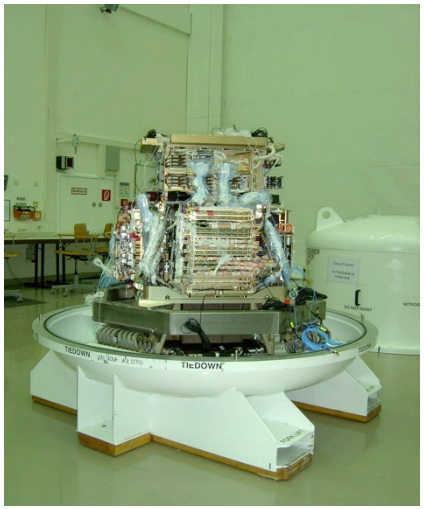
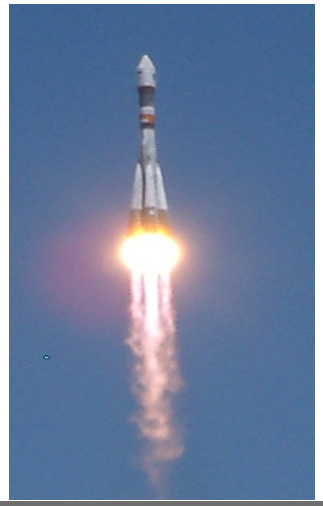
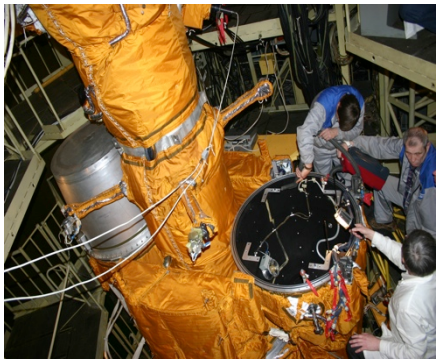
Main results of the PAMELA space experiment after 8 years in orbit

Roberta Sparvoli - University of Rome Tor Vergata & INFN, Italy



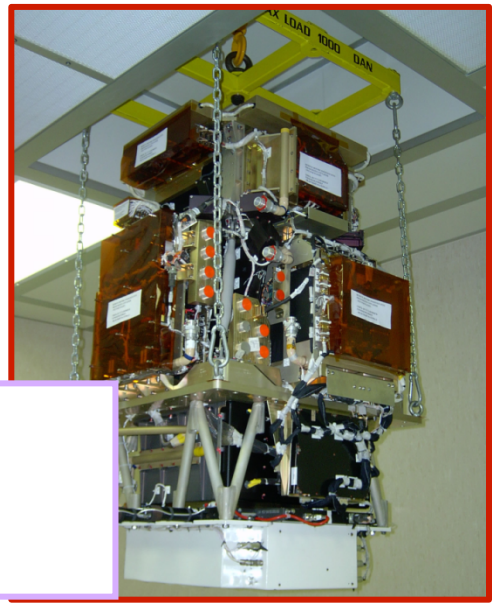




TEVPA 2014 – Amsterdam , 24th June 2014

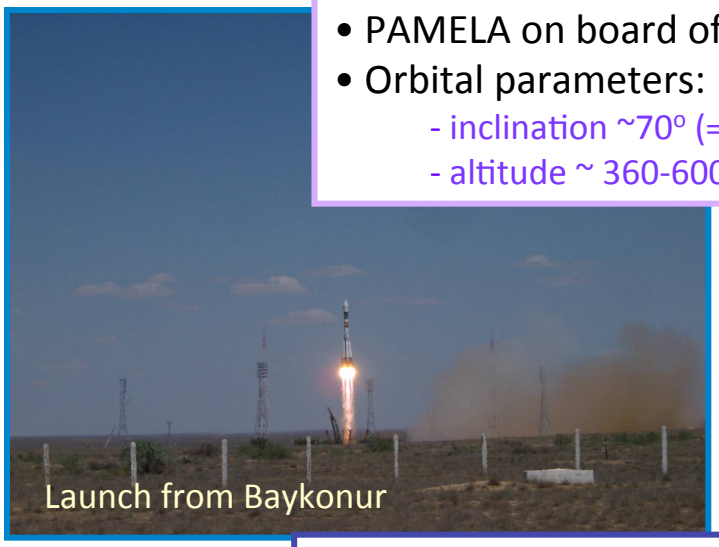
PAMELA

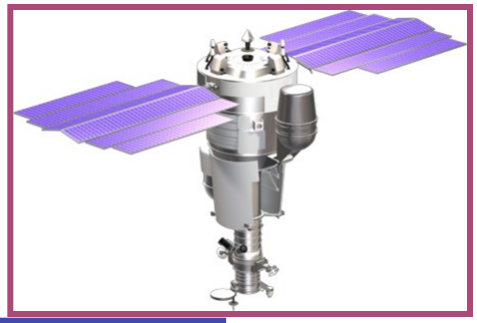
Payload for Matter/antimatter Exploration and Light-nuclei Astrophysics



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

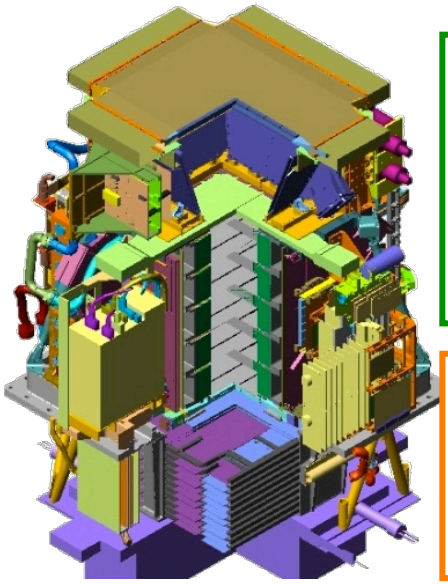
- PAMELA on board of Russian satellite **Resurs DK1**
- Orbital parameters:
  - inclination ~70° (⇒ low energy)
  - altitude ~ 360-600 km (elliptical) – now 500 km (circular)





→ **Launched on 15th June 2006**

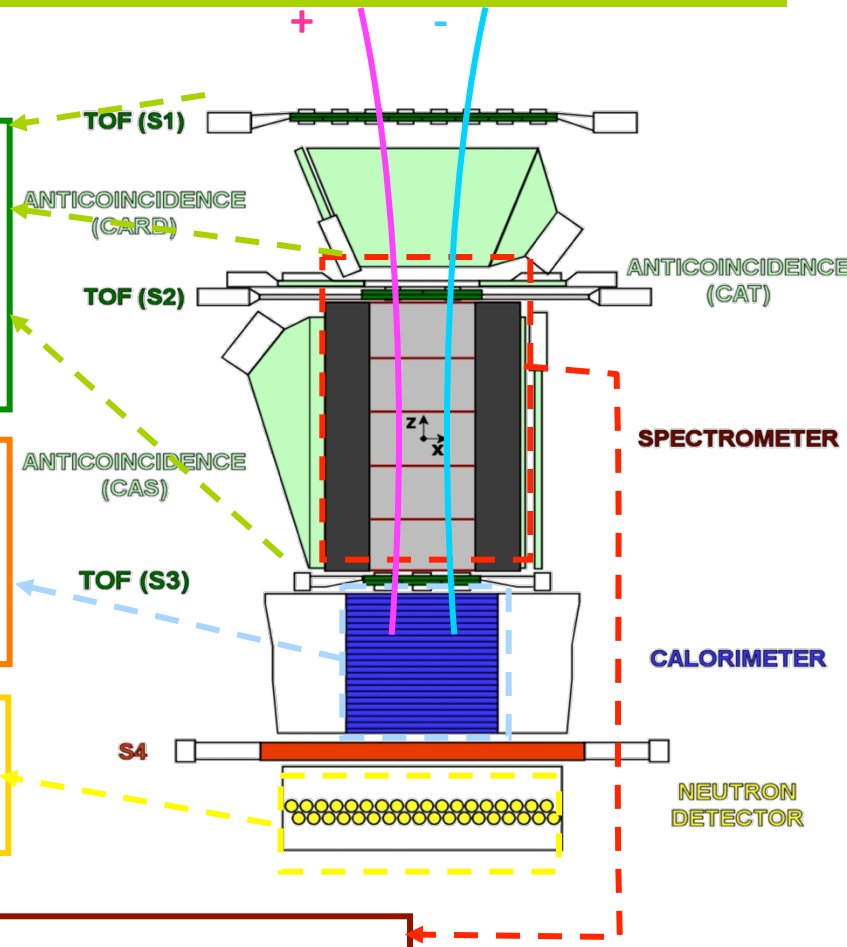
→ **PAMELA in continuous data-taking mode since then!**



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 X_0, 0.6 λ_I)
- Discrimination e+ / p, anti-p / e^- (shower topology)
- Direct E measurement for e^-

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



PAMELA detectors

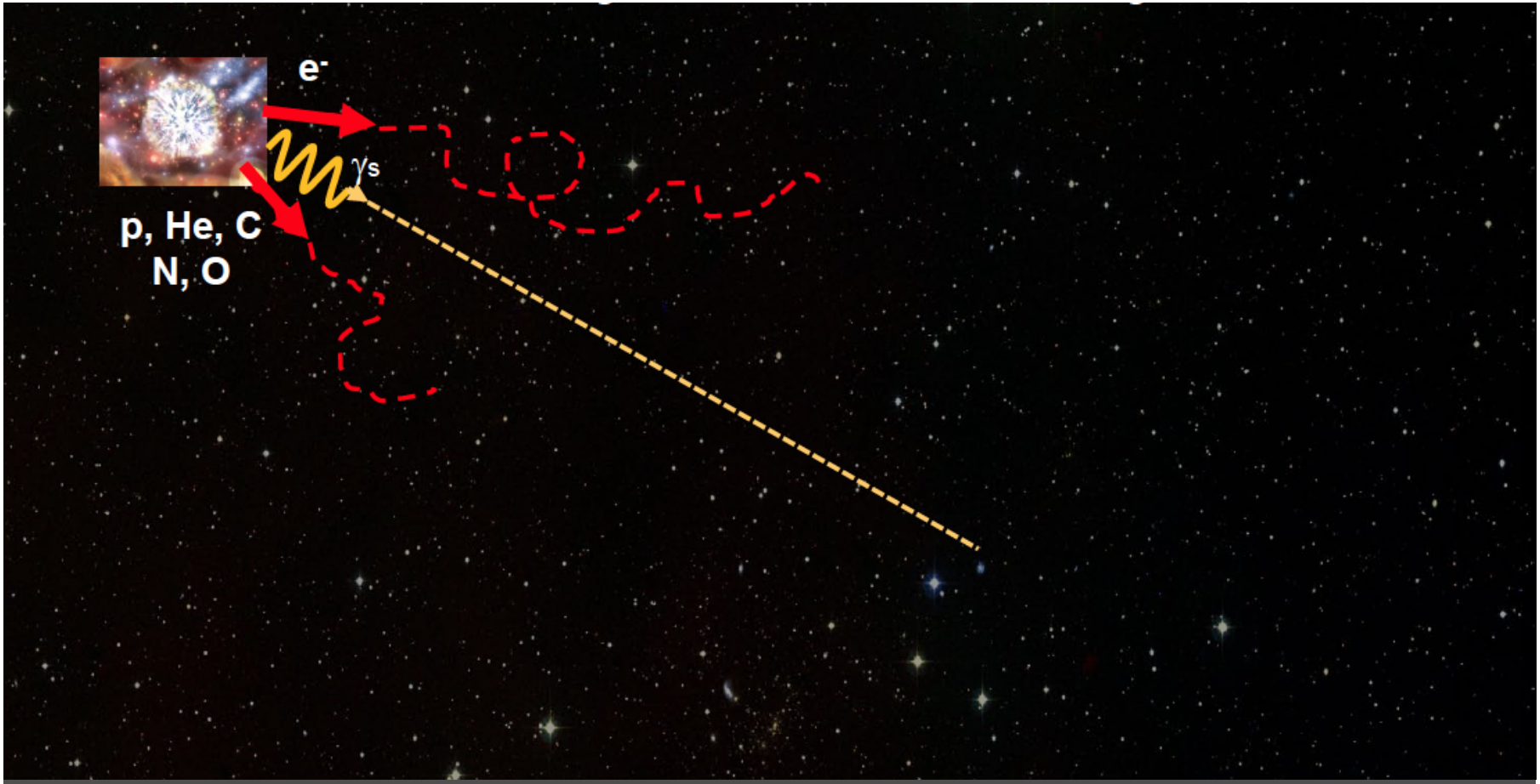
Main requirements:
- **high-sensitivity antiparticle identification**
- **precise momentum measurement**

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

PAMELA published results

- **Antiproton flux + antiproton/proton ratio** (100 MeV-200 GeV)
- **Positron flux + positron/electron ratio** (100 MeV-200 GeV)
- **Electron flux** (1 – 500 GeV)
- **Proton and helium flux** (1 GeV – 1.2 TeV)
- **B/C ratio** (500 MeV – 100 GeV)
- **H and He isotope flux**
- **AntiHe/He**
- **Proton flux vs. time** – solar modulation
- **Trapped antiproton flux**
- **SEP data**



Absolute fluxes of primary GCRs

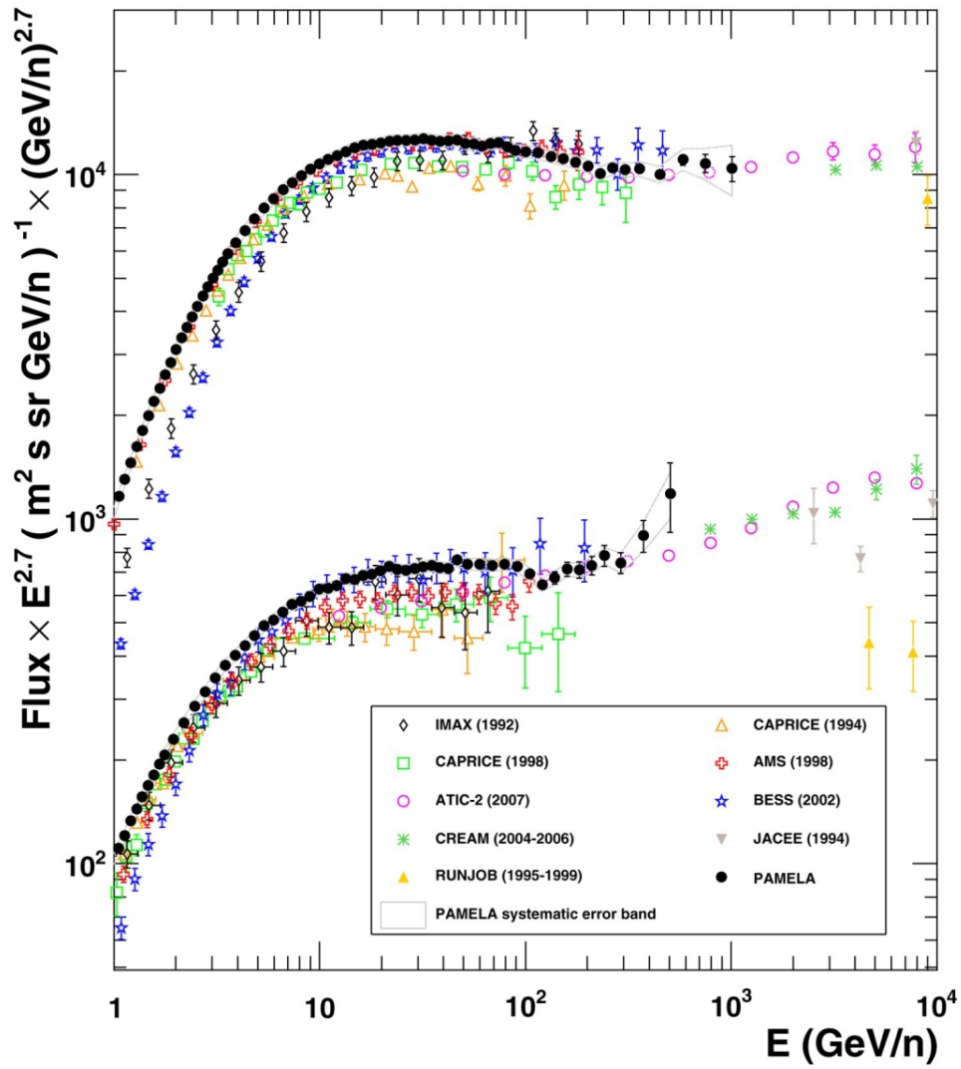
Protons, helium nuclei, light nuclei, electrons

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

H & He absolute fluxes

Adriani et al. , Science 332 (2011) 6025



Deviations from single power law (SPL):

Spectra gradually soften in the range 30÷230 GV

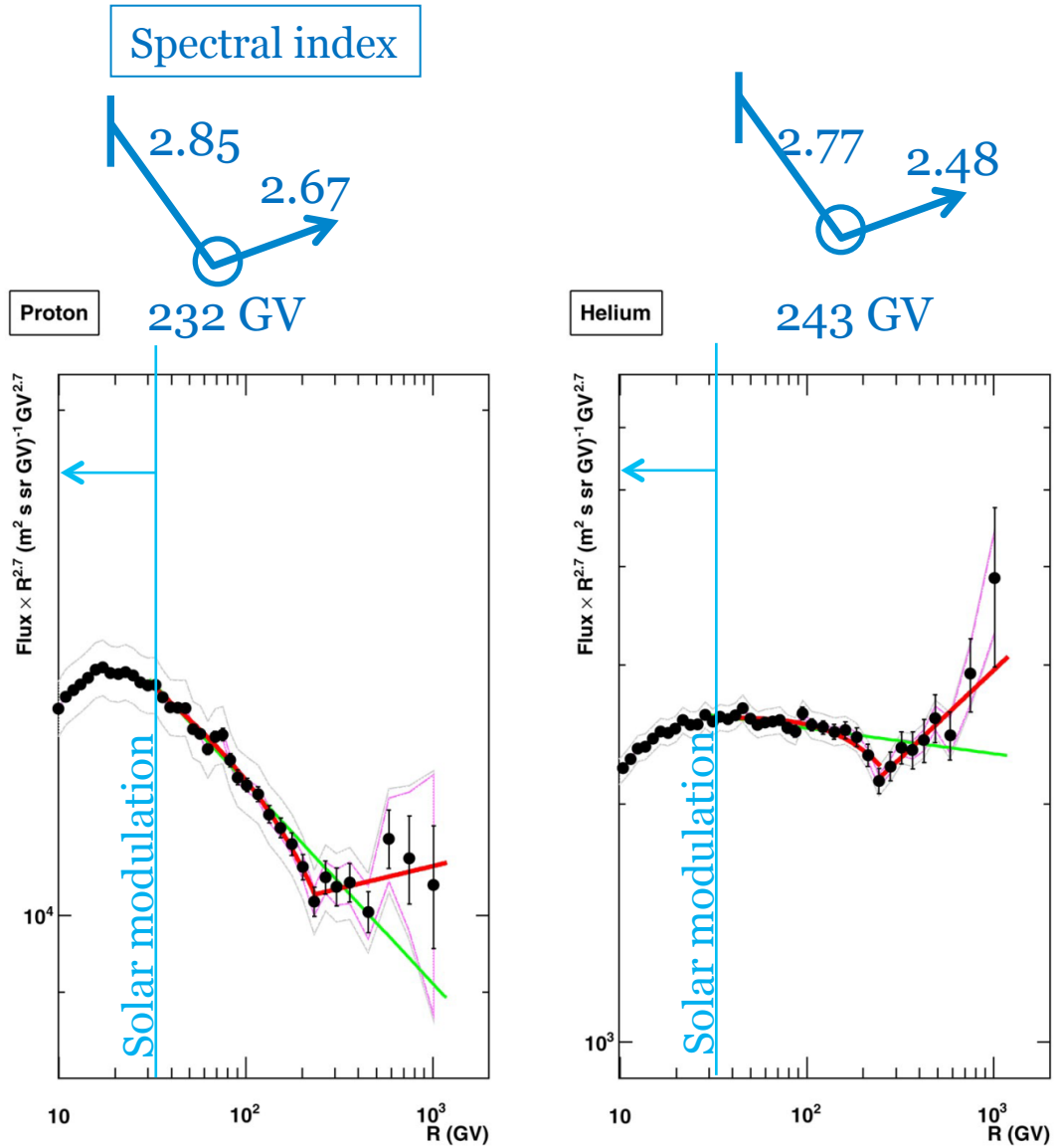
Spectral hardening @ ~ 235 GV

Eg: statistical analysis for protons

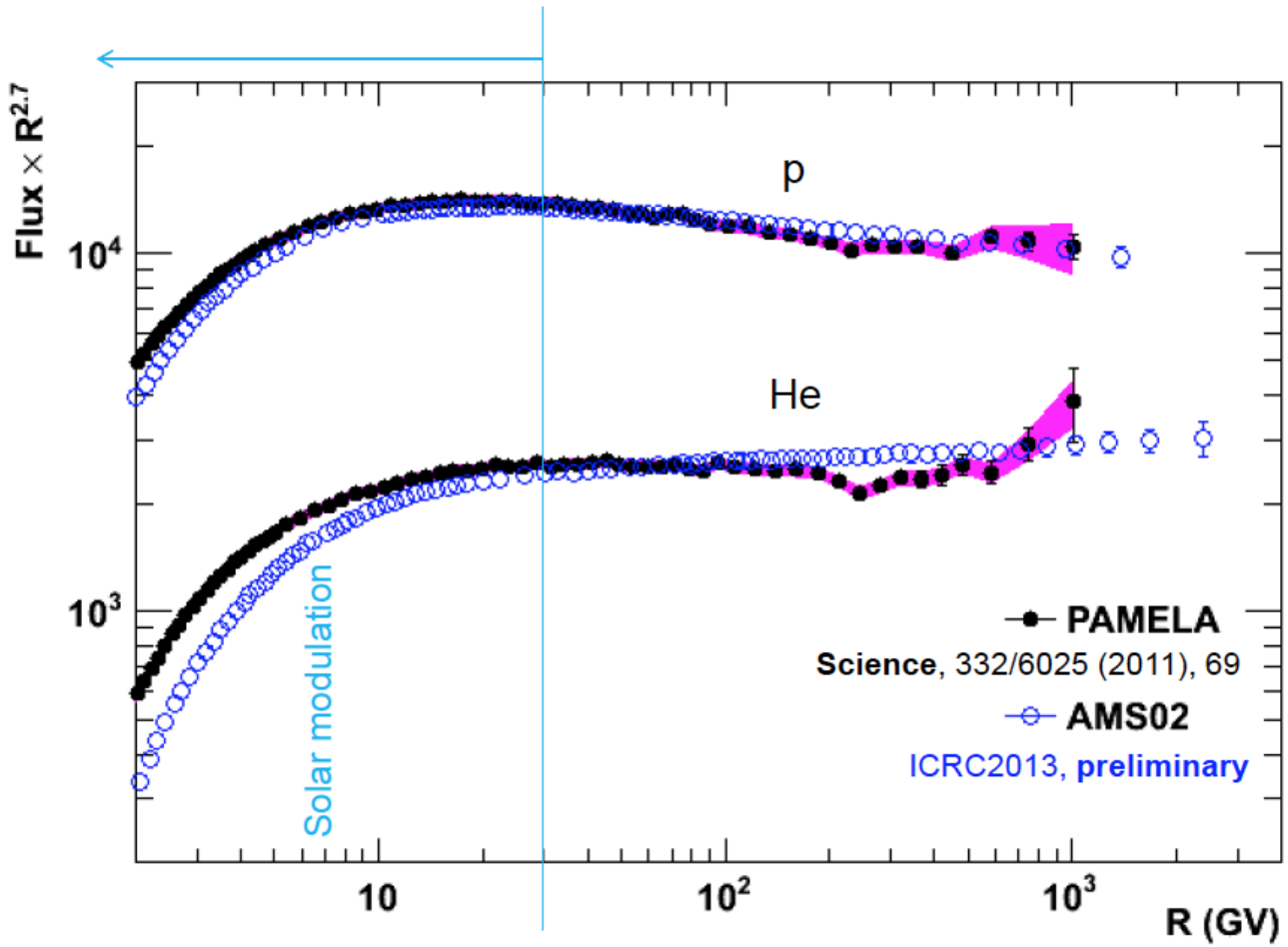
SPL hp in the range 30÷230 GV rejected @ >95% CL

SPL hp above 80 GV rejected @ >95% CL

H & He absolute fluxes @ high energy

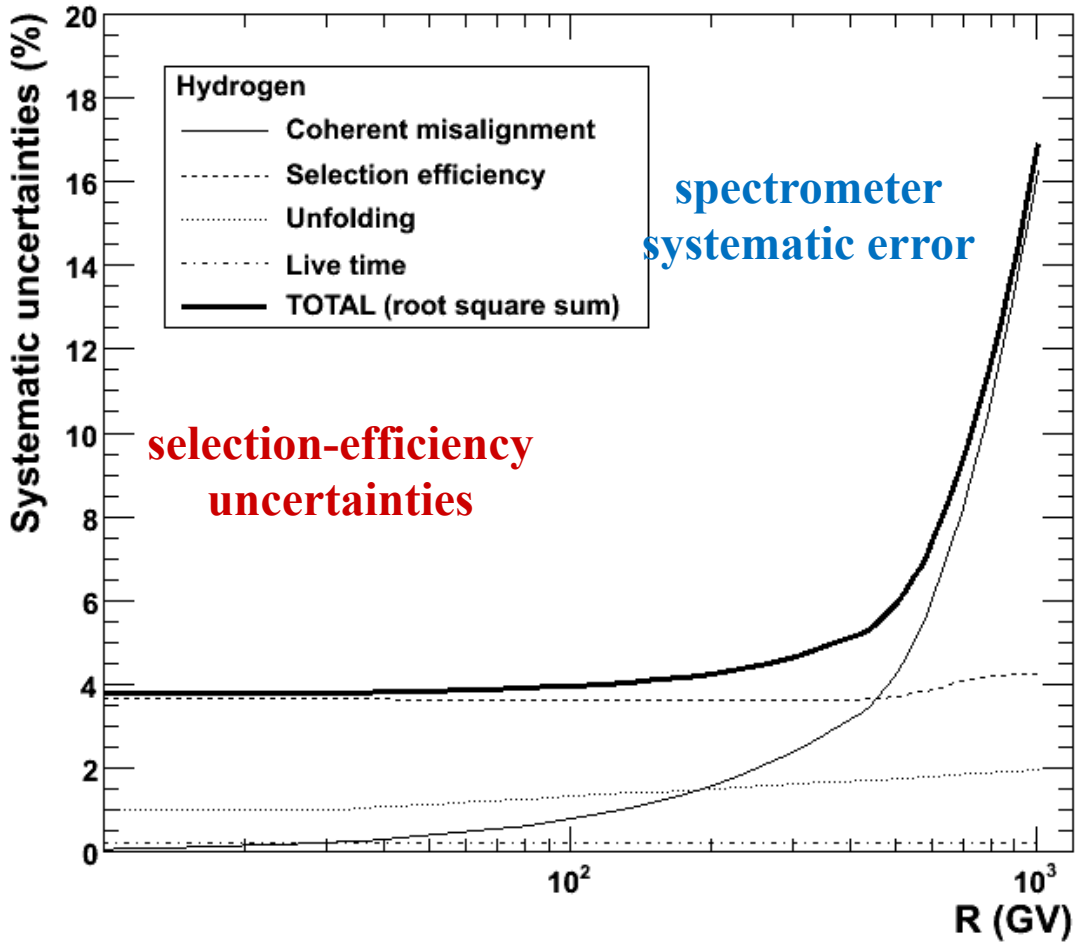


Comparison with AMS: p and He



Overall systematic uncertainties

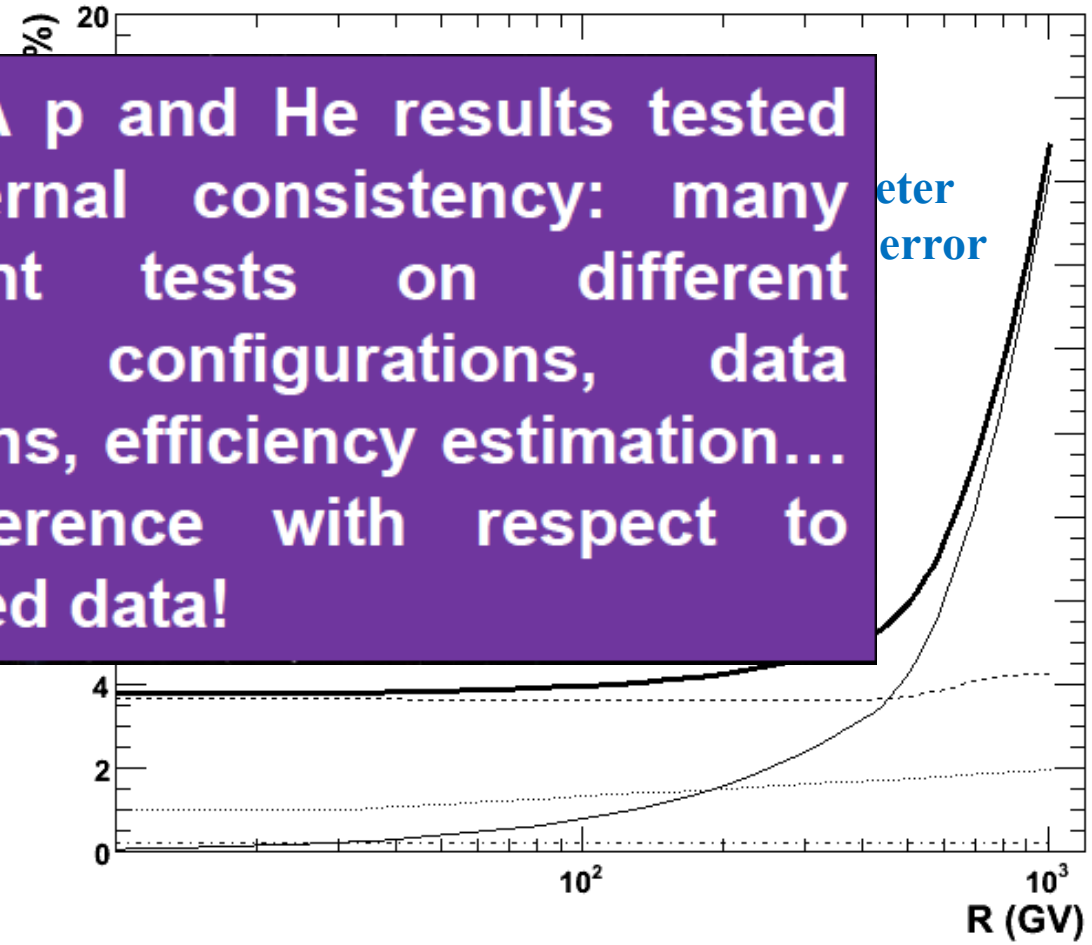
- At low R selection-efficiency uncertainties dominate
- Above 500 GV tracking-system (coherent) misalignment dominates



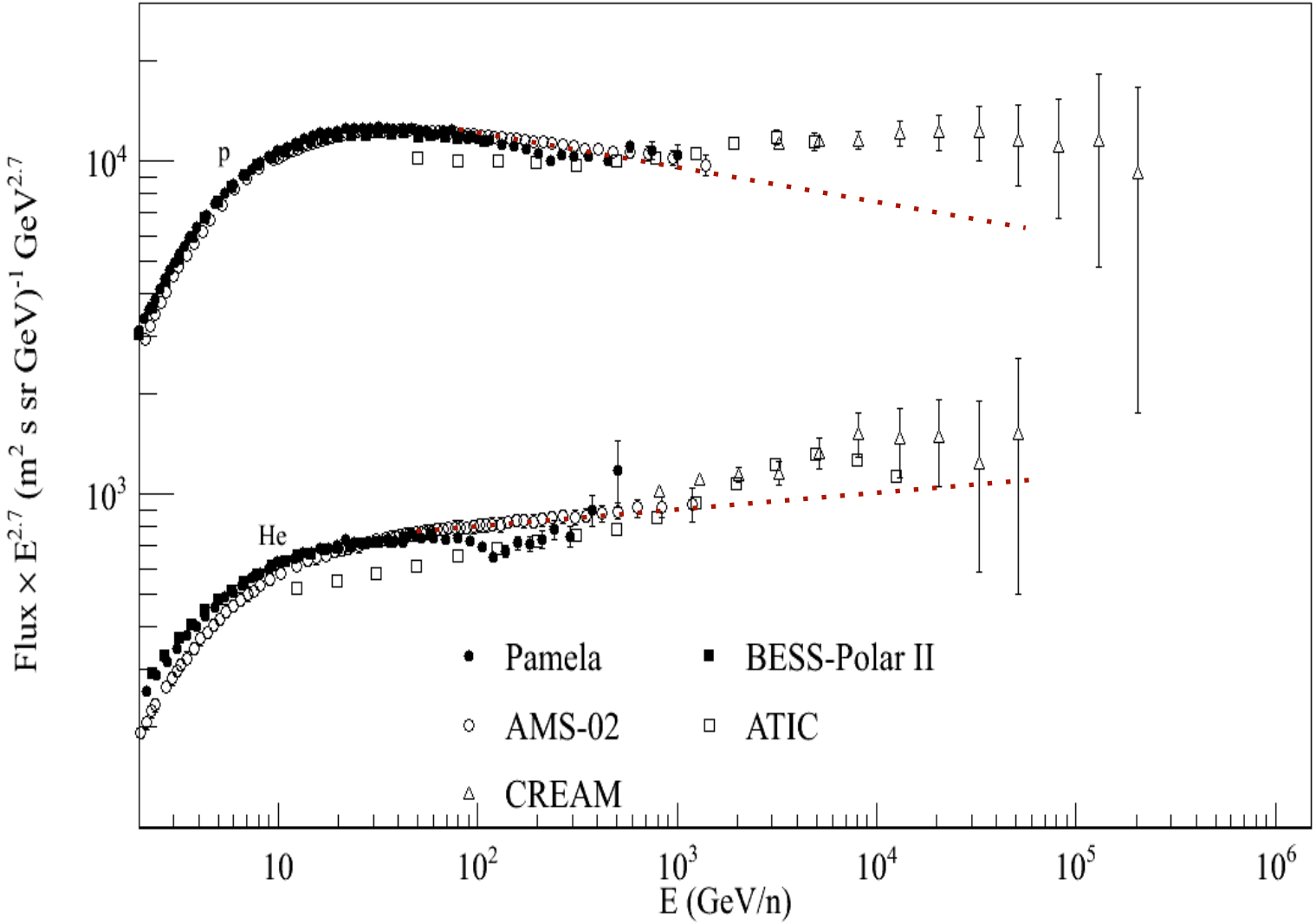
Overall systematic uncertainties

- At low R s
  efficiency
  uncertainti
  dominate
- Above 50
  tracking-sy
  (coherent)
  misalignment
  dominates

PAMELA p and He results tested for internal consistency: many reduntant tests on different detector configurations, data selections, efficiency estimation… no difference with respect to published data!



Global picture: good agreement with some "tension"



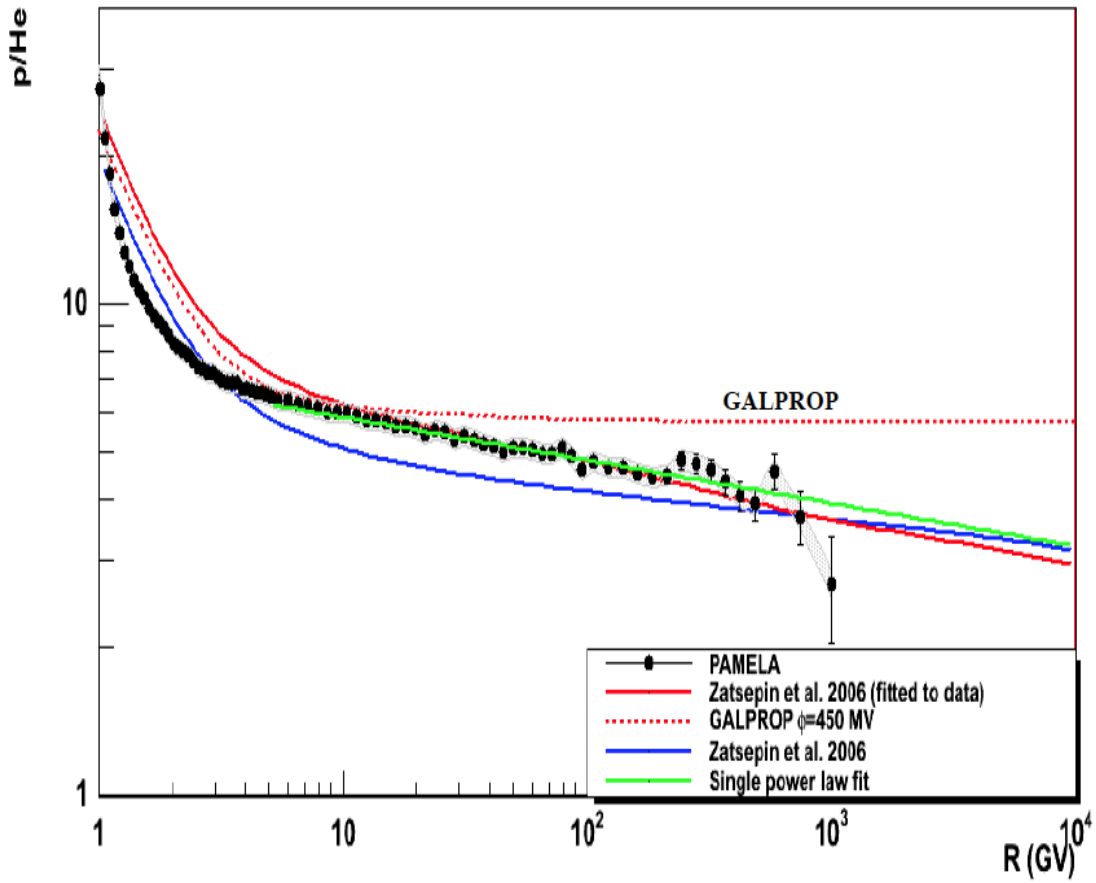
A solid measurements, where almost all systematics cancel dout.

First clear evidence of **different H and He slopes above ~ 10 GV.**

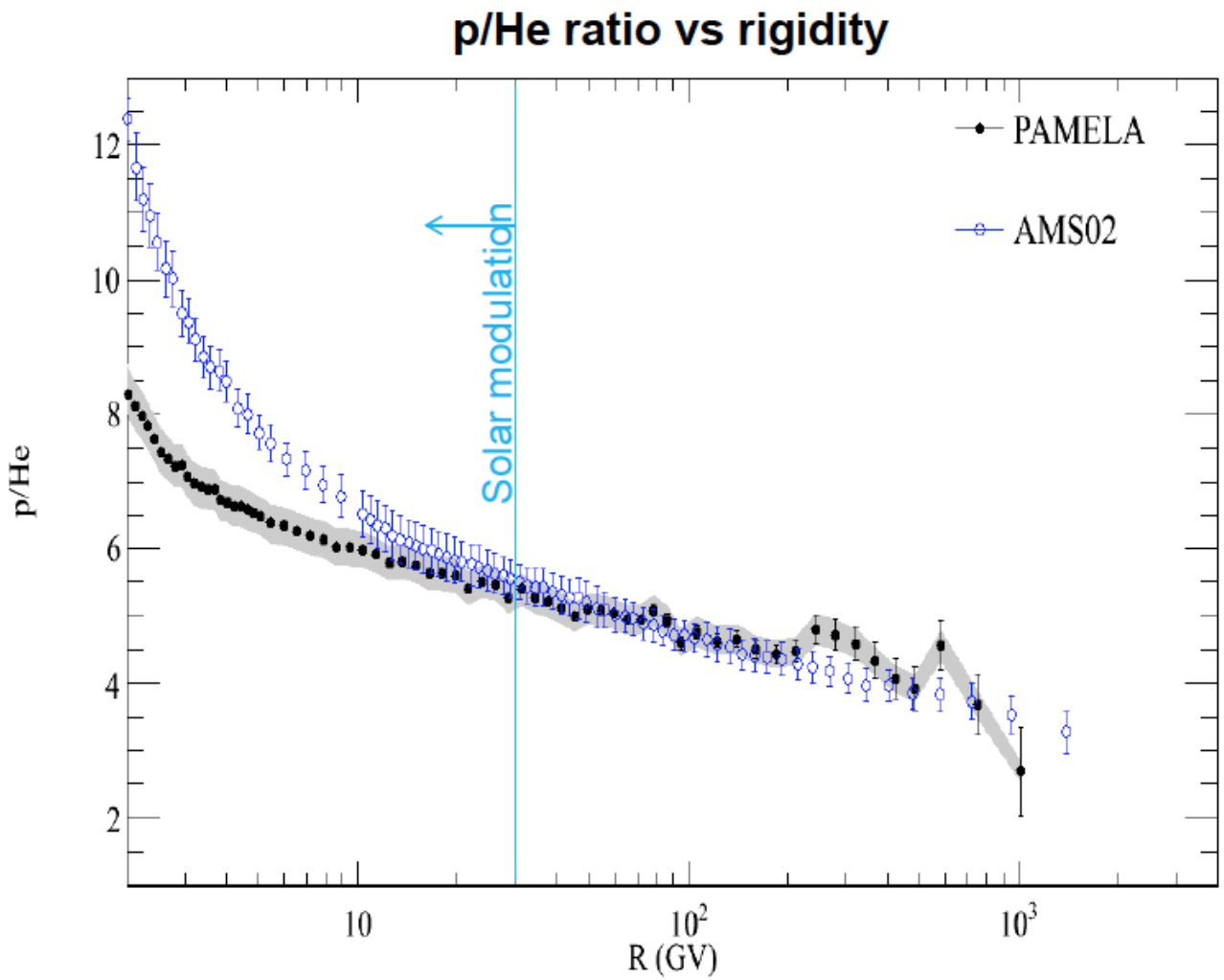
Ratio described by a **single power law** (in spite of the evident structures in the individual spectra)

H/He ratio vs Rigidity

O. Adriani et al., Science, vol. 332 no. 6025 (2011), arXiv: 1103.4055



Comparison with AMS: p/He



Two independent ways to determine electron energy:

Spectrometer

Most precise

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

Calorimeter

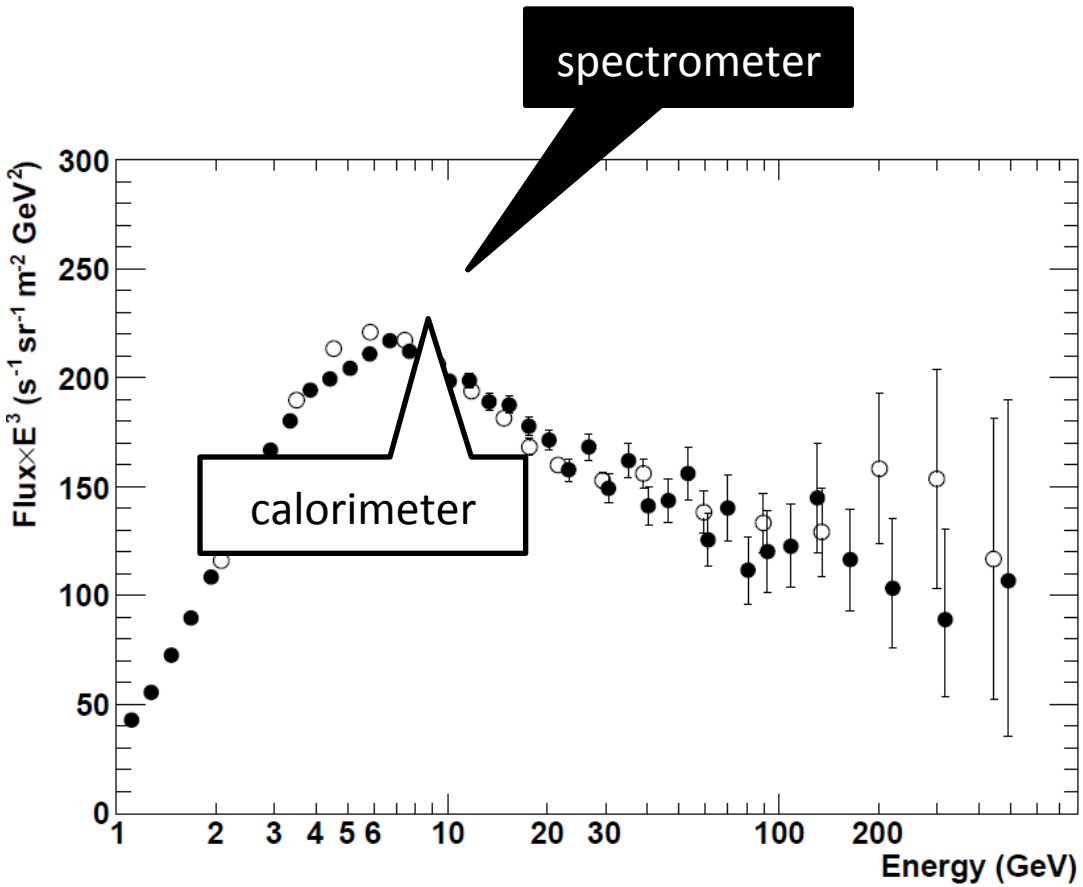
Gaussian resolution

No energy-loss correction required

Strong containment requirements

Electron energy measurements

Adriani et al. , PRL 106 (2011) 201101

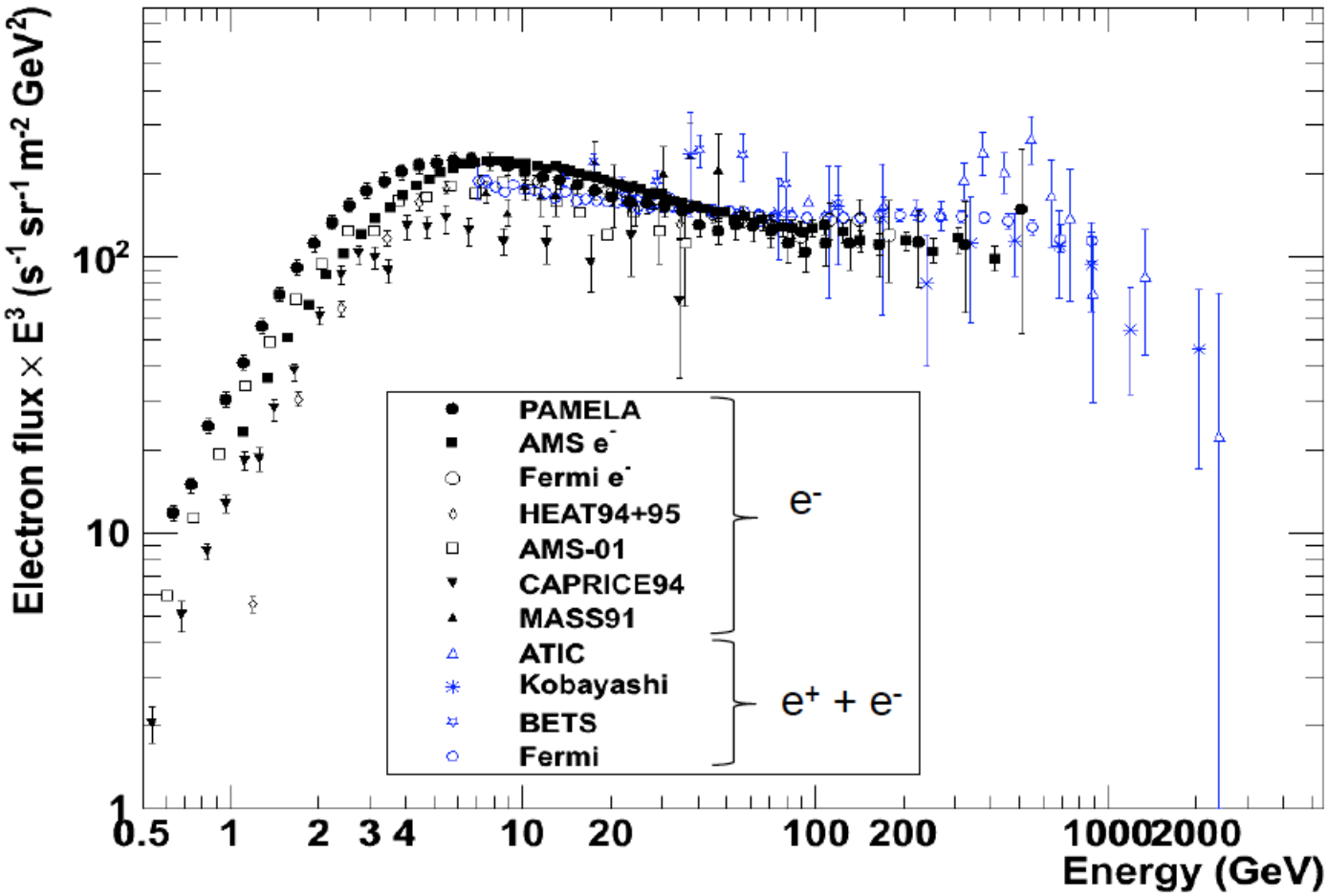


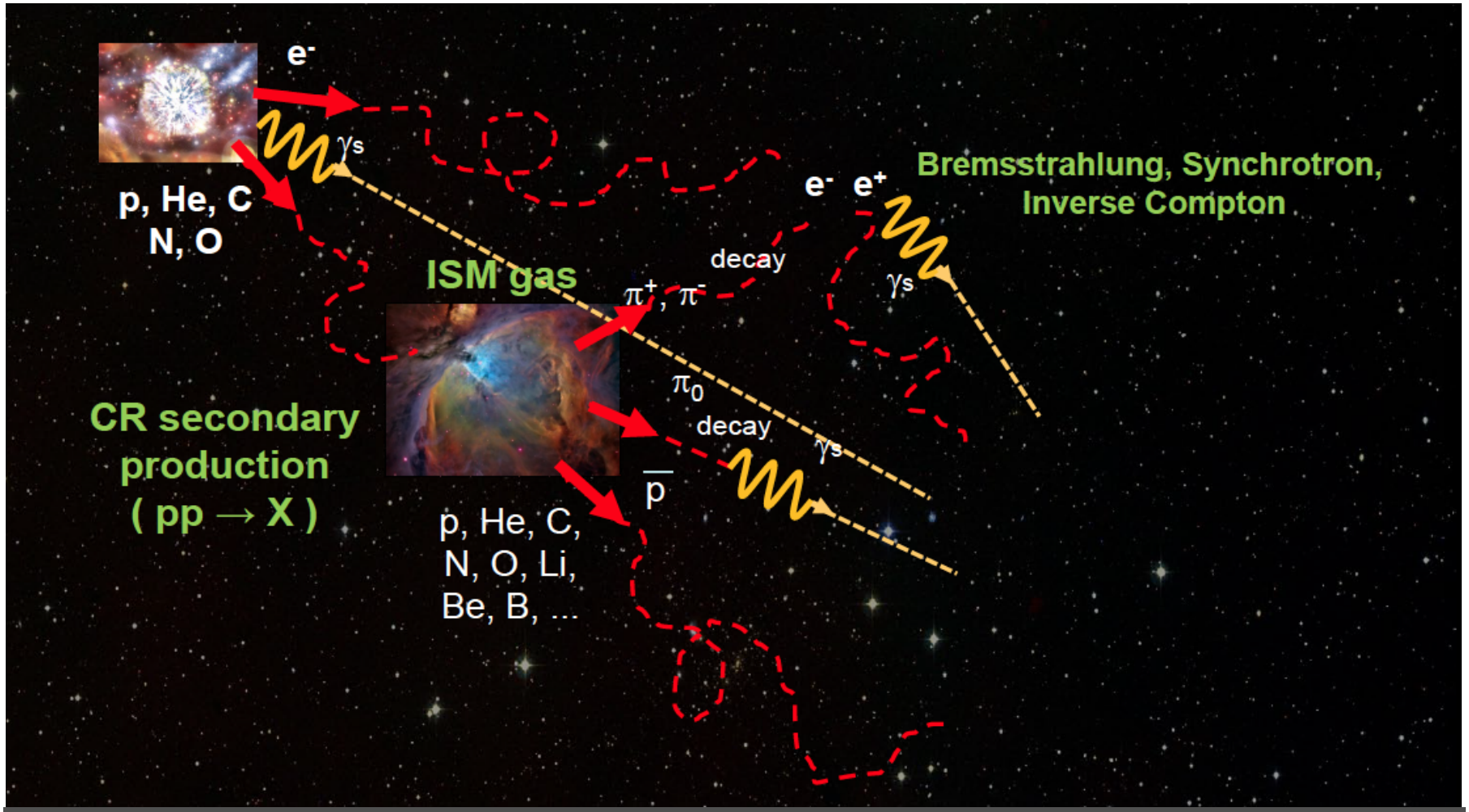
Electron identification:

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

Electron absolute flux

O. Adriani et al., Phys. Rev. Lett. 106, 201101 (2011)





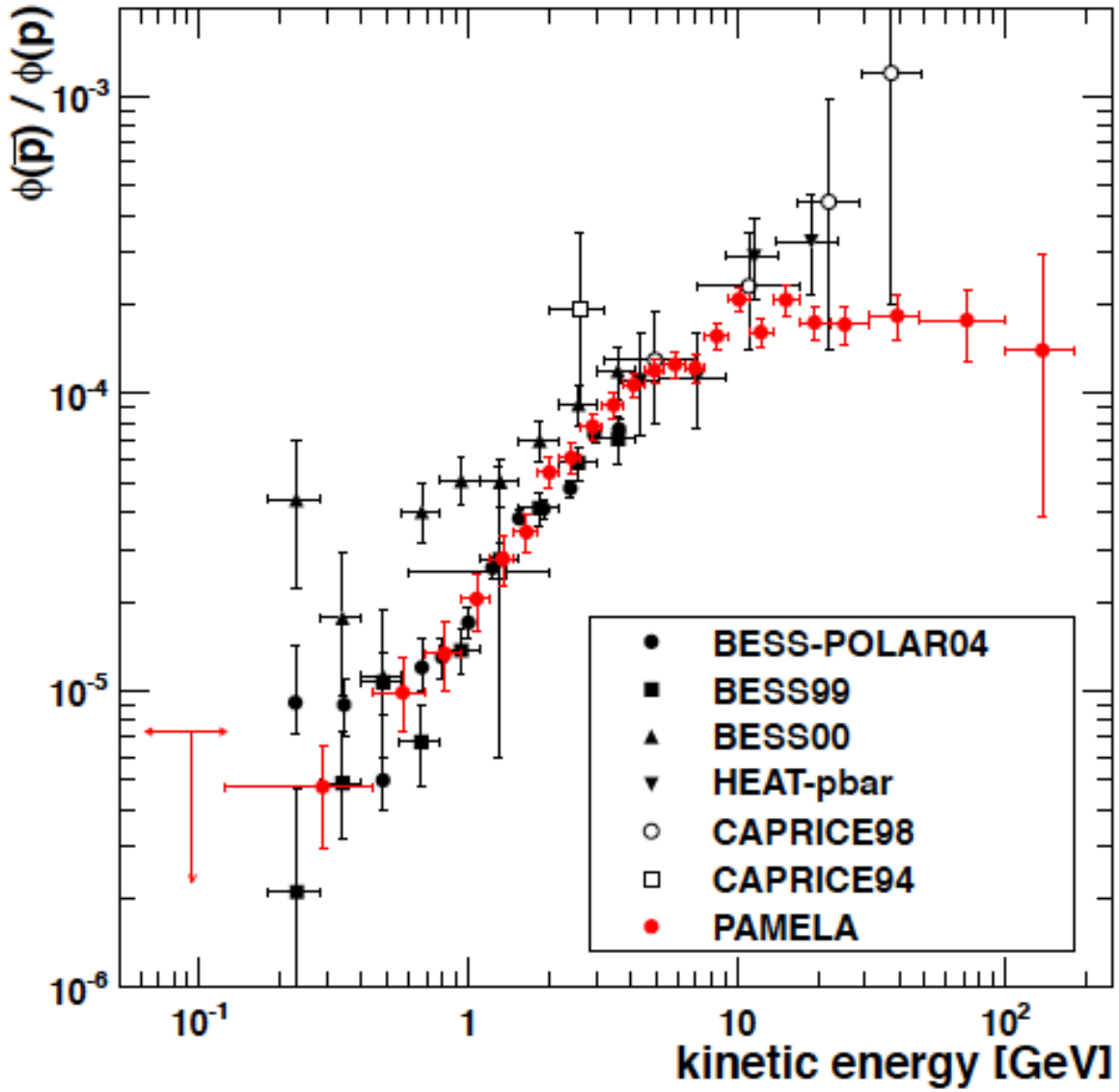
Secondary cosmic rays

Antiparticles (antiprotons, positrons), secondaries from homogeneously distributed interstellar matter (light nuclei)

Adriani et al. - PRL 105 (2010) 121101

100 MeV- 200 GeV

Largest energy range covered so far !



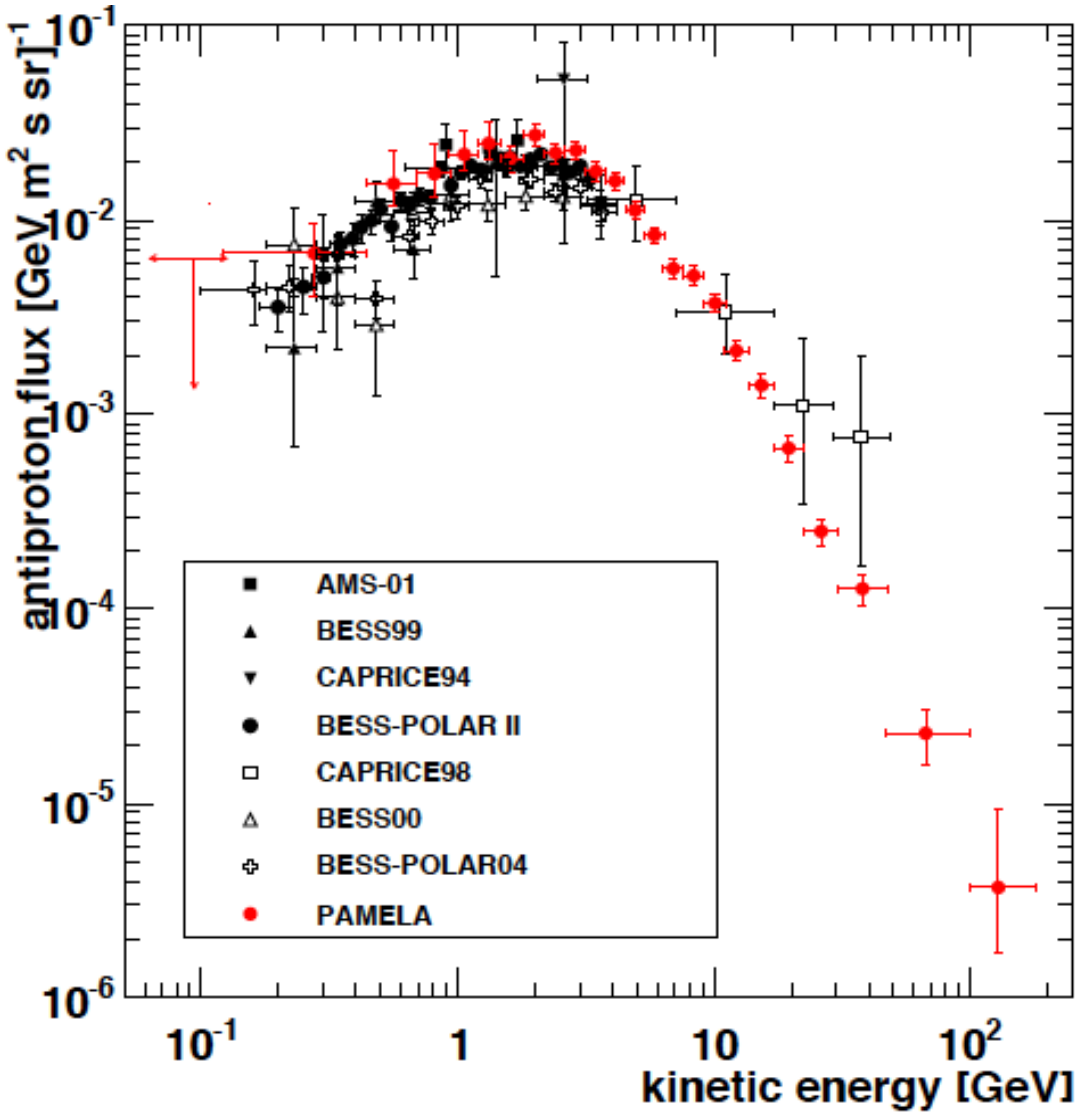
Antiproton-to-proton ratio

100 MeV- 200 GeV

Adriani et al. - PRL 105 (2010) 121101

100 MeV- 200 GeV

Largest energy range covered so far !



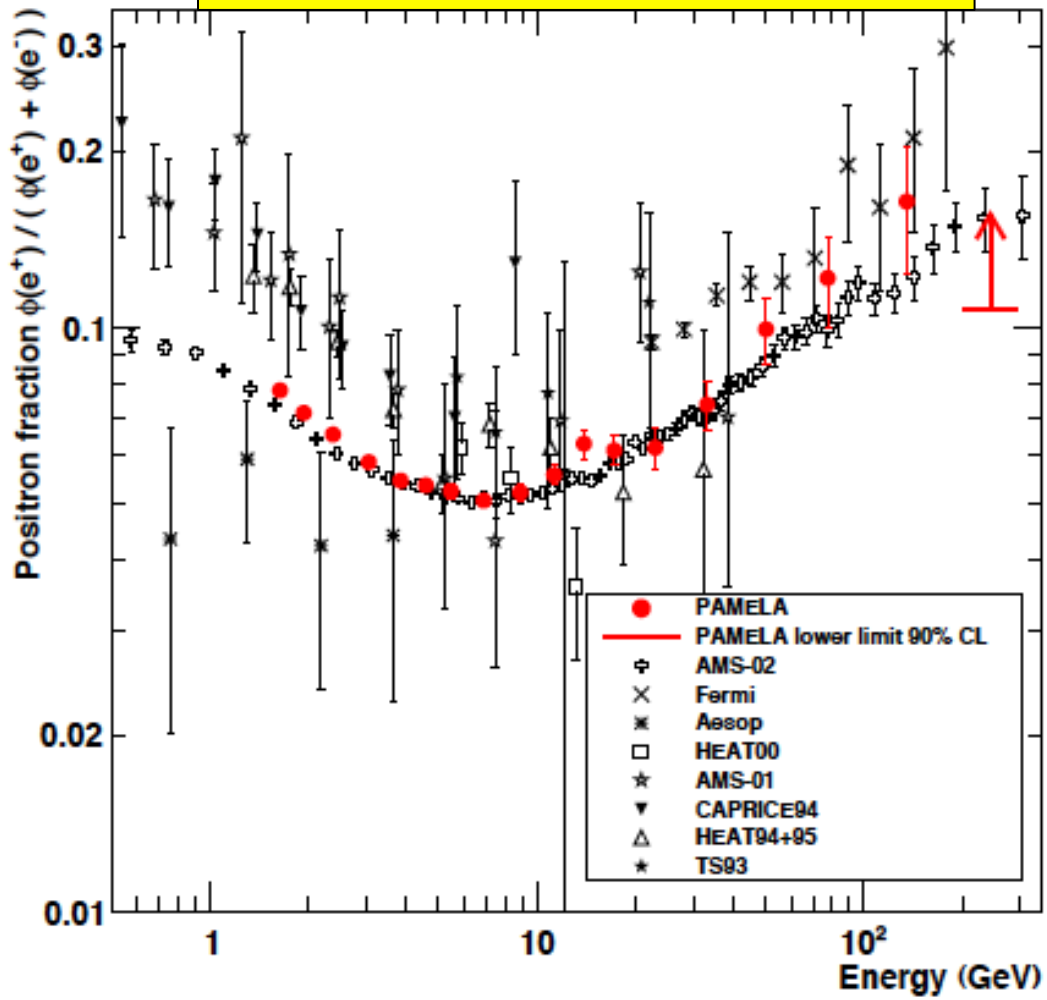
Antiproton flux

100 MeV- 200 GeV

Positron fraction

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

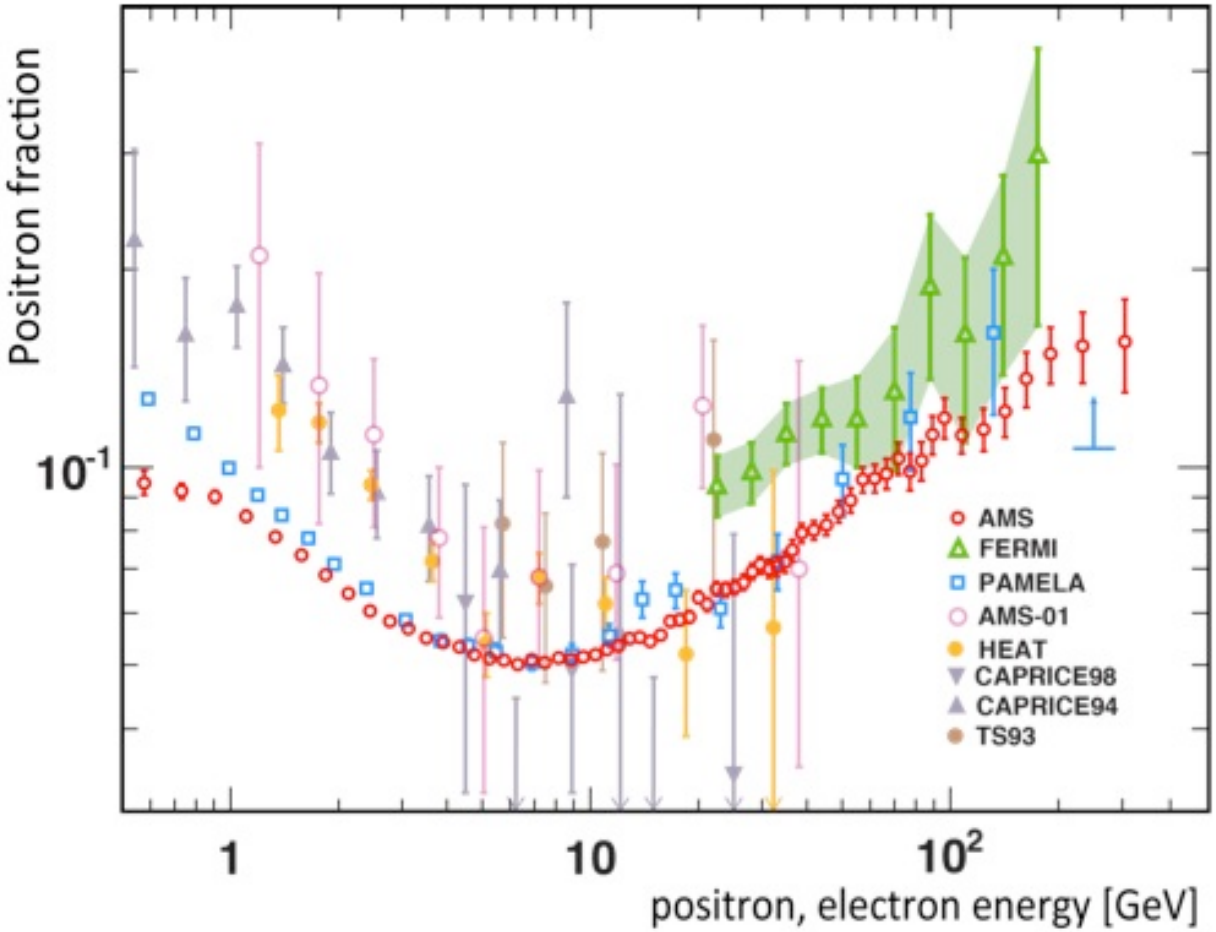
Adriani et al. , Nature 458 (2009) 607
Adriani et al., AP 34 (2010) 1



Good agreement with FERMI and AMS data

Positron fraction – global agreement

M. Aguilar et al, PRL 110, 2013

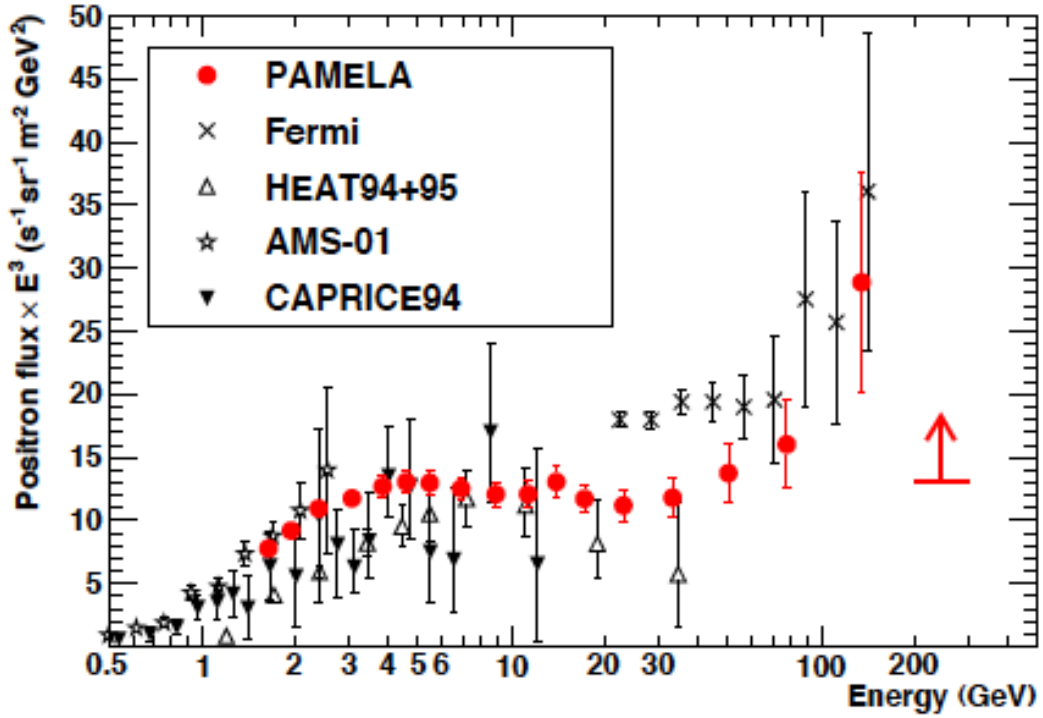


Adriani et al. , PRL **111** (2013) 081102 (2013)

Clear evidence →

The positron fraction increase is due to an increase in the positron flux and not in a decrease of the electron one.

Positron flux



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

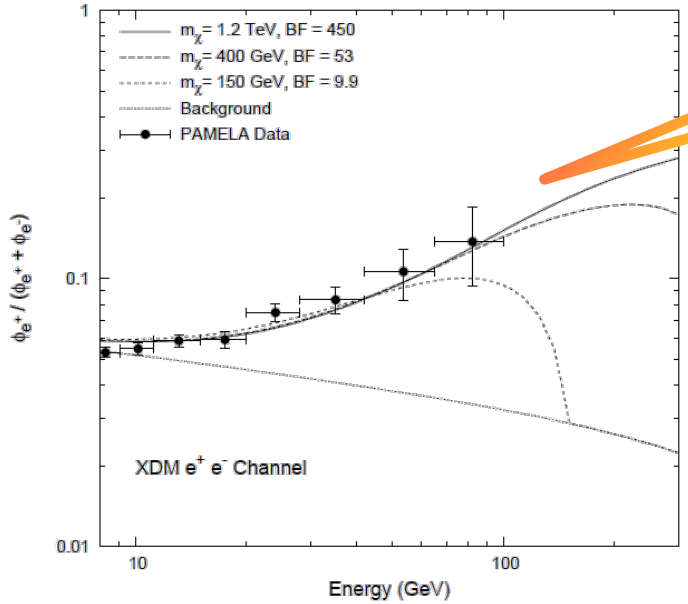
Positron-excess interpretations

<u>Dark matter</u>

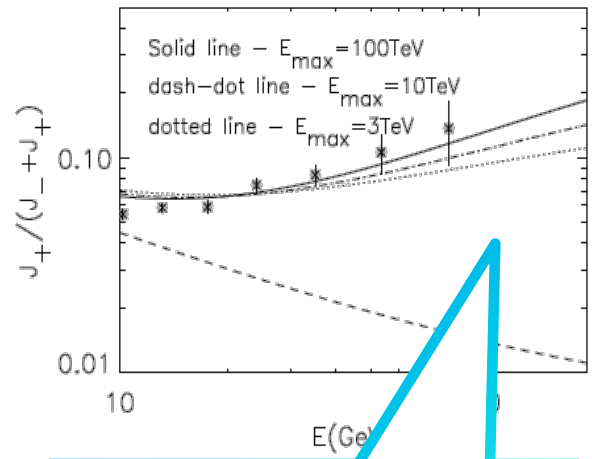
- boost factor required
- lepton vs hadron yield must be consistent with p-bar observation

<u>Astrophysical processes</u>

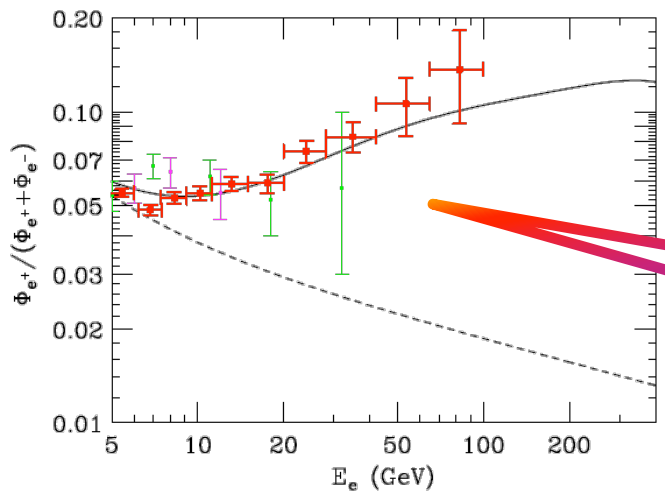
- known processes
- large uncertainties on environmental parameters



Contribution from **DM annihilation**.

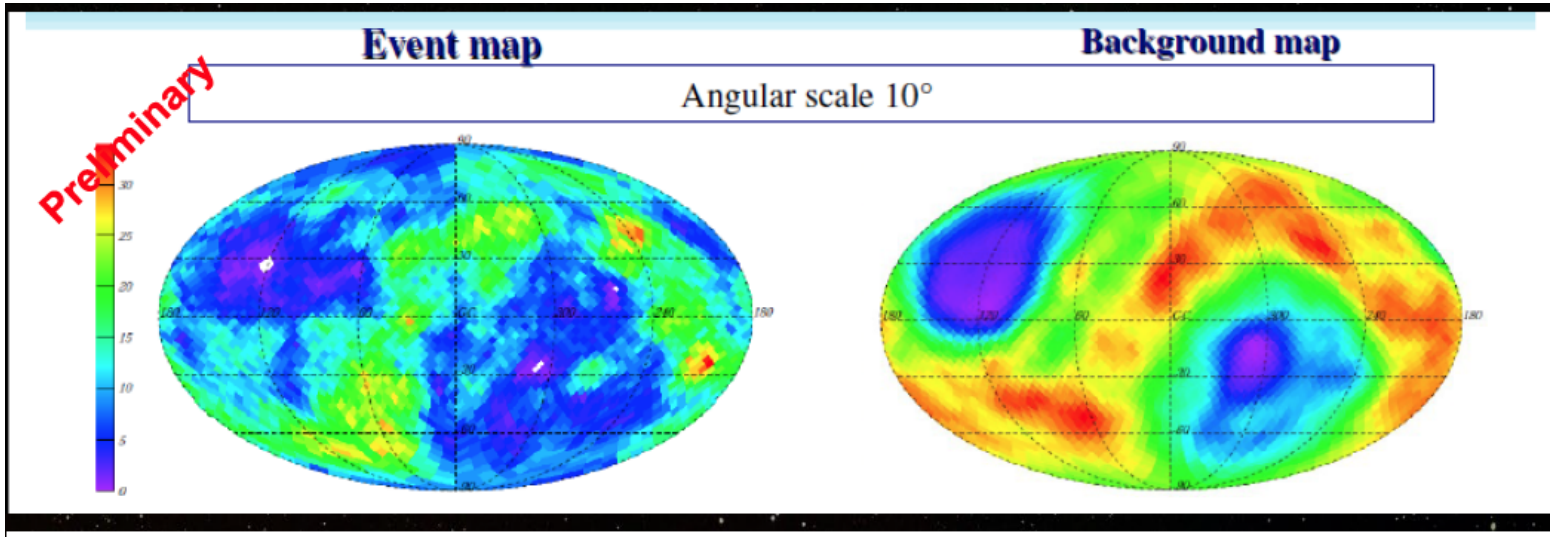


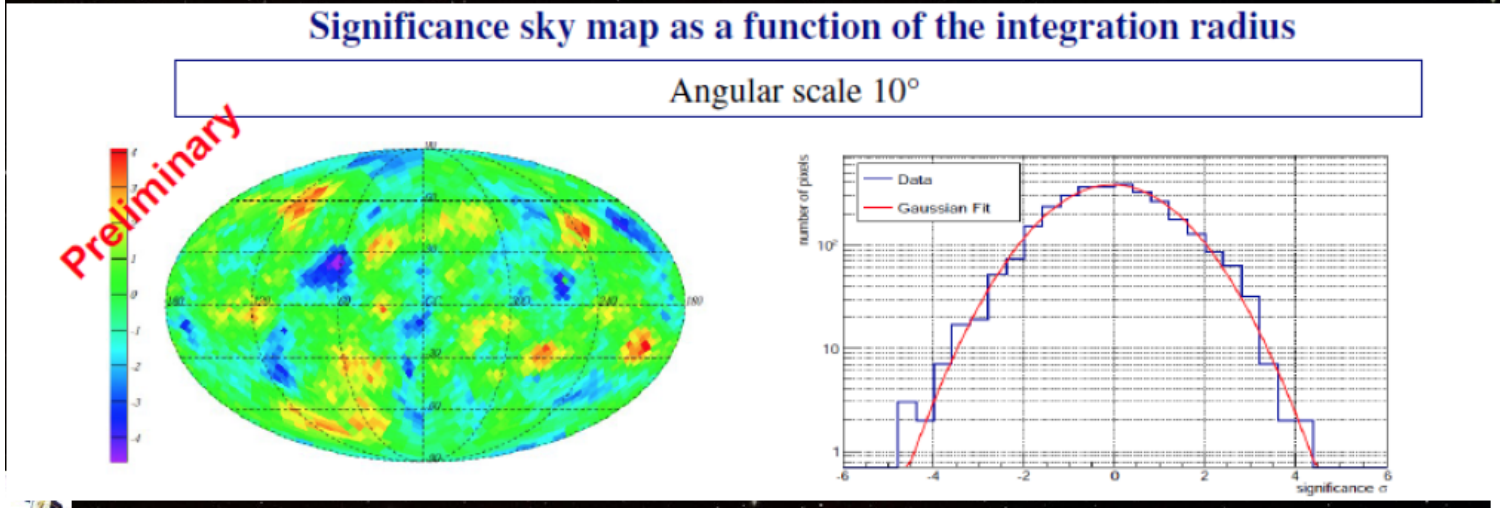
e+ (and e-) produced as **secondaries** in the CR acceleration sites (e.g. SNR)



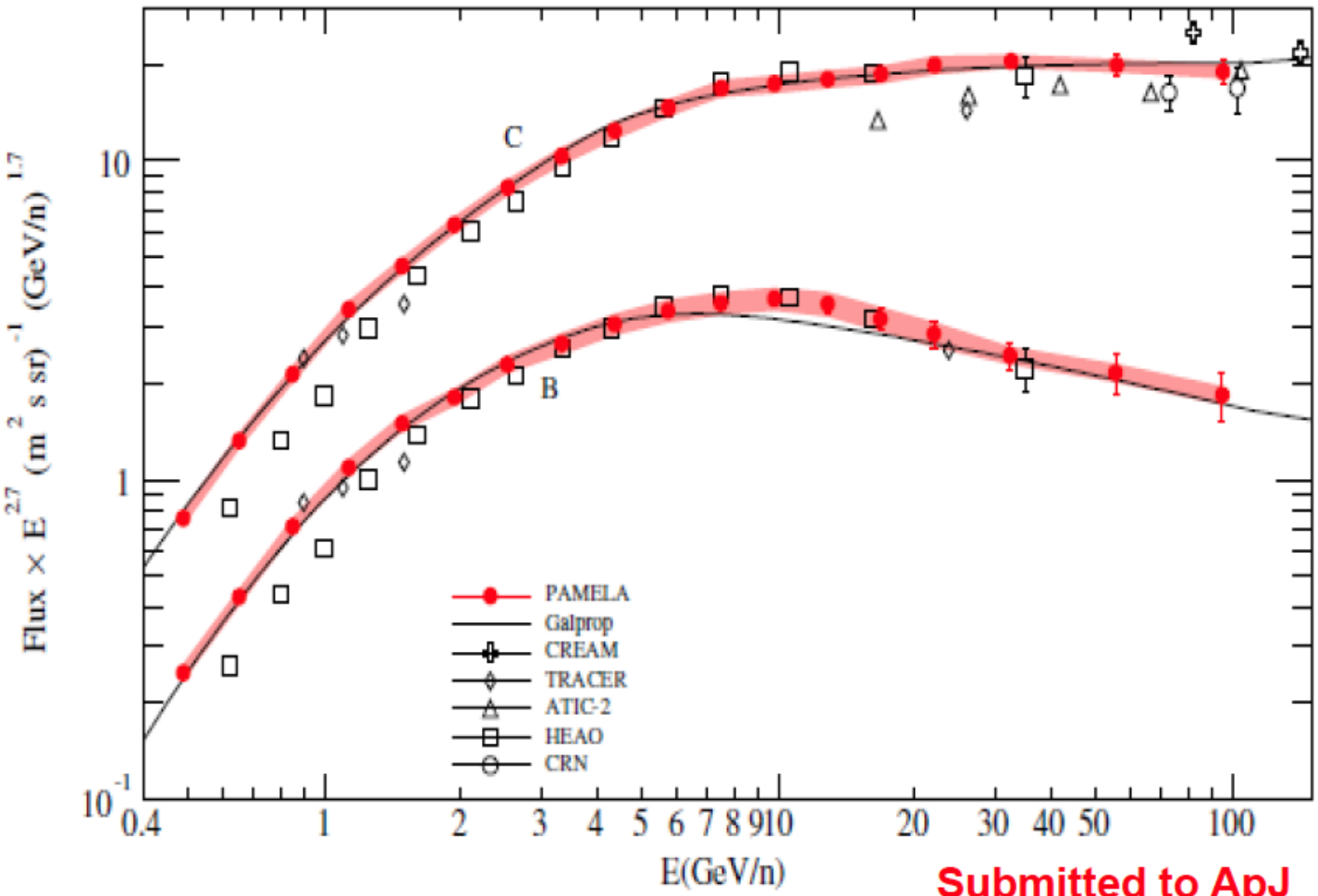
Contribution from diffuse mature & nearby young **pulsars**.

Positrons: isotropic distribution



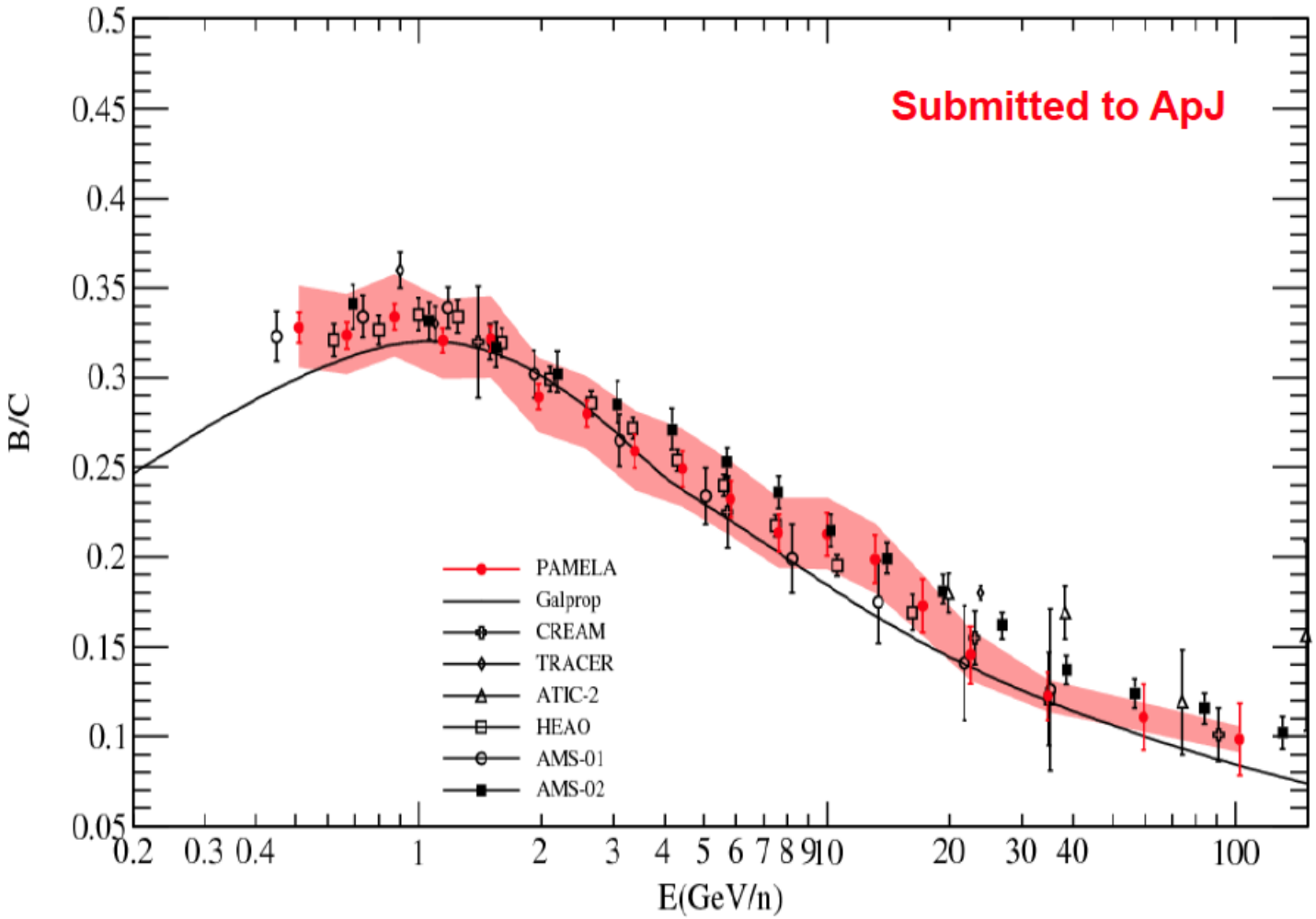


B and C fluxes



Submitted to ApJ

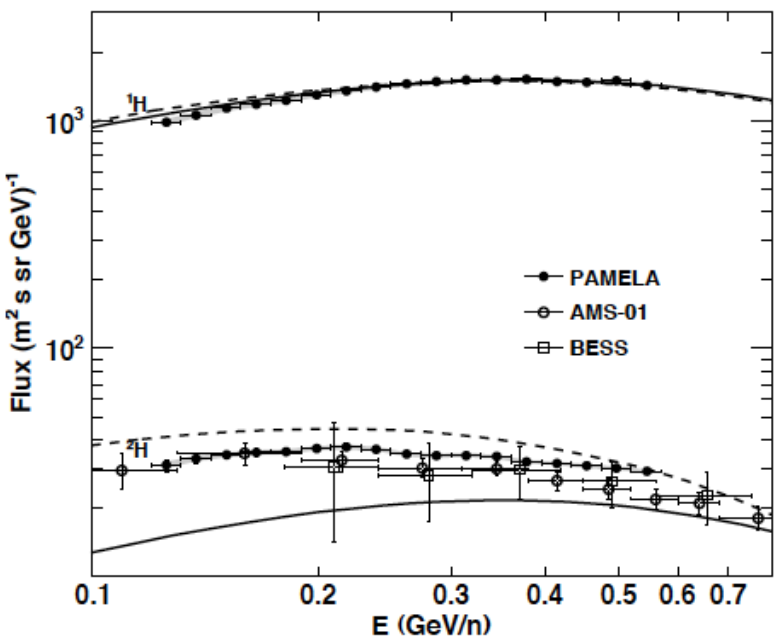
B/C ratio


Submitted to ApJ
B/C
E(GeV/n)
PAMELA
Galprop
CREAM
TRACER
ATIC-2
HEAO
AMS-01
AMS-02

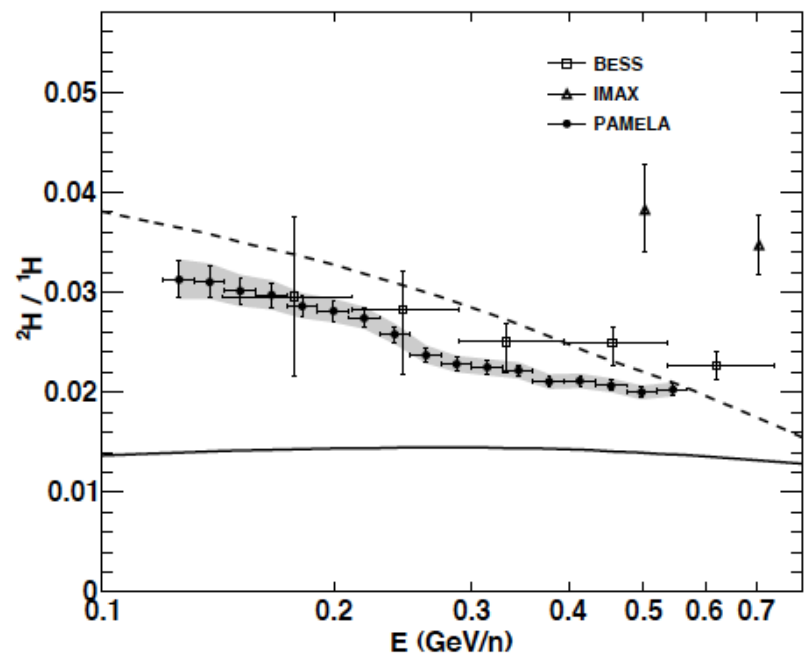
Isotopes: H^1 and H^2

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

H isotope fluxes



$^2H/^1H$ ratio

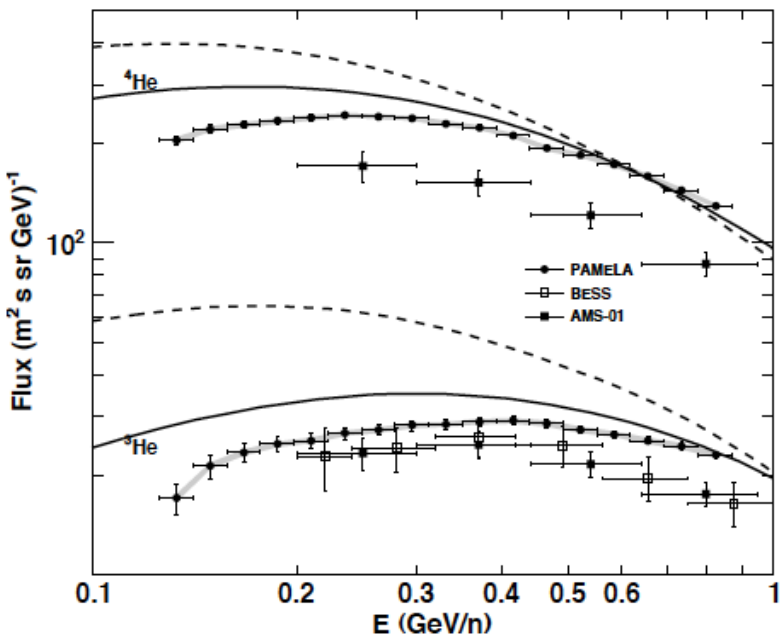


PAMELA's are the most complete measurements so far

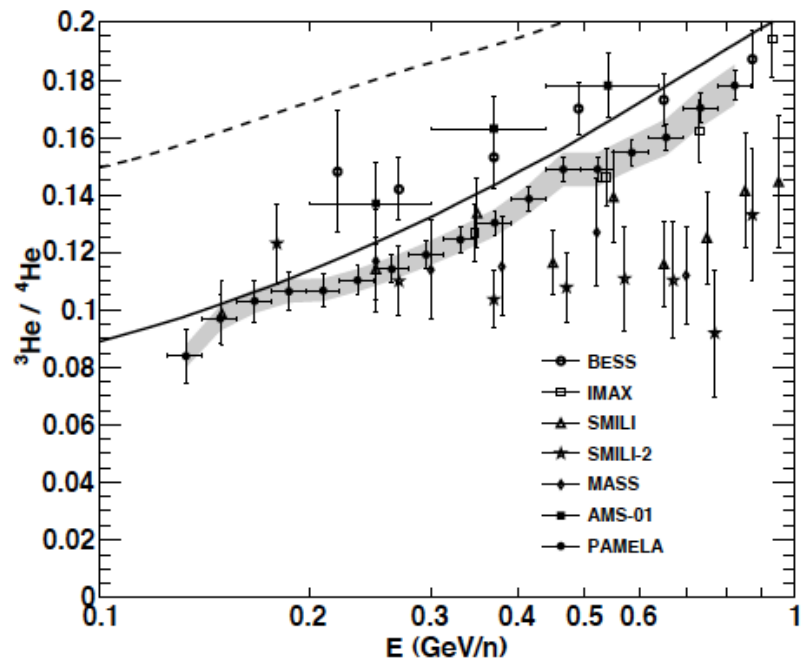
Isotopes: He^3 and He^4

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

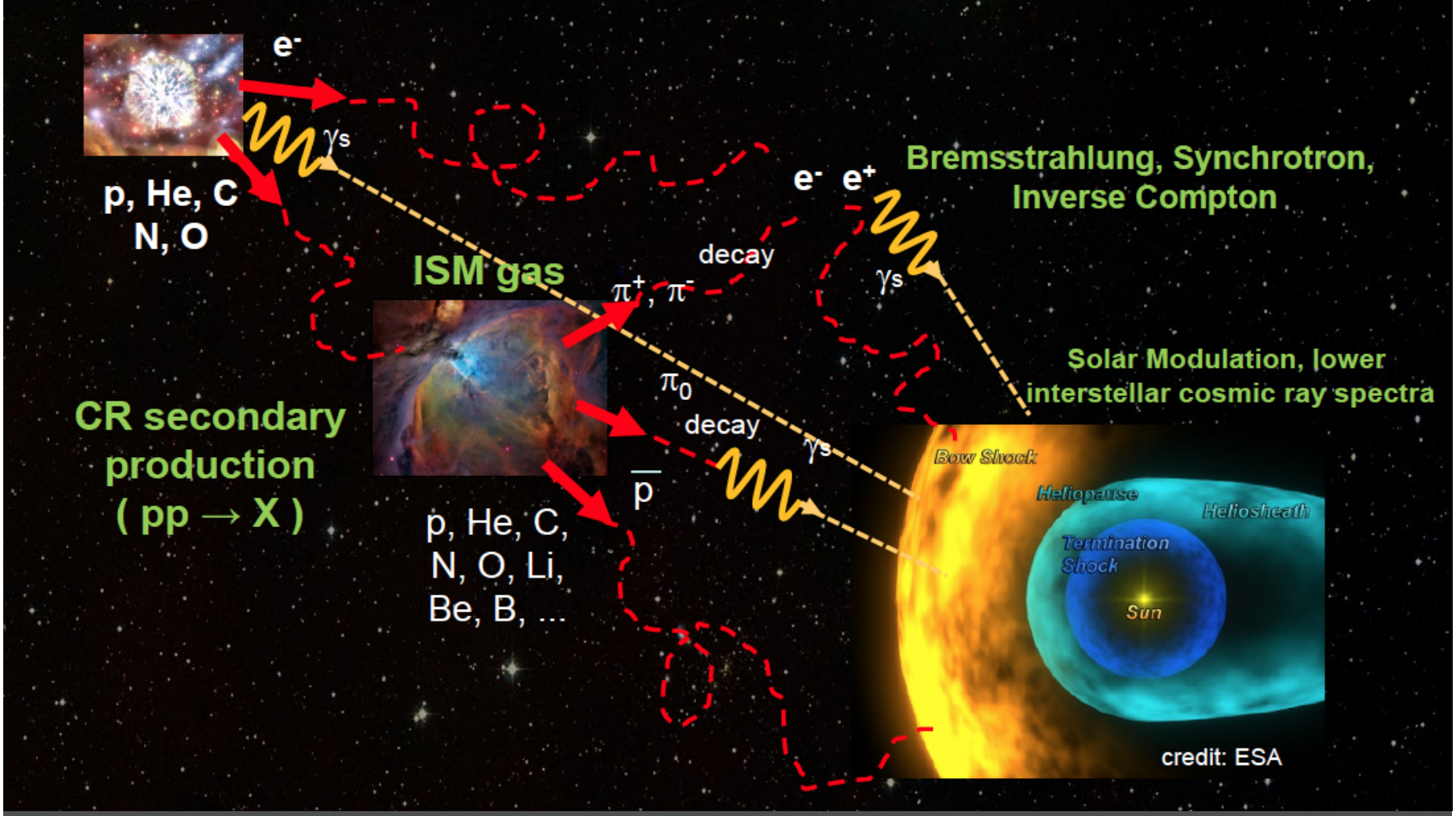
He isotope fluxes



^{3}He/^{4}He ratio



PAMELA's are the most complete measurements so far



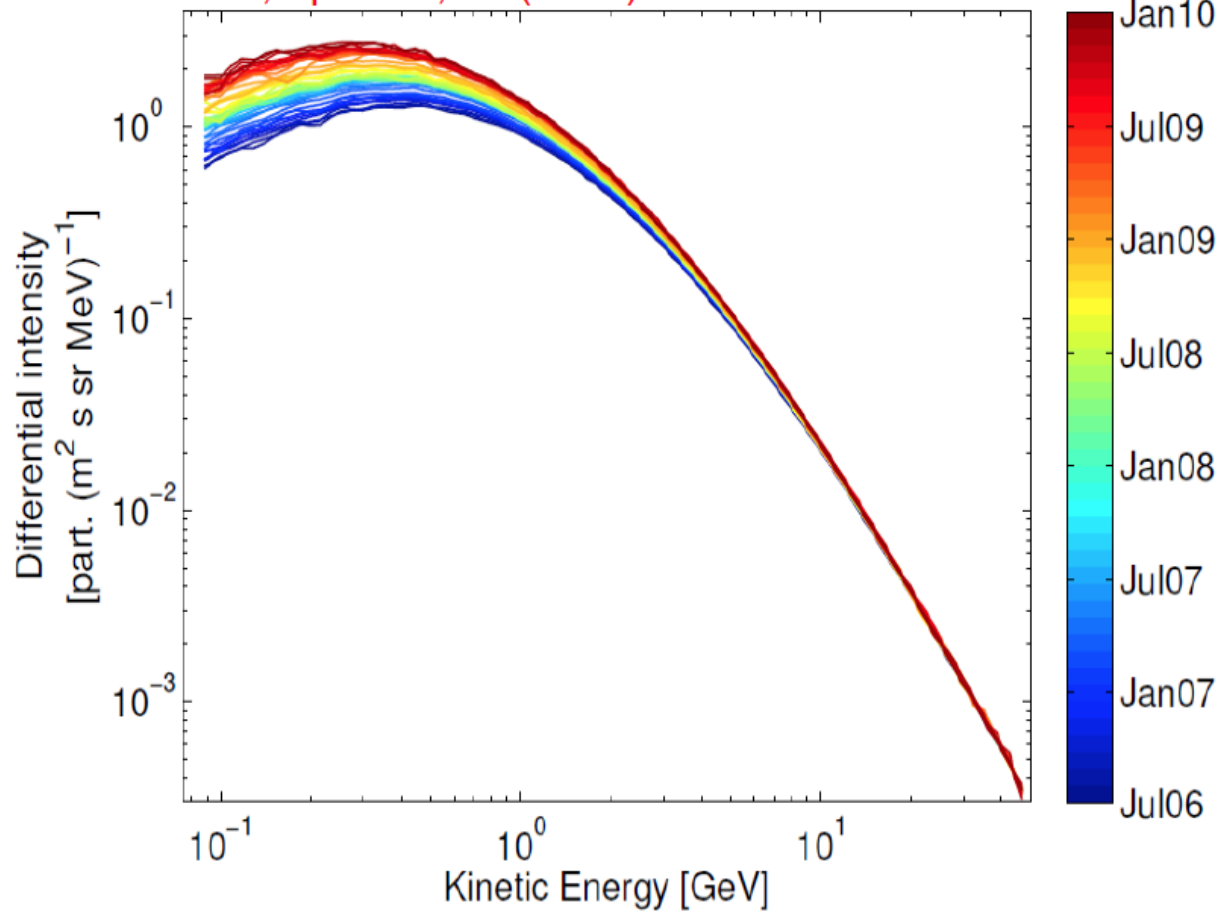
Cosmic rays in the heliosphere

Solar modulation: proton spectra

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)**.

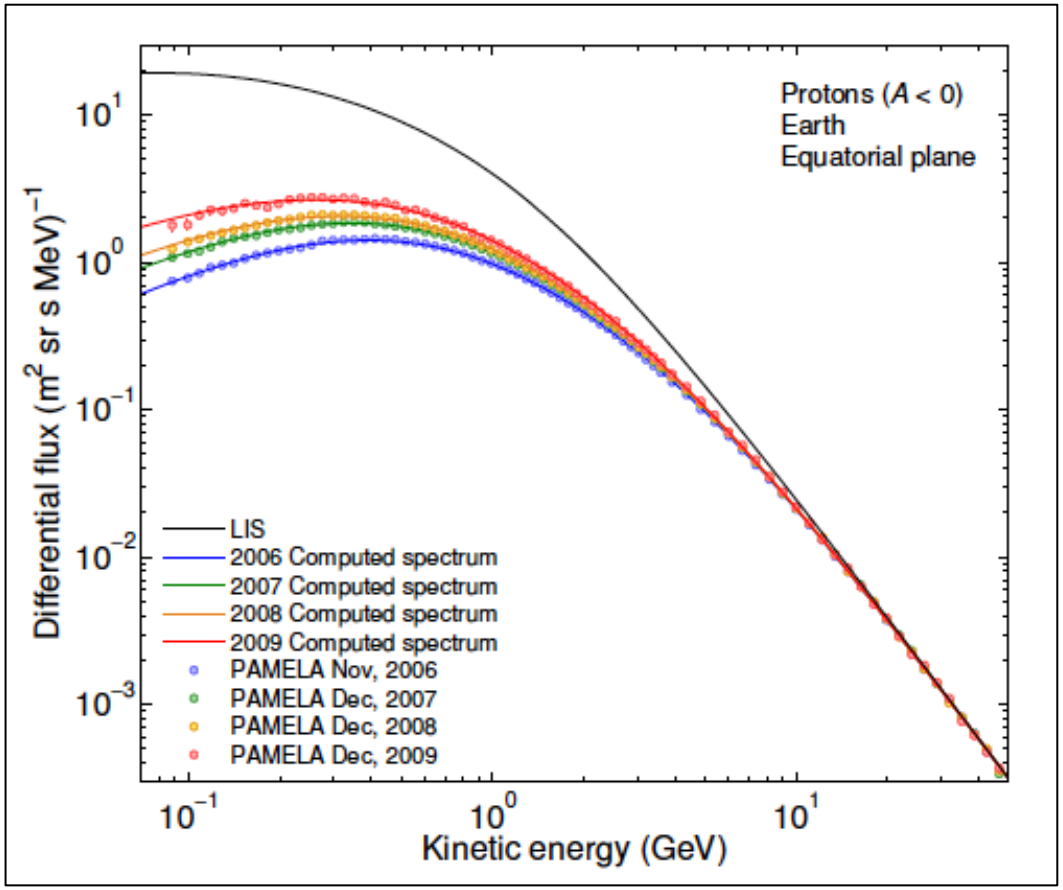
The region between the blue and red curves indicates the **spread in proton fluxes during this time.**

O. Adriani et al., ApJ 765, 91 (2013)



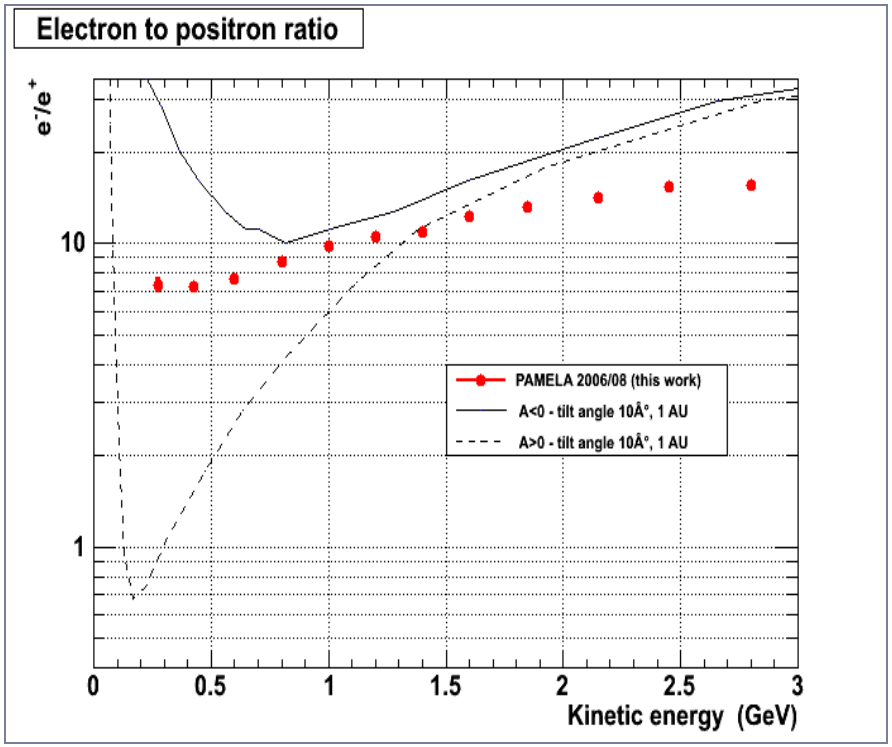
Proton spectra & LIS calculations

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

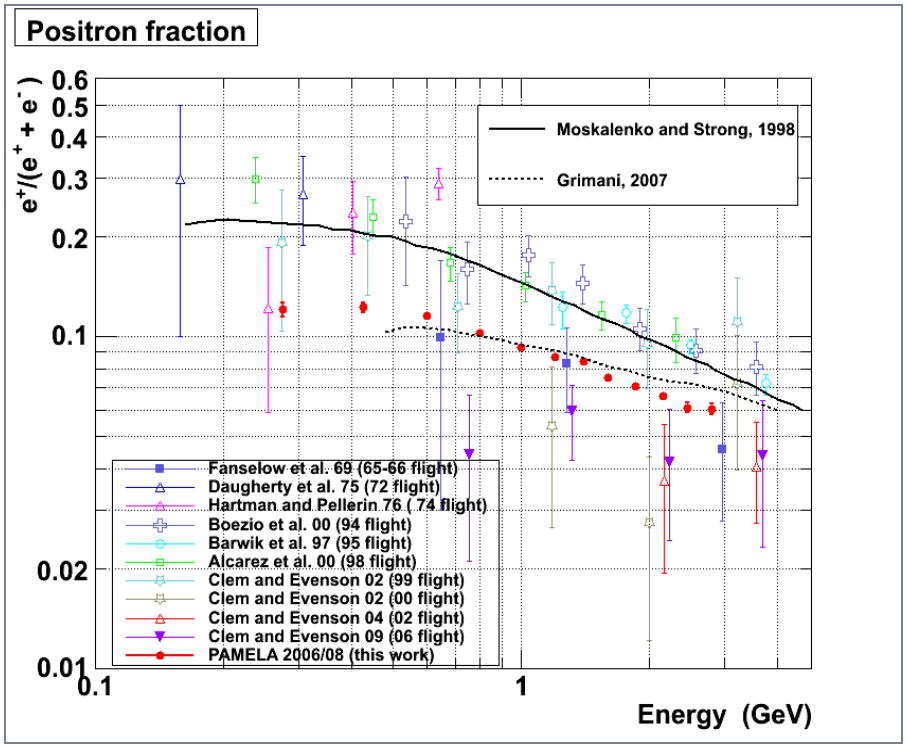


Charge-dependent solar modulation
Work in progress

PAMELA POSITRON FRACTION @ low energy

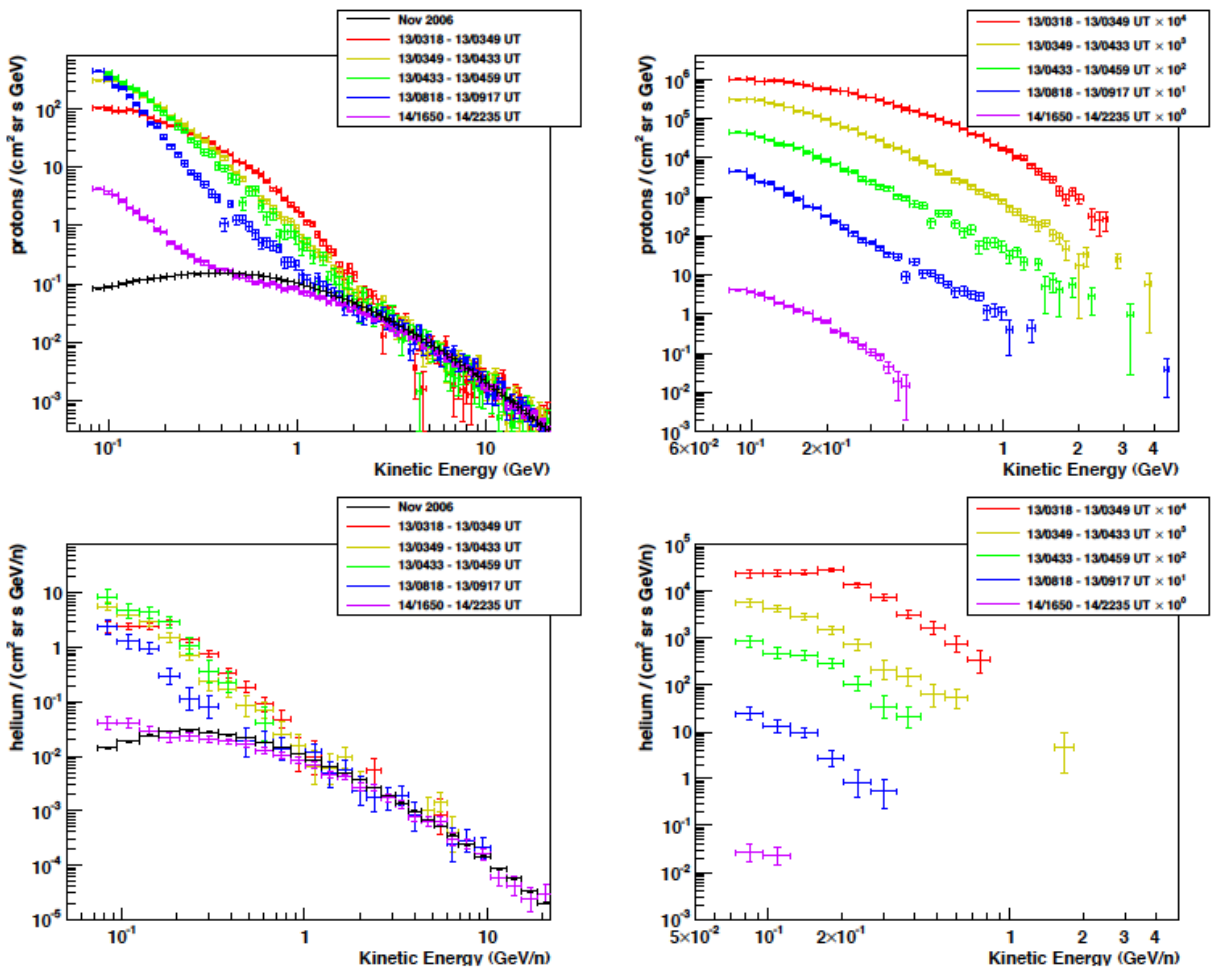


PAMELA ELECTRON to POSITRON RATIO @ low energy

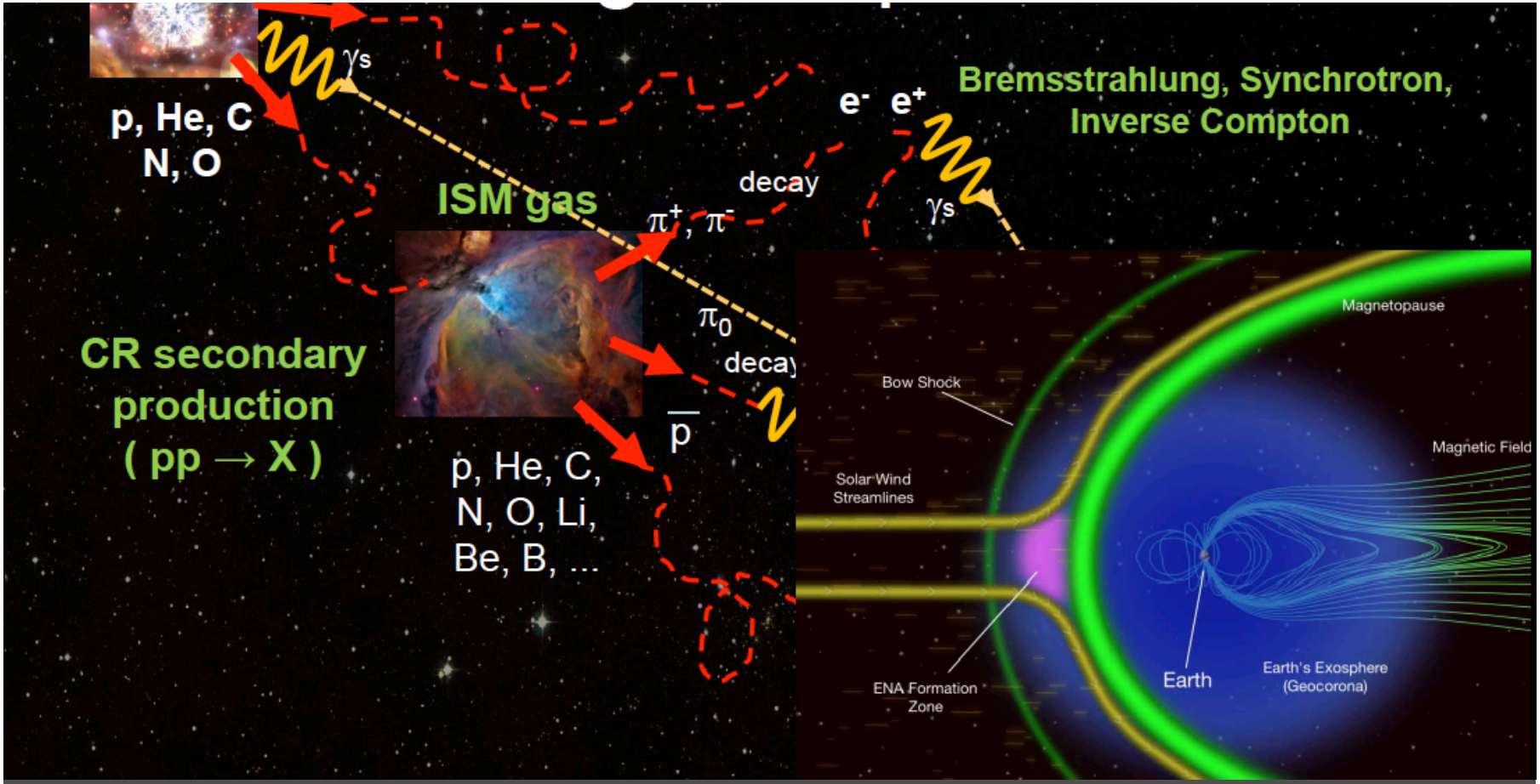


PRELIMINARY

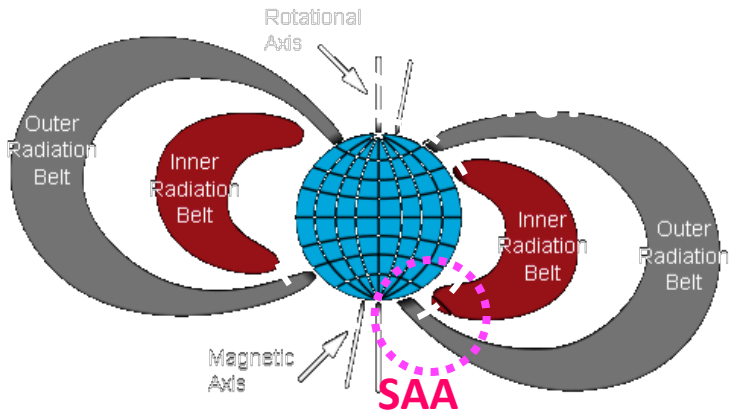
Solar events (SEP from Dec. 13, 2006)

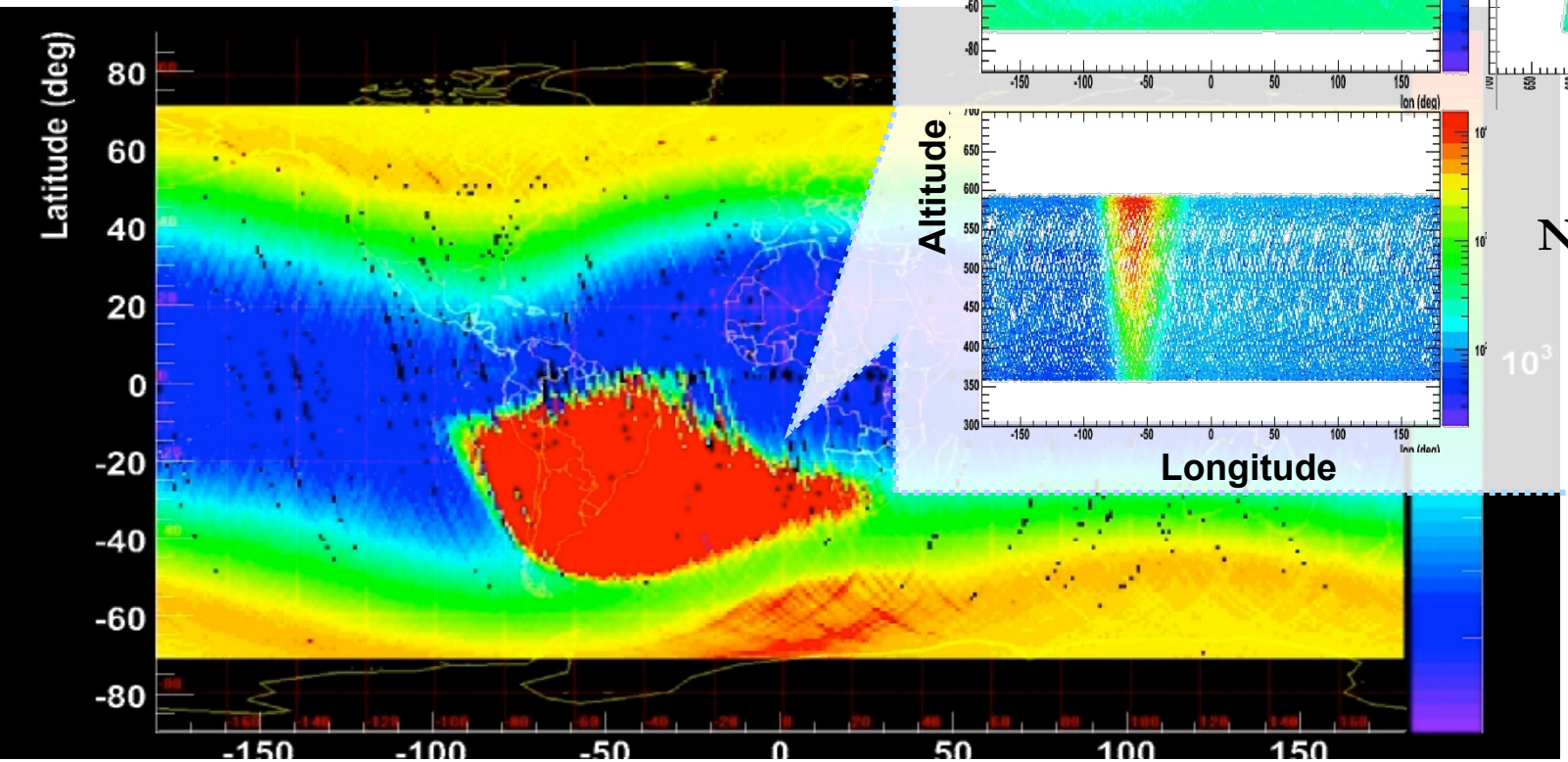


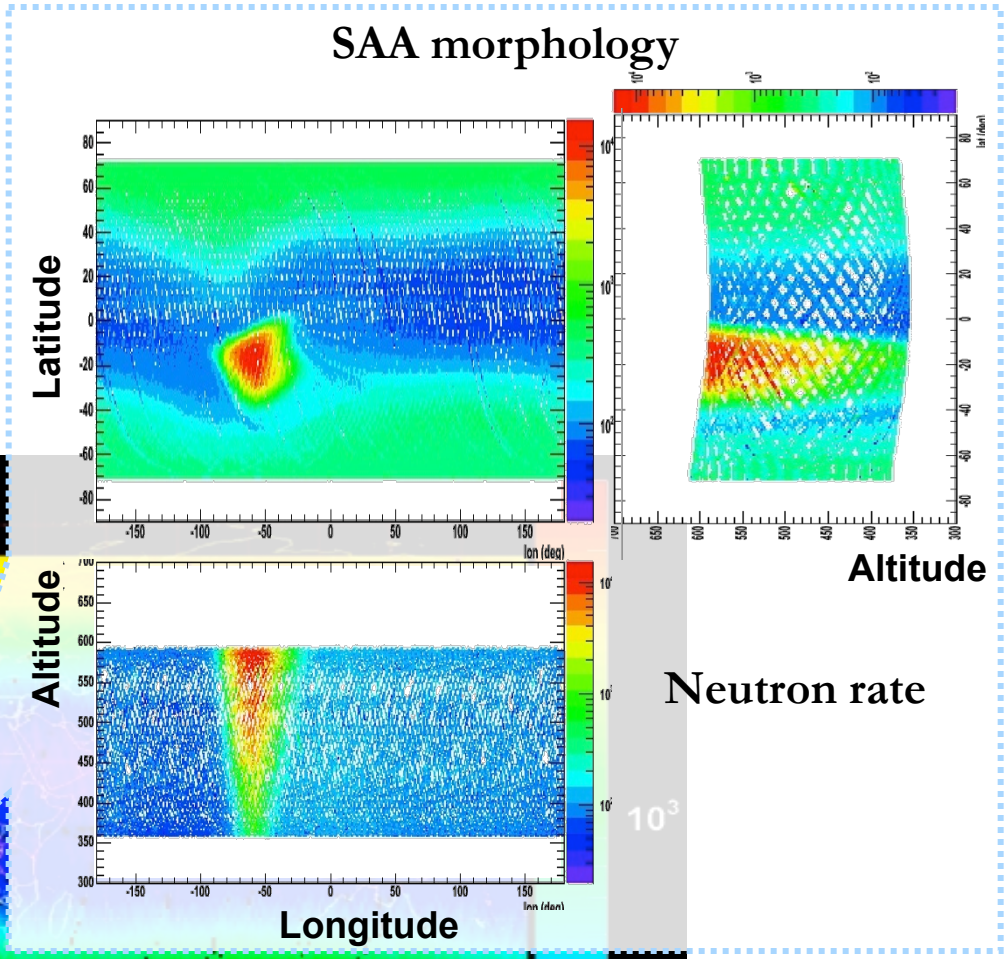
Adriani et al. - *ApJ 742 102, 2011*



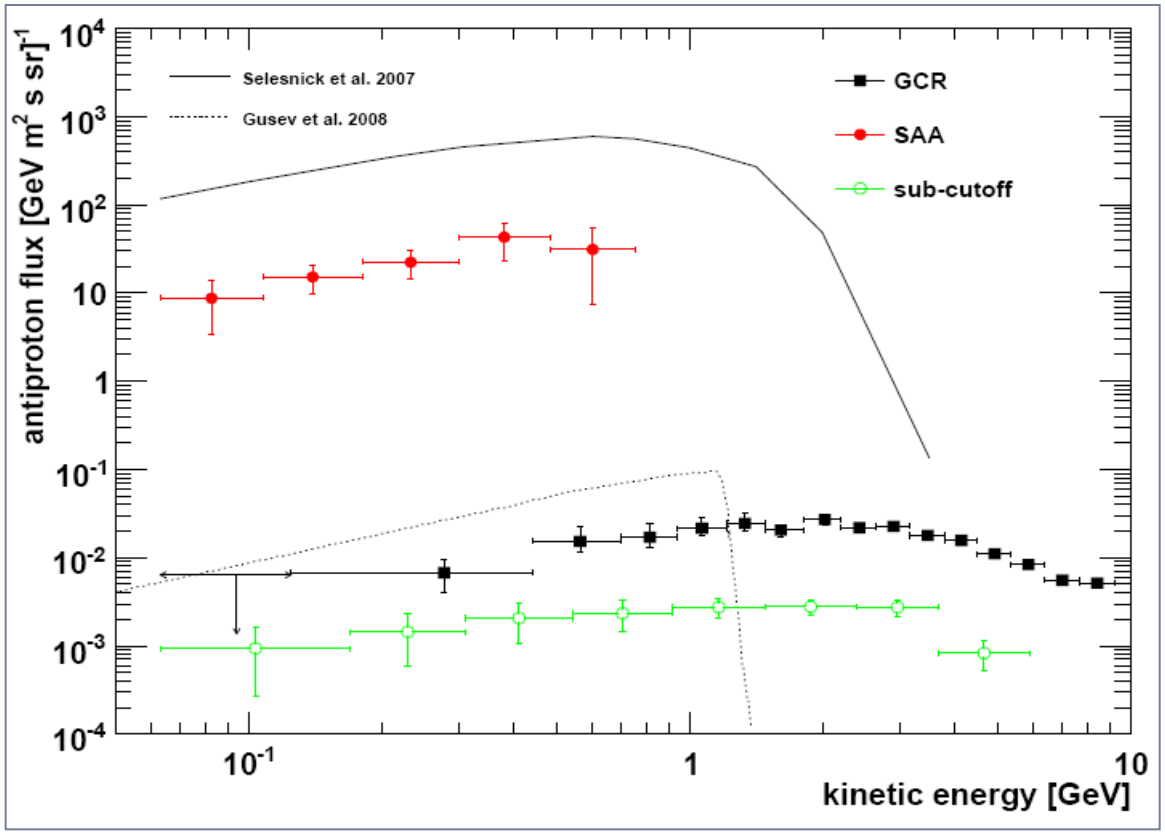
Cosmic rays in the magnetosphere


Rotational Axis
Outer Radiation Belt
Inner Radiation Belt
Inner Radiation Belt
Outer Radiation Belt
Magnetic Axis
SAA


Latitude (deg)
80
60
40
20
0
-20
-40
-60
-80
-150
-100
-50
0
50
100
150


SAA morphology
Latitude
Altitude
Altitude
Longitude
Neutron rate
10^3

Discovery of geomagnetically trapped antiprotons



First measurement of p-bar trapped in the inner belt

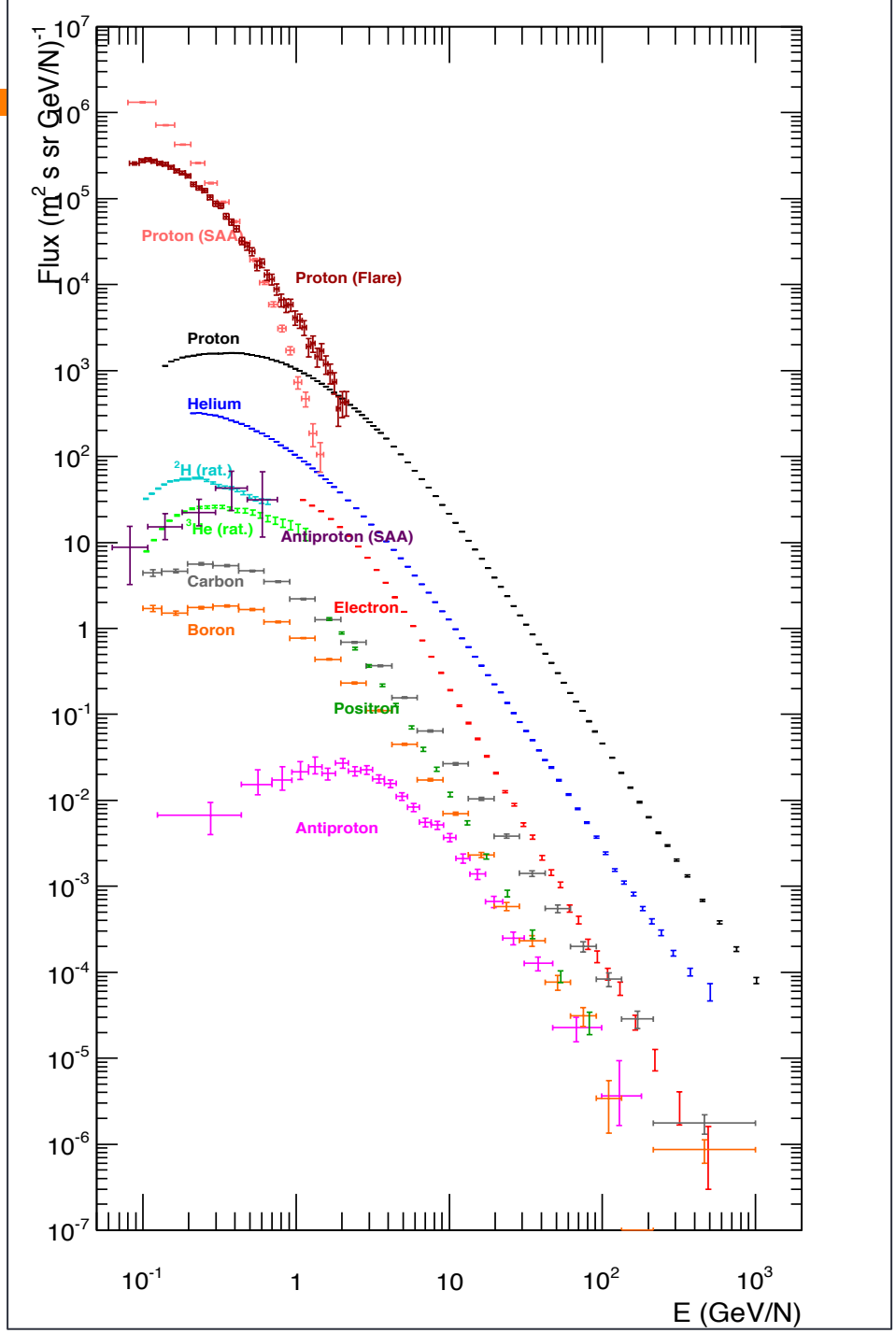
29 p-bars discovered in SAA and **traced back to mirror points**

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

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

PAMELA overall 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 8 years. Its operation time will continue until 2015.

- **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"

Submitted to Physics Reports (78 pages).

Summarizes published and unpublished

(but final) PAMELA results.