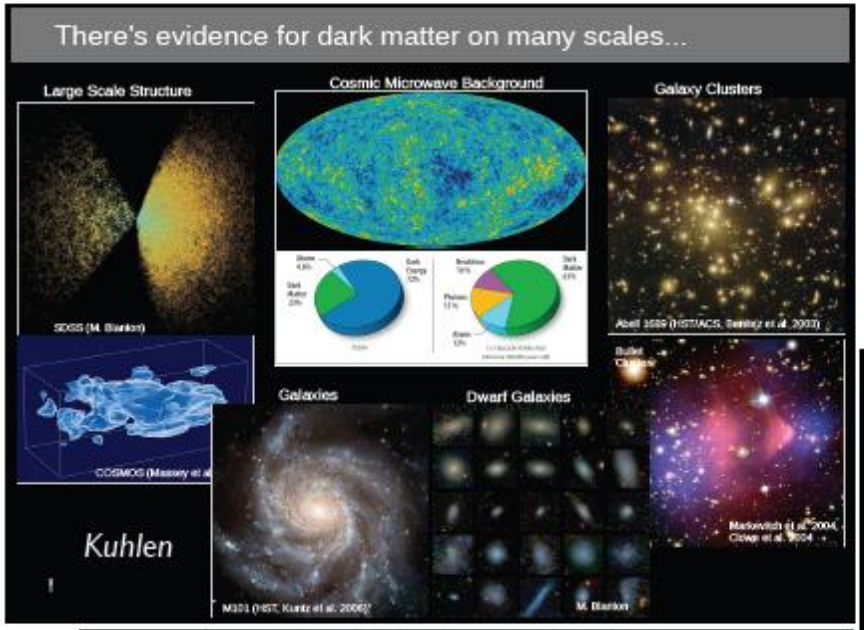
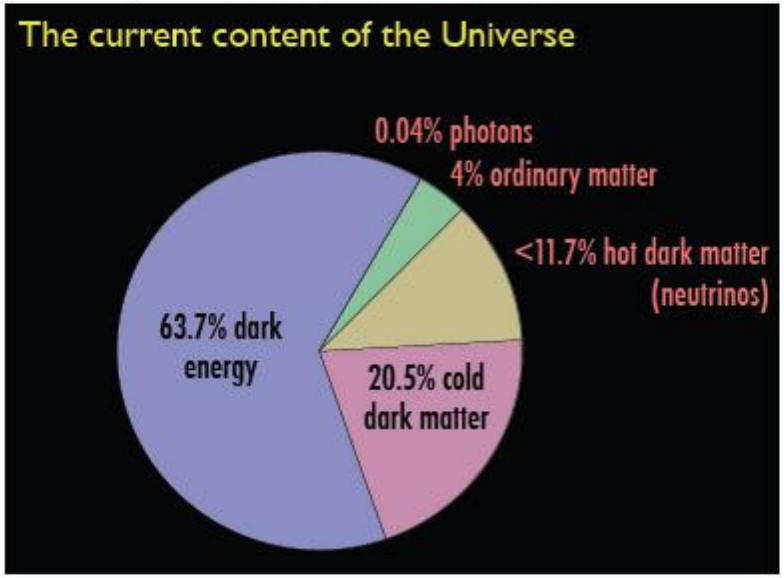
Understanding Cosmic Rays and Searching for Dark Matter with PAMELA

Roberta Sparvoli for the PAMELA Collaboration

University of Rome Tor Vergata and INFN

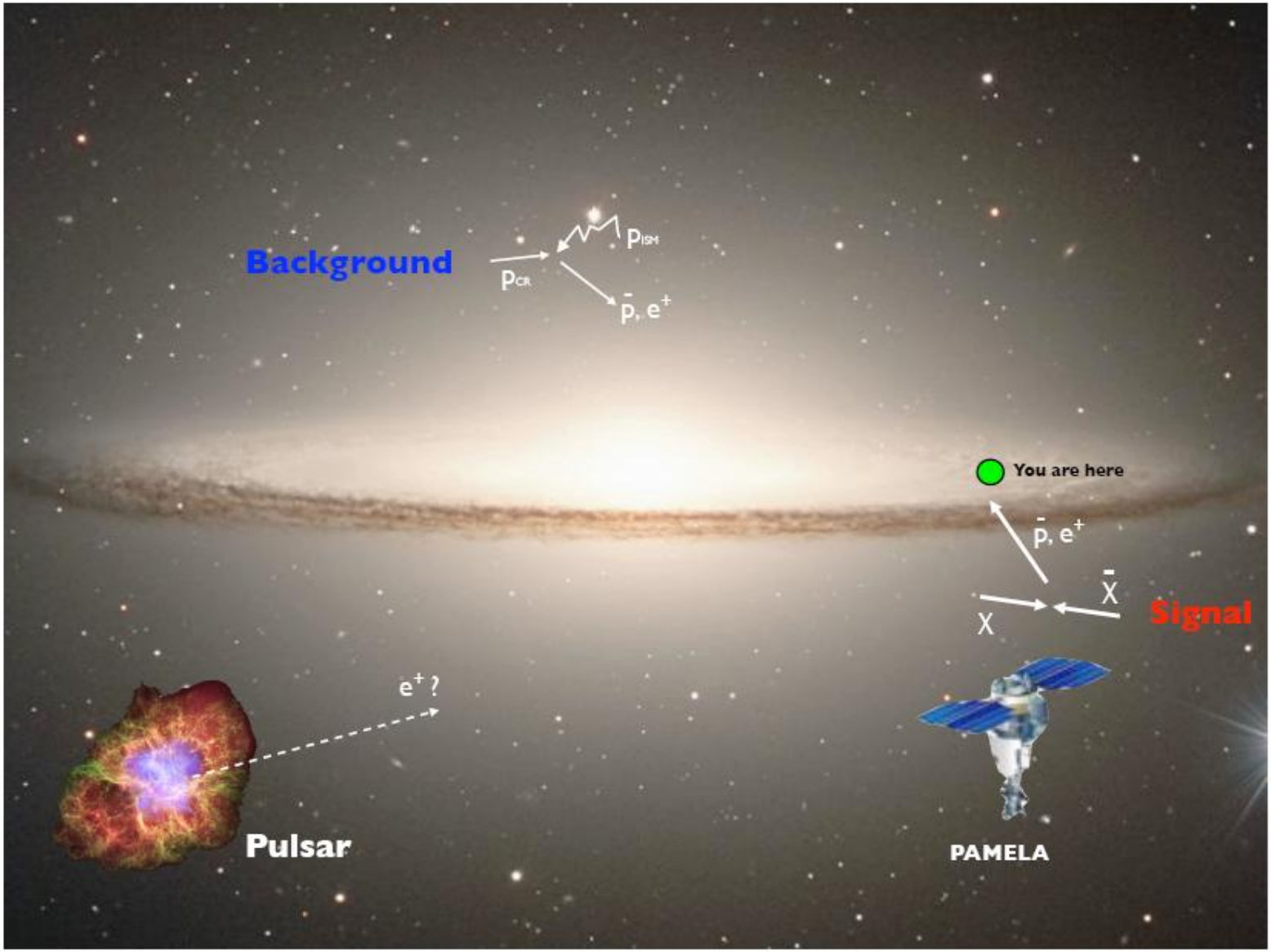
Dark Matter searches





P. Gondolo, **IDM 2008**

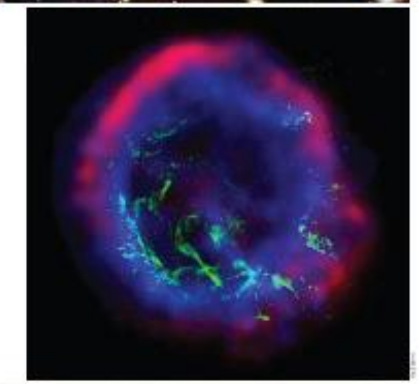
EXPECTED DM SIGNALS

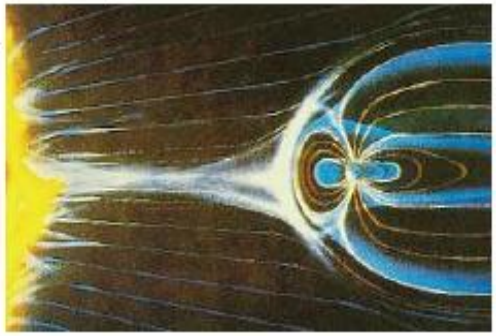


Deviations of the antiparticle spectra wrt secondary production

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)

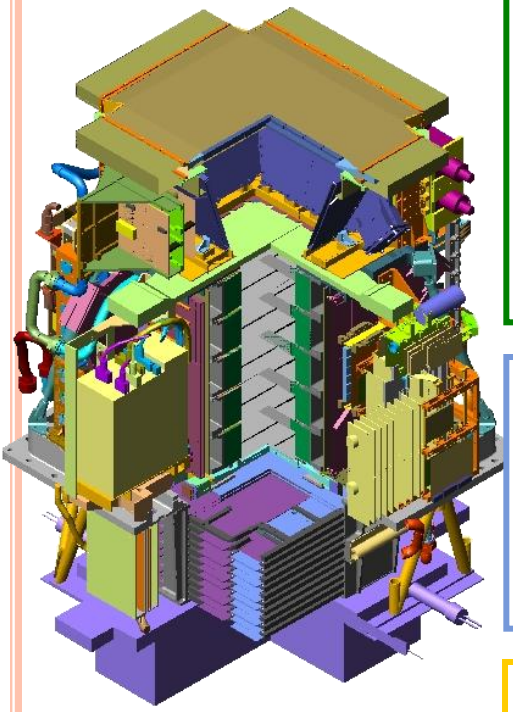
	energy range	particles in 3 years
Antiprotons	**80 MeV ÷190 GeV**	$O(10^4)$
Positrons	**50 MeV ÷ 270 GeV**	$O(10^5)$
Electrons	up to 400 GeV	$O(10^6)$
Protons	up to 700 GeV	$O(10^8)$
Electrons+positrons	up to 2 TeV	(from calorimeter)
Light Nuclei	up to 200 GeV/n	He/Be/C: $O(10^{7/4/5})$
Anti-Nuclei search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

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

PAMELA DETECTORS

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

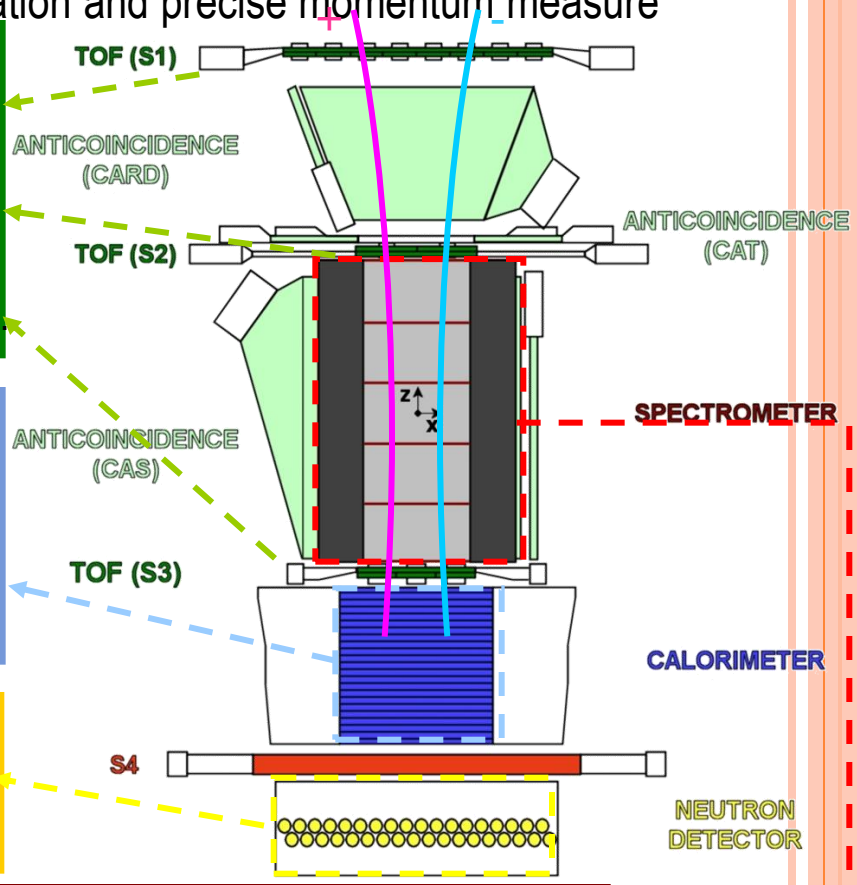


GF: 21.5 cm^2 sr
Mass: 470 kg
Size: 130x70x70 cm^3
Power Budget: 360W

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

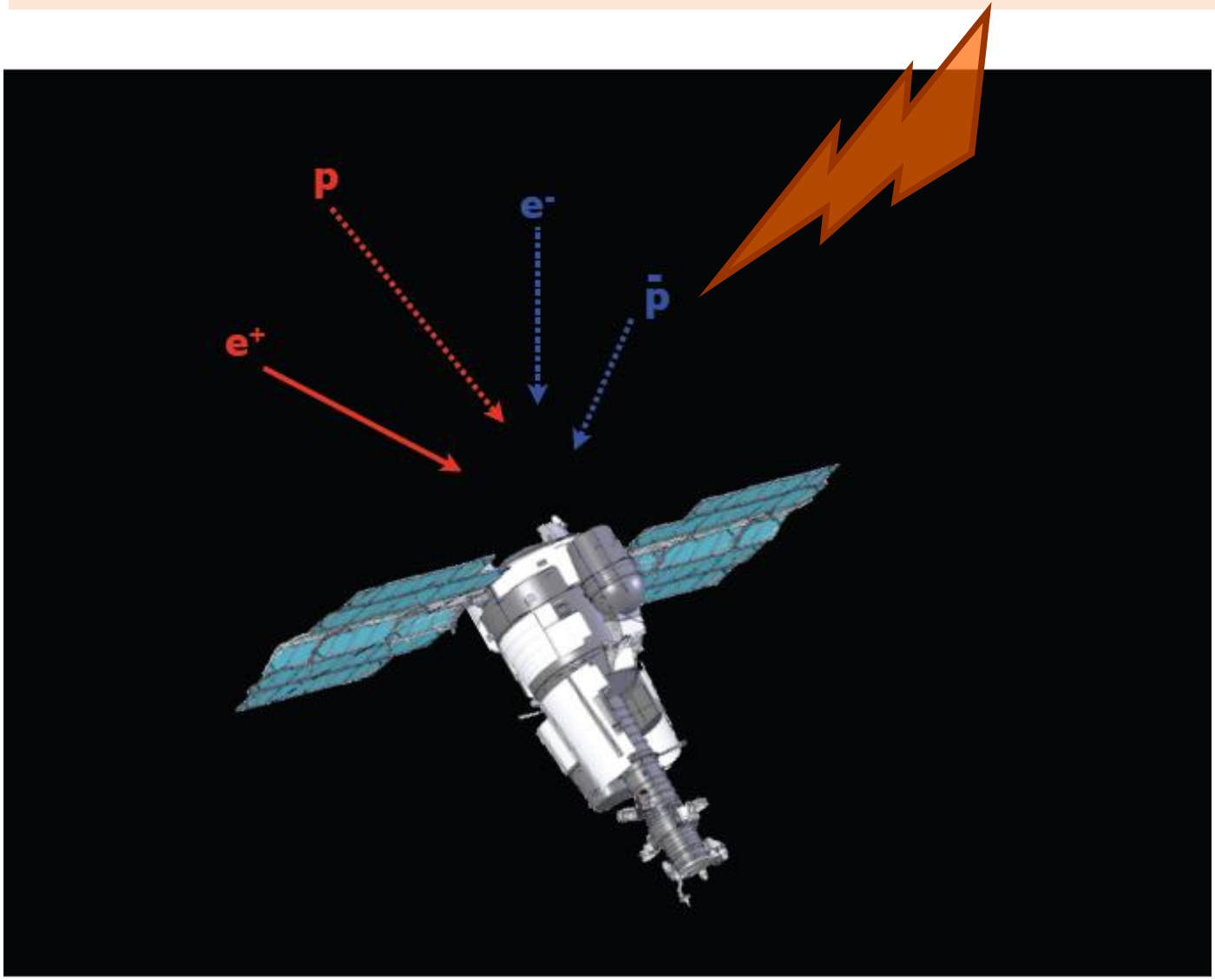
Electromagnetic calorimeter
W/Si sampling (16.3 X0, 0.6 λI)
- Discrimination e+ / p, anti-p / e^- (shower topology)
- Direct E measurement for e^-

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



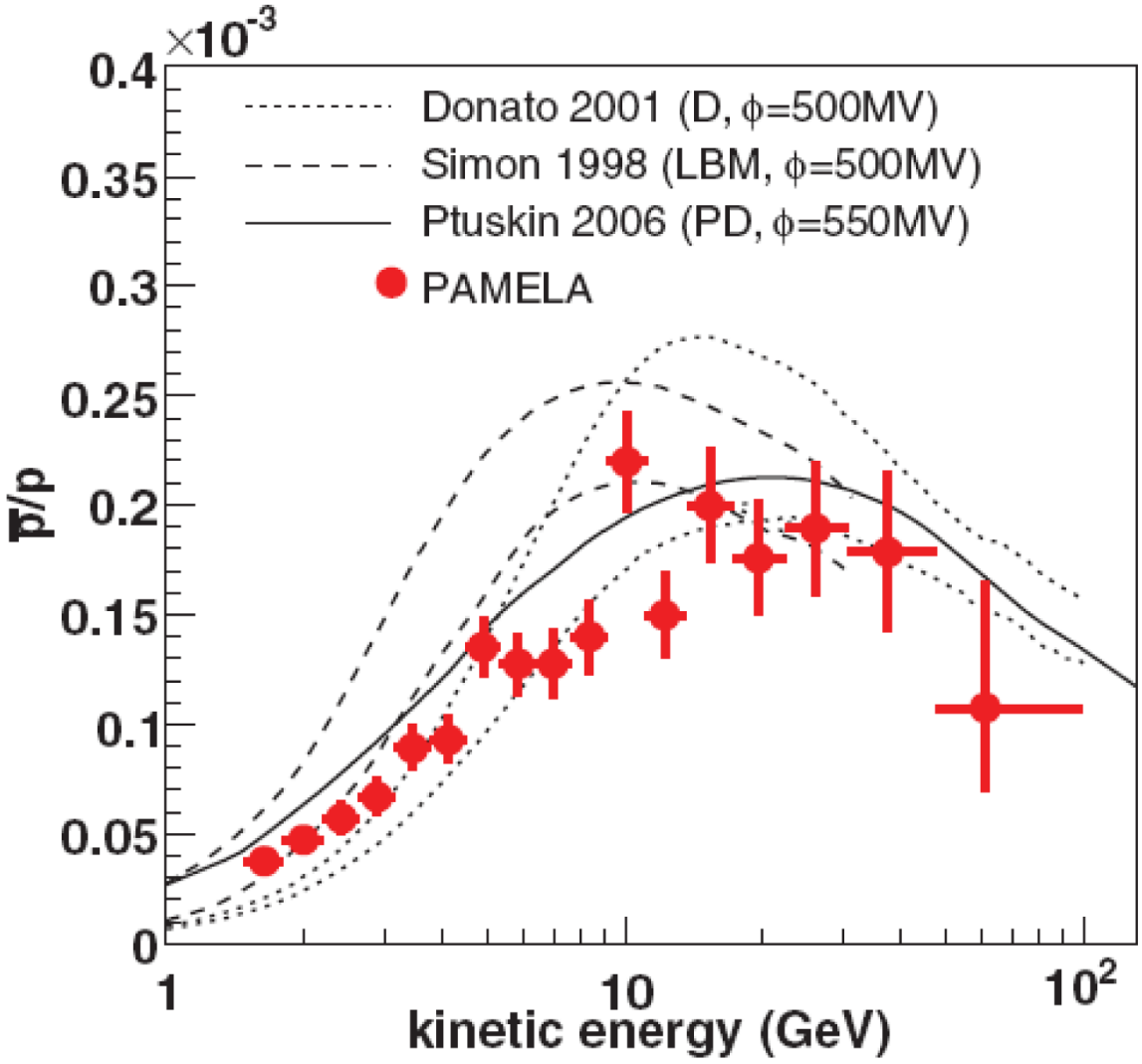
Spectrometer
microstrip silicon tracking system + permanent magnet
It provides:
- *Magnetic rigidity* → R = pc/Ze
- *Charge sign*
- *Charge value from dE/dx*

Antiprotons



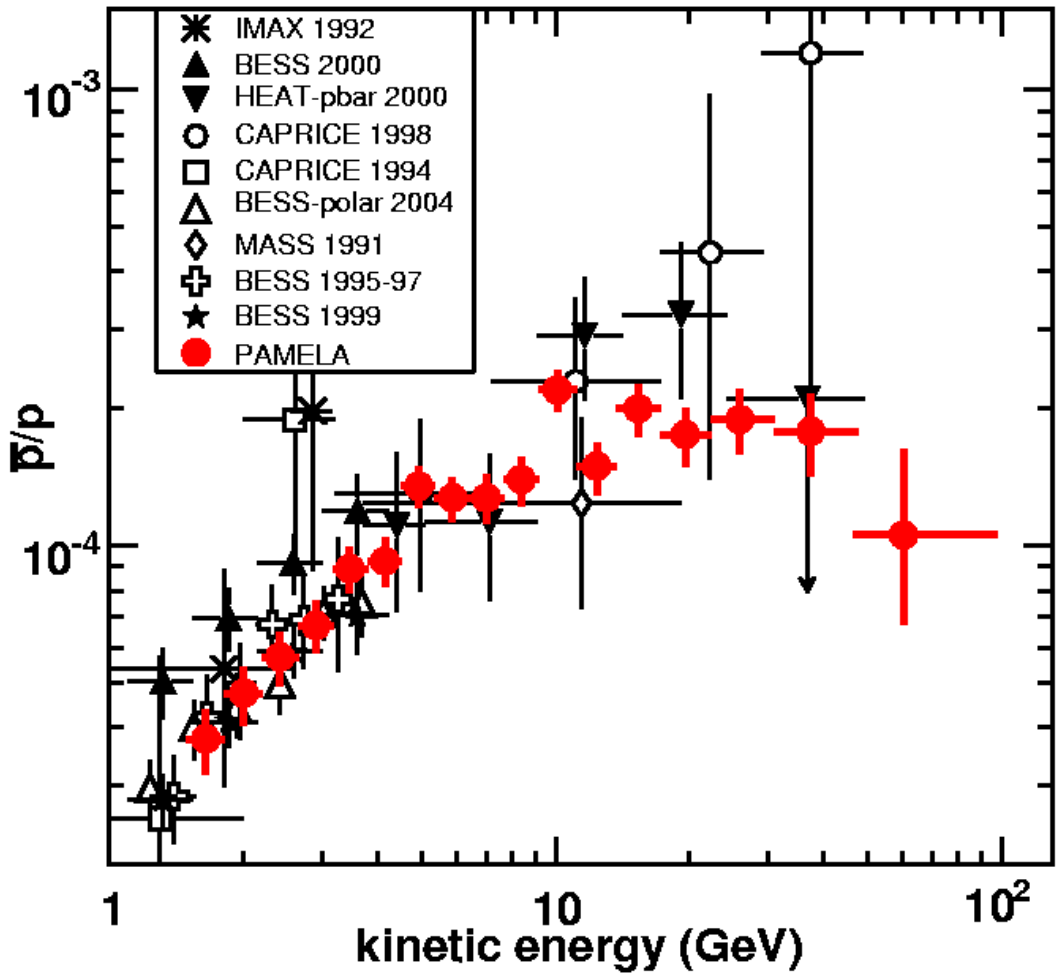
PAMELA: ANTIPROTON-TO-PROTON RATIO

PRL 102, 051101 (2009)



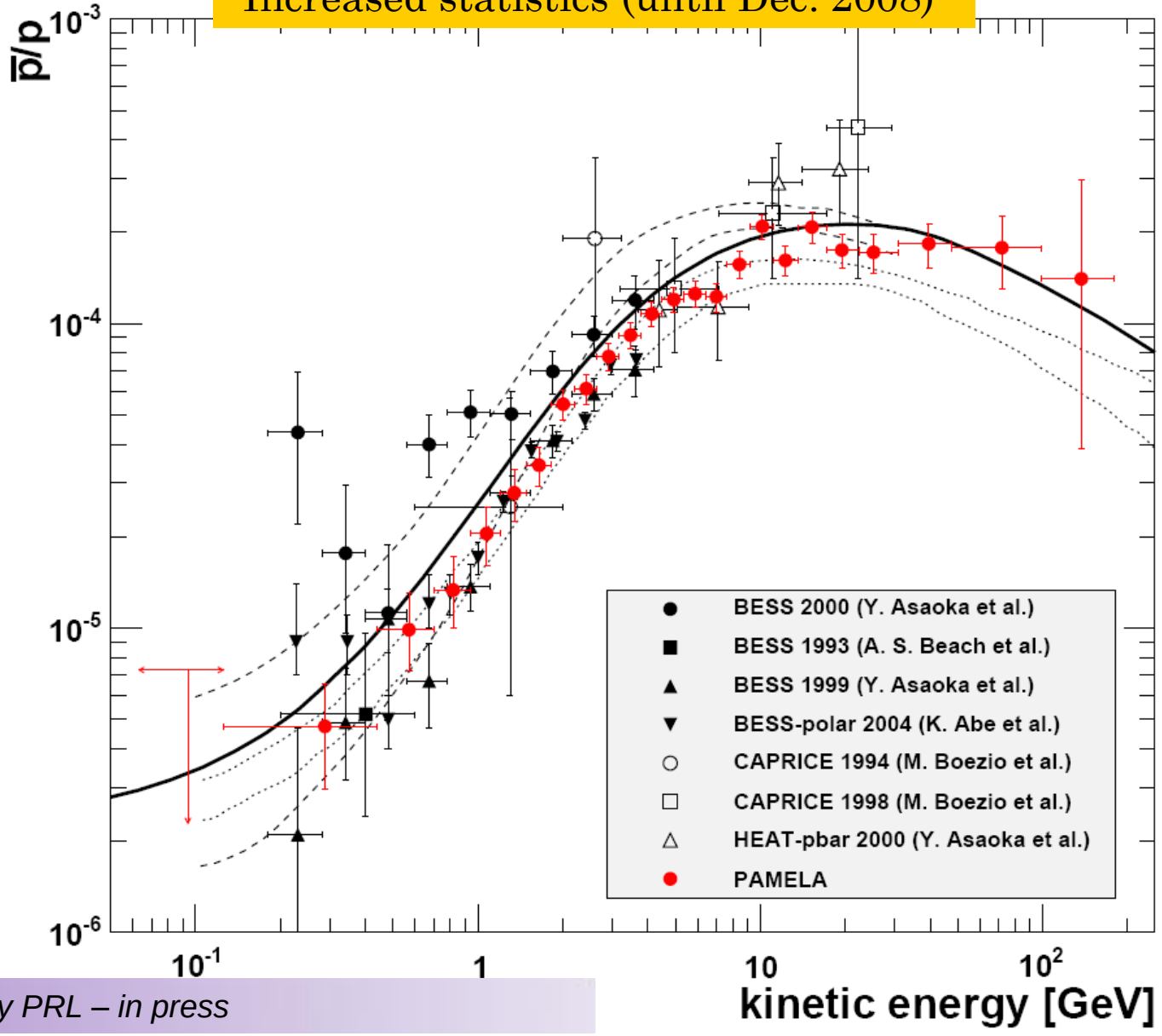
PAMELA: Antiproton-to-proton ratio

PRL 102, 051101 (2009)



ANTIPROTON-TO-PROTON RATIO: NEW DATA

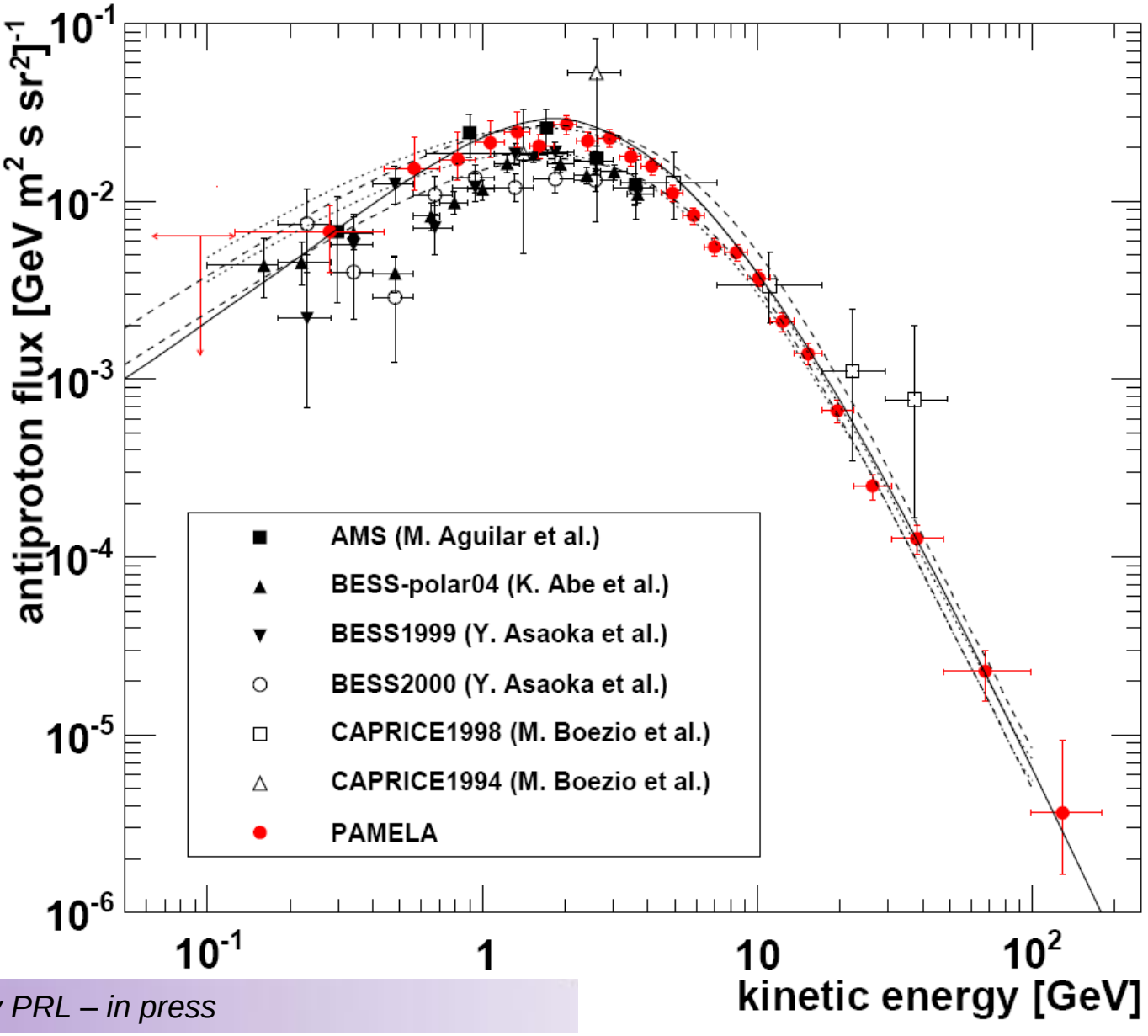
Increased statistics (until Dec. 2008)



Accepted by PRL – in press

Antiproton Flux

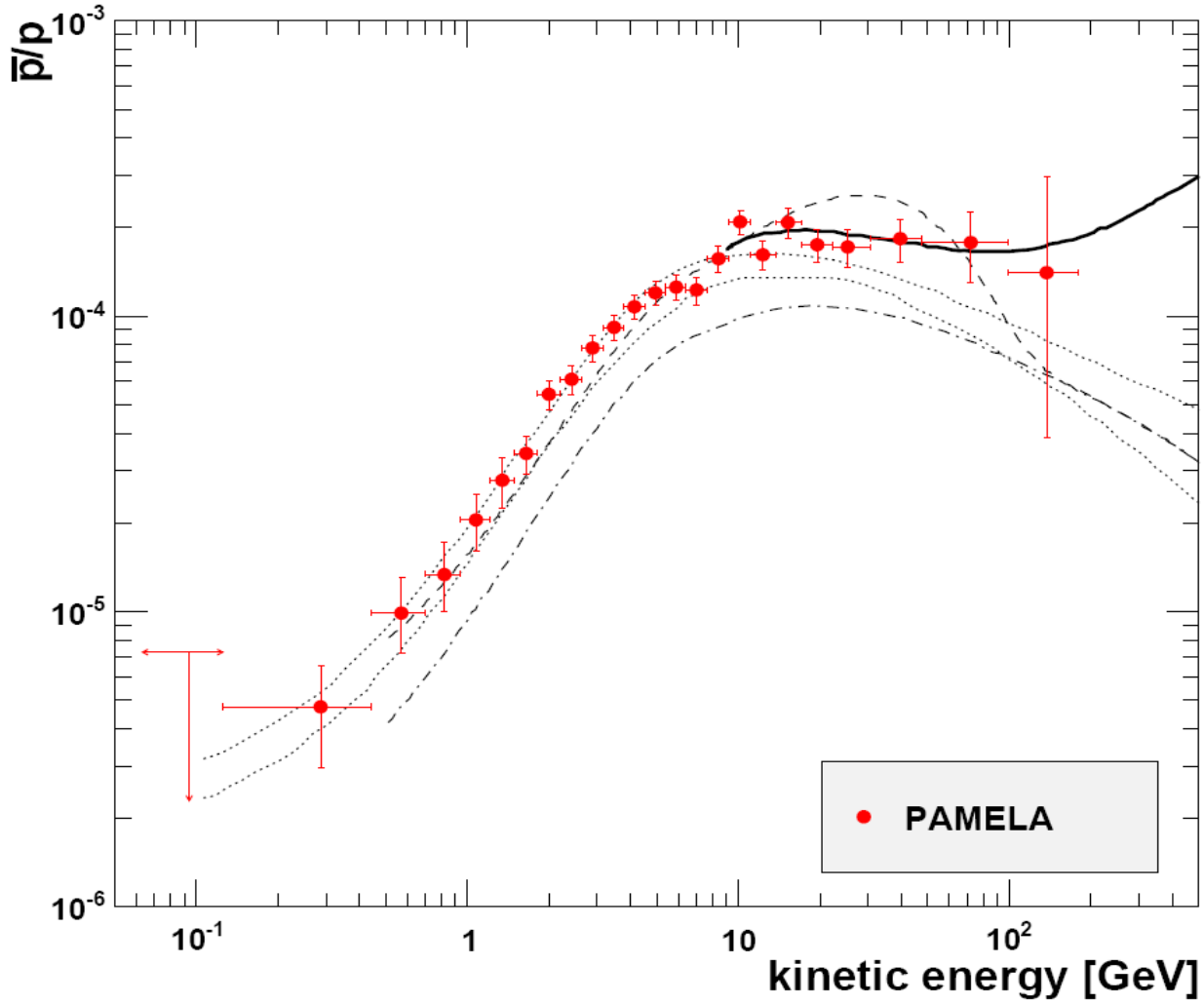
Increased statistics



Accepted by PRL – in press

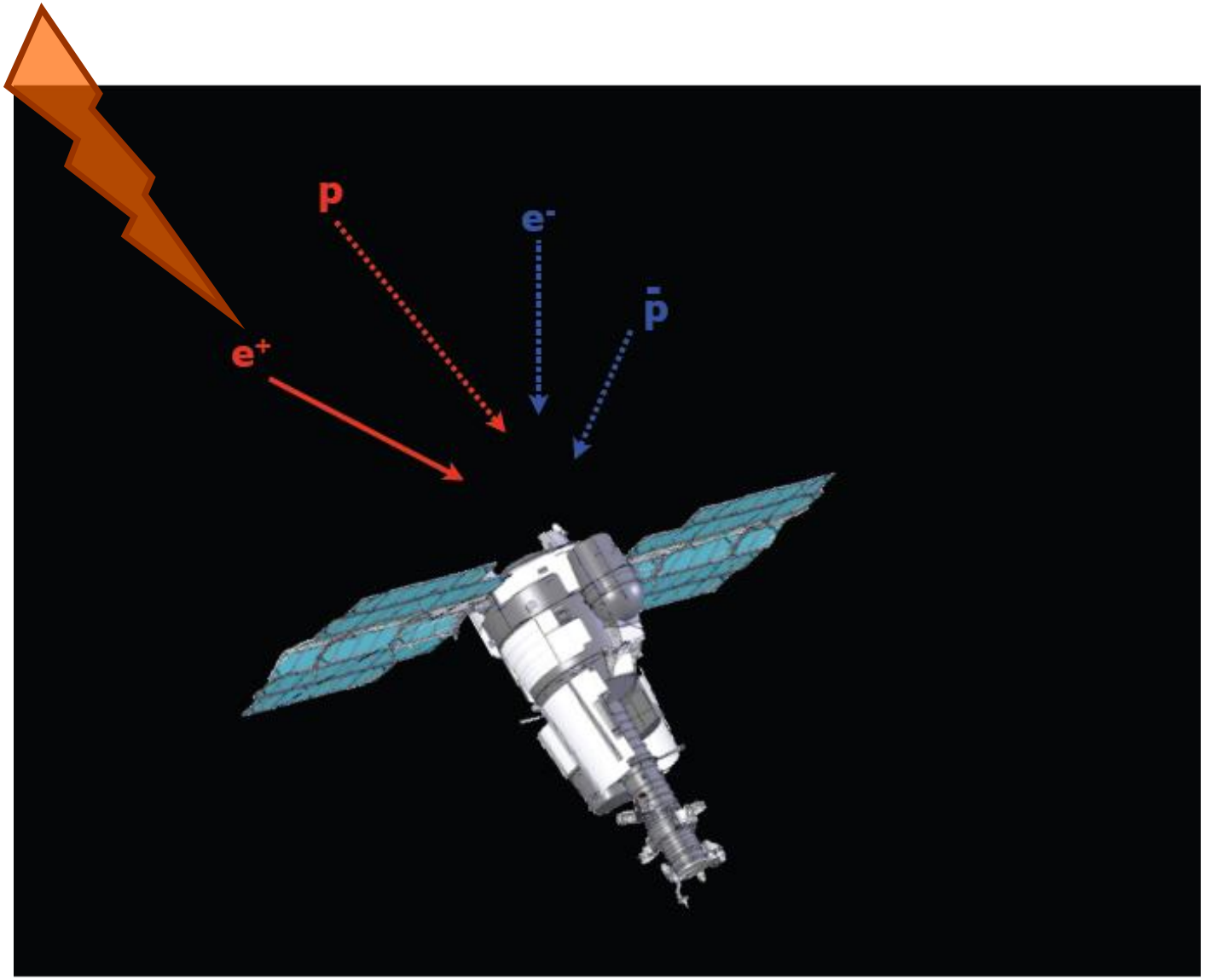
Interpretation

- PAMELA results are consistent with pure secondary production of antiprotons during the propagation of cosmic rays in the galaxy.
- The quality of PAMELA data surpasses the current precision of the theoretical modeling of the cosmic-ray acceleration and propagation mechanisms.
- Improved models are needed to allow the full significance of these experimental results to be understood.



As shown by the dashed line, a reasonable choice of propagation parameters (dashed-dotted line) allows a good description of PAMELA antiproton data with the inclusion of the wino-annihilation signal. Given current uncertainties on propagation parameters, this primary component cannot be ruled out.

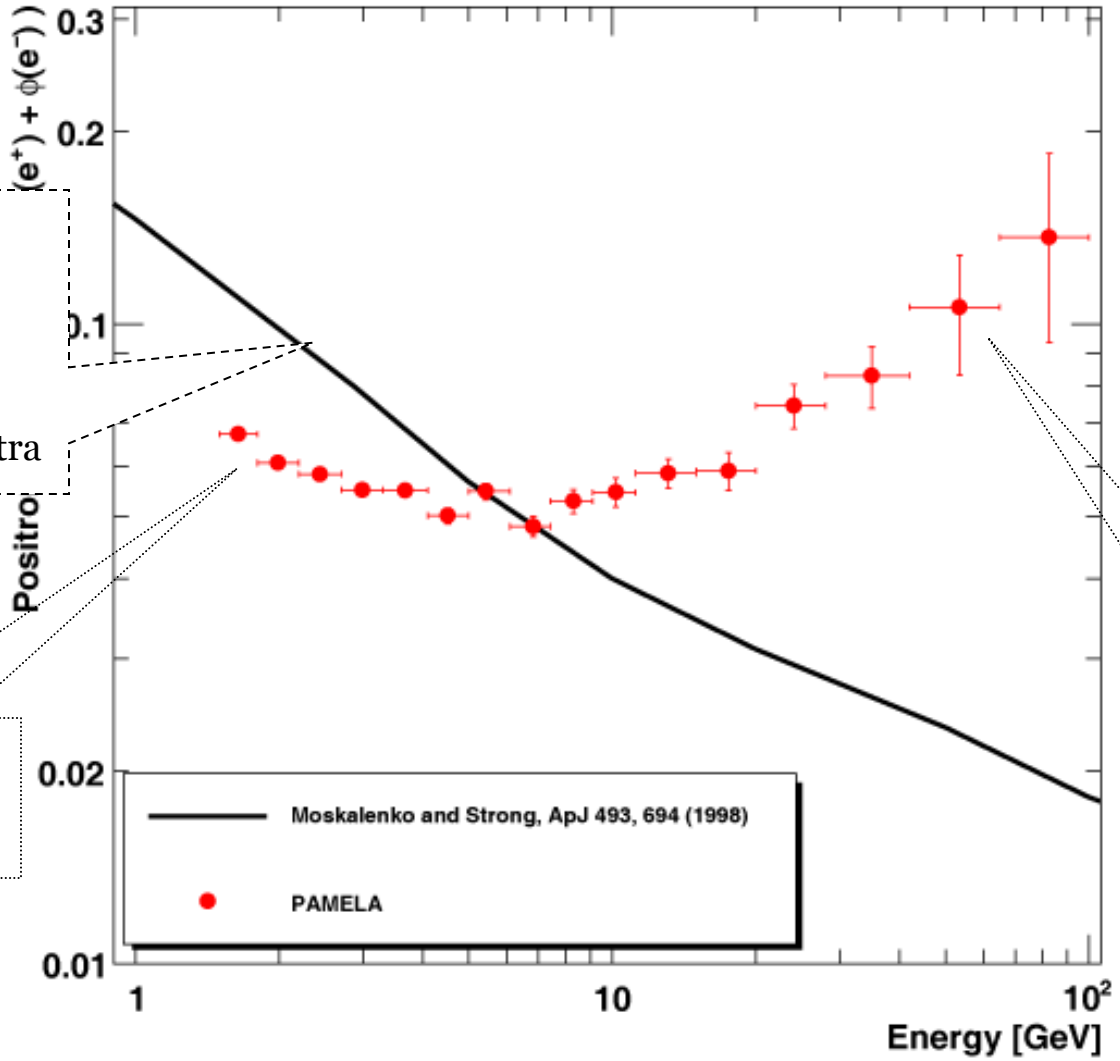
Positrons



PAMELA: POSITRON FRACTION

NATURE 458, 697, 2009

(Moskalenko & Strong 1998) GALPROP code
- Plain diffusion model
- Interstellar spectra

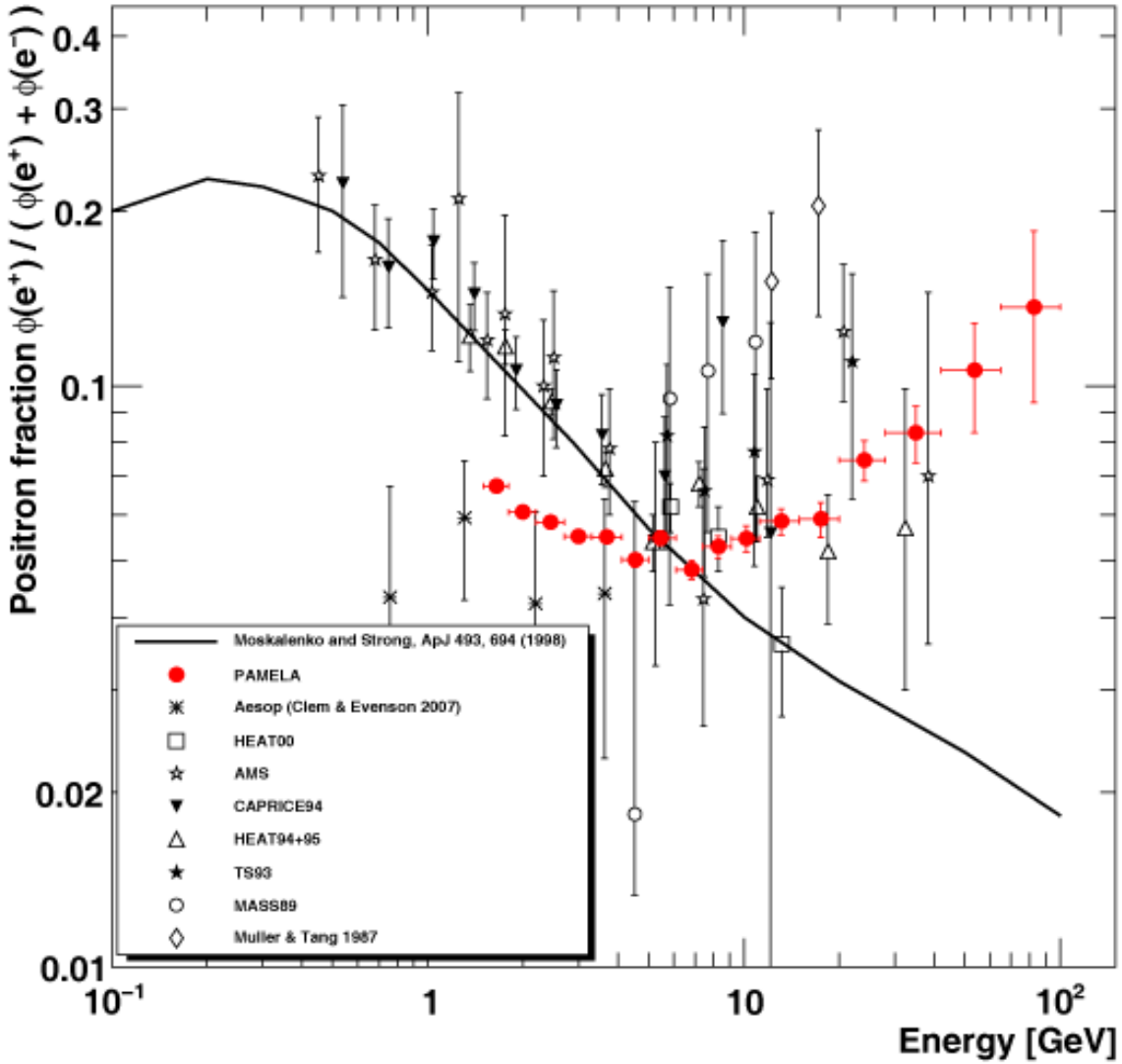


Solar modulation effects

Anomalous increasing ?

PAMELA: POSITRON FRACTION WRT OTHER EXP'S

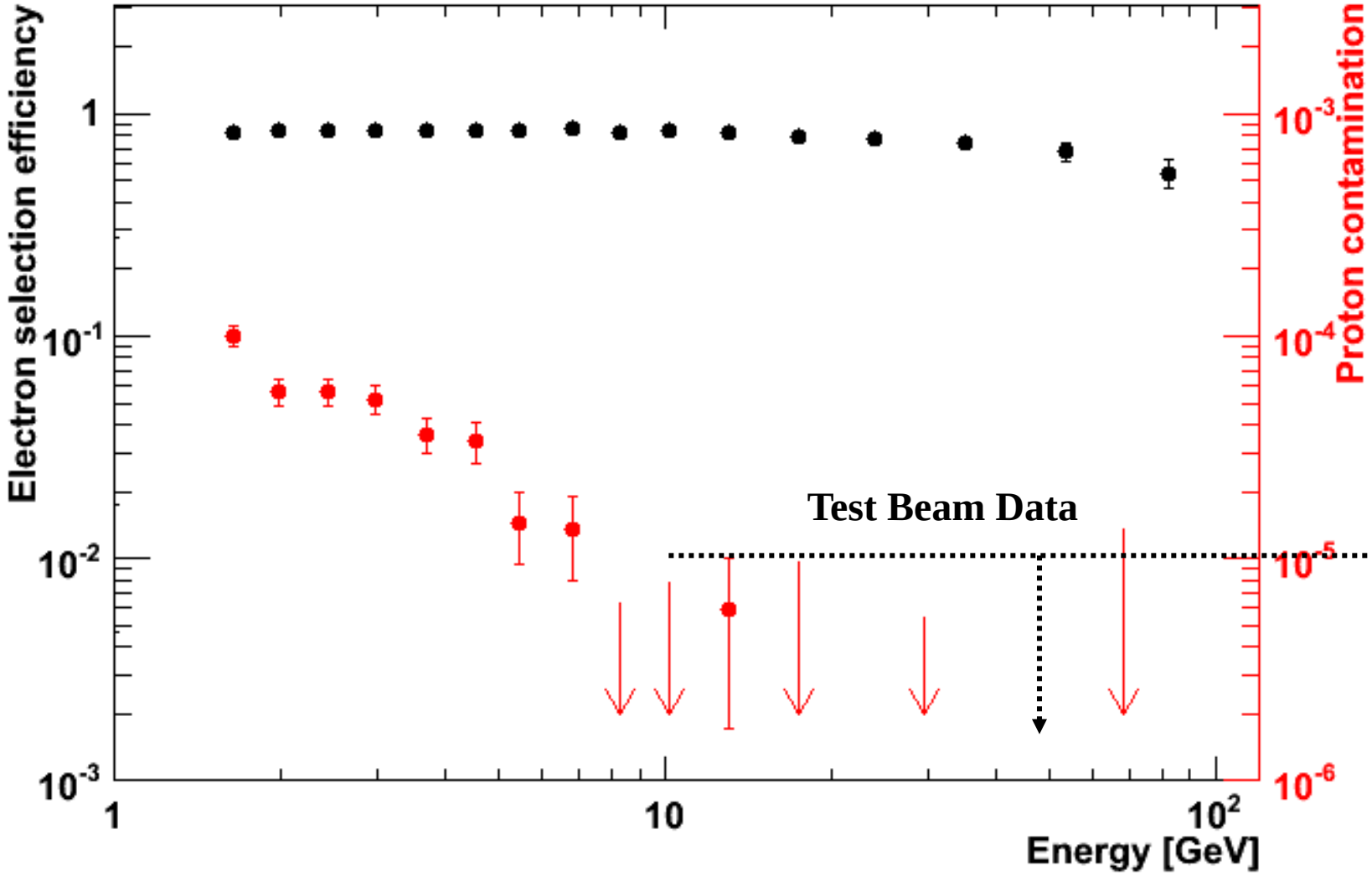
NATURE 458, 697, 2009



400

citations of this result in a year's time!

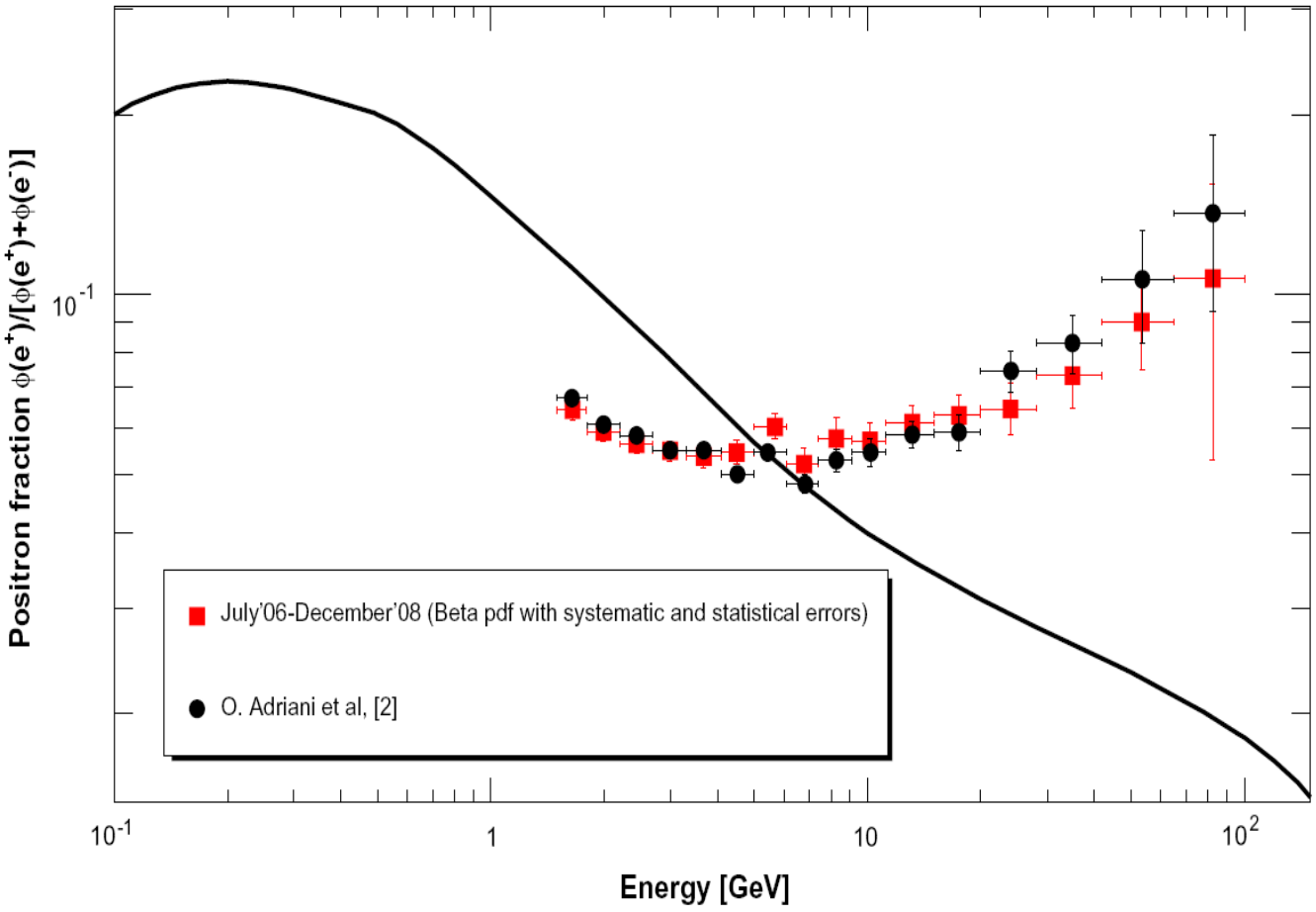
Estimated proton contamination with "pre-sampler" method



POSITRON TO ELECTRON FRACTION: NEW DATA

Data: July 2006 → December 2008

- **Factor 2.5 increase in statistics (factor 3 in the highest energy bin)**
- **Three different statistical analysis**
- **Statistical error estimated**

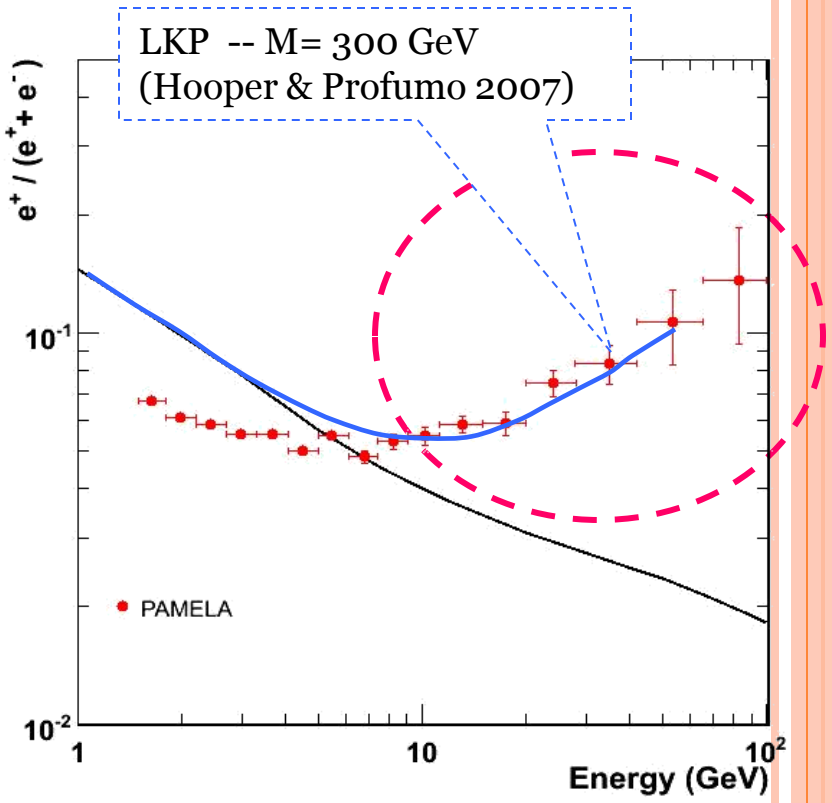


"A statistical procedure for the identification of positrons in the PAMELA experiment",
O. Adriani et al., Astroparticle Physics, 34 (2010), 1 – 11.

PRIMARY POSITRON SOURCES

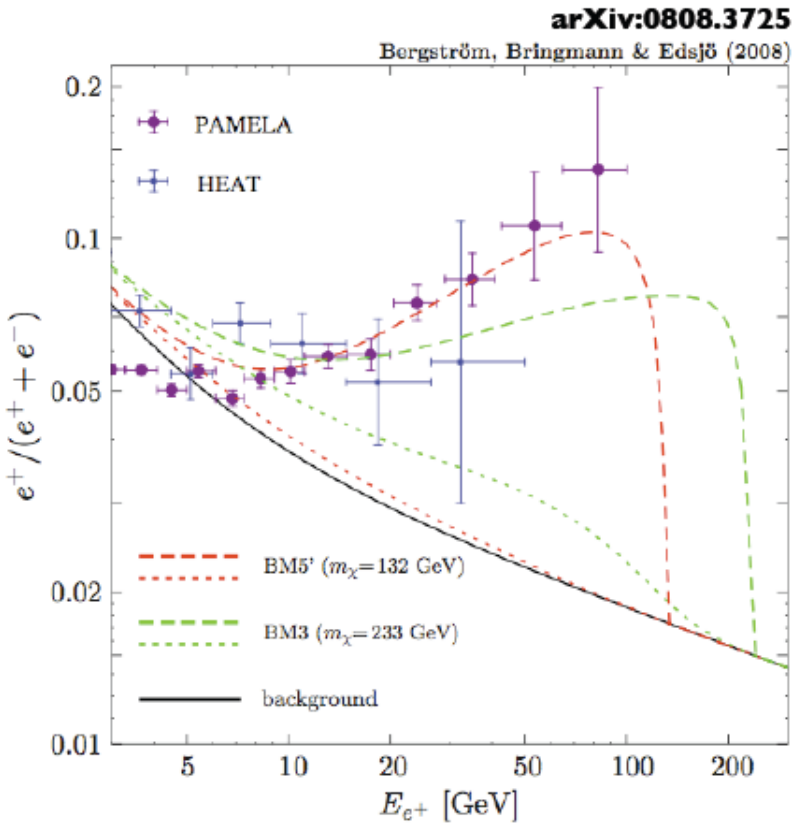
Dark Matter

- e^+ yield depend on the dominant decay channel
  - → **LSPs (SUSY)** seem disfavored due to suppression of e^+e^- final states
    - → low yield (relative to p-bar)
    - → soft spectrum from cascade decays
  - → **LKPs** seem favored 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, …)



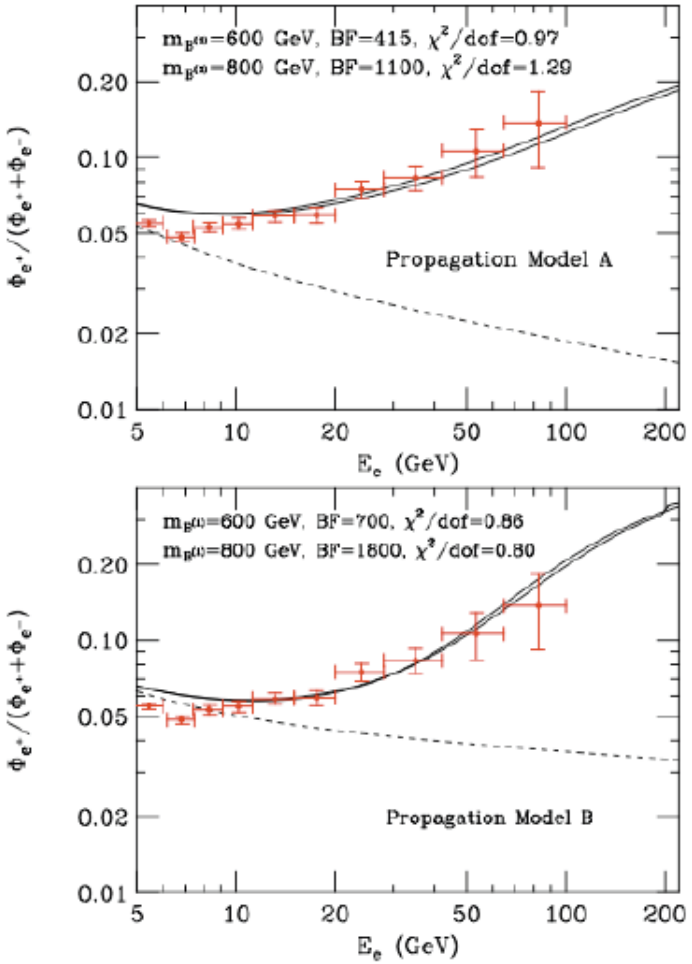
More than 150 articles claim DM is discovered !

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

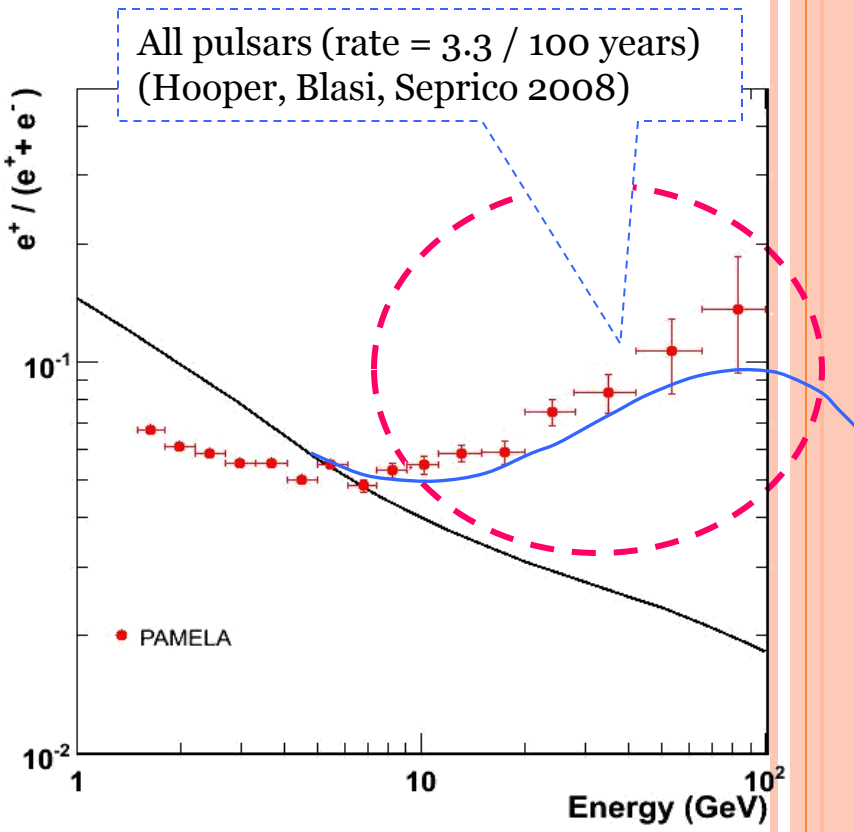


Kaluza-Klein dark matter

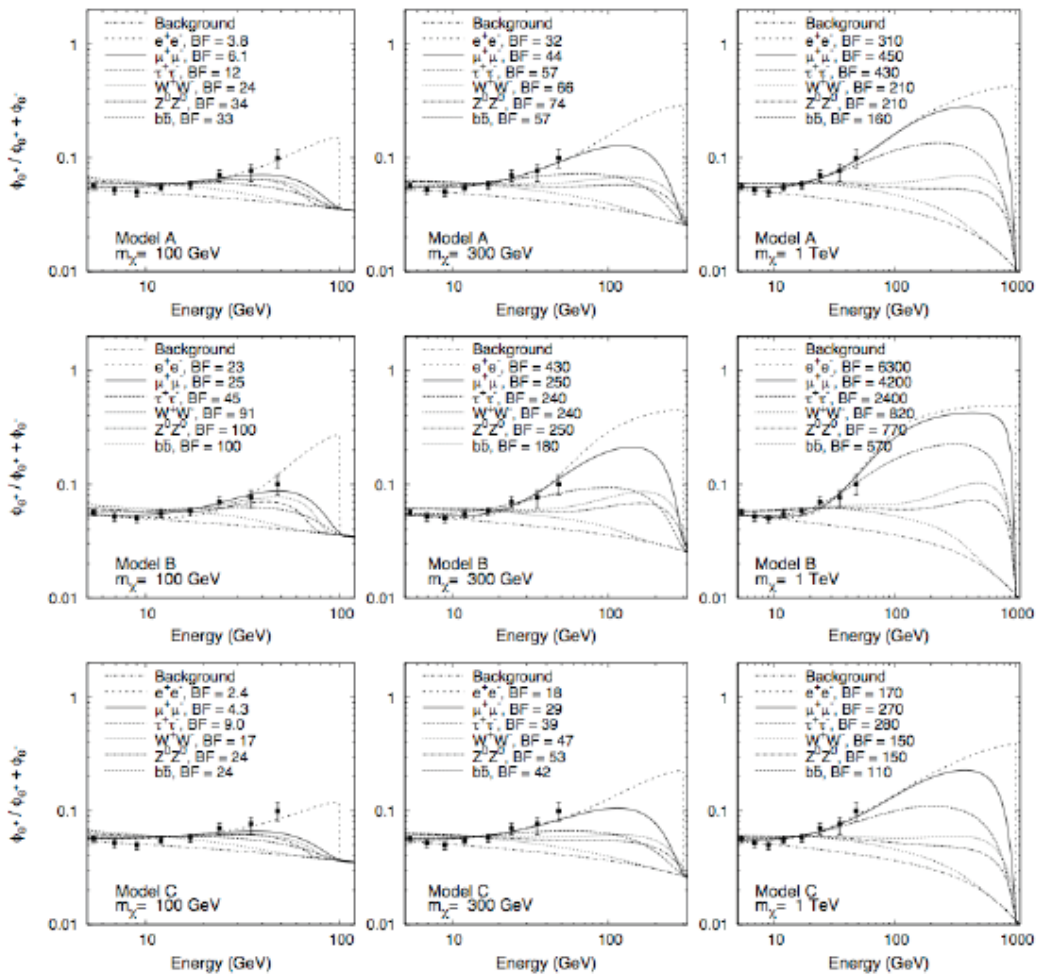
PRIMARY POSITRON SOURCES

Astrophysical processes

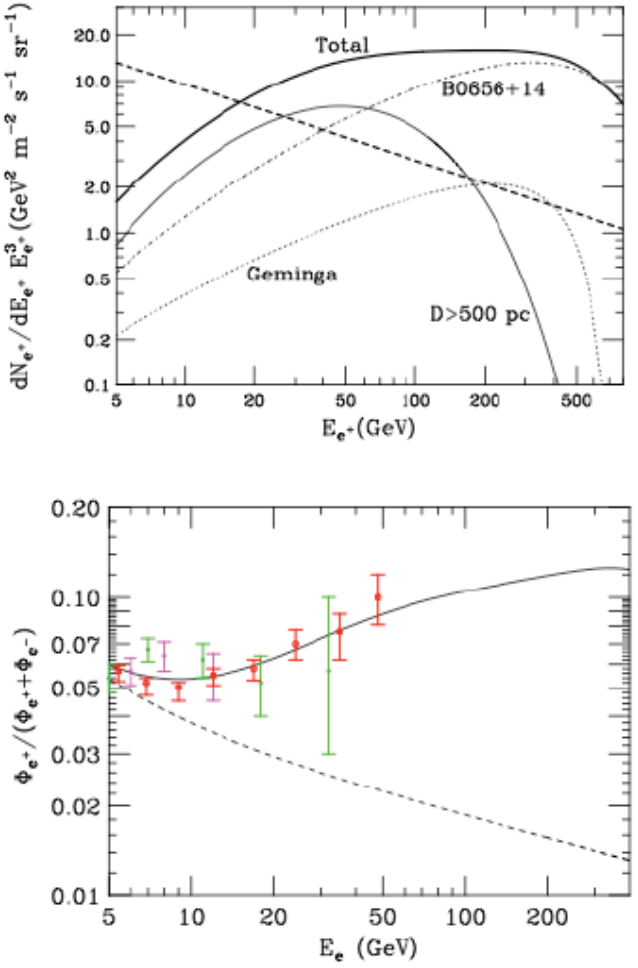
- Local **pulsars** are well-known sites of e^+e^- pair production (the spinning B of the pulsars strips e- that emit gammas then converting to pairs trapped in the cloud, accelerated and then escaping at the Poles) :
  - → they can individually and/or coherently contribute to the e^+e^- galactic flux 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

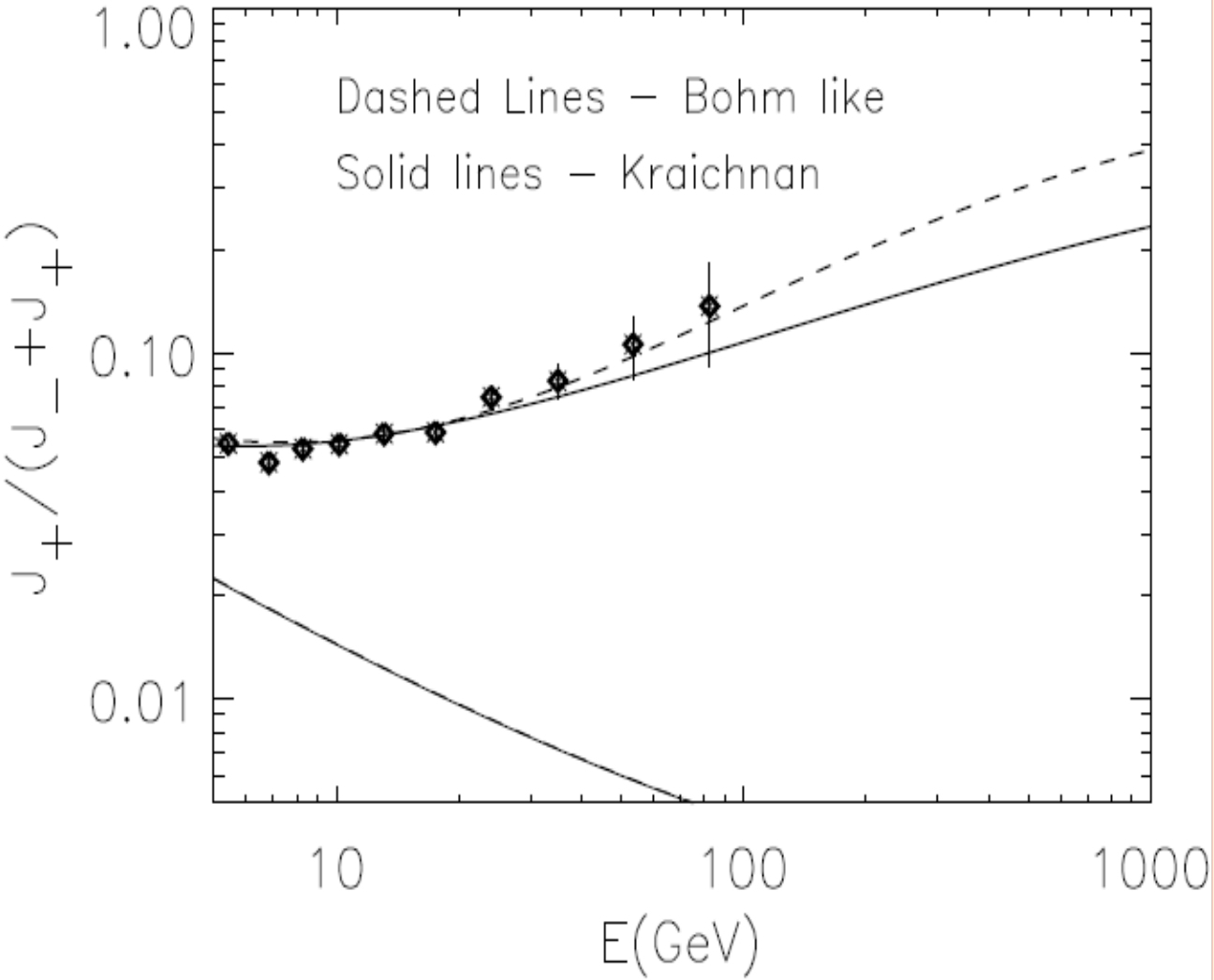
Revision of standard CR model

- 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

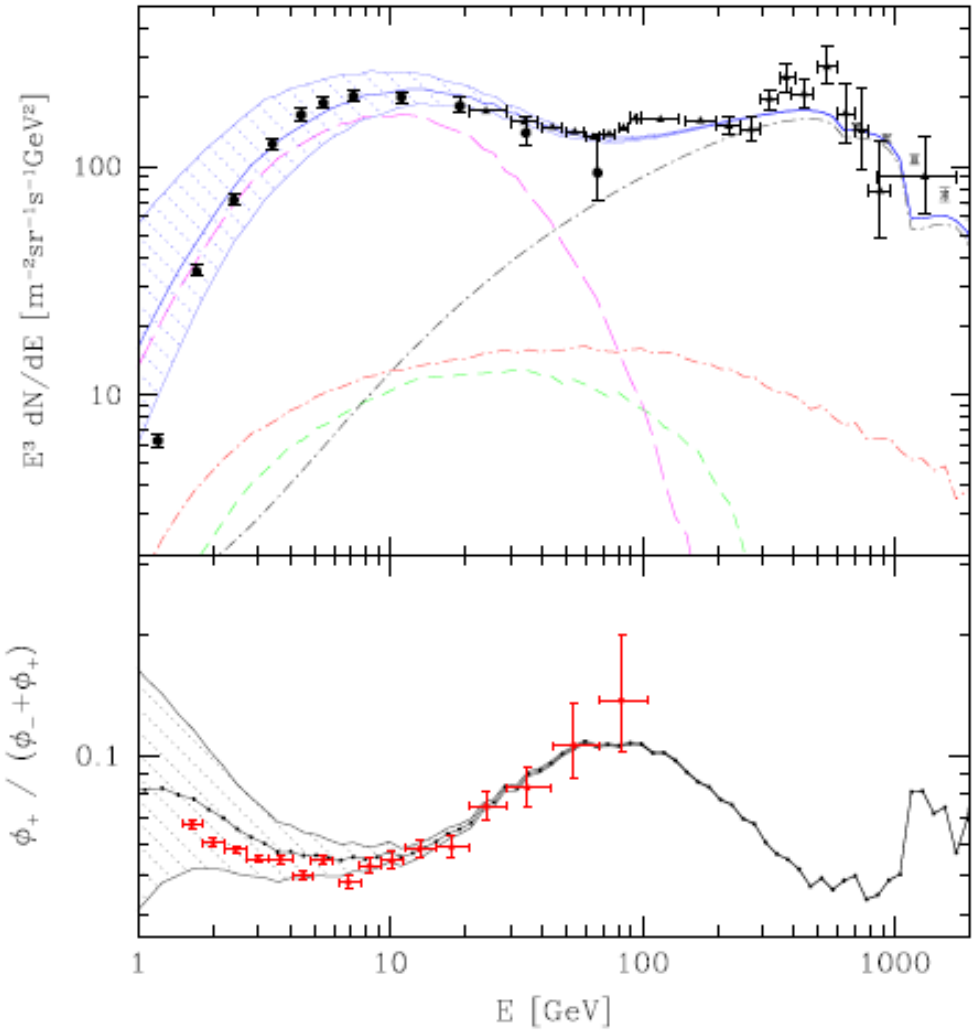
P. BLASI , PRL 103, 051104 (2009)



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



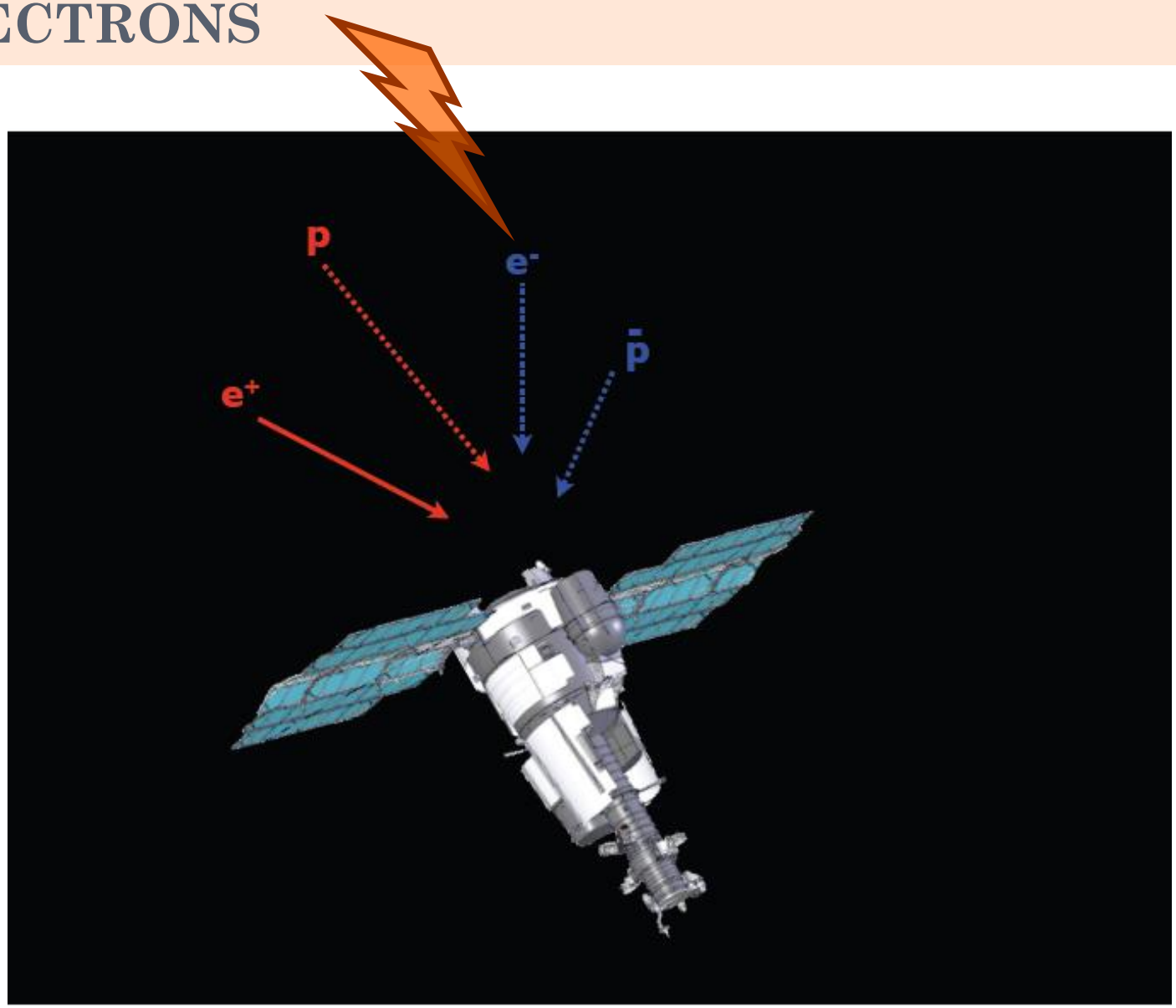
How to clarify the matter?

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)

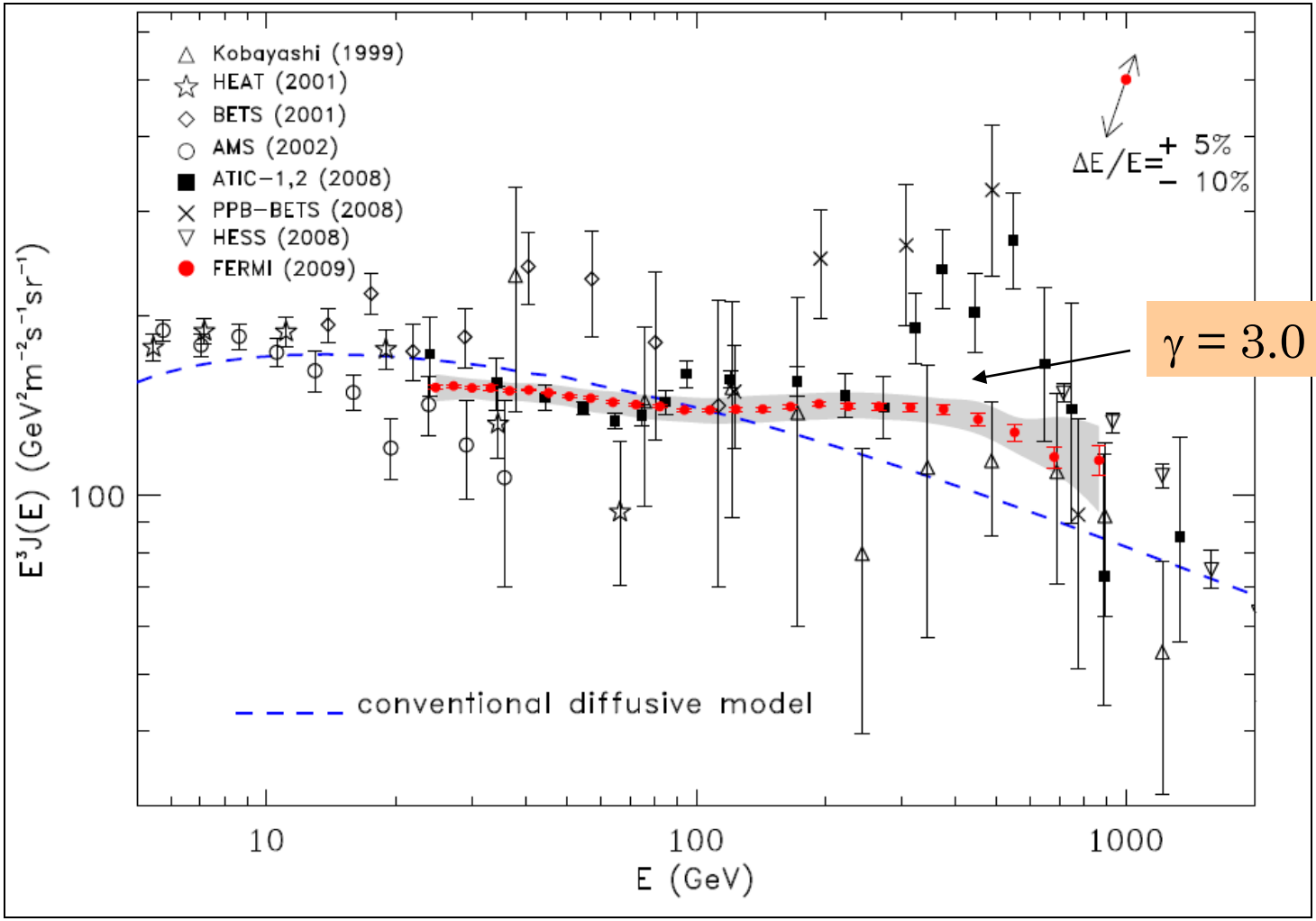
Courtesy of J. Edsjo

Electrons



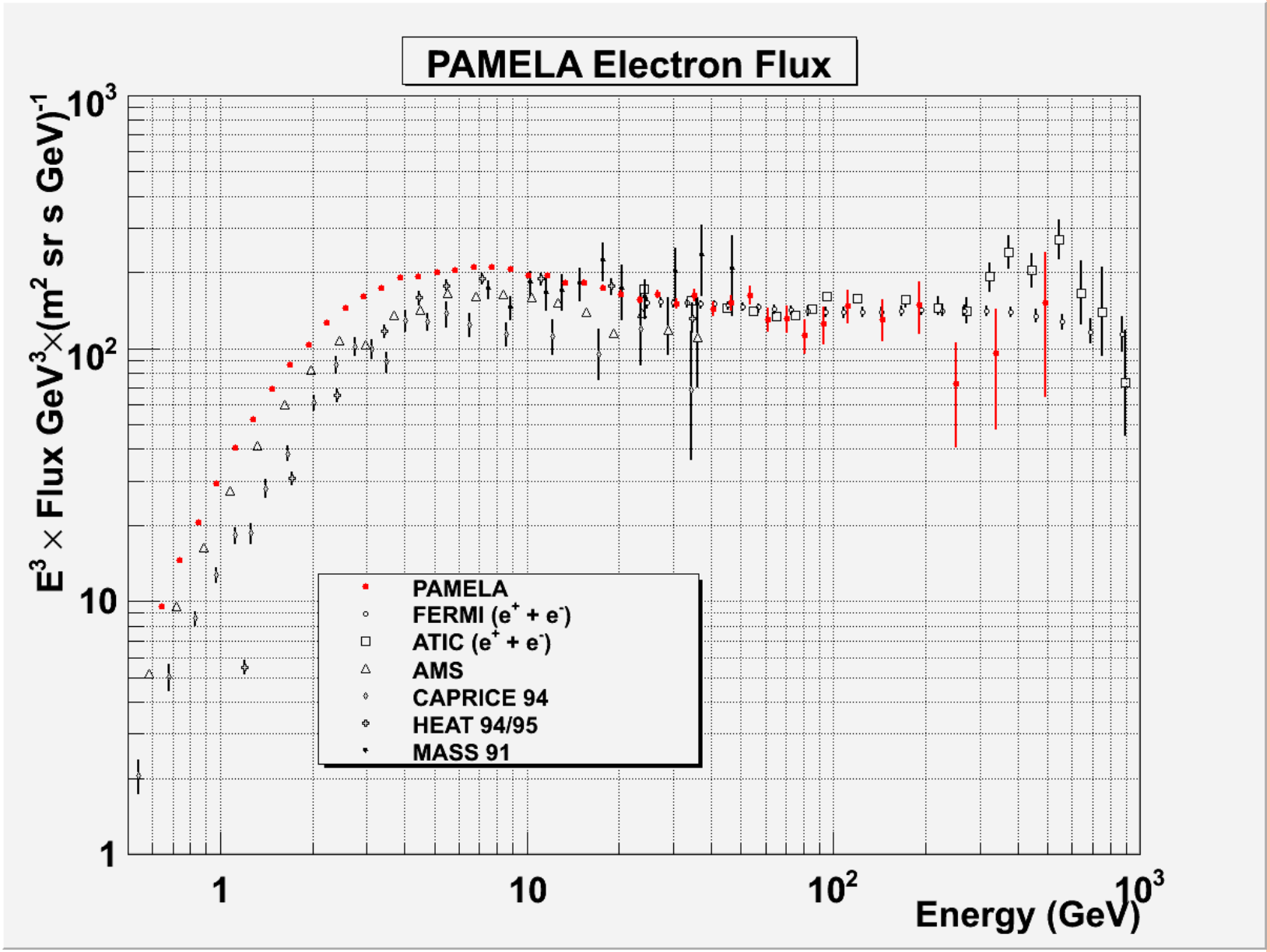
Any positron source is an electron source too …

RECENT CLAIMS OF (e^++e^-) EXCESS

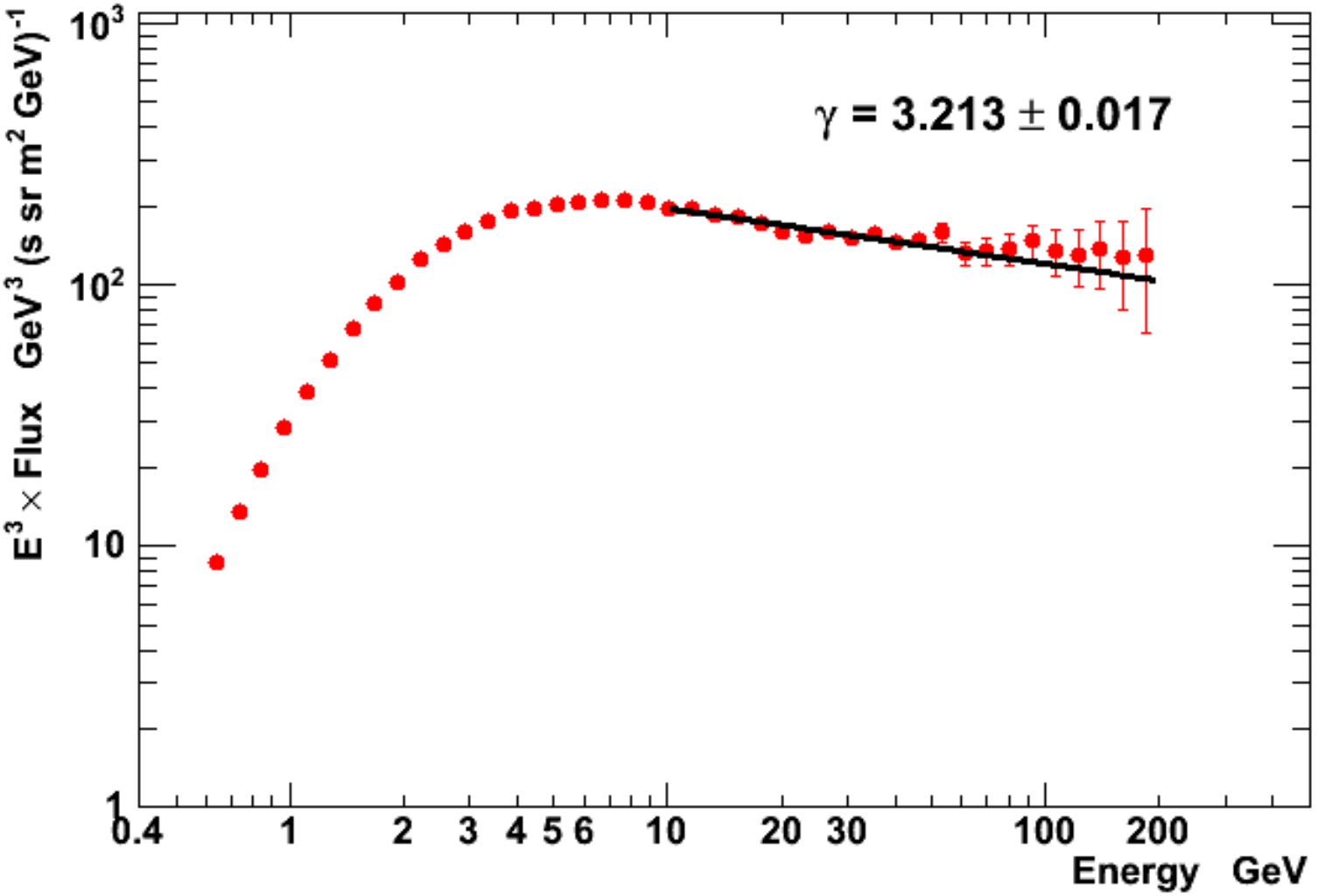


FERMI does not confirm the ATIC bump
but finds an excess wrt conventional diffusive models

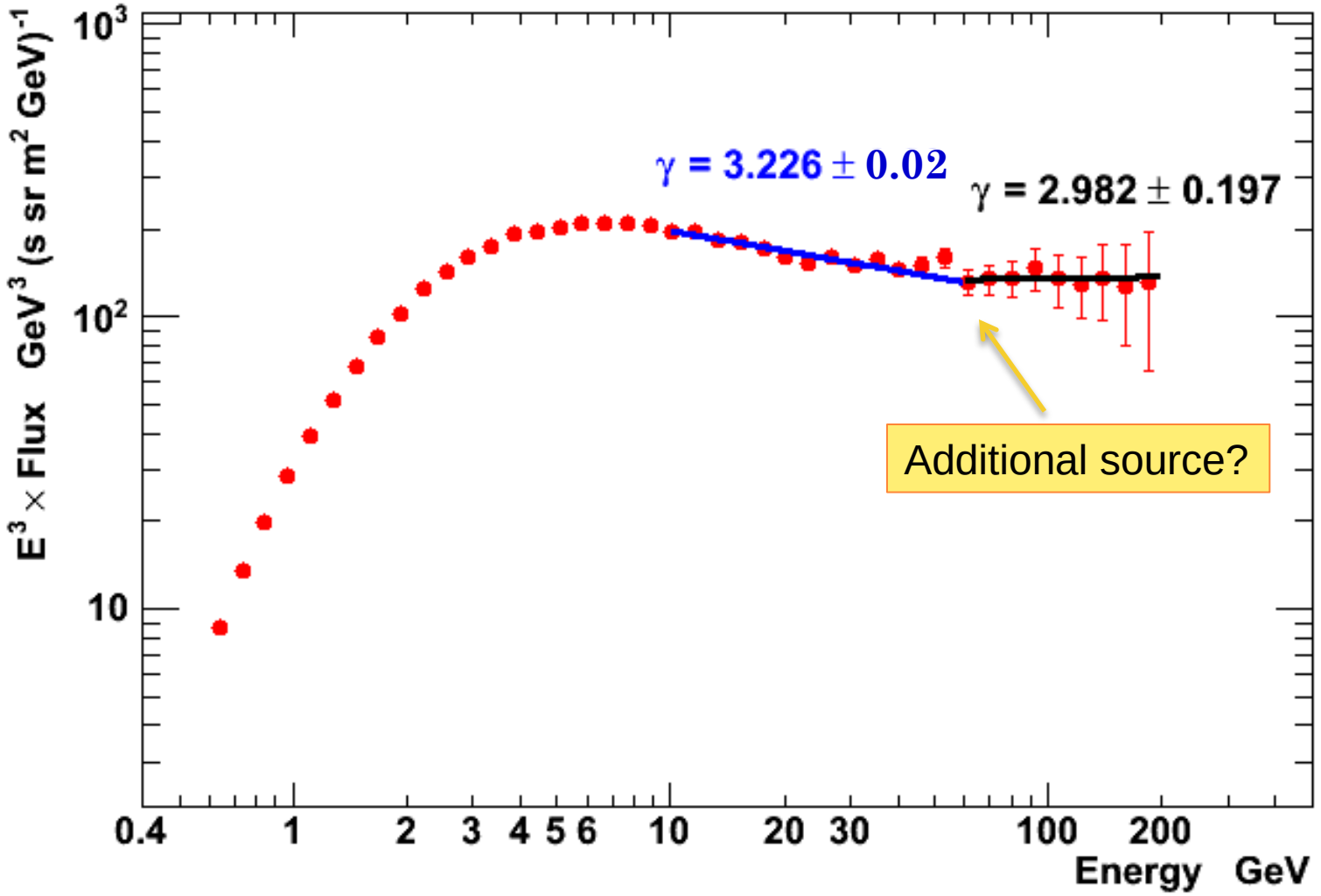
PAMELA Electron (e^-) Spectrum



PAMELA Electron (e^-) Spectrum

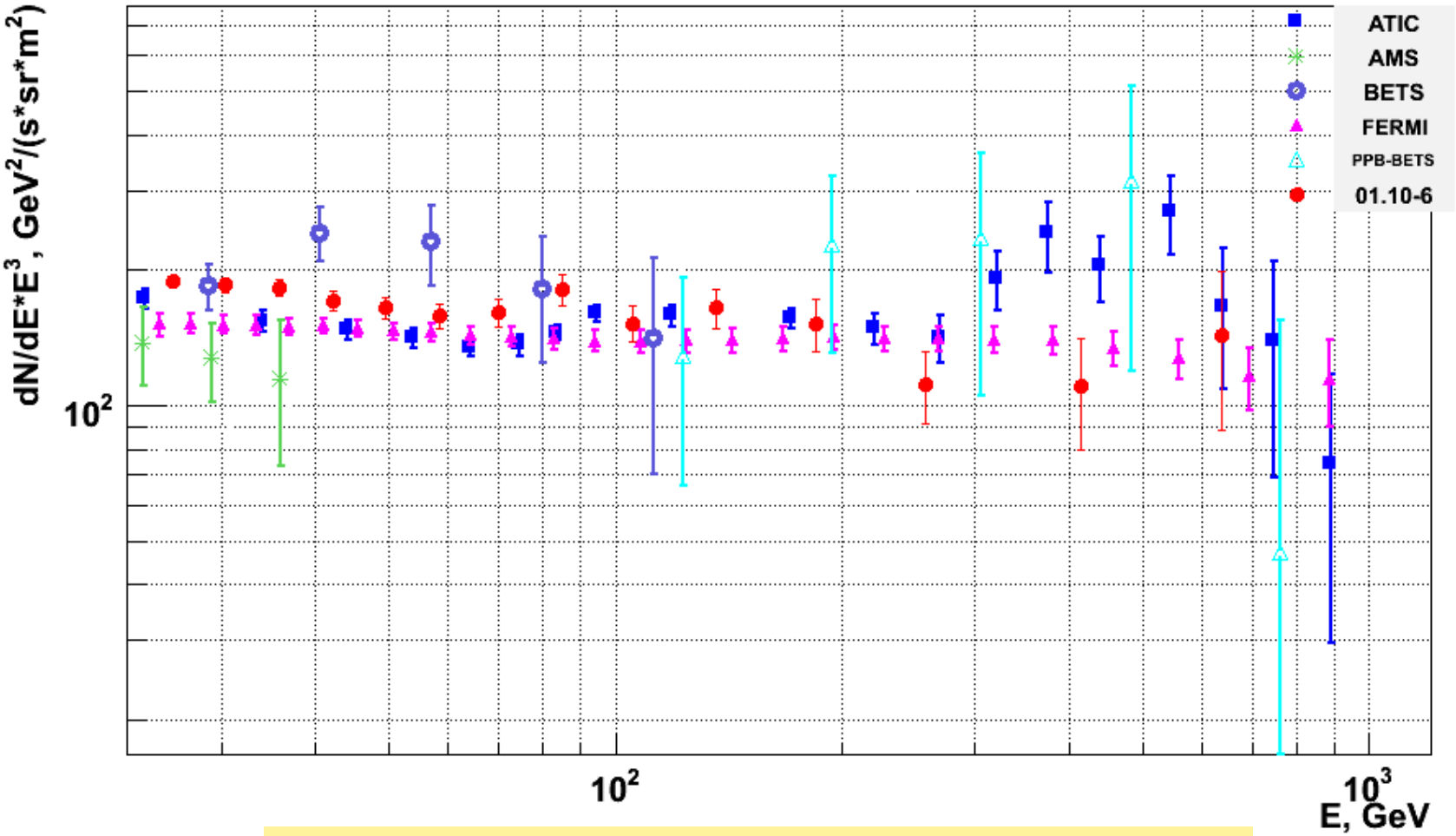


PAMELA Electron (e^-) Spectrum



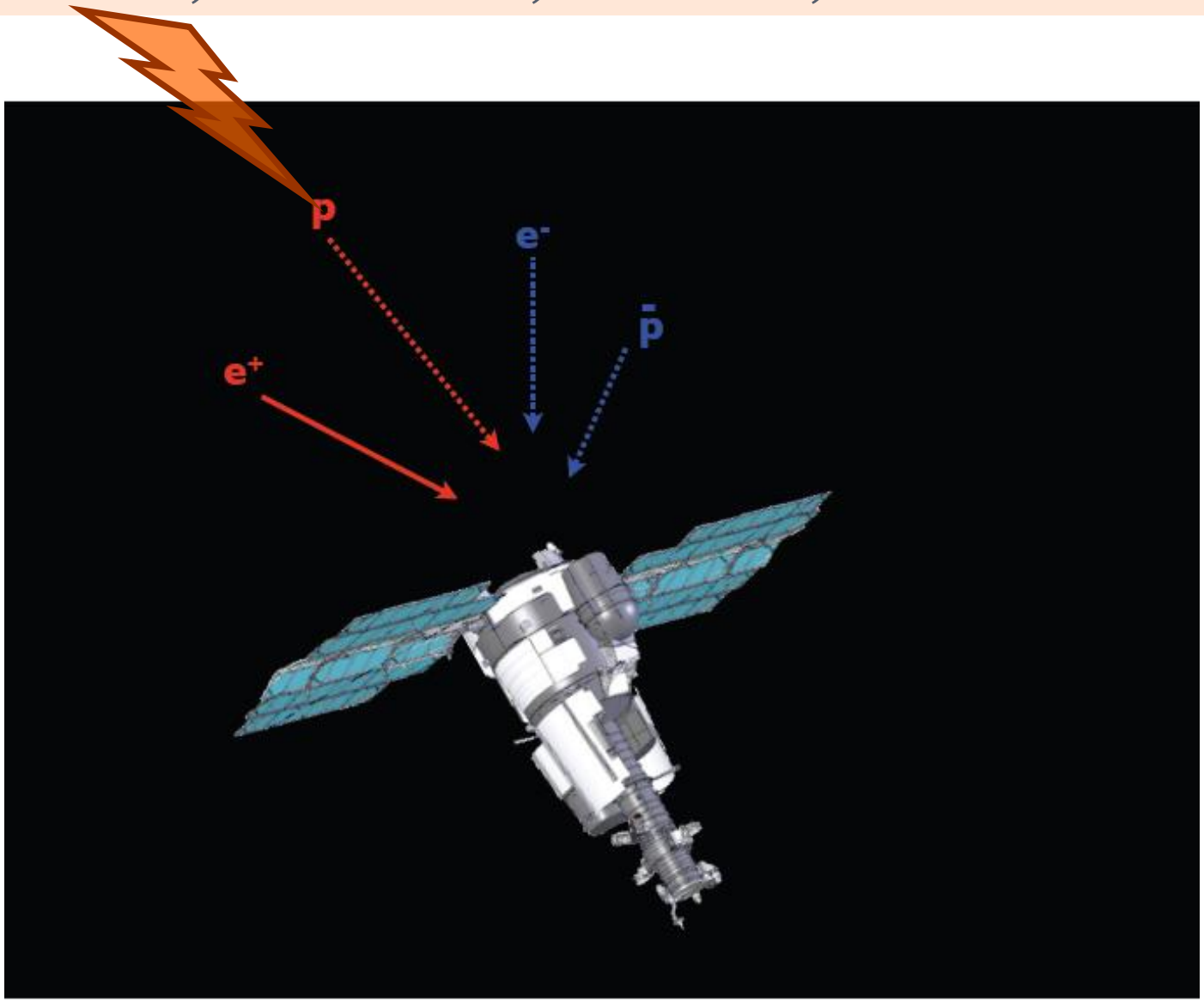
PAMELA ALL ELECTRONS→ HIGH ENERGY

VERY PRELIMINARY

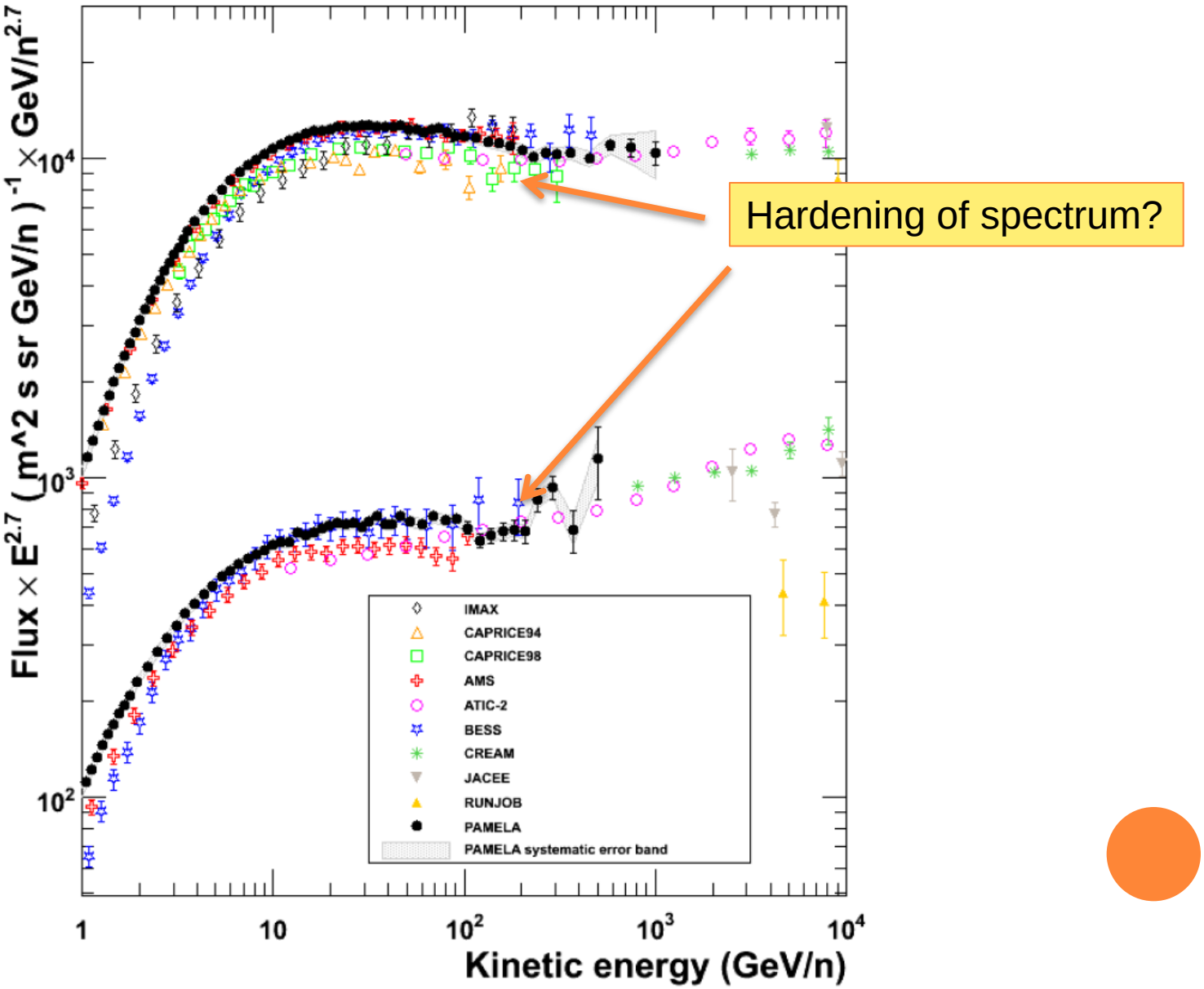


Energy measurement done with the calorimeter

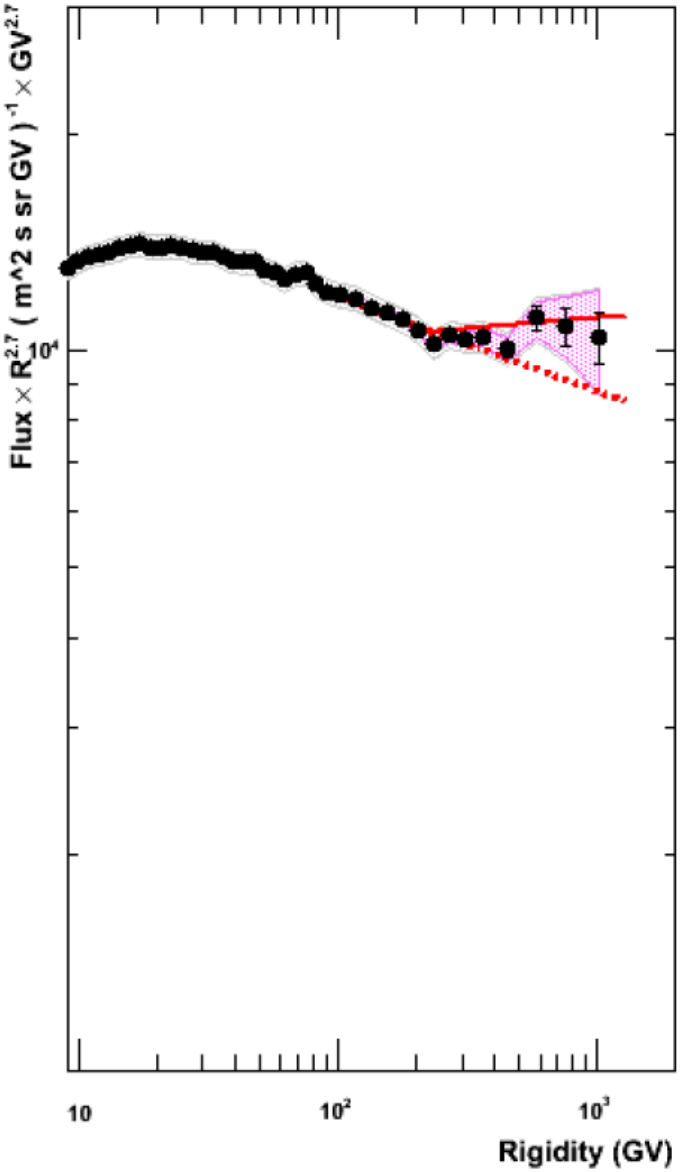
Protons, Heliums, nuclei, …

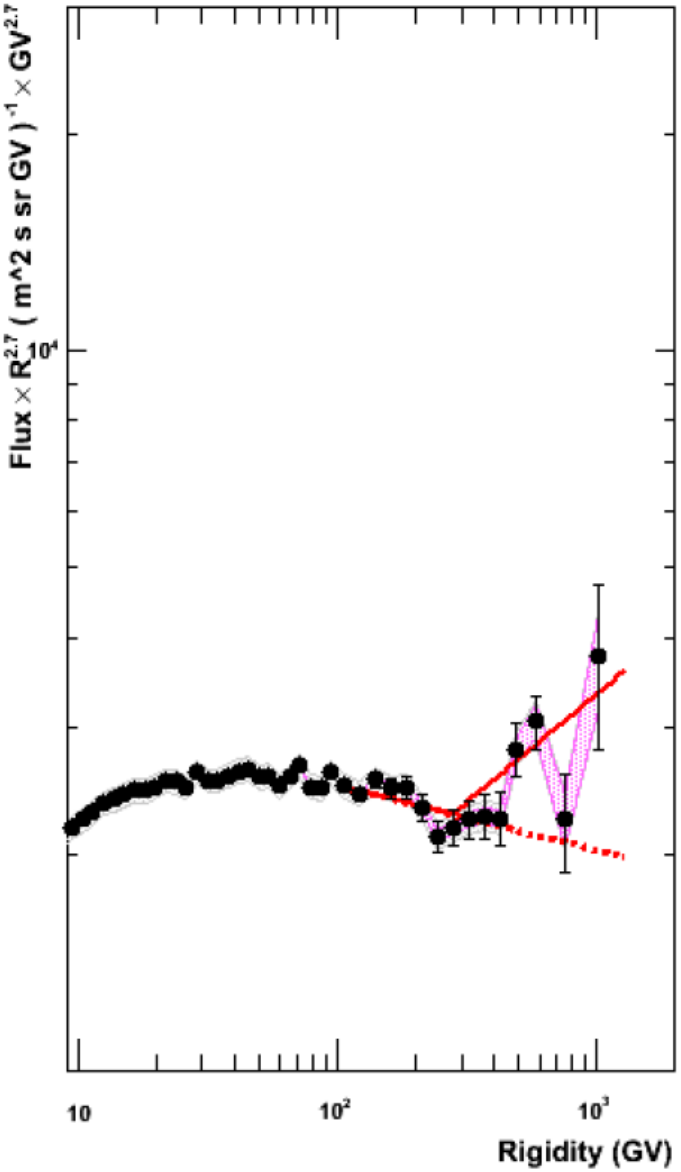


PAMELA Proton and Helium flux

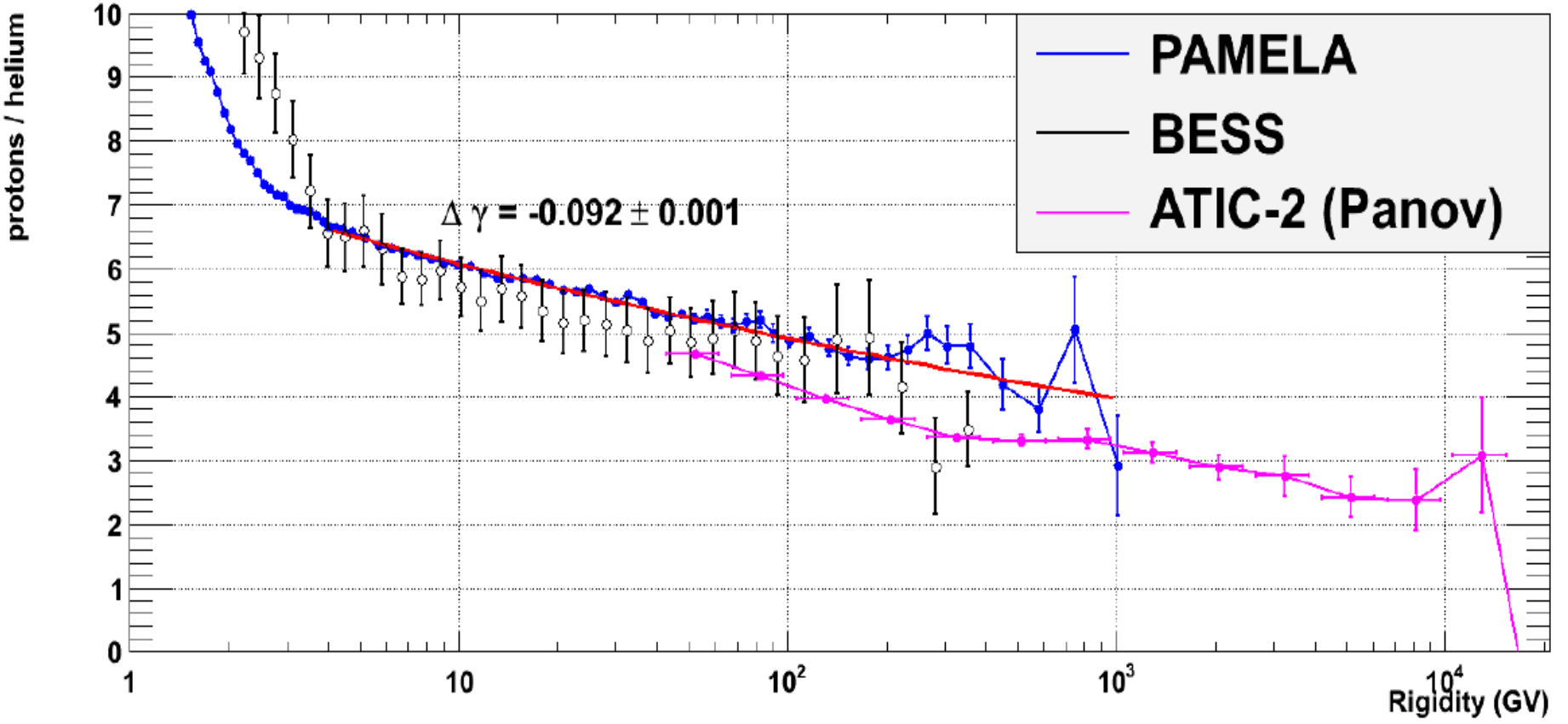


FIT WITH 2 SPECTRAL INDEXES





Proton/Helium ratio



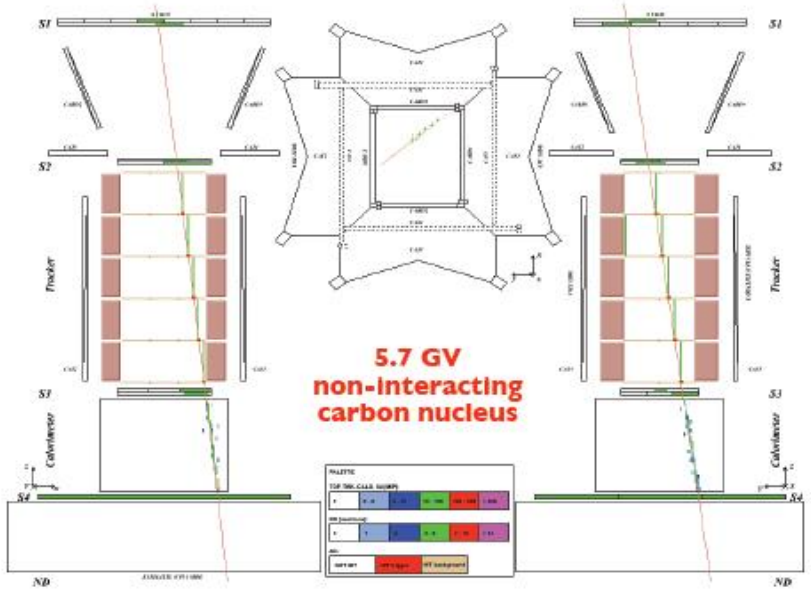
To be submitted to Science

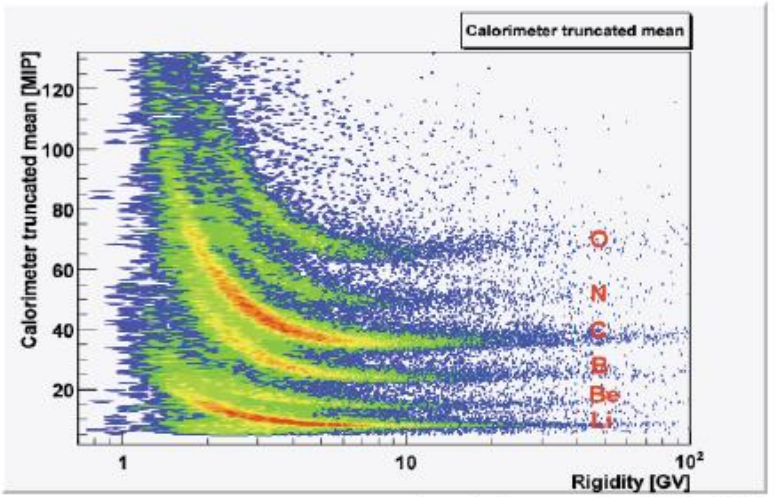
PAMELA LIGHT NUCLEI FLUXES

- **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):

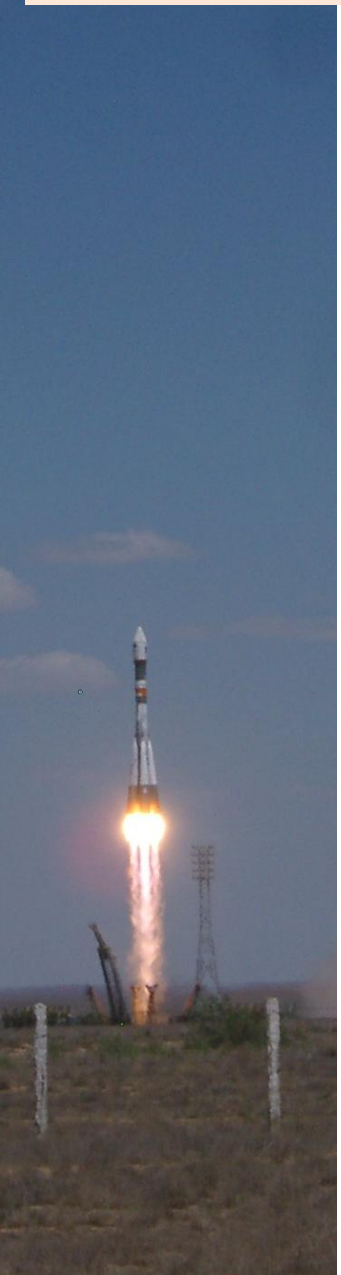
120.000 C nuclei
70.000 B nuclei





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

SUMMARY



• **PAMELA** has been in orbit and studying cosmic rays for ~48 months. >10^9 triggers registered, anc >19 TB of data has been down-linked.

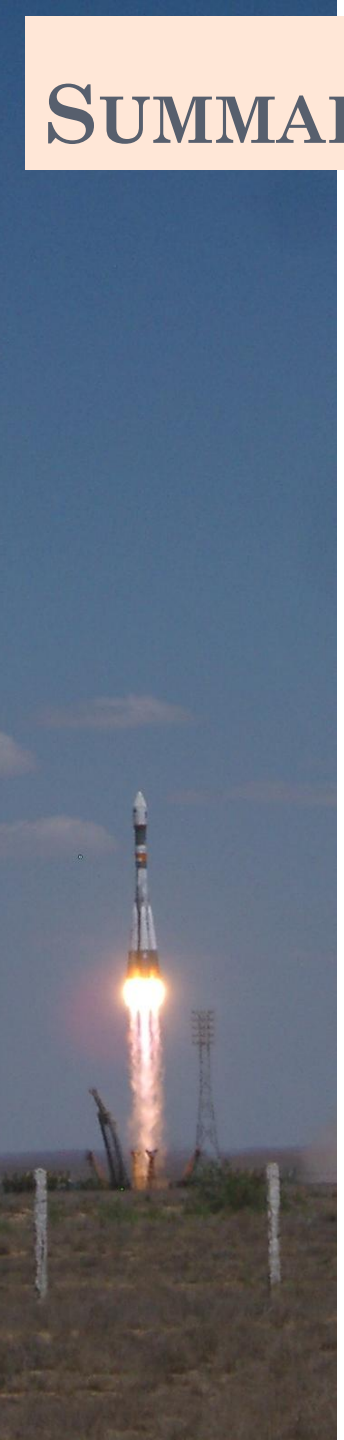
• **Antiproton-to-proton flux ratio** (~100 MeV - ~100 GeV) shows no significant deviations from secondary production expectations.

• **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 being completed 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)
- Heliosphere and magnetosphere
- Solar flares