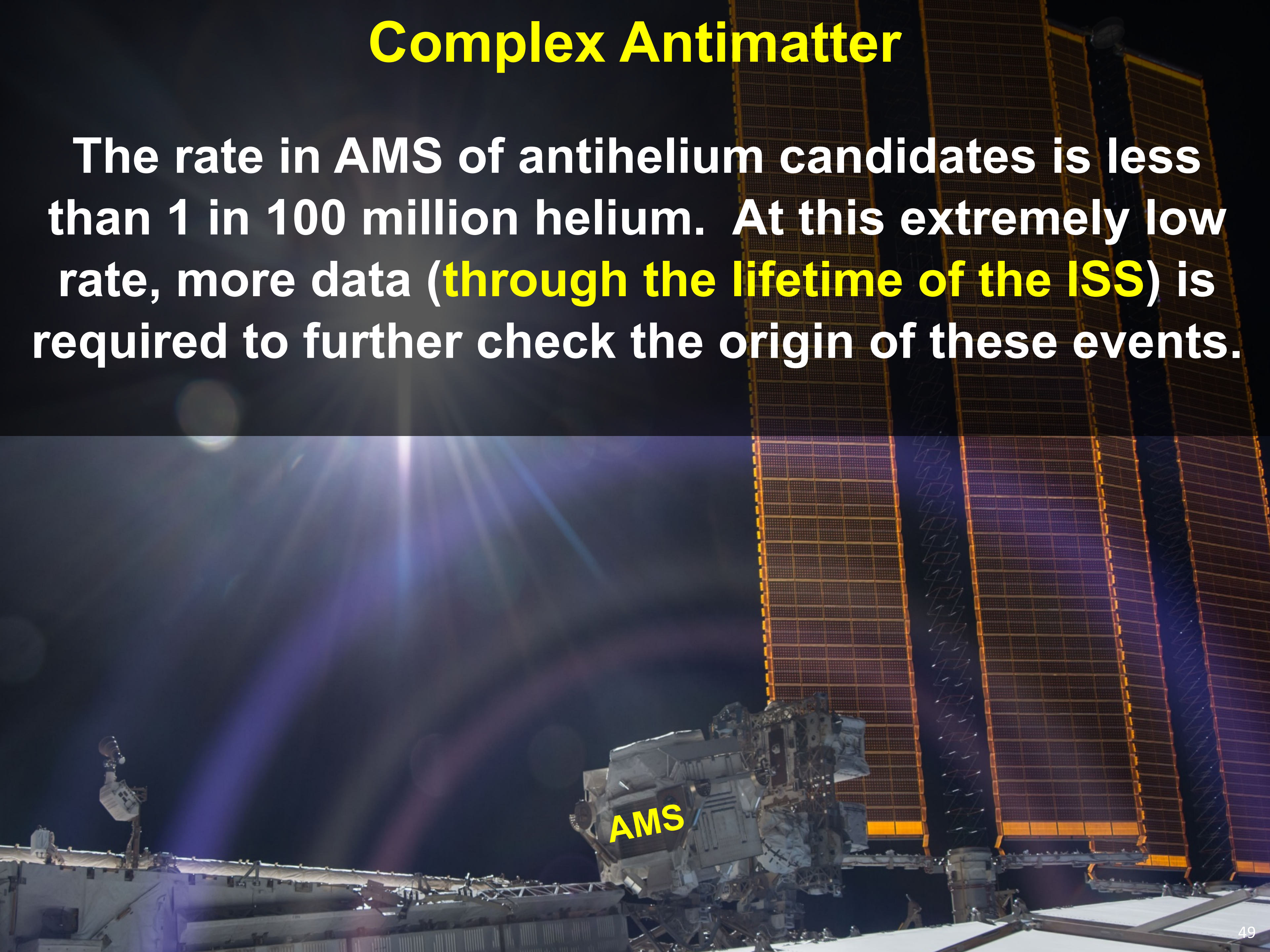
Mass = 2.96 ± 0.33 GeV/c^2

Charge (He) = +2

Mass (^{3}He) = 2.83 GeV/c^2

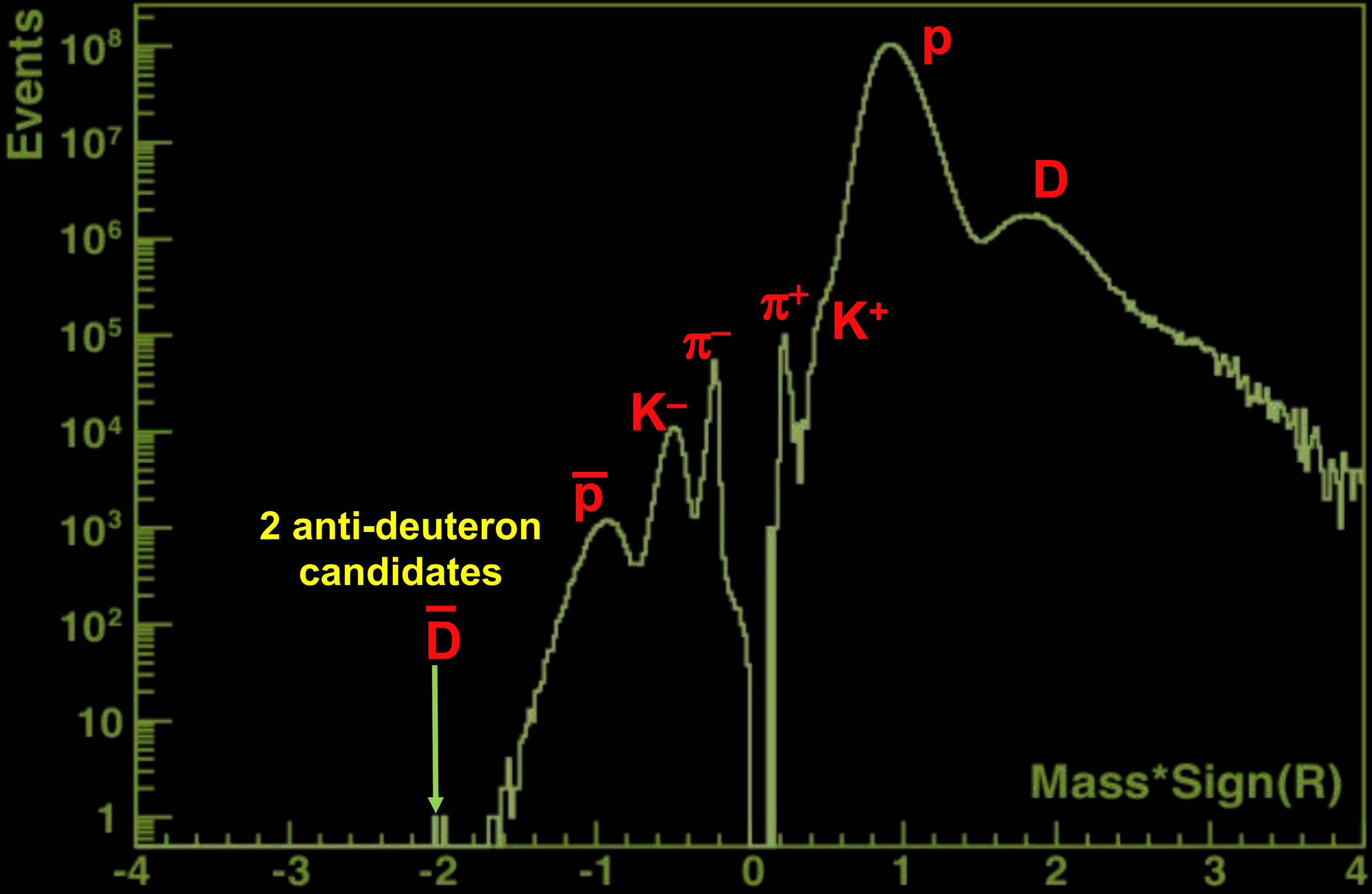
Complex Antimatter

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.



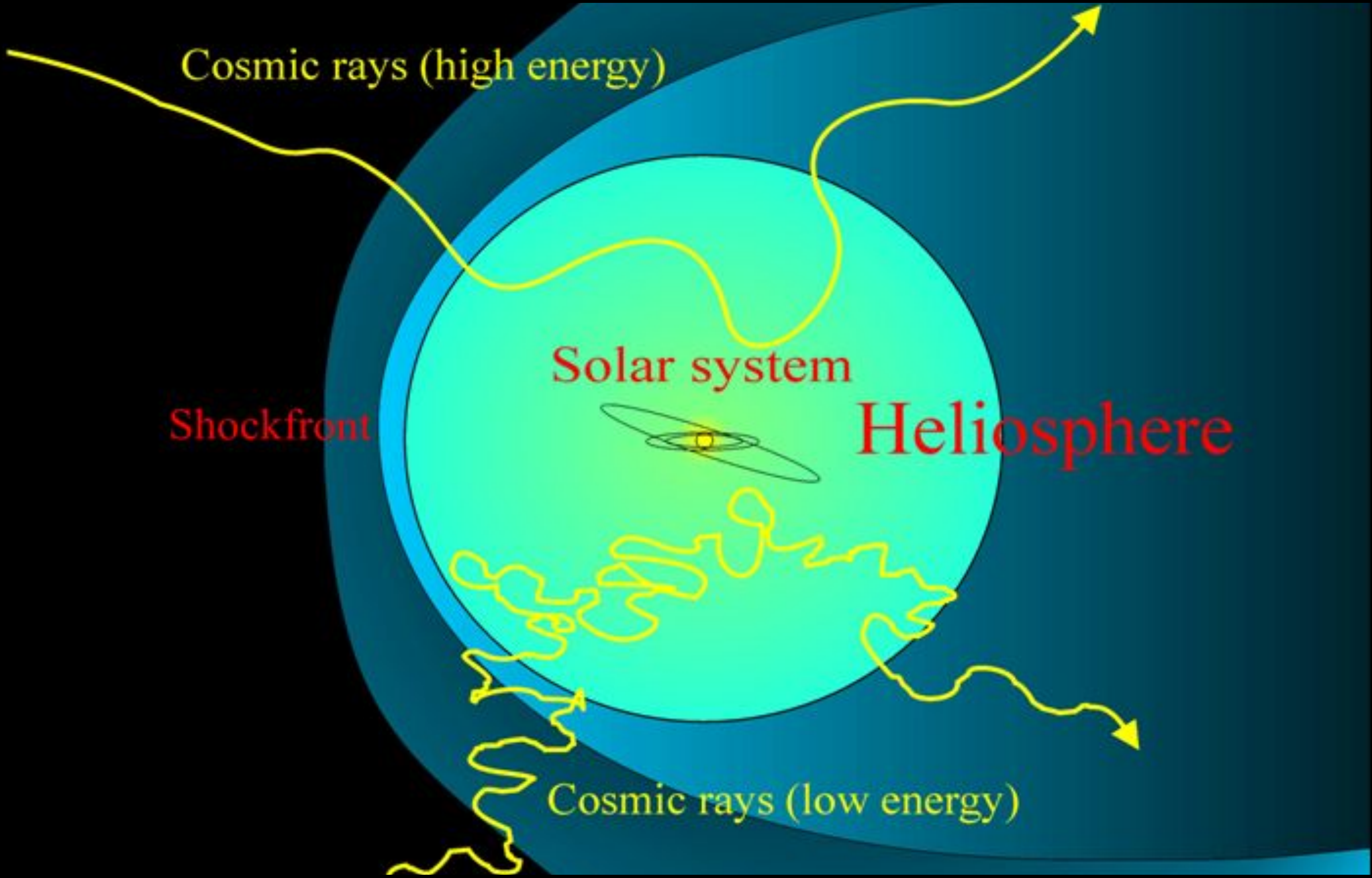
Physics of Anti-deuterons

Anti-deuterons have never been observed in space.

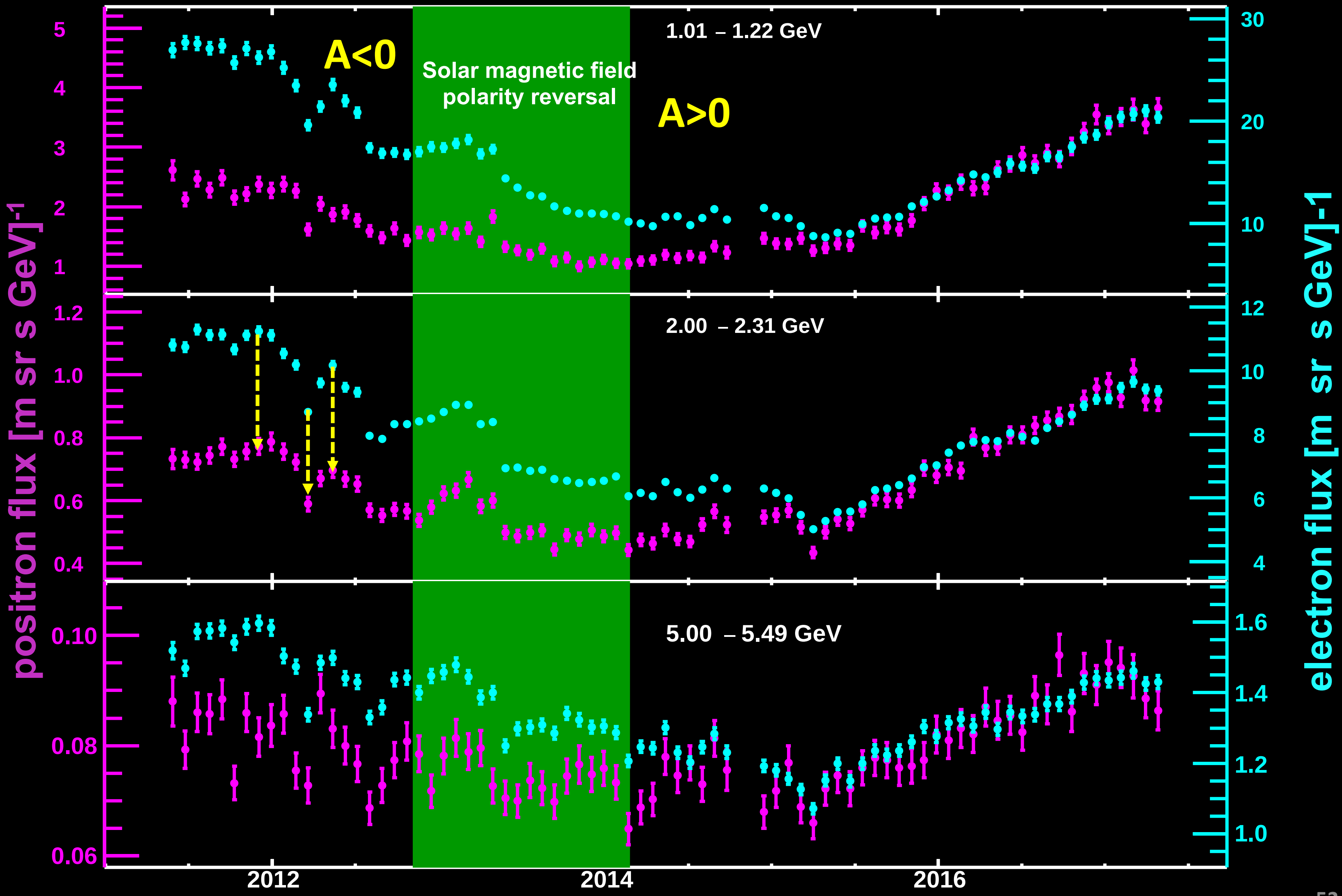

2 anti-deuteron candidates

Collecting data through the lifetime of ISS will enable us to ascertain if anti-deuterons are from Dark Matter collision.

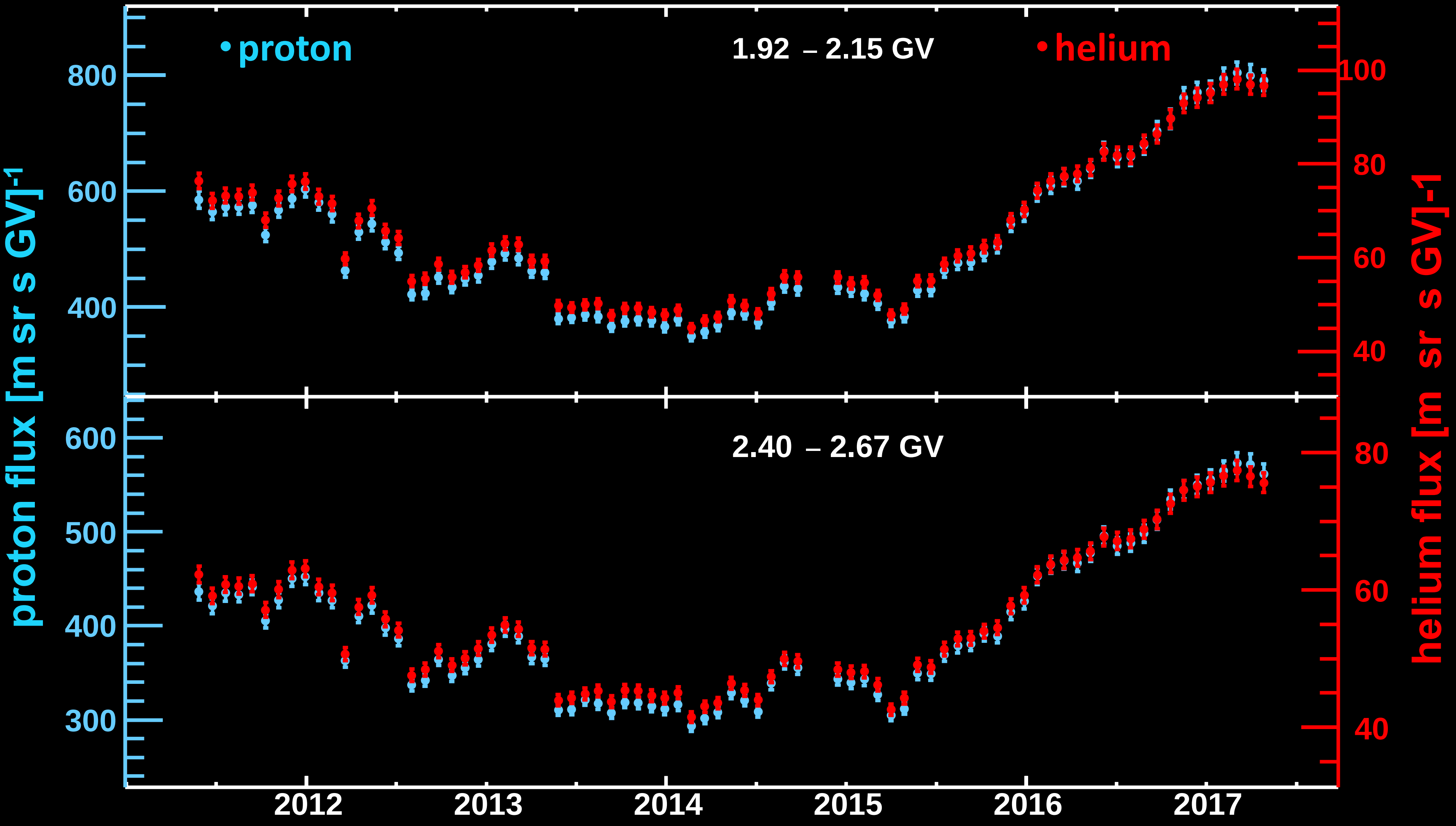
Solar Physics over an 11-year Solar Cycle: 2011 - 2024



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

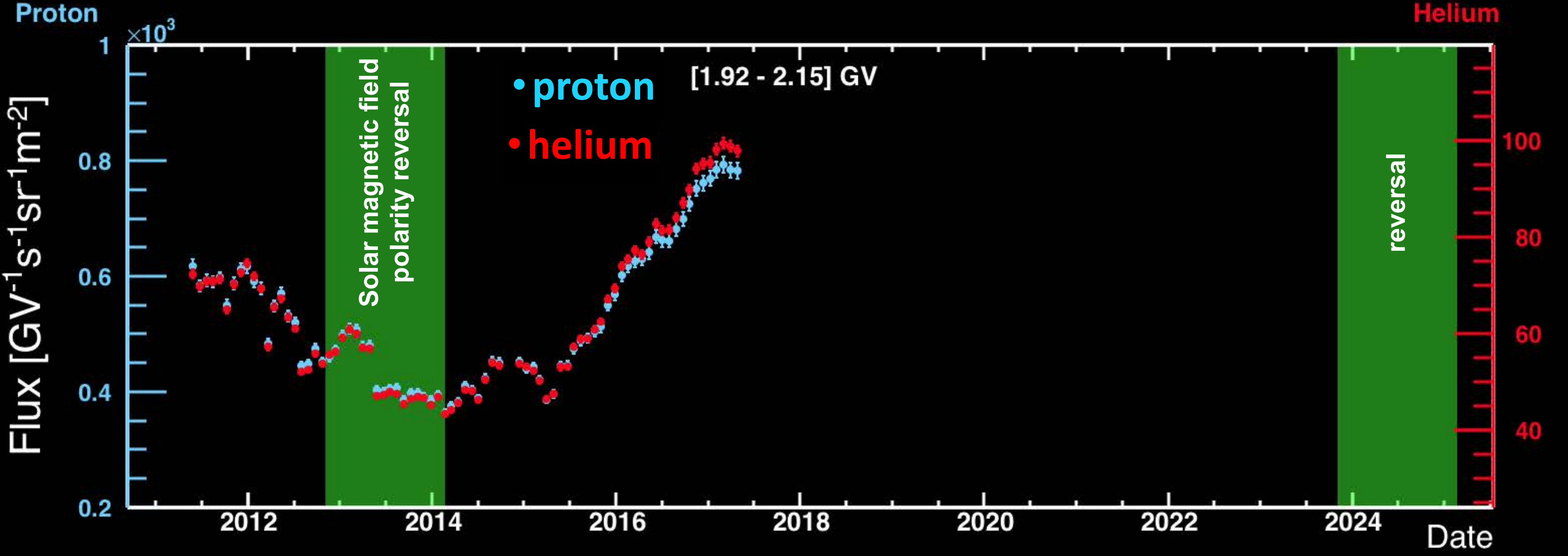


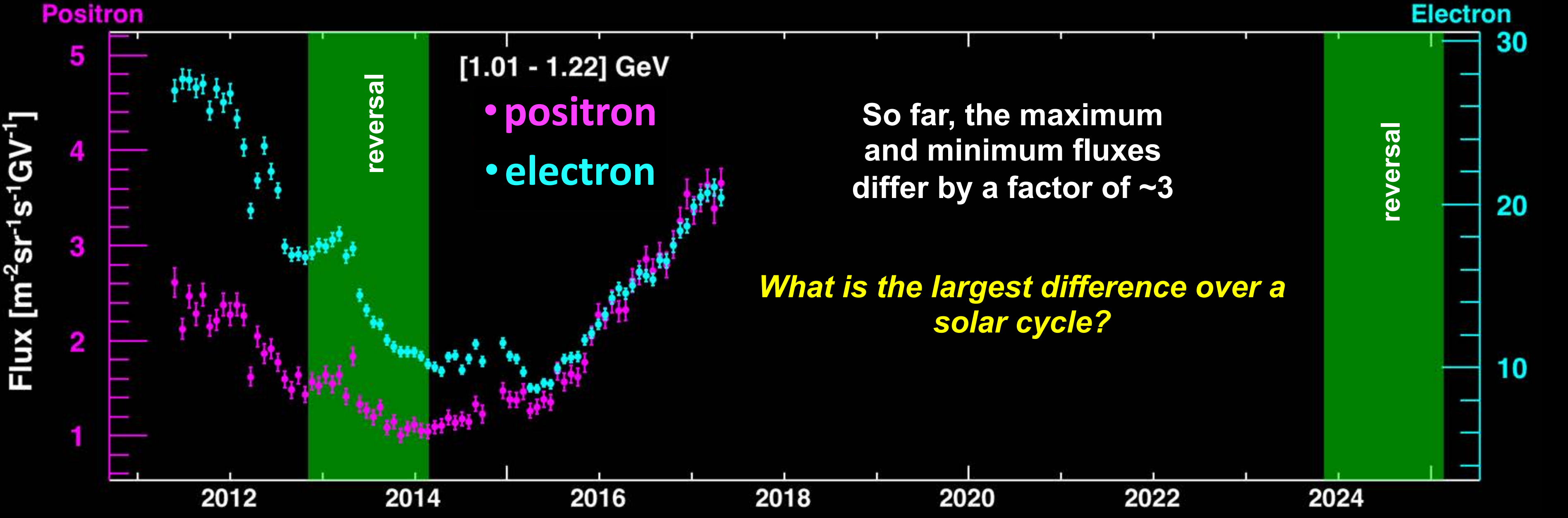
AMS Results on the Identical monthly time variation of the proton and helium fluxes over 6 years



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

Solar physics over a complete 11-year solar cycle



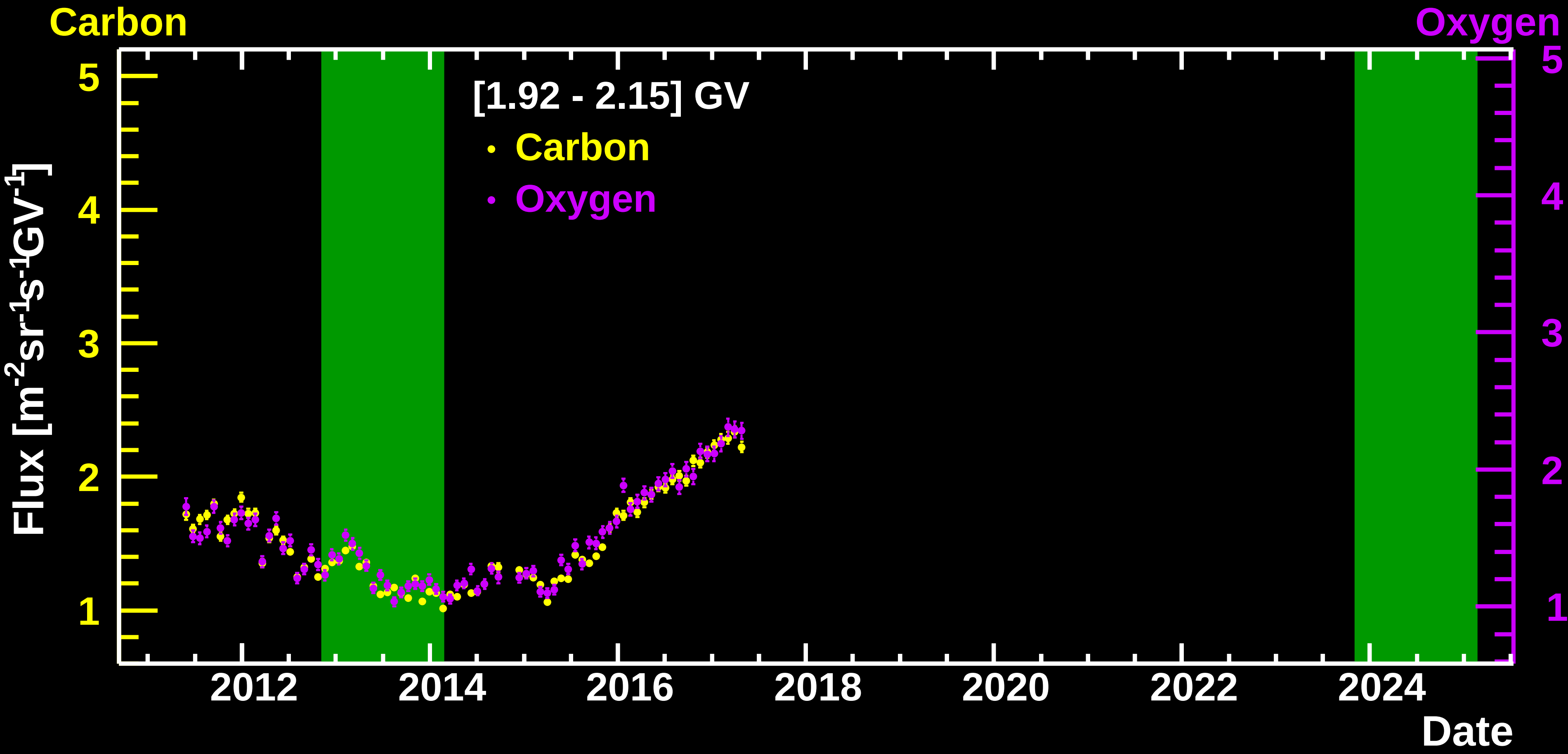


So far, the maximum and minimum fluxes differ by a factor of ~3

What is the largest difference over a solar cycle?

Solar physics over a complete 11-year solar cycle

Carbon and Oxygen

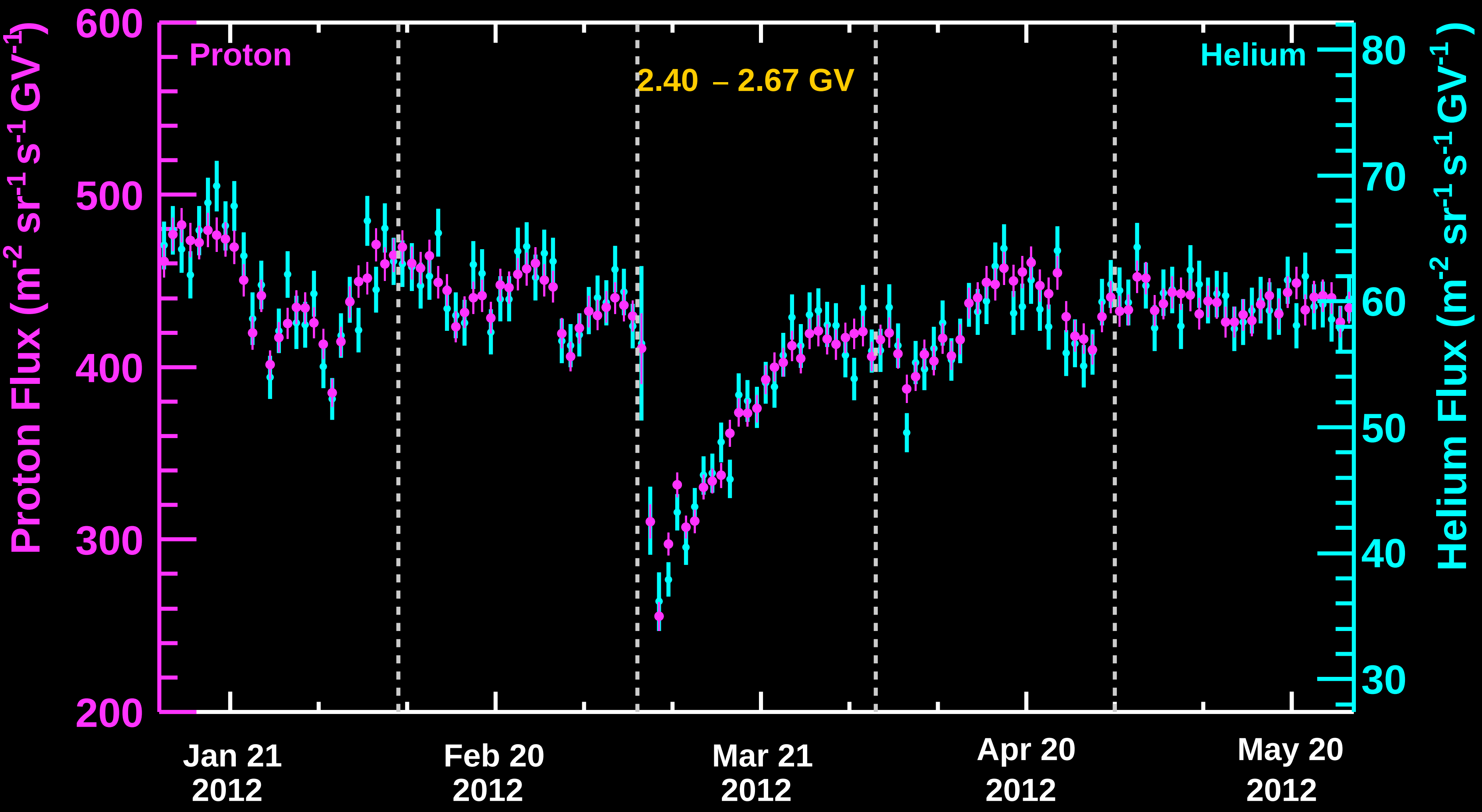


The maximum and minimum fluxes differ by a factor of ~3

What is the largest difference over a solar cycle?

Solar physics

Identical daily time variation of the p, He fluxes



Day by day, the flux can change quickly.

Question: When in the 11-year cycle is the flux a minimum?

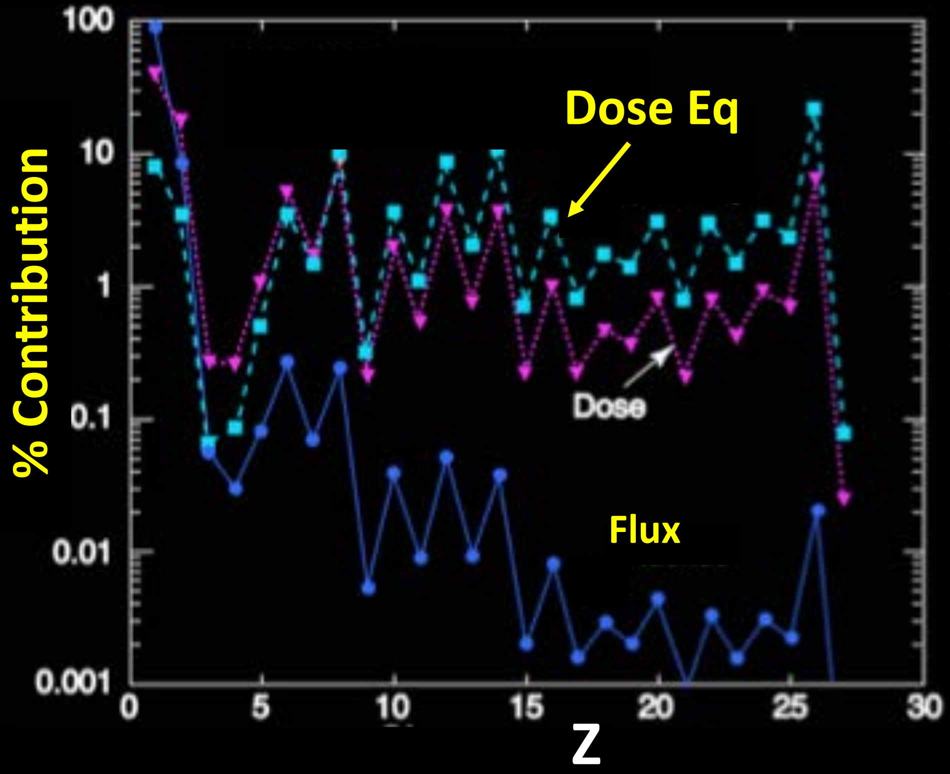
Application of AMS Solar Physics Results:

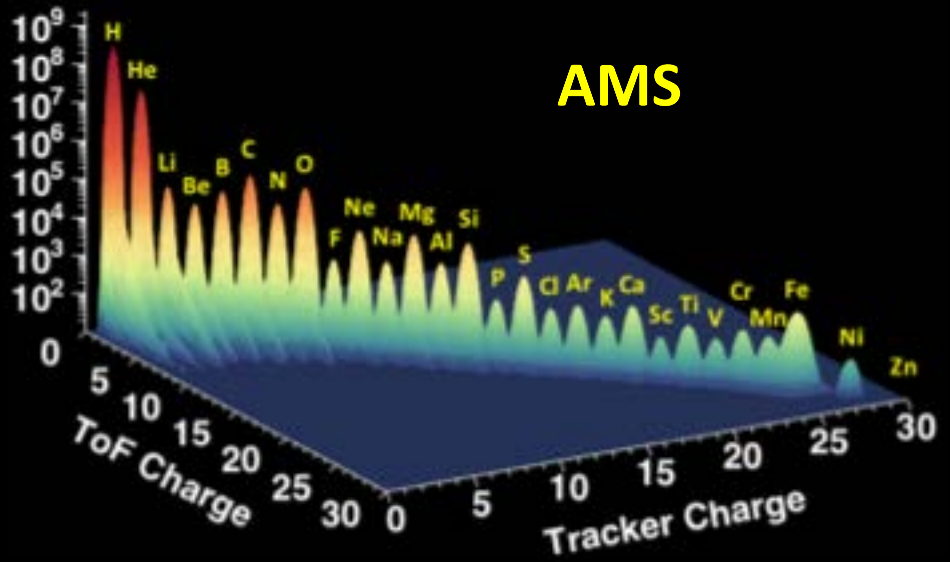
Radiation Effects and Protection for Moon and Mars Missions

Thomas A. Parnell (MSFC), Jon W. Watts Jr. (MSFC), and Tony W. Armstrong (SAIC)

Sixth ASCE Specialty Conference and Exposition on Engineering, Construction, and Operations in Space

Galactic Cosmic Ray Contribution





Radiation damage is proportional to Z^2.

It is important to measure to the highest Z.

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