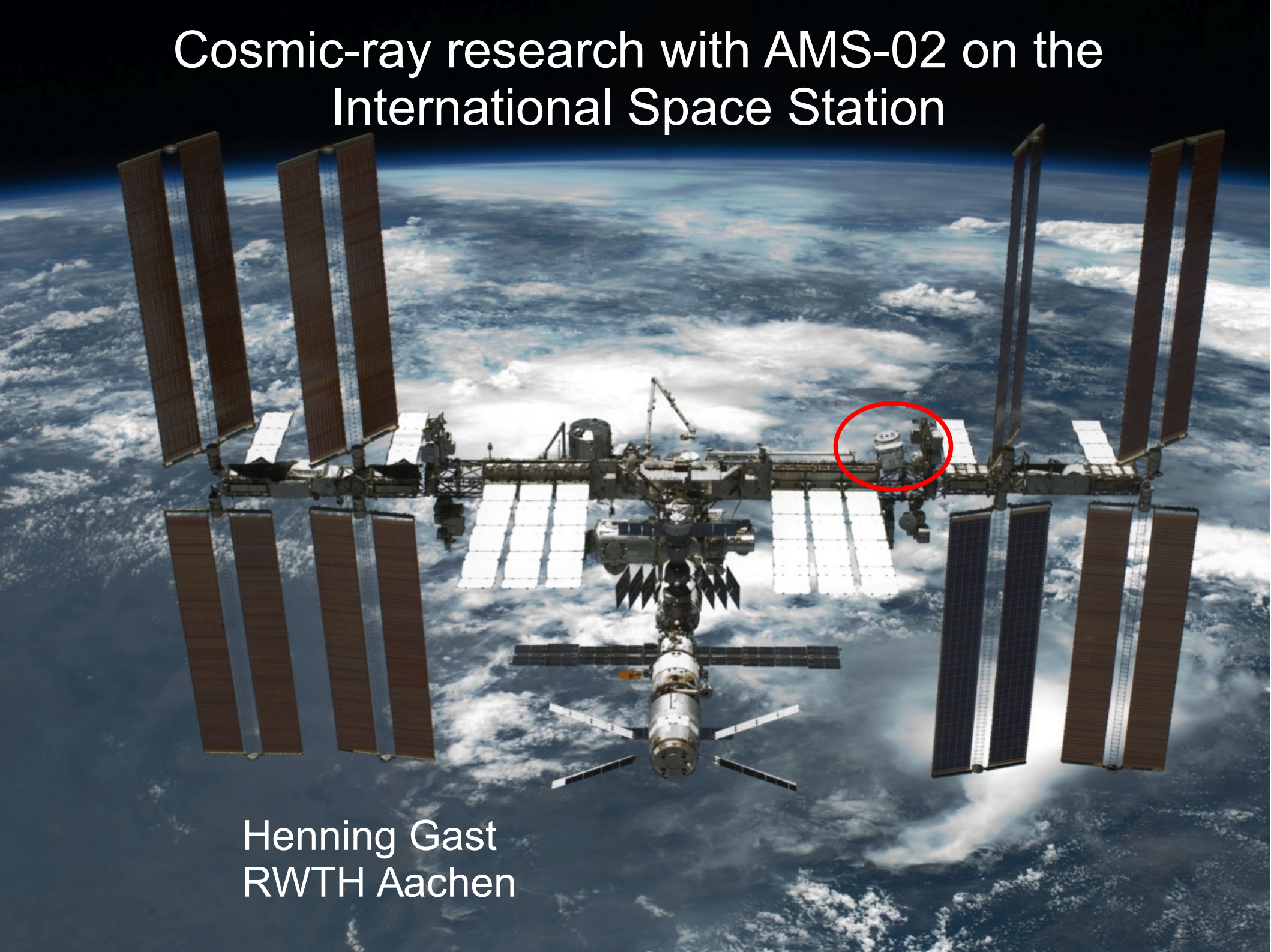
Cosmic-ray research with AMS-02 on the International Space Station



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 reboosts; 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

SOURCES FOR ILLUSTRATIONS: NASA

Transition Radiation Detector
PURPOSE: Distinguish low-mass from high-mass particles.
DESIGN: 20 stacked layers of fleece and straw tubes.
OPERATION: As a low-mass particle passes through the fibers in the fleece, it can emit an x-ray, which is detected by a row of gas-filled tubes underneath.

Anticoincidence Counter
PURPOSE: Identify particles that enter from the side.
DESIGN: Cylinder of transparent polymer tiles that glow when a charged particle passes through.
OPERATION: A particle needs to fly the length of the instrument for all the detectors to gather the necessary data. This detector registers particles that enter from the side so that the control system can discard the signal they left in other instruments.

Negatively Charged Particles

Positively Charged Particles

Time of Flight System 1
PURPOSE: Measure particle velocity and charge.
DESIGN: Sheets of transparent polymer that glows when a charged particle passes through.
OPERATION: A pair of these detectors times how fast the particle takes to cover the length of the instrument.

Magnet
PURPOSE: Bend paths of charged particles.
DESIGN: Permanent magnet with a field strength of 0.15 tesla. This magnet replaces the cryogenic superconducting magnet used in the original design, giving the instrument a longer lifetime.
OPERATION: When passing through, a positively charged particle is deflected to the left, a negatively charged one to the right.

Silicon Tracker
PURPOSE: Measure particle charge and momentum.
DESIGN: Nine planes of particle detectors.
OPERATION: The detectors trace out the path of each particle through the magnetic field.

Time of Flight System 2

Ring Imaging Cherenkov Detector
PURPOSE: Measure particle velocity.
DESIGN: Aerogel and sodium fluoride ringed by light sensors.
OPERATION: The speed of light in aerogel is 5 percent slower than in the vacuum; in sodium fluoride, 23 percent slower. A particle moving nearly at the vacuum speed of the light will emit a distinctive bluish cone of light known as Cherenkov radiation.

Electromagnetic Calorimeter
PURPOSE: Measure particle type and direction.
DESIGN: Layers of lead foil epoxied together with embedded fiber optics.
OPERATION: The particle slams into the material and produces a spray of debris; the nature of the debris identifies the particle. Unlike other instruments, the calorimeter also registers uncharged particles such as photons.

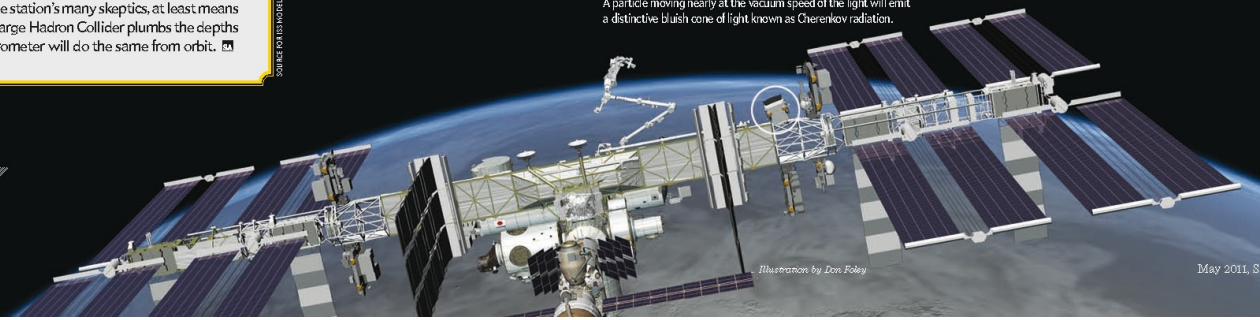
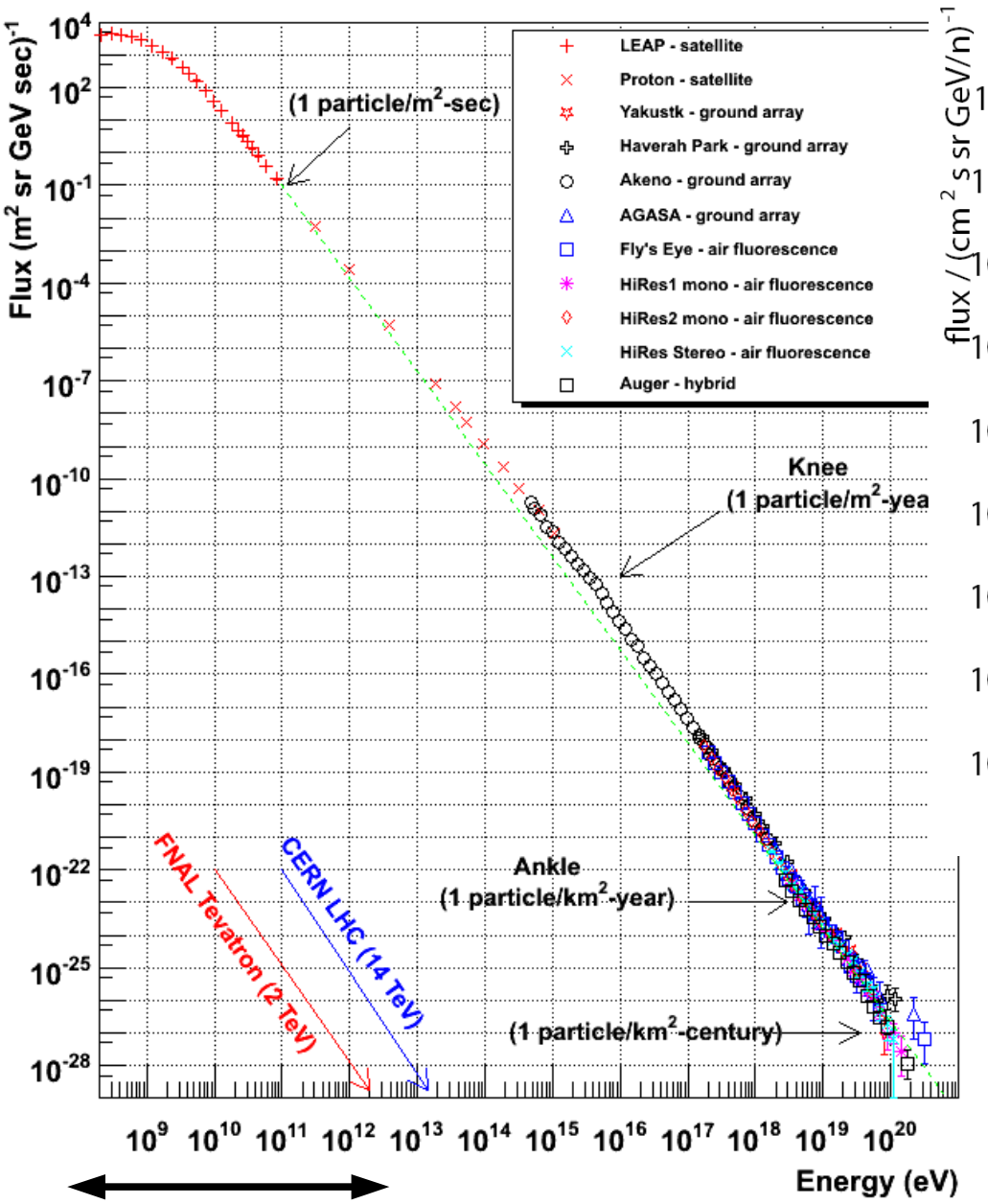


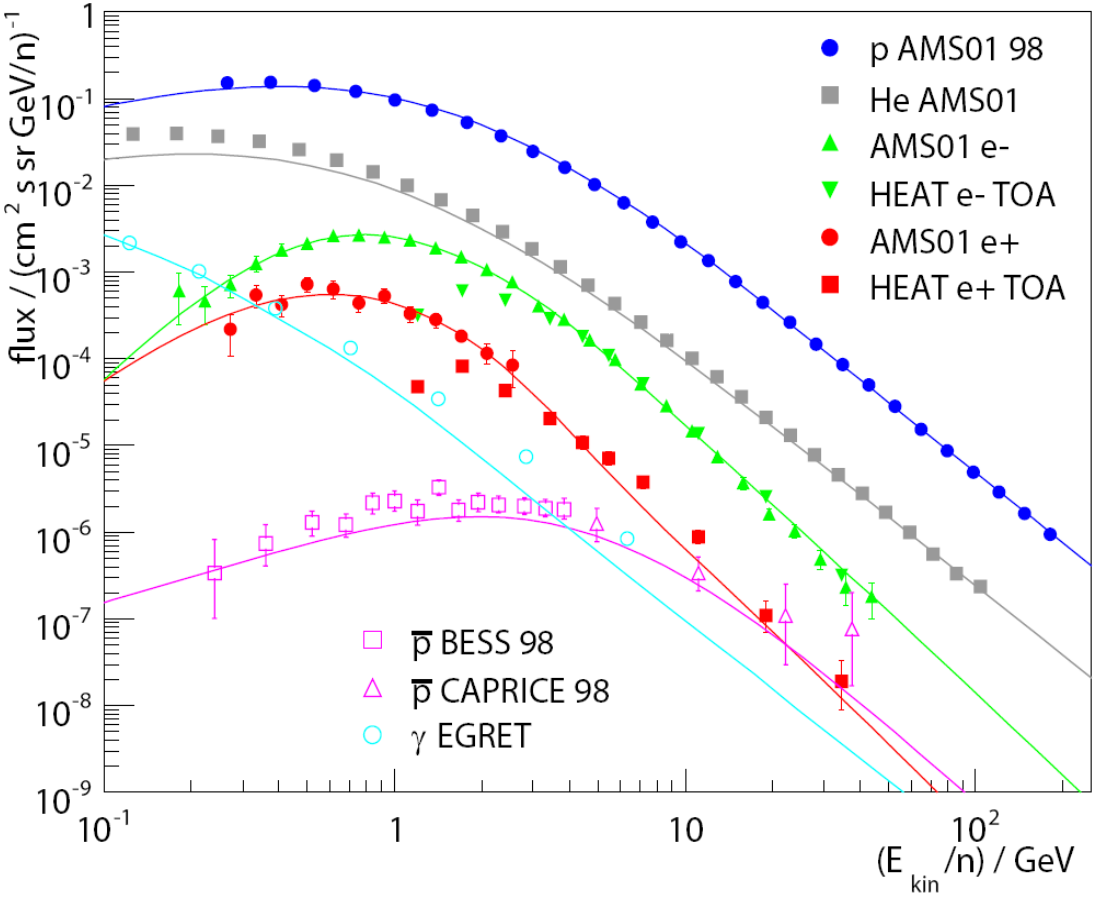
Illustration by Don Foley

Overview

- Short introduction to cosmic-ray physics
- The AMS-02 detector on the International Space Station
- First result: Cosmic-ray positron fraction

Cosmic rays: spectrum and composition





- Direction information is scrambled by interstellar magnetic fields.

Cosmic ray physics in a nutshell

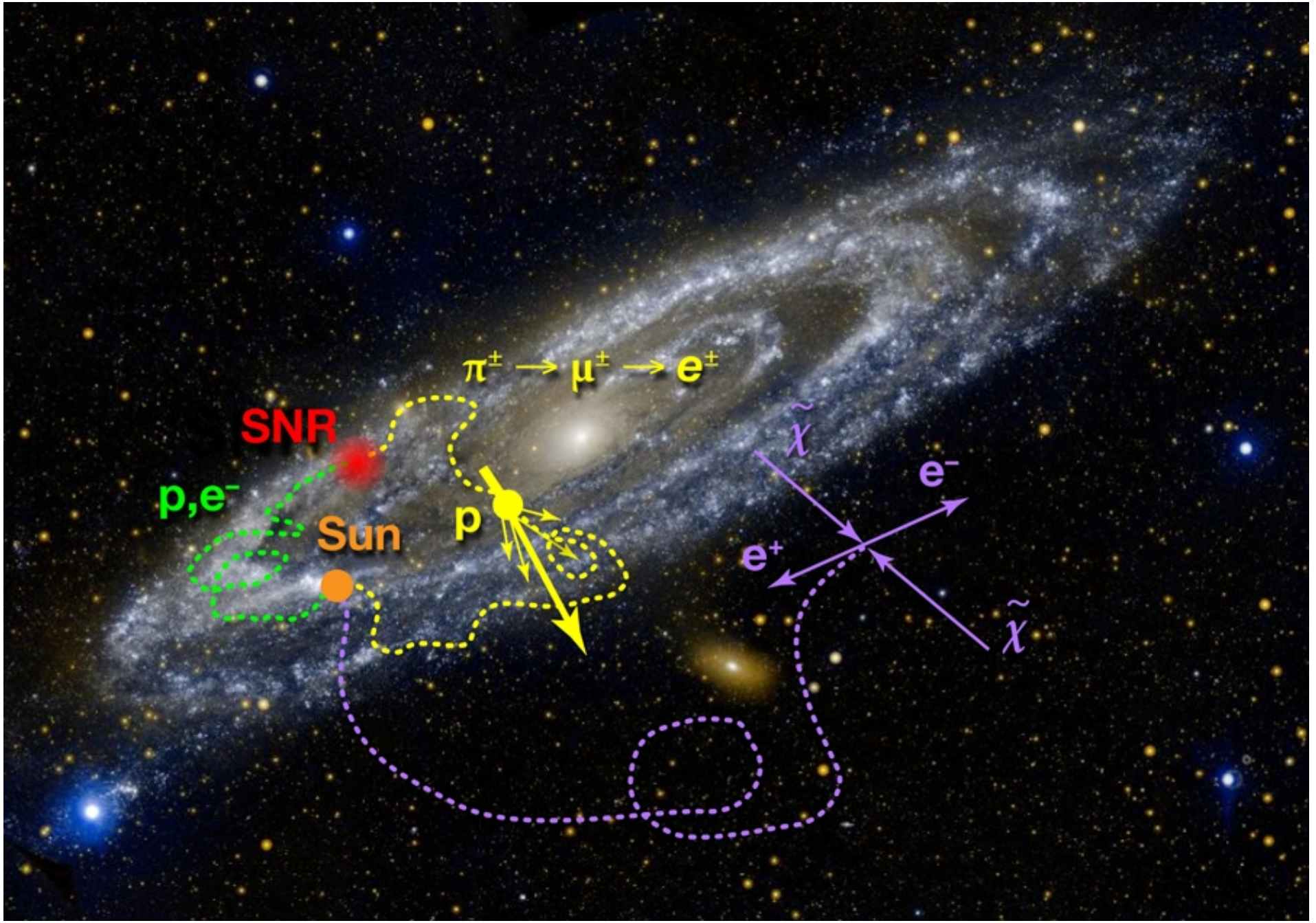
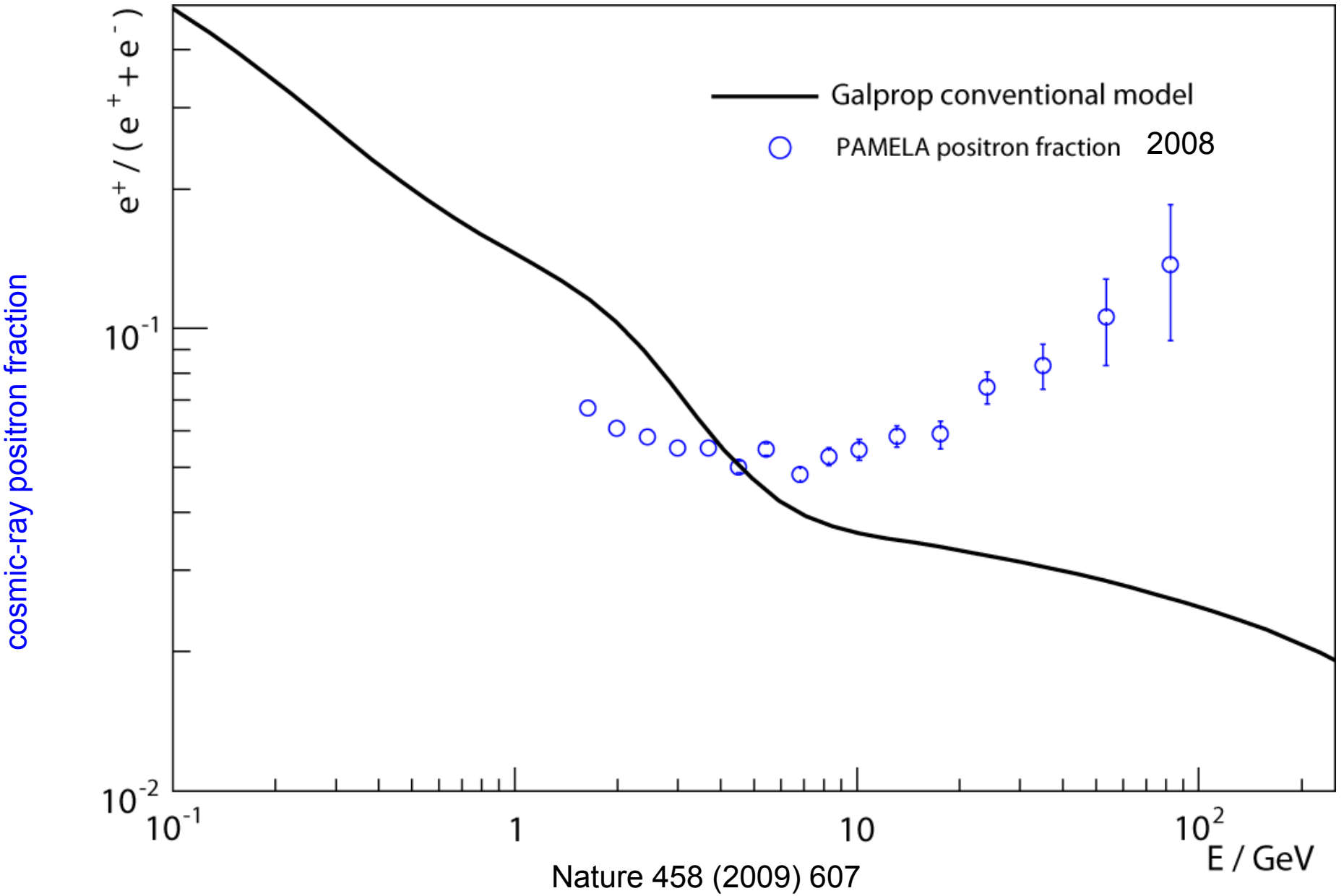


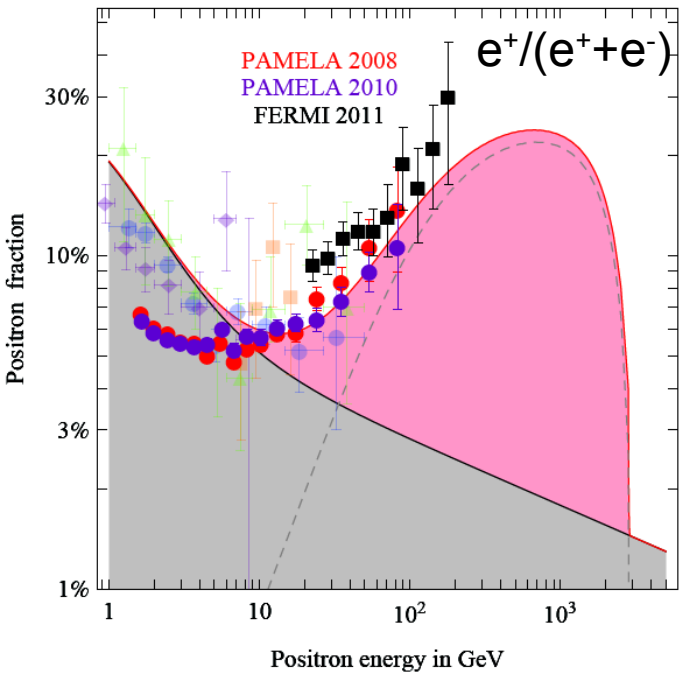
Image: GALEX, JPL-Caltech, NASA;
Drawing: APS/Alan Stonebraker

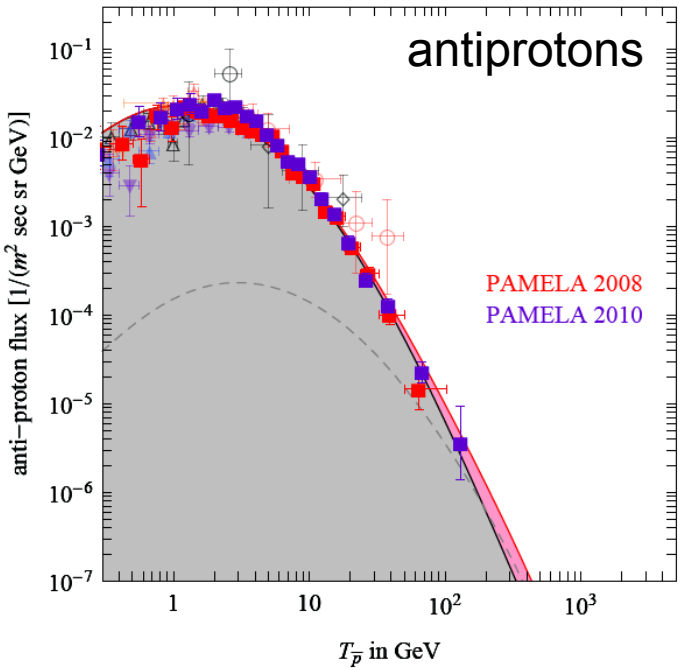
Positron fraction: Exotic sources of cosmic rays?

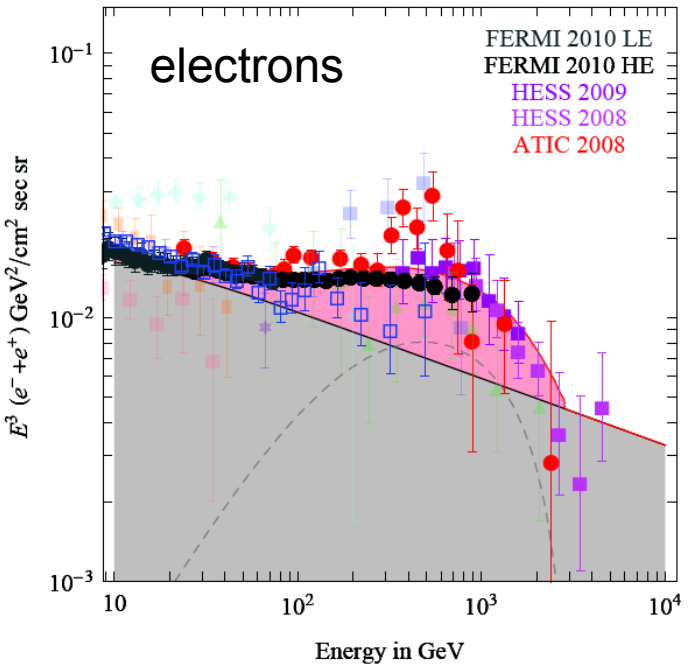


Context: Indirect search for dark matter

M. Cirelli, arXiv: 1202.1454







Example fits: 3 TeV DM particle annihilating to $\tau^+\tau^-$, with a cross section of $2 \cdot 10^{-22}$ 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*

The AMS-02 detector on the International Space Station

A US Air Force C-5 Galaxy
was used for transport
from Geneva to KSC
25. August 2010
AIR FORCE
6025

AMS-02 launch

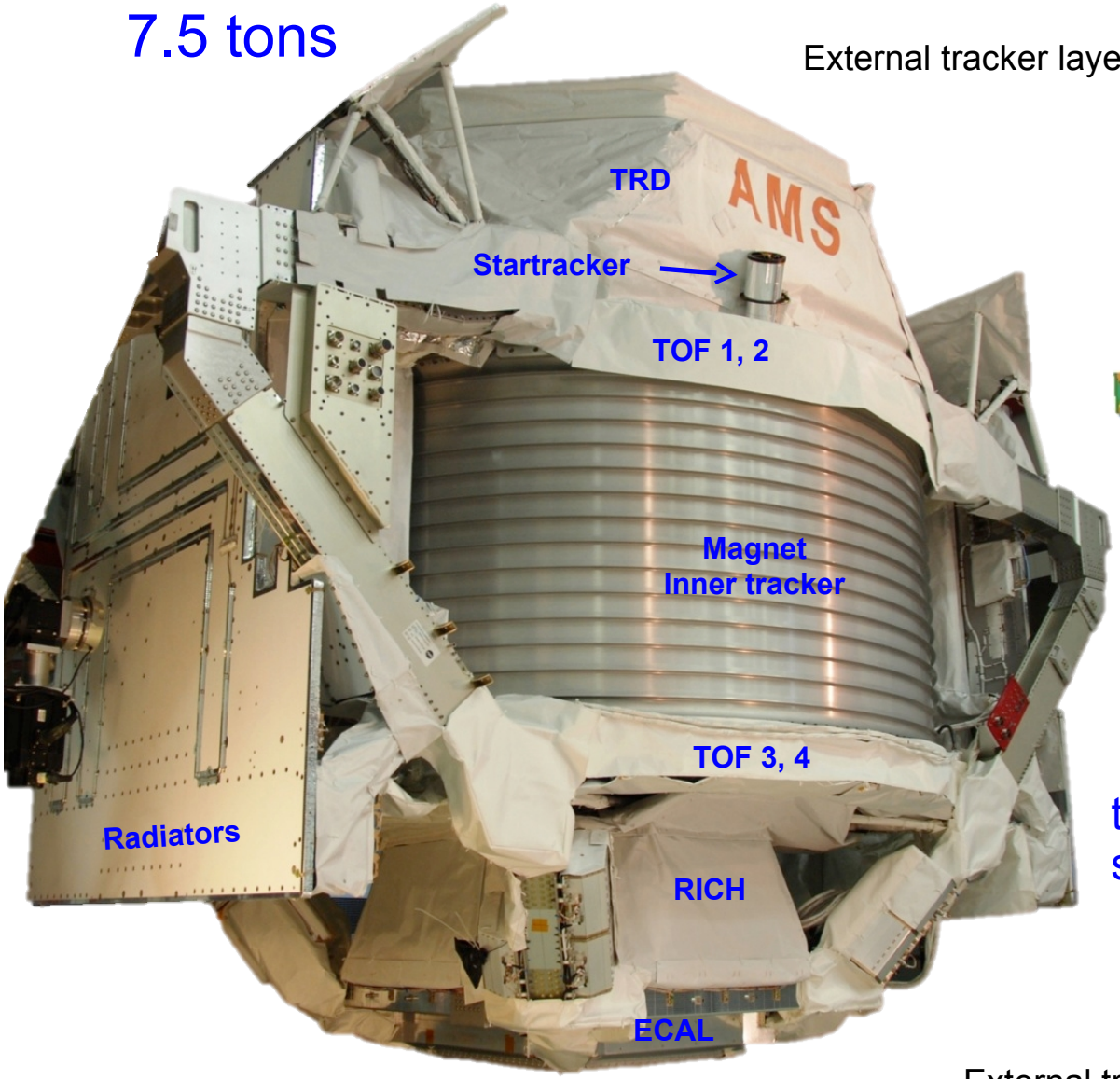
Endeavour approaches the International Space Station

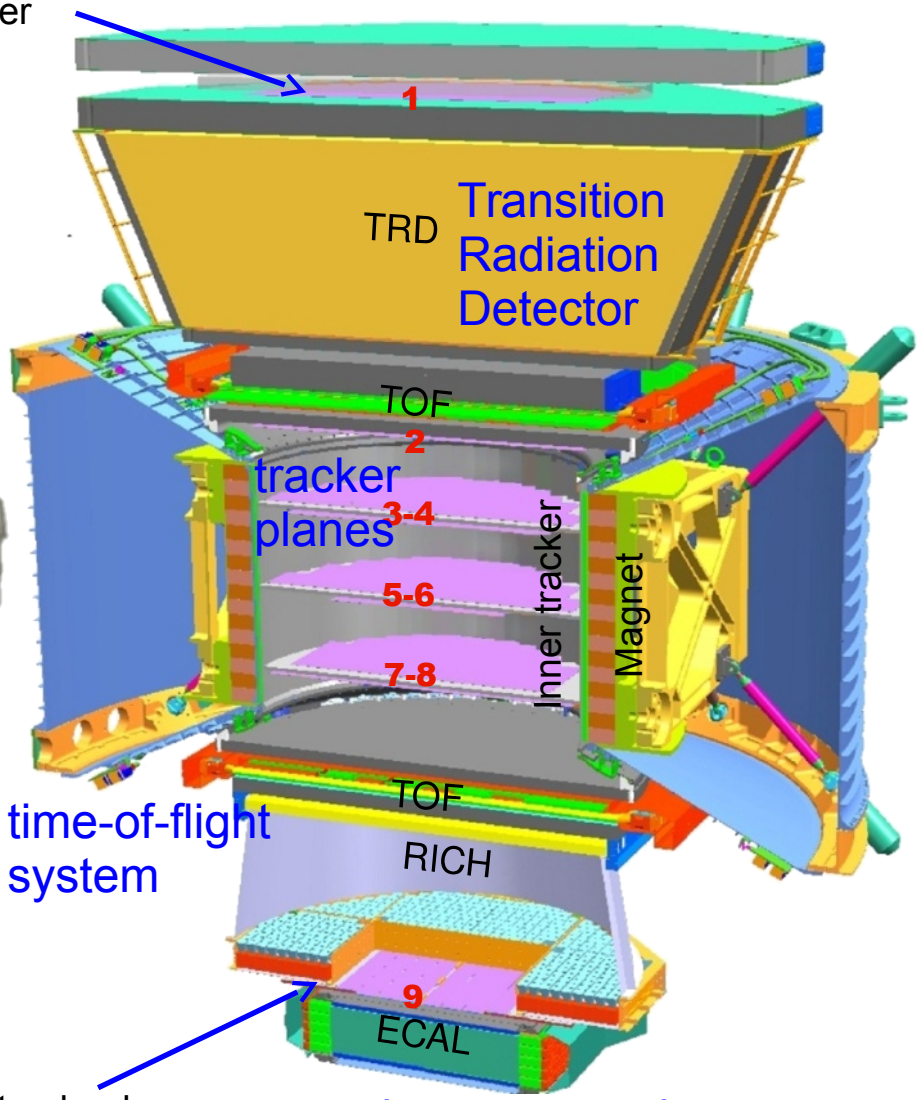
AMS installed on the ISS
Truss and taking data
May 19, 2011
Canada
AMS-02
ELC2
Canada
ELC4

5m x 4m x 3m

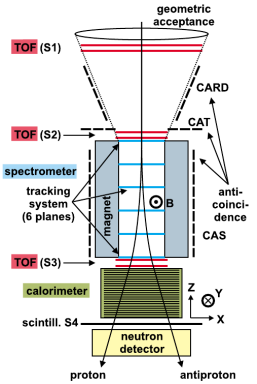
AMS-02

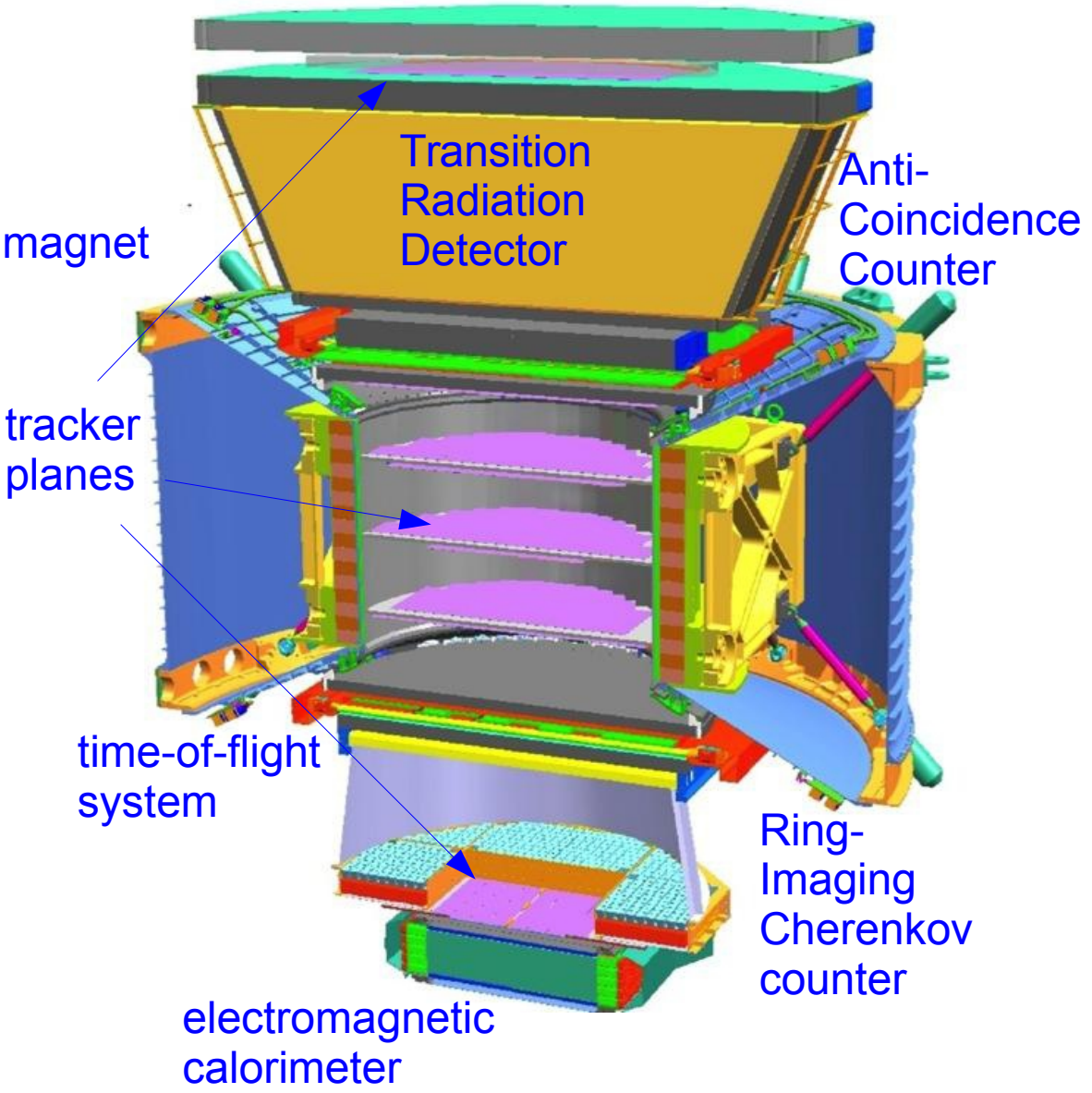
7.5 tons





PAMELA vs AMS-02



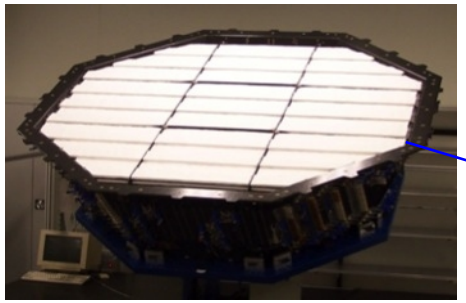


GF: 21.5 cm^2 sr

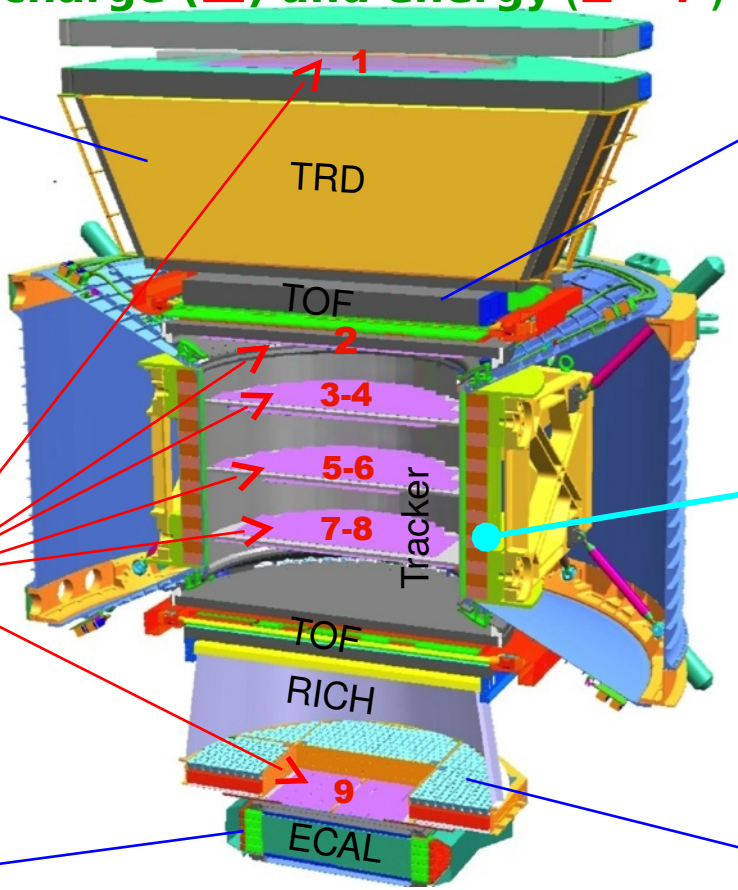
GF: 250 – 3500 cm^2 sr, depending on physics analysis

AMS-02 overview

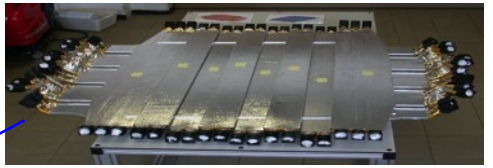
TRD
Identify e+, e-



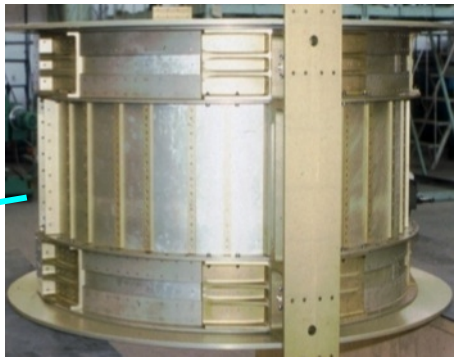
Particles and nuclei are defined by their charge (Z) and energy (E ~ P)



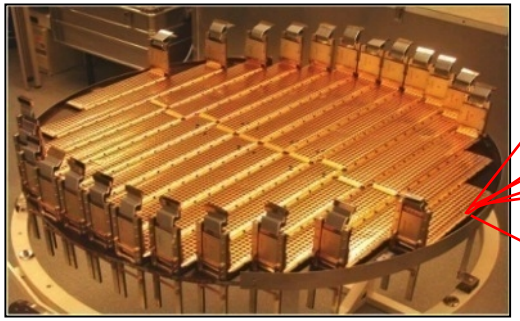
TOF
Z, E



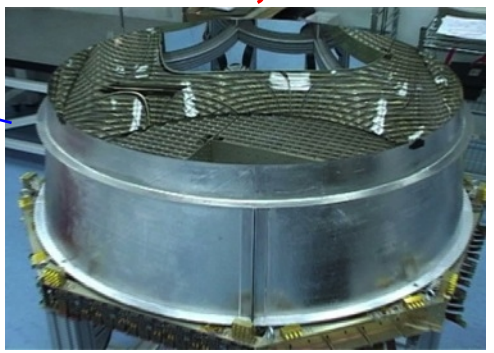
Magnet
±Z



Silicon Tracker
Z, P



RICH
Z, E



ECAL
E of e+, e-, γ

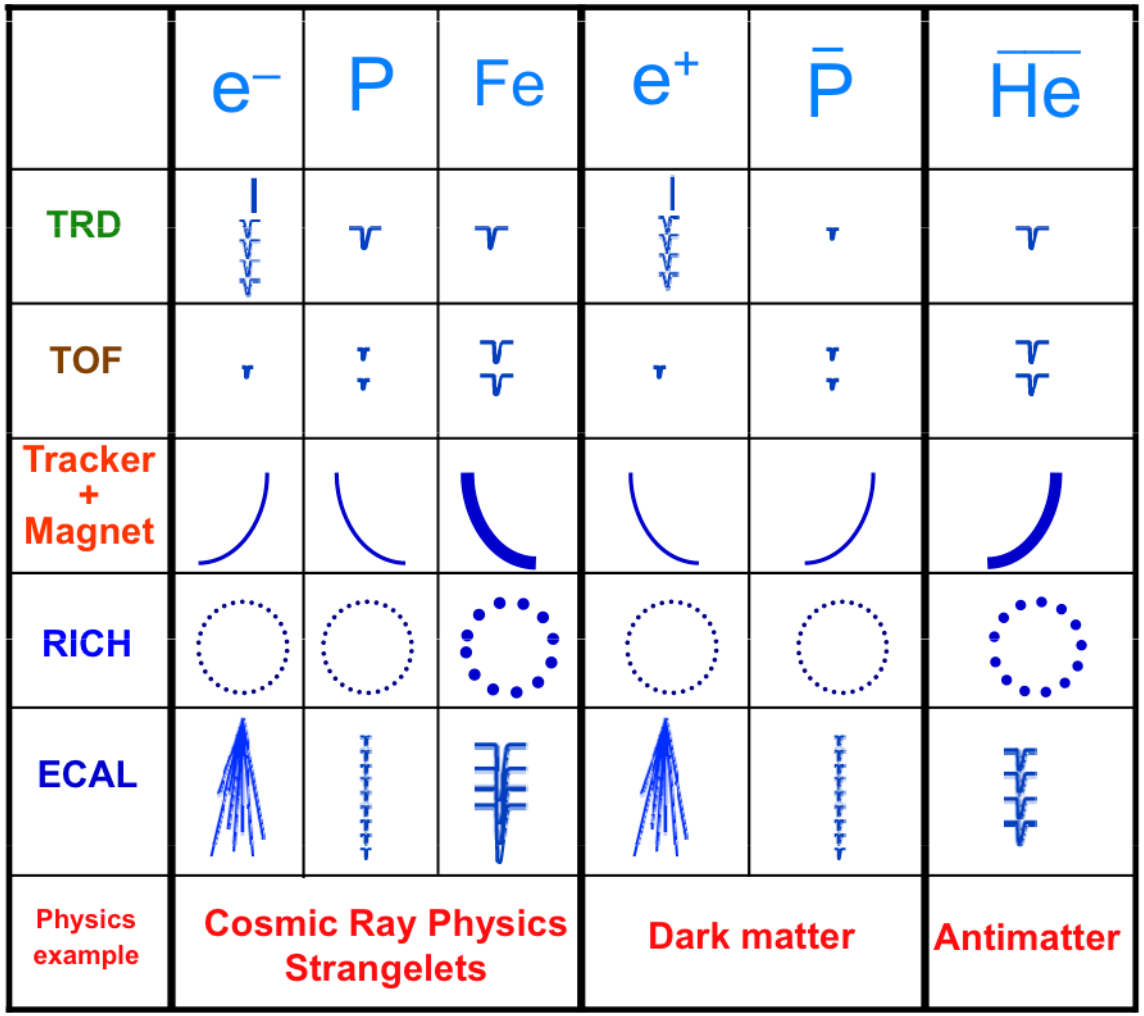
Z, P are measured independently by the Tracker, RICH, TOF and ECAL

5m x 4m x 3m

7.5 tons

AMS-02 particle identification

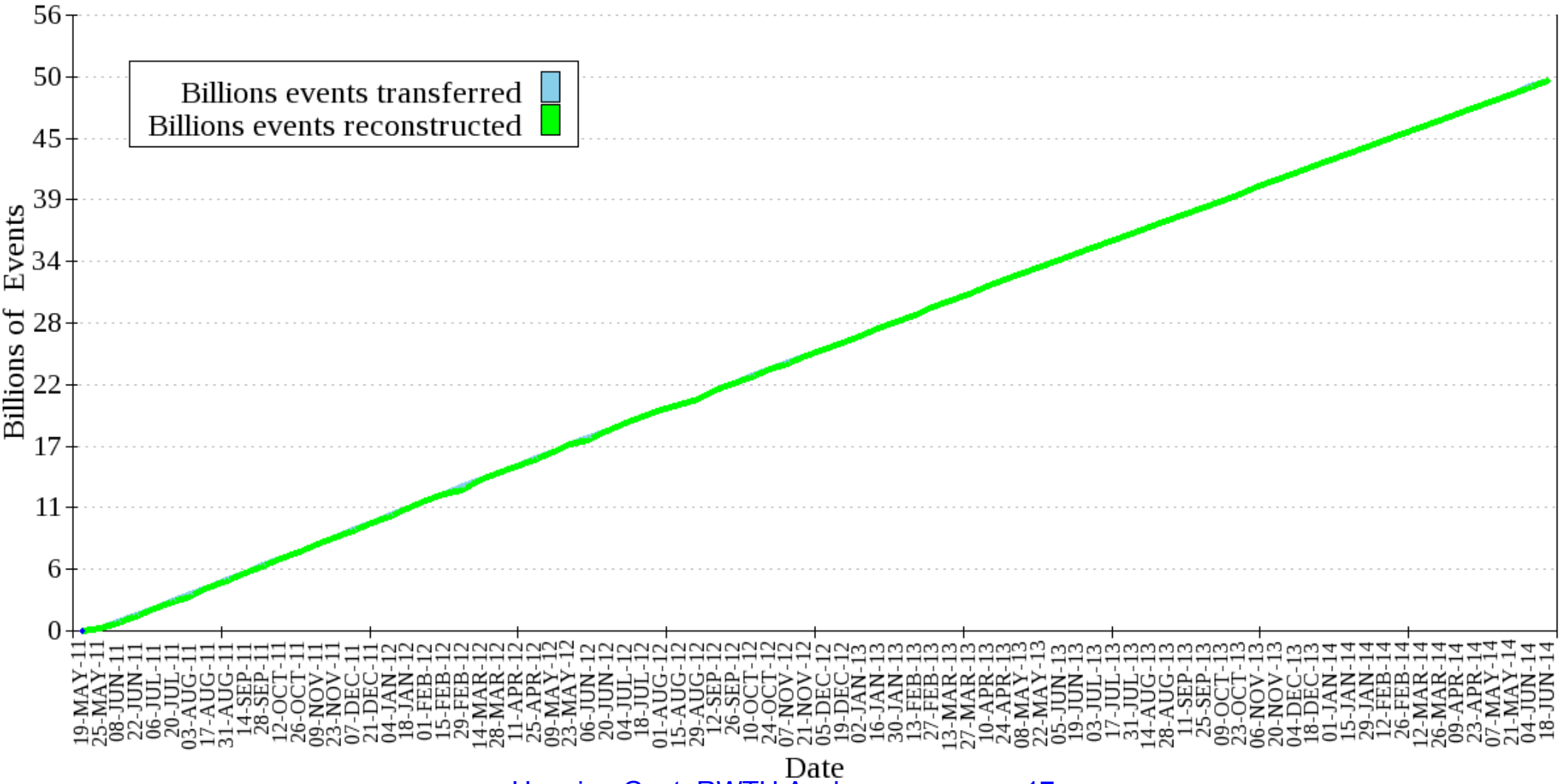
- Particle ID requires complex algorithms for each subdetector.
- Combine information from all subdetectors.
- Example: proton rejection 1:1,000,000



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.

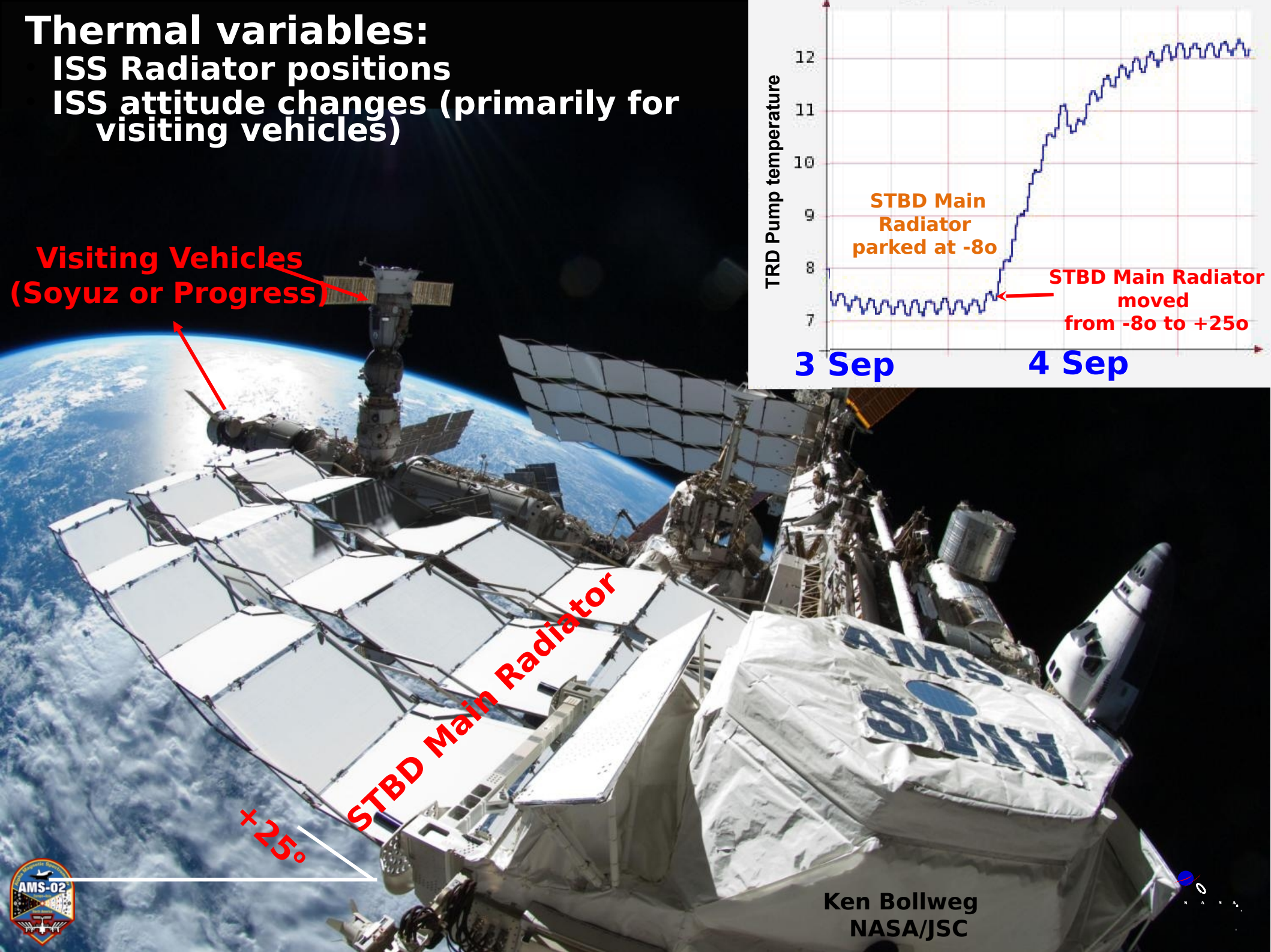
AMS-02 data taking

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



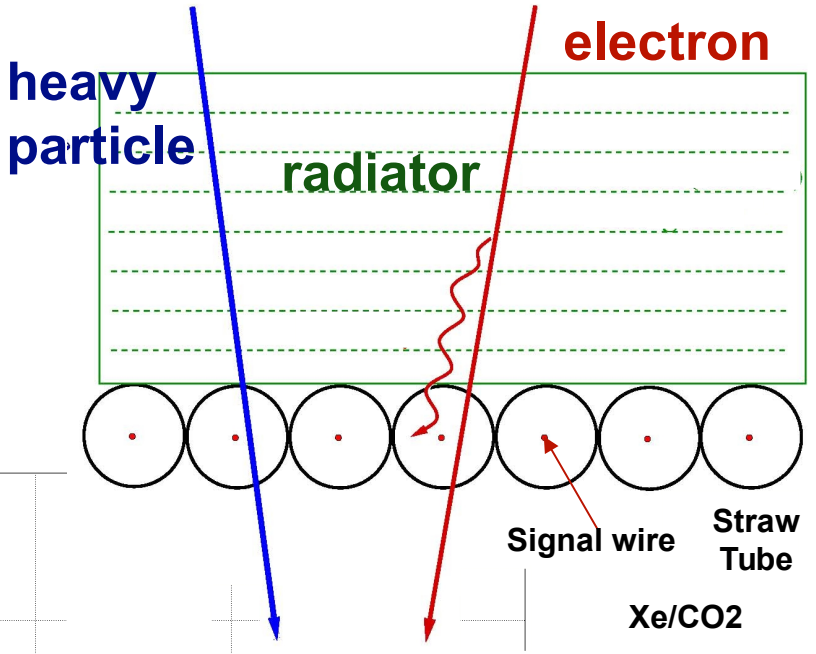
Thermal variables:

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

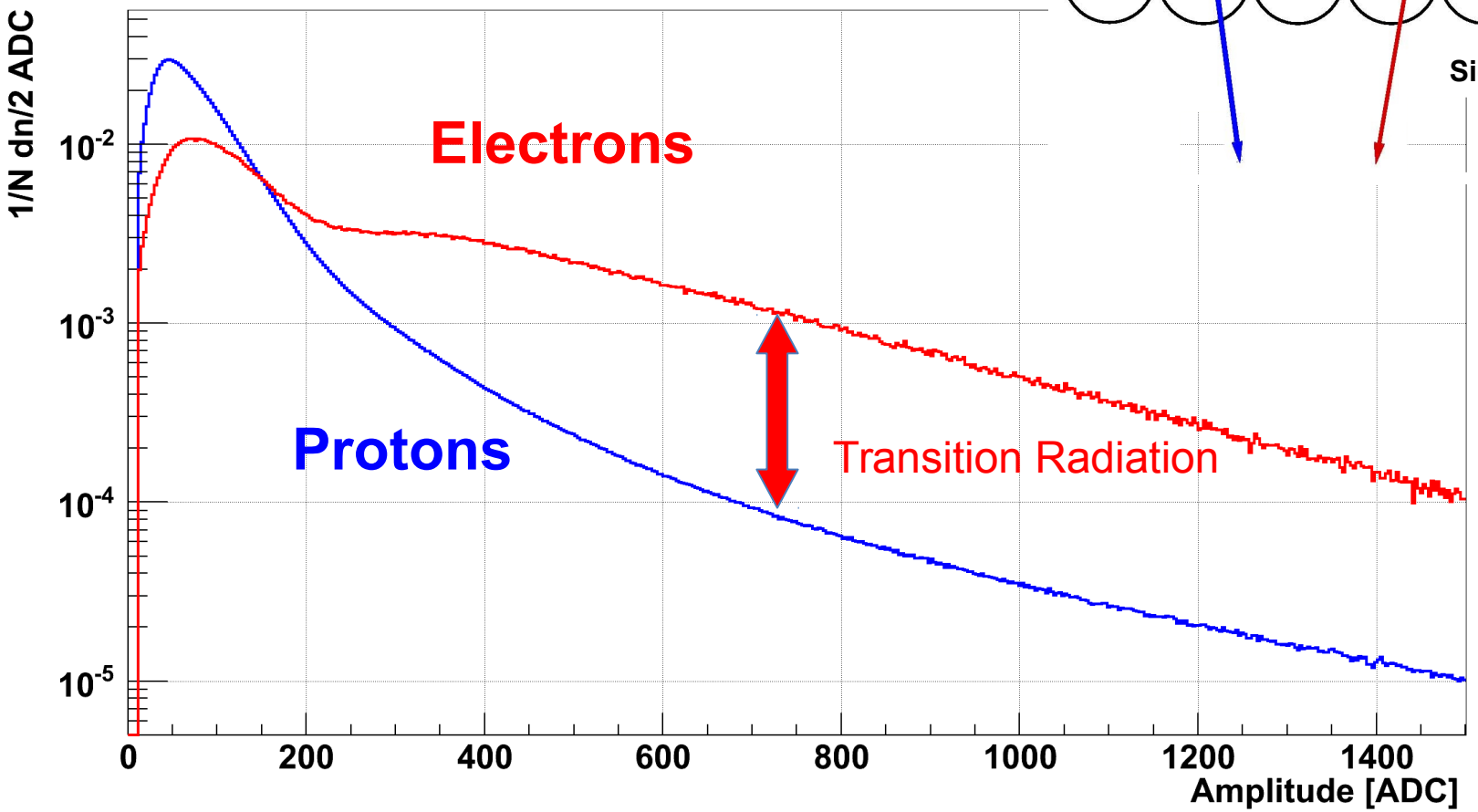


AMS-02 performance: TRD spectra

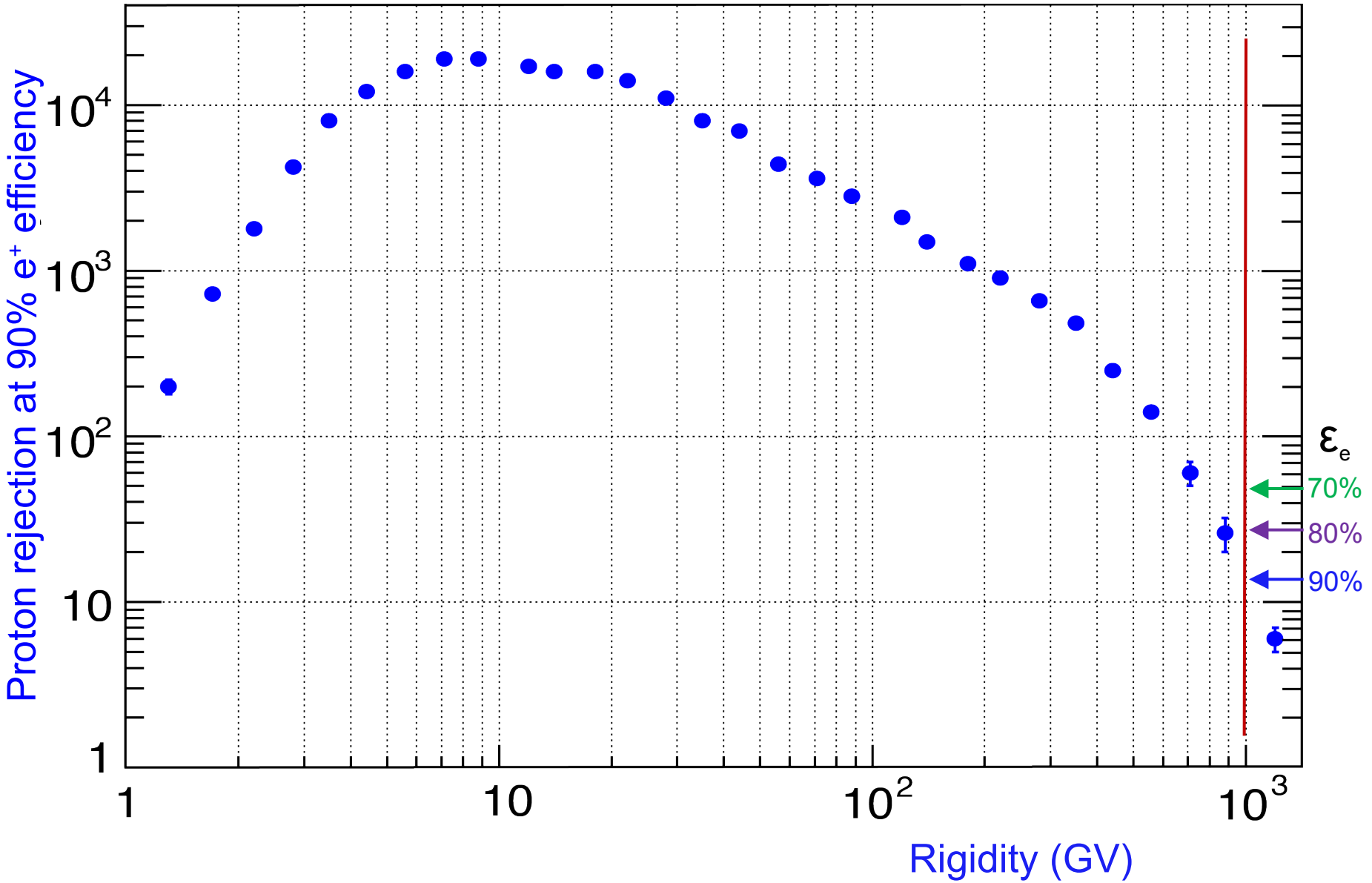
- TRD: Transition radiation detector
- TR yield proportional to γ=E/m



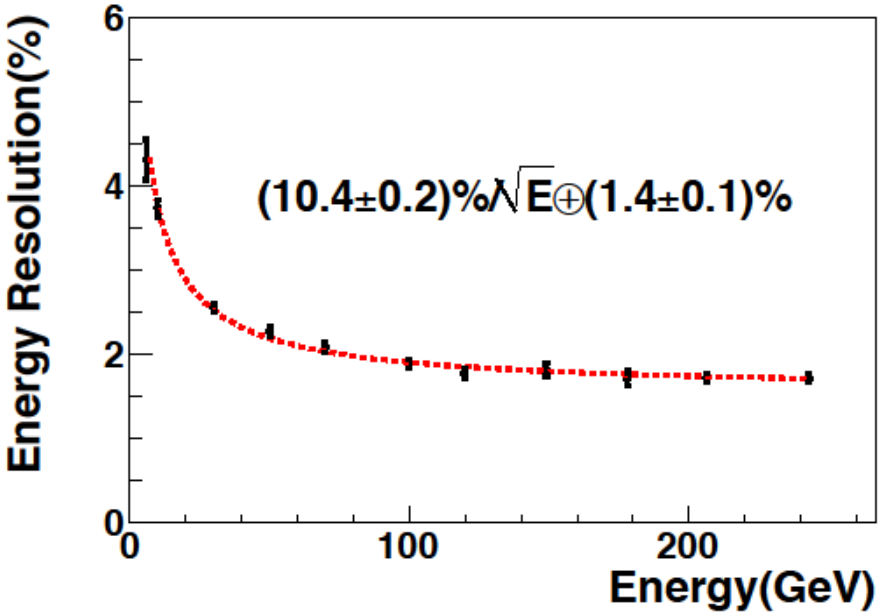
1 / 20 TRD layers, AMS flight data:

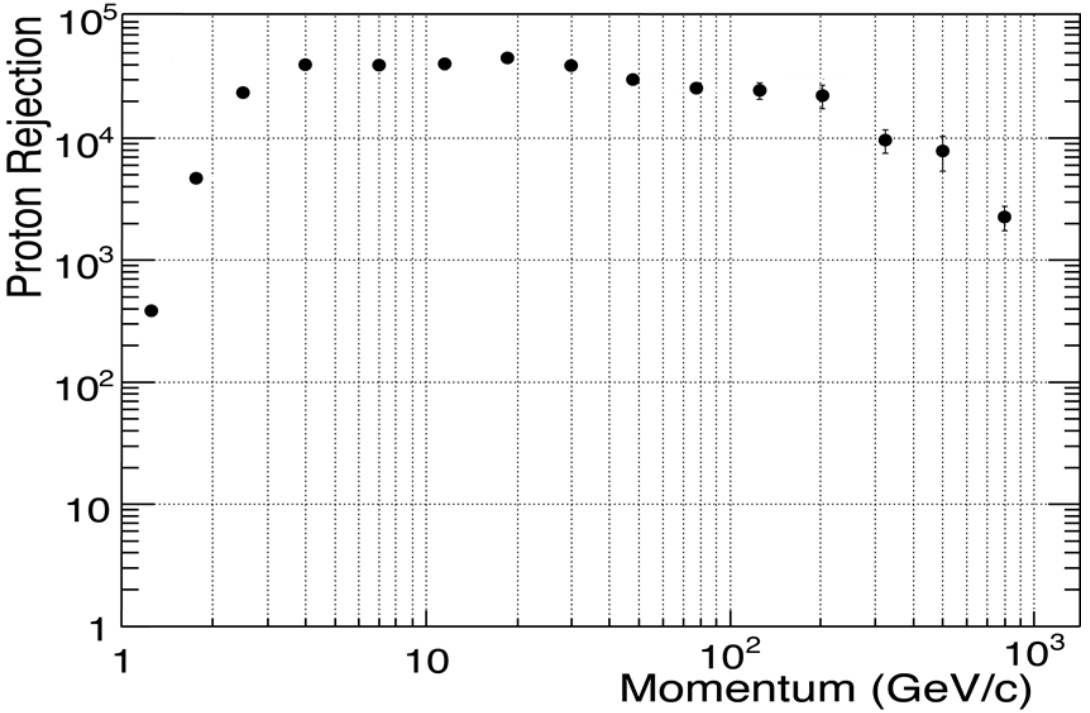


TRD proton rejection vs rigidity

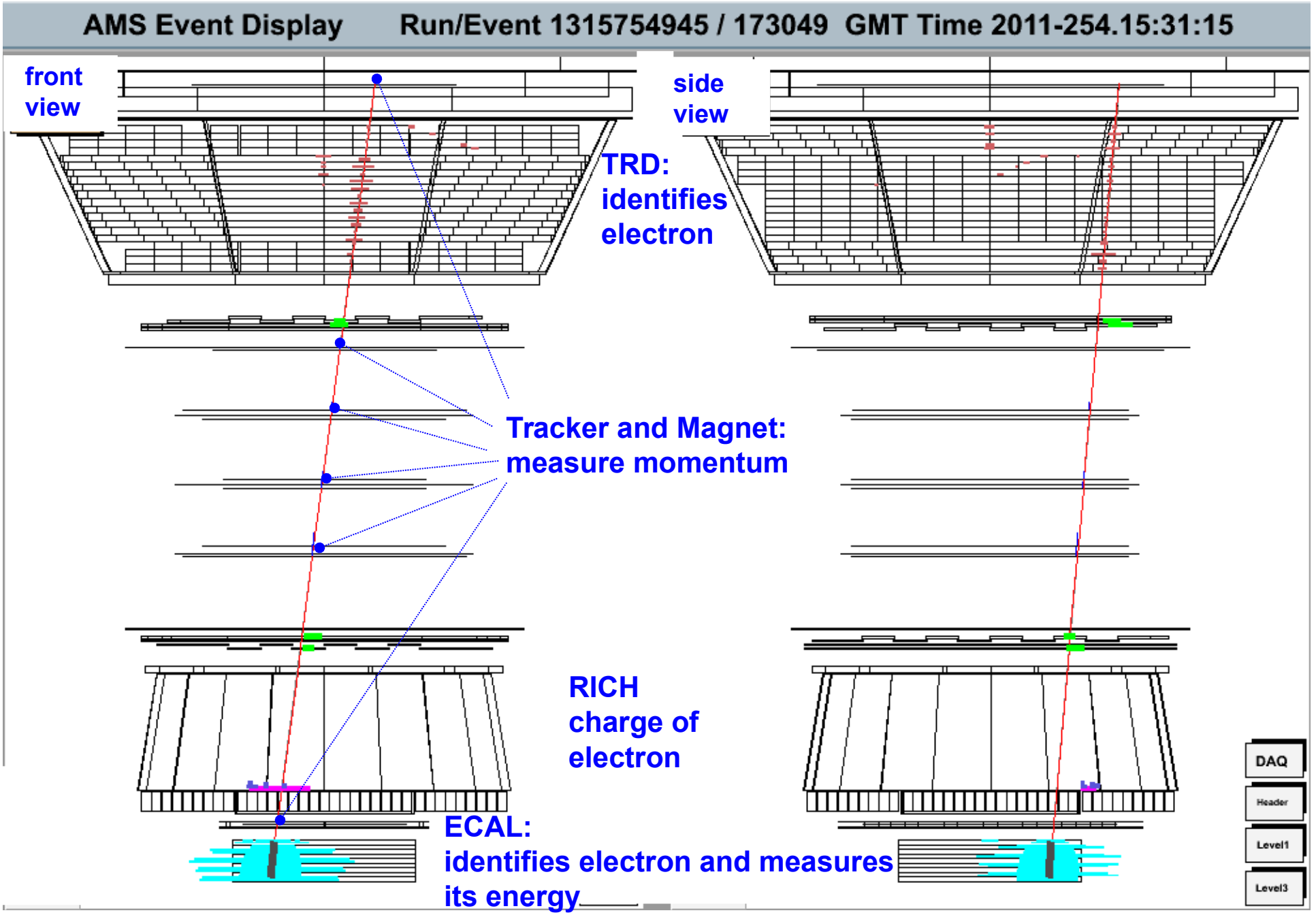


ECAL: energy resolution and proton rejection power





1.03 TeV electron



First result from AMS-02: Cosmic-ray positron fraction

"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)]

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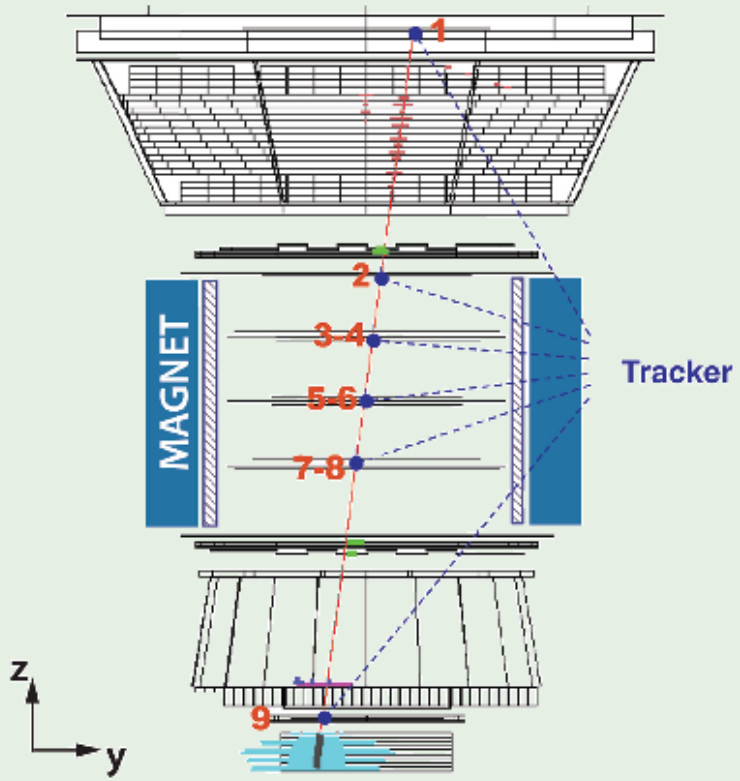
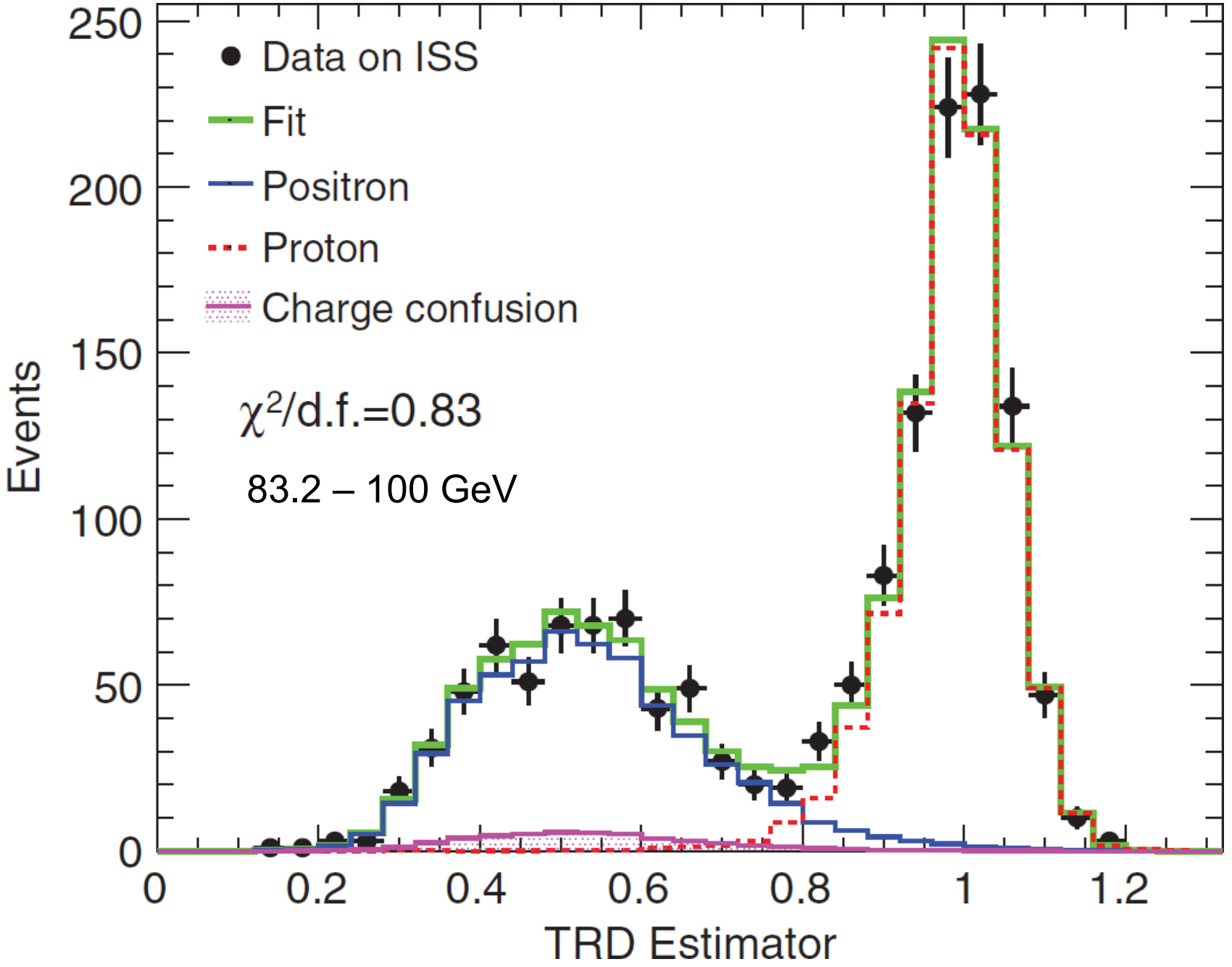


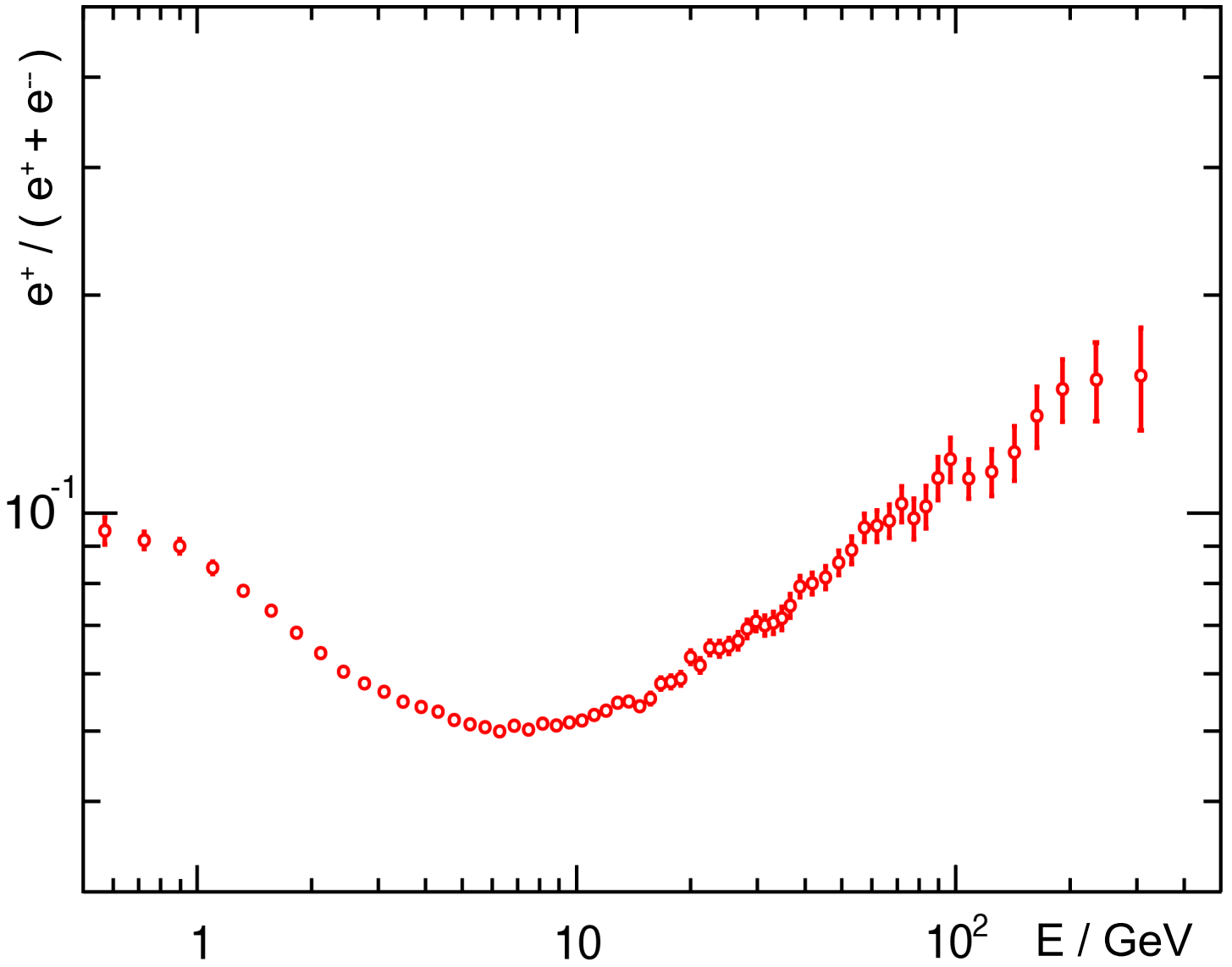
Published by
American Physical Society.
APS physics
Volume 110, Number 14

Example of positron selection

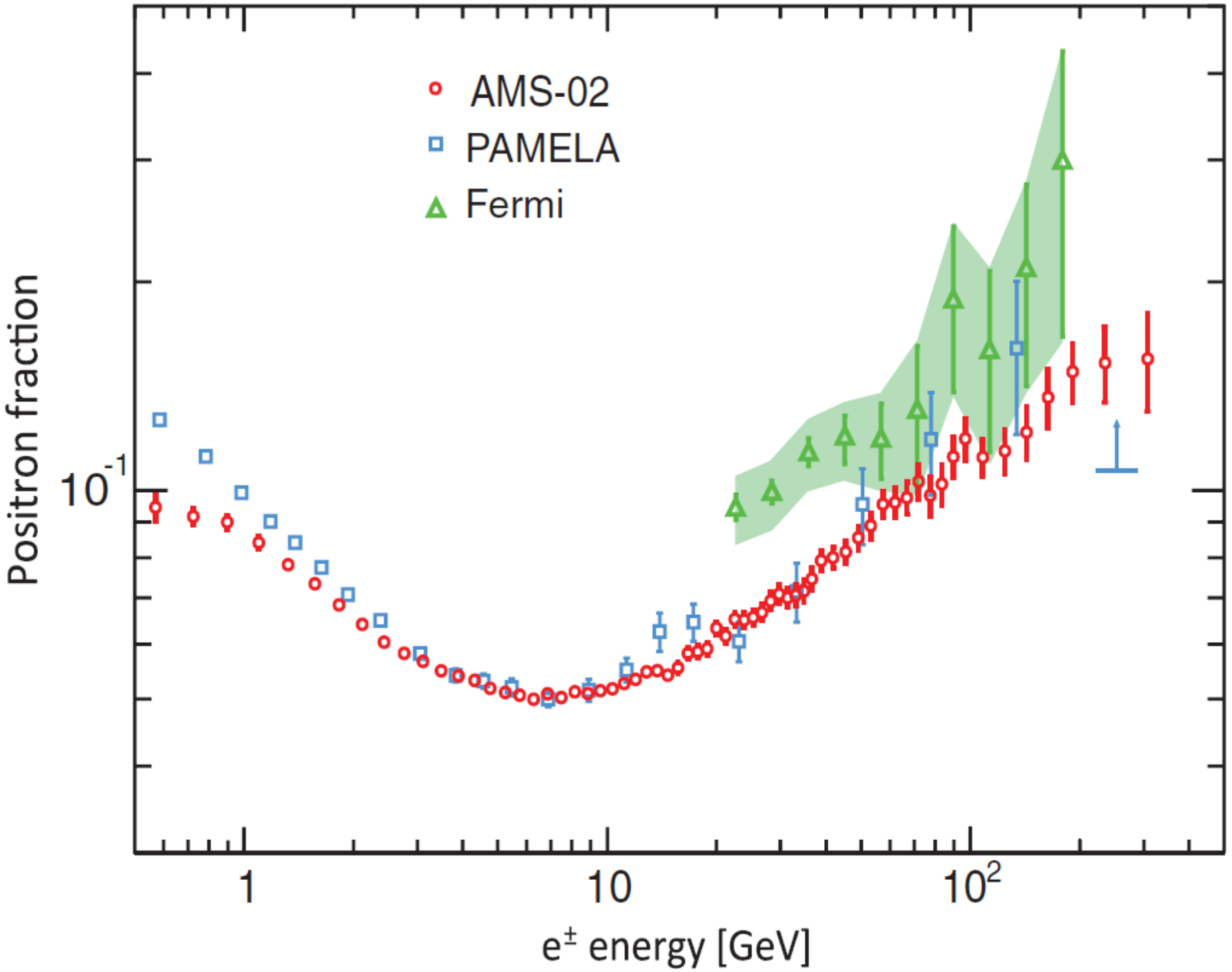


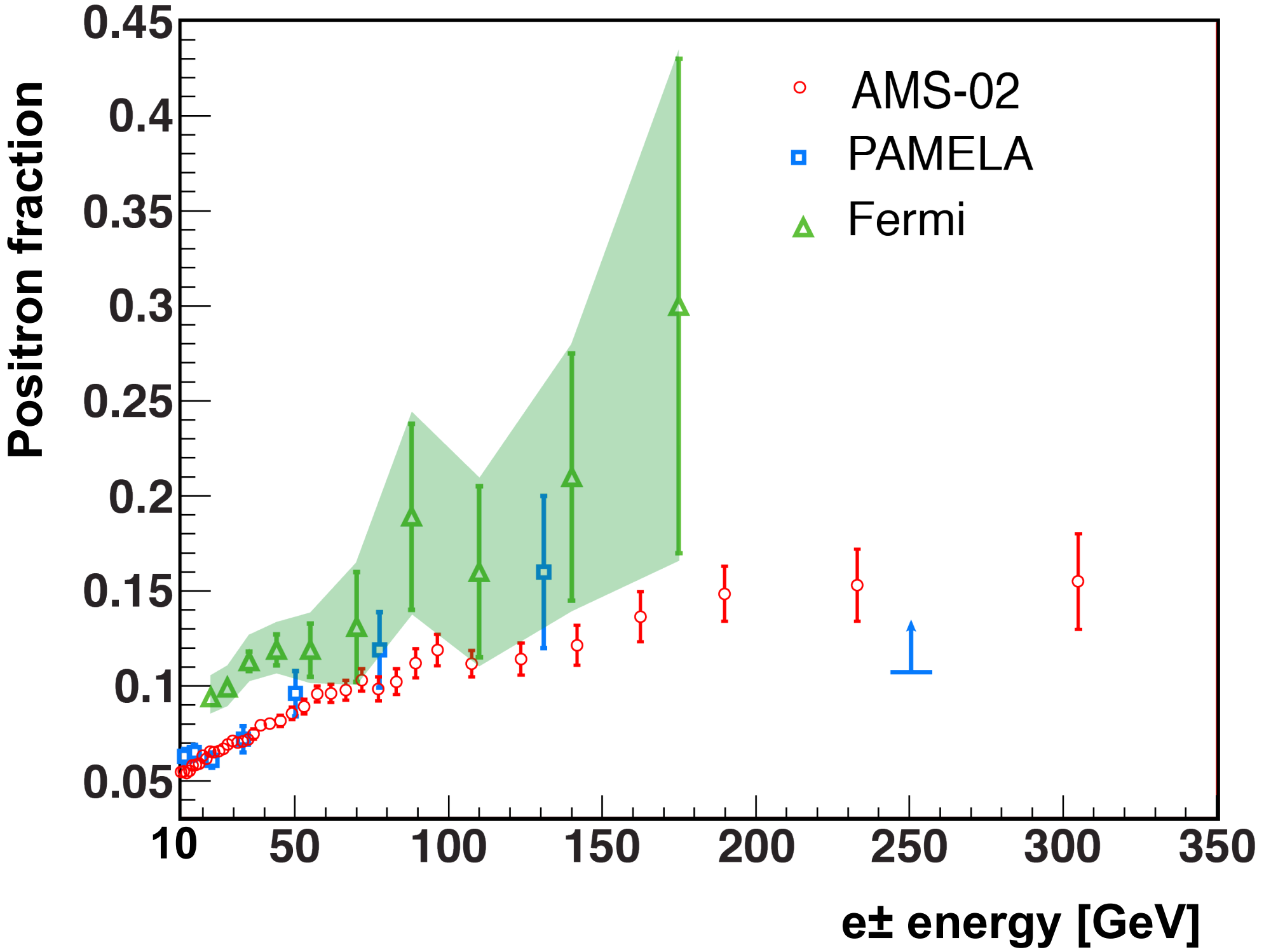
AMS-02 positron fraction

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



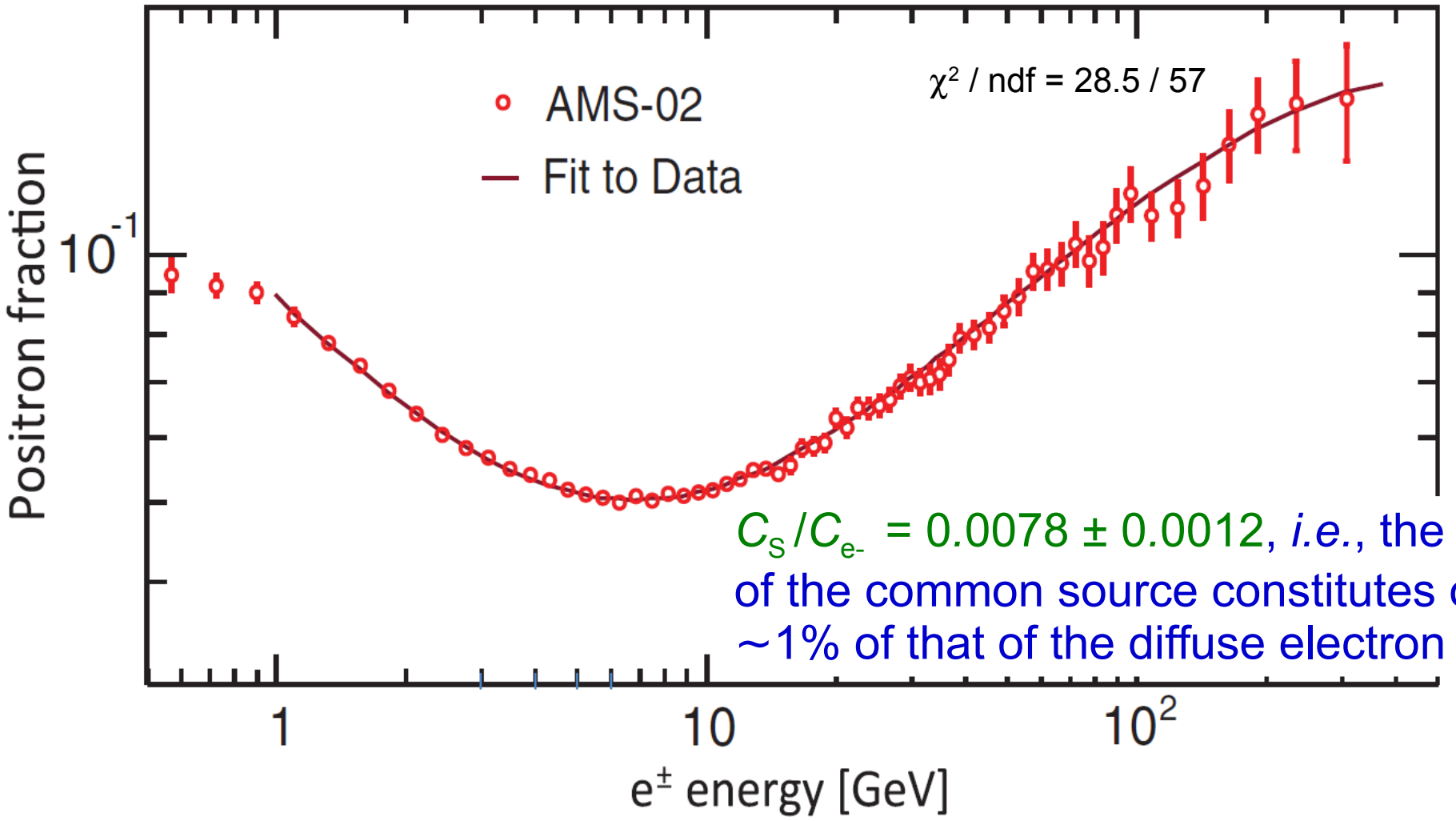
Comparison to earlier measurements




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:

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

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

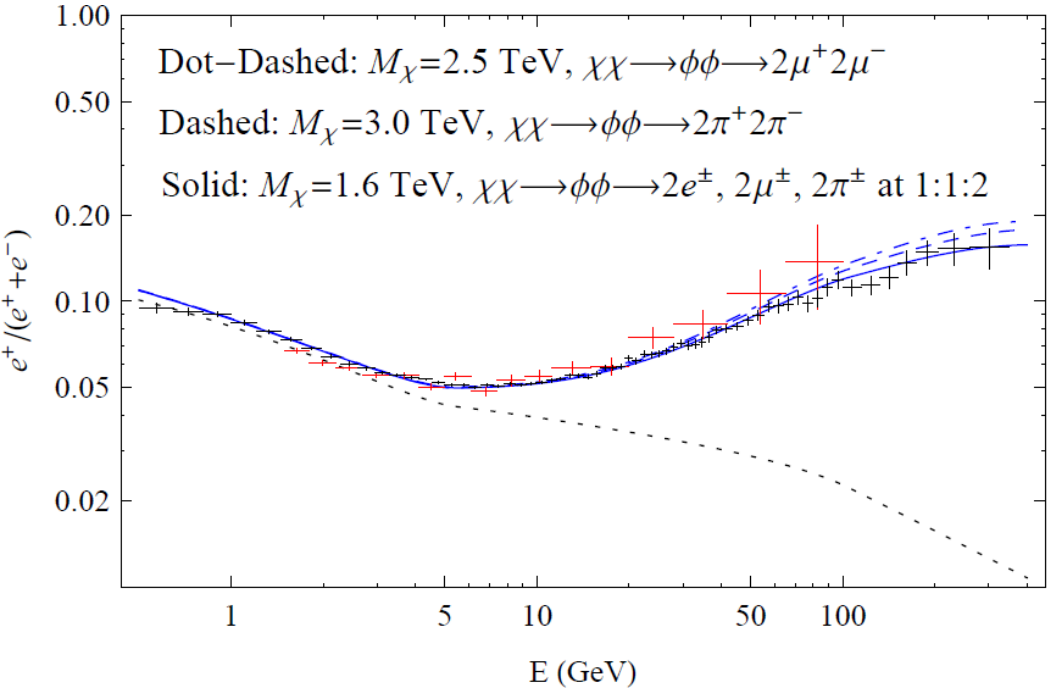
$$\delta = 3\sqrt{C_1/4\pi}$$

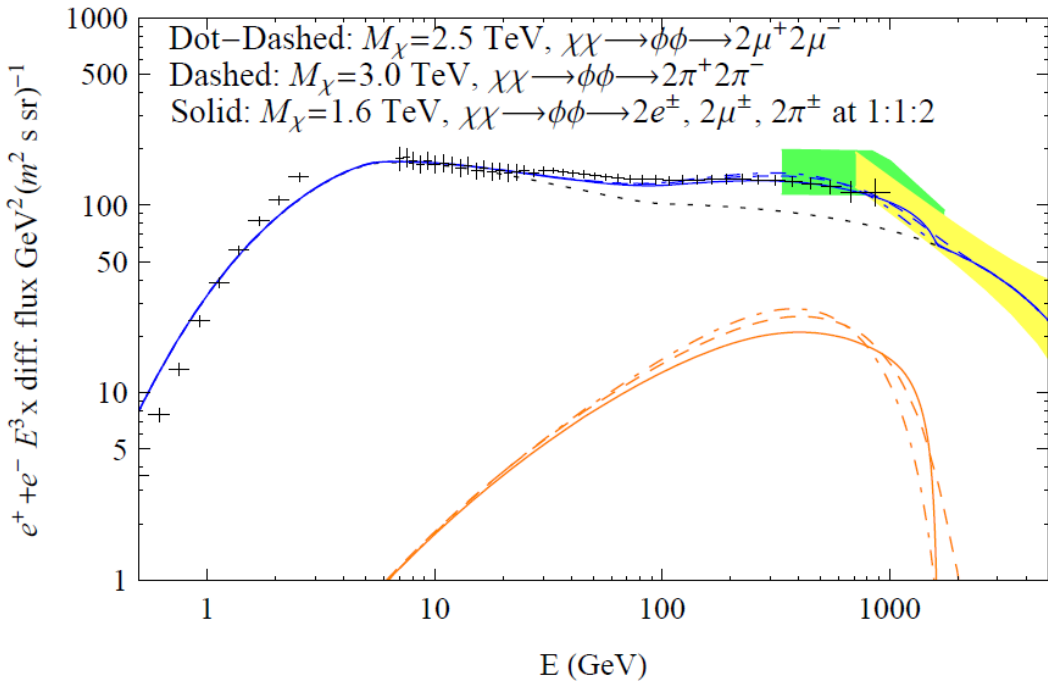
AMS-02:
$\delta < 0.036$ at the 95% confidence level.

Dark matter in the light of AMS-02 results

Cholis and Hooper,
PRD 88 (2013) 023013

- 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.)

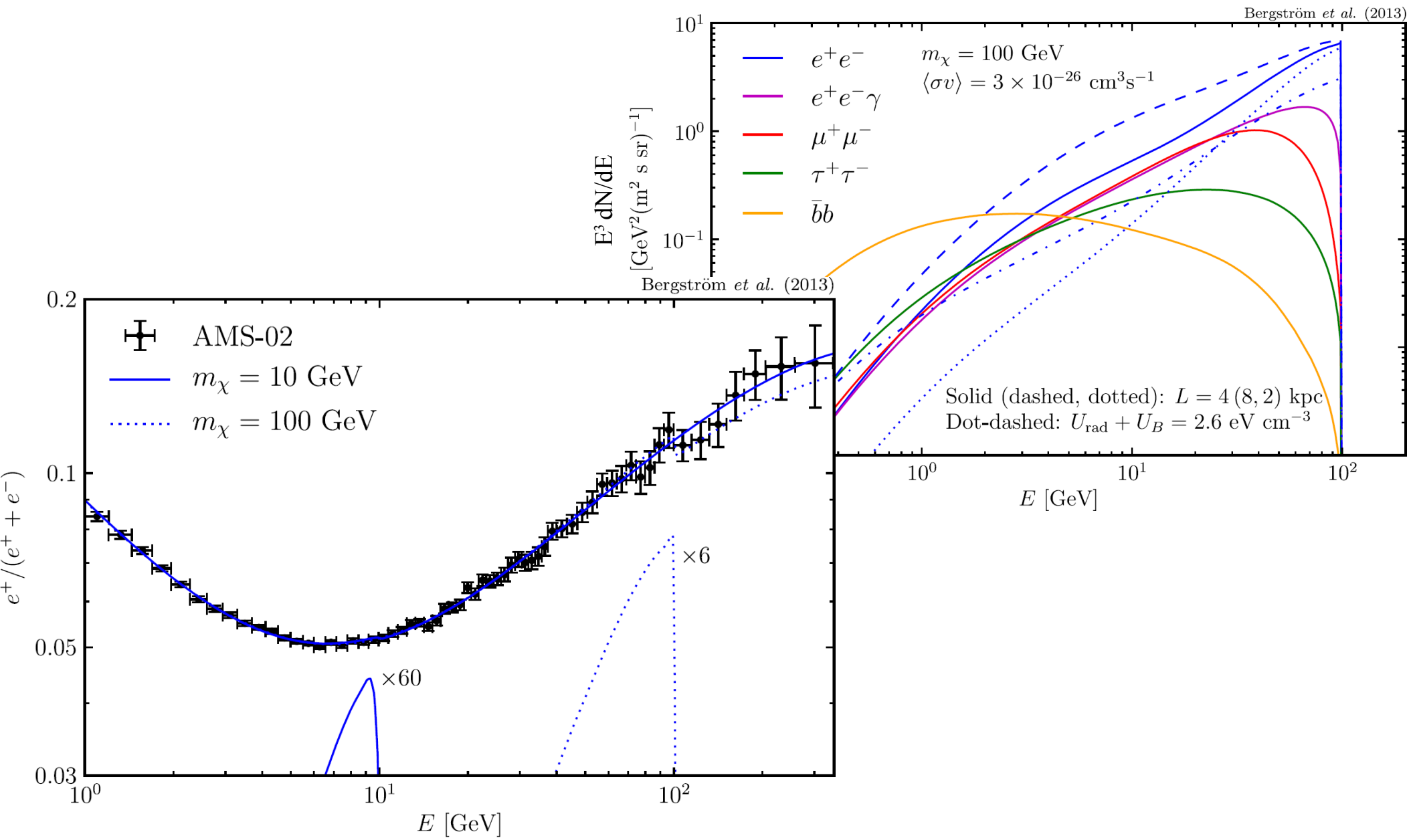




Dark matter in the light of AMS-02 results

Bergström et al., PRL 111 (2013) 171101

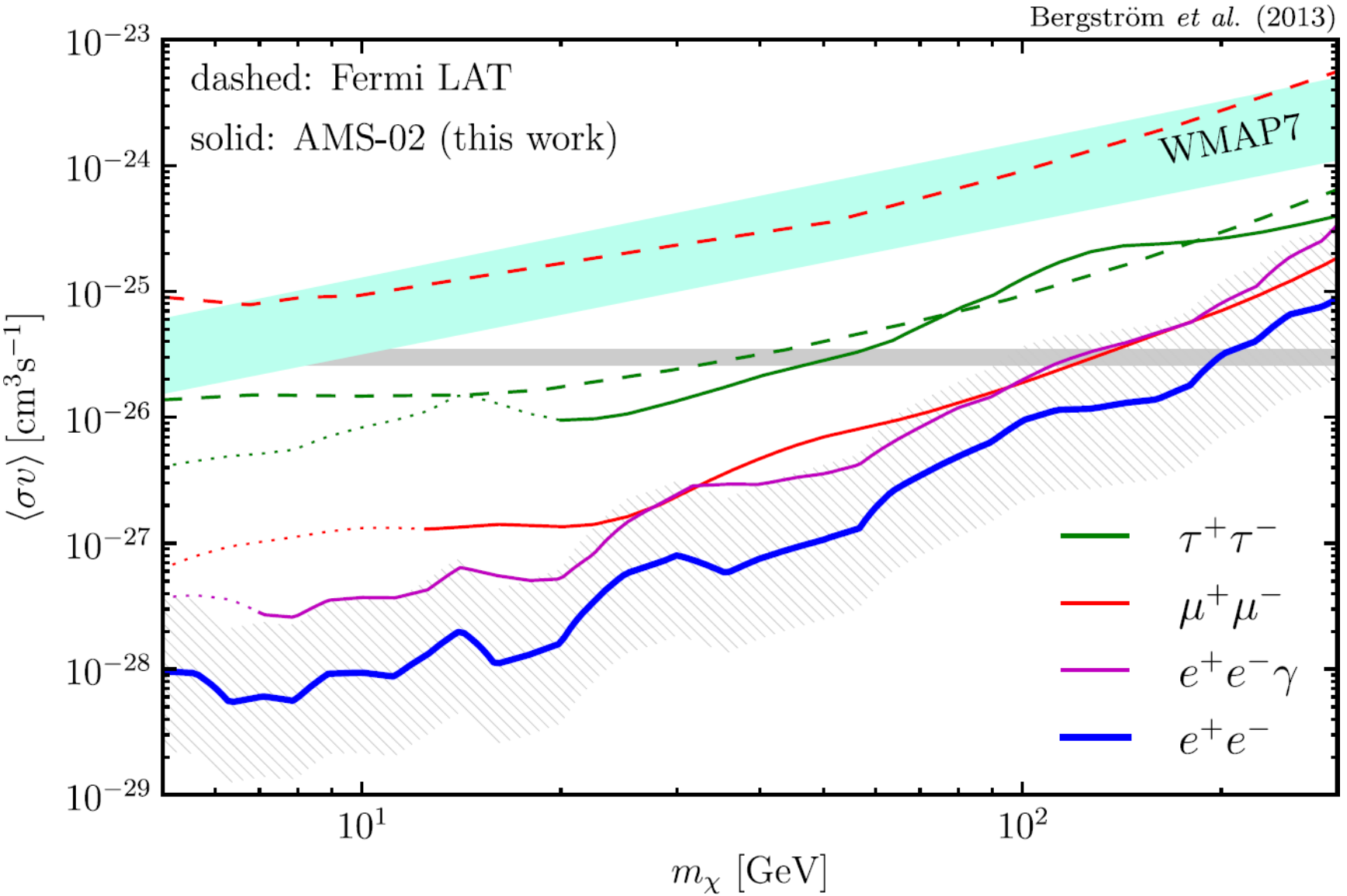
- Take generic model from AMS paper as background curve
- Try to fit lepton spectra from annihilating dark matter to AMS positron fraction



Dark matter in the light of AMS-02 results

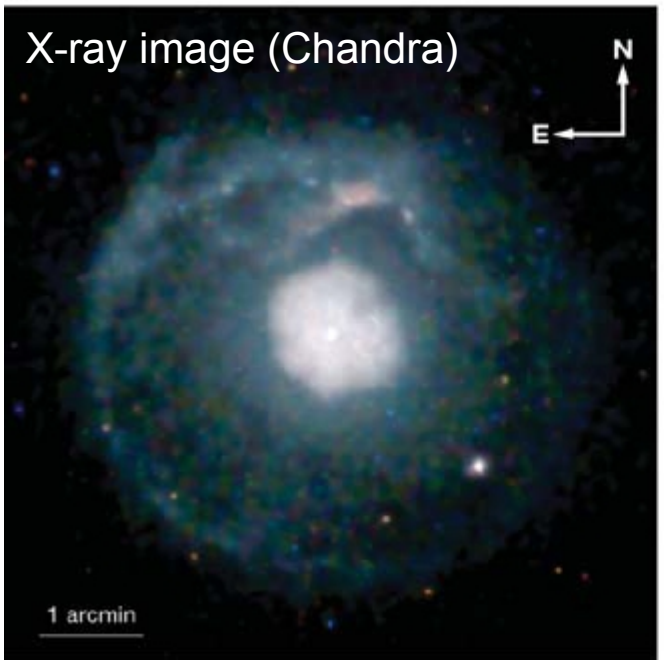
Bergström et al., PRL 111 (2013) 171101

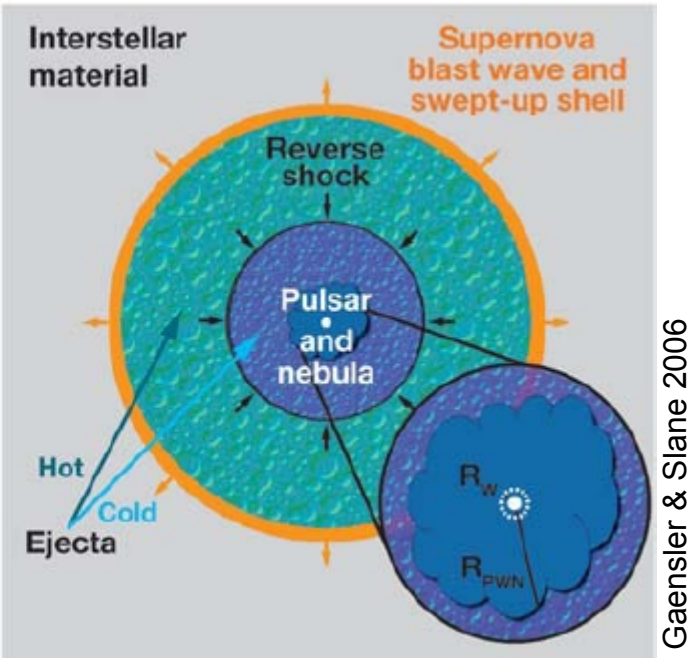
- Take generic model from AMS paper as background curve
- Try to fit lepton spectra from annihilating dark matter to AMS positron fraction



Astrophysical sources for positrons

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



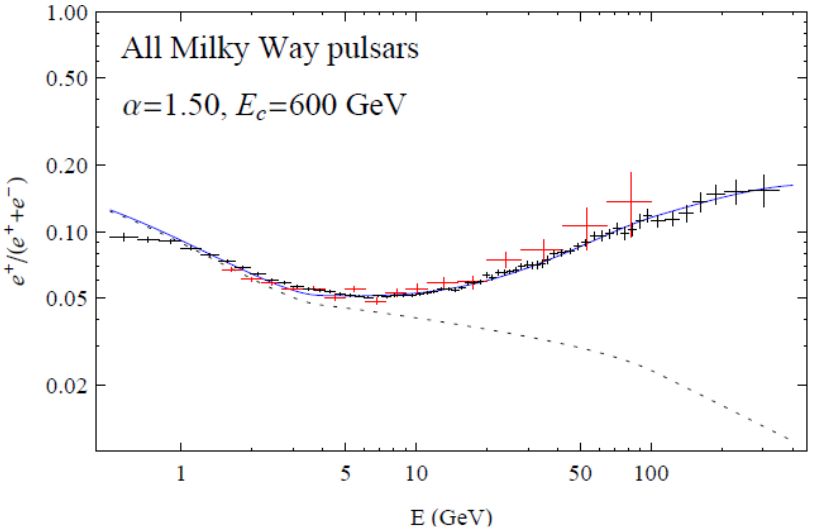


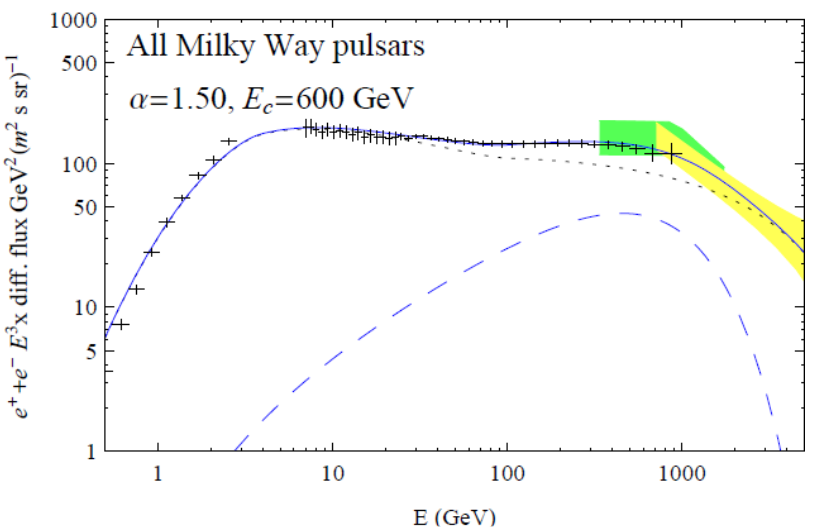
Gaensler & Slane 2006

Pulsar models also still work!

Cholis and Hooper,
PRD 88 (2013) 023013

- 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)

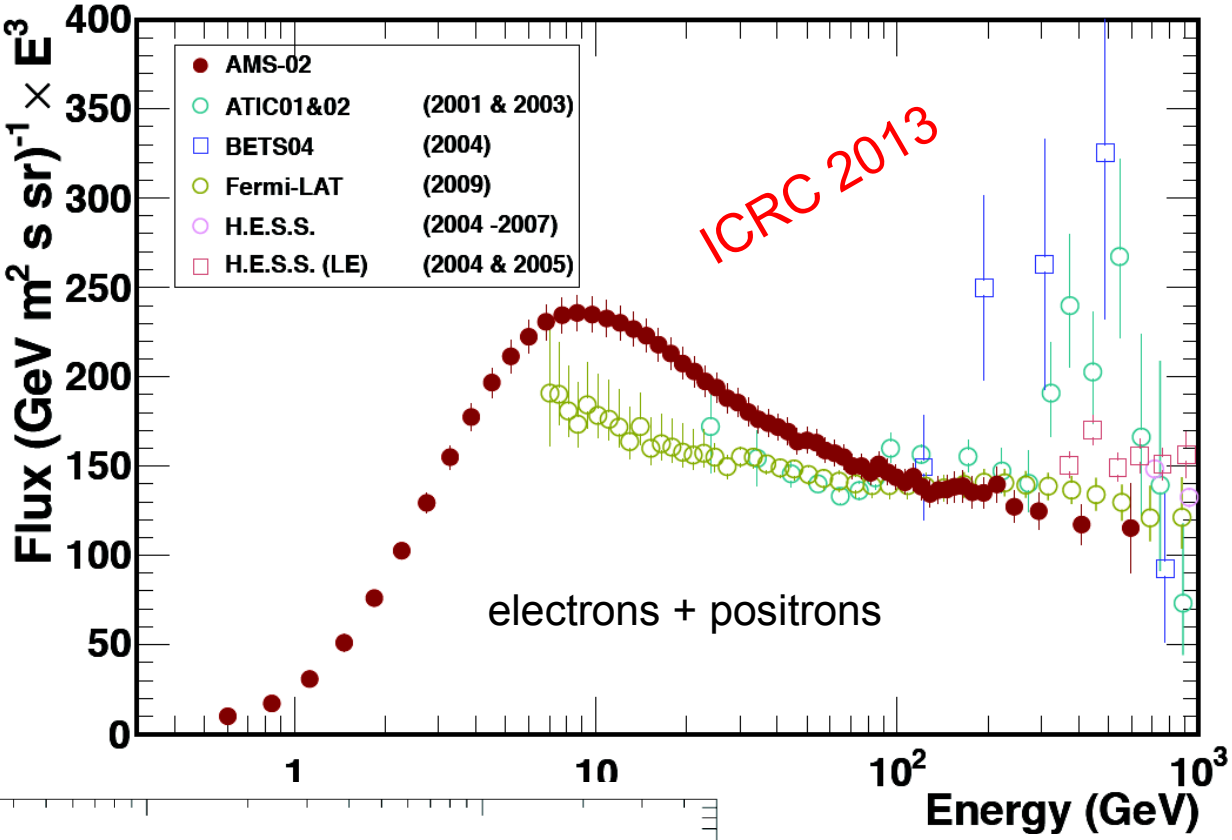


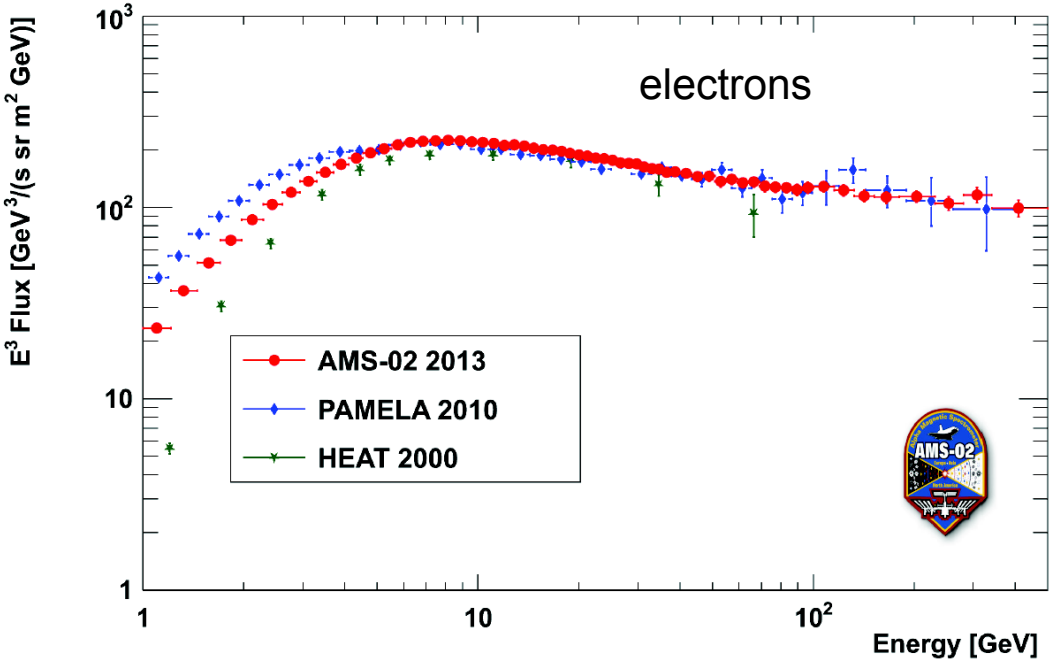


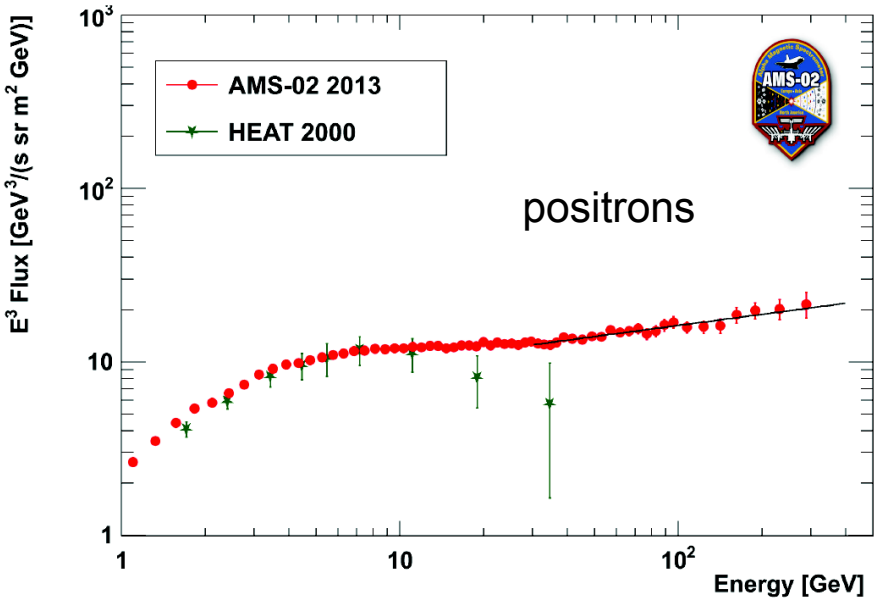
- More ideas:
  - Supernova remnants (radioactive nuclei from supernova ejecta) as positron sources (Erlykin & Wolfendale)
  - Acceleration of secondary $e^{\pm}$ produced through pp interactions inside the primary sources (Ahlers et al.)
  - Propagation effects (Blum et al.)

ICRC 2013:
Preliminary results on cosmic-ray fluxes

AMS-02 electron and positron spectra

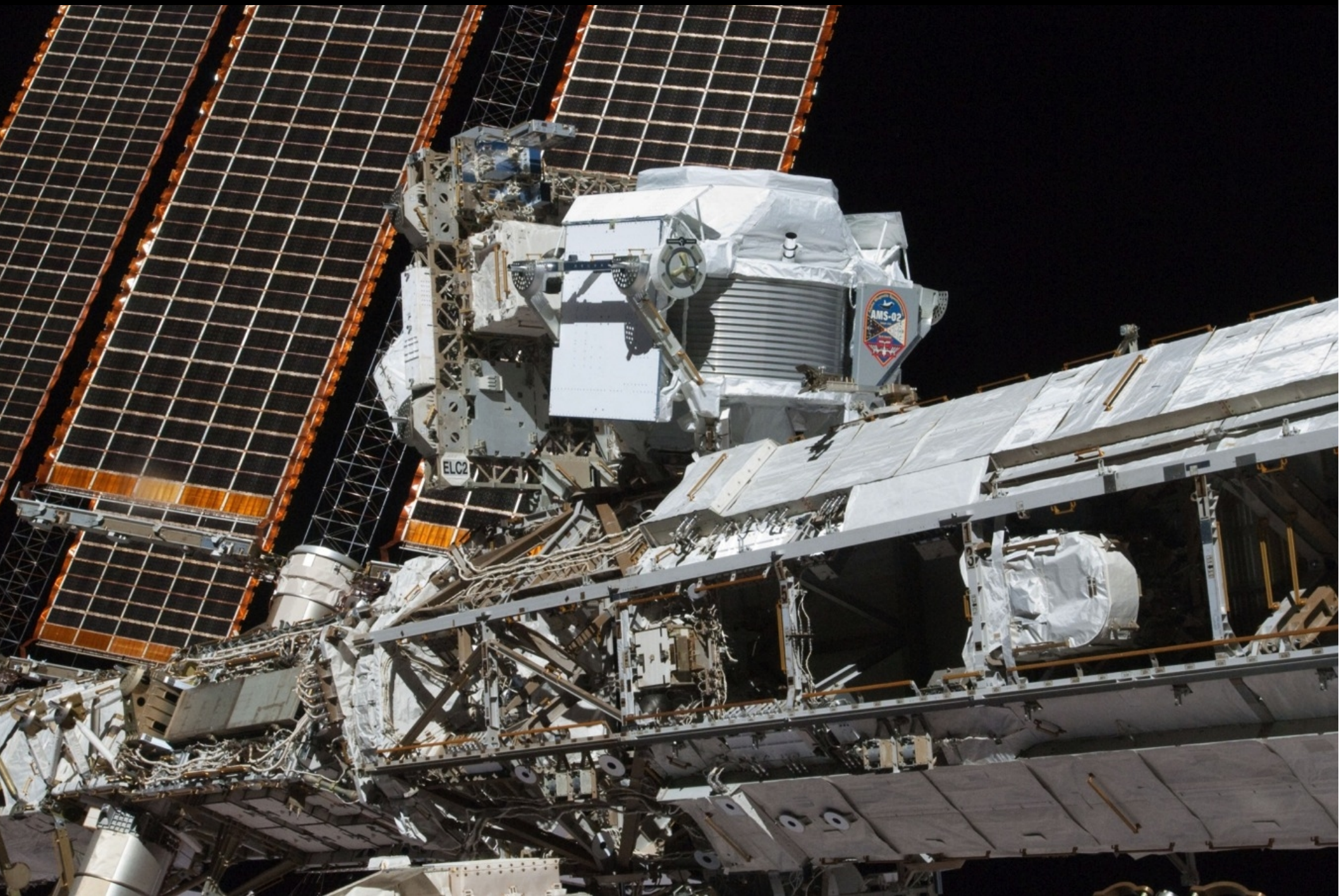






Summary

- 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 or something else (SNRs?) ?
- Measurement of anisotropy in positron fraction extremely important in this context.
- First results on major particle fluxes shown at ICRC 2013 in July.
- Coming soon:
  - update on positron fraction,
  - e+ and e- fluxes,
  - proton and helium fluxes

The Cosmos is the Ultimate Laboratory.

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