EPS-HEP2011, Grenoble July 21, 2011

Pamela main results after 5 years of data taking

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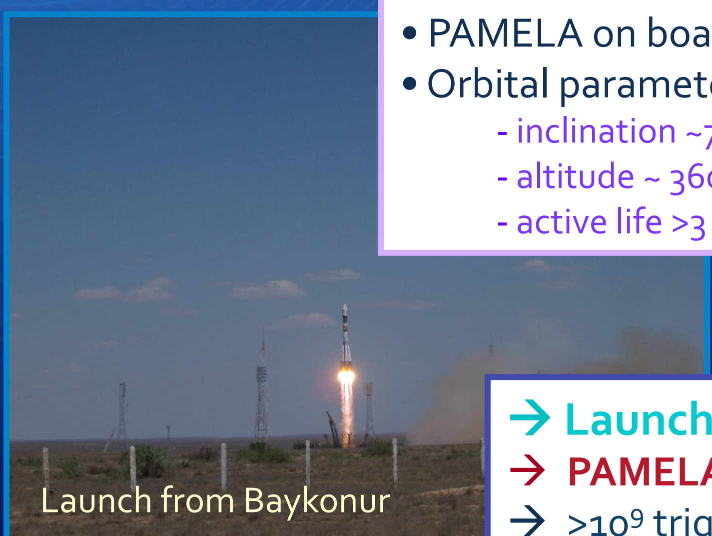
on behalf of the Pamela Collaboration

The PAMELA experiment

- **Direct** detection of CRs in space
- Precise measurement of **particles** (protons, Helium, e^-)
- Main focus on **antiparticles** (antiprotons and positrons)



Launch from Baykonur

- 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 sin**

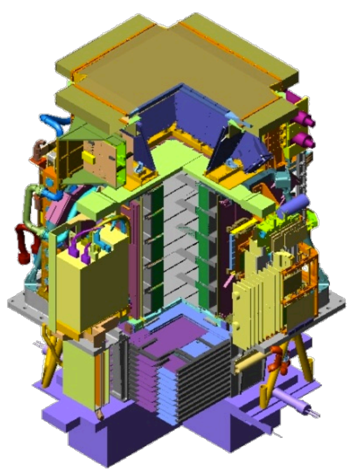
→ $>10^9$ triggers registered and >20 TB of data have been down-linked.

PAMELA detectors

Main requirements:

- high-sensitivity antiparticle identification

- precise momentum measure

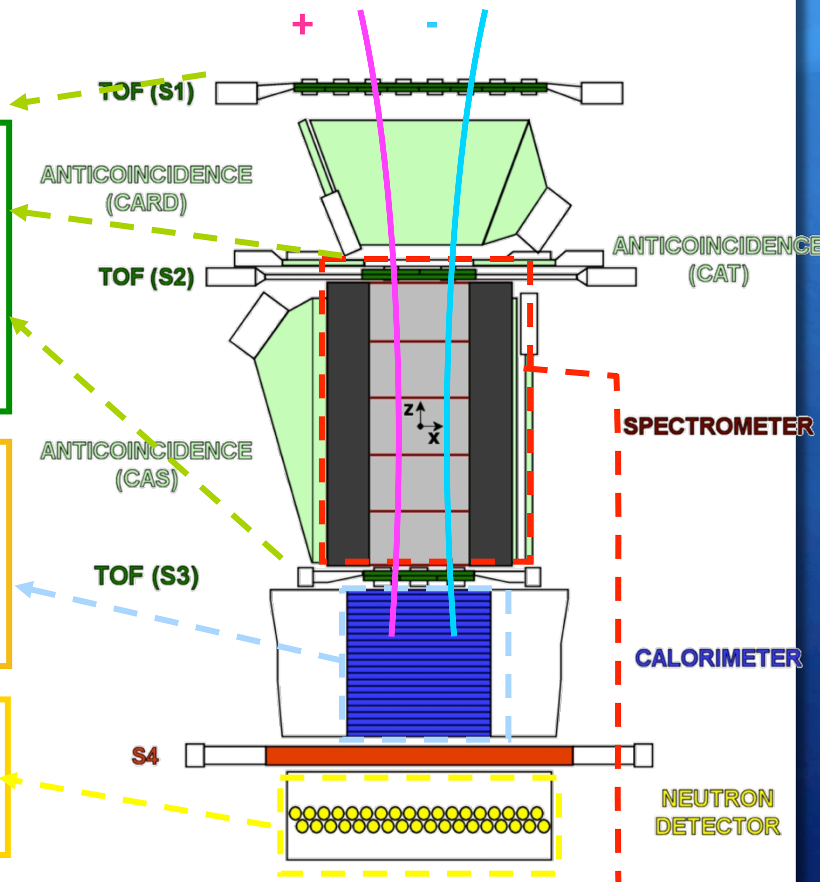


Time-Of-Flight
plastic scintillators + PMT:
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX.

Electromagnetic calorimeter
W/Si sampling (16.3 X0, 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 primaries GCRs

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Pamela main results after 5 years of data taking

Importance of p and He spectra

Precise p and He spectra measurements are very important:

- To understand astrophysical phenomena
- To study sources, acceleration and propagation in the galaxy
- To constrain the propagation models (essential for Dark Matter searches!)
- To verify/constrain the solar modulation and geomagnetic models

Big challenge from the experimental point of view:

- 1-2% precision in the absolute flux is necessary
- Detailed study and understanding of the detector systematics
- Necessity to cover a very broad energy range (100 MeV→TeV)
- Long term exposure (Detector stability)
- Transient phenomena should be taken into account (e.g. solar activity related phenomena, CME, etc.)

H & He absolute fluxes

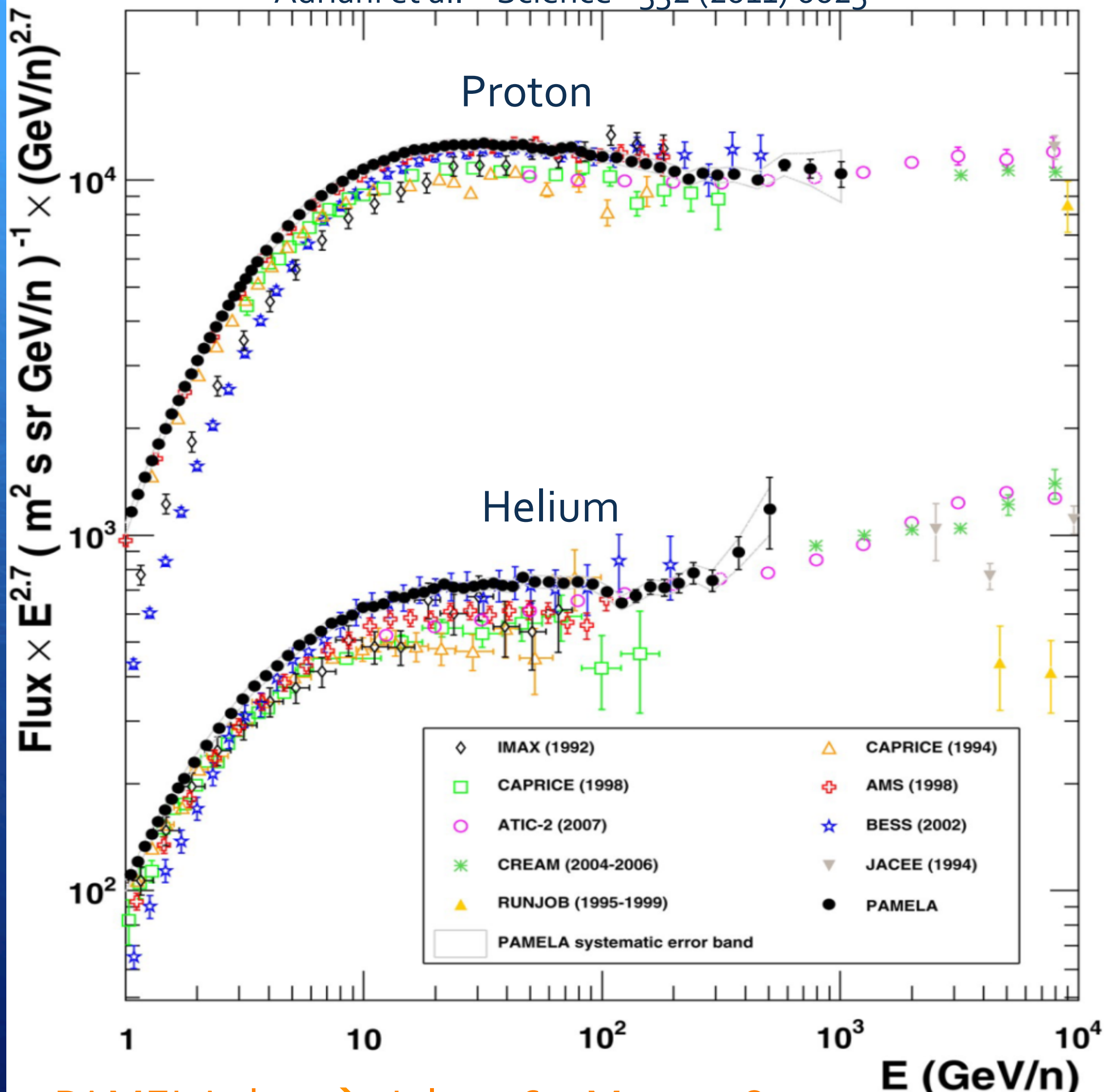
First high-statistics and high-precision measurement over three decades in energy (1 GeV – 1.2 TeV / 1 GeV – 600 GeV/n)

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



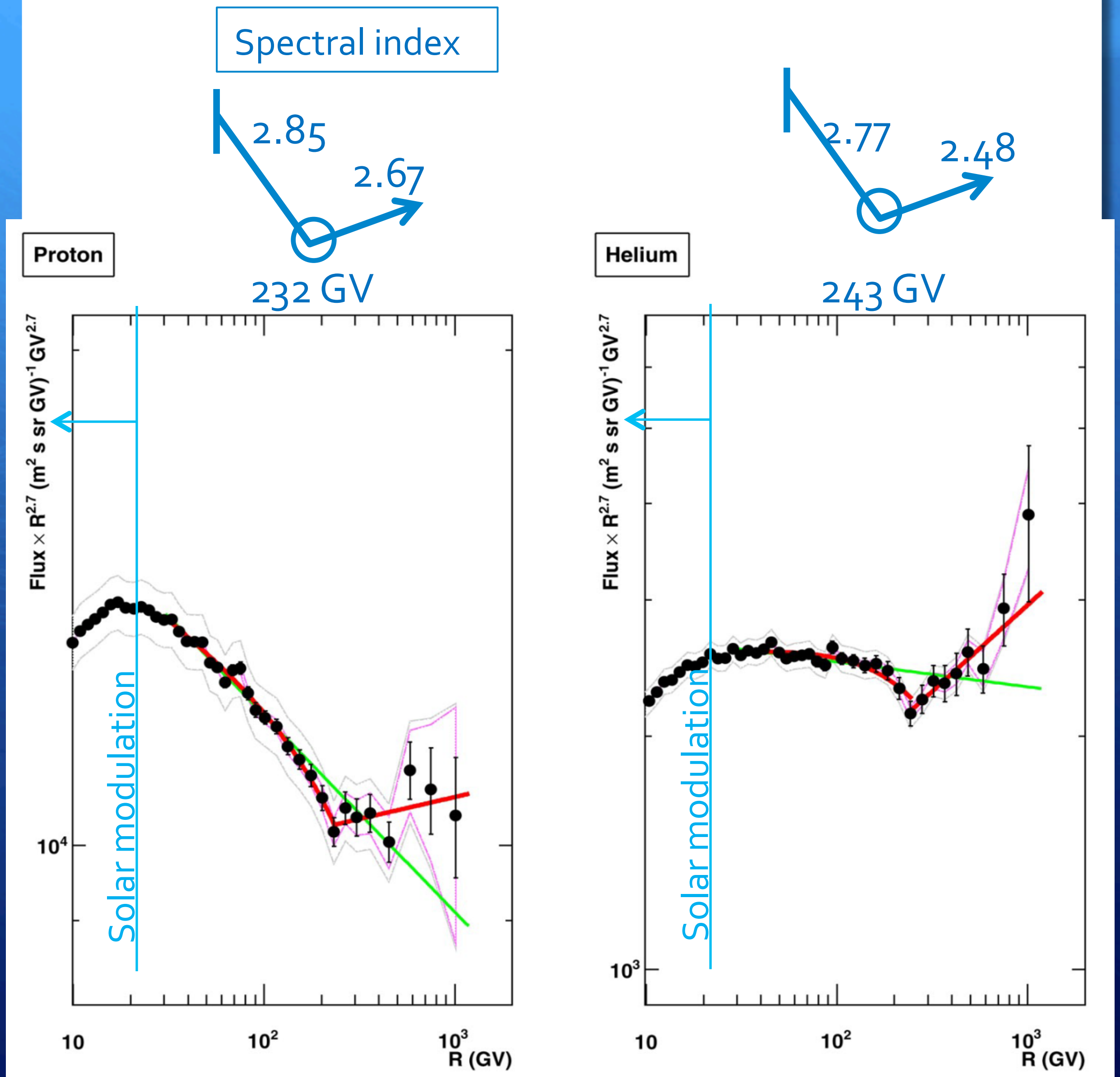
PAMELA data → Jul 2006 ÷ Mar 2008

P & He absolute fluxes @ high energy

Deviations from single power law (SPL):

Spectra gradually soften in the range 30÷230GV

Abrupt spectral hardening @ 230/250GV



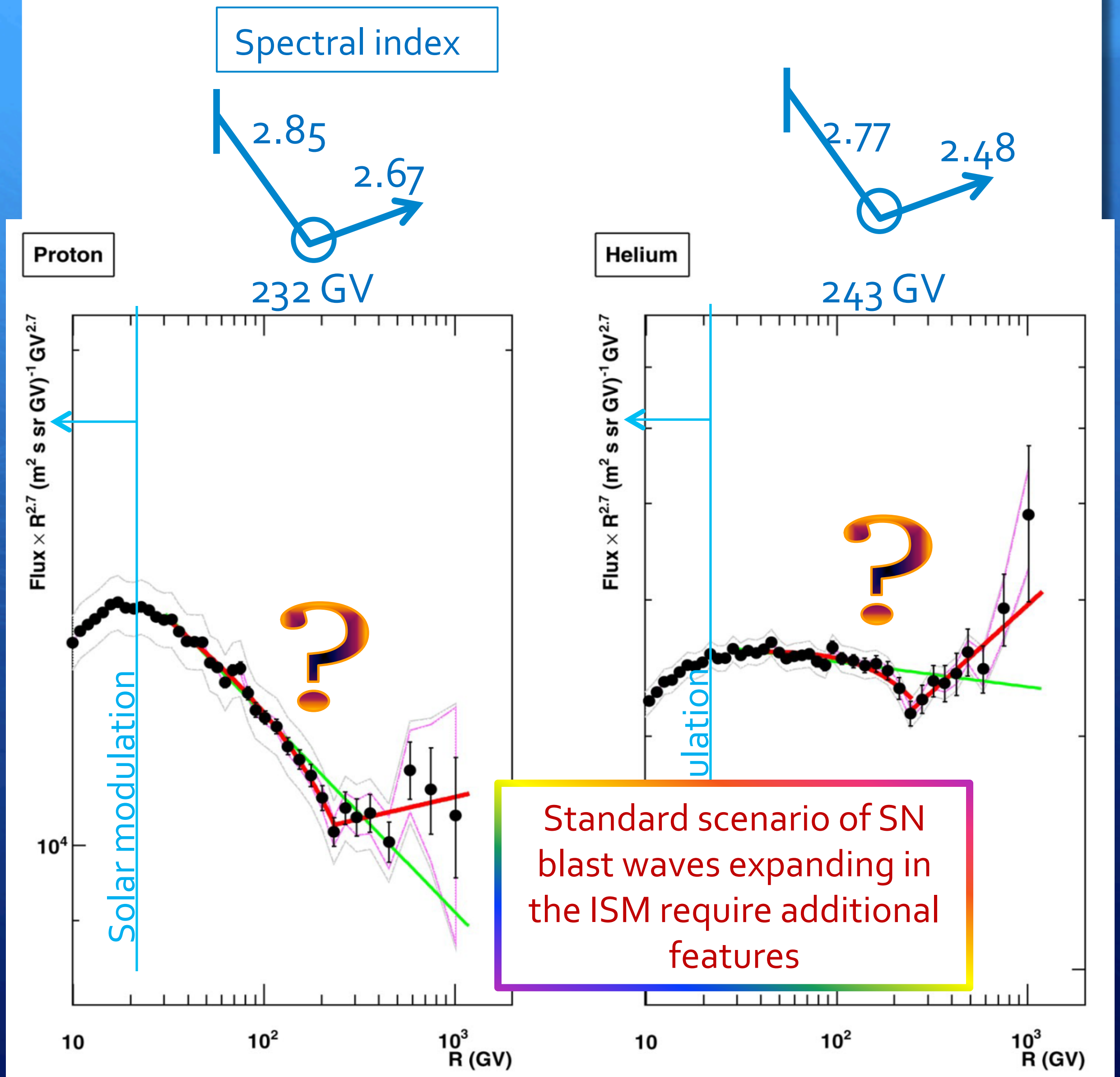
P & He absolute fluxes @ high energy

Deviations from single power law (SPL):

Spectra gradually soften in the range 30÷230GV

Abrupt spectral hardening @ 230/250GV

CR Models need certainly to be refined!



p/He ratio vs Rigidity

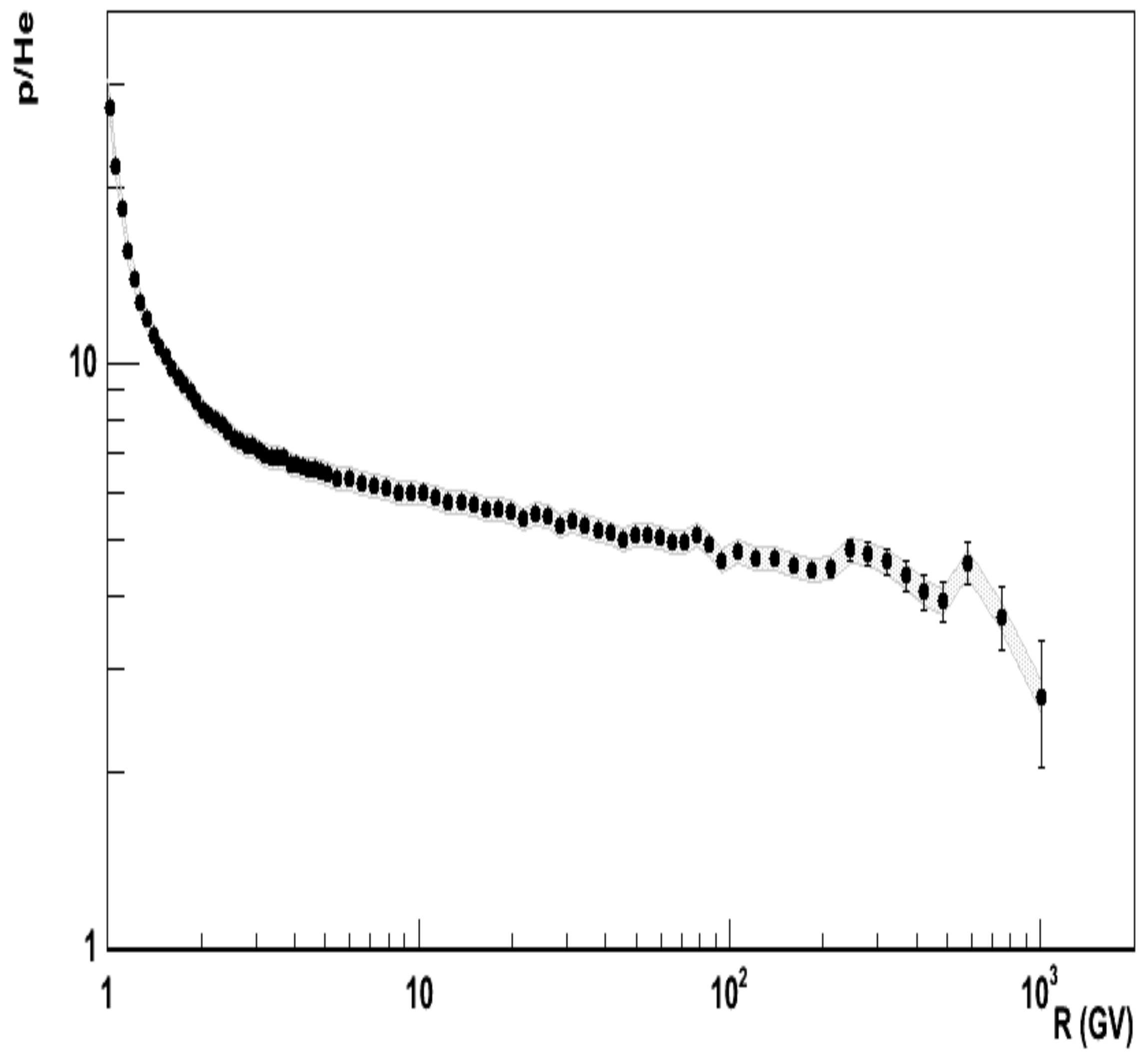
Instrumental p.o.v.

Systematic uncertainties partly cancel out

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



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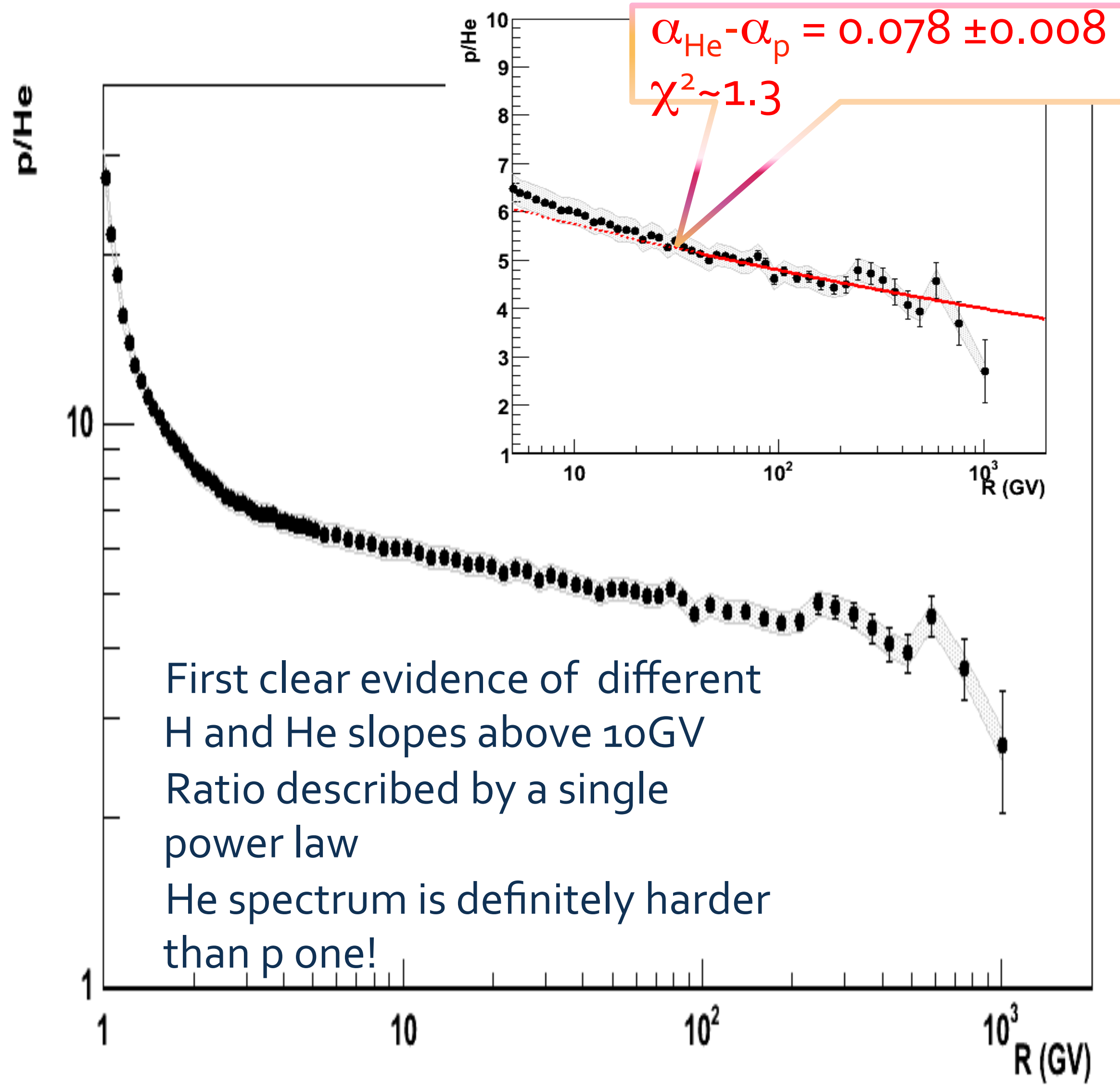


Electron energy measurement

Two independent ways to determine electron energy

1. Spectrometer

Most precise

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

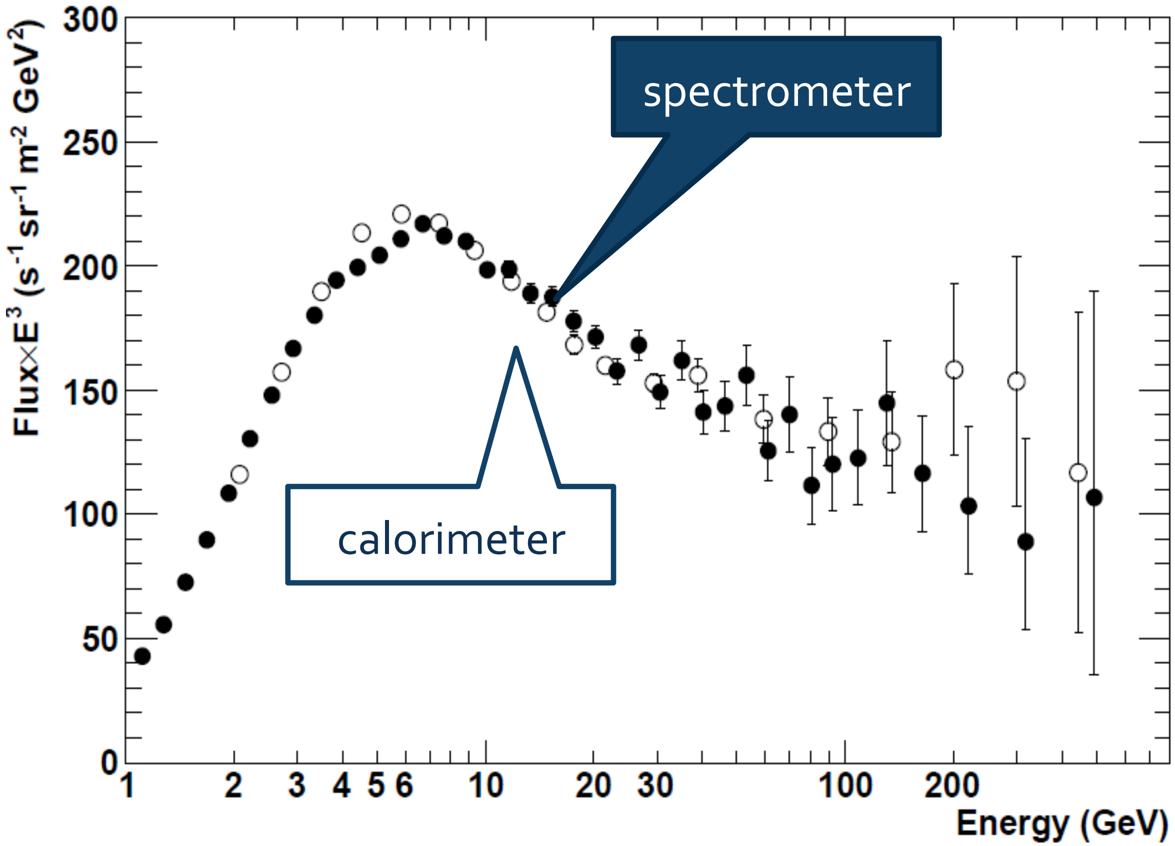
2. Calorimeter

Gaussian resolution

No energy-loss correction required

Strong containment requirements
→ smaller statistical sample

Adriani et al. – PRL 106, 201101 (2011)



Electron identification:

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

Electron absolute flux

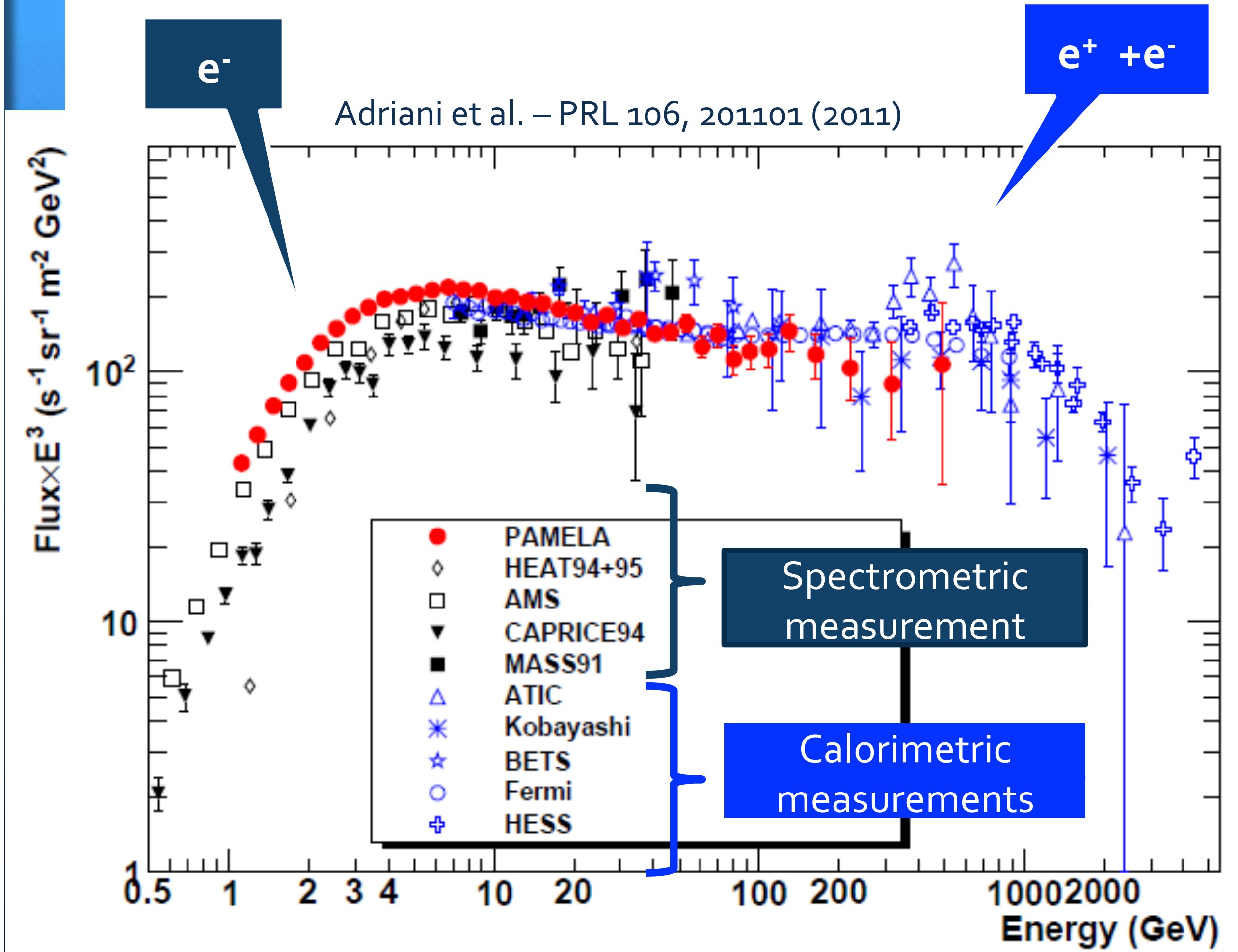
Largest energy range covered in any experiment hitherto with no atmospheric overburden (1-625 GeV)

Low energy

minimum solar activity (ϕ = 450÷550 GV)

High energy

Adriani et al. – PRL 106, 201101 (2011)



PAMELA data → Jul 2006 ÷ Jan 2010

Antiparticles

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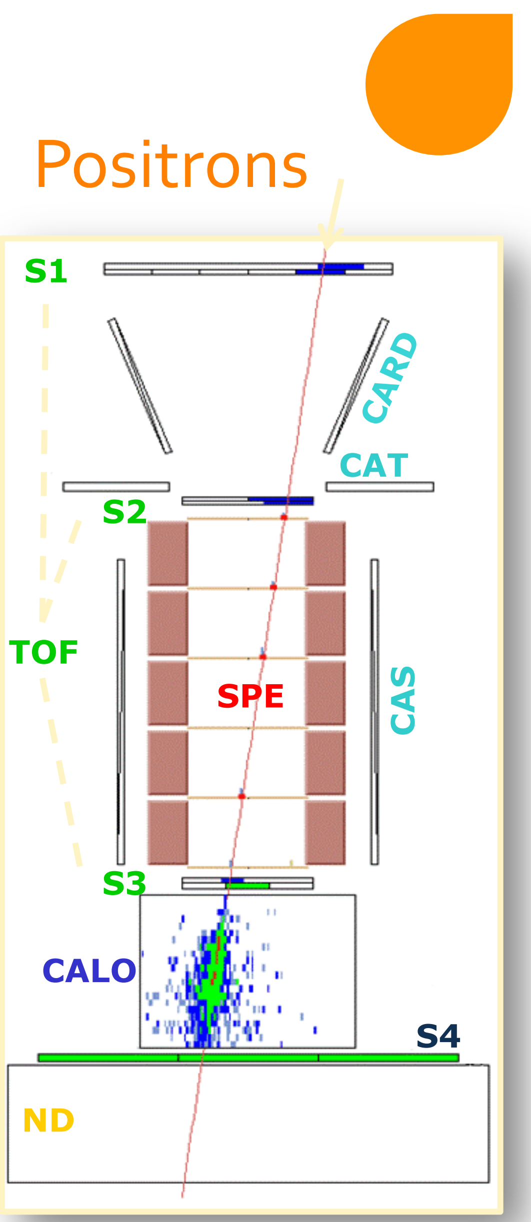


Positron/electron identification:

+ 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:
    - $\pi_o \rightarrow \gamma\gamma$ 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

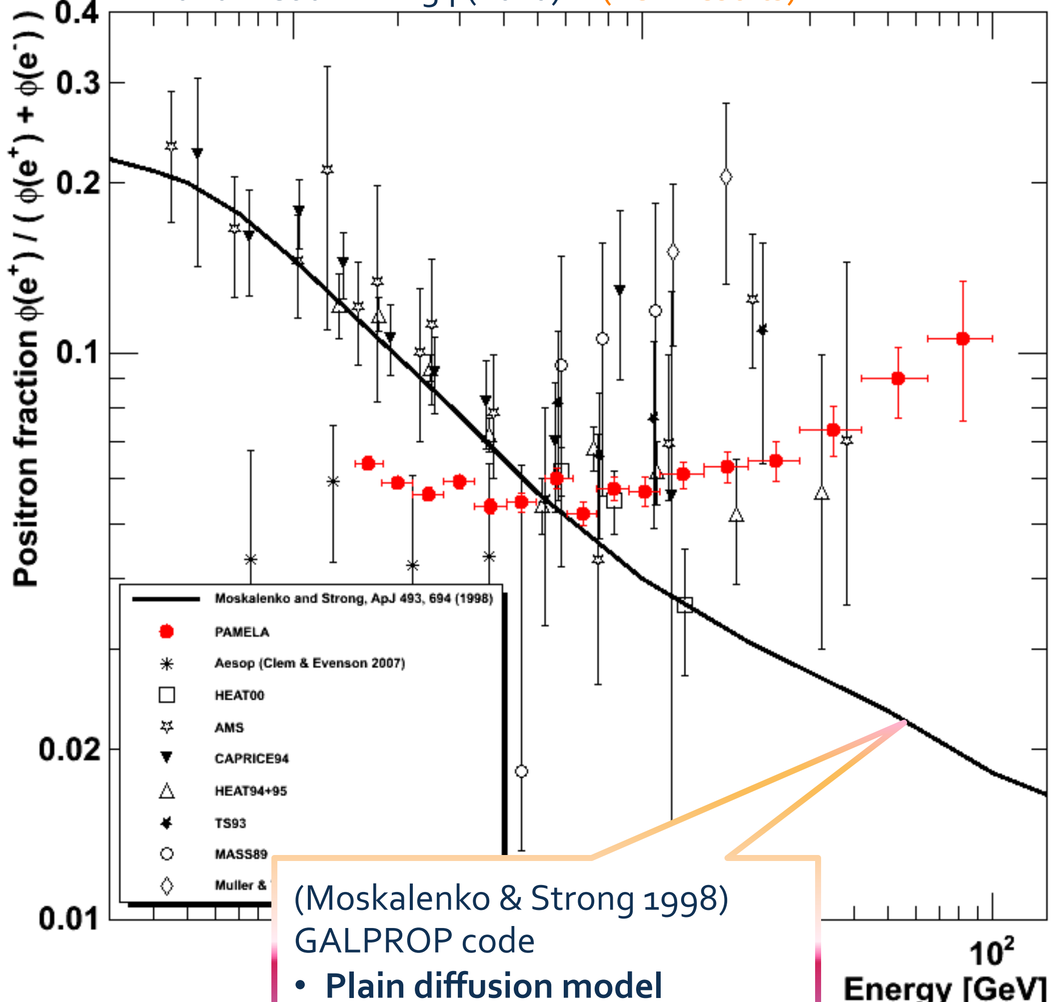
Positron fraction (1.5 GeV – 100 GeV)

Low energy
→ charge-dependent solar modulation

High energy
→ (quite robust) evidence of positron excess above 10GeV

(see eg. Serpico 2008)

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

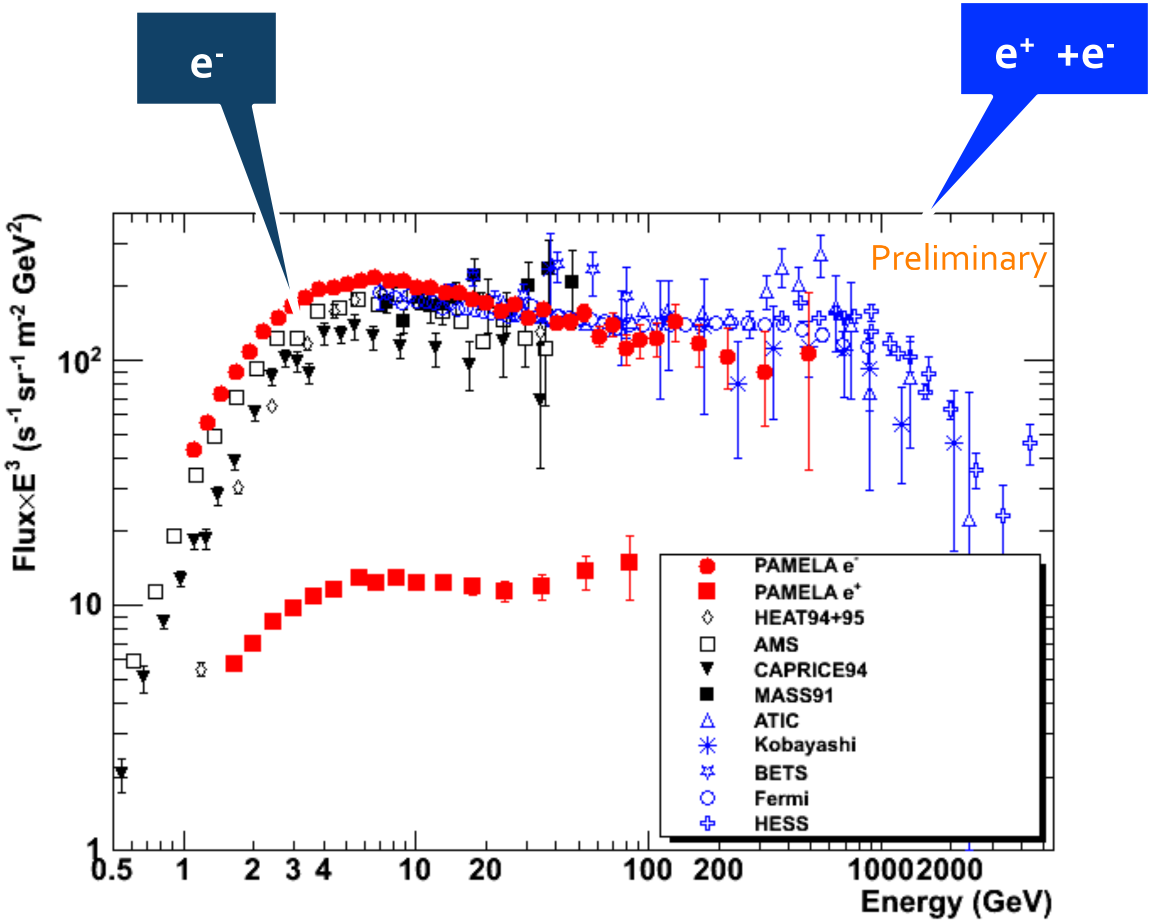


(Moskalenko & Strong 1998)
GALPROP code

- **Plain diffusion model**
- Interstellar spectra

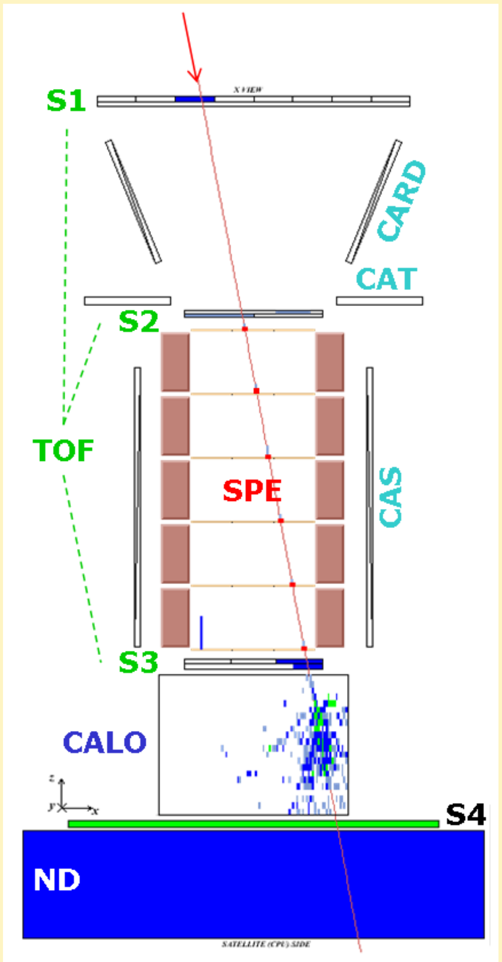
Positron absolute Flux

- Positron absolute flux has been extracted by using e⁻ flux and e⁻/(e⁺+e⁻) ratio
- Reasonable assumption that the efficiencies are the same for e⁻ and e⁺!



PAMELA data → Jul 2006 ÷ Jan 2010

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

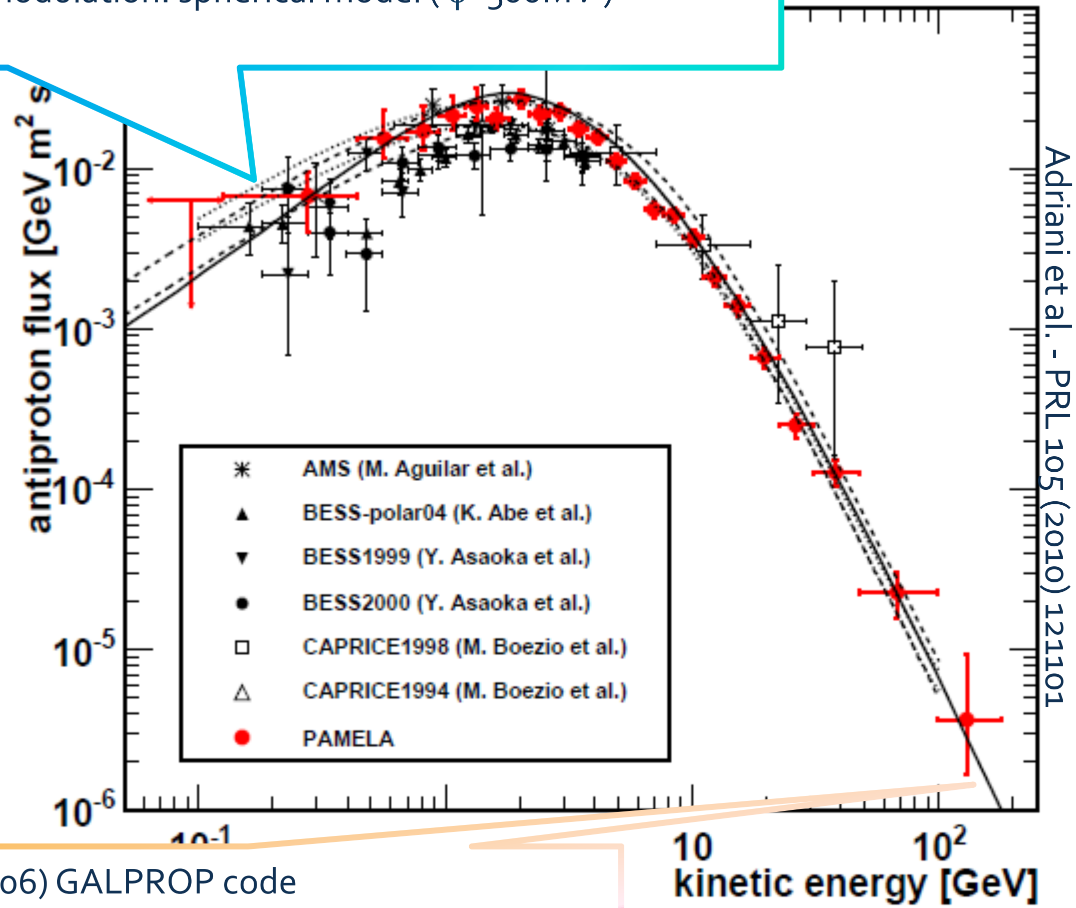
Antiproton flux (60 MeV – 180 GeV)

Largest energy range covered up to now

Overall agreement with pure secondary calculation

Experimental uncertainty (stat⊕sys) smaller than spread in theoretical curves
→ constraints on propagation paramete

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



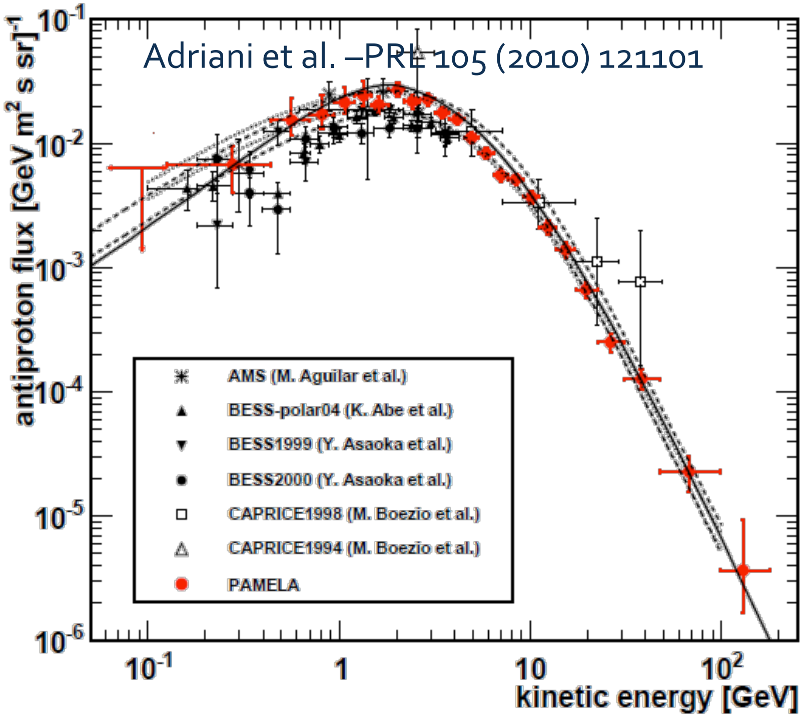
Adriani et al. - PRL 105 (2010) 121101

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

A challenging puzzle for CR physicists

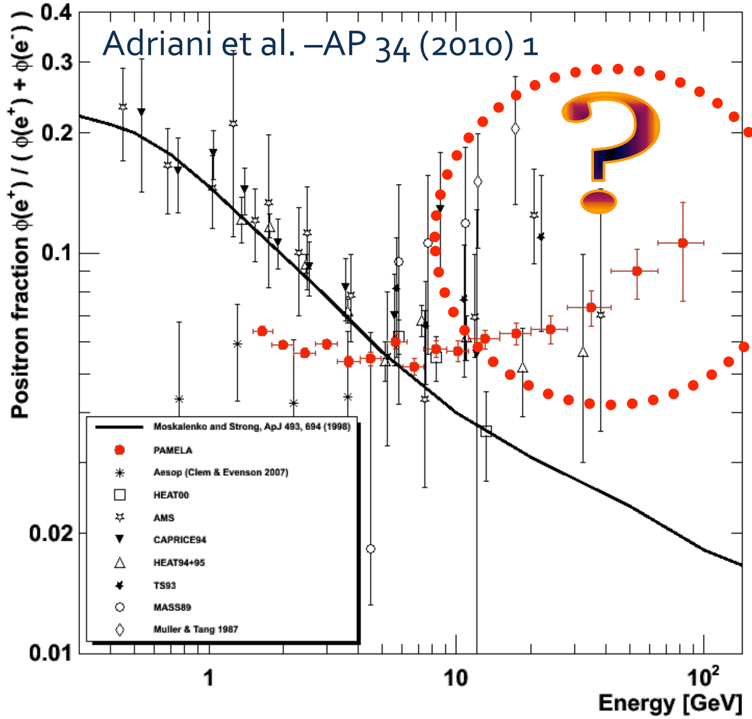
Antiprotons

→ Consistent with pure secondary production up to 180 GeV



Positrons

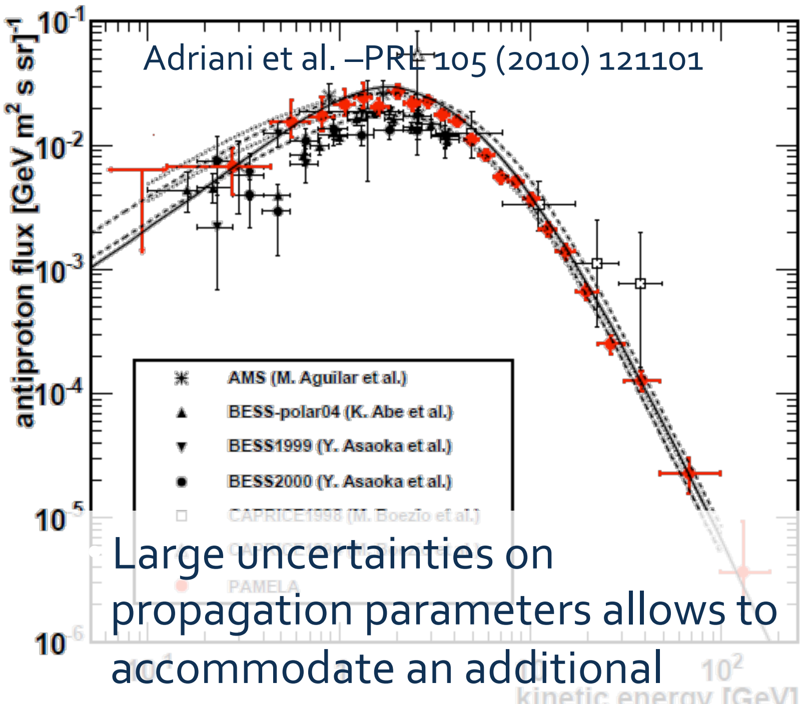
→ Evidence for an excess



A challenging puzzle for CR physicists…

Antiprotons

→ Consistent with pure secondary production up to 180 GeV

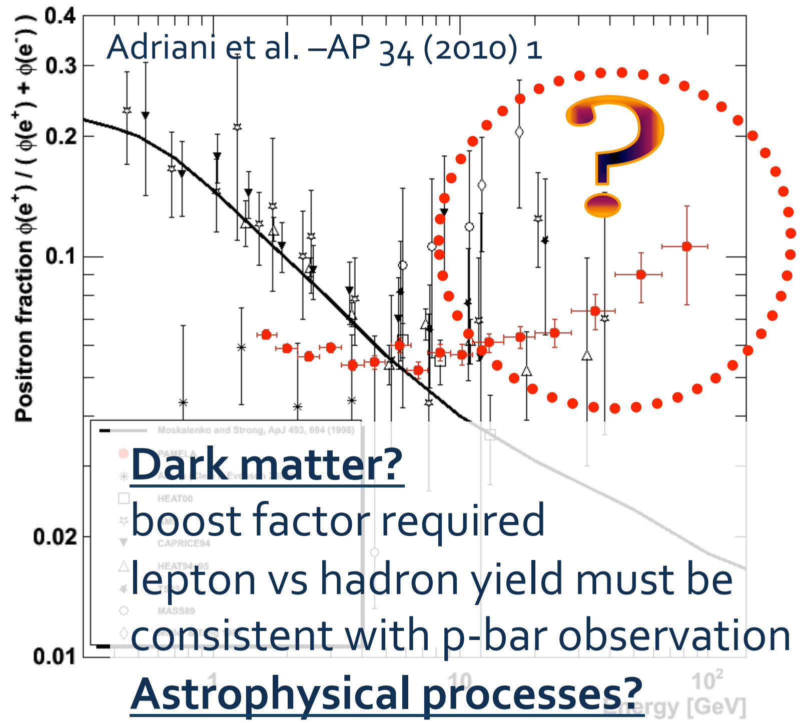


Large uncertainties on propagation parameters allows to accommodate an additional component?

A p-bar rise above 200GeV is not excluded!

Positrons

→ Evidence for an excess



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

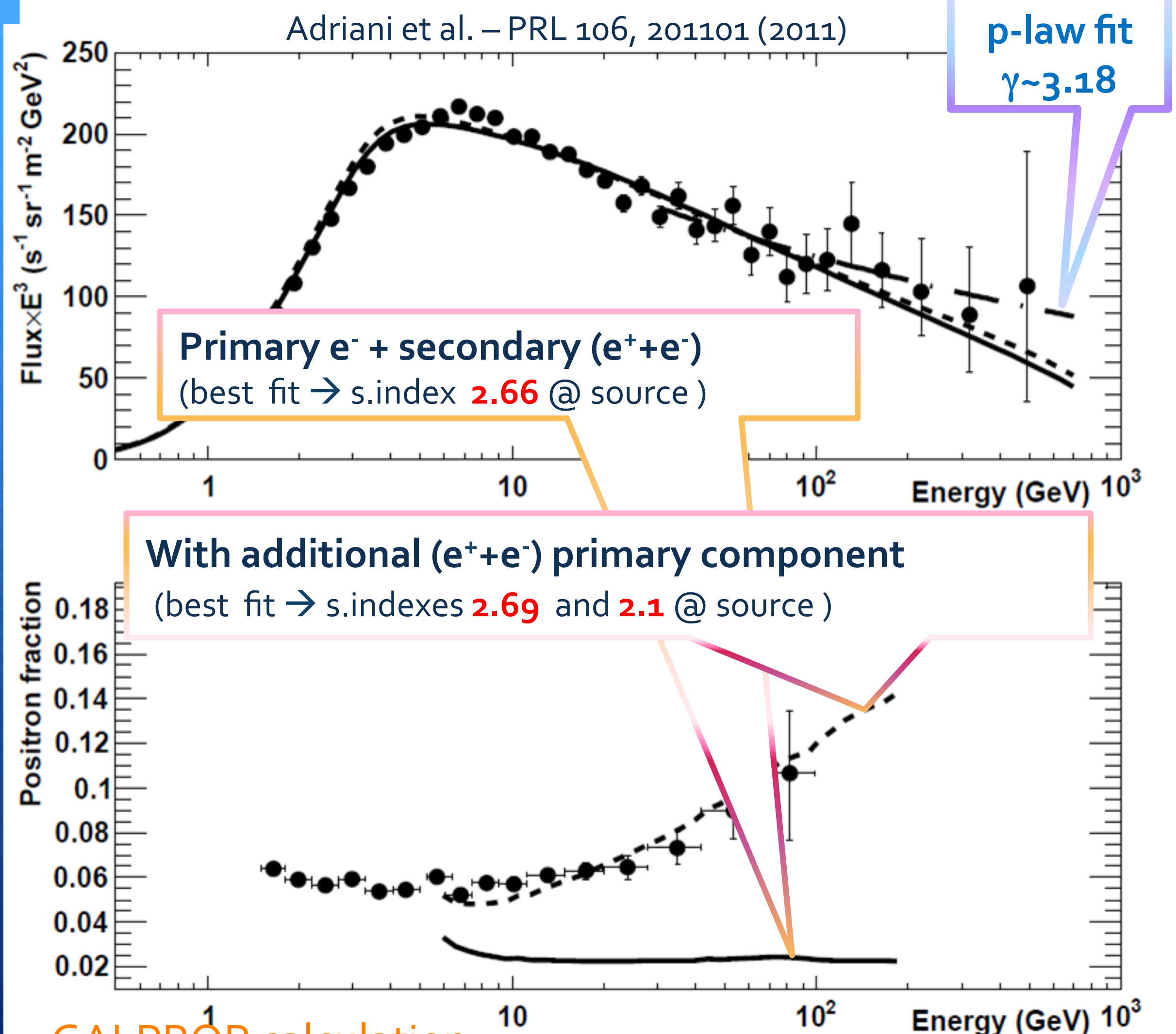
Positrons vs electrons

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 reproduce positron data



GALPROP calculation

diffusion + reacceleration (Ptuskin et al. 2006)

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

Summary and conclusions

PAMELA has been in orbit and studying cosmic rays for more than 5 years.

$>10^9$ 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.

Summary and conclusion

PAMELA has been in orbit and studying cosmi…

>10[9] triggers registered and >20 TB of d…

- **H and He absolute fluxes** … …recise measurement so far. Com… …spectral hardening at ~200GV!) → Chall… …celeration in SNRs!
- **Electron a…** … …GeV. No evident deviations from stan… … with an additional electron compo…
- **High e…** … **(>10 GeV)** → Increases significantly (and unexpected…) … Primary source?
- **Antiproton e… spectrum** → Measured up to ~200 GeV. No significant deviations from secondary production expectations.

→PAMELA is really providing significant experimental results, which help and will help in understanding CR origin and propagation, and Dark Matter puzzle

→More new and exciting results will certainly come in the next few years!

→e^+, Nuclei, Isotopes, Anti-He, LongTerm effects….

Backup slides

Antiproton-to-proton ratio

Overall agreement with pure secondary production

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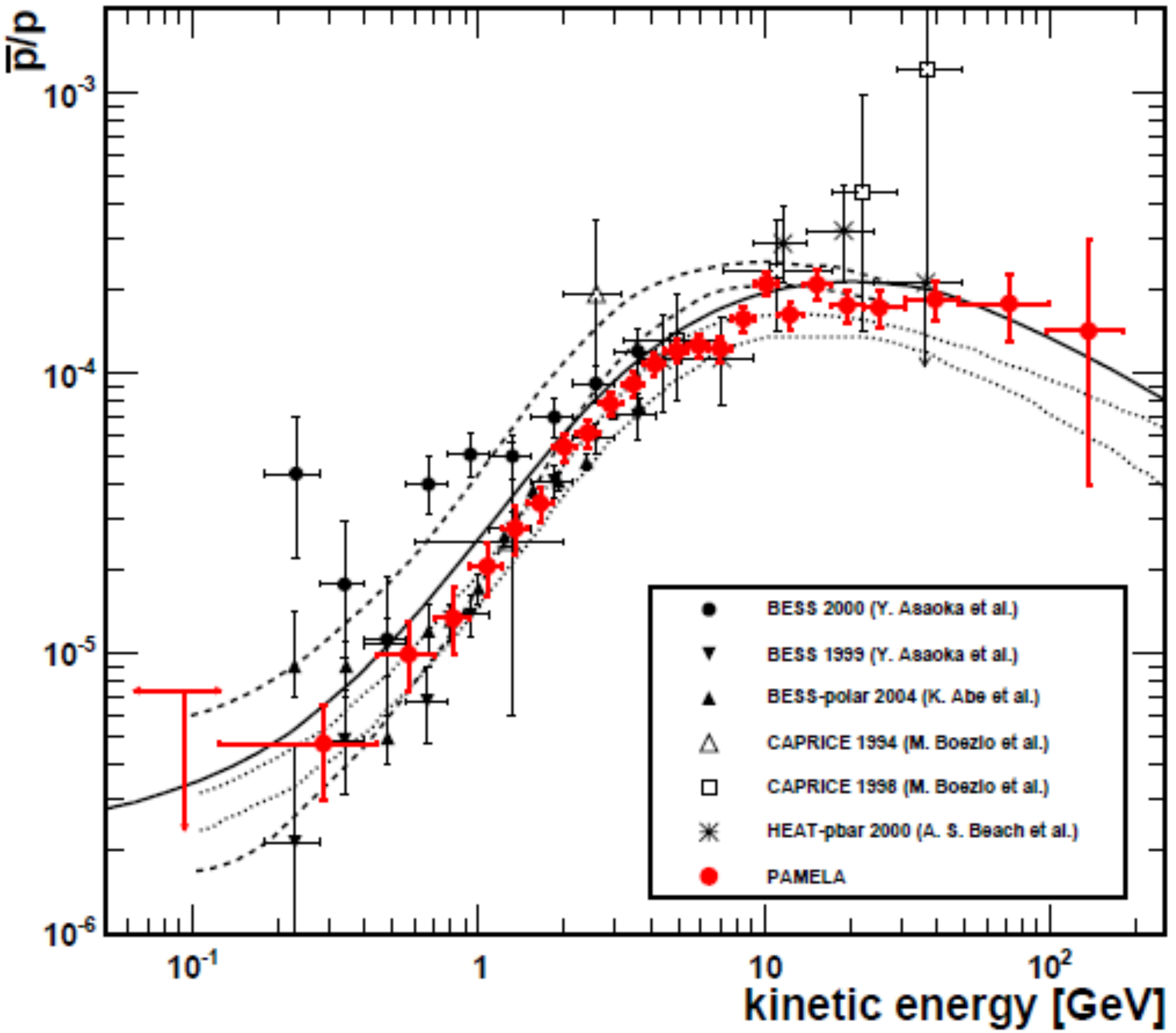


Positrons vs antiprotons

Large uncertainties on propagation parameters allows to accommodate an additional component

A p-bar rise above 200GeV is not excluded

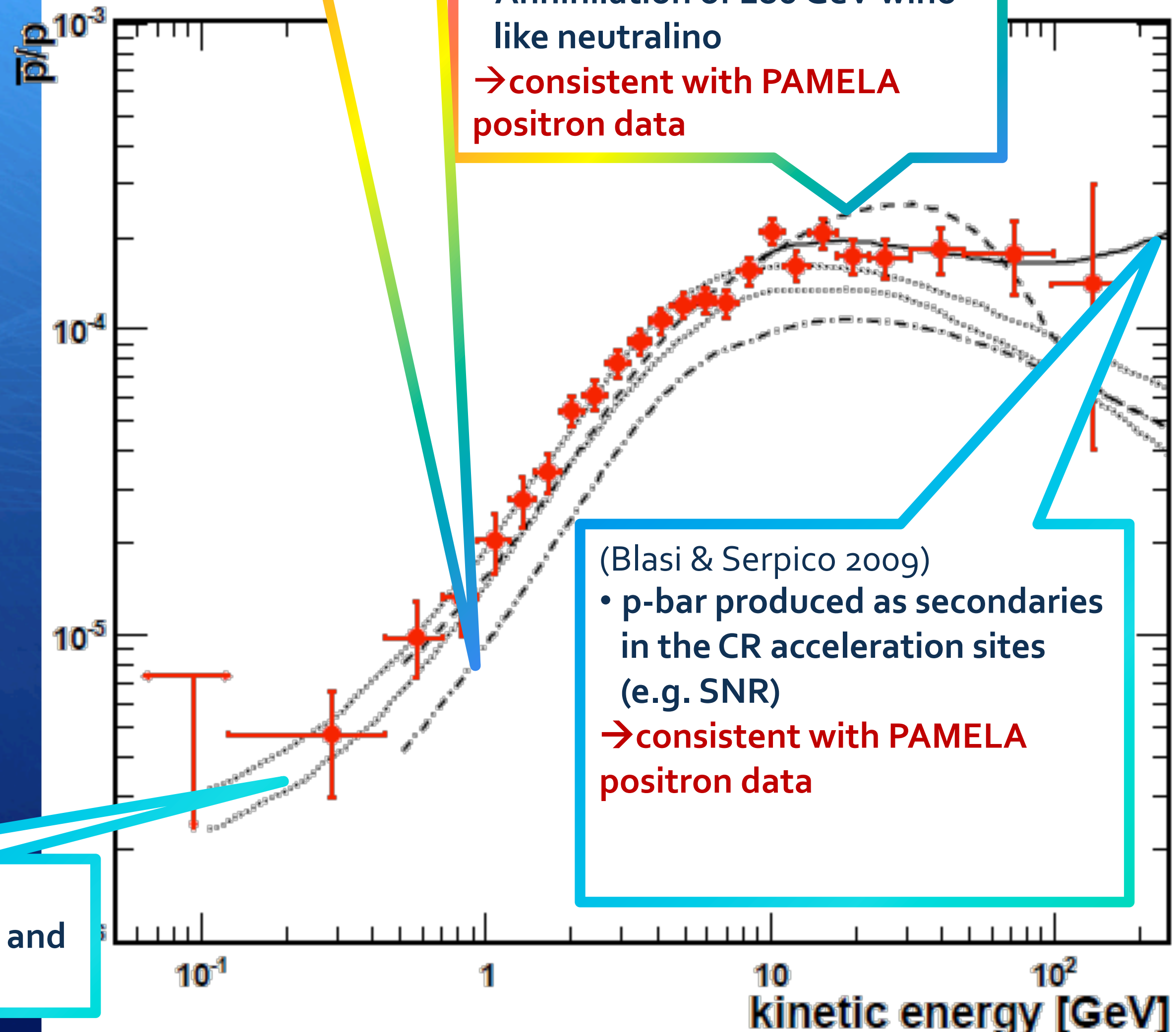
(Strong & Moskalenko 1998)
GALPROP code

+

(Kane et al. 2009)

- **Annihilation of 180 GeV wino-like neutralino**

→consistent with PAMELA positron data



(Blasi & Serpico 2009)

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

→consistent with PAMELA positron data

(Donato et al. 2009)

- **Diffusion model with convection and reacceleration**

Adriani et al. - PRL 105 (2010) 121101

Positron-excess interpretations

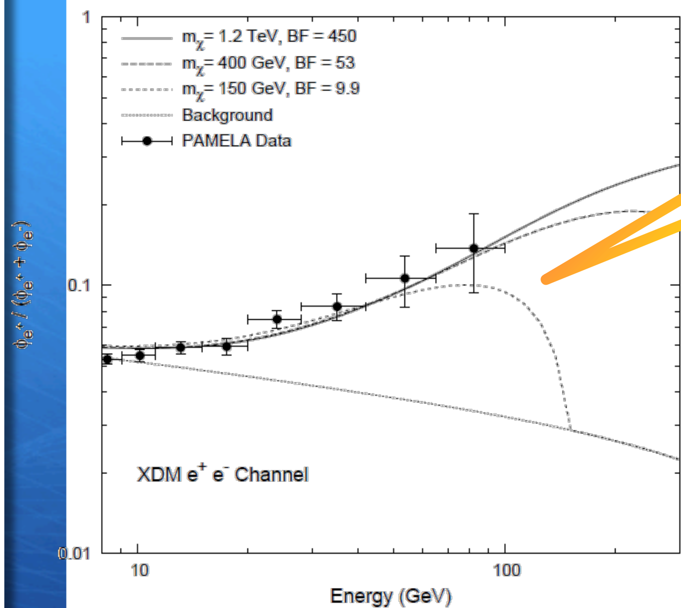
Positron-excess interpretations

Dark matter

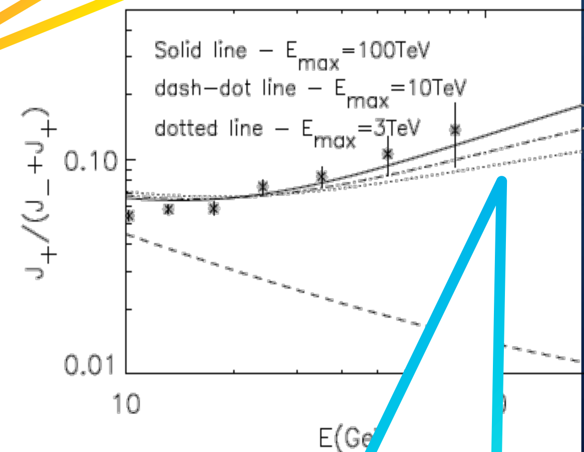
- boost factor required
- lepton vs hadron yield must be consistent with p-bar observation

Astrophysical processes

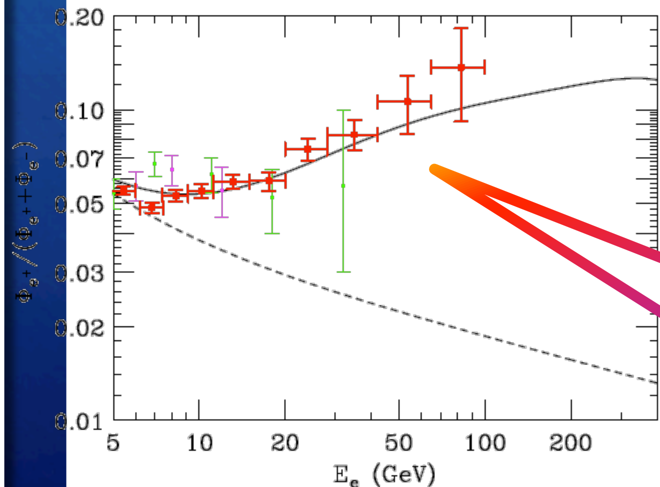
- known processes
- large uncertainties on environmental parameters



(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**.

Spectrometer systematic uncertainty

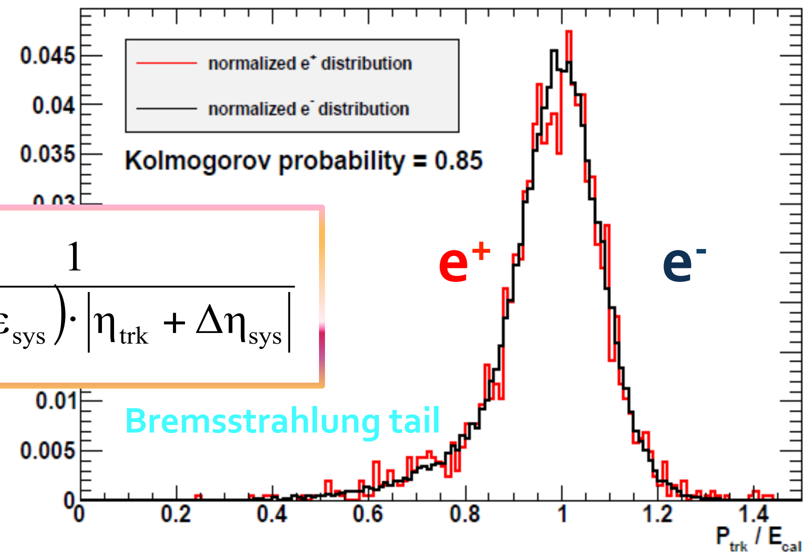
Evaluated from in-flight electron/ positron data by comparing the spectrometer momentum with the calorimeter energy

- Upper limit set by positron statistics:

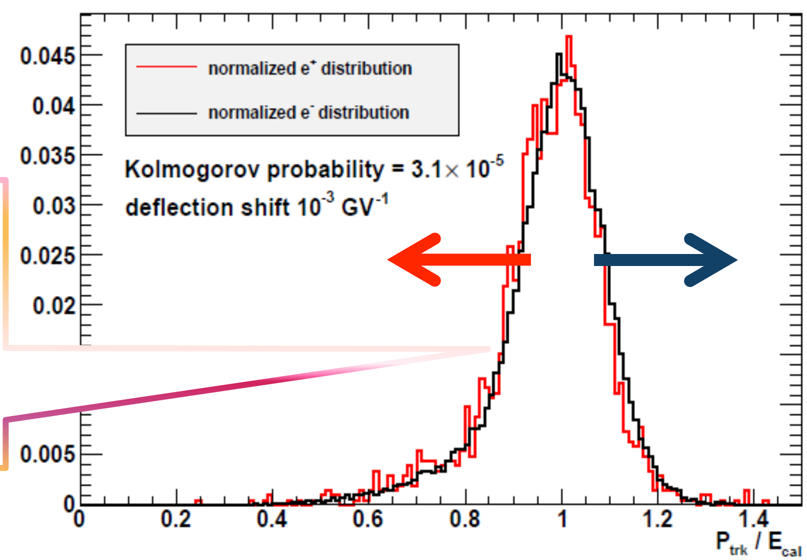
$\Delta\eta_{sys}$ ~$1\cdot10^{-4}$ GV^{-1}

(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

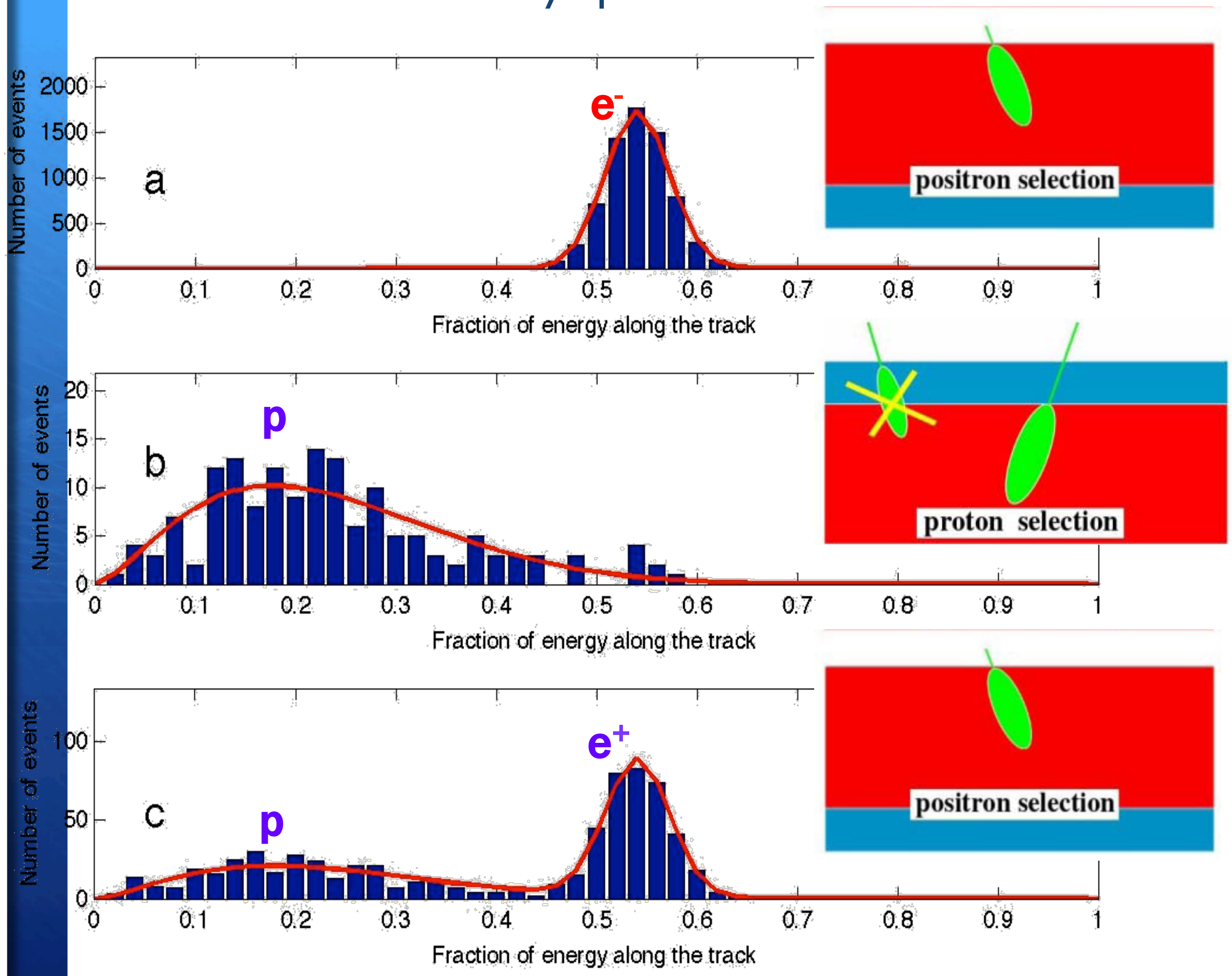
Method:

Estimation of PDFs for electron (a) and proton (b) experimental distributions

Fit of positron experimental distribution (c) with mixed PDF

Statistical errors determination with bootstrap procedure

6.1÷7.4 GV

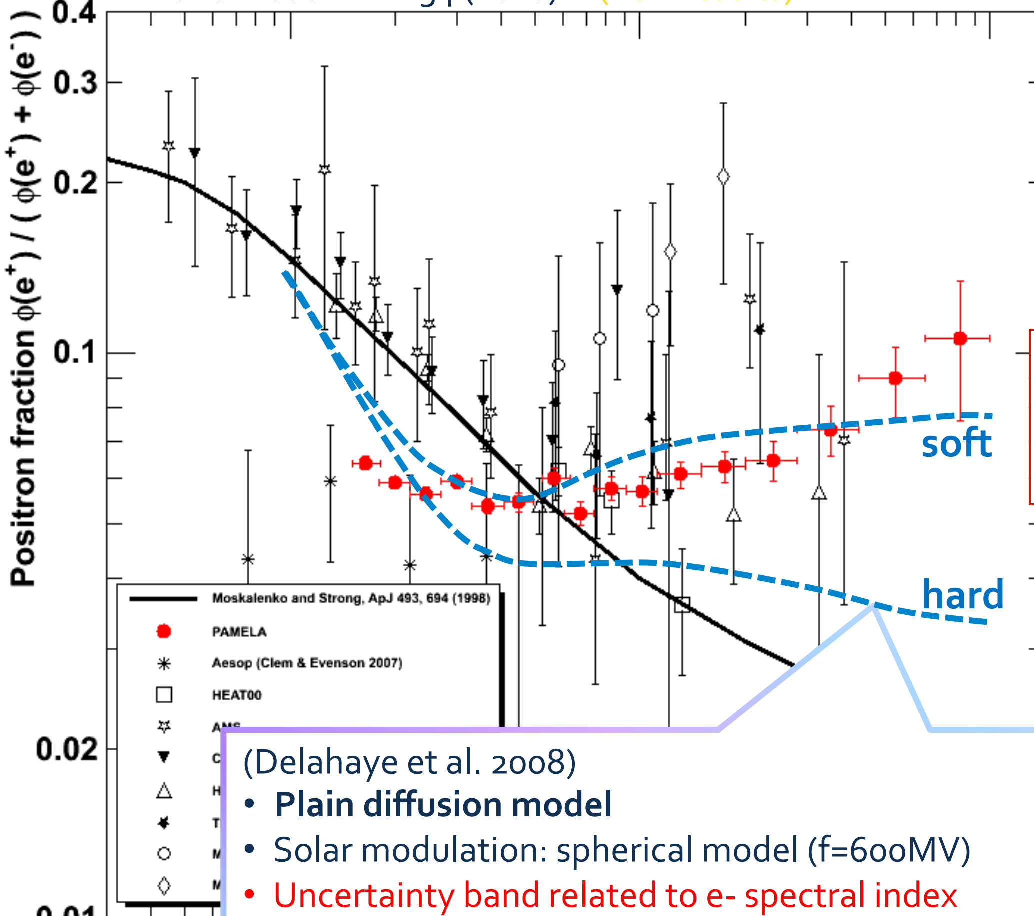


Fraction of energy along the track, after constraints on **energy-momentum match** and **shower starting point**

How significant is the excess?

Large uncertainties on secondary positron predictions

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



NB!
Ruled out by PAMELA e- measurement

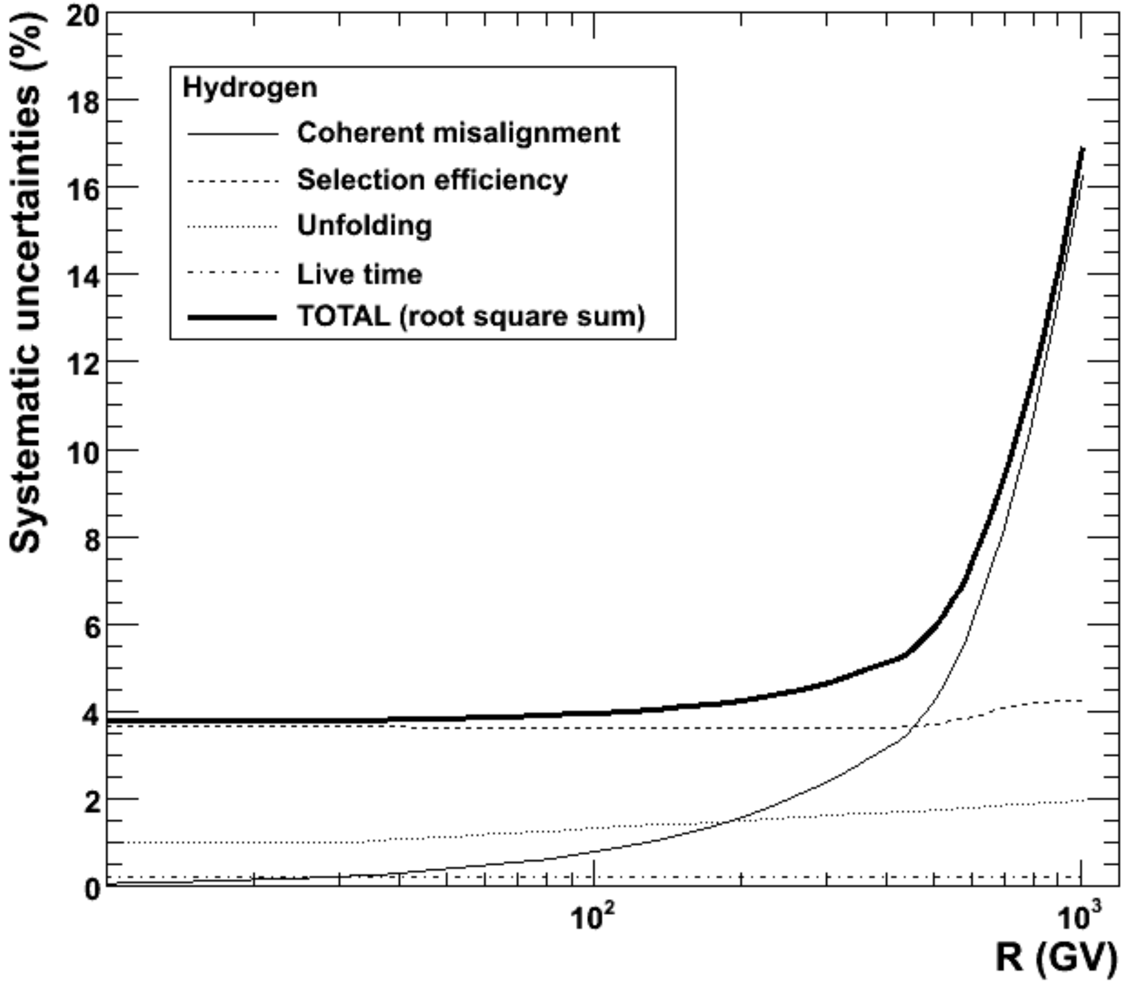
(Delahaye et al. 2008)

- **Plain diffusion model**
- Solar modulation: spherical model (f=600MV)
- Uncertainty band related to e- spectral index (γ_e = **3.44±0.1** (3σ) ⇒ MIN÷MAX)
- Additional uncertainty due to propagation parameters should be considered (factor ~6 @1GeV ~4 @high-energy)

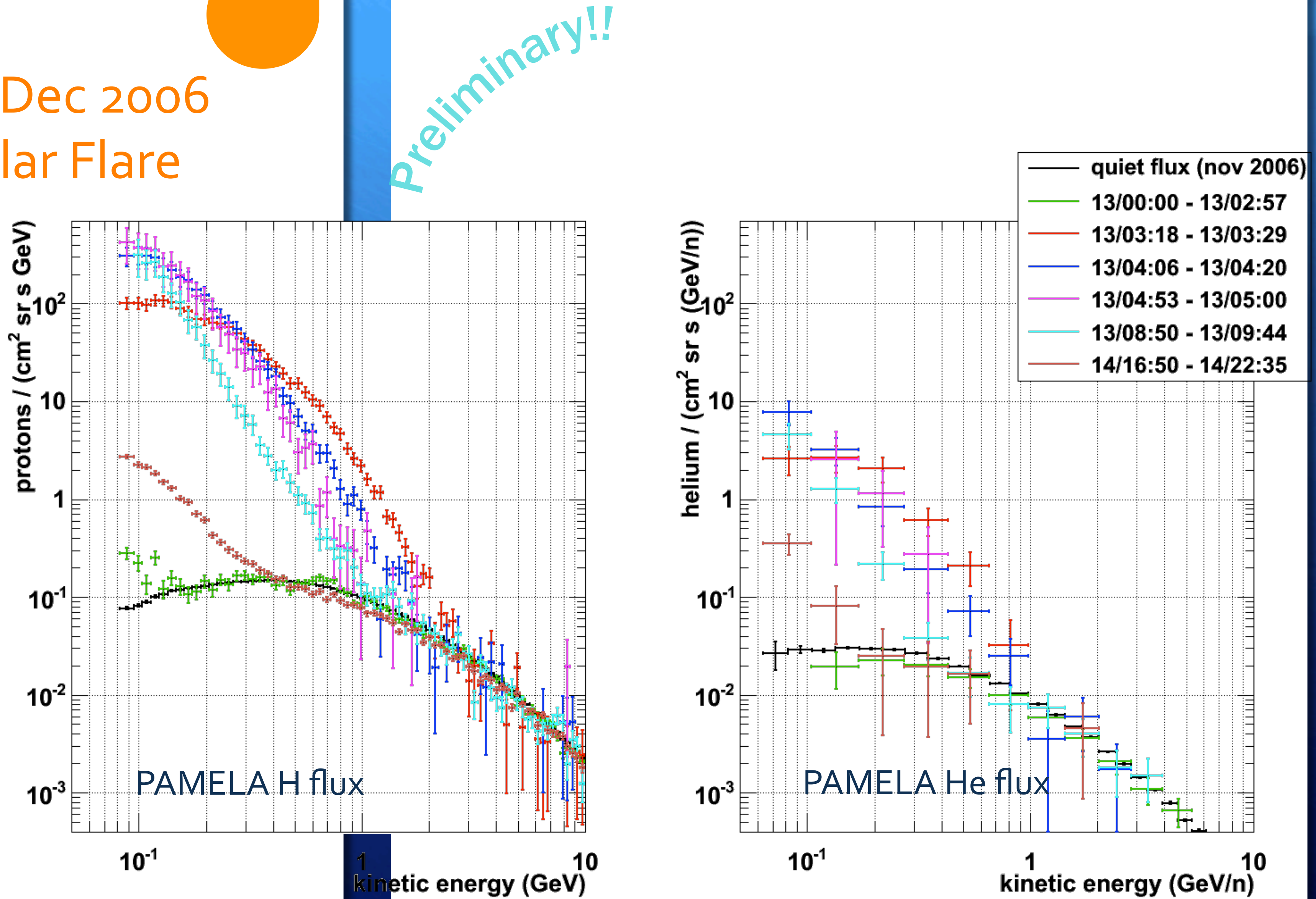
P overall systematic uncertainties

At low R selection-efficiency uncertainties dominate

Above 500GV tracking-system (coherent) misalignment dominates

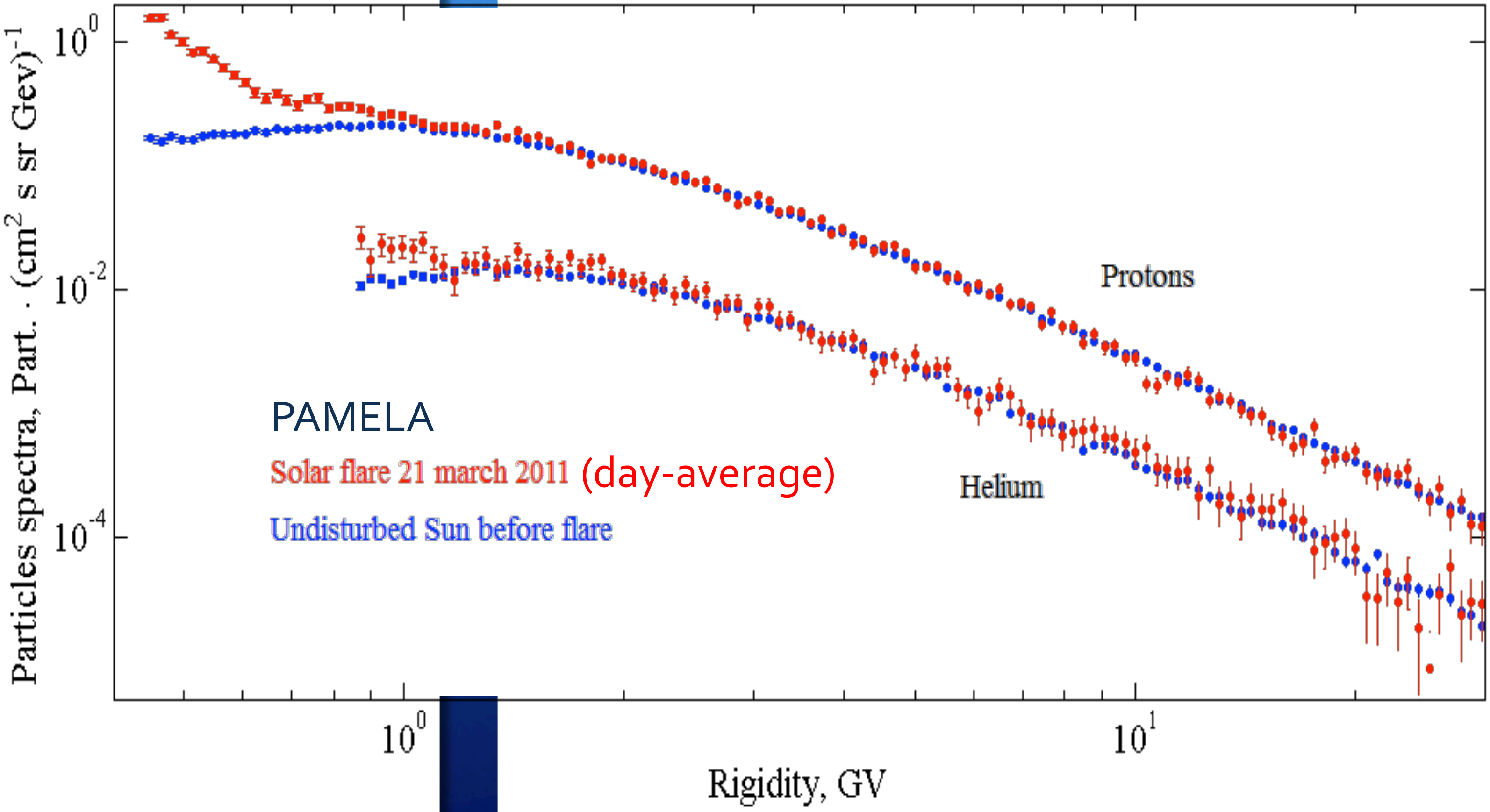


13 Dec 2006 Solar Flare



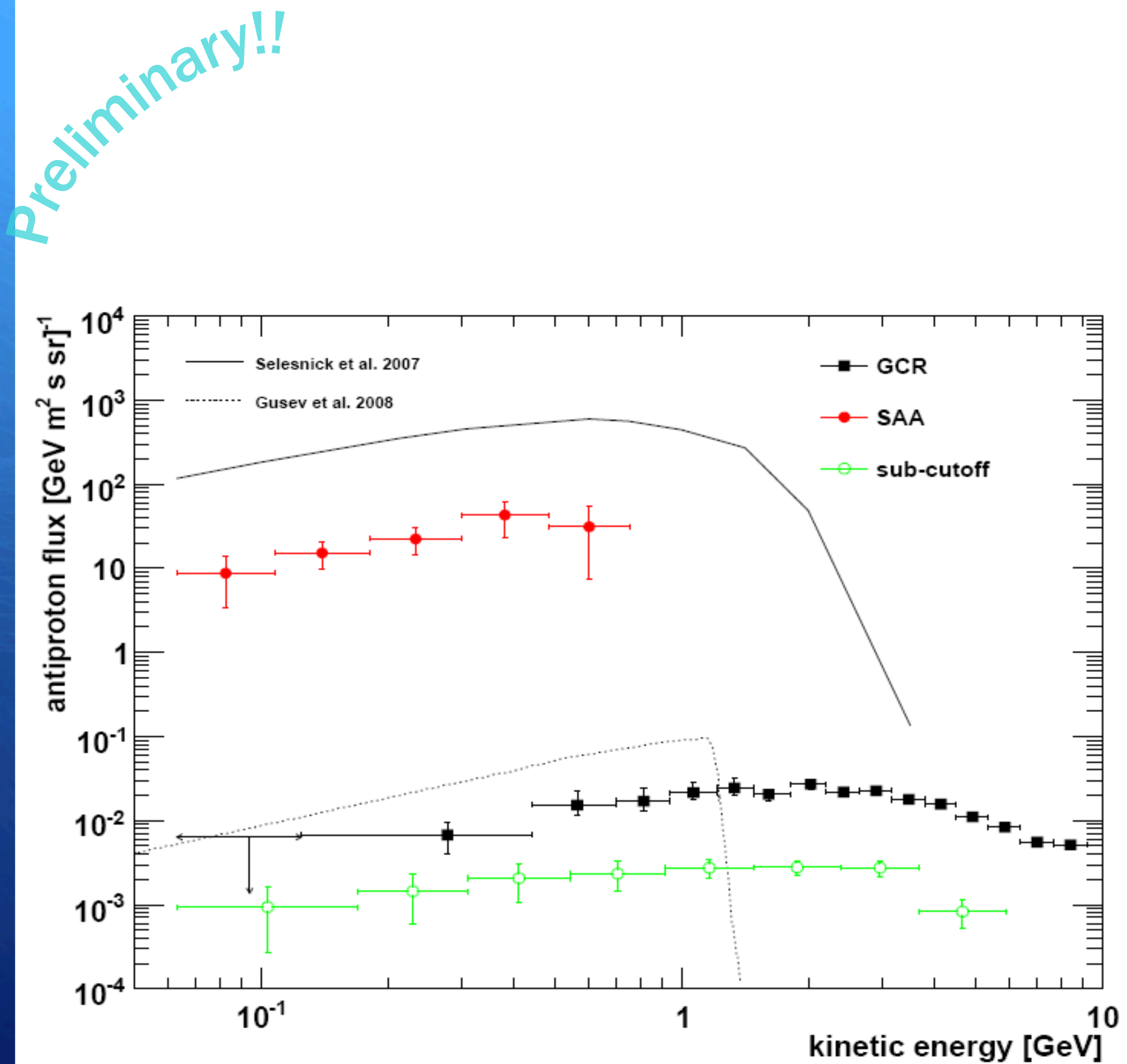
21 Mar 2011 Solar Flare

Preliminary!!

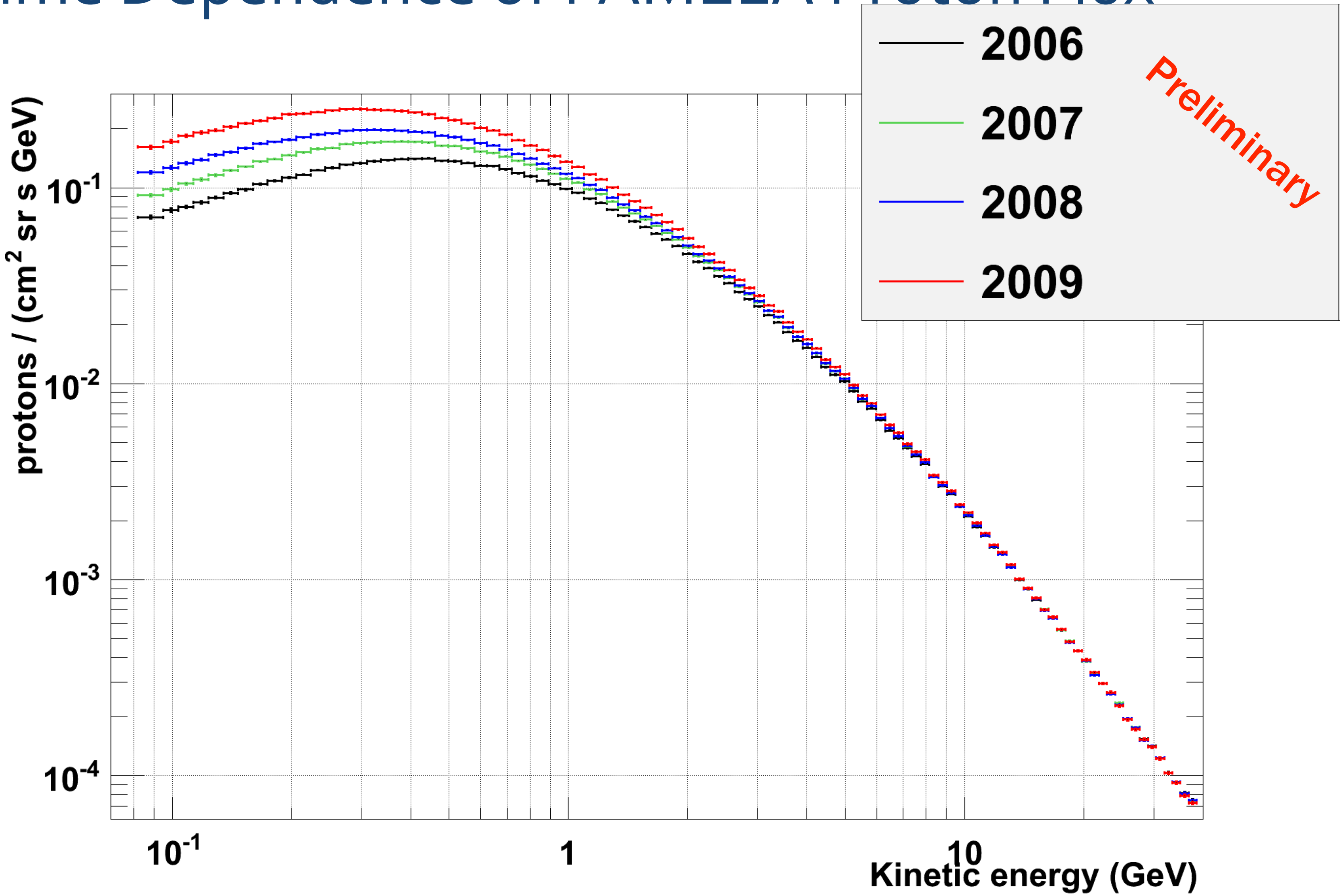


Trapped antiprotons

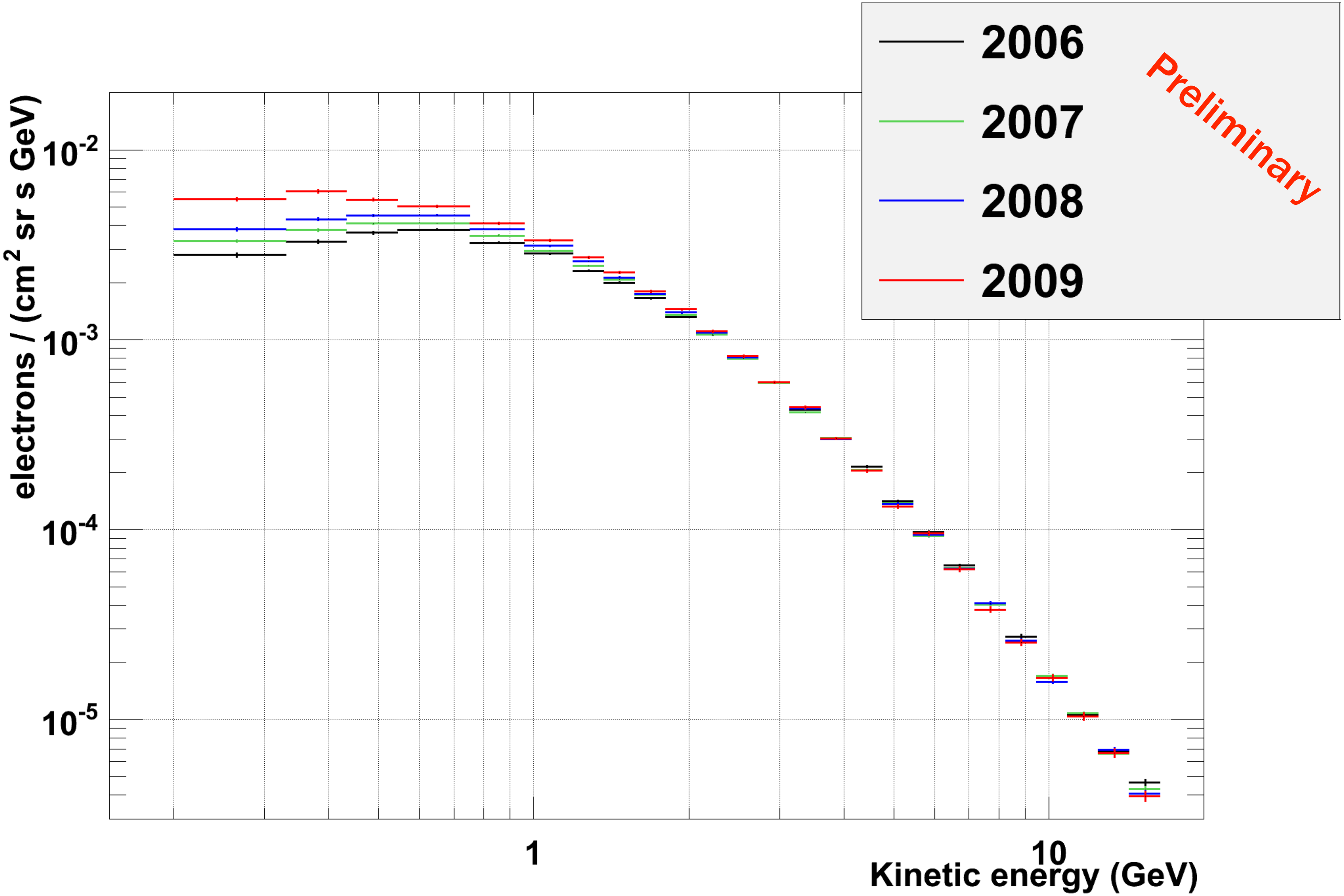
First measurement of p-bar trapped in the inner belt.

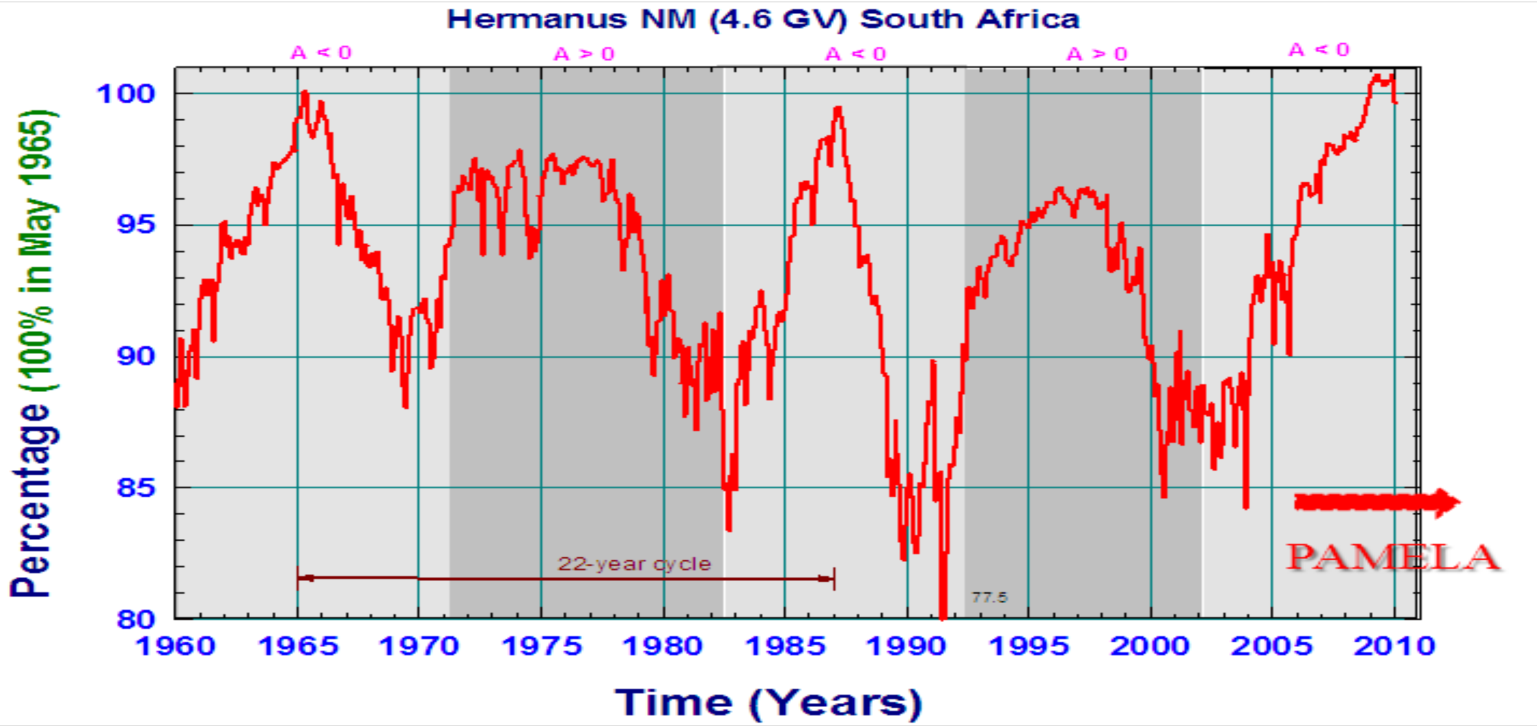


Time Dependence of PAMELA Proton Flux



Time Dependence of PAMELA Electron (e^-) Flux





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
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Time (Years)
22-year cycle
77.5
PAMELA

Pamela's scientific objectives

- ✓ Study antiparticles in cosmic rays
- ✓ Search for antimatter
- ✓ Search for dark matter (e^+ and pbar spectra)
- ✓ Study cosmic-ray propagation
- ✓ Study solar physics and solar modulation
- ✓ Study the electron spectrum (local sources?)
  - Antiprotons 80 MeV - 190 GeV
  - Positrons 50 MeV – 300 GeV
  - Electrons up to 500 GeV
  - Protons up to 700 GeV
  - Electrons+positrons up to 2 TeV (from calorimeter)
  - Light Nuclei up to 200 GeV/n He/Be/C
  - AntiNuclei search