Main results from the PAMELA space experiment after 5 years in flight

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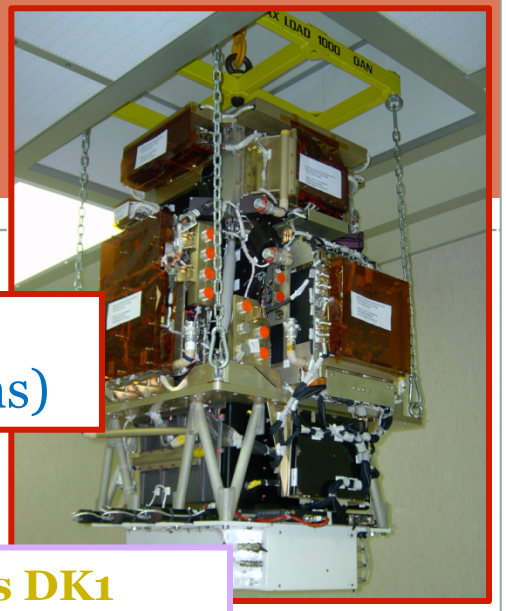
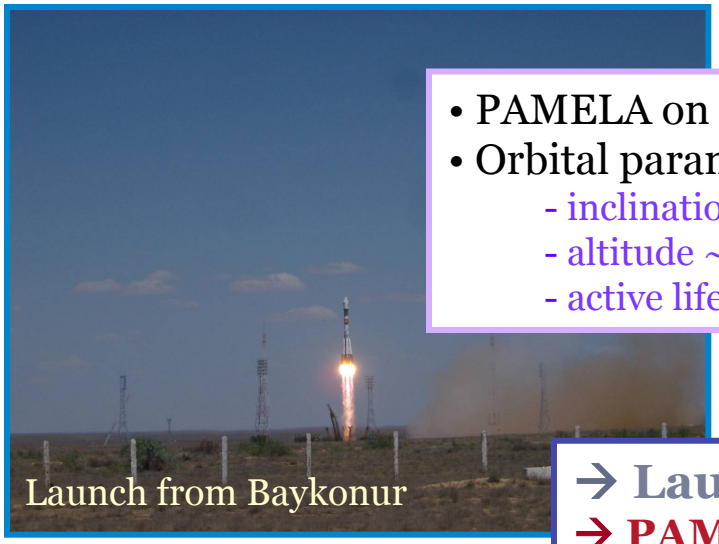
ON BEHALF OF
THE PAMELA COLLABORATION

PAMELA

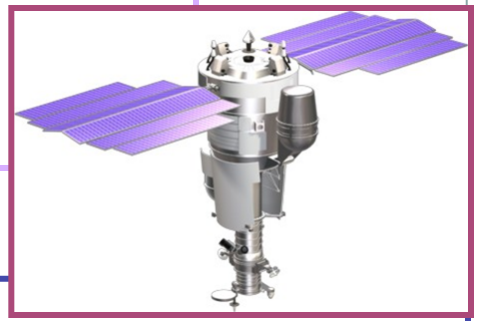
Payload for Matter/antimatter Exploration and Light-nuclei Astrophysics



- **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)
  - active life >3 years (⇒ high statistics)



→ **Launched on 15th June 2006**

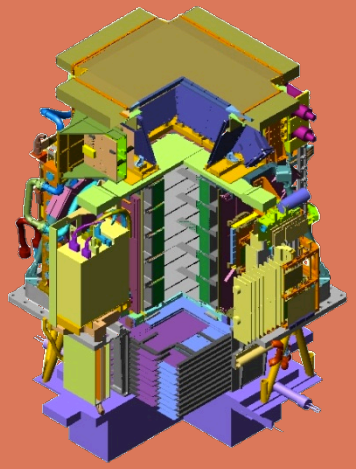
→ **PAMELA in continuous data-taking mode since then!**

PAMELA detectors

Main requirements:

- high-sensitivity antiparticle identification

- precise momentum measurement

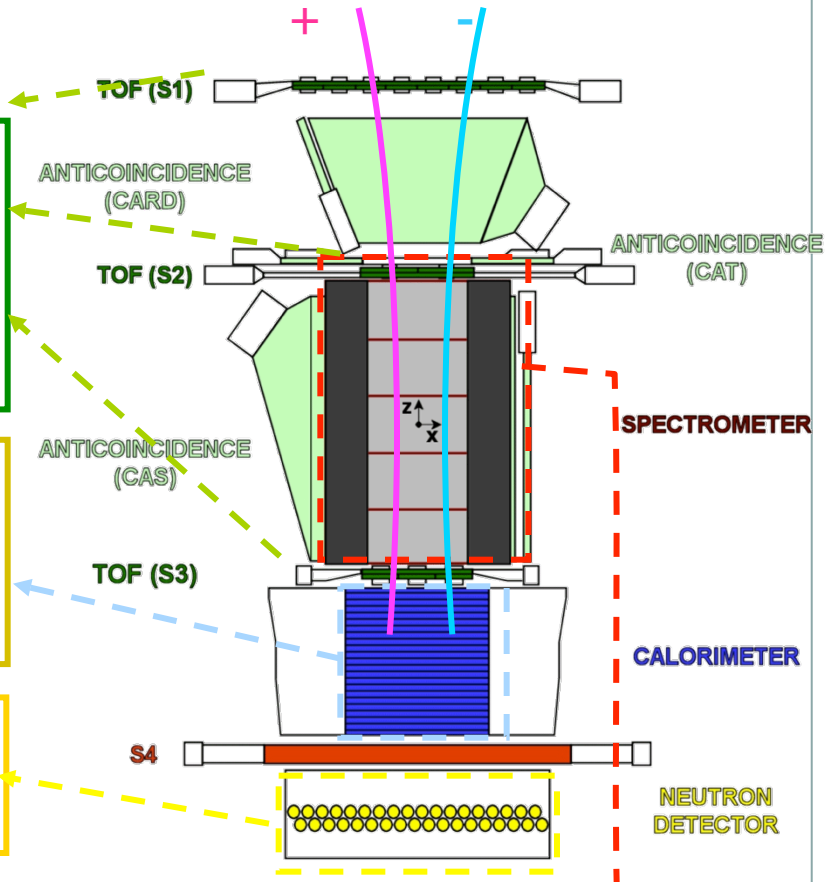


Time-Of-Flight
plastic scintillators + PMT:
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX.

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

Absolute fluxes of primary GCRs

NEEDED FOR:

(a) IDENTIFY SOURCES AND ACCELERATION PROPAGATION MECHANISMS OF COSMIC RAYS;

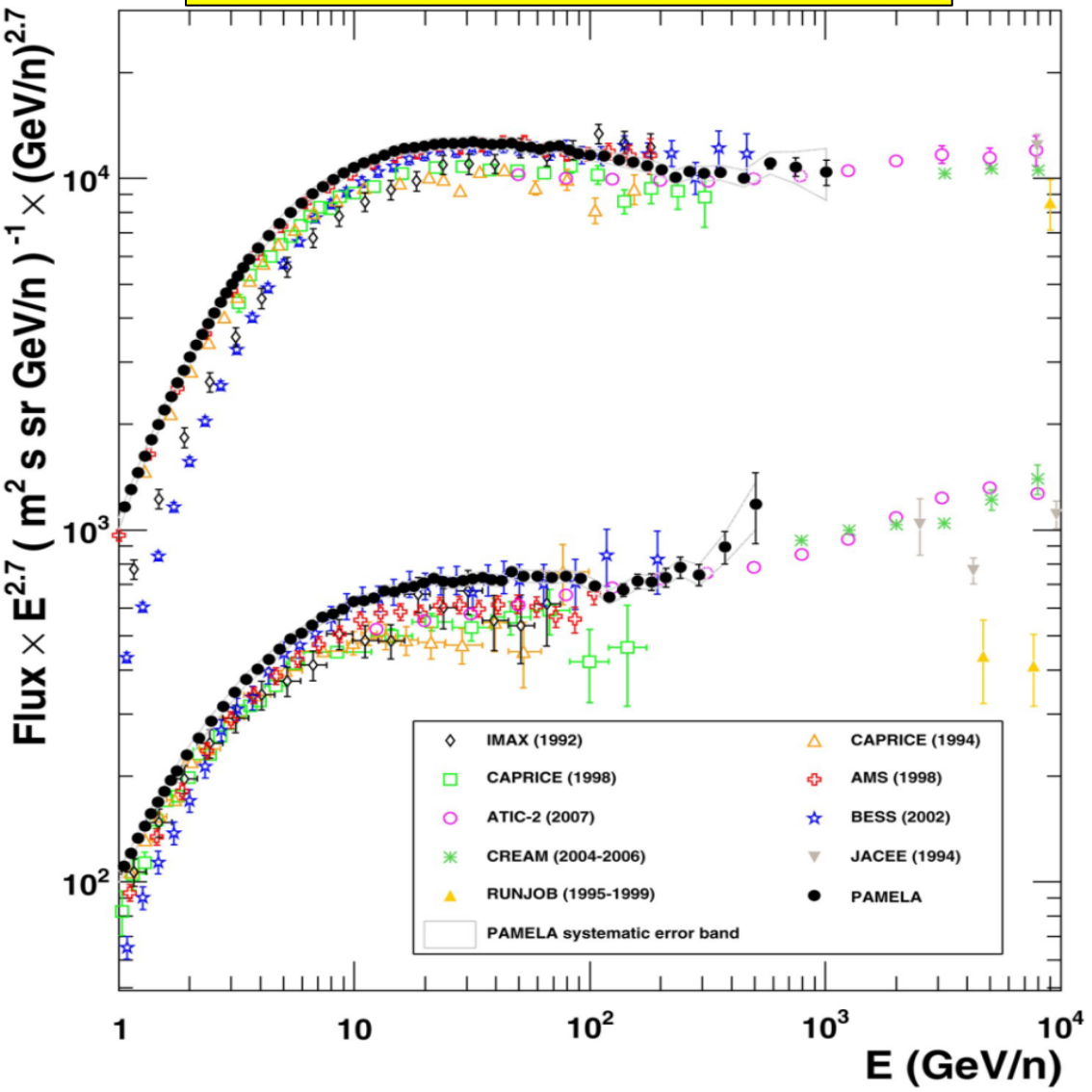
(b) ESTIMATE THE PRODUCTION OF SECONDARY PARTICLES, SUCH AS POSITRONS AND ANTIPROTONS, IN ORDER TO DISENTANGLE THE SECONDARY PARTICLE COMPONENT FROM POSSIBLE EXOTIC SOURCES;

(c) ESTIMATE THE PARTICLE FLUX IN THE GEOMAGNETIC FIELD AND IN EARTH'S ATMOSPHERE TO DERIVE THE ATMOSPHERIC MUON AND NEUTRINO FLUX.

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



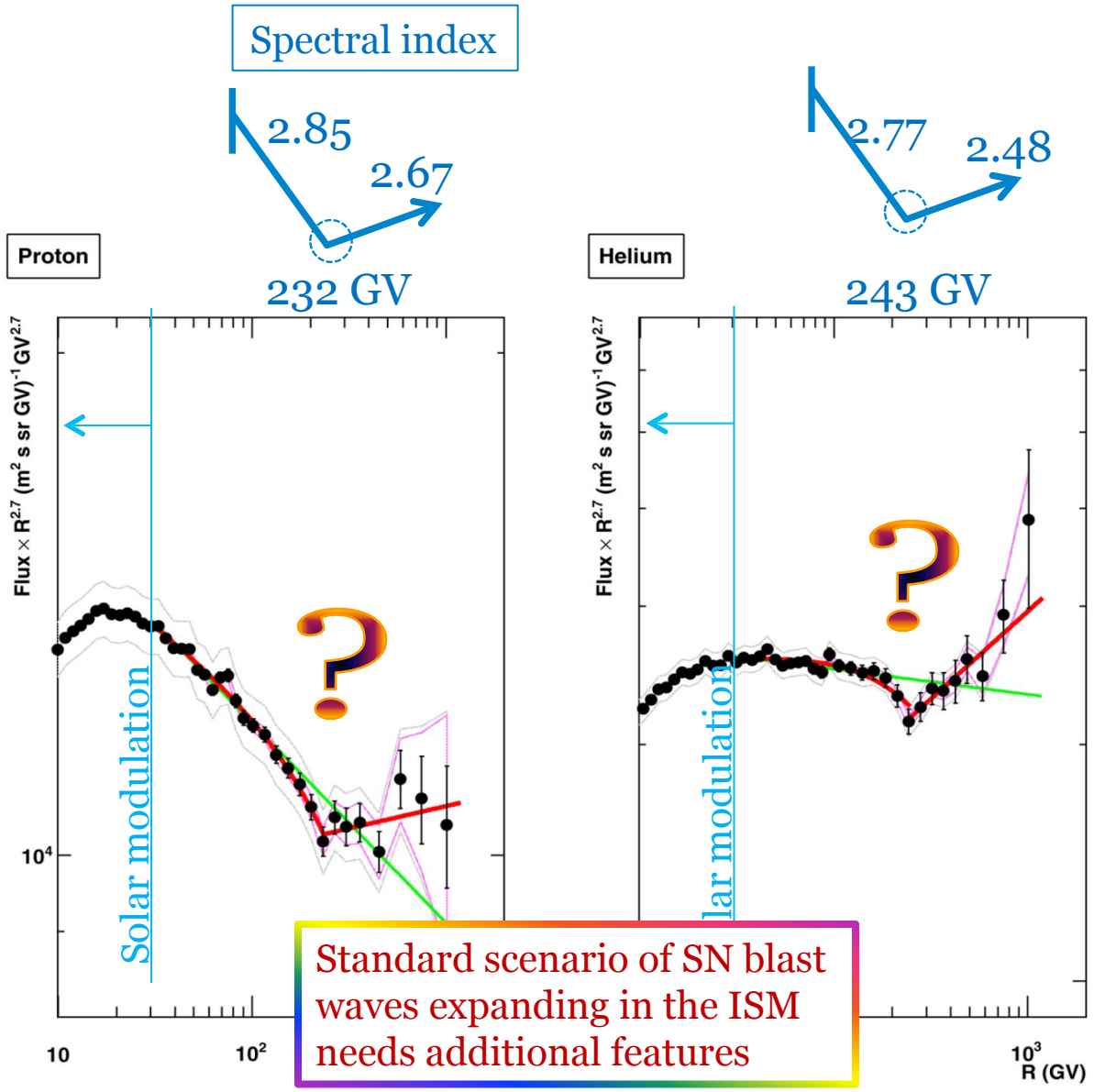
P & He absolute fluxes @ high energy

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



H/He ratio vs R

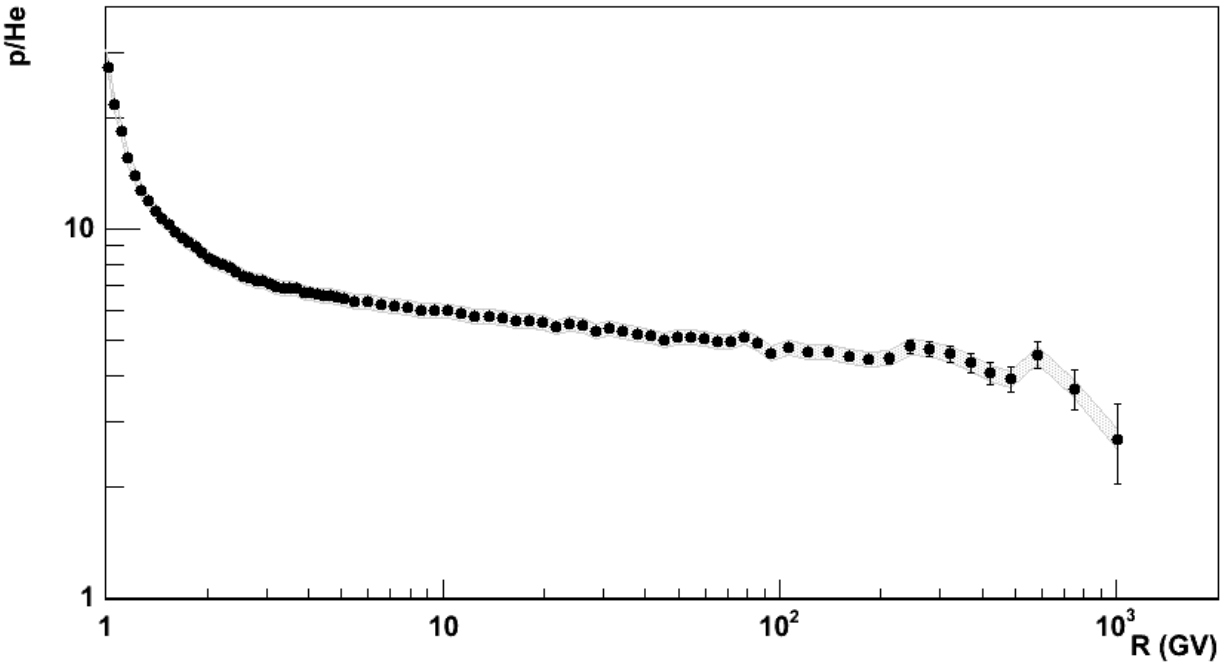
Instrumental p.o.v.

- Systematic uncertainties **partly cancel out** (livetime, spectrometer reconstruction, …)

Theoretical p.o.v.

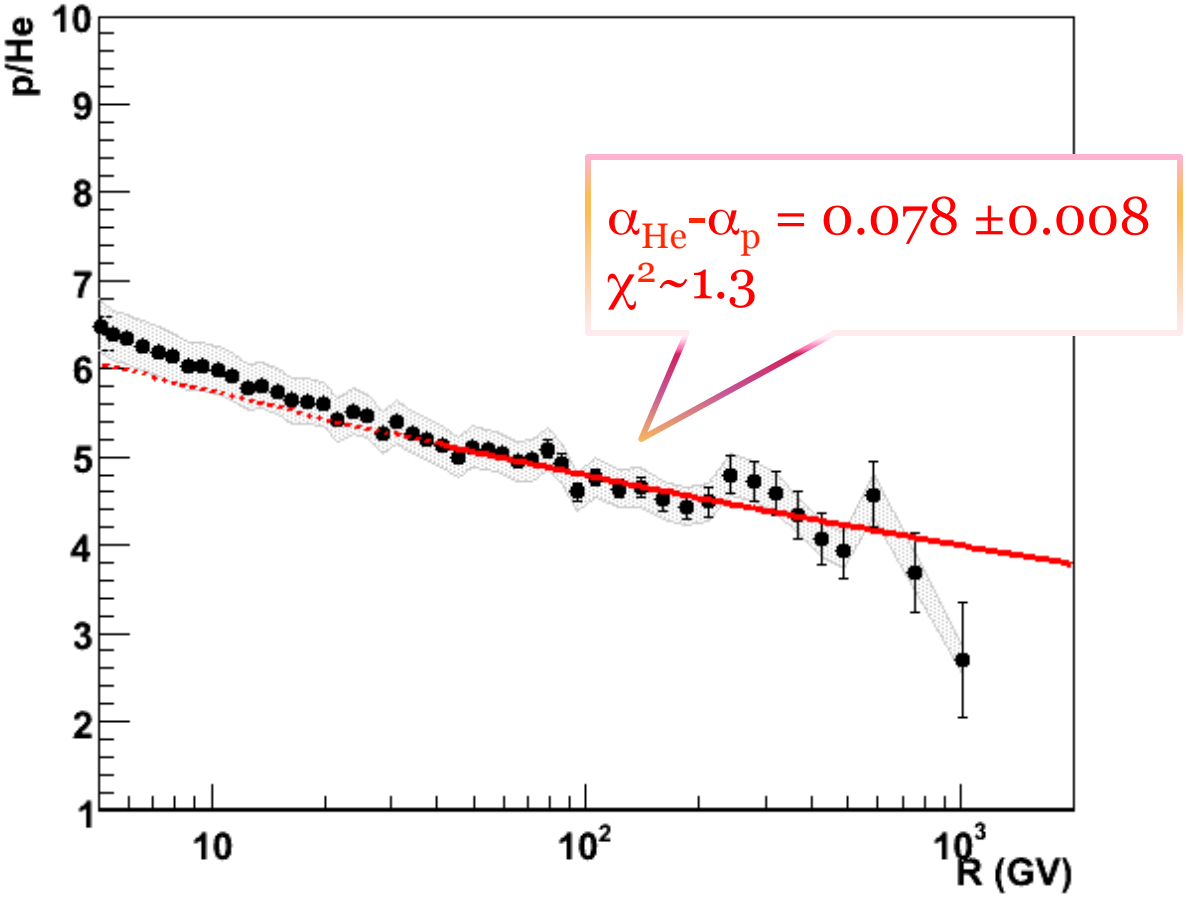
- Solar modulation negligible → information about IS spectra down to GV region
- Propagation effects (diffusion and fragmentation) negligible above ~100GV → information about source spectra

(Putze et al. 2010)



P/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)



Electron energy measurements

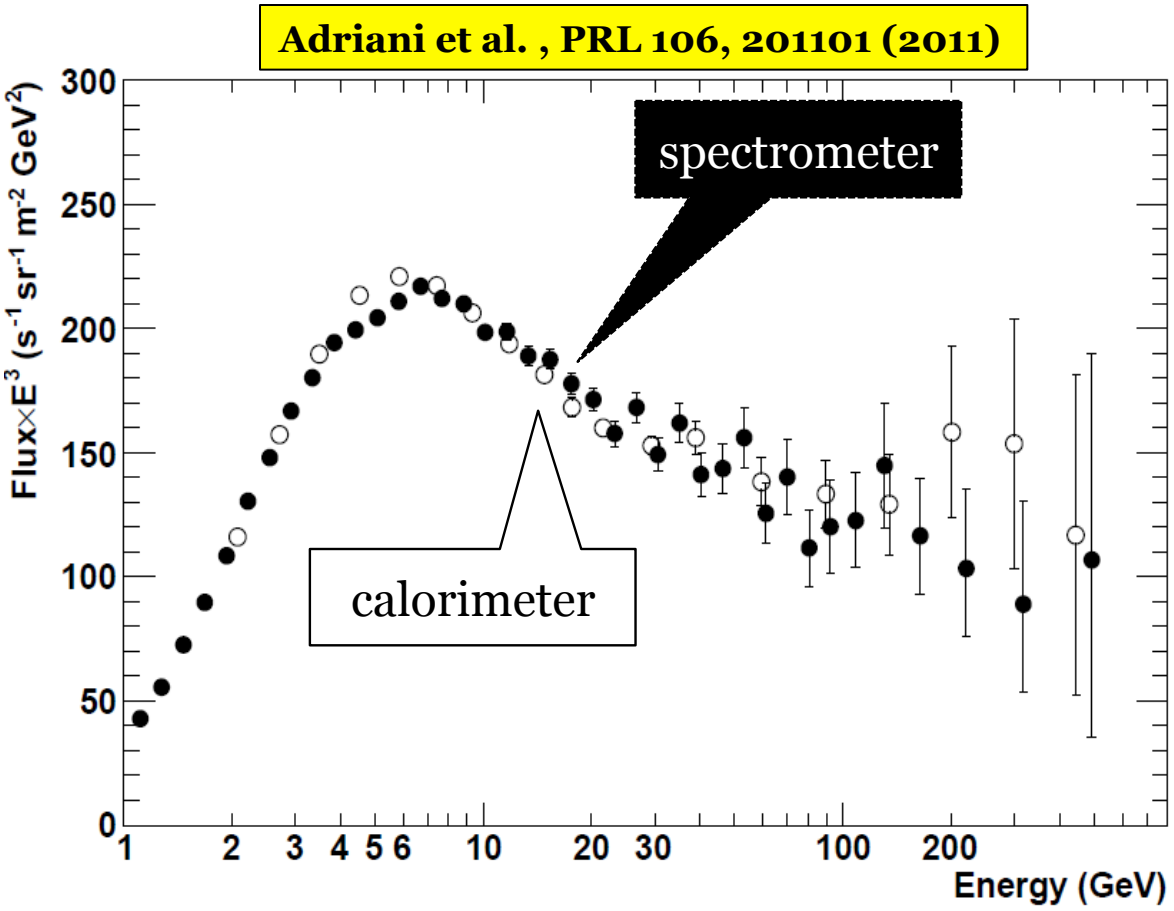
Two independent ways to determine electron energy:

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

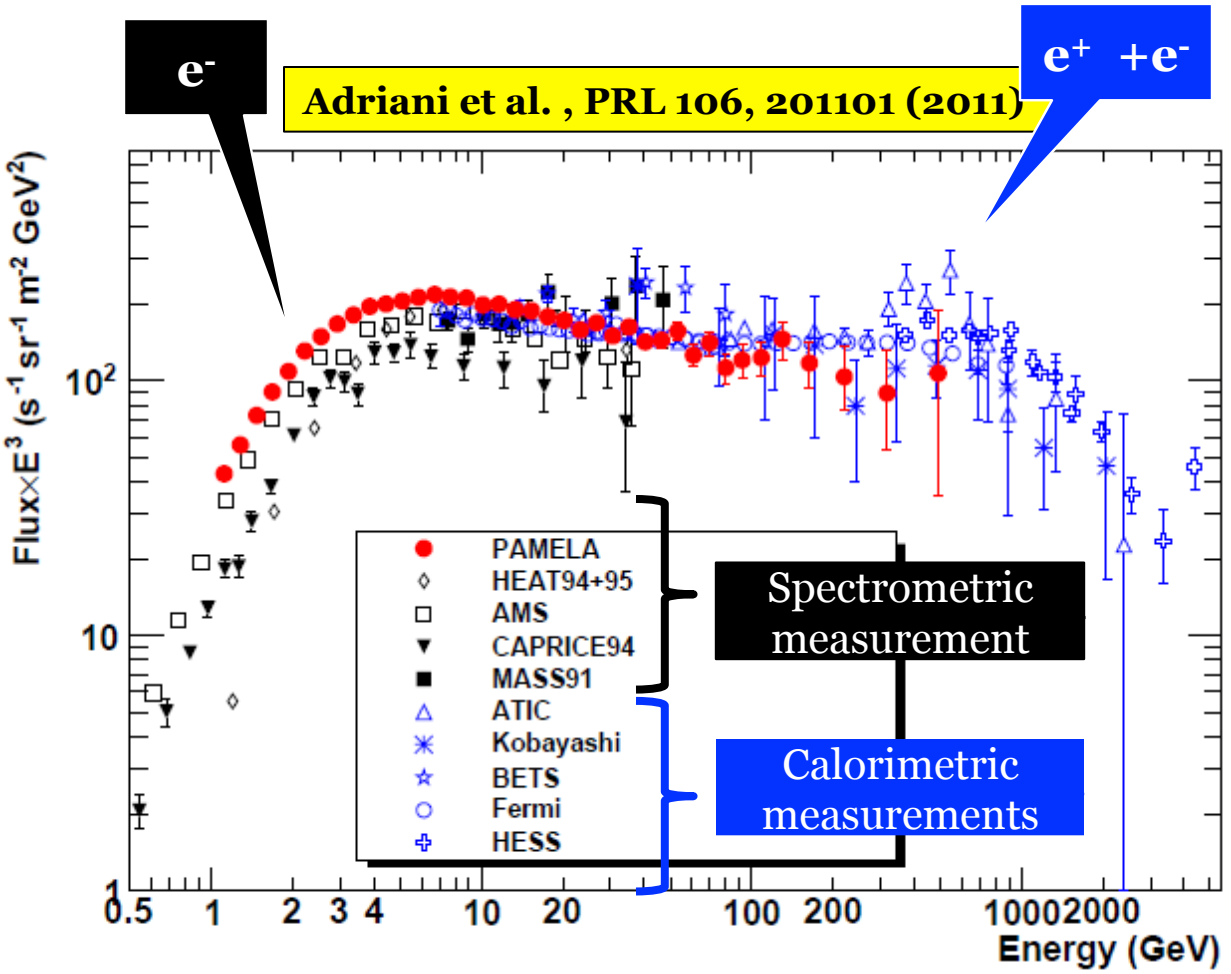


Electron identification:

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

Electron absolute flux

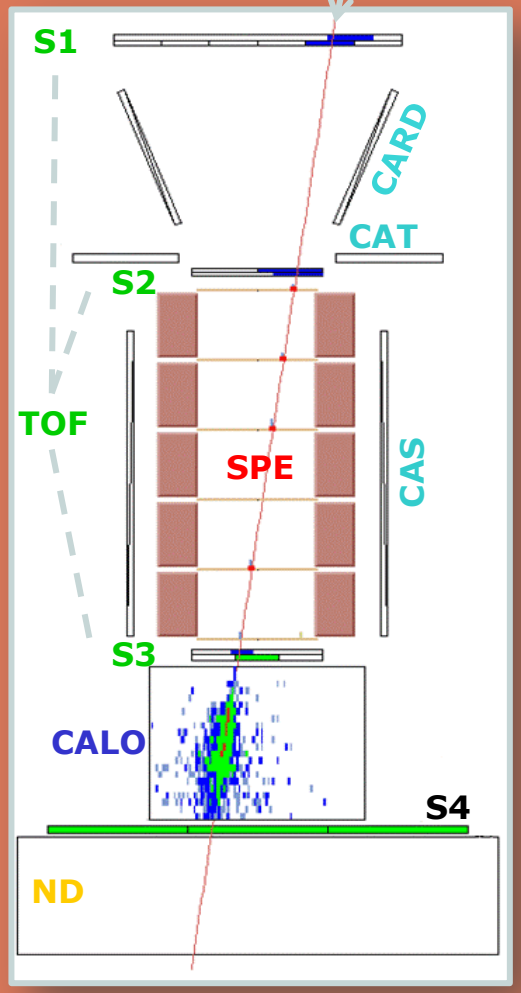
- Largest energy range covered in any experiment hitherto with no atmospheric overburden
- **Low energy**
  - minimum solar activity (ϕ = 450÷550 GV)
- **High energy**
  - No significant disagreement with recent ATIC and Fermi data
  - Softer spectrum consistent with both systematics and growing positron component



Antiparticles

SECONDARY ORIGIN, COMING FROM INTERACTION OF PRIMARI CR WITH THE INTERSTELLAR MEDIUM

Positrons



Positron/electron identification:

- Positive/negative curvature in the spectrometer
  → **e^-/e^+ separation**
- EM-like interaction pattern in the calorimeter
  → **e^+/p (and e^-/p-bar) separation**

Main issue:

- **Interacting proton background**:
  - fluctuations in hadronic shower development: $\pi_0 \rightarrow \gamma\gamma$ mimic pure e.m. showers
  - p/e^+: ~10^3 @1GV ~10^4 @100GV

→ **Robust e^+ identification**

- Shower topology + energy-rigidity match

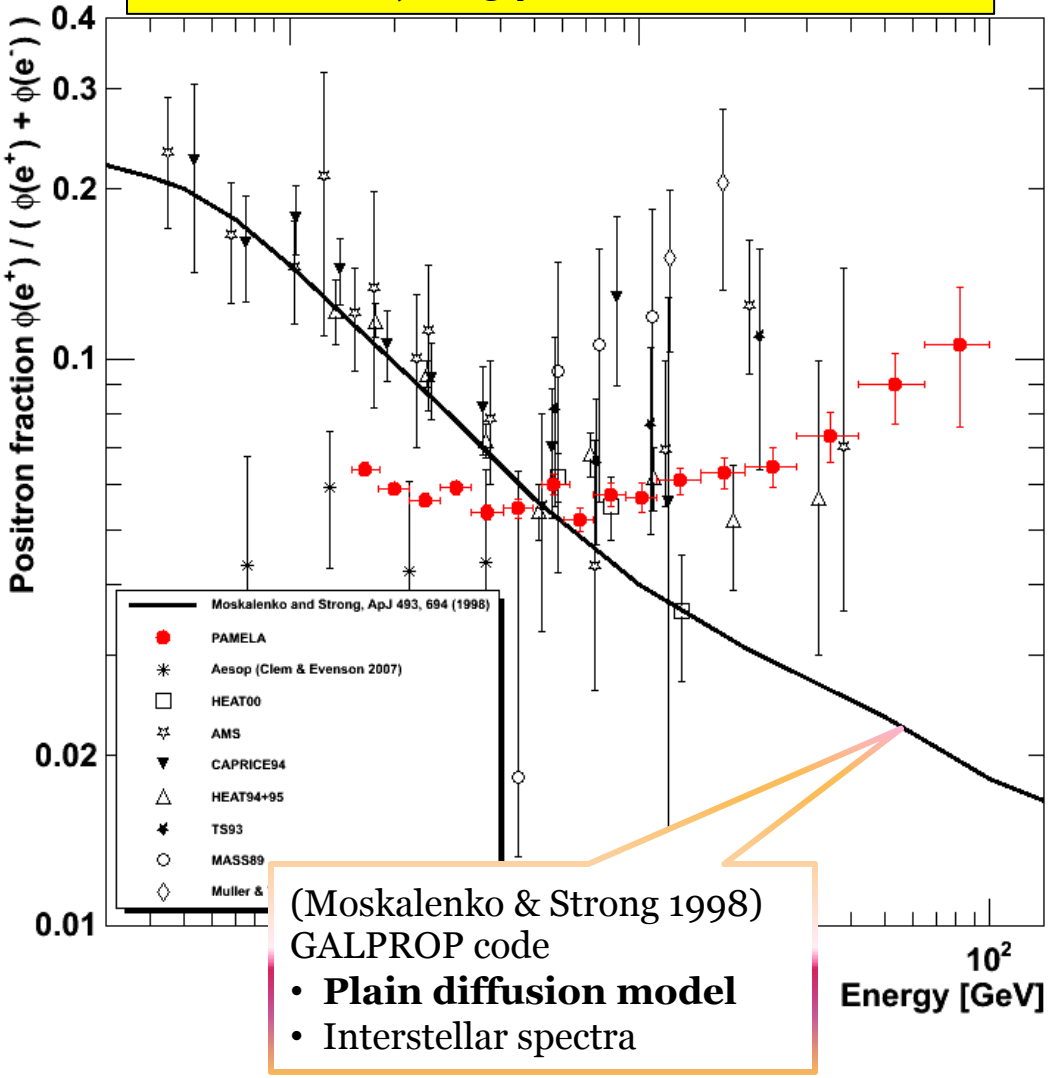
→ **Residual background evaluation**

- Done with flight data
- No dependency on simulation

Positron fraction

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

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



(Moskalenko & Strong 1998)
GALPROP code
- **Plain diffusion model**
- Interstellar spectra

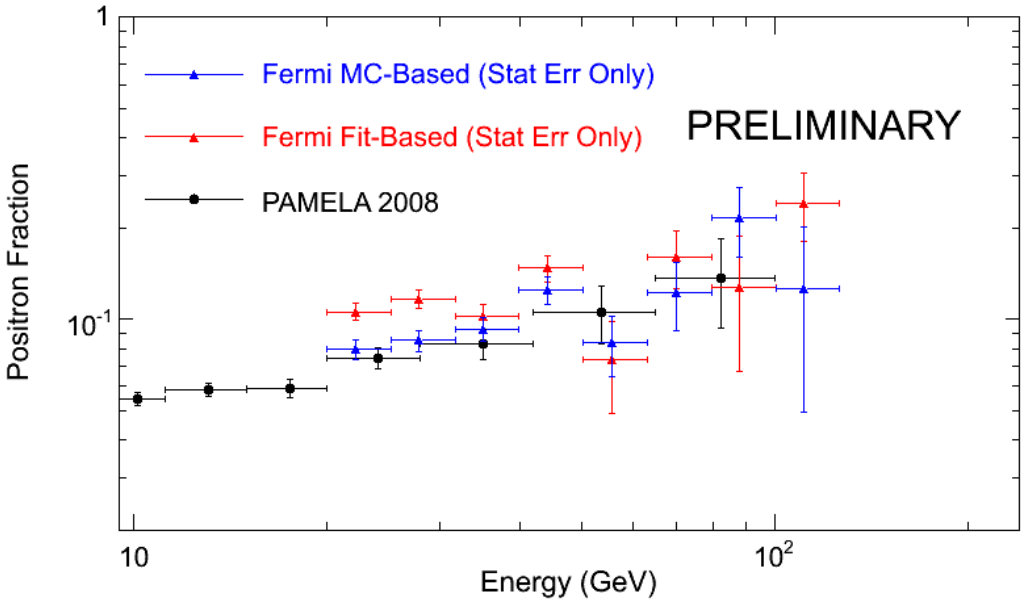
FERMI positron/ electron ratio

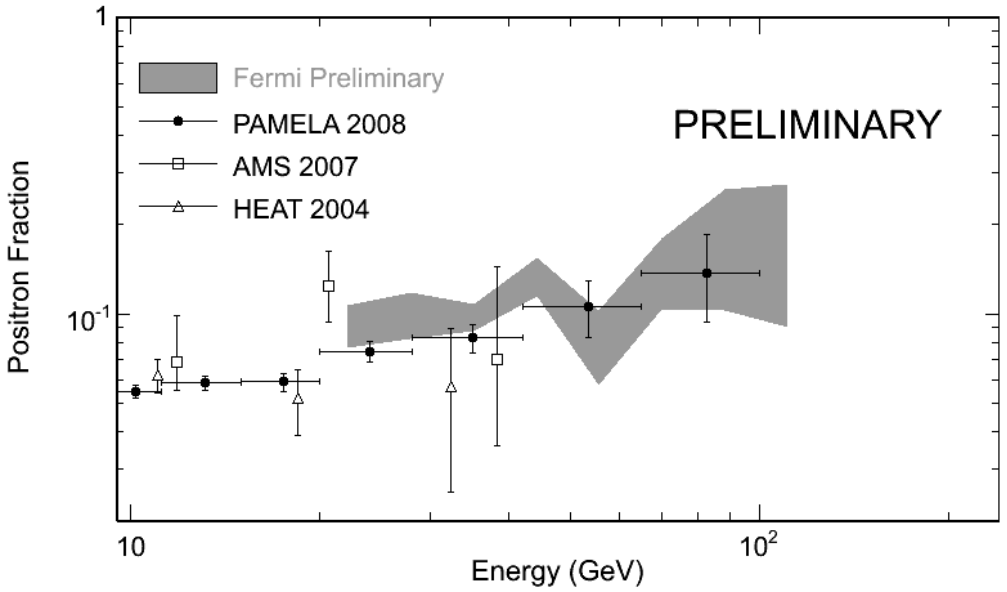
The Fermi-LAT has measured the cosmic-ray positron and electron spectra separately, between 20 – 130 GeV, using the Earth's magnetic field as a charge discriminator

The two independent methods of background subtraction,Fit-Based and MC-Based, produce consistent results

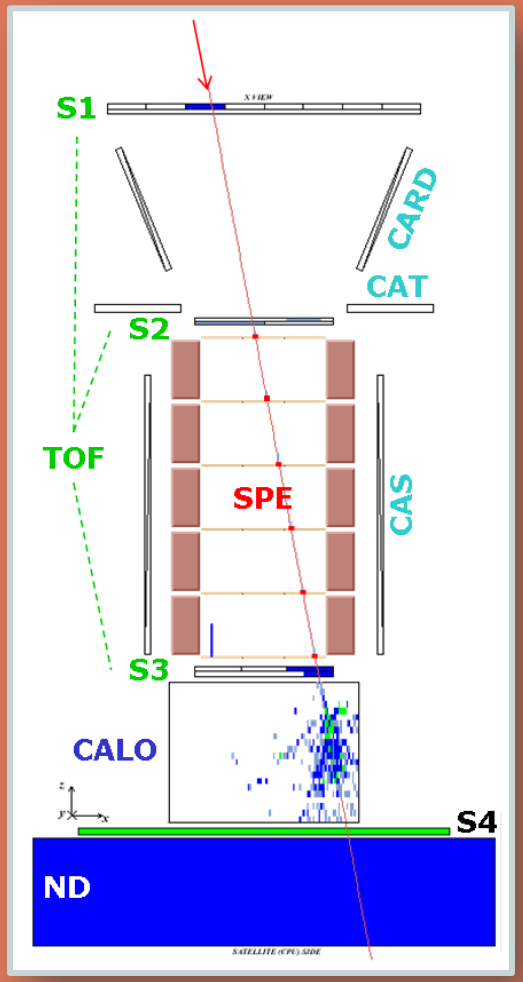
The observed positron fraction is consistent with the one measured by PAMELA

Warit Mitthumsiri et al. @ Fermi Symposium (May 2011)





Antiprotons



Antiproton/proton identification:

- Negative/positive curvature in the spectrometer
  → **p-bar/p separation**
- Rejection of EM-like interaction patterns in the calorimeter
  → **p-bar/e^- (and p/e^+) separation**

Main issue:

- **Proton "spillover" background**:
  wrong assignment of charge-sign @ high energy due to finite spectrometer resolution

→ **Strong tracking requirements**

- Spatial resolution < 4μm
- R < MDR/6

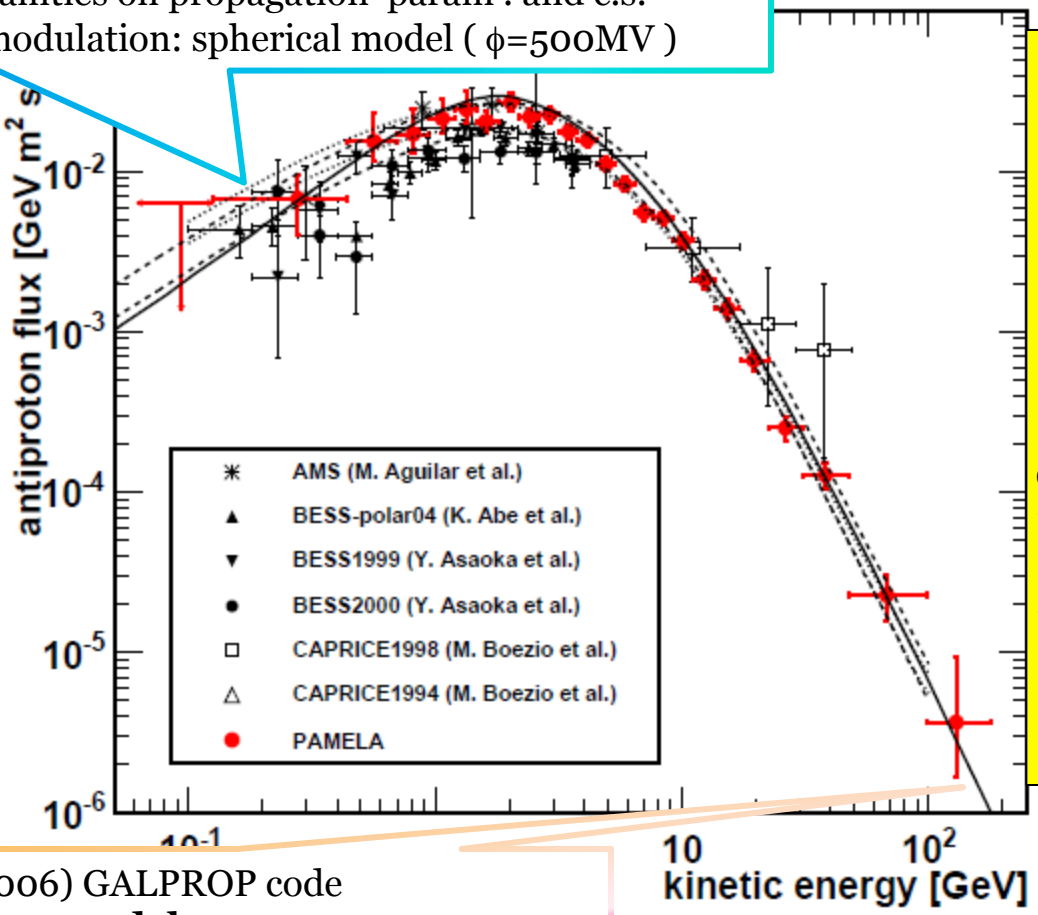
→ **Residual background subtraction**

- Evaluated with simulation (tuned with in-flight data)
- ~30% above 100GeV

Antiproton flux

- Largest energy range covered hiterto
- Overall agreement with pure secondary calculation
- Experimental uncertainty (stat⊕sys) smaller than spread in theoretical curves
  → constraints on propagation parameters

(Donato et al. 2001)
- **Diffusion model with convection and reacceleration**
- Uncertainties on propagation param . and c.s.
- Solar modulation: spherical model (ϕ=500MV)

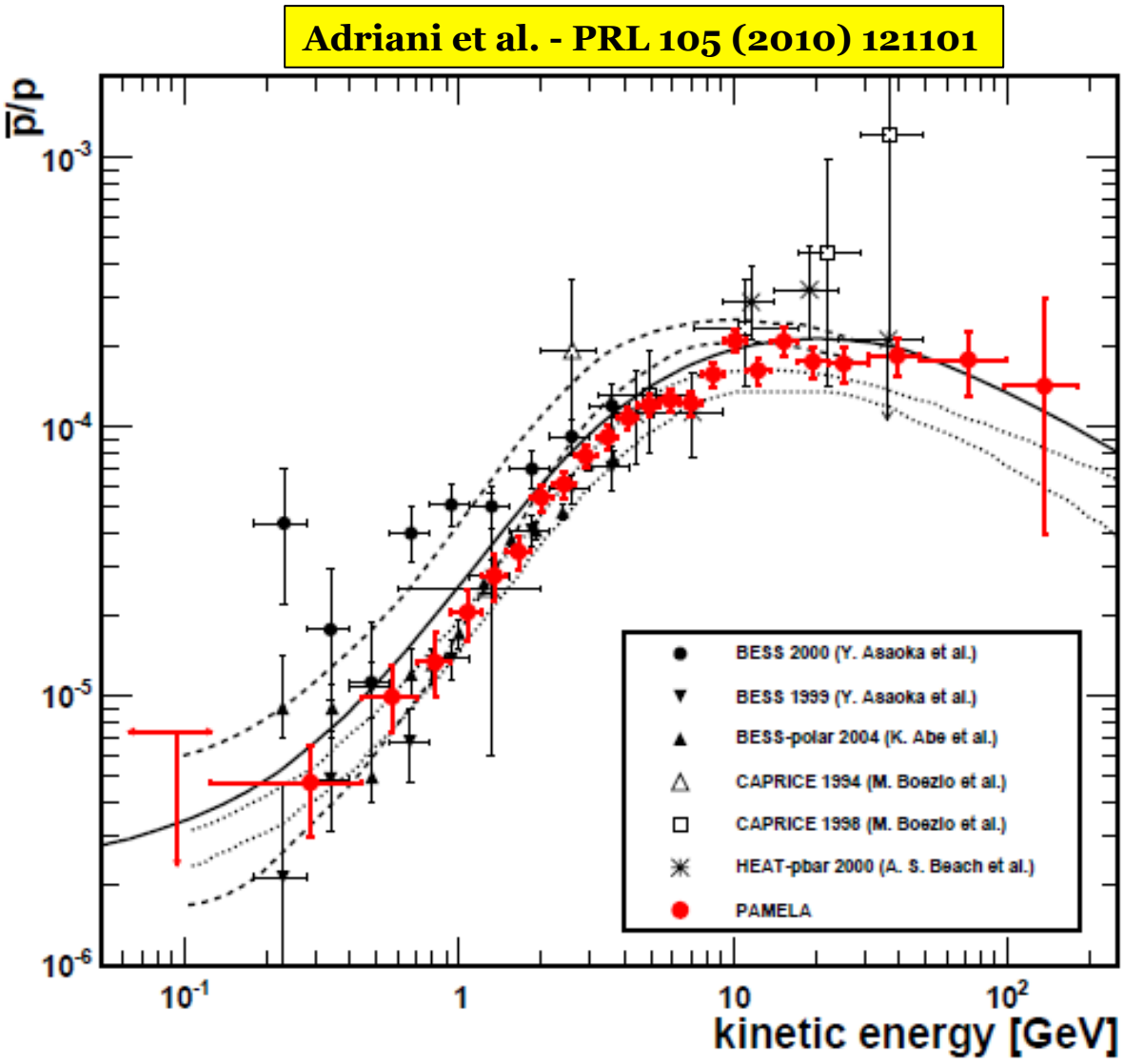


Adriani et al. - PRL 105 (2010) 121101

(Ptuskin et al. 2006) GALPROP code
- **Plain diffusion model**
- Solar modulation: spherical model (ϕ=550MV)

Antiproton-to-proton ratio

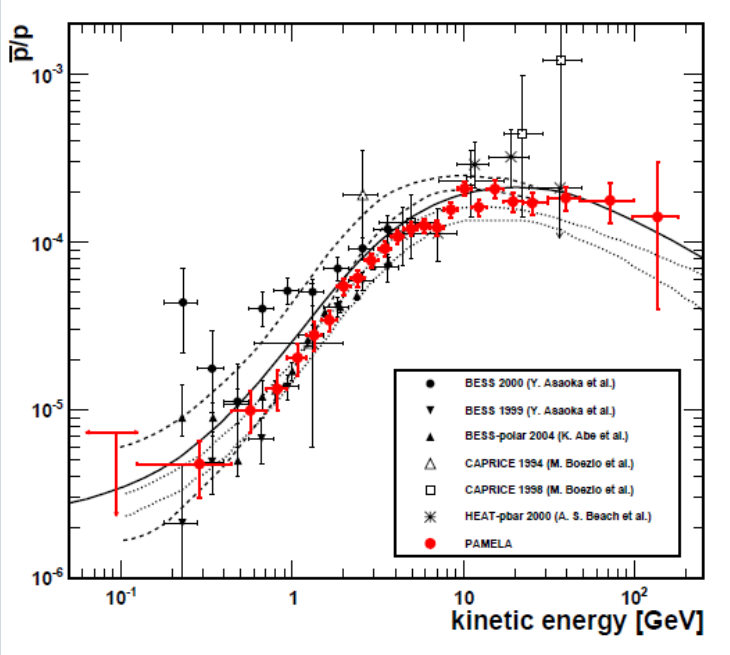
- Overall agreement with pure secondary calculation



A challenging puzzle for CR physicists

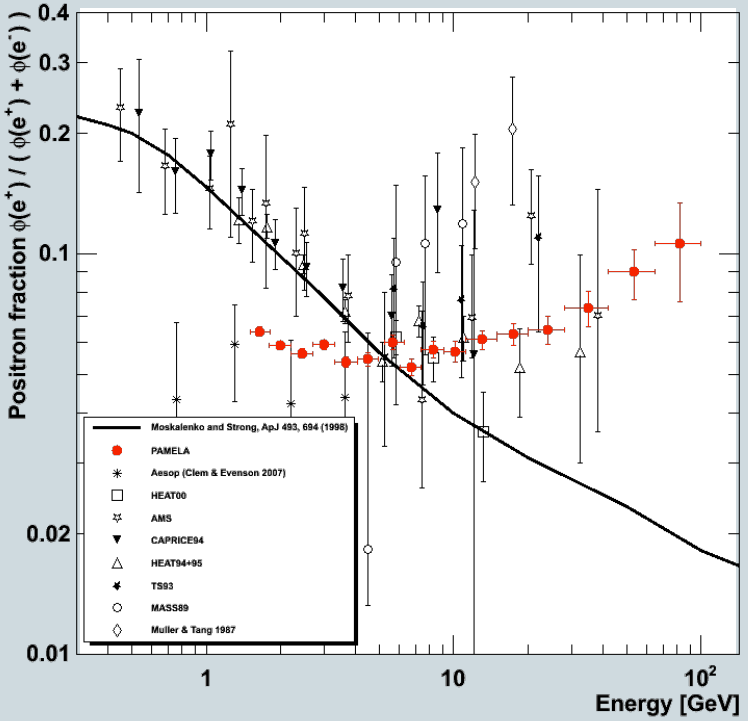
Antiprotons

→ Consistent with pure secondary production



Positrons

→ Evidence for an excess



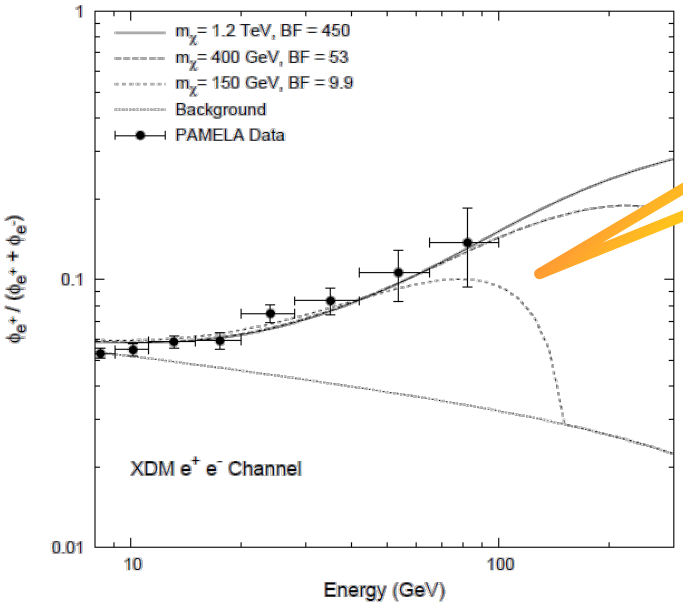
Positron-excess interpretations

Dark matter

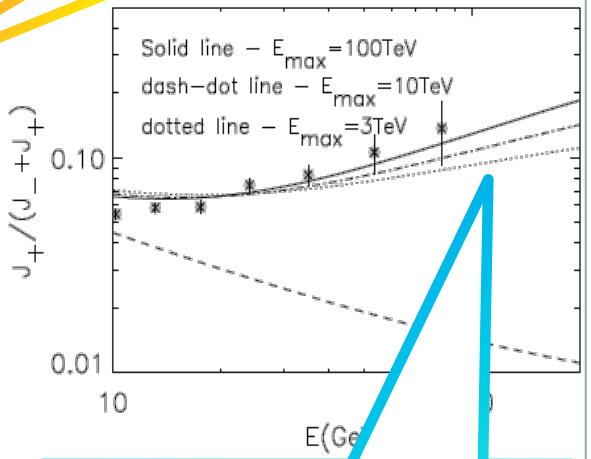
- boost factor required
- lepton vs hadron yield must be consistent with p-bar observation

Astrophysical processes

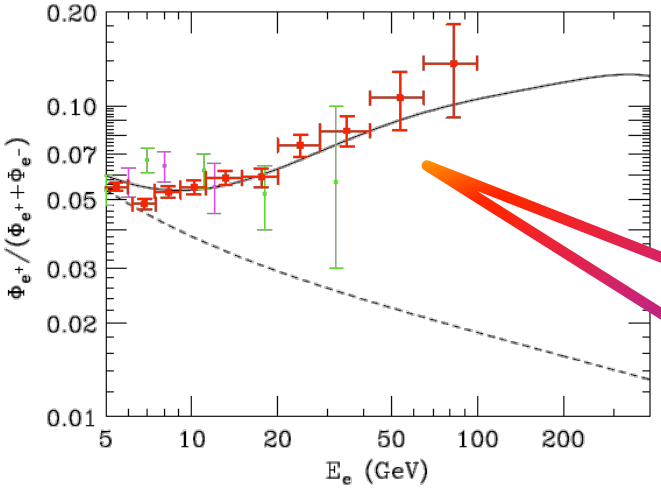
- known processes
- large uncertainties on environmental parameters



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



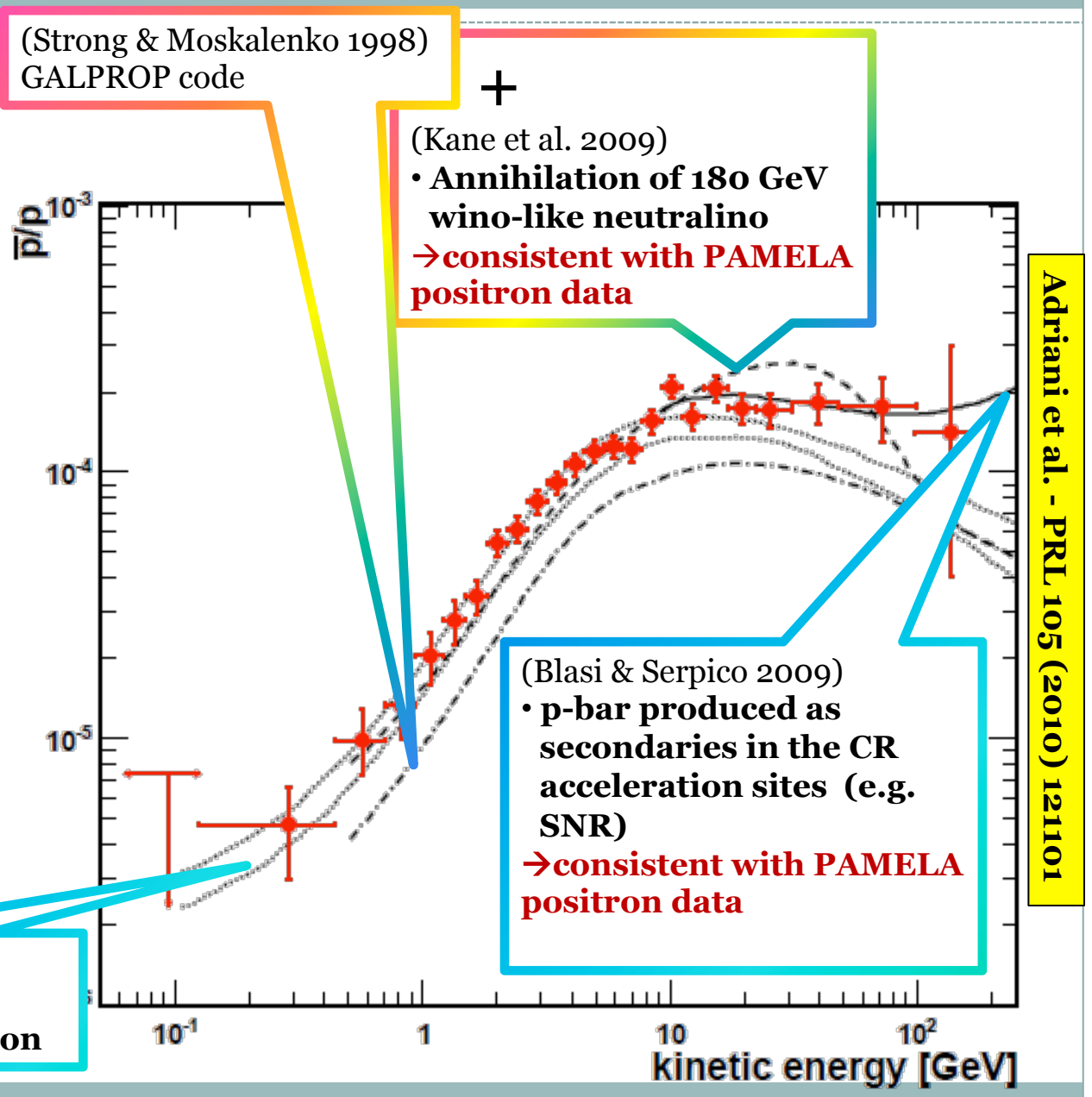
(Blasi 2009)
e+ (and e-) produced as **secondaries** in the CR acceleration sites (e.g. SNR)



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

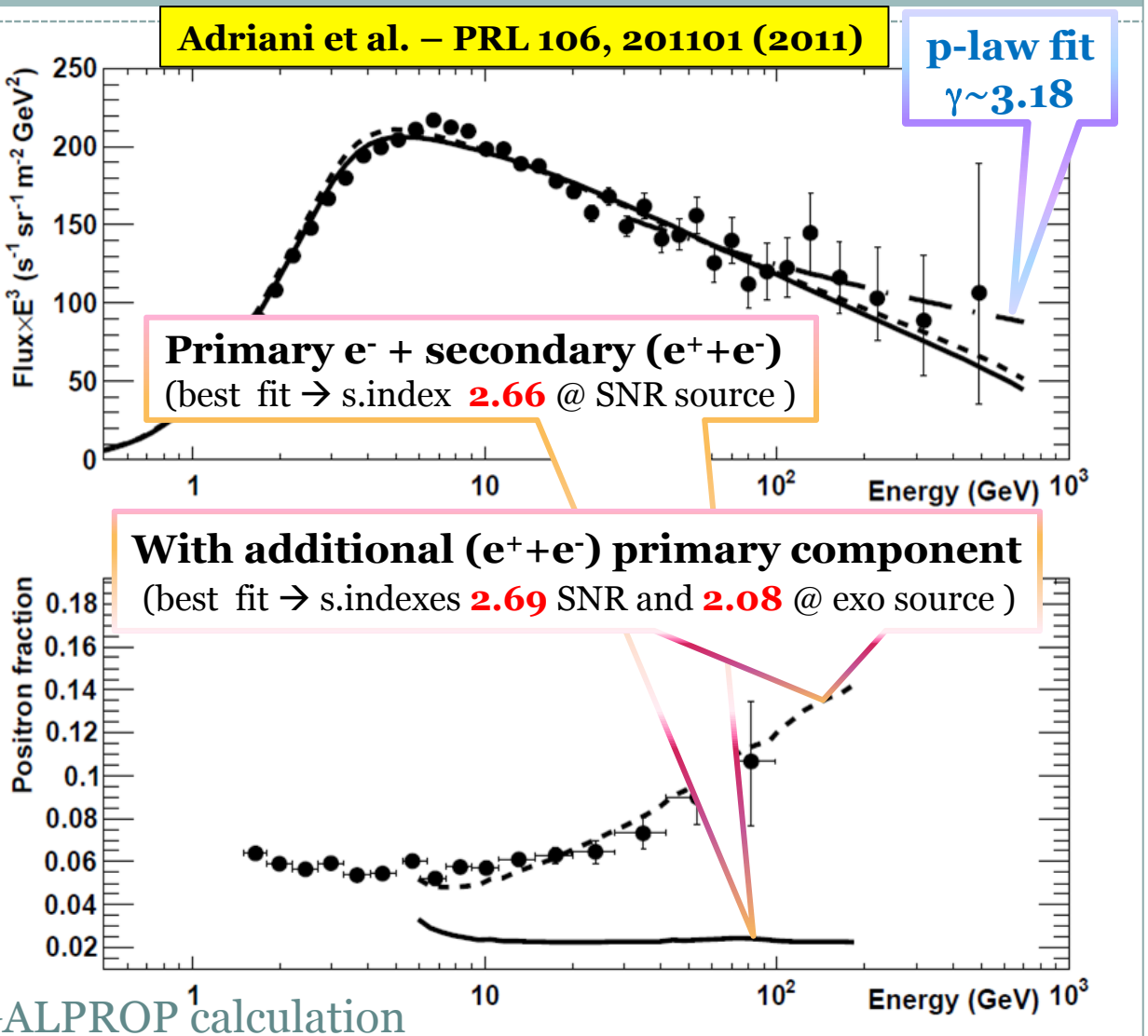
Positrons vs antiprotons

- Large uncertainties on propagation parameters allows to accommodate an additional component
- A p-bar rise above 200GeV is not excluded



Positrons vs electrons

- Fit of electron flux
- Two scenarios:
  1. **standard** (primary +secondary components)
  2. **additional primary** e^- (and e^+) component
- Electron data are not inconsistent with standard scenario, but…
- …an additional component better reproduces positron data



GALPROP calculation

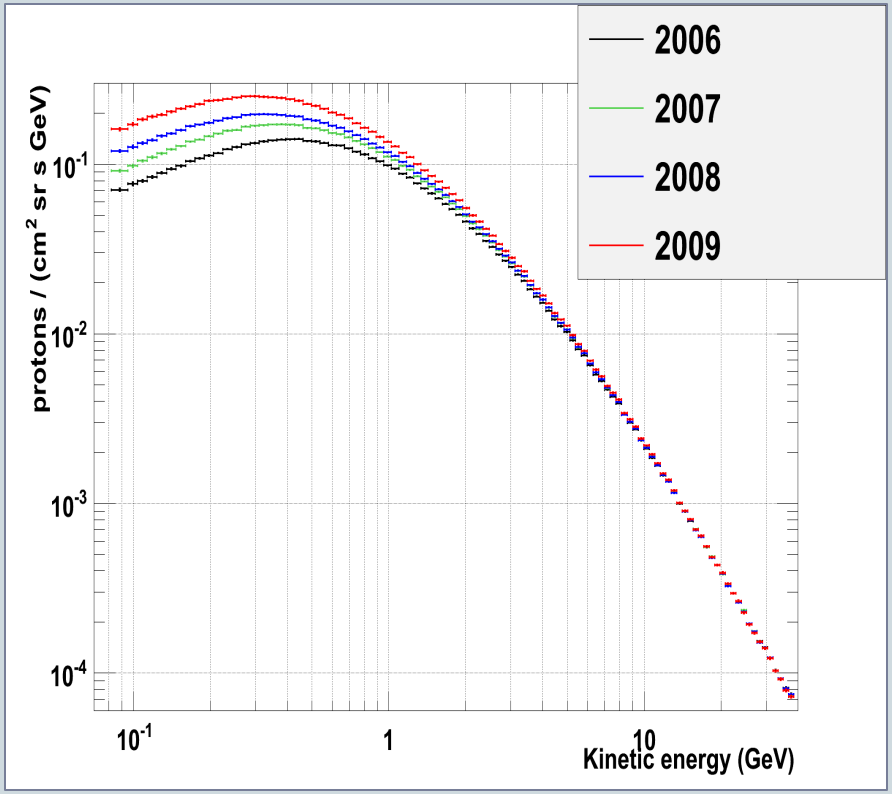
diffusion + reacceleration (Ptuskin et al. 2006)

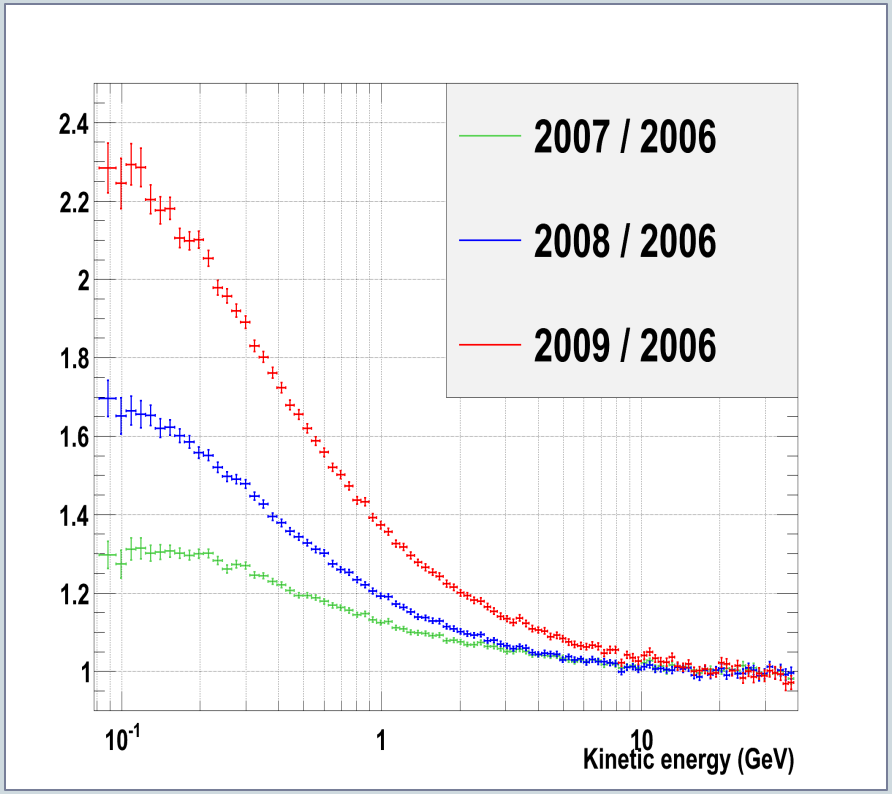
H and He primary spectra from best fit of propagated spectra to PAMELA results

Solar and terrestrial physics

Solar modulation: time dependence

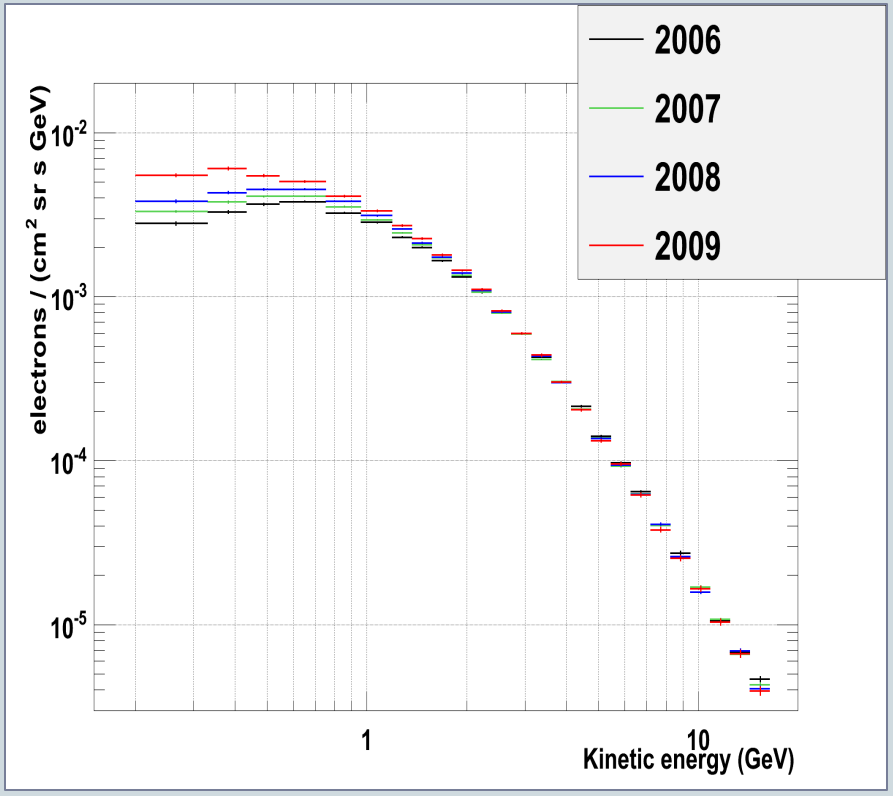
PAMELA PROTON FLUX

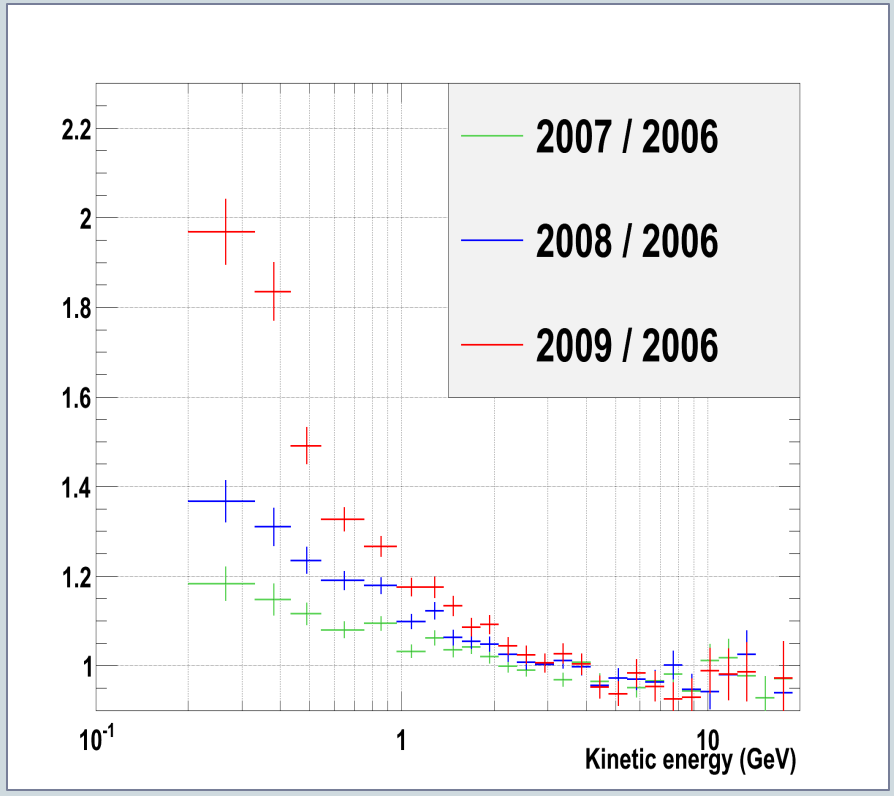




Solar modulation: time dependence

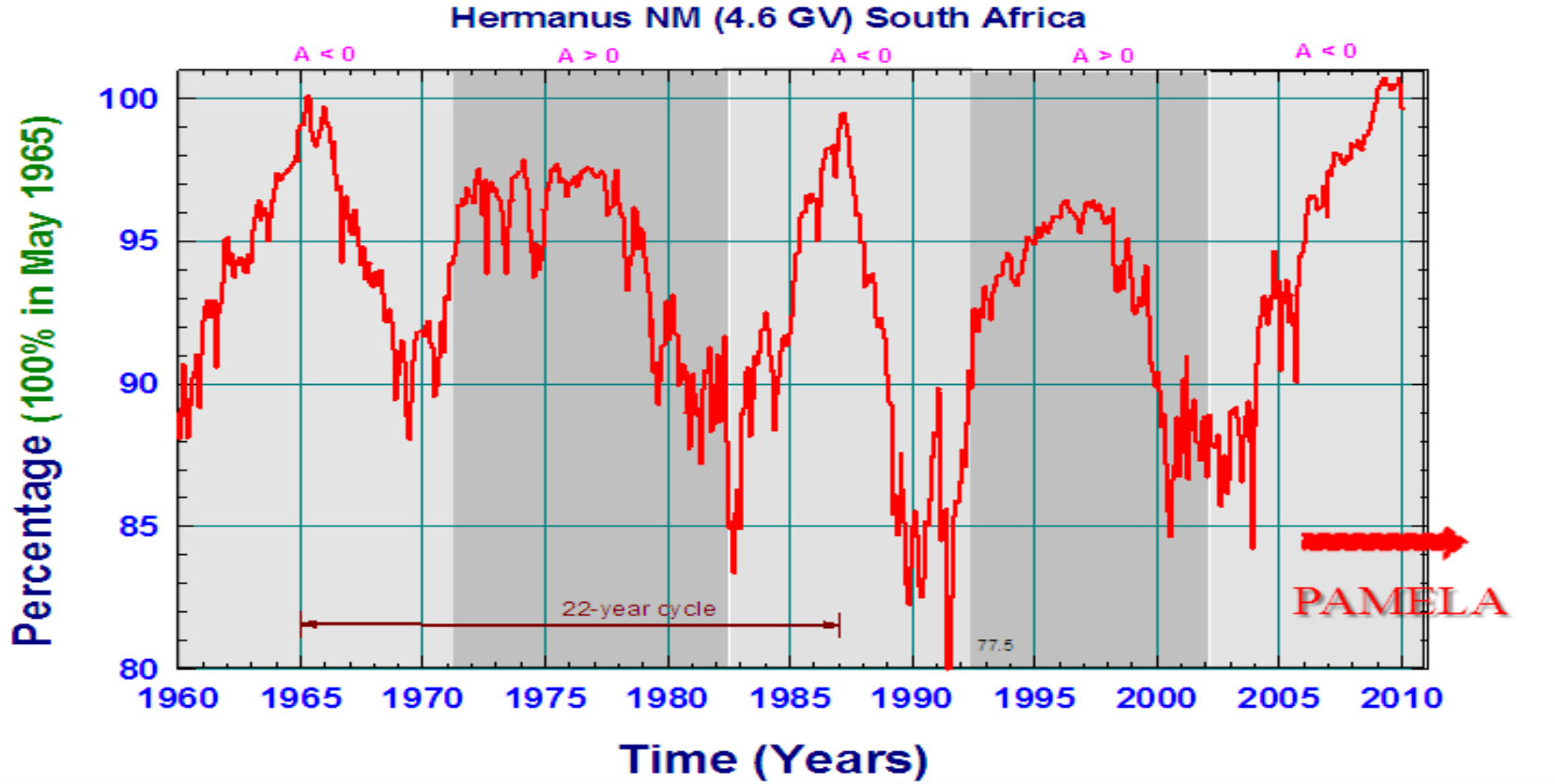
PAMELA ELECTRON FLUX





Charge-dependent solar modulation

Solar modulation depends on Sun magnetic field orientation



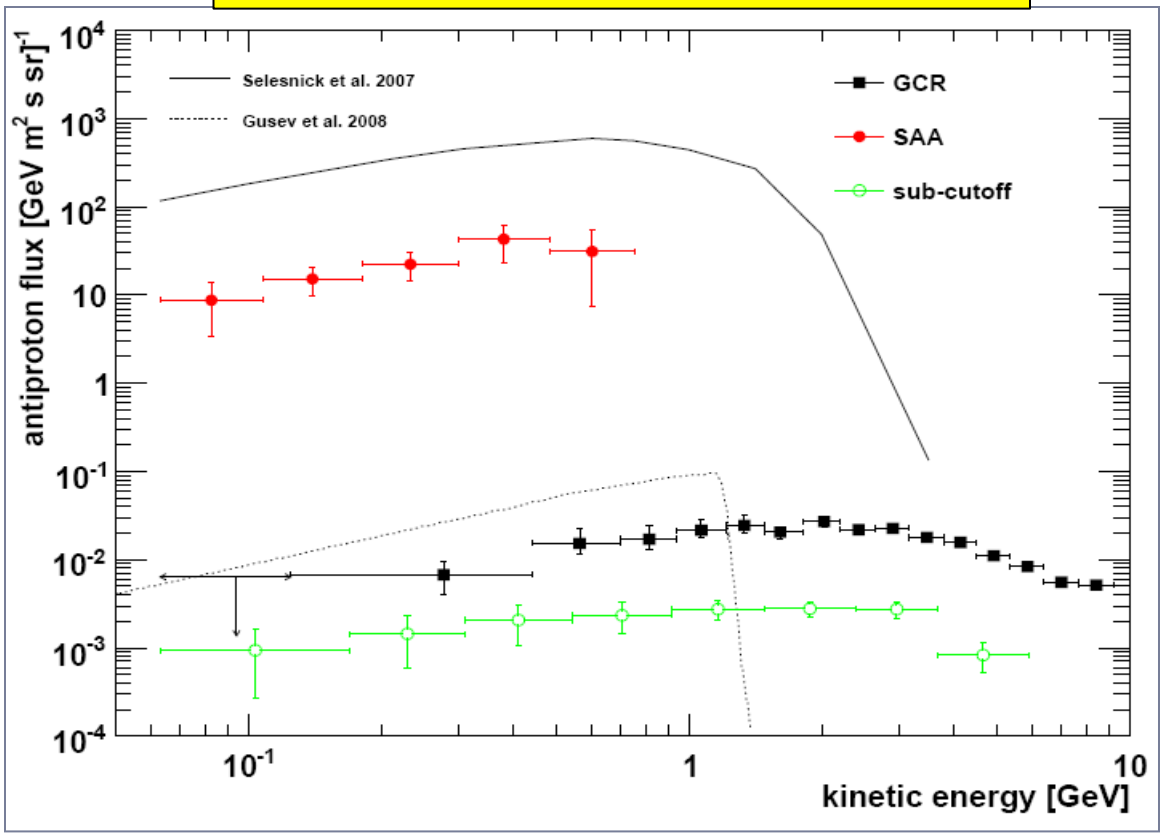
Trapped antiprotons

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

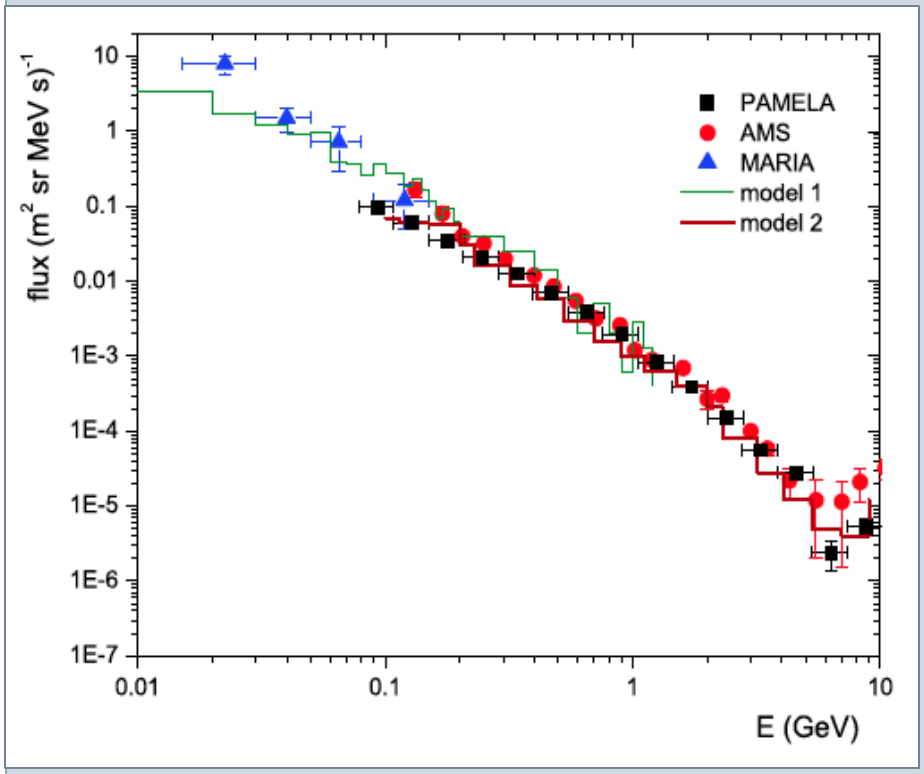
Adriani et al. – submitted to APJ Letters



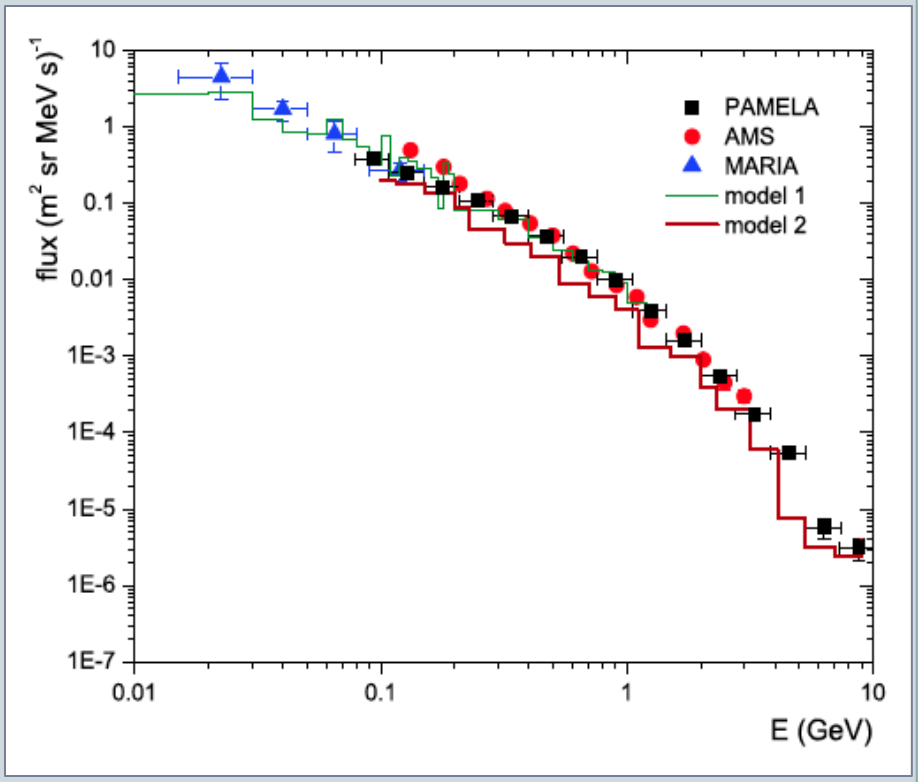
Quasi-trapped electrons and positrons

Secondary leptons produced by CR interactions with residual atmosphere and then confined

Electrons



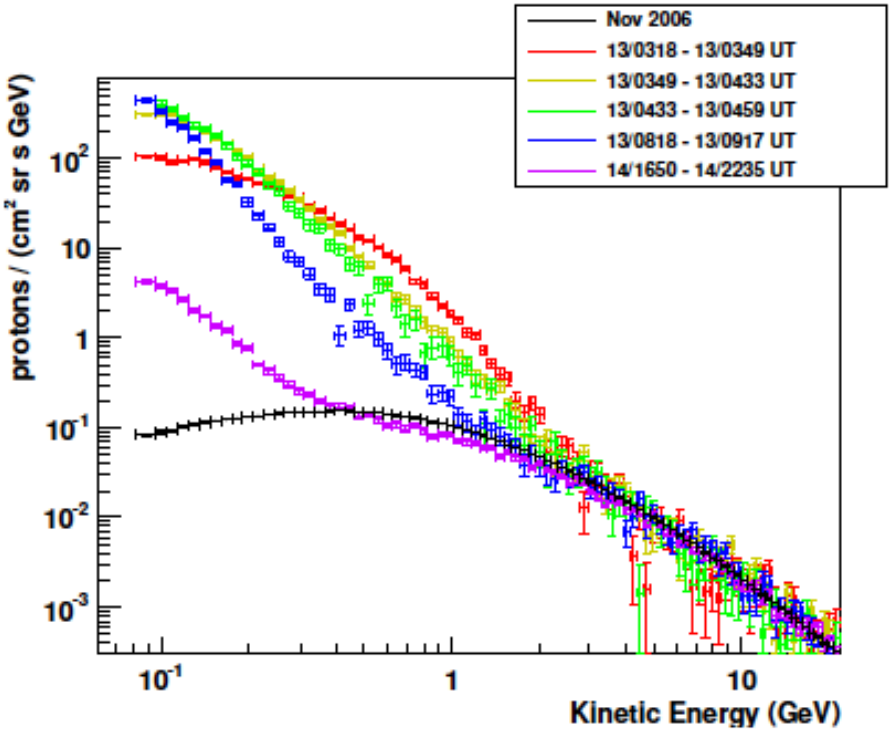
Positrons

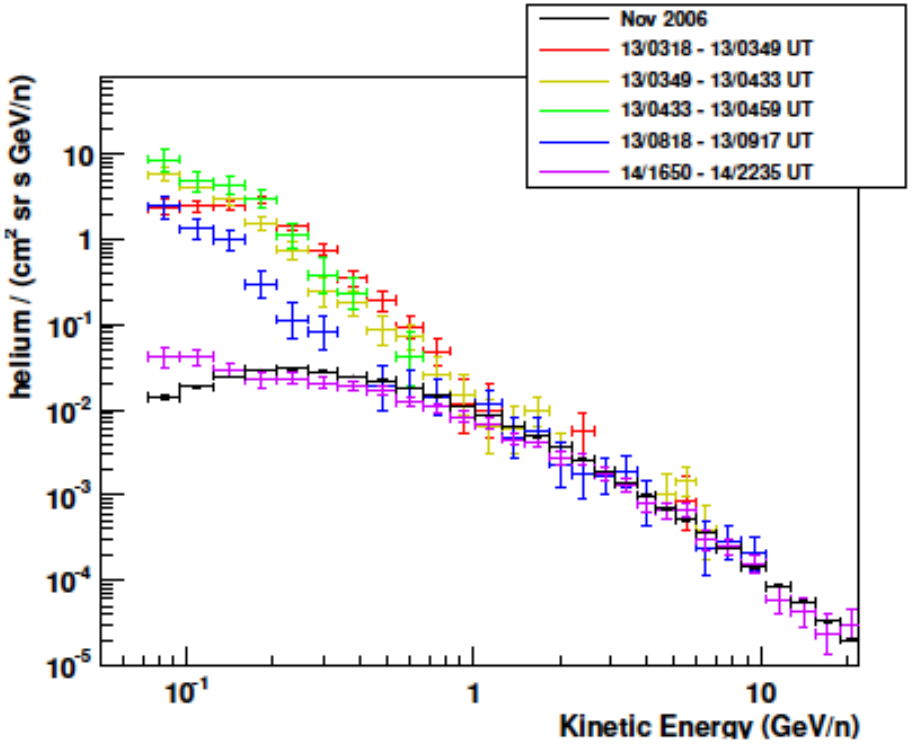


Adriani et al., Journal of Geophysical Research 114 (2009)

13 Dec 2006 Solar Flare

Adriani et al. – submitted to APJ





Summary and conclusions (1)

PAMELA has been in orbit and studying cosmic rays for ~ 5 years. Its operation time ends in 2011.

>10^9 triggers registered and >20 TB of data have been down-linked.

- **H and He absolute fluxes** → Measured up to ~1.2TV. Most precise measurement so far. Complex spectral structures observed (spectral hardening at ~200GV) → New features in the paradigm of CR acceleration in SNRs!
- **Electron absolute flux** →Measured up to ~600GeV. No evident deviations from standard scenario, but not inconsistent with an additional electron component.
- **High energy positron fraction (>10 GeV)** → Increases significantly (and unexpectedly!) with energy. → Primary source?
- **Antiproton energy spectrum** → Measured up to ~200 GeV. No significant deviations from secondary production expectations.

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

Summary and conclusions (2)

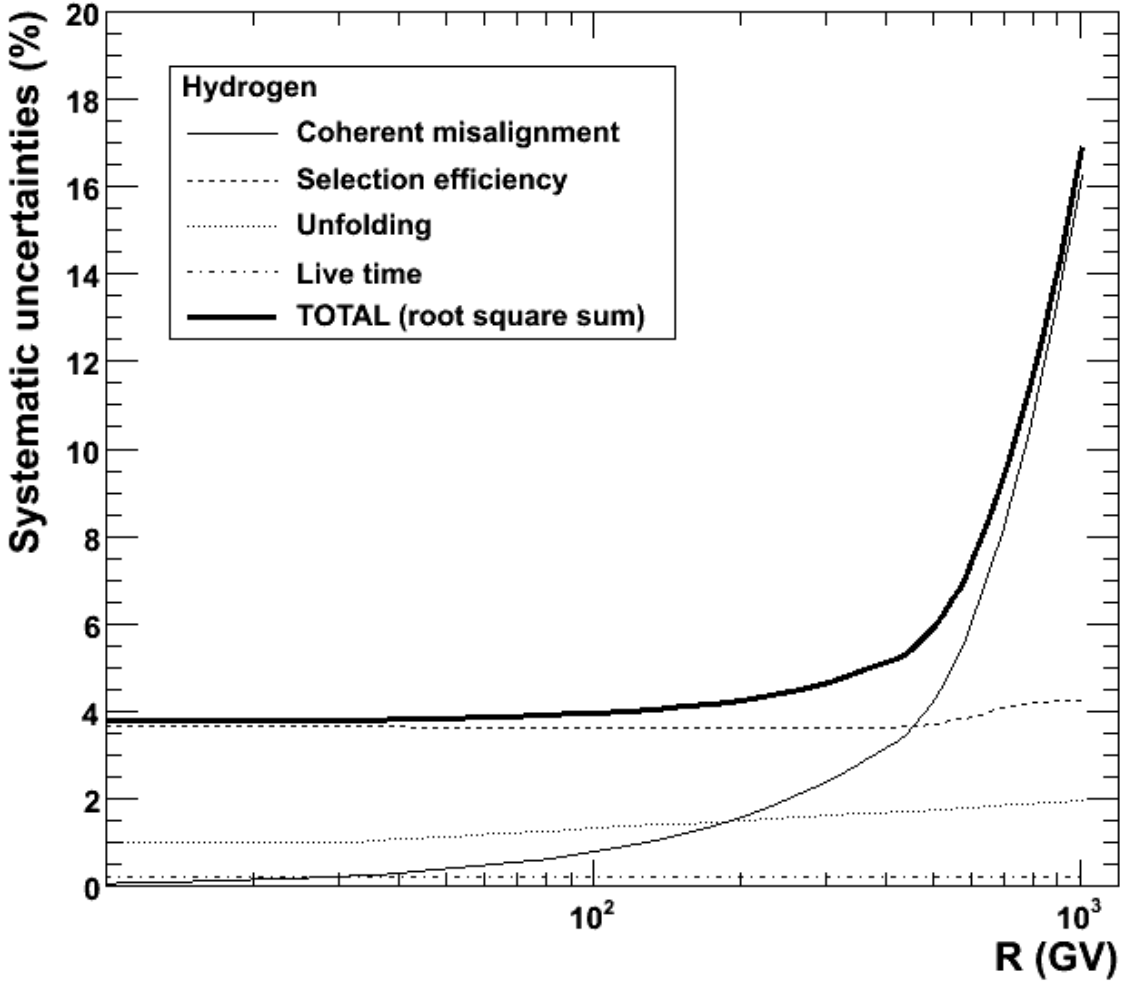
Other studies and forthcoming results:

- Upgrade of positron analysis (increased statistics, higher energy)
- Primary and secondary-nuclei abundance (up to Oxygen)
- H and He isotope abundance
- Solar modulation (long-term flux variation and charge-dependent effects)
- Upper limit to anti-He abundance

Thanks!!

Overall systematic uncertainties

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



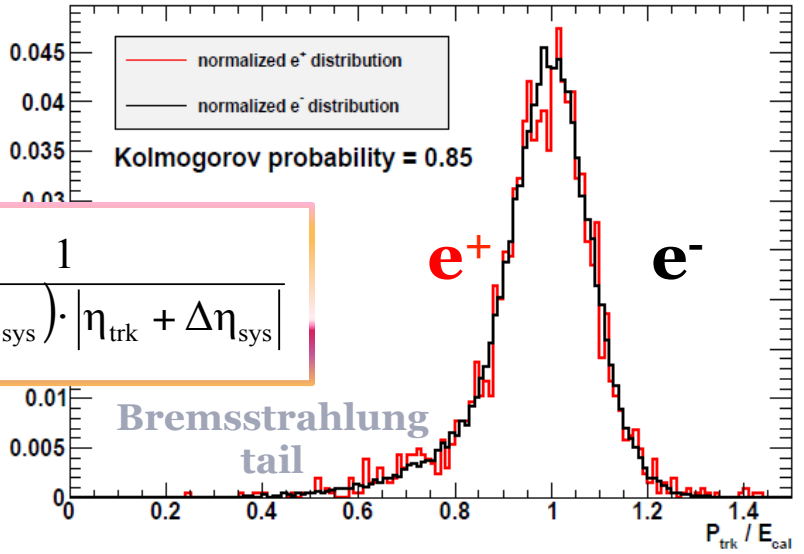
Spectrometer systematic uncertainty

- Evaluated from in-flight electron/positron data by comparing the spectrometer momentum with the calorimeter energy
- Upper limit set by positron statistics:

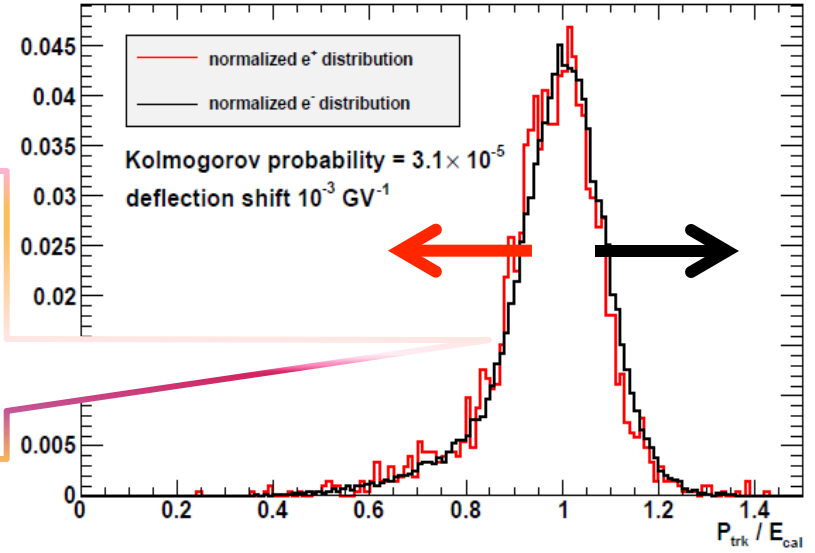
$\Delta\eta_{sys} \sim 1 \cdot 10^{-4}\ GV^{-1}$

(MDR=200÷1500TV)

$$\frac{P_{trk}}{E_{cal}} \xrightarrow{sys} \frac{1}{E_{cal}\left(1+\varepsilon_{sys}\right)\cdot\left|\eta_{trk}+\Delta\eta_{sys}\right|}$$



A systematic deflection shift causes an offset between e^- and e^+ distribution



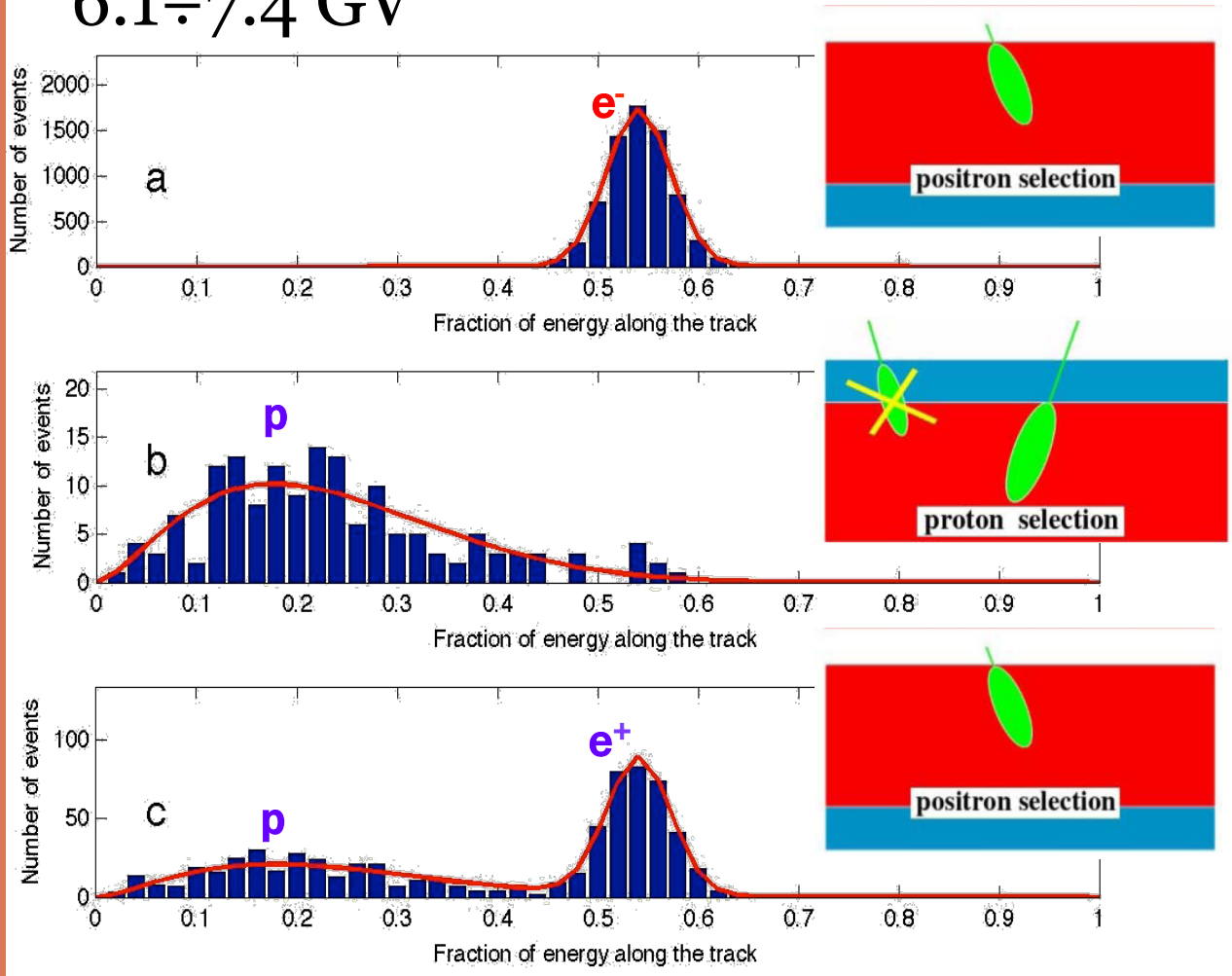
Proton background evaluation

- Background evaluated from in-flight data
- No dependence on simulation

Method:

1. Estimation of PDFs for electron (a) and proton (b) experimental distributions
2. Fit of positron experimental distribution (c) with mixed PDF
3. Statistical errors determination with bootstrap procedure

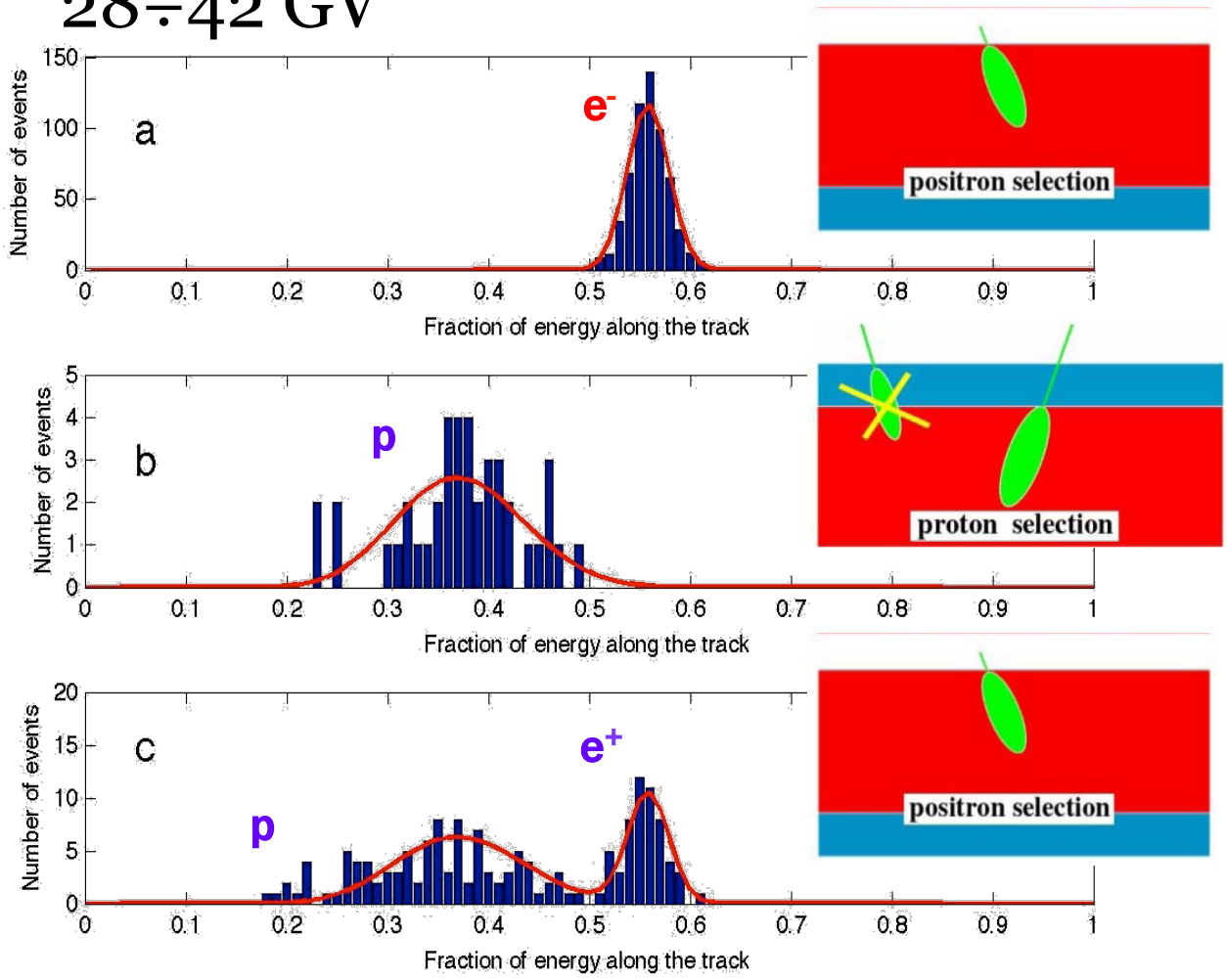
6.1÷7.4 GV



Fraction of energy along the track, after constraints on **energy-momentum match** and **shower starting point**

Proton background evaluation

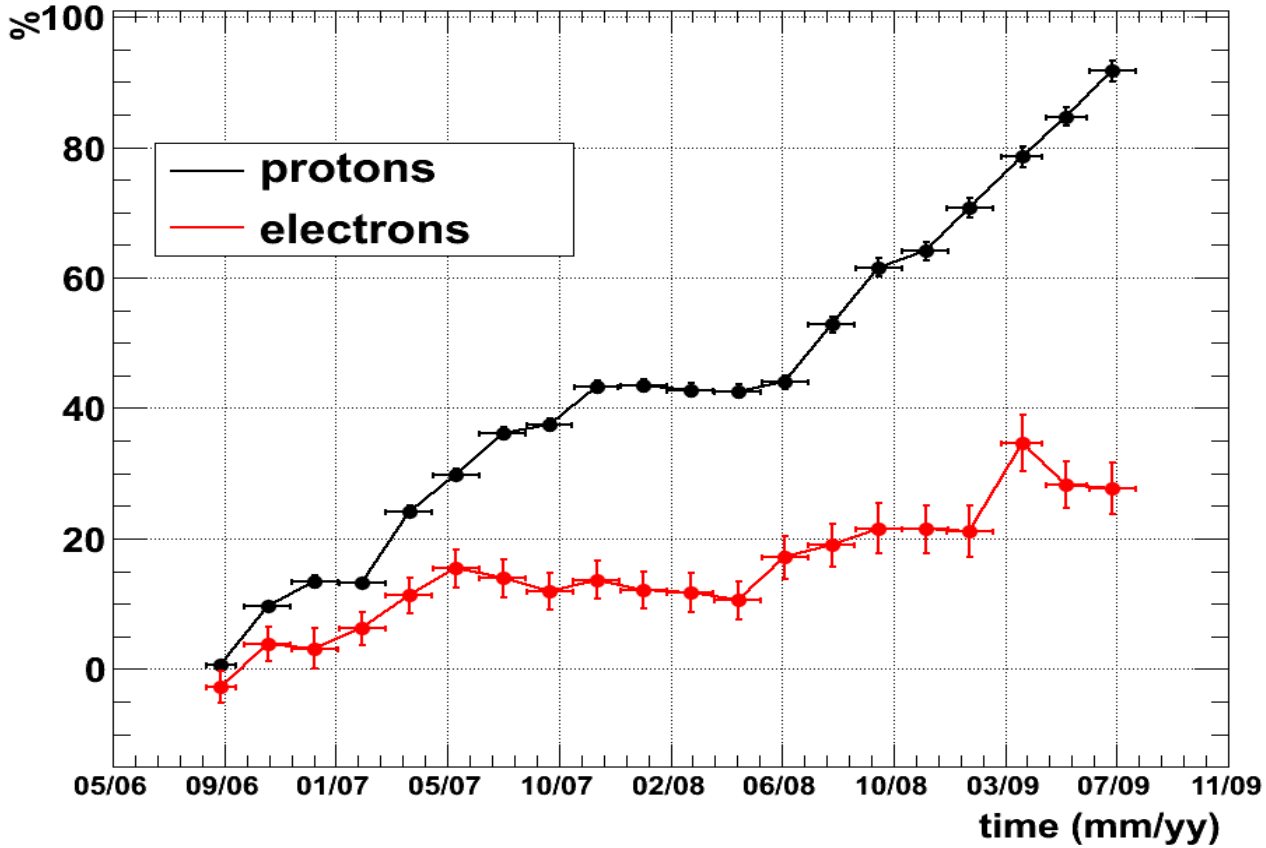
28÷42 GV



Fraction of energy along the track, after constraints on **energy-momentum match** and **shower starting point**

Time Dependence

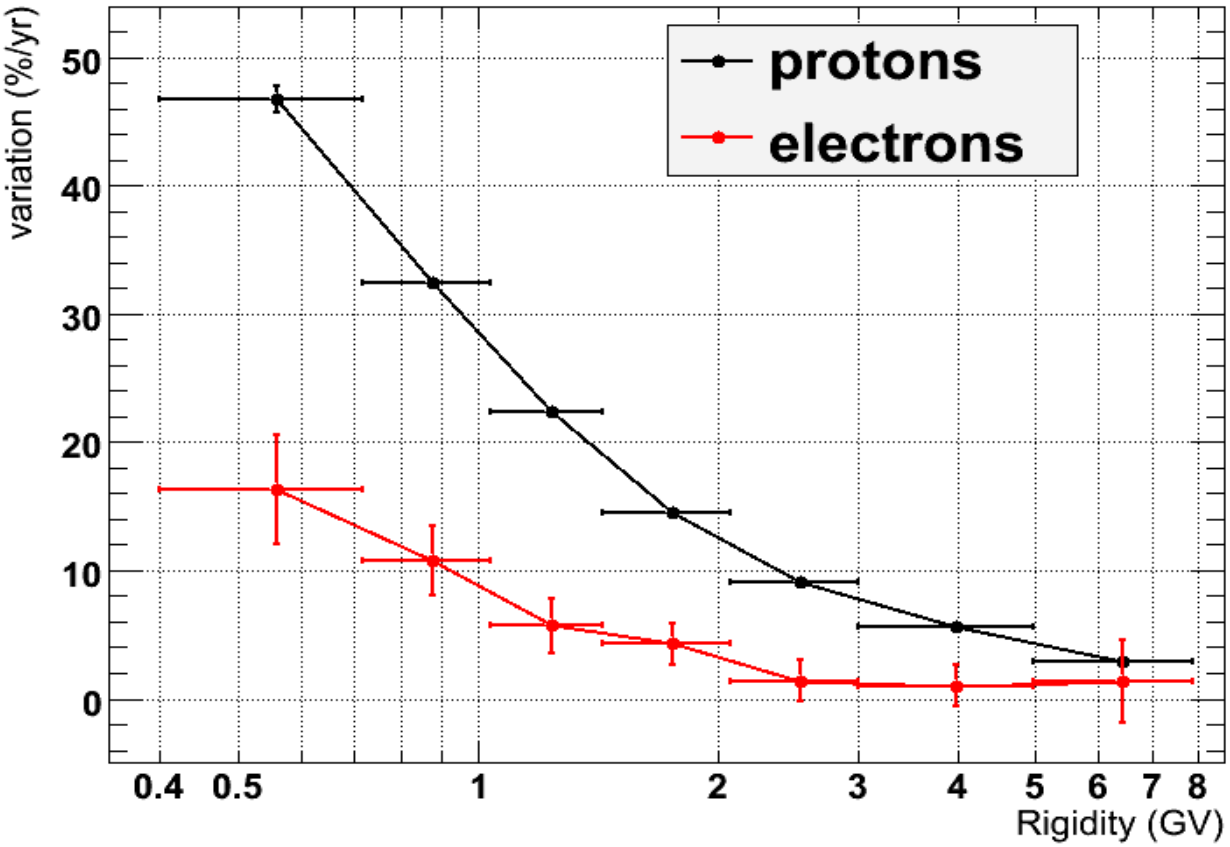
Preliminary



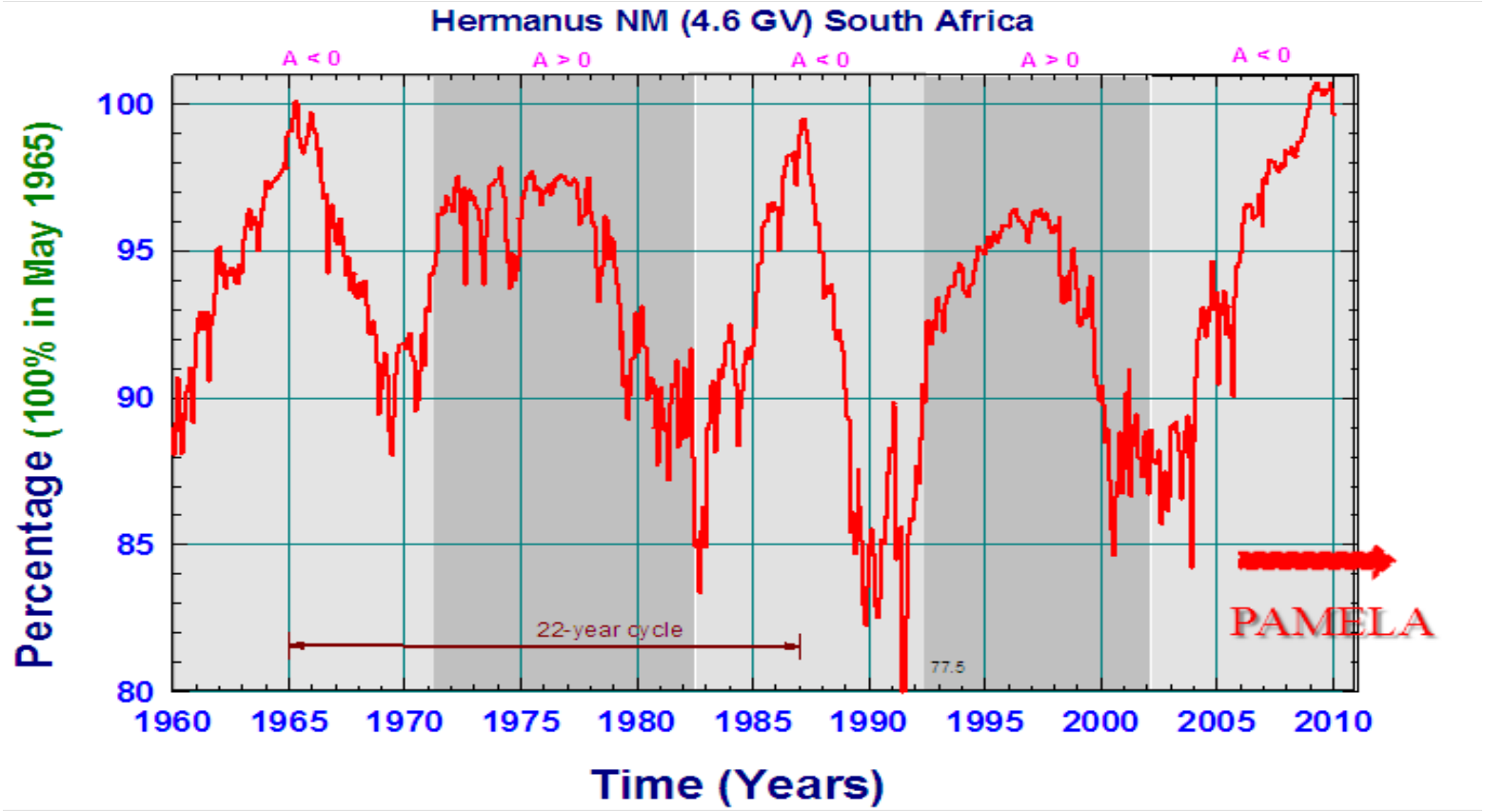
Flux variation as a function of time for rigidities between 0.72 and 1.04 GV

Time Dependence

Preliminary



Increase of the flux measured by PAMELA from July 2006 to December 2008


Hermanus NM (4.6 GV) South Africa
A < 0
A > 0
A < 0
A > 0
A < 0
Percentage (100% in May 1965)
100
95
90
85
80
22-year cycle
77.5
PAMELA
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Time (Years)