ICHEP 2010, Paris, 22-28 July 2010

Antiparticle Detection in Space for Dark Matter Search: the PAMELA Experiment

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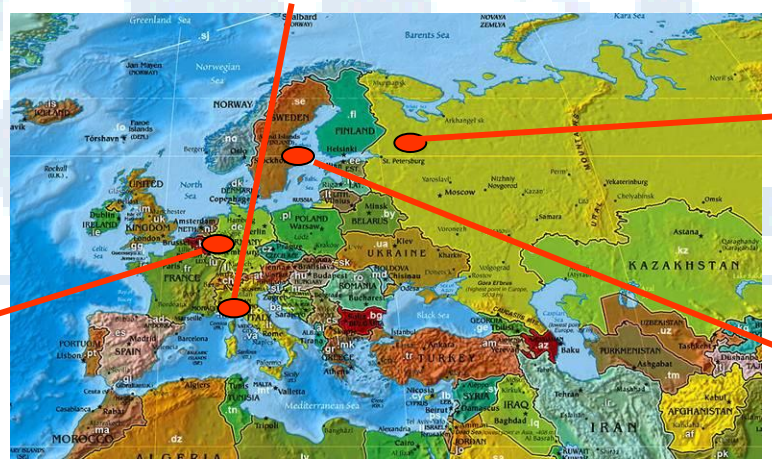
INFN – Florence, Italy

On behalf of the PAMELA collaboration

Italy: Bari, Florence, Frascati, Naples, Rome, Trieste, CNR, Florence



Russia:

Moscow

St. Petersburg

Germany:

Siegen

Sweden:

KTH, Stockholm

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	

→ **Simultaneous measurement of many cosmic-ray species**

→ **New energy range**

→ **Unprecedented statistics**

PAMELA detectors

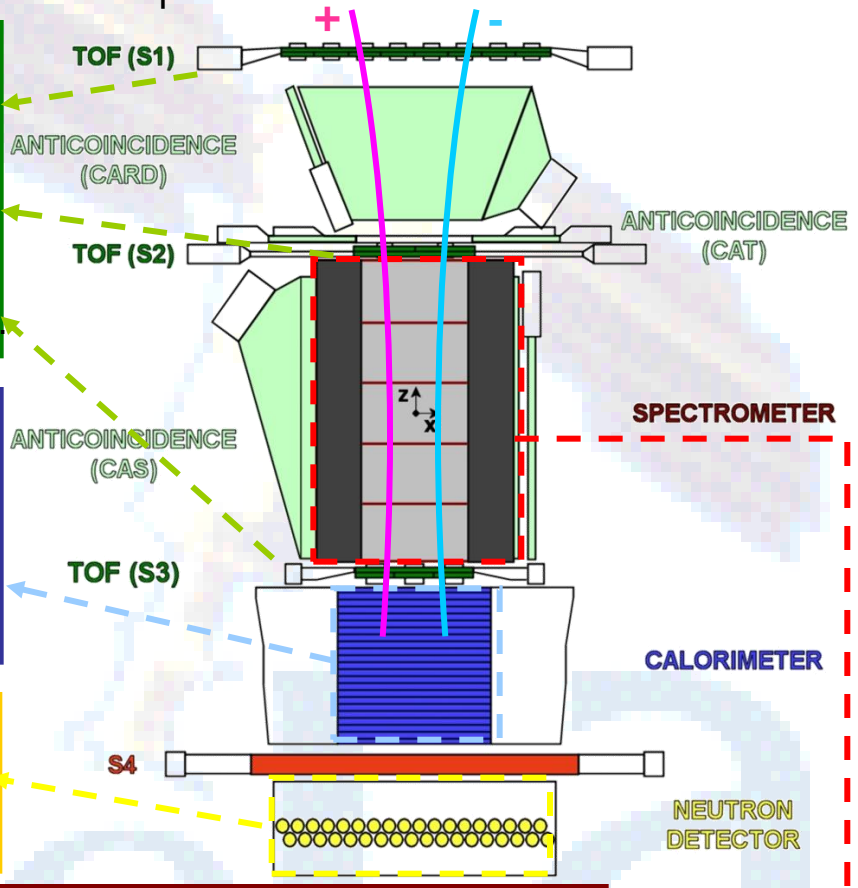
Main requirements → high-sensitivity antiparticle identification and precise momentum measurement

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 X0, 0.6 λI)
- Discrimination e+ / p, anti-p / e⁻ (shower topology)
- Direct E measurement for e⁻

Neutron detector
³He Tubes:
- 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***

PAMELA milestones

- **Launch from Baikonur: June 15th 2006, 0800 UTC.**
- **Power On: June 21st 2006, 0300 UTC.**
- **Detectors operated as expected after launch**

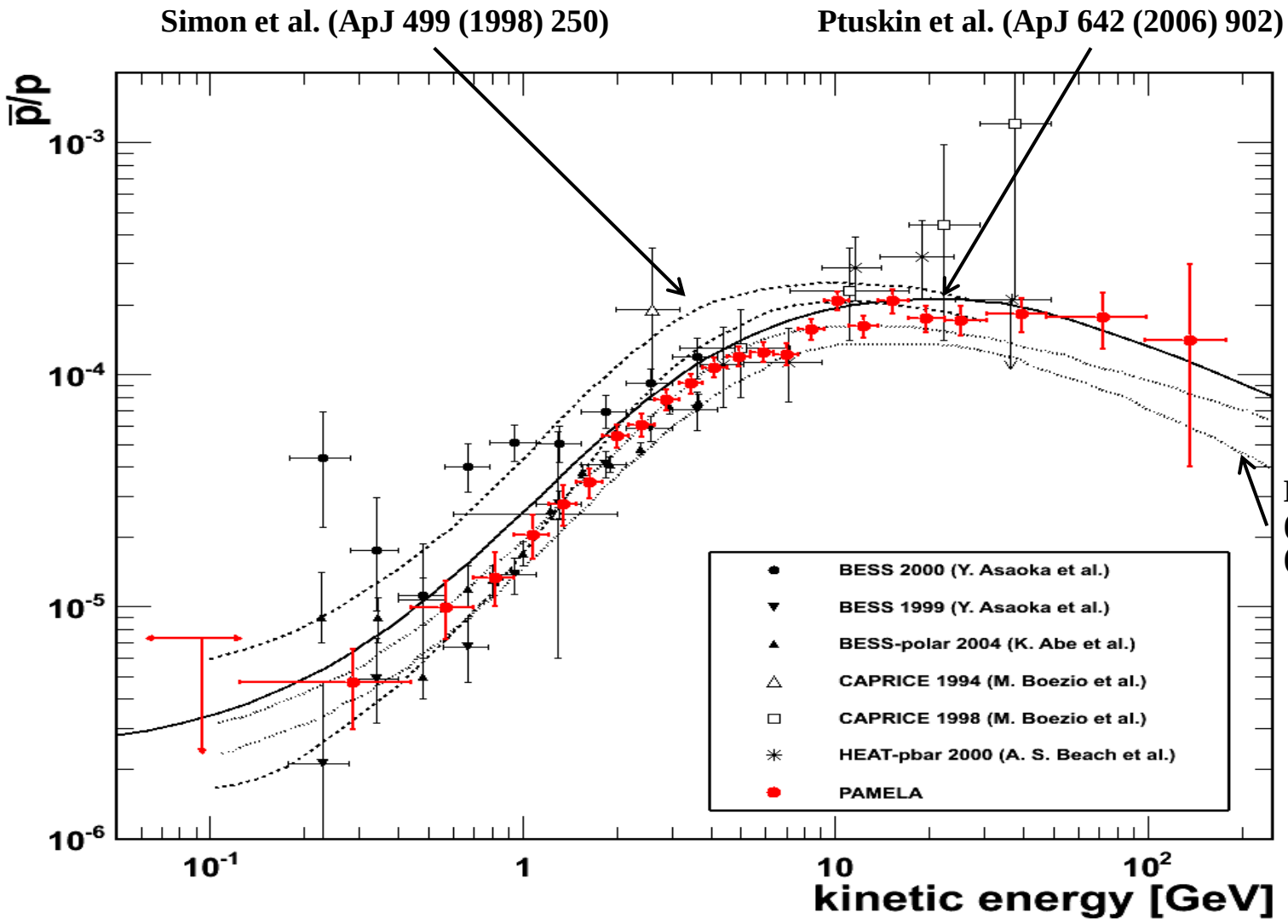
- **PAMELA in continuous data-taking mode since commissioning phase ended on July 11th 2006**

- **As of now:**
  - **1500 days in orbit**
  - **Trigger rate ~ 25 Hz**
  - **Data taking ~75% live-time**
  - **>20 TByte of raw data downlinked**
  - **>2.10^9 triggers recorded and under analysis**

- **The future: Mission extended up to December 2011**

Antiprotons

Antiproton to proton flux ratio (0.06 GeV - 180 GeV)



Systematics errors included

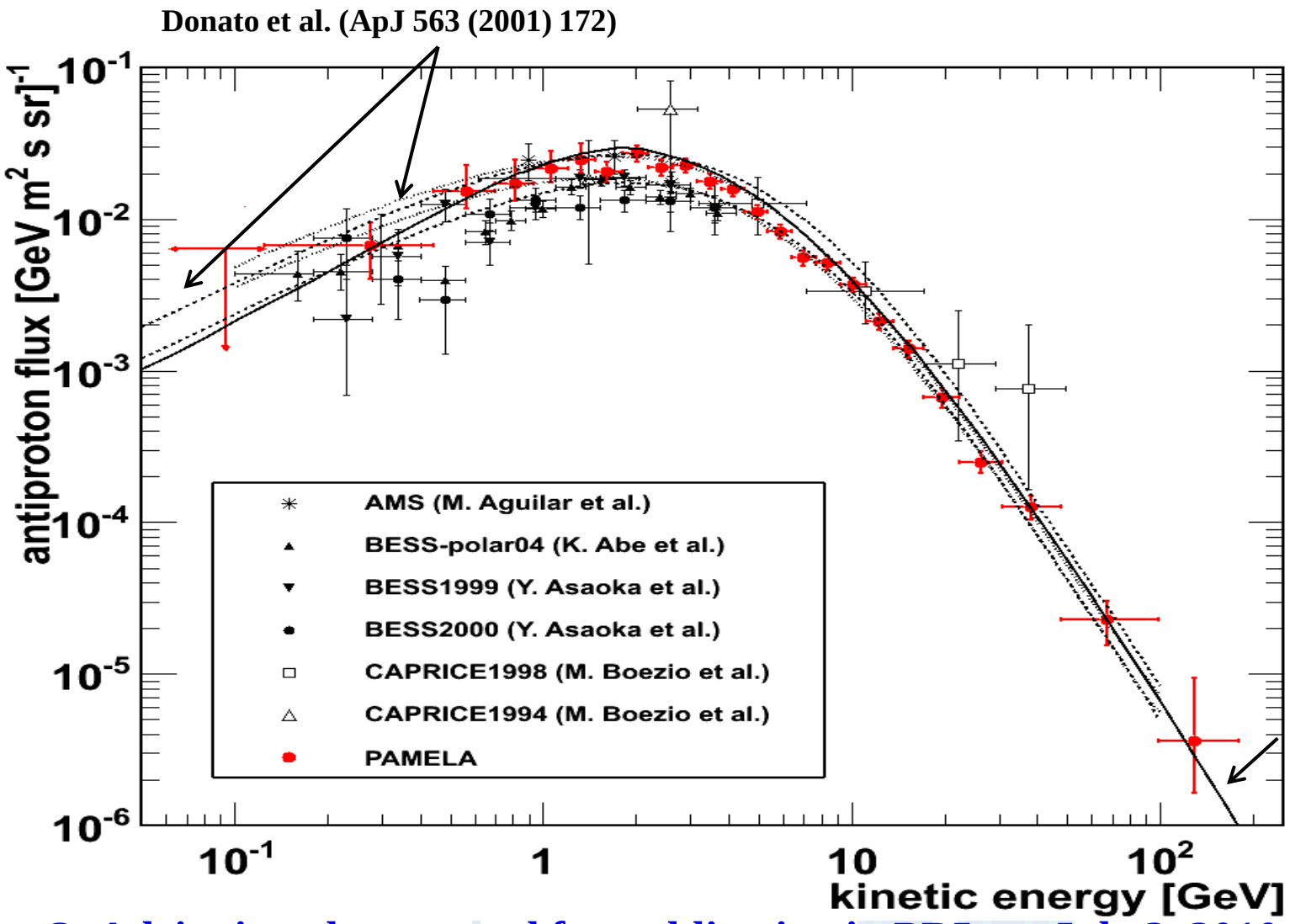
850 days

Donato et al. (PRL 102 (2009) 071301)

Systematics errors included

O. Adriani et al., accepted for publication in PRL on July 2, 2010

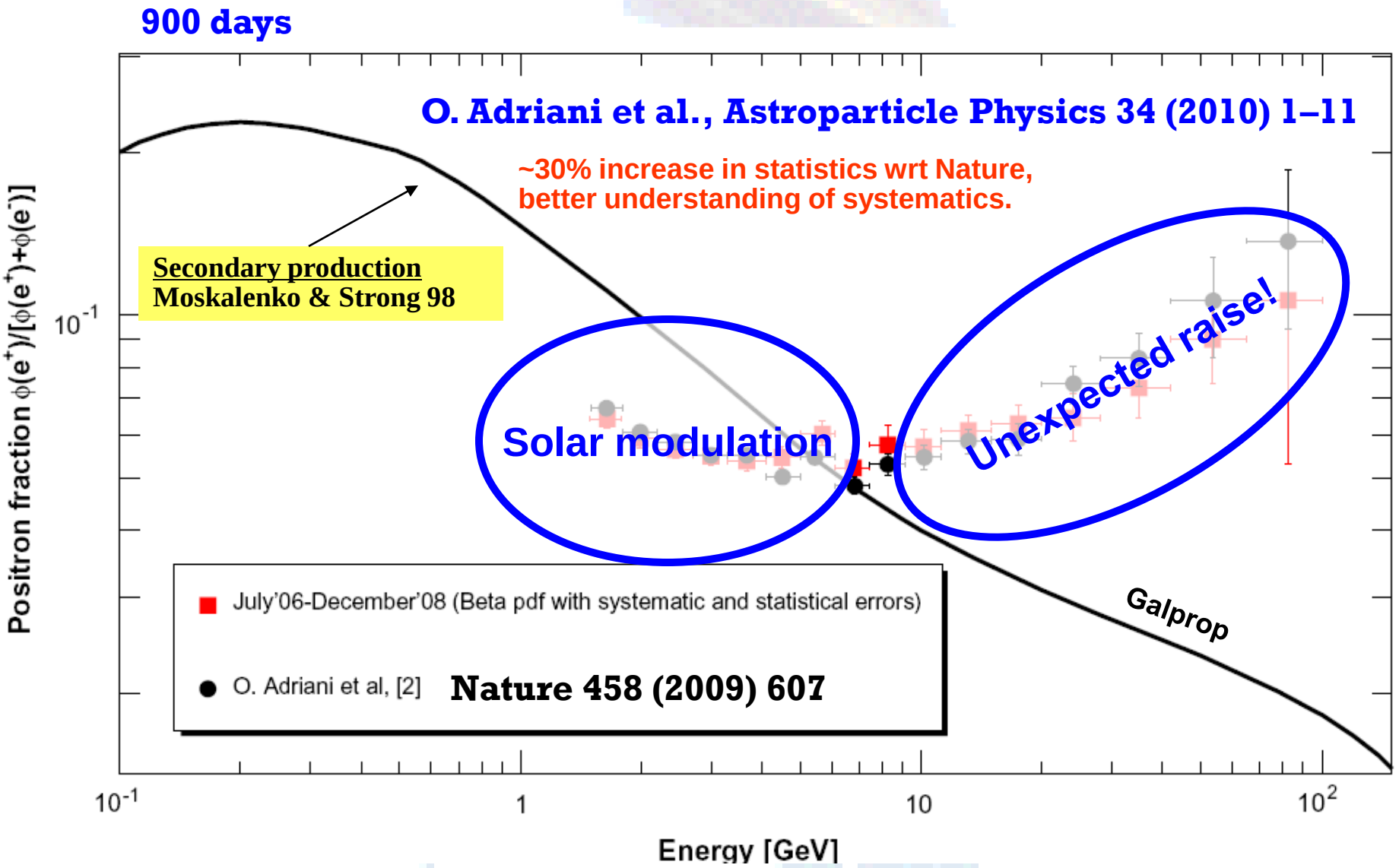
Antiproton Flux (0.06 GeV - 180 GeV)



O. Adriani et al., accepted for publication in PRL on July 2, 2010

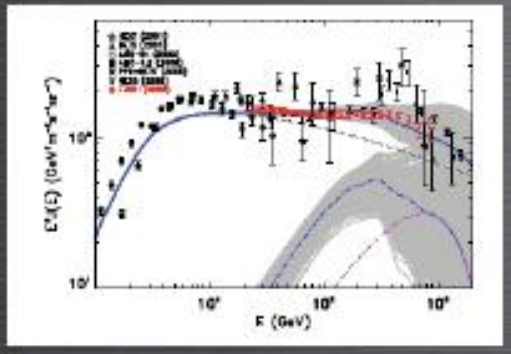
Positrons

Positron to all electron ratio



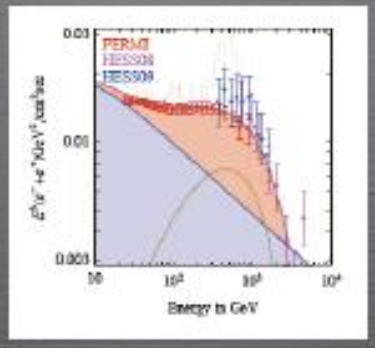
INTERPRETATION

PULSARS



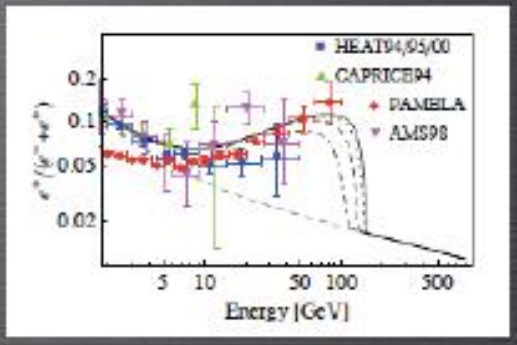
GRASSO ET AL. 2009

DM ANNIHILATION



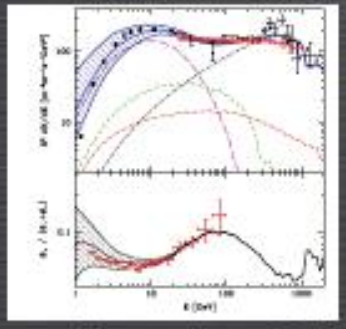
STRUMIA ET AL. 2009

DM DECAY



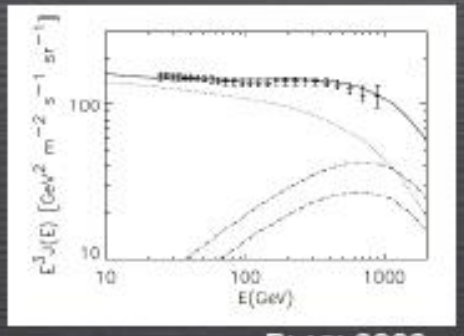
IBARRA ET AL. 2009

SNRS INHOM.



PIRAN ET AL. 2009

SNRS 2NDARY CR ACC.



BLASI 2009

... + MANY MANY OTHER MODELS (320+ CITATIONS TO PAMELA E+ PAPER AS OF SEPTEMBER 2009). SEE PIERRE SALATI'S TALK LATER THIS MORNING

560 Citations up to today!!!!!

From G. Bertone, Plenary Talk at COSMO09 Conference

Electrons

Electron flux, methods

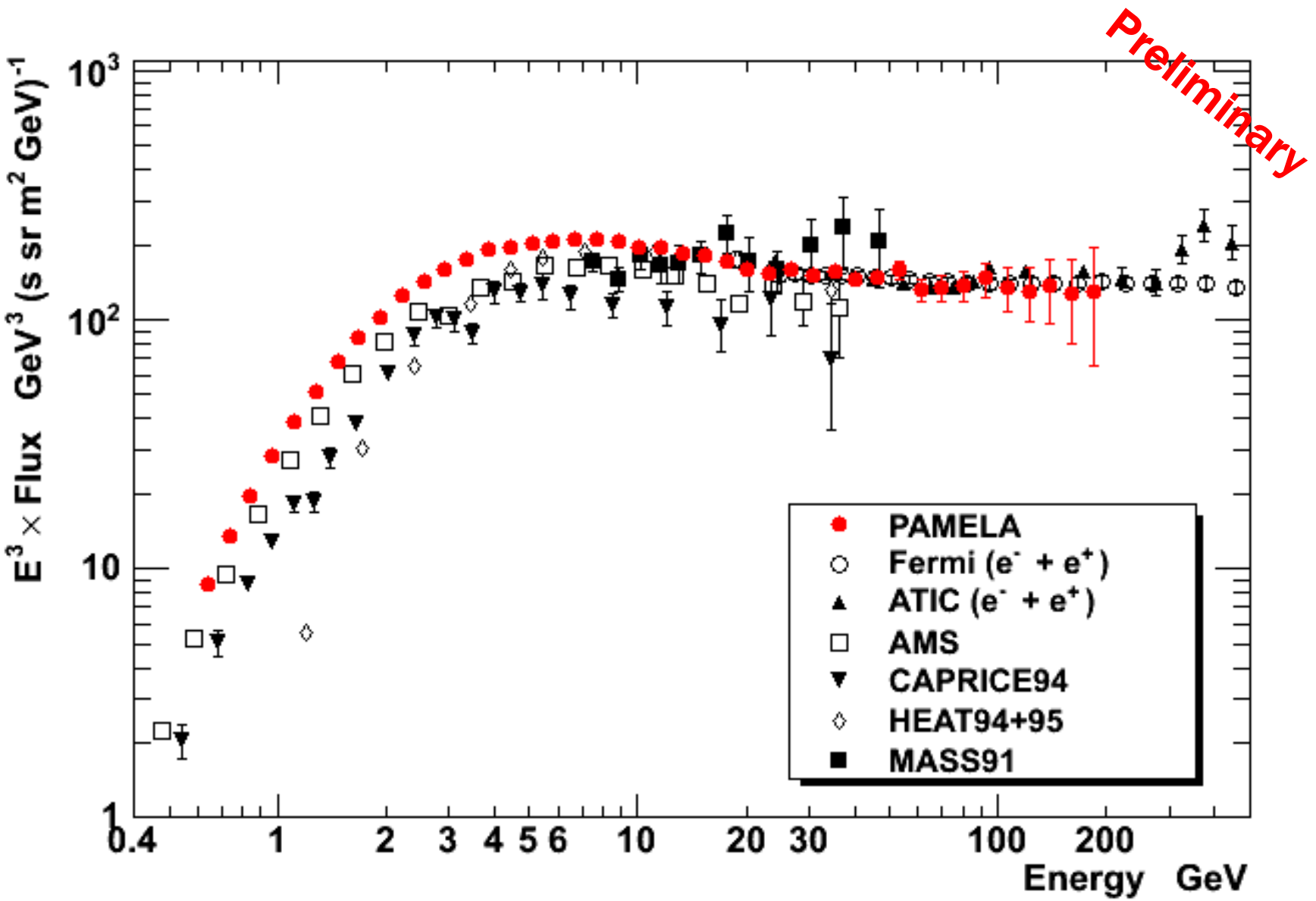
Three different approaches:

1. **Tracker-based selection**
   - **strong track quality requirements**
   - **loose calorimeter selection**
   - **energy measured by the tracker**

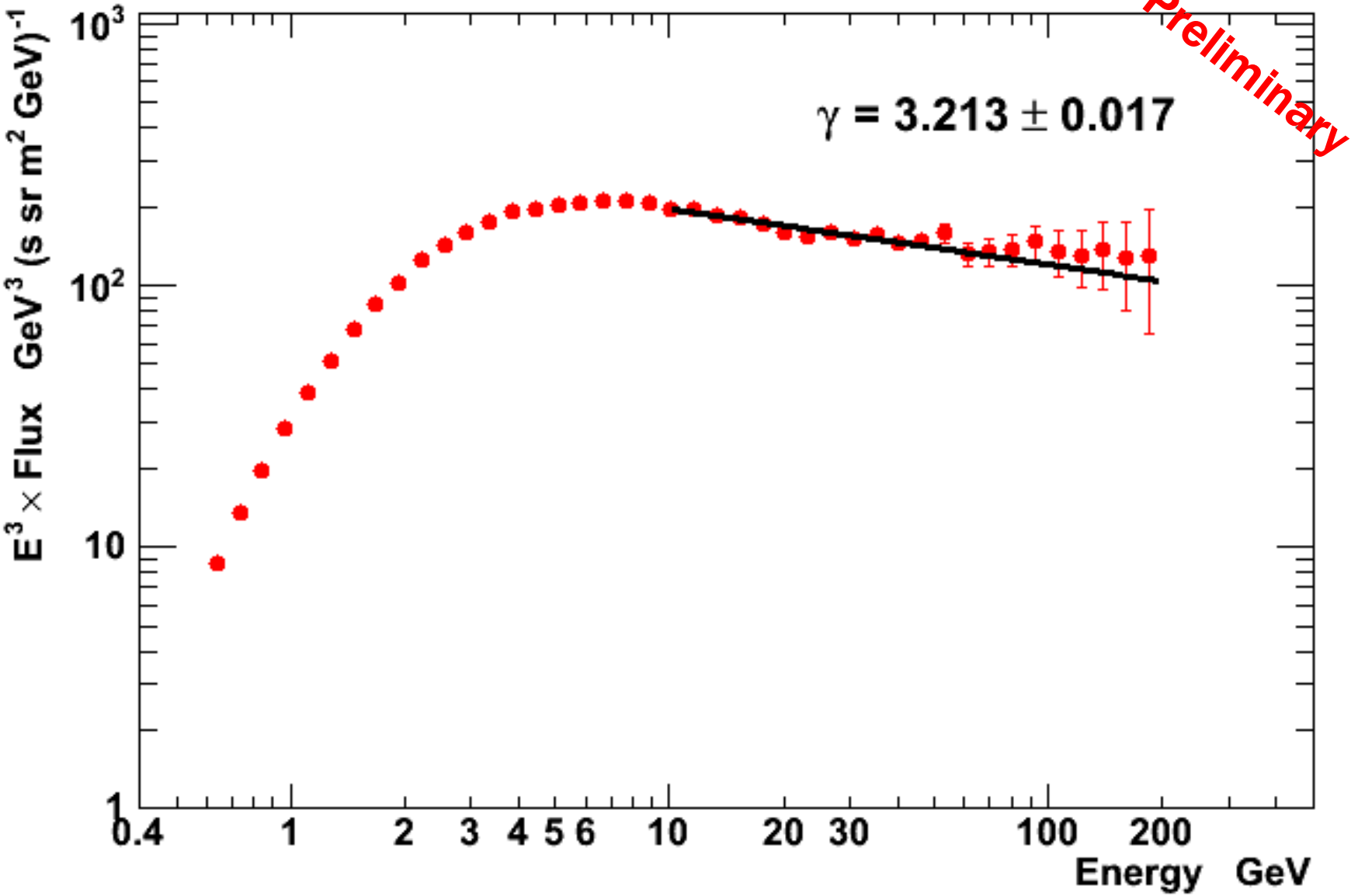
2. **Calorimeter-based selection**
   - **loose track quality requirements - negative charged particle**
   - **strong calorimeter selection**
   - **energy measured by the calorimeter**

2. **Pure calorimetric measurement:**
   - **strong calorimeter selection**
   - **energy measured by the calorimeter (à la ATIC/Fermi)**
   - **e^-+e^+ flux**

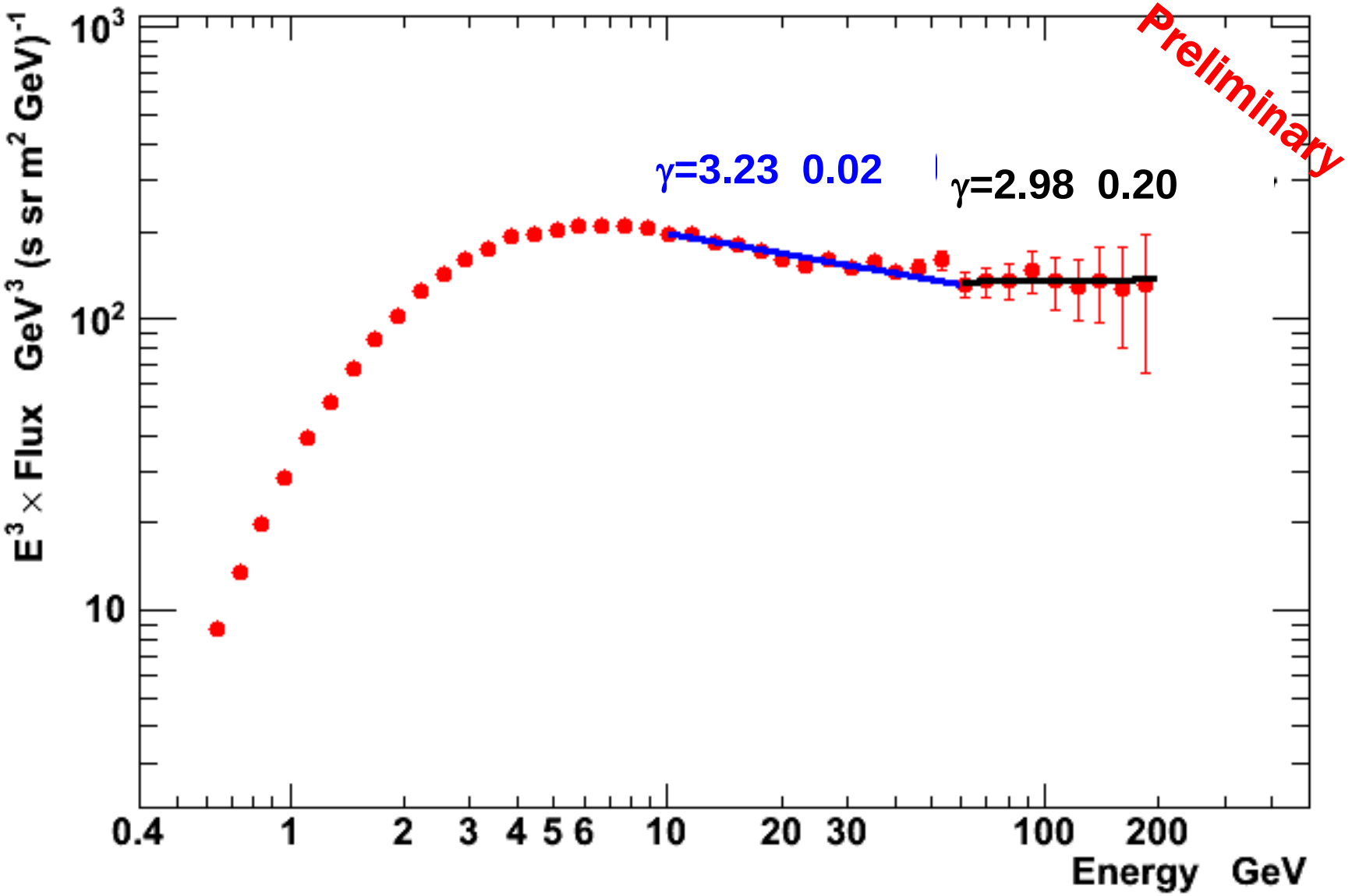
PAMELA Electron (e^-) Spectrum (x E^3)



PAMELA Electron (e^-) Spectrum (x E^3)



PAMELA Electron (e^-) Spectrum (x E^3)



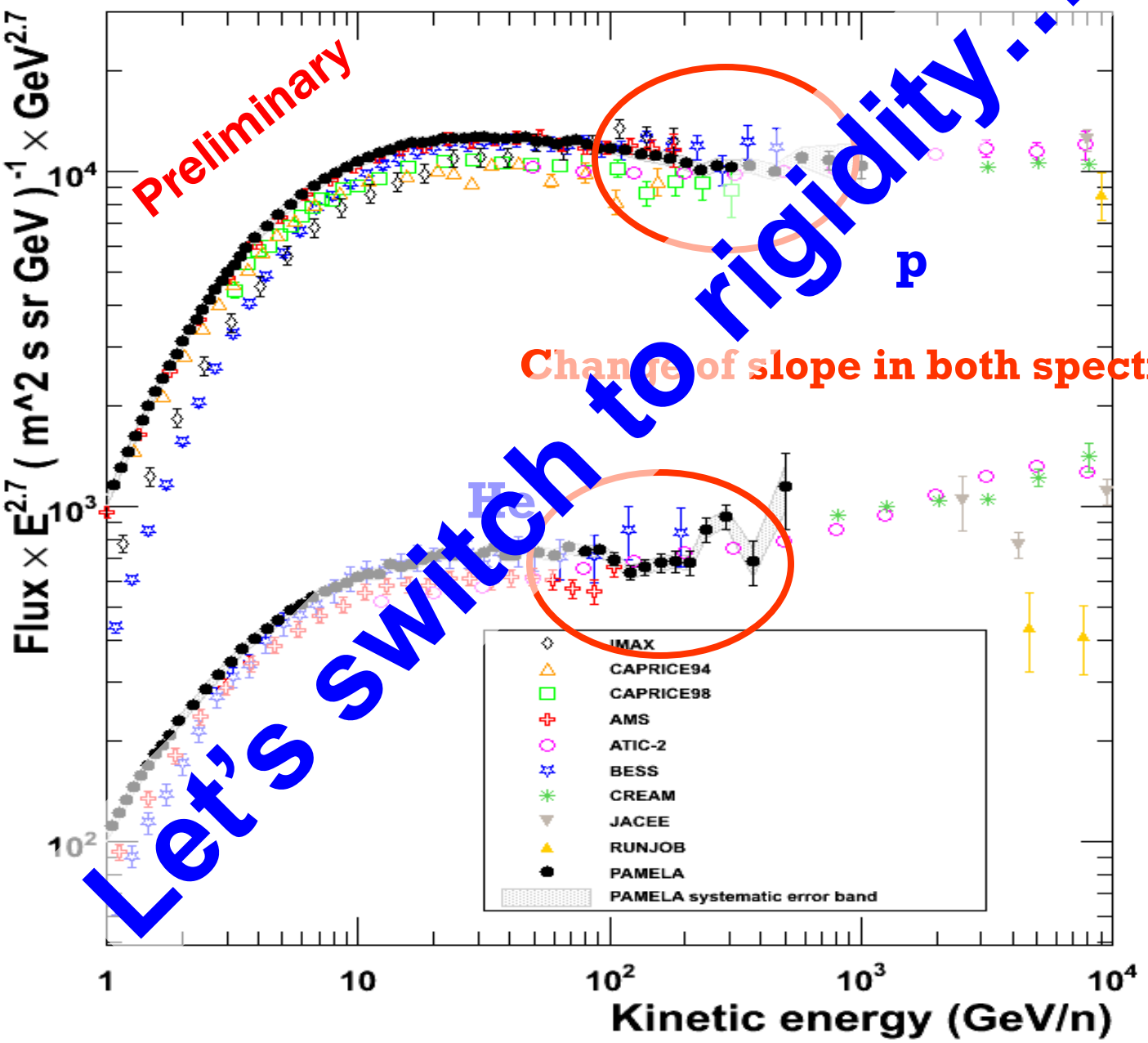
Protons & Helium

Importance of p and He spectra

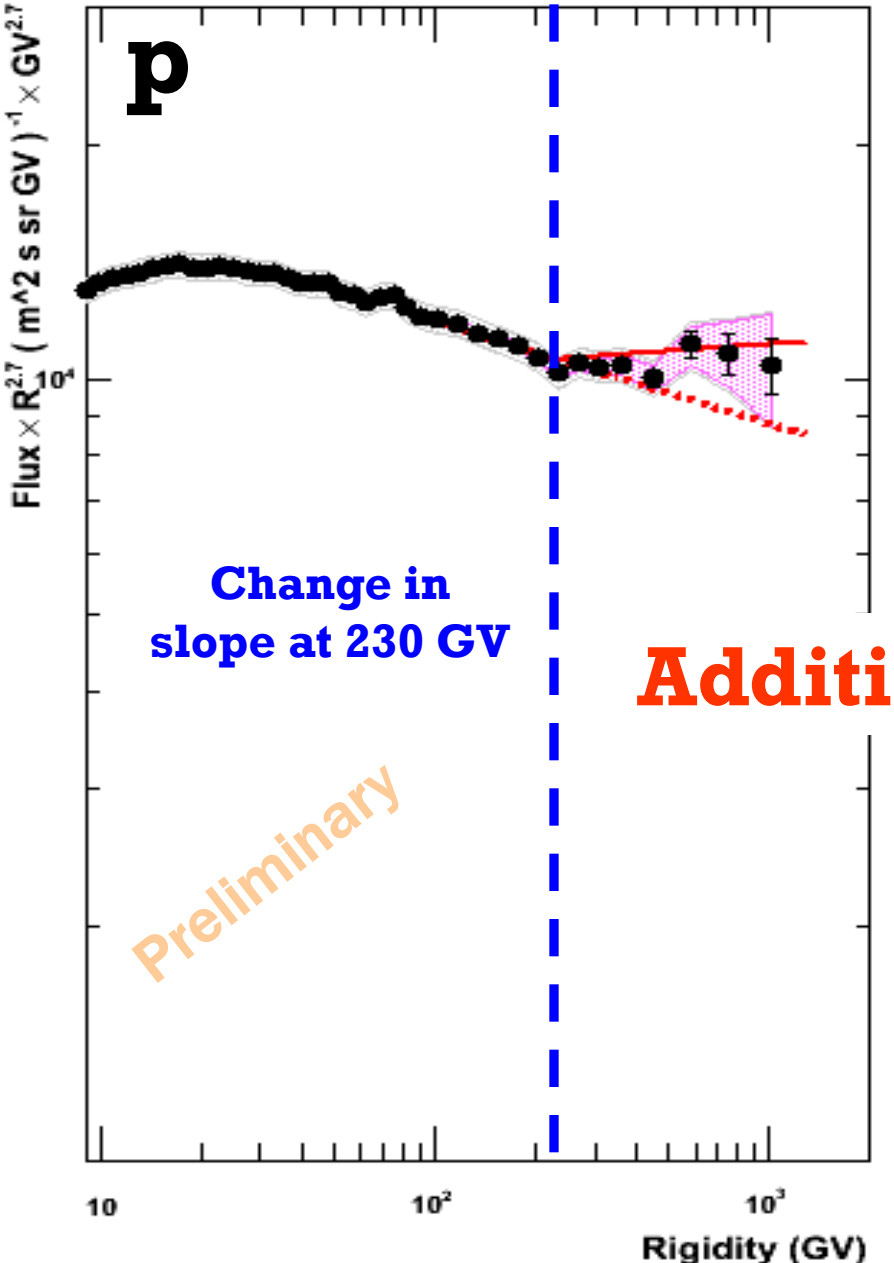
- Precise p and He spectra measurements are very important:
  - To understand astrophysical phenomena
  - To verify/constrain the solar modulation and geomagnetic models
  - To study sources, acceleration and propagation in the galaxy
  - To constrain the propagation models (essential for Dark Matter searches!) (please note, B/C is also very important!)

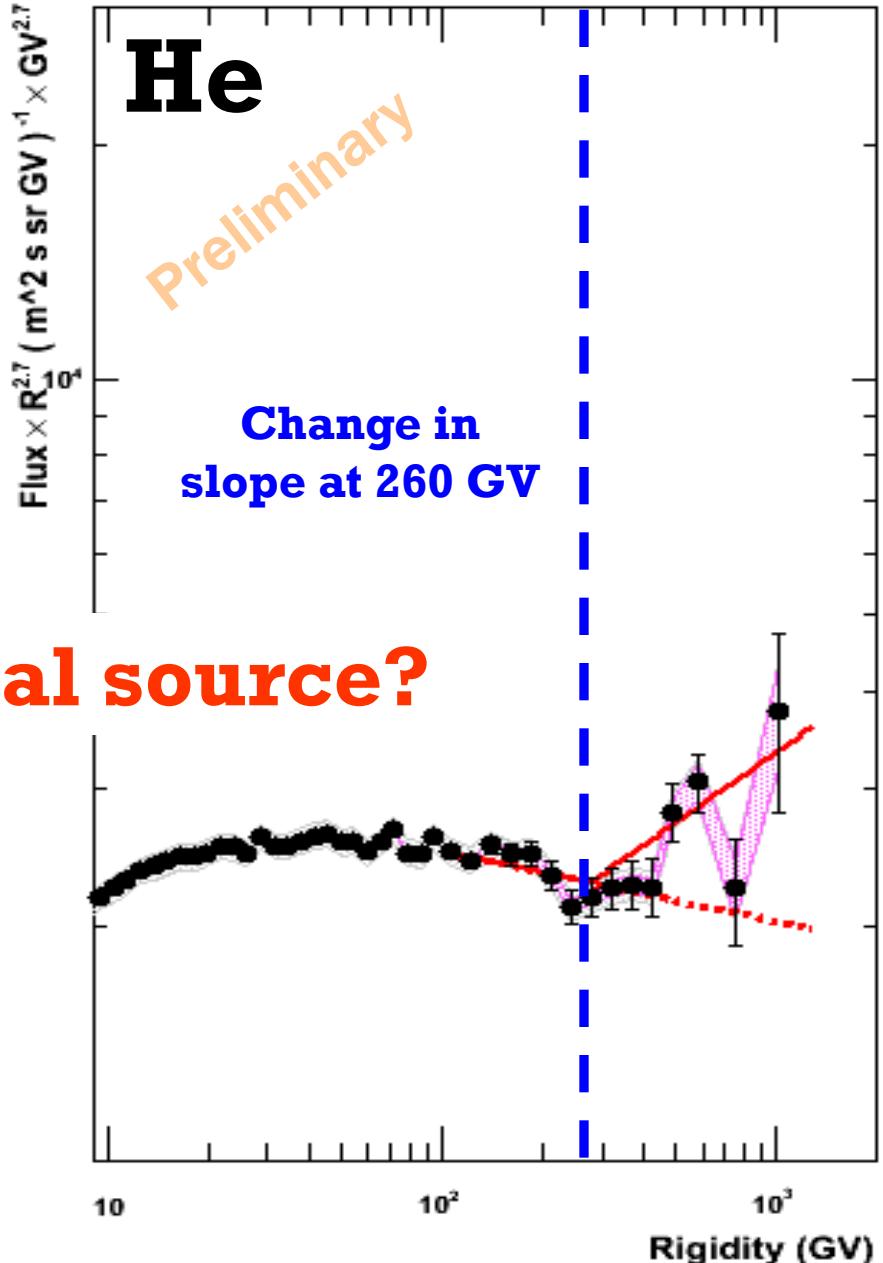
- Big challenge from the experimental point of view:
  - 1-2% precision in the absolute flux is necessary
  - Detailed study and understanding of the detector systematics
  - Necessity to cover a very broad energy range (100 MeV→TeV)
  - Long term exposure (Detector stability)
  - Transient phenomena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

Proton and Helium fluxes in KE ($xE^{2.7}$)



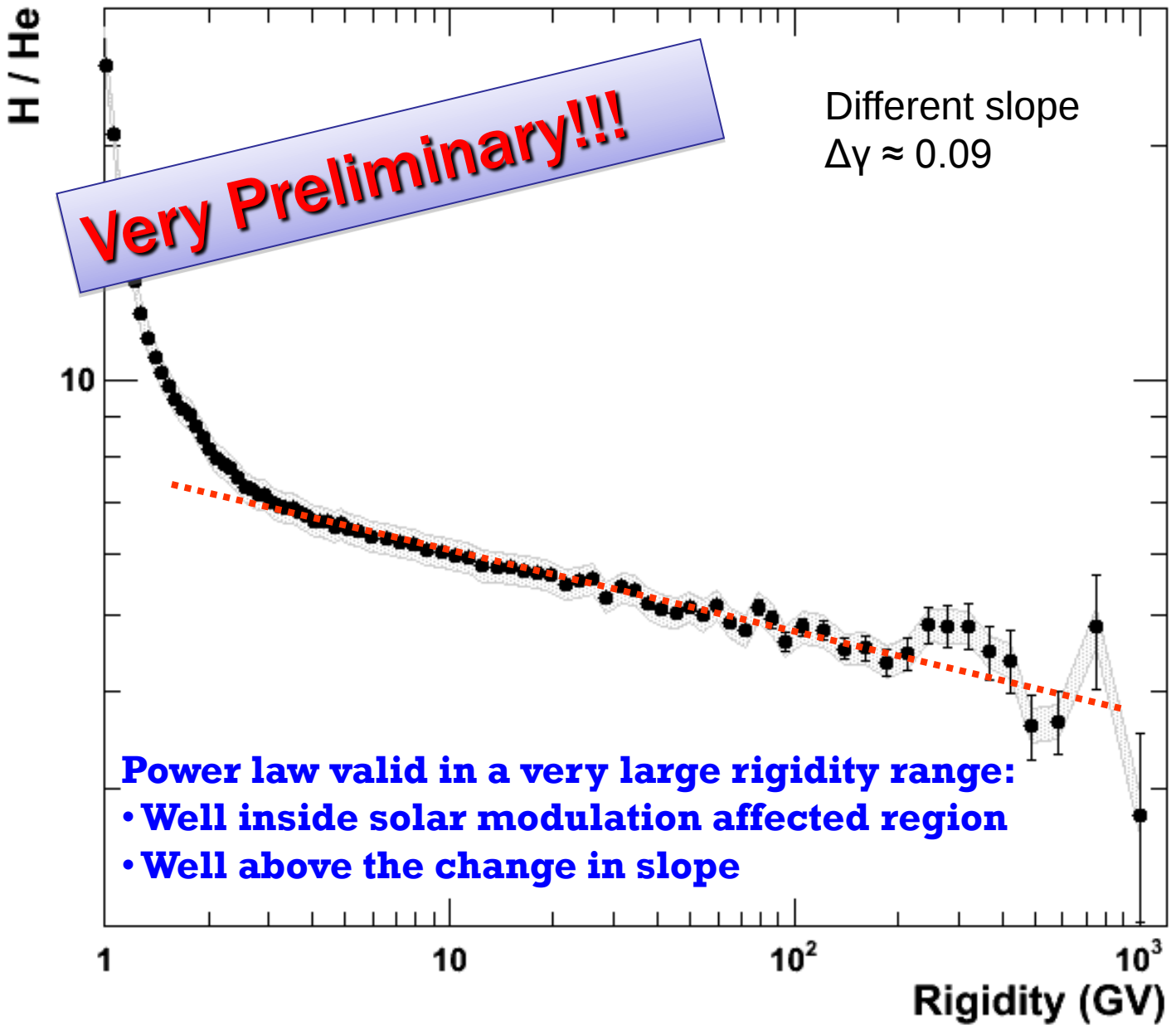
p and He spectra in Rigidity ($xR^{2.7}$)





Additional source?

Proton to helium ratio in rigidity



Conclusions

- **PAMELA is continously taking data since July 2006**

- **We presented results from ~900 days of data:**
  - → **Antiproton charge ratio and antiproton flux (~0.06 GeV ÷180 GeV)**
    - → no evident deviations from secondary expectations
  - → **Positron charge ratio (~1 GeV ÷100 GeV)**
    - → **Clear excess with respect to secondary production models**
    - → More data to come at higher energies (**up to 300 GeV**, spillover limit) could help to clarify the origin of the eccess
  - → **Preliminary Electron spectrum up to 200 GeV**
    - → Spectral features that may point to additional components.
    - → Analysis is ongoing to increase the statistics and expand the measurement of the **e^- spectrum up to ~500 GeV**
    - → All electron ($e^- + e^+$) spectrum up to ~1 TV later on
  - → **Preliminary Proton and Helium spectra up to ~ TeV**
    - → p and He spectral index are different
    - → Change of spectral index in both spectra at a similar rigidity value
    - → p/He ratio in Rigidity shows a single power law behavior from ~ GV/c up to ~ TV/c

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

→ **Pamela mission has been officially extended up to 2011**

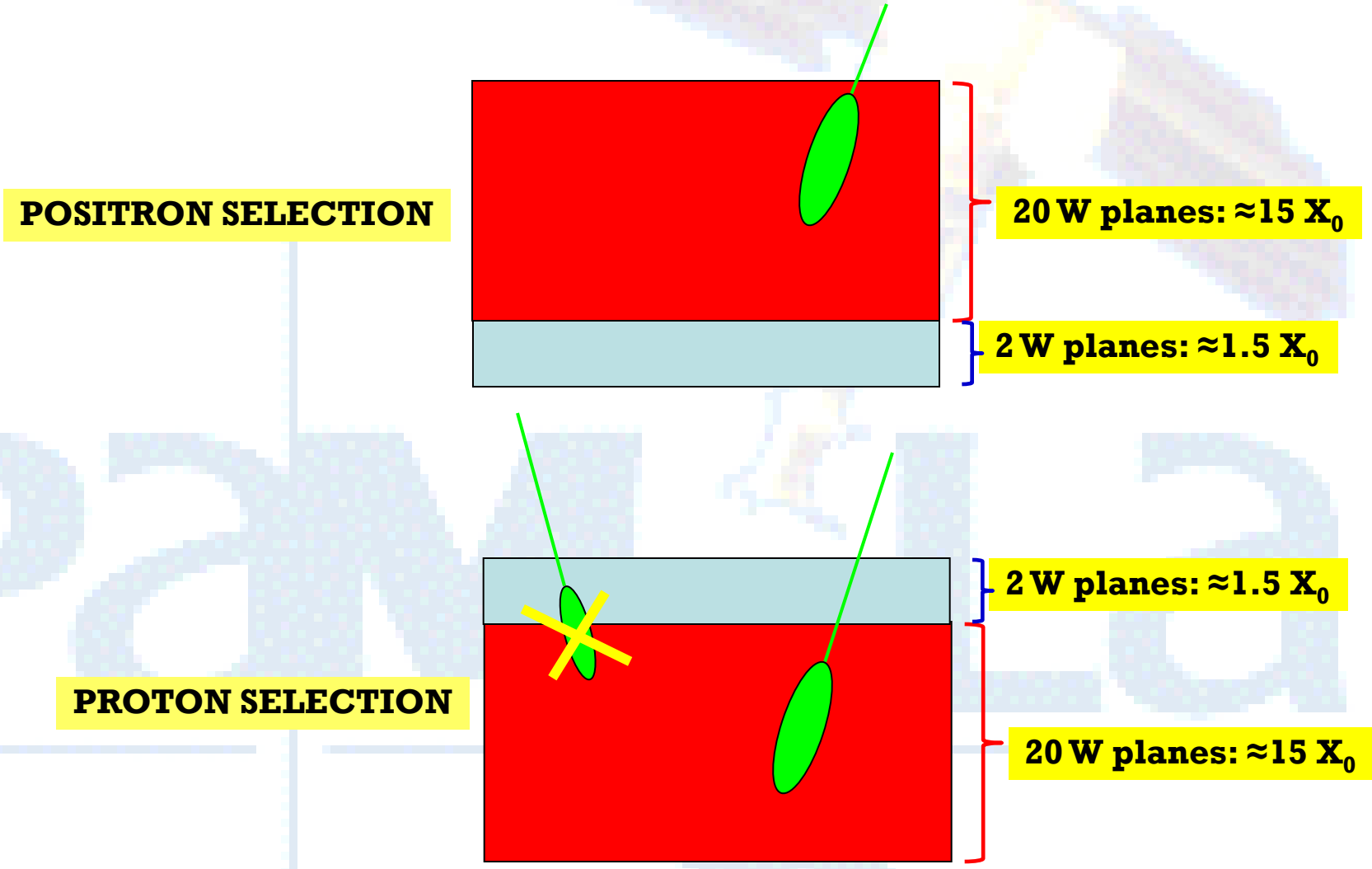
→ **More new and exciting results will certainly come in the next few years!**

Backup slides

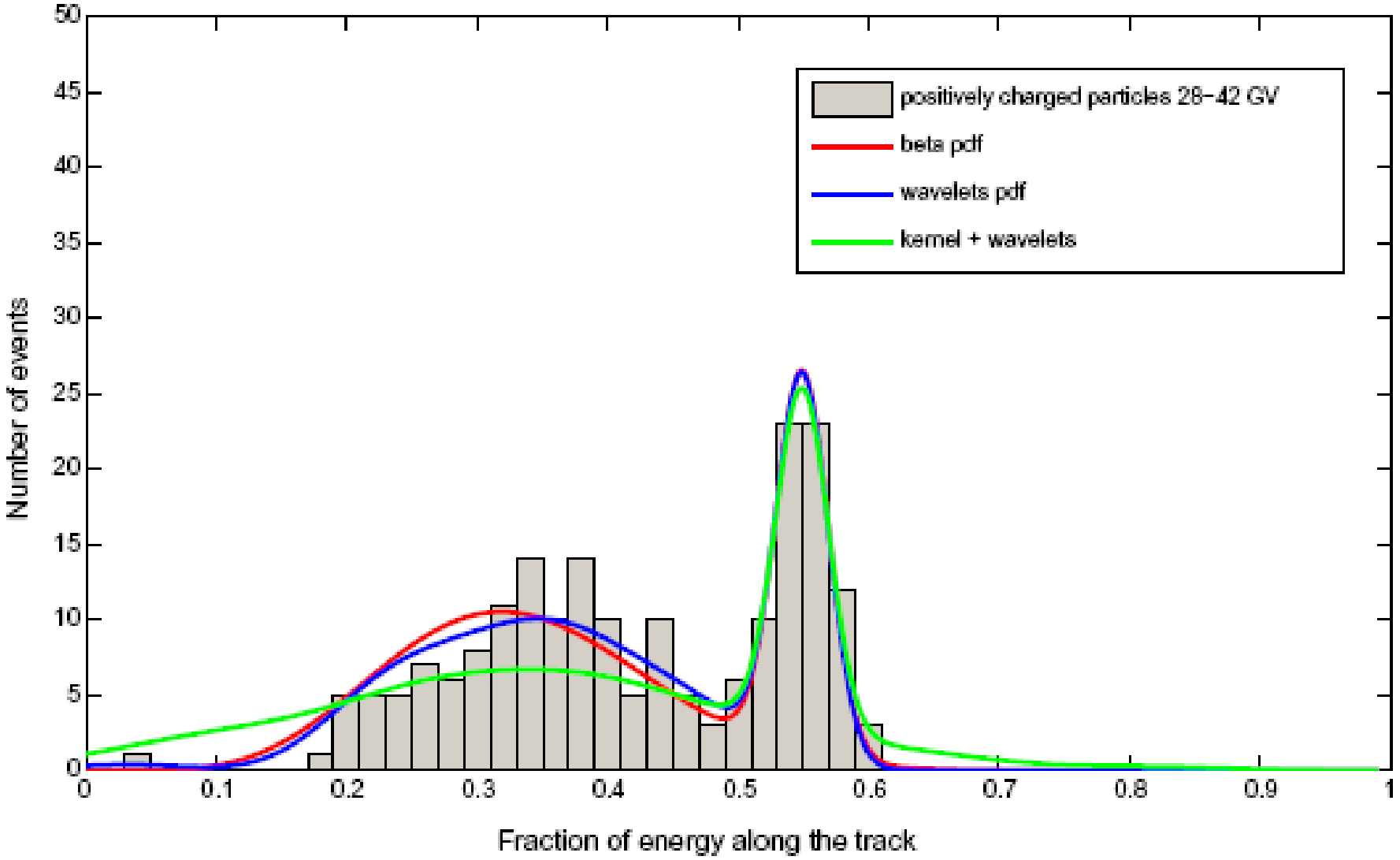
The "pre-sampler" method

Selection of a pure sample of protons from flight data

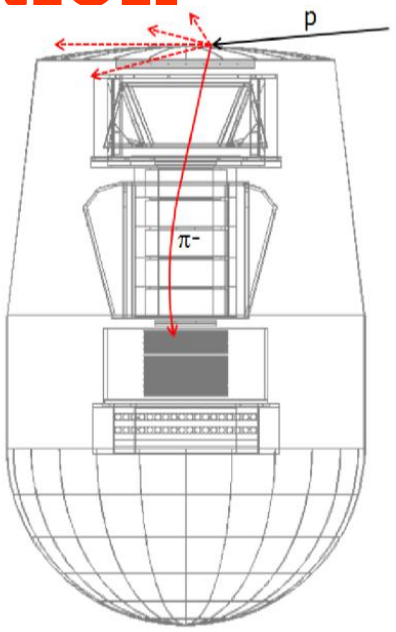
CALORIMETER: 22 W planes: 16.3 X_0



Different statistical methods used to extract signal and background

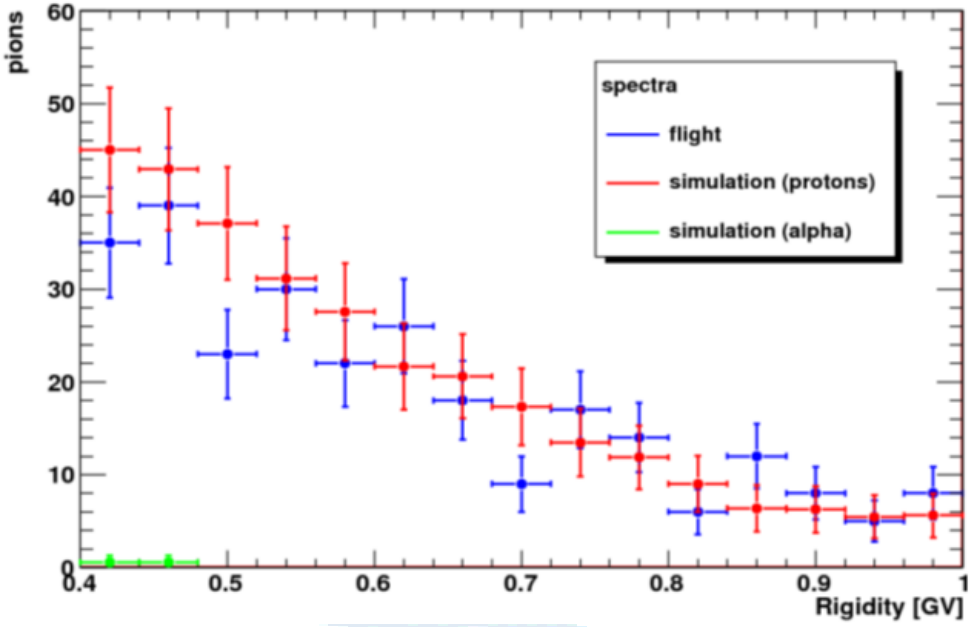


Residual pion contamination

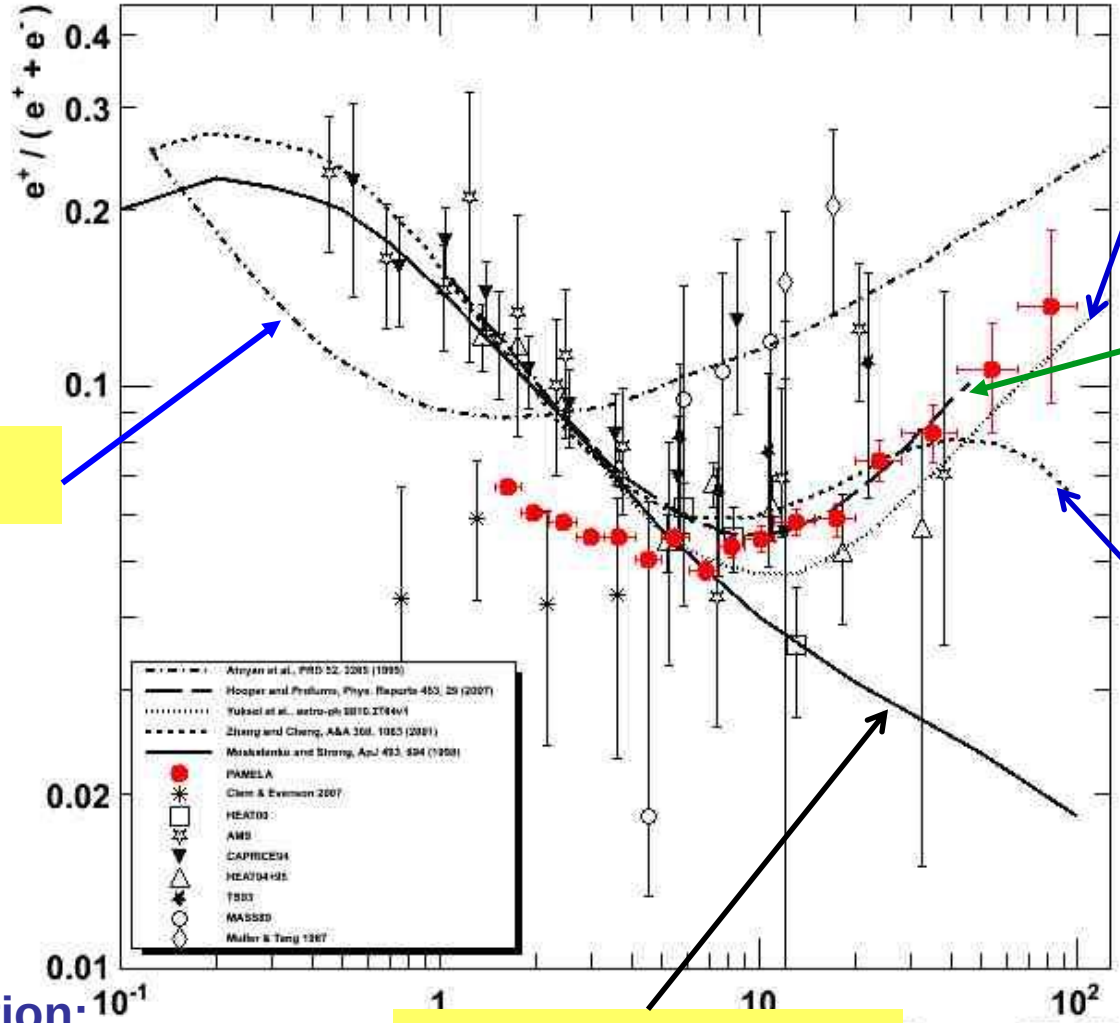


- Protons interacting in the material surrounding PAMELA can generate π^- which mimic p-bar.
- Residual contamination of π^- passing selection cuts estimated with extensive and accurate FLUKA2006-based simulation.
  - Contamination is ~ 10% at 1 GeV, < 1% above 3 GeV.

- Simulation results are validated by comparison with flight data (<1 GV pion sample).



Interpretation of PAMELA Positron Fraction



Pulsar Component
Atoyan et al. 95

Pulsar Component
Yüksel et al. 08

KKDM (mass 300 GeV)
Hooper & Profumo 07

Pulsar Component
Zhang & Cheng 01

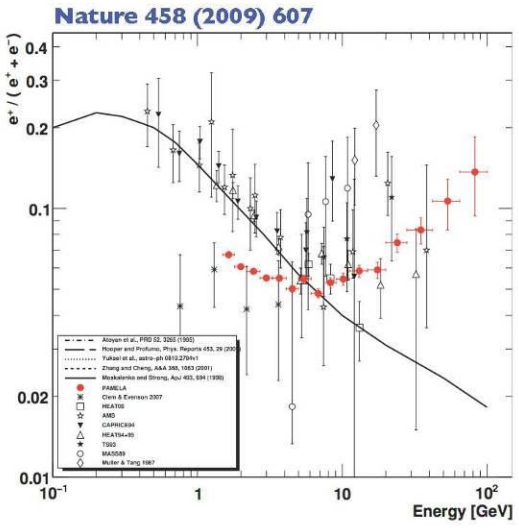
Secondary production
Moskalenko & Strong 98

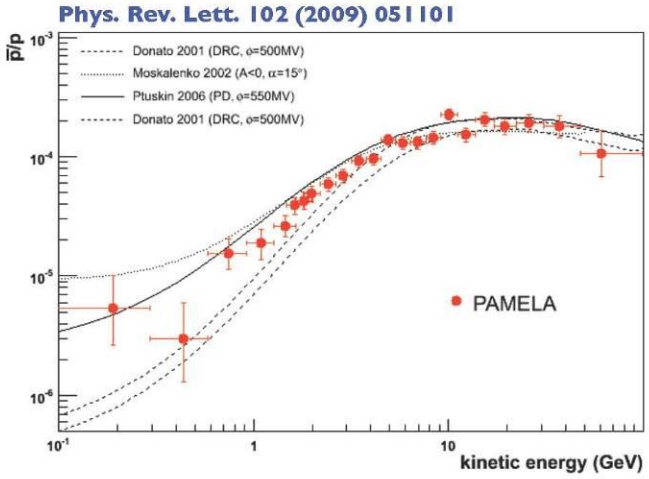
DM interpretation:
- Leptophilic decays
- Majorana DM
- KK DM
- …

Astro Physical Interpretation:
- Pulsar
- …

The antiproton (and e^-) results should be taken into account!!!!!

DM interpretation of positron eccess





- 'Leptophilic' decays are favoured.

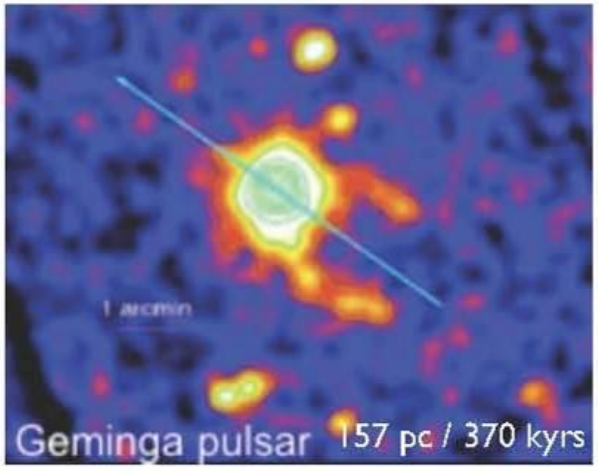
- Sharp rise! DM annihilation spectrum from SUSY is too soft (qq or WW dominant final states).

- The required DM annihilation rate is much higher ($\times 10^{2\text{-}3}$) than predicted for a thermal relic from Big Bang.
  - Inhomogeneous DM distribution?
  - Enhanced $\sigma_{ann.}$, e.g. Sommerfeld effect?

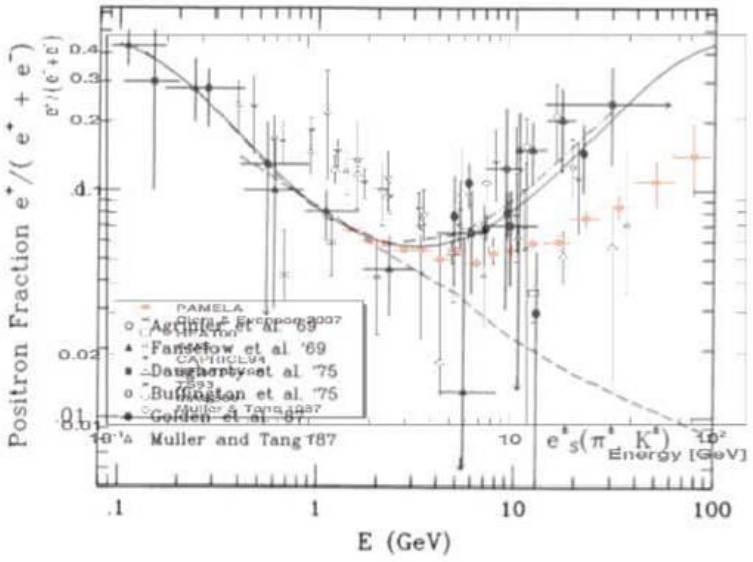
- **NB:** model builders must not overproduce **antiprotons** (or gammas)

An astrophysical explanation?

- Dark matter provides a spectacular solution to the rising positron fraction
- However, **pulsars** offer a standard astrophysical solution...
- Strong spinning **B** → accelerated electrons → synchrotron emission → electromagnetic showers produced in pulsar magnetosphere → e^+
- Efficient energy loss from synchrotron and inverse Compton energy losses, so source must be 'close' (< few kpc) and 'young' (~10^5 years)



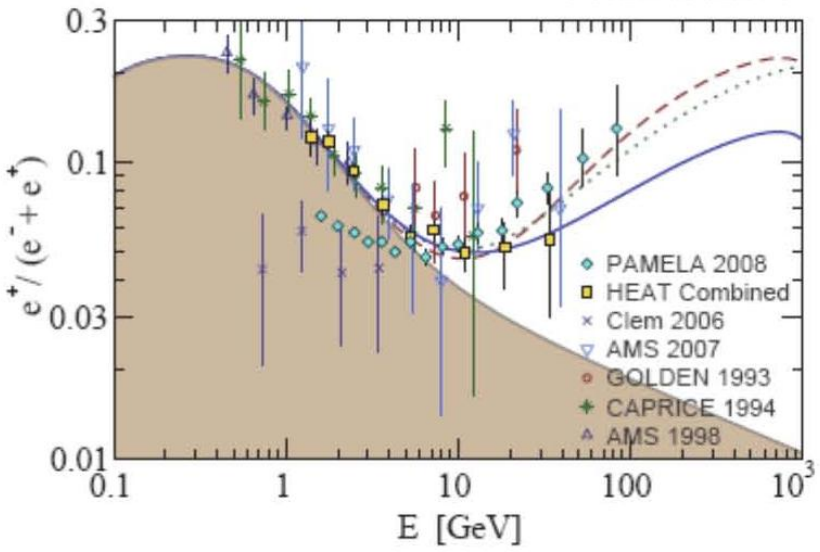
... and Fermi is updating the catalogue!



Already considered 20 years ago!
A. Boulares, Ap. J. 342 (1989) 807

Pulsar examples

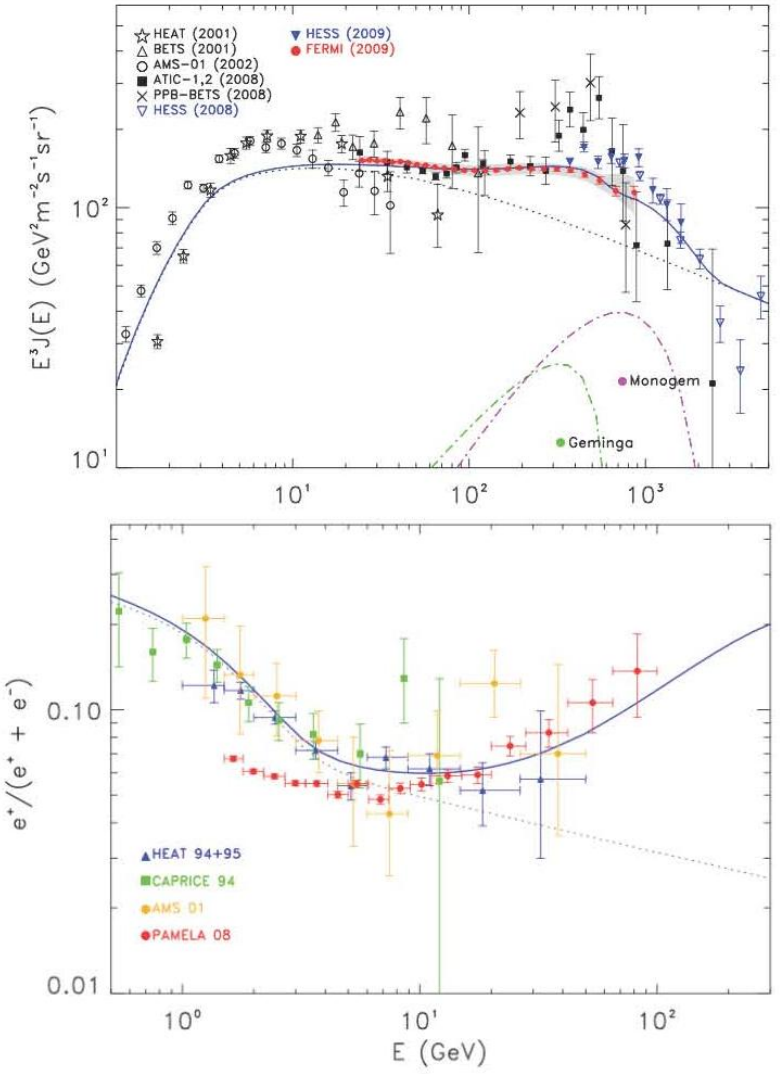
Yüksak et al.
arXiv:0810.2784



Geminga (d ~ 250 $\pm^{250}_{62}$ pc)

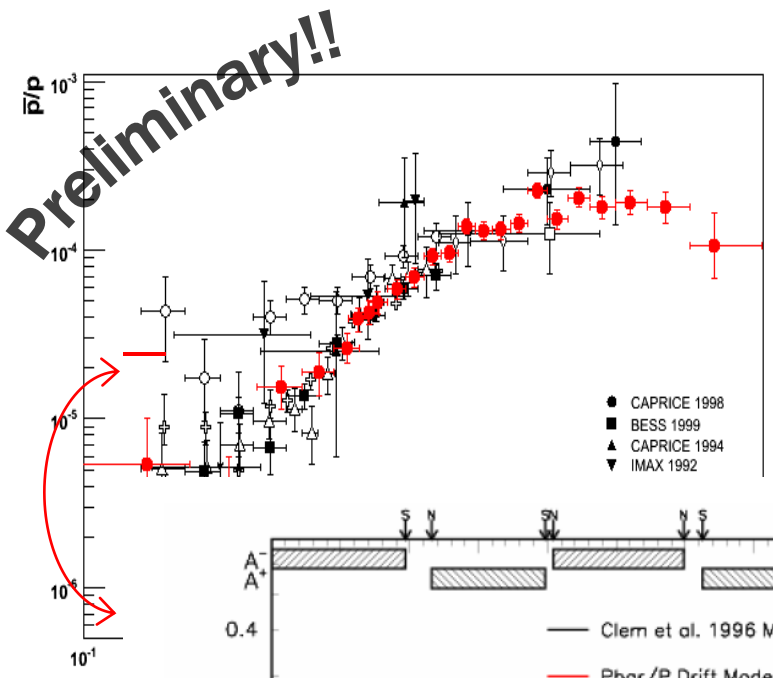
- TeV emission recently discovered by Milagro (Abdo et al., Ap.J. 664 L91 (2007))
- Different distance, age and pulsar energy considered

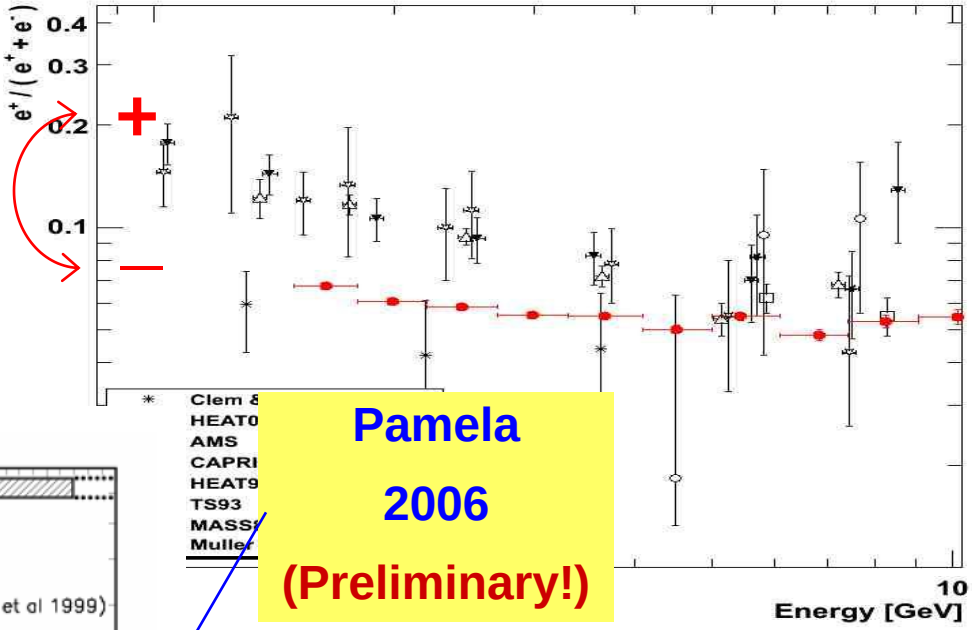
D. Grasso et al.
arXiv:0905.0636v3



Fit to **Fermi** and **PAMELA** data with known (ATNF catalogue) nearby, mature pulsars and with nominal **e+/e- injection** parameters

Charge dependent solar modulation

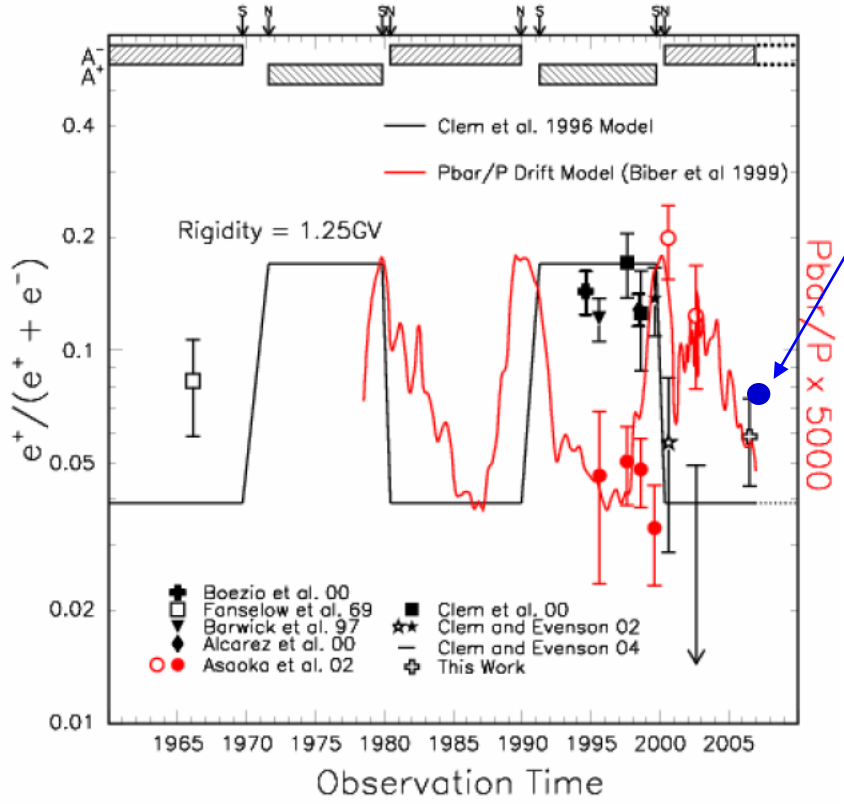




Pamela

2006

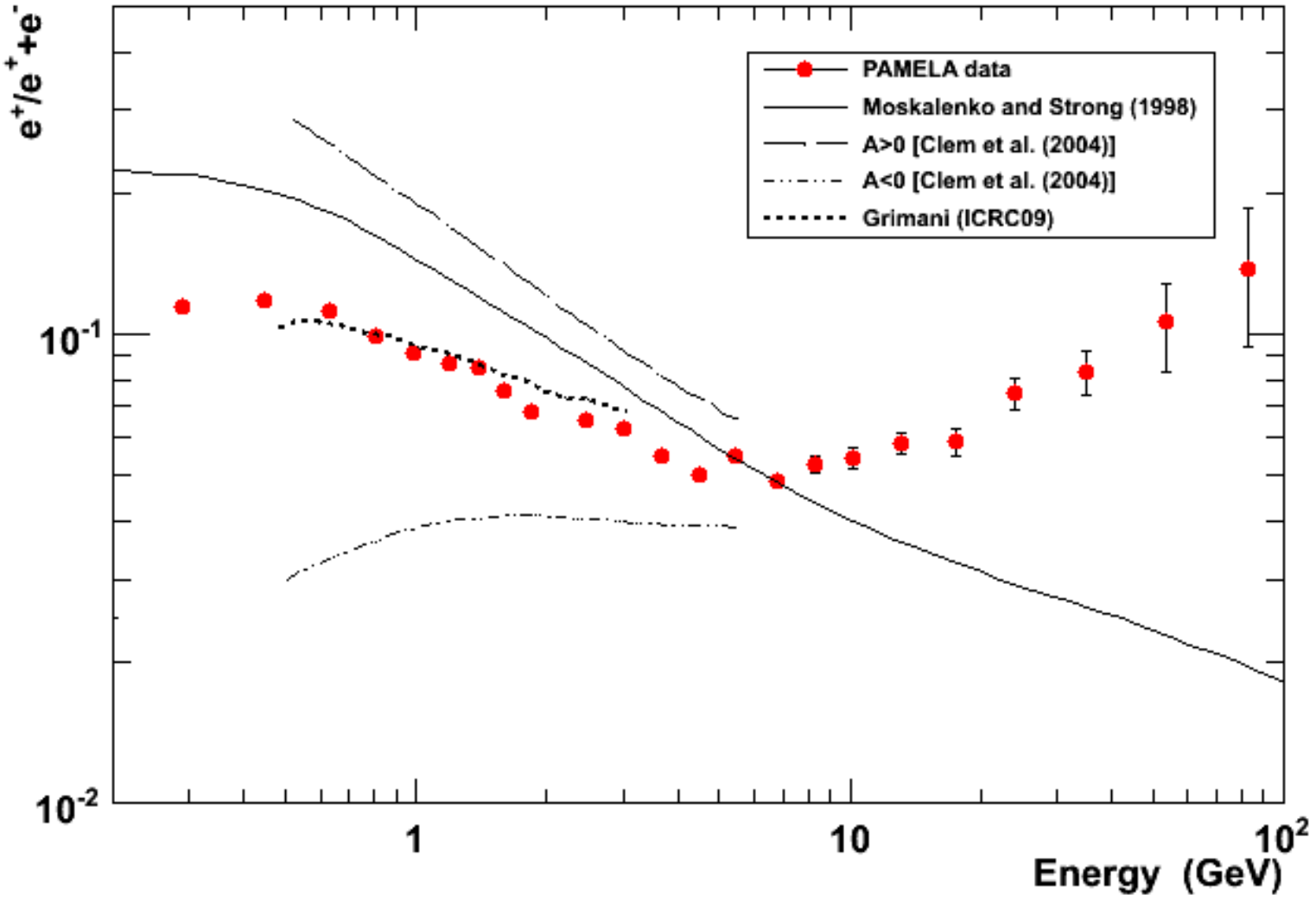
(Preliminary!)



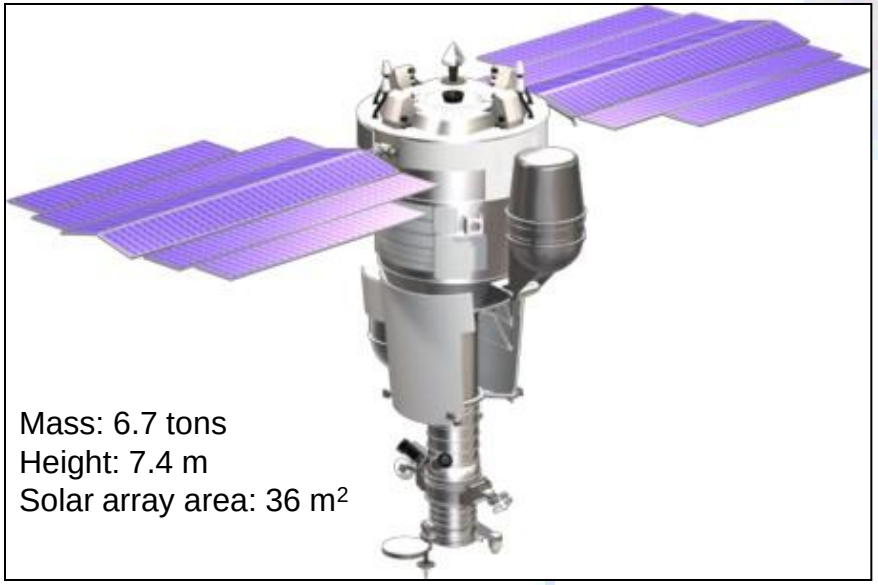
Study of charge sign dependent effects

- ***Asaoka Y. et al. Phys. Rev. Lett. 88, 051101, 2002.***
- ***Bieber, J.W., et al. Phys. Rev. Lett. 84, 674, 1999.***
- ***J. Clem et al. 30th ICRC 2007***
- ***U.W. Langner, M.S. Potgieter, Advances in Space Research 34, 2004.***

Positron Fraction

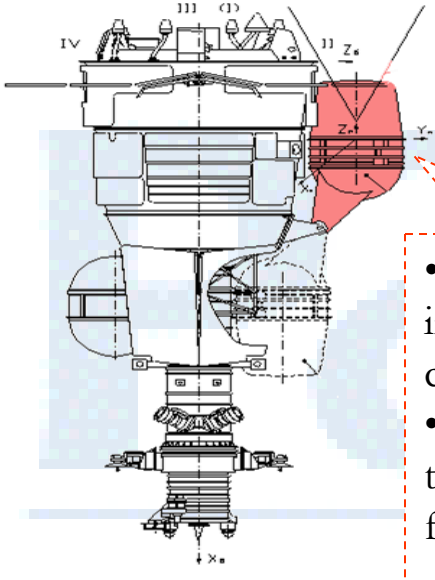


The Resurs DK-1 spacecraft

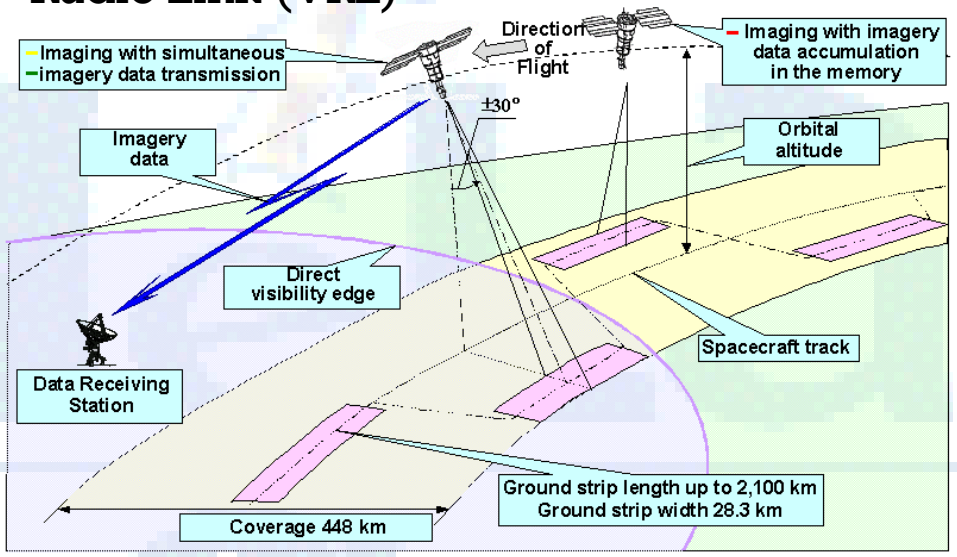


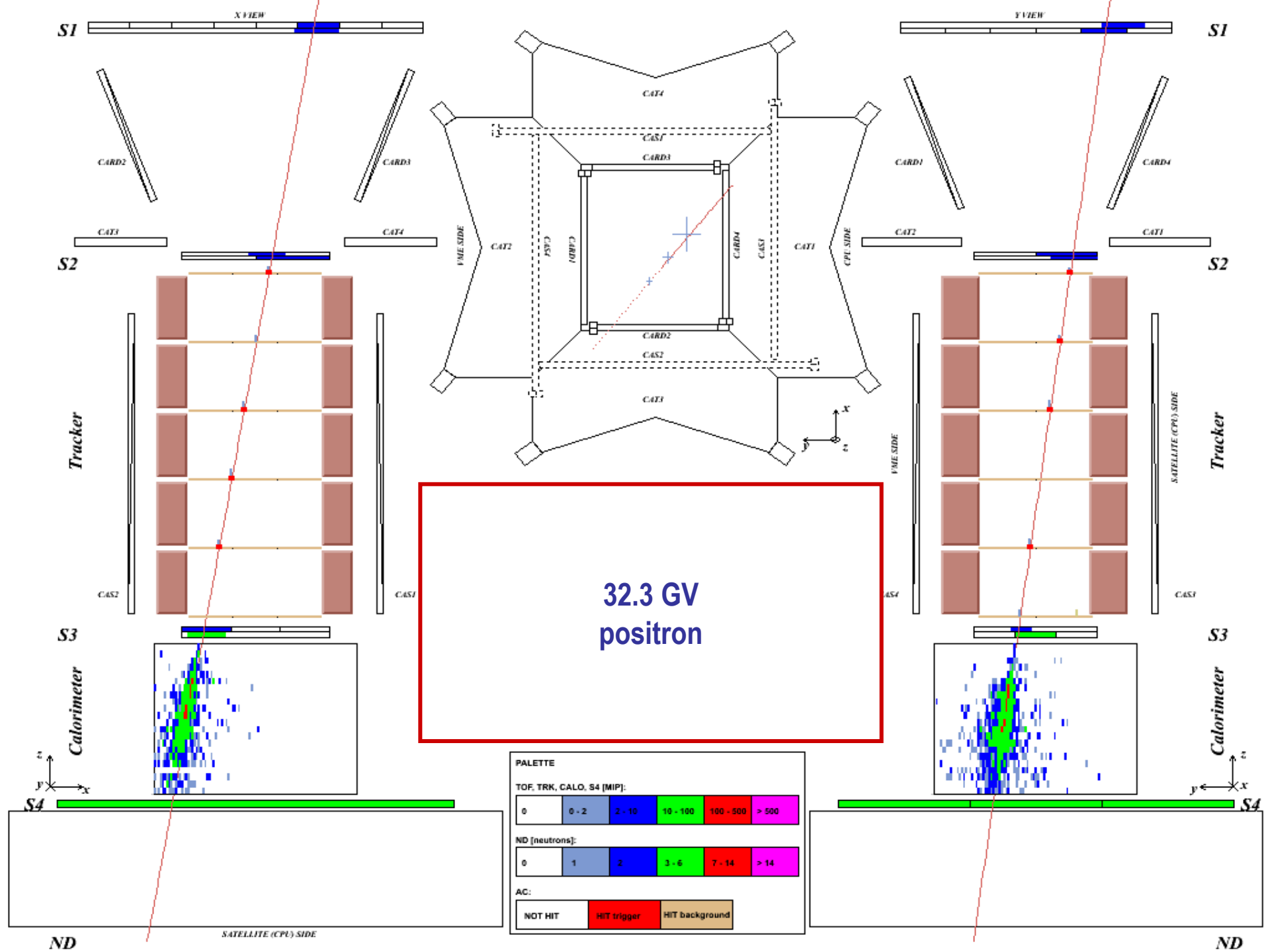
Mass: 6.7 tons
Height: 7.4 m
Solar array area: 36 m^2

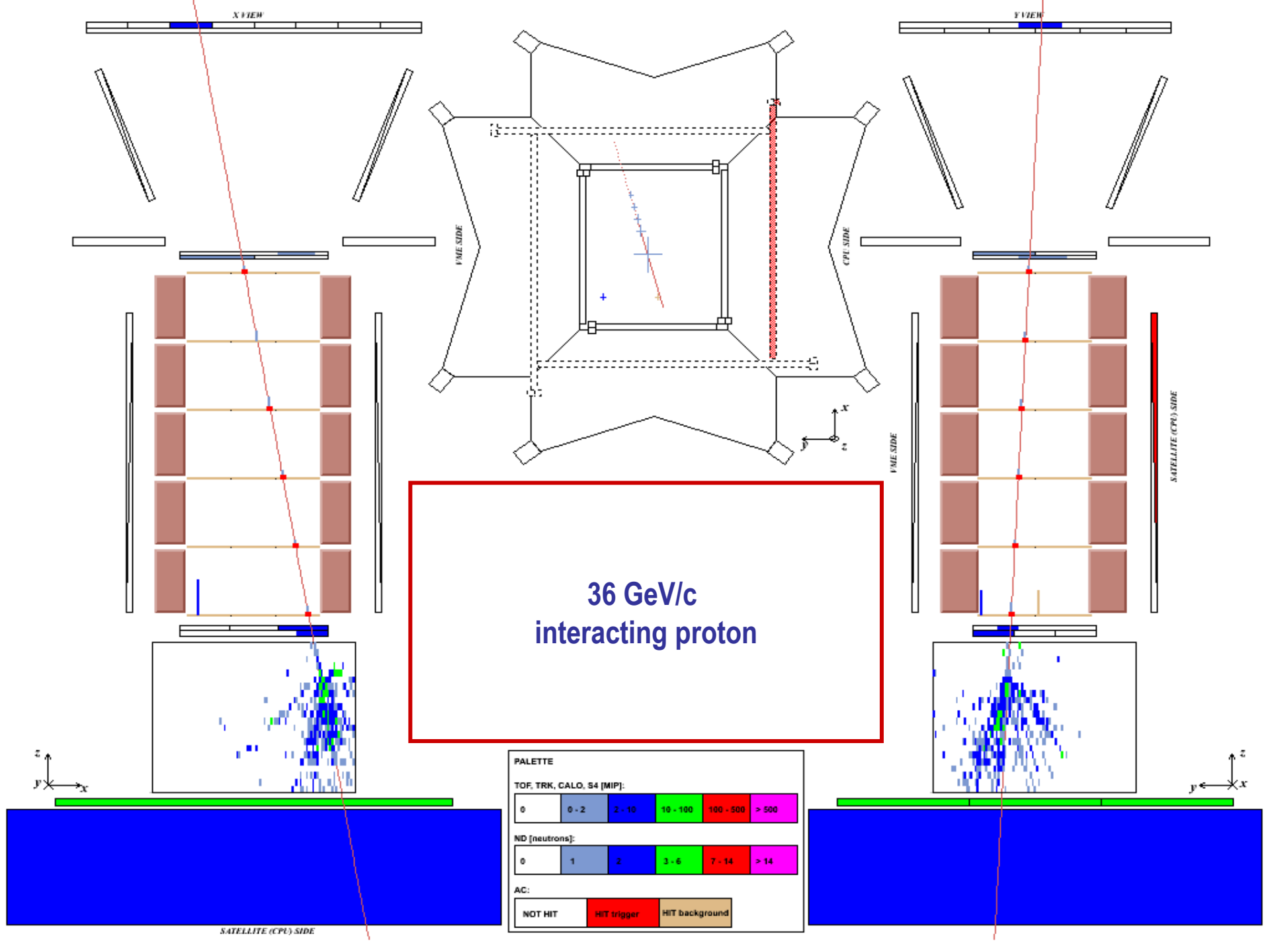
- Multi-spectral remote sensing of earth's surface
  - *-near-real-time high-quality images*
- Built by the Space factory TsSKB Progress in Samara (Russia)
- **Operational orbit parameters:**
  - **-inclination ~70°**
  - **-altitude ~ 360-600 km (elliptical)**
- **Active life >3 years**
- Data transmitted via Very high-speed Radio Link (VRL)



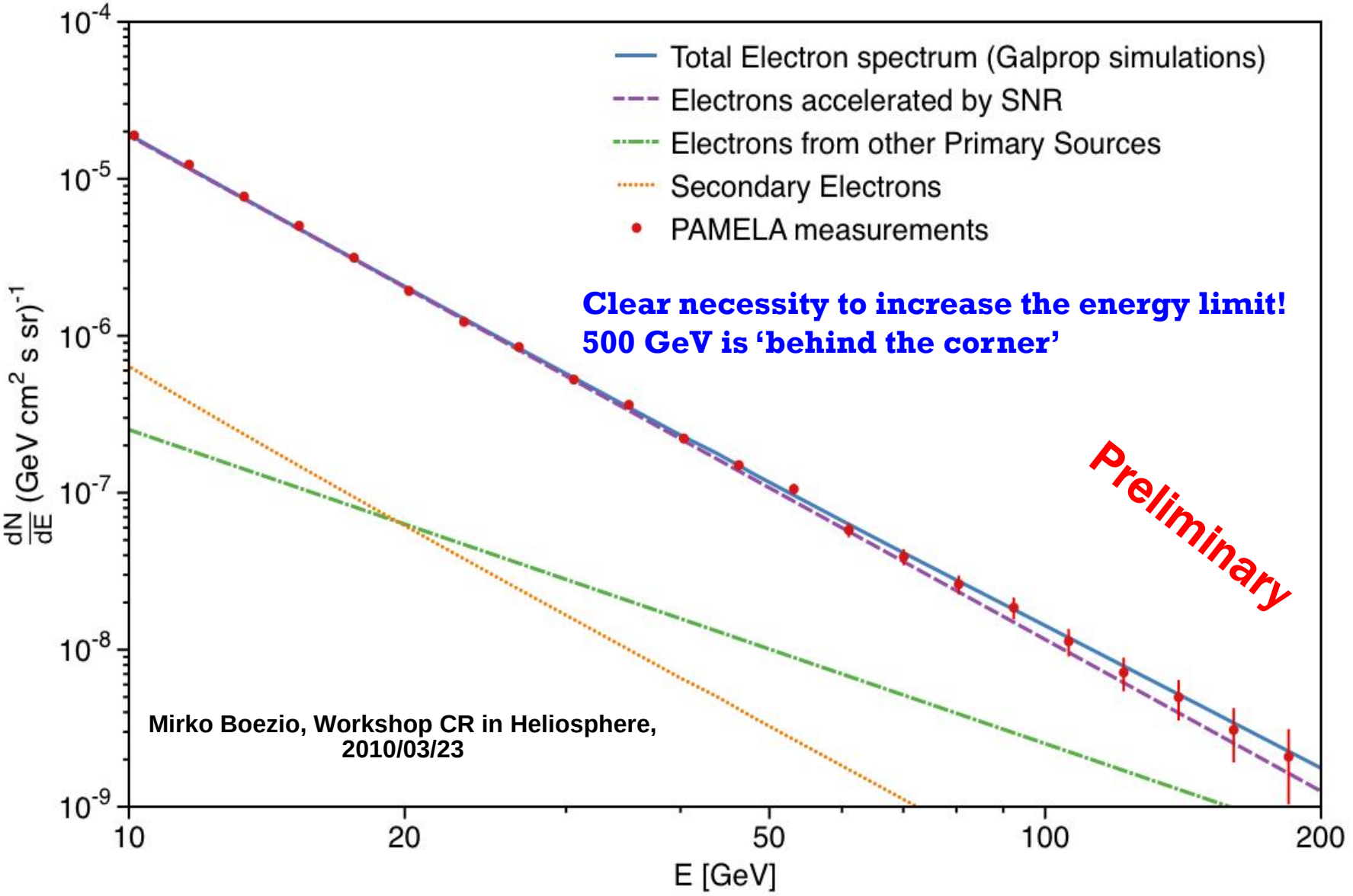
- PAMELA mounted inside a pressurized container
- moved from parking to data-taking position few times/year




S1
X VIEW
CARD2
CARD3
CAT3
CAT4
S2
Tracker
CAS2
CAS1
S3
Calorimeter
S4
ND
SATELLITE (CPU) SIDE
CAT4
CAS1
CARD3
VME SIDE
CAT2
PSFC
CAMEX
CARD4
CAS3
CAT1
CPU SIDE
CARD2
CAS2
CAT3
32.3 GV
positron
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background
Y VIEW
CARD1
CARD4
CAT2
CAT1
VME SIDE
SATELLITE (CPU) SIDE
CAS4
CAS3


X VIEW
Y VIEW
VME SIDE
CPU SIDE
VME SIDE
SATELLITE (CPU) SIDE
36 GeV/c
interacting proton
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background
SATELLITE (CPU) SIDE

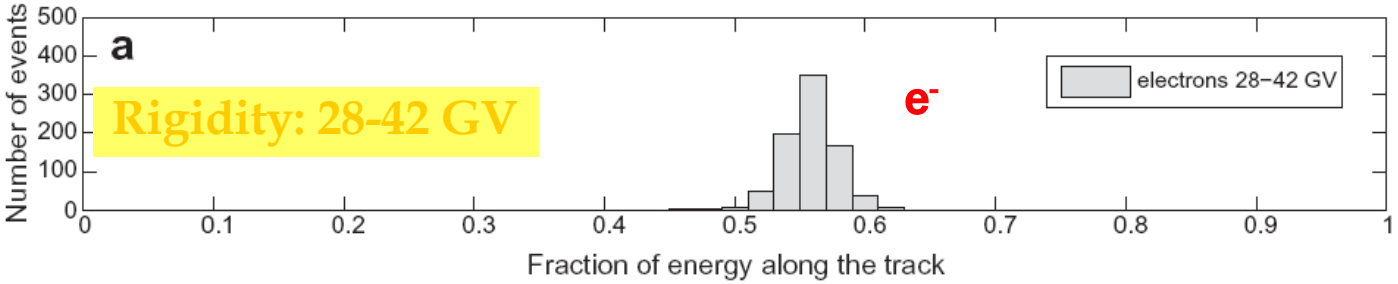
PAMELA Electron (e^-) Spectrum vs Galprop predictions (using e^+ results)

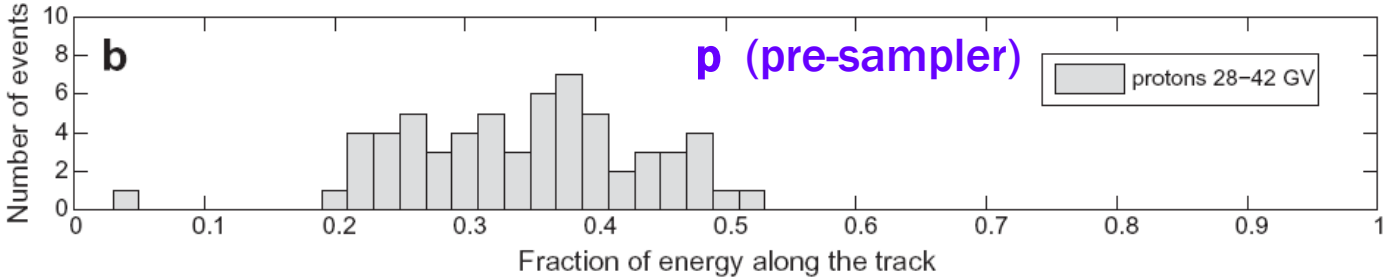


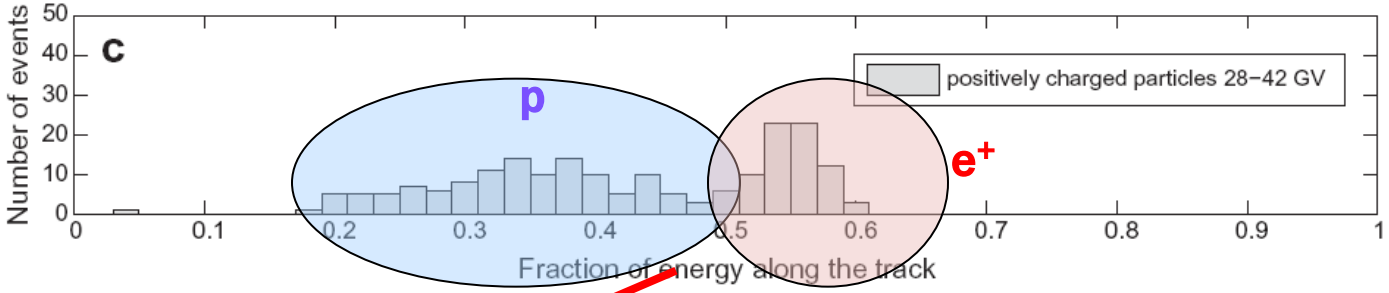
High energy positron analysis (~900 days)

The main difficulty for the positron measurement is the **interacting-proton background**:

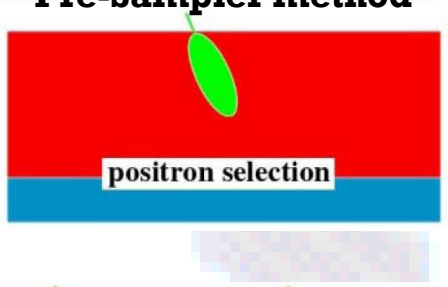
- fluctuations in hadronic shower development $\Rightarrow \pi_0 \rightarrow \gamma\gamma$ might mimic pure e.m. showers
- proton spectrum harder than positron $\Rightarrow p/e^+$ increase for increasing energy (from 10^3 at 1 GeV to 10^4 at 100 GeV)

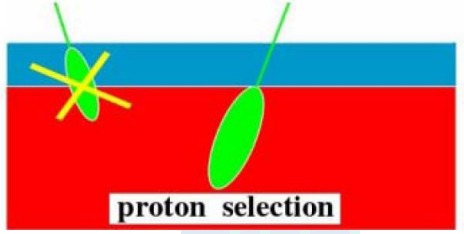






Pre-Sampler method





Estimation of contamination directly from the data!!!!

Topological variable F:
Fraction of Energy inside 0.3 R_M

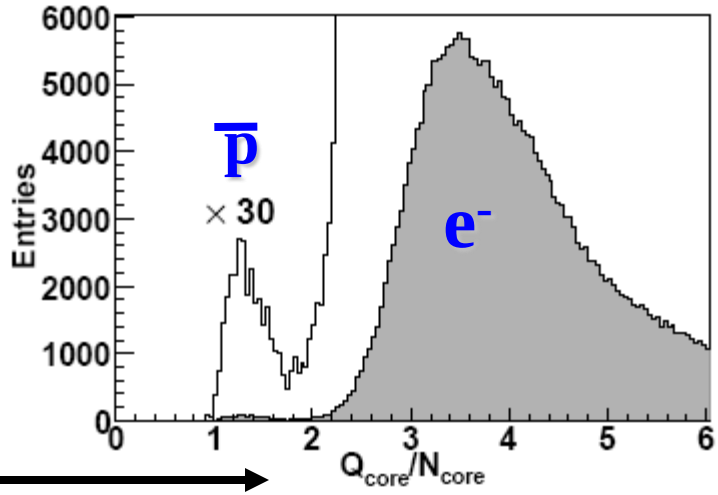
Antiproton Identification

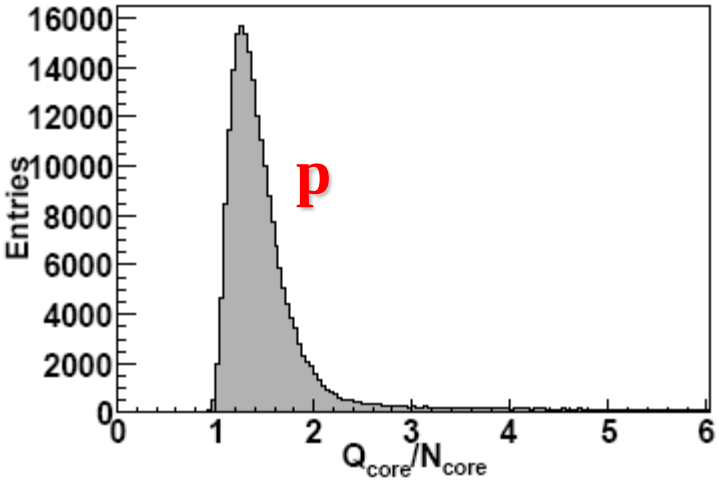
Events selected from ~ 850 days of data

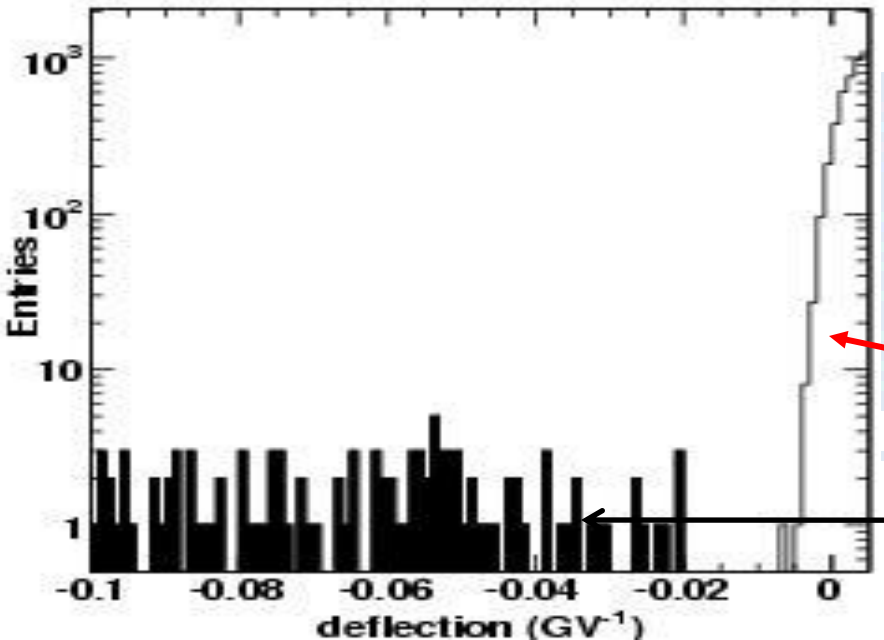
Spectrometer is the crucial device

Precise knowledge of GF, Live time and trigger ε for Flux measurement

Calorimeter
Selection based on topological variables:
energy density in the shower core weighted by the depth in the calorimeter.







Tracker Identification

Protons (& spillover)

Antiprotons