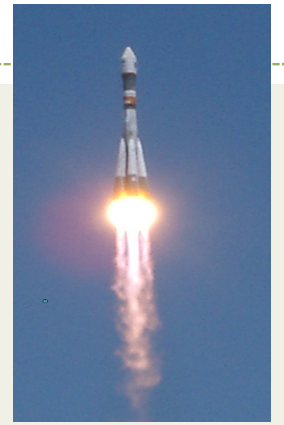
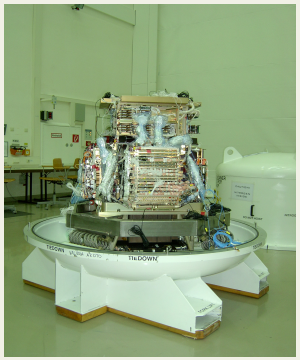
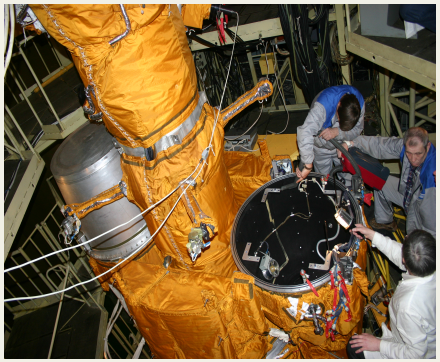
Recent results from the space experiment PAMELA



ROBERTA SPARVOLI

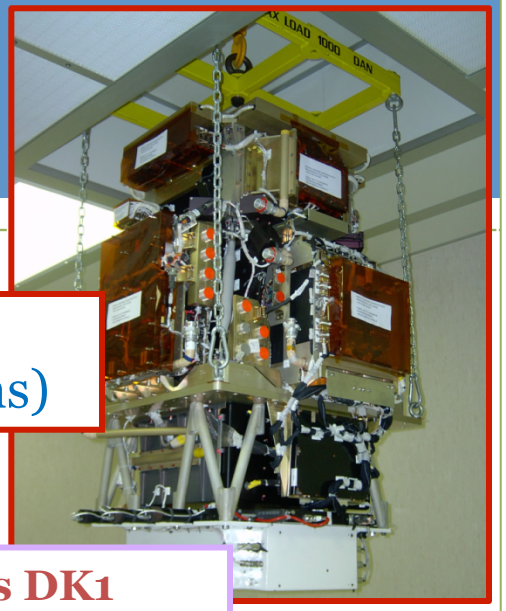
UNIVERSITY OF ROME TOR VERGATA
& INFN (ITALIAN NATIONAL INSTITUTE OF NUCLEAR PHYSICS)



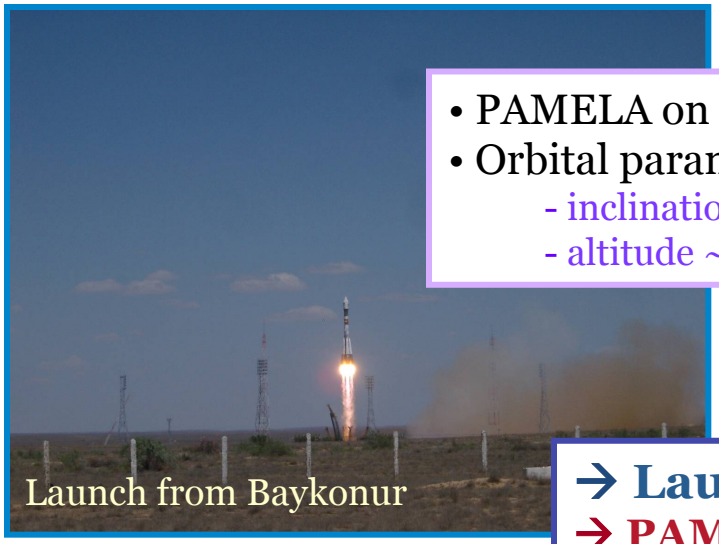


PAMELA

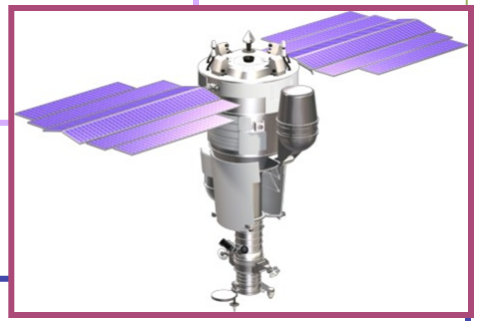
Payload for Matter/antimatter Exploration and Light-nuclei Astrophysics



- **Direct** detection of CRs in space
- Main focus on **antiparticles** (antiprotons and positrons)



- PAMELA on board of Russian satellite **Resurs DK1**
- Orbital parameters:
  - inclination ~70° (⇒ low energy)
  - altitude ~ 360-600 km (elliptical)



→ **Launched on 15th June 2006**

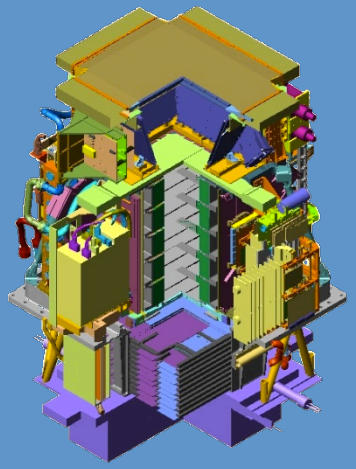
→ **PAMELA in continuous data-taking mode since then!**

PAMELA detectors

Main requirements:

- high-sensitivity antiparticle identification

- precise momentum measurement

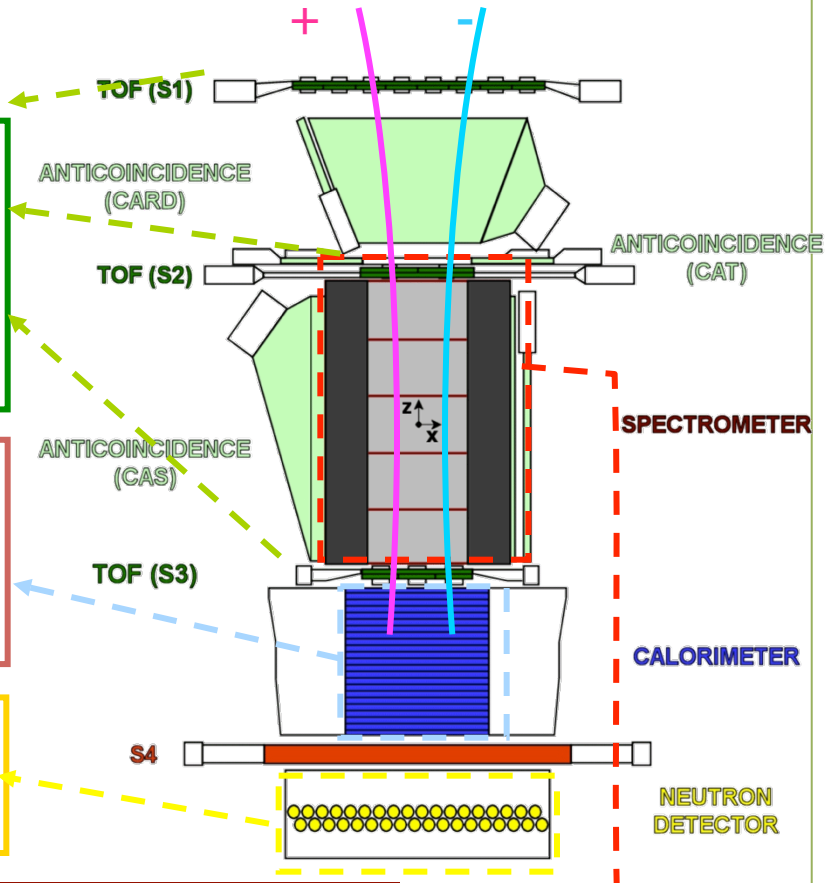


Time-Of-Flight
plastic scintillators + PMT:
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX.

Electromagnetic calorimeter
W/Si sampling (16.3 Xo, 0.6 λI)
- Discrimination e+ / p, anti-p / e⁻ (shower topology)
- Direct E measurement for e⁻

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

Spectrometer
microstrip silicon tracking system + permanent magnet
It provides:
- *Magnetic rigidity* → R = pc/Ze
- *Charge sign*
- *Charge value from dE/dx*



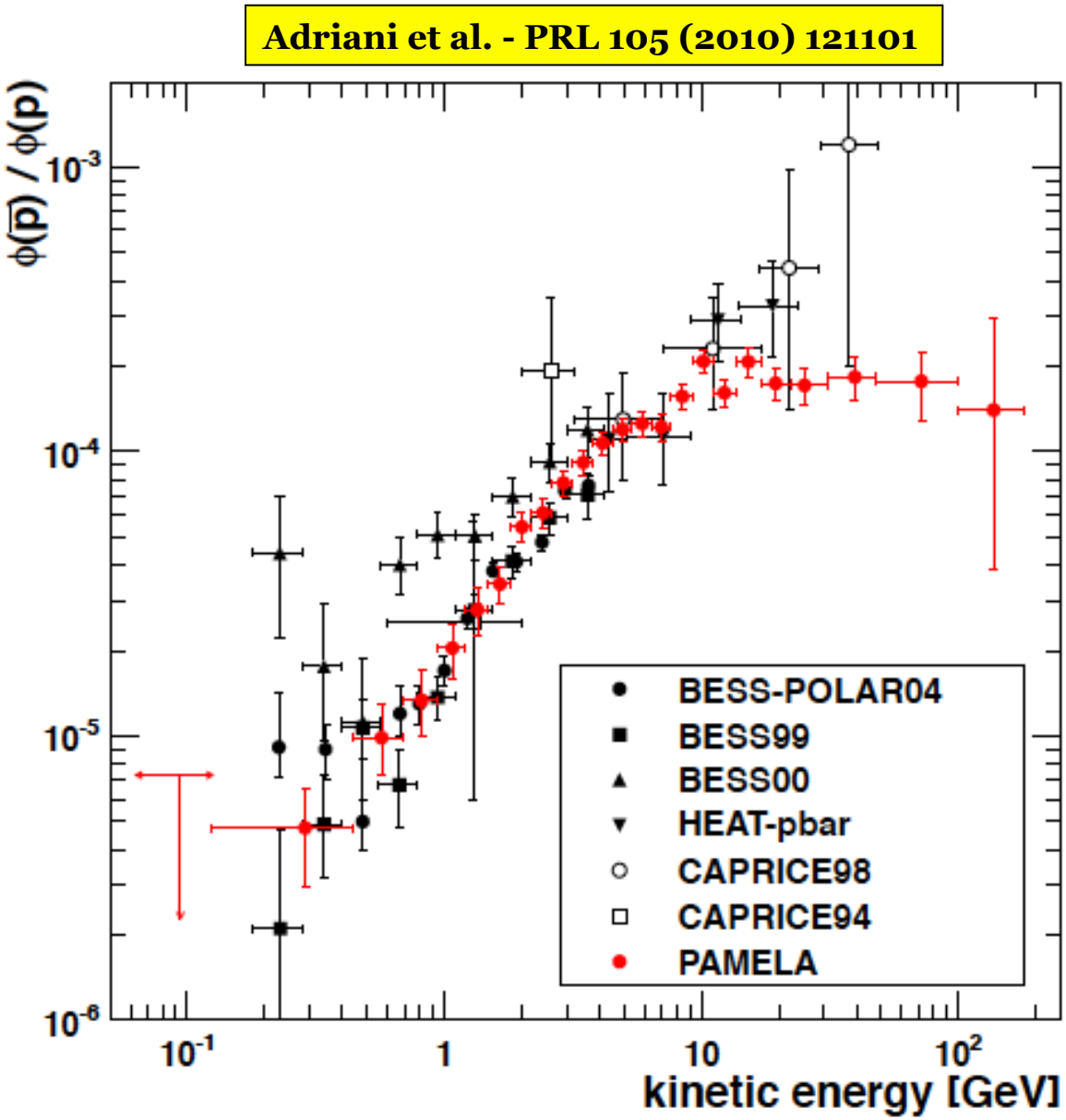
GF: 21.5 cm^2 sr
Mass: 470 kg
Size: 130x70x70 cm^3
Power Budget: 360W

Antiparticles

Antiproton-to-proton ratio

100 MeV- 200 GeV

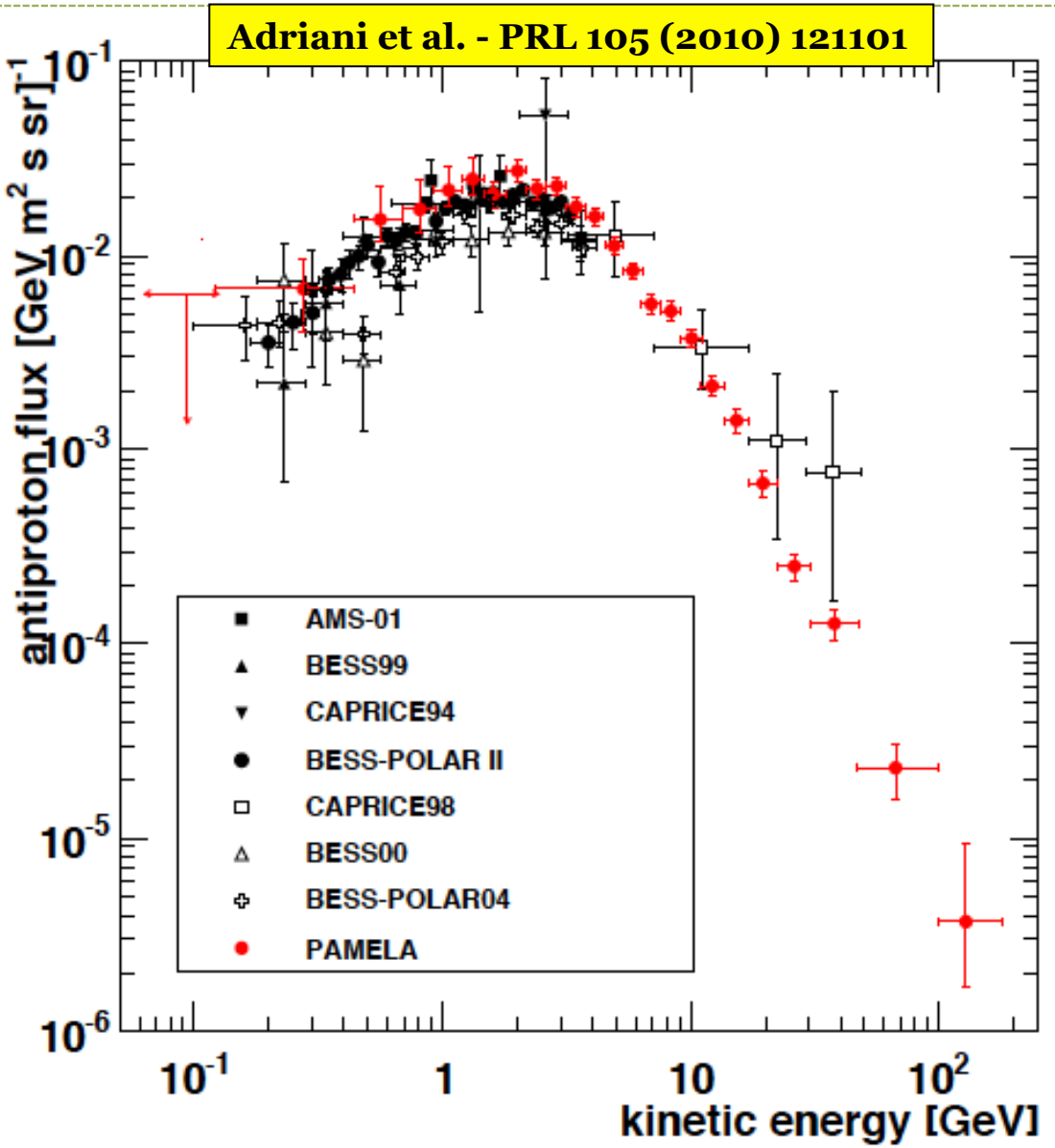
Largest energy range covered so far !



Antiproton flux

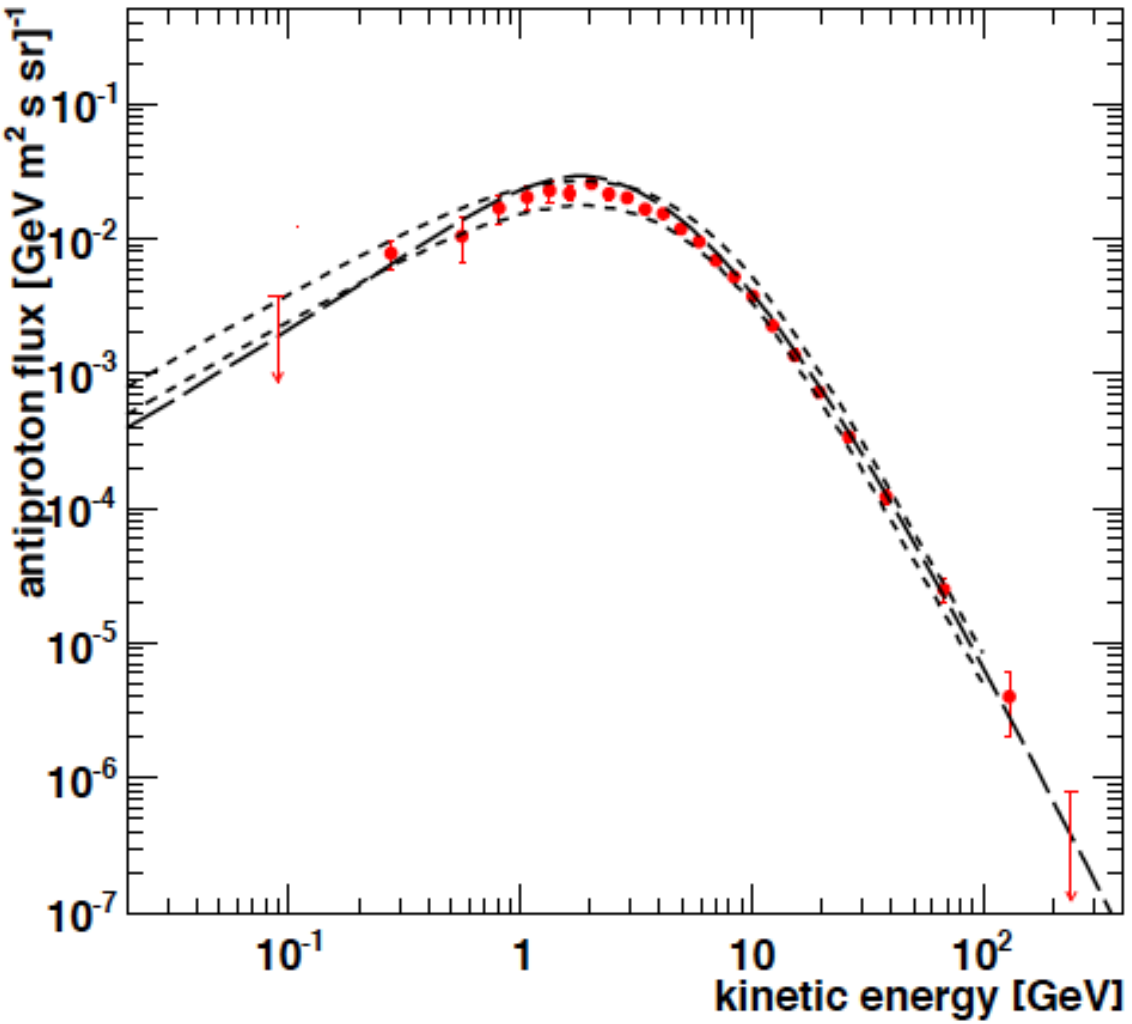
100 MeV- 200 GeV

Largest energy range covered so far !



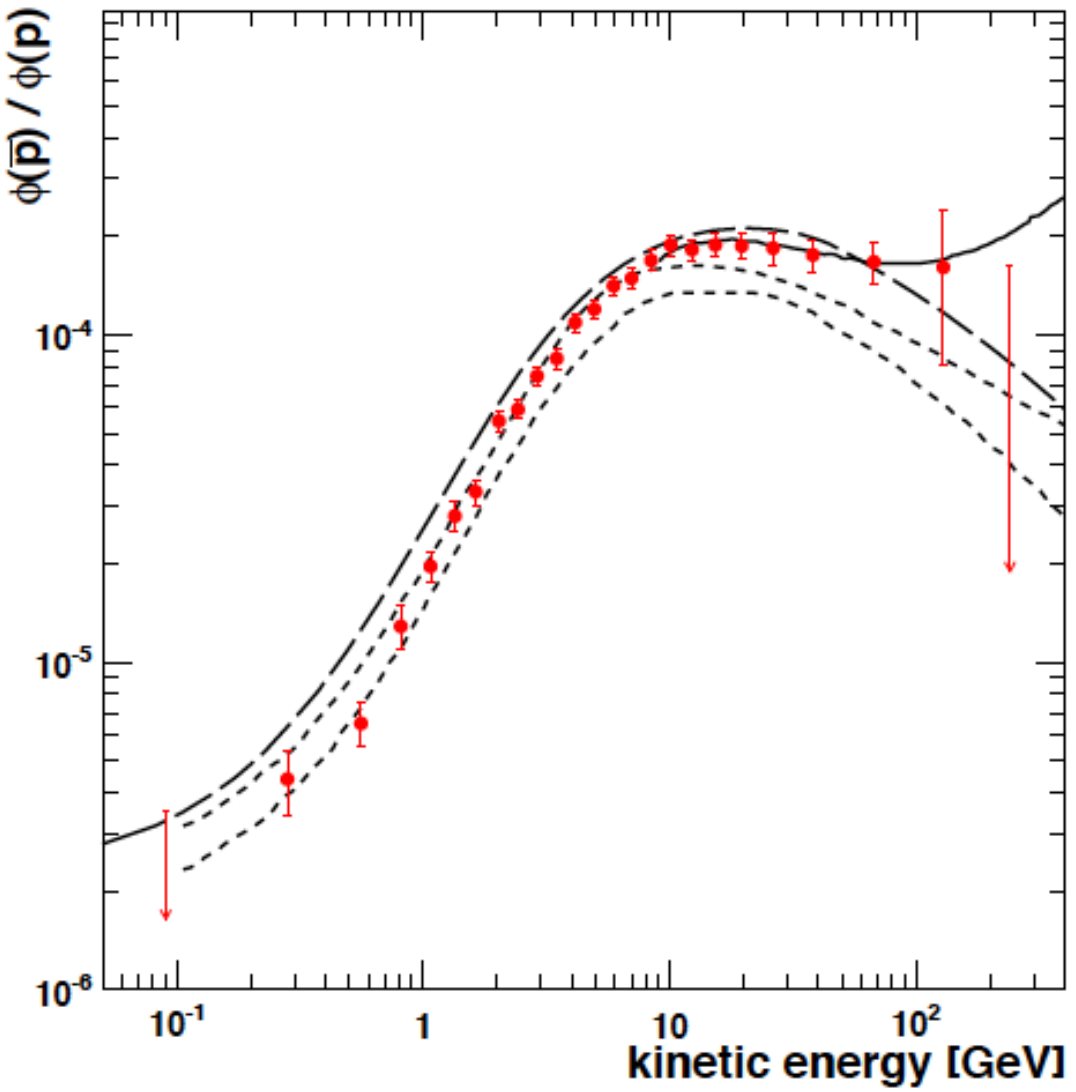
New antiproton flux –> 300 GeV

Using all data till 2010 and multivariate classification algorithms
40% increase in antip respect to published analysis



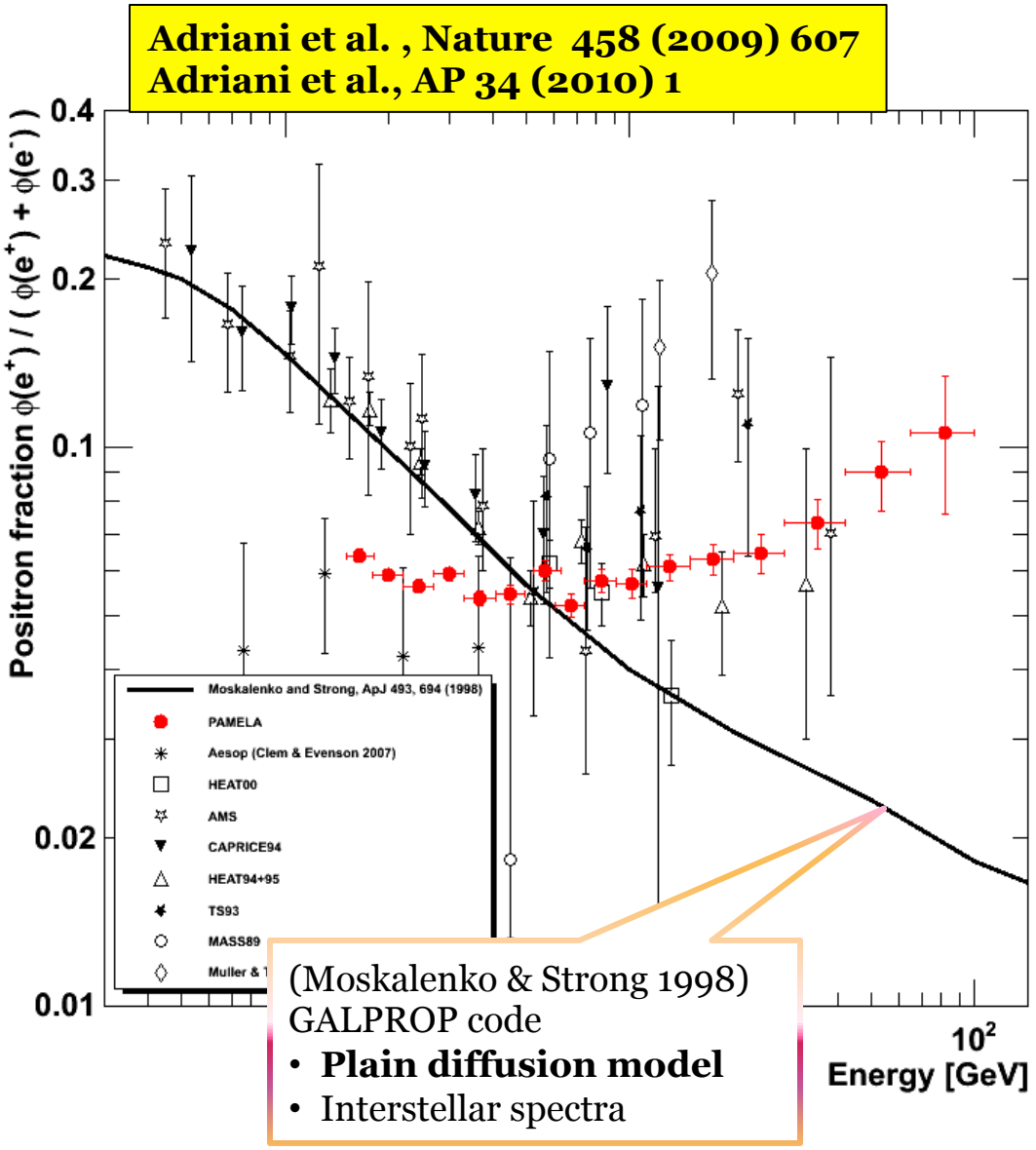
New antiproton/ proton ratio → 300 GeV

Overall agreement with models of pure secondary calculations for solar minimum **(constraints at low and high energy for DM models!)**



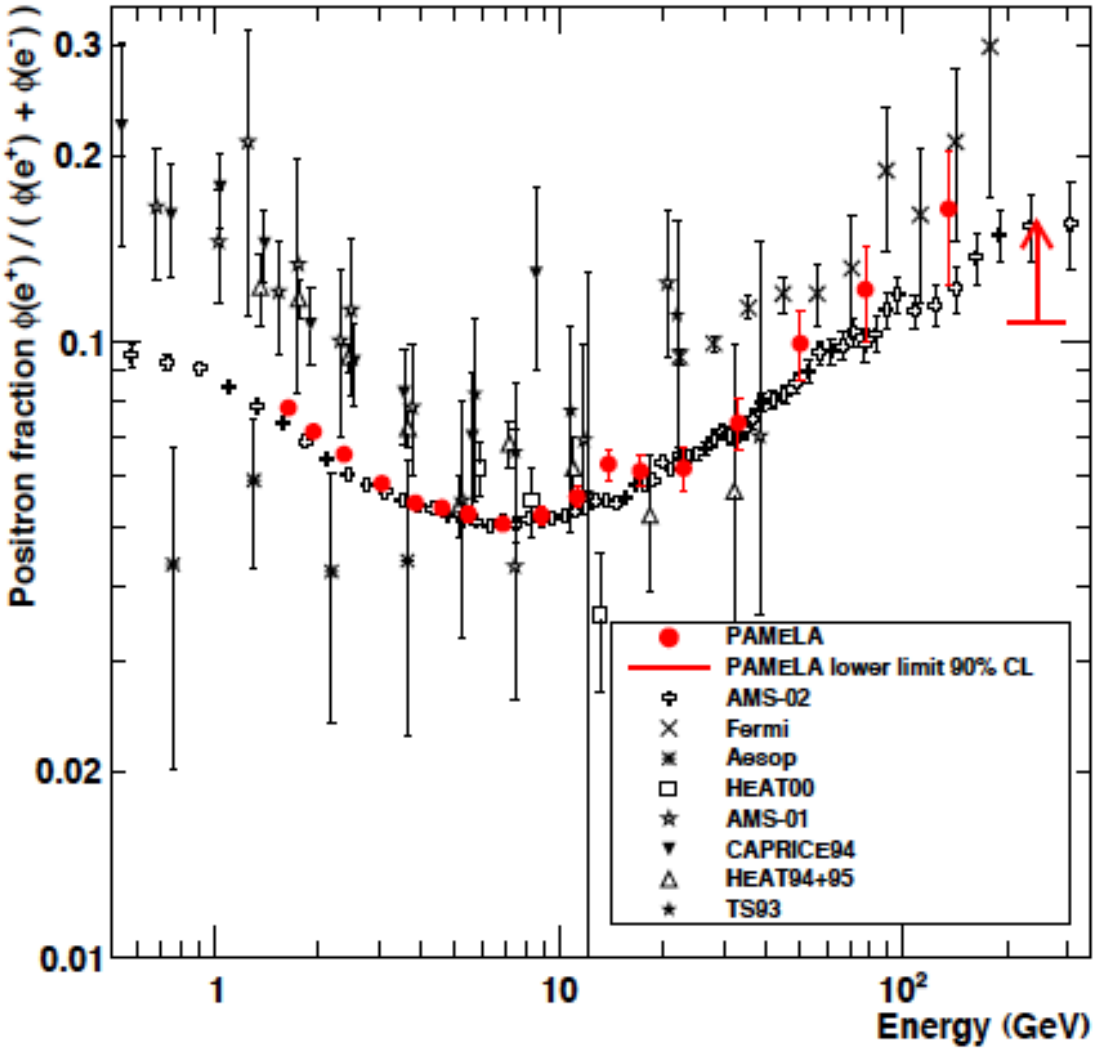
Positron fraction

- **Low energy**
  → charge-dependent solar modulation (see later)
- **High energy**
  → (quite robust) evidence of positron excess above 10 GeV



New positron fraction data → 300 GeV

Using all data till 2010 and multivariate classification algorithms about factor 2 increase in positron statistics respect to published analysis



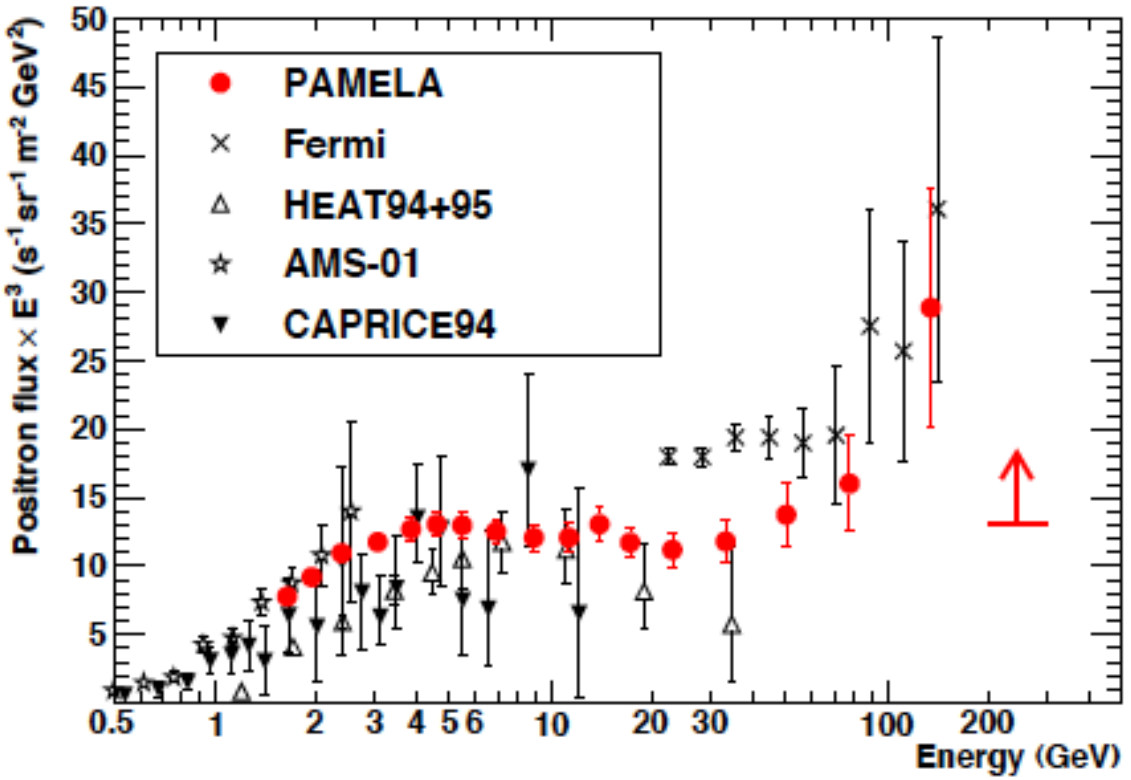
Good agreement with FERMI and AMS data

New positron flux

The paper has been highlighted with a Synopsis on the Physics website

http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.111.081102

Adriani et al. , PRL 111 (2013) 081102
Published August 19, 2013



In the highest bin a lower limit has been estimated with 90% confidence level, due to a possible overestimation of the proton contamination.

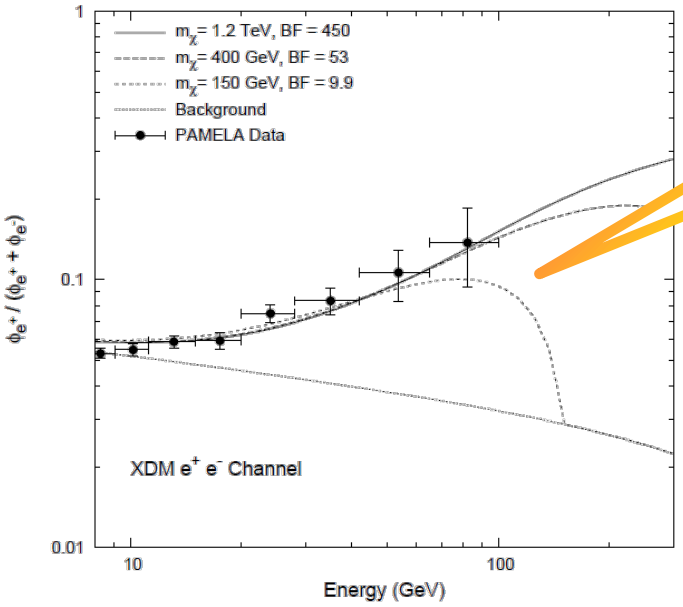
Positron-excess interpretations

Dark matter

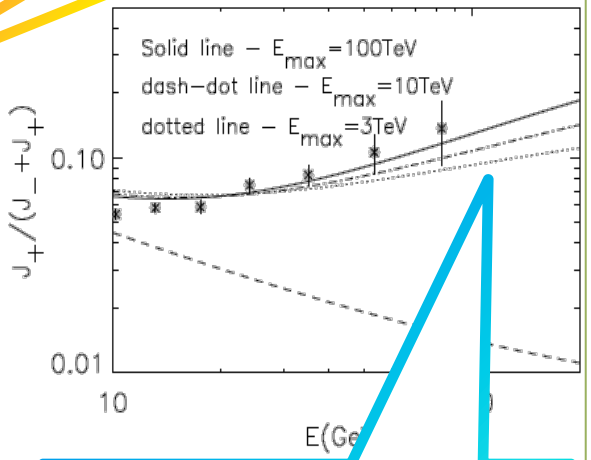
- boost factor required
- lepton vs hadron yield must be consistent with p-bar observation

Astrophysical processes

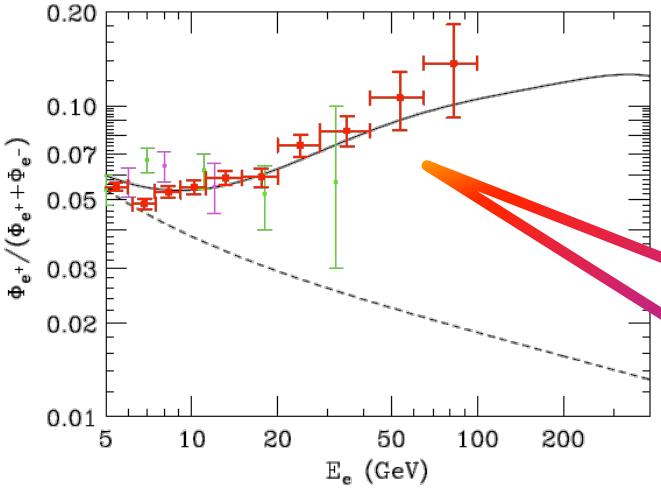
- known processes
- large uncertainties on environmental parameters



(Cholis et al. 2009)
Contribution from **DM annihilation**.



(Blasi 2009)
e+ (and e-) produced as **secondaries** in the CR acceleration sites (e.g. SNR)



(Hooper, Blasi and Serpico, 2009)
contribution from diffuse mature & nearby young **pulsars**.

Anisotropy studies (p up to 1 TeV)

Data set

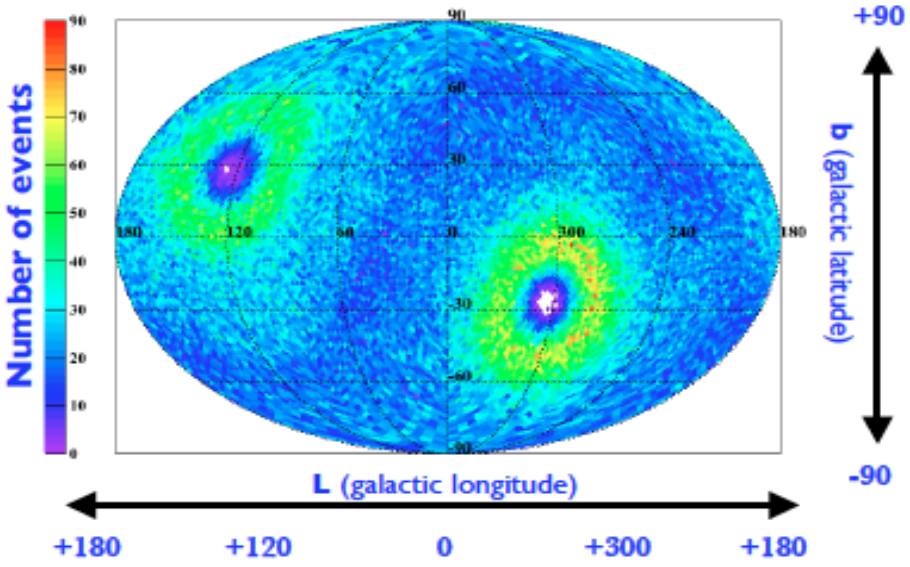
R <10 GV solar modulation effects dominate ⇒ only events with R >> 10 GV (30GV)

analyzed data July 2006 - June 2010 (~1200 days)

high quality data good pointing information

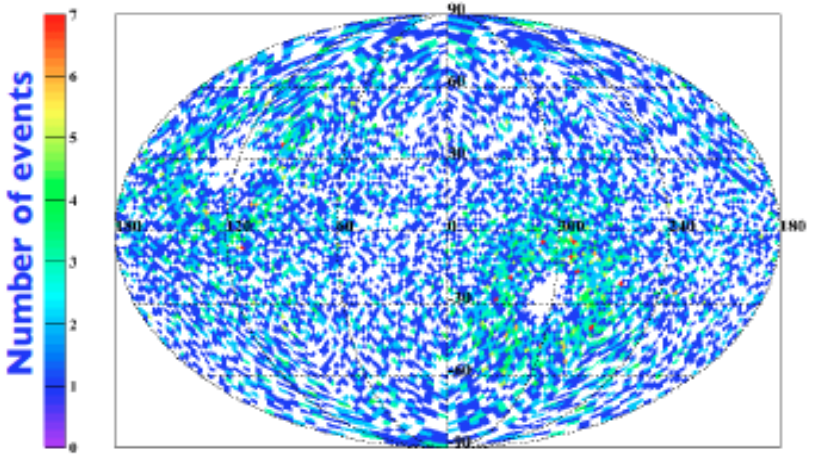
AR well below the angular scales used in this study

R ≥ 40 GV ~ 3.28 x 10^5 events



the Galactic Center (l,b) =(0,0)
is in the middle of this map

R ≥ 230 GV ~ 1.10 x 10^4 events



The sky is visualized using the healpix pixelization
-bins with same solid angle
-12288 equal are pixel (~10^{-3} sr)
(nside =32)

Data analysis

- *observed events (N_{on}-real map) in each angular window of the sky*

- *calculate the expected number of events (N_{off}) in each angular bin of the sky (background or coverage map) under the assumption of an isotropic proton flux*

background map obtained with:

-) shuffling technique

- *compare the real and the background map to study deviations from isotropy of the real map*

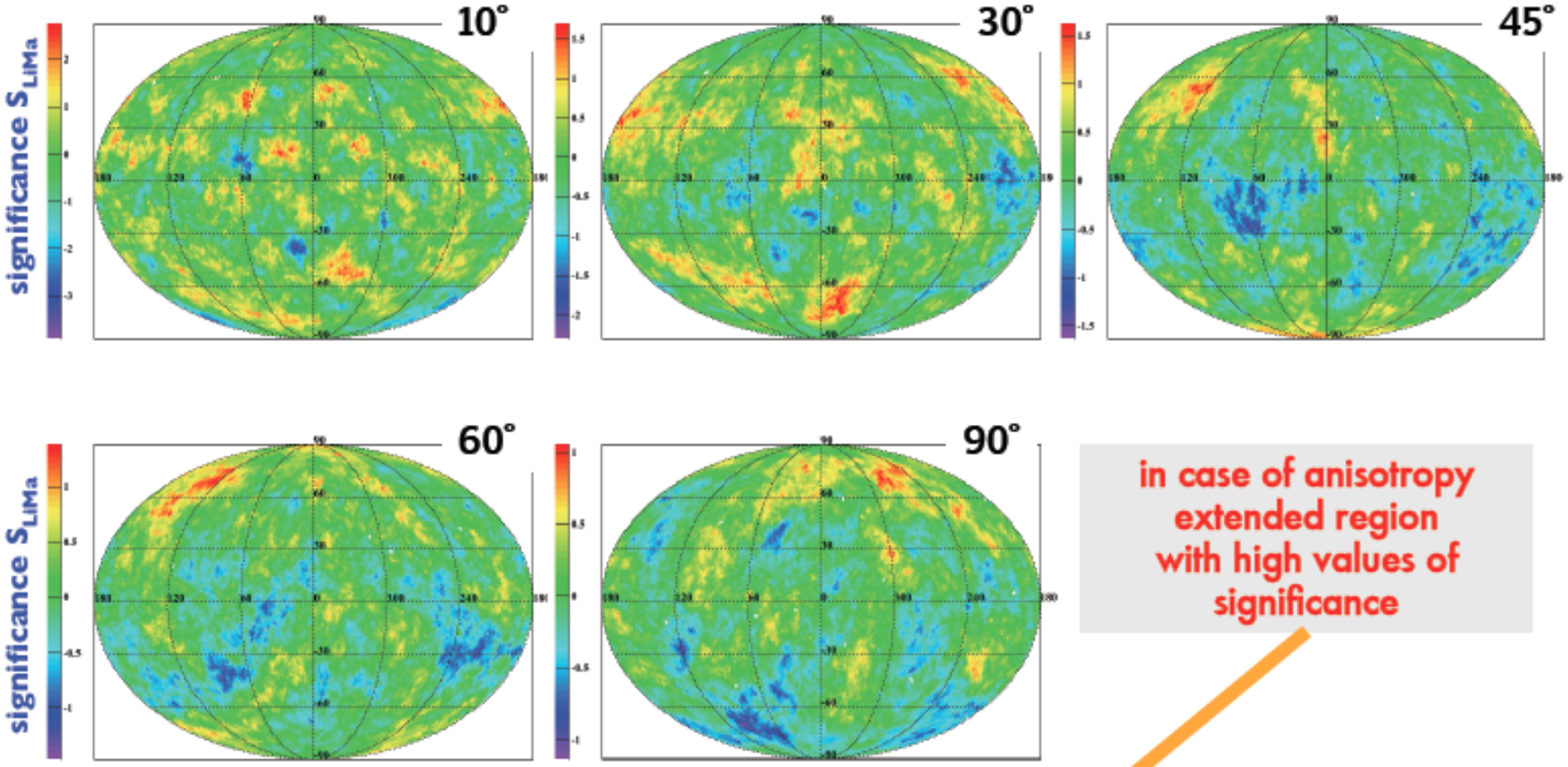
two approaches used to search flux excess:

-) significance test adopted by Li & Ma
-) spherical armonic analysis

Significance sky maps (1)

significance sky maps for events with R ≥ *40 GV*
as a function of the integration radius

galactic coordinates



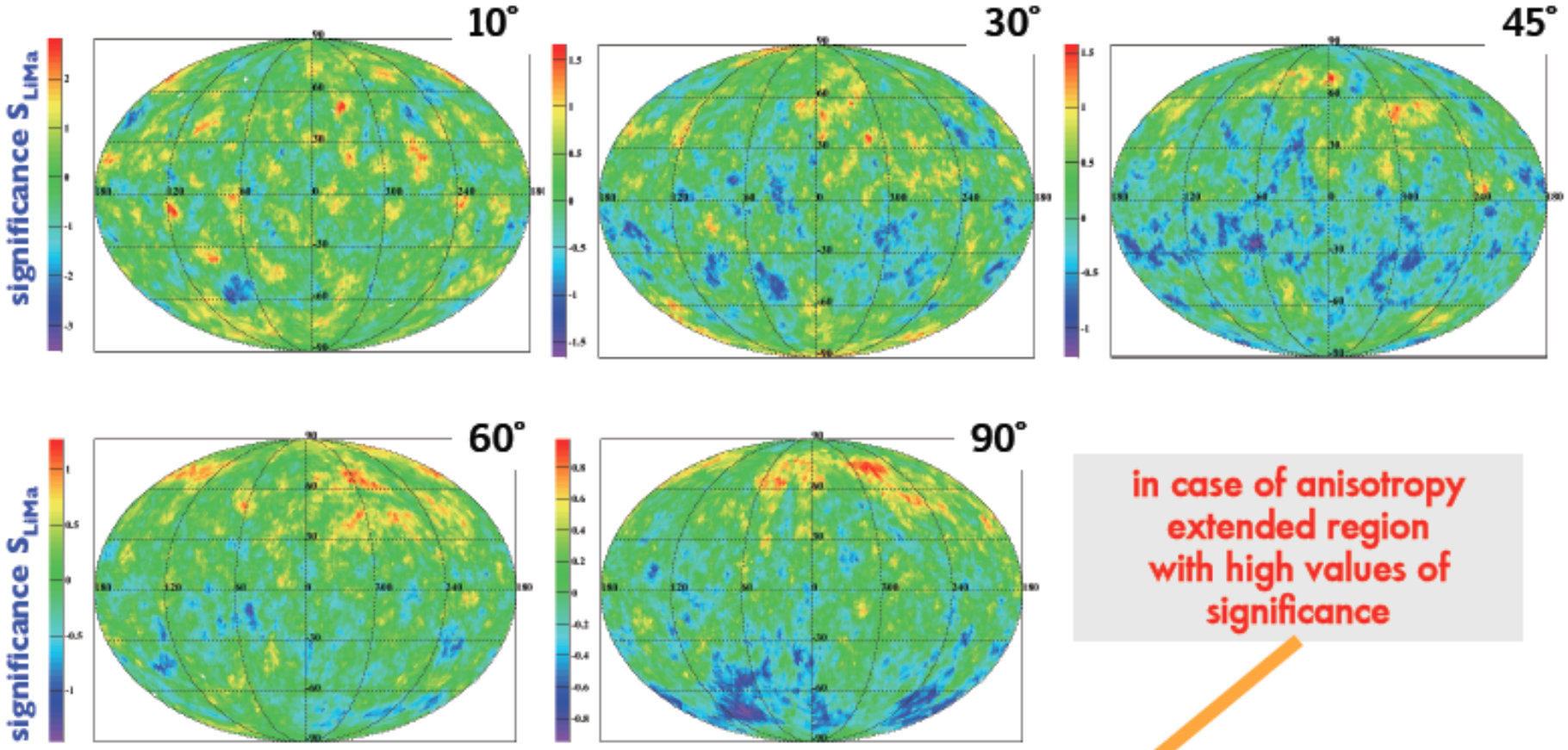
in case of anisotropy extended region with high values of significance

no evidence of excess for each opening angle

Significance sky maps (2)

significance sky maps for events with R ≥ *230 GV*
as a function of the integration radius

galactic coordinates

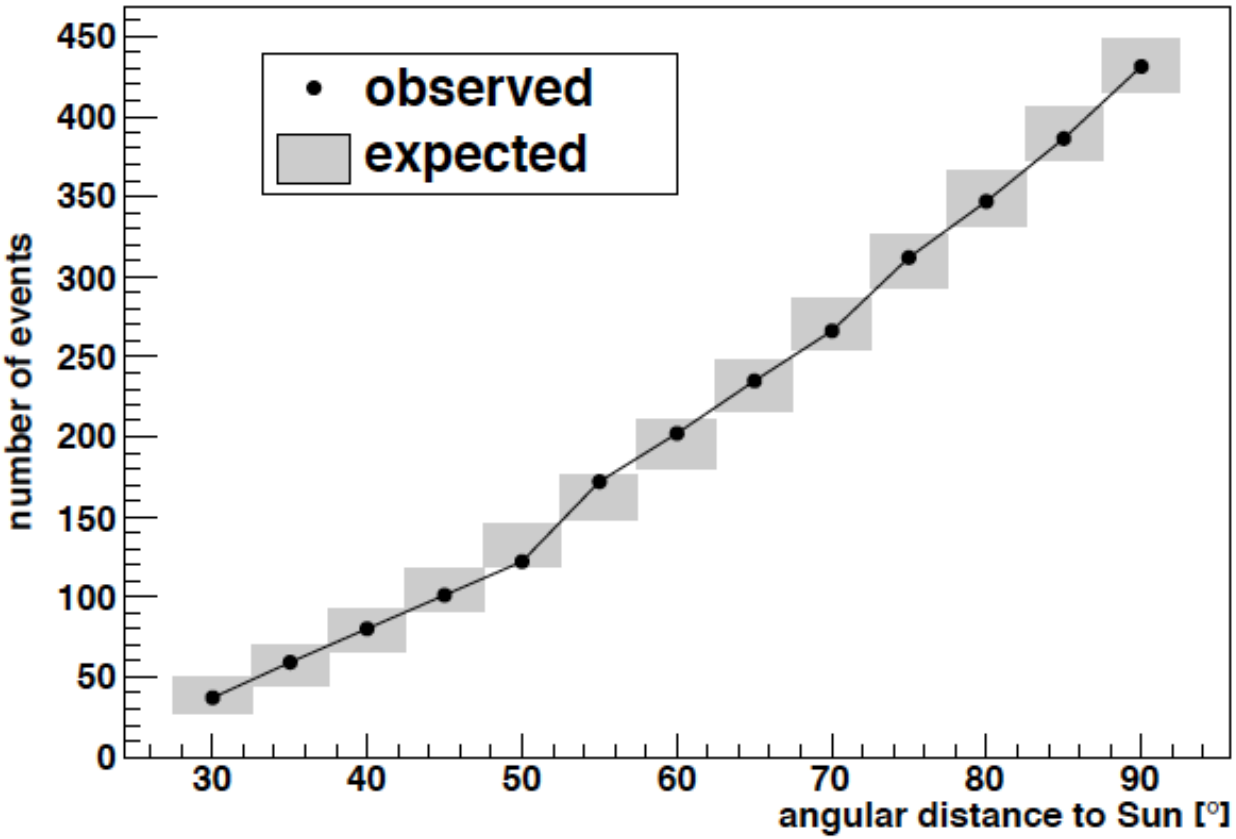


in case of anisotropy extended region with high values of significance

no evidence of excess for each opening angle

Search for an excess in the Sun direction

No significant departure from isotropy is observed



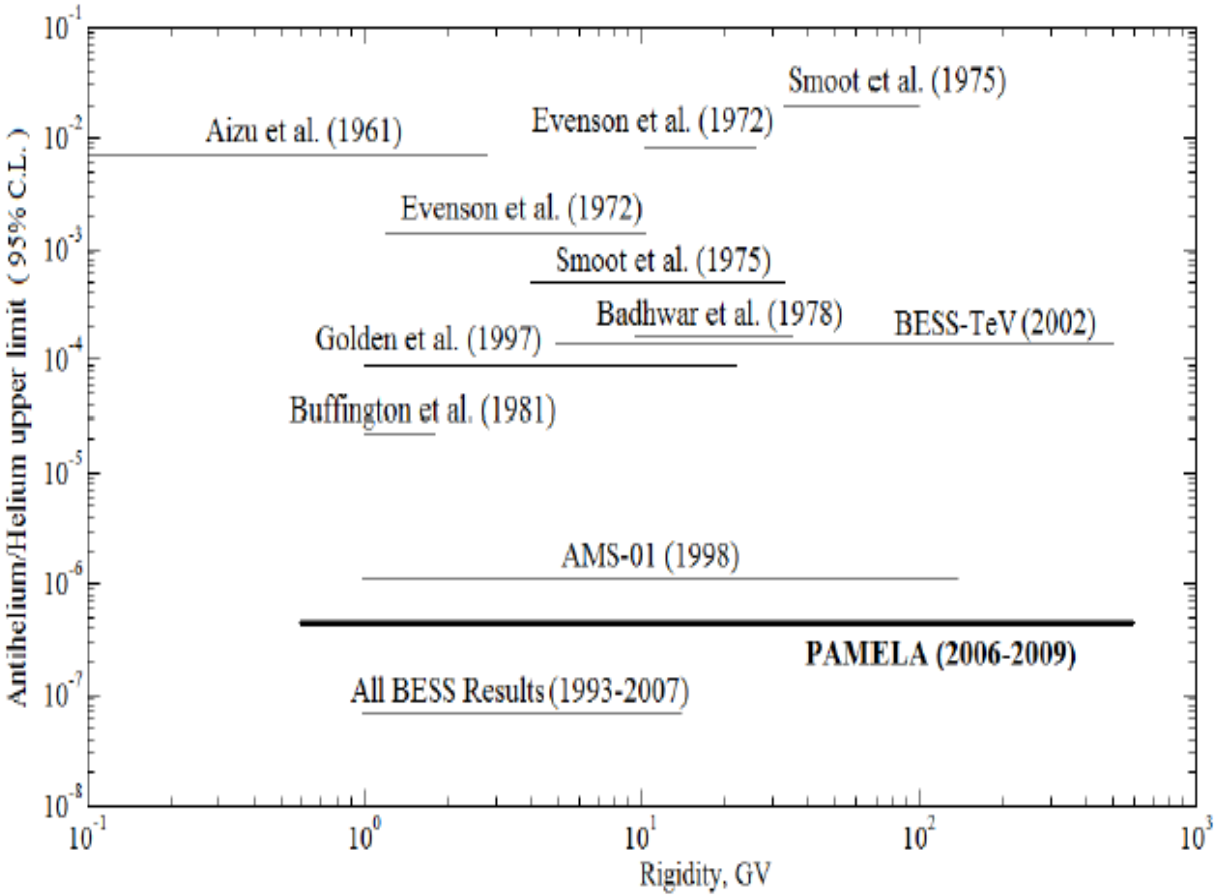
Cumulative number of events with E> 40 GeV as a function of the angular distance from the direction of the Sun. The grey boxes are the background.

AntiHe/He

No antiHe detected in a sample of 6.330.000 events with |Z|>=2,

from 0.6 to 600 GV.

Widest energy range ever reached

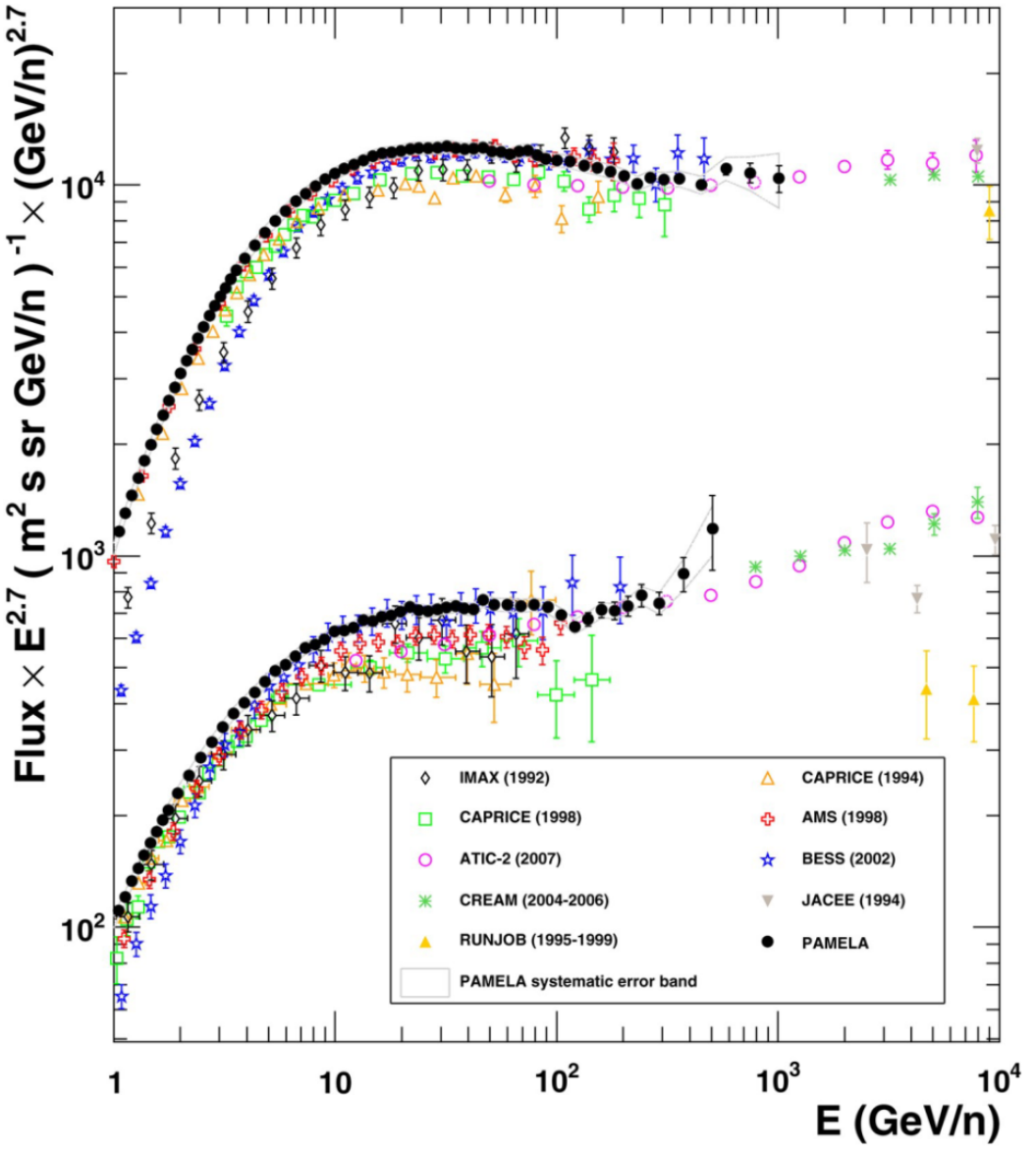


Absolute fluxes of primary GCRs

H & He absolute fluxes

- First high-statistics and high-precision measurement over three decades in energy
- Dominated by systematics (~4% below 300 GV)
- **Low energy**
  → minimum solar activity (ϕ = 450÷550 GV)
- **High-energy**
  → a complex structure of the spectra emerges…

Adriani et al. , Science 332 (2011) 6025



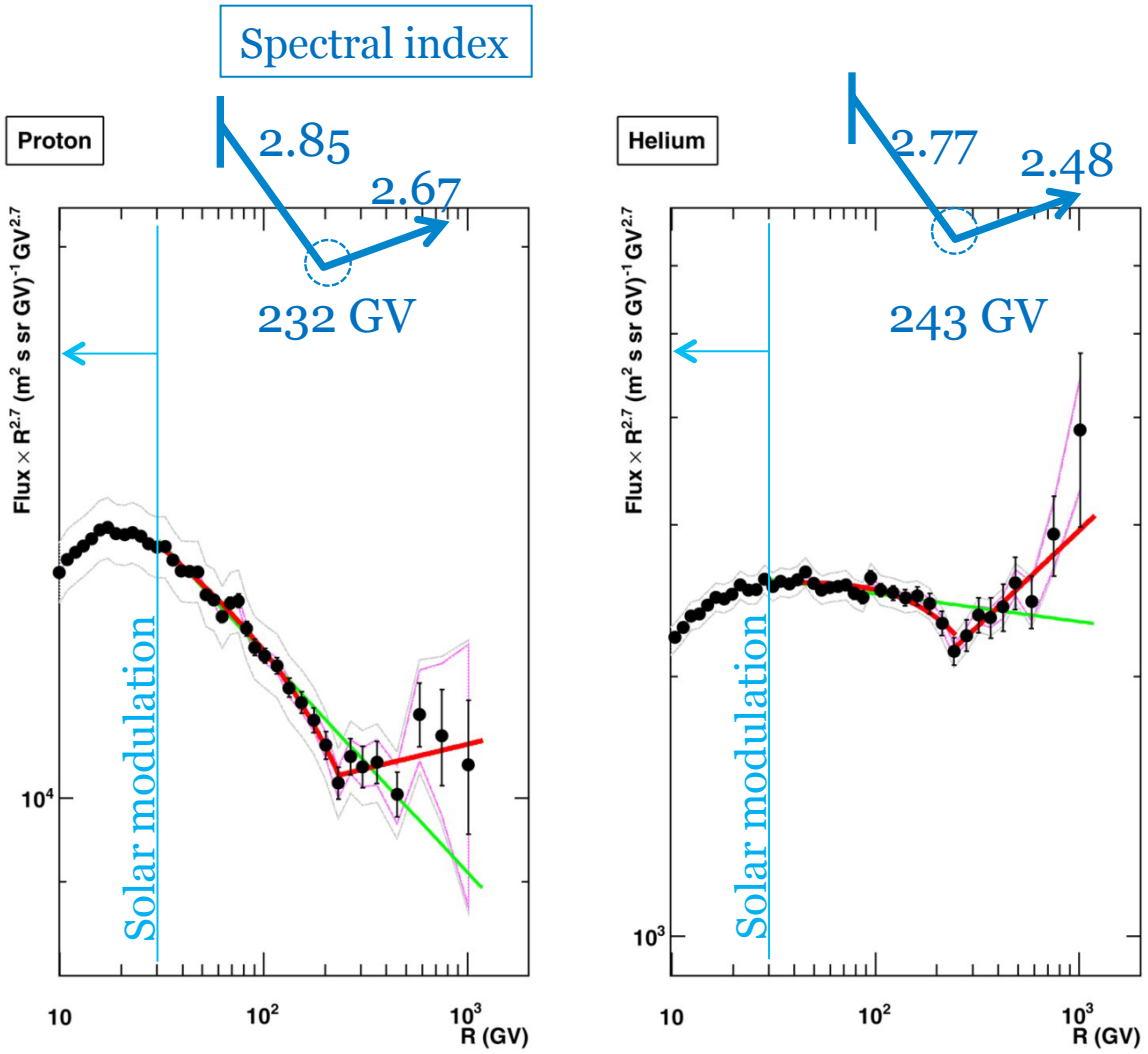
H & He absolute fluxes @ high energy

Deviations from single power law (SPL):

- Spectra gradually soften in the range 30÷230GV
- **Abrupt spectral hardening @ ~235GV**

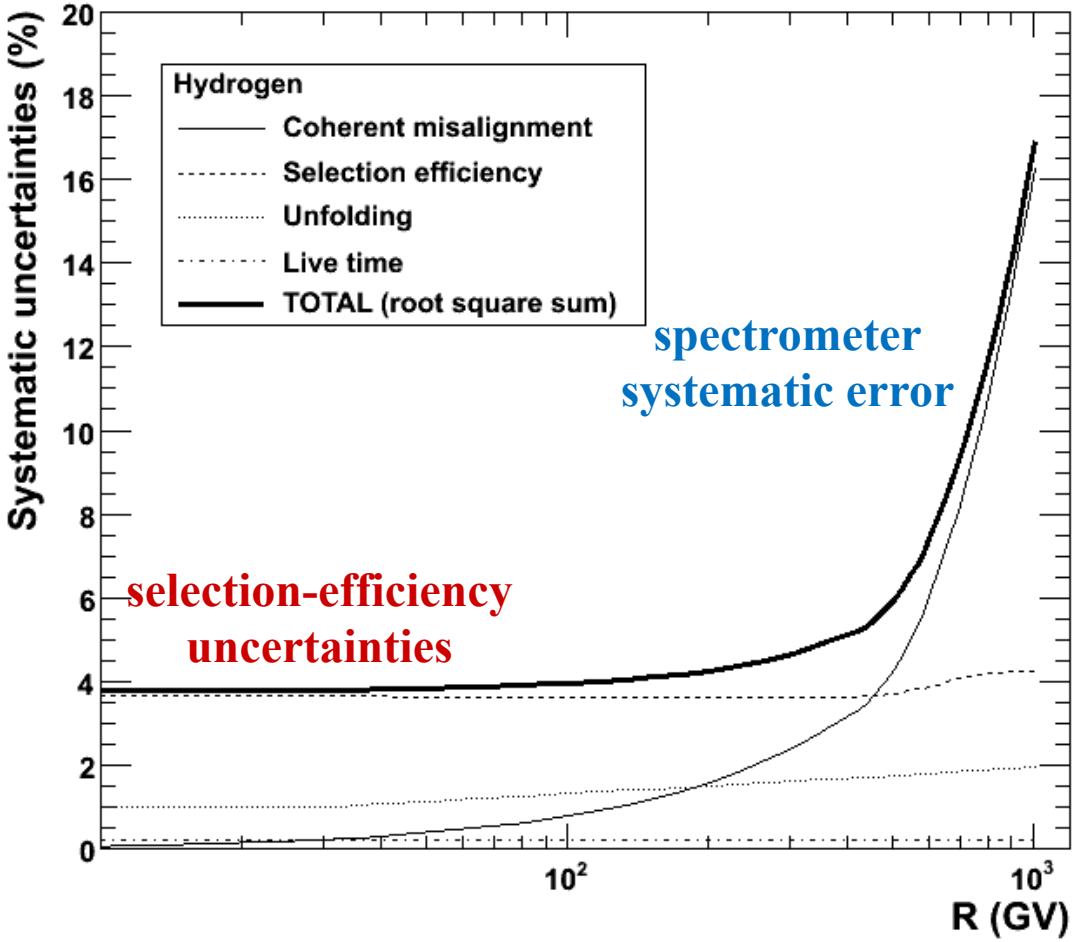
Eg: statistical analysis for protons

- SPL hp in the range 30÷230 GV rejected @ >95% CL
- SPL hp above 80 GV rejected @ >95% CL



Overall systematic uncertainties

- At low R selection-efficiency uncertainties dominate
- Above 500 GV tracking-system (coherent) misalignment dominates



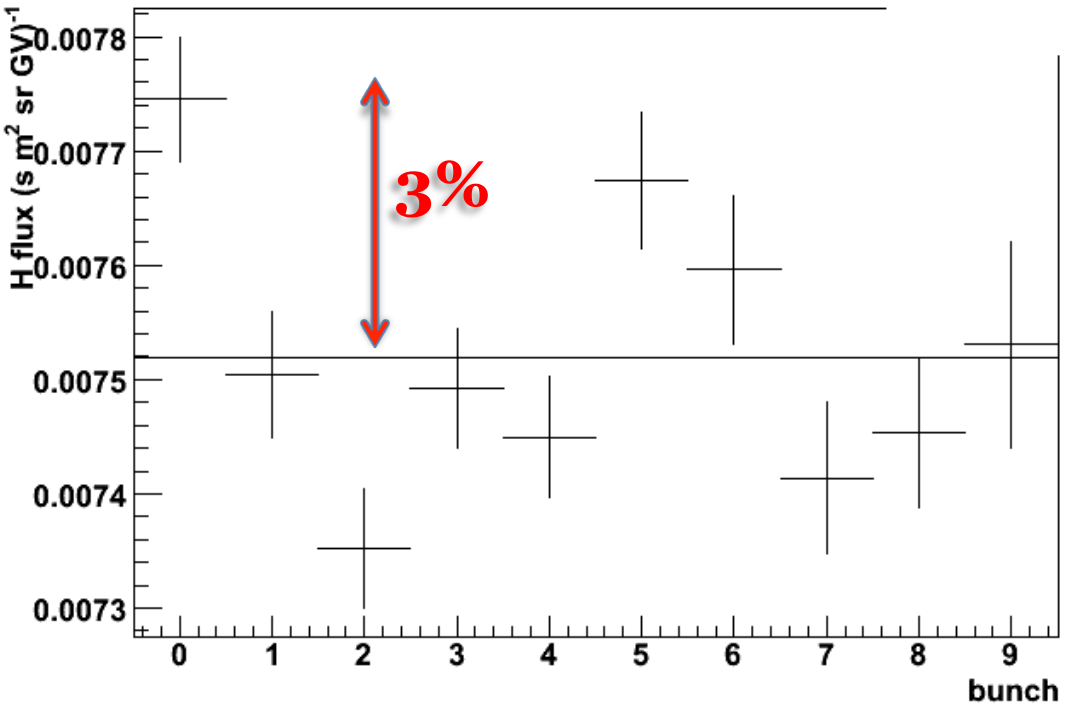
Check of systematics

Fluxes evaluated by varying the selection conditions:

- Flux vs time
- Flux vs polar/ equatorial
- Flux vs reduced acceptance
- Flux vs different tracking conditions (⇒ different response matrix)

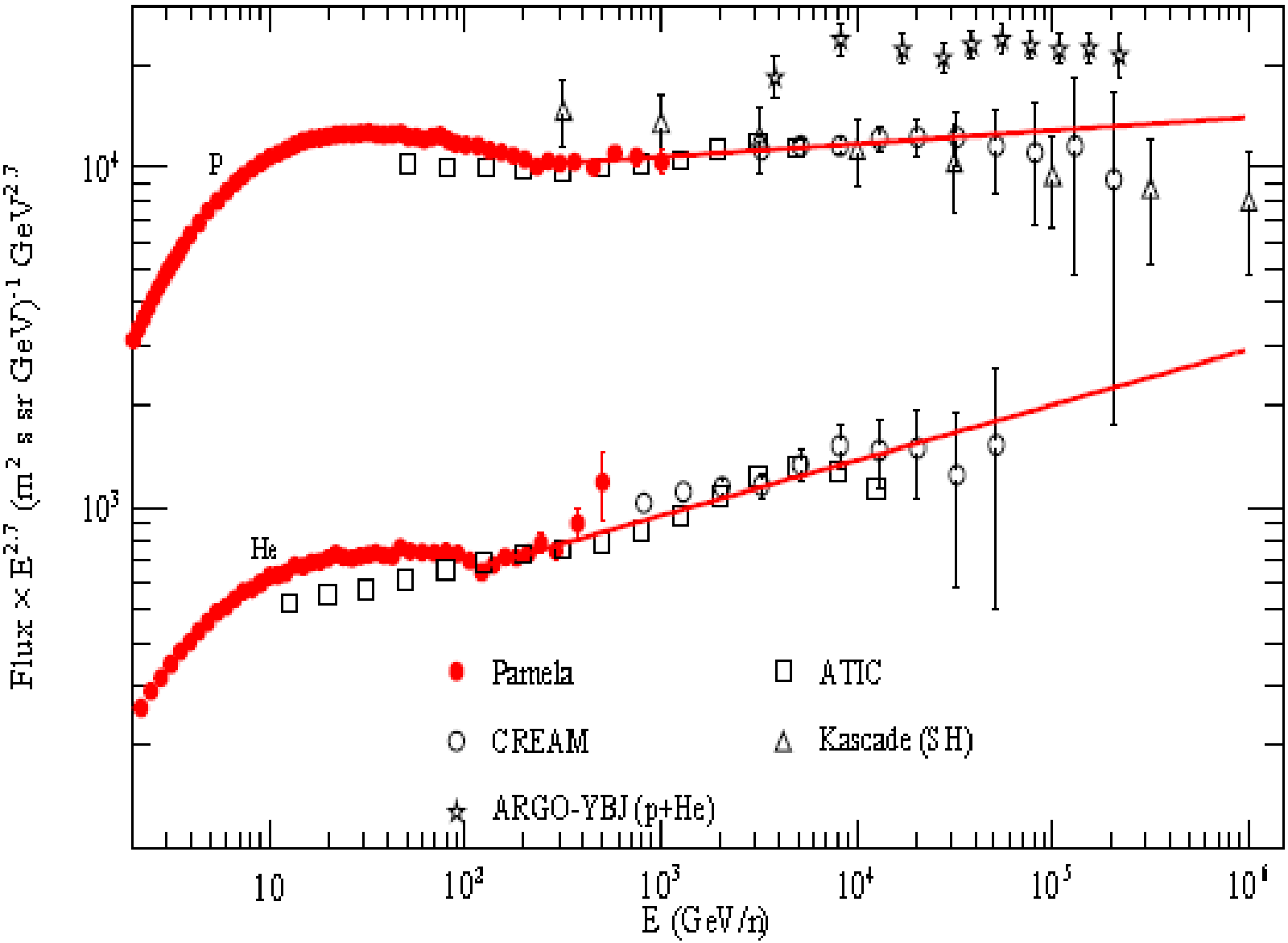
…

Integral proton flux (>50GV)



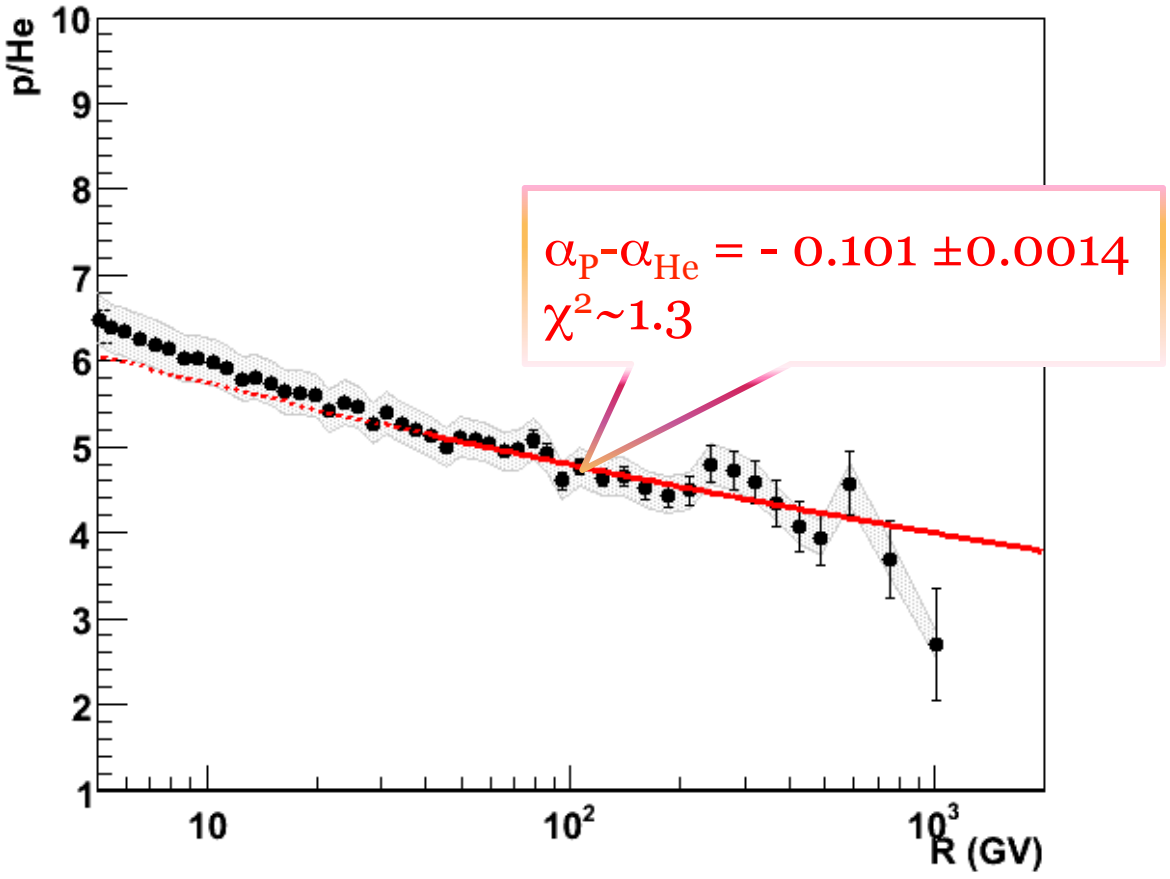
Time interval (2 months)

Comparison with high-energy experiments



H/He ratio vs R

- First clear evidence of **different H and He slopes above ~10GV**
- Ratio described by a **single power law** (in spite of the evident structures in the individual spectra)

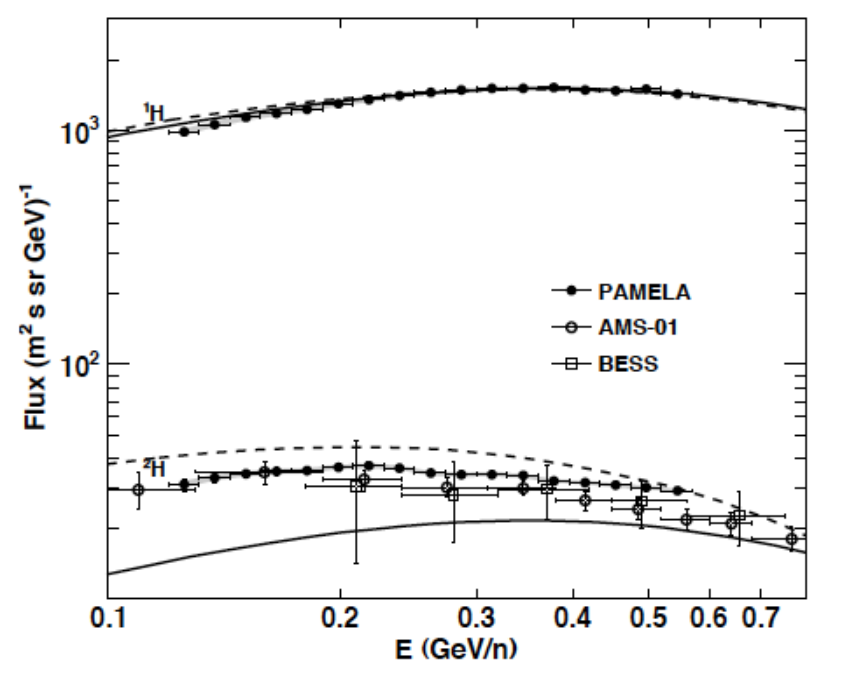


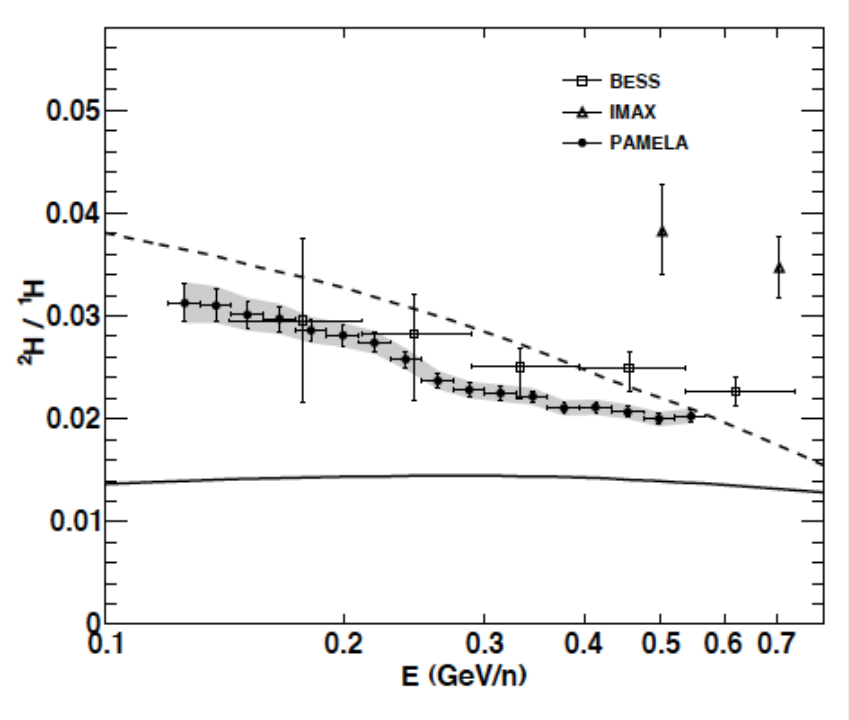
Isotopes

H isotope fluxes

$^2H/^1H$ ratio

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





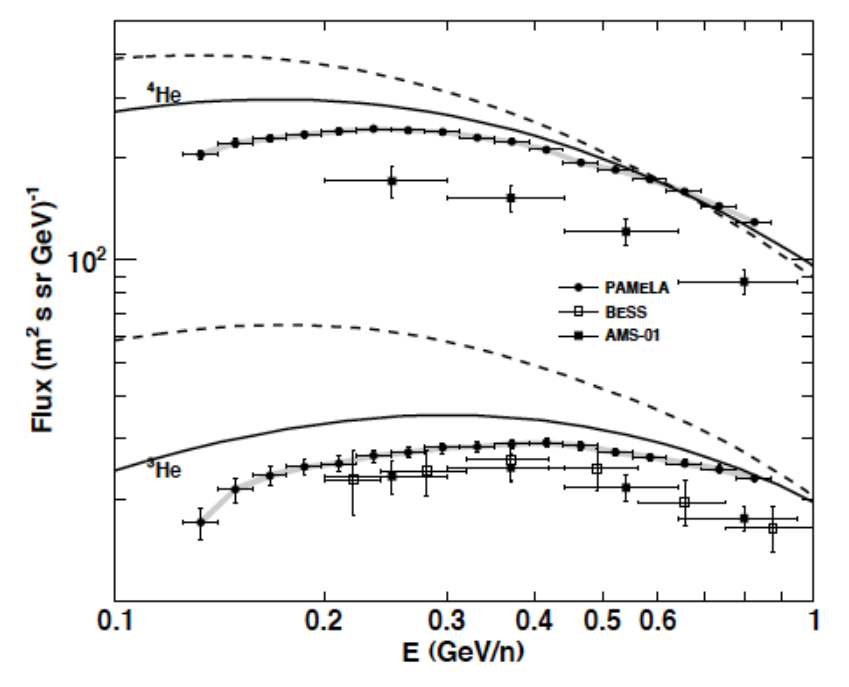
PAMELA's are the most complete measurements so far

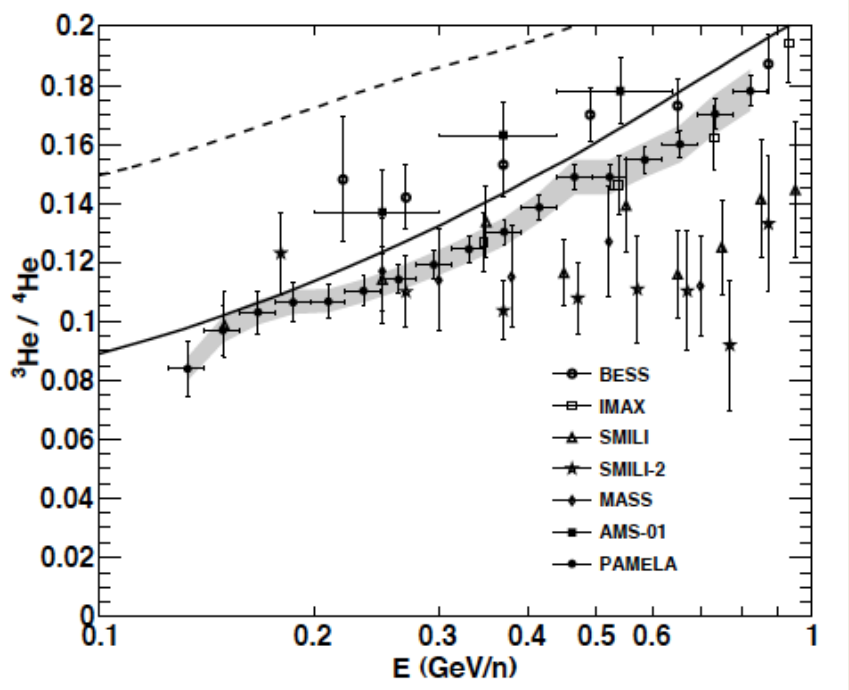
Isotopes

He isotope fluxes

$^3He/^4He$ ratio

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





PAMELA's are the most complete measurements so far

Electron energy measurements

Two independent ways to determine electron energy:

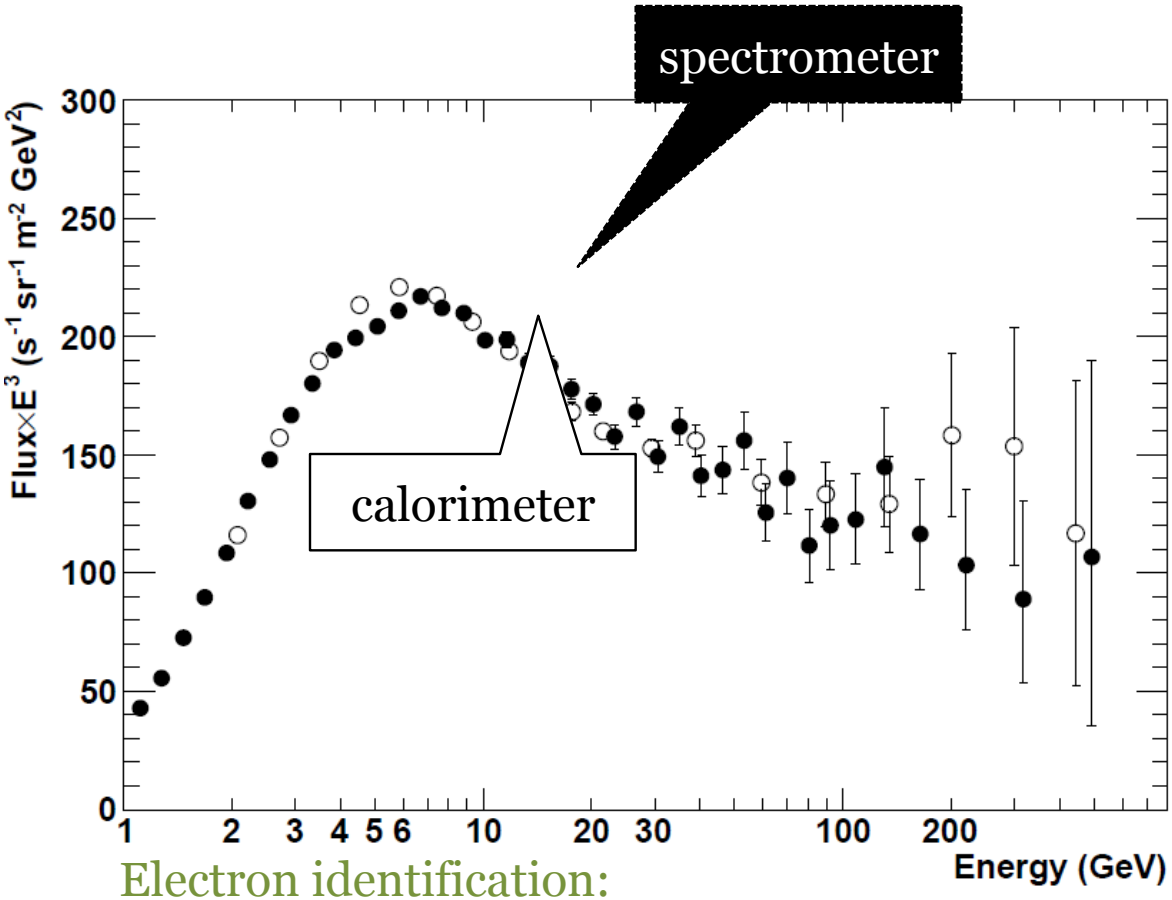
1. Spectrometer

- Most precise
- Non-negligible energy losses (bremsstrahlung) above the spectrometer → unfolding

2. Calorimeter

- Gaussian resolution
- No energy-loss correction required
- Strong containment requirements → smaller statistical sample

Adriani et al. , PRL 106 (2011) 201101

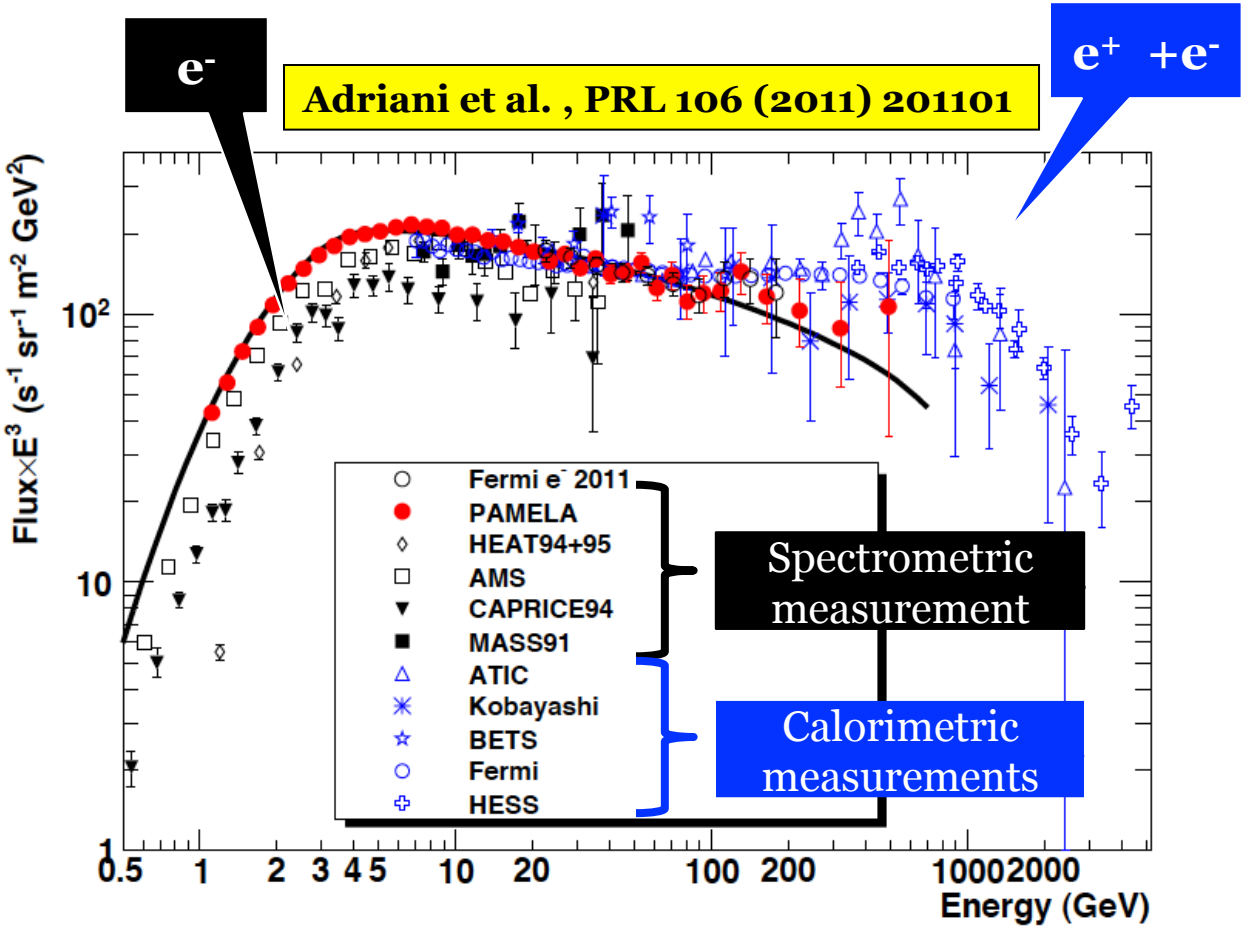


Electron identification:

- Negative curvature in the spectrometer
- EM-like interaction pattern in the calorimeter

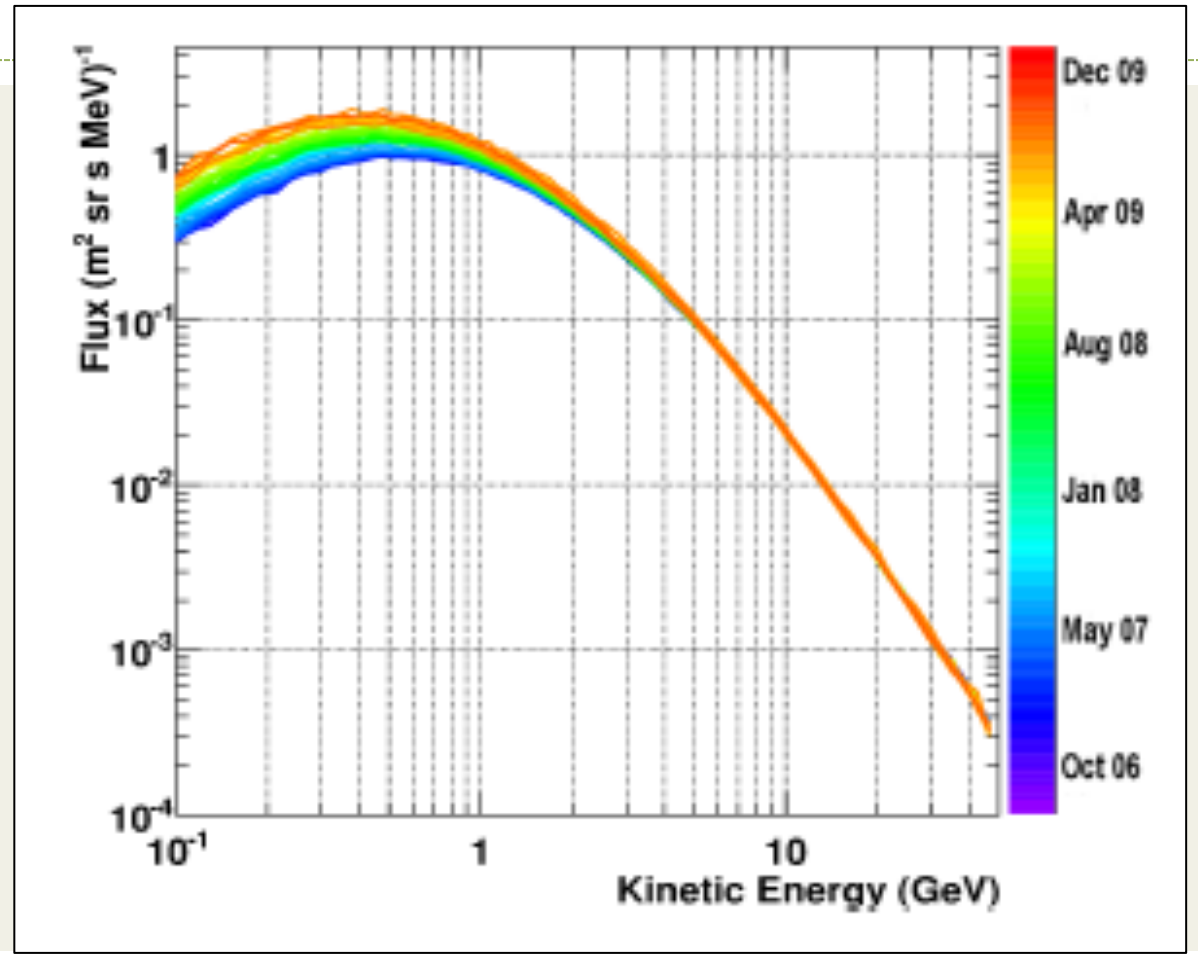
Electron absolute flux

- Largest energy range covered in any experiment hitherto with no atmospheric overburden
- **Low energy**
  - minimum solar activity (ϕ = 450÷550 GV)
- **High energy**
  - Significant disagreement with GALPROP calculations (that assumes a continuous distribution of the sources).



Solar and terrestrial physics

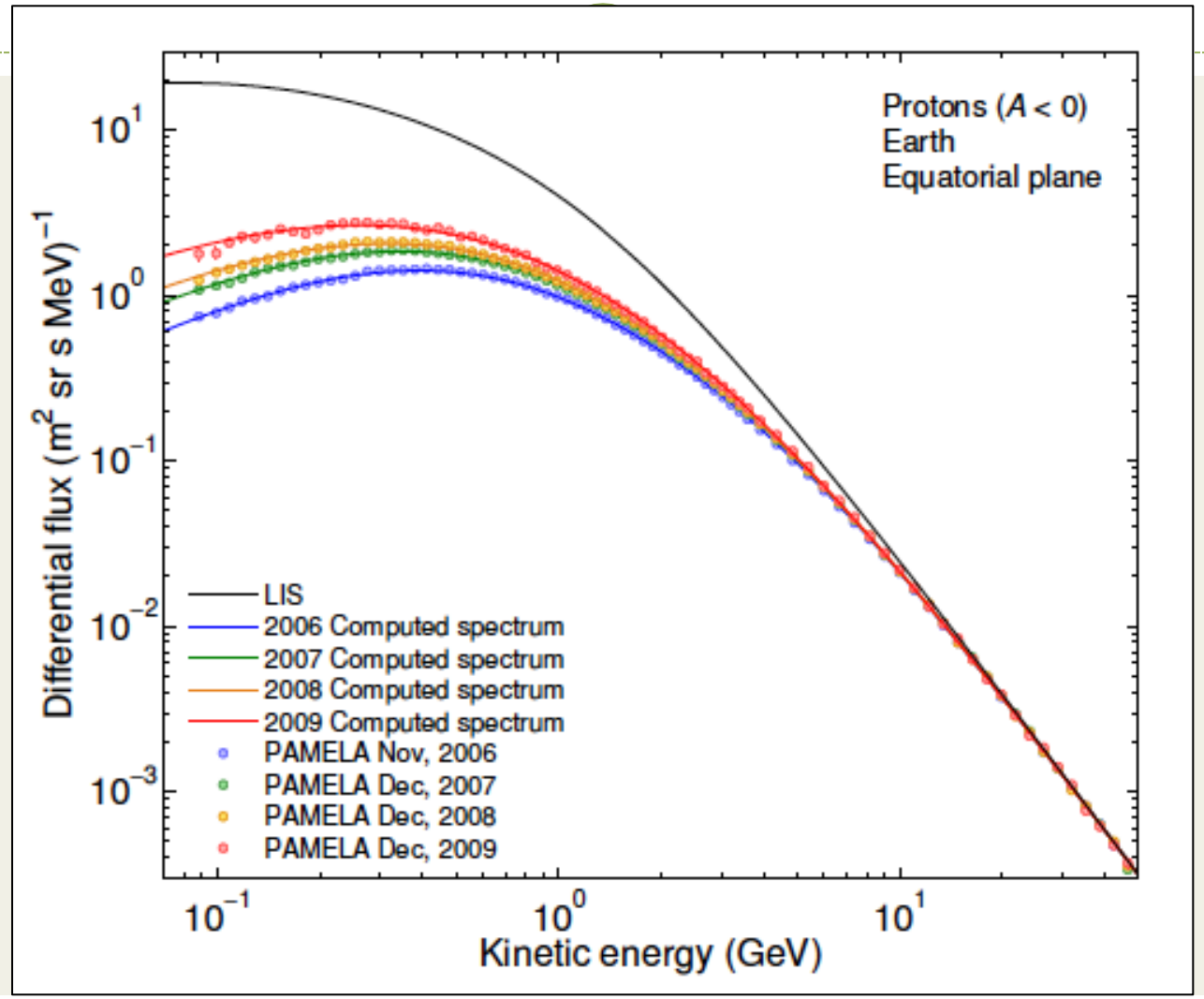
Solar modulation: proton spectra



Adriani et al, *ApJ 765 (2013) 91*

The evolution of the proton energy spectrum as particle intensities approached the period of minimum solar activity, from July 2006 (violet), to December 2009 (red). The region between the blue and red curves indicates the spread in proton fluxes during this time.

Proton spectra & LIS calculations

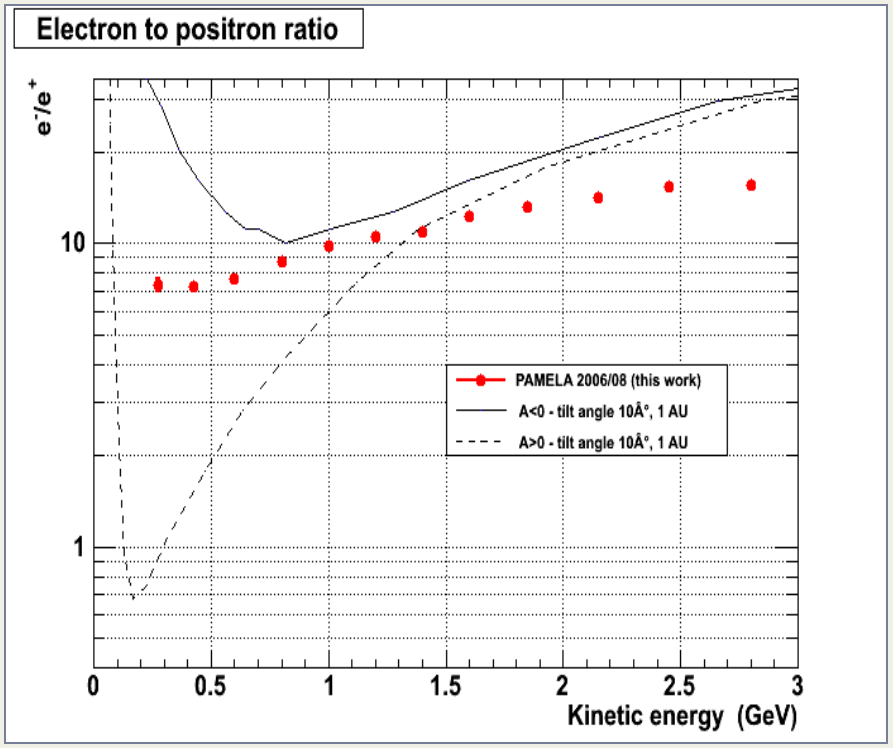


LIS based on that by Langner and Potgieter, modified at high energies to match PAMELA data

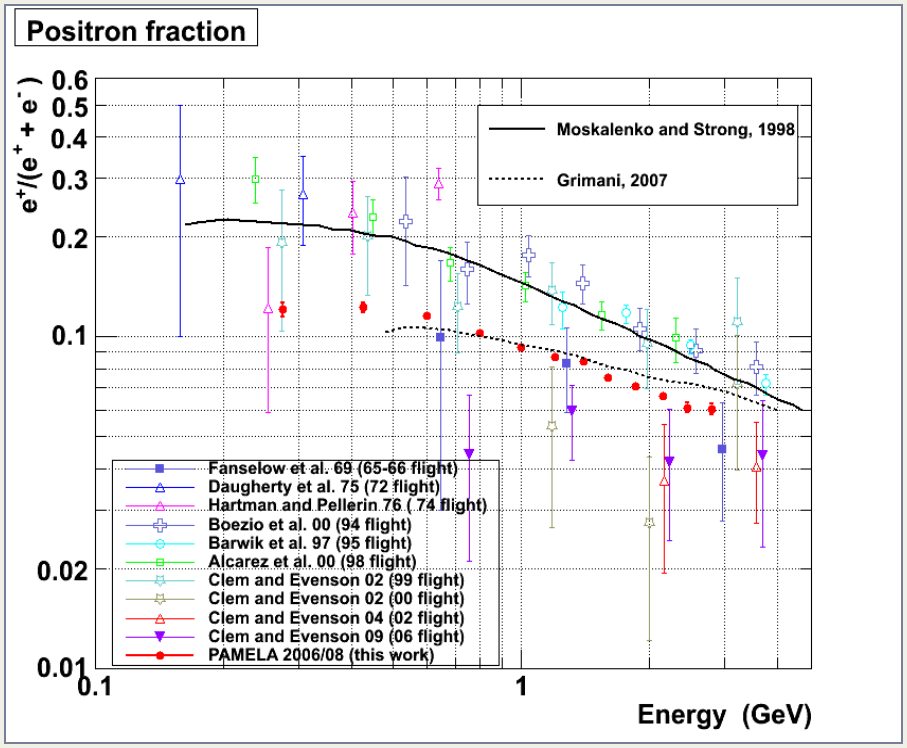
Charge-dependent solar modulation
Work in progress

PAMELA ELECTRON to POSITRON RATIO @ low energy

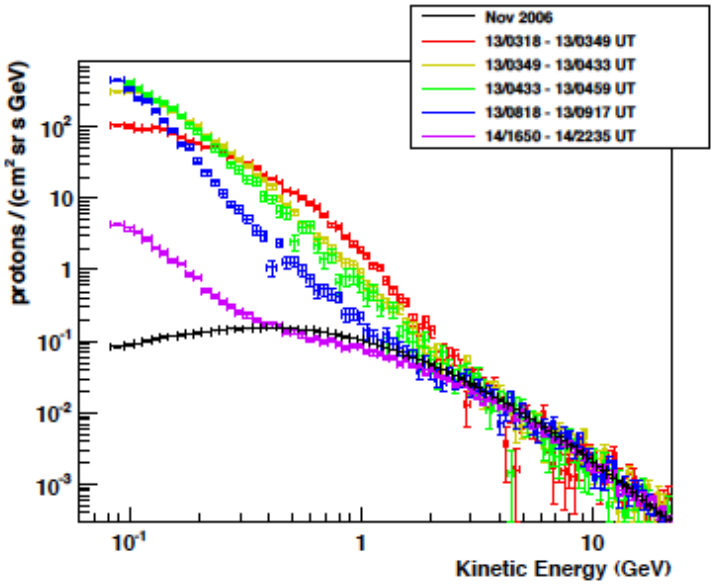
PRELIMINARY

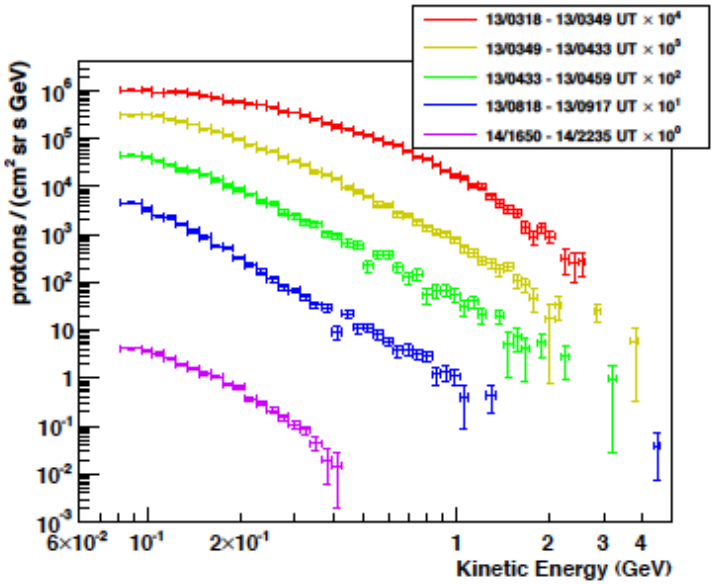


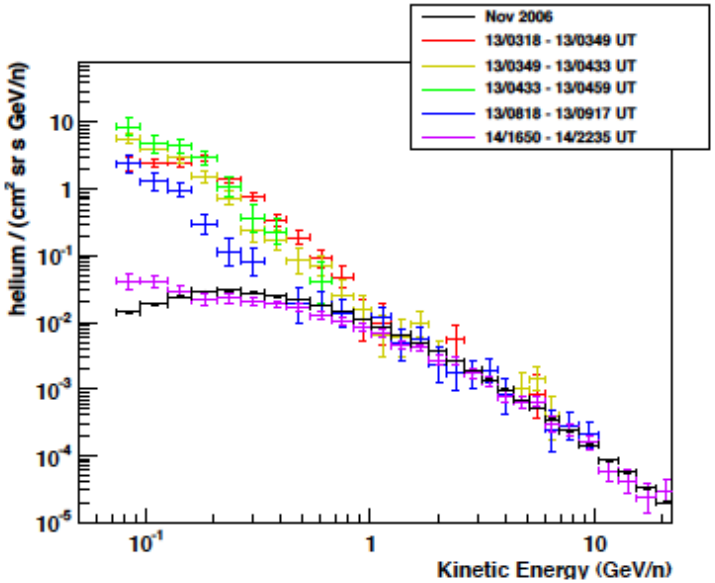
PAMELA POSITRON FRACTION @ low energy

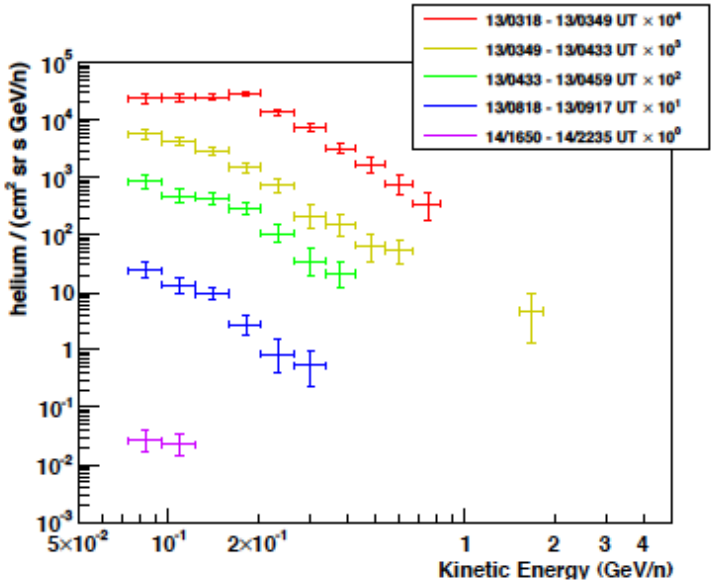


Solar events (SEP from Dec. 13, 2006)



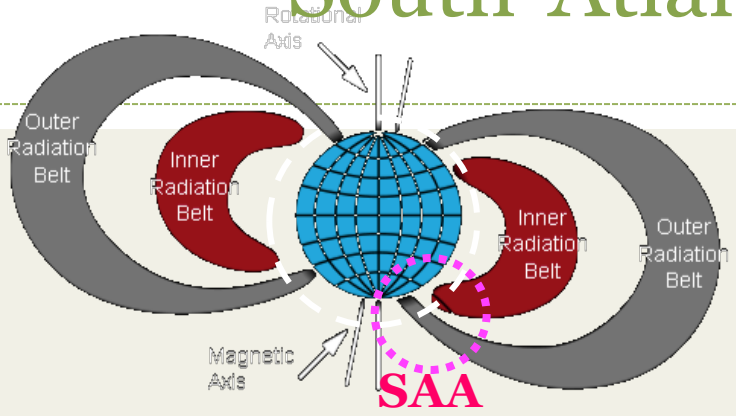


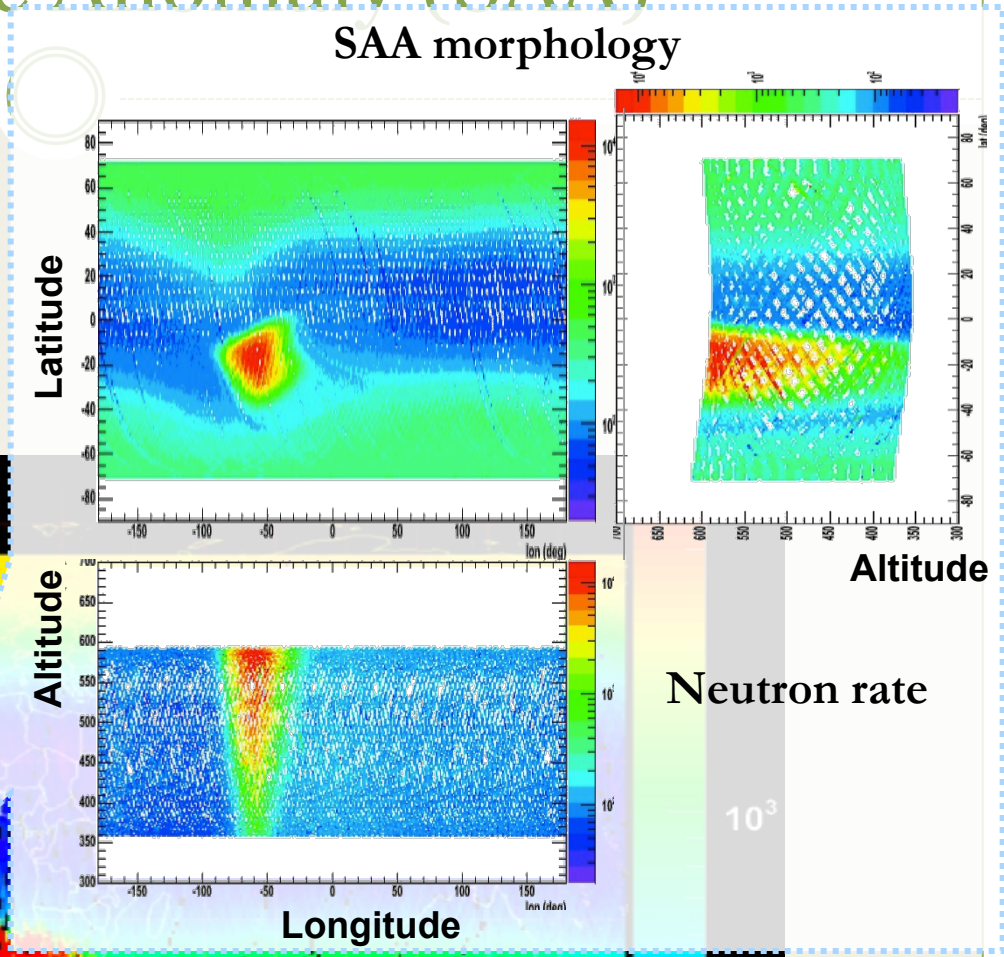




Adriani et al. - *ApJ 742 102, 2011*

South-Atlantic Anomaly (SAA)



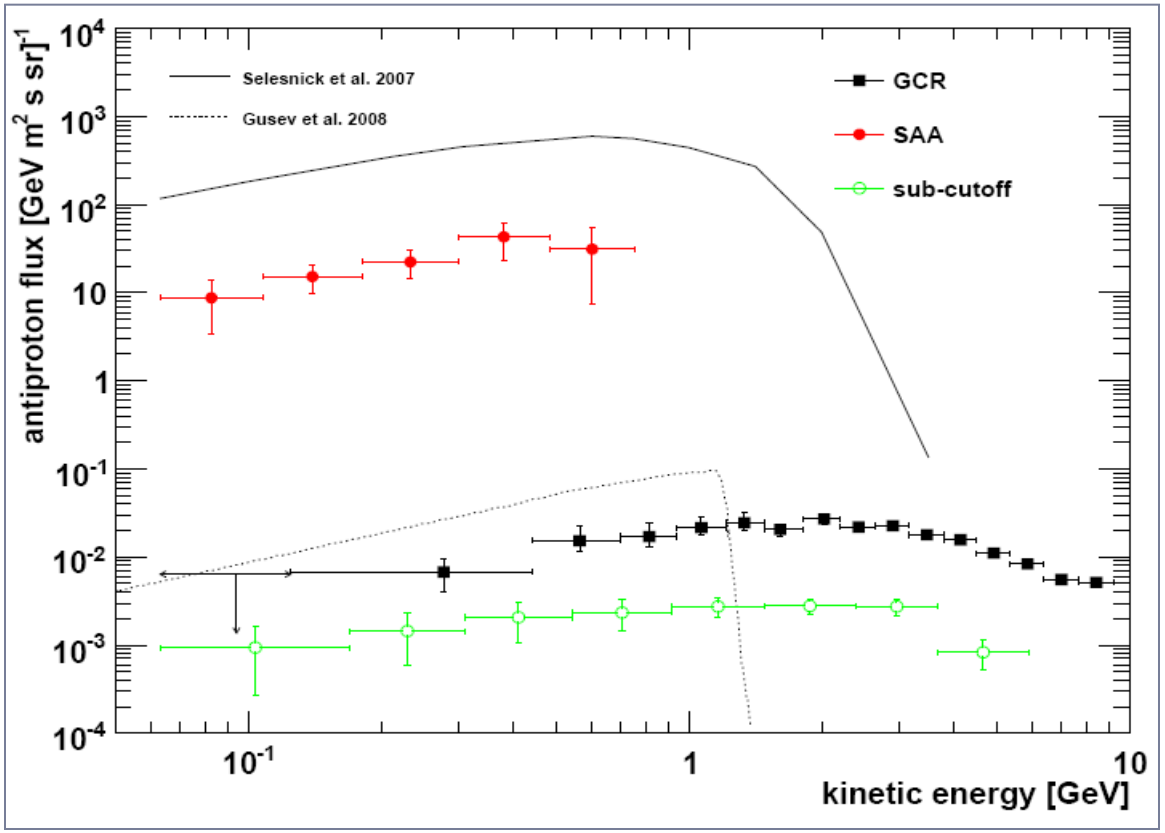


Discovery of geomagnetically Trapped antiprotons

First measurement of p-bar trapped in the inner belt

29 p-bars discovered in SAA and **traced back to mirror points**

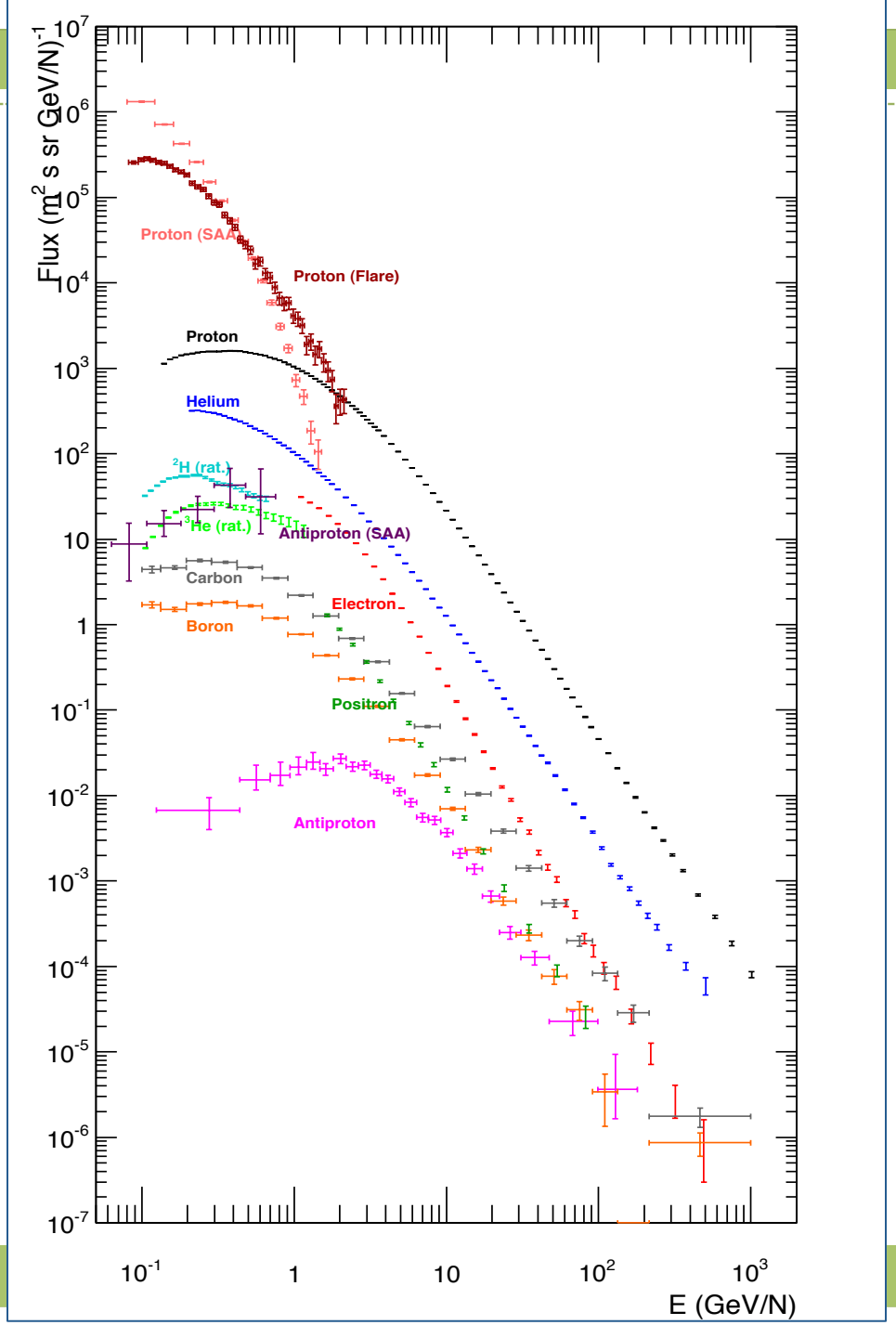
p-bar flux exceeds GRC flux by **3 orders of magnitude,** as expected by models



Adriani et al. ***ApJ 737 (2011) L29***

All particles PAMELA results

Results span 4 decades in energy and 13 in fluxes



Summary and conclusions (1)

PAMELA has been in orbit and studying cosmic rays for more 7 years. Its operation time will continue in 2014.

- **Antiproton energy spectrum and ratio** → Measured up to ~300 GeV. No significant deviations from secondary production expectations.
- **High energy positron fraction (>10 GeV)** → Measured up to ~300 GeV. Increases significantly (and unexpectedly!) with energy. **→ Primary source?**
- **Positron flux ->** Consistent with a new primary source.
- **Anisotropy studies:** no evidence of anisotropy.
- **AntiHe/He ratio:** broader energy range ever achieved.

Summary and conclusions (2)

- **H and He absolute fluxes →** Measured up to ~1.2 TV. **Complex spectral structures observed (spectral hardening at ~200 GV).**
- **H and He isotope fluxes and ratio ->** most complete measurements so far.
- **Electron absolute flux →**Measured up to ~600 GeV. Possible deviations from standard scenario, not inconsistent with an additional electron component.

- **Solar physics**: measurement of modulated fluxes and solar-flare particle spectra
- **Physics of the magnetosphere**: first measurement of trapped antiproton flux.

Other studies and forthcoming results:

- *Primary and secondary-nuclei abundance (up to Oxygen)*
- *Solar modulation (long-term flux variation and charge-dependent effects)*
- *Solar events: several new events under study*

PAMELA on Physics Reports

"The PAMELA Space Mission: Heralding a New Era in Precision Cosmic Ray Physics"

Ready to be submitted to
Physics Reports (78 pages).

Summarizes published and unpublished (but final) PAMELA results.