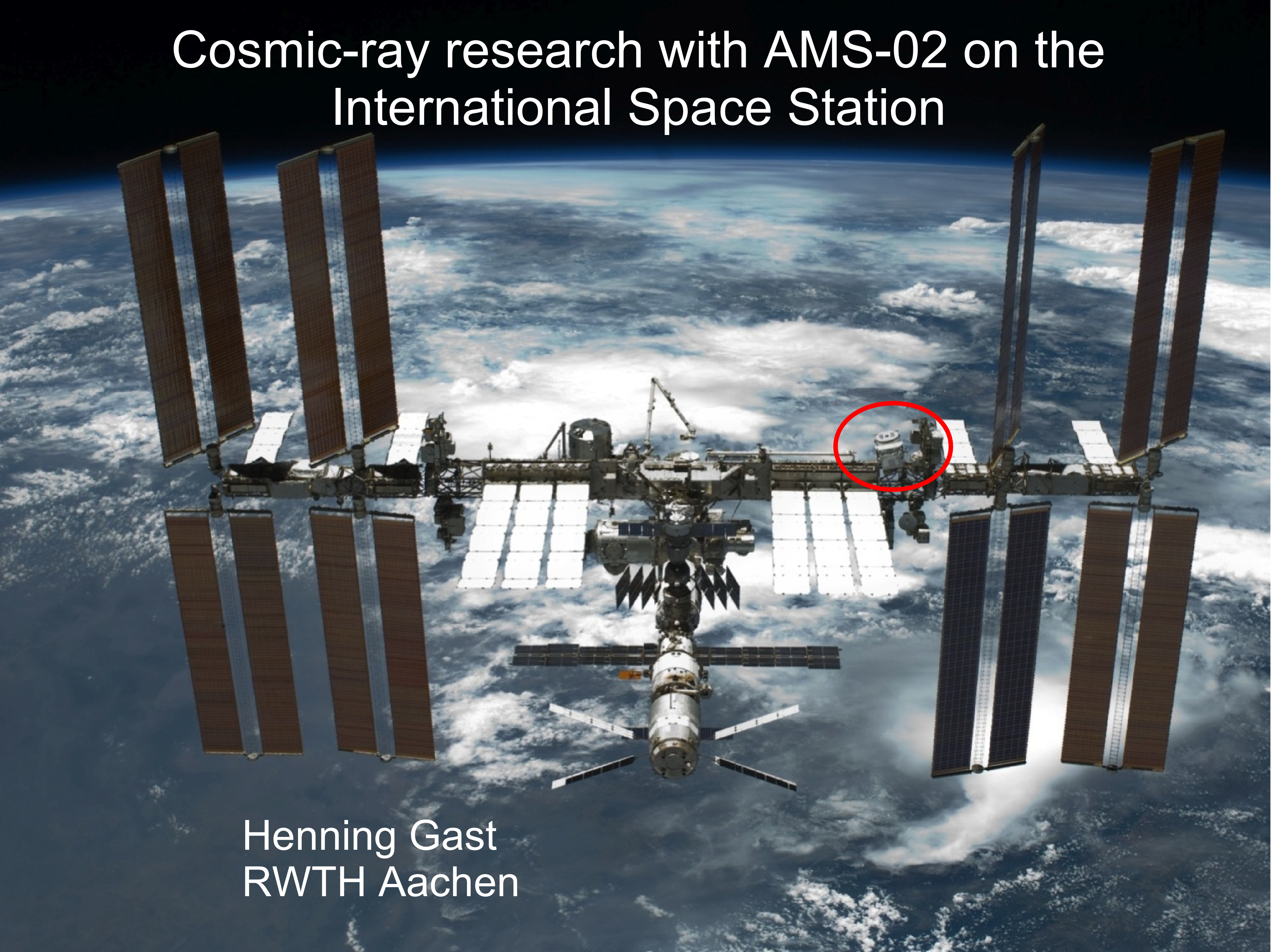
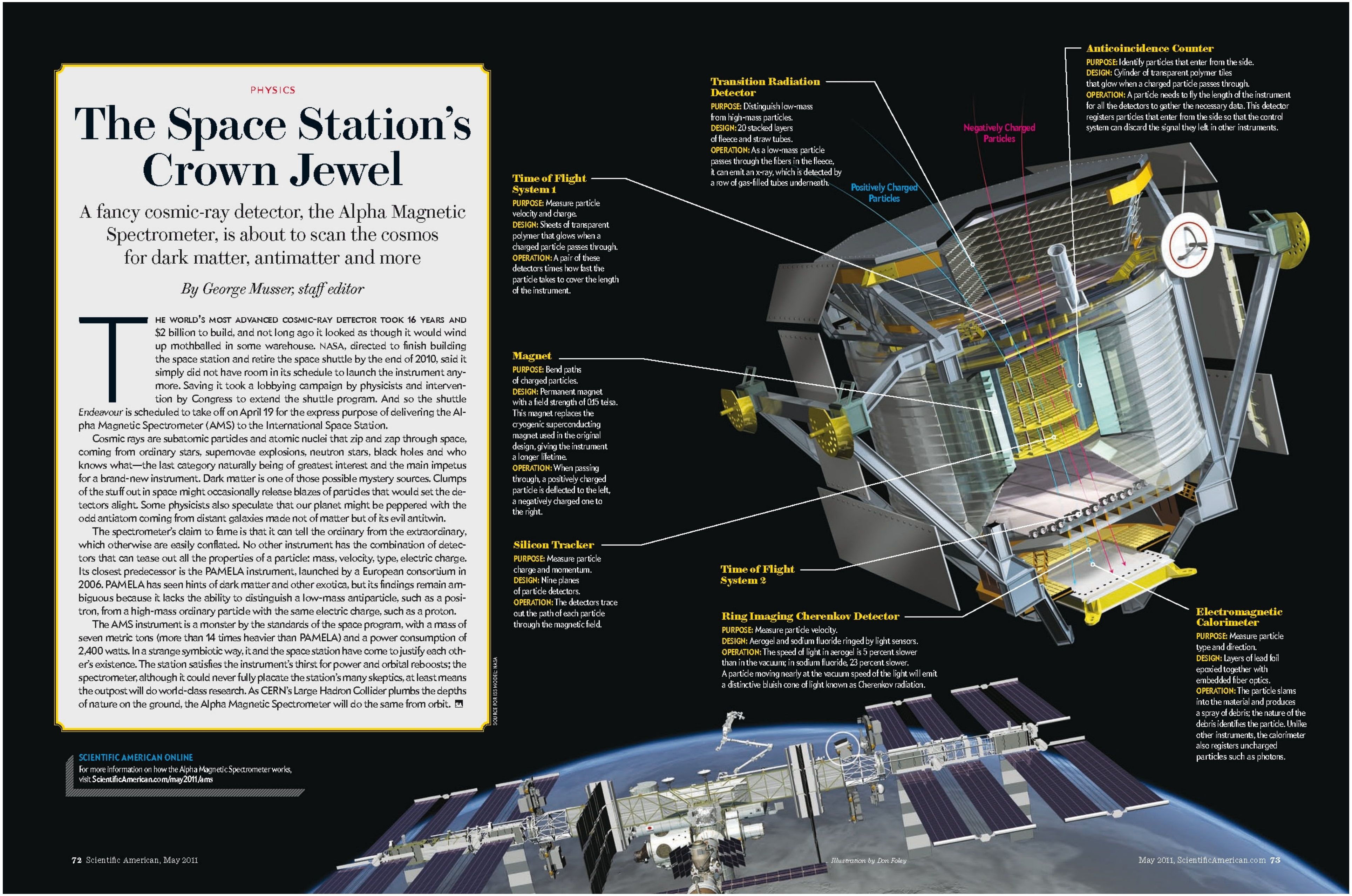
Cosmic-ray research with AMS-02 on the International Space Station



Henning Gast
RWTH Aachen

Scientific American, May 2011



PHYSICS

The Space Station's Crown Jewel

A fancy cosmic-ray detector, the Alpha Magnetic Spectrometer, is about to scan the cosmos for dark matter, antimatter and more

By George Musser, staff editor

THE WORLD'S MOST ADVANCED COSMIC-RAY DETECTOR TOOK 16 YEARS AND $2 billion to build, and not long ago it looked as though it would wind up mothballed in some warehouse. NASA, directed to finish building the space station and retire the space shuttle by the end of 2010, said it simply did not have room in its schedule to launch the instrument anymore. Saving it took a lobbying campaign by physicists and intervention by Congress to extend the shuttle program. And so the shuttle *Endeavour* is scheduled to take off on April 19 for the express purpose of delivering the Alpha Magnetic Spectrometer (AMS) to the International Space Station.

Cosmic rays are subatomic particles and atomic nuclei that zip and zap through space, coming from ordinary stars, supernovae explosions, neutron stars, black holes and who knows what—the last category naturally being of greatest interest and the main impetus for a brand-new instrument. Dark matter is one of those possible mystery sources. Clumps of the stuff out in space might occasionally release blazes of particles that would set the detectors alight. Some physicists also speculate that our planet might be peppered with the odd antiatom coming from distant galaxies made not of matter but of its evil antitwin.

The spectrometer's claim to fame is that it can tell the ordinary from the extraordinary, which otherwise are easily conflated. No other instrument has the combination of detectors that can tease out all the properties of a particle: mass, velocity, type, electric charge. Its closest predecessor is the PAMELA instrument, launched by a European consortium in 2006. PAMELA has seen hints of dark matter and other exotica, but its findings remain ambiguous because it lacks the ability to distinguish a low-mass antiparticle, such as a positron, from a high-mass ordinary particle with the same electric charge, such as a proton.

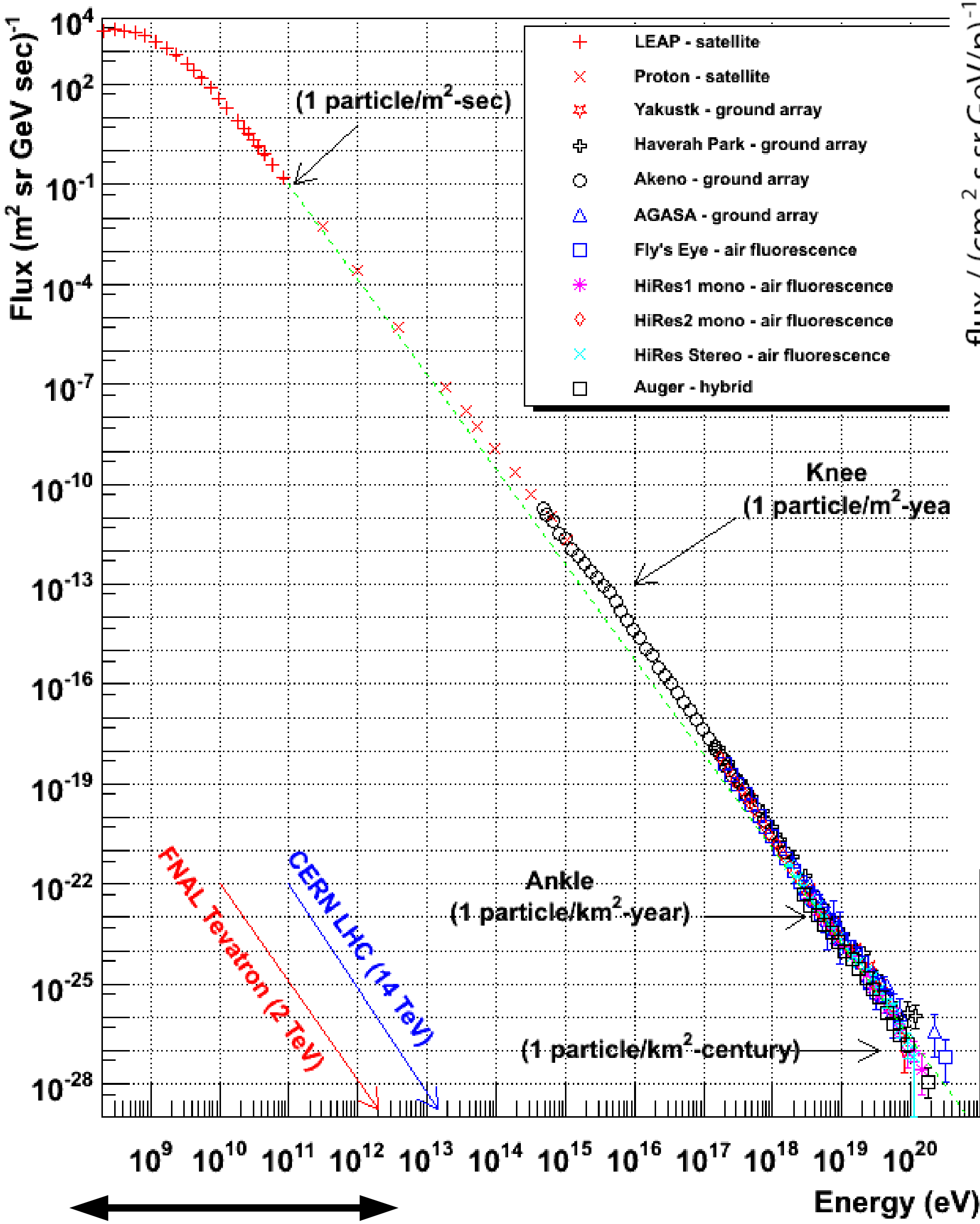
The AMS instrument is a monster by the standards of the space program, with a mass of seven metric tons (more than 14 times heavier than PAMELA) and a power consumption of 2,400 watts. In a strange symbiotic way, it and the space station have come to justify each other's existence. The station satisfies the instrument's thirst for power and orbital reboots; the spectrometer, although it could never fully placate the station's many skeptics, at least means the outpost will do world-class research. As CERN's Large Hadron Collider plumbs the depths of nature on the ground, the Alpha Magnetic Spectrometer will do the same from orbit.

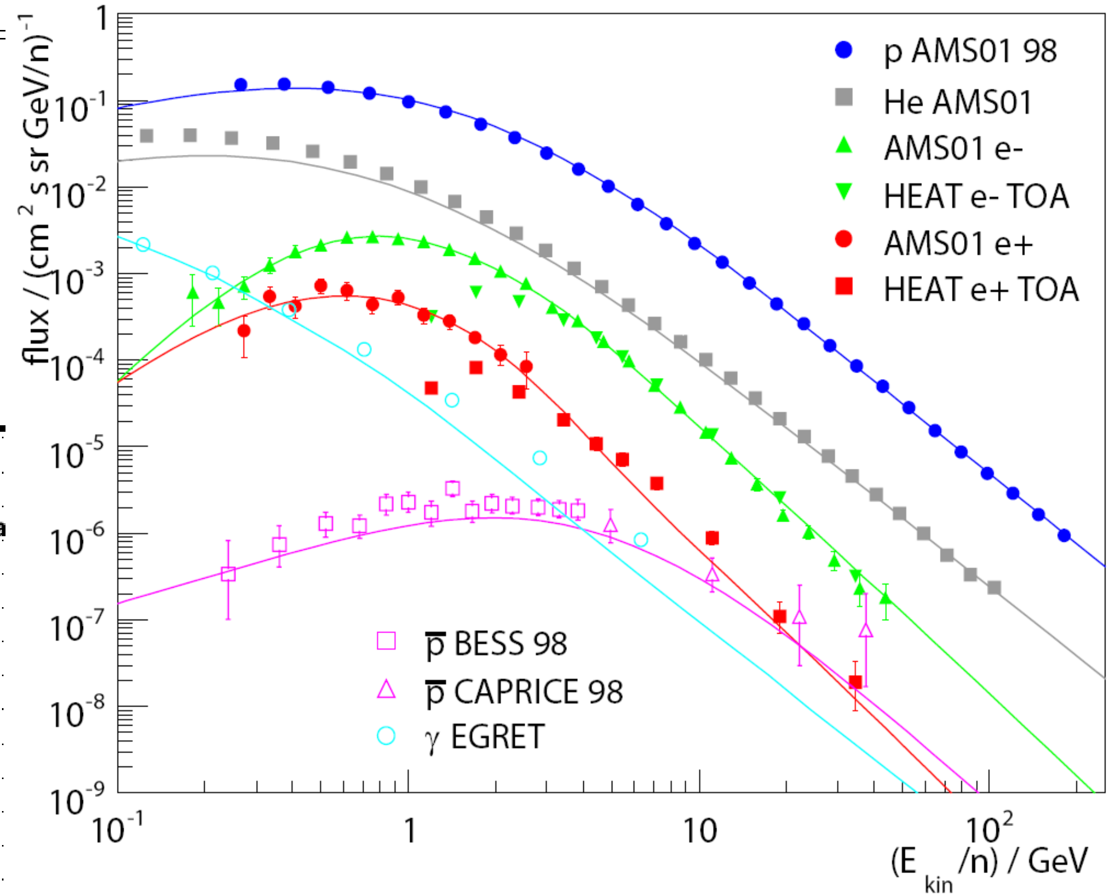
SCIENTIFIC AMERICAN ONLINE
For more information on how the Alpha Magnetic Spectrometer works, visit ScientificAmerican.com/may2011/ams

72 Scientific American, May 2011

May 2011, ScientificAmerican.com 73

Cosmic rays: spectrum and composition





- Direction information is scrambled by interstellar magnetic fields.

Cosmic ray physics in a nutshell

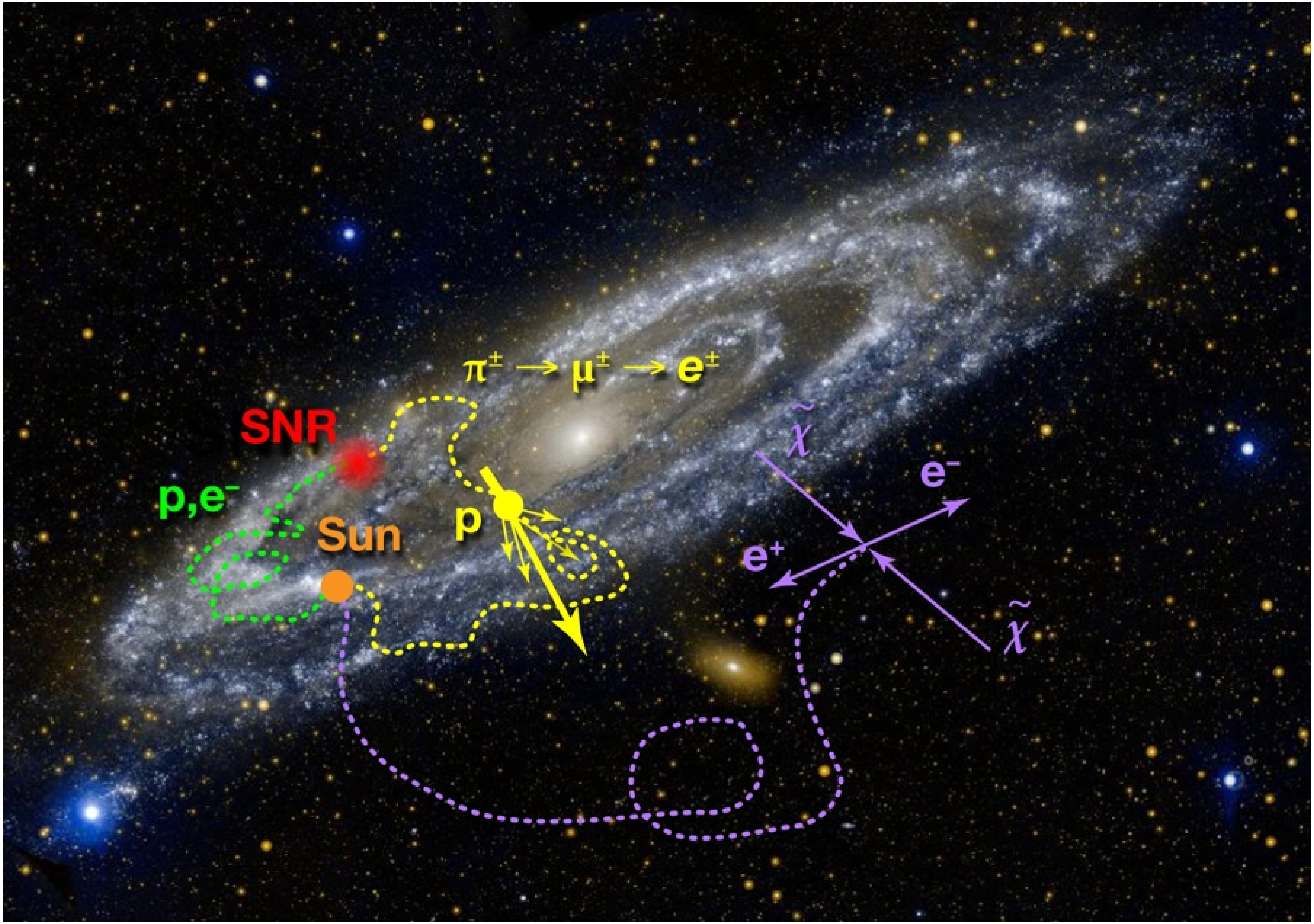
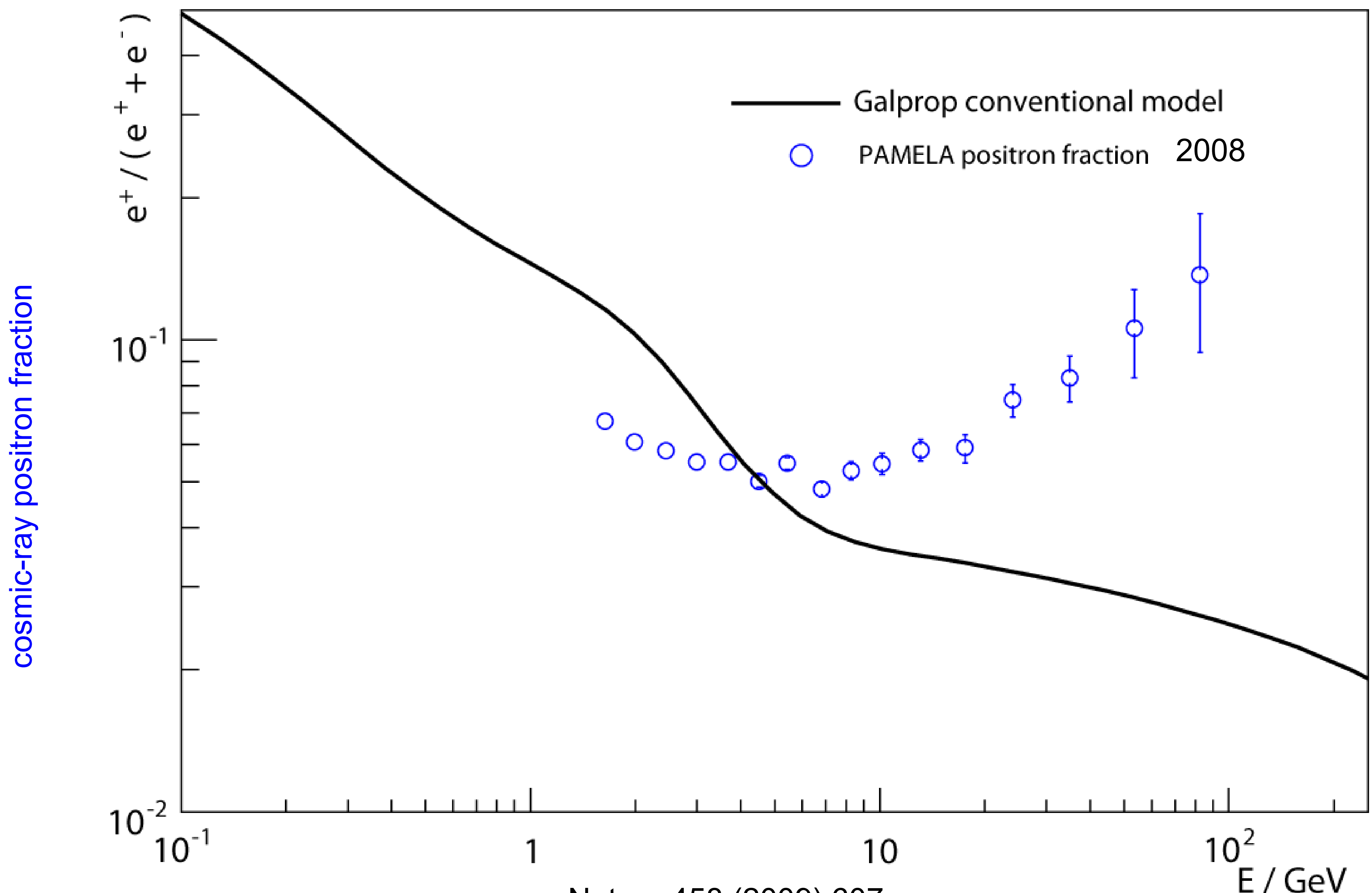


Image: GALEX, JPL-Caltech, NASA;
Drawing: APS/Alan Stonebraker

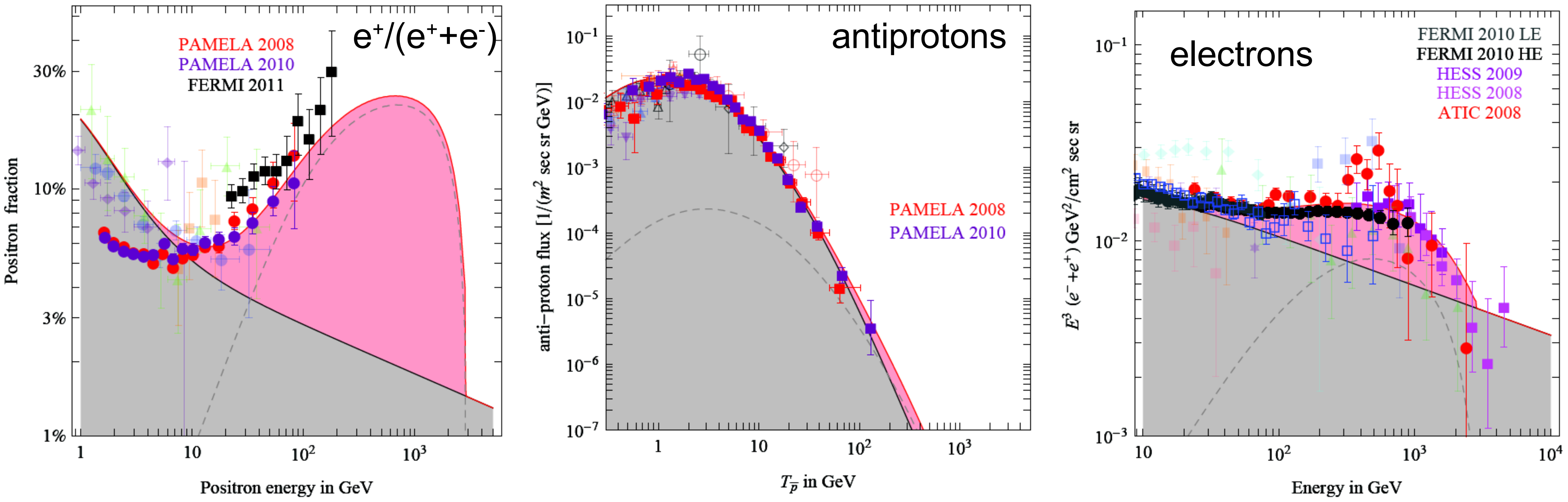
Positron fraction: Exotic sources of cosmic rays?



Nature 458 (2009) 607

Context: Indirect search for dark matter

M. Cirelli, arXiv: 1202.1454



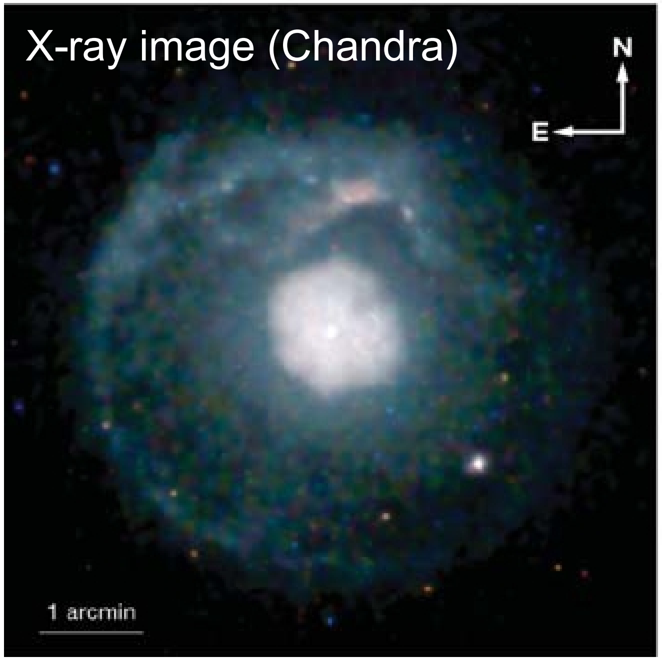
Example fits: 3 TeV DM particle annihilating to $\tau^+\tau^-$, with a cross section of $2\cdot10^{-22}$ cm^3/s

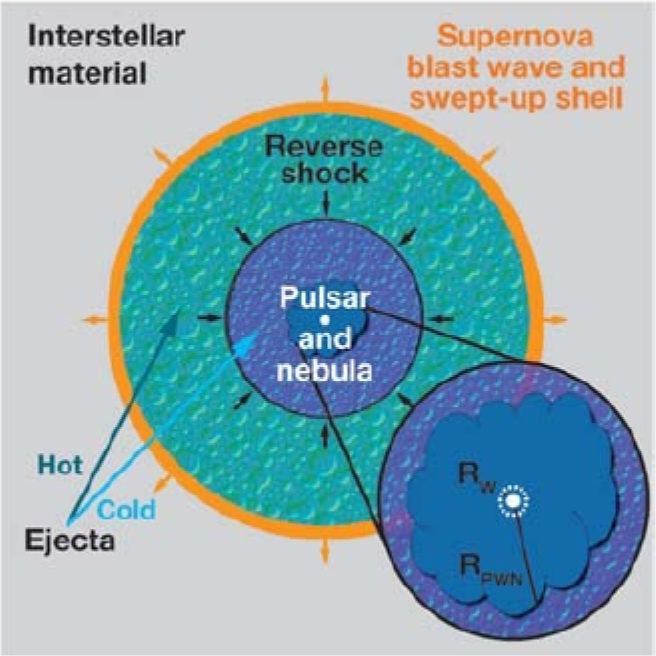
Interpreting antimatter and electron spectra in terms of dark matter requires:

- particle mass of a few TeV
- leptophilic annihilation
- *very large annihilation cross section*

Astrophysical sources for positrons

Positrons inevitably produced in magnetosphere of pulsars and accelerated in pulsar wind nebula.

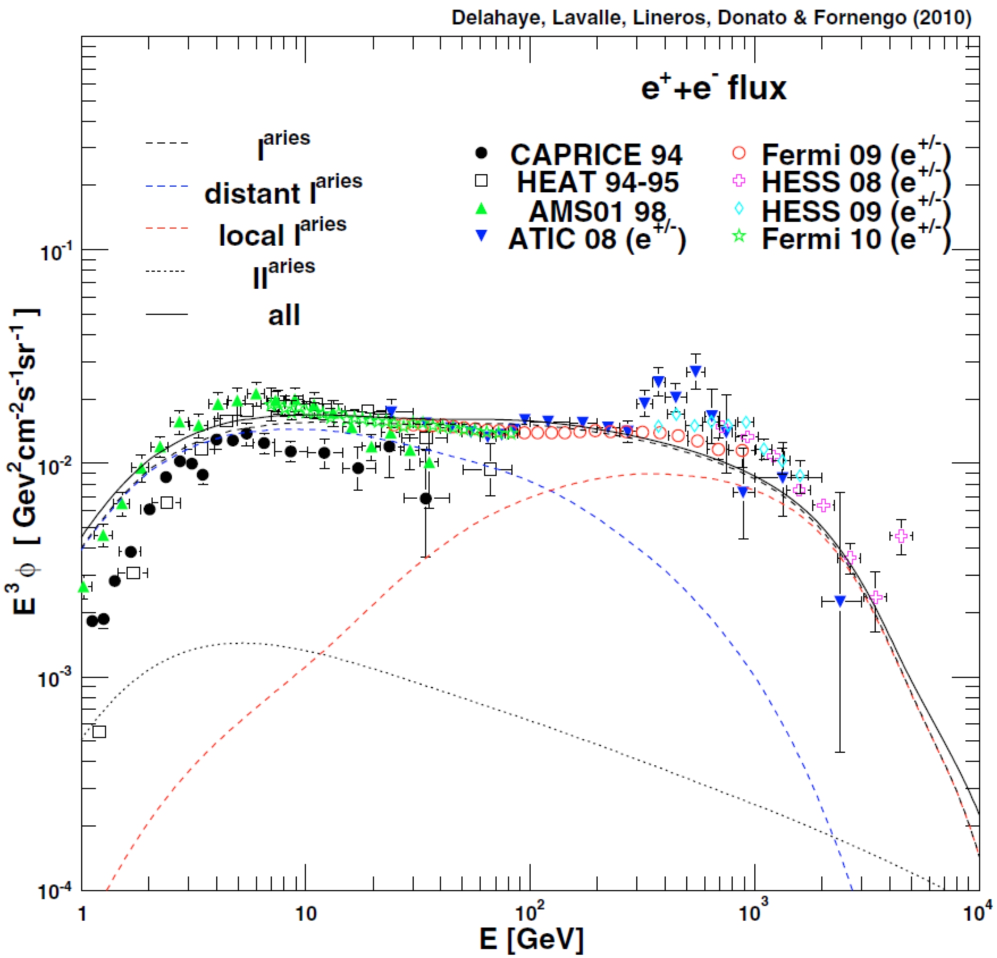


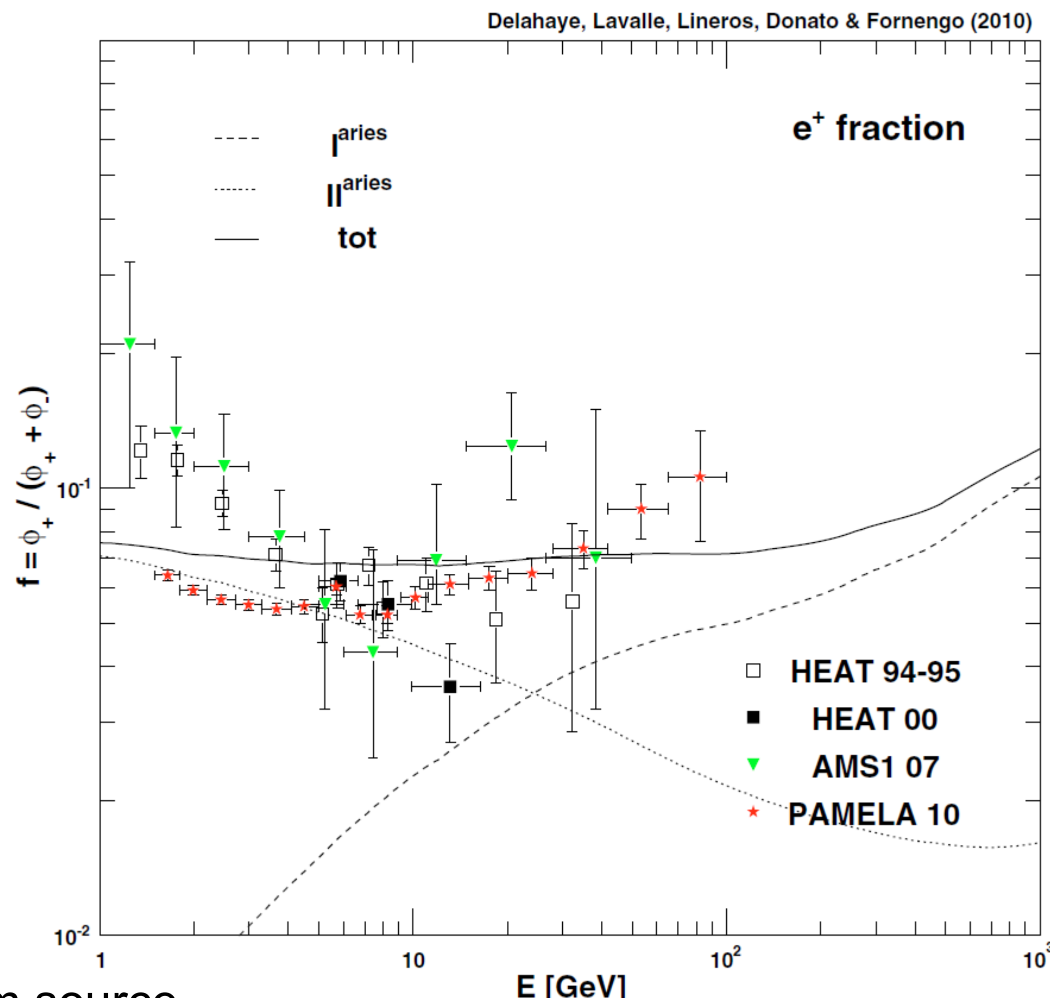


Gaensler & Slane 2006

Context: Astrophysical sources for positrons

Positrons inevitably produced in magnetosphere of pulsars and accelerated in pulsar wind nebula.





Large uncertainties (order of magnitude) from source modeling and propagation.

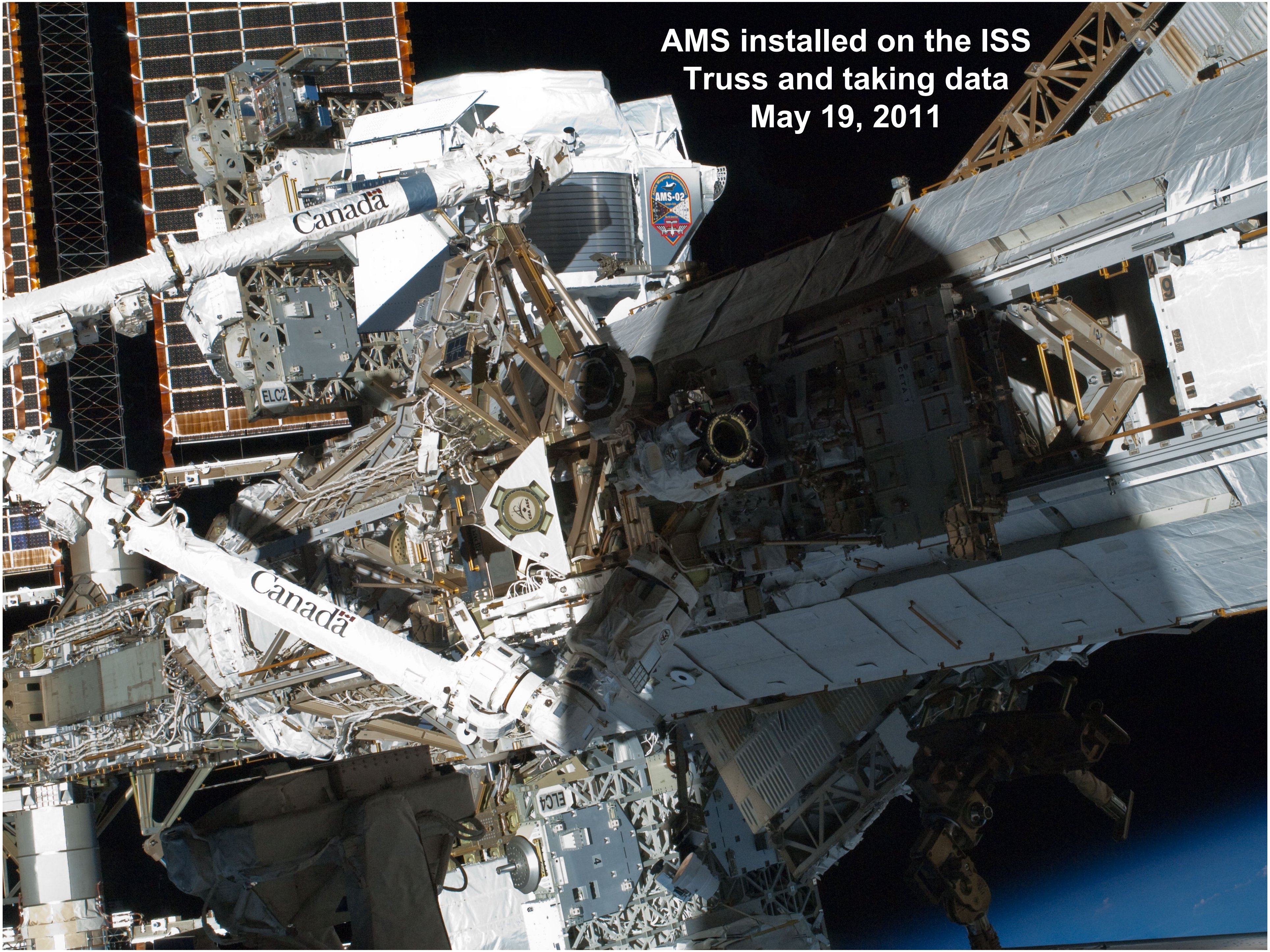
No exotic physics needed to explain rising positron fraction.

e.g.:
Delahaye et al., A&A 524 (2010) A51
Blasi & Amato 2010, 1007.4745

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

AMS-02 launch

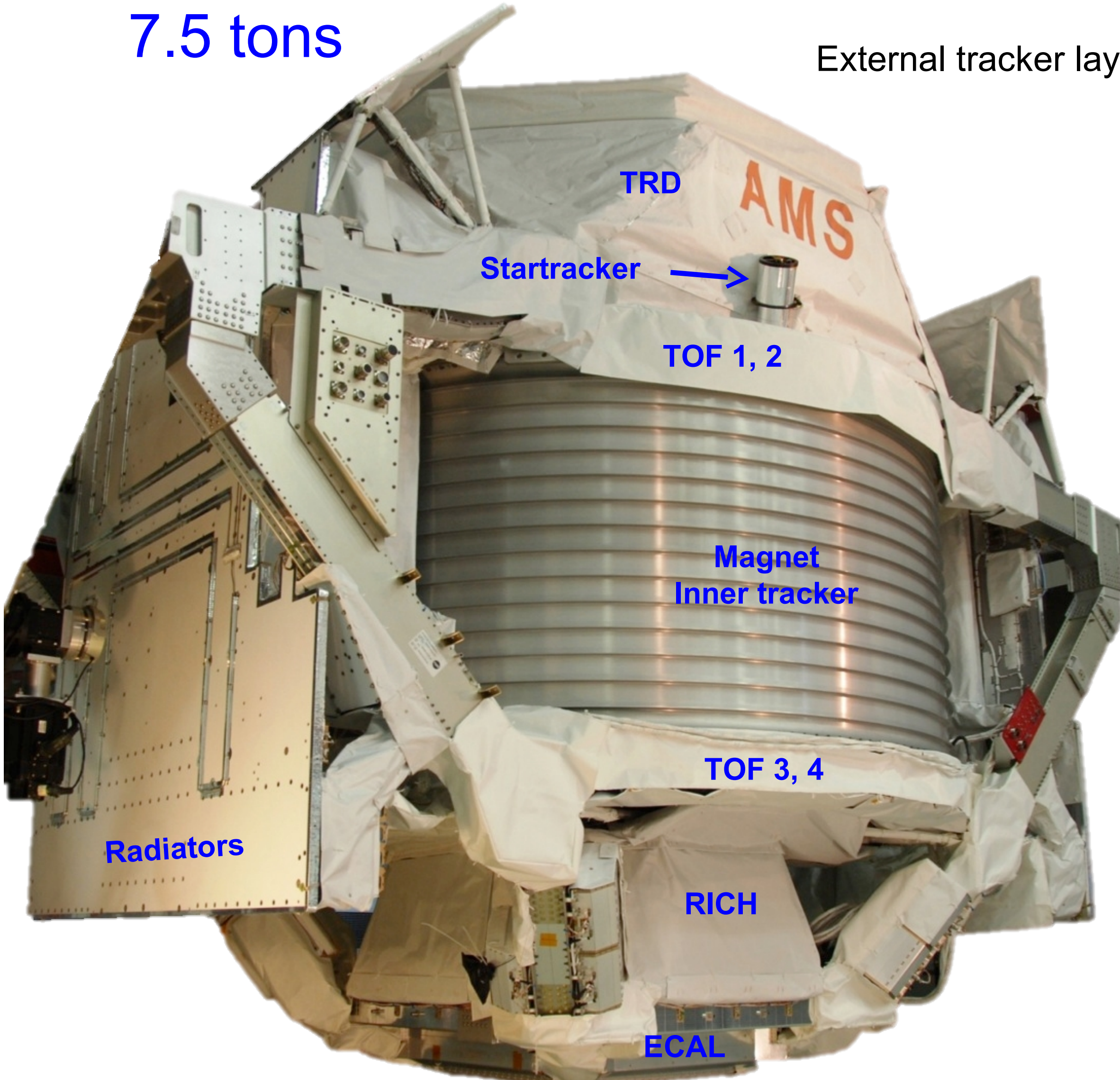
Endeavour approaches the International Space Station

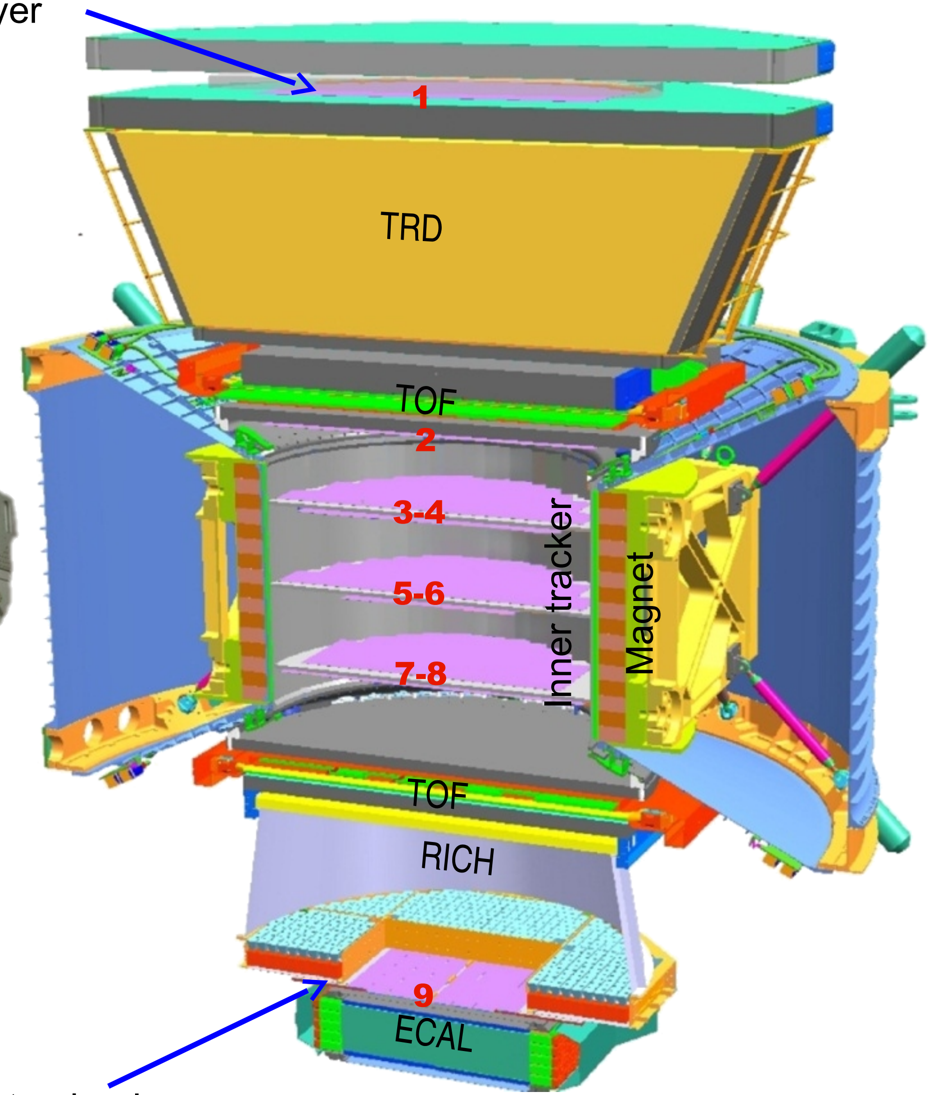

AMS installed on the ISS
Truss and taking data
May 19, 2011
Canada
AMS-02
ELC2
Canada
ELC4

AMS-02

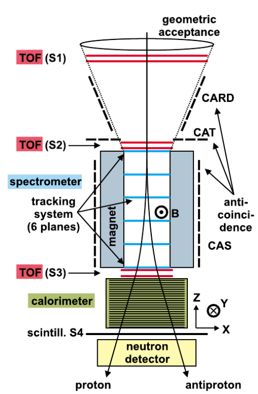
5m x 4m x 3m

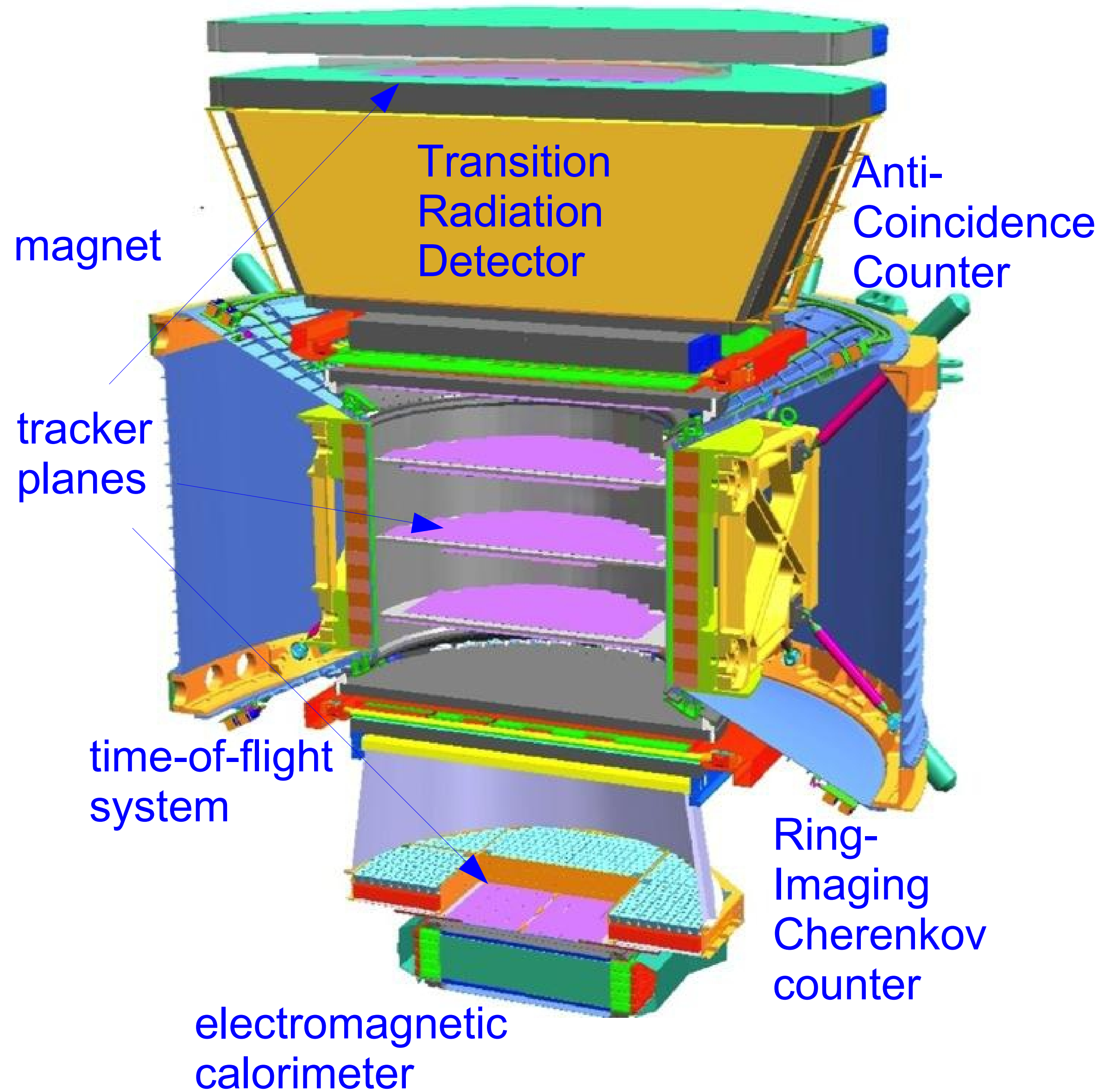
7.5 tons





PAMELA vs AMS-02



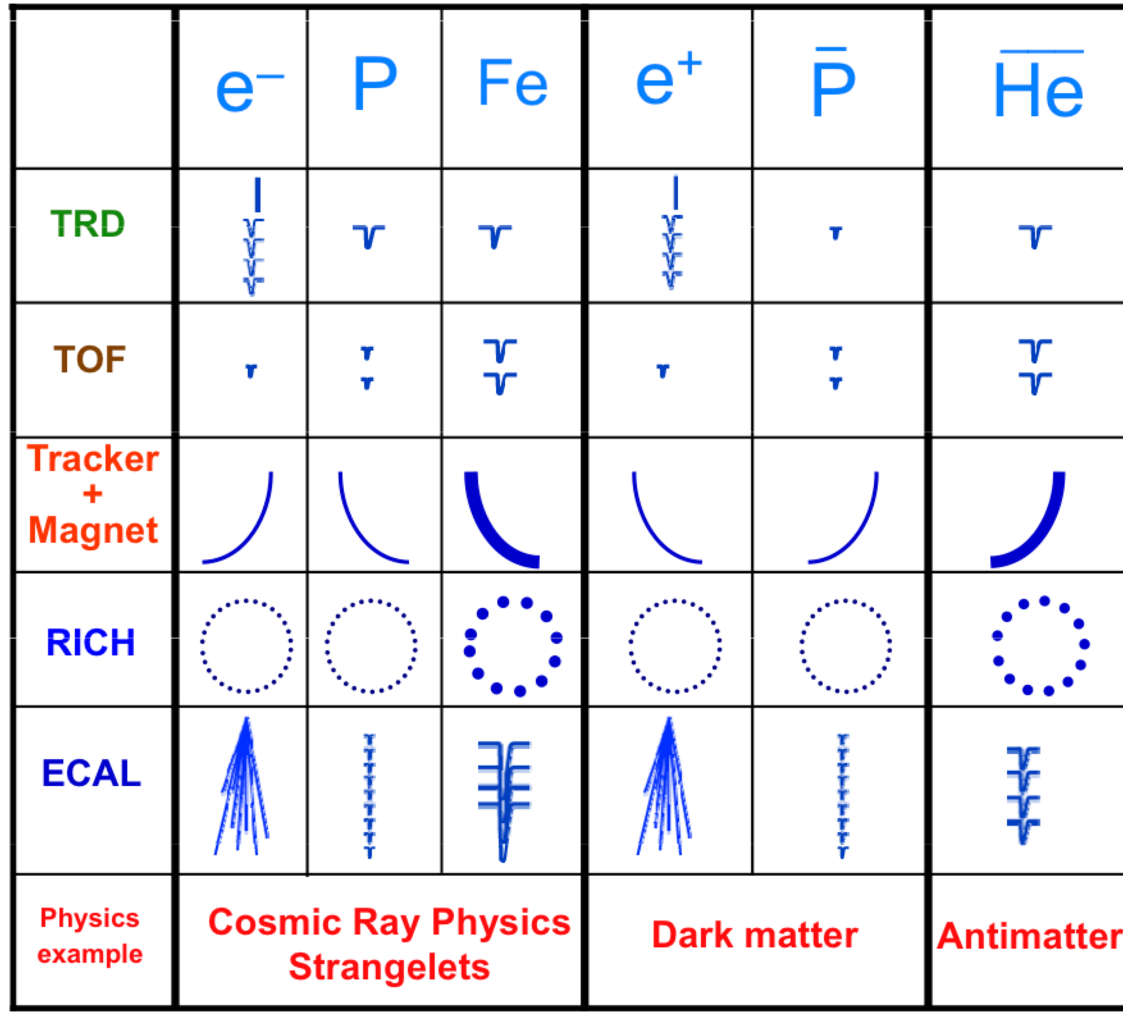


GF: 21.5 cm^2 sr

GF: 250 – 3500 cm^2 sr, depending on physics analysis

AMS-02 particle identification

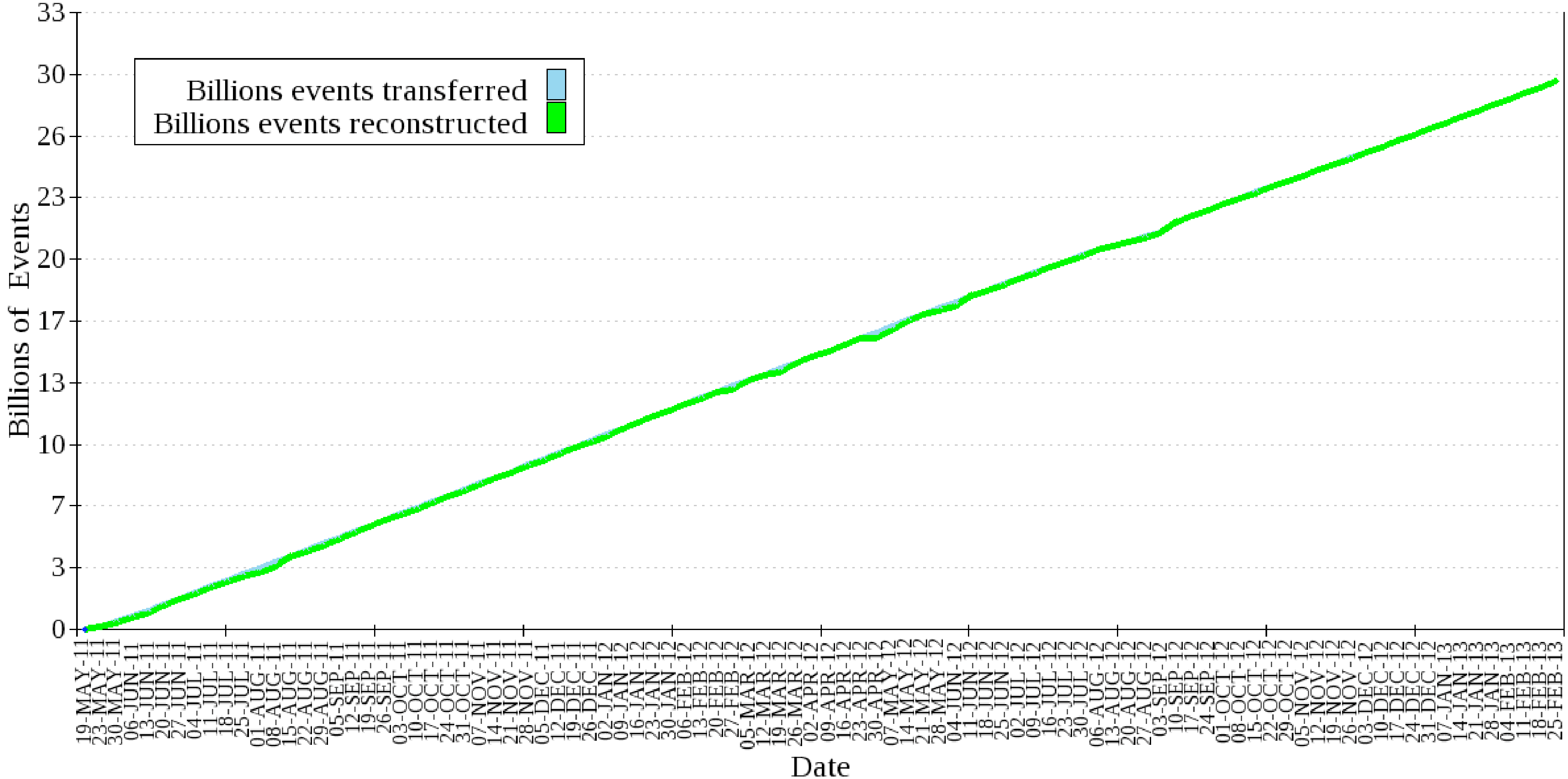
- Particle ID requires complex algorithms for each subdetector.
- Combine information from all subdetectors.
- Example: proton rejection 1:1,000,000



Cosmic rays are measured at up to 2 KHz and data is generated at ~7 Gbit/s, reduced on board to an average of ~10 Mbit/s.

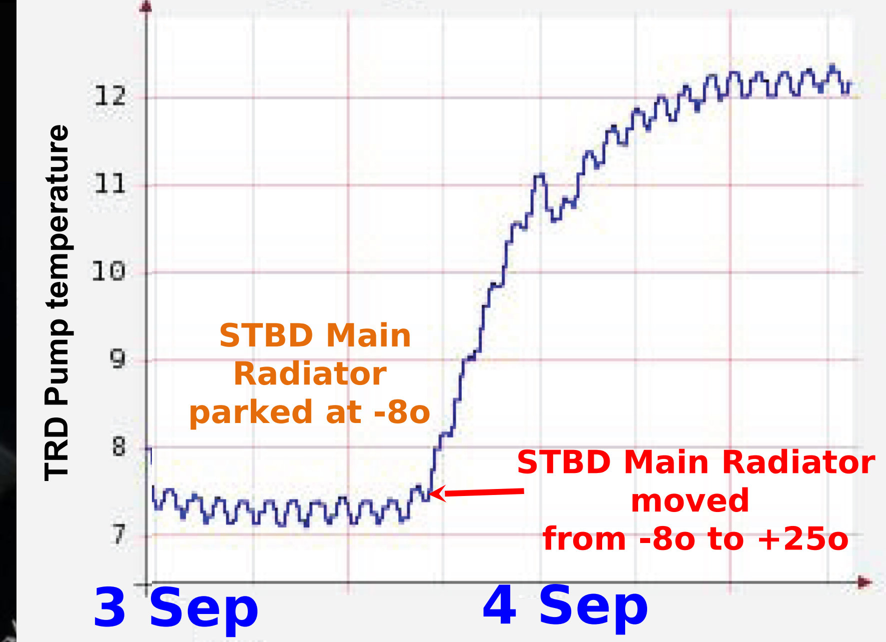
AMS-02 data taking

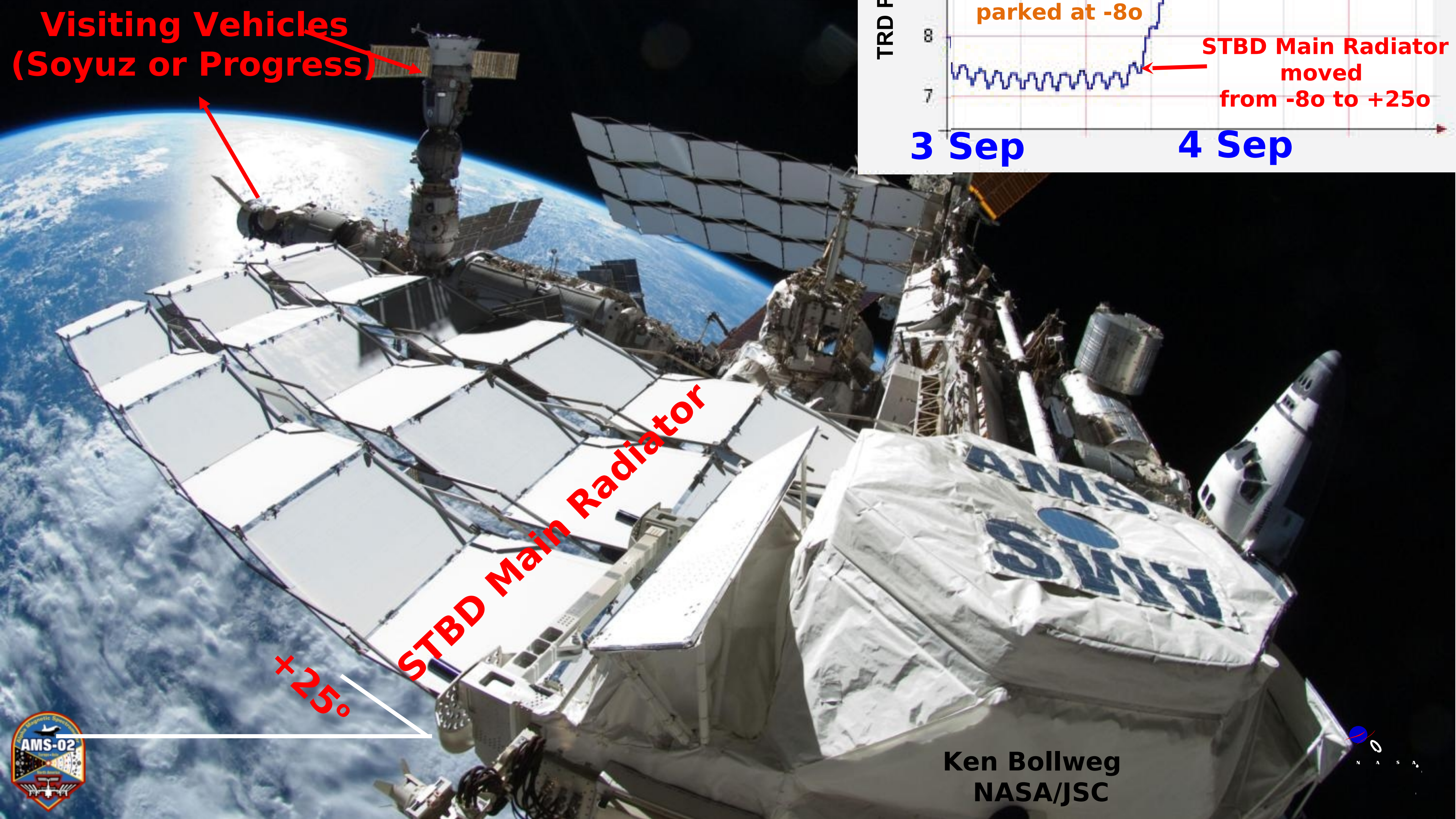
- For every year of AMS flight:
- 20 TB raw data
- 160 TB reconstructed event data
- Data handling non-trivial!



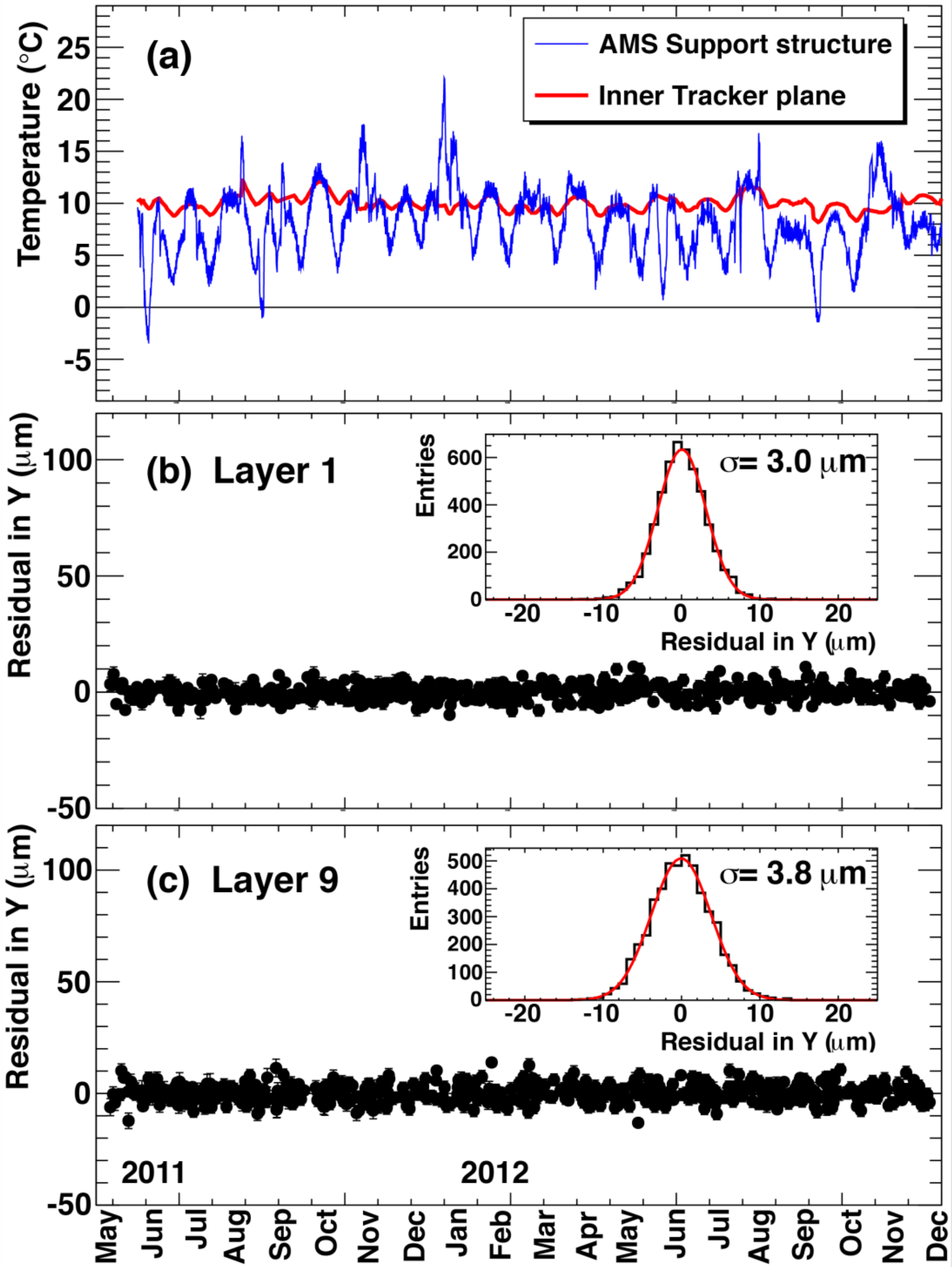
Thermal variables:

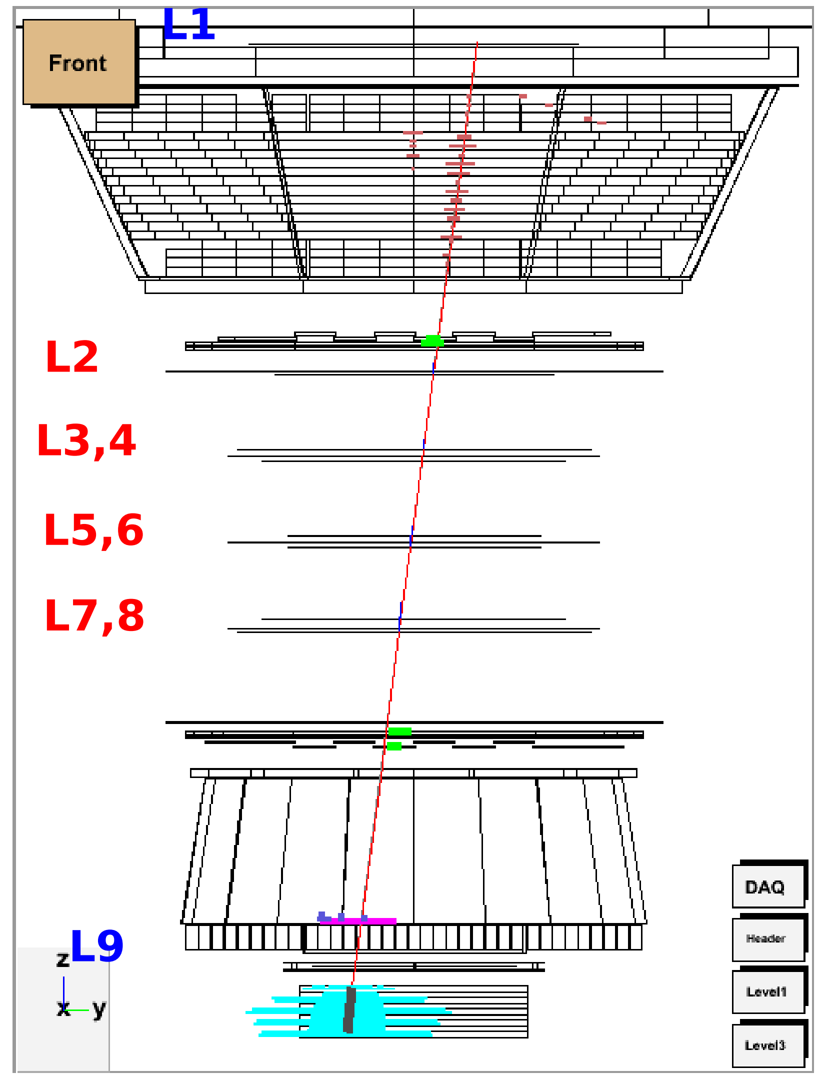
- ISS Radiator positions
- ISS attitude changes (primarily for visiting vehicles)





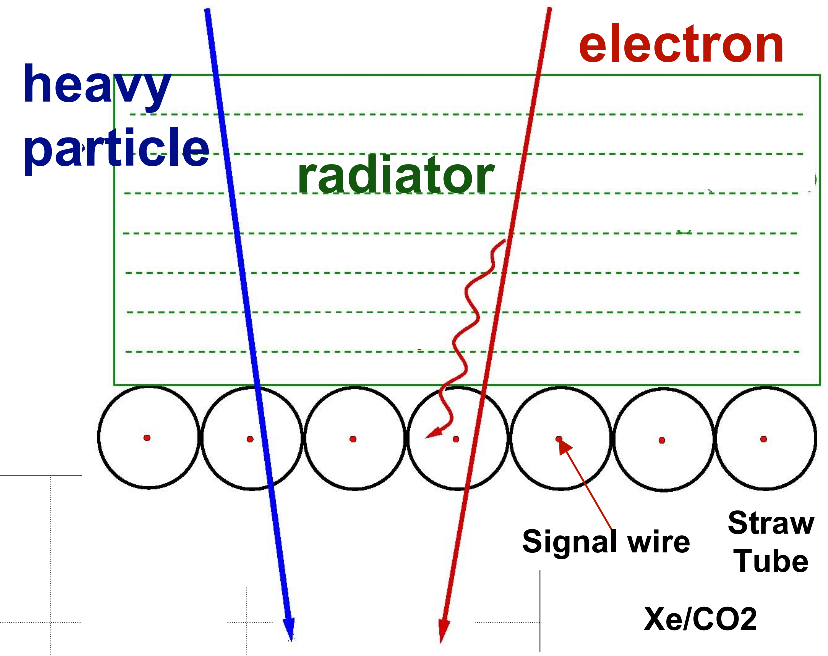
Tracker: Stability of alignment of outer tracker planes



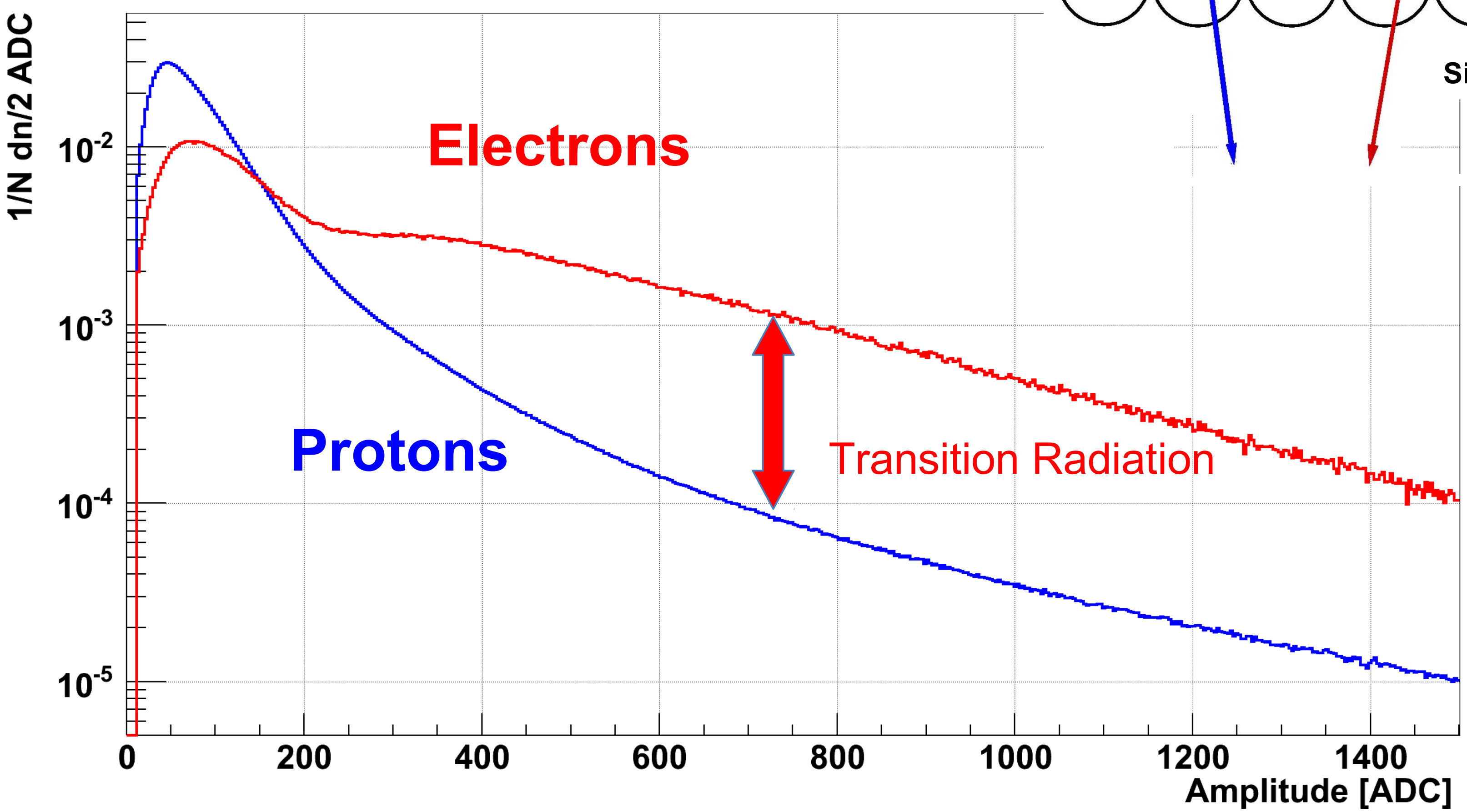


AMS-02 performance: TRD spectra

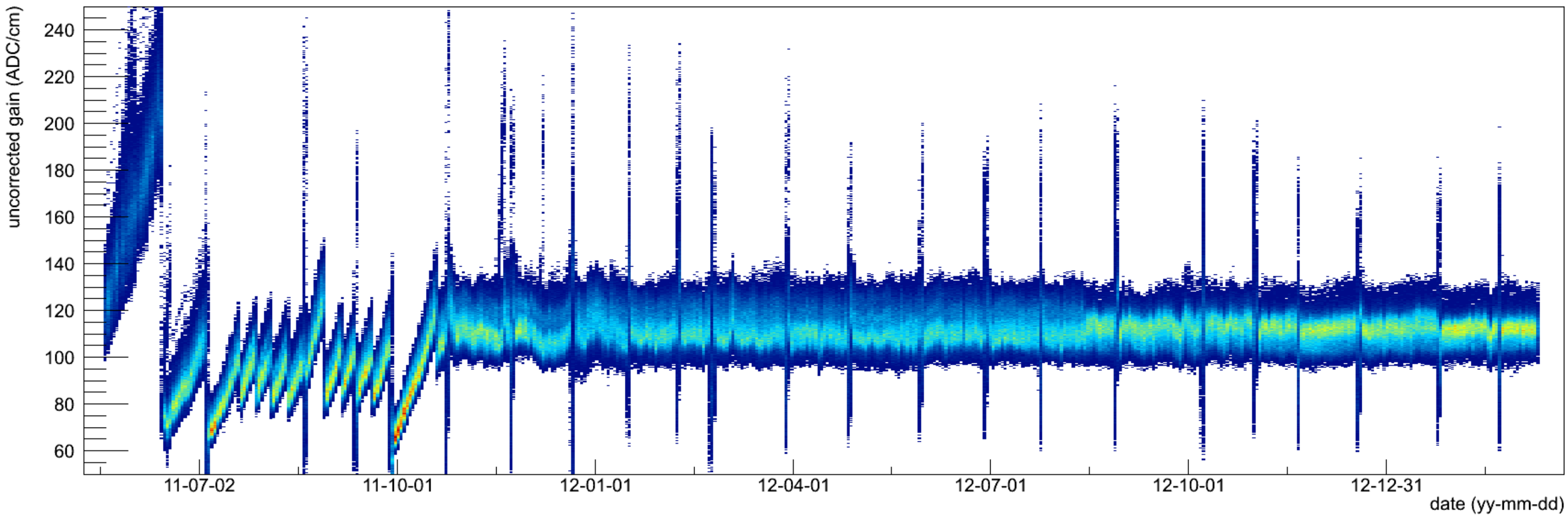
- TRD: Transition radiation detector
- TR yield proportional to γ=E/m

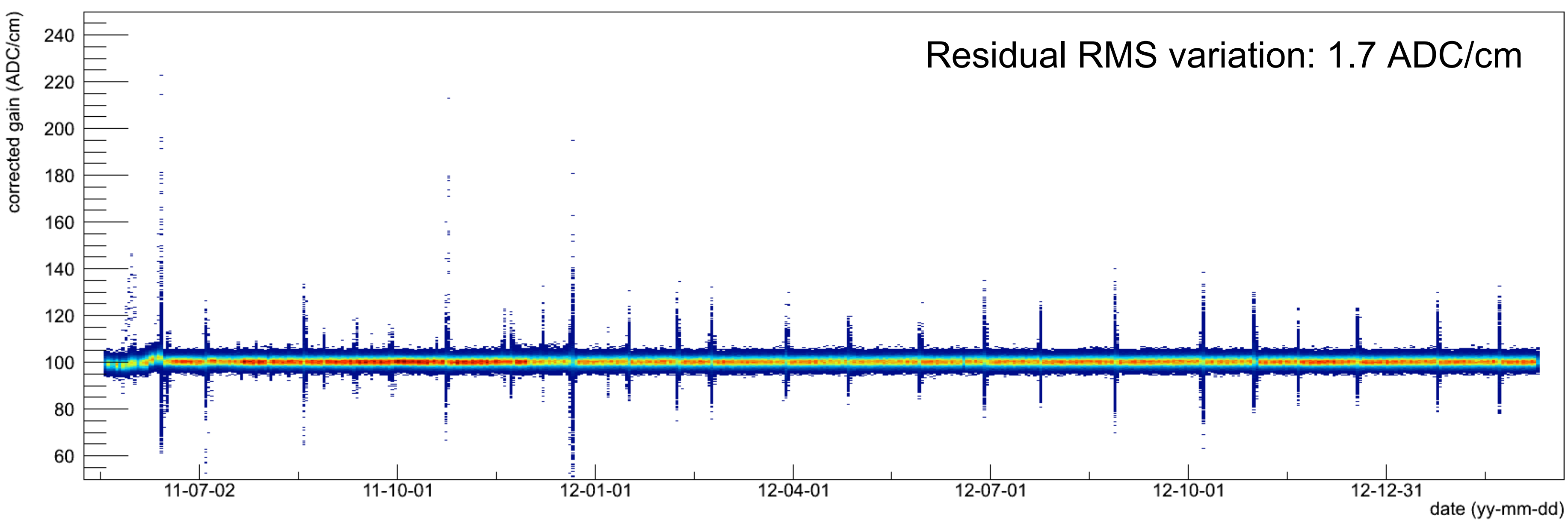


1 / 20 TRD layers, AMS flight data:

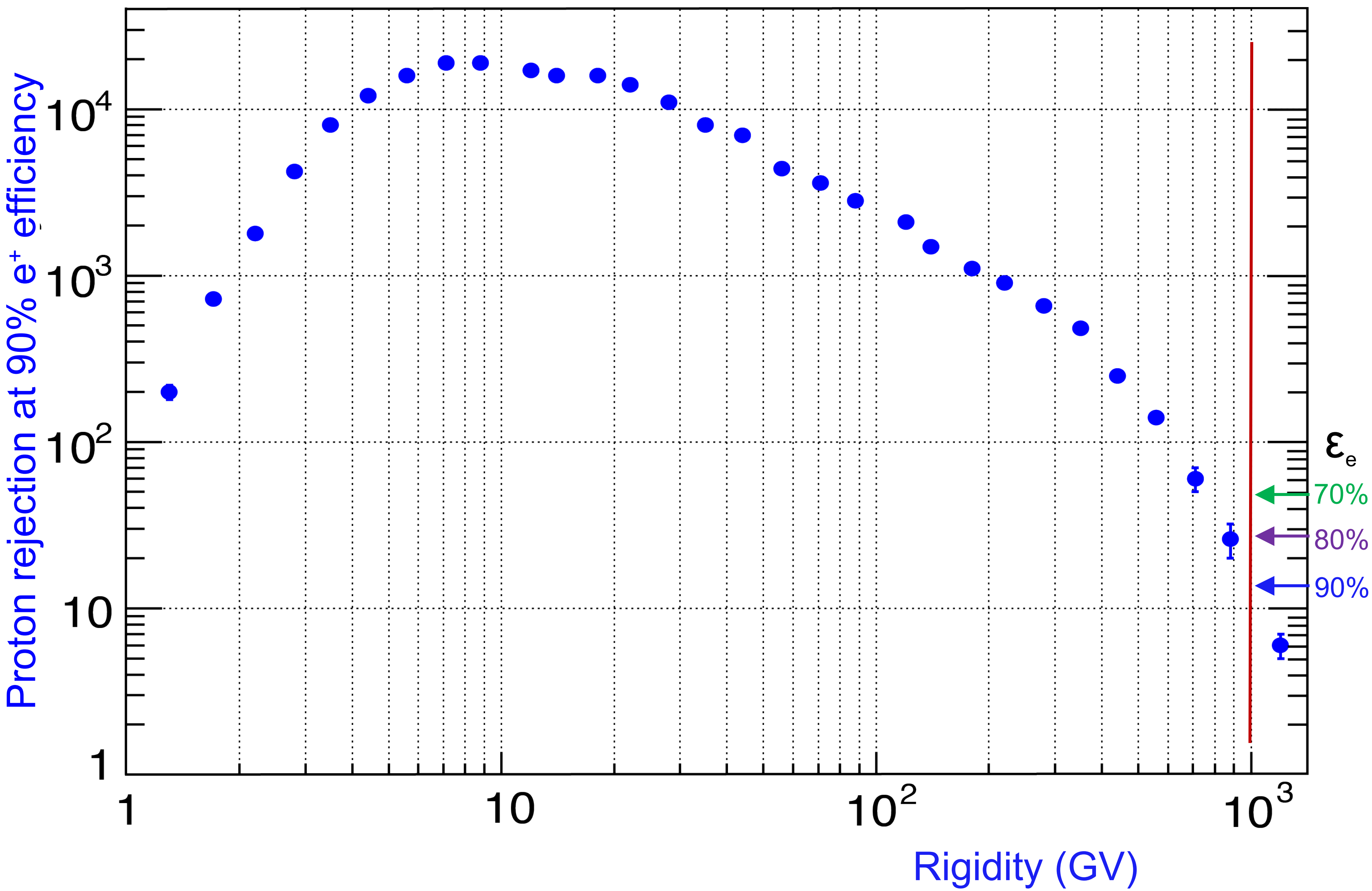


Gain calibration

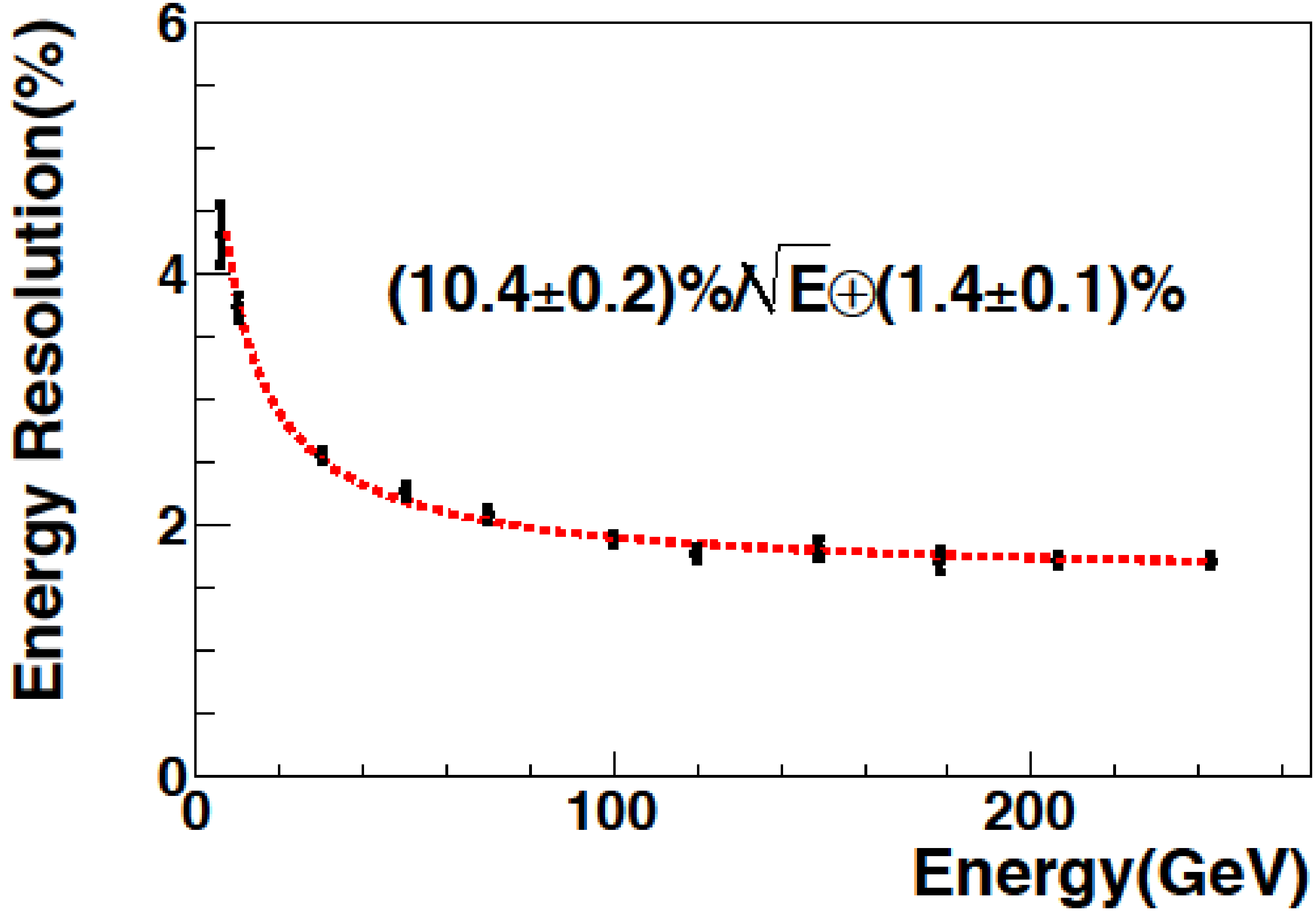




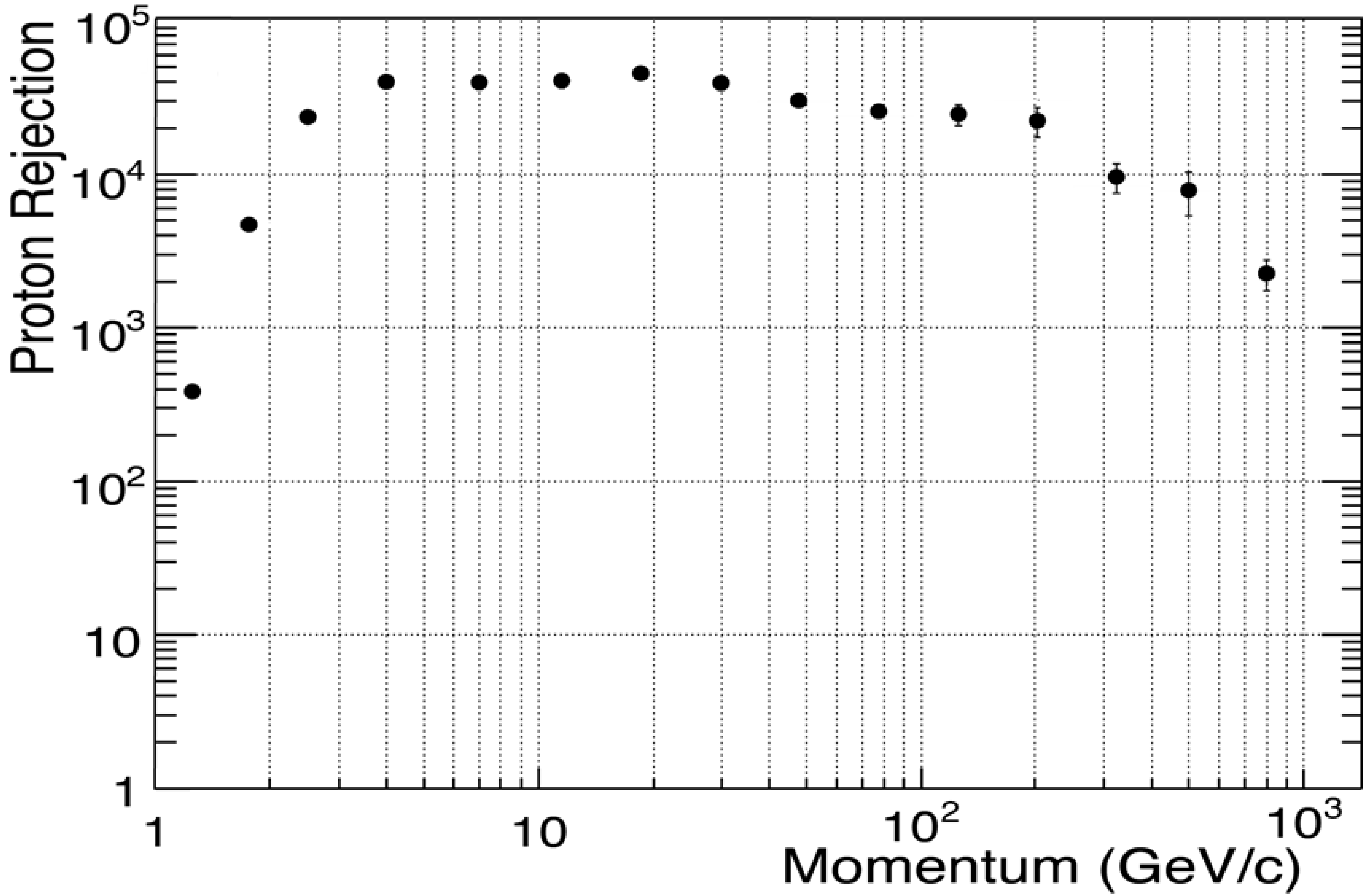
TRD proton rejection vs rigidity



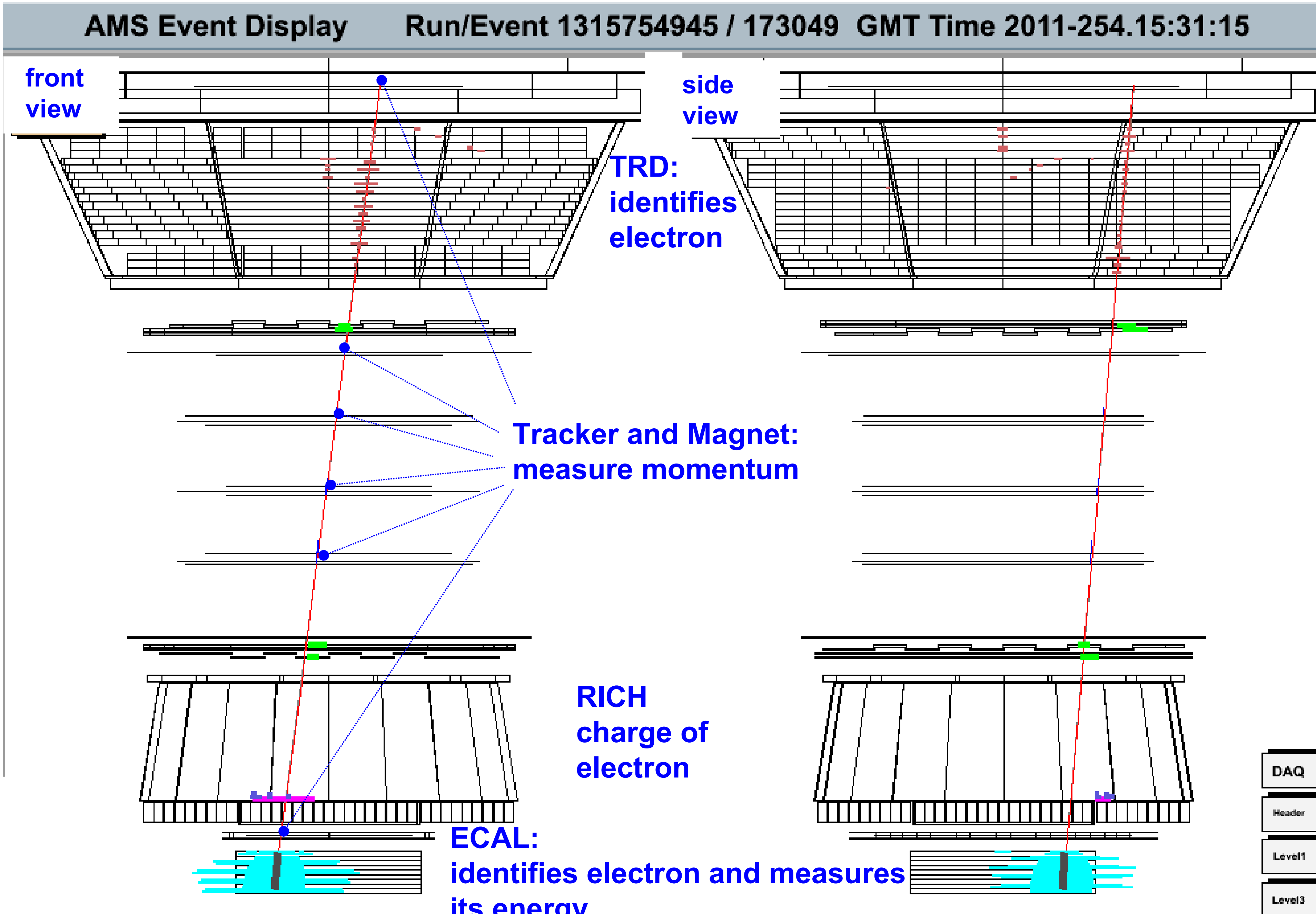
ECAL: energy resolution



ECAL: proton rejection power



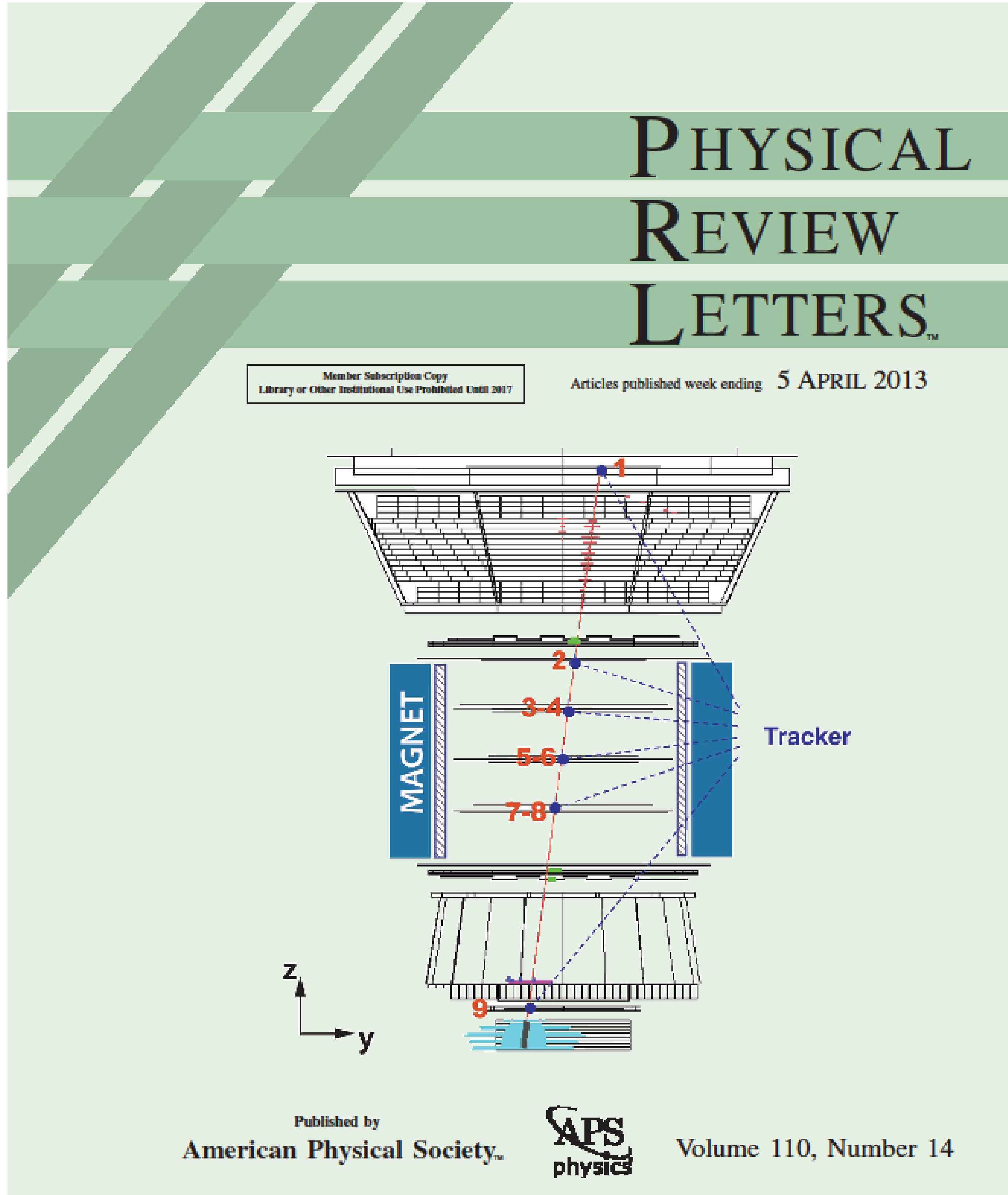
1.03 TeV electron



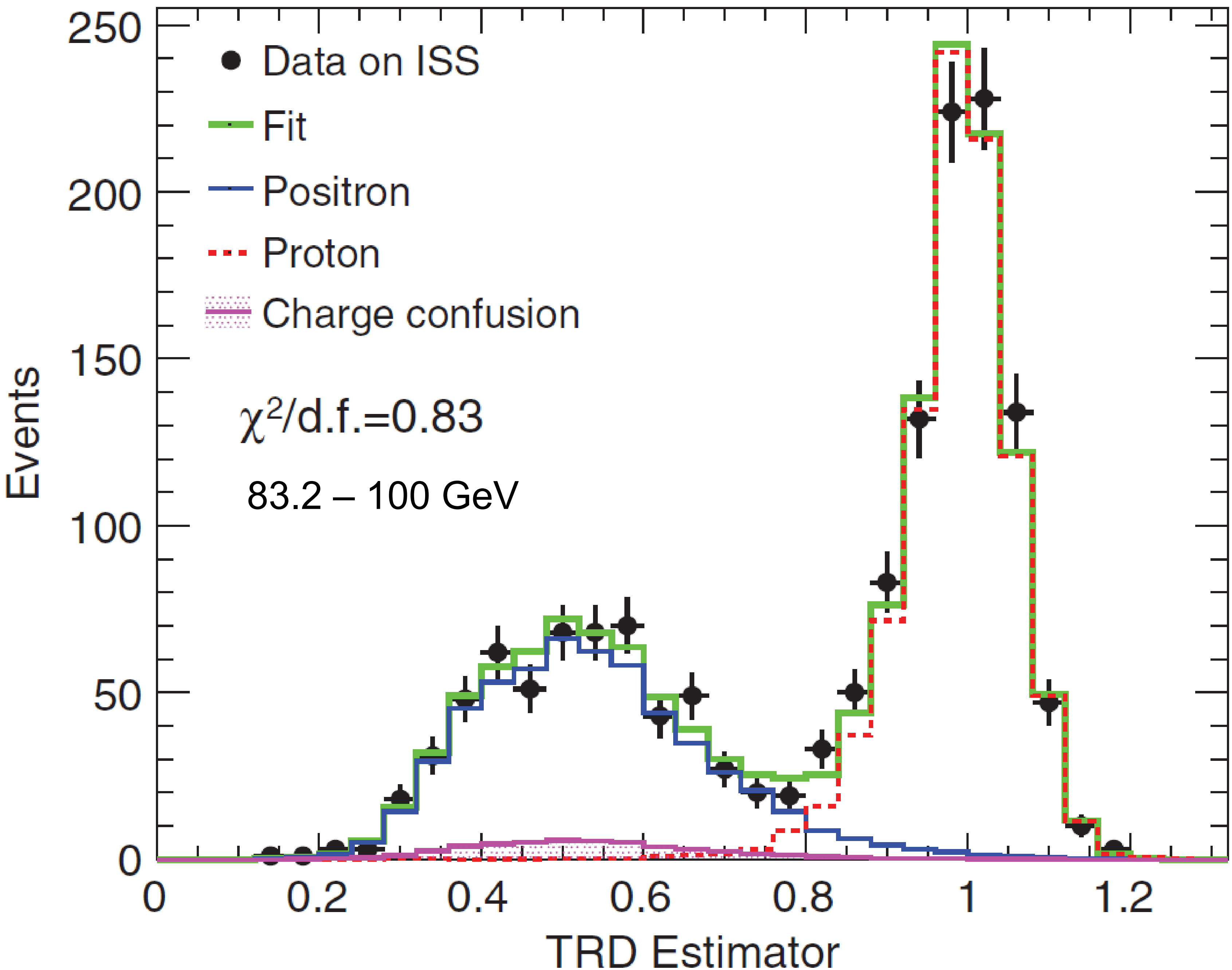
"First Result from the AMS on the ISS: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5-350 GeV"

6.8 million positrons and electrons in final data sample

Selected for a Viewpoint in Physics and an Editors' Suggestion [Aguilar,M. et al (AMS Collaboration) Phys. Rev. Lett. 110, 141102 (2013)]

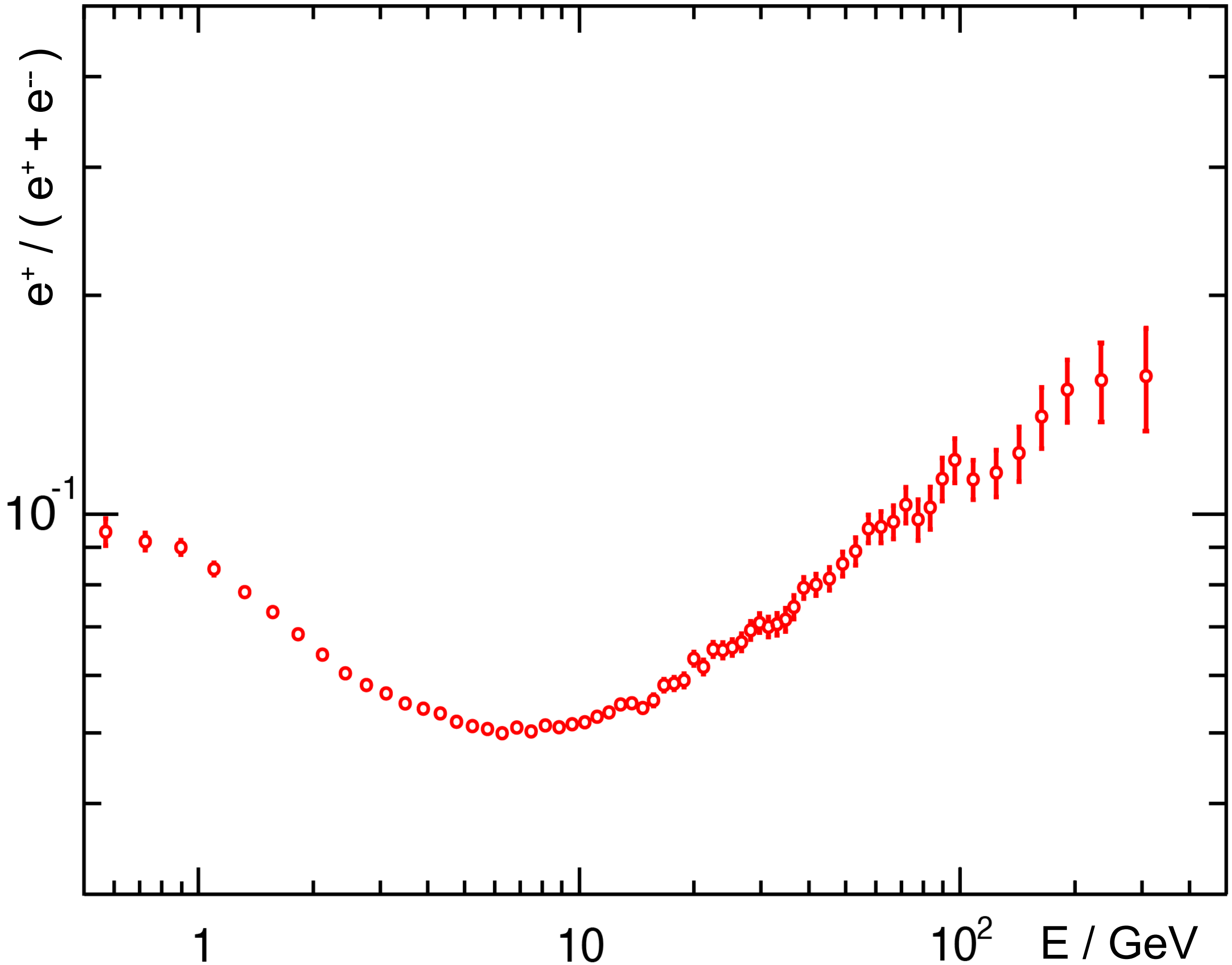


Example of positron selection

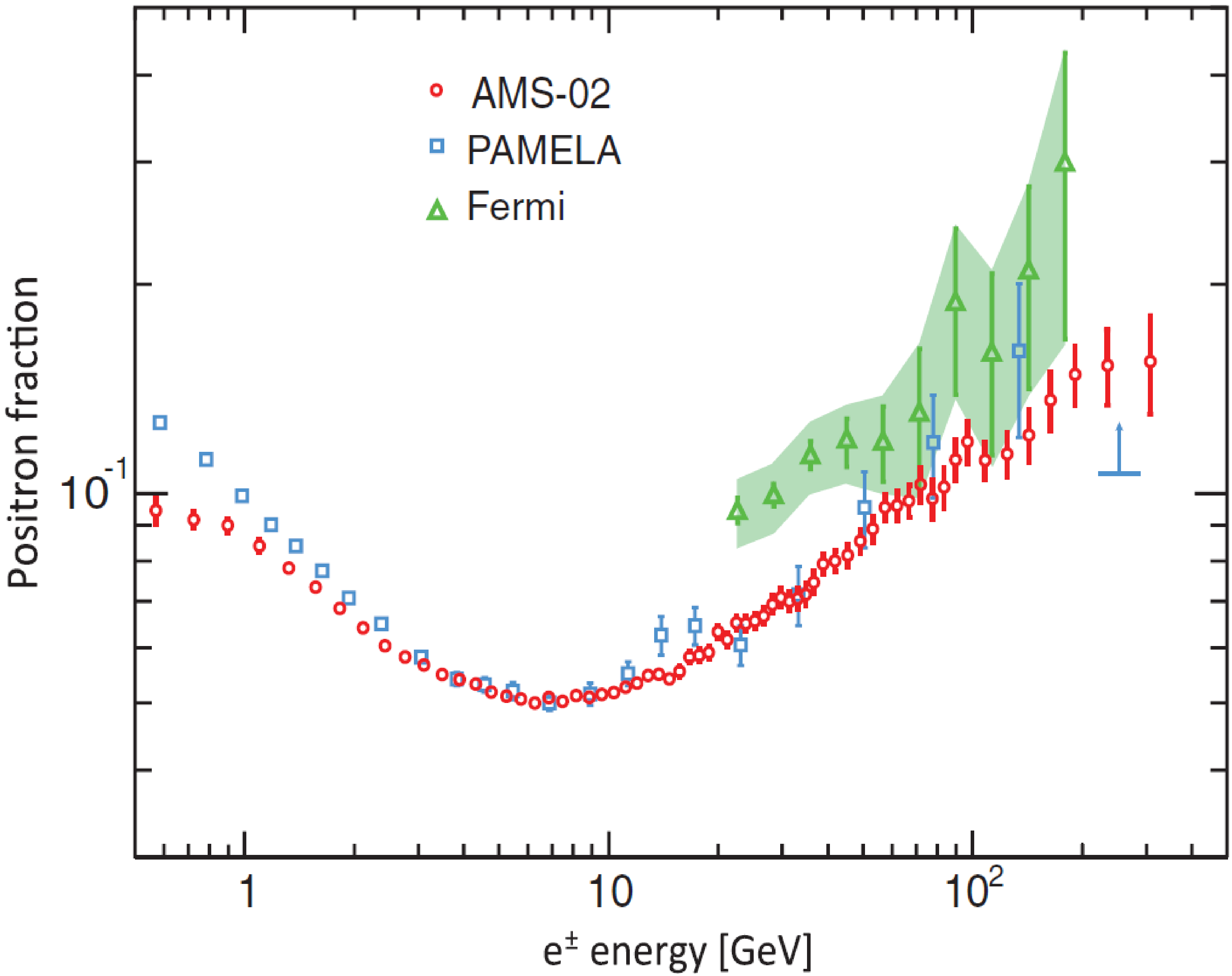


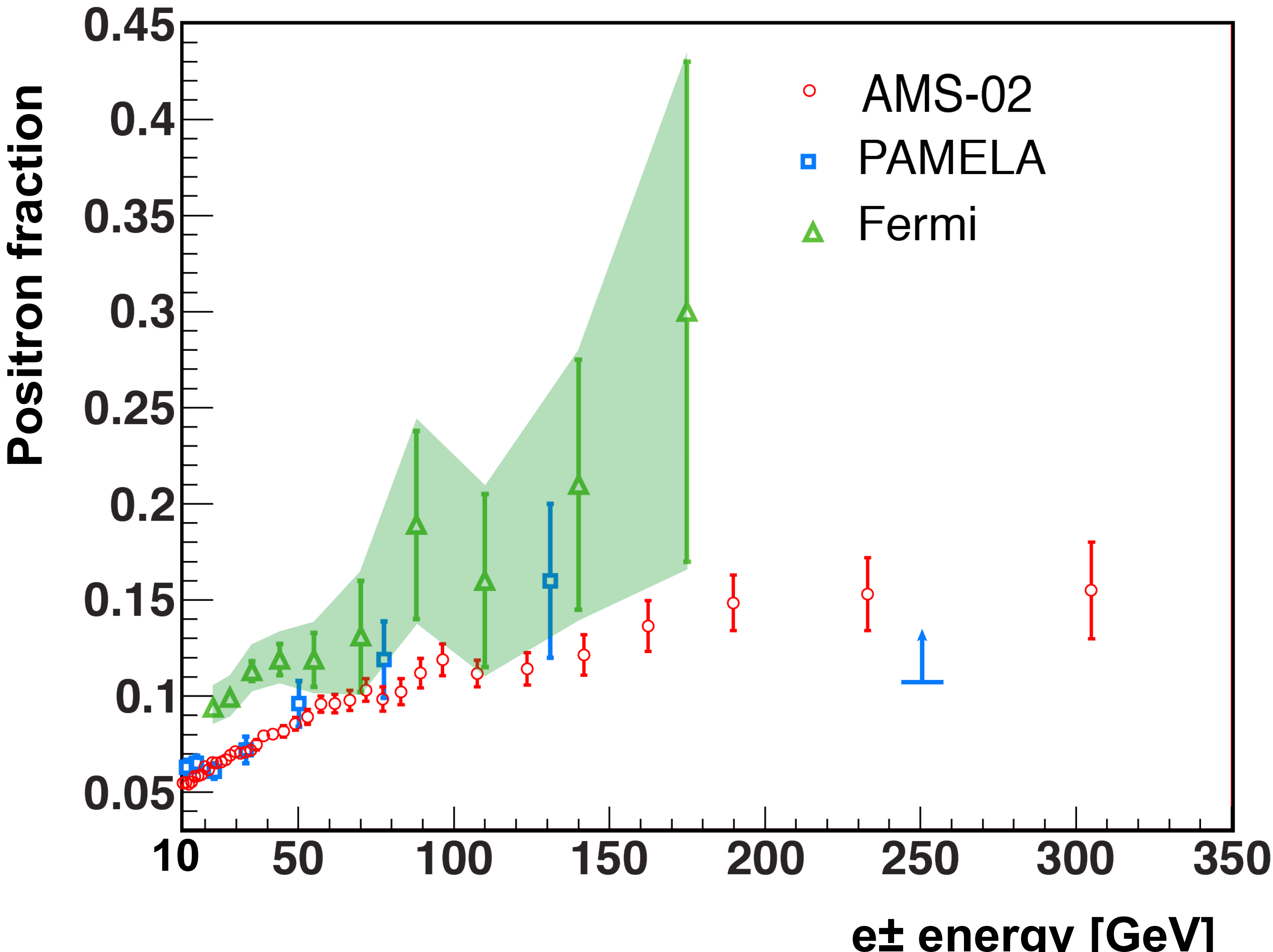
AMS-02 positron fraction

- Steady increase from 10 to ~250 GeV
- No structure in the spectrum



Comparison to earlier measurements

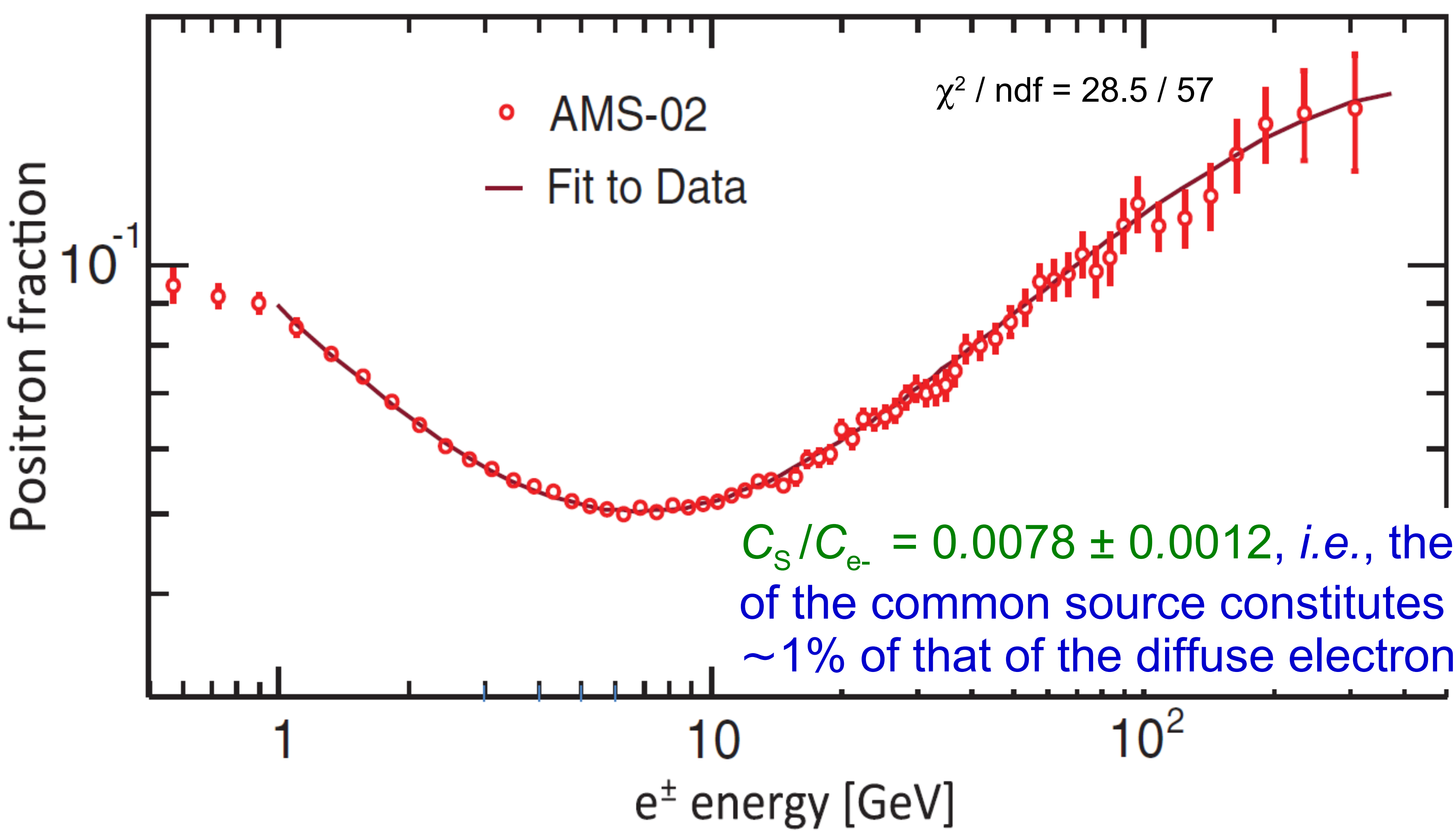




Positron fraction
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
10
50
100
150
200
250
300
350
e± energy [GeV]
AMS-02
PAMELA
Fermi

A simple model

$$\Phi_{e^+} = C_{e^+} E^{-\gamma_{e^+}} + C_s E^{-\gamma_s} e^{-E/E_s}$$
$$\Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_s E^{-\gamma_s} e^{-E/E_s}$$



C_S/C_{e-} = 0.0078 ± 0.0012, *i.e.*, the weight of the common source constitutes only ~1% of that of the diffuse electron flux

Limit on dipole anisotropy

- Data are consistent with isotropic distribution of arrival directions:

$$\frac{r_e(b, l)}{\langle r_e \rangle} - 1 = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\pi/2 - b, l)$$

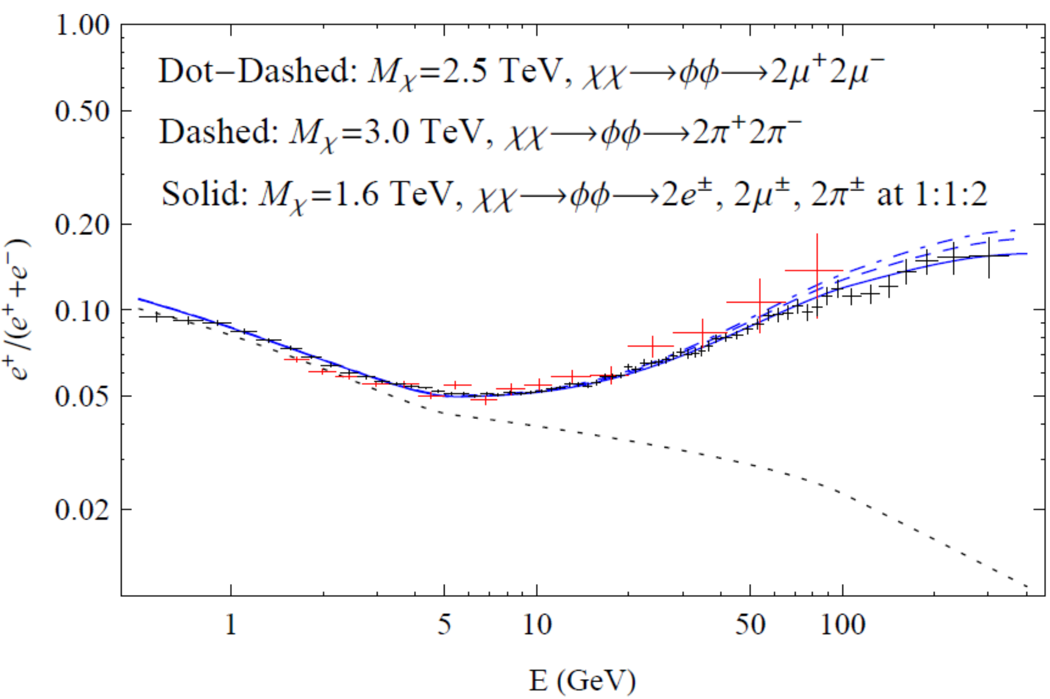
$$C_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2.$$

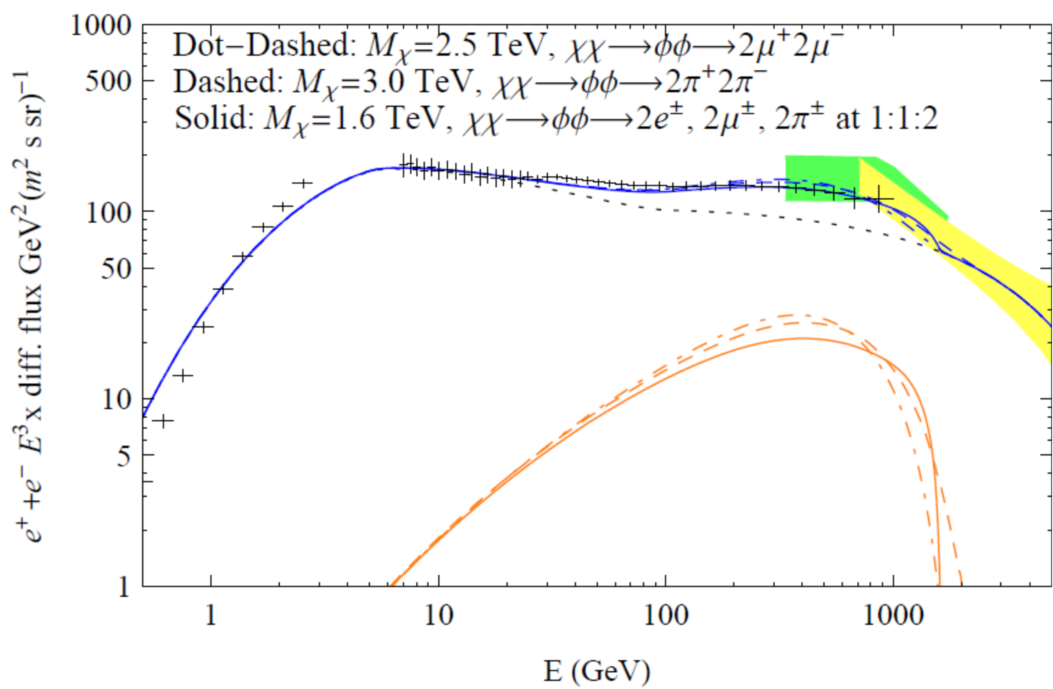
$$\delta = 3\sqrt{C_1/4\pi}$$

AMS-02:
$\delta < 0.036$ at the 95% confidence level.

Dark matter in the light of AMS-02 results

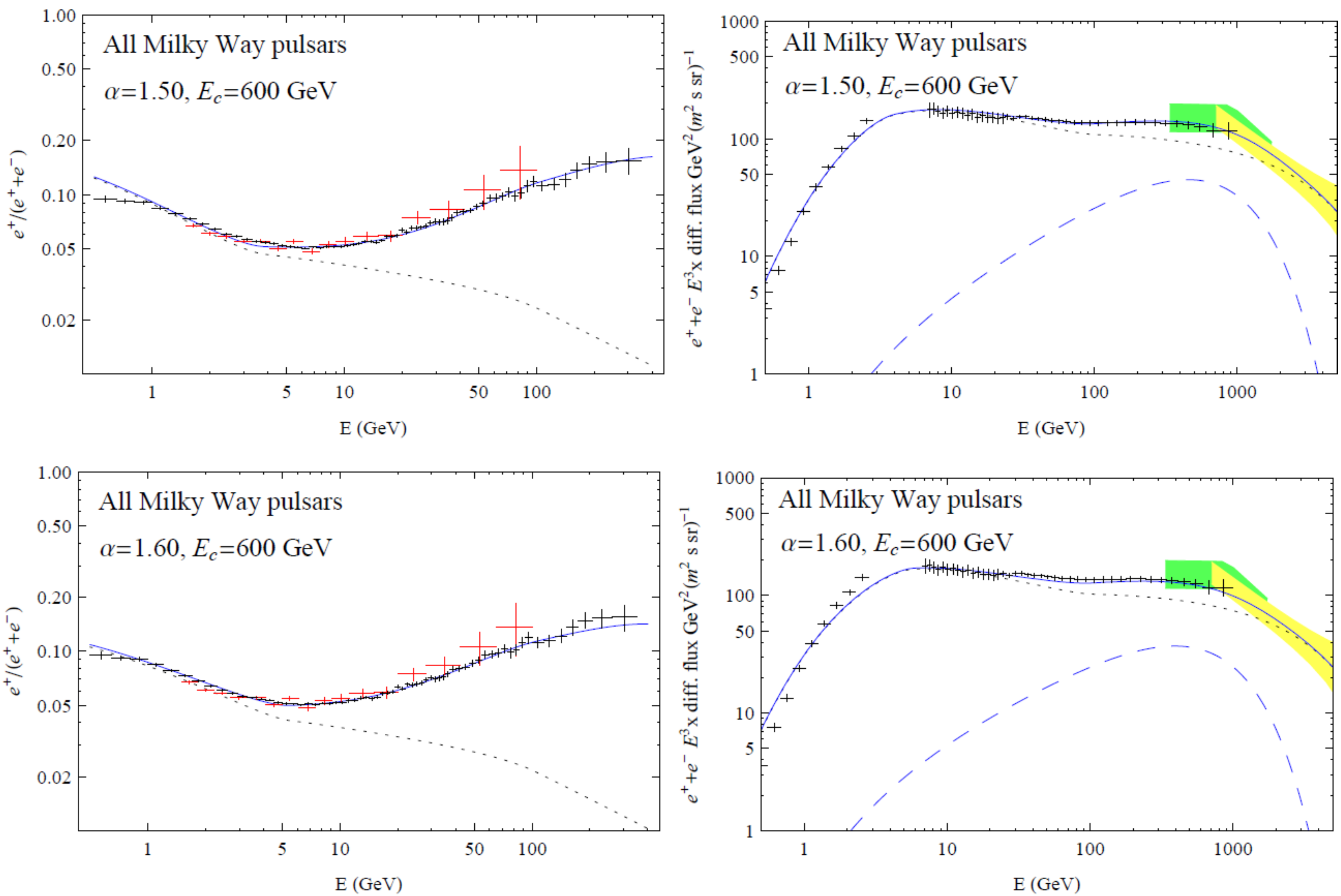
- Cholis & Hooper, 1304.1840:
  Dark matter annihilating directly to $e^+ e^-$ or $\mu^+ \mu^-$ no longer capable of describing observed rise in positron fraction.
- Annihilation via light intermediate states into muons and pions consistent with data, for DM masses of 1.5 – 3 TeV, $\langle\sigma v\rangle$ as high as (6 – 23) x 10^{-24} cm^3/s
- Describing the Fermi all-electron spectrum at the same time requires spectral break in cosmic-ray electrons. (May be expected if single or few local sources dominate.)





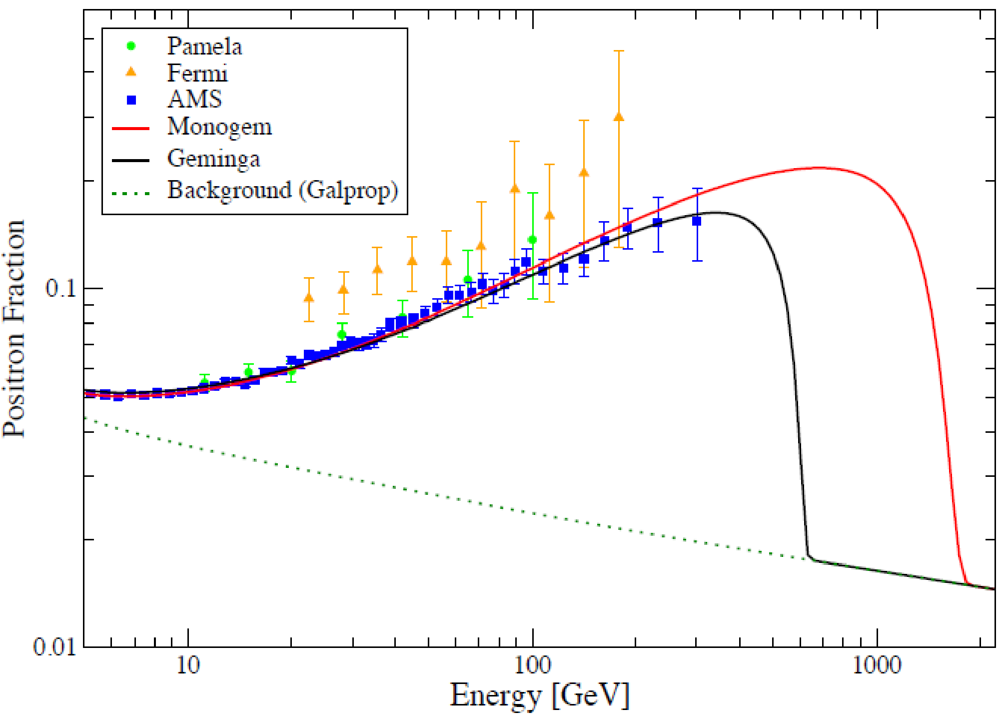
Pulsar models also still work!

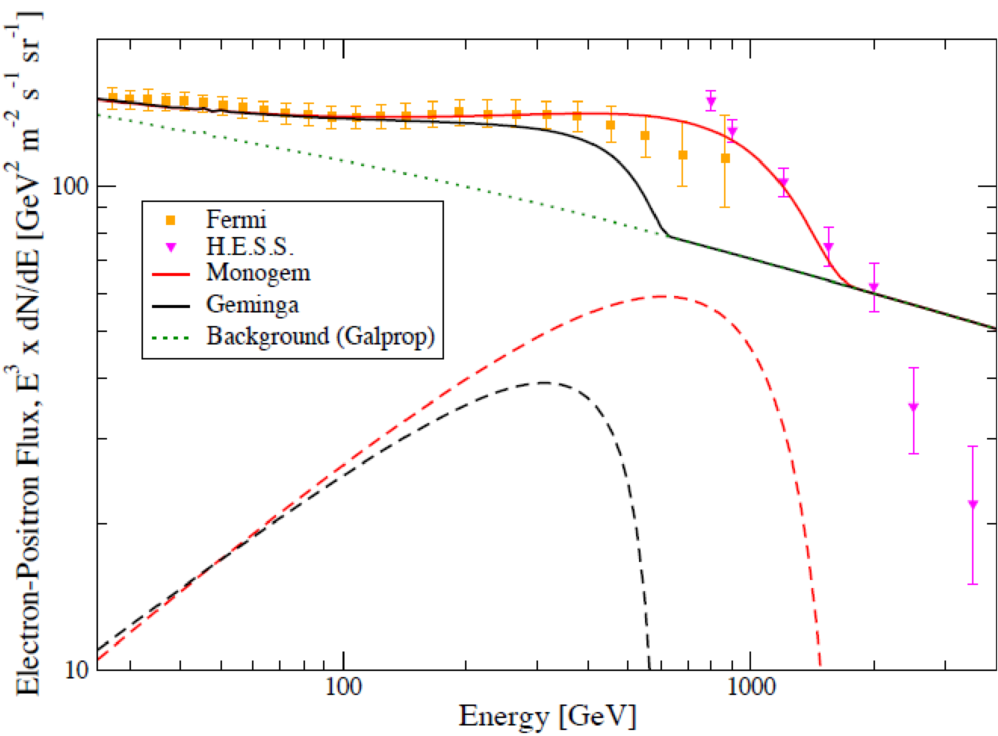
- Sum of known pulsars, assuming
  - exponentially cutoff power law spectra
  - 10-20% of spin-down power converted to CR acceleration
  - break in CR electron spectrum as before (spectral hardening at 100 GeV)



Pulsar models in the context of AMS-02 data

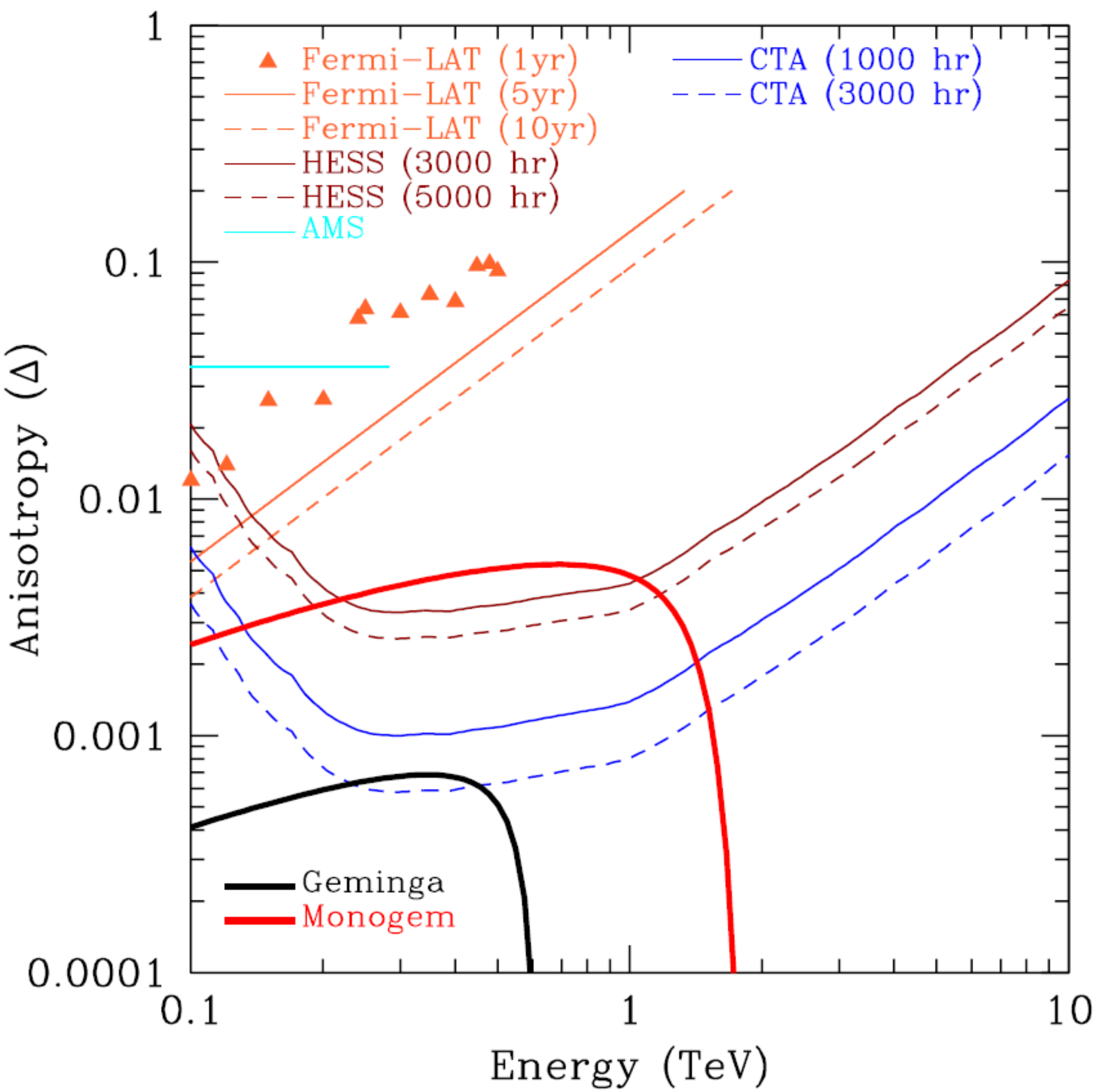
- Linden & Profumo, 1304.1791:
  Background from secondary production plus nearby mature pulsar naturally fits AMS-02 positron fraction and Fermi all-electron spectrum.
- Geminga and Monogem as possible candidates.





Anisotropies

- Smoking gun signature for pulsar models:
  Anisotropy in the arrival directions of CR positrons and electrons.
- Authors propose using archival ACT data to search for anisotropy.



$$\Delta = \frac{N_f - N_b}{N_f + N_b}$$

A hint for charge asymmetry in electron/positron excess?

- Masina & Sannino, 1304.2800:
- Consider AMS-02 positron fraction and Fermi-LAT all-electron flux.
- Model positron and electron fluxes as sum of background plus unknown component:

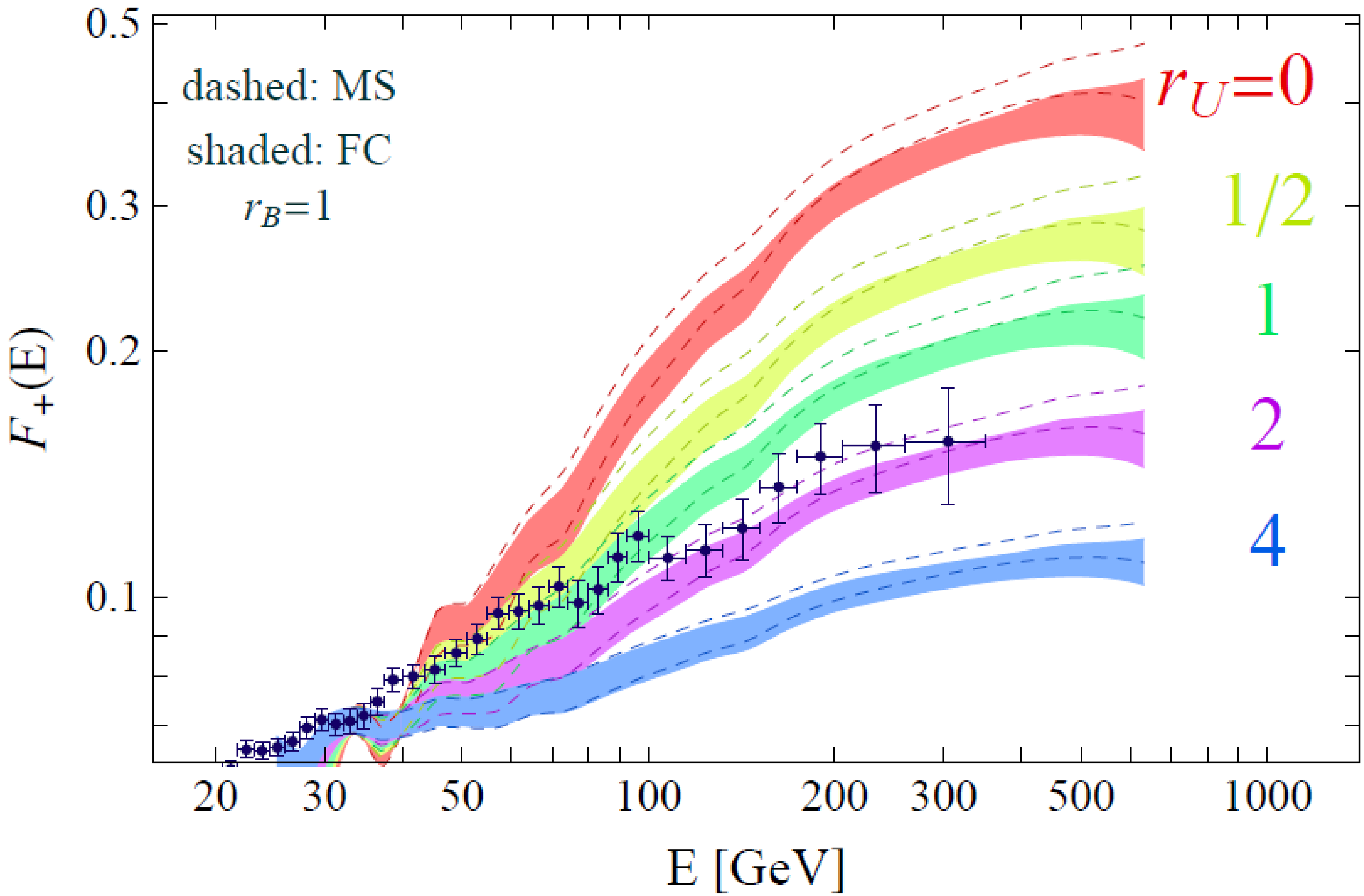
$$\phi_{e^+}(E) = \phi^U_{e^+}(E) + \phi^B_{e^+}(E) \,, \quad \phi_{e^-}(E) = \phi^U_{e^-}(E) + \phi^B_{e^-}(E)$$

- Assume background model (e.g. Galprop, simple power-law).
- Goal: Study charge asymmetry in unknown source component:

$$r_U(E) \equiv \frac{\phi^U_{e^-}(E)}{\phi^U_{e^+}(E)}$$

A hint for charge asymmetry in electron/positron excess?

- Data favour deviation of charge ratio from unity, unless somewhat extreme value for electron background spectral index adopted.



- Pulsar and dark matter annihilation models generically predict charge symmetry.
- Example for charge asymmetry: DM decay to $\mu^- \tau^+$ (lepton-flavour violation!)

AMS Physics Potential

- **Searches for primordial antimatter:**
  - Anti-nuclei: **He, …**
- **Dark Matter searches:**
  - **e+ , e± , p , …**
  - simultaneous observation of several signal channels.
- **Searches for new forms of matter:**
  - **strangelets, …**
- **Measuring CR spectra – refining propagation models;**
- **Identification of local sources of high energy photons (~TeV):**
  - **SNR, Pulsars, PBH, …**
- **Study effects of solar modulation on CR spectra over 11 year solar cycle**
- **…**

"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

Summary

- Cosmic-ray research aims at answering fundamental questions about our Universe.
- AMS-02 will be the leading instrument in its field for many years to come.
- Data analysis is an extremely complex endeavour:
  - challenging environment in space
  - interplay of different sub-detectors
  - enormous data volume
- AMS-02 has measured cosmic-ray positron fraction with exquisite precision:
  - Steady increase from 10 to ~250 GeV
  - No structure in the spectrum
- Results have profound impact on the modelling of CR sources: dark matter or pulsar wind nebulae?
- Measurement of anisotropy in positron fraction extremely important in this context.

The Cosmos is the Ultimate Laboratory.

Cosmic rays can be observed at energies higher than any accelerator.