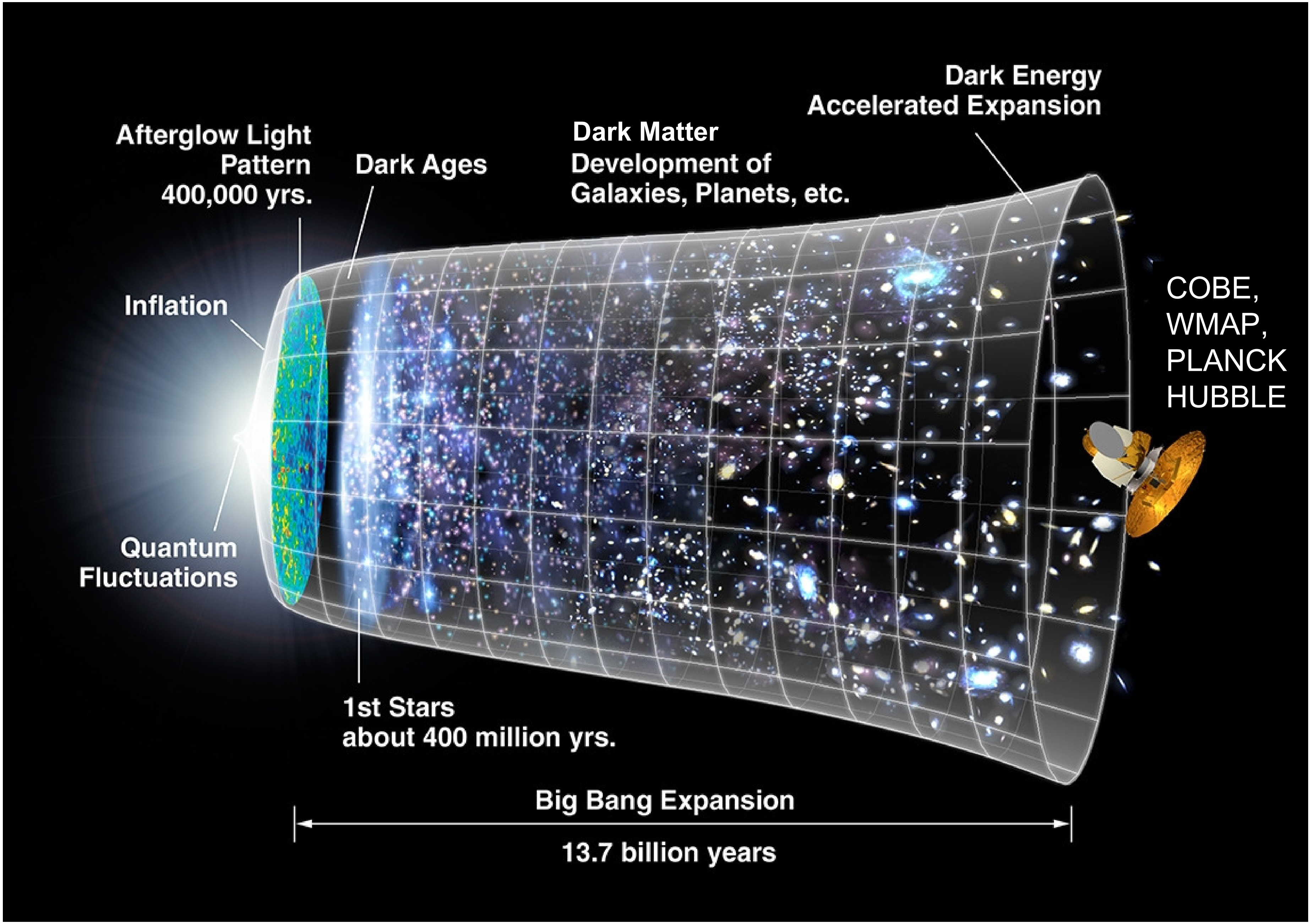
Cosmic-ray research with AMS-02 on the International Space Station

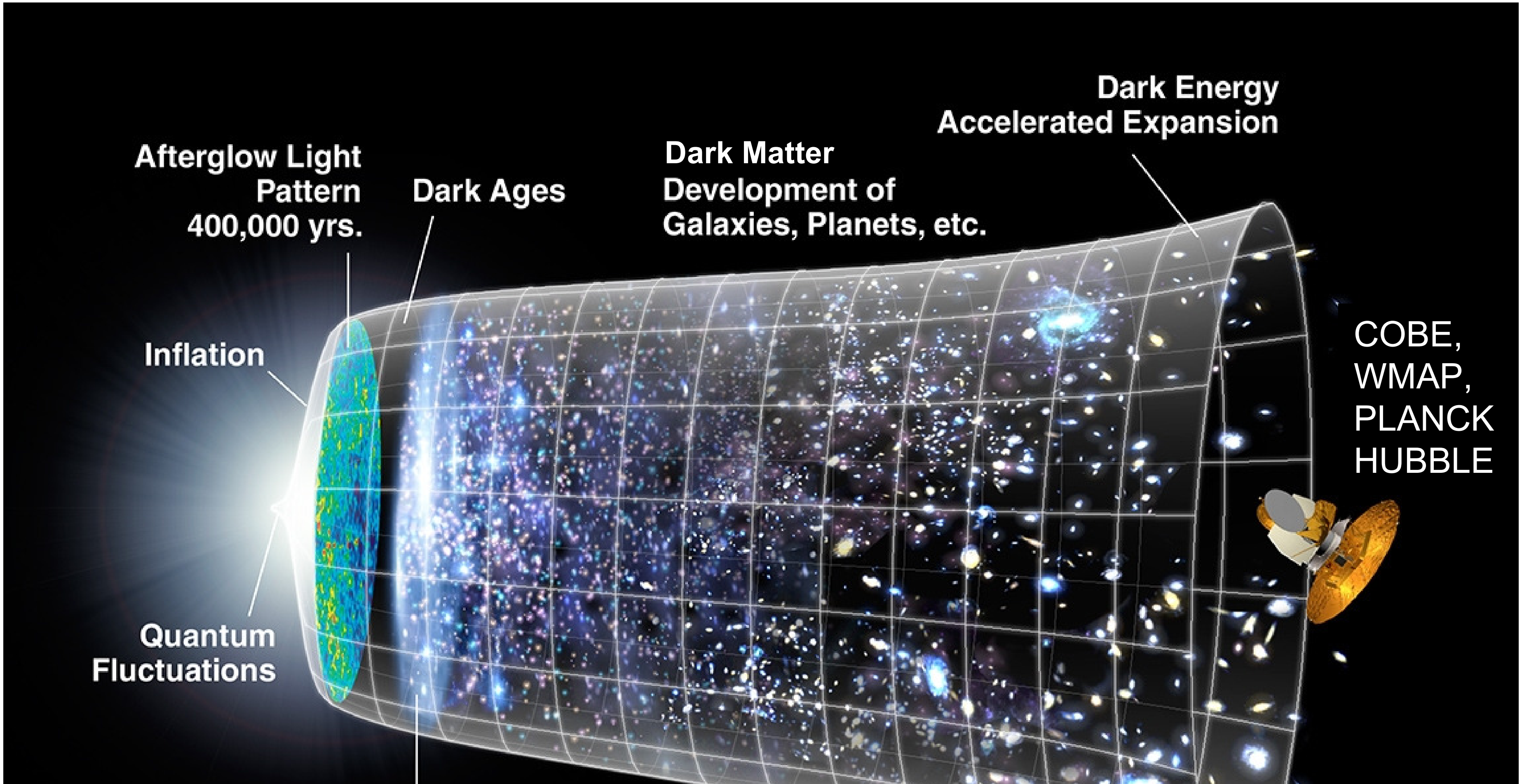
Henning Gast
RWTH Aachen

Fundamental questions



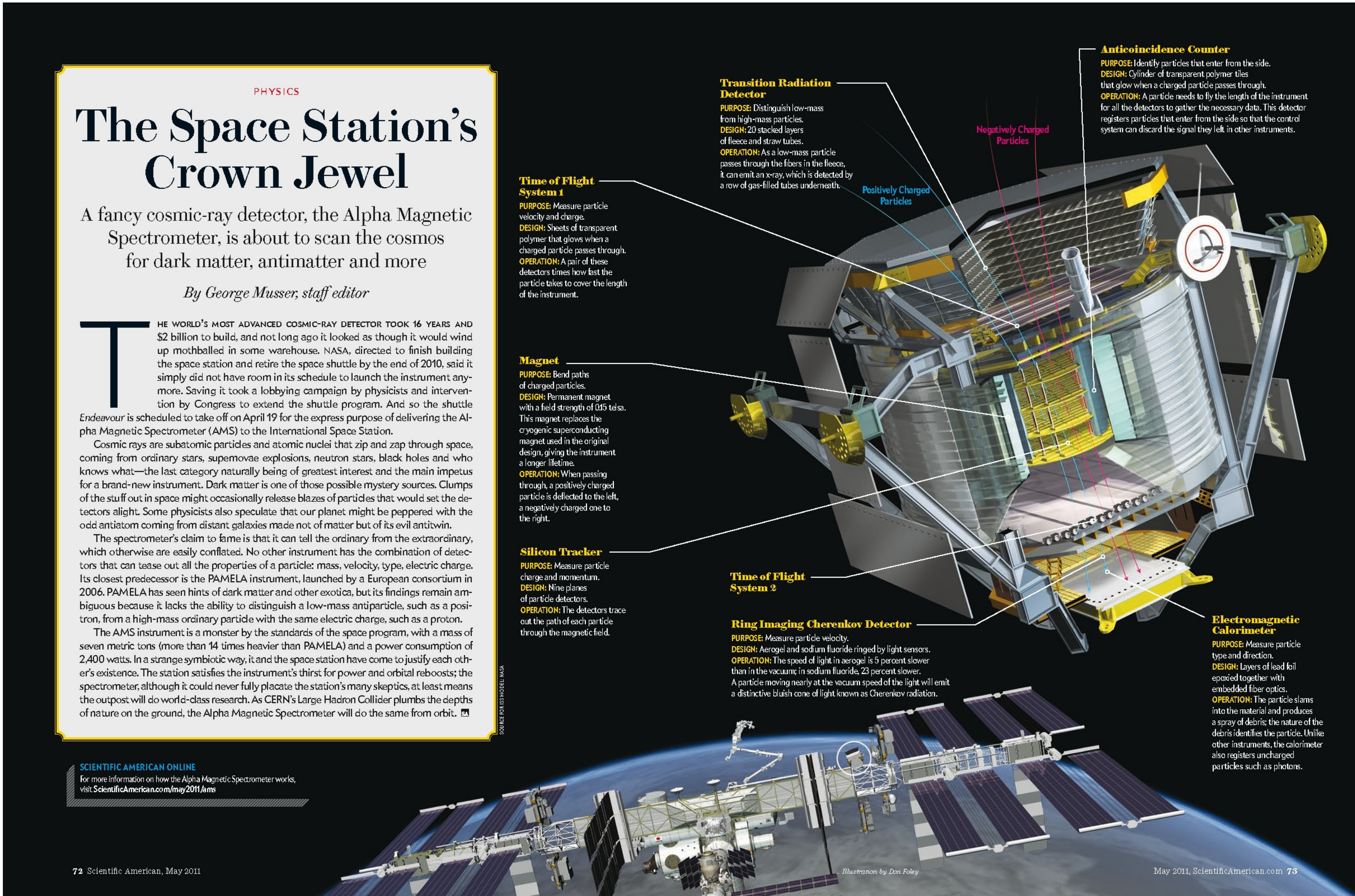
COBE,
WMAP,
PLANCK
HUBBLE

Fundamental questions



- What are the building blocks of the Universe?
- What is the nature of dark matter?
- What happened to cosmic antimatter?

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. SA

SOURCE FOR ISS MODEL: NASA

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

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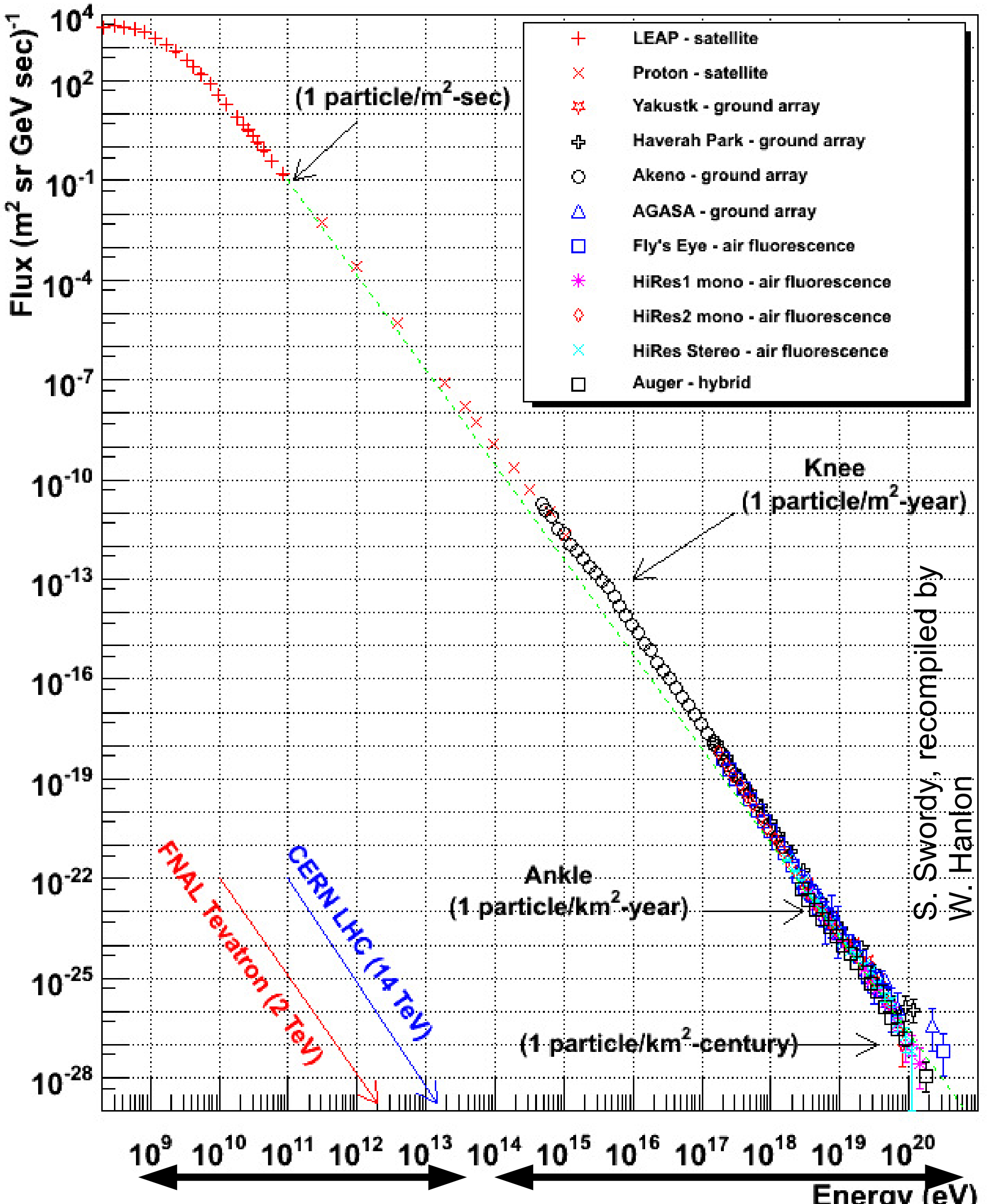
May 2011, ScientificAmerican.com 73

Overview

- Cosmic rays as messengers of our cosmic surroundings
- Sources and propagation of cosmic rays
- Introduction to AMS-02 physics
- AMS-02 on the International Space Station
- First result from AMS-02: Positron fraction measurement
- Interpretation of AMS-02 results

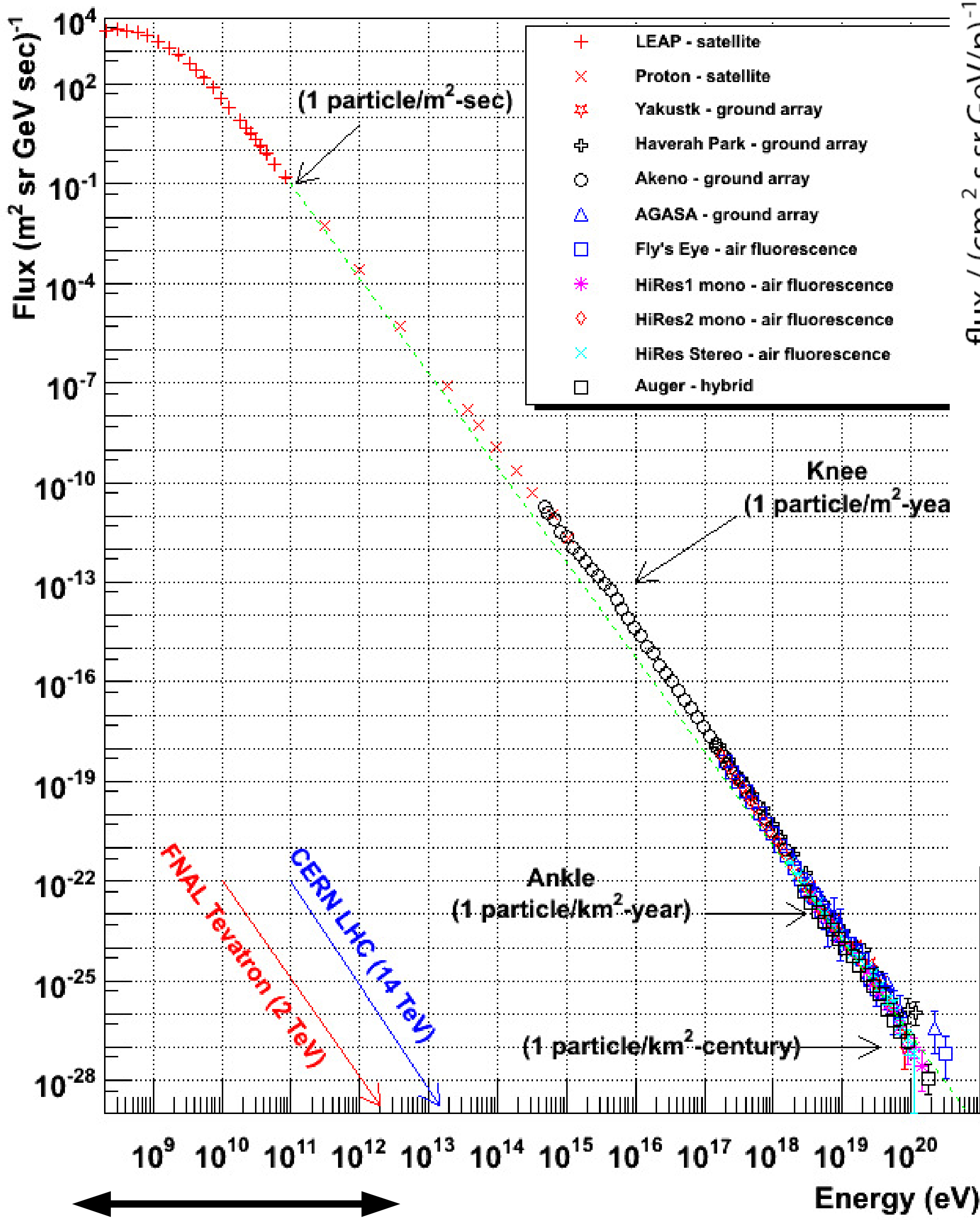
Cosmic-ray spectrum

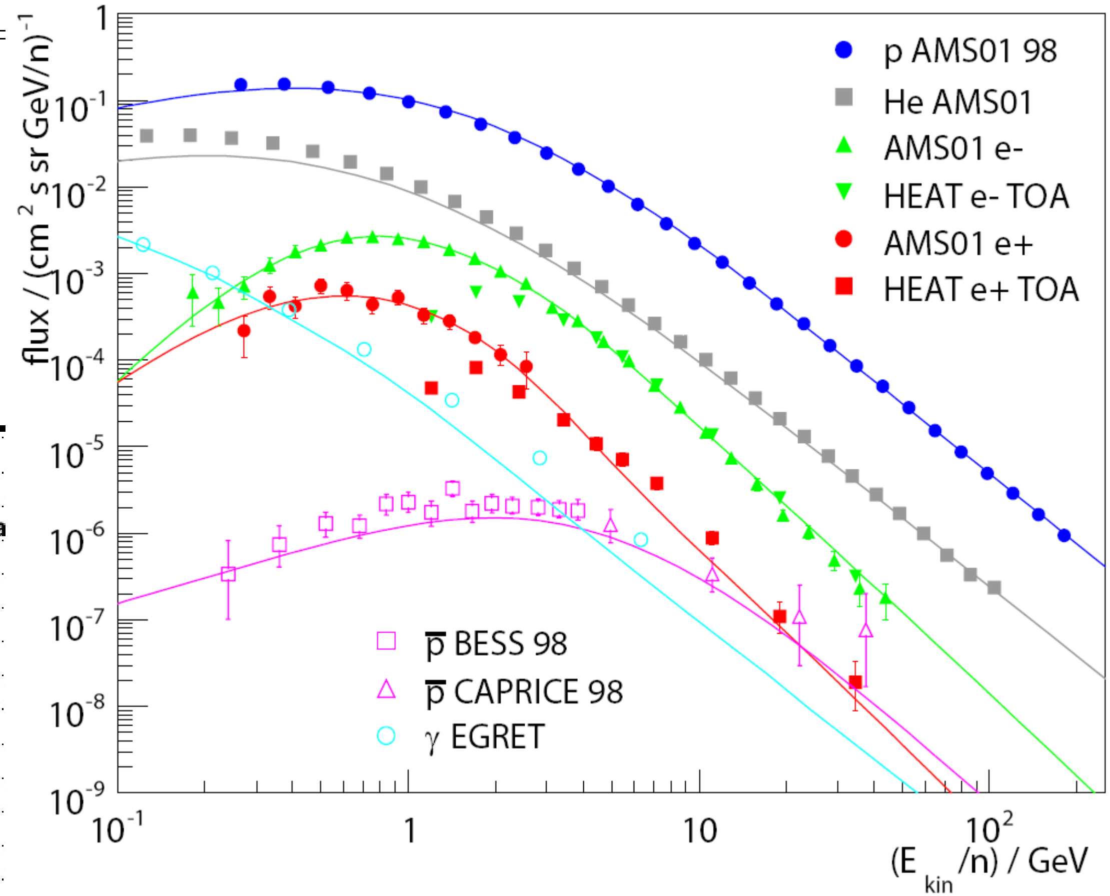


direct measurements:
space-based or balloon-based

ground-based measurements

Spectrum and composition





- Where are cosmic rays accelerated?
    - galactic cosmic rays?
    - extragalactic cosmic rays?
- Direction information is scrambled by interstellar magnetic fields.

Cosmic ray physics in a nutshell

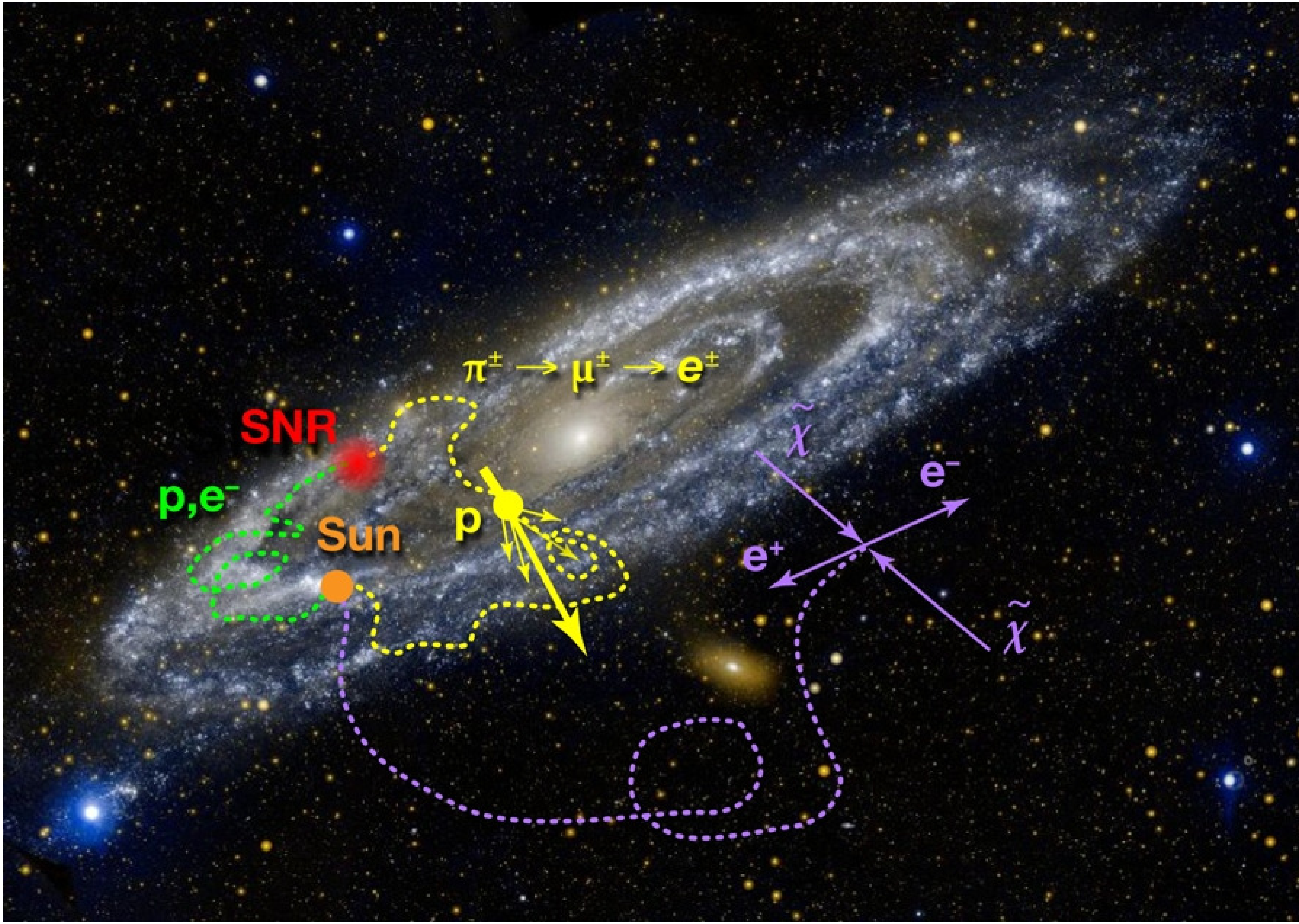
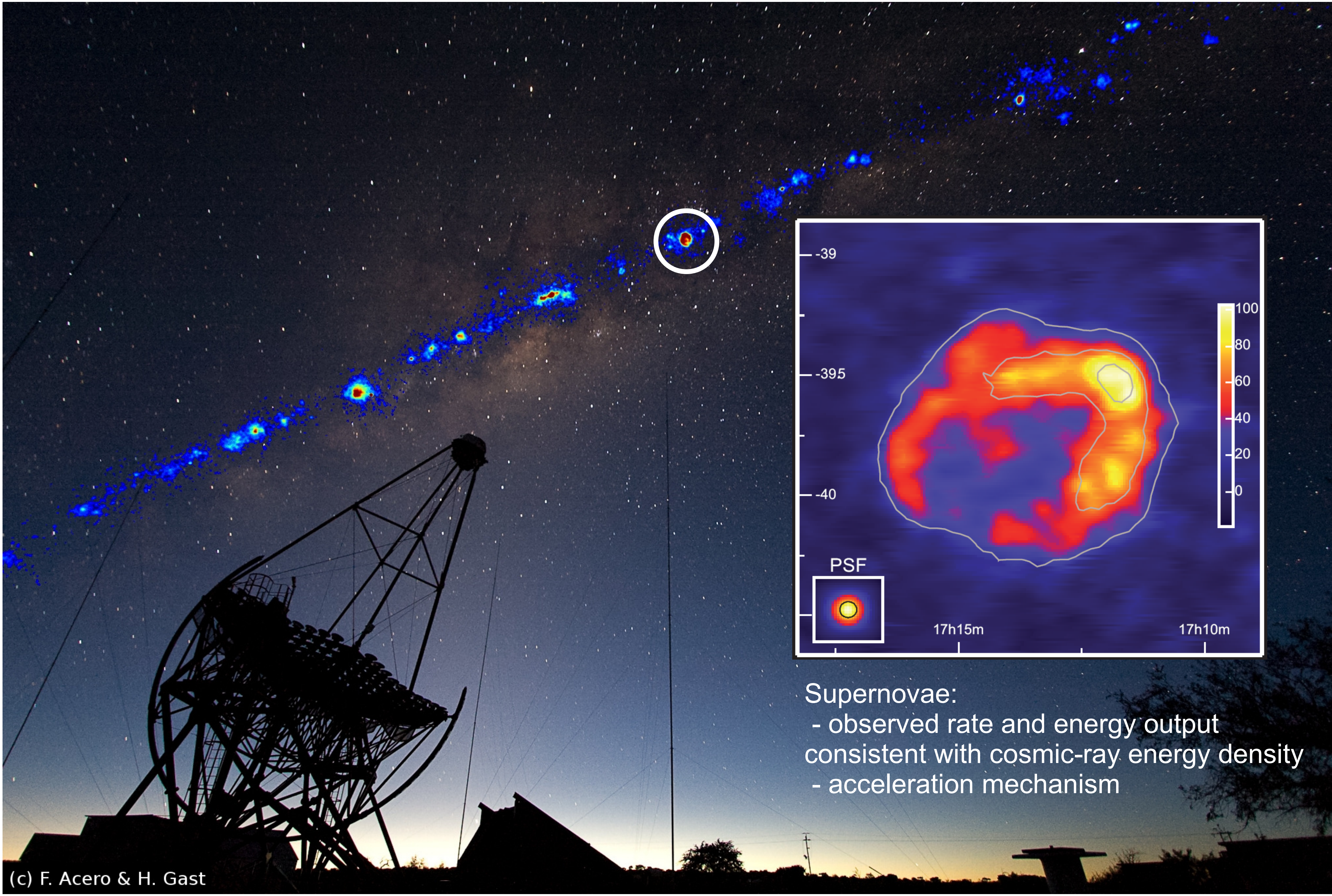


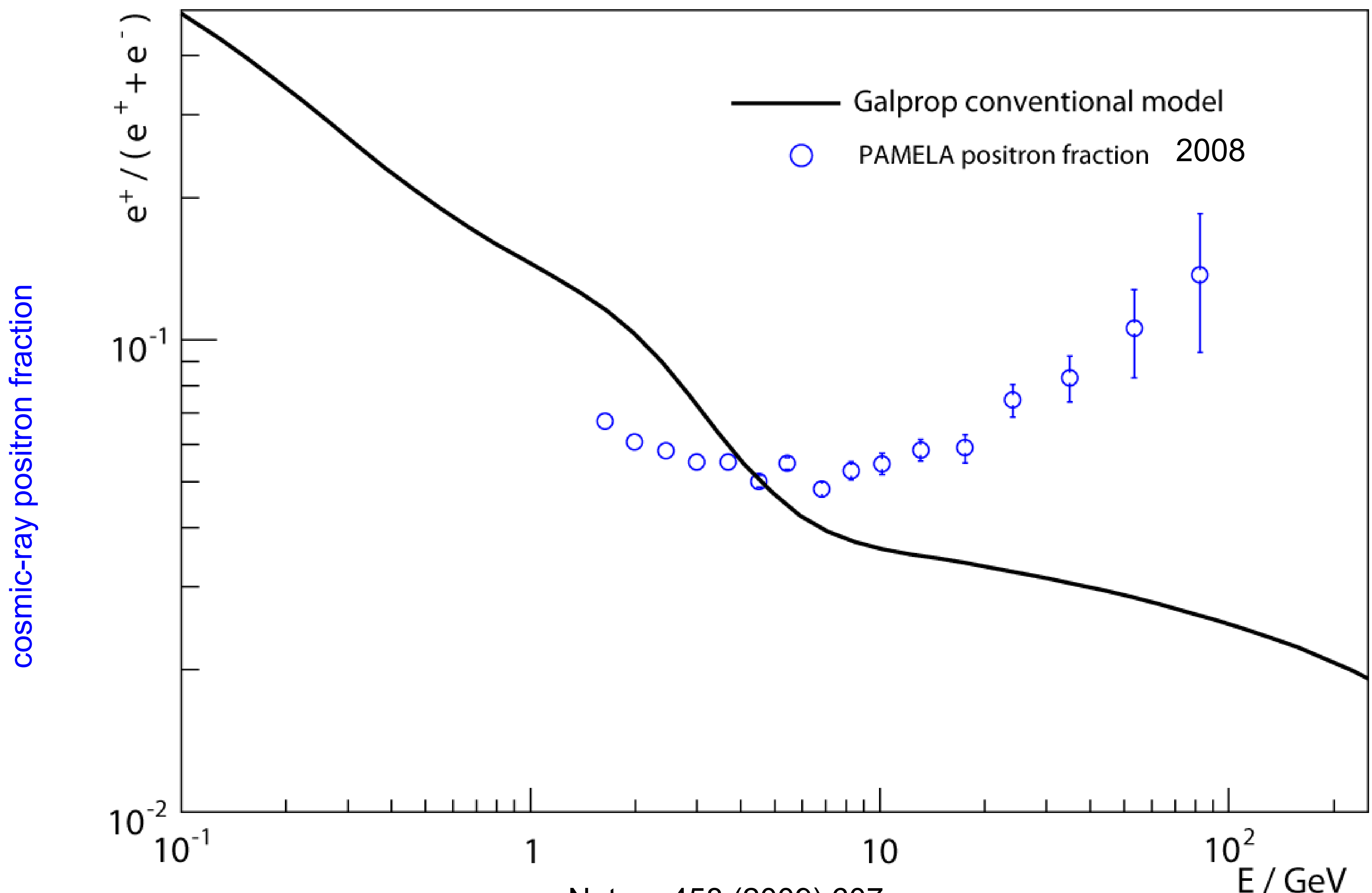
Image: GALEX, JPL-Caltech, NASA; Drawing: APS/Alan Stonebraker

Sources of cosmic rays



Supernovae:
- observed rate and energy output consistent with cosmic-ray energy density
- acceleration mechanism

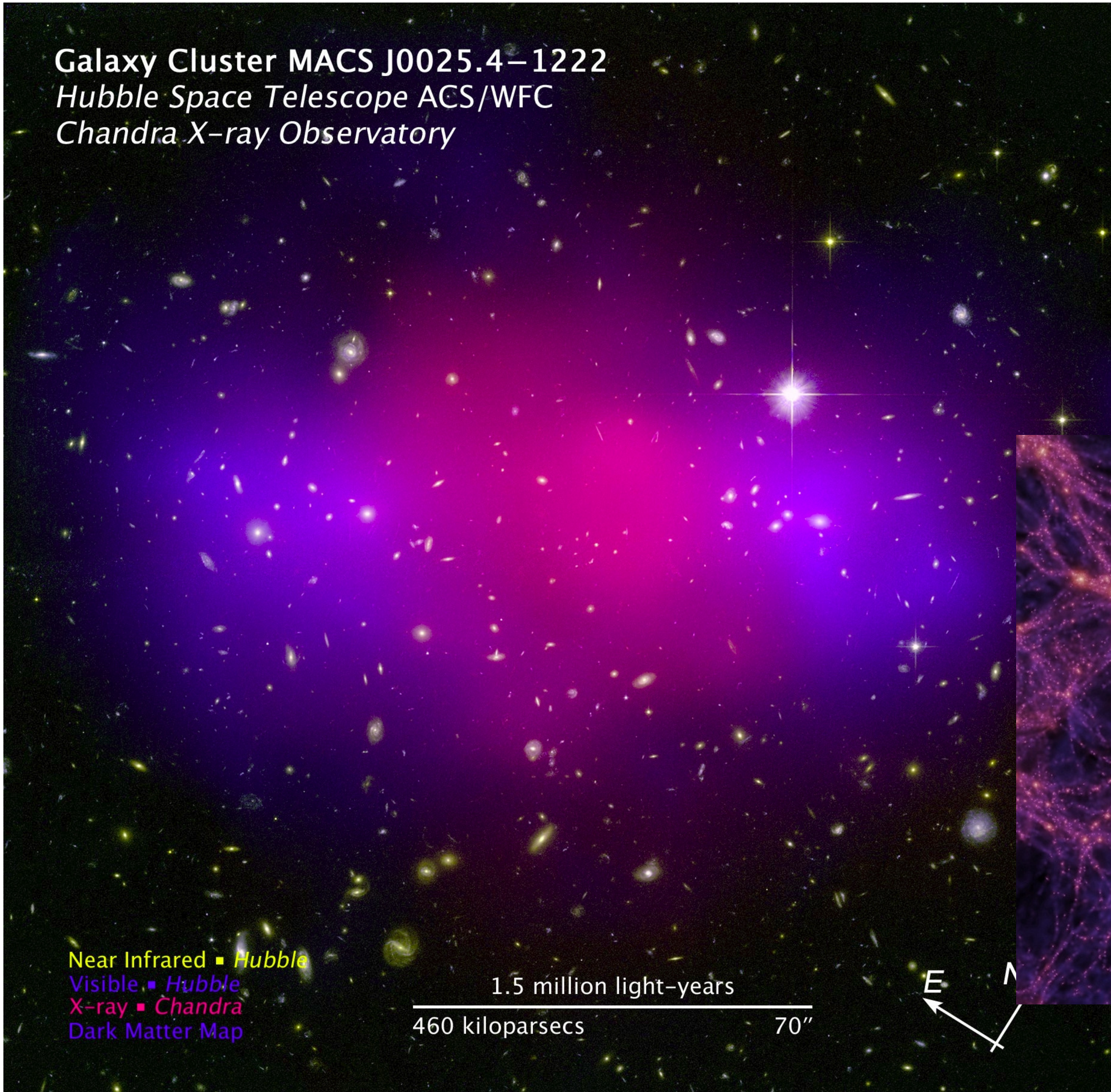
Positron fraction: Exotic sources of cosmic rays?

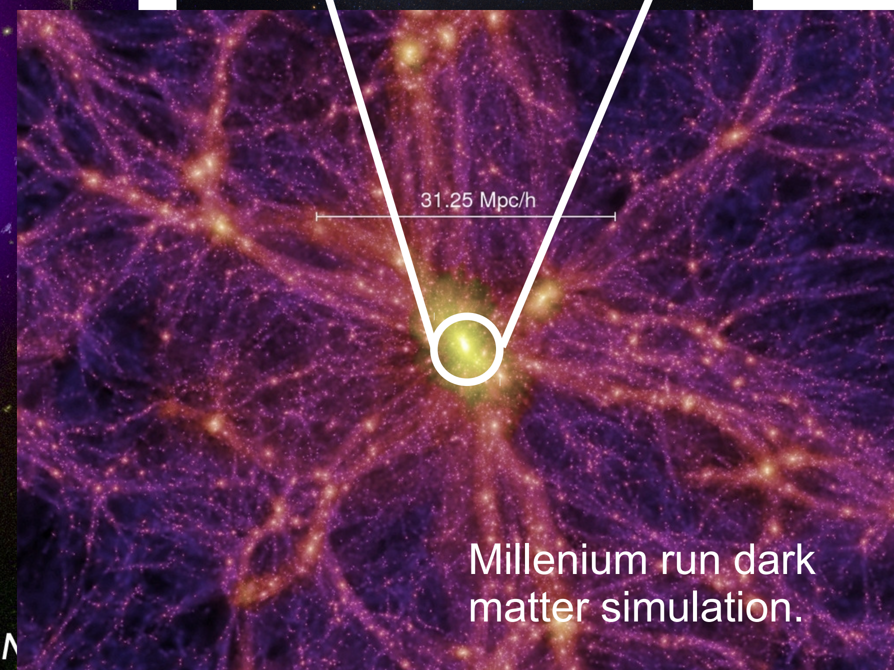


Nature 458 (2009) 607

AMS-02 physics

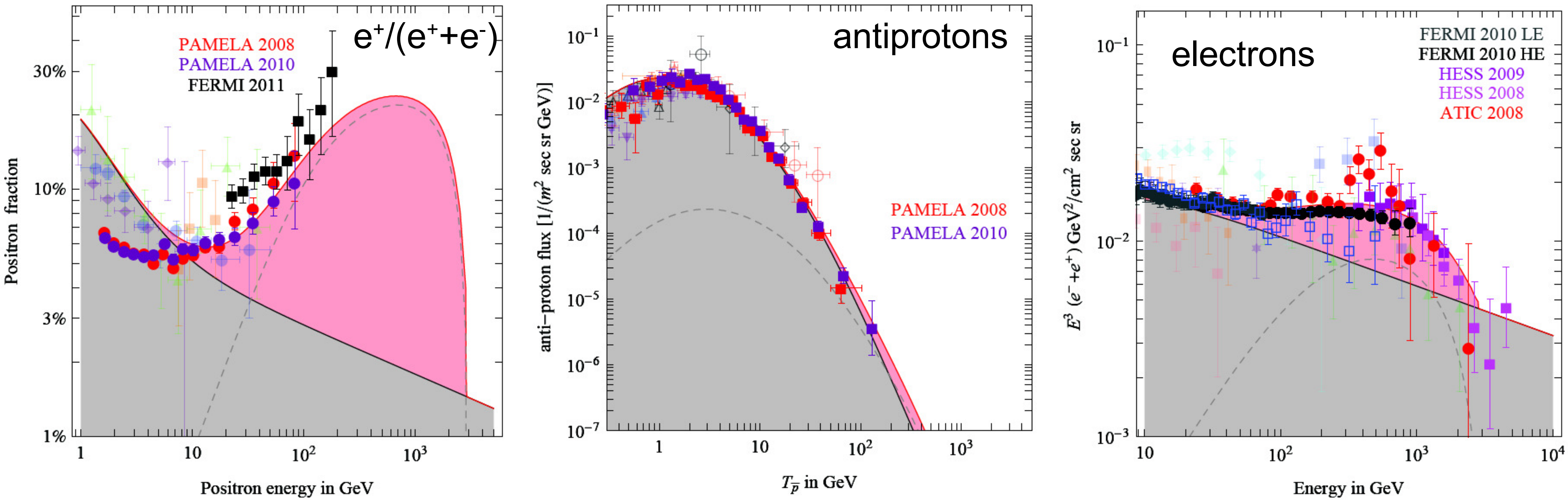
- Exotic sources? Example: Indirect search for dark matter.





Indirect search for dark matter

M. Cirelli, arXiv: 1202.1454



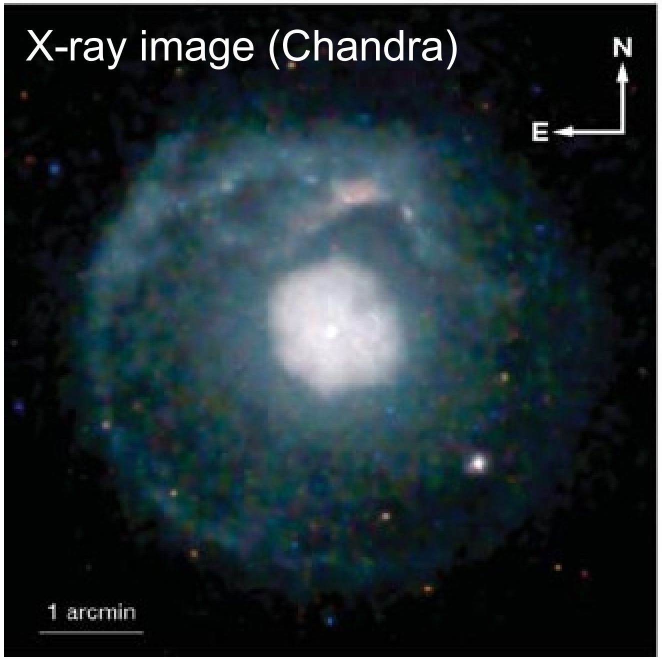
Example fits: 3 TeV DM particle annihilating to $\tau^+\tau^-$, with a cross section of $2 \cdot 10^{-22}$ cm^3/s

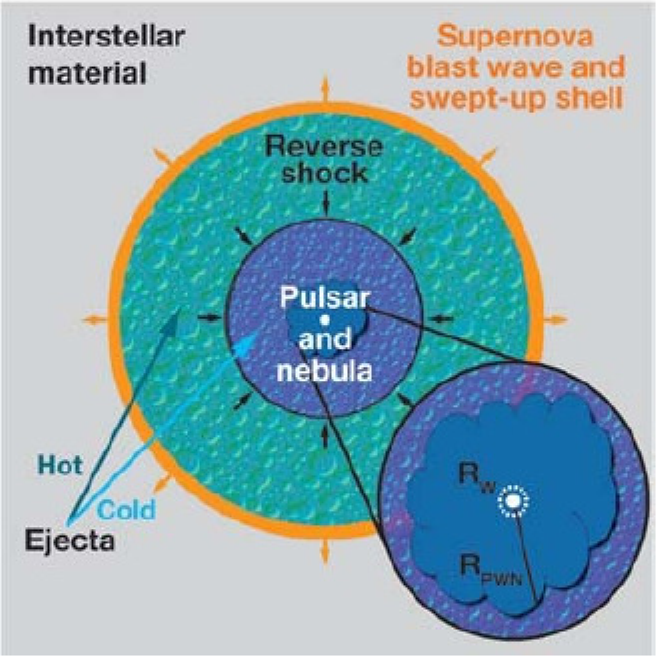
Interpreting antimatter and electron spectra in terms of dark matter requires:

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

Astrophysical sources for positrons

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





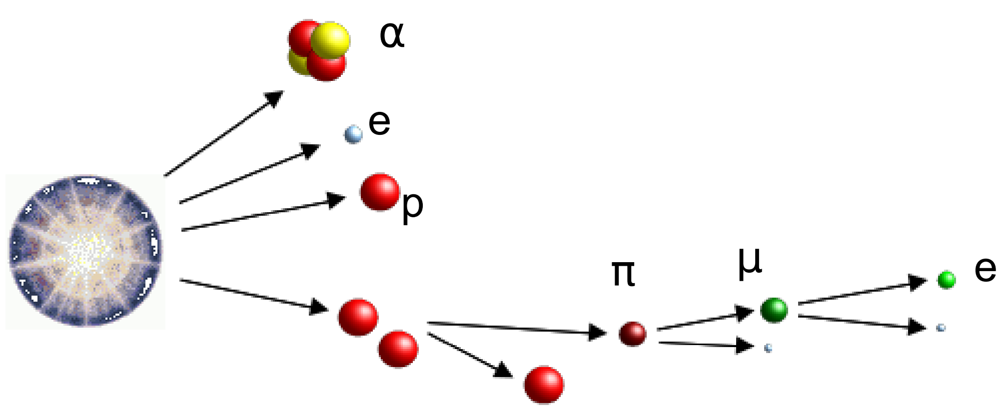
Gaensler & Slane 2006

Cosmic-ray propagation

$$\frac{\partial \psi}{\partial t} = q(\vec{r}, t) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left(\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right) - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$

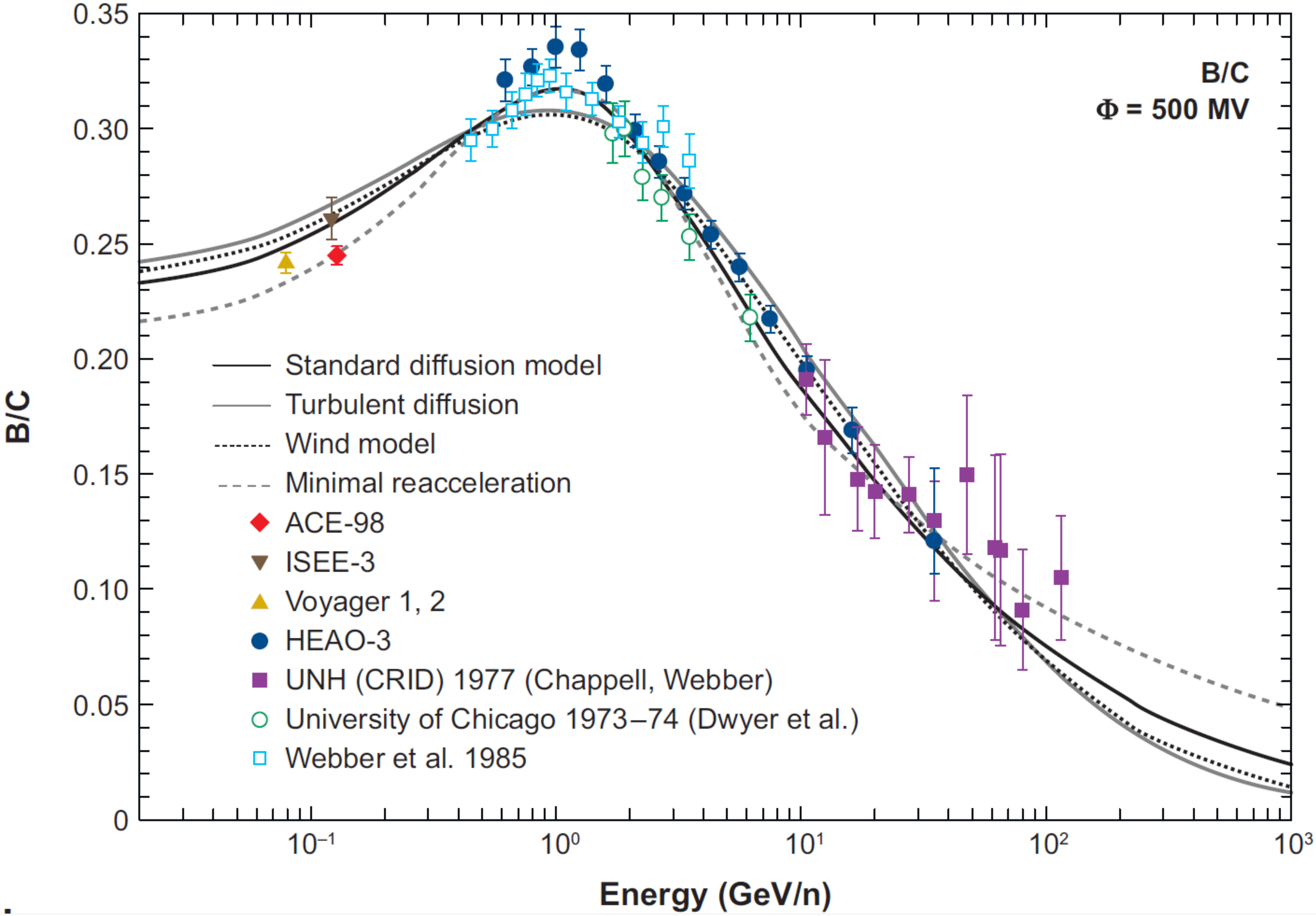
source term, diffusion, convection, diffusive reacceleration, energy losses, fragmentation, decay

- Equation for CR density, $\mathit{flux}\ F = \frac{c}{4\pi} \psi$
- Equations for different species are coupled: fragmentation of one species yields source of another, e.g. C → B ("secondary production").
- Energy losses for electrons: mainly inverse Compton scattering and synchrotron radiation.
- Diffusion coefficient $D_{xx} \sim 4 \times 10^{28}$ cm²/s and increases with momentum as $p^{0.3-0.6}$
- Numerical solution: *Galprop* code.



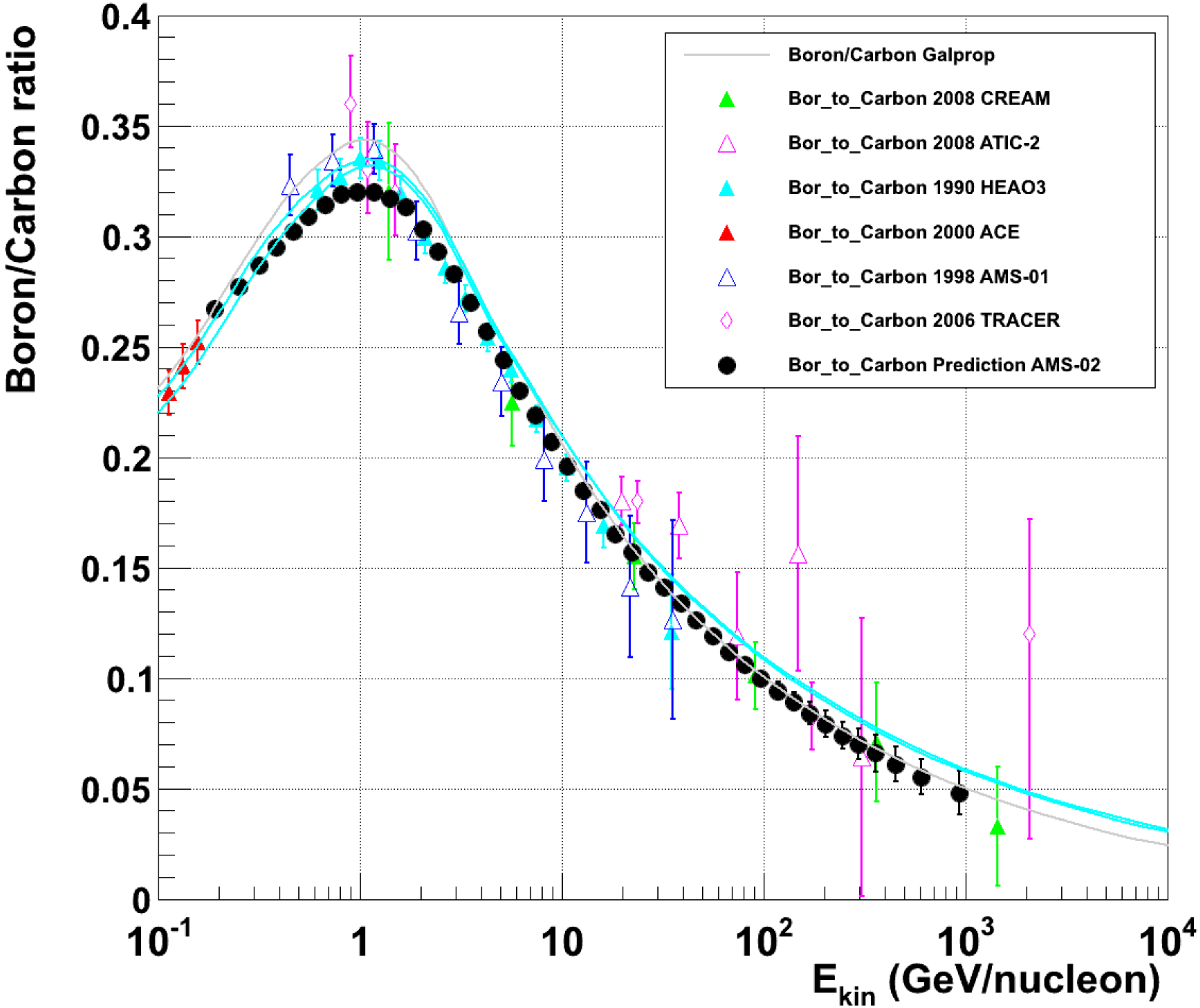
AMS-02 physics

- Propagation of cosmic rays.



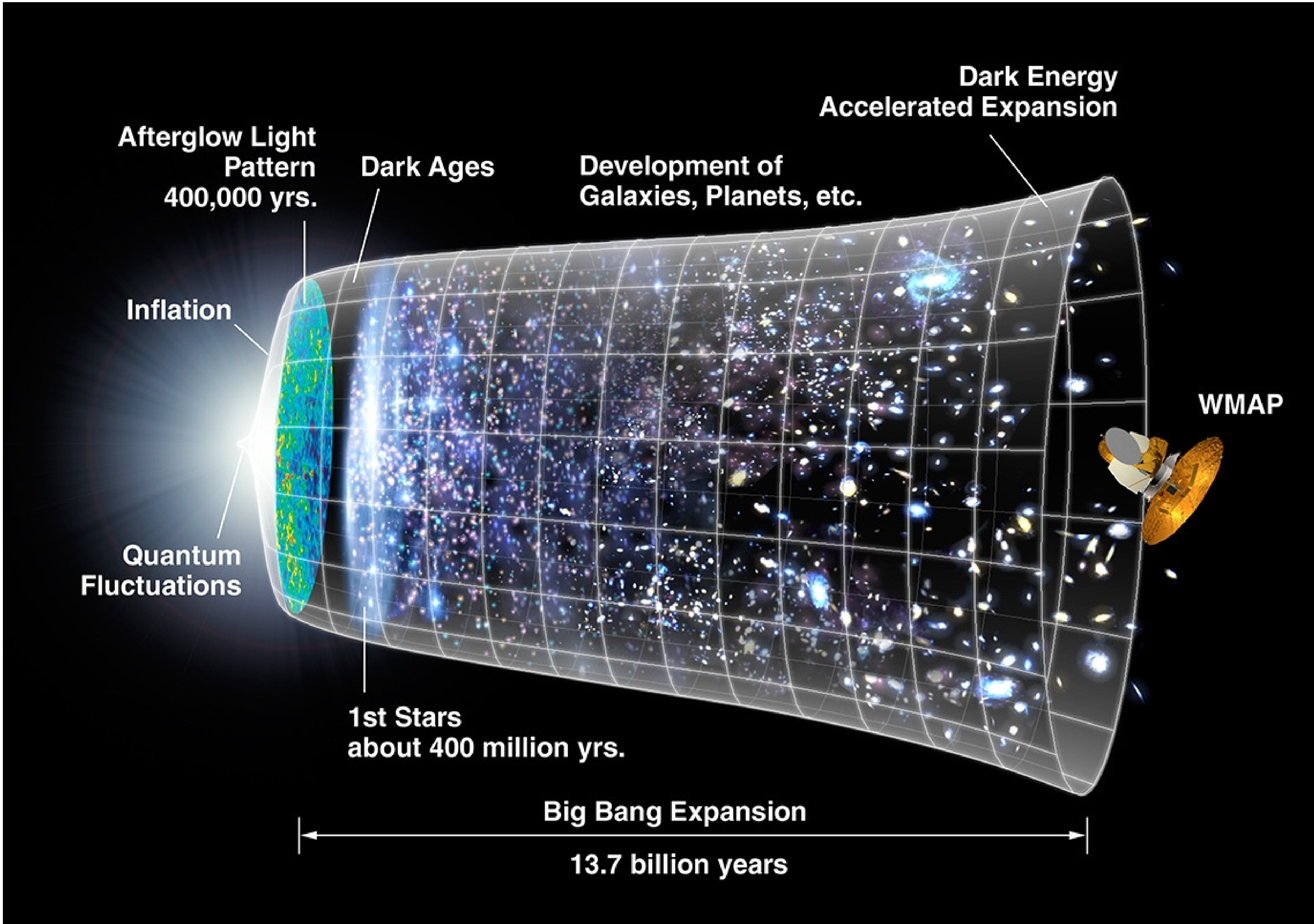
AMS-02 physics

- Propagation of cosmic rays.



AMS-02 physics

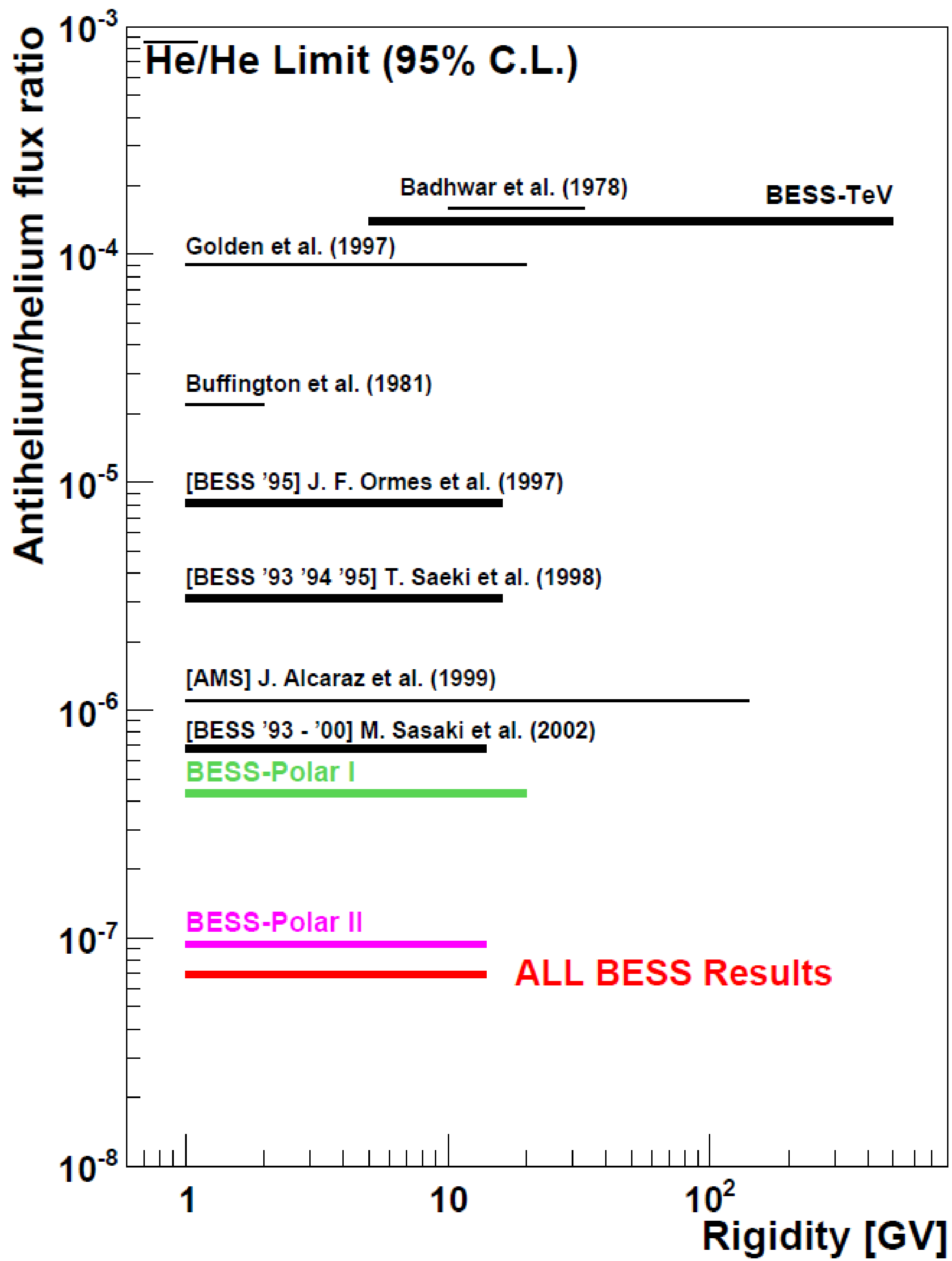
- Anti-nuclei from anti-galaxies?



Limits on anti-Helium

- Limit on anti-Helium fraction from BESS and BESS-polar data (1-20 GeV): 6.9 x 10^{-8} at 95% CL assuming anti-He to have same spectral shape as He

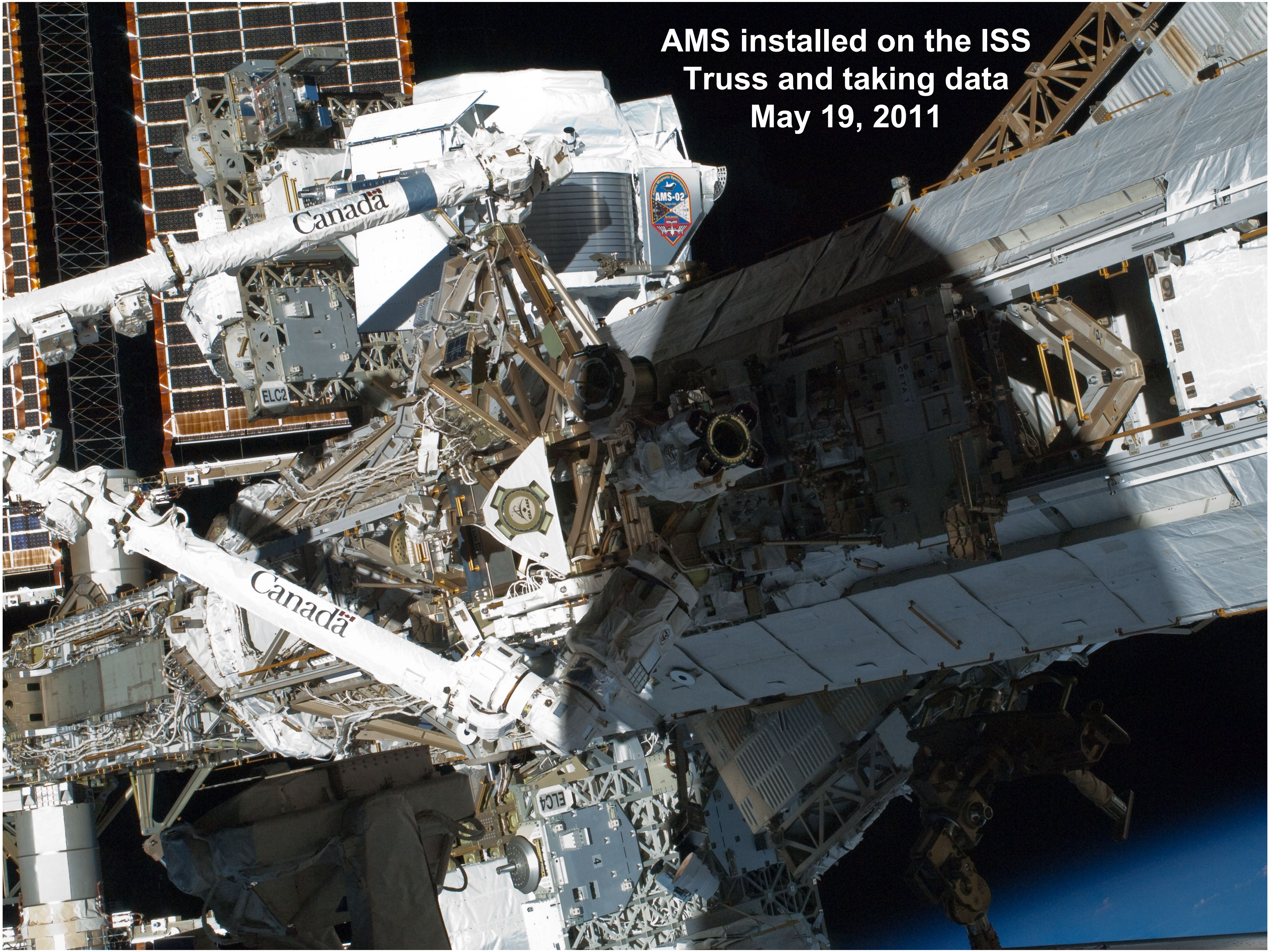
arXiv: 1201.2967




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

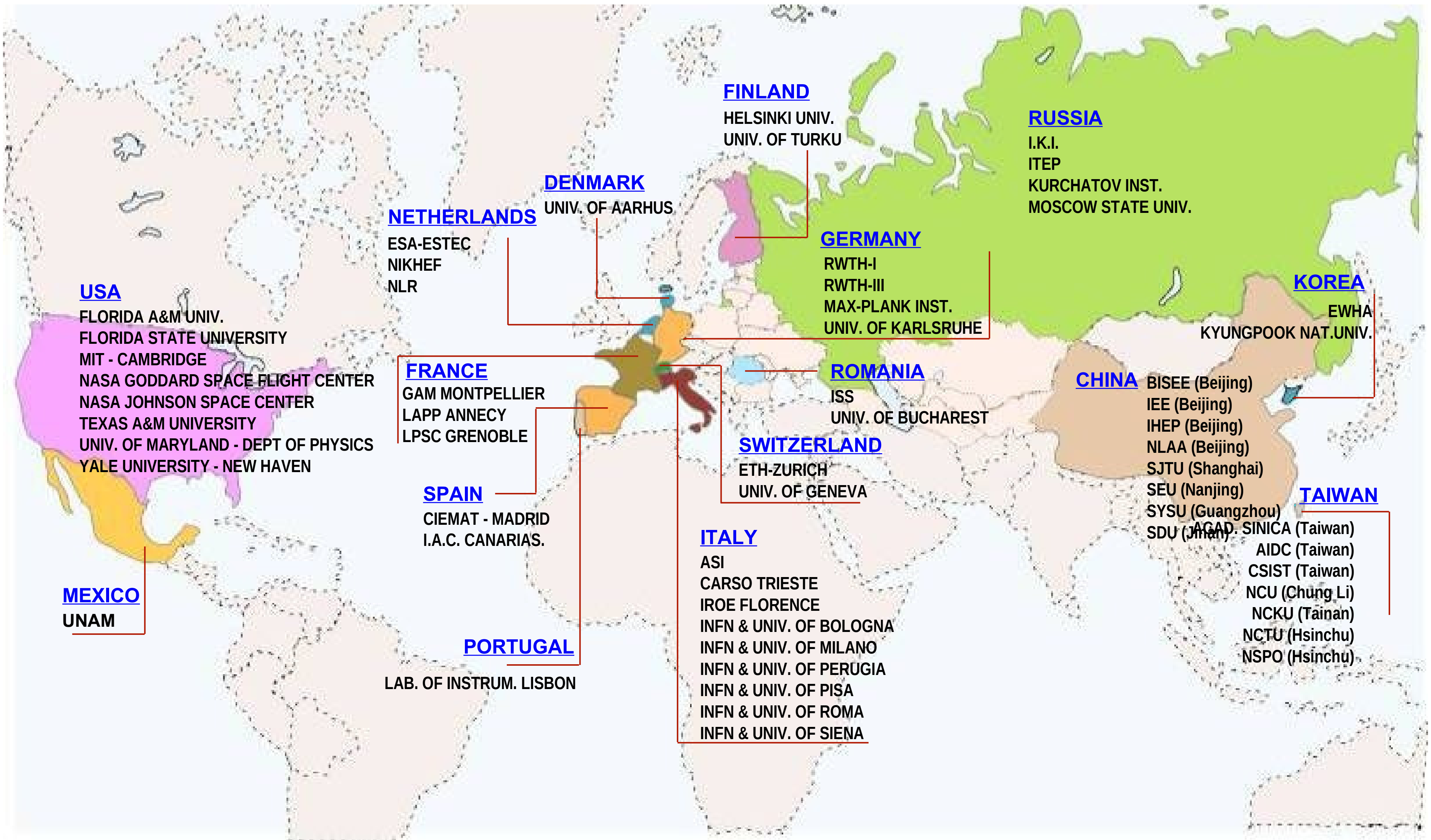
AMS-02 launch


Endeavour
AMS
Endeavour approaches the International Space Station


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

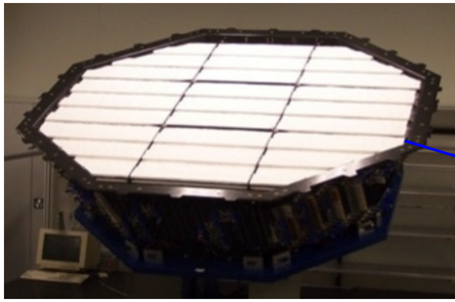
AMS-02 Collaboration

AMS is US Dept of Energy (DOE) led International Collaboration
16 Countries, 60 Institutes and 600 Physicists, 17 years

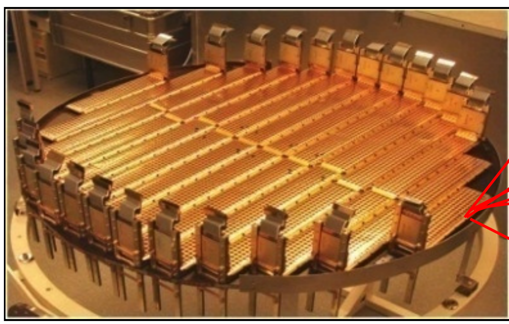


AMS-02 overview

TRD
Identify e+, e-

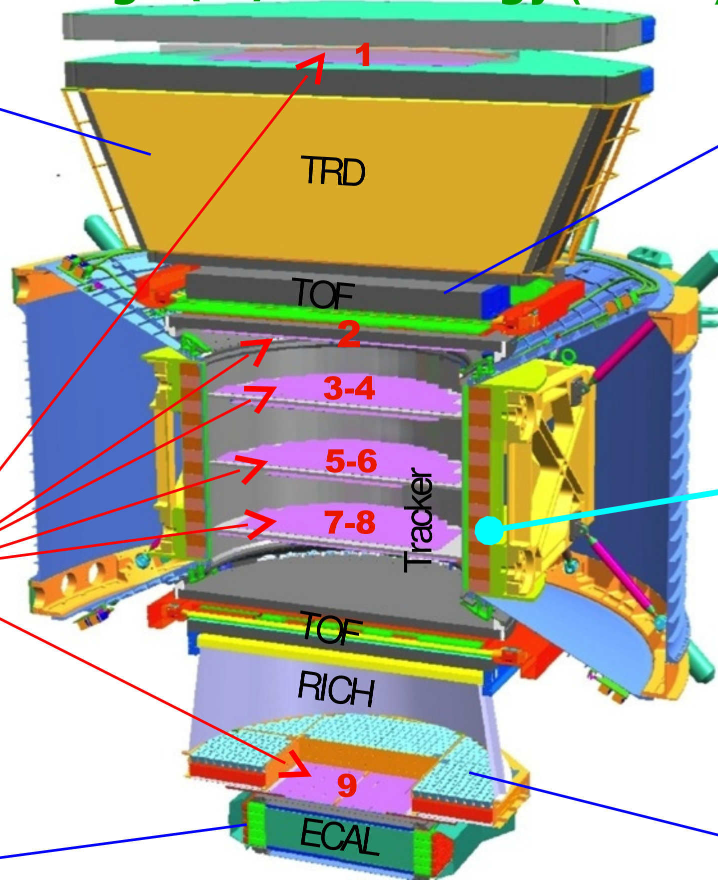


Silicon Tracker
Z, P

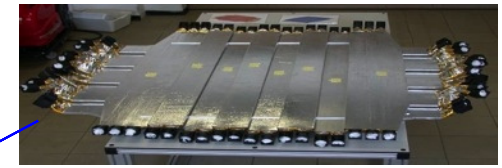


ECAL
E of e+, e-, γ

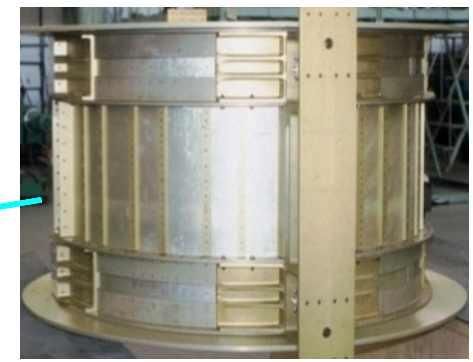
Particles and nuclei are defined by their charge (Z) and energy (E ~ P)



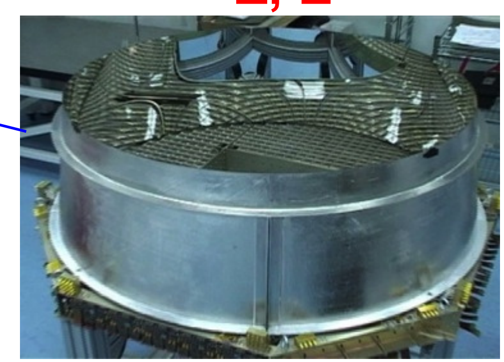
TOF
Z, E



Magnet
±Z



RICH
Z, E

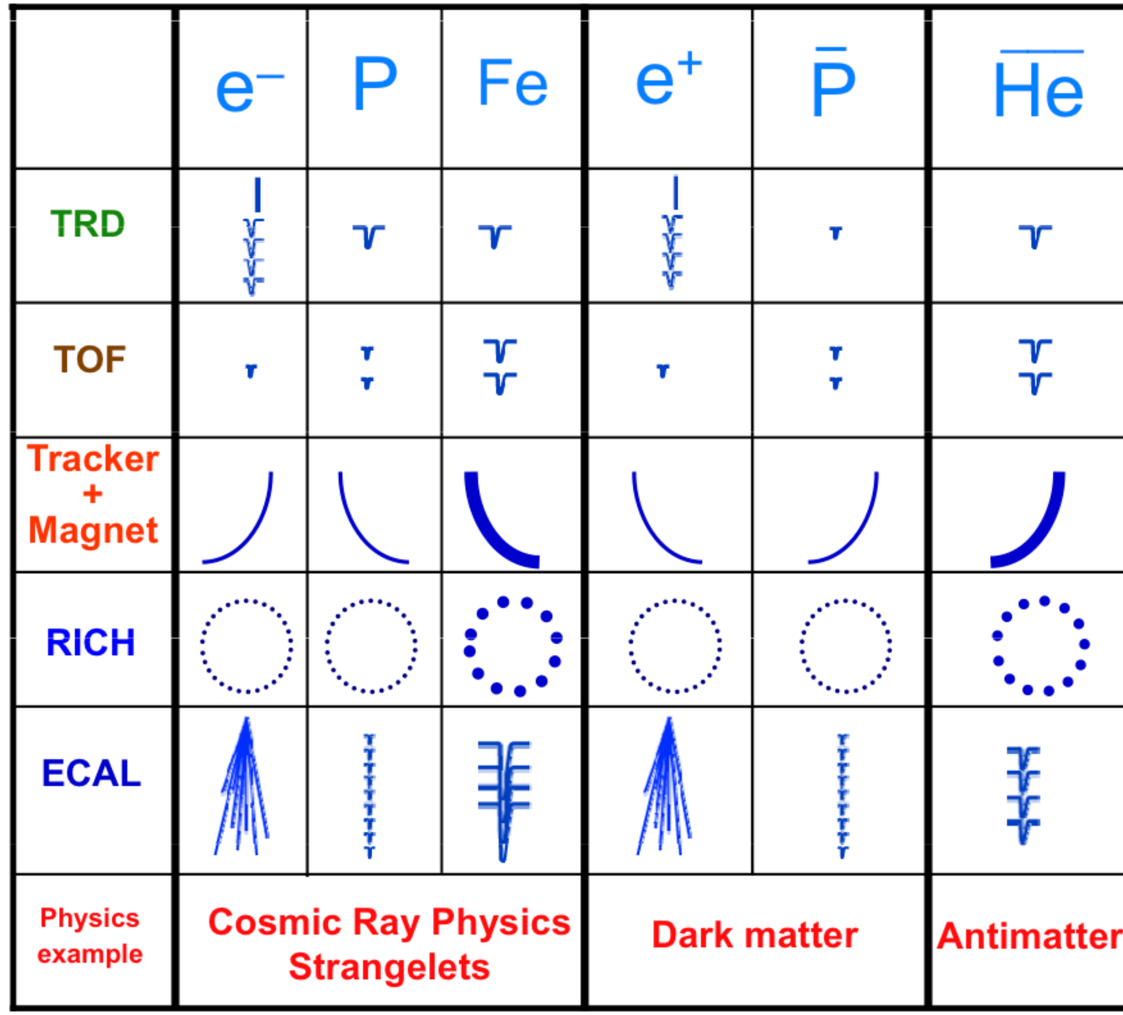


Z, P are measured independently by the Tracker, RICH, TOF and ECAL

weight: 8.5 tons, volume: 64 m^3

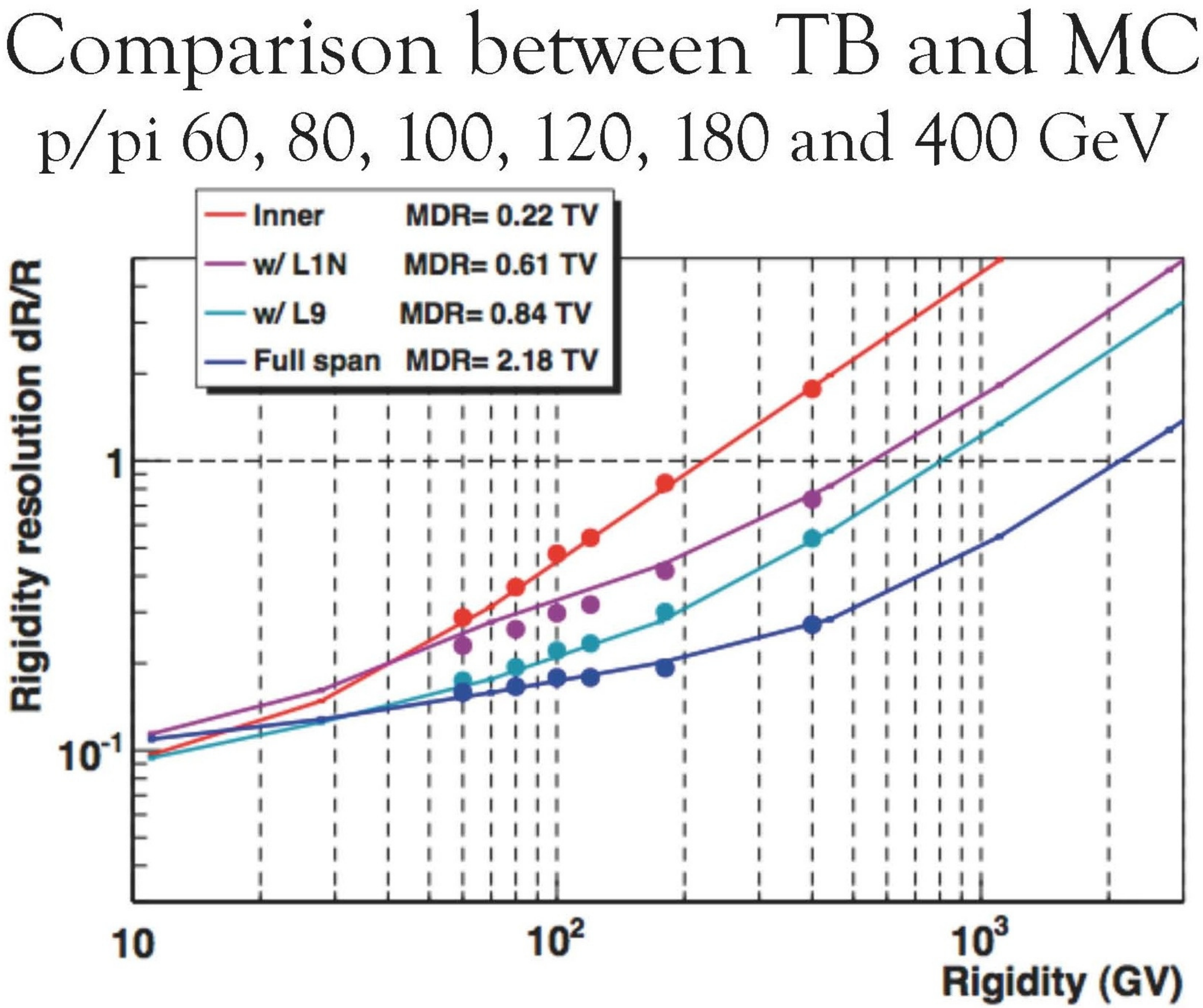
AMS-02 particle identification

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

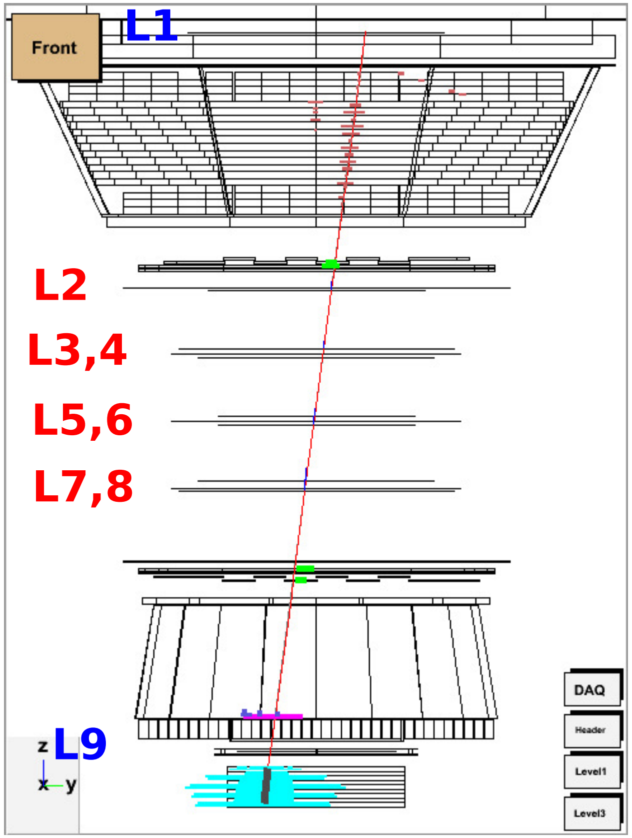


Cosmic rays are measured at up to 2 KHz and data is generated at ~7 Gbit/s, reduced on board to an average of ~10 Mbit/s.

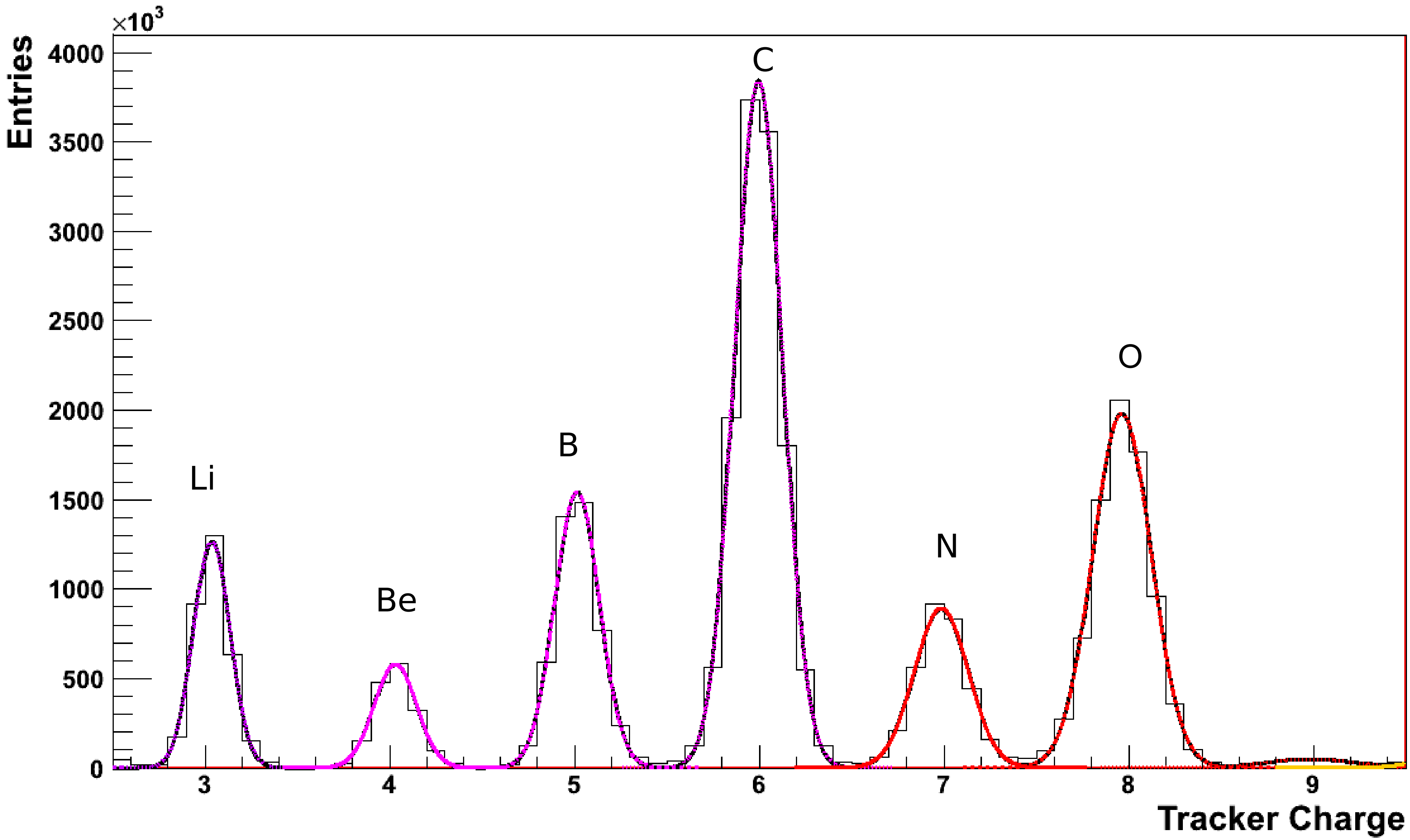
Tracker: Rigidity resolution



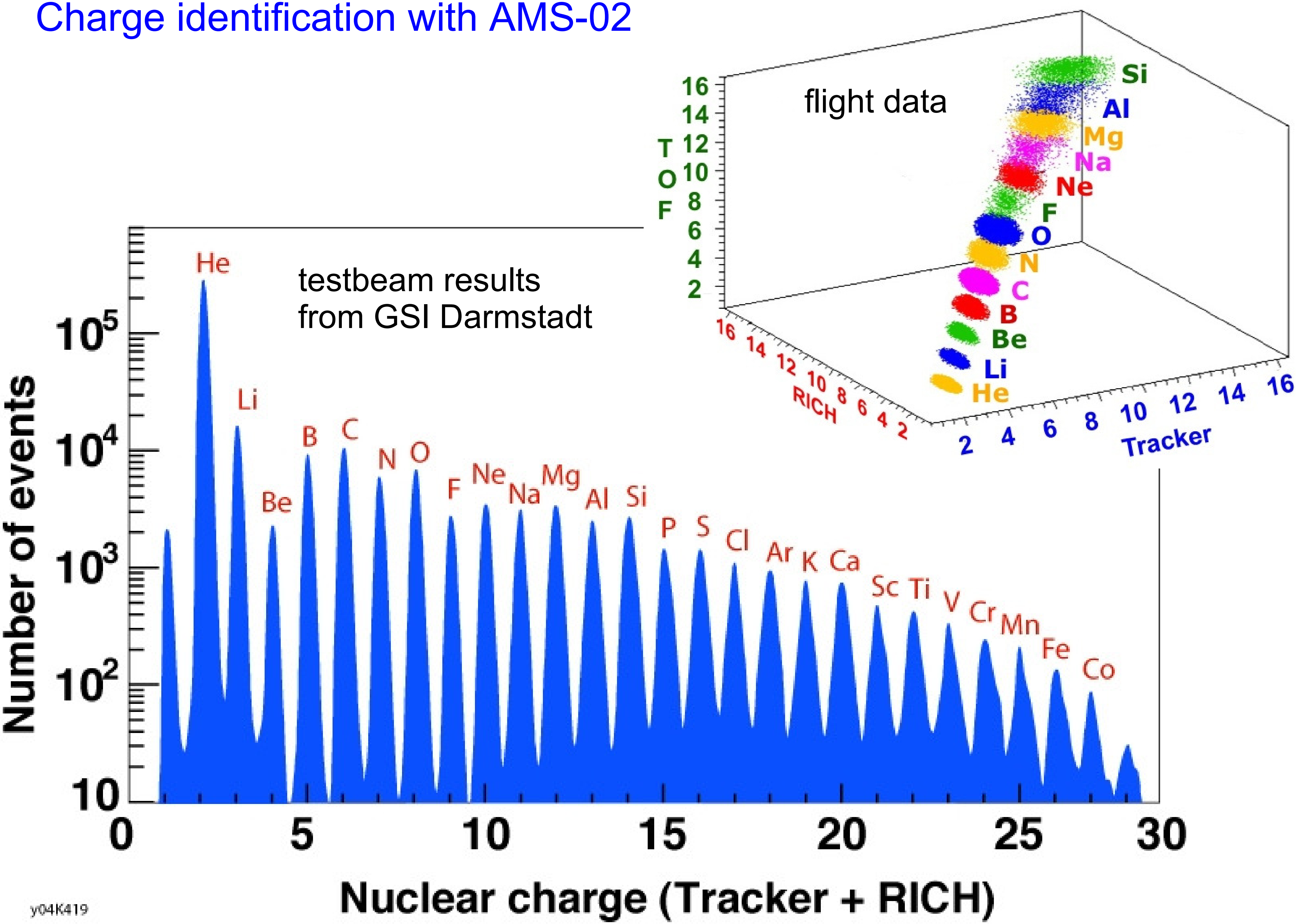
CERN beamtest data



Tracker: Charge measurement



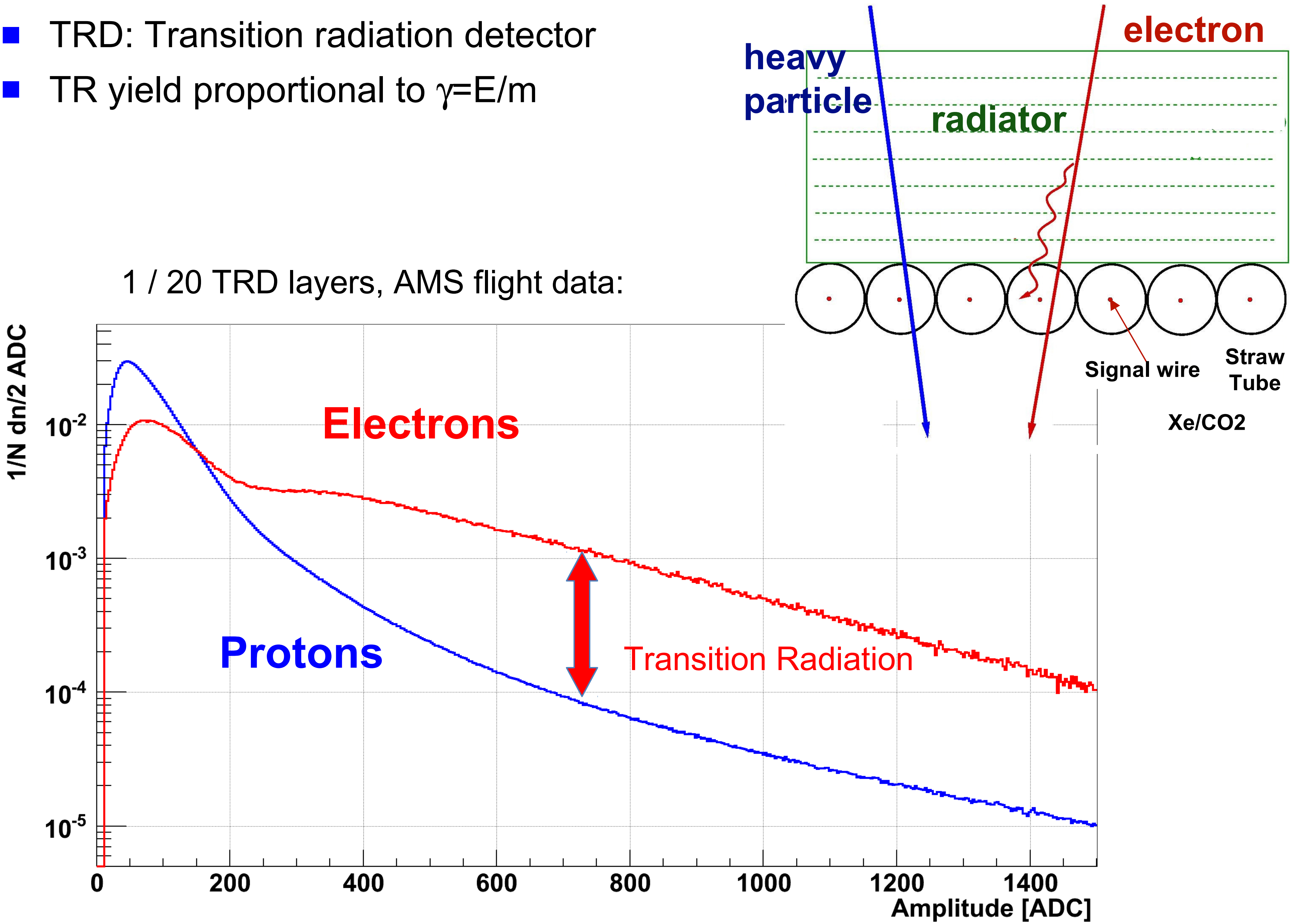
Charge identification with AMS-02



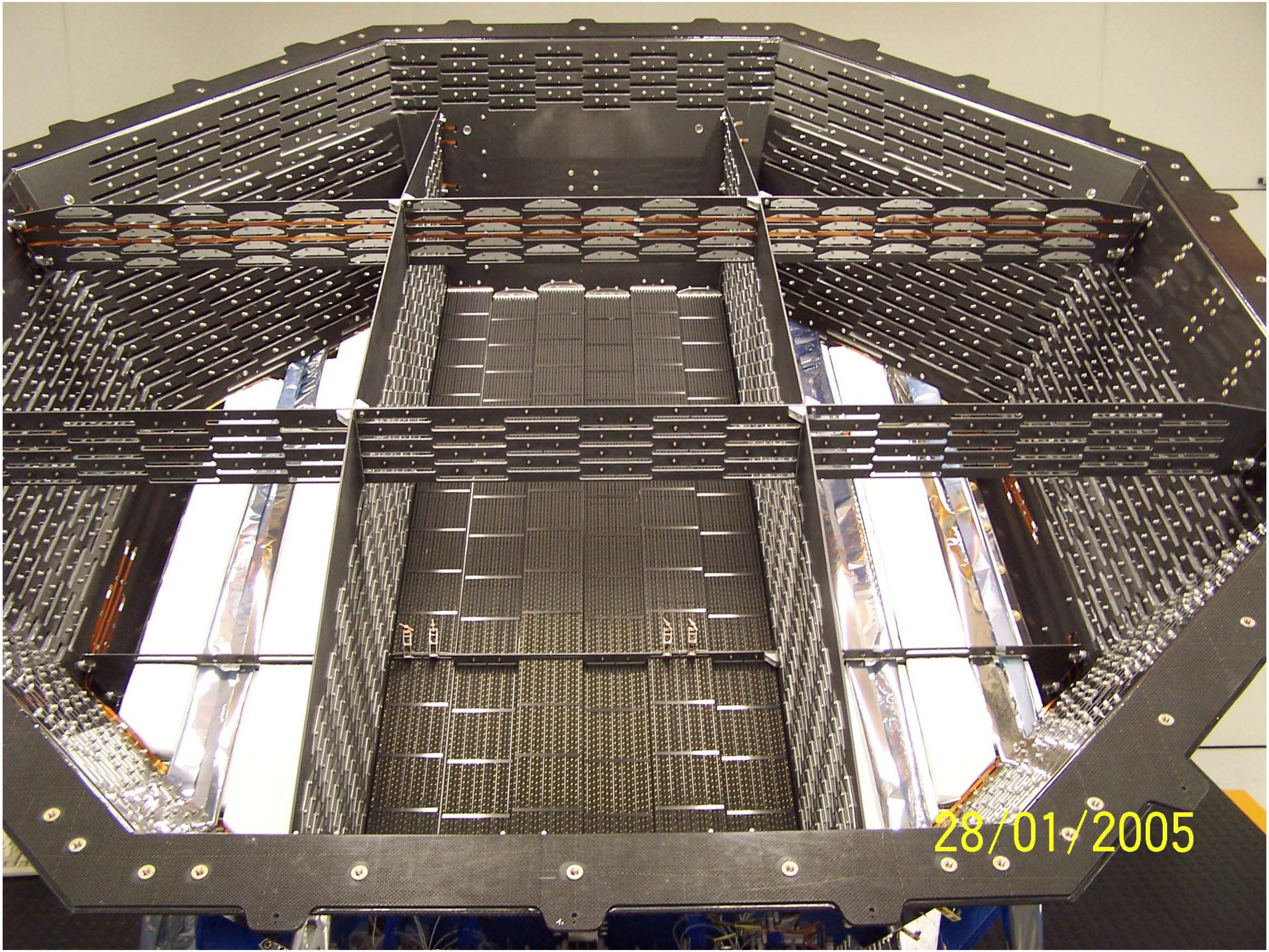
AMS-02 performance: TRD spectra

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

1 / 20 TRD layers, AMS flight data:



AMS-02 TRD developed and built in Aachen



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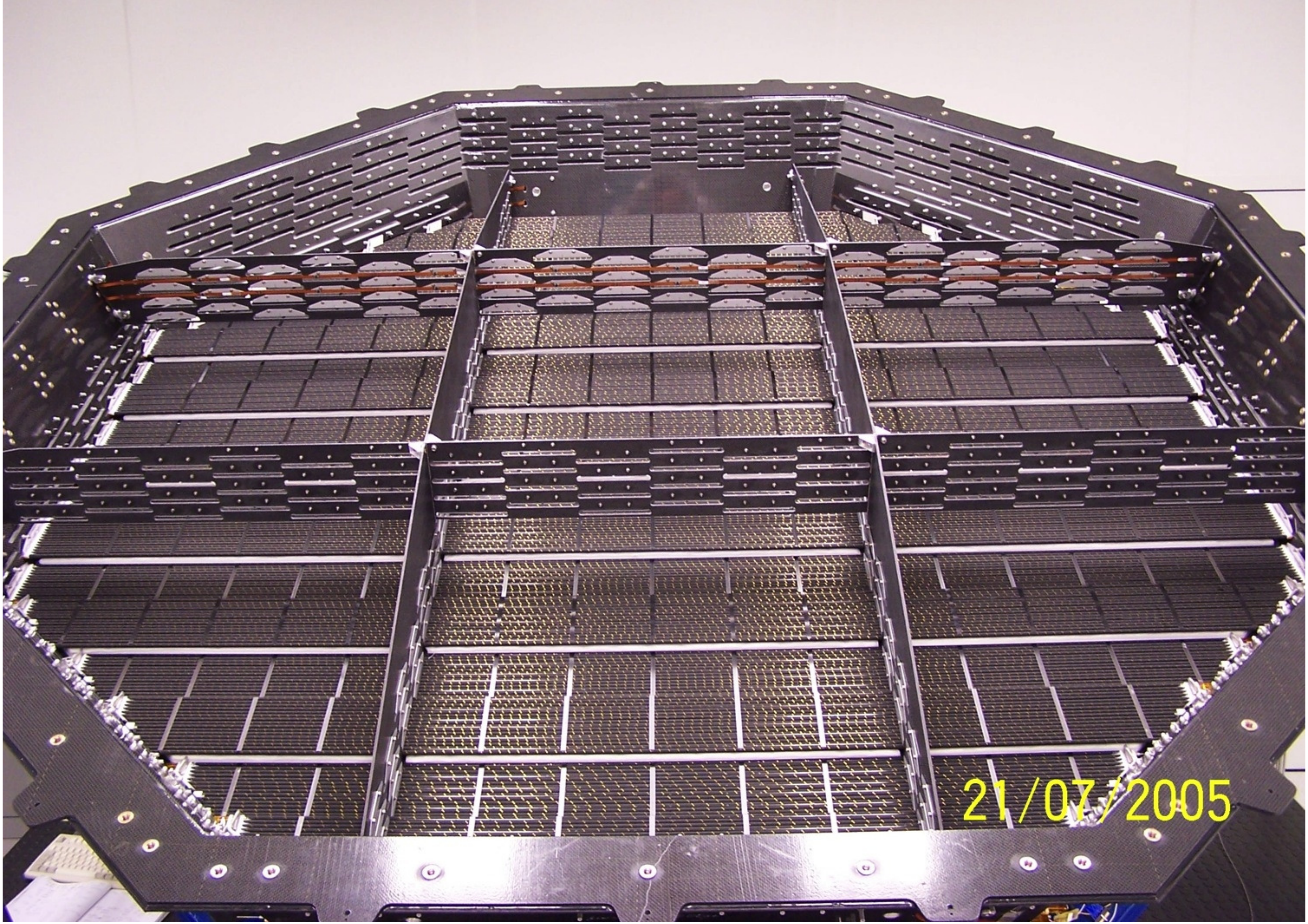
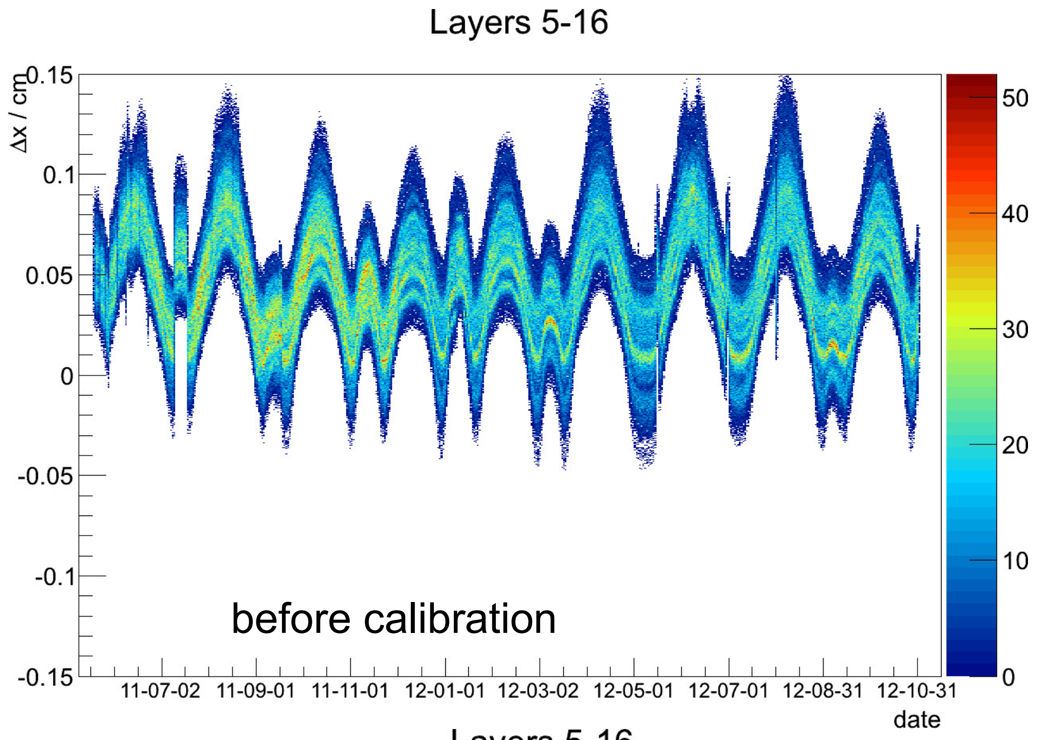
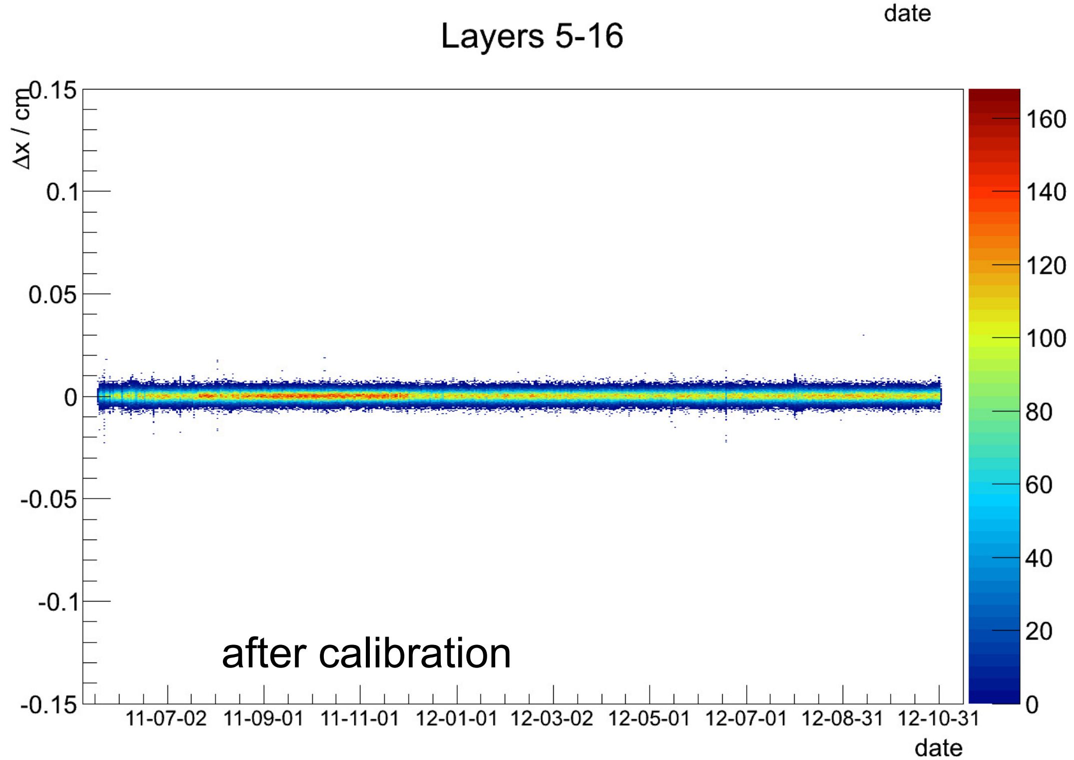
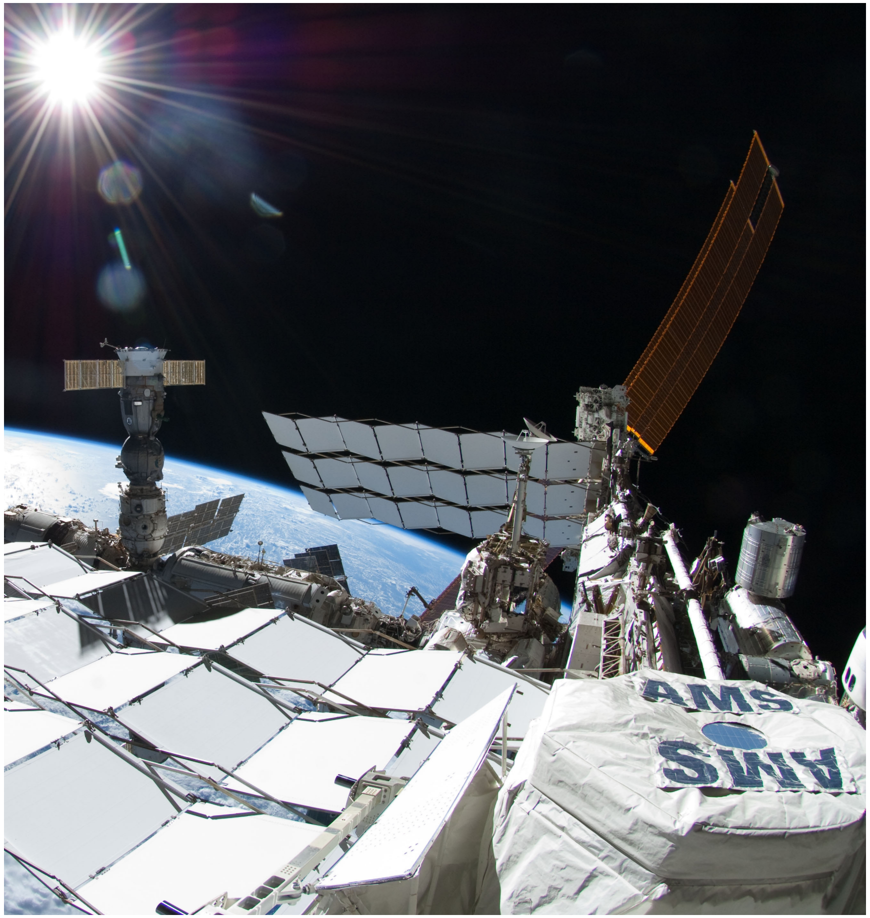


Alignment corrections

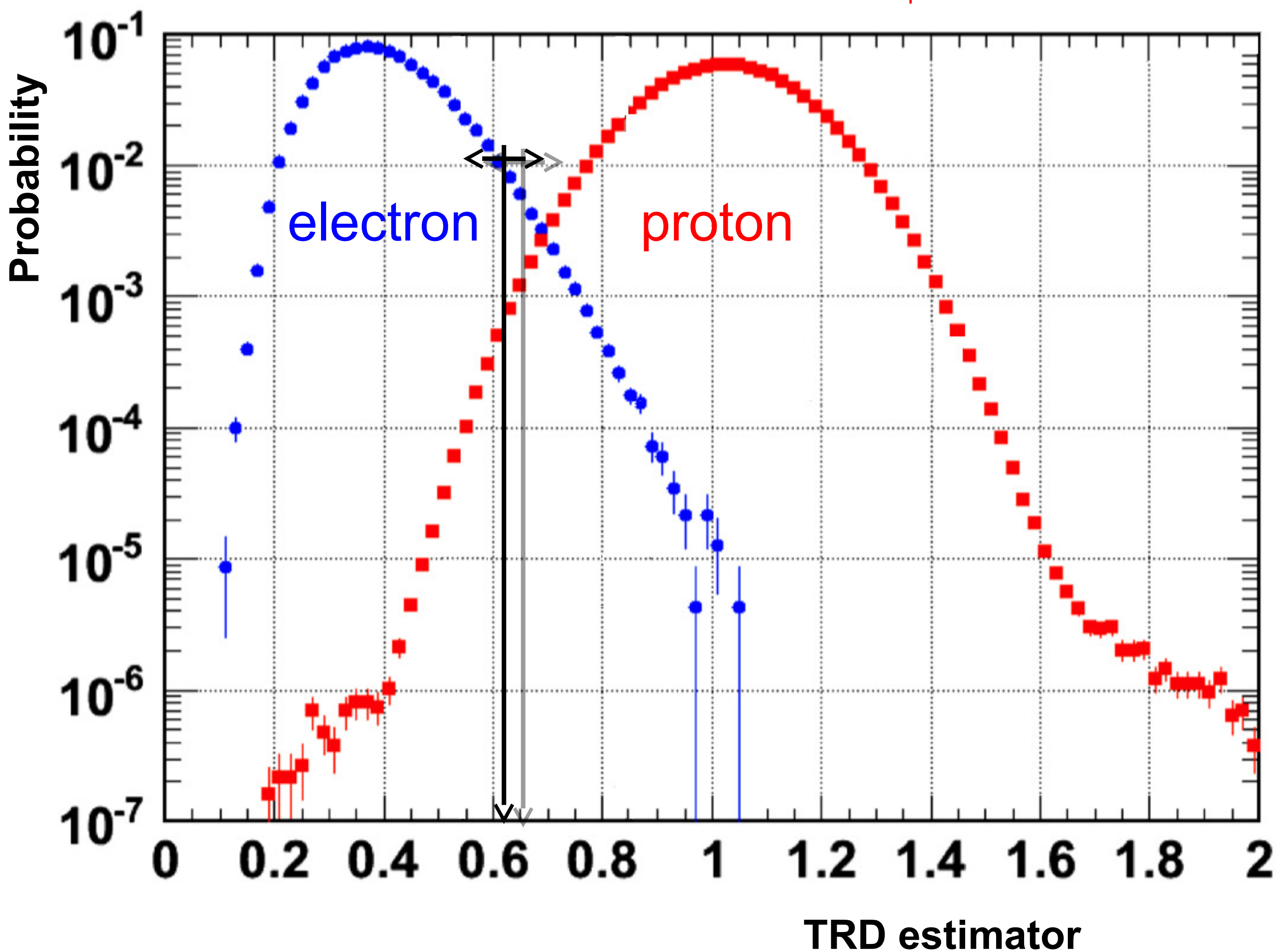






TRD electron-proton separation

TRD estimator = $-\ln(P_e/(P_e+P_p))$

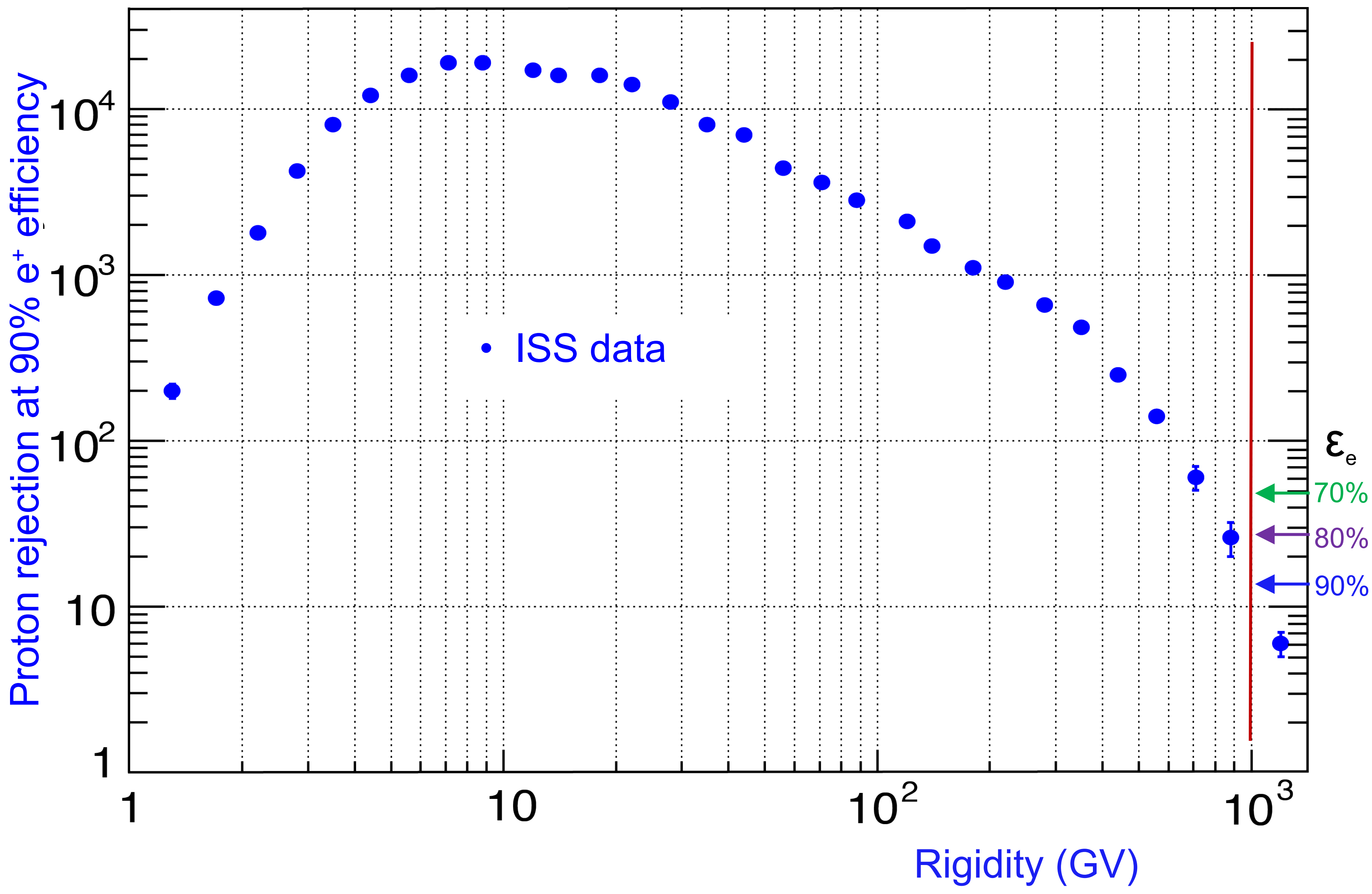


Normalized probabilities P_e and P_p

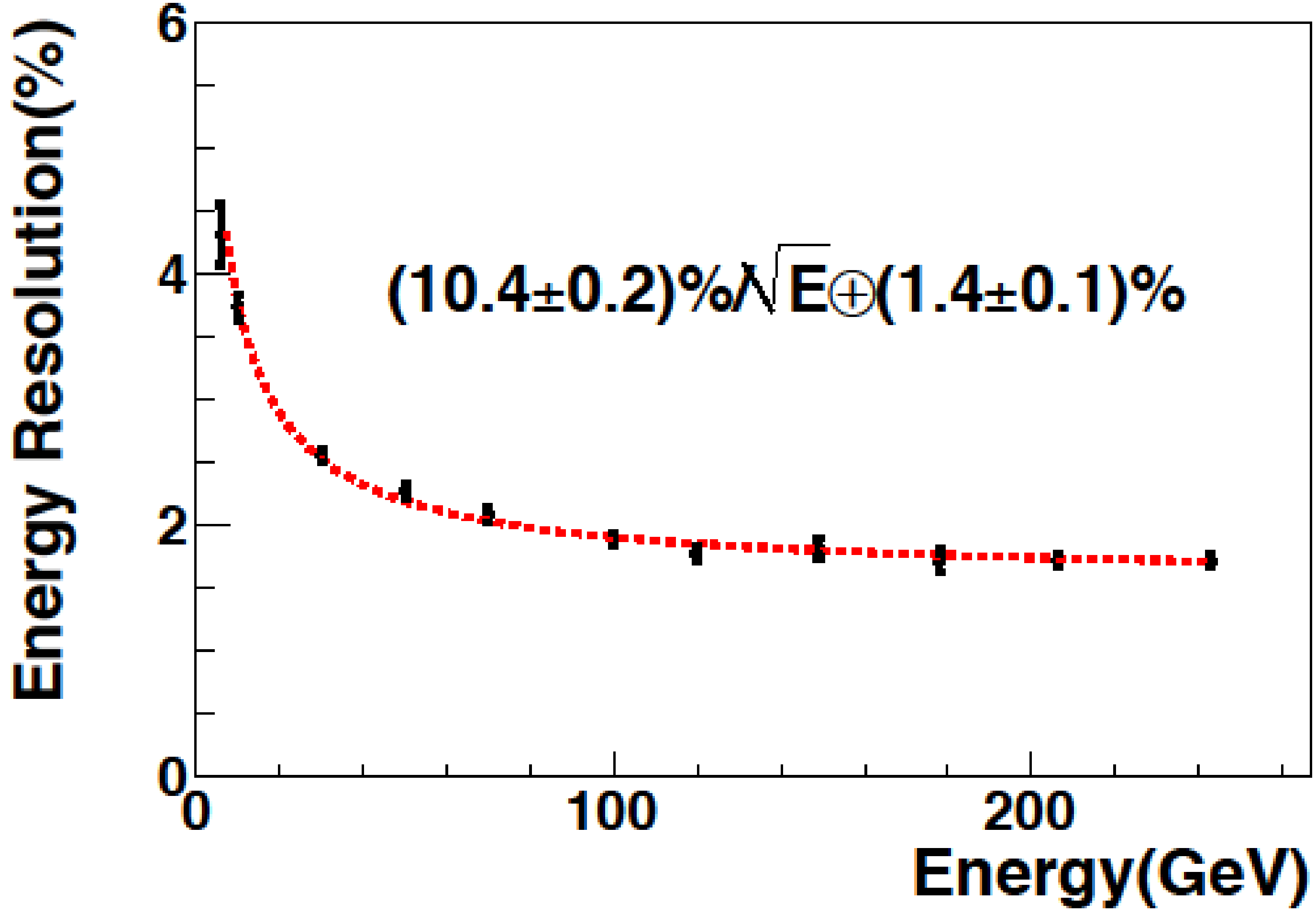
$$P_e = \sqrt[n]{\prod_i^n P_e^{(i)}(A)}$$

$$P_p = \sqrt[n]{\prod_i^n P_p^{(i)}(A)}$$

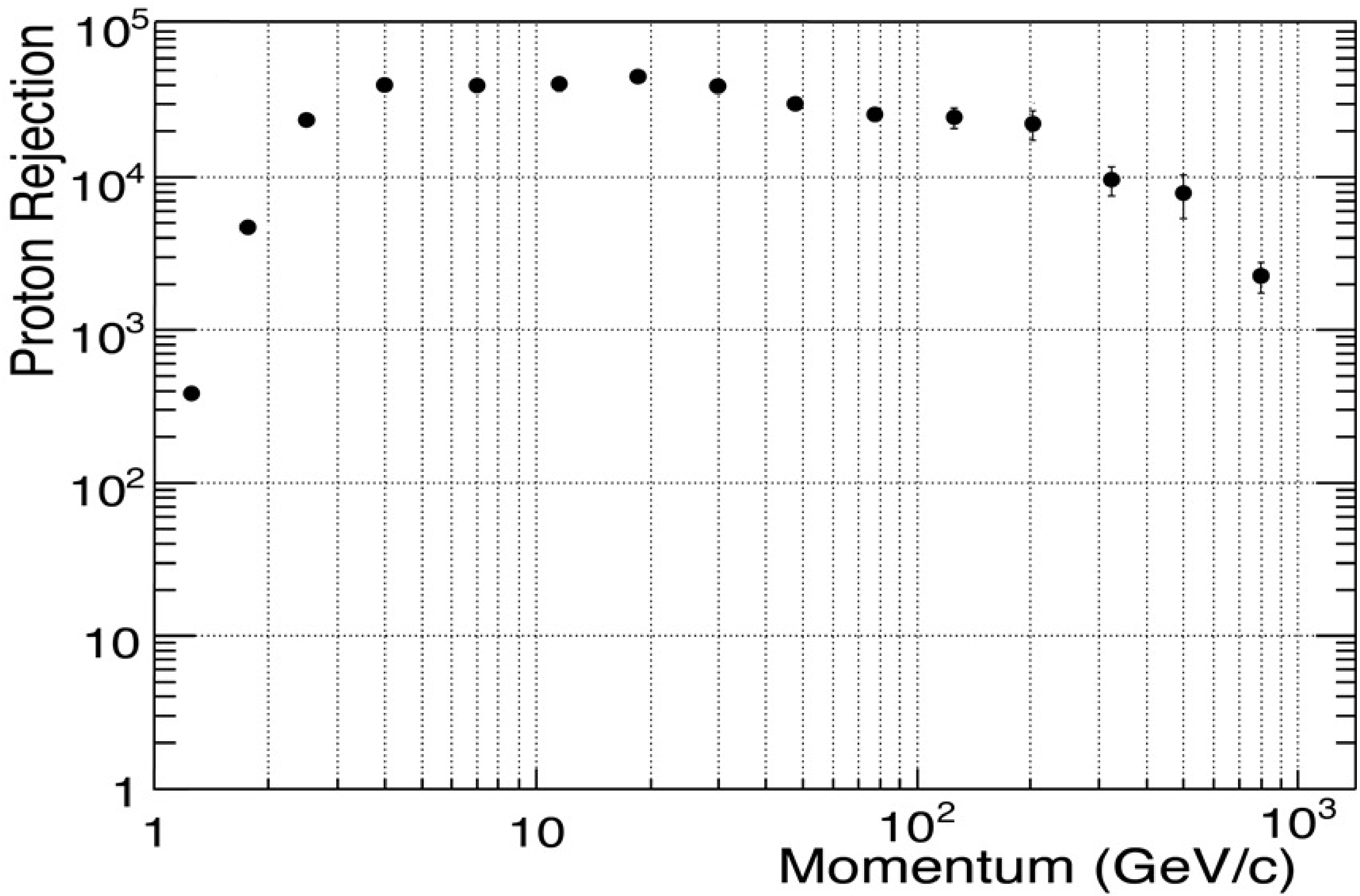
TRD performance on ISS



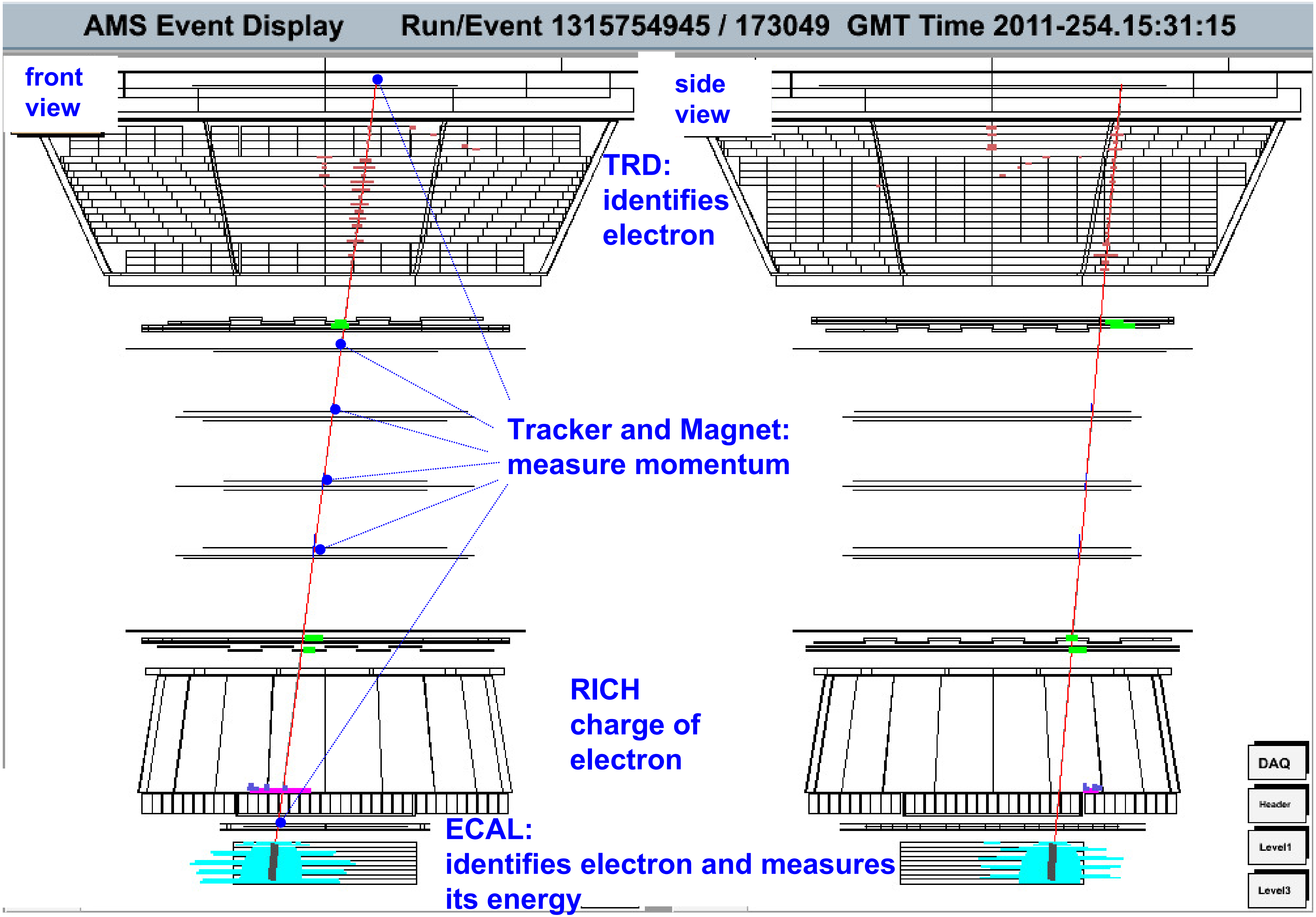
ECAL: energy resolution

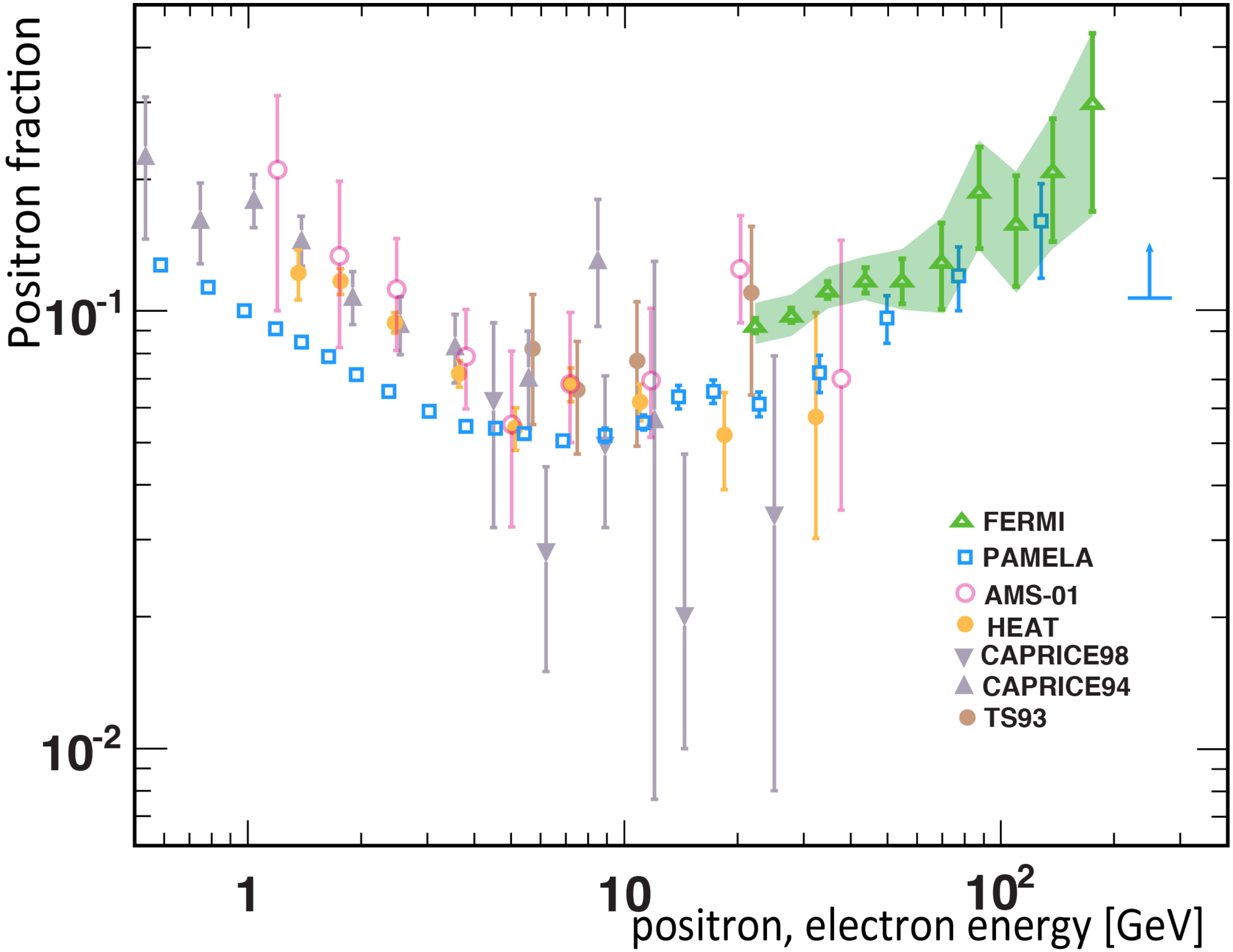


ECAL: proton rejection power



1.03 TeV electron



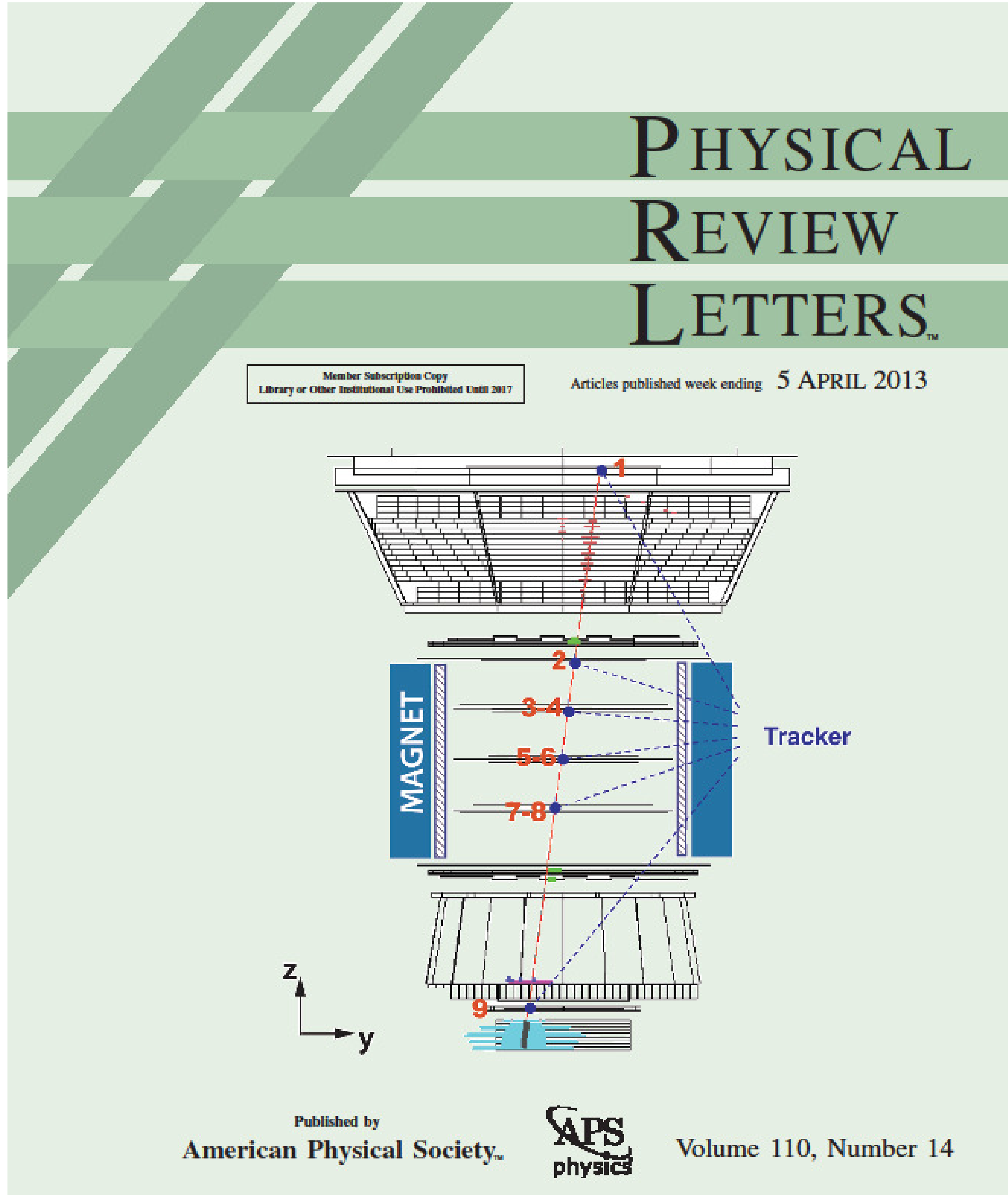


Over the first eighteen months of operations in space, AMS has collected over 25 billion events.

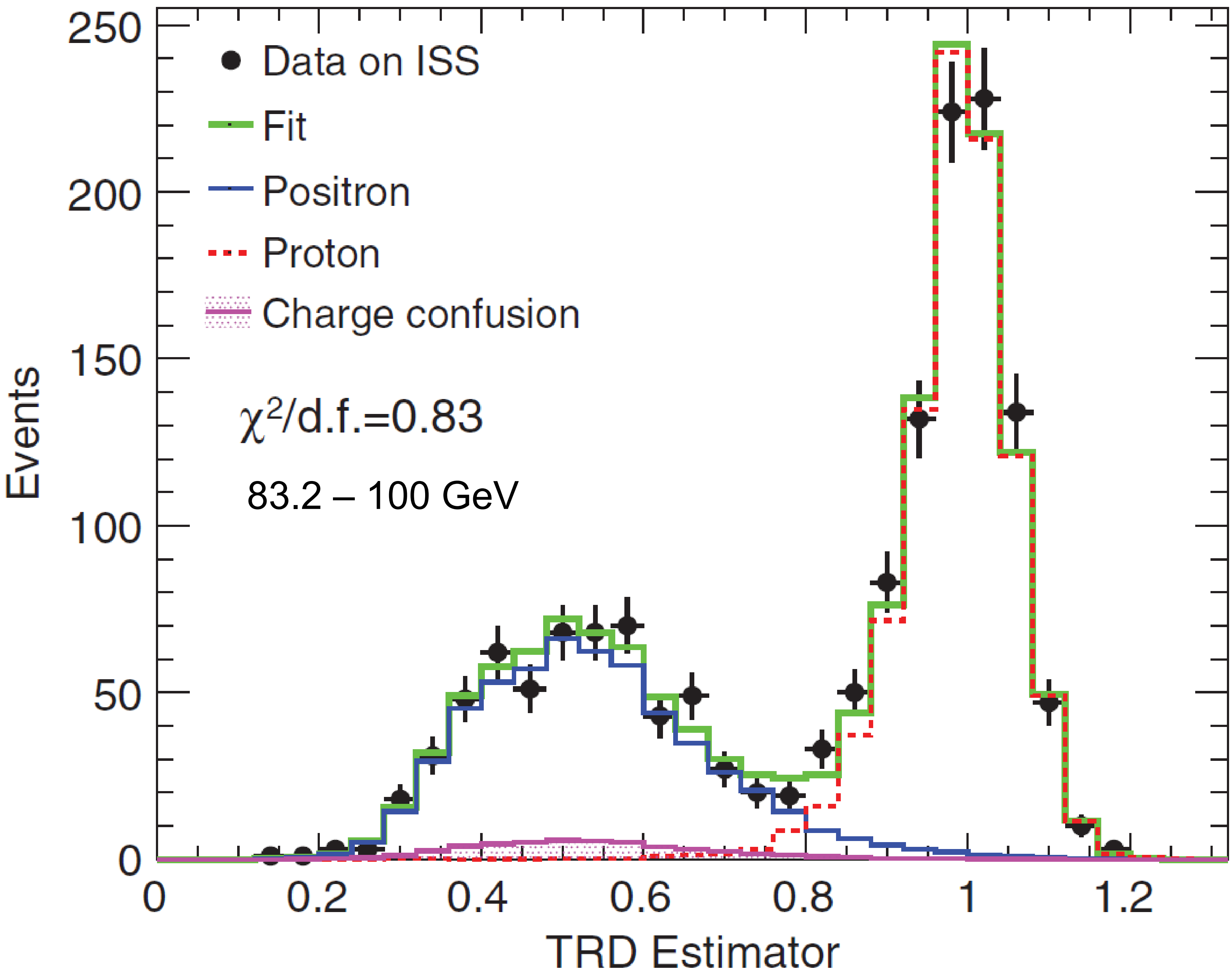
6.8 million are electrons or positrons.

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

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

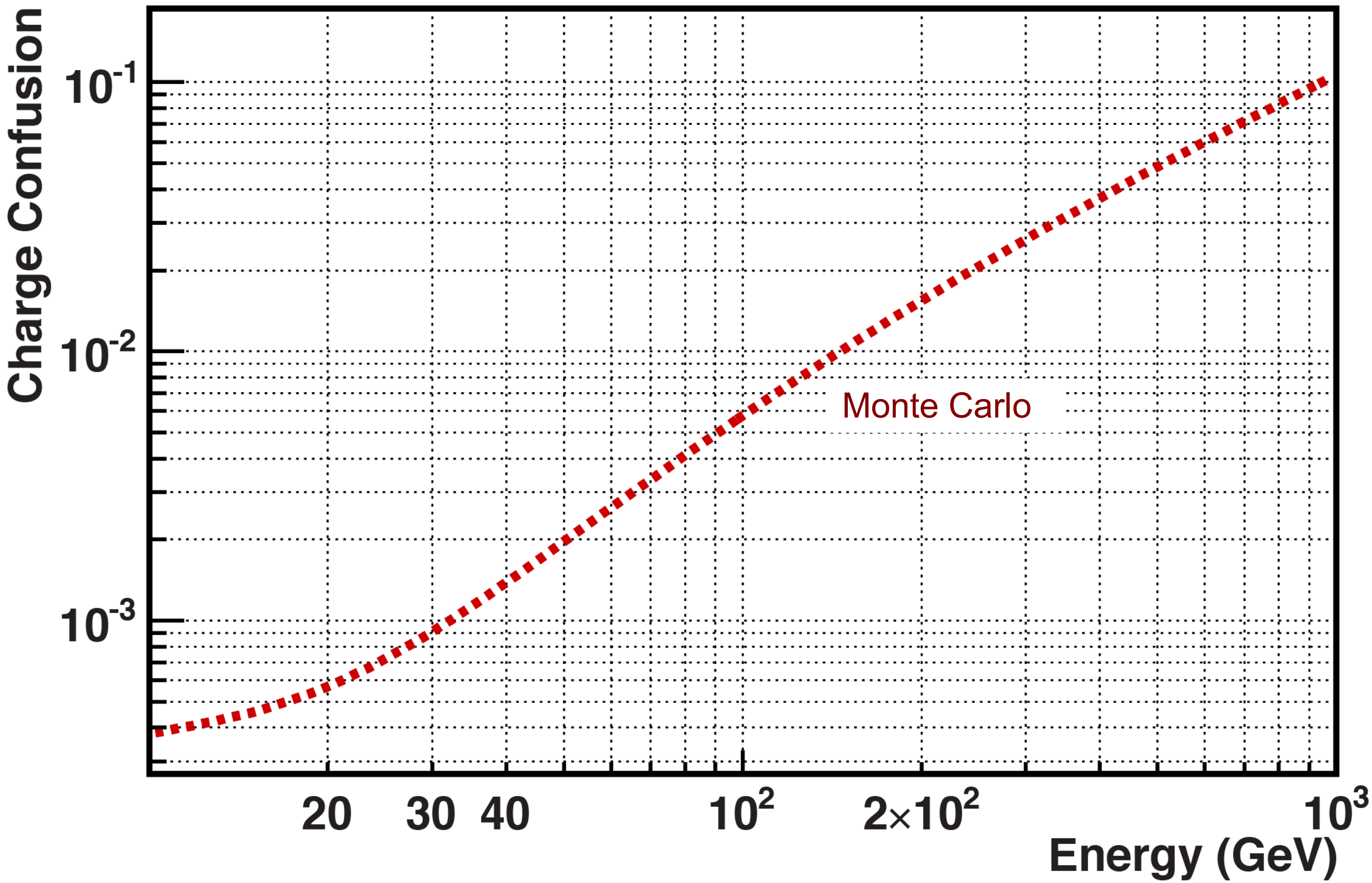


Example of positron selection



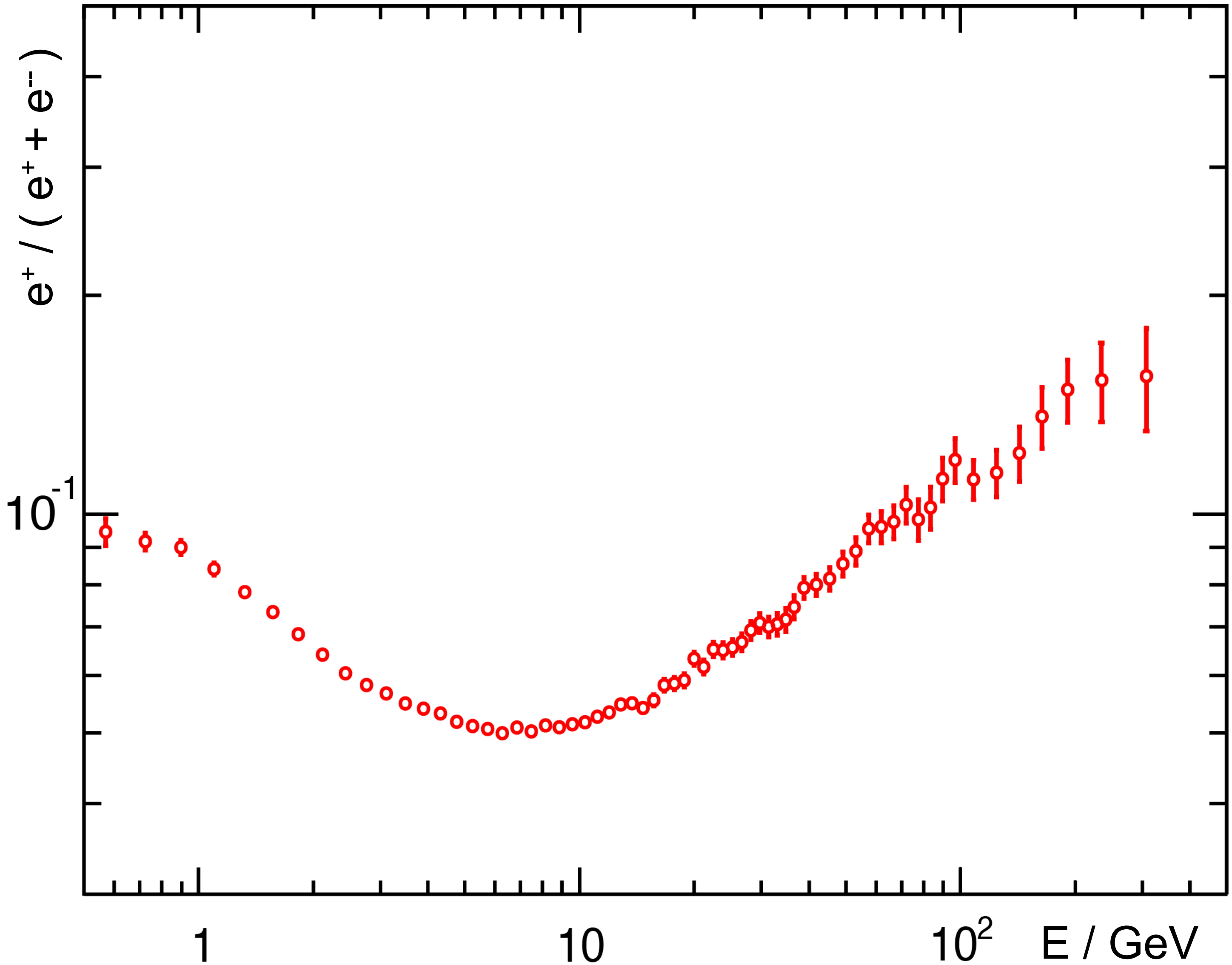
Charge confusion

- Two effects:
  - Large angle scattering
  - Secondary tracks along path of primary track
- Both effects well reproduced by Monte Carlo simulation

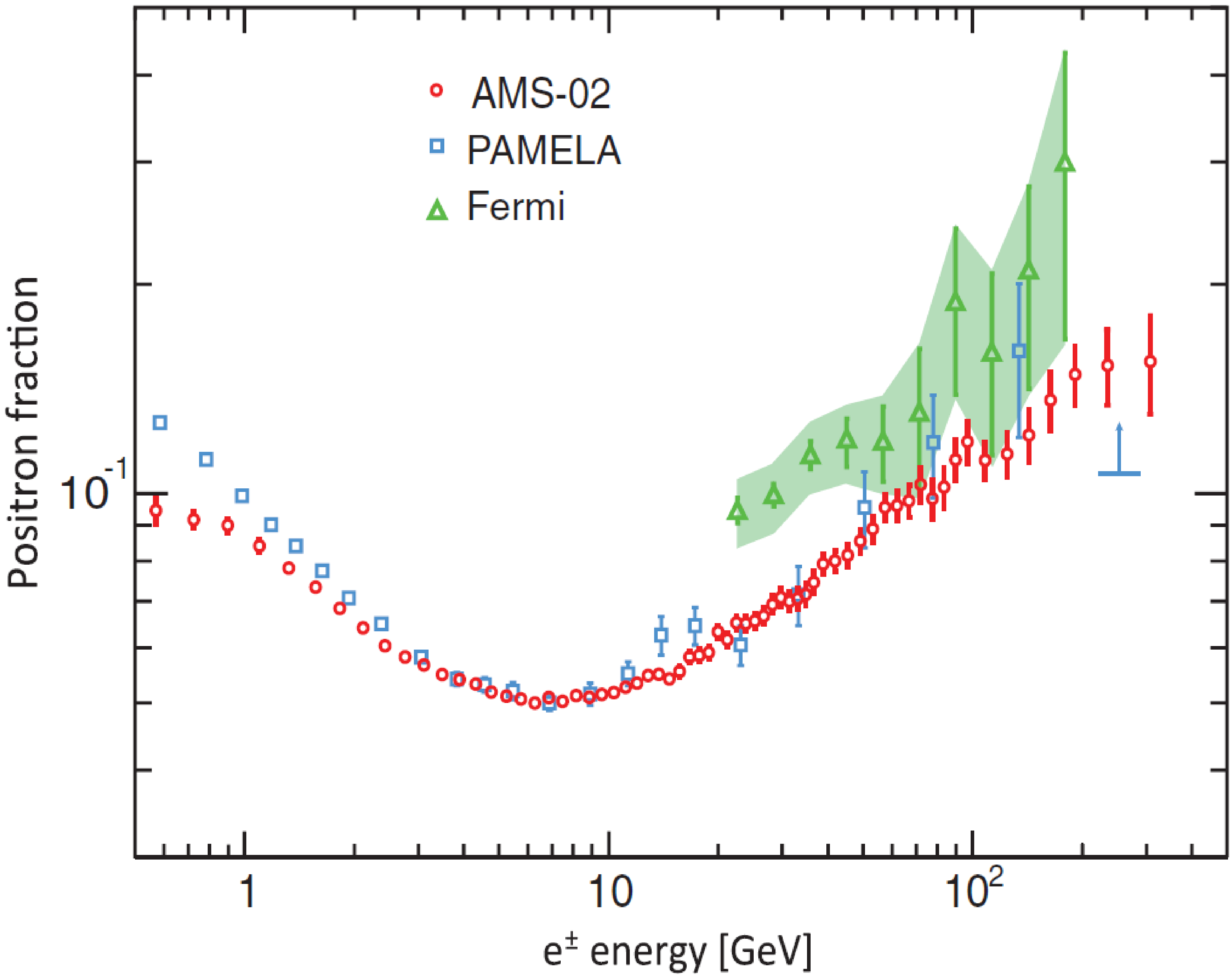


AMS-02 positron fraction

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



Comparison to earlier measurements



A simple model

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

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

- Assume diffuse power law components for positron and electron fluxes, characterized by
  - spectral indices γ_{e+} and γ_{e-}
  - positron amplitude C_{e+} and (arbitrary) electron amplitude C_{e-}
- In addition, assume a common source for positrons and electrons, described by an exponentially cutoff power law with
  - spectral index γ_s and amplitude C_s
  - cutoff energy E_S
- Model has 5 free parameters

A simple model

$\gamma_{e-} - \gamma_{e+} = -0.63 \pm 0.03$, *i.e.*, the diffuse positron spectrum is less energetic than the diffuse electron spectrum;

$\gamma_{e-} - \gamma_{s} = 0.66 \pm 0.05$, *i.e.*, the source spectrum is more energetic than the diffuse electron spectrum;

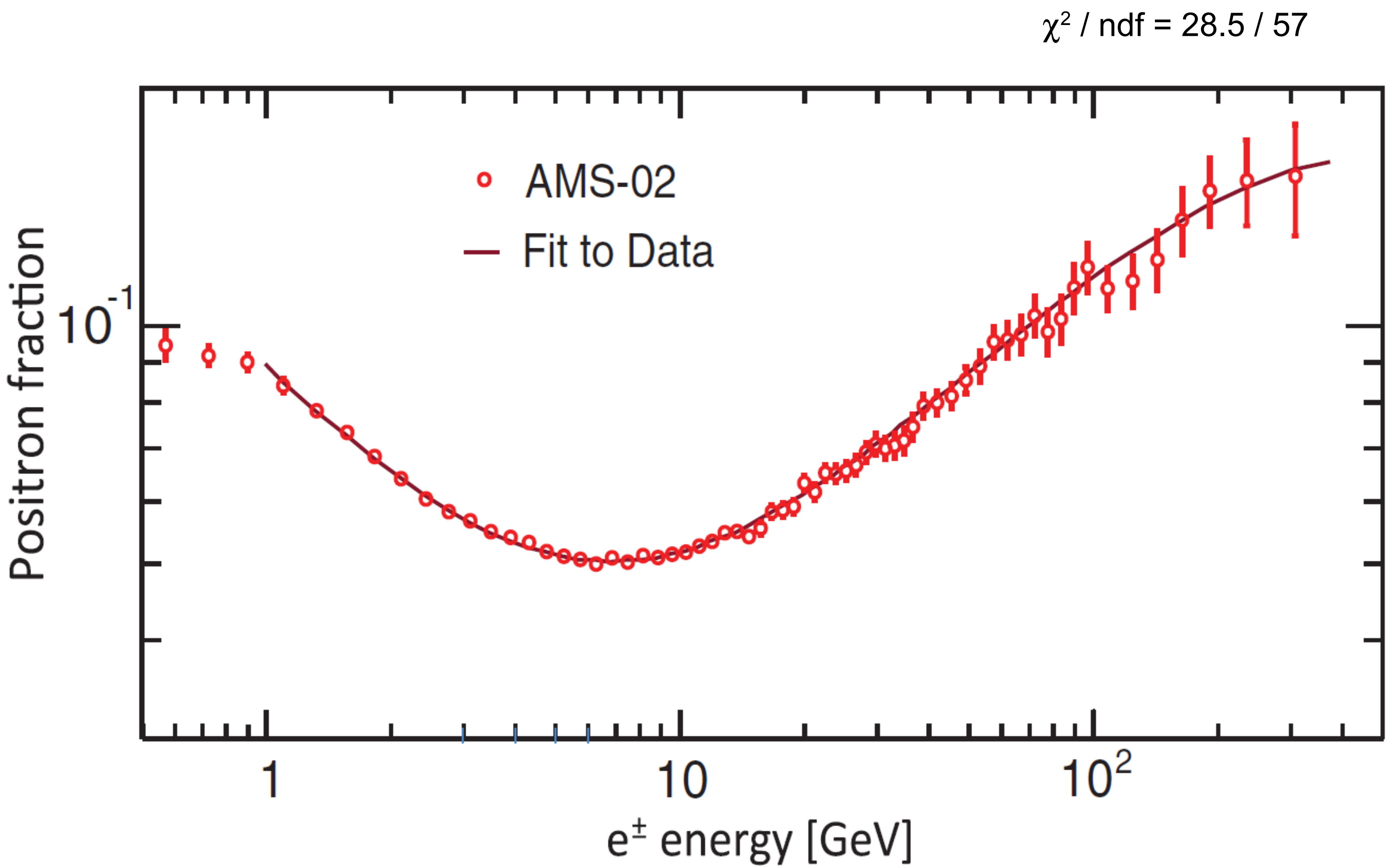
$C_{e+} / C_{e-} = 0.091 \pm 0.001$, *i.e.*, the weight of the diffuse positron flux amounts to ~10% of that of the diffuse electron flux;

$C_{S} / C_{e-} = 0.0078 \pm 0.0012$, *i.e.*, the weight of the common source constitutes only ~1% of that of the diffuse electron flux;

$1/E_{s} = 0.0013 \pm 0.0007\ \mathrm{GeV}^{-1}$,

corresponding to a cutoff energy of 760^{+1000} GeV.

A simple model



Limit on dipole anisotropy

- Data are consistent with isotropic distribution of arrival directions:

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

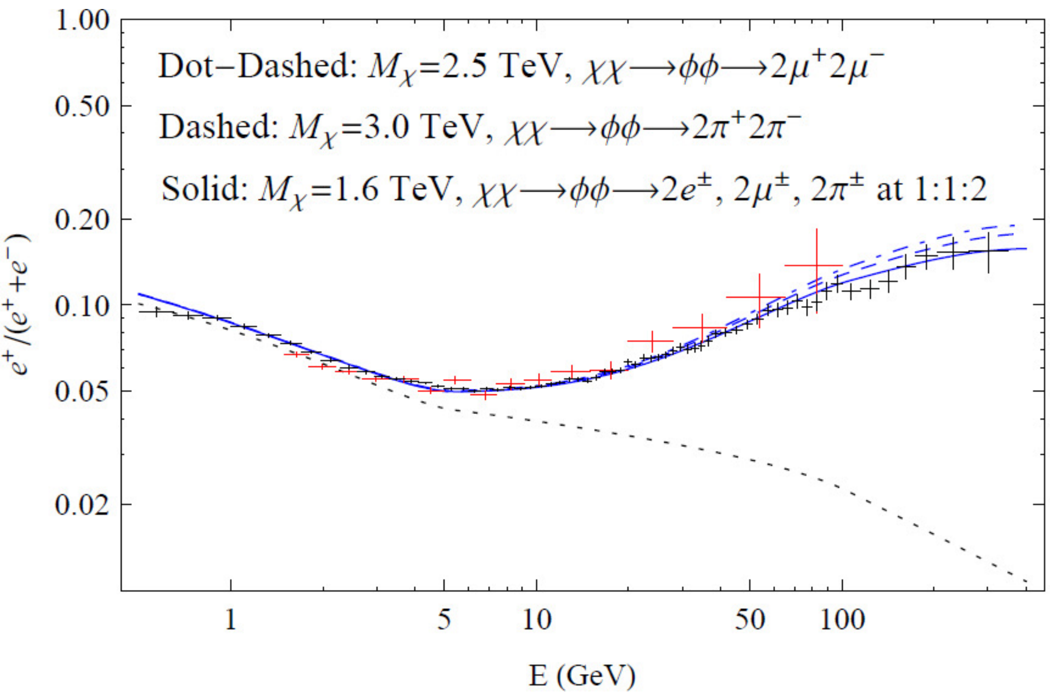
$$C_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2.$$

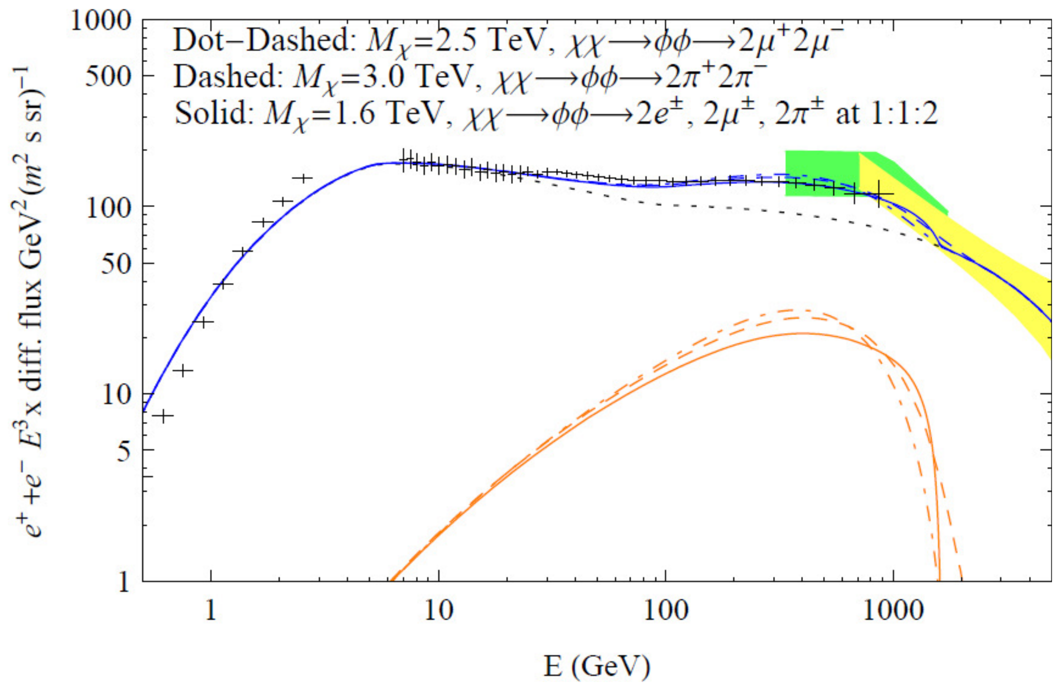
$$\delta = 3\sqrt{C_1/4\pi}$$

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

Dark matter in the light of AMS-02 results

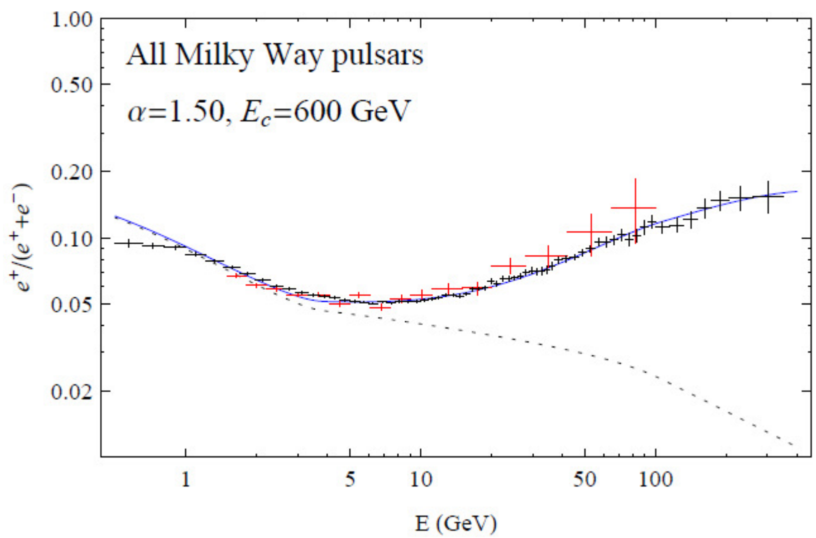
- Cholis & Hooper, 1304.1840:
  Dark matter annihilating directly to $e^+ e^-$ or $\mu^+ \mu^-$ no longer capable of describing observed rise in positron fraction.
- Annihilation via light intermediate states into muons and pions consistent with data, for DM masses of 1.5 – 3 TeV, $\langle\sigma v\rangle$ 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.)

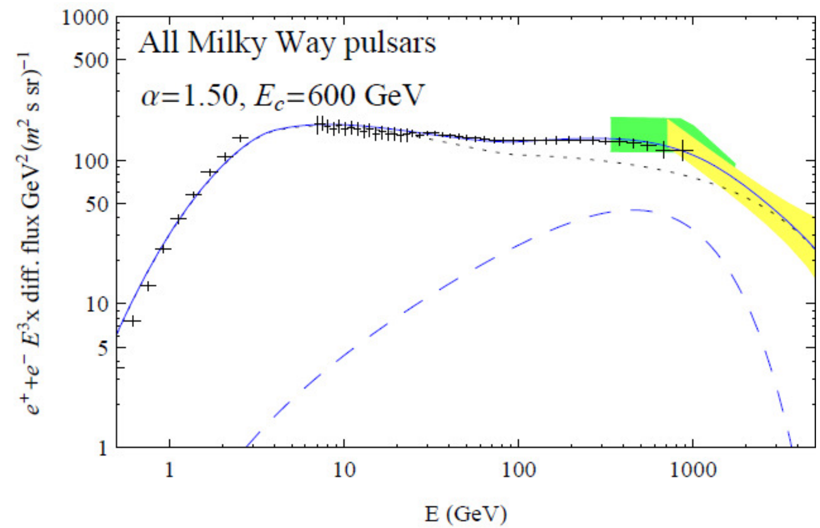


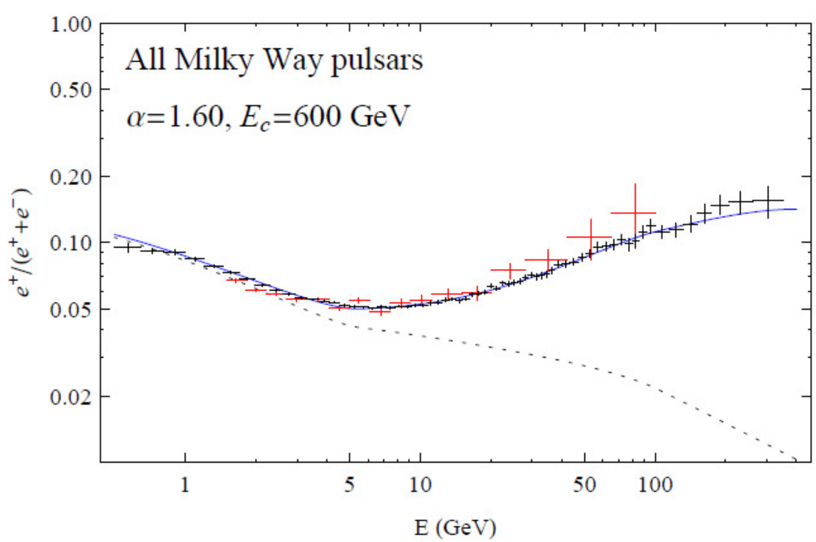


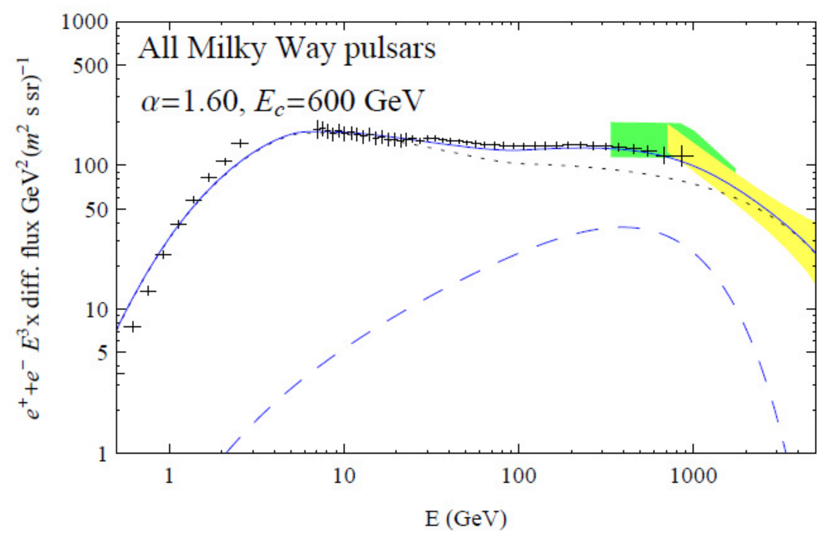
Pulsar models also work!

- 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)



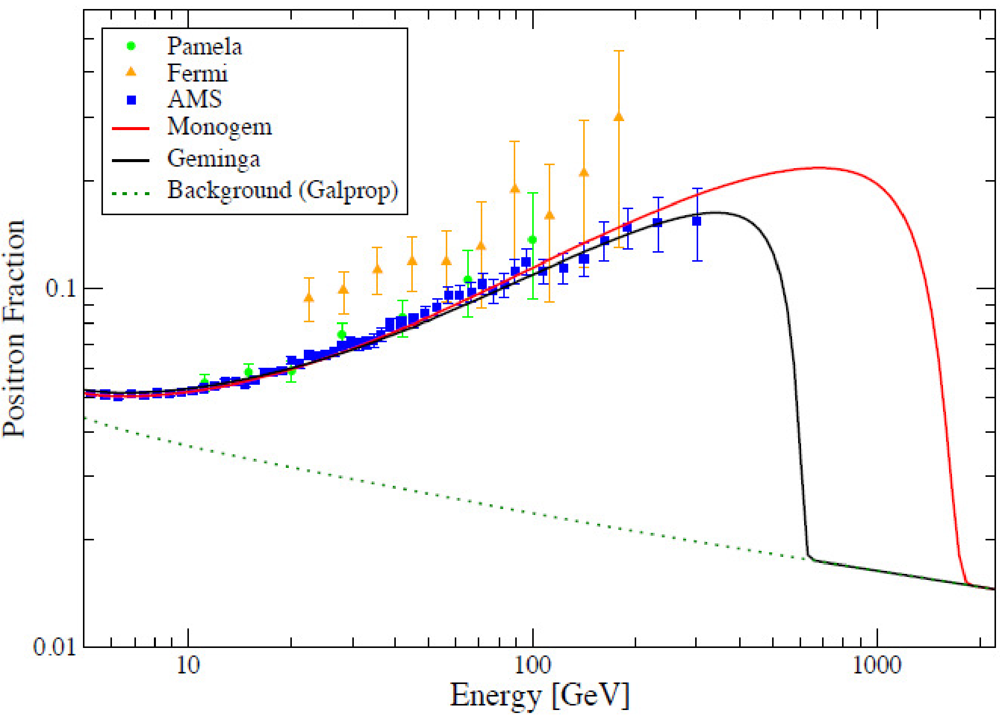


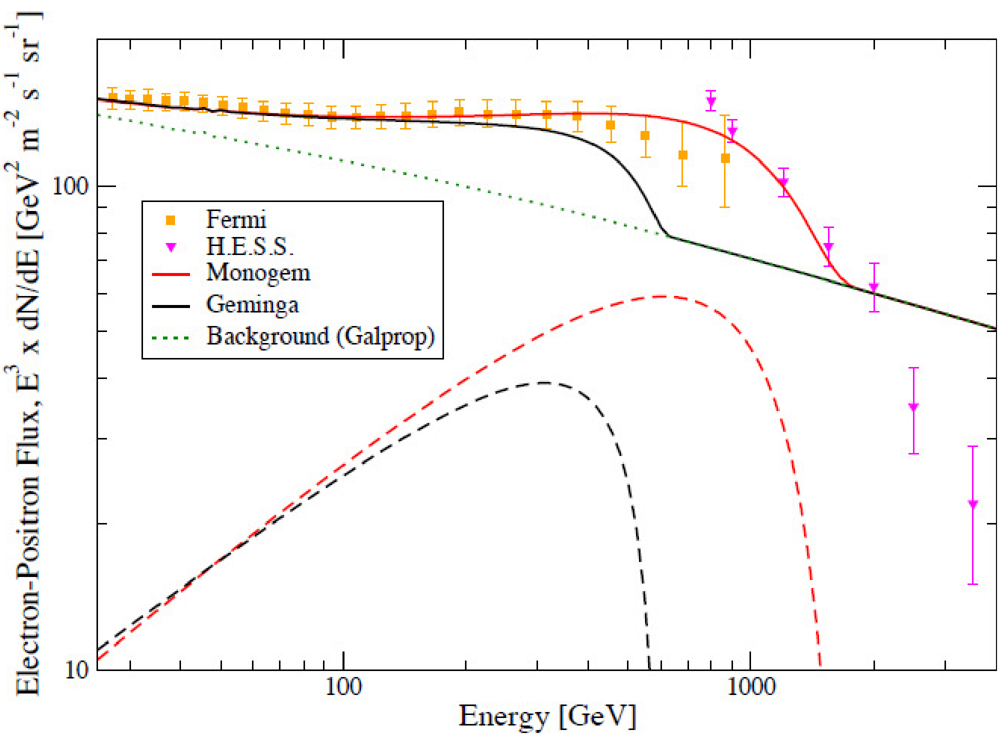




Pulsar models in the context of AMS-02 data

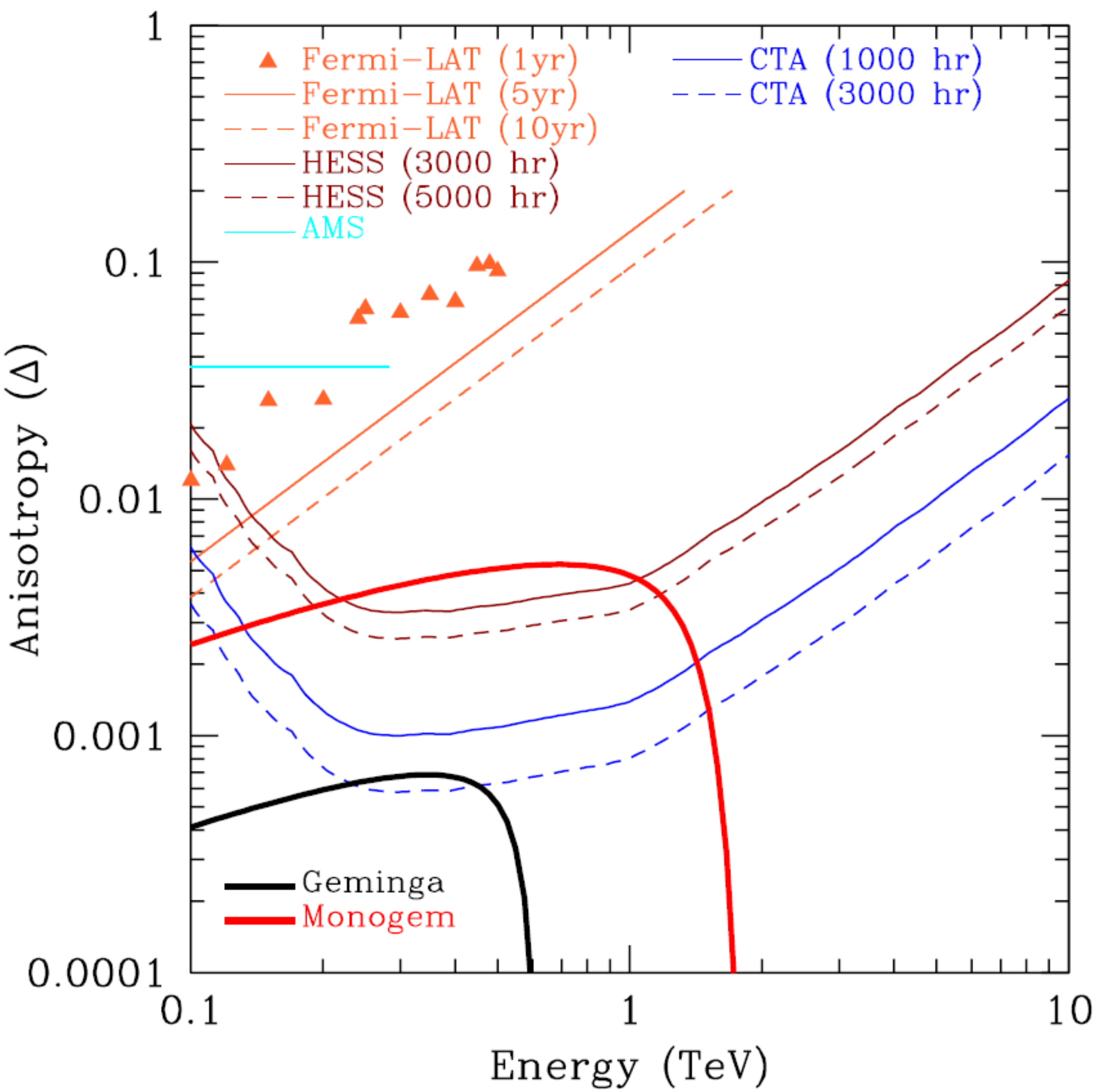
- Linden & Profumo, 1304.1791:
  Background from secondary production plus nearby mature pulsar naturally fits AMS-02 positron fraction and Fermi all-electron spectrum.
- Geminga and Monogem as possible candidates.





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:

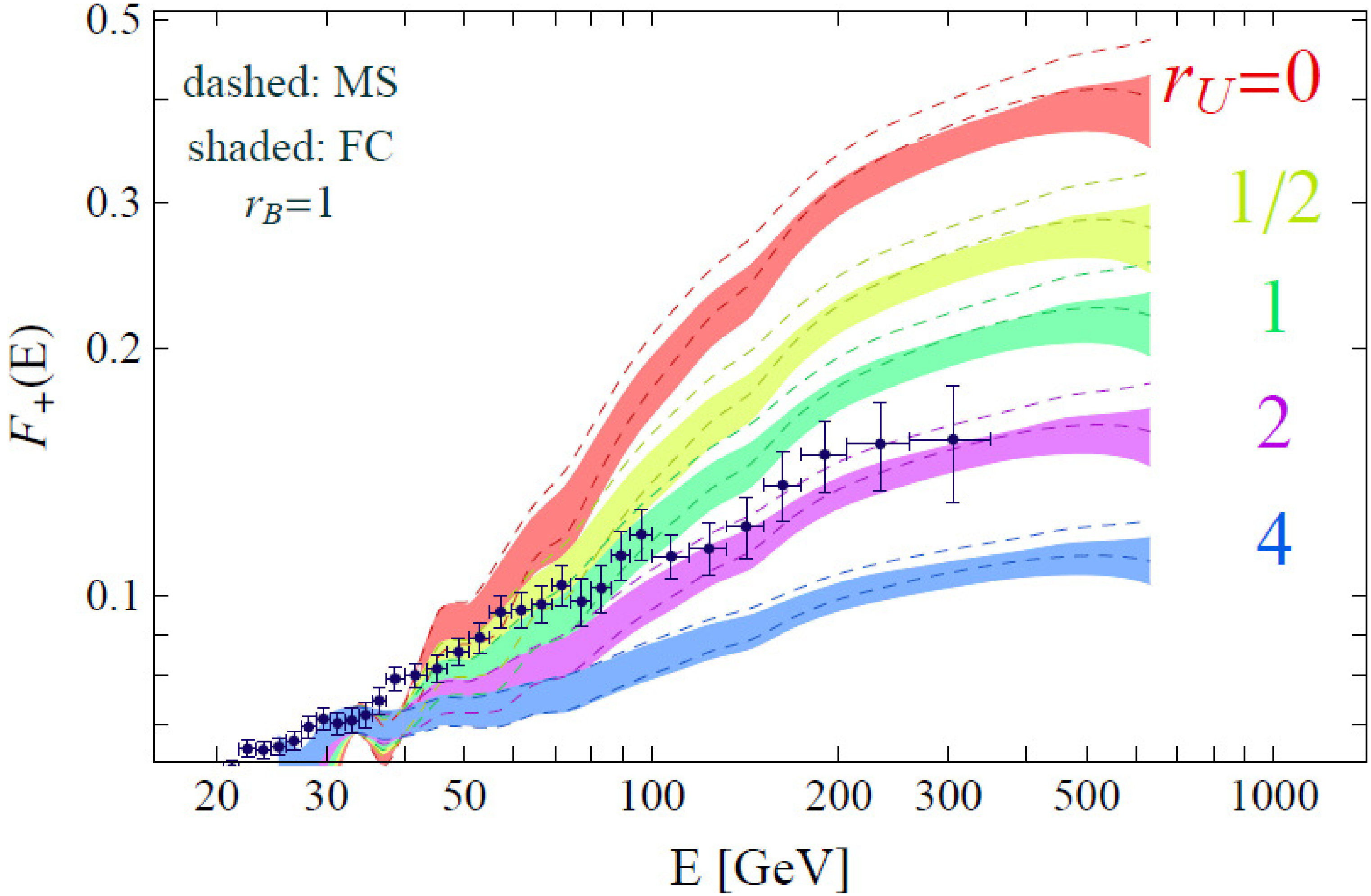
$$\phi_{e^+}(E) = \phi^U_{e^+}(E) + \phi^B_{e^+}(E)\,, \quad \phi_{e^-}(E) = \phi^U_{e^-}(E) + \phi^B_{e^-}(E)$$

- 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!)

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.