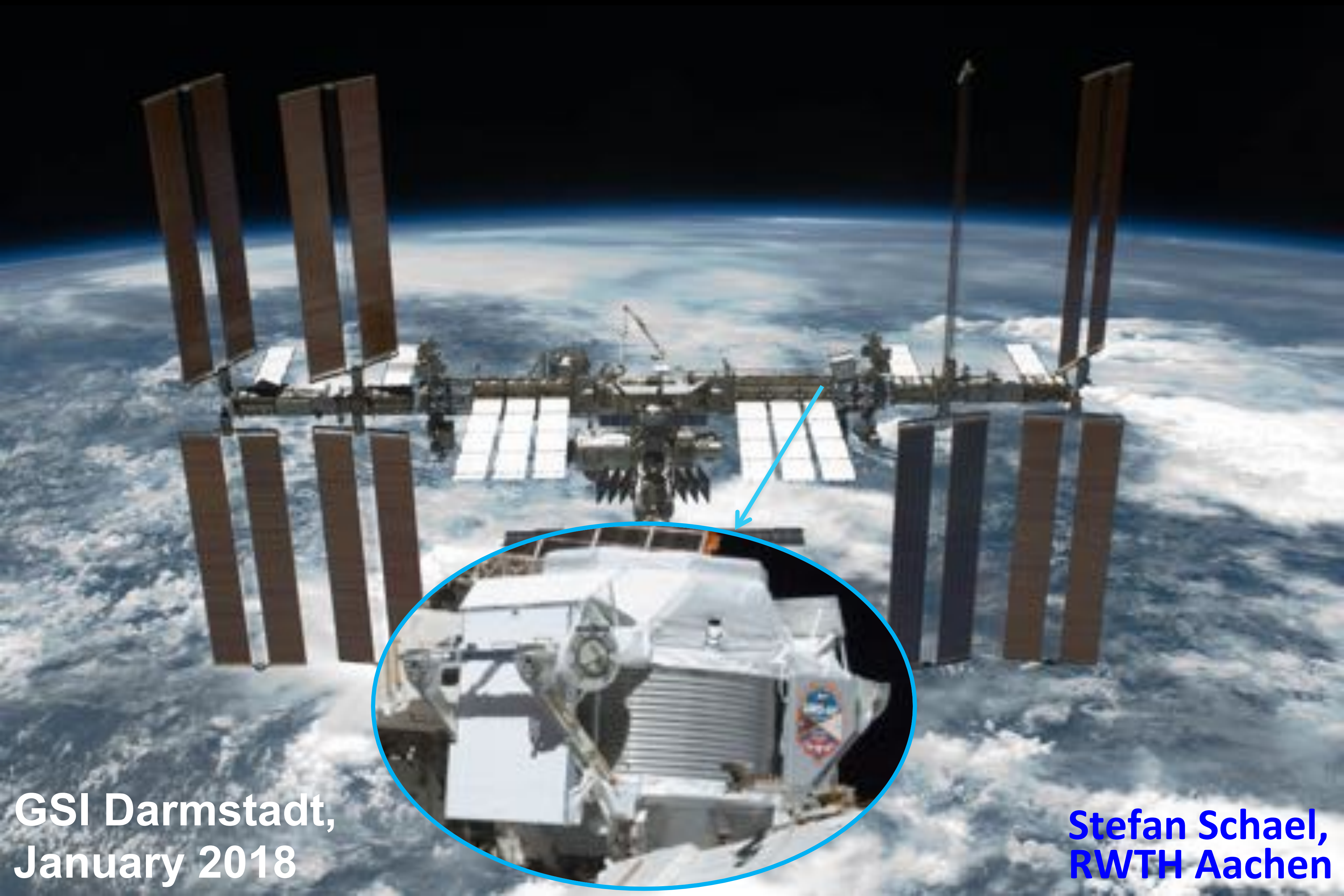
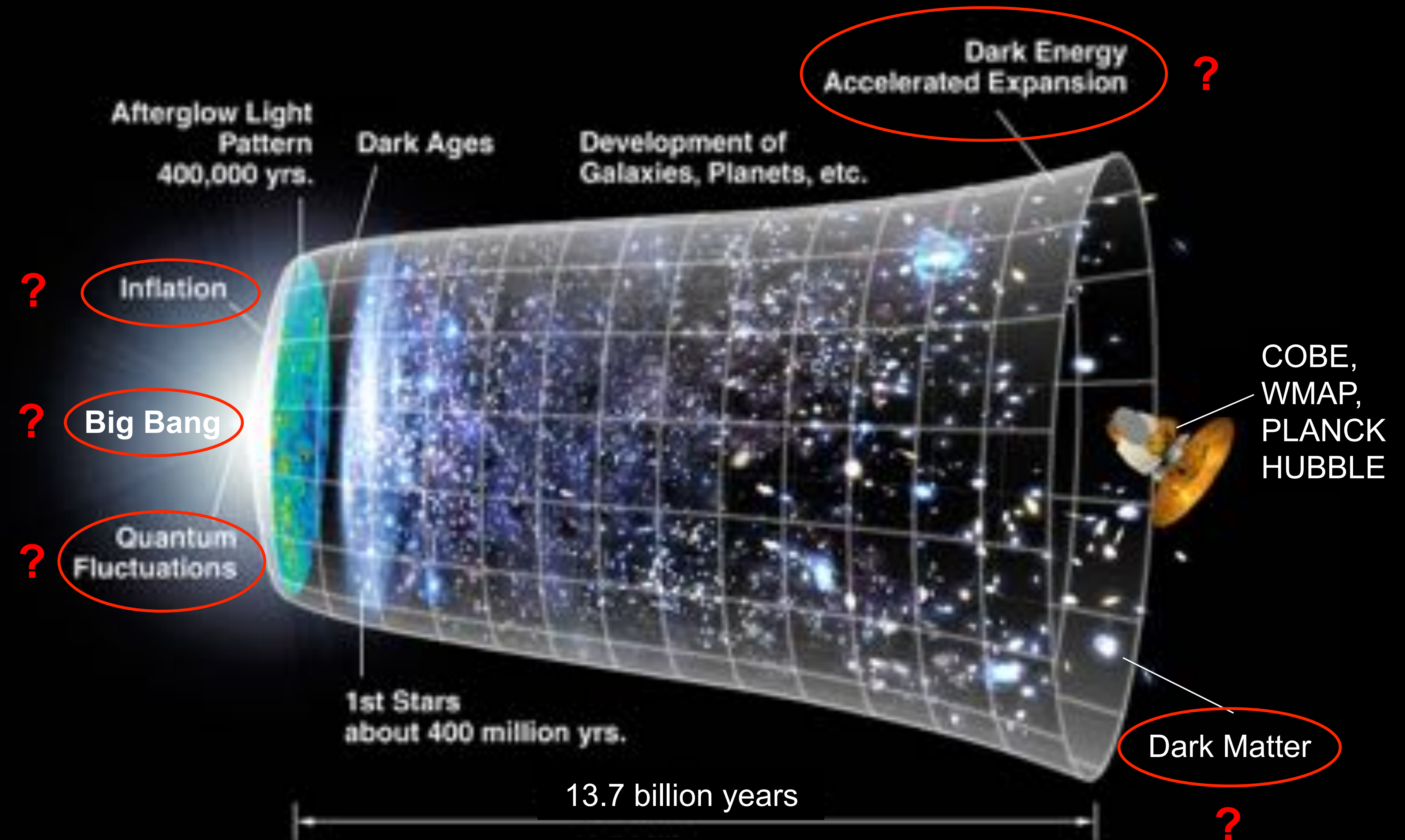
# First six years of AMS on the ISS



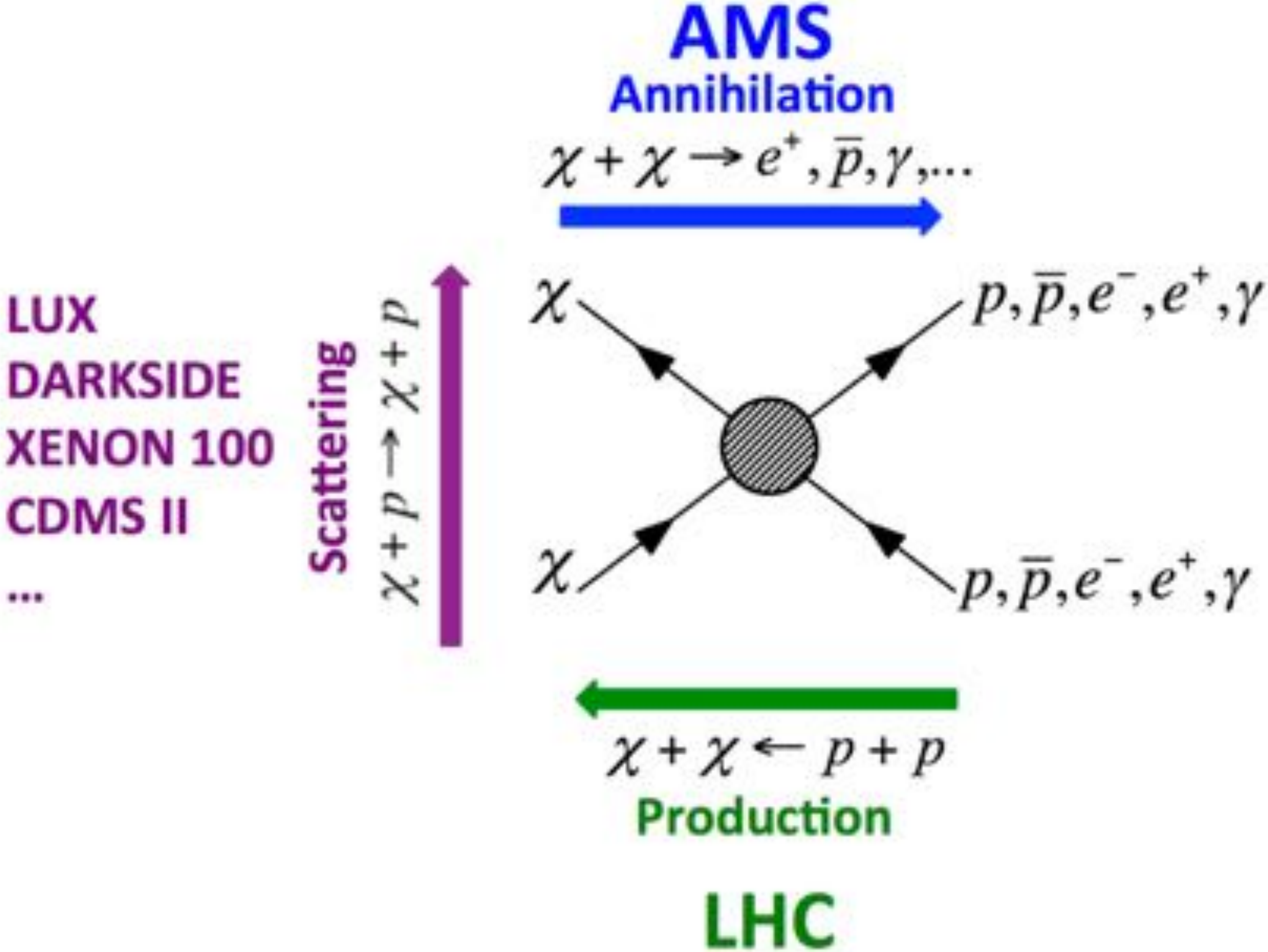
GSI Darmstadt,
January 2018

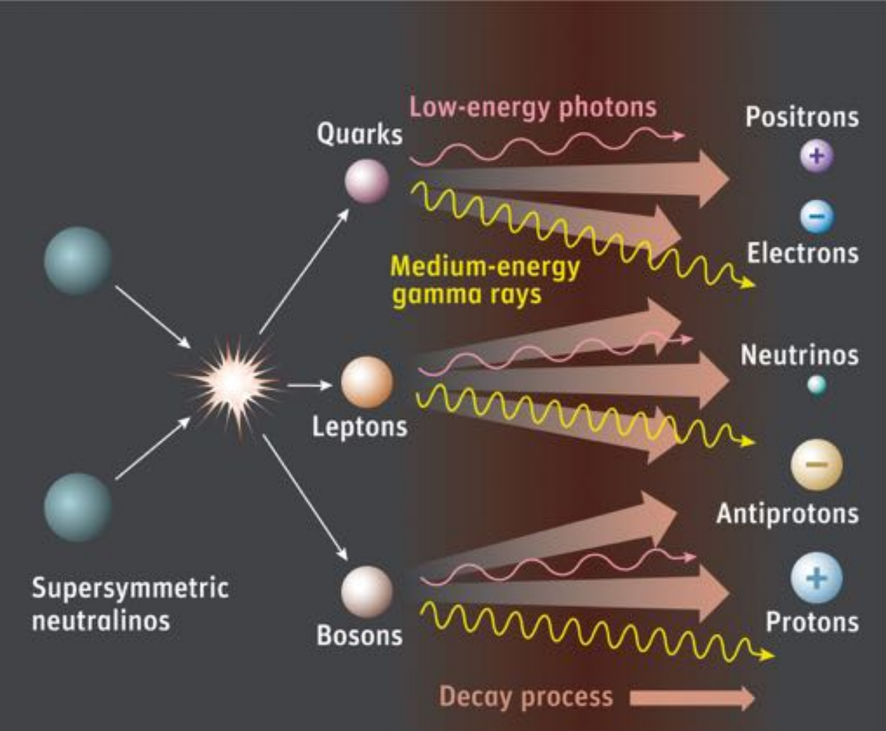
Stefan Schael,
RWTH Aachen

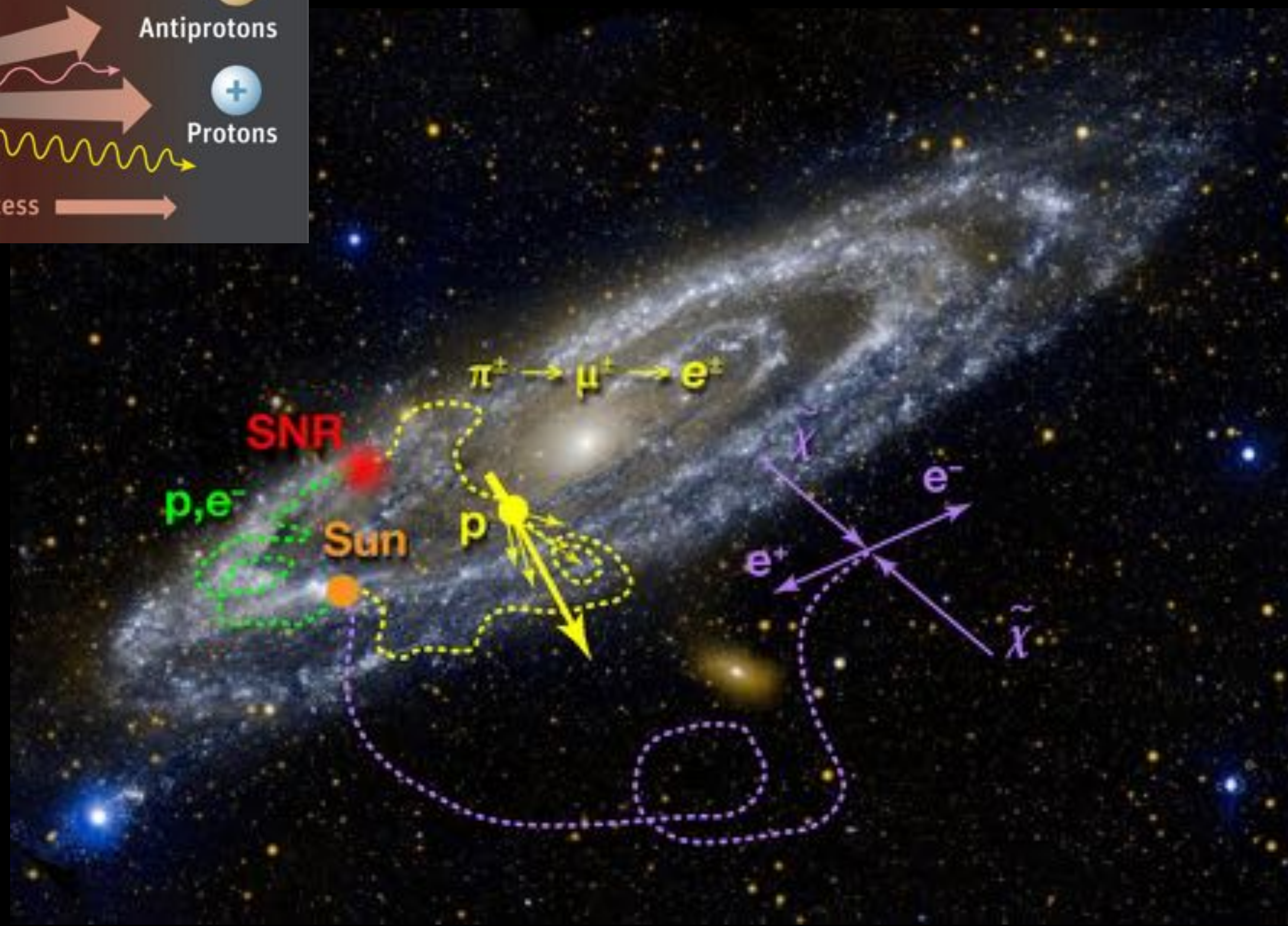


Dark Energy
Accelerated Expansion
?
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
?
Inflation
?
Big Bang
?
Quantum
Fluctuations
COBE,
WMAP,
PLANCK
HUBBLE
1st Stars
about 400 million yrs.
Dark Matter
13.7 billion years
?

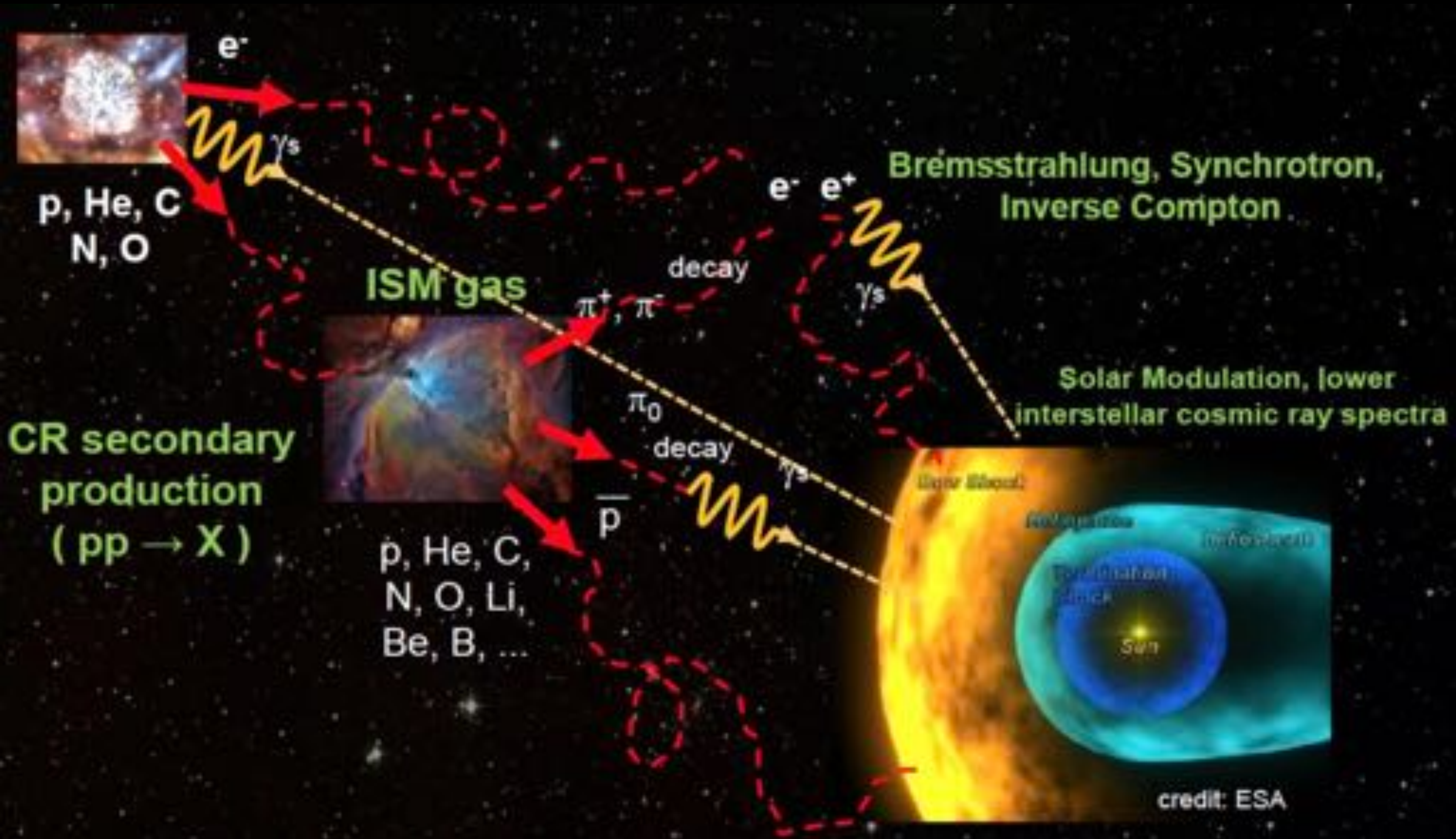
# Three independent methods to search for Dark Matter



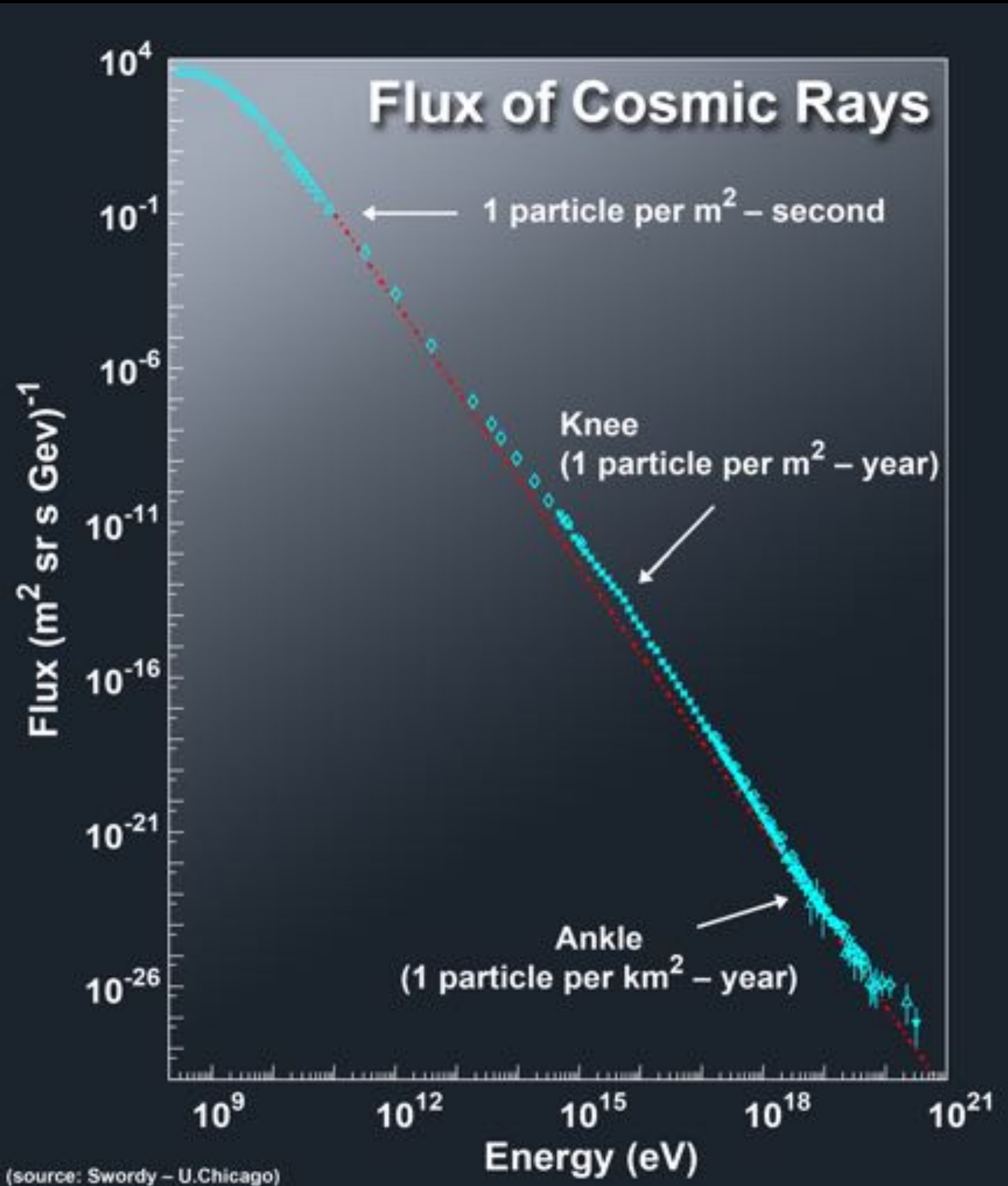

Low-energy photons
Quarks
Positrons
Electrons
Medium-energy
gamma rays
Neutrinos
Leptons
Antiprotons
Supersymmetric
neutralinos
Bosons
Protons
Decay process


$\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$
SNR
p,$e^-$
Sun
p
$\tilde{\chi}$
$e^-$
$e^+$
$\tilde{\chi}$

# Light primary cosmic ryas: p, He, C, N, O and $e^-$

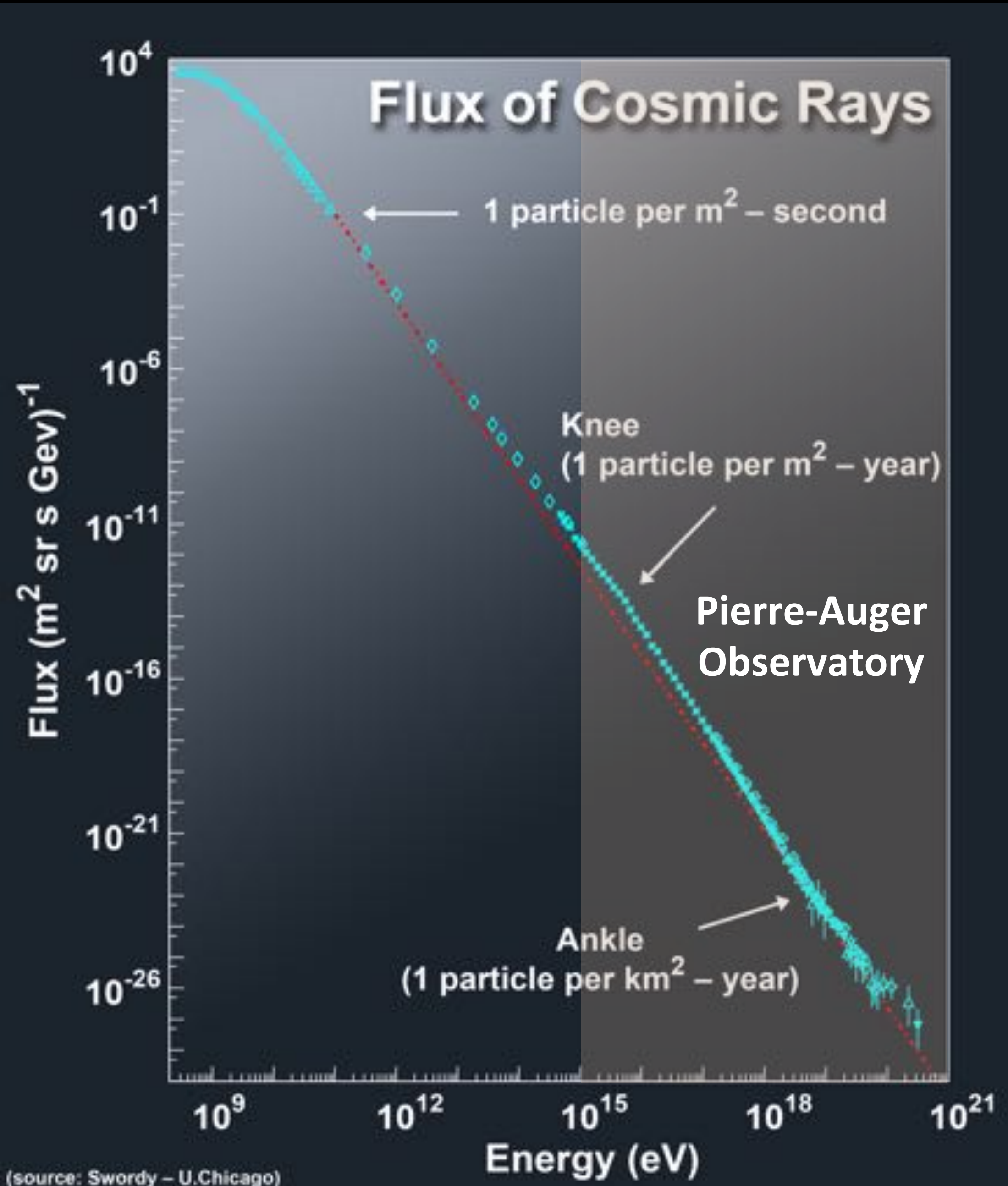


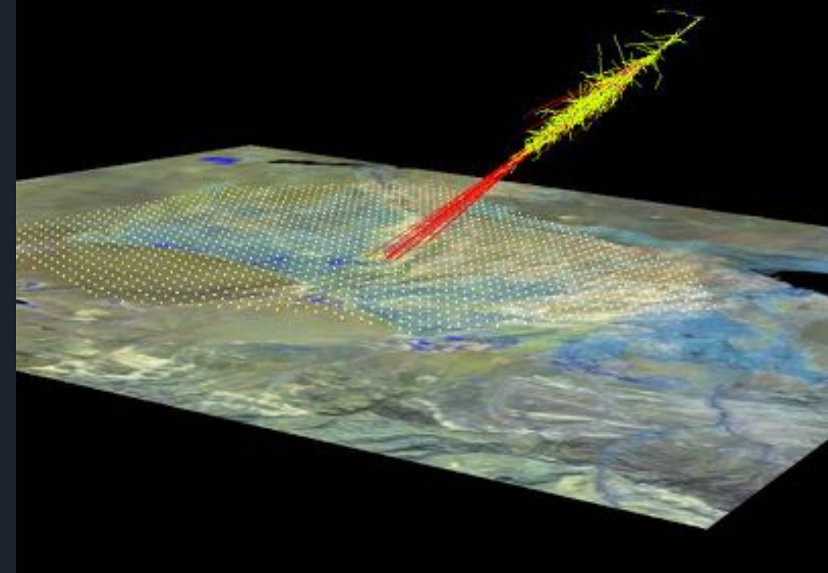

Light secondary cosmic ryas: Li, Be, B and $e^+$, $\bar{p}$

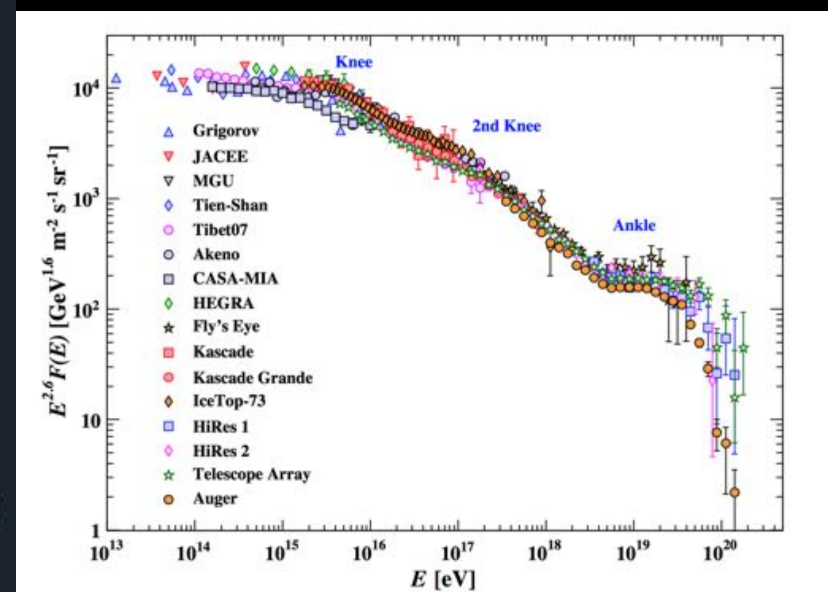


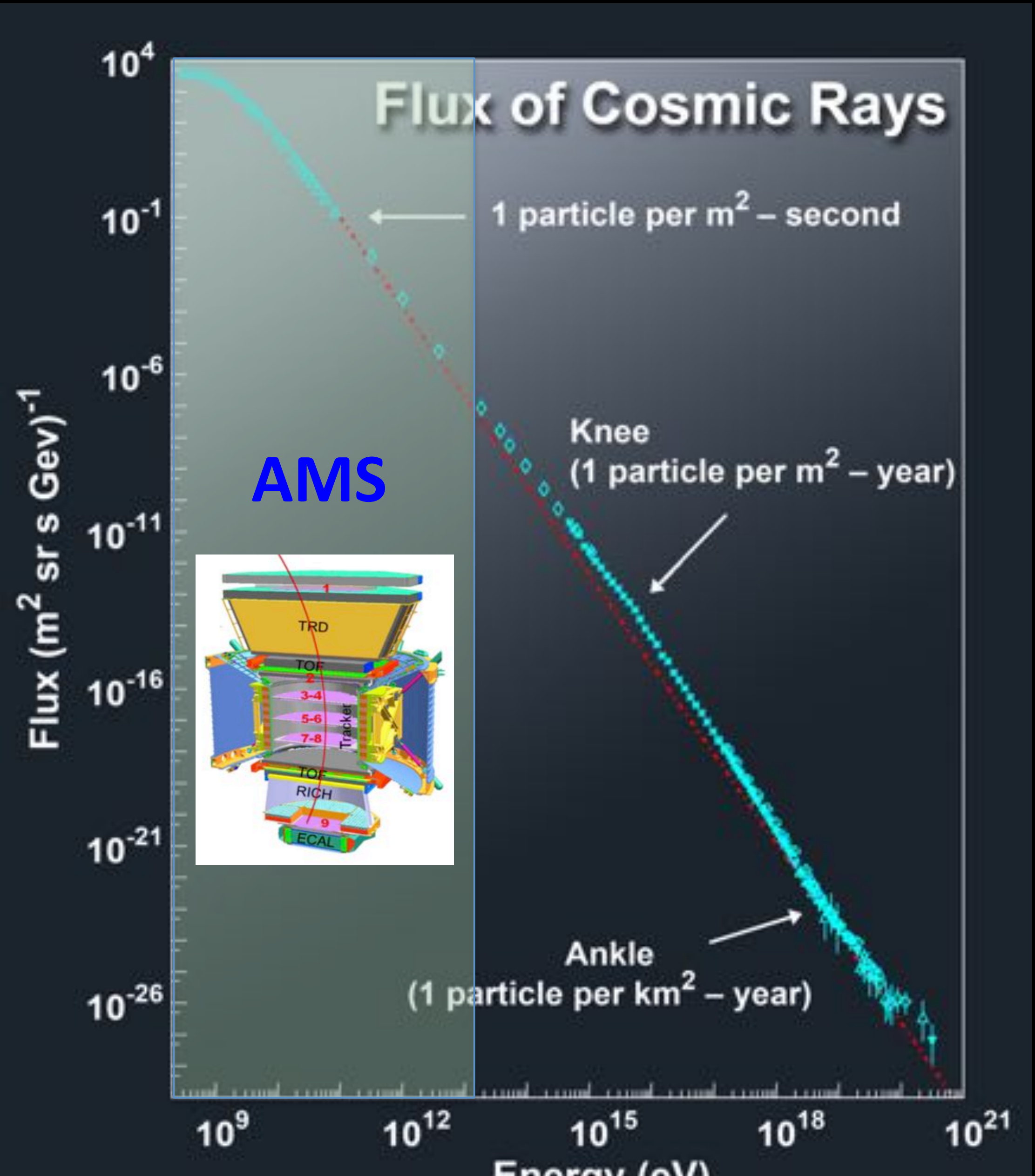
Flux of Cosmic Rays
1 particle per m2 – second
Knee
(1 particle per m2 – year)
Ankle
(1 particle per km2 – year)
Flux (m2 sr s Gev)-1
10^4
10^-1
10^-6
10^-11
10^-16
10^-21
10^-26
10^9
10^12
10^15
10^18
10^21
Energy (eV)
(source: Swordy – U.Chicago)

## Pierre-Auger-Observatorium, Argentinien, 3000 km²

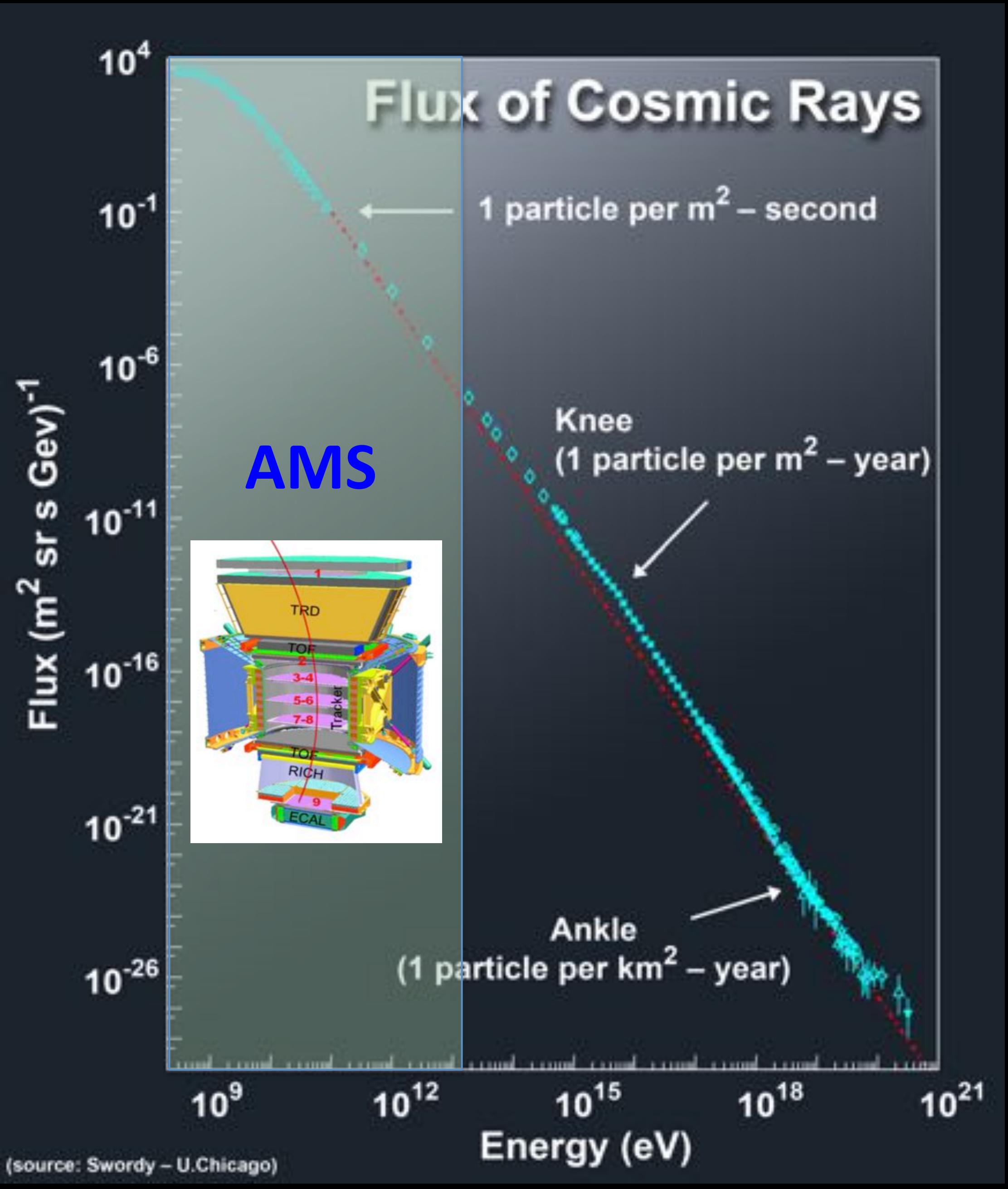


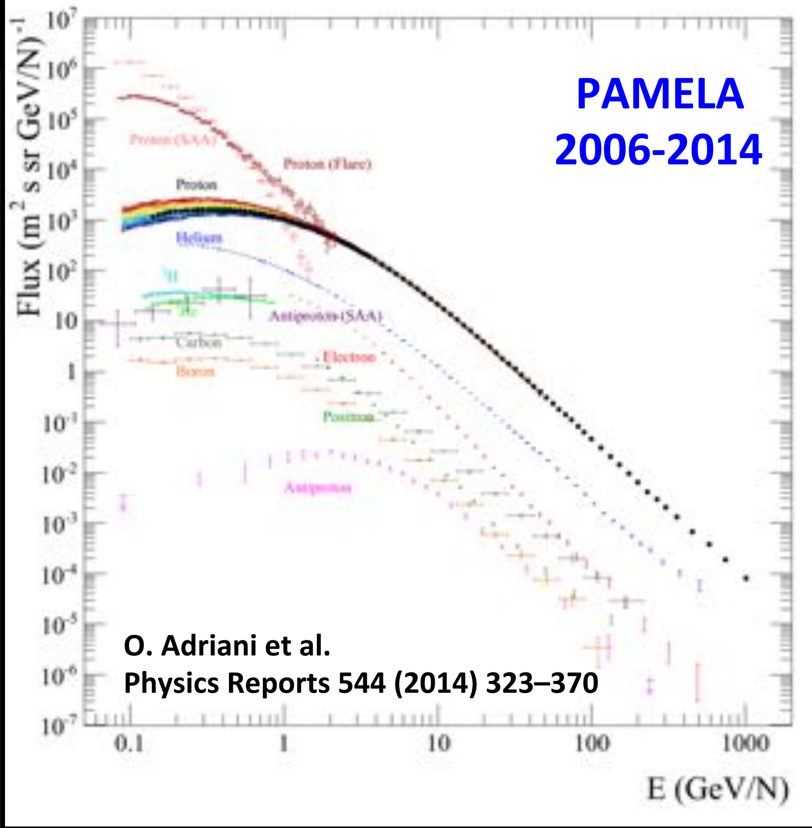



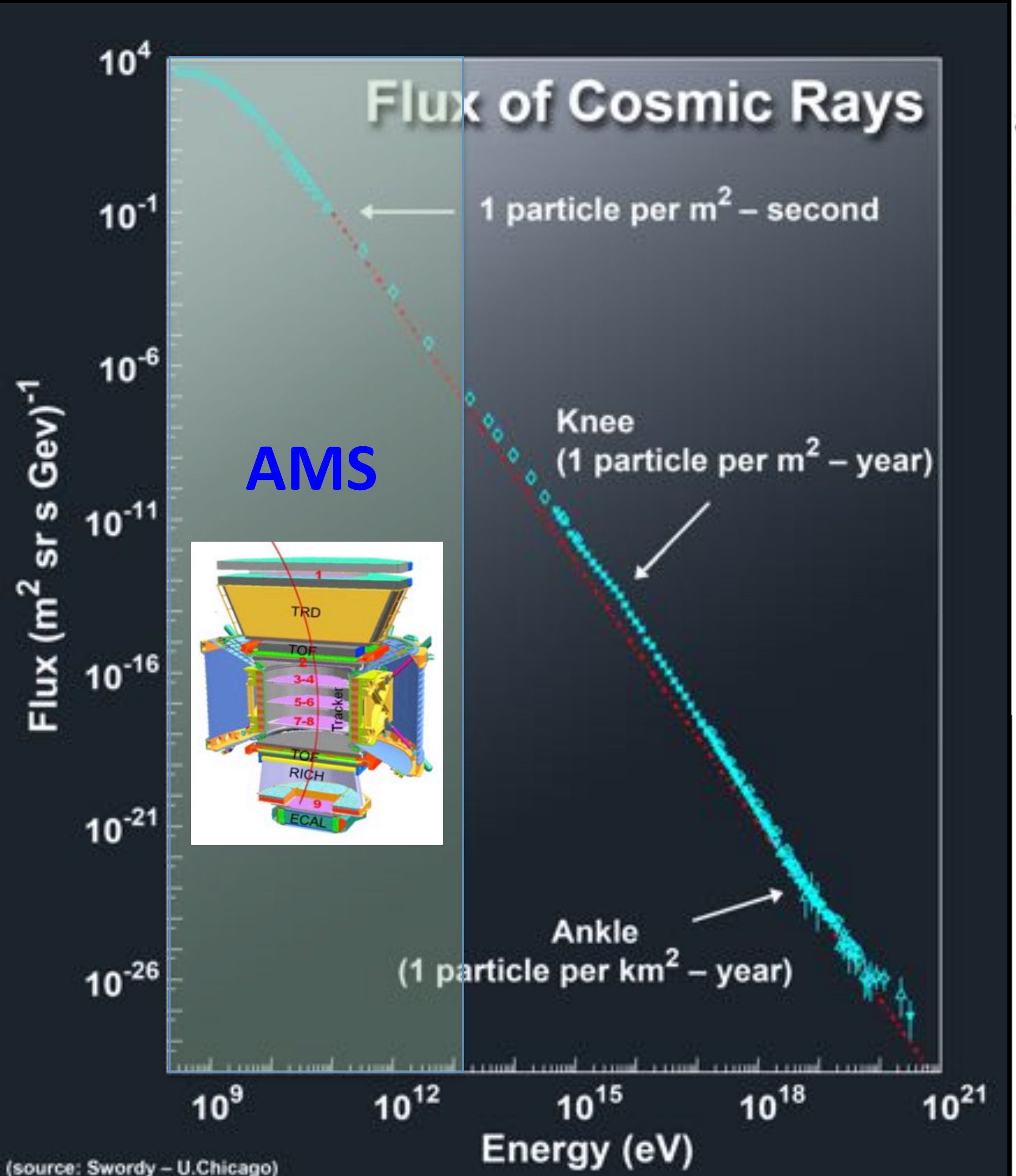


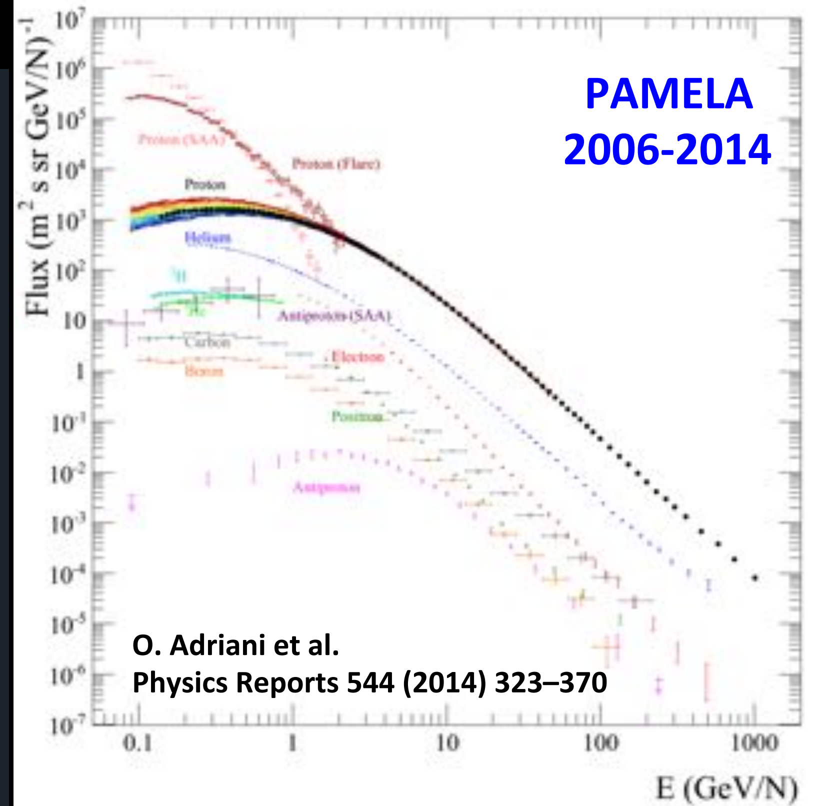


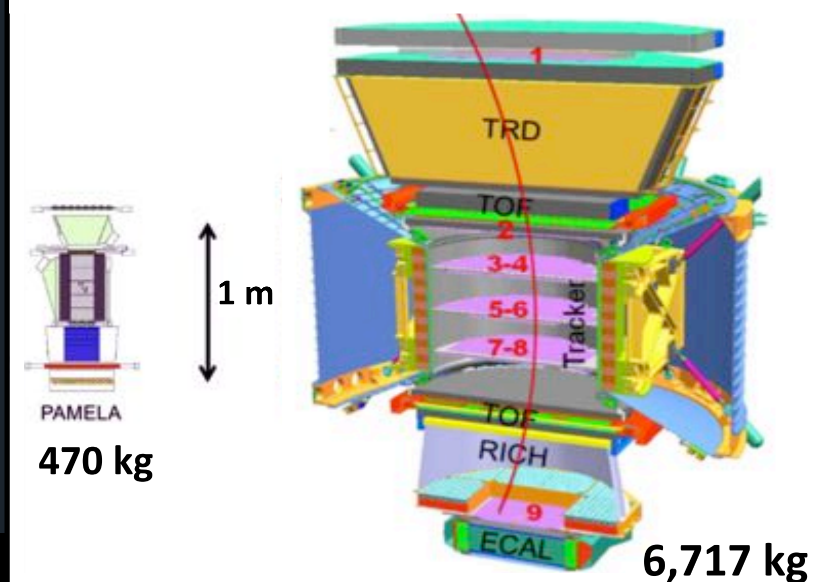
(source: Swordy – U.Chicago)


Flux of Cosmic Rays
1 particle per m² – second
Knee
(1 particle per m² – year)
Ankle
(1 particle per km² – year)
AMS
TRD
TOF
Tracker
RICH
ECAL
Flux (m² sr s Gev)⁻¹
Energy (eV)
(source: Swordy – U.Chicago)

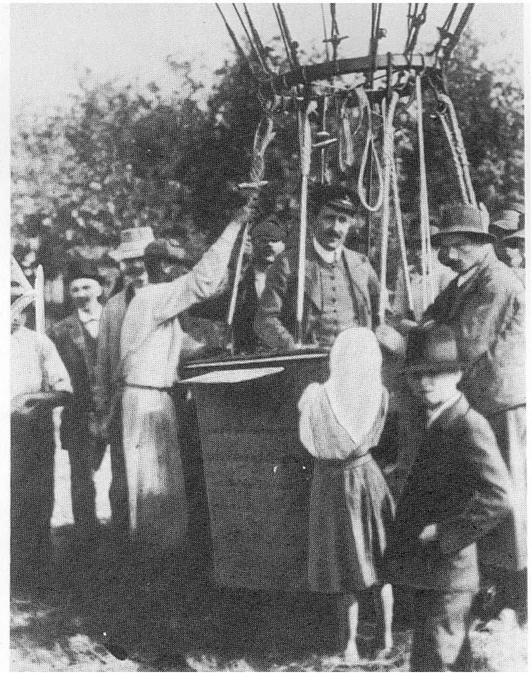

PAMELA
2006-2014
O. Adriani et al.
Physics Reports 544 (2014) 323–370
Flux (m² s sr GeV/N)⁻¹
E (GeV/N)
Proton (Flare)
Proton
Helium
Carbon
Boron
Electron
Positron
Antiprotons


Flux of Cosmic Rays
1 particle per m2 – second
Knee
(1 particle per m2 – year)
Ankle
(1 particle per km2 – year)
AMS
TRD
TOF
Tracker
RICH
ECAL
Flux (m2 sr s Gev)-1
Energy (eV)
10^4
10^-1
10^-6
10^-11
10^-16
10^-21
10^-26
10^9
10^12
10^15
10^18
10^21
(source: Swordy – U.Chicago)


PAMELA
2006-2014
Proton (SAA)
Proton (Flare)
Proton
Helium
Antiproton (SAA)
Carbon
Boron
Electron
Positron
Antiproton
O. Adriani et al.
Physics Reports 544 (2014) 323–370
Flux (m2 s sr GeV/N)-1
E (GeV/N)
0.1
1
10
100
1000

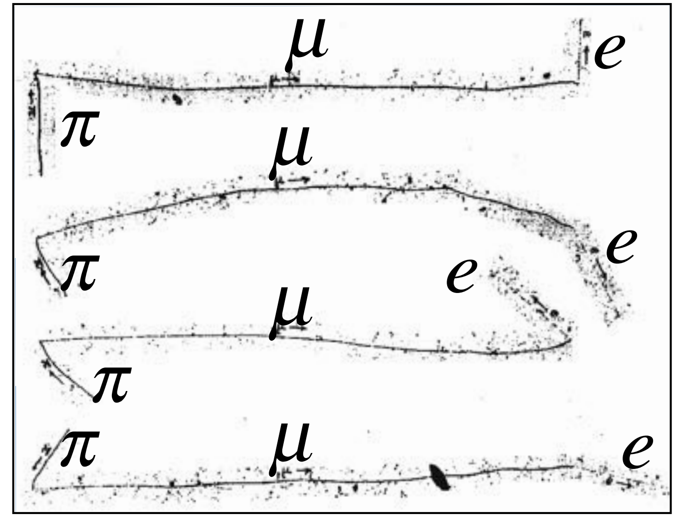

PAMELA
470 kg
1 m
TRD
TOF
Tracker
TOF
RICH
ECAL
6,717 kg

# Physics of Charged Cosmic Rays



1912: Discovery of Cosmic Rays
V. Hess

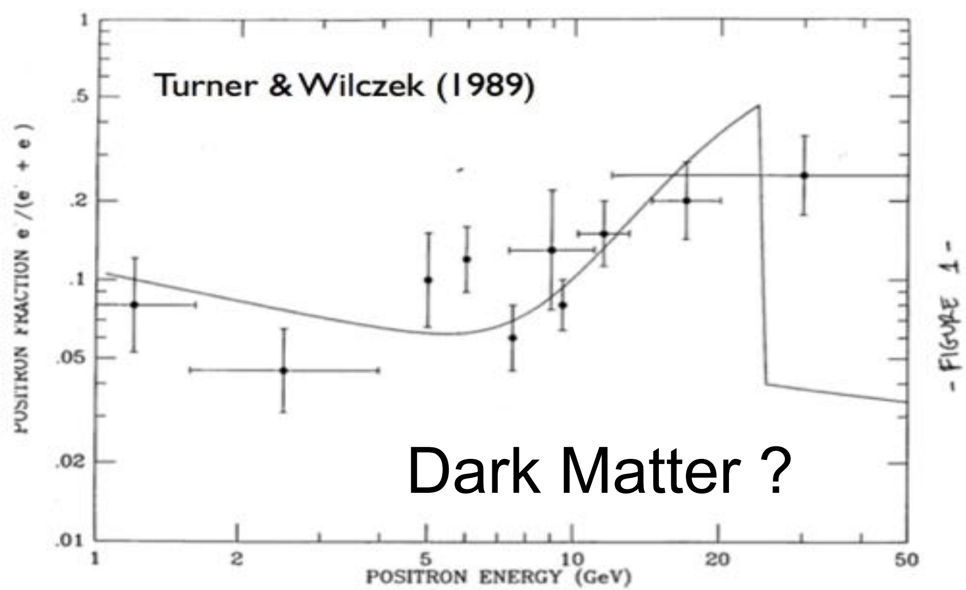
1932: Discovery of positron
C.D. Anderson

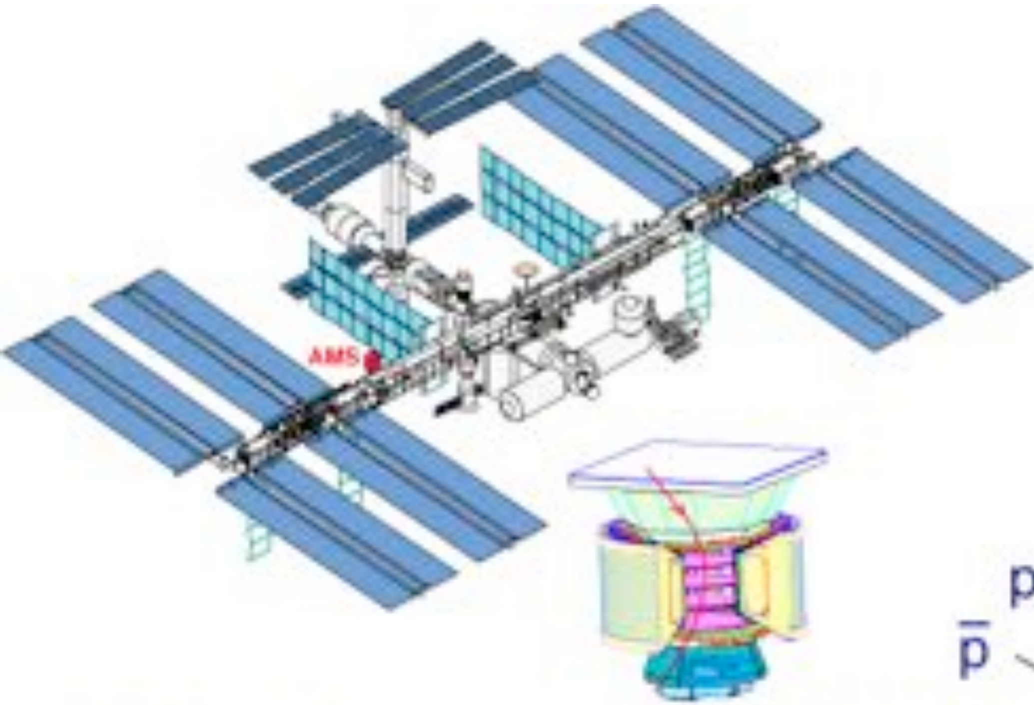



1947: Discovery of pions
C. Powell

Discoveries of

- 1936: Muon ($\mu$)
- 1938: $10^{15}$ eV CR
- 1949: Kaon (K)
- 1949: Lambda ($\Lambda$)
- 1952: Xi ($\Xi$)
- 1953: Sigma ($\Sigma$)





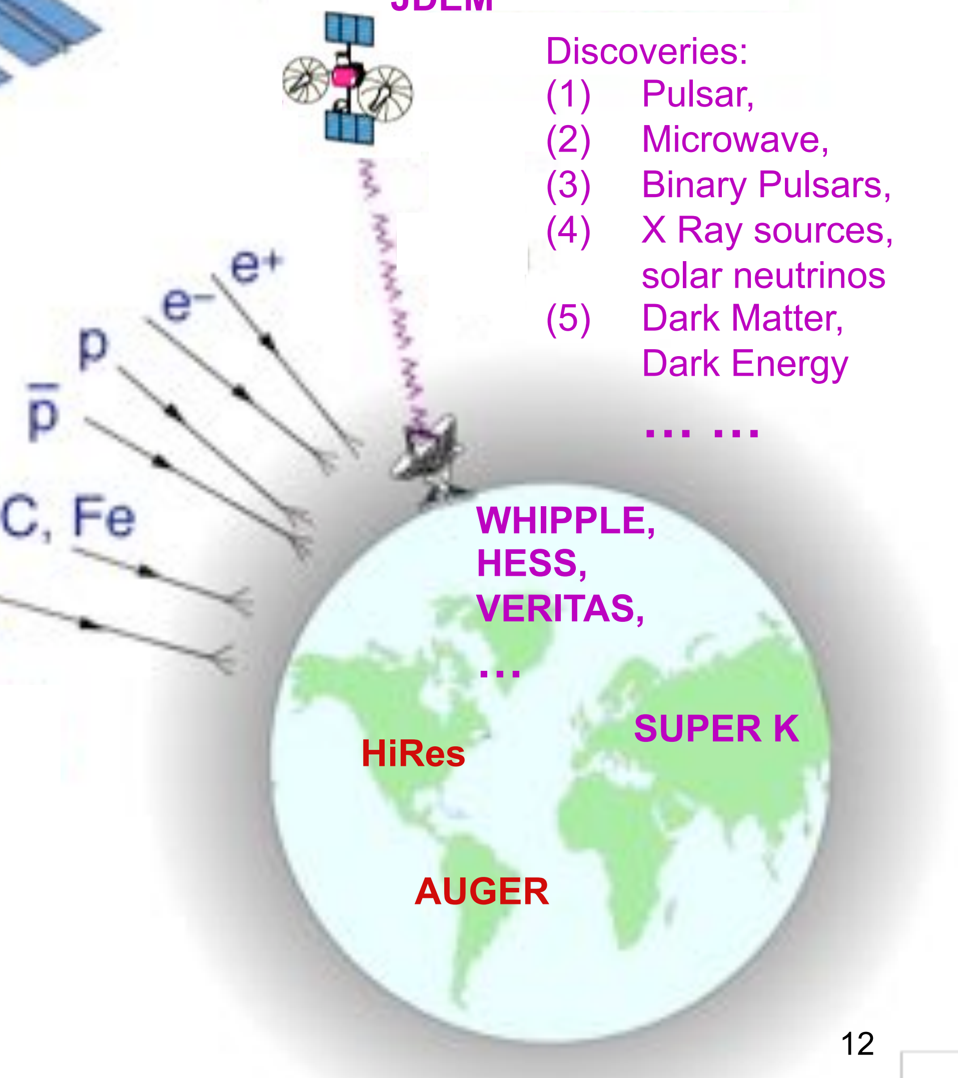

1- Neutral component: $\gamma, \nu$

**Hubble, Chandra, GLAST, JWST, JDEM**

Discoveries:

(1) Pulsar,
(2) Microwave,
(3) Binary Pulsars,
(4) X Ray sources, solar neutrinos
(5) Dark Matter, Dark Energy

**… …**

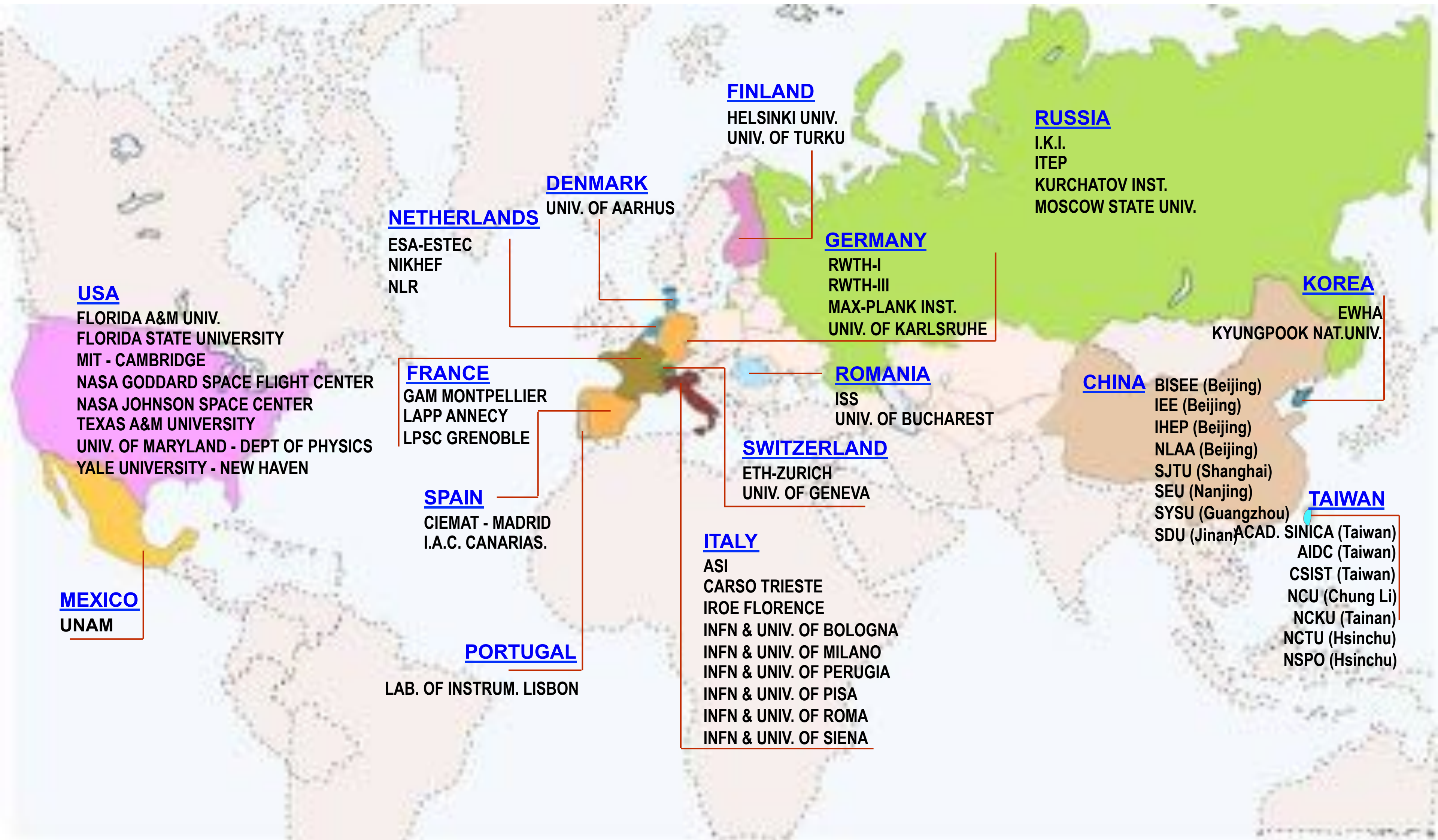



2- Charged component: He, Be, C, Fe

*S. Ting*, MIT

# AMS is US Dept of Energy (DOE) led International Collaboration

## 16 Countries, 60 Institutes and 600 Physicists, 17 years



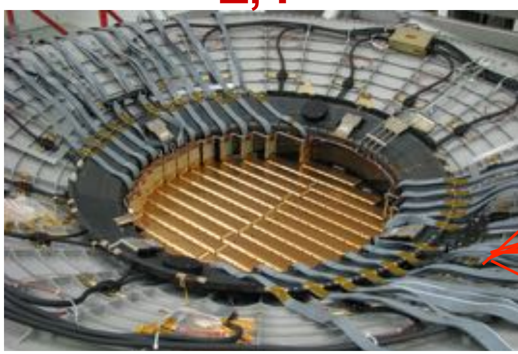

**The detectors were built all over the world and assembled at CERN, near Geneva, Switzerland**

# AMS: A TeV precision, multipurpose spectrometer

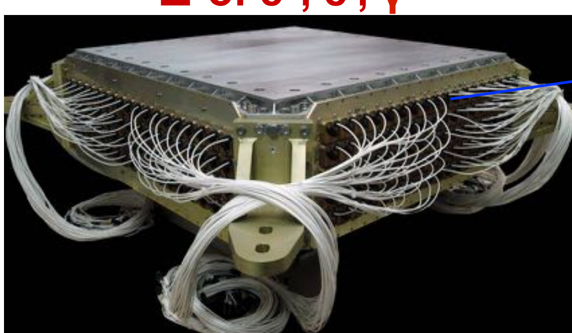
Particles and nuclei are defined by their charge (Z) and energy (E ~ P)

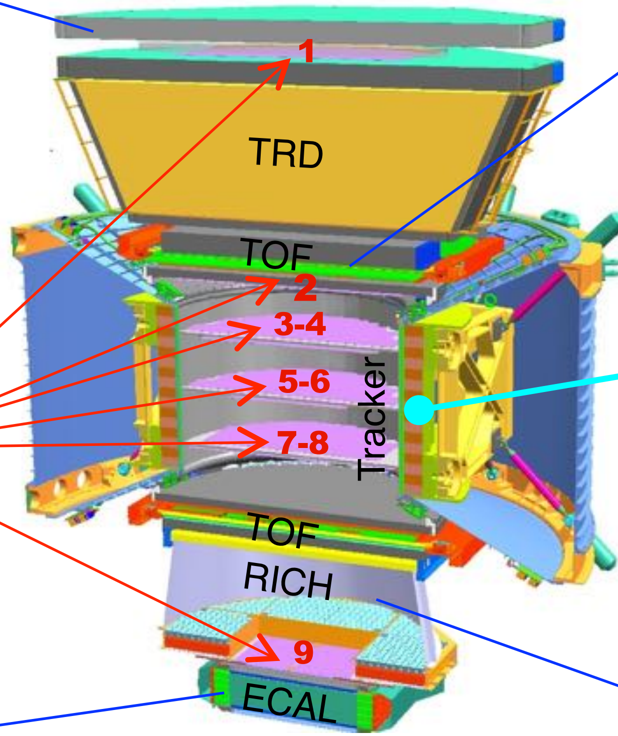
**TRD**
Identify $e^+$, $e^-$

**Silicon Tracker**
Z, P



**ECAL**
E of $e^+$, $e^-$, $\gamma$

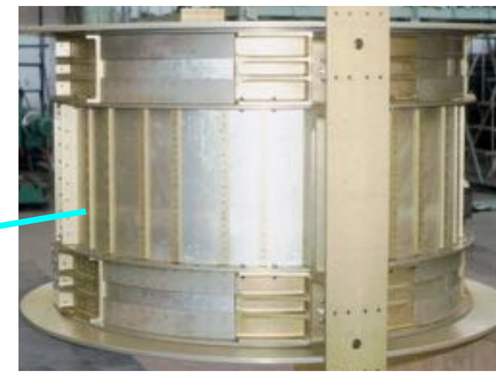




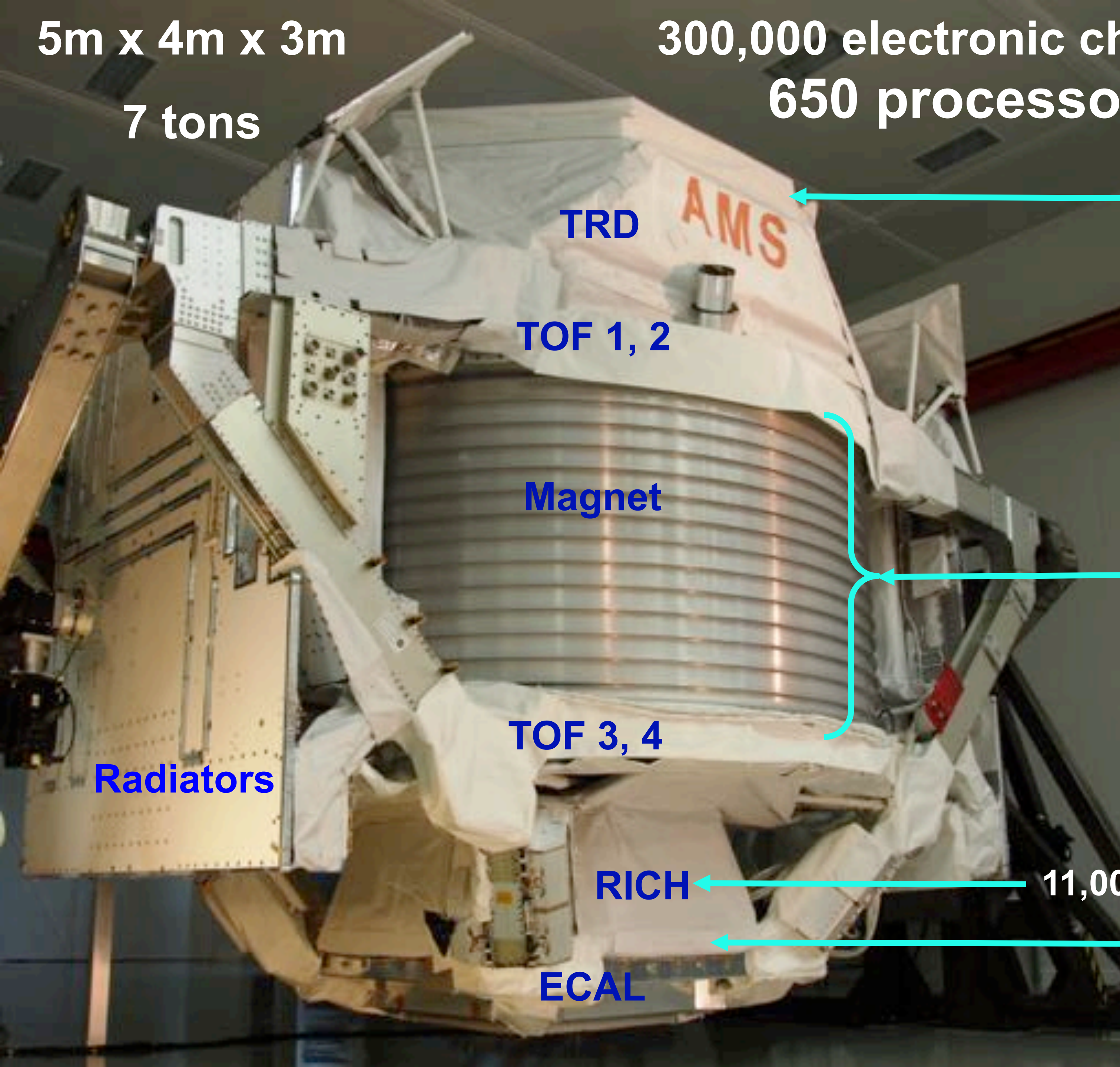

*Z, P are measured independently by the Tracker, RICH, TOF and ECAL*

**TOF**
Z, E

**Magnet**
±Z



**RICH**
Z, E


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


…WE JUST DECIDED LAUNCHING MONEY DIRECTLY INTO SPACE WAS CHEAPER …
NASA
£
€
¥
CHF
DM
FFR
Lira
UNIT
© 1993 OHMAN—OREGONIAN

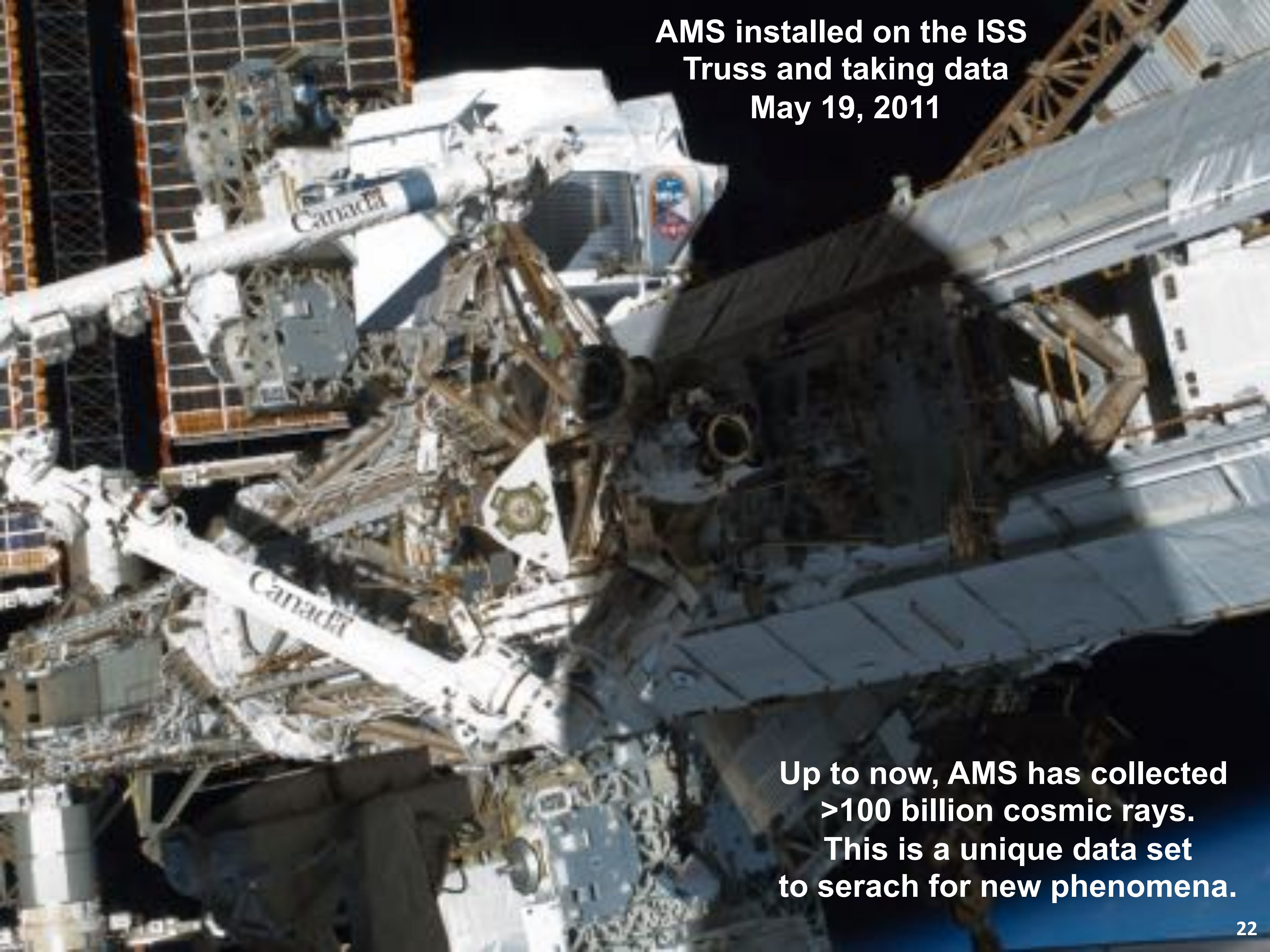
A US Air Force C-5 Galaxy
has been used for transport
from Geneva to KSC
25. August 2010


AMS

# Closing Endeavour's Payload Bay Doors at the Launch Pad

STS-134 launch May 16, 2011 @ 08:56 AM

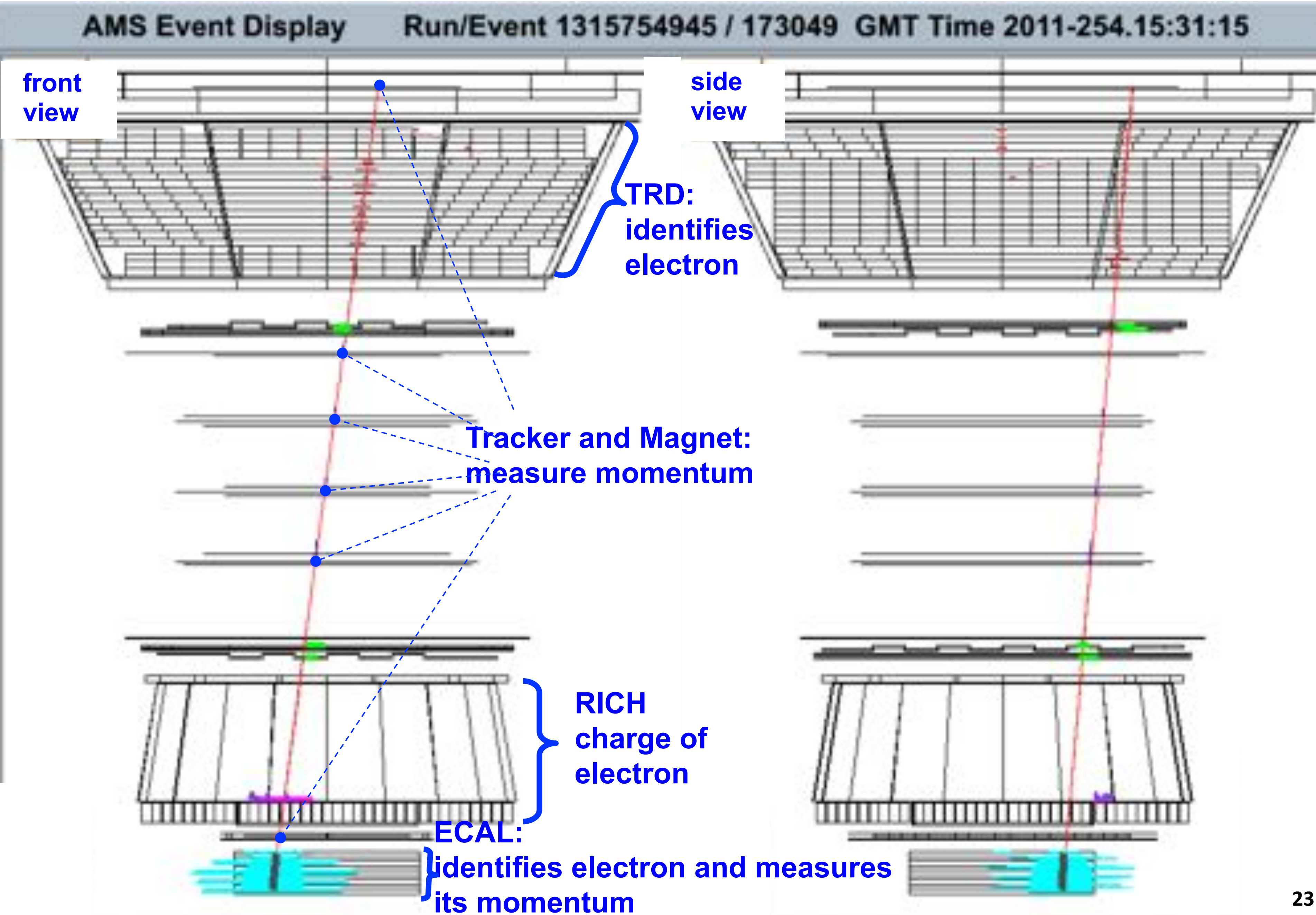
Endeavour approaches the International Space Station

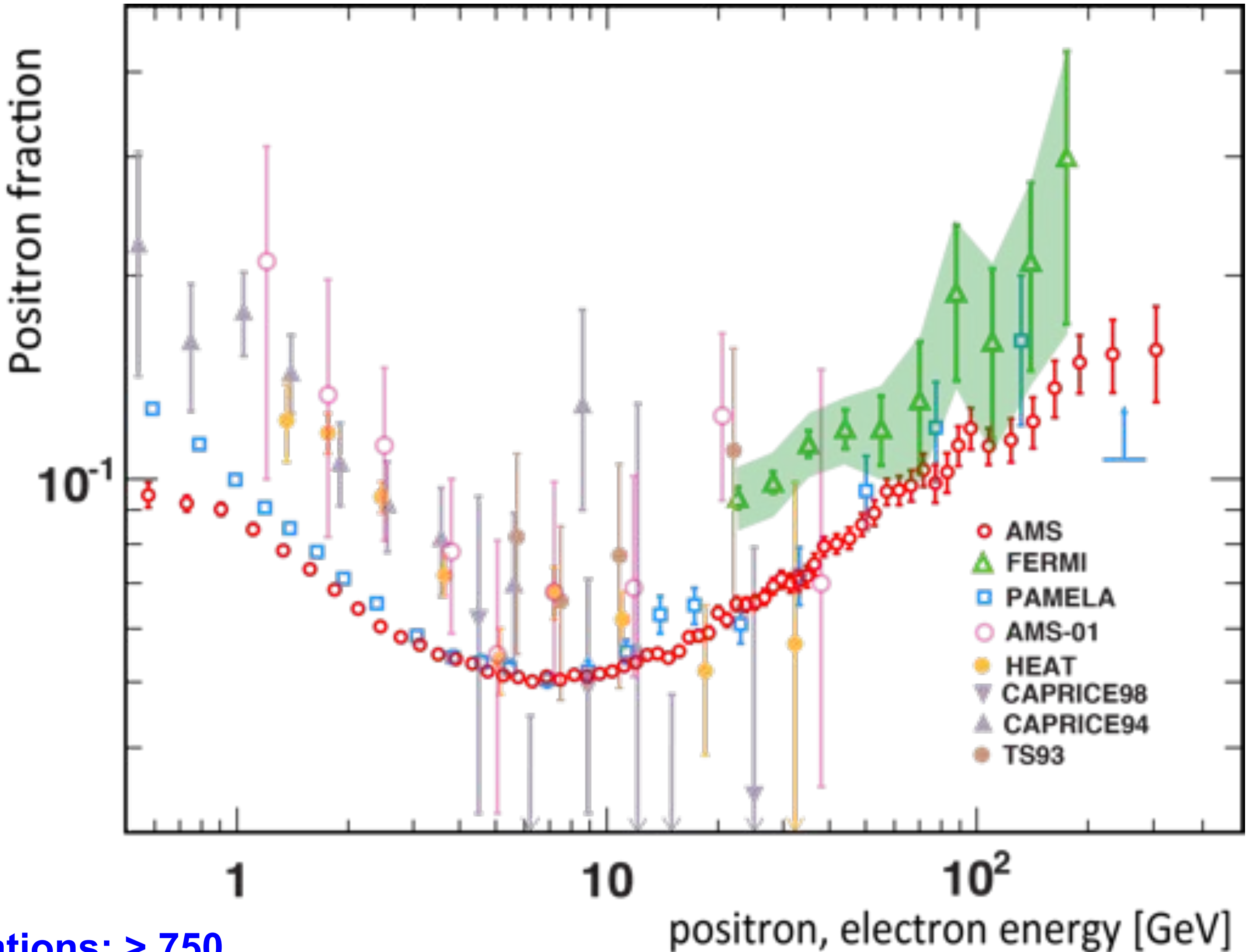


**AMS installed on the ISS Truss and taking data May 19, 2011**

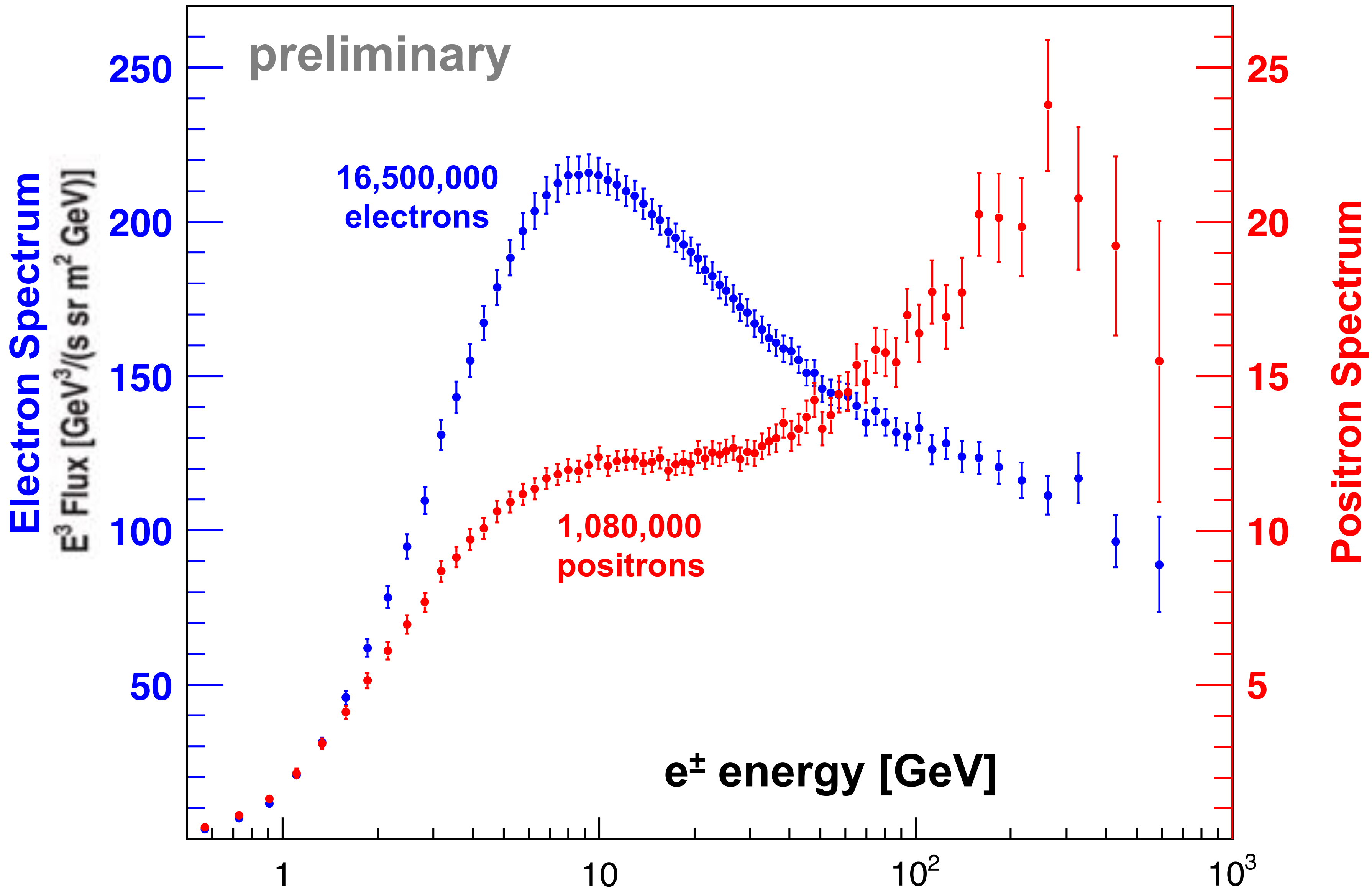
**Up to now, AMS has collected >100 billion cosmic rays. This is a unique data set to serach for new phenomena.**

# 1.03 TeV electron



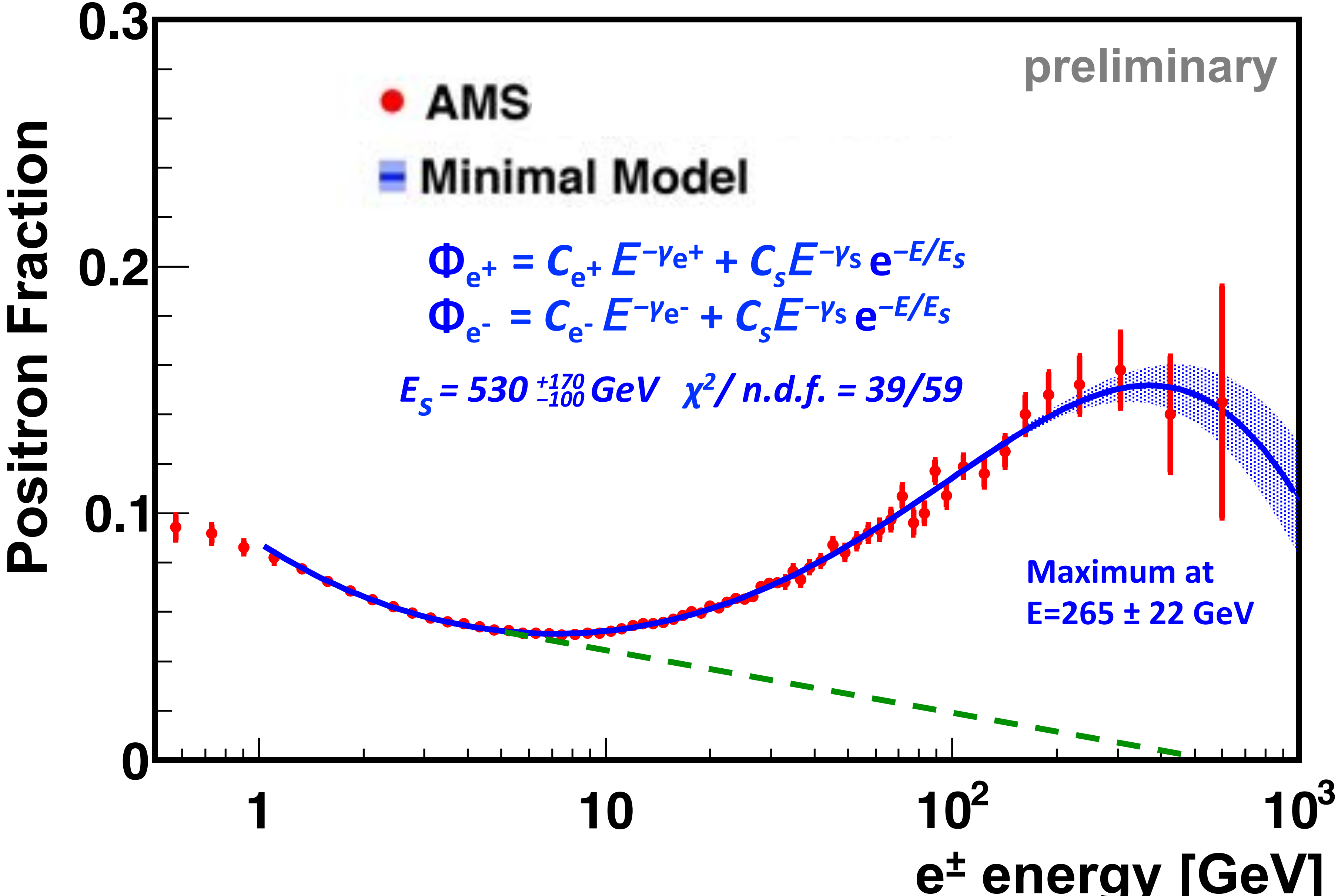



Citations: > 750

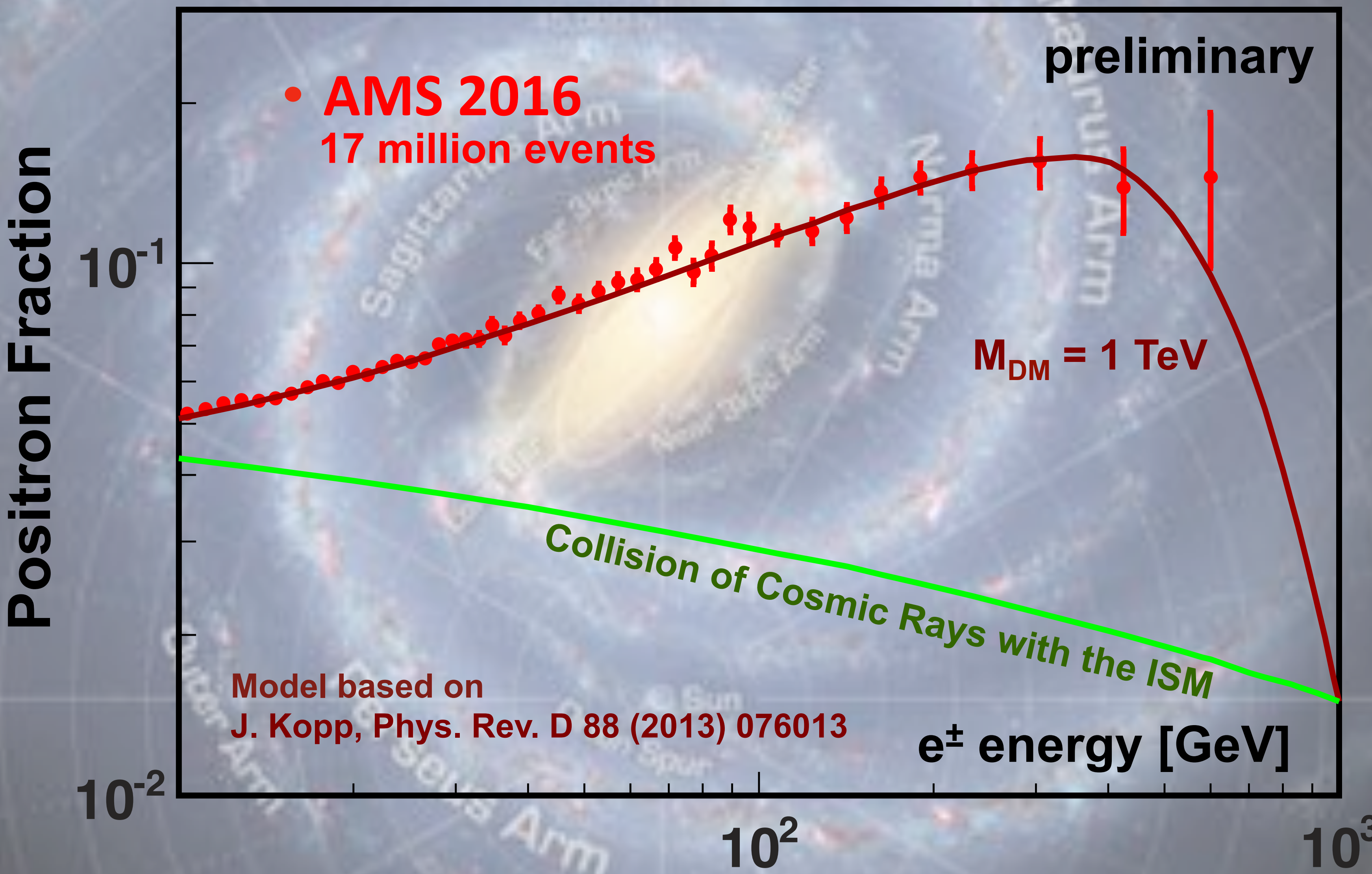



- The electron flux and the positron flux are different in their magnitude and energy dependence
- Electrons and positrons have a different origin.

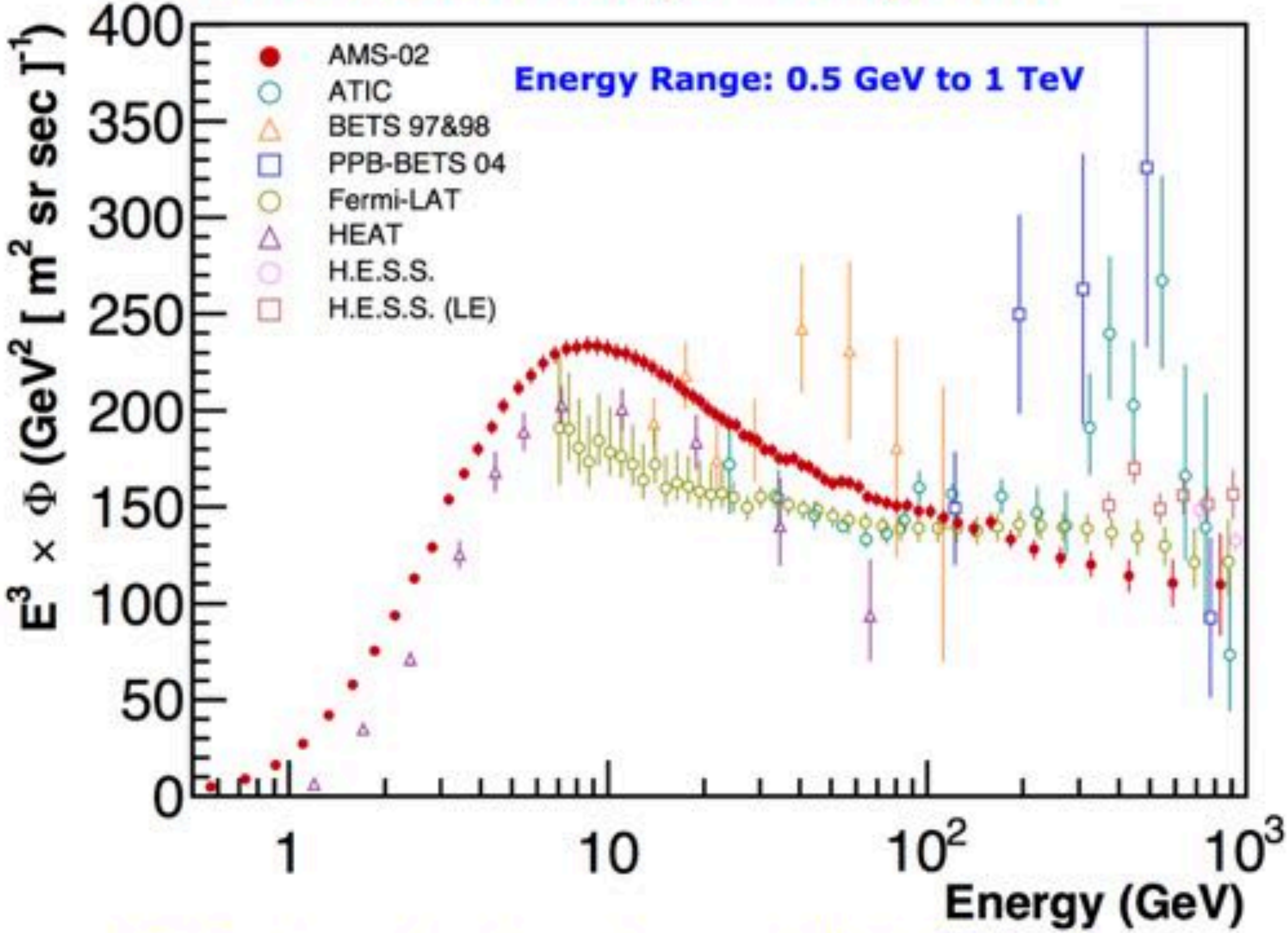
# Positron Fraction 2016

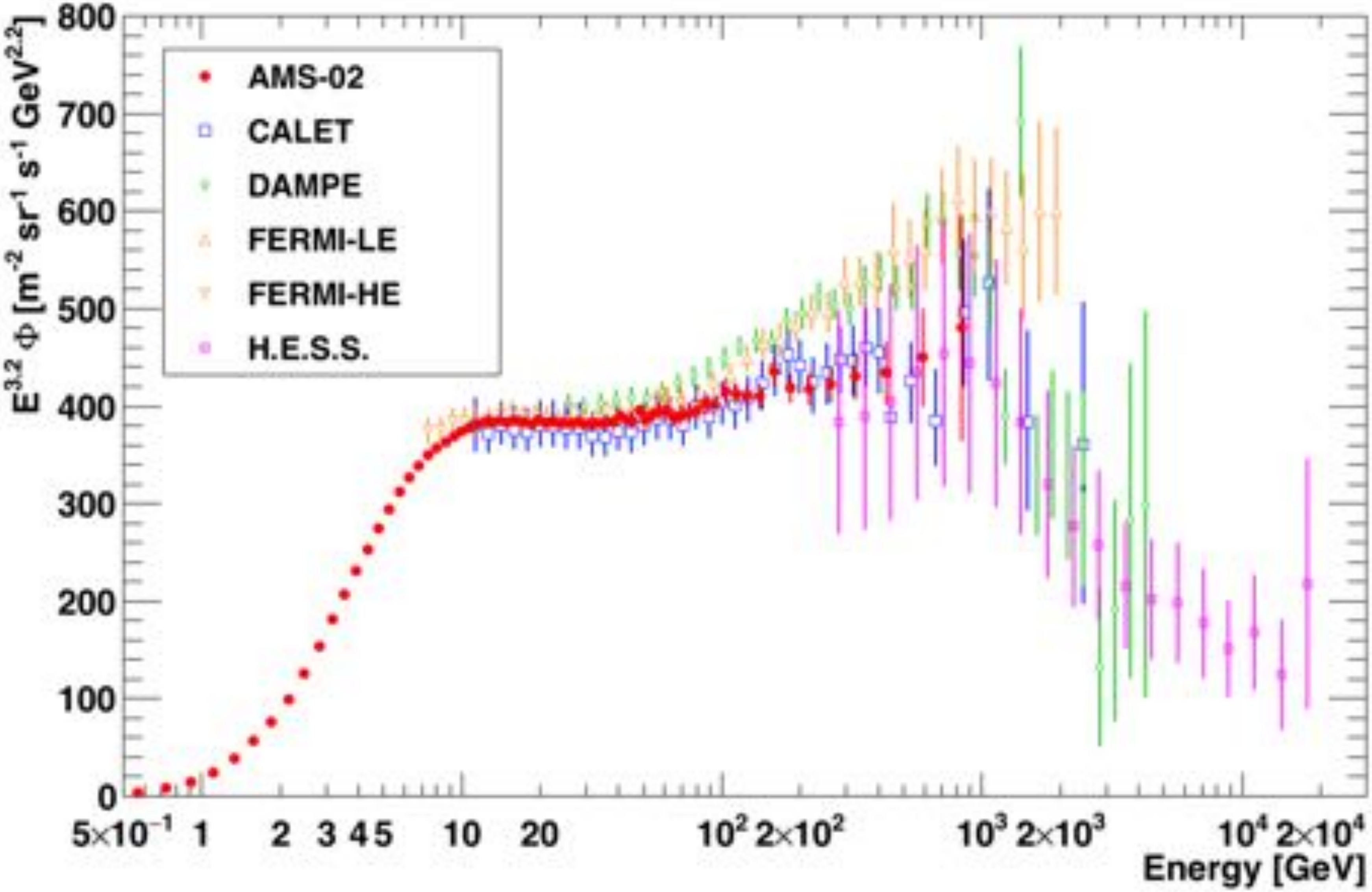


# Comparison of the positron fraction measurement with a Dark Matter model



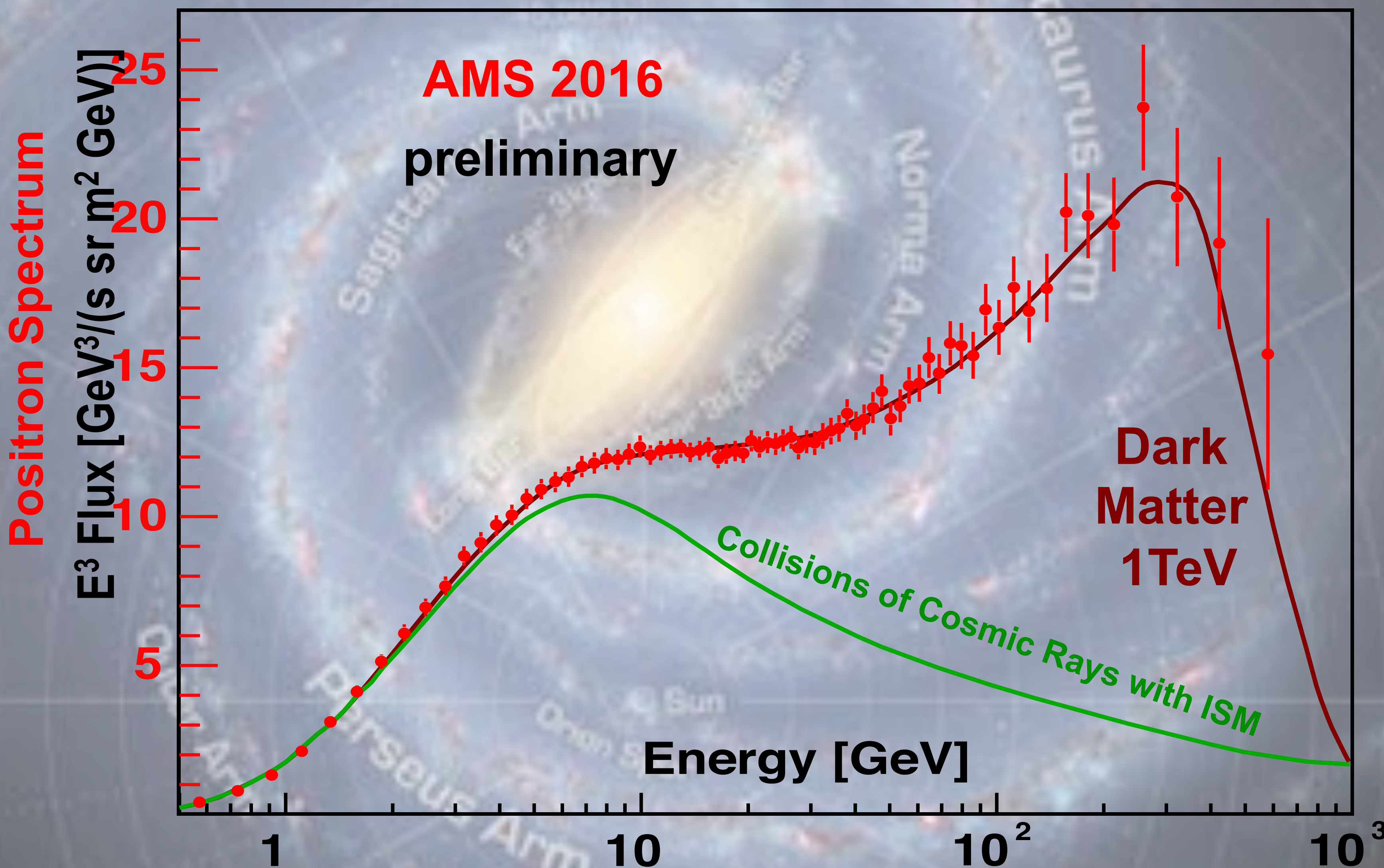
# AMS Results: $(e^+ + e^-)$ flux



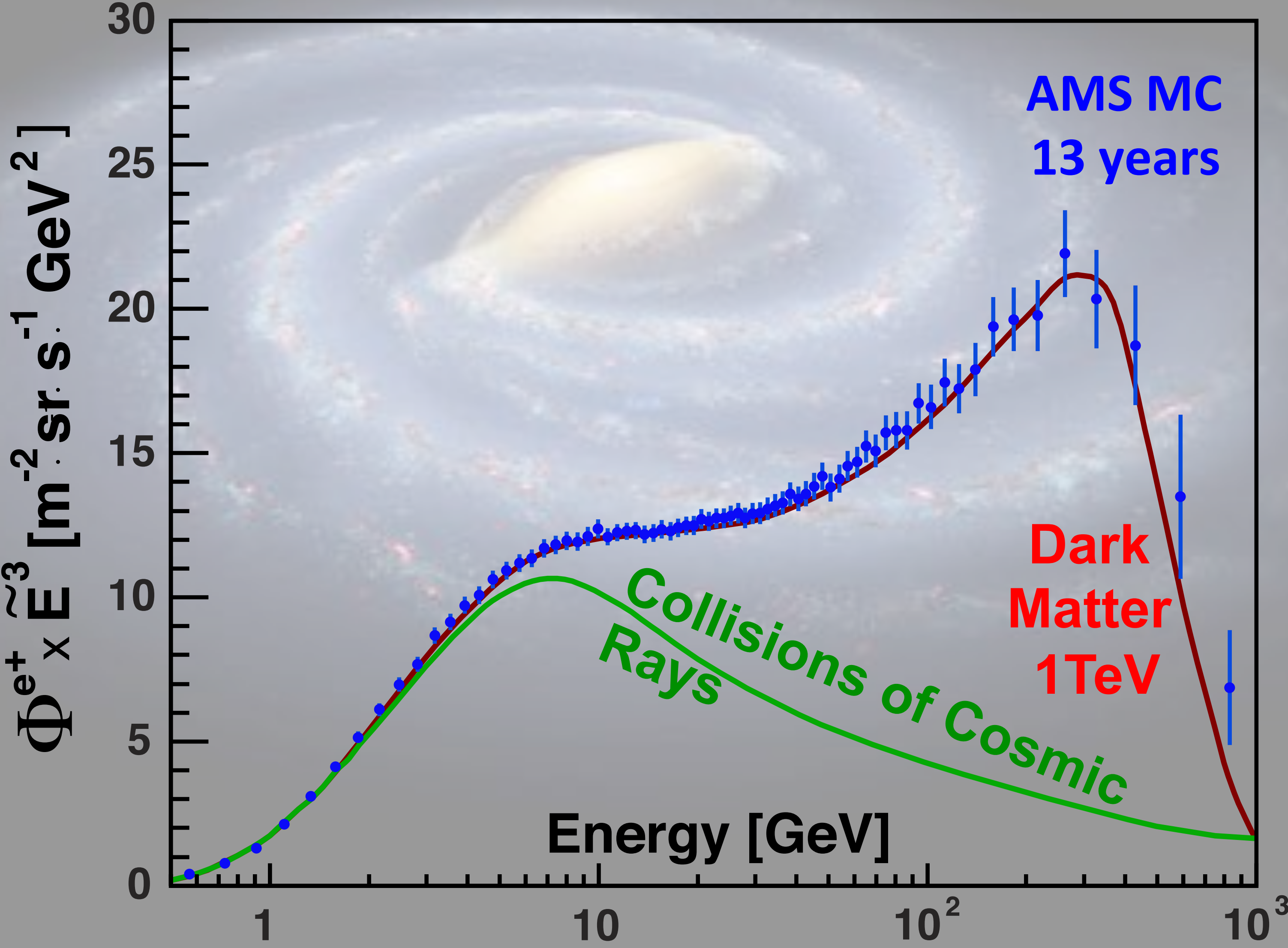



- **The origin of the difference between (AMS, CALET, H.E.S.S.) and (FERMI, DAMPE) is not clear.**
- **A sharp cut-off in the ($e^+ + e^-$) Flux is visible at E≈1 TeV, the origin is not understood.**

# The AMS results are in excellent agreement with a Dark Matter Model

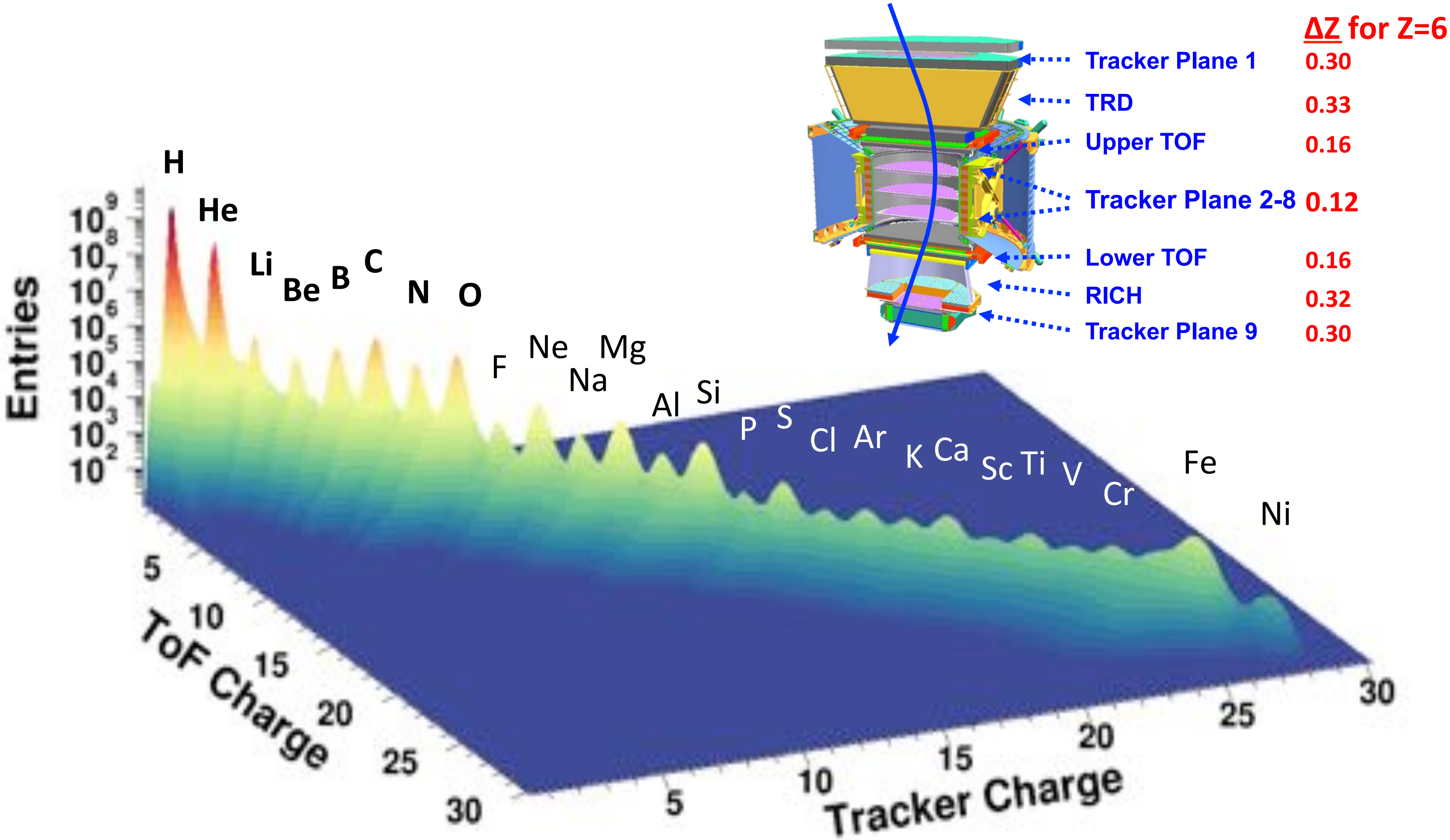


# 2024: Extend measurement to 1 TeV

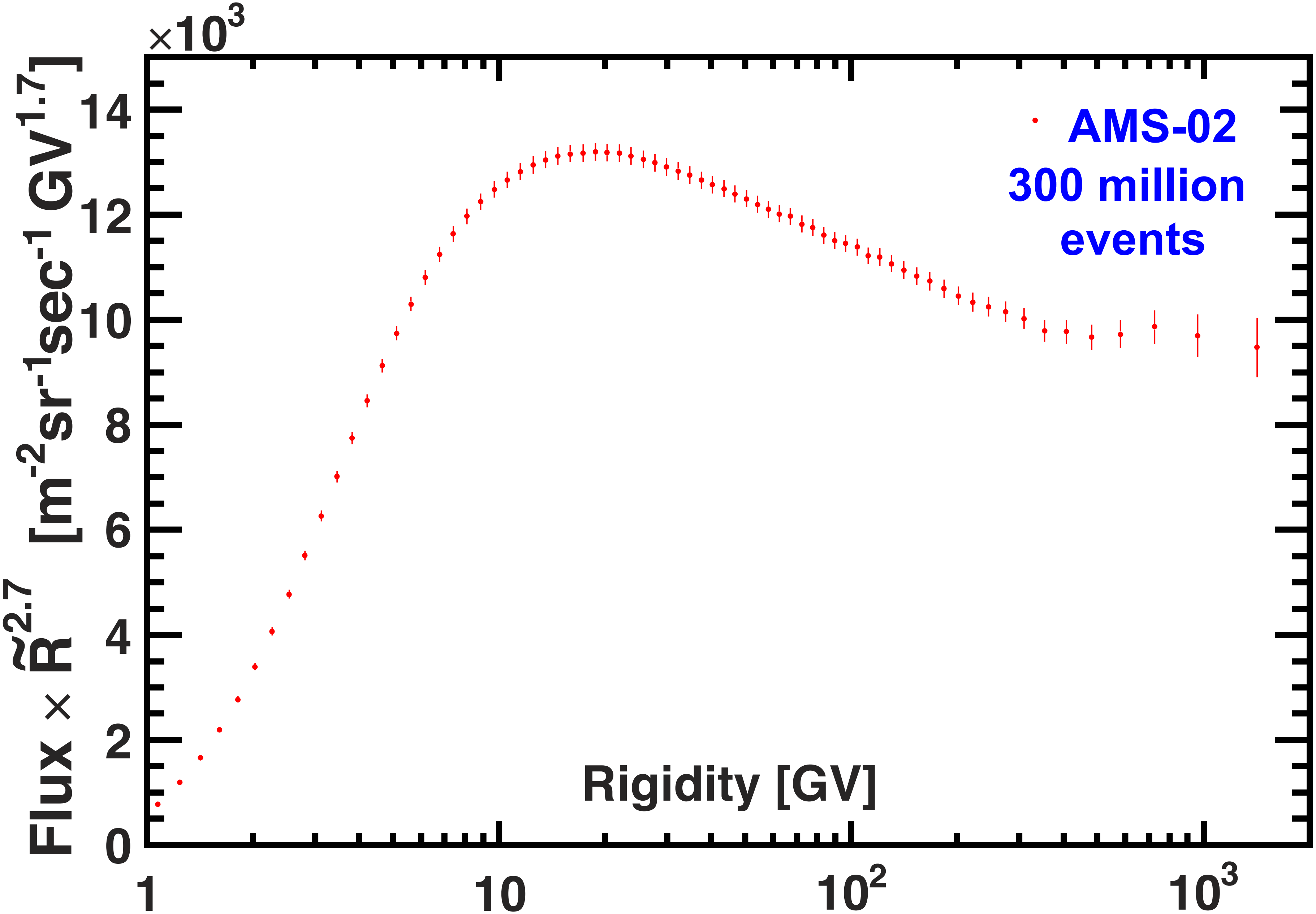


# Cosmic Nuclei

## AMS has seven instruments which independently identify different elements



# AMS Proton Flux, accuracy 1%

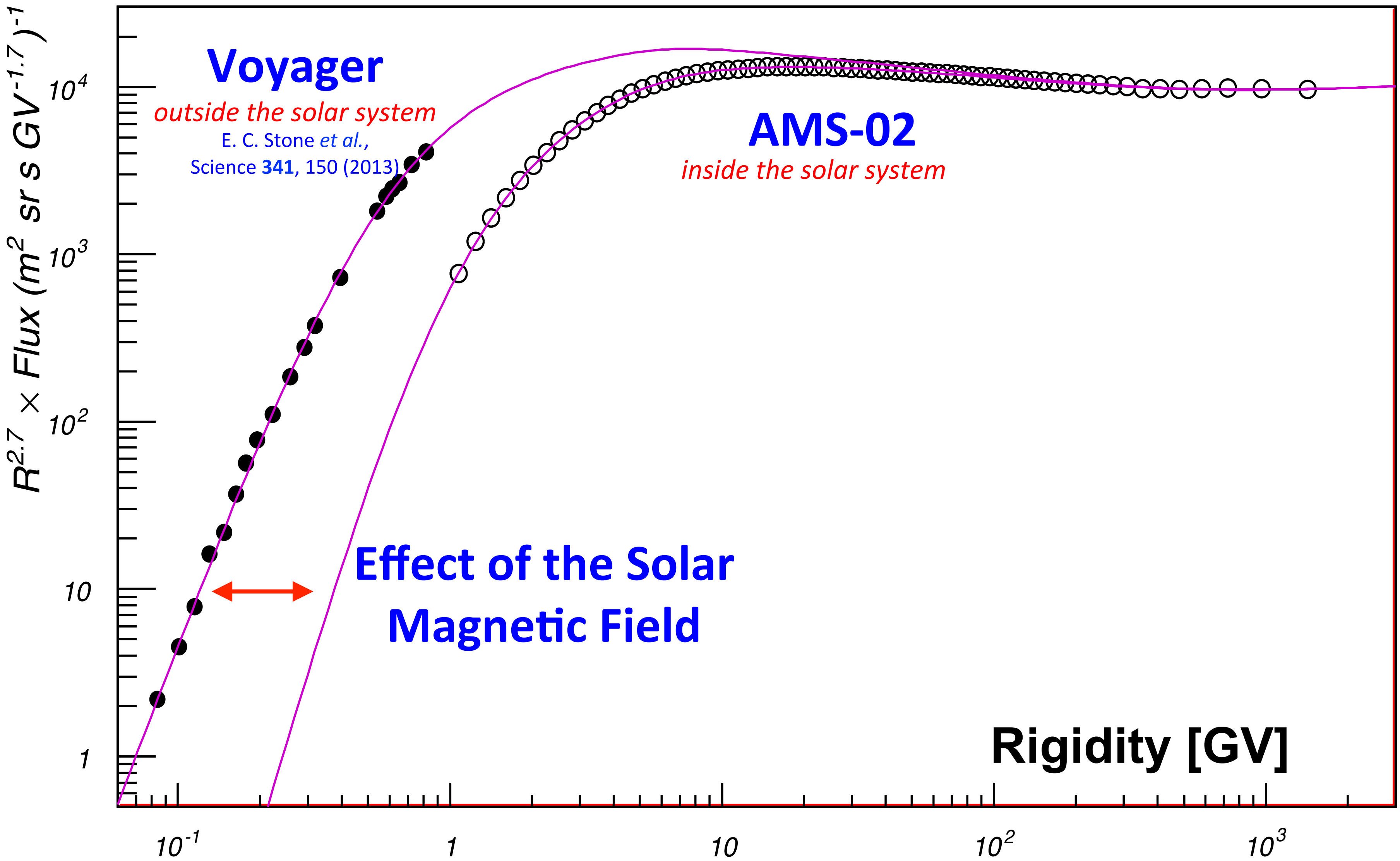



M. Aguilar *et al*., Phys. Rev. Lett. **114**, 171103 (2015)

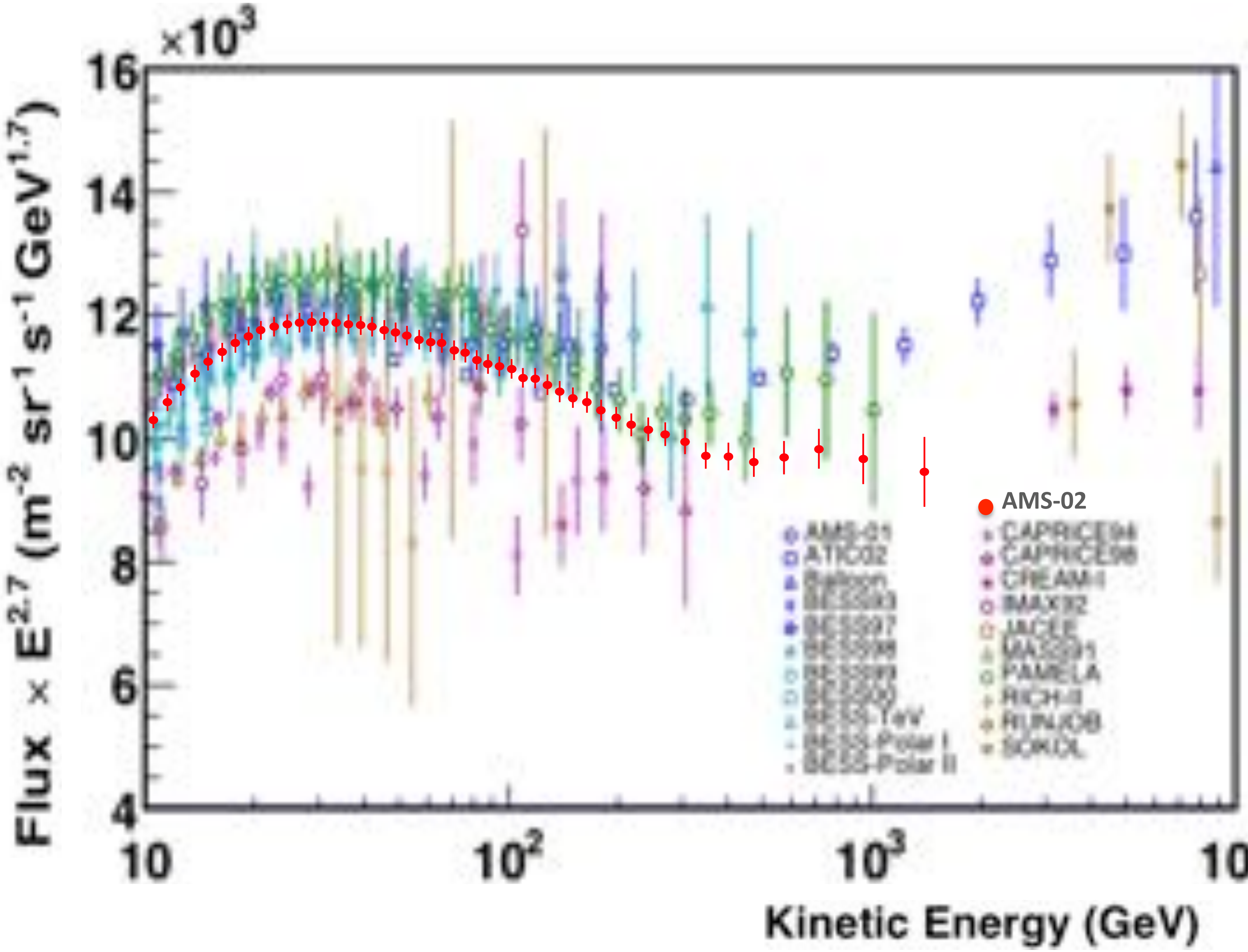

Once every 176 years the giant planets are lined up for a Grand Tour, and in 1977 the Voyagers were launched on humankind's longest journey

# Understanding of the Solar Magnetic Field:

## The proton flux and the effect of the solar magnetic field

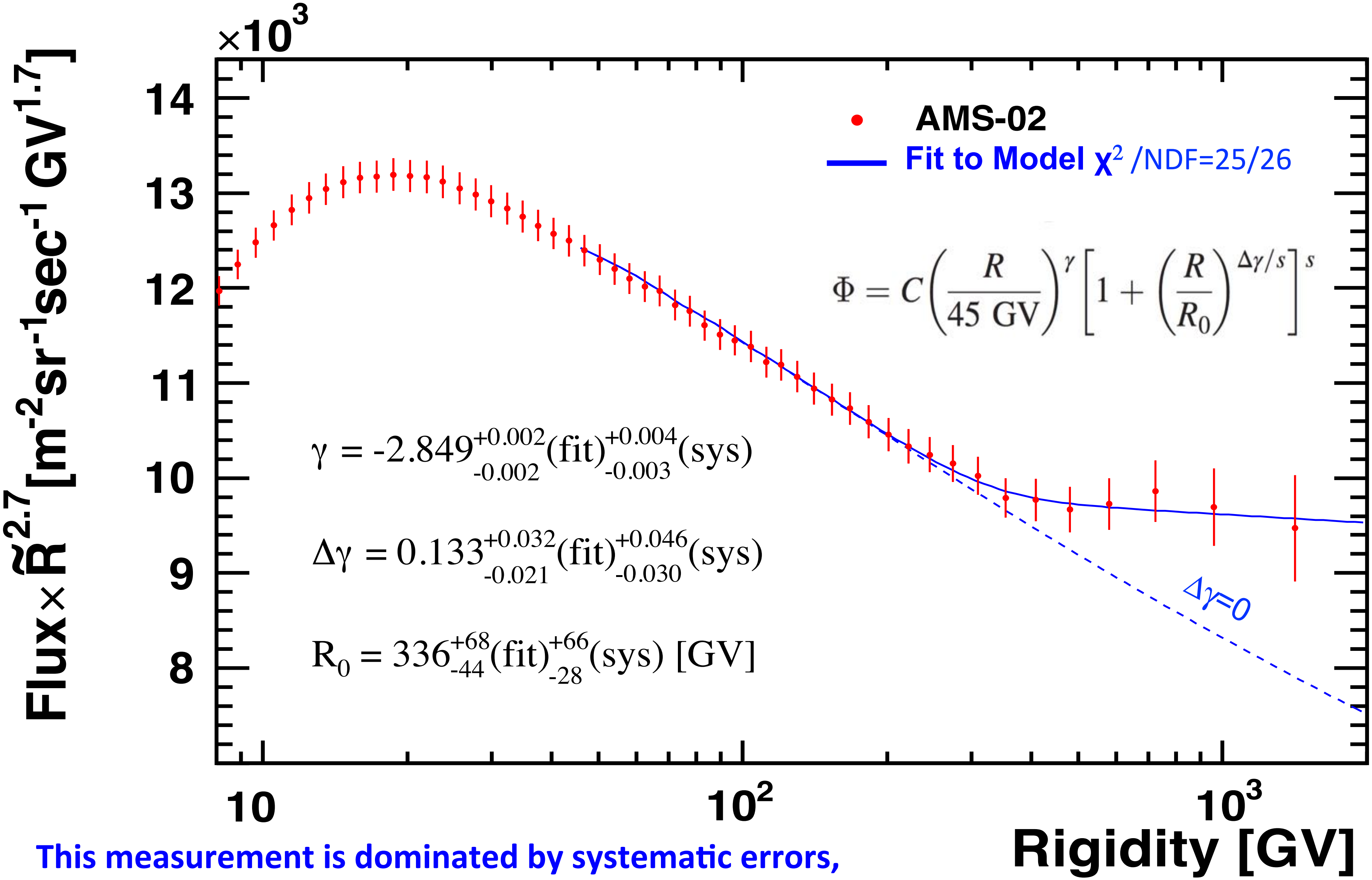



C. Corti *et al.*, ApJ **829**, 8 (2016)



$\times 10^3$
Flux $\times$ E$^{2.7}$ (m$^{-2}$ sr$^{-1}$ s$^{-1}$ GeV$^{1.7}$)
Kinetic Energy (GeV)
AMS-02
AMS-01
ATIC02
Balloon
BESS93
BESS97
BESS98
BESS99
BESS00
BESS-TeV
BESS-Polar I
BESS-Polar II
CAPRICE94
CAPRICE98
CREAM-I
IMAX92
JACEE
MASS91
PAMELA
RICH-II
RUNJOB
SOKOL

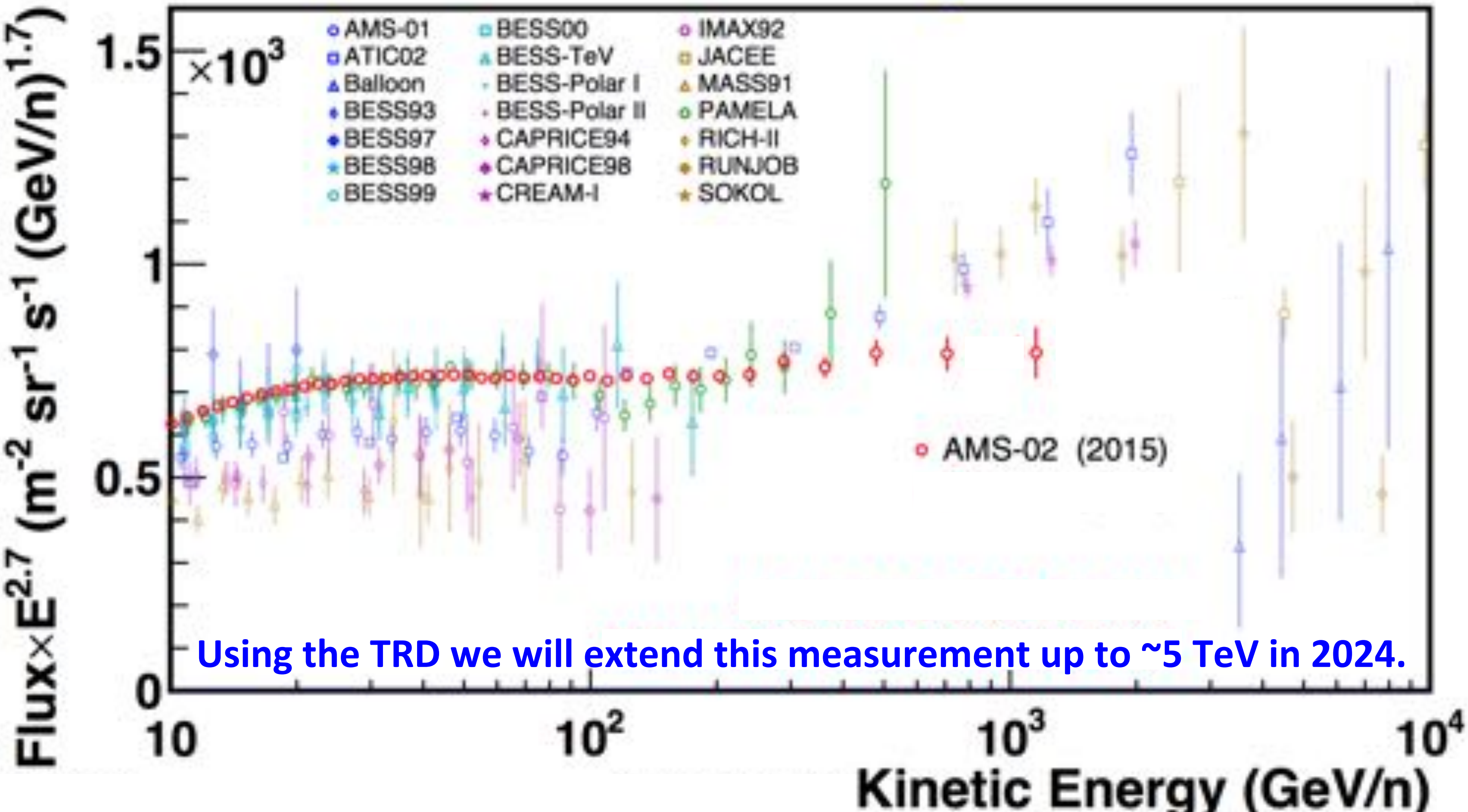
## It was expected that the proton flux could be described with a single power law with spectral index γ=-2.7.




This measurement is dominated by systematic errors, we will therefore not be able to improve it.

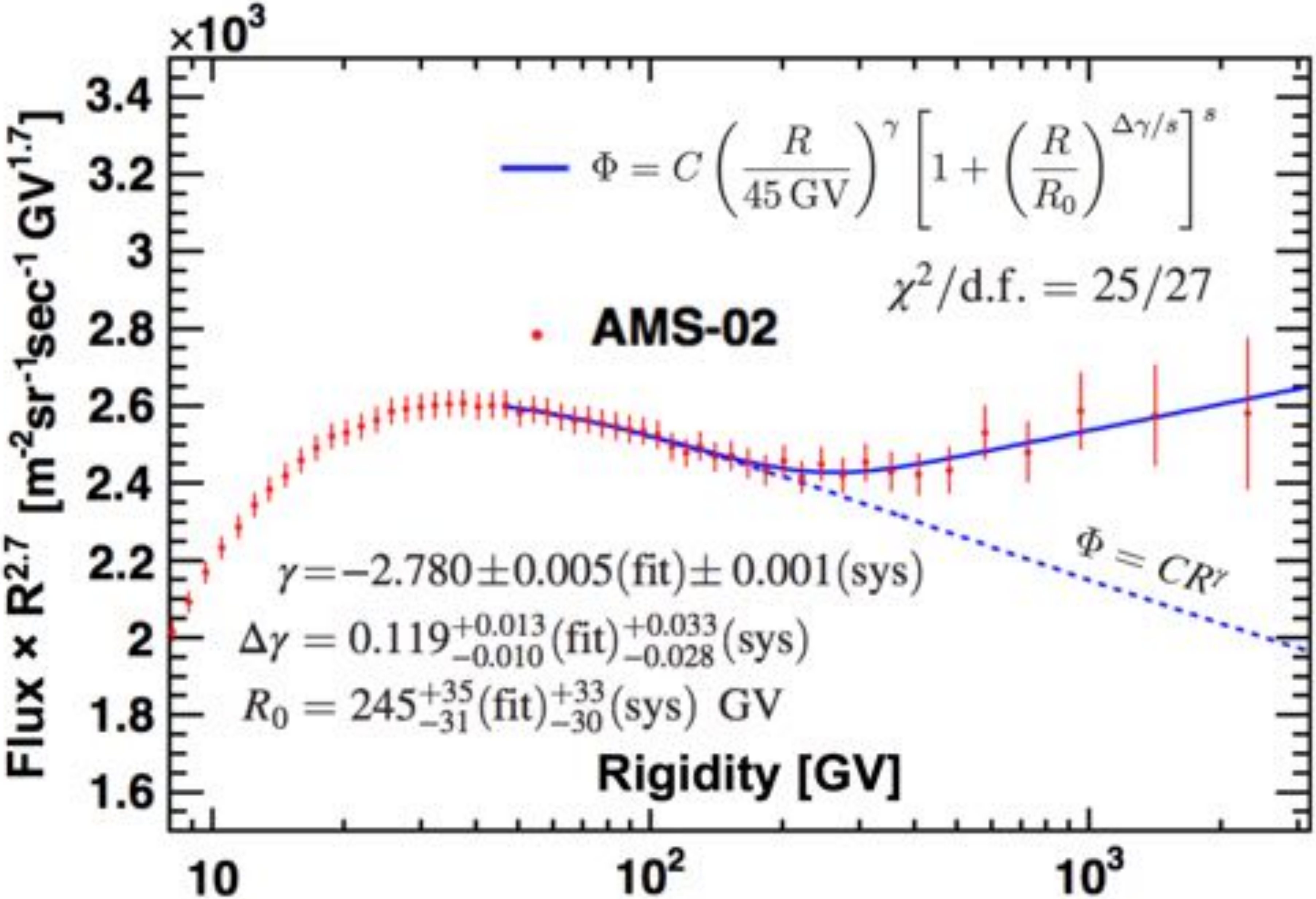
# Precision Measurement of the Helium Flux in Primary Cosmic Rays of Rigidities 1.9 GV to 3 TV with the Alpha Magnetic Spectrometer on the International Space Station

50 million helium nuclei

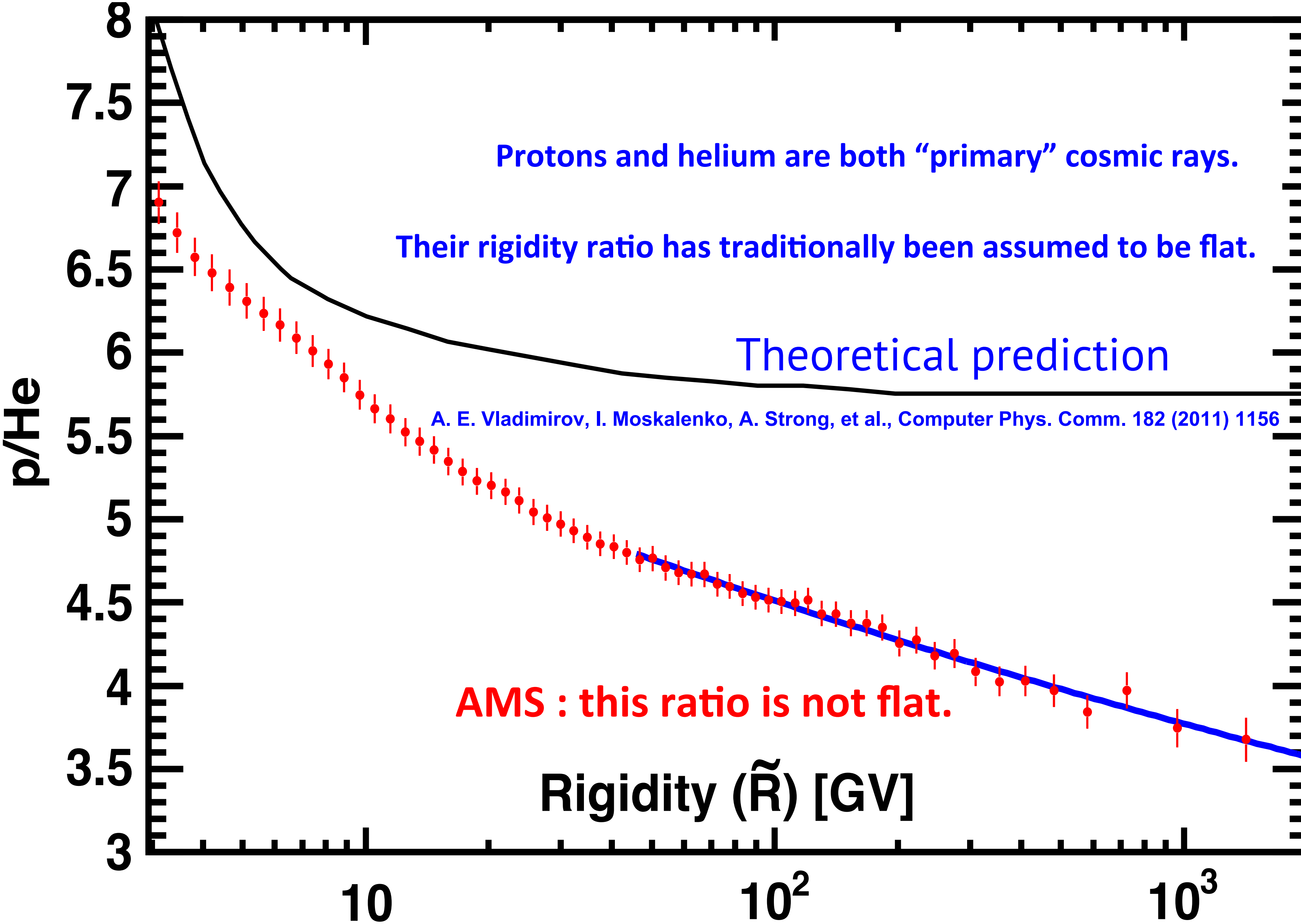



Using the TRD we will extend this measurement up to ~5 TeV in 2024.

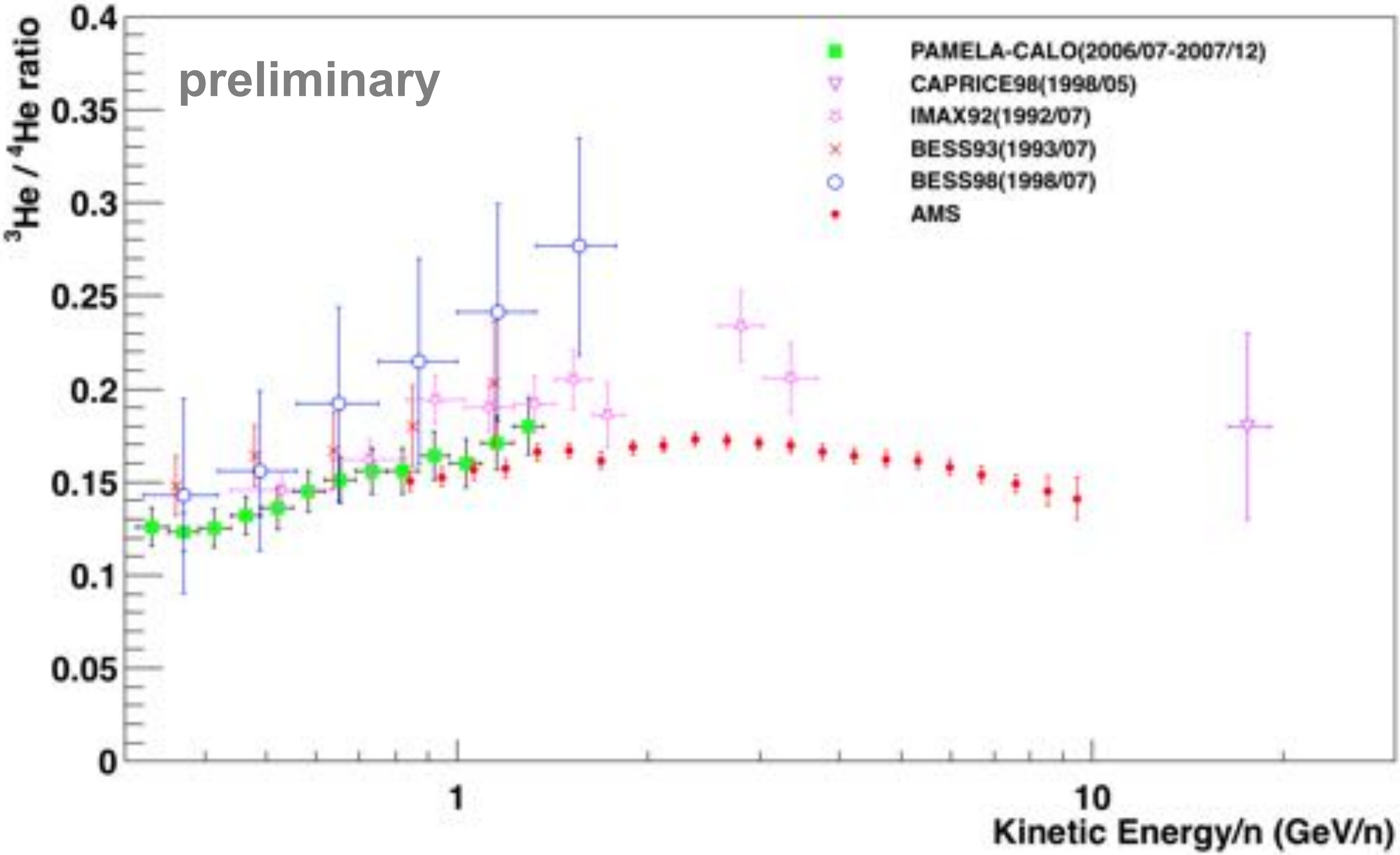
**It was expected that the He flux could be described with a single power law with spectral index γ=-2.7.**



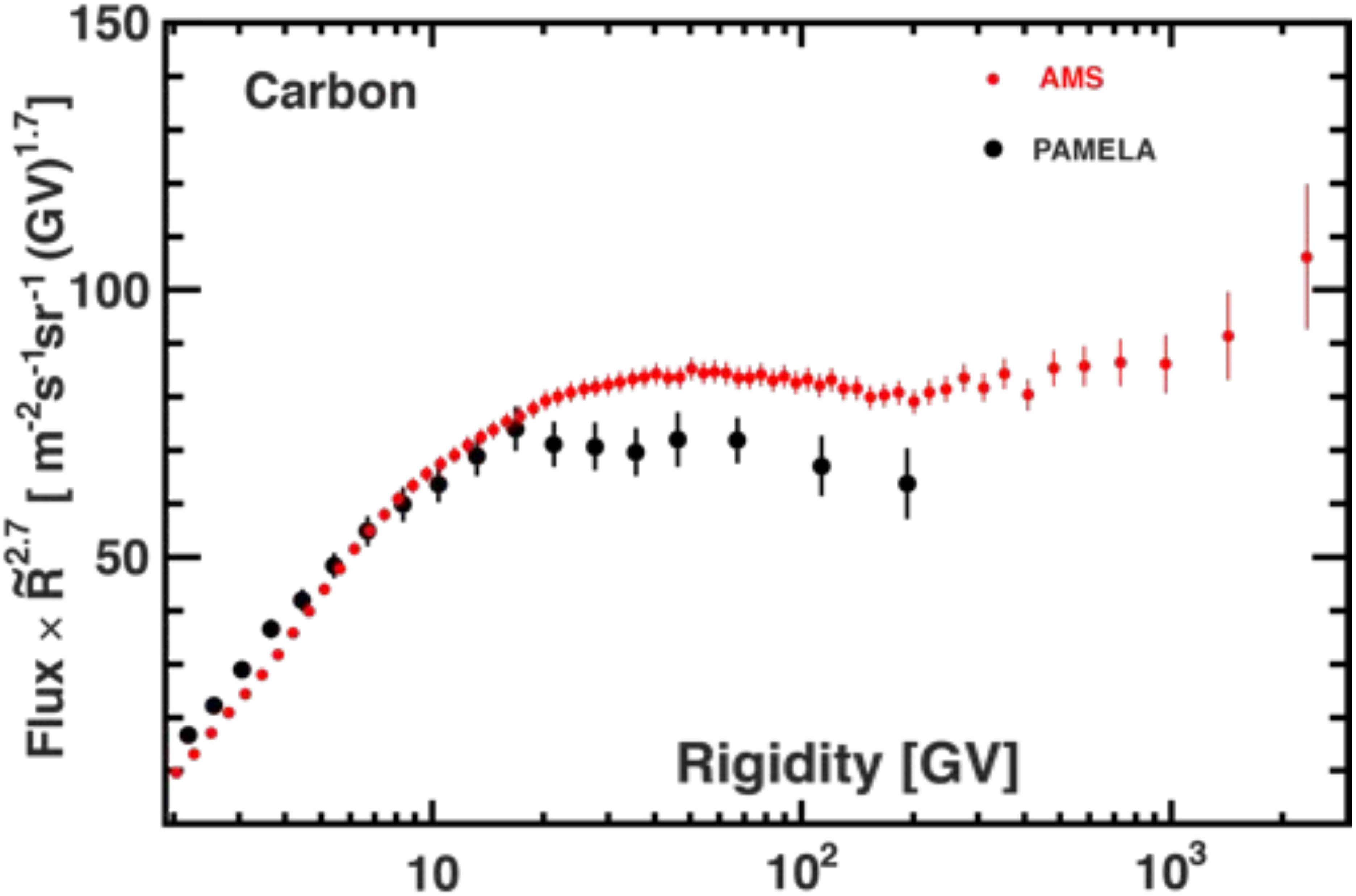
# The AMS proton/helium flux ratio



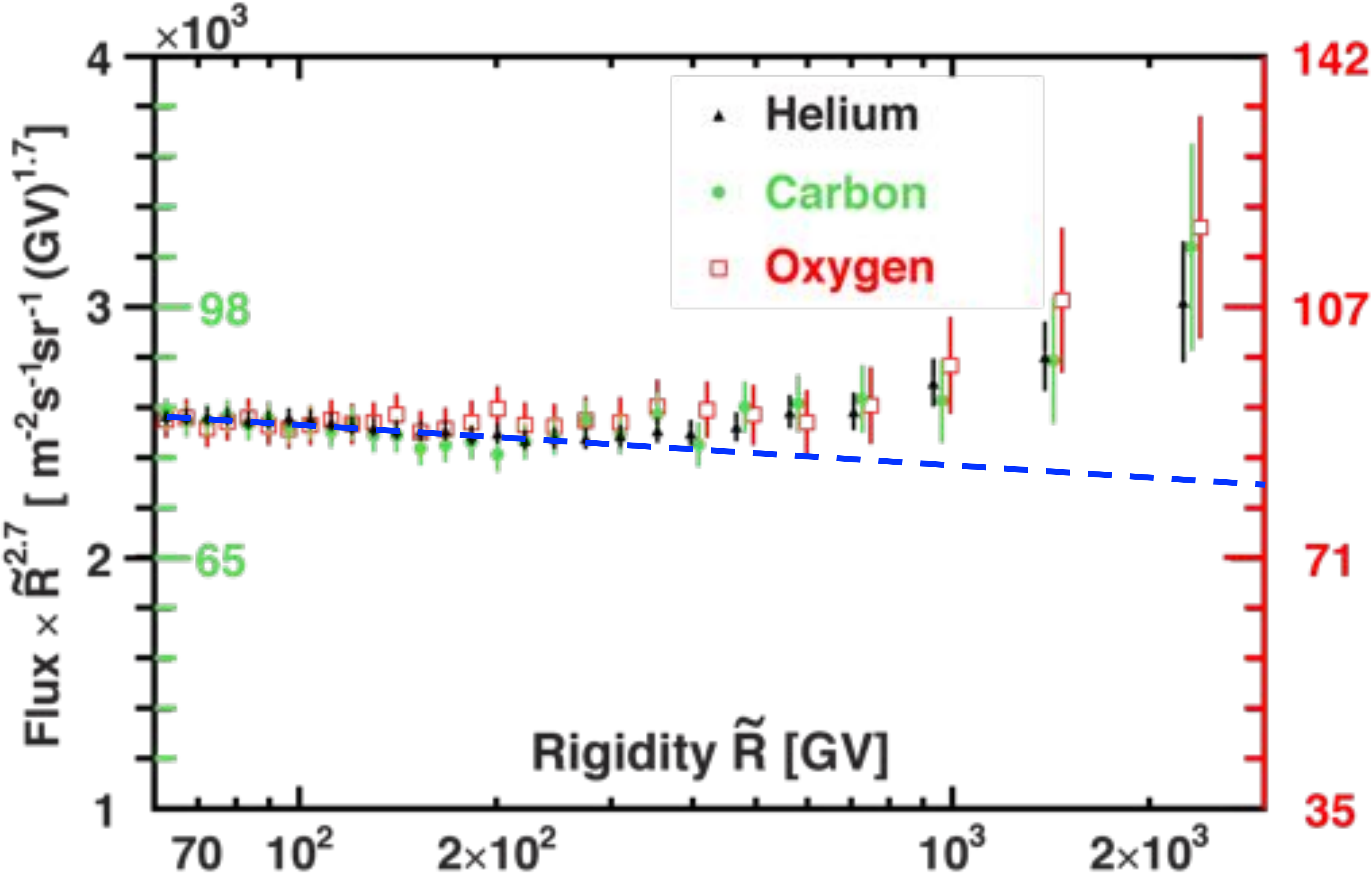
# Helium isotopic composition



# The AMS Result on the Carbon Flux

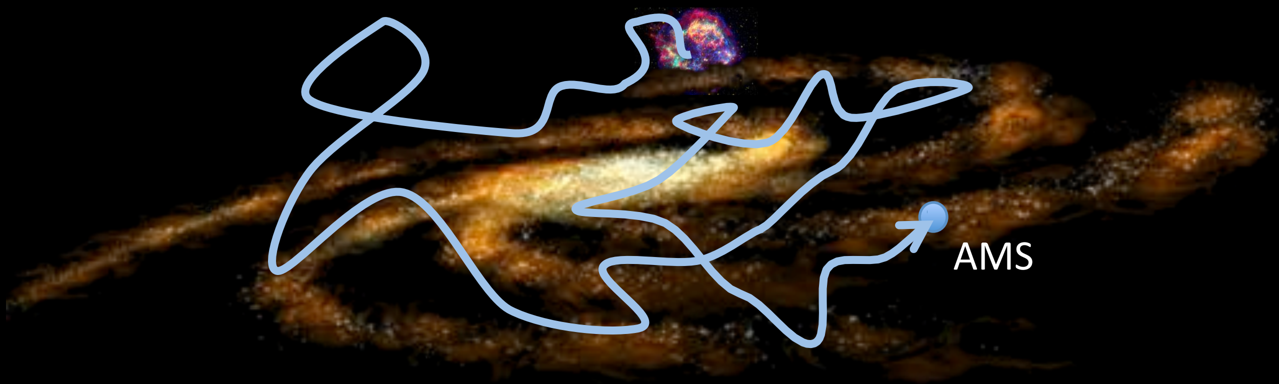


## Rigidity dependence of Primary Cosmic Rays

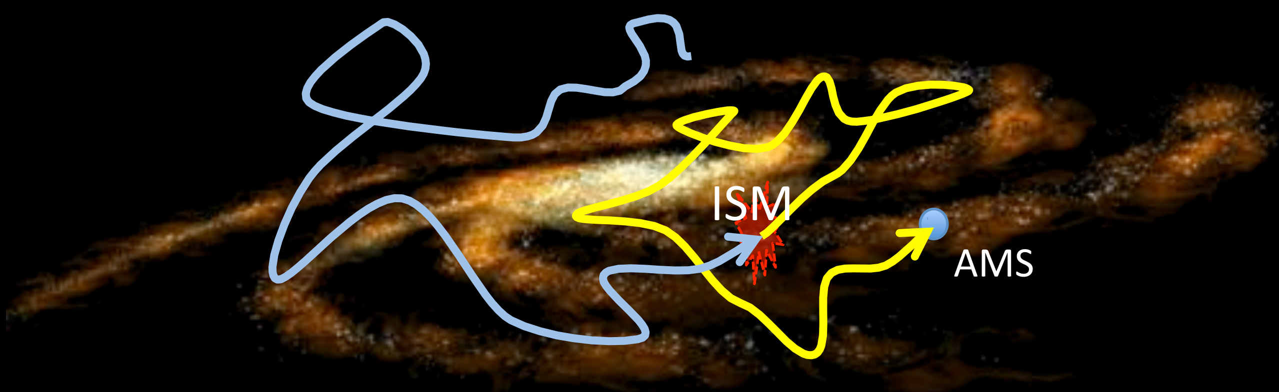



**Above 60 GV,**
**these fluxes have identical rigidity dependence.**

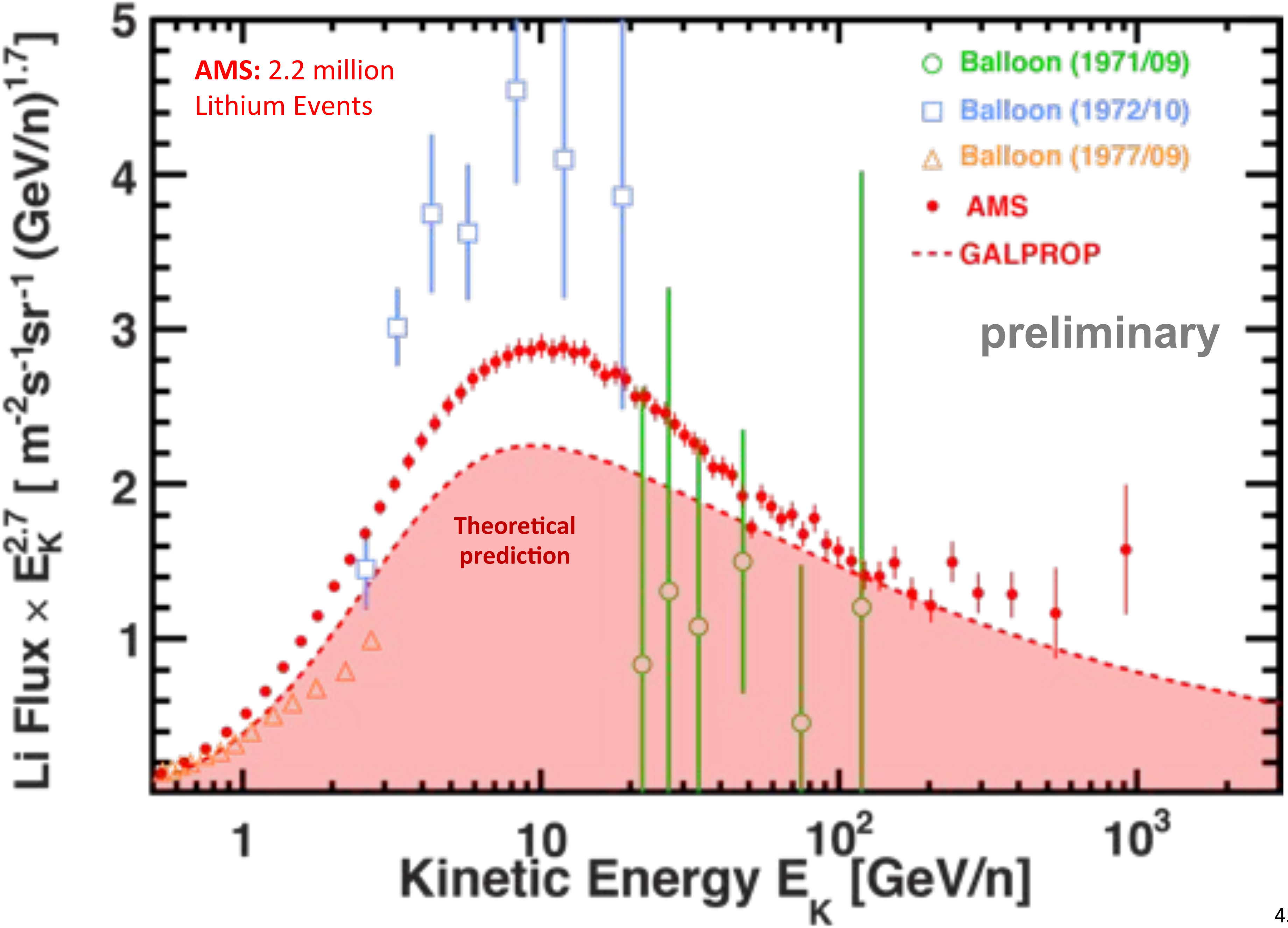
# Primary Cosmic Rays (p, He, C, O, …)



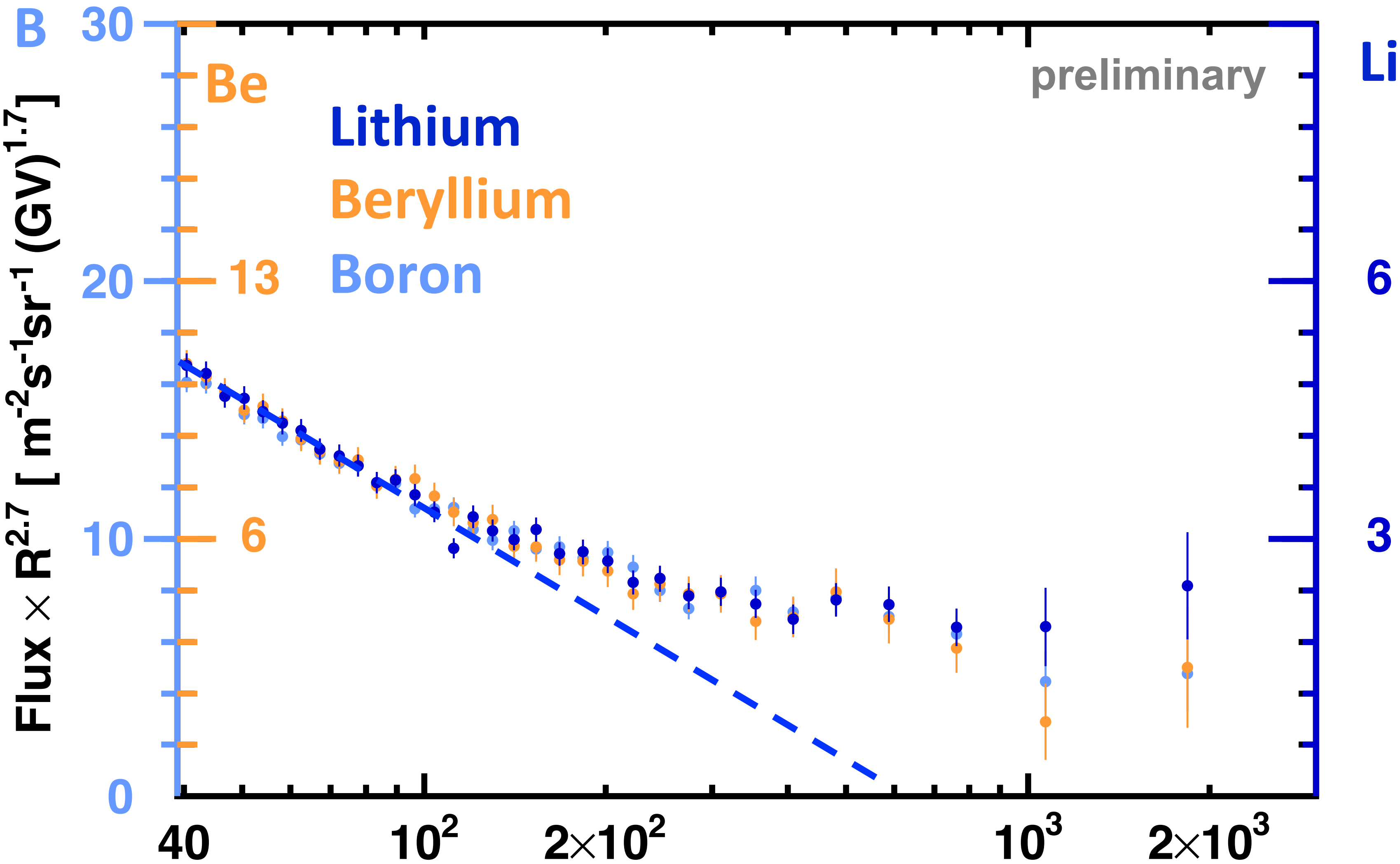

# Secondary Cosmic Rays (Li, Be, B, …)



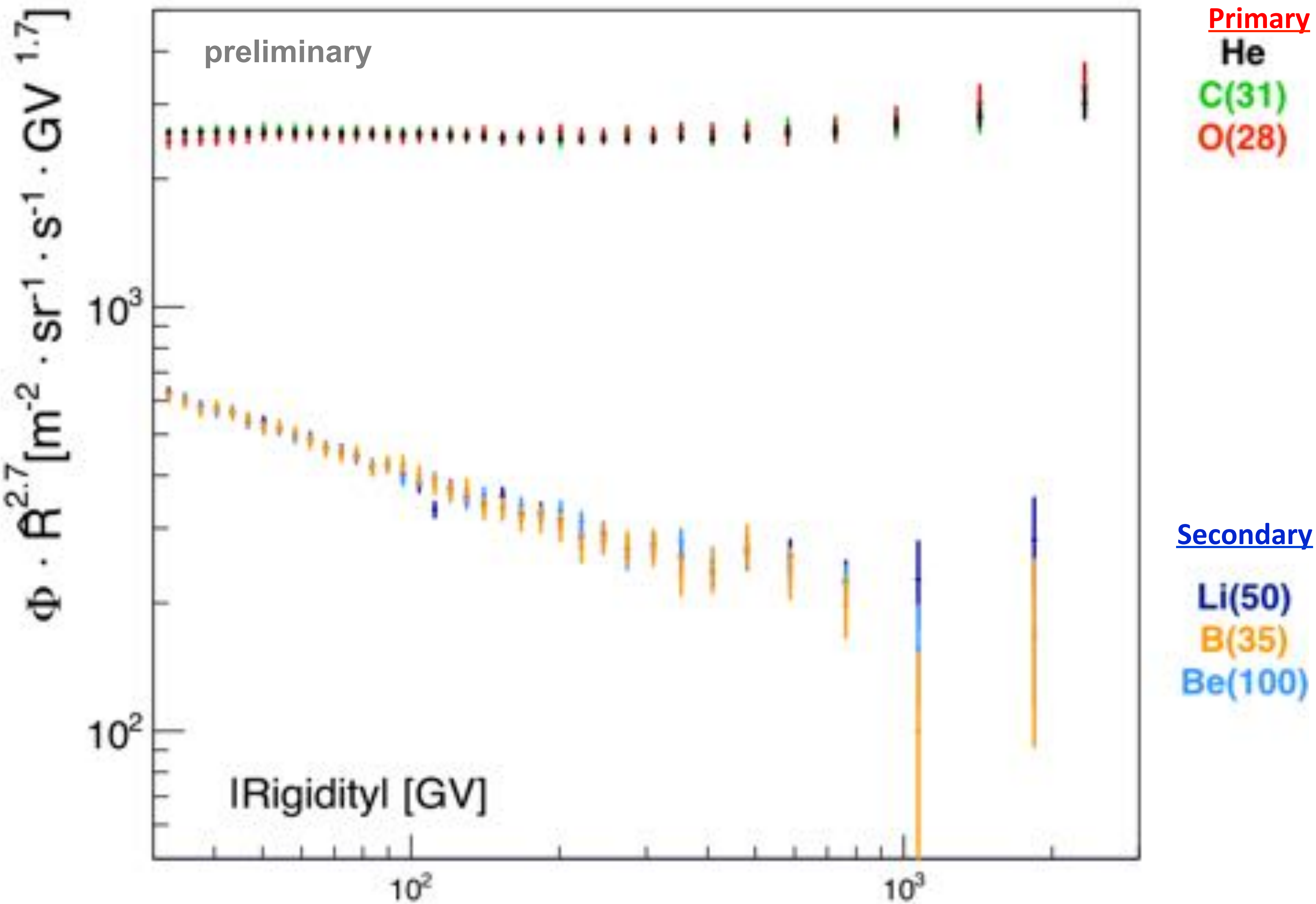
# The AMS Result on the Lithium Flux

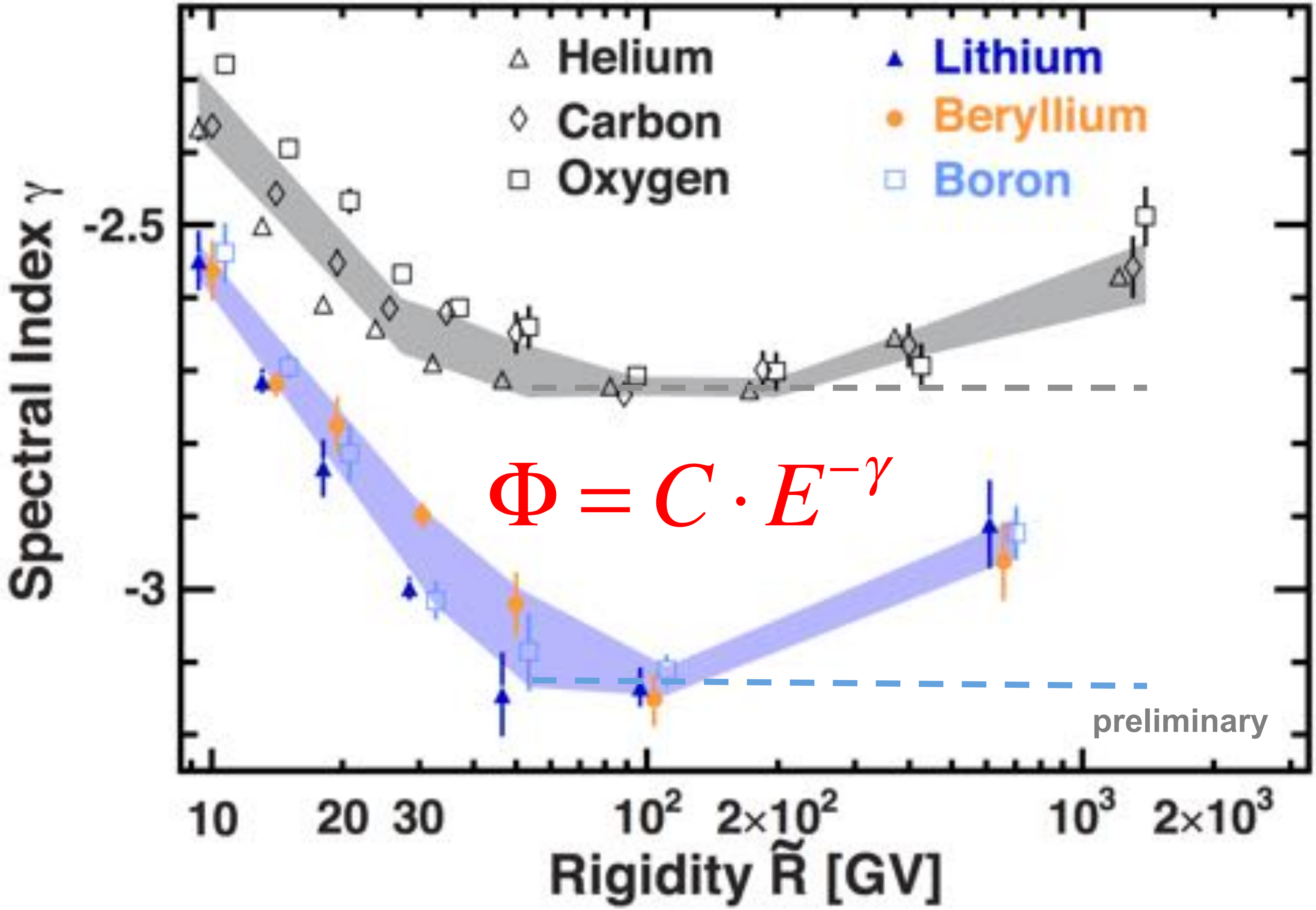


# Secondary cosmic rays Li, Be, and B have identical rigidity dependence.



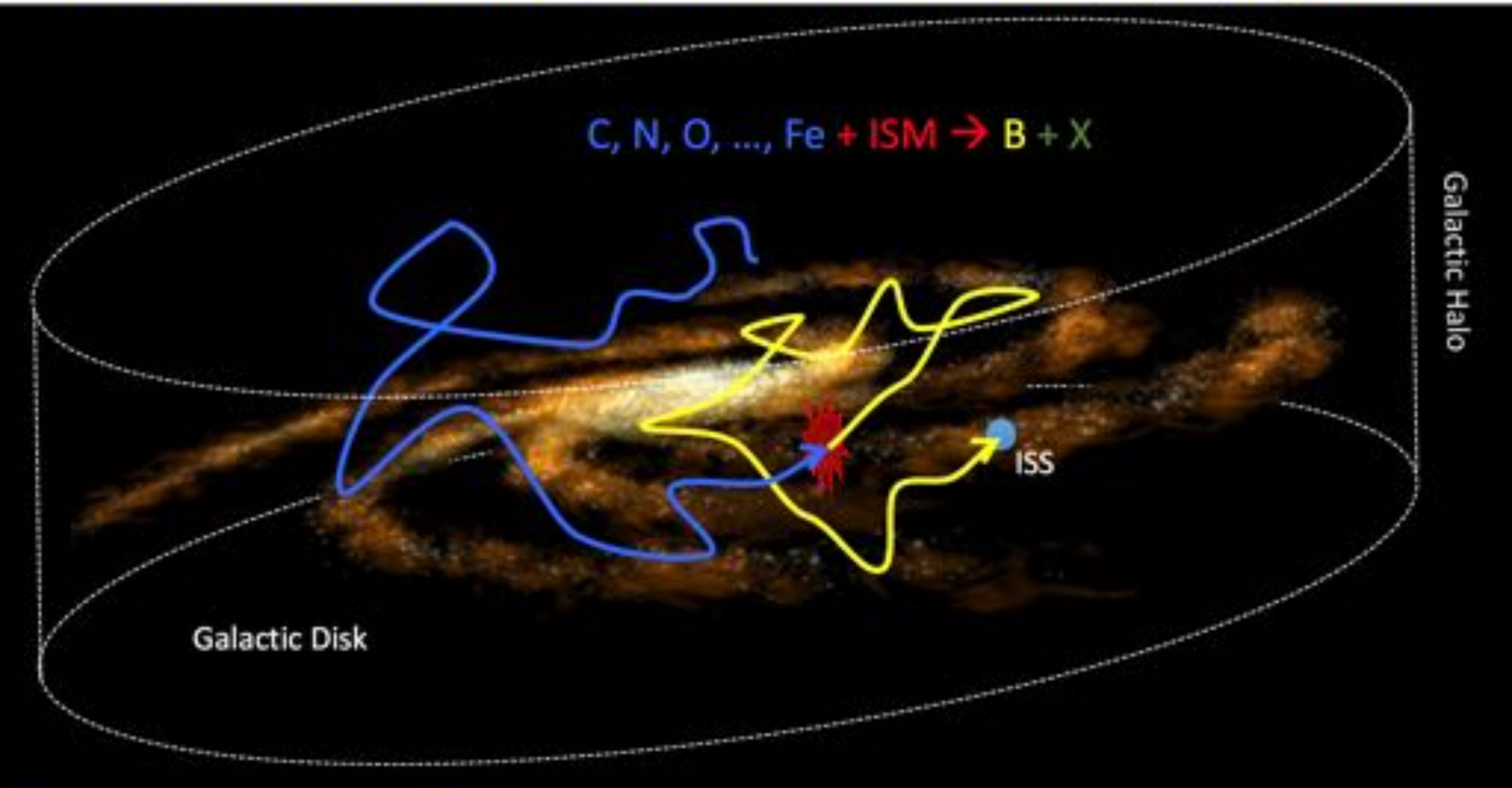
# "Secondary" cosmic rays have a different rigidity dependence than "primary" cosmic rays.





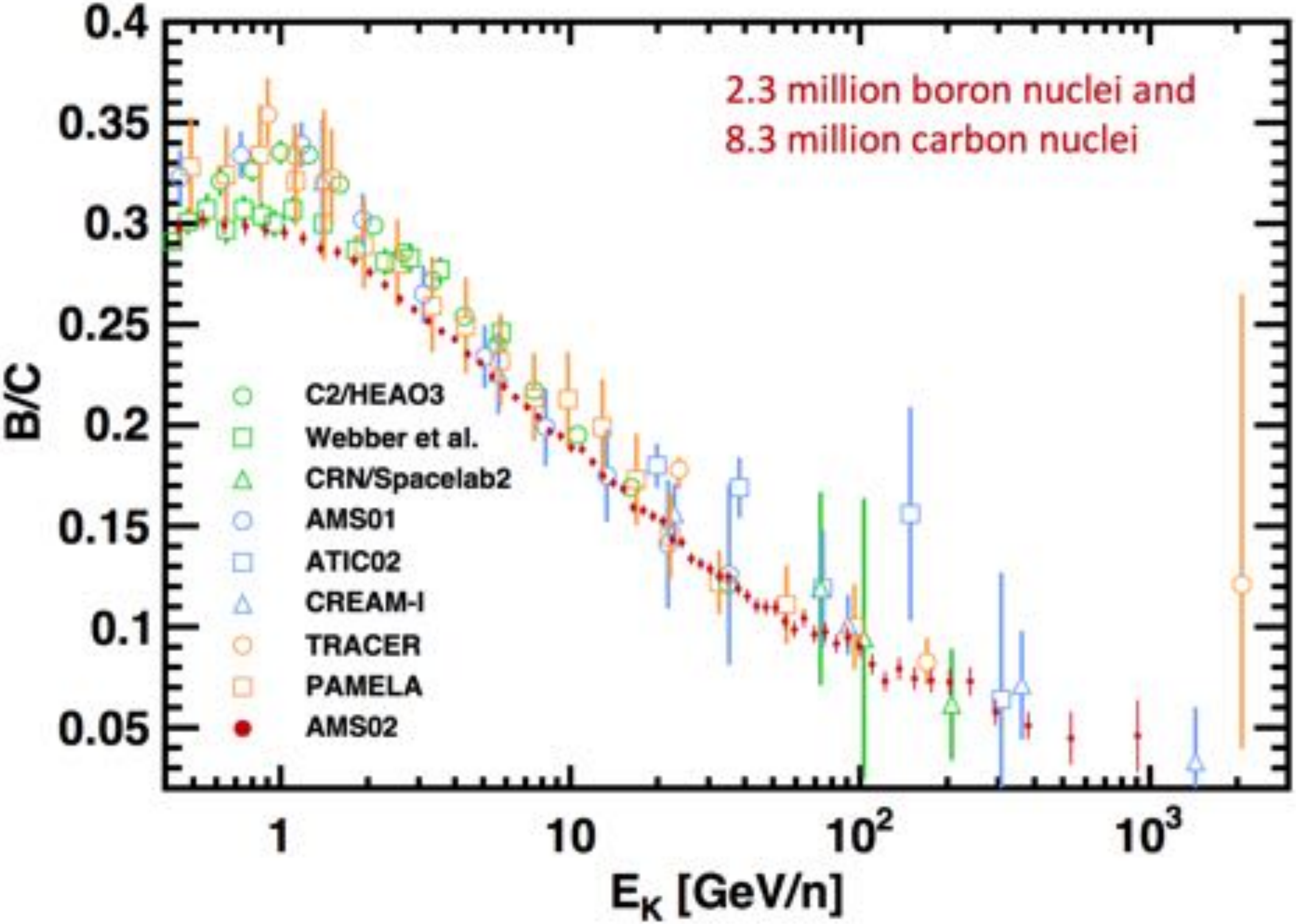

**Above ~200 GV the Li, Be, and B fluxes all harden more than the He, C, and O fluxes.**

# Flux Ratios: Boron/Carbon and cosmic ray propagation




The boron-to-carbon ratio (B/C) is important in the determination of cosmic ray propagation. Boron is assumed to be produced from the collision of primary cosmic rays, such as carbon (C), with the interstellar medium (ISM), hence the B/C ratio provides information on cosmic ray propagation.

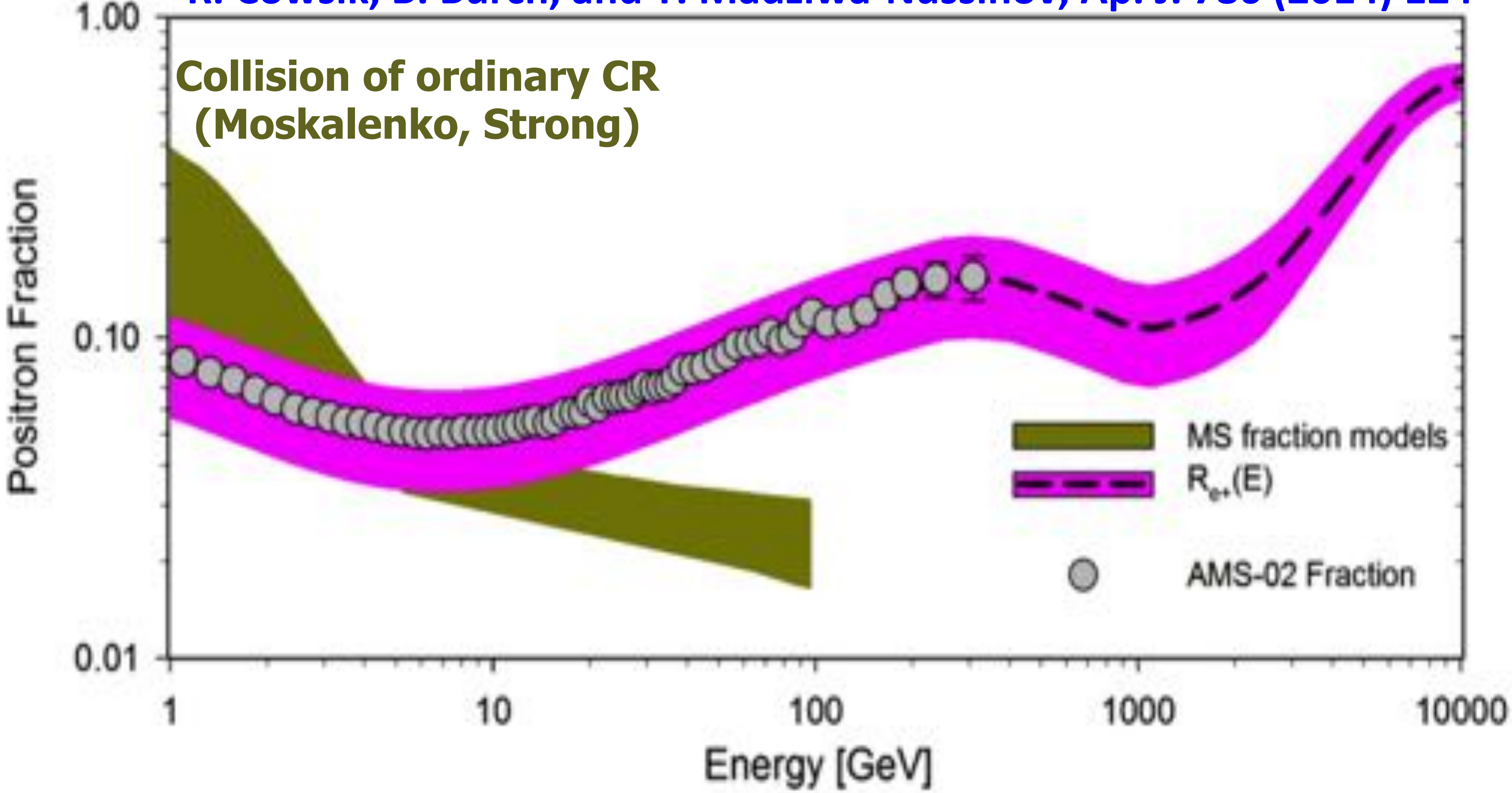
# The AMS boron-to-carbon (B/C) flux ratio

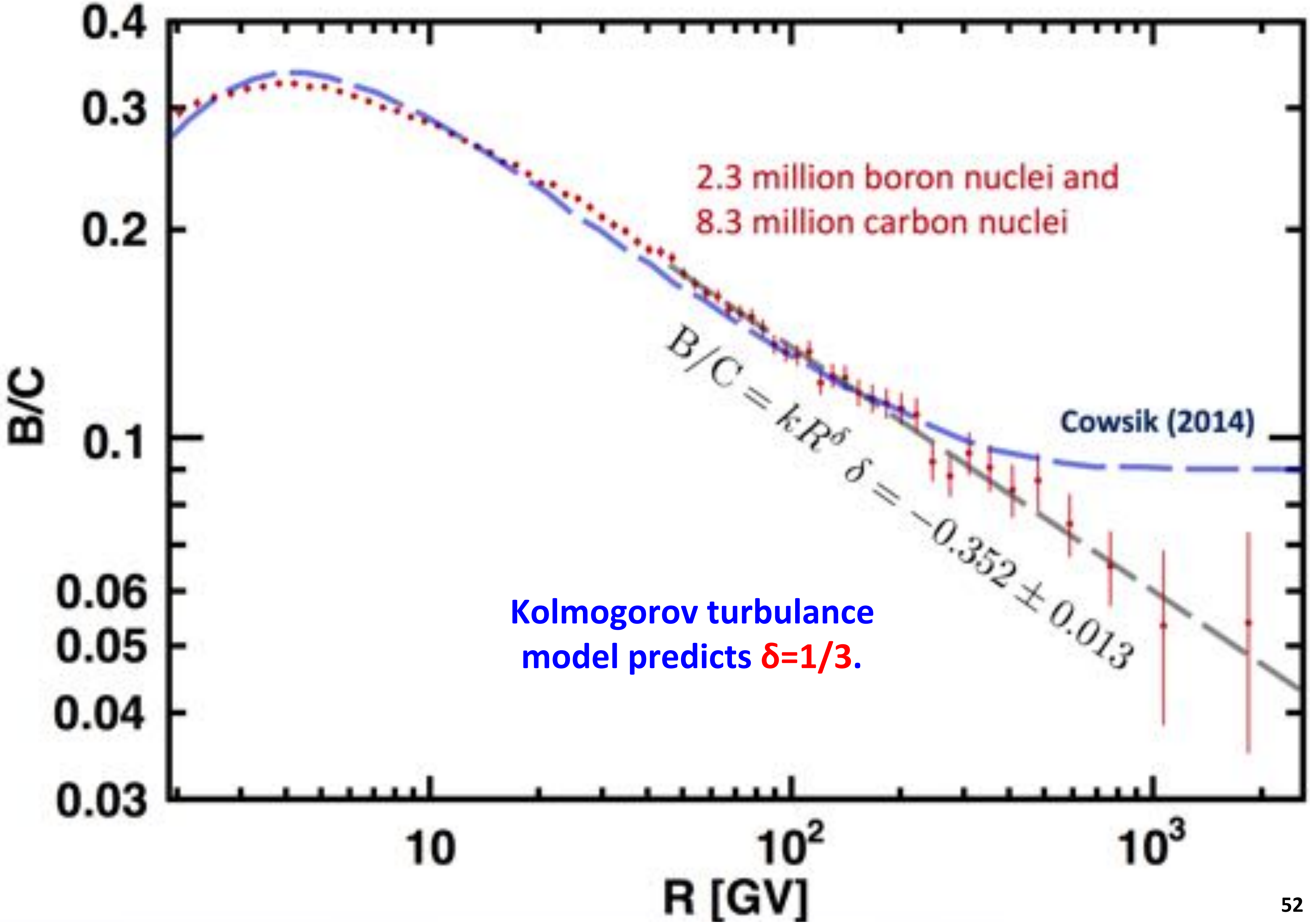


## Theoretical models to explain the AMS positron fraction. Among the 100's of models there are three classes:

a) dark matter
b) new forms of propagation
c) pulsars.

**b) An example of new propagation:**
R. Cowsik, B. Burch, and T. Madziwa-Nussinov, Ap. J. 786 (2014) 124

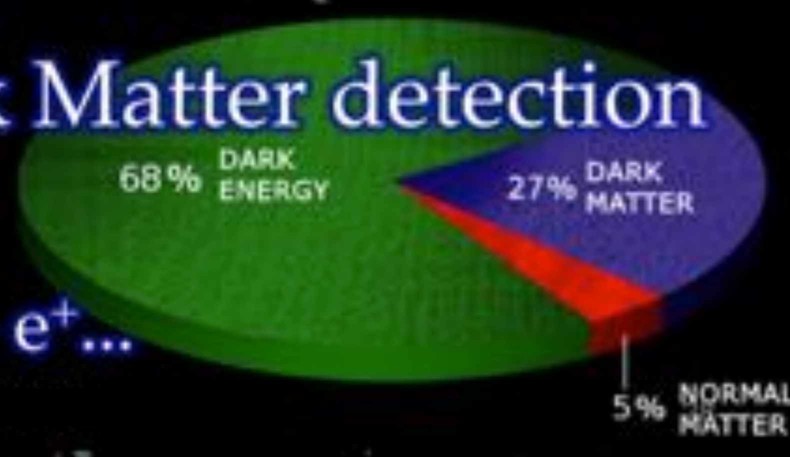



2.3 million boron nuclei and
8.3 million carbon nuclei
Cowsik (2014)
$B/C = kR^{\delta}$ $\delta = -0.352 \pm 0.013$
Kolmogorov turbulance
model predicts $\delta$=1/3.
B/C
R [GV]
0.4
0.3
0.2
0.1
0.06
0.05
0.04
0.03
10
$10^2$
$10^3$

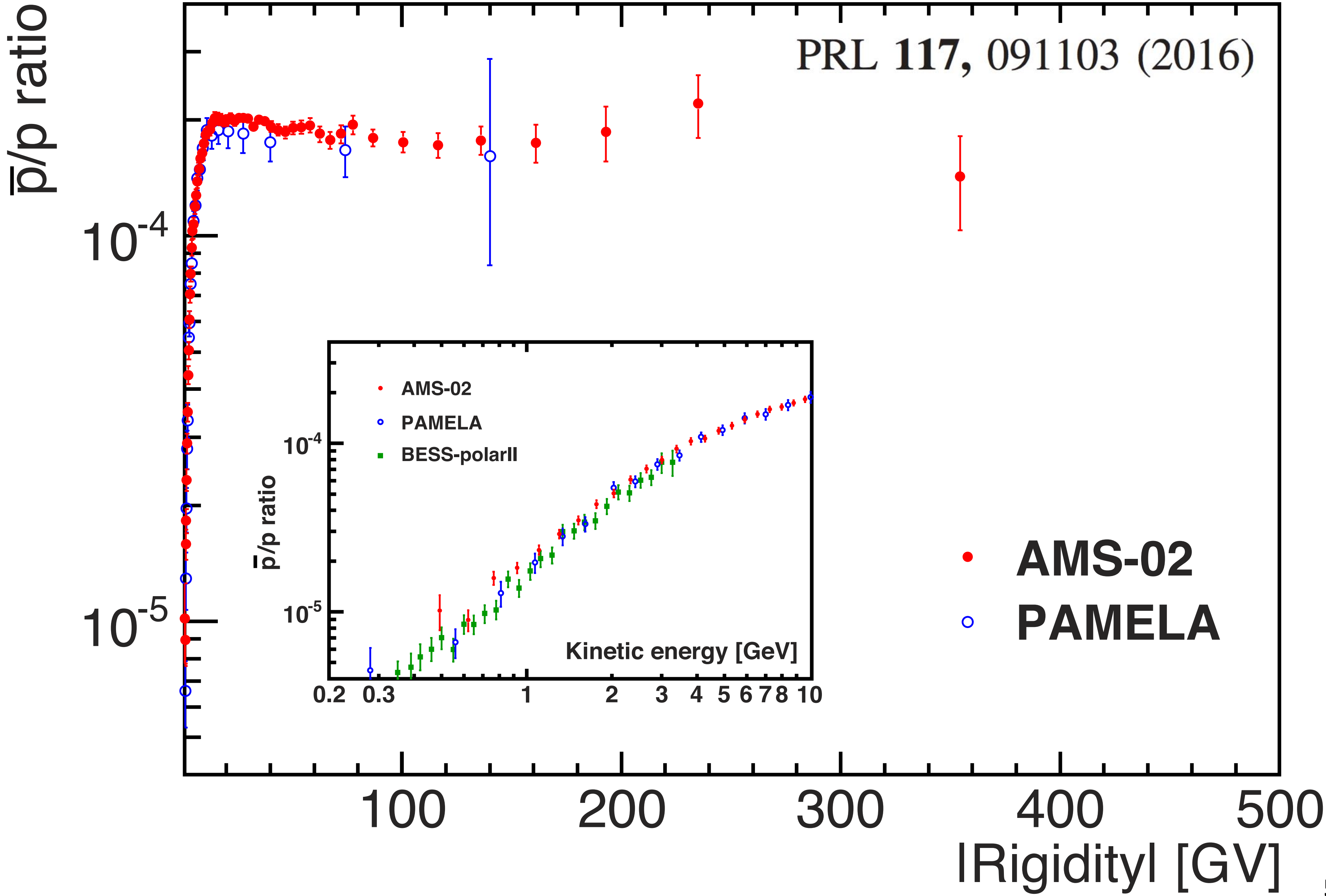
# Measurement of Antiproton flux

Physics importance

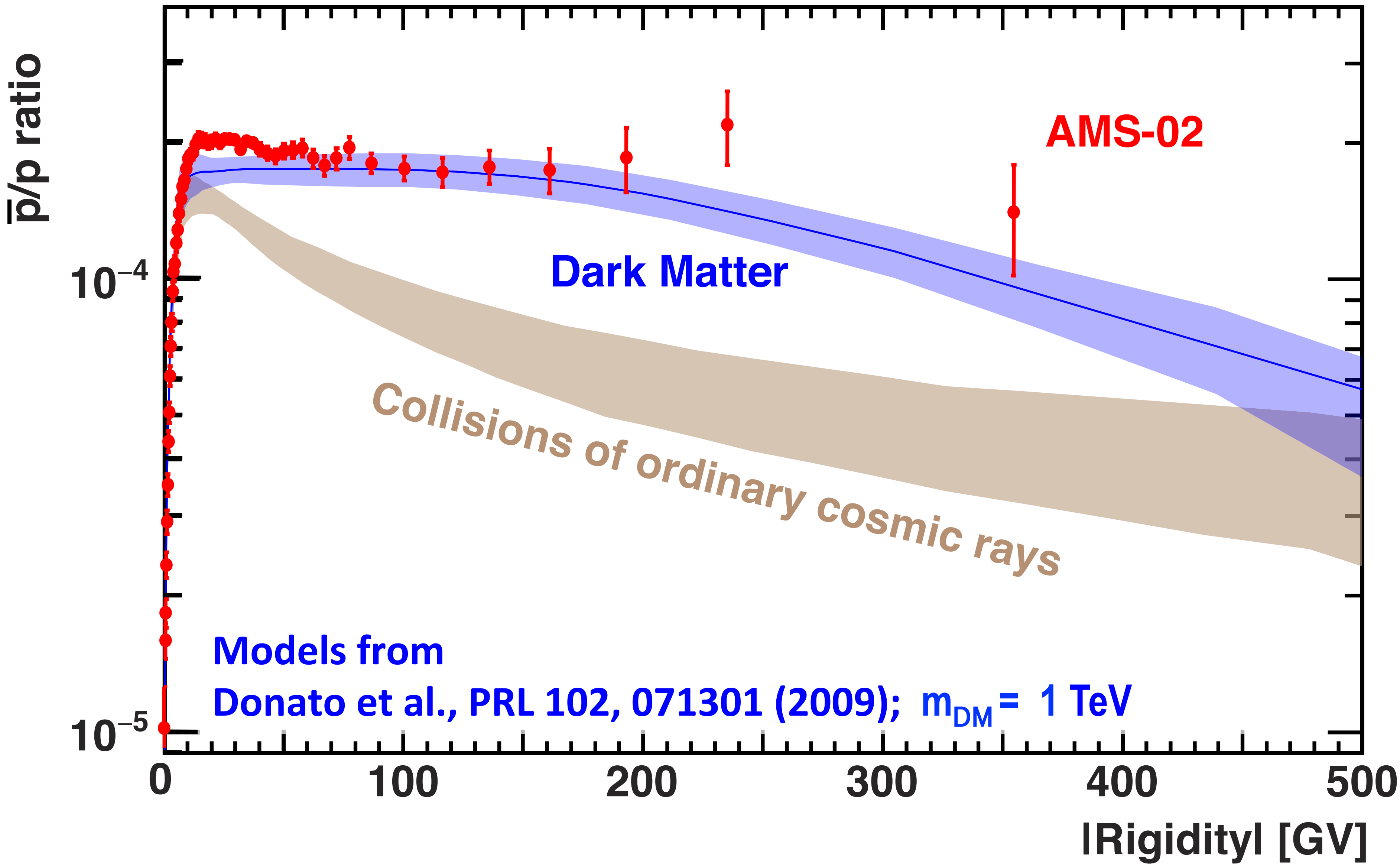
- Antiprotons : Only ~$10^{-4}$ of cosmic ray particles
- Produced by cosmic ray collisions
  e.g. $pN \rightarrow \bar{p}$...
- Probe of indirect Dark Matter detection
  e.g. $\chi\chi \rightarrow \bar{p}$...
  Complementary to $\chi\chi \rightarrow e^{+}$...



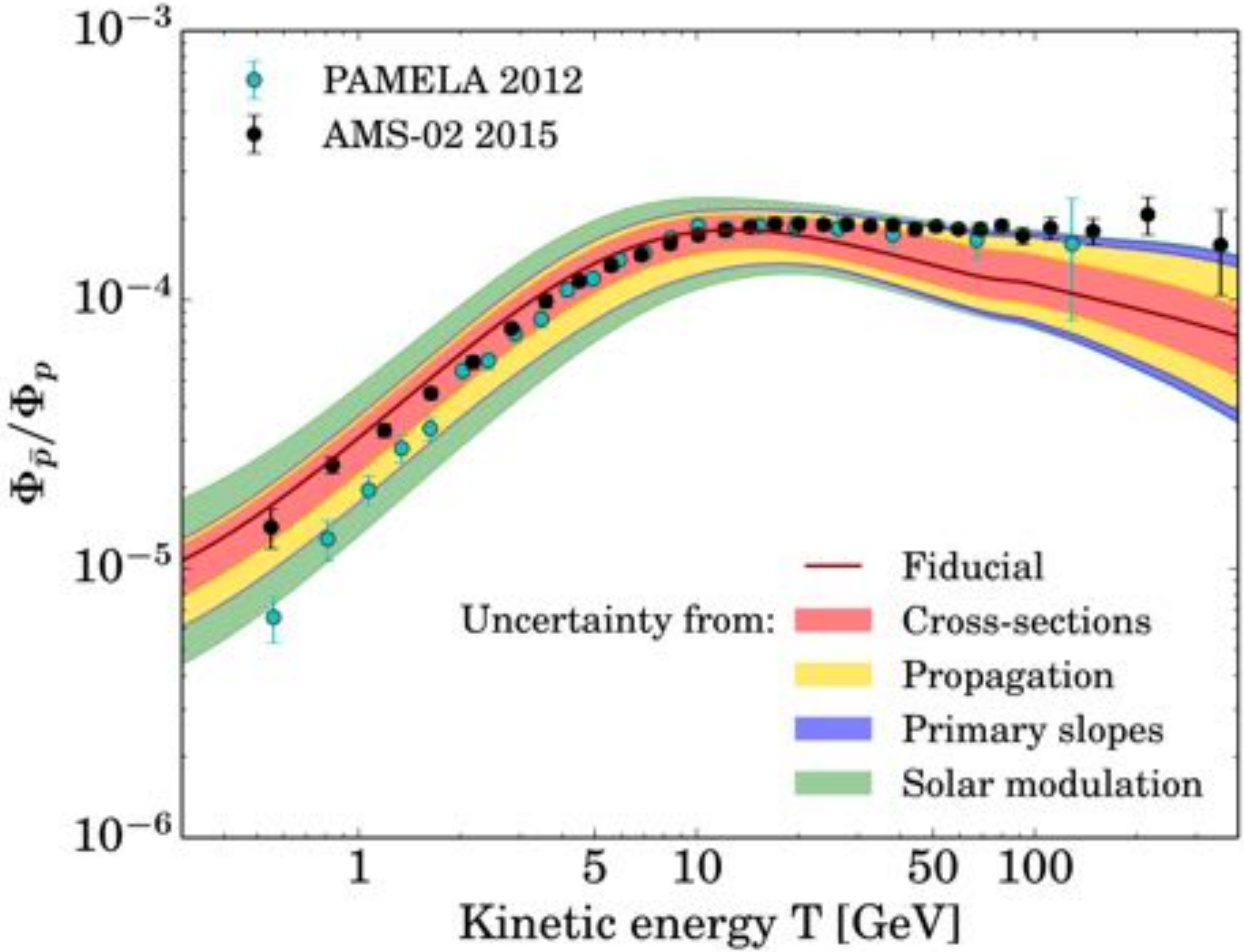
# AMS results on the $\bar{p}/p$ flux ratio



# AMS $\bar{p}/p$ results and modeling

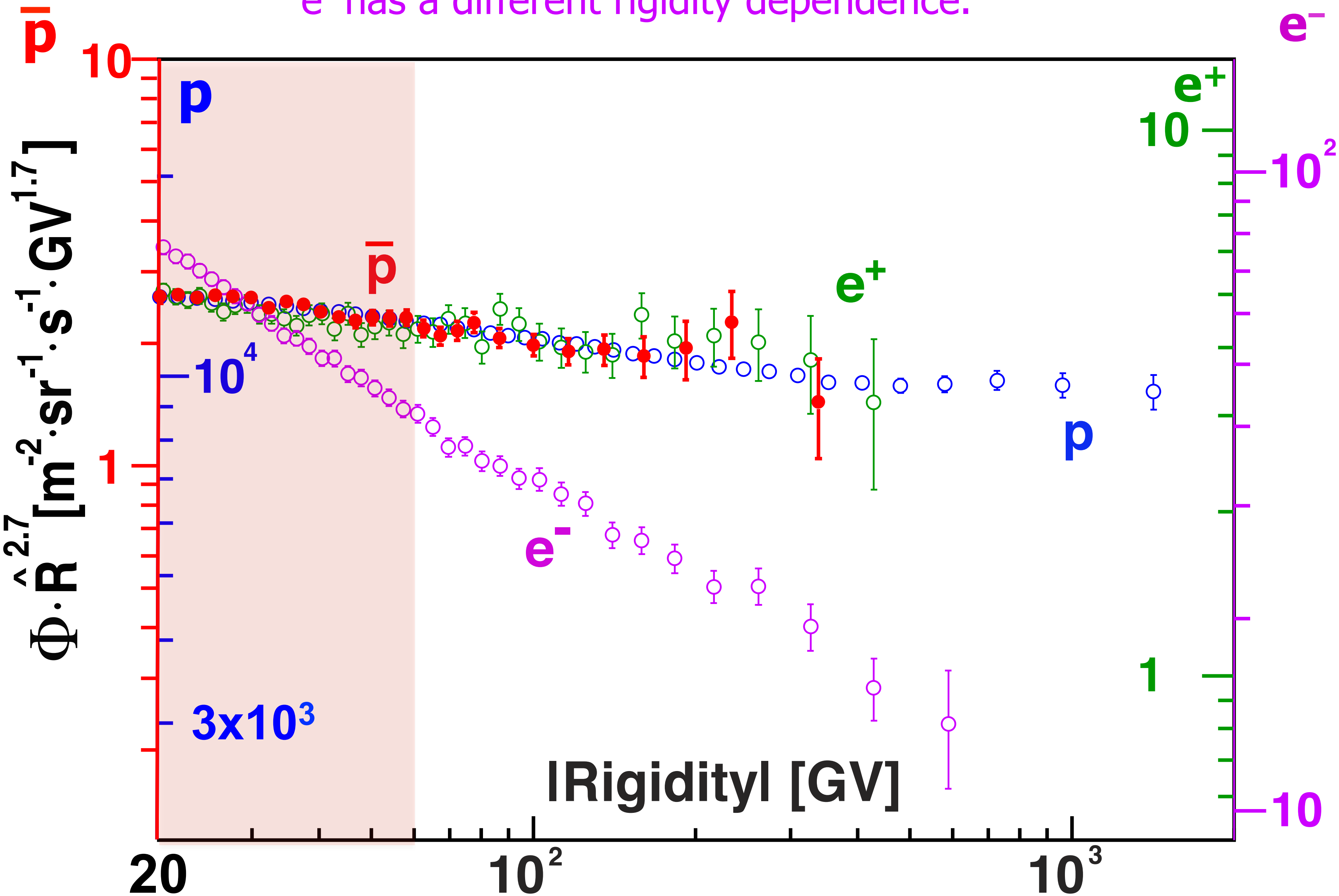


G.Giesen et al., JCAP09(2015) 023



Unexpected Result: The Rigidity Dependence of Elementary Particles $e^+$, $\bar{p}$, p are identical from 60-500 GV.

$e^-$ has a different rigidity dependence.




M. Aguilar *et al.*, Phys. Rev. Lett. **117,** 091103 (2016)

The Space Station has become a unique platform for precision physics research.

*"The most exciting objective of AMS is to probe the unknown; to search for phenomena which exist in nature that we have not yet imagined nor had the tools to discover."*

*S. Ting*