AMS and PAMELA: Spectrum and Composition of Cosmic Rays Below the Knee

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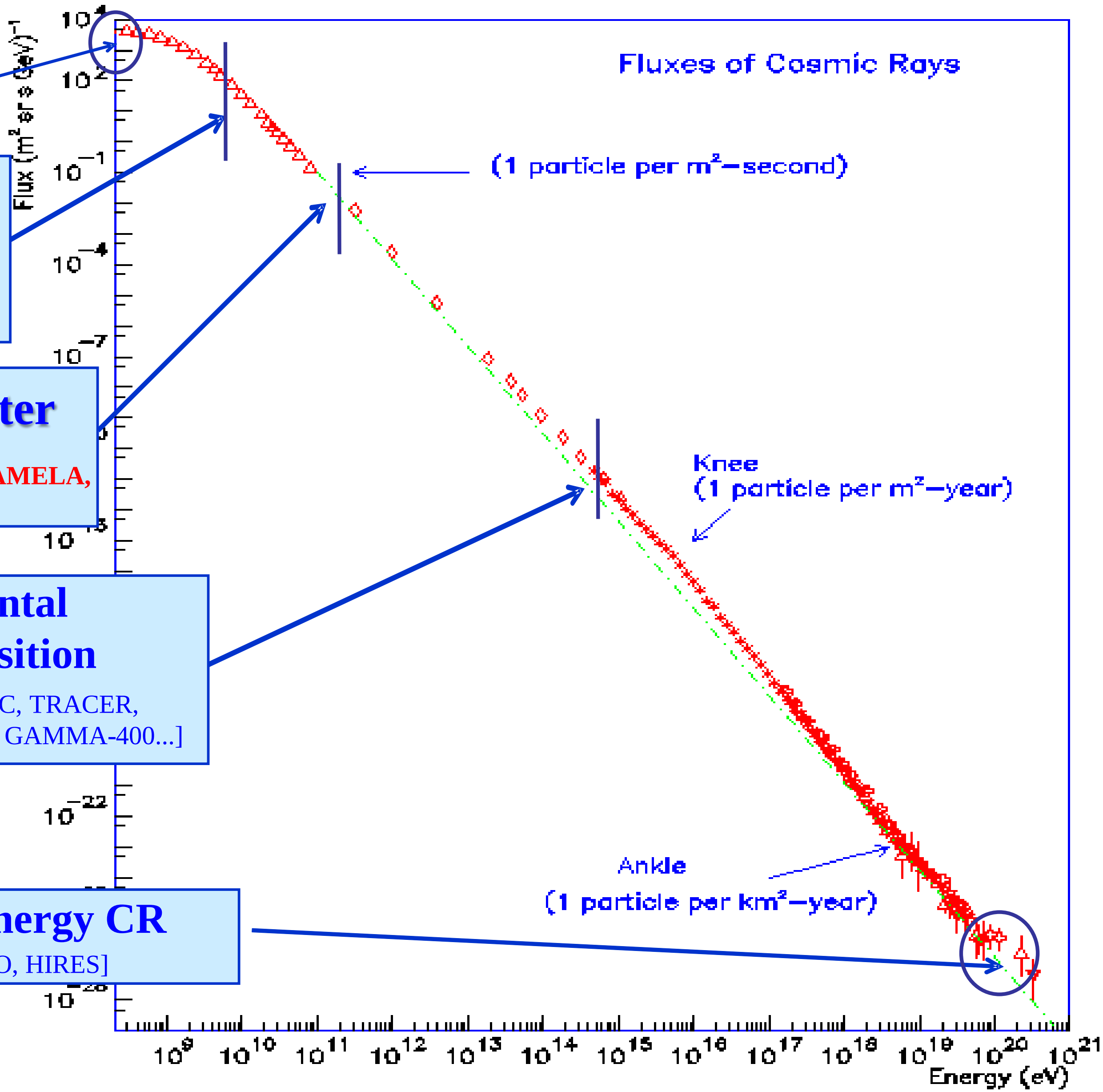
INFN Trieste, Italy

ECRS 2014, Kiel
September 1th 2014



High Z
[ENTICE, ECCO]

Isotopic composition
[ACE]
Solar Modulation

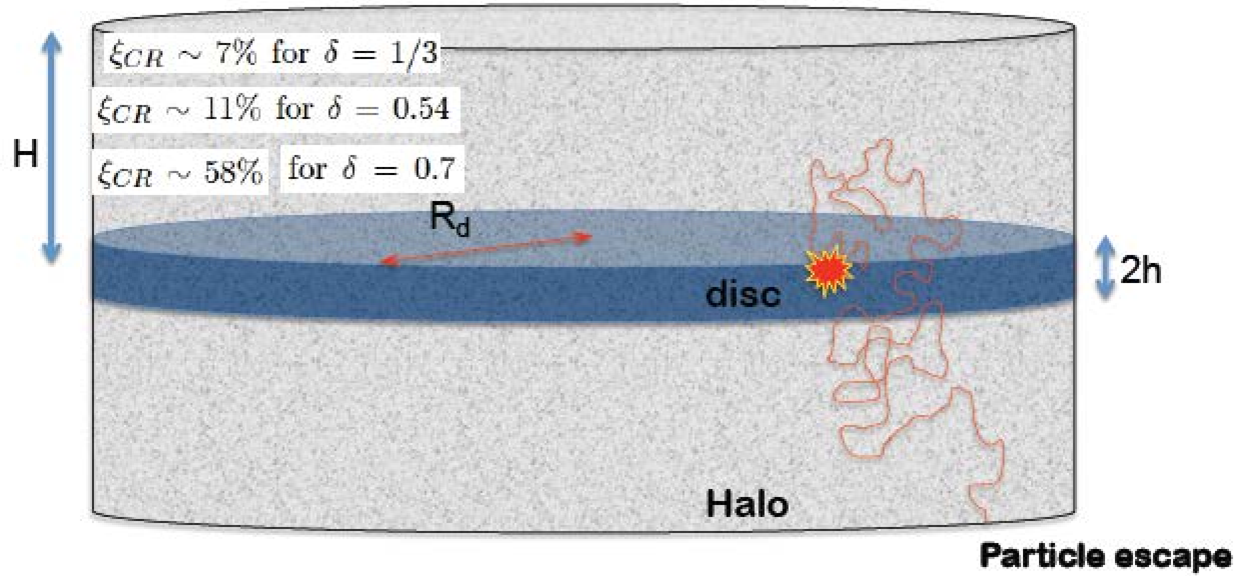
Antimatter
[HEAT,BESS, **PAMELA, AMS**]

Elemental Composition
[CREAM, ATIC, TRACER, CALET, DAMPE, GAMMA-400...]

Extreme Energy CR
[AUGER, EUSO, HIRES]

J. Cronin ,T.K. Gaisser & S.P. Swordy, Sci. Amer. 276 (1997) 44

Pillars of the SNR paradigm



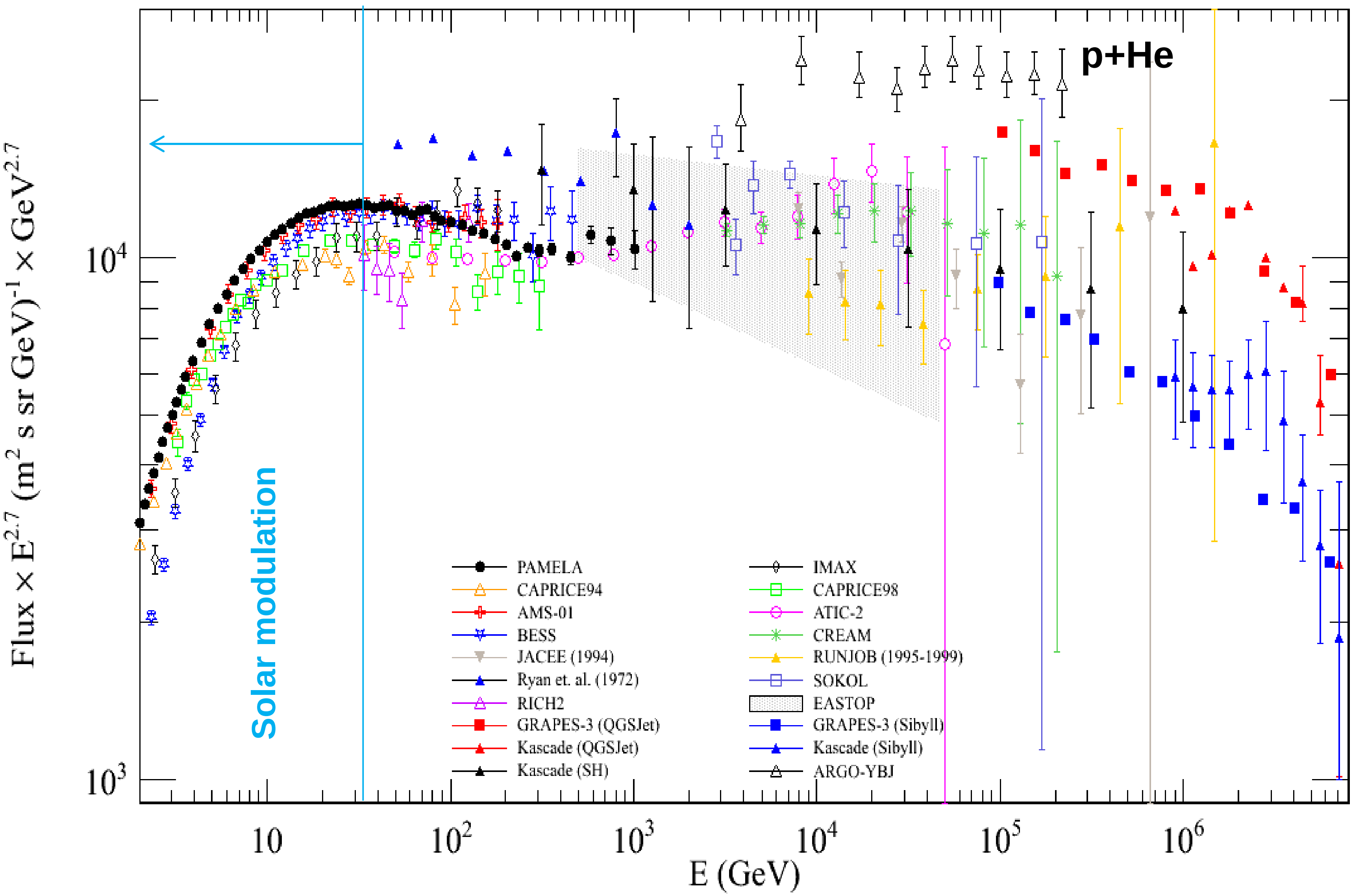
CRs IN SNR → DIFFUSIVE SHOCK ACCELERATION, Q(E)~E$^{-\gamma}$

PROPAGATION OF CRs IN THE GALAXY with D(E)~E$^{\delta}$ → n(E)~E$^{-\gamma-\delta}$

P. Blasi, TeVPA 2011, Stockholm

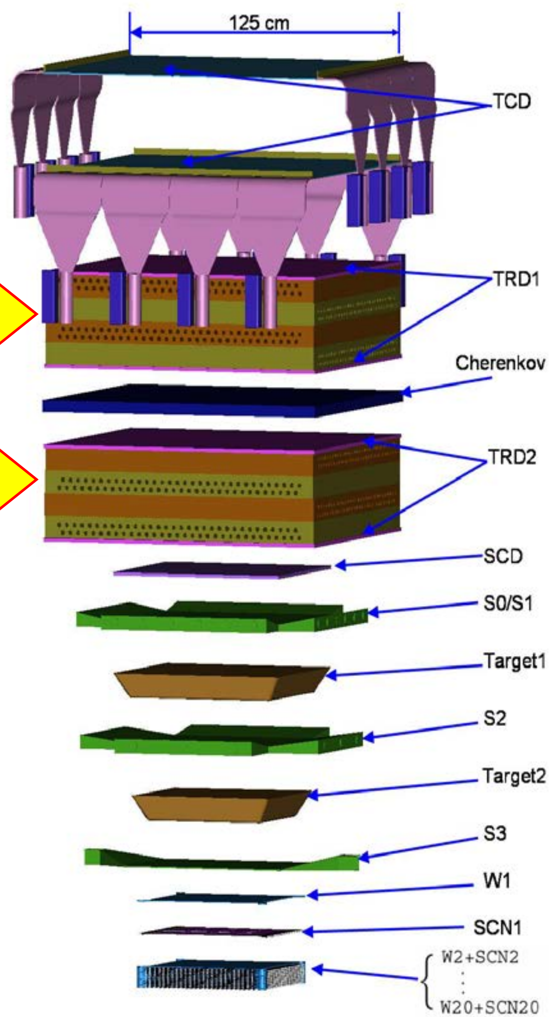
Proton & Helium Nuclei Spectra

Proton (Hydrogen) Spectrum



Detector Systems in CREAM-1

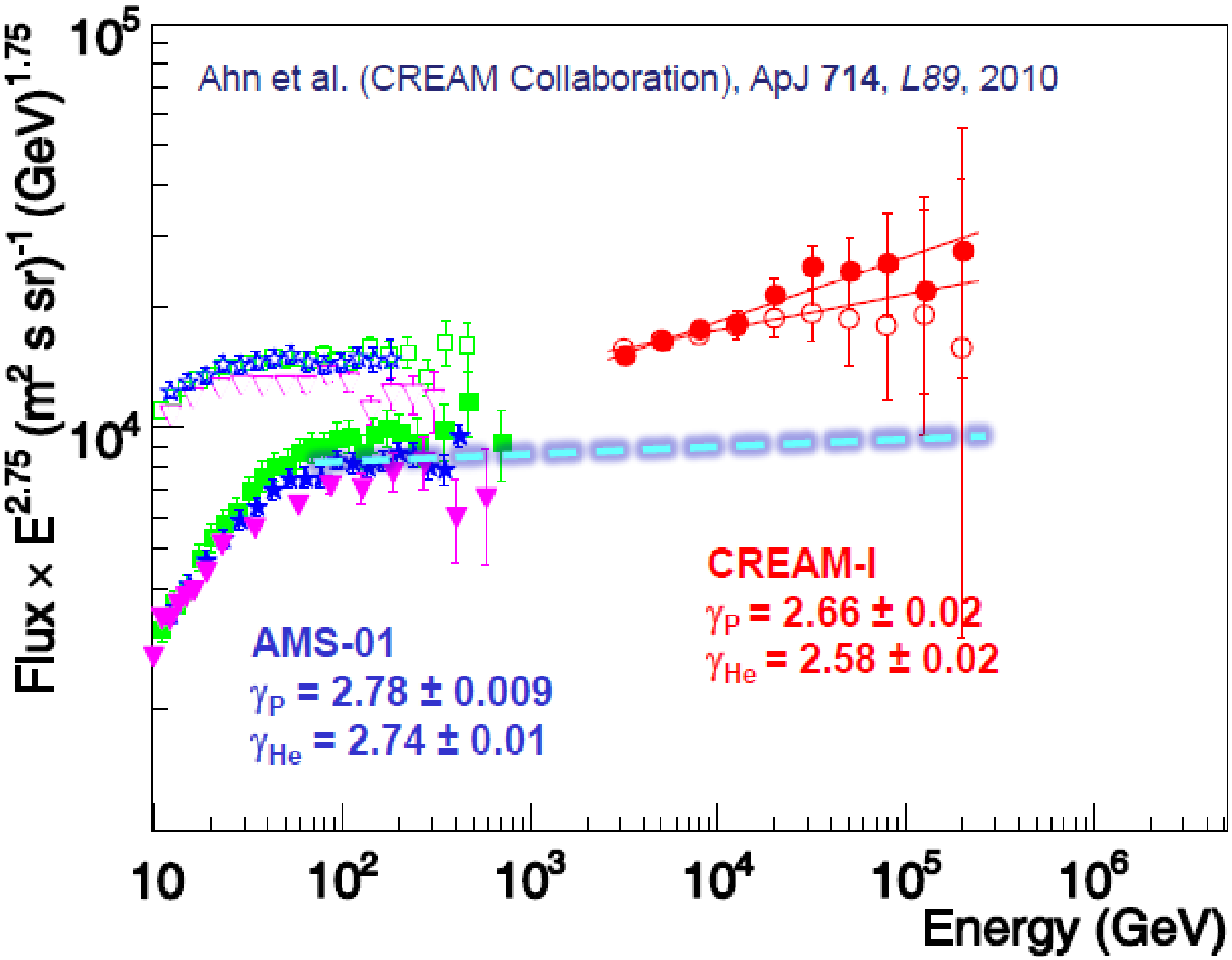
- **TCD**: Timing Charge Detector
  - ✓ Trigger and Charge
- **TRD**: Transition Radiation Detector
  - ✓ Tracking
  - ✓ Lorentz Factor for $Z \geq 3$



CER: Cherenkov Detector
–Charge/Velocity for $Z \geq 3$

calorimeter module

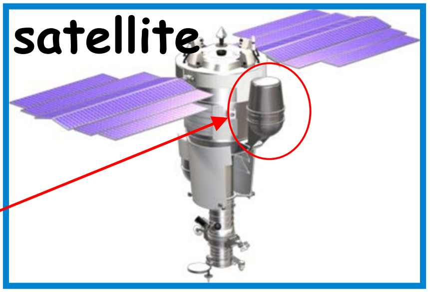
CREAM spectra harder than prior lower energy experiments



E. S. Seo, TeVPA 2013, Irvine.

The PAMELA experiment

Resurs DK1 satellite



Satellite-borne experiment

⁕

No atmospheric effects

Mission details

Orbit and altitude:

- elliptical, 360 – 600 km (up to 2010)
- circular, 600 km (since 2010)

Orbit inclination: 70°

Planned duration: 3 years

Launch: 15th June 2006

Technical data

Mass ~ 470 kg

Height ~ 1.3 m

Power cons. ~ 355 W

Downlink rate ~ 10 GB/day

Current status

8 years in orbit

Data taking LT ~ 75%

~ 50 TB of raw data

The PAMELA collaboration

Italy

Bari

Naples

Florence

Rome

Trieste

Russia

Moscow

St. Petersburg

Sweden

Stockholm

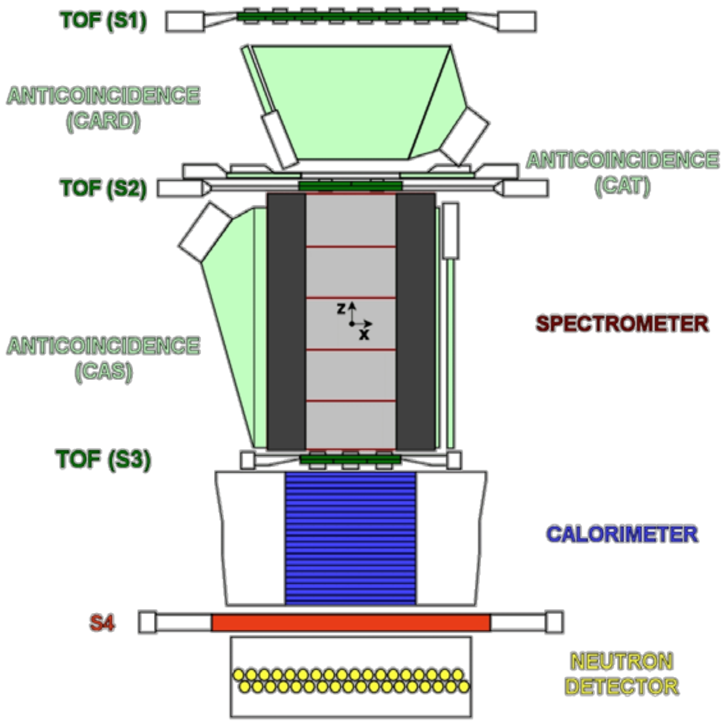
Germany

Siegen

Aimed at light particles (up to oxygen)

Main focus on antiparticles

The PAMELA detector



Time-Of-Flight (TOF)
Plastic scintillators + PMT
- Trigger
- Albedo rejection
- Mass identification up to 1 GeV
- Charge identification from dE/dX

Anticoincidence
Plastic scintillators + PMT
- Multi-particle and interacting event rejection

Electromagnetic calorimeter
W/Si sampling (16.3 X_0, 0.6 λ_I)
- e^+/p, e^-/p discrimination (shower topology)
- Direct energy measurement for $e^\pm$

Spectrometer
Microstrip silicon tracking system + perm. magnet
- magnetic rigidity R = pc/Ze
  - sign of charge
  - charge value from dE/dx

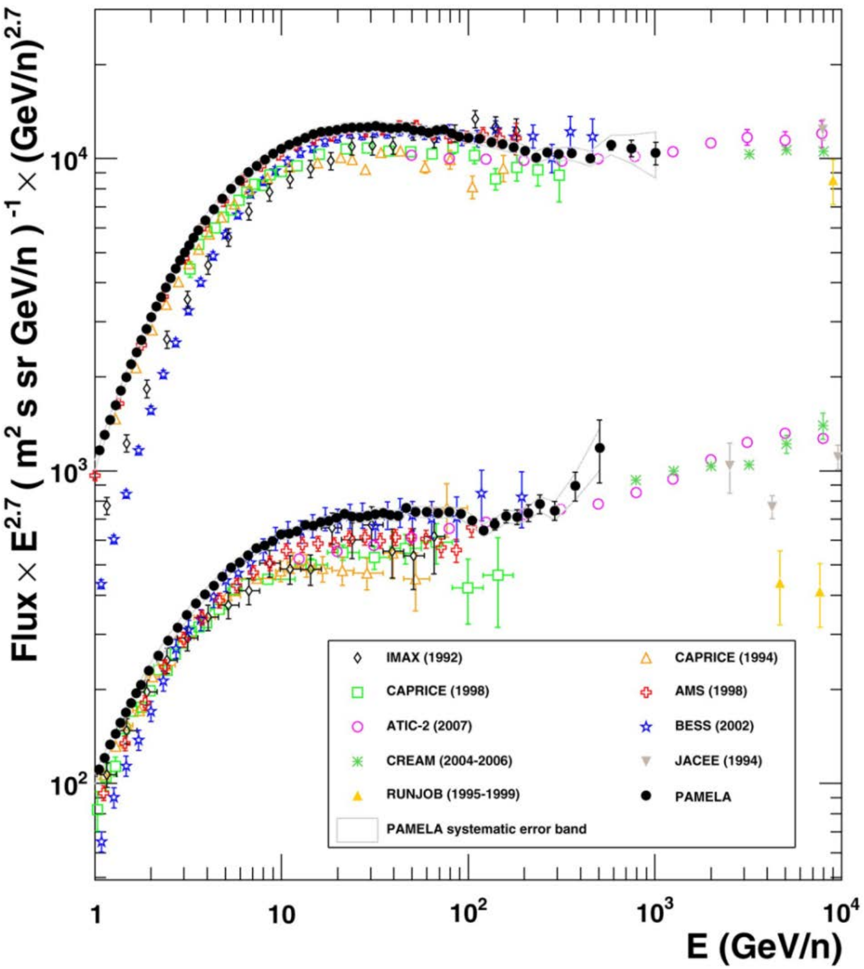
Neutron detector
36 ^{3}He counters
- High-energy e/h discrimination

Optimized for |Z|~1 particles

Tracking performance: σ_x = 3 µm, σ_y = 11 µm, MDR = 1.2 TV

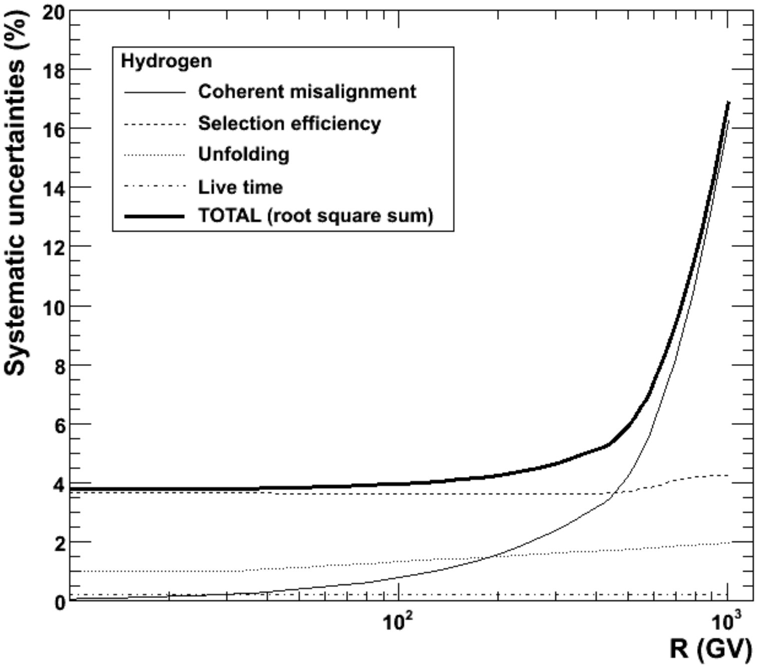
INFN Istituto Nazionale di Fisica Nucleare

H and He absolute fluxes

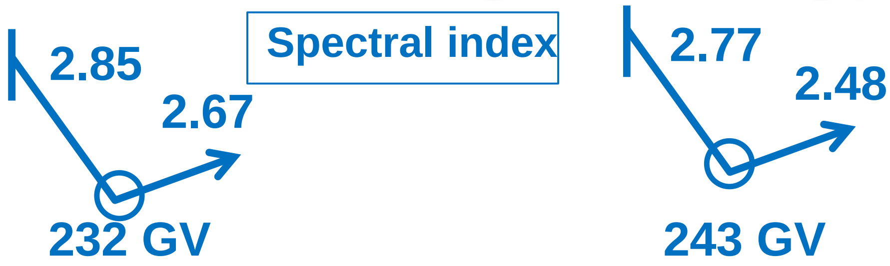


O. Adriani et al., Science 332 (2011) 6025

- First high-statistics and high-precision measurement over three decades in energy
- Dominated by systematics (~4% below 300 GV):



H & He absolute fluxes @ high energy



Deviations from single power law (SPL):

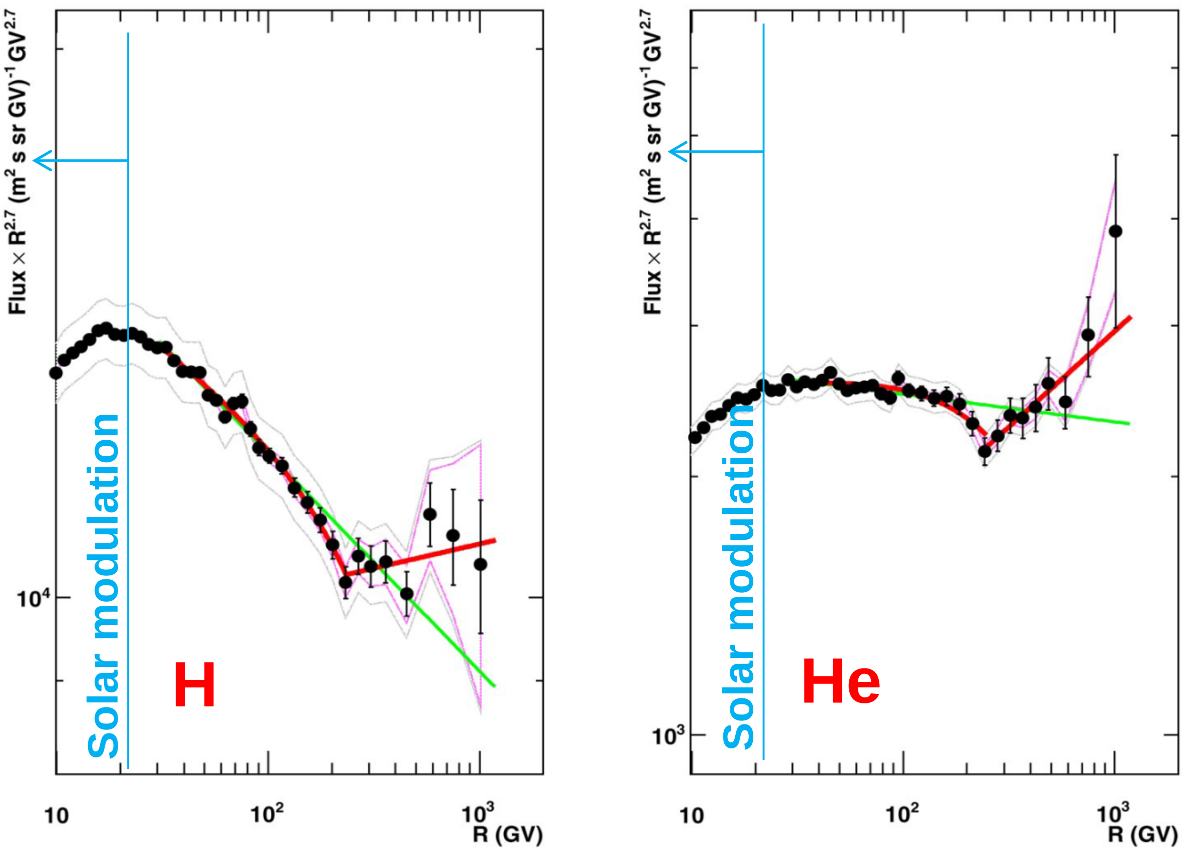
- Spectra gradually soften in the range 30÷230GV
- Spectral hardening @ R~235GV Δγ~0.2÷0.3

SPL is rejected at 98% CL

Origin of the structures?

(e.g. see **P. Blasi, arXiv:1312.1590**)

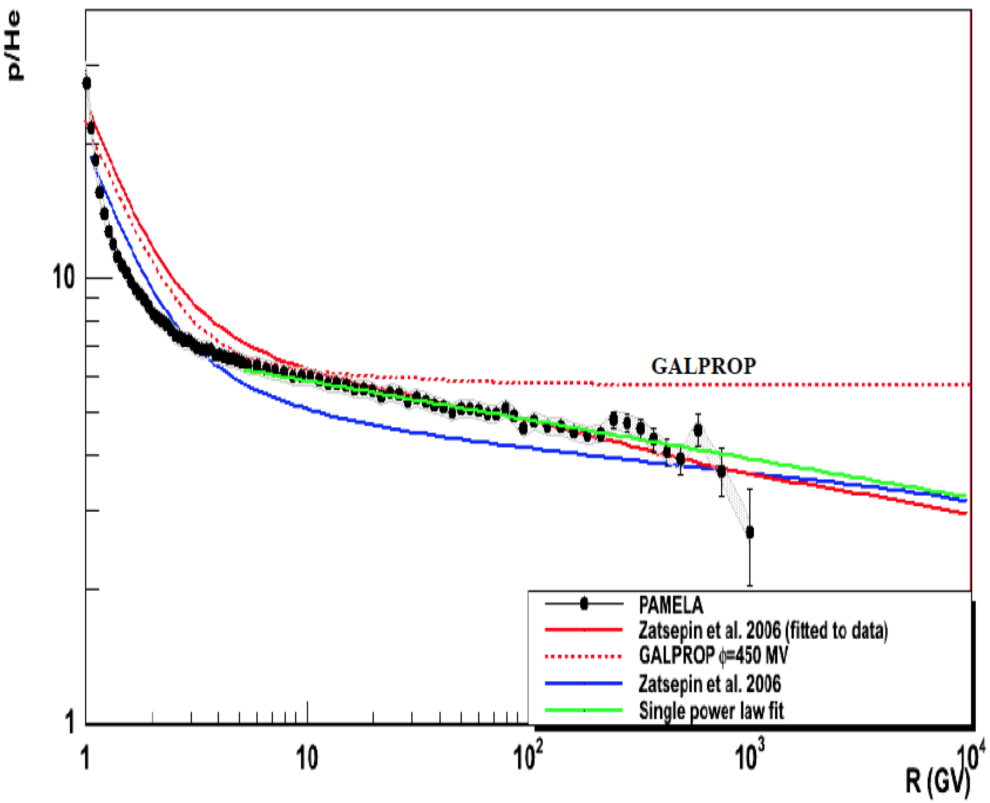
- At the sources: multi-populations, etc.?
- Propagation effects?



Mirko Boezio, ECRS 2014, Kiel, 2014/09/01

O. Adriani et al., Science 332 (2011) 69

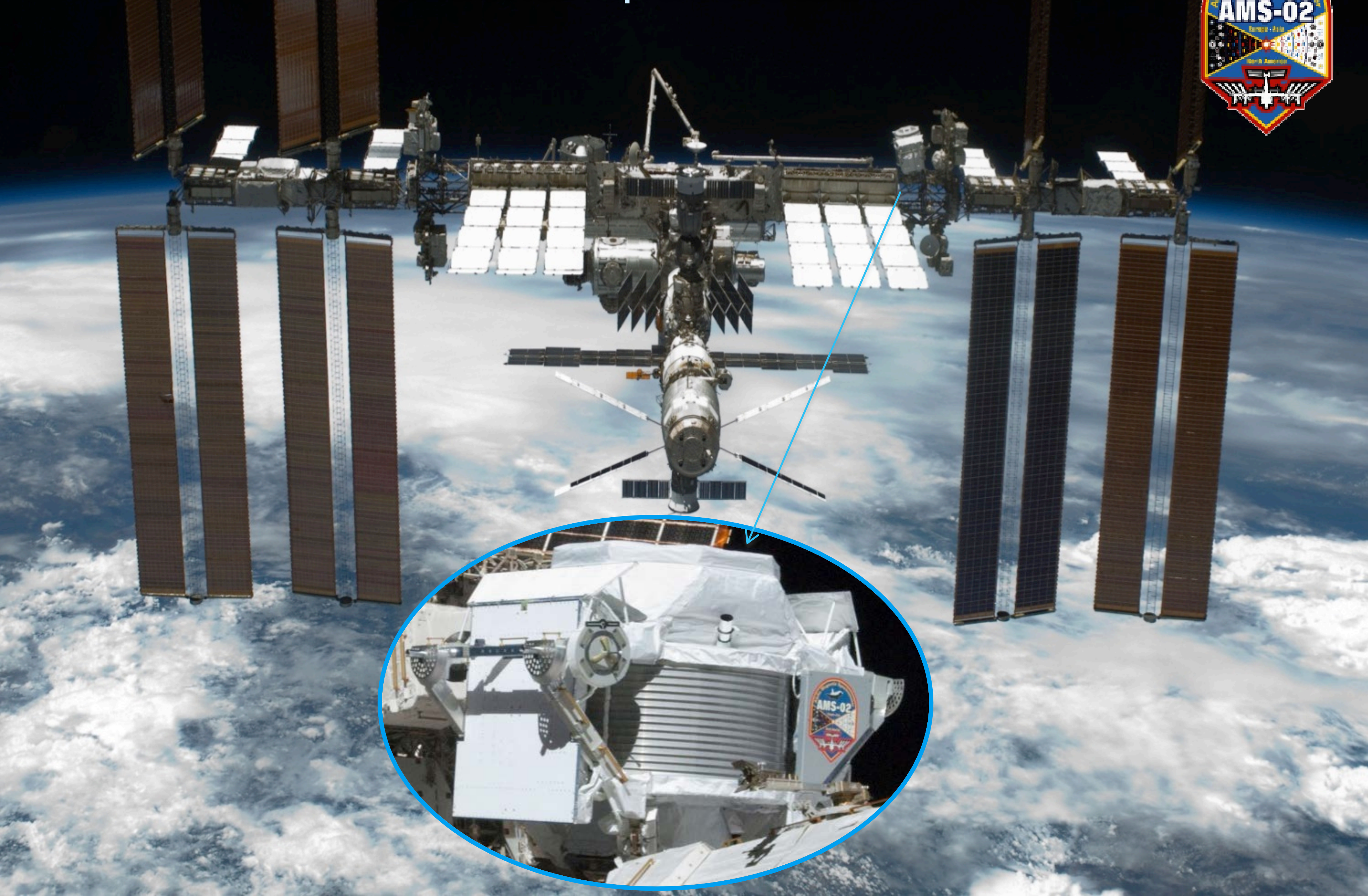
PAMELA H/He ratio



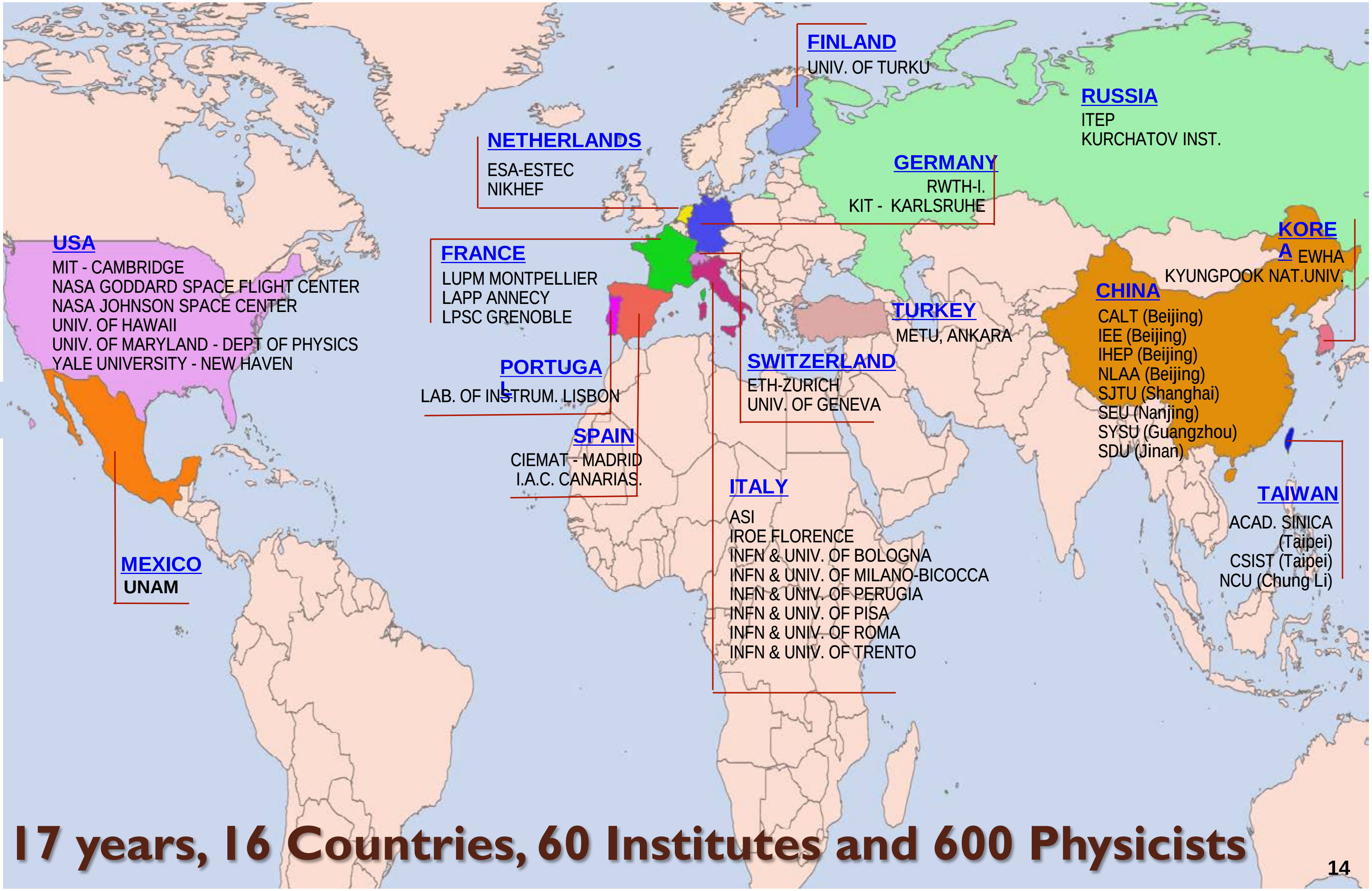
Adriani et al. , Science 332 (2011) 6025

- A robust measurement, where many systematics cancel out
- First clear evidence of different H and He slopes above ~ 10 GV
- Ratio described by a single power law (in spite of the evident structures in the individual spectra)

The Alpha Magnetic Spectrometer (AMS) on the International Space Station



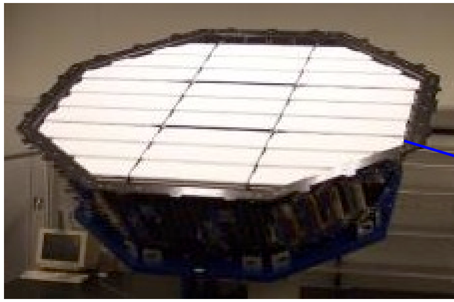
AMS: A worldwide Collaboration



17 years, 16 Countries, 60 Institutes and 600 Physicists

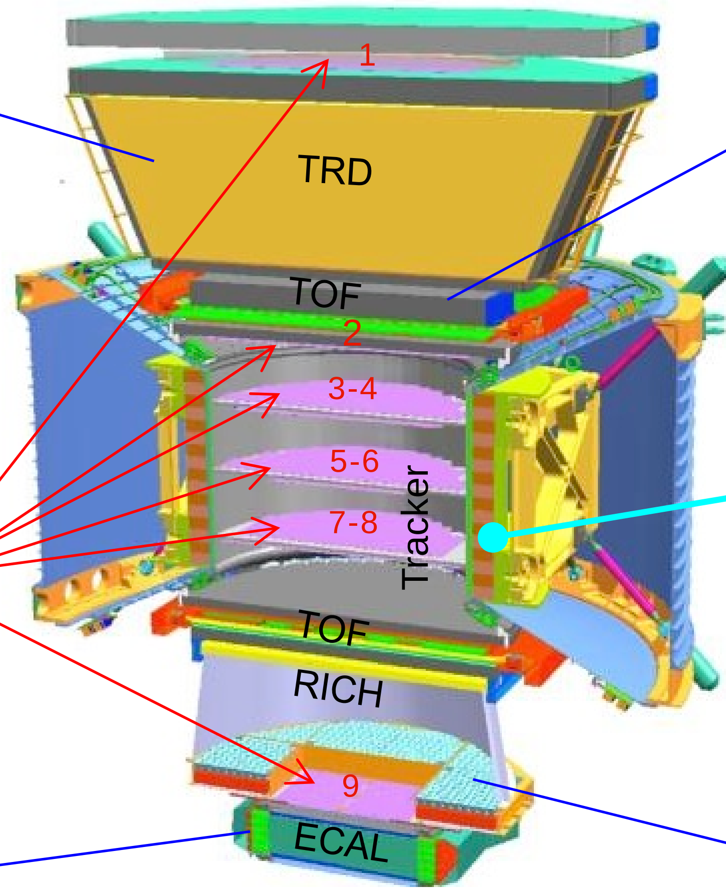
AMS : A TeV precision, multipurpose spectrometer

Transition Radiation Detector
Identify electrons

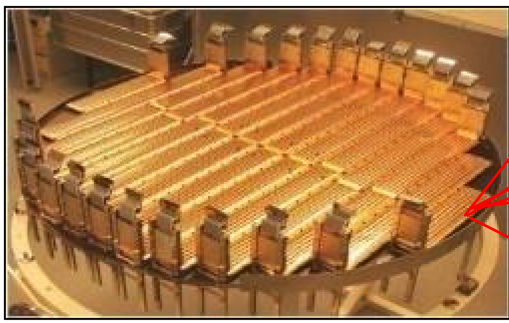


Particles are defined by their charge (Z) and energy (E) or momentum (P)

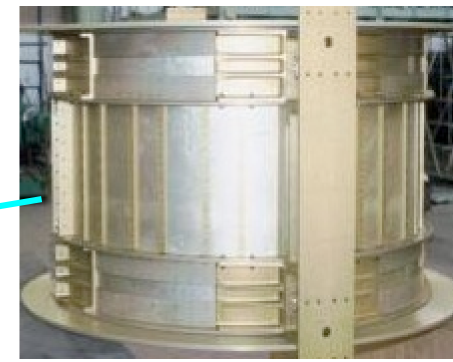
Time of Flight
Z, E



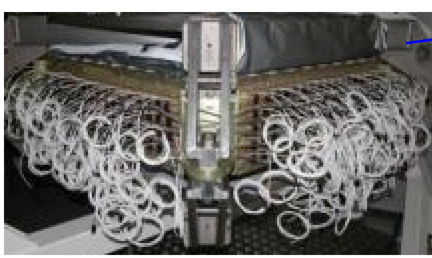
Silicon Tracker
Z, P



Magnet
±Z



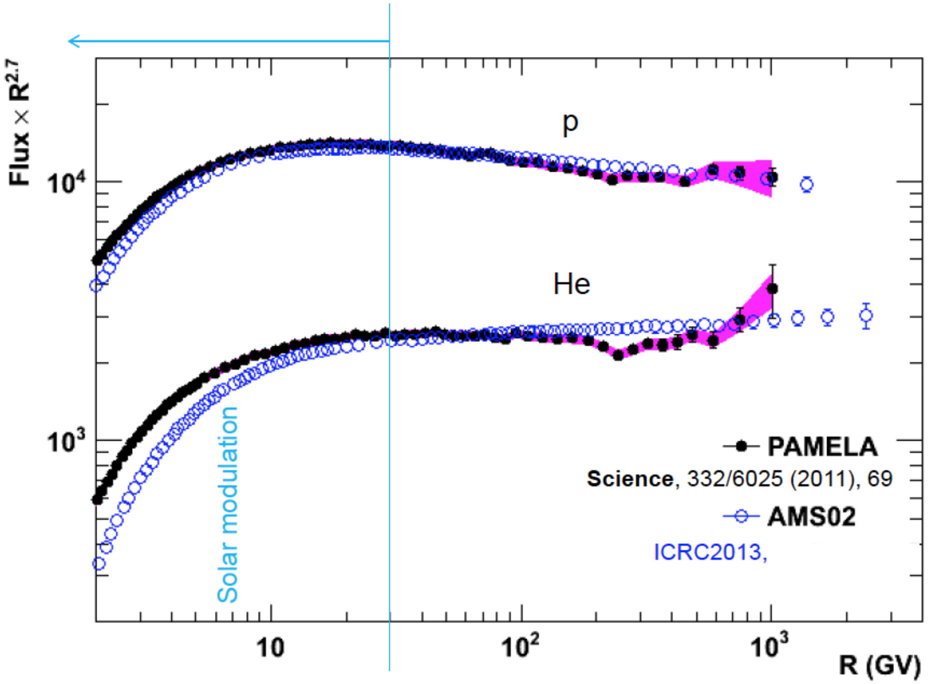
Electromagnetic Calorimeter
E of electrons

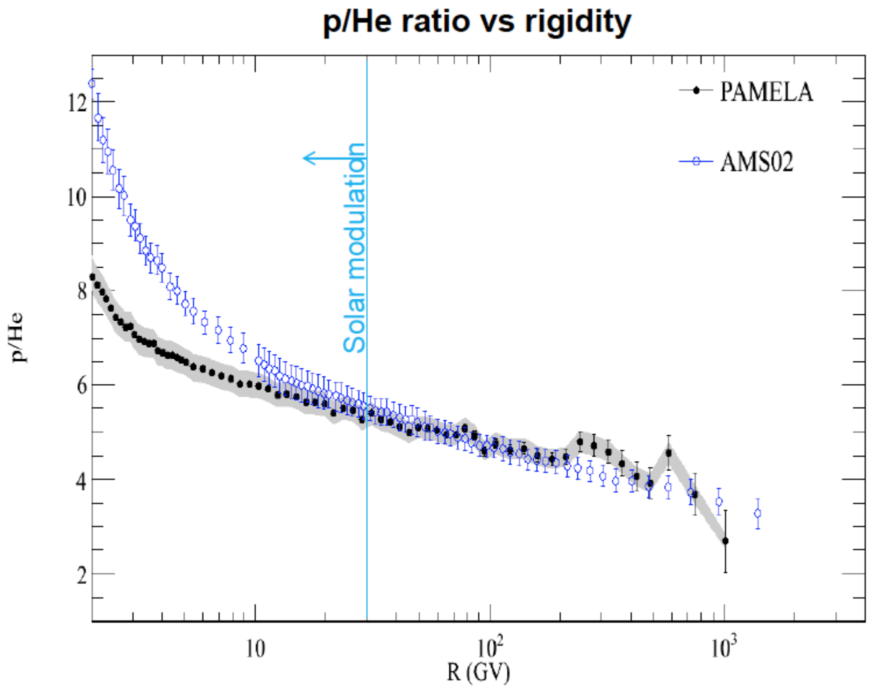


Ring Imaging Cherenkov
Z, E

The Charge and Energy (momentum) are measured independently by many detectors

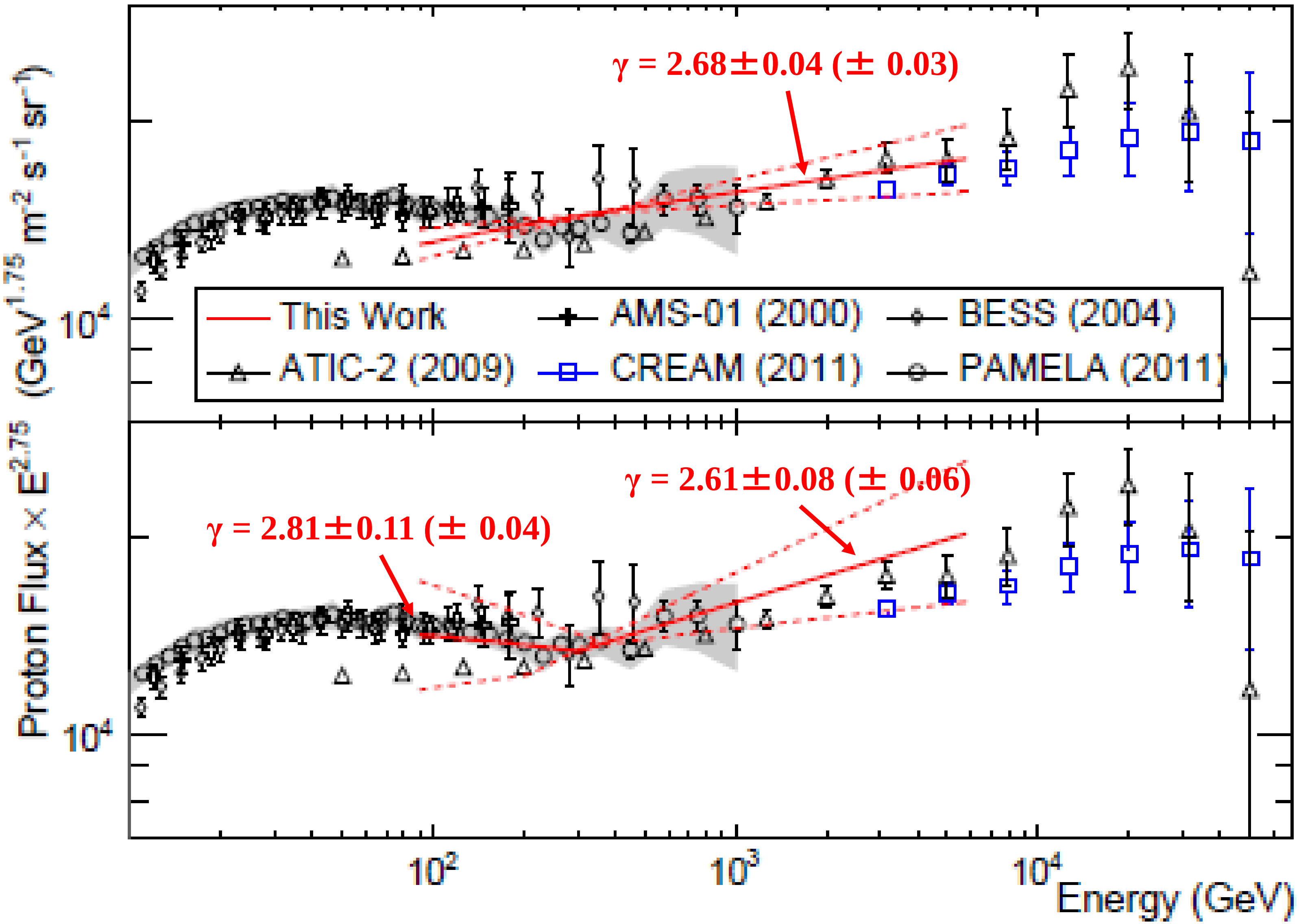
AMS-02 Comparison with PAMELA





- PAMELA: softening in the range 30 – 230 GV, spectral hardening @ 235 GV
- AMS-02: well described by a SPL
- H/He: good agreement

Inferred cosmic-ray p spectrum from Fermi



M. Ackermann et al., PRL 112 (2014) 151103

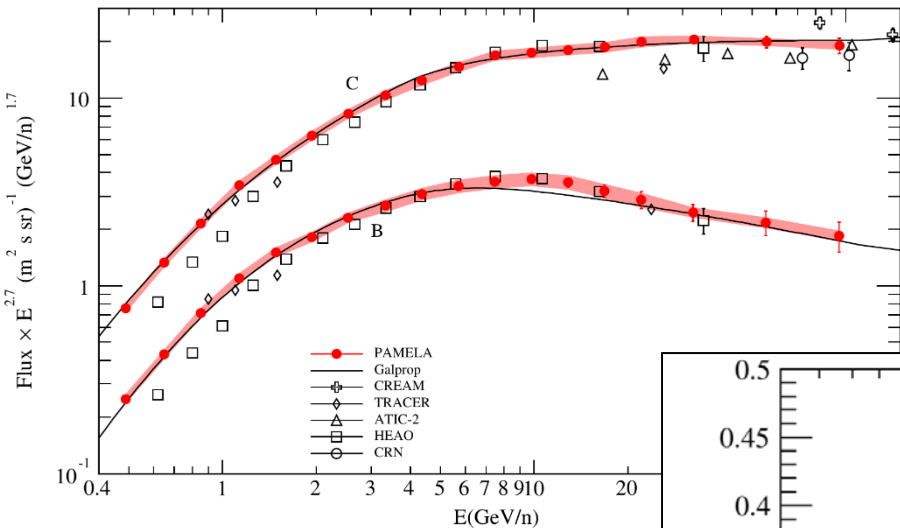
Light Nuclei and Isotopes

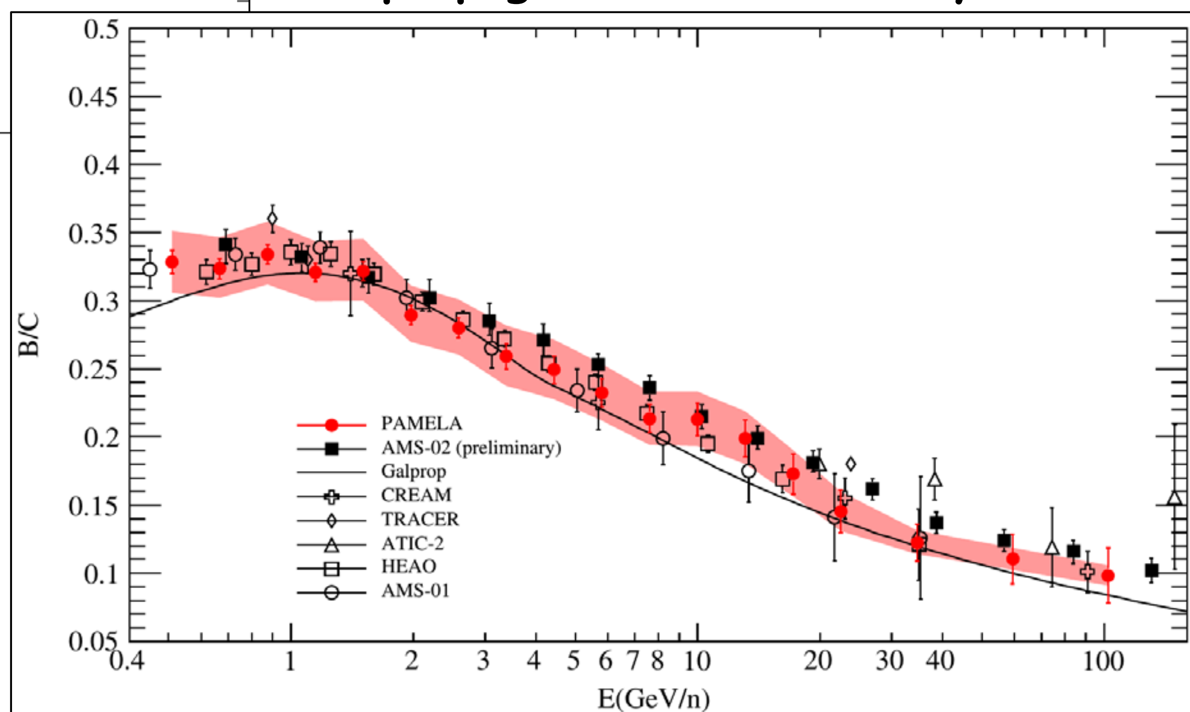
- **Tuning of cosmic-ray propagation models with measurements of secondary/primary flux ratio**

- **$^{2}H/^{1}H$ and $^{3}He/^{4}He$ are complimentary to B/C measurements in constraining propagation models (Coste et al., A&A 539 (2012) A88)**

Boron and carbon fluxes and B/C

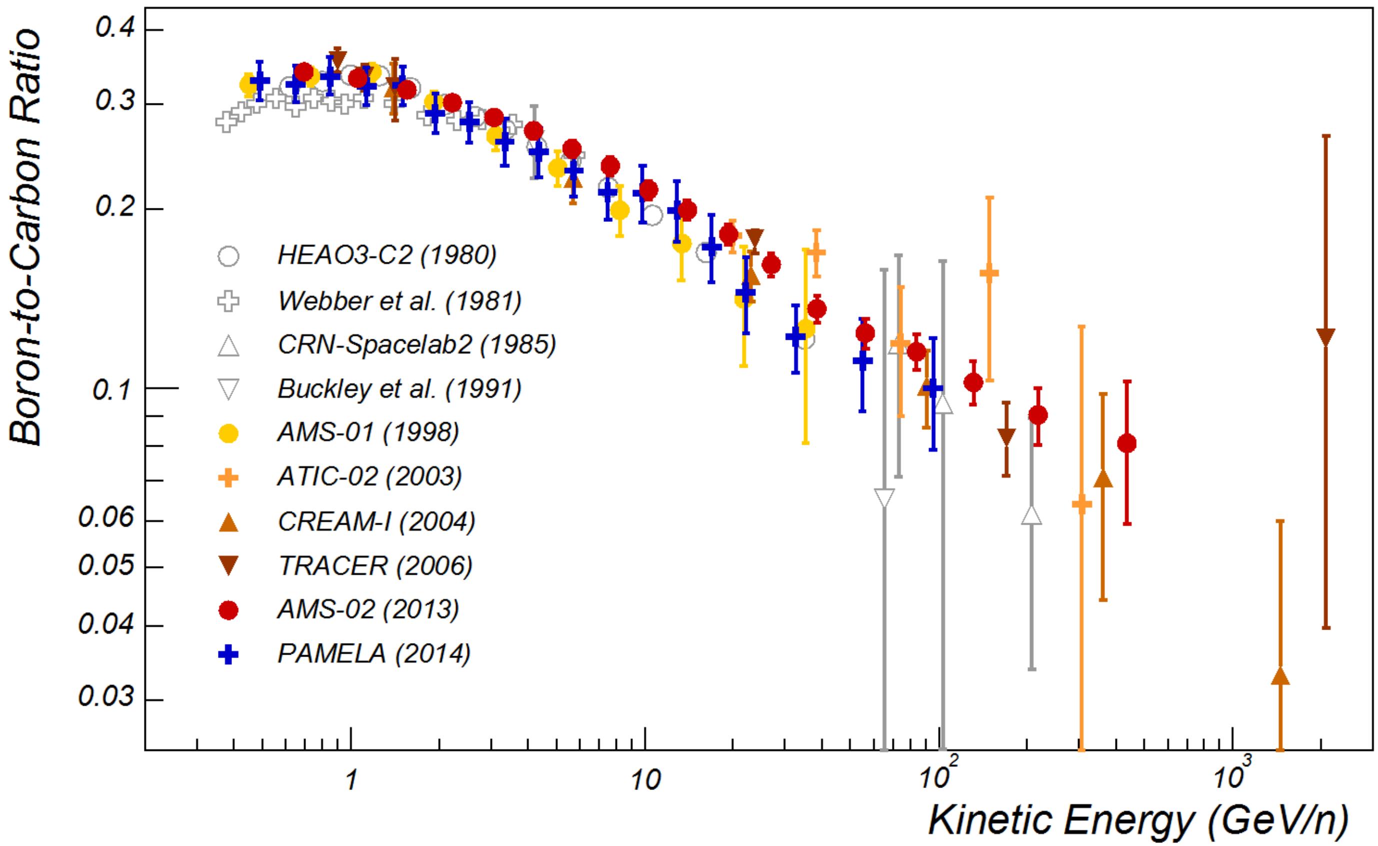
- Tracking performance:
  - σ_x = 14 μm, σ_y = 19 μm
  - MDR = 250 GV
- Modelization of cosmic-ray propagation in the Galaxy





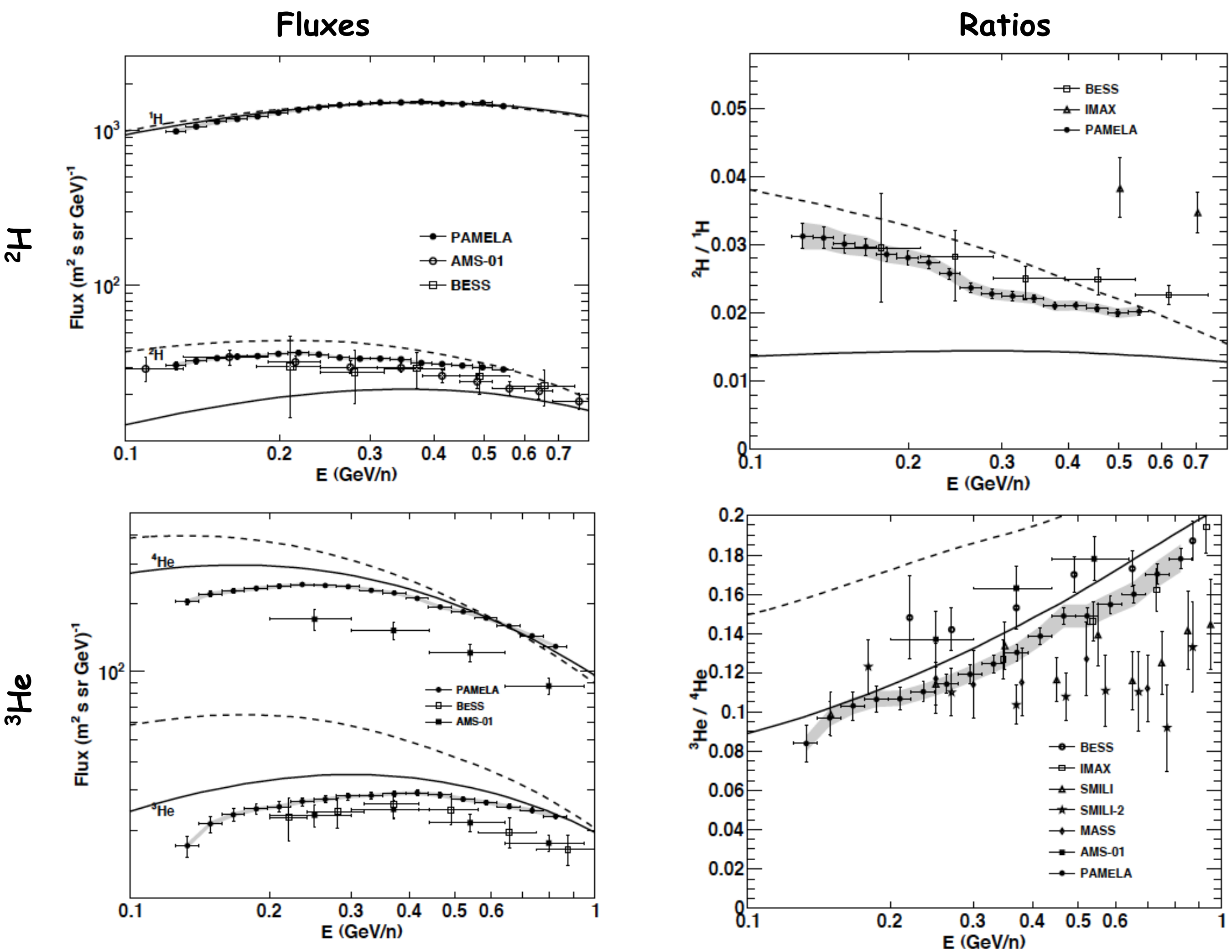
Adriani et al., ApJ 791 (2014), 93

AMS B/C



AMS-02 (ICRC-2003) → incoming pub up to 1 TeV

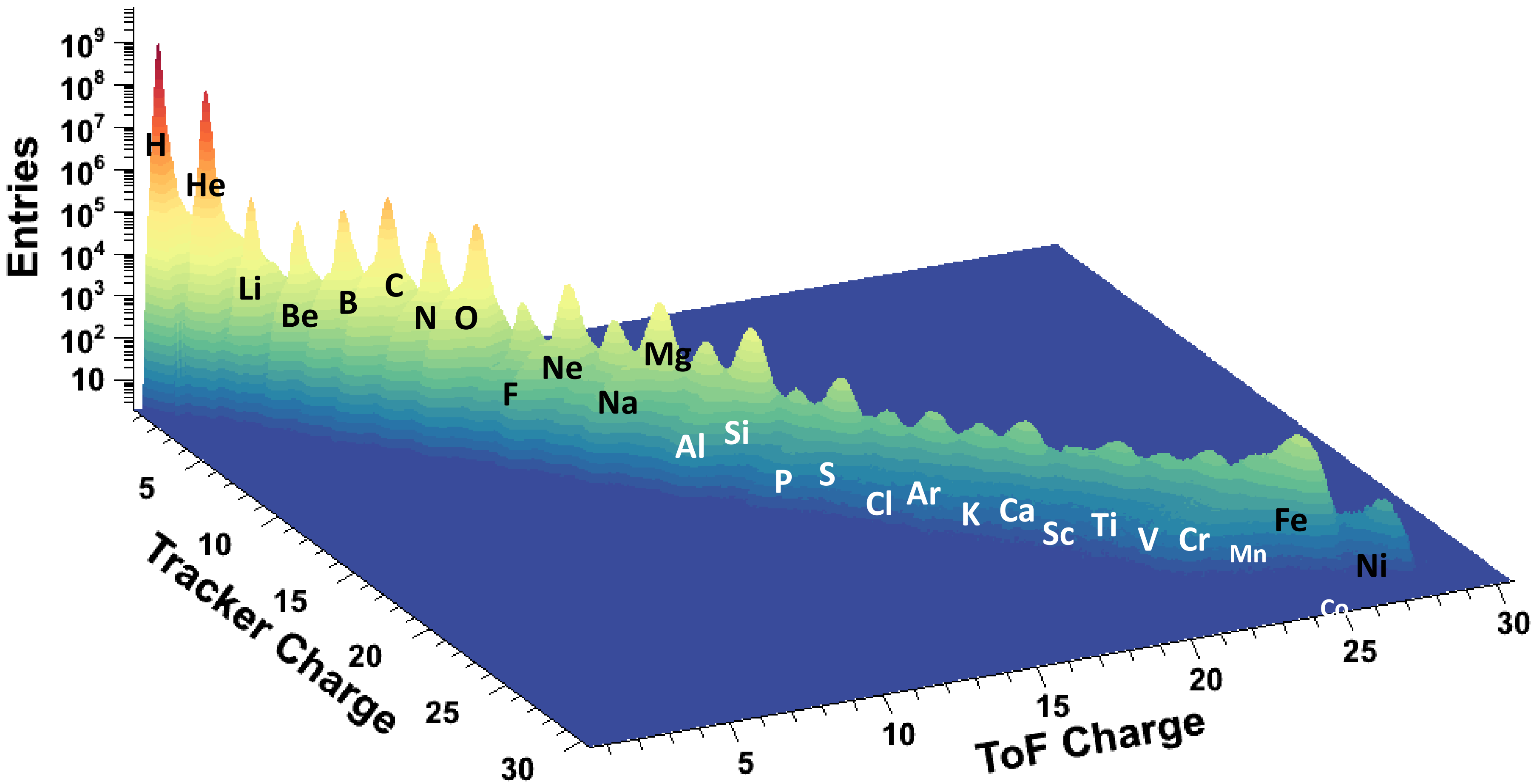
PAMELA H and He isotopes



- Modelization of cosmic-ray propagation in the Galaxy
- Most complete available measurement

Adriani et al., ApJ 770 (2013), 2

AMS Measurement of Periodic Table

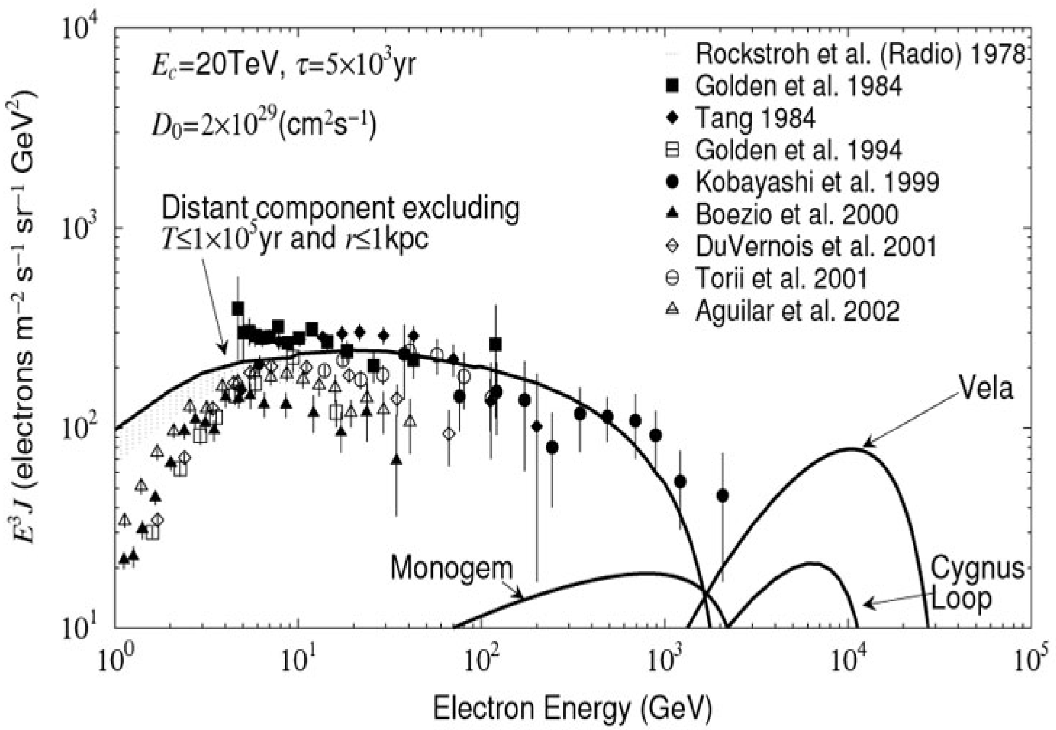


Electrons

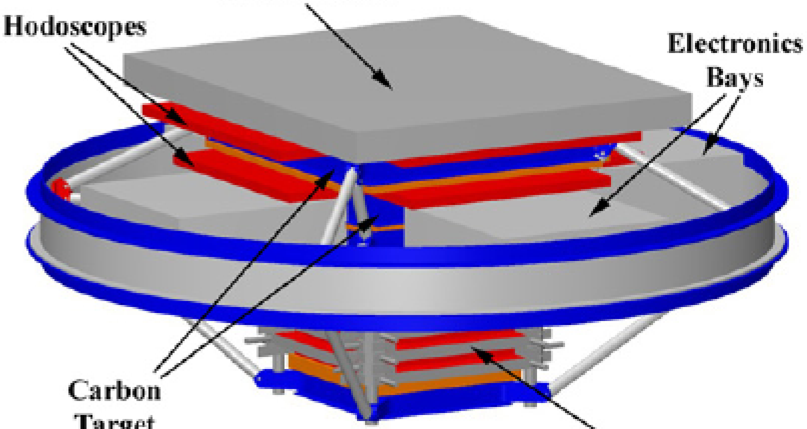
Electrons can tell us about local GCR sources

- **High energy electrons have a high energy loss rate ∝ E^2**
  - **Lifetime of ~10^5 years for >1 TeV electrons**
- **Transport of GCR through interstellar space is a diffusive process**
  - **Implies that source of high energy electrons are < 1 kpc away**

Only a handful of SNR meet the lifetime & distance criteria
Kobayashi et al., ApJ 601 (2004) 340 calculations show structure in electron spectrum at high energy

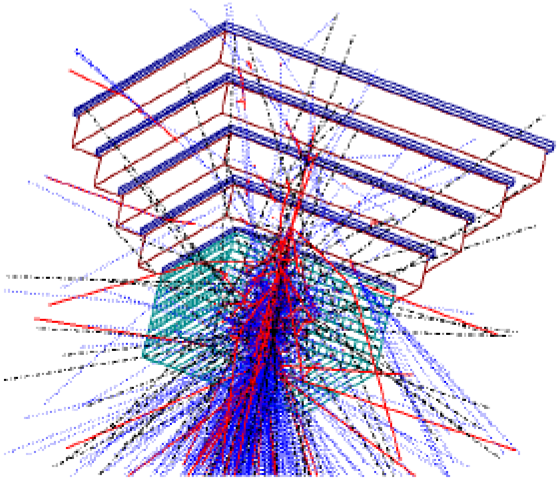


ATIC Instrument

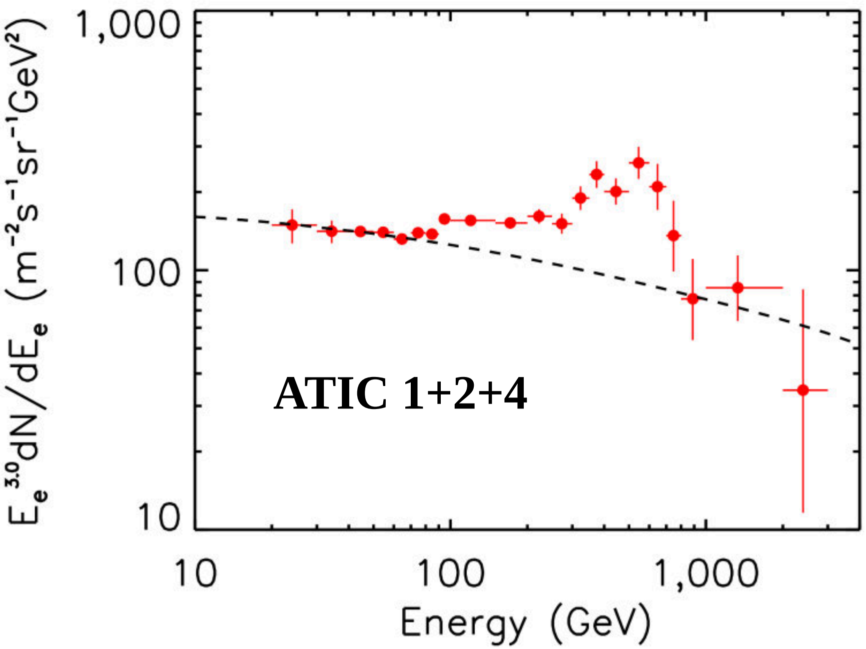


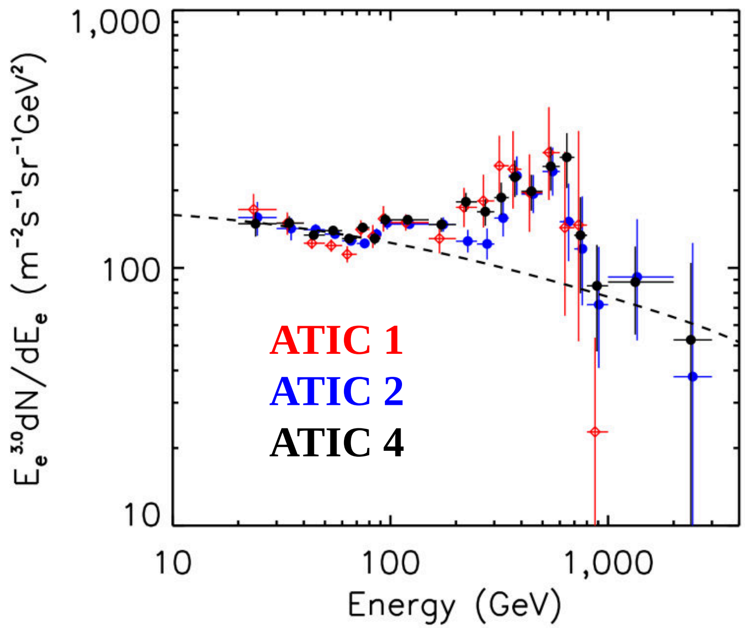
Antarctic Flights:

- <u>12/28/00 - 1/13/01</u>
- <u>12/29/02 – 1/18-03</u>
- 12/27/07 – 1/15/08



Results from three ATIC flights





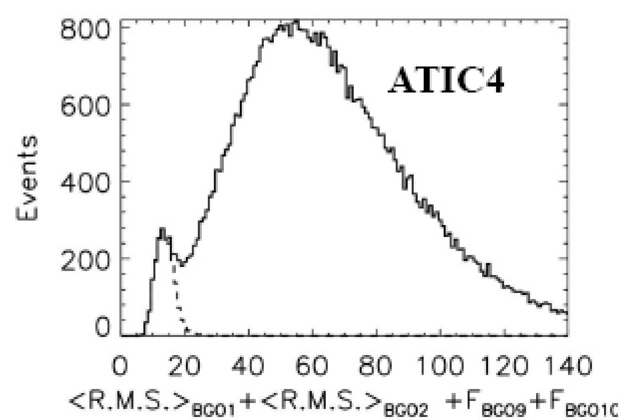
"Source on/source off" significance of bump for ATIC1+2 is about 3.8 sigma

J Chang *et al. Nature* **456**, 362 (2008)

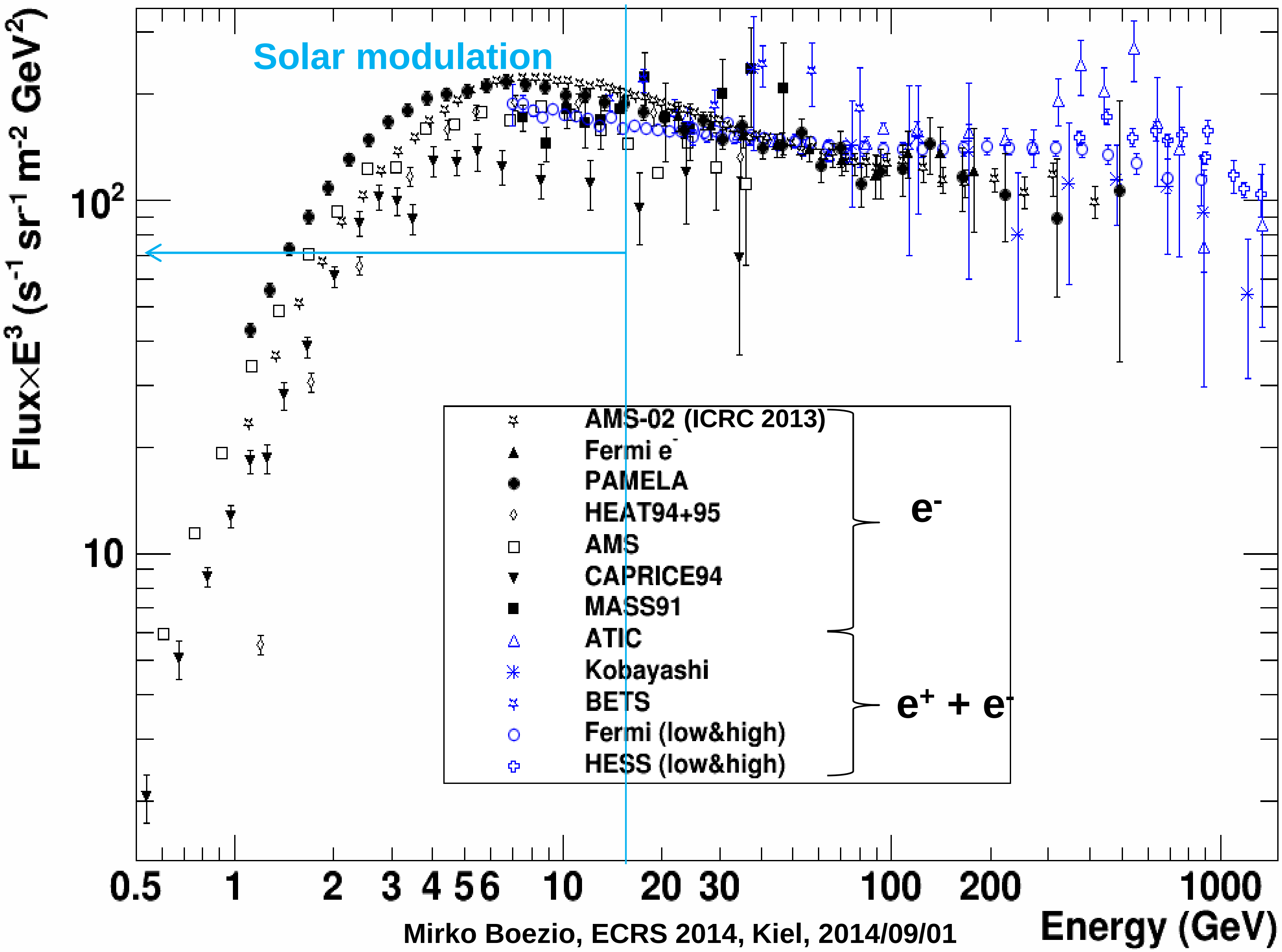
ATIC-4 with 10 BGO layers has improved e , p separation. **(~4x lower background)**

"Bump" is seen in all three flights.

Significance for ATIC1+2+4 is 5.1 sigma

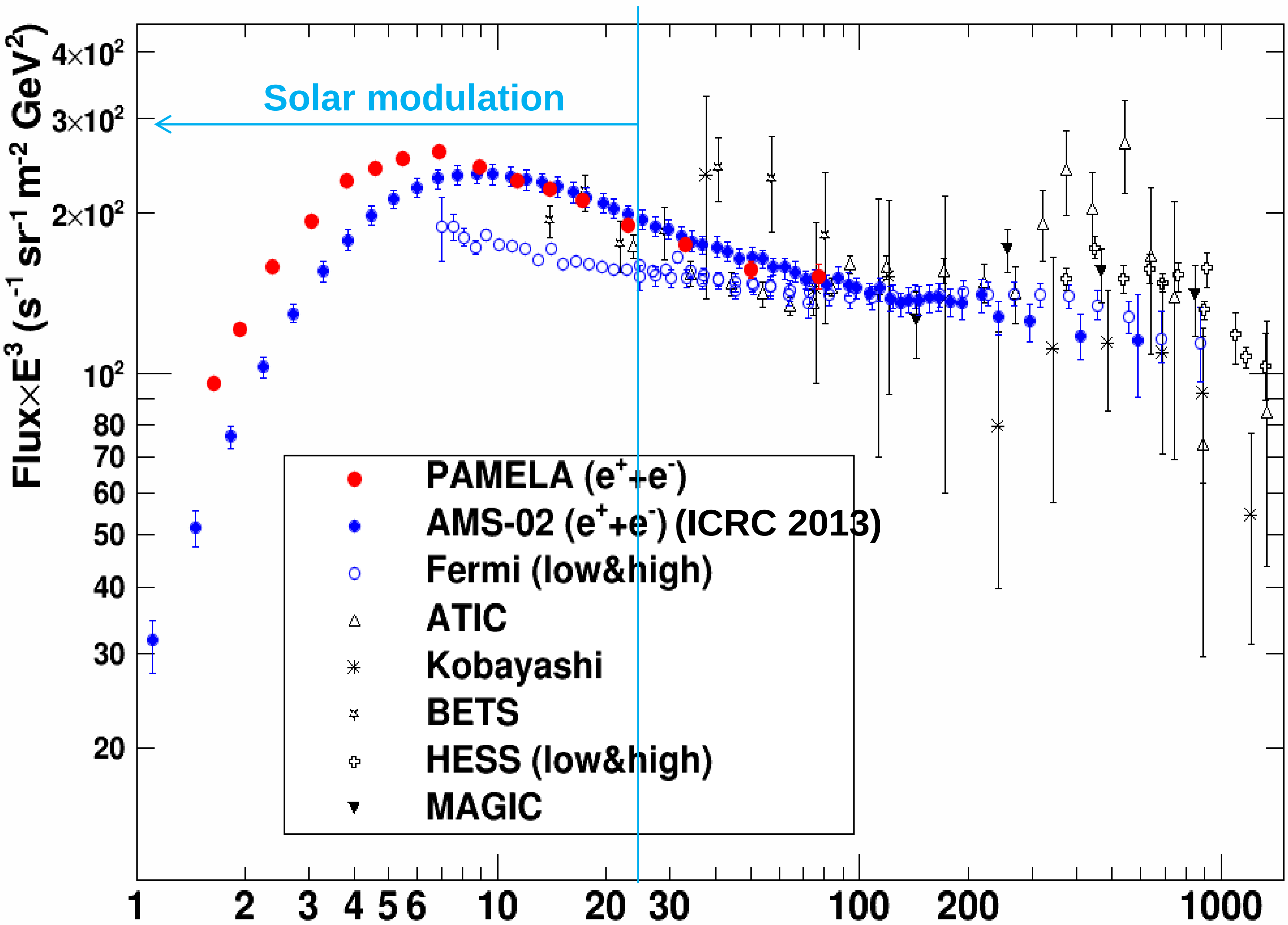


Electron Spectrum



Mirko Boezio, ECRS 2014, Kiel, 2014/09/01

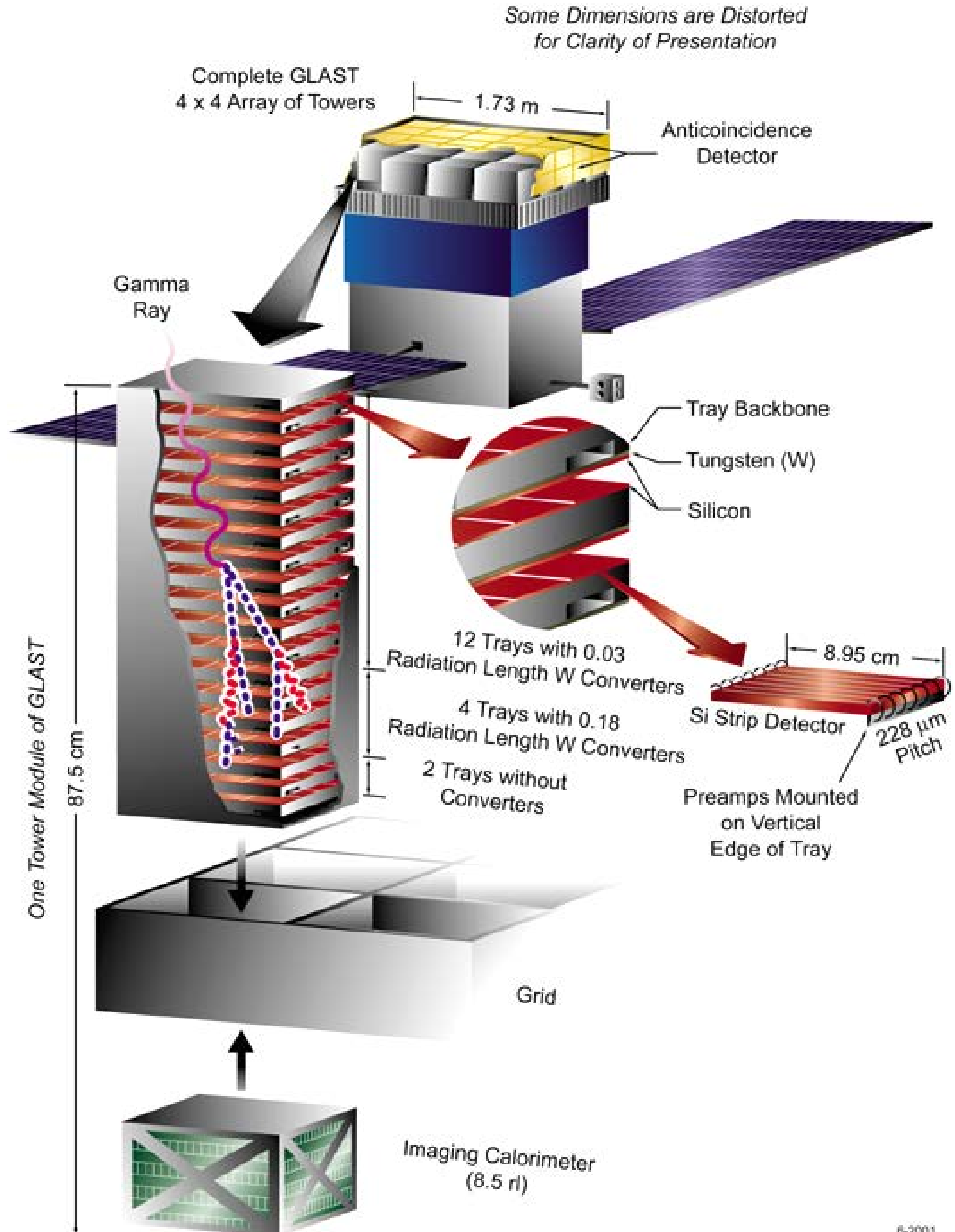
Electron (e^-+e^+) Spectrum

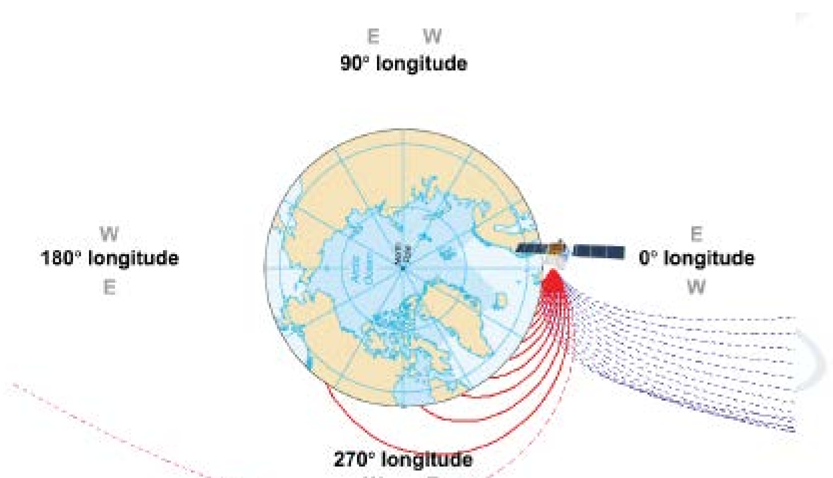


Mirko Boezio, ECRS 2014, Kiel, 2014/09/01

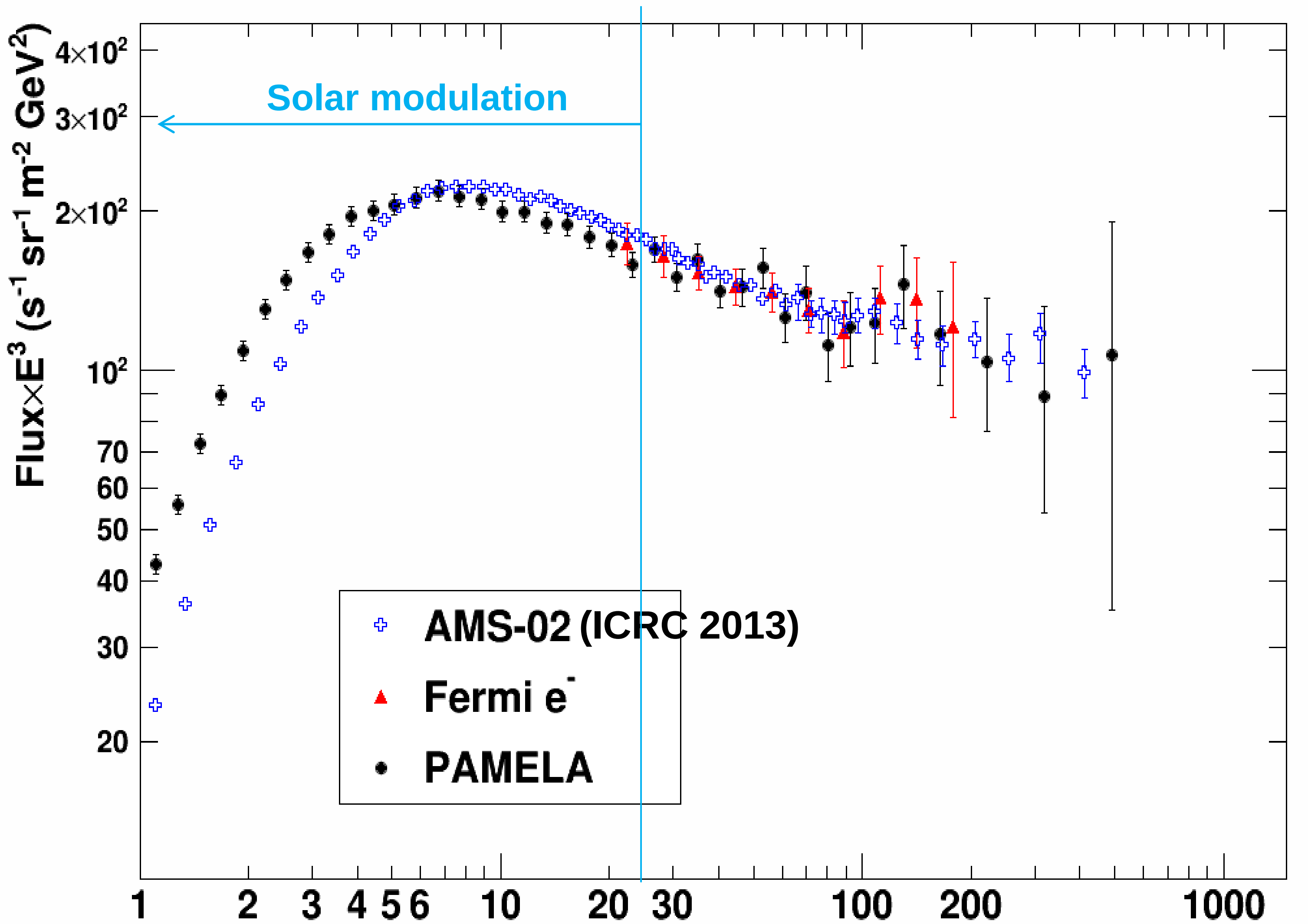
Electron (e^-) Measurements: using the Earth's Magnetic Field

GLAST/ FERMI
Gamma-Ray
Large Area Space
Telescope



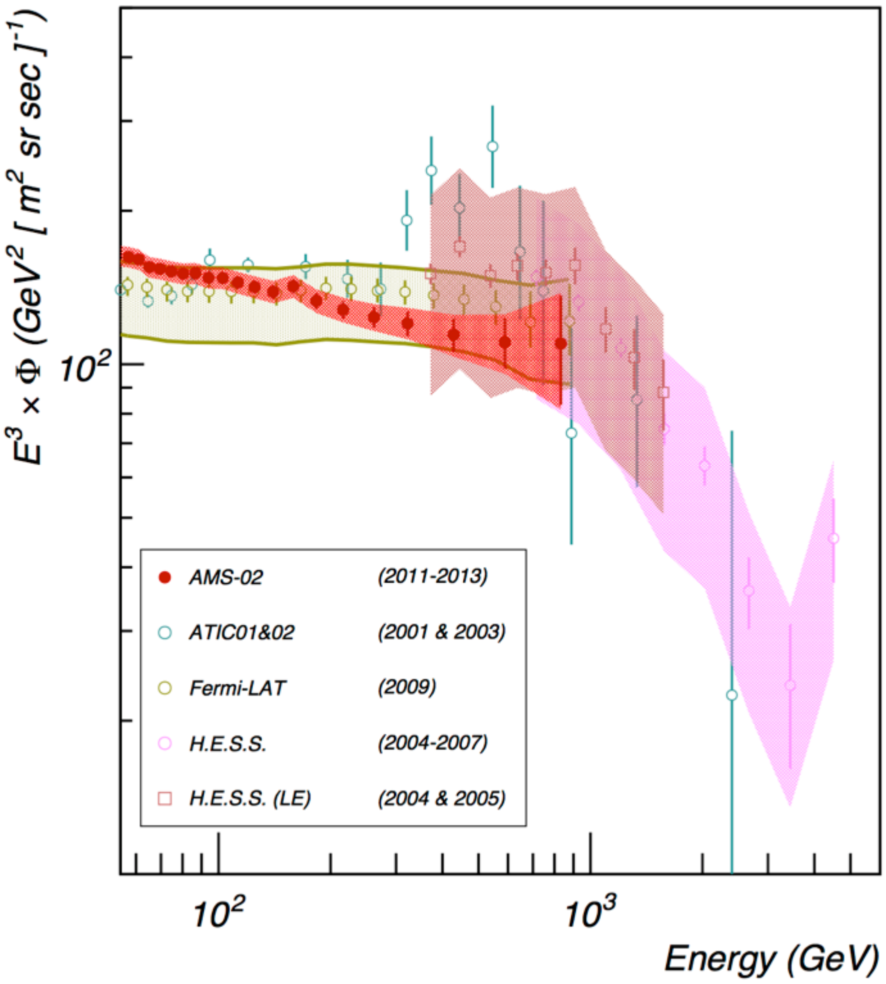


PAMELA&AMS (and Fermi) Electron (e^-) Spectrum



Mirko Boezio, ECRS 2014, Kiel, 2014/09/01

New $e^+ + e^-$ flux measurements with AMS



Taking into account also the knowledge of the energy scale….

Future Satellite Experiments with Capabilities for Electron Detection

- **CALET (Calorimeter Electron Telescope), Japanese-led international mission, launch by march 2016**

- **DAMPE (Dark Matter Particle Explorer), Chinese-led international mission, launch 2015-2016 (HERD High Energy Cosmic Radiation facility, launch ~2020?)**

- **GAMMA-400, Russian-led international mission, launch 2019**

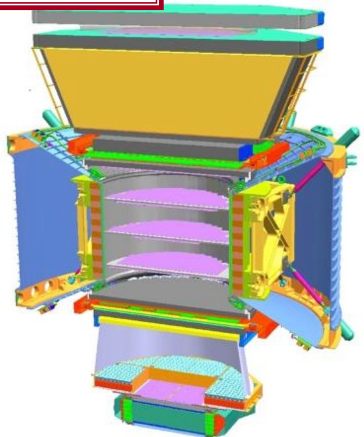
Antiparticles

Antimatter Missions in "Space"

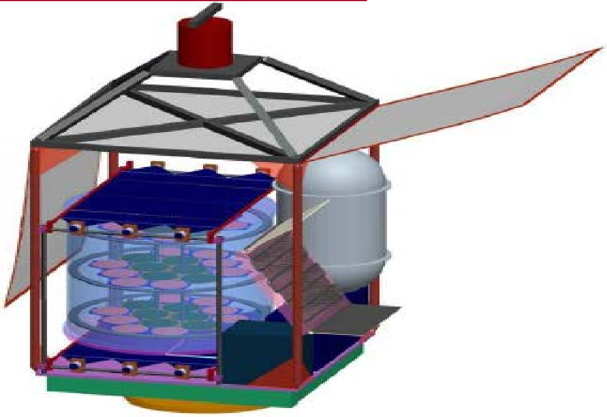
BESS LDBF
2004, 2007

PAMELA
2006-

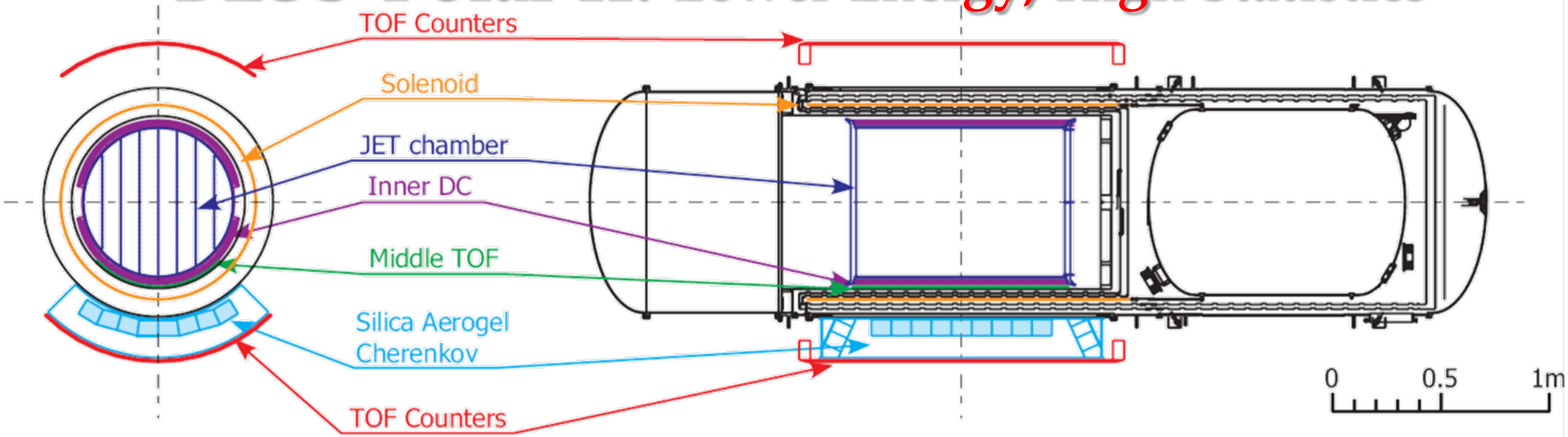
AMS-02
2011-



GAPS
2017?



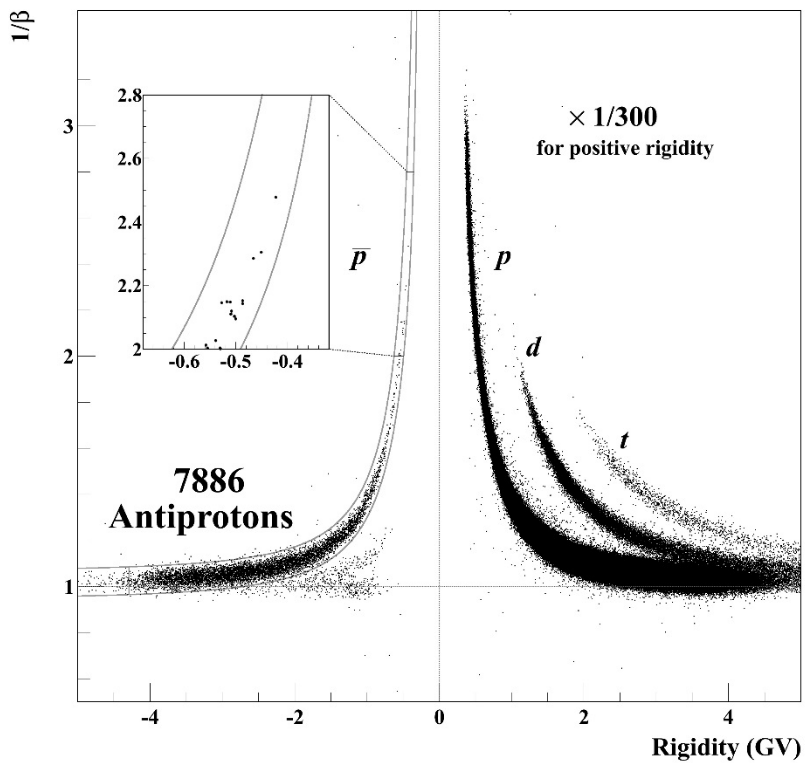
BESS-Polar II: Lower Energy, High Statistics



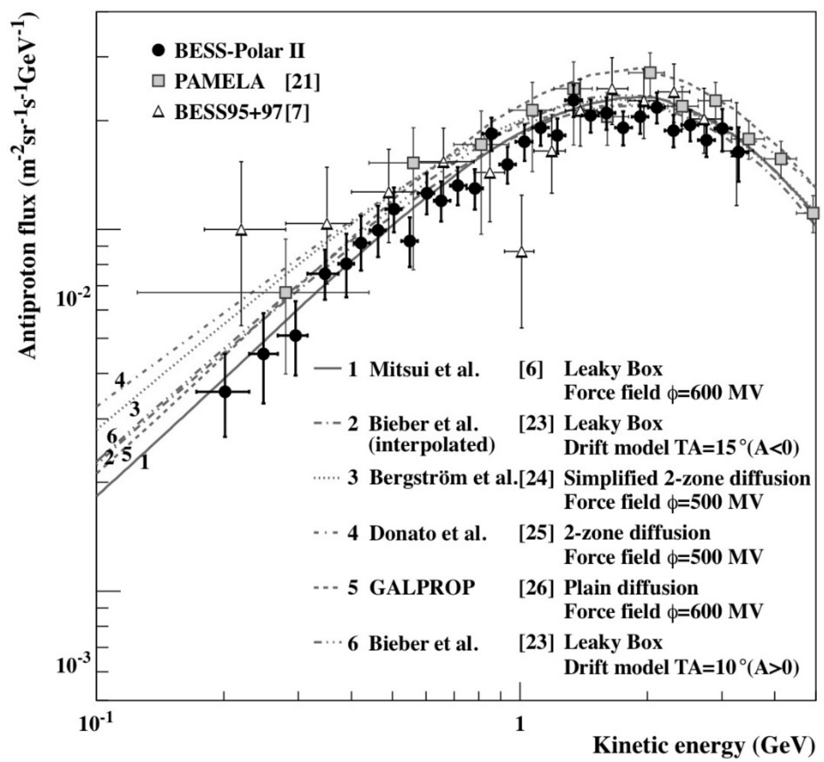
- Longer Observing Time
  - Magnet cryogen life: >25 days
    - 520 liters LHe
  - 16 TB data storage
  - Total events ~4.7 x 10^9
- Improved Reliability
  - Pressurized TOF PMT units
  - Improved electronics efficiency
- Improved Performance
  - ACC rejection power
  - Middle TOF resolution
  - Outer TOF resolution
- ~22 times present solar-minimum p-bar statistics

BESS Polar II Antiproton Measurements

BESS-Polar II Z=1 Particle Id



Antiproton Spectrum

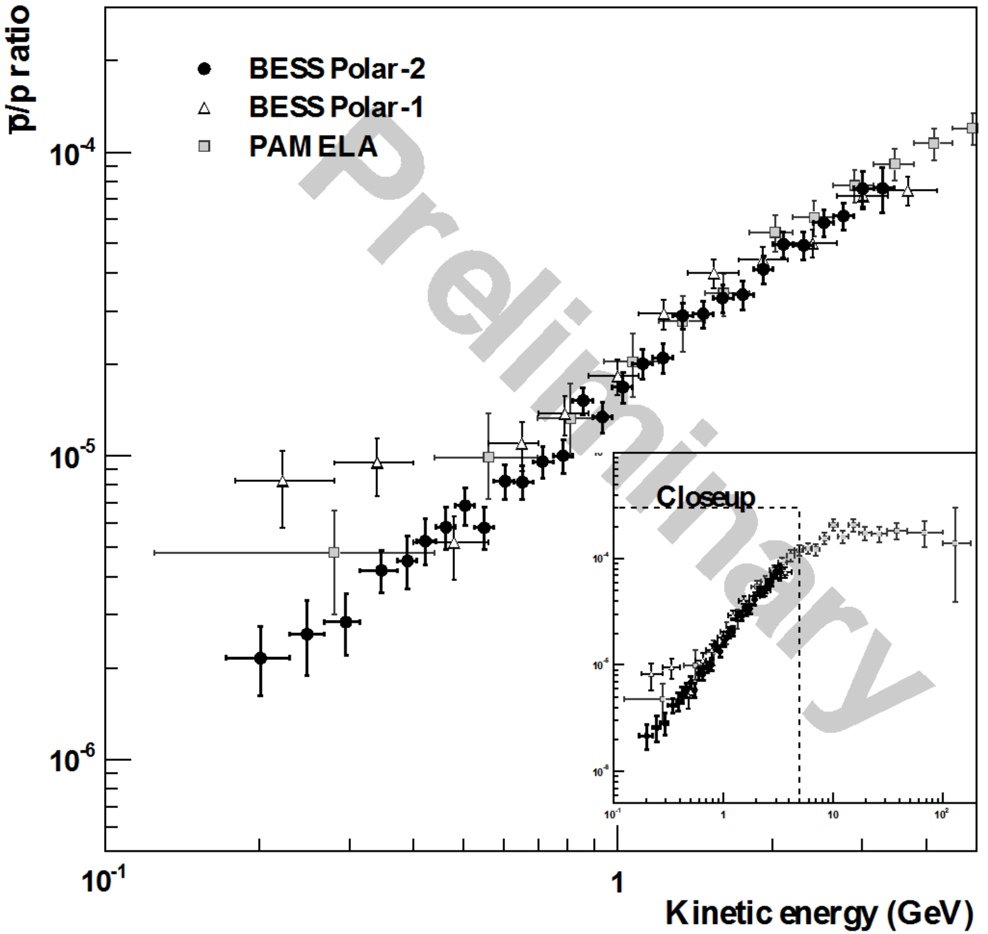


- 7886 Antiprotons ~10-20 times previous BESS solar-minimum dataset (comparison depends on energy)
- Abe *et al*., Phys. Rev. Lett.,108, 051102, 2012.

- BESS-Polar II and PAMELA spectra agree in shape but differ ~14% in absolute flux
- Both agree in shape with secondary calculations

J. W. Mitchell, TeVPA 2013

Antiproton/Proton Ratio



- Excellent agreement between BESS-Polar II and PAMELA in common energy range
- BESS-Polar I ratio flatter at low energy than BESS-Polar II or PAMELA due to solar modulation

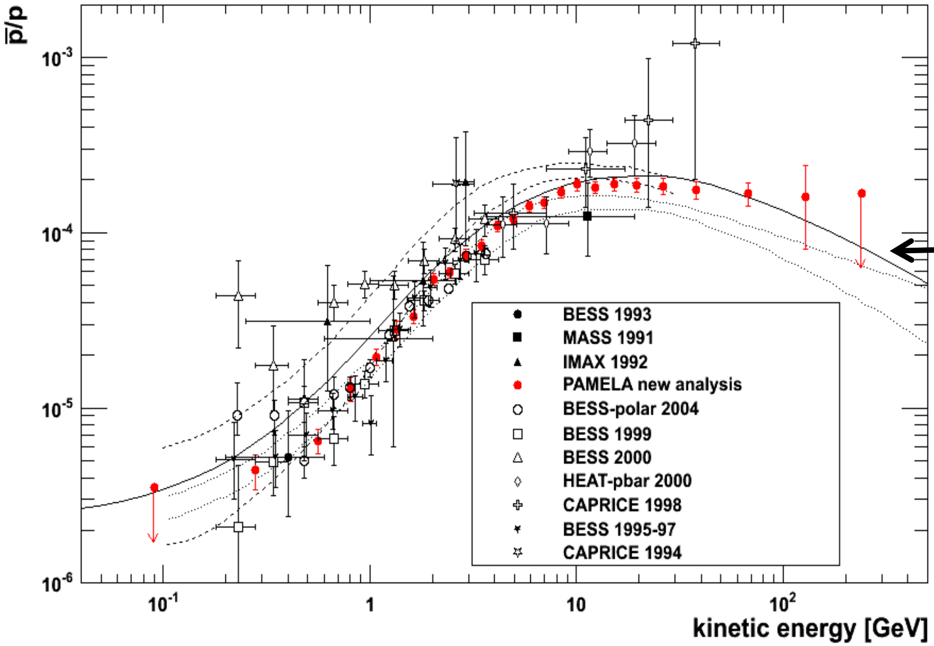
J. W. Mitchell, TeVPA 2013

Positrons and Antiprotons with PAMELA & AMS

See also talks by R. Battiston and

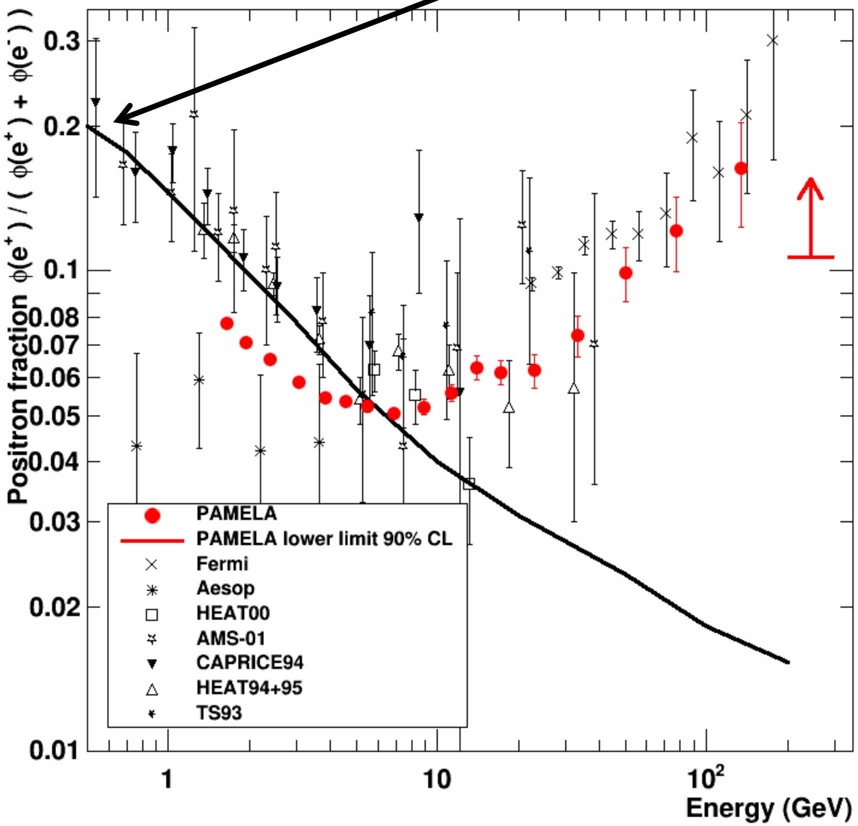
L. Bergström

PAMELA Antiparticle Results: Ratios



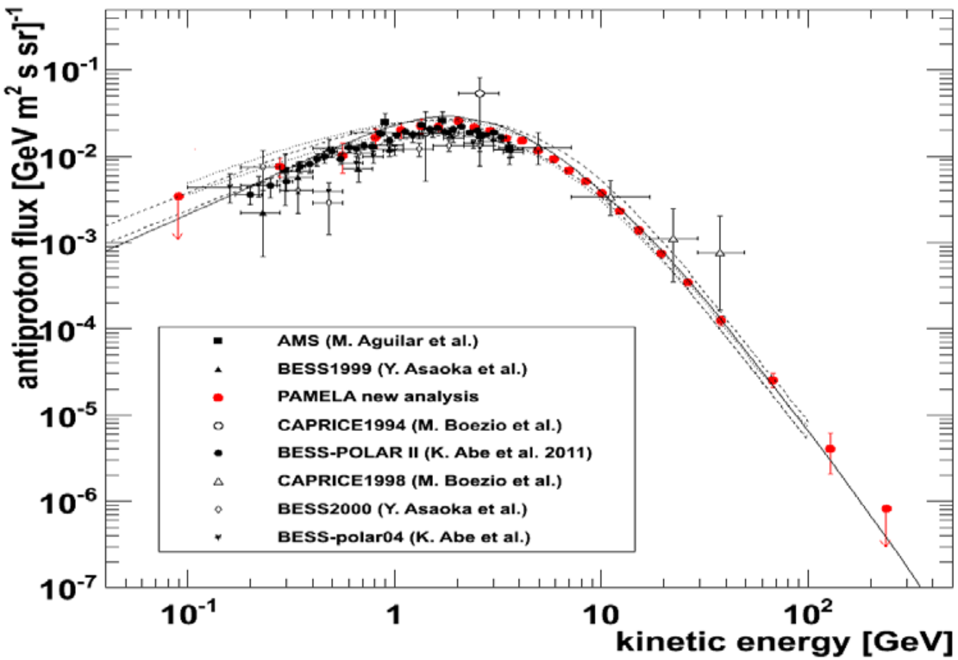
O. Adriani et al,
PRL 102 (2009) 051101;
PRL 105 (2010) 121101;
Phys. Rep. (2014).

Secondary production calculations



O. Adriani et al.,
Nature 458 (2009) 607;
Astropart. Phys. 34 (2010) 1;
PRL 111 (2013) 081102.

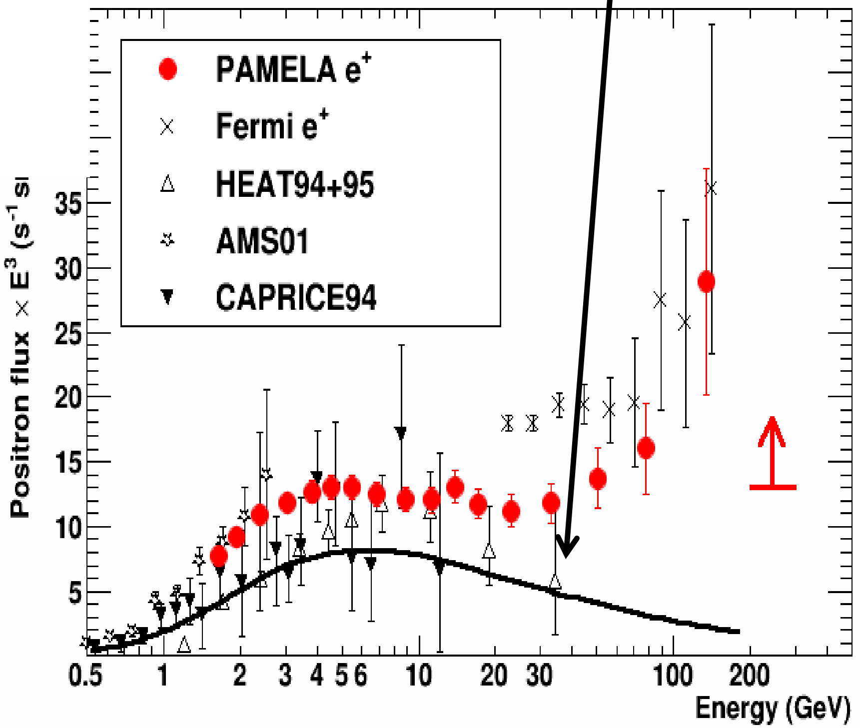
PAMELA Antiparticle Results: Fluxes



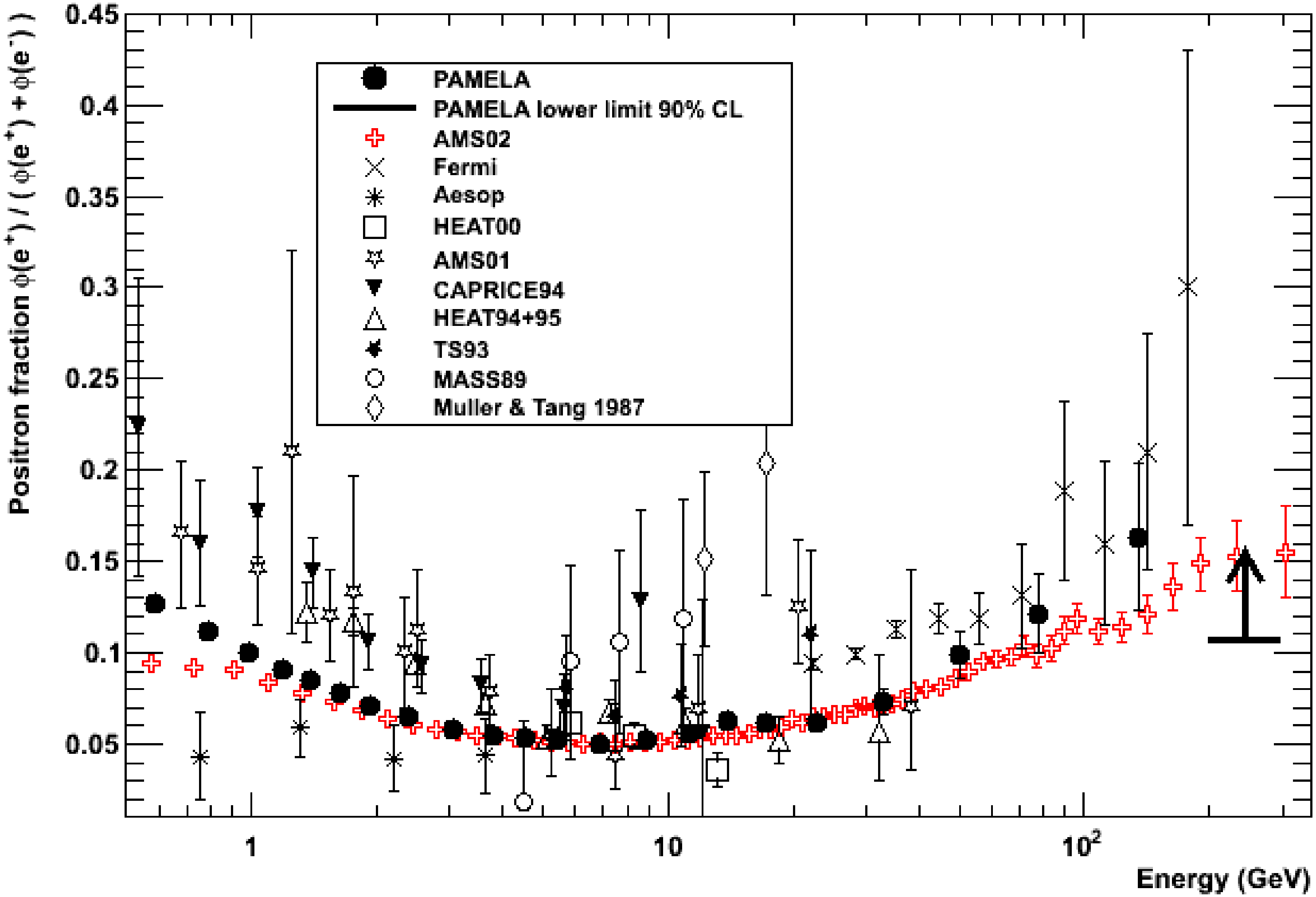
O. Adriani et al,
PRL 105 (2010) 121101;
Phys. Rep. (2014).

Secondary production calculations

O. Adriani et al.,
PRL 111 (2013) 081102.

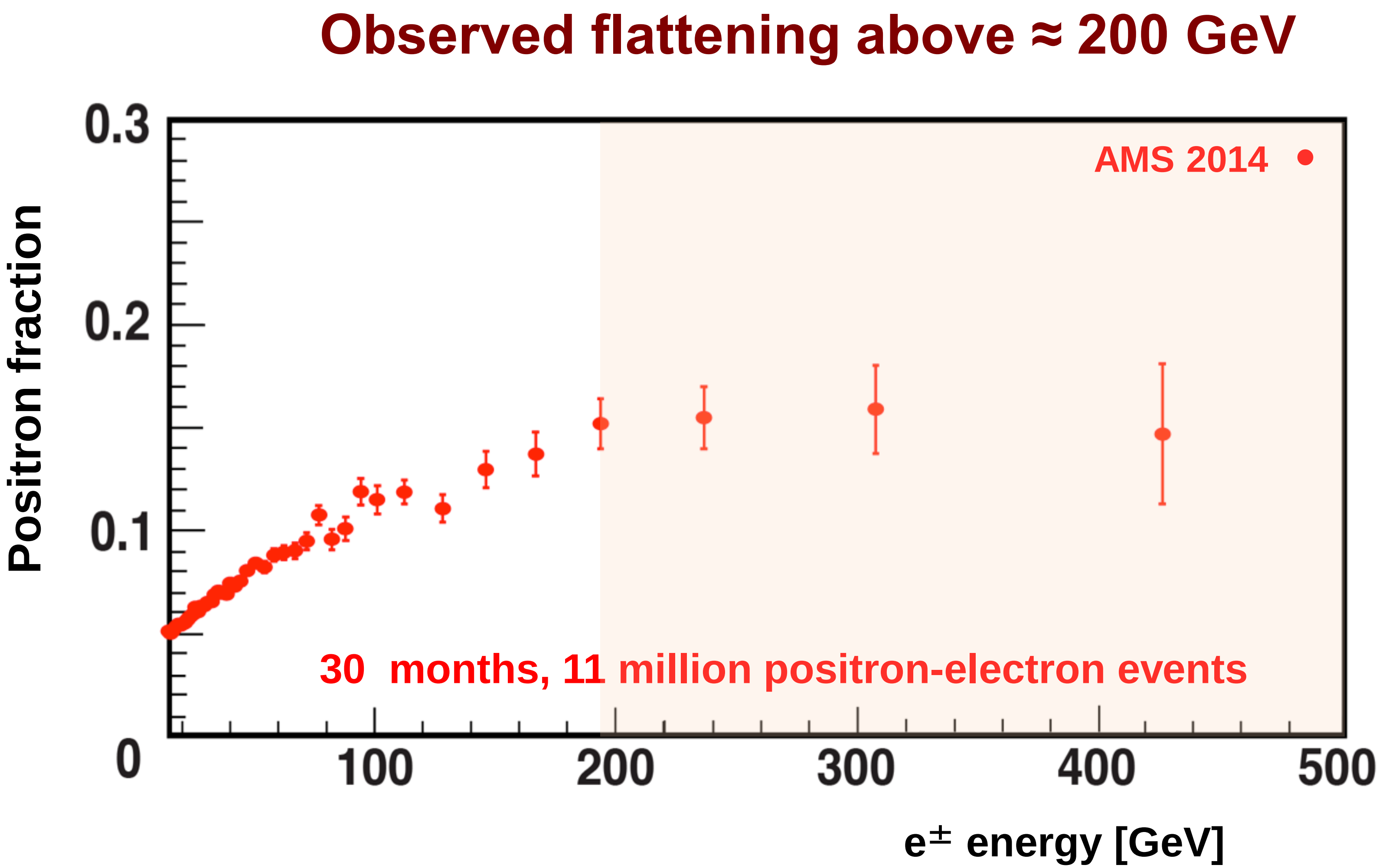


AMS Positron Fraction



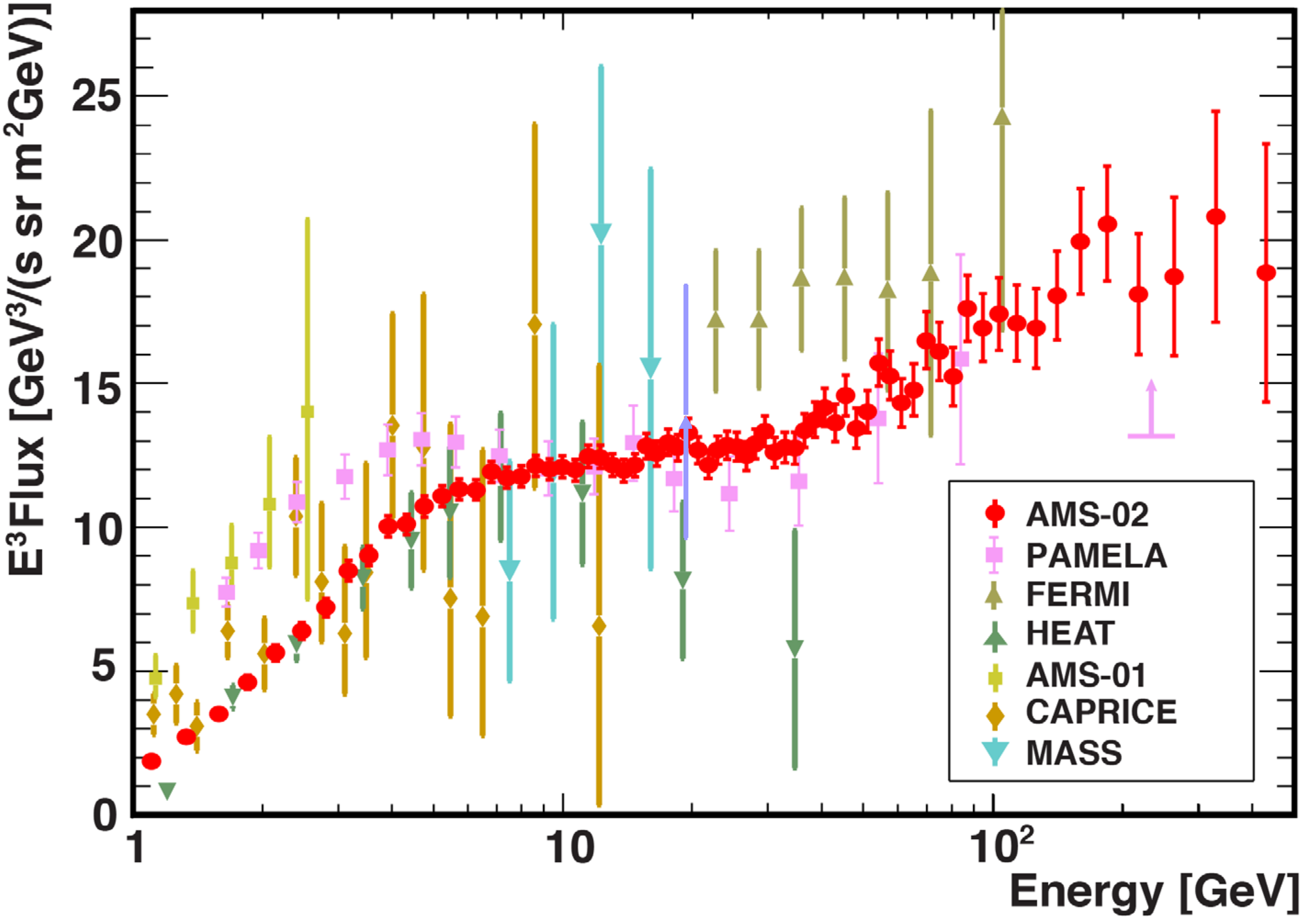
M. Aguilar, Phys.Rev.Lett. 110 (2013) 141102

2014: New Results on Positron Fraction

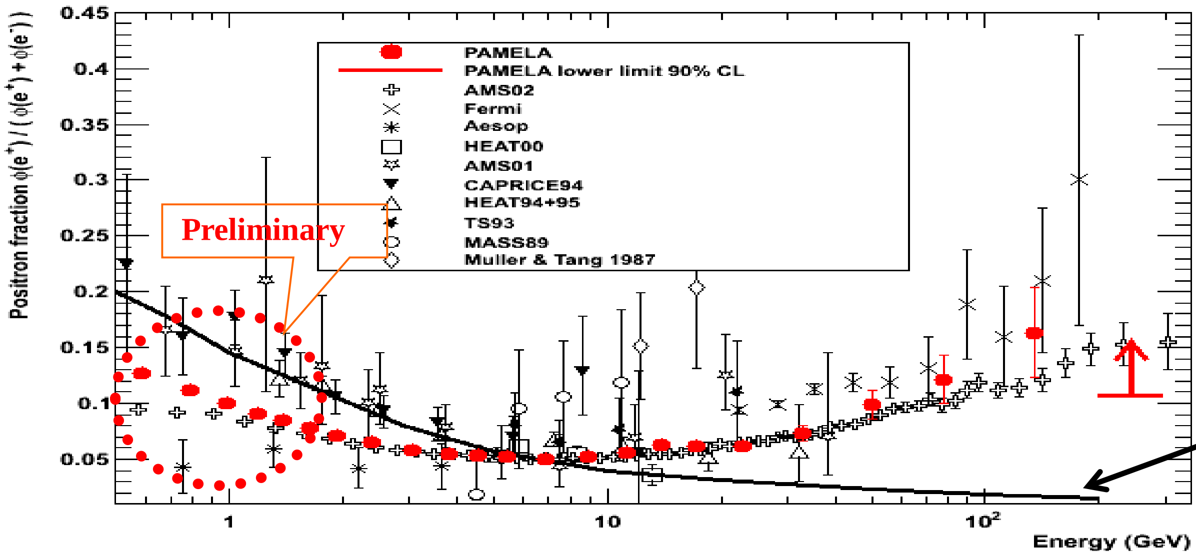


To appear in PRL

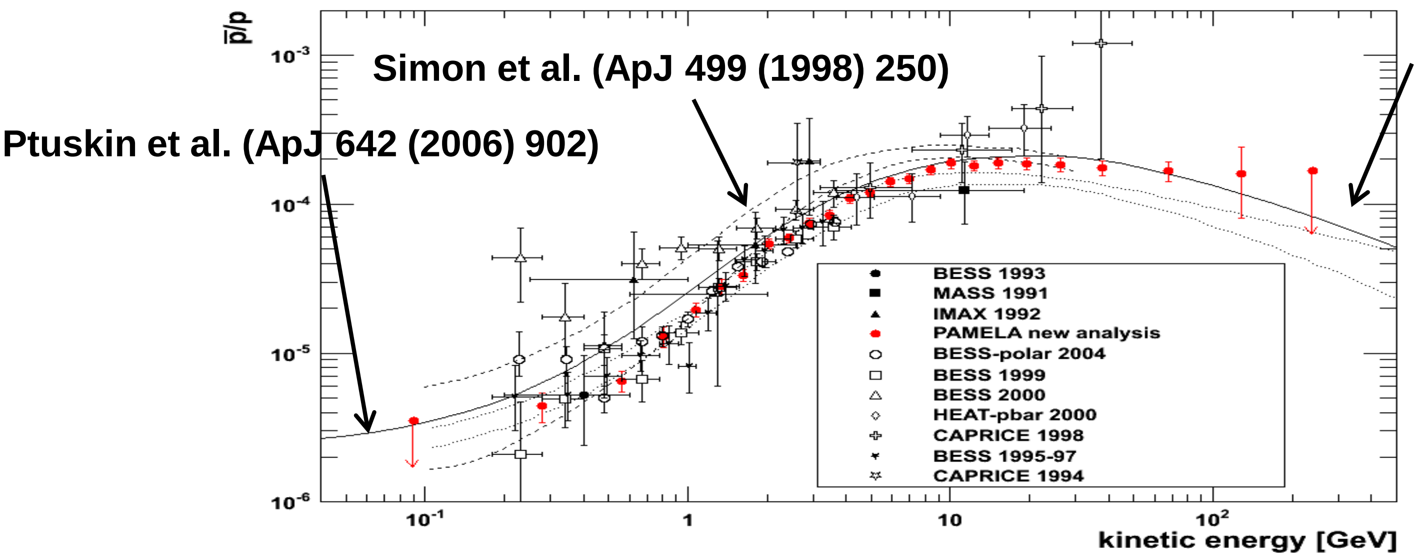
Positron Flux Data with AMS



A Challenging Puzzle for CR Physics



CR Positron spectrum significantly harder than expectations from secondary production Moskalenko & Strong 98



Donato et al. (PRL 102 (2009) 071301)

But antiprotons in CRs are in agreement with secondary production

Implications

A rising positron fraction requires:

1. **An additional component of positrons with spectrum flatter than CR primary electrons (see talks by R. Battiston and L. Bergström)**

2. **A diffusion coefficient with a weird energy dependence (BUT this should reflect in the CR spectrum as well)**

3. **Subtleties of Propagation**

Courtesy by P. Blasi

Conclusions

- **Cosmic-Ray/Astroparticle physics from is a fascinating field, fertile and rich of scientific potentials.**
- **PAMELA and AMS have and are going to present very precise measurements of the cosmic-ray energy spectra, their composition and their antimatter component.**
- **Additionally, new experiments are developed that will directly detect cosmic rays and significally extend the energy range and statistical significance of their energy spectra.**
- **Stay tuned, interesting times ahead!**

Thanks!