Understanding Cosmic Rays and Searching for Dark Matter with PAMELA

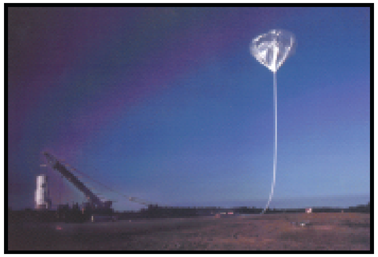
Roberta Sparvoli for the PAMELA Collaboration
University of Rome Tor Vergata and INFN

PAMELA DESIGN PERFORMANCE

	energy range
Antiprotons	**80 MeV ÷190 GeV**
Positrons	**50 MeV ÷ 300 GeV**
Electrons	up to 600 GeV
Protons	up to 1 TeV
Heliums	up to 400 GeV/n
Electrons+positrons	up to 2 TeV
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

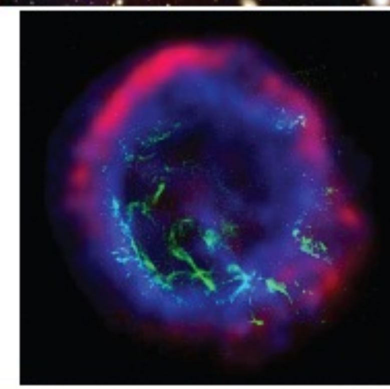
- **Unprecedented statistics and new energy range for cosmic ray physics**
  - e.g. contemporary antiproton & positron energy, $E_{max} \approx 50$ GeV
- Simultaneous measurements of many species
  - constrain secondary production models

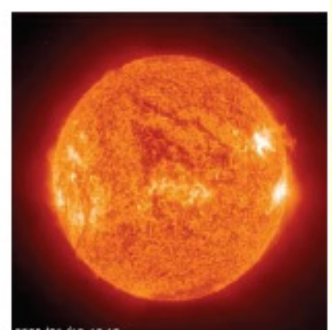
I HEAT-PBAR flight ~ 25 days PAMELA data
I CAPRICE98 flight ~ 5 days PAMELA data



PAMELA Scientific goals

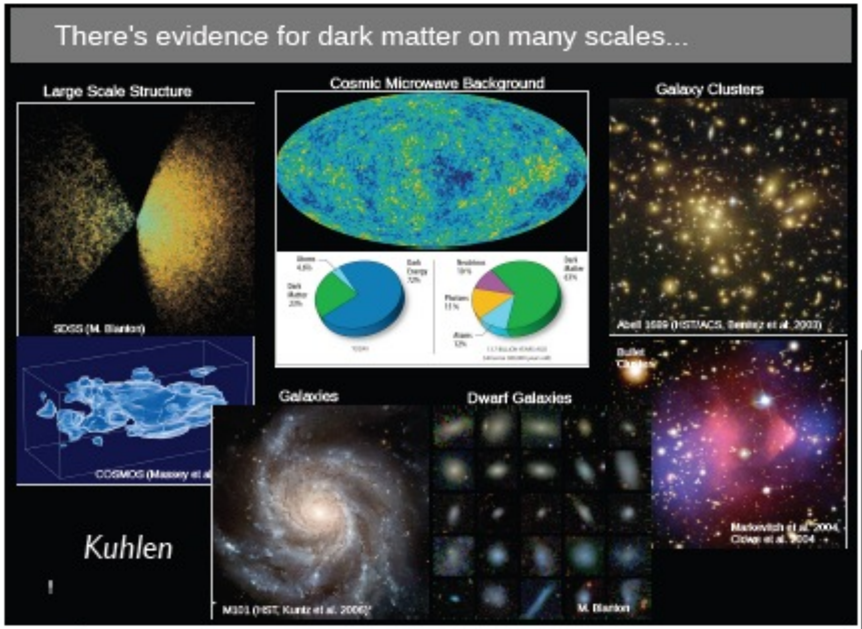
- **Search for dark matter annihilation**
- Search for antihelium (primordial antimatter)
- Study of cosmic-ray propagation (light nuclei and isotopes)
- Study of electron spectrum (local sources?)
- Study solar physics and solar modulation
- Study terrestrial magnetosphere

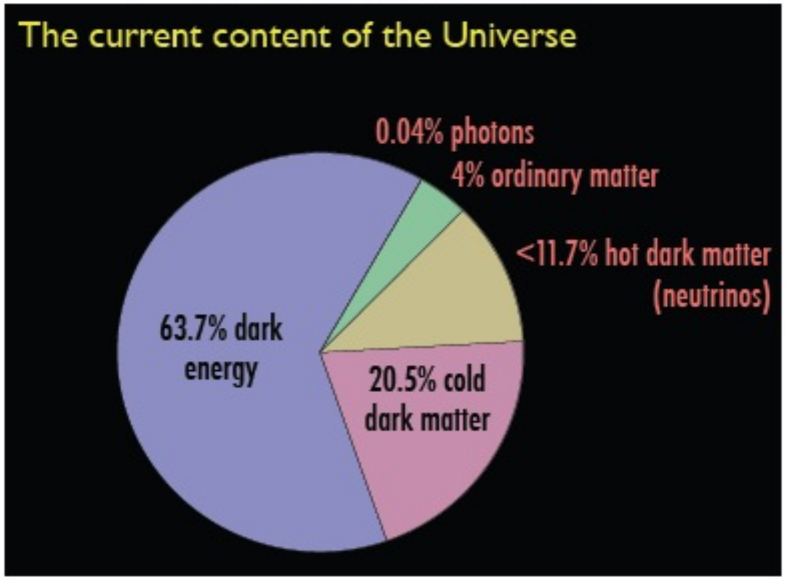




Launch : 15 June 2006

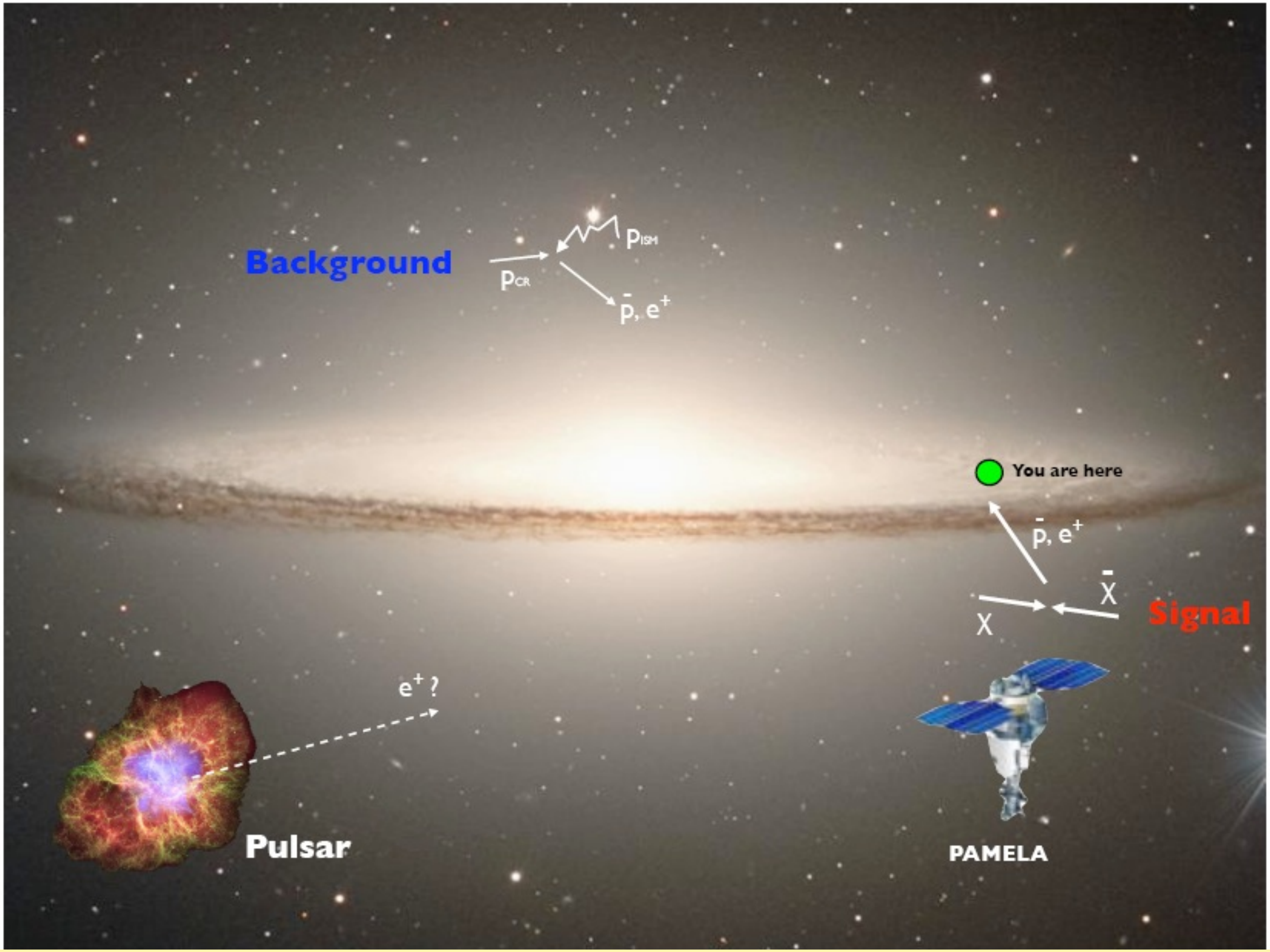
Dark Matter searches





P. Gondolo, **IDM 2008**

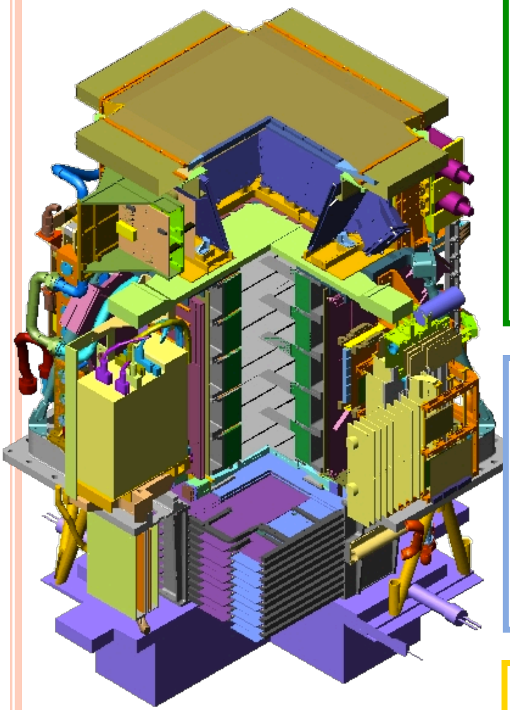
EXPECTED DM SIGNALS



Deviations of the antiparticle spectra wrt secondary production

PAMELA DETECTORS

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

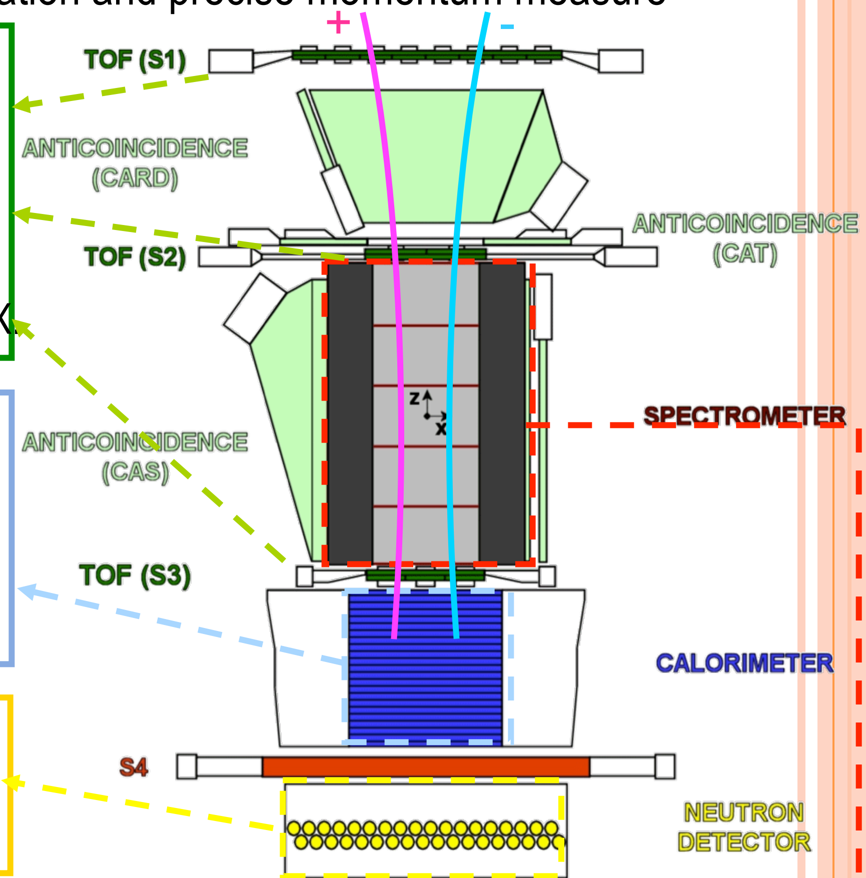


GF: 21.5 cm^2 sr
Mass: 470 kg
Size: 130x70x70 cm^3
Power Budget: 360W

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

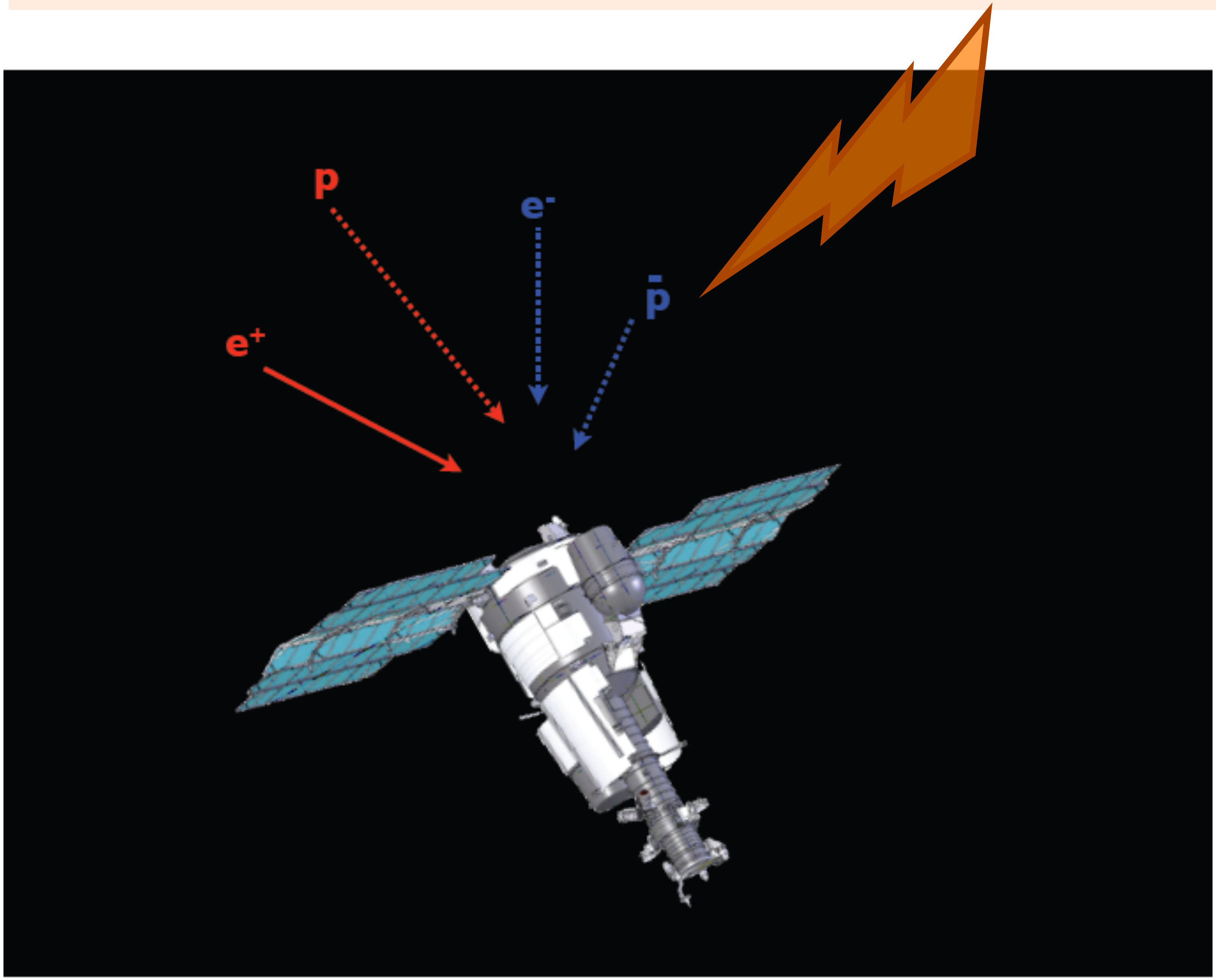
Electromagnetic calorimeter
W/Si sampling (16.3 X_0, 0.6 λ_I)
- Discrimination e^+ / p, anti-p / e^- (shower topology)
- Direct E measurement for e^-

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



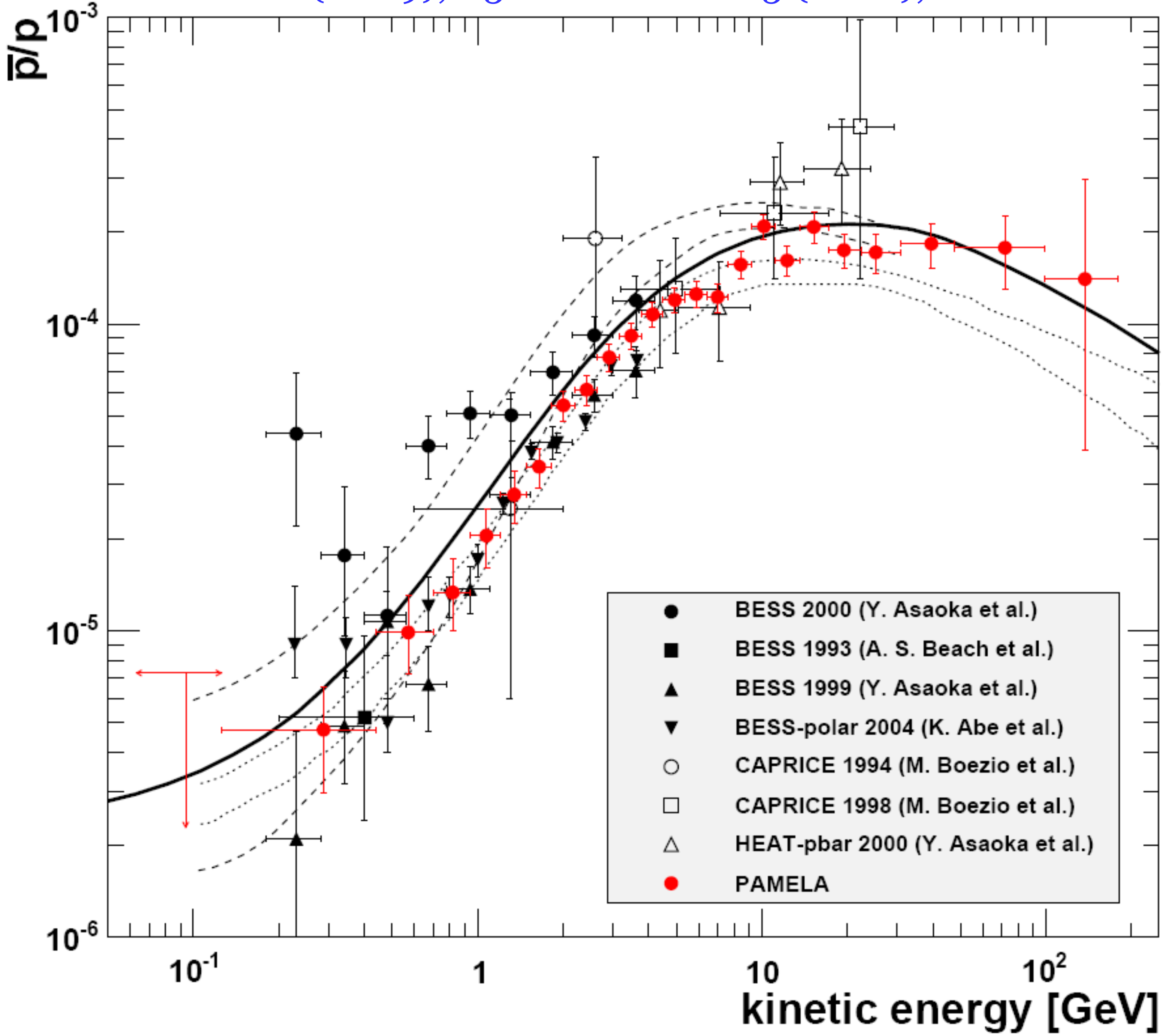
Spectrometer
microstrip silicon tracking system + permanent magnet
It provides:
- *Magnetic rigidity* → R = pc/Ze
- *Charge sign*
- *Charge value from dE/dx*

ANTIPROTONS

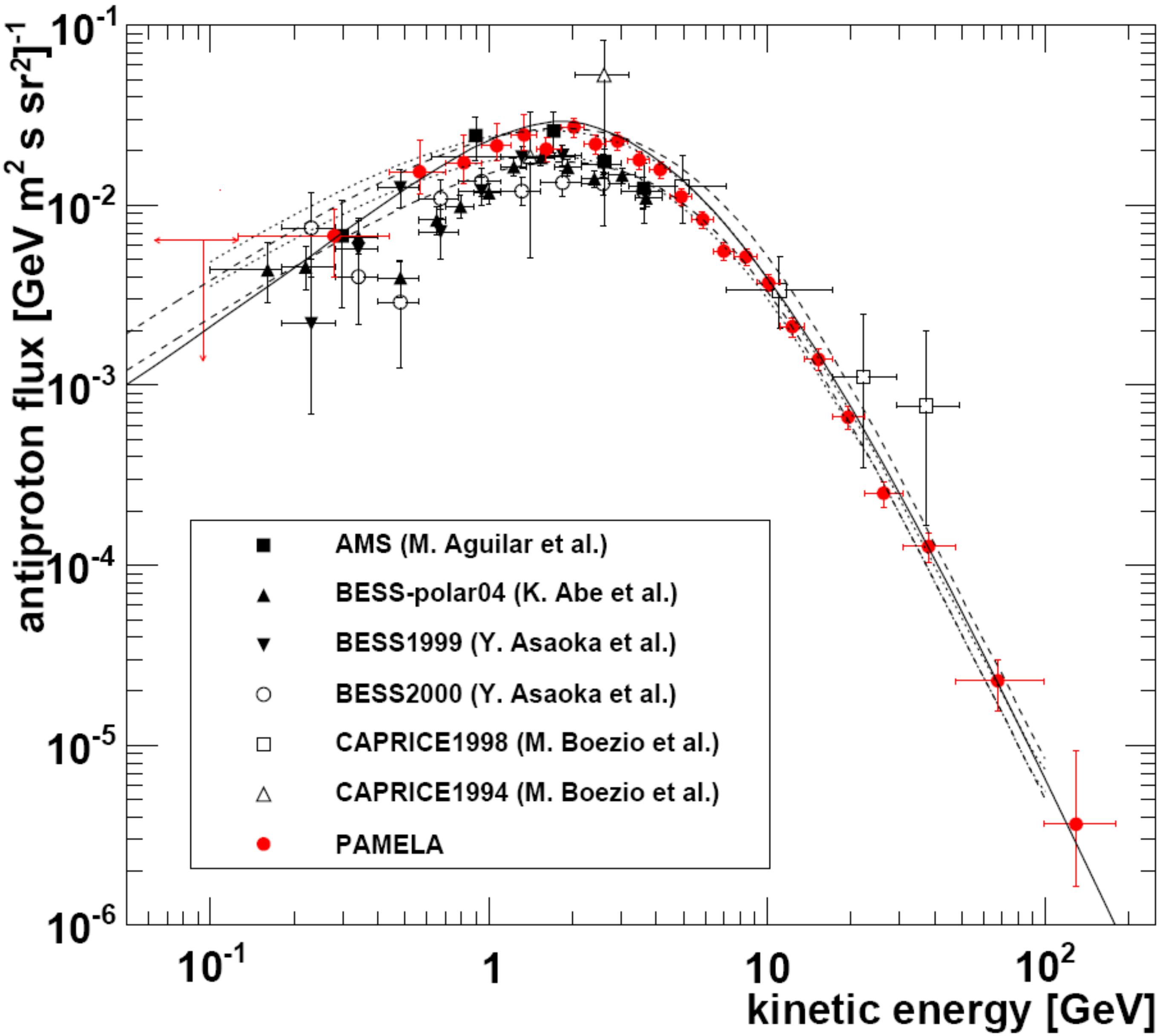


Antiproton-to-proton ratio

PRL 102 (2009), 051101 + PRL 105 (2010), 121101

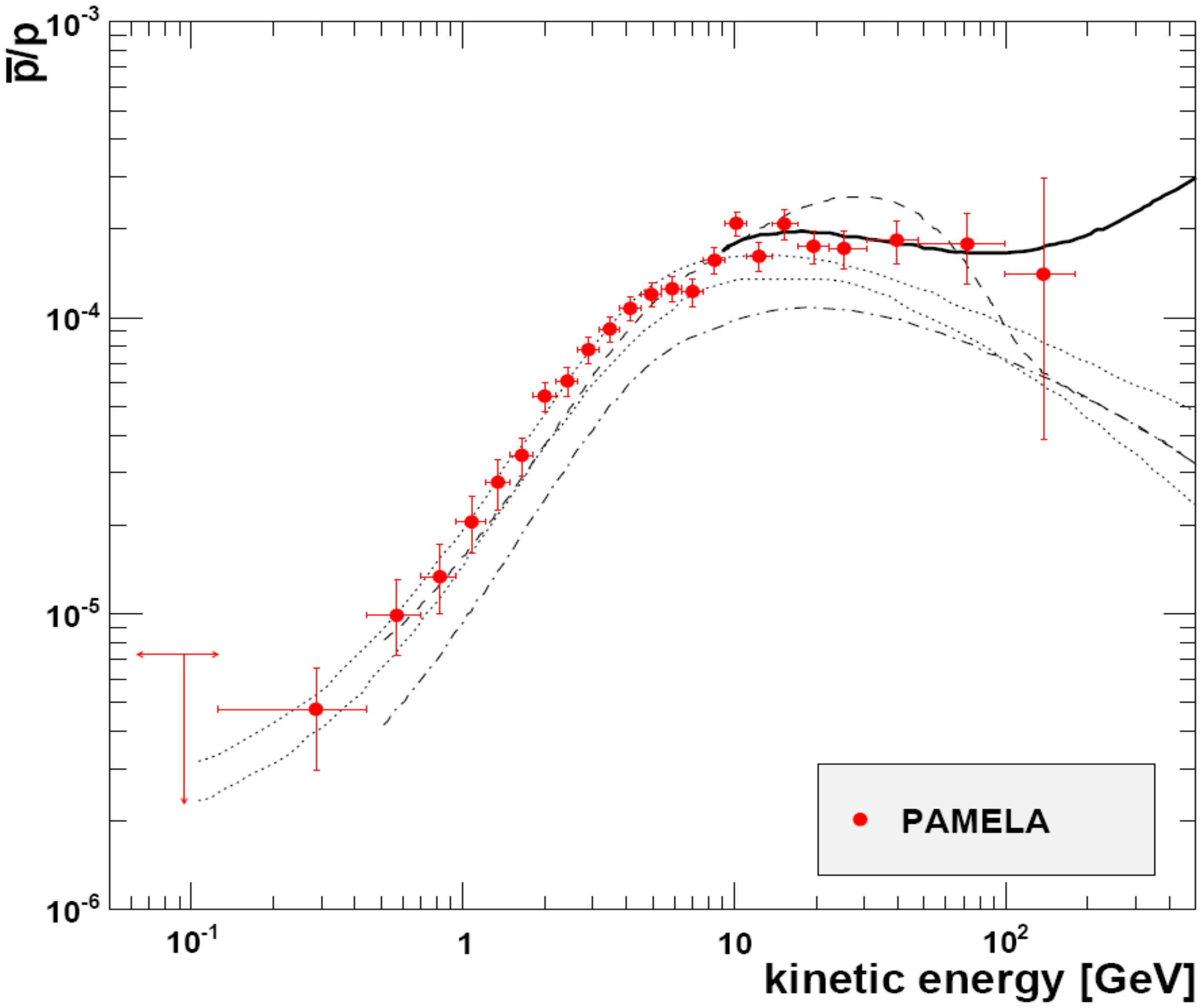


Antiproton Flux



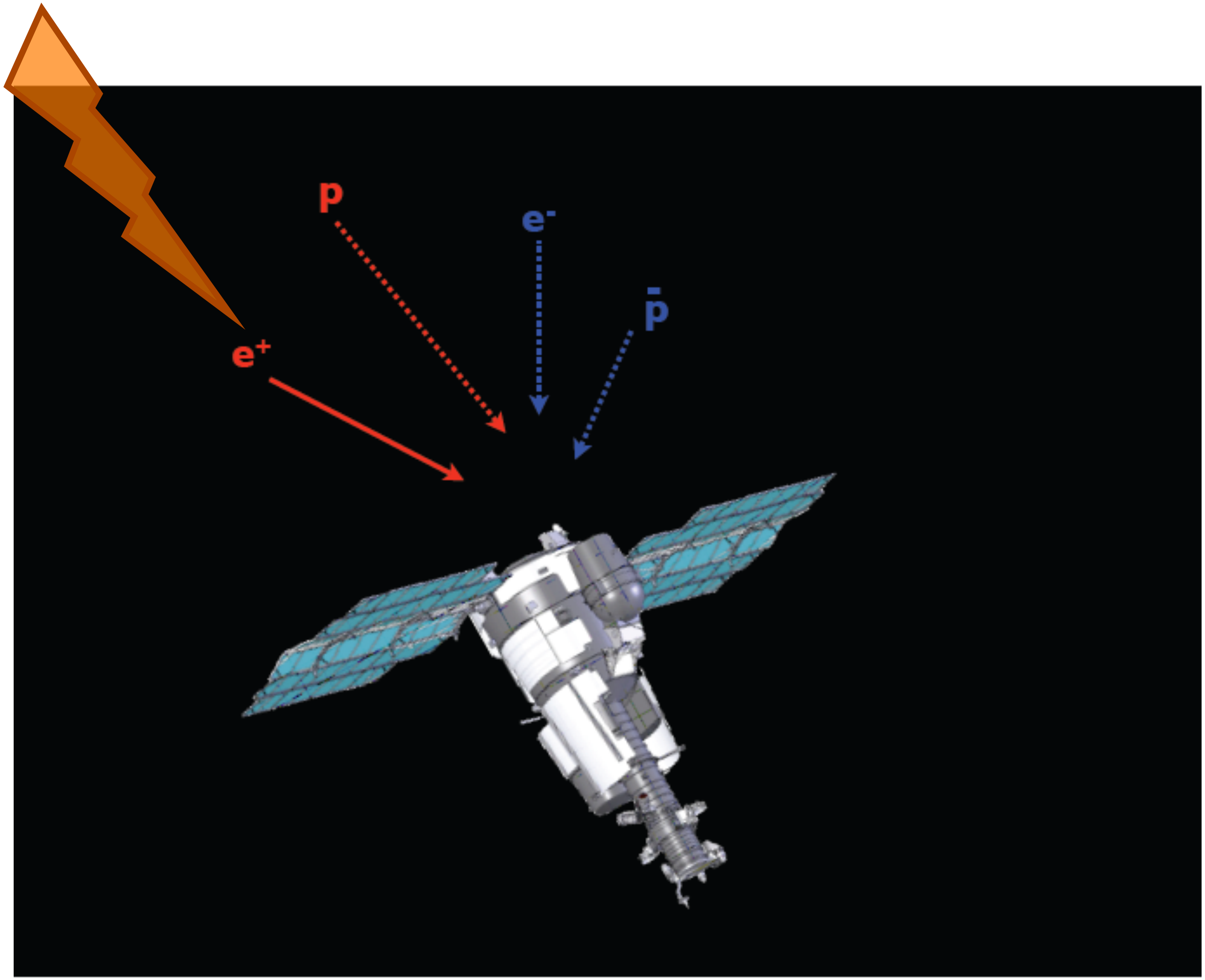
Interpretation

- 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.



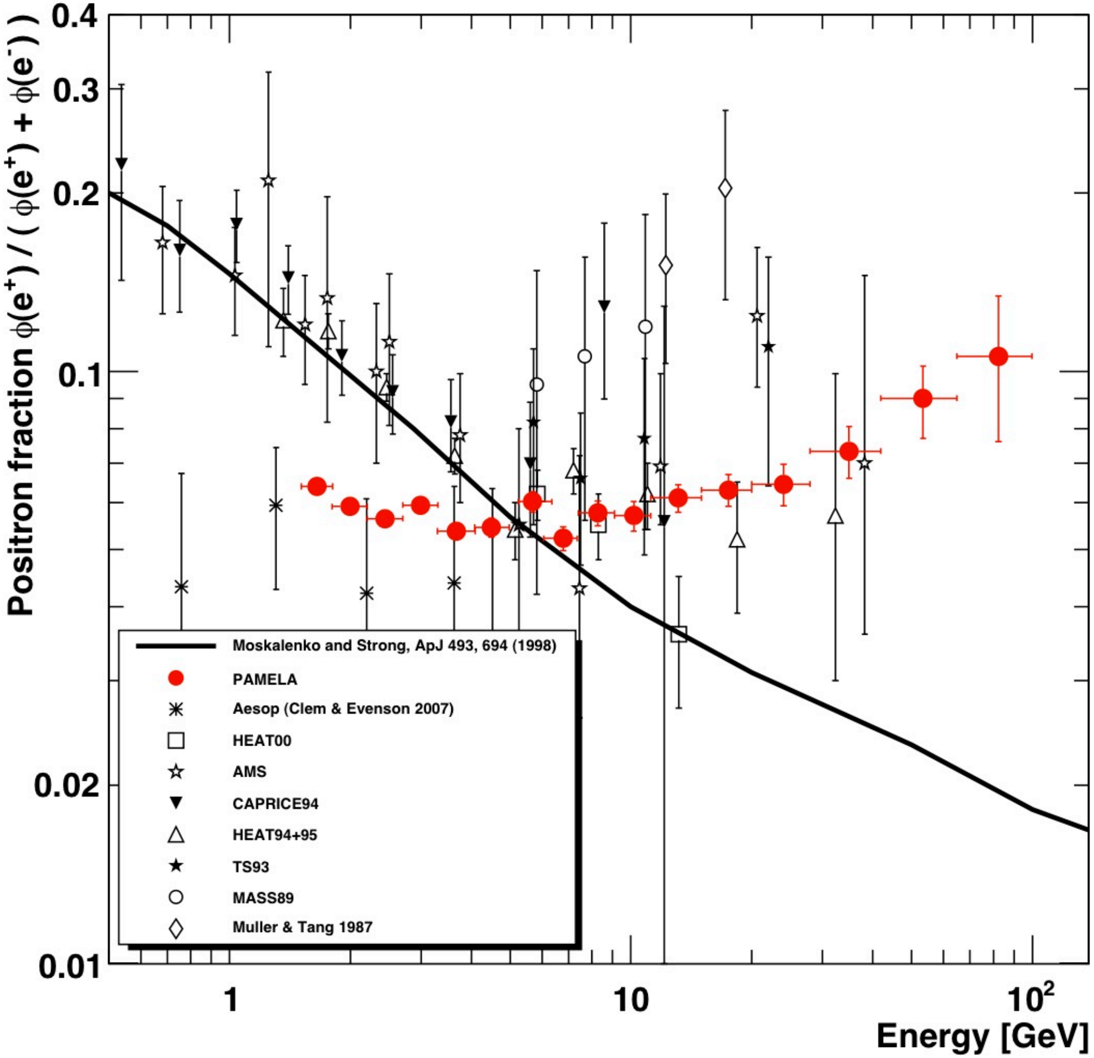
As shown by the dashed line, a reasonable choice of propagation parameters (dashed-dotted line) allows a good description of PAMELA antiproton data with the inclusion of the wino-annihilation signal. Given current uncertainties on propagation parameters, this primary component cannot be ruled out.

POSITRONS



PAMELA: POSITRON (e^+ / e^++e^-) FRACTION

NATURE 458 (2009), 697 + Astrop. Phys. 34 (2010), 1



400

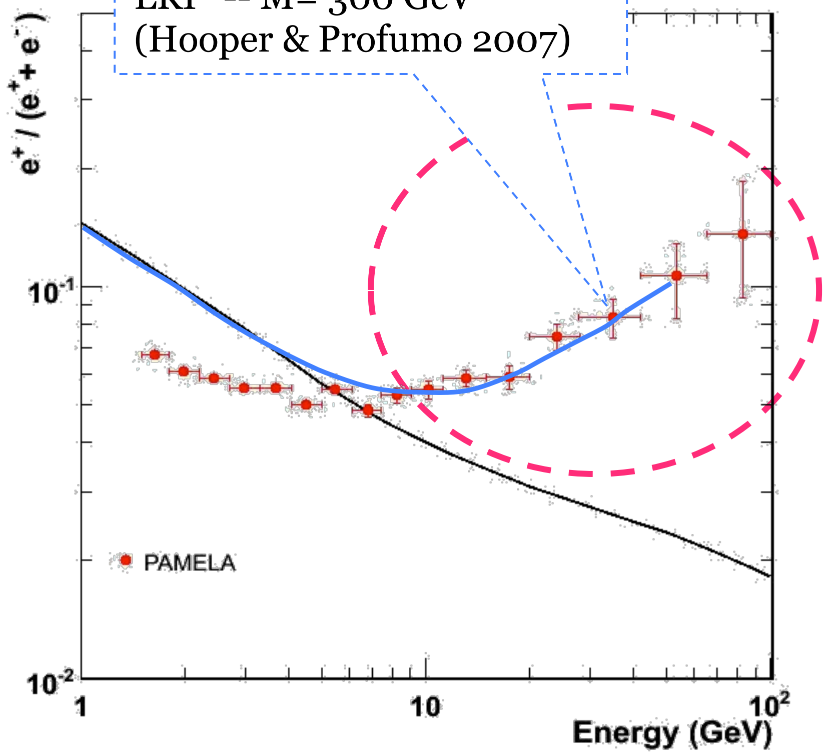
citations of this result in a year's time!

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, …)

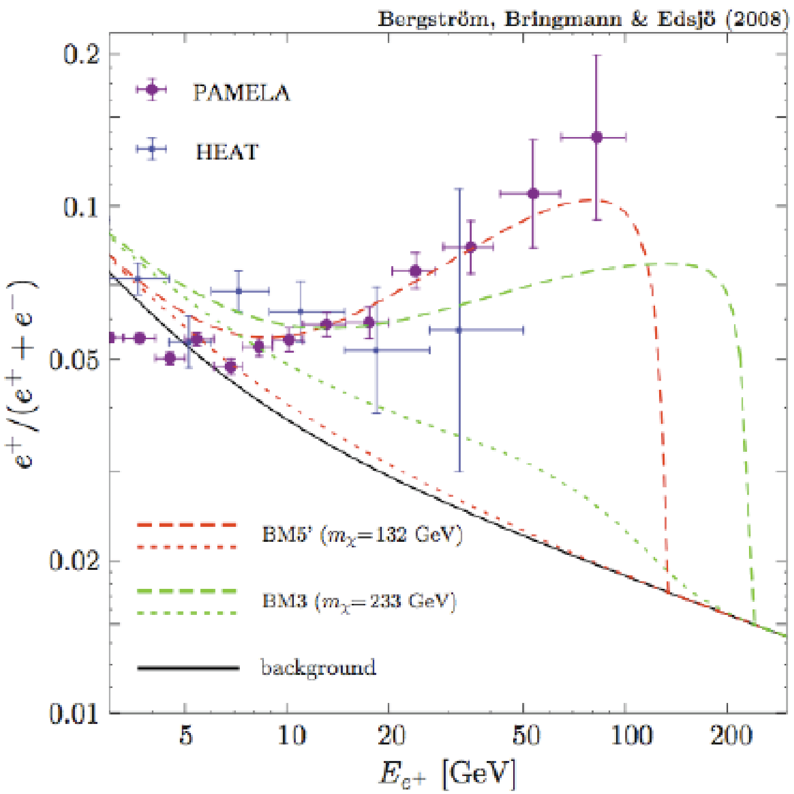
LKP -- M= 300 GeV
(Hooper & Profumo 2007)



More than 150 articles claim DM is discovered !

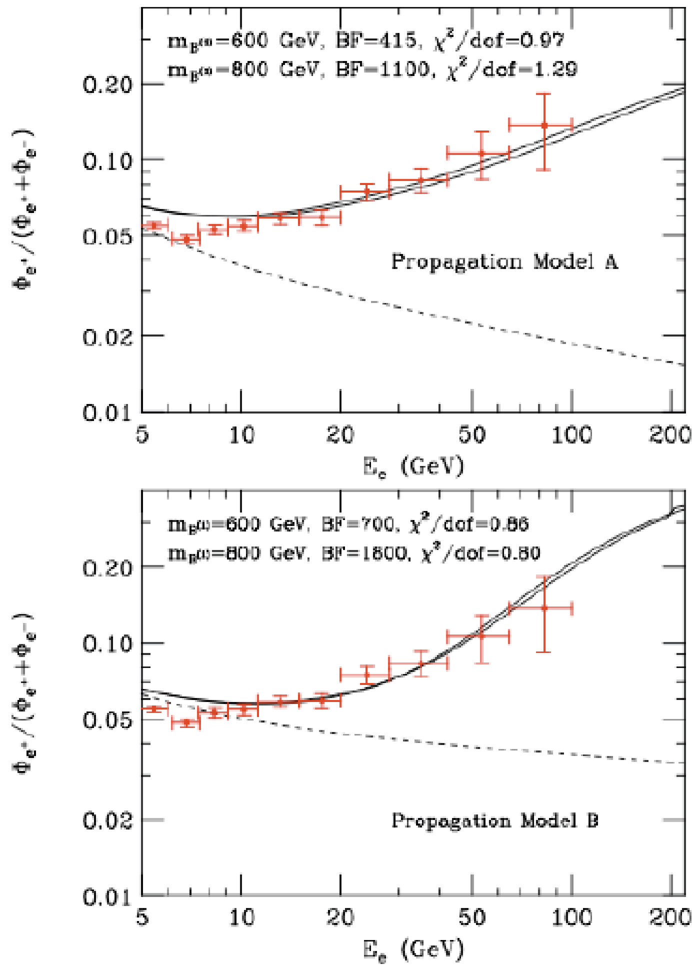
EXAMPLE: DARK MATTER

arXiv:0808.3725



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

Hooper and Zurek
arXiv:0902.0593v1

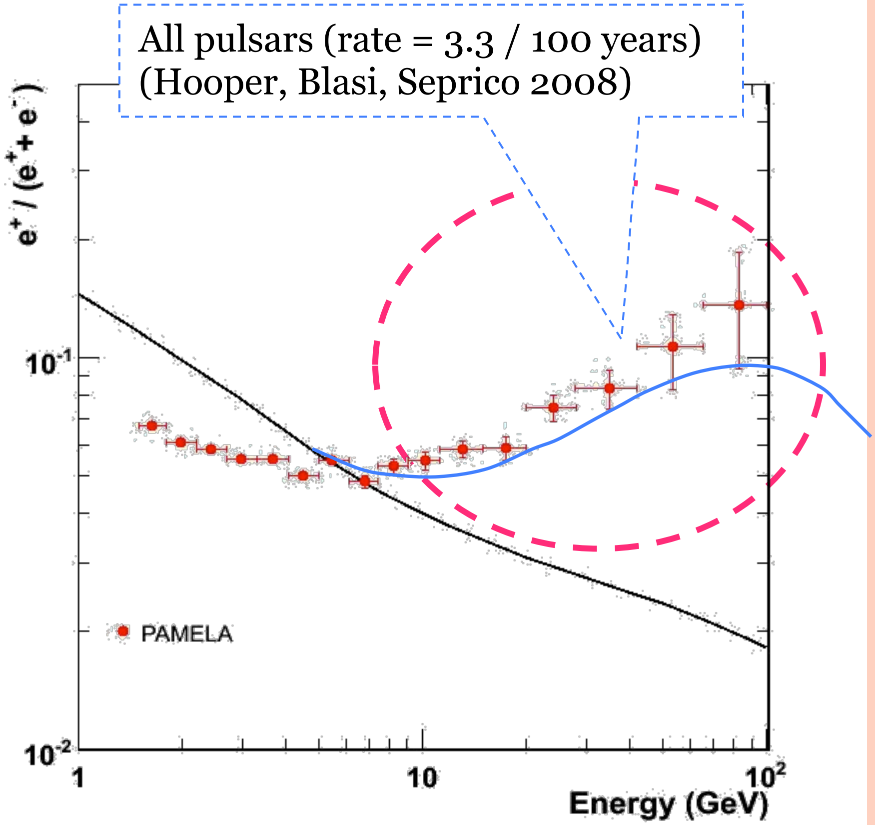


Kaluza-Klein dark matter

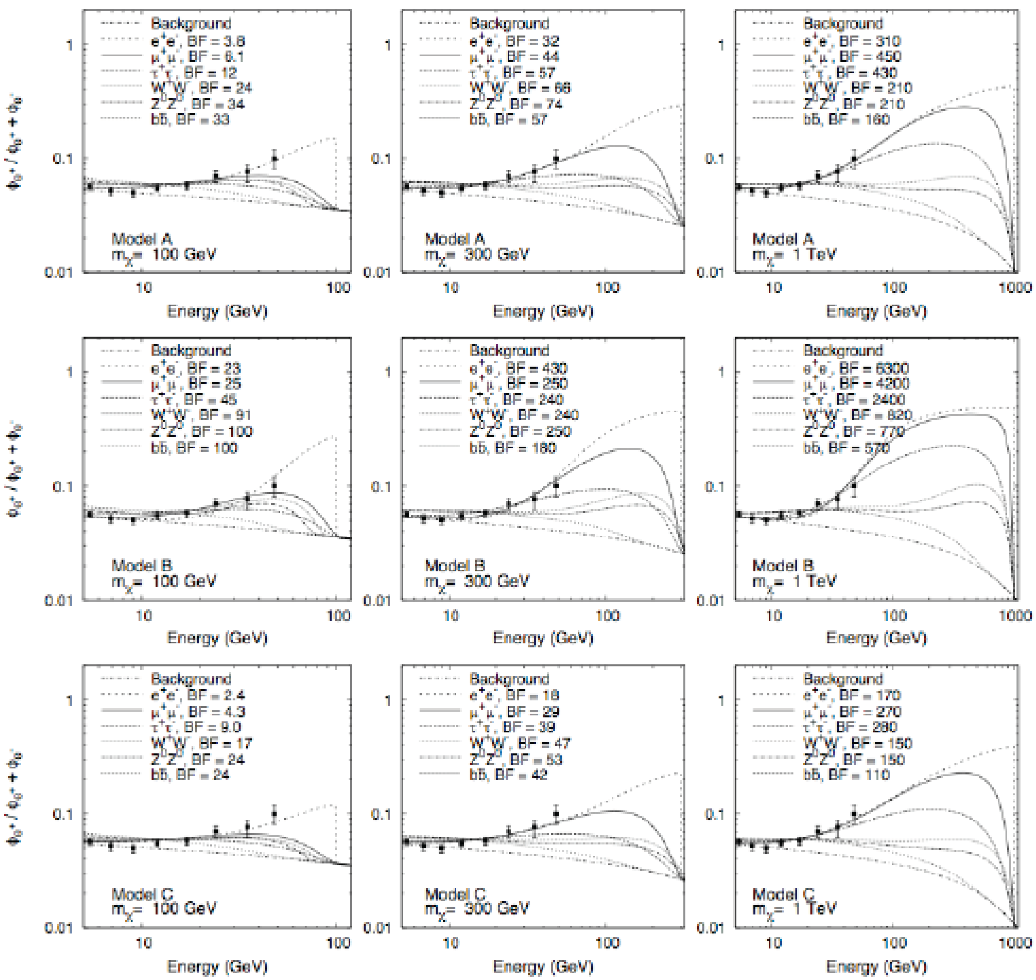
PRIMARY POSITRON SOURCES

Astrophysical processes

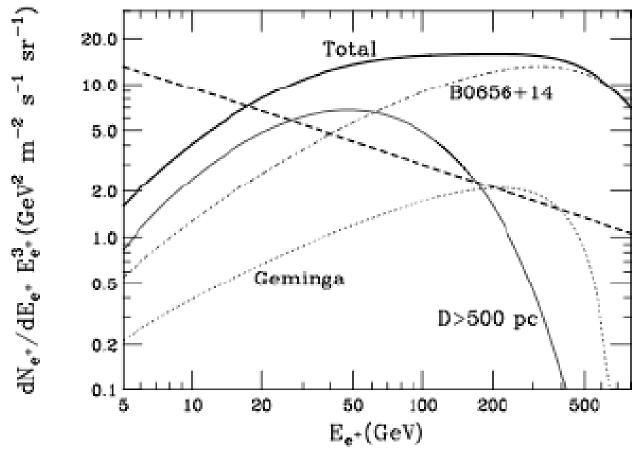
- Local **pulsars** are well-known sites of e^+e^- pair production (the spinning B of the pulsars strips e- that emit gammas then converting to pairs trapped in the cloud, accelerated and then escaping at the Poles) :
  → they can individually and/or coherently contribute to the e^+e^- galactic flux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

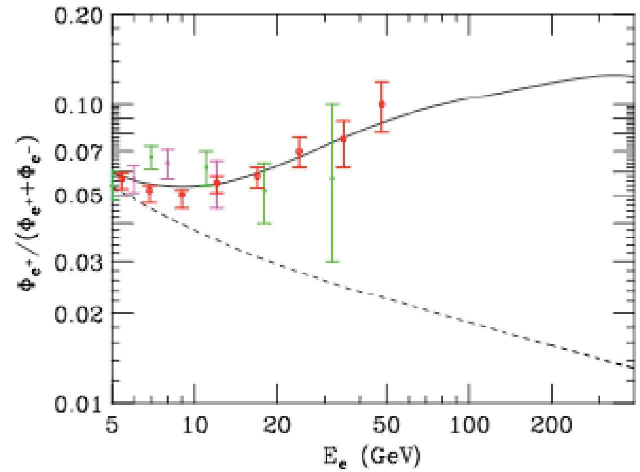


EXAMPLE: PULSARS



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





Hooper, Blasi, and Serpico
arXiv:0810.1527

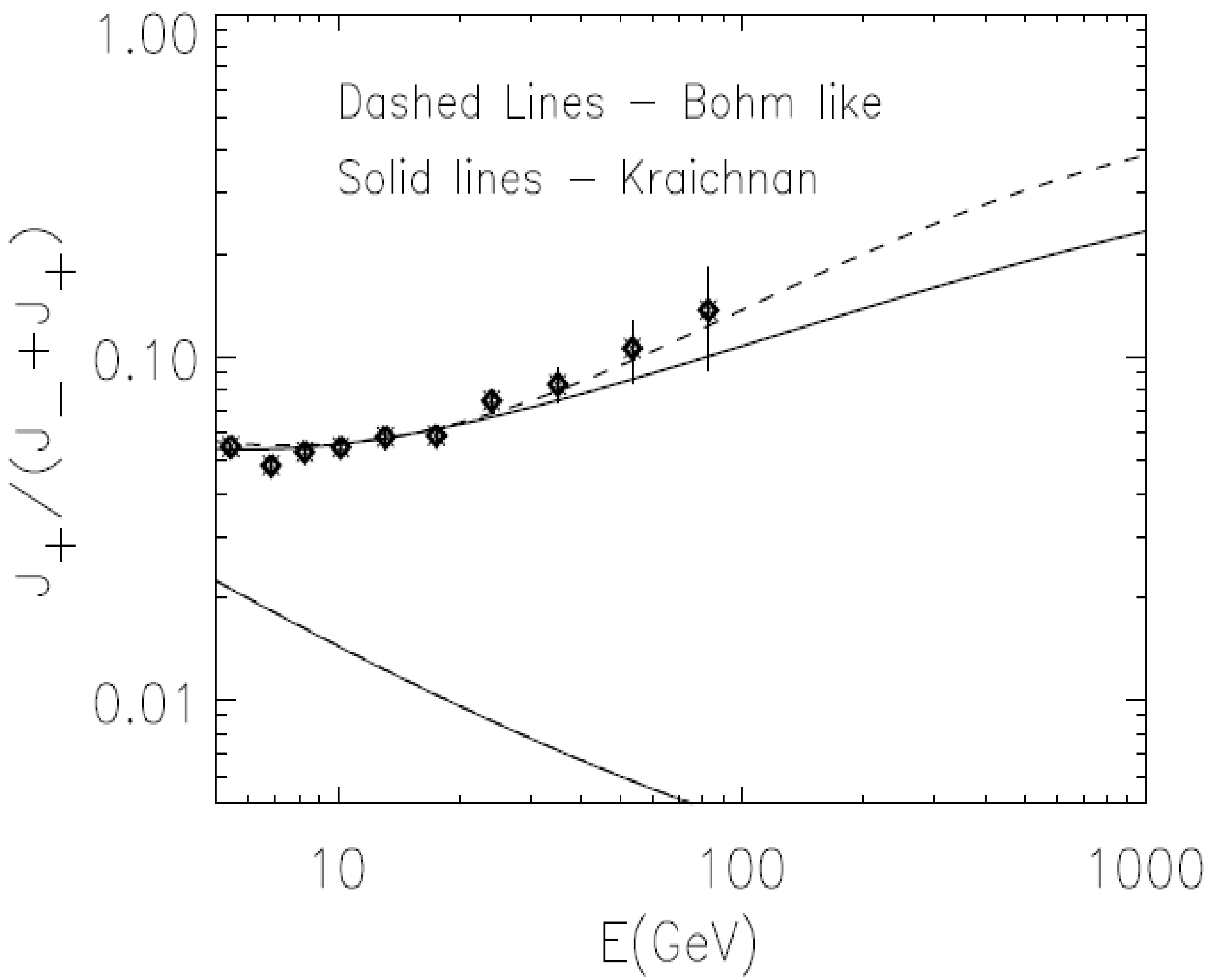
Revision of standard CR model

- Pairs created also in the acceleration sites (e.g. in old SNRs): in standard model, only primary CRs are accelerated in SNRs. In reality, secondary production takes place also in the acceleration sites;

- Distribution of CR sources not homogeneus (SNRs more in spiral arms): the assumption of homogenous distribution of SNRs is not valid for electrons, which reach us from a small distance where inhomogeneity can play an important role.

POSITRONS FROM OLD SNR'S

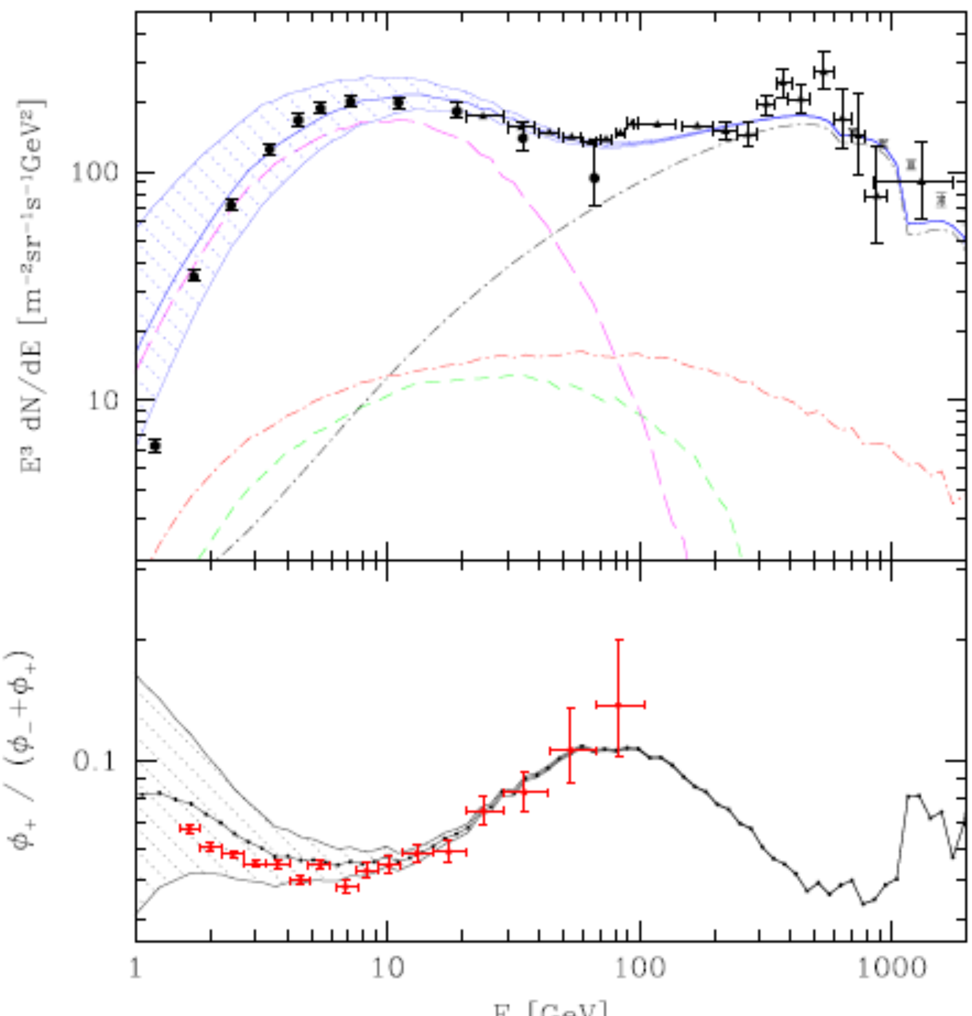
P. BLASI , PRL 103, 051104 (2009)



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



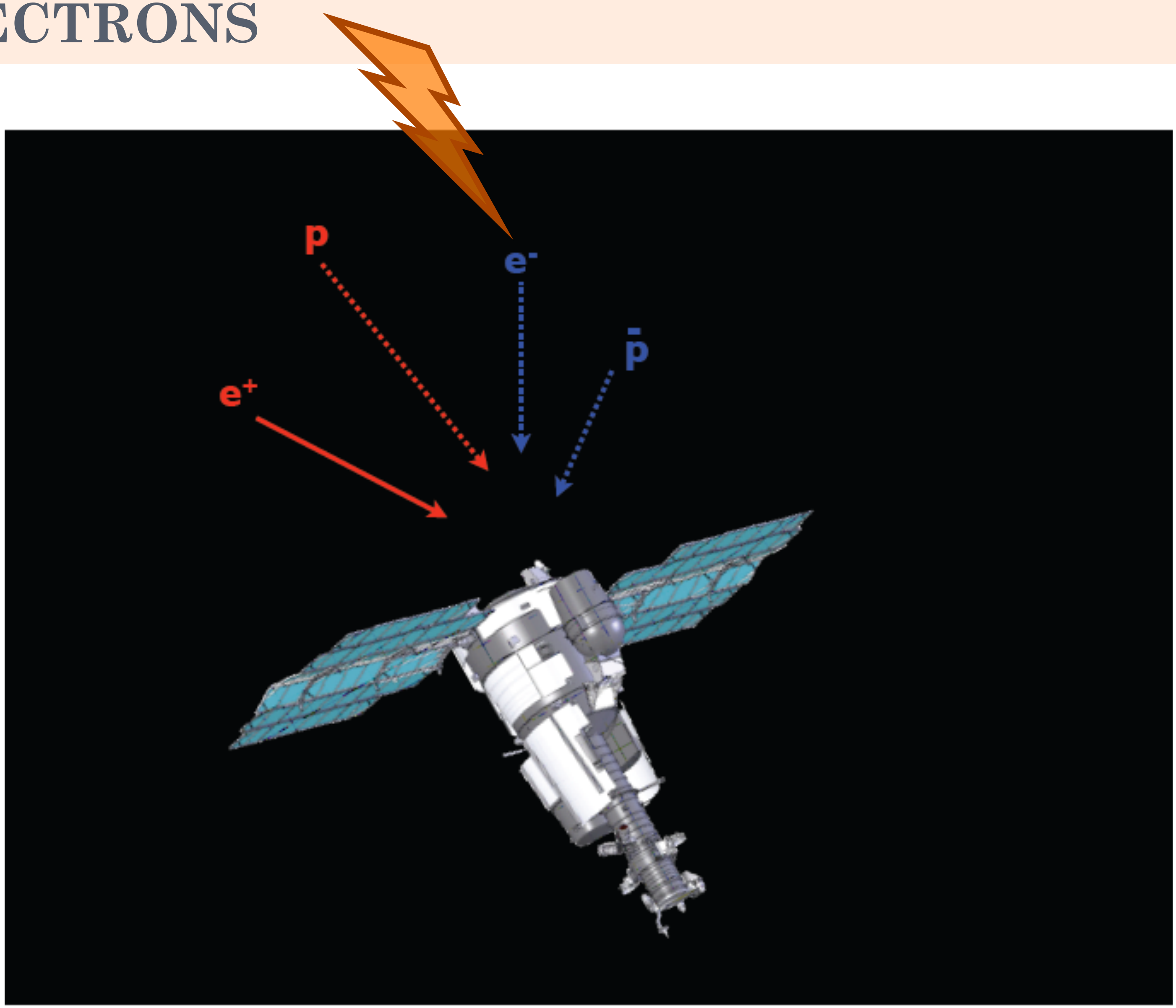
HOW TO CLARIFY THE MATTER?

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)

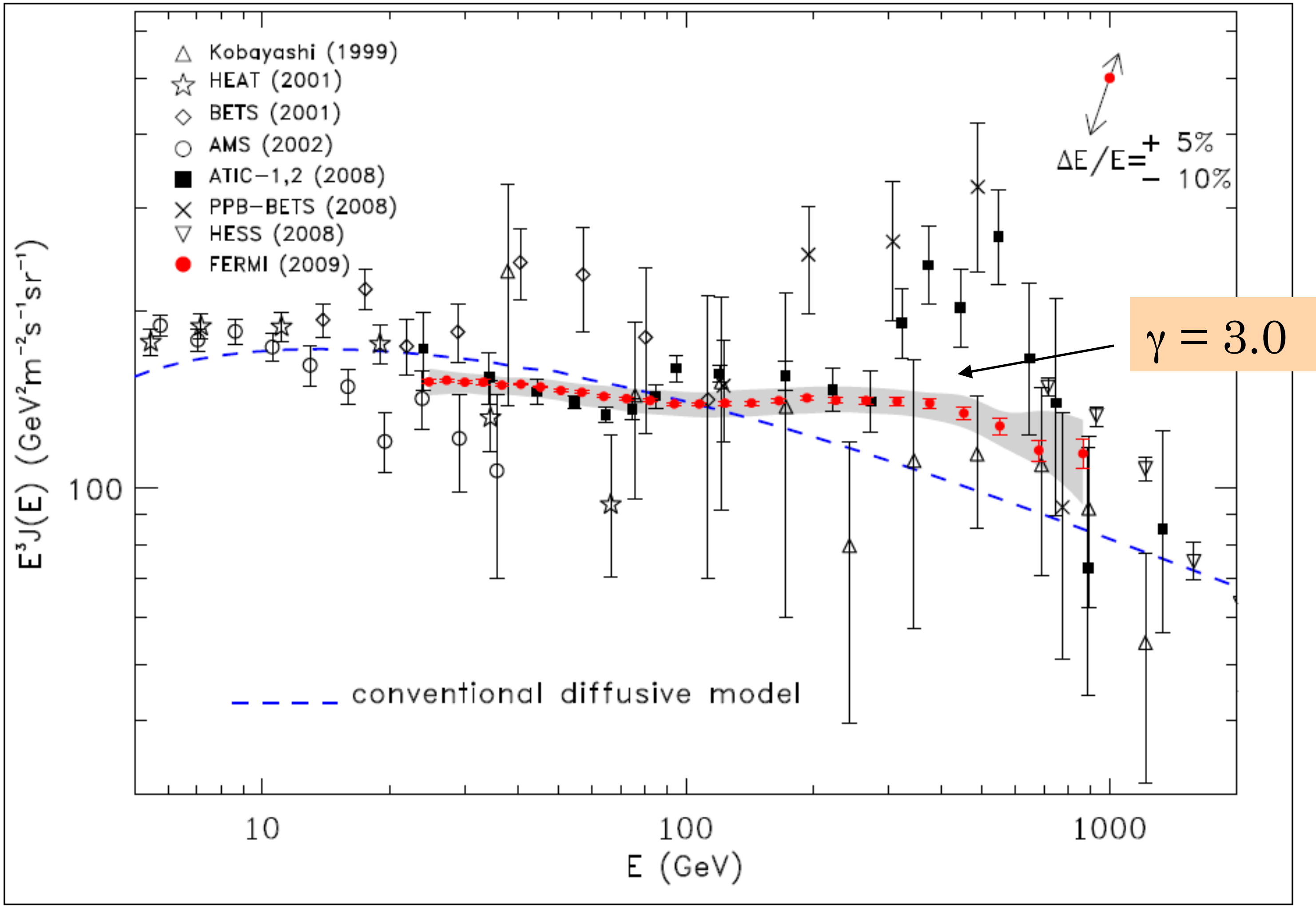
Courtesy of J. Edsjo

Electrons



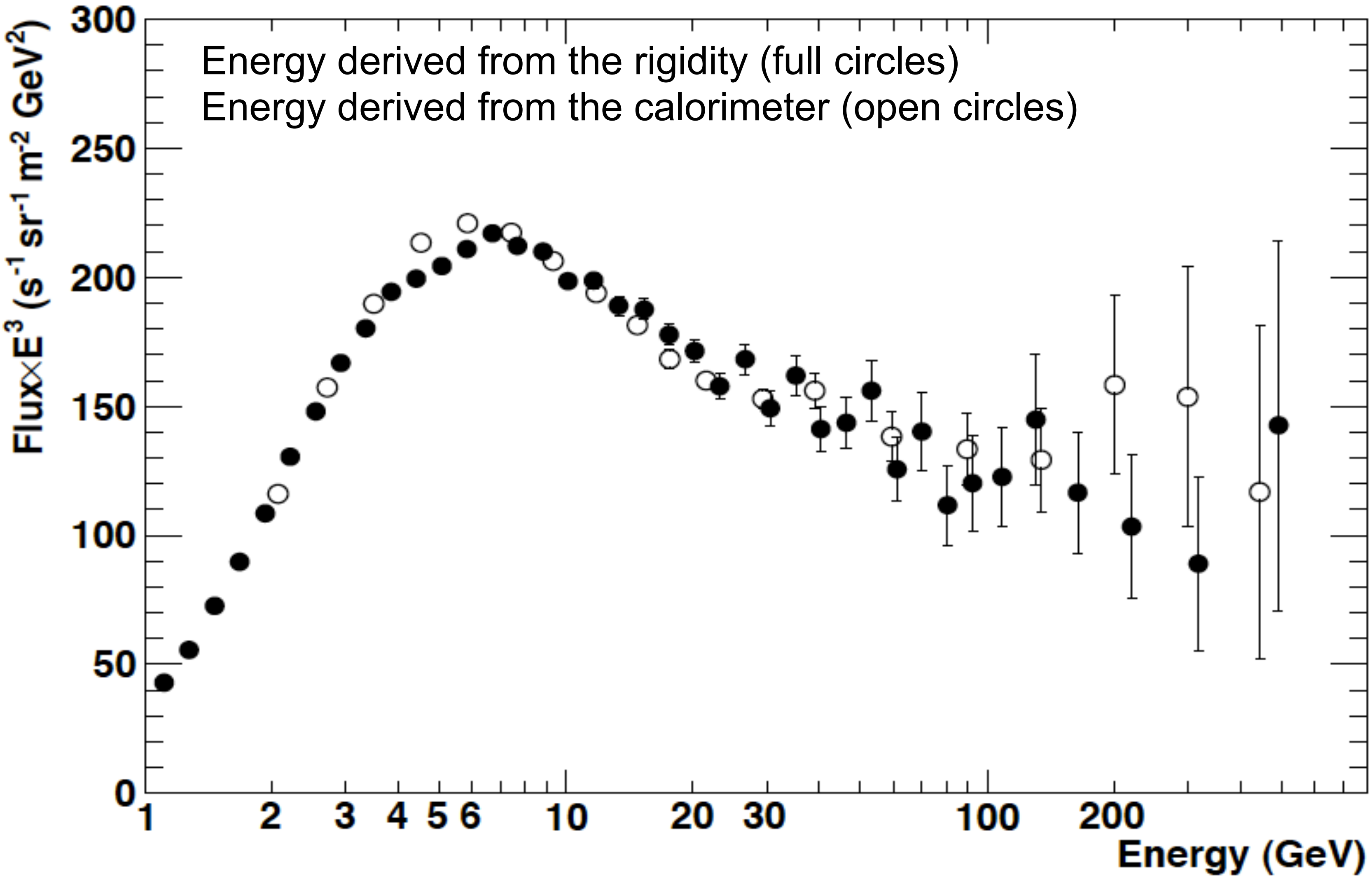
Any positron source is an electron source too …

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



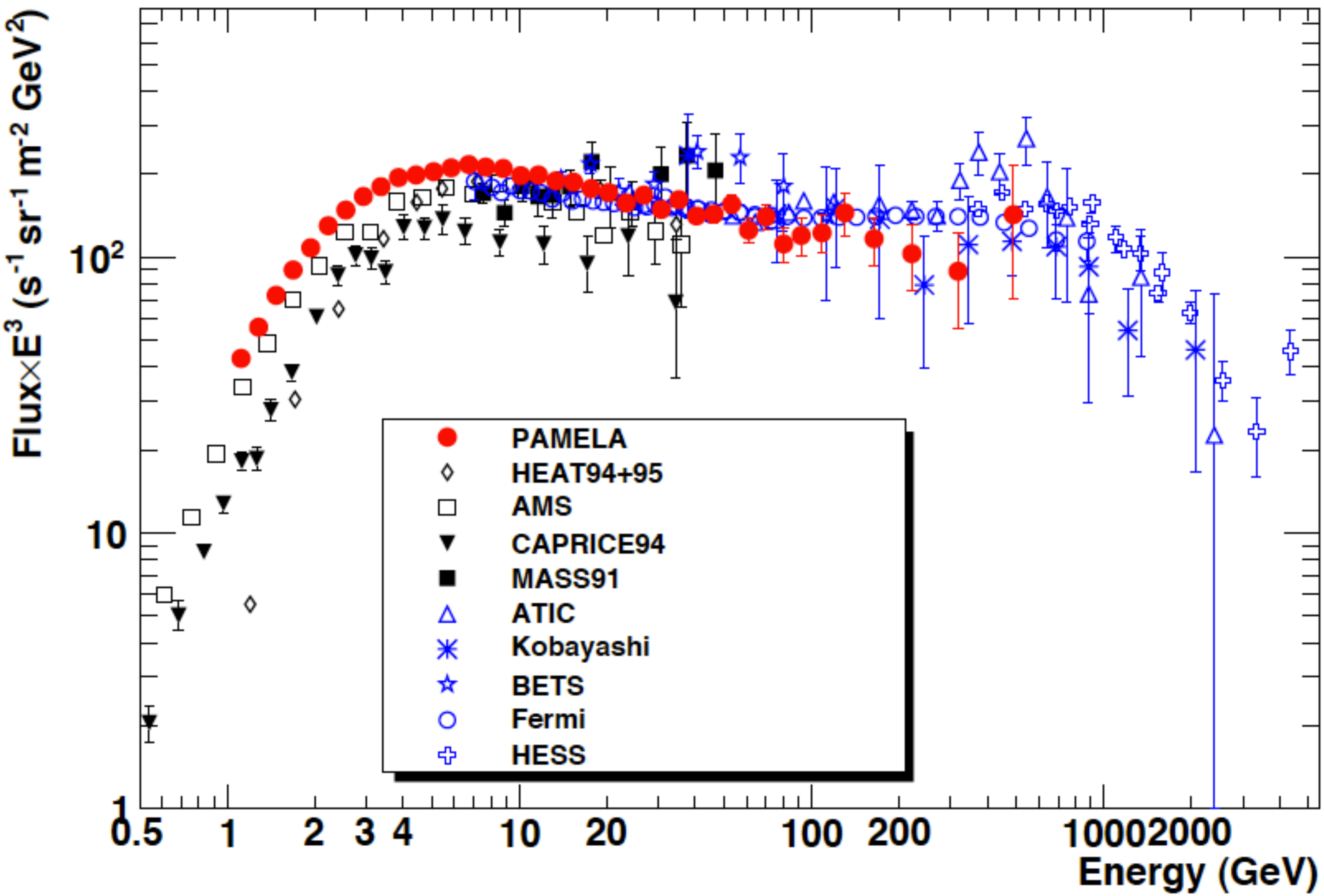
FERMI does not confirm the ATIC bump
but finds an excess wrt conventional diffusive models

PAMELA negative Electron (e^-) Spectrum

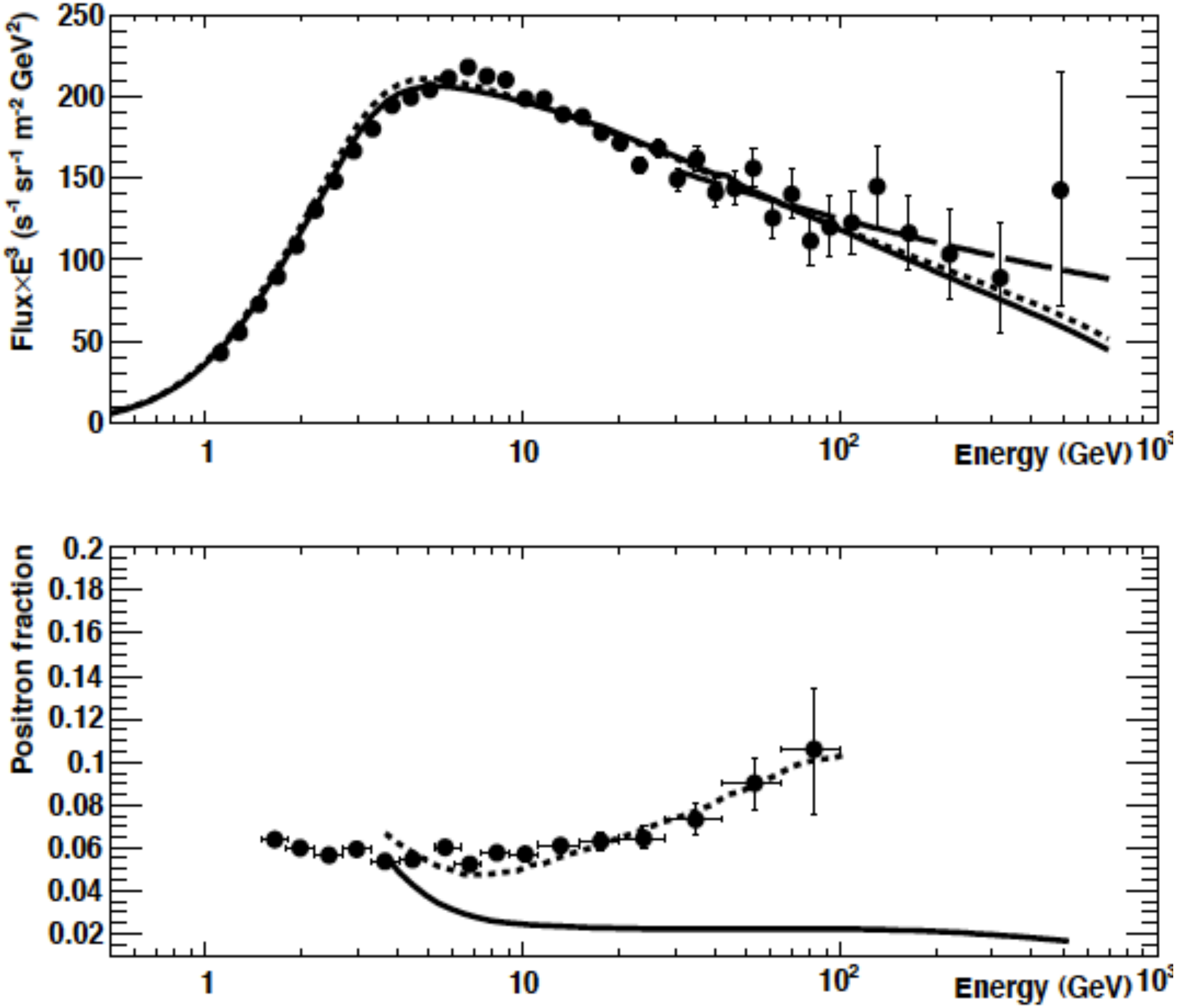


Submitted to PRL

PAMELA Electron (e⁻) Spectrum



Best Fit to the Electron Data



Solid line (top&bottom): Standard GALPROP calculation with reacceleration (tuned on P and He PAMELA data).

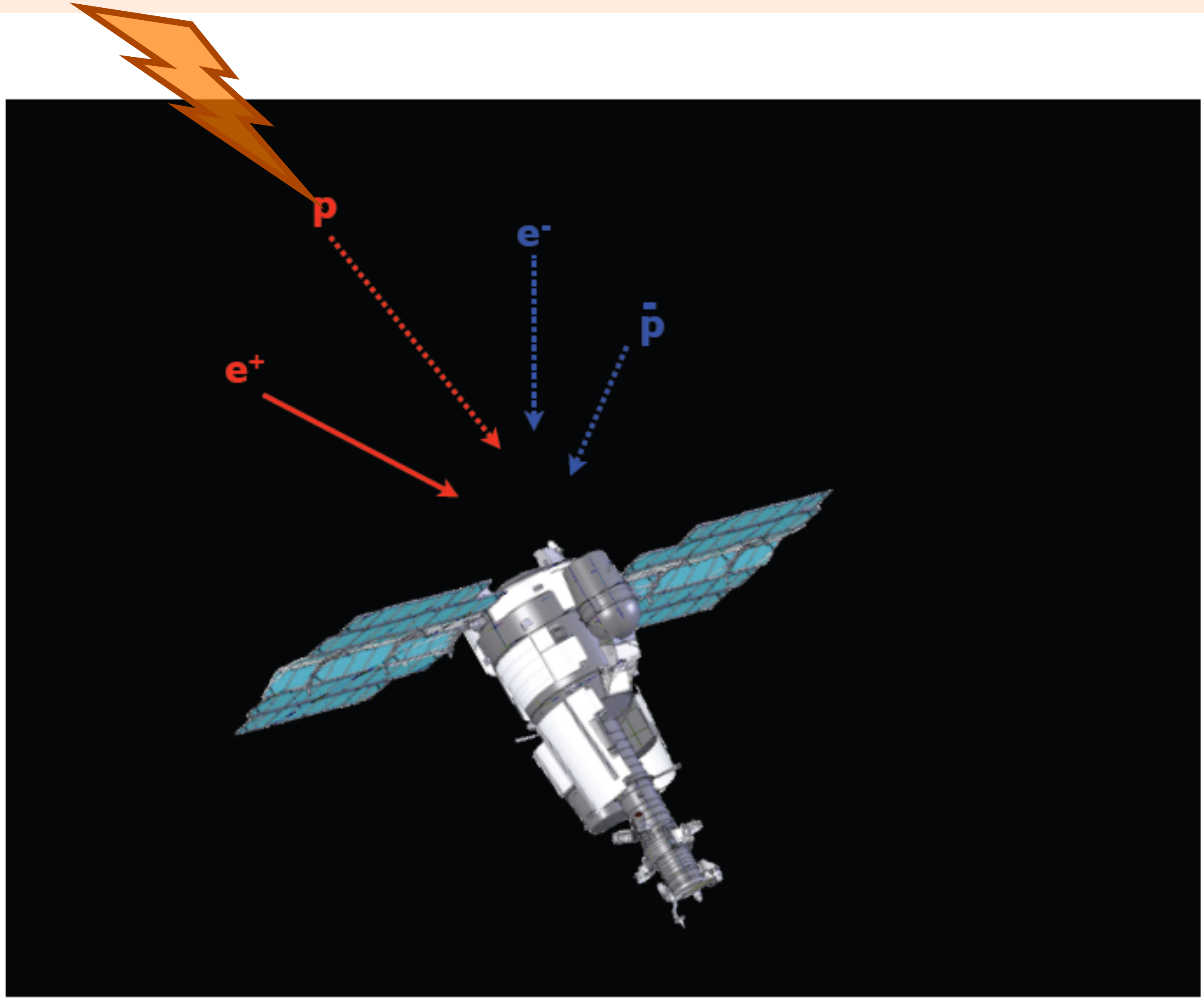
Dashed line (top): Single power-law fit to The data abive 30 GeV (gamma= - 3.18)

Dotted line (top&bottom): Same GALPROP calculation with additional cosmic-ray electron (and positron) component

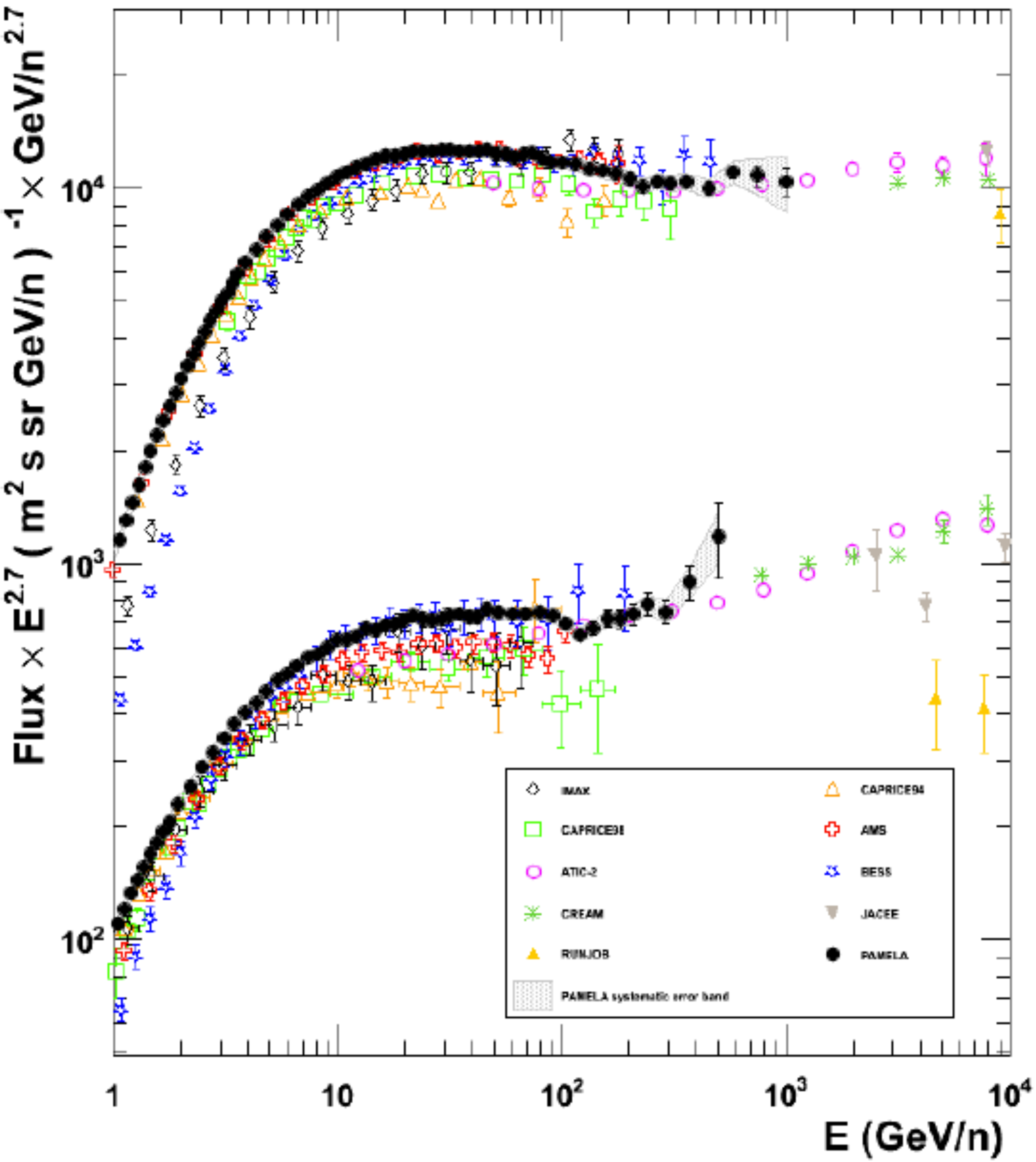
INTERPRETATION

- PAMELA electron data not inconsistent with standard production and propagation models;
- Some level of incompatibility between the data suggest a revision of the models;
- The best fit is obtained when a new electron (and positron) source, with a standard single power-lae spectrum, is included. This accomodates PAMELA electron and positron (and p and He) results.

Protons and Heliums



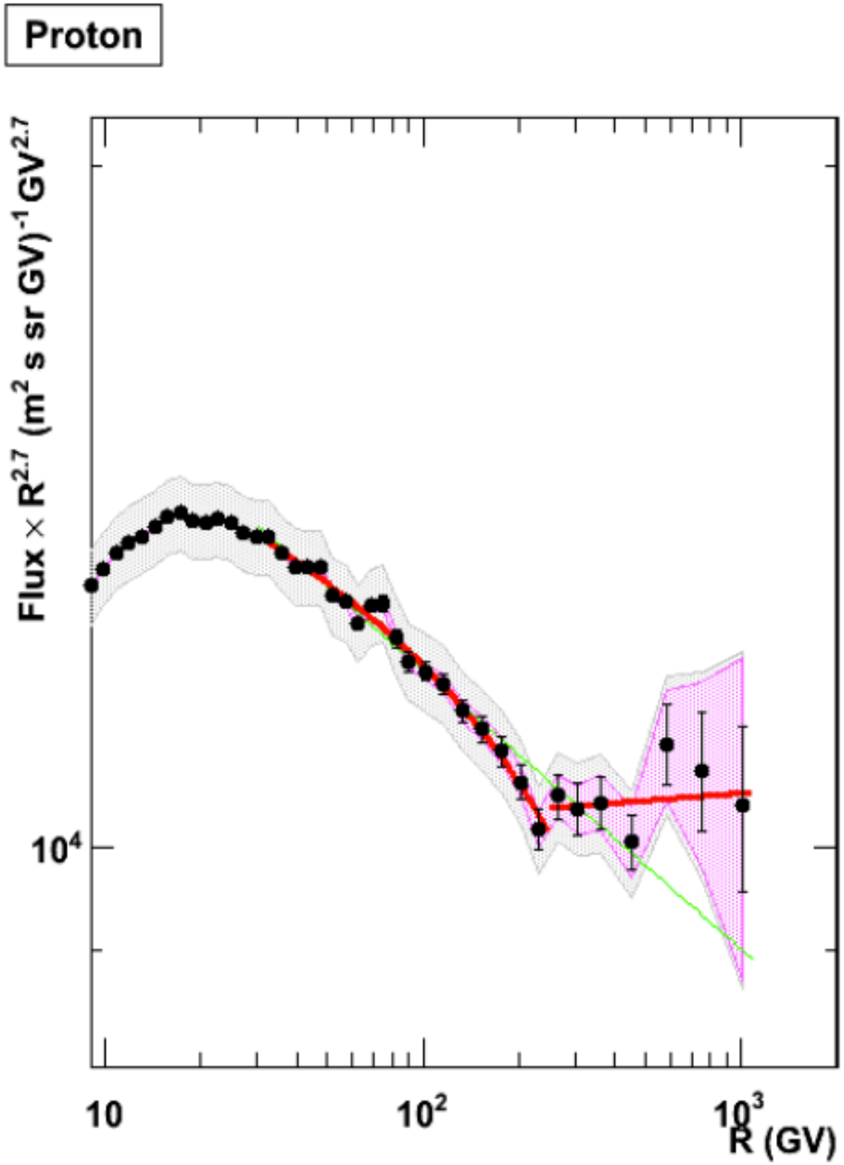
PAMELA Proton and Helium flux

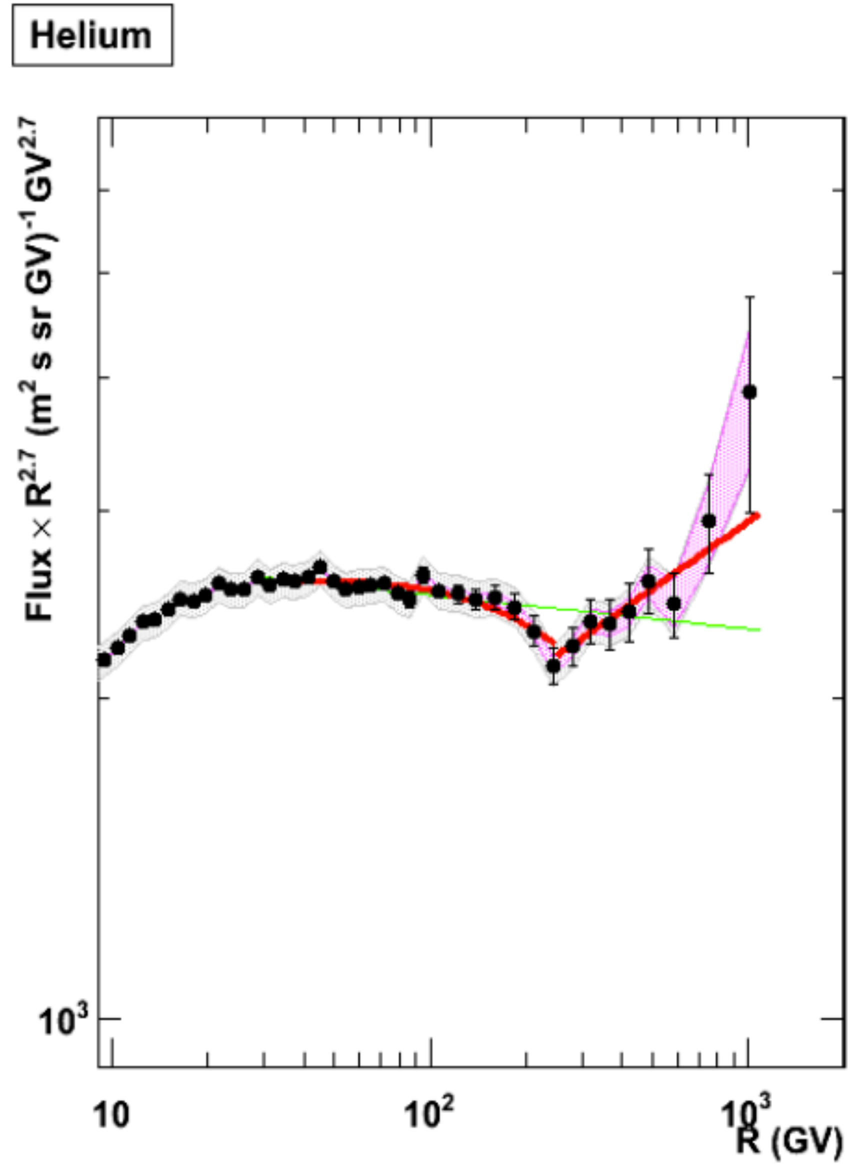


Accepted by SCIENCE
In press

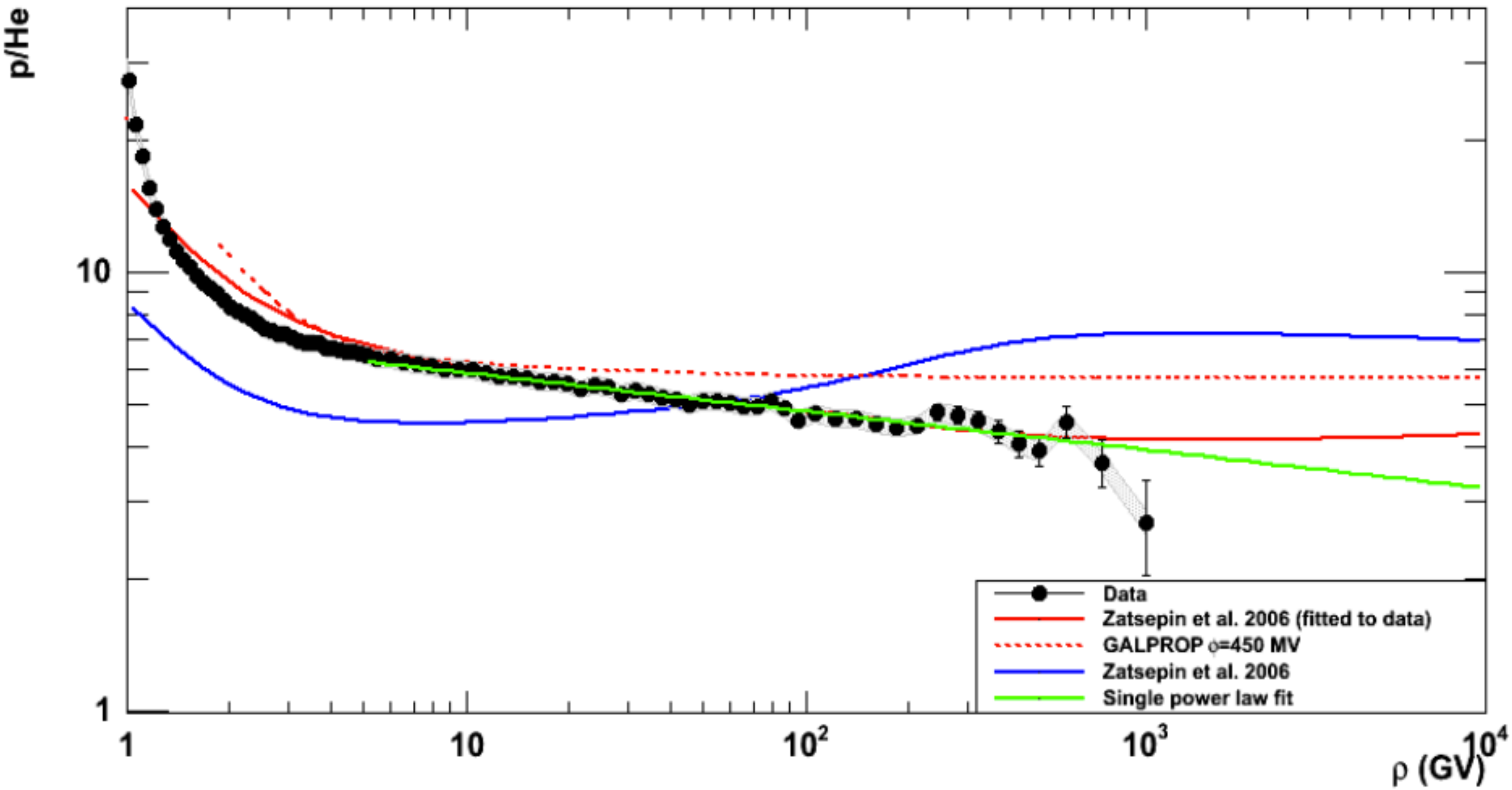
Hardening of the proton and helium spectra at 200 GV, corresponding to 200 GeV for p and 100 GeV/n for He

FIT WITH 2 SPECTRAL INDEXES





PROTON/HELIUM RATIO



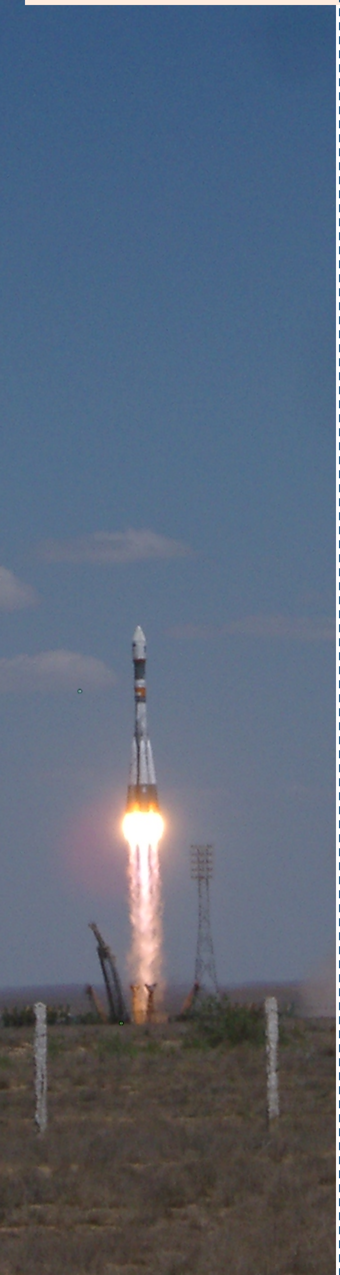
Different from what assumed so far, p and He do not have the same spectral index, but their ratio decreased monotonically

$$\Delta_\gamma = \gamma_p - \gamma_{he} = 0.101 \pm 0.0014(stat) \pm 0.0001(sys)$$

STILL TO COME ….

- Absolute **<u>positron flux</u>** (easily derived by the positron fraction and electron flux…);
- **<u>Light nuclei</u>** <u>fluxes</u> **<u>and secondary/primary</u>** <u>ratios</u>;
- Effects of **solar modulation** on low-energy CR fluxes;
- Magnetospheric physics (SAA, Van Allen belts)
- …….

SUMMARY



Interesting features in cosmic rays seen by PAMELA in 4 years analysis

PAMELA data are showing complex mechanisms in CR production and propagation models:

- **Positron fraction:** need an additional source, or additional mechanisms of secondary particle acceleration;
- **Electron flux:** spectrum up to ~ 650 GeV shows spectral features that may point to additional components;
- **Proton and Helium fluxes**: hardening of the spectra at high energies (effects on the yield of secondary particles at high energies!!), and different spectral indexes among the two (different acceleration mechanisms?).

All data can be still explained in terms of standard astrophysics and CR production and propagation

Still room for exotic solutions