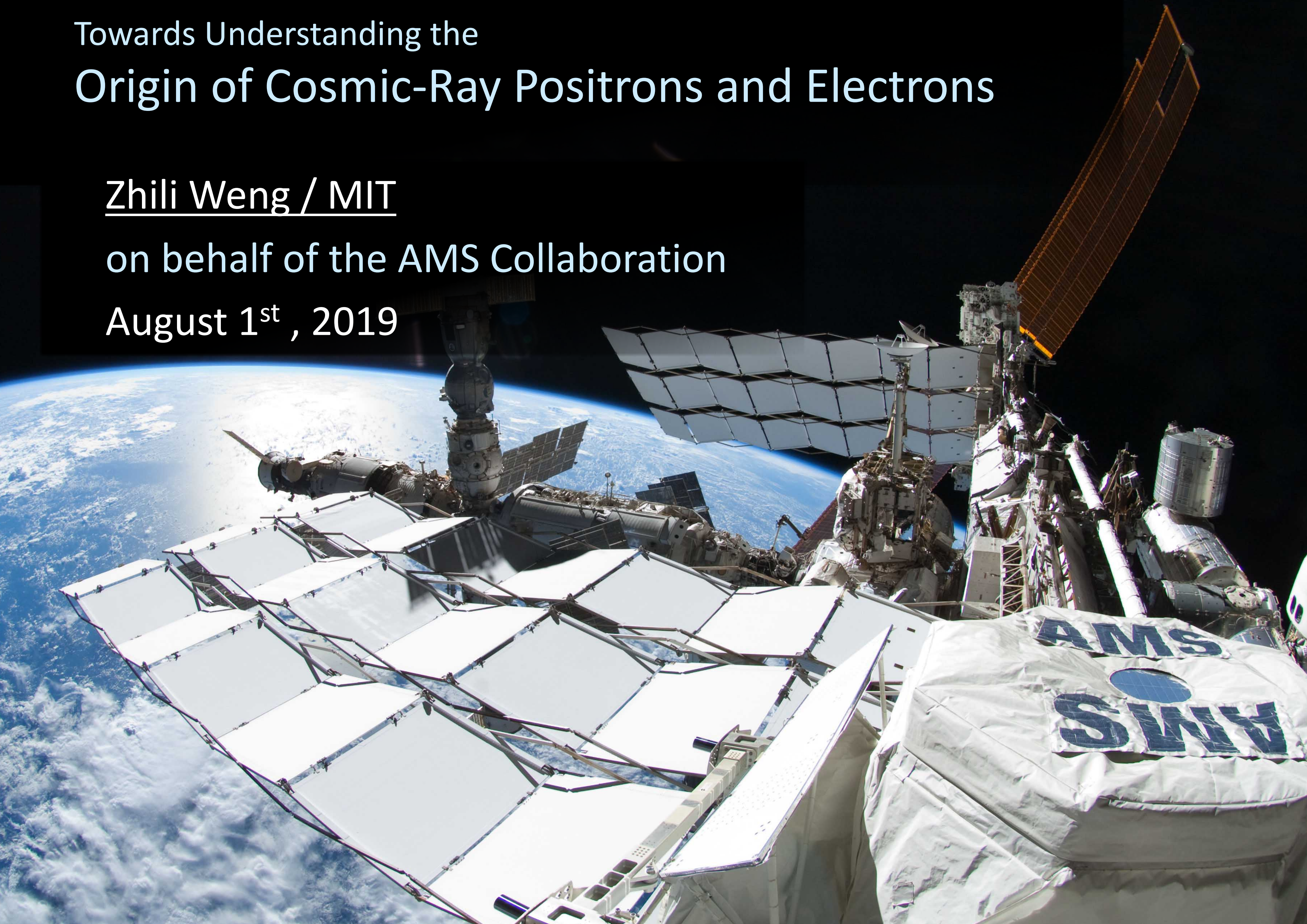
Towards Understanding the

Origin of Cosmic-Ray Positrons and Electrons

Zhili Weng / MIT

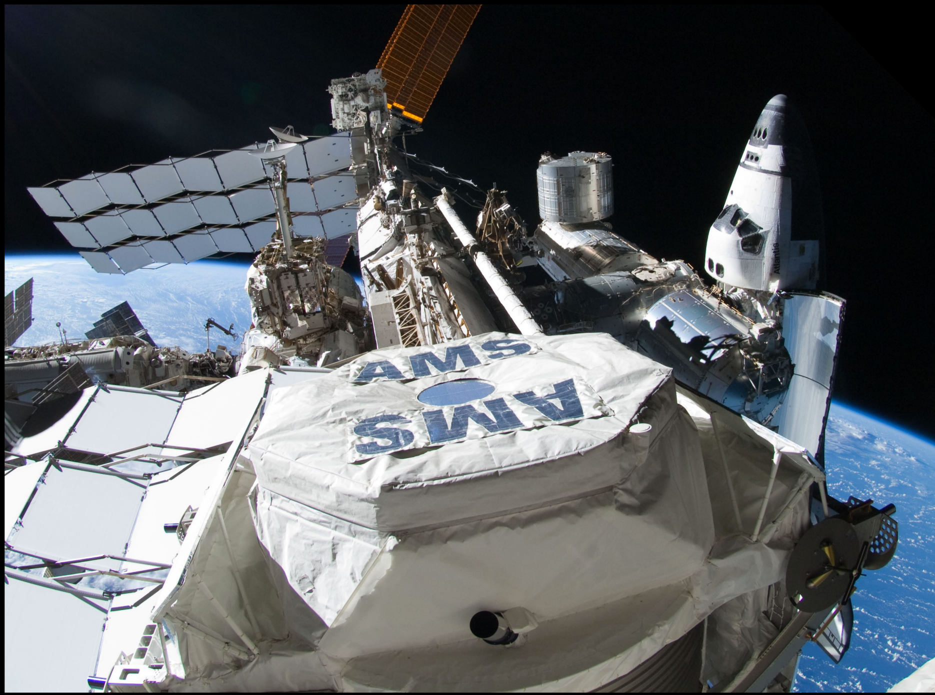
on behalf of the AMS Collaboration

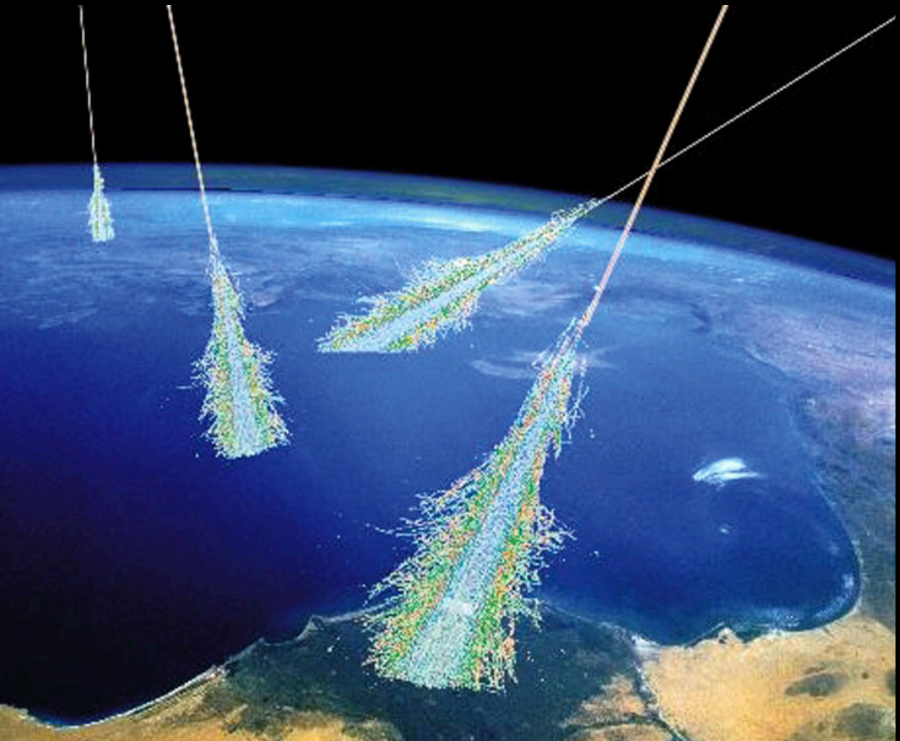
August 1st , 2019



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

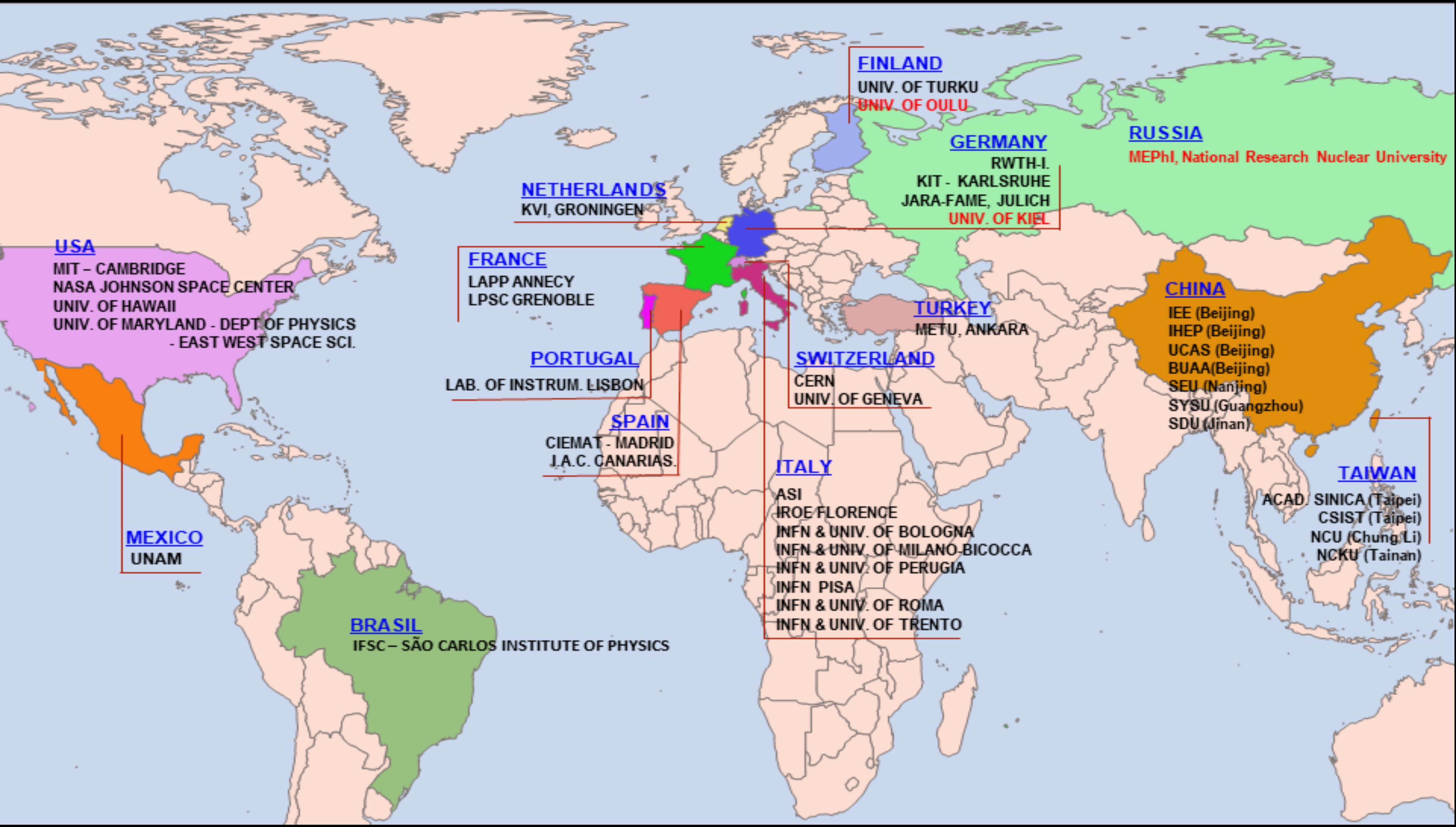
Charged cosmic rays
are absorbed by the
100 km of Earth's atmosphere
(10m of water).





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

AMS: an International Collaboration
15 Countries, 42 Institutes and over 600 Physicists

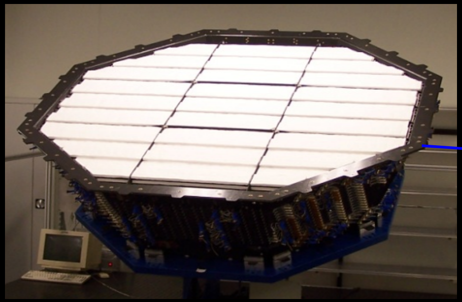


AMS is strongly supported by DOE and NASA

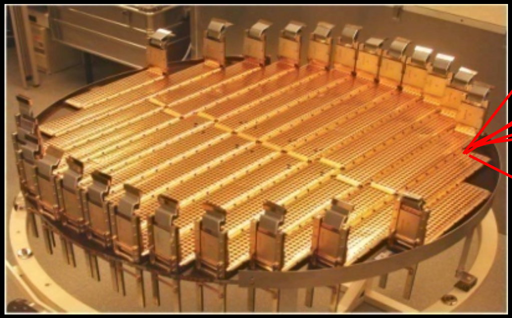
AMS is a space version of a precision detector used in accelerators.

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

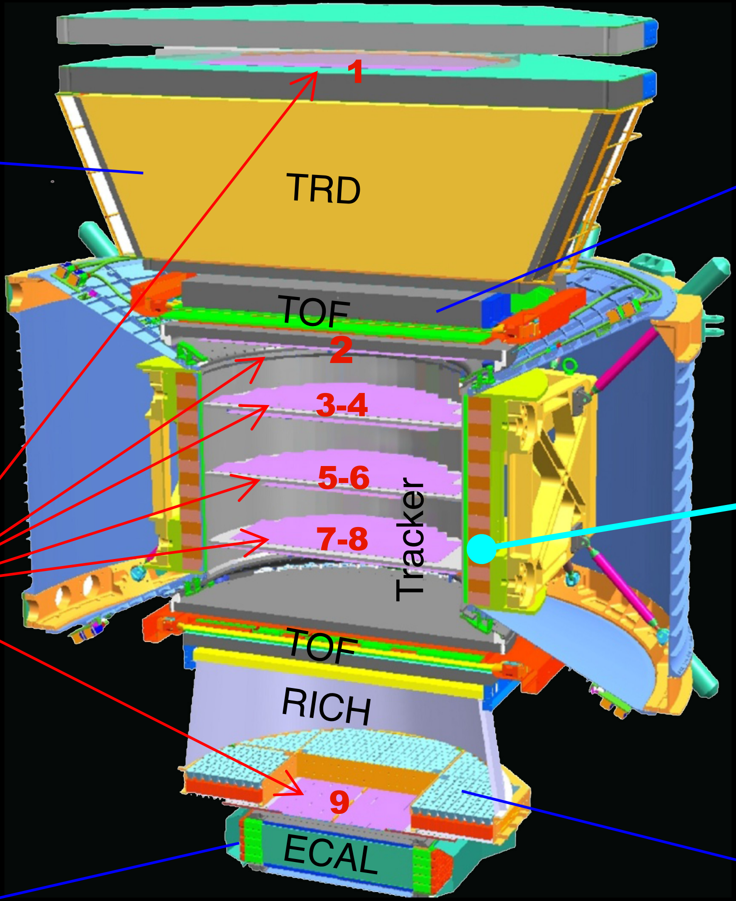
Transition Radiation Detector (TRD)



Silicon Tracker

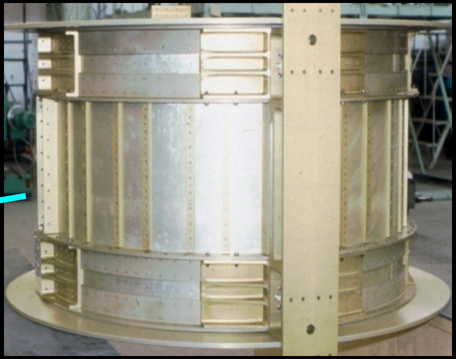


Electromagnetic Calorimeter (ECAL)

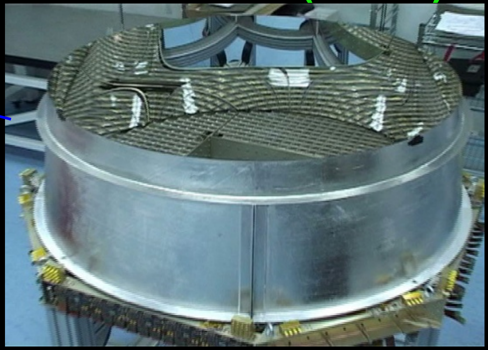


Time of Flight Detector (TOF)

Magnet



Ring Imaging Cherenkov (RICH)

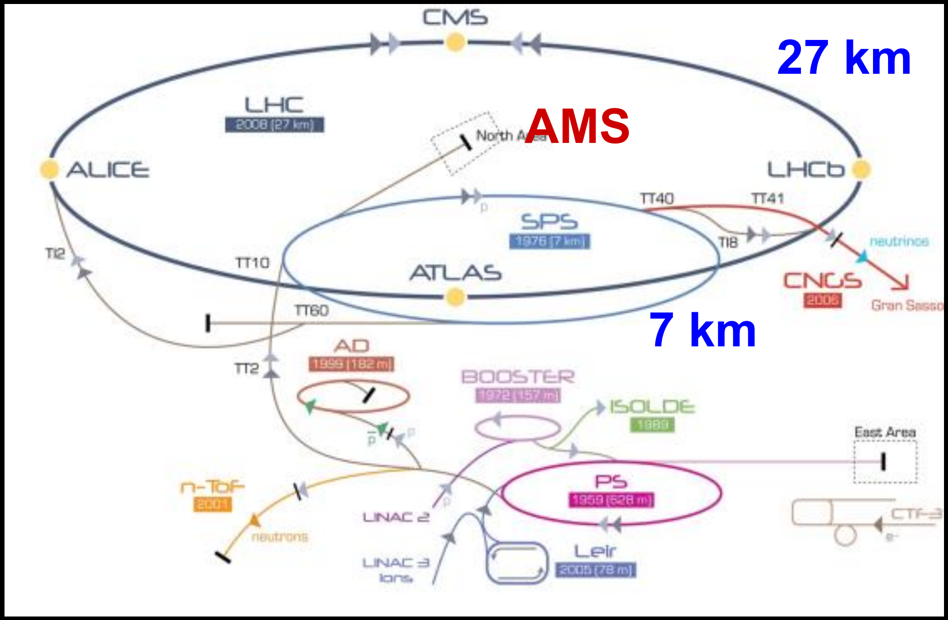


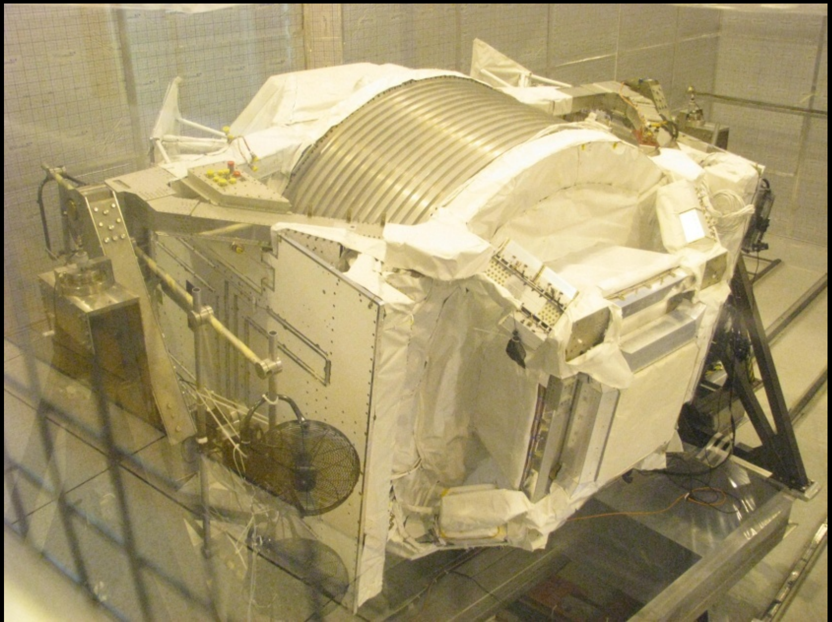
Z and P

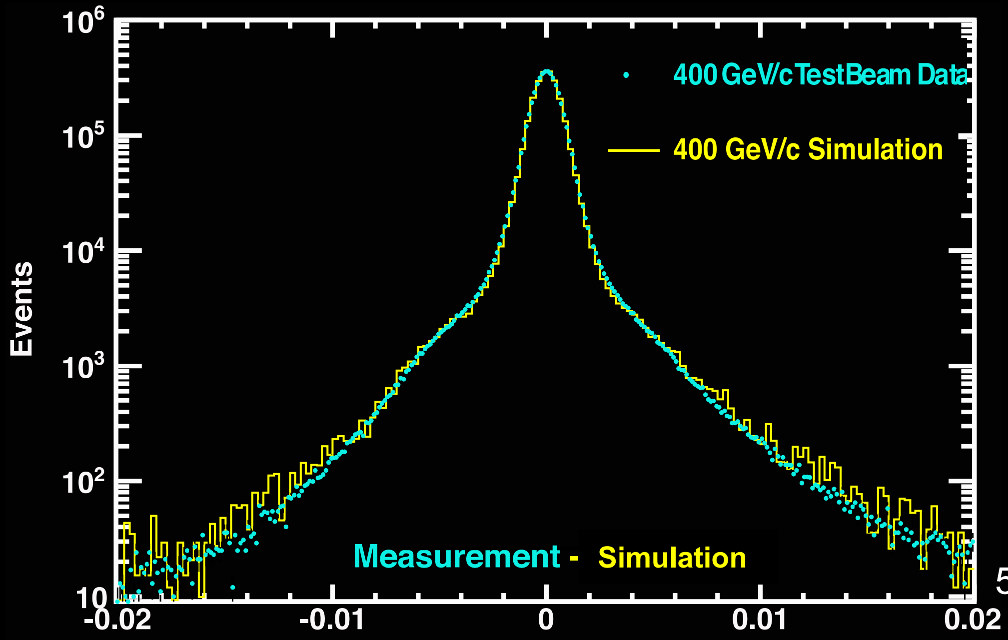
are measured independently by the Tracker, RICH, TOF and ECAL

Calibration at CERN

with different particles at different energies

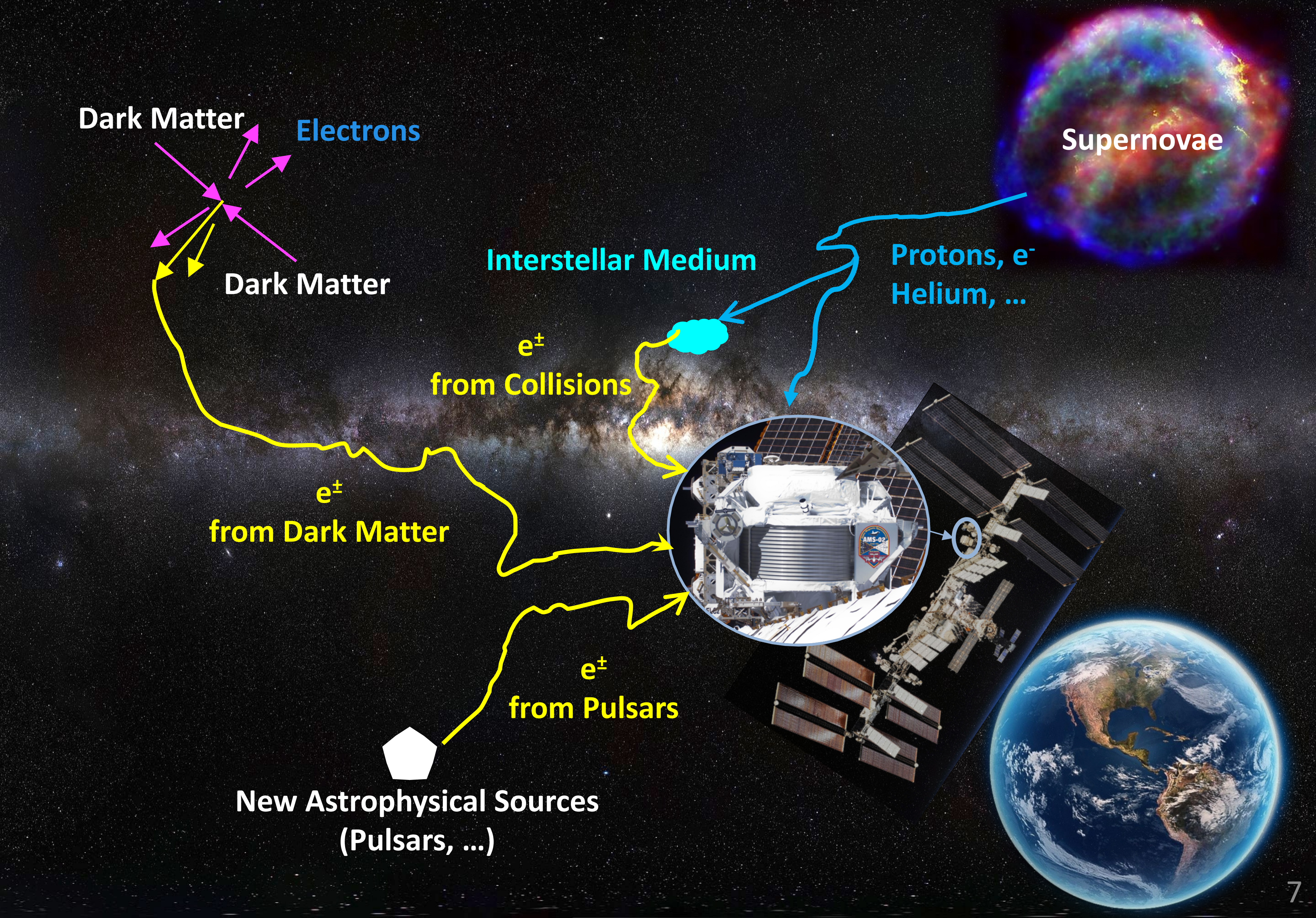




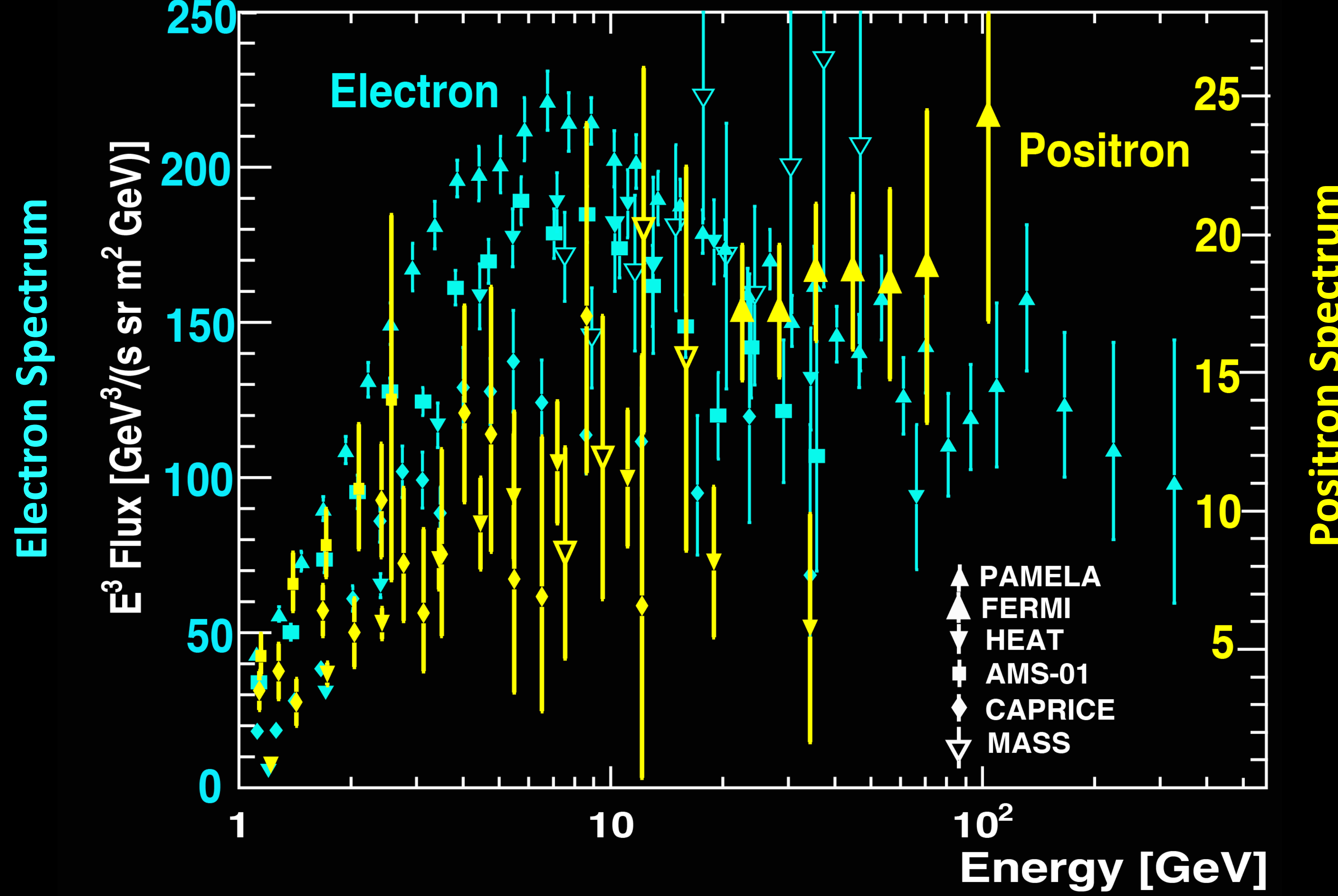



In 8 years,
over 140 billion
charged cosmic rays
have been measured by AMS

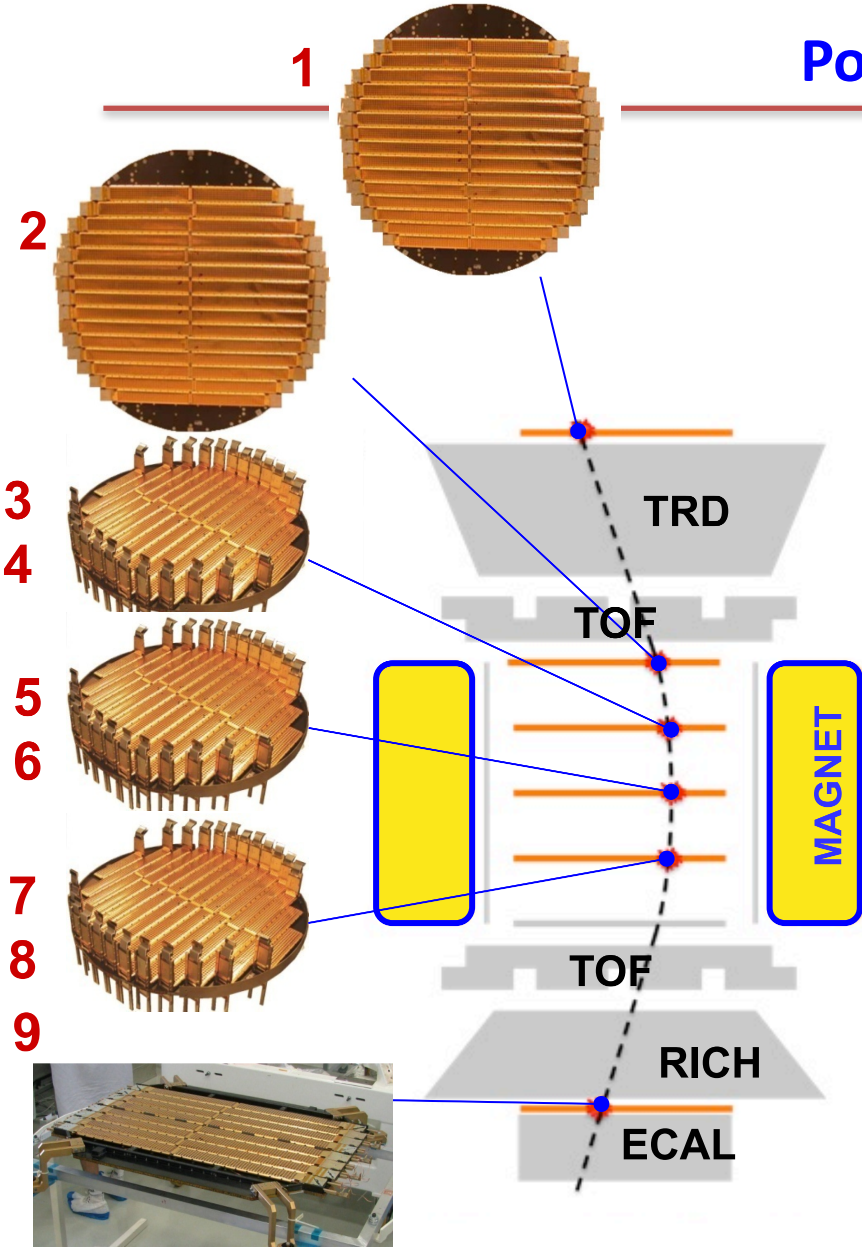
The Origins of Cosmic Positrons and Electrons



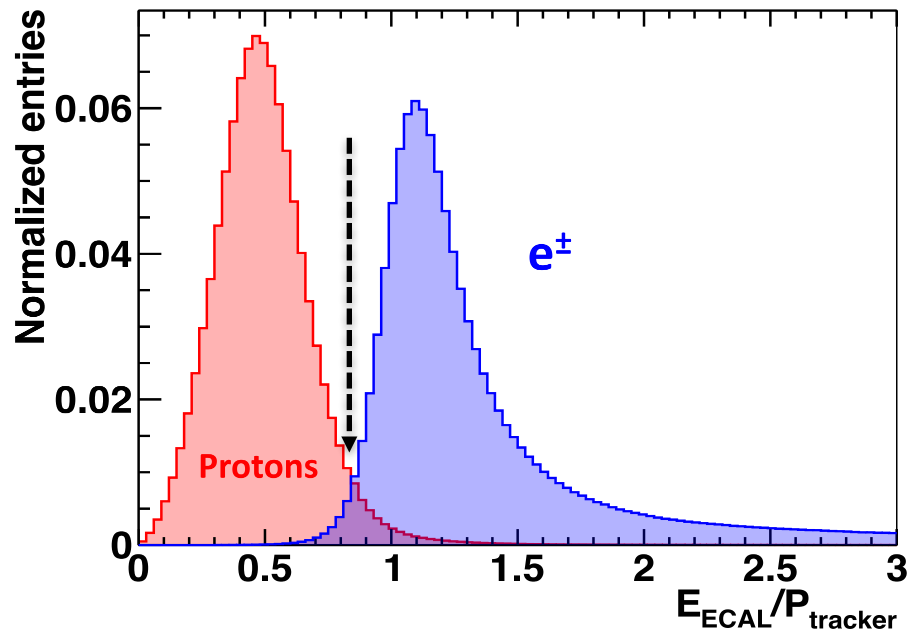
Electron and Positron spectra before AMS



Positrons Measurement in AMS



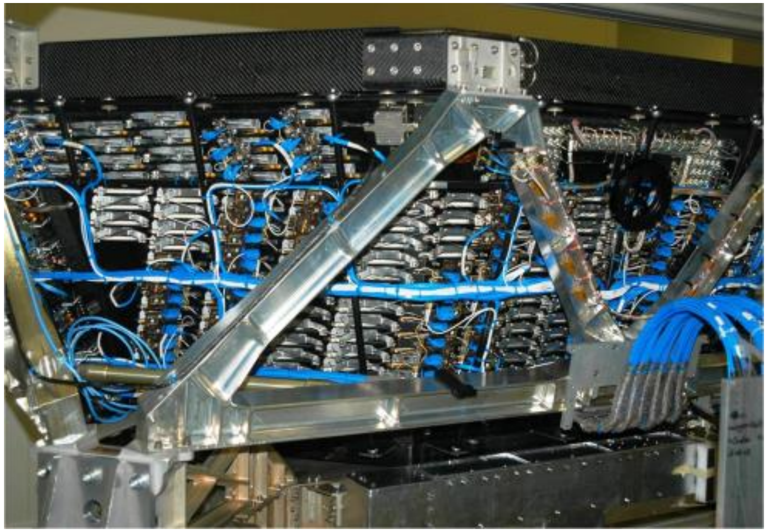
- Tracker and Magnet Measures the sign and magnitude of the positron and electron to few TeV.
- Unique particle identification capability : Independent Momentum and Energy measurement

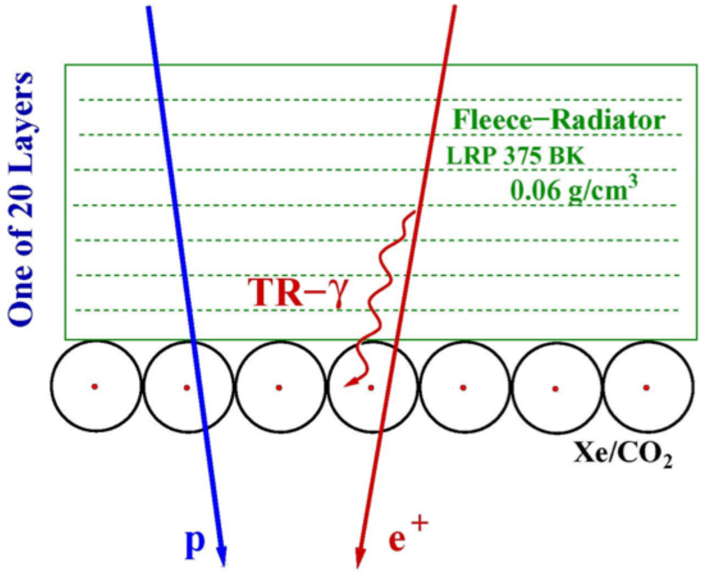


L1 to L9: 3m level arm;
single point resolution 10 µm;

- Identify electron charge confusion:
  - Large angle scattering,
  - Interaction with detector materials.
  - Identified and measured from data using Charge confusion estimator Λ_{CC}

Electrons and Positrons Identification



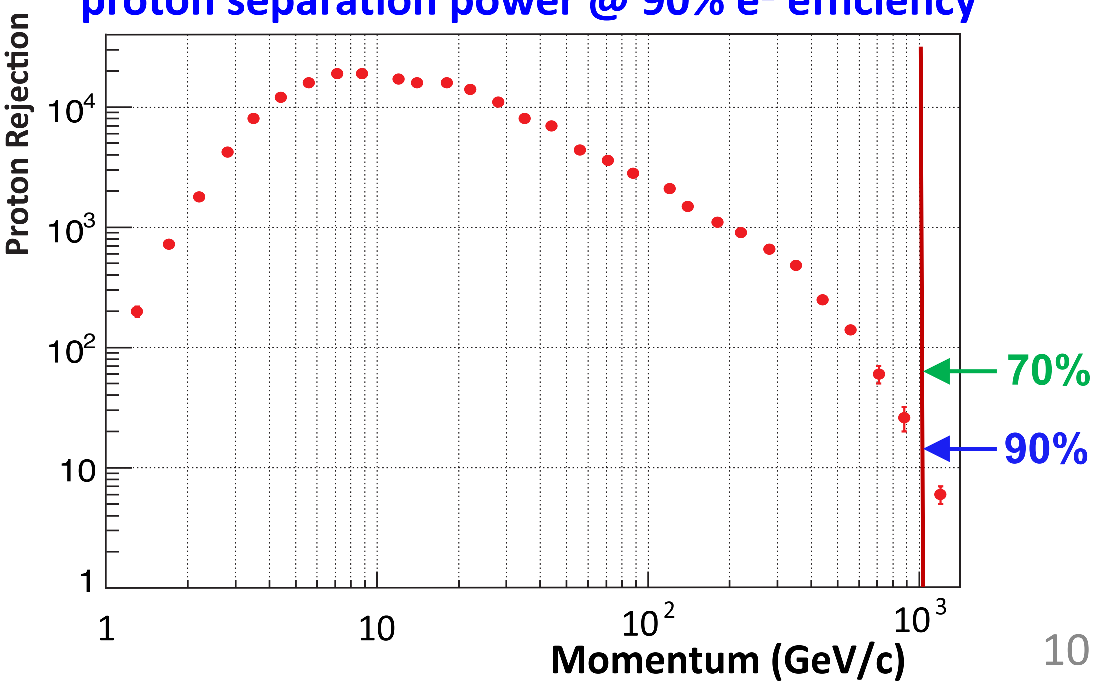


- Identify $e^{\pm}$ from protons using transition radiation

- Combine 20 layers proportional tubes signal into TRD estimator Λ_{TRD}

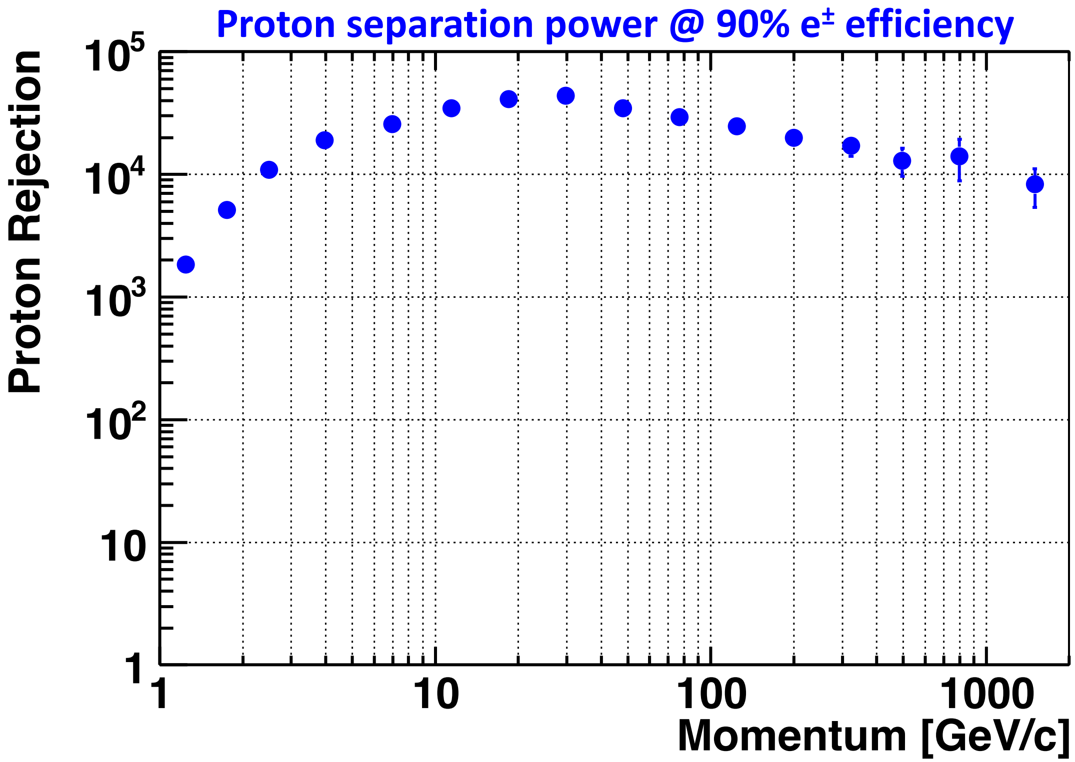
- Reject protons with high efficiency

proton separation power @ 90% $e^{\pm}$ efficiency



Electrons and Positrons Identification

- ECAL : 17 X_0 , TeV Precision 3D measurement of the energy and shower development of electrons and positrons.
- ECAL energy scale error: 2.5% at 1TeV
- Proton separation power > 10^4 : remove majority of the proton backgrounds



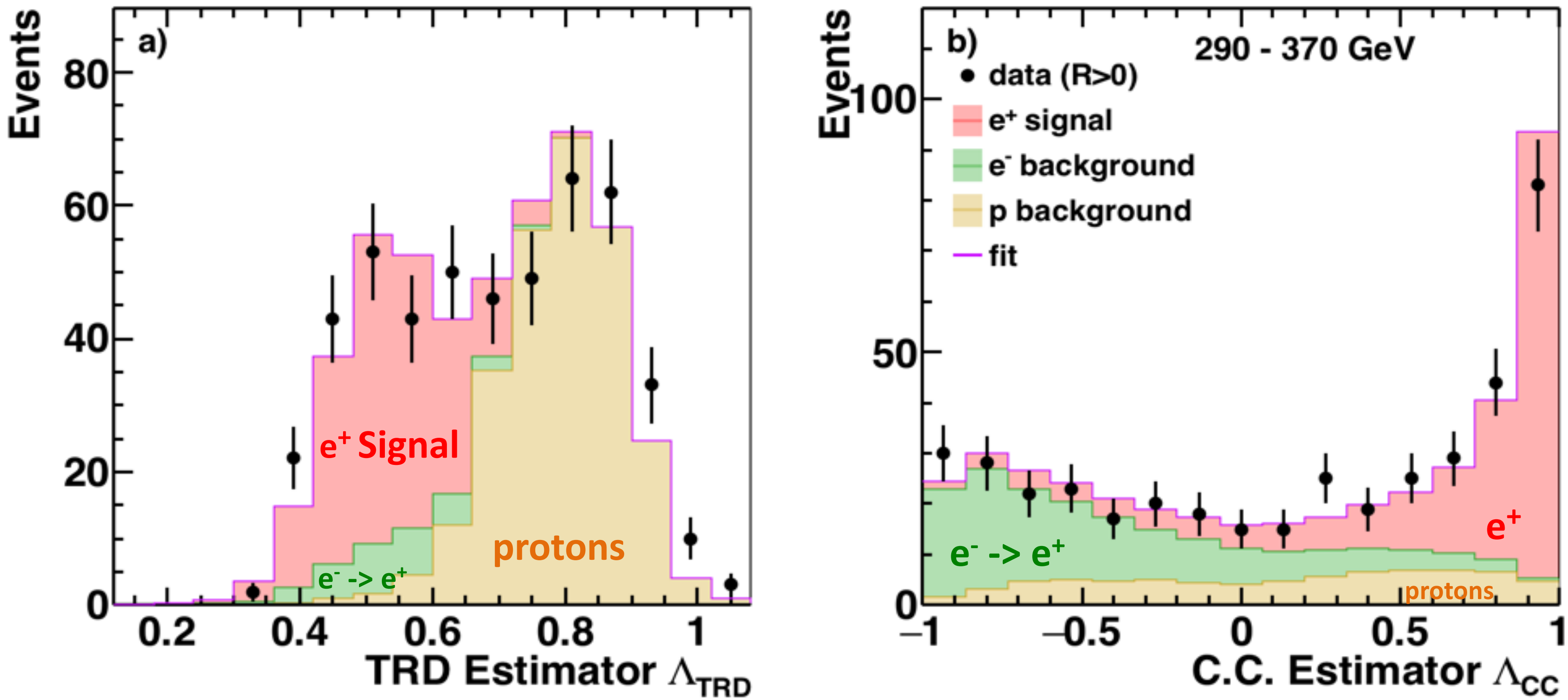
TRD and ECAL are separated by the Magnet

They have independent particle identification: combined rejection > 1 in 10^6

Positrons Measurement in AMS

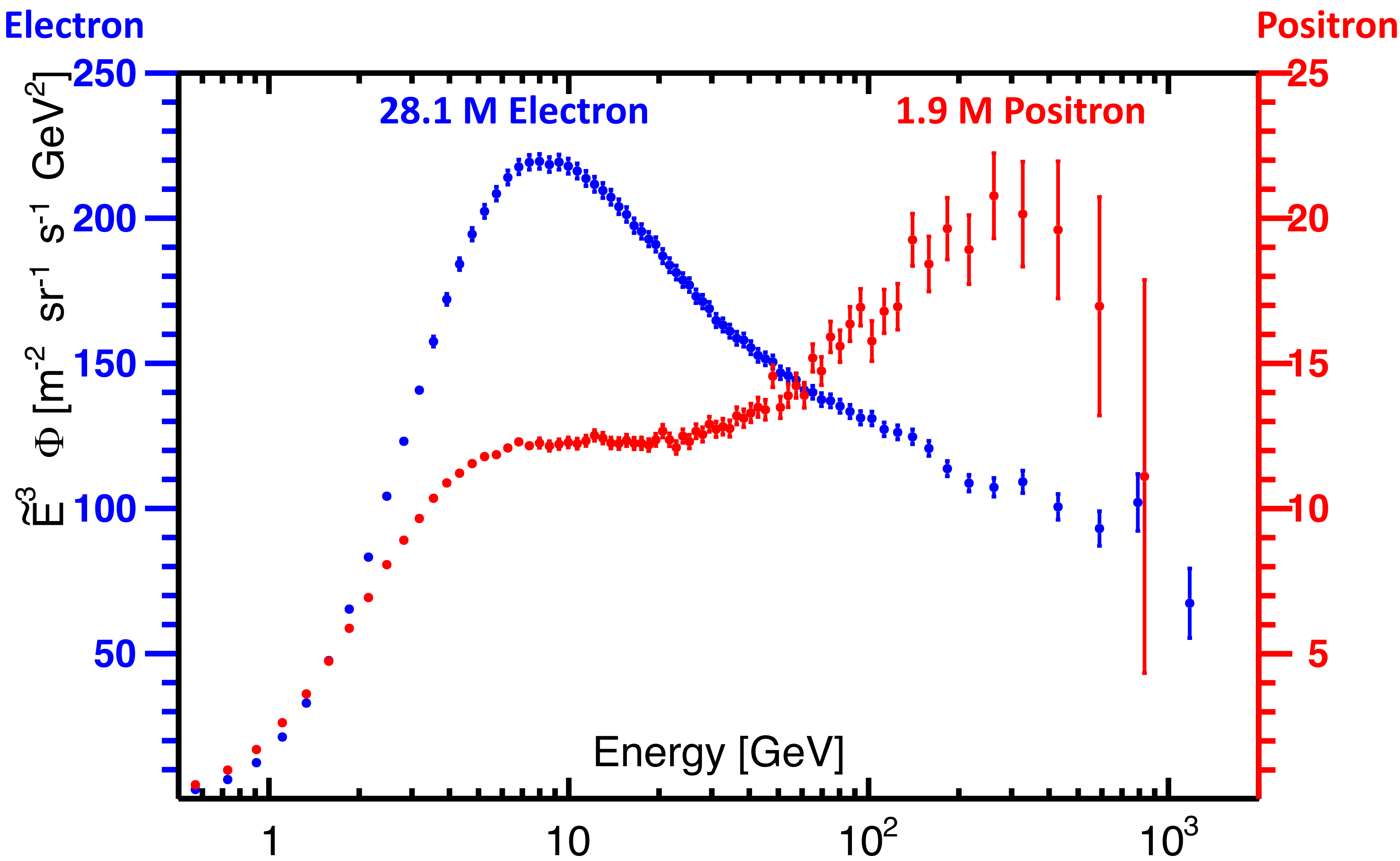
- For each bin, number of e^+ are obtained from a fit to data sample in $(\Lambda_{TRD} - \Lambda_{CC})$ plane
- Precision determination of Signal and Background from Data
  - Positron Signal are clearly identified in the signal region of Λ_{TRD} and Λ_{CC}
  - Proton : identified by TRD estimator Λ_{TRD}
  - Electron charge confusion measured from data using Charge confusion estimator Λ_{CC}

Fit to Data, Positive Rigidity, 290 – 370 GeV



In 6.5 Years: 1.9 million positrons， 28.1 million electrons

Latest AMS Results on Positrons and Electrons

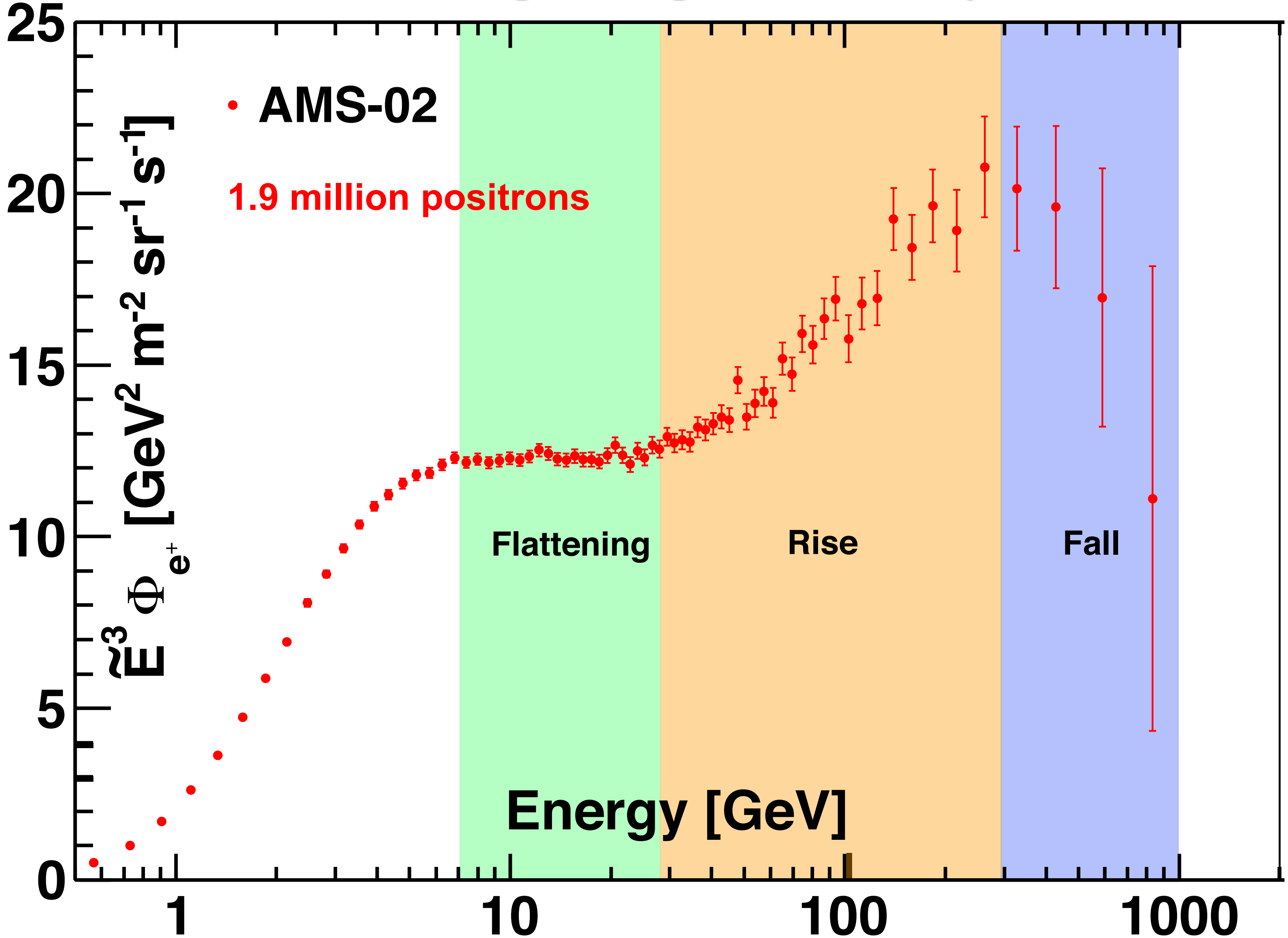


Latest measurement by AMS greatly improve the measurement accuracy and extend the energy to uncharted region.

PHYSICAL REVIEW LETTERS **122,** 041102 (2019)

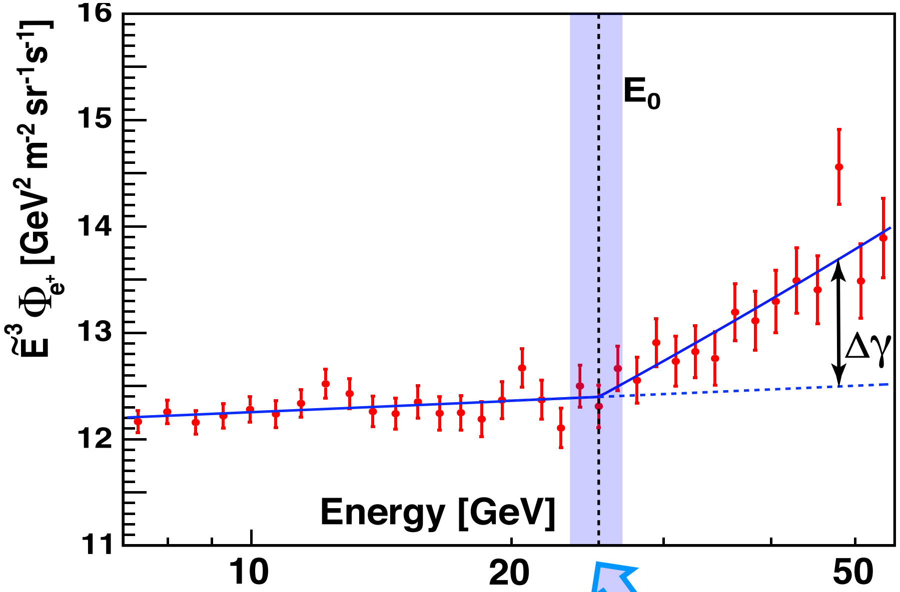
Editors' Suggestion

Towards Understanding the Origin of Cosmic-Ray Positrons



Positron spectrum exhibits complex energy dependence

Distinctive properties of Positron Spectrum



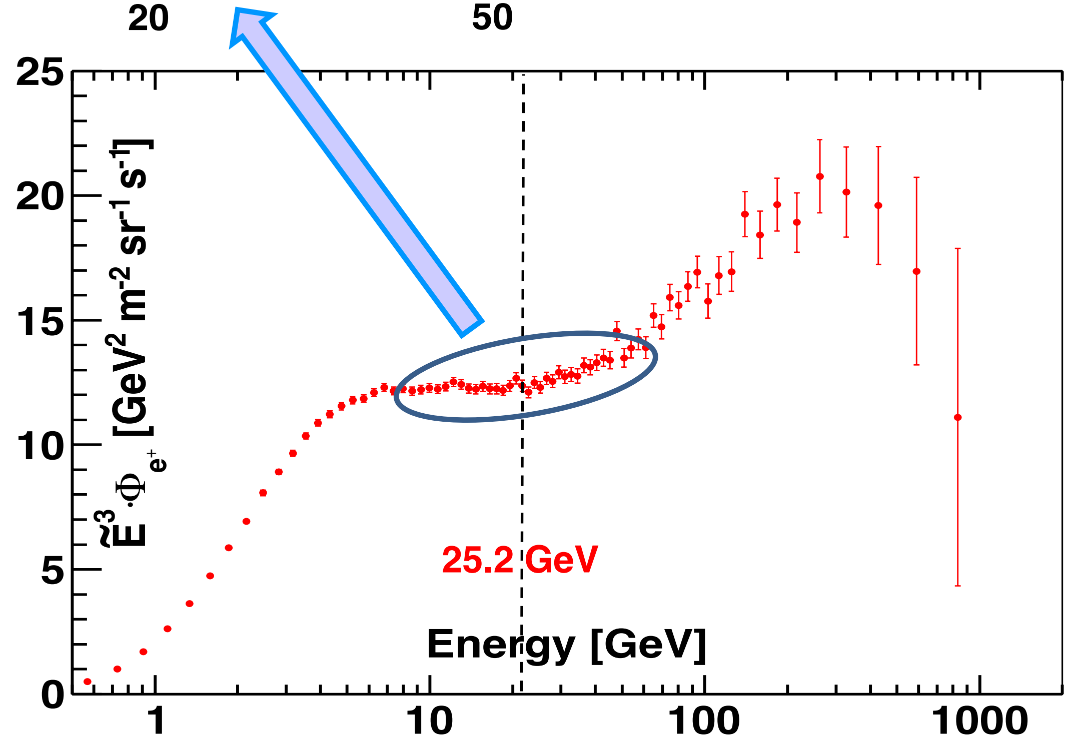
Fits of the data to

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

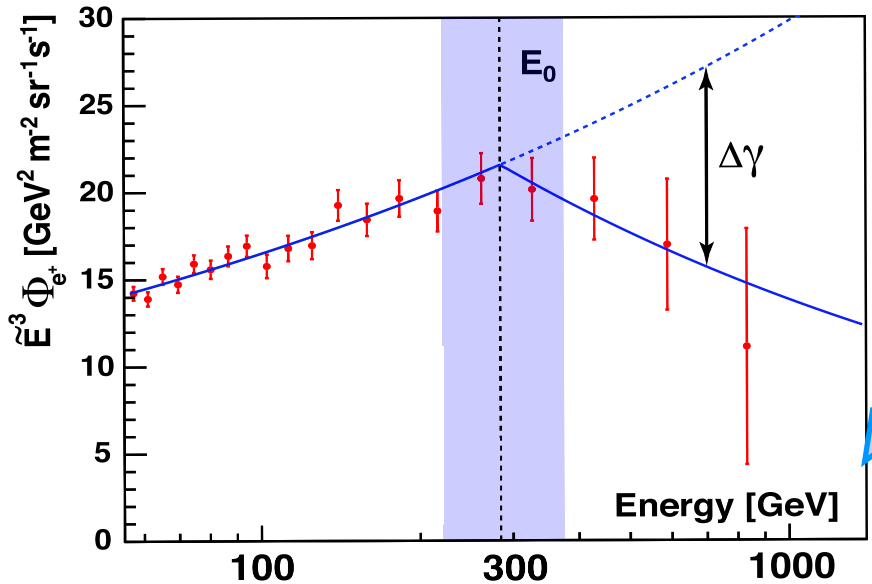
A significant excess above

$E_0 = 25.2 \pm 1.8$ GeV

The significance of this change is more than 6σ



Distinctive properties of Positron Spectrum



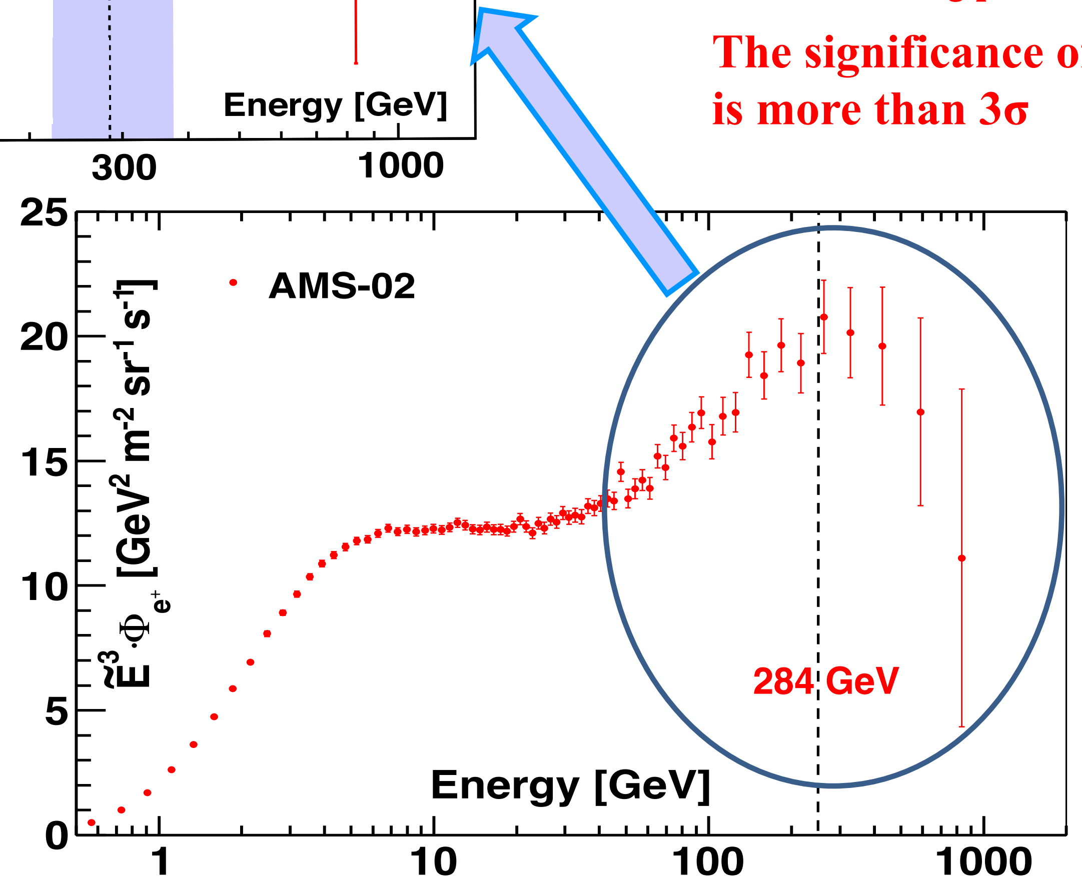
Fits of the data to

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

A sharp drop-off at

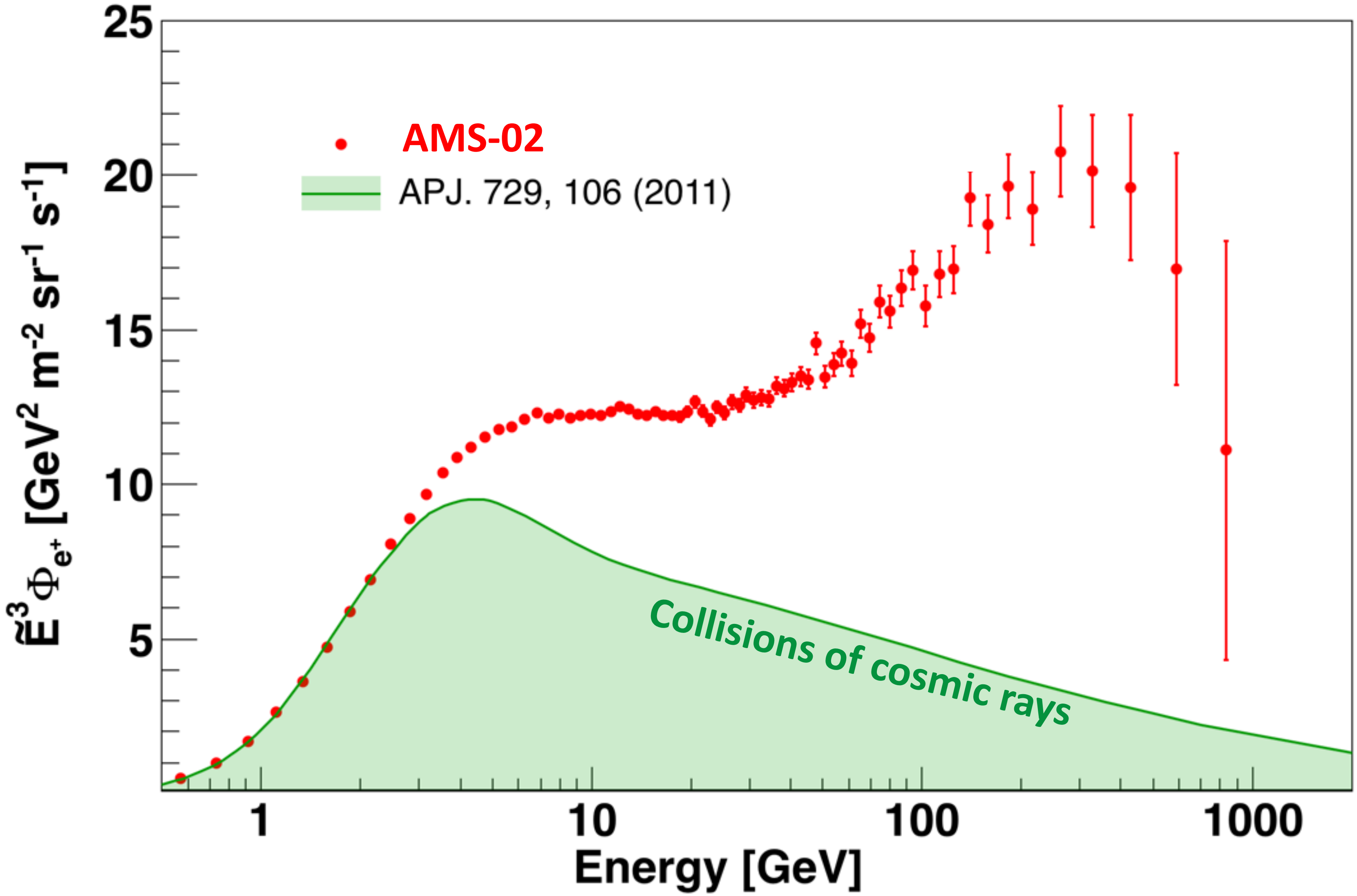
$$E_0 = 284^{+91}_{-64}\ \text{GeV}$$

The significance of this change is more than 3σ



The Origin of Cosmic-Ray Positrons

These distinct behavior can not be explained by traditional cosmic ray models.



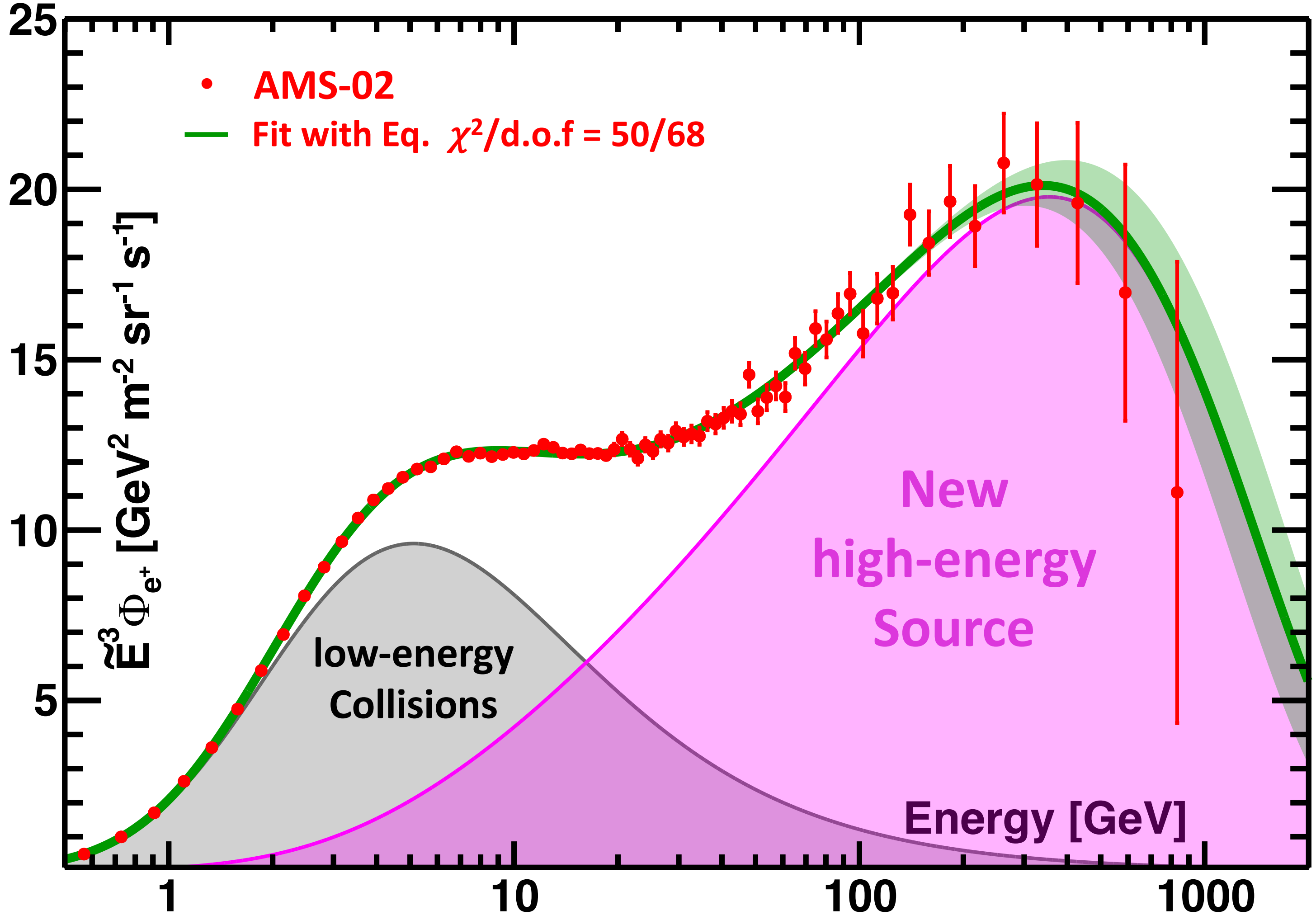
The positron flux by far exceeds the prediction from collision of cosmic rays, requiring a primary source of e^+

The positron flux is the sum of two components:

Low-energy from collisions plus a new source at high-energy

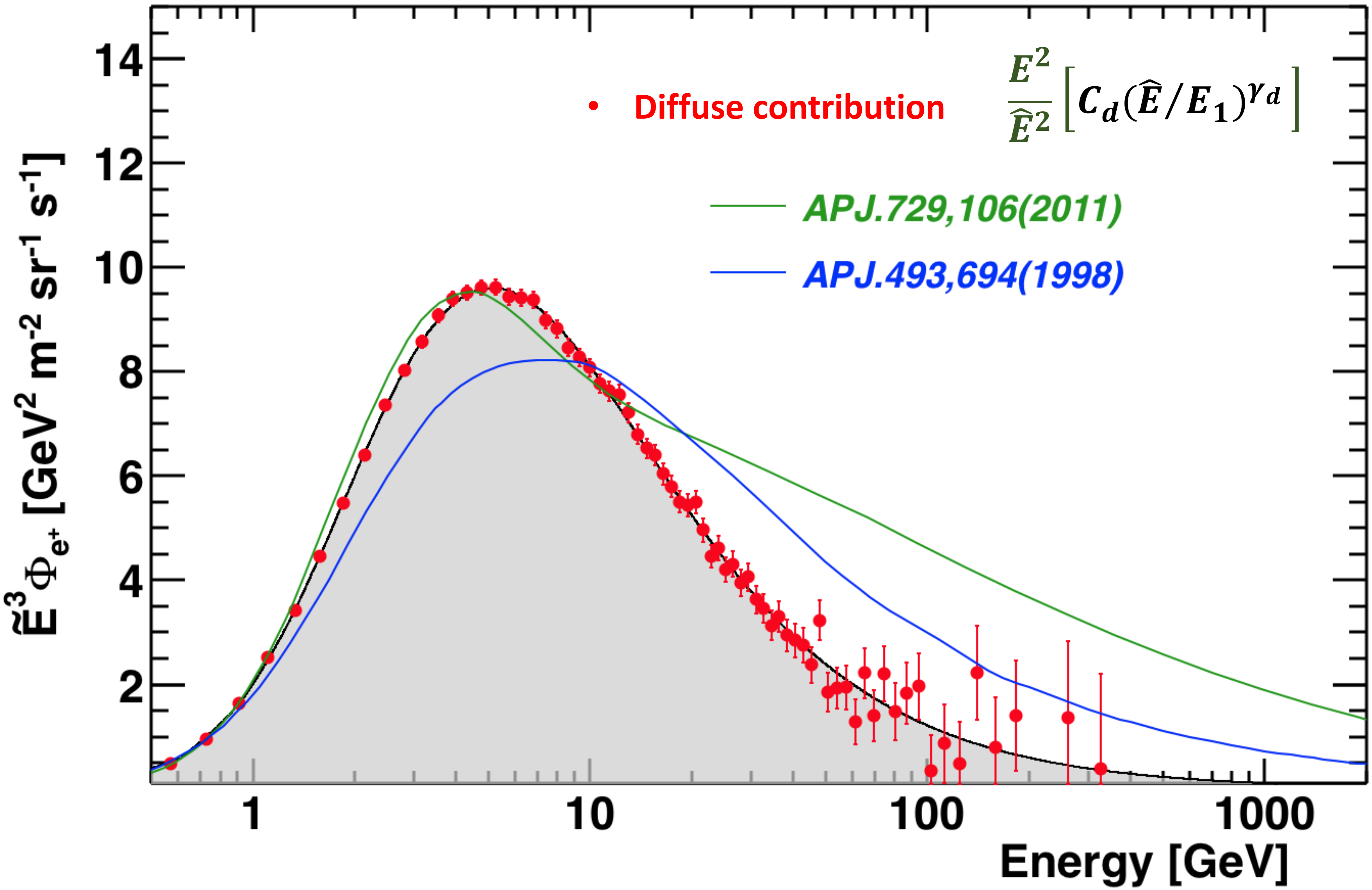
Collisions　　　　Source

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

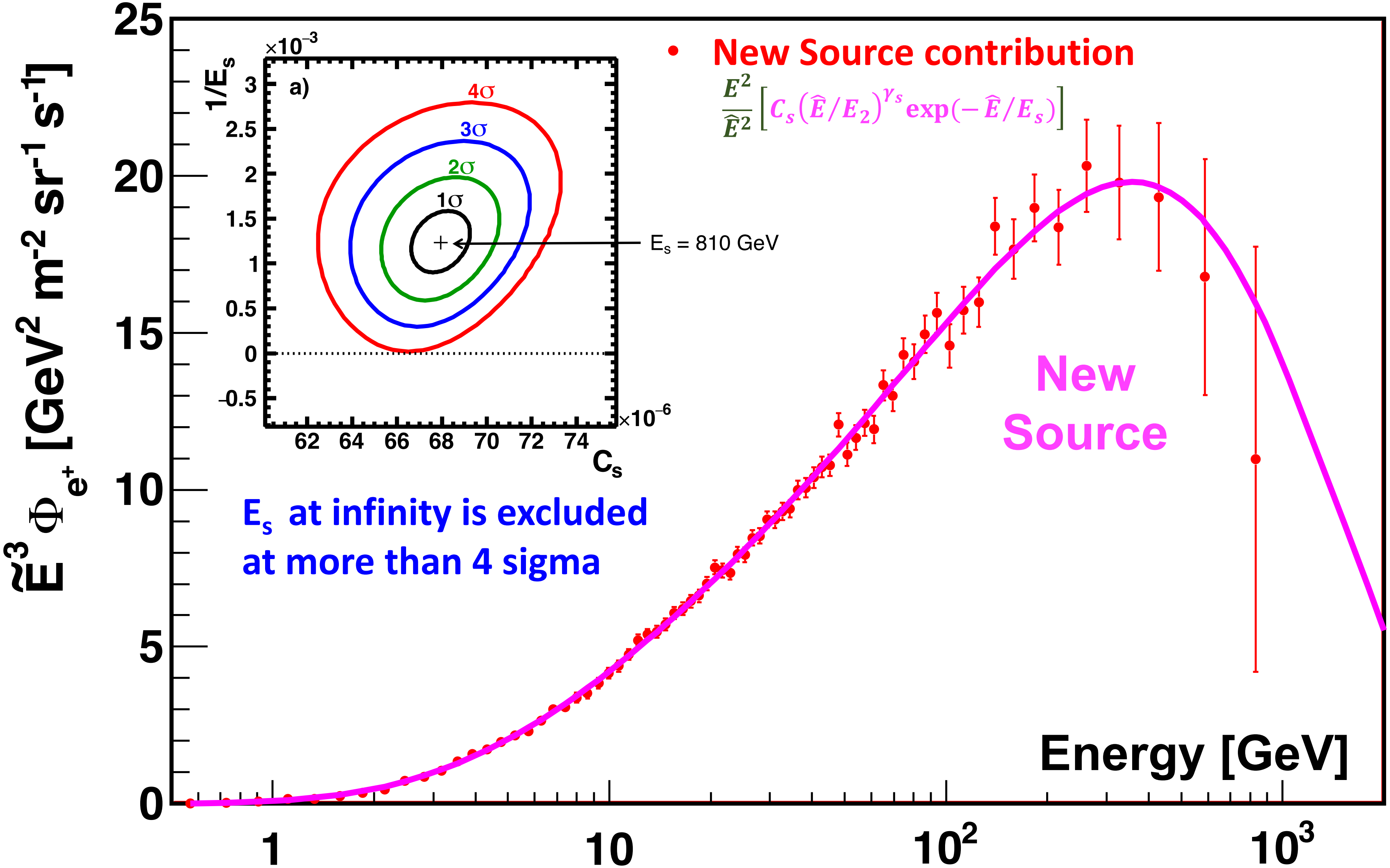


The Origin of Positrons at low energy

At low energy, positron comes from collision of cosmic rays.



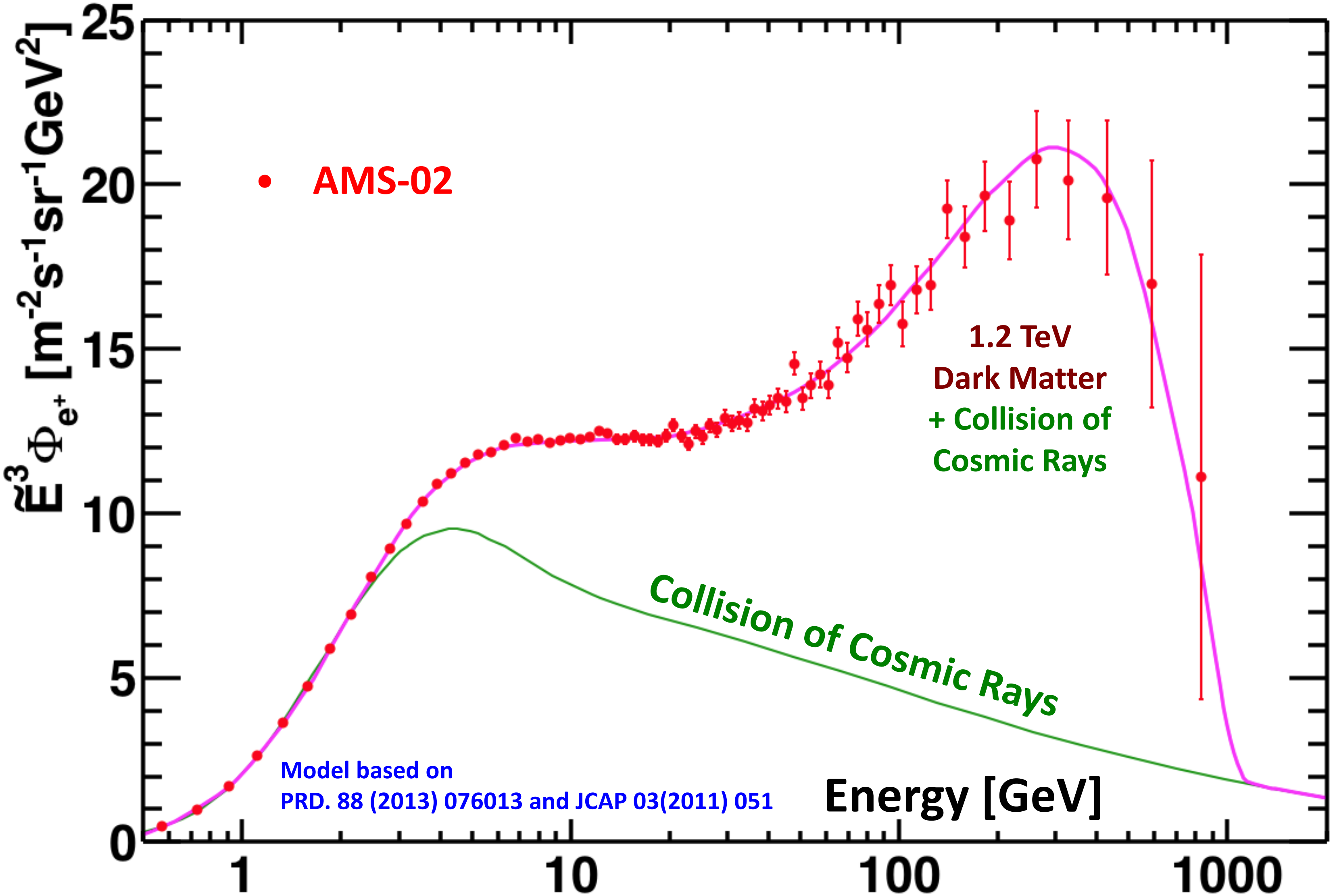
The Origin of Positrons at high energy



Energy cutoff of the source term $E_s = 810^{+310}_{-180}$ GeV

The Origin of Positrons at high energies

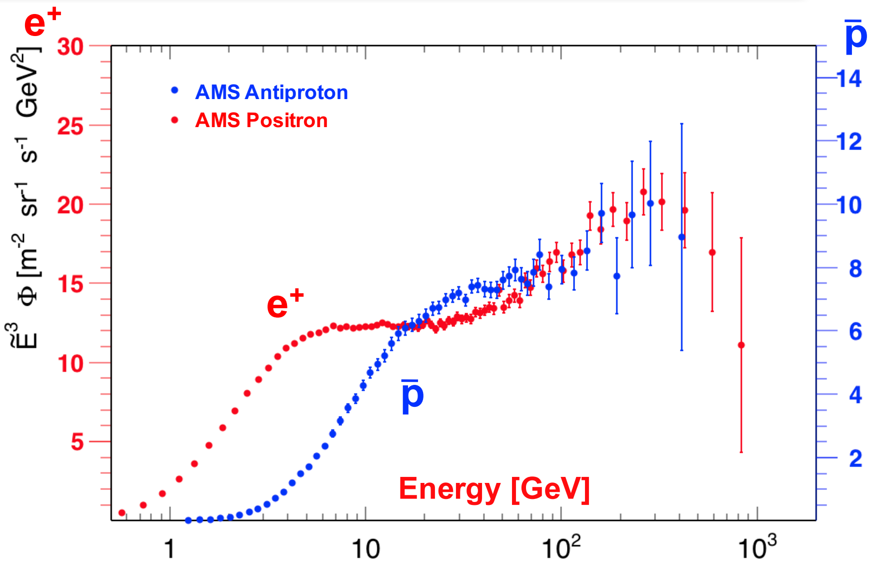
1) Particle origin: Dark Matter



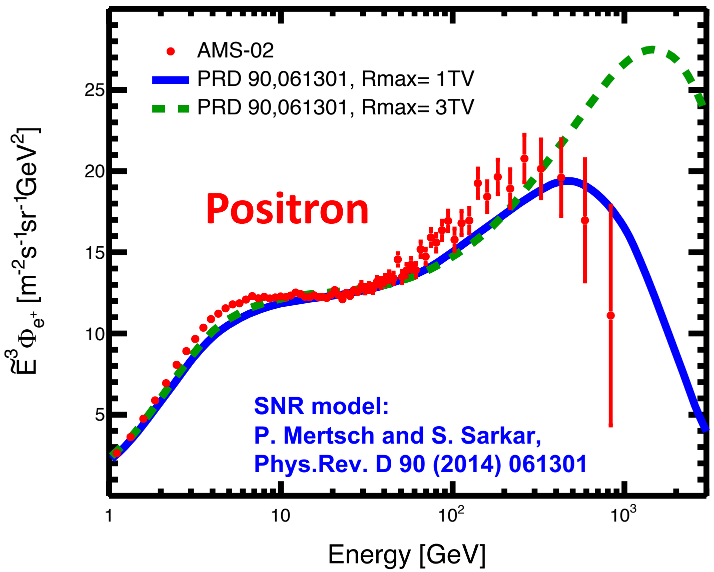
The AMS results appear to be in agreement with a 1.2 TeV Dark Matter Model

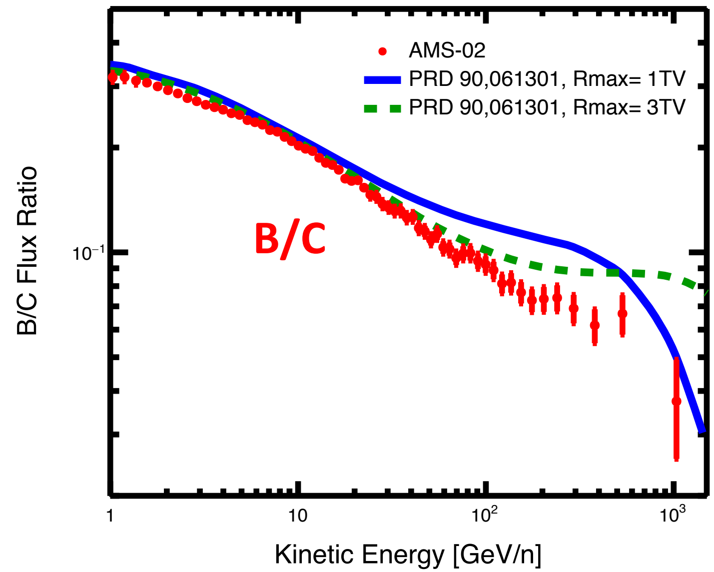
2) Possible Astrophysical Sources of Positron

- Point sources like Pulsars will imprint an observable anisotropy in e^+ direction. Up to now, the positron flux is consistent with isotropy.
- AMS measurement shows that antiproton and positron have similar behavior above 60GeV. Pulsars do not produce antiprotons.



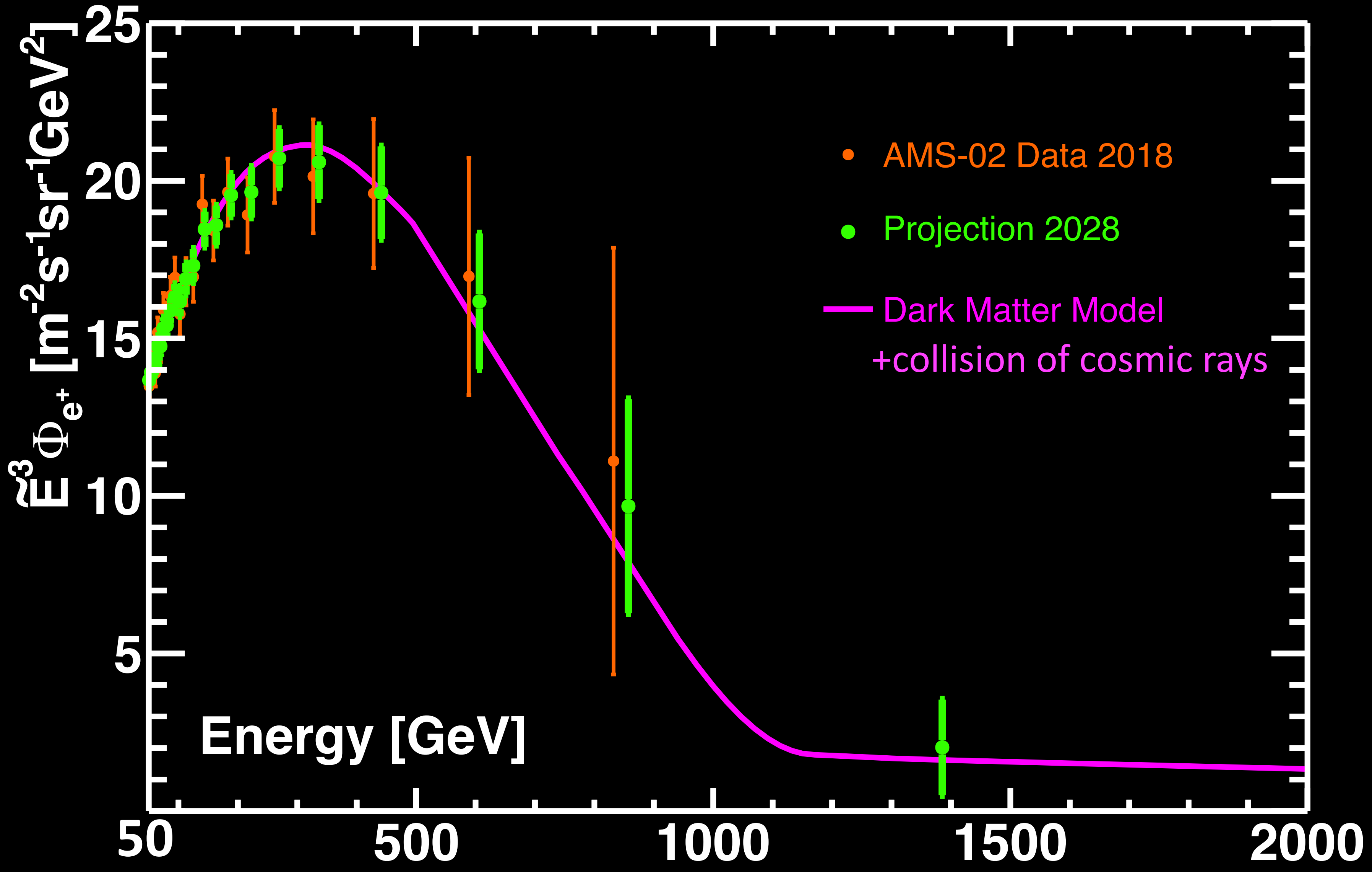
- Models with secondary particle(positron, boron,) accelerated by Supernova remnants do not agree with precision AMS measurements.





Precision measurements from AMS on Primaries, Secondaries, antiprotons, and positron, electron anisotropy would distinguish different origins of cosmic-ray positrons

AMS will extend the measurements beyond 1 TeV



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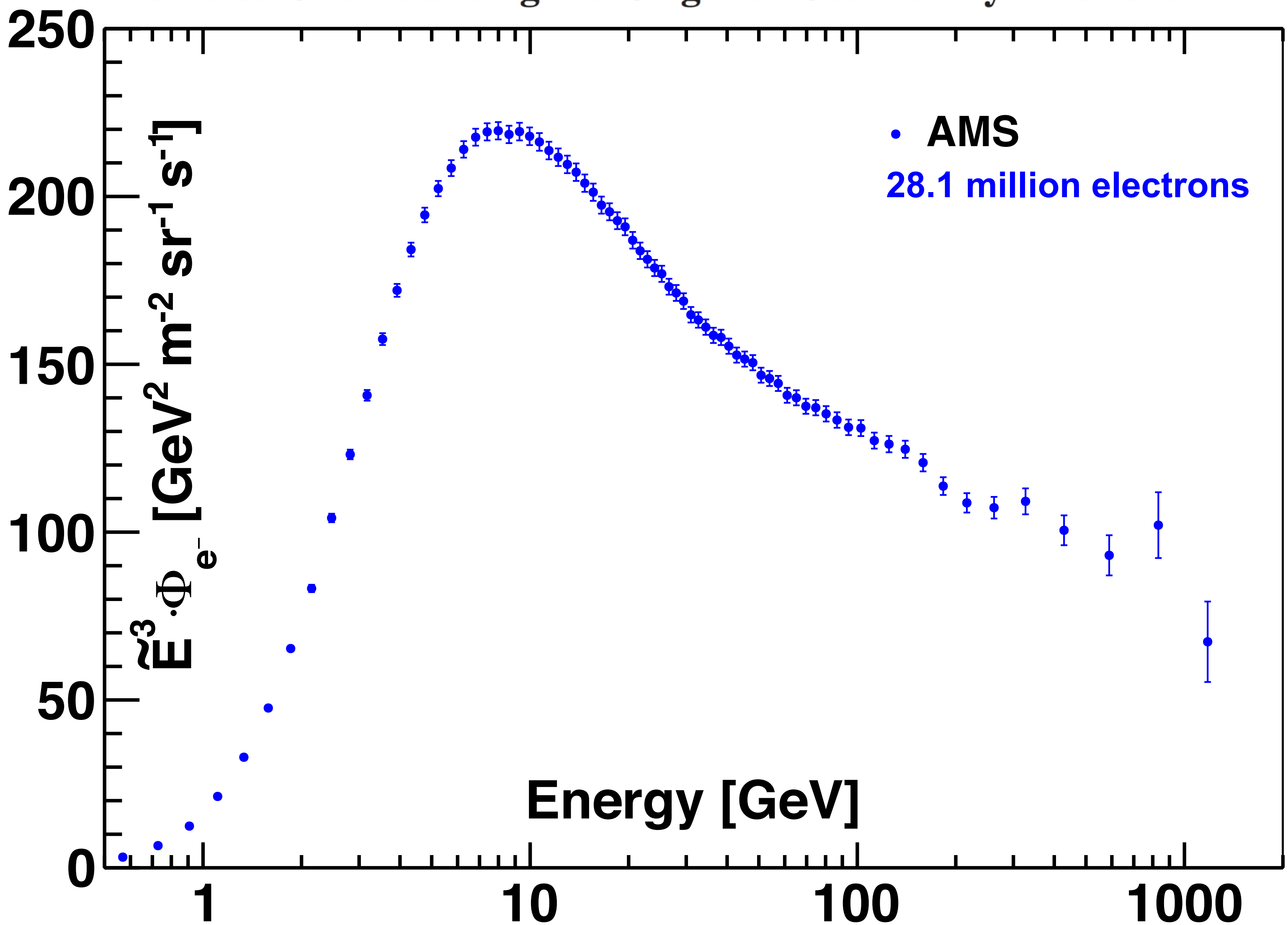
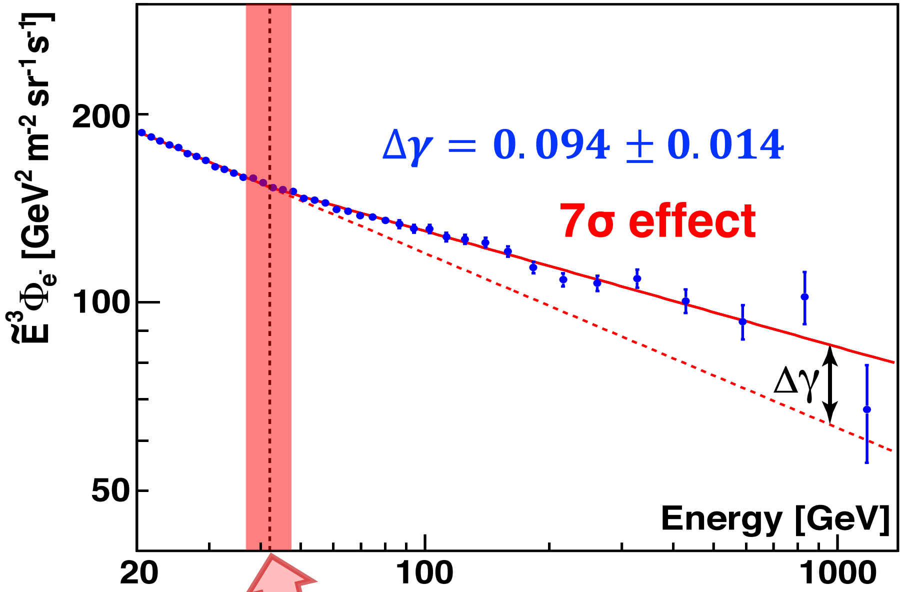
Towards Understanding the Origin of Cosmic-Ray Electrons



Electron have distinctly different magnitudes and energy dependences than positrons

Energy dependence of electron flux:

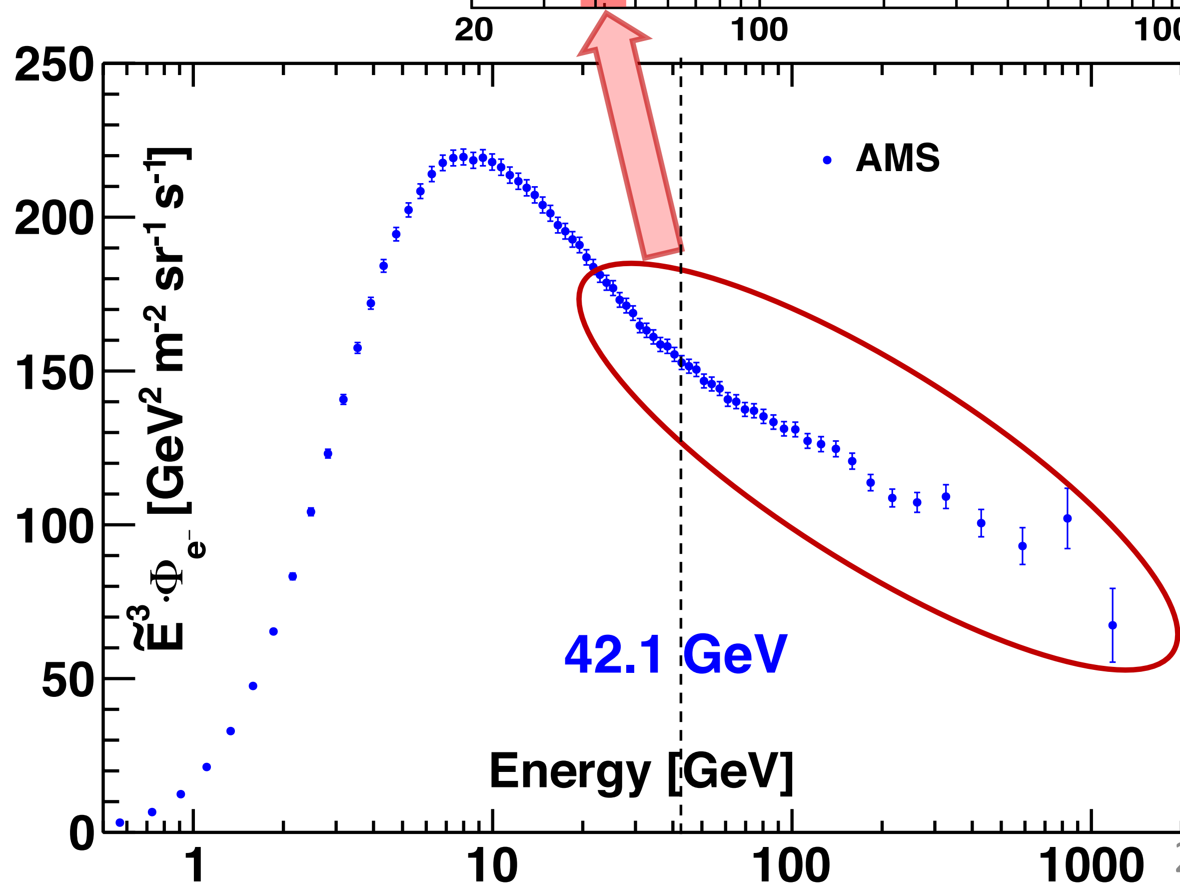


Fit to the electron data:

$$\Phi_{e^-}(E) = \begin{cases} CE^{\gamma}, & E \le E_0; \\ CE^{\gamma}(E/E_0)^{\Delta\gamma}, & E > E_0. \end{cases}$$

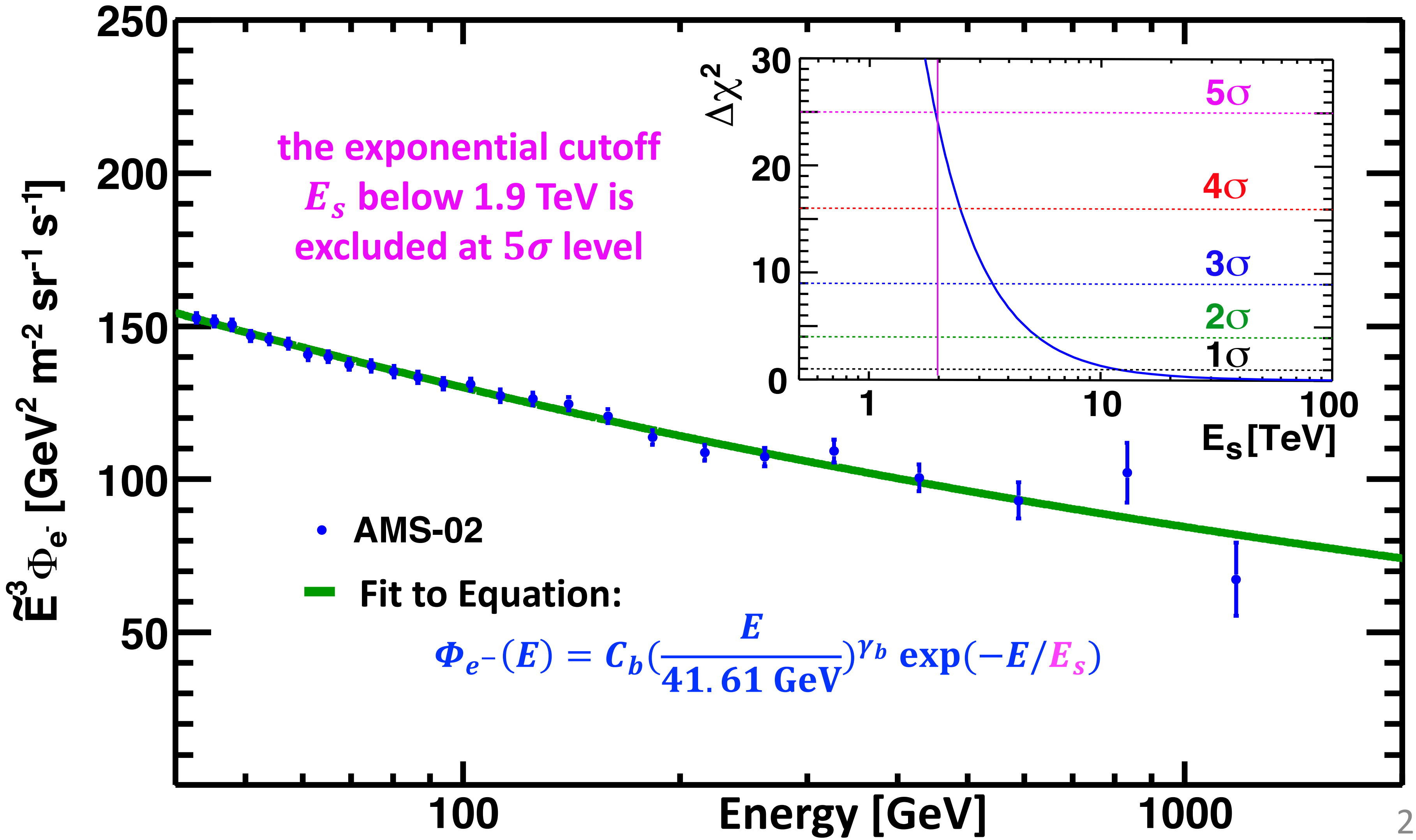
A significant excess above $42.1^{+5.4}_{-5.2}$ GeV

The significance of this change is established at more than 7σ



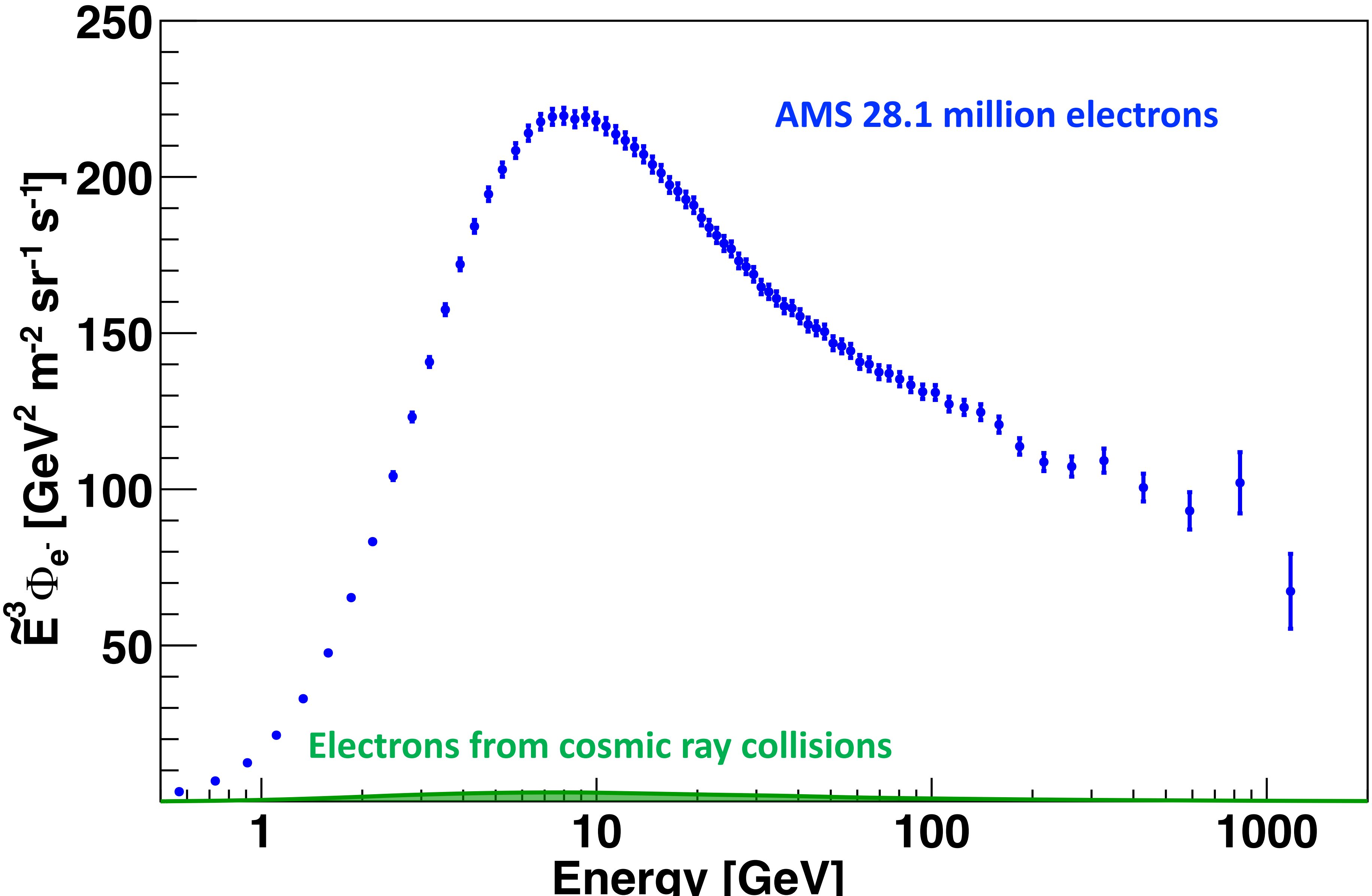
Study of high energy cutoff in the electron flux

Contrary to 4σ exponential cutoff at 810^{+310}_{-180} GeV in the positron flux, the electron flux does not show a cutoff below 1.9 TeV.



The Origins of Cosmic Electrons (I)

The contribution from cosmic ray collisions is negligible

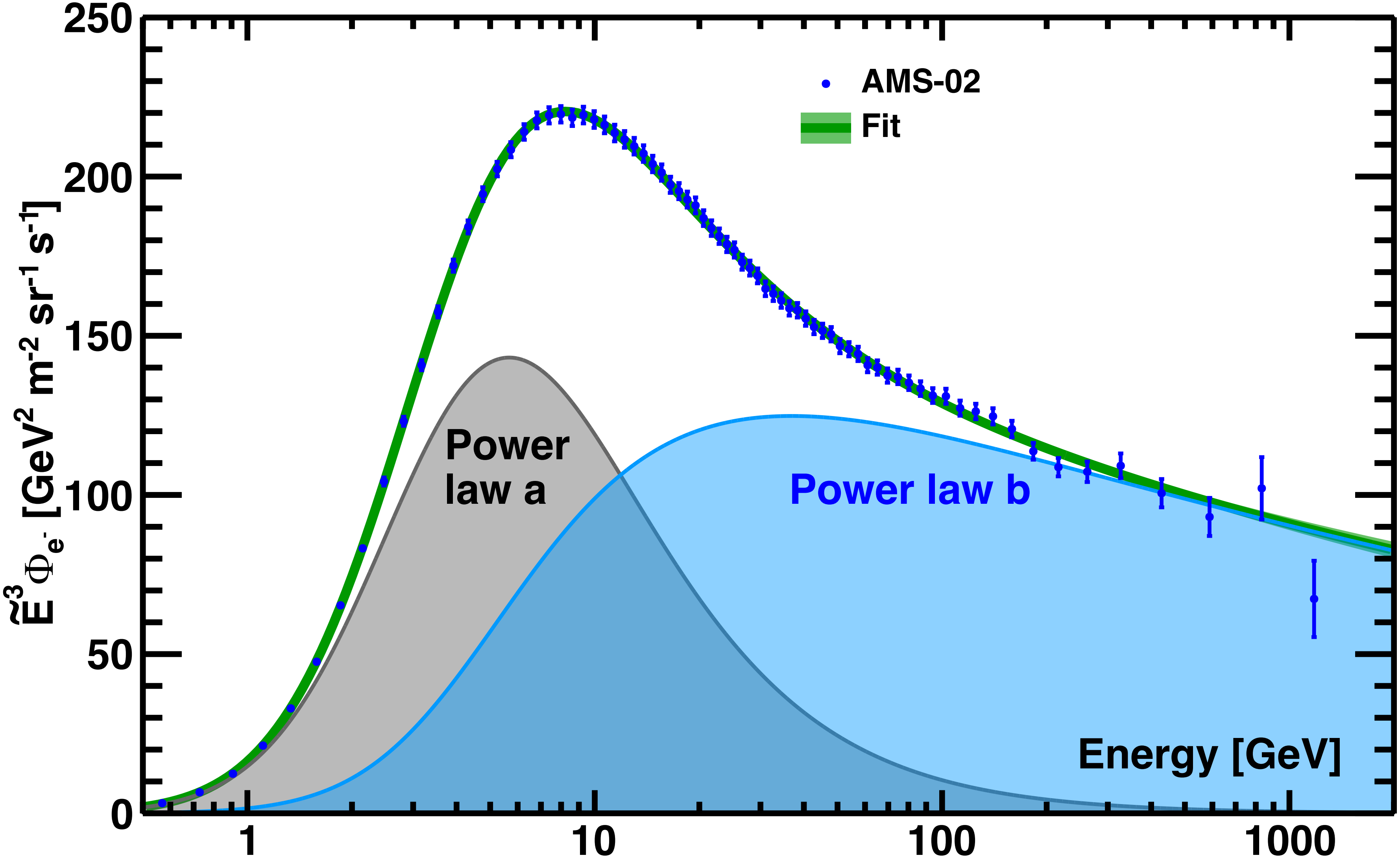


The Origins of Cosmic Electrons (II)

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

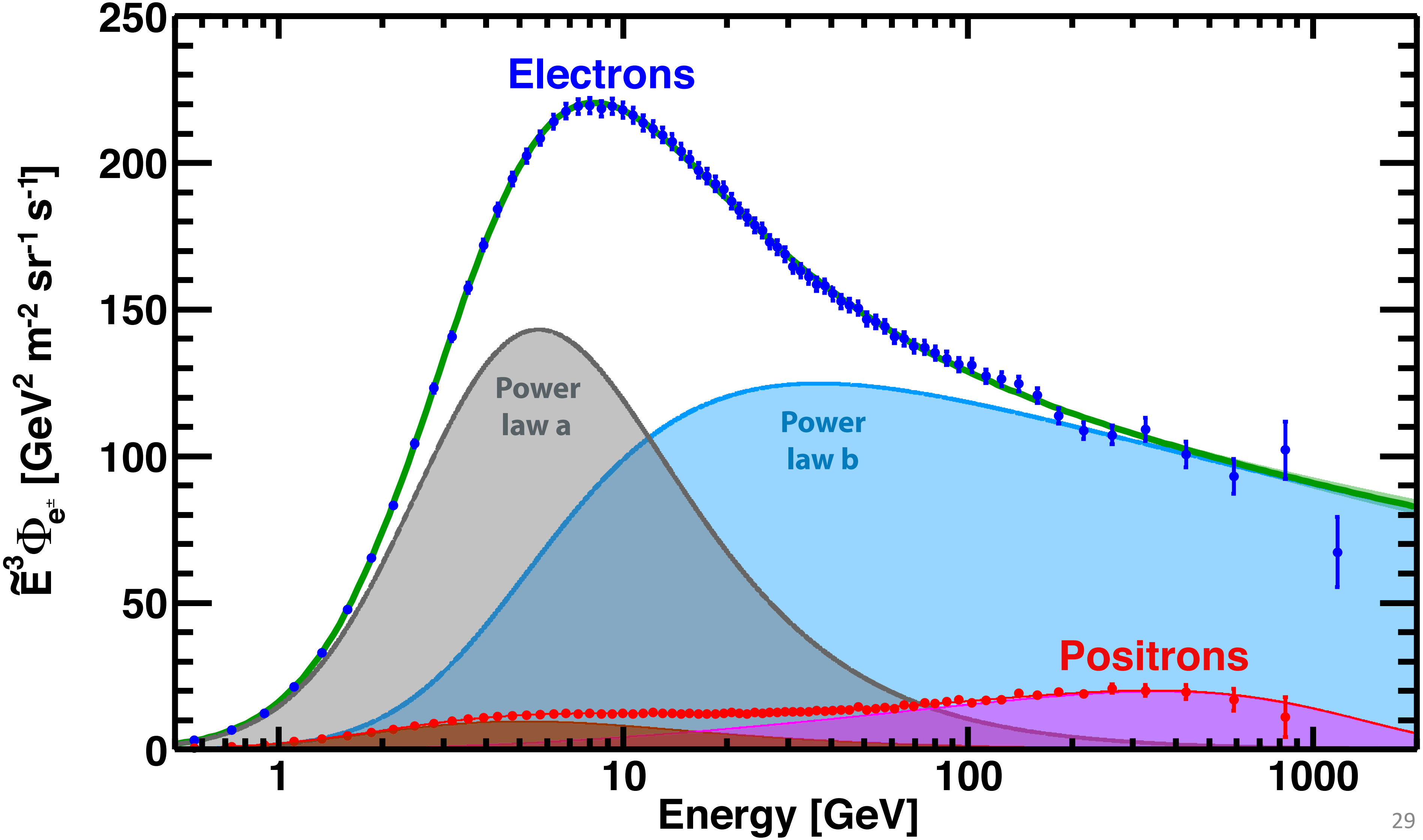
$$\Phi_{e^-}(E) = \frac{E^2}{\hat{E}^2}\left[1 + \left(\hat{E}/E_t\right)^{\Delta\gamma_t}\right]^{-1}\left[C_a\left(\hat{E}/E_a\right)^{\gamma_a} + C_b\left(\hat{E}/E_b\right)^{\gamma_b}\right]$$

Solar & low-energy Power laws *a* *b*



Origins of Cosmic Electrons and Positrons

The cosmic ray electrons originate from different sources than high energy positrons.



Conclusion and Outlooks

- **The positron flux exhibits distinctive energy dependence:**
  (a) a significant excess starting from 25.2±1.8 GeV
  (b) a sharp drop-off above 284 GeV,

- **These properties are not explained by ordinary CR models:**
  An primary source of high energy positrons.

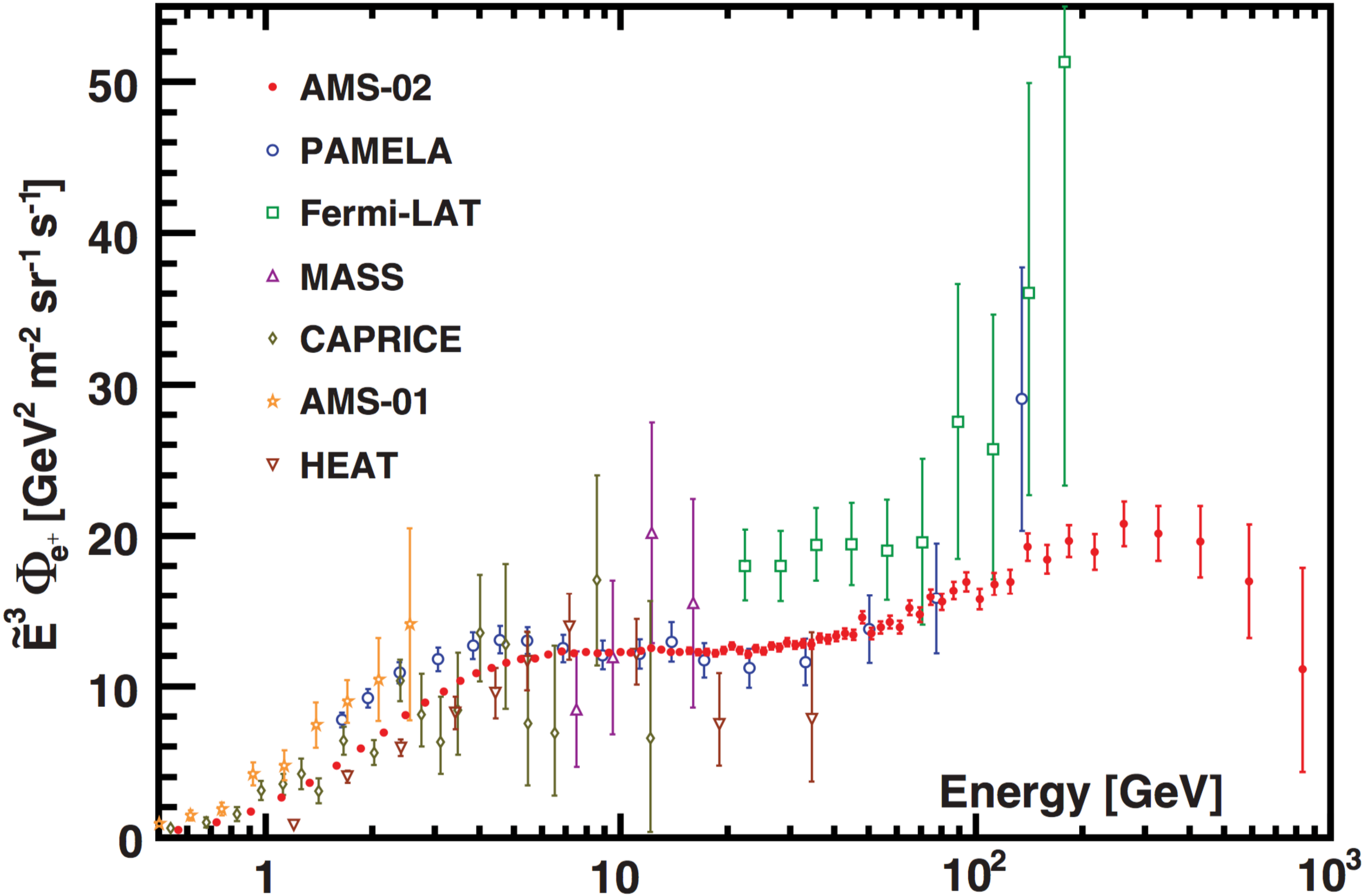
- **The positron flux is well described by the sum of a diffuse term and a new source term with a finite energy cutoff at 810 GeV, with a significance of more than 4σ.**

- **The electron flux exhibits a significant excess starting from $42.1^{+5.4}_{-5.2}$GeV.**
- **The electron flux is well described by the sum of two power law component. High energy electrons originate from different sources than high energy positrons**

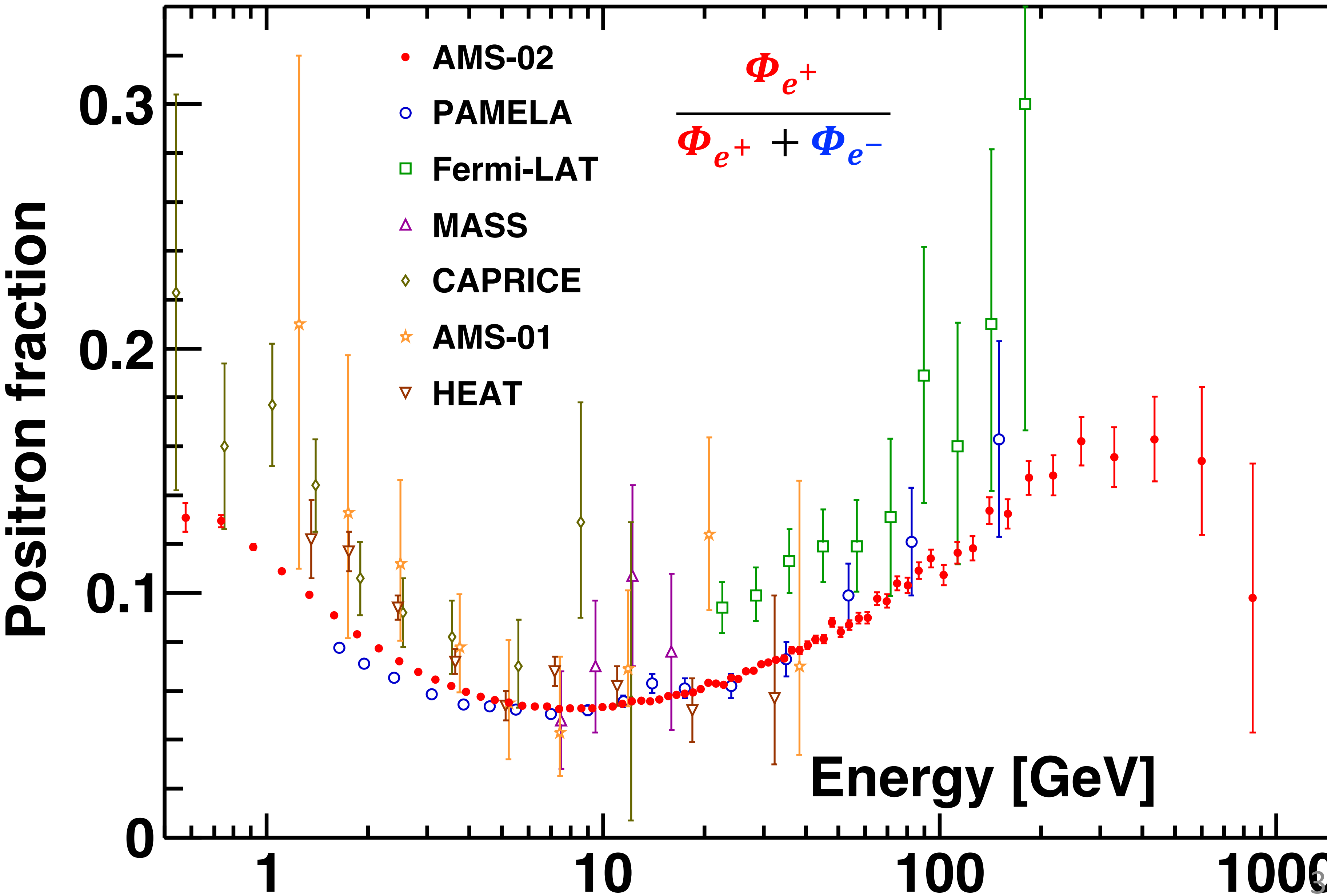
- **By continuing the measurement through the live time of the Space Station, we will be able to improve the accuracy and extend to higher energy, and determine the origin of high energy positrons and electrons.**


AMS
AMS

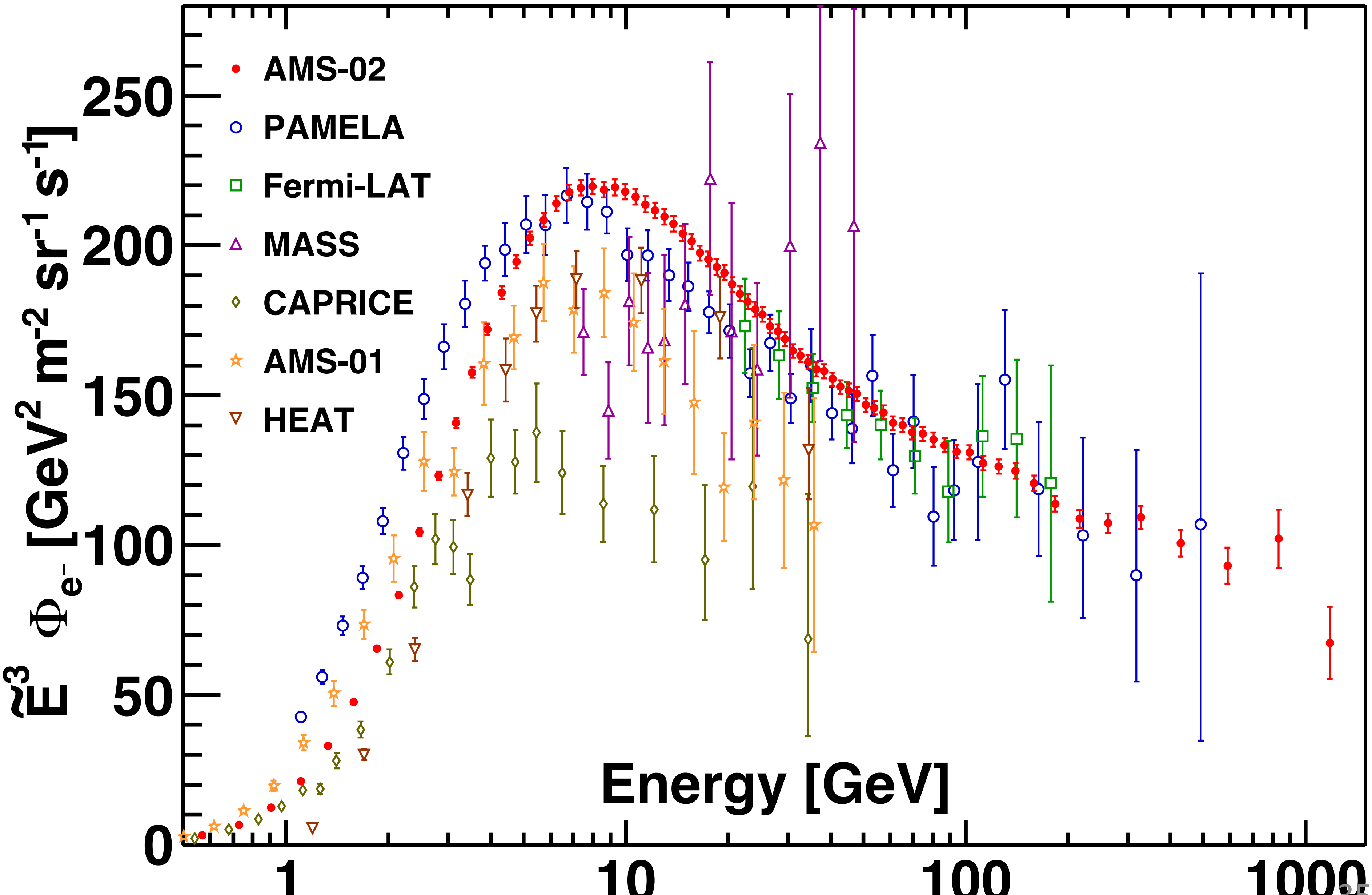
AMS Positron flux with earlier experiments



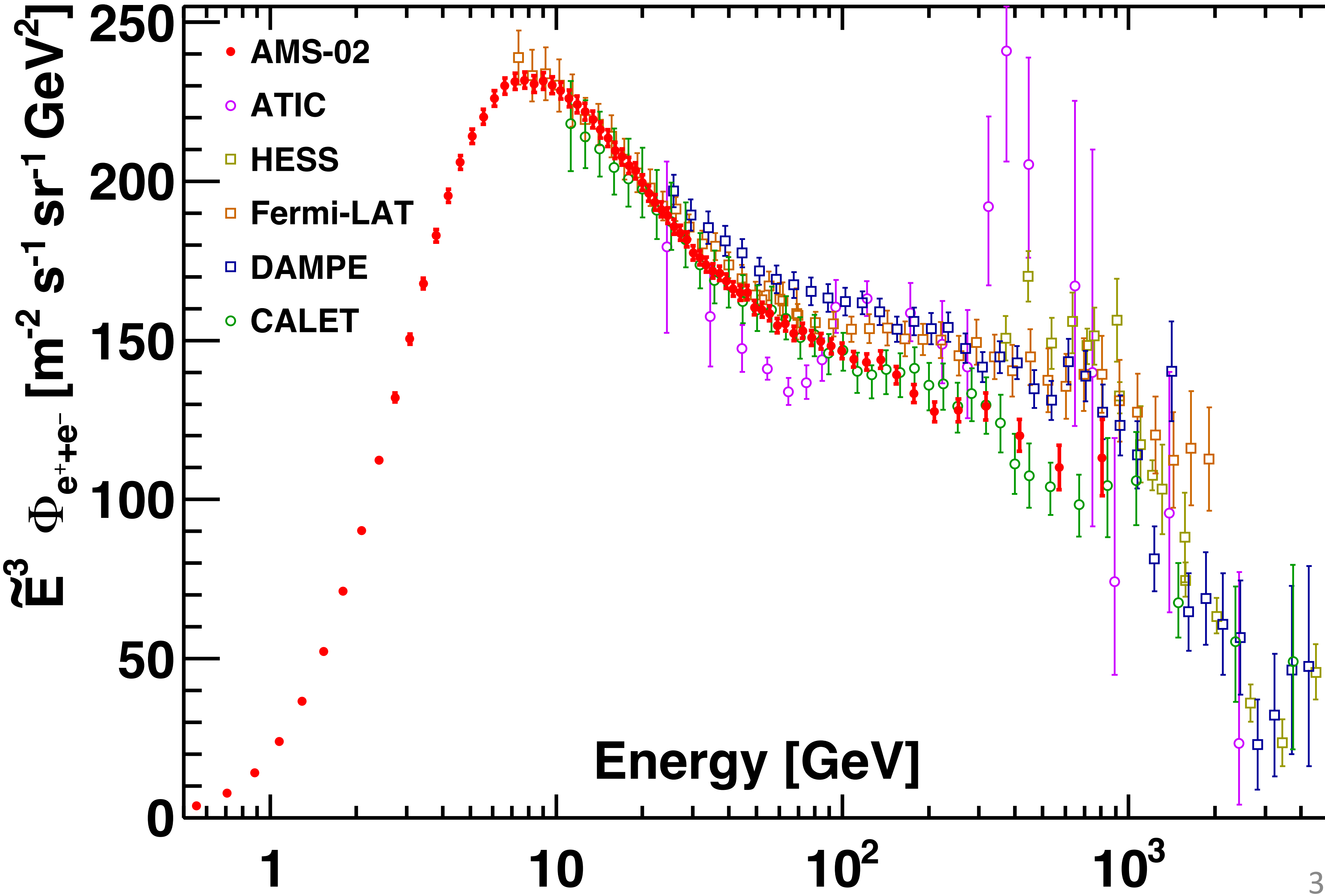
AMS positron fraction together with earlier measurements



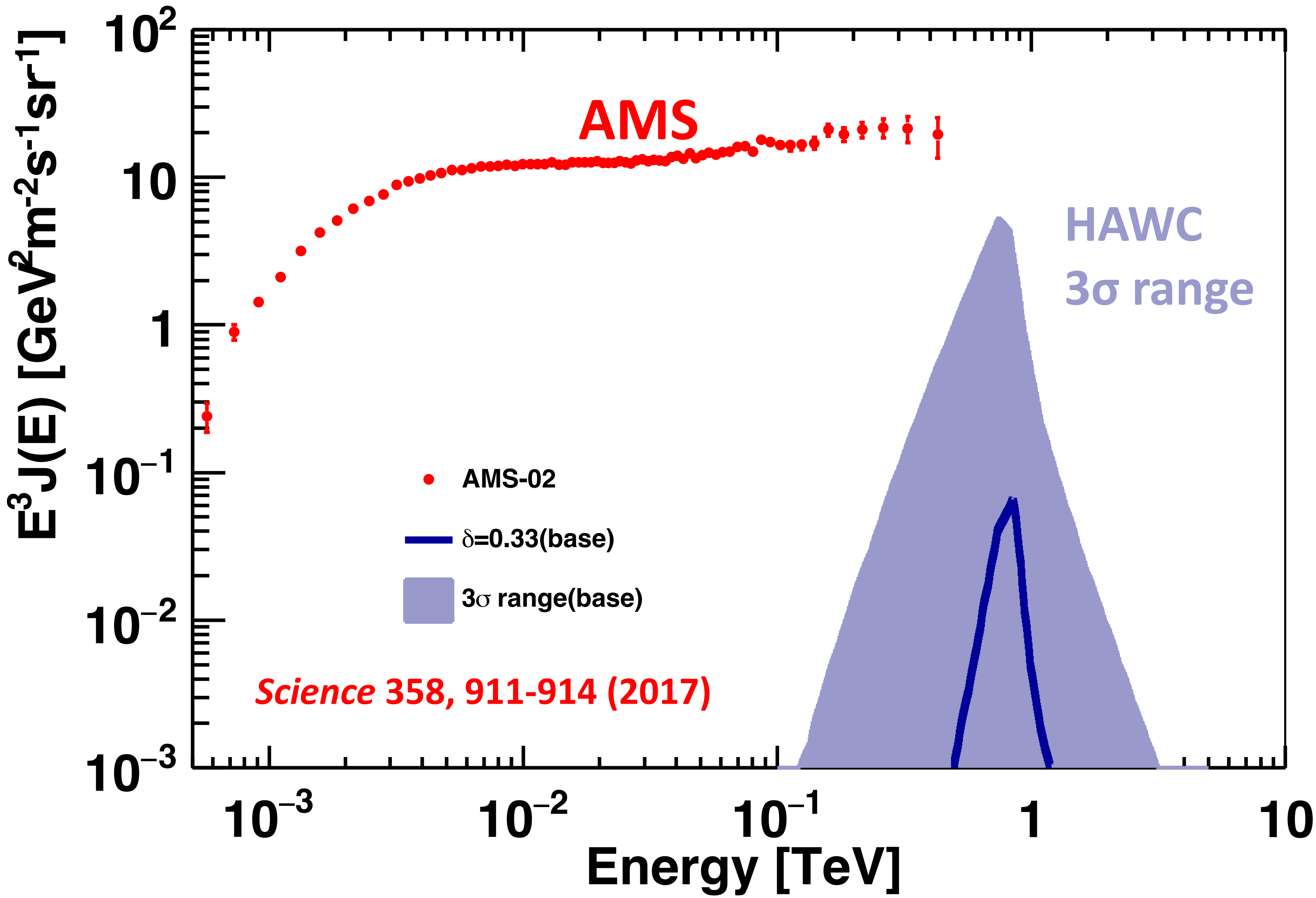
AMS Electron flux with earlier experiments



AMS (electron + positron) spectrum with earlier measurements



HAWC rules out that the positron excess is from nearby pulsars



In addition, AMS Measurement of positron, electron anisotropy will distinguish and constrain Pulsar origin of high energy $e^{\pm}$

A sample of papers on AMS data from more than 2000 publications

Dark Matter

1) J. Kopp, Phys. Rev. D 88, 076013 (2013);
2) L. Feng, R.Z. Yang, H.N. He, T.K. Dong, Y.Z. Fan and J. Chang Phys.Lett. B728 (2014) 250
3) M. Cirelli, M. Kadastik, M. Raidal and A. Strumia ,Nucl.Phys. B873 (2013) 530
4) M. Ibe, S. Iwamoto, T. Moroi and N. Yokozaki, JHEP 1308 (2013) 029
5) Y. Kajiyama and H. Okada, Eur.Phys.J. C74 (2014) 2722
6) K.R. Dienes and J. Kumar, Phys.Rev. D88 (2013) 10, 103509
7) L. Bergstrom, T. Bringmann, I. Cholis, D. Hooper and C. Weniger, PRL 111 (2013) 171101
8) K. Kohri and N. Sahu, Phys.Rev. D88 (2013) 10, 103001
9) A. Ibarra, A.S. Lamperstorfer and J. Silk, Phys.Rev. D89 (2014) 063539
10) Y. Zhao and K.M. Zurek, JHEP 1407 (2014) 017
11) C. H. Chen, C. W. Chiang, and T. Nomura, Phys. Lett. B 747, 495 (2015)
12) H. B. Jin, Y. L. Wu, and Y.-F. Zhou, Phys.Rev. D92, 055027 (2015)
13) A. Reinert and M. W. Winkler JCAP 01 (2018) 055

and many other excellent papers **…**

New Propagation Models

1) R.Cowsik, B.Burch, and T.Madziwa-Nussinov, Ap.J. 786 (2014) 124
2) K. Blum, B. Katz and E. Waxman, Phys.Rev.Lett. 111 (2013) 211101
3) R. Kappl and M. W. Winkler, J. Cosmol. Astropart. Phys. 09 (2014) 051
4) G.Giesen, M.Boudaud, Y.Gènolini, V.Poulin, M.Cirelli, P.Salati and P.D.Serpico, JCAP09 (2015) 023;
5) C.Evoli, D.Gaggero and D.Grasso, JCAP 12 (2015) 039.
6) R.Kappl, A.Reinert, and M.W.Winkler, arXiv:1506.04145 (2015)

and many other excellent papers …

New Astrophysical Sources

1) T. Linden and S. Profumo, Astrophys.J. 772 (2013) 18
2) P. Mertsch and S. Sarkar, Phys.Rev. D 90 (2014) 061301
3) I. Cholis and D. Hooper, Phys.Rev. D88 (2013) 023013
4) A. Erlykin and A.W. Wolfendale, Astropart.Phys. 49 (2013) 23
5) P.F. Yin, Z.H. Yu, Q. Yuan and X.J. Bi, Phys.Rev. D88 (2013) 2, 023001
6) A.D. Erlykin and A.W. Wolfendale, Astropart.Phys. 50-52 (2013) 47
7) E. Amato, Int.J.Mod.Phys.Conf.Ser. 28 (2014) 1460160
8) P. Blasi, Braz.J.Phys. 44 (2014) 426
9) D. Gaggero, D. Grasso, L. Maccione, G. DiBernardo and C Evoli, Phys.Rev. D89 (2014) 083007
10) M. DiMauro, F. Donato, N. Fornengo, R. Lineros and A. Vittino, JCAP 1404 (2014) 006
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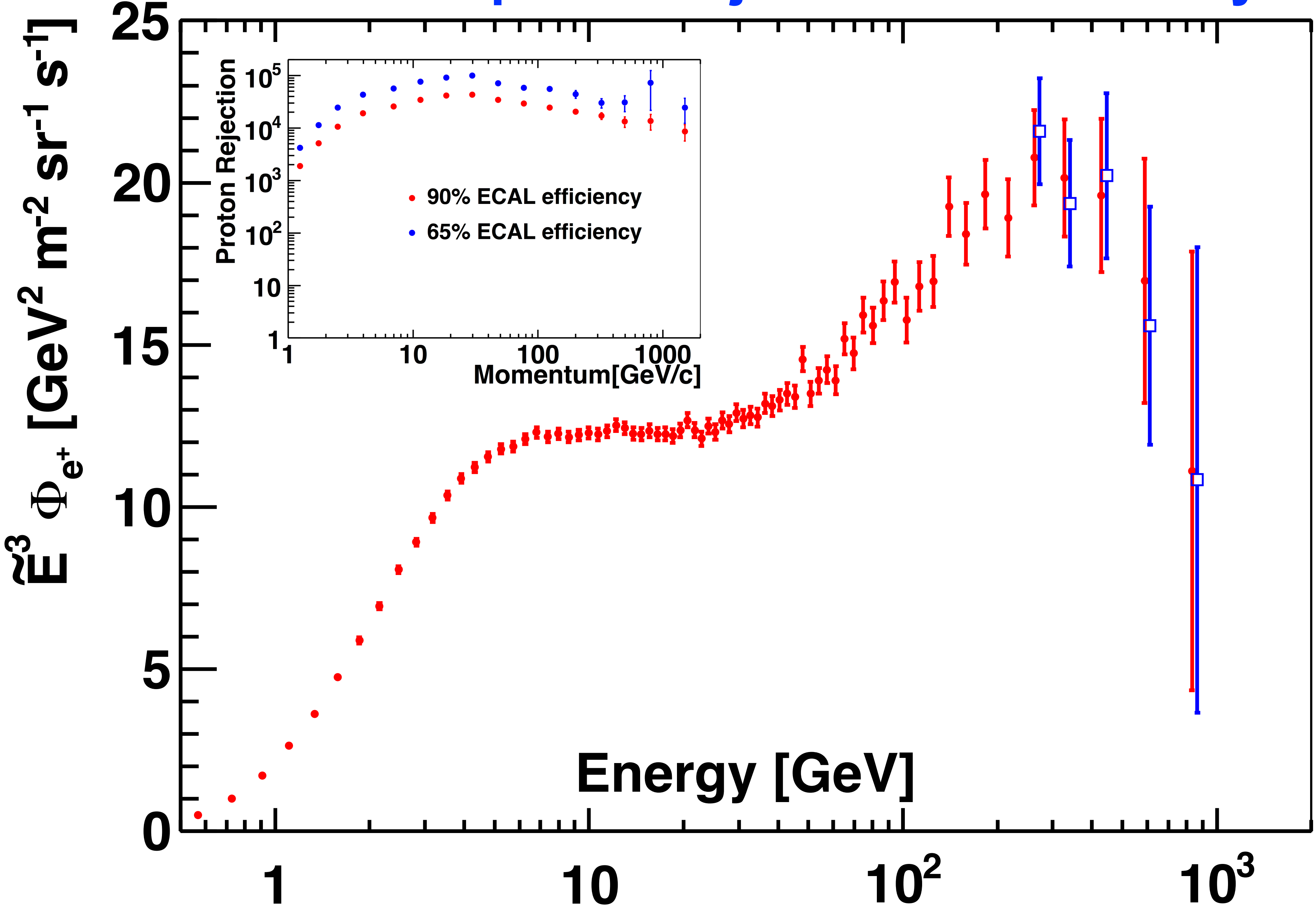
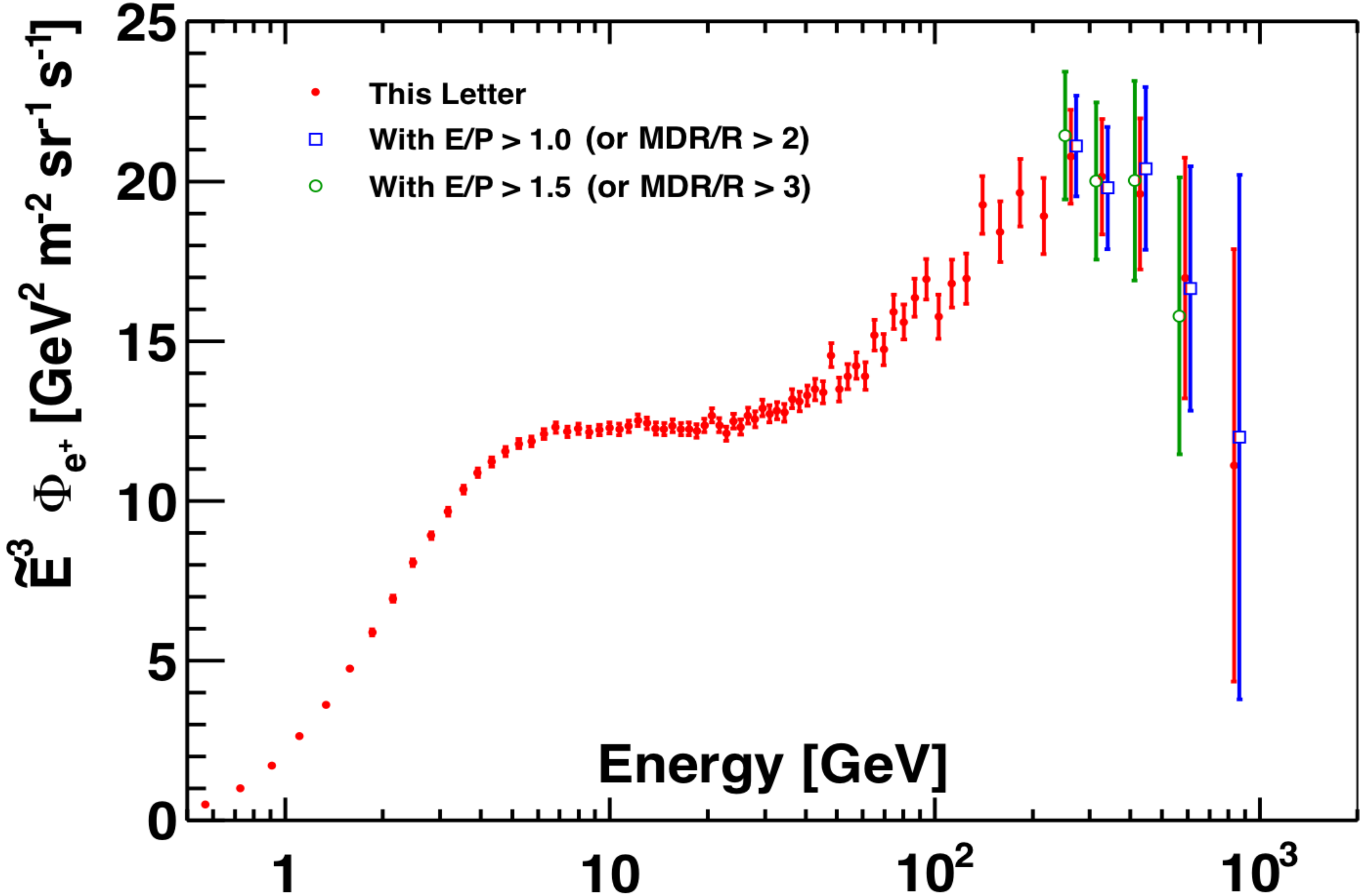
and many other excellent papers …

Consistency check:

Positron flux with proton rejection increased by x3



Consistency check:
Positron flux with E/P selections



The Origins of Cosmic Electrons (II)

The existence of a high energy charge symmetric source term

$$\Phi_{e^-}(E) = C_{e^-}(E/E_1)^{\gamma_{e^-}} + f_{e^-}\, C_s^{e^+}(E/E_2)^{\gamma_s^{e^+}} \exp(-E/E_s^{e^+})$$

- AMS Electron flux is consistent both with or without a charge symmetrical source
- It's not possible to extract any additional information on the existence and properties of the source term using the electron flux alone.