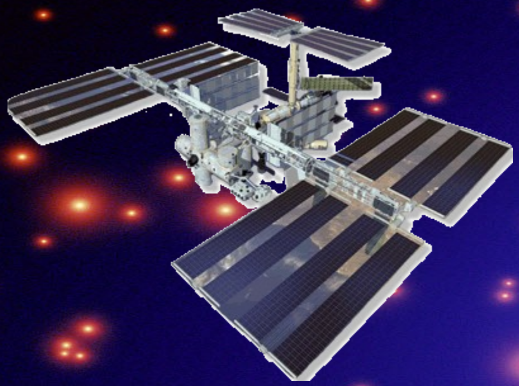
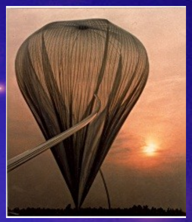
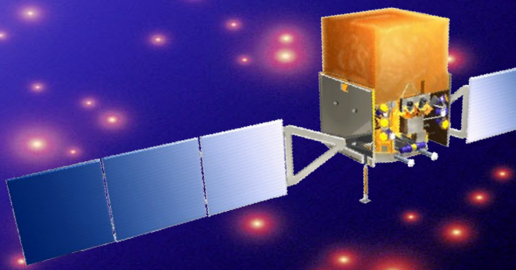
# Studying Cosmic Rays
# with Balloon and Space Experiments





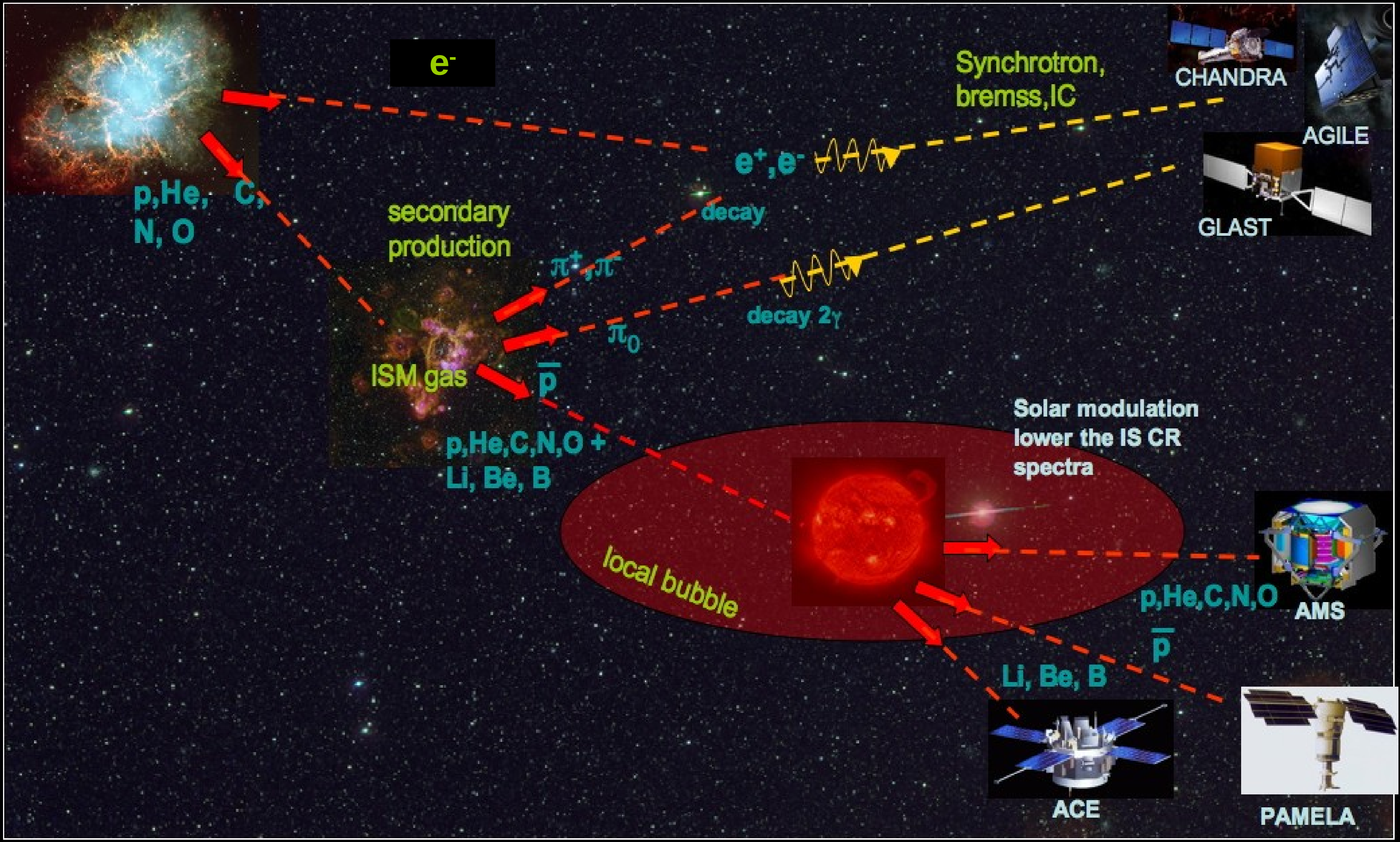


*Piergiorgio Picozza*
*INFN and University of Rome Tor Vergata*

*INFN, National Laboratories of Frascati*

*October 29, 2012*

# COSMIC RAYS PRODUCTION MECHANISMS



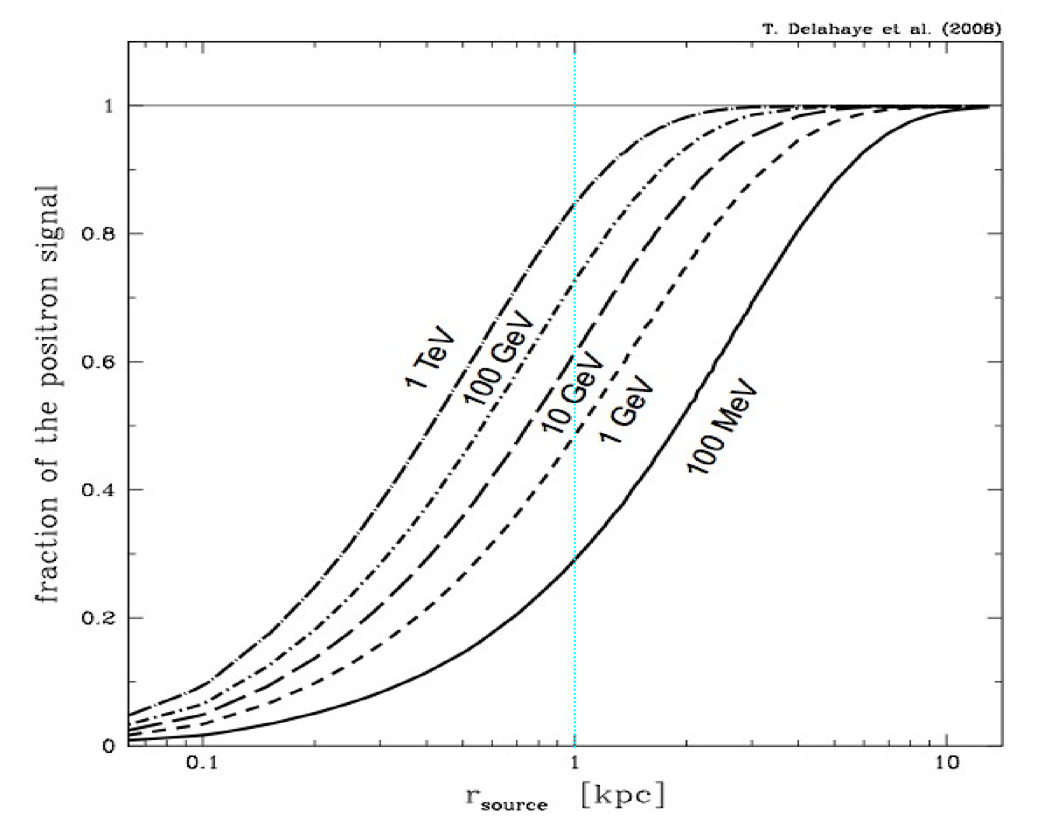
# Where do electrons and positrons come from?

Mostly locally within 1 Kpc, due to the energy losses by Synchrotron Radiation and Inverse Compton

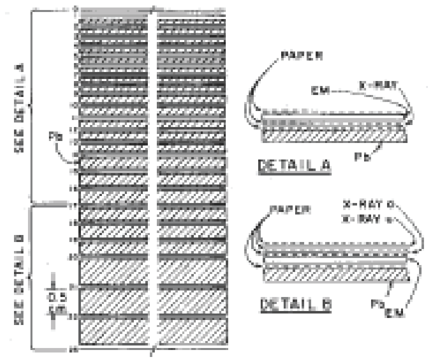
**Typical lifetime**

$$\tau \simeq 5 \cdot 10^5 \text{yr} \left(\frac{1\,\text{TeV}}{E}\right)$$

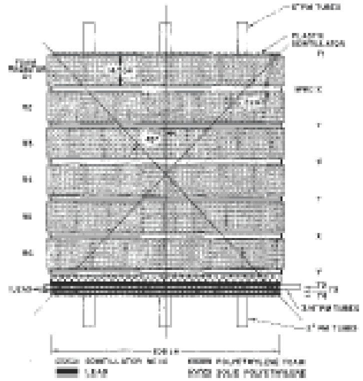
**Antiprotons within 10 Kpc**



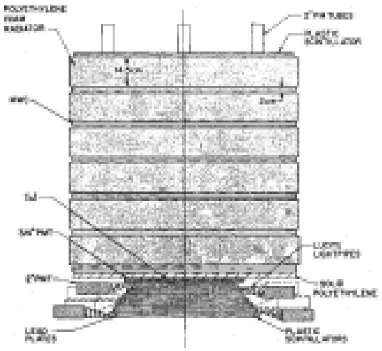
# All electron inclusive spectrum




Emulsion chambers (1968–79)
30 GeV–1.5 TeV [8.2 r. l.]



Hartman (1977)
9–300 GeV [8 r. l.]



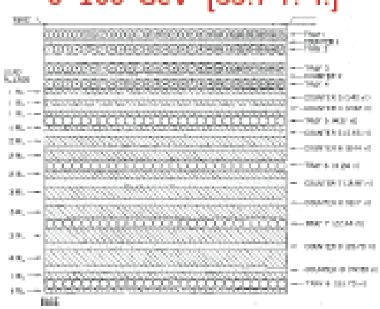
Tang (1980)
4–280 GeV [18.5 r. l.]

1970

1980

2000

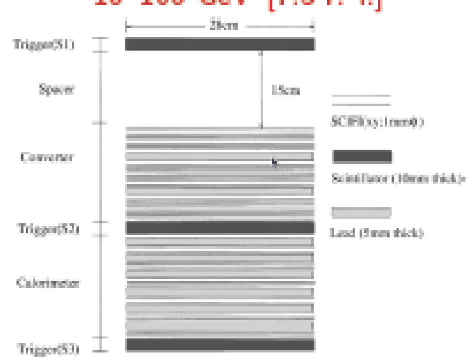
Meegan (1969–73)
6–100 GeV [33.7 r. l.]



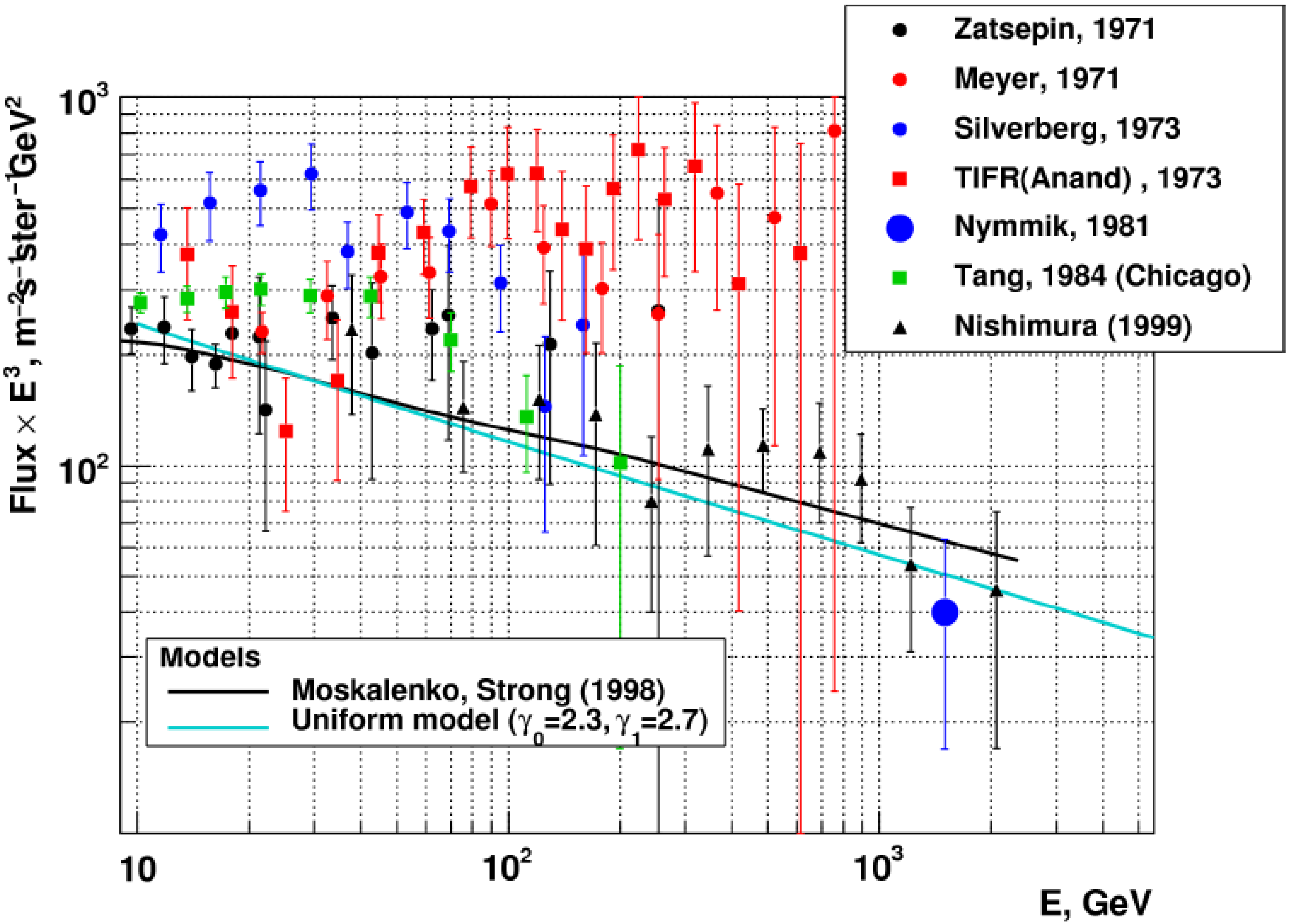
## Detector concepts

- Imaging calorimeters (energy measurement *and* background rejection).
- Many different implementations explored.

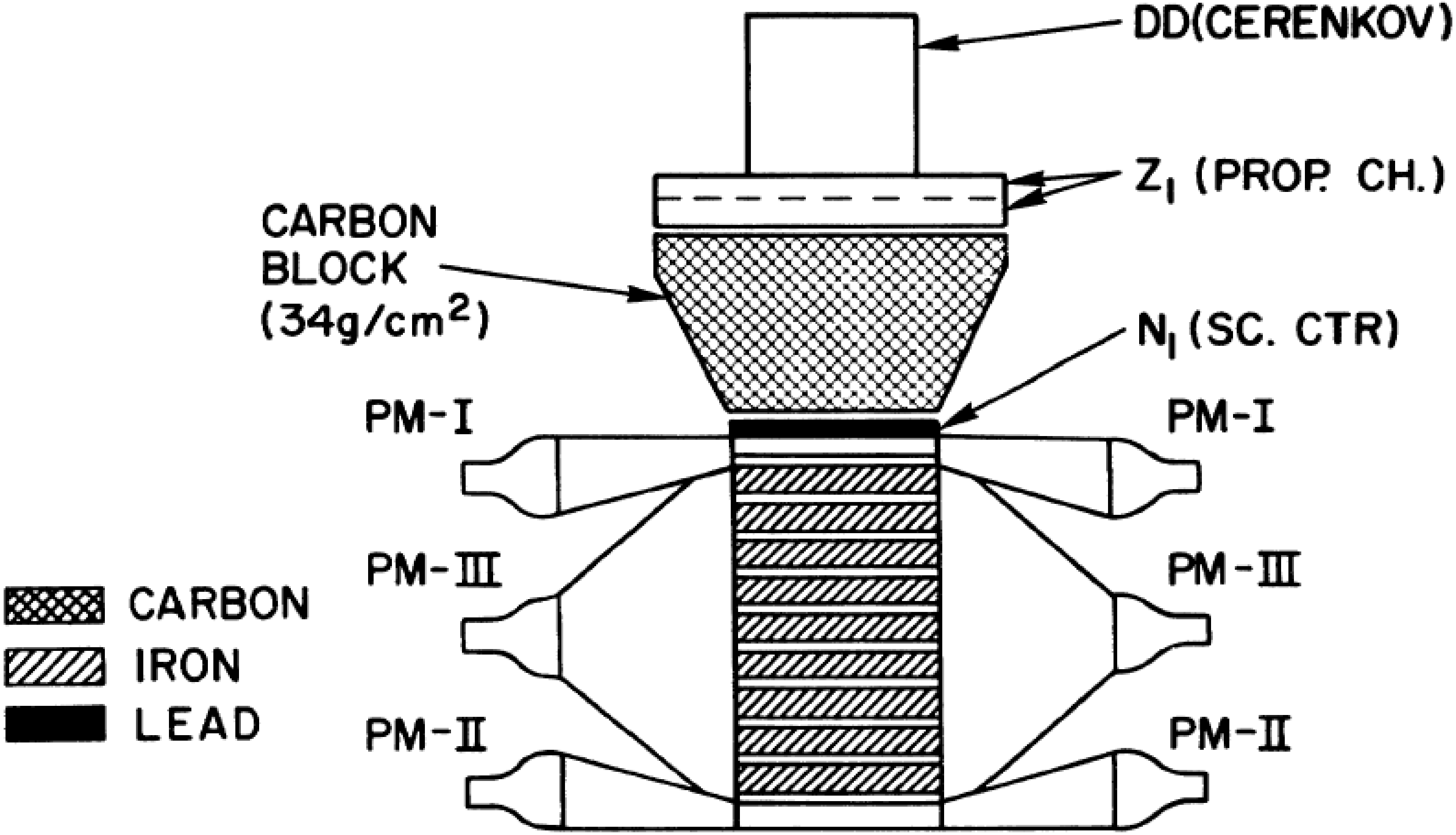
BETS (1997–98)
10–100 GeV [7.3 r. l.]



# Electrons ($e^-$ + $e^+$) - early experiments (1970-2000)



# Proton satellite experiments (Grigorov 1967)




SCHEMATIC DIAGRAM OF THE INSTRUMENT

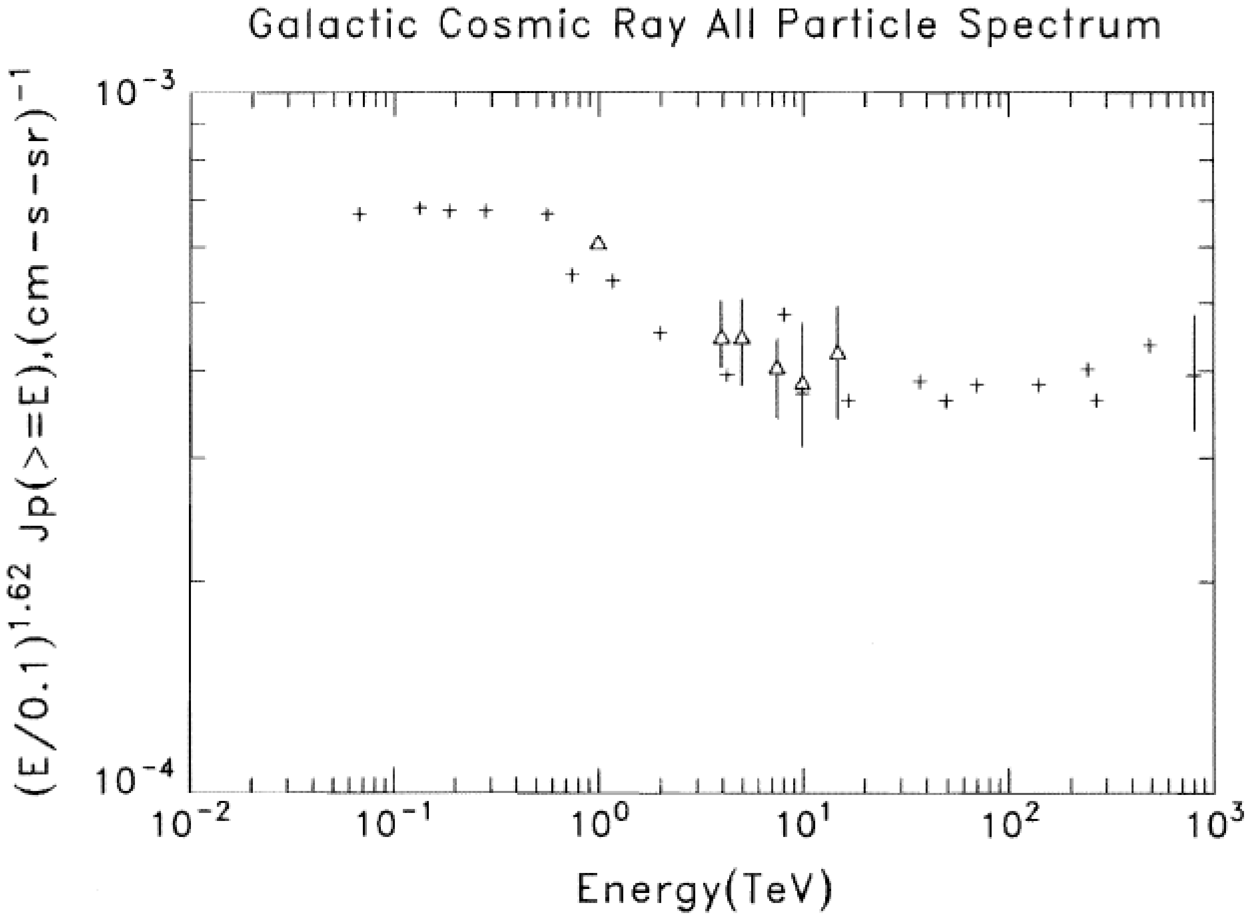



Figure 3: This figure is taken from Grigorov (1990). It shows measurements of the galactic cosmic ray all particle spectrum from the Proton Satellites (+'s) and from the sum of the elemental spectra measured in the Sokol experiment (triangles).

# Proton spectrum    Helium spectrum

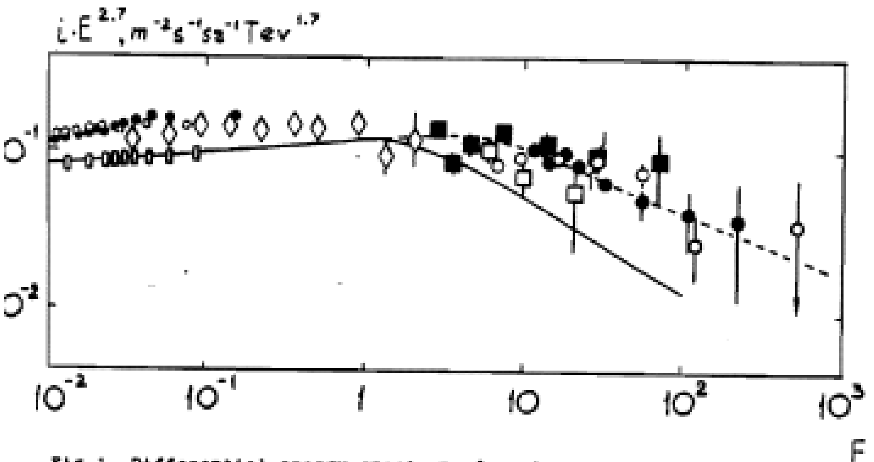



Fig.1. Differential energy spectrum of protons.

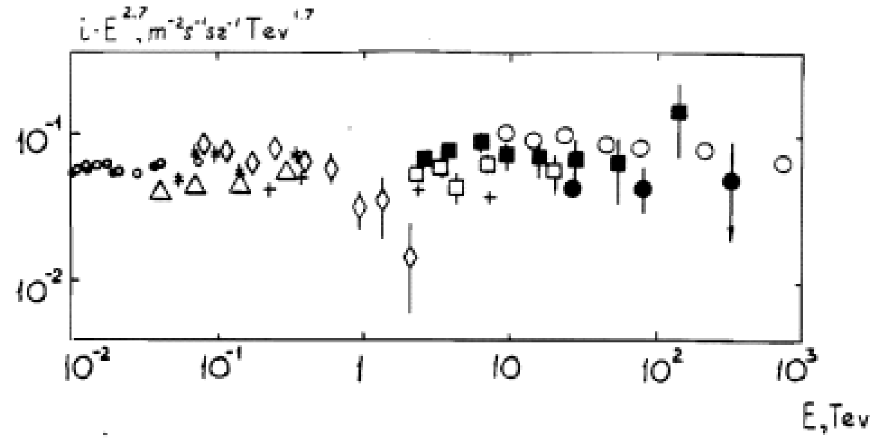
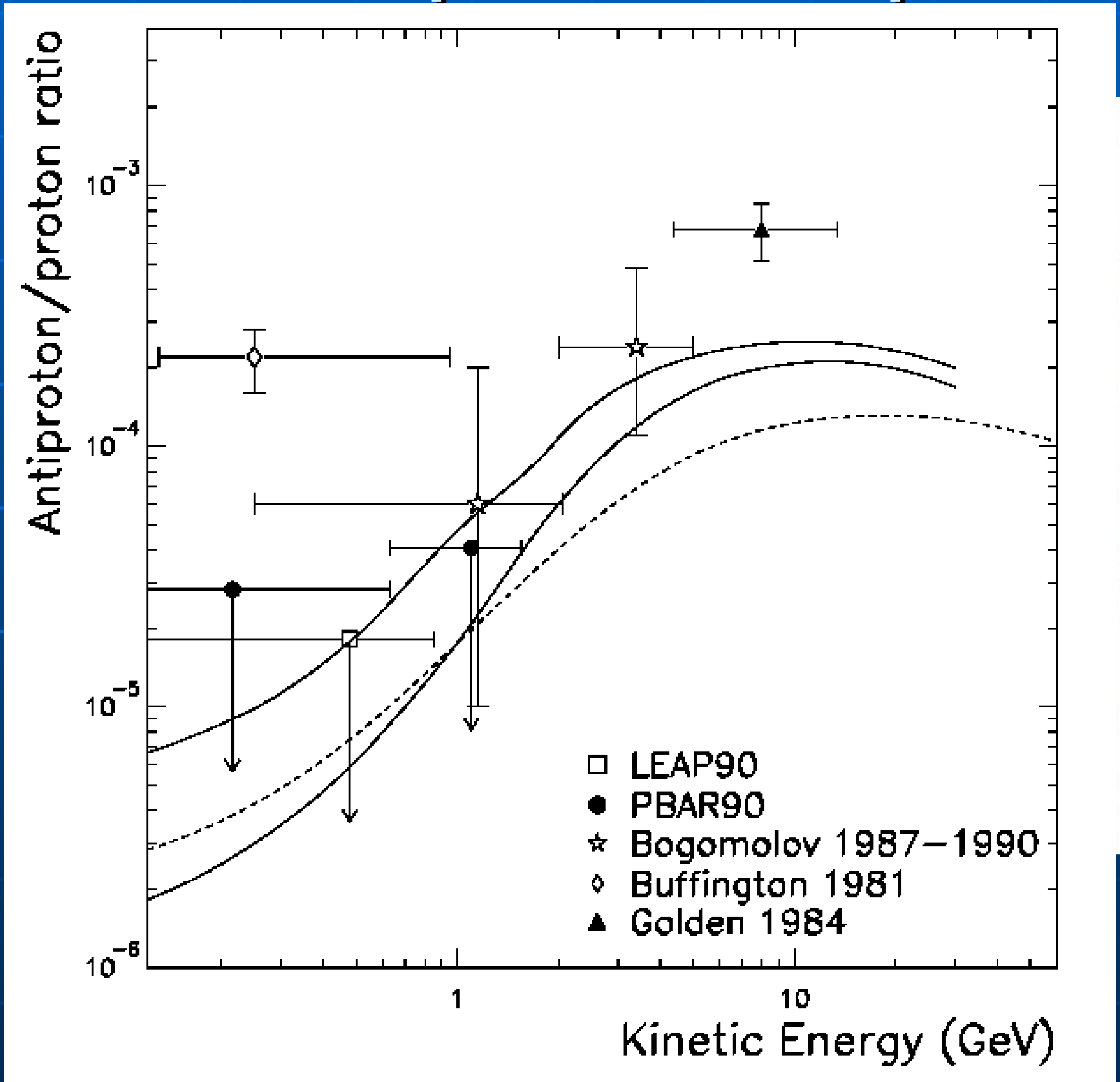
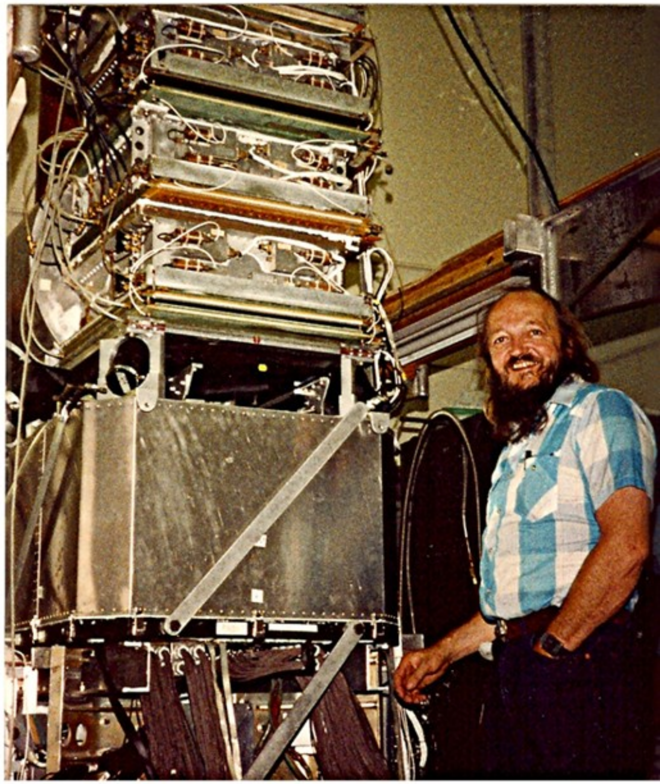


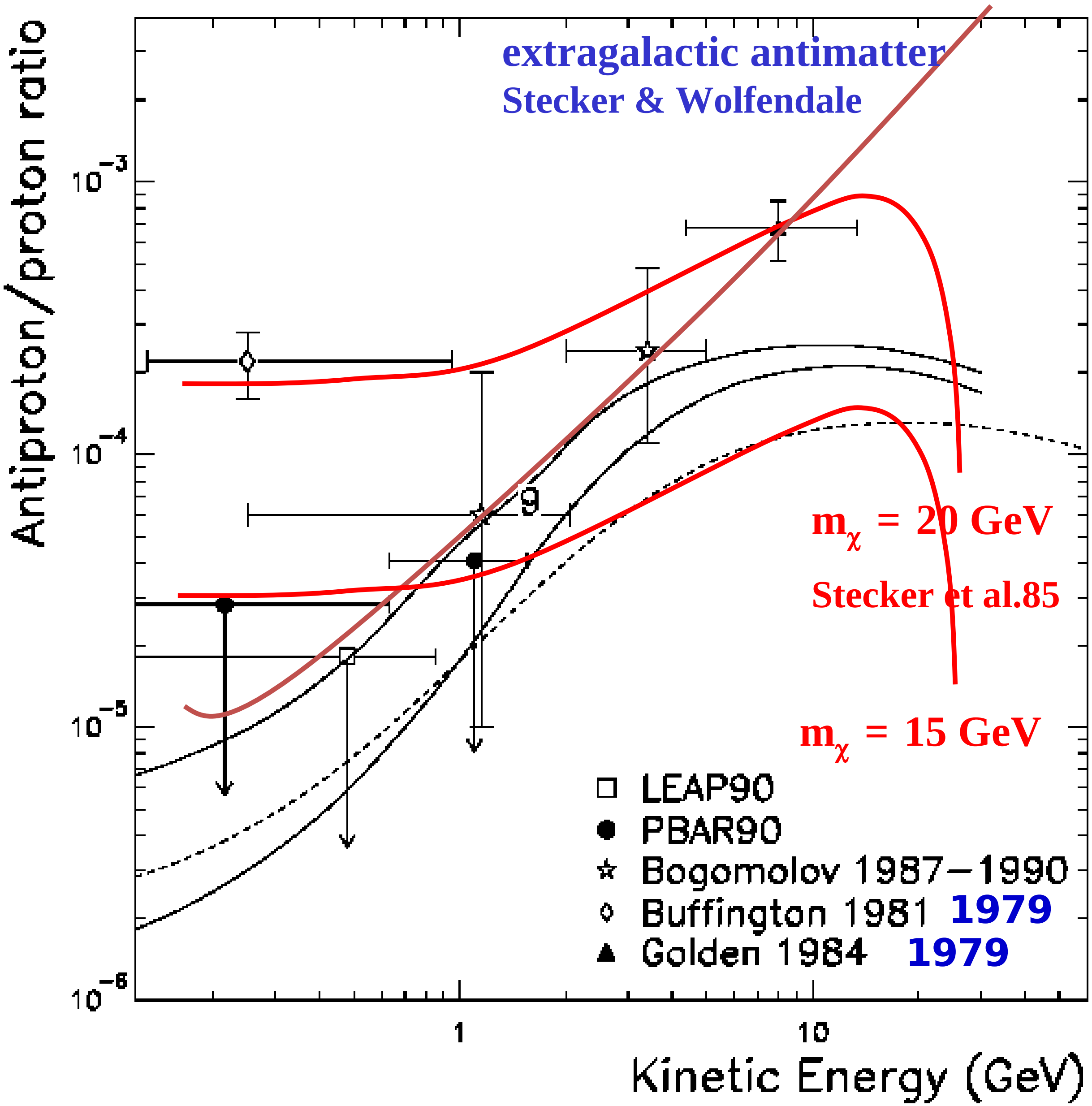

Fig.2. Helium nucleus spectrum.

# Antiproton to proton ratio

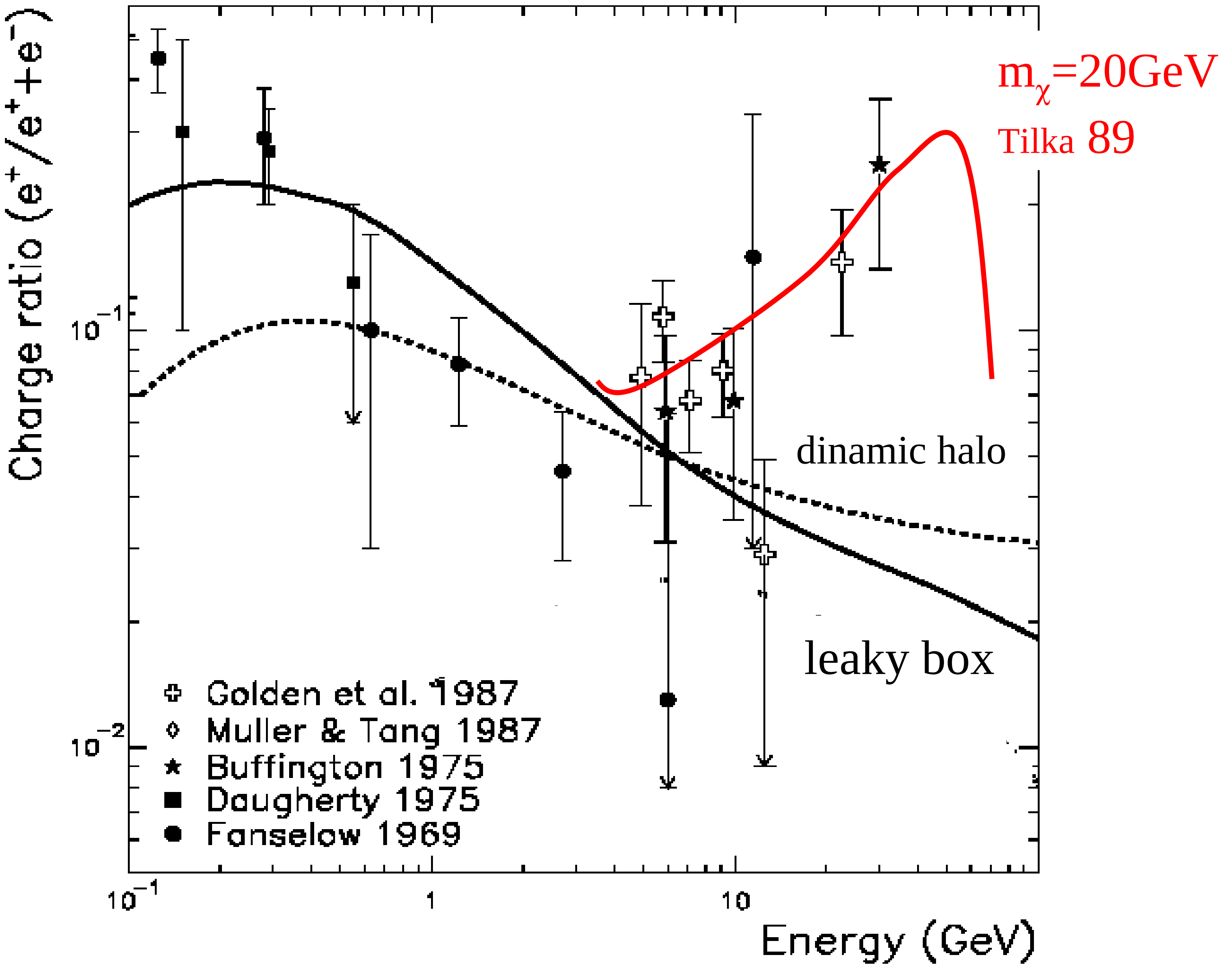


# Antiproton/proton ratio before 1990



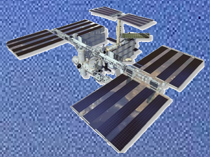
# Balloon data : Positron fraction before 1990



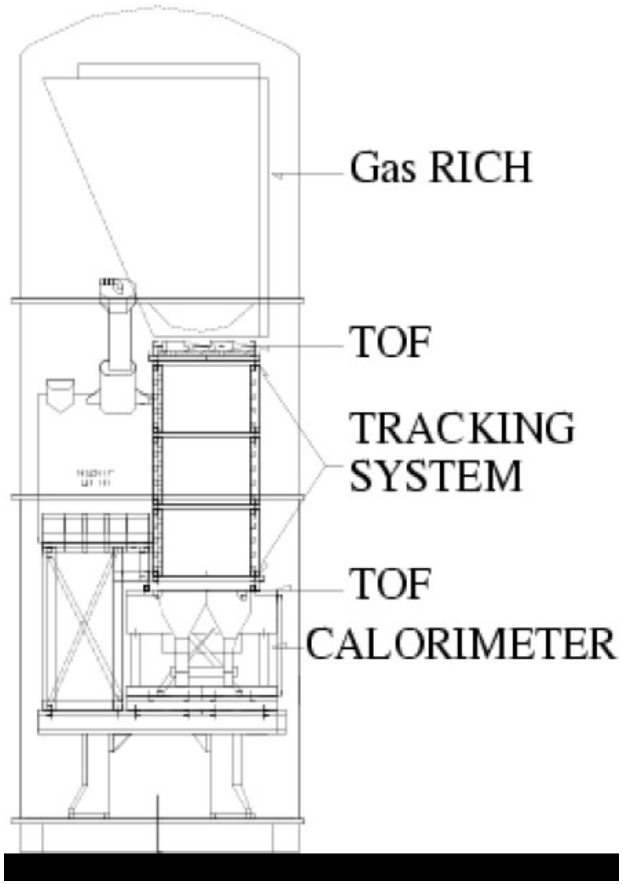
# Antimatter Search

## Wizard Collaboration

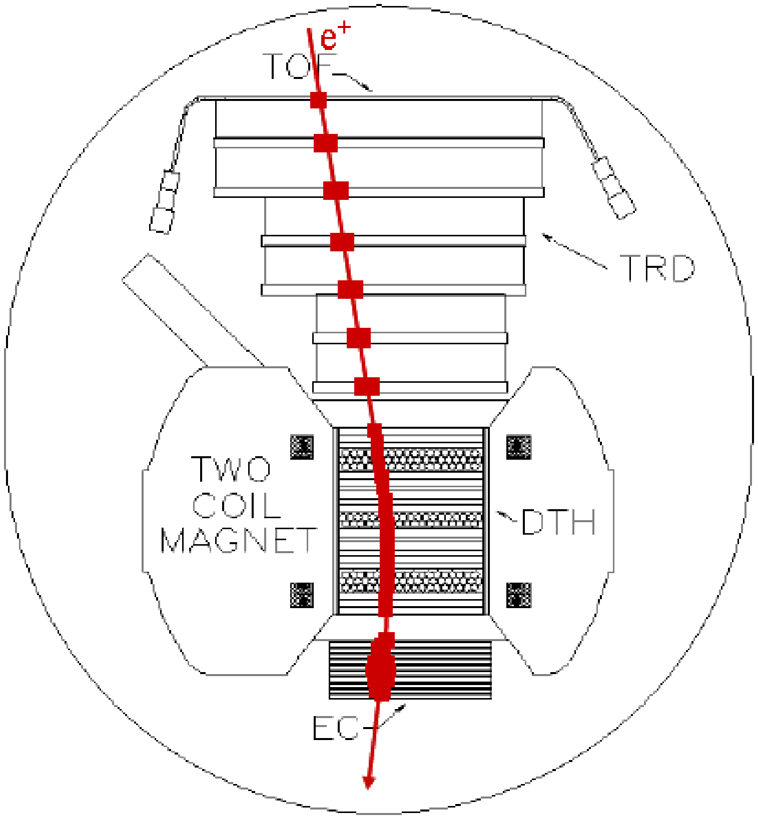
- MASS – 1,2 (89,91)
- TrampSI (93)
- CAPRICE (94, 97, 98)
- BESS (93, 95, 97, 98, 2000)
- Heat (94, 95, 2000)
- IMAX (96)
- AMS-01 (1998)



# CAPRICE

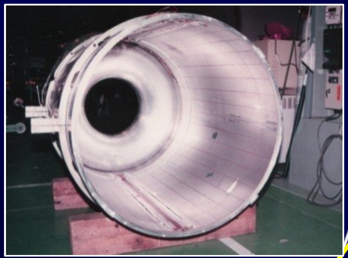


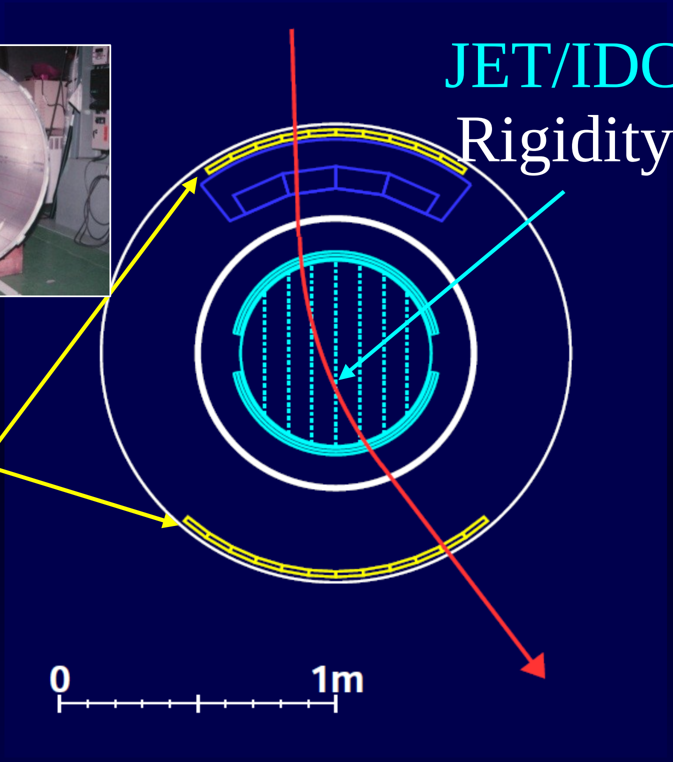

# HEAT

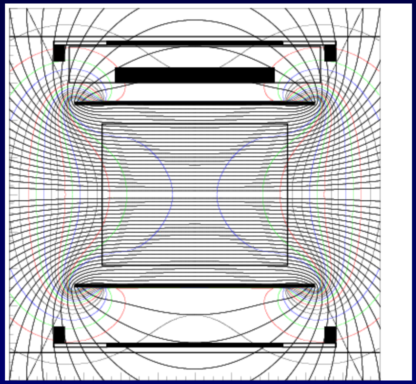


# BESS Detector

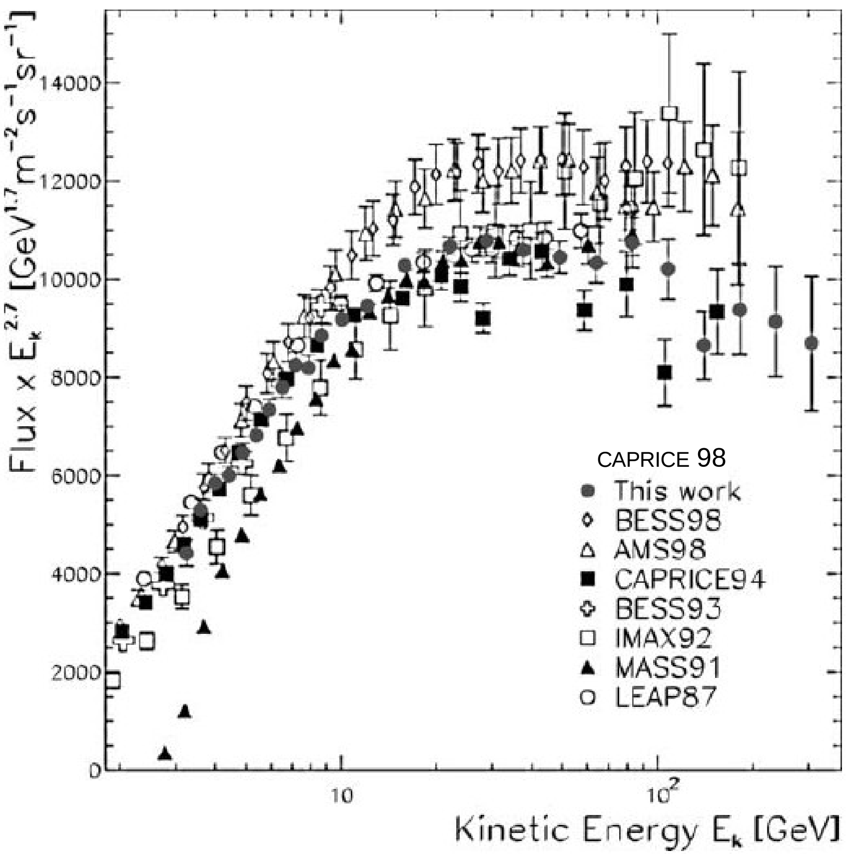
- **Rigidity measurement**
  - SC Solenoid (L=1m, B=1T)
  - Min. material (4.7g/cm$^2$)
  - Uniform field
  - Large acceptance
- Central tracker
  - (Drift chamber
  - $\delta$ ~200$\mu$m
- ***Z, m* measurement**
  - $R, \beta$ --> $m = ZeR\sqrt{1/\beta^2 - 1}$
  - $dE/dx$ --> $Z$



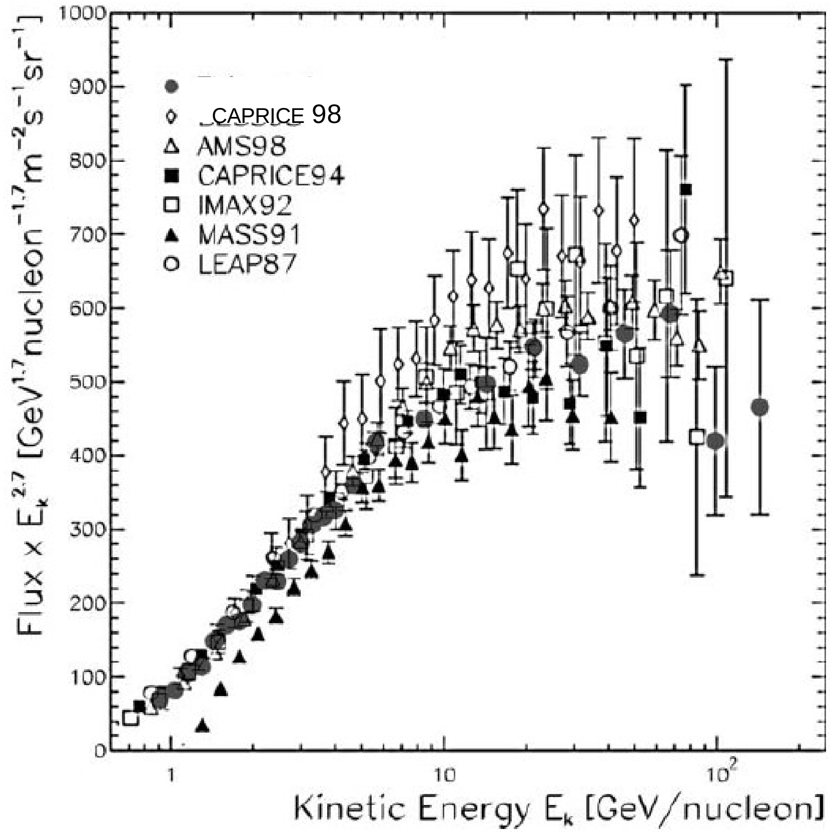


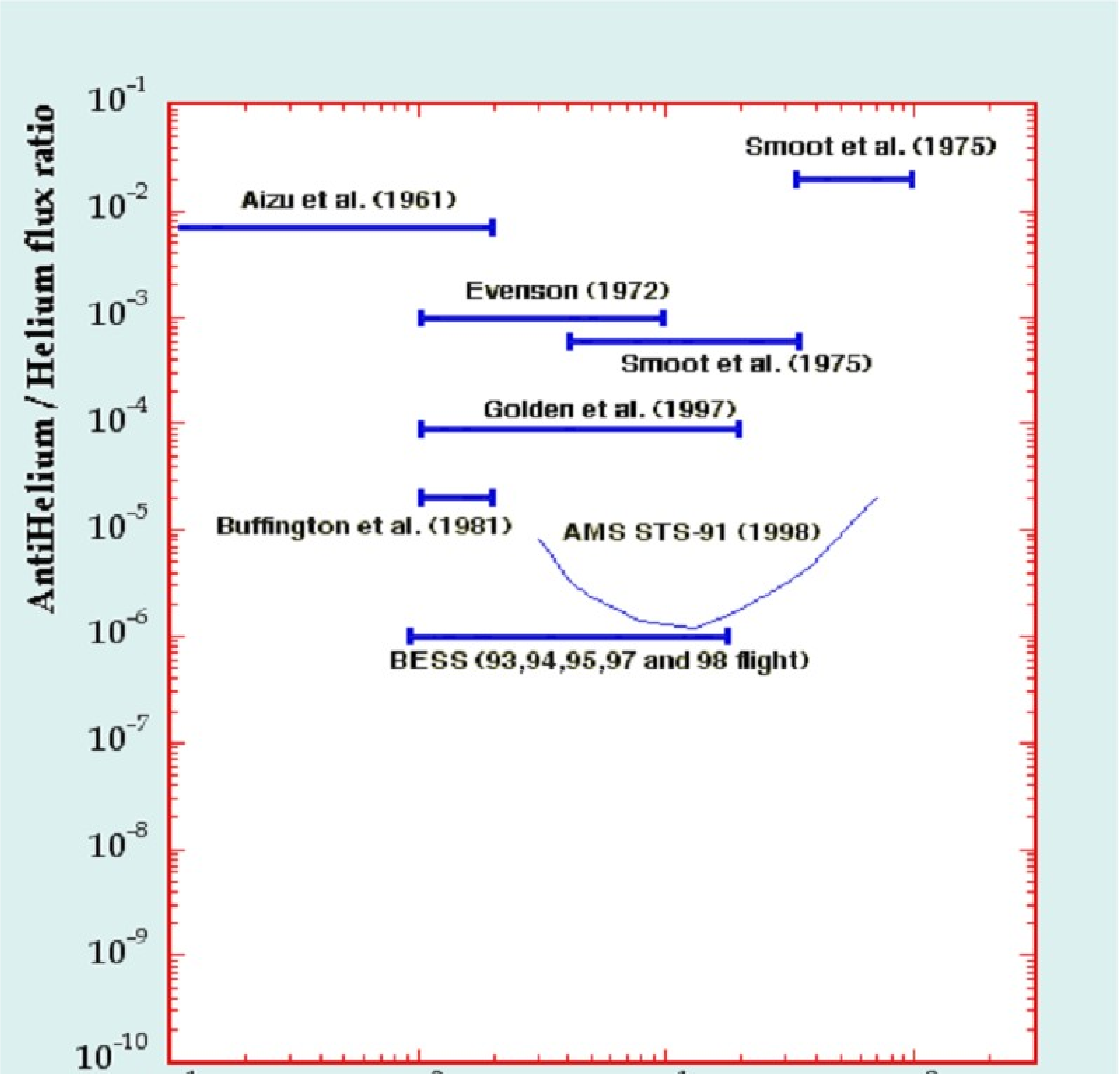
# Proton flux




# Helium flux



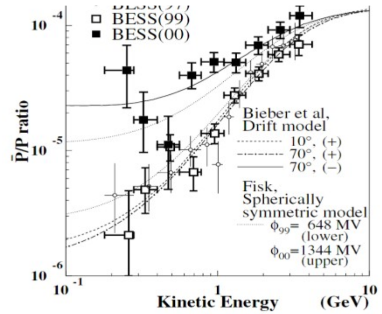
# ANTIMATTER LIMITS



# Cosmic Ray Antimatter

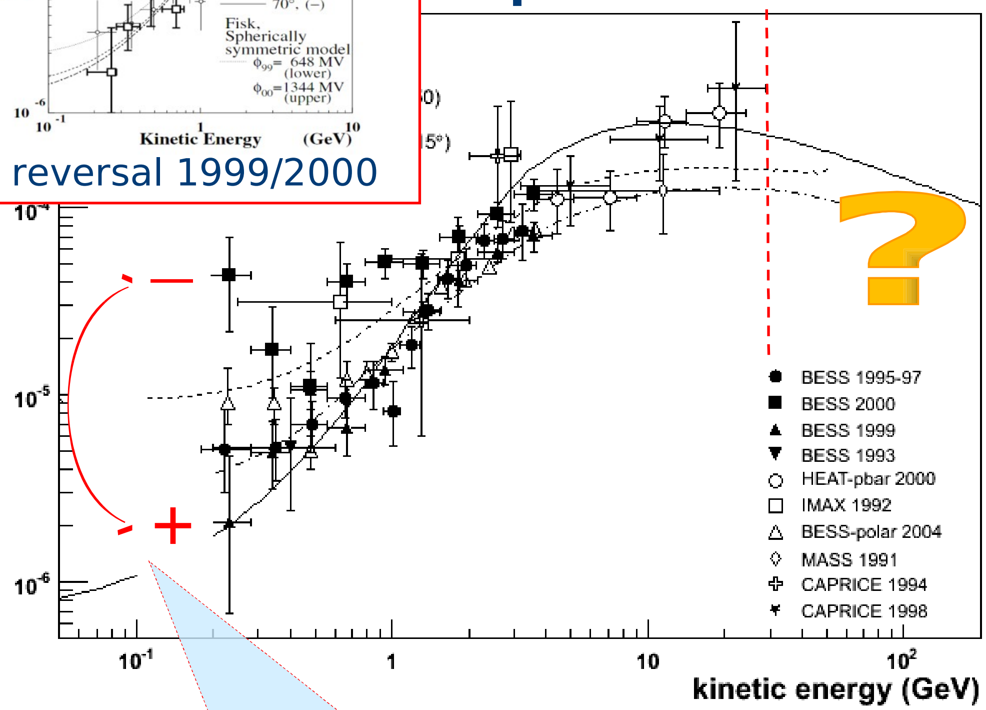
**Charge-dependent solar modulation**

Asaoka Y. Et al. 2002




reversal 1999/2000

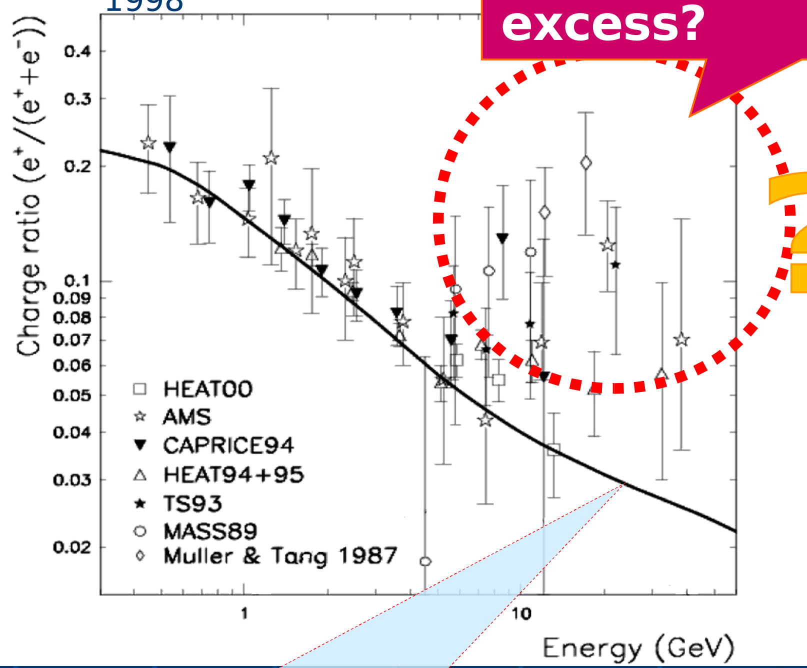
## Antiprotons




## Positrons

— Moskalenko & Strong 1998

**Positron excess?**




CR + ISM → **p-bar** + …

kinematic threshold: 5.6 GeV for the reaction $pp \rightarrow ppp\bar{p}$

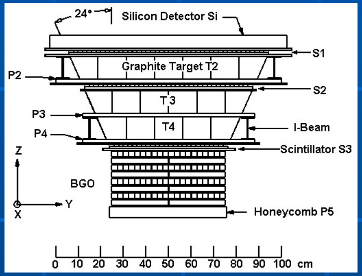
CR + ISM → $\pi^{\pm}$ + x → $\mu^{\pm}$ + x → **$e^{\pm}$** + x

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

# Space Missions and LDF

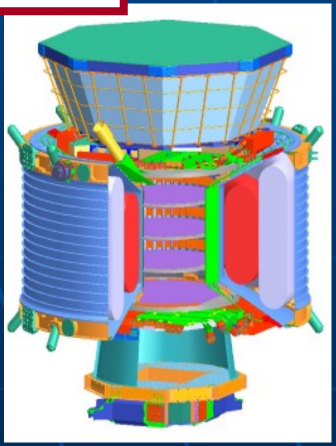
**PAMELA**
**15-06-2006**

**ATIC**
**2002 - 2007**



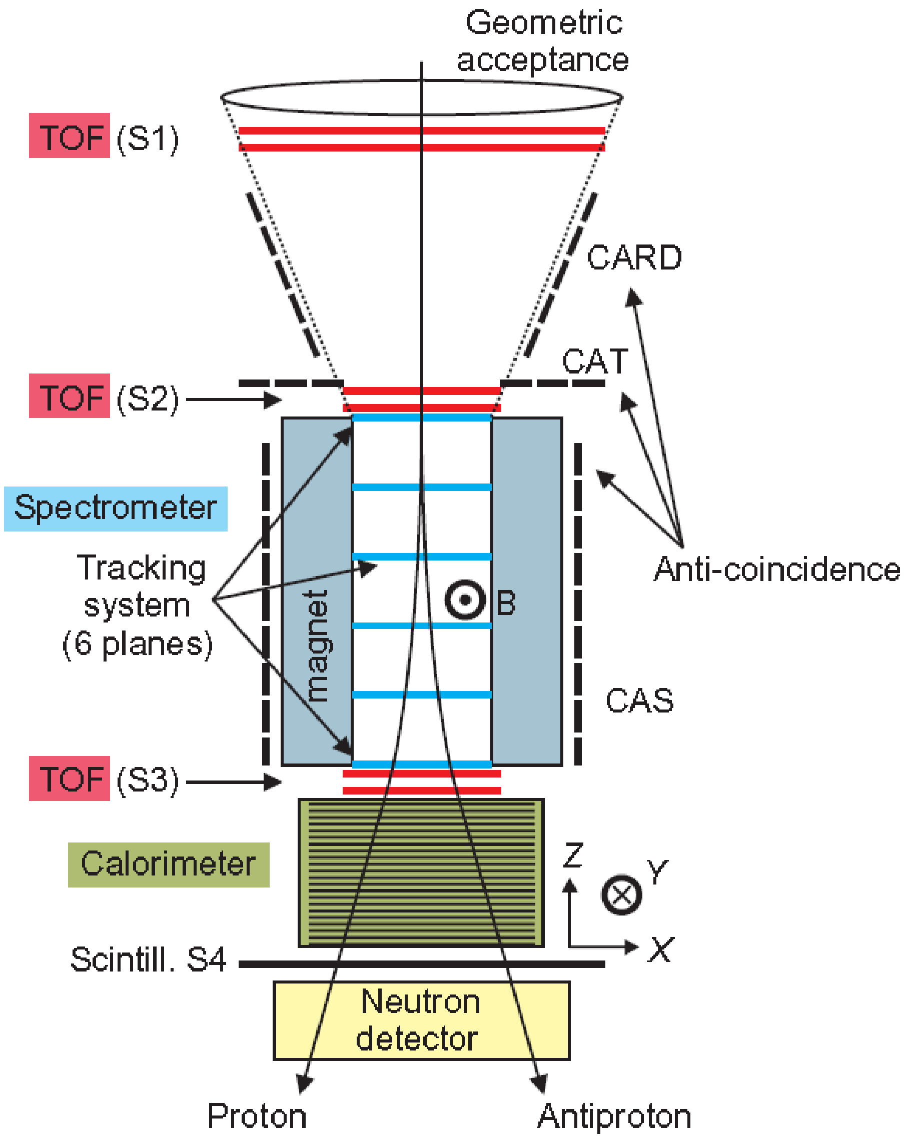

**BESS**
**13-12-2004 23-12-2007**

**AMS-02**
**16 -5-2011**

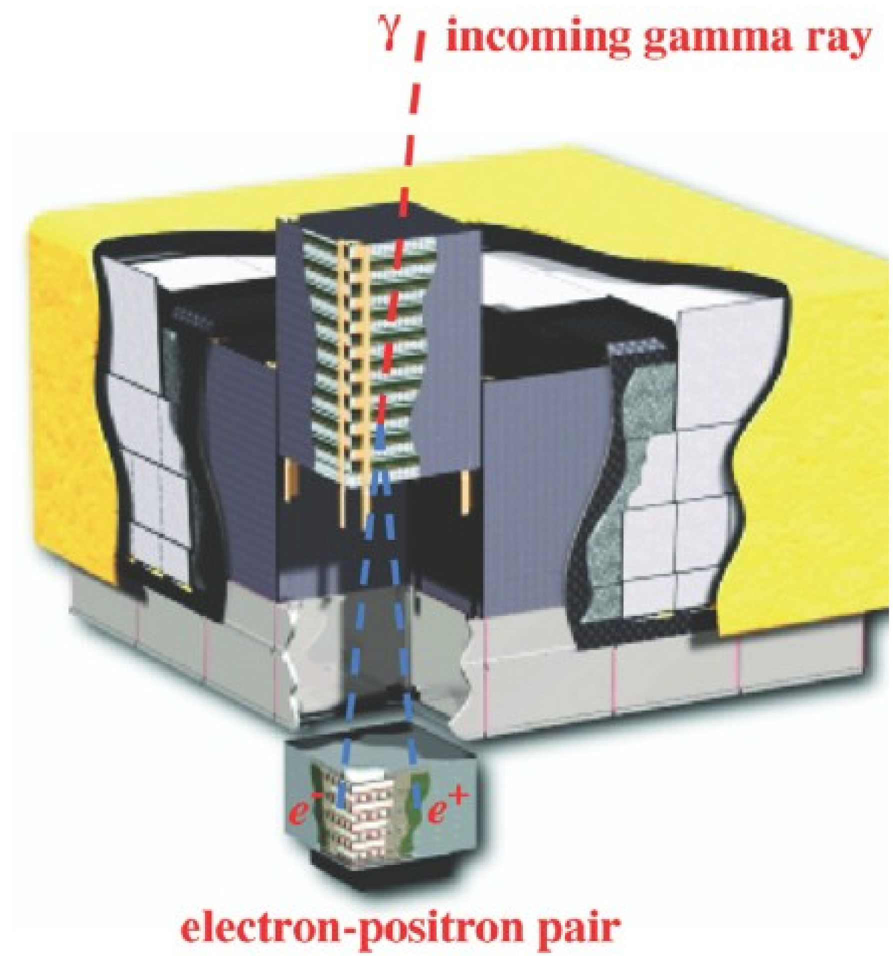


**Fermi/GLAST**
**11-6-2008**

## PAMELA



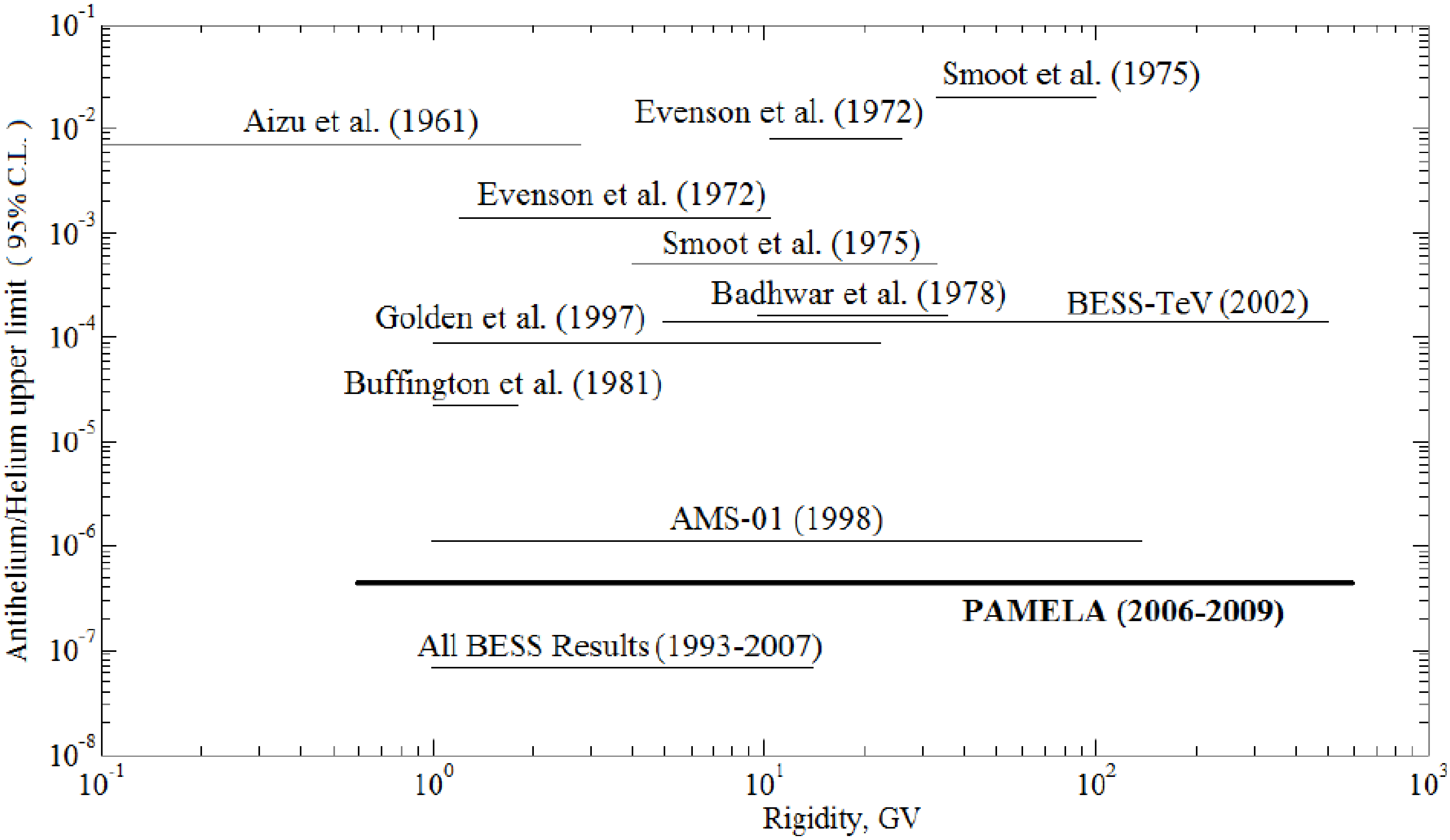

## FERMI



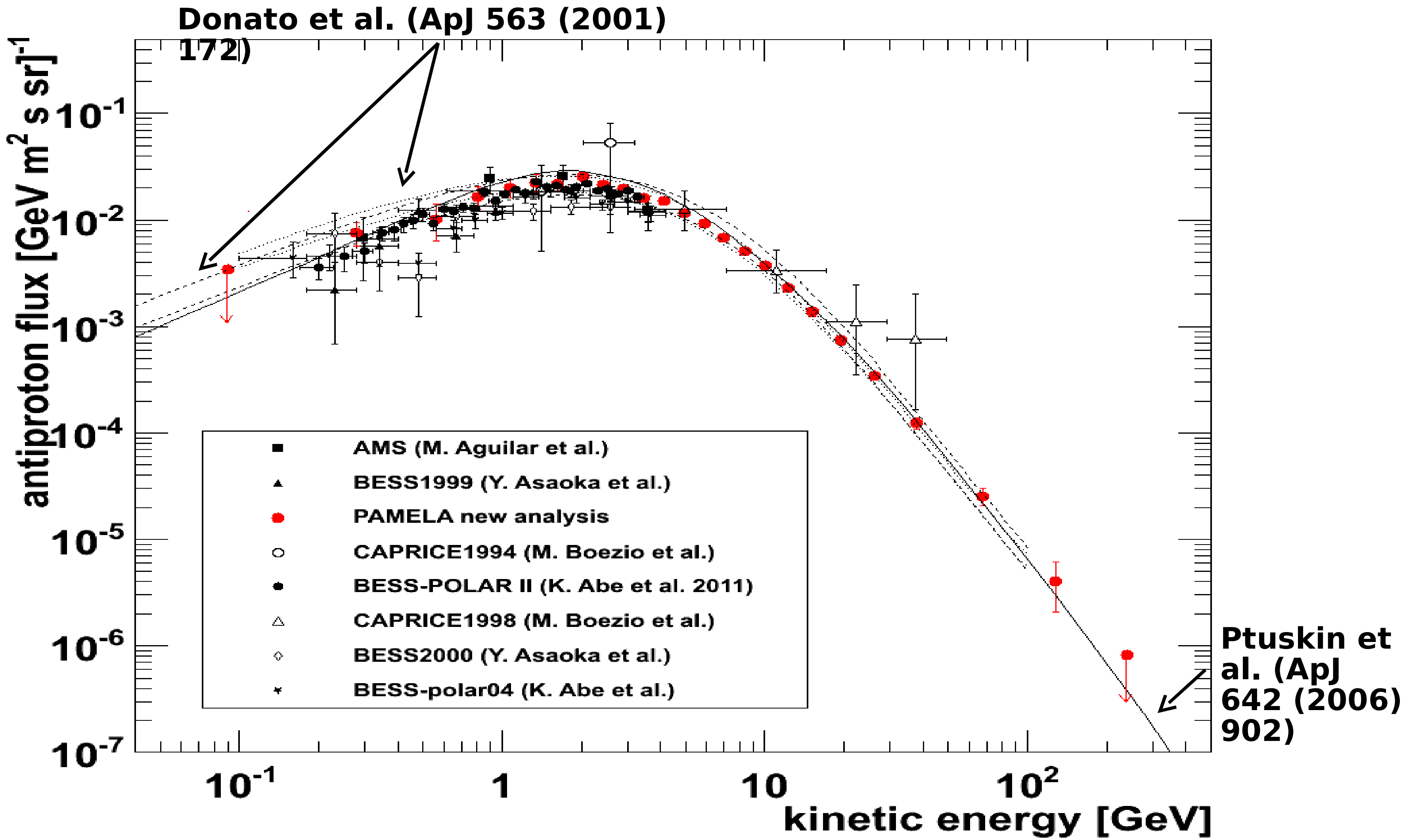
# Antiparticles

Antimatter and Dark Matter Search

# Antimatter limits



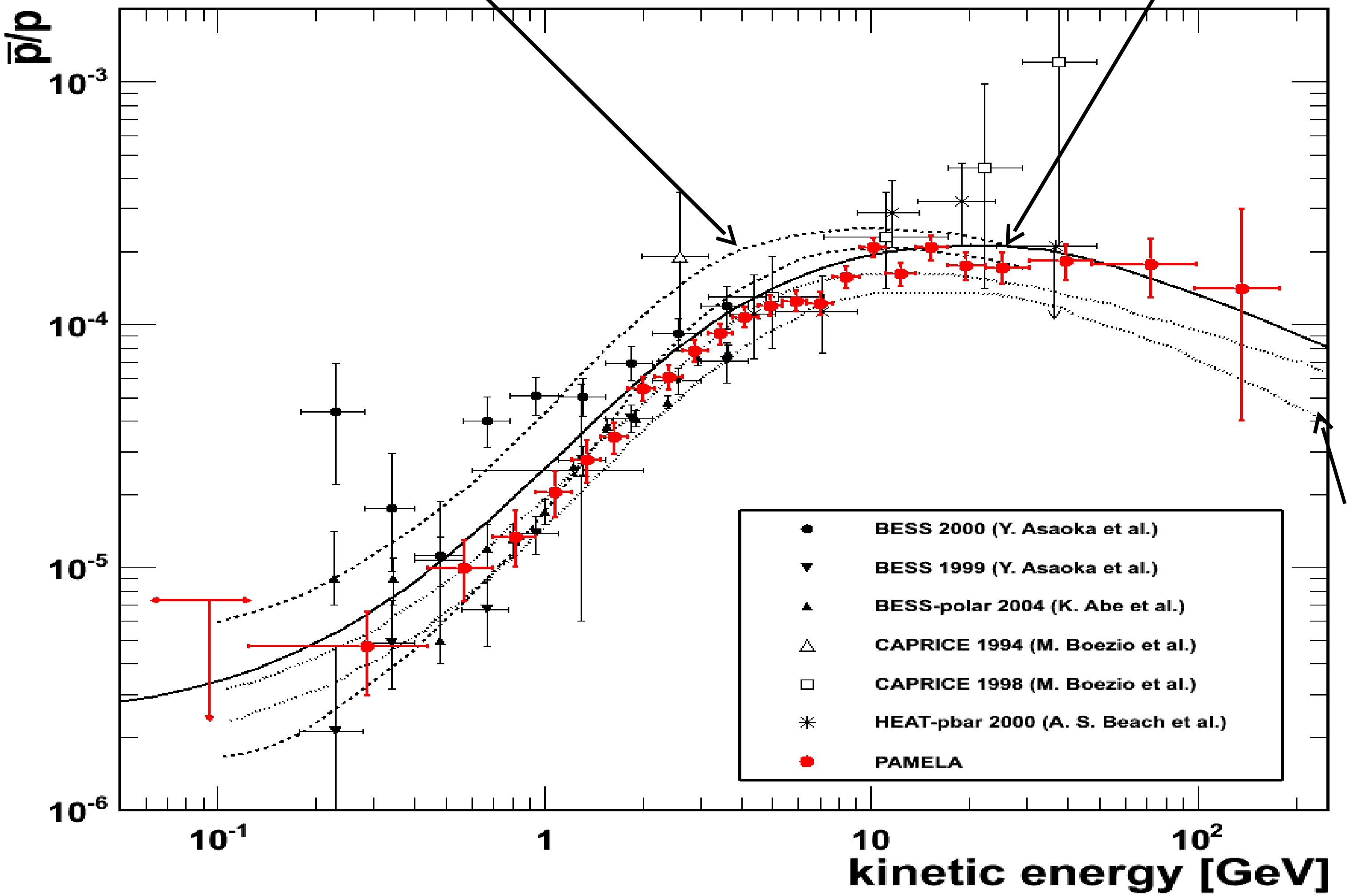
# Antiproton Flux



# Antiproton to proton ratio (0.06 GeV - 180 GeV)

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

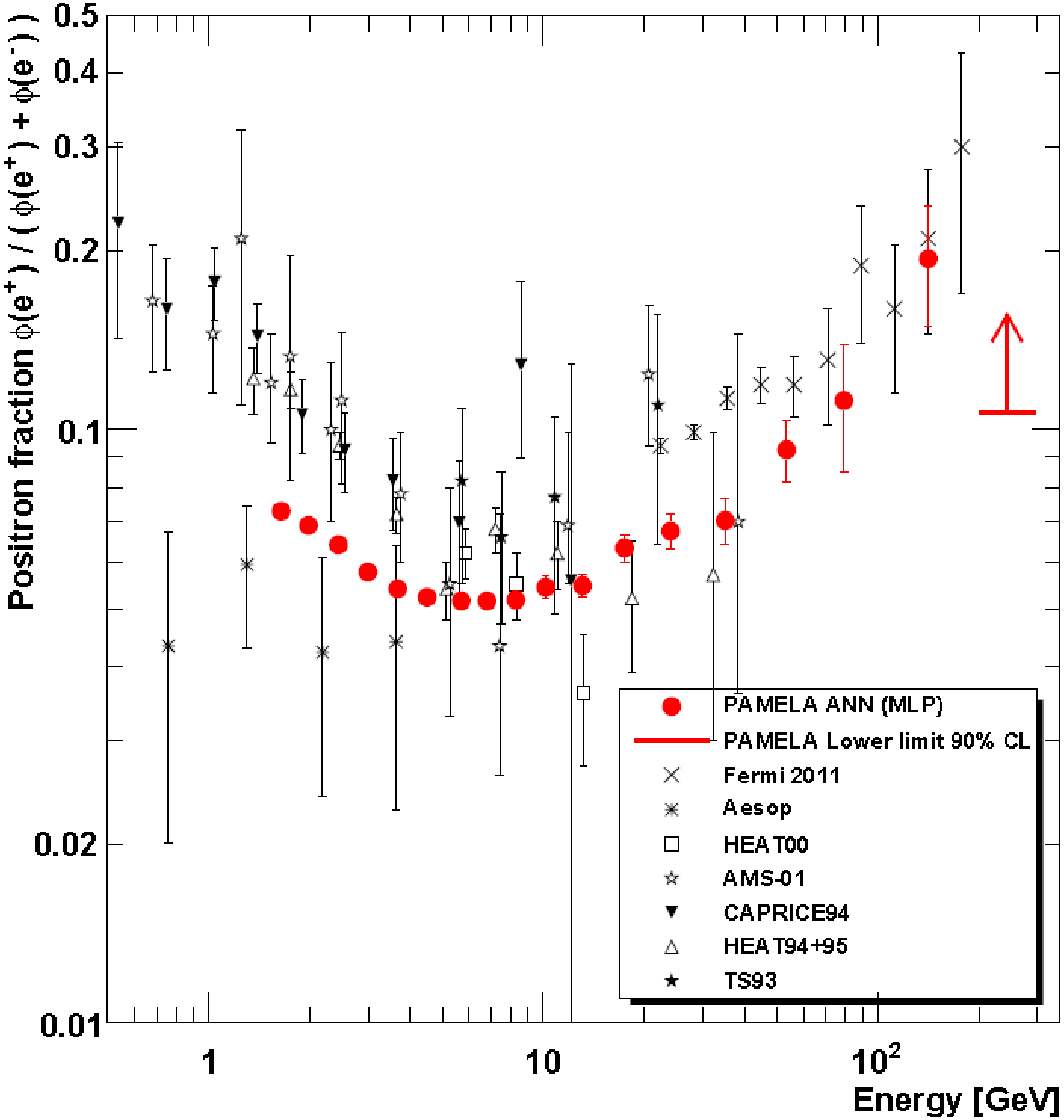
Ptuskin et al. (ApJ 642 (2006) 902)

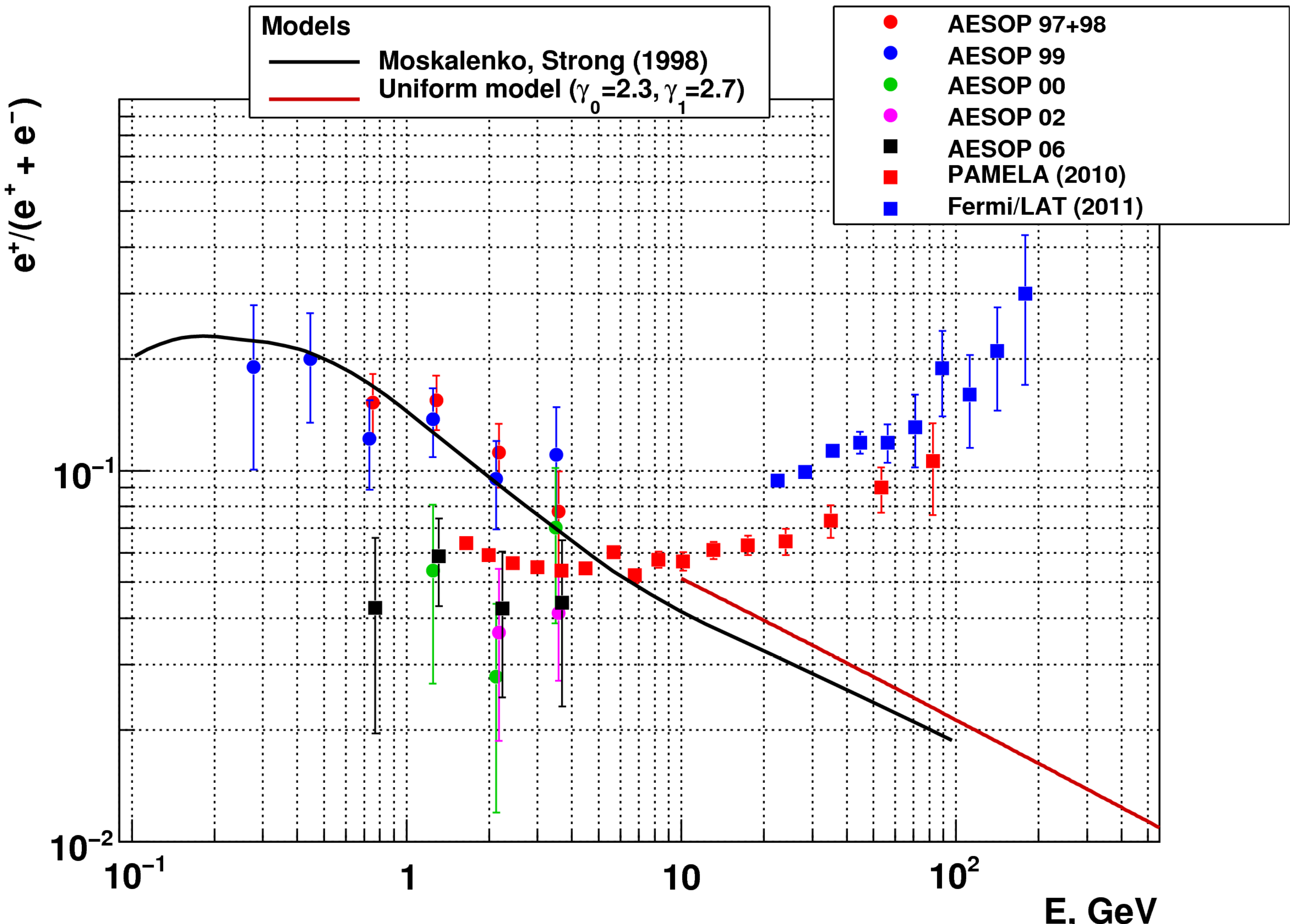



Donato et al. (PRL 102 (2009) 071301)

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

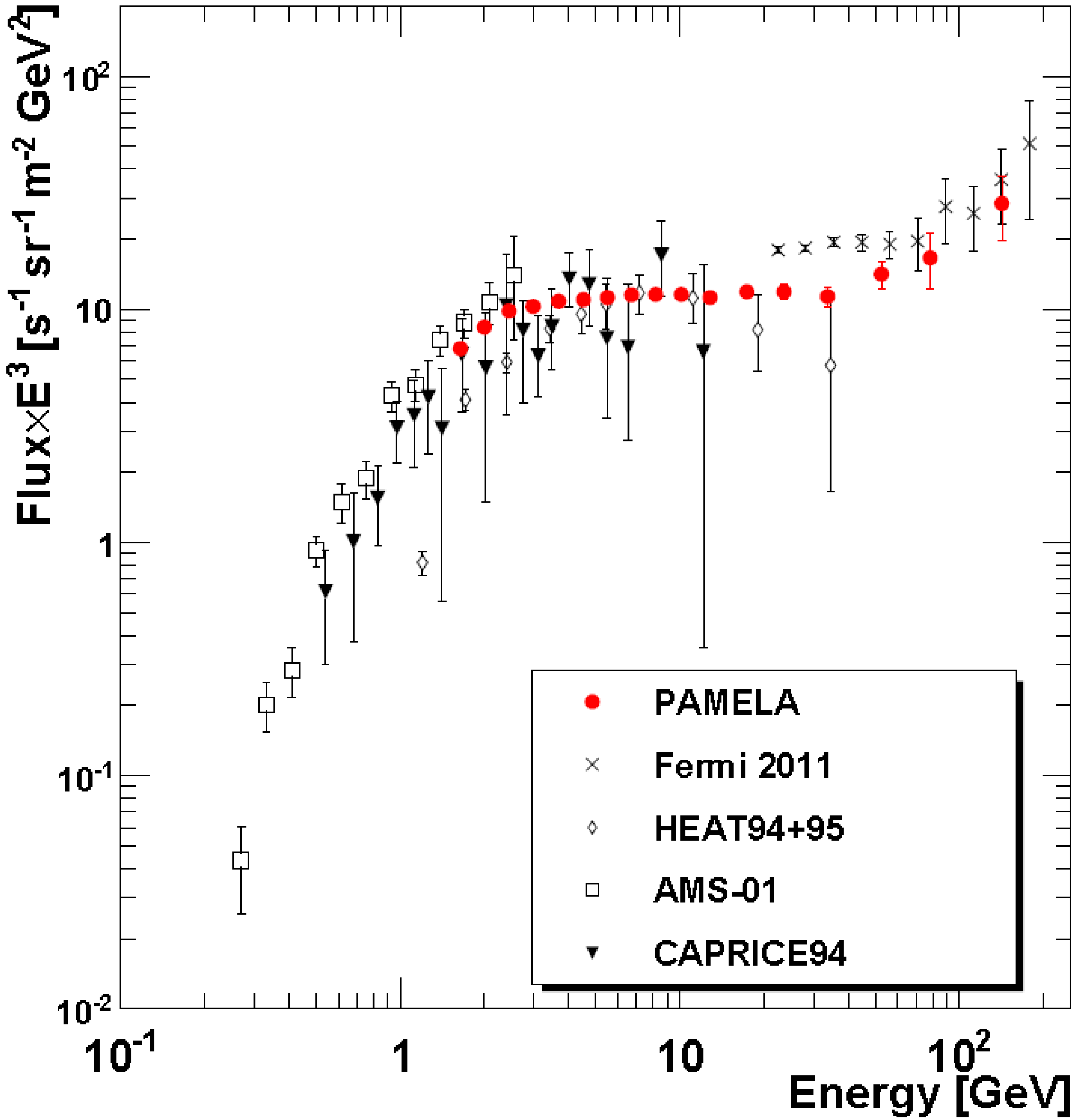
# Positron to Electron Fraction



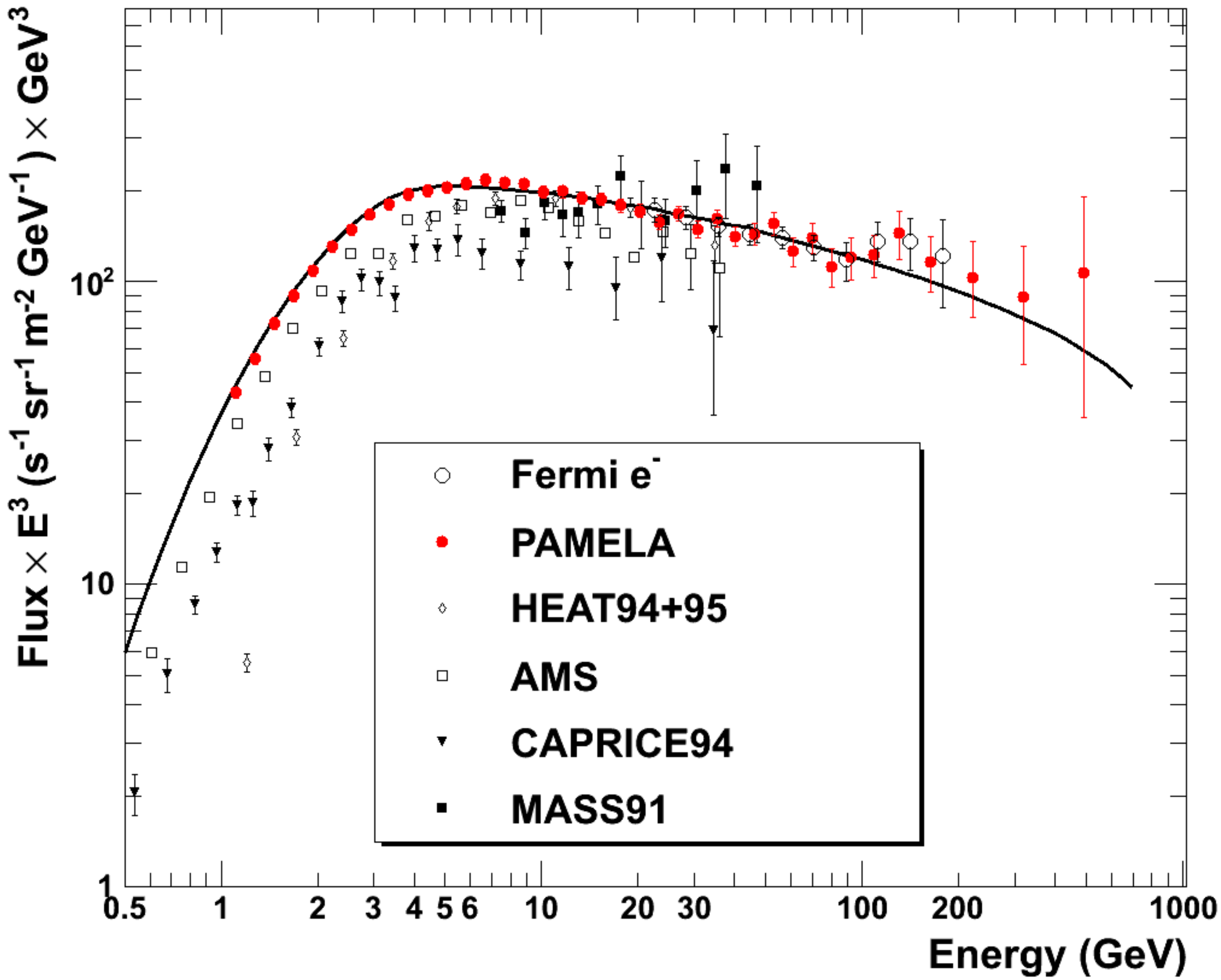


Models
Moskalenko, Strong (1998)
Uniform model (γ0=2.3, γ1=2.7)
AESOP 97+98
AESOP 99
AESOP 00
AESOP 02
AESOP 06
PAMELA (2010)
Fermi/LAT (2011)
e+/(e+ + e−)
10−1
10−2
10−1
1
10
102
E, GeV

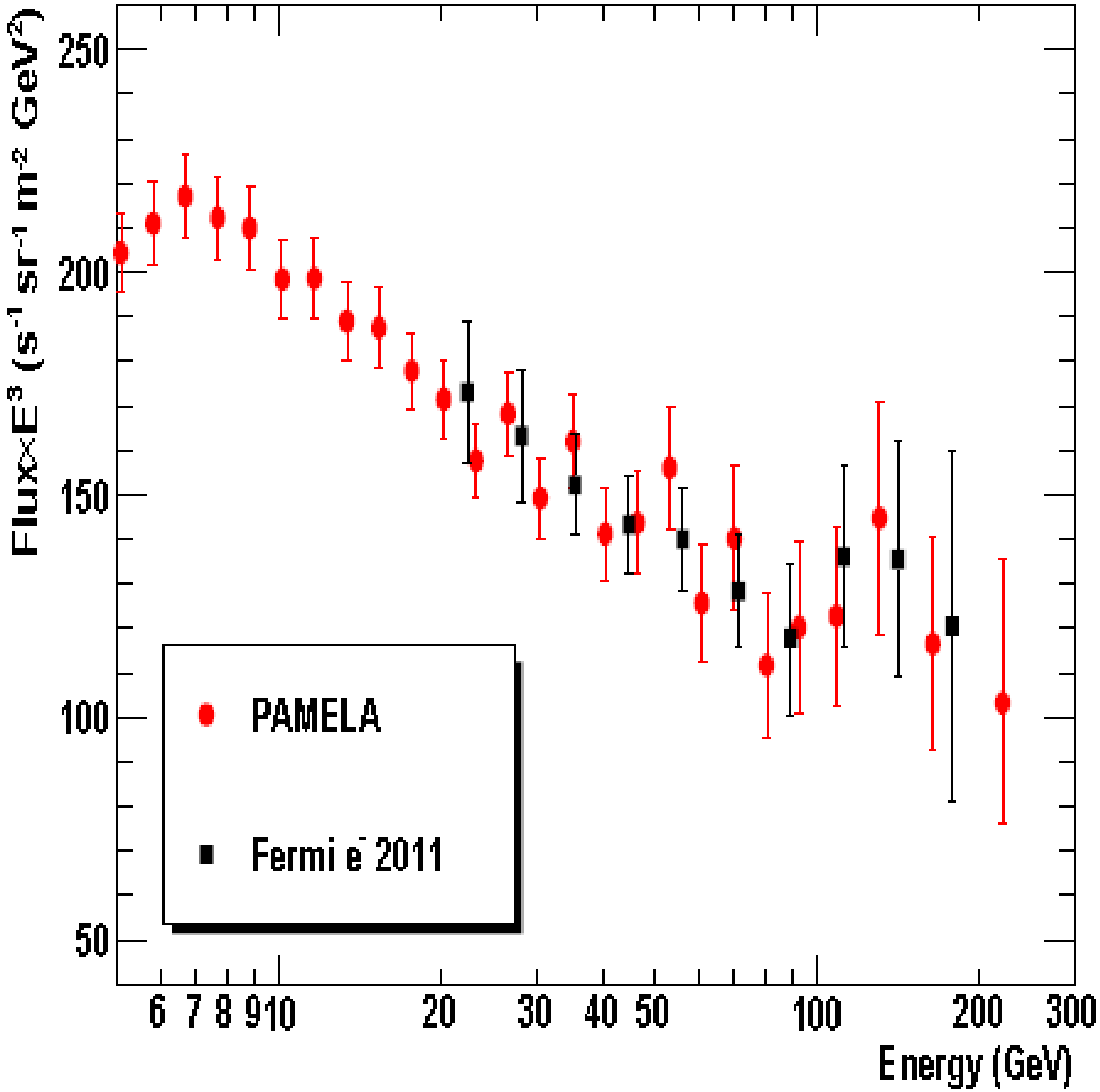
# Positron flux



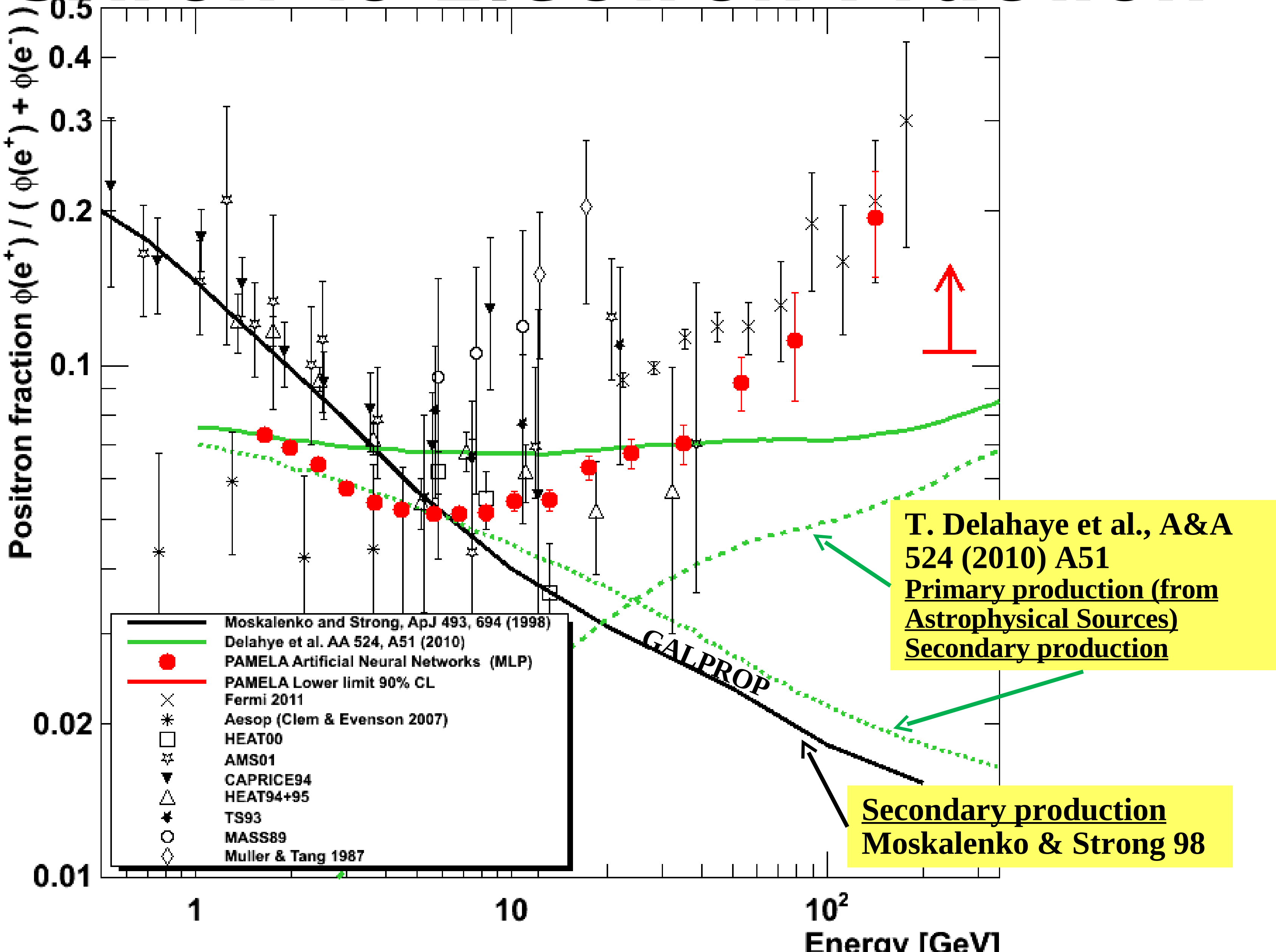
# Electron flux



# PAMELA and FERMI electrons



# Positron to Electron Fraction



**PRIMARY PROTONS:**

$$n_{CR}(E) = N_{CR}(E)\, R\, \tau_{esc}(E) \propto E^{-\gamma} E^{-\delta}$$

**PRIMARY ELECTRONS:**

$$n_e(E) = N_e(E)\, R\, \mathrm{Min}\left[\tau_{esc}(E), \tau_{loss}(E)\right] \propto E^{-\gamma_e} E^{-\beta}$$

**b= d for diffusion**
**b=1 for losses**

**SECONDARY POSITRONS INJECTION:**

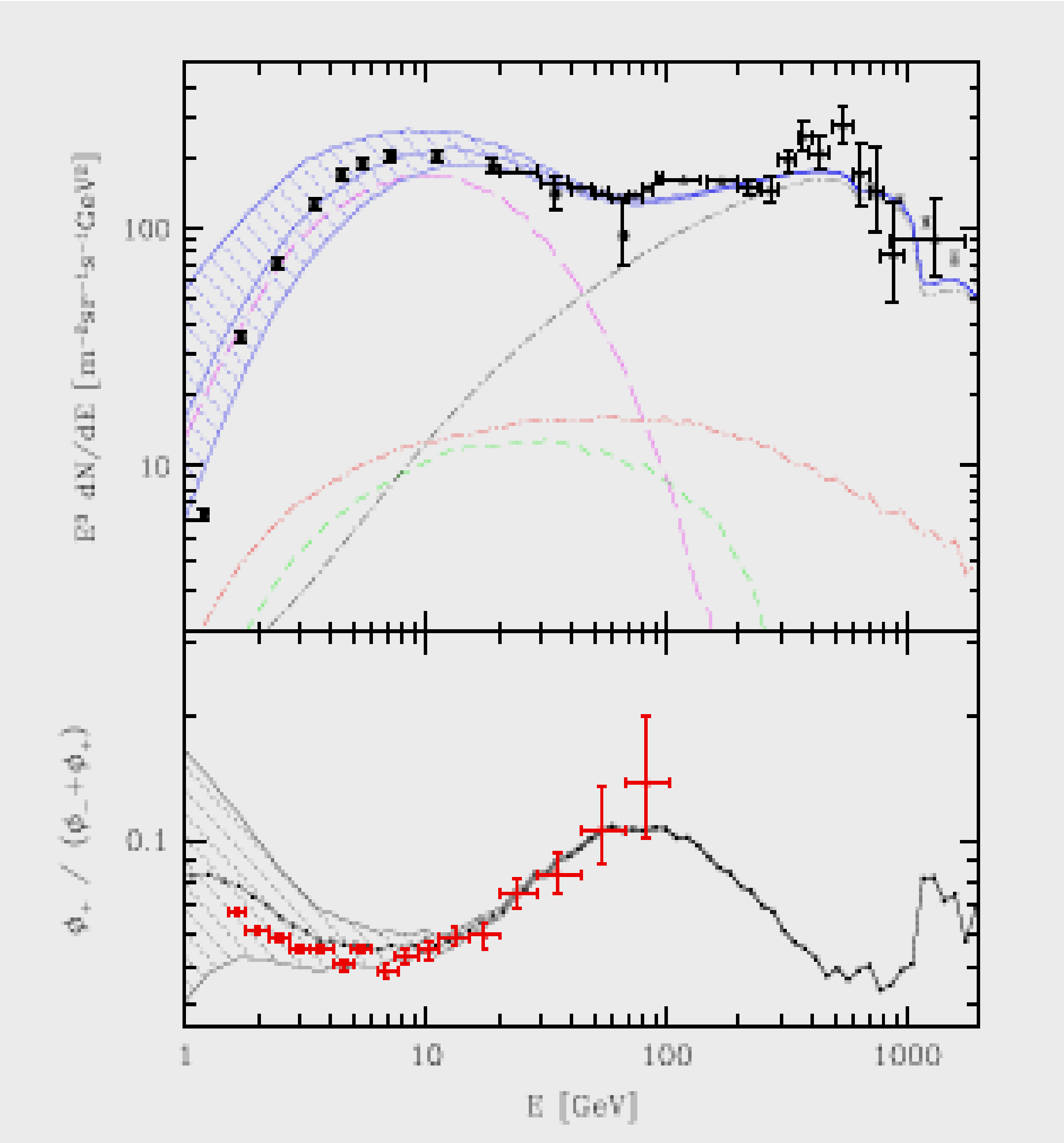
$$q_+(E')dE' = n_{CR}(E)dE\, n_H\, \sigma_{pp}\, c \propto E^{-\gamma-\delta}$$

**SECONDARY POSITRONS EQUILIBRIUM:**

$$n_+(E) = q_+(E)\, \mathrm{Min}\left[\tau_{esc}(E), \tau_{loss}(E)\right] \propto E^{-\gamma-\delta-\beta}$$

$$\frac{n_+}{n_e} \propto E^{-(\gamma-\gamma_e)-\delta}$$

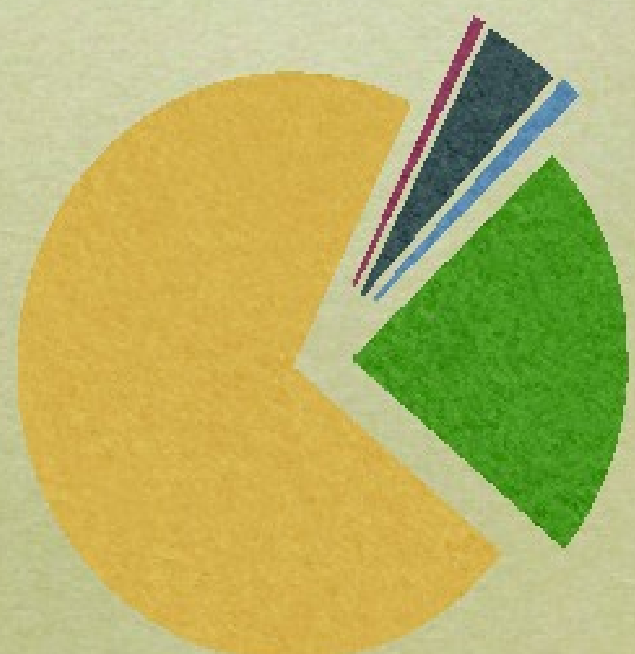
# SNR Density in the Galaxy




N.J. Shaviv et al.,
PRL 103 (2009) 111302;

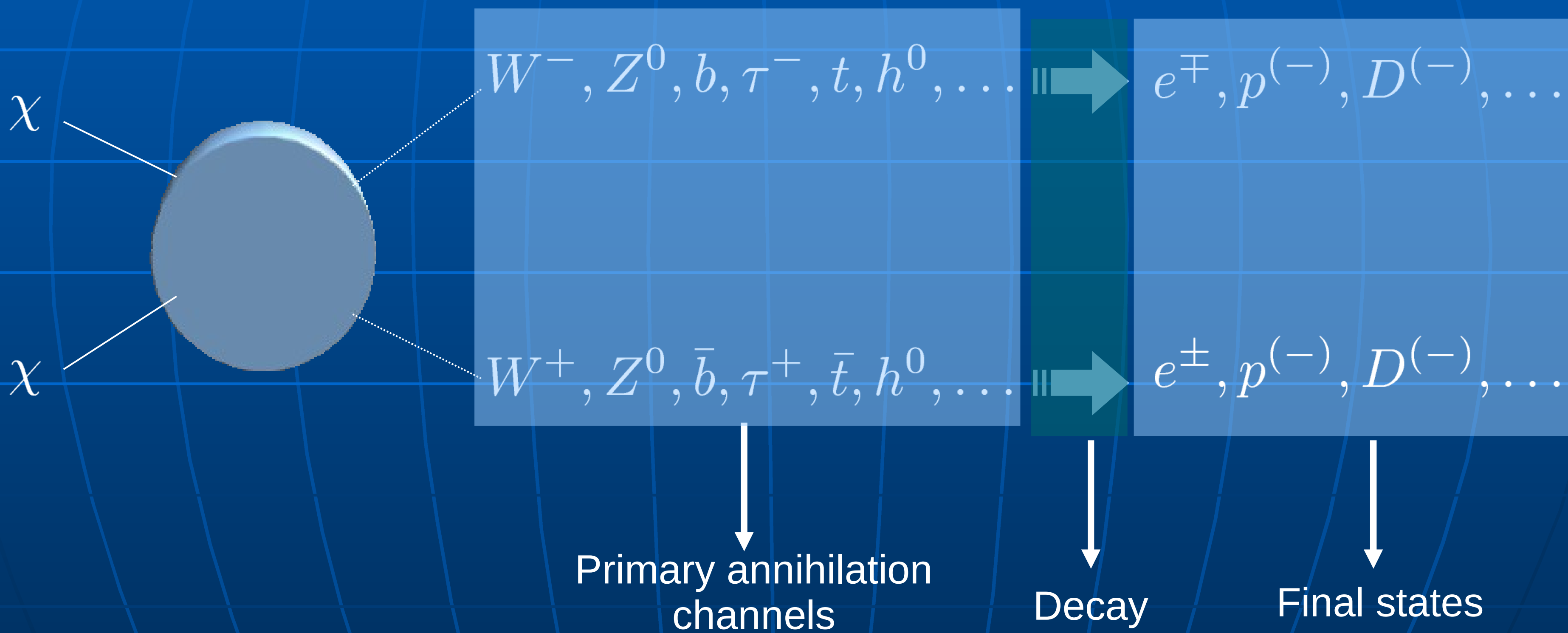
# THE UNIVERSE ENERGY BUDGET

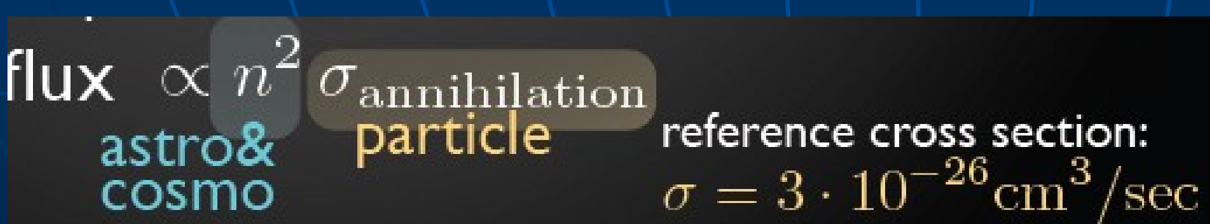
- *Stars and galaxies are only ~0.5%*
- *Neutrinos are ~0.1–1.5%*
- *Rest of ordinary matter (electrons, protons & neutrons) are 4.4%*
- *Dark Matter 23%*
- *Dark Energy 73%*
- *Anti-Matter 0%*
- *Higgs Bose-Einstein condensate* $\sim 10^{62}\%$??



# DM annihilations

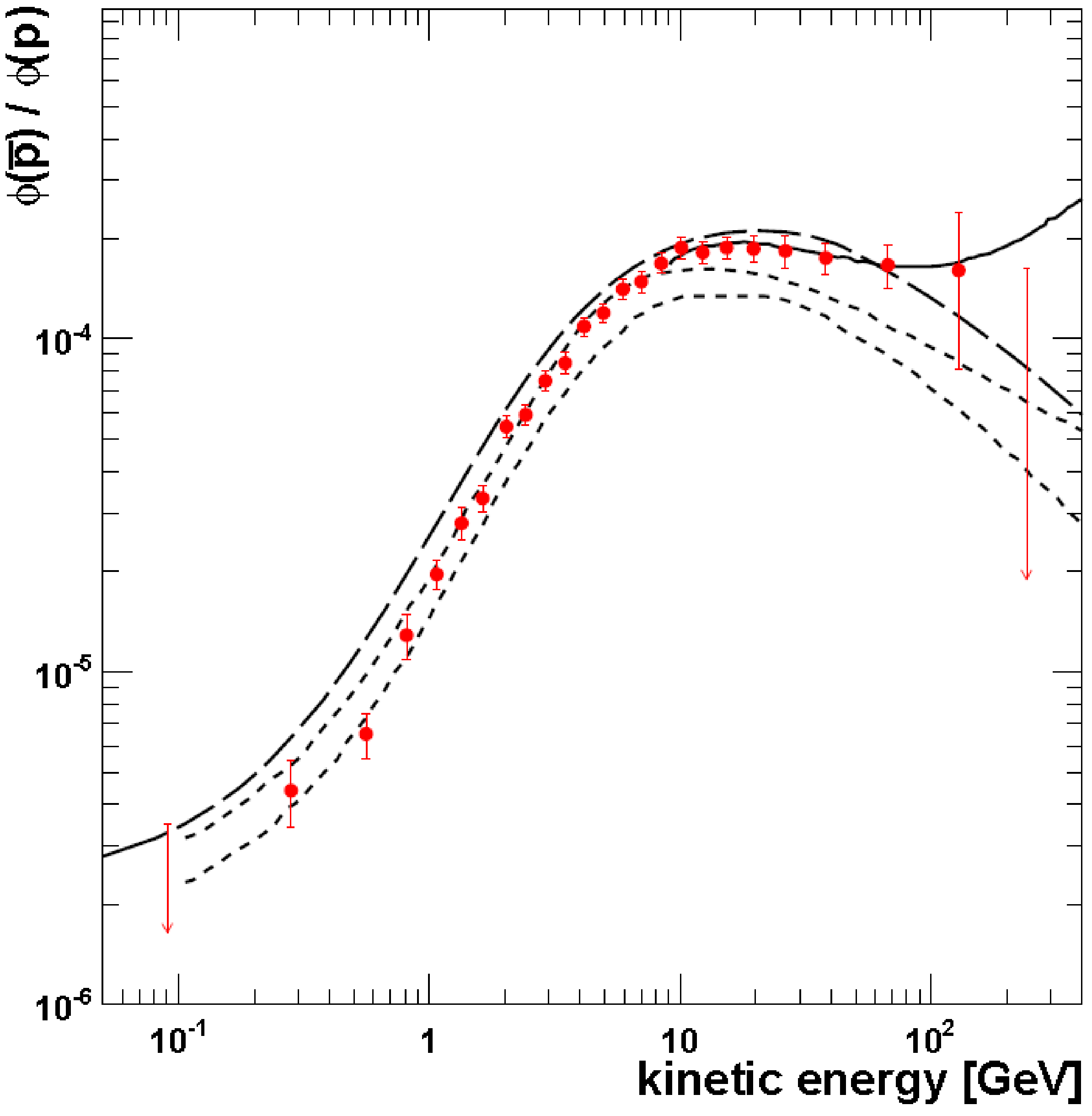
DM particles are stable. They can annihilate in pairs.




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

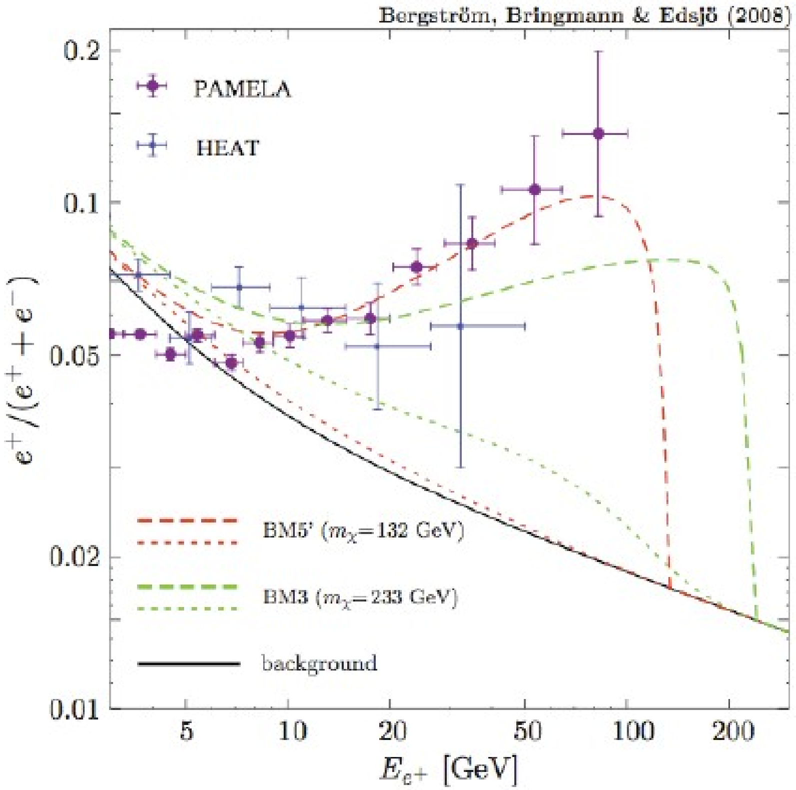
# PAMELA antiproton to proton ratio



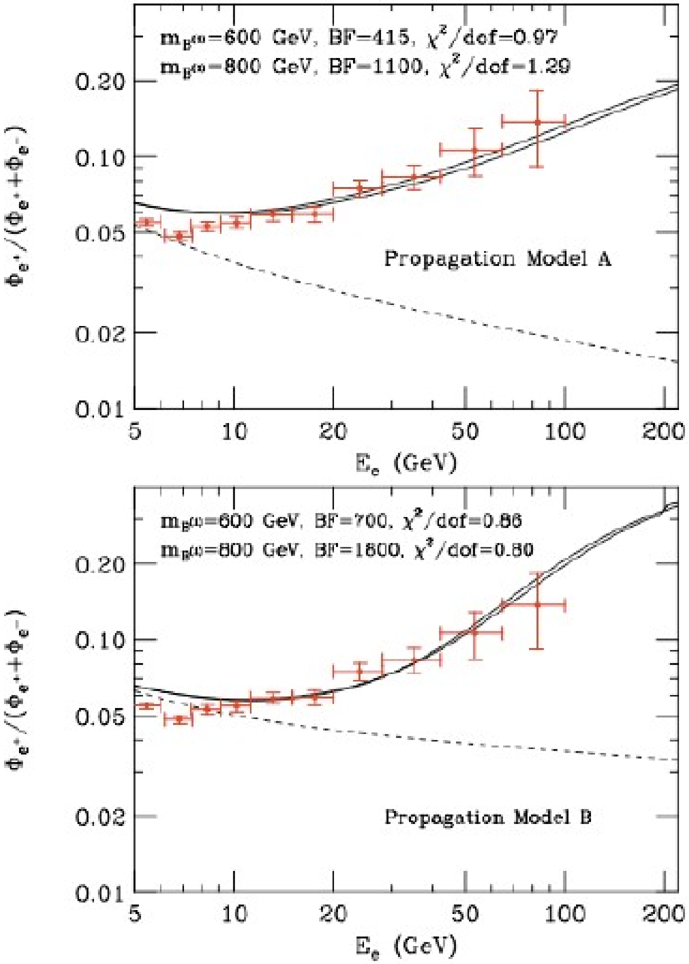
# Example: Dark Matter

Phys.Rev.D79:103529,2009

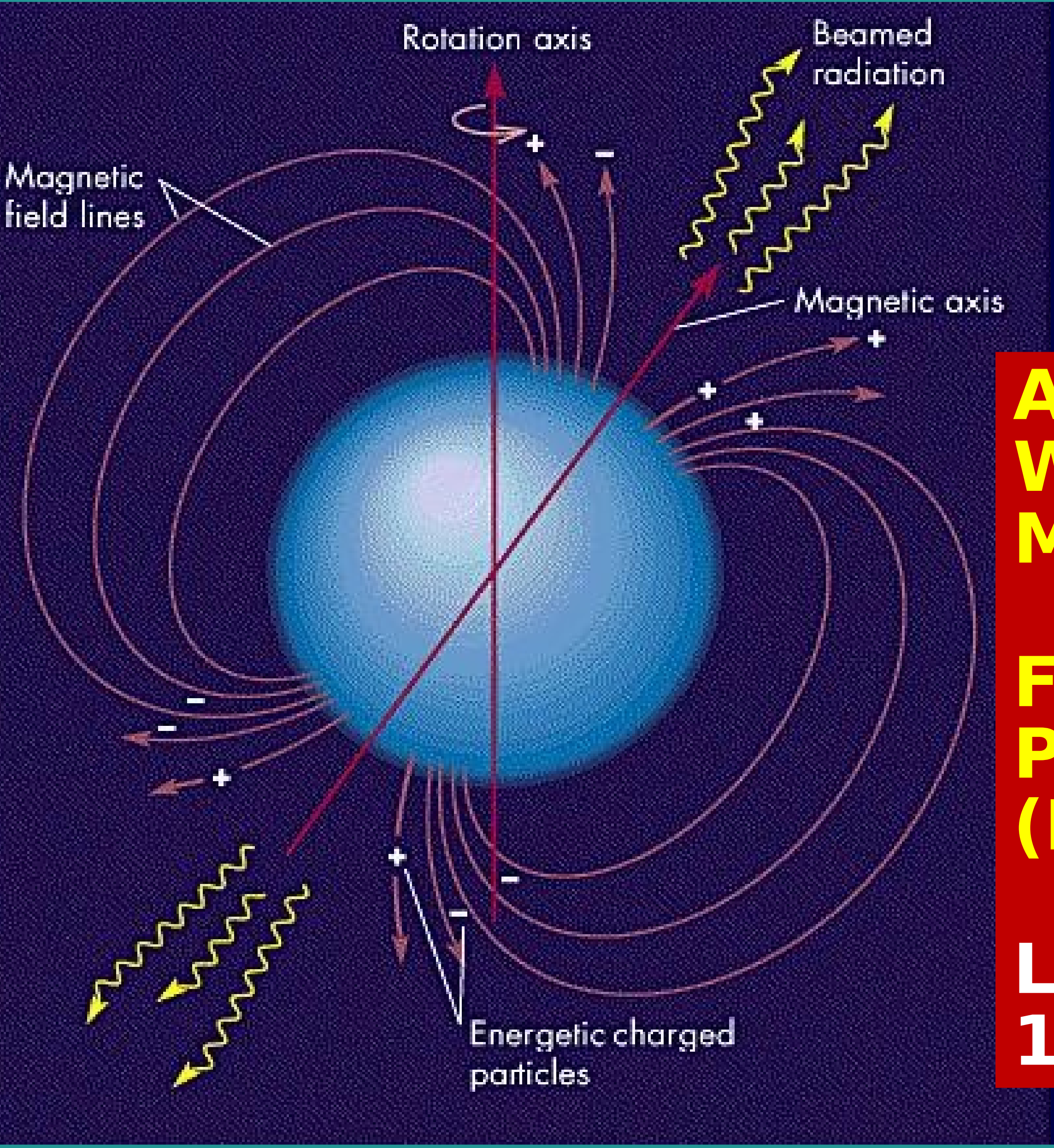
Phys.Rev.D8:103520,2008




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




Kaluza-Klein dark matter

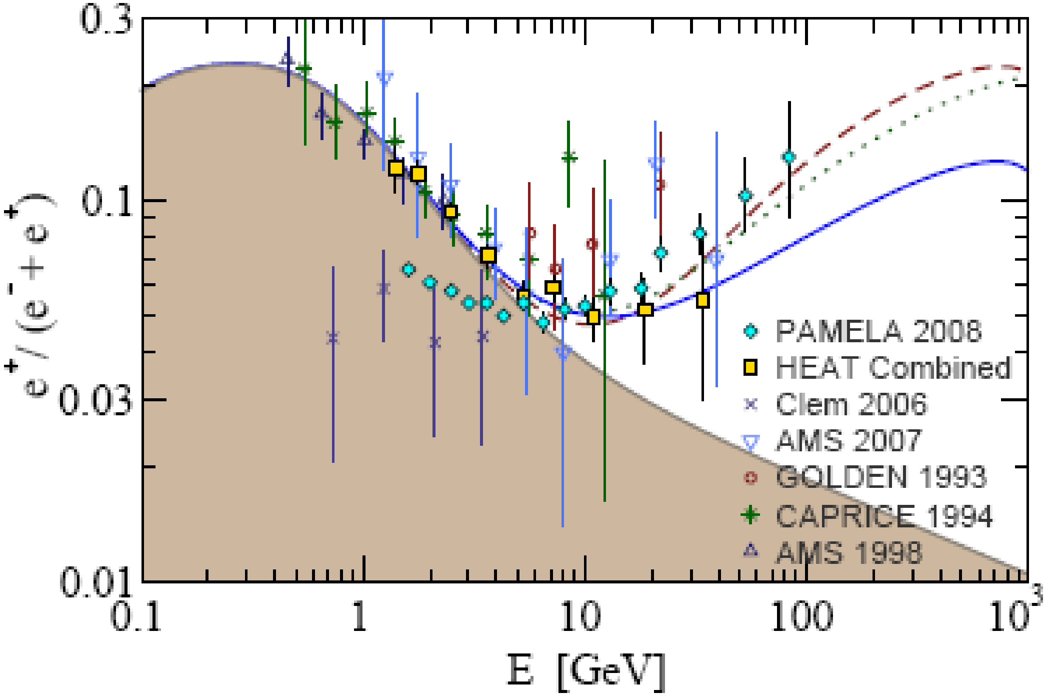



**A NEUTRON STAR WITH A STRONG MAGNETIC FIELD:**

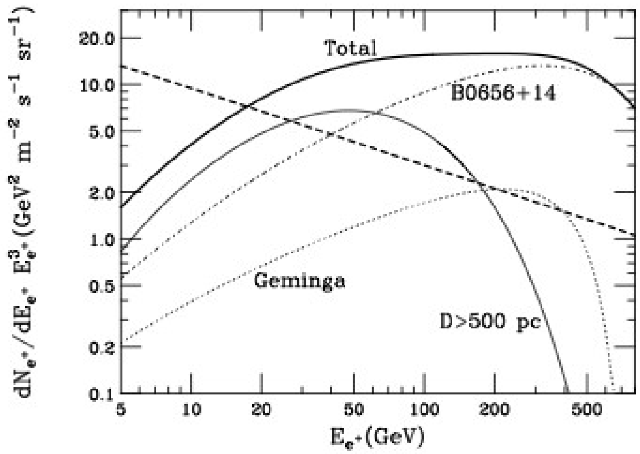
**FAST ROTATING PULSAR (P = 33 msec)**

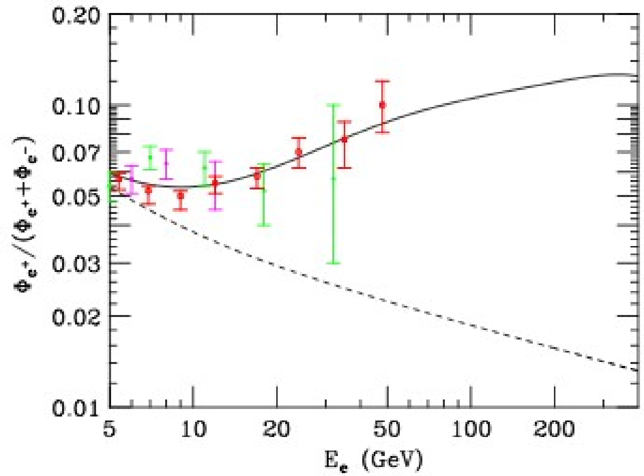
**L(spindown) = 5 $10^{38}$ erg/s**

# Example: pulsars




H. Yüksak et al., arXiv:0810.2784v2
Contributions of e- & e+ from Geminga assuming different distance, age and energetic of the pulsar

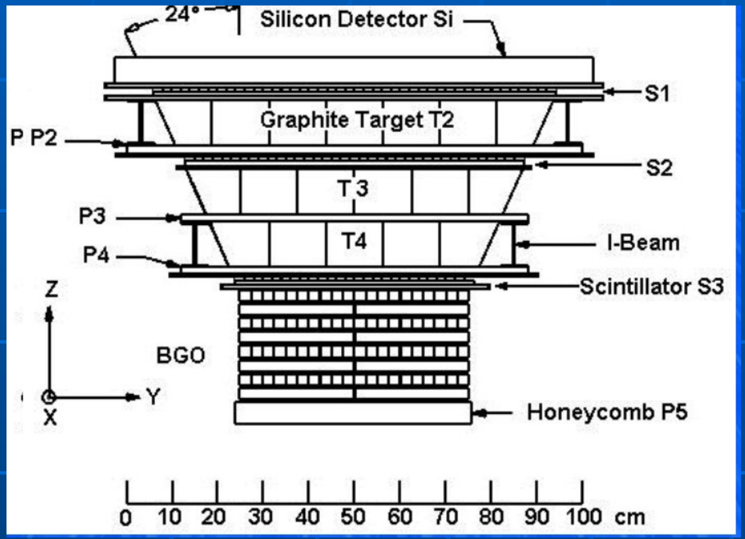


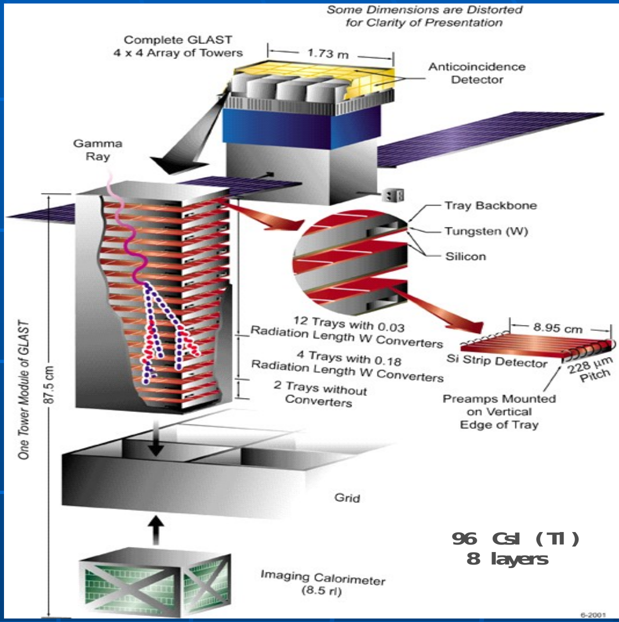

Hooper, Blasi, and Serpico
arXiv:0810.1527

# All electron spectrum

ATIC

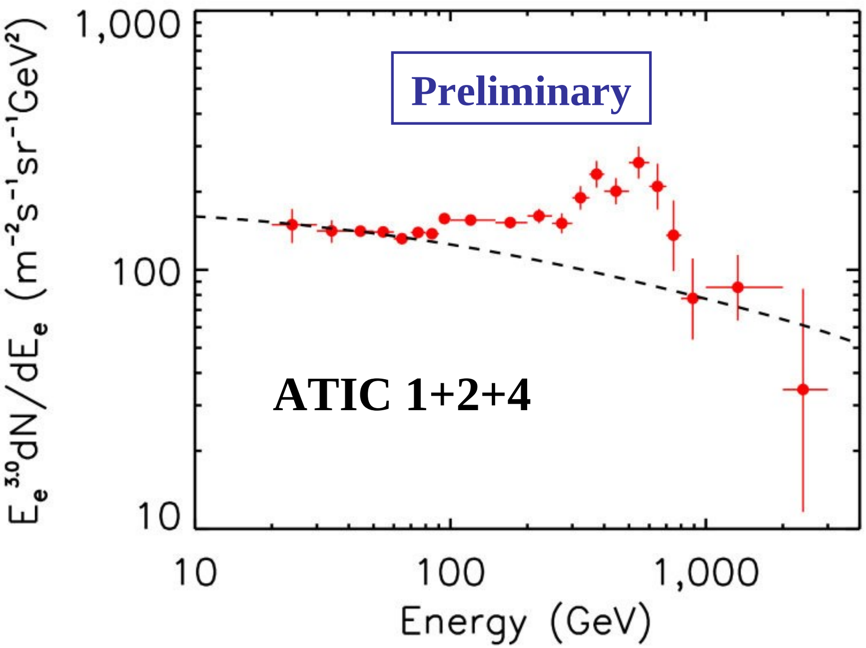


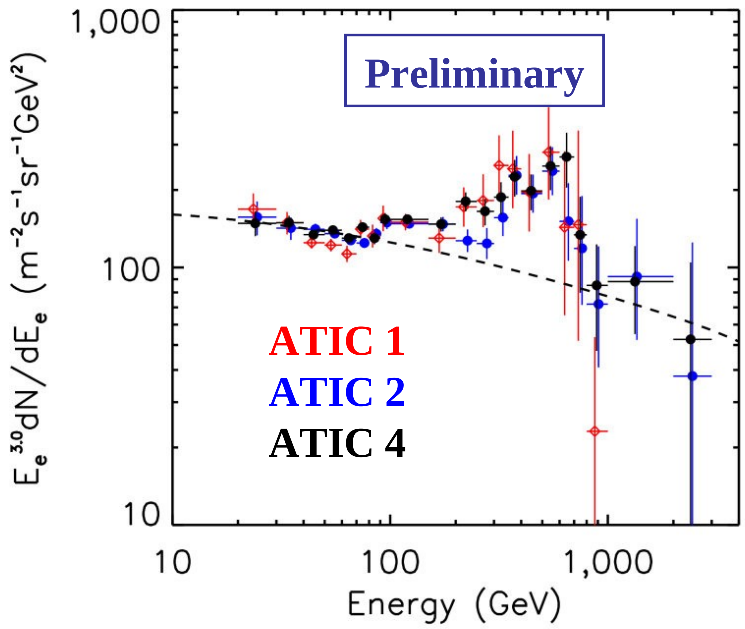

Fermi/LAT




HESS

# All three ATIC flights are consistent




"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)**

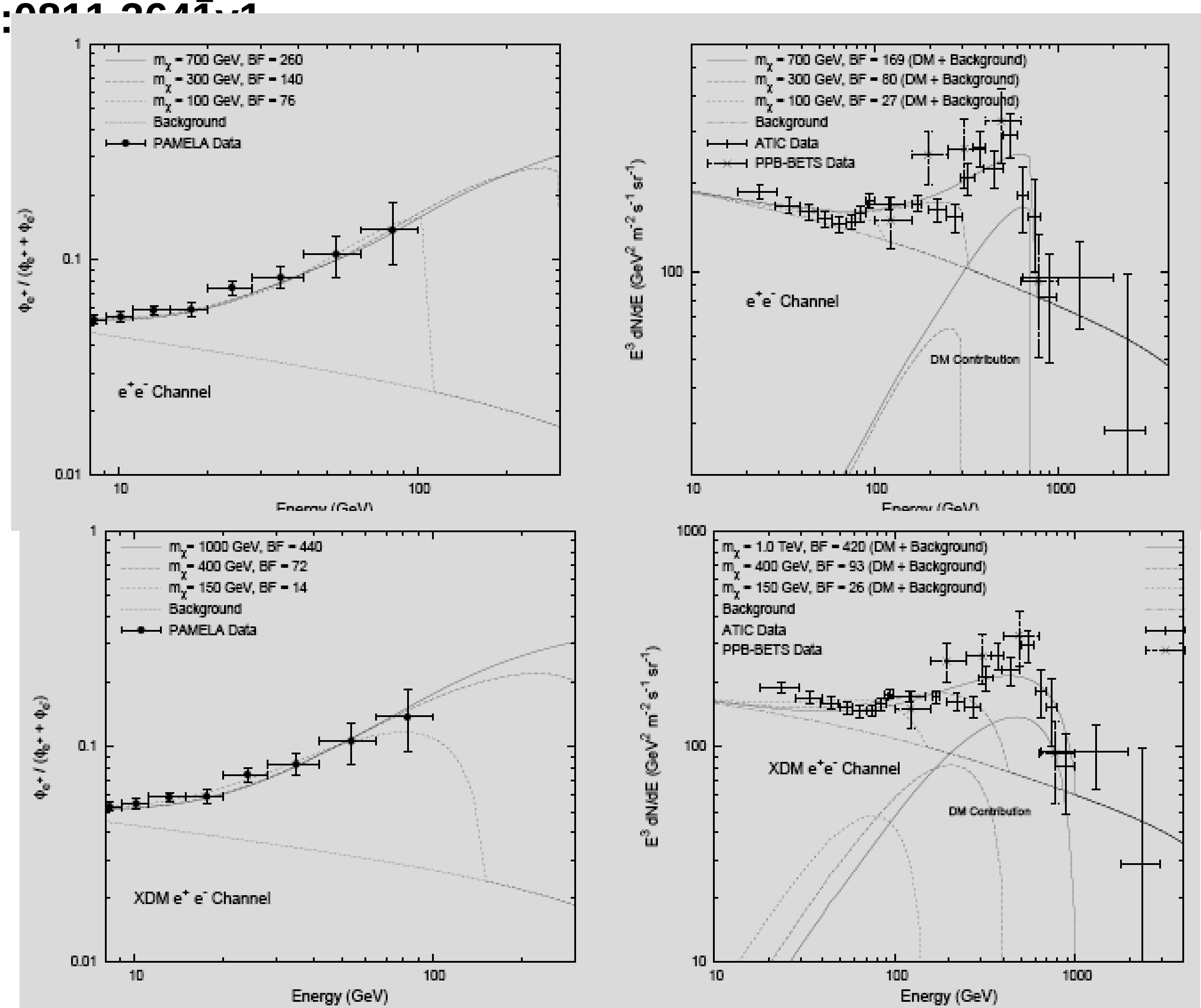
"Bump" is seen in all three flights.

Significance for ATIC1+2+4 is 5.1 sigma

# Example: DM

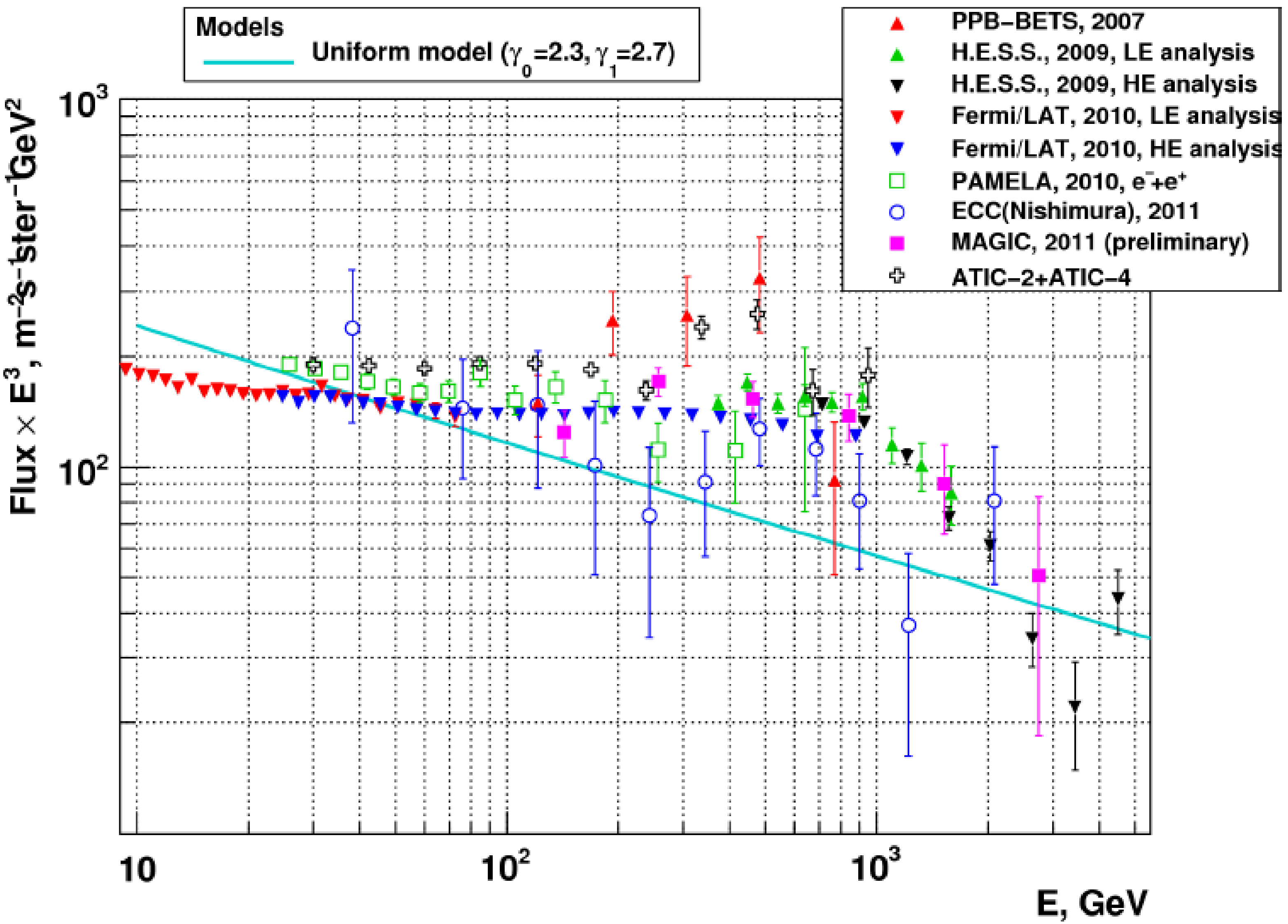
I. Cholis et al.

arXiv:0811.3641v1

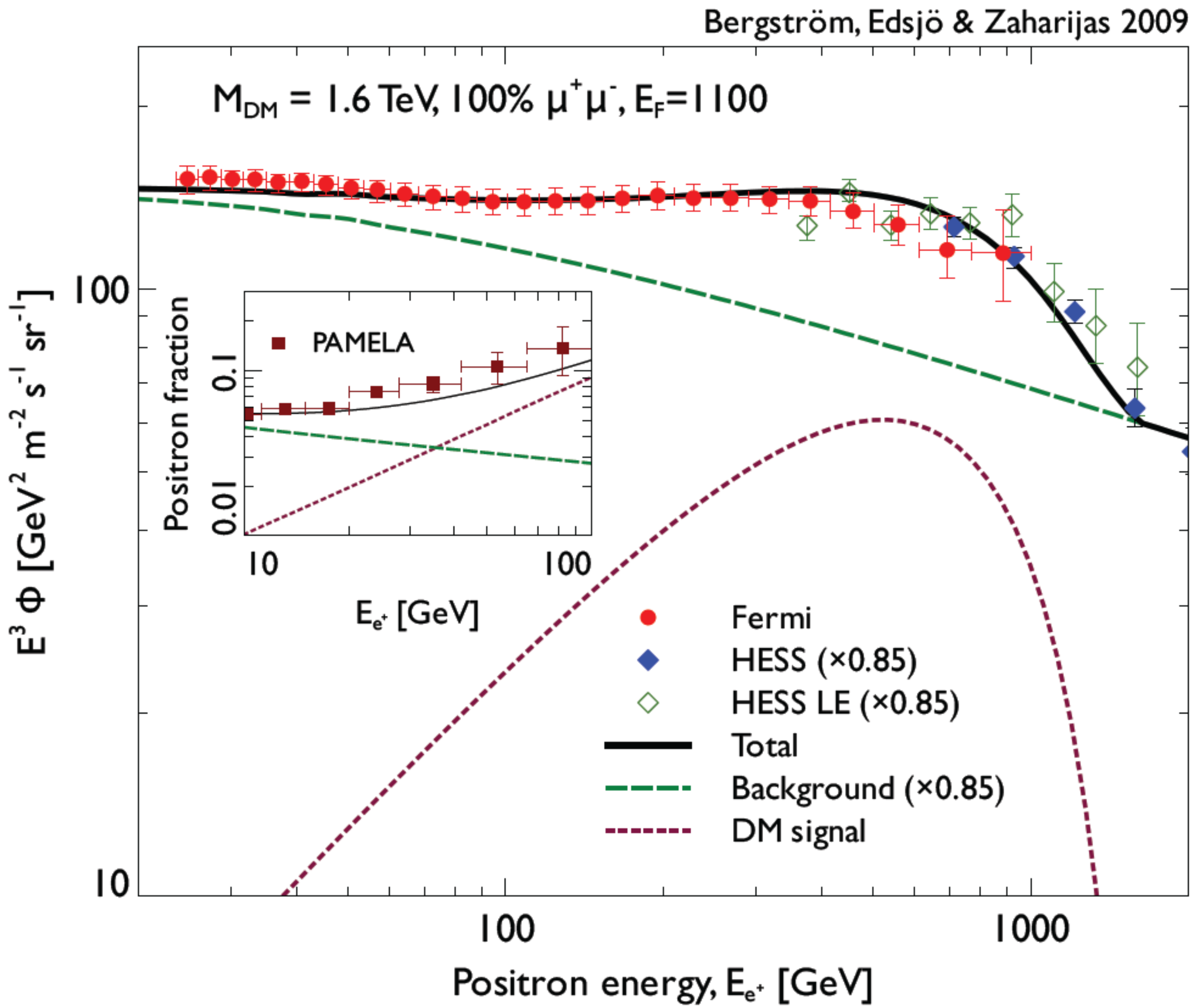



- Propose a new light boson ($m_\Phi \leq$ GeV), such that $\chi\chi \rightarrow \Phi\Phi$; $\Phi \rightarrow e^+e^-$, $\mu^+\mu^-$, ...
- Light boson, so decays to antiprotons are kinematically suppressed

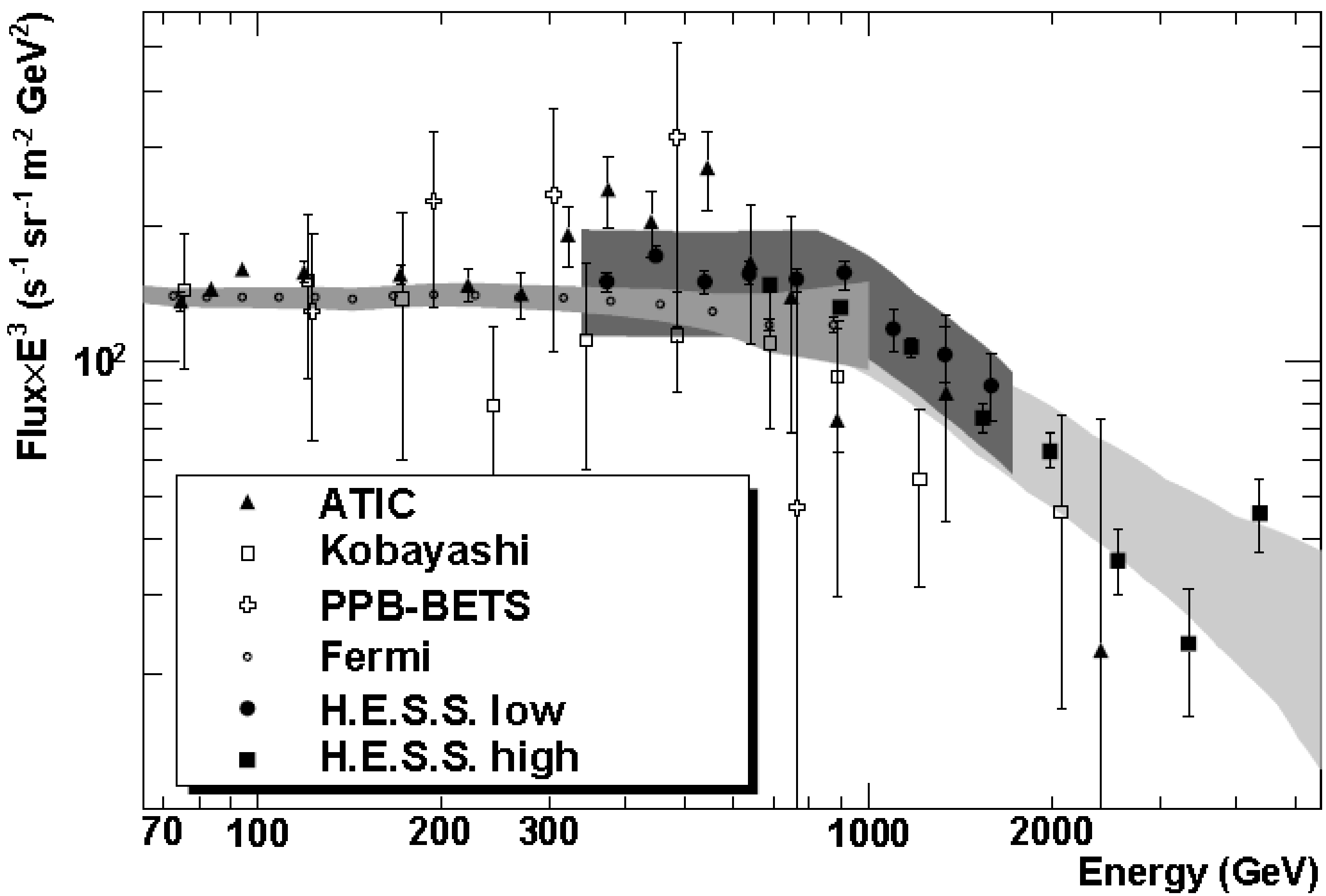
# All Electron Spectrum



# Fermi ($e^+$+ $e^-$) *and* PAMELA ratio
# Bergstrom et al. Phys.Rev.Lett.103:031103,2009

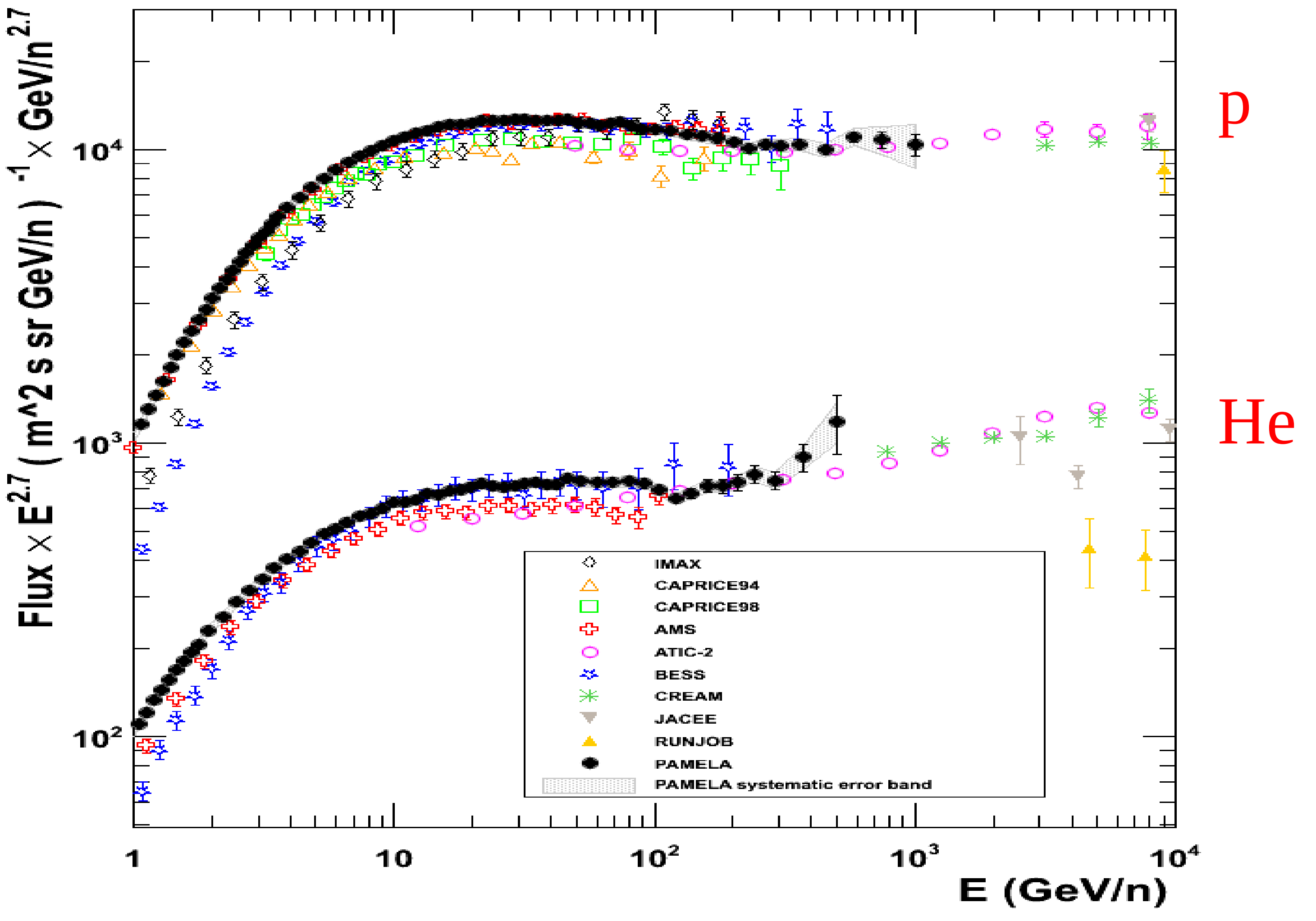


# All electron spectrum



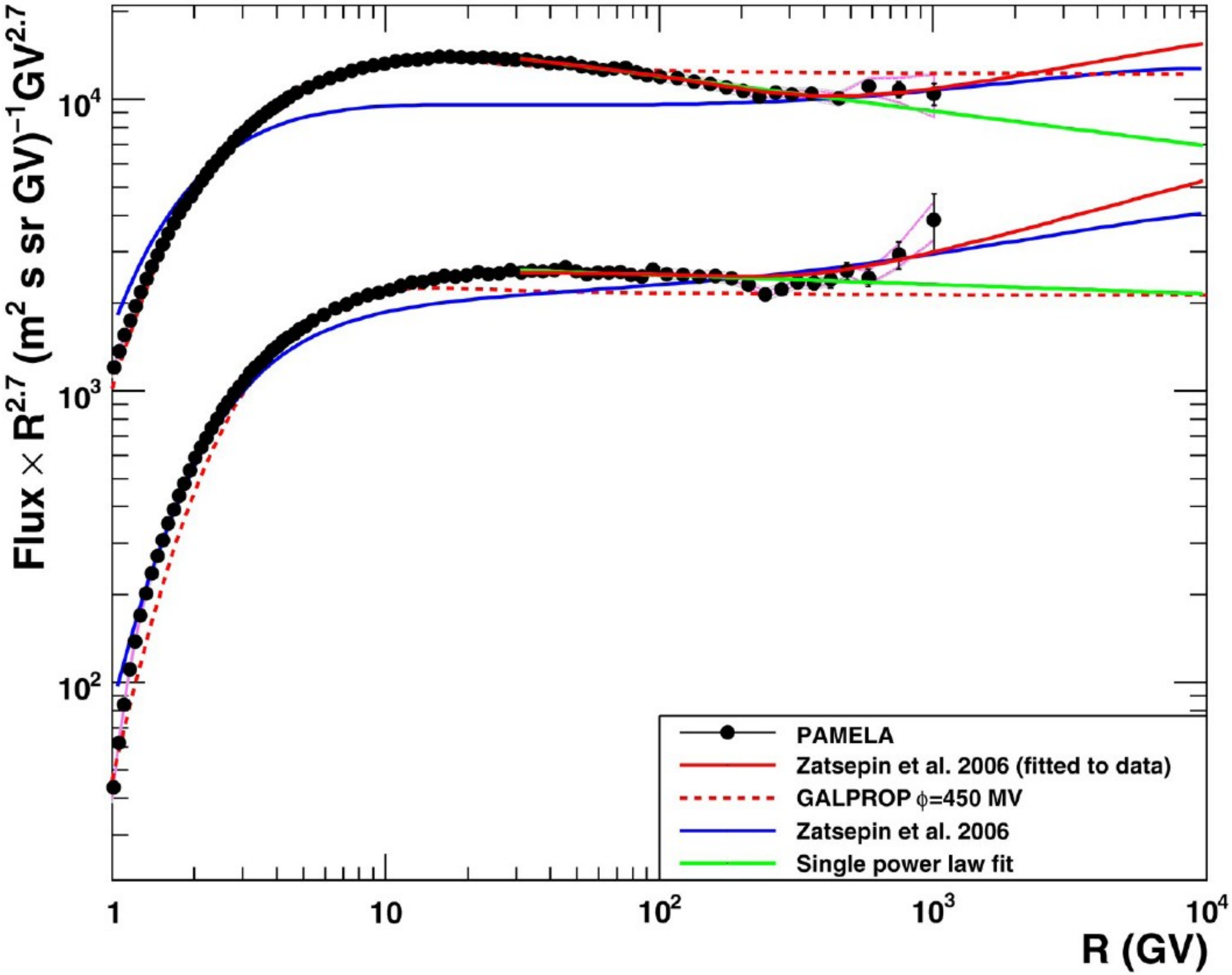
# Cosmic Ray Spectra

# Proton and Helium fluxes

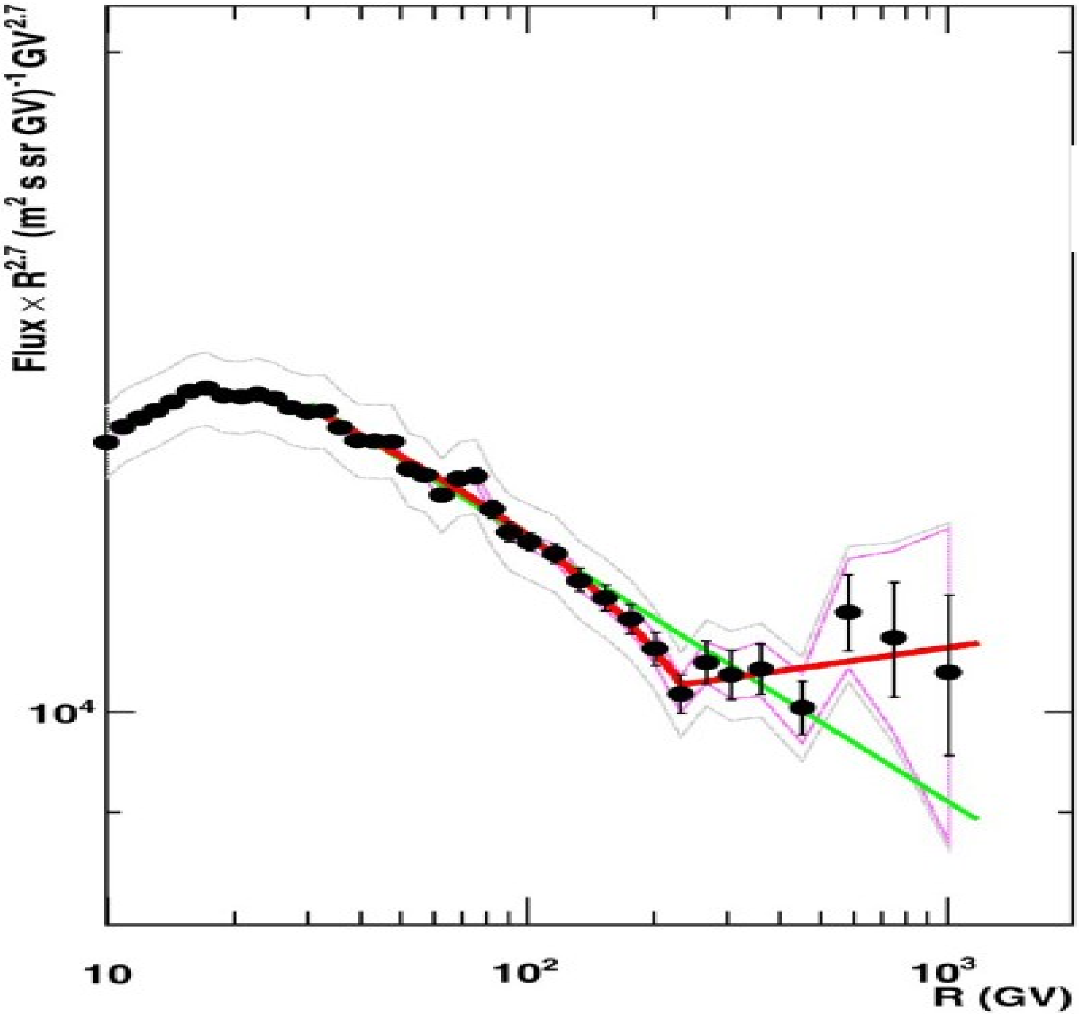



Science 332,69 (2011)

# Proton and Helium fluxes



# Proton Flux

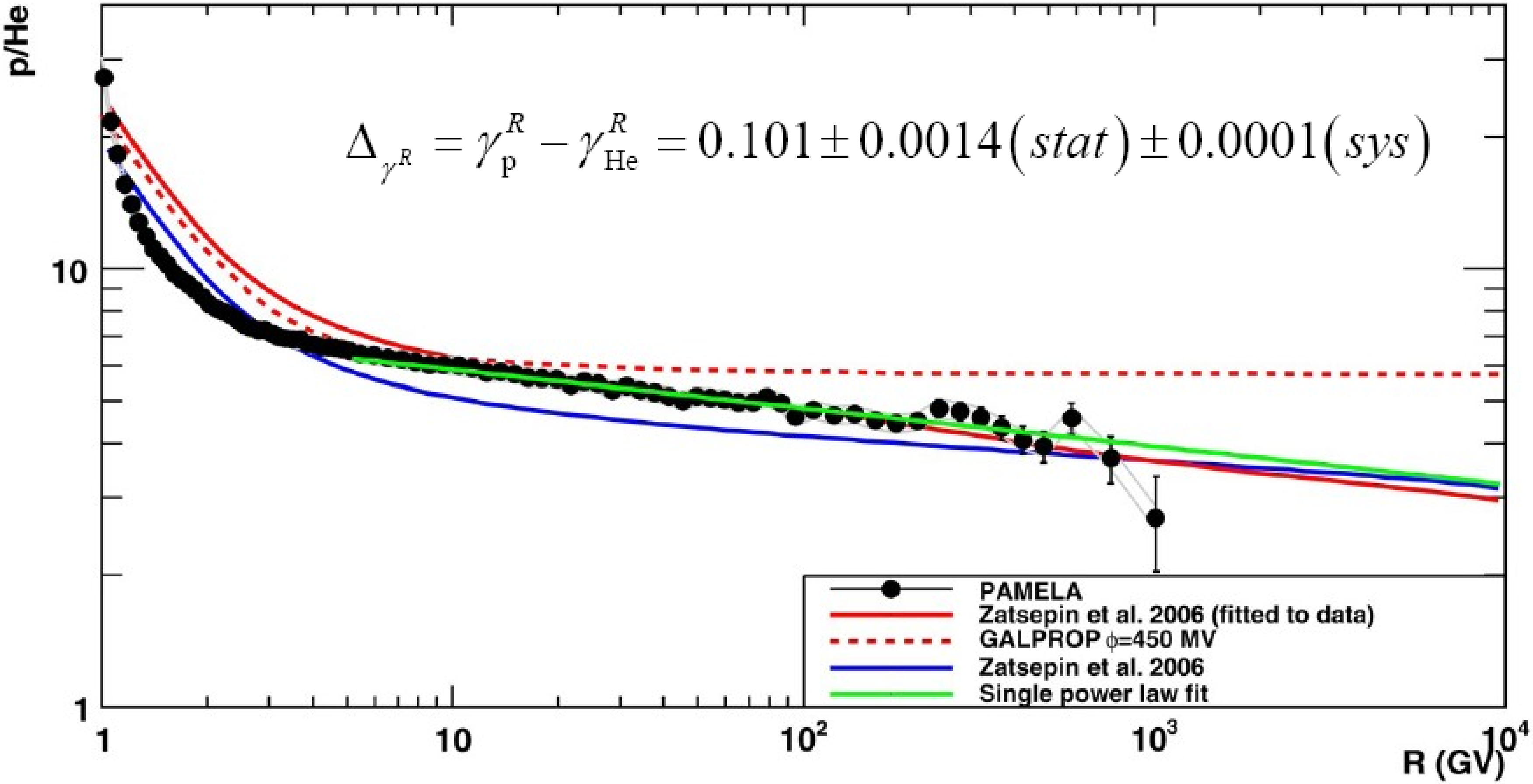



$$\gamma^{R}_{30-80\mathrm{GV,p}} = 2.801 \pm 0.007(stat) \pm 0.002(syst)$$

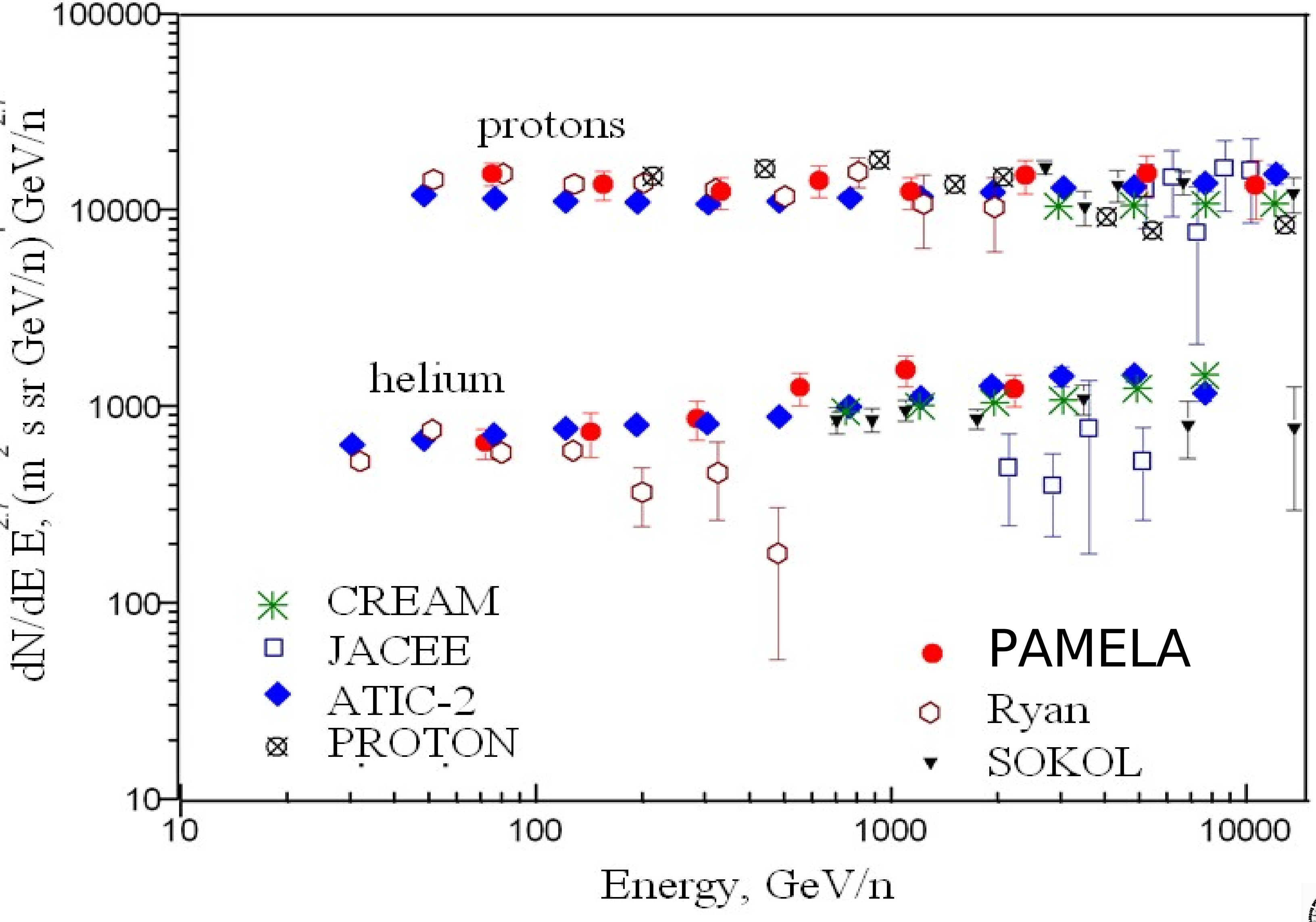
$$\gamma^{R}_{80-230\mathrm{GV,p}} = 2.850 \pm 0.015(stat) \pm 0.004(syst)$$

$$\gamma^{R}_{>232\mathrm{GV,p}} = 2.67 \pm 0.03 \pm 0.05$$

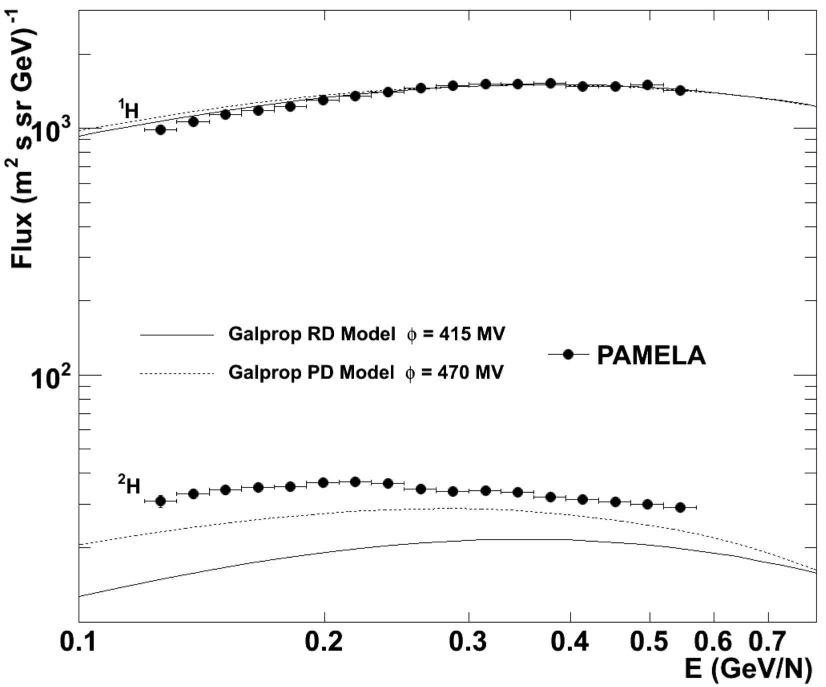
# Proton to Helium ratio

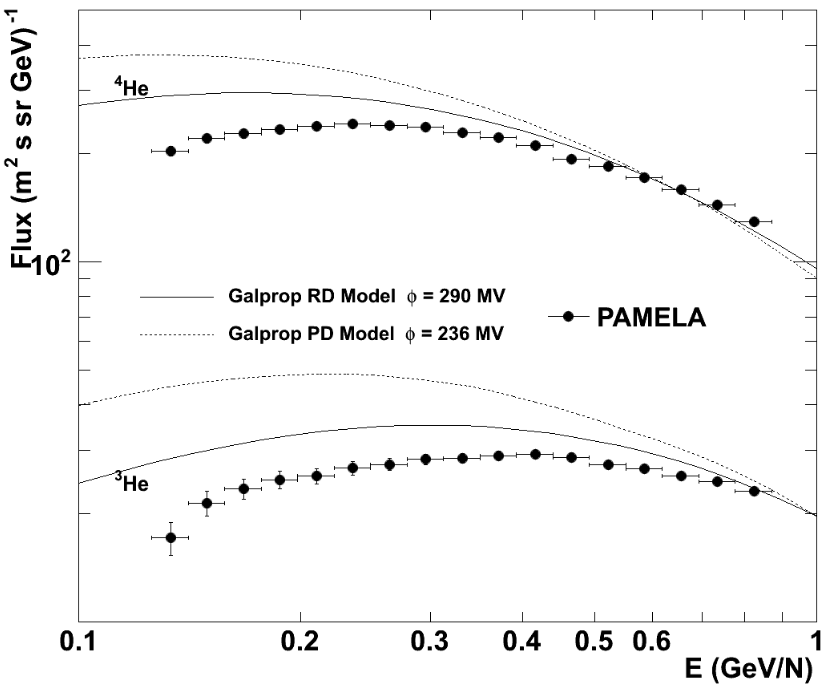


# Proton and Helium fluxes

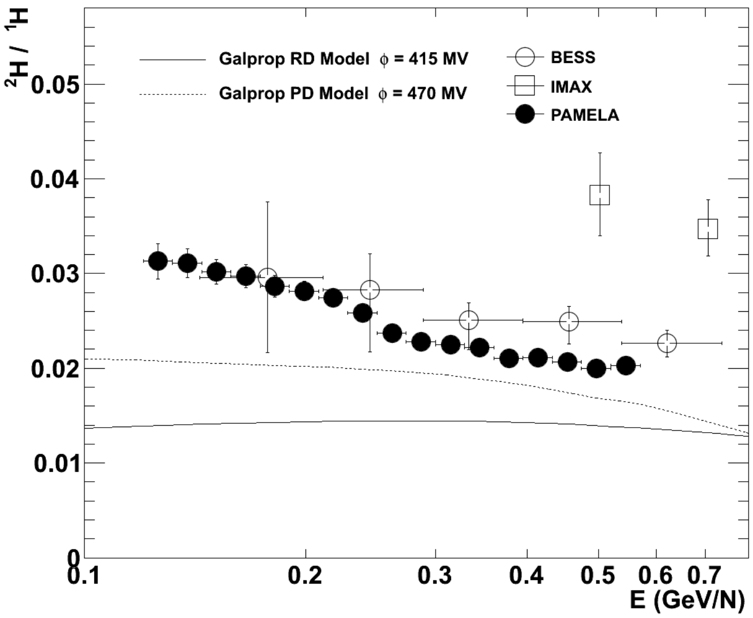


# He3

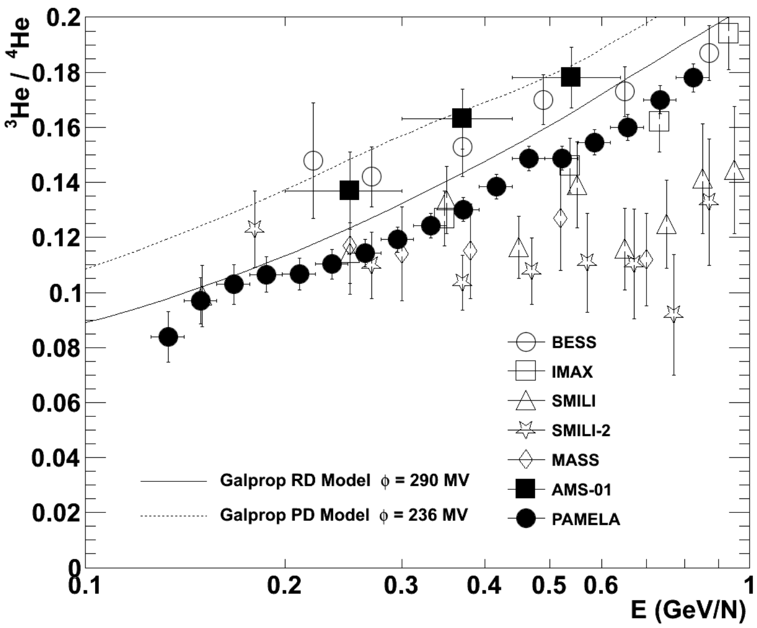

Flux (m2 s sr GeV)-1
10^3
10^2
1H
2H
Galprop RD Model φ = 415 MV
Galprop PD Model φ = 470 MV
PAMELA
0.1
0.2
0.3
0.4
0.5
0.6
0.7
E (GeV/N)


Flux (m2 s sr GeV)-1
10^2
4He
3He
Galprop RD Model φ = 290 MV
Galprop PD Model φ = 236 MV
PAMELA
0.1
0.2
0.3
0.4
0.5
0.6
1
E (GeV/N)

# Deuterium

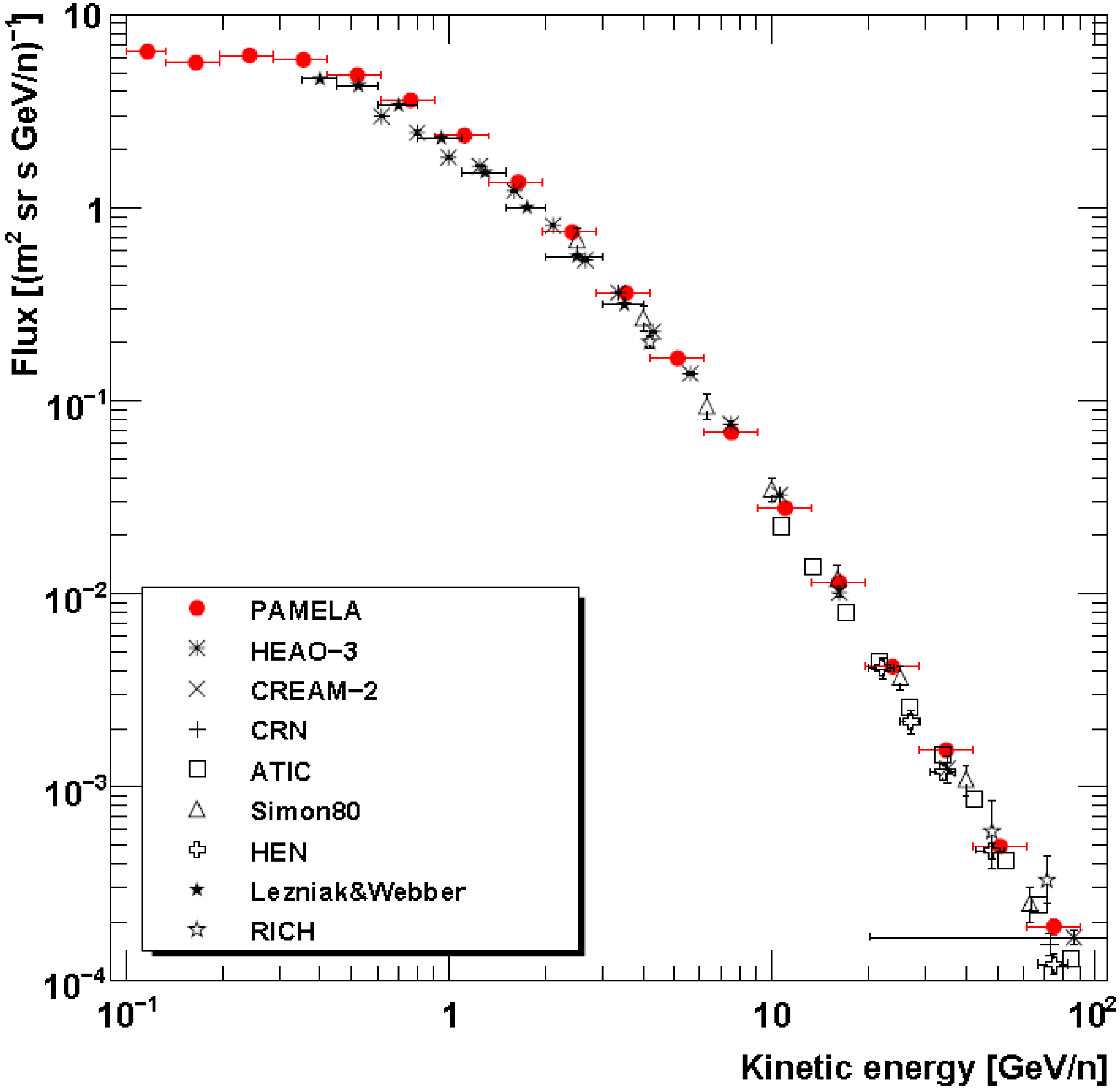


$^2H$ / $^1H$
Galprop RD Model φ = 415 MV
Galprop PD Model φ = 470 MV
BESS
IMAX
PAMELA
0
0.01
0.02
0.03
0.04
0.05
0.1
0.2
0.3
0.4
0.5
0.6
0.7
E (GeV/N)

$^3He$ / $^4He$
BESS
IMAX
SMILI
SMILI-2
MASS
AMS-01
PAMELA
Galprop RD Model φ = 290 MV
Galprop PD Model φ = 236 MV
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.1
0.2
0.3
0.4
0.5
0.6
1
E (GeV/N)

# Carbon Flux



Flux [(m^2 sr s GeV/n)^-1]
10
1
10^-1
10^-2
10^-3
10^-4
10^-1
1
10
10^2
Kinetic energy [GeV/n]
PAMELA
HEAO-3
CREAM-2
CRN
ATIC
Simon80
HEN
Lezniak&Webber
RICH

# Solar Modulation of galactic cosmic rays

- **Study of solar modulation**

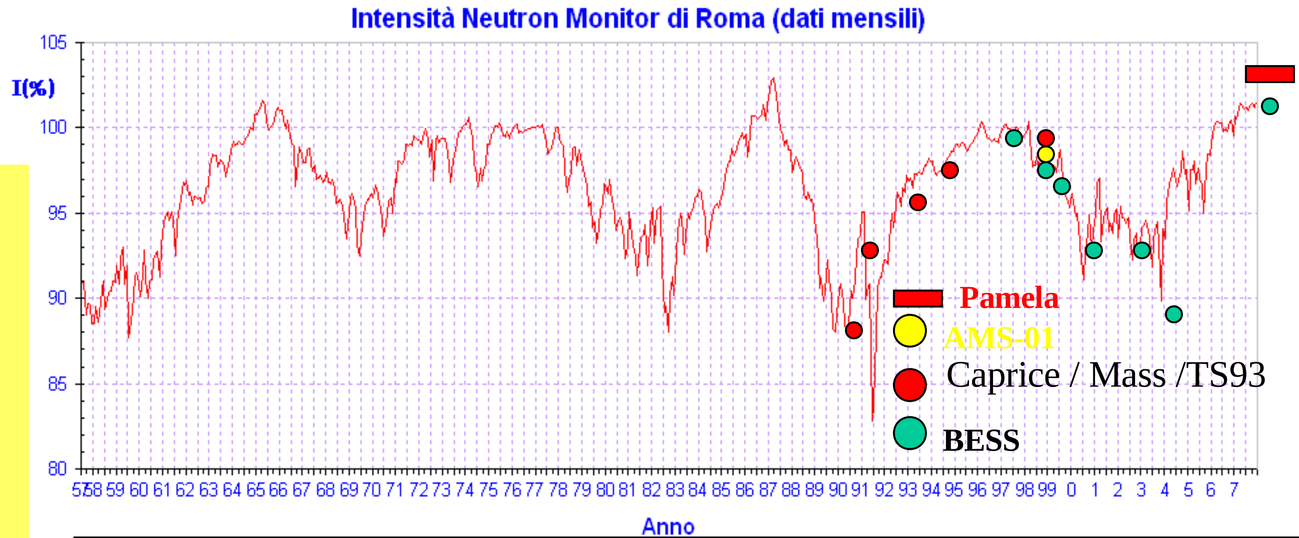
- **Study of charge sign dependent effects**

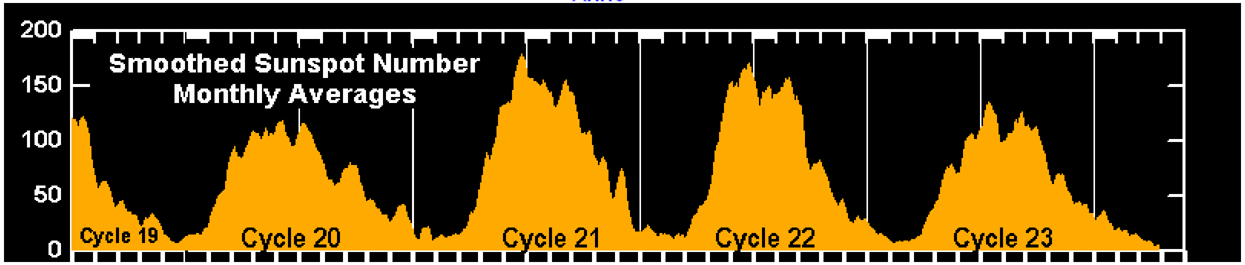

*Asaoka Y. et al. 2002, Phys. Rev. Lett. 88, 051101),*

*Bieber, J.W., et al. Physi-cal Review Letters, 84, 674, 1999.*

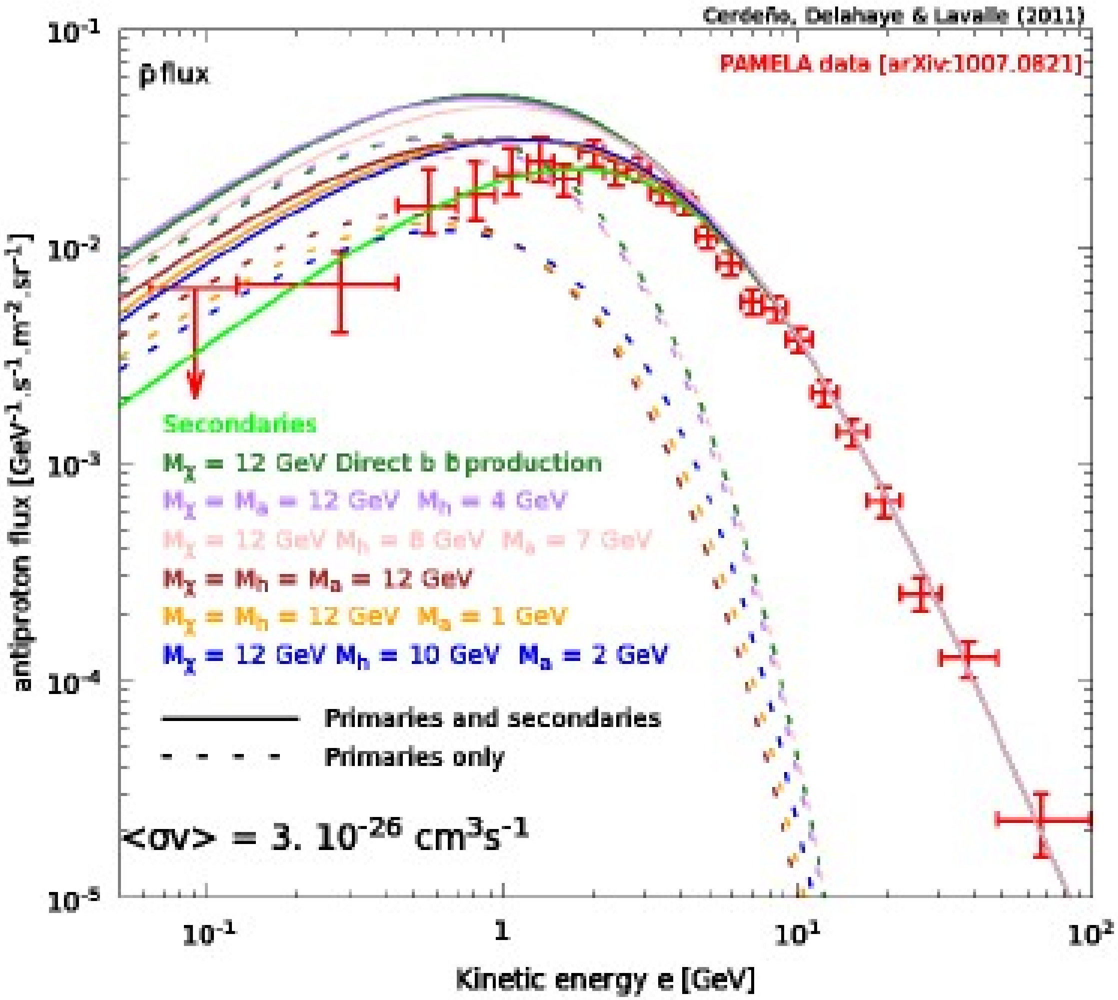
*J. Clem et al. 30th ICRC 2007*

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

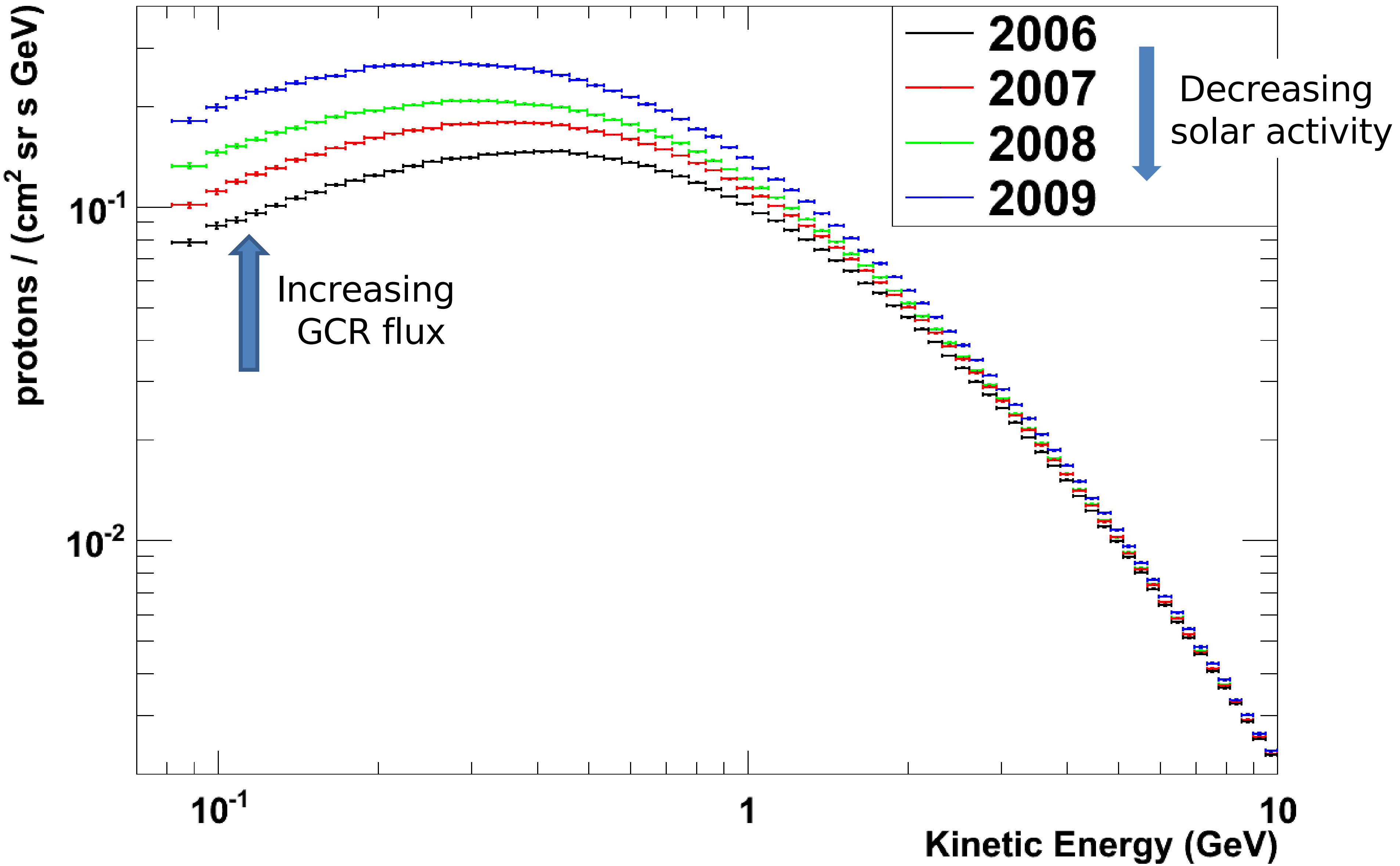
# Cosmic-Ray Antiprotons and DM limits



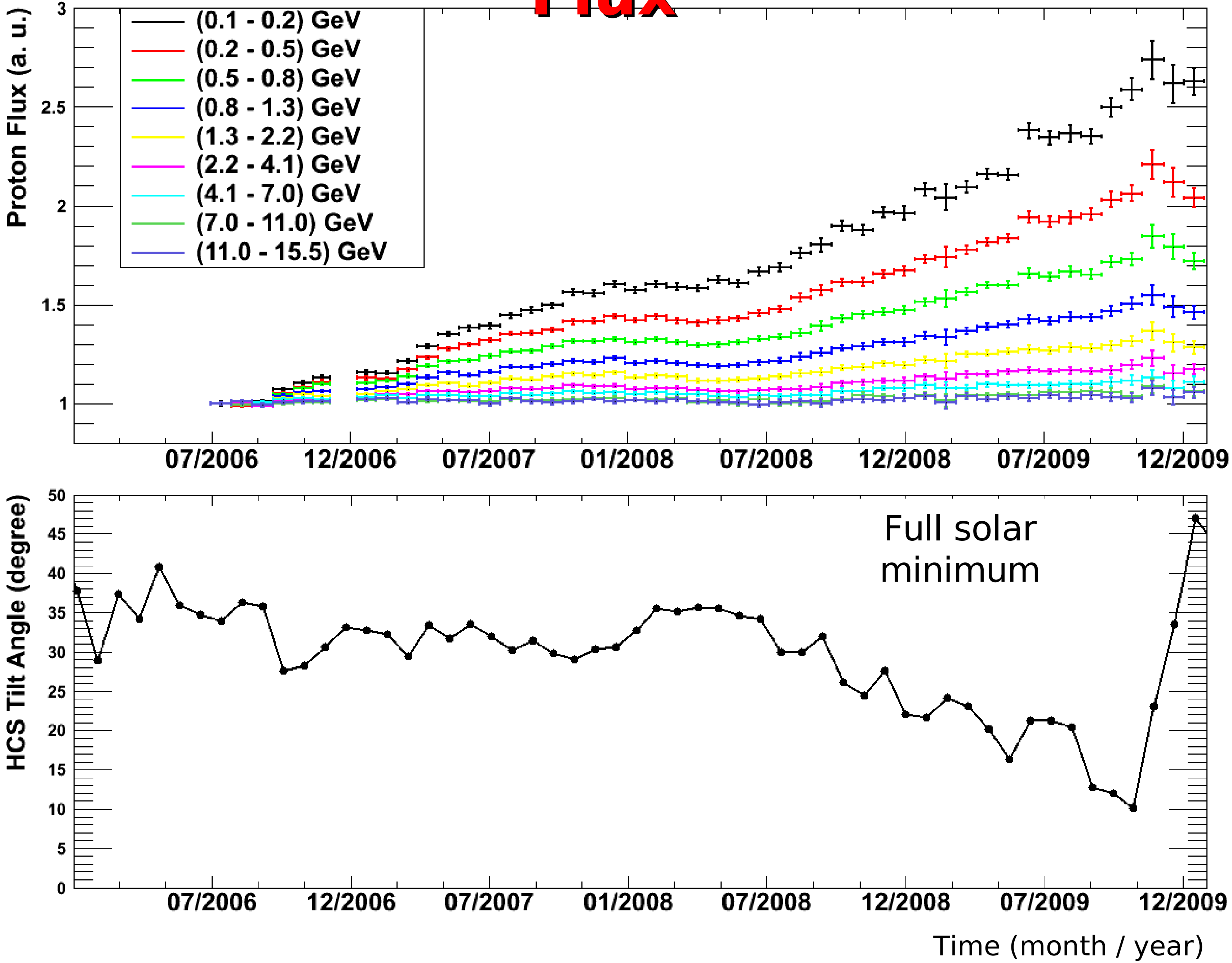

**D. G. Cerdeno, T. Delahaye & J. Lavalle, arXiv: 1108:1128**
**Antiproton flux predictions for a 12 GeV WIMP annihilating into different mass combinations of an intermediate two-boson state which further decays into quarks.**

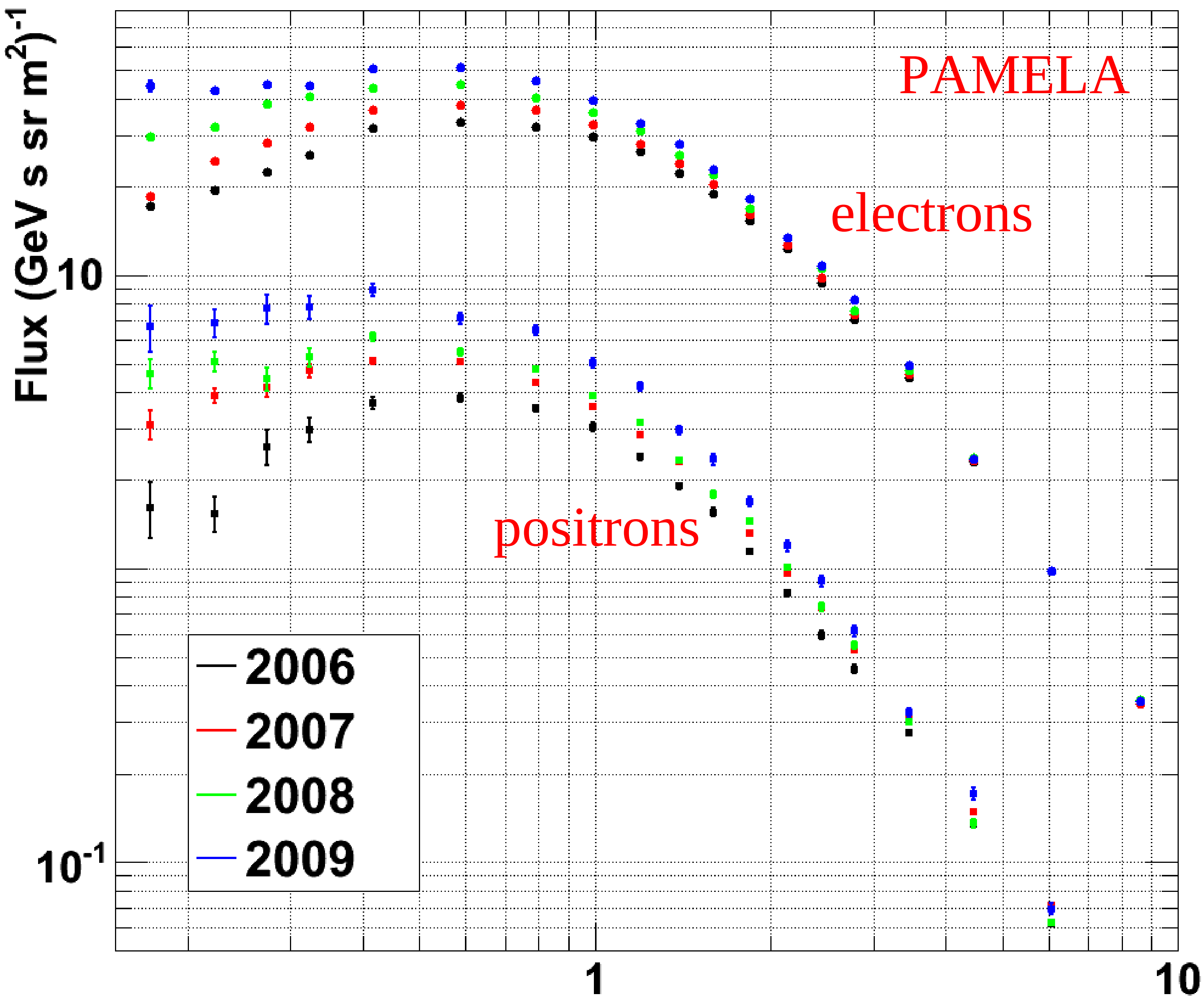
**See also:**
- **M. Asano, T. Bringmann & C. Weniger, arXiv:1112.5158.**
- **M. Garny, A. Ibarra & S. Vogl, arXiv:1112.5155**
- **R. Kappl & M. W. Winkler, arXiv:1140.4376**

# Time Dependence of PAMELA Proton Flux



# Time Dependence of PAMELA Proton Flux



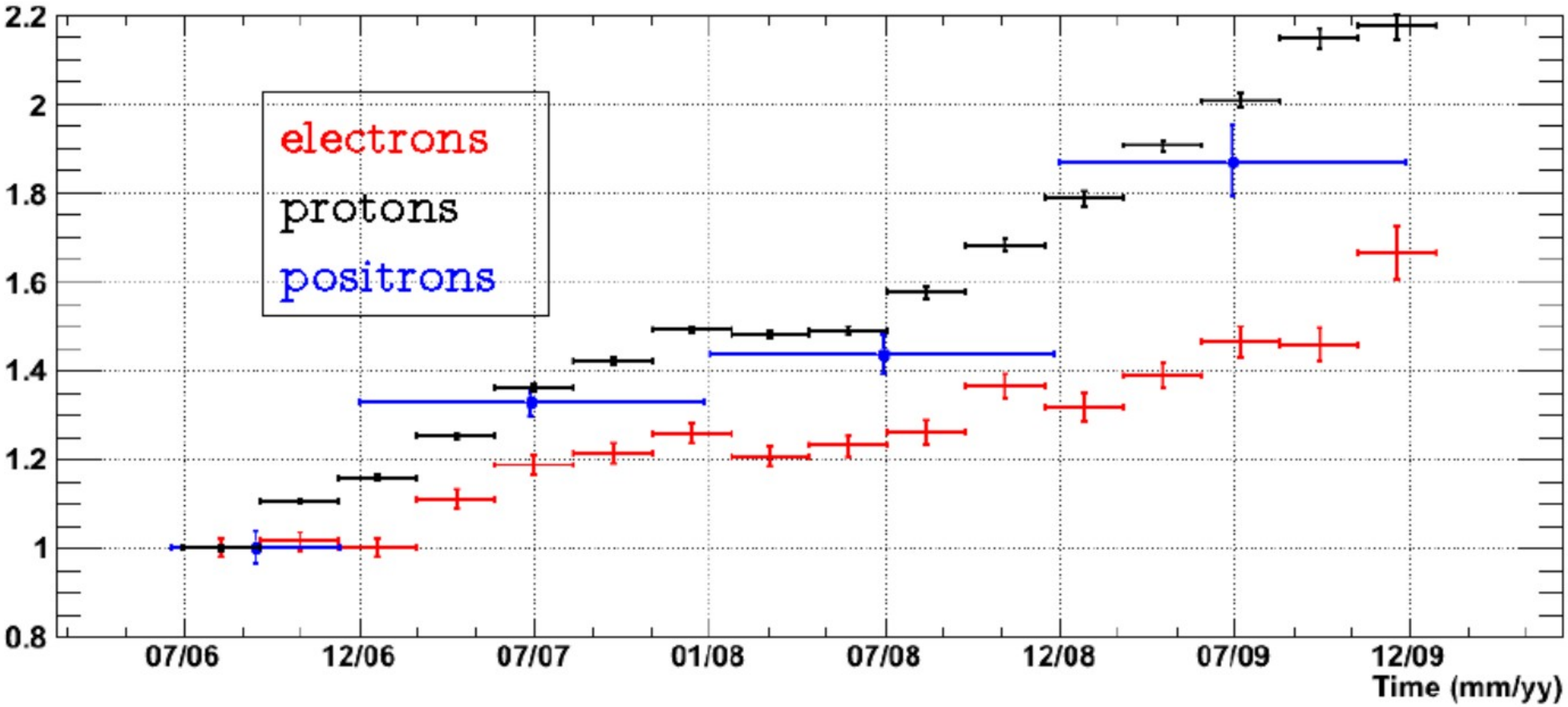


PAMELA
electrons
positrons
Flux (GeV s sr m$^2$)$^{-1}$
10
$10^{-1}$
1
10
2006
2007
2008
2009

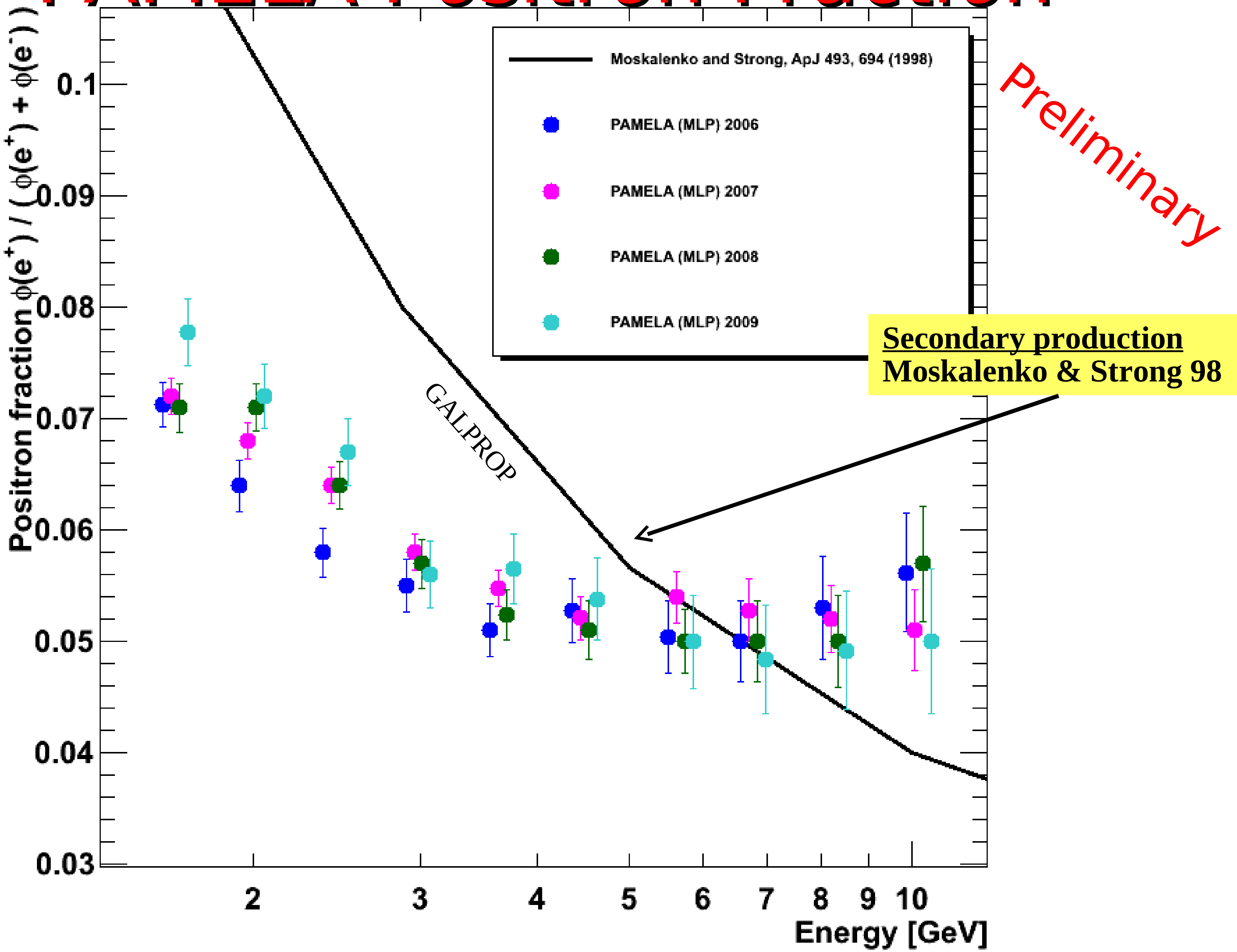
# Fluxes in time

PAMELA

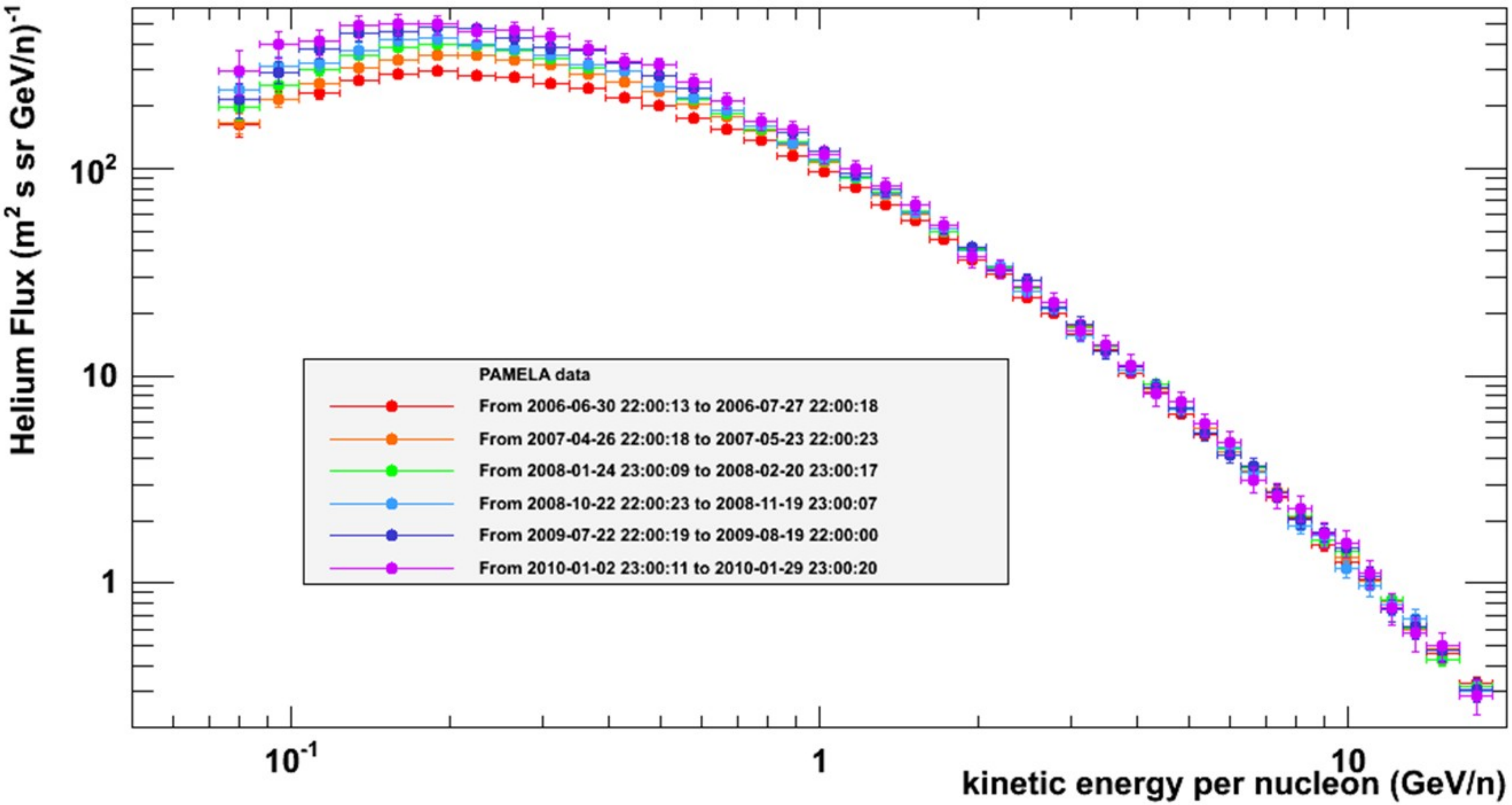
range: 0.4 – 0.71 GeV



# PAMELA Positron Fraction

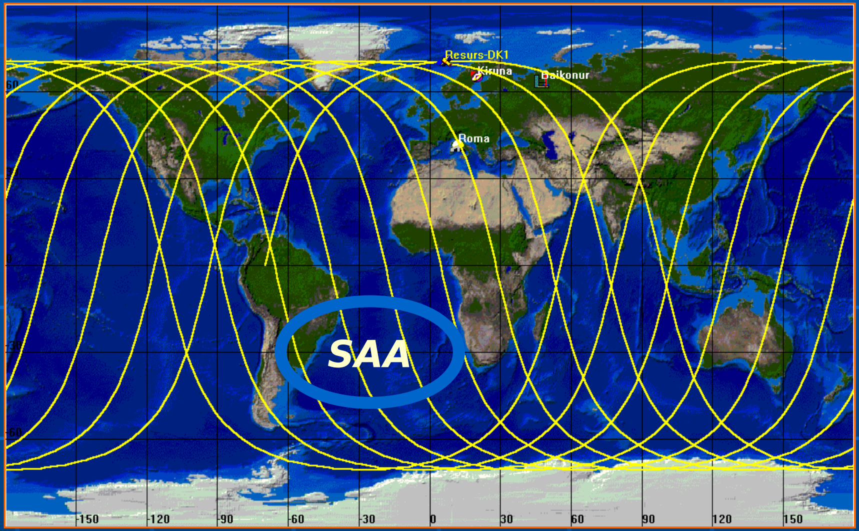


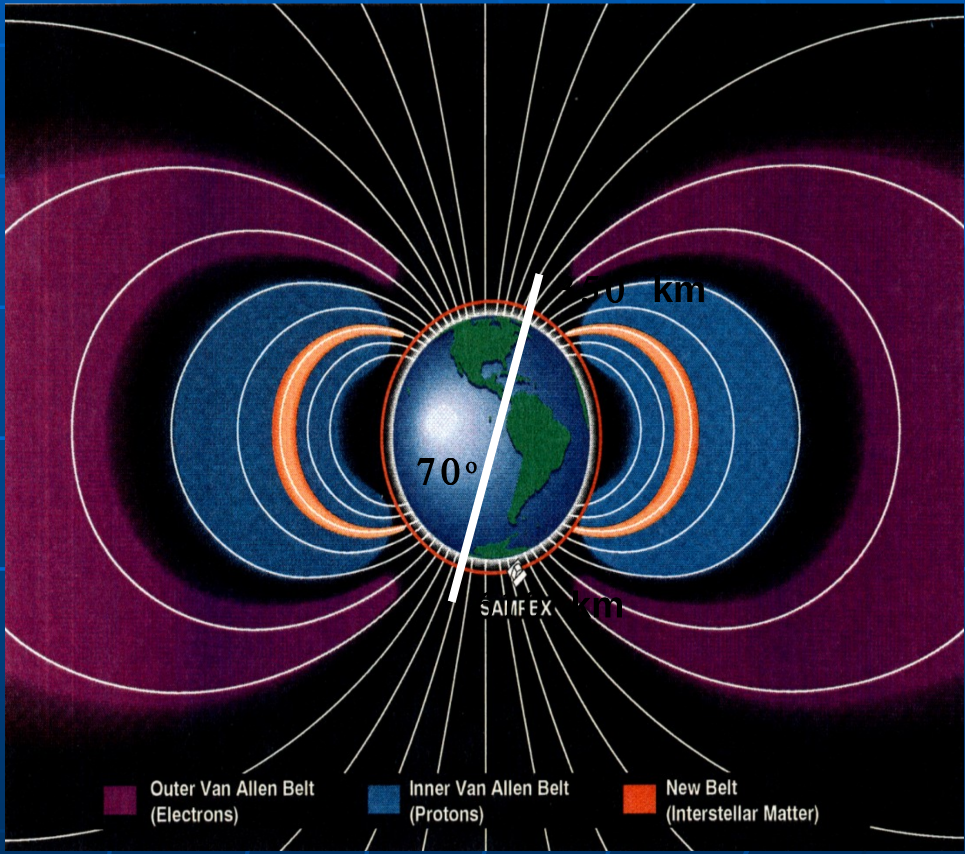
# Time Dependence of PAMELA Helium Flux



# South Atlantic Anomaly

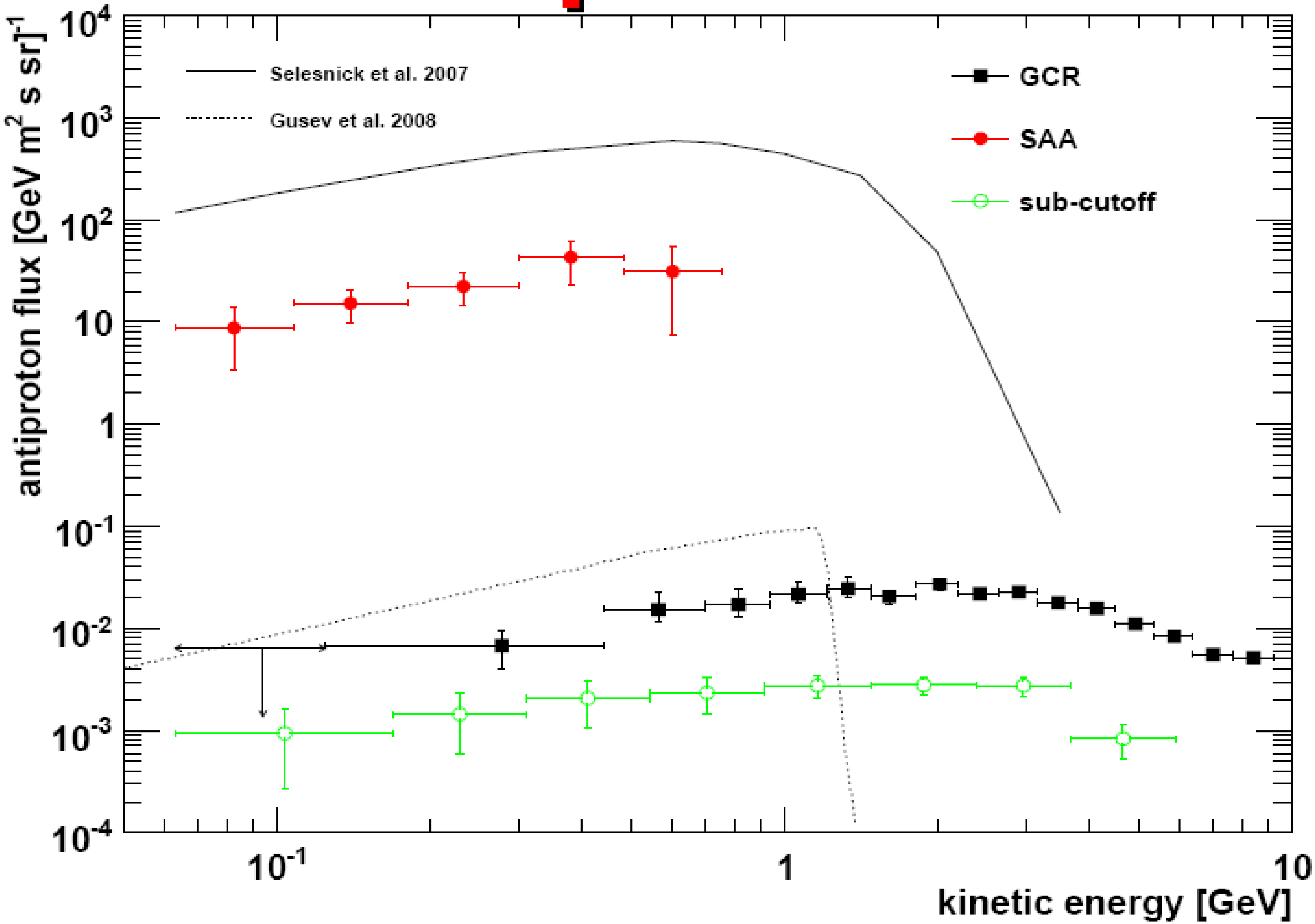
# Orbit Characteristics



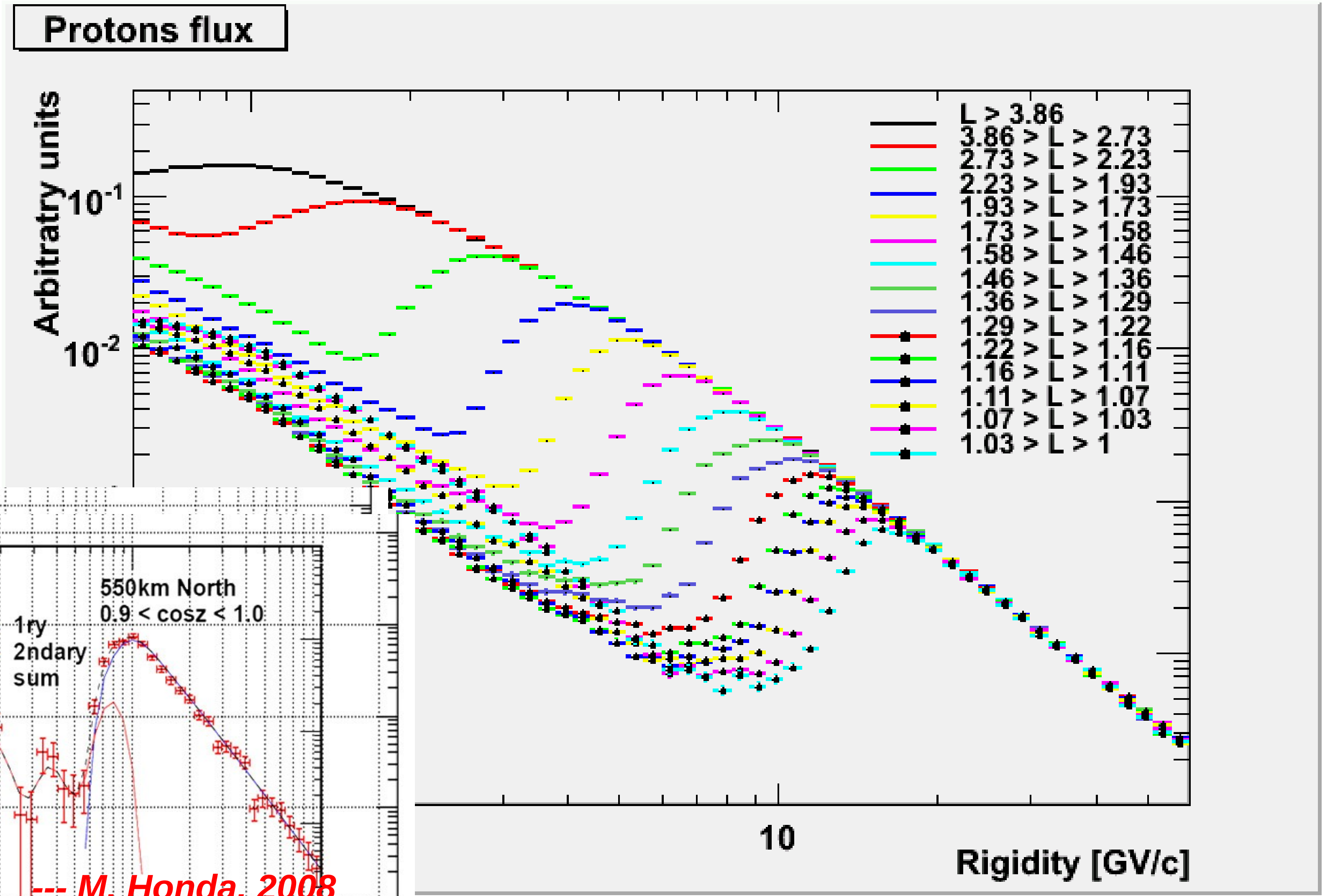

- Low-earth elliptical orbit
- 350 – 610 km
- Quasi-polar (70$^{o}$ inclination)
- SAA crossed

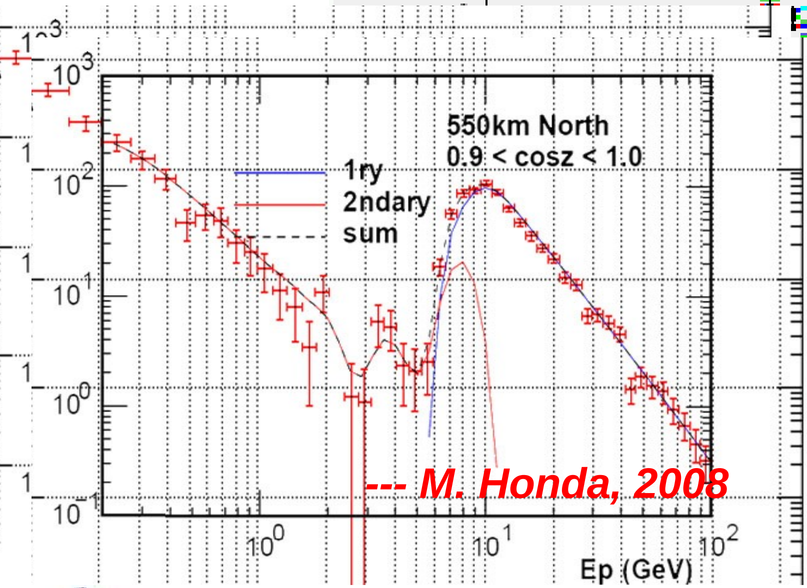
# PAMELA trapped antiprotons




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

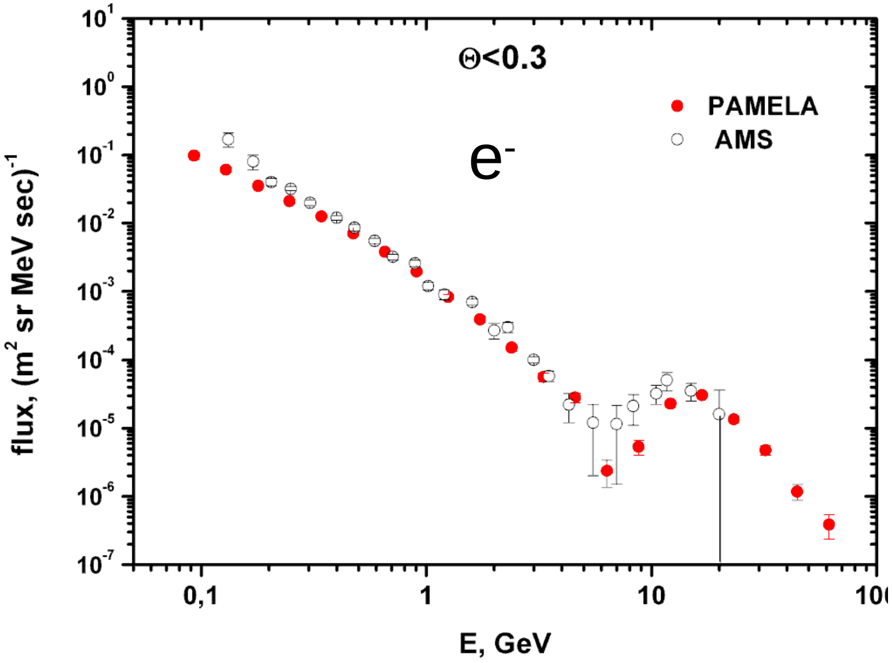
# Subcutoff particle spectra

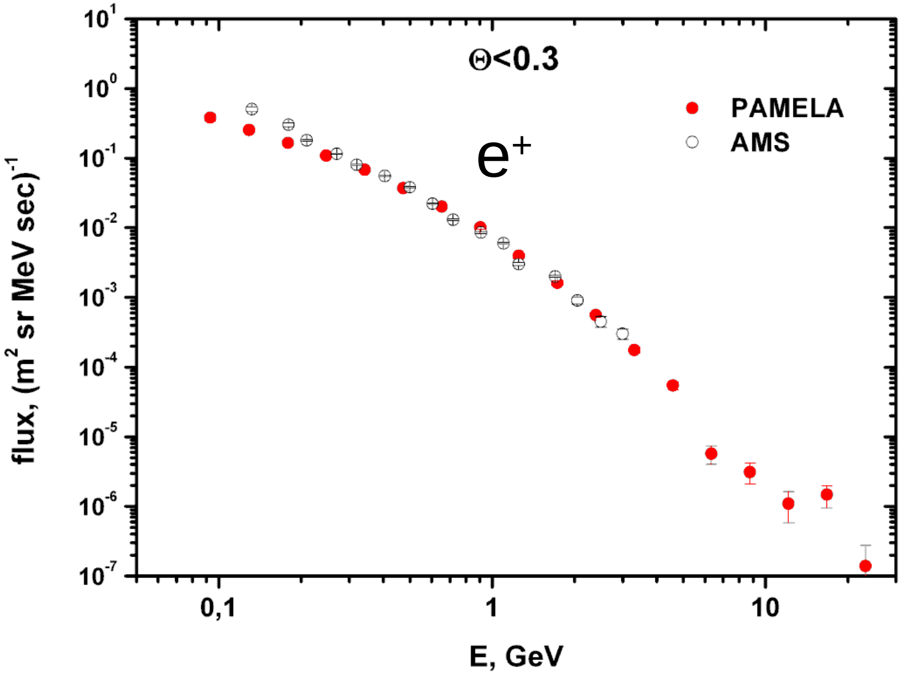



--- *M. Honda, 2008*

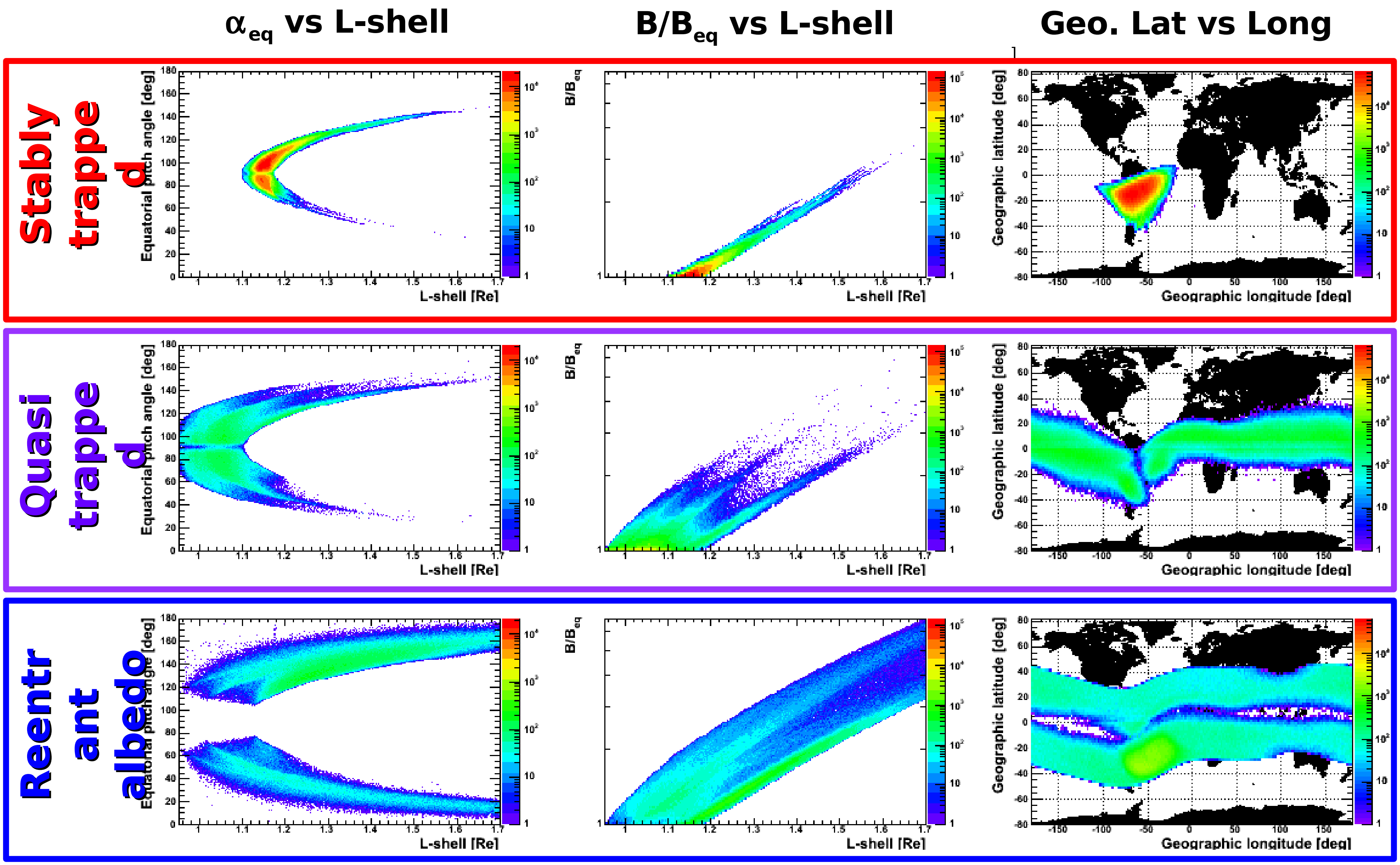
# Subcut-off electrons and positrons



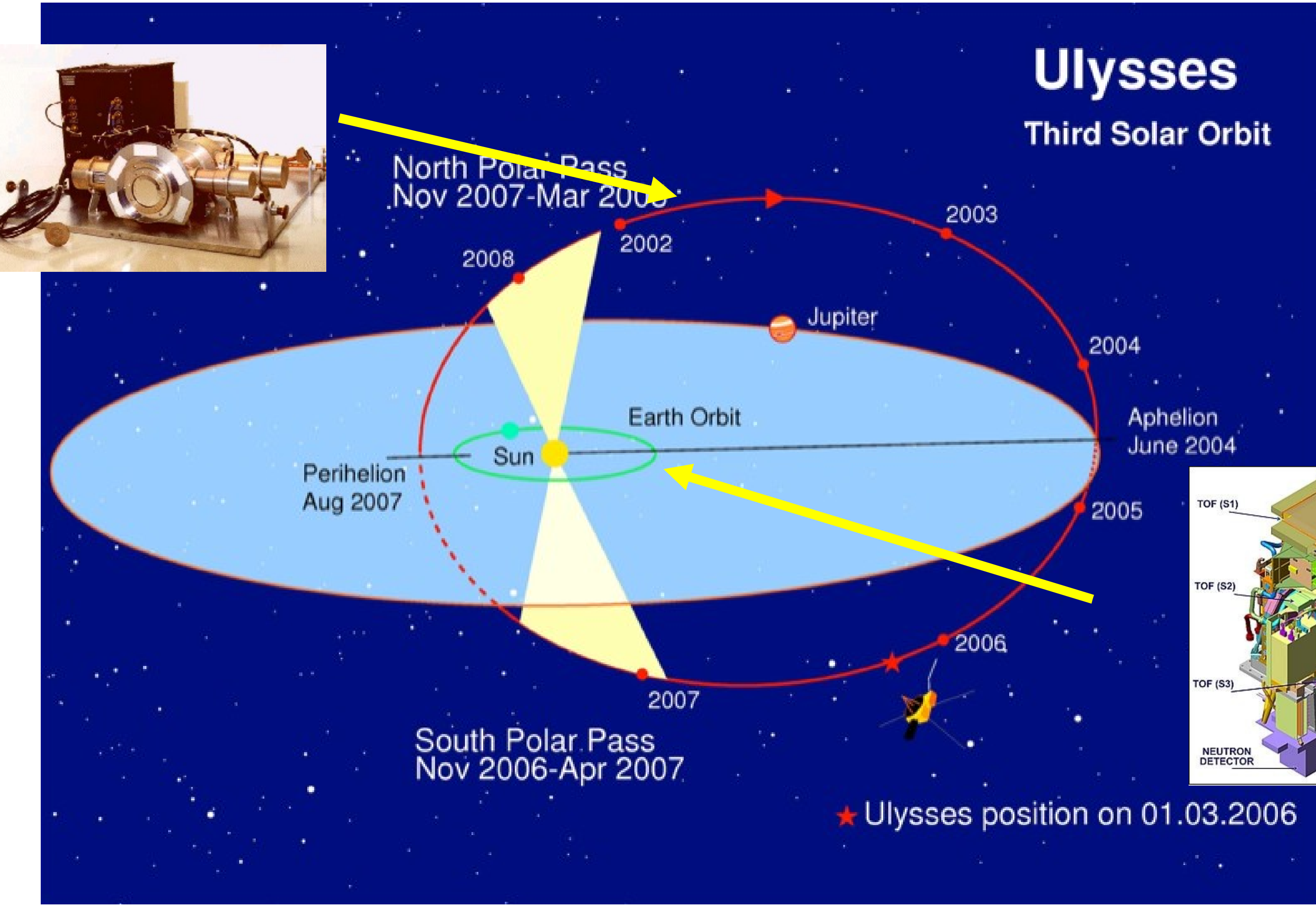



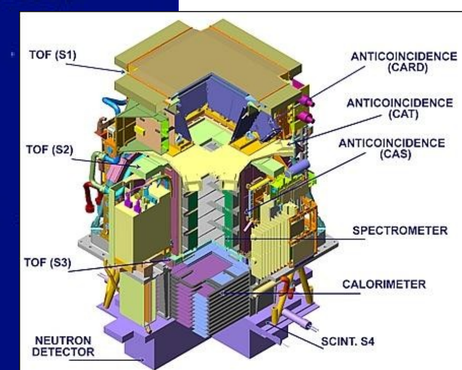

ICRC≠≠558

# Distributions of sub-cutoff proton counts



# Gradients in the Heliosphere, PAMELA & ULYSSES

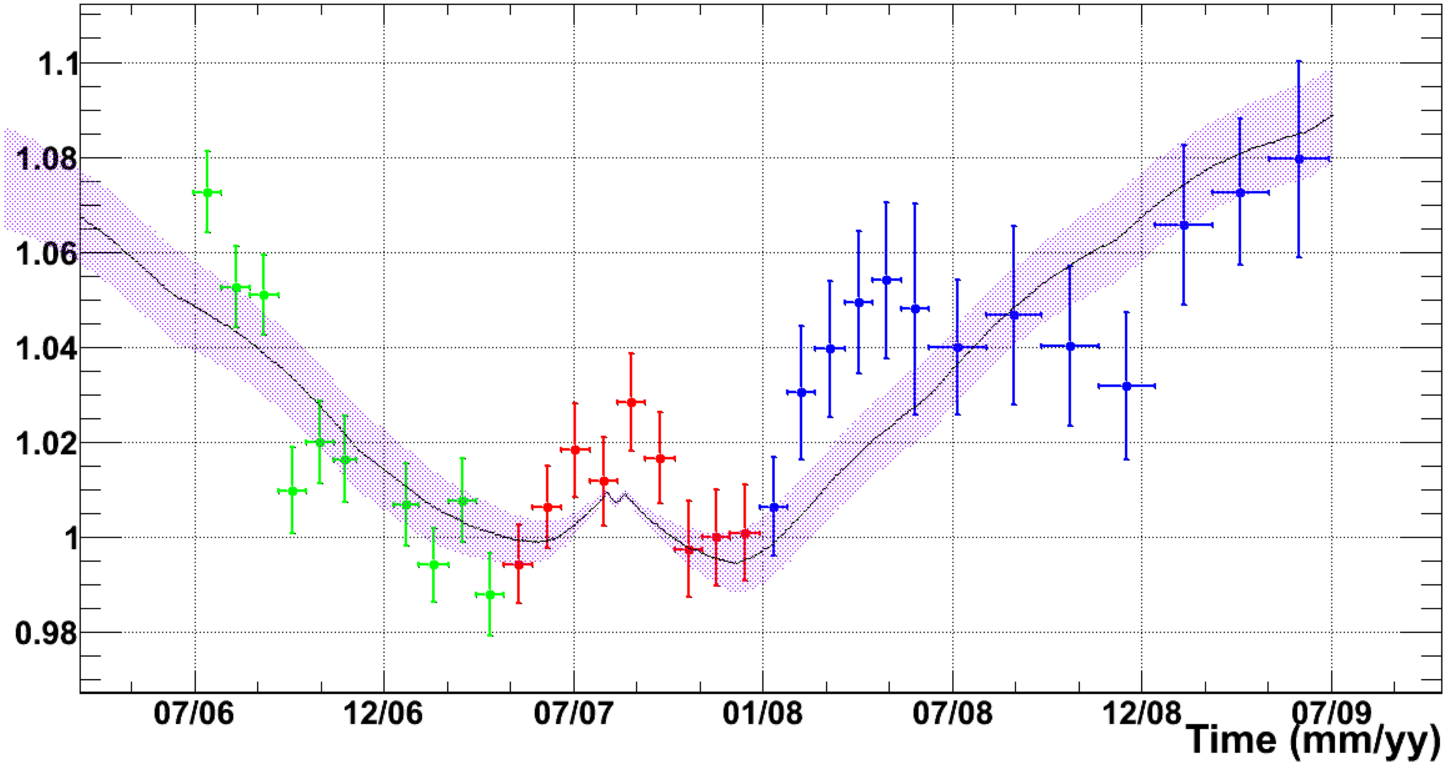



$$ln\Big(\frac{I(t,R,\theta)}{I_{PAMELA}(t)}\Big) = G_R R + G_\theta \theta$$

ICRC≠≠569

# Spatial gradients




1.97 GV - 2.07 GV

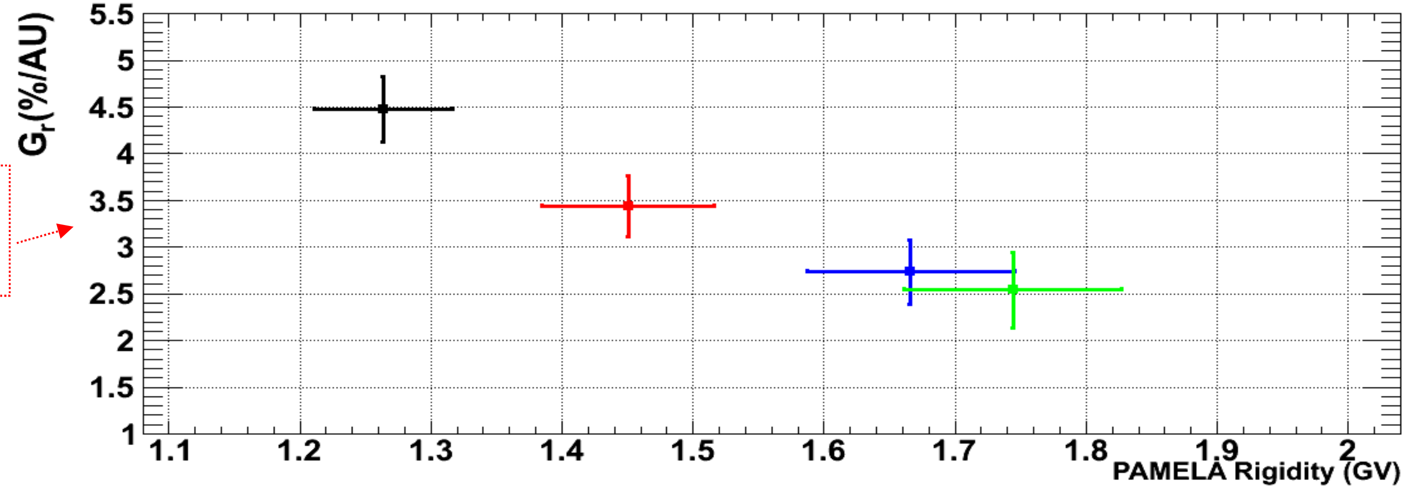
$$\frac{J_U}{J_P} = exp(G_r \cdot \Delta r) \cdot exp(G_\theta \cdot \Delta\theta)$$

$G_r$: $(2.51 \pm 0.1)\%/AU$ $G_\theta$: $(-0.025 \pm 0.002)\%/deg$

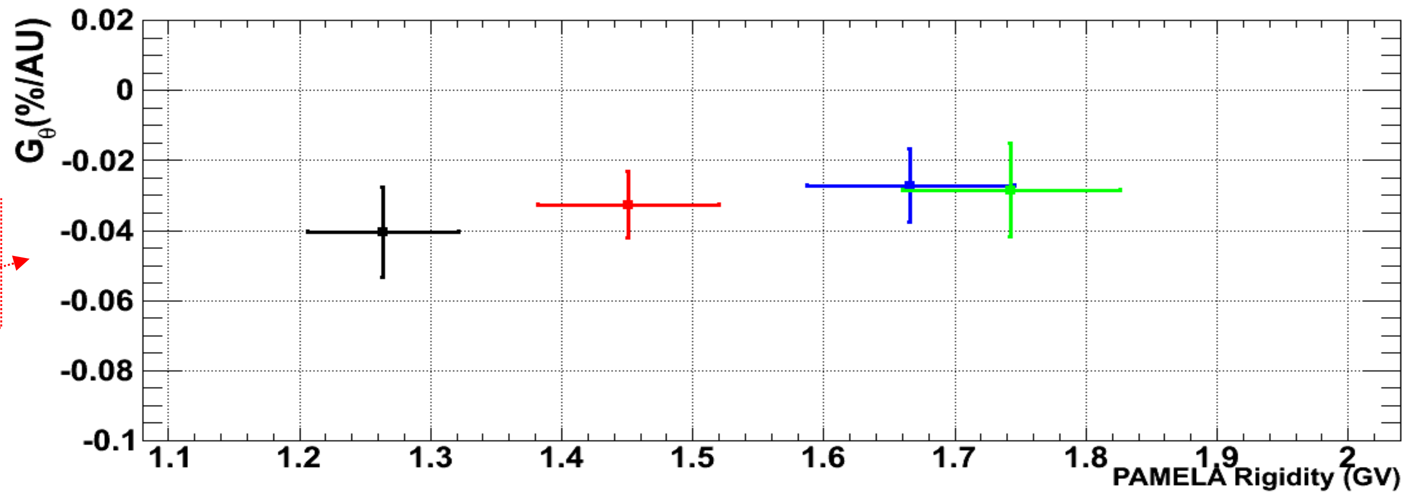
Comparison of the proton flux measured between 1.97 and 2.07 GV by PAMELA and ULYSSES as a function of time

# Proton gradients in the heliosphere – PAMELA

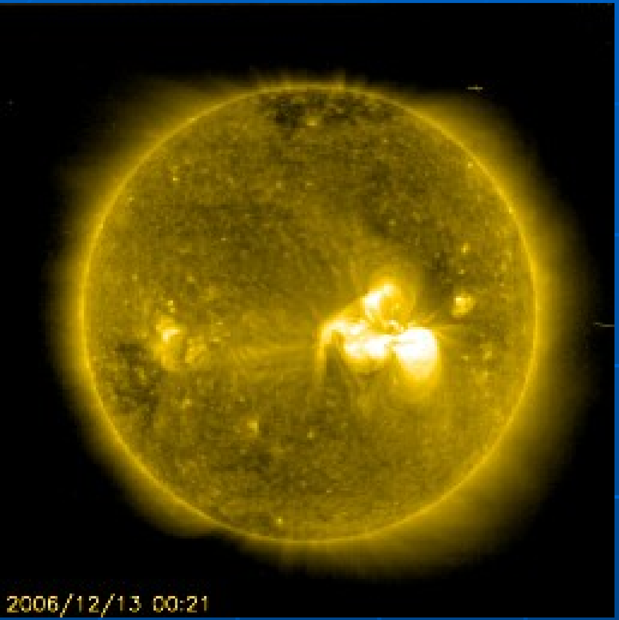
Radial gradient

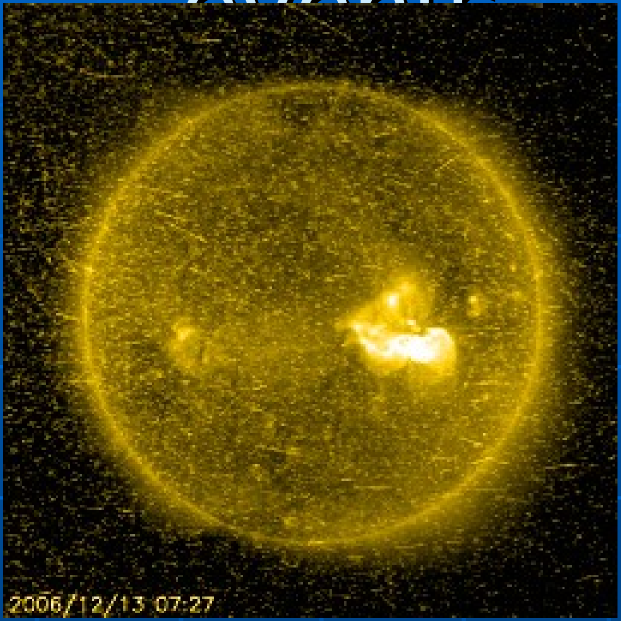


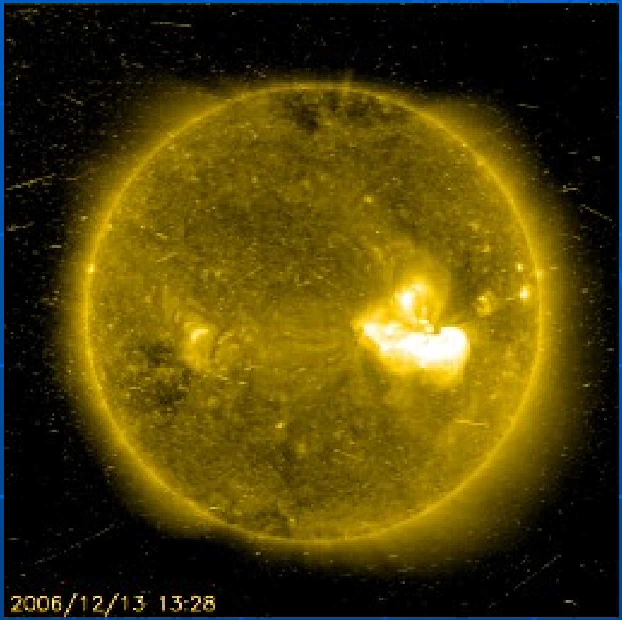

Latitudinal gradient



# December 2006 Solar particle events

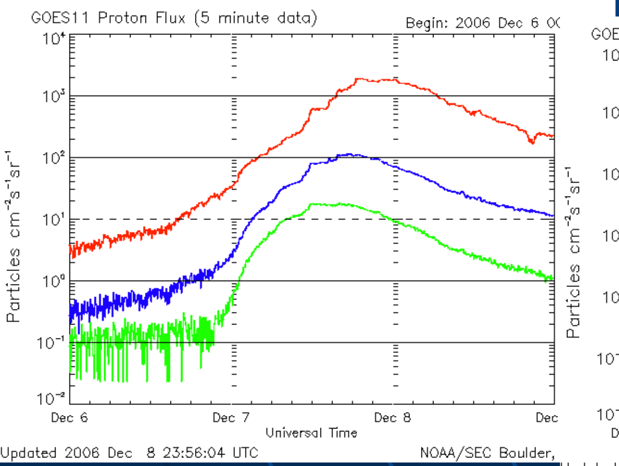


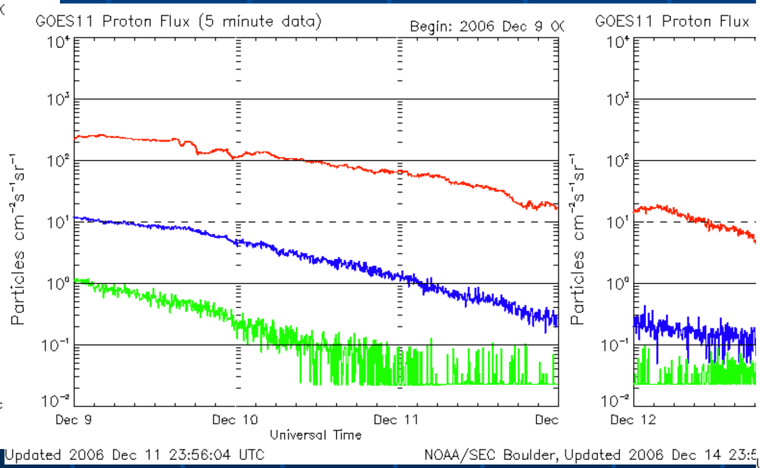



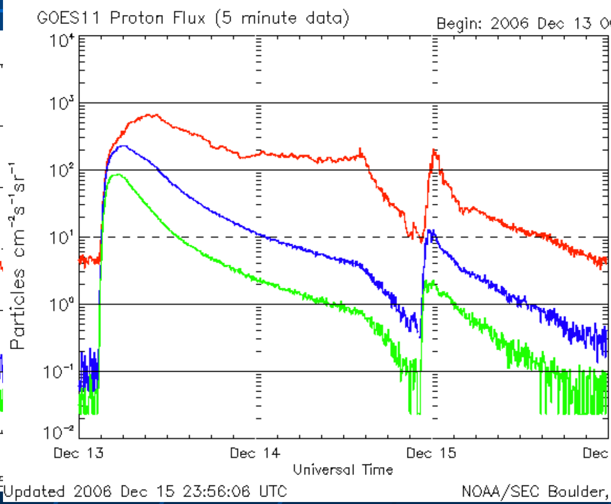




Dec 13th largest CME since 2003, anomalous at sol min

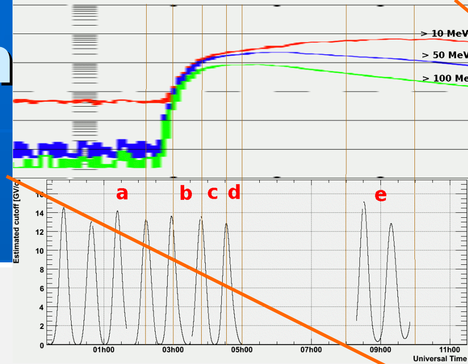
X3.4 solar flare,

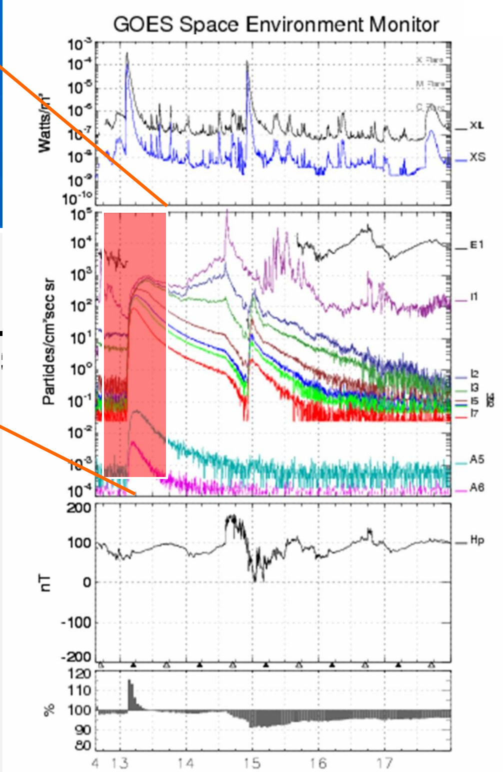


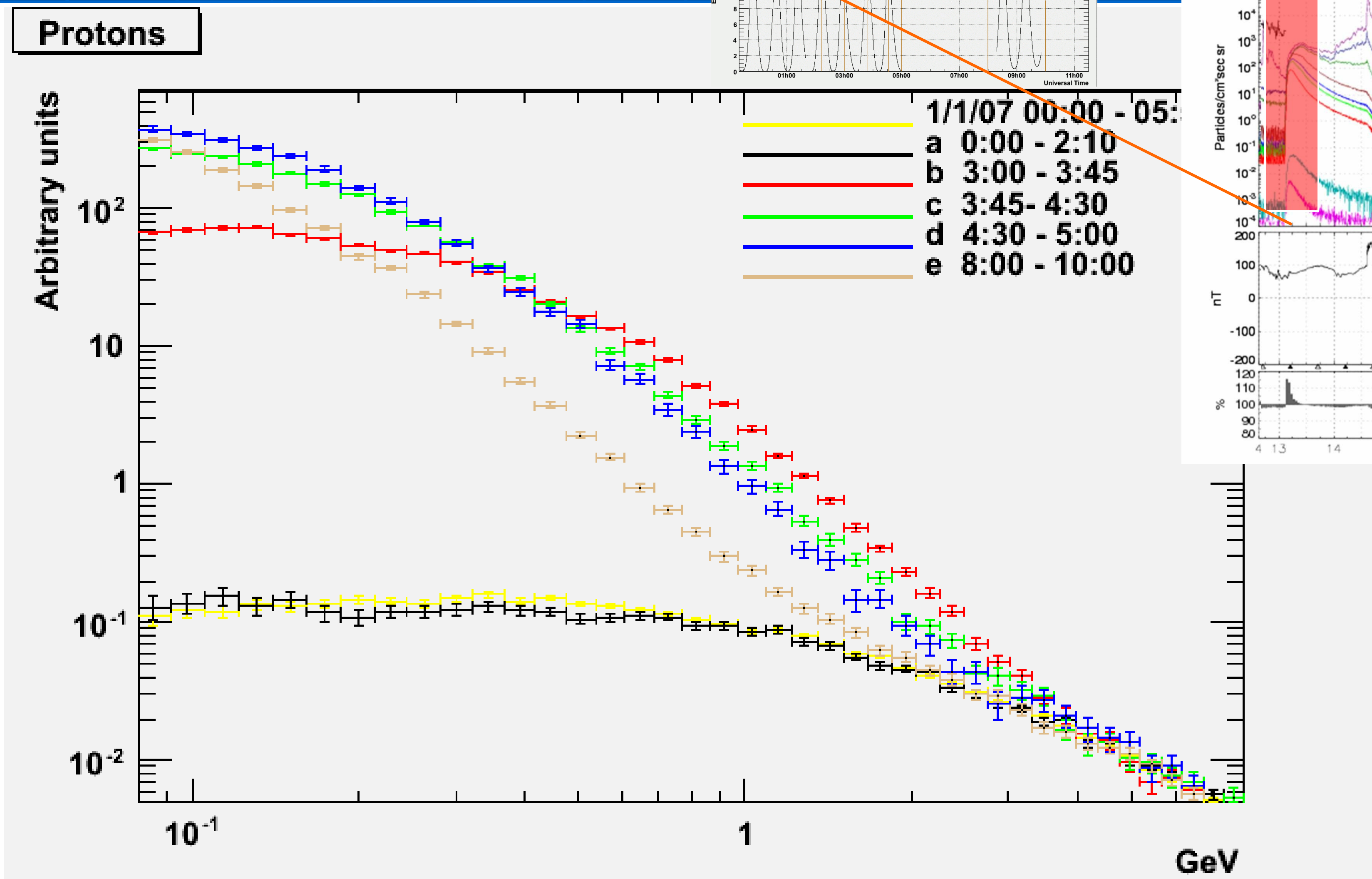



# cember 13th 2006 even

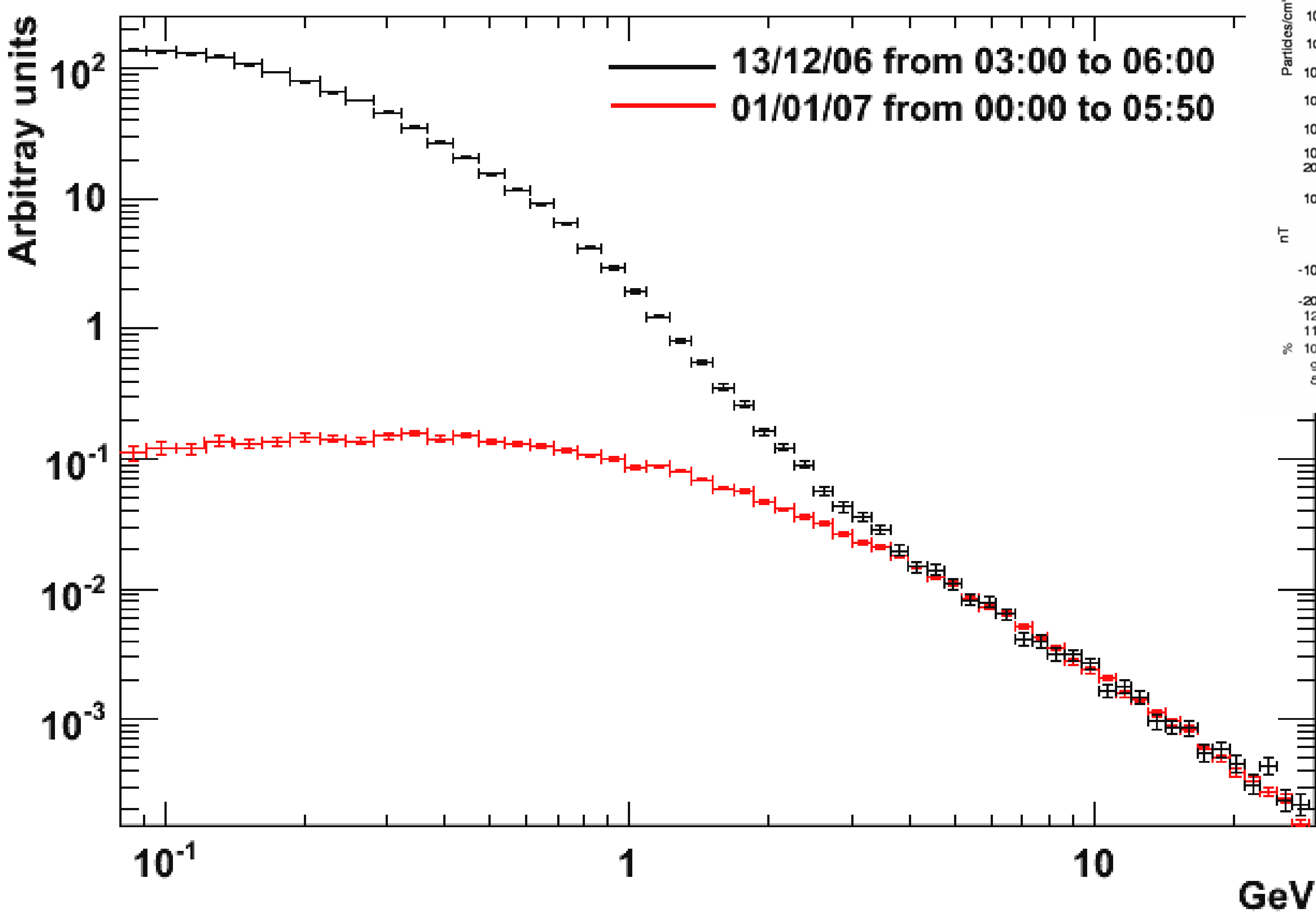


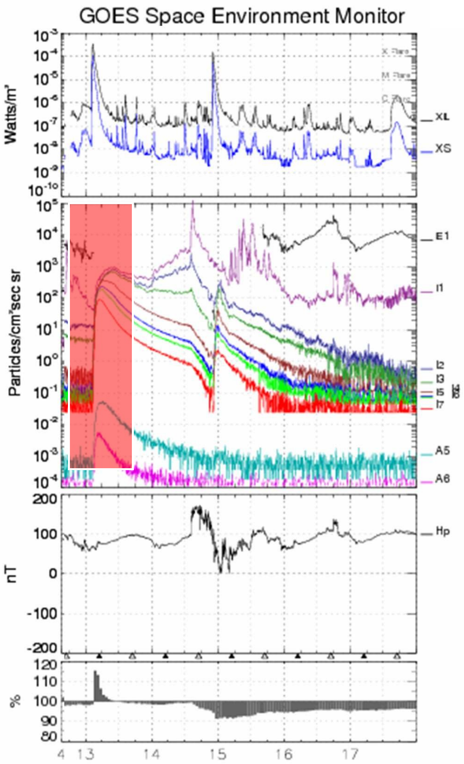



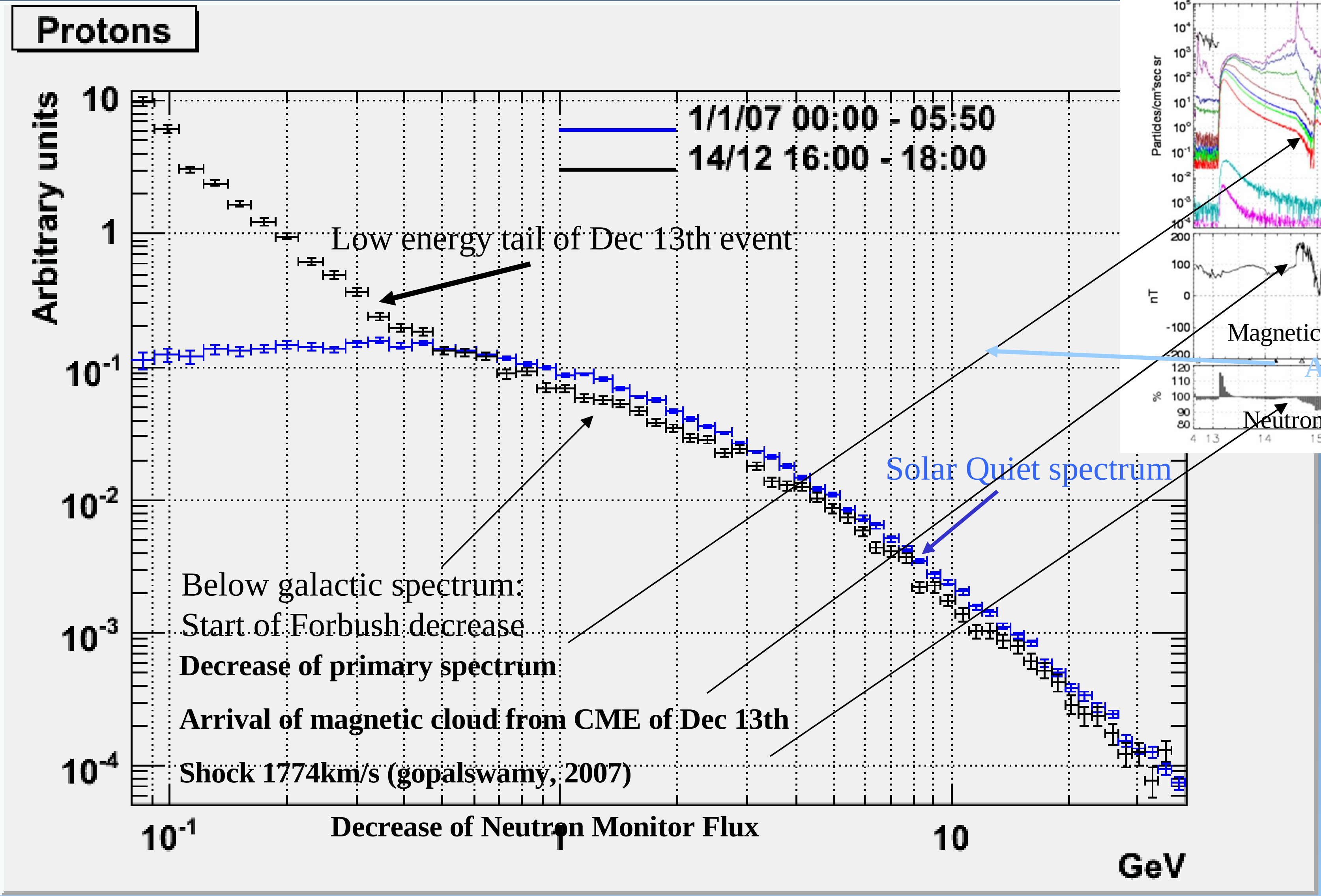

*Preliminary!*

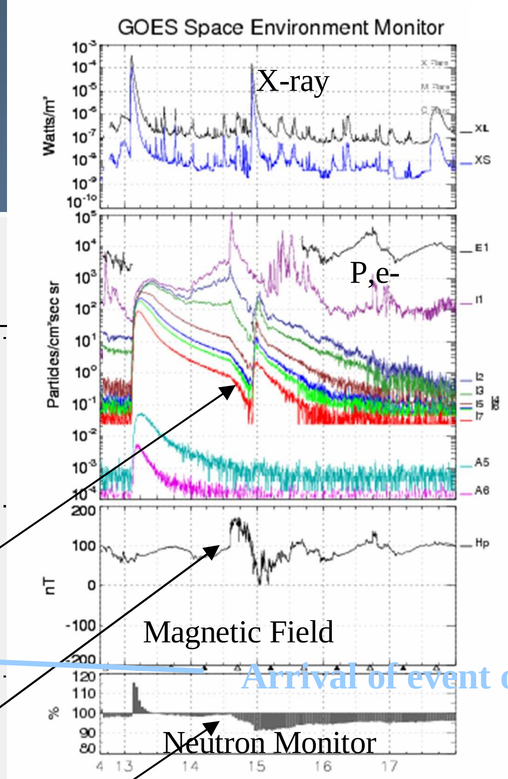
# December 13th 2006 He differential spectrum



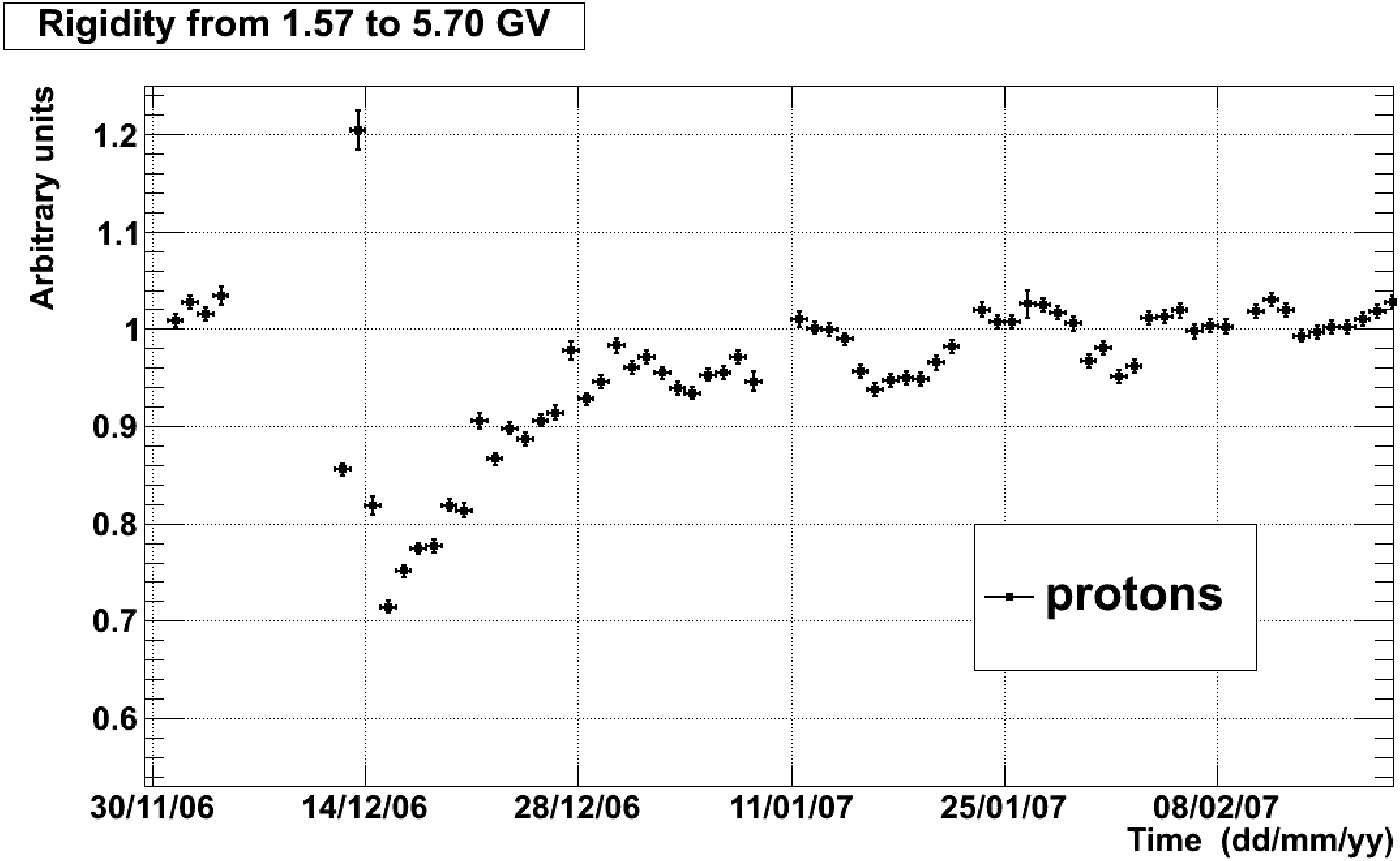



# December 14th 2006: Forbush decrease

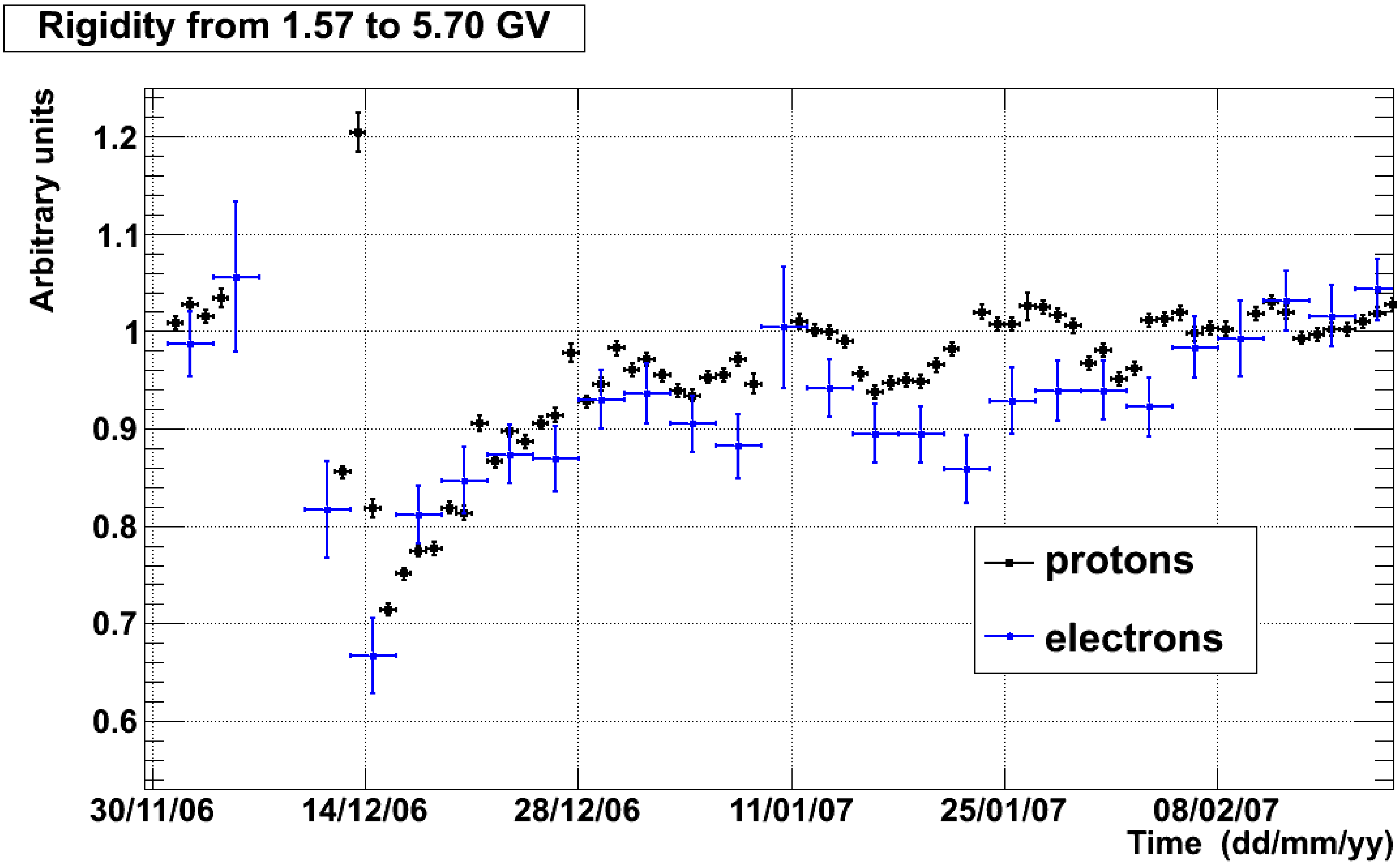


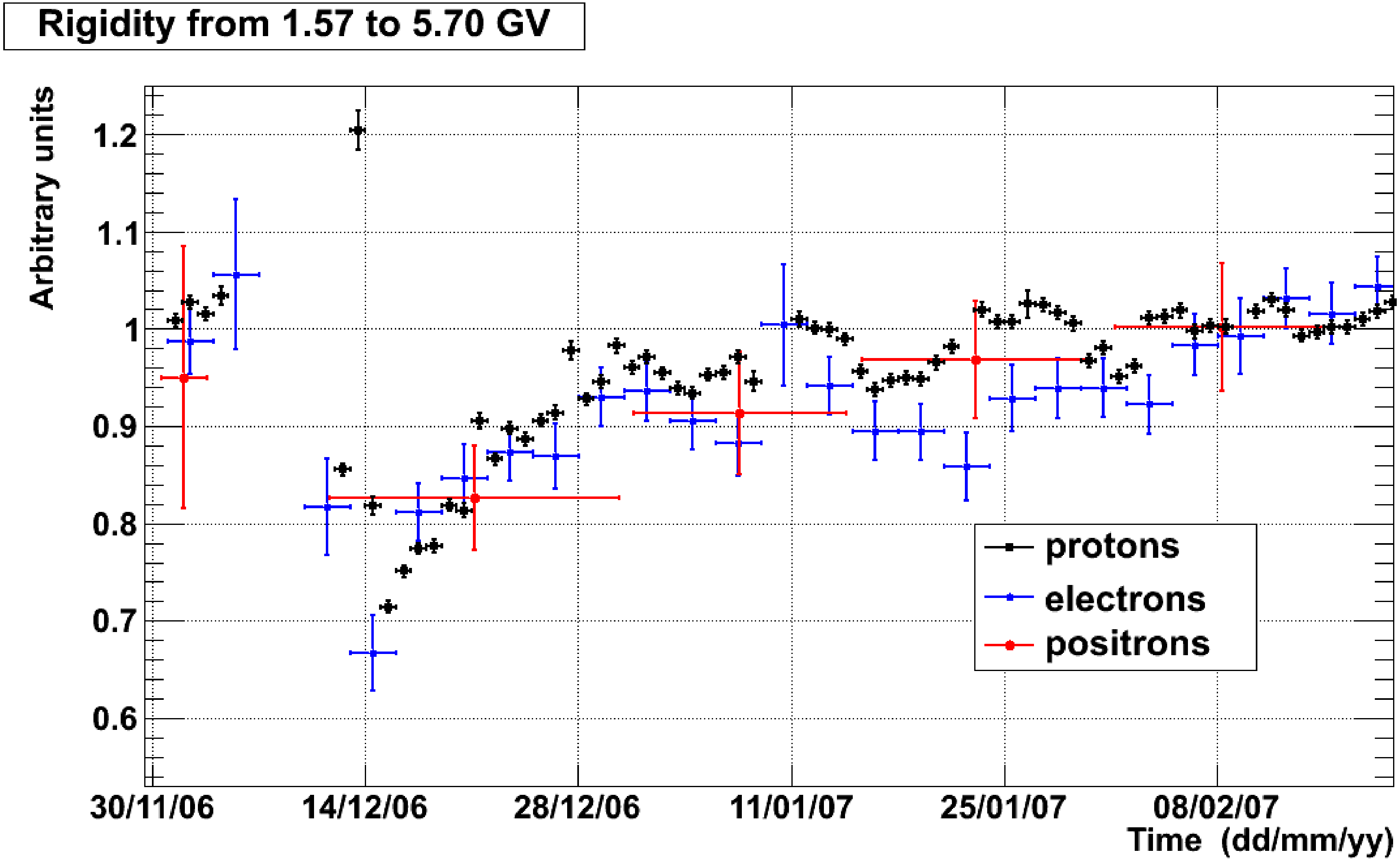
# Forbush decrease – protons



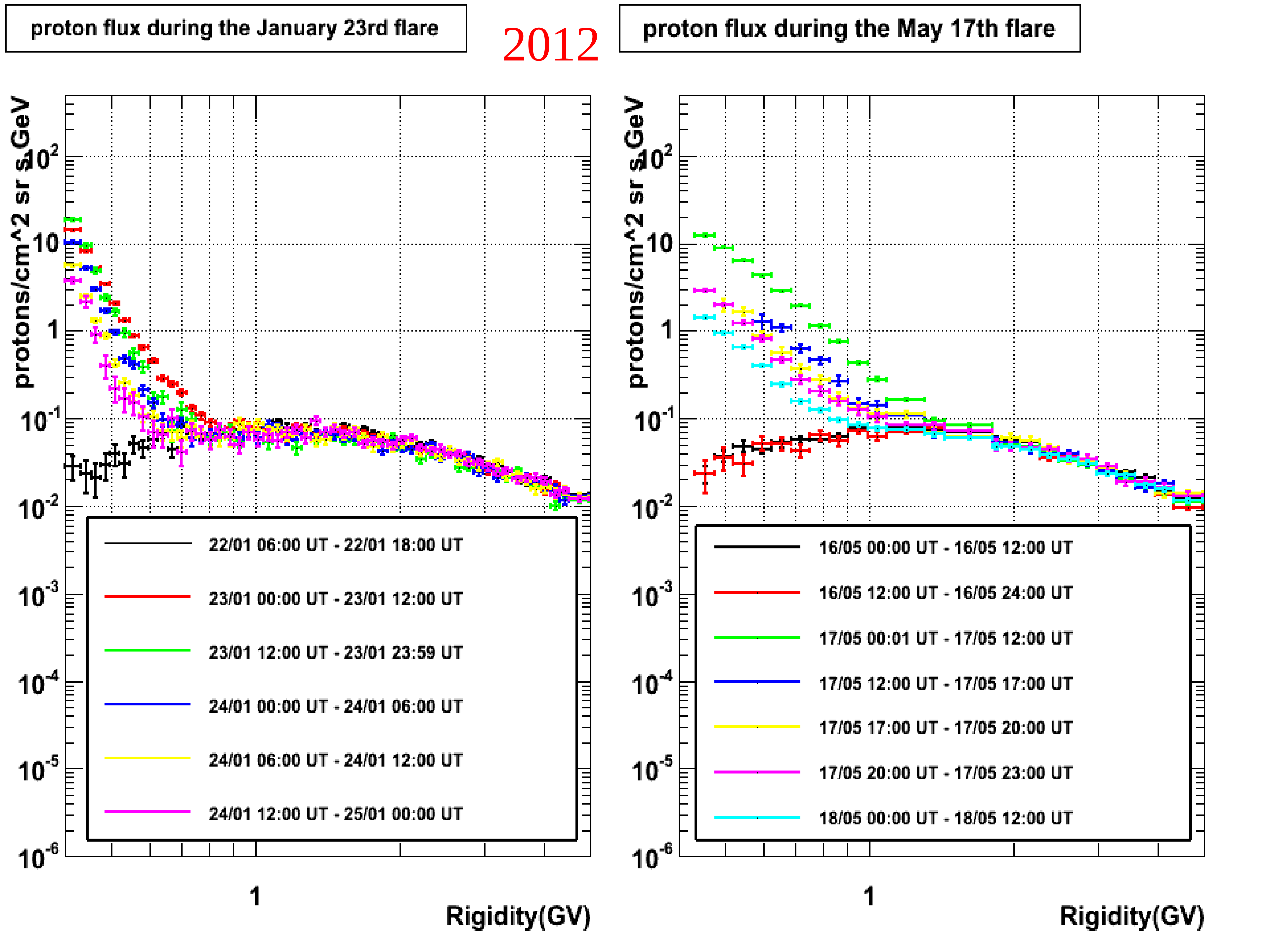
# Forbush decrease – protons and electrons



# Forbush decrease – protons, electrons and positrons

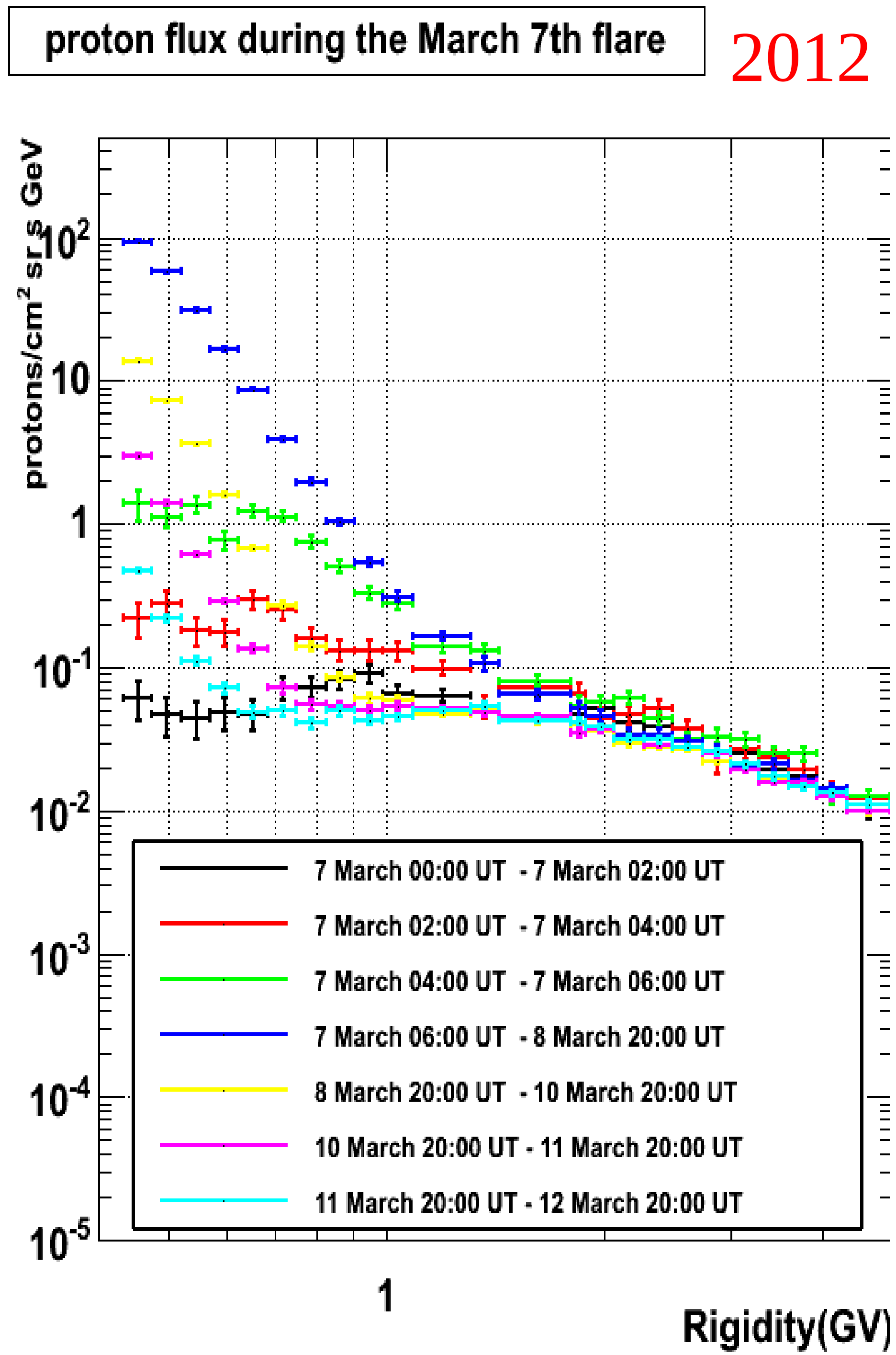


2012

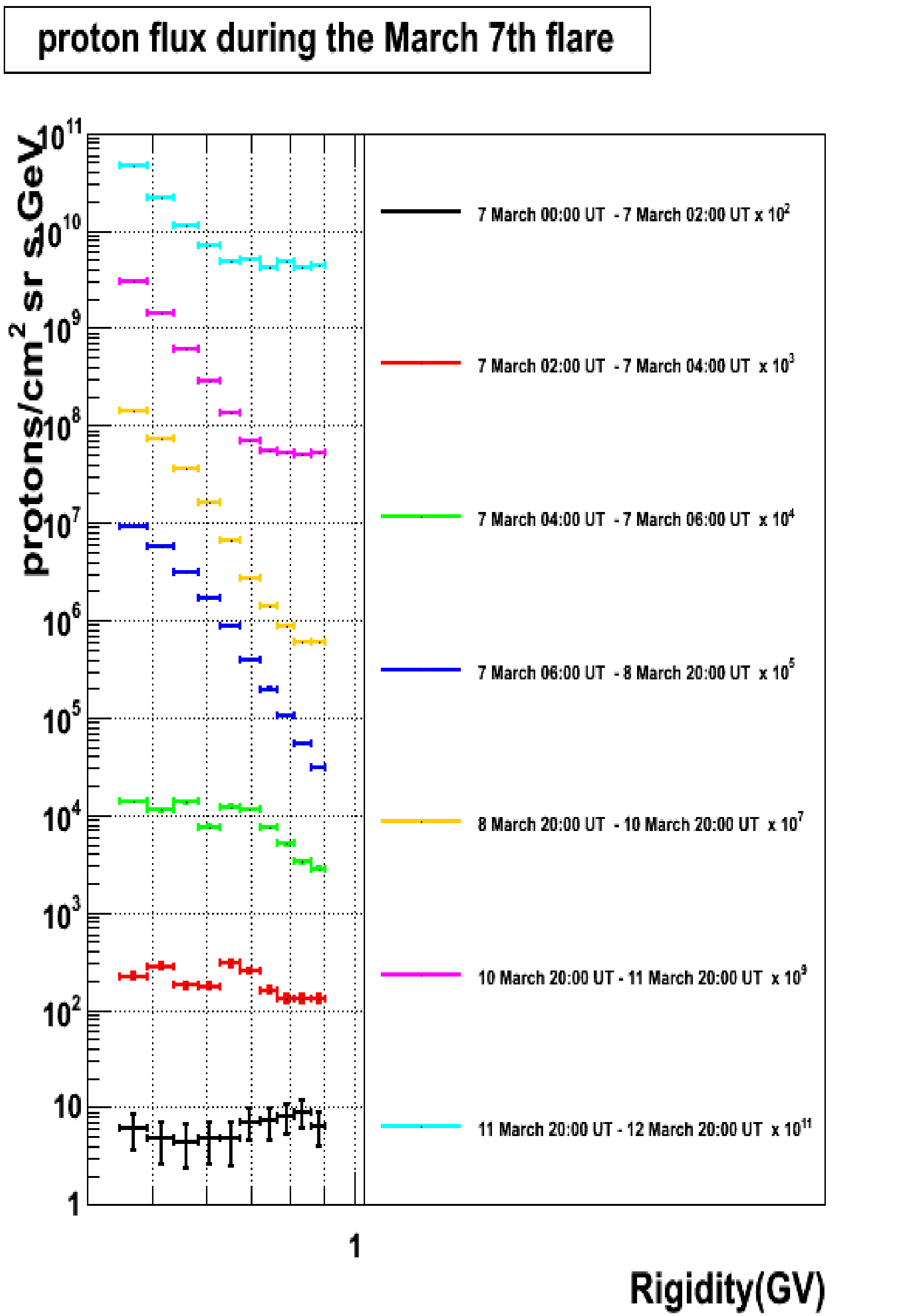


proton flux during the January 23rd flare
protons/cm^2 sr s GeV
Rigidity(GV)
22/01 06:00 UT - 22/01 18:00 UT
23/01 00:00 UT - 23/01 12:00 UT
23/01 12:00 UT - 23/01 23:59 UT
24/01 00:00 UT - 24/01 06:00 UT
24/01 06:00 UT - 24/01 12:00 UT
24/01 12:00 UT - 25/01 00:00 UT
proton flux during the May 17th flare
protons/cm^2 sr s GeV
Rigidity(GV)
16/05 00:00 UT - 16/05 12:00 UT
16/05 12:00 UT - 16/05 24:00 UT
17/05 00:01 UT - 17/05 12:00 UT
17/05 12:00 UT - 17/05 17:00 UT
17/05 17:00 UT - 17/05 20:00 UT
17/05 20:00 UT - 17/05 23:00 UT
18/05 00:00 UT - 18/05 12:00 UT

# 2012

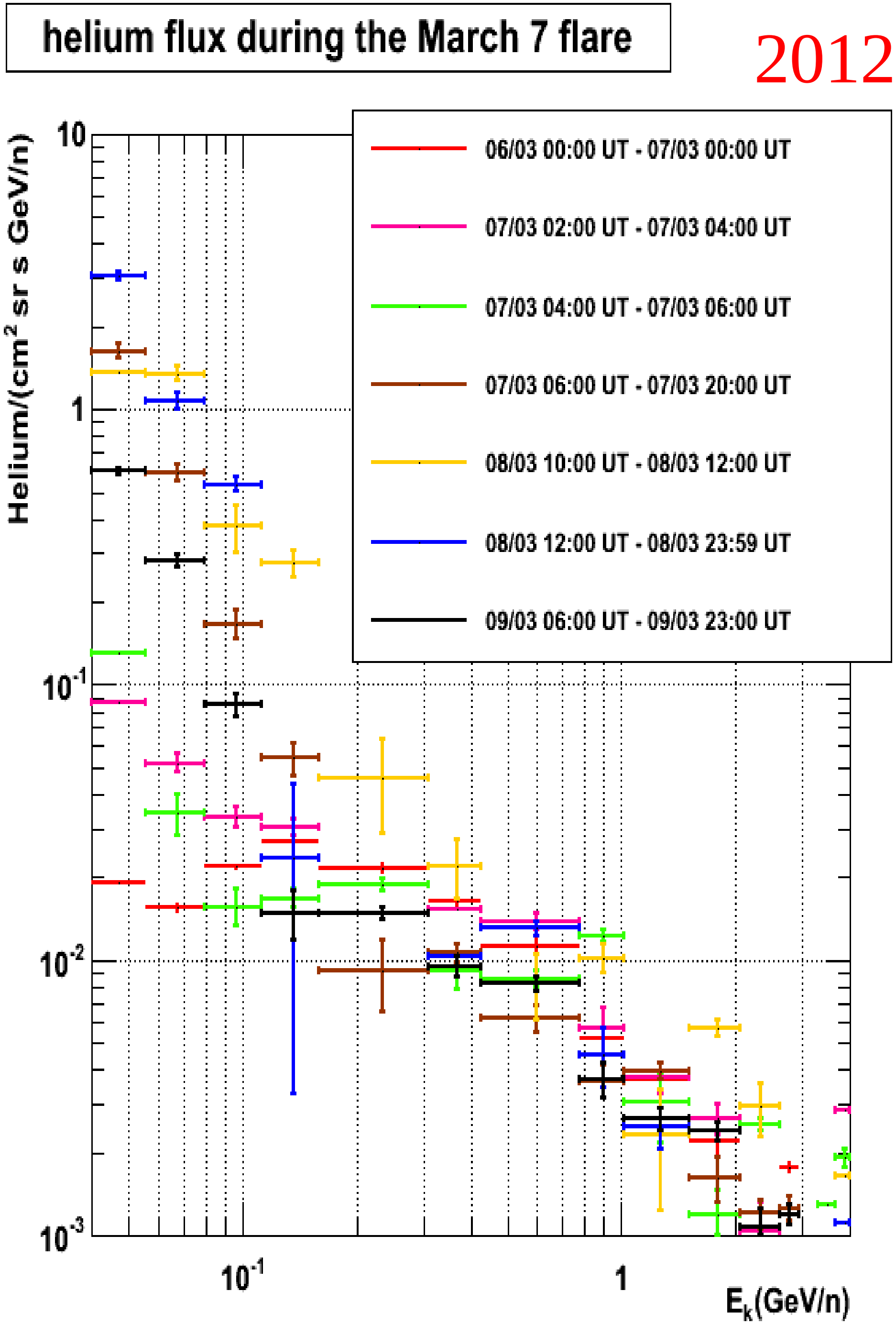


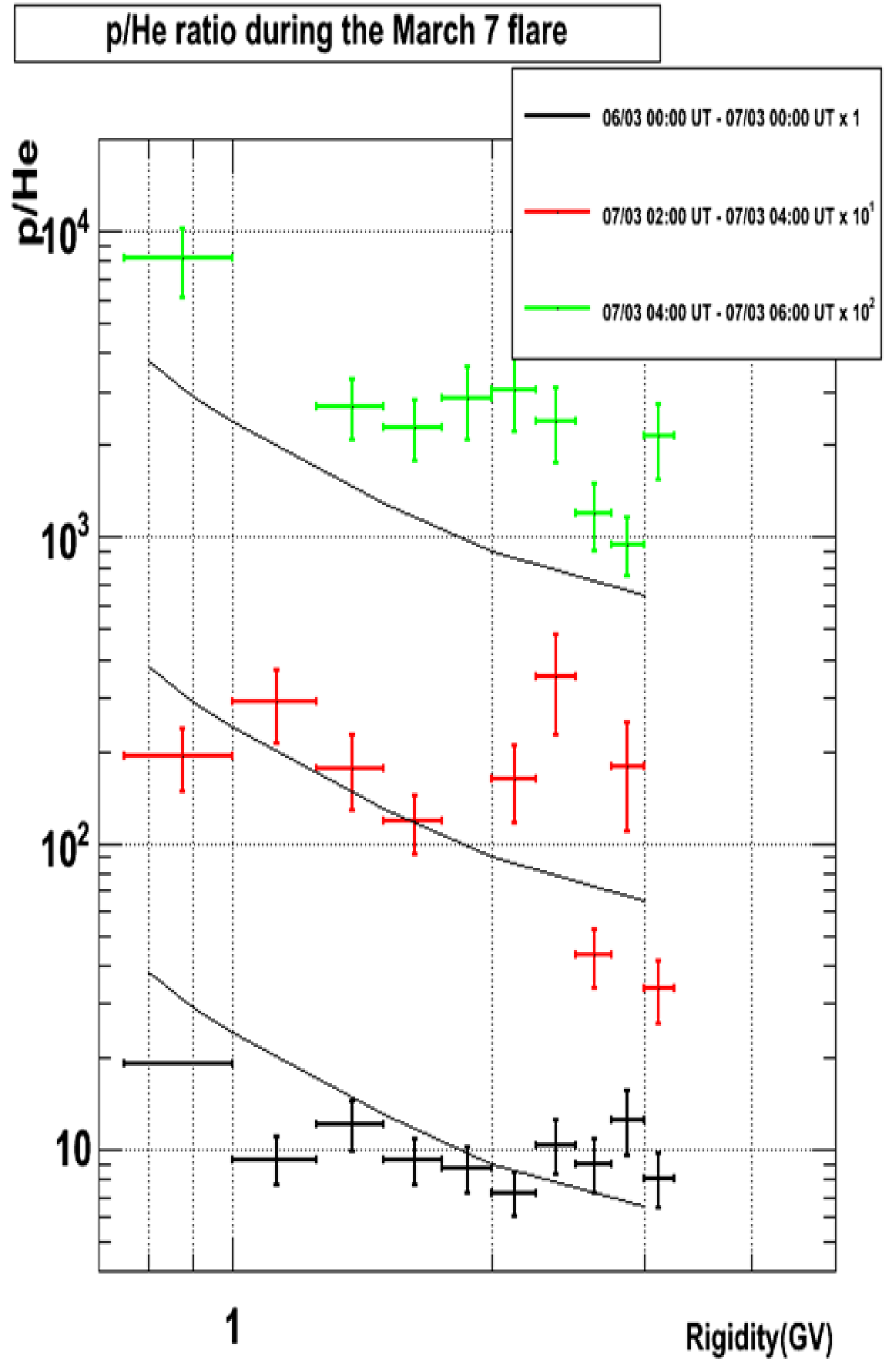
proton flux during the March 7th flare
protons/cm² sr s GeV
Rigidity(GV)
7 March 00:00 UT - 7 March 02:00 UT
7 March 02:00 UT - 7 March 04:00 UT
7 March 04:00 UT - 7 March 06:00 UT
7 March 06:00 UT - 8 March 20:00 UT
8 March 20:00 UT - 10 March 20:00 UT
10 March 20:00 UT - 11 March 20:00 UT
11 March 20:00 UT - 12 March 20:00 UT

proton flux during the March 7th flare
protons/cm² sr s GeV
Rigidity(GV)
7 March 00:00 UT - 7 March 02:00 UT x 10²
7 March 02:00 UT - 7 March 04:00 UT x 10³
7 March 04:00 UT - 7 March 06:00 UT x 10⁴
7 March 06:00 UT - 8 March 20:00 UT x 10⁵
8 March 20:00 UT - 10 March 20:00 UT x 10⁷
10 March 20:00 UT - 11 March 20:00 UT x 10⁹
11 March 20:00 UT - 12 March 20:00 UT x 10¹¹

2012

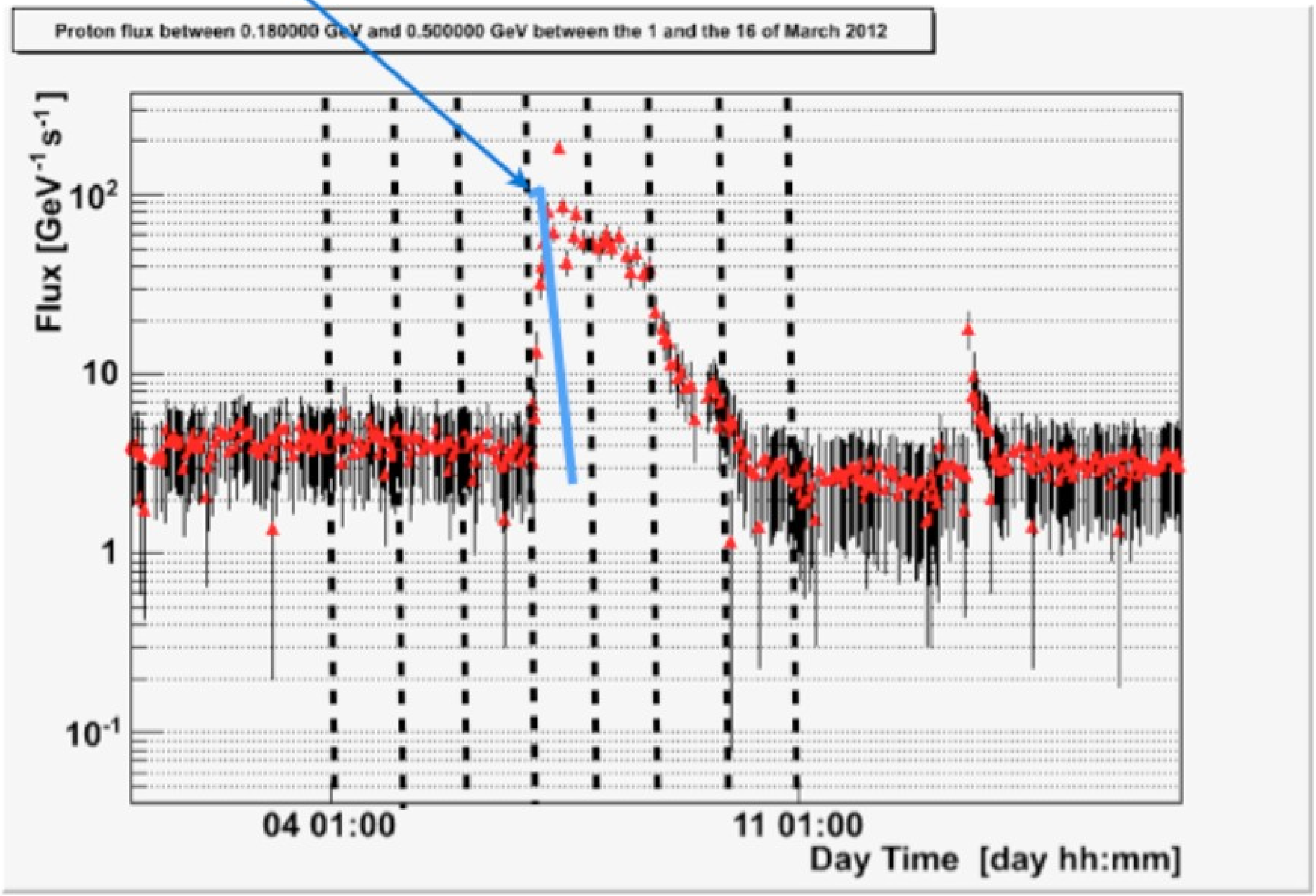

helium flux during the March 7 flare
Helium/(cm$^2$ sr s GeV/n)
06/03 00:00 UT - 07/03 00:00 UT
07/03 02:00 UT - 07/03 04:00 UT
07/03 04:00 UT - 07/03 06:00 UT
07/03 06:00 UT - 07/03 20:00 UT
08/03 10:00 UT - 08/03 12:00 UT
08/03 12:00 UT - 08/03 23:59 UT
09/03 06:00 UT - 09/03 23:00 UT
10
1
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-1}$
1
$E_k$(GeV/n)


p/He ratio during the March 7 flare
06/03 00:00 UT - 07/03 00:00 UT x 1
07/03 02:00 UT - 07/03 04:00 UT x $10^1$
07/03 04:00 UT - 07/03 06:00 UT x $10^2$
p/He
$10^4$
$10^3$
$10^2$
10
1
Rigidity(GV)

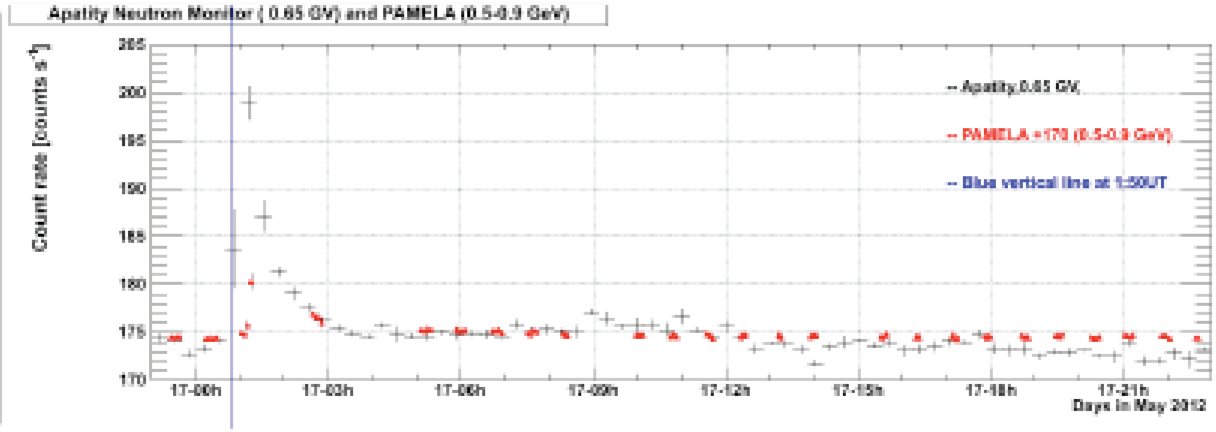
# Solar event March 2012

Fermi/LAT > 100 MeV emission lasted ~ 20 hrs

6/19/12 4:11 PM

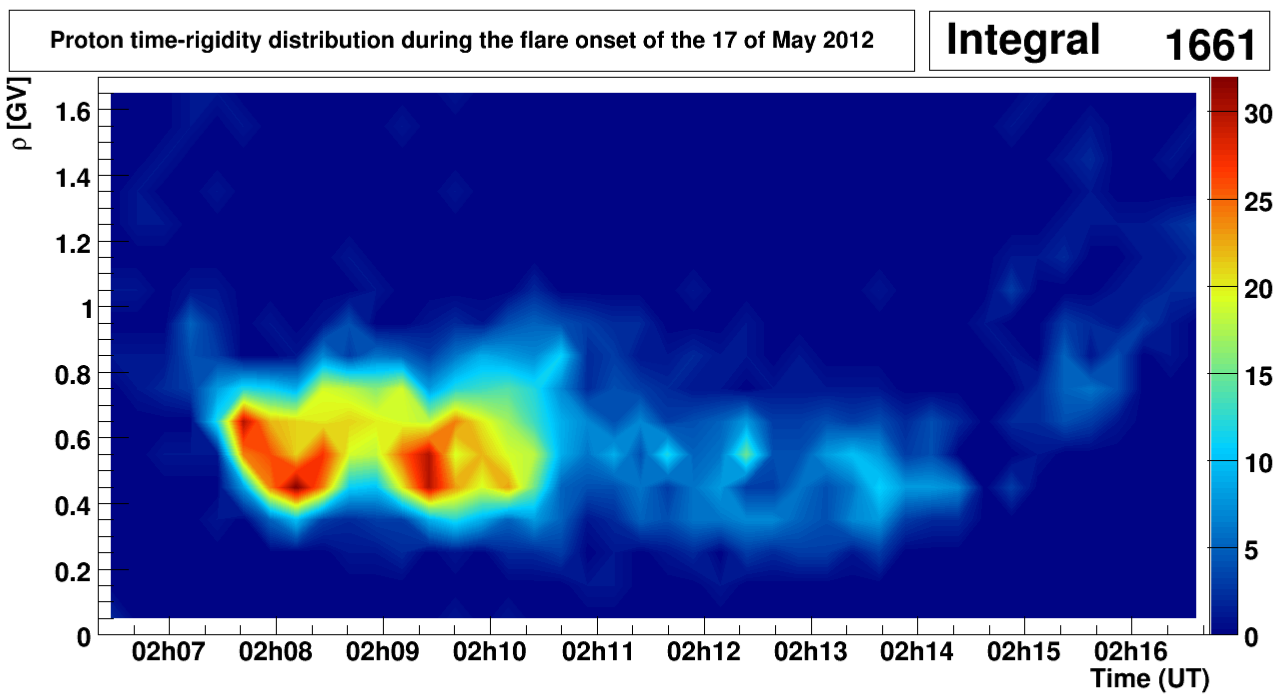


# Evento Solare 17 Maggio 2012

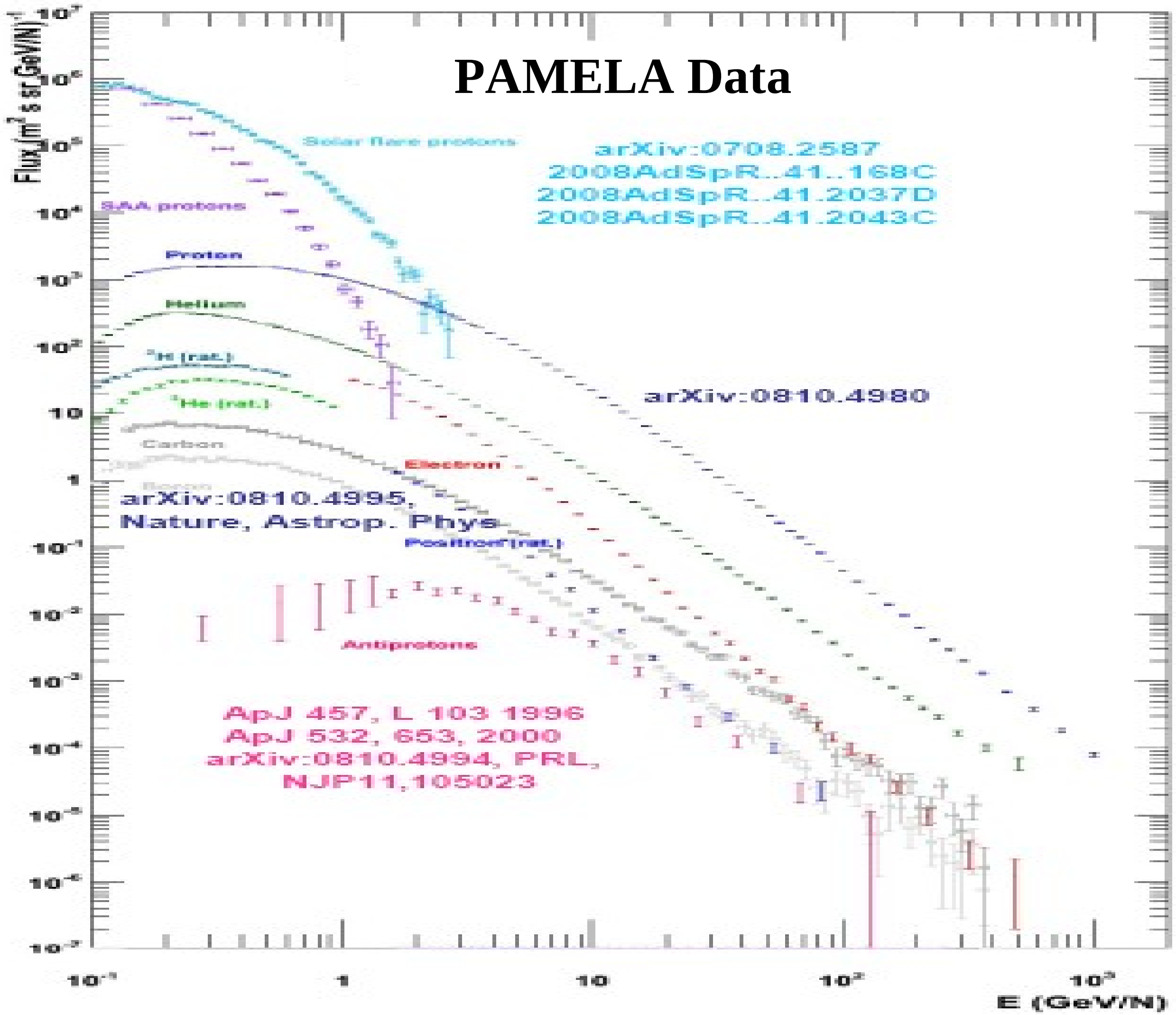



**L'evento del 17 maggio era un evento impulsivo (classe M5.1) ben connesso magneticamente con la Terra. Si tratta del primo GLE dal 2006.**

**PAMELA era perfettamente posizionata per vedere l'inizio ed il picco dell'evento.**
**L'inizio appare essere leggermente in ritardo rispetto al NM Apatity ma PAMELA riesce a misurarlo con risoluzione del minuto e migliore.**



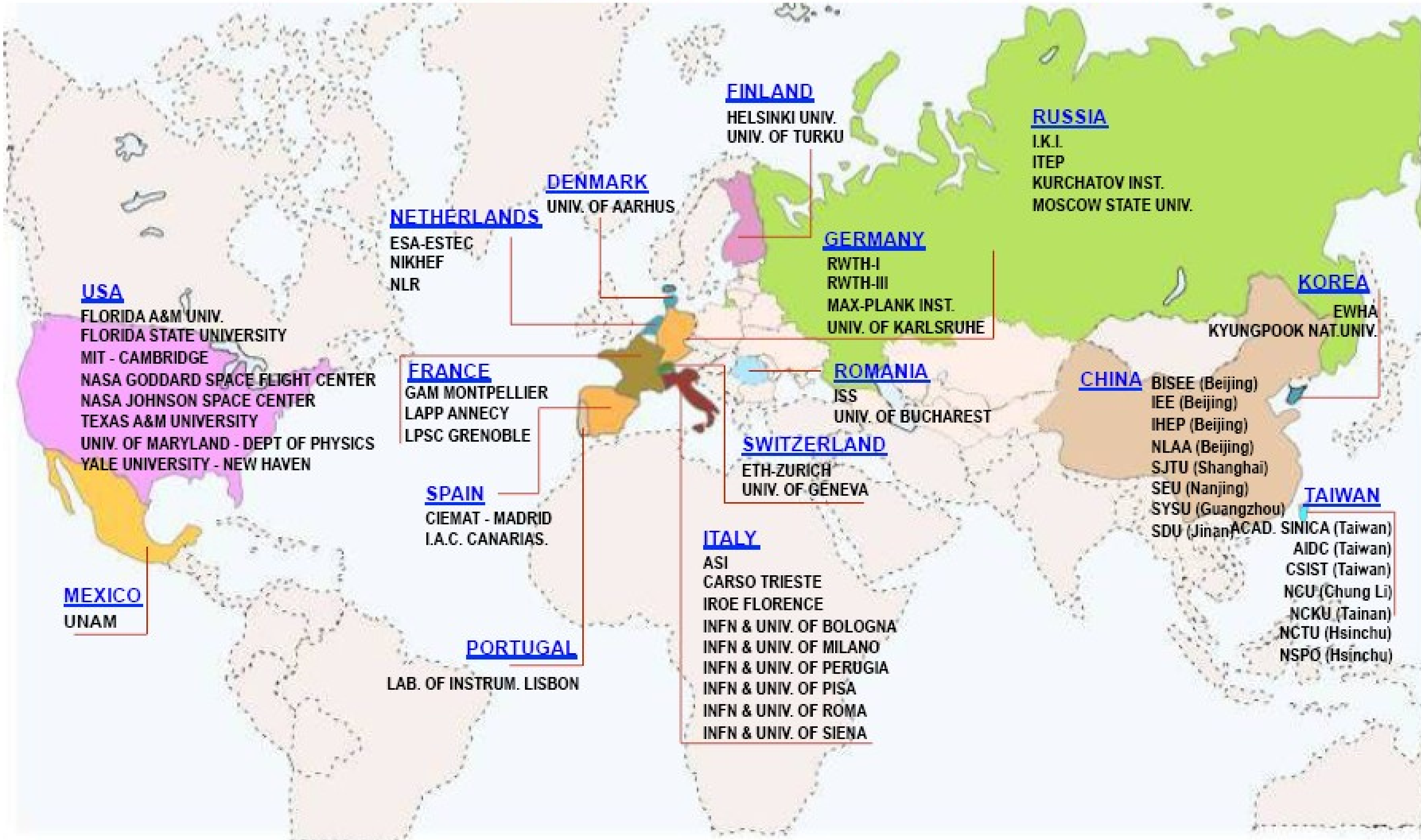
# Summary PAMELA Results



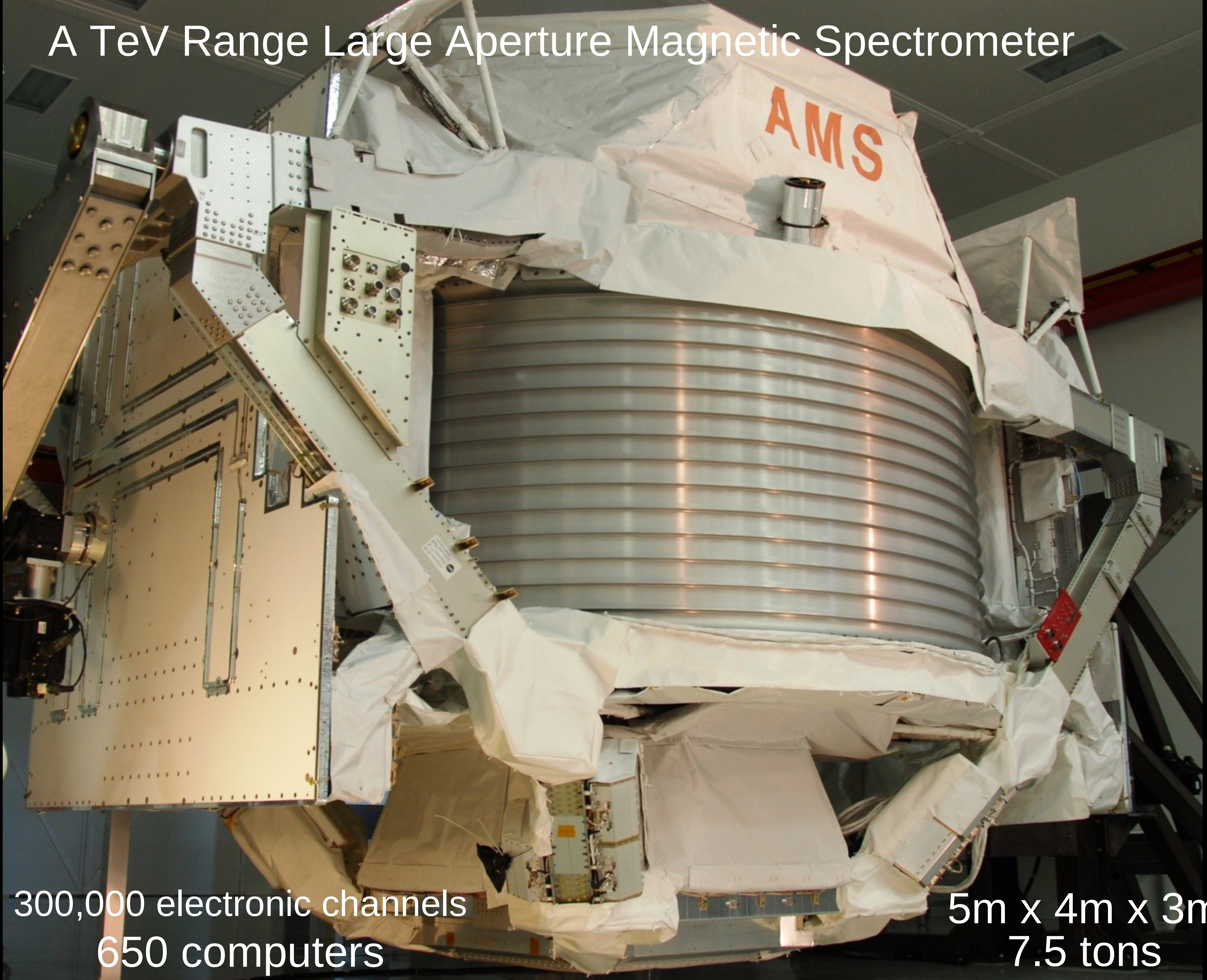
# The Alpha Magnetic Spectrometer Experiment on the International Space Station

# AMS is US Dept of Energy (DOE) led International Collaboration

## 16 Countries, 60 Institutes and 600 Physicists, 17 years




**The detectors were built all over the world and assembled at CERN, near Geneva, Switzerland**


A TeV Range Large Aperture Magnetic Spectrometer
AMS
300,000 electronic channels
650 computers
5m x 4m x 3m
7.5 tons

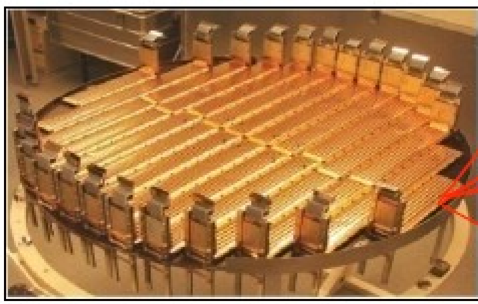

AMS is installed on the ISS
Truss and fully operational
since May 19, 2011
ELC2

# AMS consitst of 5 sub-detetcors which provide reduandant information for particle identification

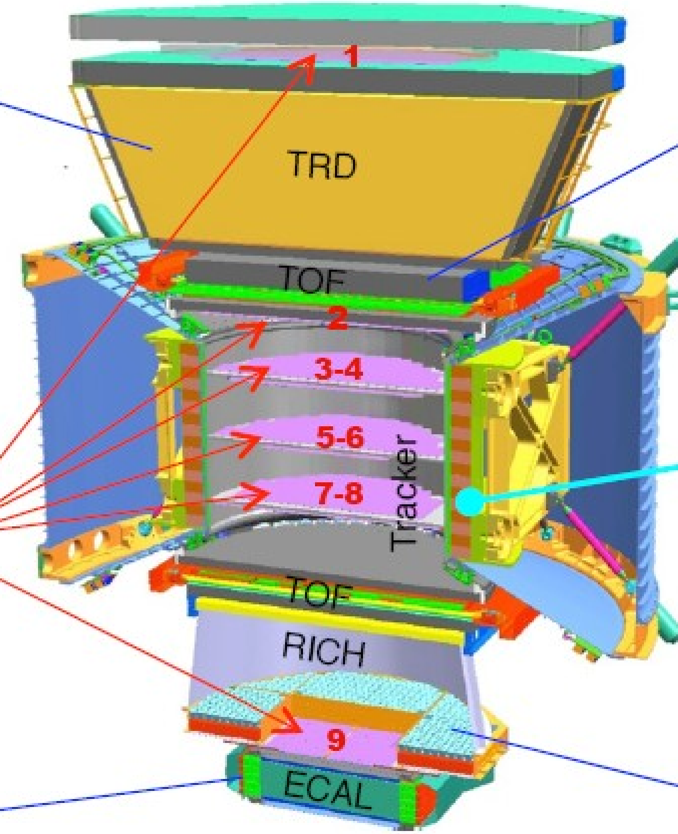
Particles and nuclei are defined by their charge (**Z**) and energy (**E ~ P**)

**TRD**
**Identify e+, e-**

**Silicon Tracker**
**Z, P**

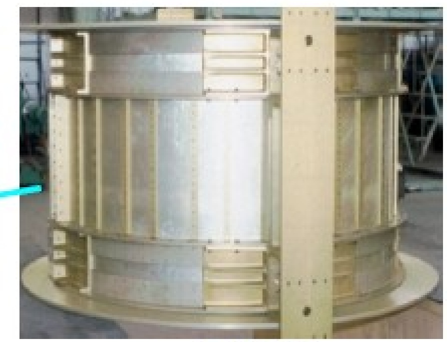


**ECAL**
**E of e+, e-, γ**




**TOF**
**Z, E**

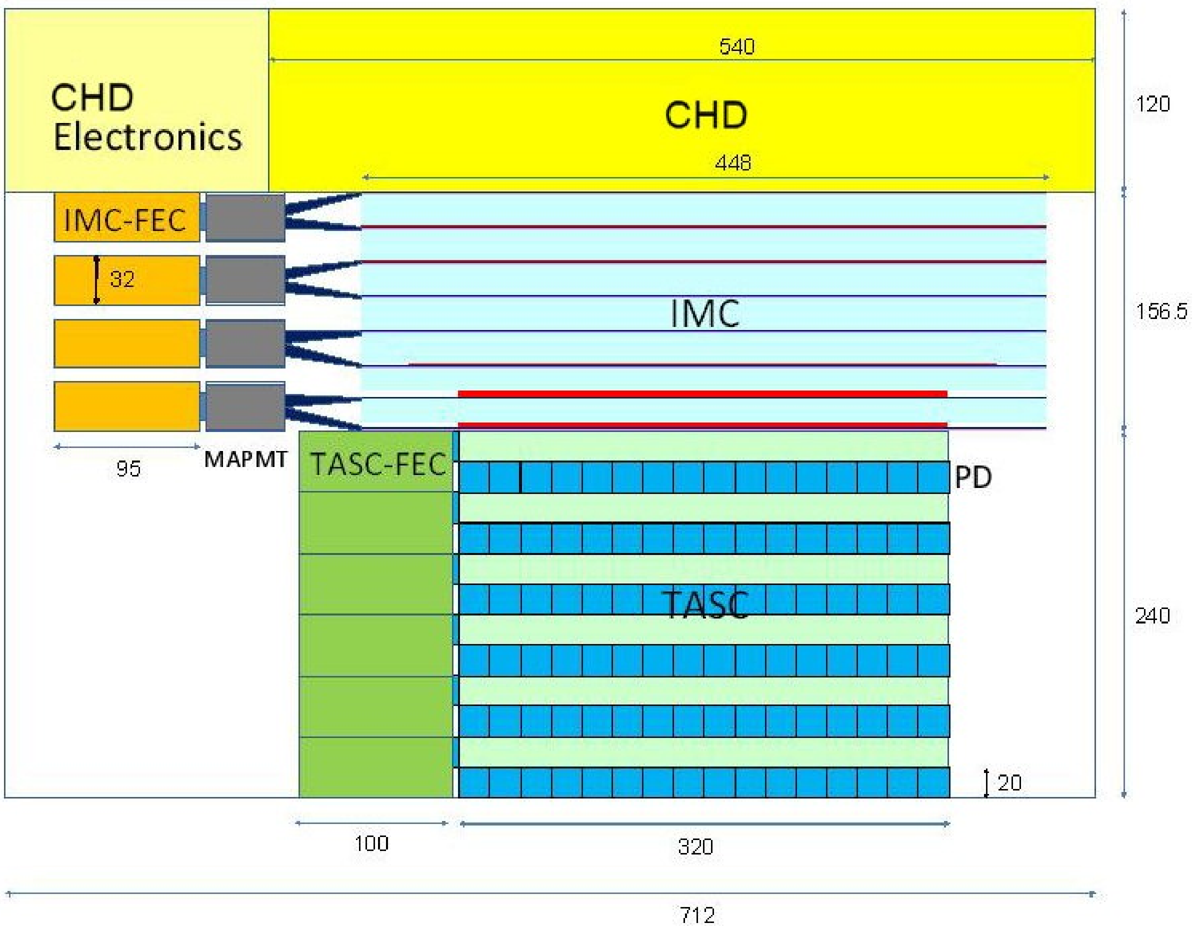
**Magnet**
**±Z**



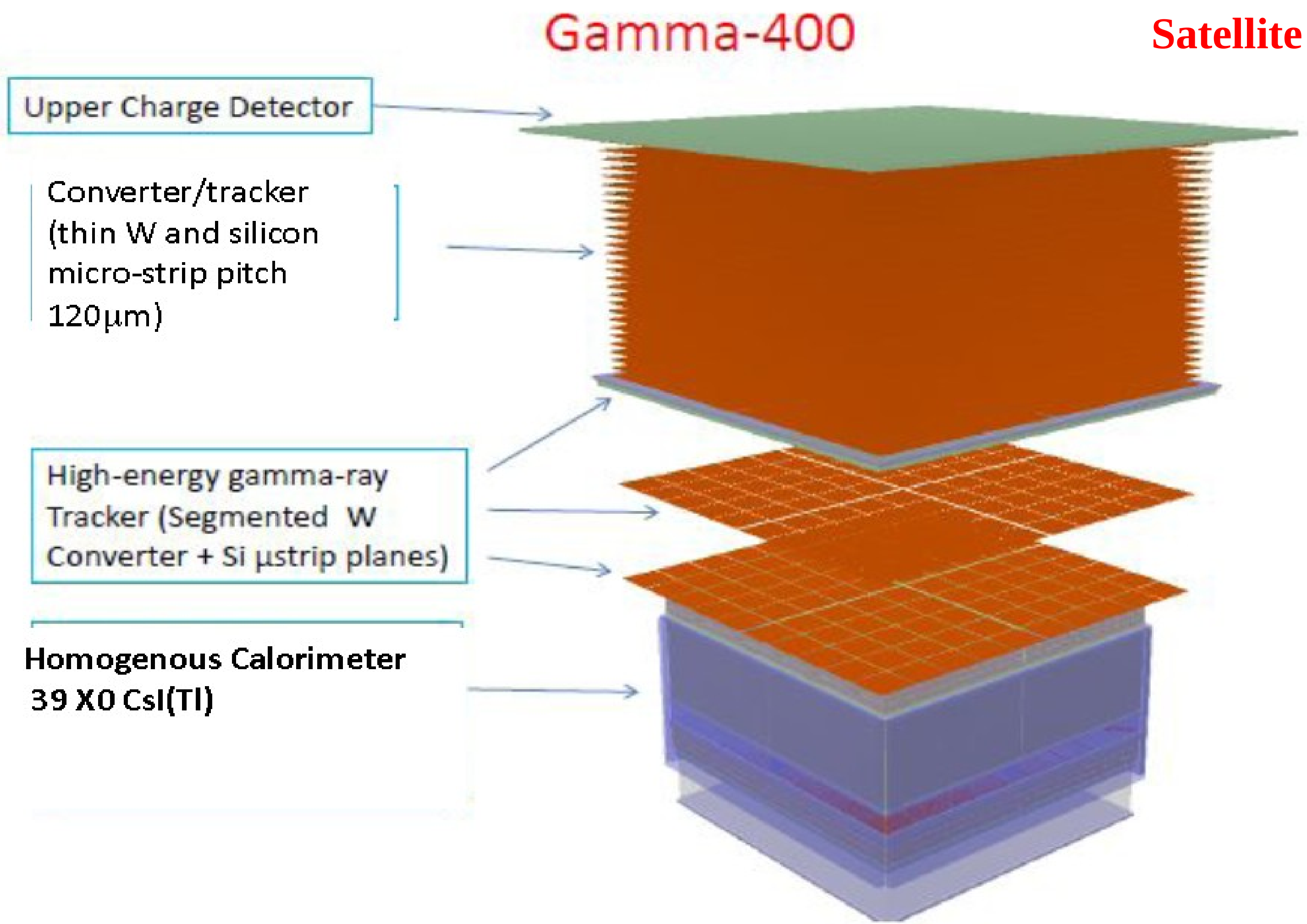
**RICH**
**Z, E**

*Z, P are measured independently by the Tracker, RICH, TOF and ECAL*

# CALET KIBO-ISS

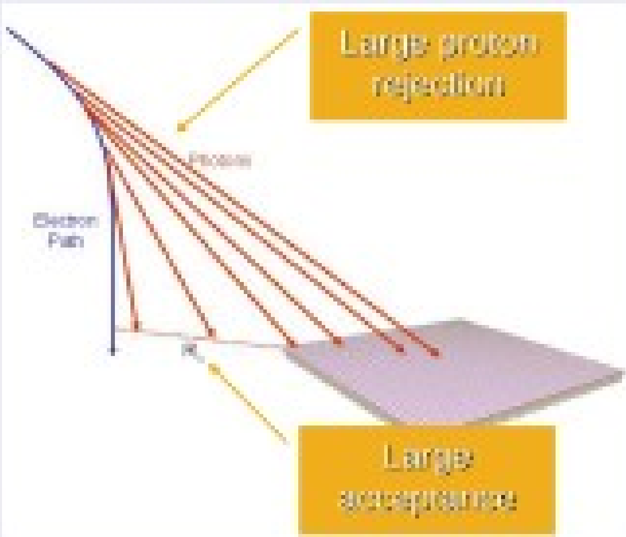



**Electrons up to 20 TeV**
**Launch 2015**



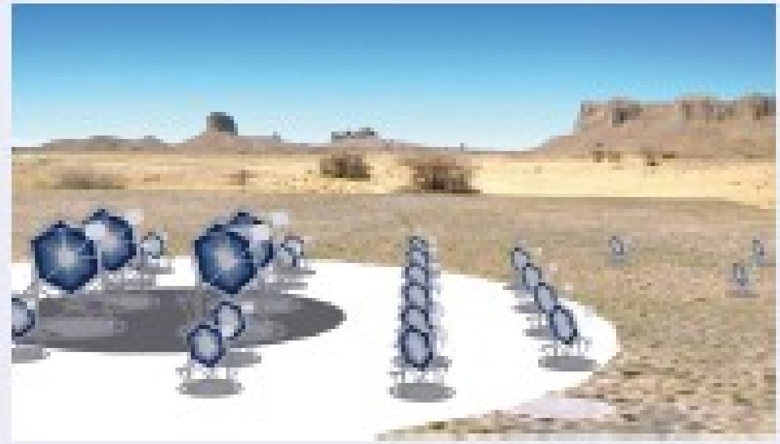

- *Launch foreseen by end 2018*
- gamma-rays from 30 MeV up to 300GeV energies
- electrons/positrons in the TeV energy range and beyond
- proton/ion cosmic-rays up to the "knee"

## CREST (Cosmic Ray Electron Synchrotron Telescope)




- Two Antarctic LDBFs [redacted].
- All electrons from 2 TeV to 50 TeV.
- Detect synchrotron radiation of primary electron as it passes through Earth's magnetic field: 1024 $BaF_2$ crystal with hermetic ACD.
- Signal: line of photons arriving nearly simultaneously (mean energy 10 keV–5 MeV, related to the primary electron energy).

## CTA



- Planning for the next-generation ground-based gamma-ray observatories started.

[redacted]

- Sensitivity improved by one order of magnitude.
- All electrons up to $\approx$ 10 TeV.

# Thanks!

http:// pamela.roma2.infn.it