PAMELA – Five Years of Cosmic Ray Observation from Space

Emiliano Mocchiutti
INFN Trieste, Italy

On behalf of the PAMELA collaboration

Ajdovščina, University of Nova Gorica

June 8, 2011

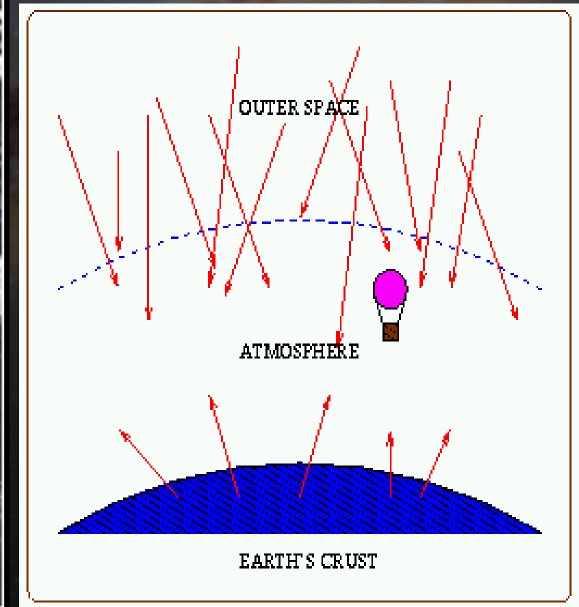
Presentation outline

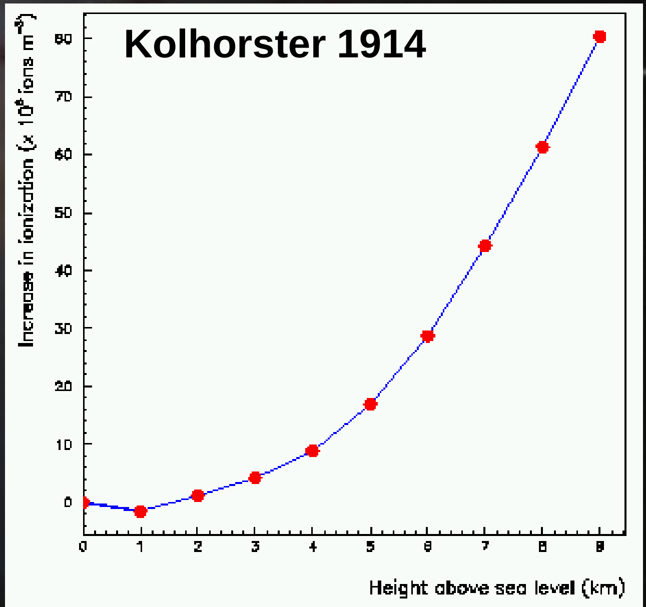
- Introduction
- PAMELA scientific goals
- PAMELA apparatus
- Anti-particles and particles with PAMELA
- Interpretation of the results
- Other PAMELA measurements
- Summary

Cosmic rays – introduction

The discovery of cosmic rays

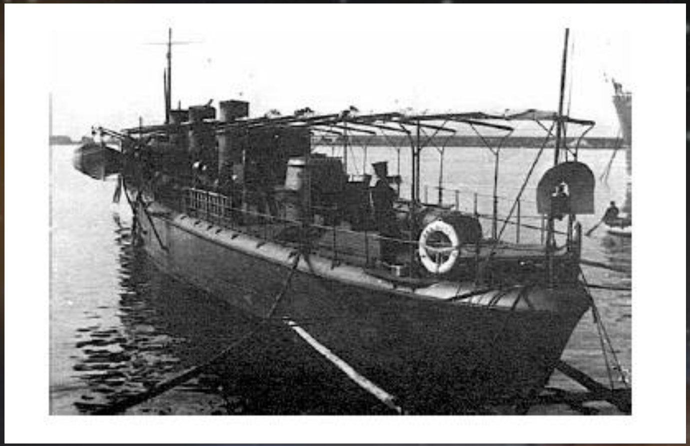
- Victor Hess ascended to 5000 m in a balloon in 1912
- ... and noticed that his electroscope discharged more rapidly as altitude increased
- Not expected, as background radiation was thought to be terrestrial
- NPP 1936 (with Carl ‘e+’ Anderson)





The discovery of cosmic rays

Domenico Pacini
1878 – 1934



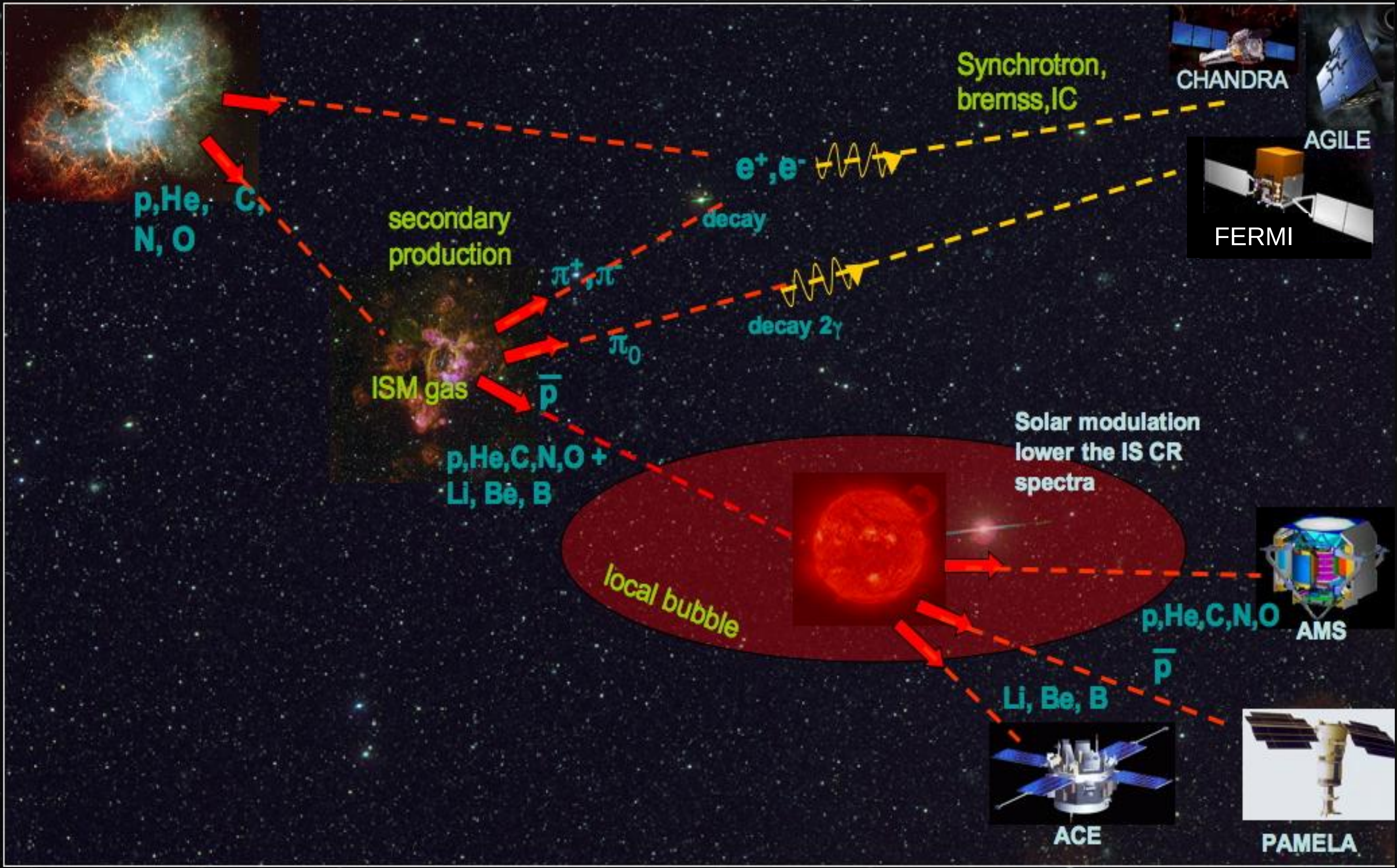
- **Domenico Pacini in 1911 placed his electroscopes underwater...**
- **... and noticed that his electroscopes discharged more slowly as sea depth increased**

- **He concluded that "*a sizable cause of ionization exists in the atmosphere, originating from penetrating radiation, independent of the direct action of radioactive substances in the soil*" [Il Nuovo Cimento VI/III, 93 (1912) - arXiv: 1002.1810v1]**

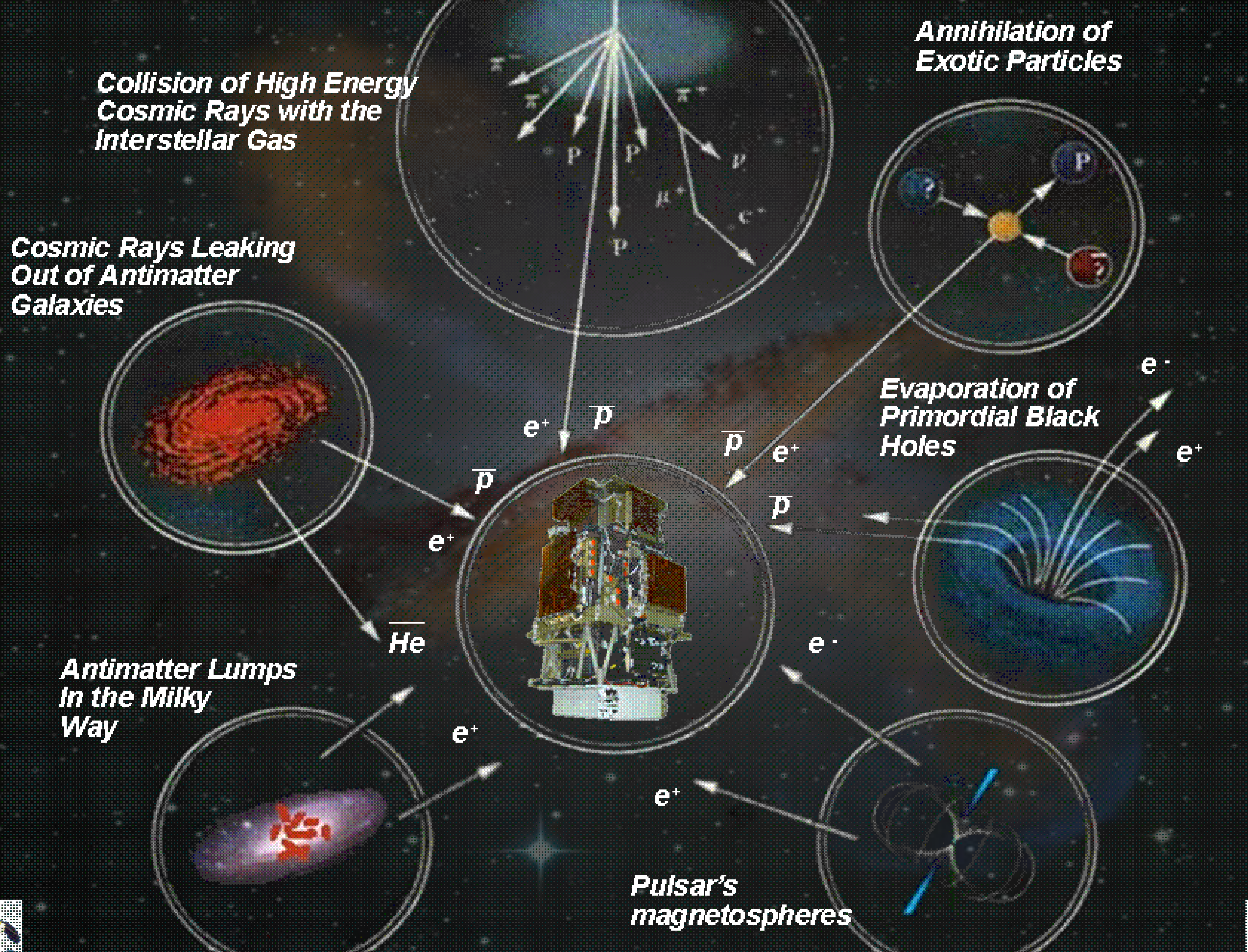
My short paper "Die Frage der durchdring. Strahlung ausserterrestrischen Ursprunges" is a report of a public conference, and therefore has no claim of completeness. Since it reported the first balloon measurements, I did not provide an in-depth explanation of your sea measurements, which are well known to me. Therefore please excuse me for my unkind omission, that was truly far from my aim ... - V. Hess [arXiv: 1002.2888v2]

P. Carlson and A. De Angelis Eur. Phys. J. H 35, 309-329 (2010)

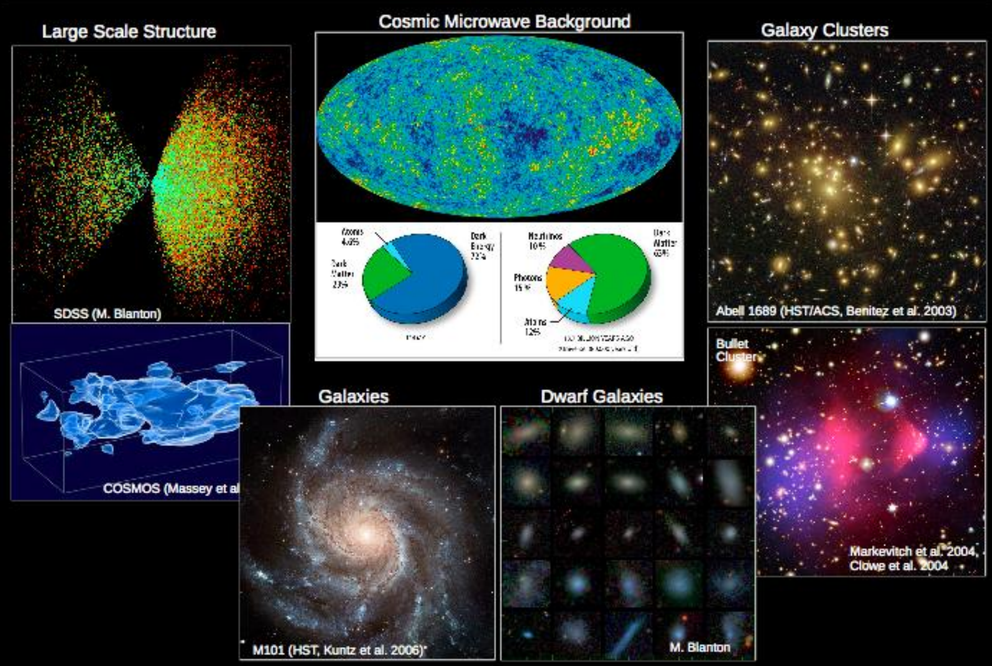
Cosmic rays production



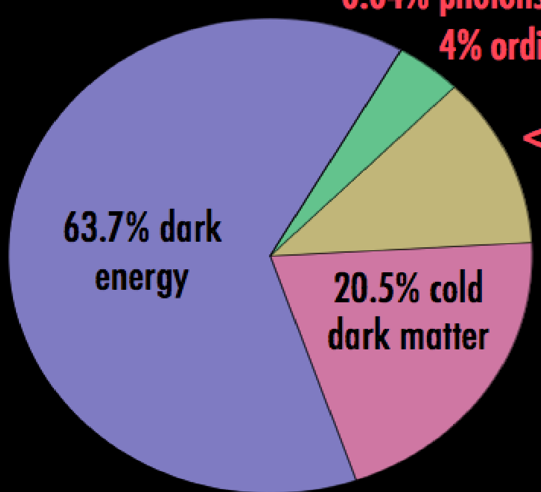
ANTI-PARTICLES



There's evidence for dark matter on many scales...



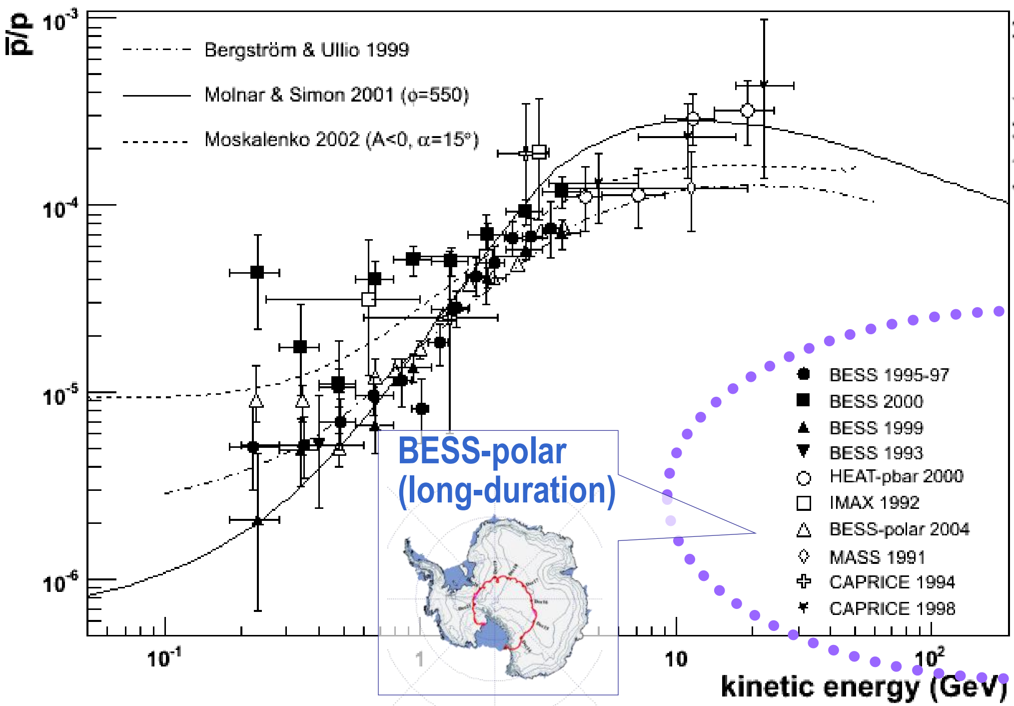
The current content of the Universe



Searches for WIMP Dark Matter

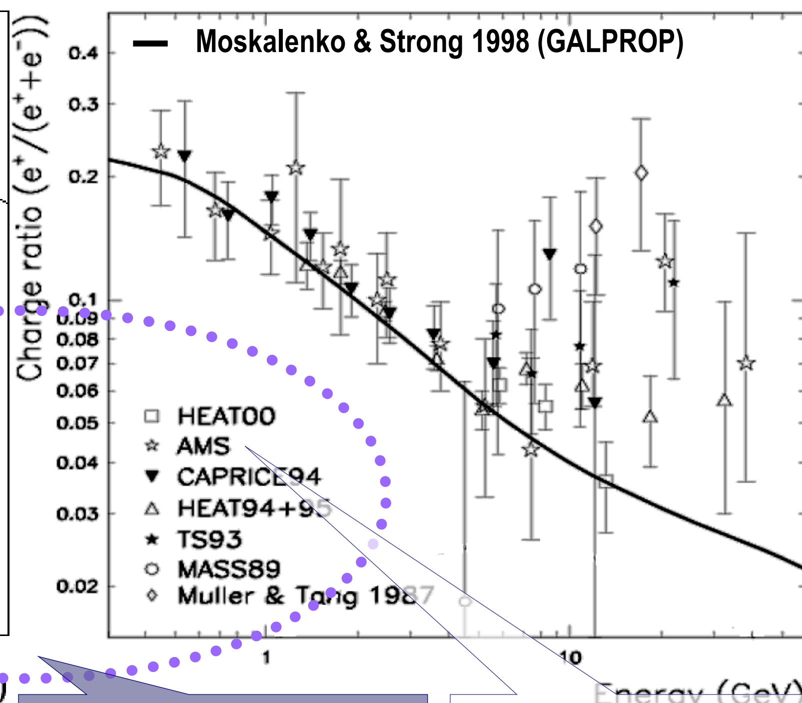
CR Antiparticles: available data before PAMELA

Antiprotons



BESS-polar (long-duration)

Positrons



- low exposure (~days)
  ⇒ large statistical errors
- atmospheric secondaries (~5g/cm²)
  ⇒ additional systematic uncertainty @low-energy

“Standard” balloon-borne experiments

AMS-01: space shuttle, 1998

PAMELA Collaboration

Italy

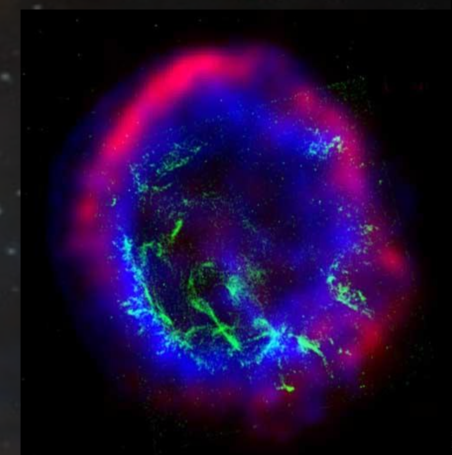
INFN | Bari | Florence | Frascati | Naples | Rome | Trieste | CNR, Florence

Germany: Siegen

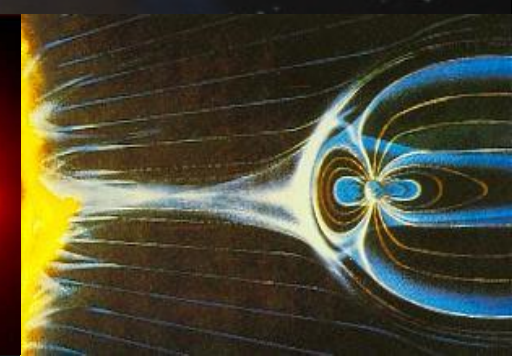
Sweden: KTH, Stockholm

Russia: Moscow / St. Petersburg

Scientific goals

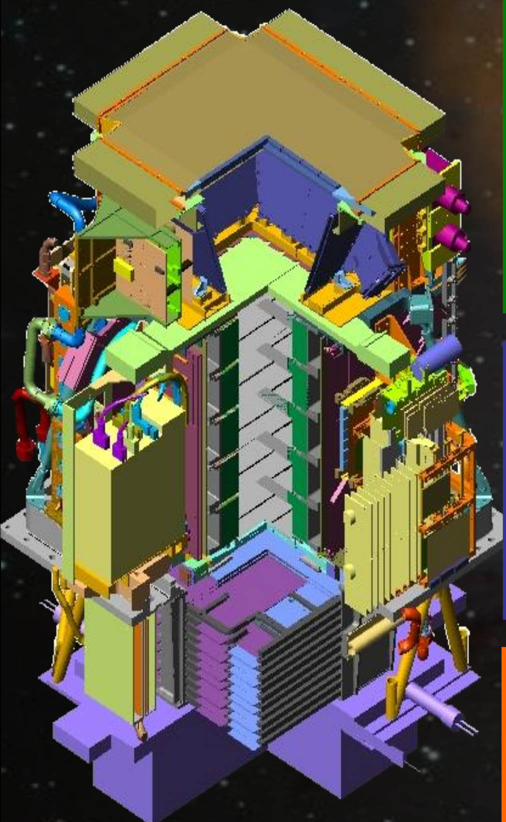


- Search for dark matter annihilation
- Search for antihelium (primordial antimatter)
- Study of cosmic-ray propagation (light nuclei and isotopes)
- Study of electron spectrum (local sources?)
- Study solar physics and solar modulation
- Study terrestrial magnetosphere



PAMELA apparatus

PAMELA detectors



Time-Of-Flight

plastic scintillators + PMT:

- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX

Electromagnetic calorimeter

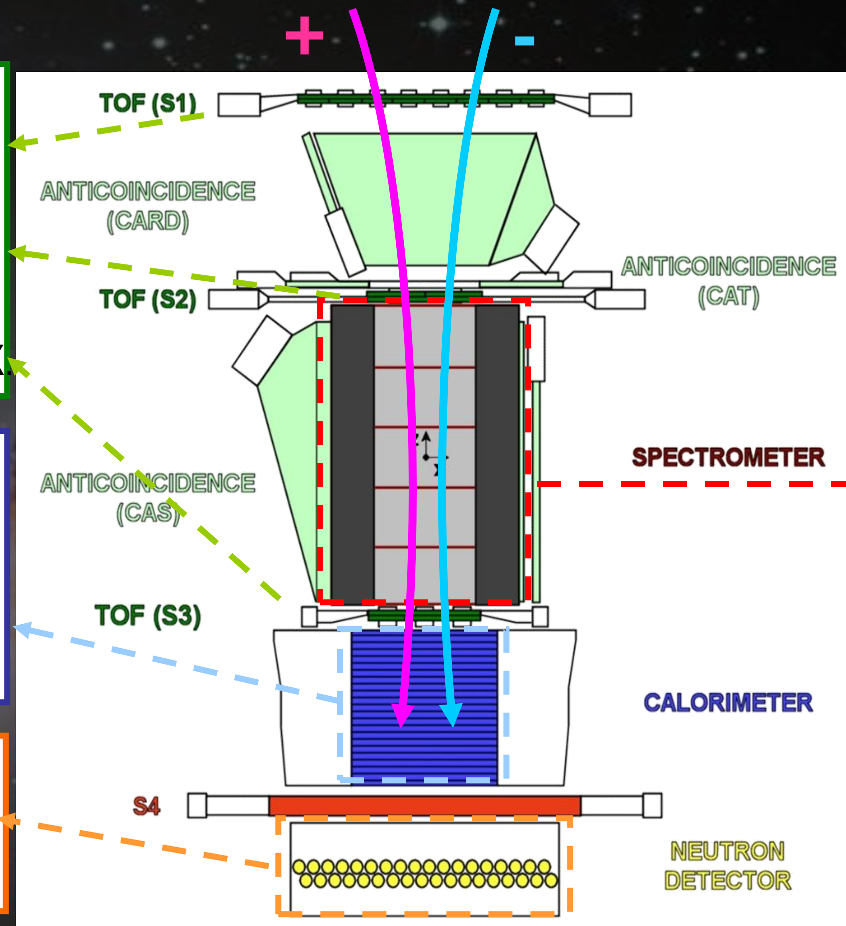
W/Si sampling (16.3 X_0, 0.6 λ_I)

- Discrimination e^+ / p, p-bar / e^- (shower topology)
- Direct E measurement for e^-

Neutron detector

^{3}He tubes + polyethylene moderator:

- High-energy e/h discrimination



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

Spectrometer

microstrip silicon tracking system + permanent magnet

It provides:

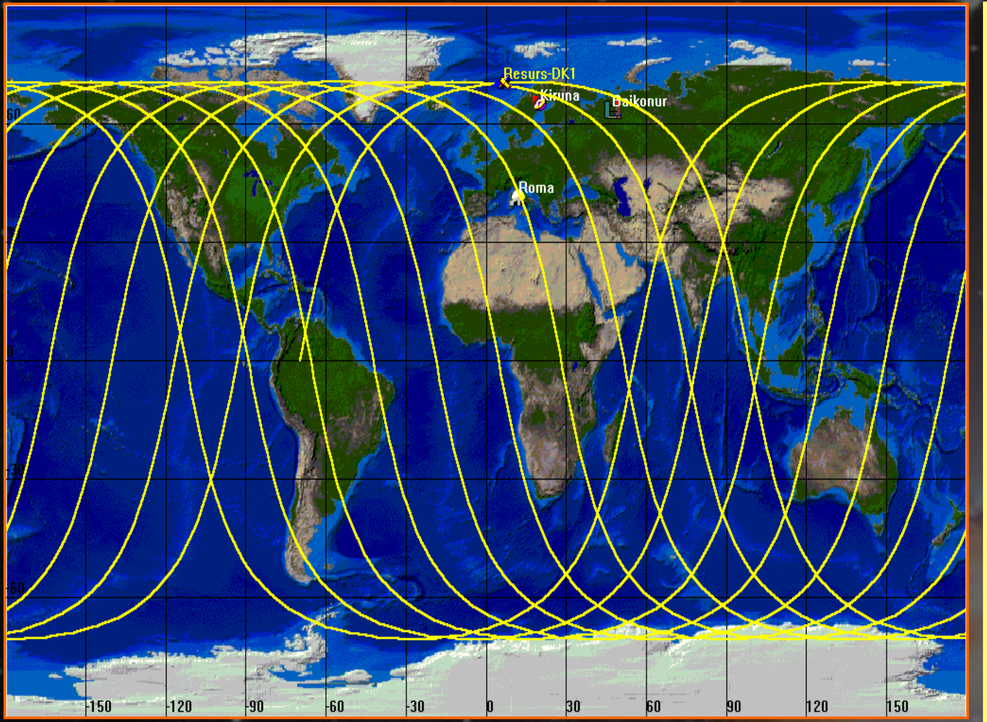
- Magnetic rigidity → R = pc/Ze
- Charge sign
- Charge value from dE/dx

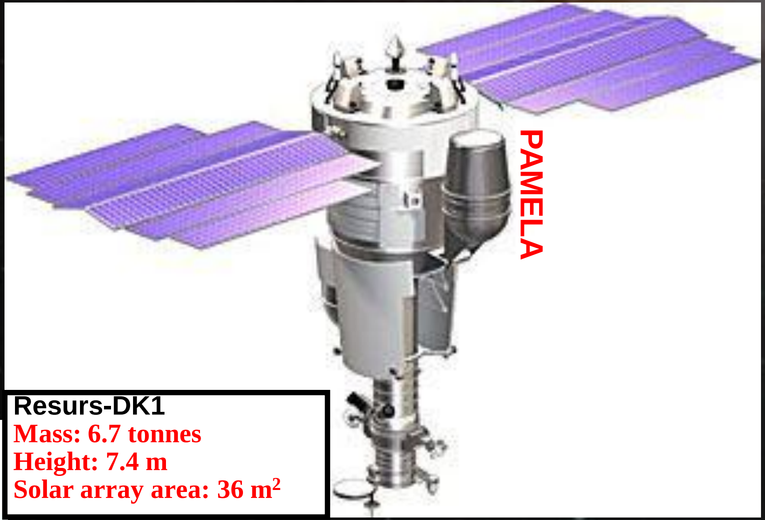
Design Performance

	energy range
• 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 (calorimeter)
• Light Nuclei (He/Be/C)	up to 200 GeV/n
• Anti-Nuclei search	sensitivity of 3×10^{-8} in $\overline{He}/He$

→ Simultaneous measurement of many cosmic-ray species
→ New energy range
→ Unprecedented statistics

Resurs-DK1 satellite and orbit





Resurs-DK1
Mass: 6.7 tonnes
Height: 7.4 m
Solar array area: 36 m^2

- Resurs-DK1: multi-spectral imaging of earth's surface
- PAMELA mounted inside a pressurized container
- Launch 15/06/2006 - lifetime >3 years (assisted), extended till end 2011
- Data transmitted to NTsOMZ, Moscow via high-speed radio downlink. ~16 GB per day
- Quasi-polar and elliptical orbit (70.0°, 350 km - 600 km) – from 2010 circular orbit (70.0°, 600 km)
- Traverses the South Atlantic Anomaly
- Crosses the outer (electron) Van Allen belt at south pole

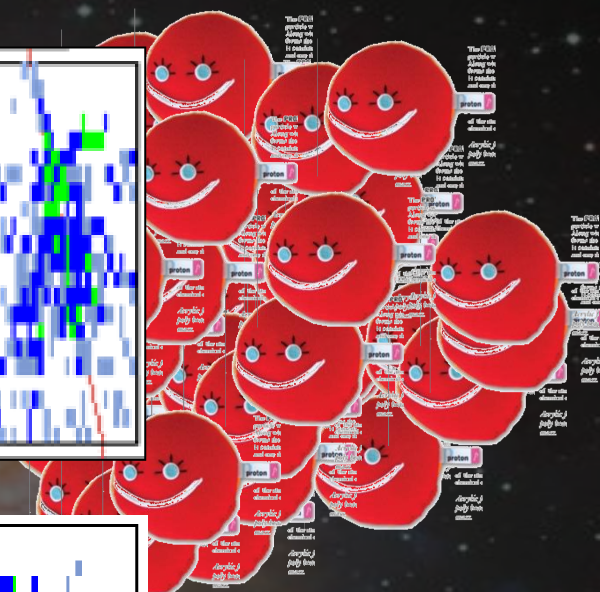
PAMELA antiprotons

Antiproton identification

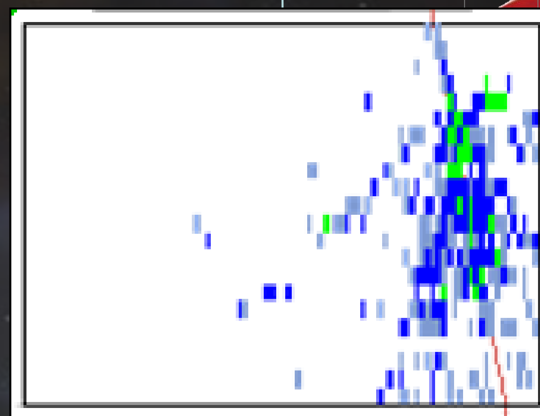
CHARGE ONE NEGATIVE

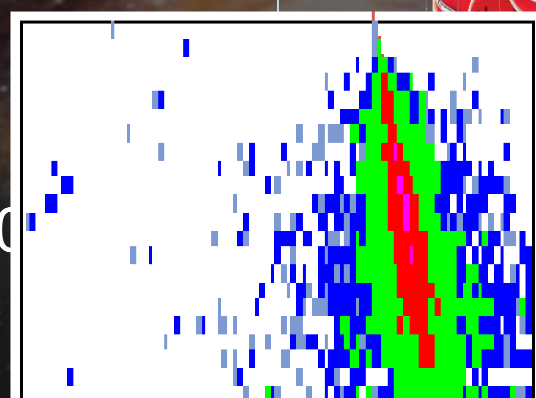
CHARGE ONE POSITIVE

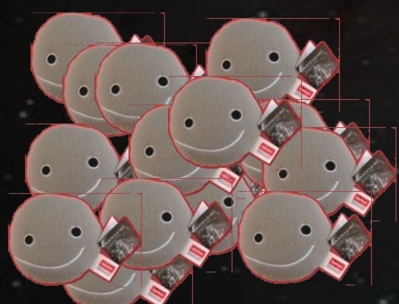
1 $\bar{p}$



10^4 p







10

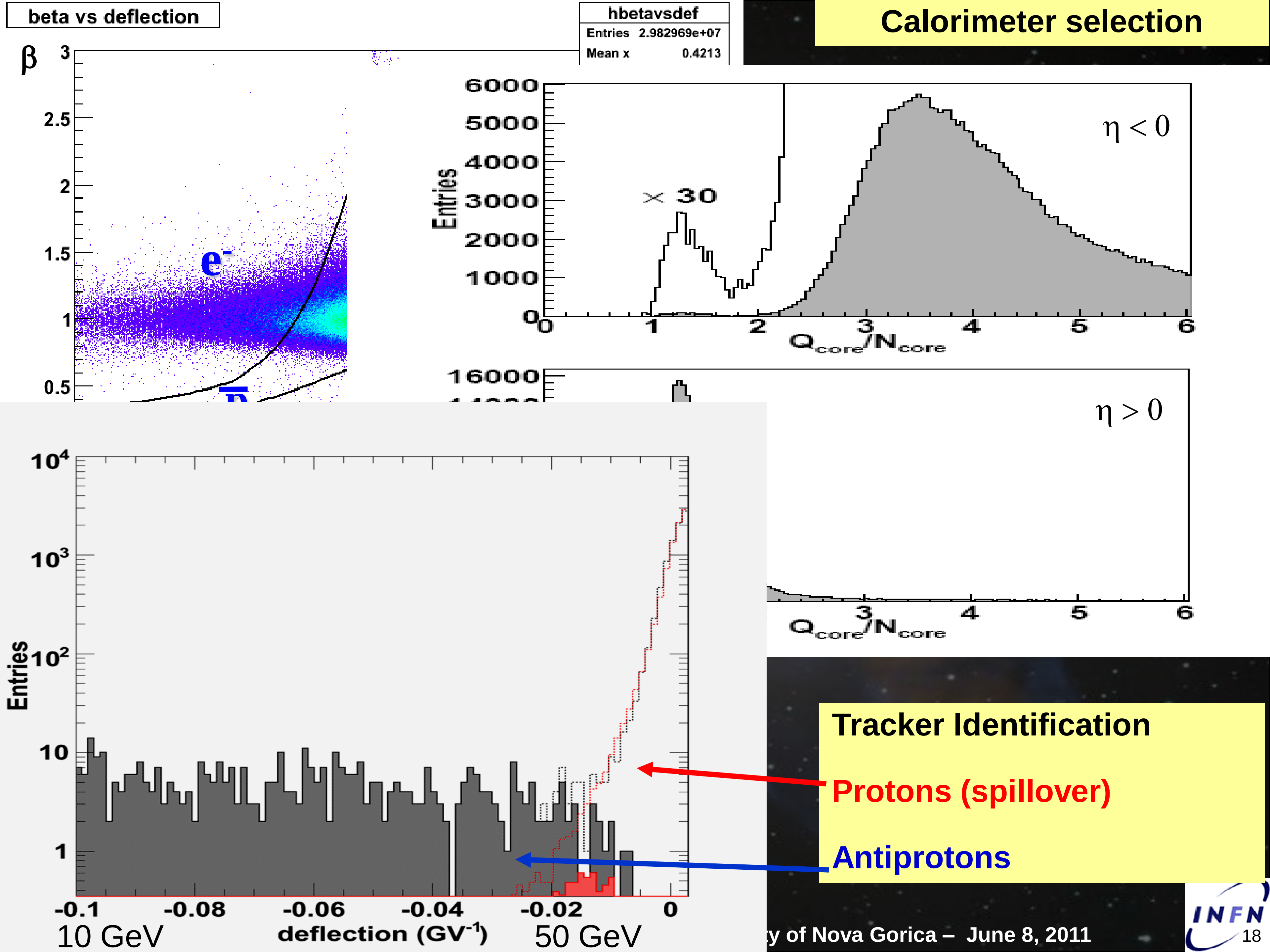
10 e^+

|Z|=1 (dE/dx vs R) → Tracker & ToF

β vs R consistent with M_p → ToF

p-bar/e^- and p/e^+ separation → CALO

Calorimeter selection

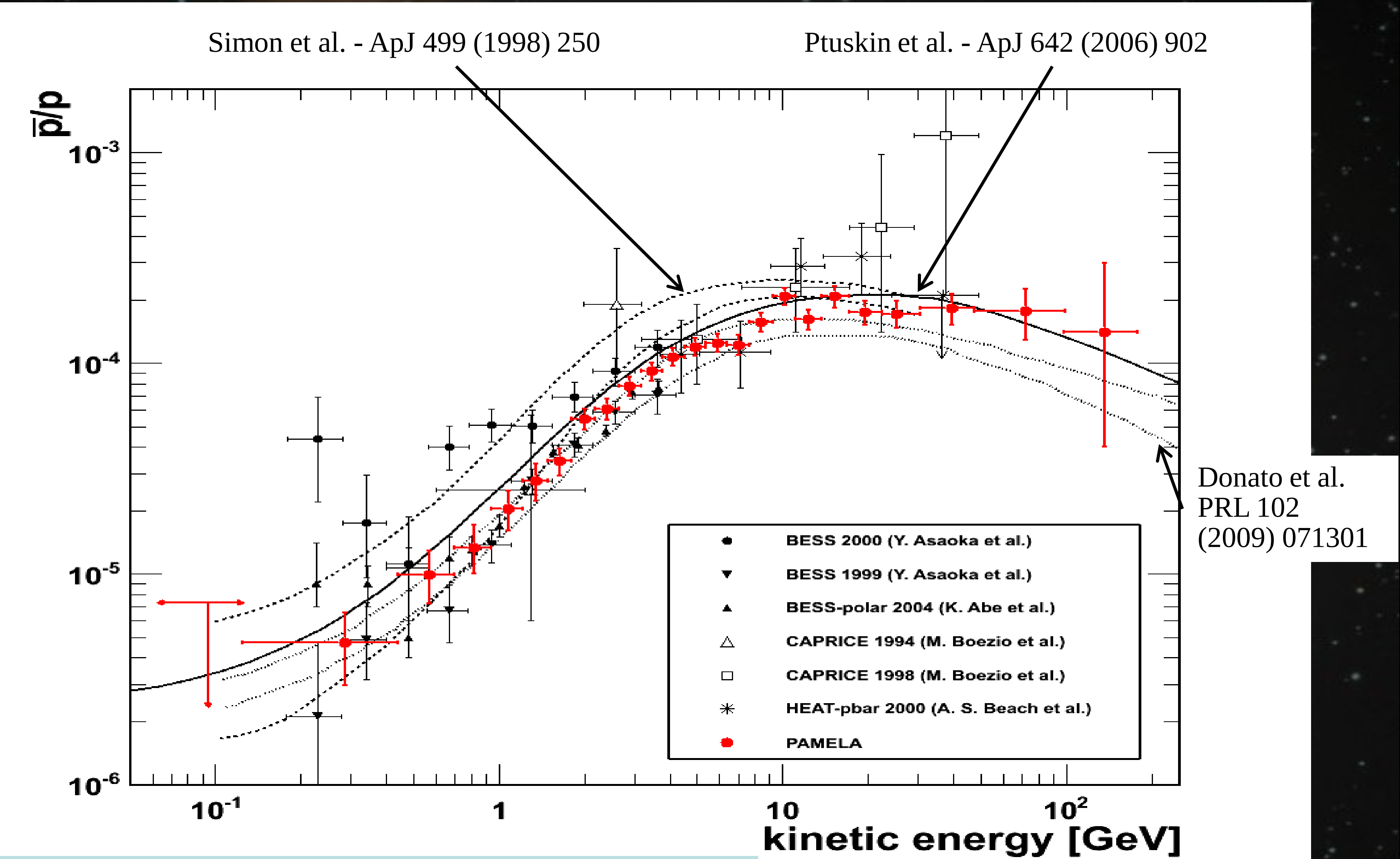


Tracker Identification

Protons (spillover)

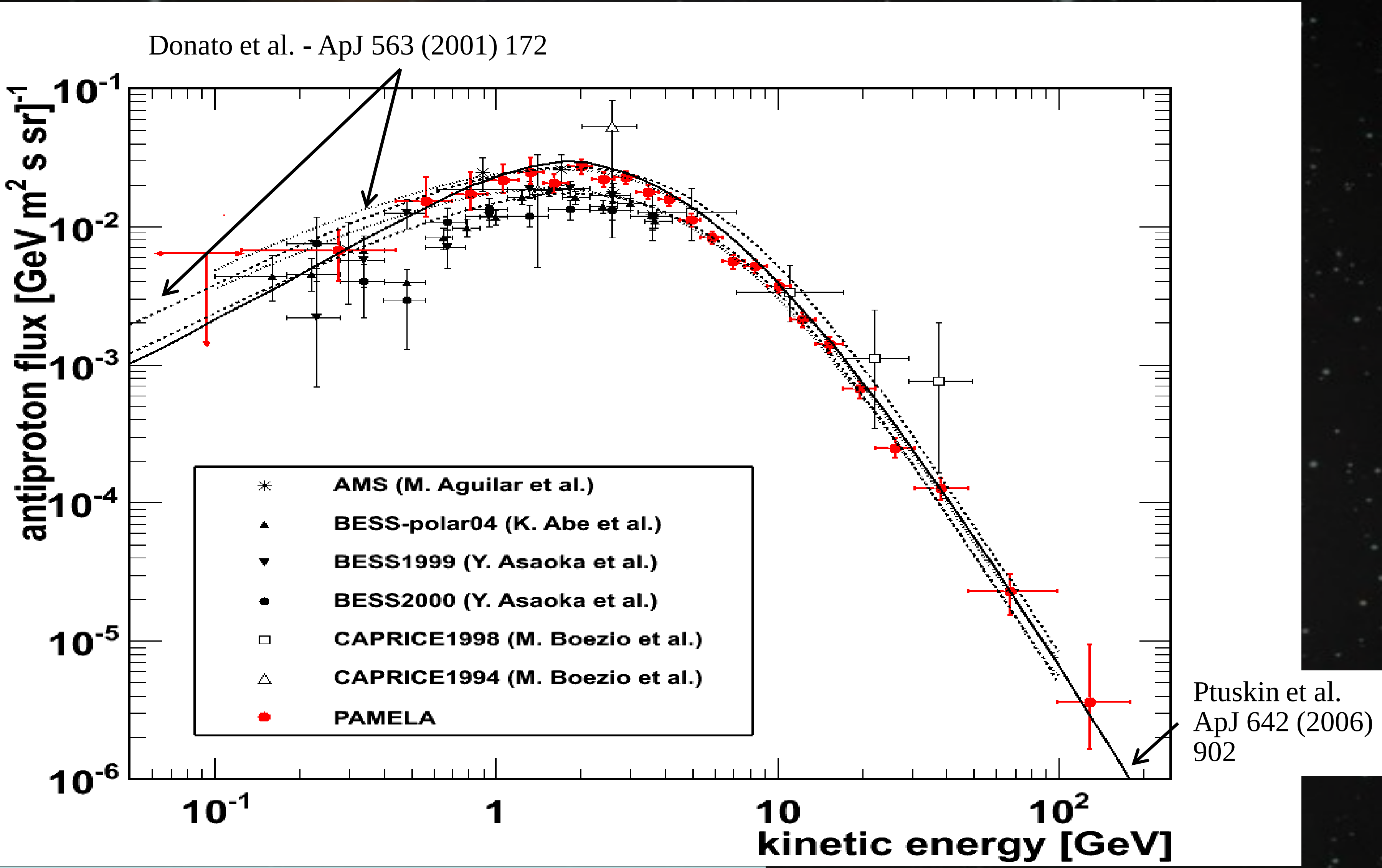
Antiprotons

PAMELA antiproton to proton ratio



Adriani et al., Phys. Rev. Lett. 105:121101, 2010
arXiv:1007.0821

PAMELA antiproton spectrum



Adriani et al., Phys. Rev. Lett. 105:121101, 2010
arXiv:1007.0821

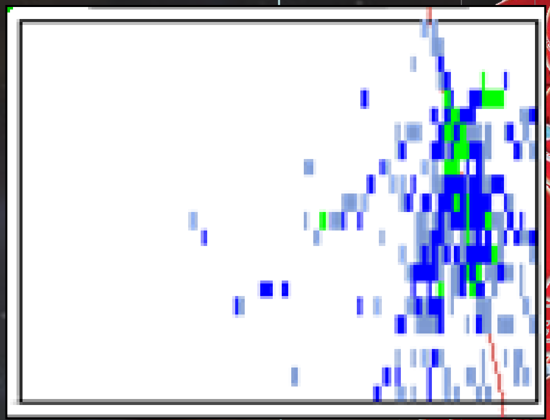
PAMELA positrons

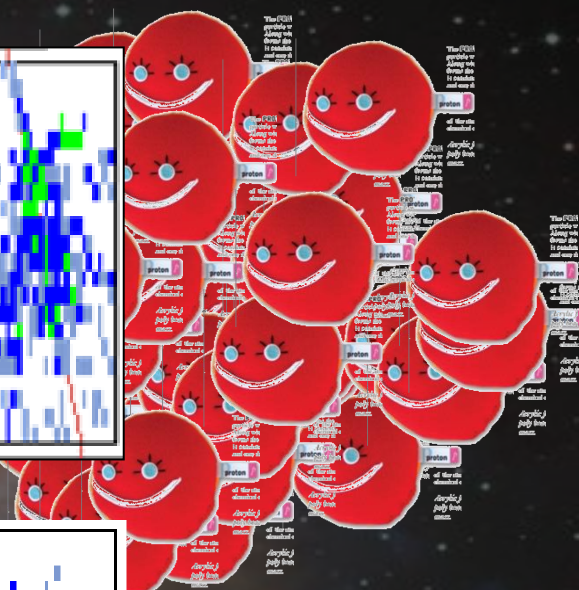
Positron identification

CHARGE ONE NEGATIVE

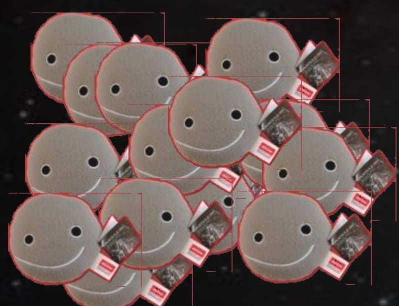
CHARGE ONE POSITIVE

1 p-bar

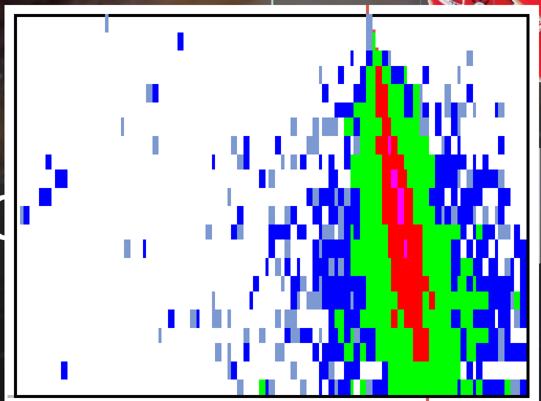




10^4 p



10



10 e^+

|Z|=1 (dE/dx vs R) → Tracker & ToF

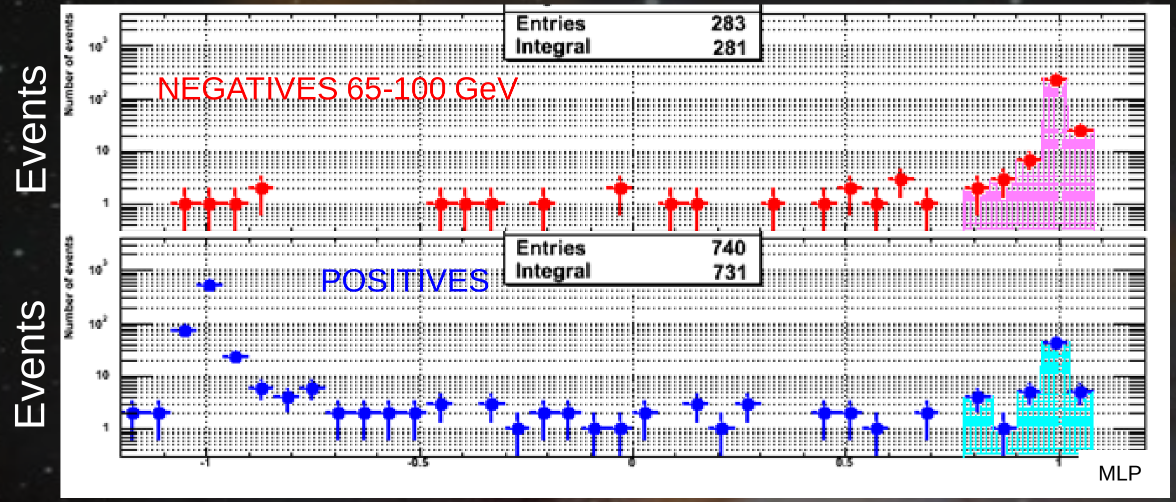
β vs R consistent with M_p → ToF

p-bar/e^- and p/e^+ separation → CALO

Analysis Approaches

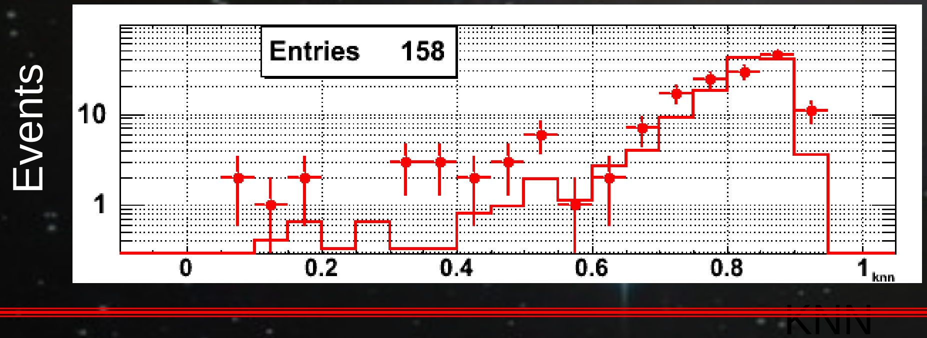
1. Cut analysis

apply a set of cuts on observables, take the survival number of events



2. Spectral analysis

choose one observable, fit the distribution and take the integral



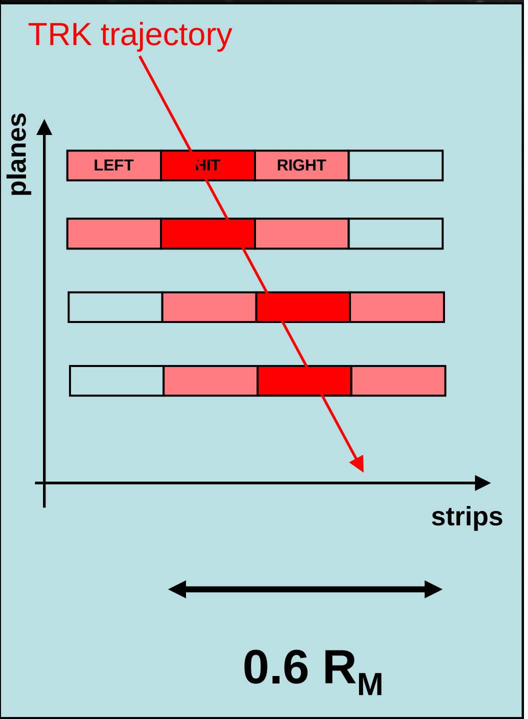
+ shape of signal and background from flight data

Positron selection

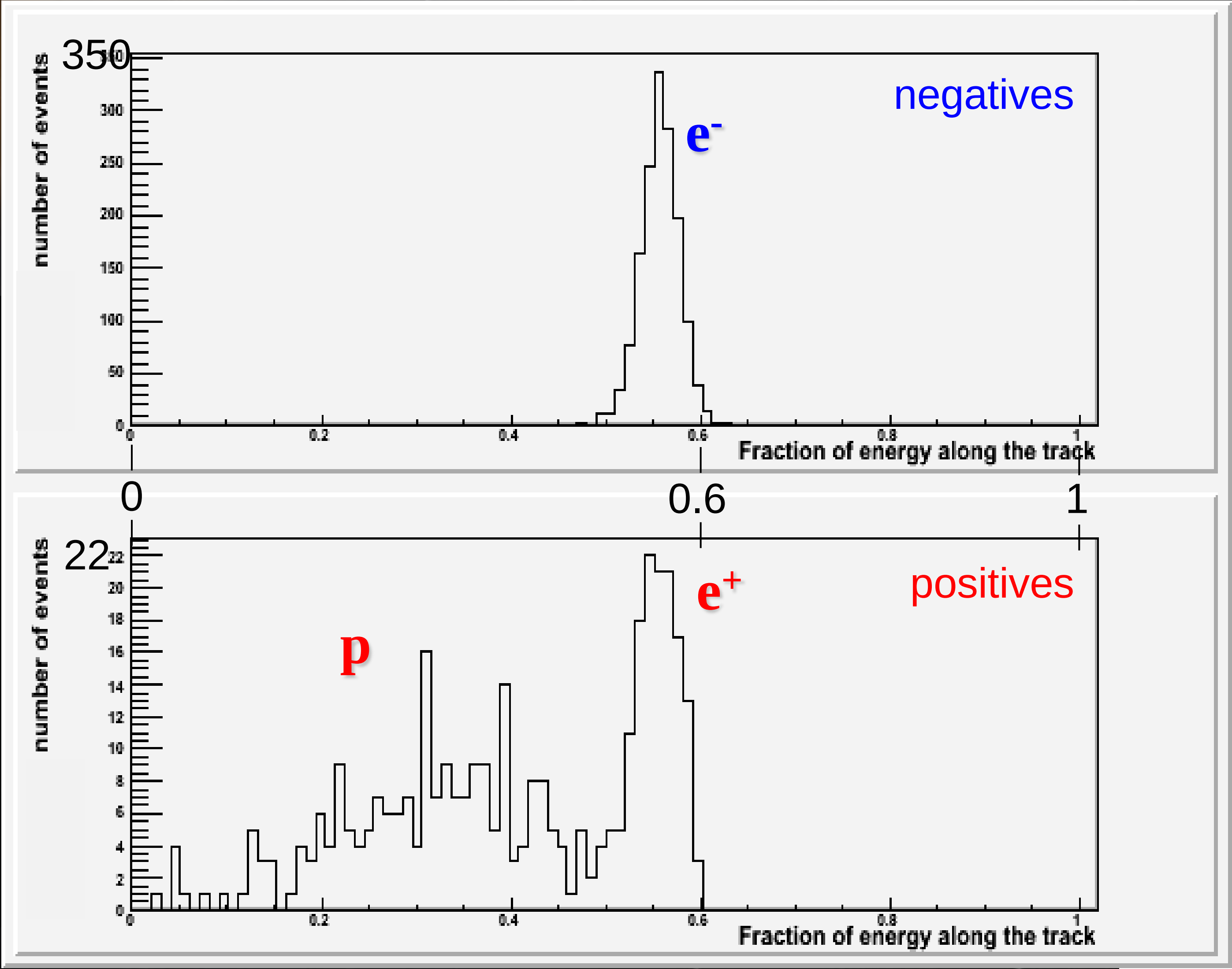
Pre-selections:

- Energy-momentum match
- Starting point of shower

Rigidity: 20-30 GV



Fraction of energy released along the track (left, hit, right) in the calorimeter

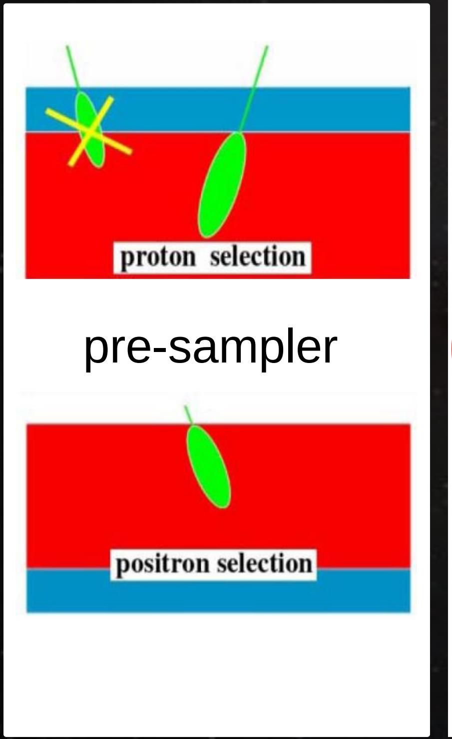


Background estimation from data

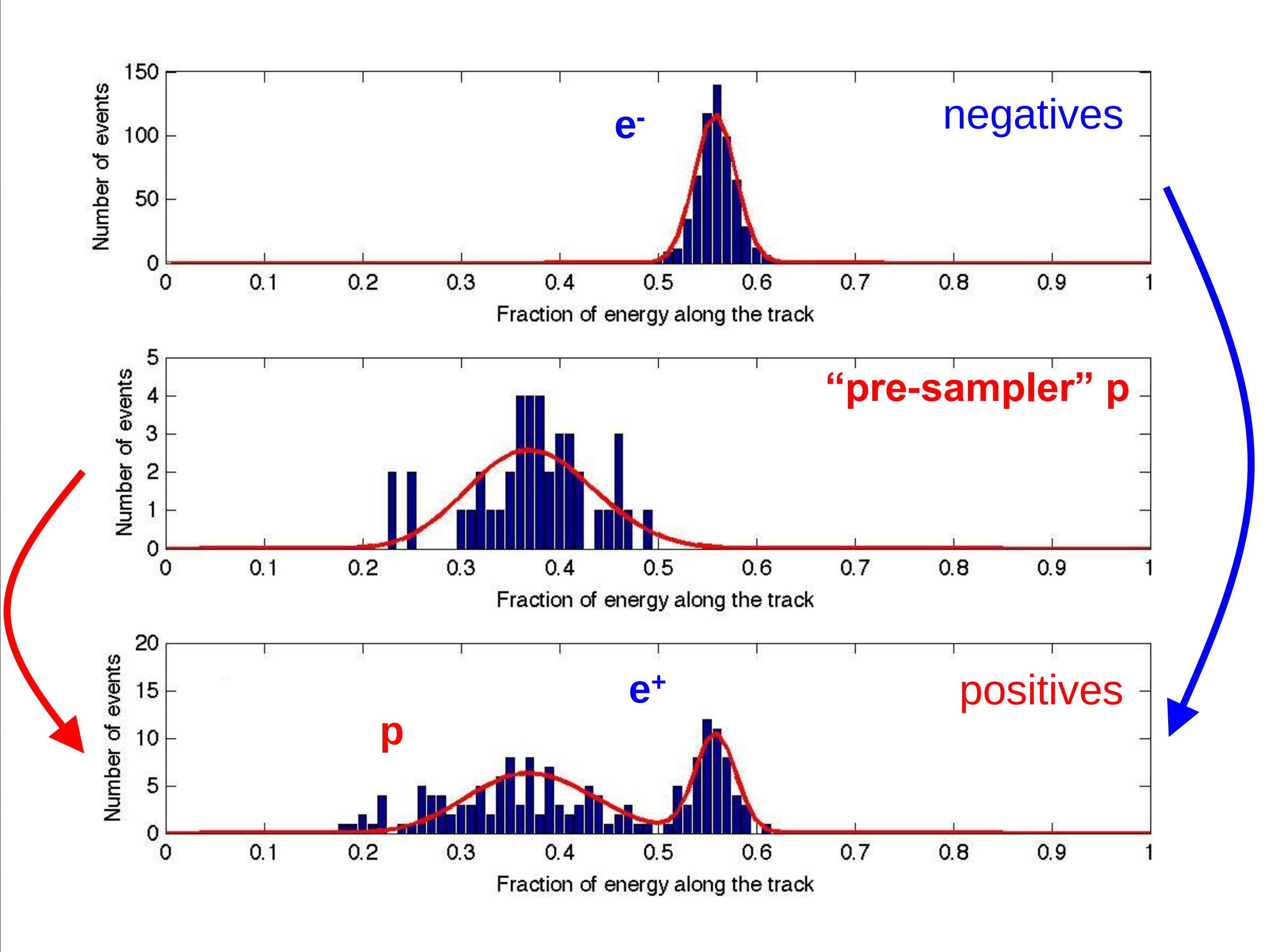
Pre-selections:

- Energy-momentum match
- Starting point of shower

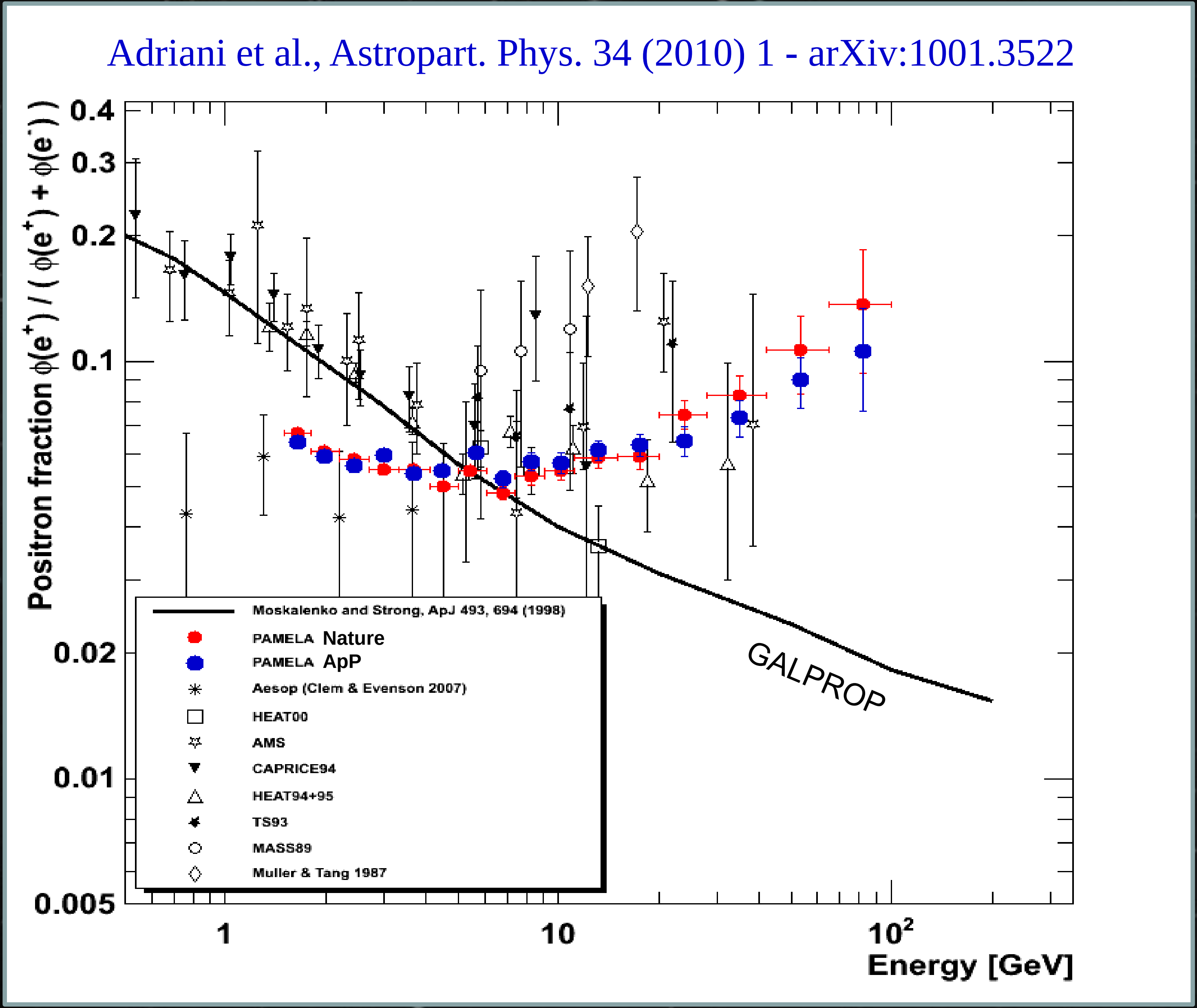
Rigidity: 28-42 GV



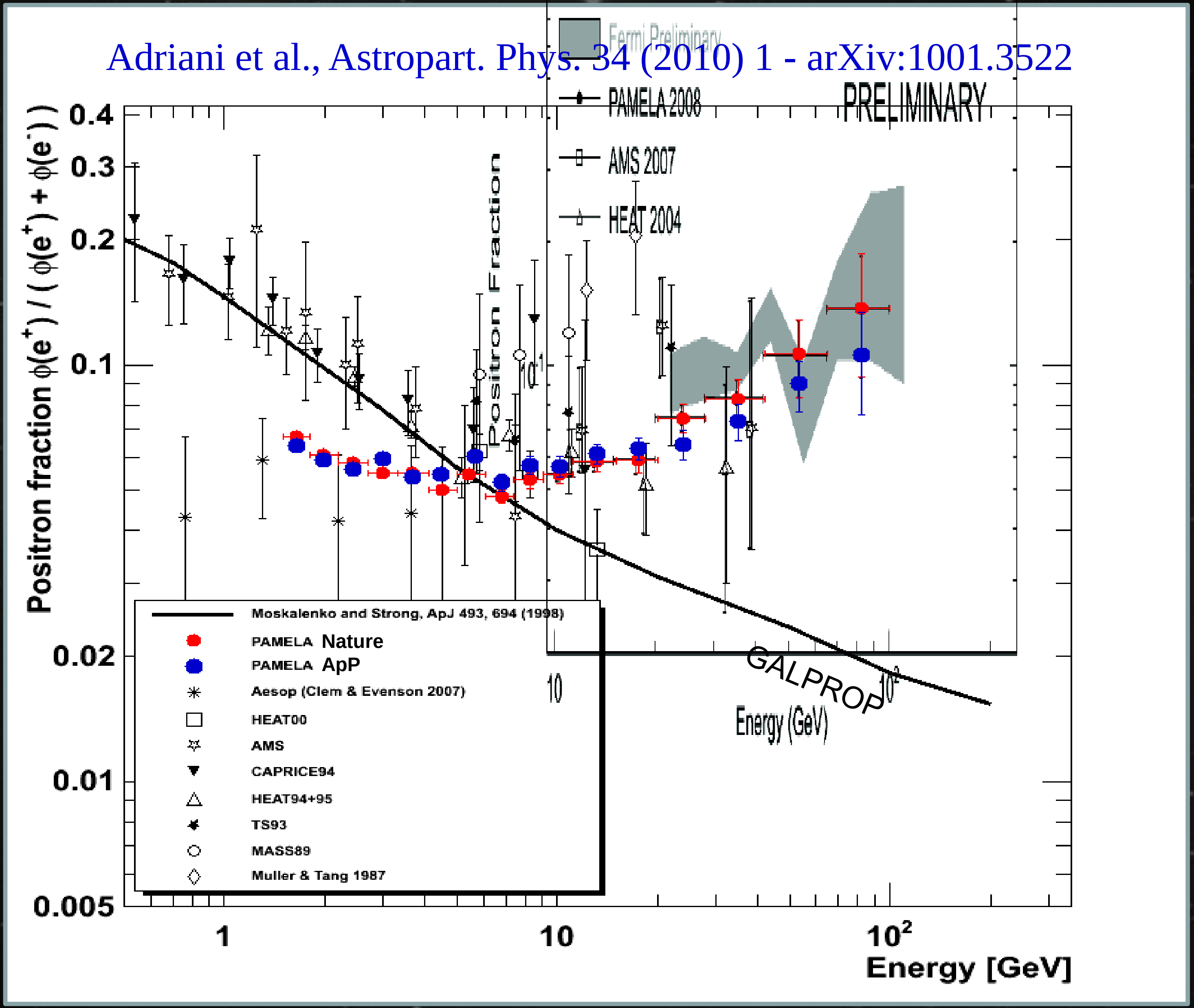
Fraction of energy released along the track (left, hit, right) in the calorimeter



Positron to Electron Fraction



Positron to Electron Fraction

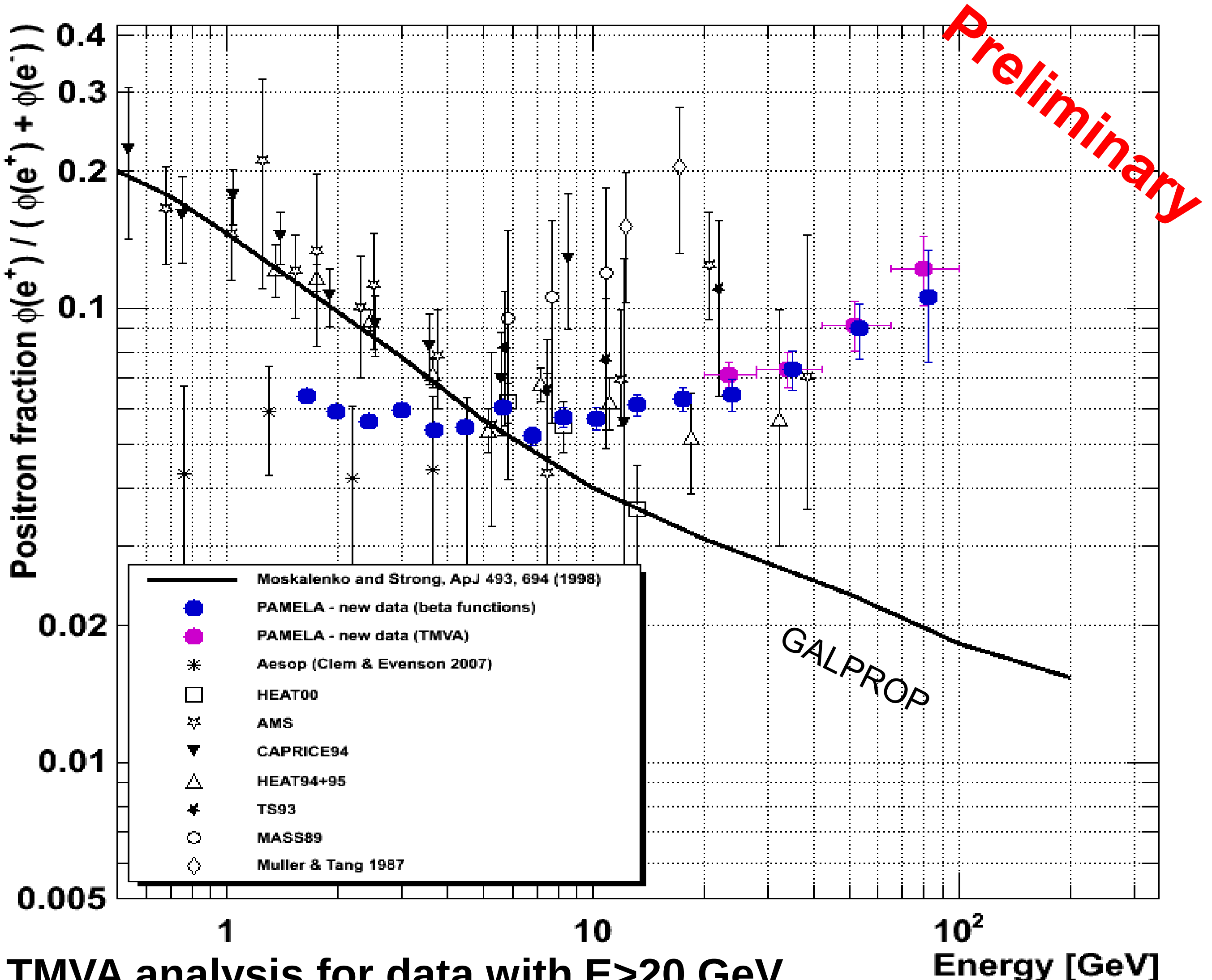


Extending the positron fraction measurement

No pre-sampler method, full calorimeter:

- No proton sample from flight data
- Simulations & Test beam data needed
- Protons rejection and background estimation using TMVA

Positron to Electron Fraction



TMVA analysis for data with E>20 GeV

Positron to Electron Fraction

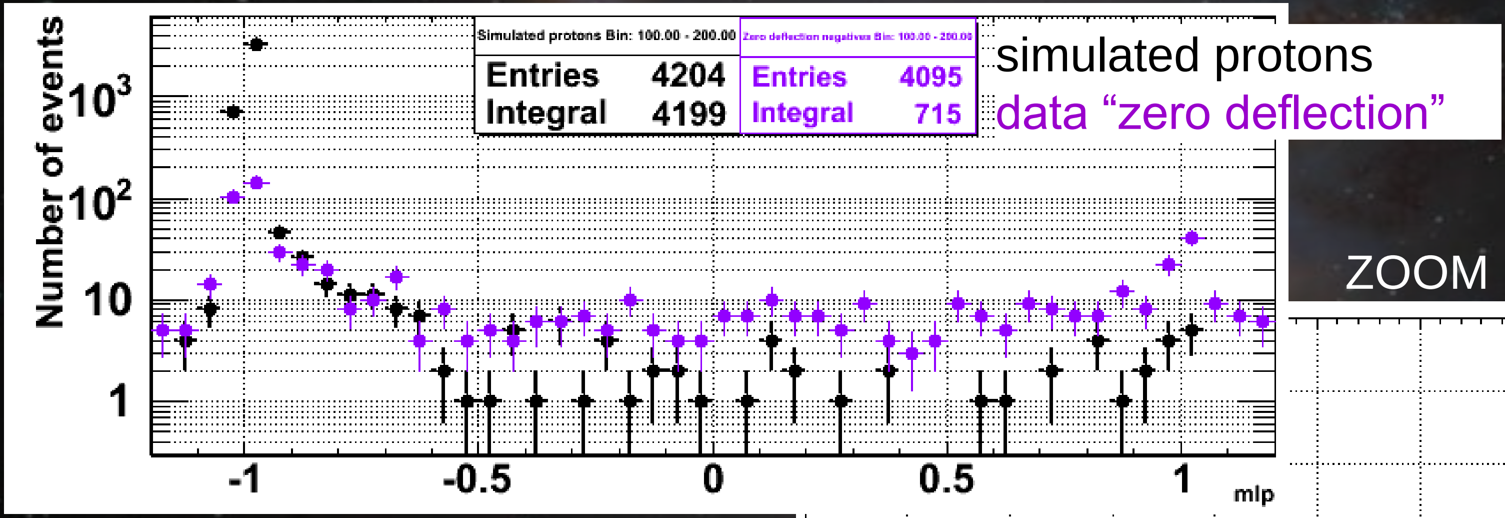
TMVA analysis for data with E>20 GeV

Estimate of the lower limit

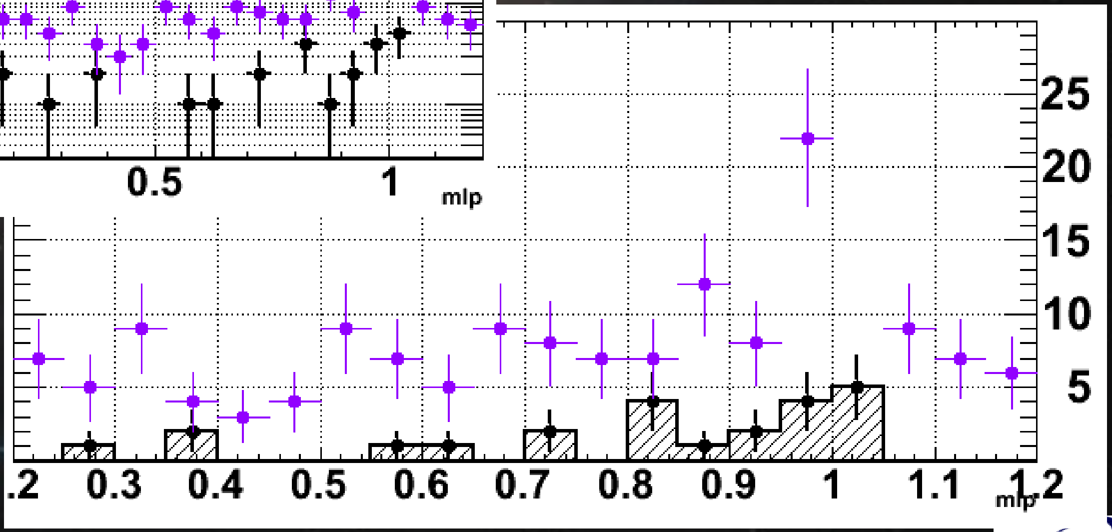
- Take flight data events with abs deflection < 0.001 GV
- Assign to those events a fake rigidity in the considered bin
- Apply the classifier

Worst possible scenario of high energy protons emulating positrons reconstructed in the wrong energy bin

100-200 GeV



ZOOM Linear scale

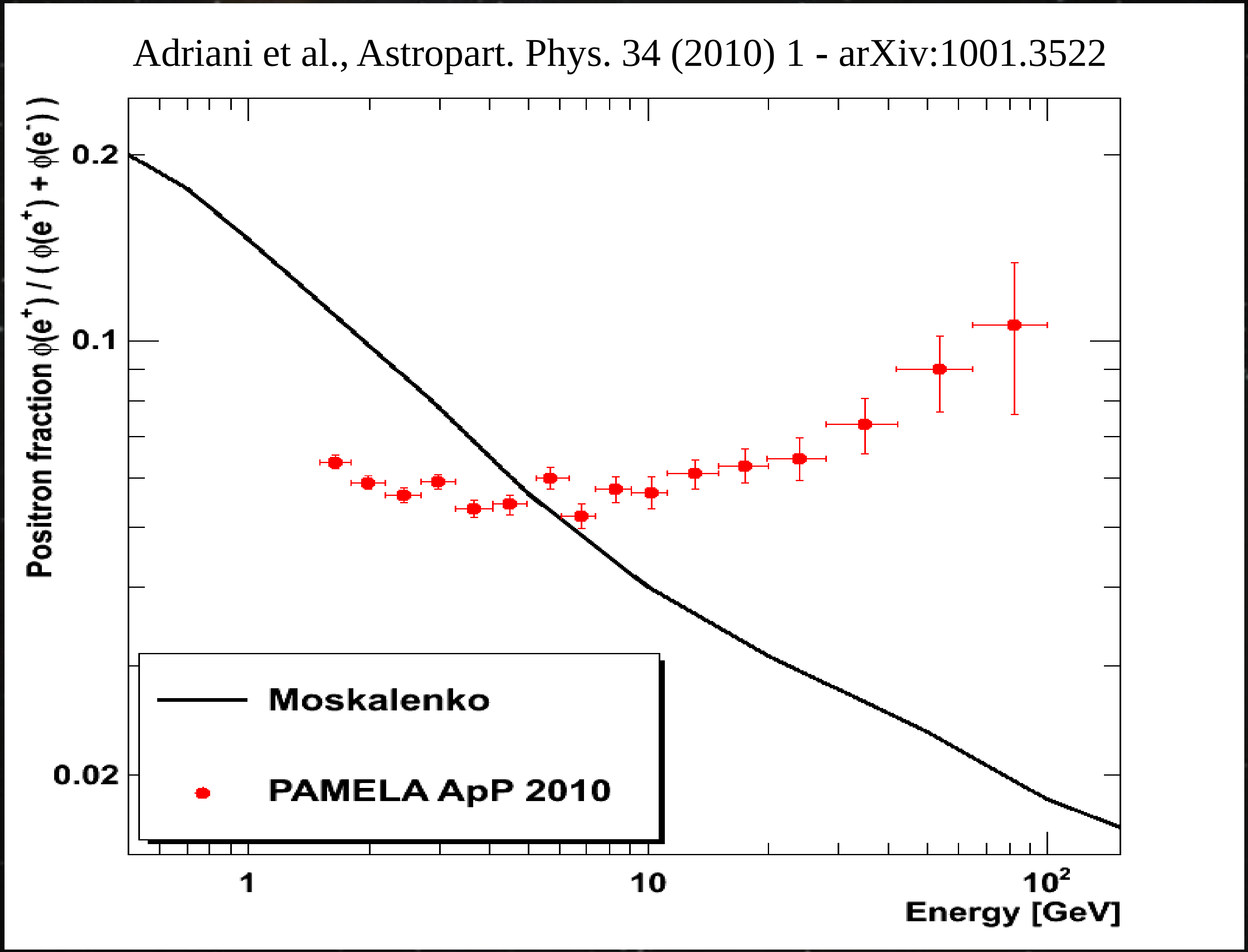


Estimate of the lower limit

Preliminary

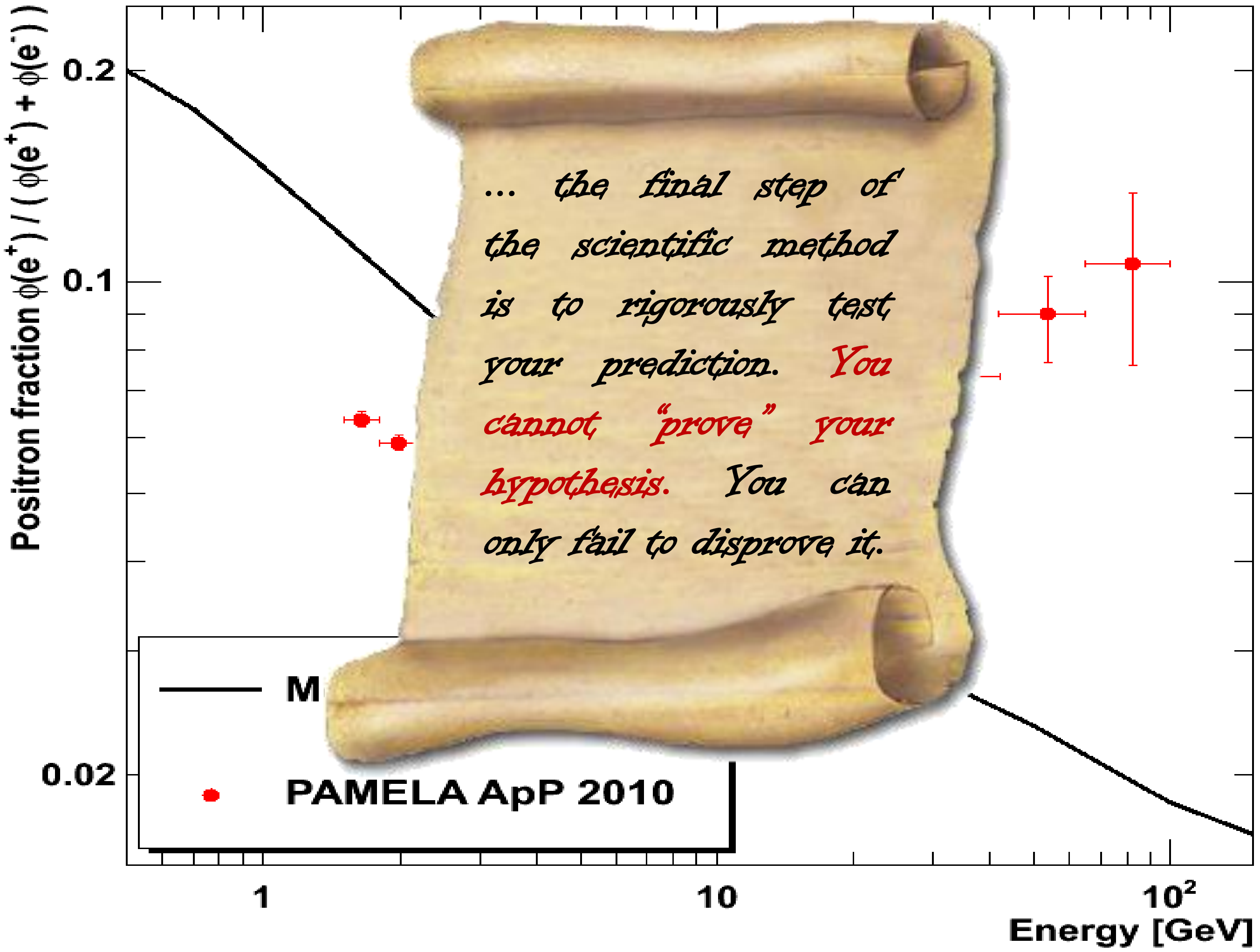
Positrons fraction interpretation: PAMELA as CR observatory

PAMELA Positron Fraction

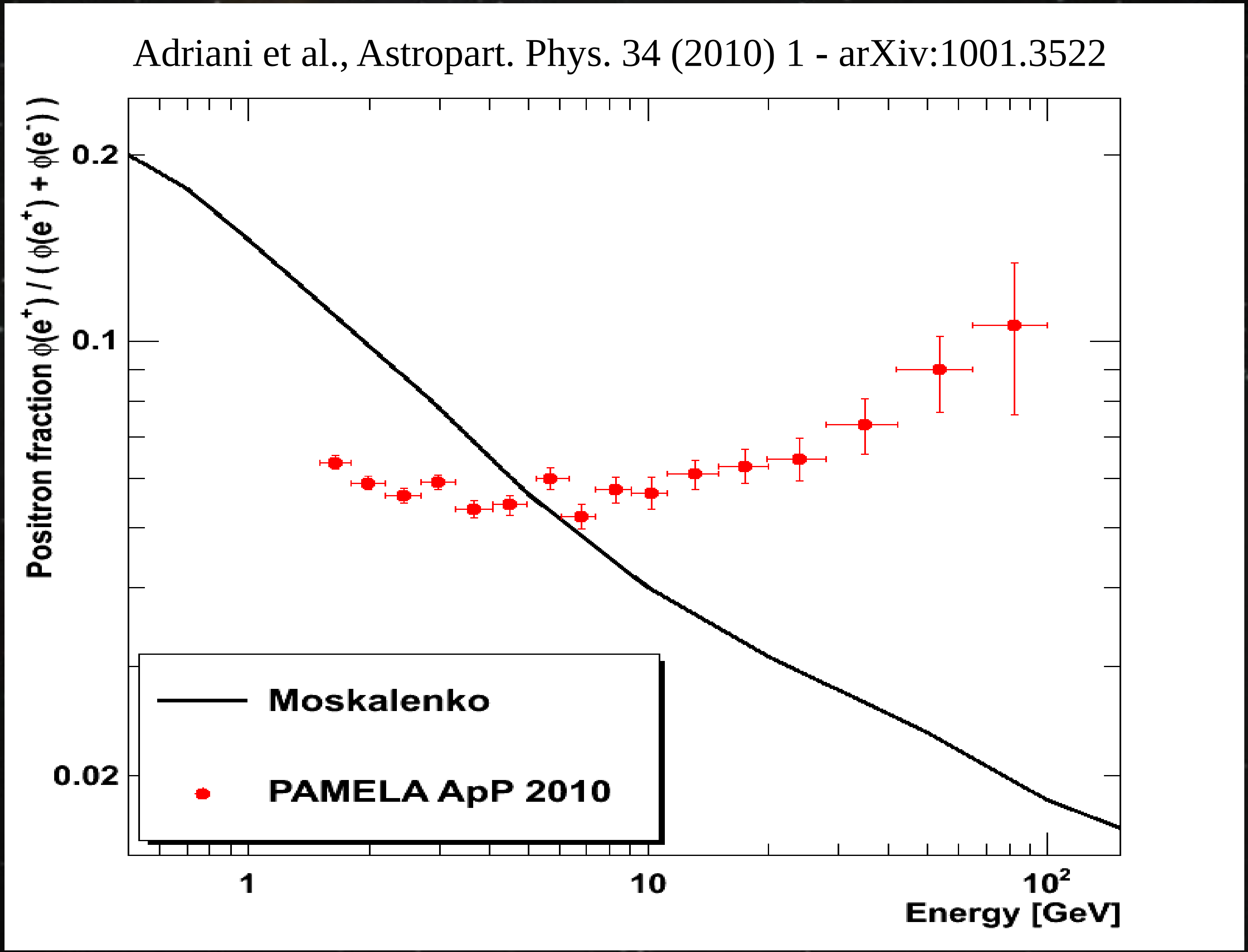


PAMELA Positron Fraction

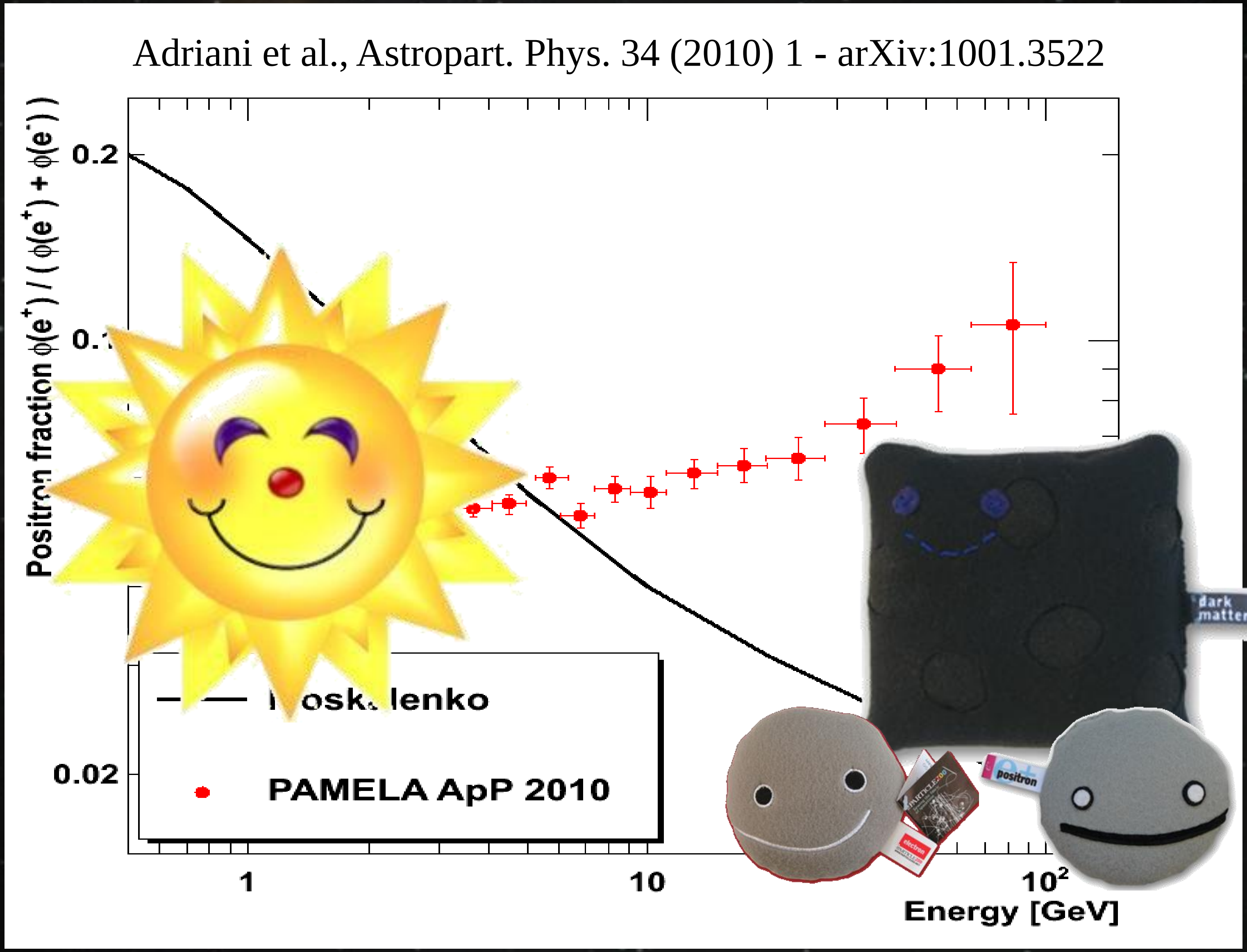
Adriani et al., Astropart. Phys. 34 (2010) 1 - arXiv:1001.3522



PAMELA Positron Fraction



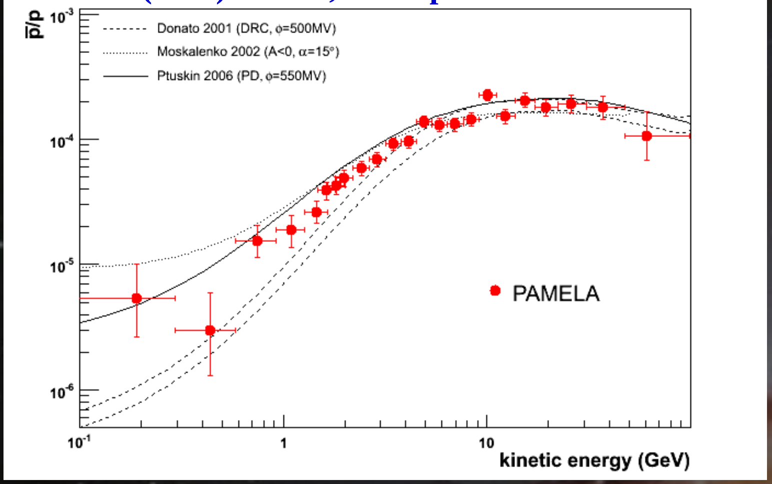
PAMELA Positron Fraction



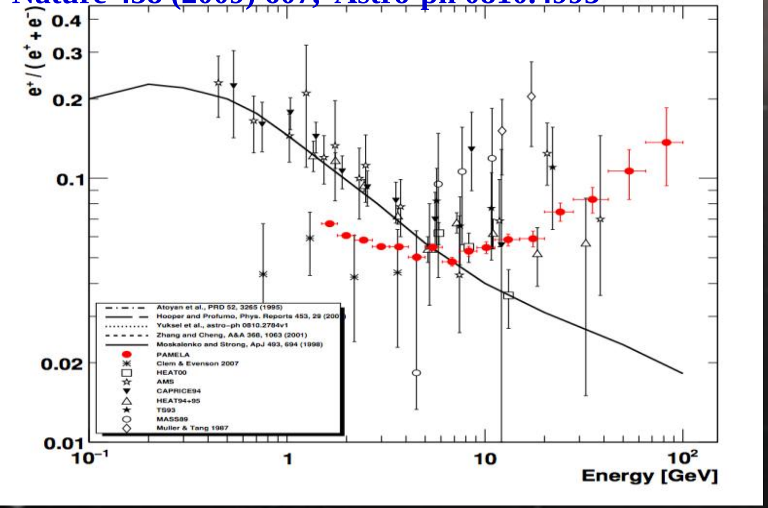
http://www.particlezoo.net

During first week after PAMELA results posted on arXiv (October 28, 2008)

PRL 102 (2009) 051101, Astro-ph 0810.4994



Nature 458 (2009) 607, Astro-ph 0810.4995



⇒

1. 0808.3725 DM
2. 0808.3867 DM
3. 0809.2409 DM

0810.2784 Pulsar

4846 DM / pulsar

DM

8.

9. 0810.

10. 0810.539

11. 0810.5557 DM
12. 0810.4147 DM
13. 0811.0250 DM
14. 0811.0477 DM

...

PAMELA data cited by >720 papers on arXiv (at present)

Reasons for the positron fraction to rise

(slide adapted from I. Moskalenko talk, PAMELA Workshop, Rome, May 2009)

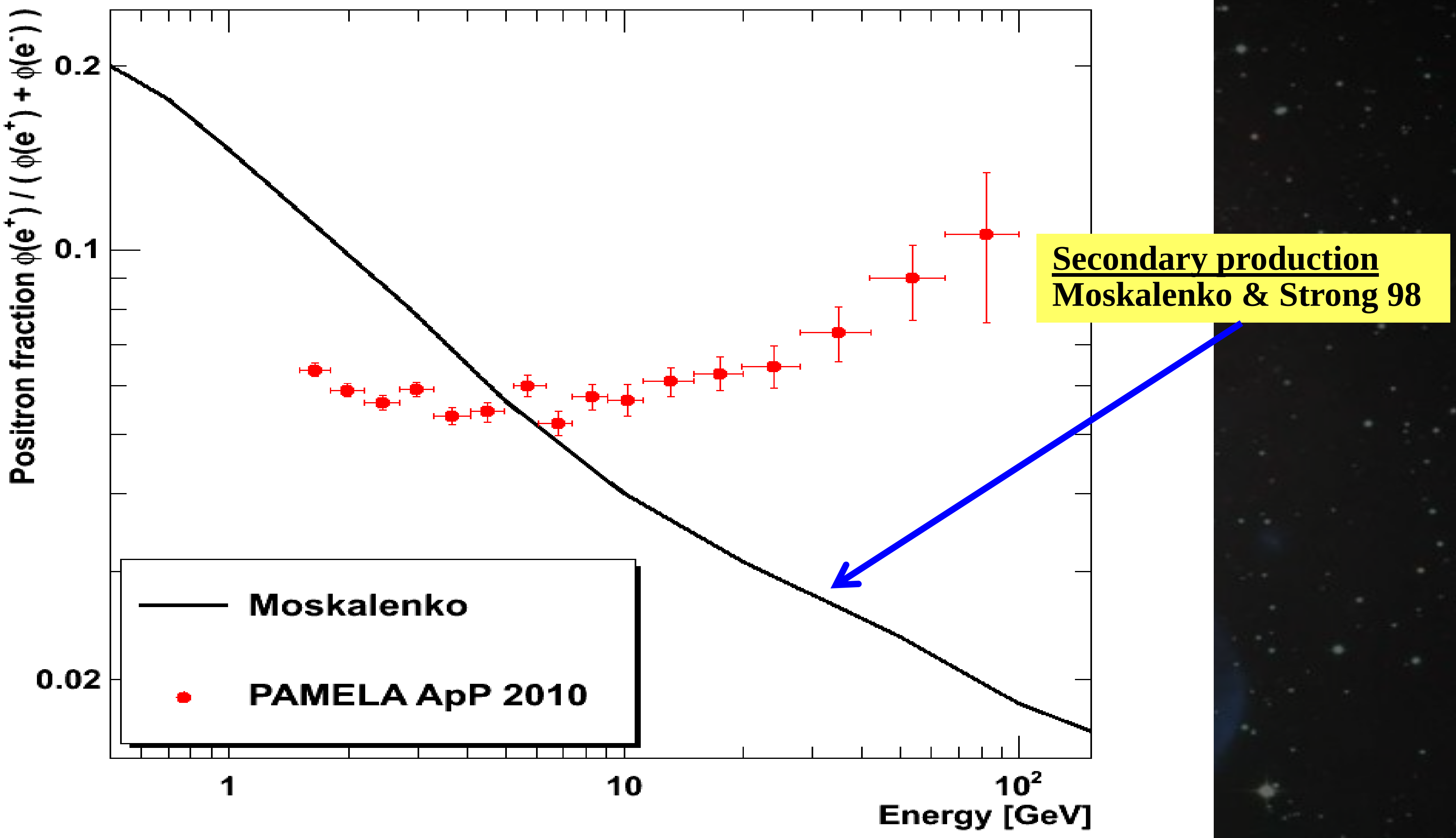
- **Main reason – primary positrons are perhaps unavoidable**
- **There is no deficit in papers explaining the PAMELA positron excess (>200 papers since Oct 2008!):**
  - **Various species of the dark matter (~170)**
  - **Pulsars**
  - **SNRs**
  - **Microquasar**
  - **a GRB nearby**
  - **…**
- **Perhaps we have to discuss a deficit of positrons, not their excess!**

Unfortunately, they could be all wrong!

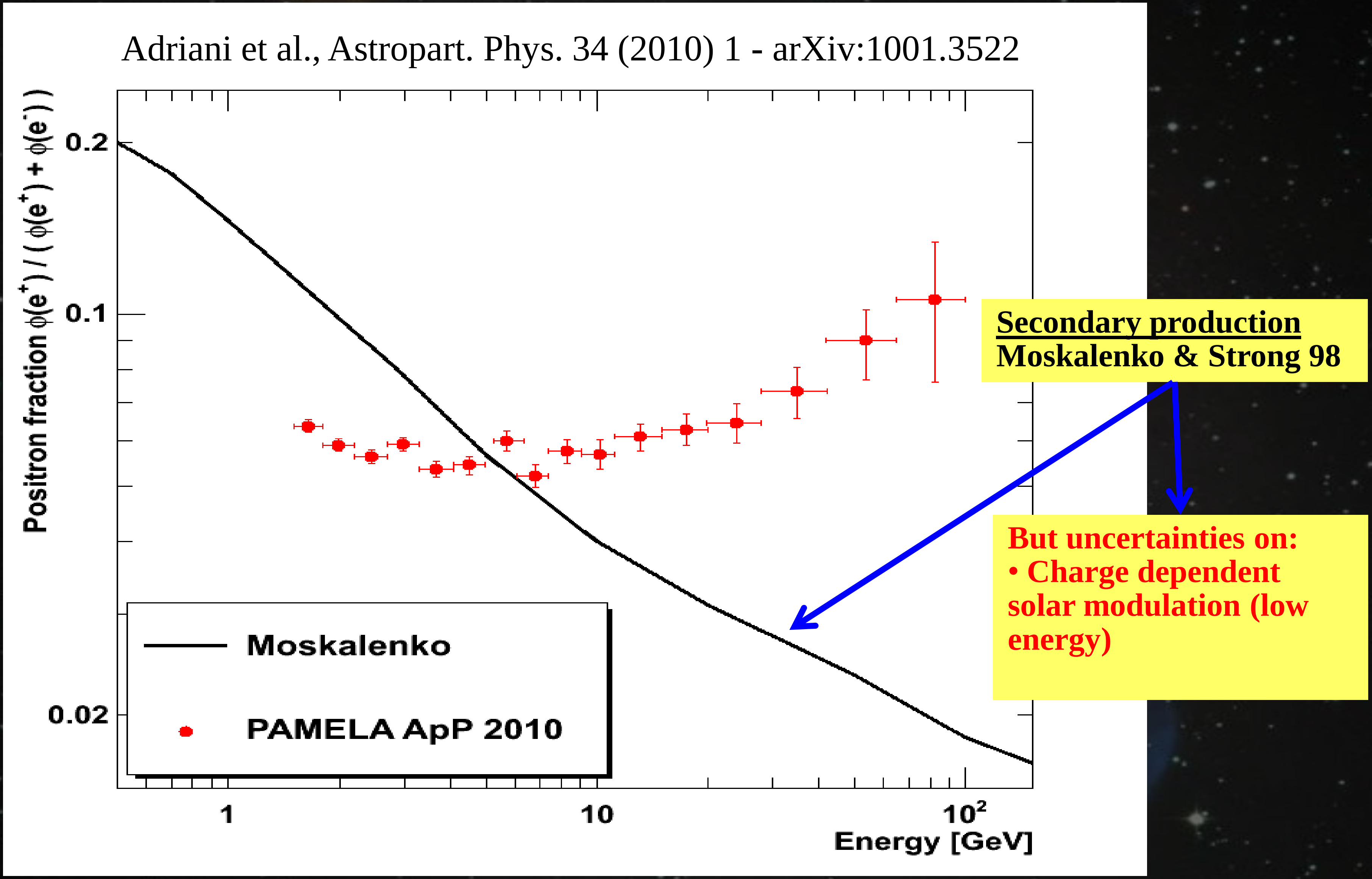
Reason – we do not know precisely the background and thus can't get an idea of the spectrum of the primary positron component

PAMELA Positron Fraction

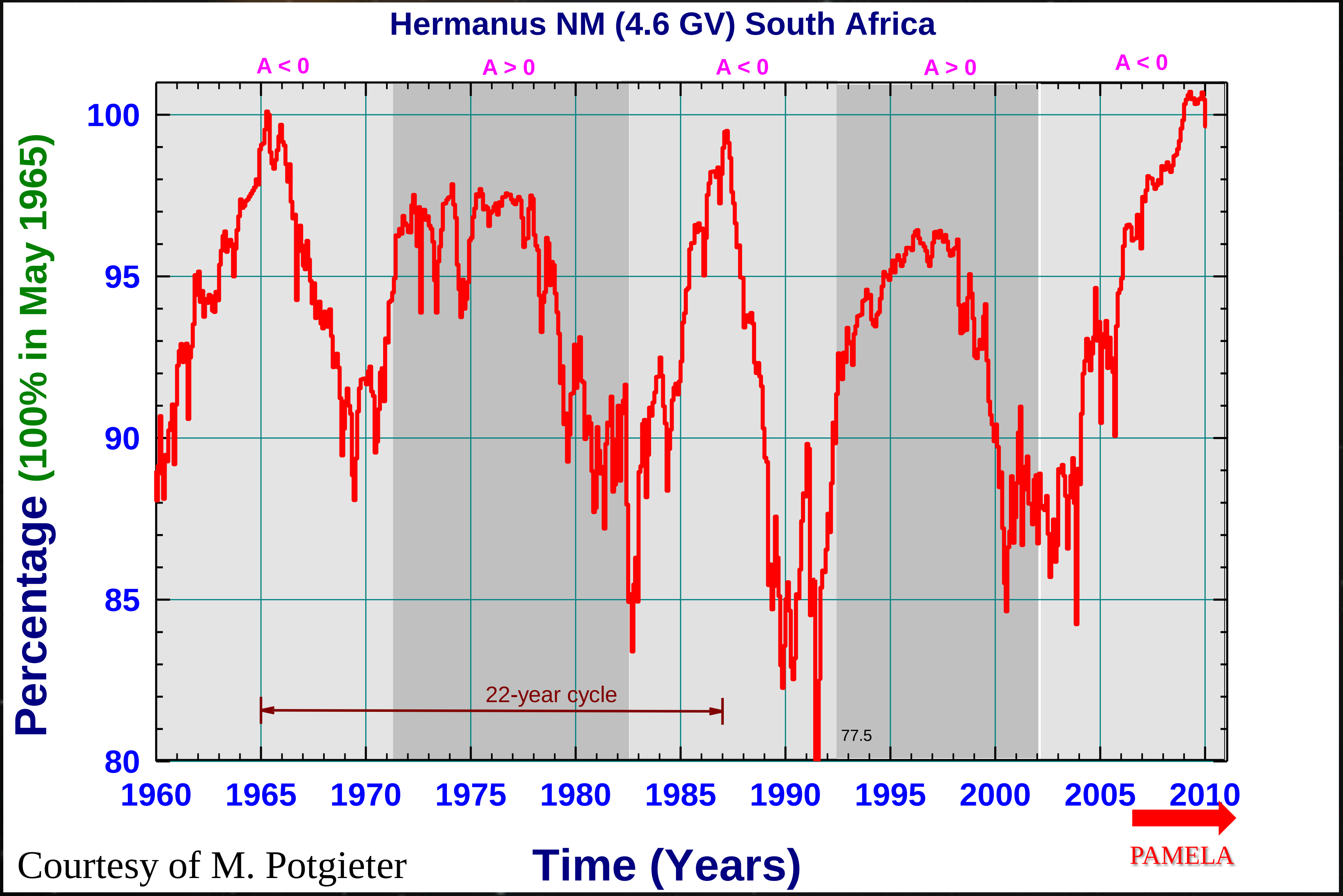
Adriani et al., Astropart. Phys. 34 (2010) 1 - arXiv:1001.3522



PAMELA Positron Fraction

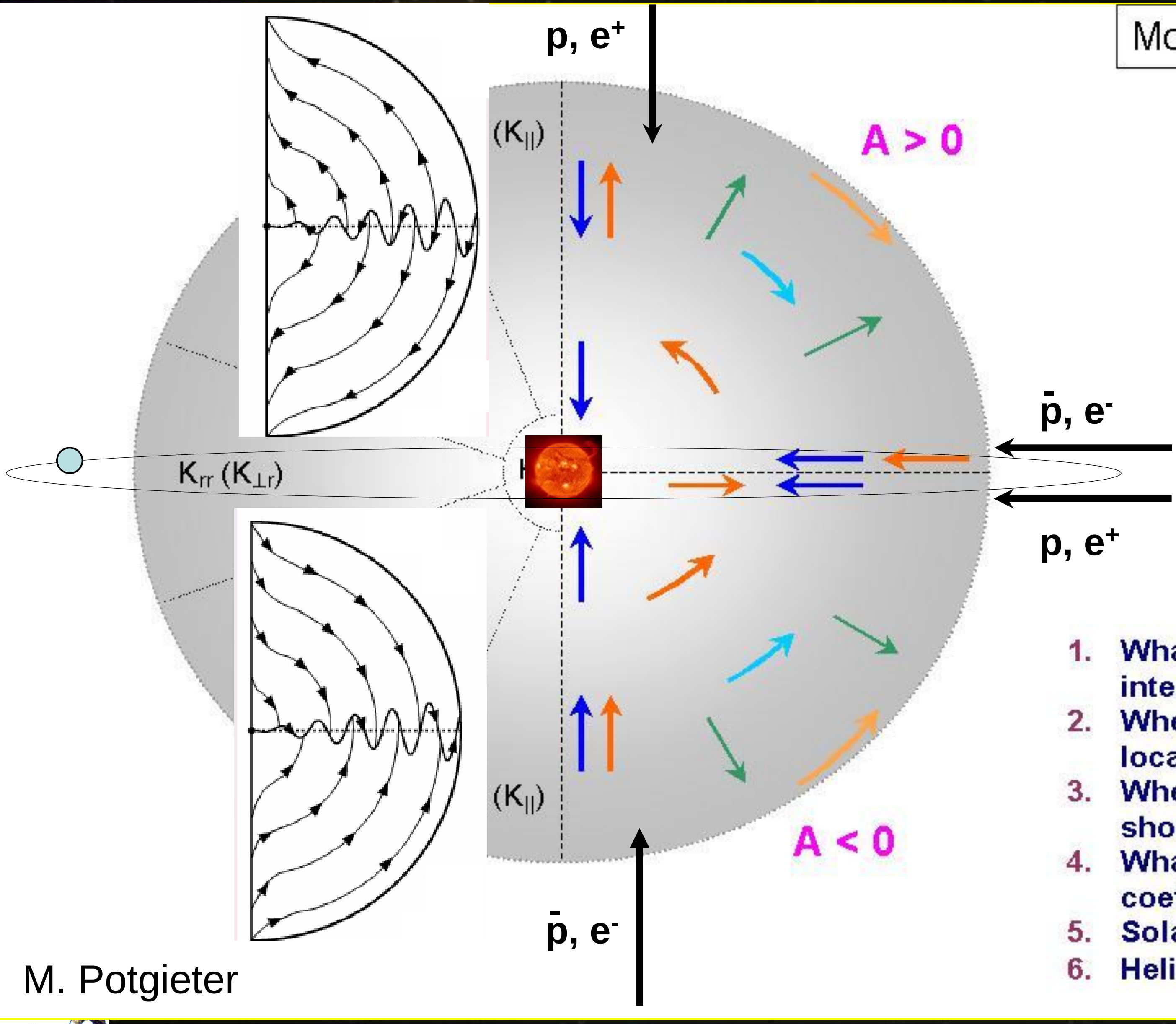


Solar Modulation of Galactic Cosmic Rays



Courtesy of M. Potgieter

Charge dependent solar modulation



Modulation mechanisms

- Convection
- Diffusion
- Perpendicular diffusion
- G,C & NS Drifts
- Shock-drift

1. What are the local interstellar spectra?
2. Where is the outer boundary located?
3. Where is the termination shock located?
4. What are the diffusion coefficients? (r, t)
5. Solar wind profile?
6. Heliospheric magnetic field?

M. Potgieter

Time Dependence of PAMELA Proton Flux

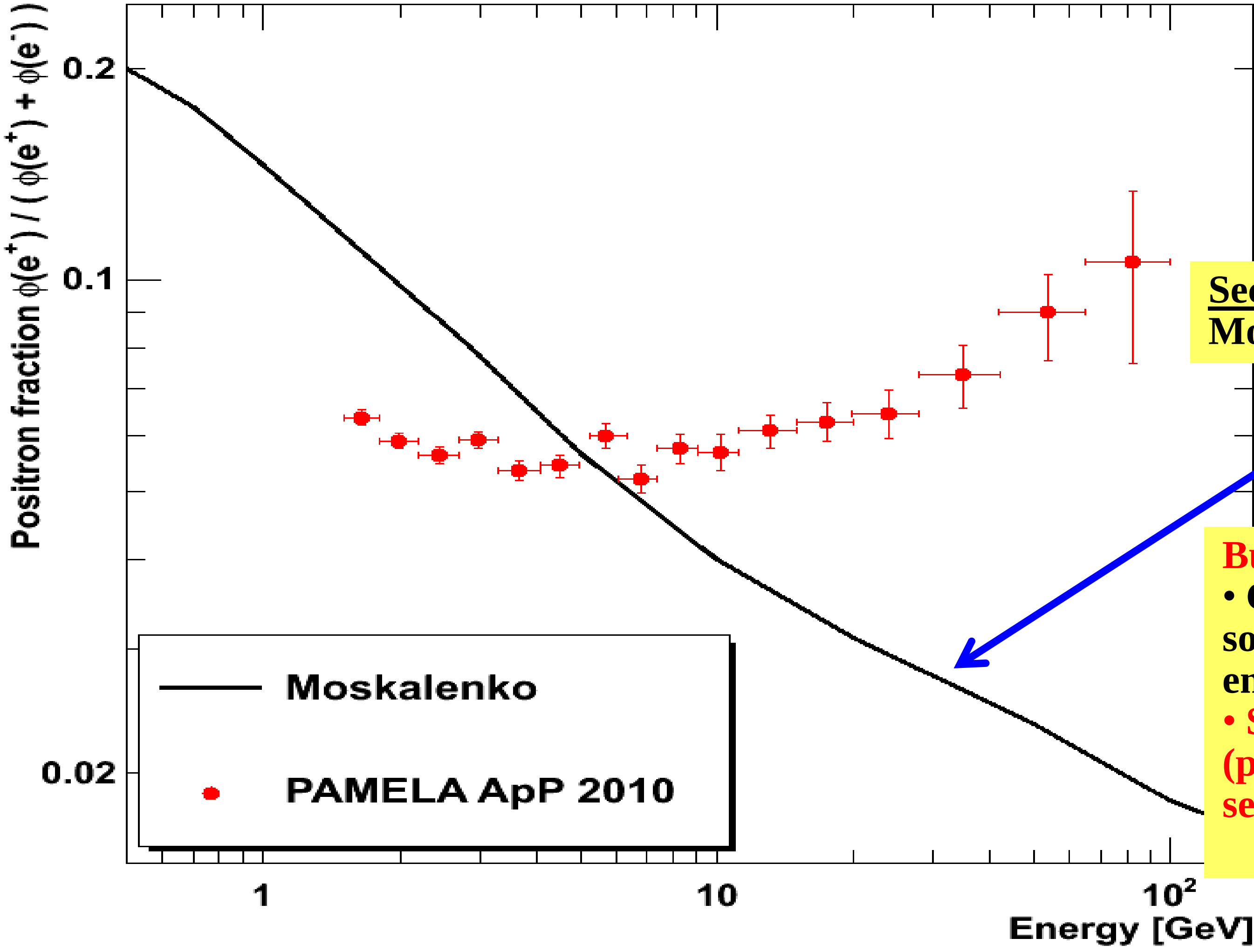
Time dependence: p and e^-

Preliminary

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

PAMELA Positron Fraction

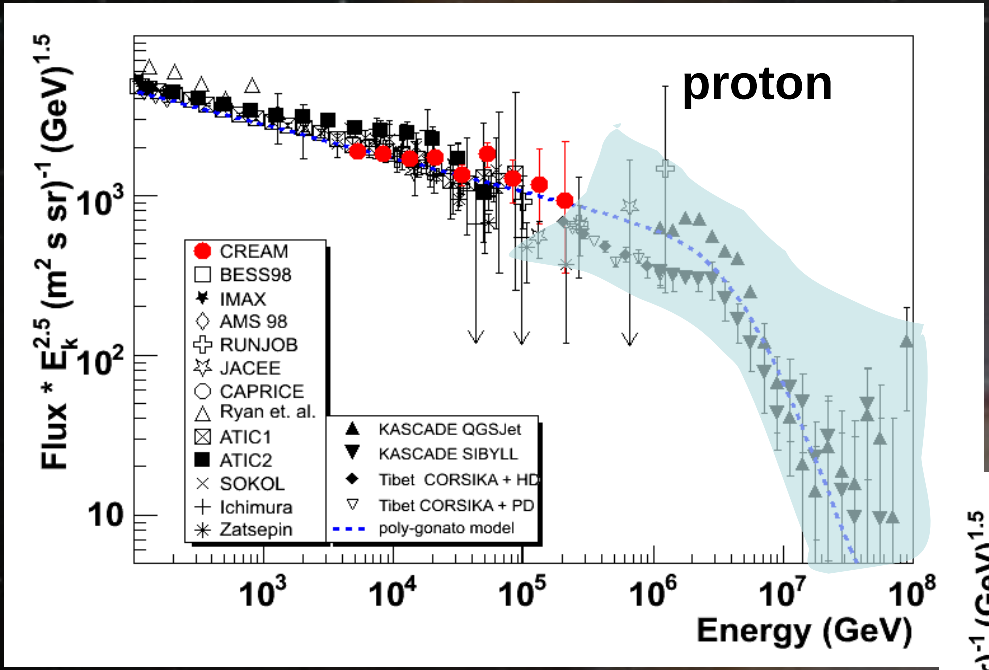
Adriani et al., Astropart. Phys. 34 (2010) 1 - arXiv:1001.3522

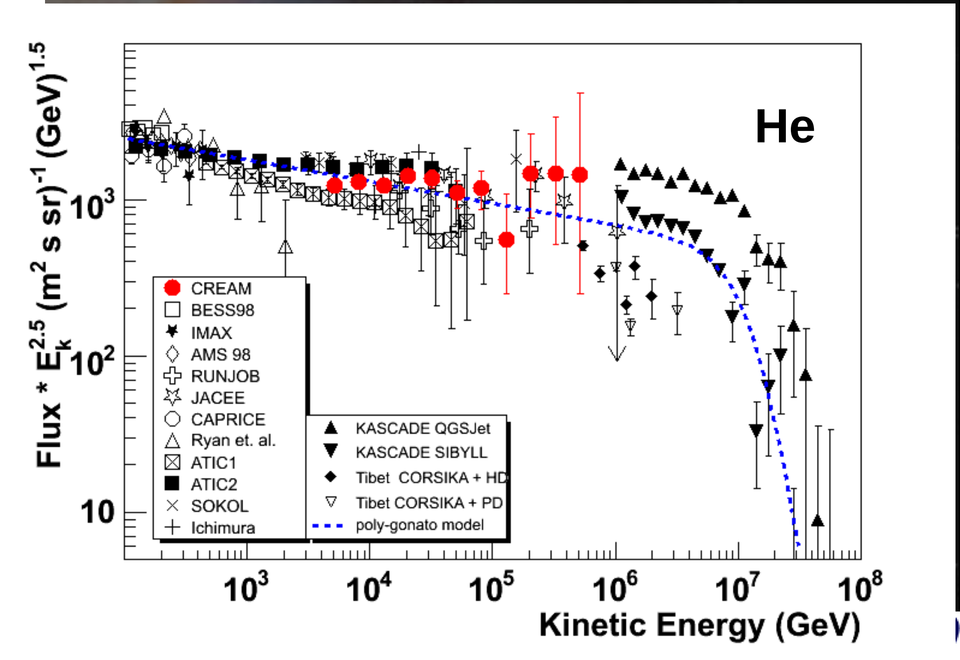


<u>Secondary production</u>
Moskalenko & Strong 98

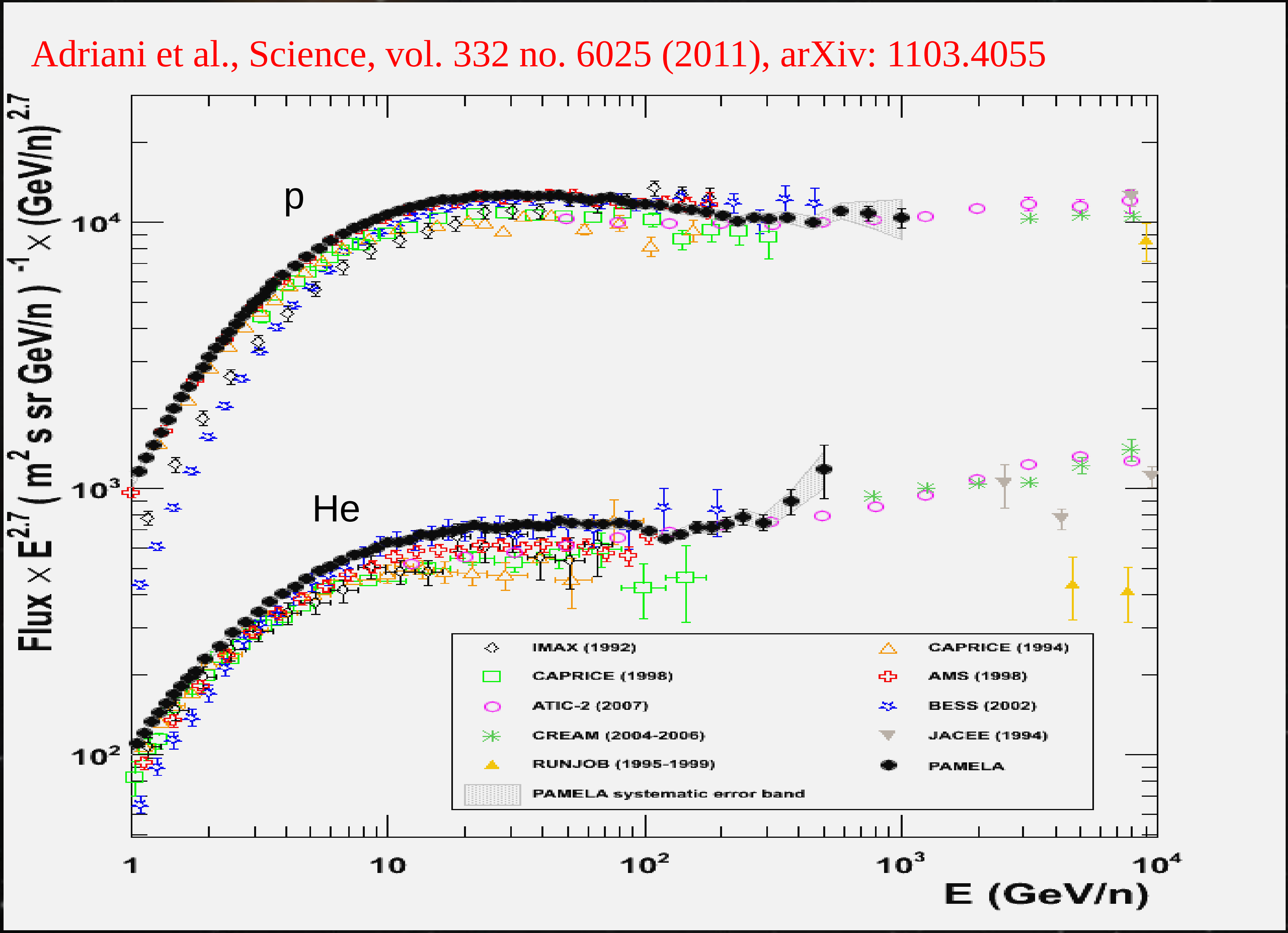
But uncertainties on:
- **Charge dependent solar modulation (low energy)**
- **Secondary production (primary fluxes, cross section)**

Galactic H and He spectra



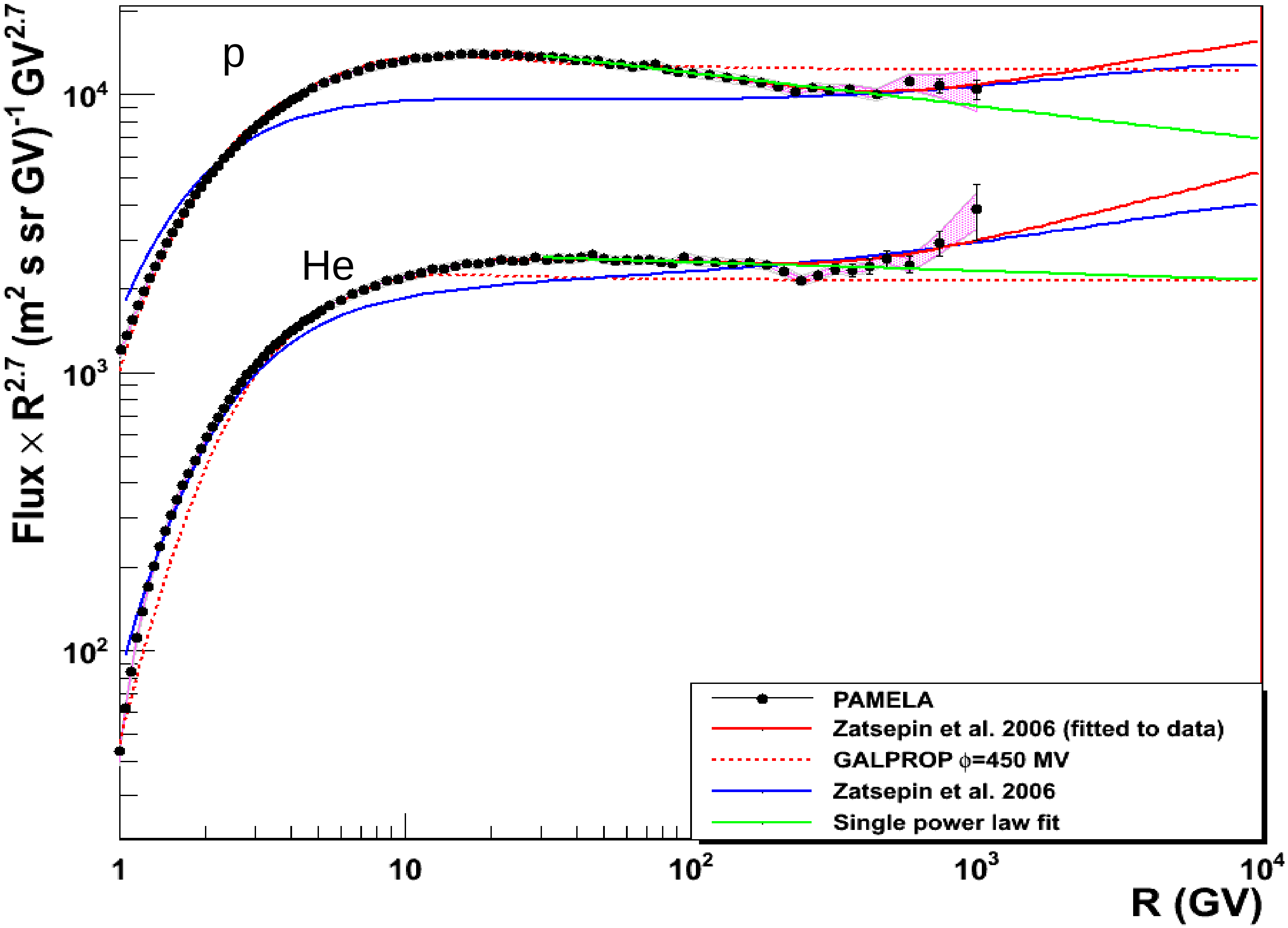


Proton and Helium Nuclei Spectra



Proton and Helium Nuclei Spectra

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



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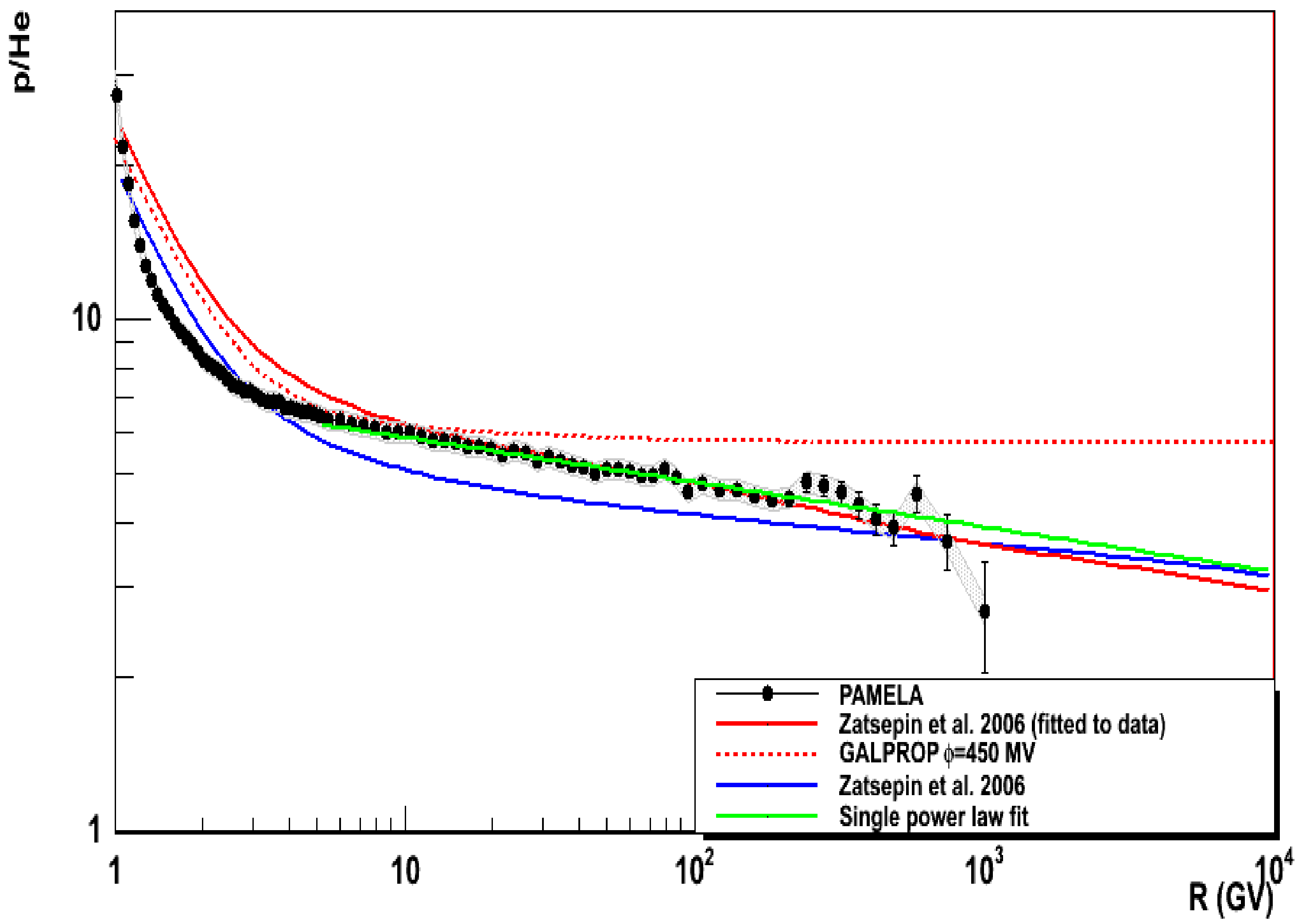
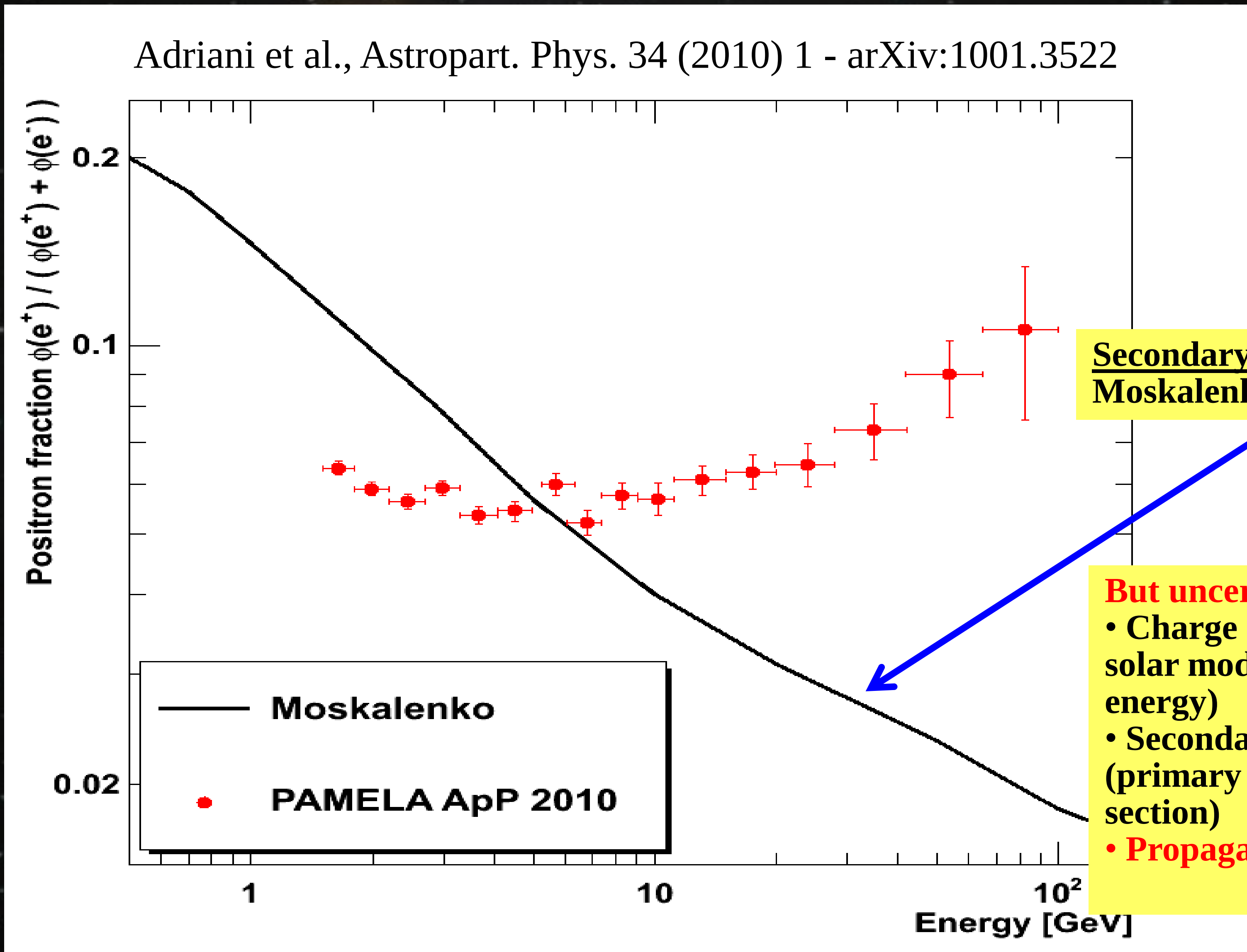


PAMELA Positron Fraction



Secondary production
Moskalenko & Strong 98

But uncertainties on:

- **Charge dependent solar modulation (low energy)**
- **Secondary production (primary fluxes, cross section)**
- **Propagation models**

Boron and Carbon nuclei Spectra

Carbon

Boron

PAMELA B/C

LBM

$$\frac{N_S}{N_P} \propto \lambda_{esc} \cdot \sigma_{P \to S}$$

Preliminary!!

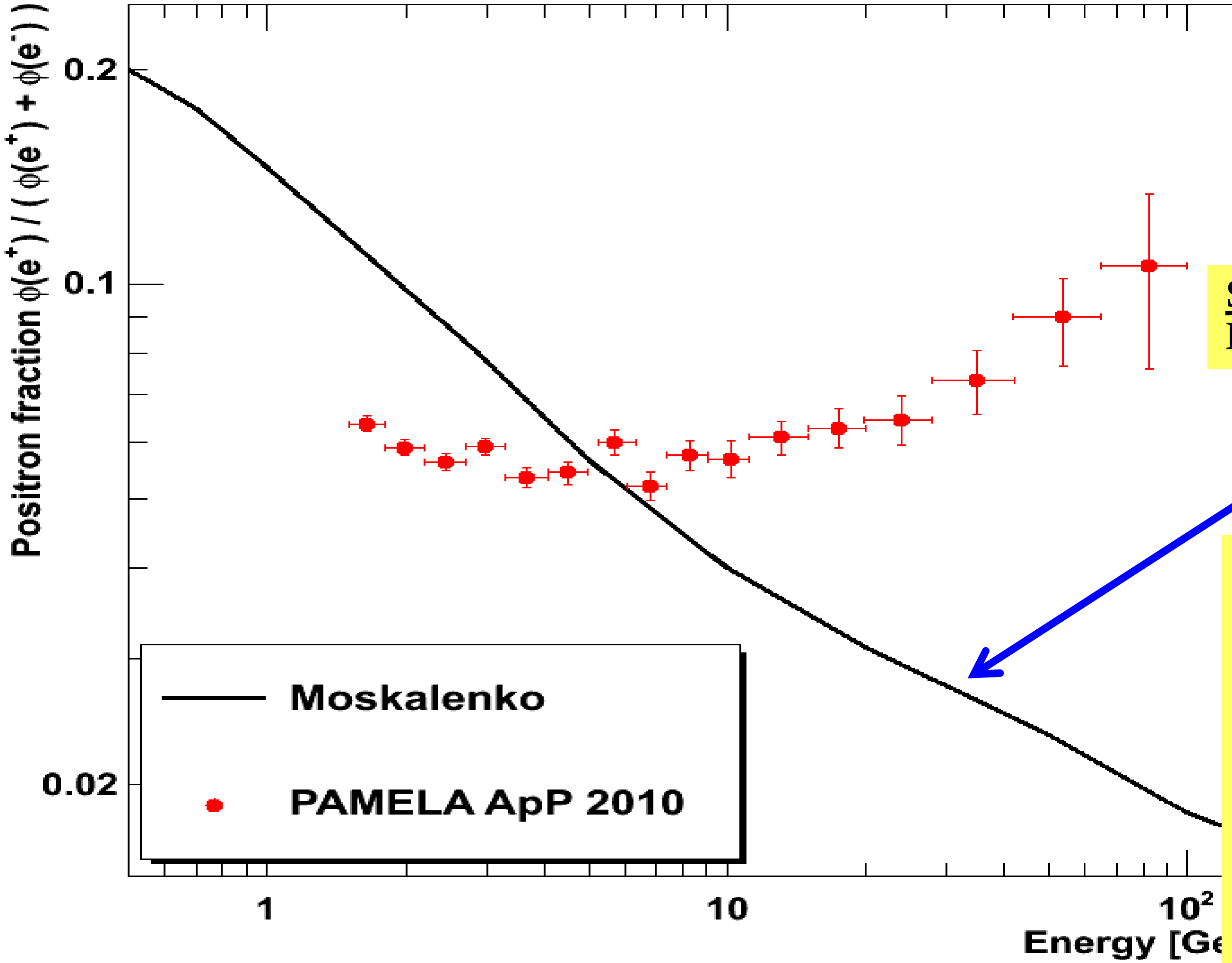
- **B nuclei of secondary origin:**
  CNO + ISM $\rightarrow$ B + …
- **Local secondary/primary ratio sensitive to average amount of traversed matter (λ_{esc}) from the source to the solar system**

<u>Local secondary abundance:</u>
$\Rightarrow$ study of galactic CR propagation

(B/C used for tuning of propagation models)

PAMELA Positron Fraction

Adriani et al., Astropart. Phys. 34 (2010) 1 - arXiv:1001.3522



Secondary production
Moskalenko & Strong 98

But uncertainties on:

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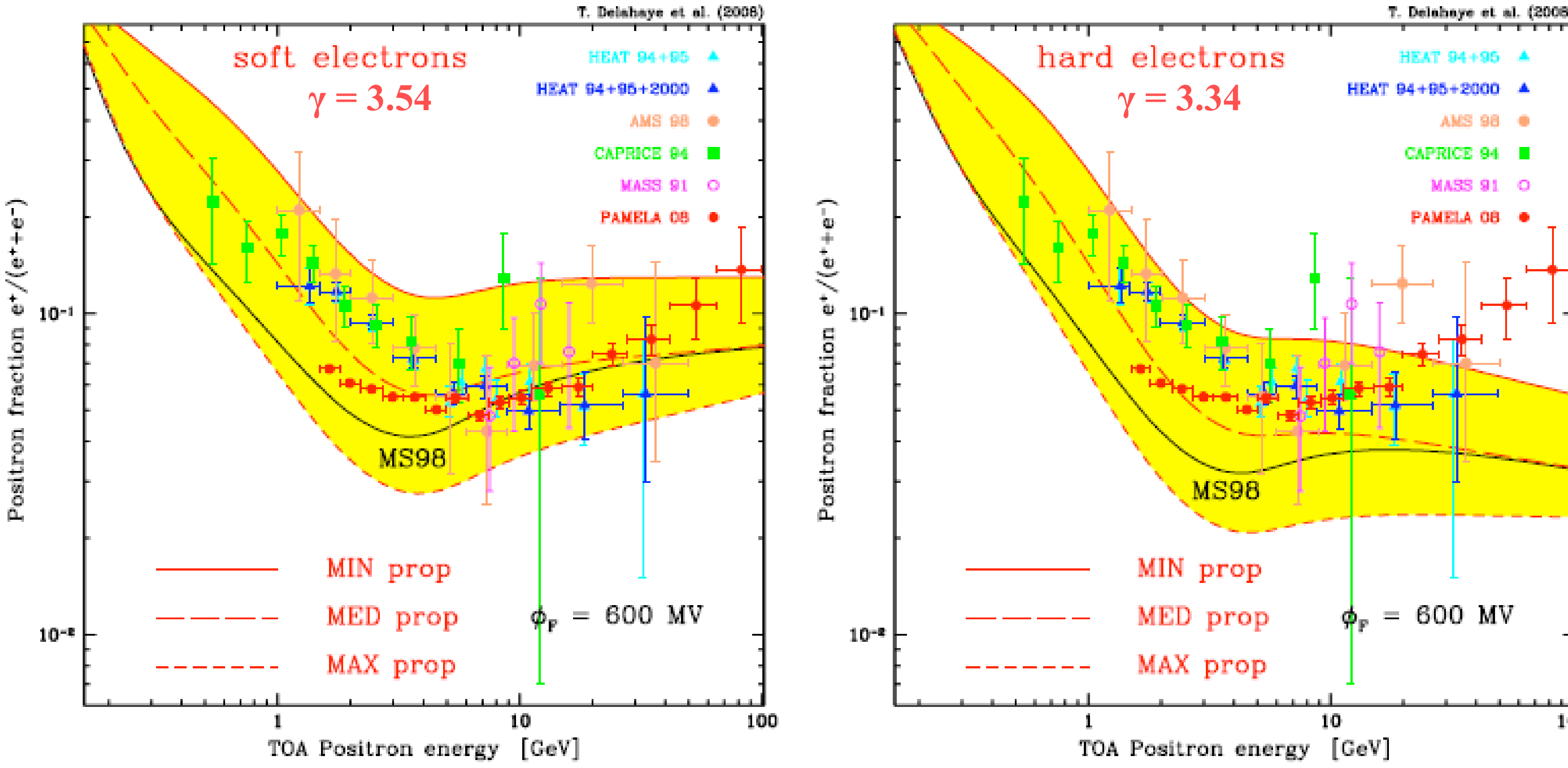
- **Propagation models**
- **Electron (e-) spectrum**

Theoretical uncertainties on "standard" positron fraction

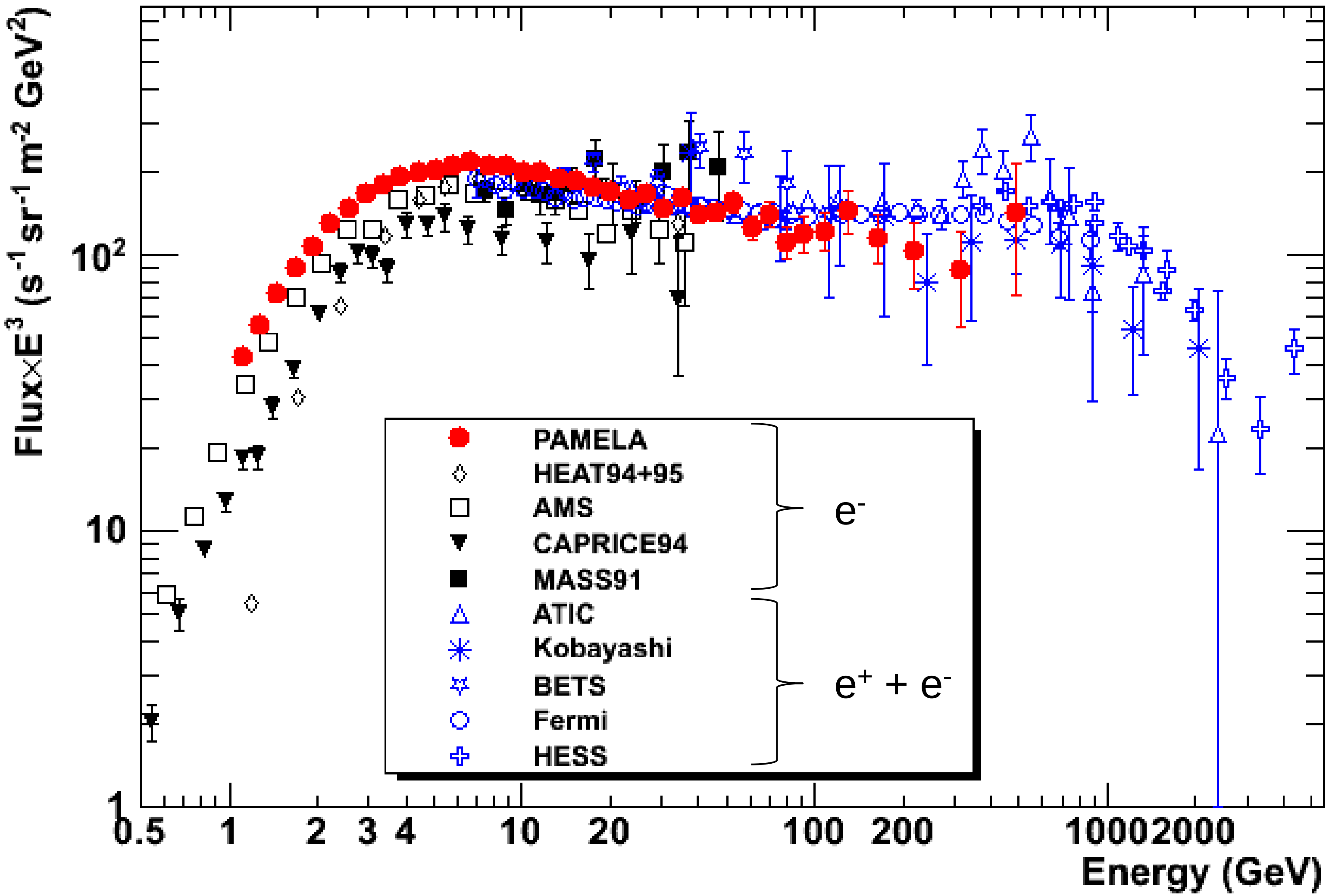


T. Delahaye et al., arXiv: 0809.5268v3

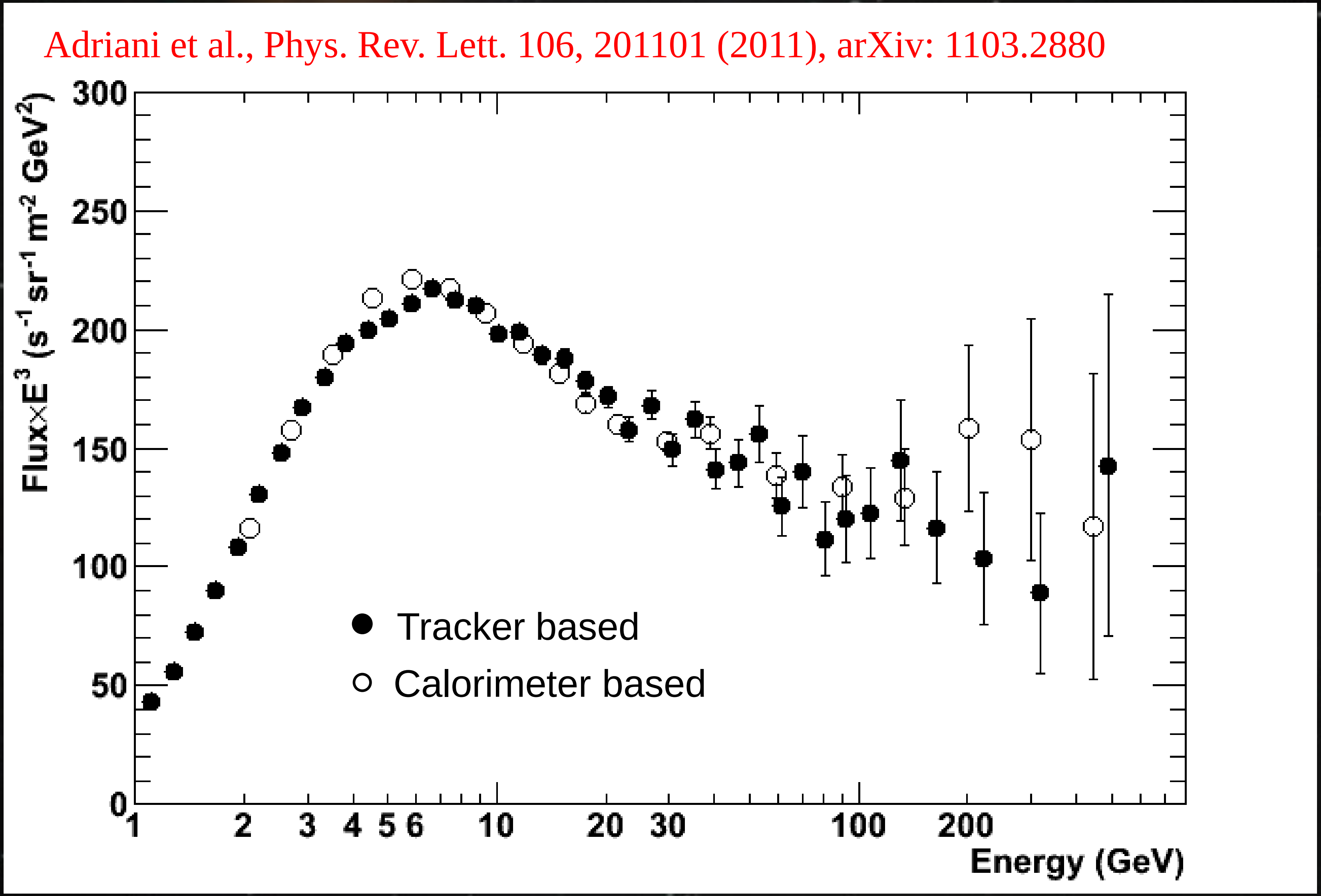
Average of older experiments (pre-PAMELA): $\gamma \sim 3.3$

PAMELA electron (e^-) spectrum

Adriani et al., Phys. Rev. Lett. 106, 201101 (2011), arXiv: 1103.2880



PAMELA electron (e^-) spectrum



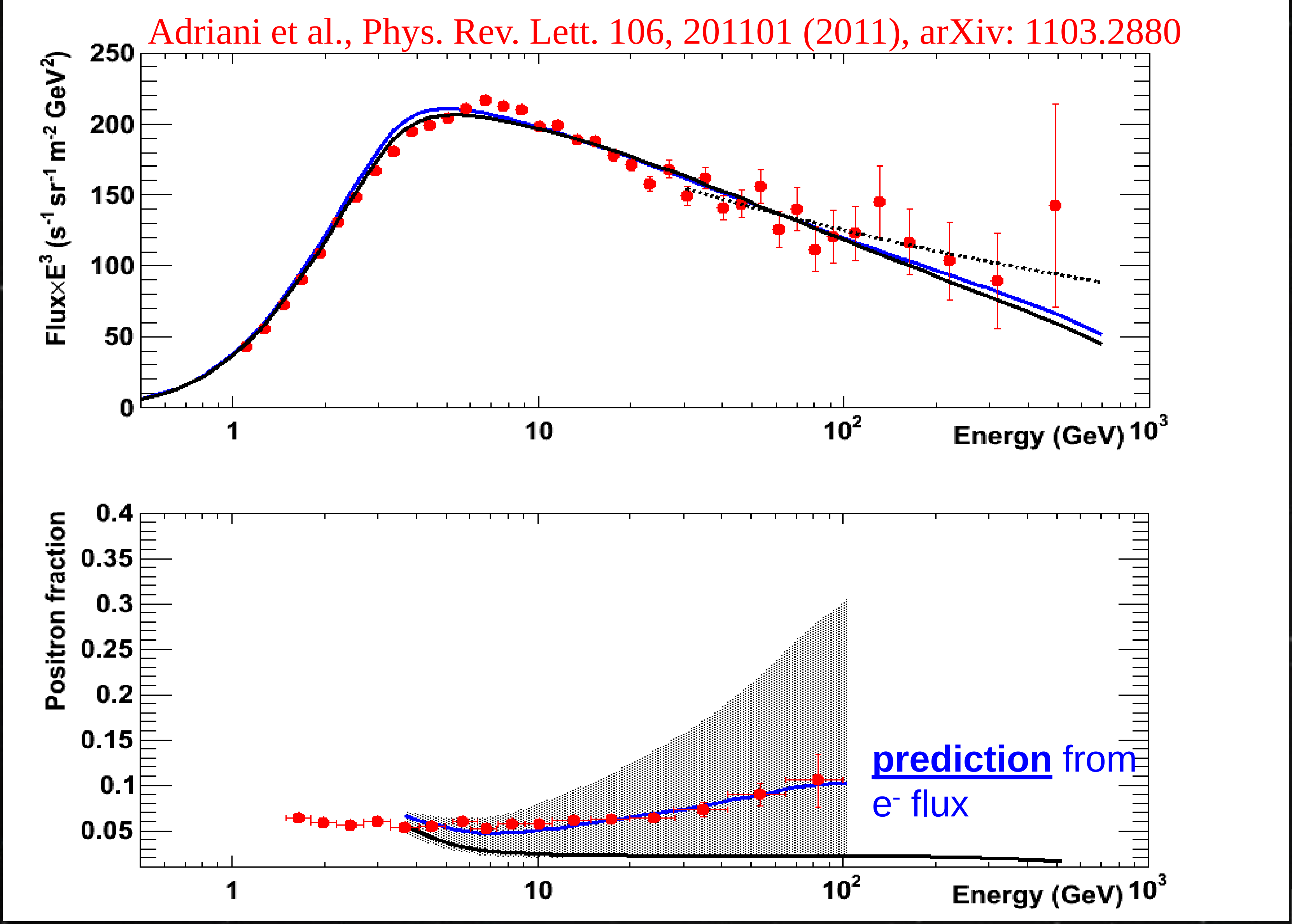
PAMELA positron (e^+) spectrum

Comments on electrons and positrons background

- Background is not known precisely <u>but</u> the positron fraction is expected to decrease with increasing energy.

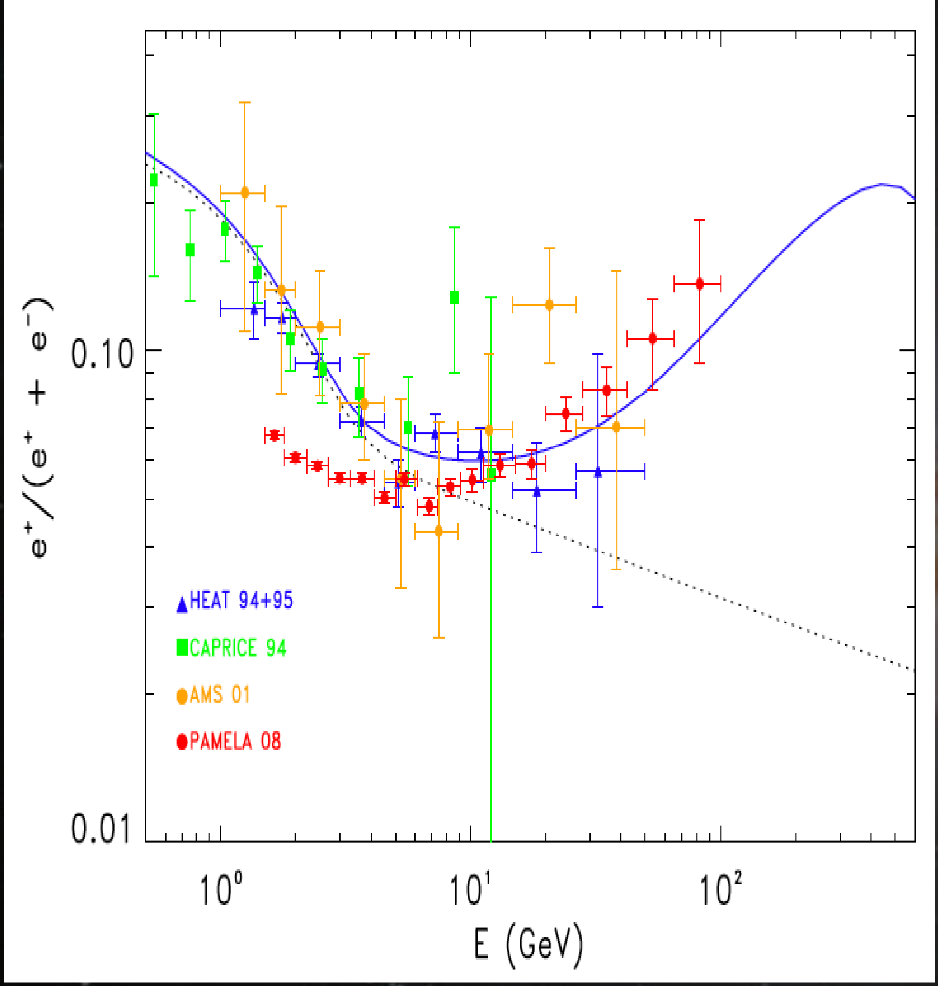
- PAMELA is providing useful set of data needed to better understand the positron measurement, for the first time a single experiment is measuring (with same systematic errors) a wide set of data.

PAMELA electron (e^-) spectrum

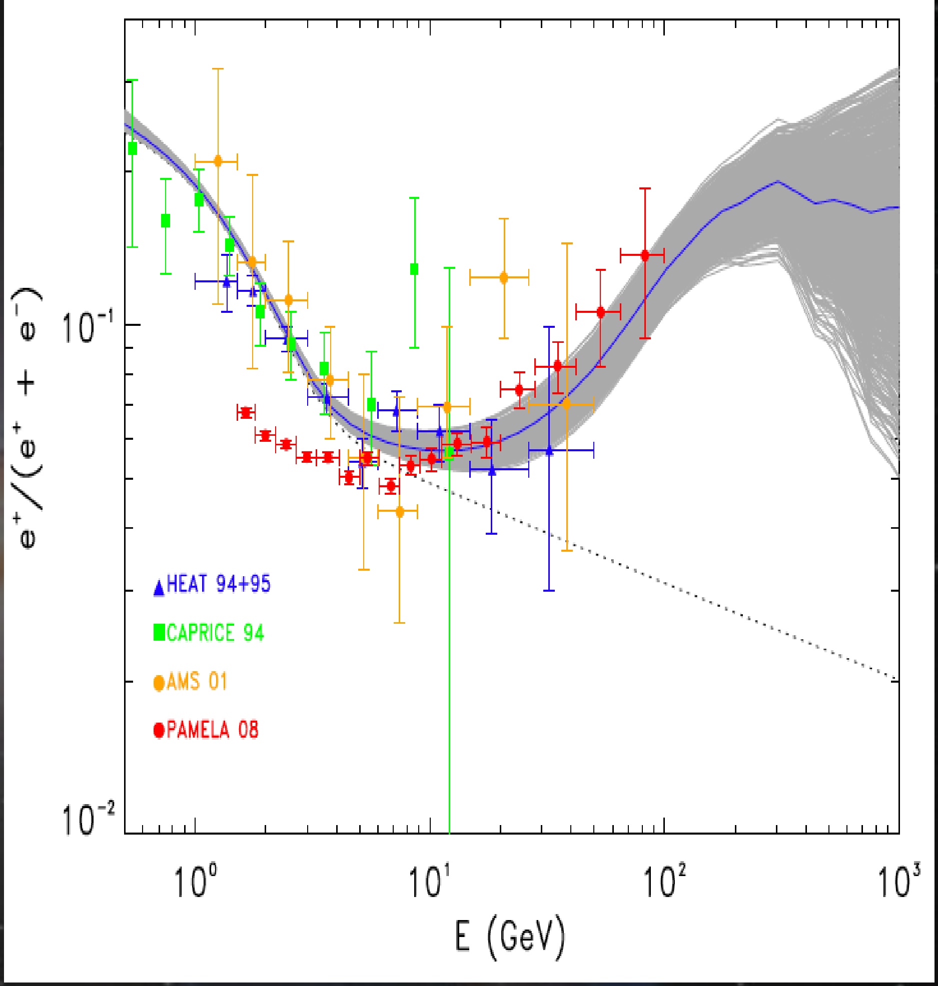


Astrophysical explanations: pulsars

S. Profumo, APS, 050409



Known nearby, mature pulsars and with a single, nominal choice for the e+/e- injection parameters



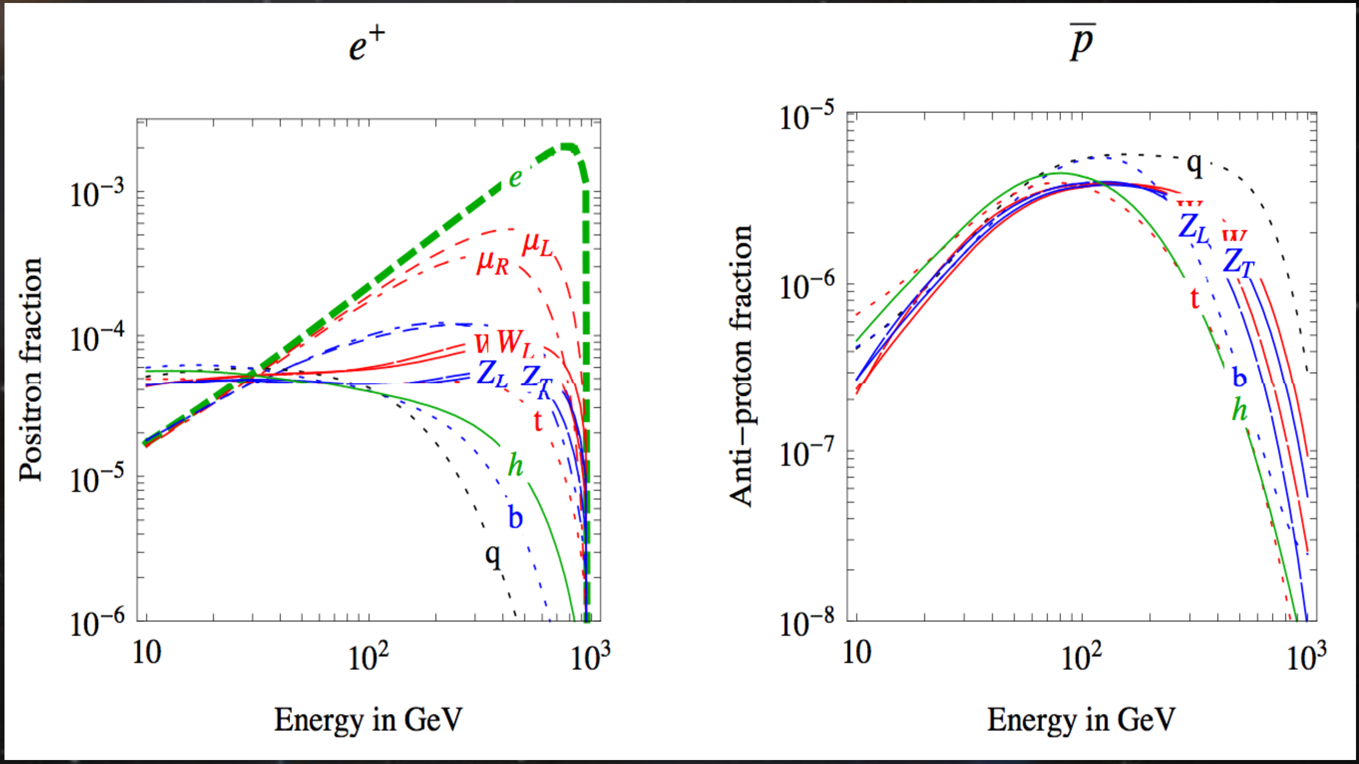
Randomly vary the pulsar parameters relevant for e+e- production (injection spectrum, e+e- production efficiency, PWN "trapping" time)

Dark Matter annihilations

Resulting spectrum for positrons and antiprotons M_{WIMP}= 1 TeV

The flux shape is completely determined by:

1) WIMP mass
2) Annihilations channels



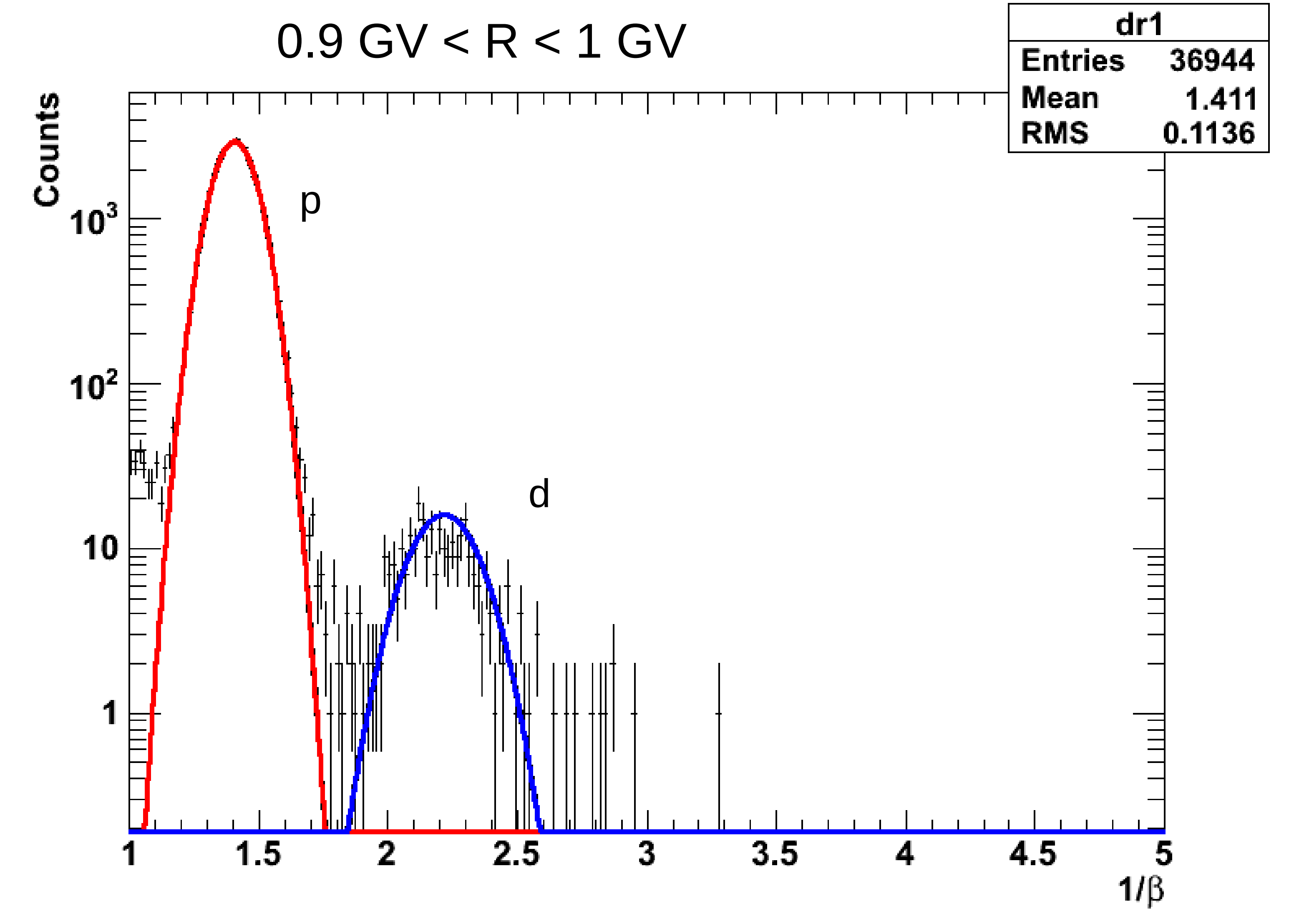
Comparing pulsars with DM

L. Bergström

	Pulsars	Dark Matter
Known to exist?	√	√
Free parameters	Many (order of 100 ?)	4 for PAMELA-consistent models. (2 for branching ratio between different leptons, Mass, E_F)
Basic mechanism to give required flux known?	Maybe. (An unclear point is the escape probability – could be less than 1%)	Yes. Sommerfeld enhancement plus substructure boost
Predictions for electron spectrum	Should show some ”bumpiness” due to different pulsars contributing	Should have universal shape at energies from 100 – 600 GeV, the high-energy spectrum will depend on where in the decay chain e^+e^- are created
”Smoking gun” signature	Bumpiness, perhaps anisotropy (small, percent level)	Diffuse gamma-ray could show an excess starting between 100 – 300 GeV

PAMELA: isotopes, radiation belts, solar physics

H isotopes separation

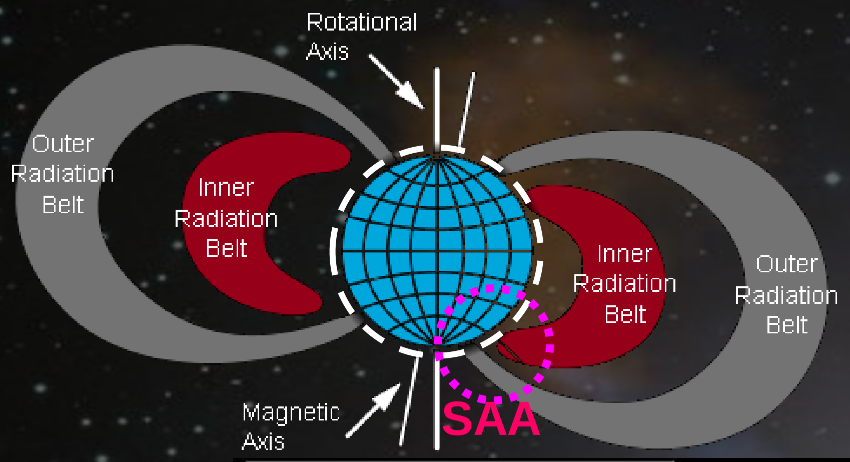


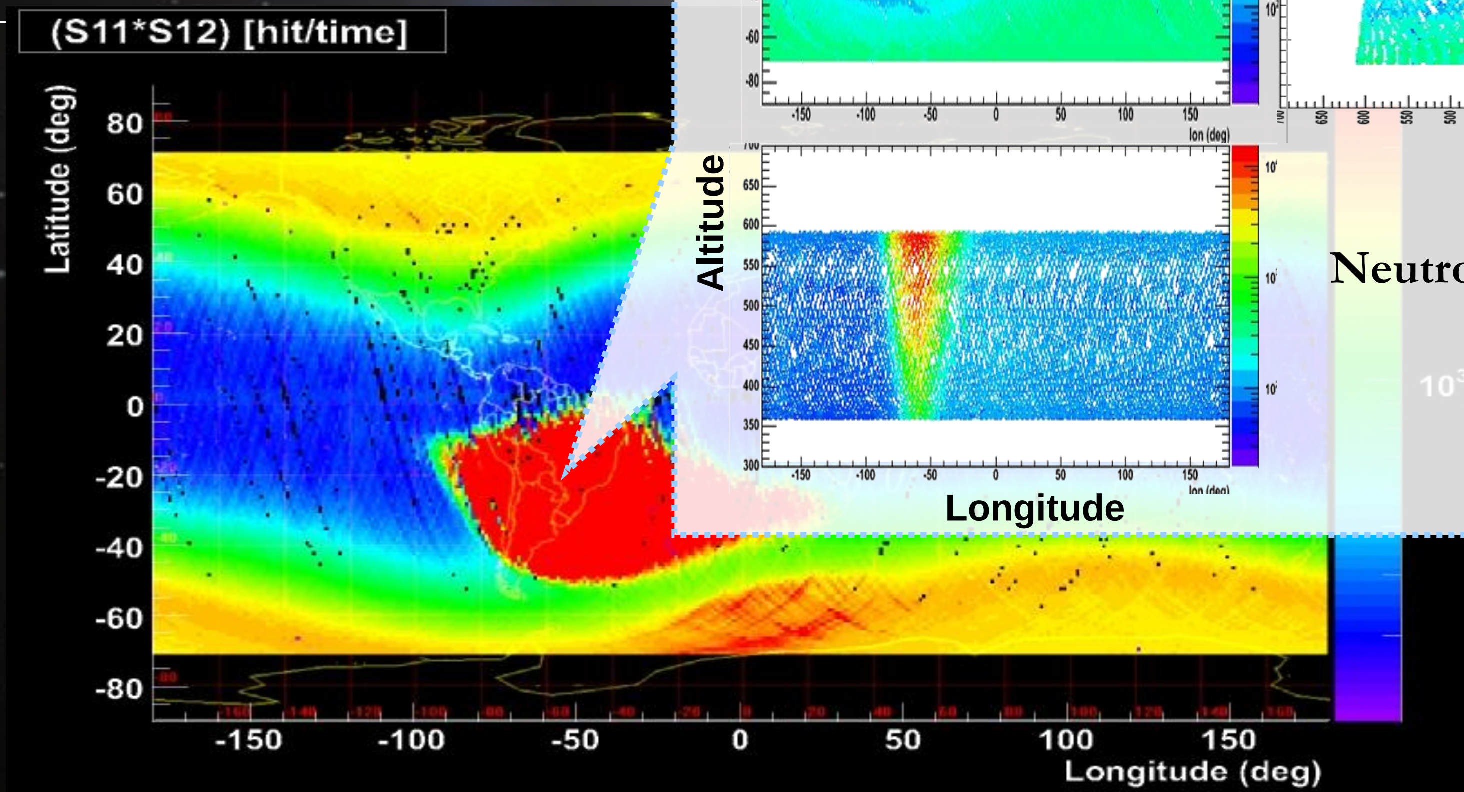
PAMELA d/p

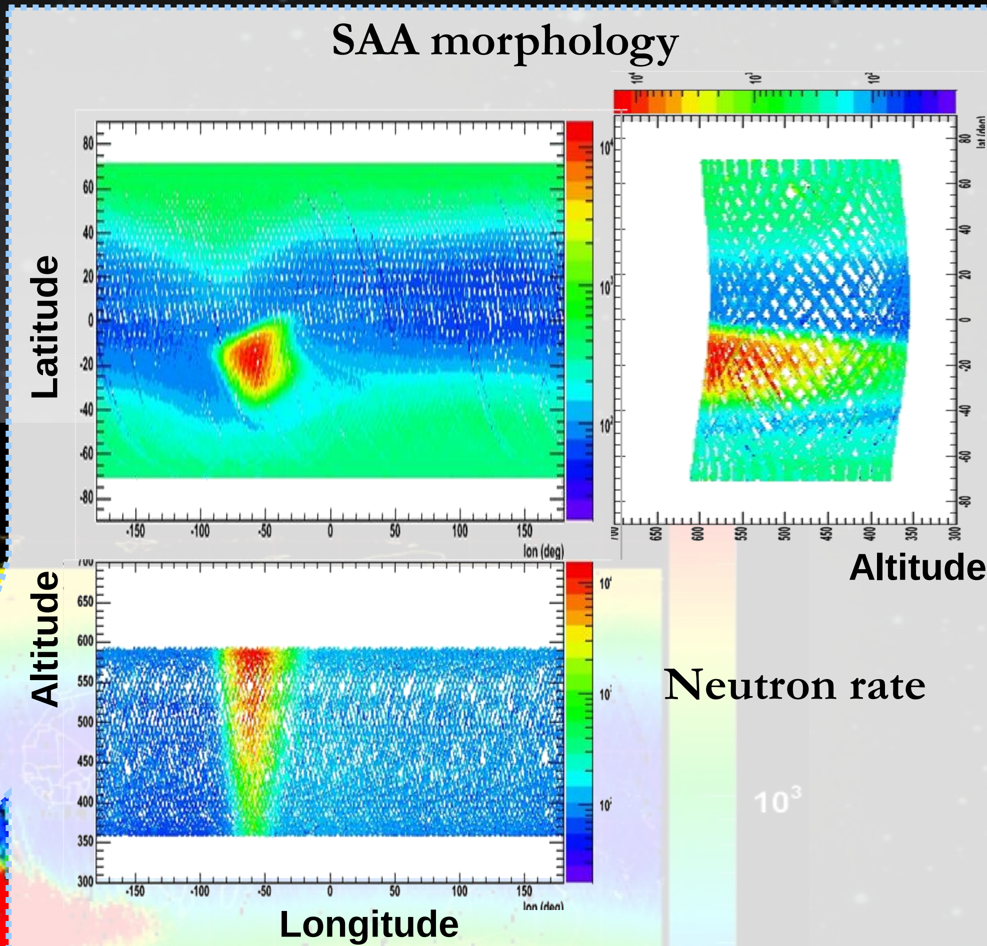
Preliminary

PAMELA $^3He/^4He$

South-Atlantic Anomaly (SAA)





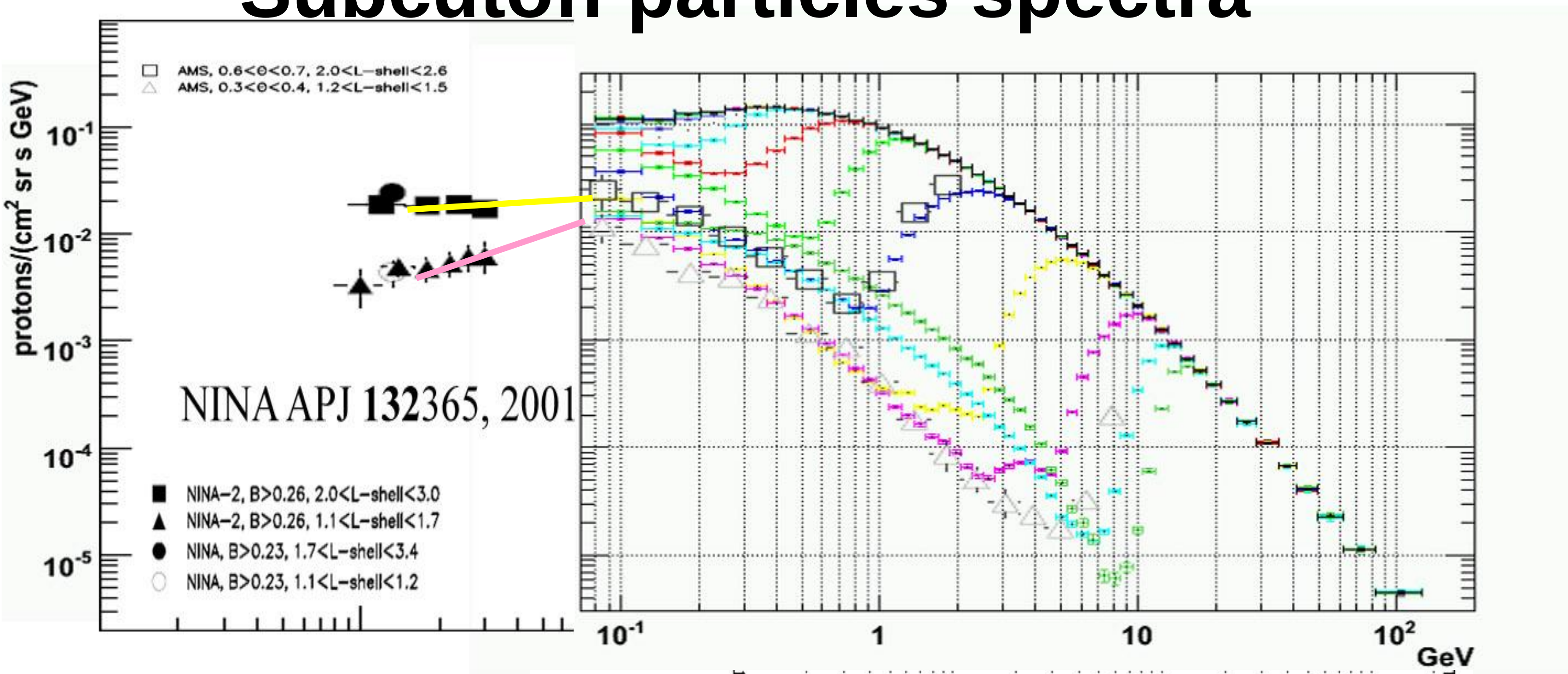


PAMELA trapped antiprotons

Preliminary

Antiprotons inside SAA
Galactic Antiprotons
Antiprotons below cutoff at equator

Subcutoff particles spectra

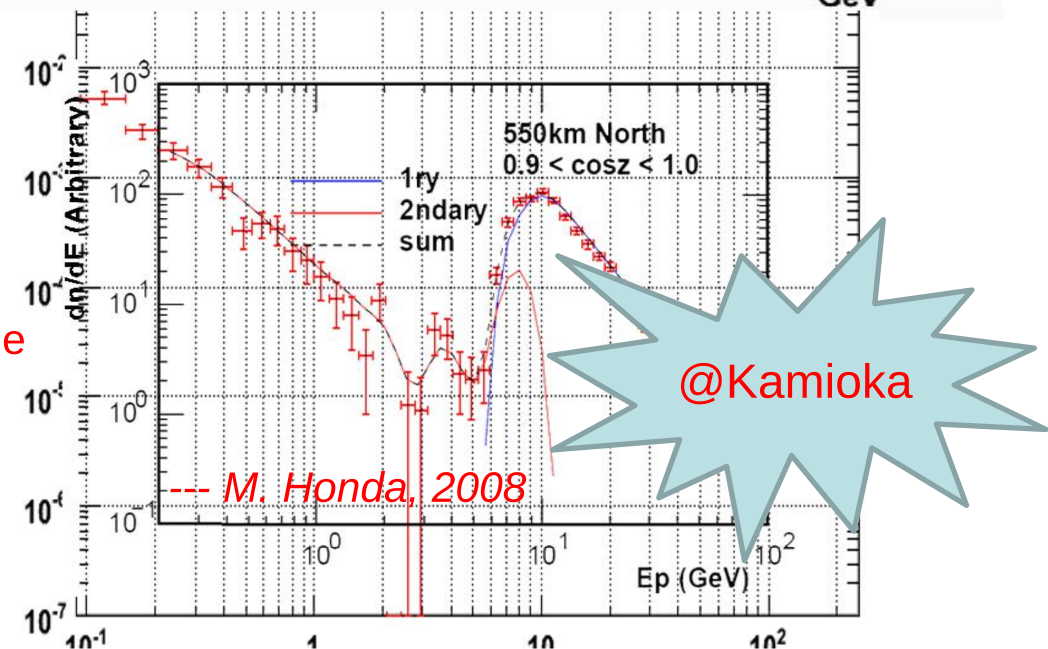


→Atmospheric neutrino contribution

→Astronaut dose on board ISS

→Indirect measurement of cross section in the atmosphere

→ Agile e Glast background estimation



Solar Physics: December 13th 2006 event

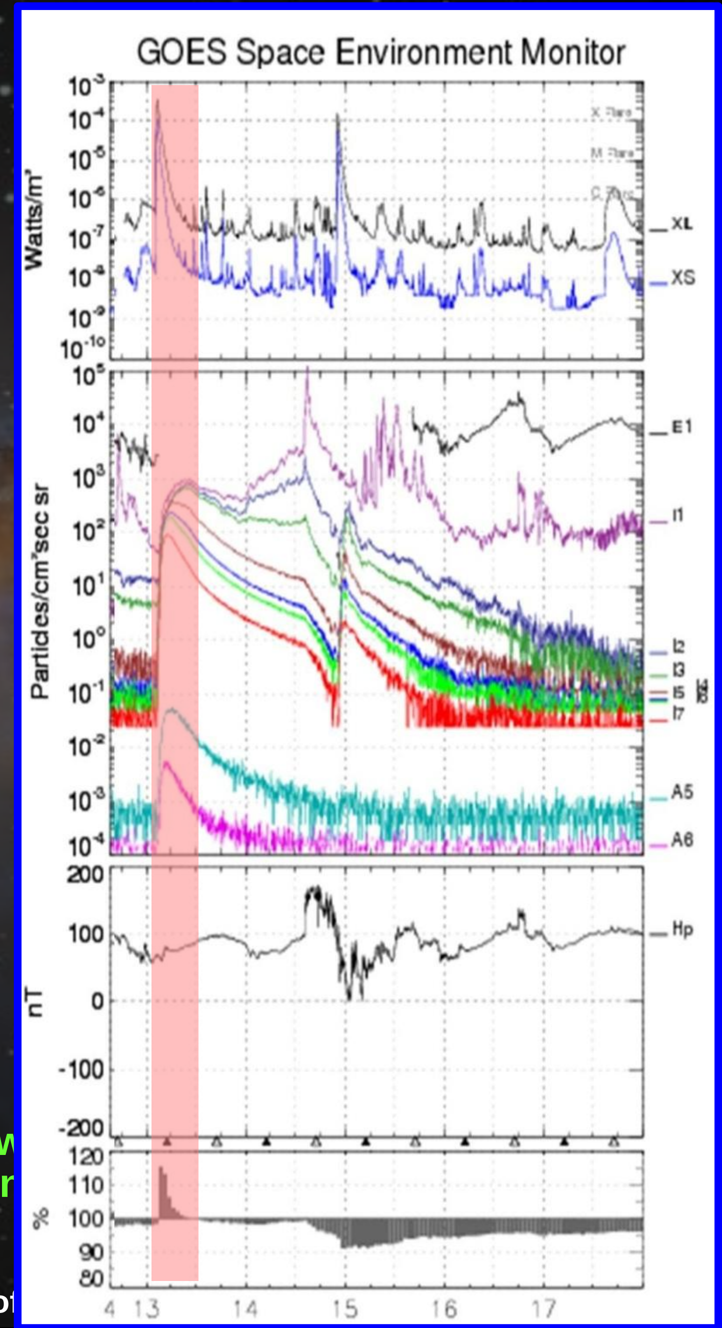
- from 2006-12-1 to 2006-12-4
- from 2006-12-13 00:23:02 to 2006-12-13 02:57:46
- from 2006-12-13 02:57:46 to 2006-12-13 03:49:09
- from 2006-12-13 03:49:09 to 2006-12-13 04:32:56
- from 2006-12-13 04:32:56 to 2006-12-13 04:59:16
- from 2006-12-13 08:17:54 to 2006-12-13 09:17:34

Decrease of high energy component

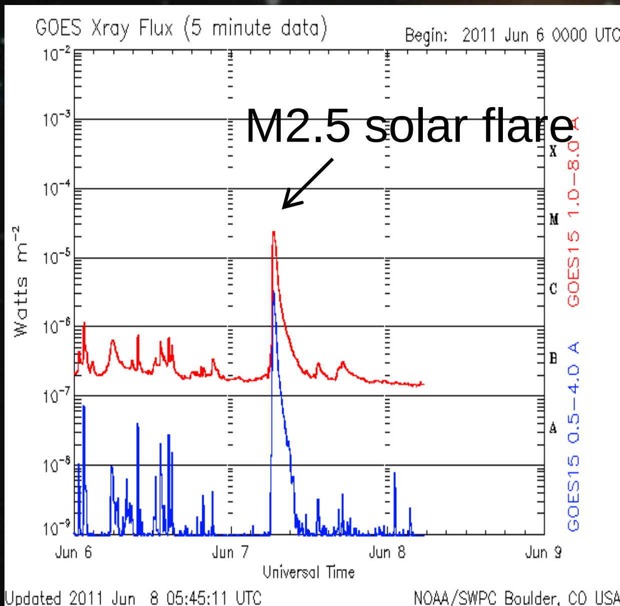
Increase of low energy component

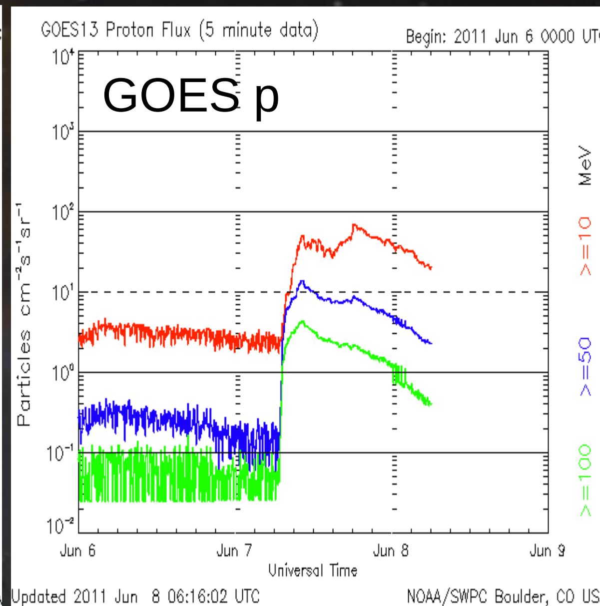
Preliminary

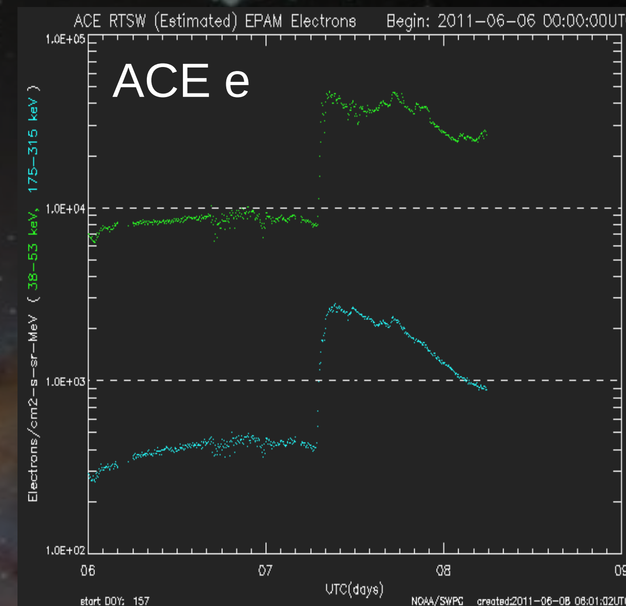
Increase of low energy compor

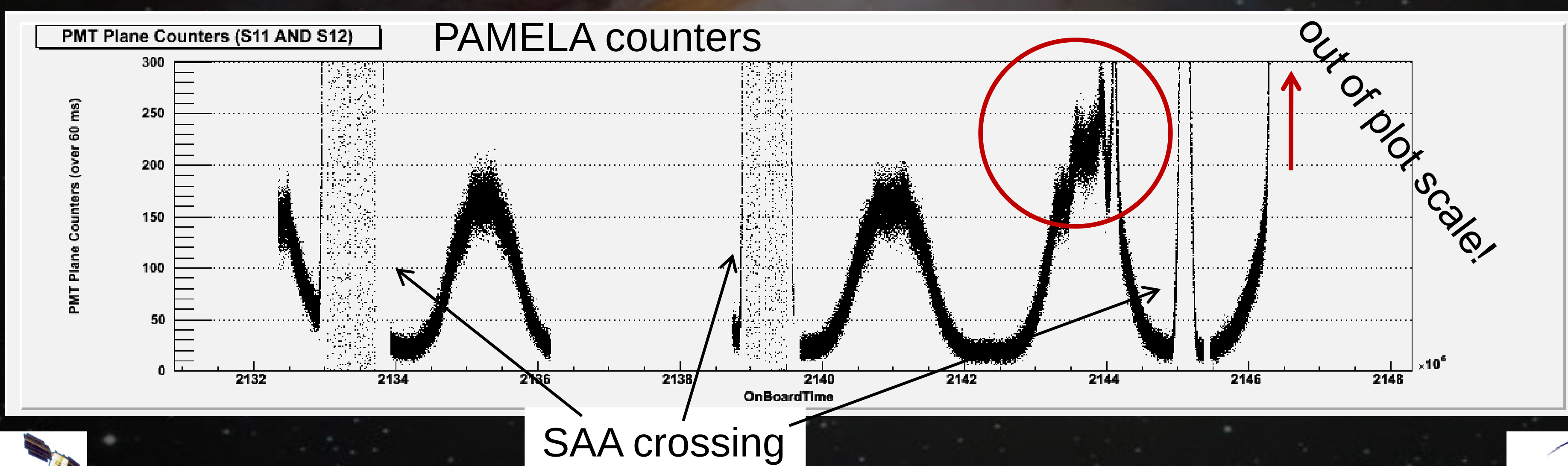


Solar Physics: now









Summary

- PAMELA has been in orbit and studying cosmic rays for 1821 days (~5 years). >10^9 triggers registered and >19 TB of data has been down-linked.

- Antiproton-to-proton flux ratio and antiproton energy spectrum (~100 MeV - ~200 GeV) show no significant deviations from secondary production expectations.

- High energy positron fraction (>10 GeV) increases significantly (and unexpectedly!) with energy. Primary source?

- The e^- spectrum up to 600 GeV shows spectral features that may point to additional components.

- Analysis ongoing to finalize the antiparticle measurements (positron flux, positron fraction), continuous study of solar modulation effects at low energy.

- AMS launched! waiting for results to compare contemporary measurements.