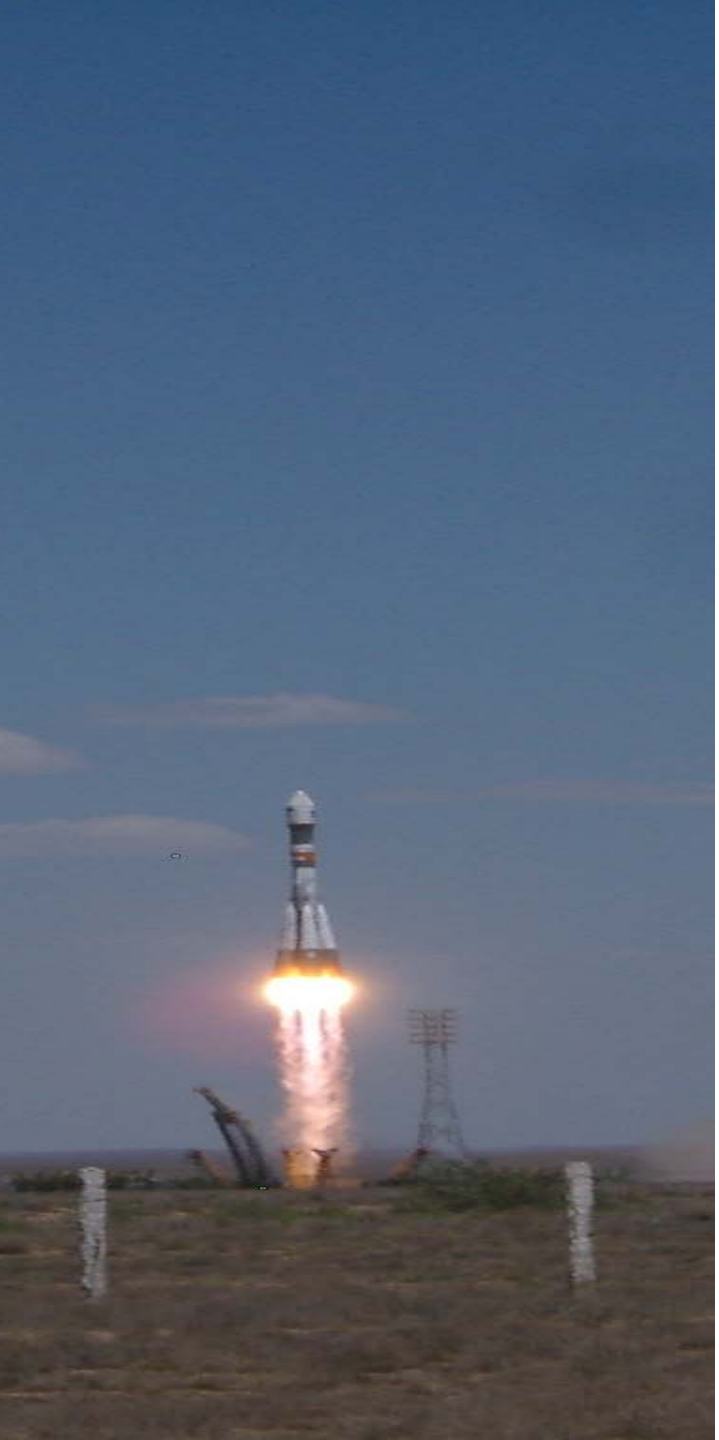


# Indirect Detection of Dark Matter with PAMELA

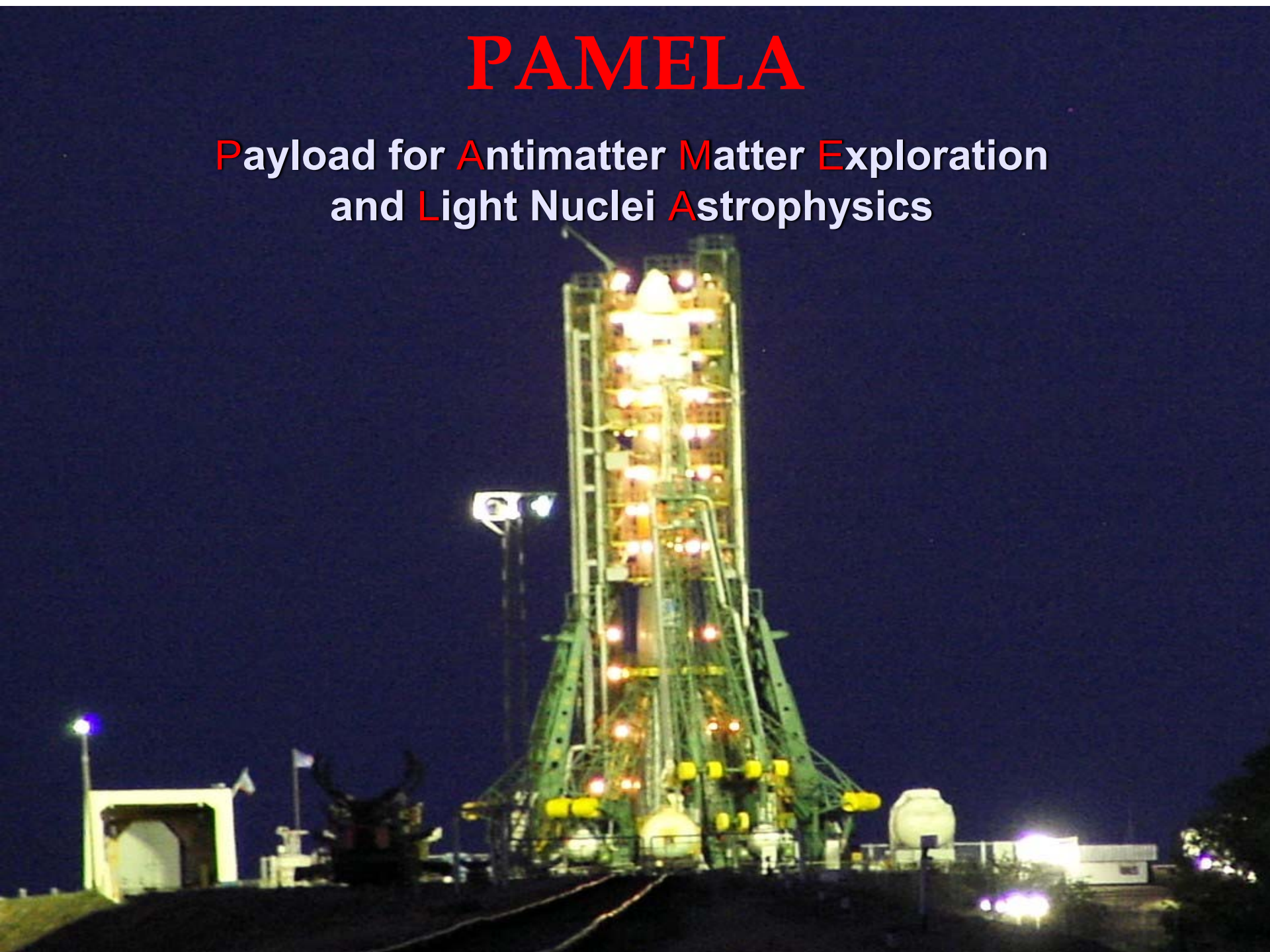

**Mirko Boezio**
*INFN Trieste, Italy*


**On behalf of the PAMELA collaboration**

**LHC and Dark Matter Workshop**
*January 6th 2009*

# PAMELA

**Payload for Antimatter Matter Exploration and Light Nuclei Astrophysics**



# PAMELA Collaboration

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

Russia:

Moscow
St. Petersburg

Germany:

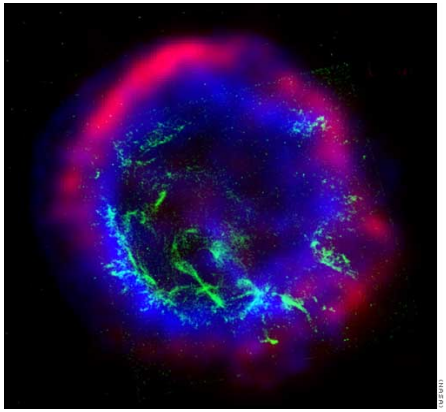
Siegen

Sweden:

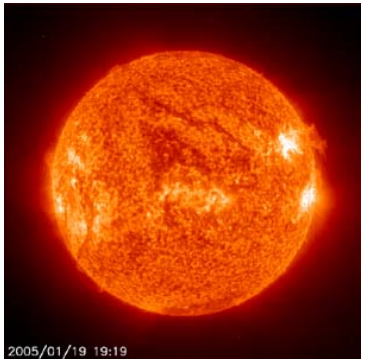
KTH, Stockholm

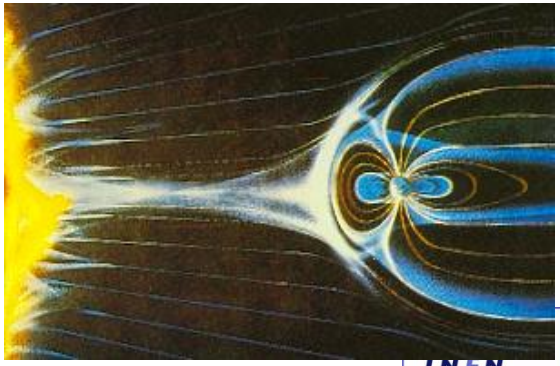
# Scientific goals

- **Search for dark matter annihilation**
- **Search for antihelium (primordial antimatter)**

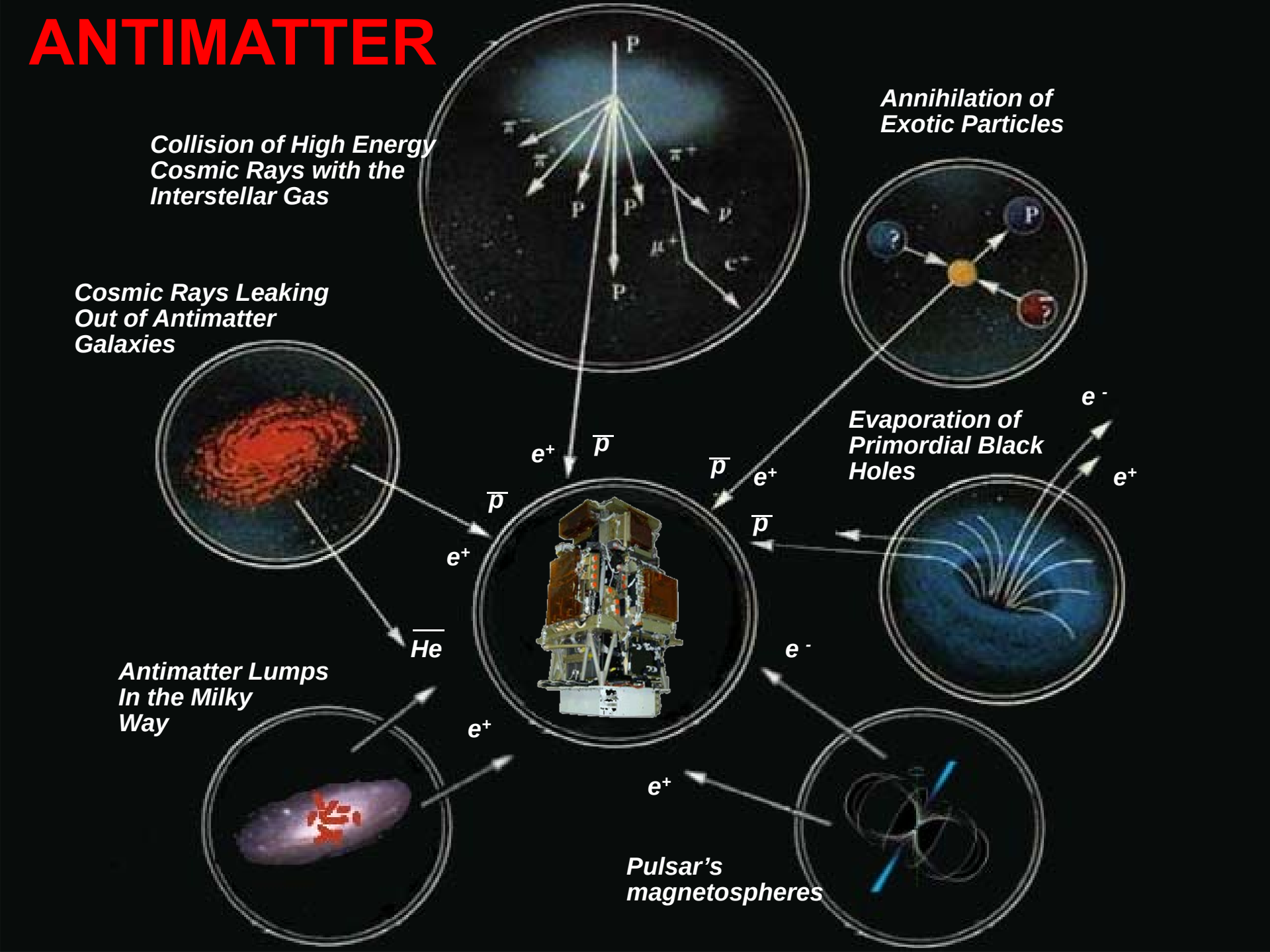


- **Study of cosmic-ray propagation (light nuclei and isotopes)**
- **Study of electron spectrum (local sources?)**
- **Study solar physics and solar modulation**
- **Study terrestrial magnetosphere**



# ANTIMATTER


Collision of High Energy Cosmic Rays with the Interstellar Gas
Annihilation of Exotic Particles
Cosmic Rays Leaking Out of Antimatter Galaxies
Evaporation of Primordial Black Holes
Antimatter Lumps In the Milky Way
Pulsar's magnetospheres
P
e+
e -
p
He

# PAMELA detectors

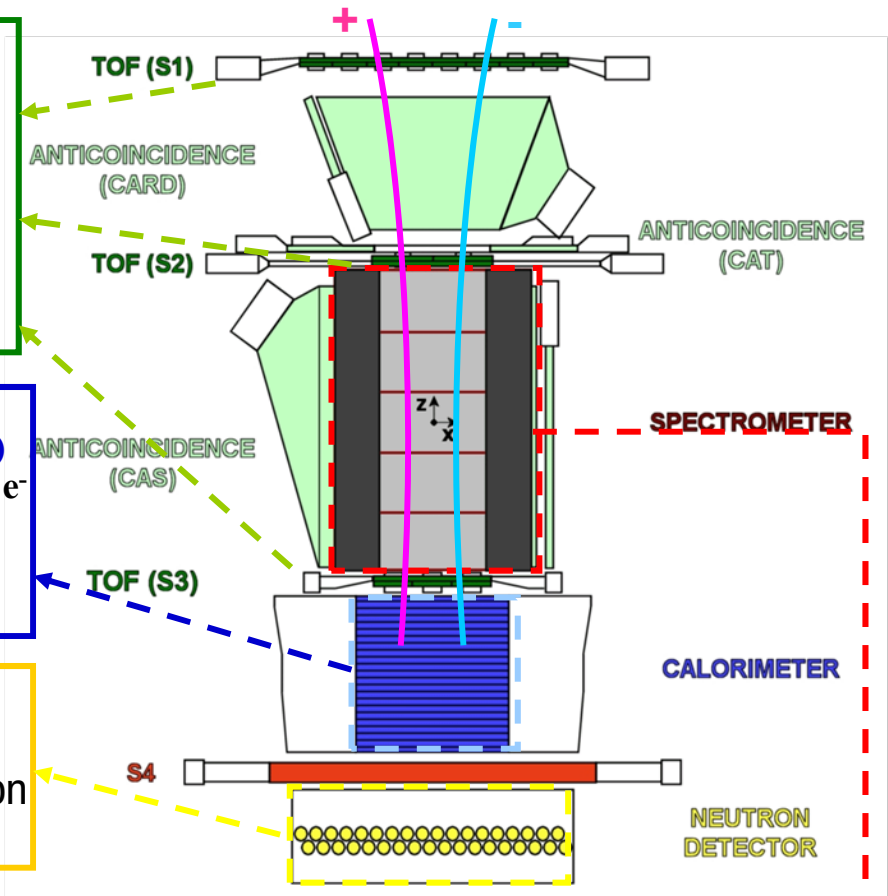
**Main requirements → high-sensitivity antiparticle identification and precise momentum measure**

**GF: 21.5 cm² sr**
**Mass: 470 kg**
**Size: 130x70x70 cm³**
**Power Budget: 360W**

**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 λI)**
- **Discrimination e+ / p, anti-p / e⁻ (shower topology)**
- **Direct E measurement for e⁻**

Neutron detector
plastic scintillators + PMT:
- High-energy e/h discrimination



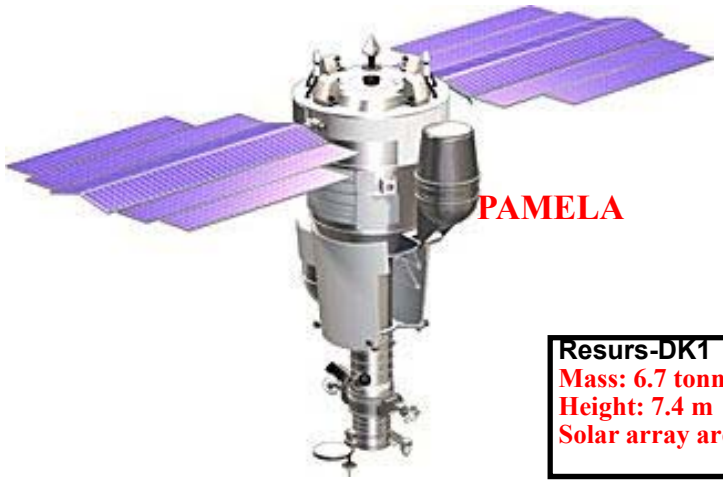

**Spectrometer**
**microstrip silicon tracking system + permanent magnet**
**It provides:**
- ***Magnetic rigidity*** → **R = pc/Ze**
- ***Charge sign***
- ***Charge value from dE/dx***

# Design Performance

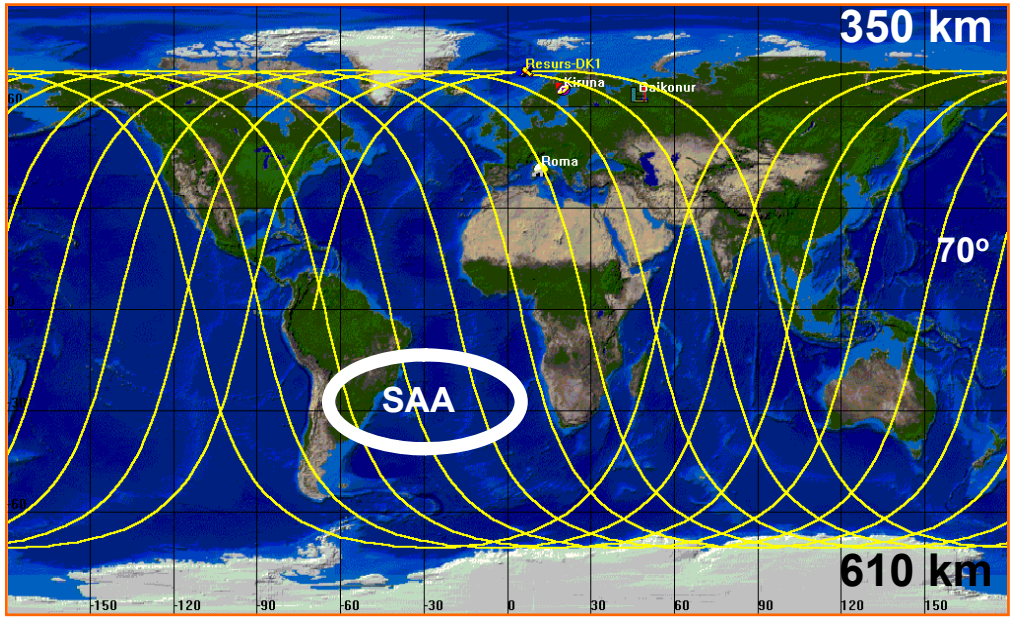
| | energy range |
|---|---|
| • Antiprotons | 80 MeV - 150 GeV |
| • Positrons | 50 MeV – 300 GeV |
| • Electrons | up to 500 GeV |
| • Protons | up to 700 GeV |
| • Electrons+positrons | up to 2 TeV (from calorimeter) |
| • Light Nuclei (He/Be/C) | up to 200 GeV/n |
| • AntiNuclei search | sensitivity of $3 \times 10^{-8}$ in $\overline{\text{He}}$/He |

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

# Resurs-DK1 satellite + orbit




**Resurs-DK1**
Mass: 6.7 tonnes
Height: 7.4 m
Solar array area: 36 m²




~90 mins

- Resurs-DK1: multi-spectral imaging of earth's surface
- PAMELA mounted inside a pressurized container
- Lifetime >3 years (assisted)
- 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)
- Traverses the South Atlantic Anomaly
- Crosses the outer (electron) Van Allen belt at south pole

# PAMELA milestones

Launch from Baikonur → June 15th 2006, 0800 UTC.

'First light' → June 21st 2006, 0300 UTC.

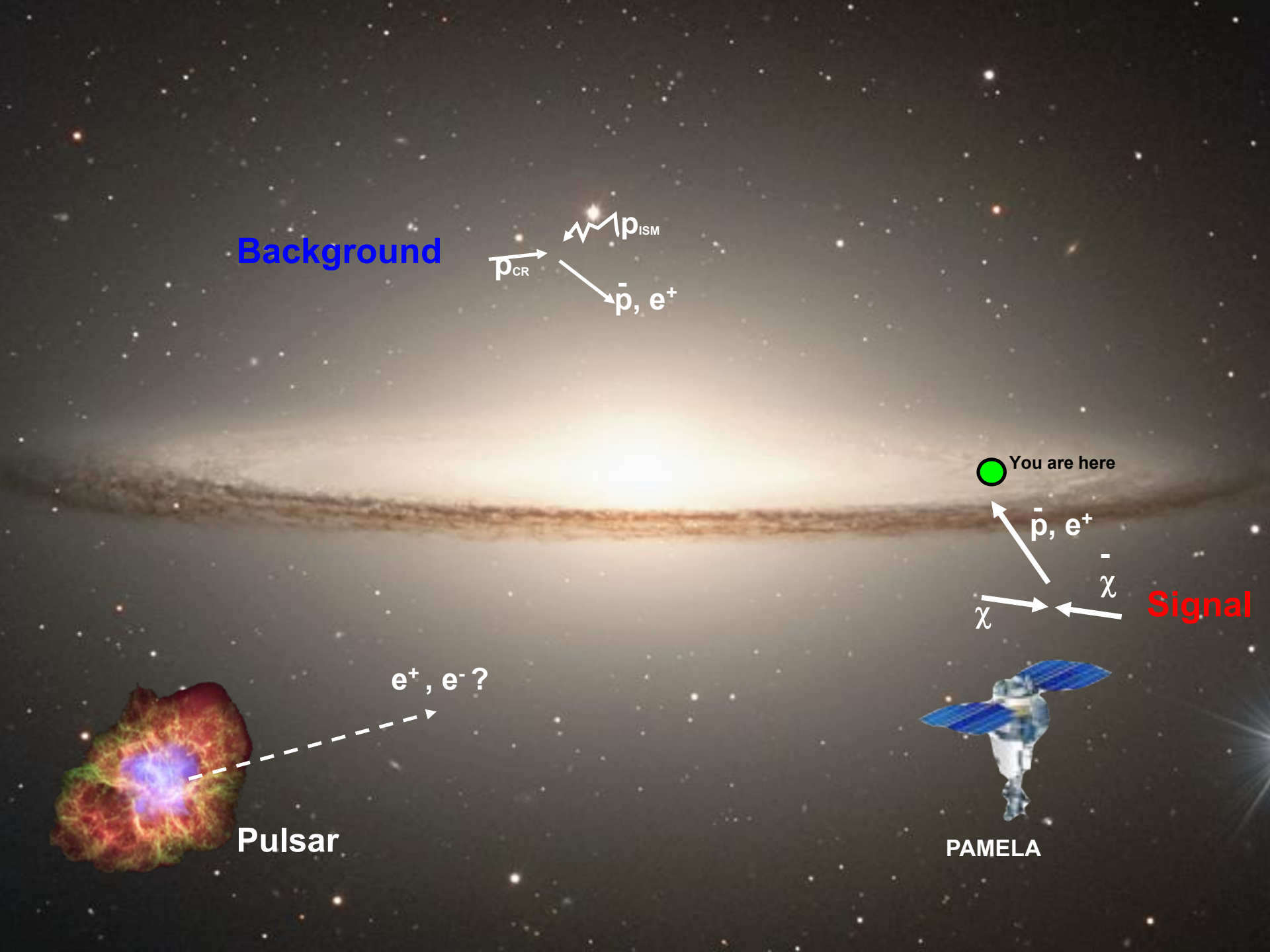
- Detectors operated as expected after launch
- Different trigger and hardware configurations evaluated

→ PAMELA in continuous data-taking mode since commissioning phase ended on July 11th 2006

*Main antenna in NTsOMZ*

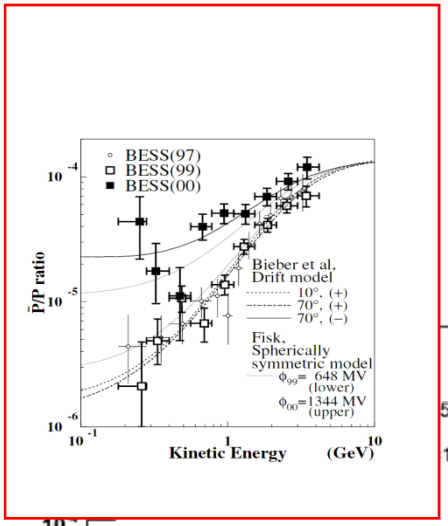
Trigger rate* ~25Hz
Fraction of live time* ~ 75%
Event size (compressed mode) ~5kB
25 Hz x 5 kB/ev → ~ 10 GB/day
(*outside radiation belts)

Till ~now:
~700 days of data taking
~12 TByte of raw data downlinked
~$12 \cdot 10^8$ triggers recorded and analyzed
(Data from April till now under analysis)

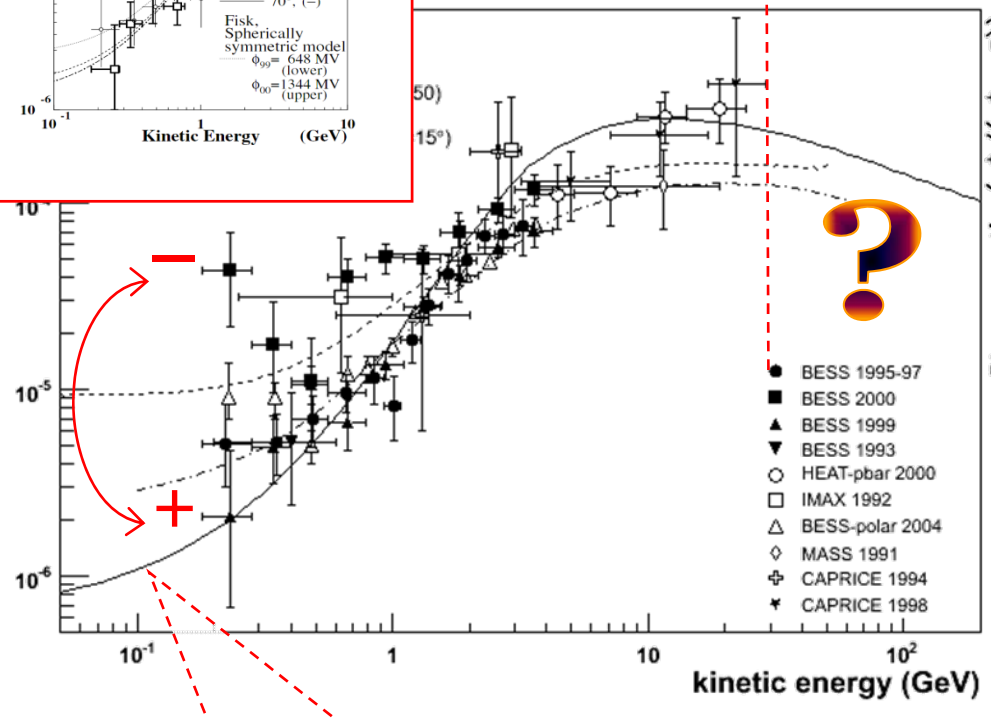

Background
$p_{ISM}$
$p_{CR}$
$\bar{p}$, $e^+$
You are here
$\bar{p}$, $e^+$
$\bar{\chi}$
$\chi$
Signal
$e^+$ , $e^-$ ?
Pulsar
PAMELA

# CR antimatter

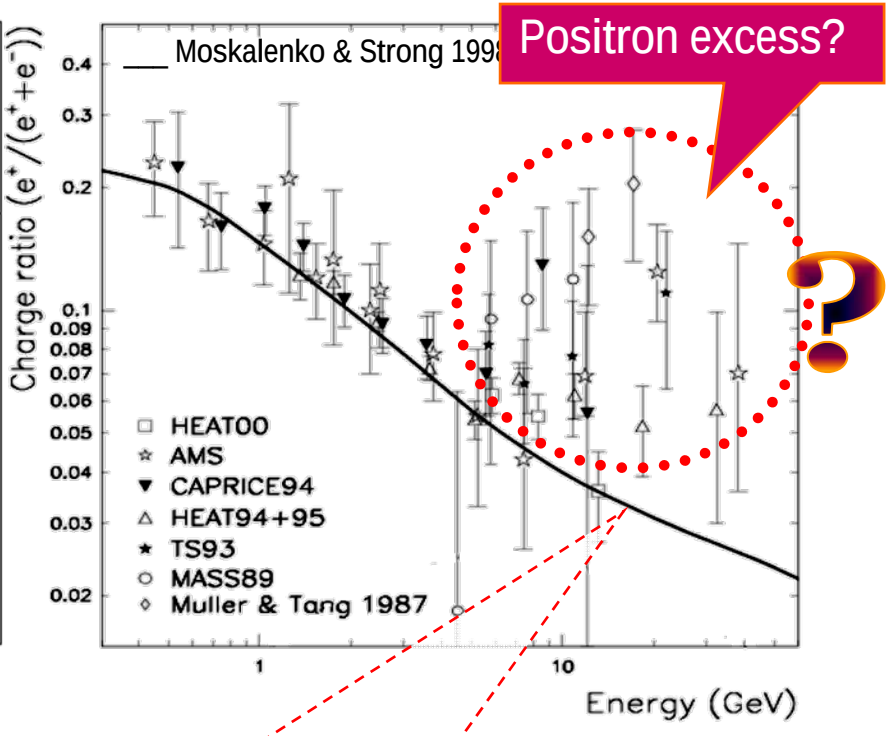
## Present status




### Antiprotons




### Positrons




CR + ISM → **p-bar** + …

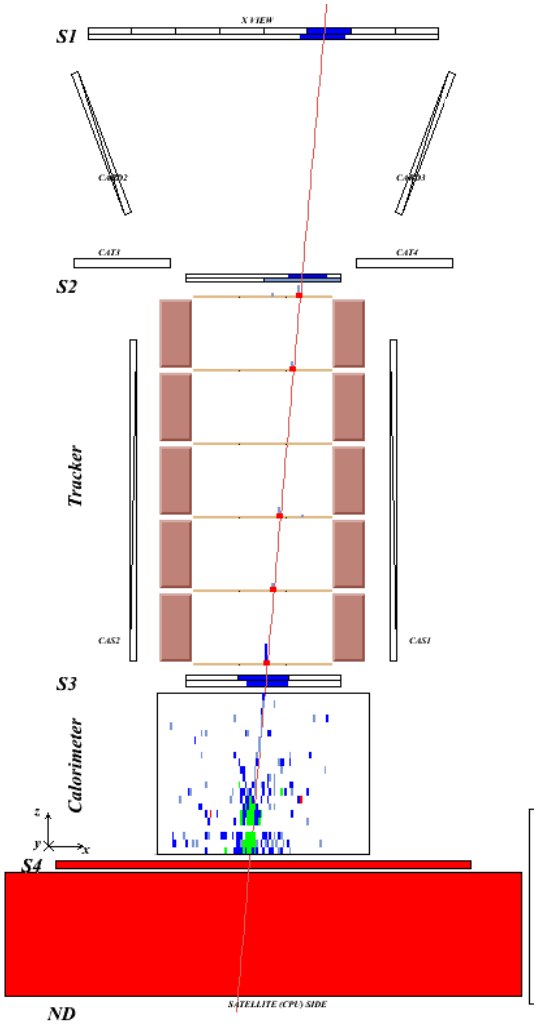
kinematic treshold:
5.6 GeV for the reaction

$pp \rightarrow \bar{p}ppp$

CR + ISM → $\pi^{\pm}$ + x → $\mu^{\pm}$ + x → $e^{\pm}$ + x

CR + ISM → $\pi^0$ + x → $\gamma\gamma$ → $e^{\pm}$

# Antiproton / positron identification



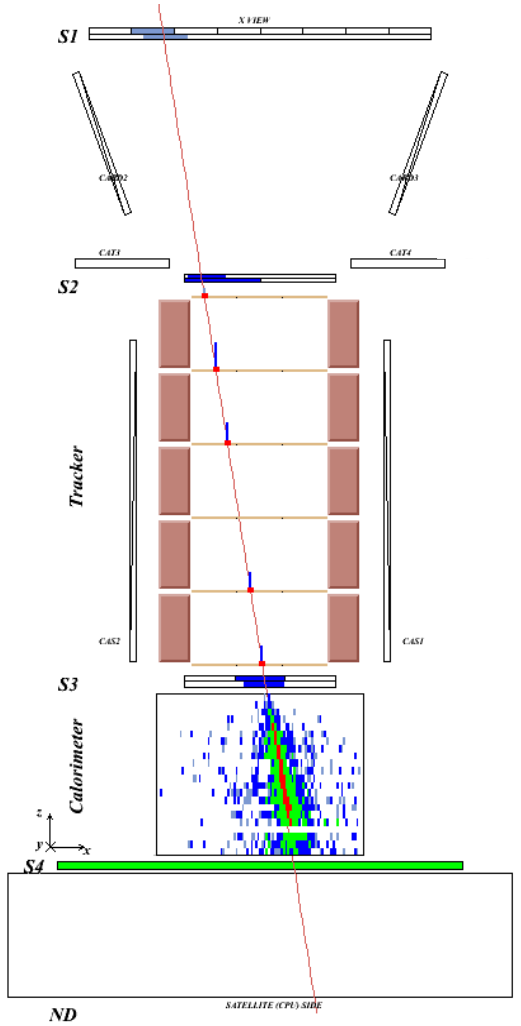

**Antiproton**
**(NB: $e^-/p \sim 10^2$)**

**Time-of-flight:** trigger, albedo rejection, mass determination (up to 1 GeV)

**Bending in spectrometer:** sign of charge

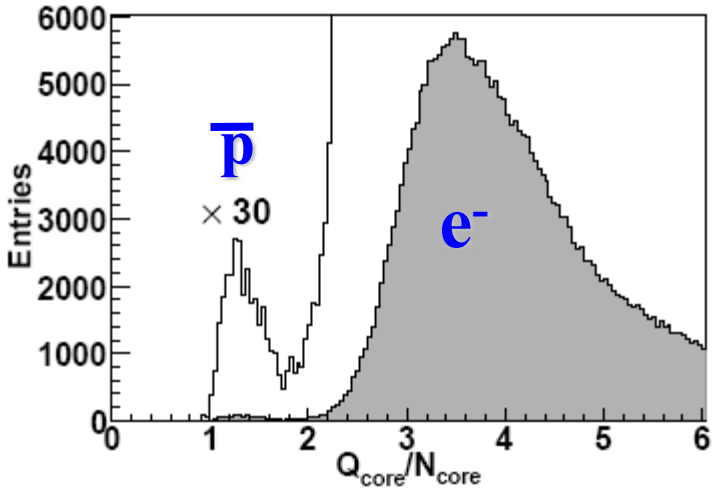
**Ionisation energy loss (dE/dx):** magnitude of charge

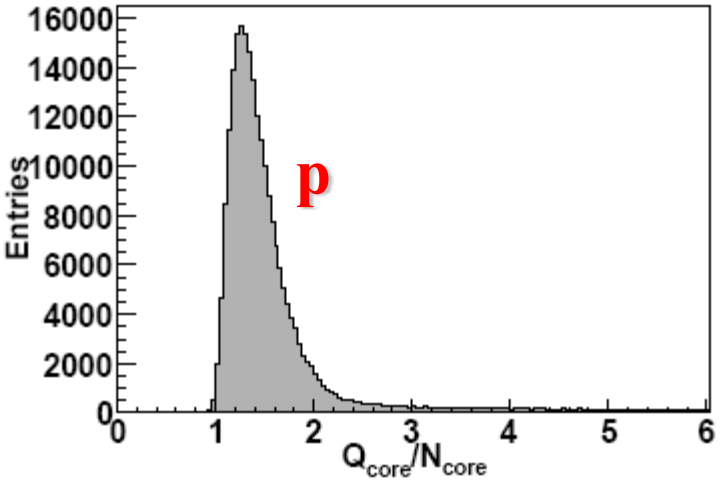
**Interaction pattern in calorimeter:** electron-like or proton-like, electron energy

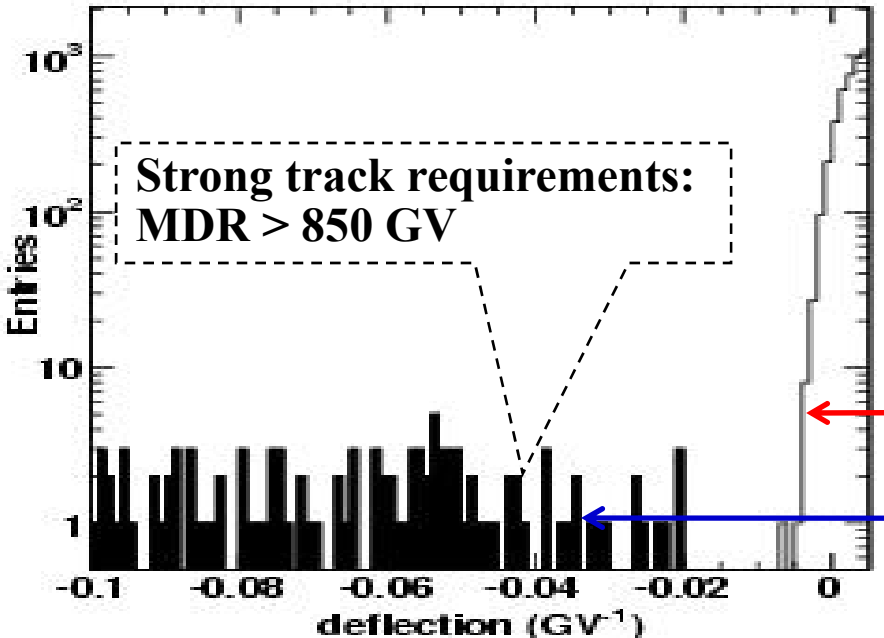



**Positron**
**(NB: $p/e^+ \sim 10^{3\text{-}4}$)**

**Calorimeter selection**



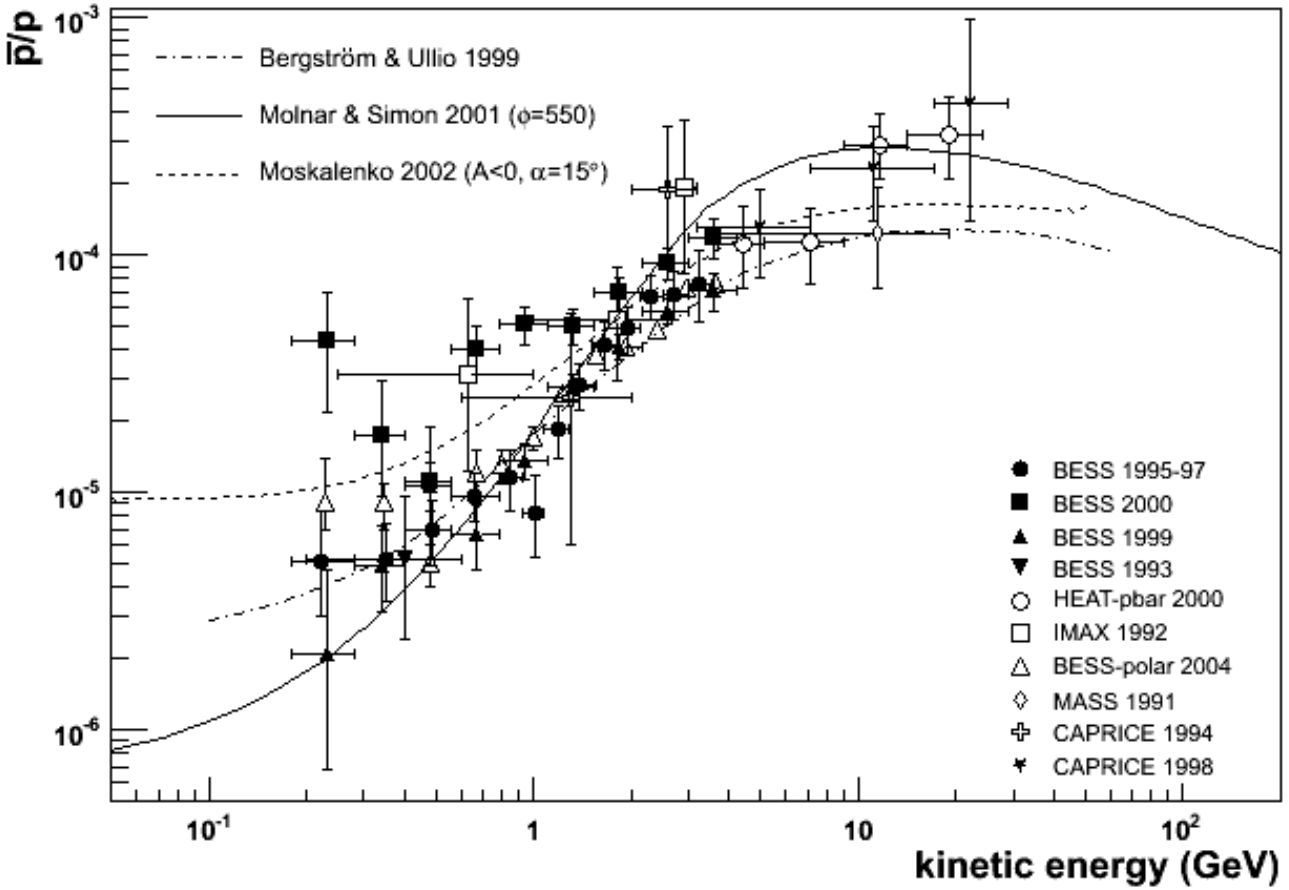




**Tracker Identification**

**Protons (& spillover)**

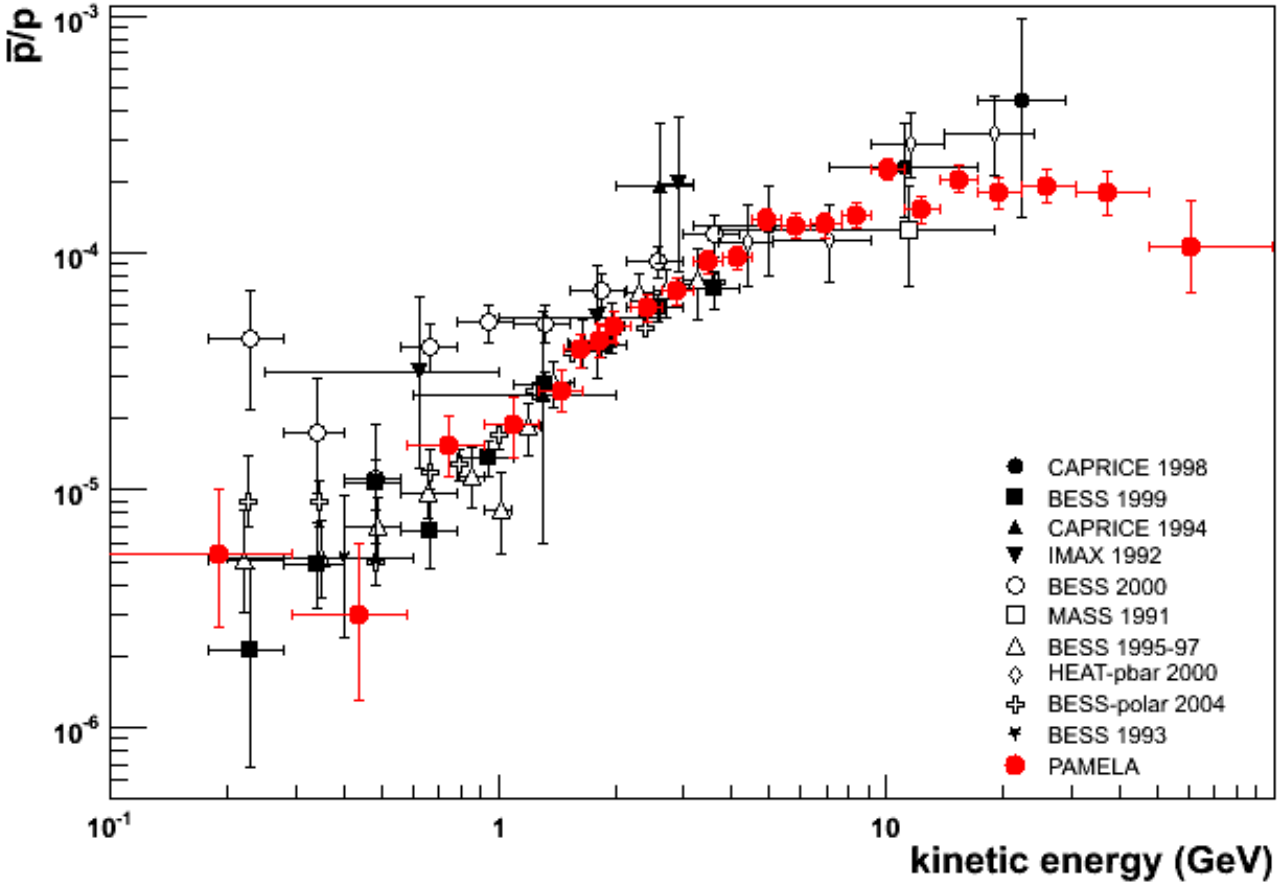
**Antiprotons**

# Pre-PAMELA antiproton to proton flux ratio

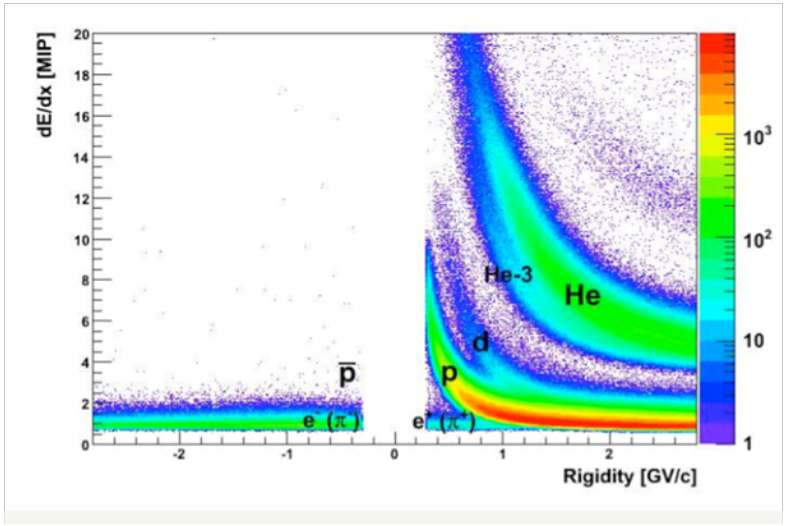


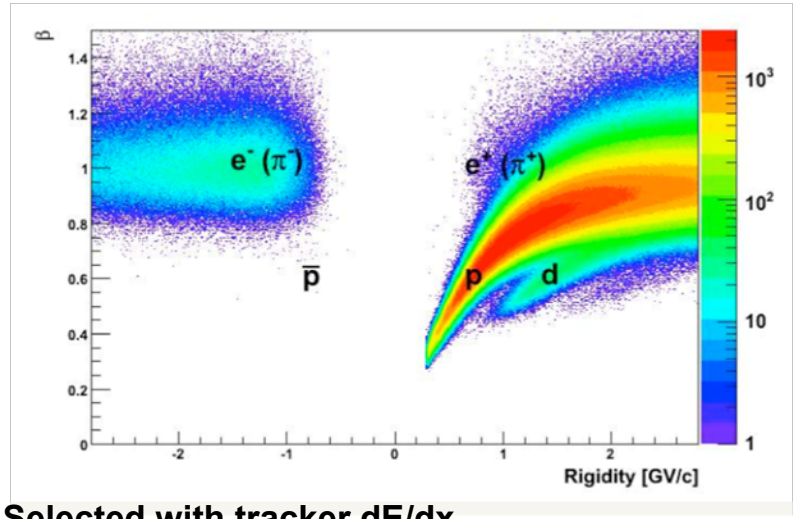
# Antiproton to proton flux ratio

**Astro-ph 0810.4994, to appear in PRL**

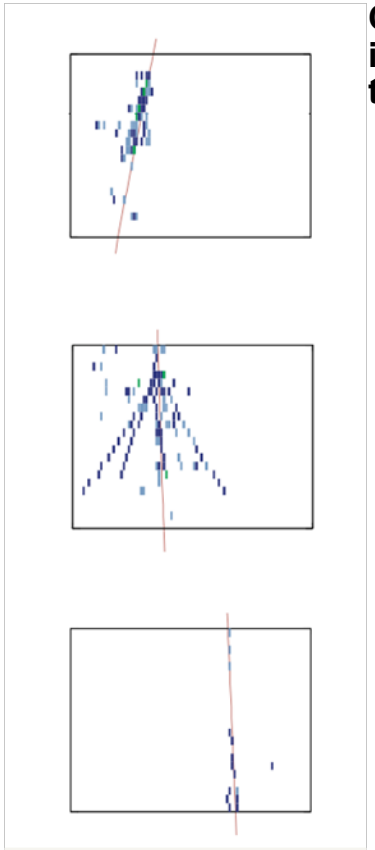


# Low energy antiproton selection



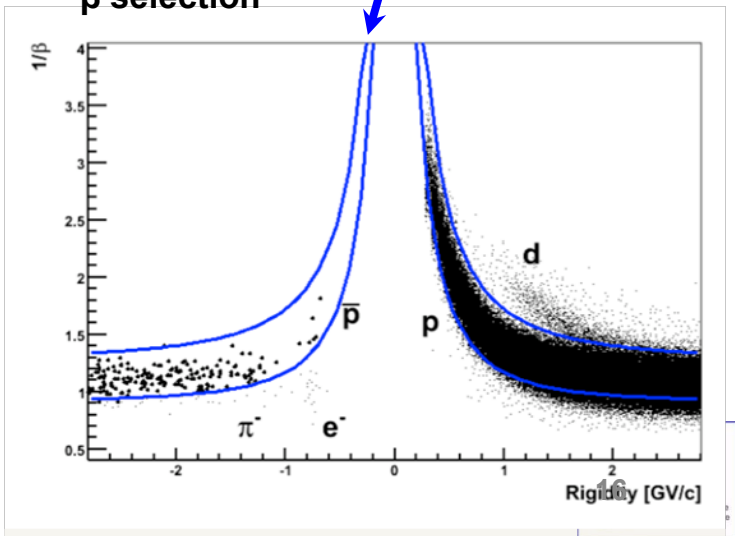

Selected with tracker dE/dx



Calorimeter interaction topology

Selected antiprotons

β selection

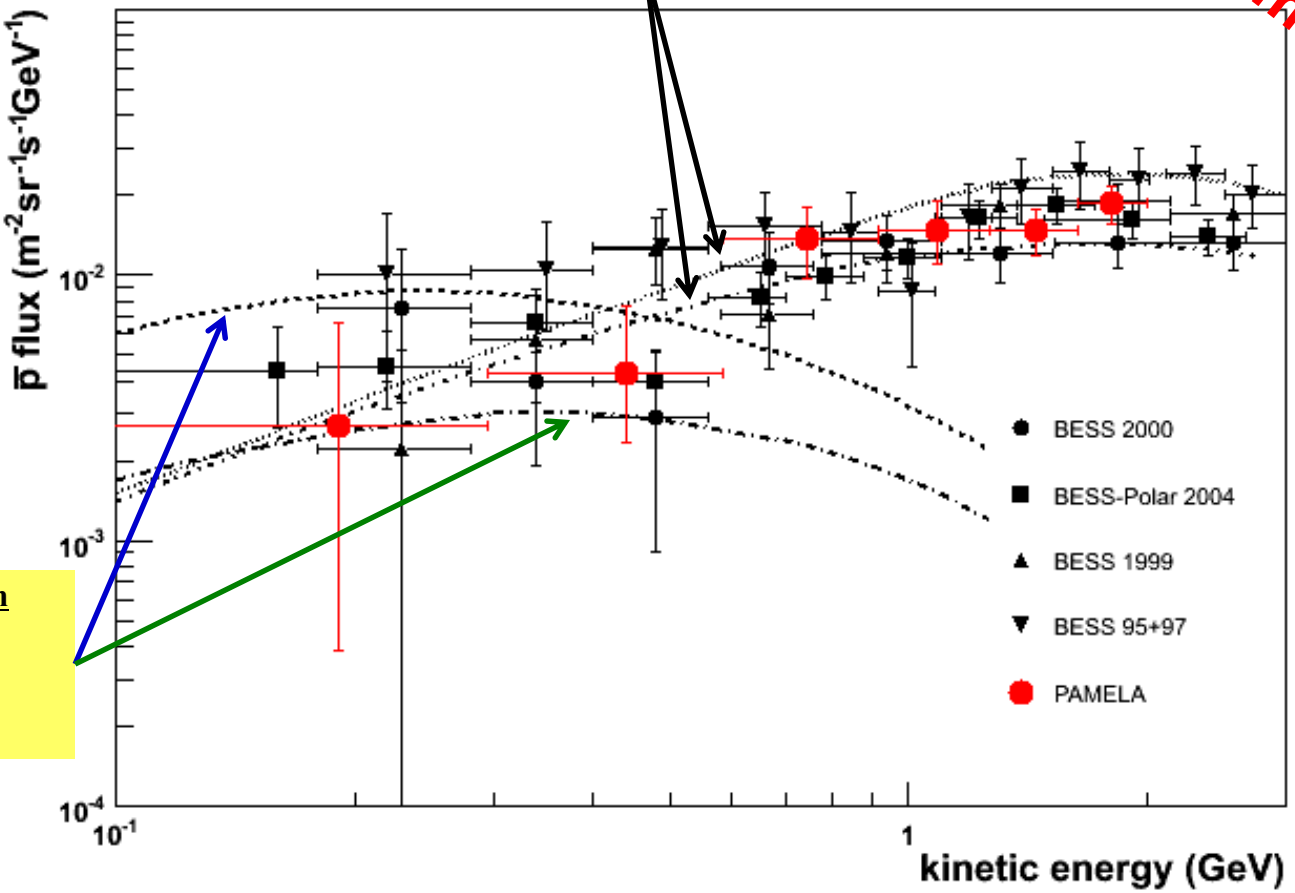


# Antiproton Flux

statistical errors only

**Secondary production**

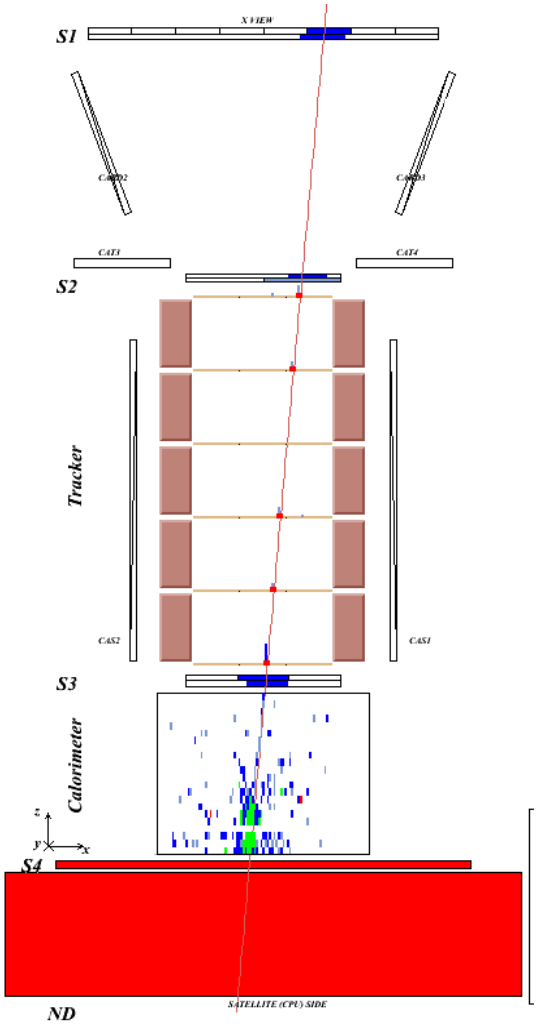
Preliminary




**Primary production**
**Evaporation Mini Black Holes:**
**Yoshimura et al.**
**Maki et al.**

From Petter Hofverberg's PhD Thesis

# Proton / positron discrimination

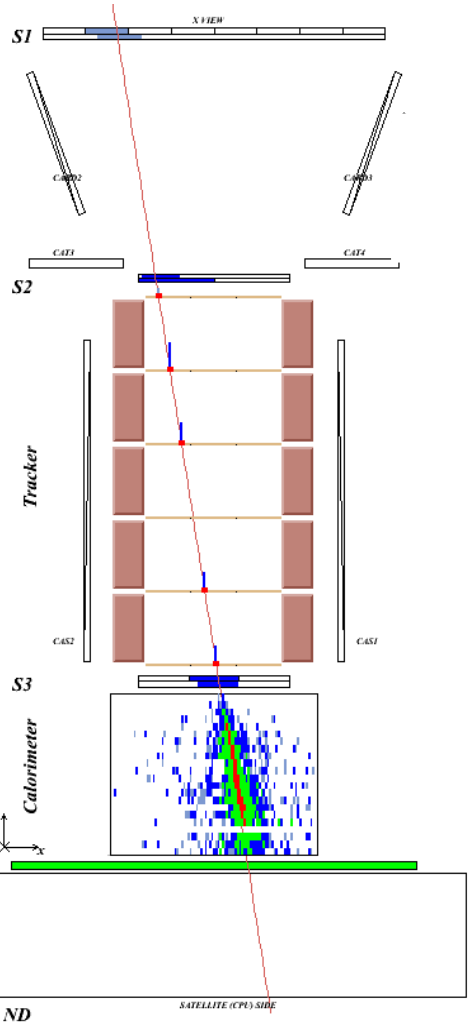



**Time-of-flight:**
**trigger, albedo rejection, mass determination (up to 1 GeV)**

**Bending in spectrometer:**
**sign of charge**

**Ionisation energy loss (dE/dx):**
**magnitude of charge**

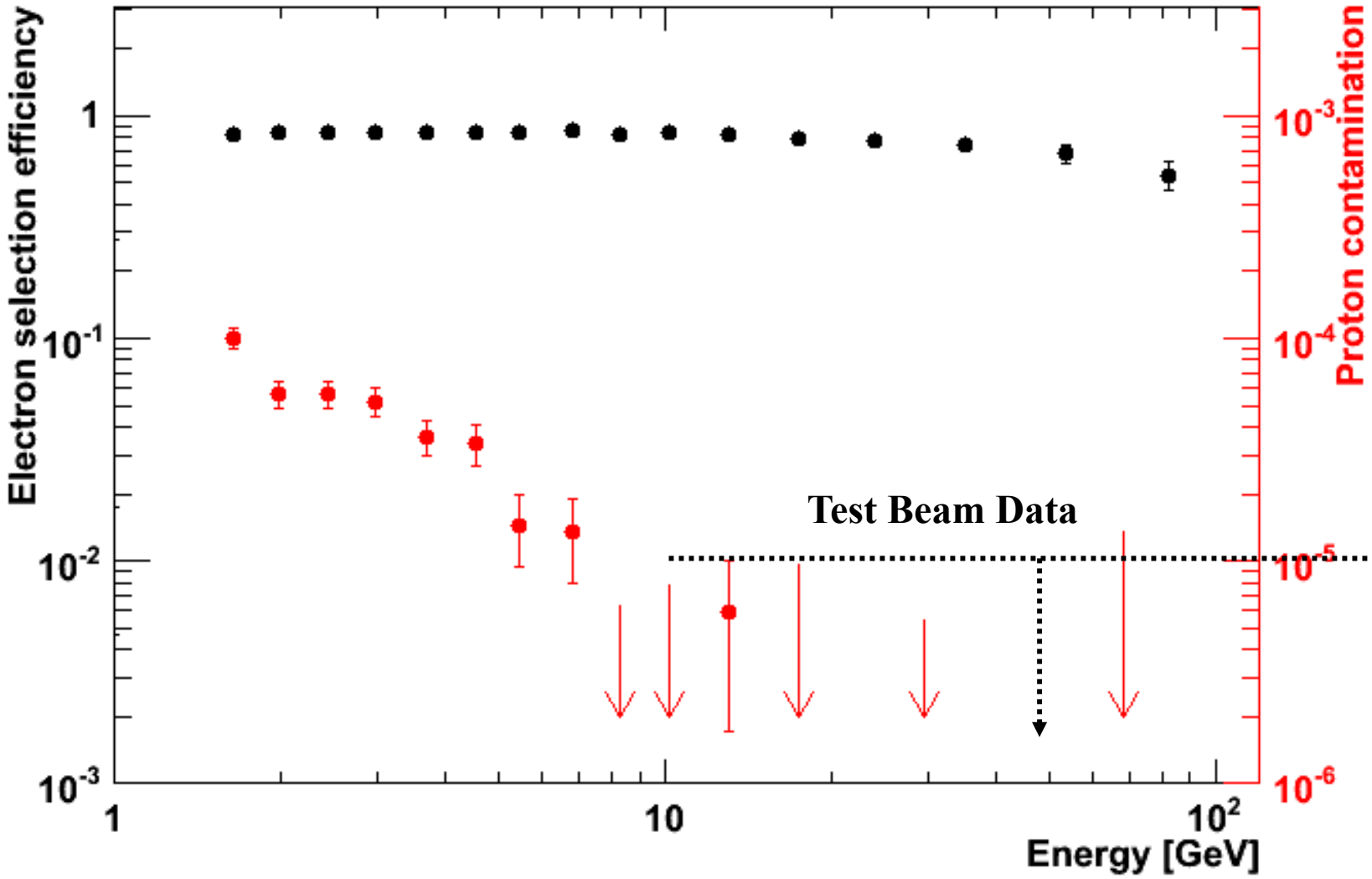
**Interaction pattern in calorimeter:**
**electron-like or proton-like, electron energy**



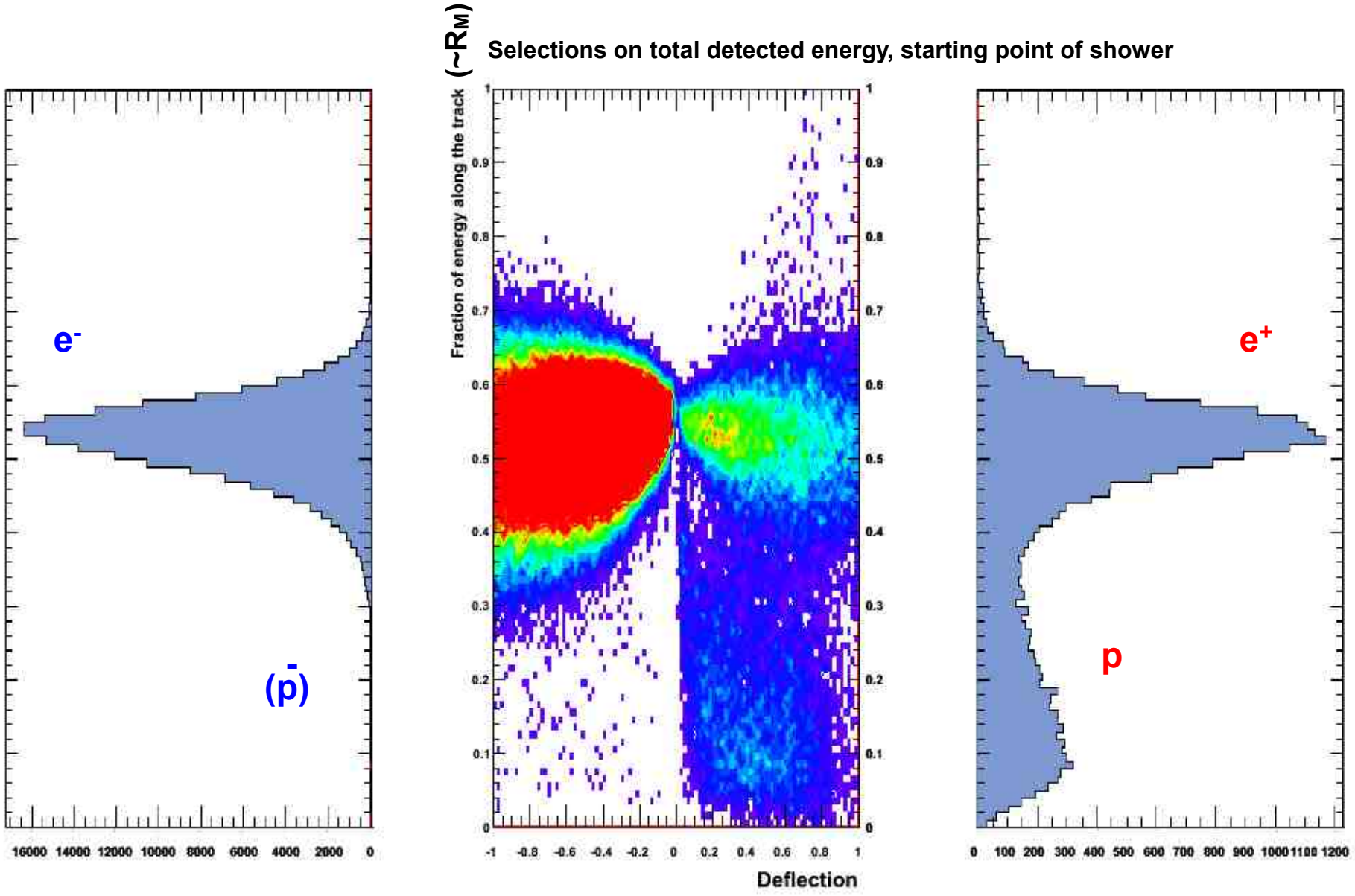

**Proton**

**Positron**

# Positron selection with calorimeter



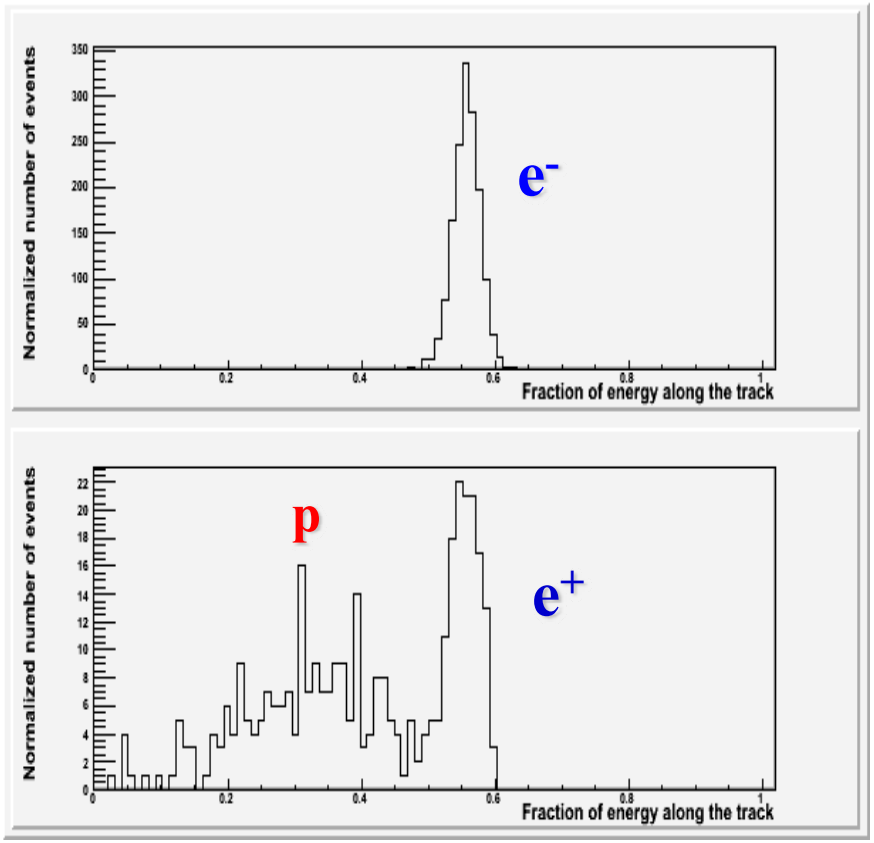
**Selections on total detected energy, starting point of shower**



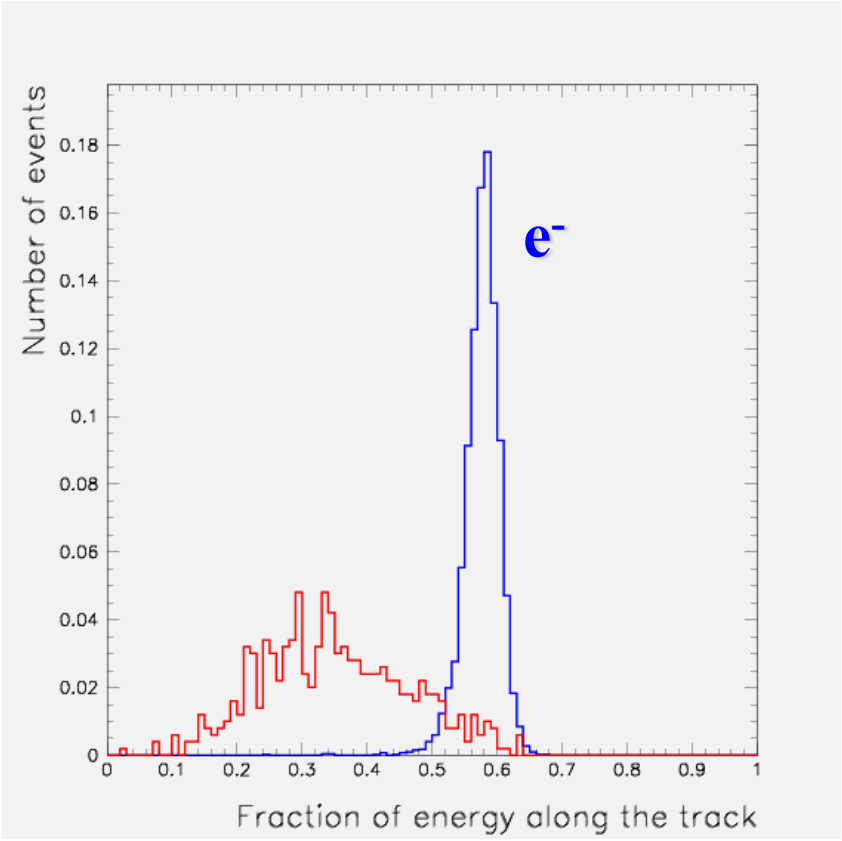
# Positron selection with calorimeter

**Fraction of charge released along the calorimeter track (left, hit, right)**

**Flight data: rigidity: 20-30 GV**




**Test beam data Momentum: 50GeV/c**

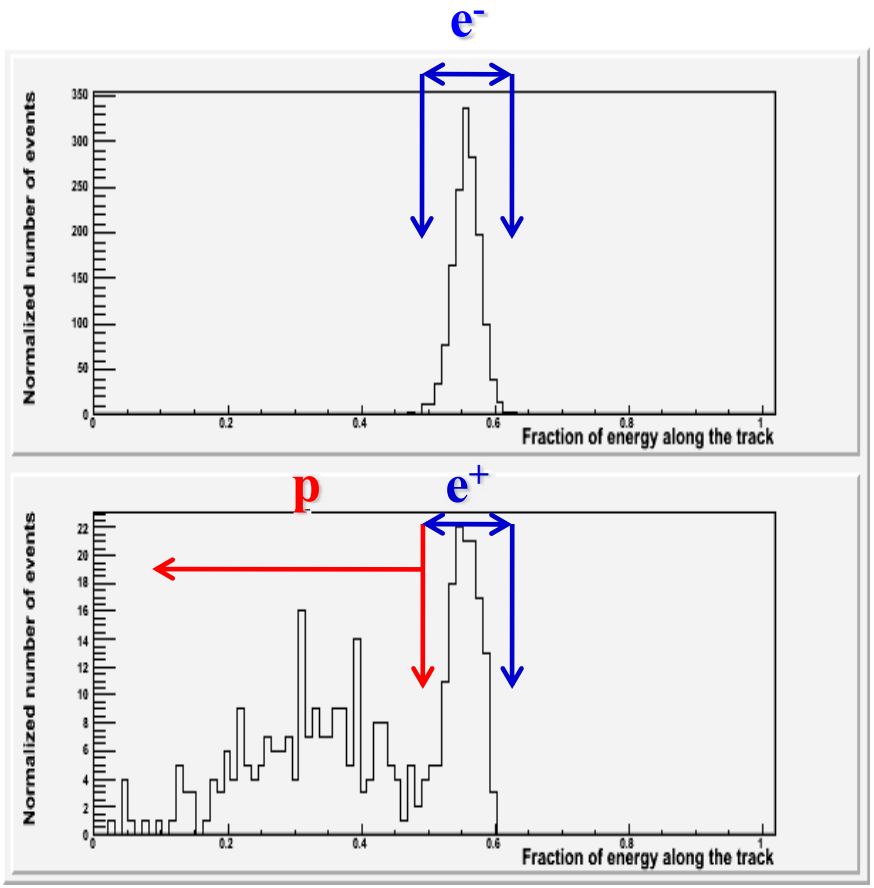



- **Energy-momentum match**
- **Starting point of shower**

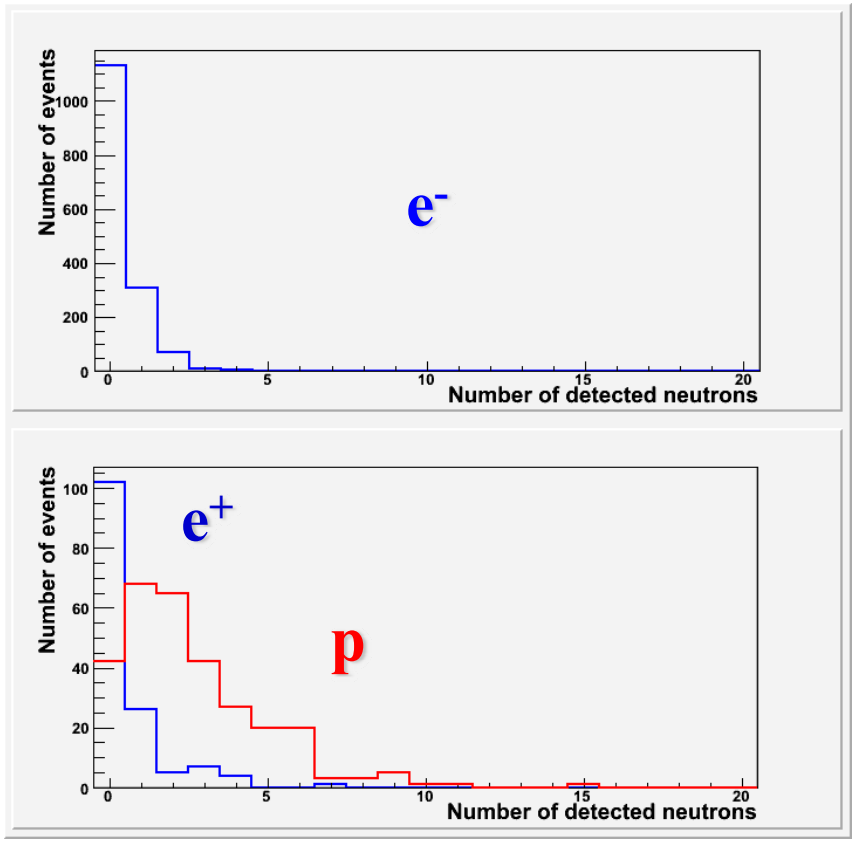
# Positron selection

**Rigidity: 20-30 GV**

**Fraction of charge released along the calorimeter track (left, hit, right)**




**Neutrons detected by ND**

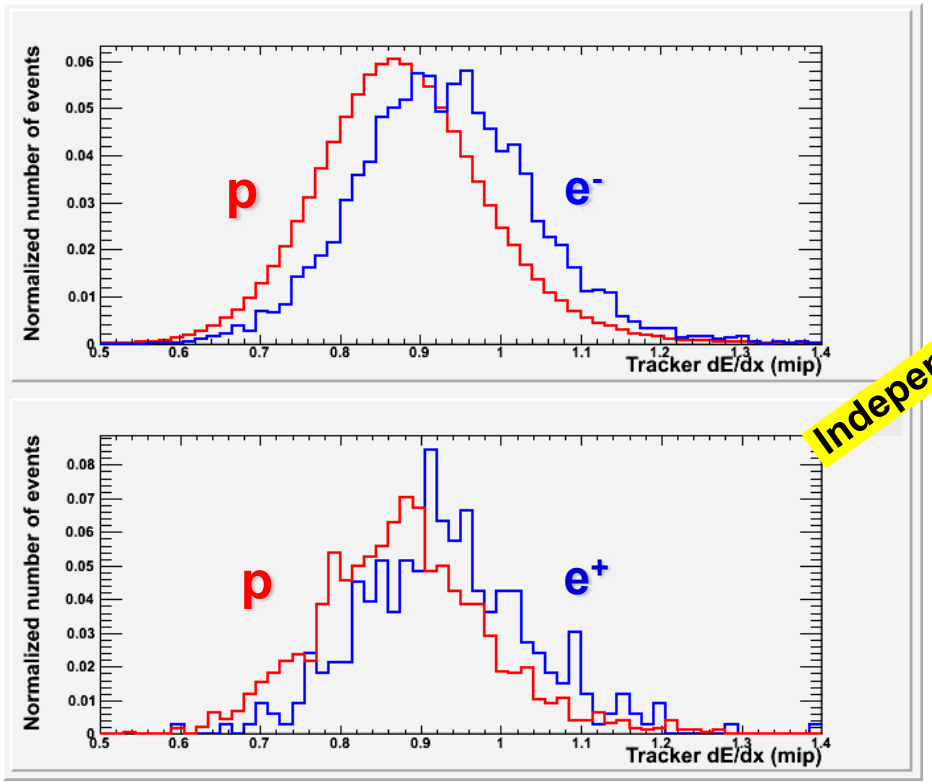


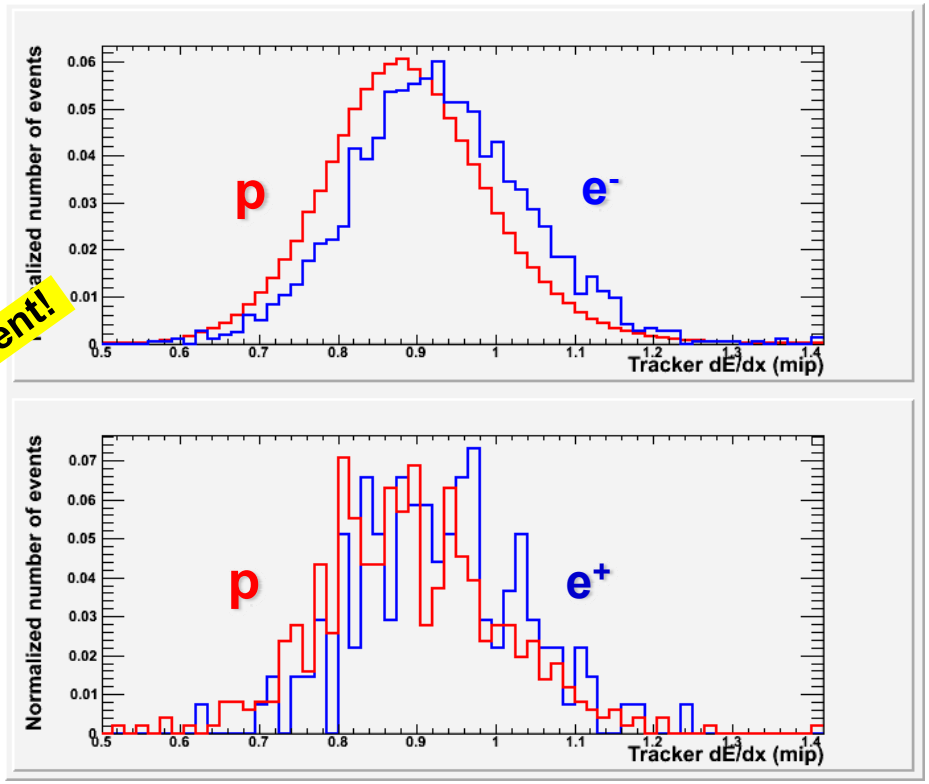

- **Energy-momentum match**
- **Starting point of shower**

# Positron selection with dE/dX

**Energy loss in silicon tracker detectors:** $-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$

**TOP: positive (mostly p) and negative events (mostly $e^-$)**




Independent!





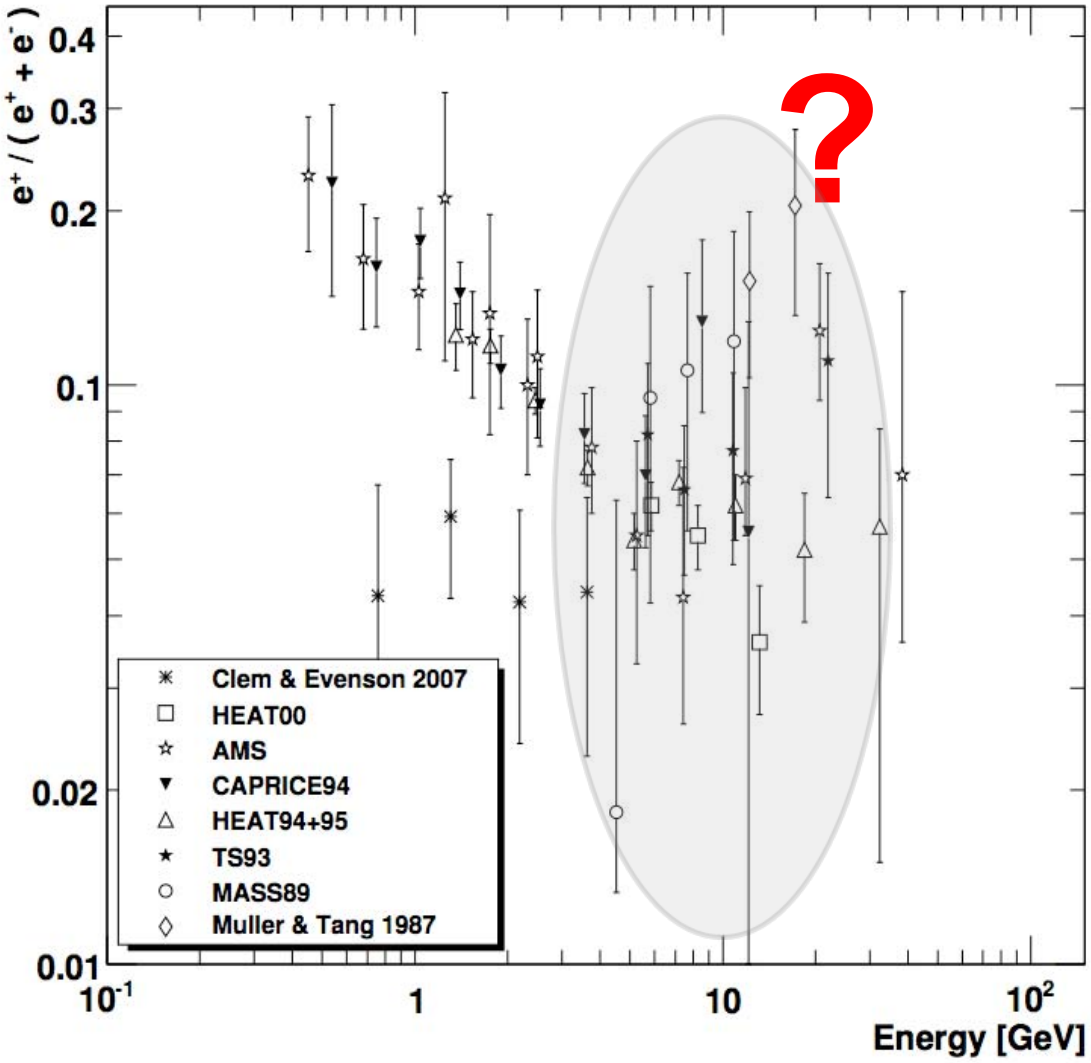


**BOTTOM: positive events identified as p and $e^+$ by transverse profile method**

**Rigidity: 10-15 GV**

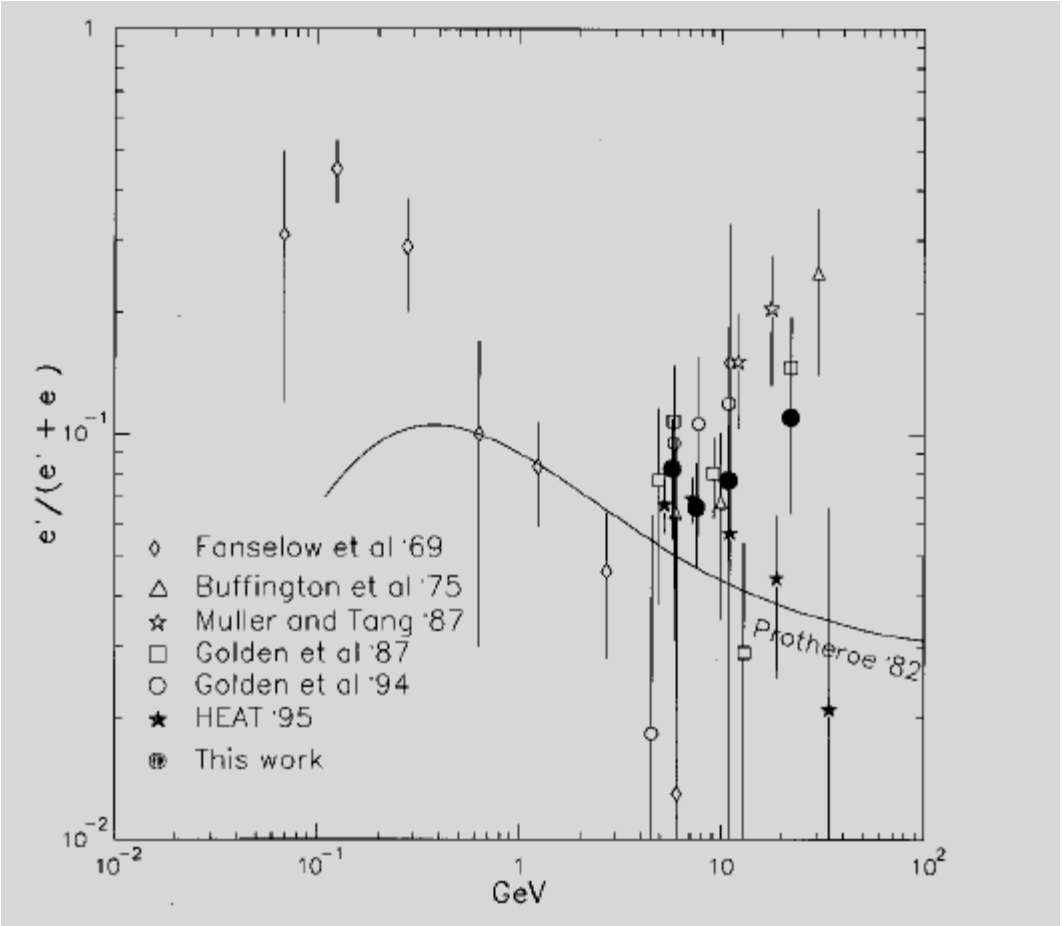
**Rigidity: 15-20 GV**

# Pre-PAMELA positron fraction

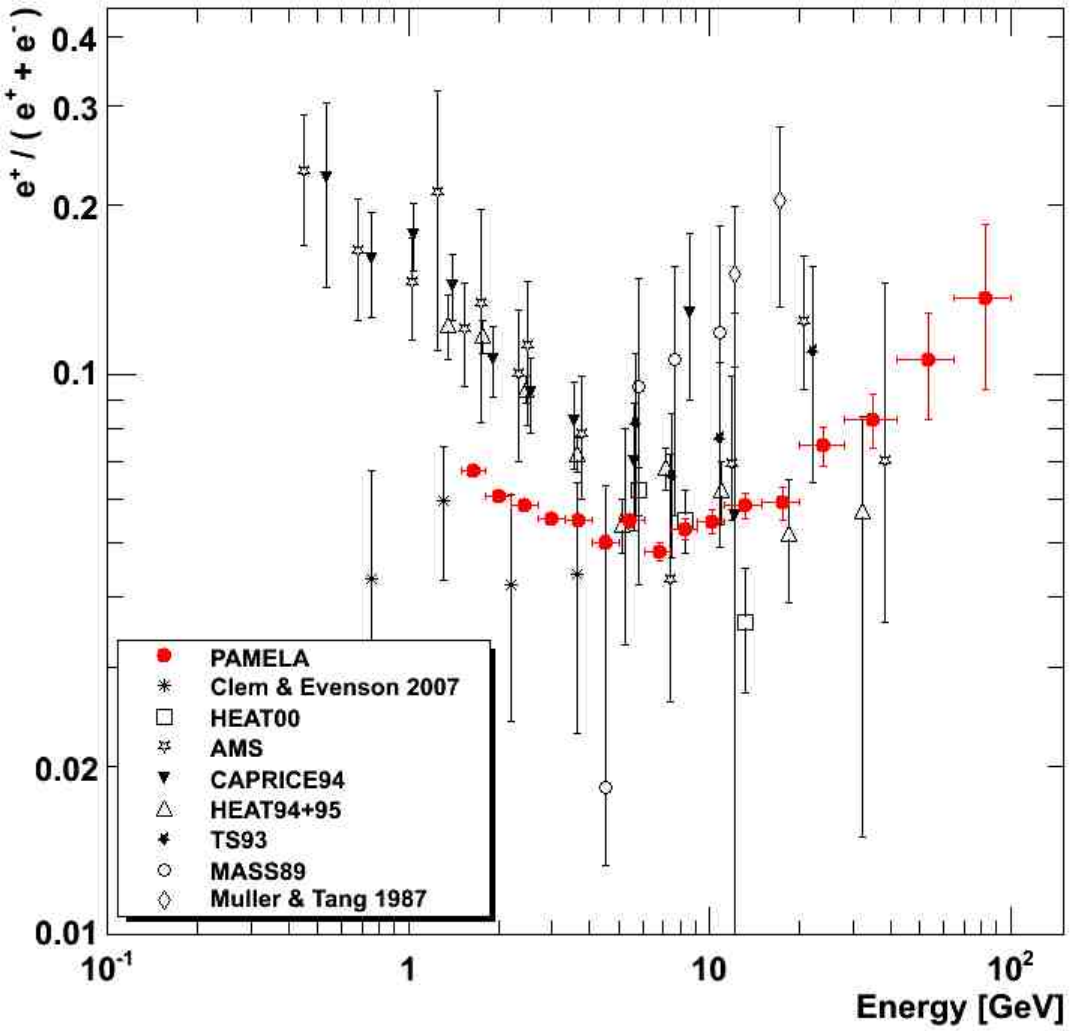


# Interlude: positron fraction history

**R. Golden et al., ApJ 457 L103 (1996)**
**"It may be pointed out that our results do not exhibit the trend shown by Barwick et al. (1995) [HEAT94], in which the positron fraction decreases with energy."**



# Positron to Electron Fraction



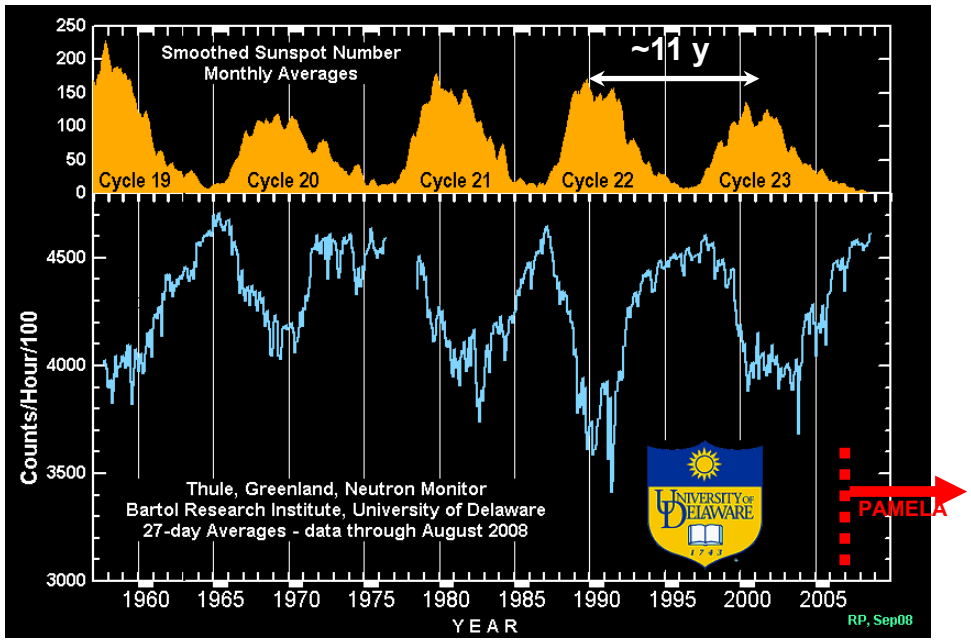

**End 2007:**
**~10 000 $e^+$ > 1.5 GeV**

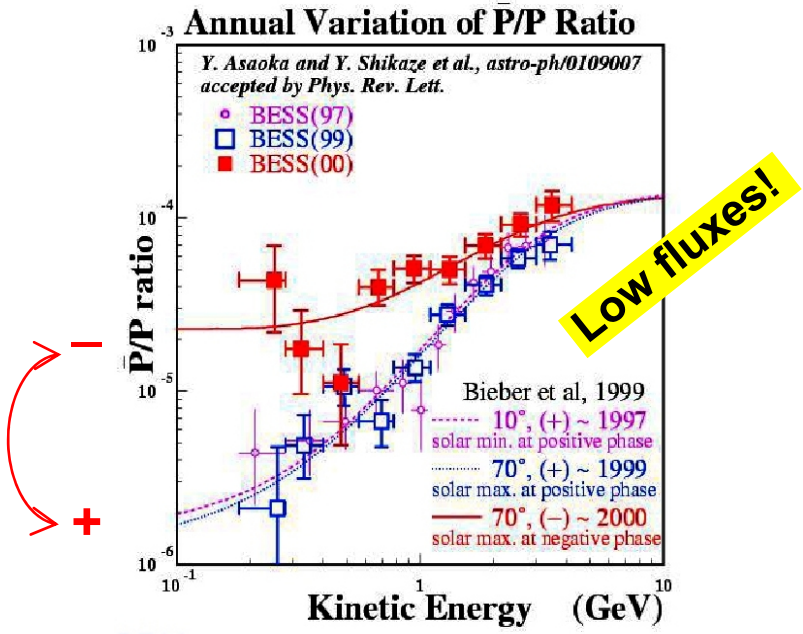
**~2000 > 5 GeV**

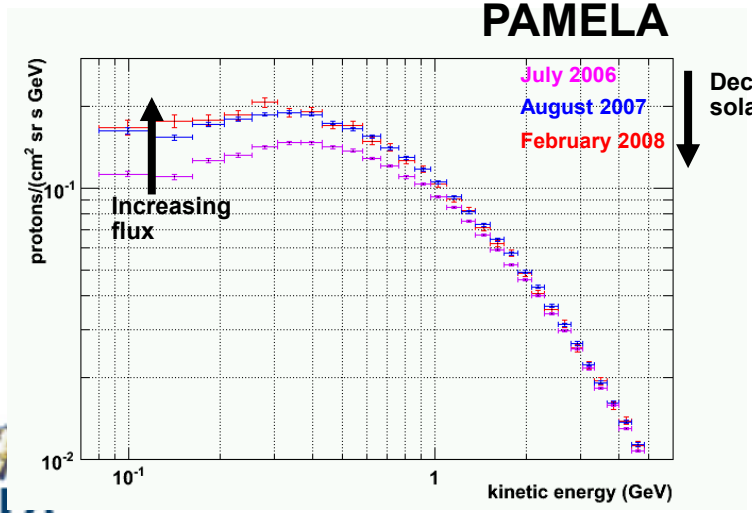
**Astro-ph 0810.4995**

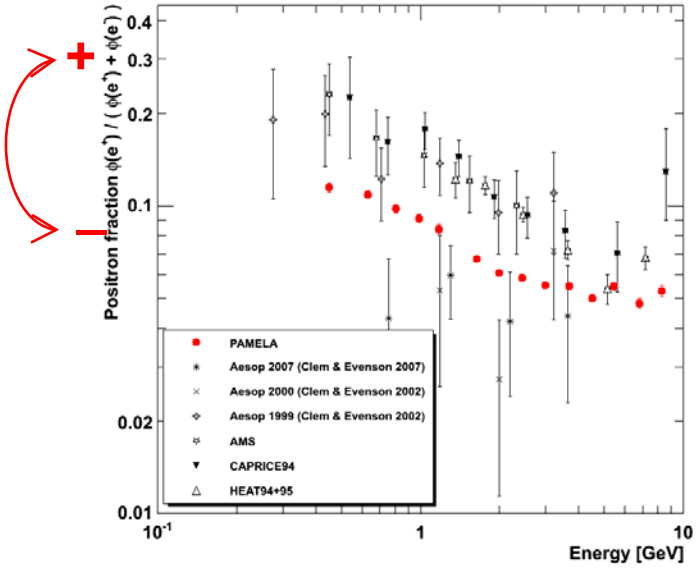
# Solar modulation

$A^+$ $A^-$ $A^+$ $A^-$

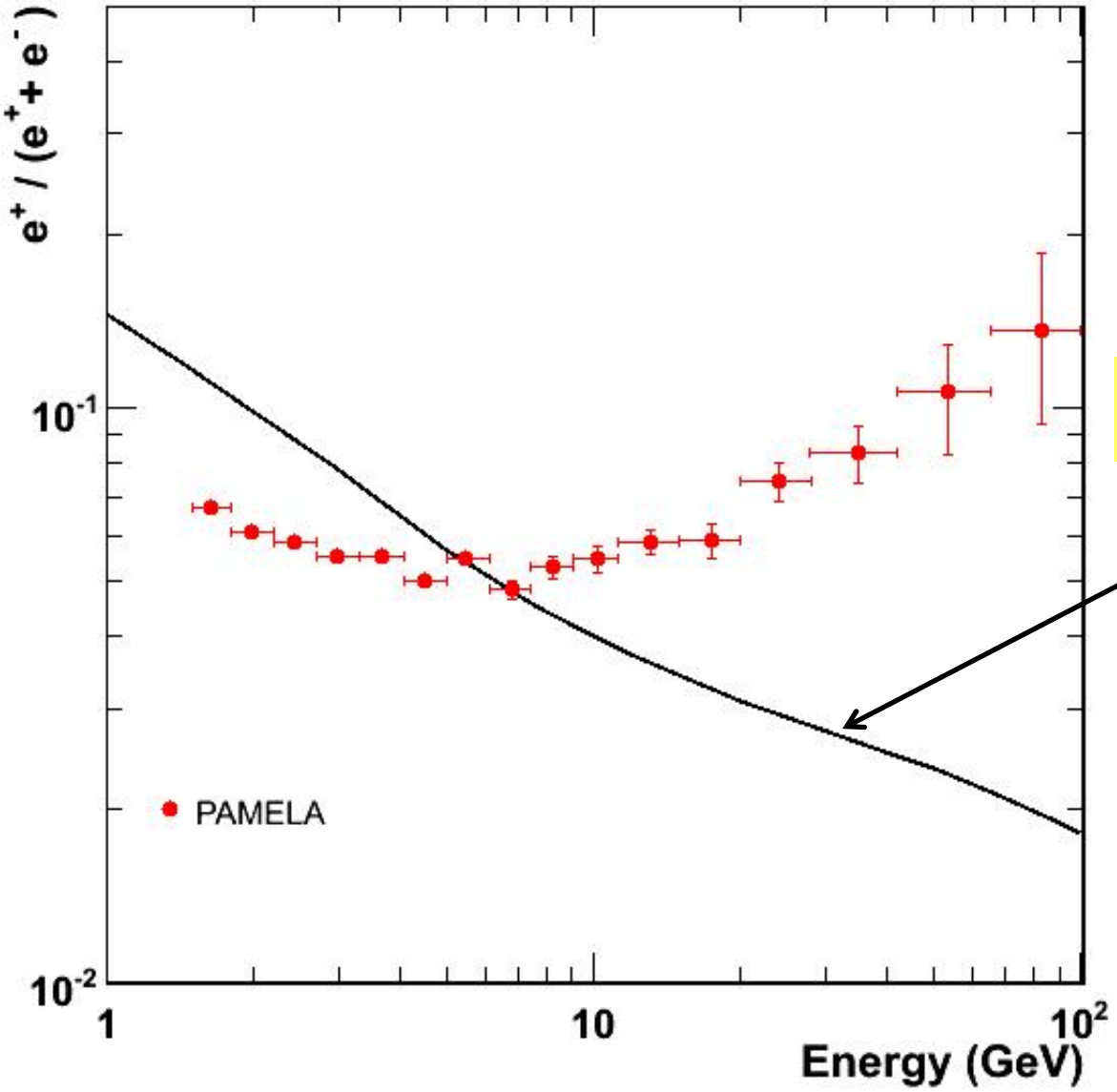


# PAMELA Positron Fraction

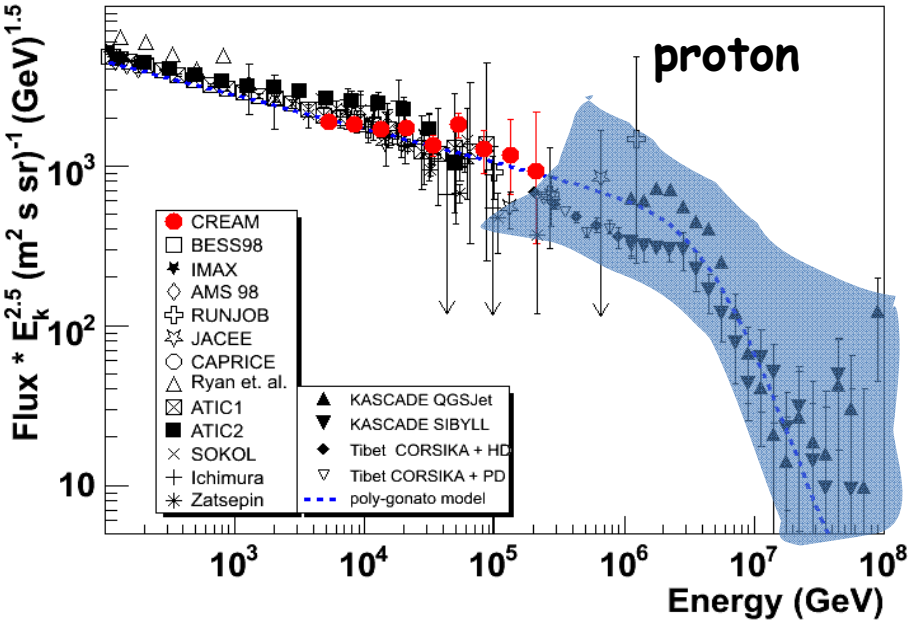


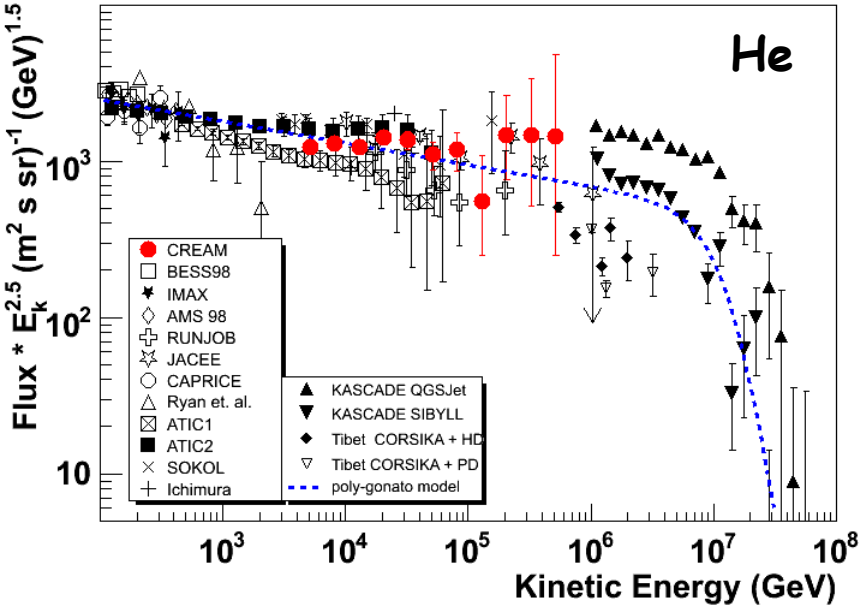

**Secondary production**
**Moskalenko & Strong 98**

**But uncertainties on:**
- **Secondary production (primary fluxes, cross section)**

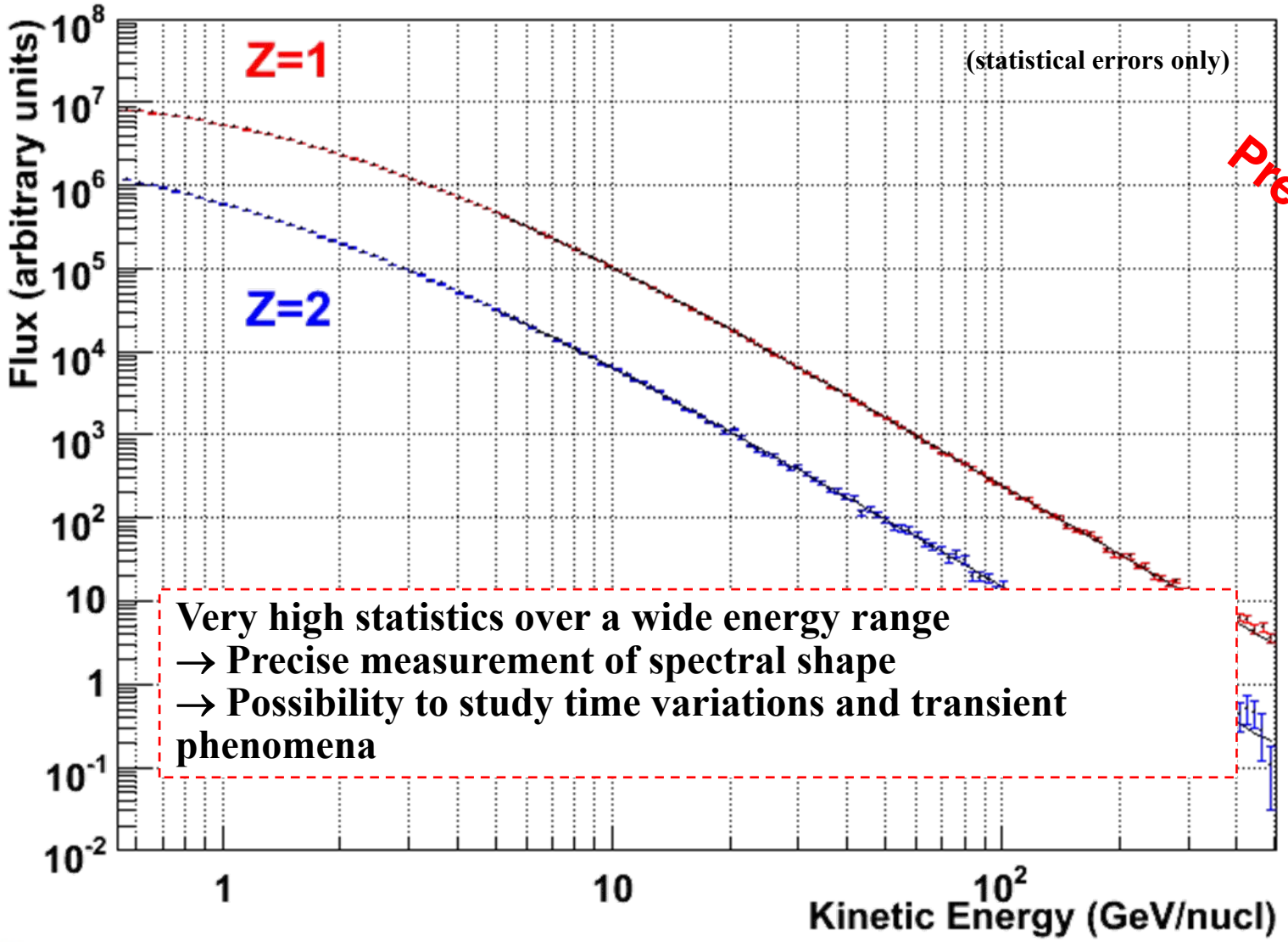
**See Joakim Edsjo's talk for more on uncertainties**

# Galactic H and He spectra

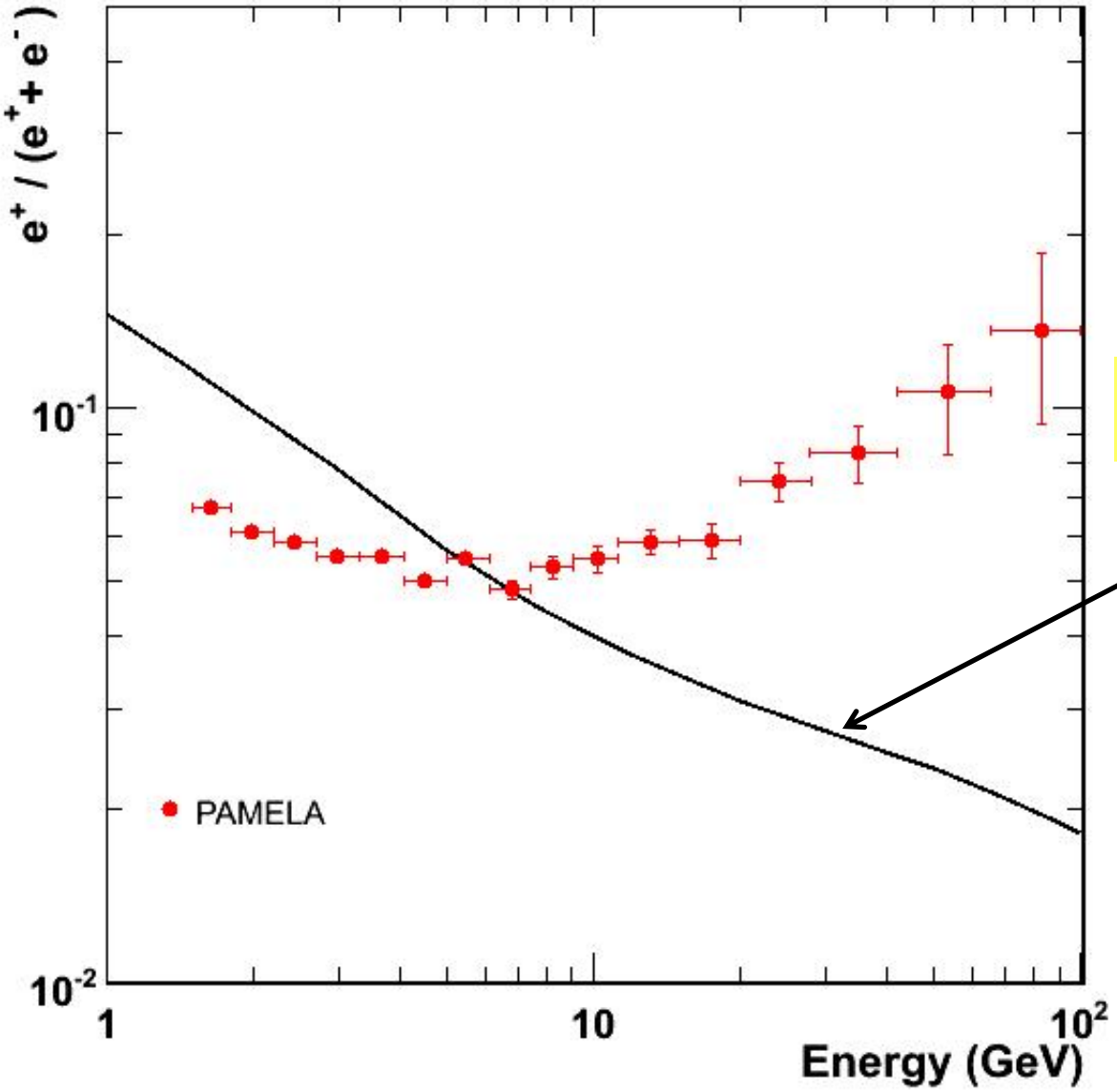


# Galactic H and He spectra



# PAMELA Positron Fraction



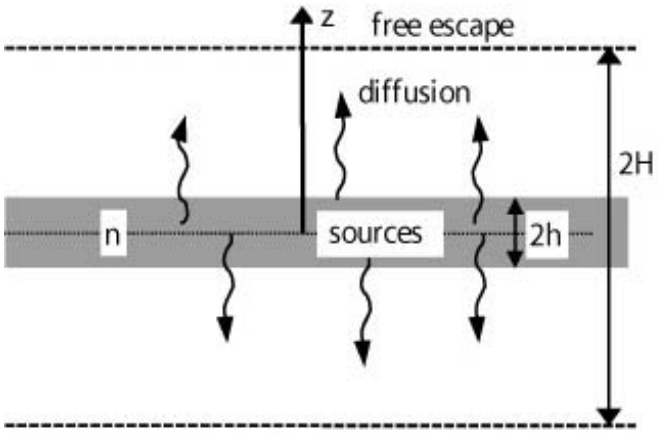

**Secondary production**
**Moskalenko & Strong 98**

**But uncertainties on:**
- **Secondary production (primary fluxes, cross section)**
- **Propagation models**

# Diffusion Halo Model

$$\frac{\partial N_i(E,z,t)}{\partial t} = D(E)\cdot\frac{\partial^2}{\partial z^2}N_i(E,z,t) - N_i(E,z,t)\left\{\frac{1}{\tau_i^{\mathrm{int}}(E,z)} + \frac{1}{\gamma(E)\tau_i^{dec}}\right\}$$

diffusion — interaction and decay



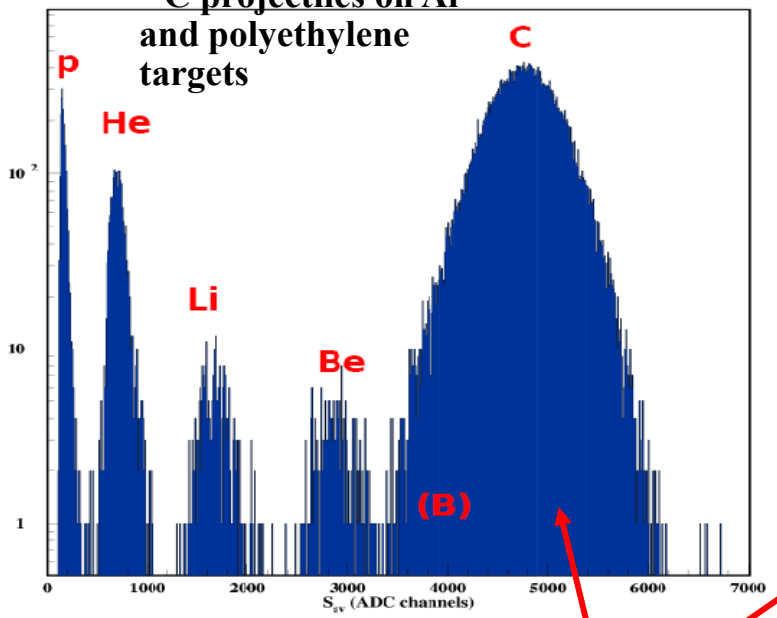

$$+ \sum_{k>i}\frac{N_k(E,z,t)}{\tau_{\mathrm{int}}^{k\to i}(E,z)} + Q_i(E,z)$$

secondary production — primary sources

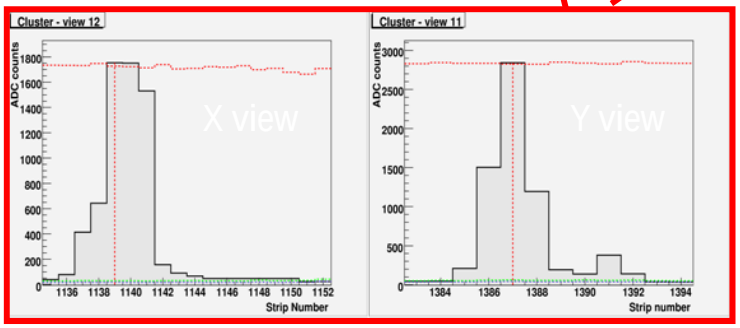
$$-\frac{\partial}{\partial E}\left\{\left\langle\frac{\partial E}{\partial t}\right\rangle\cdot N_i(E,z,t)\right\} + \frac{1}{2}\frac{\partial^2}{\partial E^2}\left\{\left\langle\frac{\Delta E^2}{\Delta t}\right\rangle\cdot N_i(E,z,t)\right\}$$

energy changing processes
(ionisation, reacceleration)

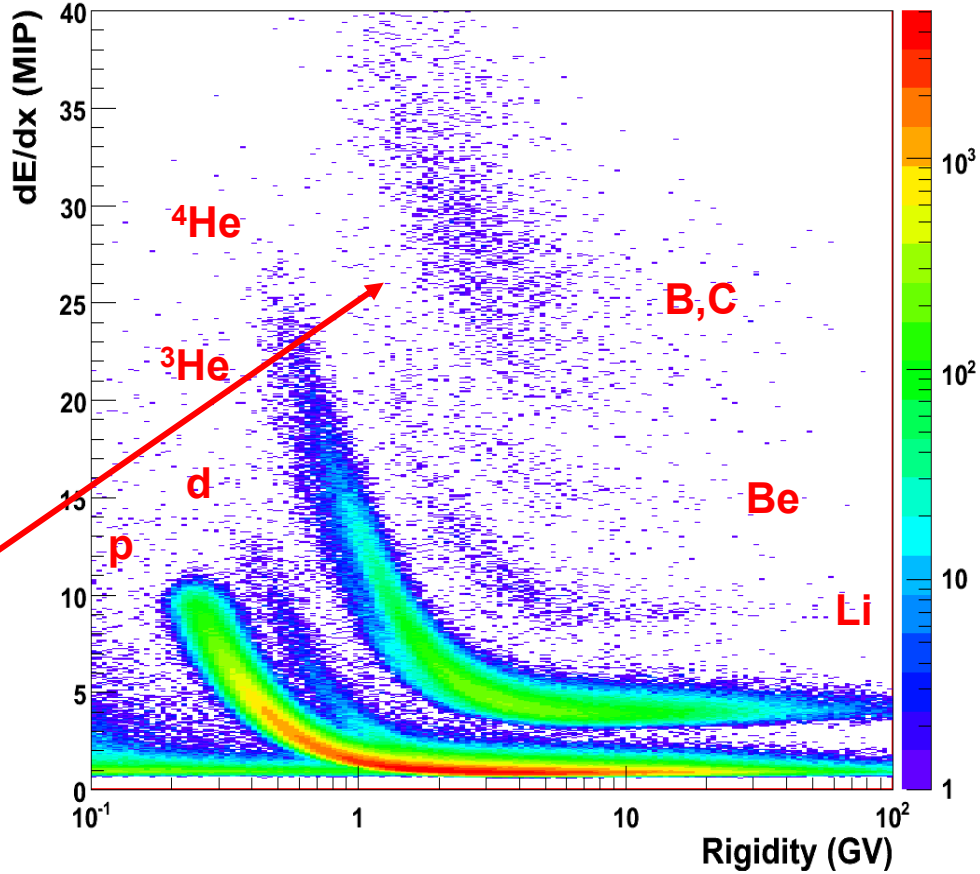
# Charge identification capabilities (tracker)




Saturated clusters

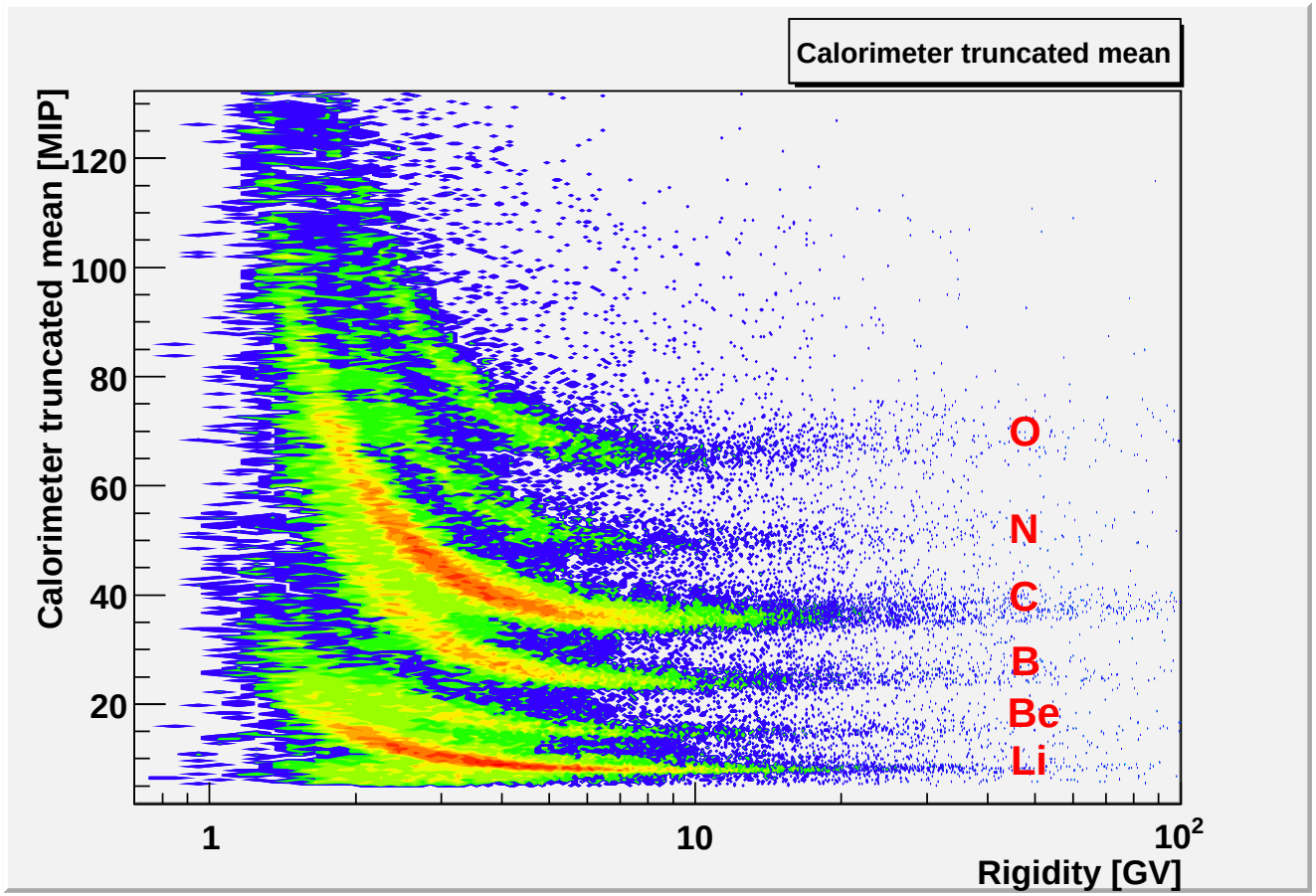



flight data (preliminary)




- Good charge discrimination of H and He
- Single-channel saturation at ~10MIP affects B/C discrimination

# Charge identification capabilities (calorimeter)




**Truncated mean of multiple dE/dx measurements in different silicon planes**

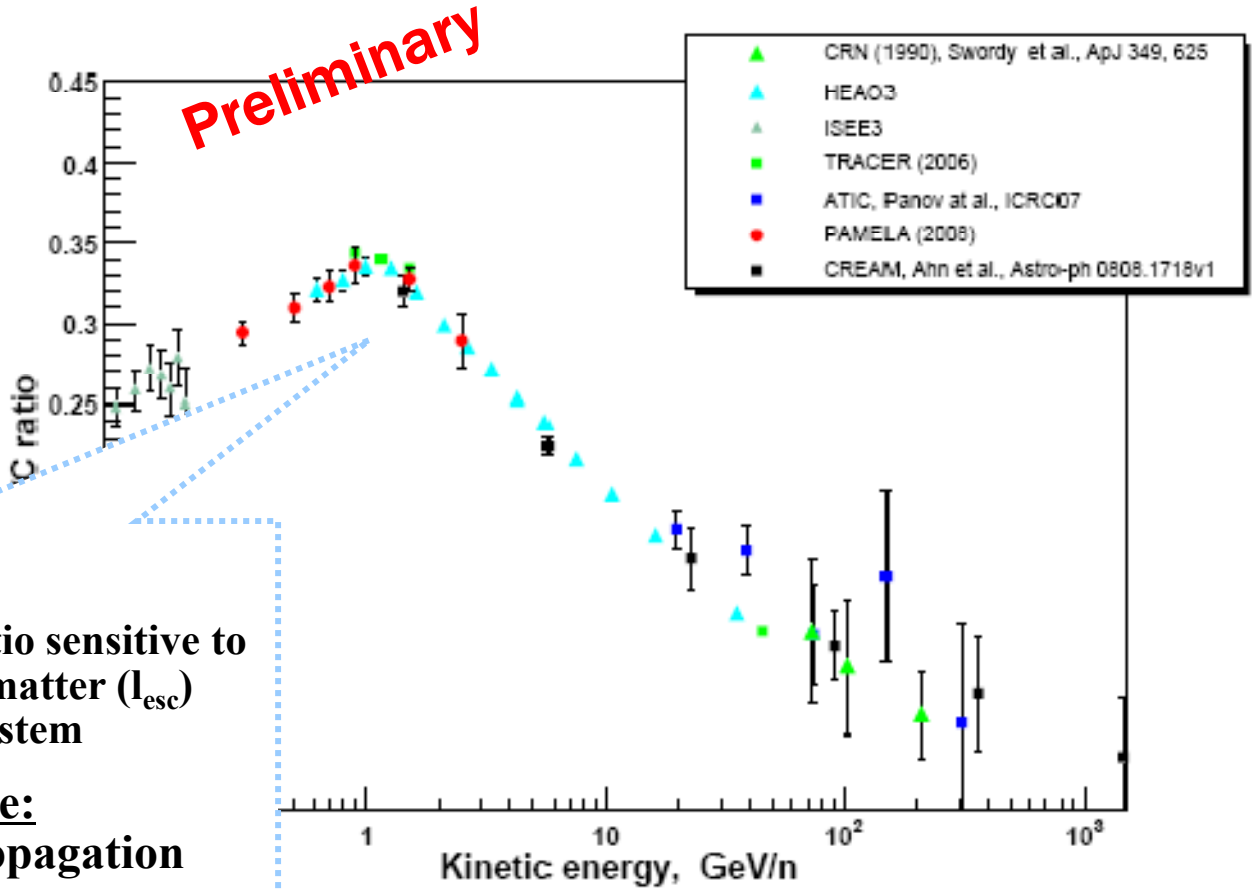
# Secondary nuclei

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

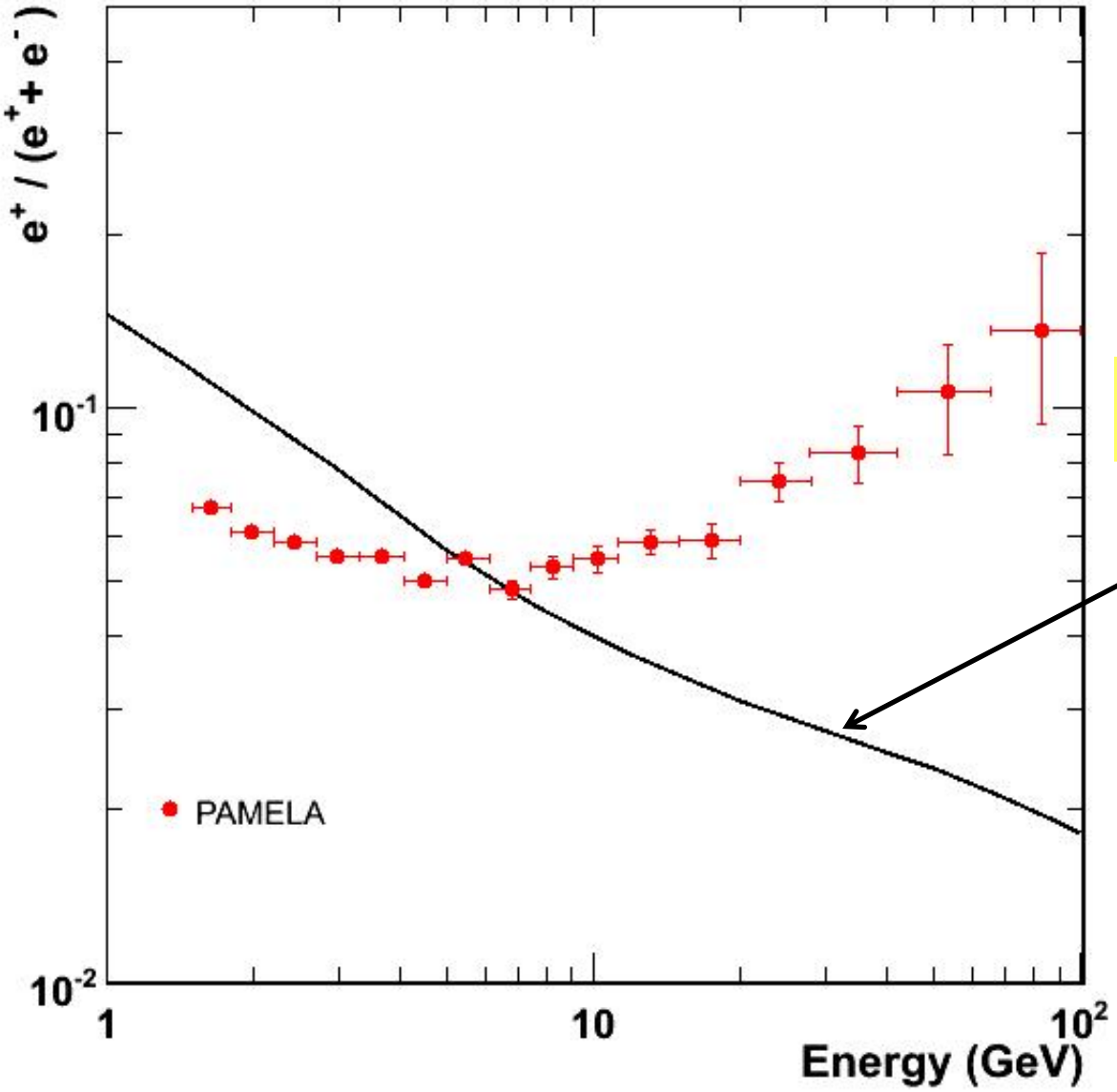
- **B nuclei of secondary origin:**
  **CNO + ISM → B + …**
- **Local secondary/primary ratio sensitive to average amount of traversed matter ($l_{esc}$) from the source to the solar system**

**<u>Local secondary abundance:</u>**
**⇒ study of galactic CR propagation**

**(B/C used for tuning of propagation models)**



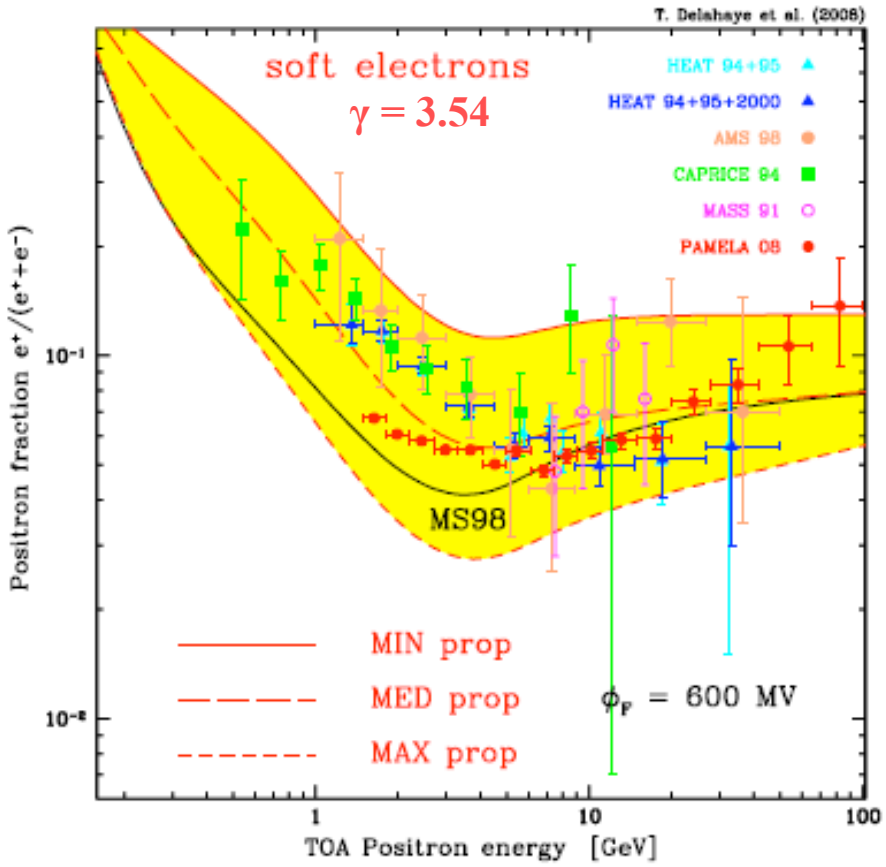
# PAMELA Positron Fraction

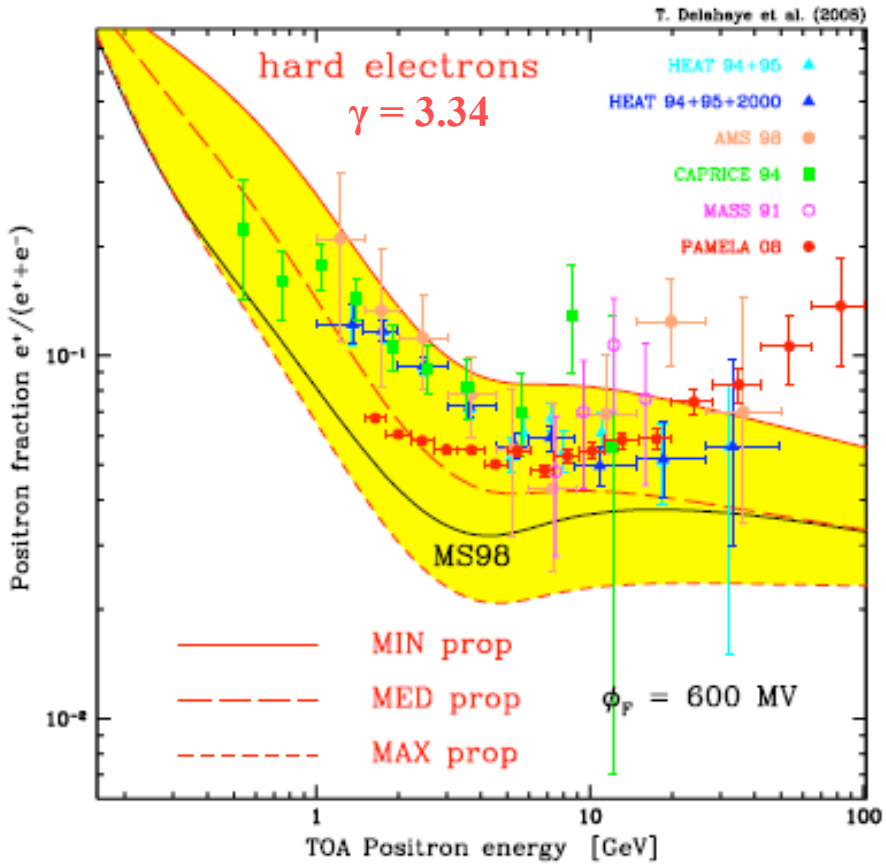



**Secondary production**
**Moskalenko & Strong 98**

**But uncertainties on:**
- **Secondary production (primary fluxes, cross section)**
- **Propagation models**
- **Electron spectrum**

# Theoretical uncertainties on "standard" positron fraction

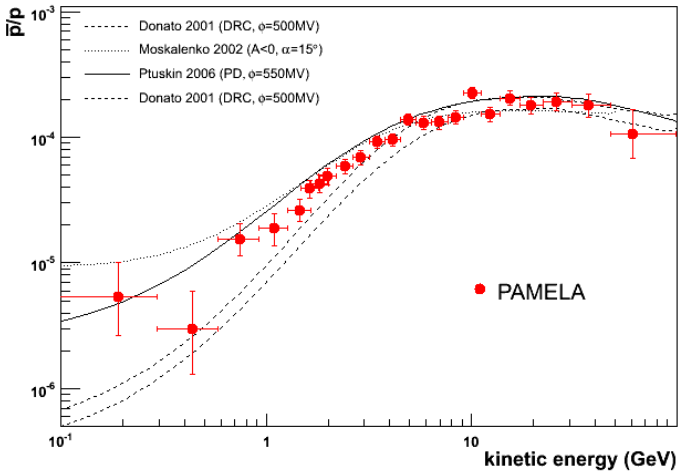


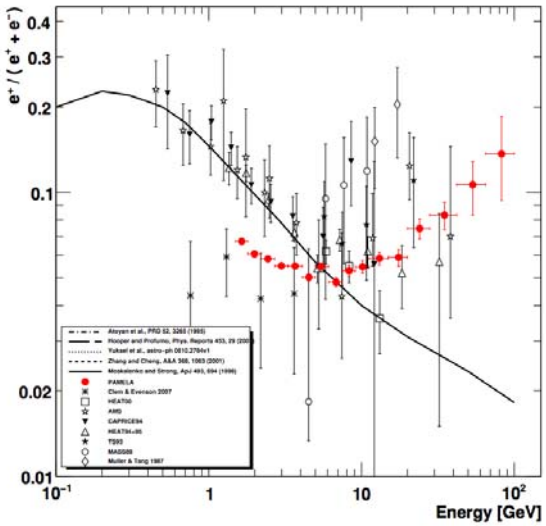

**T. Delahaye et al., arXiv: 0809.5268v3**

# During first week after PAMELA results posted on arXiv

PRL, under review (arXiv 0810.4994)

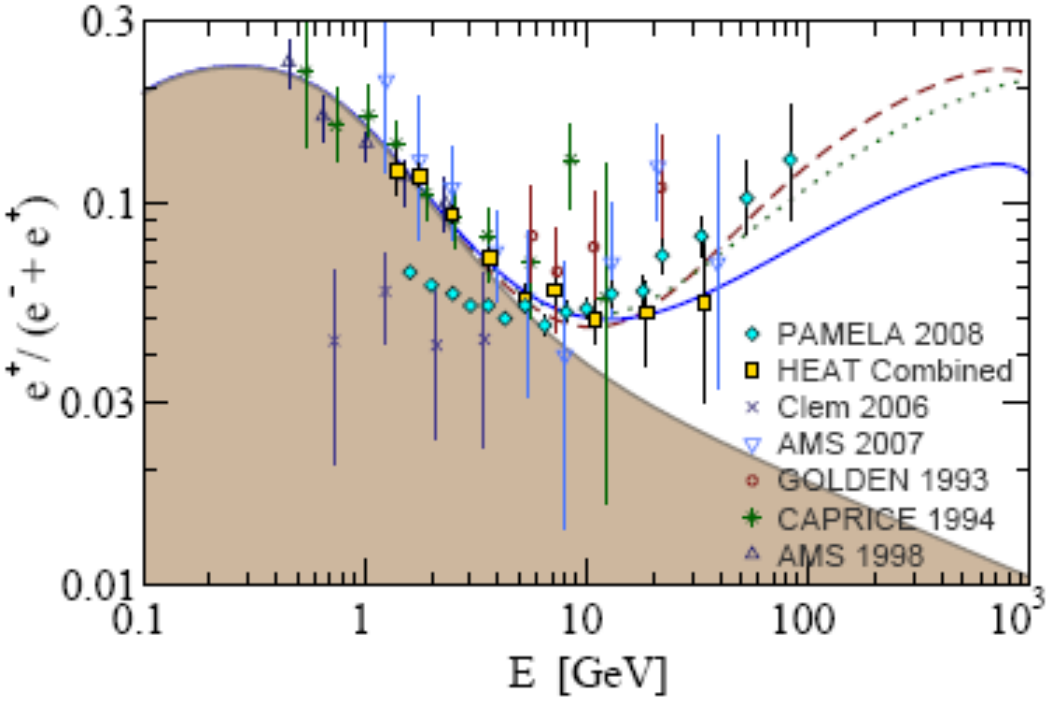



arXiv 0810.4995)

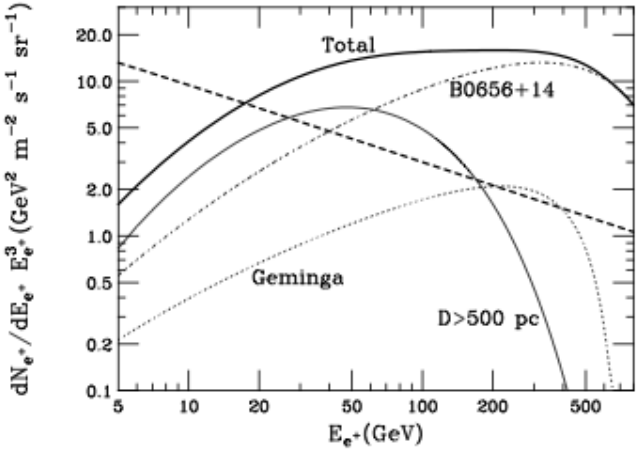


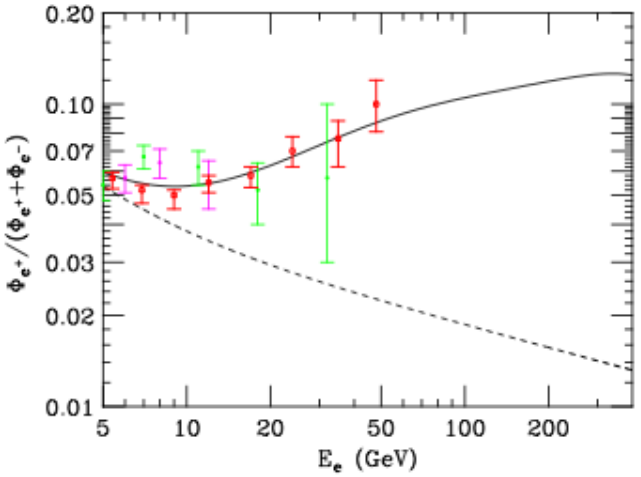

- 0808.3725 DM
- 0808.3867 DM
- 0809.2409 DM
- 0810.2784 Pulsar
- 0810.4846 DM / pulsar
- 0810.5292 DM
- 0810.5344 DM
- 0810.5167 DM
- 0810.5304 DM
- 0810.5397 DM
- 0810.5557 DM
- 0810.4147 DM
- 0811.0250 DM
- 0811.0477 DM

# Example: pulsars



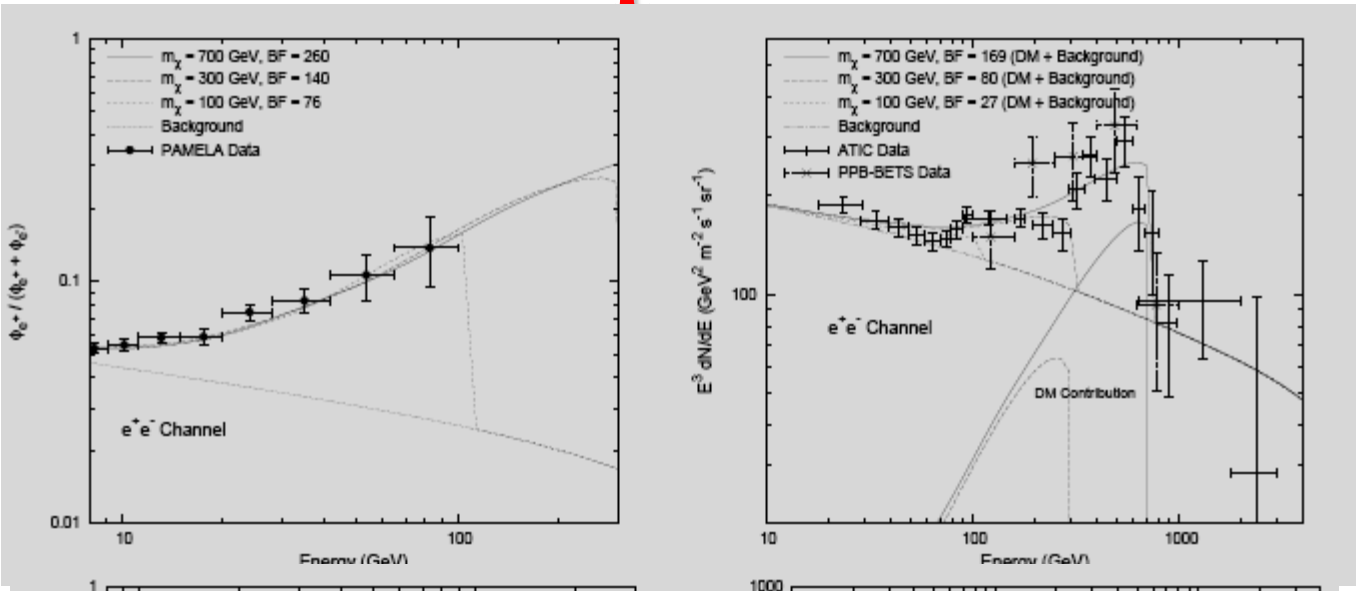

H. Yüksak et al., arXiv:0810.2784v2
Contributions of e- & e+ from Geminga assuming different distance, age and energetic of the pulsar



Hooper, Blasi, and Serpico
arXiv:0810.1527

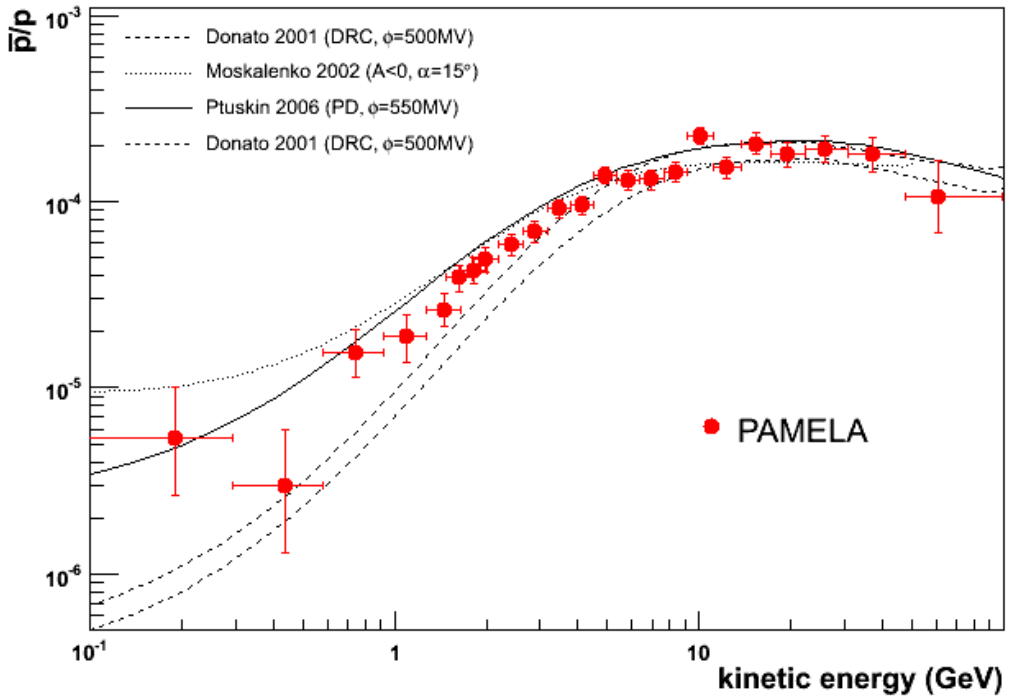
# Example: DM




I. Cholis et al. arXiv:0811.3641v1

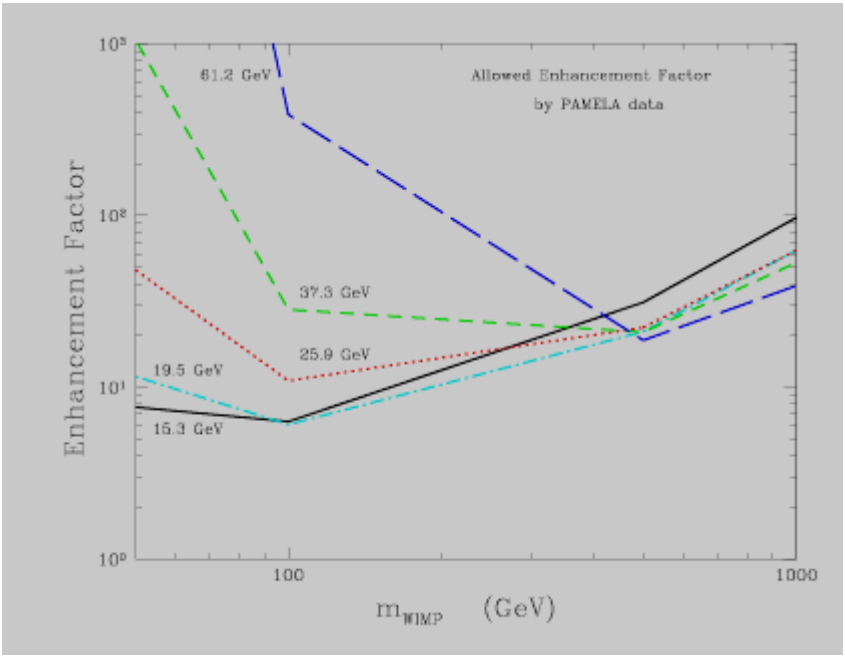
See Neal Weiner's talk

# PAMELA $\bar{p}/p$ implication on DM



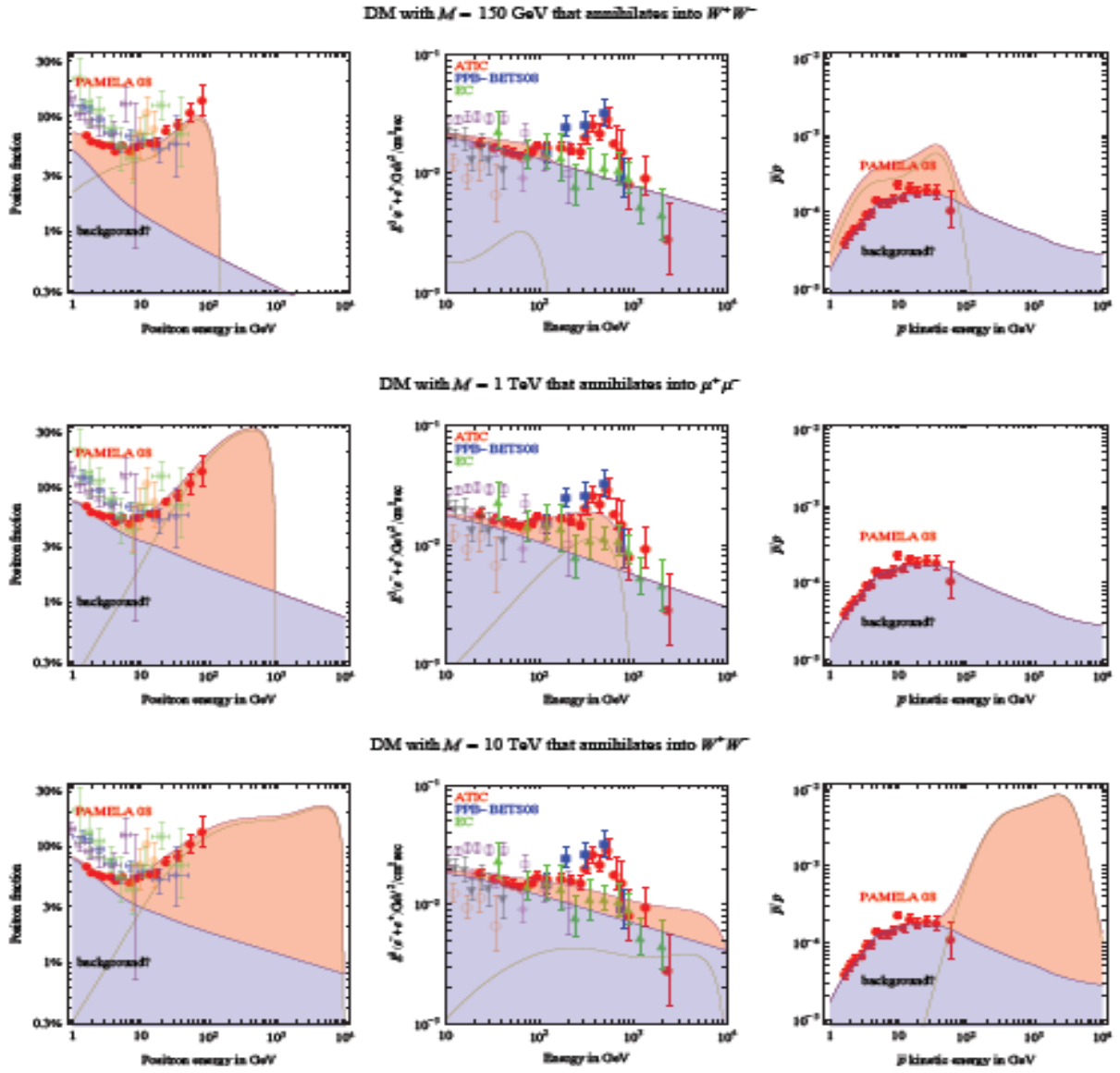

**Secondary Production Models**

**Donato et al., arXiv: 0810.5292v1**



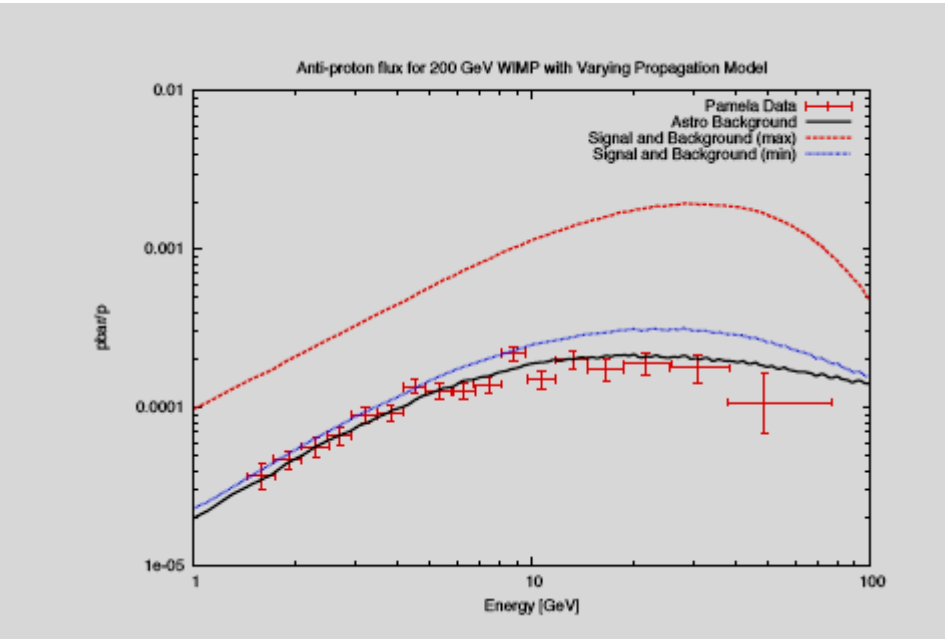

**Upper limit for enhancement factor for thermal WIMP DM flux as a function of the WIMP mass**

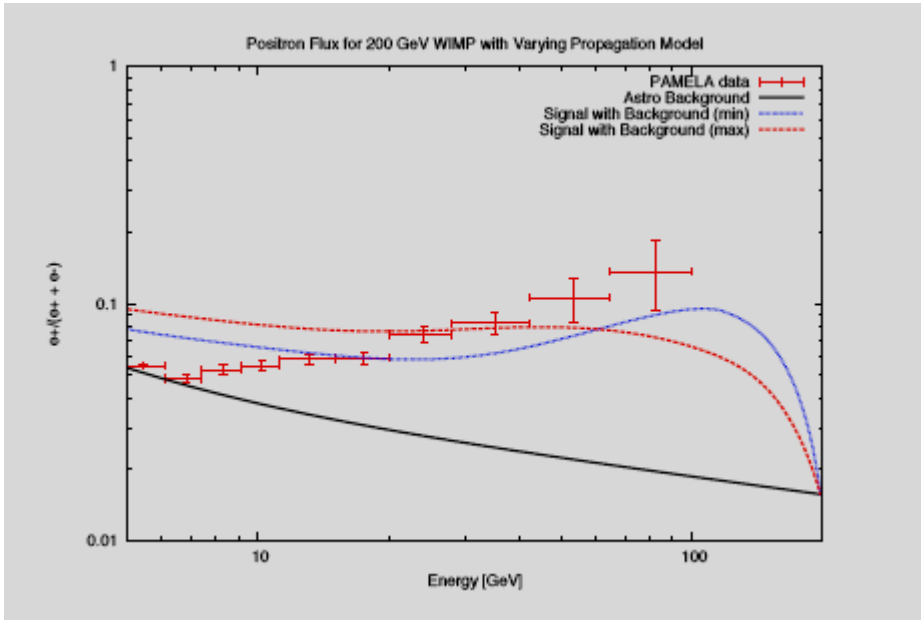
# Example: $e^-$, $e^- + e^+$, $\bar{p}$ with DM




**M. Cirelli et al., arXiv: 0809.2409v3**

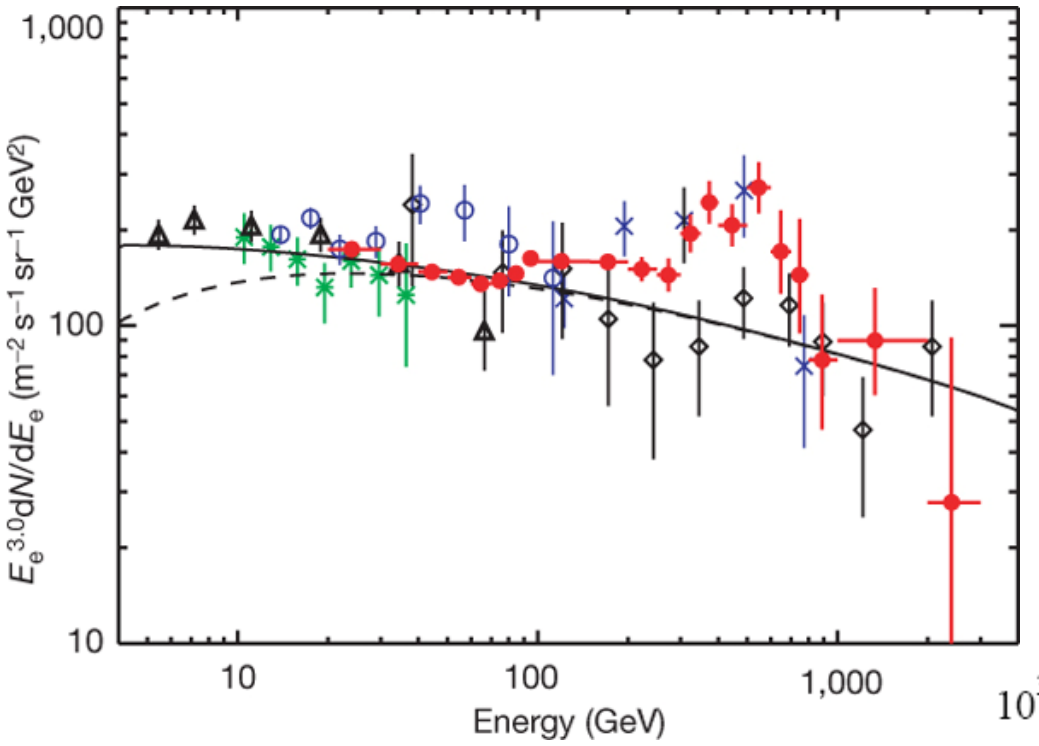
# Example: $e^+$ & $\bar{p}$ DM



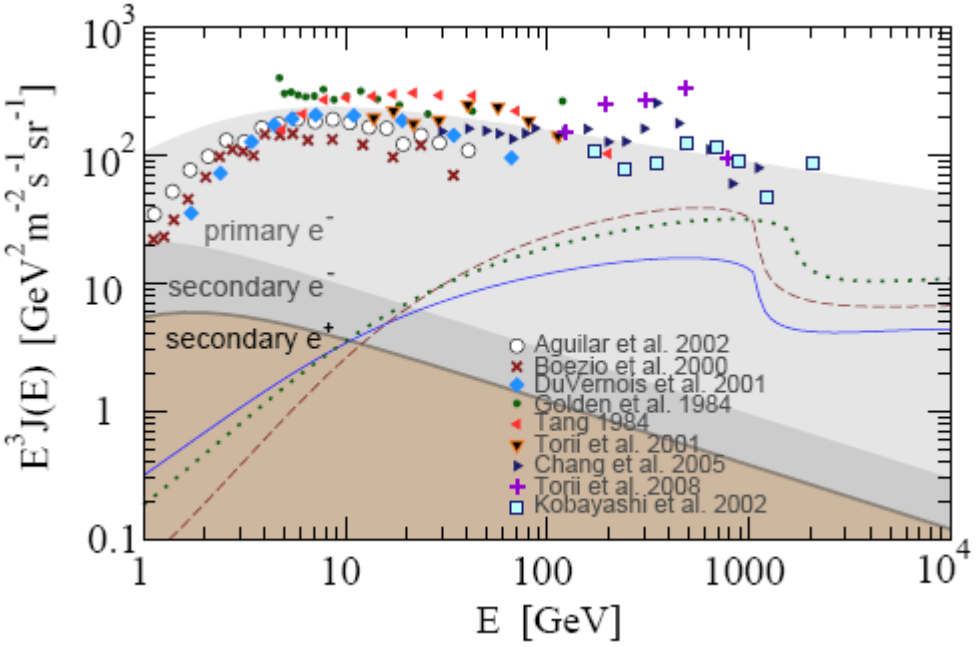

**P. Grajek et al., arXiv: 0812.4555v1**

**See Gordon Kane's talk**

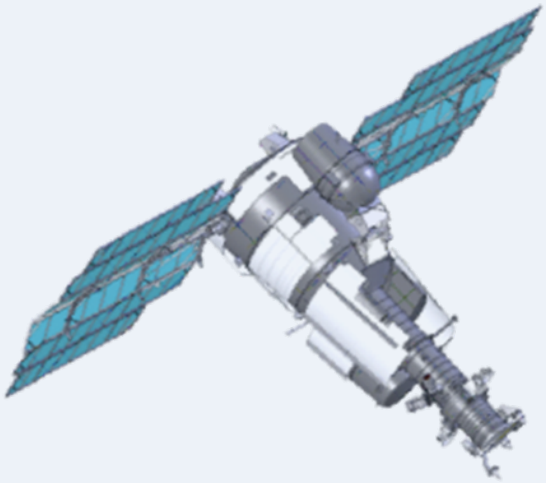


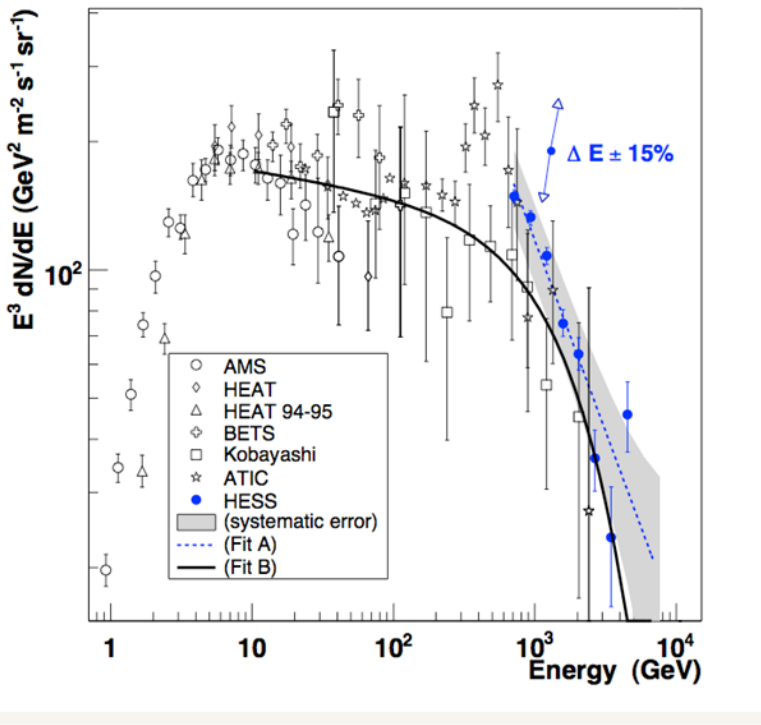

**J. Chang *et al. Nature* 456, 362-365 (2008)**

**H. Yüksak et al., arXiv:0810.2784v2 Contributions of e- & e+ from Geminga assuming different distance, age and energetic of the pulsar**



# Future observations of electrons





**Fermi GST: $\Phi_e^{\pm}$ up to ~700 GeV**

# Summary

- PAMELA has been in orbit and studying cosmic rays for ~30 months. >$10^9$ triggers registered, and >10 TB of data has been down-linked.

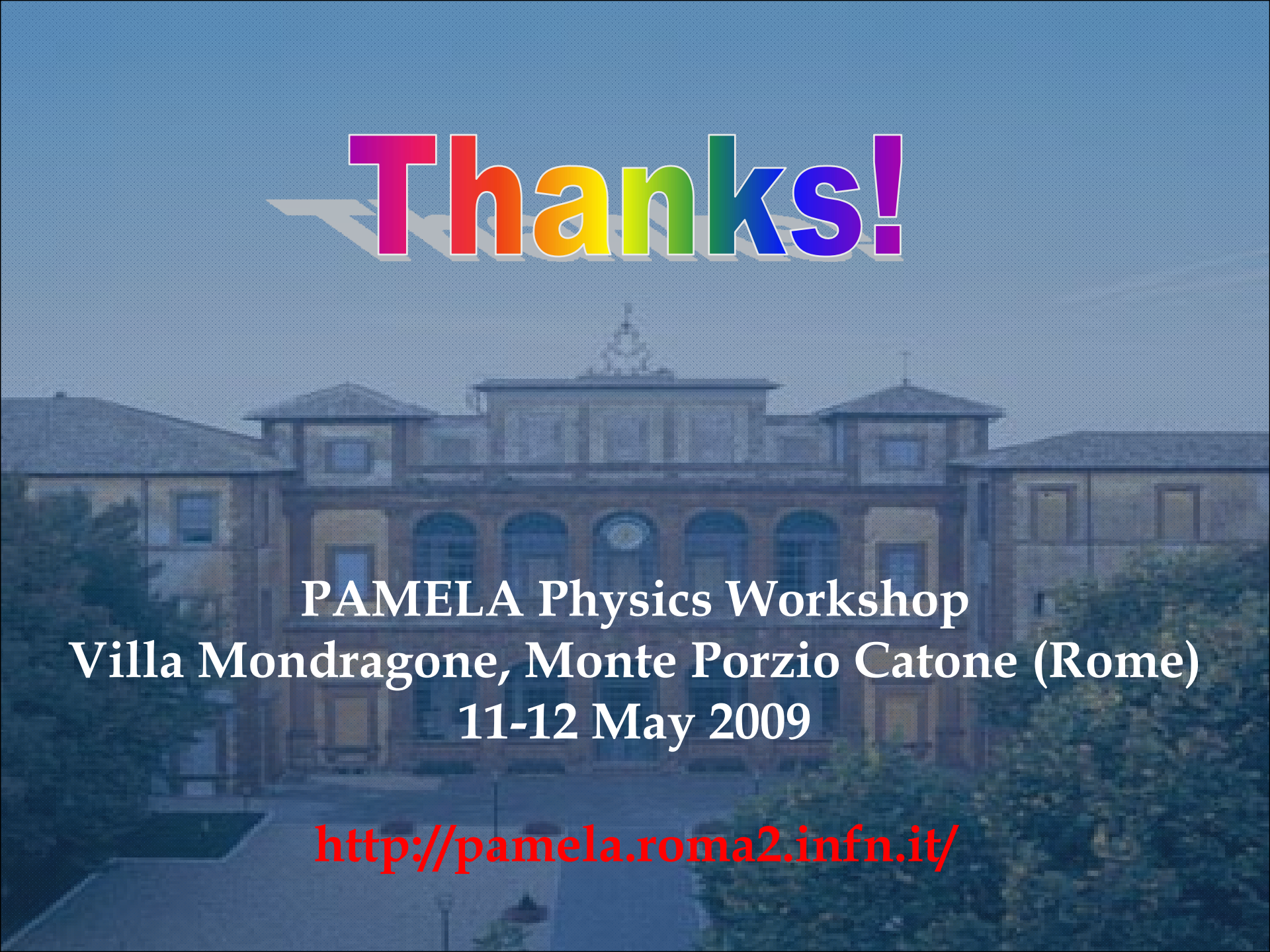
- Antiproton-to-proton flux ratio (~100 MeV - ~100 GeV) shows no significant deviations from secondary production expectations. Additional high energy data in preparation (up to ~150 GeV).

- High energy positron fraction (>10 GeV) increases significantly (and unexpectedly!) with energy. Primary source?
- Data at higher energies will help to resolve origin of rise (spillover limit ~300 GeV).

- Analysis ongoing to measure the $e^-$ spectrum up to ~500 GeV, $e^+$ spectrum up to ~300 GeV and all electrum ($e^- + e^+$) spectrum up to ~1 TV.

http://pamela.roma2.infn.it

INFN Istituto Nazionale di Fisica Nucleare


Thanks!
PAMELA Physics Workshop
Villa Mondragone, Monte Porzio Catone (Rome)
11-12 May 2009
http://pamela.roma2.infn.it/