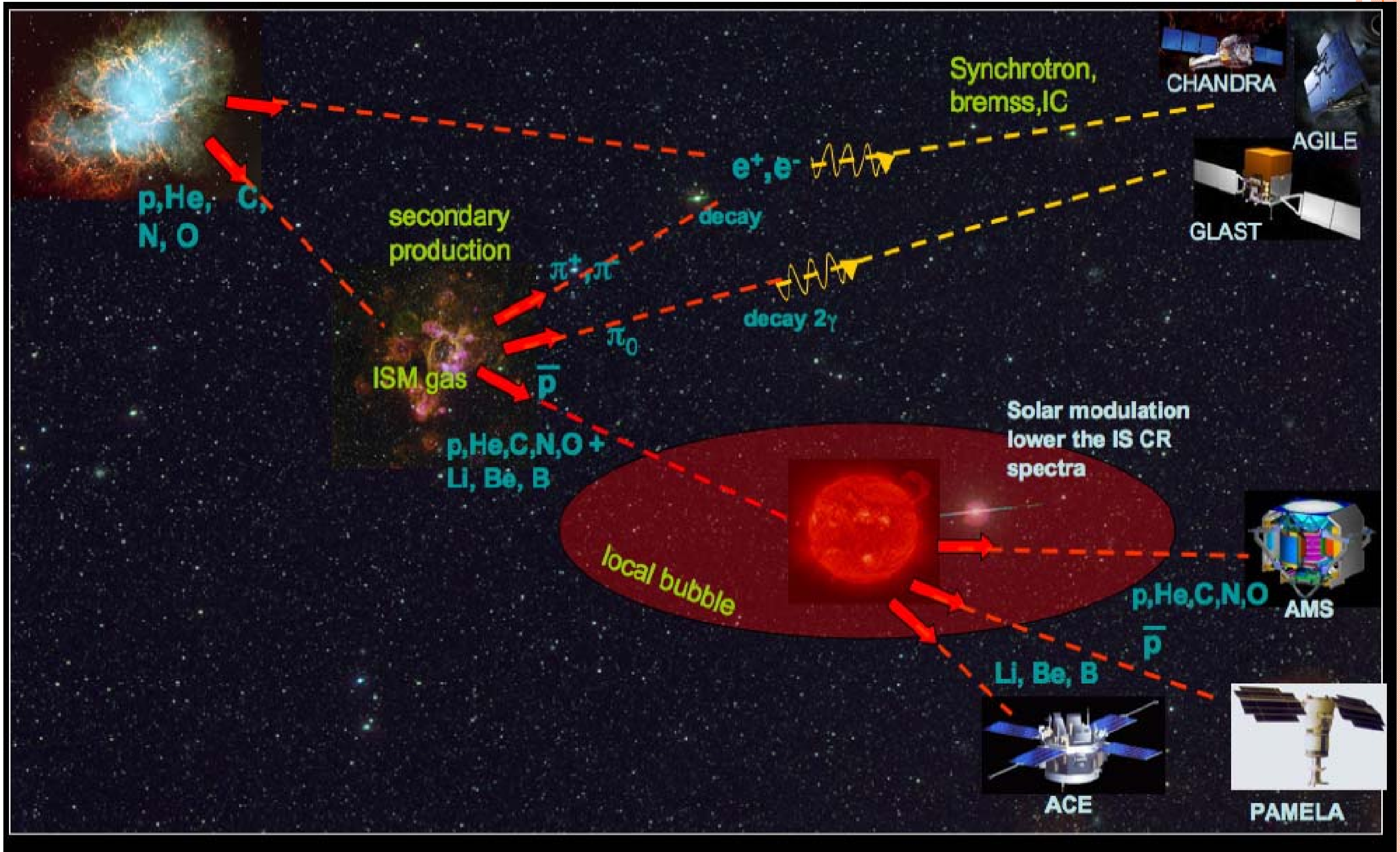
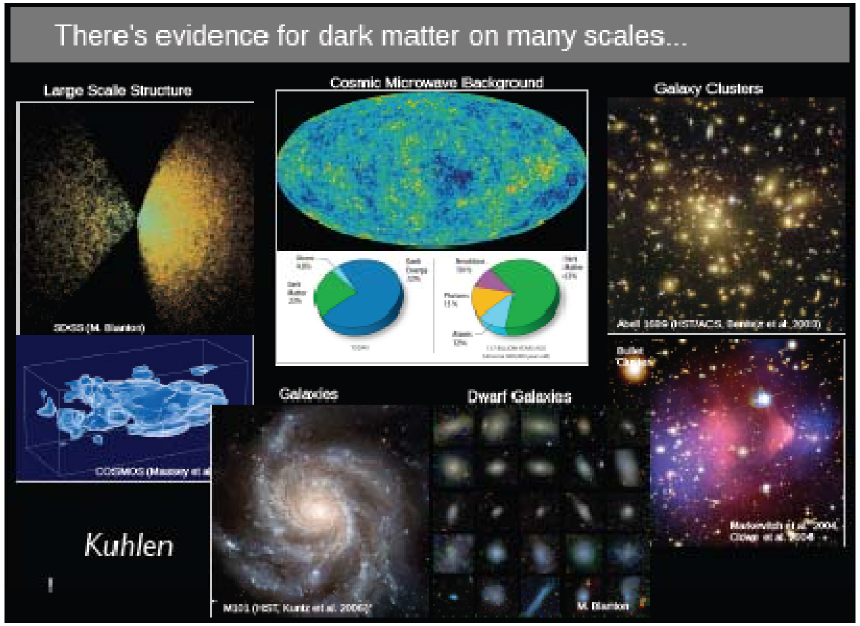
Understanding Cosmic Rays and Searching for Dark Matter with PAMELA

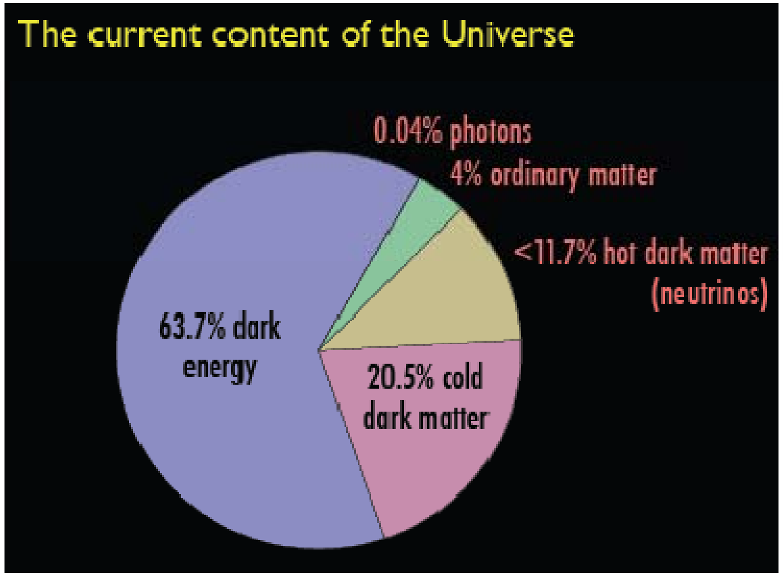
Roberta Sparvoli for the PAMELA Collaboration
University of Rome Tor Vergata and INFN

Cosmic Rays production mechanisms



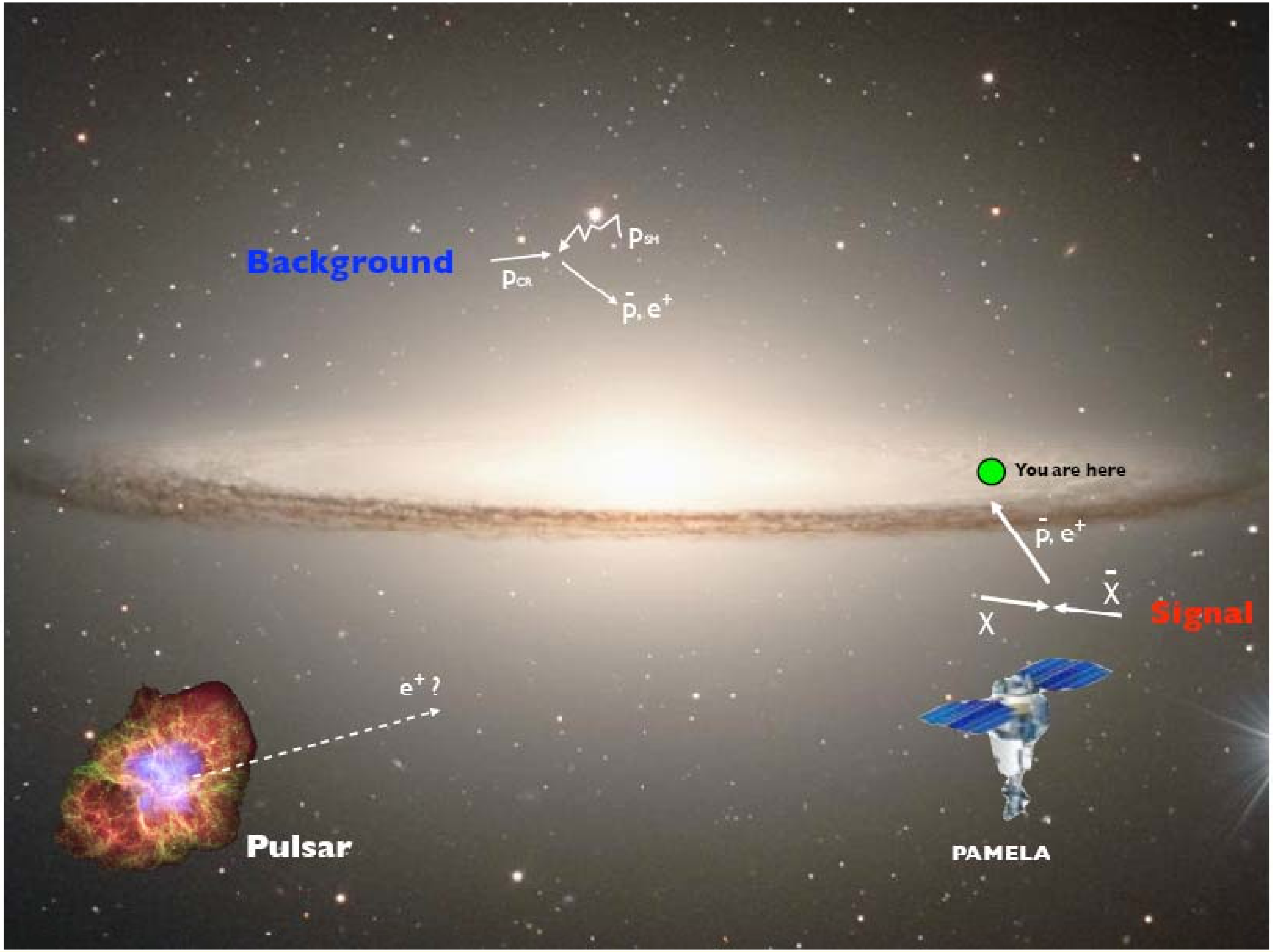
DARK MATTER SEARCHES





P. Gondolo, IDM 2008

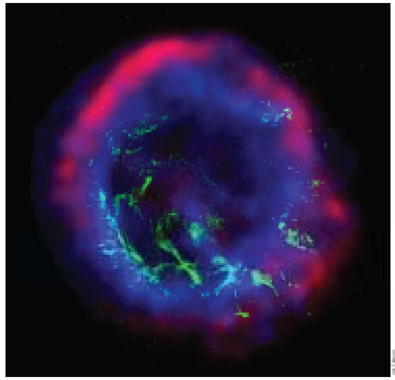
EXPECTED DM SIGNALS

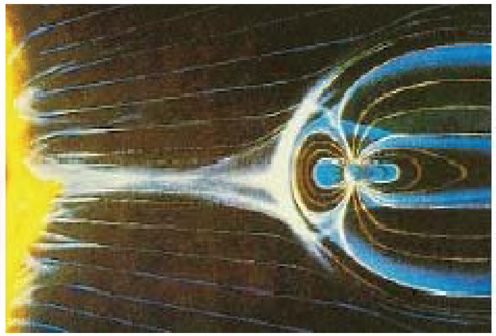


Deviations of the antiparticle spectra wrt secondary production

PAMELA 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





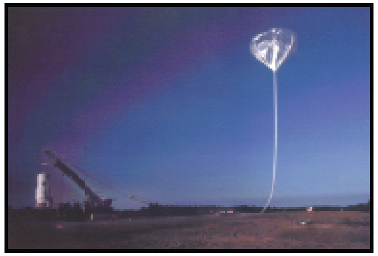
PAMELA DESIGN PERFORMANCE

Magnetic curvature & trigger — spillover — shower containment — Maximum detectable rigidity (MDR)

	energy range		particles in 3 years
Antiprotons	**80 MeV ÷190 GeV**		$O(10^4)$
Positrons	**50 MeV ÷ 270 GeV**		$O(10^5)$
Electrons	up to 400 GeV		$O(10^6)$
Protons	up to 700 GeV		$O(10^8)$
Electrons+positrons	up to 2 TeV	(from calorimeter)	
Light Nuclei	up to 200 GeV/n	He/Be/C:	$O(10^{7/4/5})$
Anti-Nuclei search	sensitivity of $3\text{x}10^{-8}$ in anti-He/He		

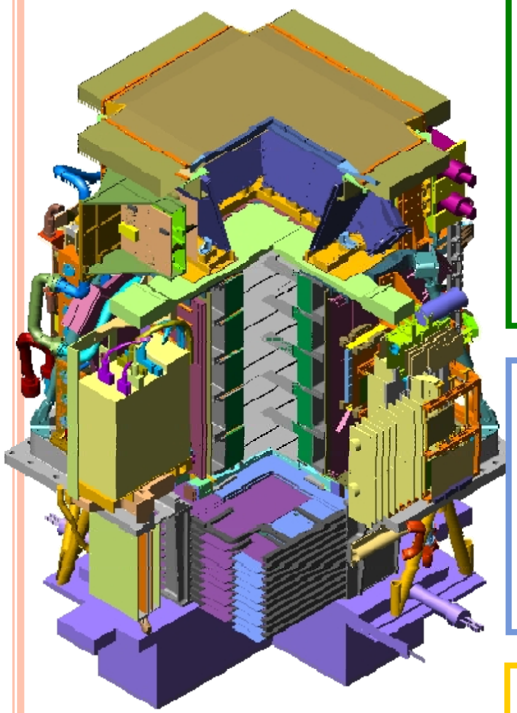
- **Unprecedented statistics and new energy range for cosmic ray physics**
  - e.g. contemporary antiproton & positron energy, $E_{max} \approx 50$ GeV
- Simultaneous measurements of many species
  - constrain secondary production models

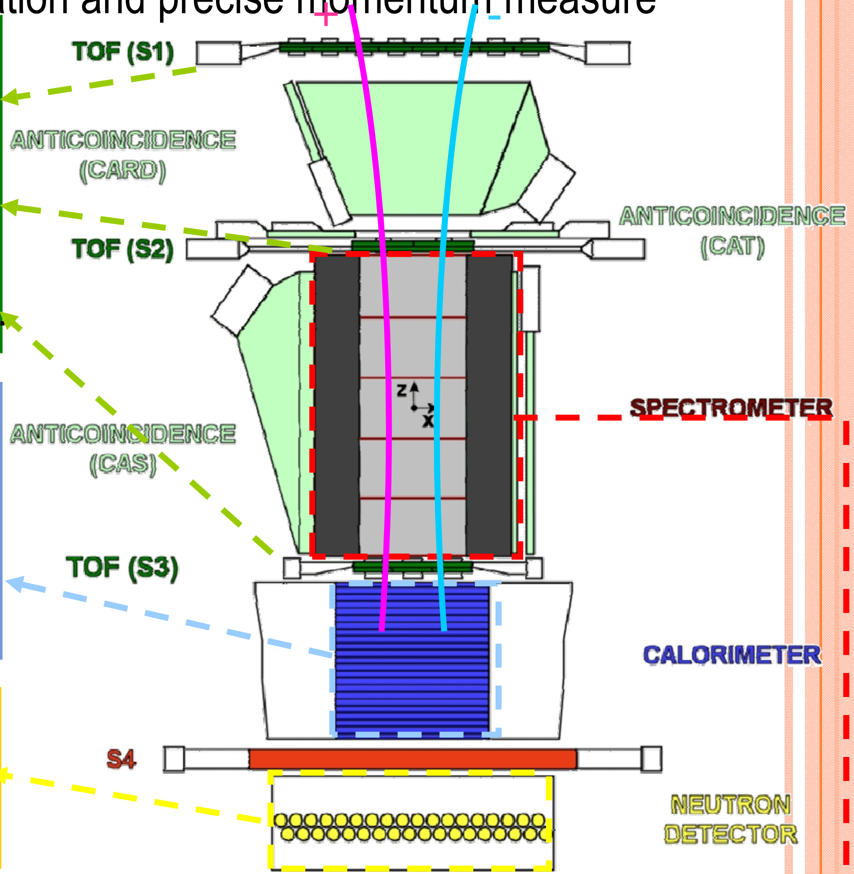
HEAT-PBAR flight ~ 25 days PAMELA data
CAPRICE98 flight ~ 5 days PAMELA data



PAMELA DETECTORS

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





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

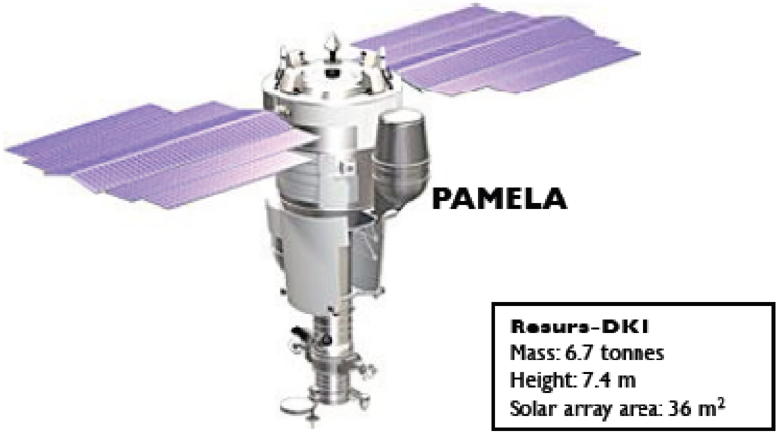
Electromagnetic calorimeter
W/Si sampling (16.3 X0, 0.6 λI)
- Discrimination e+ / p, anti-p / e^- (shower topology)
- Direct E measurement for e^-

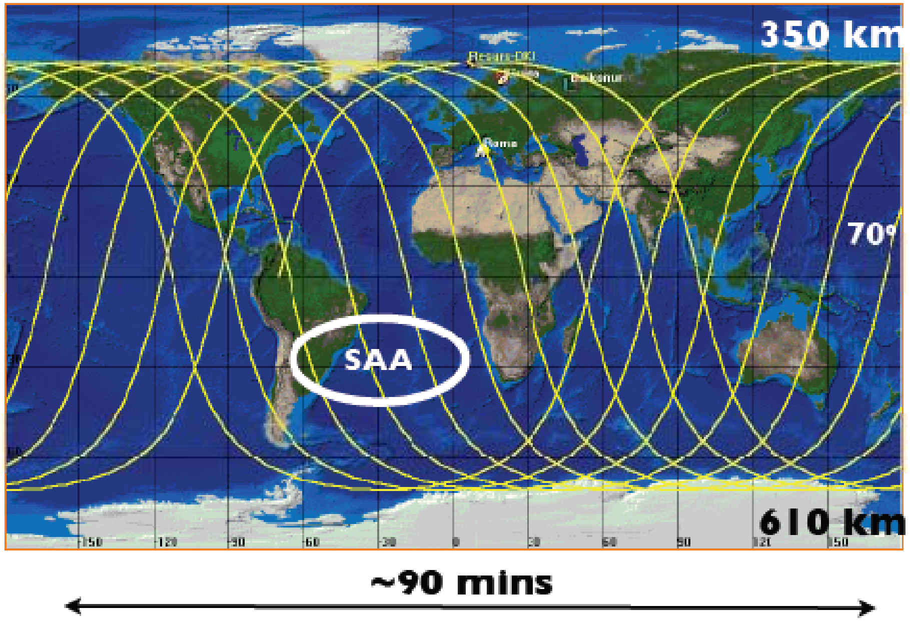
Neutron detector
36 He3 counters
- High-energy e/h discrimination

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

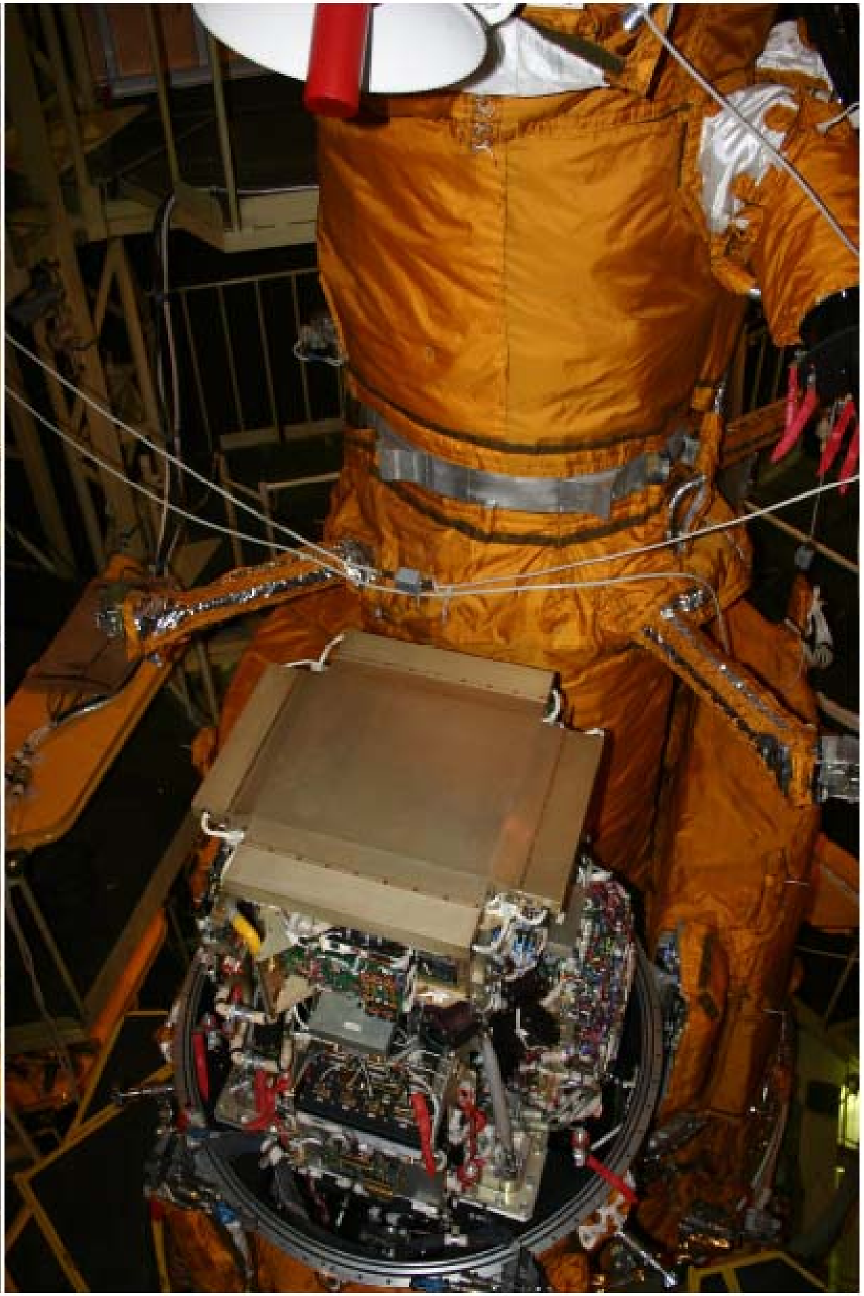
Spectrometer
microstrip silicon tracking system + permanent magnet
It provides:
- *Magnetic rigidity* → R = pc/Ze
- *Charge sign*
- *Charge value from dE/dx*

THE RESURS DK-1 SPACECRAFT





- **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. ~15 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

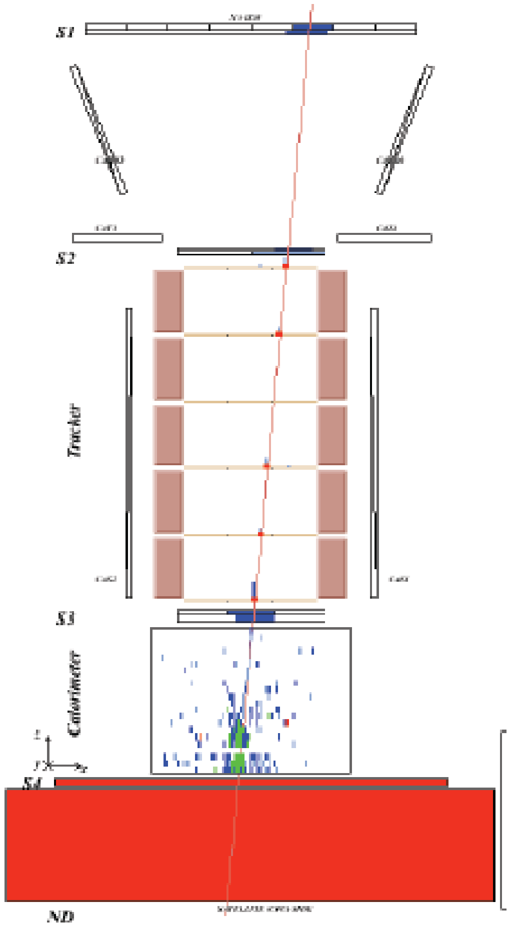



Launch: 15th June 2006, 0800 UTC

PAMELA STATUS

- **Today 1350 days in flight**
- **data taking ~73% live-time**
- **>19 TBytes of raw data downlinked**
- **>2. 10^9 triggers recorded and under analysis**

ANTIPROTON/POSITRON DISCRIMINATION



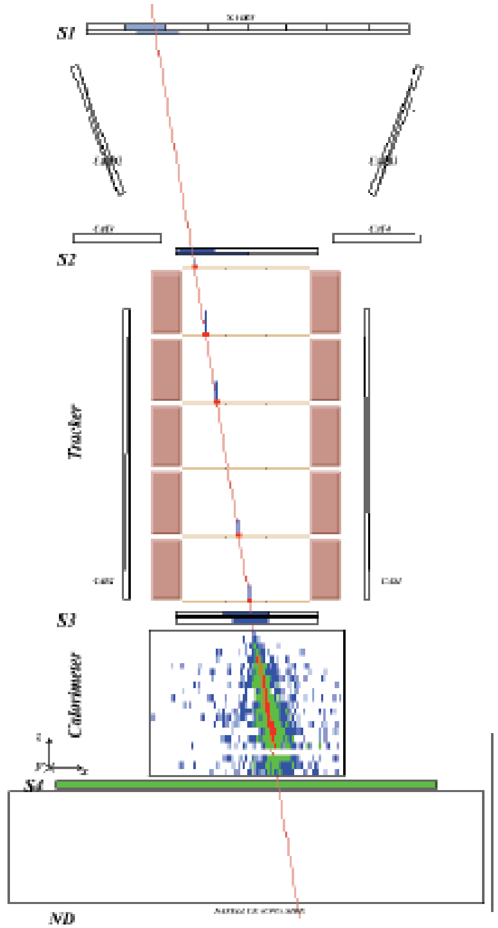
Antiproton
(NB: $e^{-}/\bar{p} \sim 10^{2}$)

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

Bending in spectrometer:
sign of charge
energy measurement

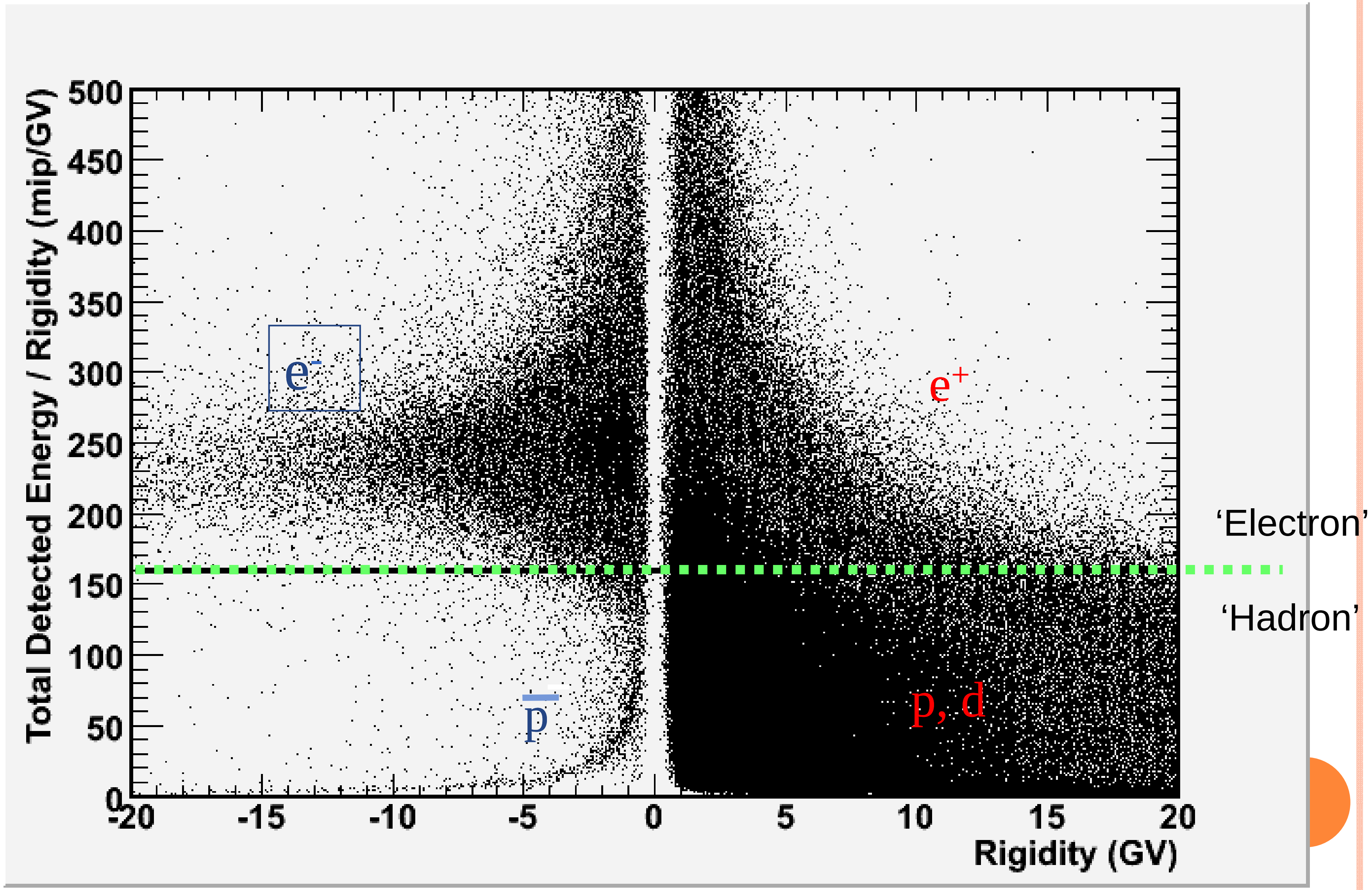
Ionisation energy loss (dE/dx):
magnitude of charge

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

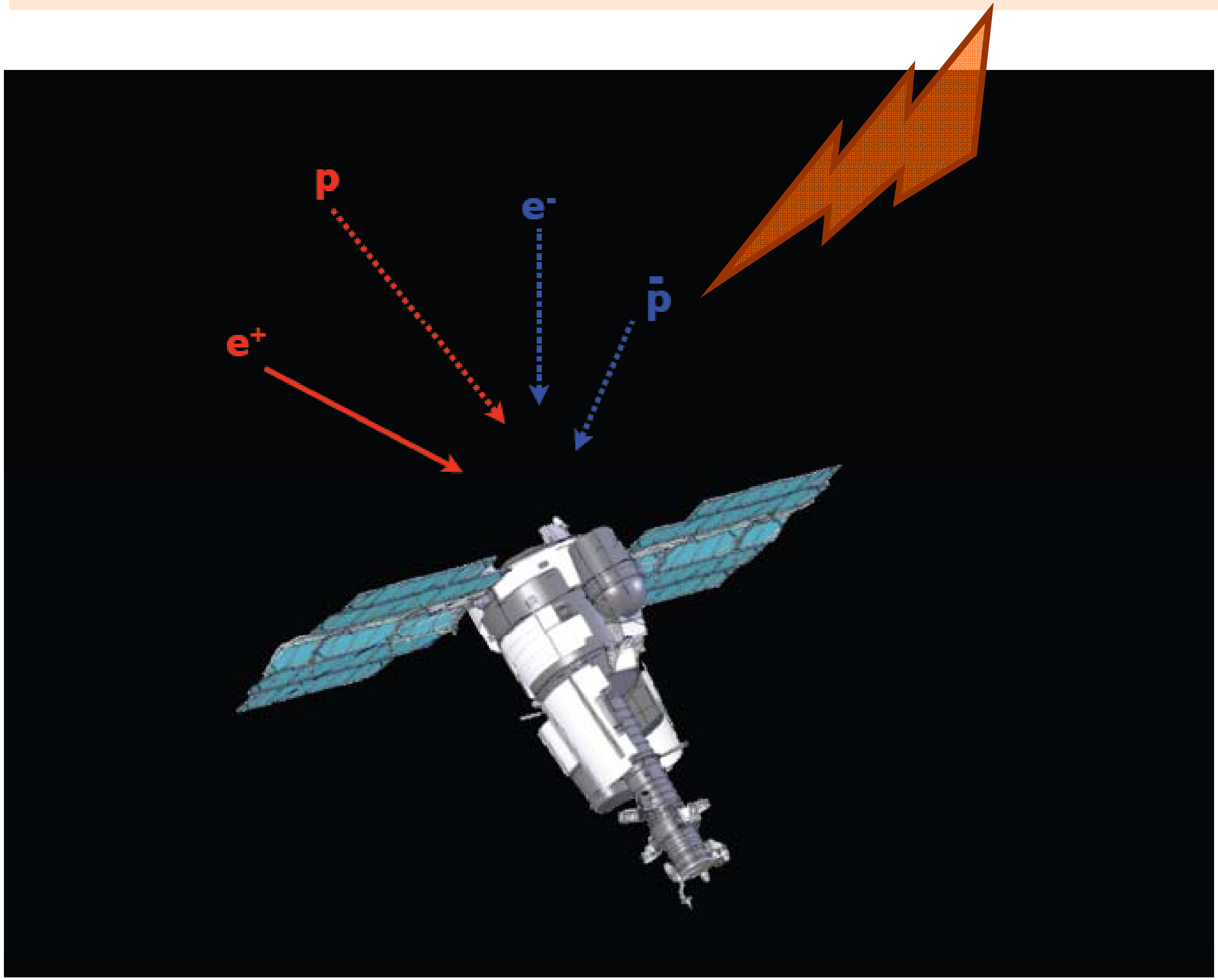


Positron
(NB: $p/e^{+} \sim 10^{3-4}$)

ANTIPARTICLE SELECTION



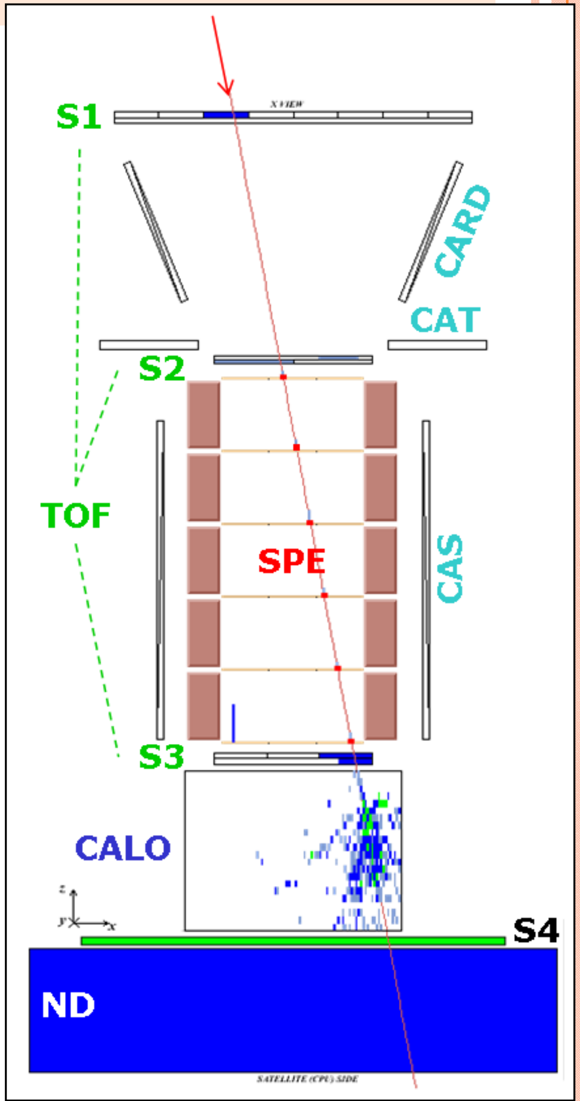
ANTIPROTONS



HIGH-ENERGY ANTIPROTON ANALYSIS

- Antiproton/proton identification:
  - rigidity (R) → SPE
  - |Z|=1 (dE/dx vs R) → SPE&ToF
  - β vs R consistent with M_p → ToF
  - p-bar/p separation (charge sign) → SPE
  - p-bar/e^- (and p/e^+) separation → CALO
- Dominant background → spillover protons:
  - finite deflection resolution of the SPE ⇒ wrong assignment of charge-sign @ high energy
  - proton spectrum harder than antiproton ⇒ p/p-bar increase for increasing energy (10^3 @1GV 10^4 @100GV)

→ Required strong SPE selection



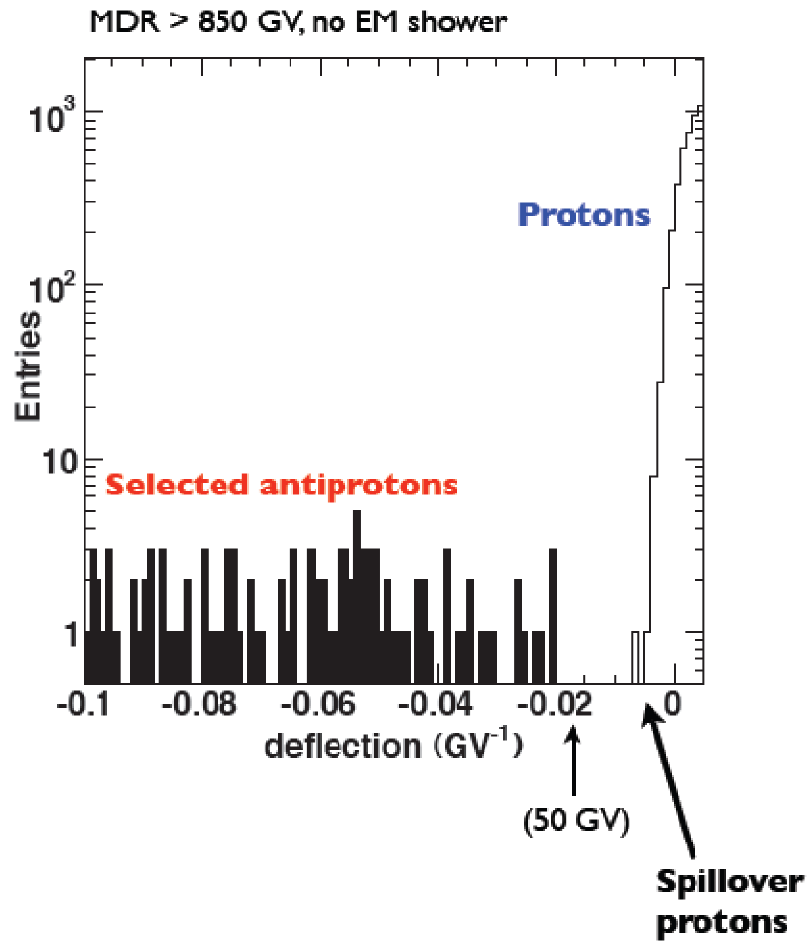
PROTON-SPILLOVER BACKGROUND

- **Spectrometer tracking information is crucial for high-energy antiproton selection**

- **Finite spectrometer resolution - high rigidity protons may be assigned wrong sign-of-charge**
- Also background from scattered protons

- **Eliminate 'spillover' using strict track cuts** (χ^2, lever arm, no δ-rays, etc)
- MDR > 10 × reconstructed rigidity

- **Spillover limit for antiprotons expected to be ~200 GeV.**

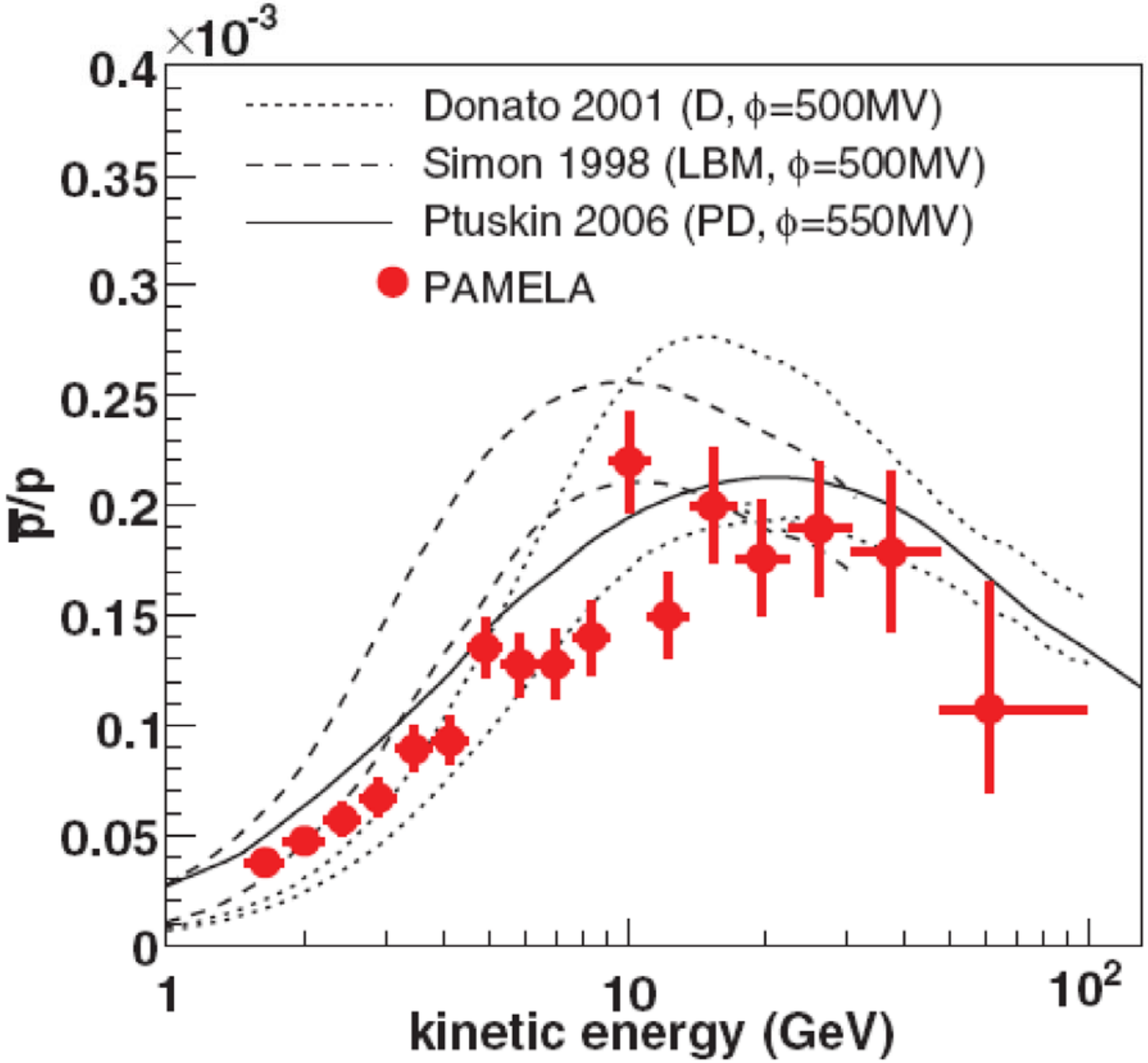


Electrons: efficiently removed by CALO

Pions (from interactions in dome) : about 3% in the pbar sample

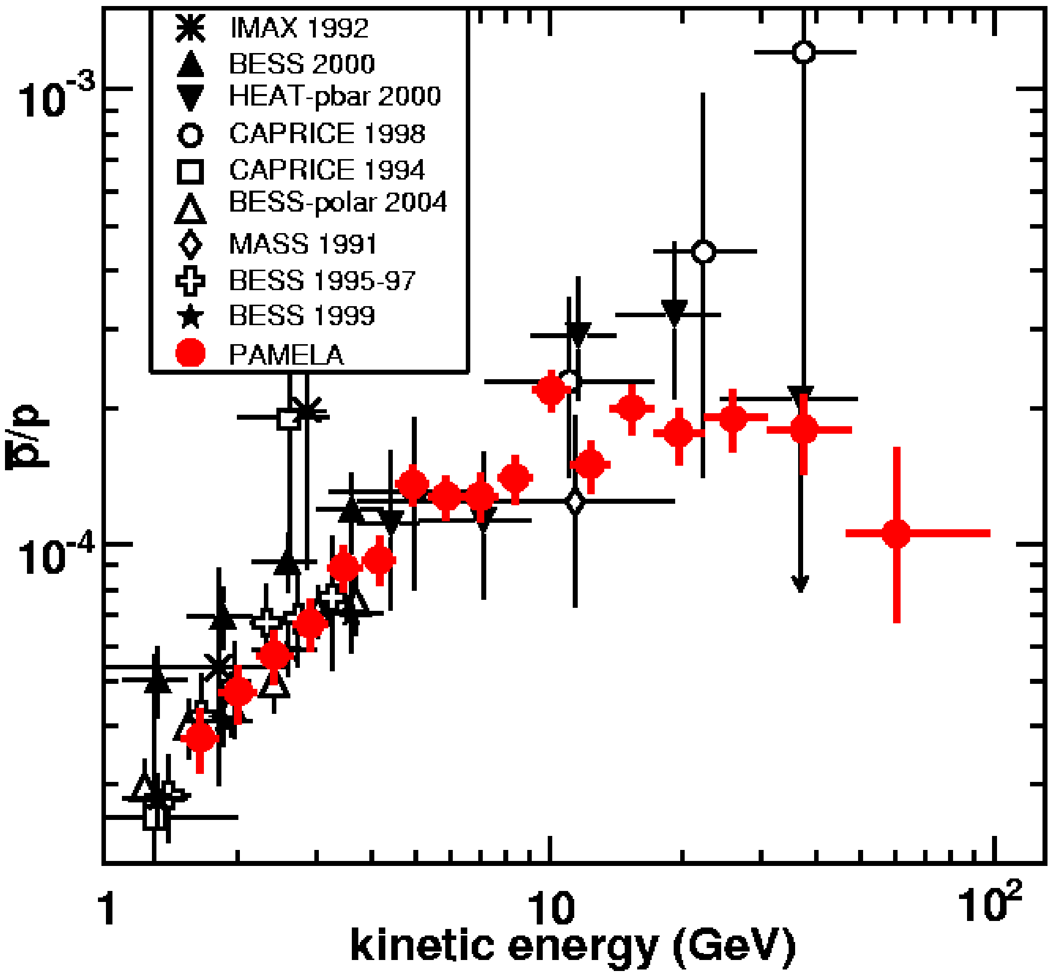
PAMELA: ANTIPROTON-TO-PROTON RATIO

PRL 102, 051101 (2009)



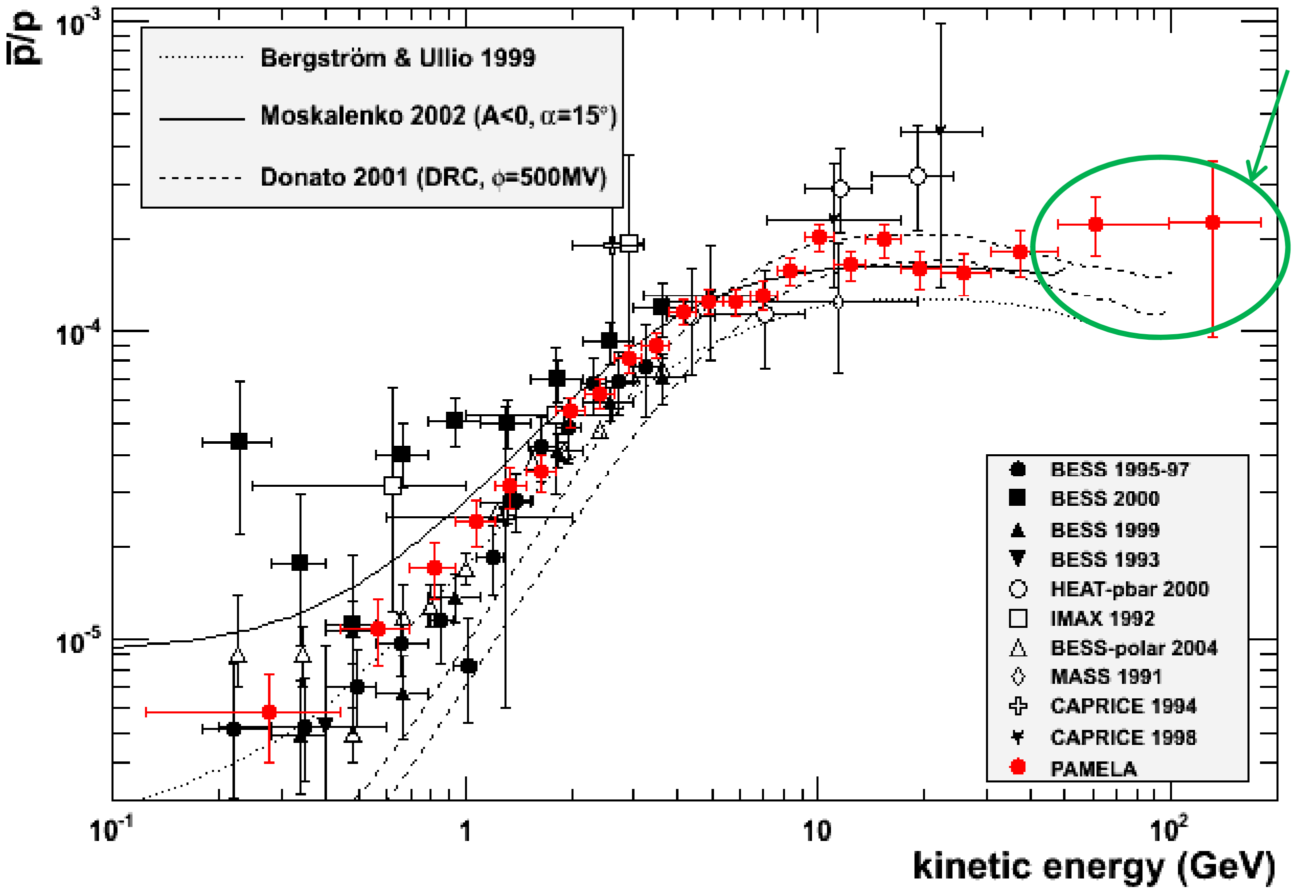
PAMELA: ANTIPROTON-TO-PROTON RATIO

PRL 102, 051101 (2009)



ANTIPROTON-TO-PROTON RATIO: NEW DATA

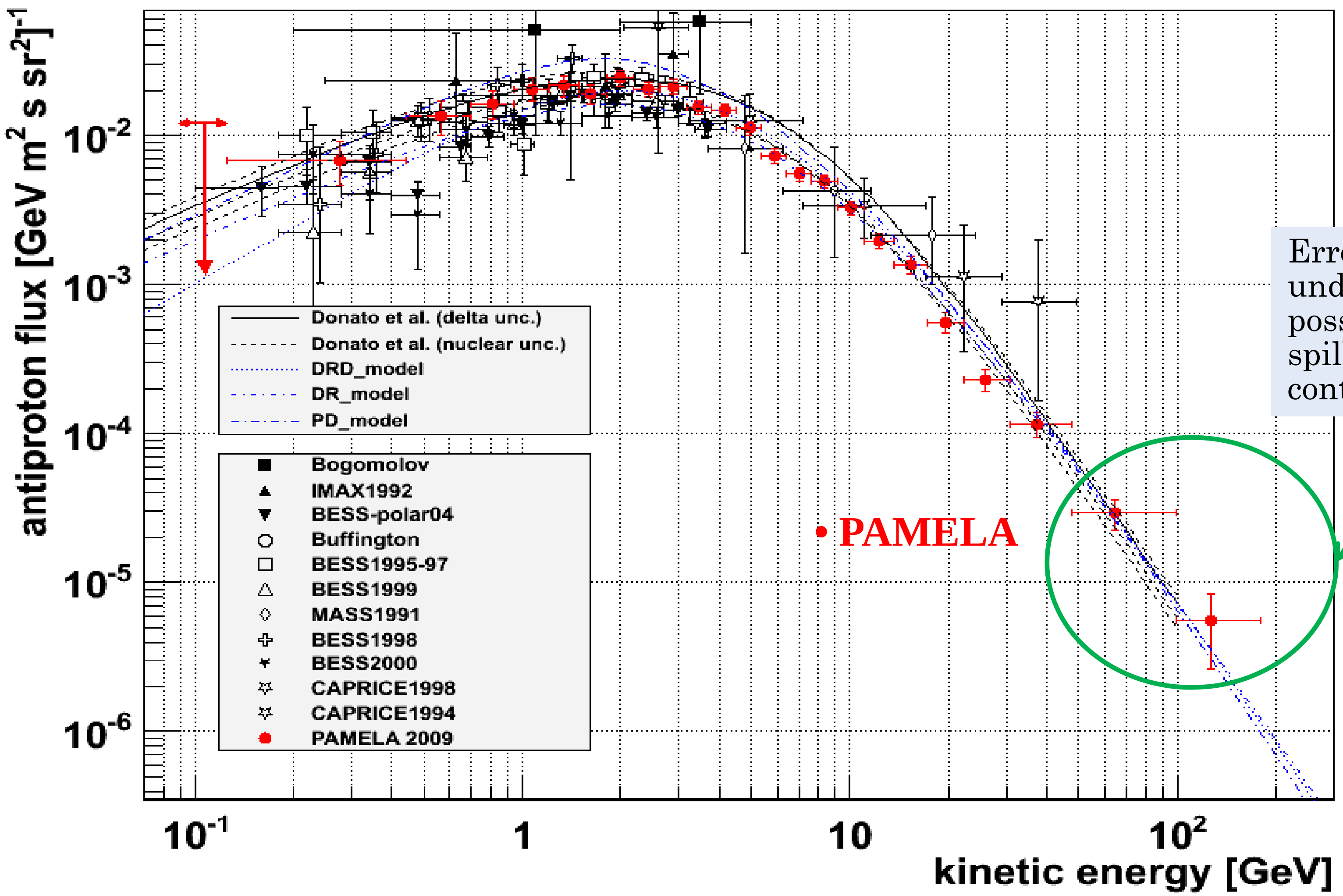
Increased statistics (until Dec. 2008)



Errors might be underestimated, possible residual spillover-proton contamination

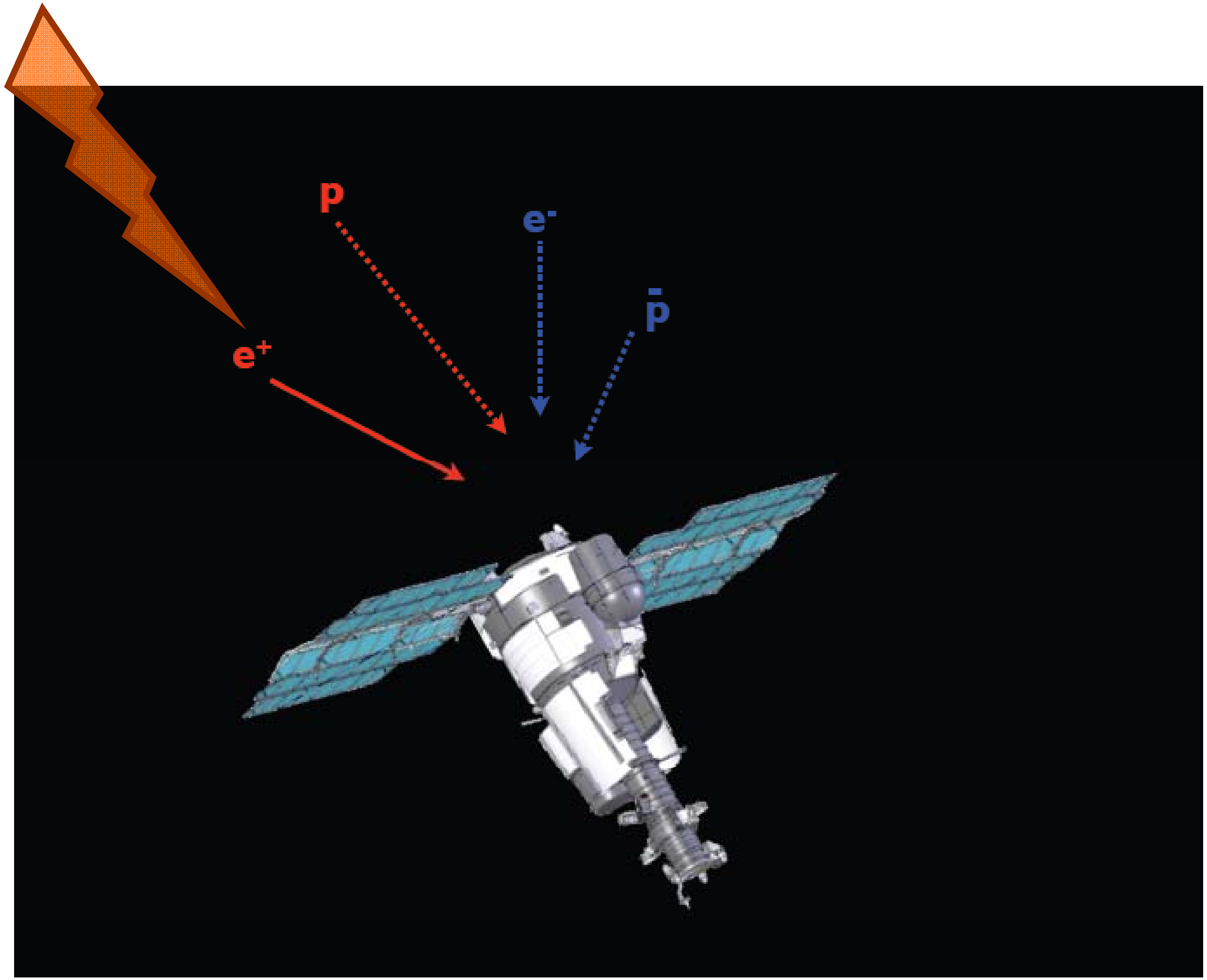
ANTIPROTON FLUX

Increased statistics



Errors underestimated, possible residual spillover-proton contamination

POSITRONS

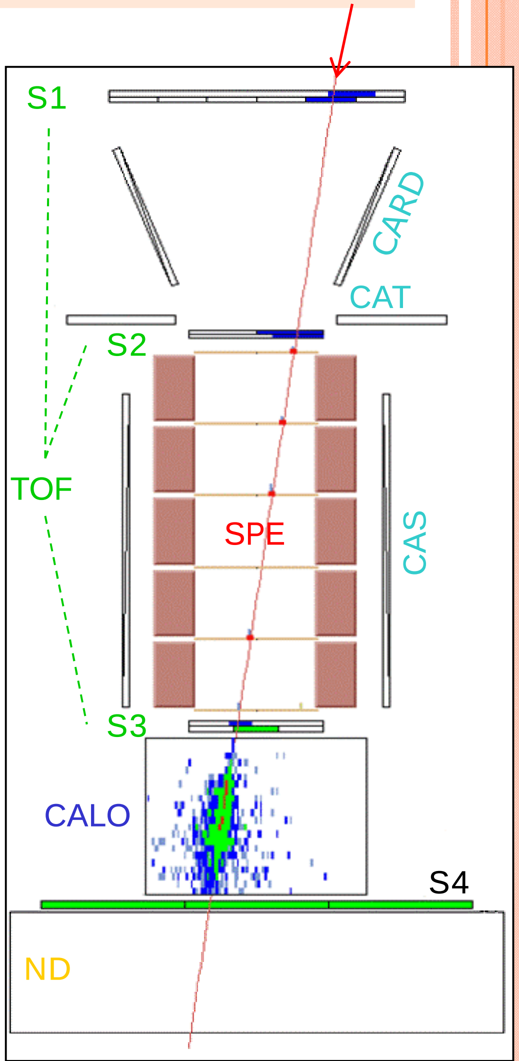


HIGH-ENERGY POSITRON ANALYSIS

- Electron/positron identification:
  - rigidity (R) → SPE
  - |Z|=1 (dE/dx=MIP) → SPE&ToF
  - β=1 → ToF
  - e^-/e^+ separation (charge sign) → SPE
  - e^+/p (and e^-/p-bar) separation → CALO

- Dominant background → interacting protons:
  - fluctuations in hadronic shower development ⇒ $\pi_0 \rightarrow \gamma\gamma$ might mimic pure em showers
  - proton spectrum harder than positron ⇒ p/e^+ increase for increasing energy (10^3 @1GV 10^4 @100GV)

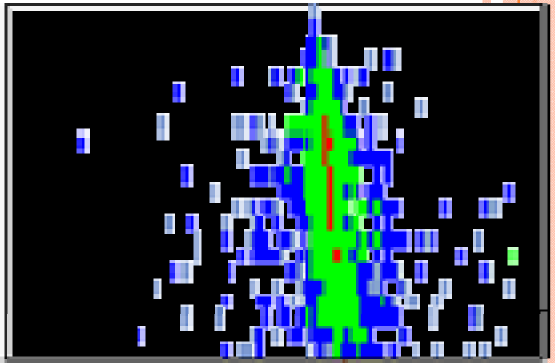
→ Required strong CALO selection



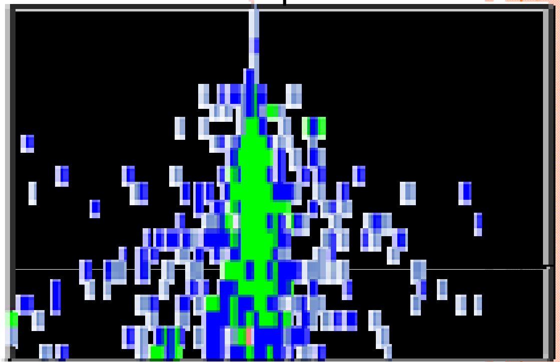
POSITRON IDENTIFICATION WITH CALO

- Identification based on:
  - **Shower topology** (lateral and longitudinal profile, shower starting point)
  - **Total detected energy** (energy-rigidity match)
- Analysis key points:
  - **Tuning/check of selection criteria with:**
    - test-beam data
    - simulation
    - flight data → dE/dx from SPE & neutron yield from ND
  - **Selection of pure proton sample from flight data** ("pre-sampler" method):
    - ***Background-suppression method***
    - ***Background-estimation method***

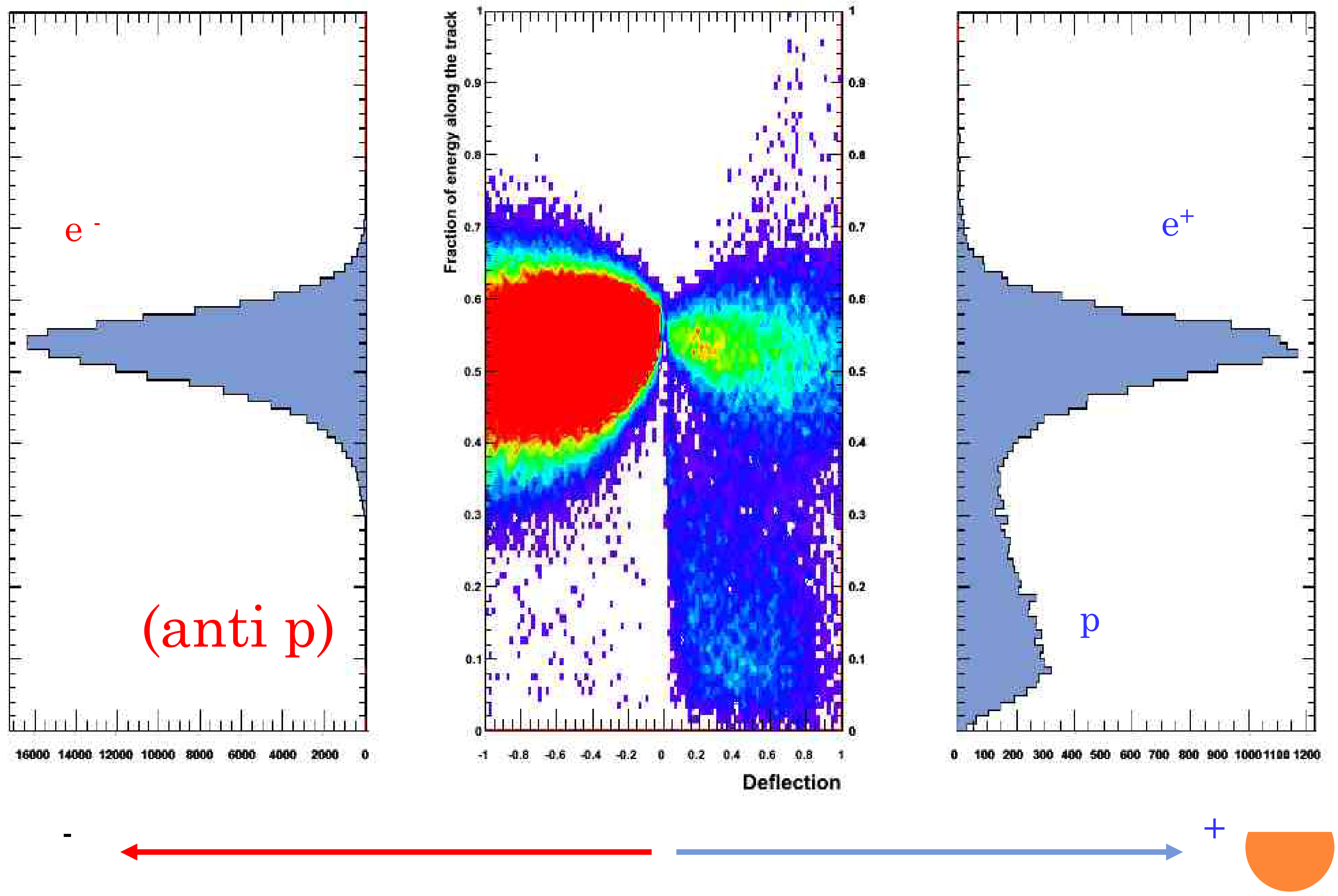
51 GV positron



80 GV proton



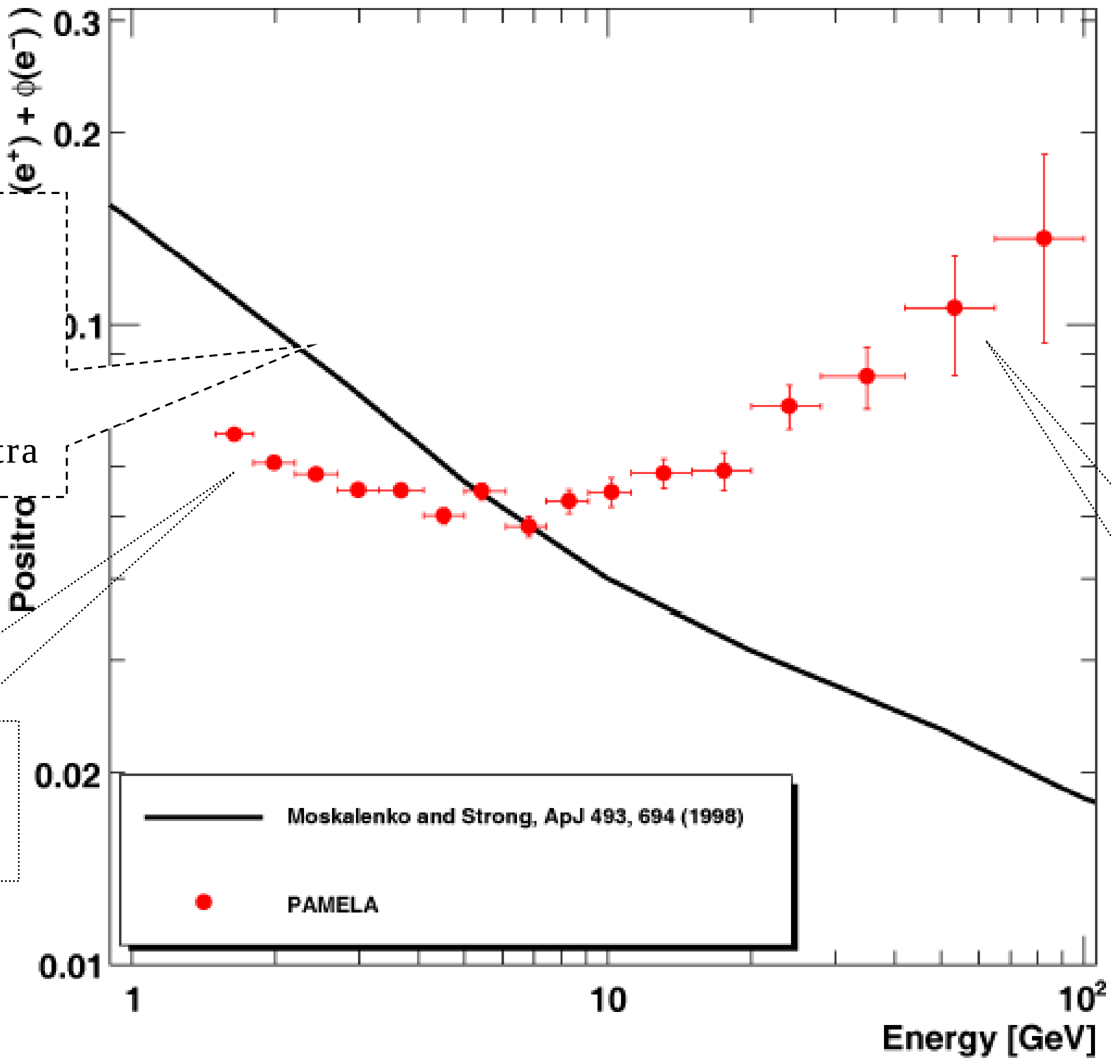
Final results make <u>NO USE</u> of test-beam and/or simulation calibrations.
The measurement is based only on flight data
with the <u>background-estimation</u> method



e -
(anti p)
Fraction of energy along the track
Deflection
e+
p
-
+

PAMELA: Positron fraction

NATURE 458, 697, 2009



(Moskalenko & Strong 1998) GALPROP code

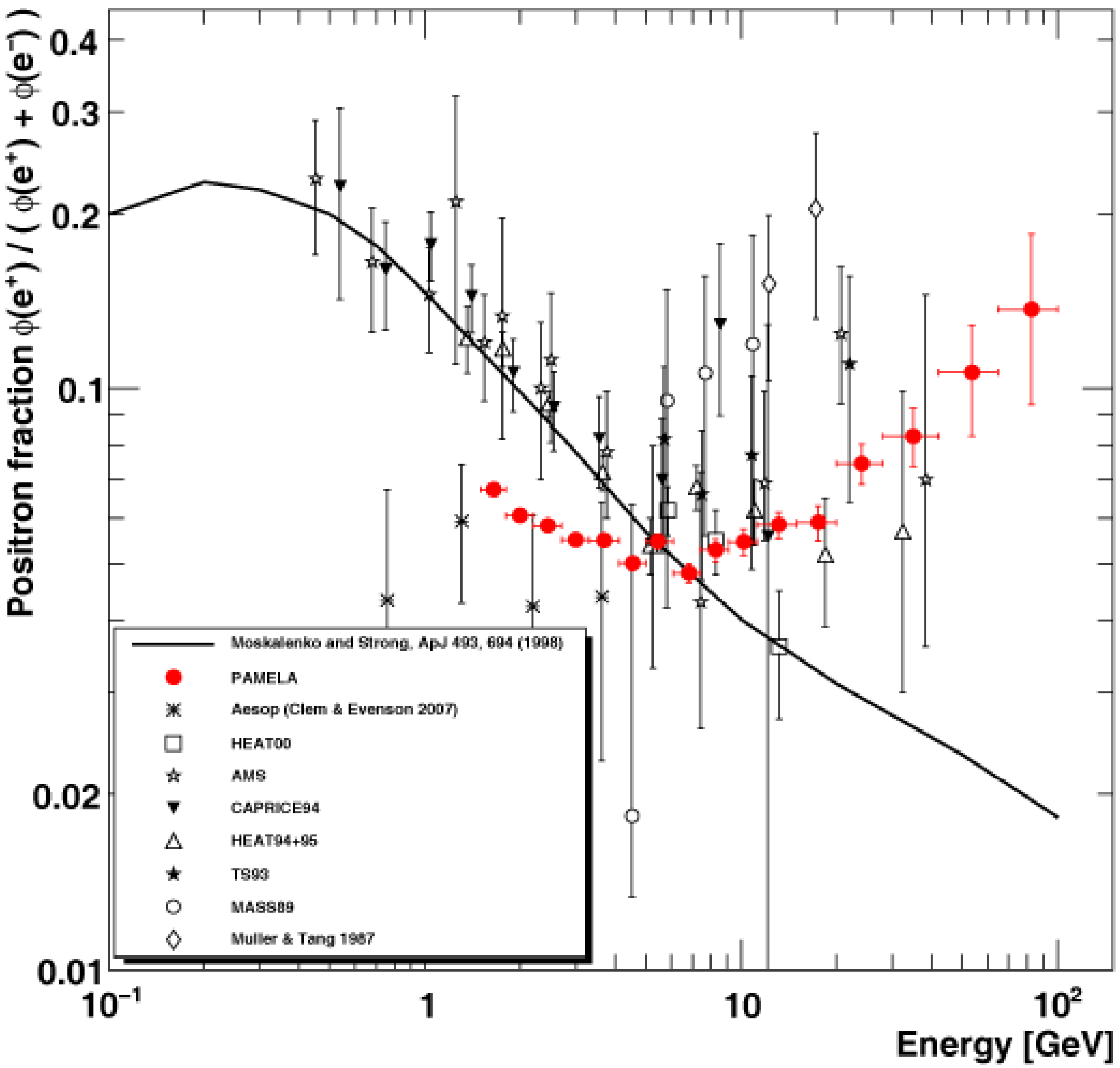
- Plain diffusion model
- Interstellar spectra

Solar modulation effects

Anomalous increasing ?

PAMELA: Positron fraction wrt other exp's

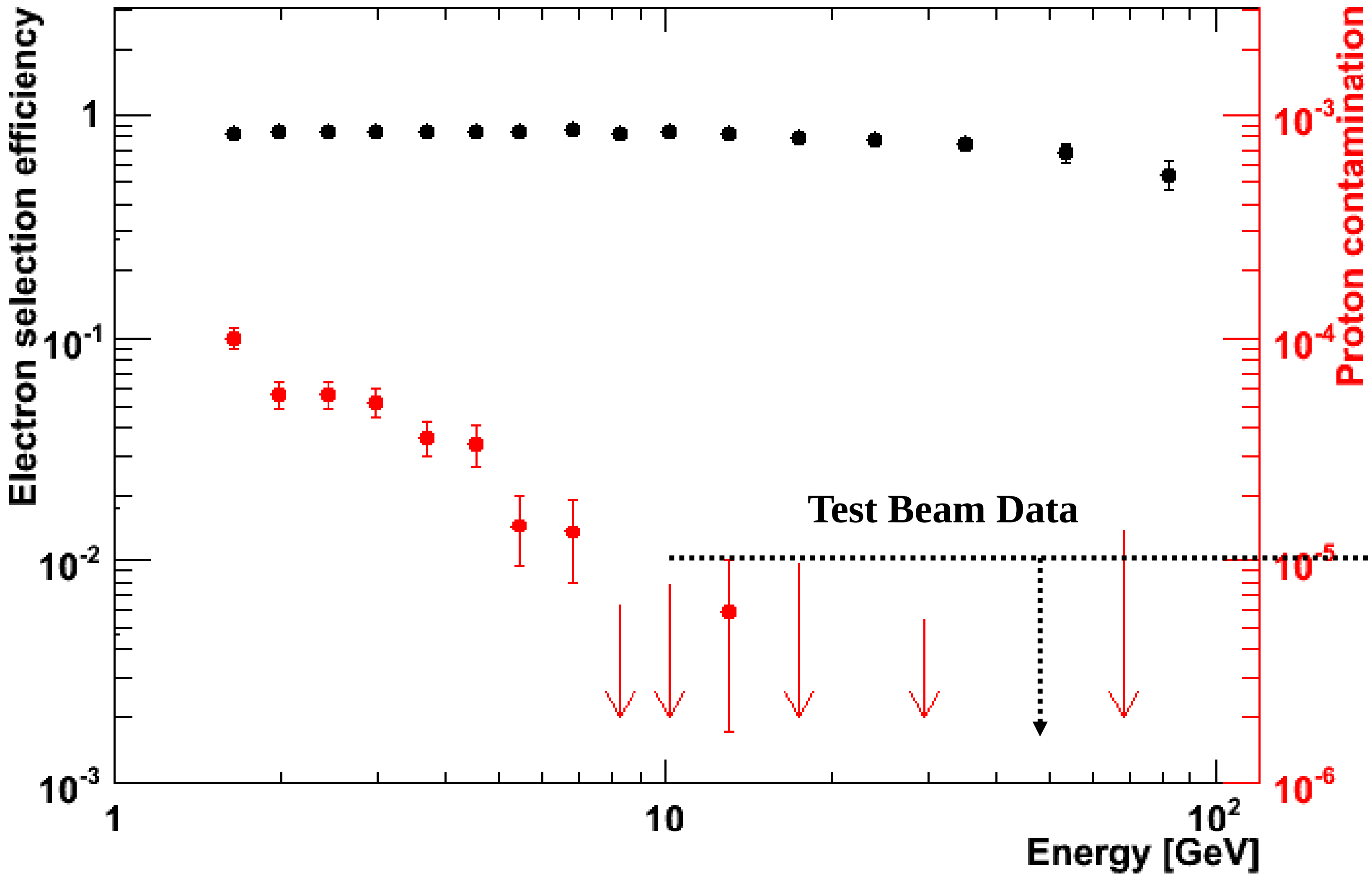
NATURE 458, 697, 2009



400

citations of this result in a year's time!

Estimated proton contamination with "pre-sampler" method

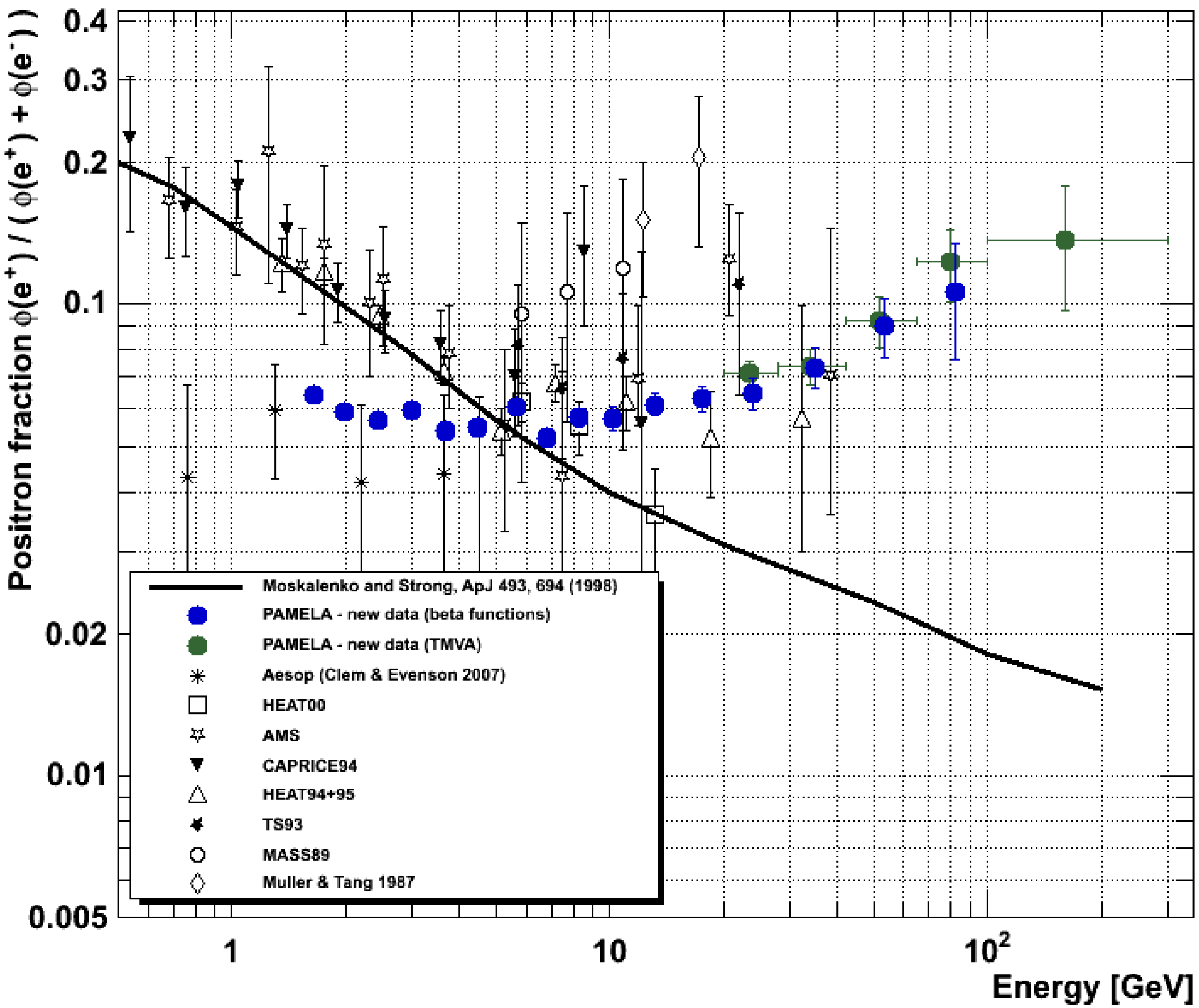


POSITRON TO ELECTRON FRACTION: NEW DATA

Data: July 2006 → December 2008

Two different analysis methods

Factor 2.5 increase in statistics (factor 3 in the highest energy bin)

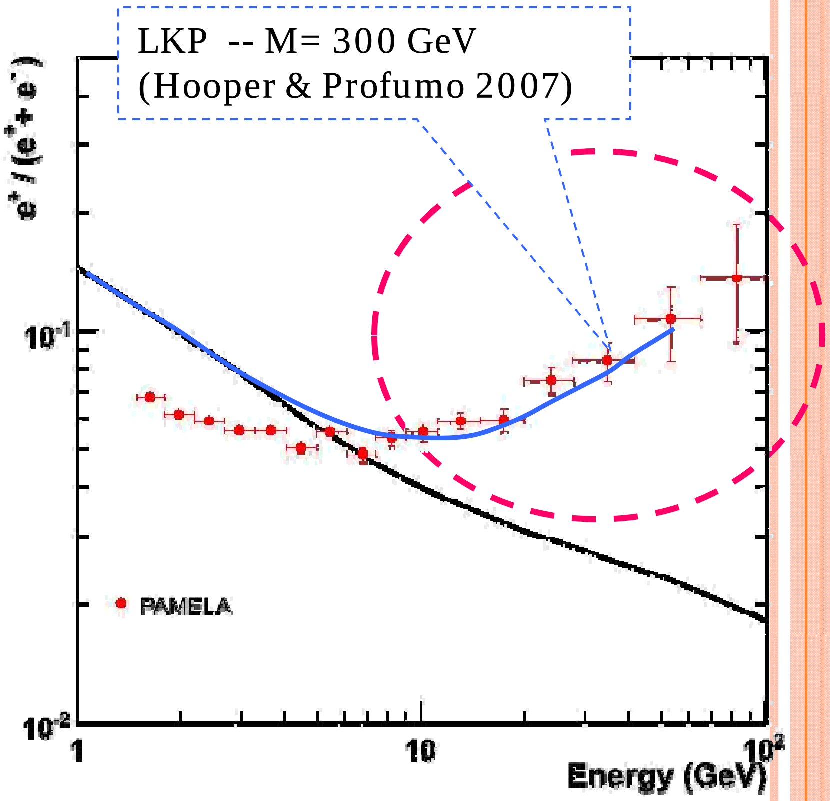


"A statistical procedure for the identification of positrons in the PAMELA experiment", O. Adriani et al., astro-ph, arXiv: 1001.3522v1, in publication on APP !

PRIMARY POSITRON SOURCES

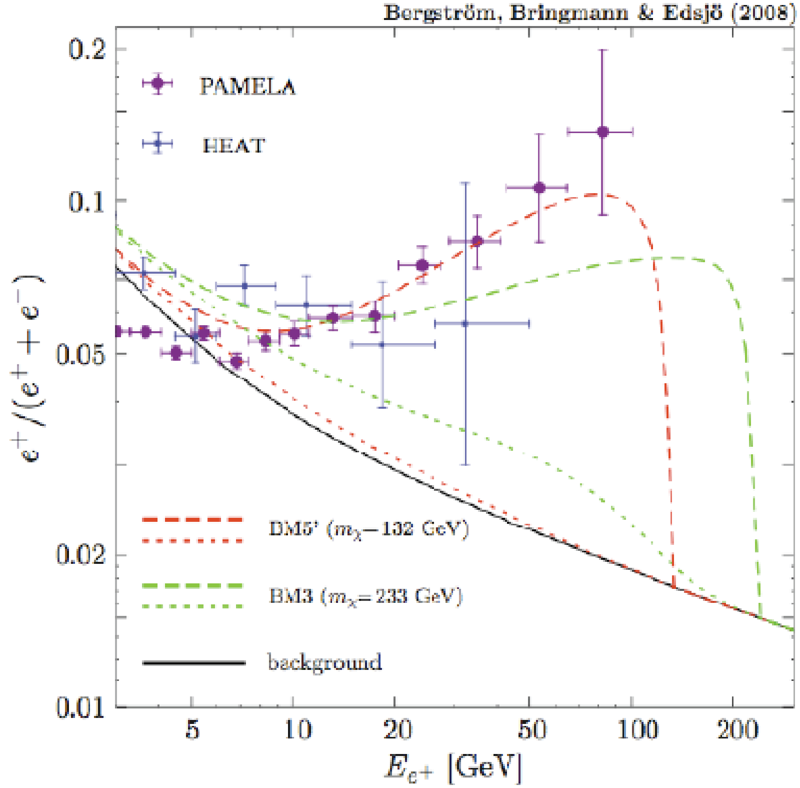
Dark Matter

- e^+ yield depend on the dominant decay channel
  - → **LSPs (SUSY)** seem <u>disfavored</u> due to suppression of e^+e^- final states
    - → low yield (relative to p-bar)
    - → soft spectrum from cascade decays
  - → **LKPs** seem <u>favored</u> because can annihilate directly in e^+e^-
    - → high yield (relative to p-bar)
    - → hard spectrum with pronounced cutoff @ M_{LKP} (>300 GeV)
- Boost factor required to have a sizable e^+ signal
  - → NB: constraints from p-bar data!!
- Other hypothesys possible and under study (i.e. Minimal DM Model, decaying DM, new gauge bosons, …)



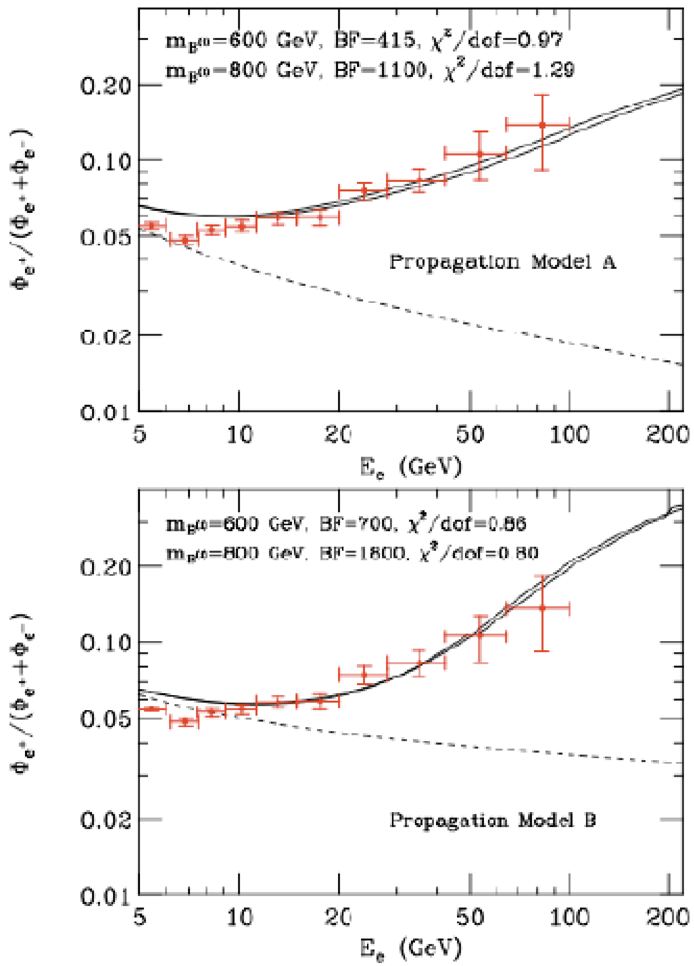
More than 150 articles claim DM is discovered !
M. Cirelli's talk later …

EXAMPLE: DARK MATTER



Majorana DM with **new** internal bremsstrahlung correction. NB: requires annihilation cross-section to be 'boosted' by >1000.

Hooper and Zurek
arXiv:0902.0593v1

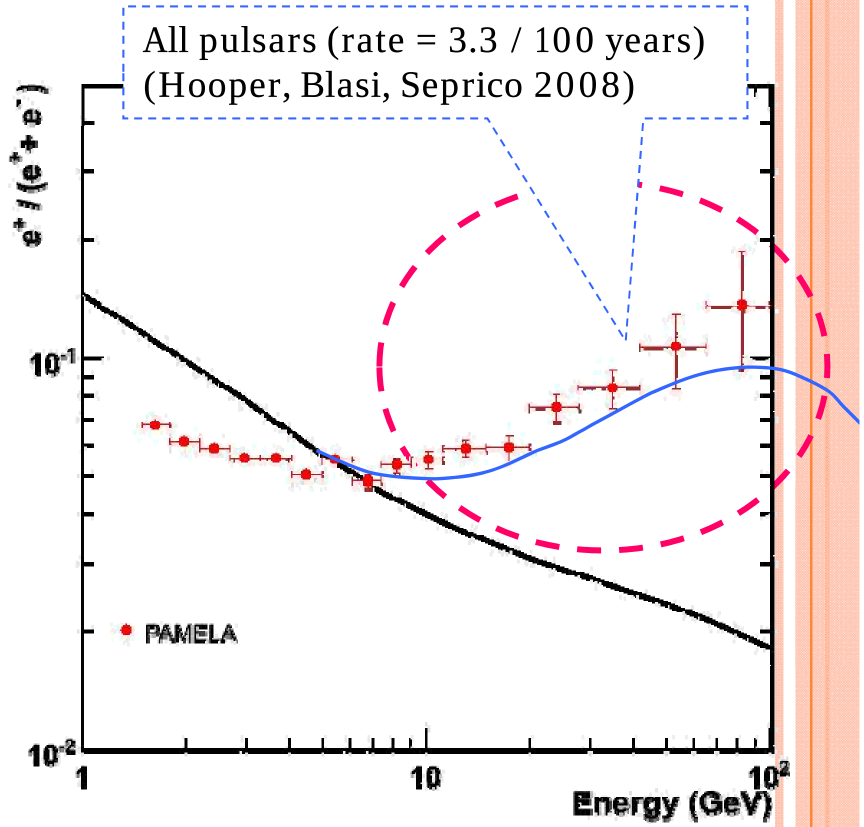


Kaluza-Klein dark matter

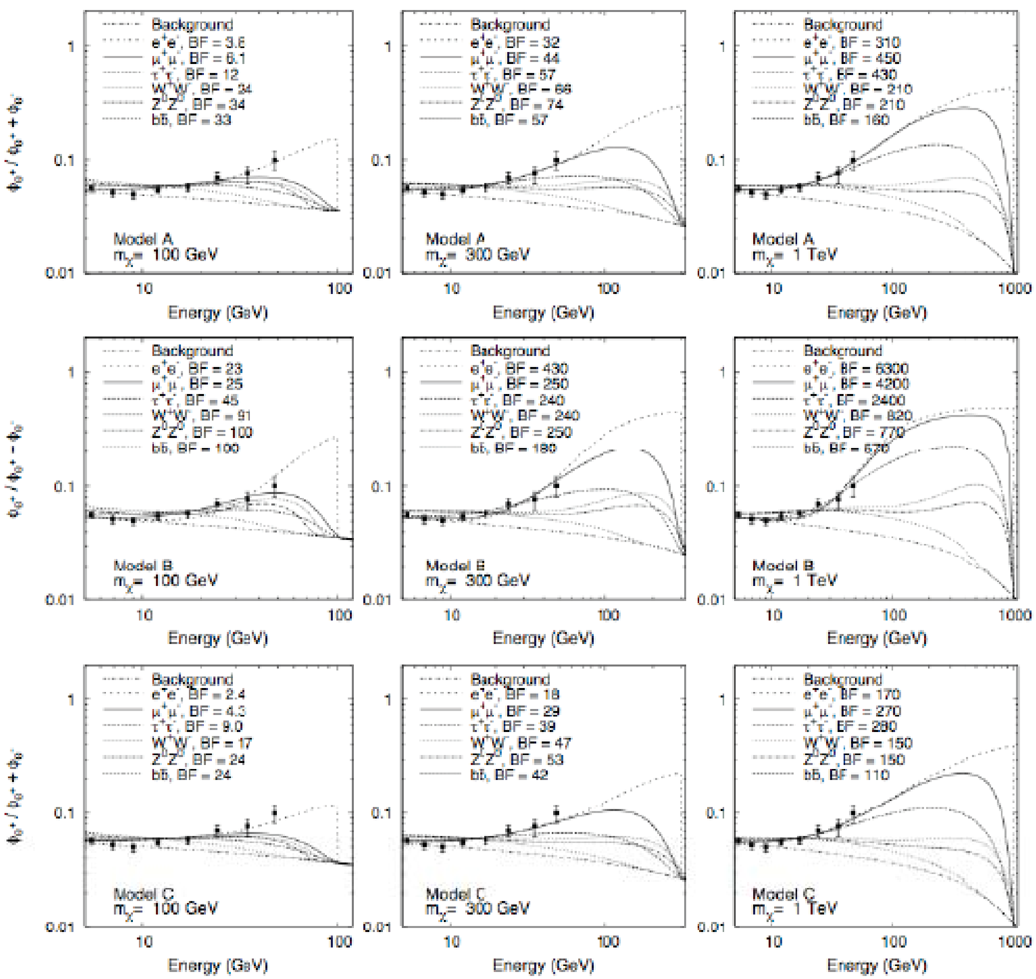
PRIMARY POSITRON SOURCES

Astrophysical processes

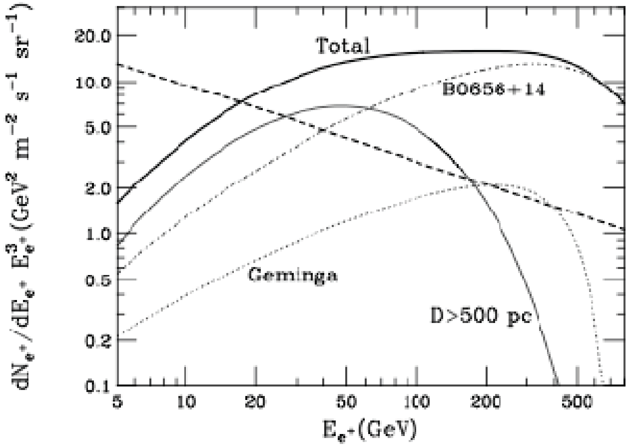
- Local **pulsars** are well-known sites of e^+e^- pair production (the spinning B of the pulsars strips e- that emit gammas then converting to pairs trapped in the cloud, accelerated and then escaping at the Poles) :
  - → they can individually and/or coherently contribute to the e^+e^- galactic flux and explain the PAMELA e^+ excess (both spectral feature and intensity)
    - → No fine tuning required
  - → if one or few nearby pulsars dominate, anisotropy could be detected in the angular distribution
    - → possibility to discriminate between pulsar and DM origin of e^+ excess

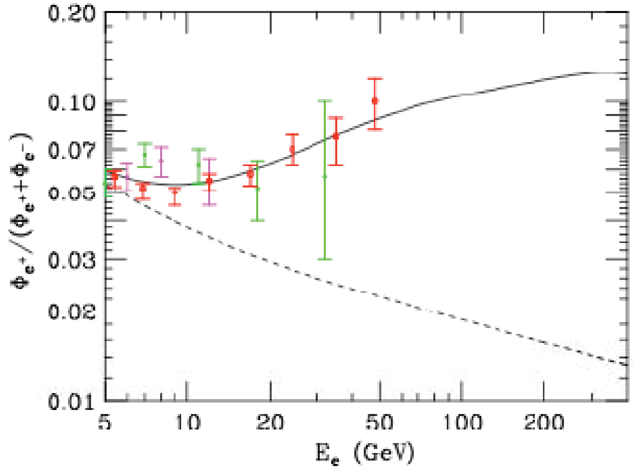


EXAMPLE: PULSARS



Cholis, Goodenough, Hooper, Simet, and Weiner
arXiv:0809.1683





Hooper, Blasi, and Serpico
arXiv:0810.1527

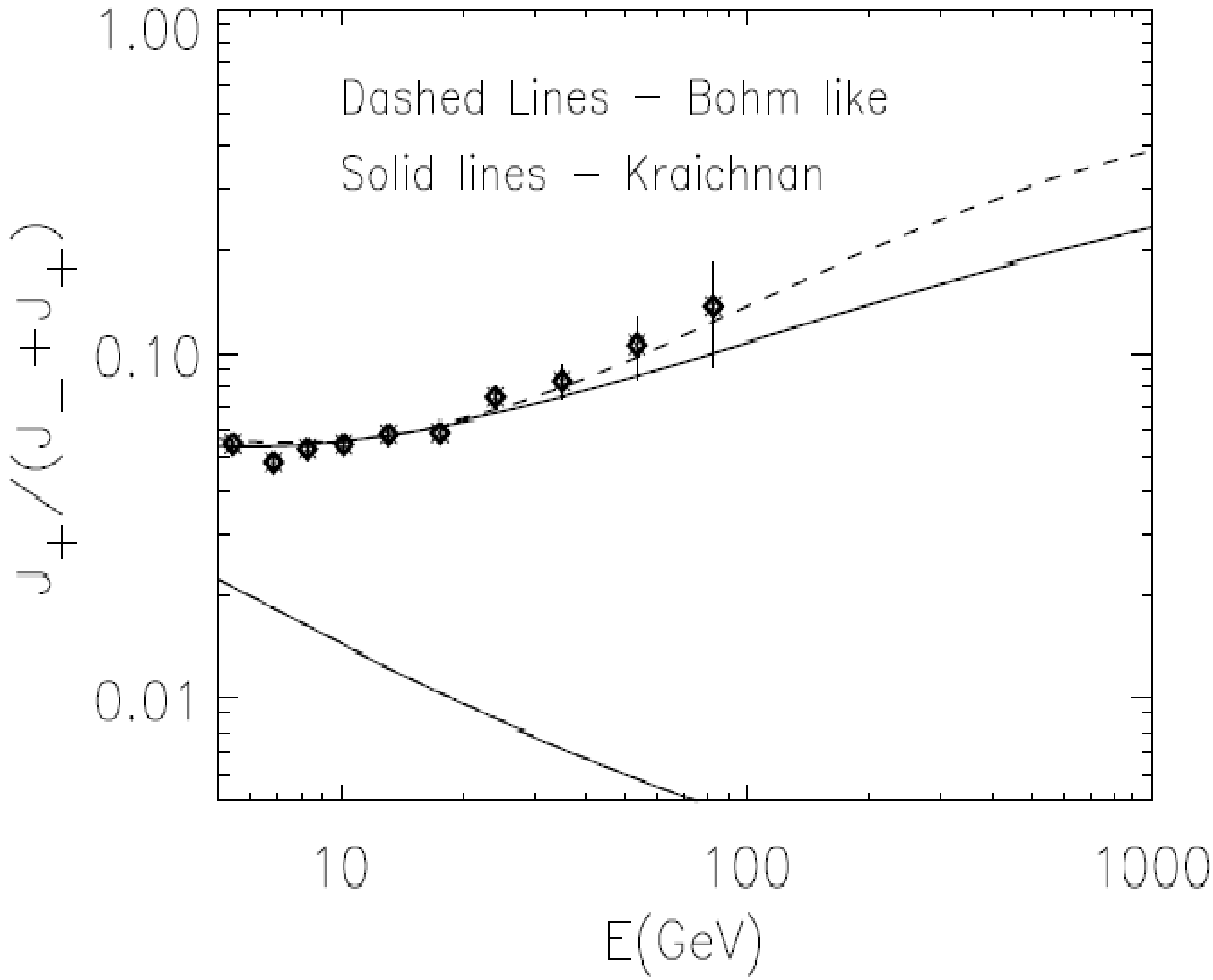
Revision of standard CR model

- Pairs created also in the acceleration sites (e.g. in old SNRs);

- Distribution of CR sources not homogeneus (SNRs more in spiral arms)

Positrons from old SNR's

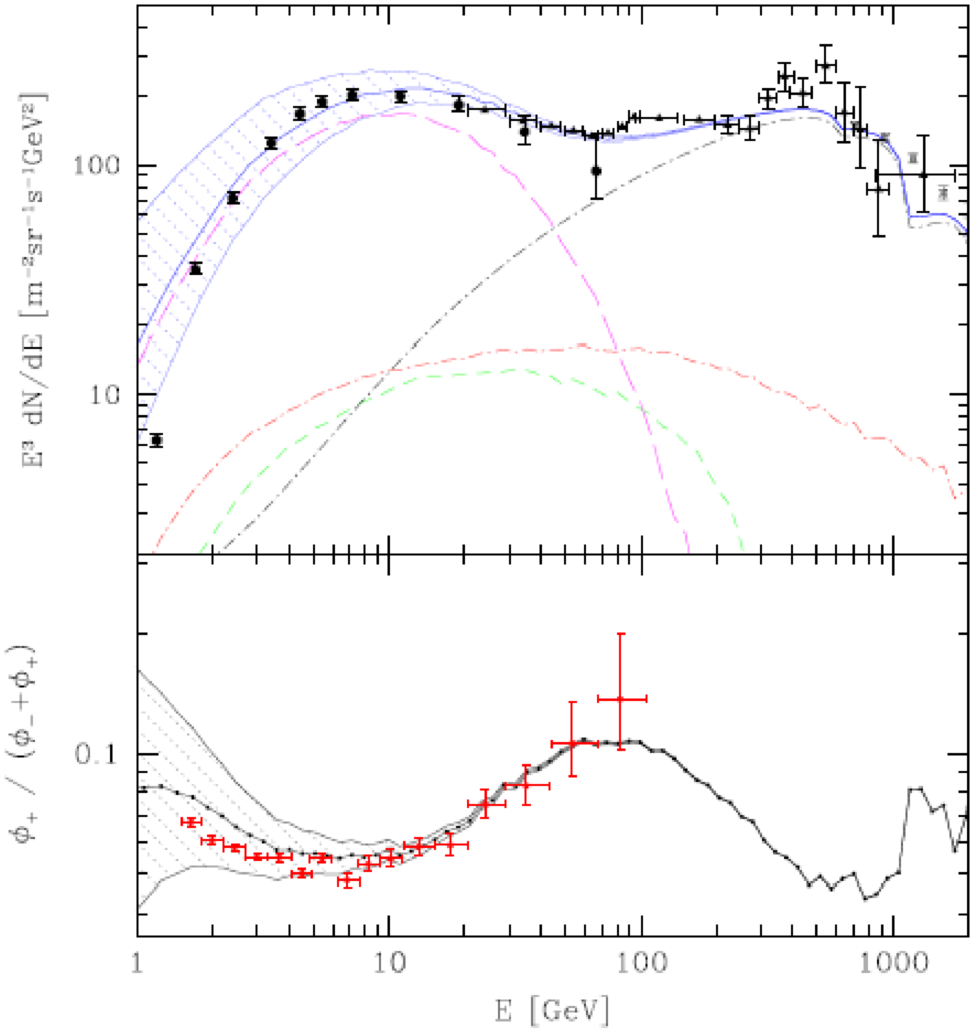
P. Blasi , PRL 103, 051104 (2009)



Positrons (and electrons) produced as secondaries in the sources (e.g. SNR) where CRs are accelerated.
But also other secondaries are produced: significant increase expected in the $\bar{p}/p$ and B/C ratios.

EXPLANATION WITH SUPERNOVAE REMNANTS

SHAVIV, NAKAR & PIRAN, ASTRO-PH.HE 0902.0376



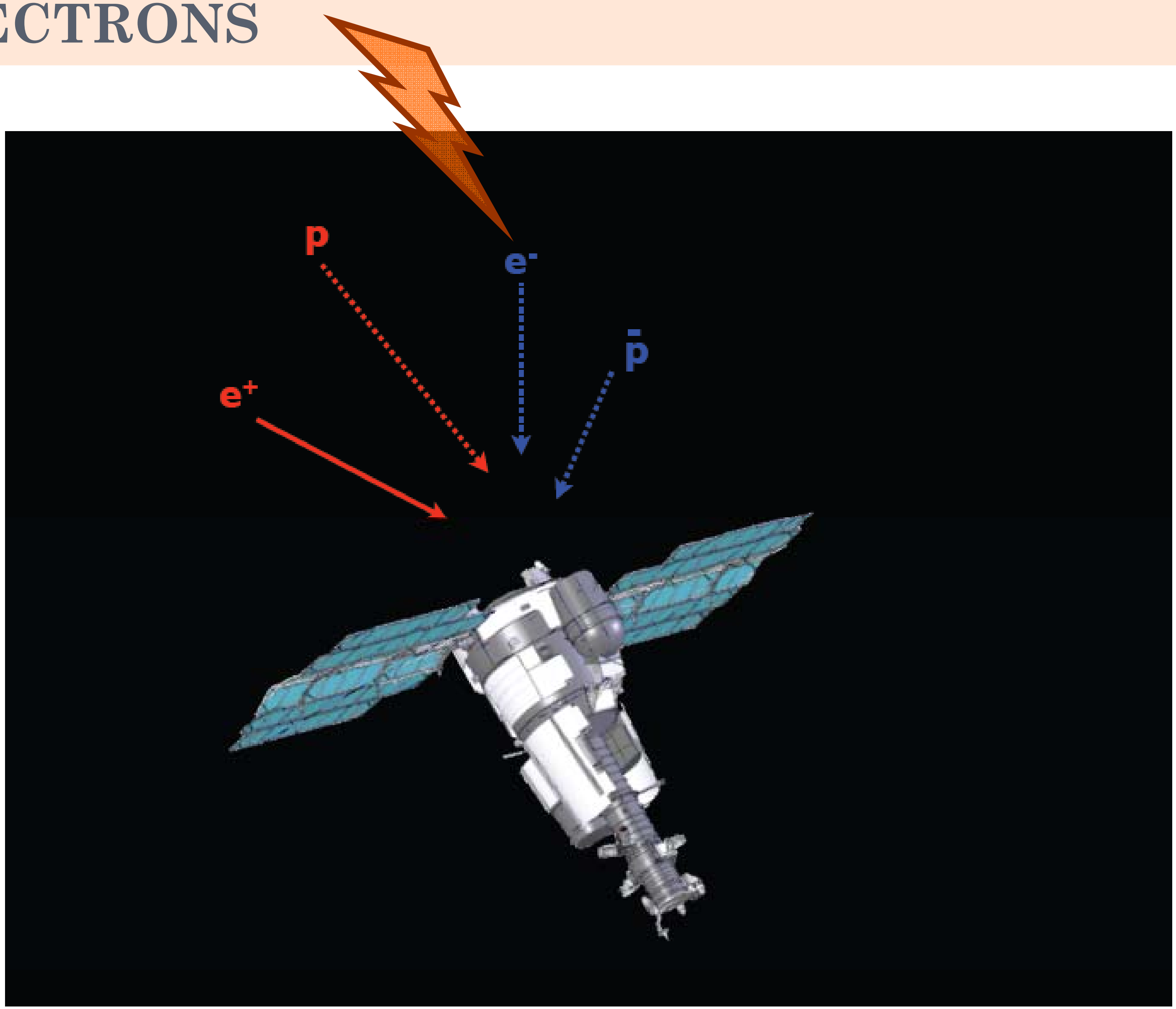
How to clarify the matter?

Pulsars (Serpico, Bucciantini)	New SNRs mechanisms (Blasi, Mertsch)	Localized SNR (Piran)	Dark matter (Donato, Ullio, Gaggero, Cuoco)	?
Uncertainties				
• Acceleration model (polar cap, outer gap, …) • Injection spectrum $E^{-\alpha}$? • Release into the ISM (when, how much?) • Source locations, ages, …	• Environmental parameters at SNR (production mechanism) • Distance to closest source • Cut-off energies • …	• Source properties • Local environment • Diffusion model • …	• Particle physics model • Particle physics enhancement (Sommerfeld) • Substructure enhancement (halo model) • …	?
Tests				
• Anisotropy of flux • Fluctuations in spectrum (arXiv: 0903.1310) • consistency checks (gamma, X-ray, …)	• Antiproton fluxes • Secondary nuclei	• Positron fraction down at several hundred GeV • B/C, antiprotons • Anisotropy	• FSR & IC photons • Continuing positron fraction rise • CMBR distortions • LHC signatures	?

+ need updated background model (with e.g. proper handling of local sources)

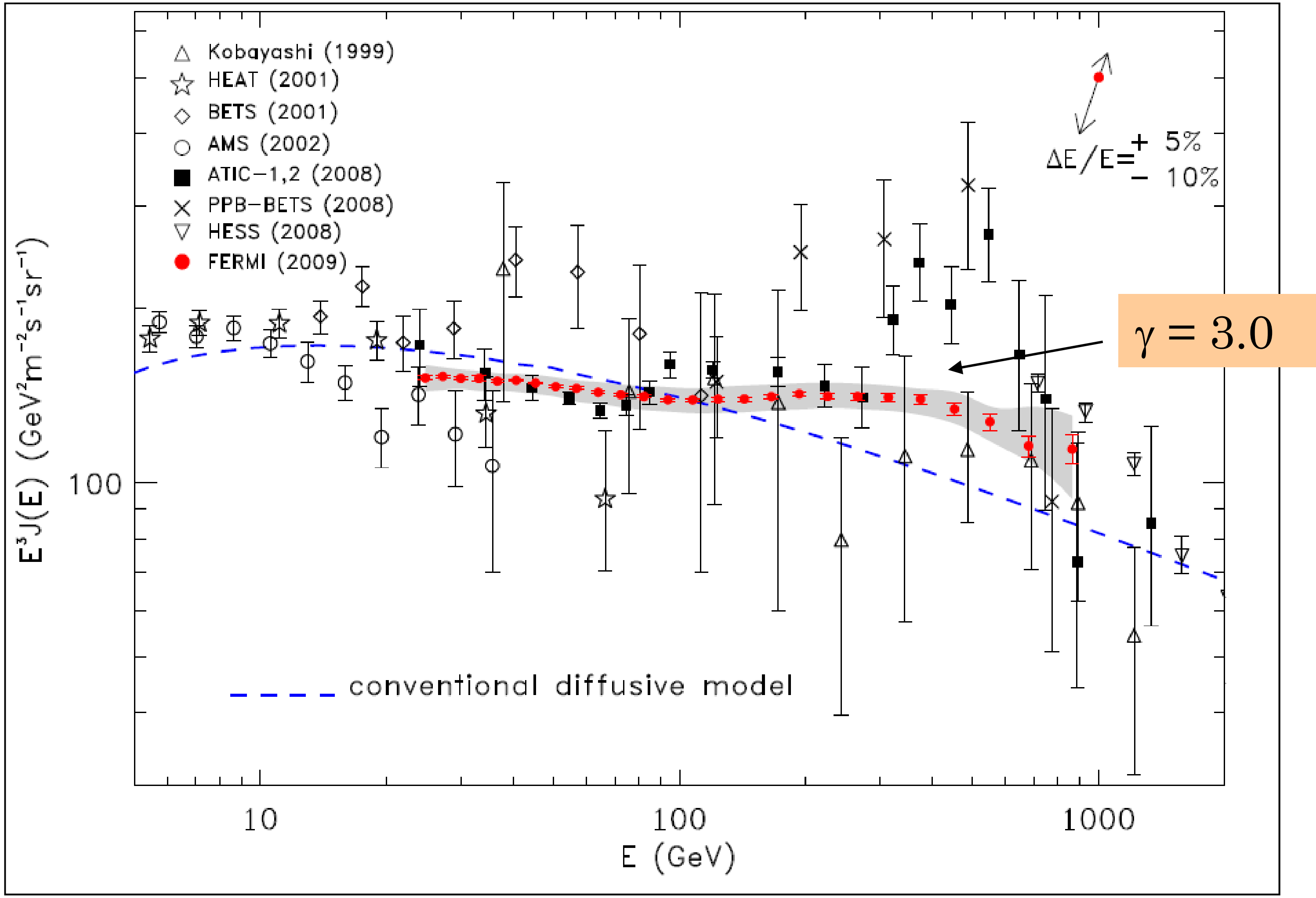
Courtesy of J. Edsjo

ELECTRONS



Any positron source is an electron source too …

RECENT CLAIMS OF ($e^{+}+e^{-}$) EXCESS



FERMI does not confirm the ATIC bump
but finds an excess wrt conventional diffusive models

PAMELA ELECTRON FLUX MEASUREMENTS

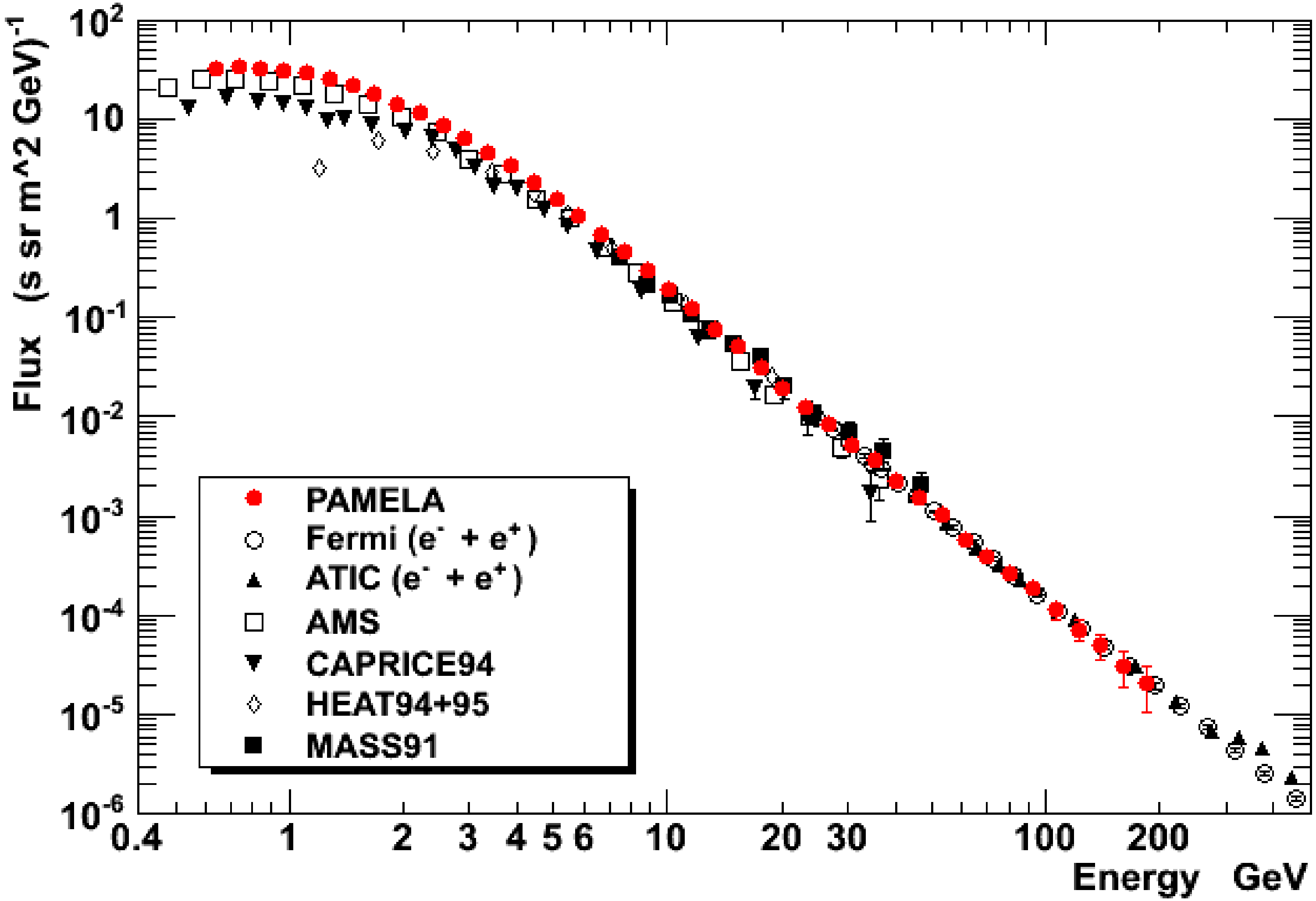
Key points wrt other experiments (ATIC, HESS, FERMI) :

- Combination of CALO and SPECTROMETER allow energy self-calibration in flight → no dependence on ground calibrations or MC simulations
- Very deep CALO (16 X_0) → containment of the shower maximum beyond 1 TeV
- Neutron detector help proton rejection, especially at high energy
- No atmospheric contamination
- Possibility to disentangle electrons from positrons

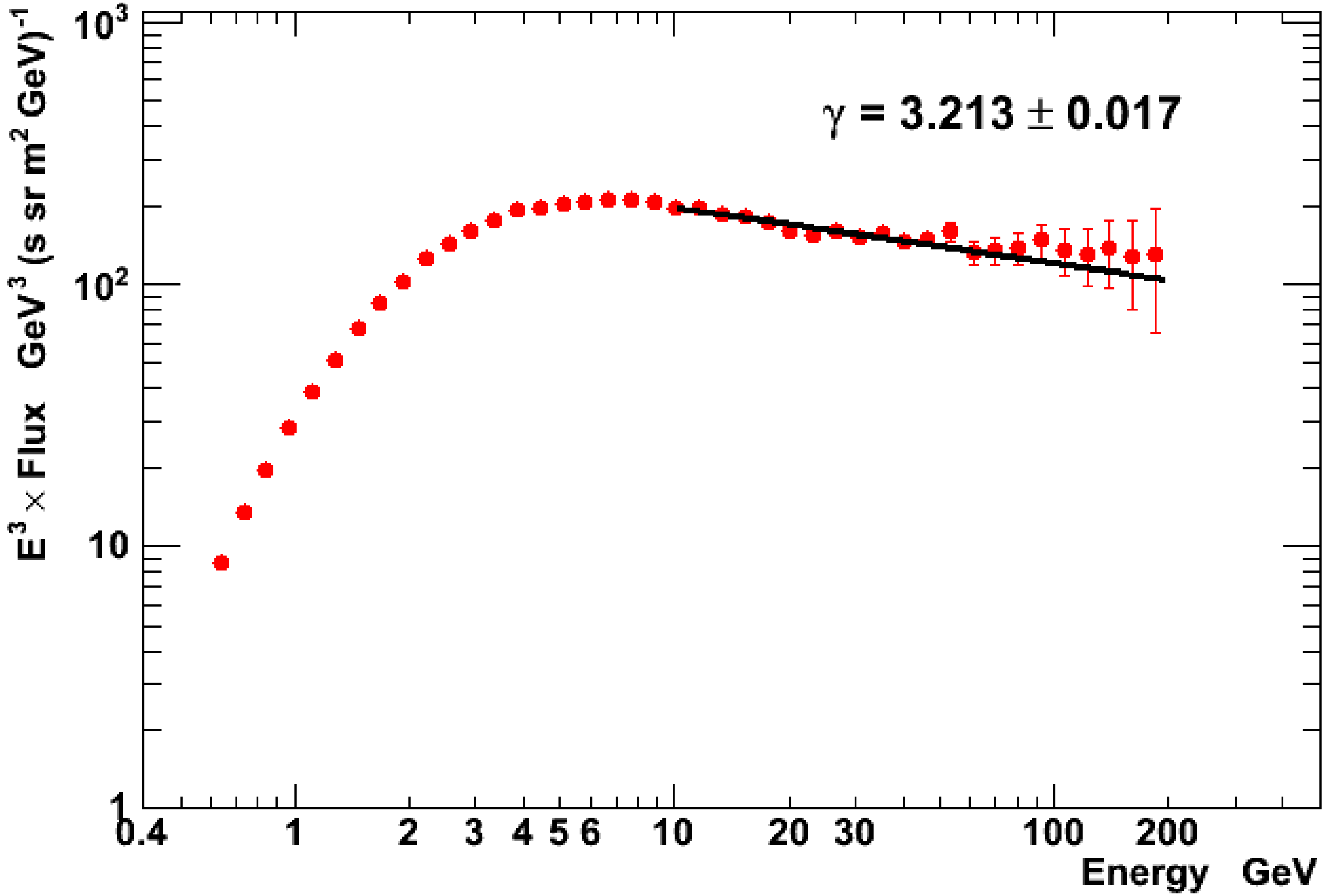
But ..

- Smaller acceptance → lower statistics

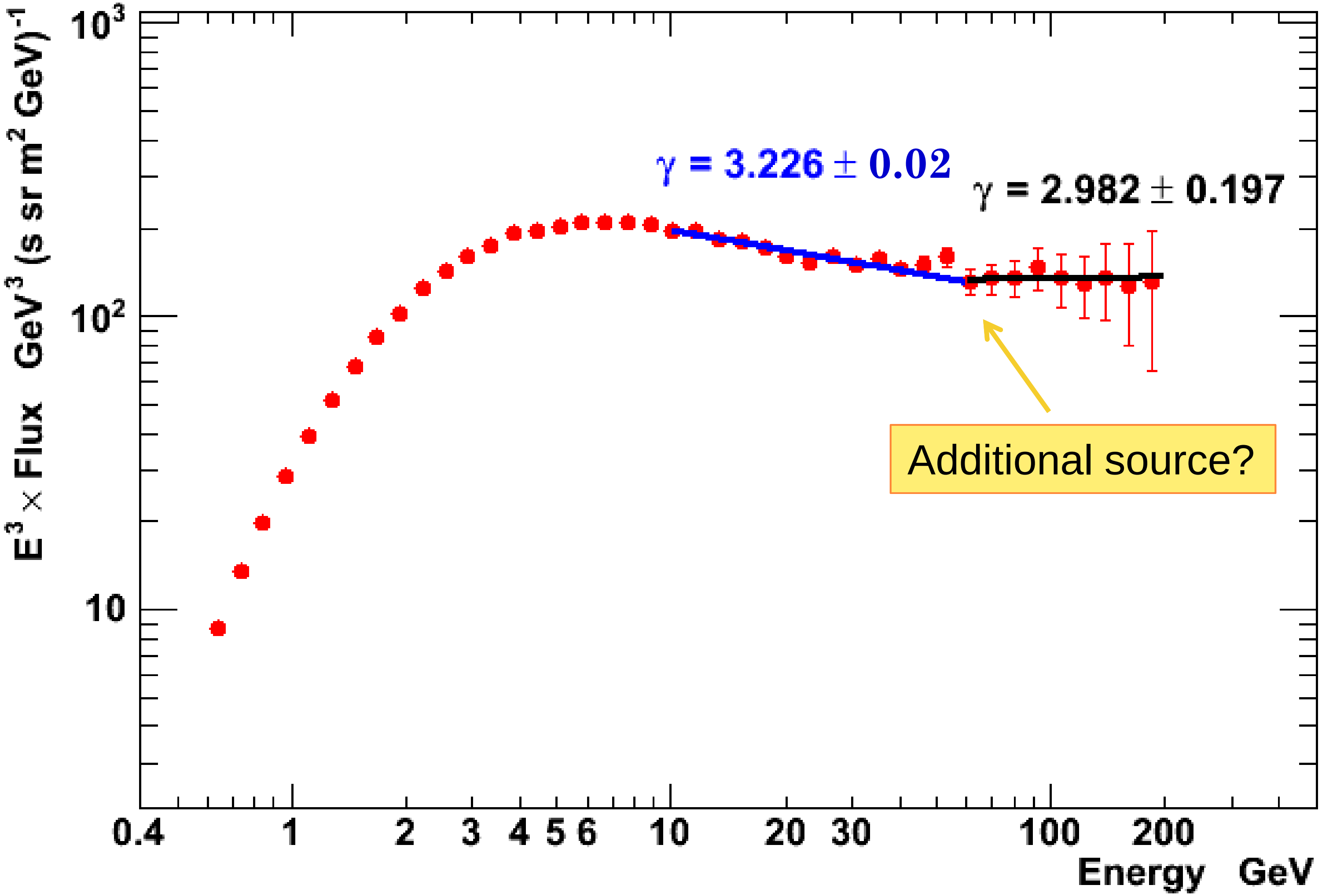
PAMELA Electron (e^-) Spectrum



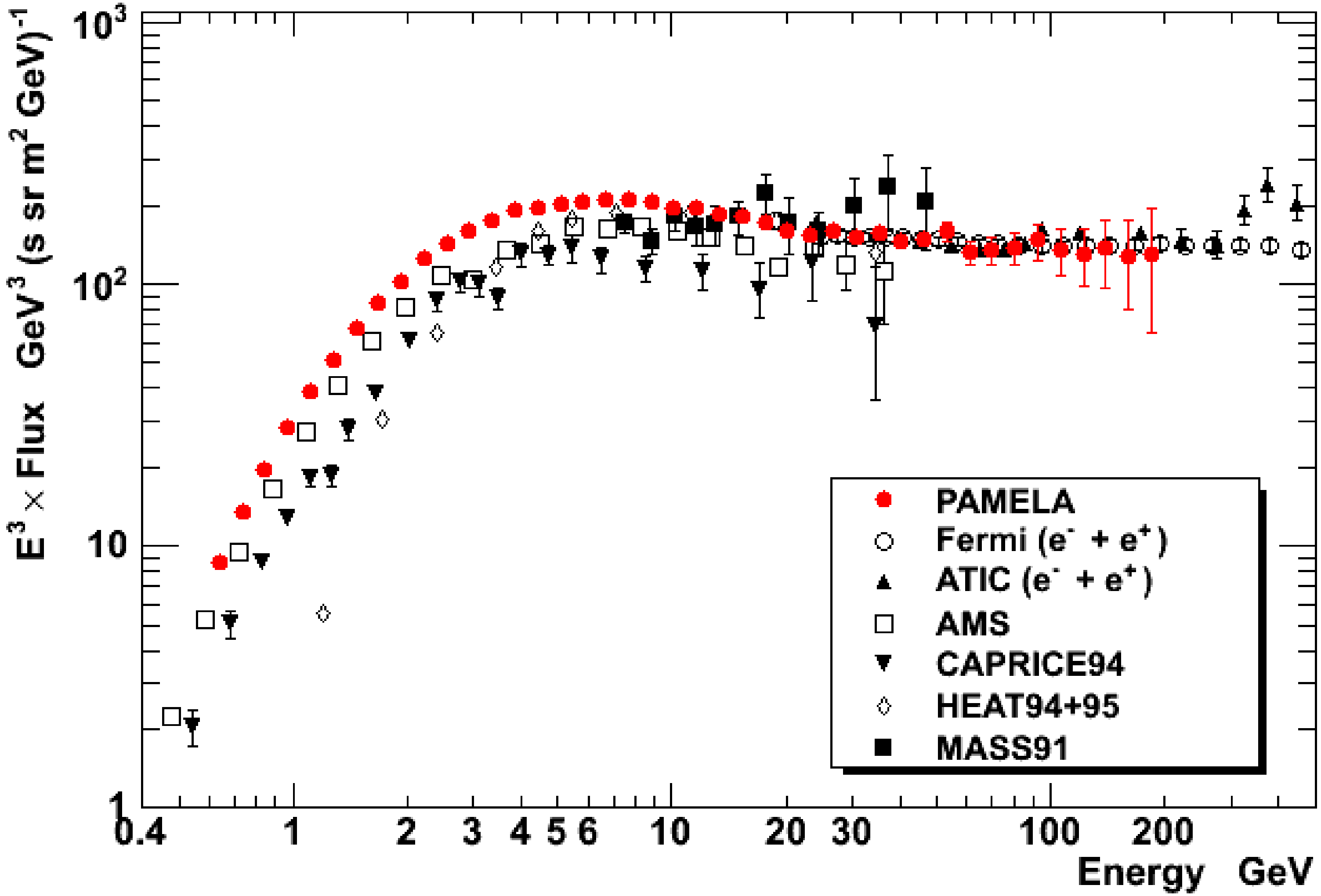
PAMELA Electron (e^-) Spectrum



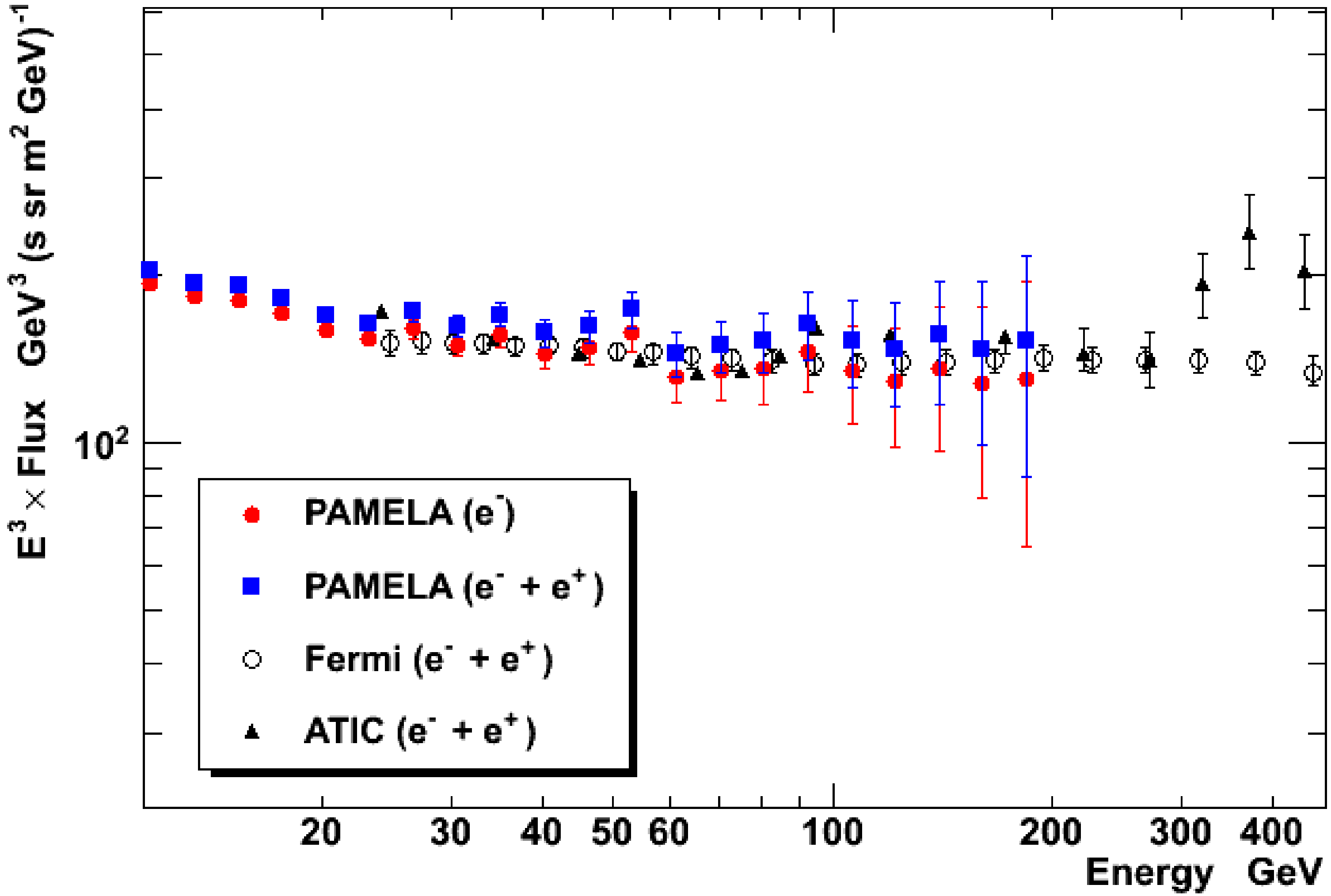
PAMELA ELECTRON (e^-) SPECTRUM



PAMELA Electron (e^-) Spectrum

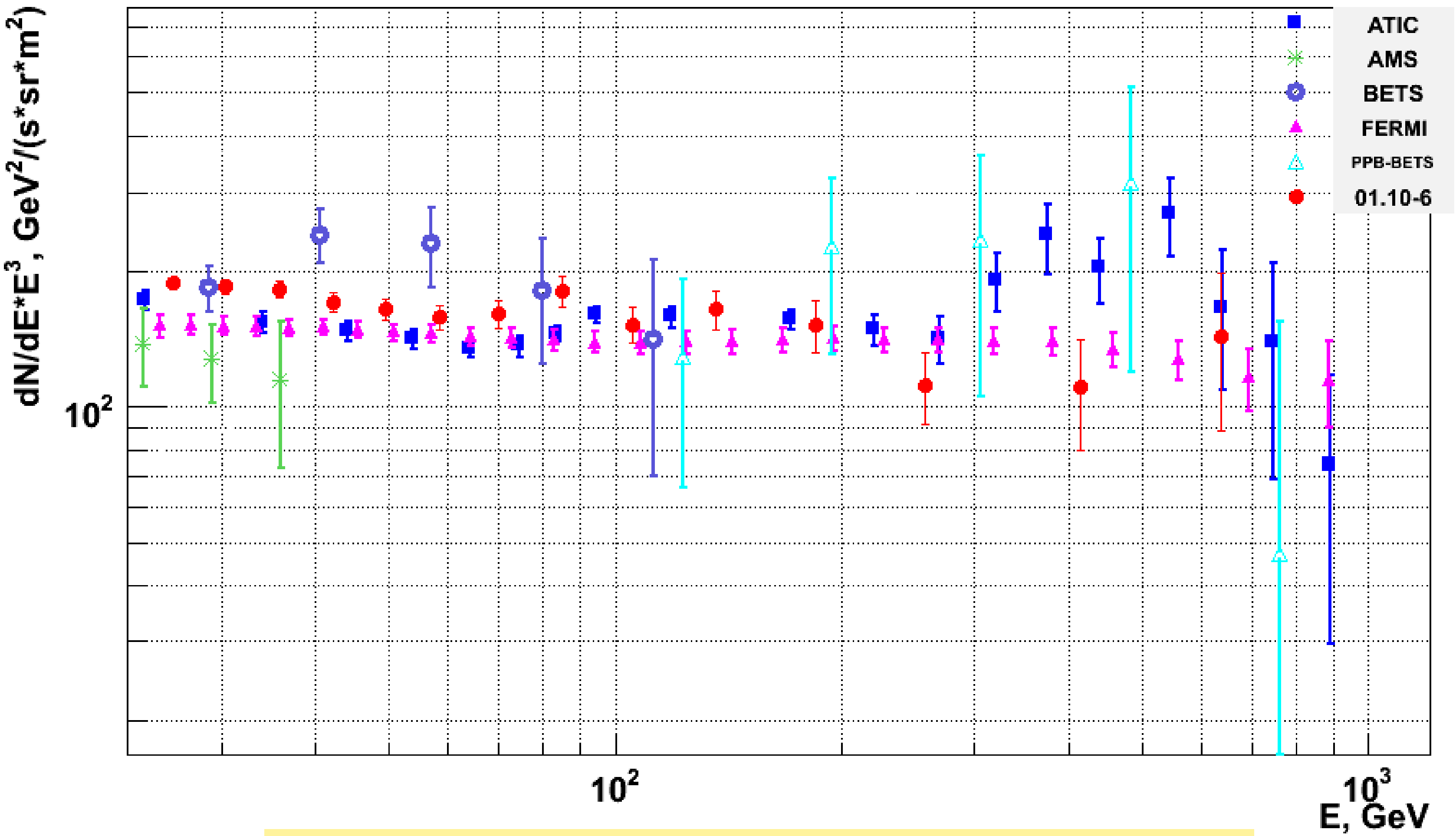


PAMELA ELECTRON ($e^+ + e^-$) SPECTRUM



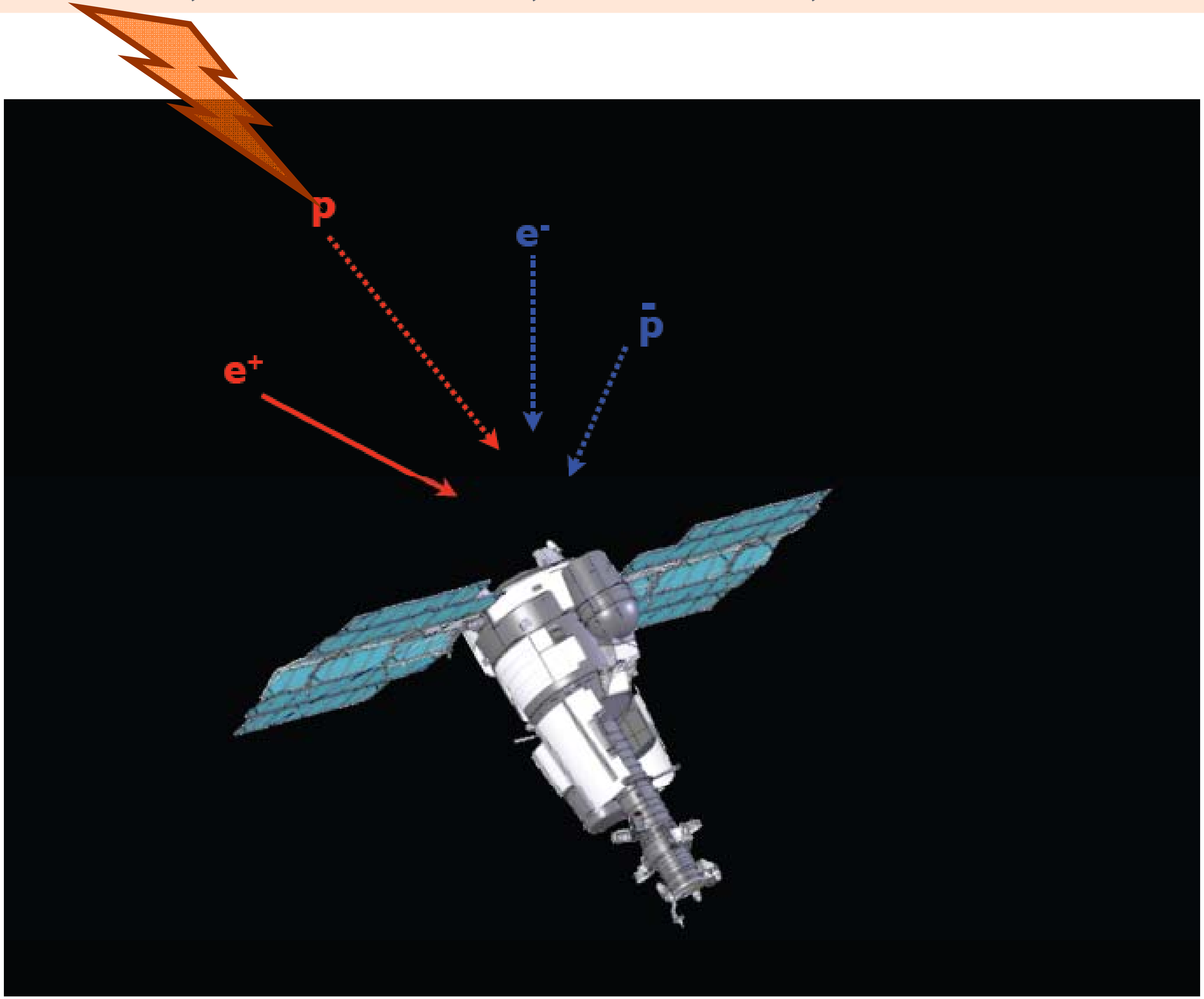
PAMELA ALL ELECTRONS→ HIGH ENERGY

VERY PRELIMINARY

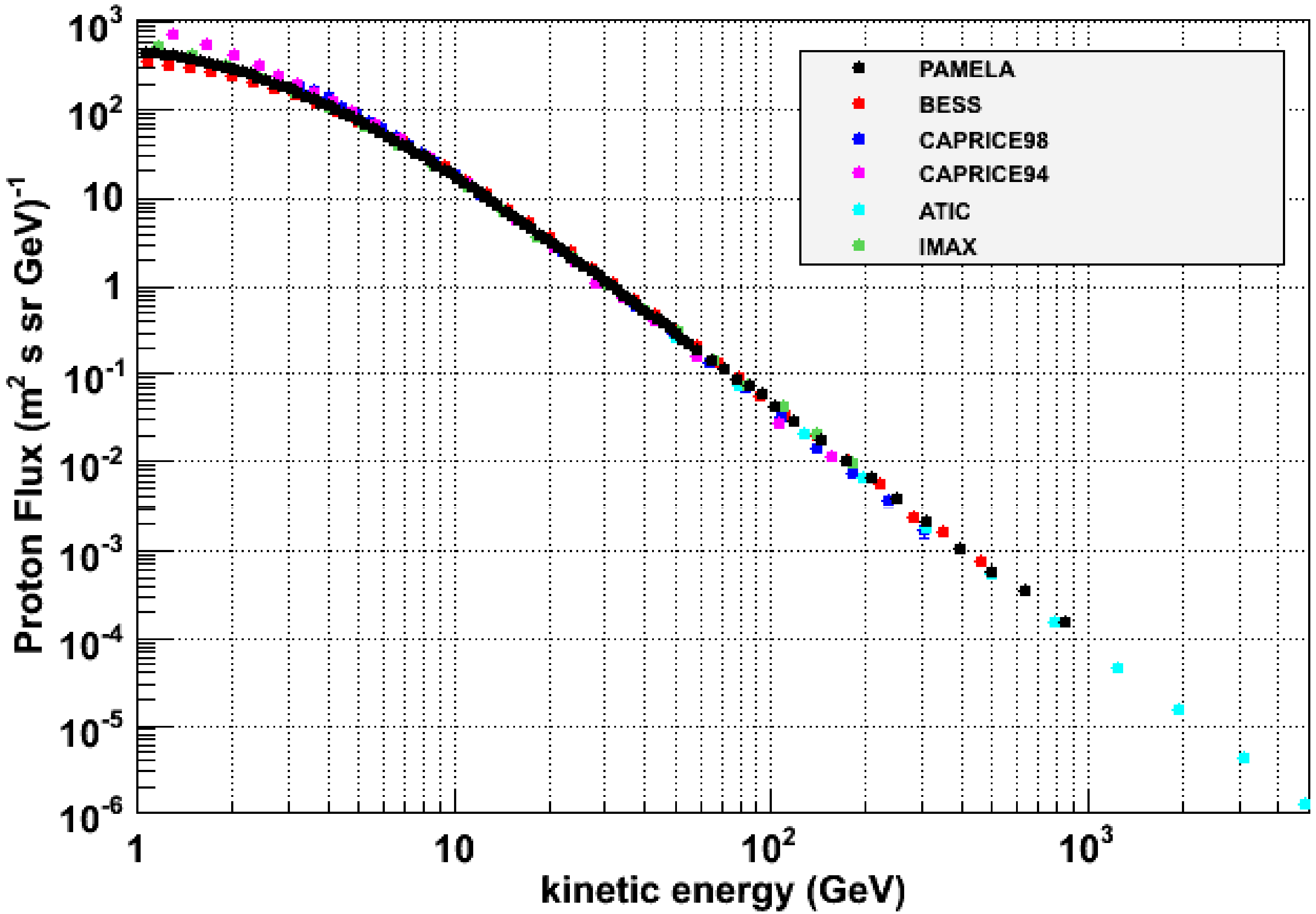


Energy measurement done with the calorimeter

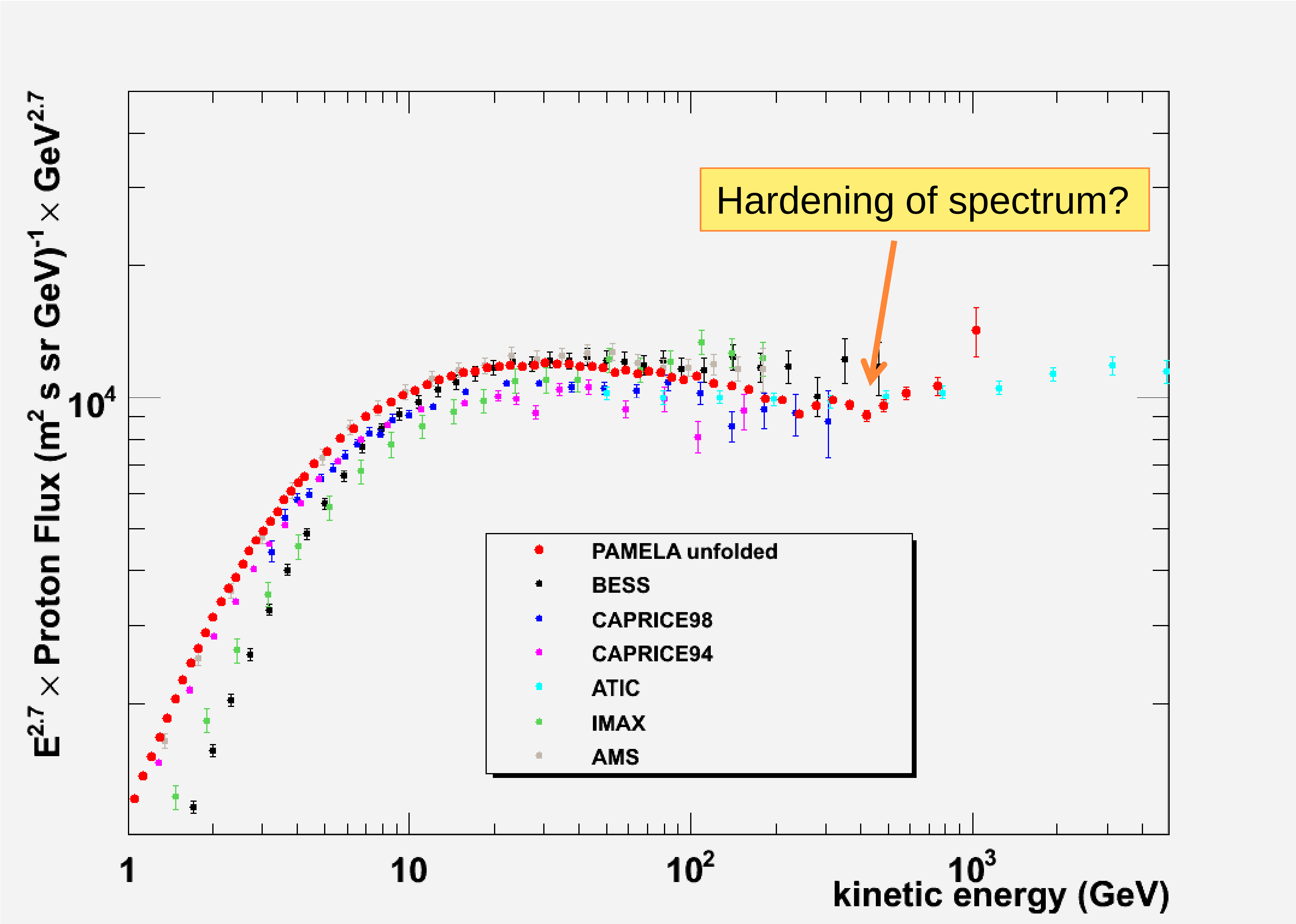
PROTONS, HELIUMS, NUCLEI, ...



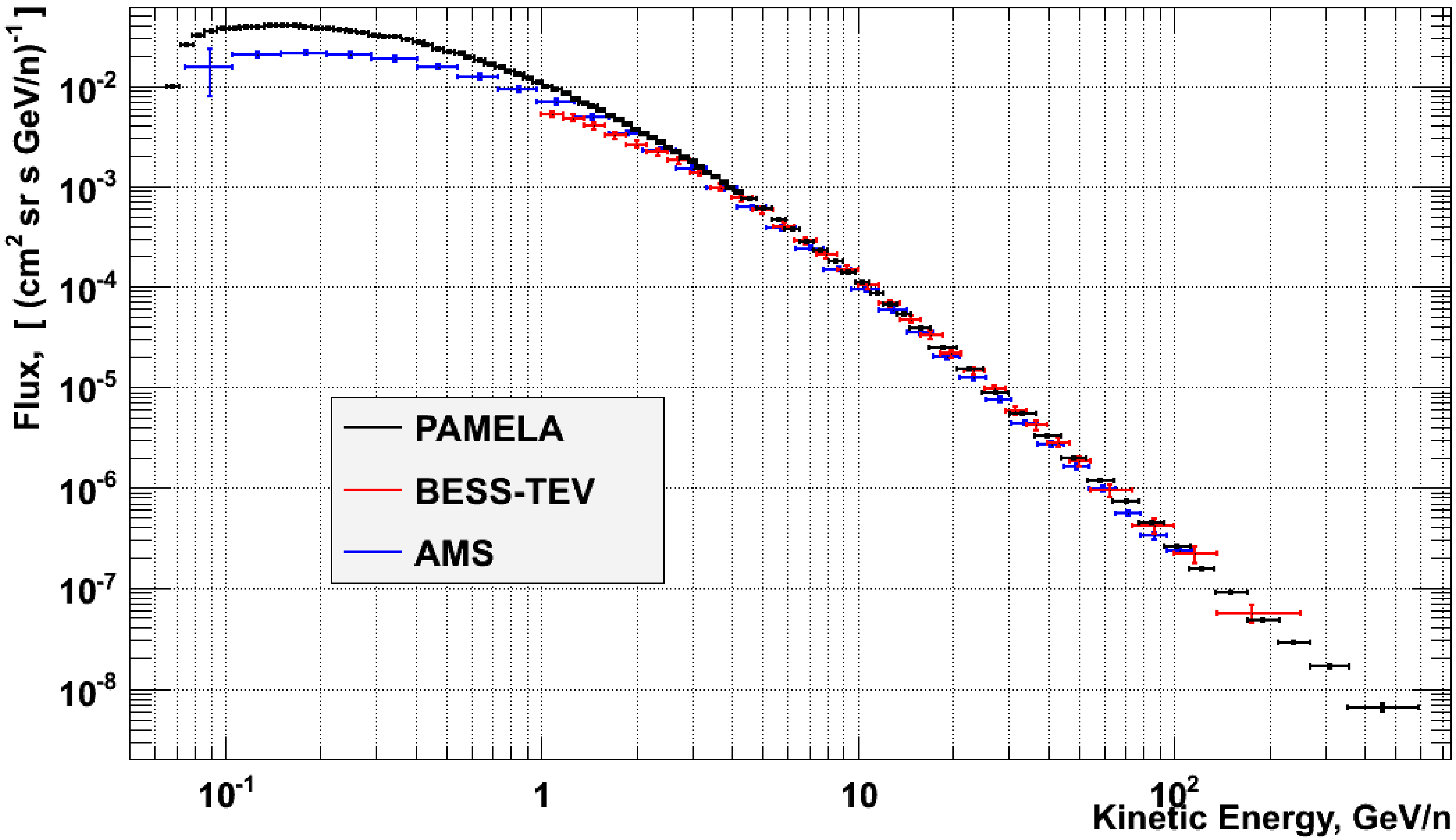
PAMELA PROTON FLUX



PAMELA Proton flux

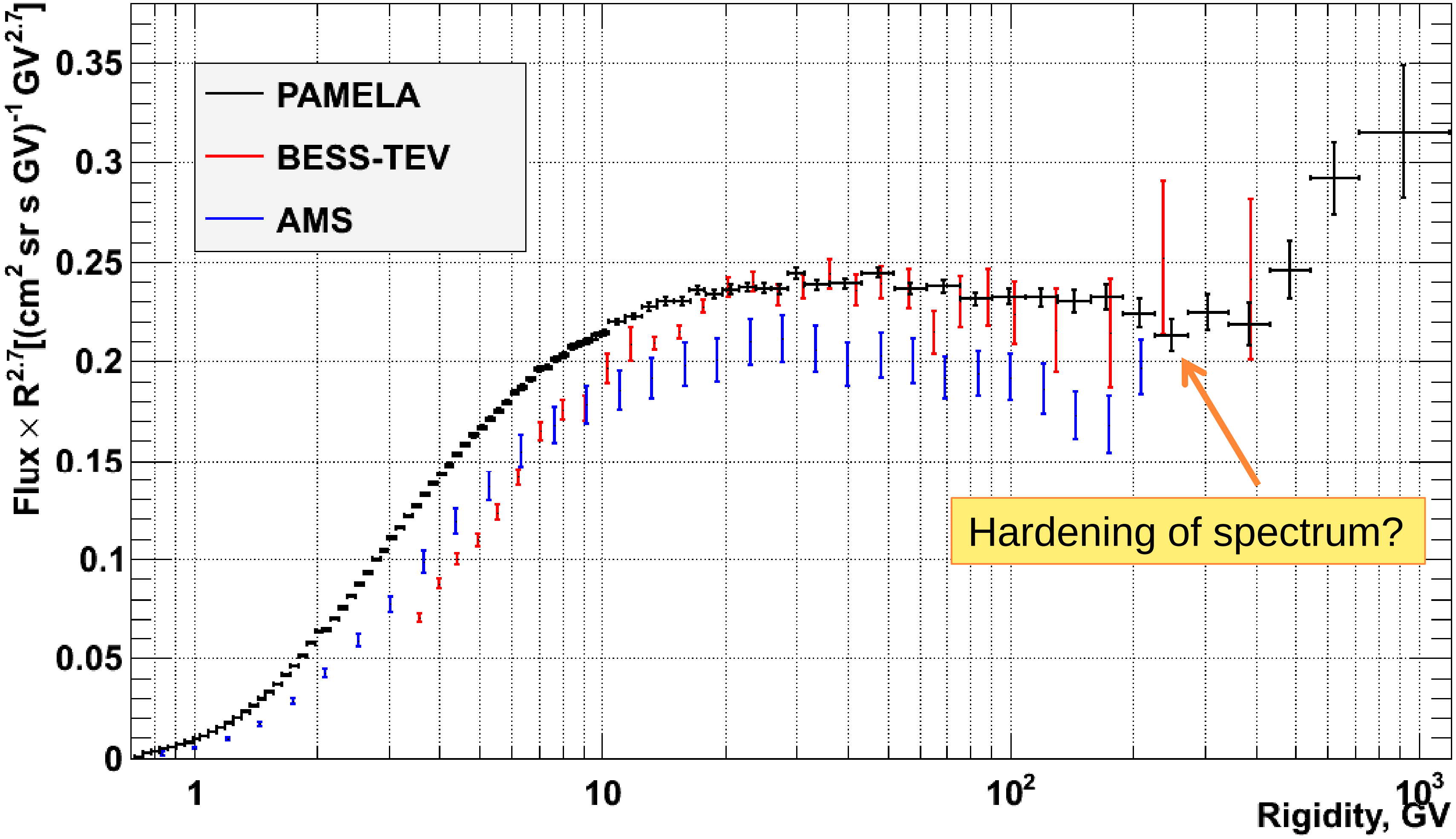


PAMELA Helium flux



PAMELA Helium flux

RED:BESS-Tev, BLUE:AMS, BLACK: PAMELA

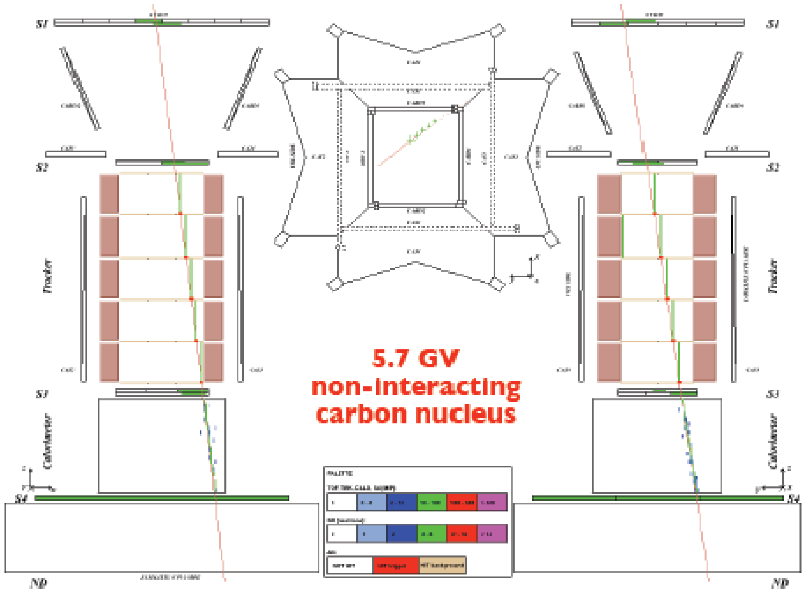


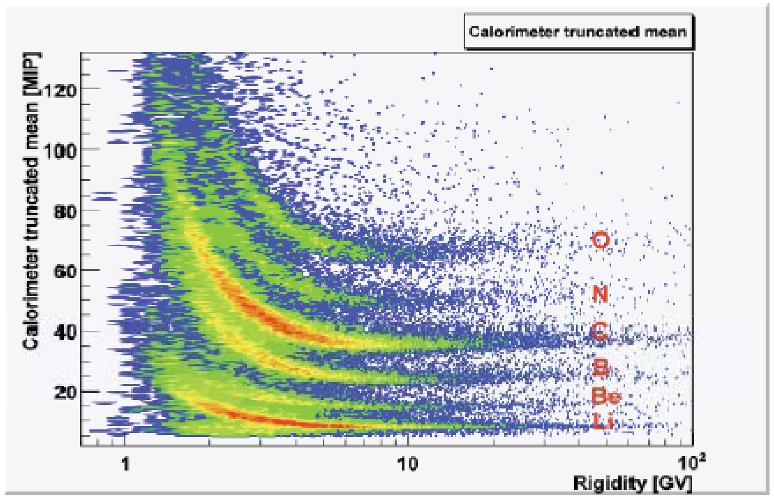
PAMELA SECONDARY/PRIMARY NUCLEI RATIOS

- **Important input to secondary production + propagation models**
  - Secondary to primary ratios:
    - B / C
    - Be / C
    - Li / C
  - Helium and hydrogen isotopes:
    - ^{3}He / ^{4}He
    - d / He

Currently collected (data analyzed until Dec. 2008):

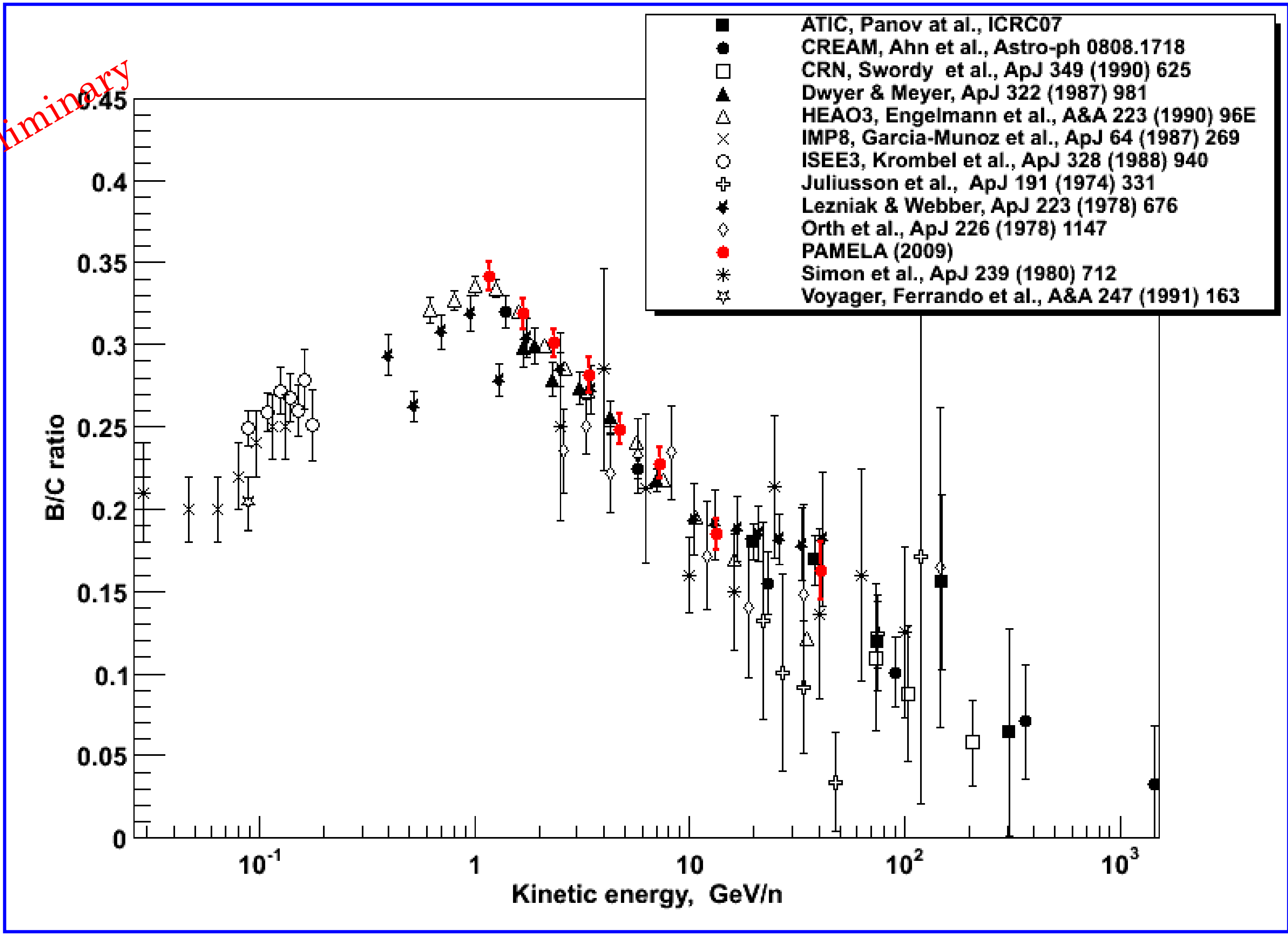
120.000 C nuclei
70.000 B nuclei



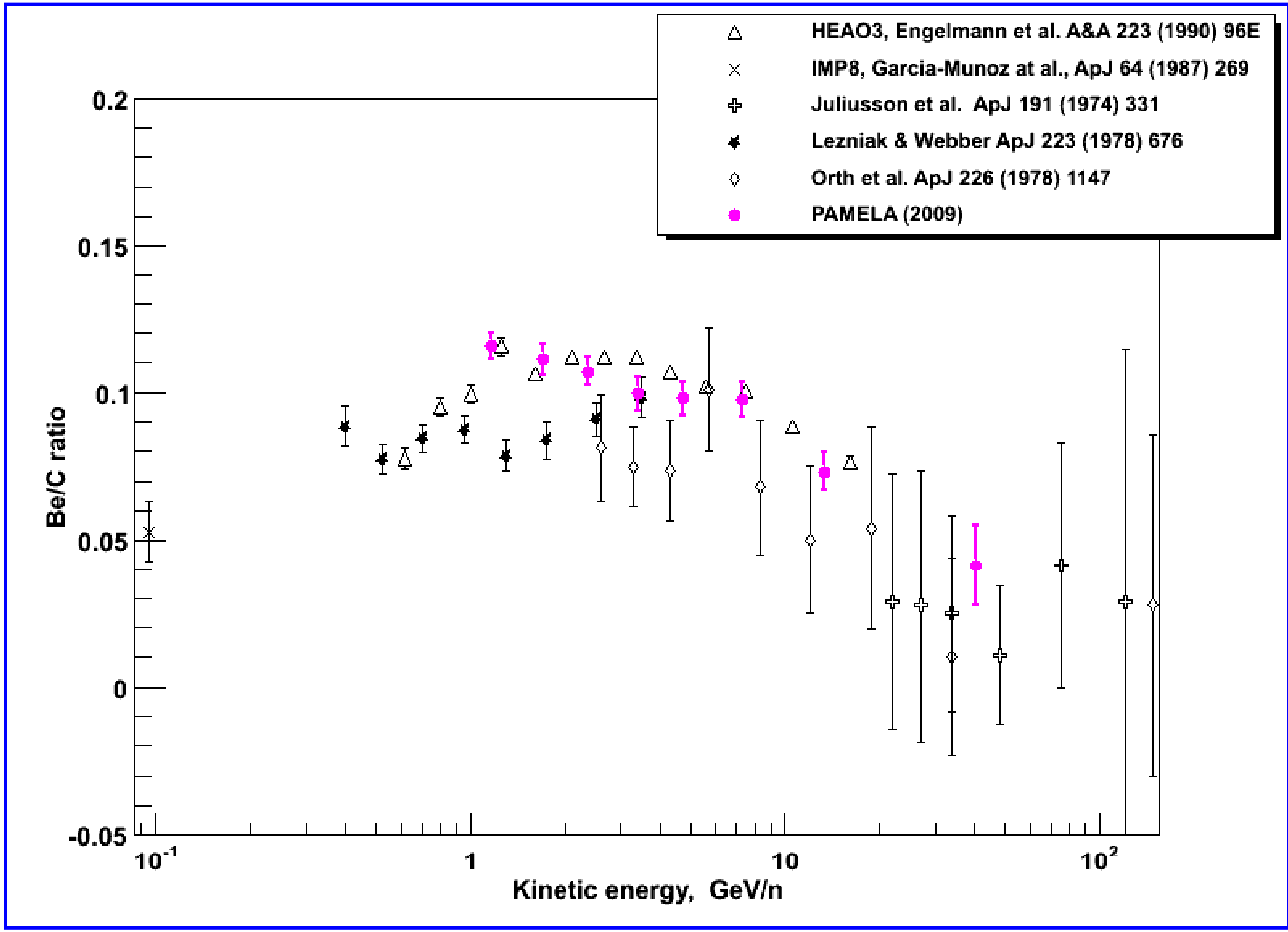


Truncated mean of multiple dE/dx measurements in different silicon planes

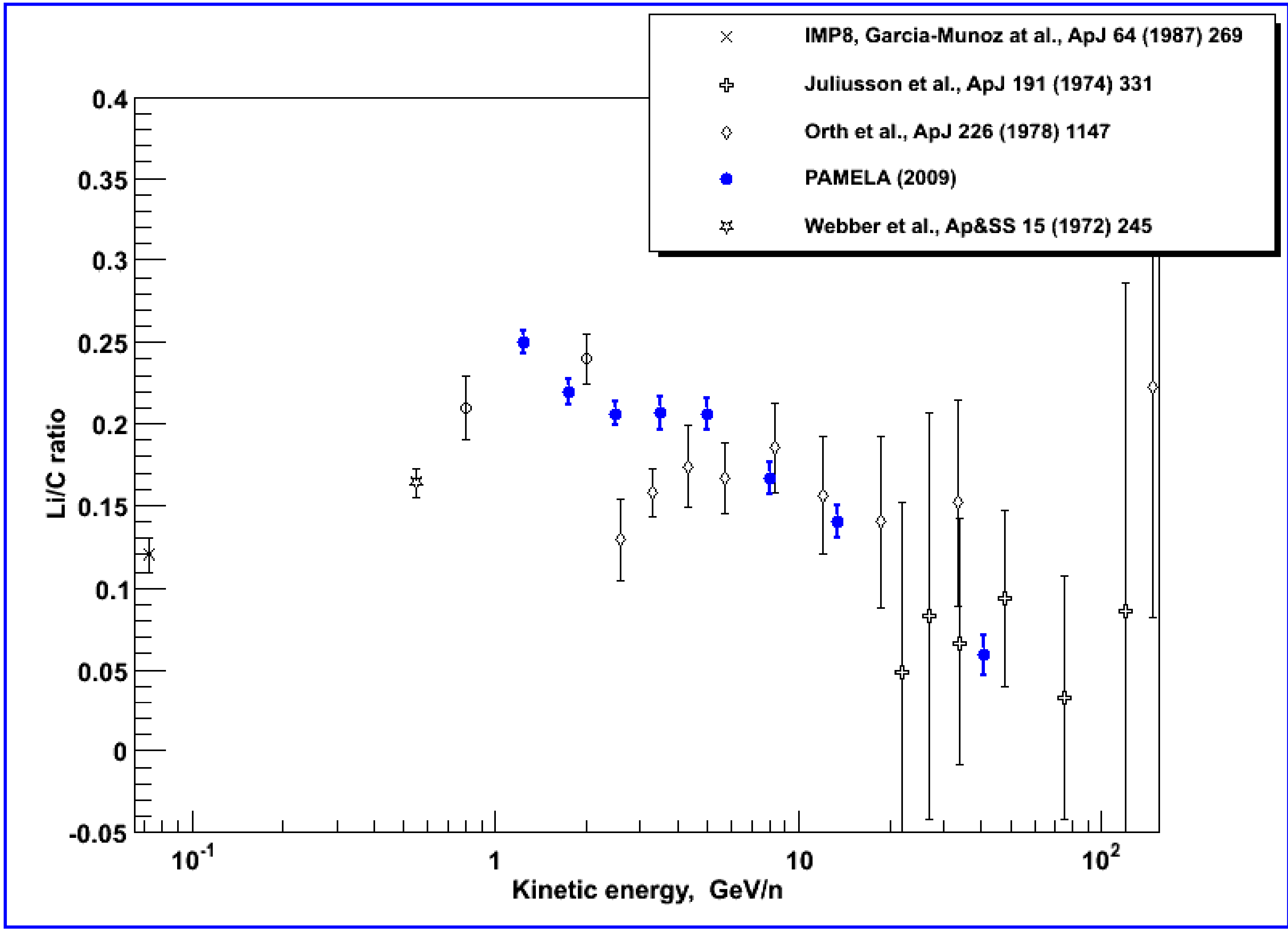
PAMELA SECONDARY/PRIMARY: B/C



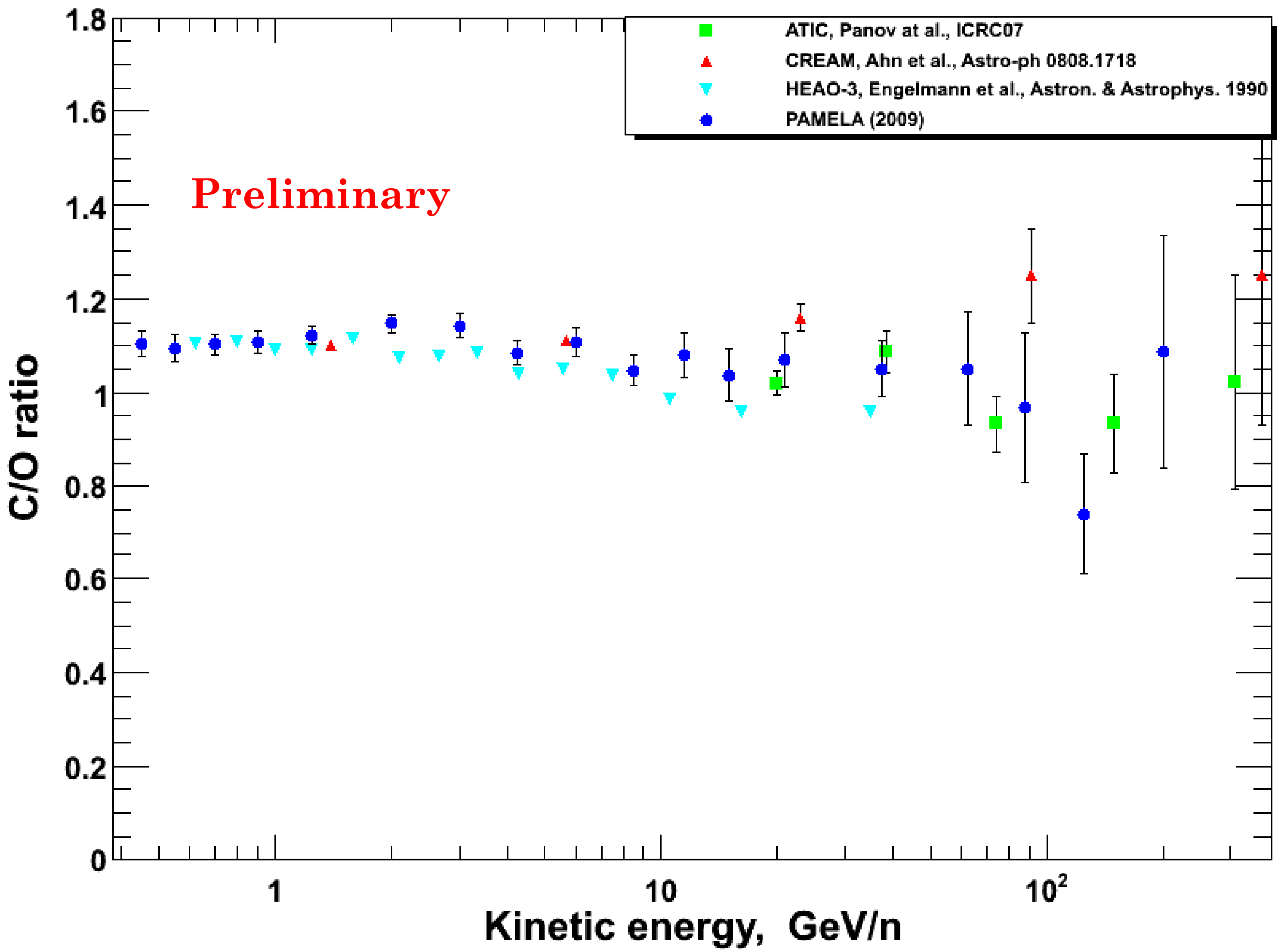
PAMELA SECONDARY/PRIMARY: BE/C



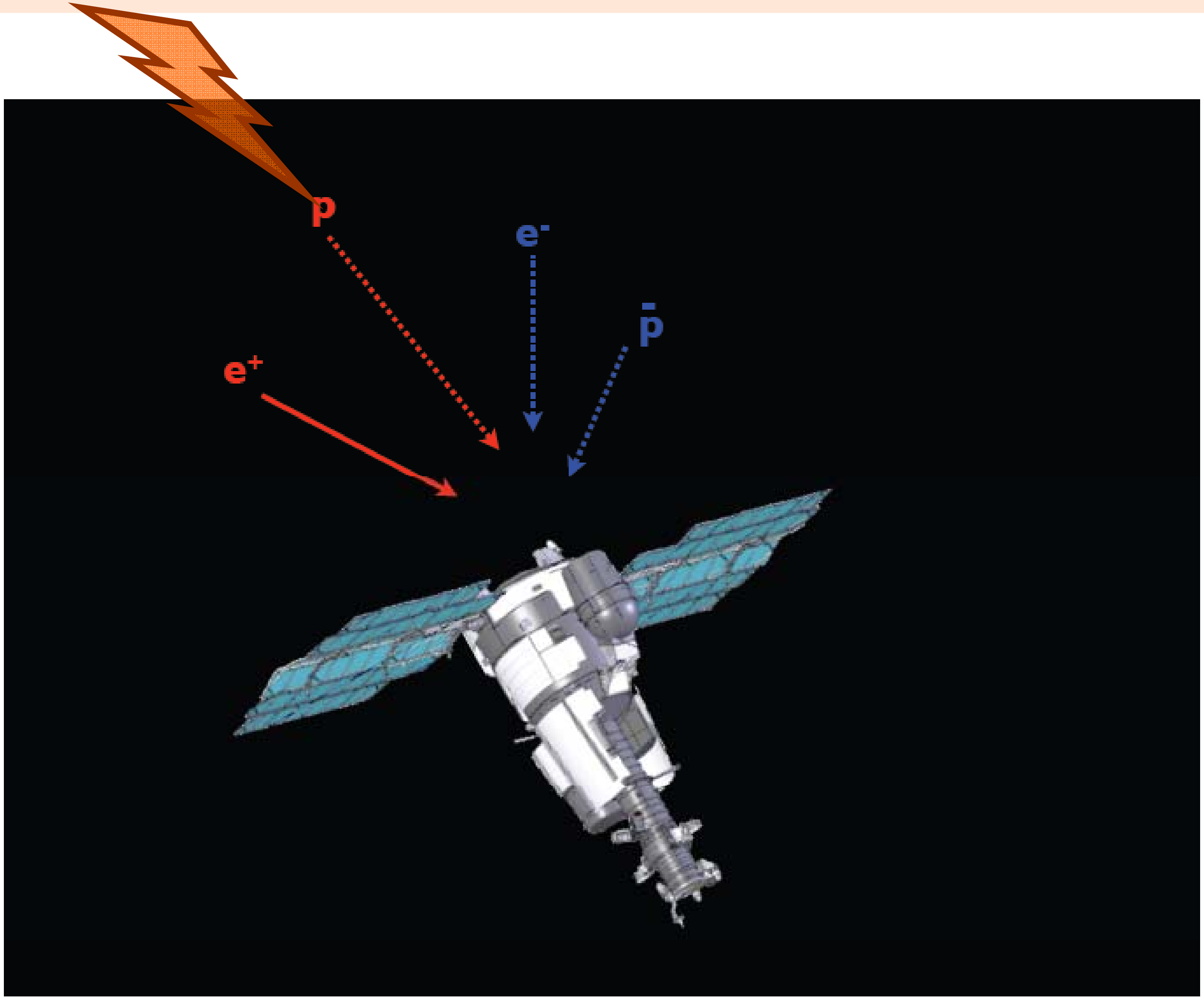
PAMELA SECONDARY/PRIMARY: LI/C



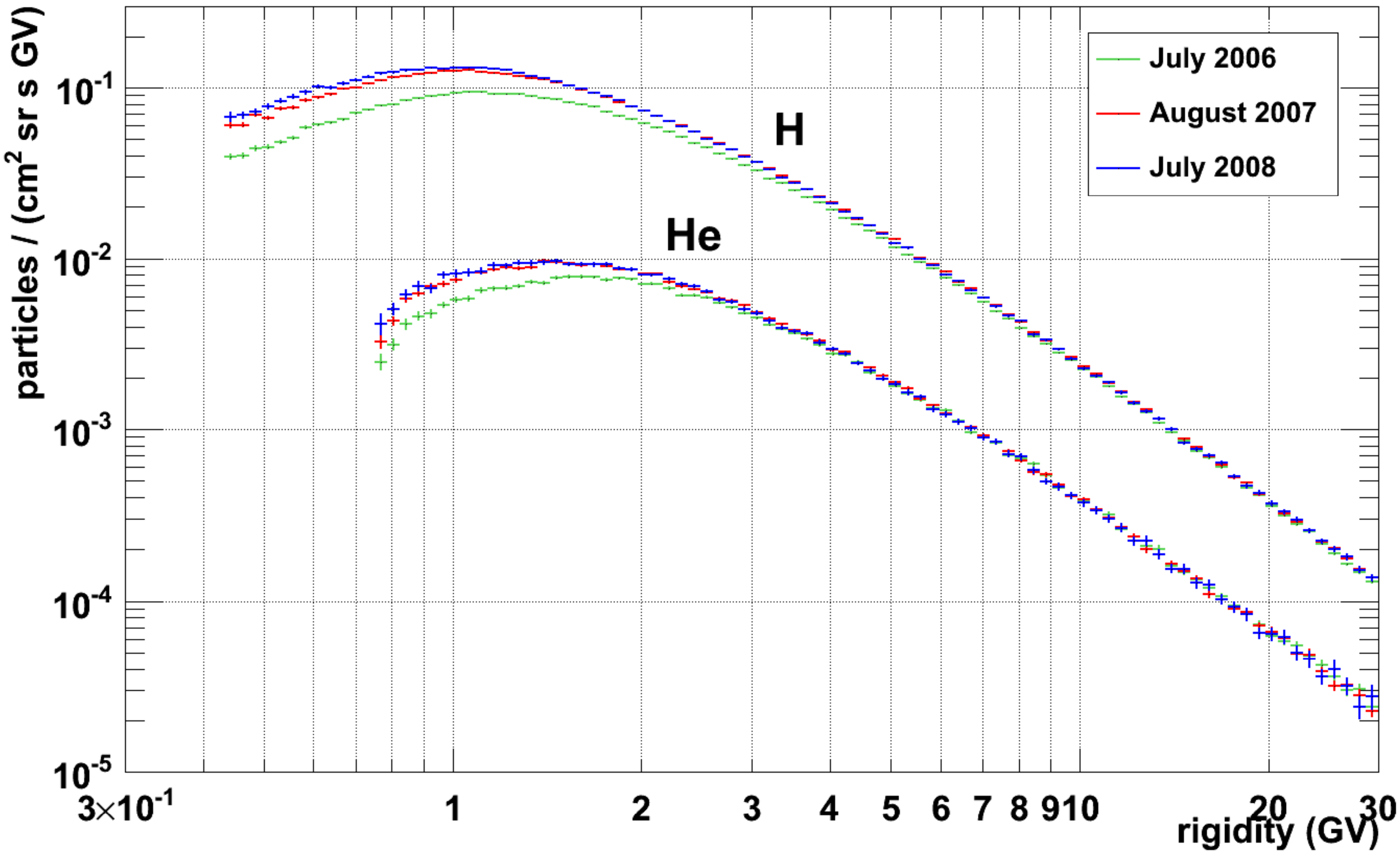
C/O RATIO


ATIC, Panov at al., ICRC07
CREAM, Ahn et al., Astro-ph 0808.1718
HEAO-3, Engelmann et al., Astron. & Astrophys. 1990
PAMELA (2009)
Preliminary
C/O ratio
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
10
10^2
Kinetic energy, GeV/n

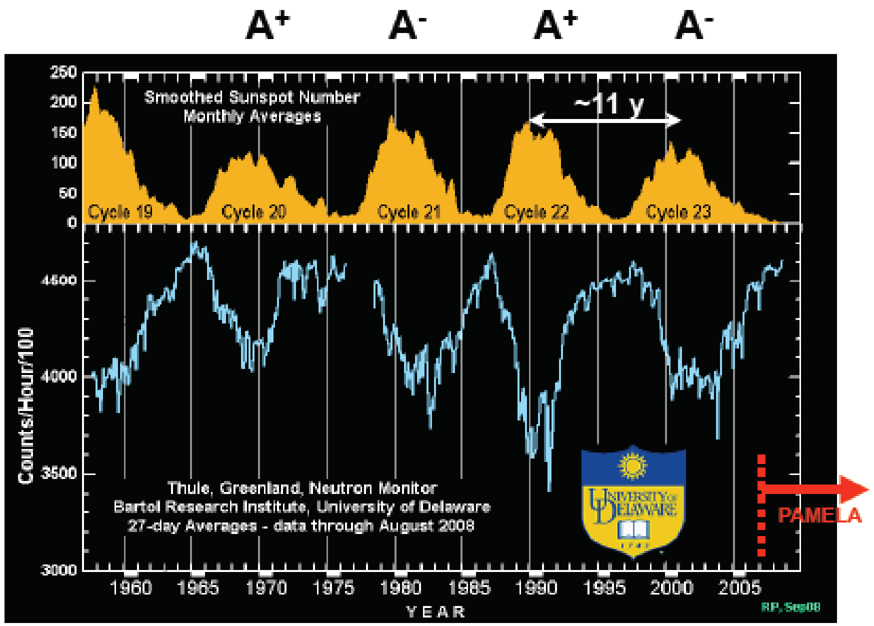
HELIOSPHERE AND MAGNETOSPHERE

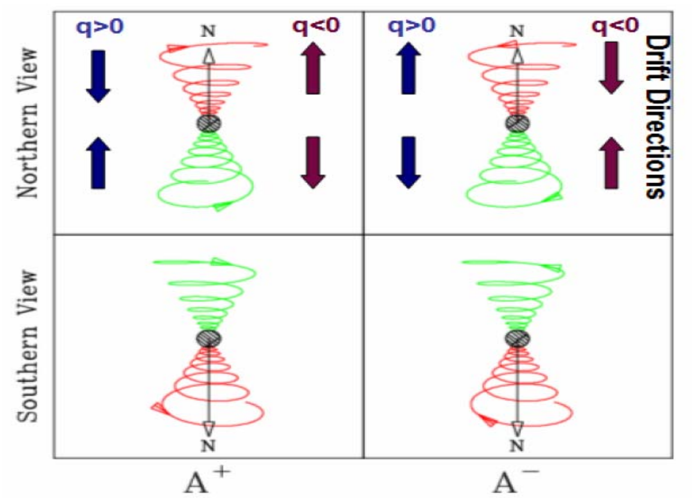


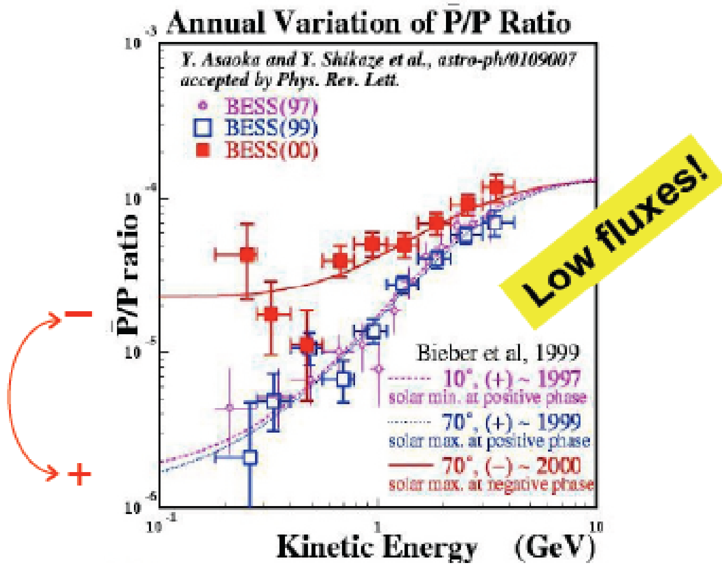
SOLAR MODULATION

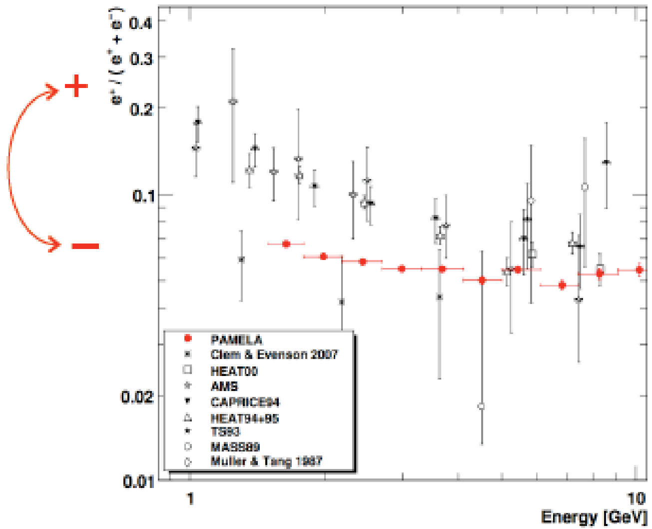


LOW ENERGY e^+: CHARGE DEPENDENT SOLAR MODULATION EFFECTS

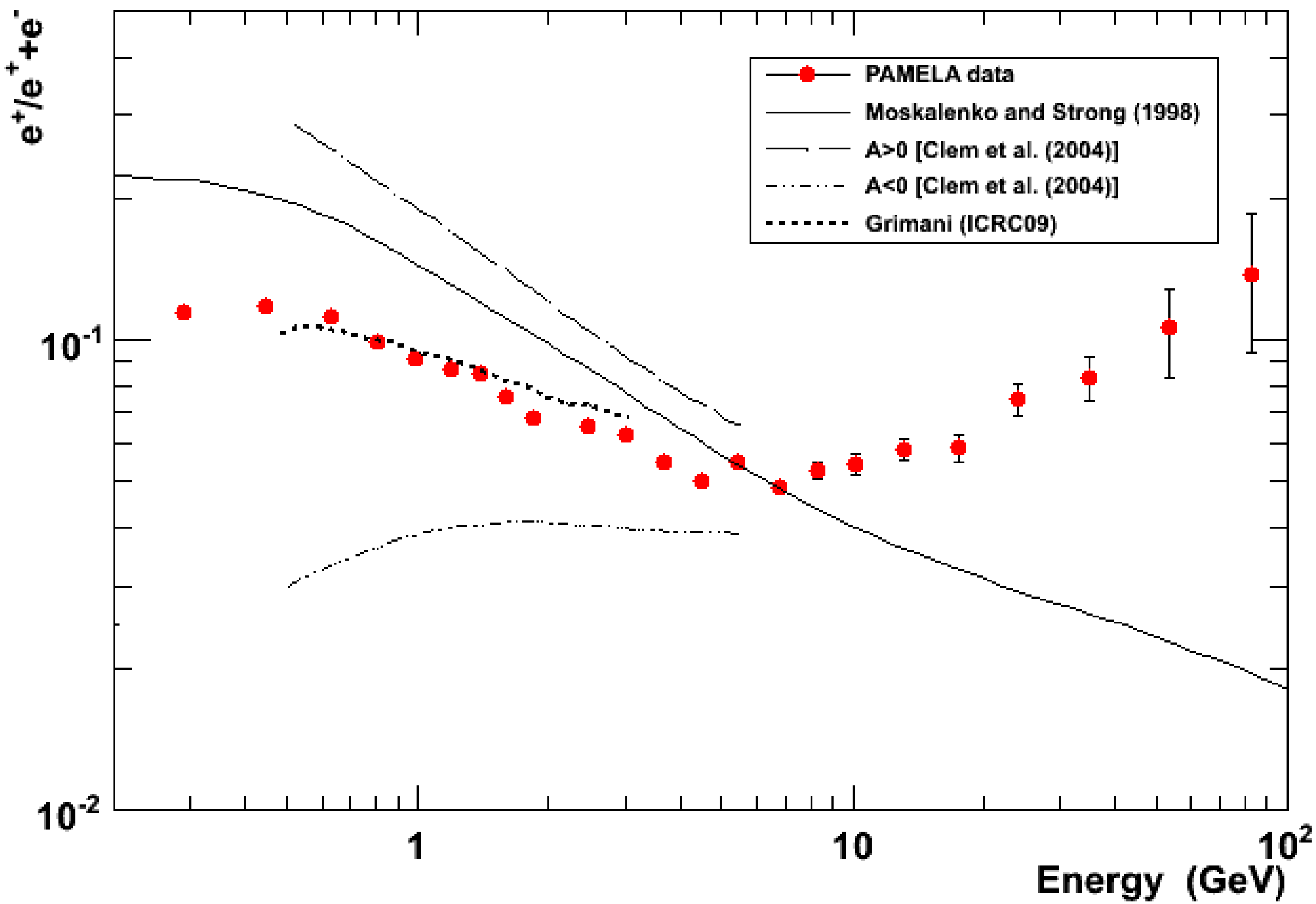






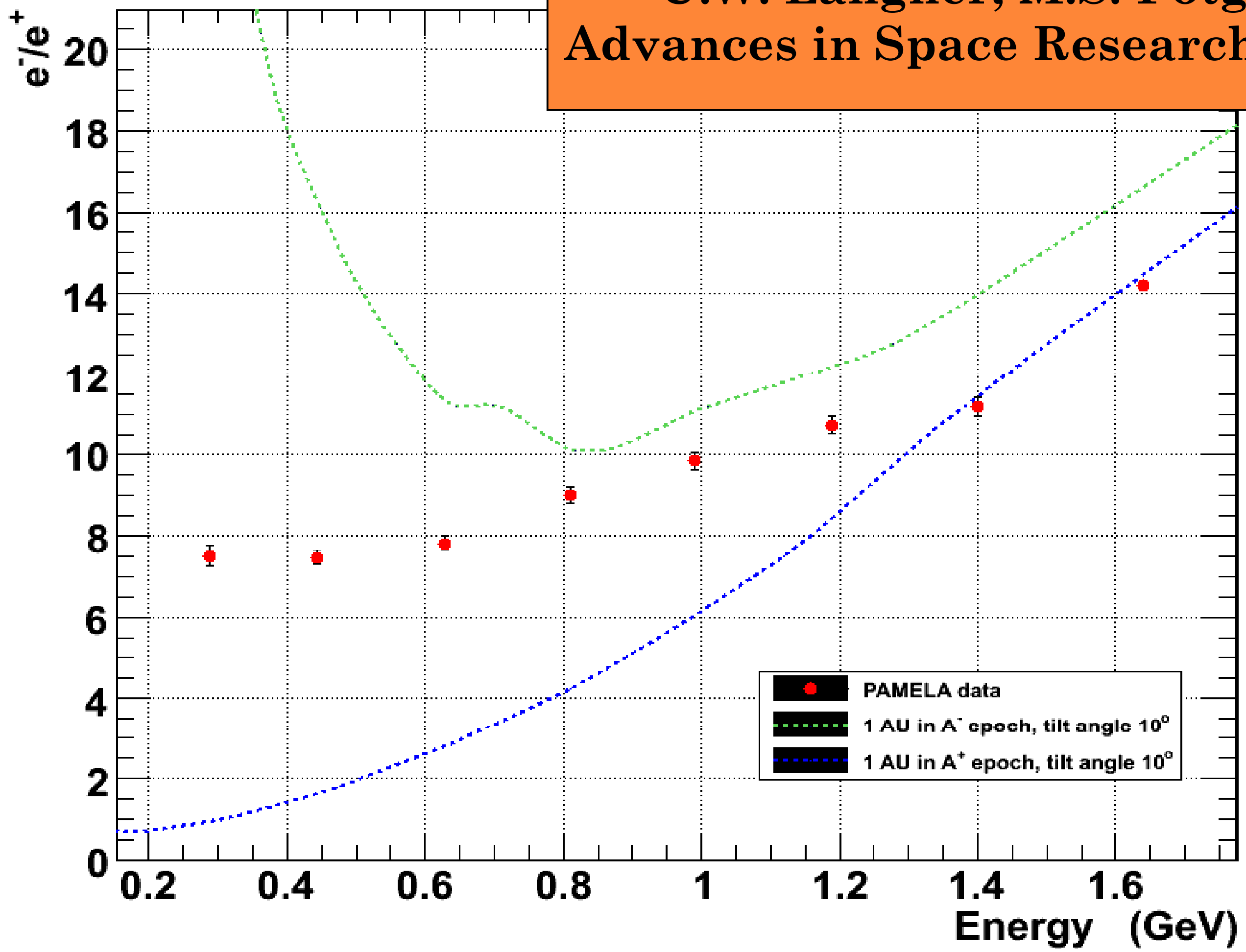


CHARGE-DEPENDENT SOLAR MODULATION IN THE POSITRON FRACTION



PAMELA ELECTRON-TO-POSITRON RATIO AND THEORETICAL MODELS

U.W. Langner, M.S. Potgieter, Advances in Space Research 34 (2004)



Jointy work with M. Potgieter's group in South-Africa going on

PHYSICS OF THE MAGNETOSPHERE

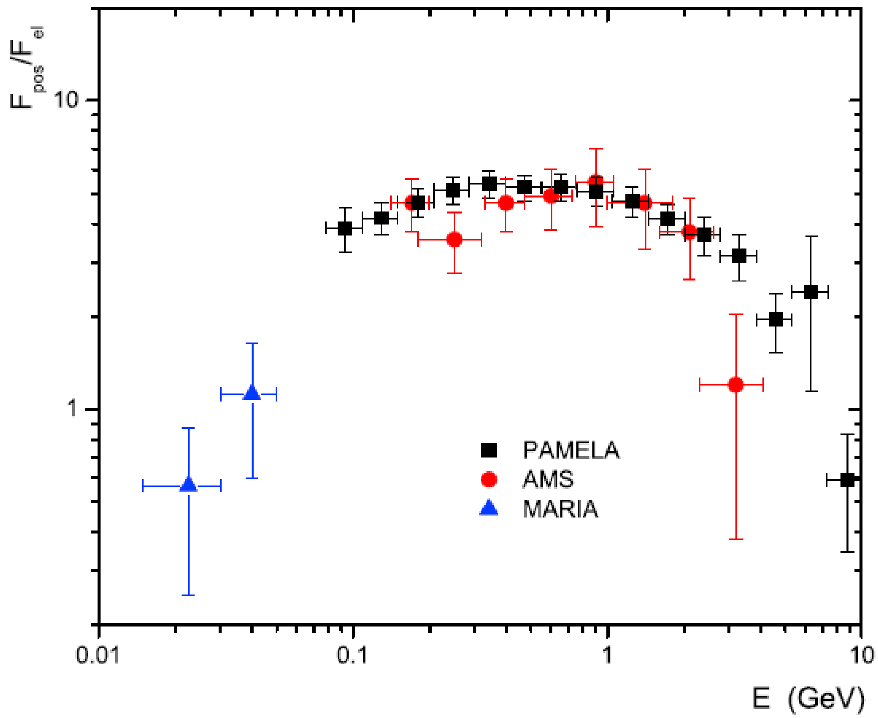


Figure 4. Measurements of the positron to electron flux ratio in the equatorial region (L shell < 1.2; B shell > 0.23 G).

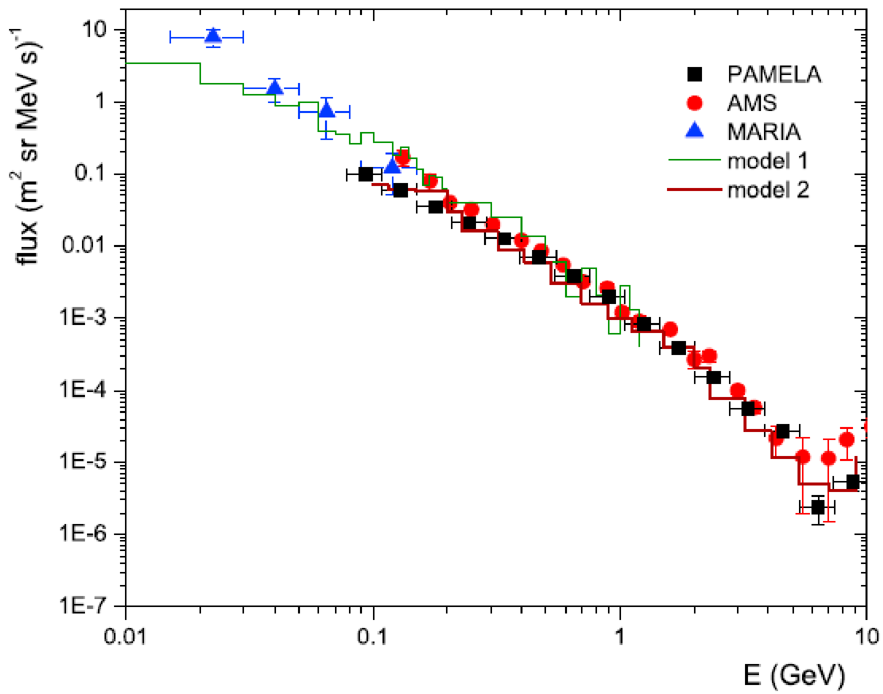
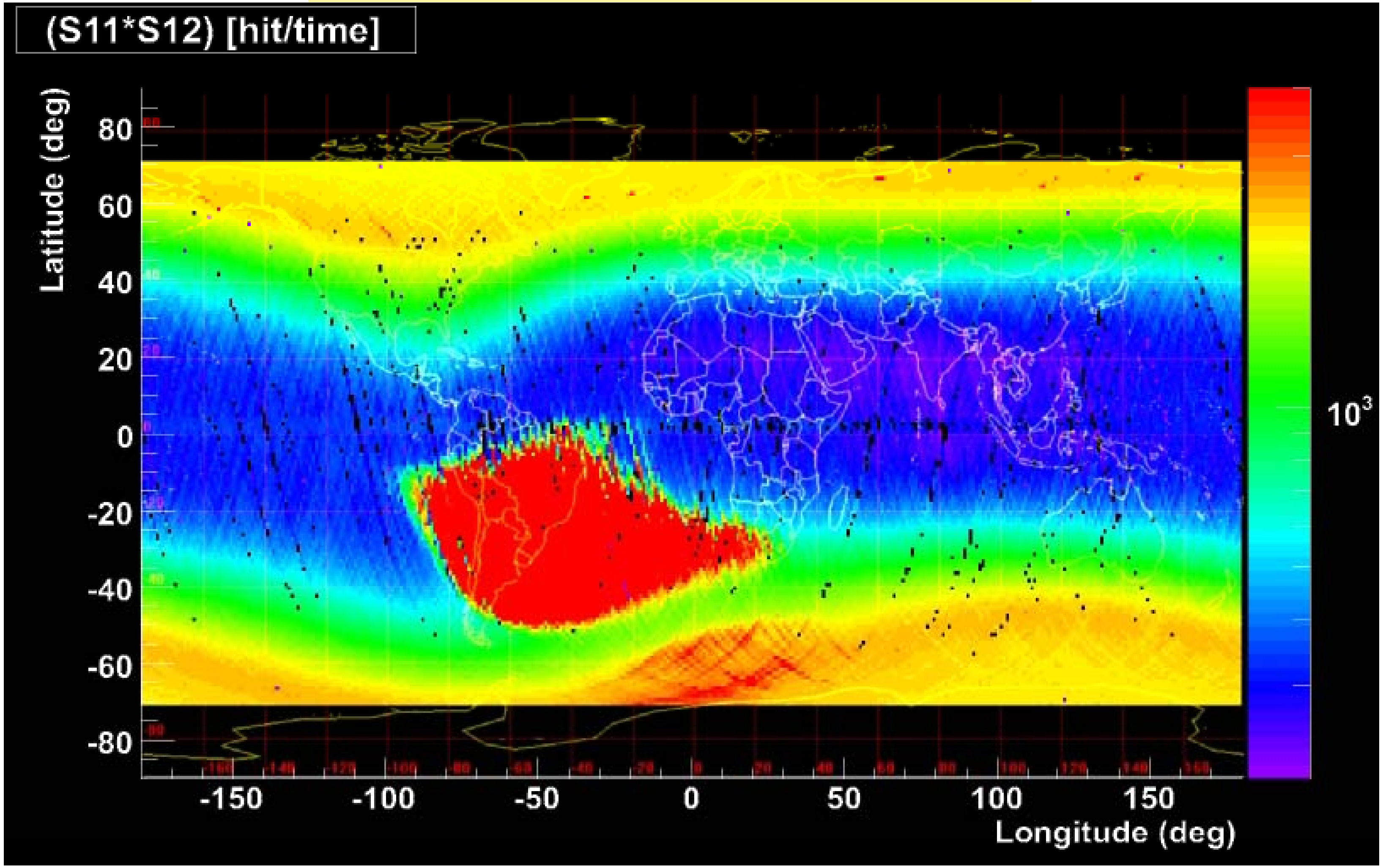


Figure 6. The differential energy spectrum of quasi-trapped electrons. The PAMELA result is compared to other measurements and theoretical models. Model 1, *Koldashov et al.* [1995]; model 2, *Derome et al.* [2001].

Measurements of quasi-trapped electron and positron fluxes with PAMELA
Journal of Geophysical Research, 114, A12, pag. A12218, 2009

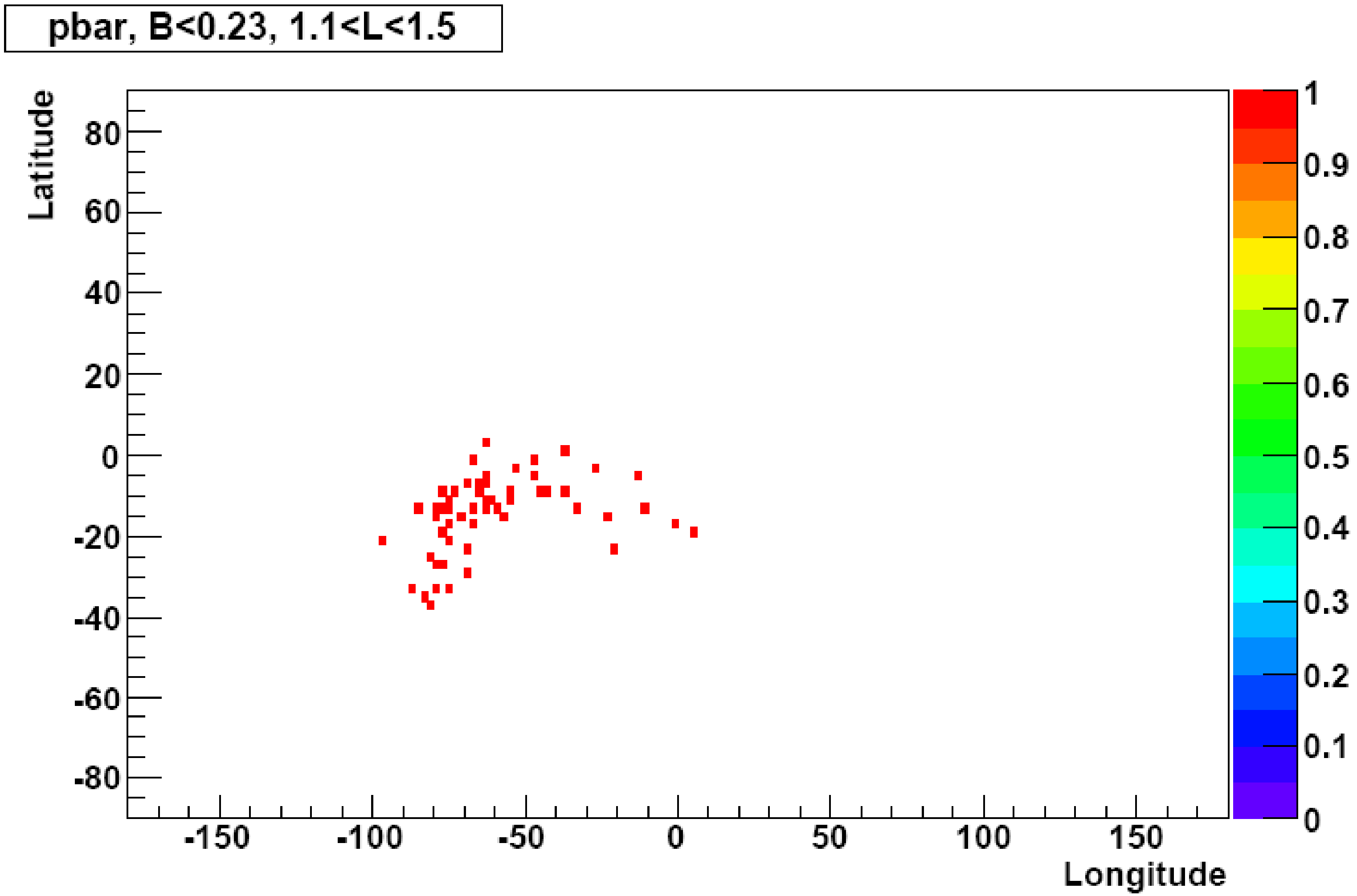
PHYSICS OF THE MAGNETOSPHERE

Pamela World Map: 350 – 650 km alt



36 MeV p, 3.5 MeV e-

Subcutoff Antiprotons in SAA



SUMMARY

- **PAMELA** has been in orbit and studying cosmic rays for ~44 months. $>10^9$ triggers registered, anc >19 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).

- **Low energy positron fraction** (~1.5 - ~5 GeV) shows solar modulation effects. Excellent statistics!

- **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).

http://pamela.roma2.infn.it

SUMMARY

Interesting features in cosmic ray data seen by PAMELA in last months' analysis:

- **Electron flux:** spectrum up to ~200 GeV shows 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 and e^+ spectrum up to ~300 GeV (all electrum (e-+ e+) spectrum up to ~1 TV).

- **Proton and Helium fluxes**: hardening of the spectrum at high energies:
  - Effects of propagation and reacceleration?
  - Harder spectral sources?
  - Possible hadron sources (seen by other experiments as anisotropies?)

Other measurements under study:

- New antiHe limits
- Strange matter (particles with high A/Z)
- Solar flares