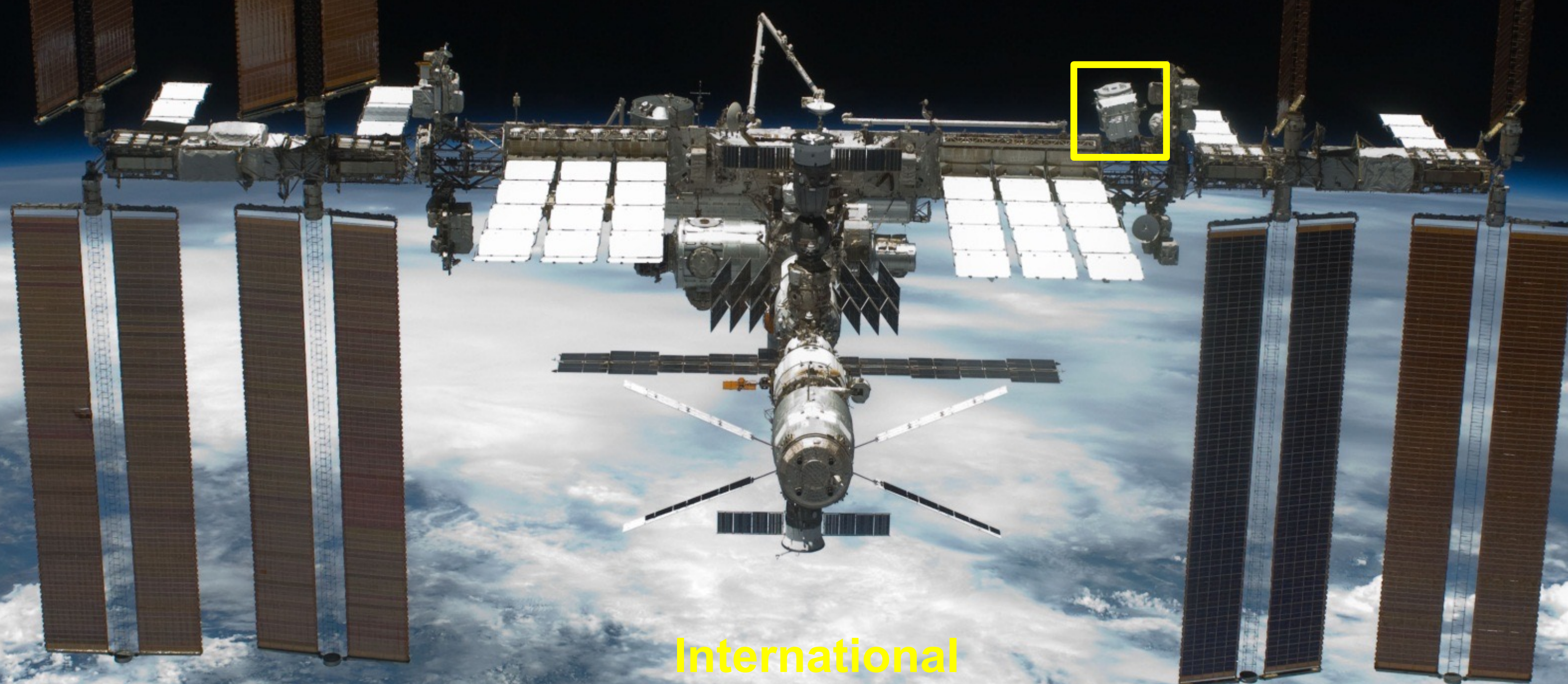
Misure di precisione di raggi cosmici con AMS-02 sulla ISS

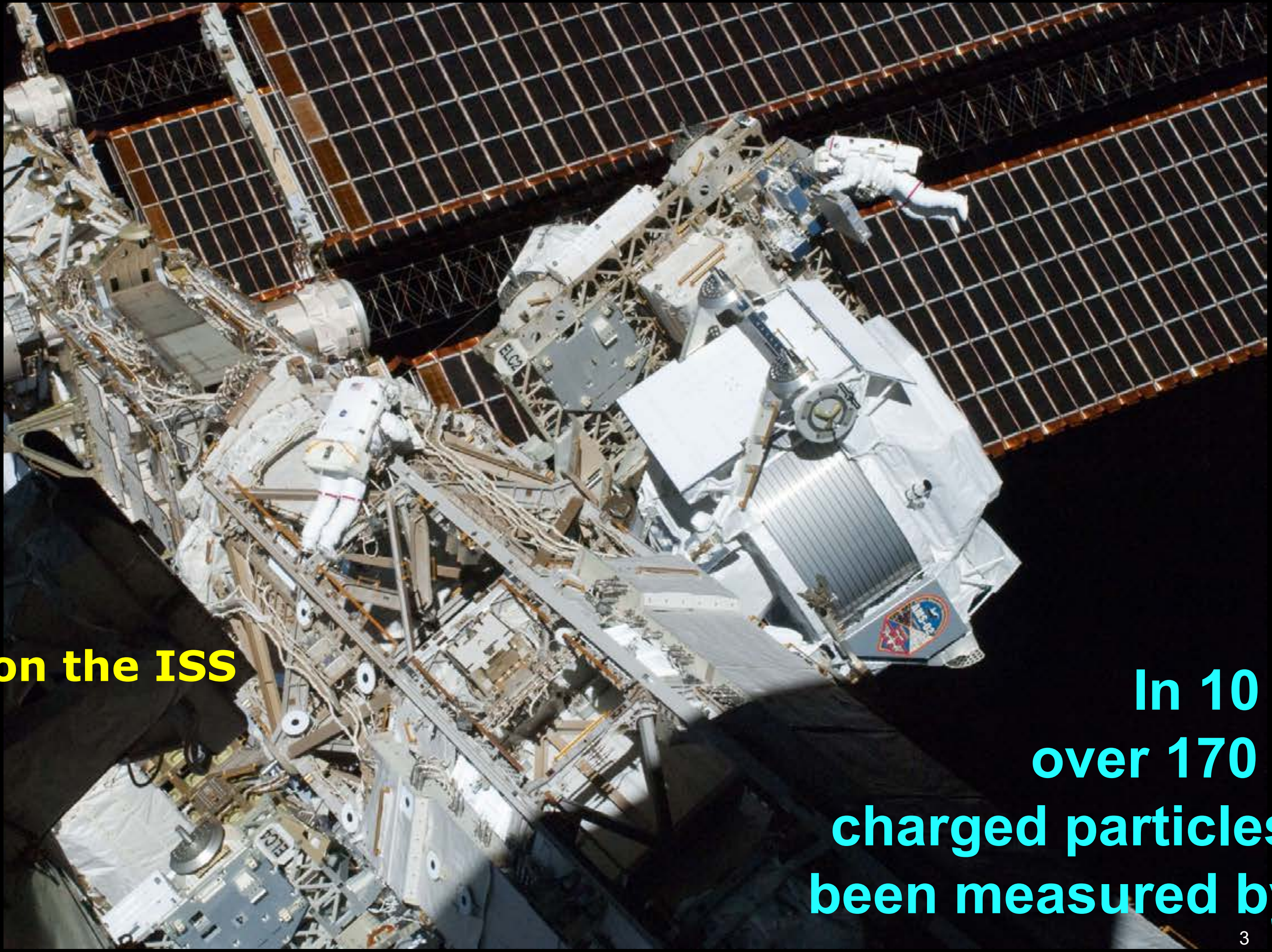
Roberto Battiston
Trento University and INFN-TIFPA



International
Cosmic Day
EEE-Cref
22nd November 2022

Istituto Nazionale di Fisica Nucleare
Agenzia Spaziale Italiana

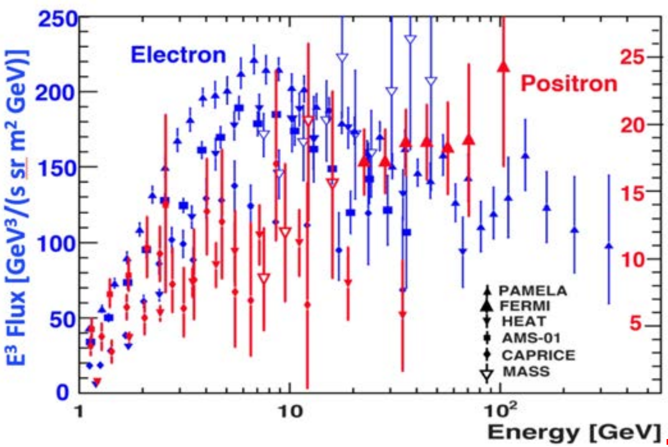
One hundred years after Hess discovery, Cosmic Rays experiements in space provide precision measurements



AMS-02 on the ISS

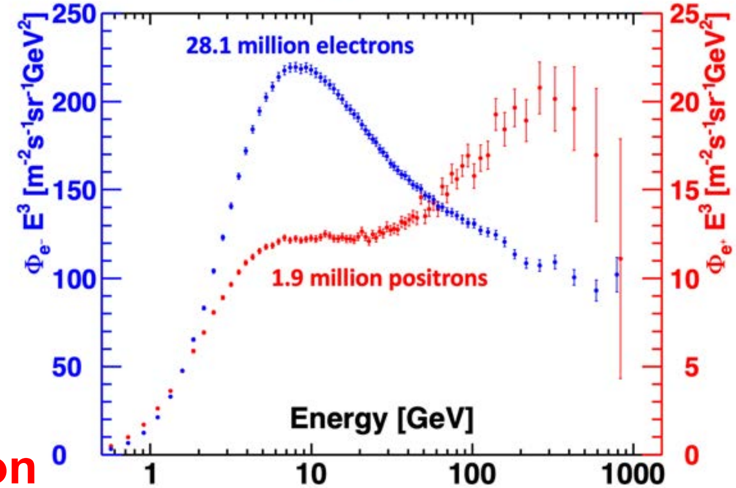
In 10 years, over 170 billion charged particles have been measured by AMS

Data of the Electron and Positron spectra before AMS



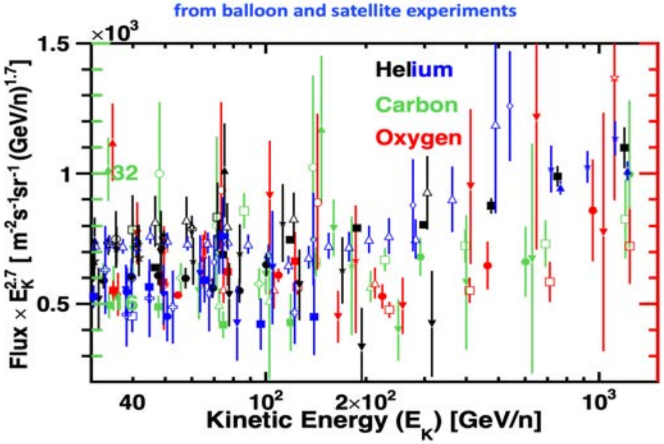
Alpha Magnetic Spectrometer AMS

Latest AMS results on positron and electron fluxes

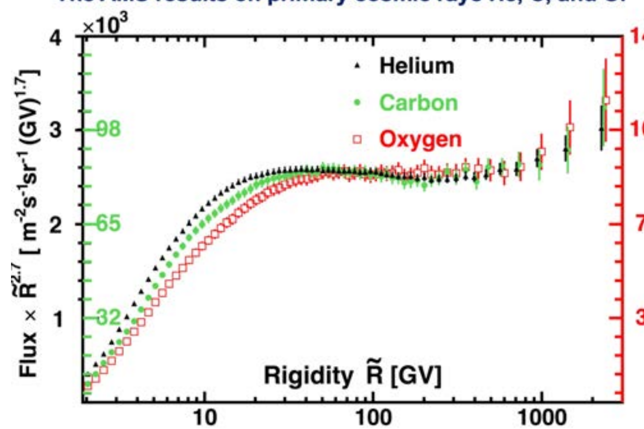


The Era of Precision Cosmic Ray measurements

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



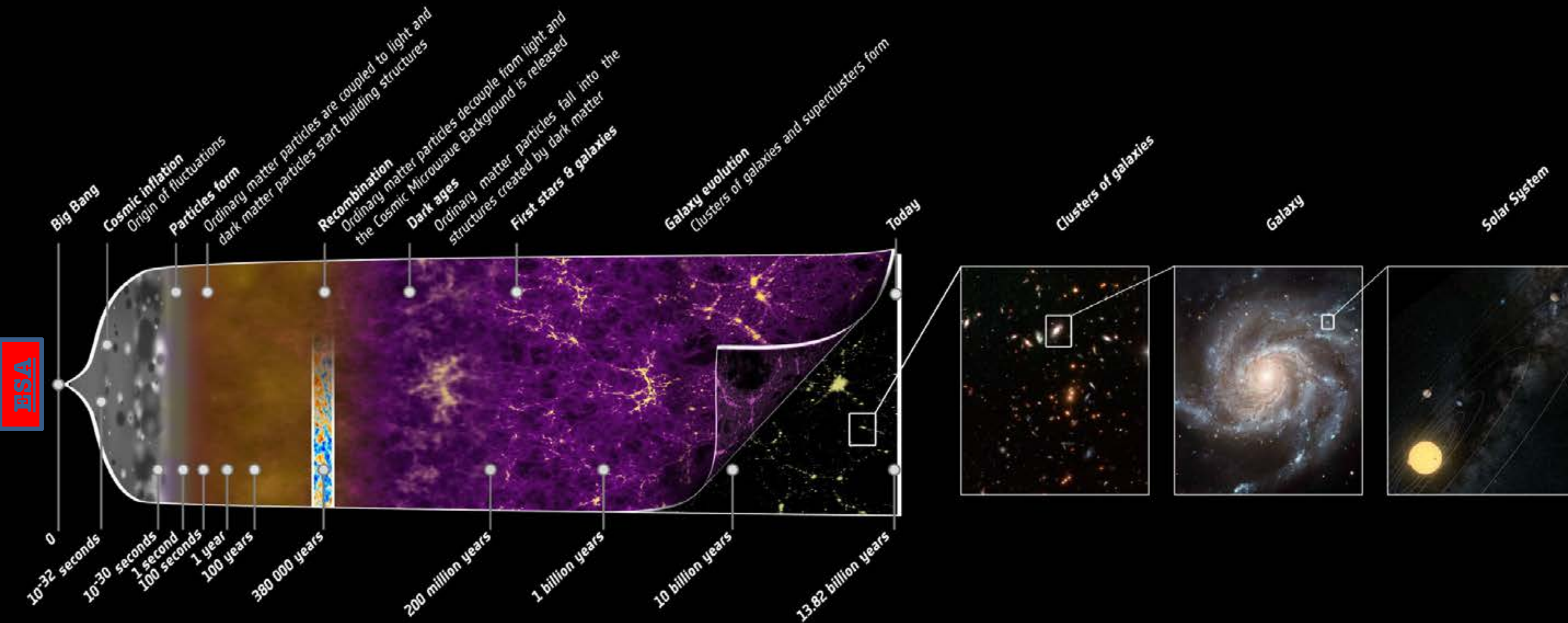
The AMS results on primary cosmic rays He, C, and O.

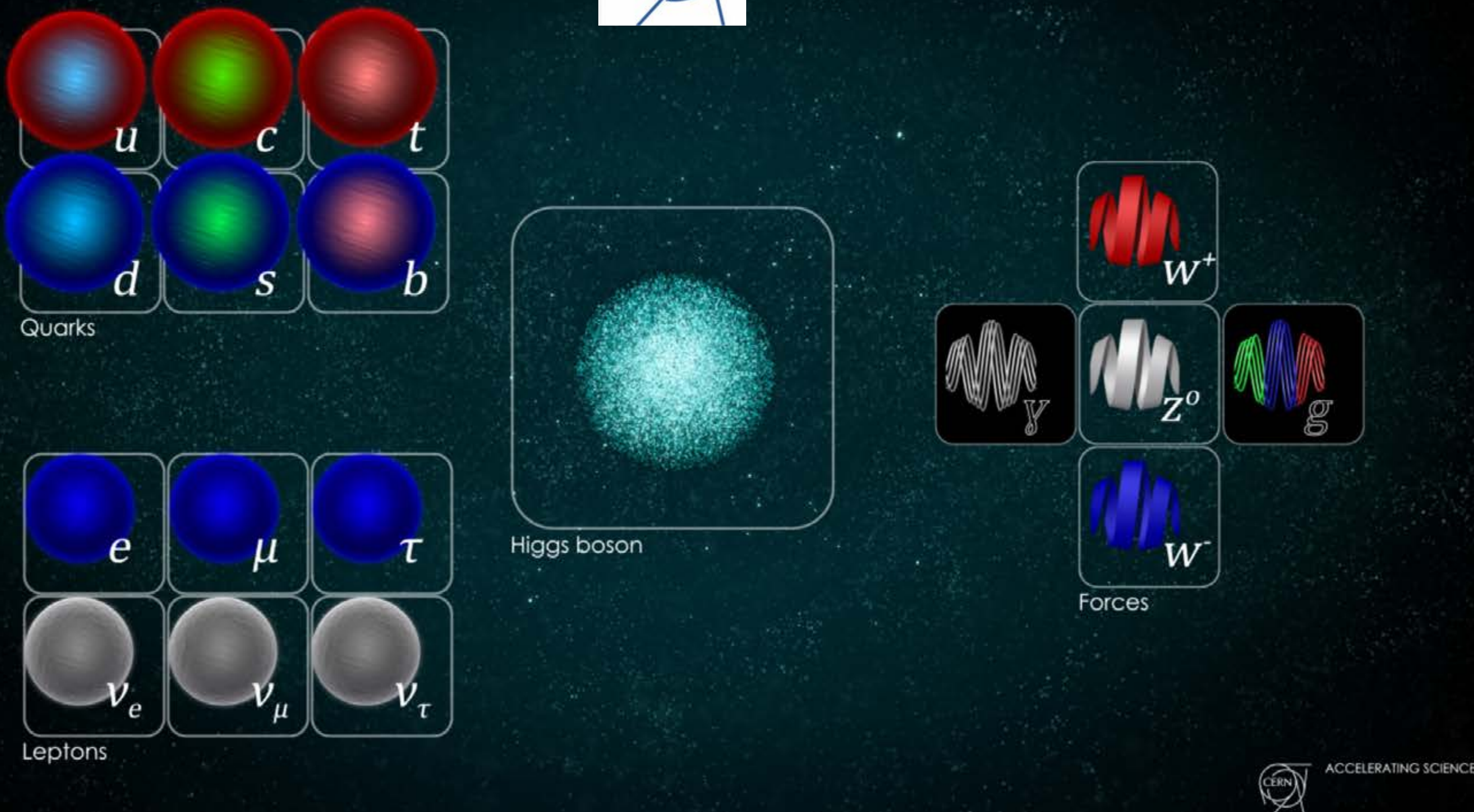


AMS results : first time % accuracy in Cosmic Ray physics

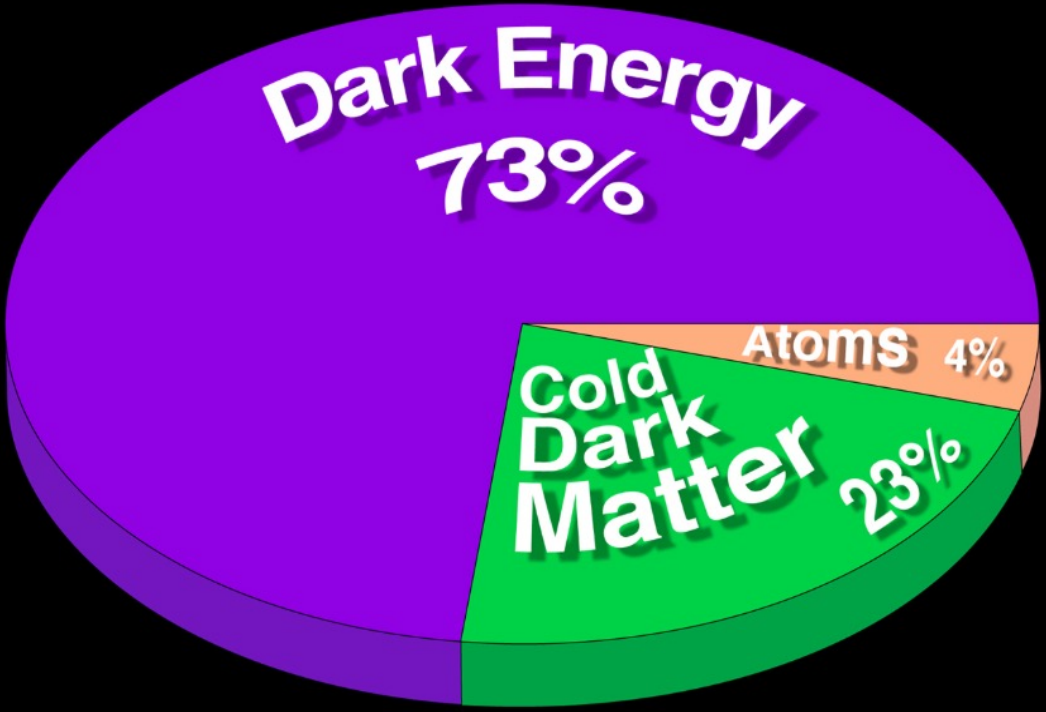
High Precision Particle Astrophysics using antimatter particles

Antimatter particles in Cosmic Rays (CR) represent a small fraction of the total flux, about $5\ 10^{-3}$ for e+, 10^{-5} for p-bar, 10^{-7} for d-bar, less than 10^{-9} for anti-^{3}He or heavier antinuclei: these tiny fluxes, however, carry a great amount of information, since the origin of antiparticles is intimately related to fundamental processes.


ESA
Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and
dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and
the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the
structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
Clusters of galaxies
Galaxy
Solar System
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years


u
c
t
d
s
b
Quarks
e
μ
τ
ν e
ν μ
ν τ
Leptons
Higgs boson
W+
γ
Z0
g
W-
Forces
ACCELERATING SCIENCE

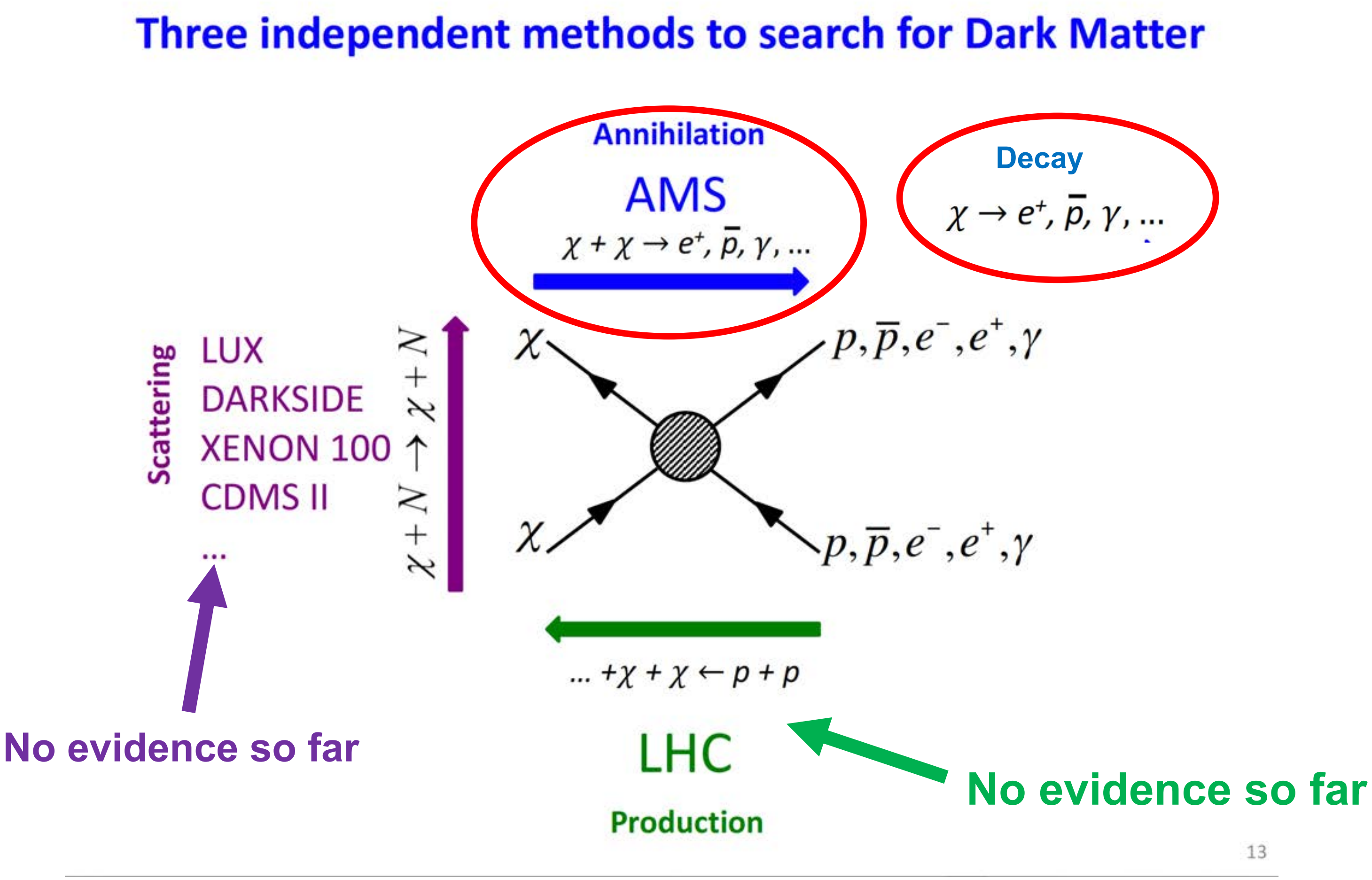
Planck



Dark matter in the universe

A jar with a very few edible candies

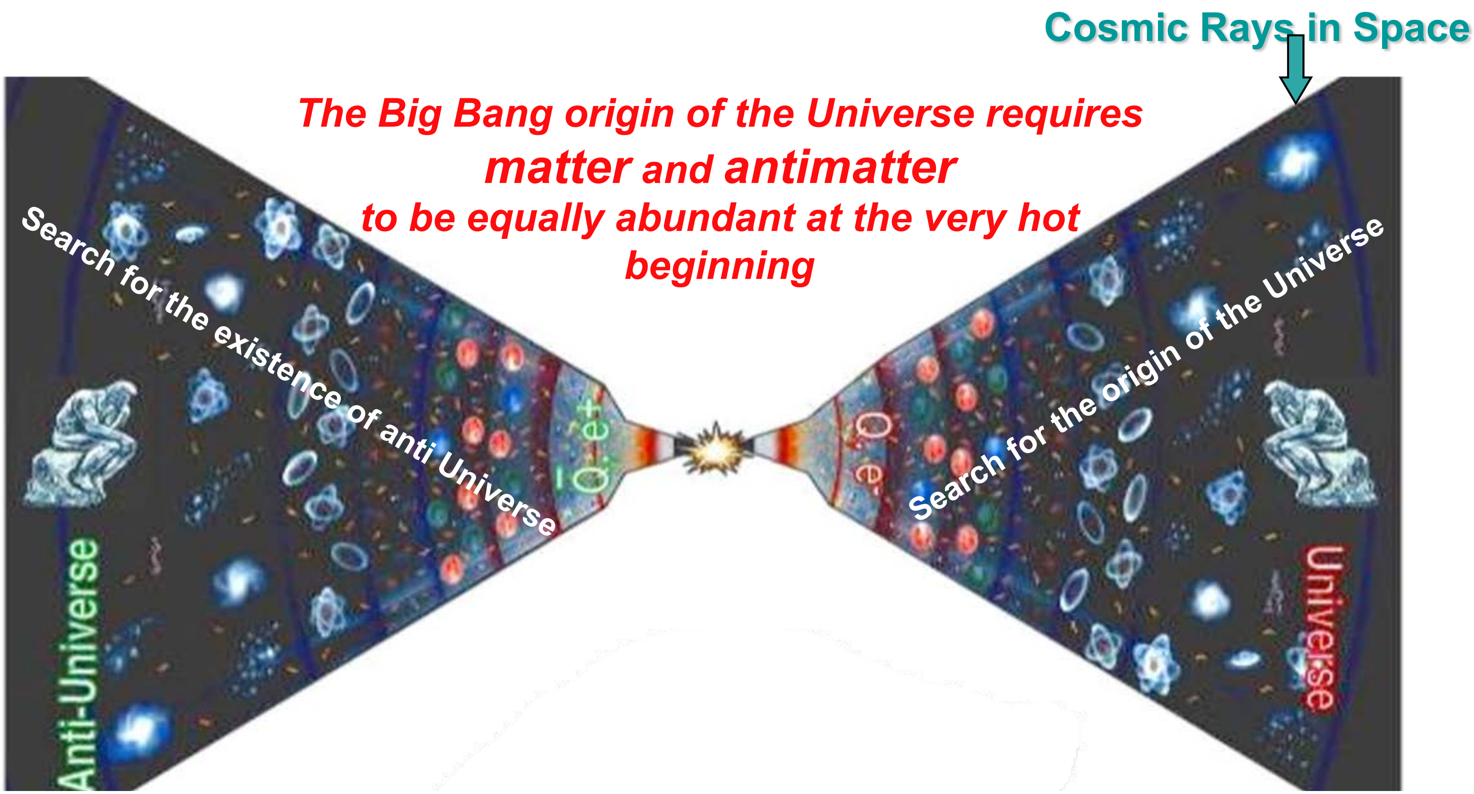
Example of physics topics for High Precision Particle Astrophysics «Search for the origin of dark matter»



Antimatter in the universe

The lost can

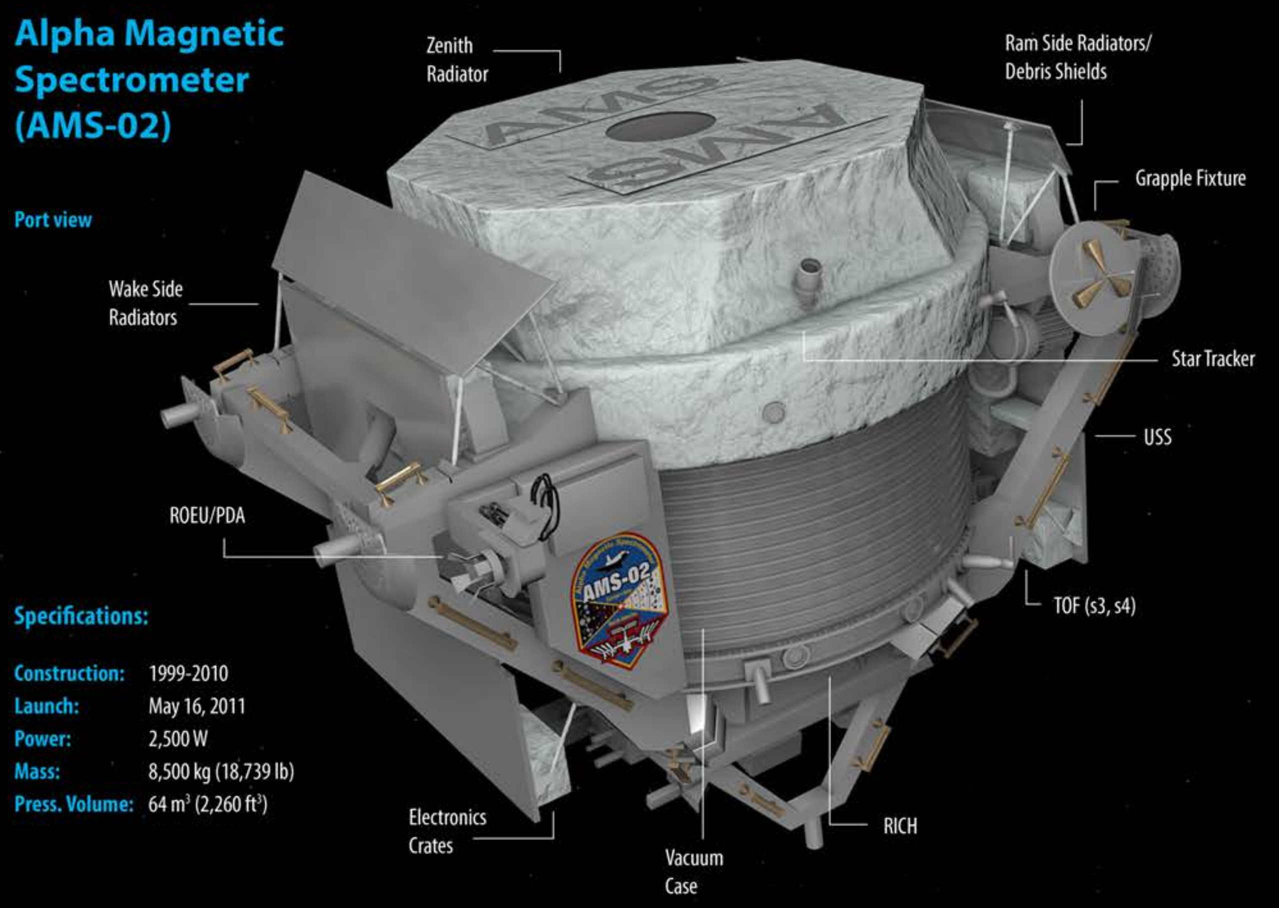
Example of physics topics for High Precision Particle Astrophysics: «Disappearance of nuclear antimatter»

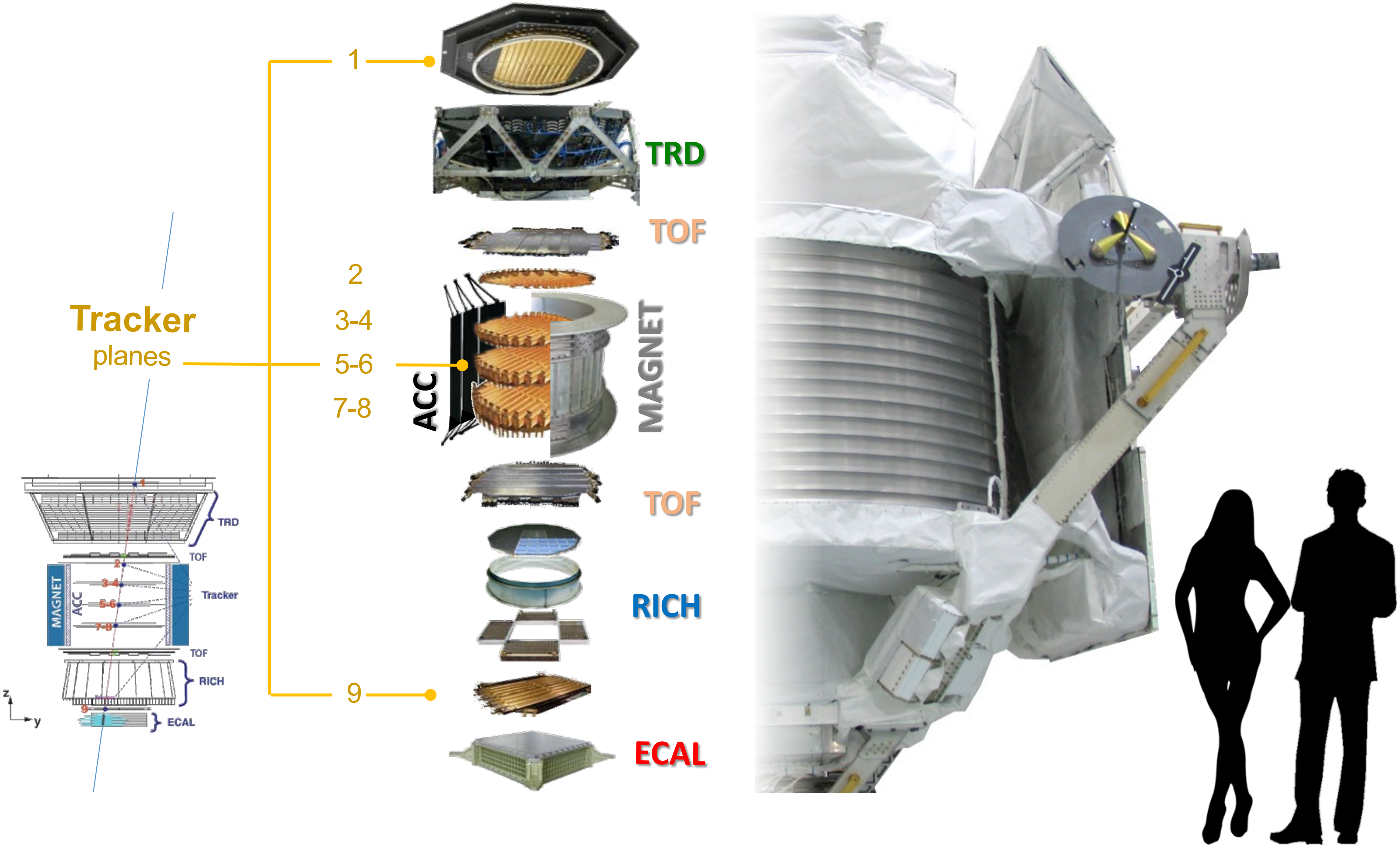


Observation and detailed study of nuclear antimatter would be a game changer in our understanding of the physics of early Universe and of the fundamental properties of particle and fields.

AMS-02: Alpha Magnetic Spectrometer

Launch 16/5/2011 (Endevour)
Construction 1999-2010
Dimensions 3 × 4 × 5 m³
Wheight 8.5 t
Power 2500 W





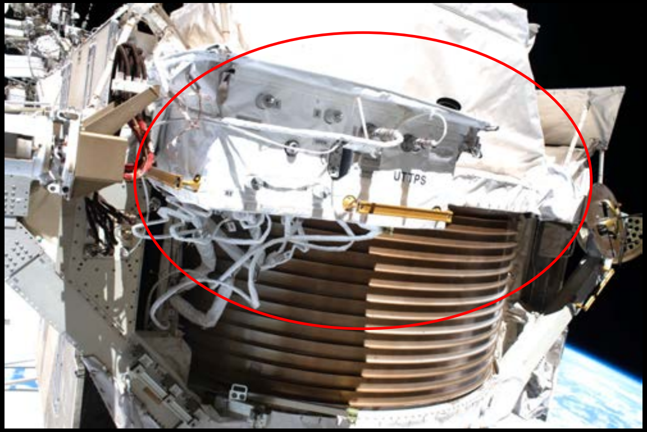
Tracker
planes
1
2
3-4
5-6
7-8
9
TRD
TOF
ACC
MAGNET
TOF
RICH
ECAL
TRD
TOF
MAGNET
ACC
Tracker
TOF
RICH
ECAL
z
y


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

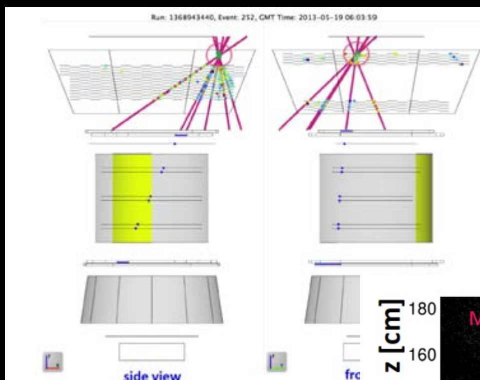
Fix of the Cooling system 2019/20

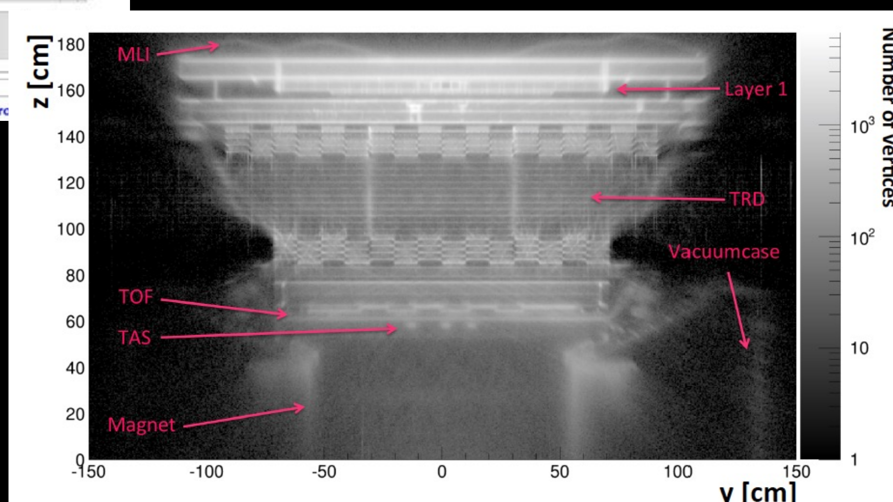
4 EVAs by

- **Luca Parmitano**
- **Andrew Morgan**

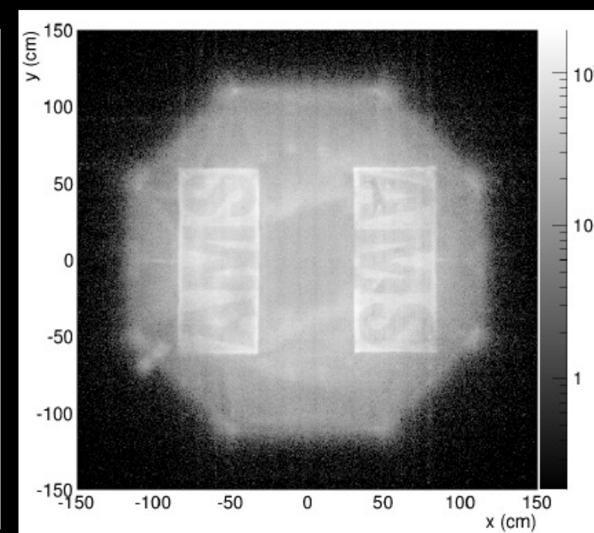


AMS “tomography” using rare nuclear interaction events produced by ith 170 billions of Cosmic Rays



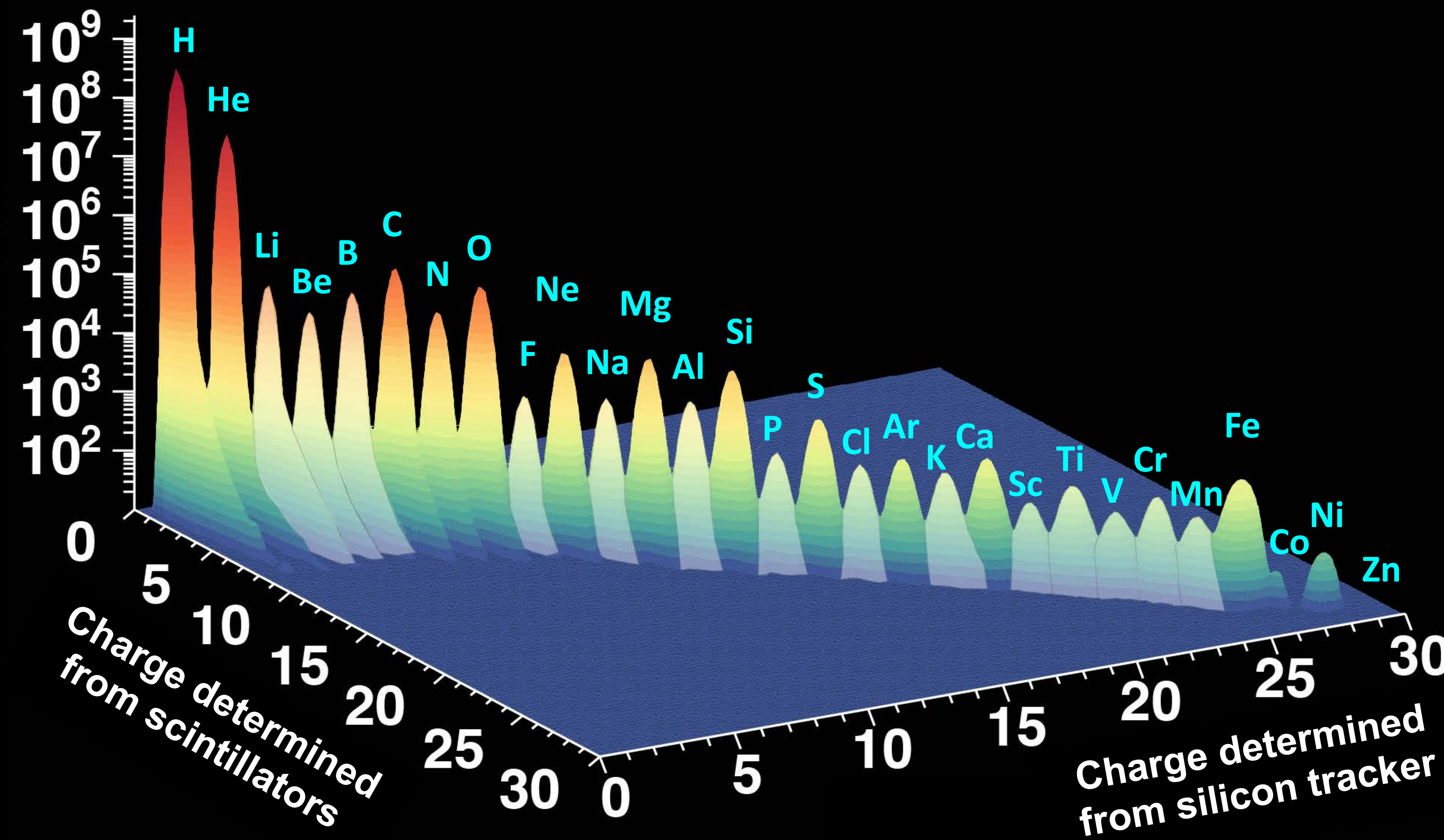


Z=178.5 cm

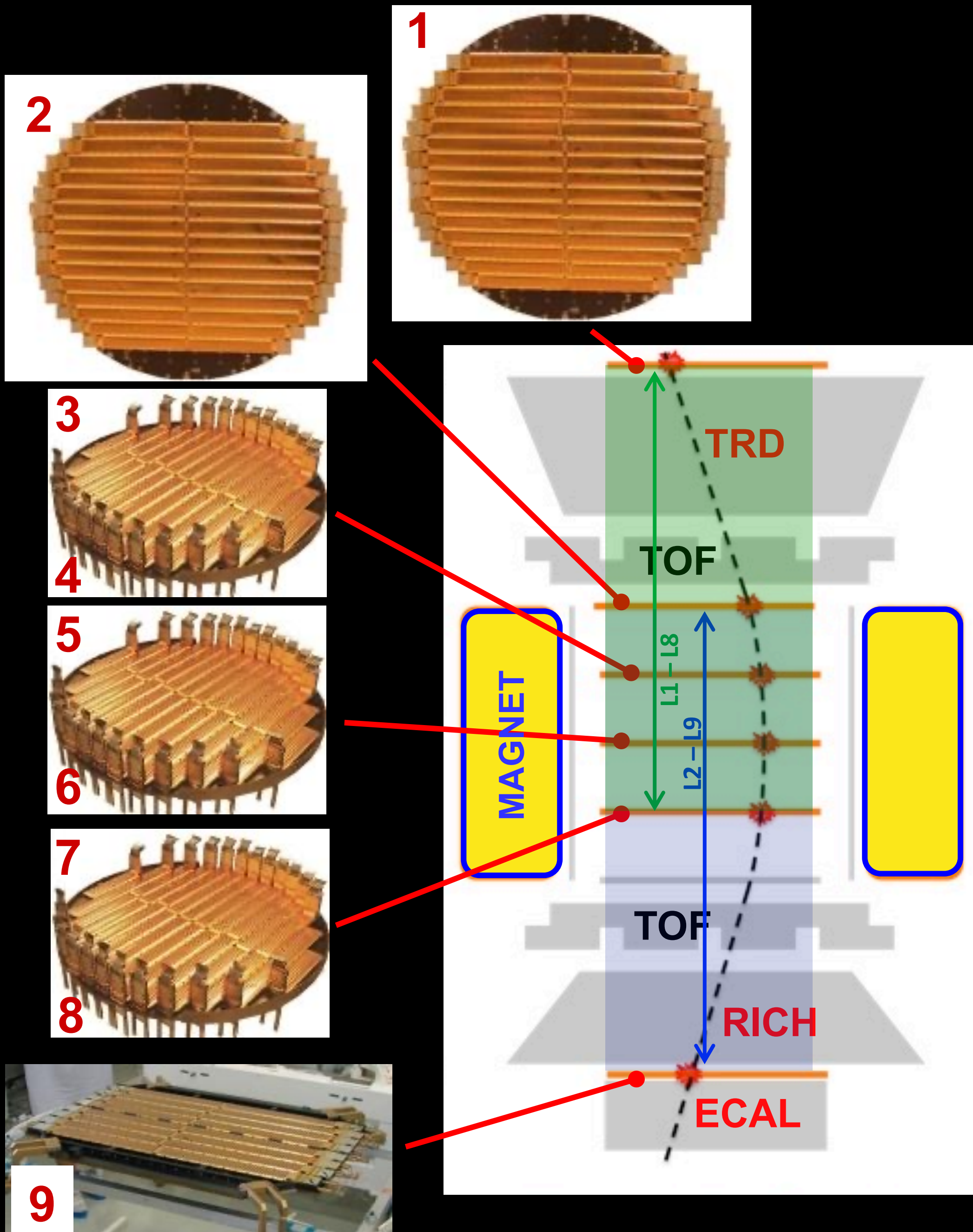


The gray scale is proportional the the number of found vertices

Precision Measurement of Cosmic Nuclei



Continuous Calibration at TeV (above CERN 0.4 TeV test beam)

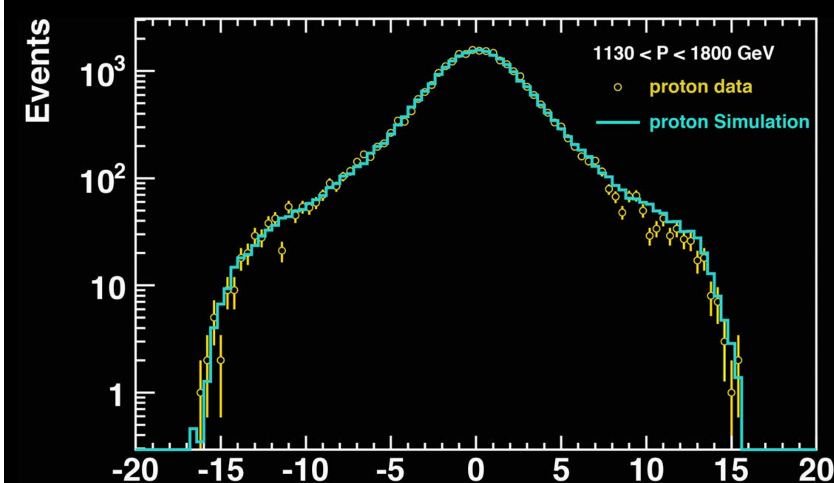


By comparing proton data and simulation from

the upper spectrometer (L1 to L8)

and

the lower spectrometer (L2 to L9)

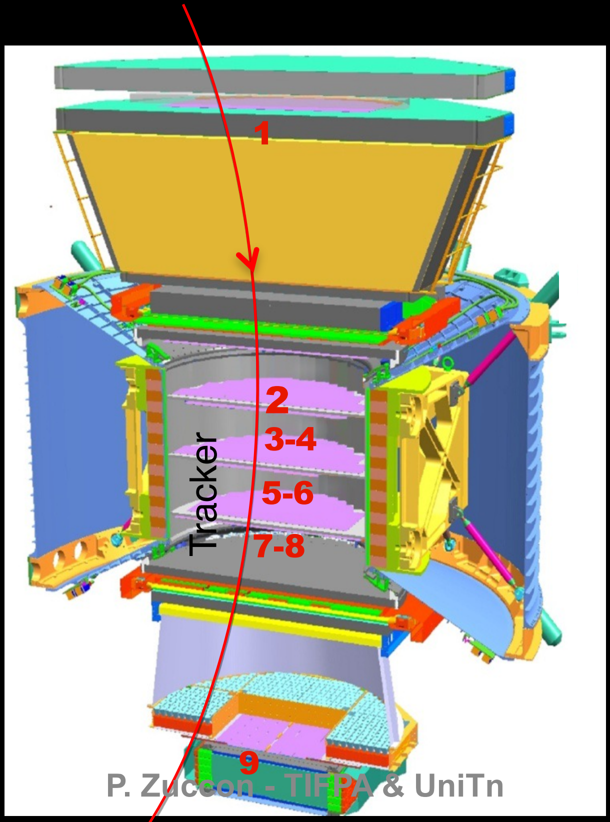


$$\frac{1}{P_{L1-L8}} - \frac{1}{P_{L2-L9}} [(\mathrm{TeV}/c)^{-1}]$$

Absolute Momentum Scale

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

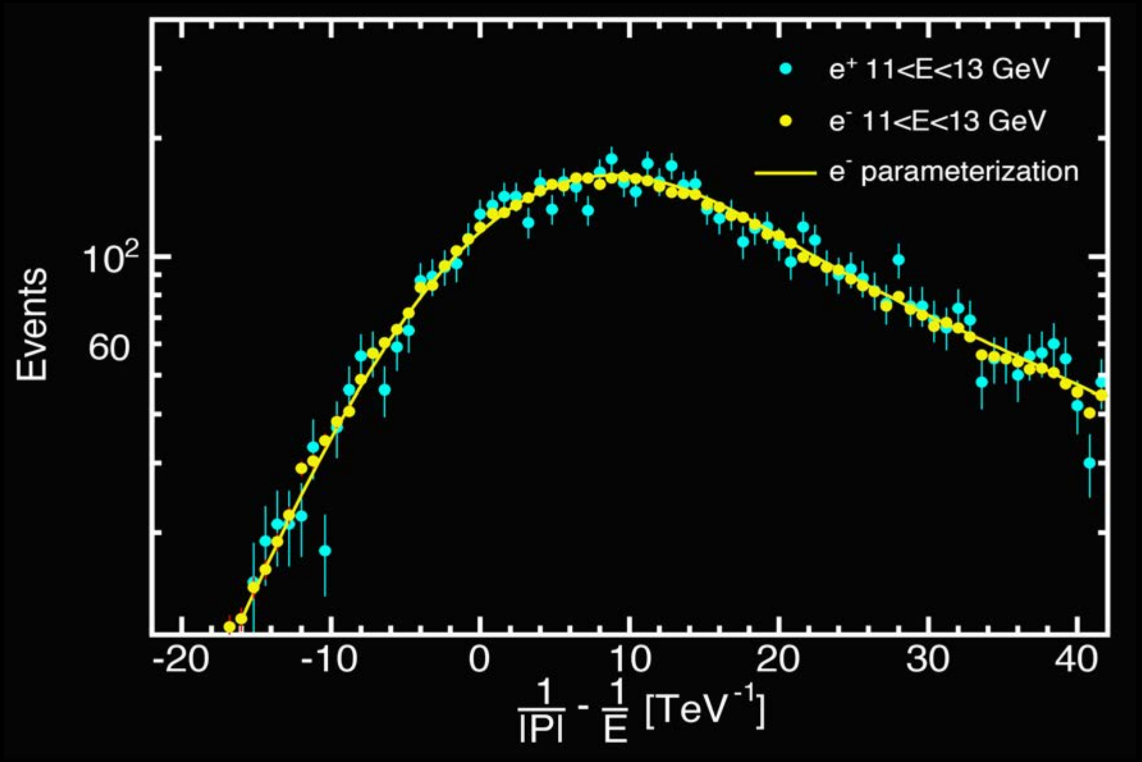
In space continuous outgassing of the carbon fiber supporting structure can affect the position of the tracker sensors at the sub-micron level.



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

Momentum Scale Verification

By matching the momentum determined by the tracker and magnet with the energy measured in the ECAL for both e^+ and e^-



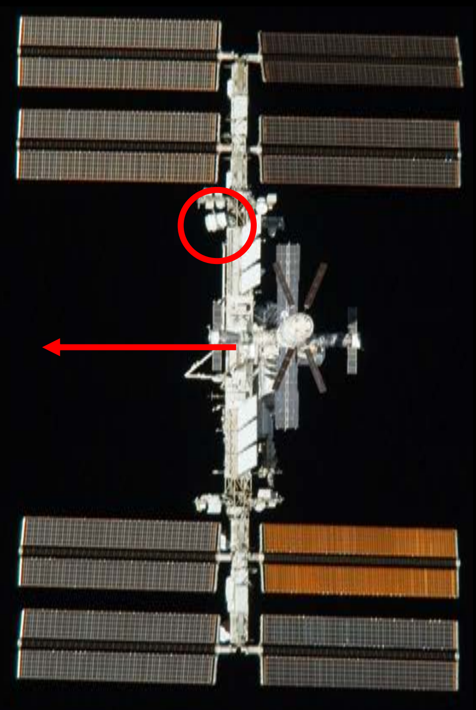
The accuracy of the momentum is determined to be 1/(30,000 GeV);

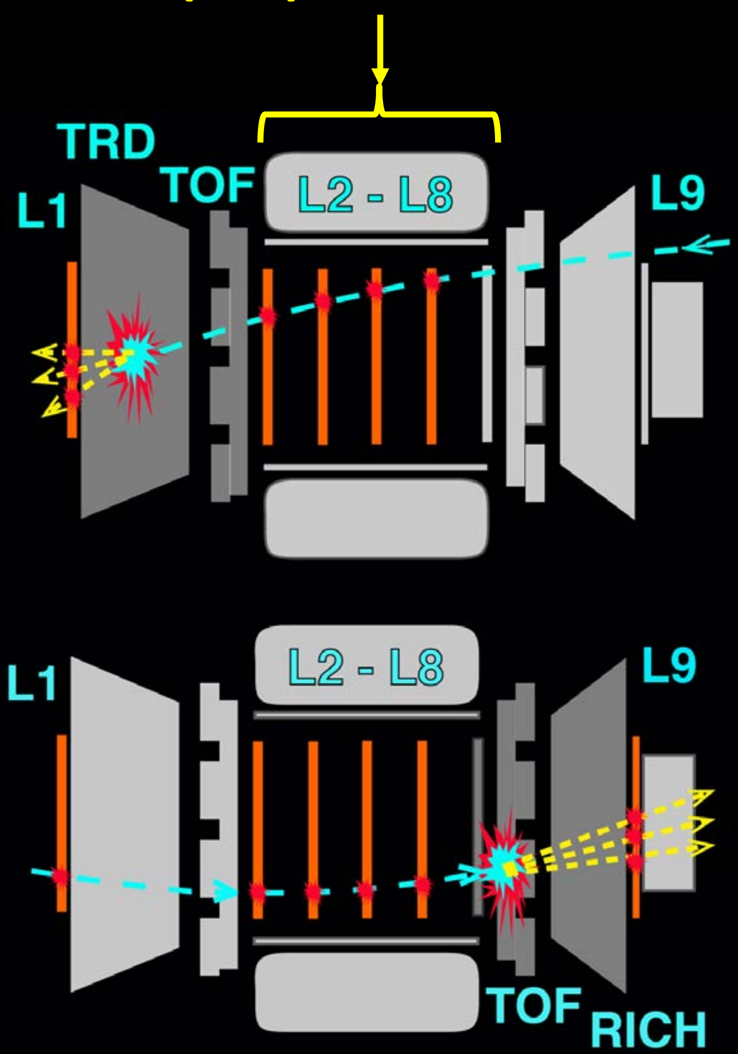
i.e., at 1 TeV the uncertainty is 3%

Precision measurement of cosmic-ray spectra requires an determination of nuclear interactions in the detector material

Define (P, Z) of nuclei with the central spectrometer

ISS horizontal



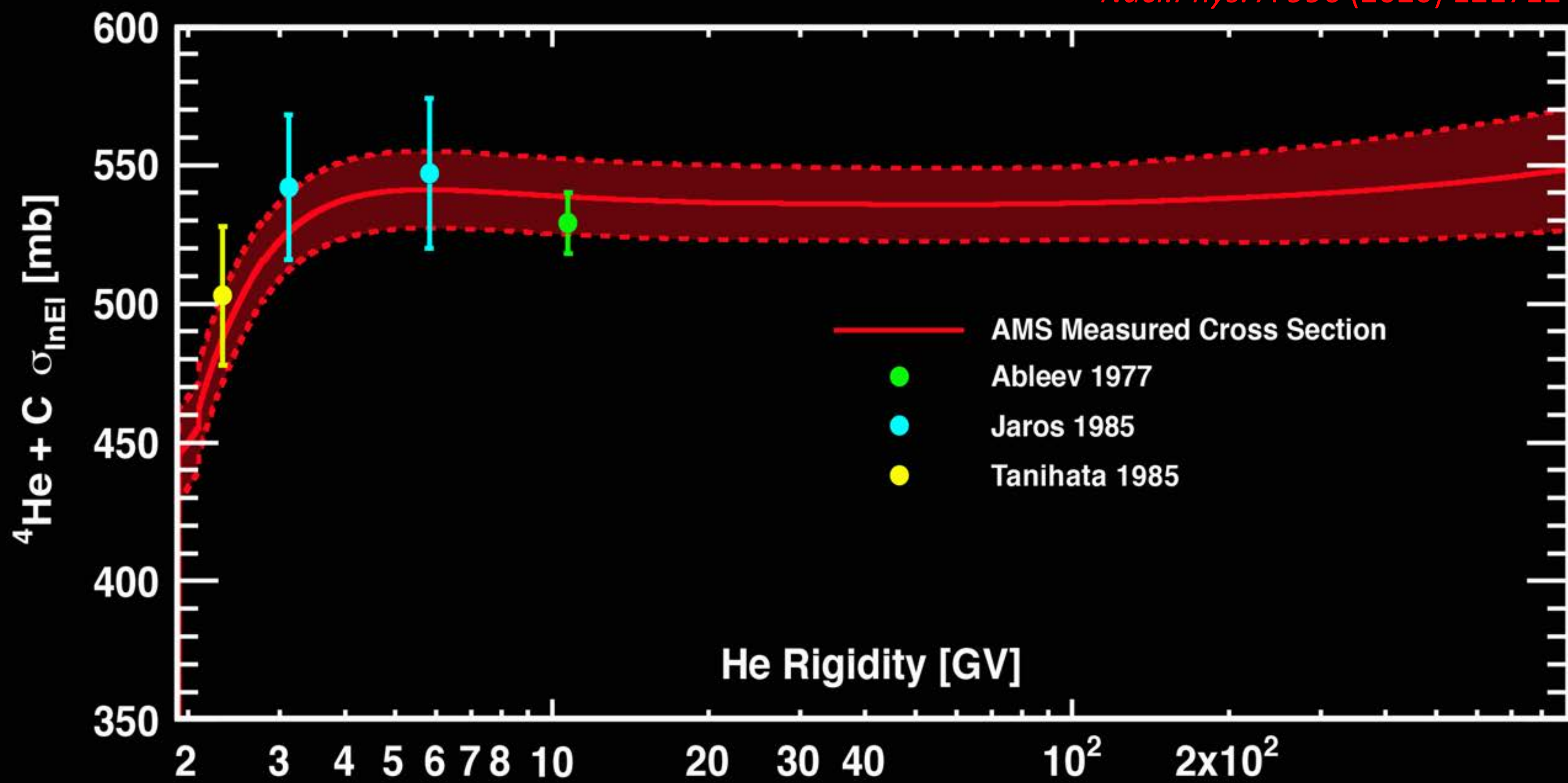


Use right-to-left nuclei to measure nuclear interactions in the TRD+TOF

Use left-to-right nuclei to measure the nuclear interactions in the TOF+RICH

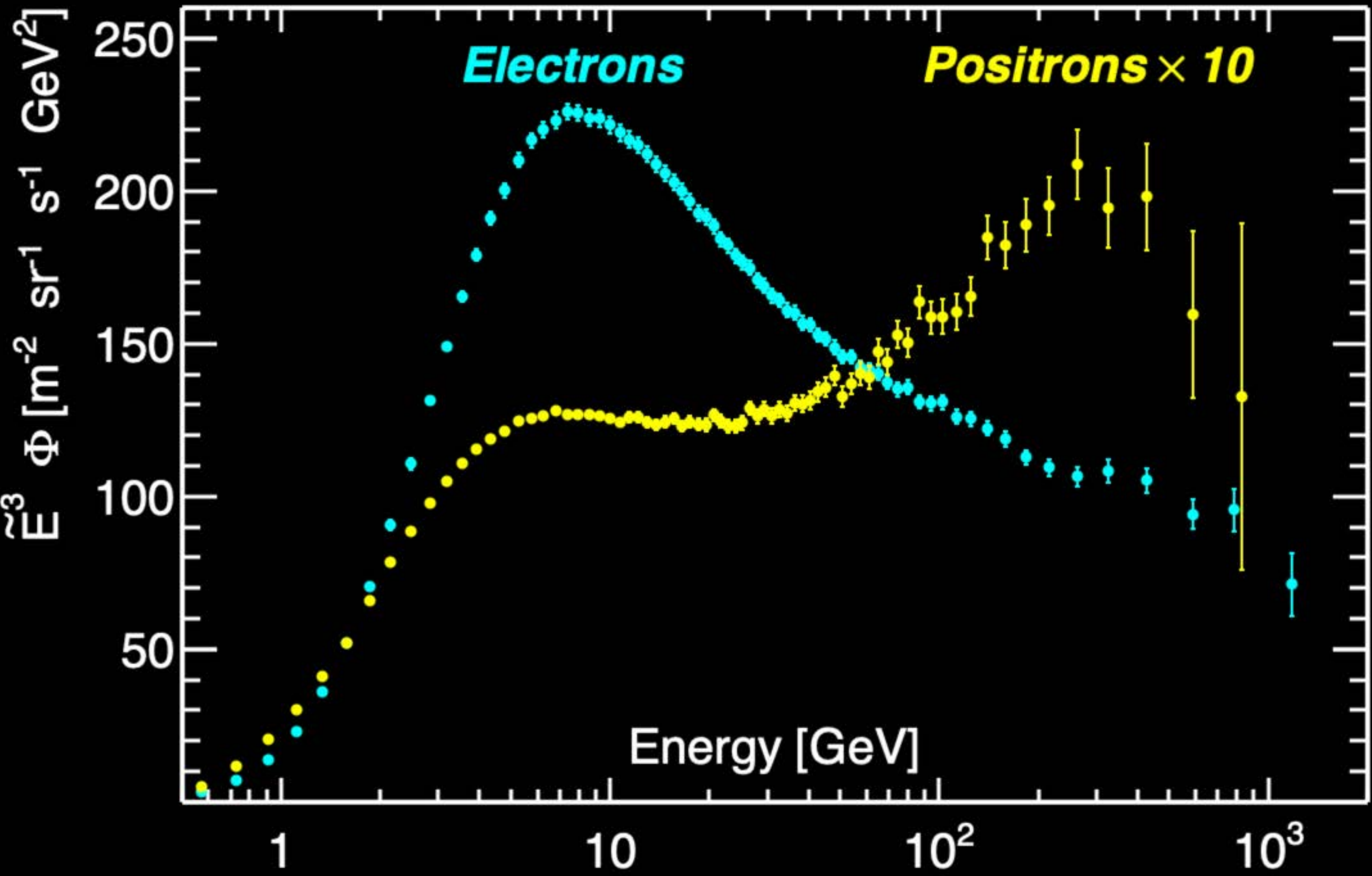
AMS Measurement of He-C Interaction Cross Section
as a function of rigidity

Nucl.Phys. A 996 (2020) 121712



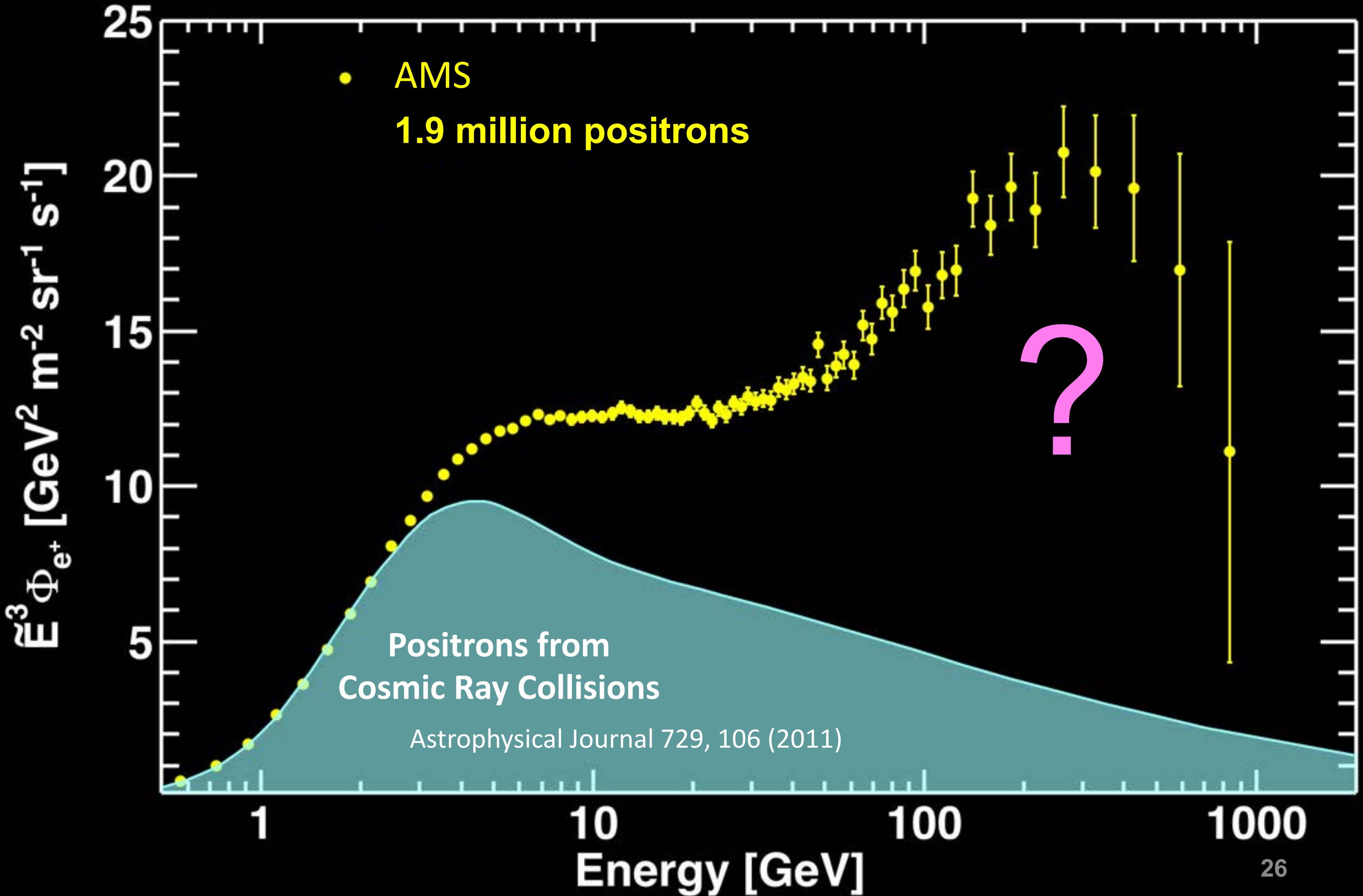
High Energy Positrons and Electrons

AMS measurements of positrons and electrons



The Origin of Positrons

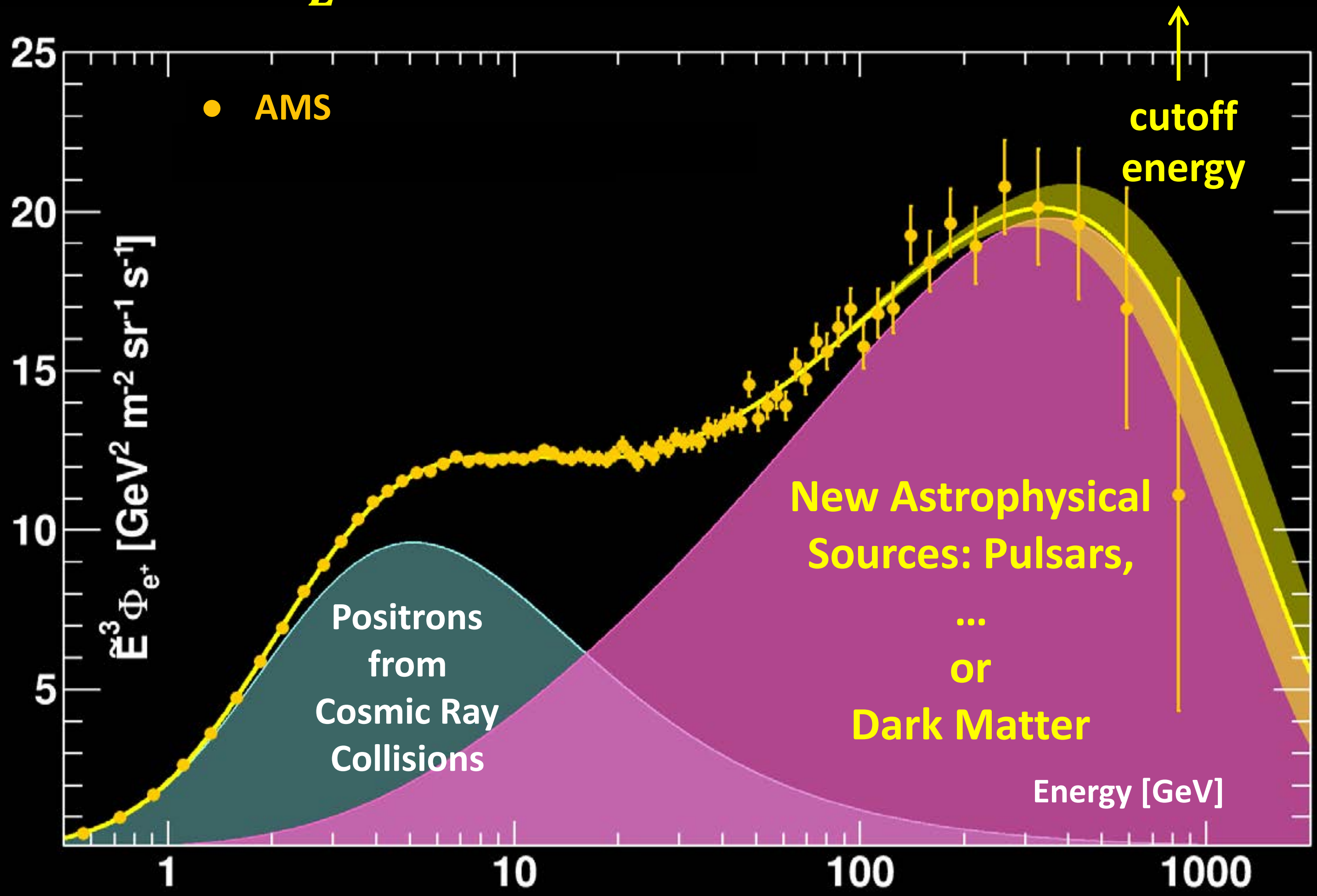
Low energy positrons mostly come from cosmic ray collisions



The Origin of Positrons

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

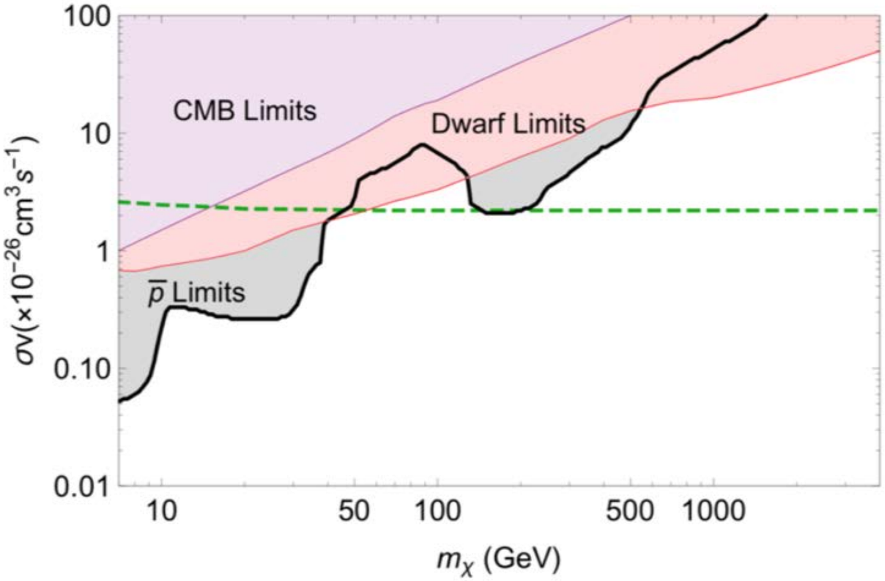
$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$

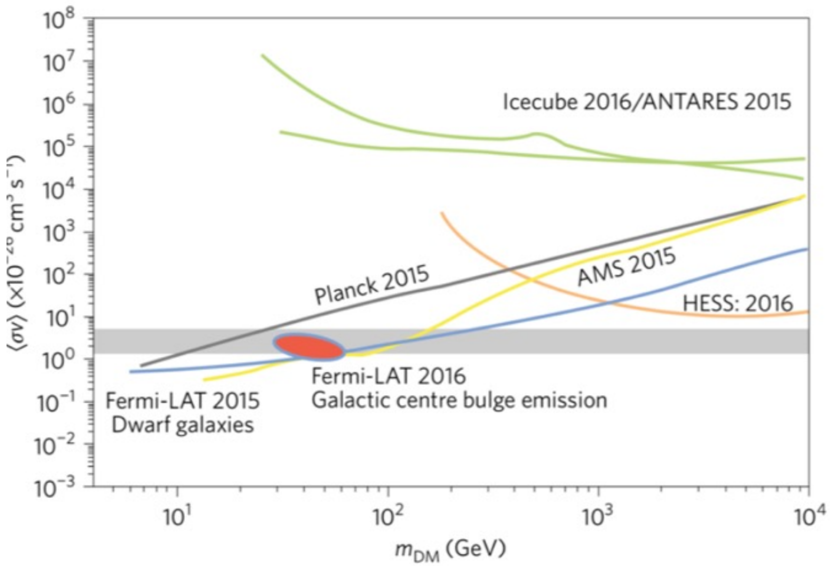


High DM masses >O(1) TeV/c^2 are also compatible with limits from LHC & direct searches

Precision measurements of the detailed features of the energy spectra and arrival directions of CR positrons and electrons at the TeV scale are needed to clarify whether DM annihilations or new astrophysics phenomena are the surce of the anomalies observed on the positron flux.

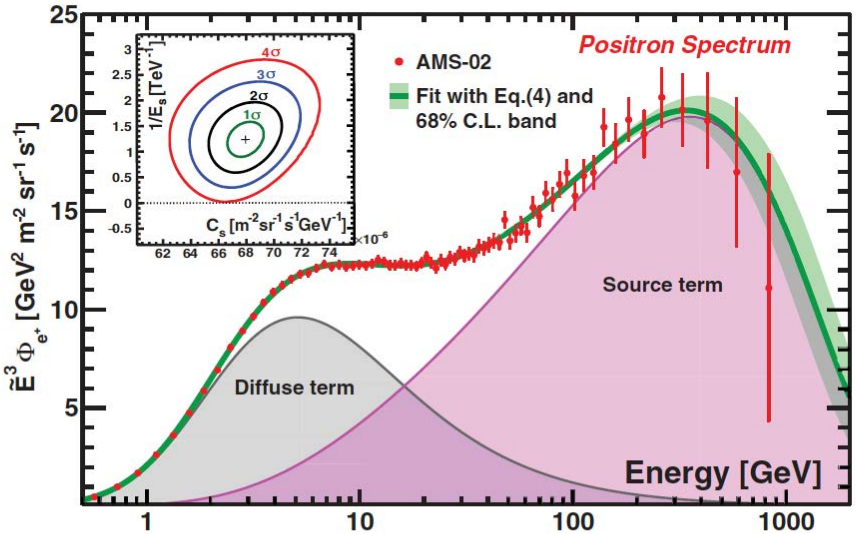
Understanding the AMS positron peak origin in term of DM:



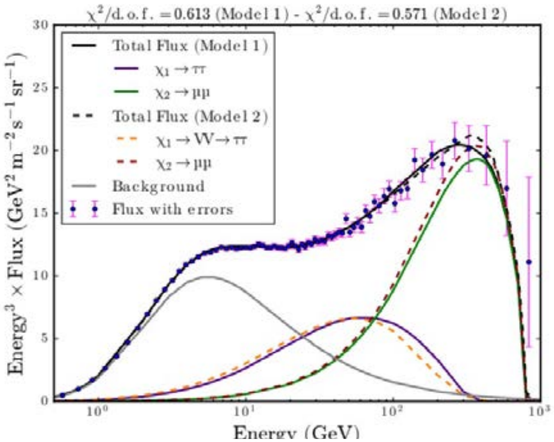


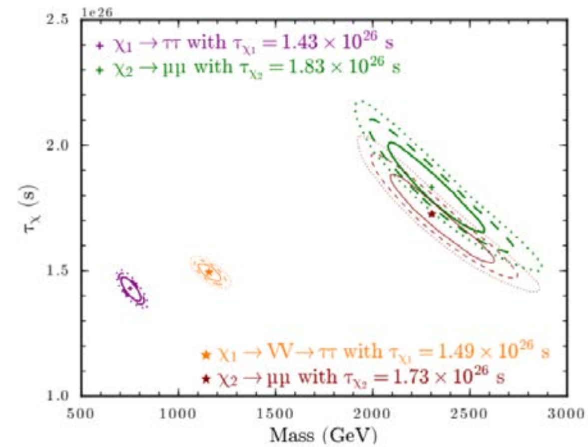
29

AMS-02 has observed a clear positron excess due to a source term



AMS Collaboration, Phys. Rev. Lett. 122, 041102 (2019)





A two component DM decay would fit the AMS e+ excess

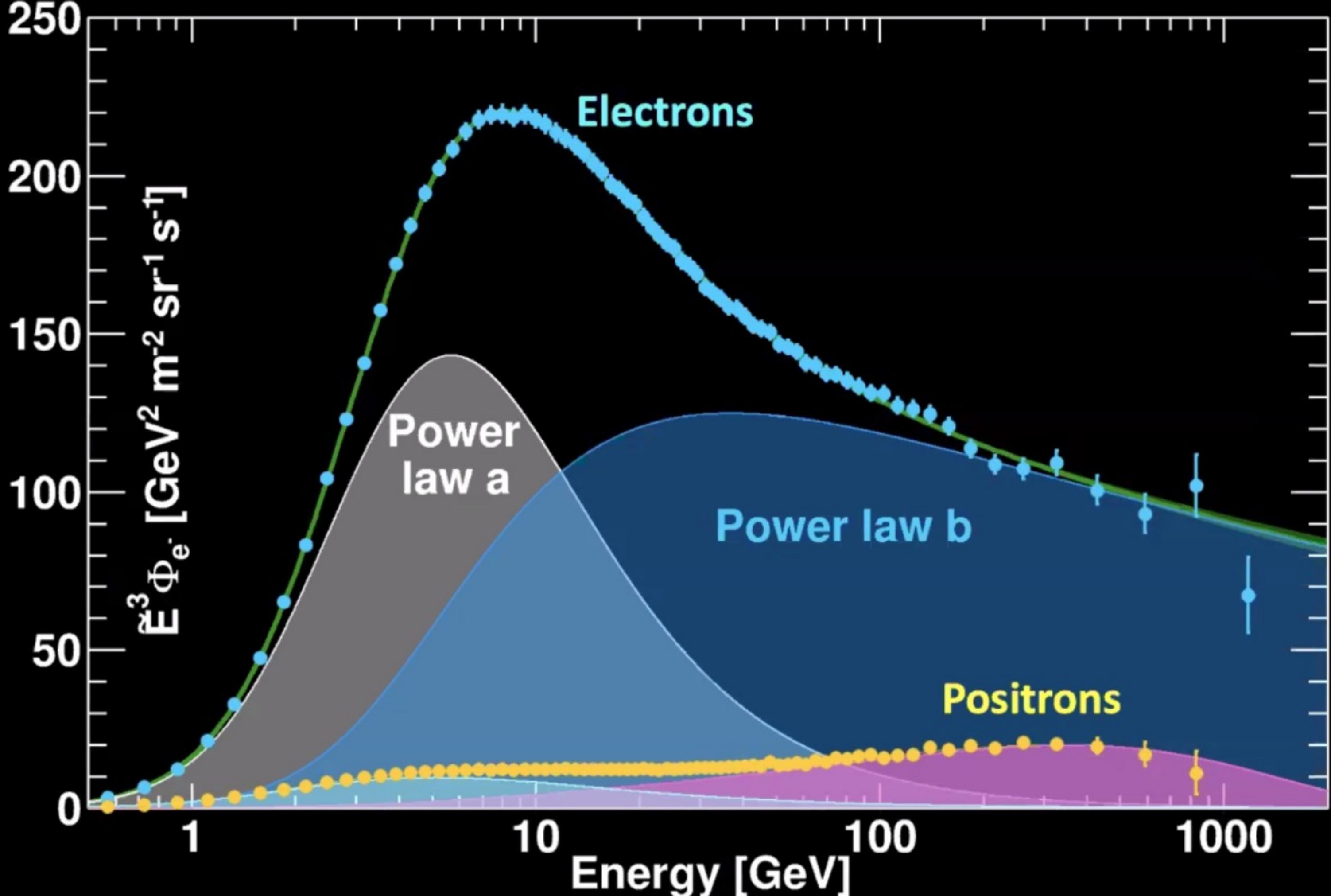
Profumo et al. arXiv:1903.07638v1 [hep-ph] 18 Mar 2019

AMS Physics Results:

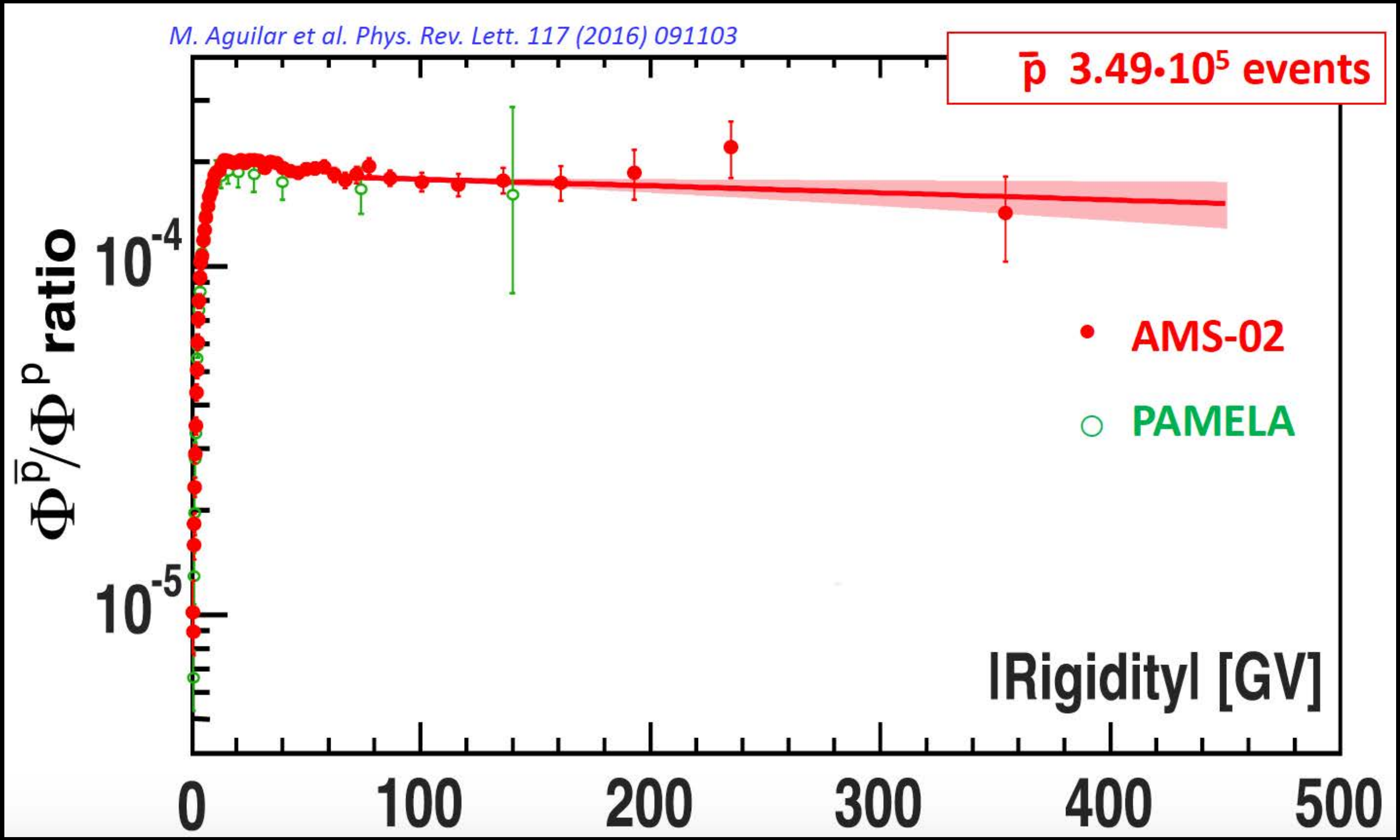
Electrons originate from different sources than positrons;

the electron spectrum comes from two power law contributions.

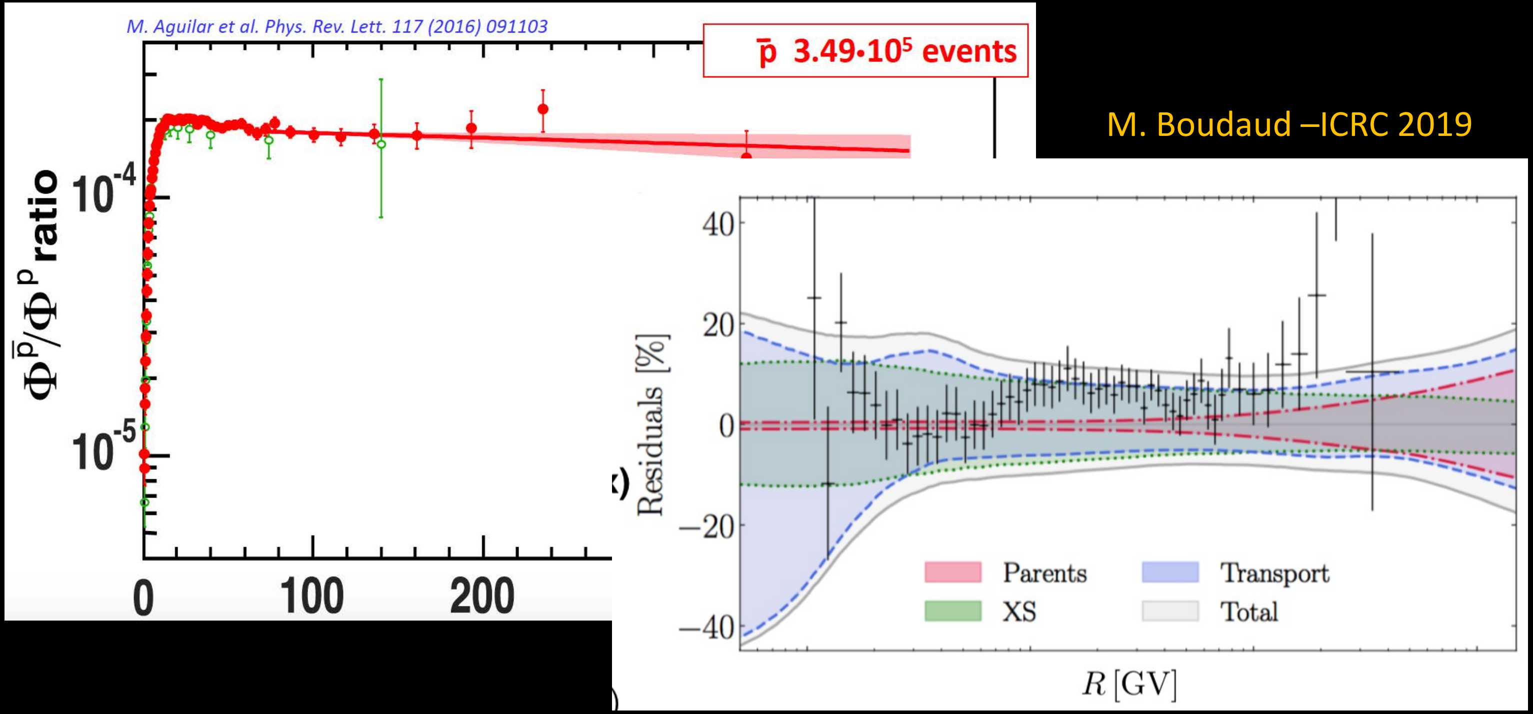
The positron flux is the sum of low-energy part from cosmic ray collisions plus a high-energy part from a new source or dark matter both with a cutoff energy E_S.



AMS anti-proton to proton ratio



AMS anti-proton to proton ratio



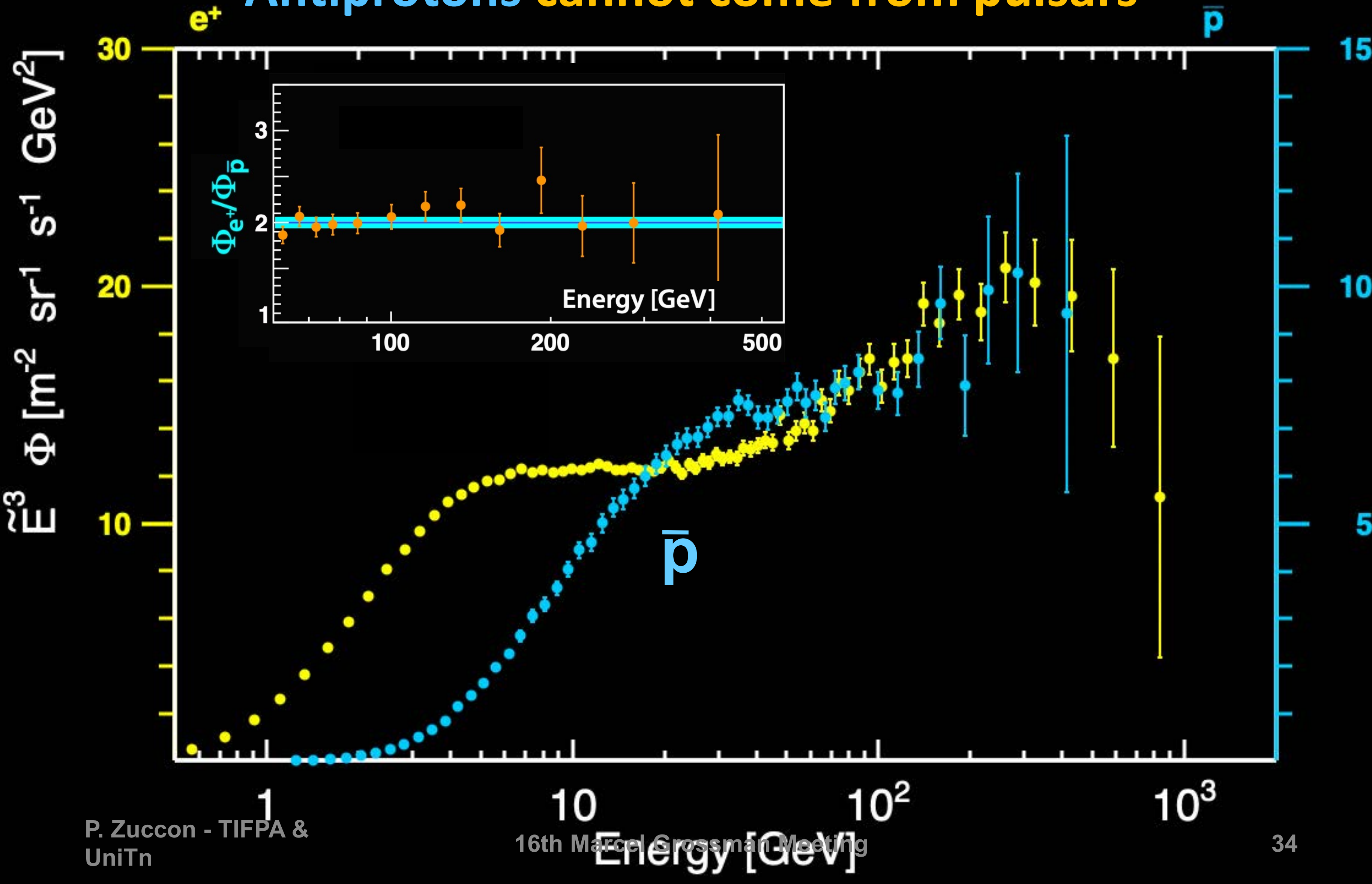
M. Boudaud –ICRC 2019

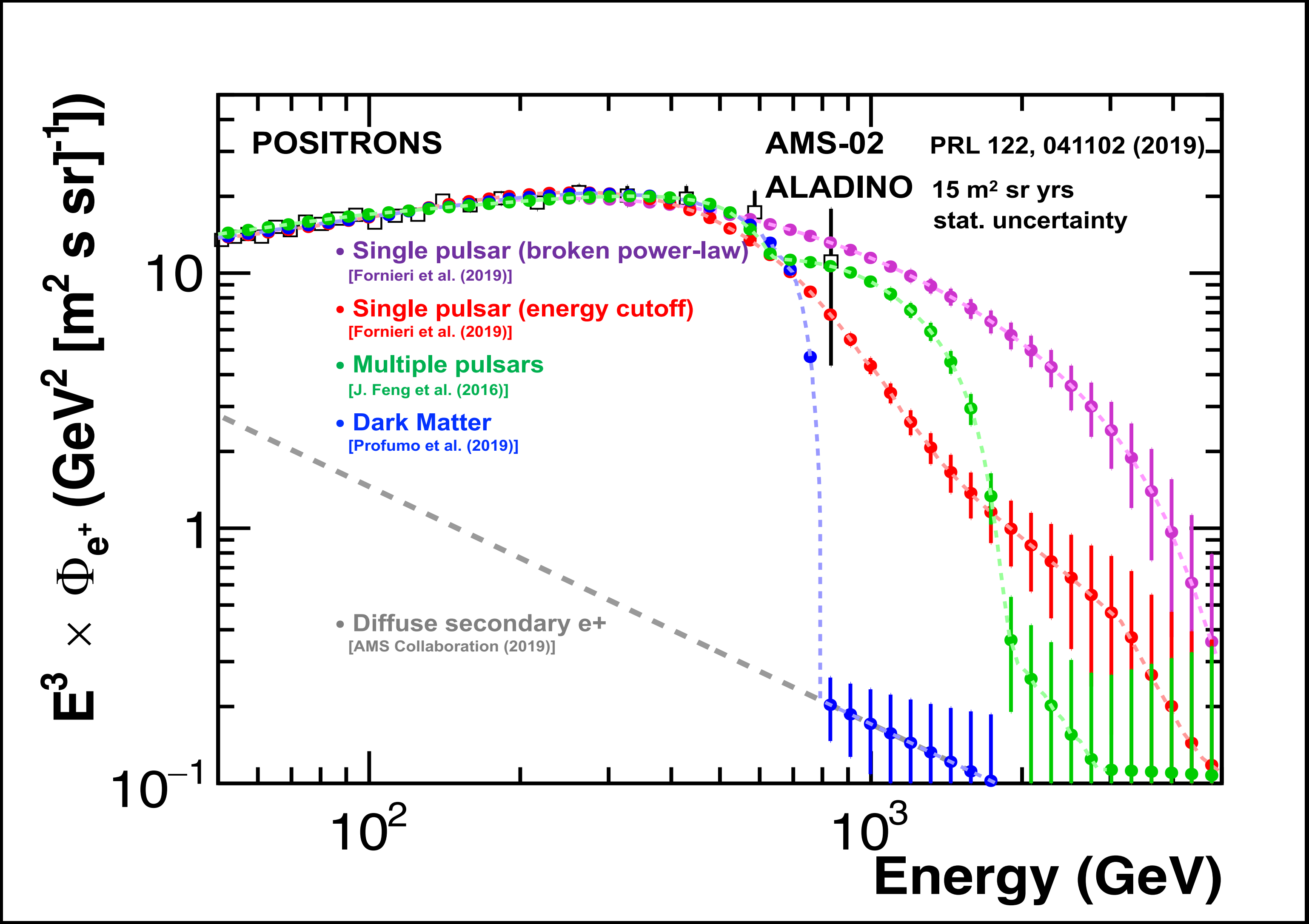
Residuals of a fit to AMS anti-protons
Shaded area represent prediciton uncaratinties

Antiprotons show a similar trend to positrons.

$$\Phi_{e^+}/\Phi_{\bar{p}} = 2.00 \pm 0.035(\text{stat.}) \pm 0.06(\text{syst.})$$

Antiprotons cannot come from pulsars

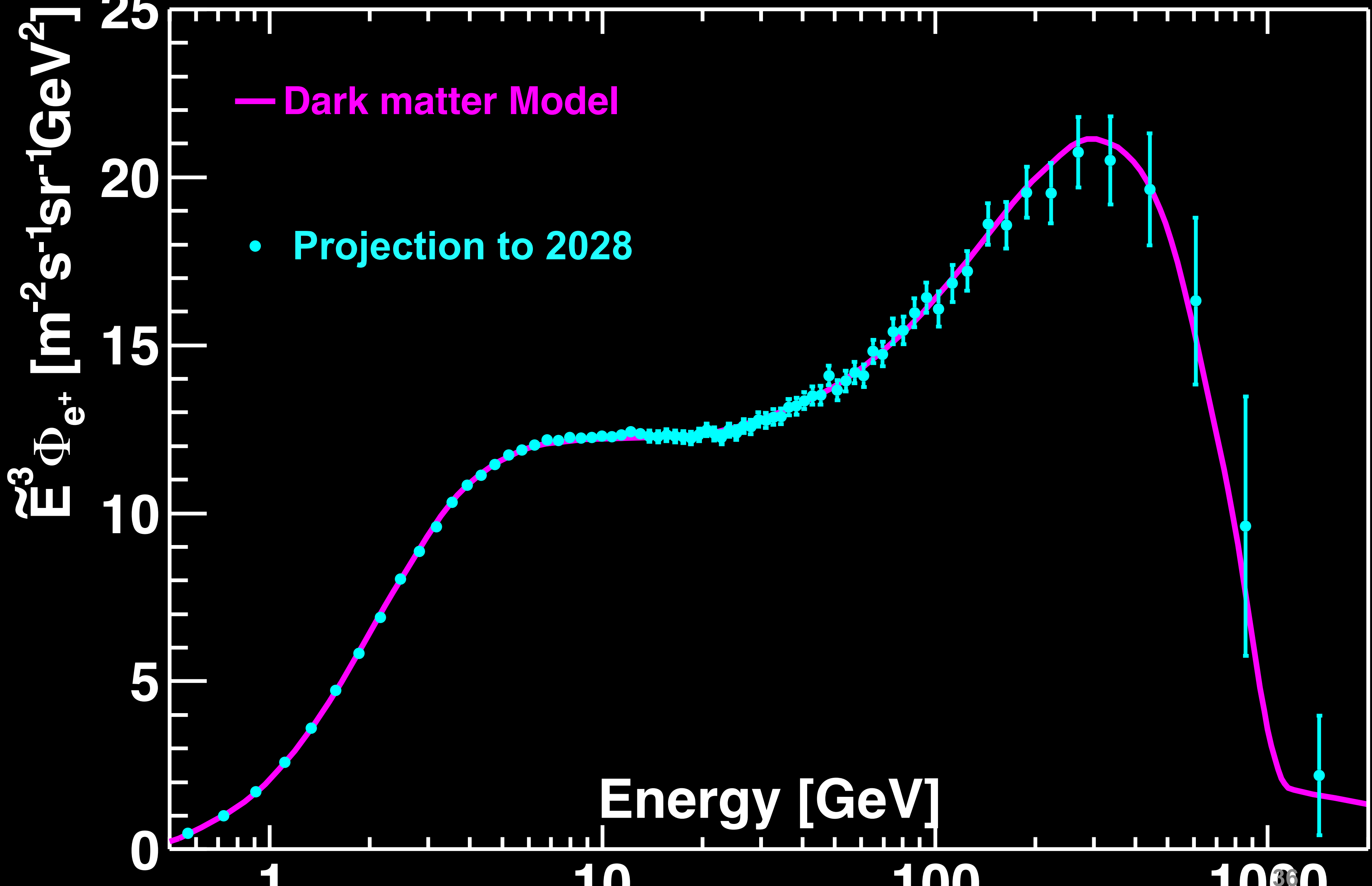




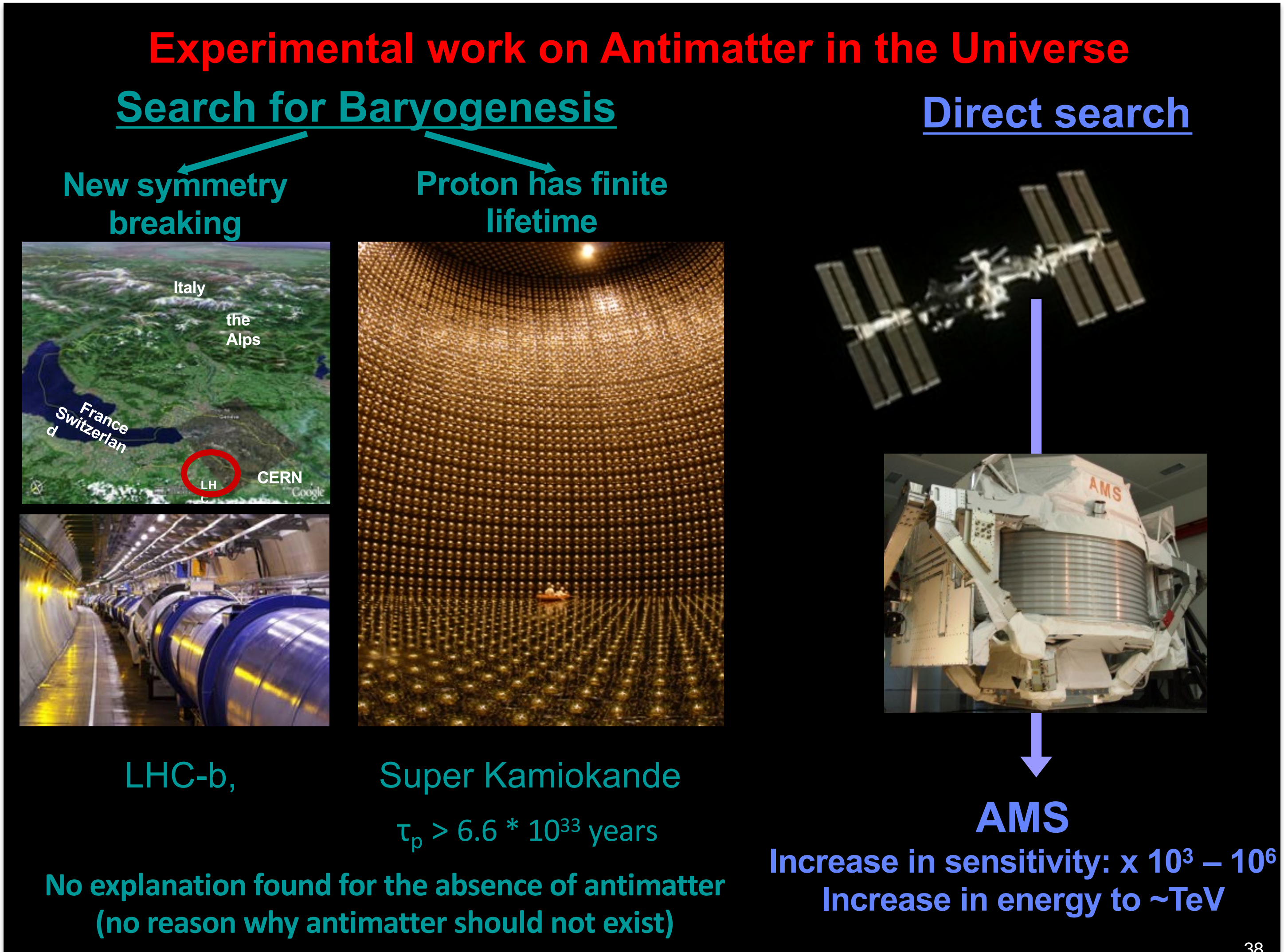
POSITRONS
AMS-02
ALADINO
PRL 122, 041102 (2019)
15 m² sr yrs
stat. uncertainty
• Single pulsar (broken power-law)
[Fornieri et al. (2019)]
• Single pulsar (energy cutoff)
[Fornieri et al. (2019)]
• Multiple pulsars
[J. Feng et al. (2016)]
• Dark Matter
[Profumo et al. (2019)]
• Diffuse secondary e+
[AMS Collaboration (2019)]
$E^3 \times \Phi_{e^+}$ (GeV^2 [m^2 s sr]$^{-1}$)
10
1
10^{-1}
10^2
10^3
Energy (GeV)

Positrons and Dark Matter Model by 2028

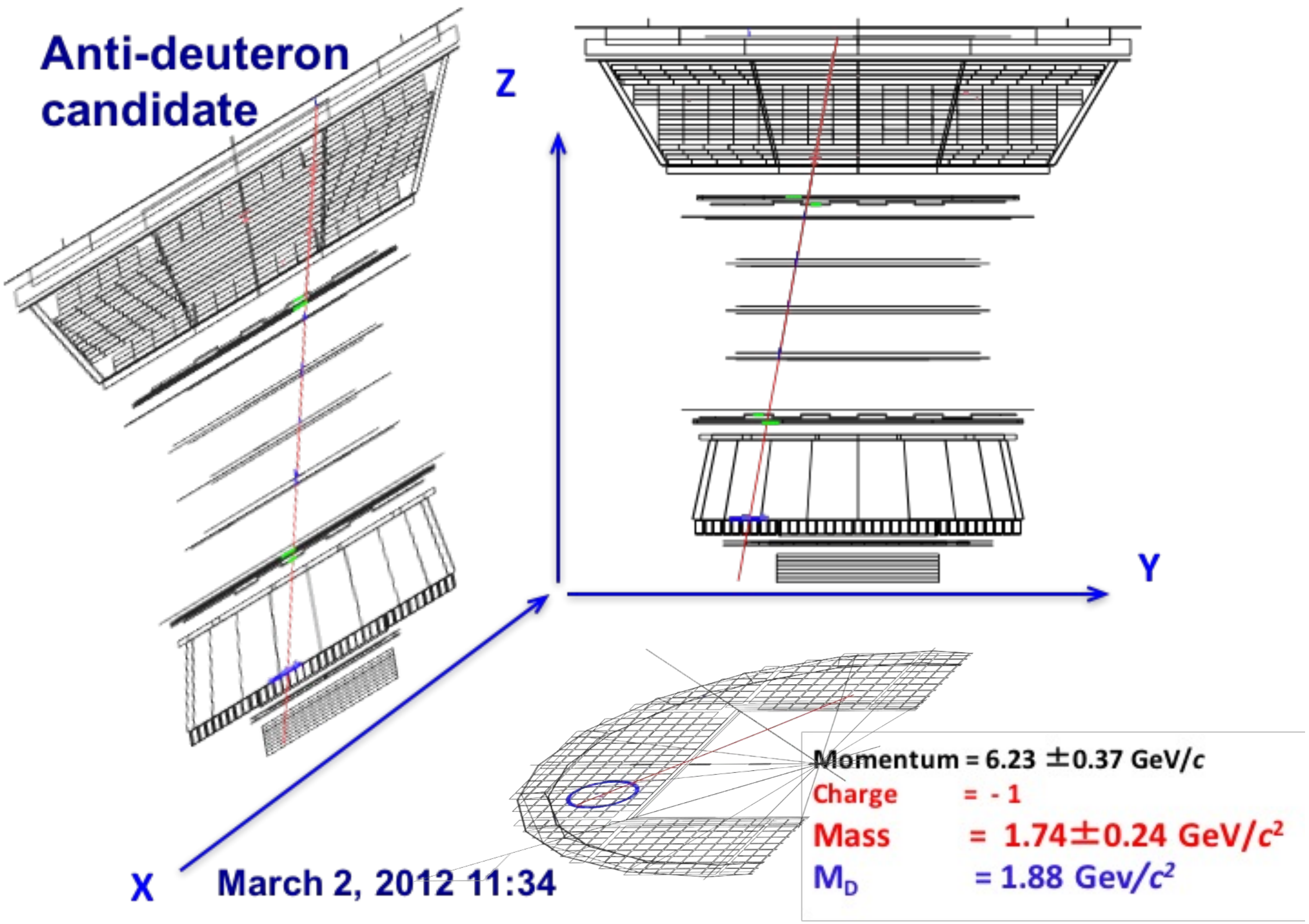
AMS will clarify the nature of positron peak



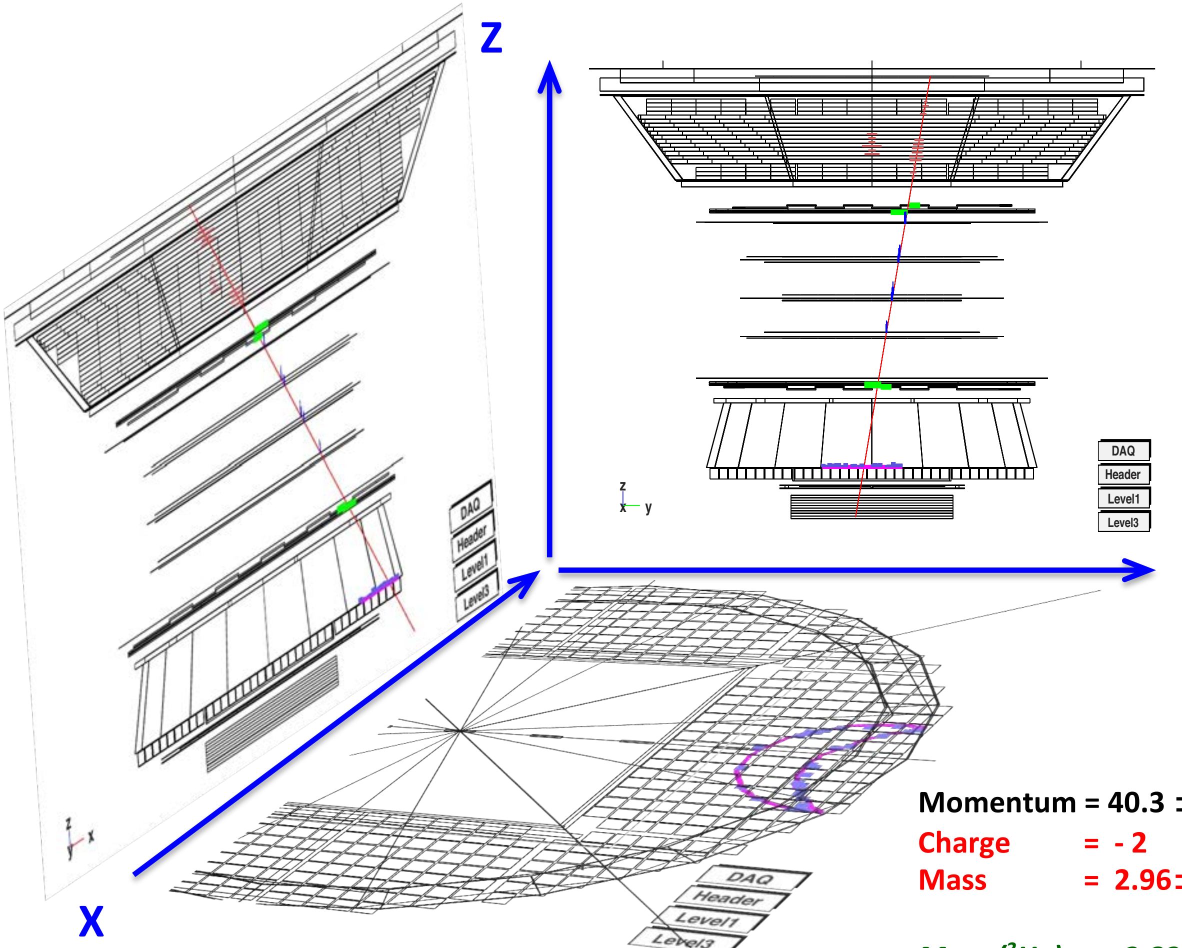
Heavy antimatter


Experimental work on Antimatter in the Universe
Search for Baryogenesis
Direct search
New symmetry breaking
Proton has finite lifetime
Italy
the Alps
France
Switzerlan
d
LH
CERN
AMS
LHC-b,
Super Kamiokande
$\tau_p > 6.6 * 10^{33}$ years
AMS
Increase in sensitivity: x $10^3 – 10^6$
Increase in energy to ~TeV
No explanation found for the absence of antimatter
(no reason why antimatter should not exist)
38

An anti-deuteron candidate (AMS preliminary)



An anti-^{3}He candidate (AMS preliminary)



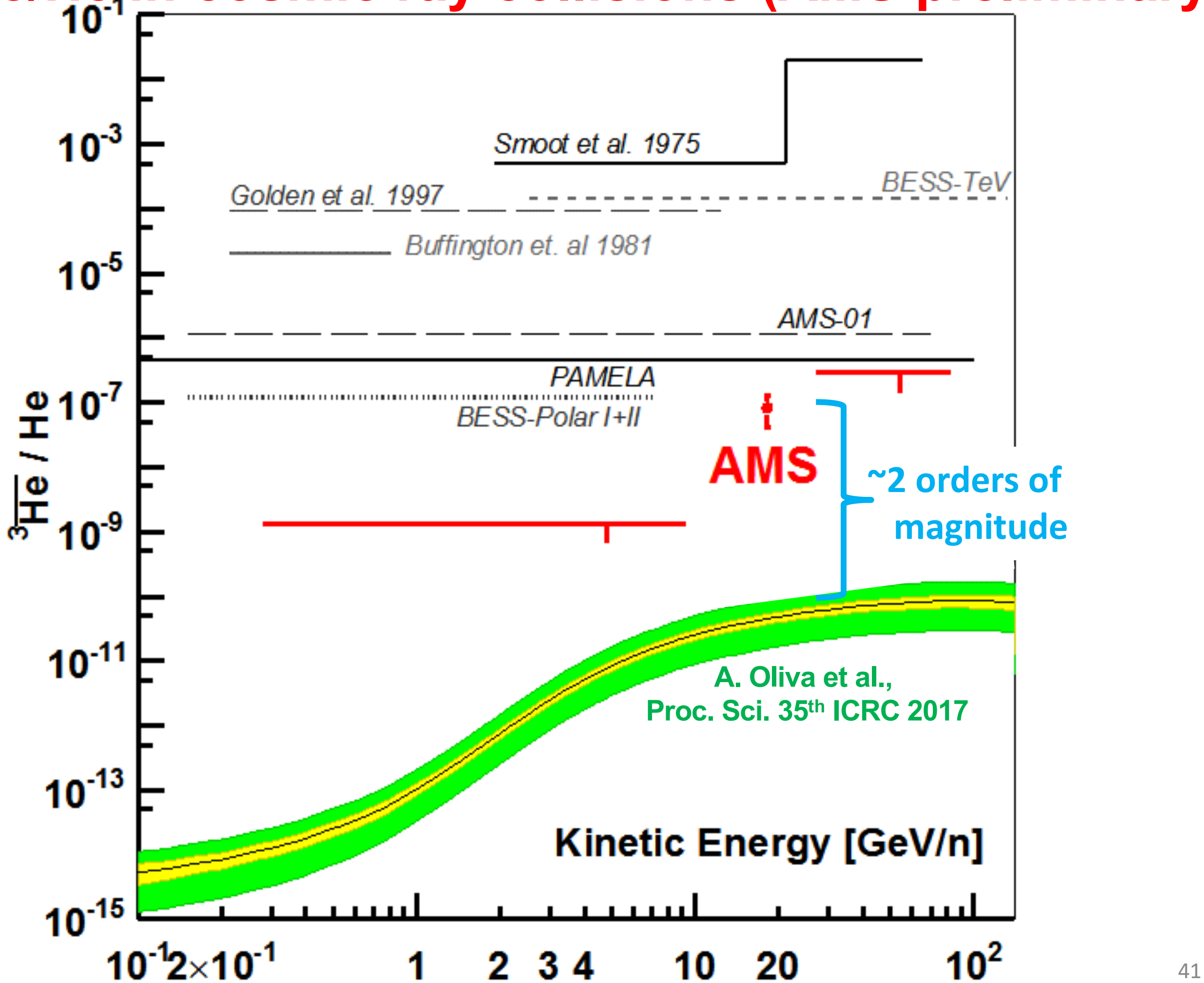
Momentum = 40.3 ±2.9 GeV/*c*

Charge = - 2

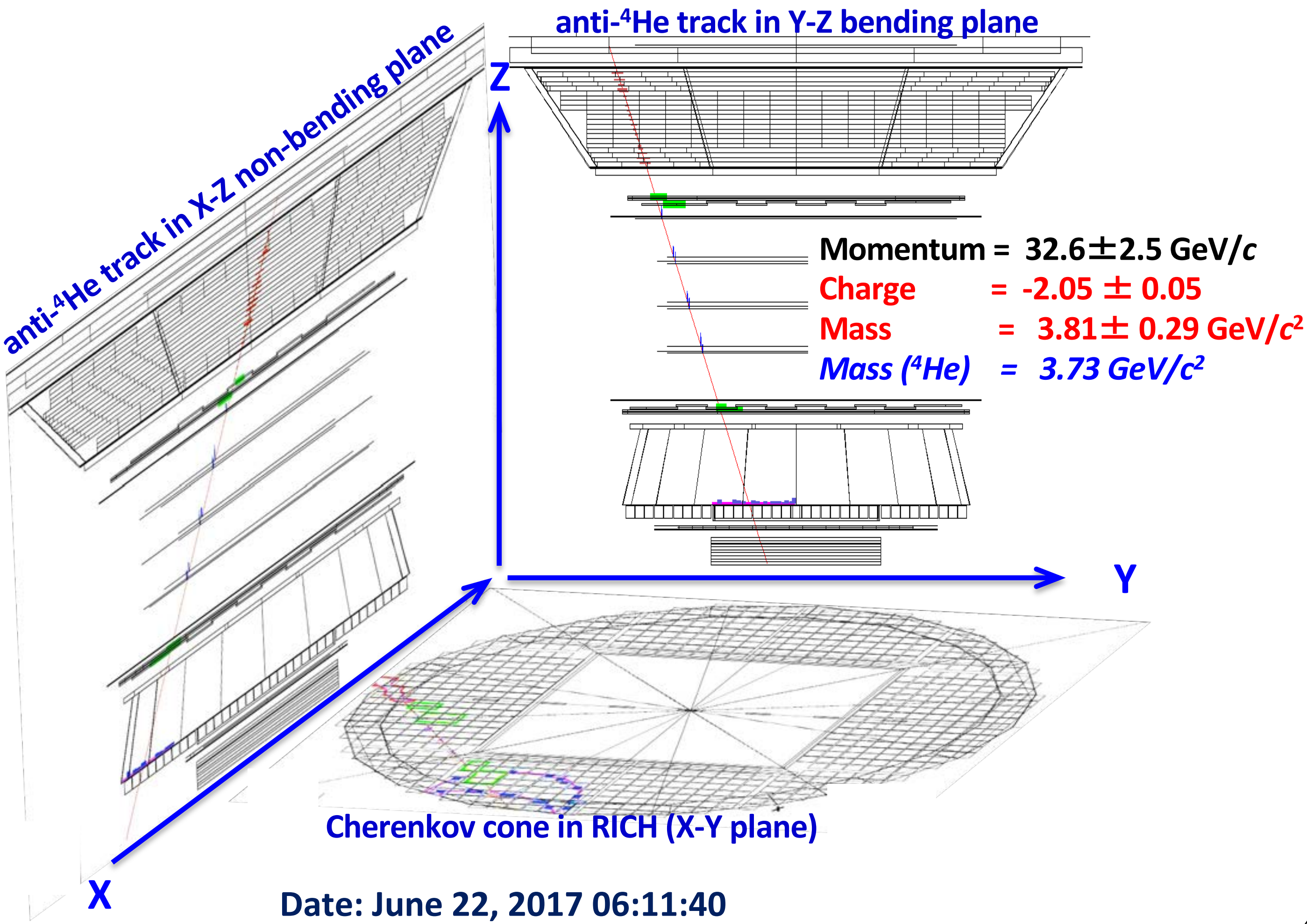
Mass = 2.96±0.33 GeV/*c*²

Mass (^{3}He) = 2.83 GeV/c²

$^{3}\overline{He}/He$ in cosmic ray collisions (AMS preliminary)

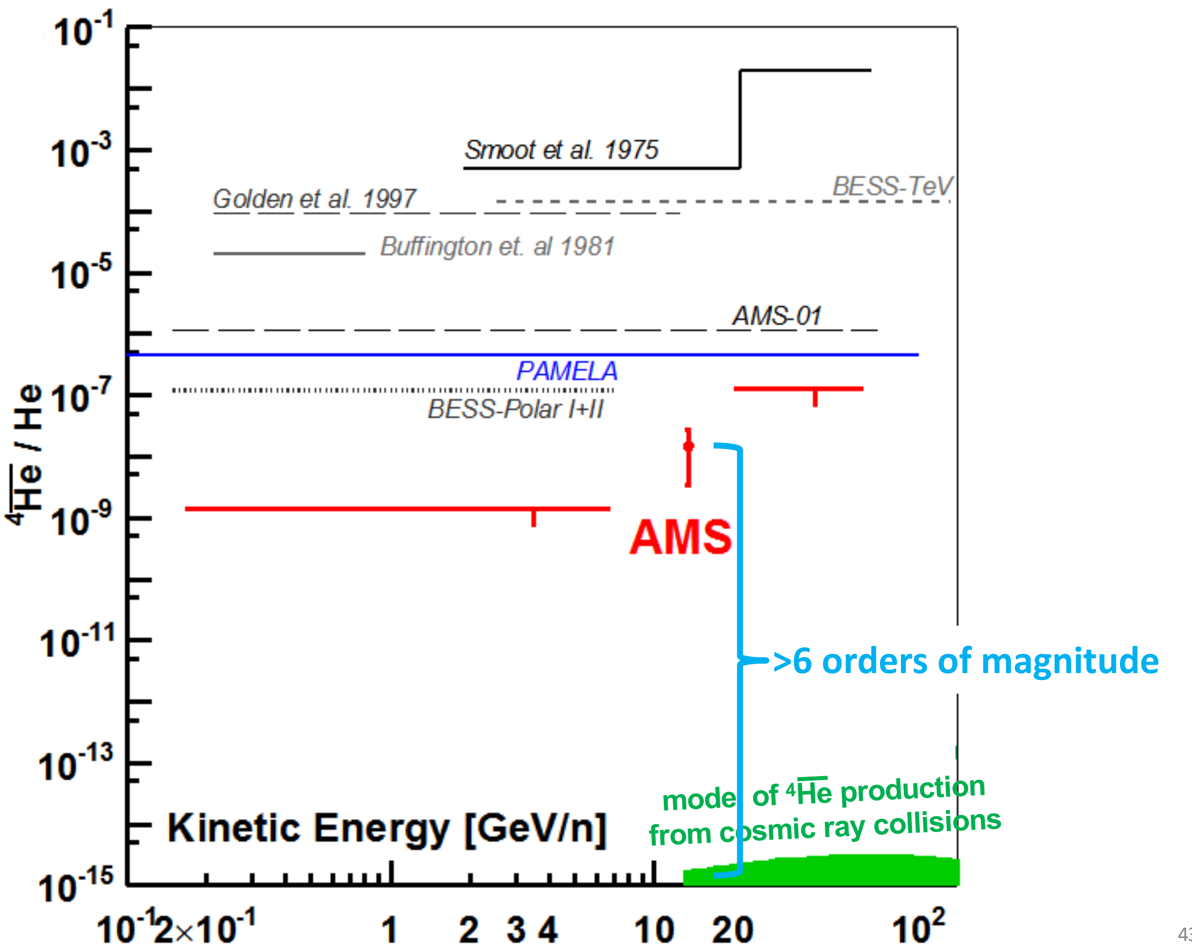


An anti-^{4}He candidate (AMS preliminary)



Date: June 22, 2017 06:11:40

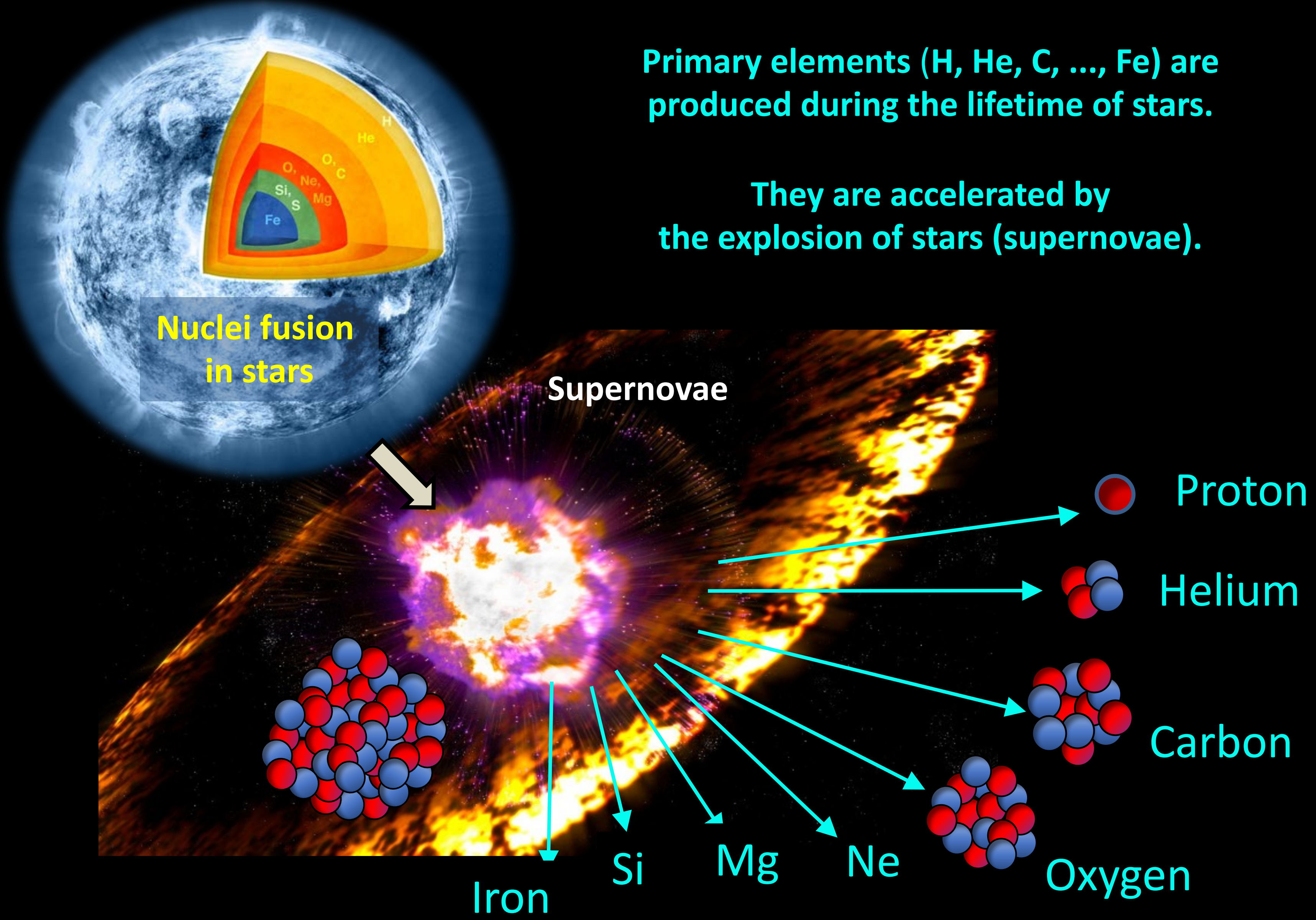
The AMS $^4\overline{He}$/He ratio is six orders of magnitude greater than predictions based on cosmic ray collisions (AMS preliminary)



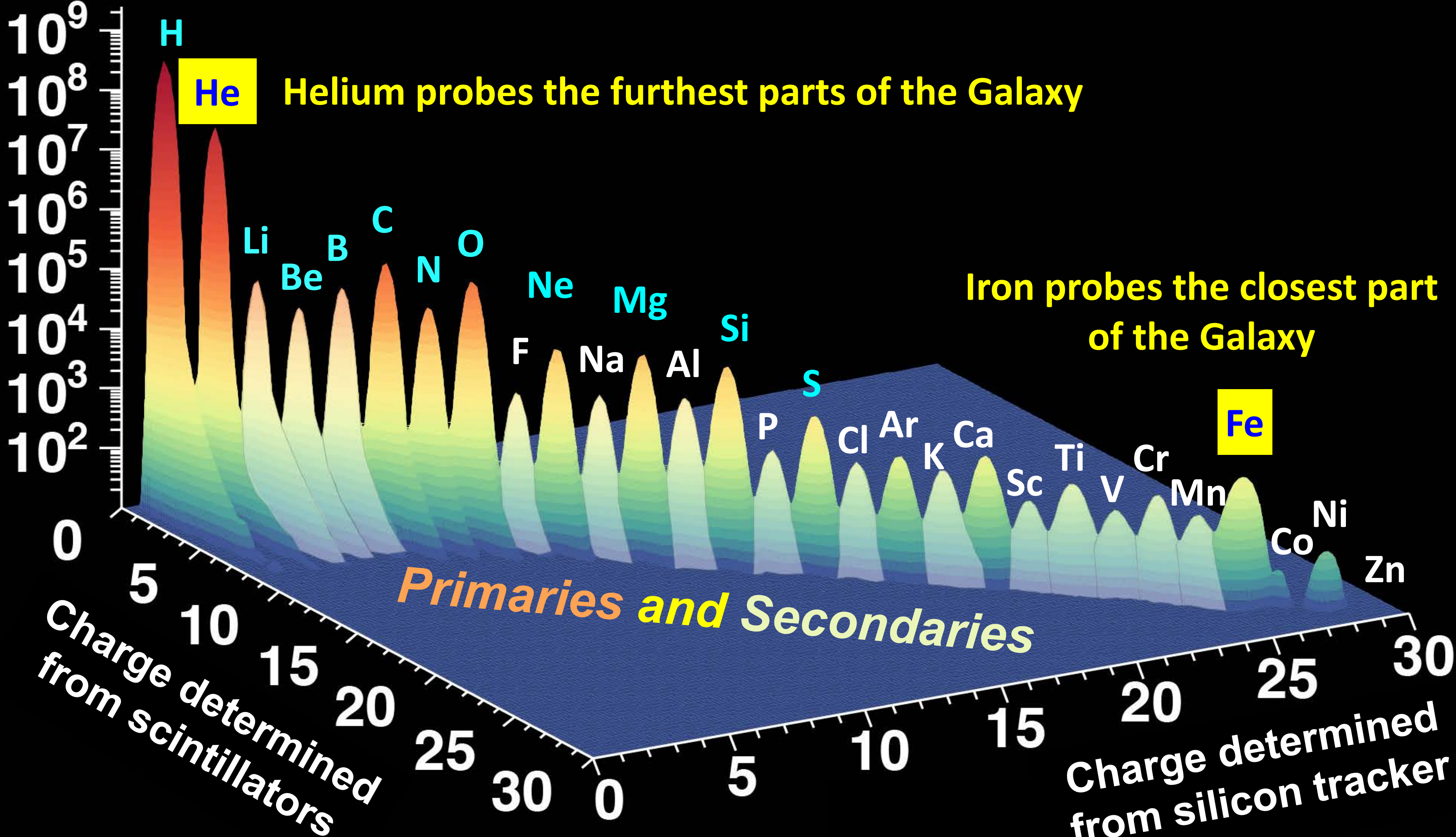
Properties of Primary Cosmic Rays

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

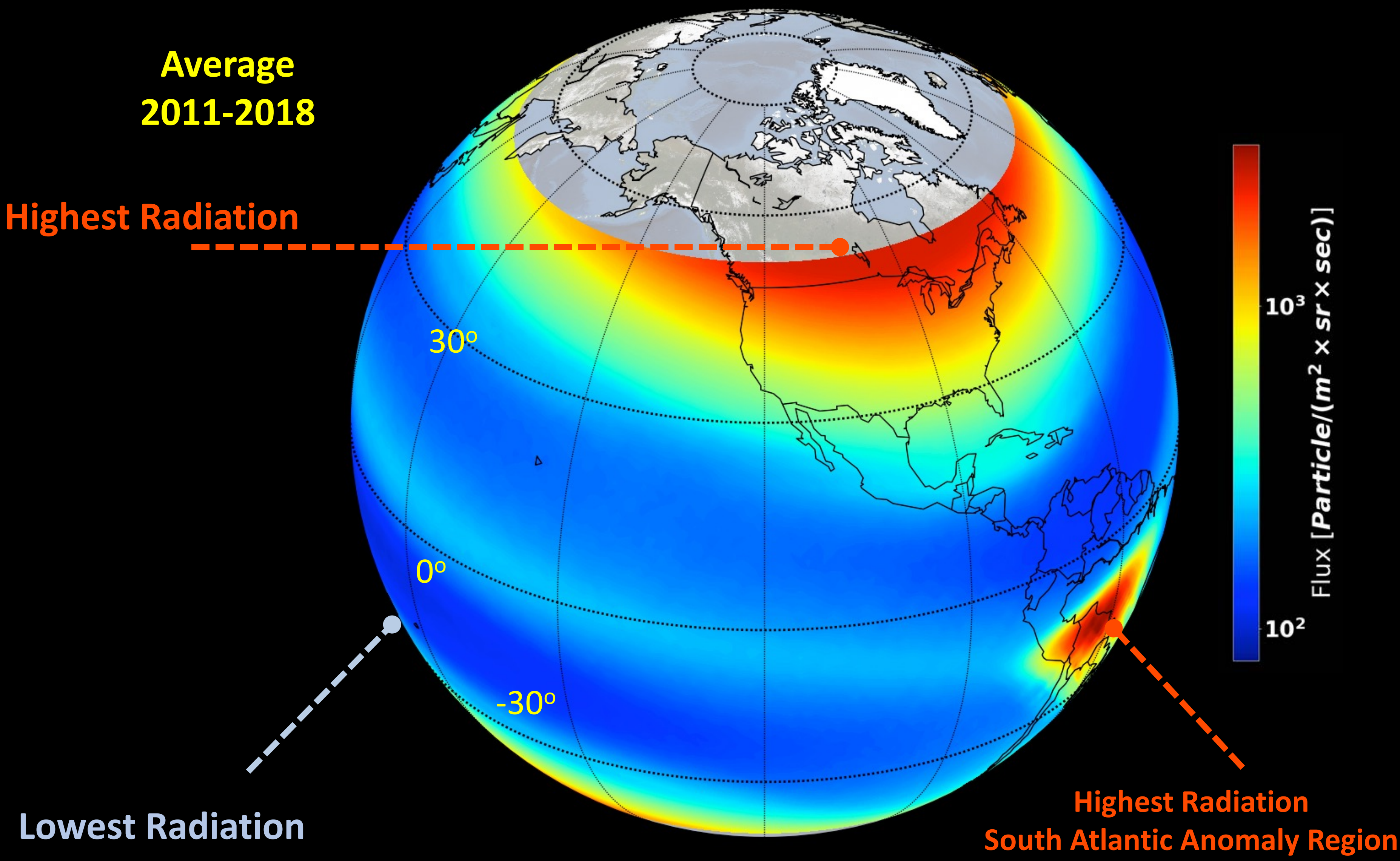
They are accelerated by the explosion of stars (supernovae).



Iron is a very important element in cosmic ray theories because it is the heaviest element produced during stellar evolution. Iron has a large interaction cross section with the interstellar medium whereas helium has the smallest cross section.

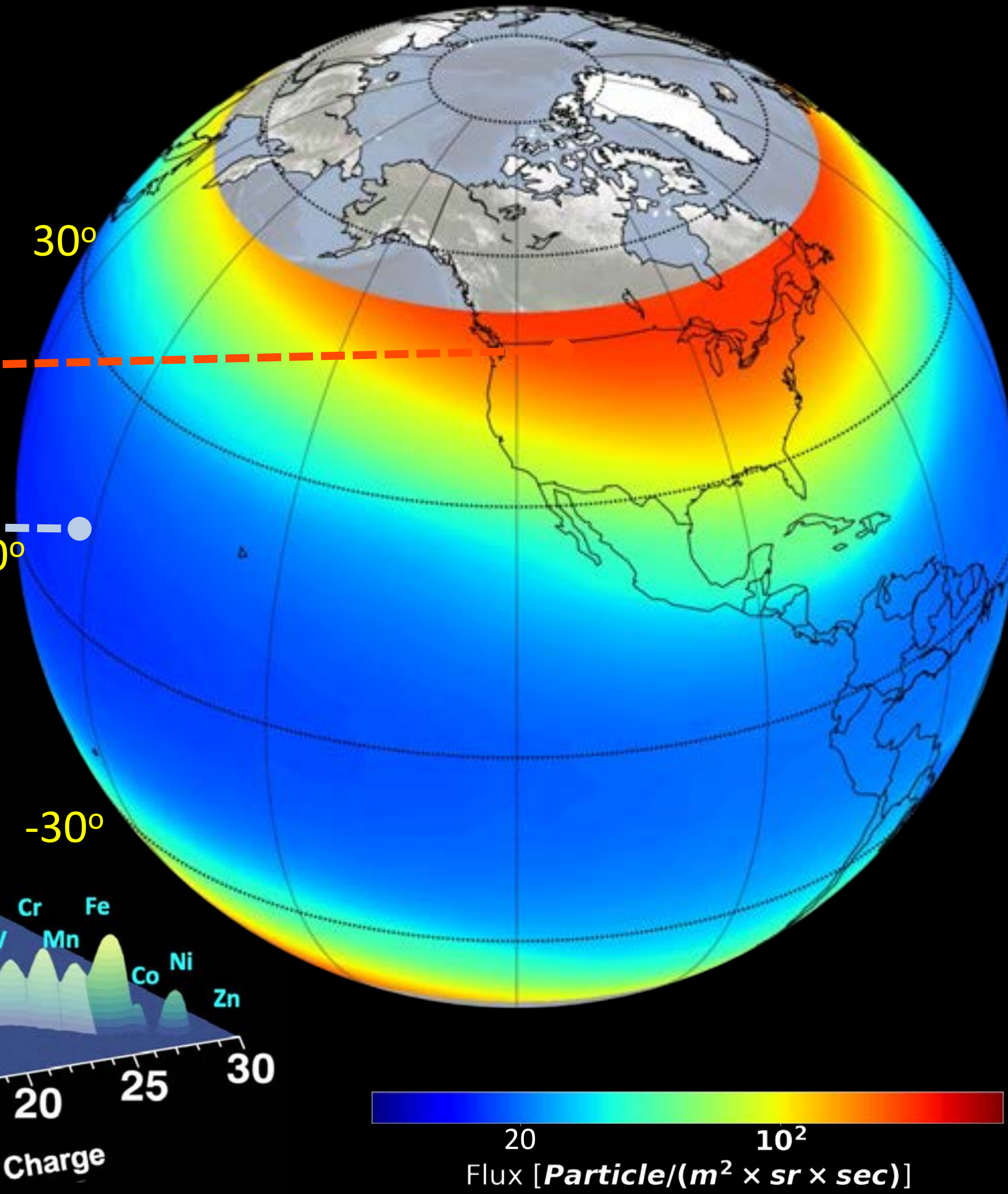


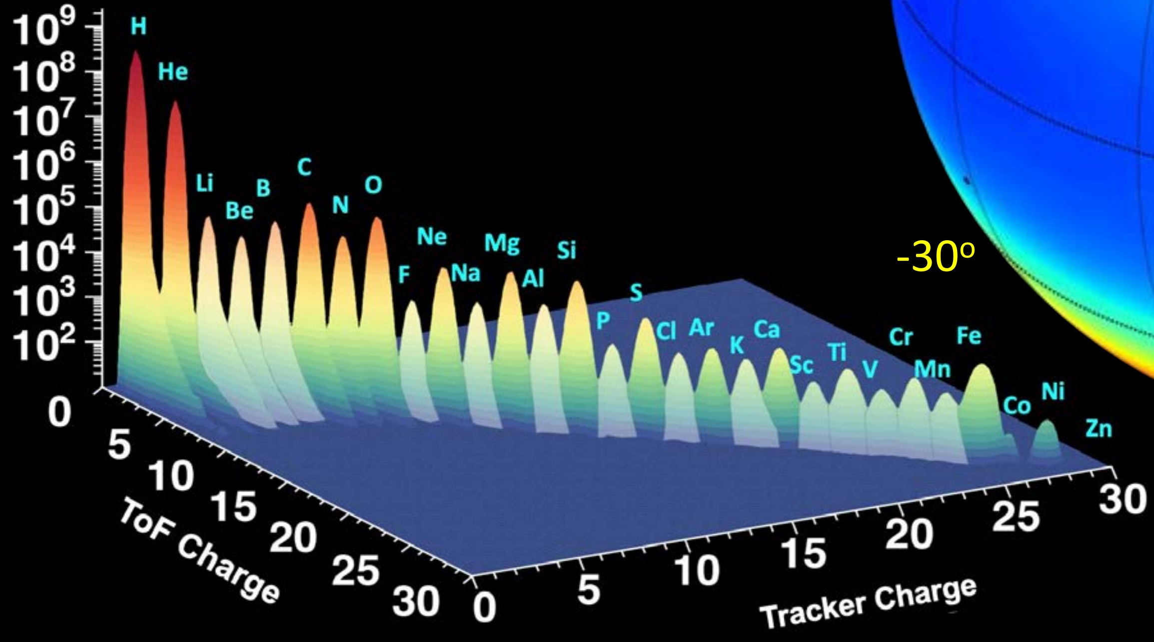
Flux of Protons above 100 MeV



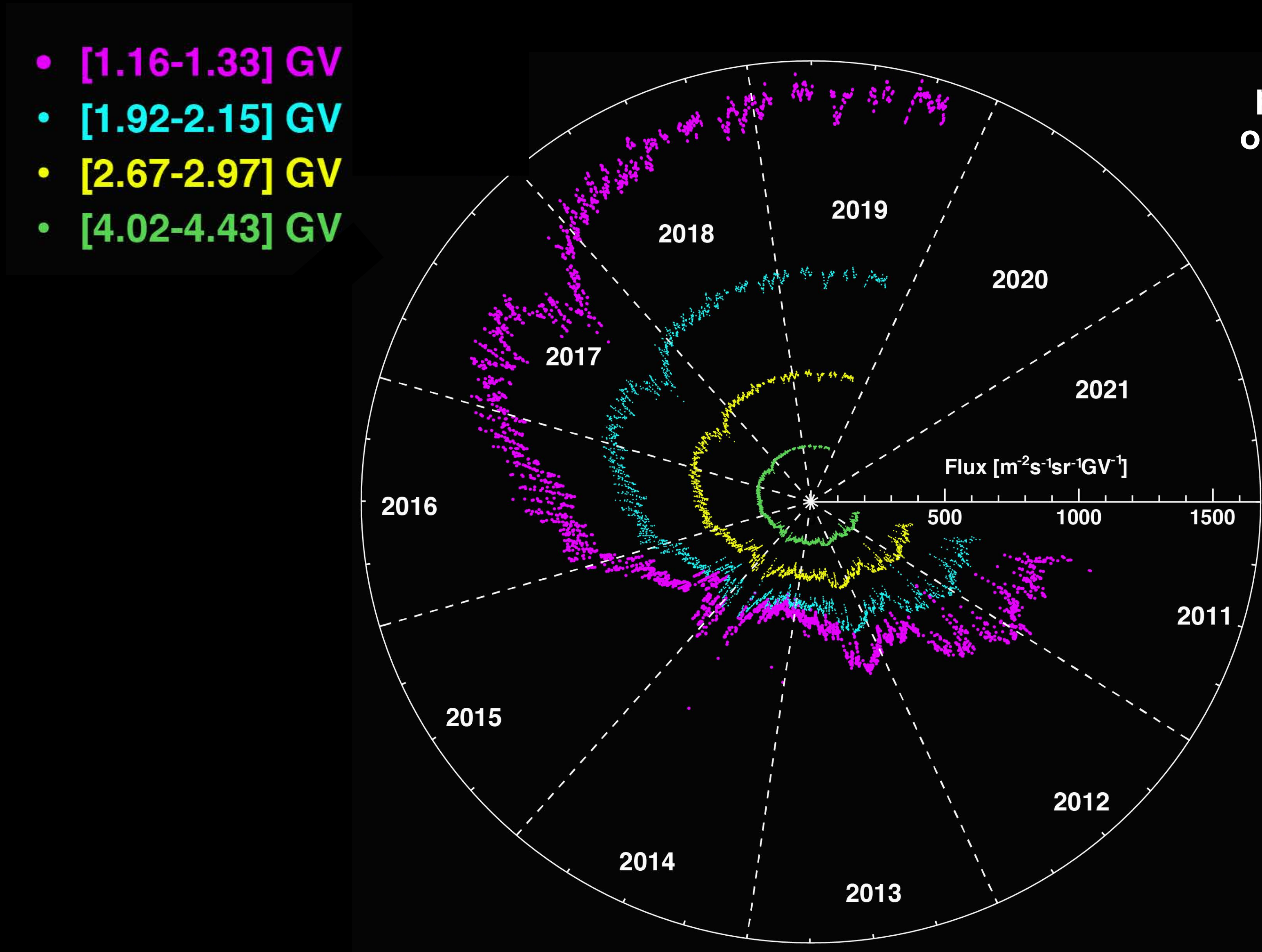
AMS Radiation Flux of Heavy Nuclei He(Z=2) to Zinc(Z=30)

Average 2011-2018



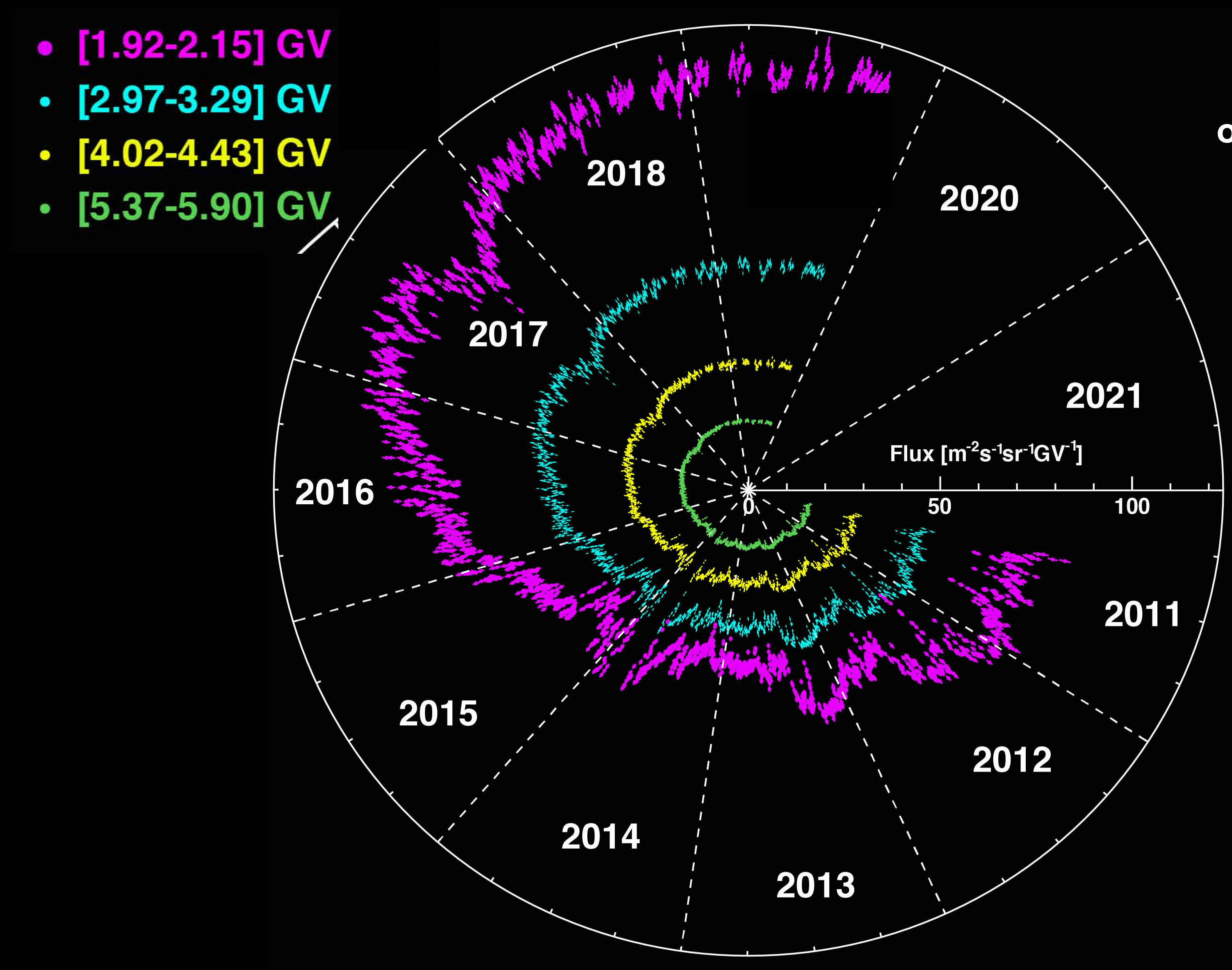


Daily Variations in the Proton Flux



Preliminary
please refer to our forthcoming publication in PRL

Daily Variations in the Helium Flux



Preliminary
please refer to our forthcoming publication in PRL

Conclusions

- AMS-02 has measured a clear positron structure around 500 GeV
- AMS-02 sensitivity to complex form of antimatter are providing interesting results
- AMS-02 is measuring with high accuracy the nuclei spectra up to Iron (and possibly just above)
- The AMS-02 measurements reveal new features
- AMS-02 can also study CR flux time dependence and its correlation with sun activity

AMS-02 Beyond 2021

- Positrons and anti-protons as probes for exotic signals
- Complete the CR spectra measurement
- Complete the CR fluxes study over a full solar cycle
- Search for heavy antimatter (few candidates observed) and anti-deuterons

AMS Publications

1) Phys. Rev. Lett. 110, 141102 (2013). Editors' Suggestion. Viewpoint in *Physics*.
Highlight of 2013. Ten-Year retrospective.
2) Phys. Rev. Lett. 113, 121101 (2014). Editors' Suggestion
3) Phys. Rev. Lett. 113, 121102 (2014). Editors' Suggestion
4) Phys. Rev. Lett. 113, 221102 (2014).
5) Phys. Rev. Lett. 114, 171103 (2015). Editors' Suggestion
6) Phys. Rev. Lett. 115, 211101 (2015). Editors' Suggestion
7) Phys. Rev. Lett. 117, 091103 (2016).
8) Phys. Rev. Lett. 117, 231102 (2016). Editors' Suggestion
9) Phys. Rev. Lett. 119, 251101 (2017).
10) Phys. Rev. Lett. 120, 021101 (2018). Editors' Suggestion. Featured in *Physics*.
11) Phys. Rev. Lett. 121, 051101 (2018).
12) Phys. Rev. Lett. 121, 051102 (2018). Editors' Suggestion
13) Phys. Rev. Lett. 121, 051103 (2018).
14) Phys. Rev. Lett. 122, 041102 (2019). Editor's Suggestion
15) Phys. Rev. Lett, 122, 101101 (2019).
16) Phys. Rev. Lett. 123, 181102 (2019). Editors' Suggestion
17) Phys. Rev. Lett. 124, 211102 (2020). Editors' Suggestion. Featured in *Physics*.
18) Physics Reports 894, 1 (2021), "The Alpha Magnetic Spectrometer (AMS) on the International Space Station: Part II – Results from the First Seven Years"
19) Phys. Rev. Lett. 126, 041104 (2021) Iron Featured in *Physics*.
20) Phys. Rev. Lett. 126, 081102 (2021) Fluorine Editors' Suggestion.