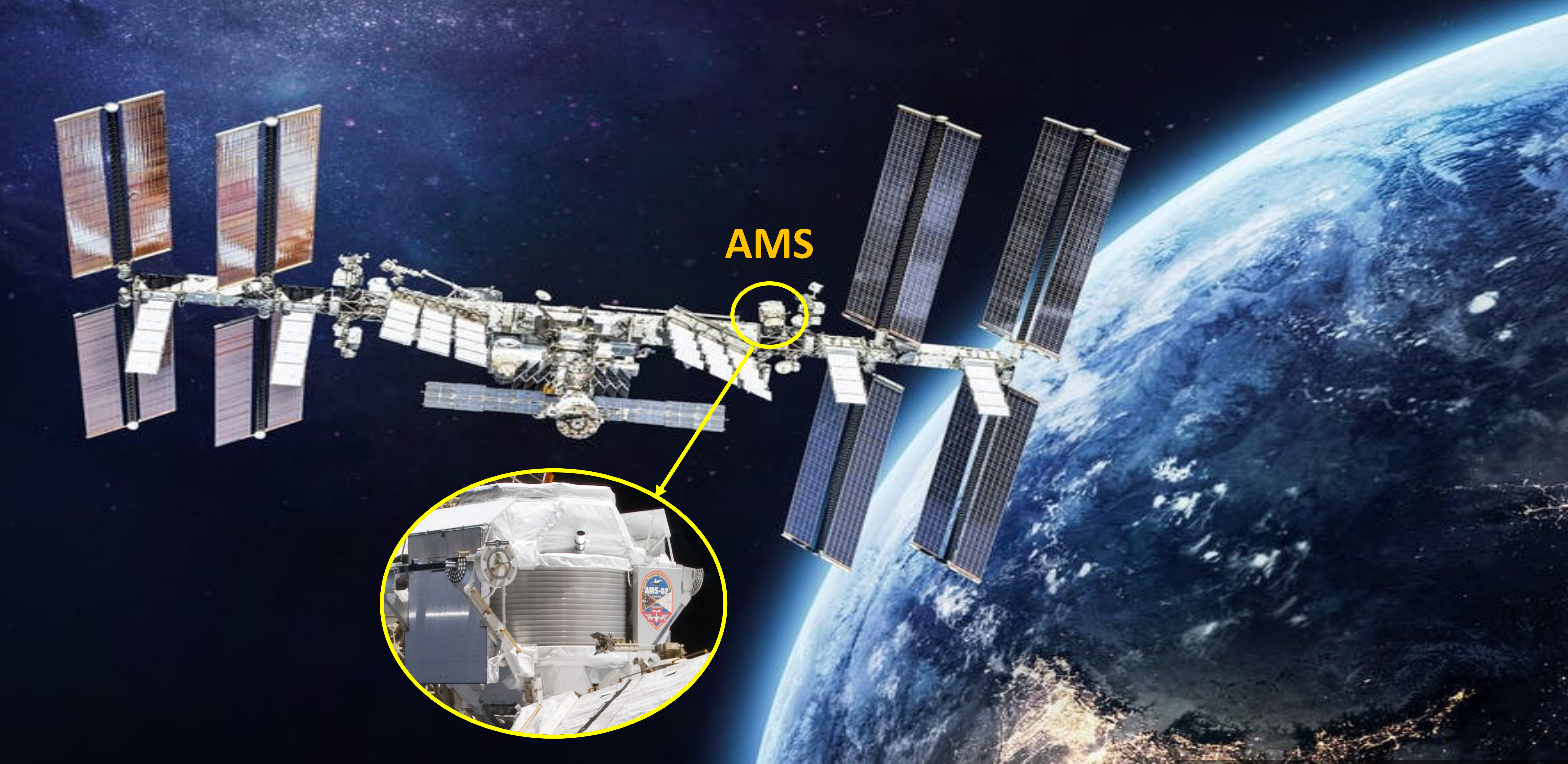
Origins of Cosmic Positrons and Electrons



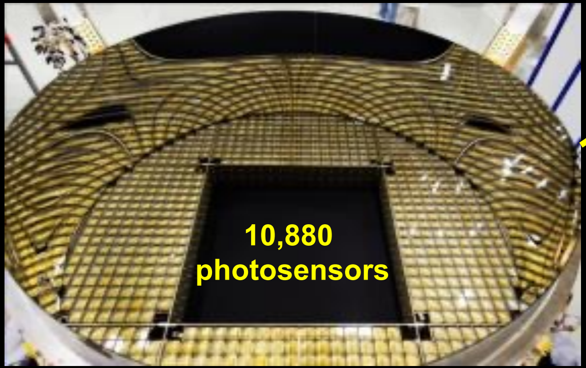
ICHEP2024, Prague
July 19, 2024
Andrei Kounine / MIT

AMS is a space version of a precision magnetic spectrometer

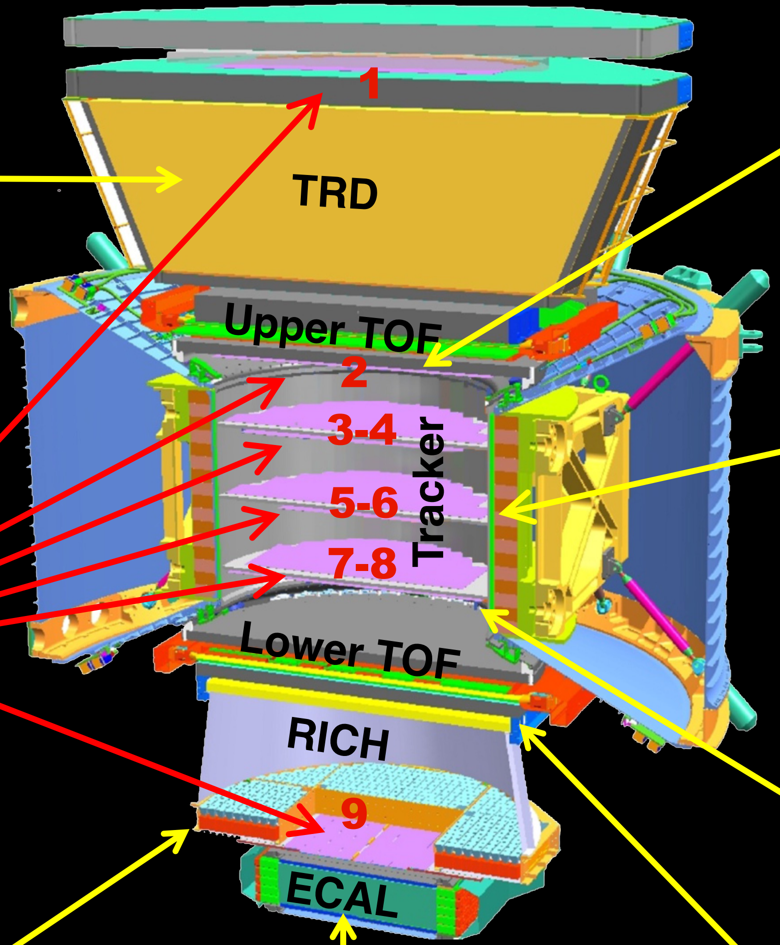
Transition Radiation Detector (TRD)
identify e^+, e^-

Silicon Tracker
measure Z, P

Ring Imaging Cerenkov (RICH)
measure Z, E



10,880 photosensors



Electromagnetic Calorimeter (ECAL)
measure E of e^+, e^-

Upper TOF measure Z, E

Magnet identify ±Z, P

Anticoincidence Counters (ACC)
reject particles from the side

09/06/2010

Lower TOF measure Z, E

AMS on ISS

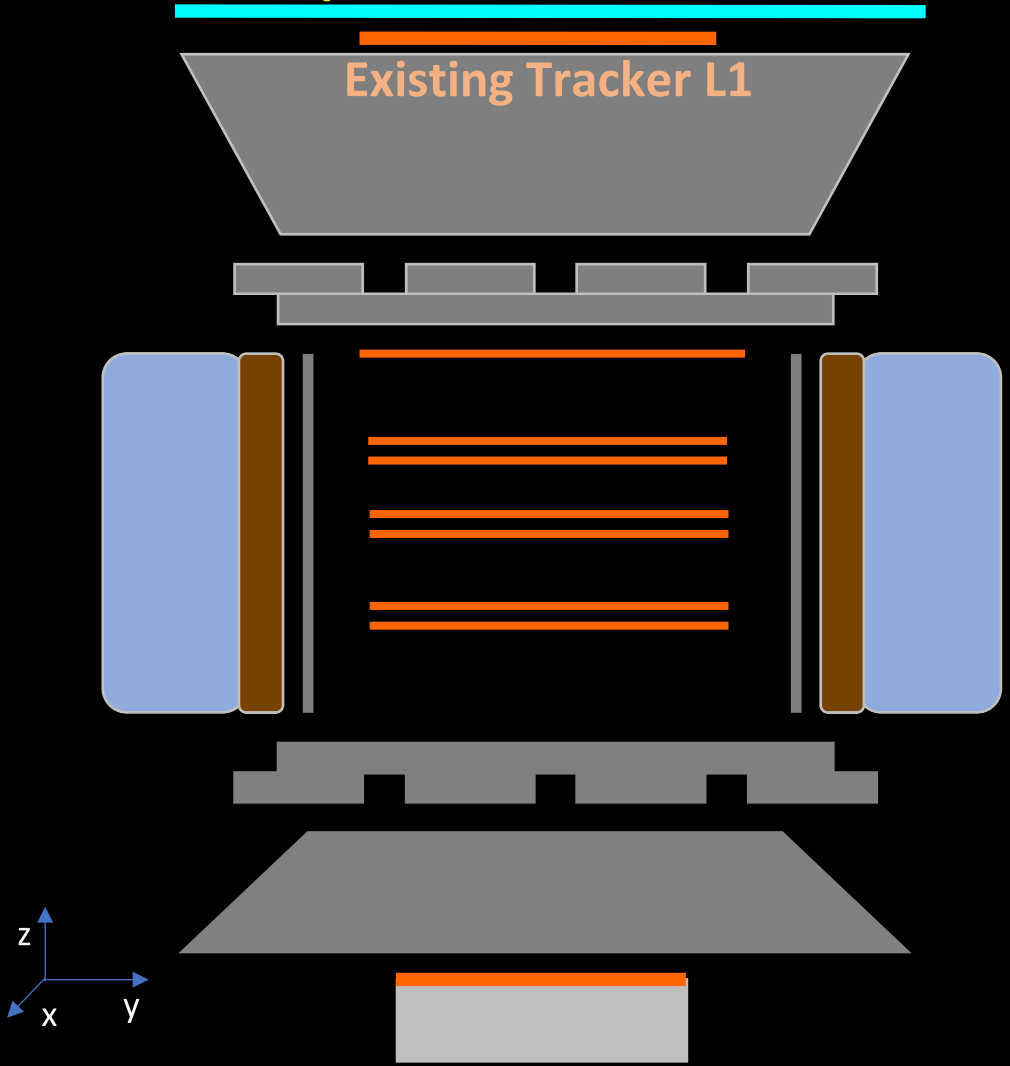
AMS 2011-2025

Continuous data-taking

Latest Results: 2011-2024

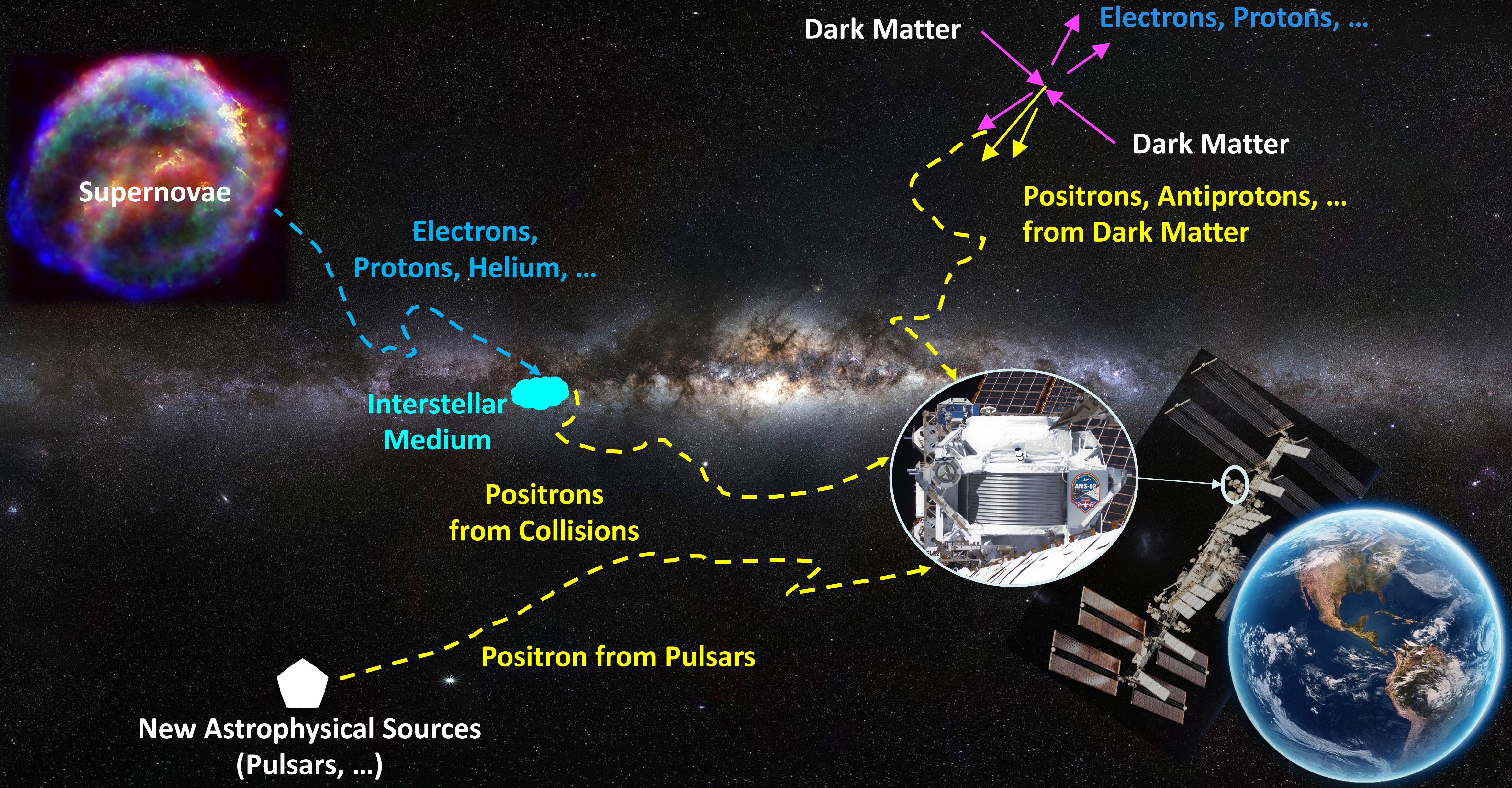
AMS 2025-2030

New $8m^2$ Silicon Tracker Layer
Acceptance increased to 300%



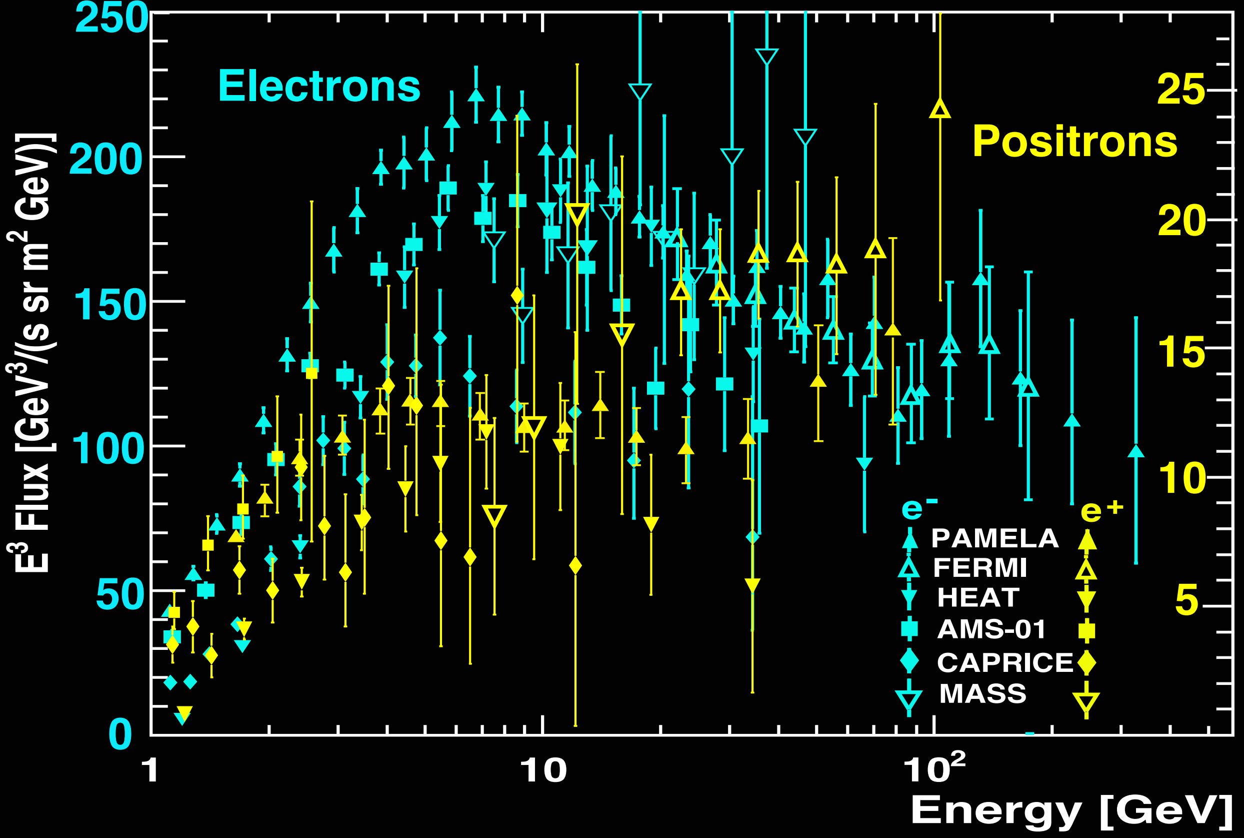
and Projections to 2030

Latest Physics Results from AMS: Study of Positrons & Electrons

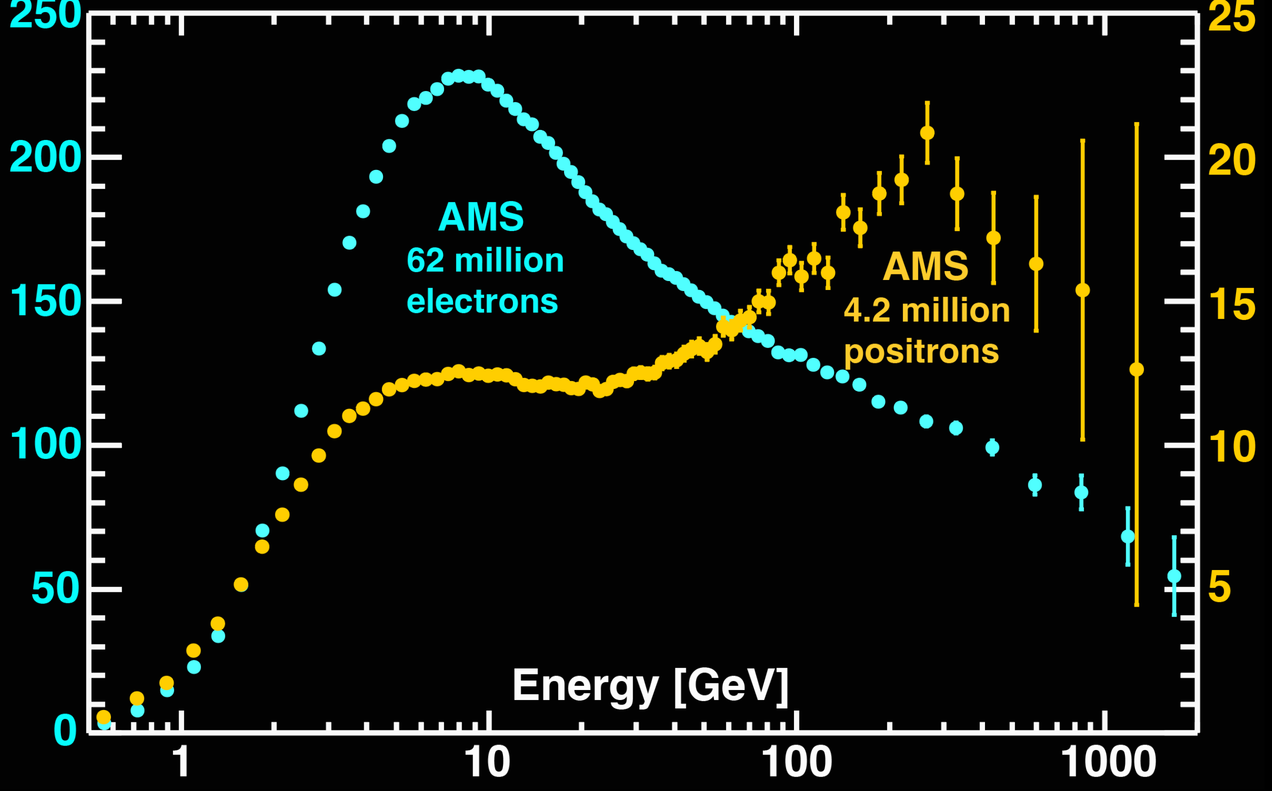


Study of Positrons & Electrons

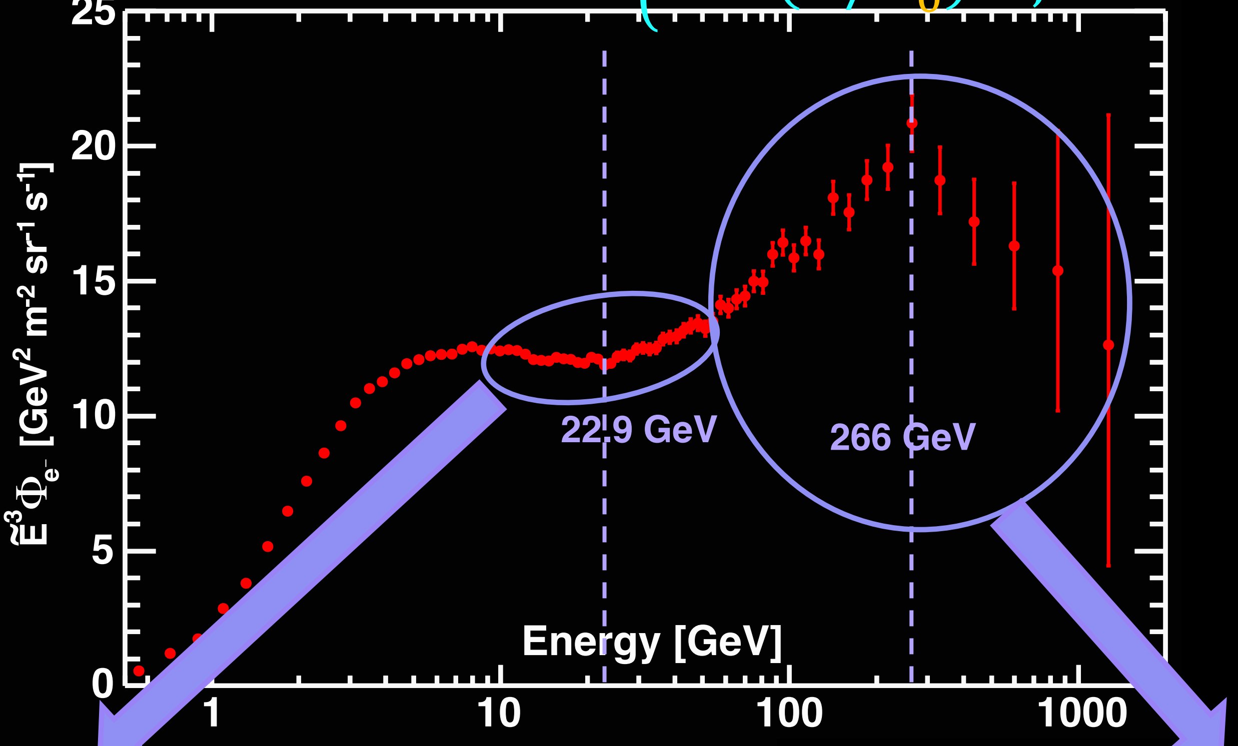
Measurements before AMS



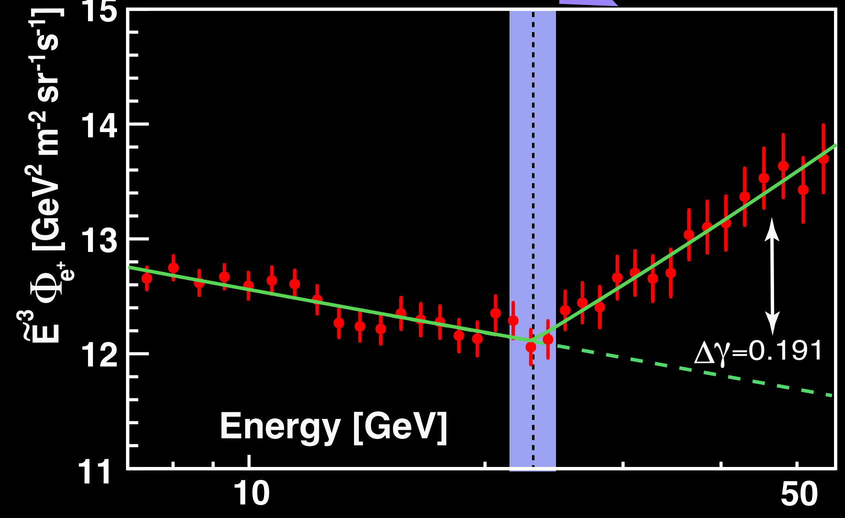
AMS measurements



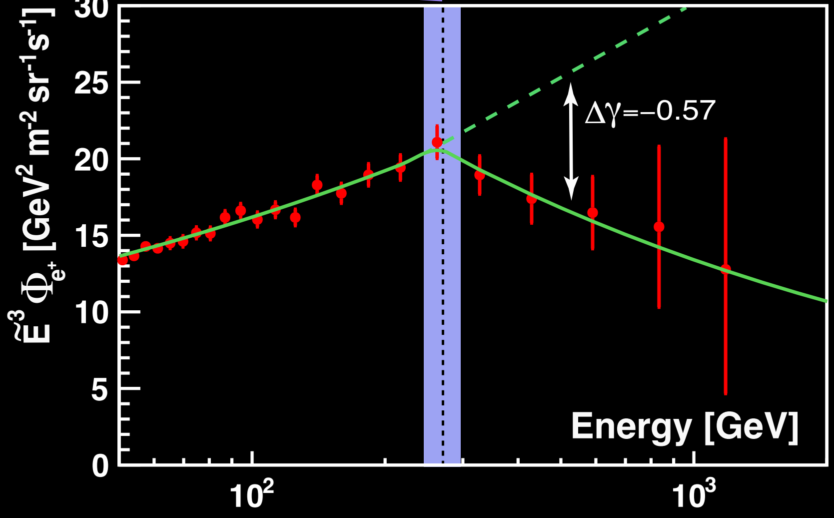
Fits of the data to $\Phi_{e^+}(E) = \begin{cases} CE^{\gamma}, & E \leq E_0; \\ CE^{\gamma}(E/E_0)^{\Delta\gamma}, & E > E_0. \end{cases}$



10σ
excess above
$E_0 = 22.9 \pm 1.0$ GeV



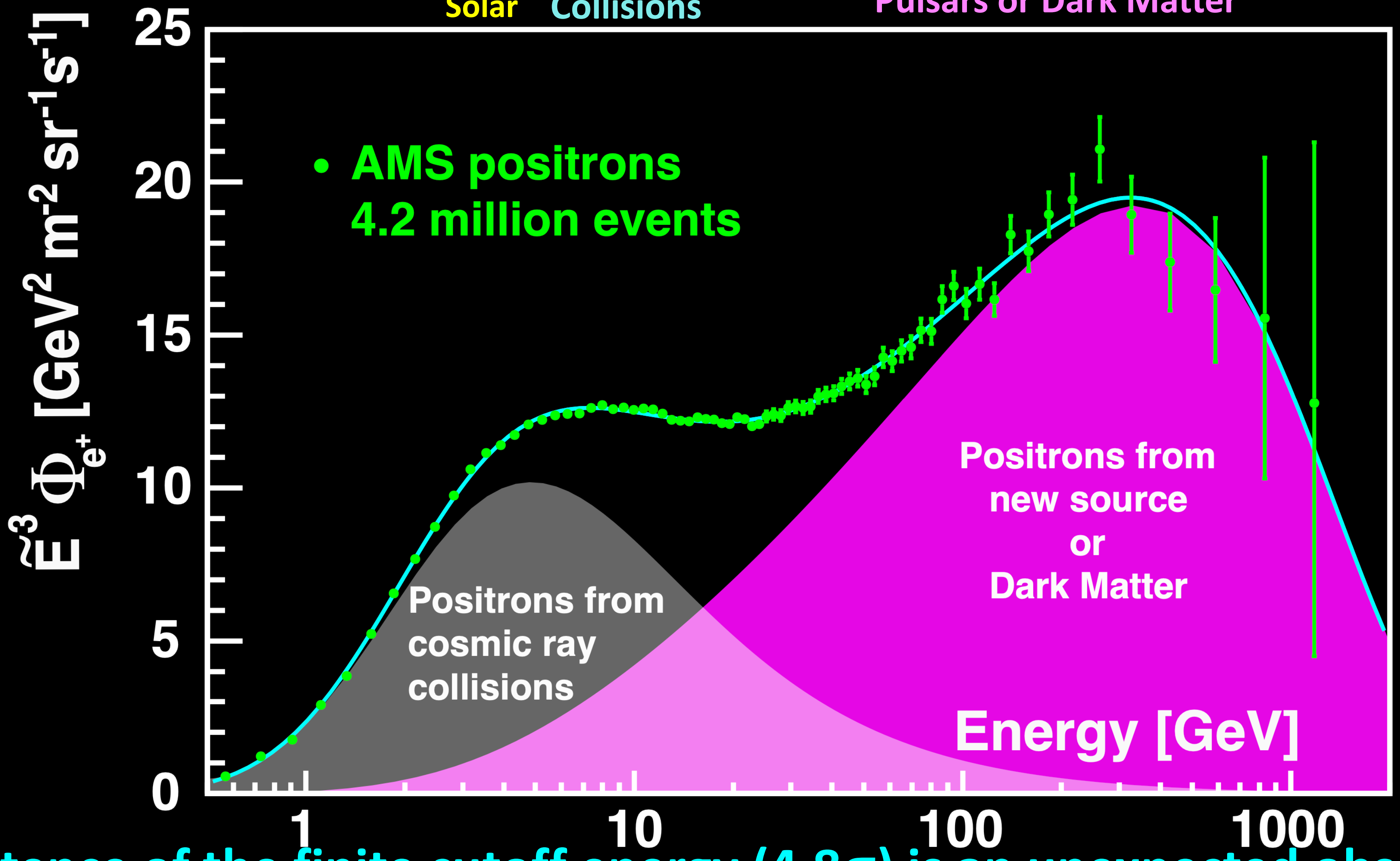
5.0σ
sharp drop-off at
$E_0 = 266^{+29}_{-27}$ GeV



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

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

Solar Collisions Pulsars or Dark Matter

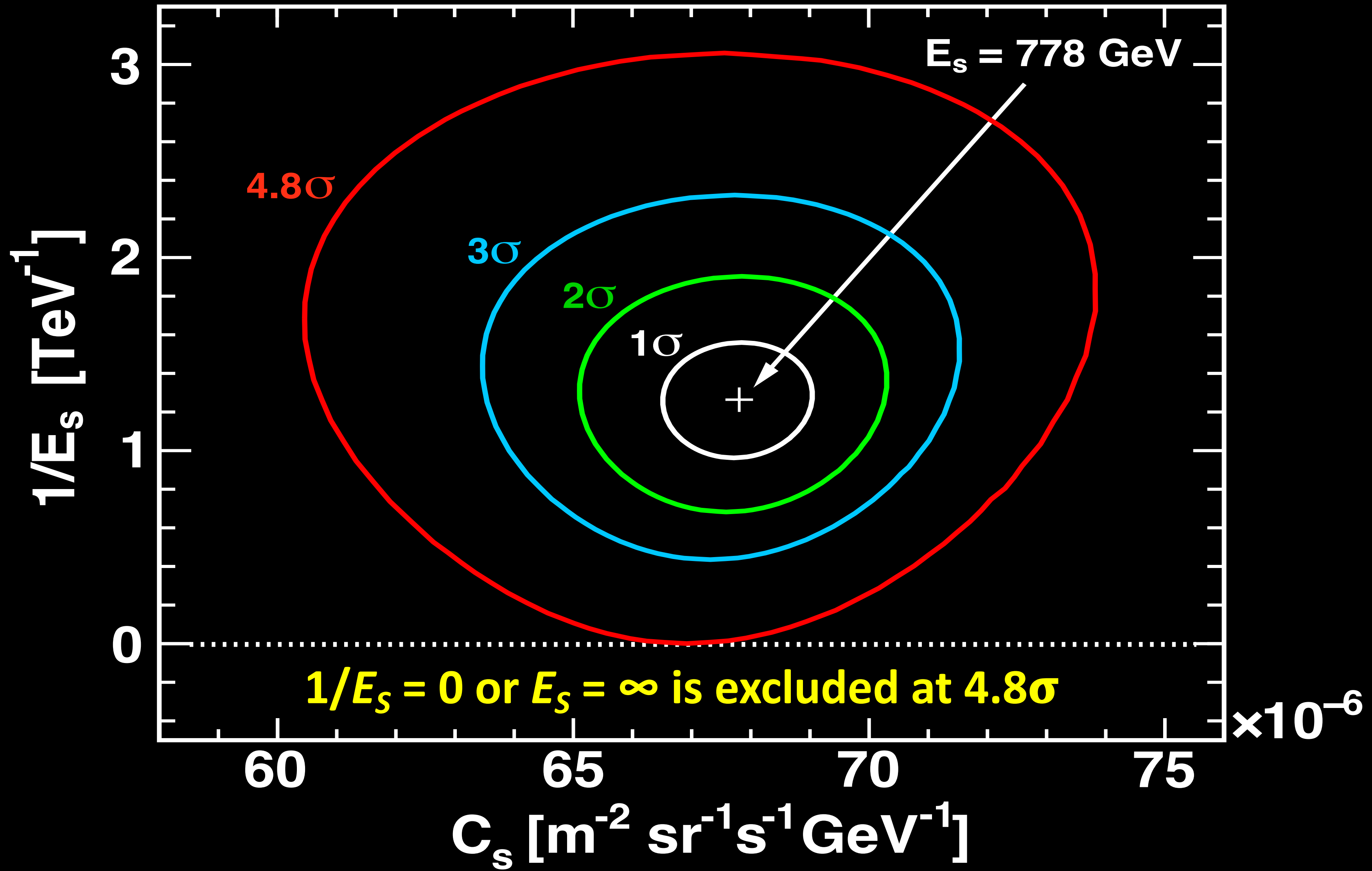


The existence of the finite cutoff energy (4.8σ) is an unexpected observation

Determination of the cutoff energy E_S

Collisions New Source or Dark Matter

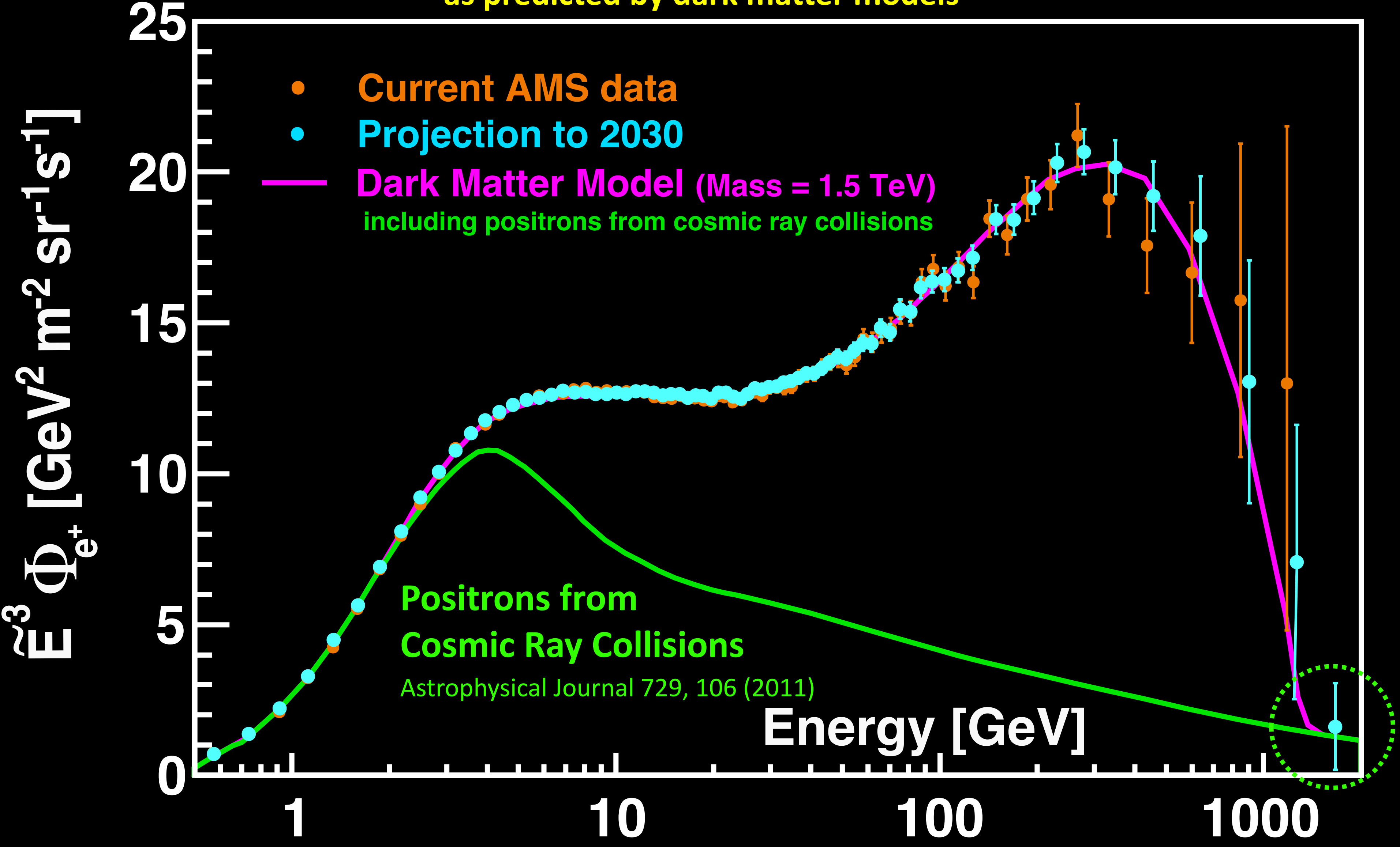
$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s\left(\hat{E}/E_2\right)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$



$1/E_S = 0$ or $E_S = \infty$ is excluded at 4.8σ

Determination of the Origin of Cosmic Positrons by 2030

AMS will ensure that the measured high energy positron spectrum indeed drops off quickly and, at the highest energies, the positrons only come from cosmic ray collisions as predicted by dark matter models



A sample of recent theoretical models explaining AMS positron and electron data (overall >3000 citations)

1) I. Krommydas, I. Cholis, Phys. Rev. D 107 (2023) 2, 023003
2) I. John, T. Linden, JCAP 12 (2021) 007
3) H. Motz, H. Okada, Y. Asaoka, and K. Kohri, Phys.Rev. D102 (2020) 8, 083019
4) Z.Q. Huang, R.Y. Liu, J.C. Joshi, X.Y. Wang, Astrophys.J. 895 (2020) 1, 53
5) R. Diesing and D. Caprioli, Phys.Rev. D101 (2020) 10
6) A. Das, B. Dasgupta, and A. Ray, Phys.Rev. D101 (2020) 6
7) F. S. Queiroz and C. Siqueira, Phys.Rev. D101 (2020) 7, 075007
8) Z.L. Han, R. Ding, S.J. Lin, and B. Zhu, Eur.Phys.J. C79 (2019) 12, 1007
9) C.Q. Geng, D. Huang, and L. Yin, Nucl.Phys. B959 (2020) 115153
10) S. Profumo, F. Queiroz, C. Siqueira, J.Phys.G 48 (2020) 1, 015006

and many other excellent papers …

Dark Matter

1) O. M. Bitter, D. Hooper, JCAP 10 (2022) 081
2) T.P. Tang, Z.Q. Xia, Z.Q. Shen, et al., Phys. Lett. B 825 (2022) 136884
3) P. Mertsch, A. Vittino, and S. Sarkar, Phys.Rev. D 104 (2021) 103029
4) P. Zhang et al., JCAP 05 (2021) 012
5) C. Evoli, E. Amato, P. Blasi, and R. Aloisio, Phys.Rev. D103 (2021) 8, 083010
6) K. Fang, X.J. Bi, S.J. Lin, and Q. Yuan, Chin.Phys.Lett. 38 (2021) 3, 039801
7) C. Evoli, P. Blasi, E. Amato, and R. Aloisio, Phys.Rev.Lett. 125 (2020) 5, 051101
8) O. Fornieri, D. Gaggero, and D. Grasso, JCAP 02 (2020) 009
9) P. Cristofari and P. Blasi, Mon.Not.Roy.Astron.Soc. 489 (2019) 1, 108
10) S. Recchia, S. Gabici, F.A. Aharonian, and J. Vink, Phys.Rev. D99 (2019) 10, 103022

and many other excellent papers …

Astrophysical sources

1) E. Silver, E. Orlando, Astrophys. J. 963 (2024) 2, 111
2) M. Di Mauro, F. Donato, M. Korsmeier, et al., Phys. Rev. D 108 (2023) 6, 063024
3) E. Amato and S. Casanova, J.Plasma Phys. 87 (2021) 1, 845870101
4) Z. Tian et al., Chin.Phys. C44 (2020) 8, 085102
5) W. Zhu, P. Liu, J. Ruan, and F. Wang, Astrophys.J. 889 (2020) 127
6) P. Liu and J. Ruan, Int.J.Mod.Phys. E28 (2019) 09, 1950073
7) R. Diesing and D. Caprioli, Phys.Rev.Lett. 123 (2019) 7, 071101
8) W. Zhu, J. S. Lan and J. H. Ruan, Int. J. Mod. Phys. E27 (2018) 1850073

and many other excellent papers …

Propagation

AMS Publications on electrons and positrons

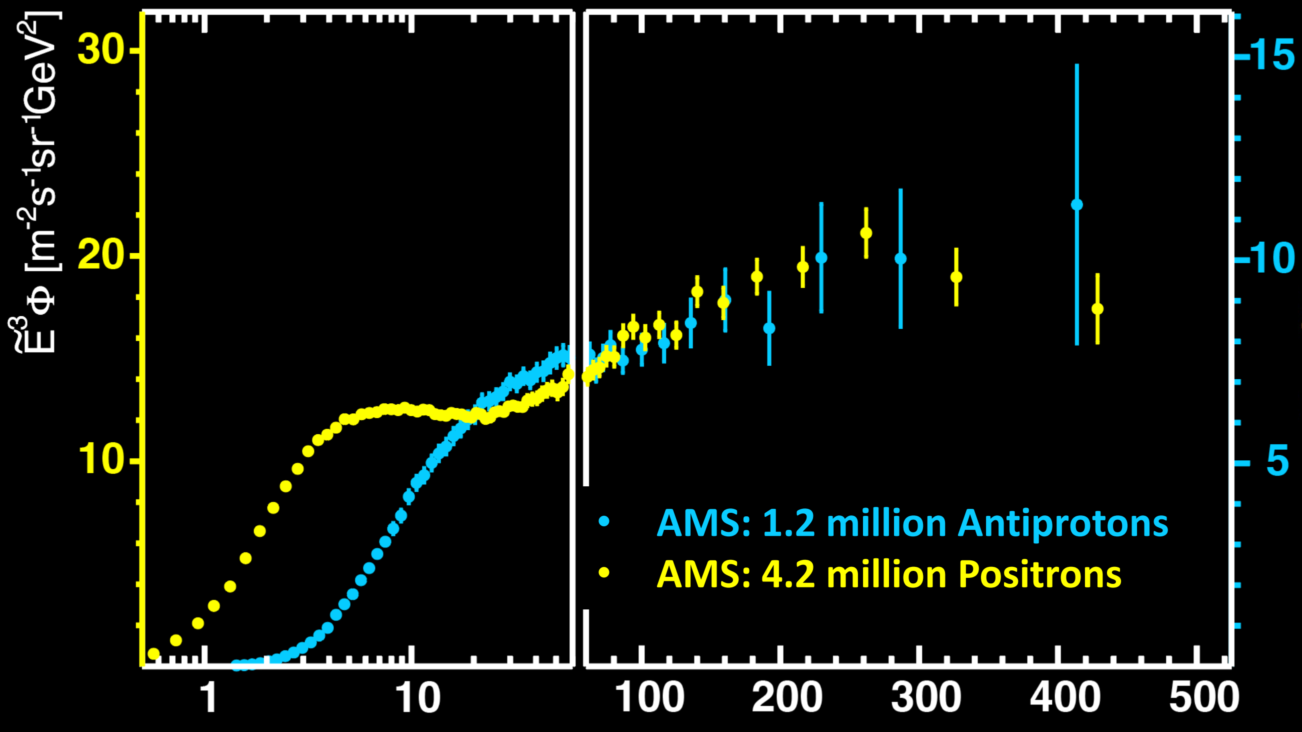
1) M. Aguilar *et. al.*, Phys. Rev. Lett. 110 (2013) 141102.
   APS Highlight of the Year 2013
   10-year Retrospective of Editors' Suggestions
2) L. Accardo *et al.*, Phys. Rev. Lett. 113 (2014) 121101.
   Editor's Suggestion
3) M. Aguilar *et. al.*, Phys. Rev. Lett. 113 (2014) 121102.
   Editor's Suggestion
4) M. Aguilar *et. al.*, Phys. Rev. Lett. 113 (2014) 221102.
5) M. Aguilar *et. al.*, Phys. Rev. Lett. 122 (2019) 041102.
   Editor's Suggestion
6) M. Aguilar *et. al.*, Phys. Rev. Lett, 122 (2019) 101101.
7) M. Aguilar et. al., Physics Reports, 894 (2021) 1.

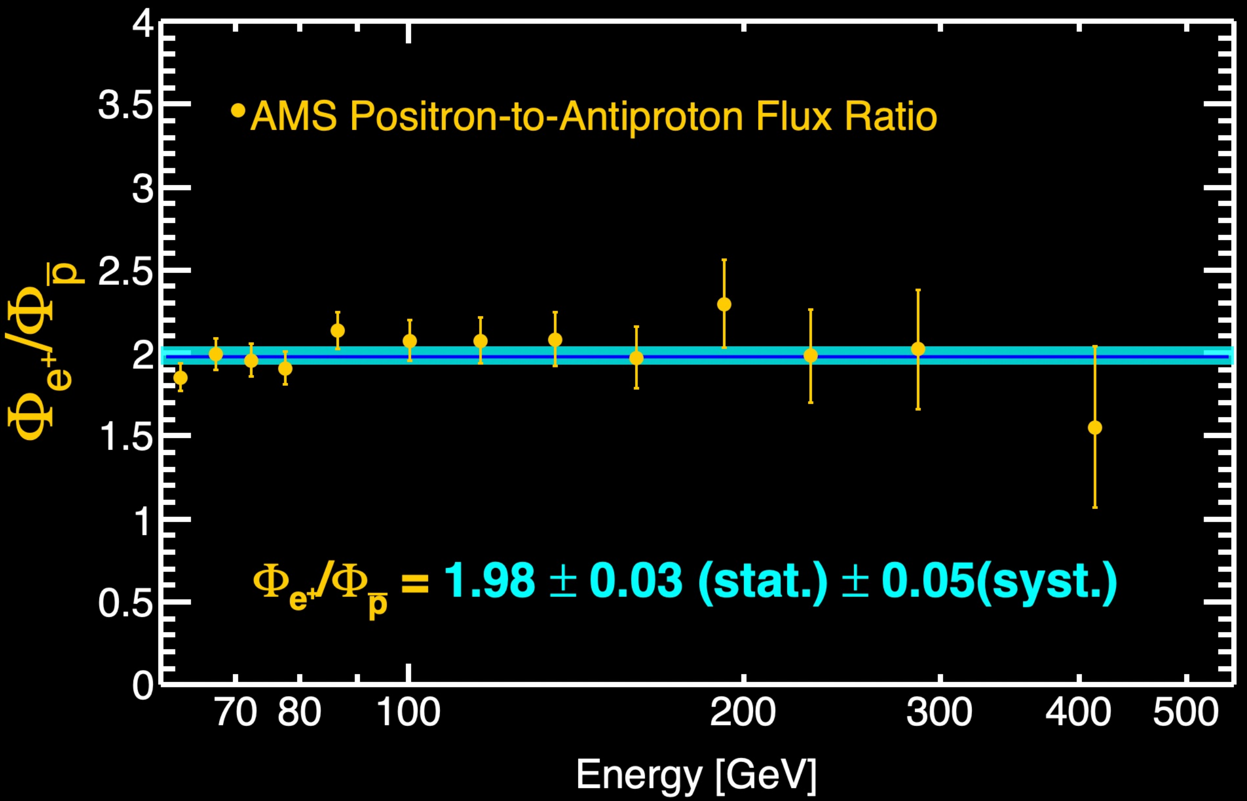
Unique Observation from AMS:

Positron and Antiproton have nearly identical energy dependence

The positron-to-antiproton flux ratio is independent of energy.

Presented by C. Zhang

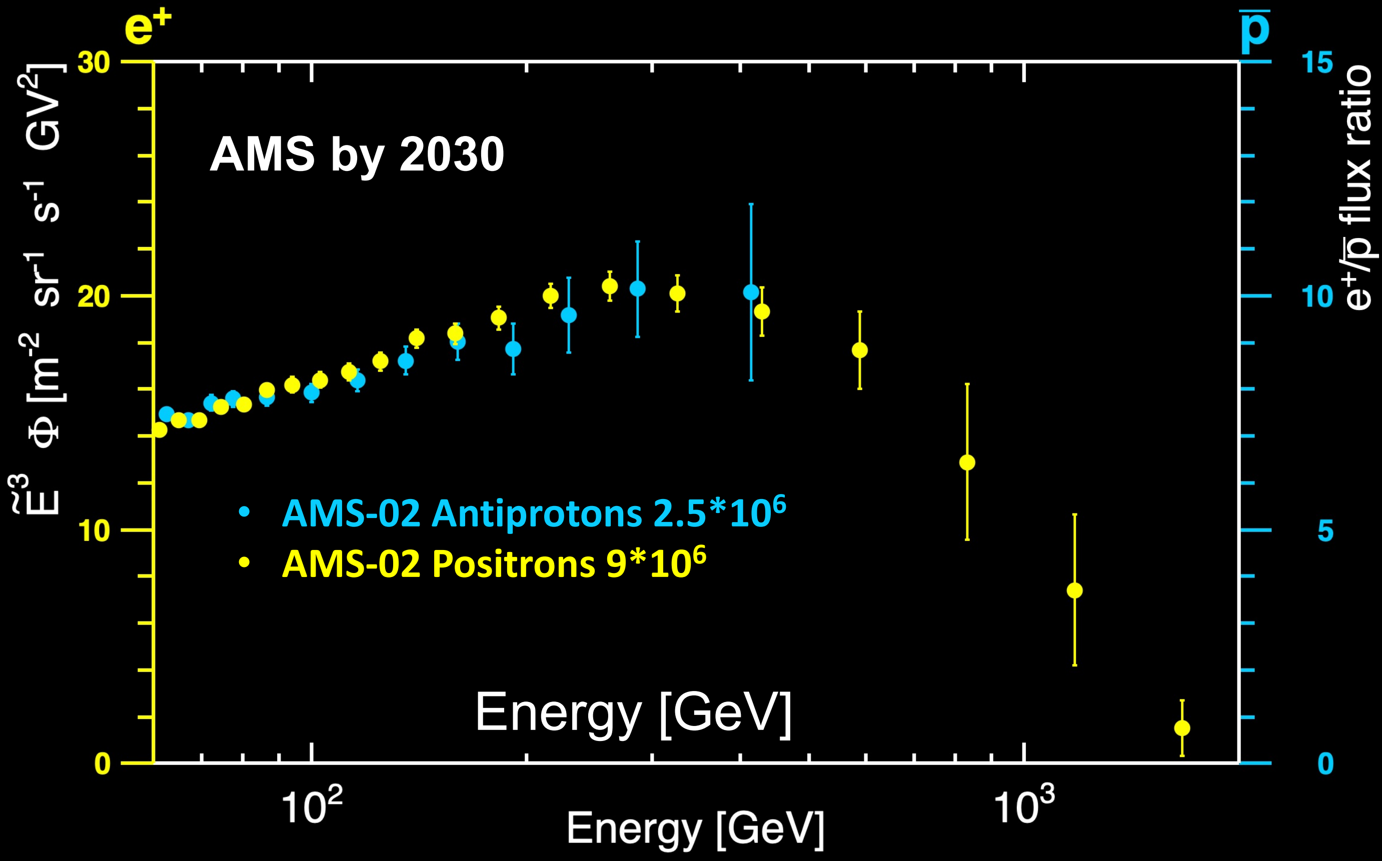


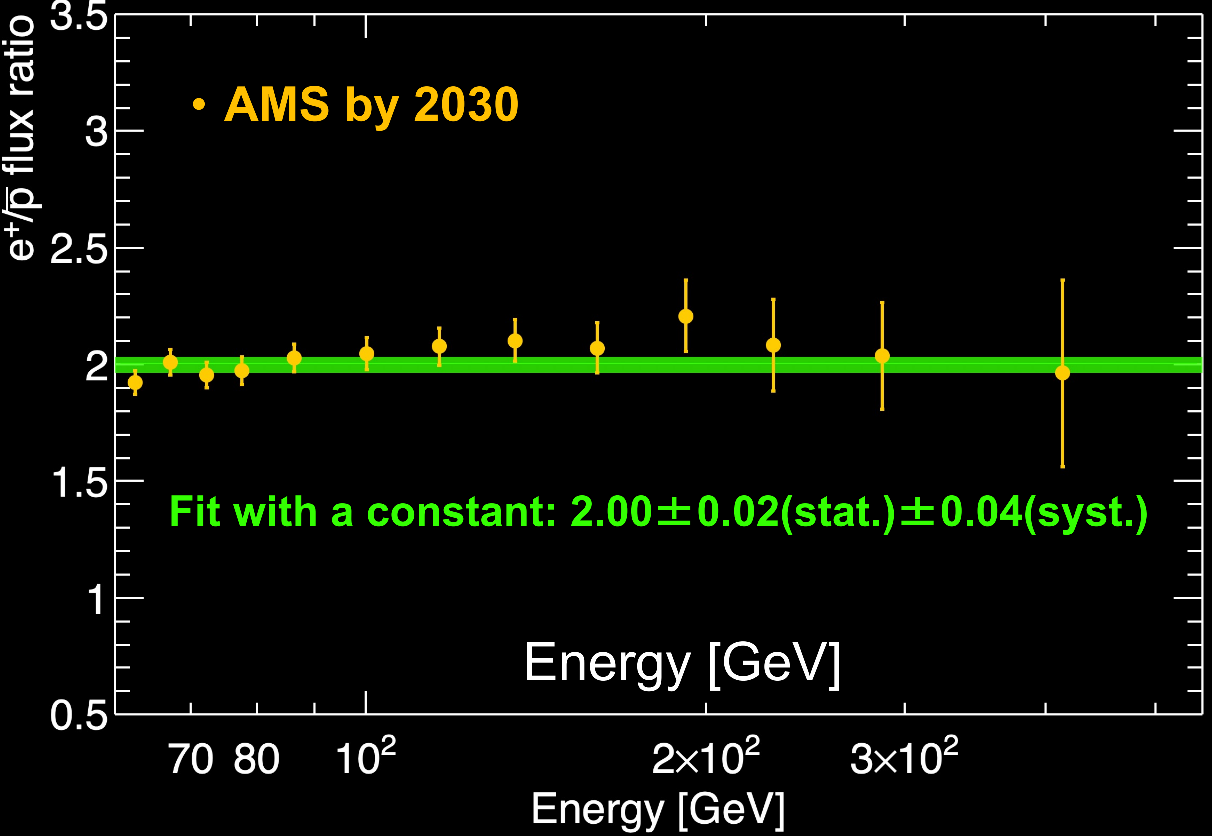


Antiprotons cannot come from pulsars.

By 2030, AMS will greatly improve the accuracy of the antiproton spectra

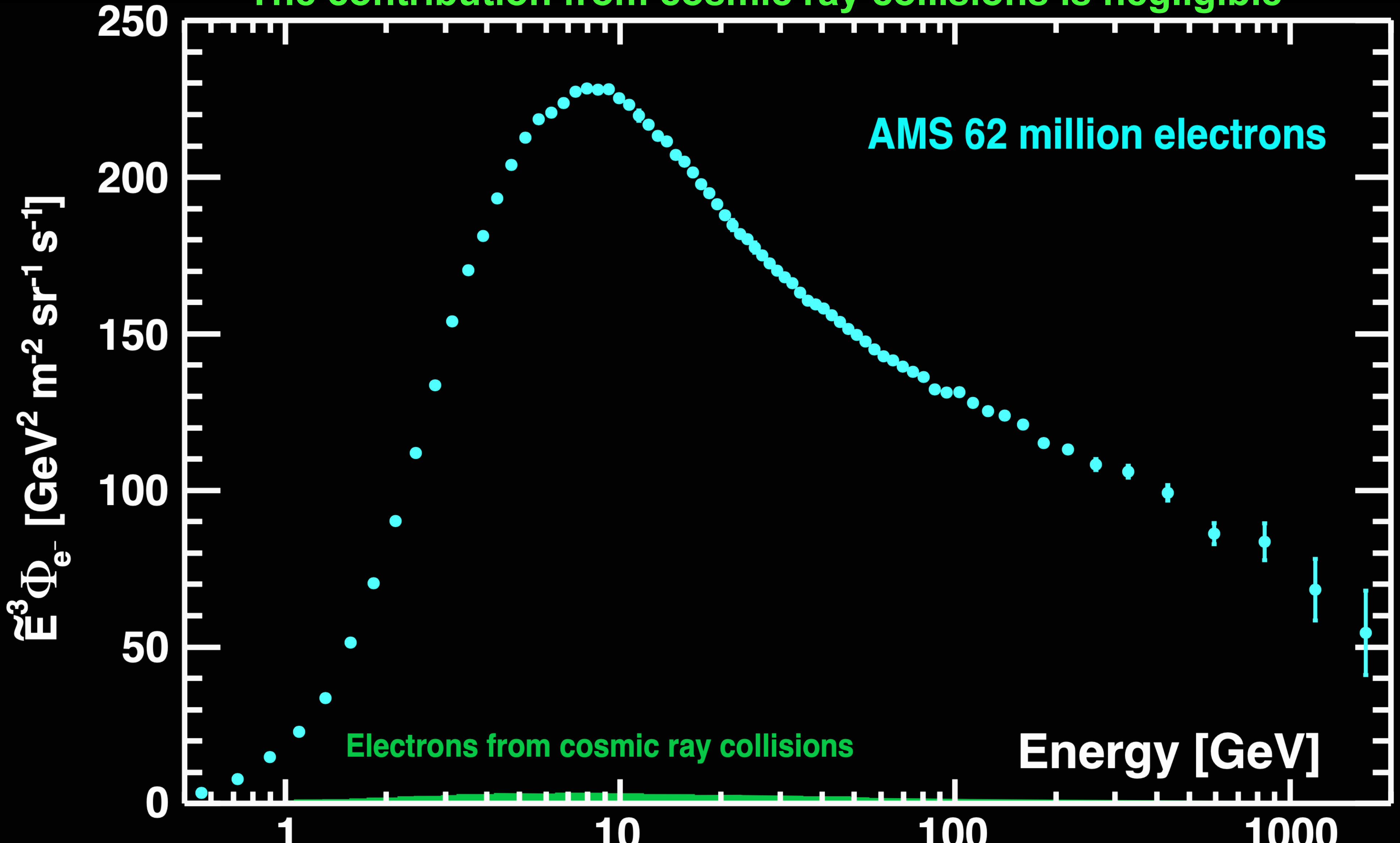
The identical behaviour of positrons and antiprotons excludes the pulsar origin of positrons





Origins of Cosmic Electrons

The contribution from cosmic ray collisions is negligible



Origins of Cosmic Electrons

Traditionally, Cosmic Ray spectrum is described by a power law function

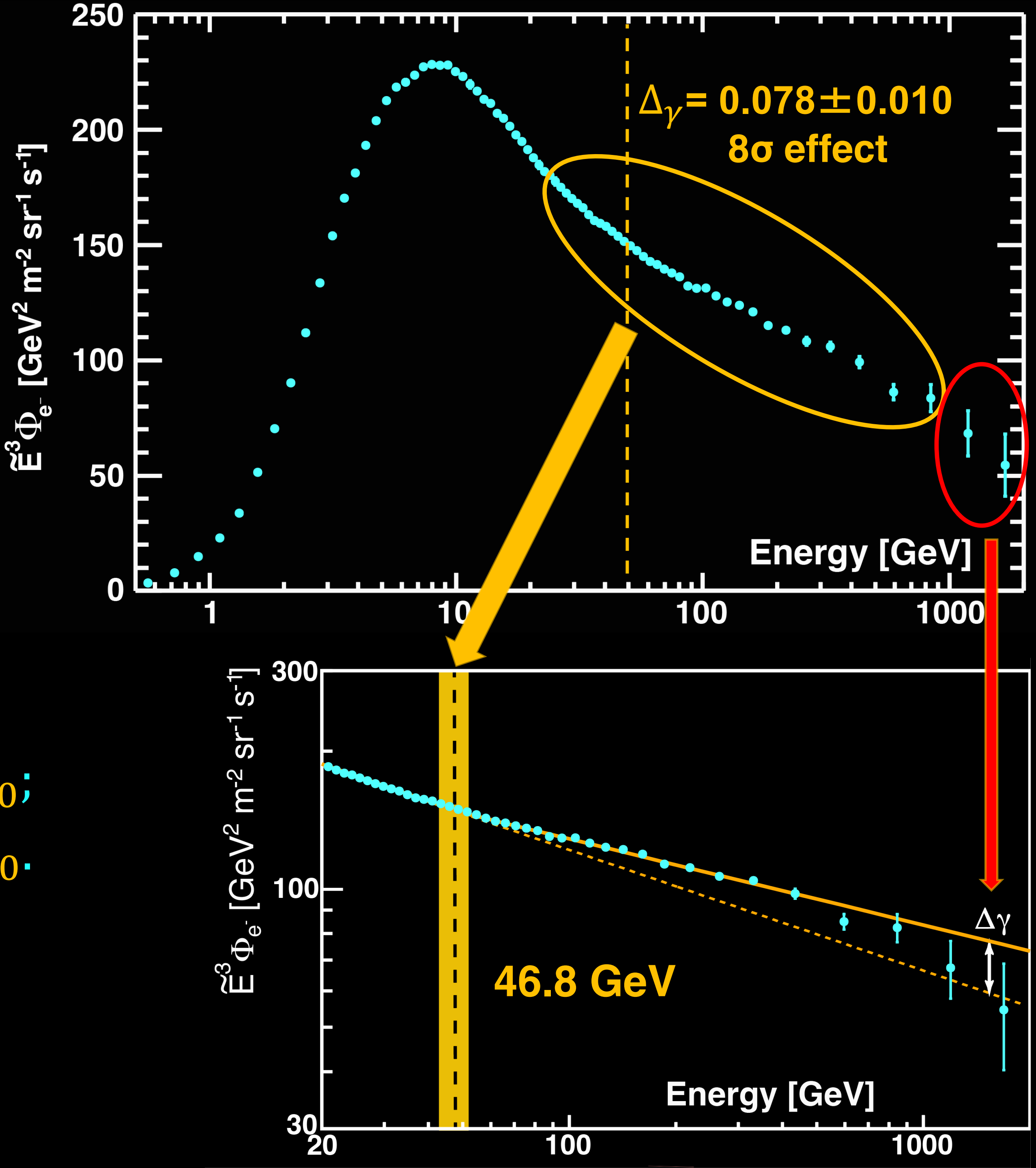
Change of the behavior at 46.8 GeV and at ~1 TeV

Fit to data

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

8 sigma excess at

E_0 = 46.8±3.1 GeV



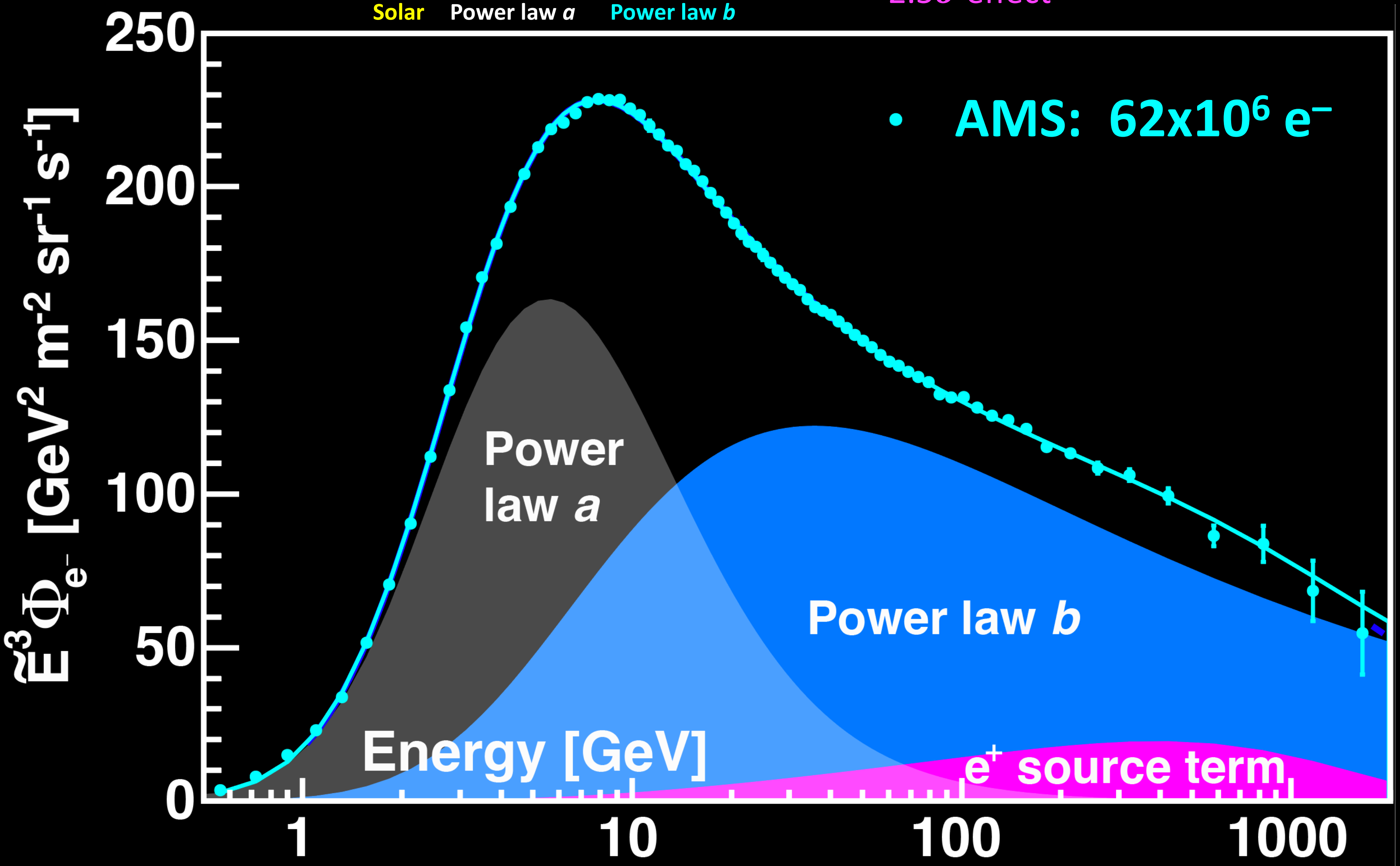
AMS Result on the electron spectrum

The spectrum fits well with two power laws (*a*, *b*) and a source term like positrons

$$\Phi_{e^-}(E) = \frac{E^2}{\widehat{E}^2}\left(C_a \widehat{E}^{\gamma_a} + C_b \widehat{E}^{\gamma_b} + \text{Positron Source Term}\right)$$

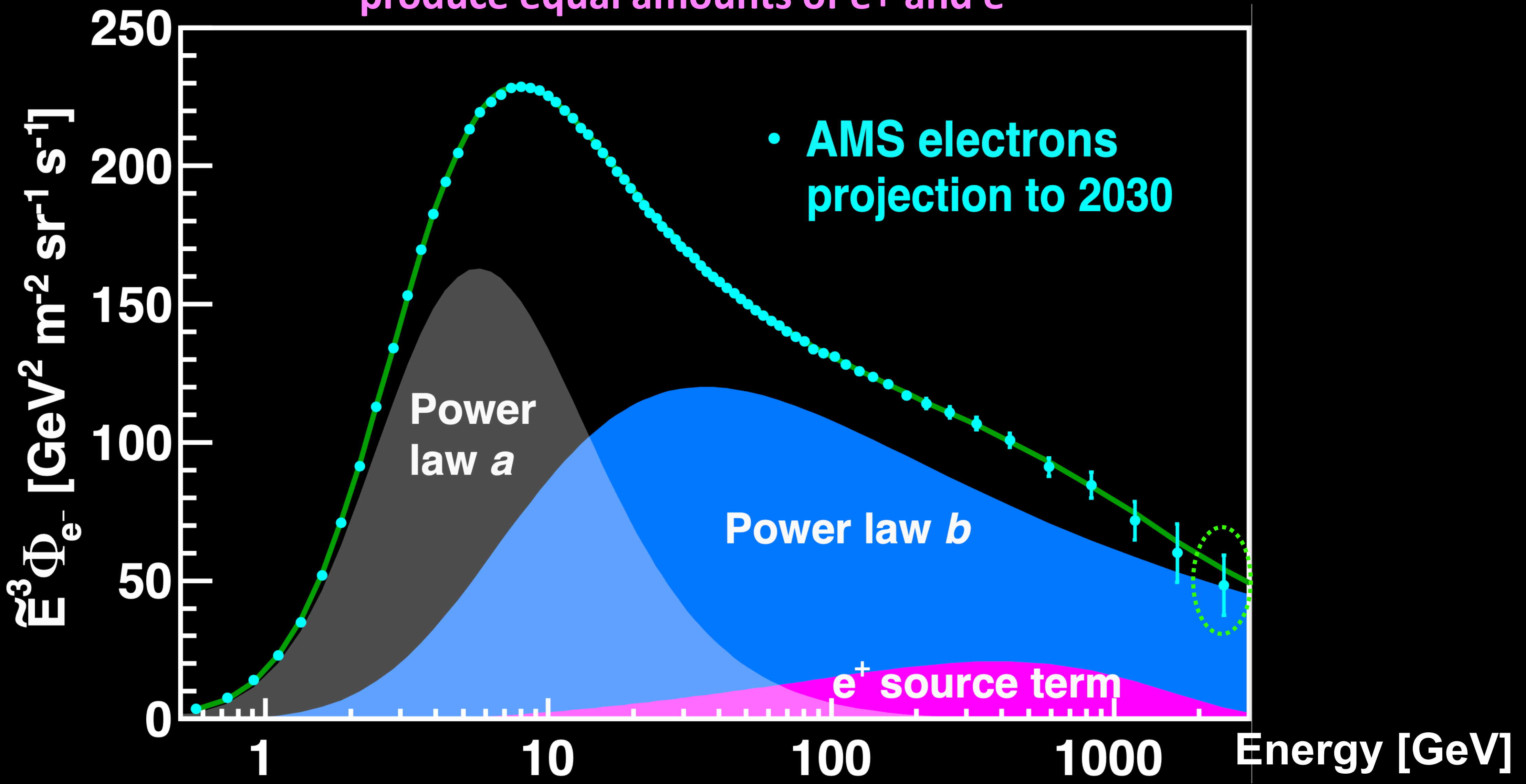
2.5σ effect

Solar Power law *a* Power law *b*

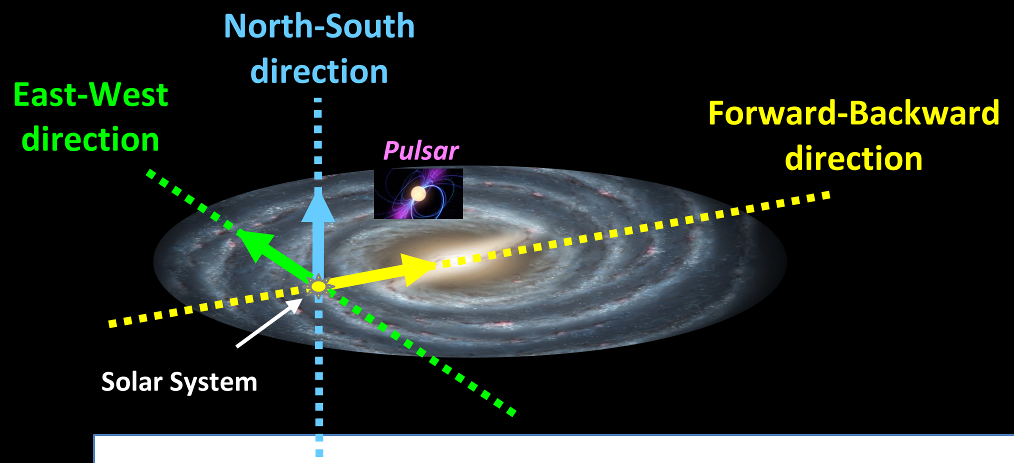


By 2030, the charge-symmetric nature of the high energy source will be established at the 4σ level

New sources, like Dark Matter or Pulsars, produce equal amounts of e+ and e–

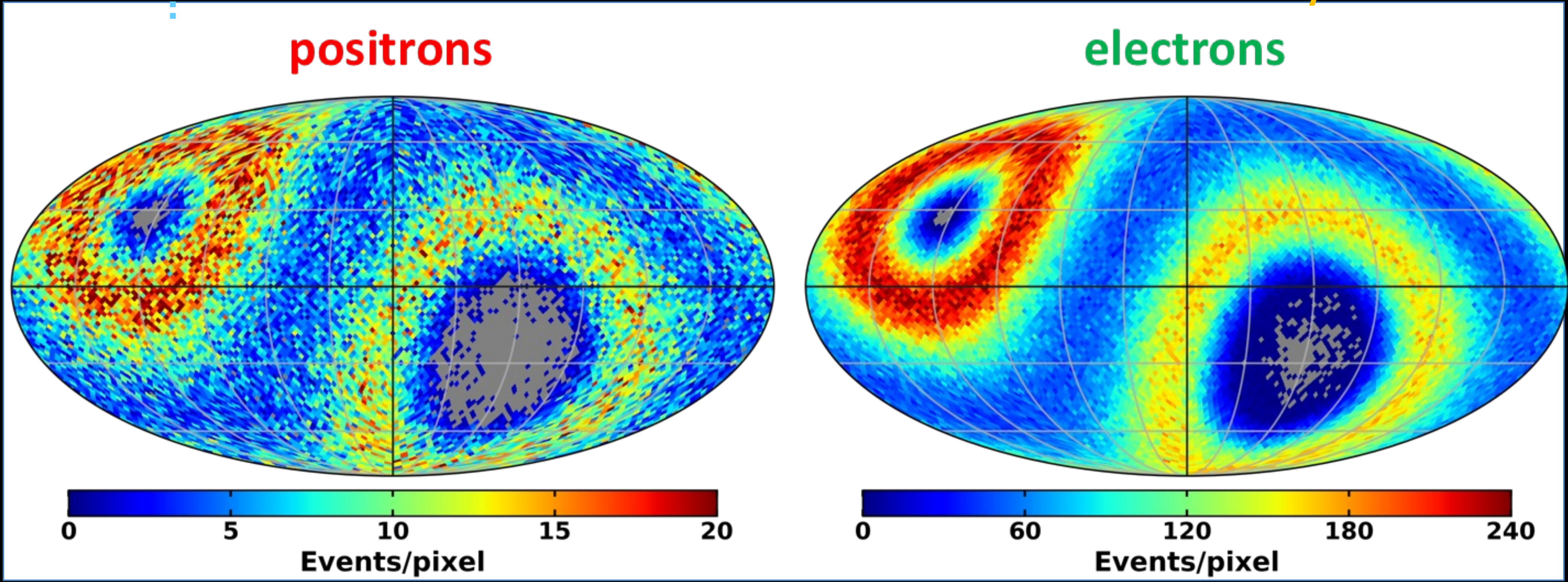


Positron Anisotropy and Dark Matter



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

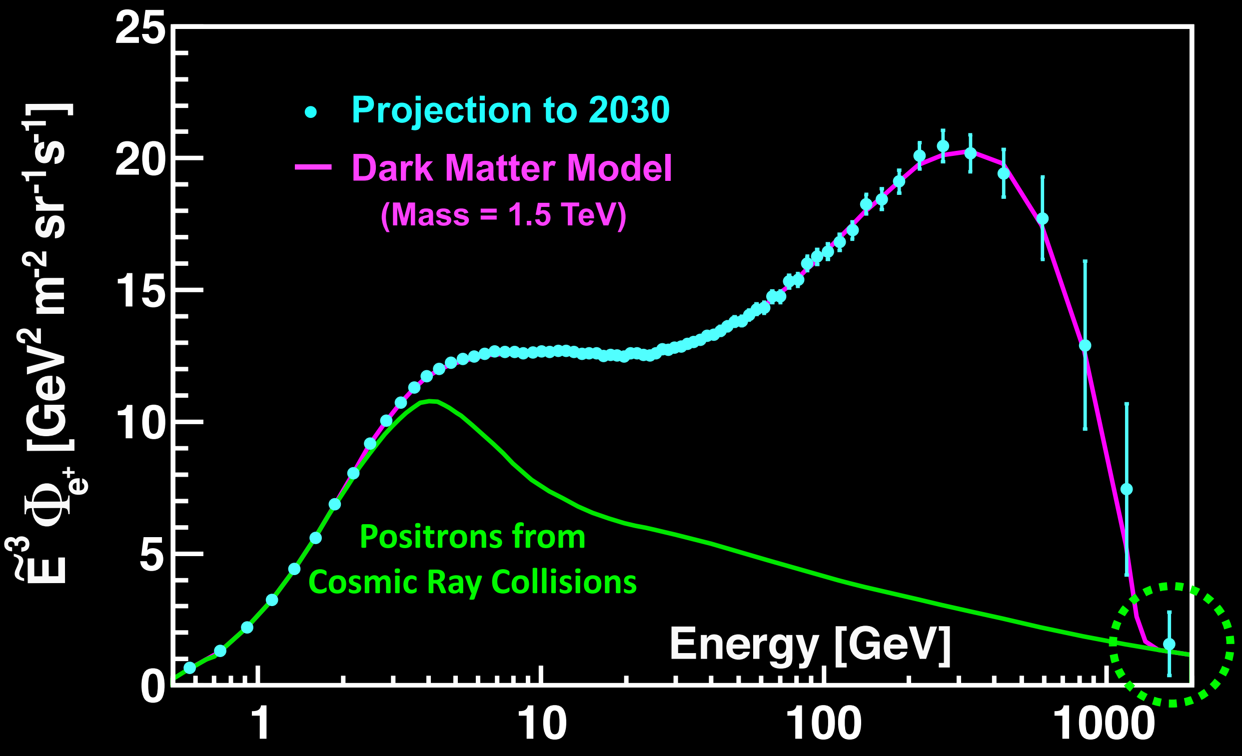
Presented by M. Molero



Dipole anisotropy: $\delta = 3\sqrt{C_1/4\pi}$ C_1 is the dipole moment

Conclusions

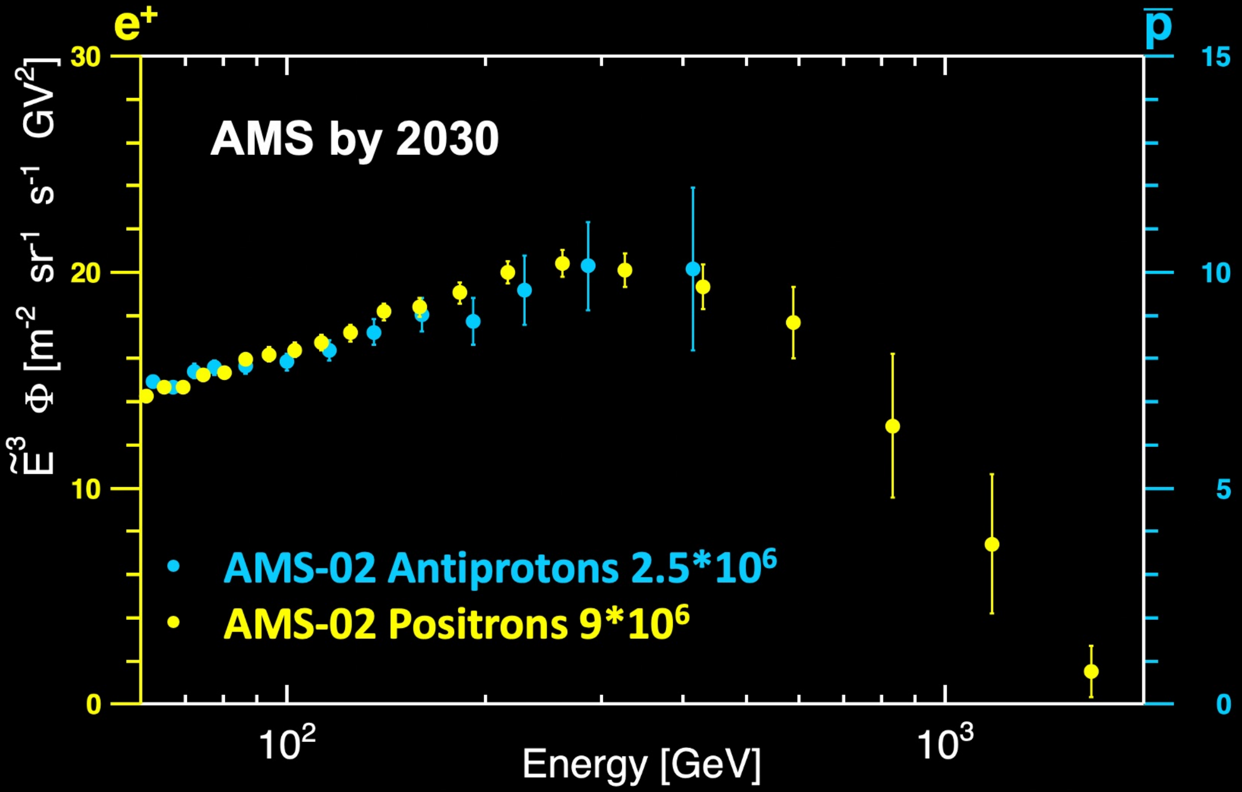
1. Positron spectrum requires an additional source of high energy positrons (e.g. DM models):
    - can’t be explained by the ordinary CR collisions
    - has an exponential cutoff with E_s=778 GeV;
    - measurement to 2030 will enable us to determine the origin of the behavior of positrons at high energies

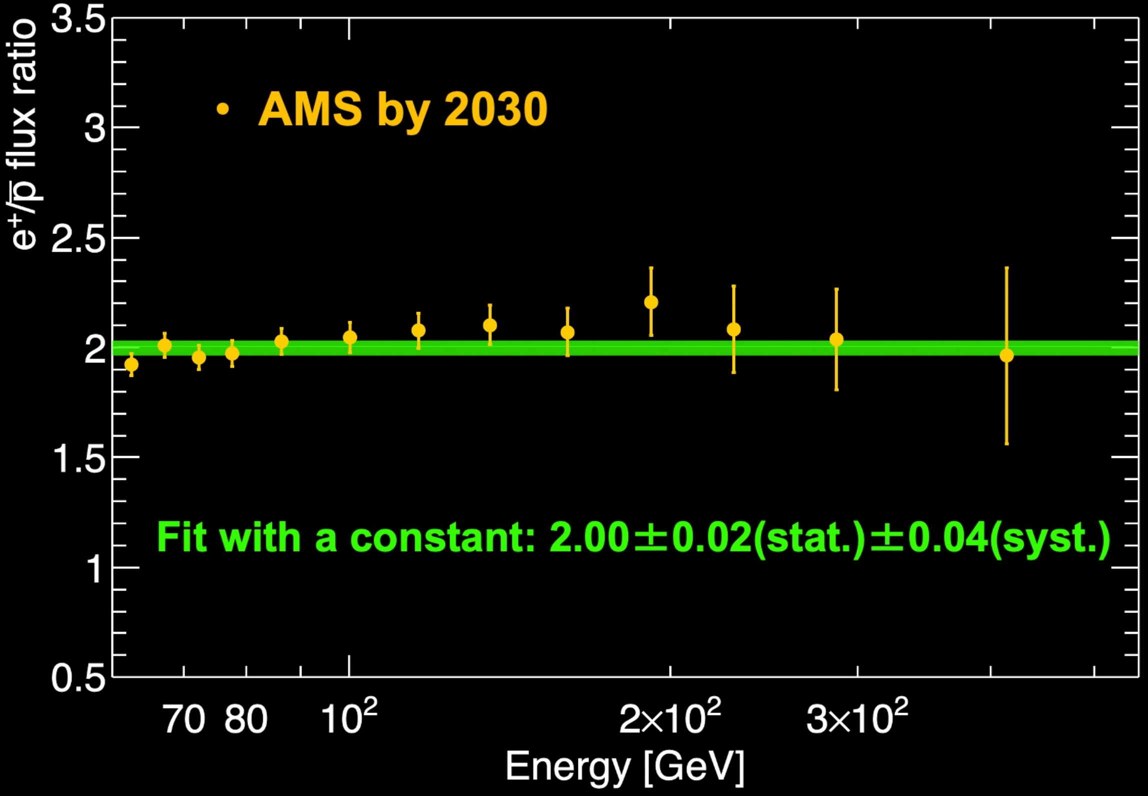


Conclusions

2. Comparison of the antiproton and positron spectra shows strikingly similar behavior of the two spectra above 60 GeV. This points to the common source of high energy antiprotons and positrons and disfavors pulsars as the origin of high energy positrons.

AMS projections to 2030





Conclusions

4. Electron spectrum shows complex behavior that can be best described by the sum of two power law functions and the contribution of the positron-like source term.
5. Significance of this observation is 2.5σ at present. With More data is needed to establish the existence of charge-symmetric positron-like source term at highest electron energies.