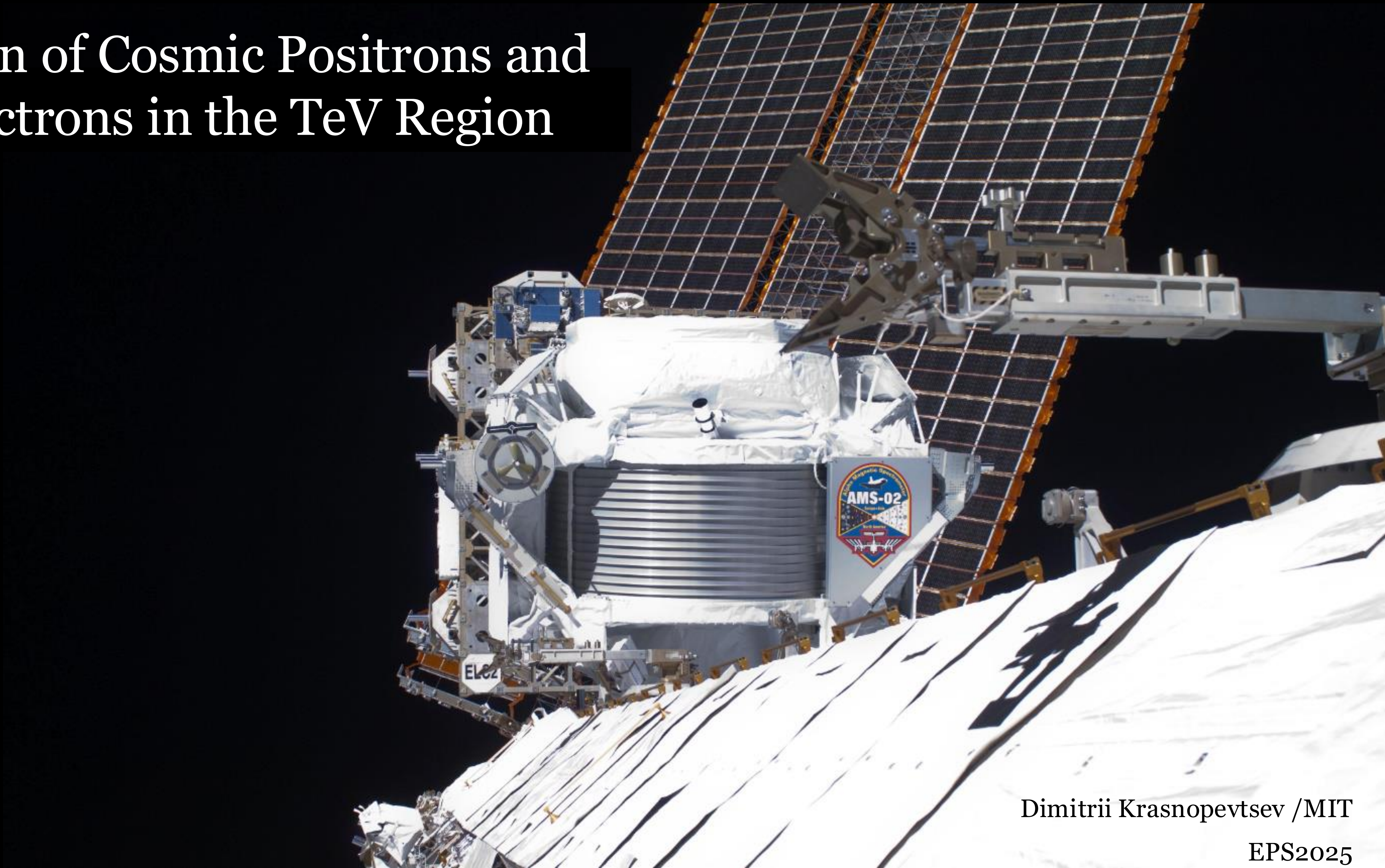
Origin of Cosmic Positrons and Electrons in the TeV Region



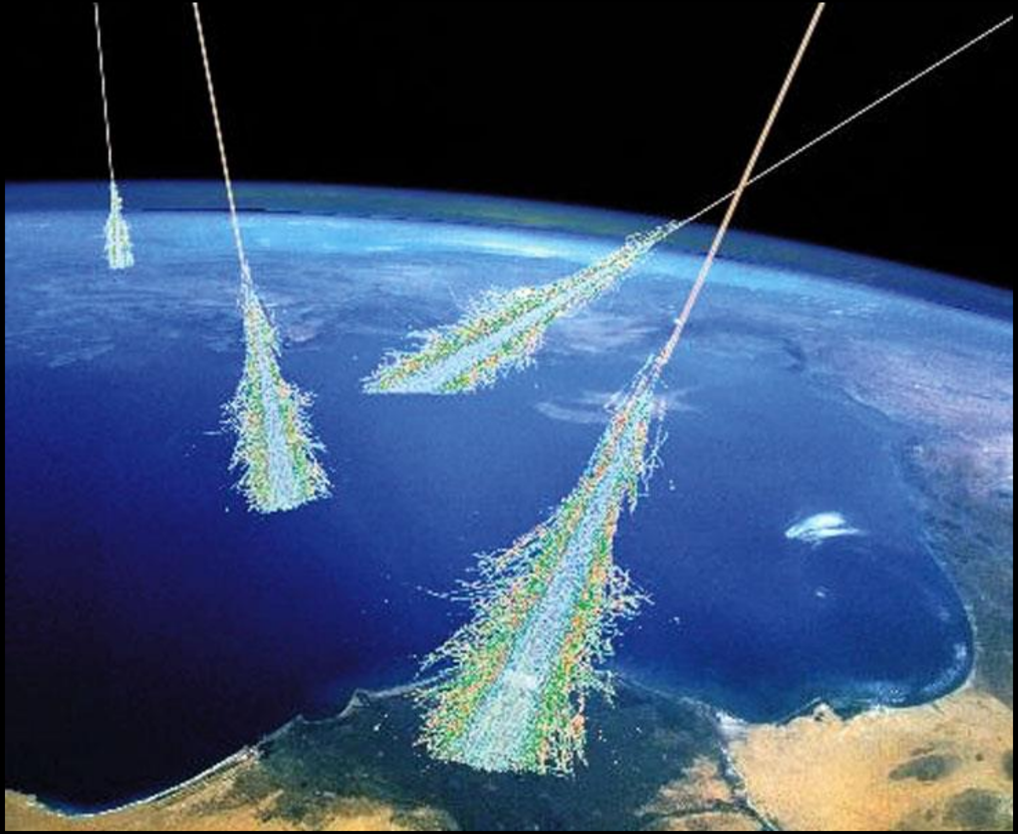
Dimitrii Krasnopevtsev /MIT

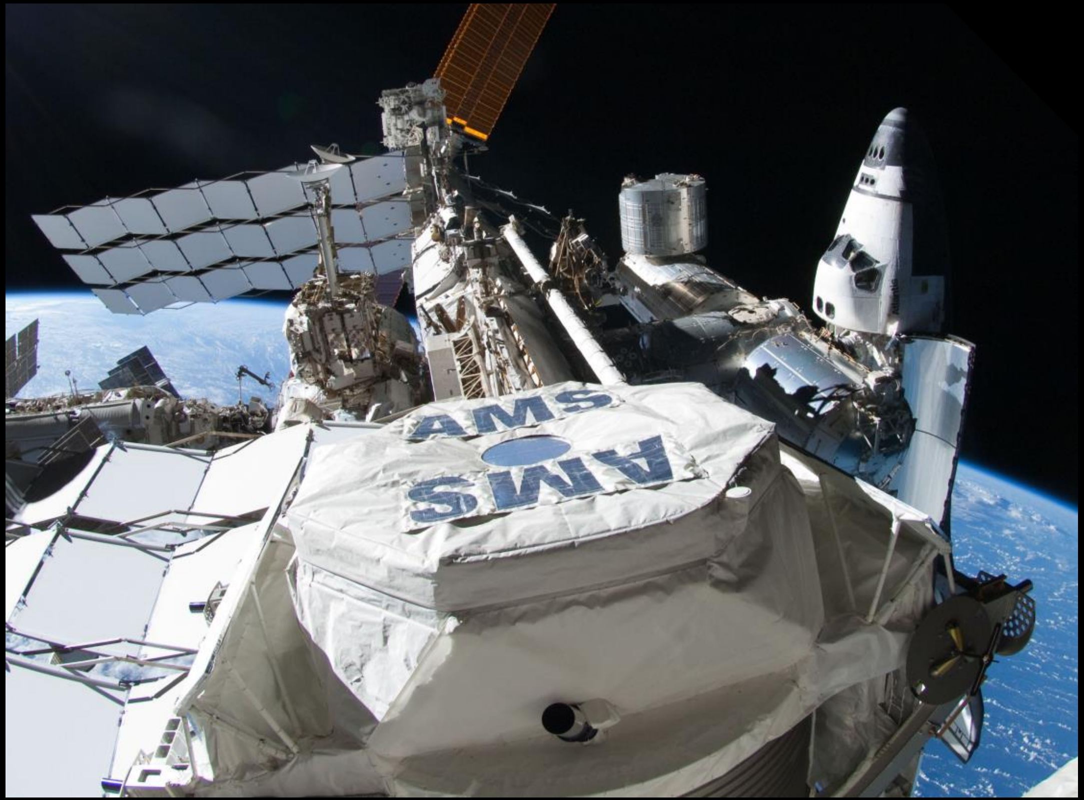
EPS2025

The physics of Alpha Magnetic Spectrometer (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.

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





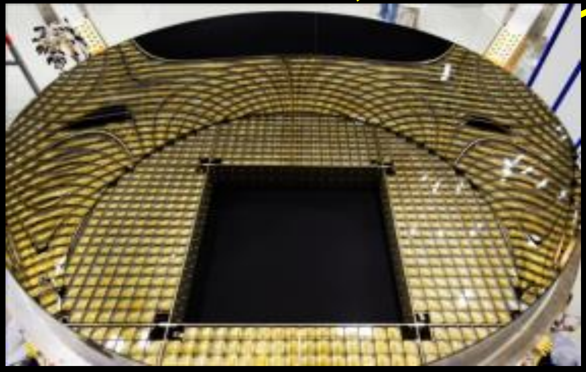
AMS on ISS provides long term precision measurements of charged cosmic rays.
Research topics: the Origin of Cosmic Rays, Physics of Dark Matter and Antimatter.

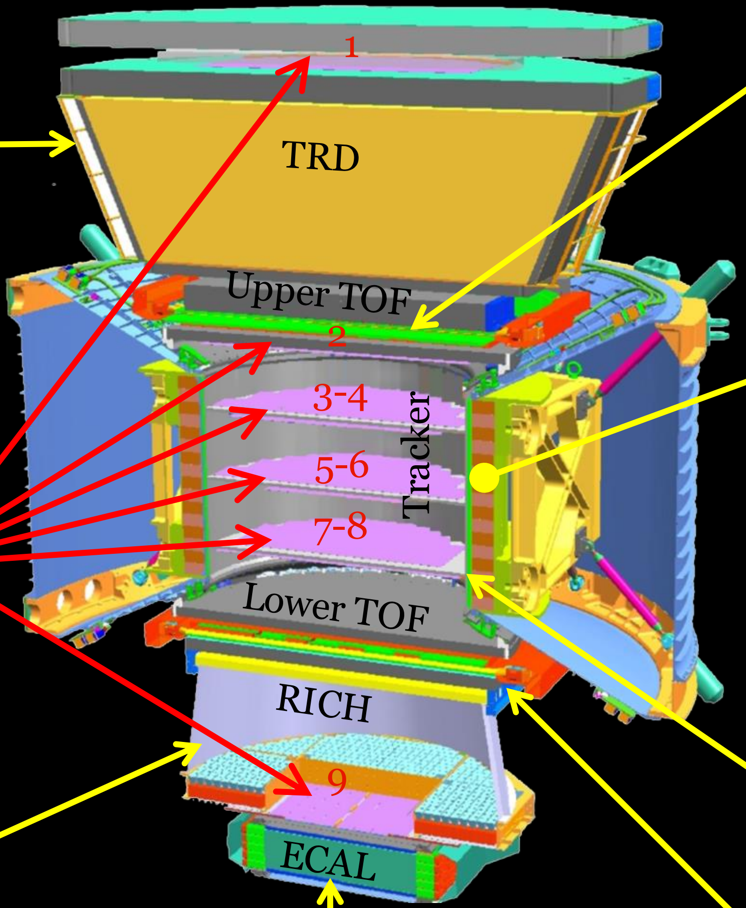
AMS is a space version of a precision detector used in accelerators

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

Silicon Tracker
measure Z, P

Ring Imaging Cerenkov (RICH)
measure Z, E





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

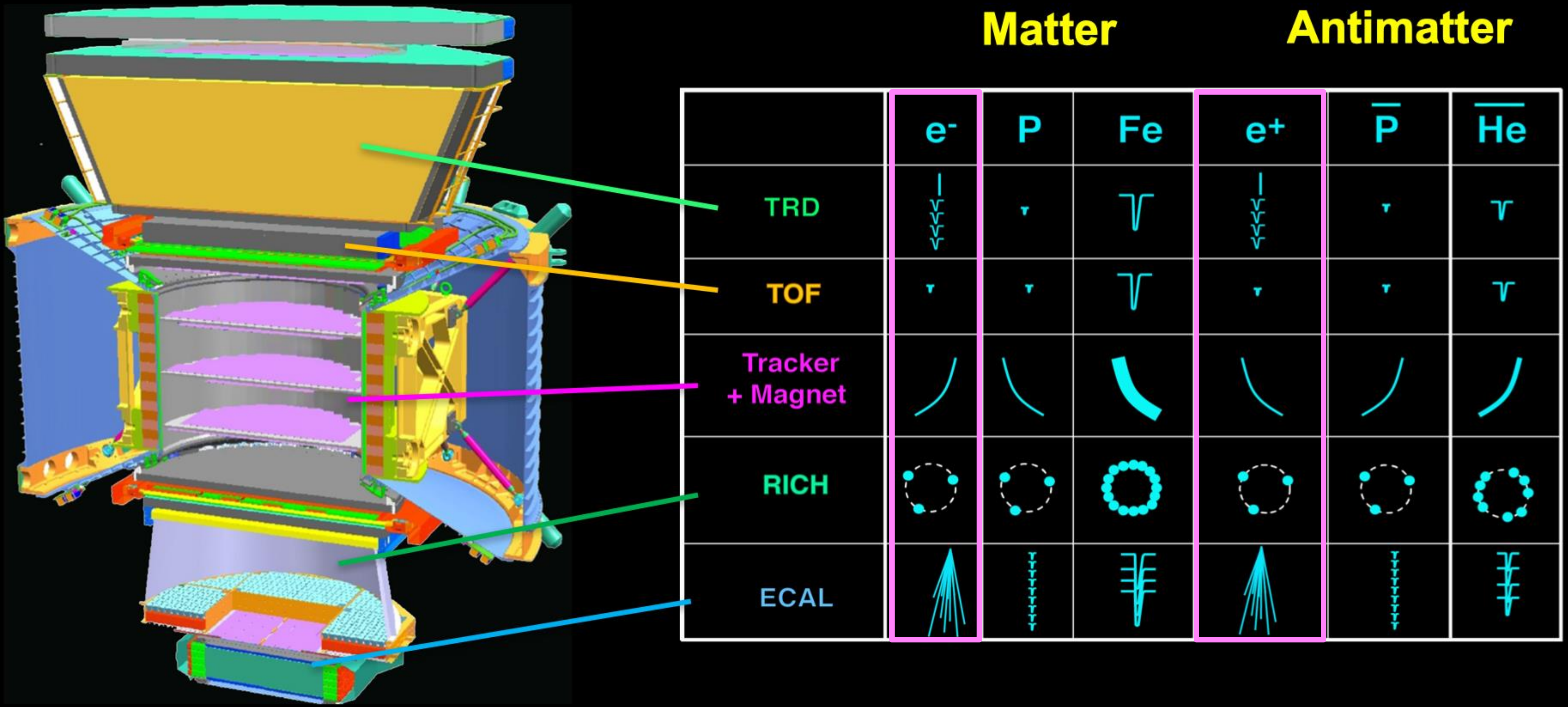
Upper TOF measure Z, E

Magnet identify ±Z, P

Anticoincidence Counters (ACC)
reject particles from the side

Lower TOF measure Z, E

AMS is a unique magnetic spectrometer in space



In 13.5 years, the detectors have performed flawlessly. AMS is able to pick out 1 positron from 1,000,000 protons; unambiguously separate positrons from electrons up to a trillion eV; and accurately measure all cosmic rays to trillions of eV.

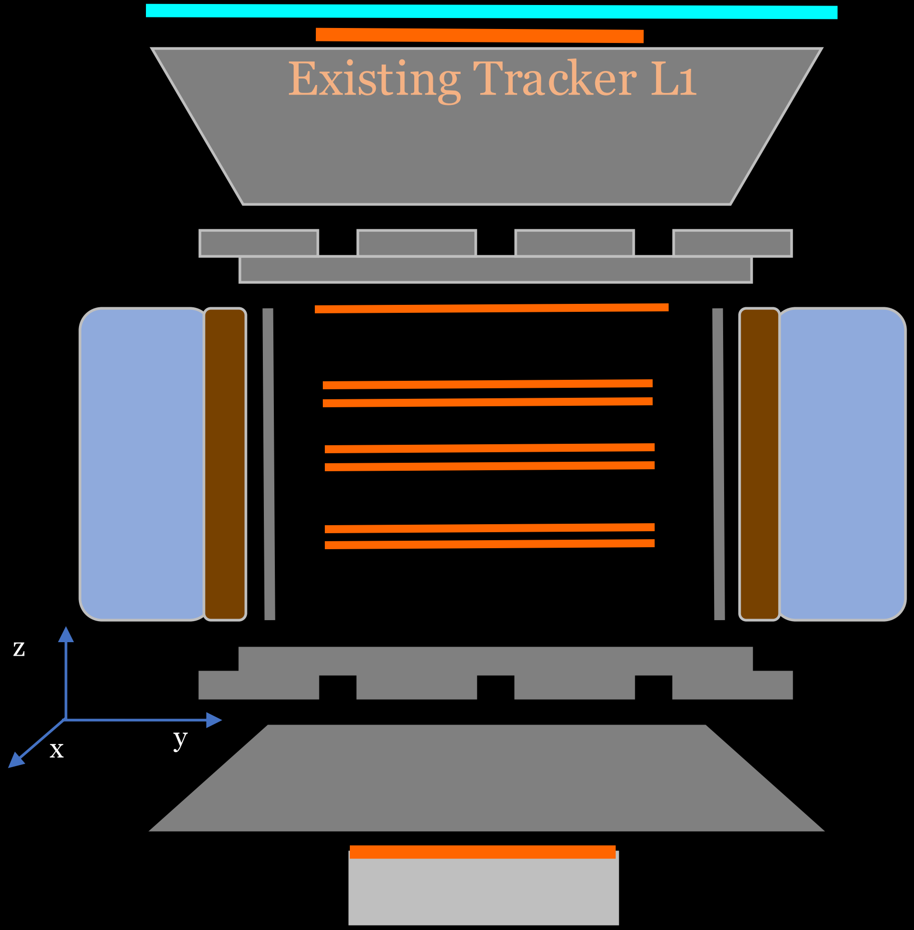
Physics prospects with AMS upgrade

AMS 2011-2026

Continuous data-taking

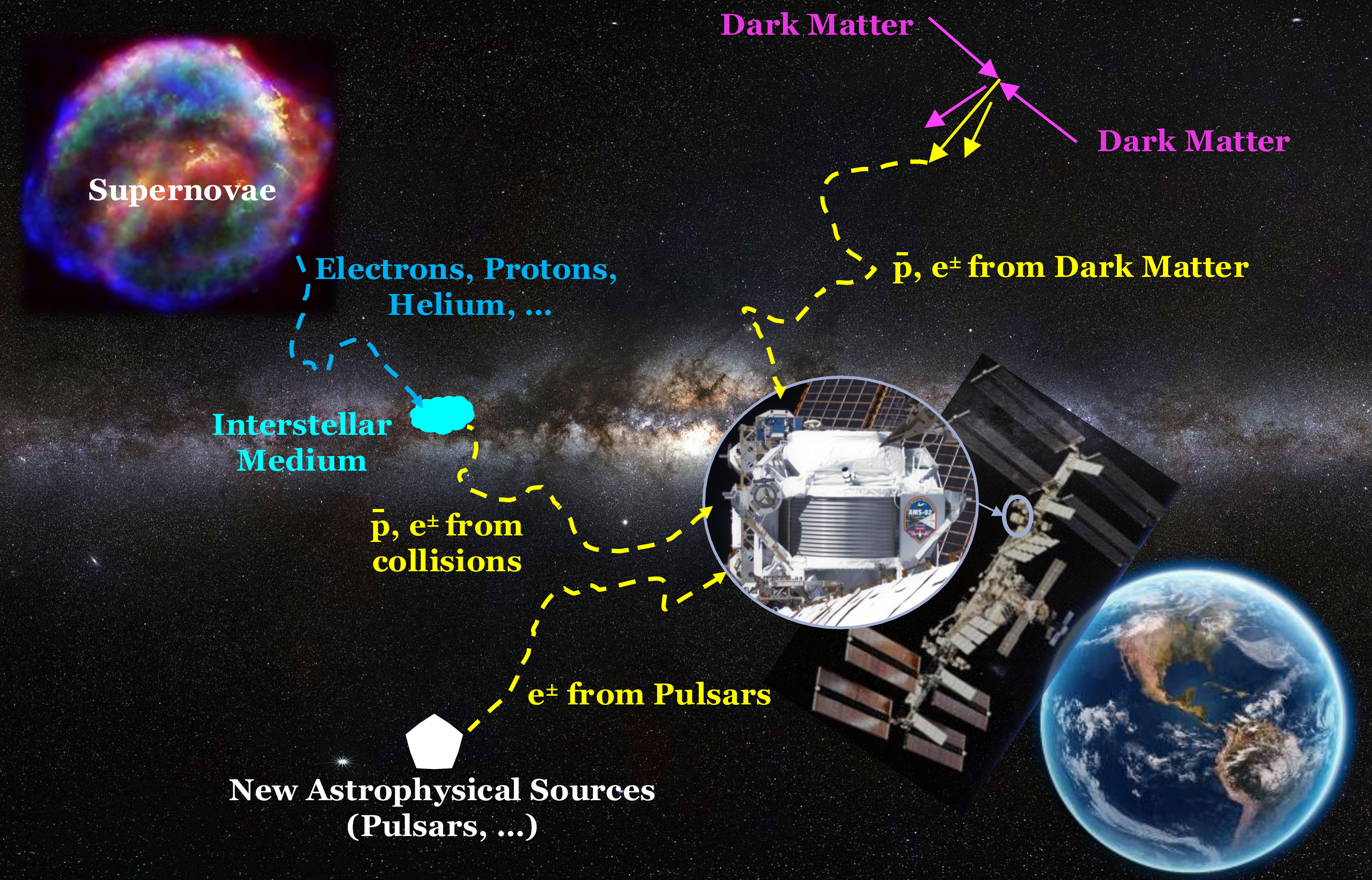
AMS 2026-2030

New 8m² Silicon Tracker Layer
Acceptance increased to 300%

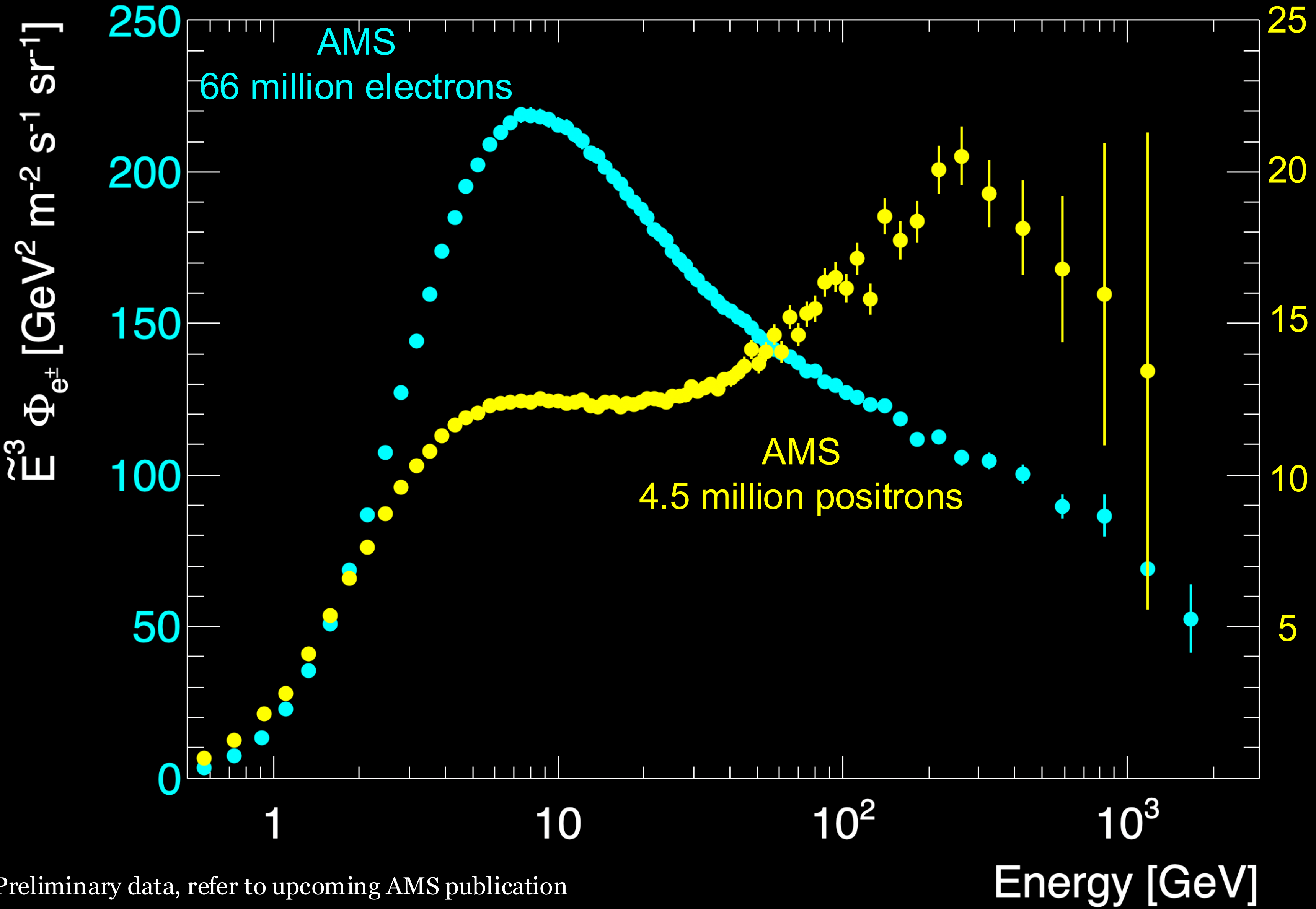


Projections to 2030

The origins of cosmic positrons, electrons

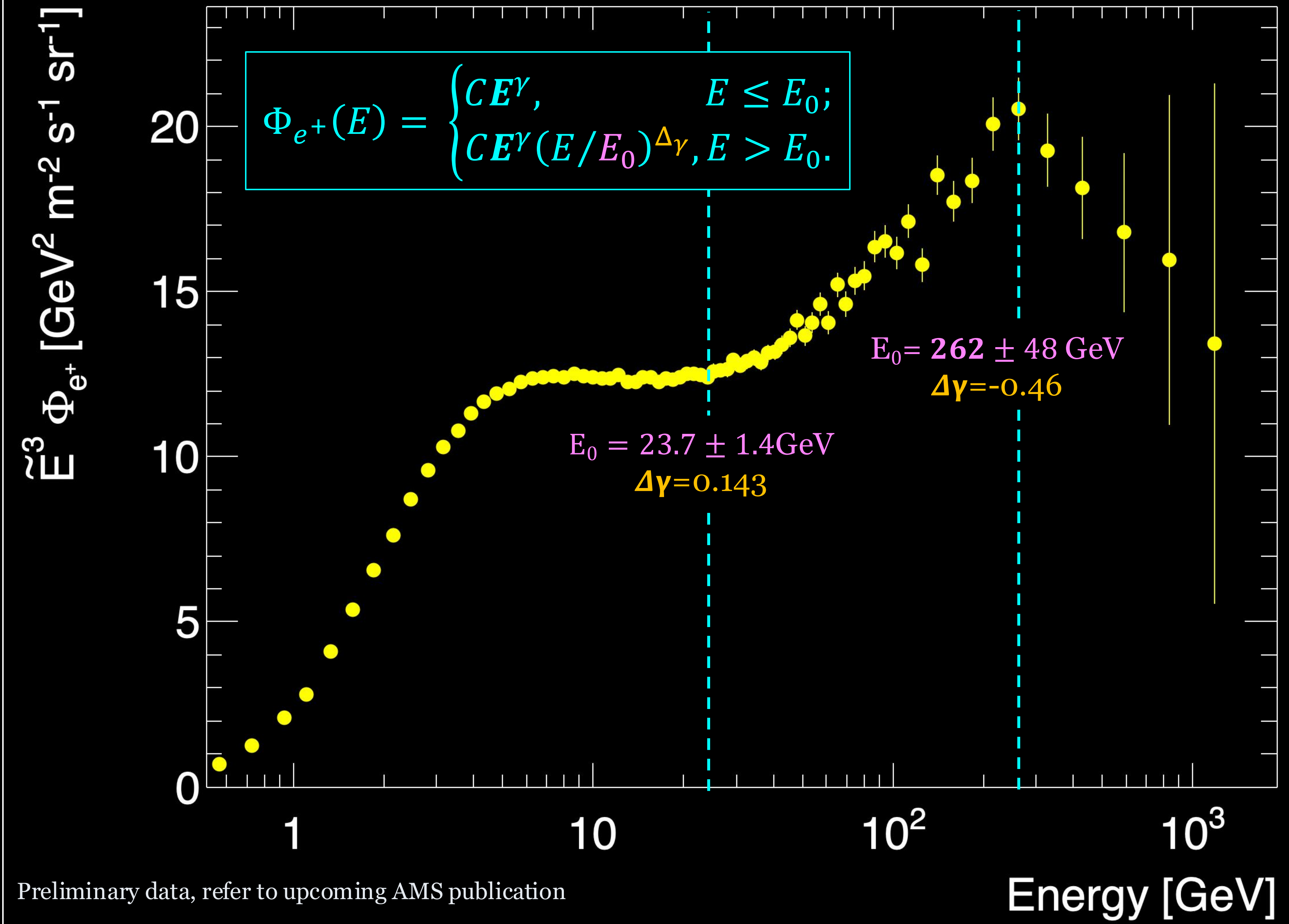


Latest Physics Results from AMS.
Studies of Electrons and Positrons



Preliminary data, refer to upcoming AMS publication

Latest Physics Results from AMS: Positrons

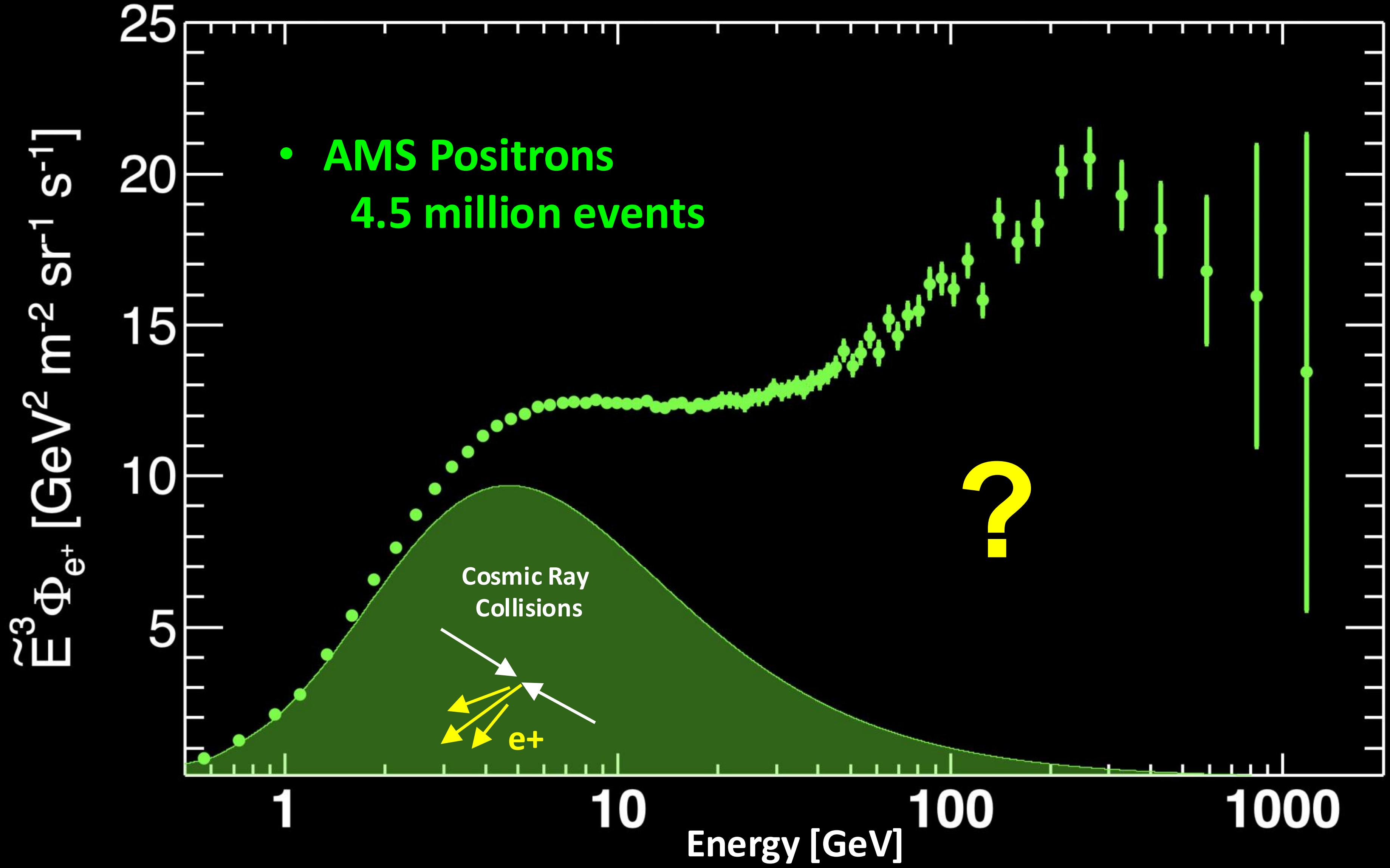


Preliminary data, refer to upcoming AMS publication

Latest Result on the positron spectrum

Low-energy positrons come from cosmic ray collisions

High-energy positrons must come from a new source



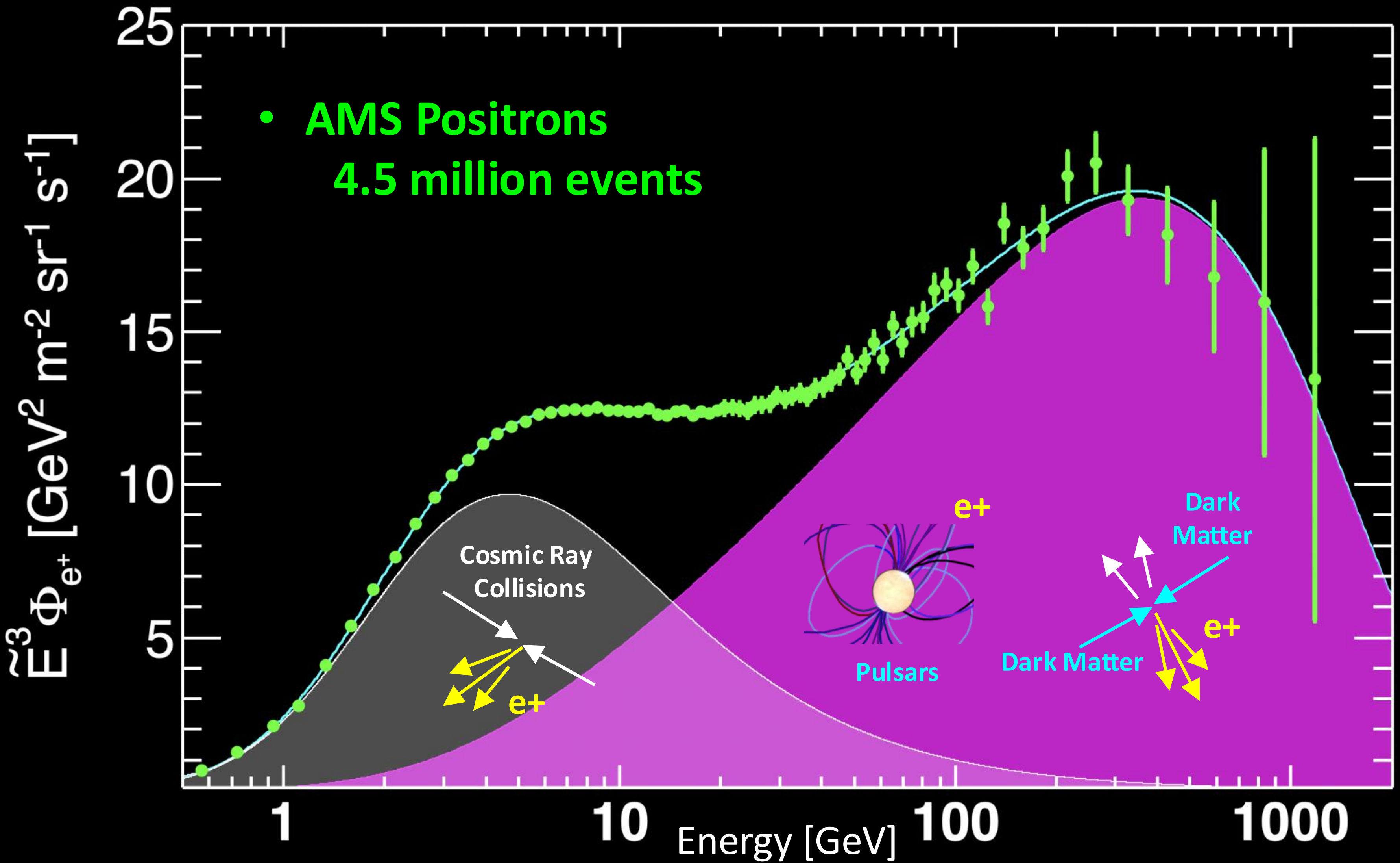
The positron flux is the sum of low-energy part from cosmic ray collisions plus a high-energy part from pulsars or dark matter with a cutoff energy

Empirical model:

χ^2/dof = 40/66

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

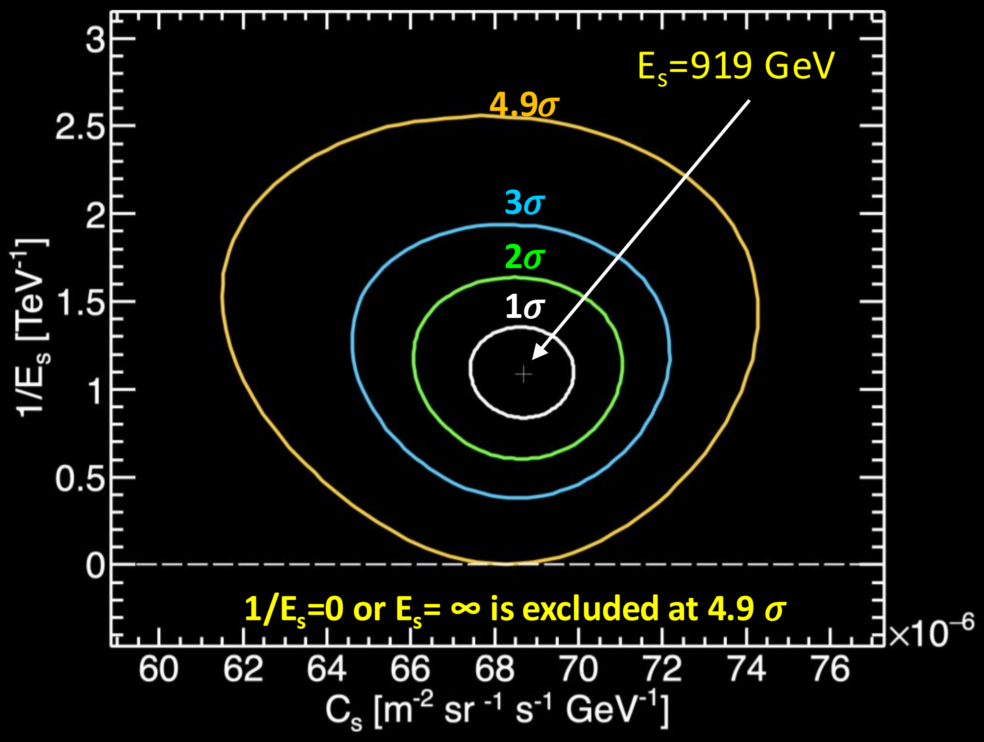
Collisions — Pulsars or Dark Matter

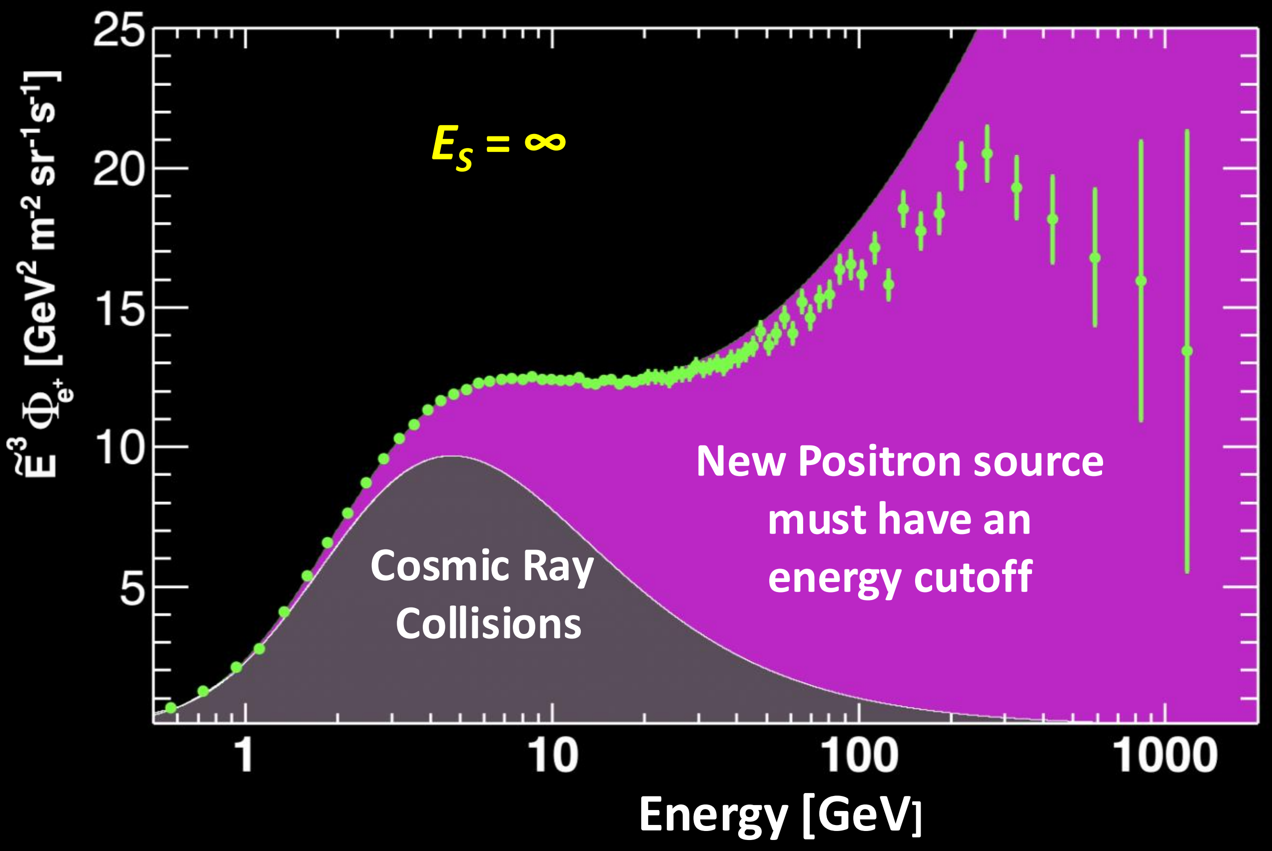


Surprising Observation: The existence of a finite cutoff energy E_S

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

Collisions — Pulsars or Dark Matter Collisions





$1/E_S = 0$ or $E_S = \infty$ is excluded at 4.9σ

A sample of recent theoretical models explaining AMS positron and electron data:

Dark Matter

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 …

Astrophysical sources

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) K. Fang, X.J. Bi, and P.F Yin, Astrophys.J. 884 (2019) 124
11) S. Recchia, S. Gabici, F.A. Aharonian, and J. Vink, Phys.Rev. D99 (2019) 10, 103022

and many other excellent papers …

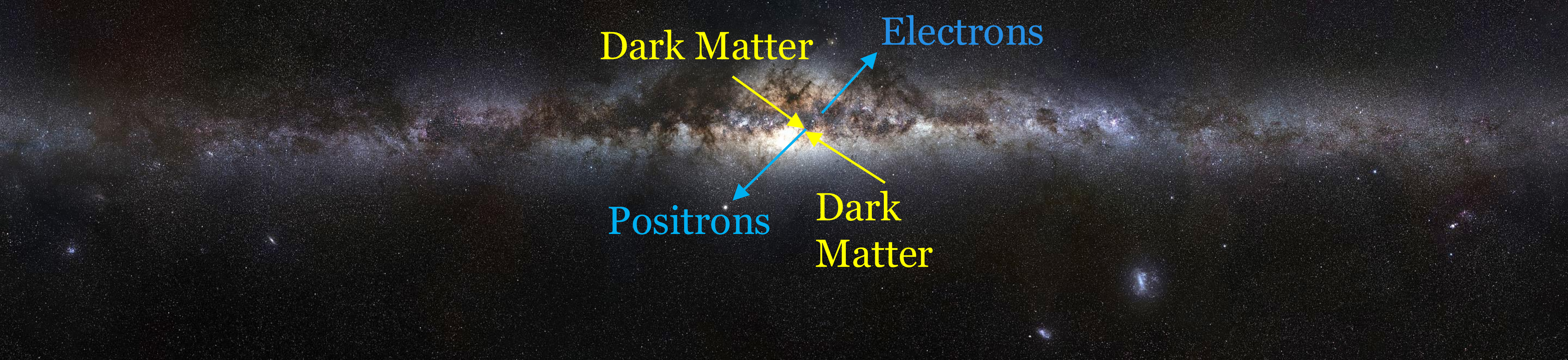
Propagation

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 …z

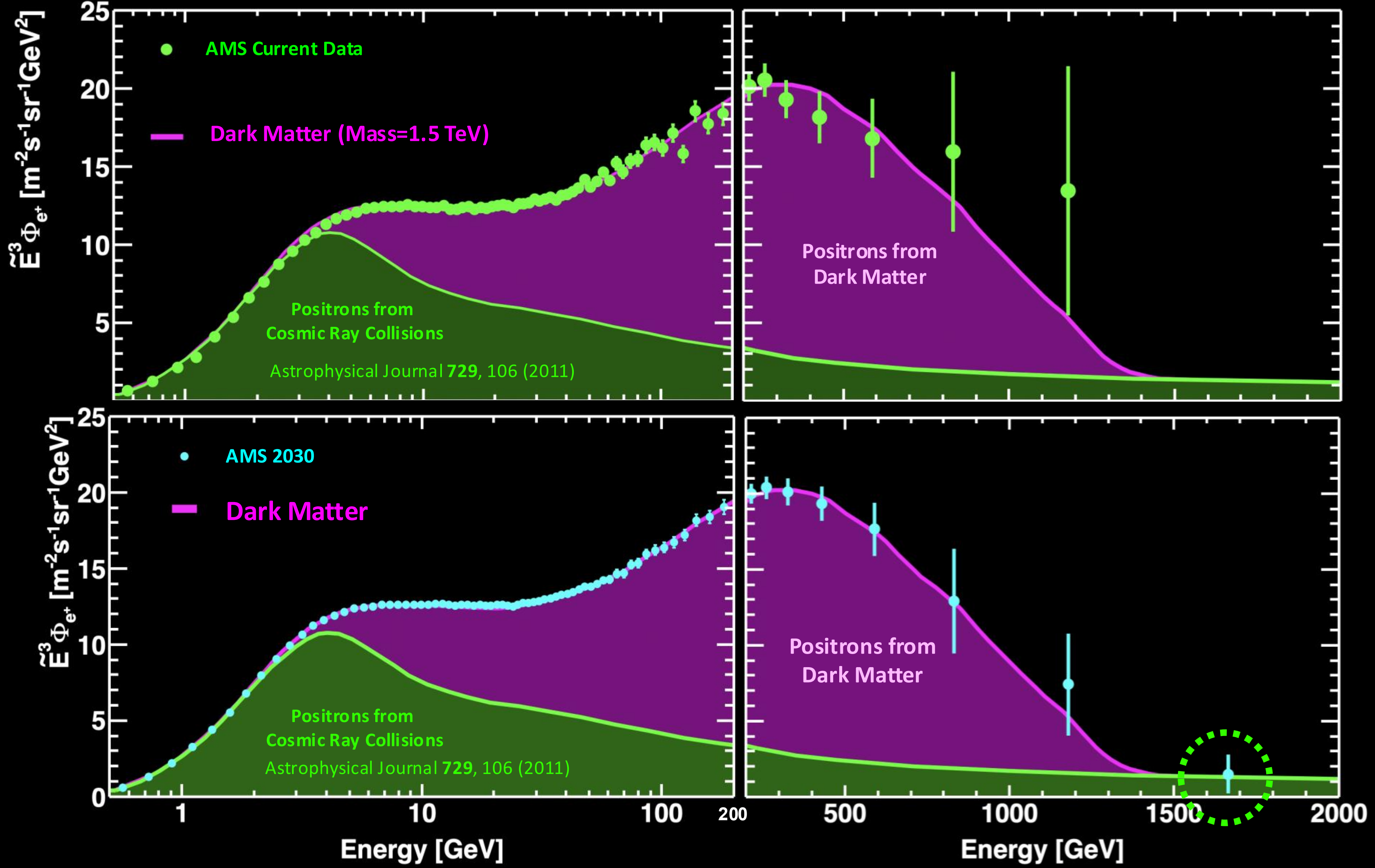
Dark Matter

Collision of Dark Matter produces positrons and electrons. Dark Matter particle have mass M and they move slowly. Before collision the total energy $\approx 2M$.



The conservation of energy and momentum requires that the positron energy must be smaller than M. So, there is a sharp cutoff in the spectra at M.

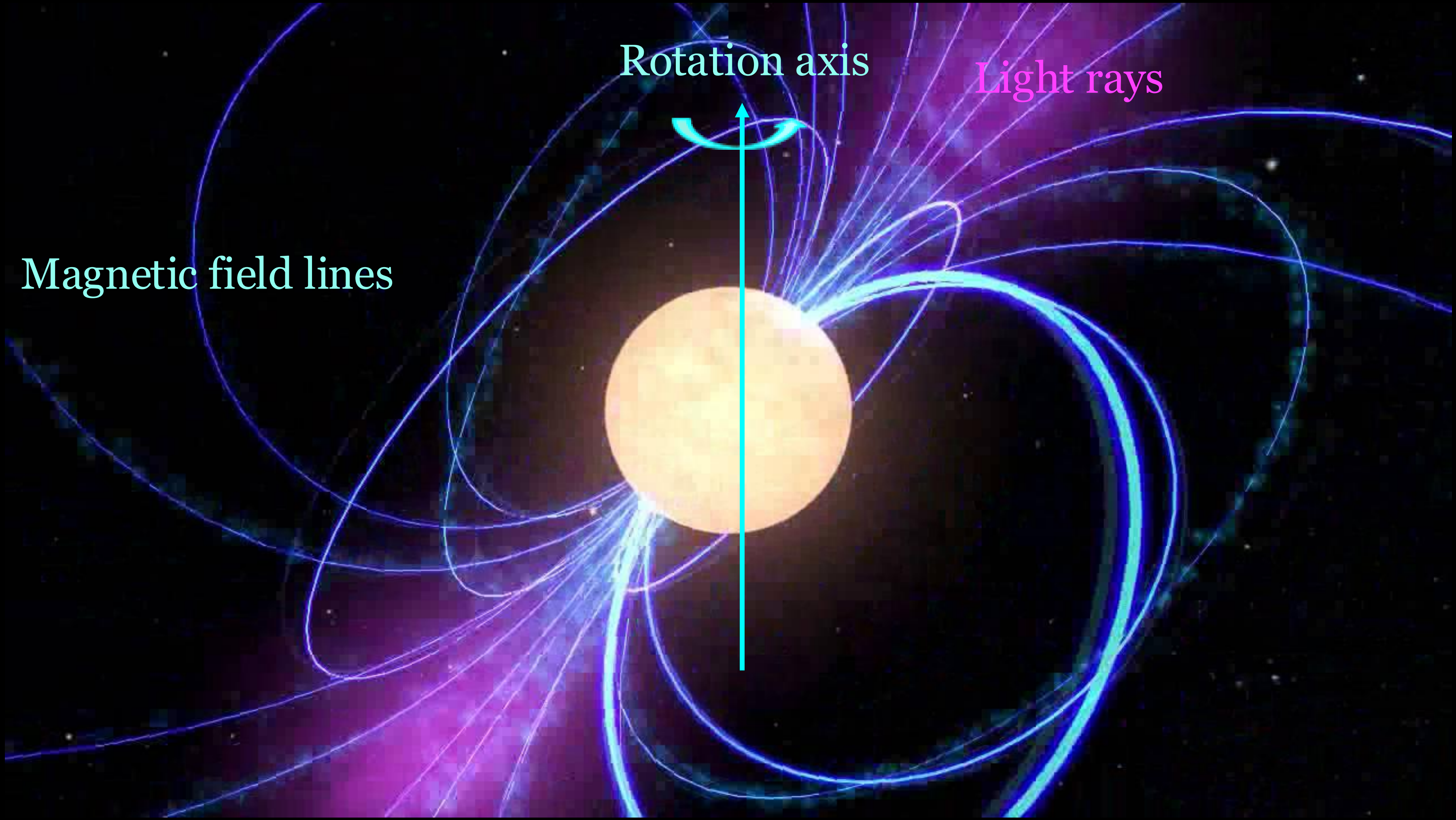
AMS Positron Spectrum and Dark Matter



By 2030, AMS will ensure that the high energy positron spectrum drops off quickly in the 0.2-2 TeV region and the highest energy positrons only come from cosmic ray collisions as predicted for dark matter collisions

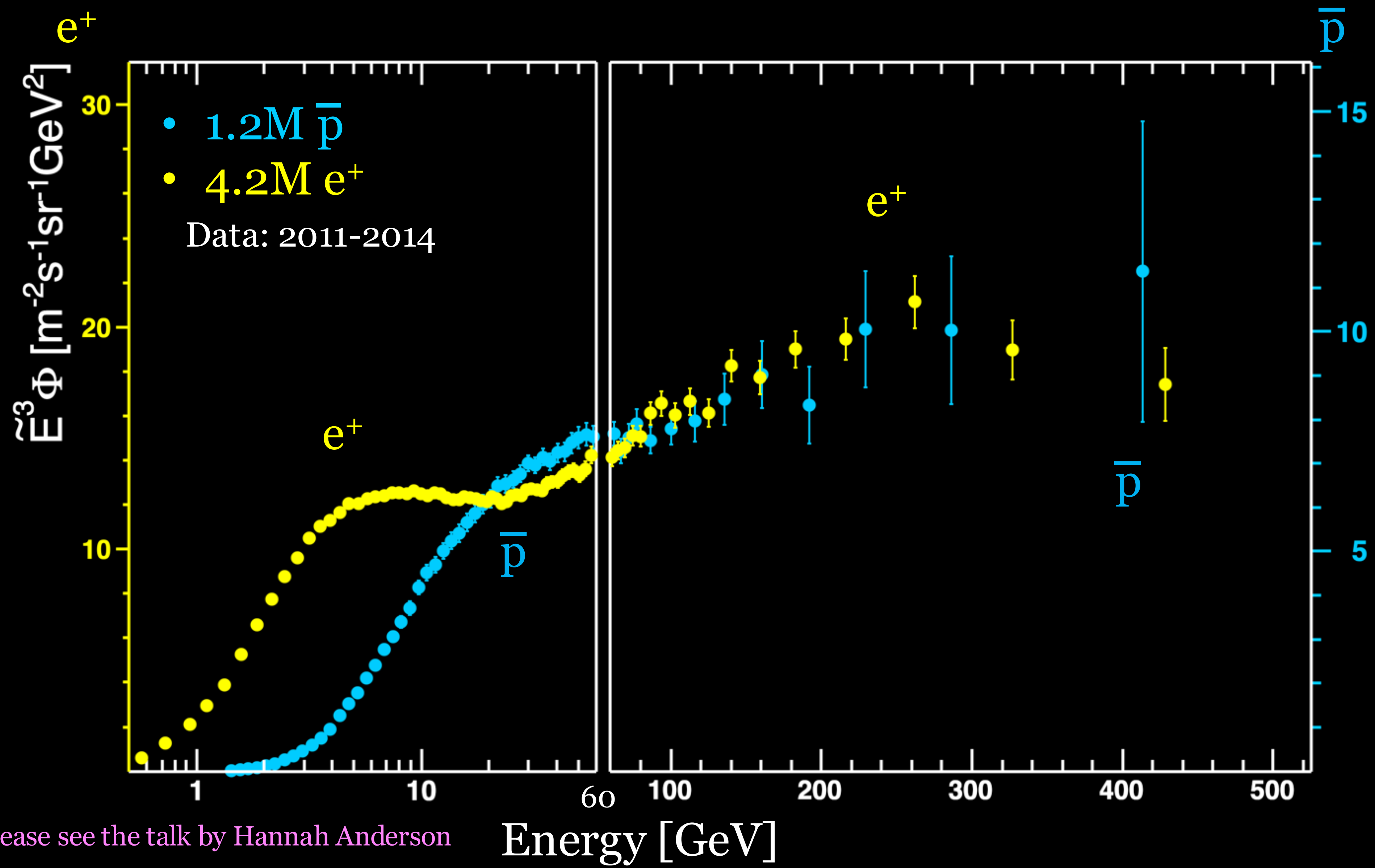
Positrons from Pulsars

1. Pulsars produce and accelerate positrons to high energies.
2. Pulsars do not produce antiprotons.



Cosmic Antiprotons

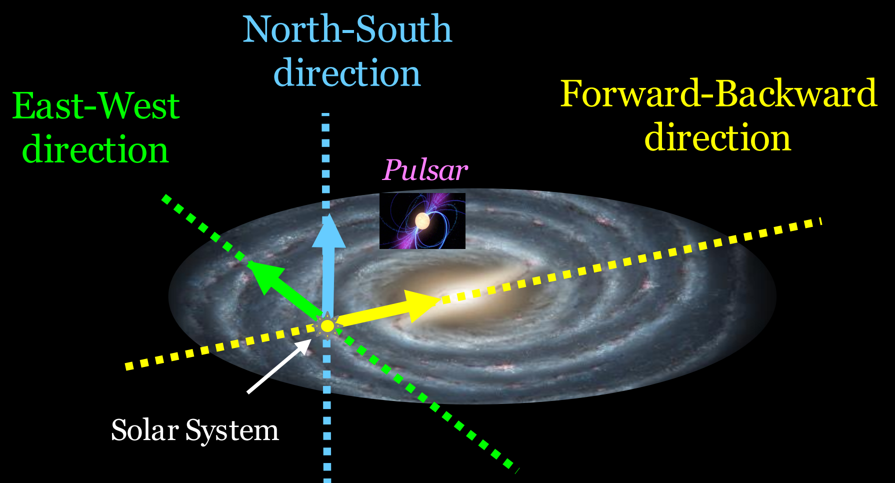
The $\bar{p}$ and e^+ fluxes have identical rigidity dependence. $\bar{p}$ are not produced by pulsars.



For more details please see the talk by Hannah Anderson

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. If the excess of positrons has a dark matter origin, it should be isotropic.

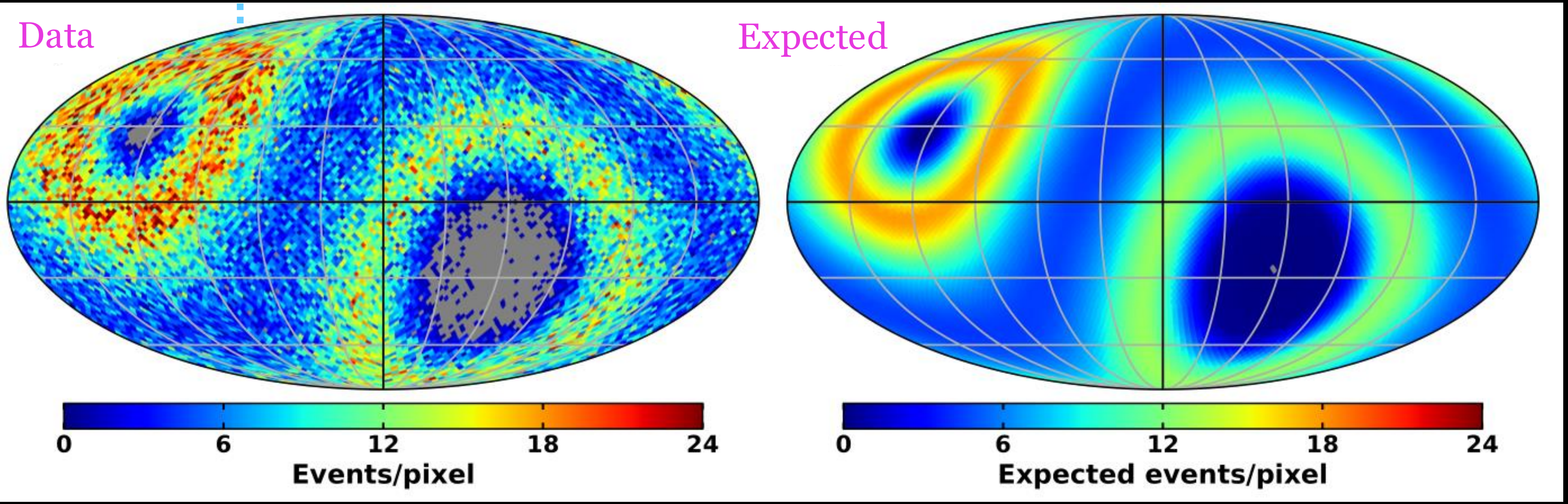


Dipole anisotropy:

$$\delta = 3\sqrt{C_1/4\pi}$$

C_1 is the dipole moment

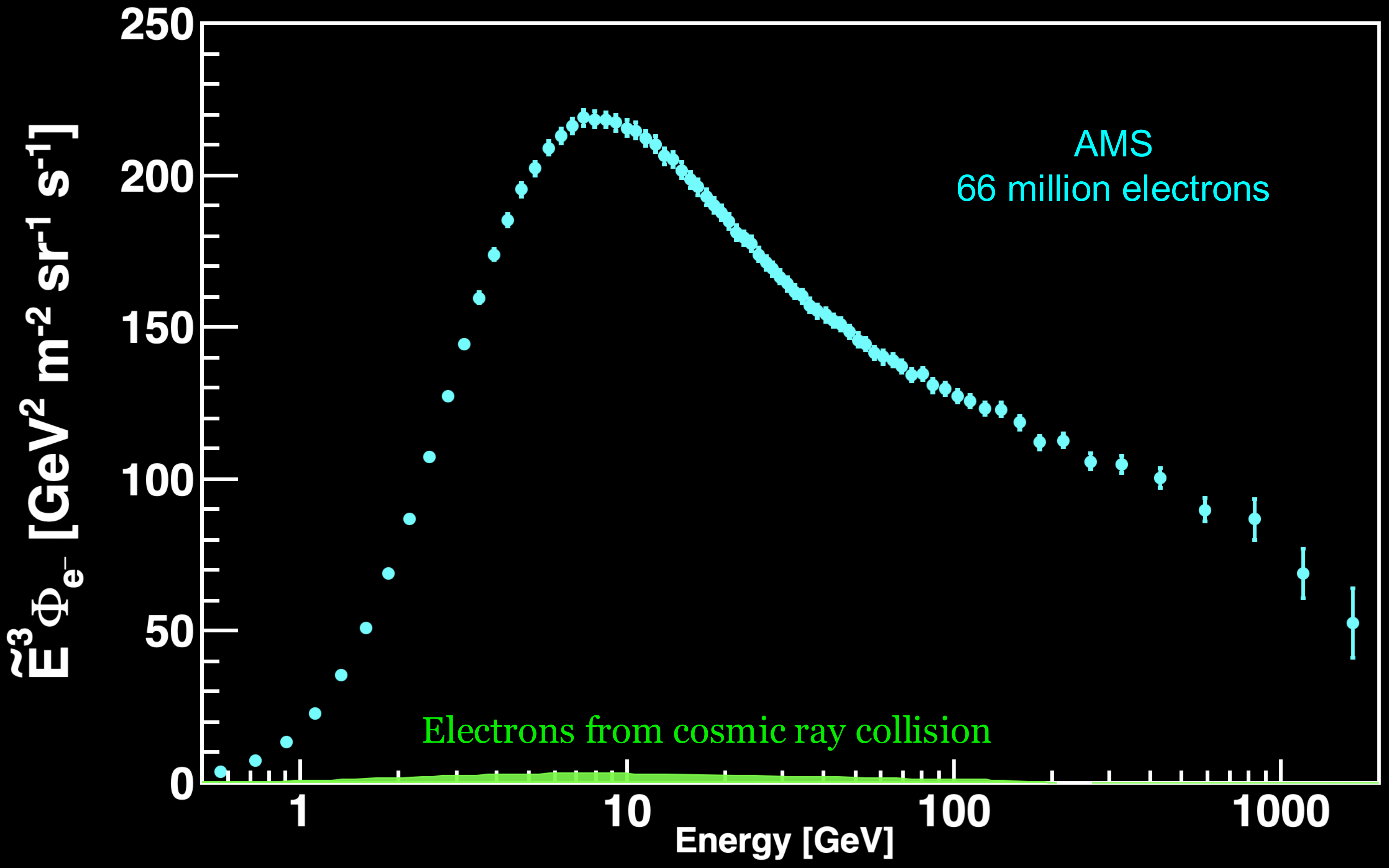
95% C.I. upper limit: $\delta < 1.44\%$ ($E_{e+} > 16$ GeV)



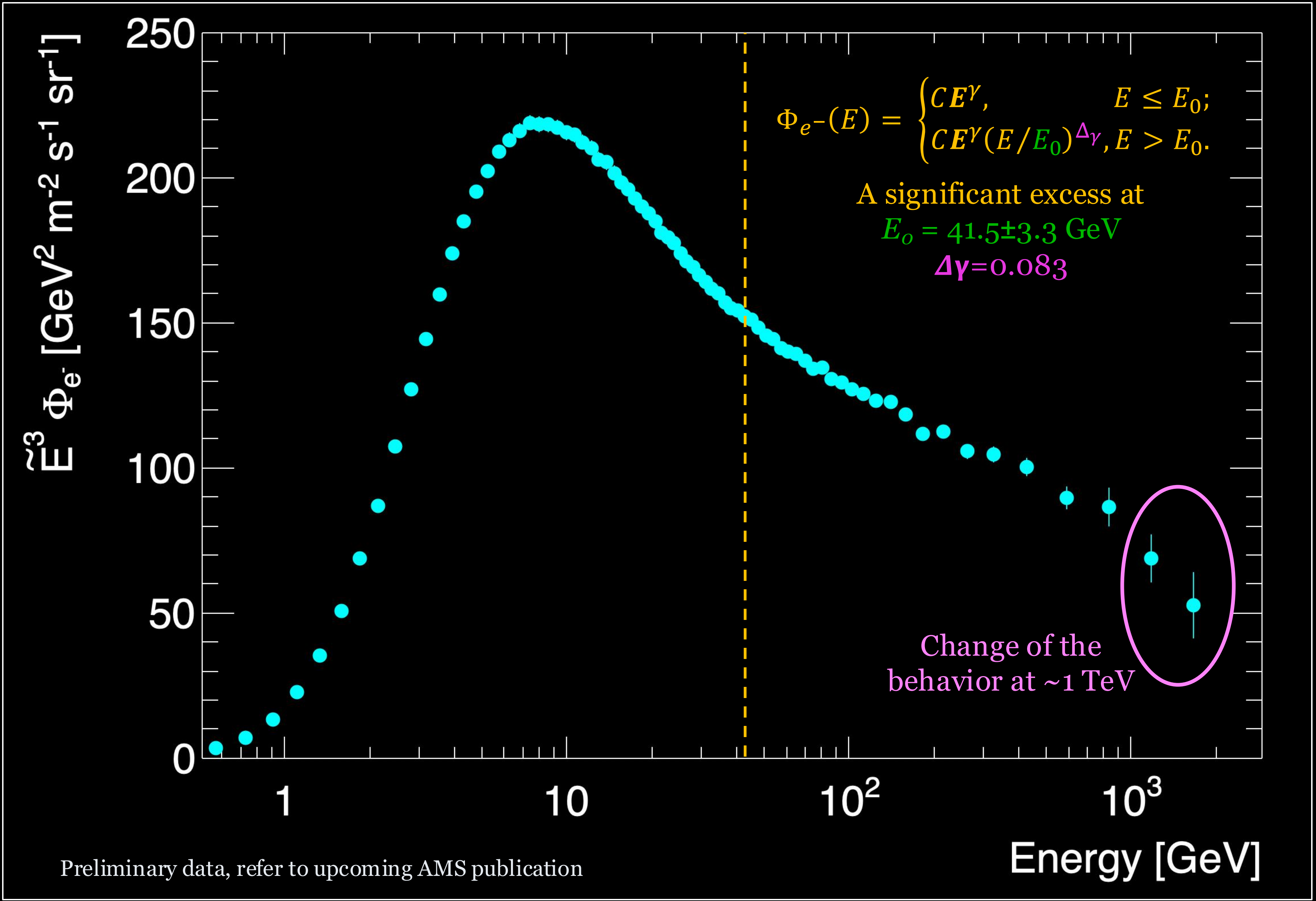
For more details please see the talk Dr. Miguel Velasco

The Origin of Electrons

The contribution from cosmic ray collisions is negligible



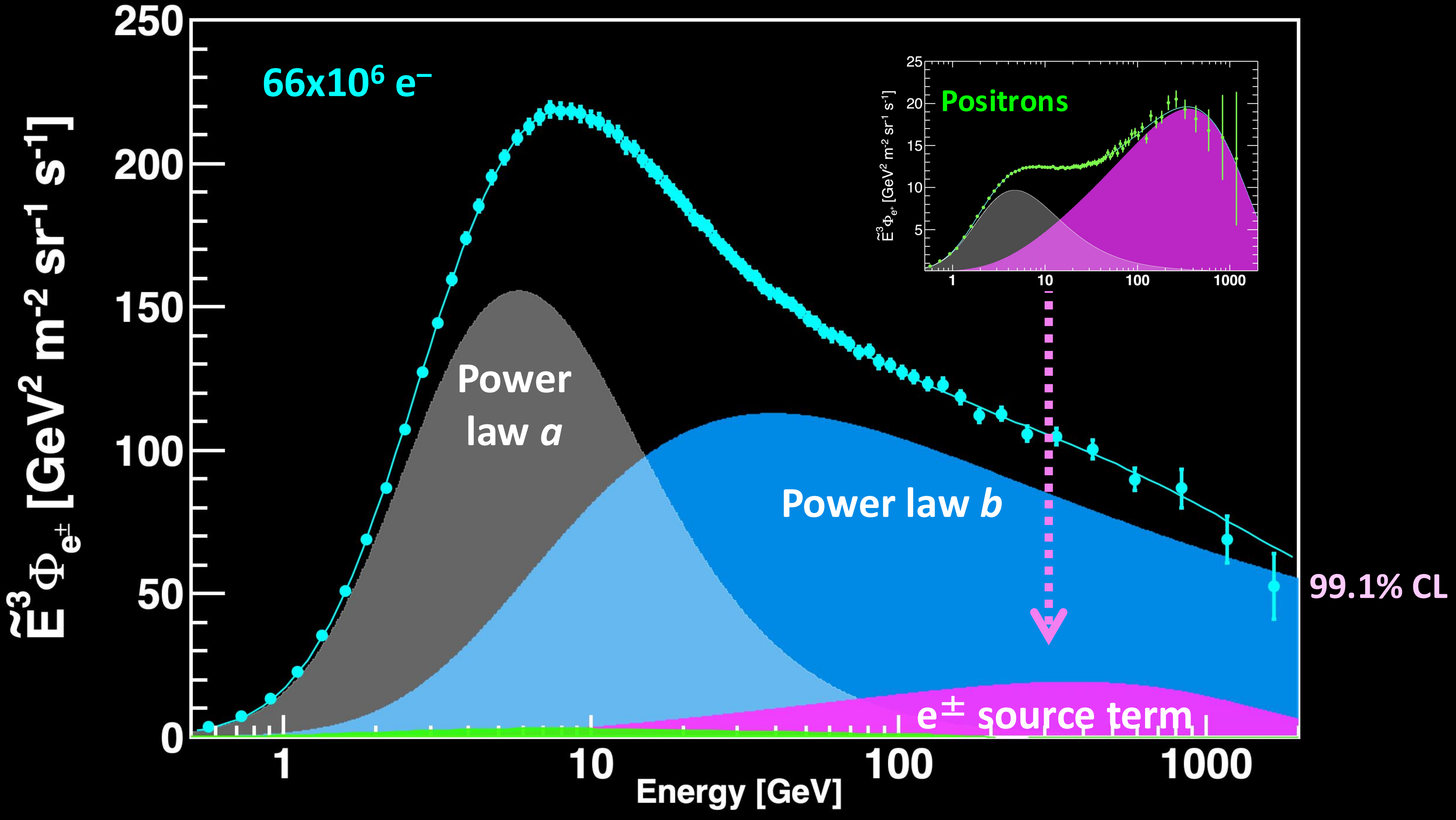
The Origin of Electrons



Latest Result on the electron spectrum

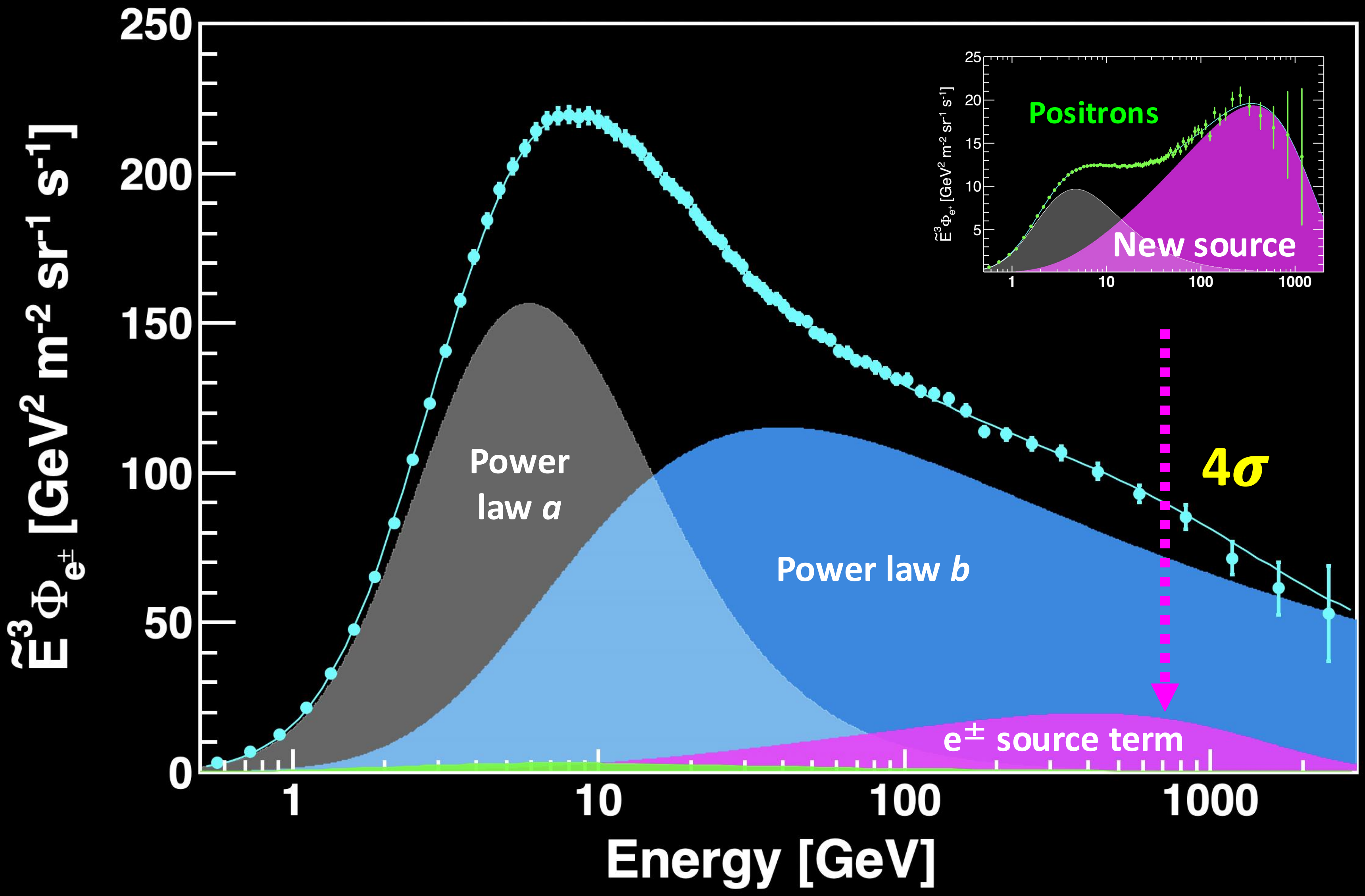
The spectrum fits well with two power laws (a, b) and the measured positron source term

Empirical model: $\Phi_{e^-}(E) = \frac{E^2}{\hat{E}^2}\left(C_a \hat{E}^{\gamma_a} + C_b \hat{E}^{\gamma_b} + \text{Positron Source Term}\right)$ $\chi^2/\text{dof} = 25/67$



New sources like Dark Matter or Pulsars produce equal amounts of e^+ and e^-

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

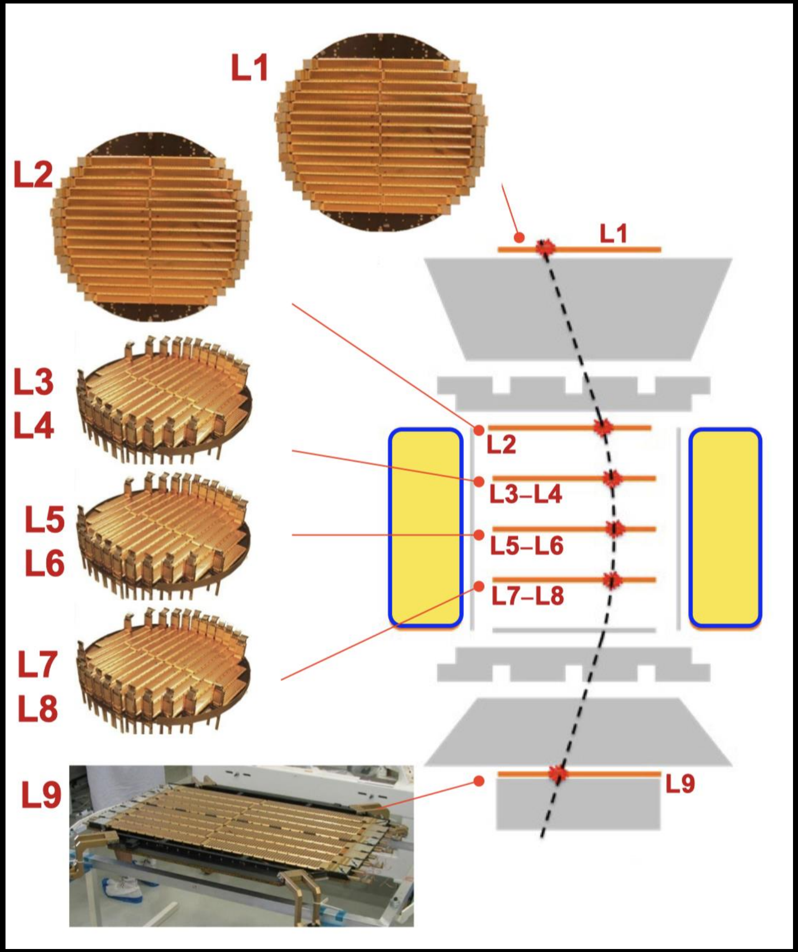


In 13.5 years on the ISS, AMS has recorded 66M electrons, 4.5M positrons. The accuracy and characteristics of the data require the development of a new comprehensive models.

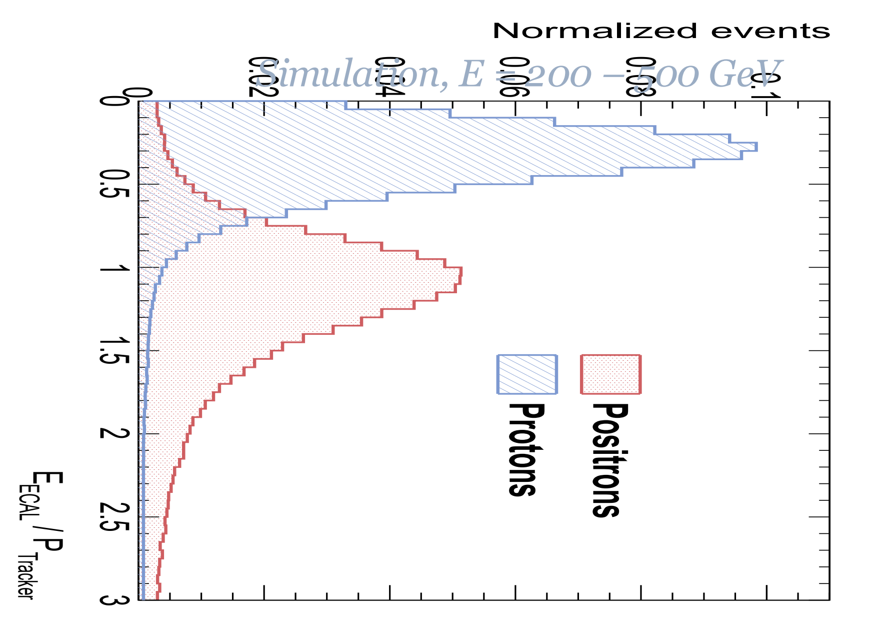
AMS will continue to collect data to 2030 with the upgraded detector.

Backup

Energy and momentum measurements



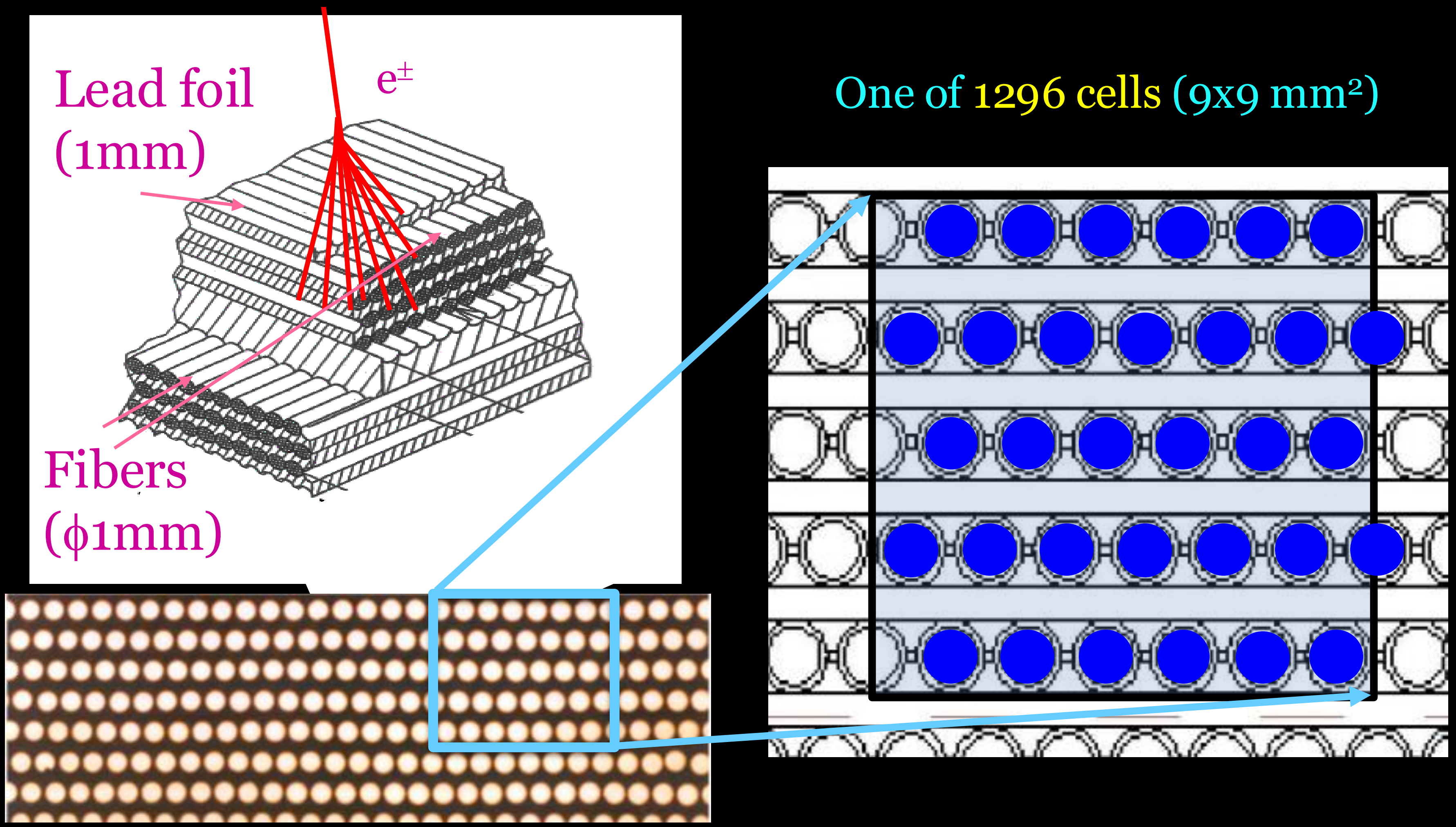
- Nine layers in AMS tracker forms 3 m lever arm
- For particle with Z=1:
  - Single point resolution is **10 µm**
  - The maximum detectable rigidity is **2 TeV**



Independent momentum (by tracker) and energy (by calorimeter) measurements allows to distinguish e± from protons

Electromagnetic Calorimeter

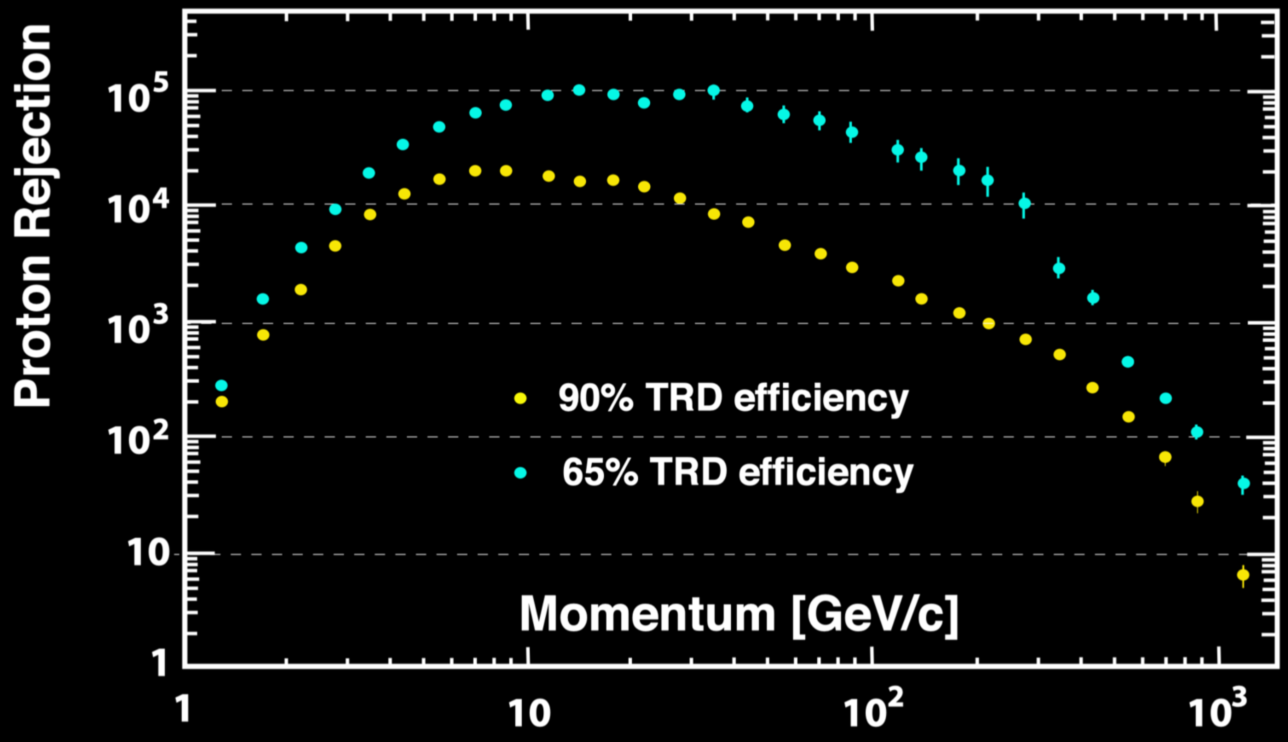
measures the highest energy electrons in space with few percent accuracy

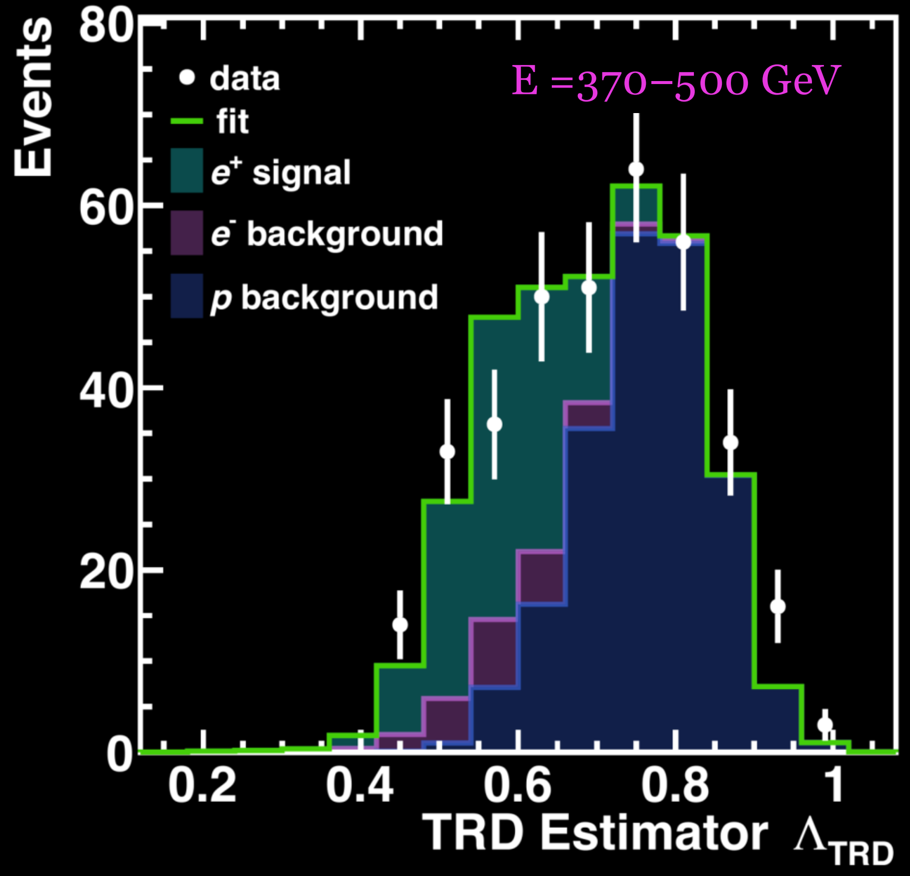


A precision, 17 X_0, TeV, 3-dimensional measurement of the directions and energies of light rays and electrons

Transition Radiation Detector

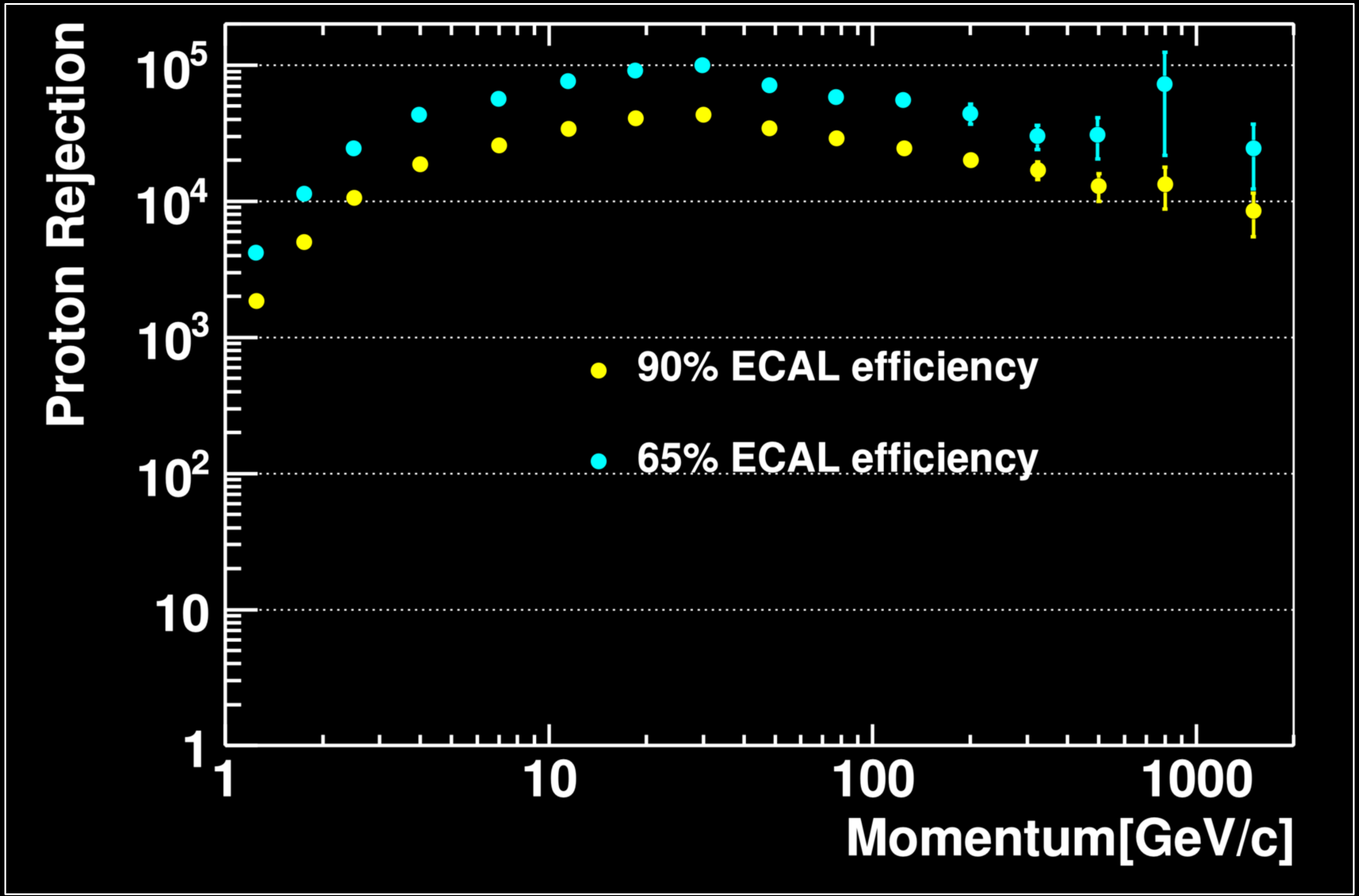
identifies positrons and electrons, rejects protons up to TeV





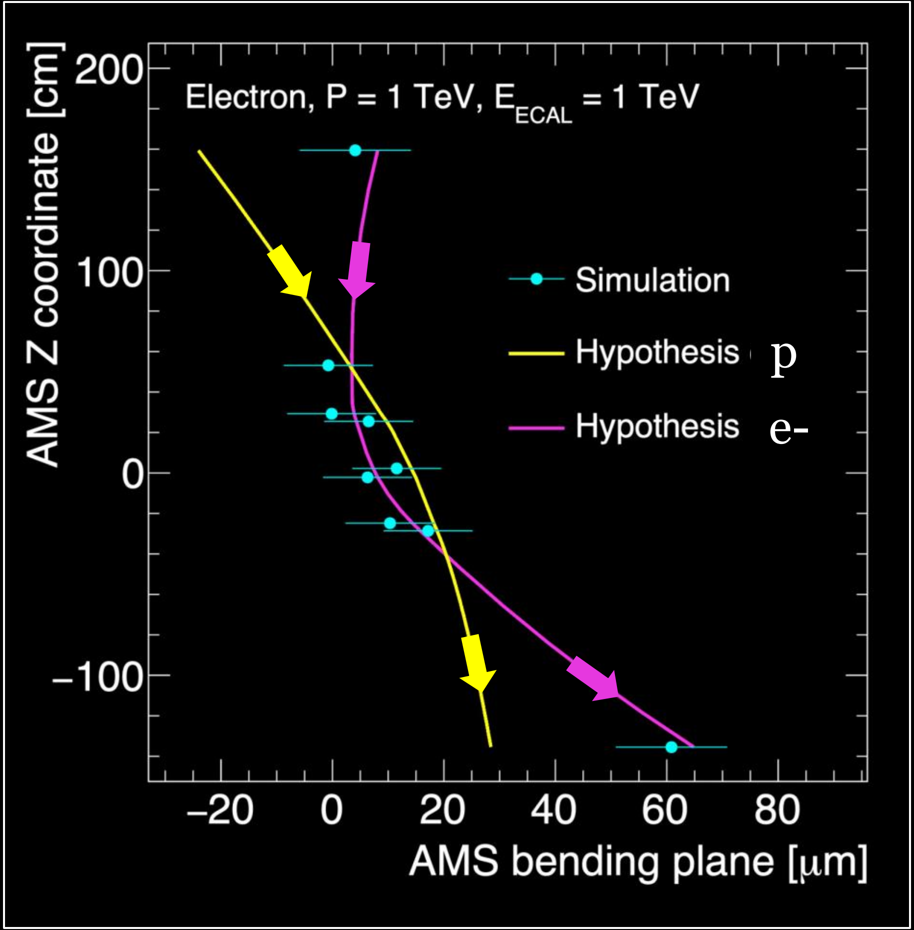
Proton background rejection with ECAL

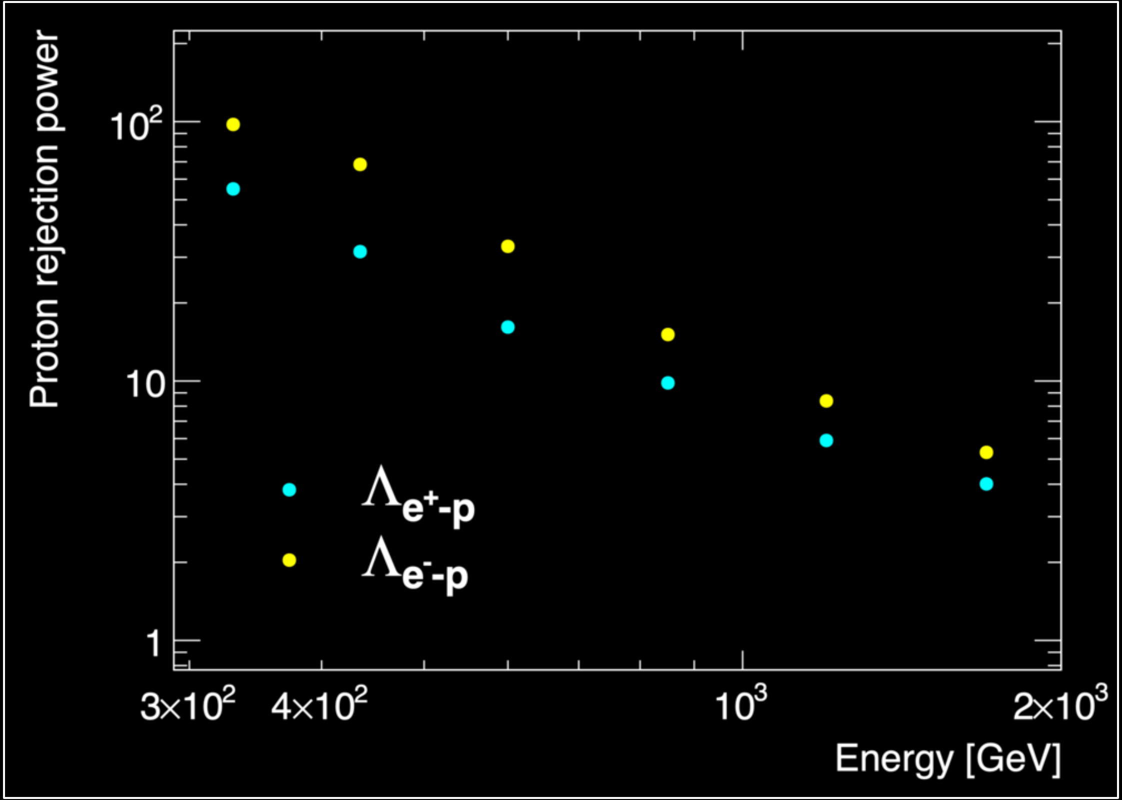
For electrons and positron measurements above 1 TeV, the ECAL provides substantial suppression of the proton background



Recent developments in particle identification

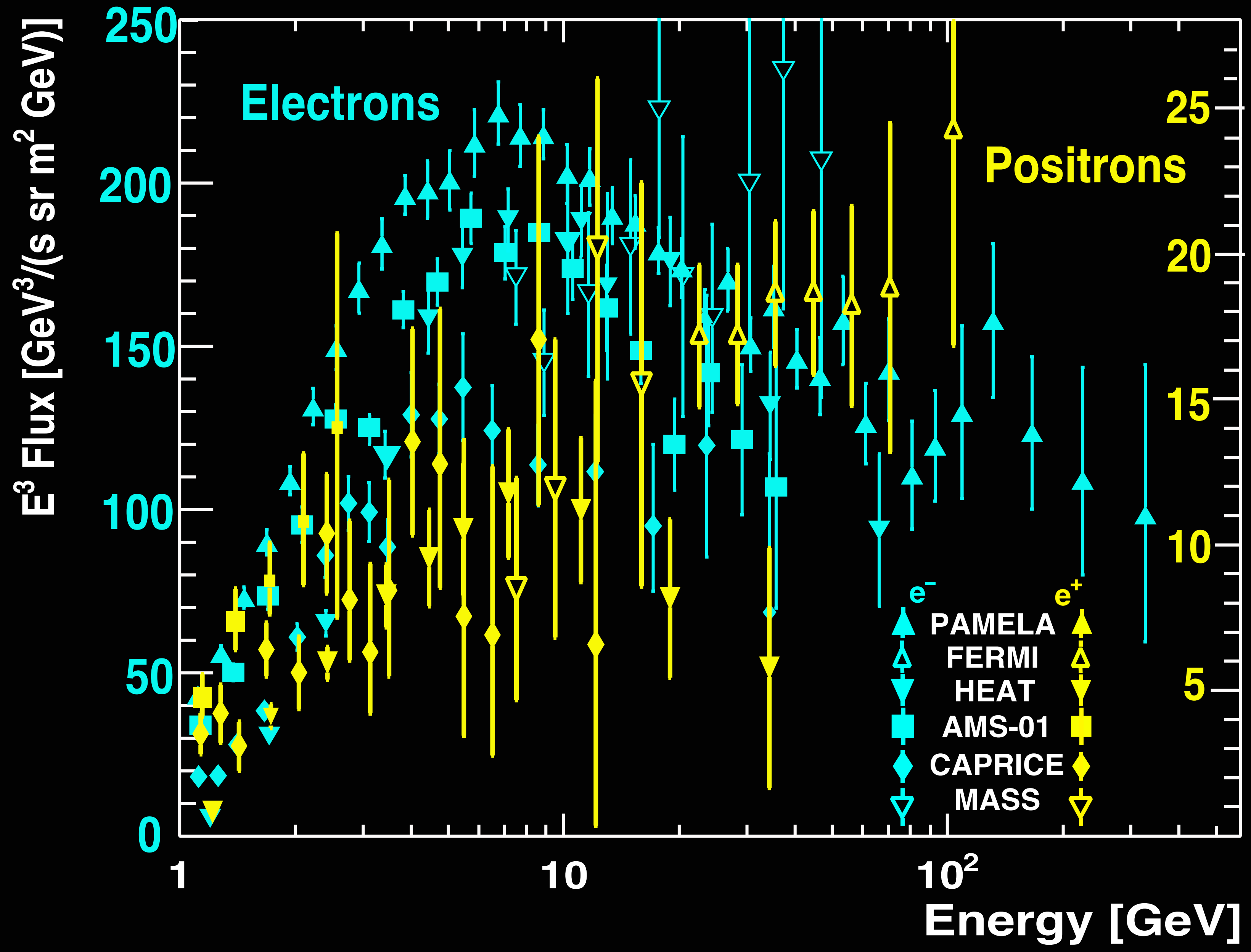
Energy measurement by ECAL defines e± momentum at top of AMS allowing particle hypothesis testing (with corresponding charge sign and energy losses) during trajectory determination.





Parameters from competing track fits along with event characteristics in tracker and TOF (charge, noise) are used to construct multivariable estimator providing an independent from TRD and ECAL suppression of the proton background at TeV scale.

Measurements of positrons and electrons before AMS



Examples of DM models discussed in the literature

DM annihilation

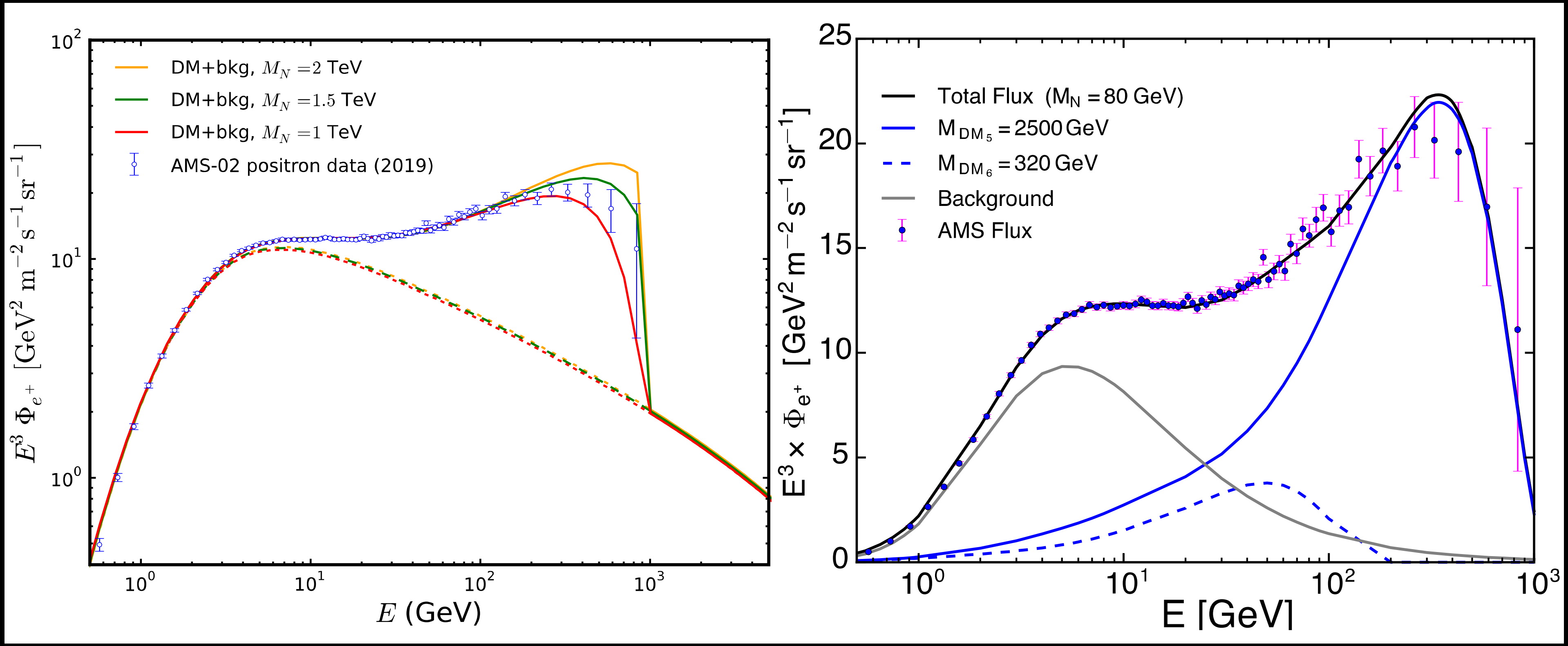
Z.L. Han, R. Ding, S.J. Lin, and B. Zhu,
Eur. Phys. J. C79 (2019) 12, 1007

$\bar{N}N \rightarrow Z'Z' \rightarrow e^+ + X$

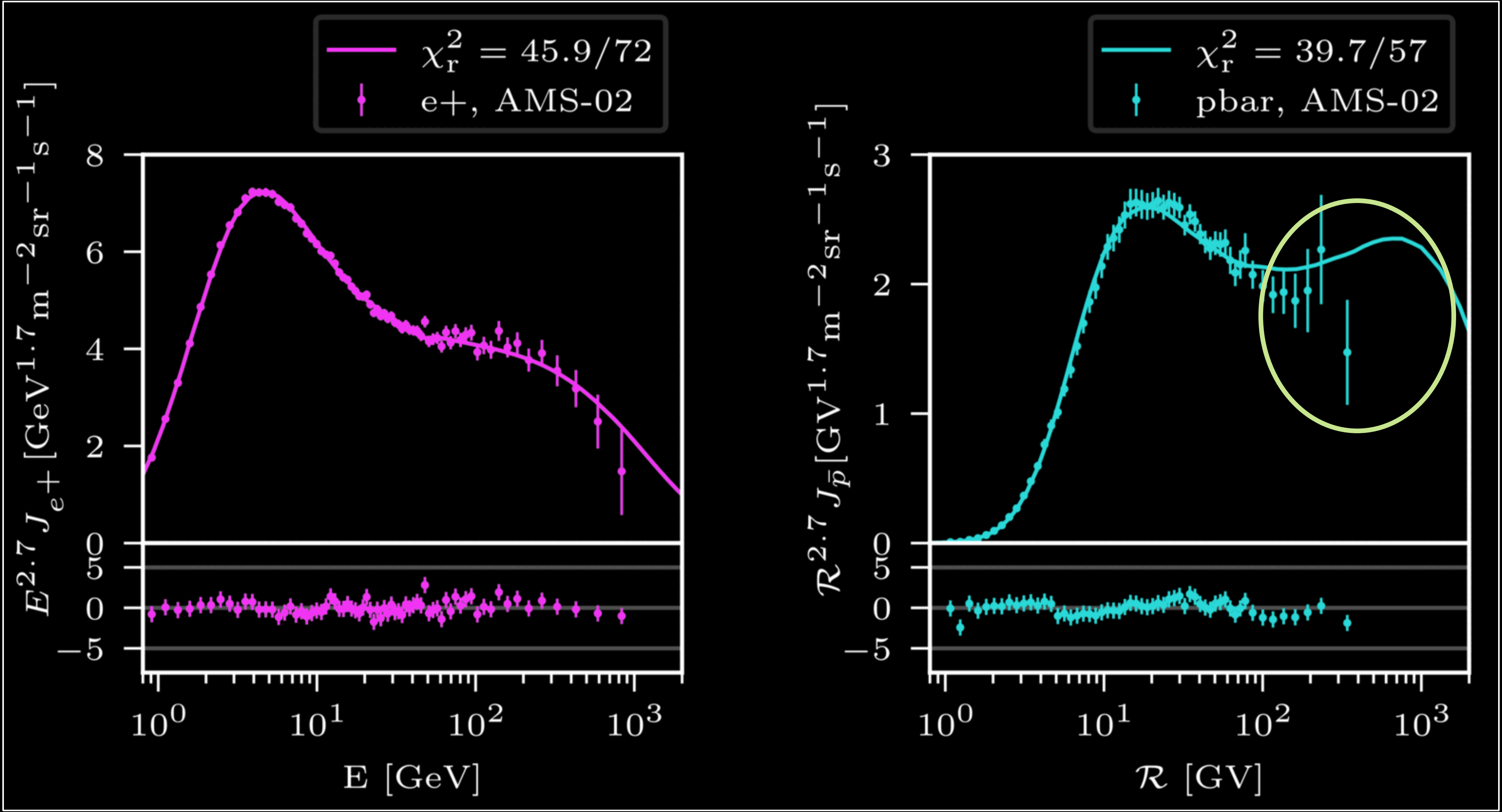
DM decays

F. Queiroz and C. Siqueira,
Phys. Rev. D 101 (2020) 7, 075007

$\chi \rightarrow \bar{N}N$; $N \rightarrow e^+ + X$



Astrophysical sources



Model: P. Mertsch, A. Vittino, S. Sarkar, PRD 104 (2021) 103029
"Explaining cosmic ray antimatter with secondaries from old supernova remnants"