# Results from PAMELA

**Mark Pearce**

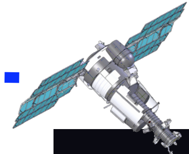
KTH / The Oskar Klein Centre for Cosmoparticle Physics

Stockholm

Sweden

37th SLAC Summer Institute / 2009-08-11

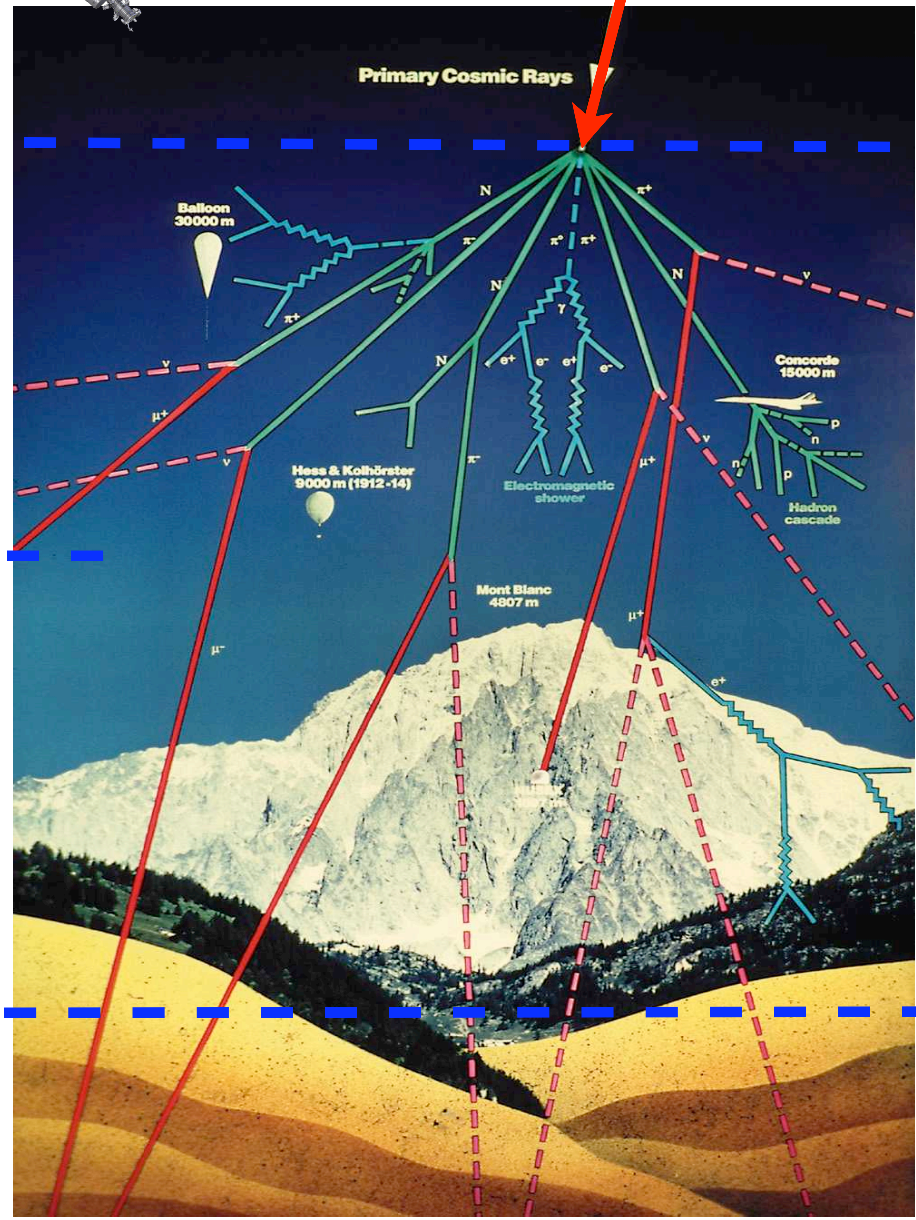
**~500 km**



Smaller detectors
but long duration.
**PAMELA!**

**Primary cosmic ray**

**Top of atmosphere**





**~40 km**

Large detectors but short duration. Atmospheric overburden ~5 g/cm$^2$.
**All previous data on cosmic antiparticles from here.**

**~5 km**

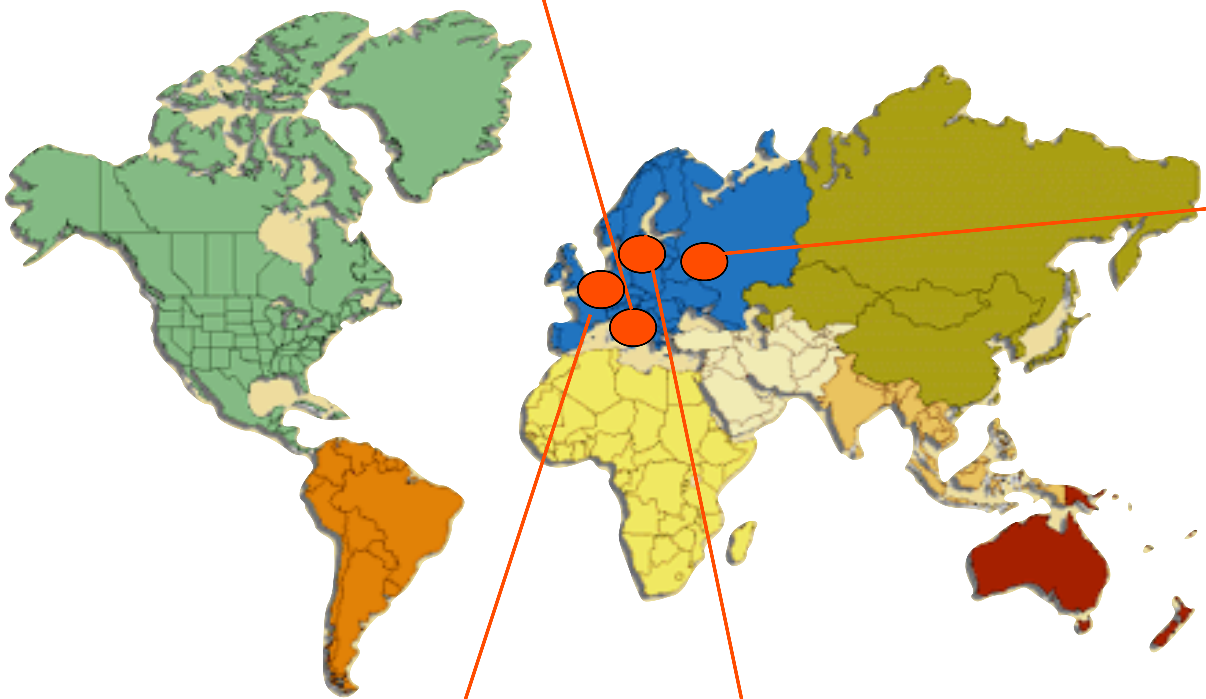
**0 m**

**Discovery!**
Victor Hess, 5 km, 1912

# PAMELA Collaboration

**Italy**

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



**Russia**

Ioffe Physico-Technical Institute

Moscow
St. Petersburg

**Germany**

Universität Gesamthochschule Siegen

Siegen

**Sweden**

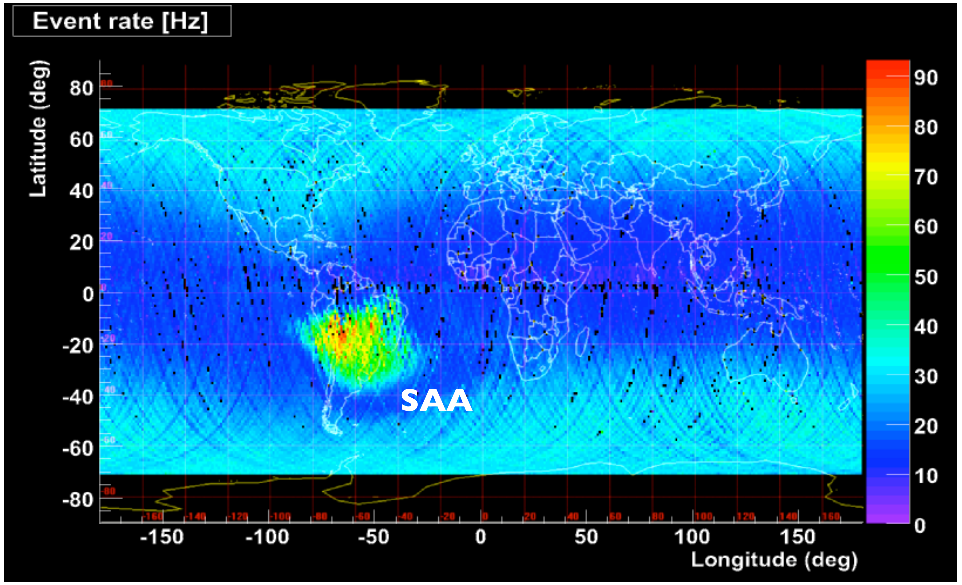
KTH VETENSKAP OCH KONST

KTH, Stockholm

# Resurs-DK1 satellite + orbit

Launched: June 15th 2006


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

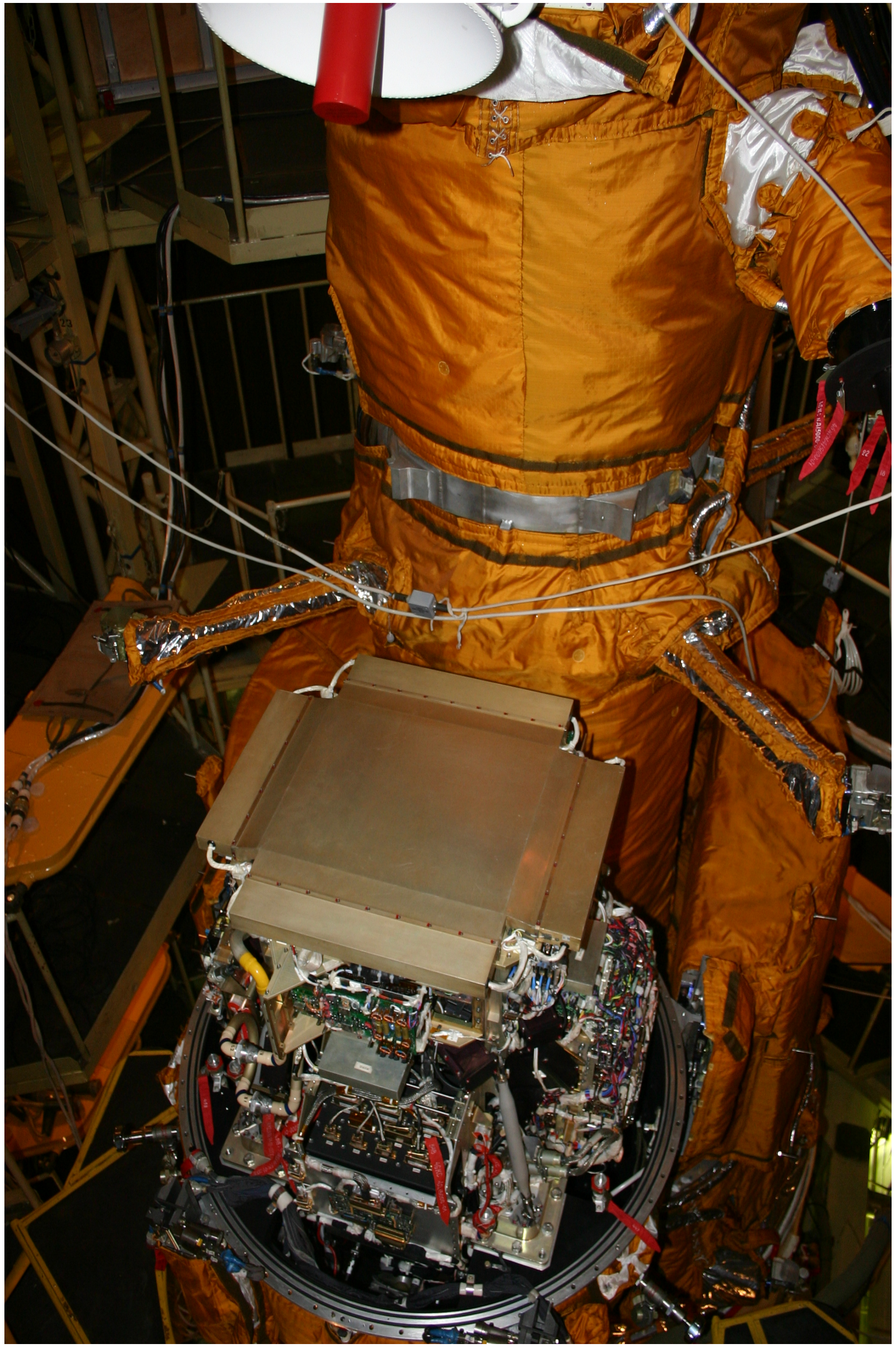



- **Resurs-DK1:** multi-spectral imaging of earth's surface
- **PAMELA mounted inside a pressurized container**

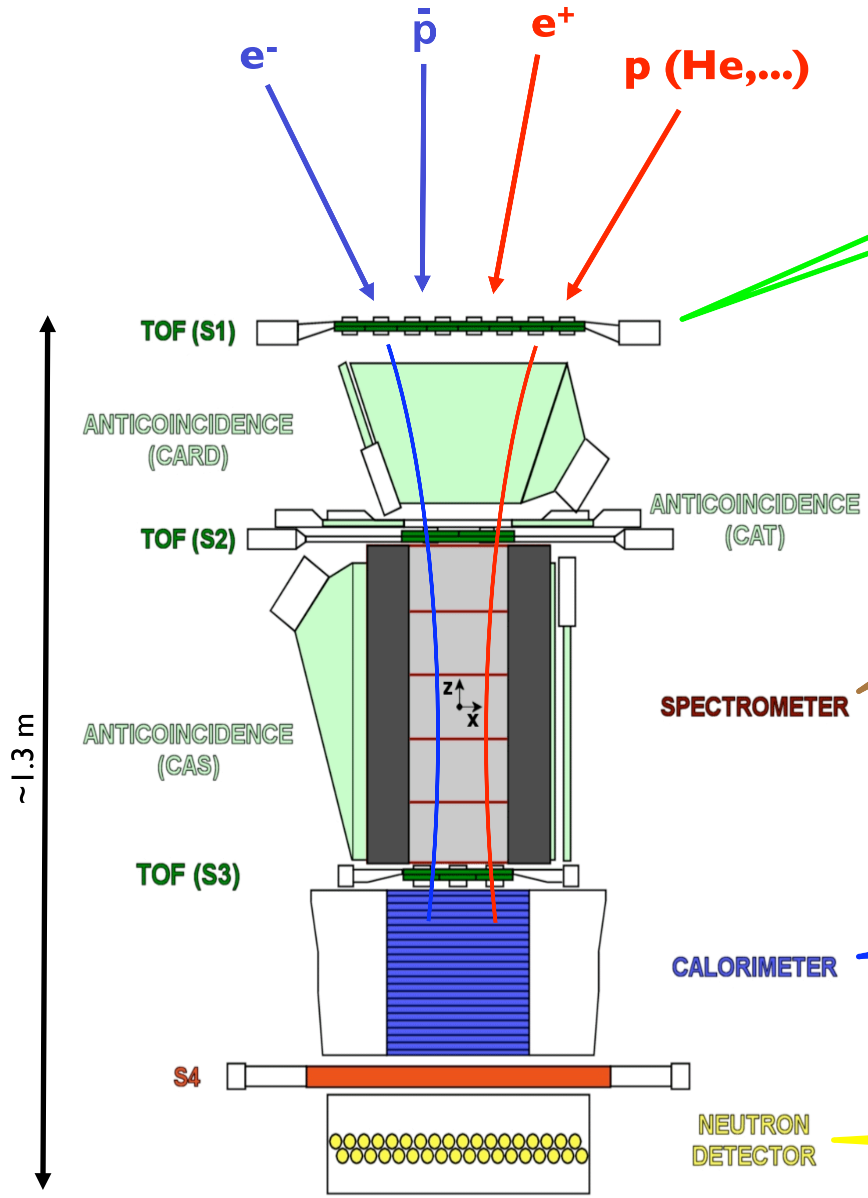
- **Quasi-polar and elliptical orbit** (70.0°, 350 km - 600 km)

- Data transmitted to NTsOMZ, Moscow via high-speed radio downlink. ~15 GB per day

- **As of ~now:**
  - ~1130 days of data taking (~73% live-time)
  - ~15 TByte of raw data downlinked
  - >$10^9$ triggers recorded and under analysis

P. Picozza et al., Astroparticle Physics 27 (2007) 296.




~470 kg / ~360 W

**Trigger, ToF, dE/dx**

- Plastic scintillator (8 mm) + PMT
- ToF resolution ~300 ps (S1-3 ToF >3 ns)
- lepton-hadron separation < 1 GeV/c

**Sign of charge, rigidity, dE/dx**

- Permanent magnet, 0.43 T - 21.5 $cm^2$sr
- 6 planes double-sided silicon strip detectors (300 μm)
- 3 μm resolution in bending view ⇒ MDR ~ 1000 GV (6 plane) ~600 GV (5 plane)

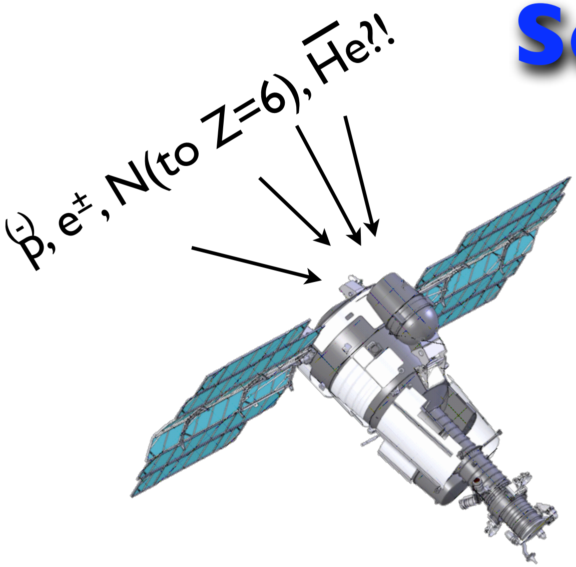
**Electron energy, dE/dx, lepton-hadron separation**

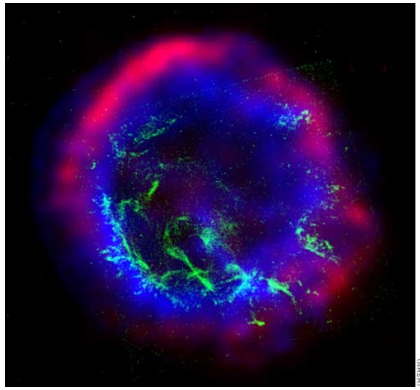
- 44 'Si-x / W / Si-y' planes (380 μm)
- 16.3 $X_0$ / 0.6 $\lambda_L$
- dE/E ~5.5 % (10 - 300 GeV)
- Self trigger > 300 GeV / 600 $cm^2$sr

**Lepton-hadron separation**

- 36 $^3He$ counters
- $^3He(n,p)T$; $E_p$ = 780 keV
- 1 cm thick poly + Cd moderator
- 200 μs collection time

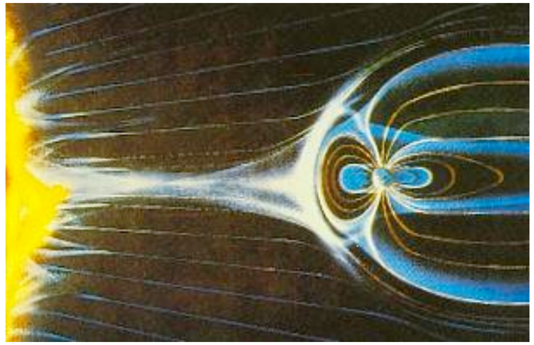
# Scientific goals



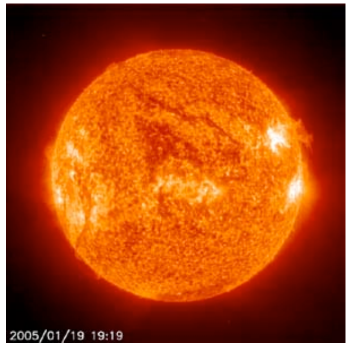
- **Search for dark matter particle annihilations**

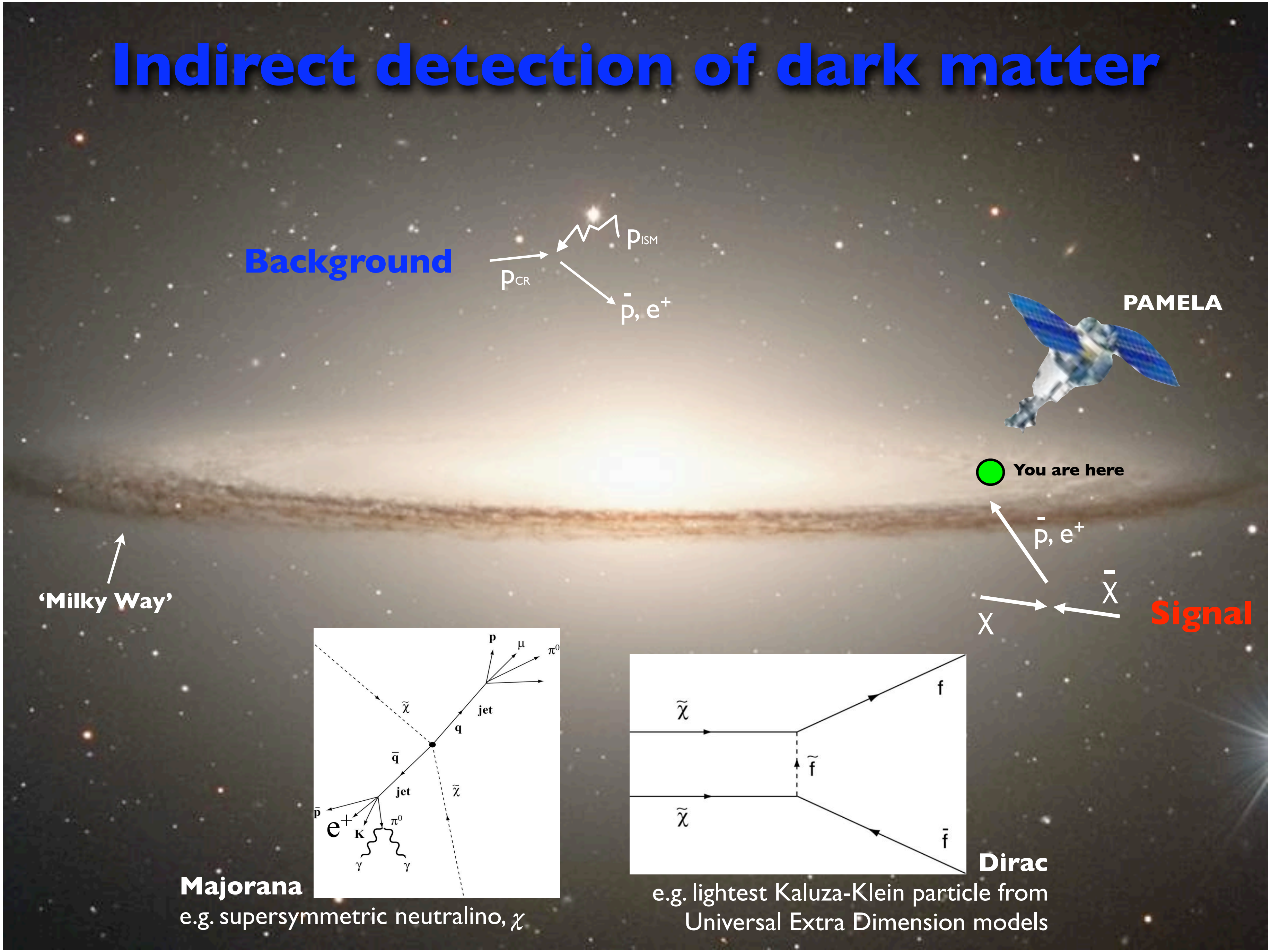
- Search for antihelium (primordial antimatter)
- Search for exotic matter (e.g. strangelets...)



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

- Study solar physics and solar modulation
- Study terrestrial magnetosphere



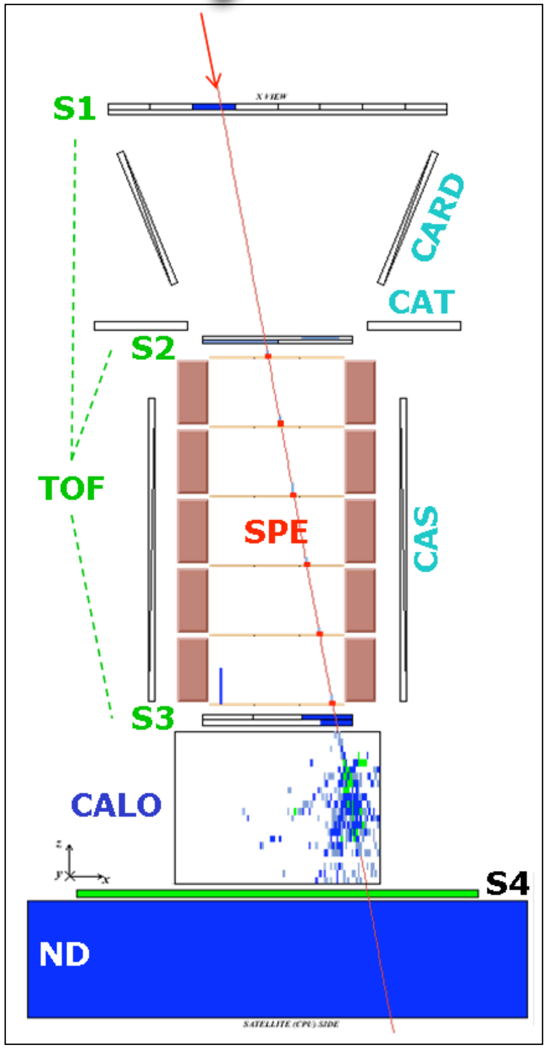

Indirect detection of dark matter
Background
p_CR
p_ISM
p̄, e+
PAMELA
You are here
p̄, e+
χ̄
χ
Signal
'Milky Way'
p
μ
π0
χ̃
jet
q
q̄
jet
χ̃
p̄
e+
K
π0
γ
γ
Majorana
e.g. supersymmetric neutralino, χ
χ̃
χ̃
f
f̃
f̄
Dirac
e.g. lightest Kaluza-Klein particle from Universal Extra Dimension models

# High energy antiproton analysis

- Data-set: July 2006 – February 2008 (~500 days)
- Collected triggers ~$10^8$
- Identified **~$10\times10^6$ protons** and **~$1\times10^3$ antiprotons** between 1.5 and 100 GeV (100 antiprotons above 20 GeV)

- **Antiproton/proton identification:**
  - Rigidity (R) from **spectrometer**
  - Select |Z|=1 (dE/dx -vs- R), **spectrometer + ToF**
  - β -vs- R consistent with proton mass, **ToF**
  - antiproton/p separation (sign-of-charge, **spectrometer**)
  - antiproton/$e^-$ (and p/$e^+$ ) separation from **calorimeter**

- Dominant background - **spillover protons**.
  - Finite deflection resolution of spectrometer - wrong assignment of sign-of-charge at high energy

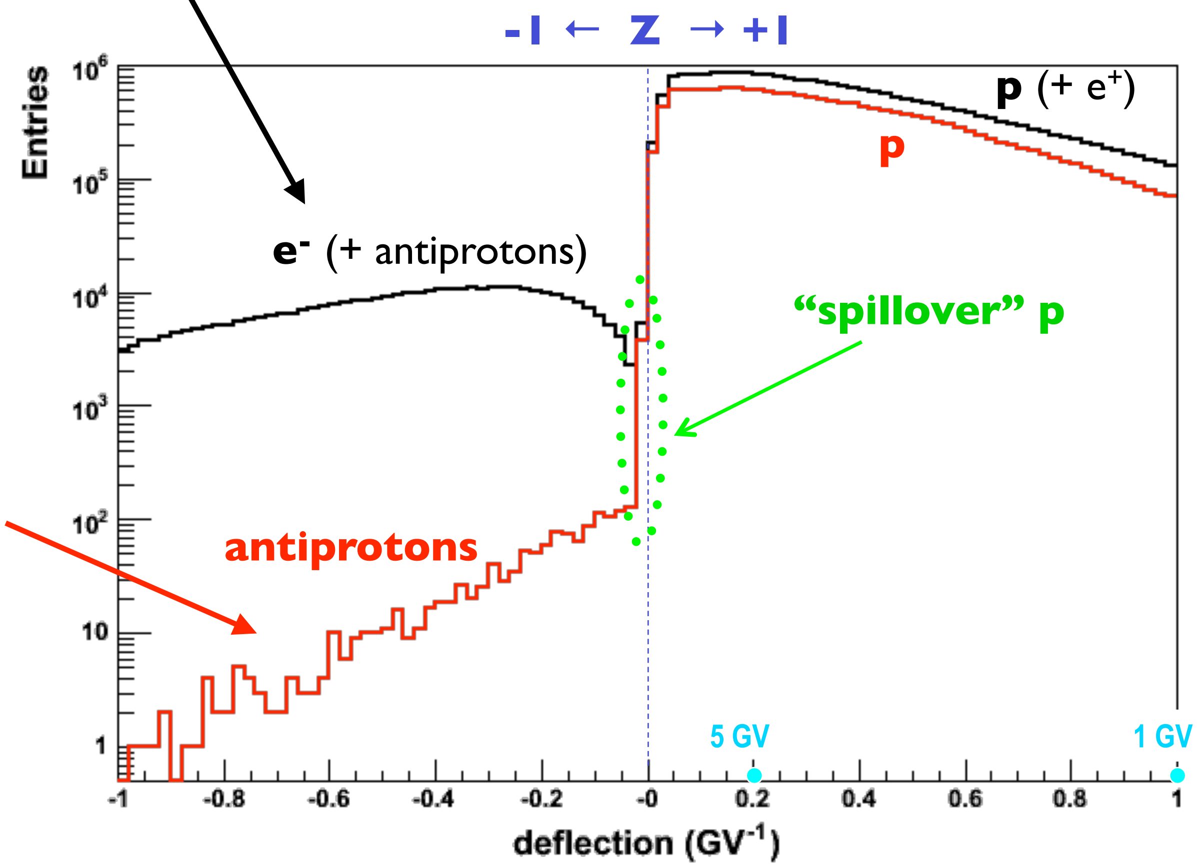



**Antiproton**
**(NB: $e^-/\bar{p}$ ~ $10^2$)**

# Antiproton identification

proton-consistency cuts
(**dE/dx -vs- R** and β **-vs- R**)

electron rejection
cuts based on
calorimeter
interaction topology

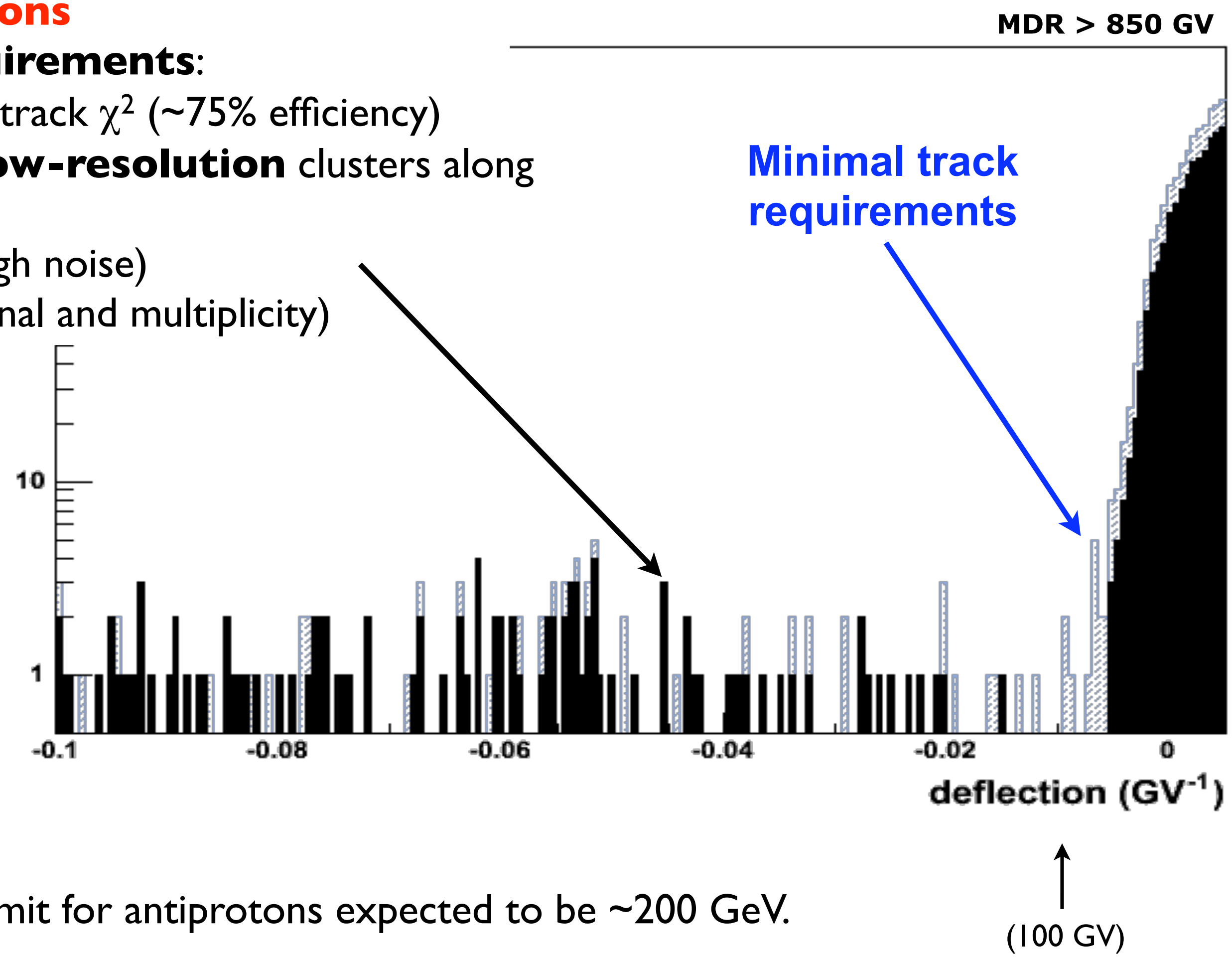


# Proton spillover

**Selected antiprotons**

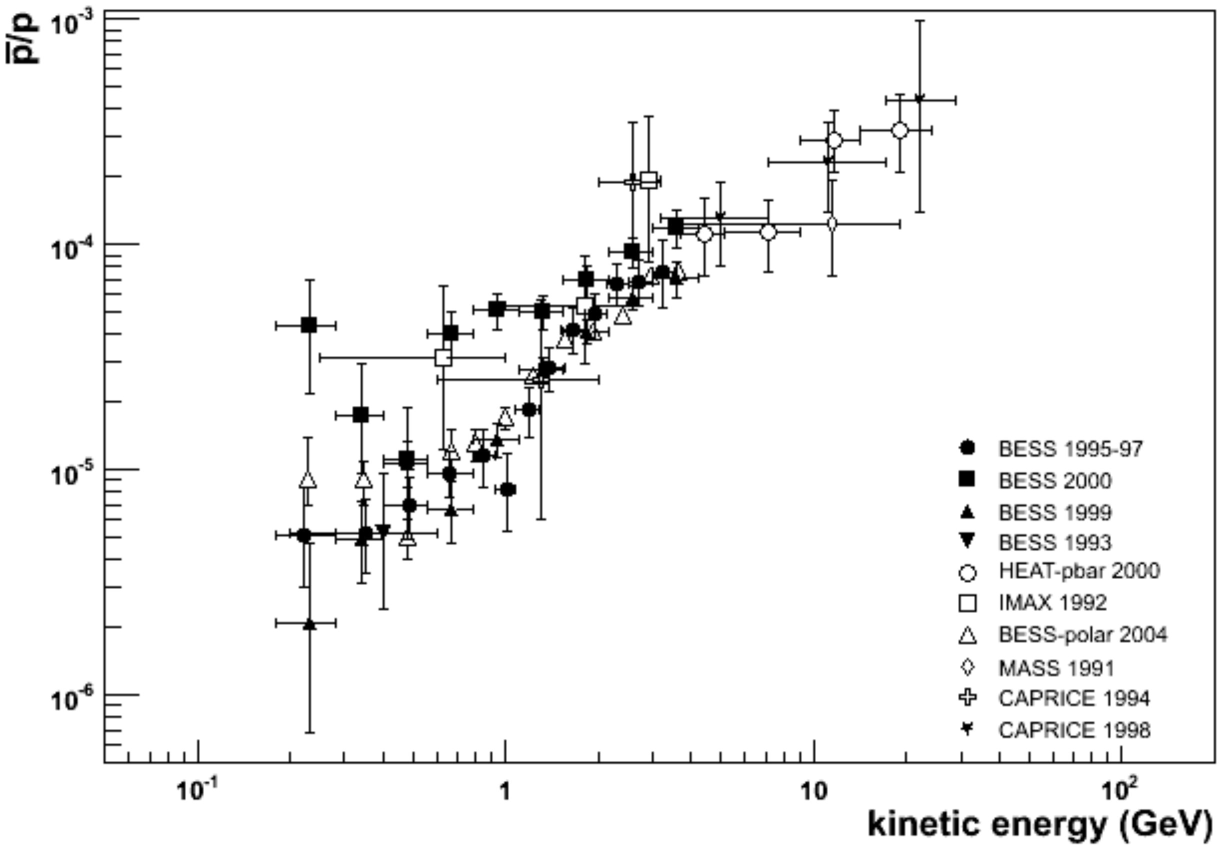
**Strong track requirements**:

- Tight constraints on track $\chi^2$ (~75% efficiency)
- Reject tracks with **low-resolution** clusters along the trajectory
  - faulty strips (high noise)
  - $\delta$-rays (high signal and multiplicity)




- Ultimate spillover limit for antiprotons expected to be ~200 GeV.

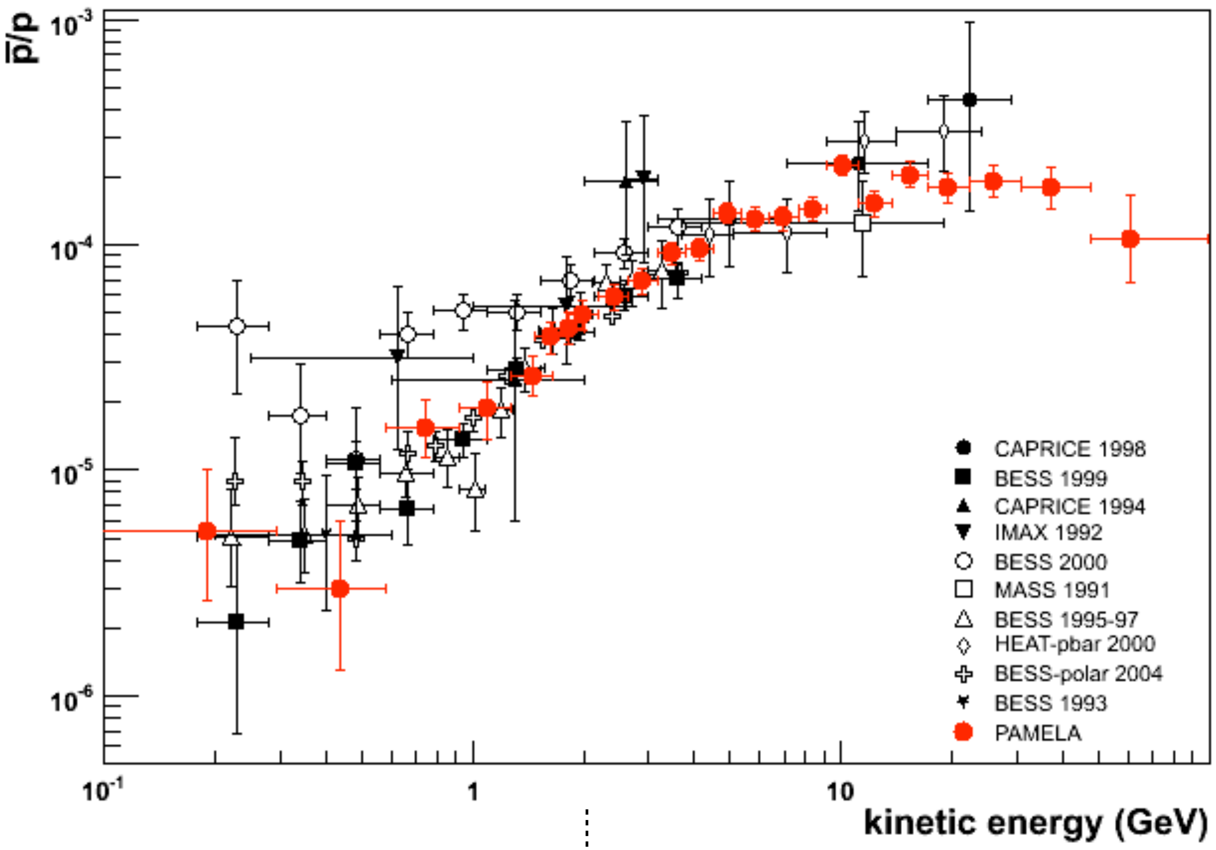
# Antiproton-to-proton flux ratio




~5 g/cm$^2$


t ~24 h

# Antiproton-to-proton flux ratio

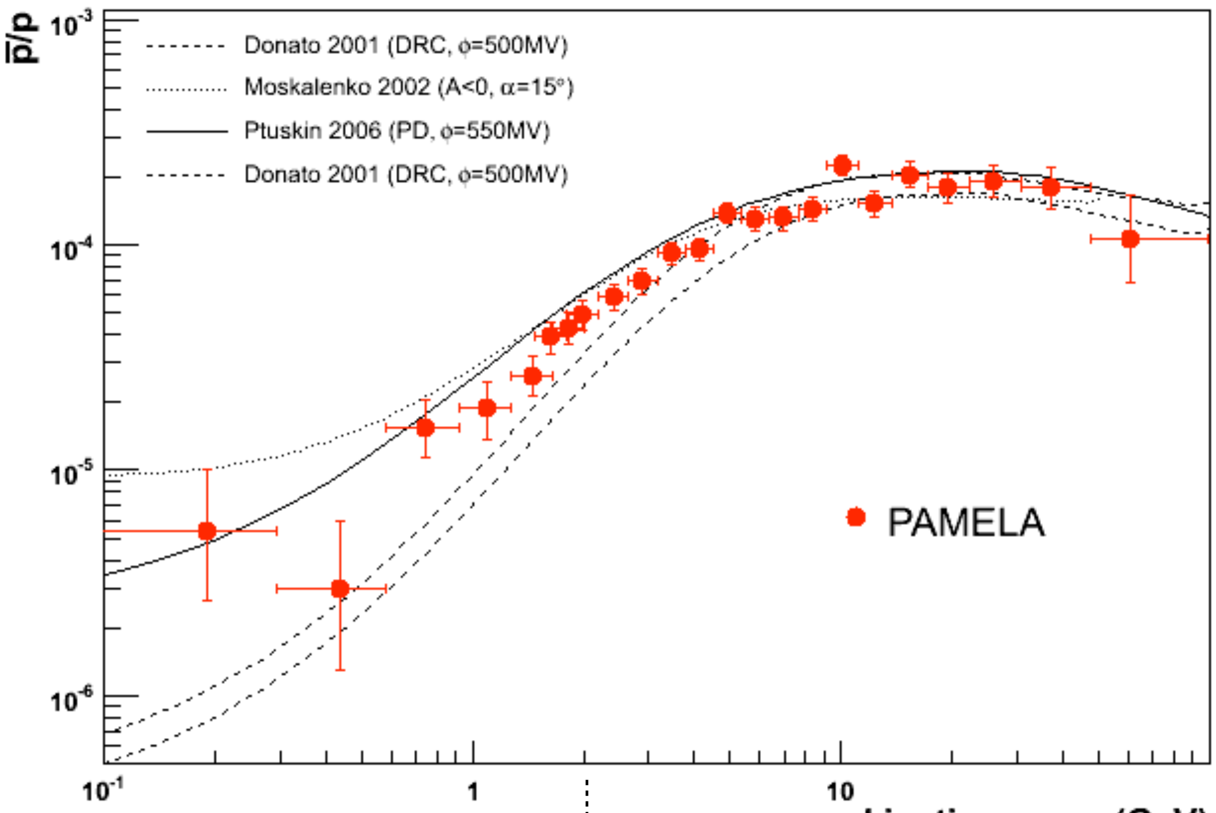



* preliminary *

P. Hofverberg,
KTH PhD Thesis

**Phys. Rev. Lett. 102, 051101**
**(2nd Feb. 2009)**

# Secondary production models




* preliminary *

P. Hofverberg,
KTH PhD Thesis

**Phys. Rev. Lett. 102, 051101**
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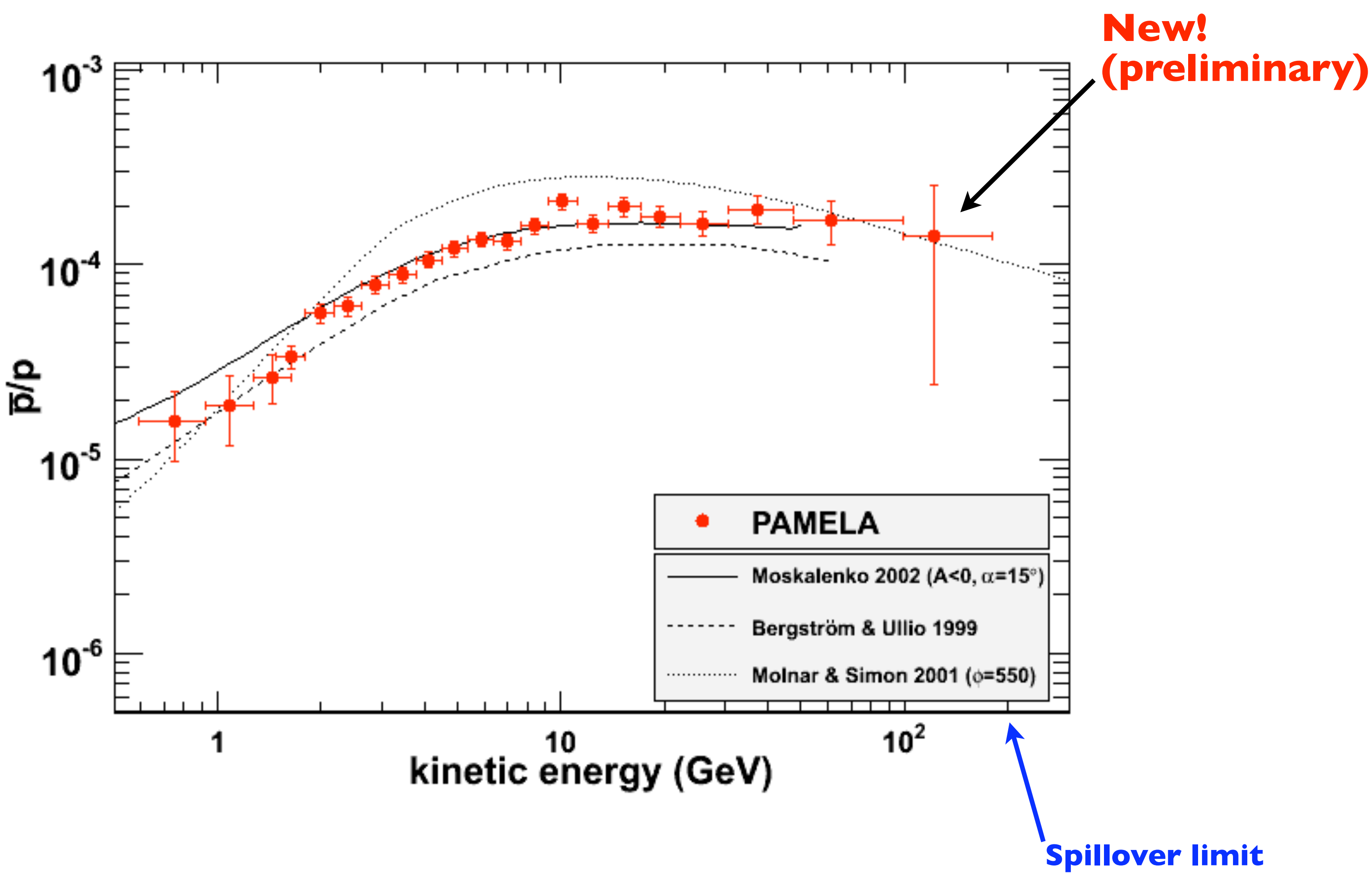
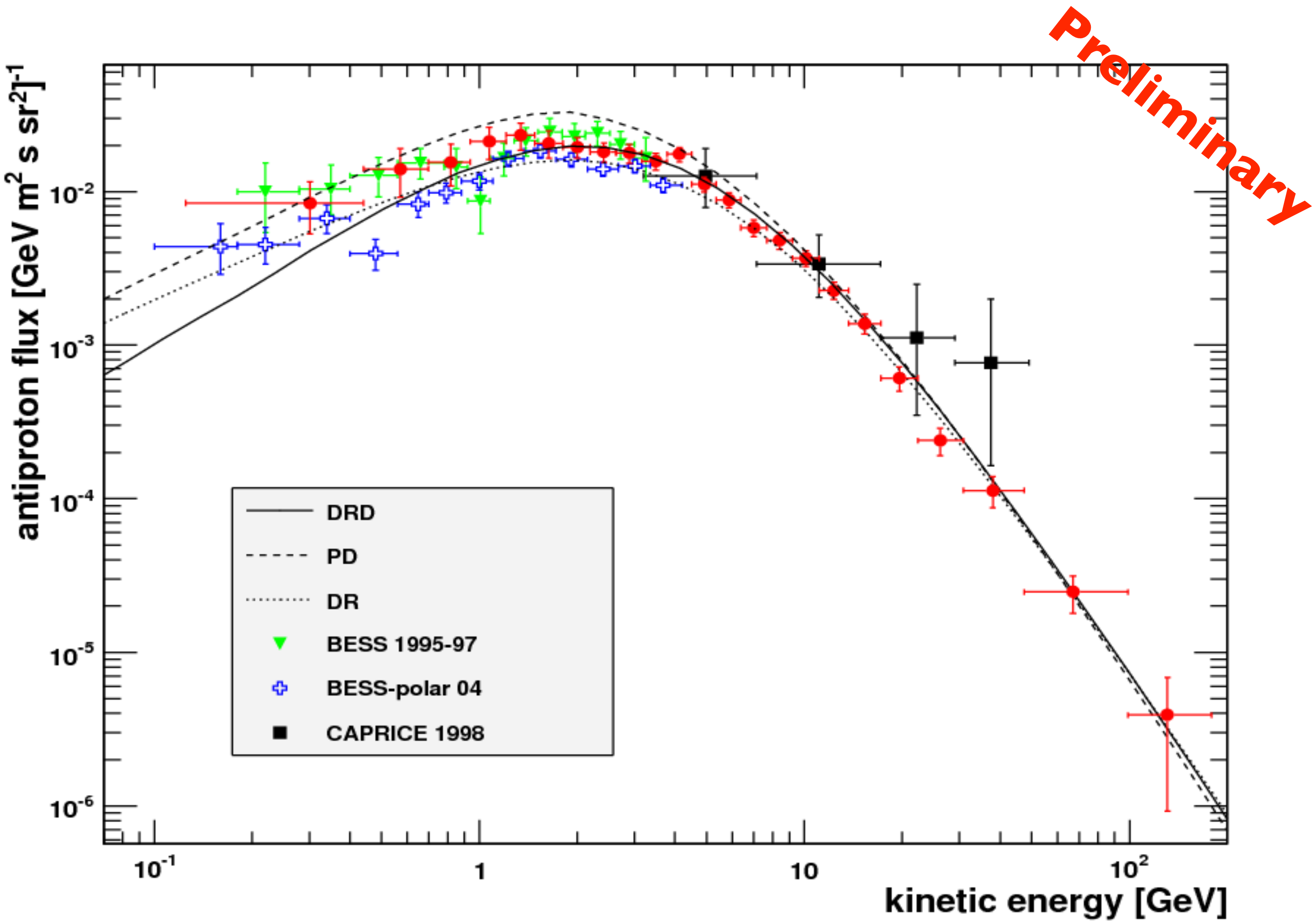
# Antiproton-to-proton flux ratio



# Antiproton flux

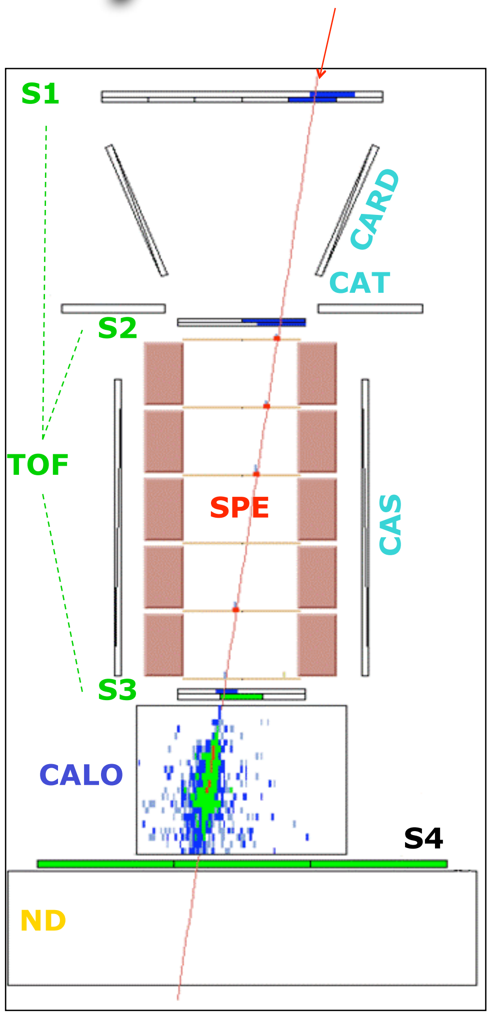


# High energy positron analysis

- Data-set: July 2006 – February 2008 (~500 days)
- Collected triggers ~$10^8$
- Identified **~$150\times10^3$ electrons** and **~$9\times10^3$ positrons** between 1.5 and 100 GeV (**180 positrons above 20 GeV** )

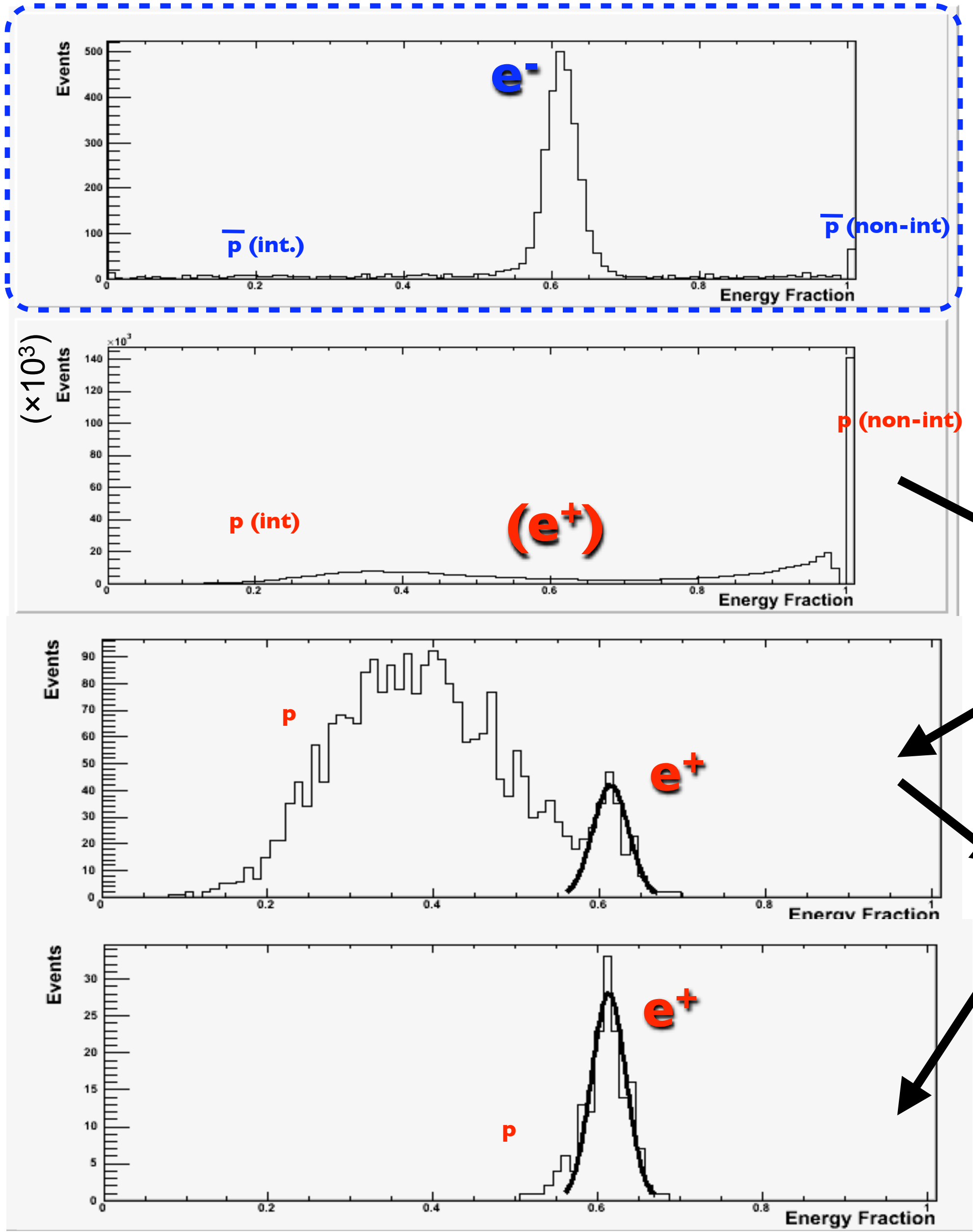
- **Electron/positron identification:**
  - Rigidity from **spectrometer**
  - $|Z|=1$ ($dE/dx$=MIP) - **spectrometer and ToF**
  - $\beta=1$ - **ToF**
  - $e^-/e^+$ separation (sign-of-charge) - spectrometer
  - $e^+/p$ (and $e^-$/antiproton) separation - calorimeter

- Dominant background - **interacting protons**.

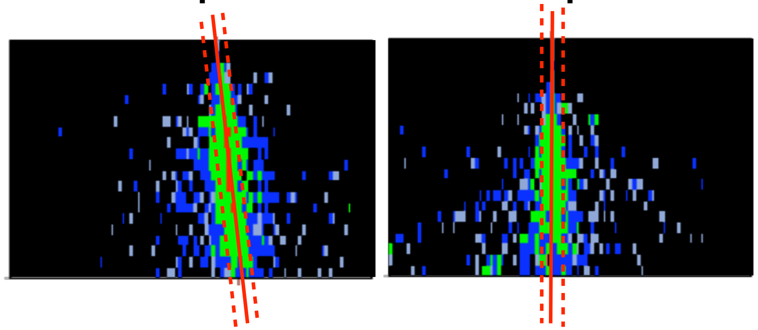



**Positron**
**(NB: $p/e^+$ ~$10^{3-4}$)**

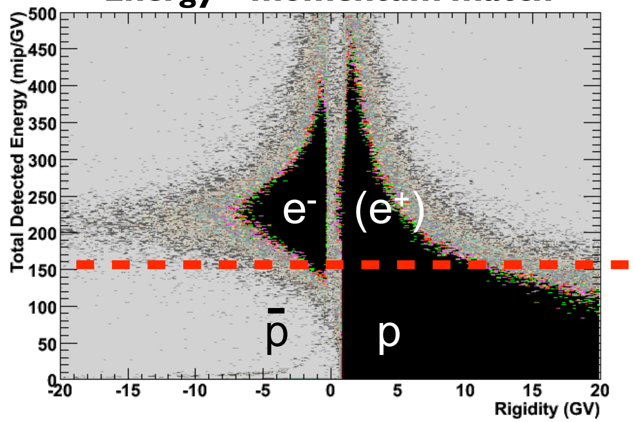
**Rigidity: 20-30 GV**



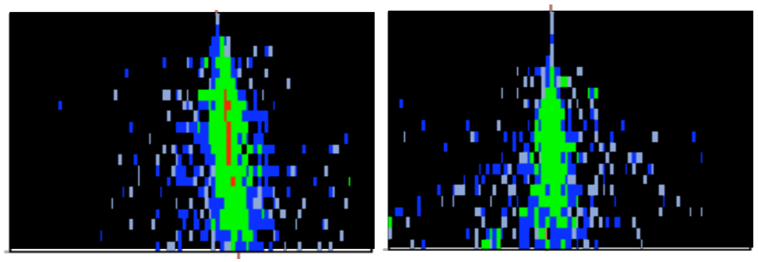

**51 GV positron** **80 GV proton**



**Energy - momentum match**




**51 GV positron** **80 GV proton**



**Starting point, lateral / longitudinal profile**

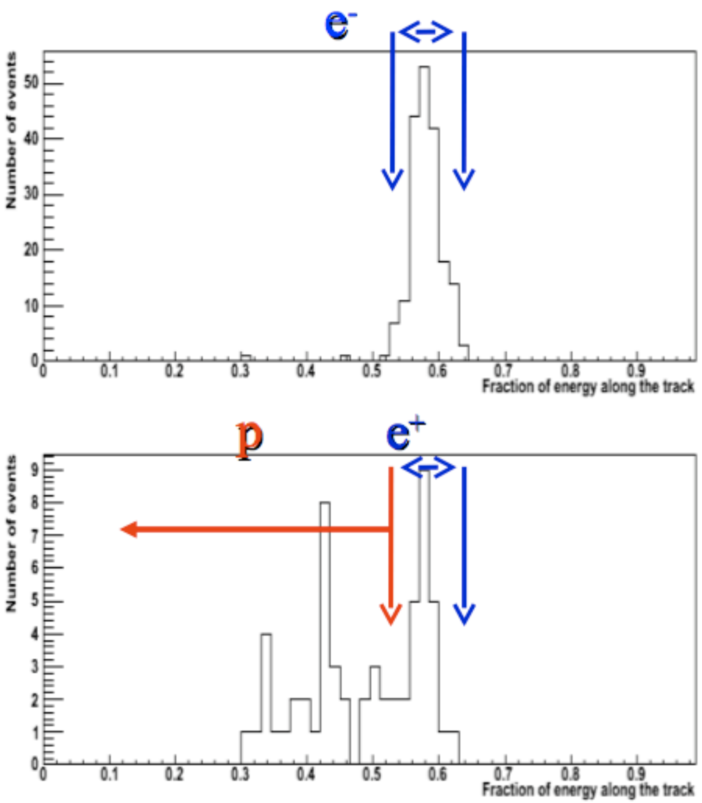
**Fraction of charge released along the calorimeter track (left/hit/right): ~0.6 $R_m$**

**NB:** background determined from data

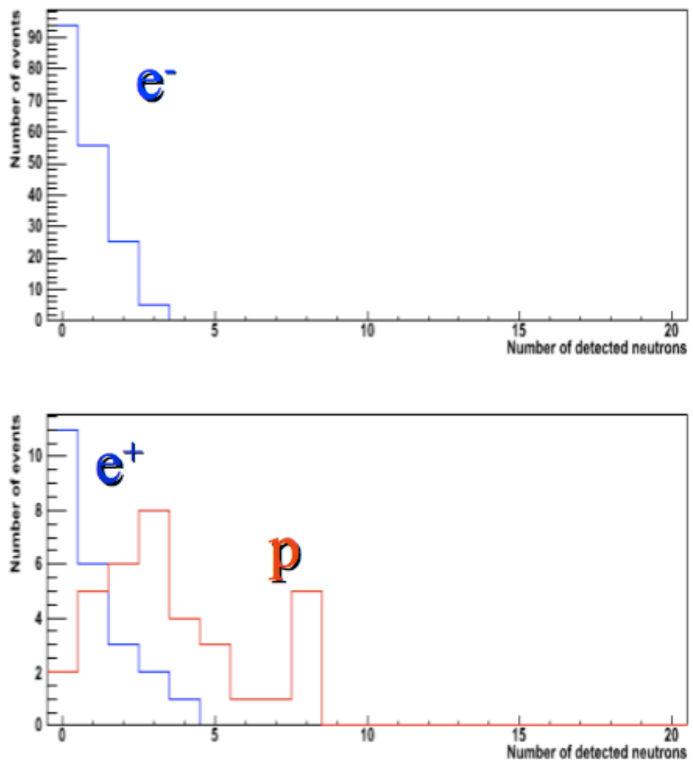
# Cross-check: neutron yield

**Rigidity: 42-65 GV**

**Fraction of charge released along the calorimeter track (left, hit, right)**

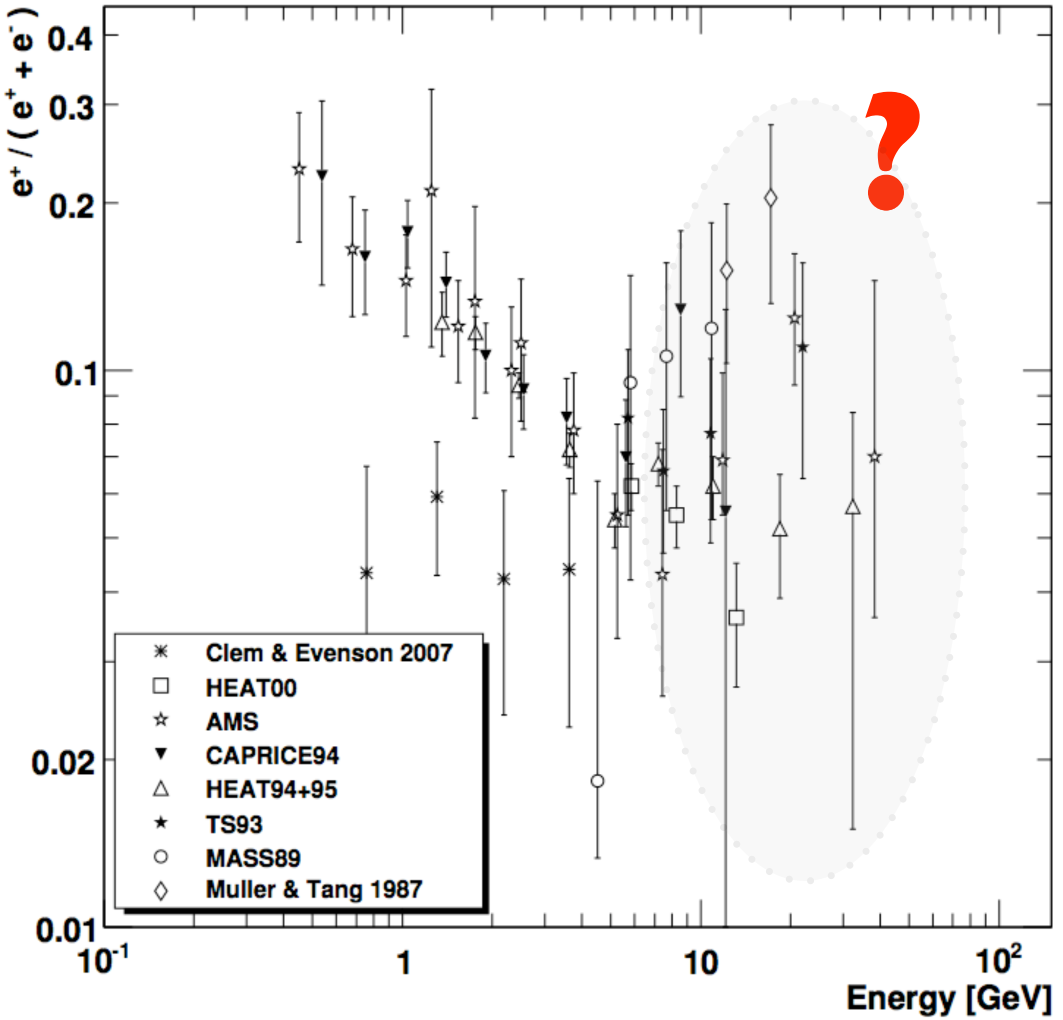



**Neutrons detected by ND**

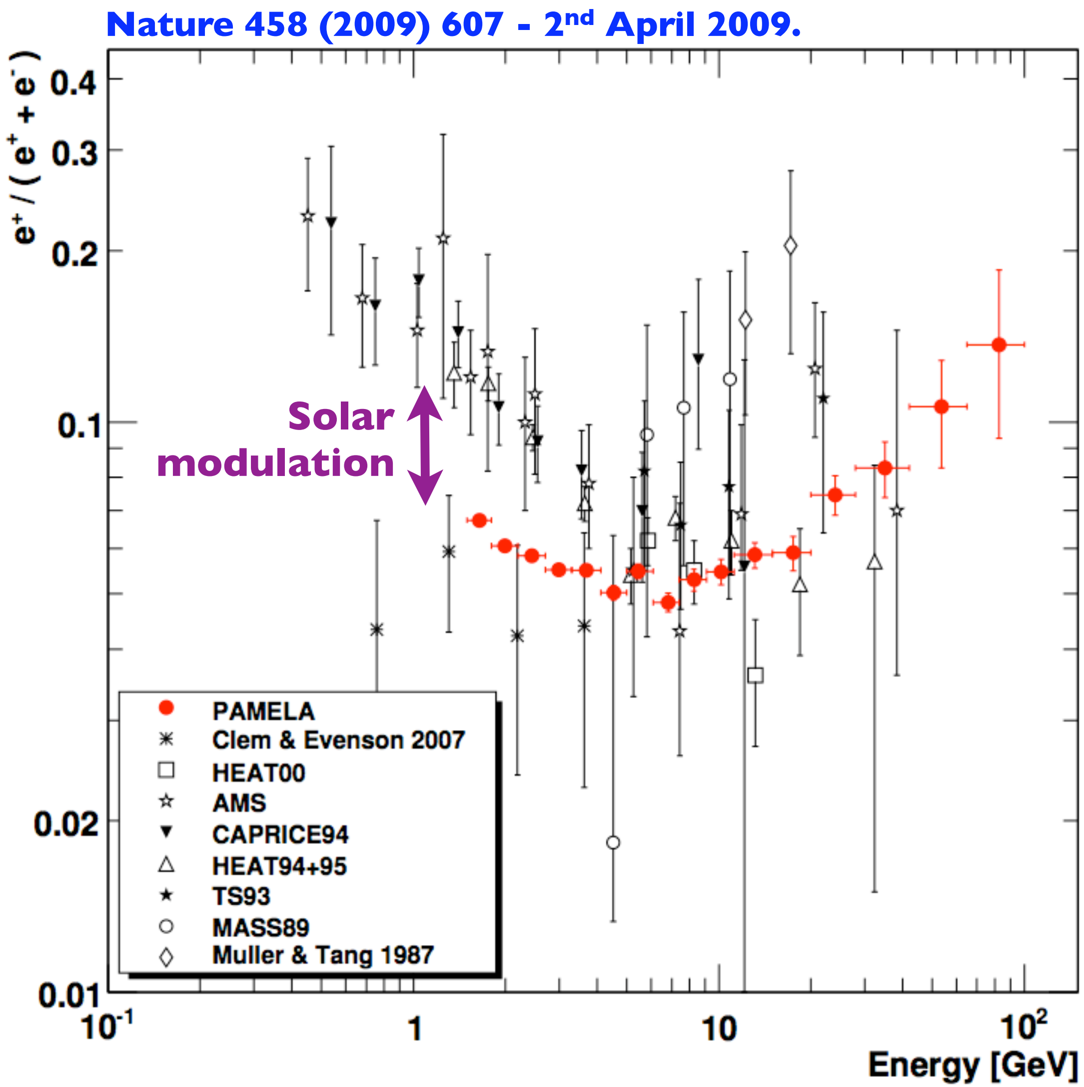



- **Energy-momentum match**
- **Starting point of shower**

# Pre-PAMELA positron fraction

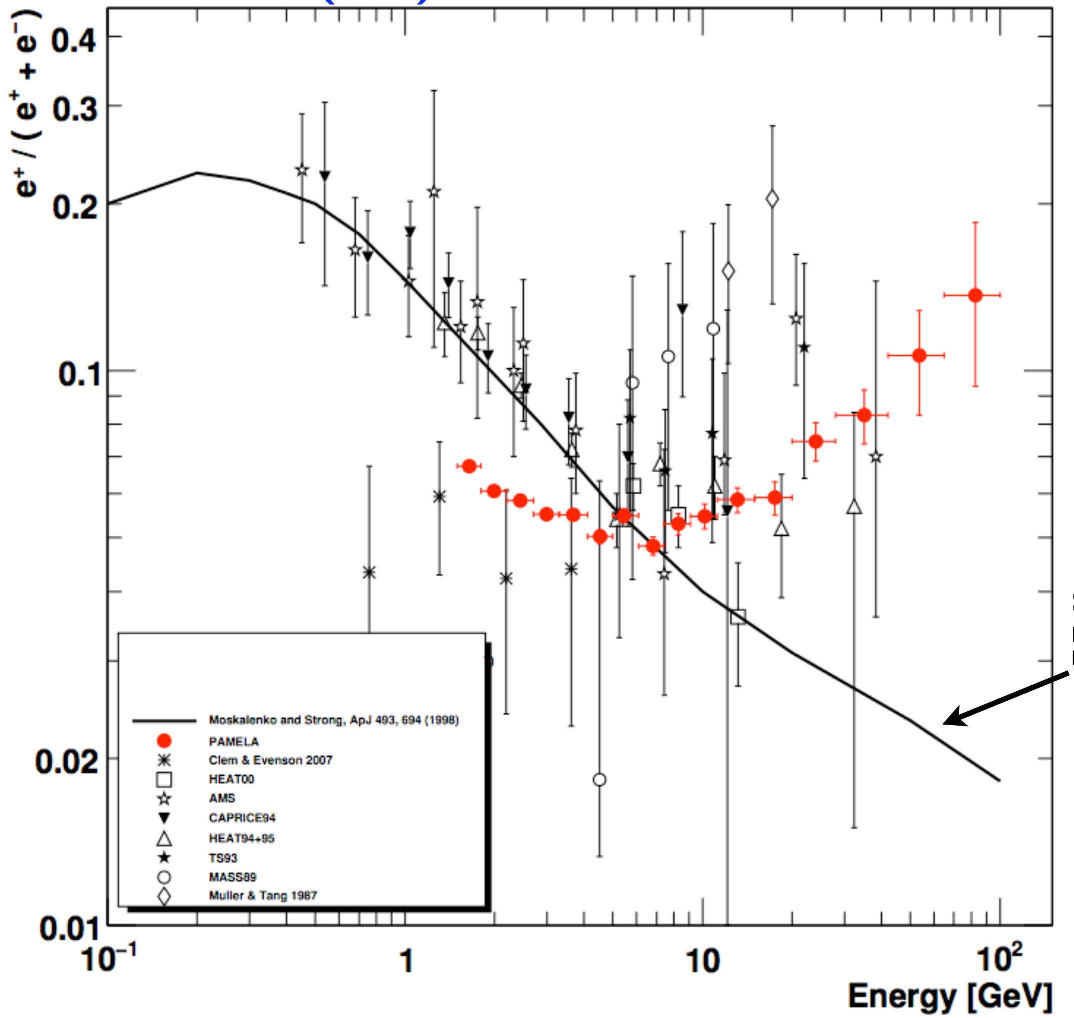


# PAMELA positron fraction



# Secondary production expectation

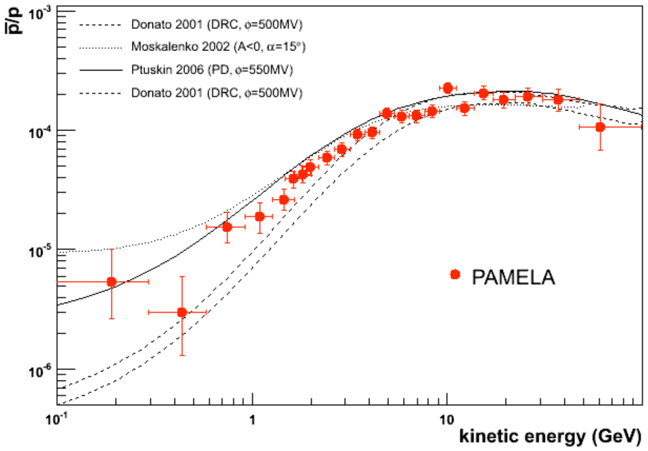
Nature 458 (2009) 607



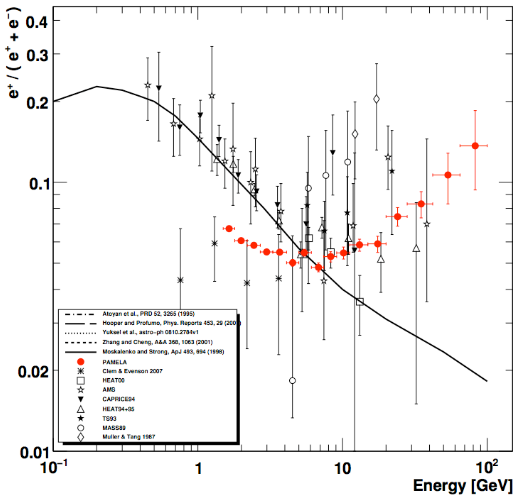

**Secondary production model**
Moskalenko + Strong, ApJ 493 (1998) 694

# Interpretation

**Phys. Rev. Lett. 102 (2009) 051101**




**Nature 458 (2009) 607**

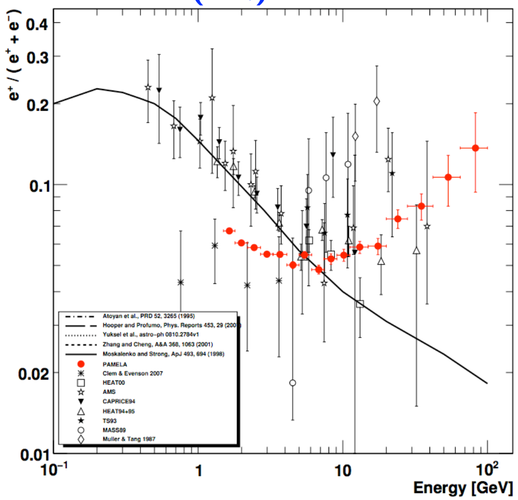



- Quite a difference between antiproton and positron results!
- A **smörgåsbord** of papers have offered interpretations
- The majority focus on **dark matter**, e.g. L. Bergström, arXiv:0903.4849 (30 March 2009):

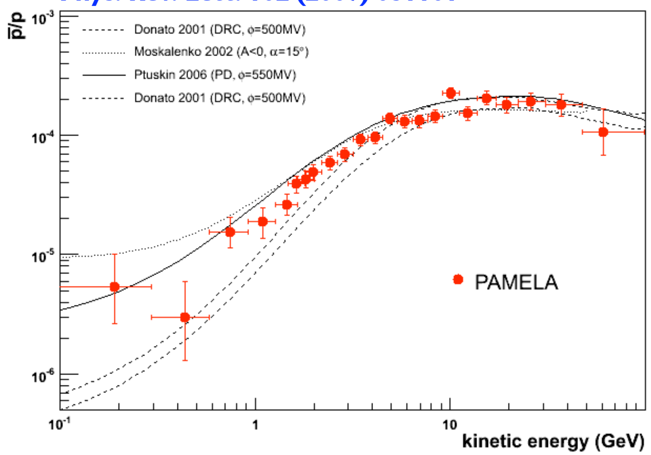

[111] M. Cirelli and A. Strumia, arXiv:0808.3867 [astro-ph]; V. Barger, W. Y. Keung, D. Marfatia and G. Shaughnessy, Phys. Lett. B **672**, 141 (2009) [arXiv:0809.0162 [hep-ph]]; J. H. Huh, J. E. Kim and B. Kyae, arXiv:0809.2601 [hep-ph]; P. D. Serpico, Phys. Rev. D **79**, 021302 (2009) [arXiv:0810.4846 [hep-ph]]; A. E. Nelson and C. Spitzer, arXiv:0810.5167 [hep-ph]; T. Bringmann, arXiv:0810.5304 [hep-ph]; R. Harnik and G. D. Kribs, arXiv:0810.5557 [hep-ph]; D. Feldman, Z. Liu and P. Nath, arXiv:0810.5762 [hep-ph]; Y. Bai and Z. Han, arXiv:0811.0387 [hep-ph]; P. J. Fox and E. Poppitz, arXiv:0811.0399 [hep-ph]; E. Ponton and L. Randall, arXiv:0811.1029 [hep-ph]; S. Baek and P. Ko, arXiv:0811.1646 [hep-ph]; A. Morselli and I. V. Moskalenko, arXiv:0811.3526 [astro-ph]; K. M. Zurek, arXiv:0811.4429 [hep-ph]; M. Taoso, S. Ando, G. Bertone and S. Profumo, arXiv:0811.4493 [astro-ph]; J. Hisano, M. Kawasaki, K. Kohri and K. Nakayama, arXiv:0812.0219 [hep-ph]; E. J. Chun and J. C. Park, arXiv:0812.0308 [hep-ph]; J. Liu, P. f. Yin and S. h. Zhu, arXiv:0812.0964 [astro-ph]; M. Pohl, arXiv:0812.1174 [astro-ph]; R. Allahverdi, B. Dutta, K. Richardson-McDaniel and Y. Santoso, arXiv:0812.2196 [hep-ph]; K. Hamaguchi, S. Shirai and T. T. Yanagida, arXiv:0812.2374 [hep-ph]; K. J. Bae, J. H. Huh, J. E. Kim, B. Kyae and R. D. Viollier, arXiv:0812.3511 [hep-ph]; J. Lavalle, arXiv:0812.3576 [astro-ph]; P. Grajek, G. Kane, D. Phalen, A. Pierce and S. Watson, arXiv:0812.4555 [hep-ph]; J. H. Huh, J. E. Kim and B. Kyae, arXiv:0812.5004 [hep-ph]; X. J. Bi, P. H. Gu, T. Li and X. Zhang, arXiv:0901.0176 [hep-ph]; S. C. Park and J. Shu, arXiv:0901.0720 [hep-ph]; I. Gogoladze, R. Khalid, Q. Shafi and H. Yuksel, arXiv:0901.0923 [hep-ph]; Q. H. Cao, E. Ma and G. Shaughnessy, arXiv:0901.1334 [hep-ph]; E. Nezri, M. H. G. Tytgat and G. Vertongen, arXiv:0901.2556 [hep-ph]; J. Mardon, Y. Nomura, D. Stolarski and J. Thaler, arXiv:0901.2926 [hep-ph]; D. J. Phalen, A. Pierce and N. Weiner, arXiv:0901.3165 [hep-ph]; H.-S. Goh, L. J. Hall and P. Kumar, arXiv:0902.0814 [hep-ph]; M. Ibe, Y. Nakayama, H. Murayama and T. T. Yanagida, arXiv:0902.2914 [hep-ph]; S. Shirai, F. Takahashi and T. T. Yanagida, arXiv:0902.4770 [hep-ph]; R. Allahverdi, B. Dutta, K. Richardson-McDaniel and Y. Santoso, arXiv:0902.3463 [hep-ph]; K. Cheung, P. Y. Tseng and T. C. Yuan, arXiv:0902.4035 [hep-ph]; L. Roszkowski, R. R. de Austri, R. Trotta, Y. L. Tsai and T. A. Varley, arXiv:0903.1279 [hep-ph]; D. P. Finkbeiner, T. Slatyer, N. Weiner and I. Yavin, arXiv:0903.1037 [hep-ph]; X. J. Bi, X. G. He and Q. Yuan, arXiv:0903.0122 [hep-ph]; K. Ishiwata, S. Matsumoto and T. Moroi, arXiv:0903.0242 [hep-ph];

# DM interpretation of positron excess

Nature 458 (2009) 607




Phys. Rev. Lett. 102 (2009) 051101




- 'Leptophilic' decays are favoured.

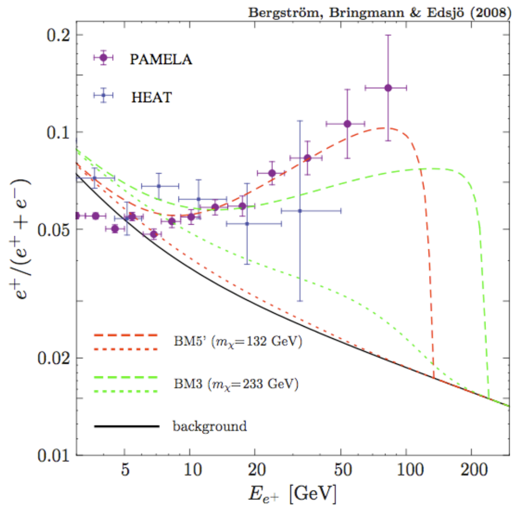
- Sharp rise! DM annihilation spectrum from SUSY is too soft (qq or WW dominant final states).

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

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

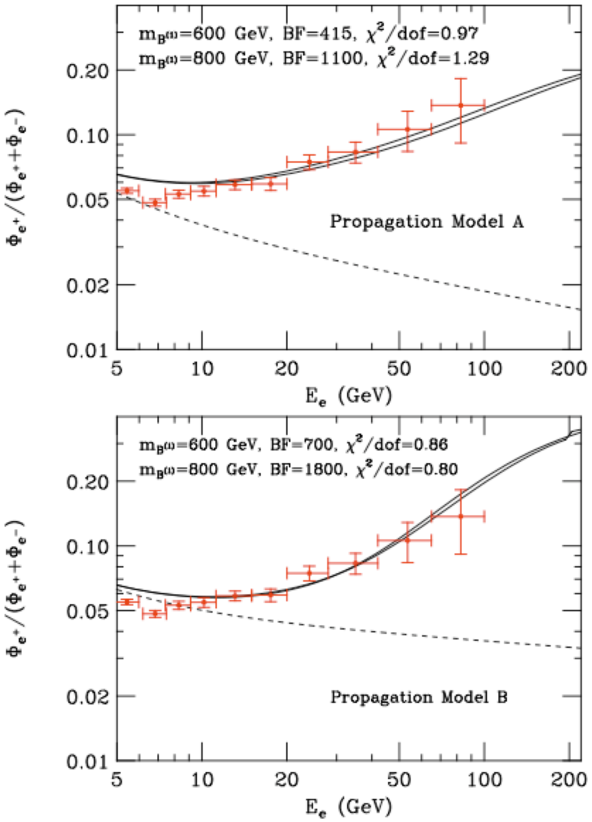
# Dark Matter examples

**arXiv:0808.3725**



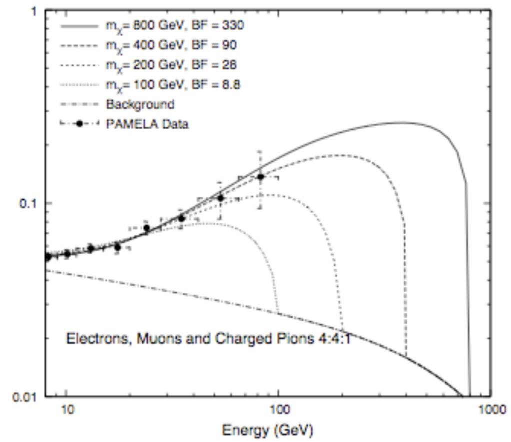

**Majorana DM** with **new** internal bremsstrahlung correction. **NB:** requires annihilation cross-section to be 'boosted' by >1000. *Does not affect antiproton fluxes, but would give large gamma-ray excess around WIMP mass (Fermi!)...*

Hooper and Zurek
**arXiv:0902.0593**




**Kaluza-Klein dark matter**

Cholis et al.,
**arXiv:0810.5344**




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

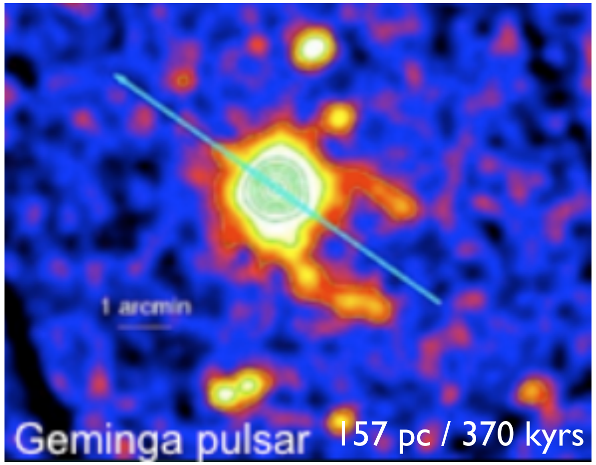
# An astrophysical explanation?

• Dark matter provides a spectacular solution to the rising positron fraction

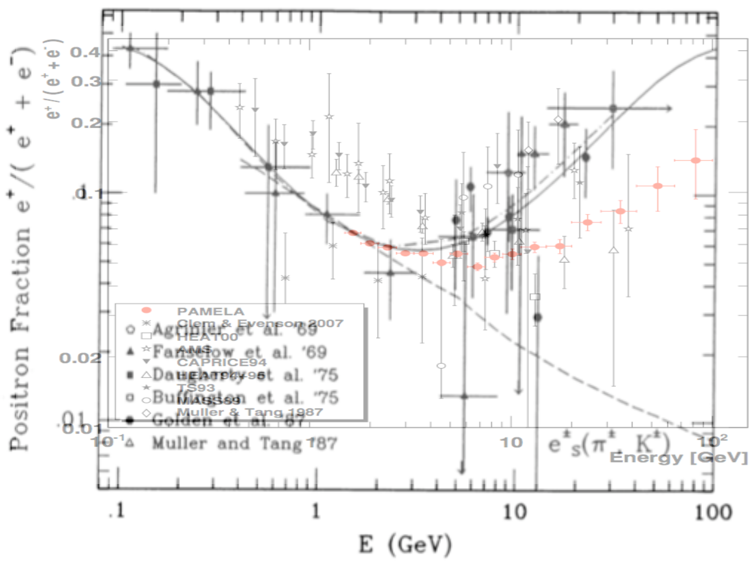
• However, **pulsars** offer a standard astrophysical solution...

• Strong spinning **B** → accelerated electrons → synchrotron emission → electromagnetic showers produced in pulsar magnetosphere → $e^+$

• Efficient energy loss from synchrotron and inverse Compton energy losses, so source must be 'close' (< few kpc) and 'young' (~$10^5$ years)




... and Fermi is updating the catalogue!

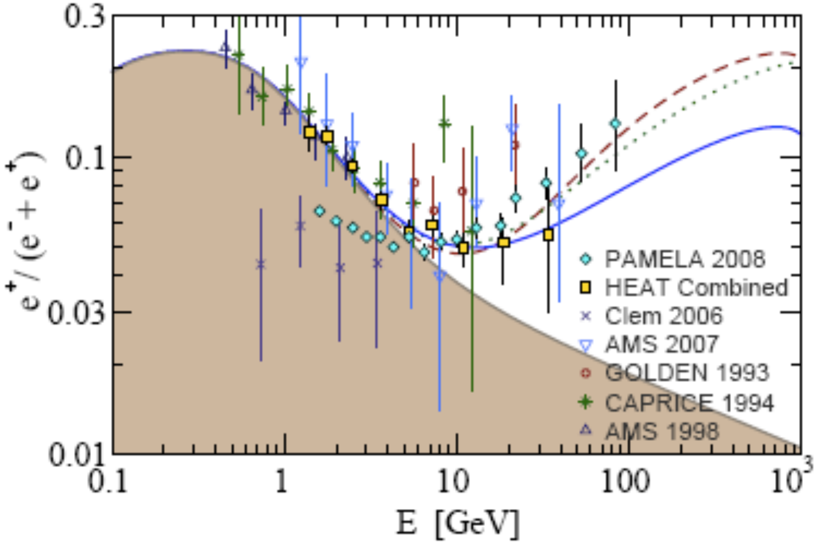



**Already considered 20 years ago!**
A. Boulares, Ap. J. 342 (1989) 807

# Pulsar examples

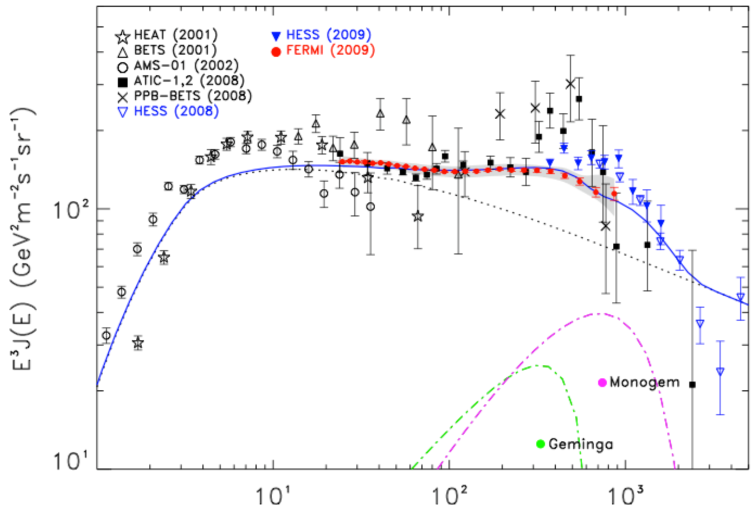
D. Grasso et al.
**arXiv:0905.0636v3**

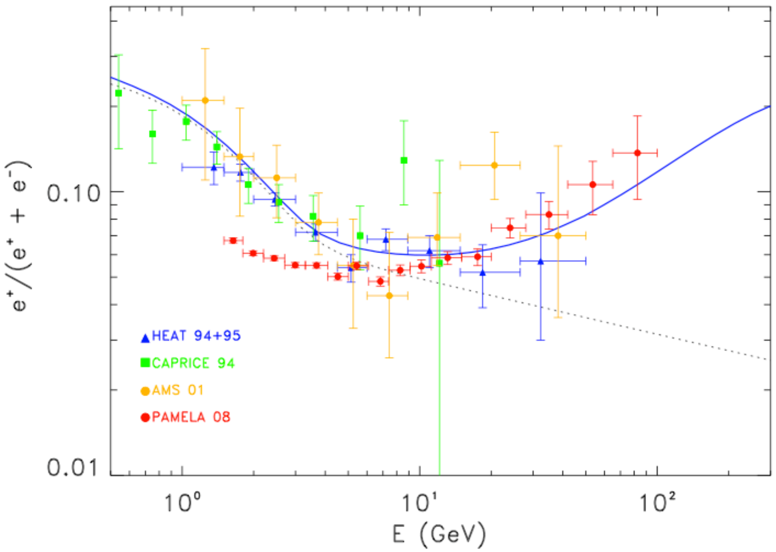
Yüksak et al.
**arXiv:0810.2784**




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

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




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

# Summary

- **PAMELA** results herald a new era of precision studies of charged cosmic rays in space

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

- **High energy positron fraction** (>10 GeV) increases significantly with energy. **Nearby primary source?** Additional data in preparation (spillover limit ~300 GeV).

- Absolute fluxes ($e^+$, $e^-$) in preparation. $e^-$ (~500 GeV), $e^\pm$ (~1 TeV).

- A plethora of interpretations are on the market. Take your pick! More data needed (watch this space!). Synergy with other instruments (e.g. Fermi) very important.

- PAMELA mission recently approved until 2011