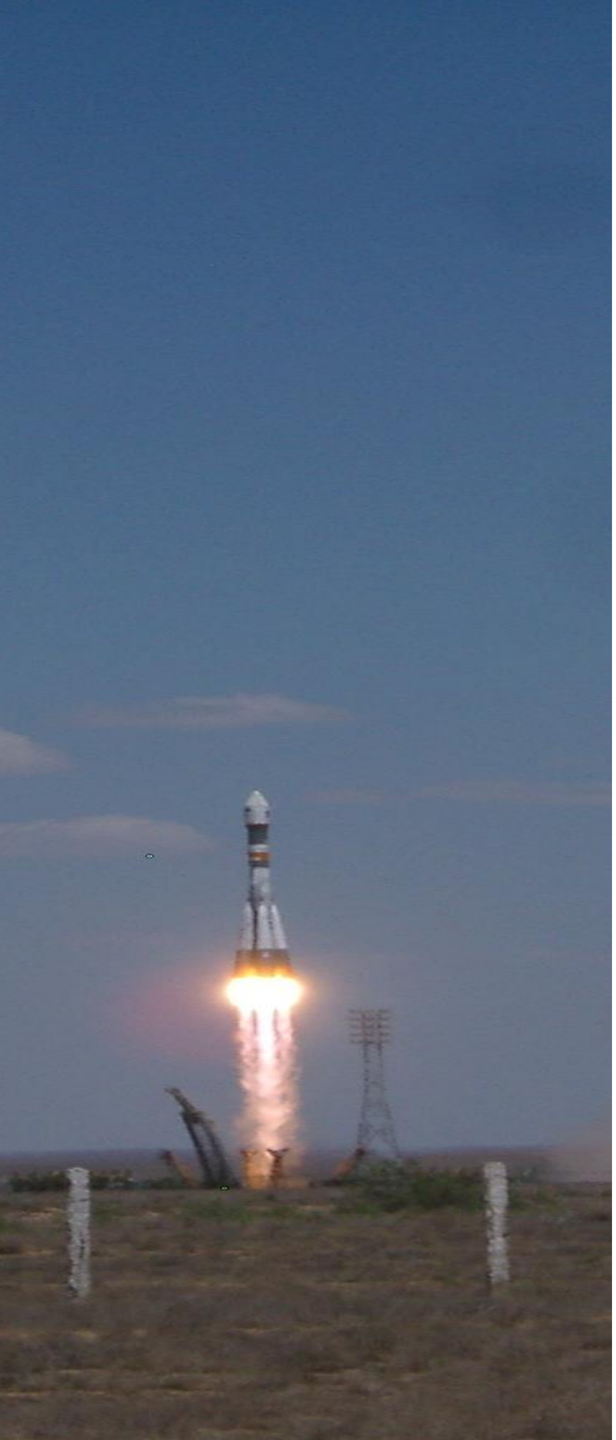


The PAMELA experiment and antimatter in the Universe

Mirko Boezio

INFN Trieste, Italy

On behalf of the PAMELA collaboration

Leap 2013, Uppsala

June 10th 2013

A Century of Cosmic Rays

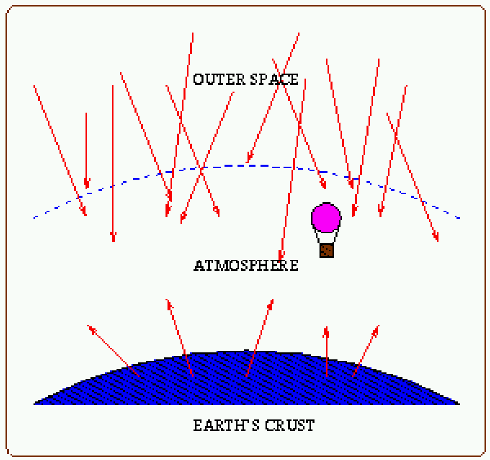
• Victor Hess ascended to 5000 m in a balloon in 1912

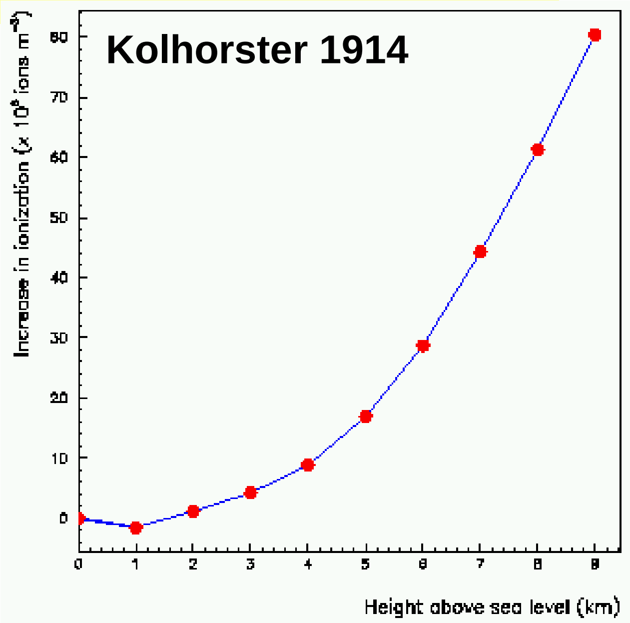
• ... and noticed that his electroscope discharged more rapidly as altitude increased

• Not expected, as background radiation was thought to be terrestrial. Extraterrestrial origin, confirming previous hints by Theodore Wulf and Domenico Pacini

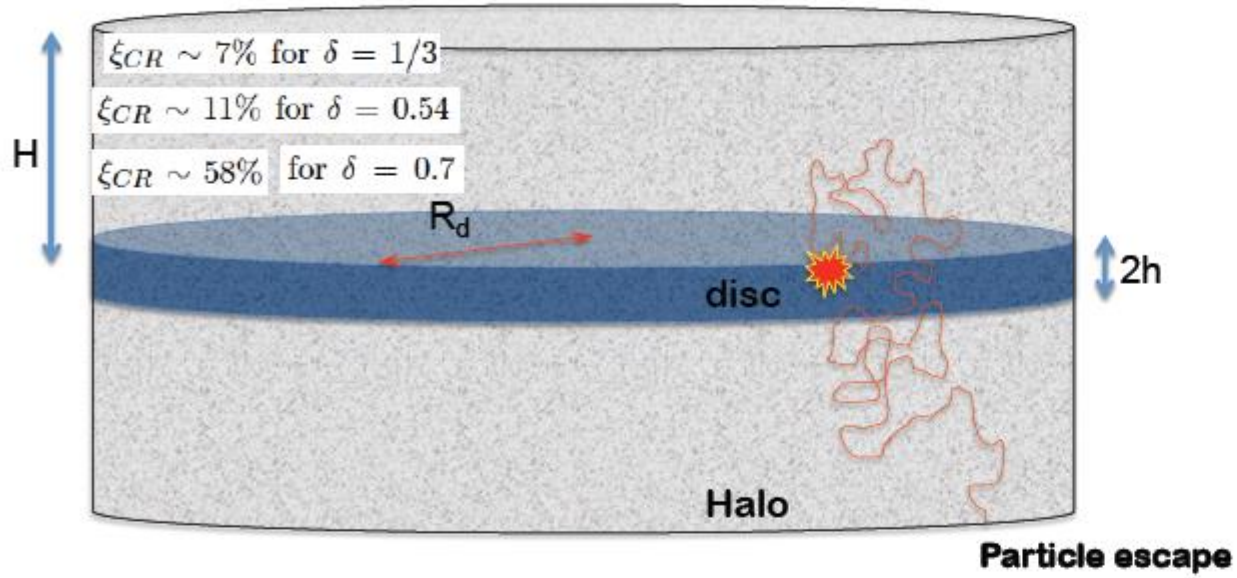
•1934: CR association to SNe proposed on energetic grounds (Baade and Zwicky)
  ○Almost 80 years later evidence is still circumstantial

•Late 70's: Diffusive shock accelerations is proposed (Krymskii 77, Bell 78)





Pillars of the SNR paradigm

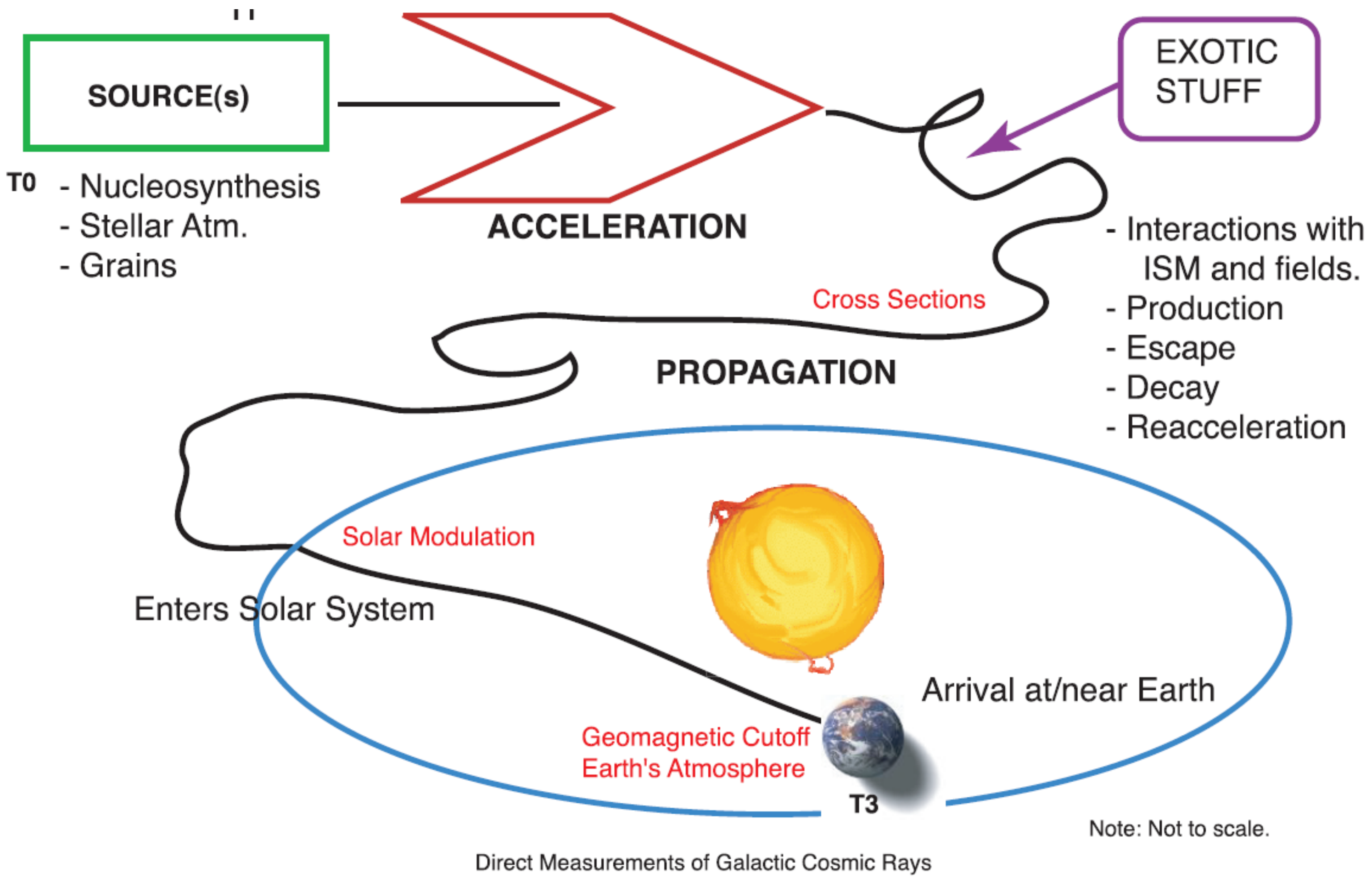


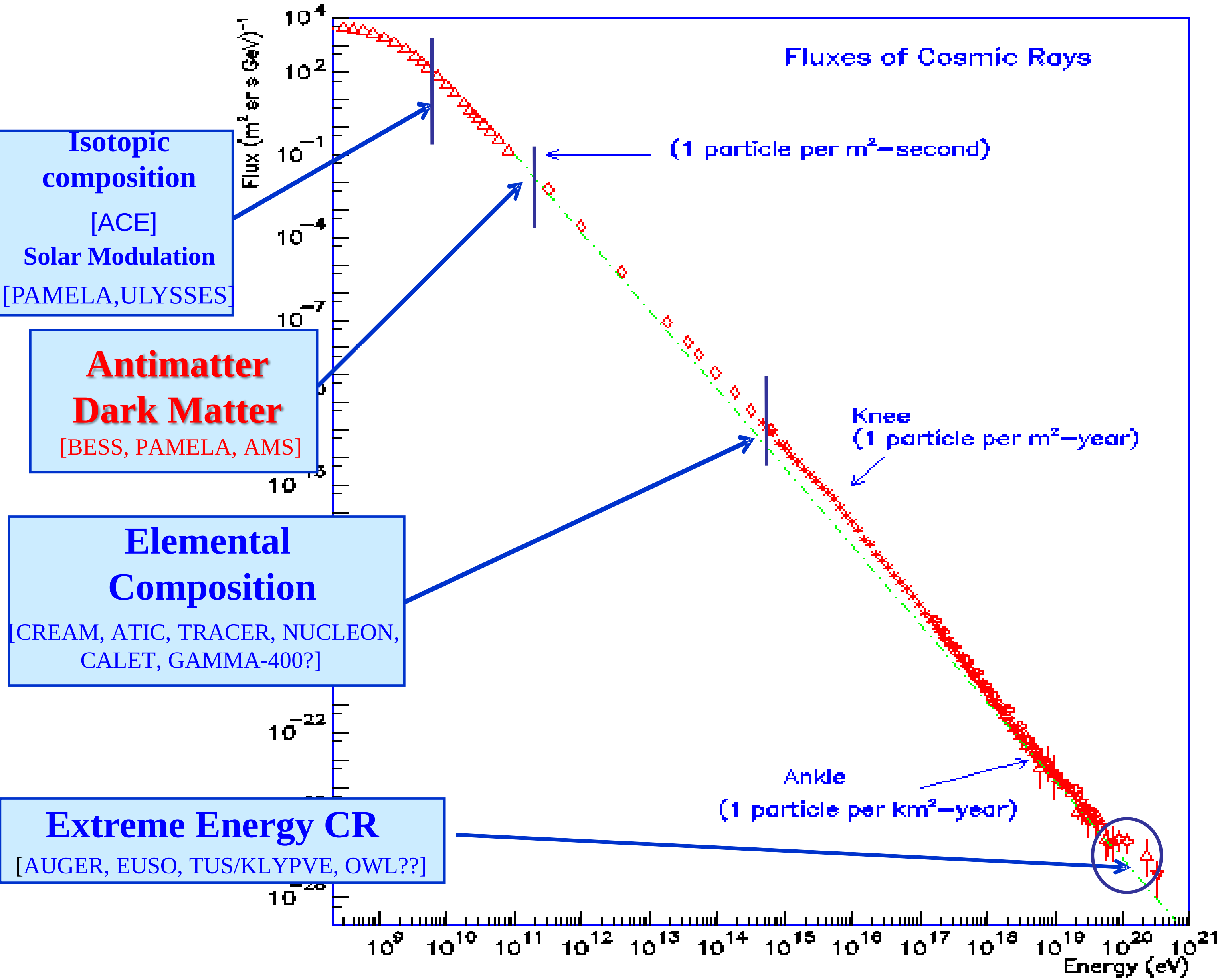
CRs IN SNR → DIFFUSIVE SHOCK ACCELERATION, $Q(E) \sim E^{-\gamma}$

PROPAGATION OF CRs IN THE GALAXY with $D(E) \sim E^{\delta}$ → $n(E) \sim E^{-\gamma-\delta}$

P. Blasi, TeVPA 2011, Stockholm 2011

Cosmic-Rays' "Life"



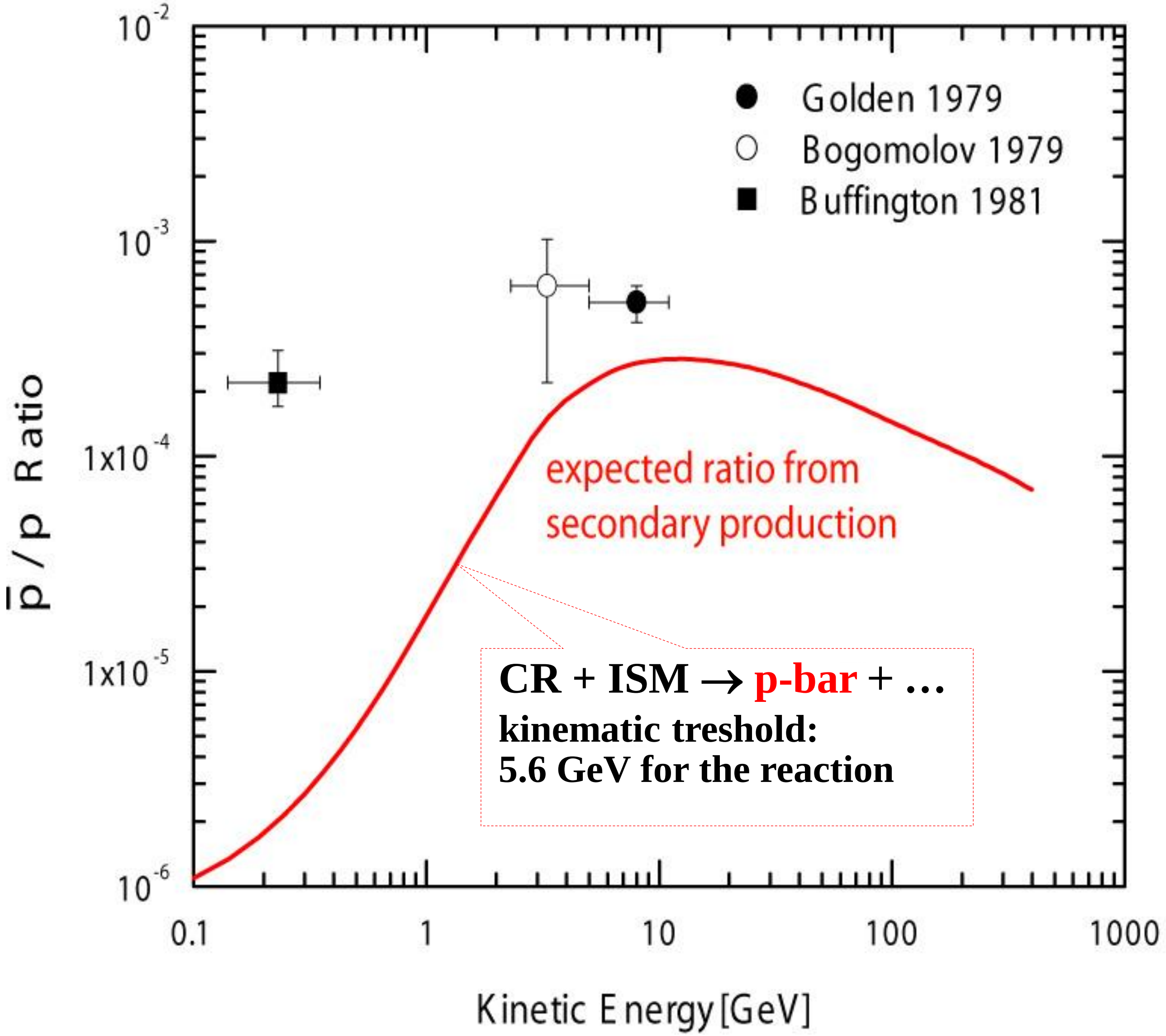


J. Cronin ,T.K. Gaisser & S.P. Swordy, Sci. Amer. 276 (1997) 44

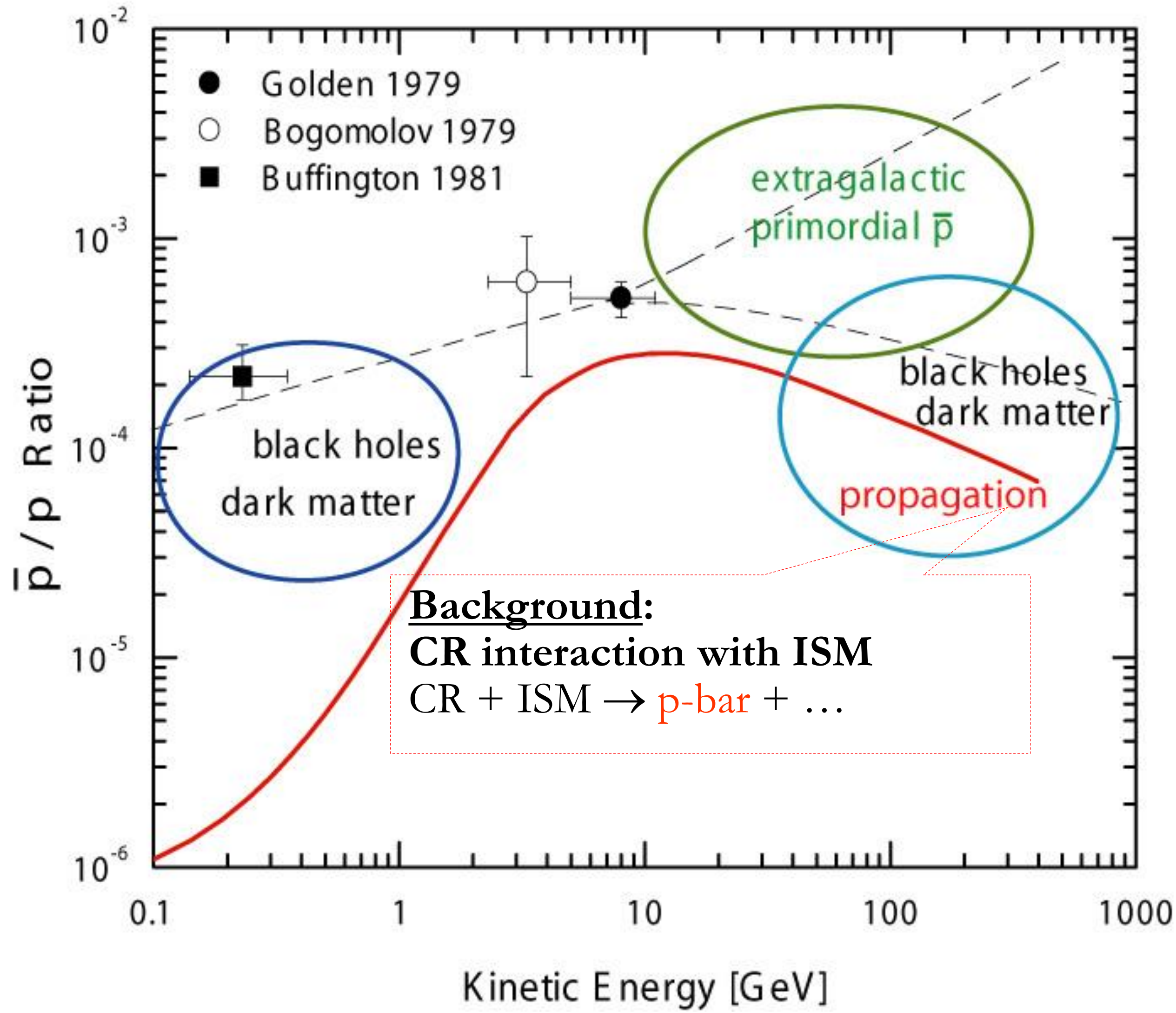
Astrophysics and Cosmology compelling Issues

- *Origin and propagation of the cosmic radiation*
- *Nature of the Dark Matter that pervades the Universe*
- *Apparent absence of cosmological Antimatter*

The first historical measurements on galactic antiprotons



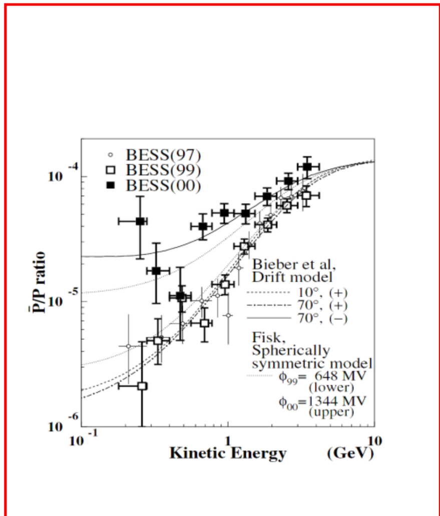
The first historical measurements of the $\bar{p}/p$ - ratio and various Ideas of theoretical Interpretations

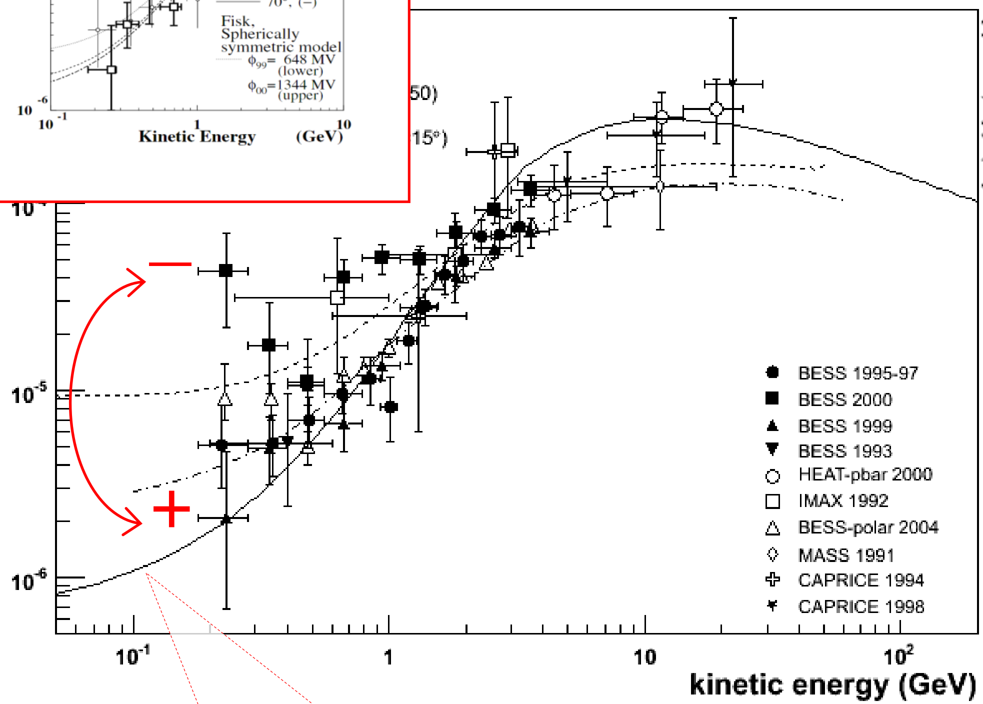


CR antimatter

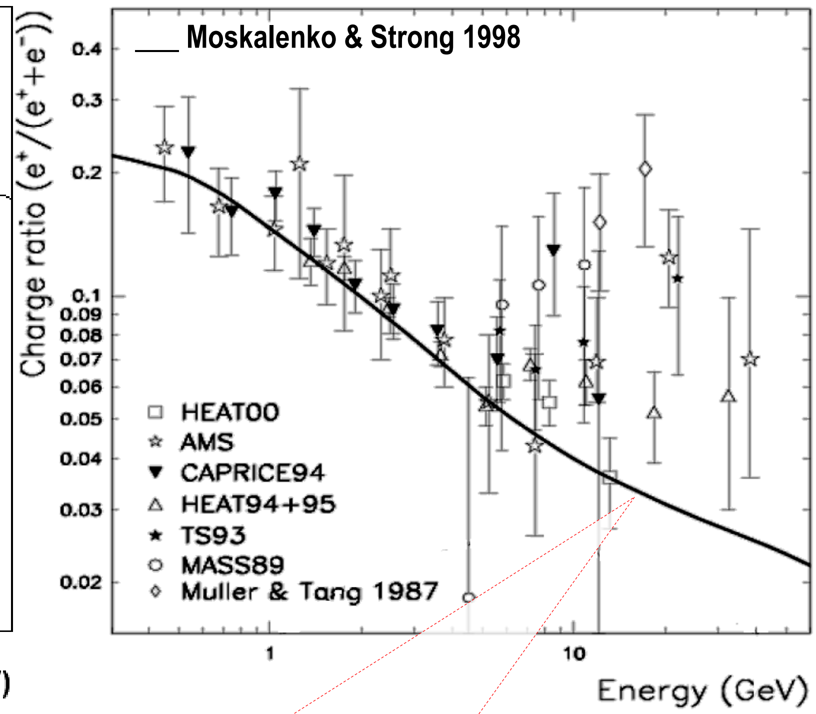
Status in 2006

Antiprotons





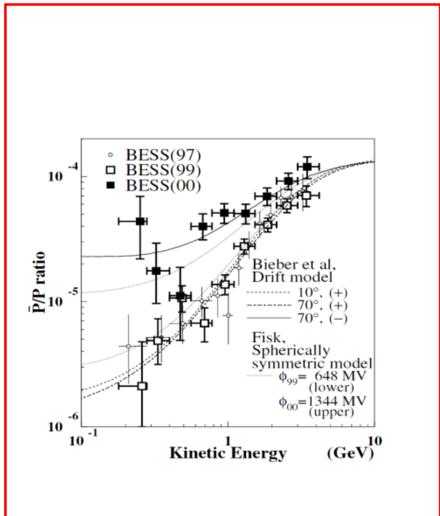
Positrons



CR + ISM → **p-bar** + …
kinematic treshold:
5.6 GeV for the reaction

$$pp \rightarrow \bar{p}ppp$$

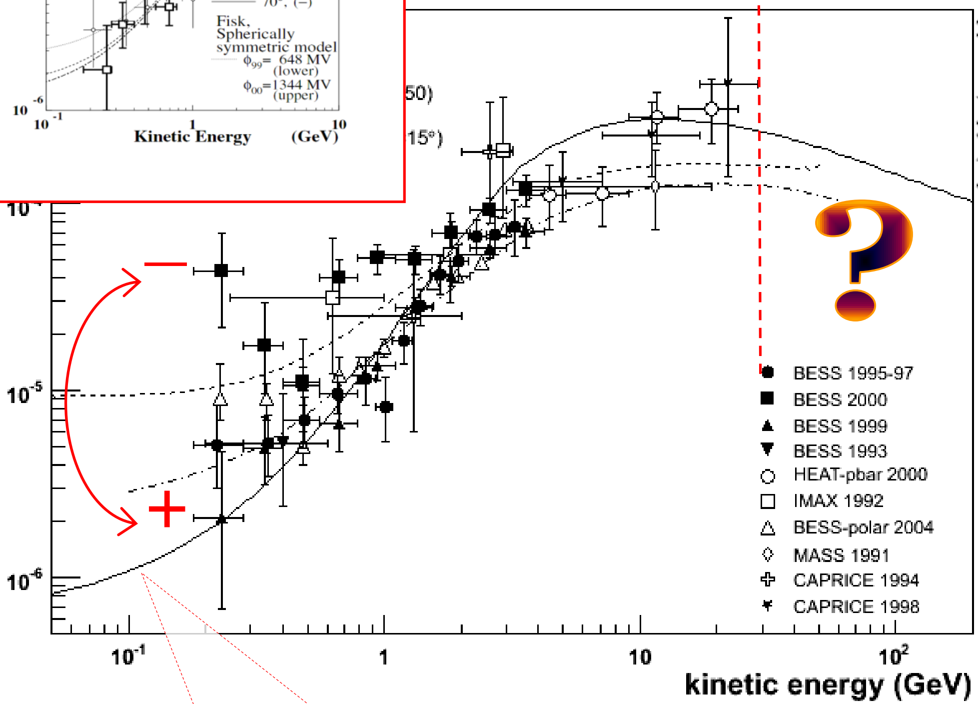
CR + ISM → $\pi^{\pm}$ + x → $\mu^{\pm}$ + x → $e^{\pm}$ + x
CR + ISM → π^0 + x → $\gamma\gamma$ → $e^{\pm}$



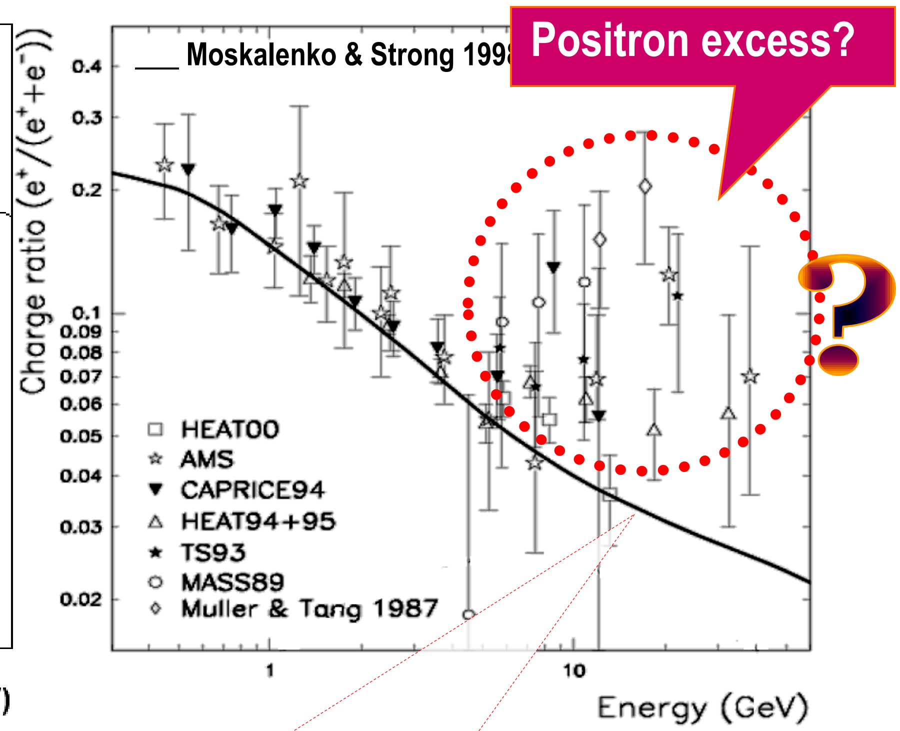
CR antimatter

Status in 2006

Antiprotons



Positrons



CR + ISM → **p-bar** + …
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$pp \rightarrow \bar{p}ppp$

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

PAMELA

Payload for Antimatter Matter Exploration and Light Nuclei Astrophysics

PAMELA Collaboration

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

Tor Vergata

LNF

IFAC

Russia:

Физический Институт

Ioffe Physico-Technical Institute

МИФИ

Moscow
St. Petersburg

Germany:

Universität Gesamthochschule Siegen

Siegen

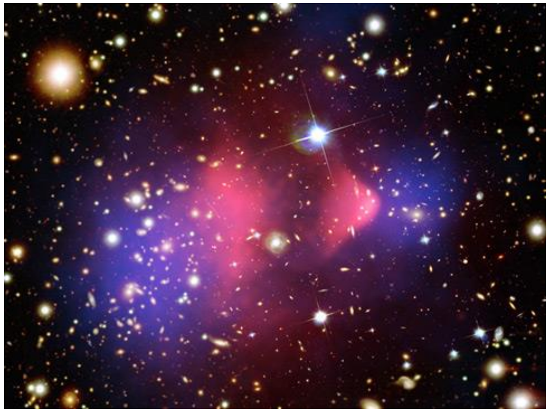
Sweden:

Kungl Tekniska Högskolan

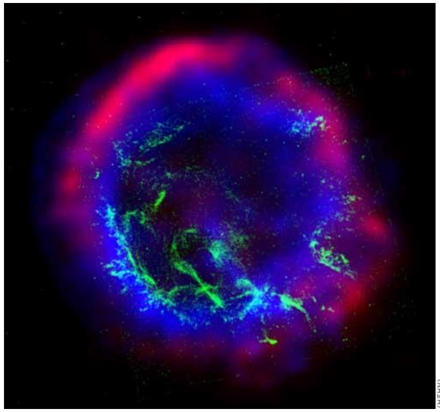
KTH, Stockholm

Scientific goals

- **Search for dark matter annihilation**

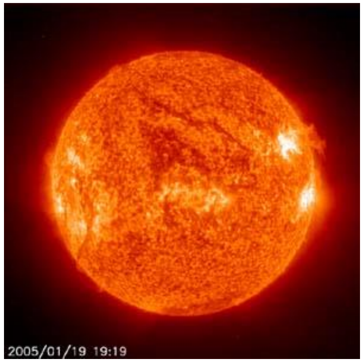


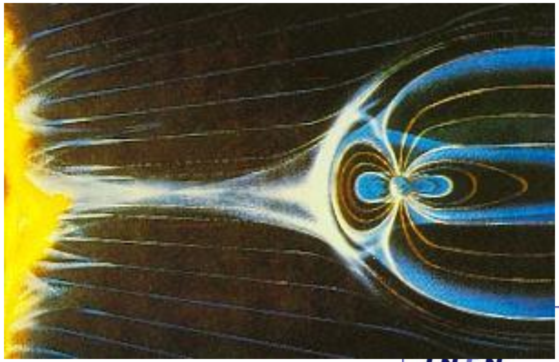
- **Search for antihelium (primordial antimatter)**
- **Search for new Matter in the Universe (Strangelets?)**



- **Study of cosmic-ray propagation (light nuclei and isotopes)**
- **Study of electron spectrum (local sources?)**

- **Study solar physics and solar modulation**
- **Study terrestrial magnetosphere**

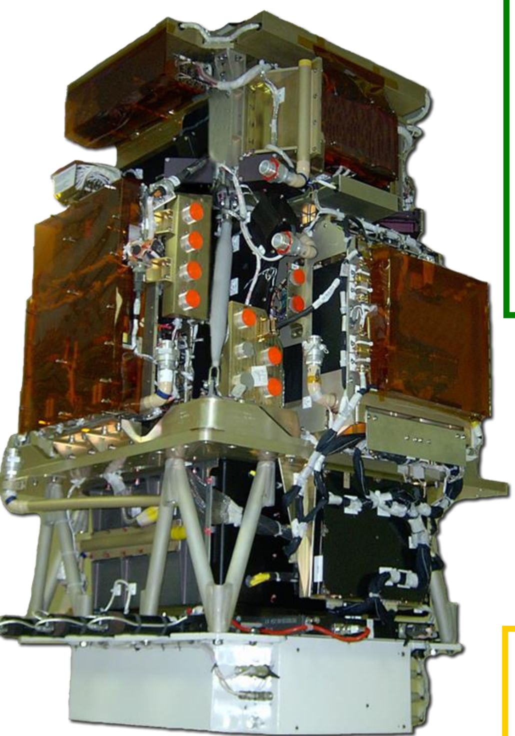




PAMELA apparatus

PAMELA detectors

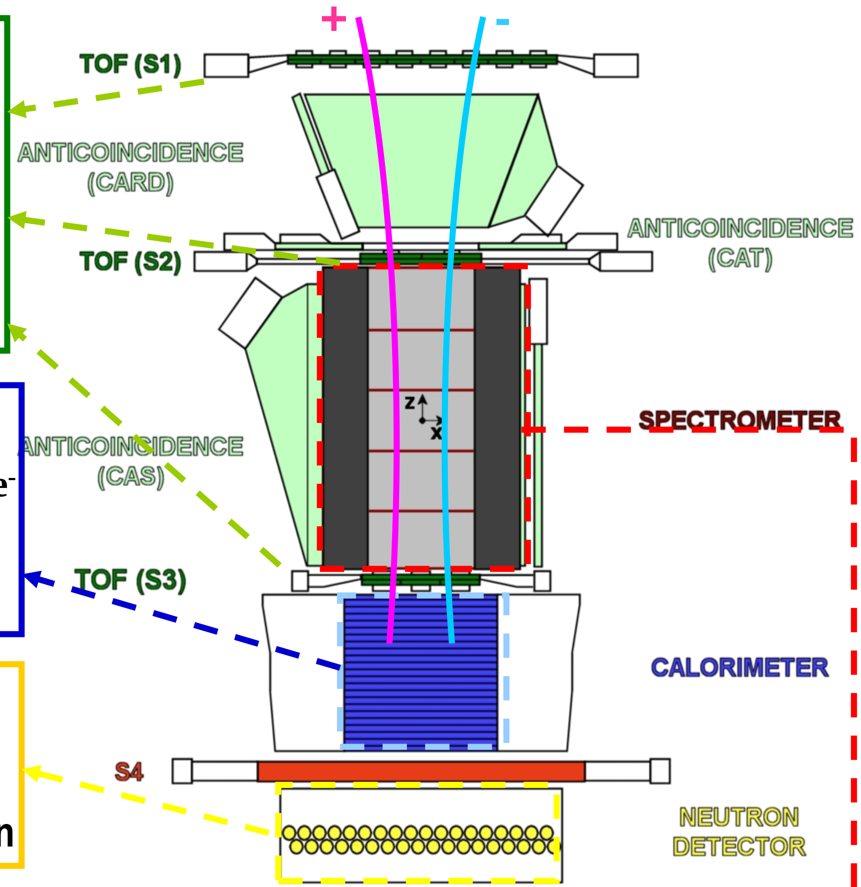
Main requirements → high-sensitivity antiparticle identification and precise momentum measure



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 X_0, 0.6 λI)
- Discrimination e+ / p, anti-p / e^- (shower topology)
- Direct E measurement for e^-

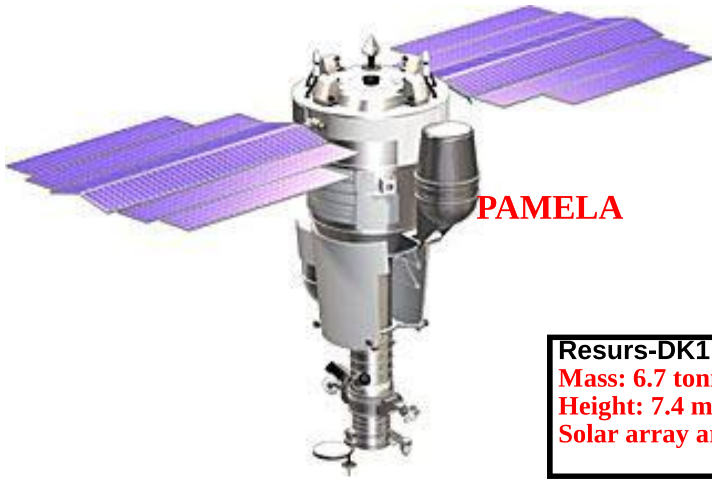
Neutron detector
^{3}He tubes + polyethylene moderator:
- High-energy e/h discrimination



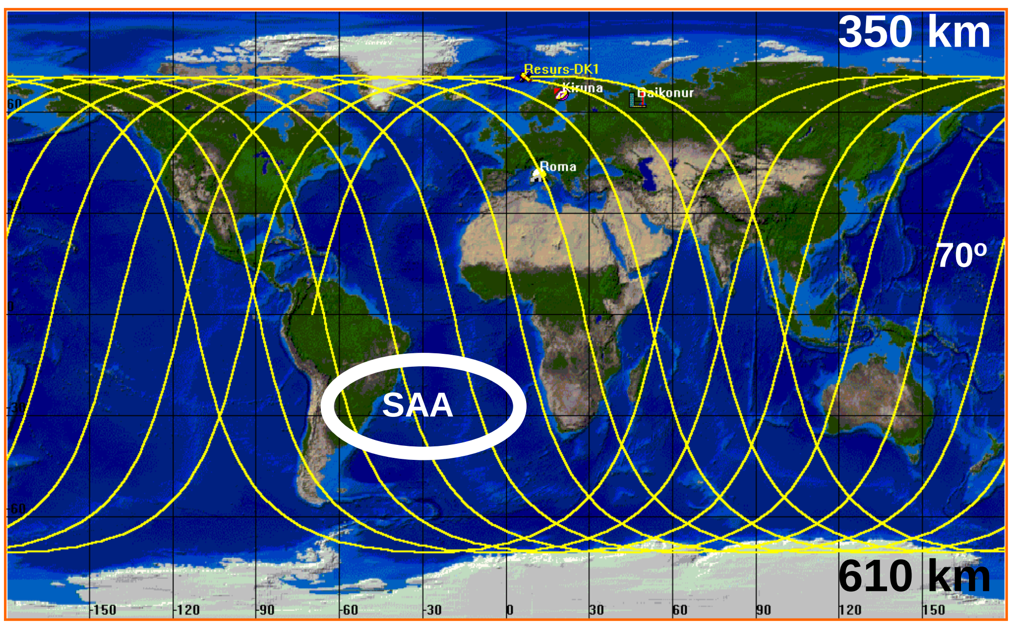
GF: 21.5 cm^2 sr
Mass: 470 kg
Size: 130x70x70 cm^3
Power Budget: 360W

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

Resurs-DK1 satellite + orbit



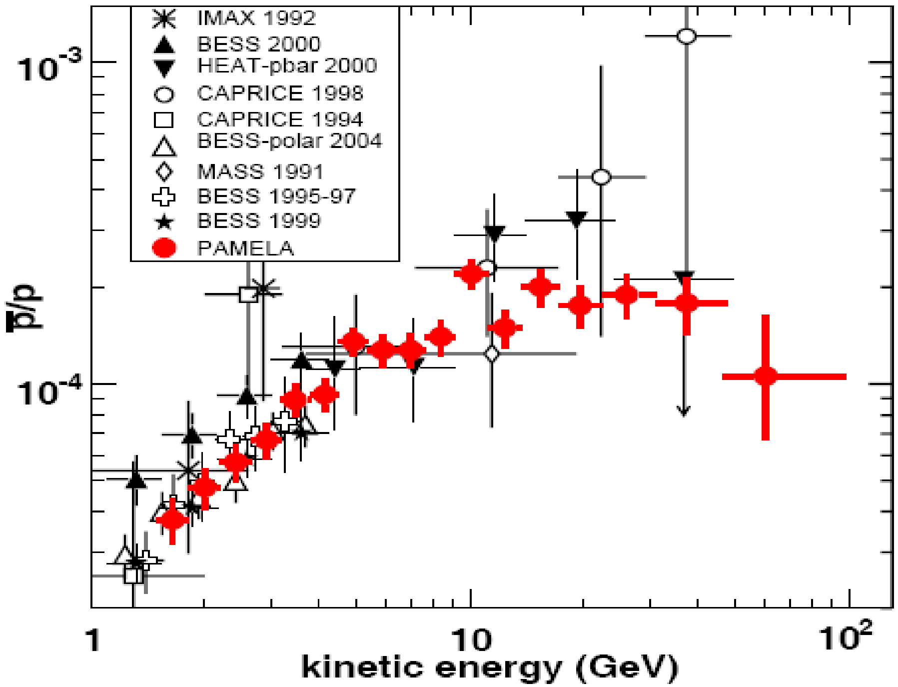
Resurs-DK1
Mass: 6.7 tonnes
Height: 7.4 m
Solar array area: 36 m^2



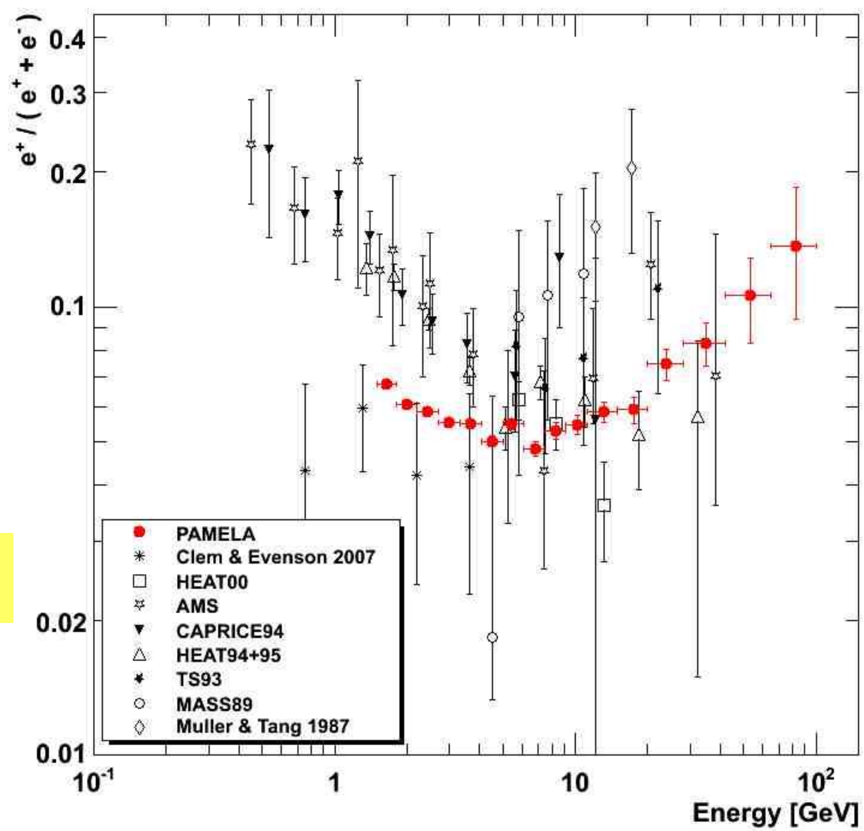
~90 mins

- **Resurs-DK1: multi-spectral imaging of earth's surface**
- **PAMELA mounted inside a pressurized container**
- **Lifetime >3 years (assisted, first time February 2009), extended till end of satellite operations**
- **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) – from 2010 circular orbit (70.0°, 600 km)**
- **Traverses the South Atlantic Anomaly**
- **Crosses the outer (electron) Van Allen belt at south pole**

Antiparticle Results



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

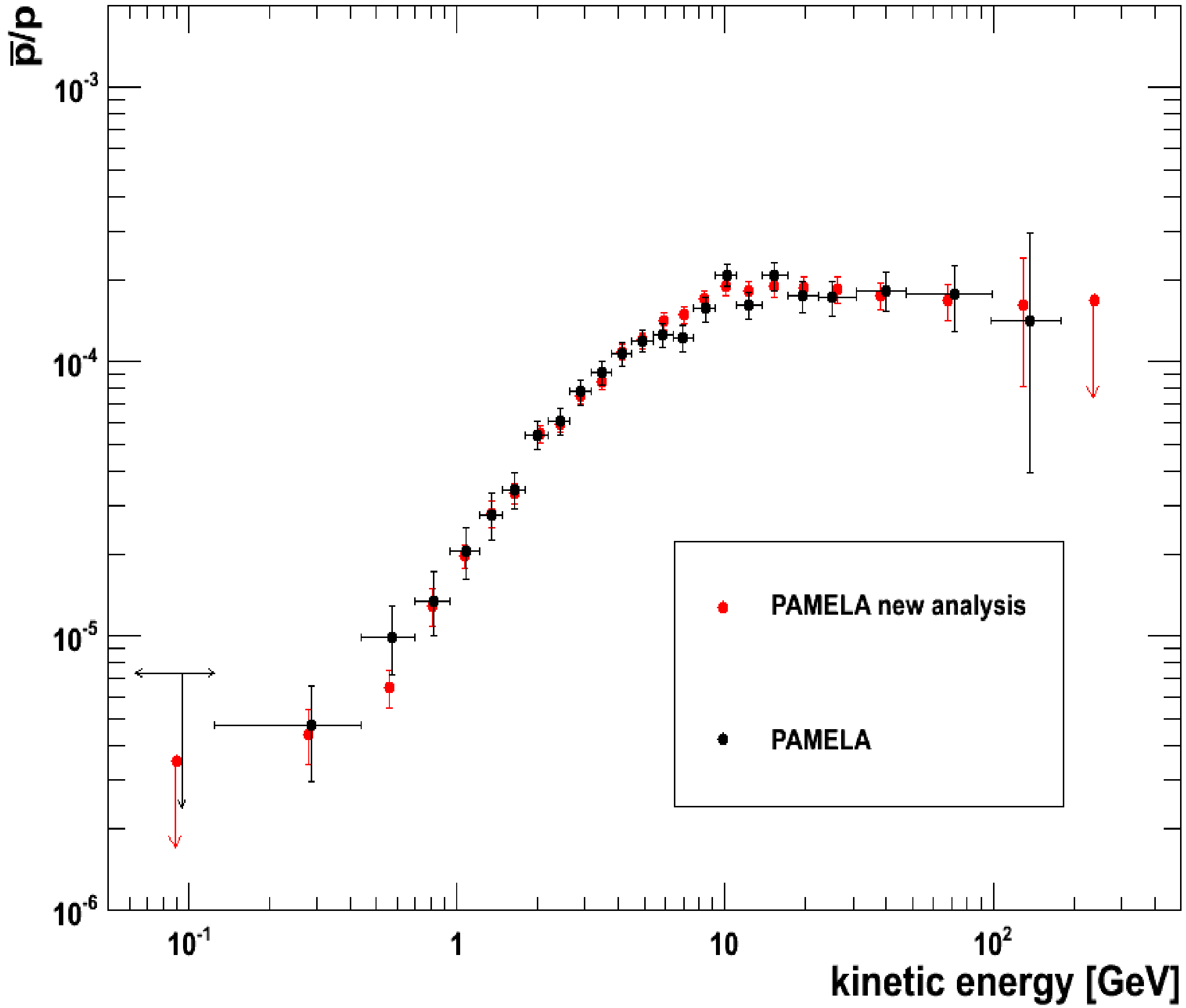


Nature 458 (2009) 607,
Astropart. Phys. 34 (2010) 1

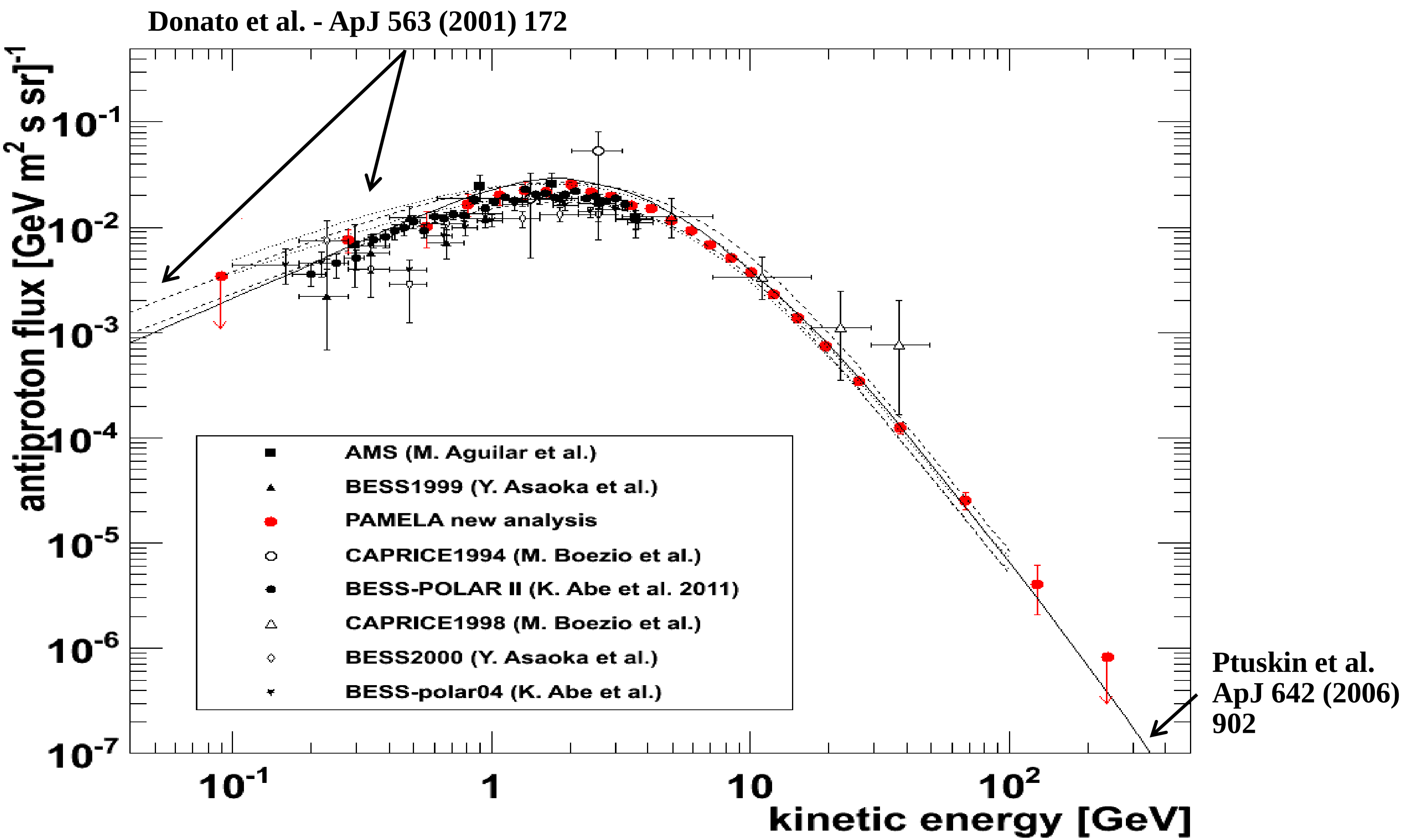
New Results

Antiproton to proton flux ratio

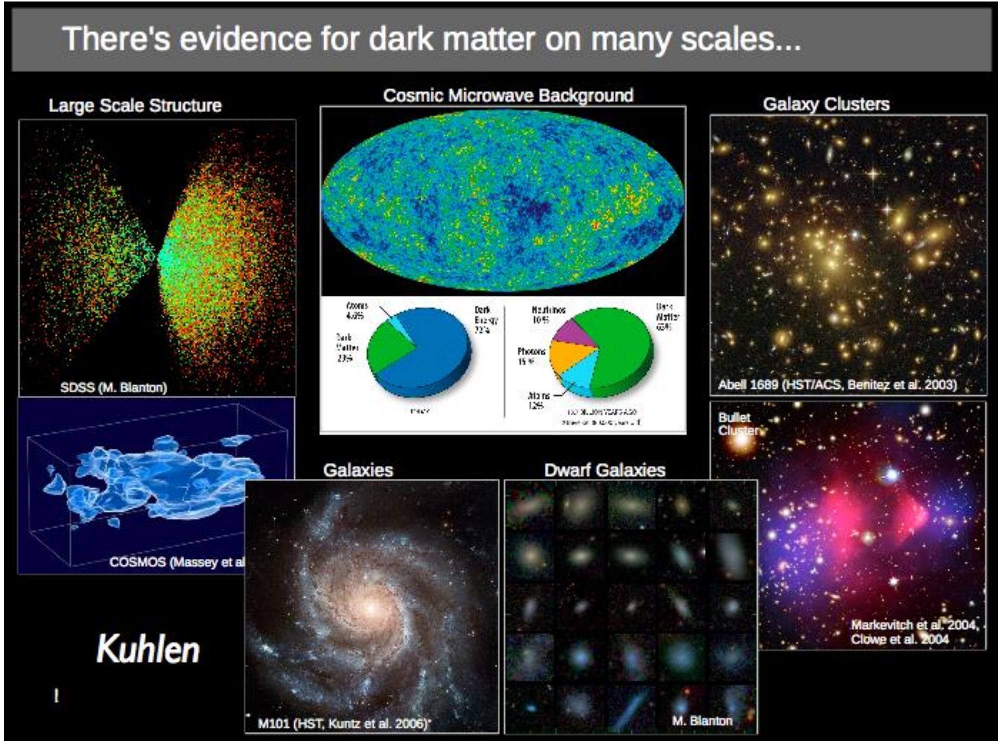
Using all data till 2010 and multivariate classification algorithms 20-50% increase in respect to published analysis

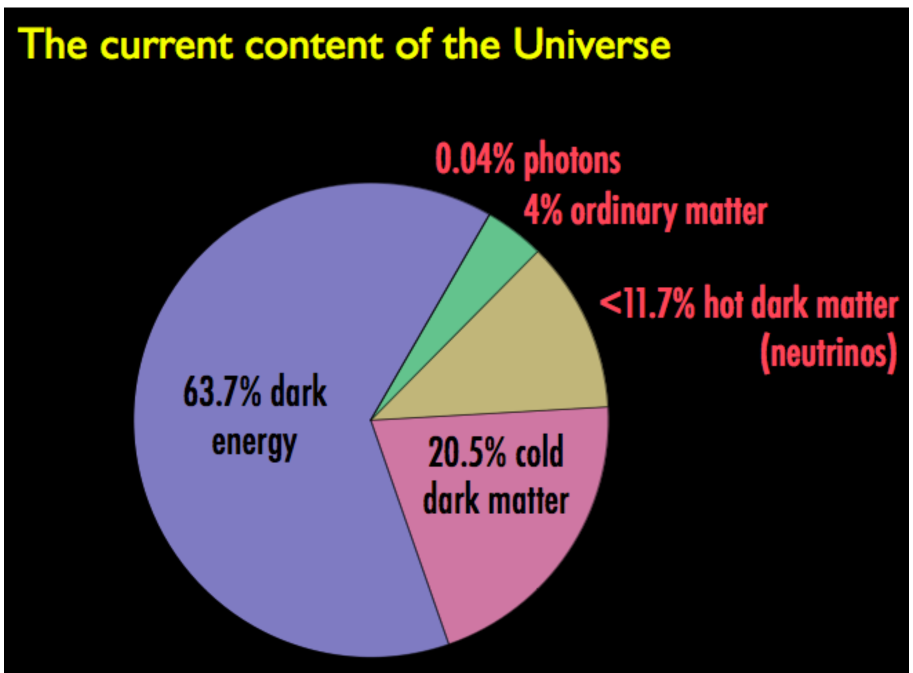


Antiproton energy spectrum



Cosmic-Ray Antiprotons and DM limits

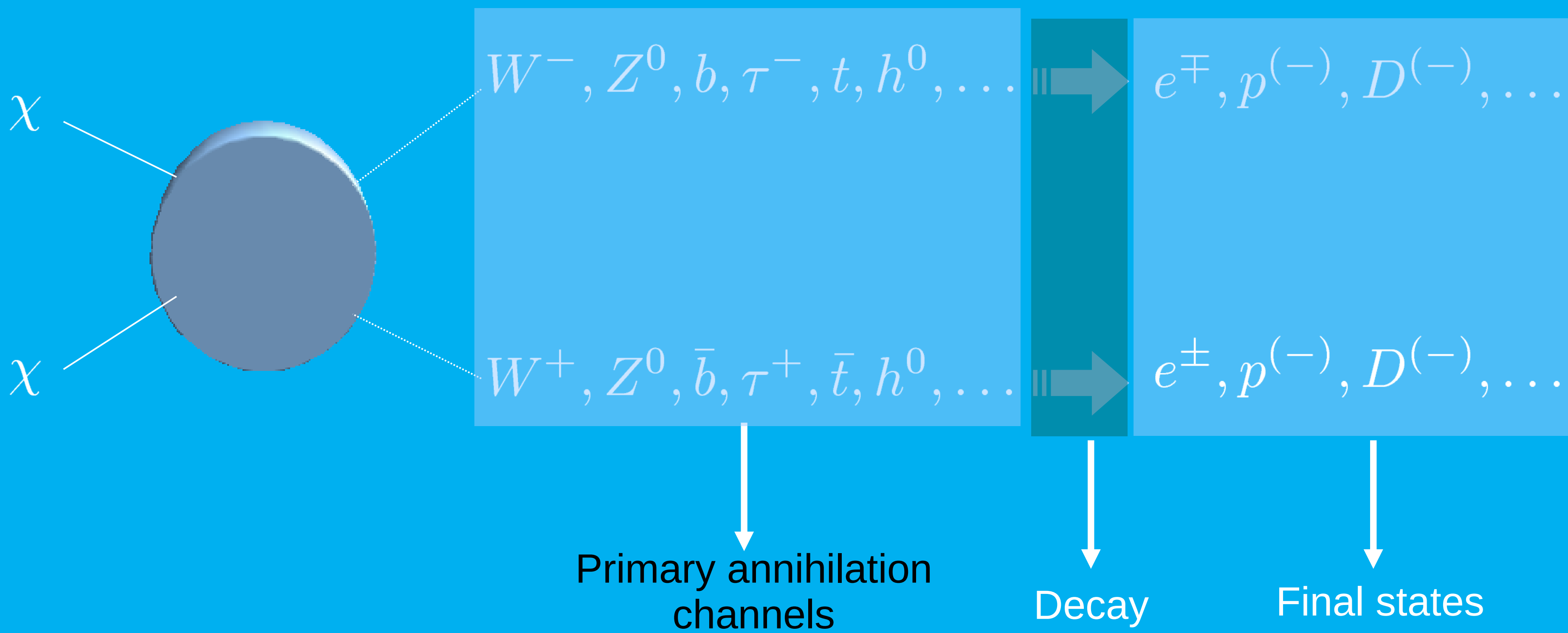




P. Gondolo, IDM 2008

DM annihilations

DM particles are stable. They can annihilate in pairs.



flux $\propto n^2 \sigma_{\text{annihilation}}$

astro& cosmo — particle

reference cross section:

$\sigma = 3 \cdot 10^{-26} \text{cm}^3/\text{sec}$

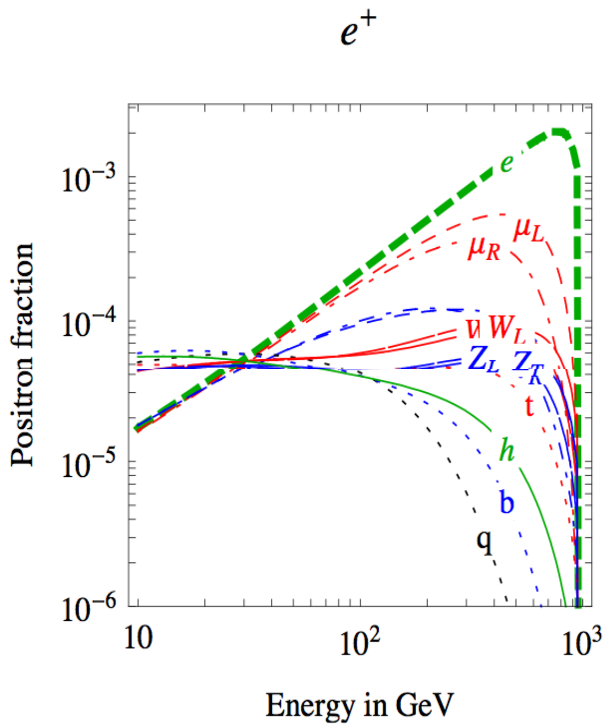
$\sigma_a = \langle \sigma v \rangle$

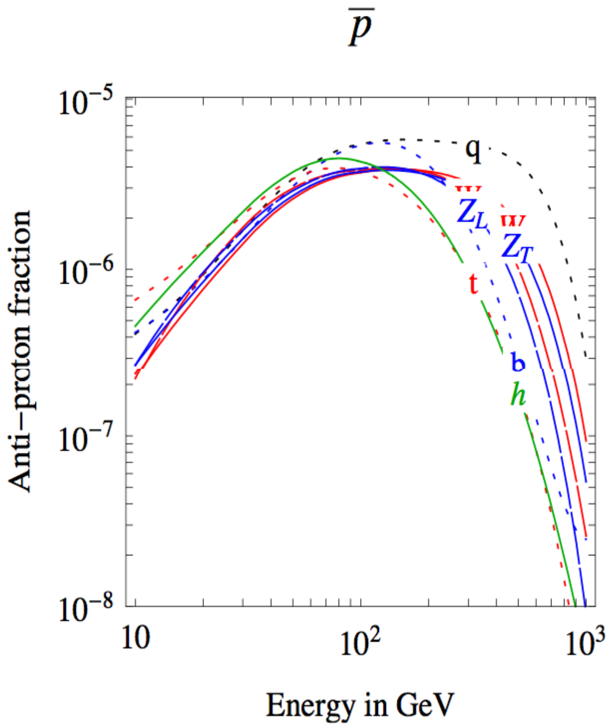
DM annihilations

Resulting spectrum for positrons and antiprotons
M_{WIMP}= 1 TeV

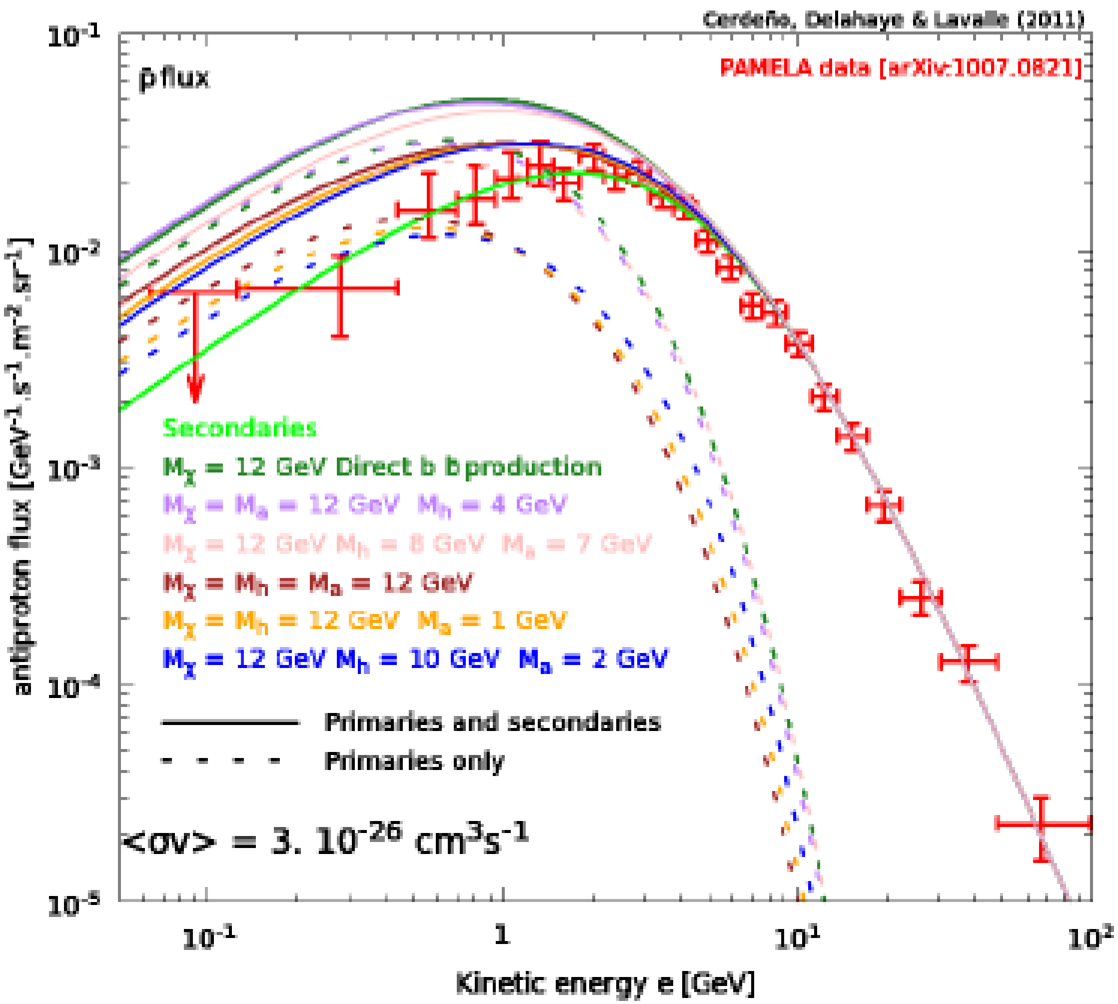
The flux shape is completely determined by:

1) WIMP mass
2) Annihilations channels





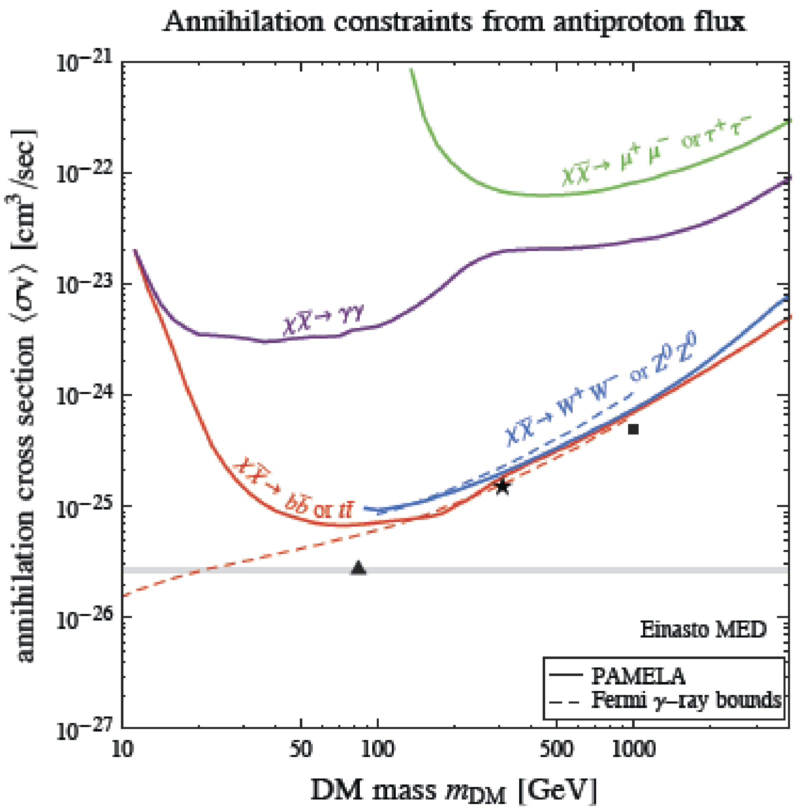
Cosmic-Ray Antiprotons and DM limits

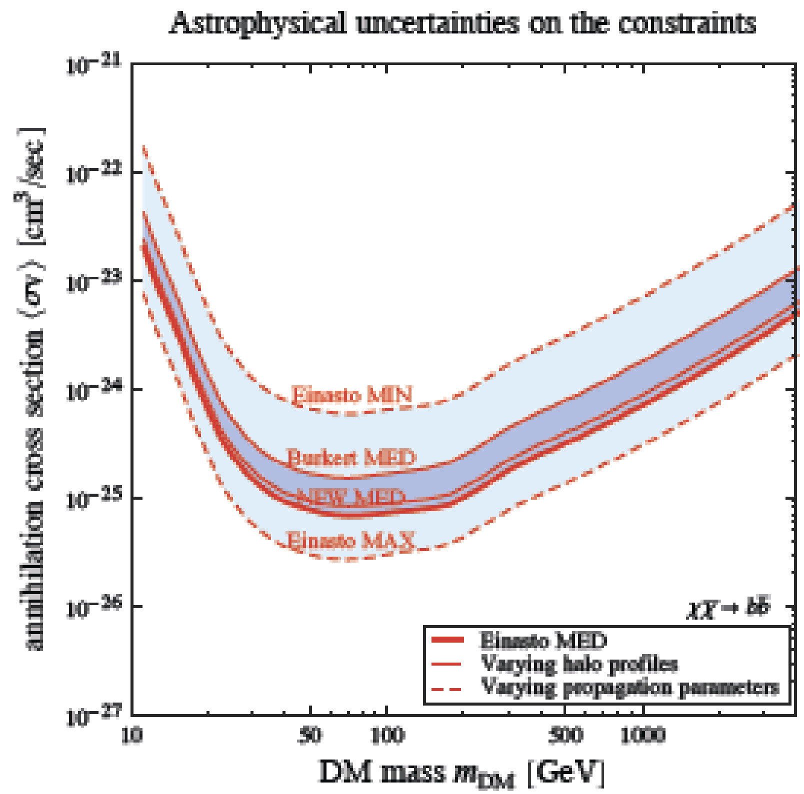


D. G. Cerdeno, T. Delahaye & J. Lavalle, Nucl. Phys. B 854 (2012) 738 Antiproton flux predictions for a 12 GeV WIMP annihilating into different mass combinations of an intermediate two-boson state which further decays into quarks.

See also:
- **M. Asano, T. Bringmann & C. Weniger, Phys. Lett. B 709 (2012) 128.**
- **M. Garny, A. Ibarra & S. Vogl, JCAP 1204 (2012) 033**
- **R. Kappl & M. W. Winkler, PRD 85 (2012) 123522**

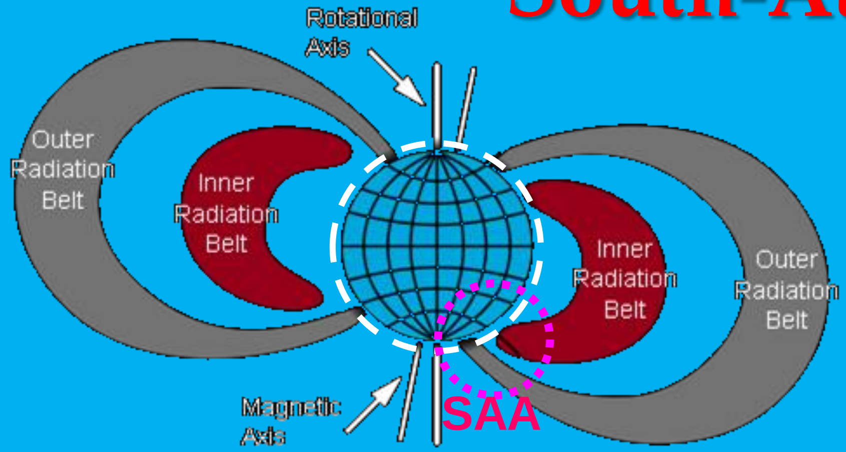
Cosmic-Ray Antiprotons and DM limits

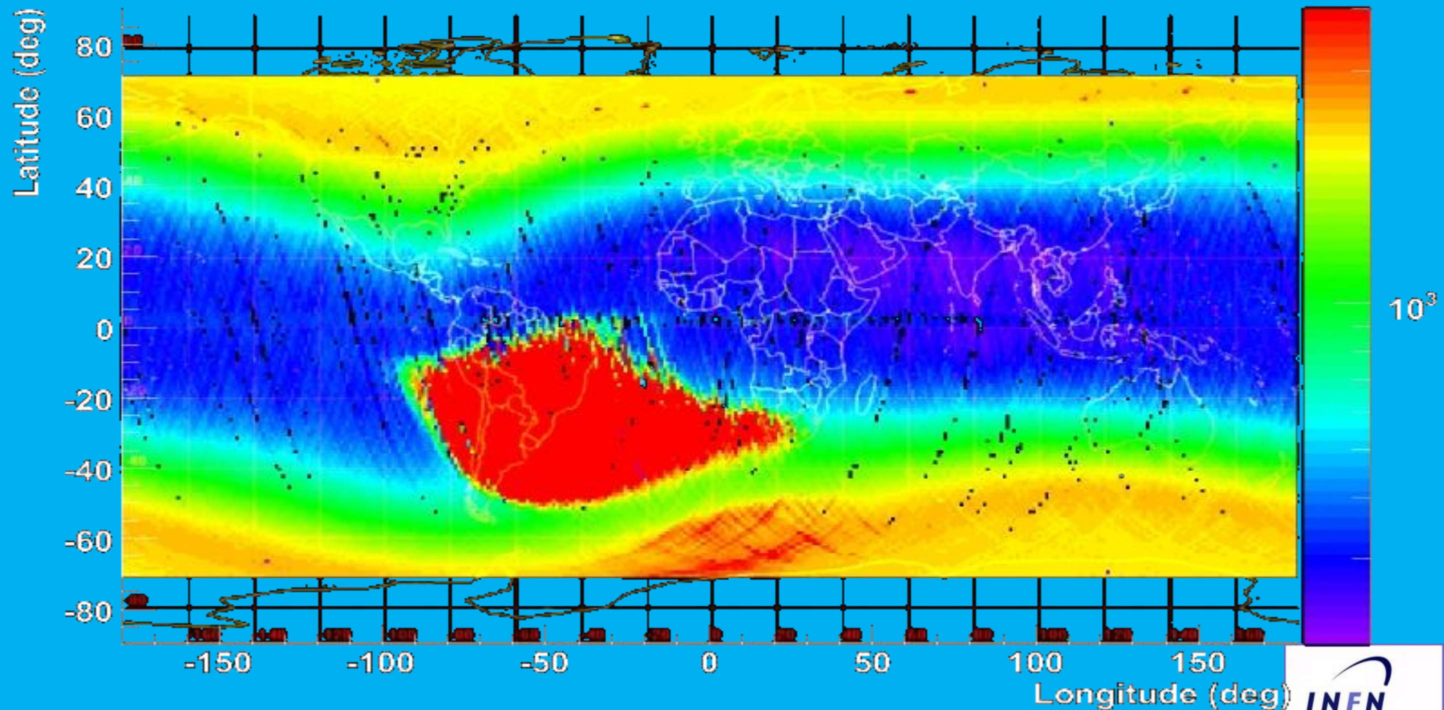




M. Cirelli & G. Giesen, arXiv: 1301:7079
"Antiprotons are a very relevant tool to constrain Dark Matter annihilation and decay, on a par with gamma rays for the hadronic channels. Current Pamela data and especially upcoming AMS-02 data allow to probe large regions of the parameter space."

Earth Magnetosphere
South-Atlantic Anomaly (SAA)





Earth Magnetosphere
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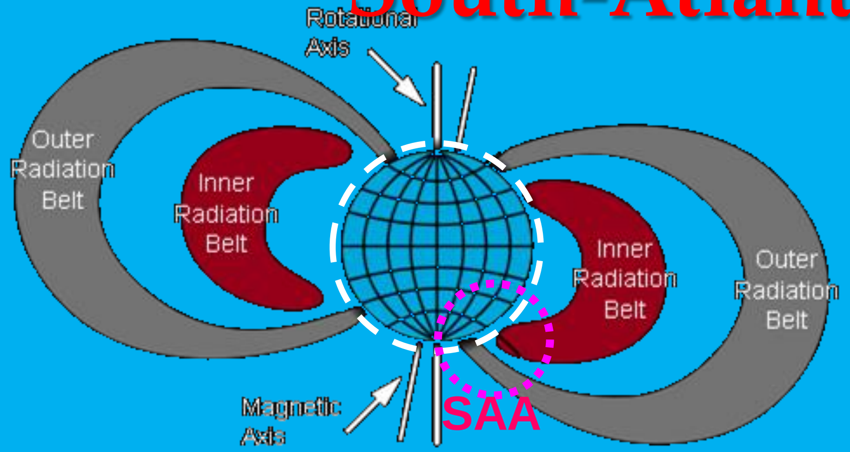
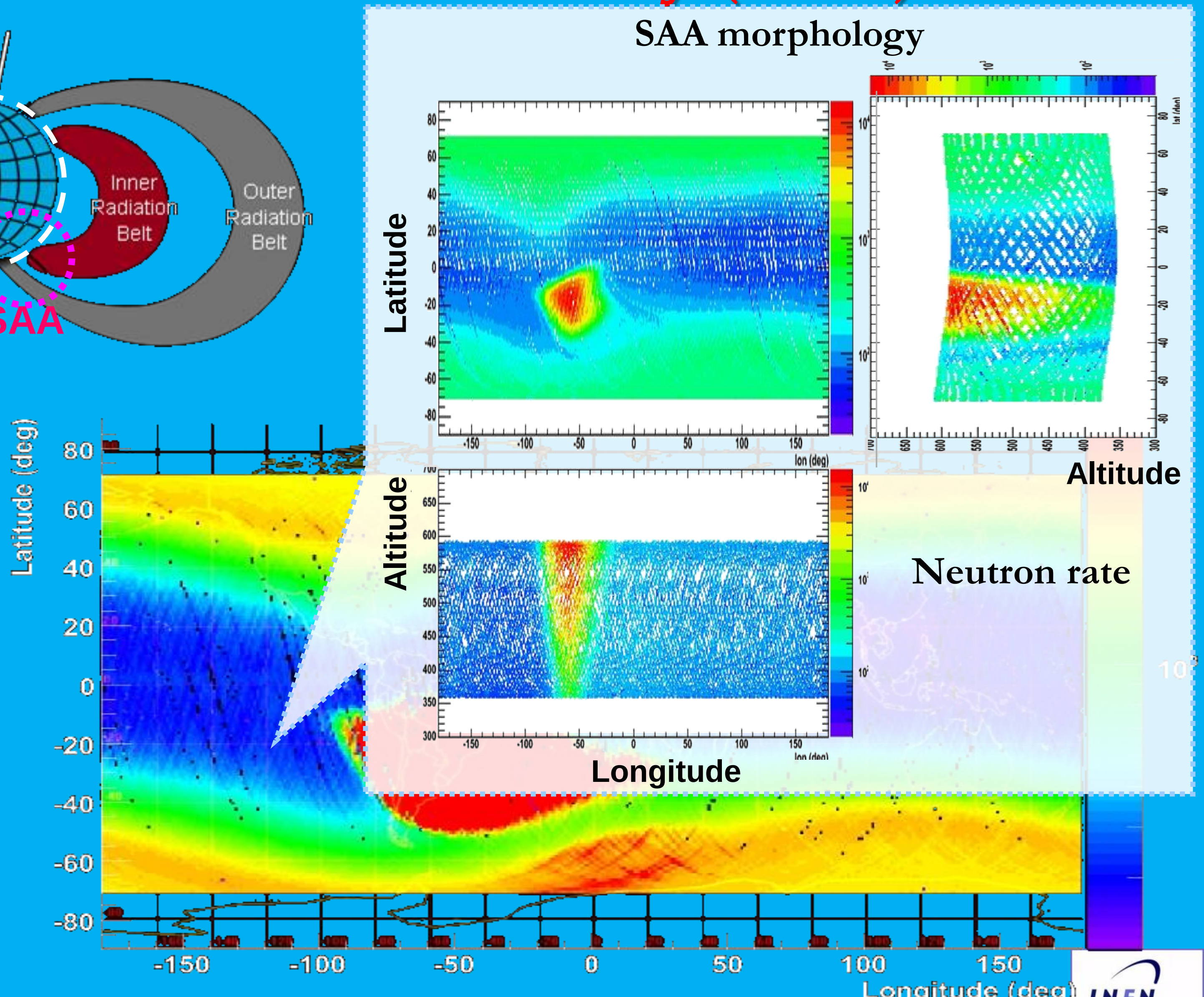
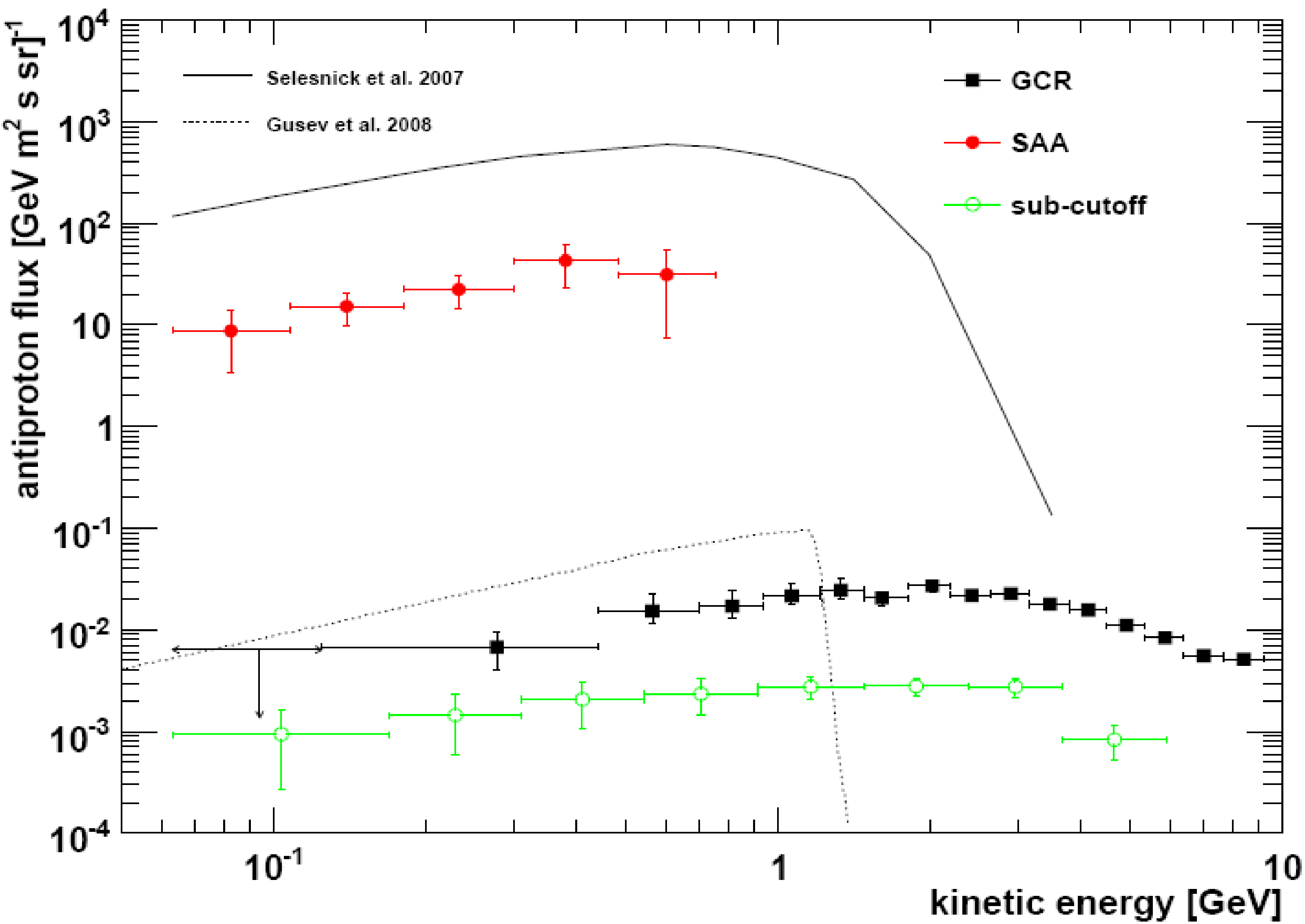




PAMELA trapped antiprotons

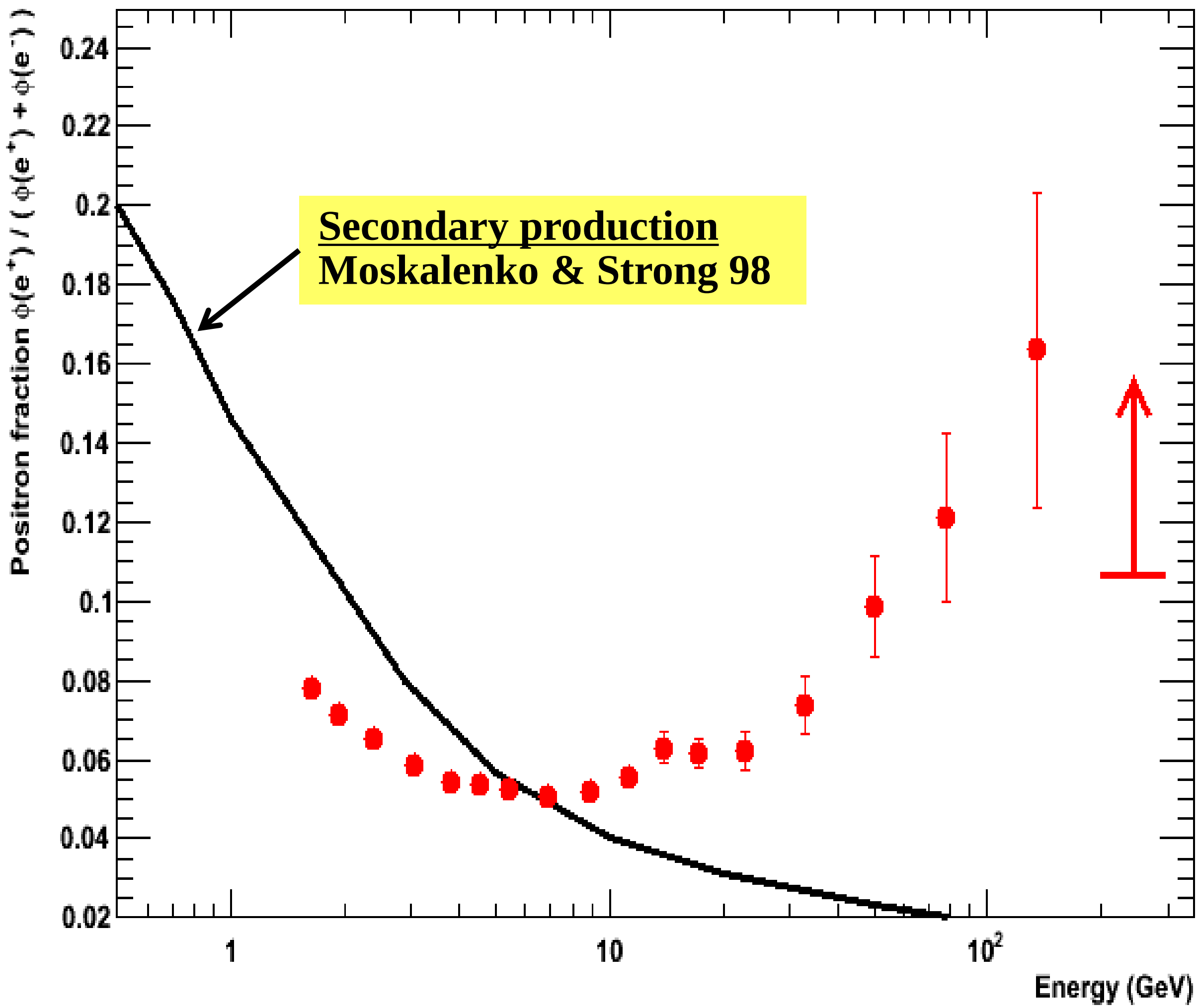


Adriani et al., APJL 737 L29 (2011); arXiv:1107.4882

Positrons (and electrons) with PAMELA

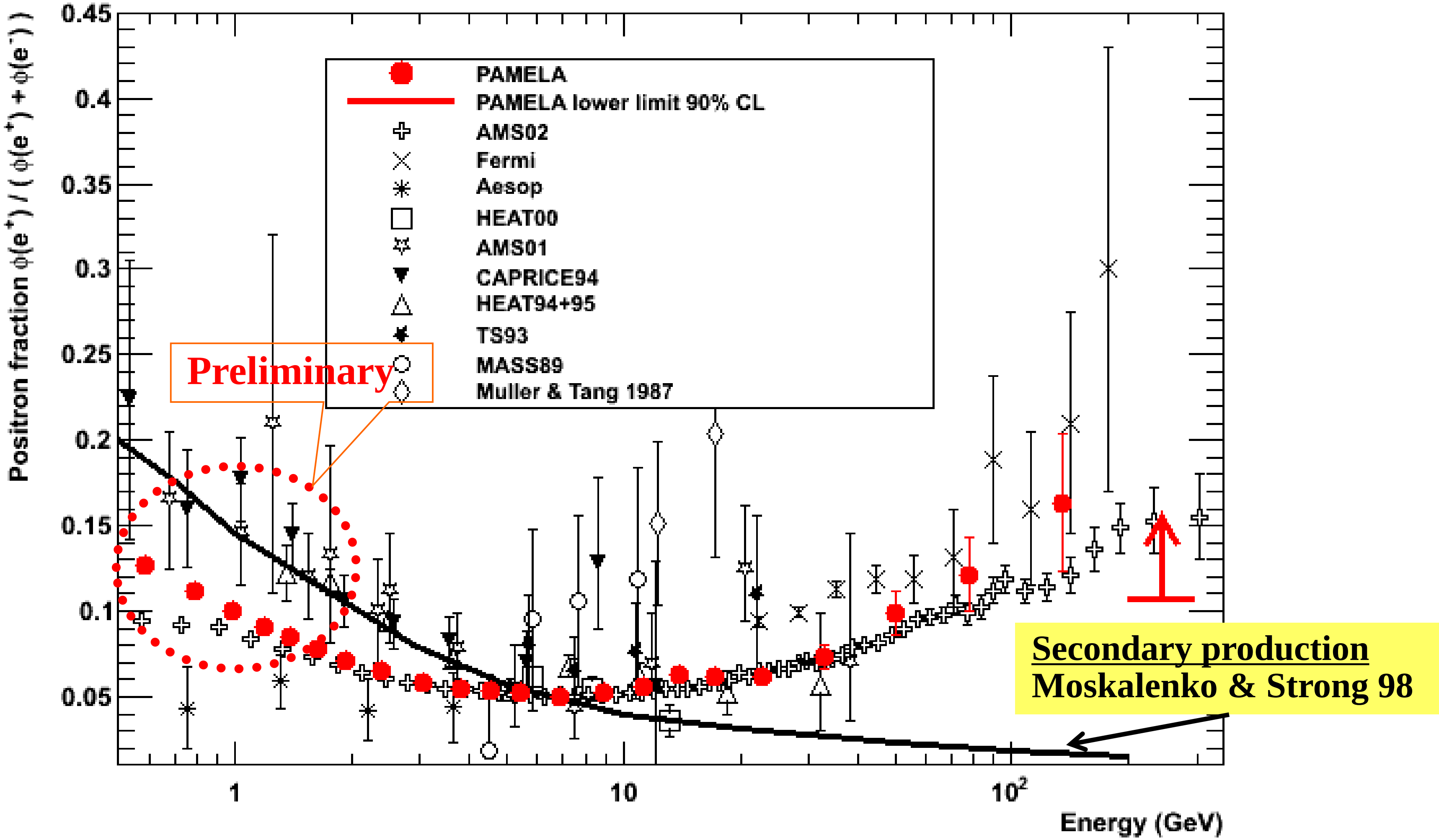
Positron to Electron Fraction

Using all data till 2010 and multivariate classification algorithms about **factor 2-3 increase in respect to published analysis**



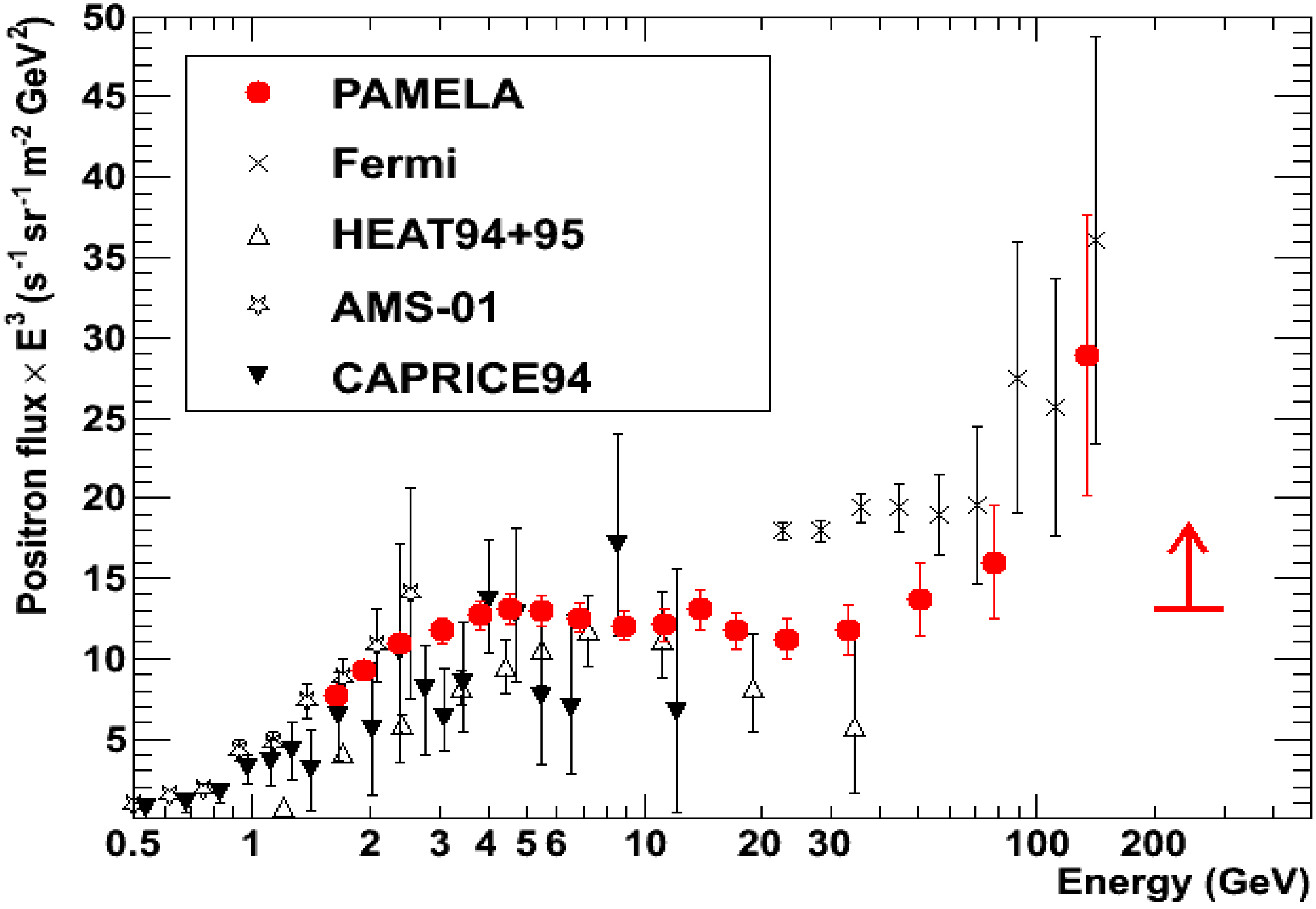
Mirko Boezio, LEAP2013, Uppsala, 2013/06/10

Positron to Electron Fraction



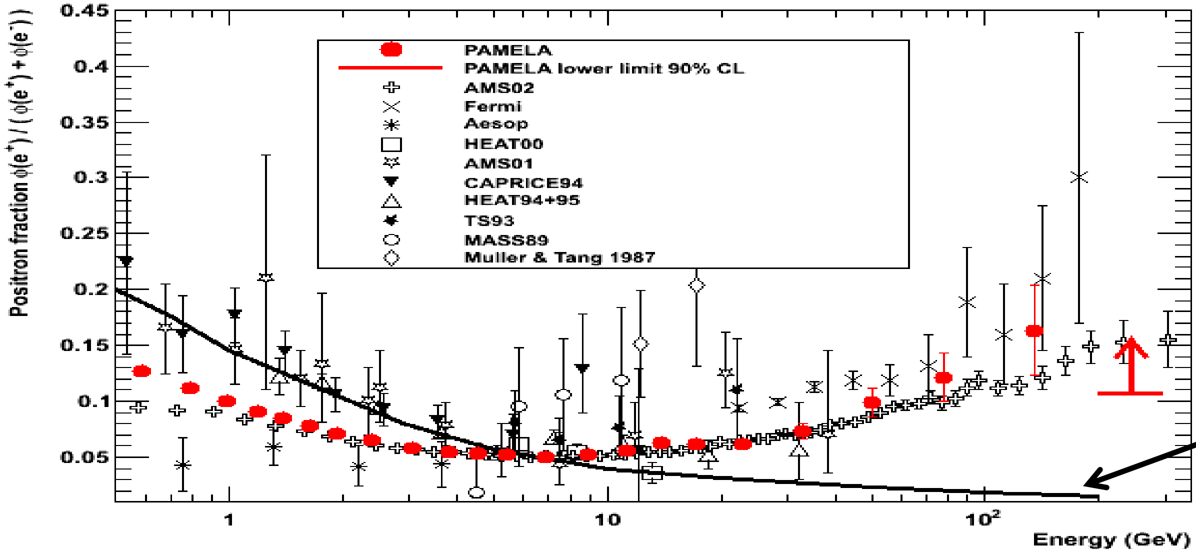
Mirko Boezio, LEAP2013, Uppsala, 2013/06/10

Positron Energy Spectrum



Mirko Boezio, LEAP2013, Uppsala, 2013/06/10

A Challenging Puzzle for CR Physics

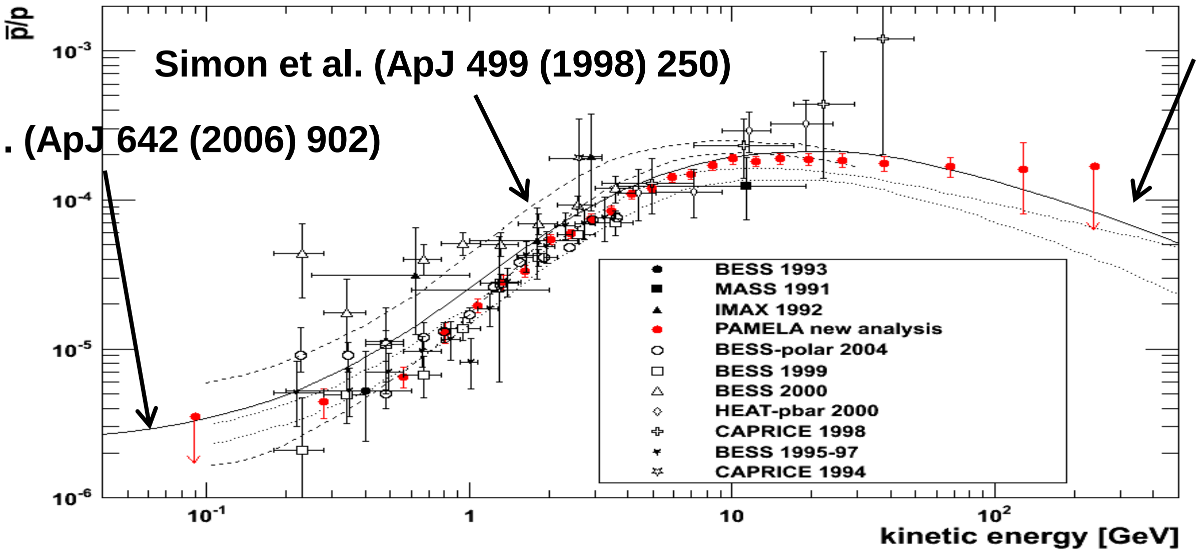


CR Positron spectrum significantly harder than expectations from secondary production Moskalenko & Strong 98

Simon et al. (ApJ 499 (1998) 250)

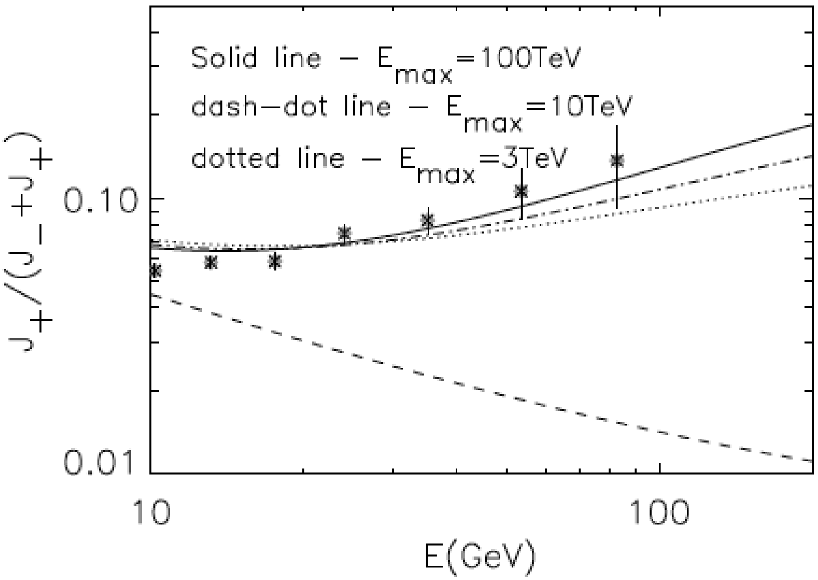
Ptuskin et al. (ApJ 642 (2006) 902)

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



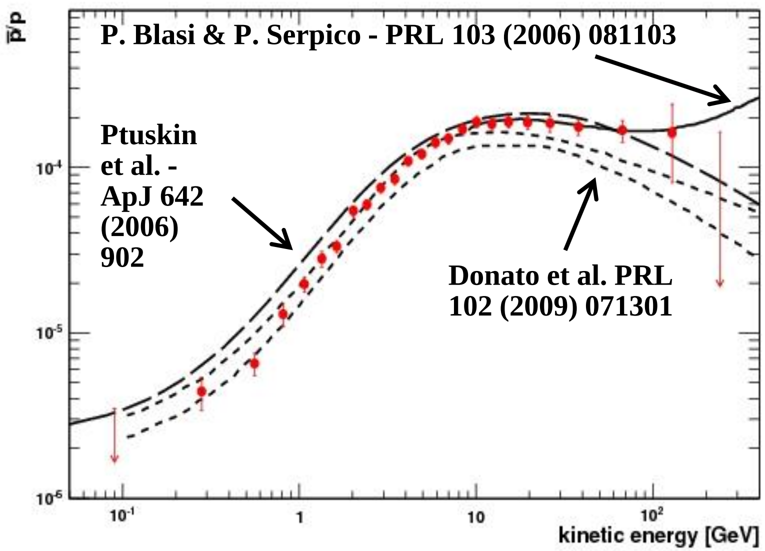
But antiprotons in CRs are in agreement with secondary production

A Challenging Puzzle for CR Physics



P.Blasi, PRL 103 (2009) 051104; arXiv:0903.2794
Positrons (and electrons) produced as secondaries in the sources (e.g. SNR) where CRs are accelerated.

A Challenging Puzzle for CR Physics



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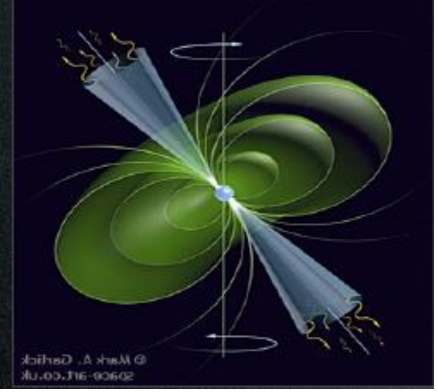
Astrophysical Explanation: Pulsars

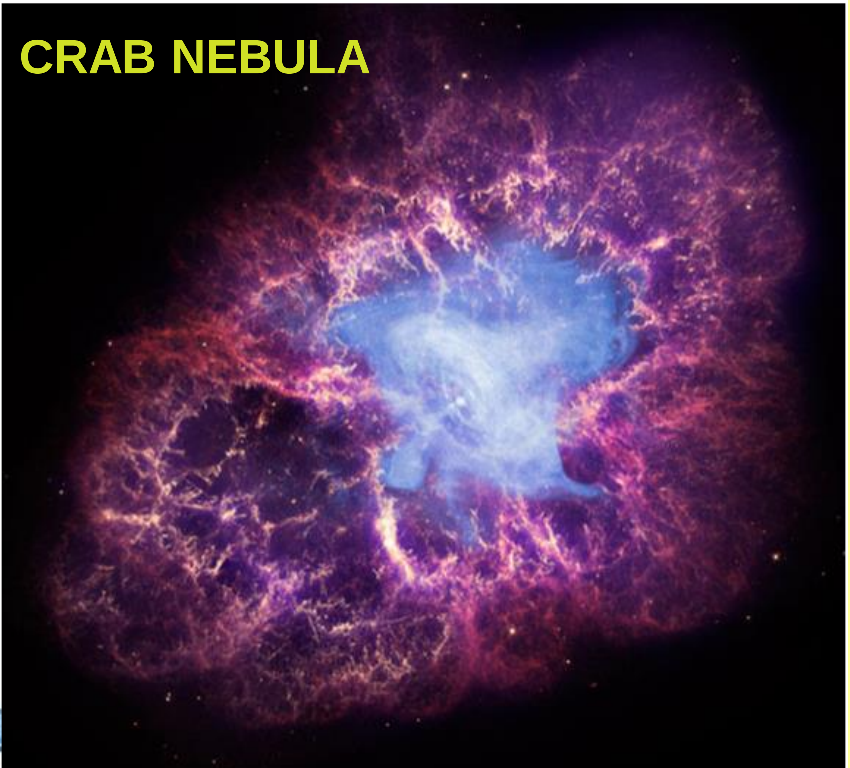


- Mechanism: the spinning B of the pulsar strips e^- that accelerated at the polar cap or at the outer gap emit γ that make production of $e^\pm$ that are trapped in the cloud, further accelerated and later released at $\tau \sim 10^5$ years.

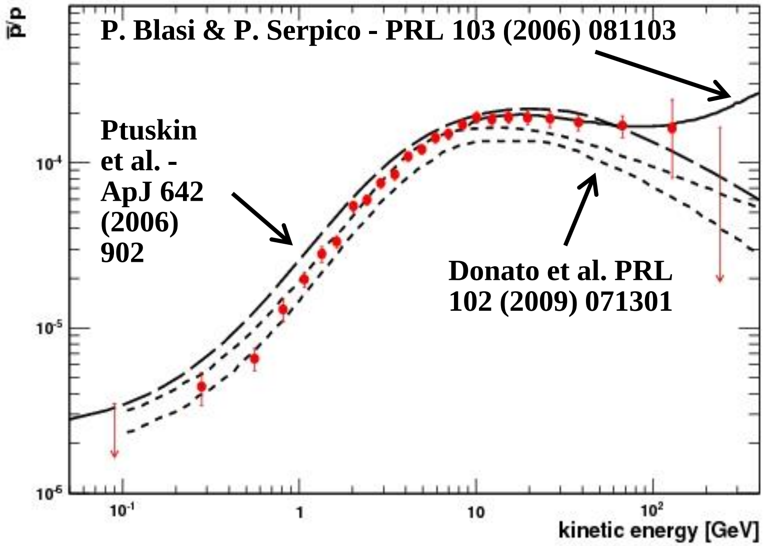
- Young ($T < 10^5$ years) and nearby (< 1kpc)
- If not: too much diffusion, low energy, too low flux.

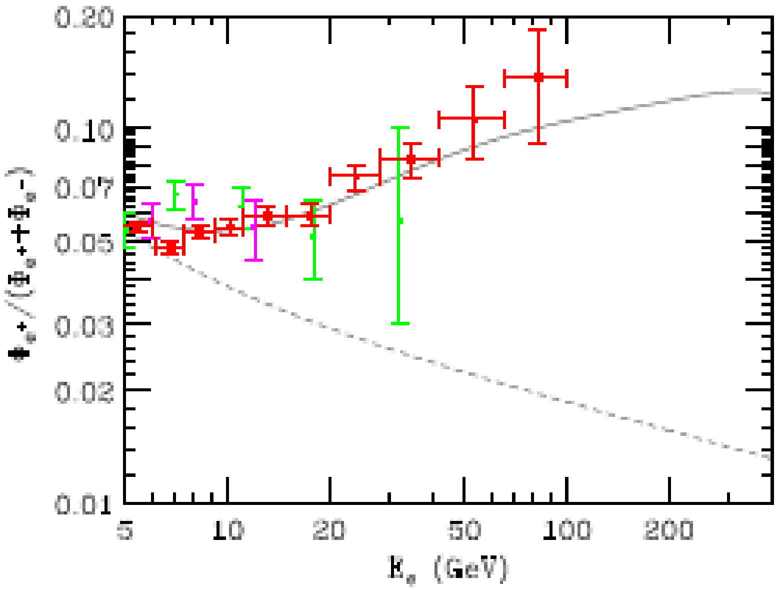
- Geminga: 157 parsecs from Earth and 370,000 years old
- B0656+14: 290 parsecs from Earth and 110,000 years old.

- Diffuse mature pulsars



A Challenging Puzzle for CR Physics



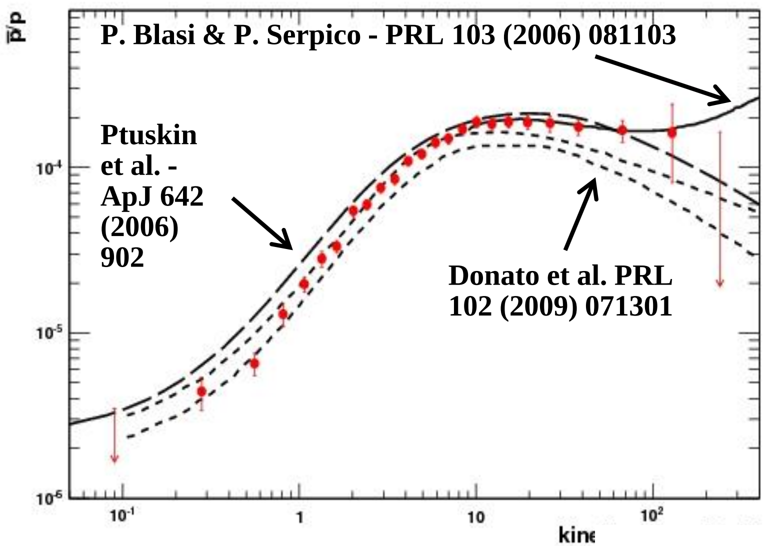


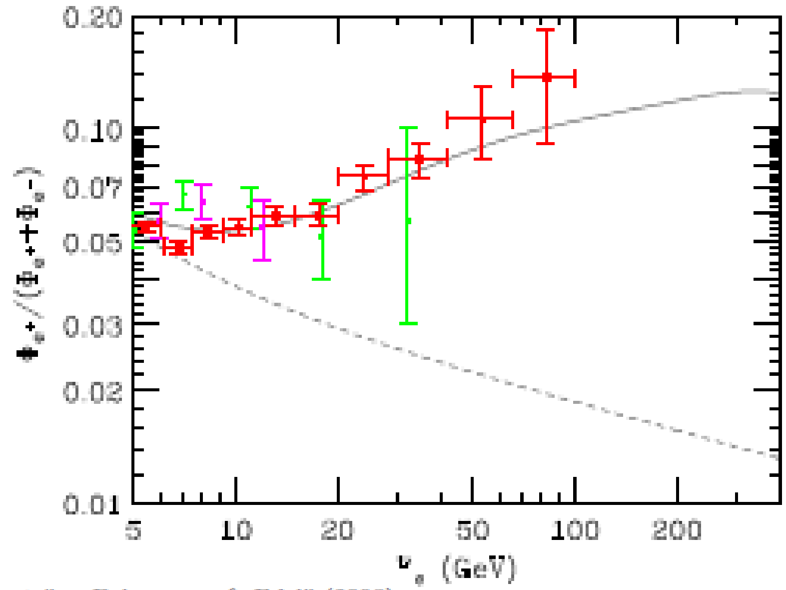
P.Blasi, PRL 103 (2009) 051104; arXiv:0903.2794
Positrons (and electrons) produced as secondaries in the sources (e.g. SNR) where CRs are accelerated.

But also other secondaries are produced: significant increase expected in the p/p and B/C ratios.

D. Hooper, P. Blasi, and P. Serpico, JCAP 0901:025,2009; arXiv:0810.1527
Contribution from diffuse mature &nearby young pulsars.

A Challenging Puzzle for CR Physics





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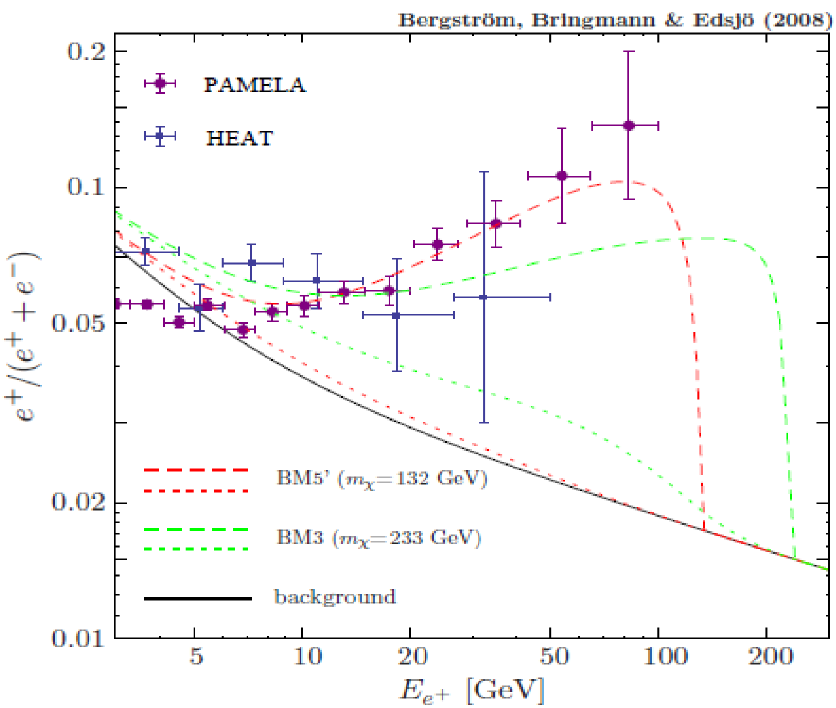
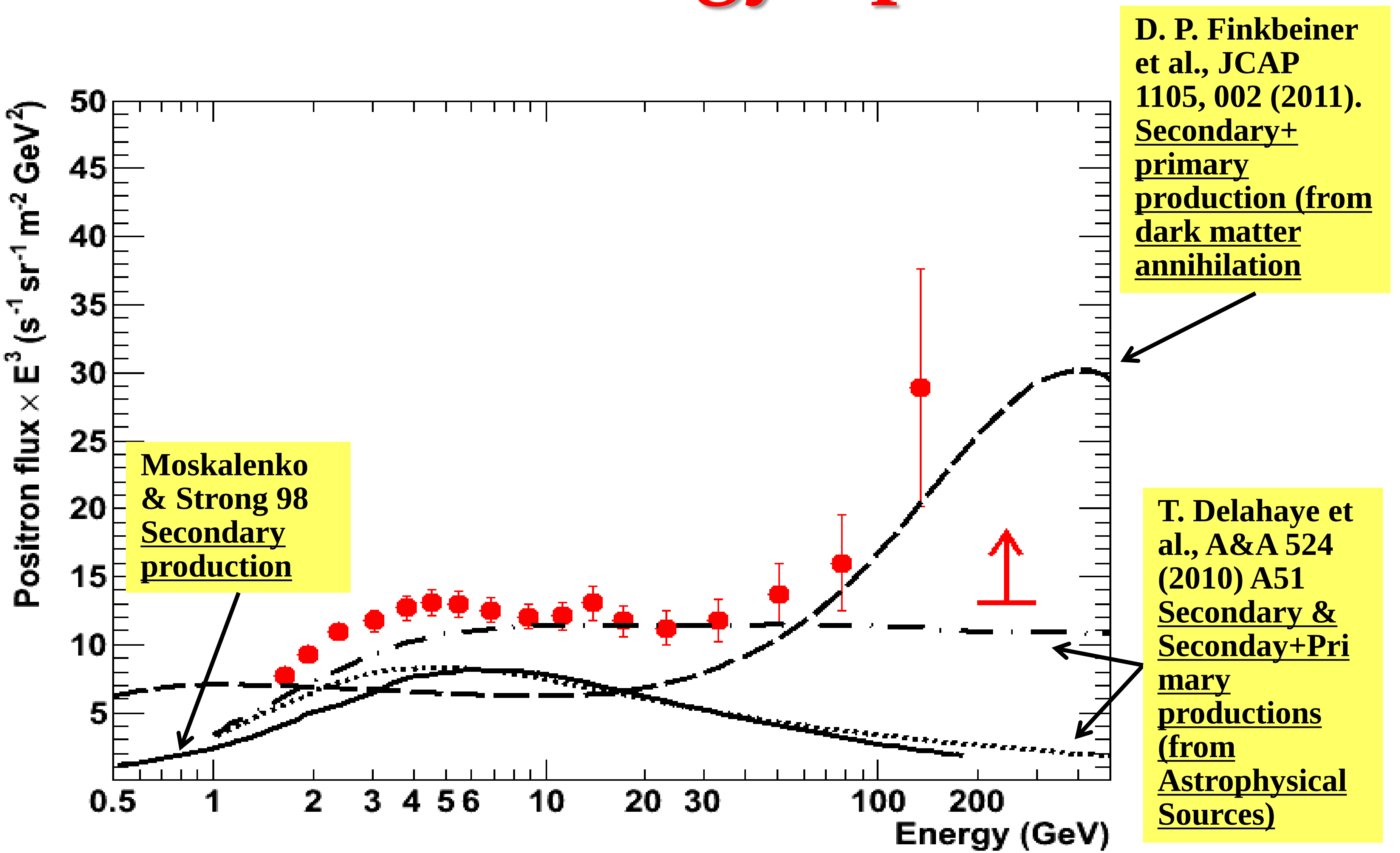


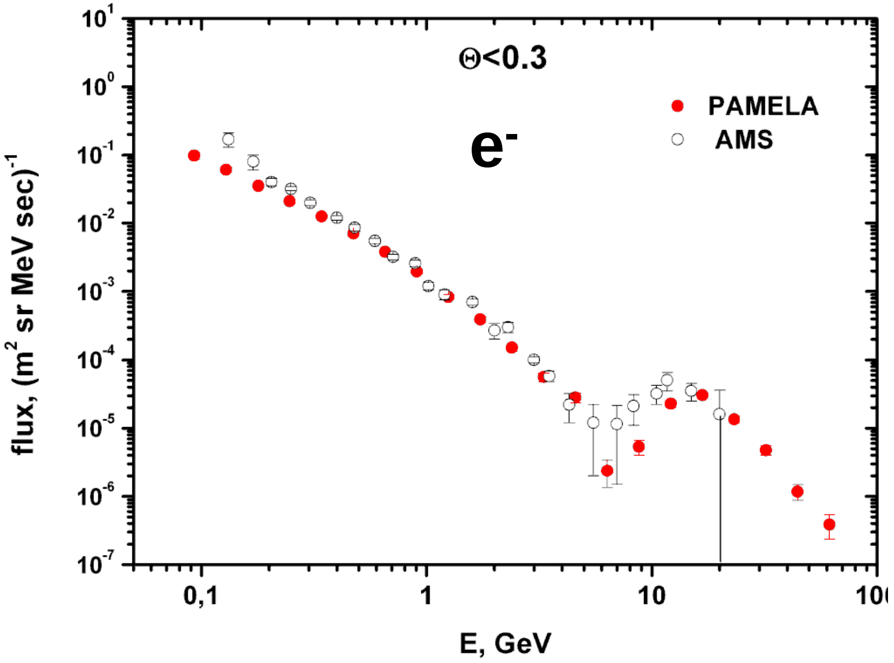
si, and P. Serpico, JCAP
Xiv:0810.1527
diffuse mature &nearby

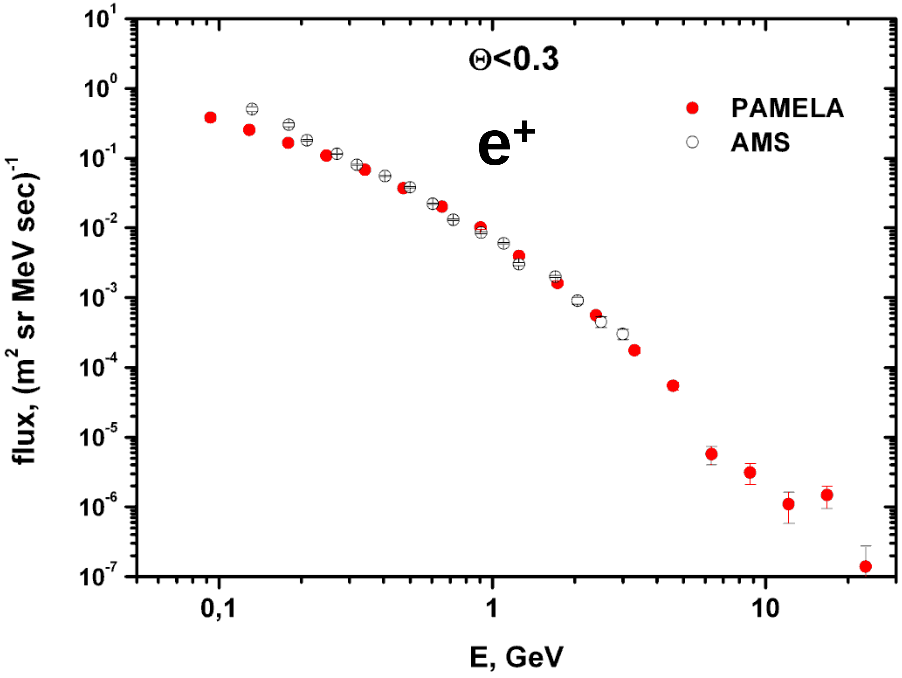
L. Bergstrom et al., Phys. Rev. D 78 (2008) 103520; arXiv:0808.3725
Contribution from DM annihilation.

Positron Energy Spectrum



Subcut-off Electrons and Positrons





Electrons

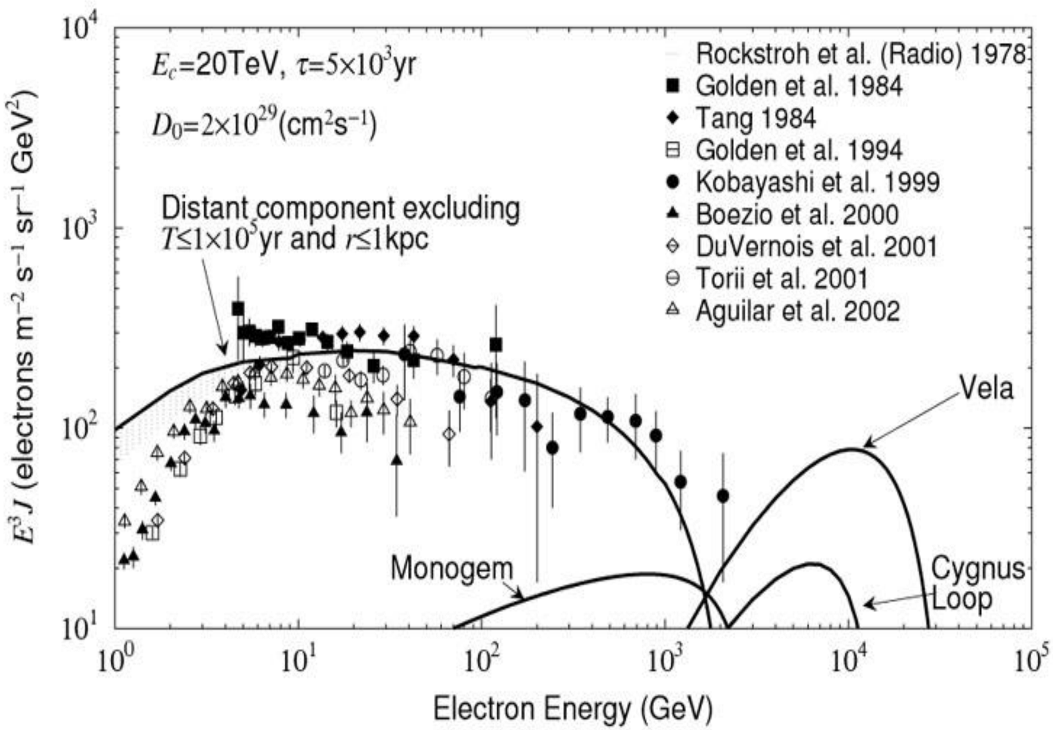
Electron Observations

- High energy electrons have a high energy loss rate ∝ E^2
  - Lifetime of ~10^5 years for >1 TeV electrons
- Transport of GCR through interstellar space is a diffusive process
  - Implies that source of high energy electrons are < 1 kpc away

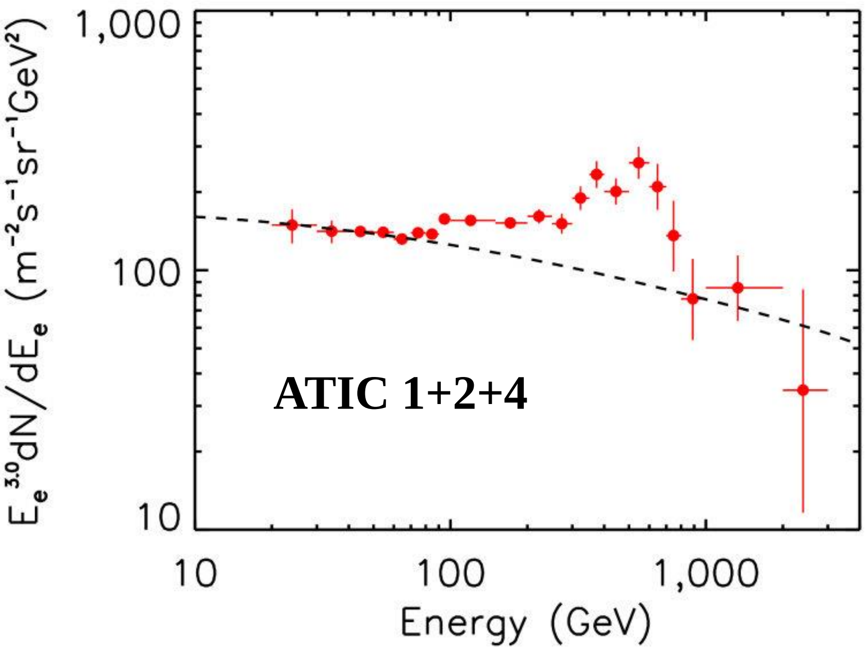
Electrons are accelerated in SNR (as seen in γ-rays)

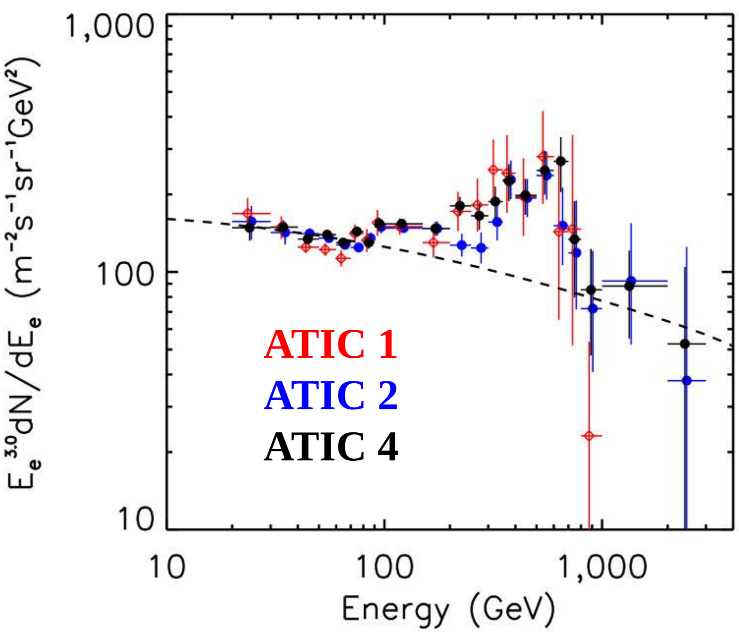
Only a handful of SNR meet the lifetime & distance criteria

Kobayashi et al (2004) calculations show structure in electron spectrum at high energy



Results from three ATIC flights



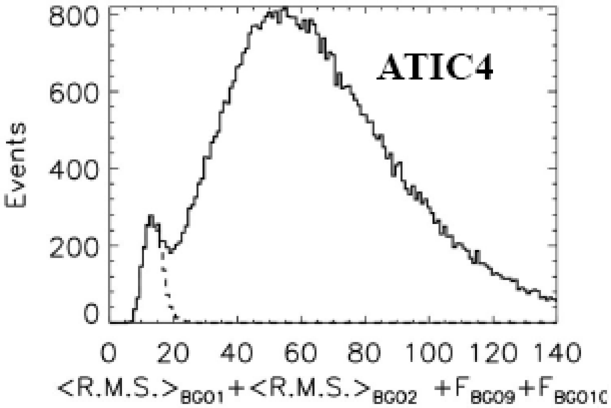


"Source on/source off" significance of bump for ATIC1+2 is about 3.8 sigma
J Chang *et al. Nature* **456**, 362 (2008)

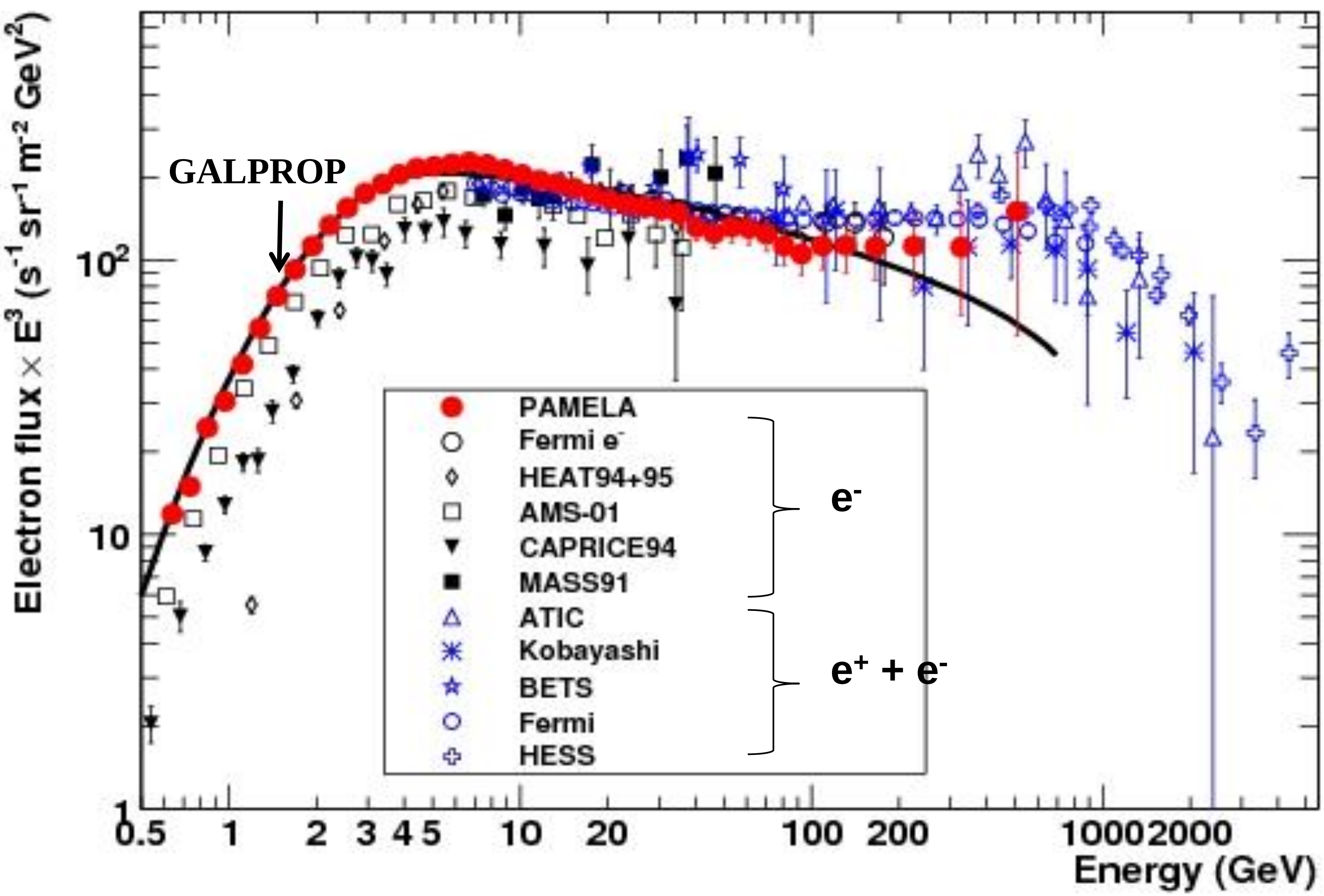
ATIC-4 with 10 BGO layers has improved e , p separation. **(~4x lower background)**

"Bump" is seen in all three flights.

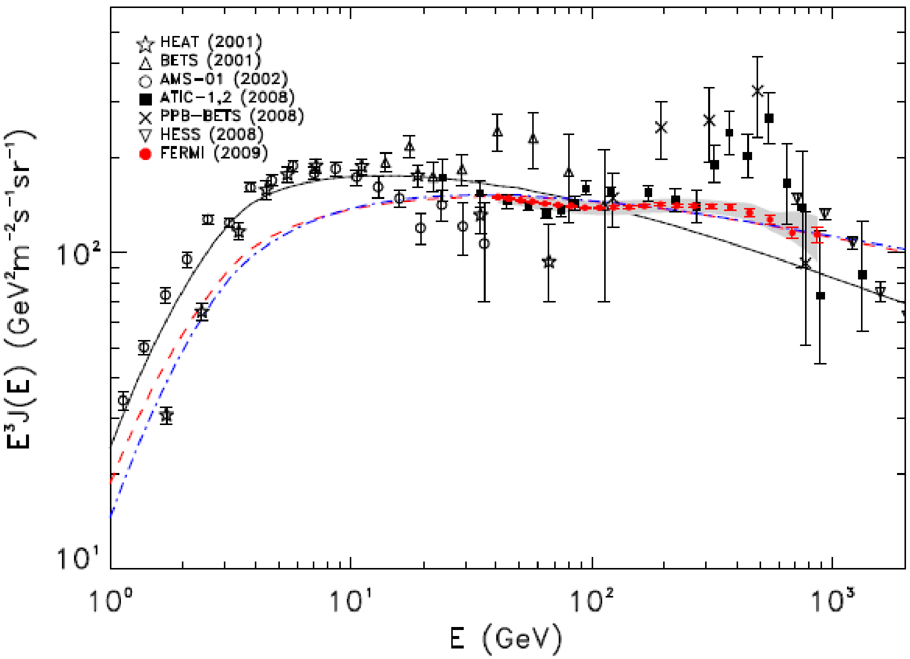
Significance for ATIC1+2+4 is 5.1 sigma



PAMELA Electron (e^-) Spectrum



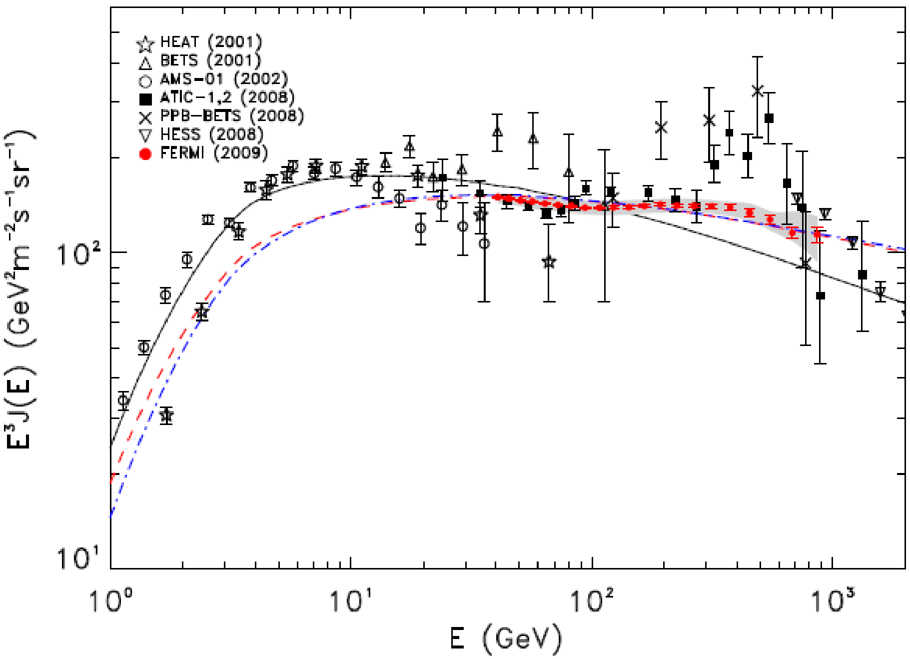
Electron Spectrum and Positron Fraction



Modify the injection indices of GALPROP?

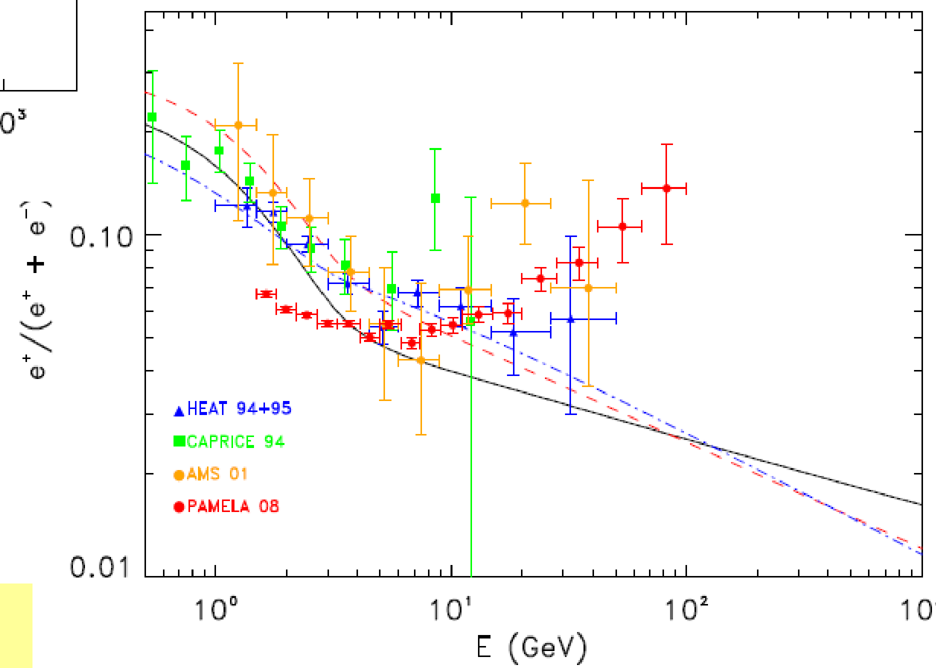
D. Grasso et al., Astropart.Phys. 32 (2009) 140; arXiv:0905.0636

Electron Spectrum and Positron Fraction

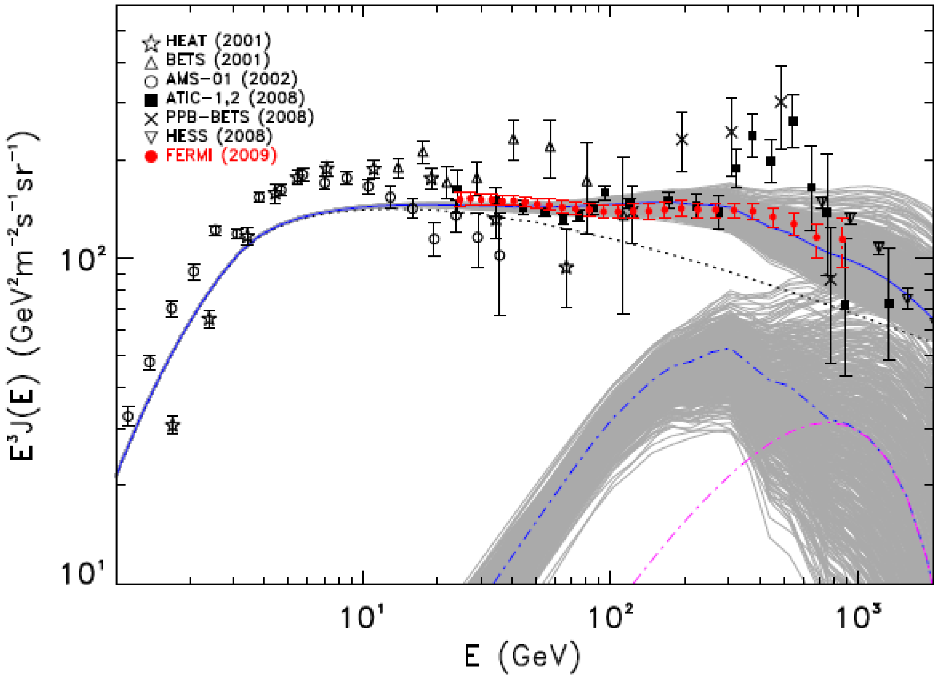


Modify the injection indices of GALPROP?

Does not fit at all the PAMELA ratio:

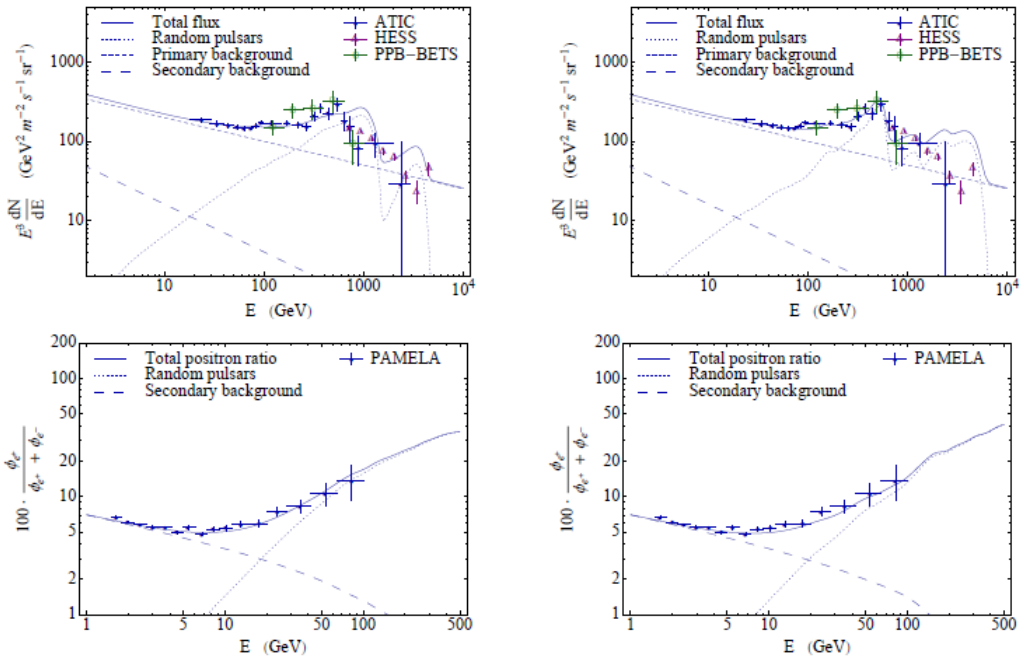


D. Grasso et al., Astropart.Phys. 32 (2009) 140; arXiv:0905.0636



Pulsar Explanation

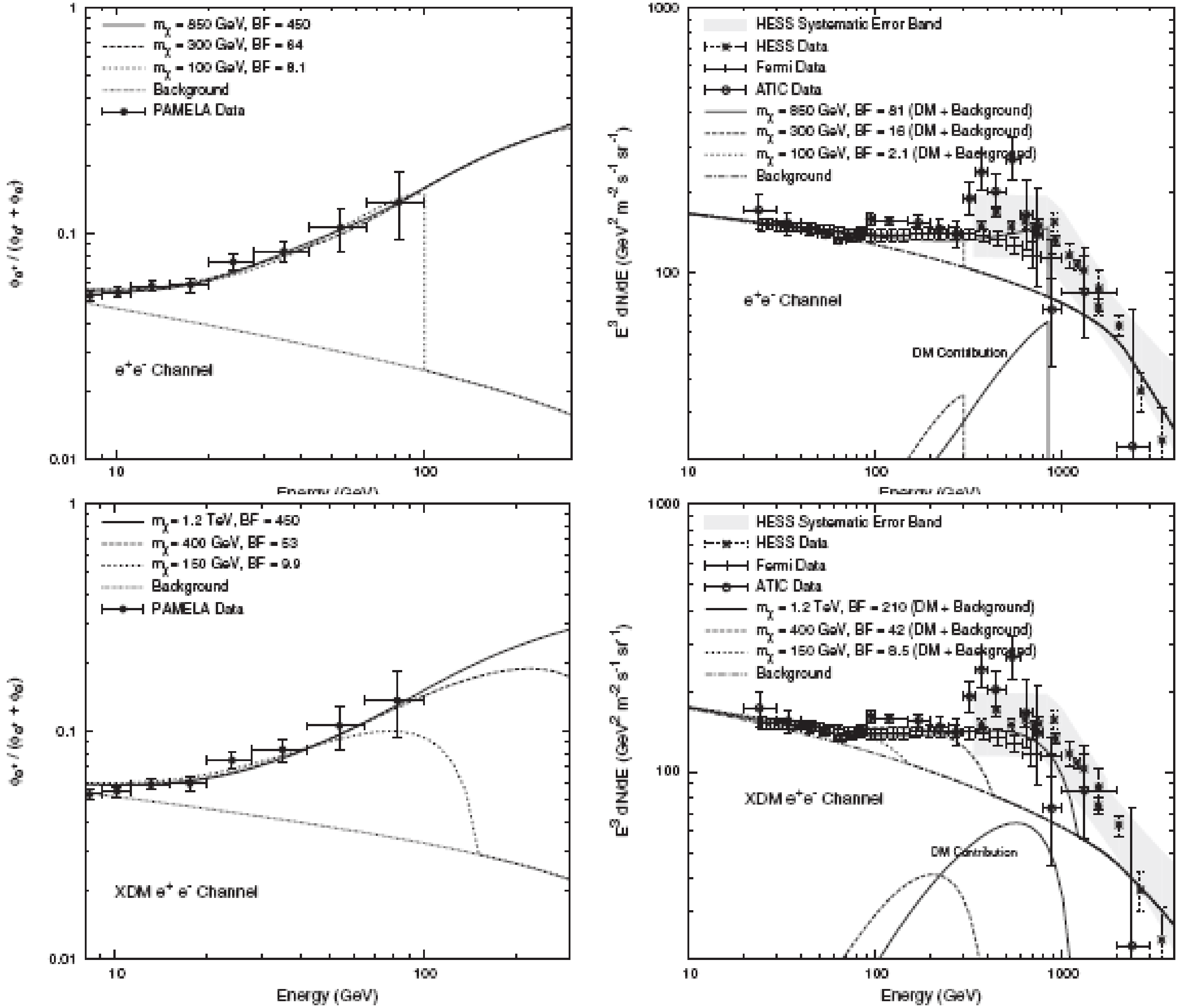
Some structure in the curve should eventually be seen for pulsars? (D. Grasso et al., Astropart. Phys. 32, 140, 2009).



D. Malyshev, I. Cholis and J. Gelfand, PRD 80 (2009) 063005

Interpretation: DM

I. Cholis et al. Phys. Rev. D 80 (2009) 123518; arXiv:0811.3641v1



- Propose a new light boson ($m_\Phi \le$ GeV), such that $\chi\chi \rightarrow \Phi\Phi$; $\Phi \rightarrow e^+e^-$, $\mu^+\mu^-$, ...
- Light boson, so decays to antiprotons are kinematically suppressed

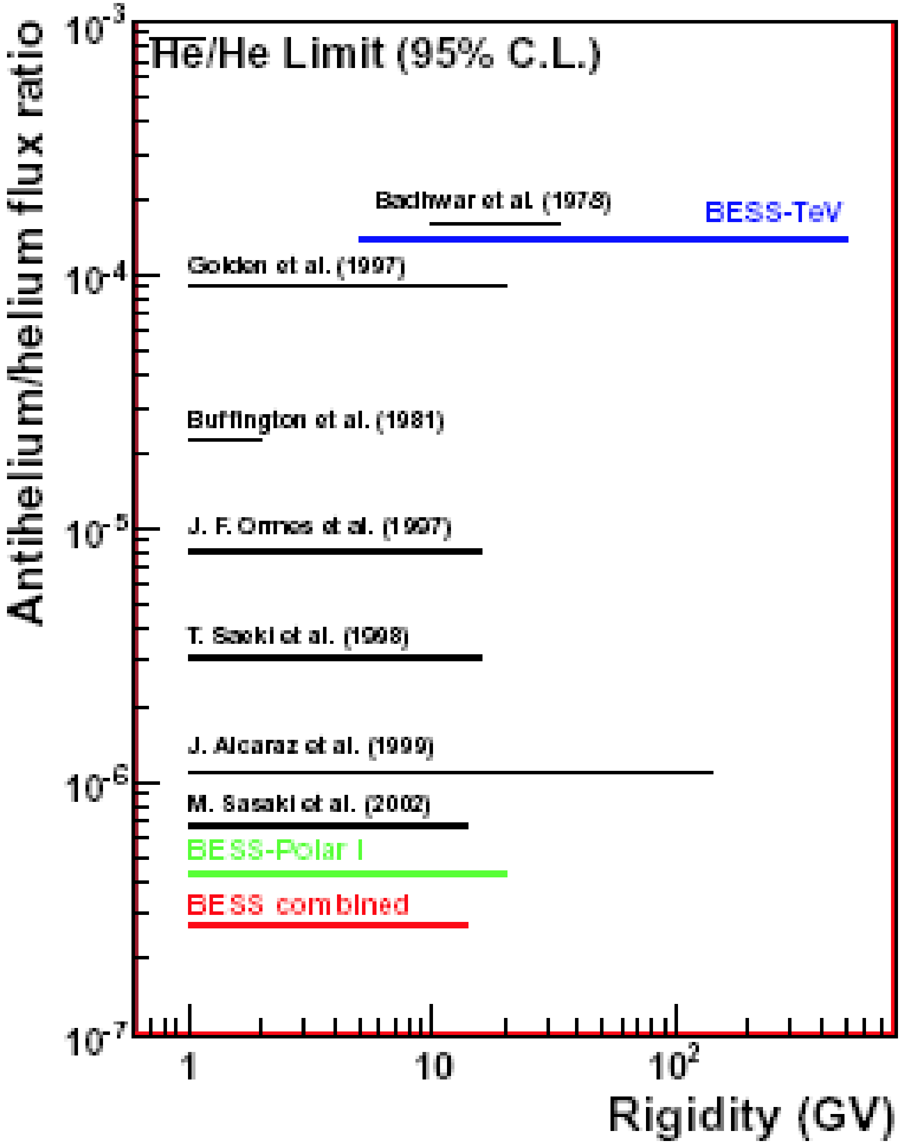
What about heavy antinuclei?

- **The discovery of one nucleus of antimatter ($Z \geq 2$) in the cosmic rays would have profound implications for both particle physics and astrophysics.**

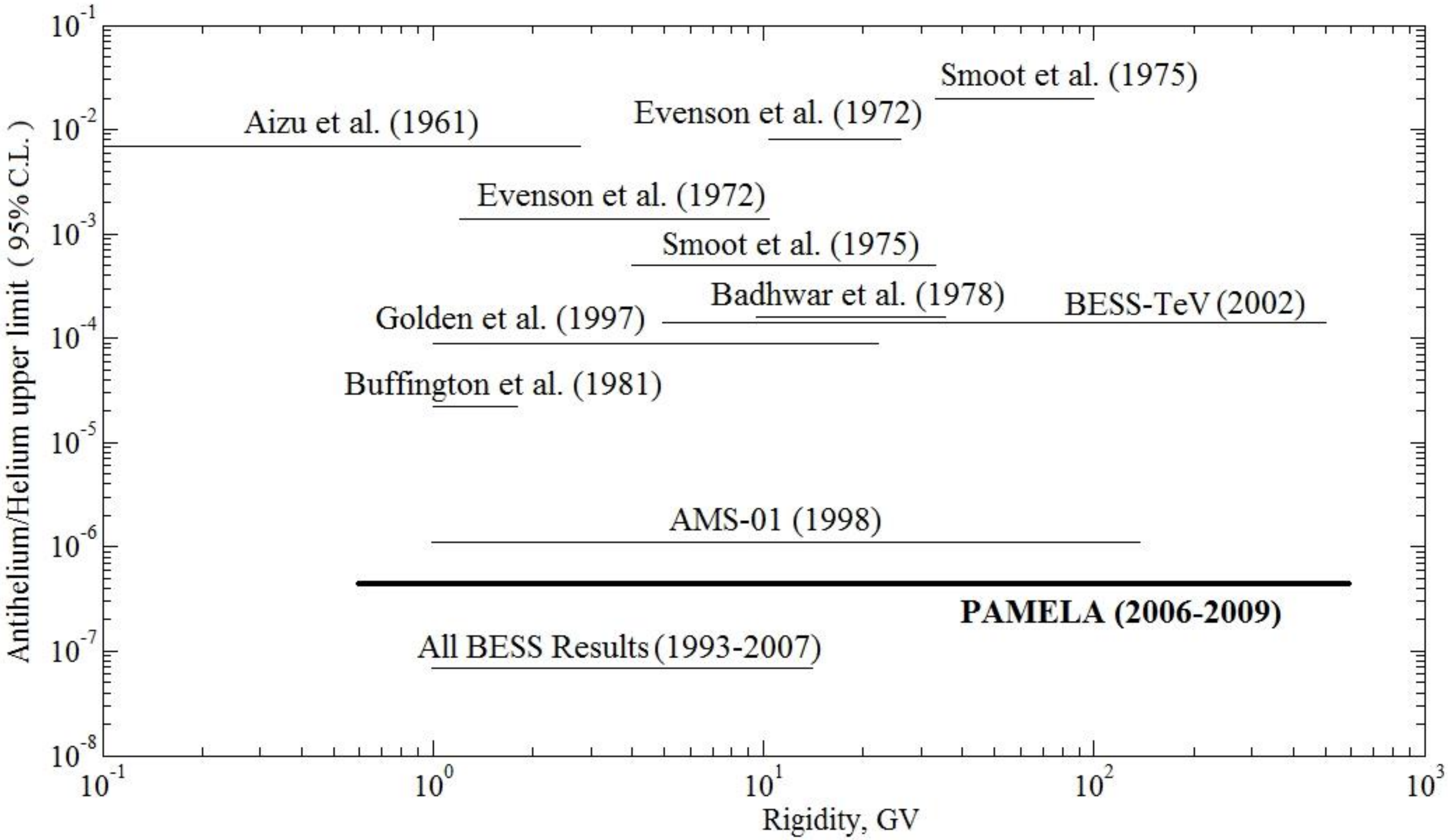
  - **For a Baryon Symmetric Universe Gamma rays limits put any domain of antimatter more than 100 Mpc away**

    (Steigman (1976) Ann Rev. Astr. Astrophys., 14, 339; Dudarerwicz and Wolfendale (1994) M.N.R.A. 268, 609, A.G. Cohen, A. De Rujula and S.L. Glashow, Astrophys. J. 495, 539, 1998)

Antimatter Search: 2006 limits

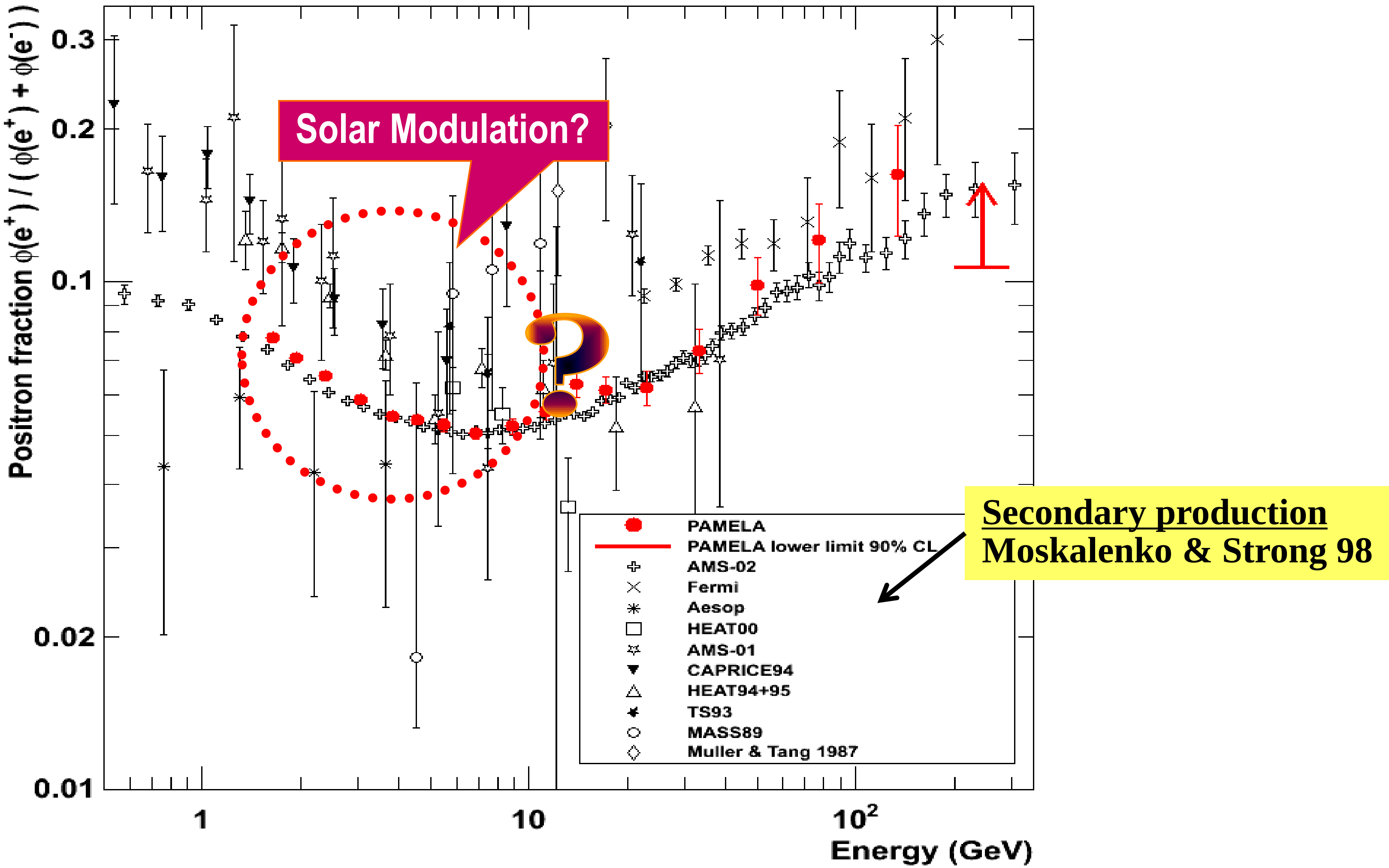


What about PAMELA & Antinuclei?



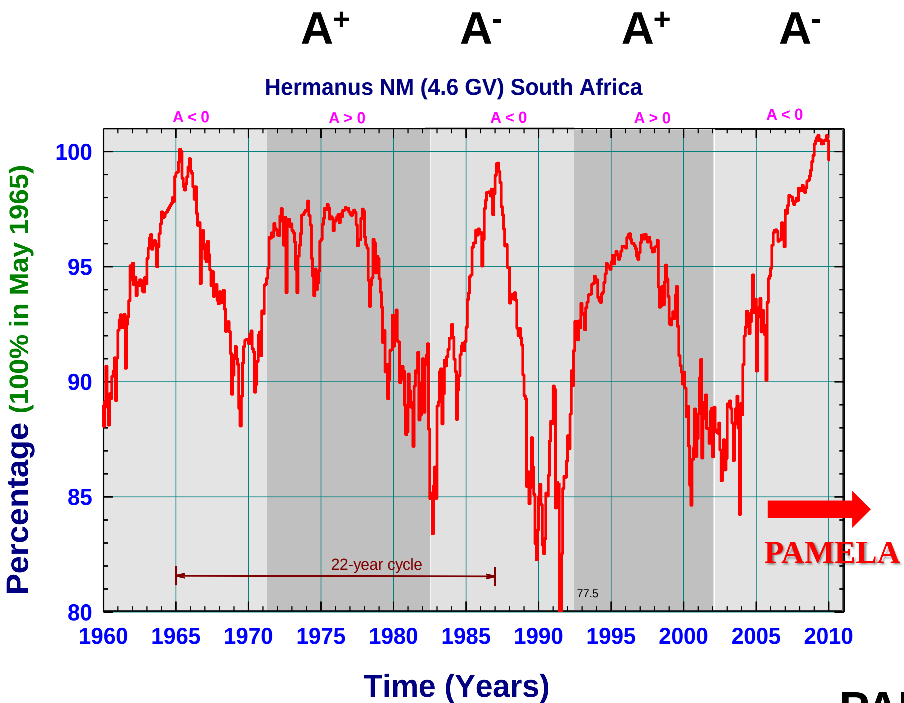
Cosmic Rays in the Heliosphere

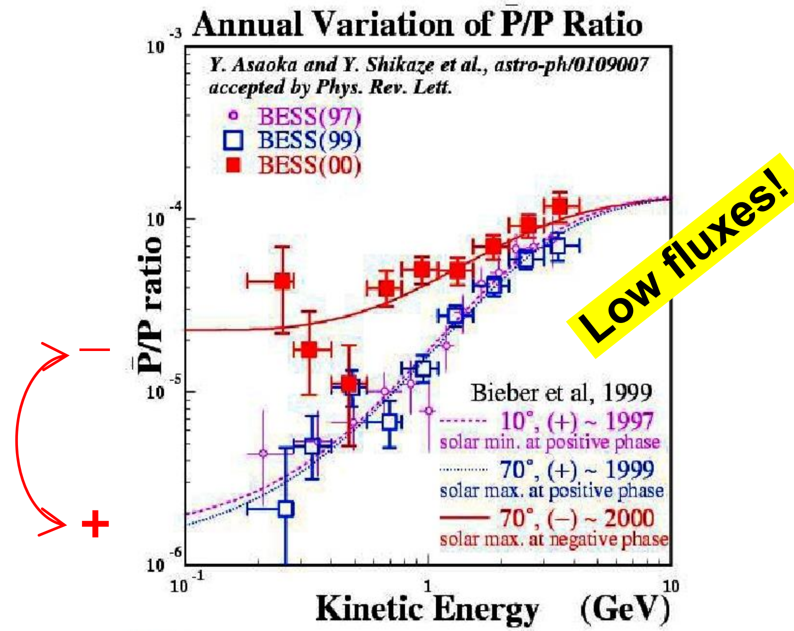
Positron to Electron Fraction



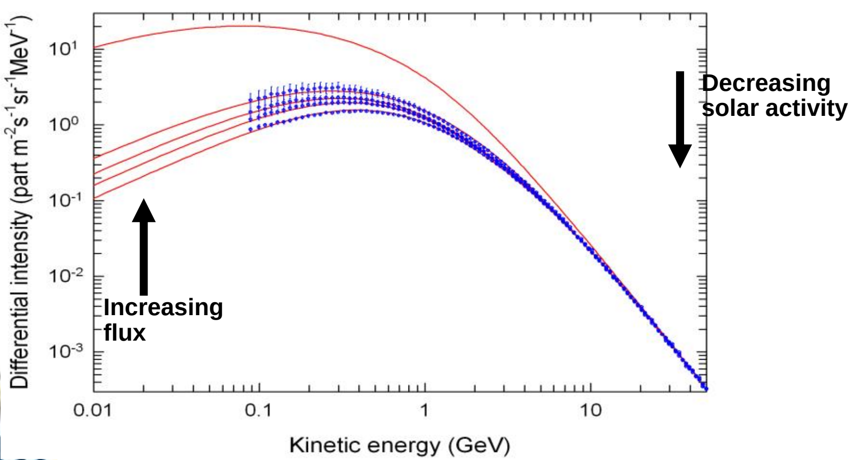
Adriani et al, Astropart. Phys. 34 (2010) 1
arXiv:1001.3522 [astro-ph.HE]

Solar modulation

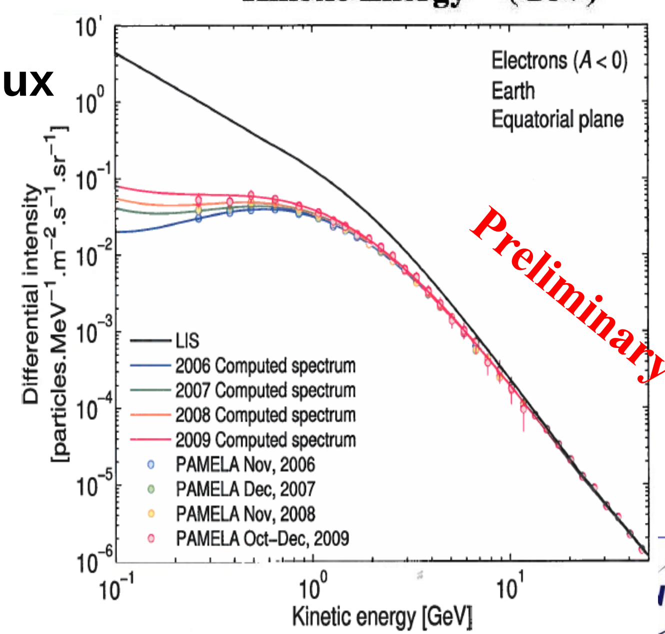




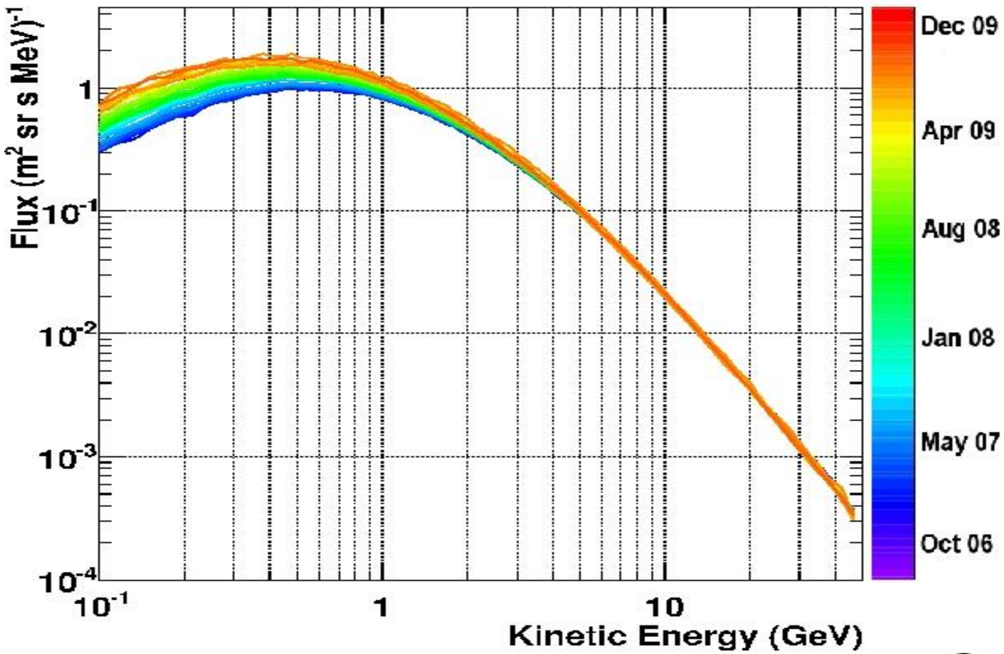
PAMELA p flux



PAMELA e^- flux

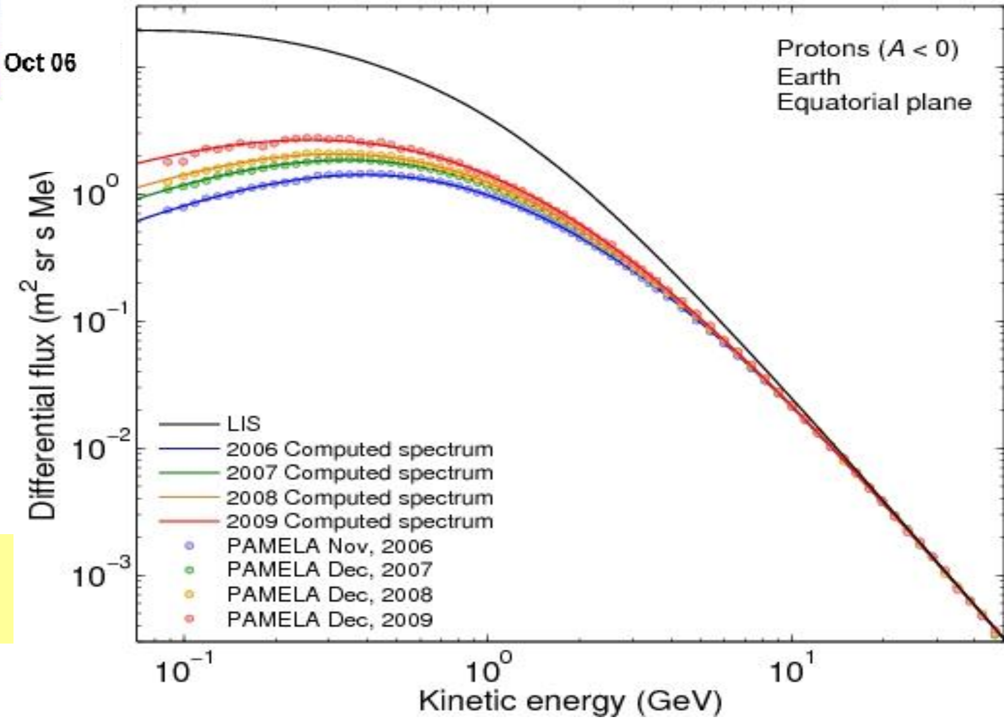


Time Dependance of the Proton Flux



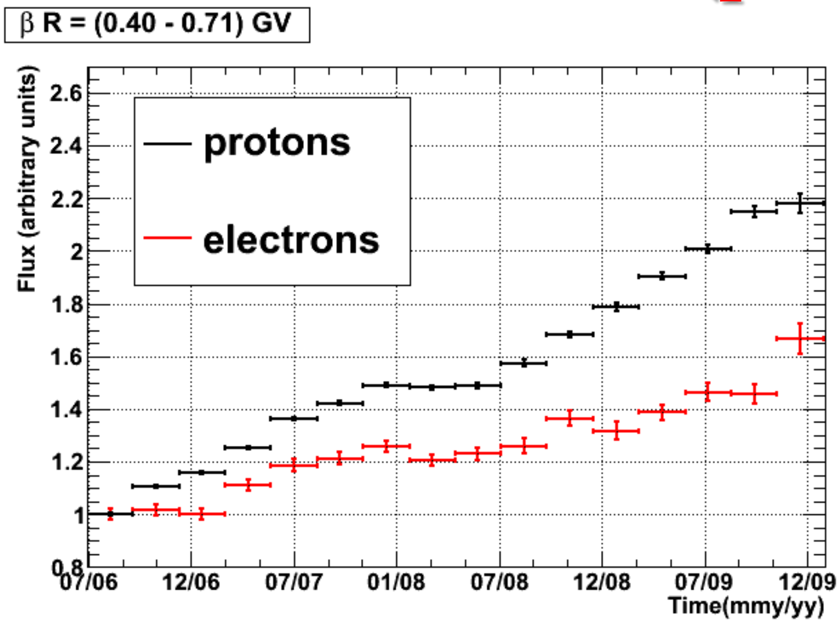
Evolution of the proton energy spectrum from July 2006 to Deember 2009

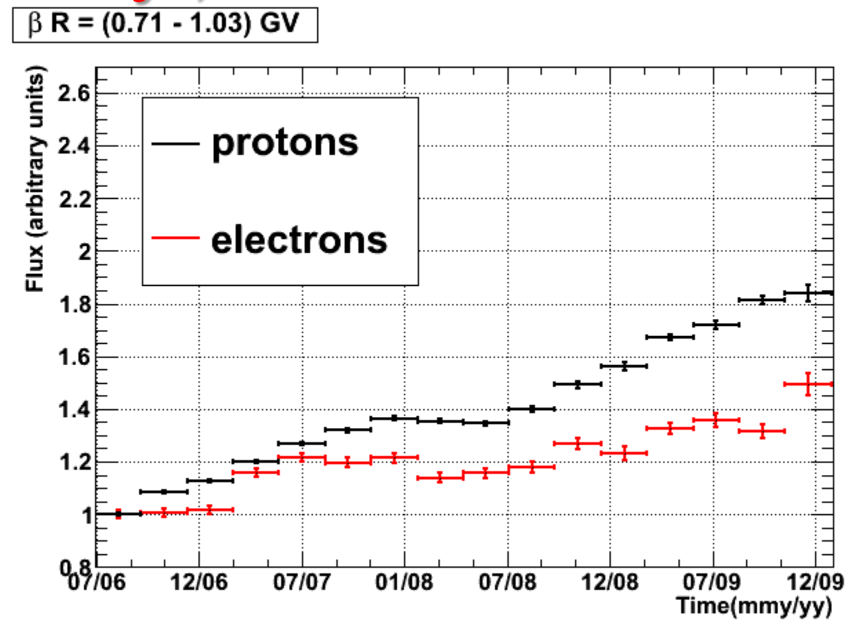
The PAMELA proton spectra over four months compared with the computed spectra

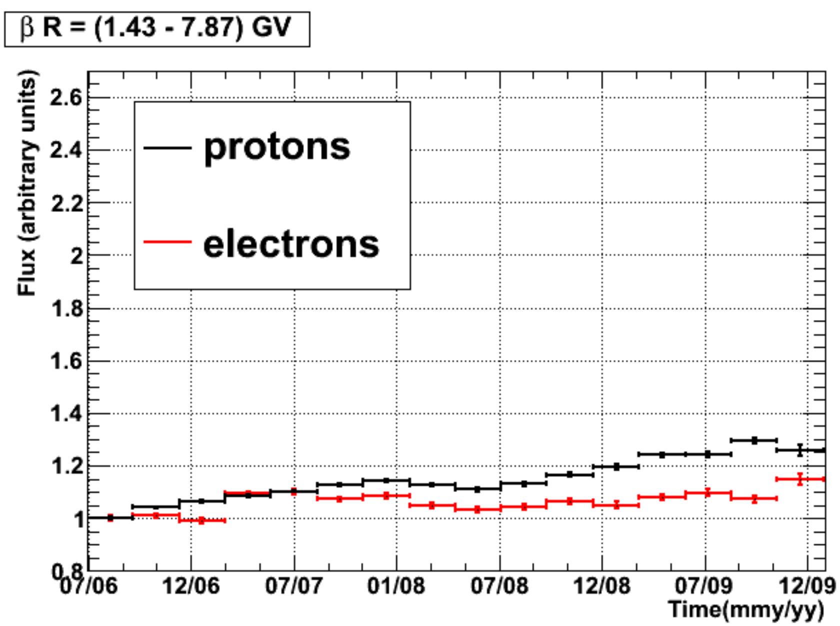


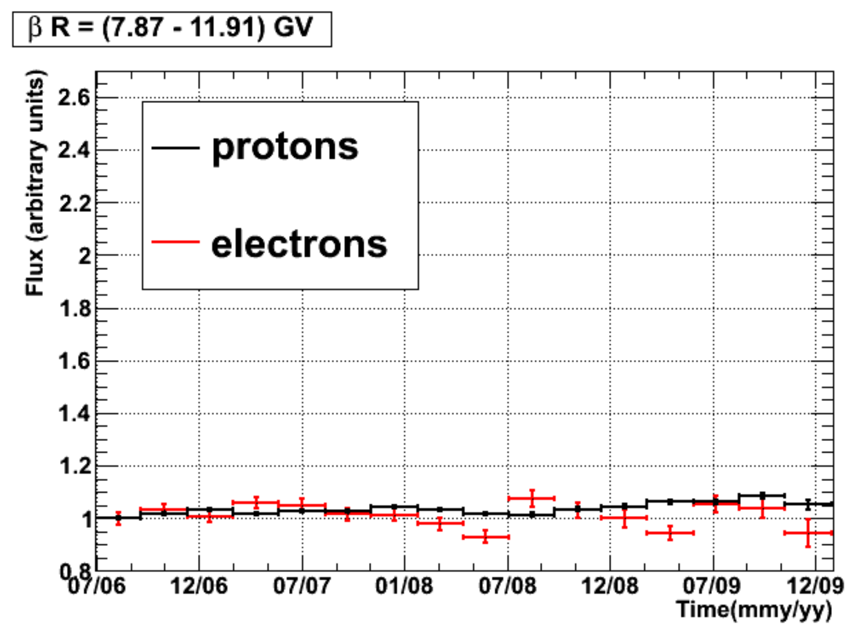
O. Adriani et al., ApJ 765 (2013) 91;
M. S. Potgieter et al., arXiv:1302.1284

Time dependence: p and e^- (preliminary!)

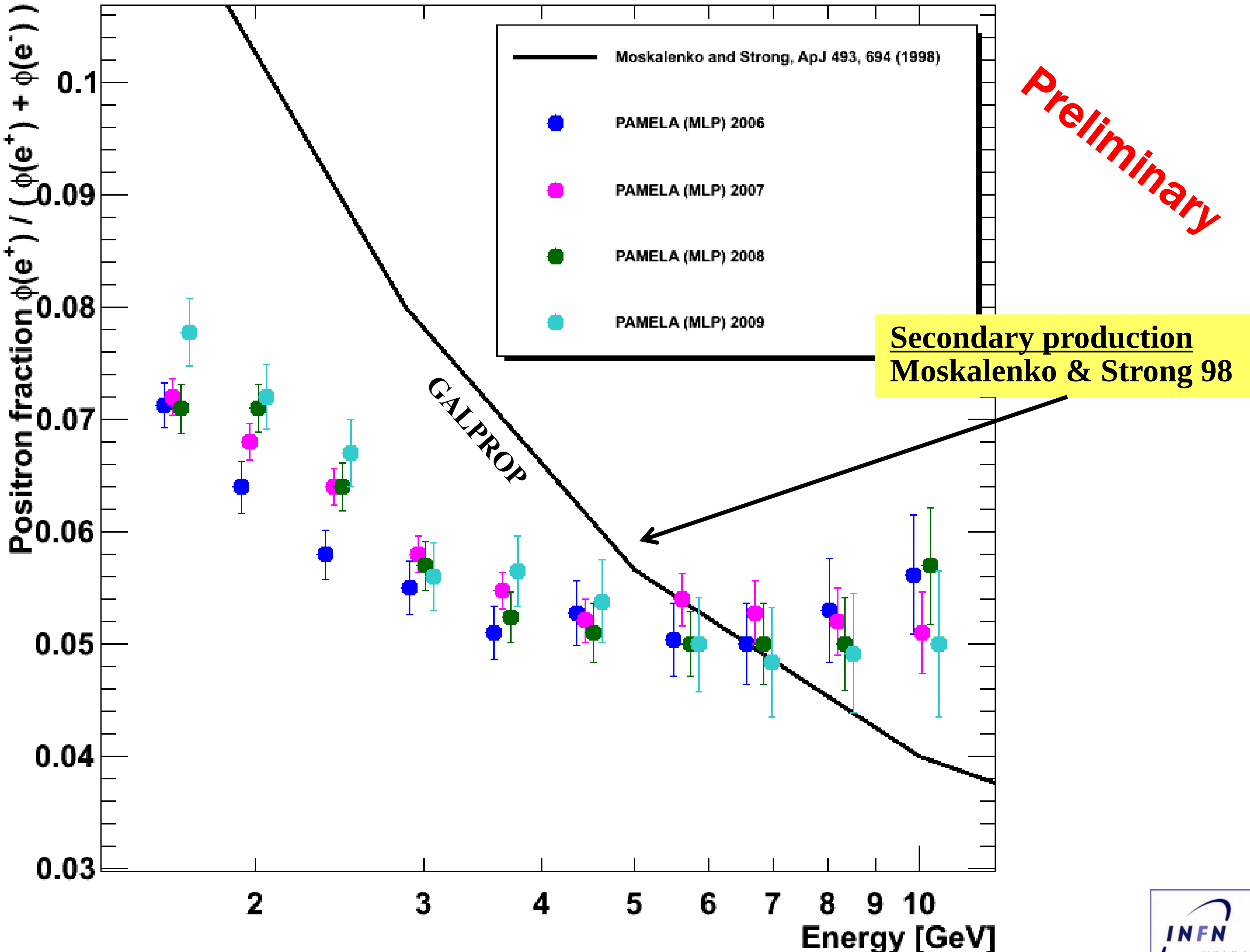




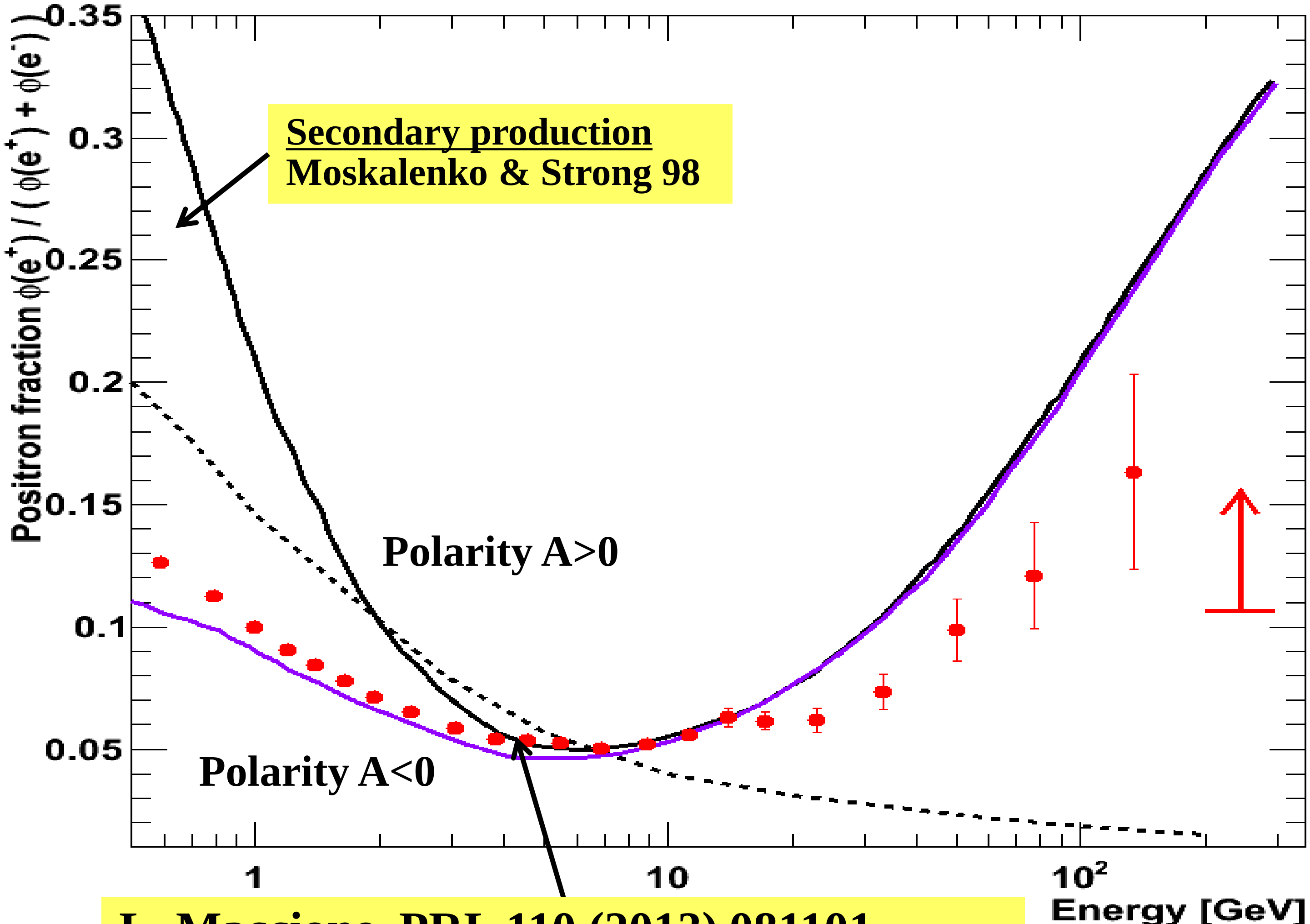




PAMELA Positron Fraction

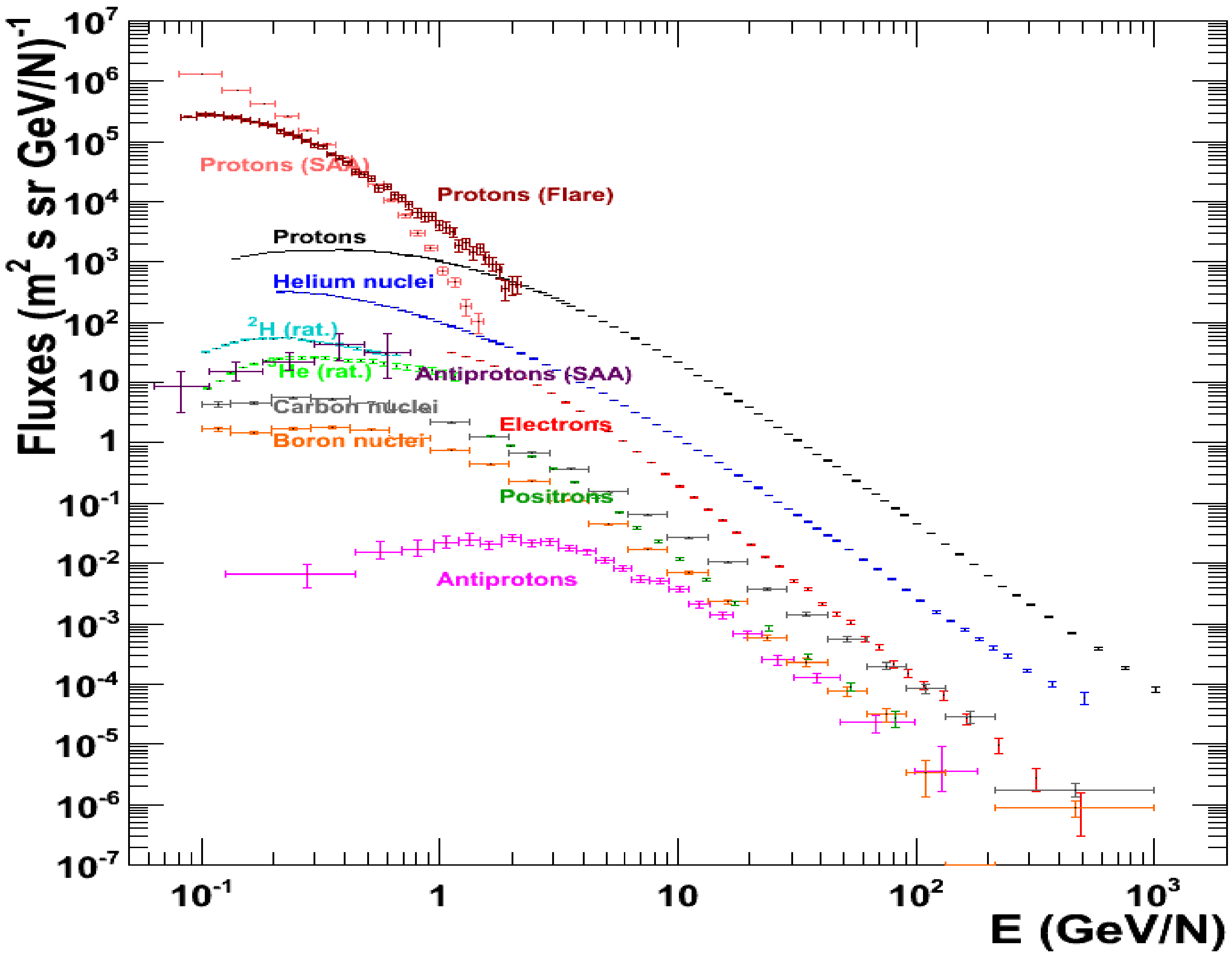


Positron to Electron Fraction



L. Maccione, PRL 110 (2013) 081101.

Summary of PAMELA results

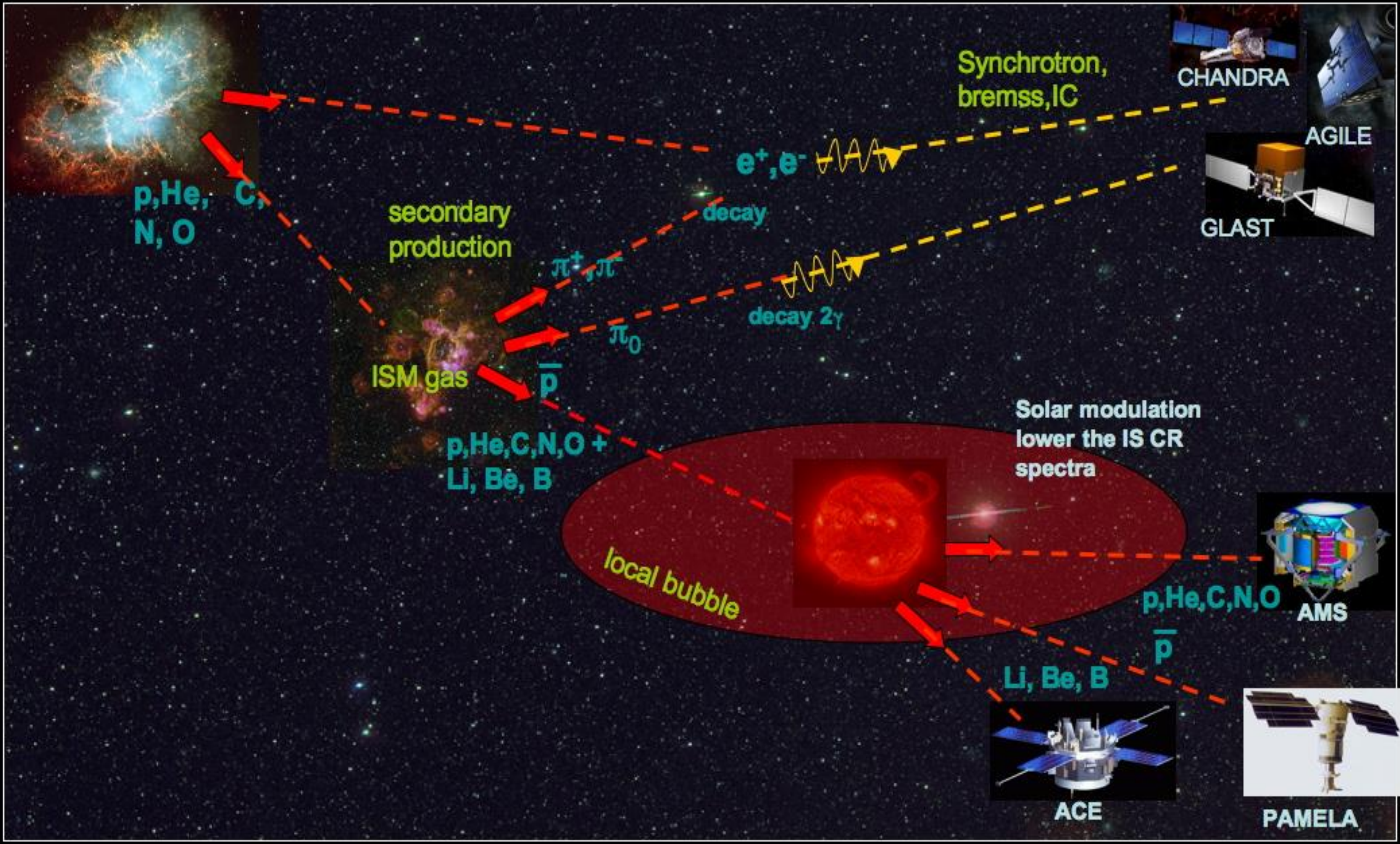


Mirko Boezio, LEAP2013, Uppsala, 2013/06/10

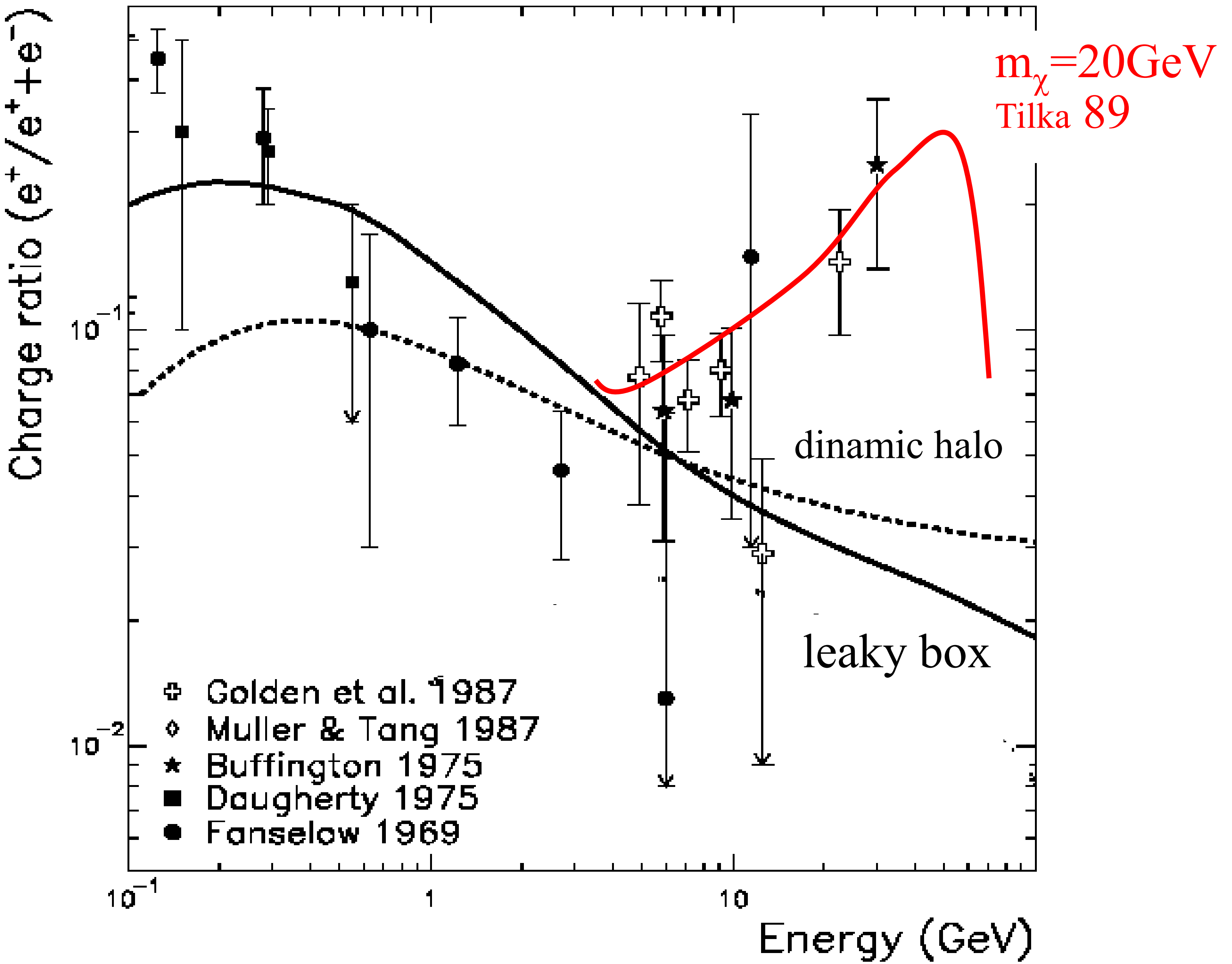
Thanks!

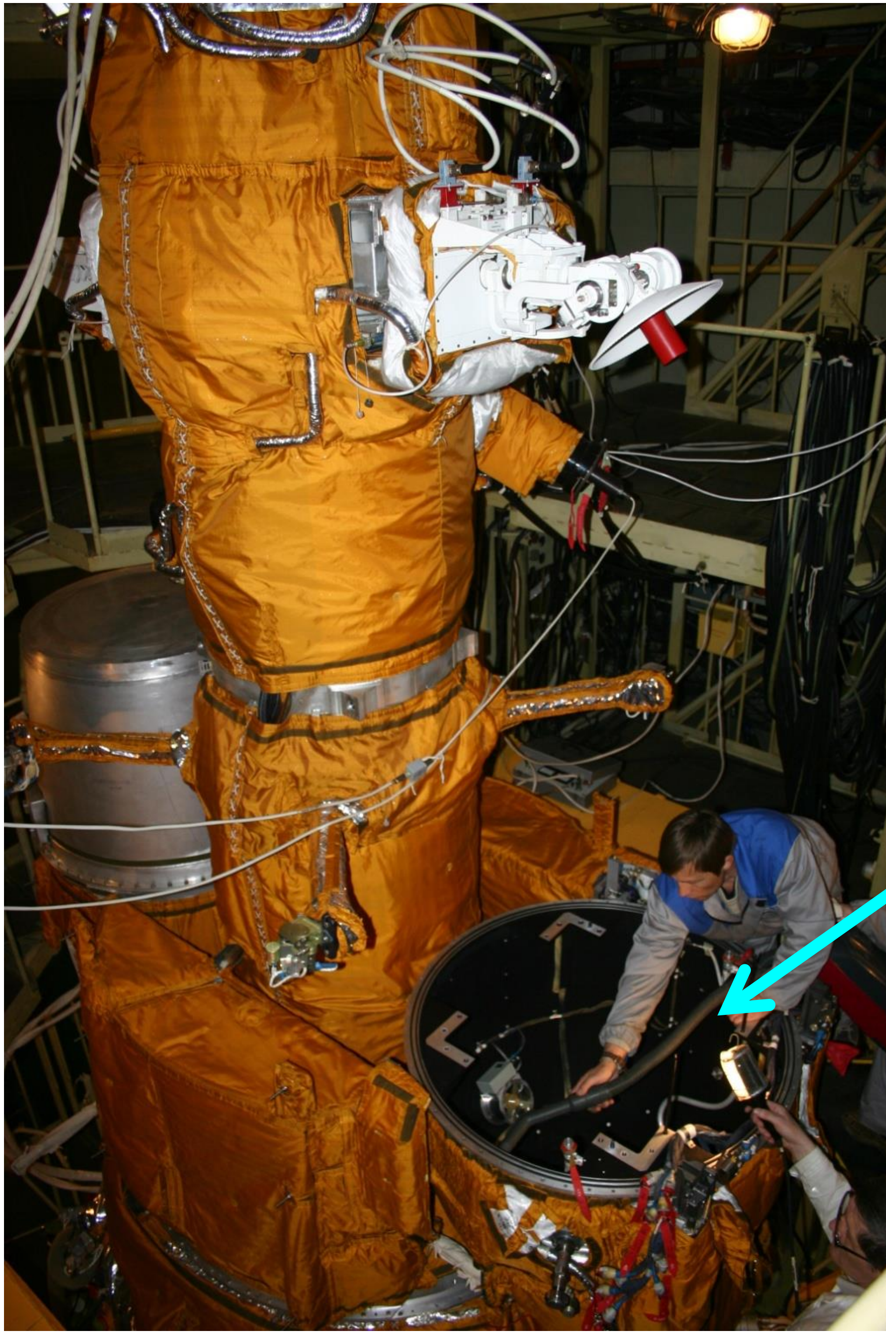
Spare Slides

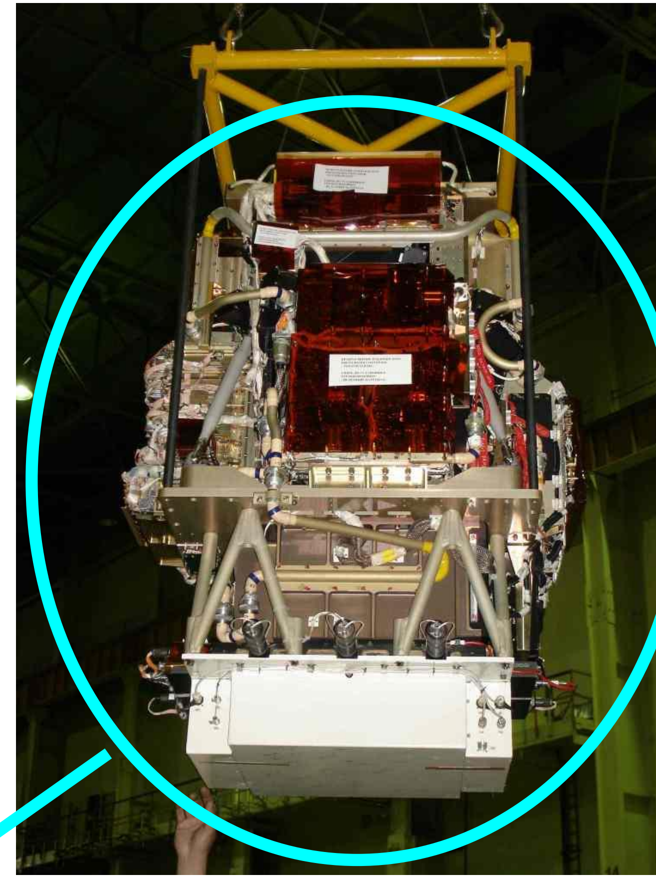
COSMIC RAYS PRODUCTION MECHANISMS



Balloon data : Positron fraction before 1990

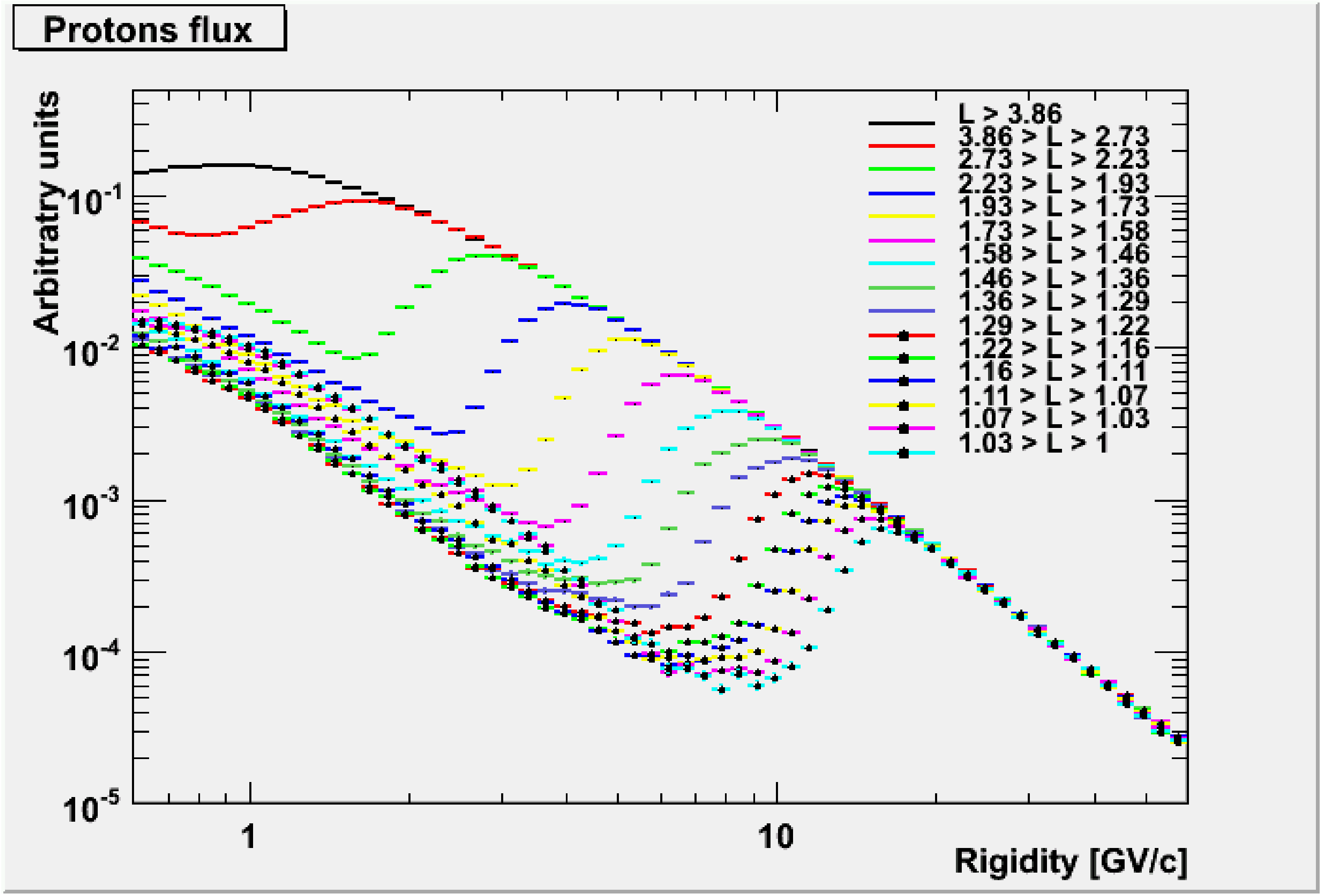






PAMELA INTEGRATION in the RESURS-DK1 satellite

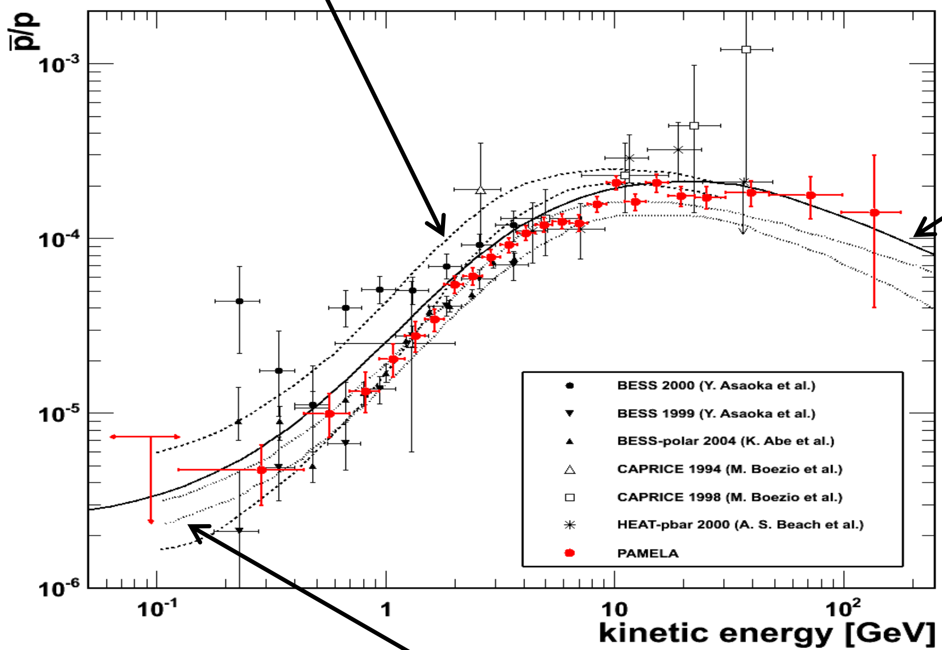
Subcutoff particles

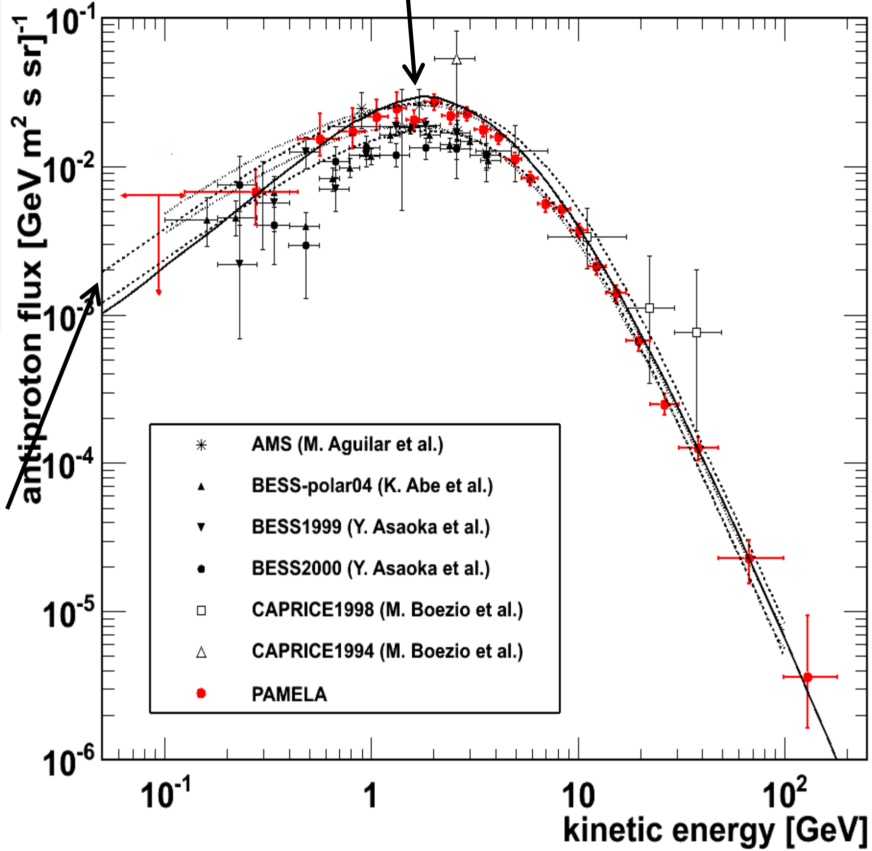


Antiproton Results

Simon et al. (ApJ 499 (1998) 250)

Ptuskin et al. (ApJ 642 (2006) 902)

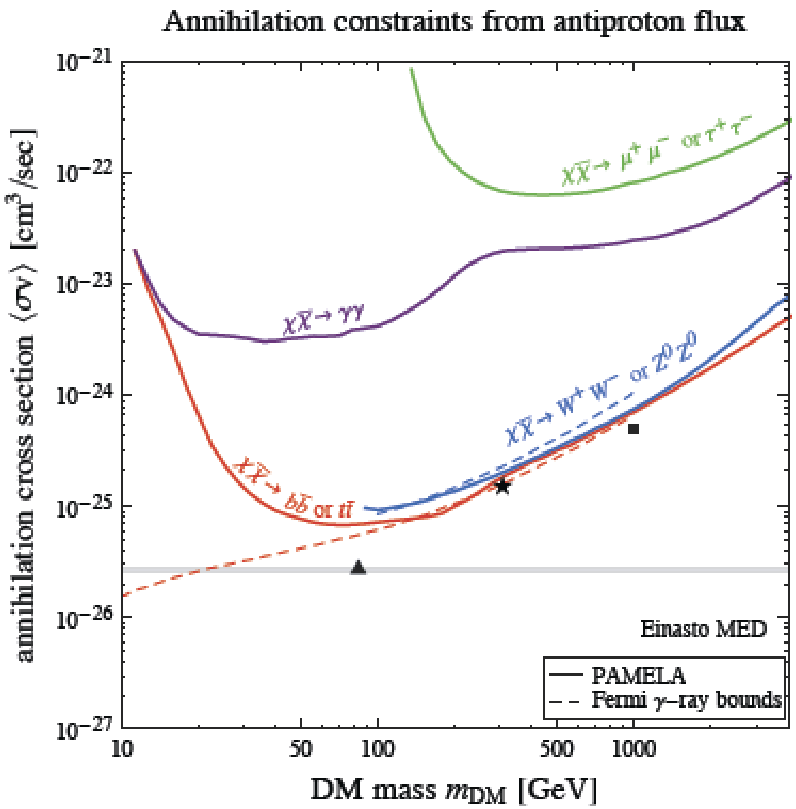


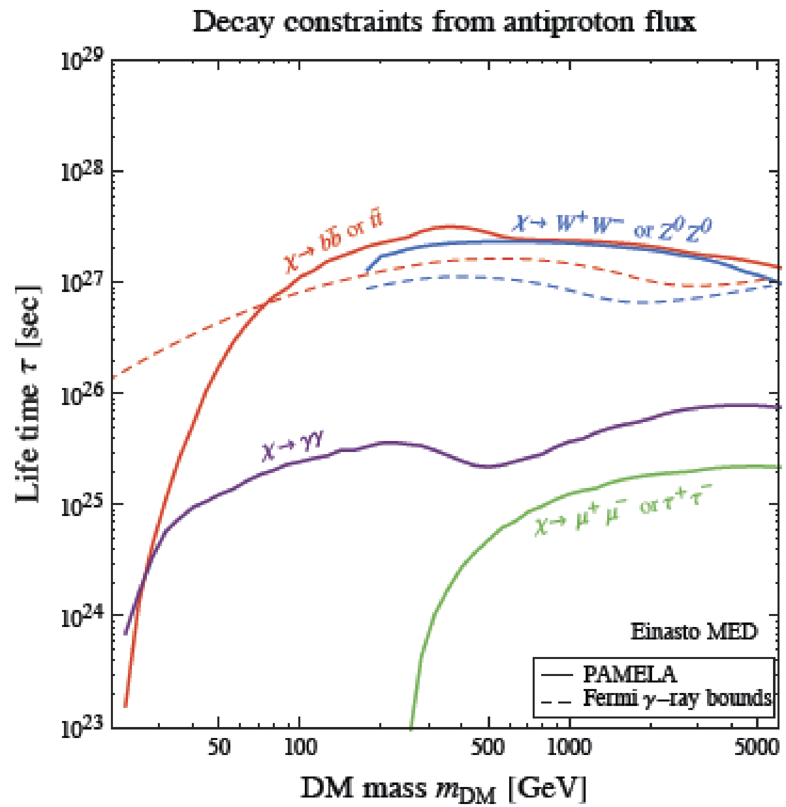


Donato et al. (PRL 102 (2009) 071301)

O. Adriani et al., PRL 102, 051101 (2009); PRL 105, 121101 (2010)

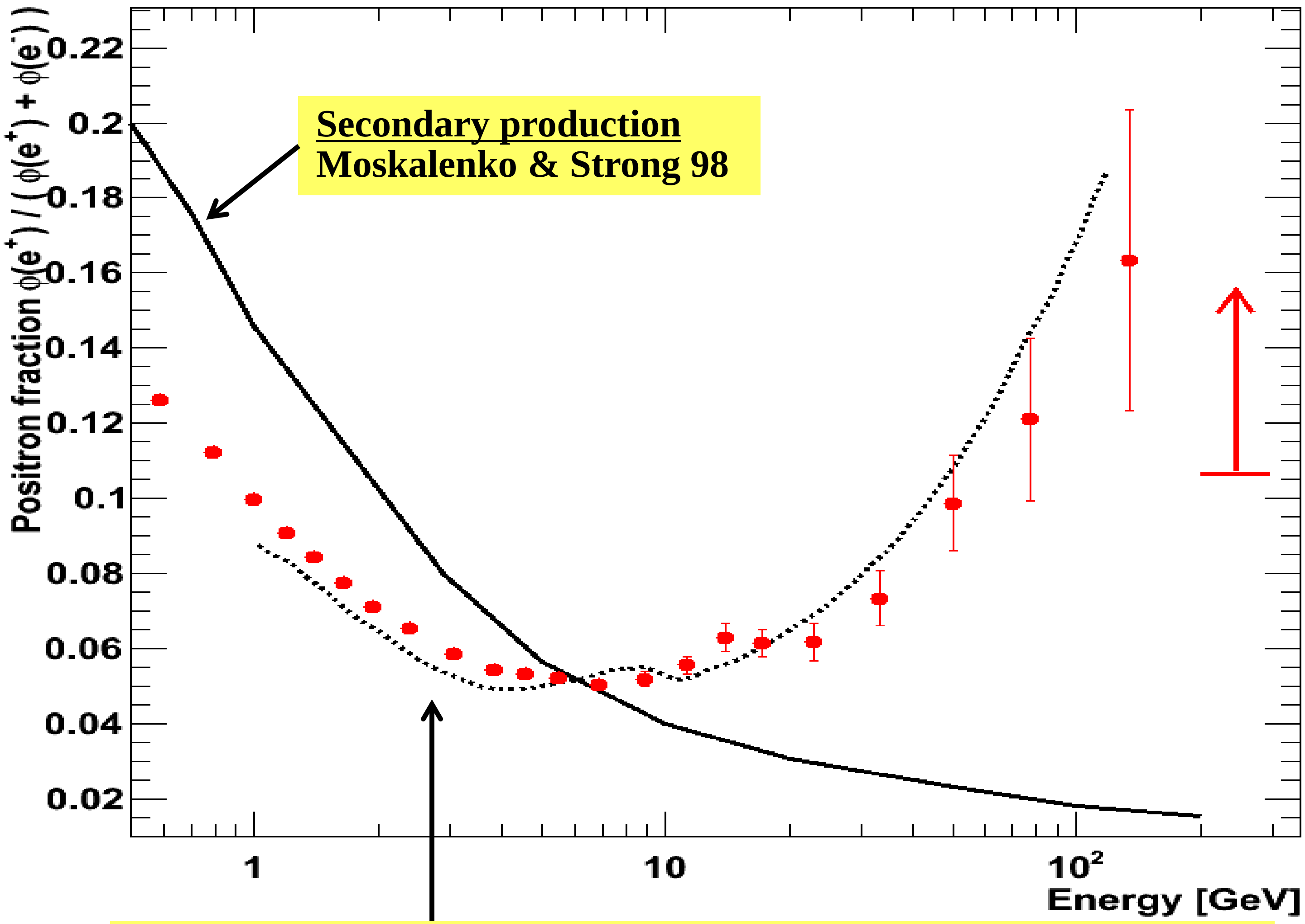
Cosmic-Ray Antiprotons and DM limits





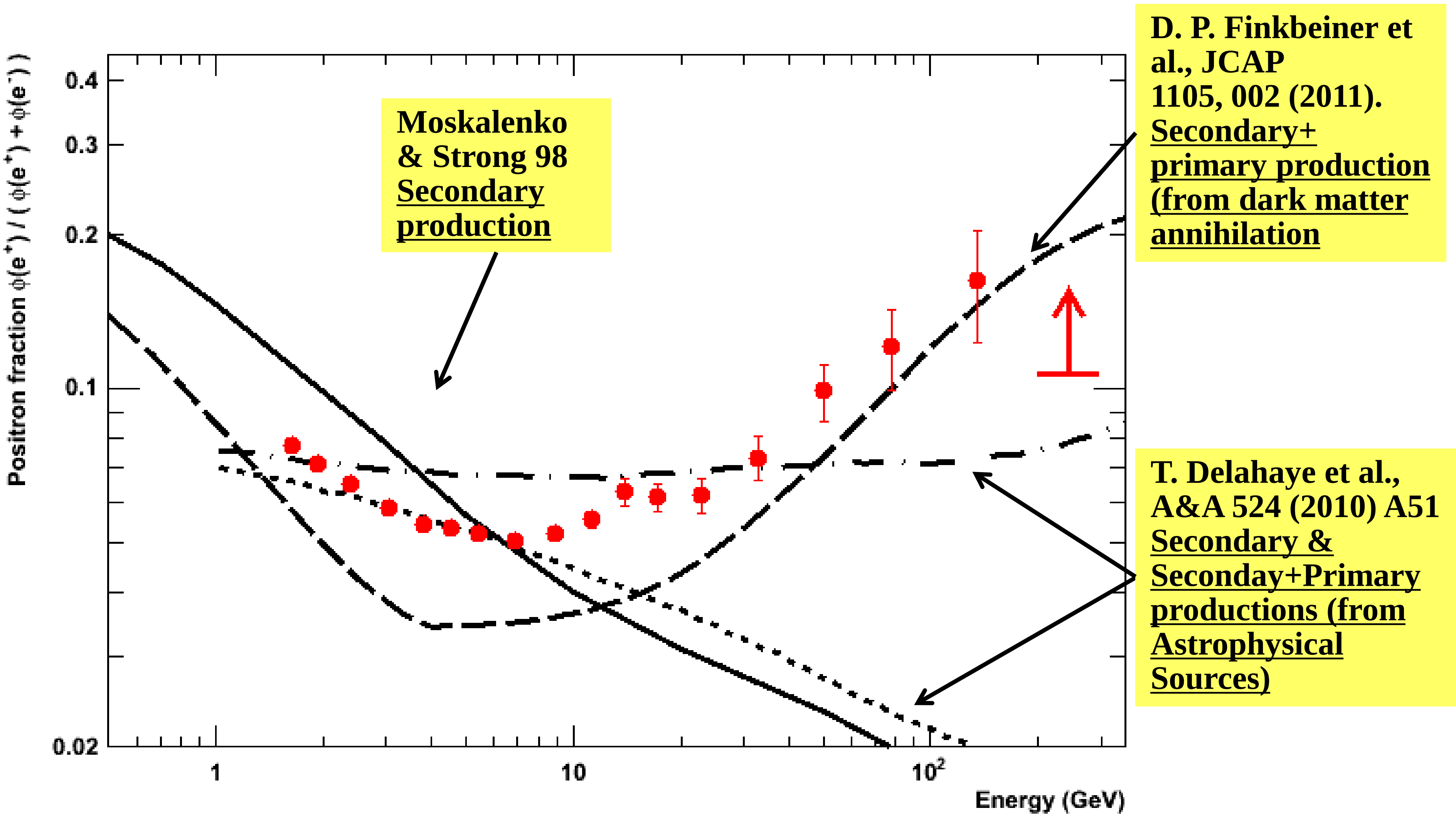
M. Cirelli & G. Giesen, arXiv: 1301:7079
"Antiprotons are a very relevant tool to constrain Dark Matter annihilation and decay, on a par with gamma rays for the hadronic channels. Current Pamela data and especially upcoming AMS-02 data allow to probe large regions of the parameter space."

Positron to Electron Fraction

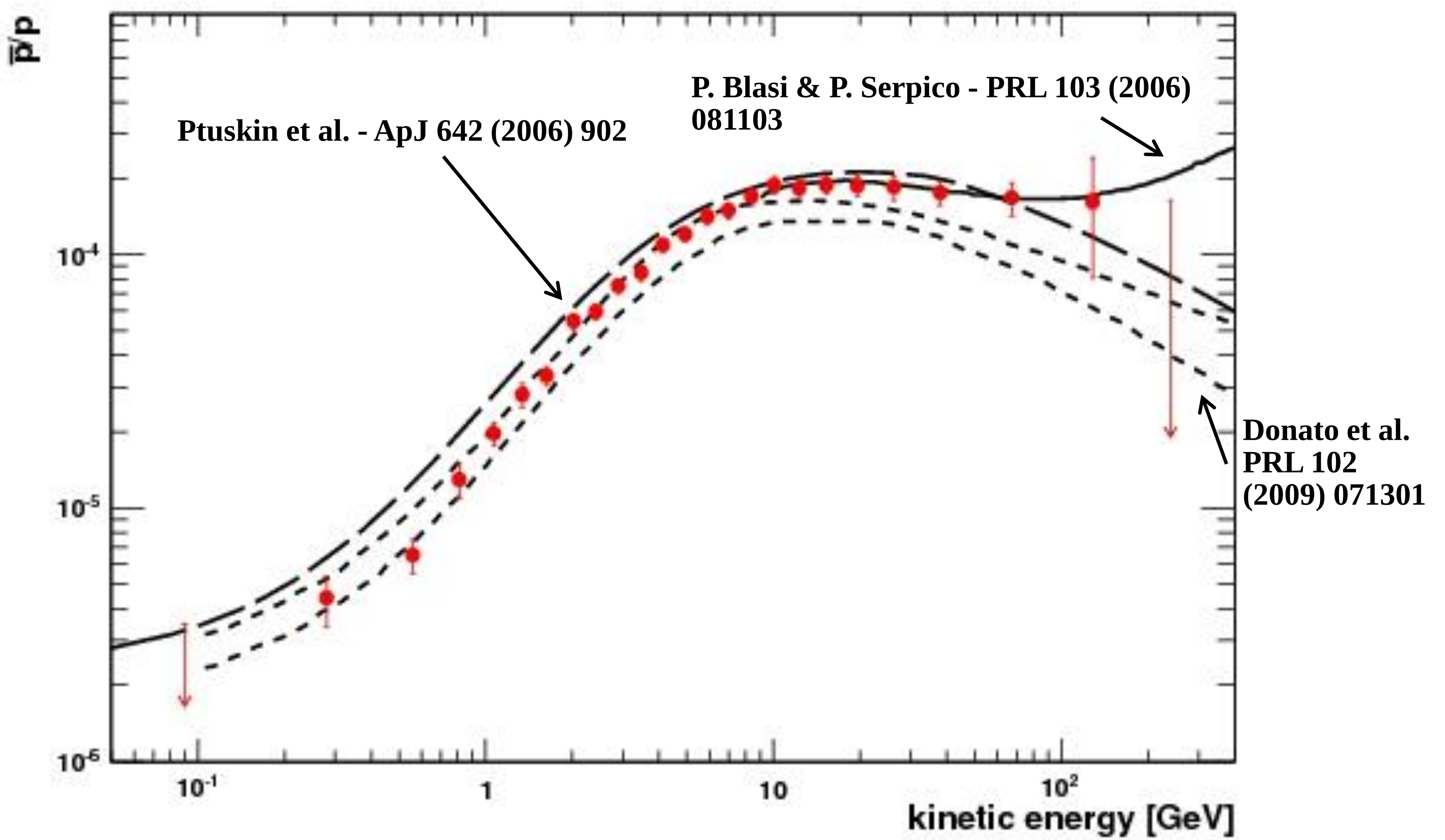


D. Hooper & W. Xue, PRL 110 (2013) 041302
Secondary production + primary production (pulsars and 10 GeV dark matter particle annihilating to charged lepton pairs)

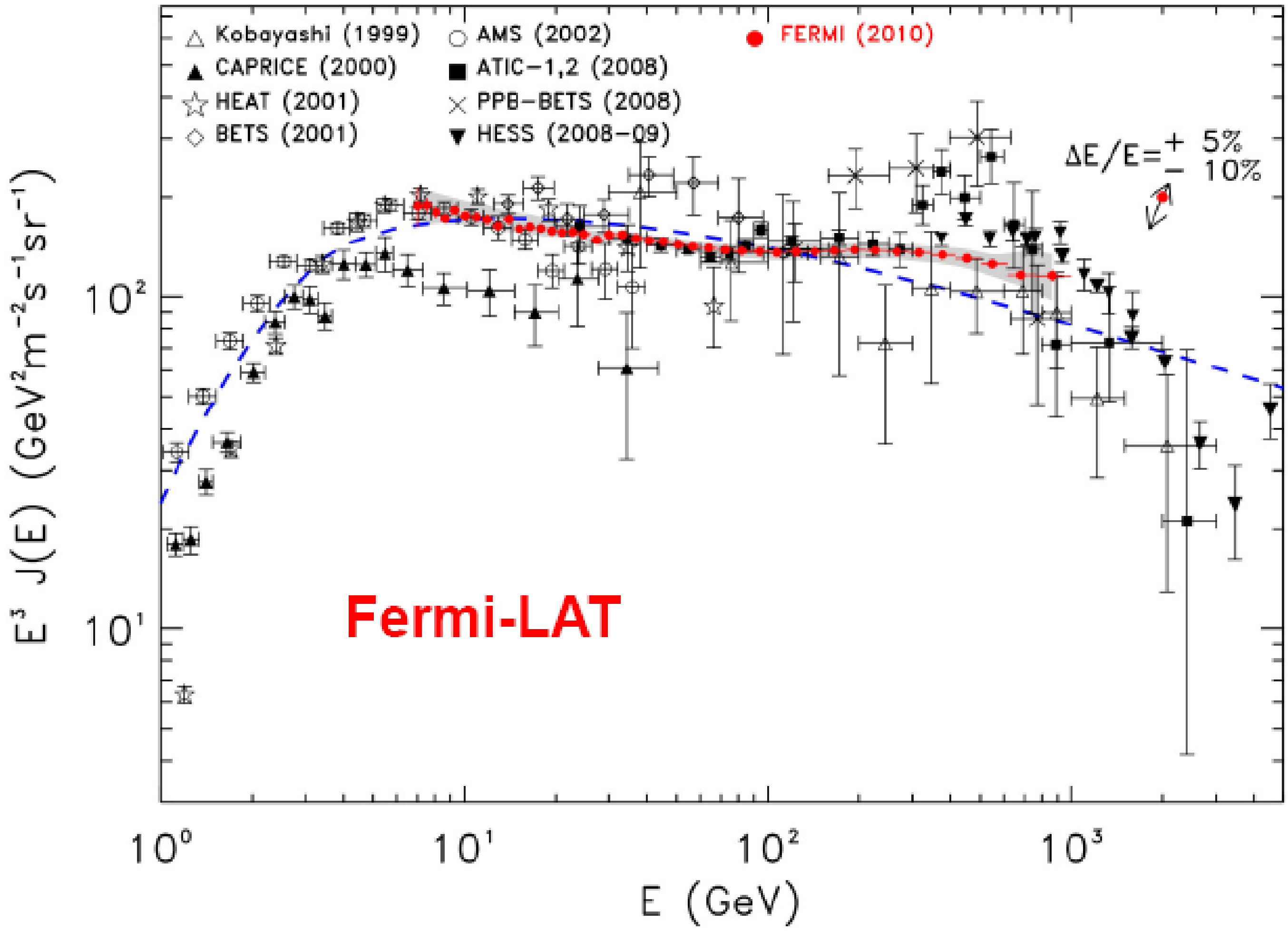
Positron to Electron Fraction



Antiproton to proton flux ratio

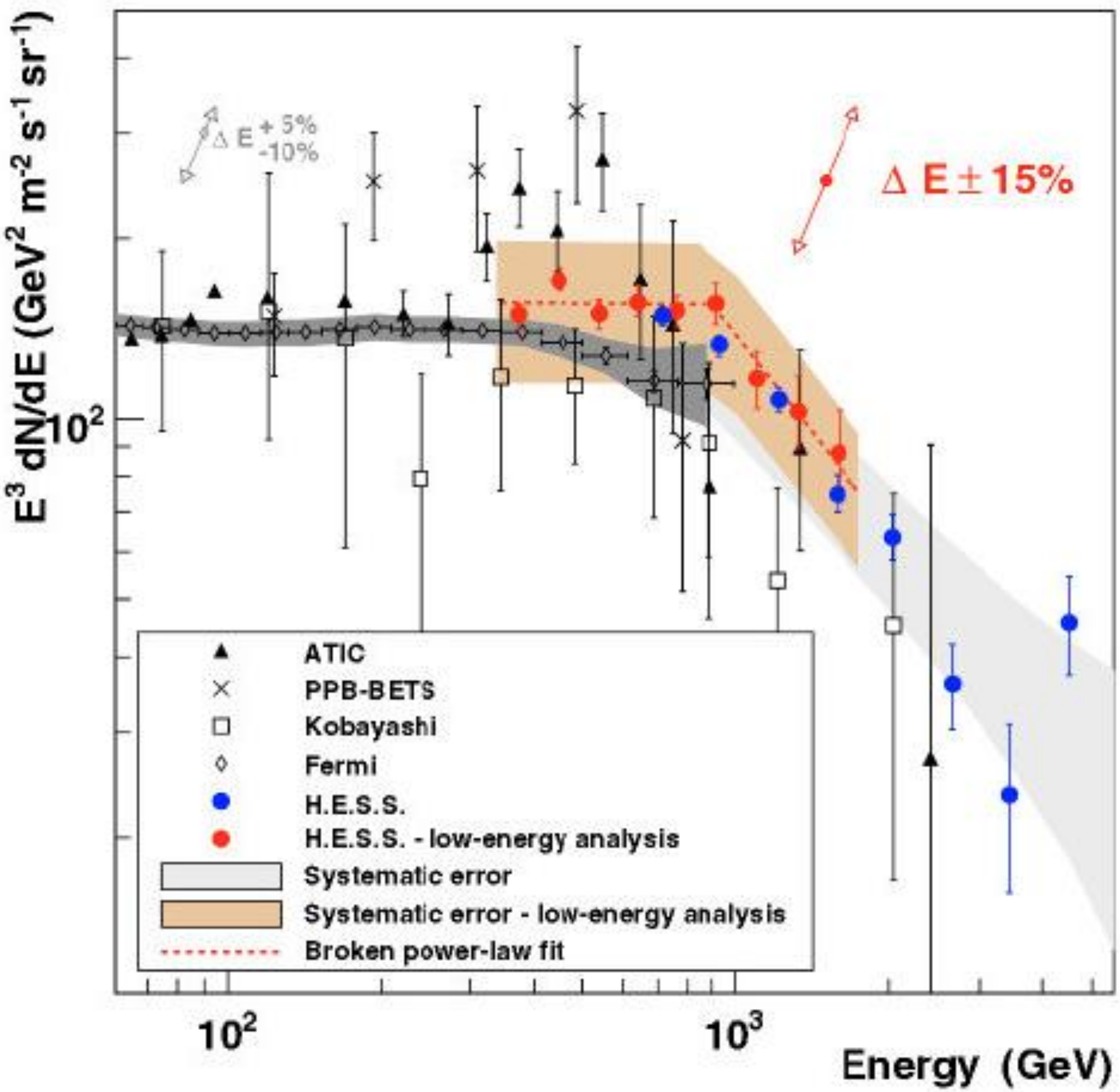


FERMI all Electron Spectrum



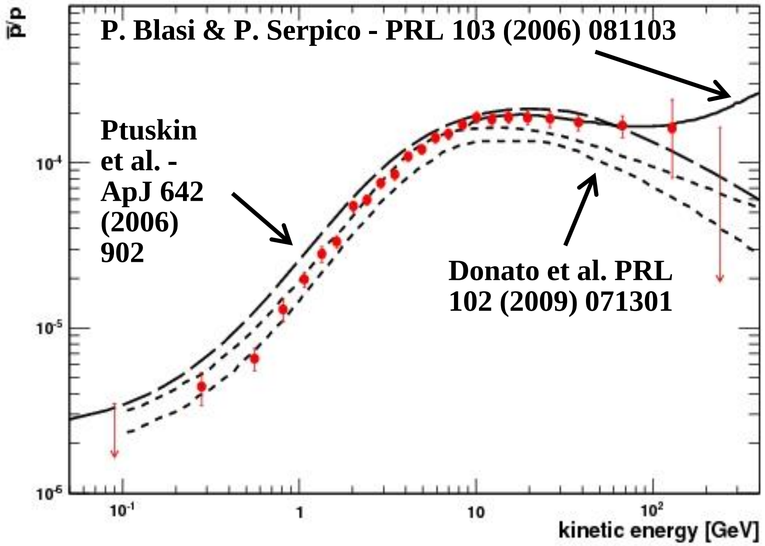
A. Abdo et al., Phys.Rev.Lett. 102 (2009) 181101
M. Ackermann et al., Phys. Rev. D 82, 092004 (2010)

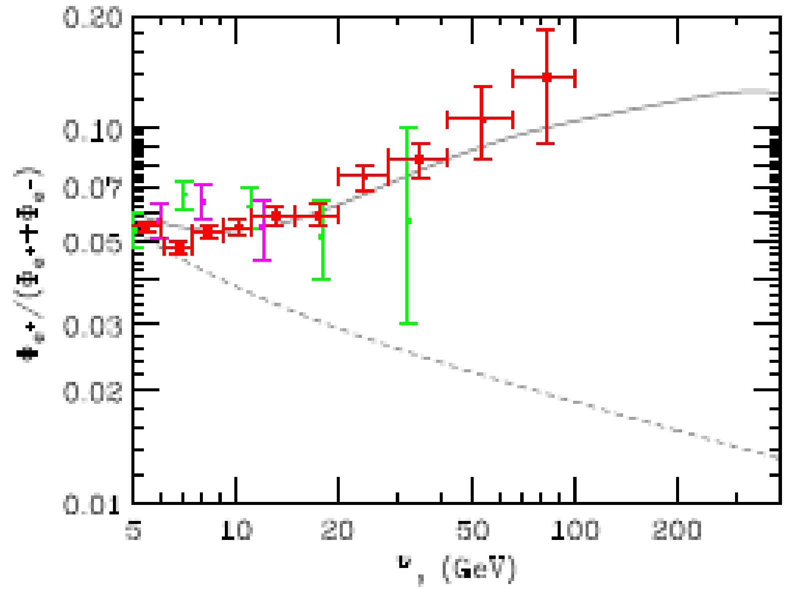
Electrons measured with H.E.S.S.



F. Aharonian et al., A&A 508 (2009) 561

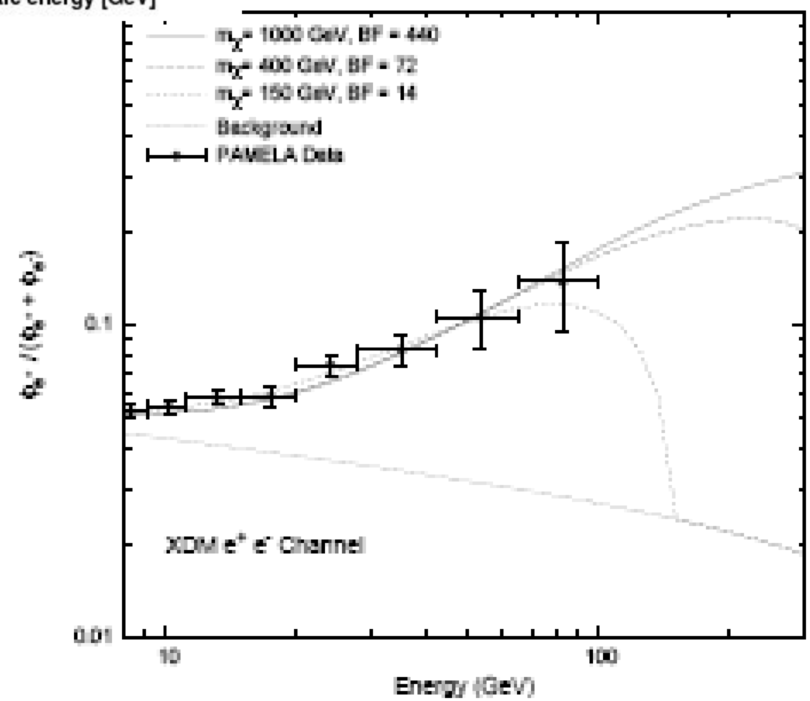
A Challenging Puzzle for CR Physics





P.Blasi, PRL 103 (2009) 051104; arXiv:0903.2794
Positrons (and electrons) produced as secondaries in the sources (e.g. SNR) where CRs are accelerated.

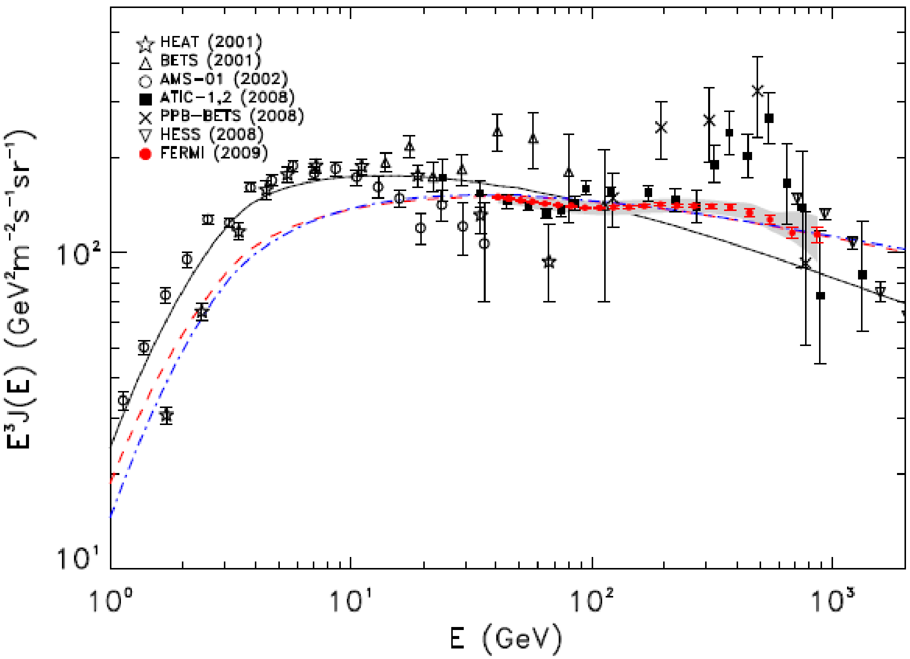
But also other secondaries are produced: significant increase expected in the p/p and B/C ratios.



i, and P. Serpico, JCAP
Xiv:0810.1527
diffuse mature &nearby

I. Cholis et al., Phys. Rev. D 80 (2009) 123518; arXiv:0811.3641v1
Contribution from DM annihilation.

Electron Spectrum and Positron Fraction



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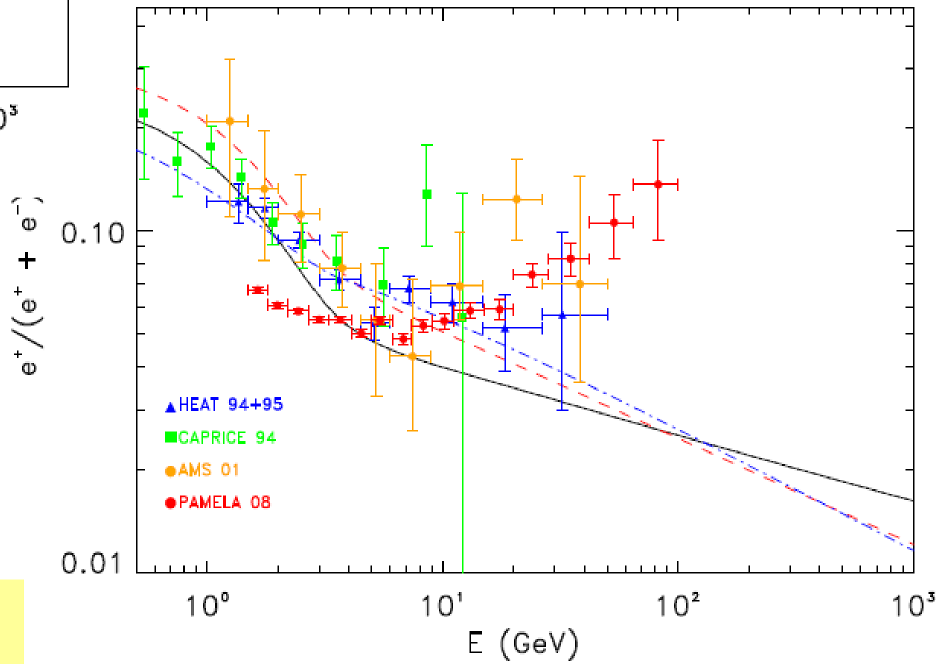
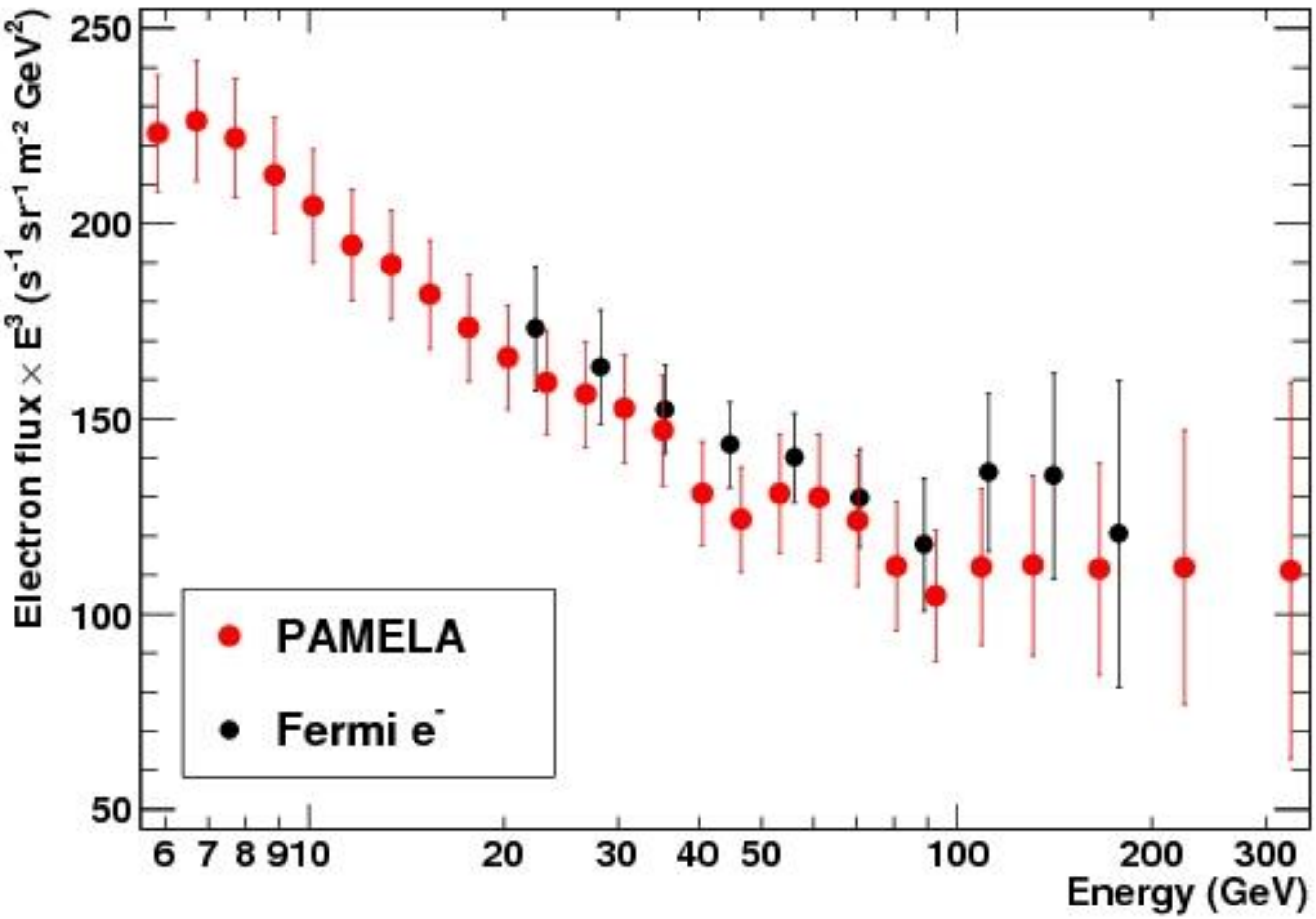
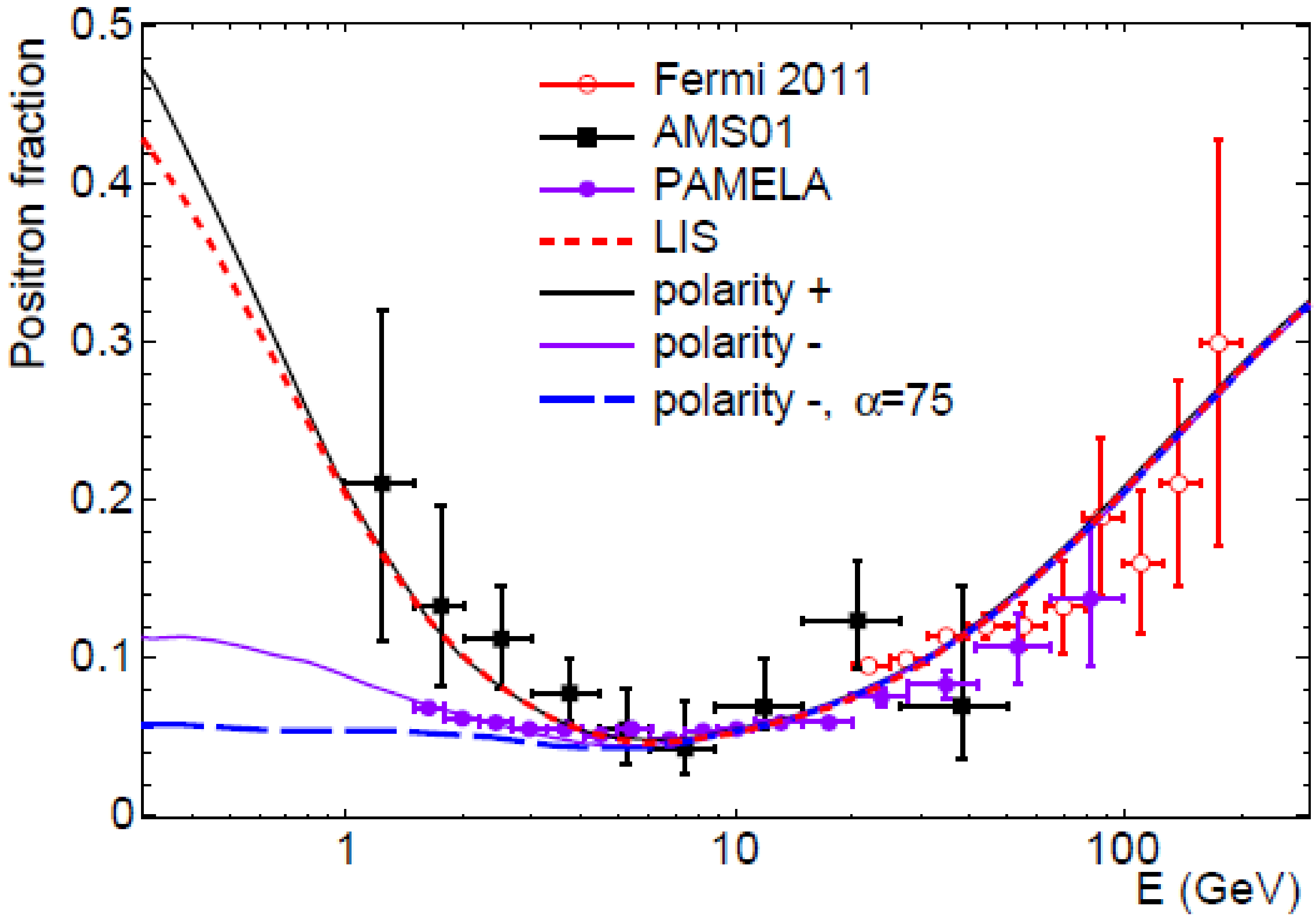


D. Grasso et al., Astropart.Phys. 32 (2009) 140; arXiv:0905.0636

PAMELA&Fermi Electron (e^-) Spectrum



Charge-Sign Dependent Solar Modulation



L. Maccione, PRL 110 (2013) 081101.