Cosmic Ray Studies with PAMELA Experiment

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INFN and University of Rome Tor Vergata

14th Lomonosov Conference on Elementary Particle Physics

MSU, Moscow
August 19 – 25, 2009

PAMELA

Payload for Antimatter Matter Exploration and Light Nuclei Astrophysics

PAMELA Collaboration

Italy: Bari, Florence, Frascati, Naples, Rome, Trieste, CNR, Florence

Russia: Moscow, St. Petersburg

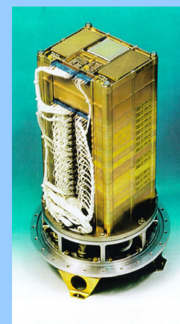
Germany: Siegen

Sweden: KTH, Stockholm

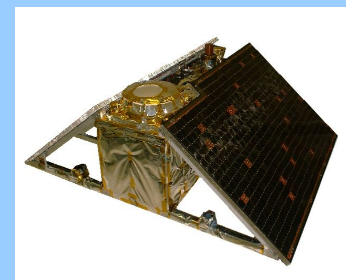
WiZard Russian Italian Missions

MASS-89, 91, TS-93, CAPRICE 94-97-98

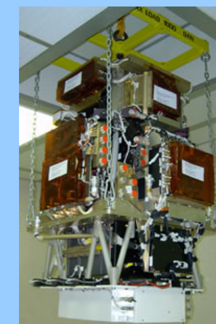
NINA-1



NINA-2



PAMELA



M 89 · M 91 · TS 93 · C 94 · C 97 · C 98 · PAMELA

…1989 · 1990 · 1991 · 1992 · 1993 · 1994 · 1995 · 1996 · 1997 · 1998 · 1999 · 2000 · 2001 · 2002 · 2003 · 2004 · 2005 · 2006 · 2007..

SILEYE-1

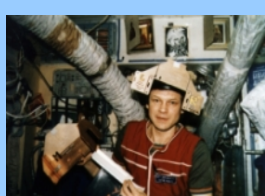
NINA-1

NINA-2

Alteino-SILEYE-3

ALTEA-SILEYE-4

SILEYE-2

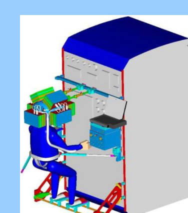


SILEYE-1

SILEYE-2

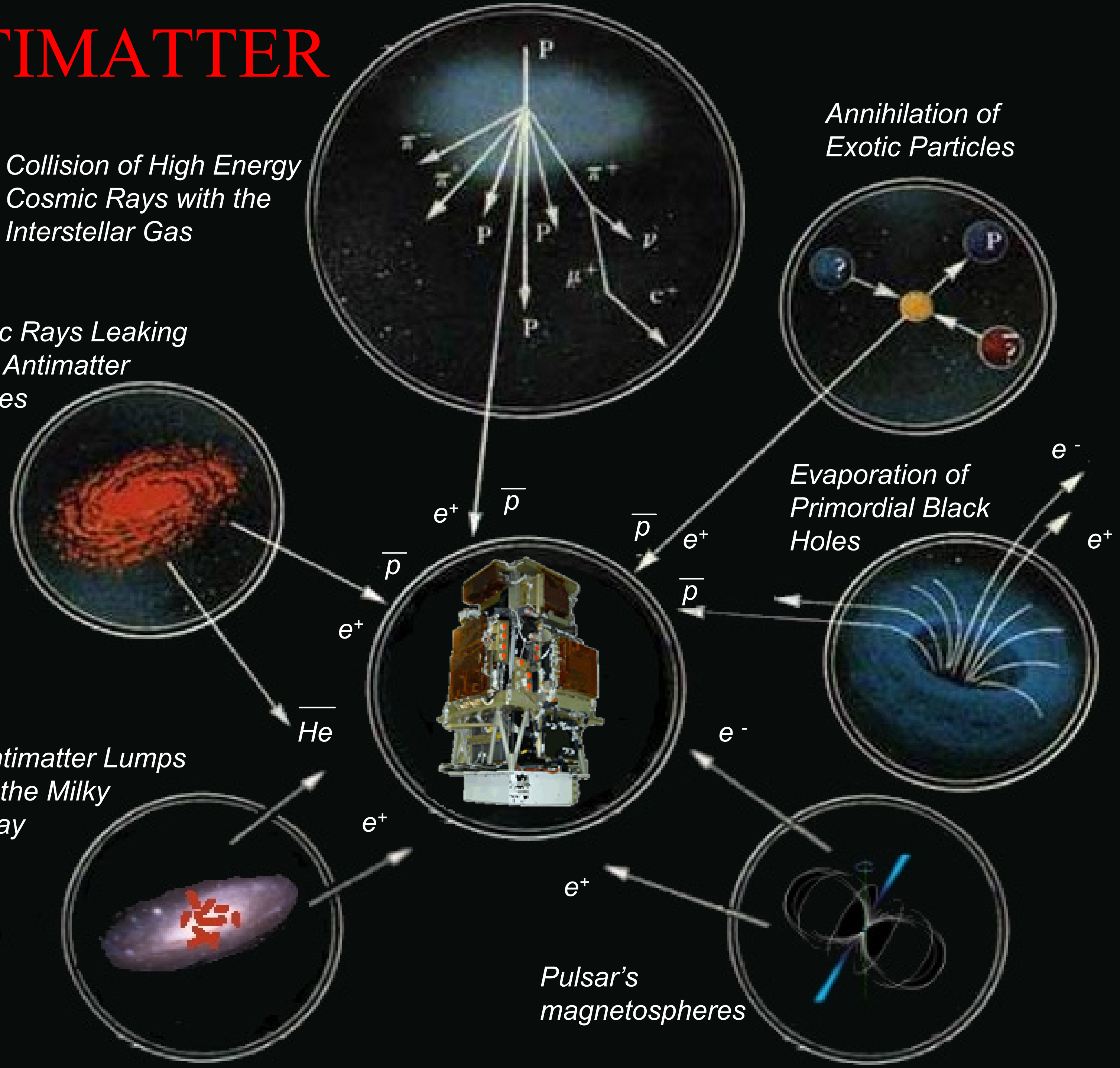
ALTEINO: SILEYE-3

LAZIO SIRAD



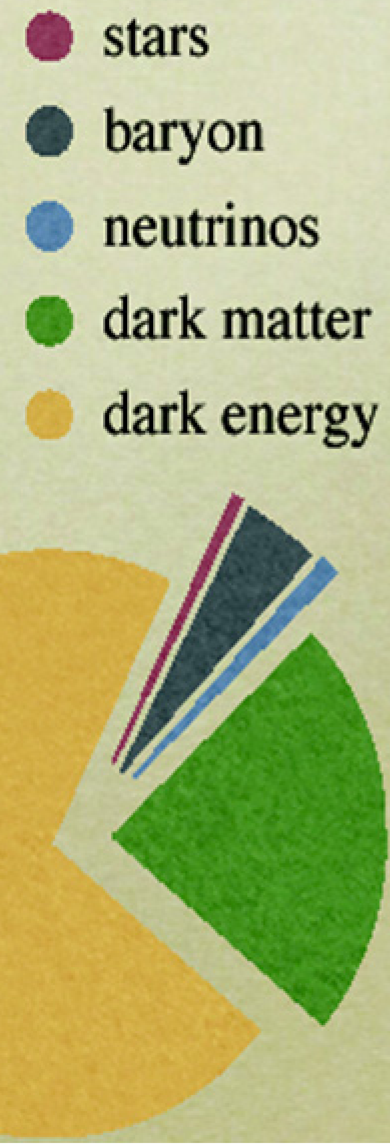
ALTEA: SILEYE-4

ANTIMATTER


Collision of High Energy Cosmic Rays with the Interstellar Gas
P
π^-
π
π^+
P
P
ν
μ^+
e^+
P
Annihilation of Exotic Particles
?
P
?
Cosmic Rays Leaking Out of Antimatter Galaxies
Evaporation of Primordial Black Holes
e^-
e^+
e^+
$\bar{p}$
$\bar{p}$
e^+
$\bar{p}$
e^+
$\bar{p}$
$\overline{He}$
e^-
Antimatter Lumps In the Milky Way
e^+
e^+
Pulsar’s magnetospheres

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 ~10^{62}%??*



The SUSY Particle Spectrum

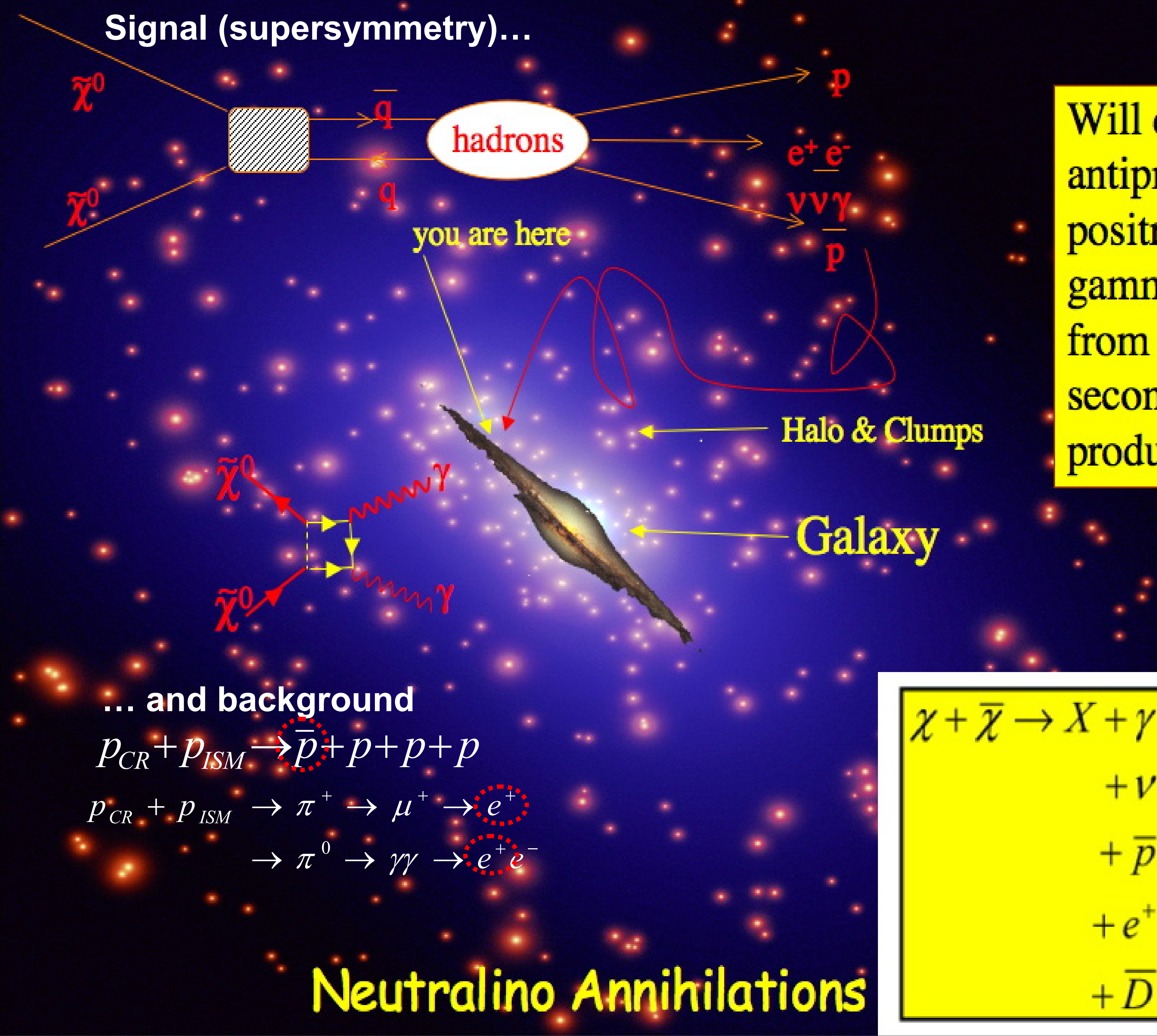
Standard Model

Particles			Sparticles		
Name	Symbol	Spin	Name	Symbol	Spin
leptons	l, ν	1/2	sleptons	$\tilde{l}_R, \tilde{l}_L, \tilde{\nu}_L$	0
quarks	q_L, q_R	1/2	squarks	$\tilde{q}_L, \tilde{q}_R (\tilde{b}_{1,2}, \tilde{t}_{1,2})$	0
photon Z boson light Higgs heavy Higgs pseudoscalar Higgs	γ Z h H A	1 1 0 0 0	neutralinos	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	1/2
W boson charged Higgs	$W\pm$ $H\pm$	1 1	charginos	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	1/2
gluon	g	1	gluino	$\tilde{g}$	1/2
graviton	G	2	gravitino	$\tilde{G}$	3/2

'LSP'
(usually)

$$\chi = N_1\tilde{\gamma} + N_2\tilde{Z}^0 + N_3\tilde{H}_1^0 + N_4\tilde{H}_2^0; \sum_{i=1}^{4} |N_i|^2 = 1$$

Mark Pearce [pearce@particle.kth.se]



Will distort the antiproton positron and gamma spectra from purely secondary production

$$\chi + \bar{\chi} \to X + \gamma$$ (GLAST-FERMI AMS-02)

$$+ \nu$$ (AMANDA / IceCube)

$$+ \bar{p}$$

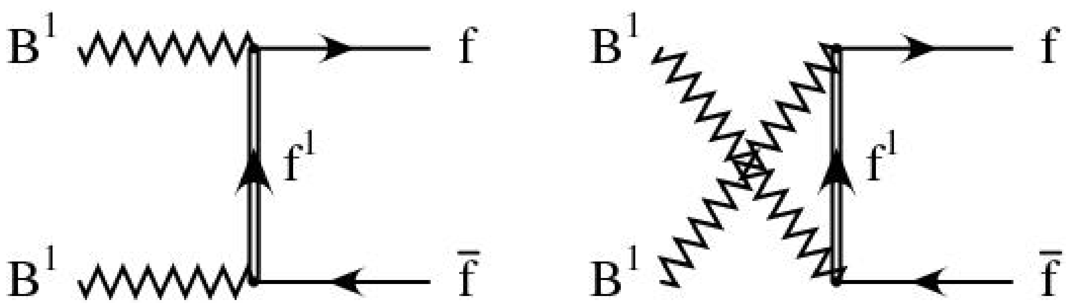
$$+ e^+$$

$$+ \bar{D}$$

PAMELA (and Bess, HEAT, AMS etc.)

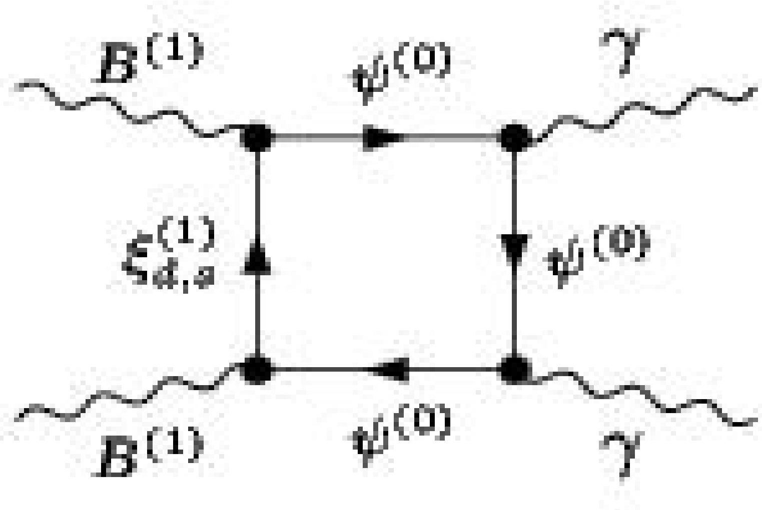
Another possible scenario:
KK Dark Matter

Lightest Kaluza-Klein Particle (LKP): $B^{(1)}$



Bosonic Dark Matter:
fermionic final states
no longer helicity suppressed.
e+e- final states directly produced.

As in the neutralino case there are 1-loop processes that produces monoenergetic
γ γ in the final state.



Decay Channels

Positron fraction from decaying dark matter: model independent analysis

Possible decay channels

AI, Tran

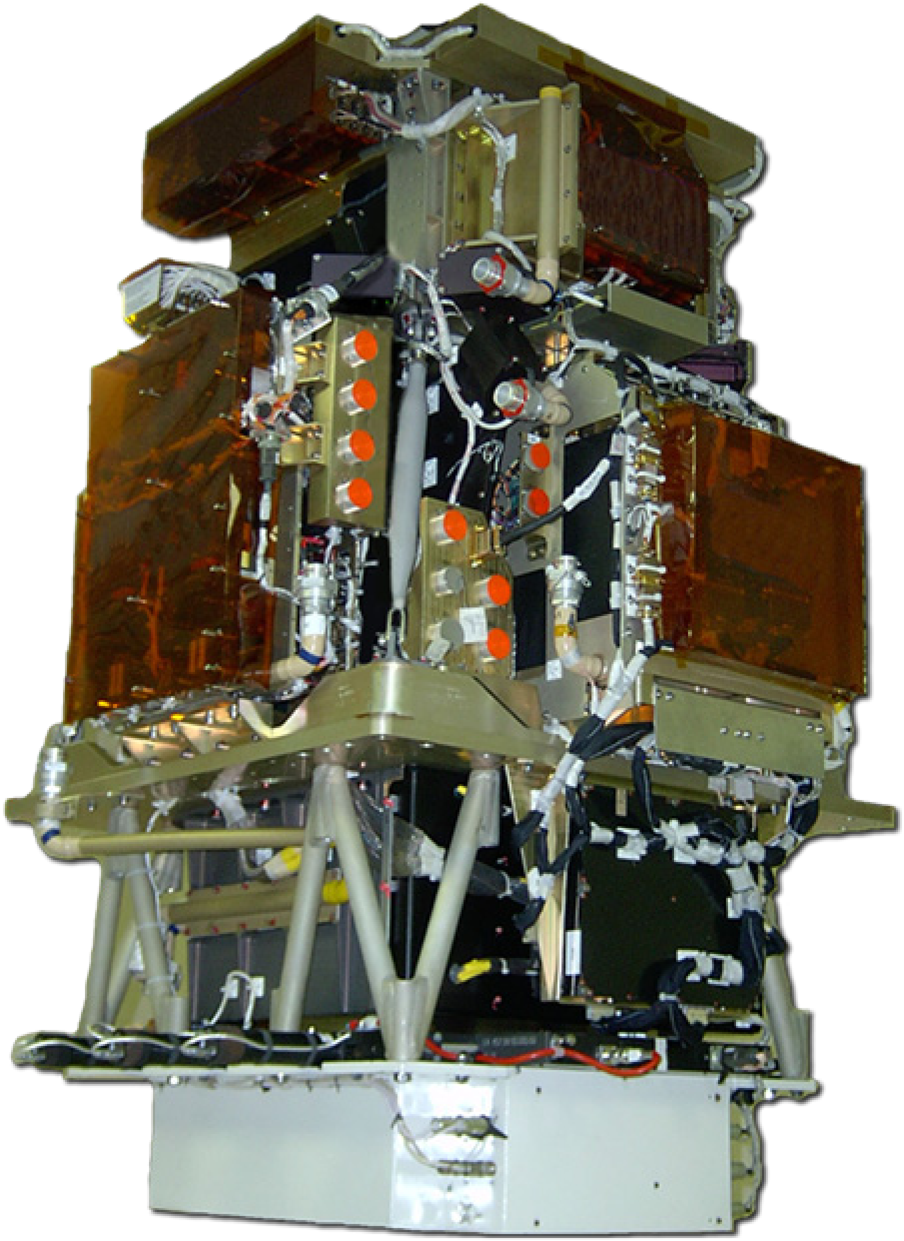
fermionic DM

- $\psi \to Z^0 \nu$
- $\psi \to W^{\pm} \ell^{\mp}$
- $\psi \to \ell^+ \ell^- \nu$

scalar DM

- $\phi \to Z^0 Z^0$
- $\phi \to W^+ W^-$
- $\phi \to \ell^+ \ell^-$

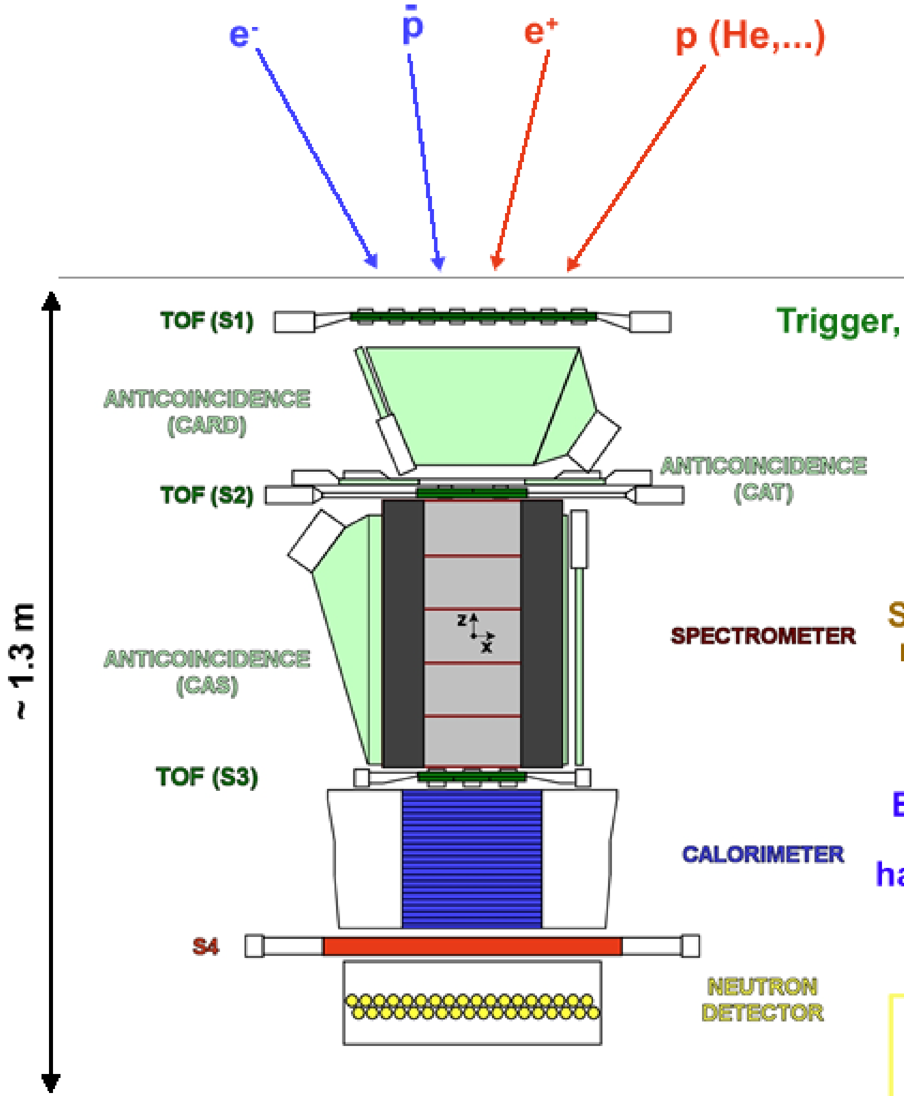
PAMELA Instrument



GF ~21.5 cm^{2}sr

Mass: 470 kg

Size: 130x70x70 cm^3



~470 Kg / ~360 W

Trigger, ToF, dE/dx

- S1, S2, S3; double layers, x-y
- plastic scintillator (8mm)
- ToF resolution ~300 ps (S1-3 ToF >3 ns)
- lepton-hadron separation < 1 GeV/c
- S1.S2.S3 (low rate) / S2.S3 (high rate)

Sign of charge, rigidity, dE/dx

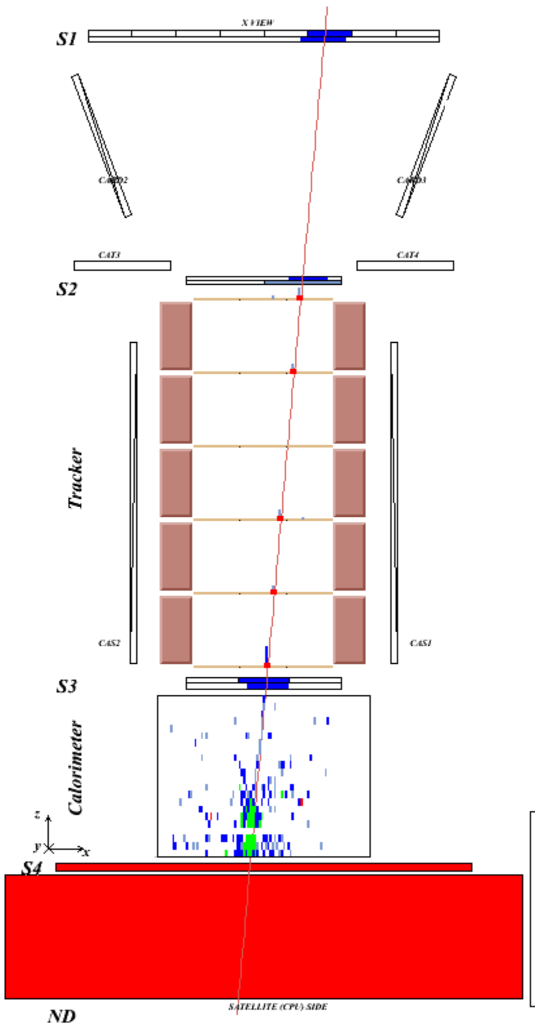
- Permanent magnet, 0.43 T
- 21.5 cm^2 sr
- 6 planes double-sided silicon strip detectors (300 μm)
- 3 μm resolution in bending view → MDR ~800 GV (6 plane) ~500 GV (5 plane)

Electron energy, dE/dx, lepton-hadron separation

- 44 Si-x / W / Si-y planes (380)
- 16.3 X0 / 0.6 L
- dE/E ~5.5 % (10 - 300 GeV)
- Self trigger > 300 GeV / 600 cm^2 sr

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

Proton / positron selection



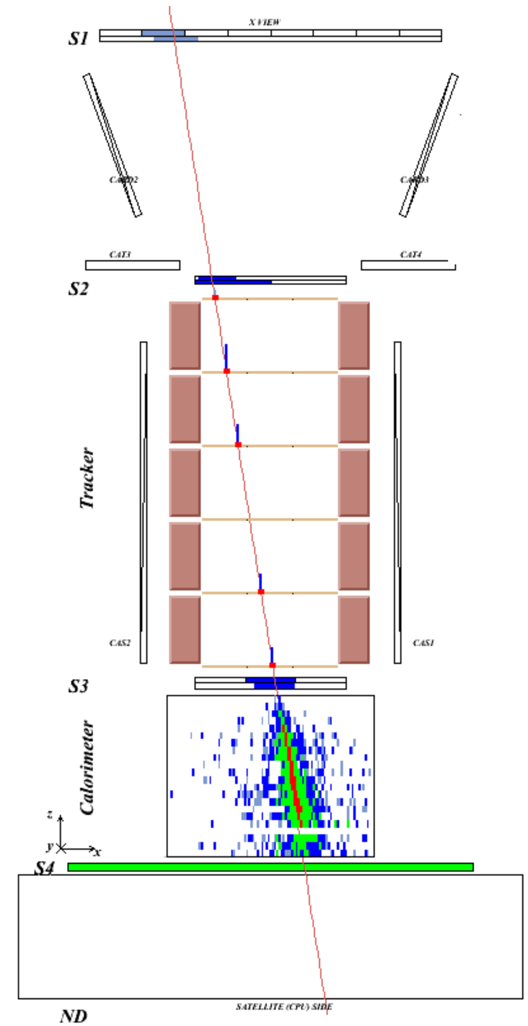
Proton

Time-of-flight:
trigger, albedo rejection, mass determination (up to 1 GeV)

Bending in spectrometer:
sign of charge

Ionisation energy loss (dE/dx):
magnitude of charge

Interaction pattern in calorimeter:
electron-like or proton-like, electron energy



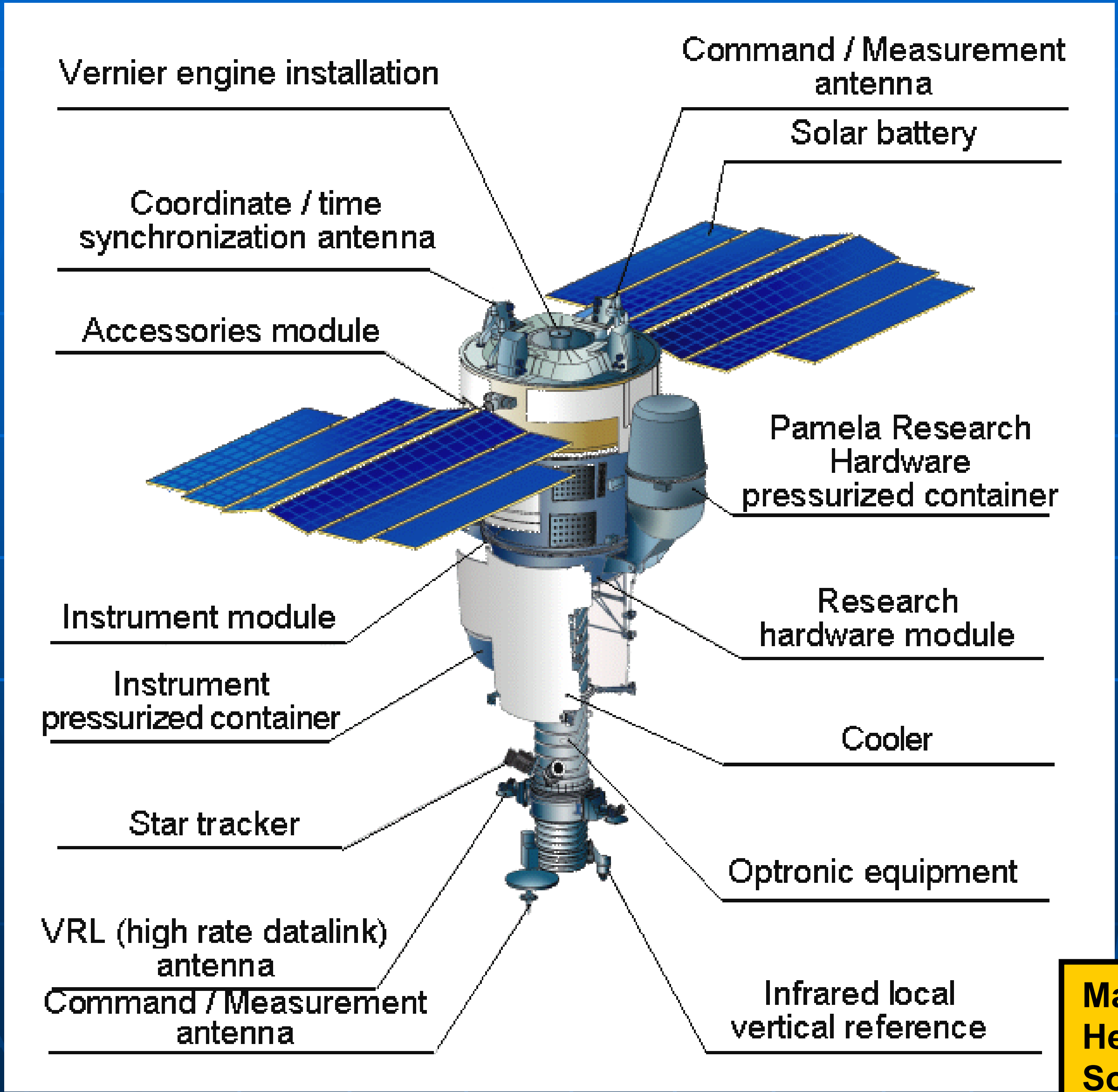
Positron

Design Performance

Energy range	
Antiprotons	80 MeV - 190 GeV
Positrons	50 MeV – 300 GeV
Electrons	up to 500 GeV
Protons	up to 1 TeV
Electrons+positrons	up to 2 TeV (from calorimeter)
Light Nuclei (He/Be/C)	up to 200 GeV/n
AntiNuclei search	sensitivity of $3x10^{-8}$ in $\overline{He}/He$

→ **Simultaneous measurement of many cosmic-ray species**
→ **New energy range**
→ **Unprecedented statistics**

Resurs-DK1 satellite

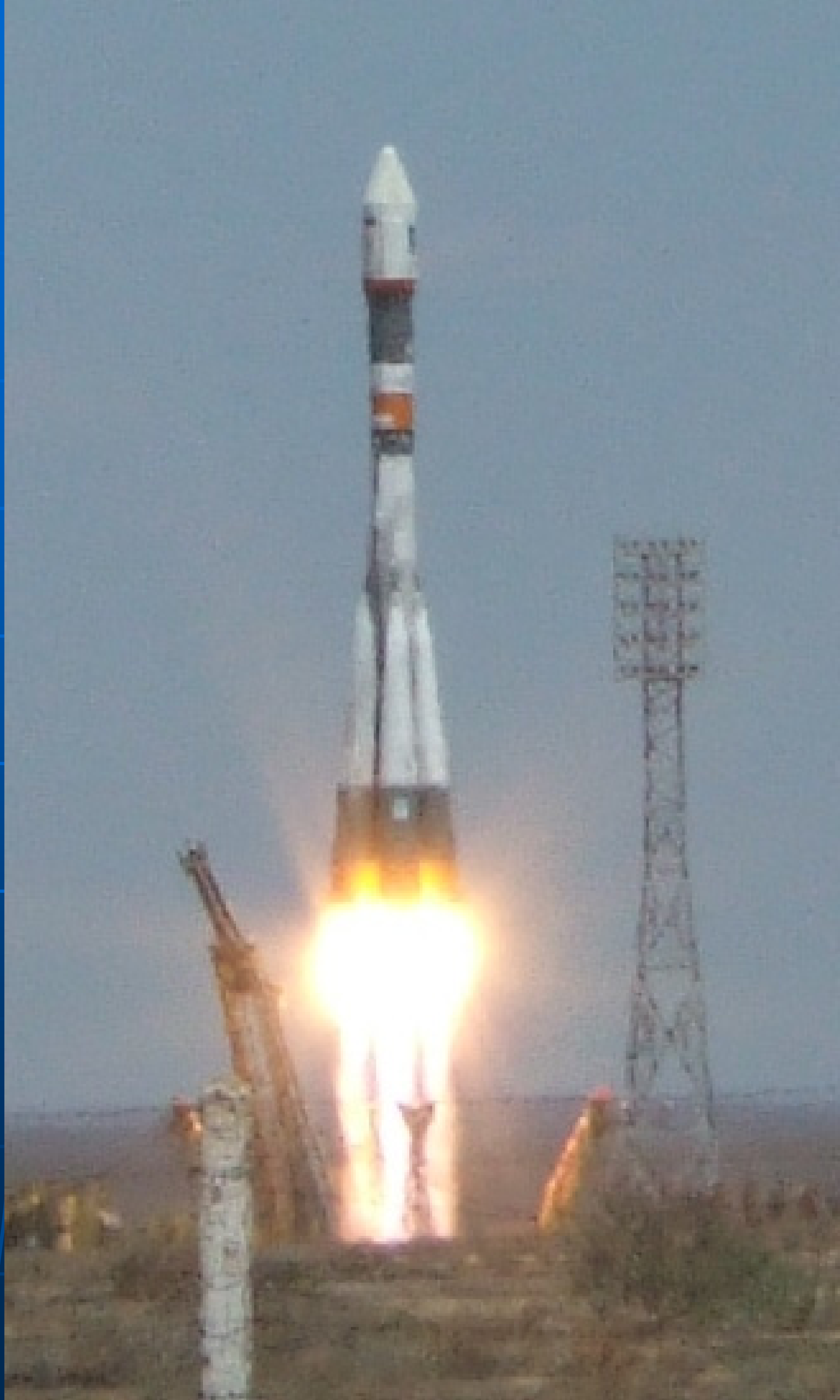


- **Main task:** multi-spectral remote sensing of earth's surface
  - Built by TsSKB Progress in Samara, Russia
- **Lifetime >3 years (assisted)**
  - Data transmitted to ground via high-speed radio downlink
- **PAMELA mounted inside a pressurized container**

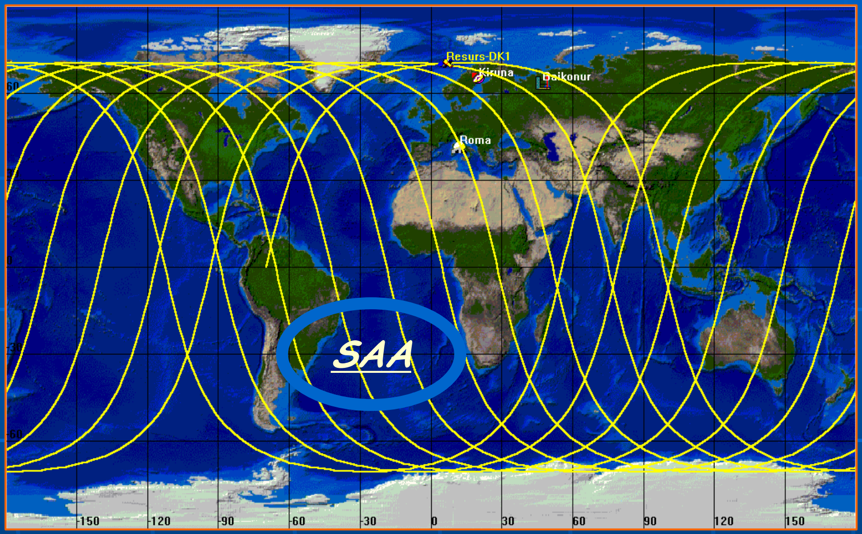
Mass: 6.7 tonnes
Height: 7.4 m
Solar array area: 36 m^2

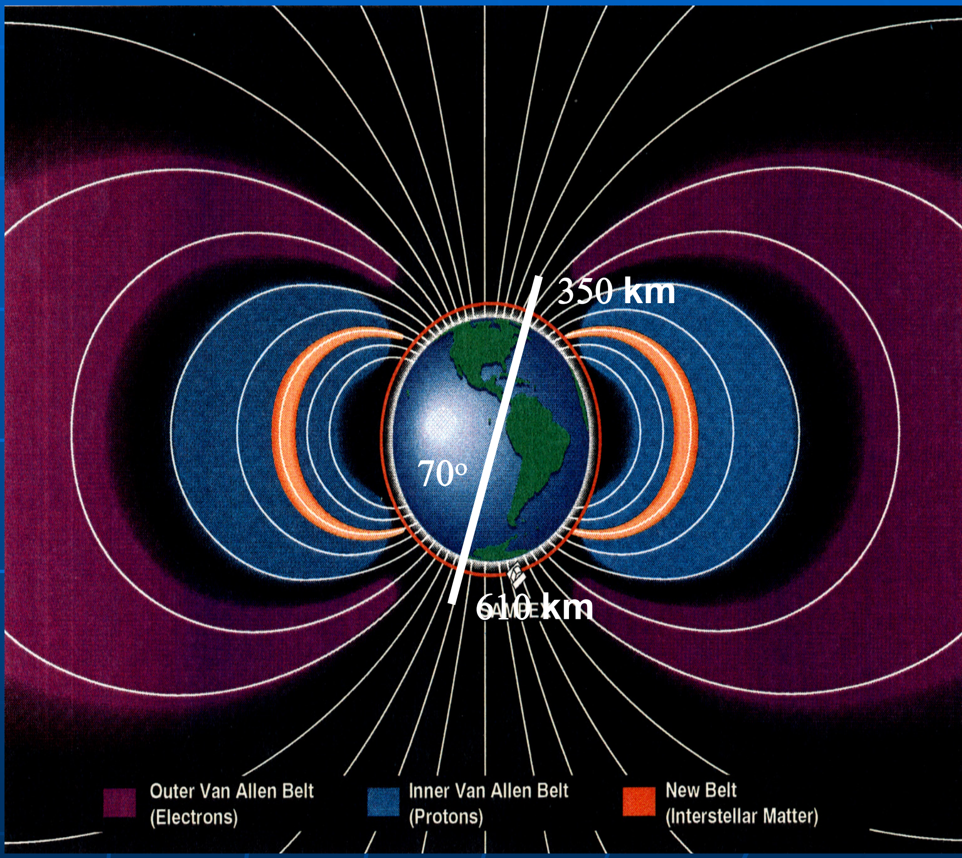
PAMELA
Launch
15 June 2006

Bajkonur Cosmodrome
(Kazakhstan)



Orbit Characteristics





- Low-earth elliptical orbit
- 350 – 610 km
- Quasi-polar (70° inclination)
- SAA crossed
- 16 Gigabytes trasmitted daily to Ground-NTsOMZ Moscow

PAMELA Status

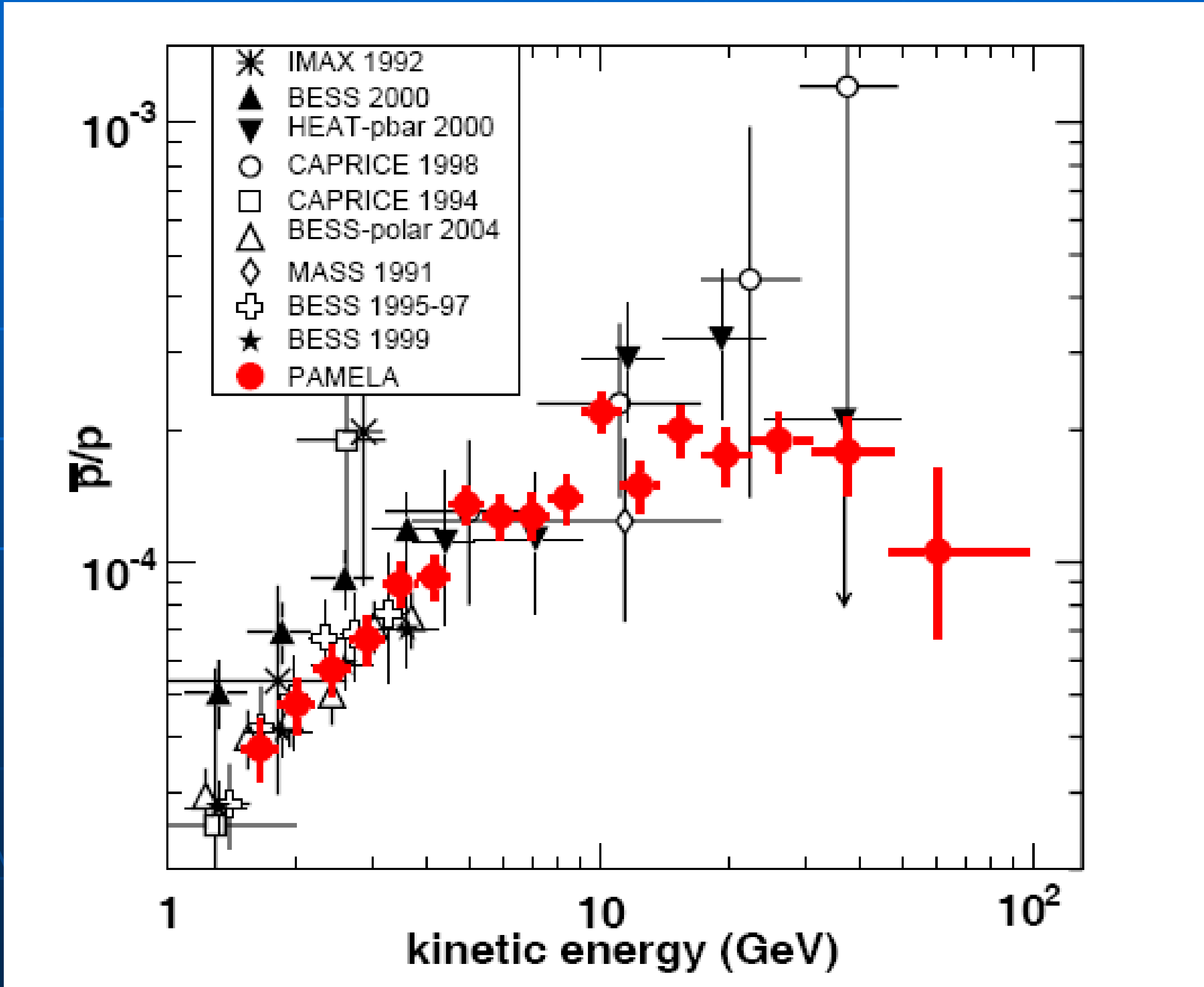
- Today 1162 days in flight
- data taking ~73% live-time

- >14 TBytes of raw data downlinked

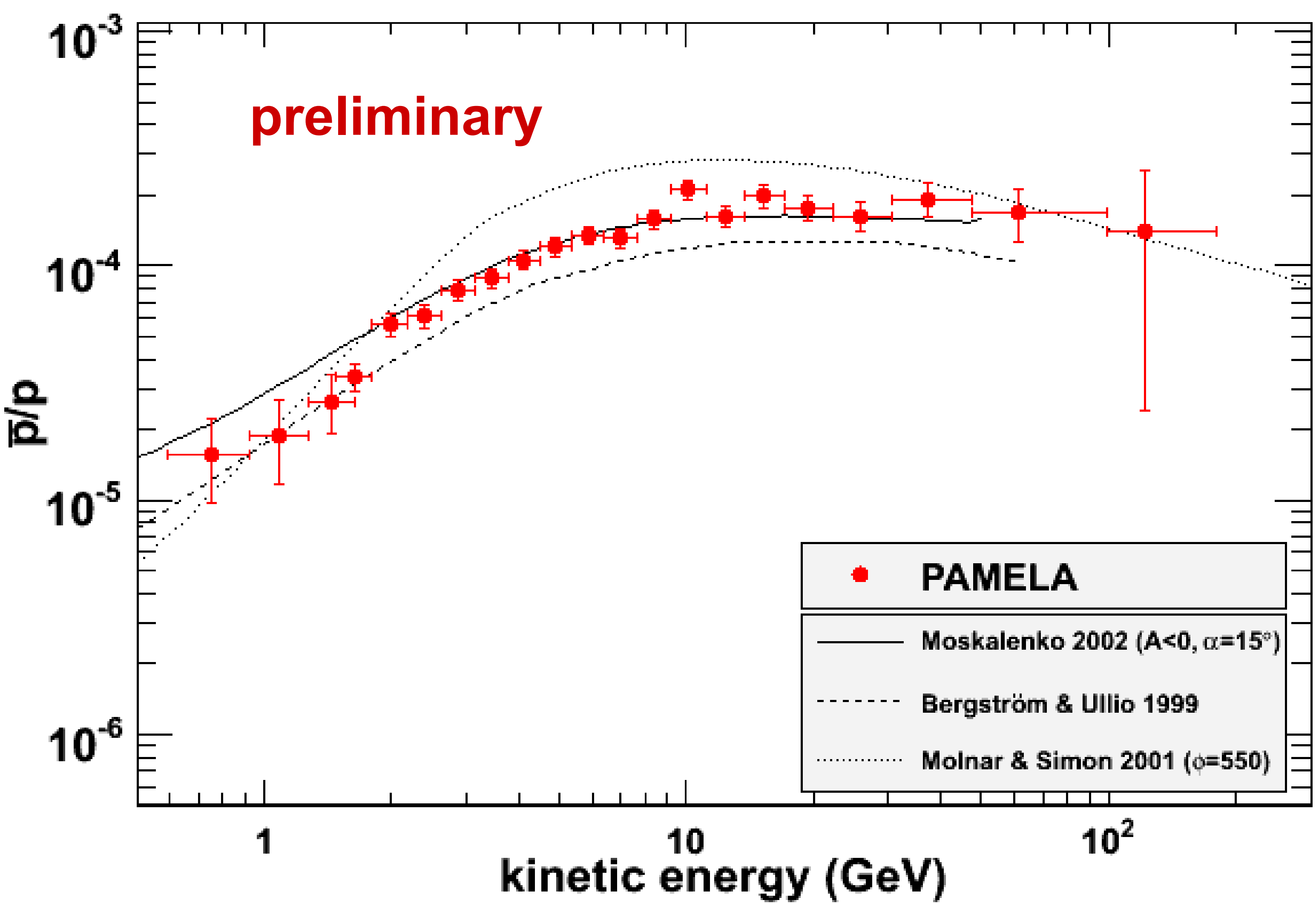
- >1.4 10^9 triggers recorded and under analysis

Antiproton to proton ratio

PRL 102, 051101 (2009)



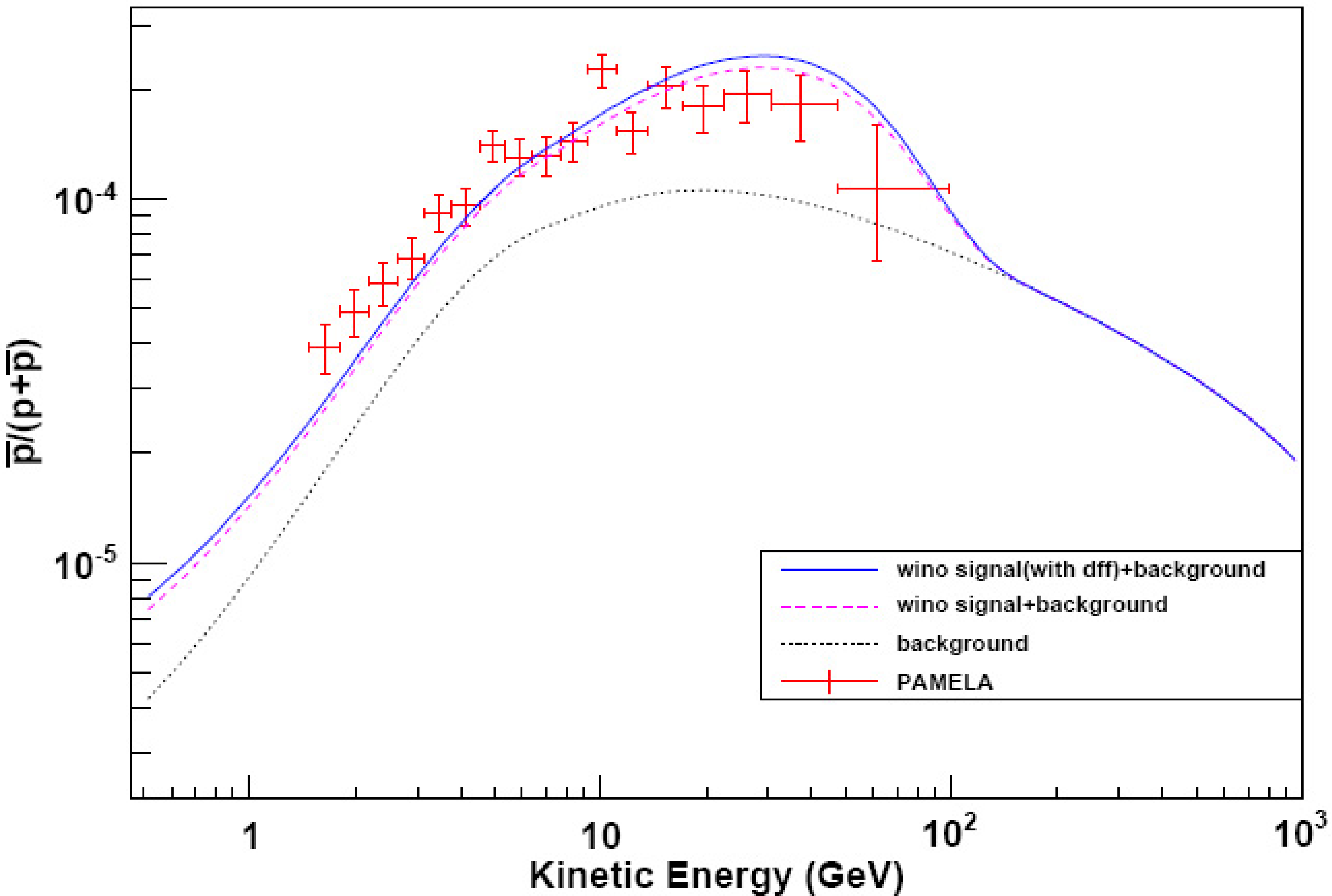
Antiproton to proton ratio

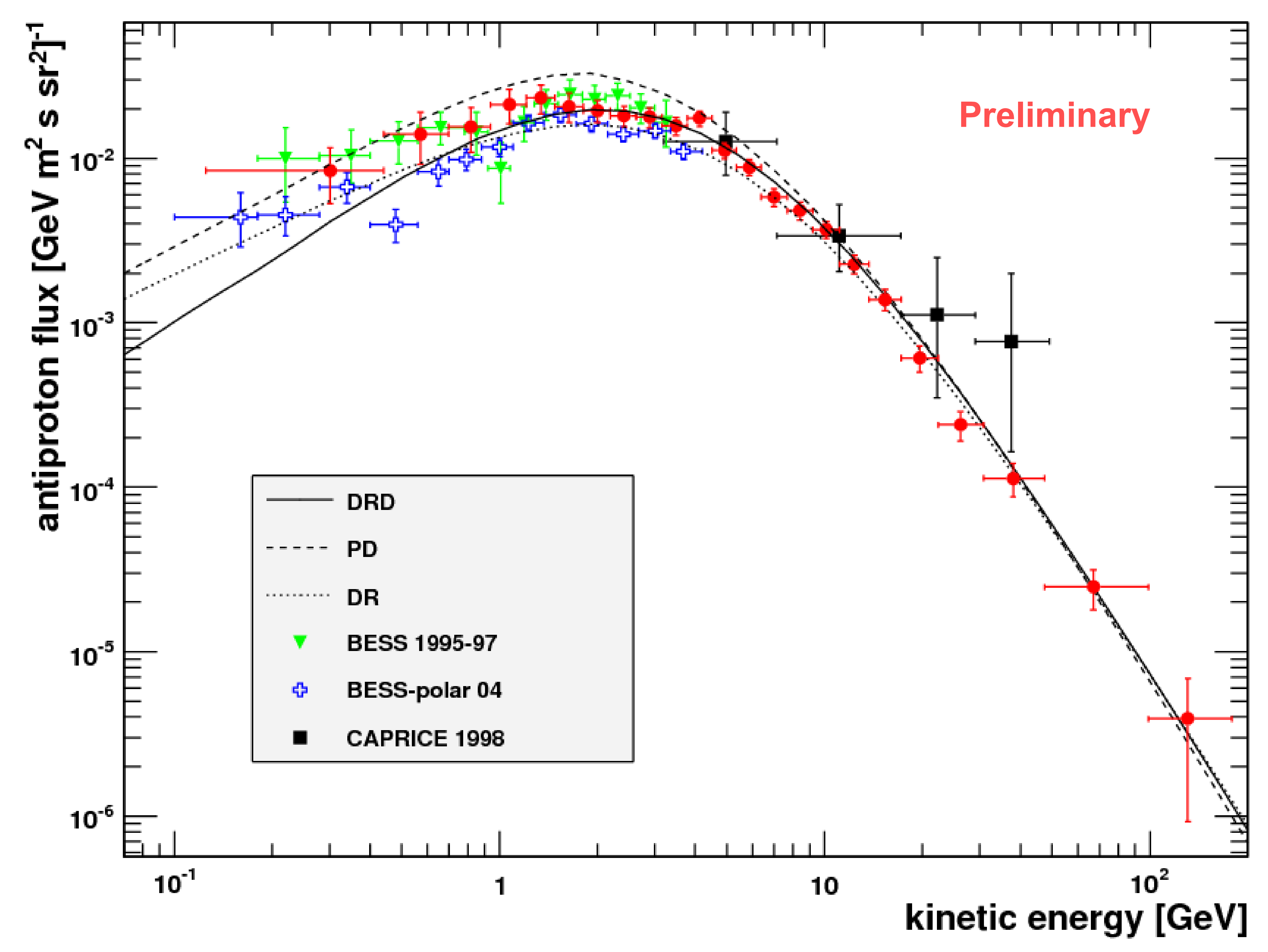


Wino Dark Matter in a non-thermal Universe

G. Kane, R. Lu, and S. Watson

arXiv:0906.4765v3 [astro-ph.HE)





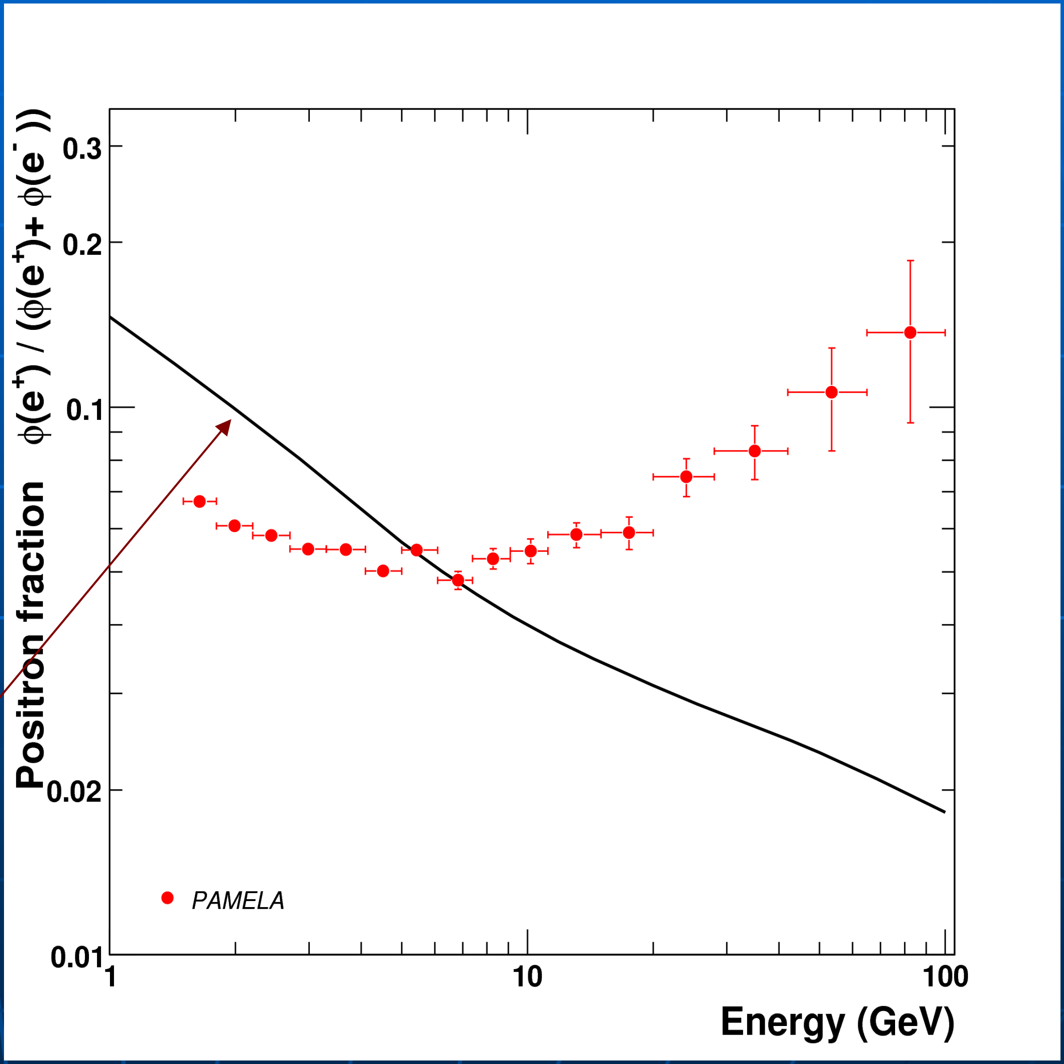
antiproton flux [GeV m^2 s sr^2]$^{-1}$
kinetic energy [GeV]
Preliminary
DRD
PD
DR
BESS 1995-97
BESS-polar 04
CAPRICE 1998

Positron to all electron ratio

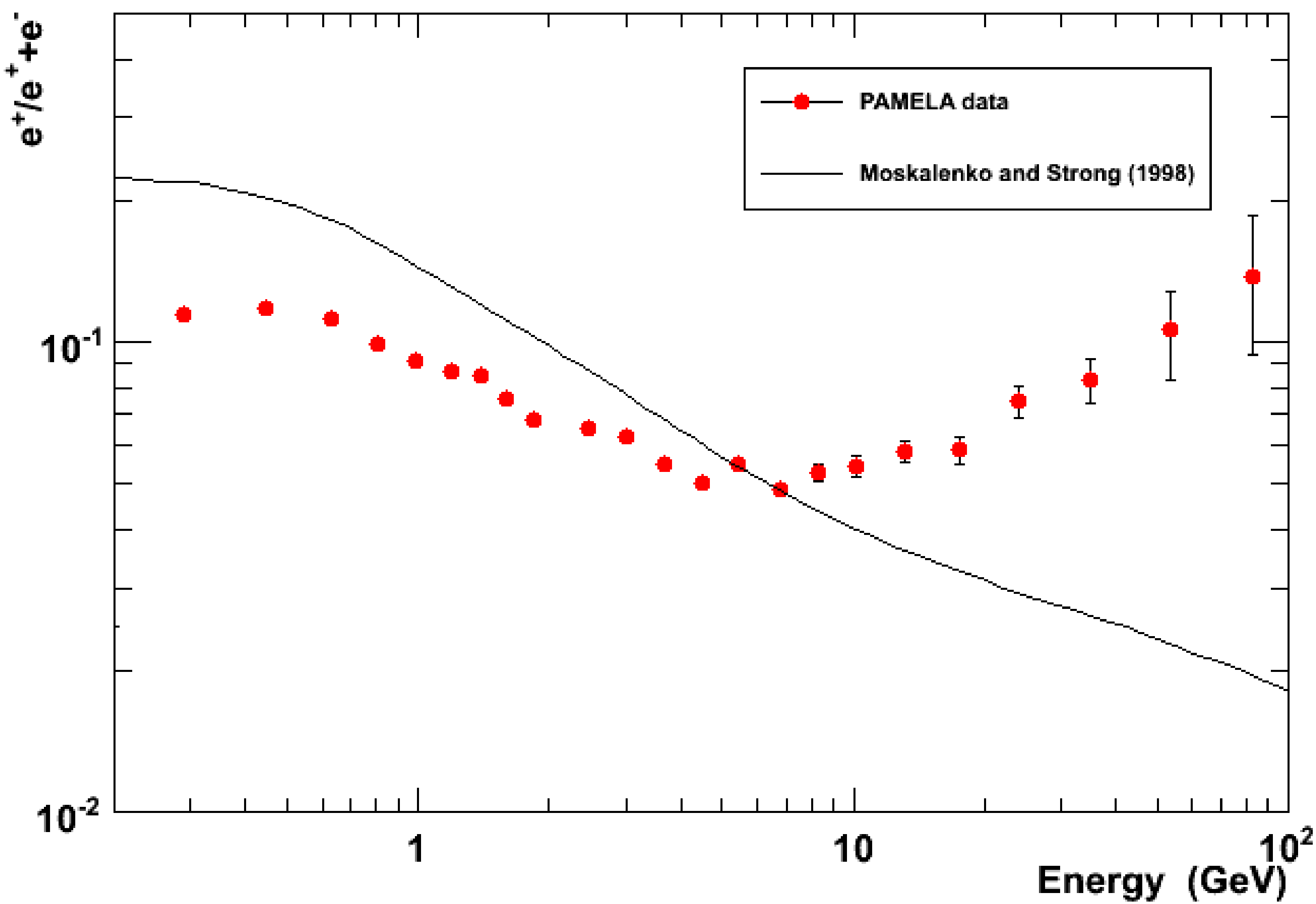
Nature 458, 697, 2009

$$R(E) = \frac{\Phi_{e^+}}{\Phi_{e^+} + \Phi_{e^-}}$$

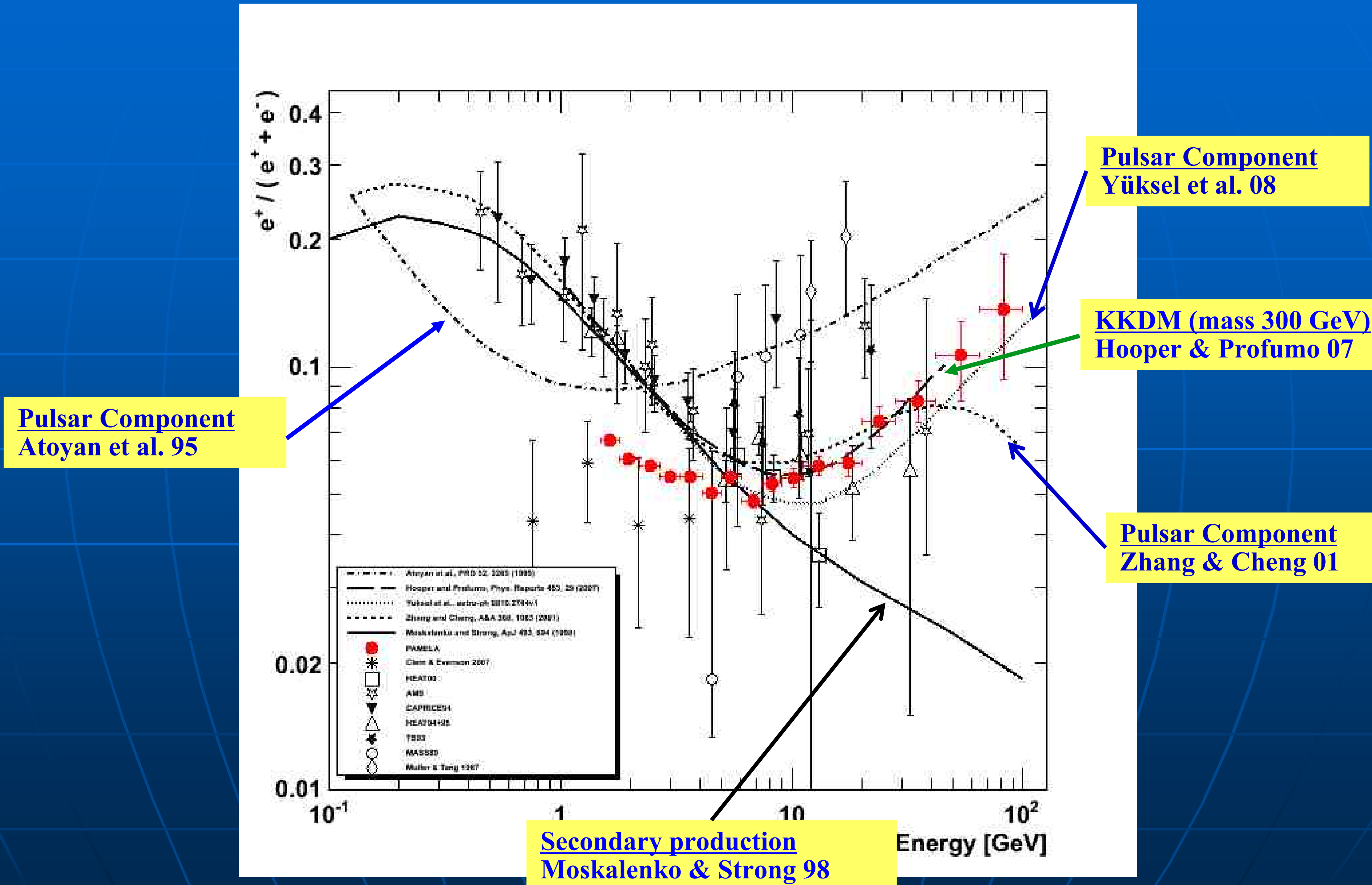
Secondary production
Moskalenko & Strong 98



Positron to all electron ratio



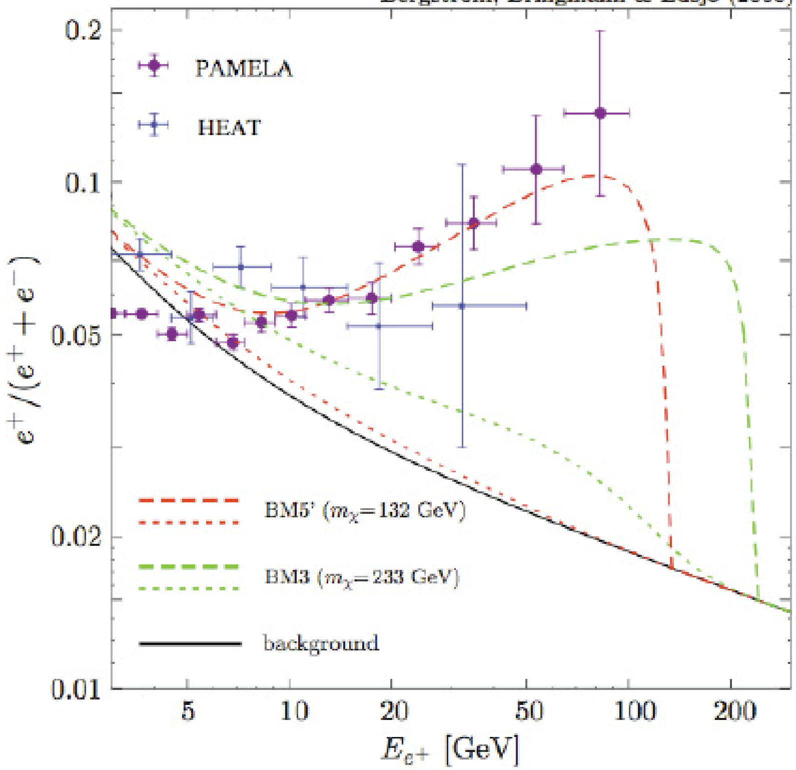
PAMELA Positron Fraction



Example: Dark Matter

arXiv:0808.3725

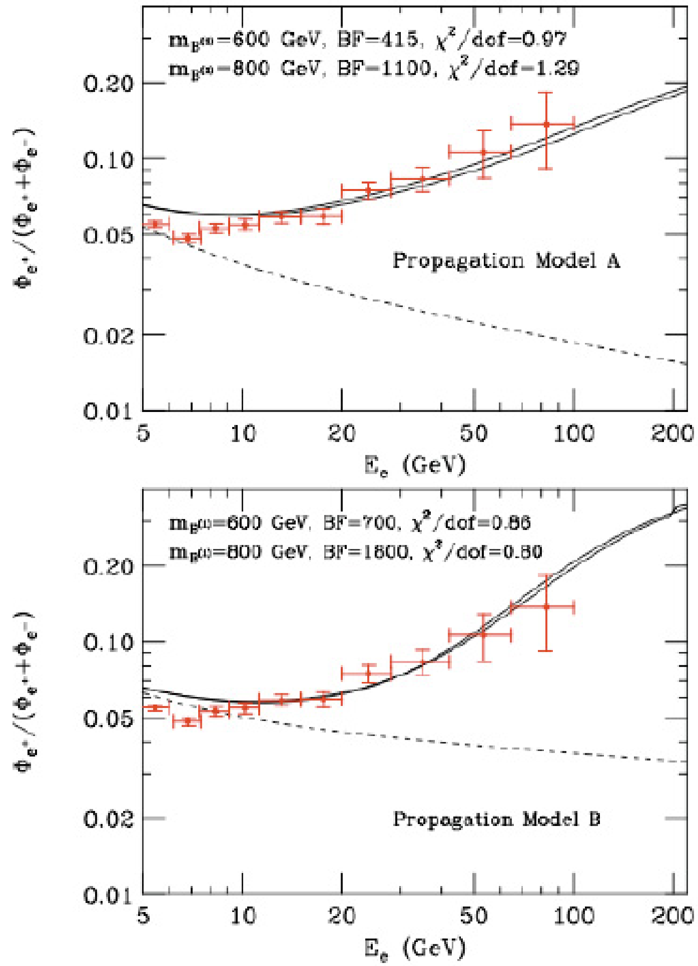
Bergström, Bringmann & Edsjö (2008)



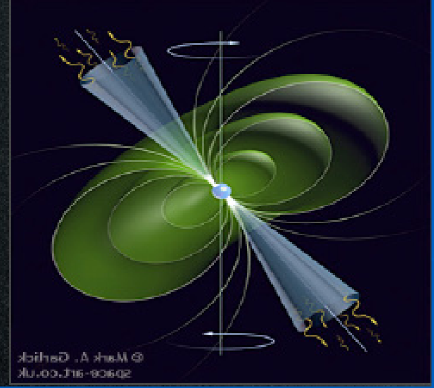
Majorana DM with **new** internal bremsstrahlung correction. NB: requires annihilation cross-section to be 'boosted' by >1000.

Hooper and Zurek

arXiv:0902.0593v1



Kaluza-Klein dark matter



Astrophysical Explanation
Pulsars

S. Profumo Astro-ph 0812-4457

- Mechanism: the spinning $\vec{\mathbf{B}}$ 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.

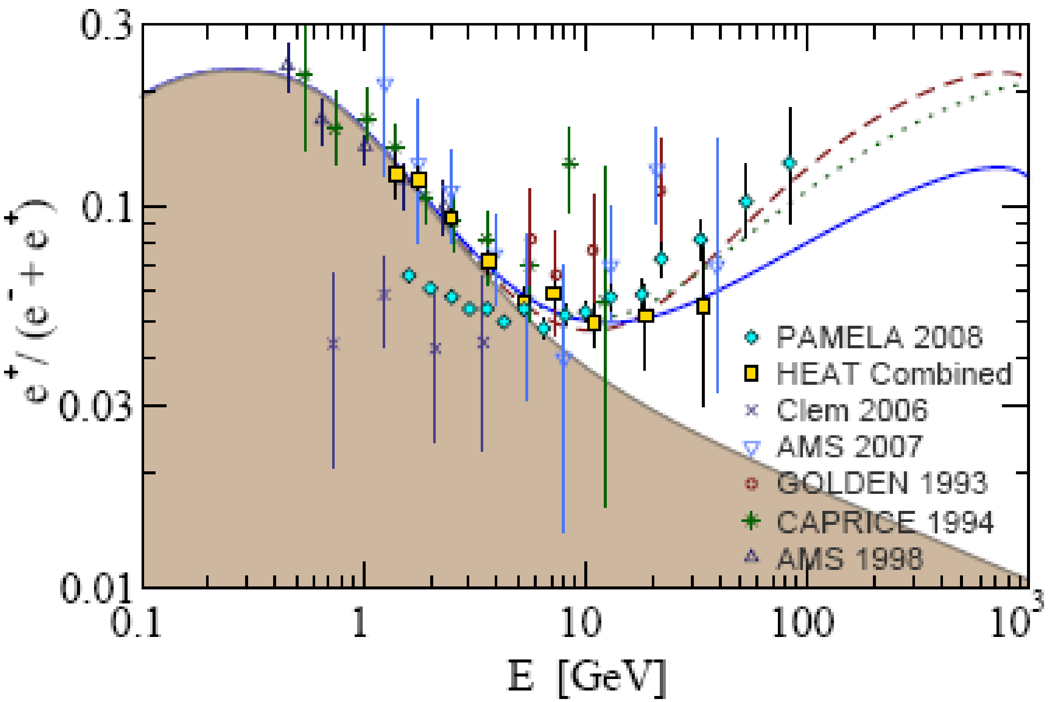
$$E_{tot} \simeq 10^{46}\ \mathrm{erg}$$

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

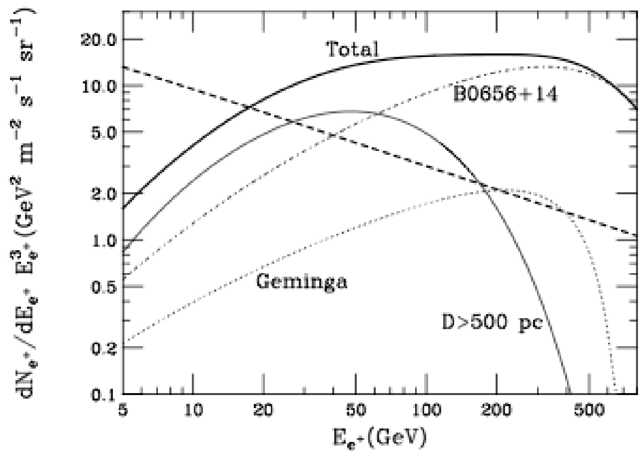
- Geminga: 157 parsecs from Earth and 370,000 years old
- B0656+14: 290 parsecs from Earth and 110,000 years old
- Many others after Fermi/GLAST

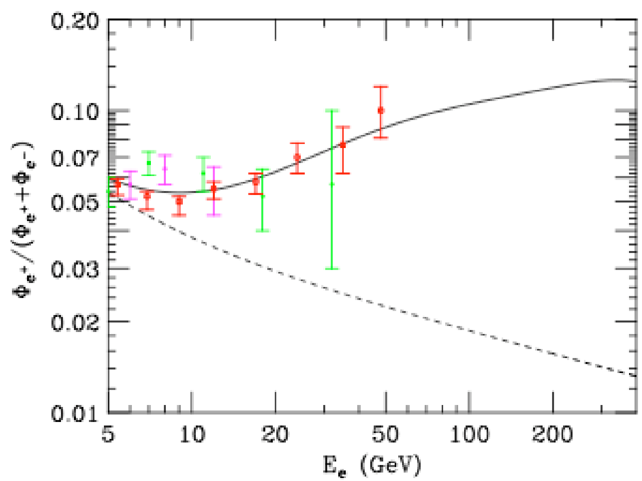
- Diffuse mature pulsars

Example: pulsars



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

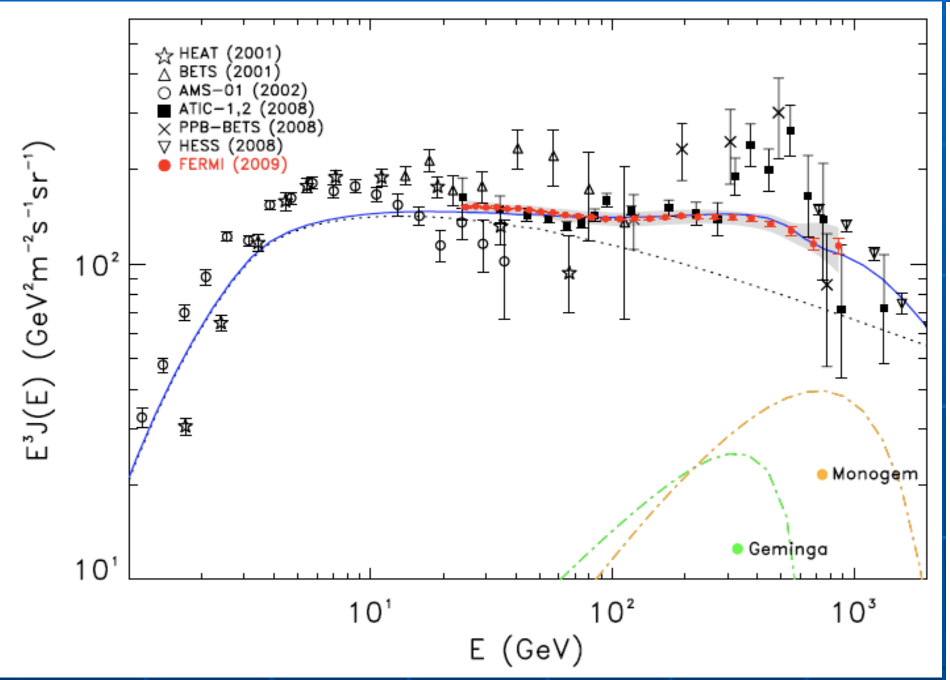


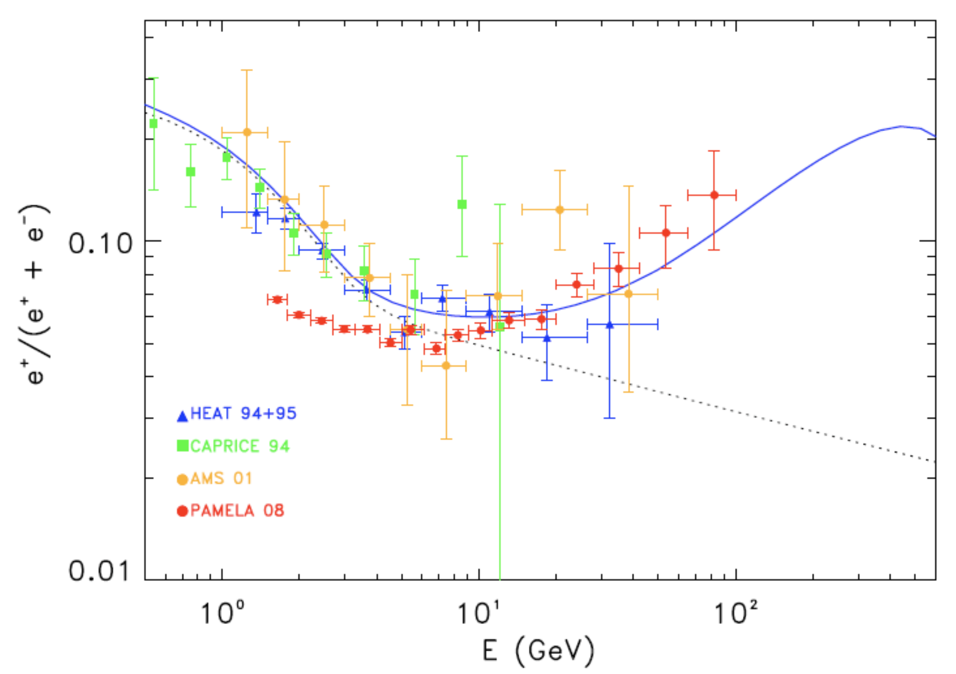


diffuse mature &nearby young pulsars
Hooper, Blasi, and Serpico
arXiv:0810.1527

Pulsars: Most significant contribution to high-energy CRE: **Nearby** (d < 1 kpc) and **Mature** (104 < T/yr < 106) Pulsars

D. Grasso et al. 0905.0636 [astro-ph.HE]





- Example of fit to both **Fermi** and **Pamela** data with known (ATNF catalogue) nearby, mature pulsars and with a single,
- nominal choice for the **e+/e- injection** parameters

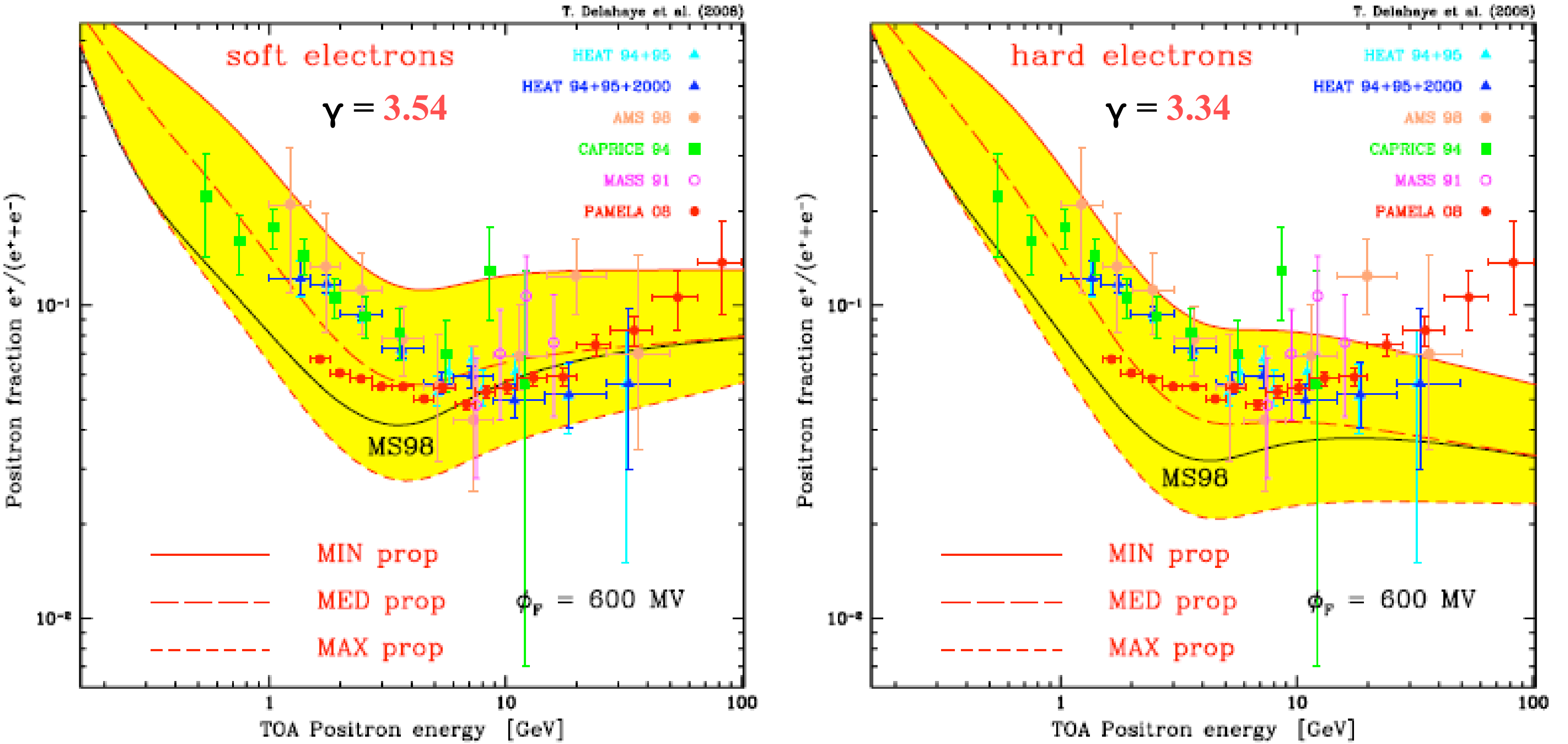
Interaction of high energy gamma-rays with star-light

F. A. Aharonian and A M Atoyan
J. Phys. G: **Nucl.** Pan. Phys. **17 (1991) 1769-1778.**

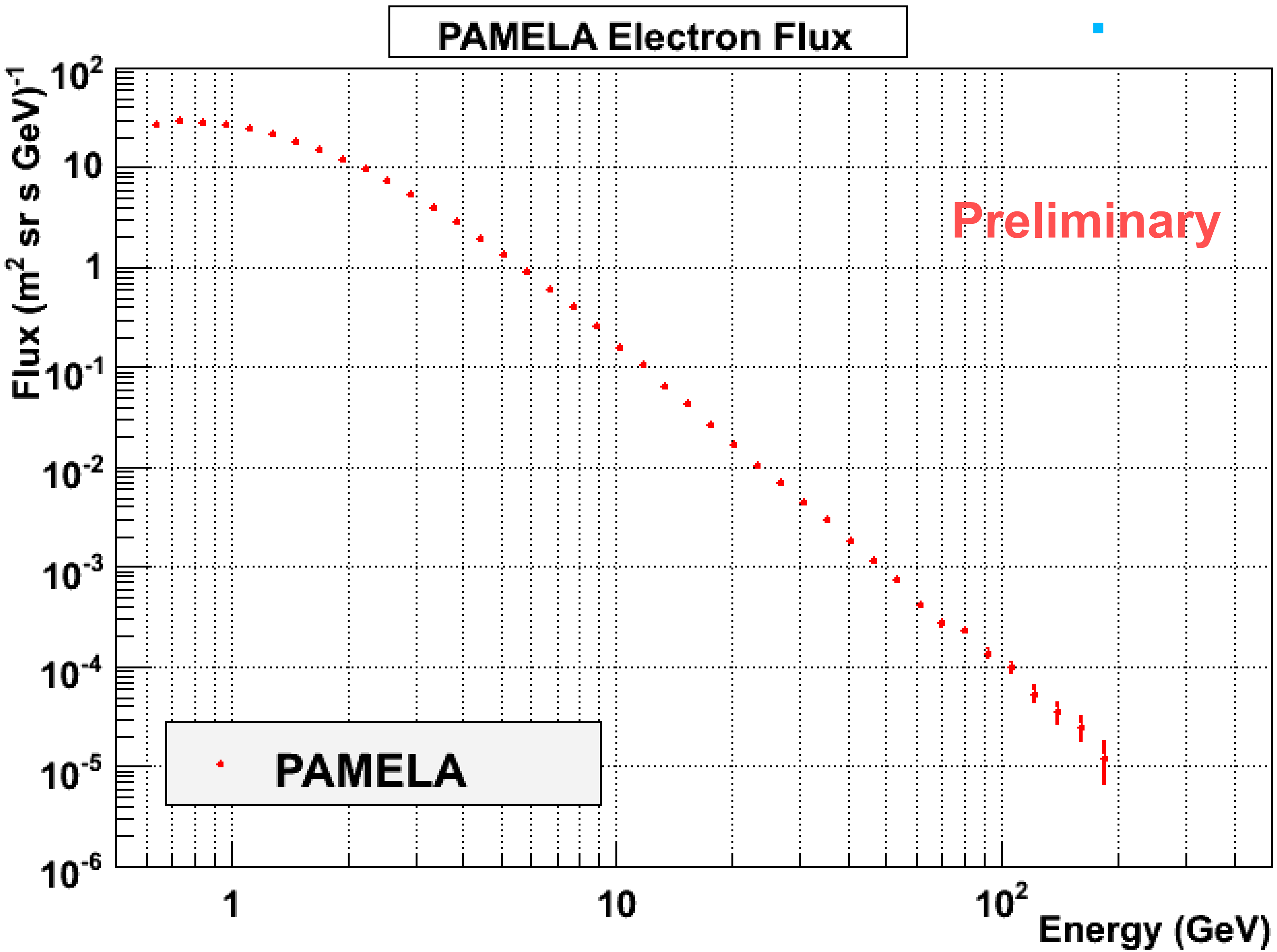
A. Eungwanichayapant and F. A. Aharonian
0907.2971v1 [astro-ph.HE]

After discovery of TeV binaries like LS5039 and LSI 61 by HESS/Magic/VERITAS in which the powerful production of high and very high energy gamma-rays is accompanied by their absorption (which leads to the modulation of the gamma-ray signal), it is clear that these objects are also sources of electron-positron pairs.

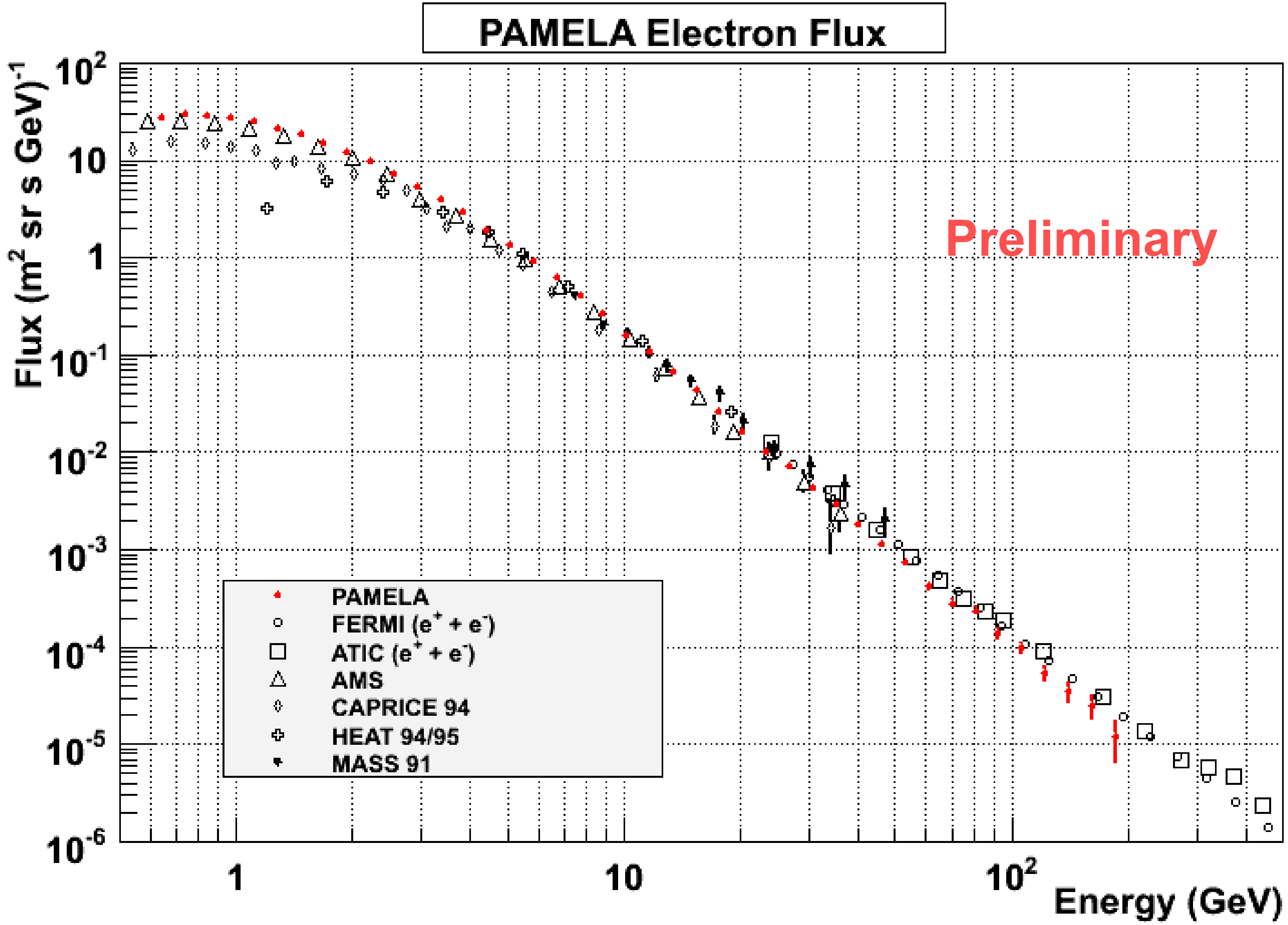
Standard Positron Fraction
Theoretical Uncertainties

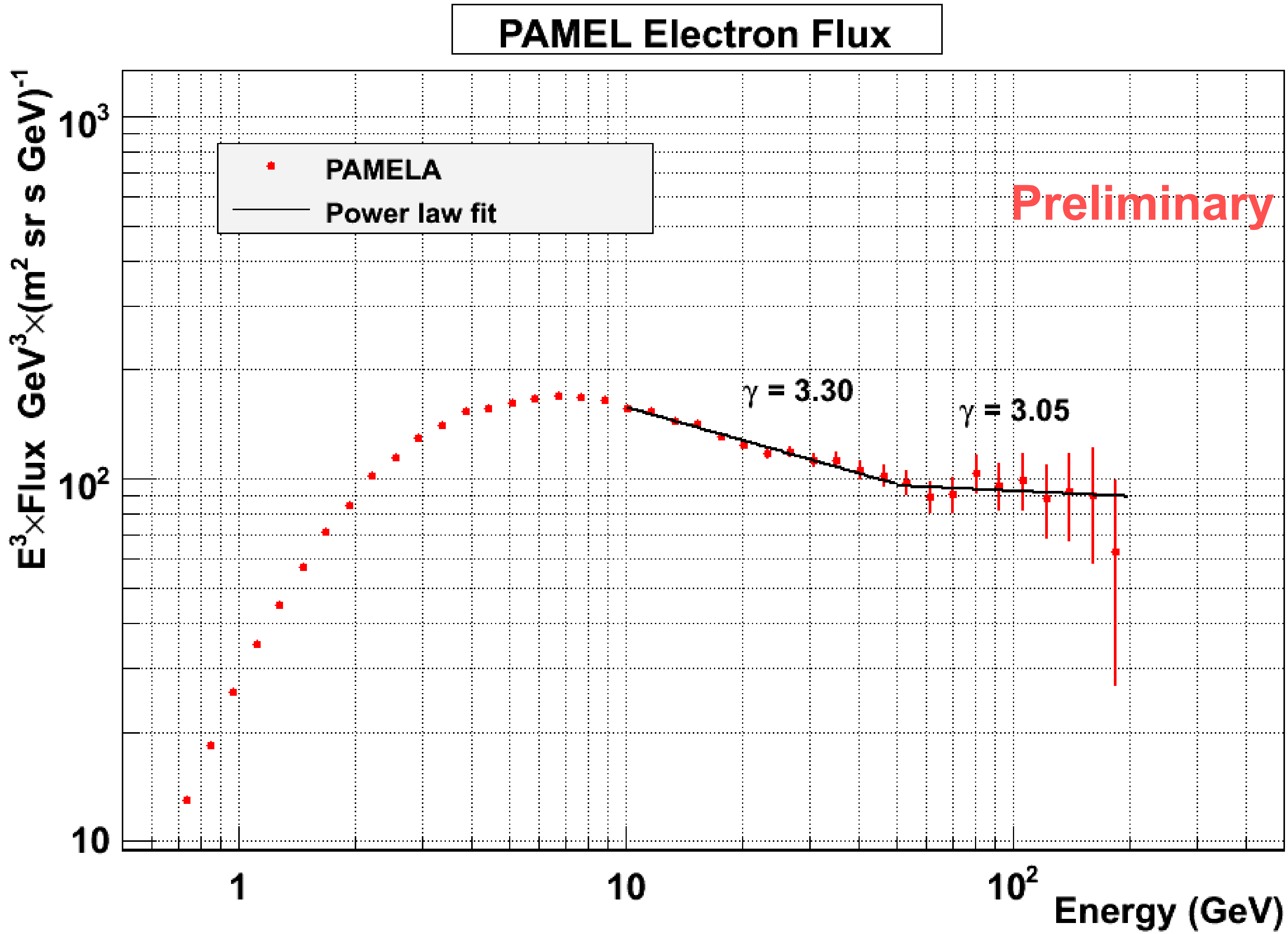


T. Delahaye et al., arXiv: 0809.5268v3



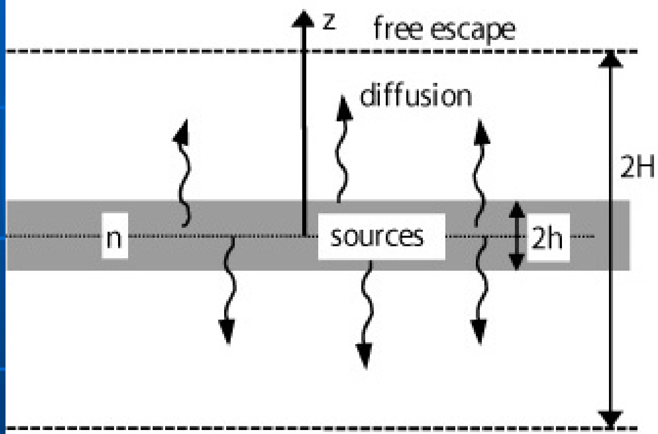
PAMELA Electron Flux
Flux (m^2 sr s GeV)$^{-1}$
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Preliminary
PAMELA
1
10
10^2
Energy (GeV)


PAMELA Electron Flux
Preliminary
Flux (m^2 sr s GeV)$^{-1}$
Energy (GeV)
PAMELA
FERMI ($e^+ + e^-$)
ATIC ($e^+ + e^-$)
AMS
CAPRICE 94
HEAT 94/95
MASS 91


PAMEL Electron Flux
PAMELA
Power law fit
Preliminary
γ = 3.30
γ = 3.05
E³×Flux GeV³×(m² sr s GeV)⁻¹
10³
10²
10
1
10
10²
Energy (GeV)

Cosmic Rays Propagation in the Galaxy

$$\frac{\partial N_i(E,z,t)}{\partial t} = \underbrace{D(E)\cdot\frac{\partial^2}{\partial z^2}N_i(E,z,t)}_{\text{diffusion}} - \underbrace{N_i(E,z,t)\left\{\frac{1}{\tau_i^{\text{int}}(E,z)} + \frac{1}{\gamma(E)\tau_i^{dec}}\right\}}_{\text{interaction and decay}}$$

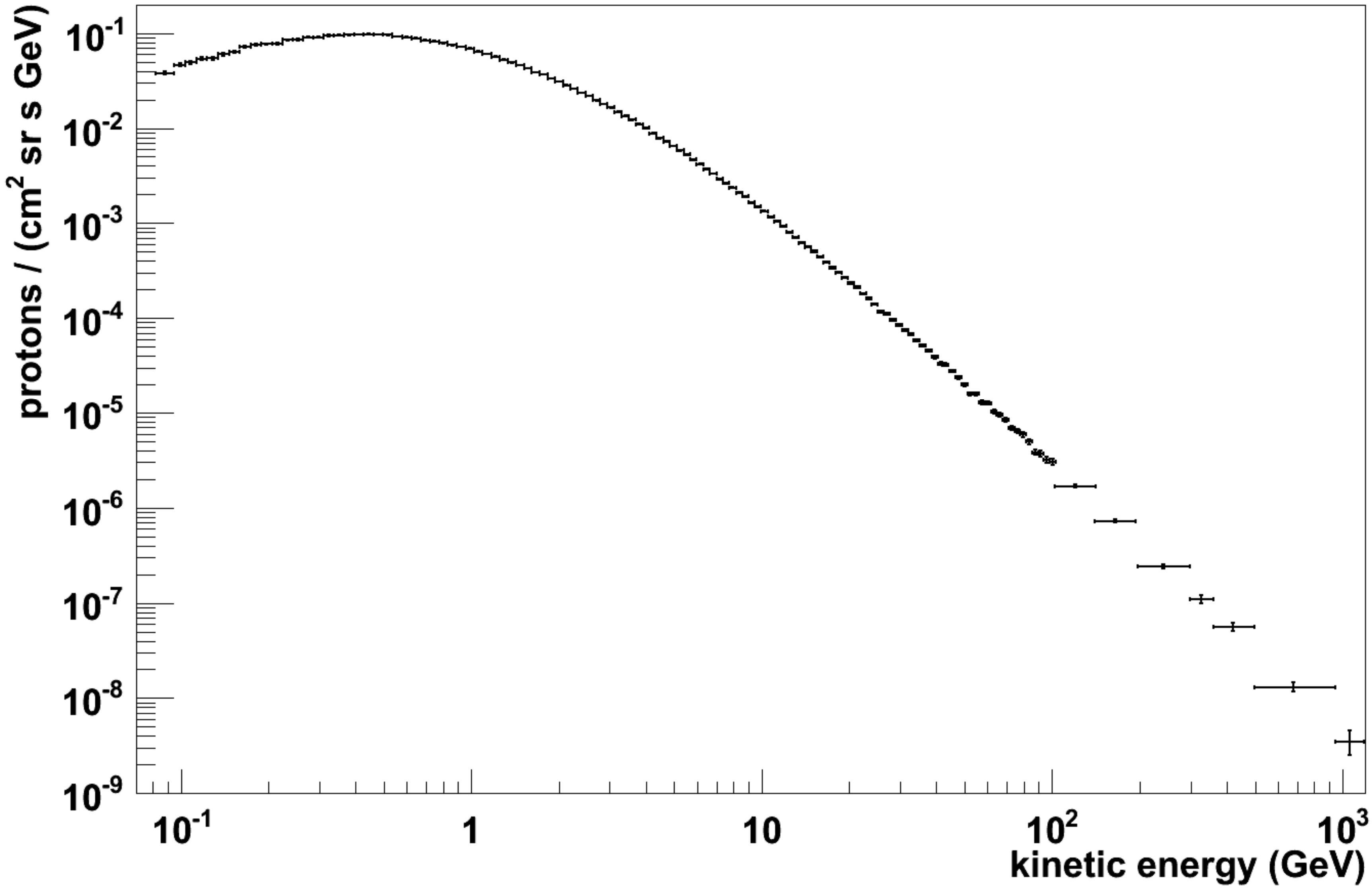


$$+ \underbrace{\sum_{k>i}\frac{N_k(E,z,t)}{\tau_{\text{int}}^{k\to i}(E,z)}}_{\text{secondary production}} + \underbrace{Q_i(E,z)}_{\text{primary sources}}$$

$$\underbrace{-\frac{\partial}{\partial E}\left\{\left\langle\frac{\partial E}{\partial t}\right\rangle\cdot N_i(E,z,t)\right\} + \frac{1}{2}\frac{\partial^2}{\partial E^2}\left\{\left\langle\frac{\Delta E^2}{\Delta t}\right\rangle\cdot N_i(E,z,t)\right\}}_{\text{energy changing processes}}$$

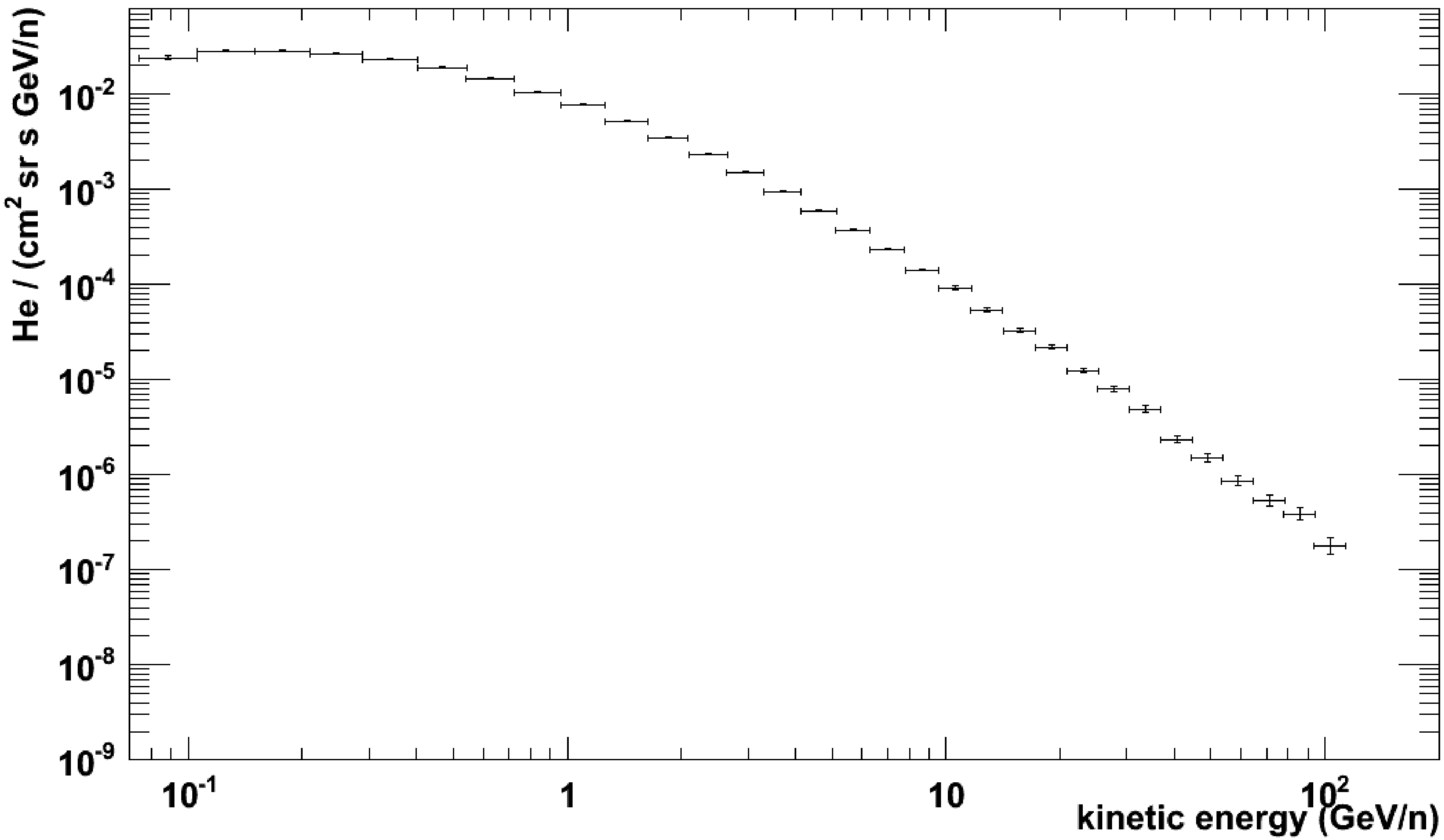
energy changing processes
(ionisation, reacceleration)

Proton flux



protons / (cm^2 sr s GeV)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-1}
1
10
10^2
10^3
kinetic energy (GeV)

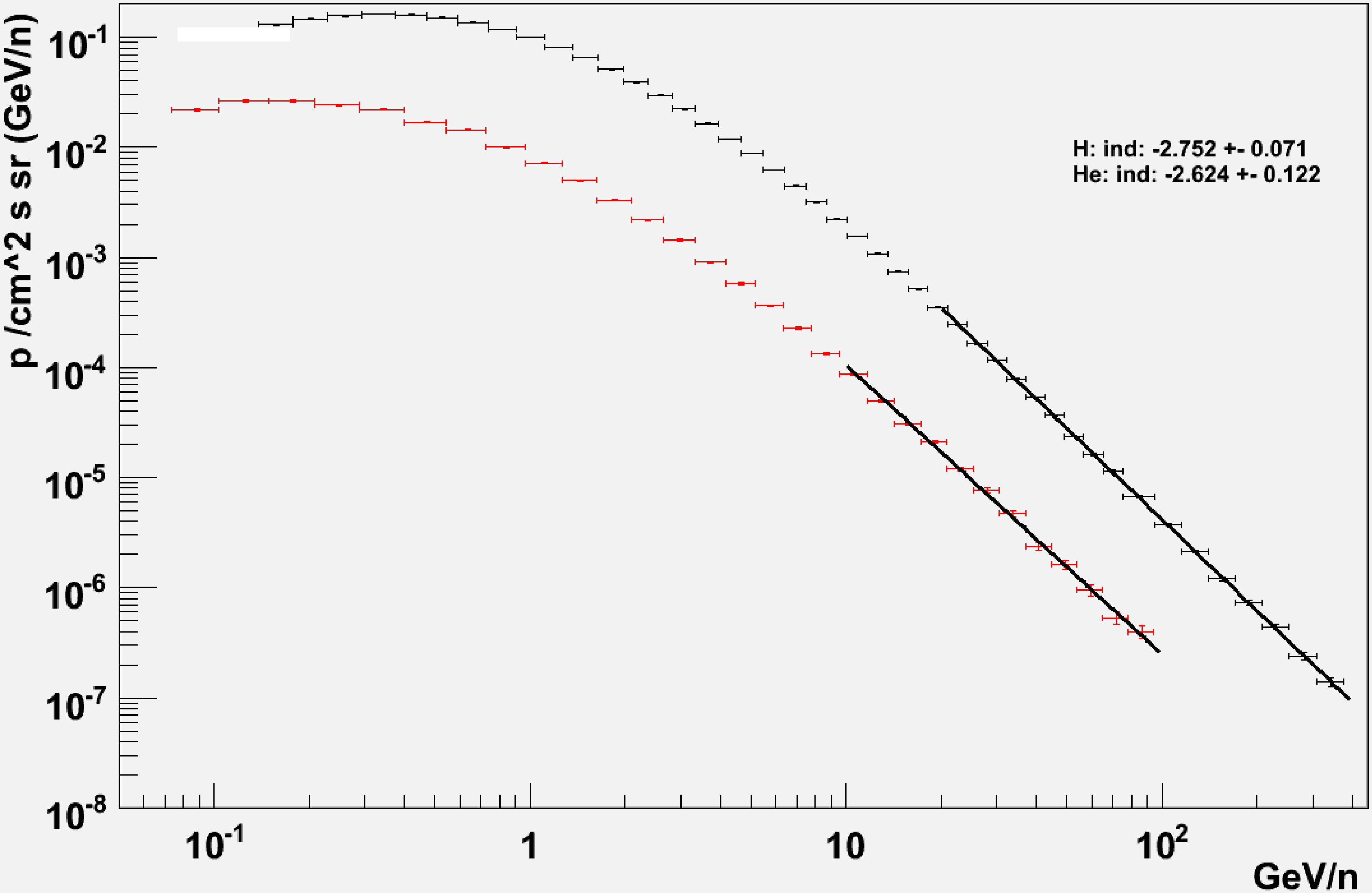
Helium flux



He / (cm^2 sr s GeV/n)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-1}
1
10
10^2
kinetic energy (GeV/n)

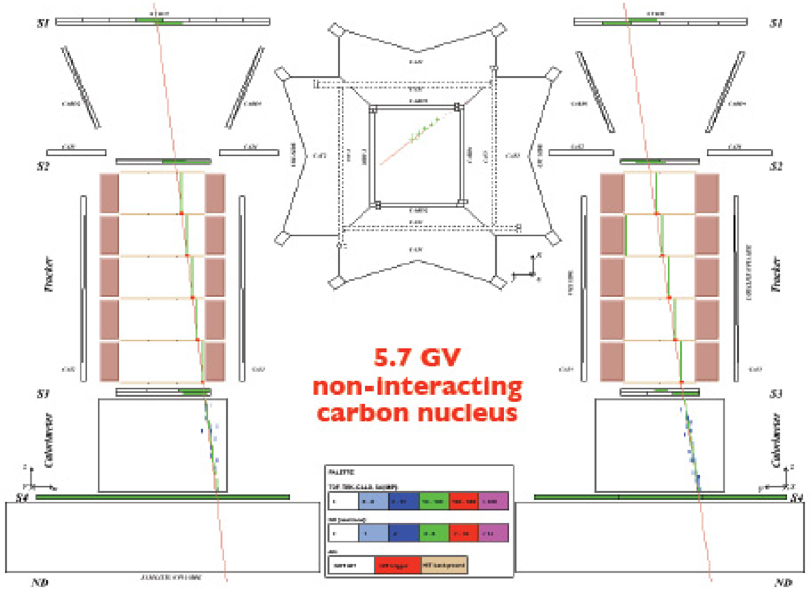
Proton and Helium spectra, July 2006

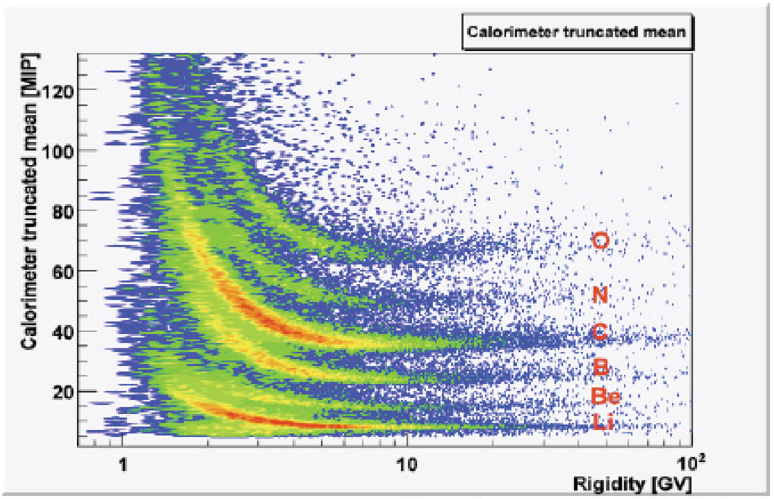
preliminary



Nuclei identification

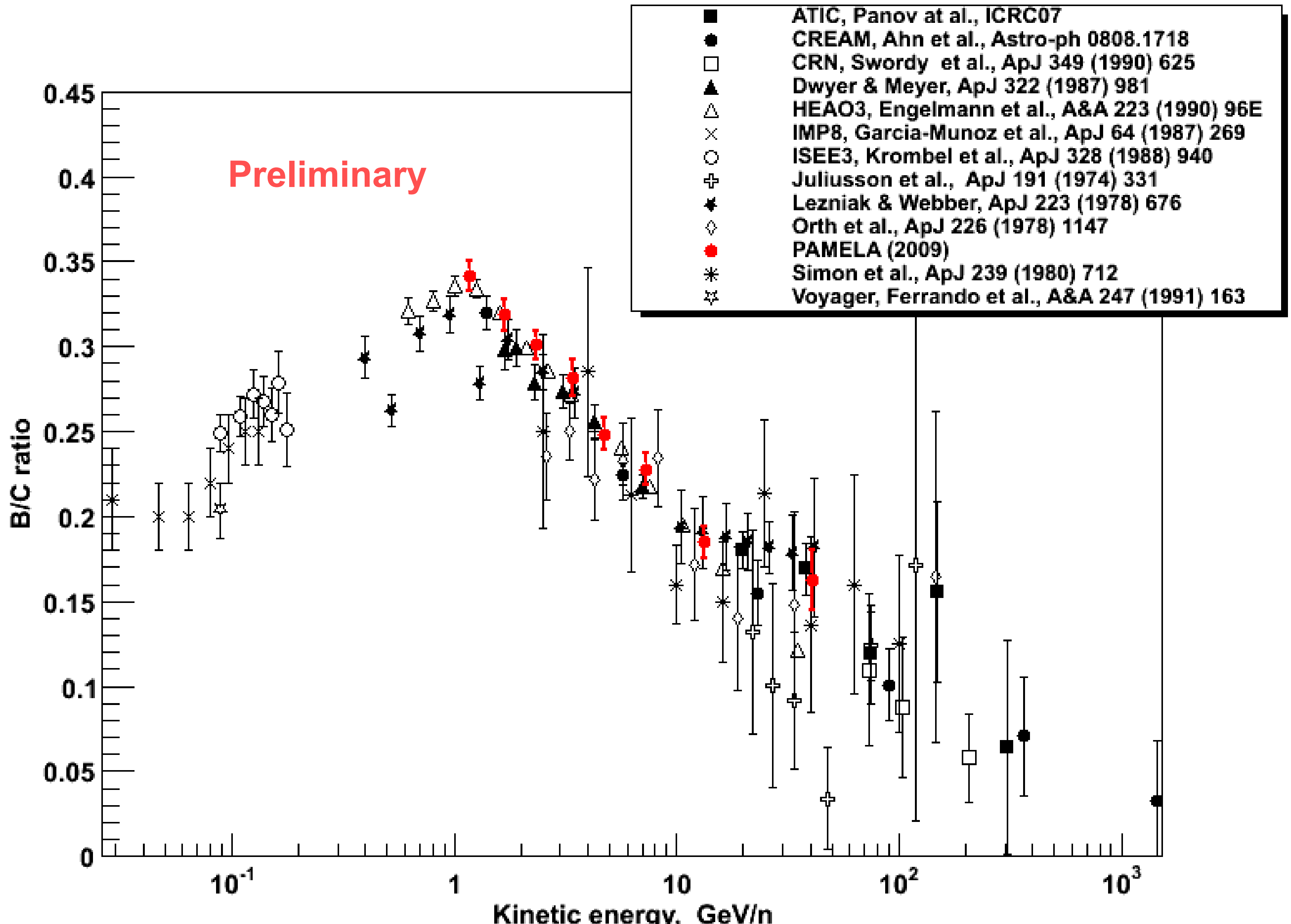
- **Important input to secondary production + propagation models**
  - Secondary to primary ratios:
    - B / C
    - Be / C
    - Li / C
  - Helium and hydrogen isotopes:
    - ^{3}He / ^{4}He
    - d / He





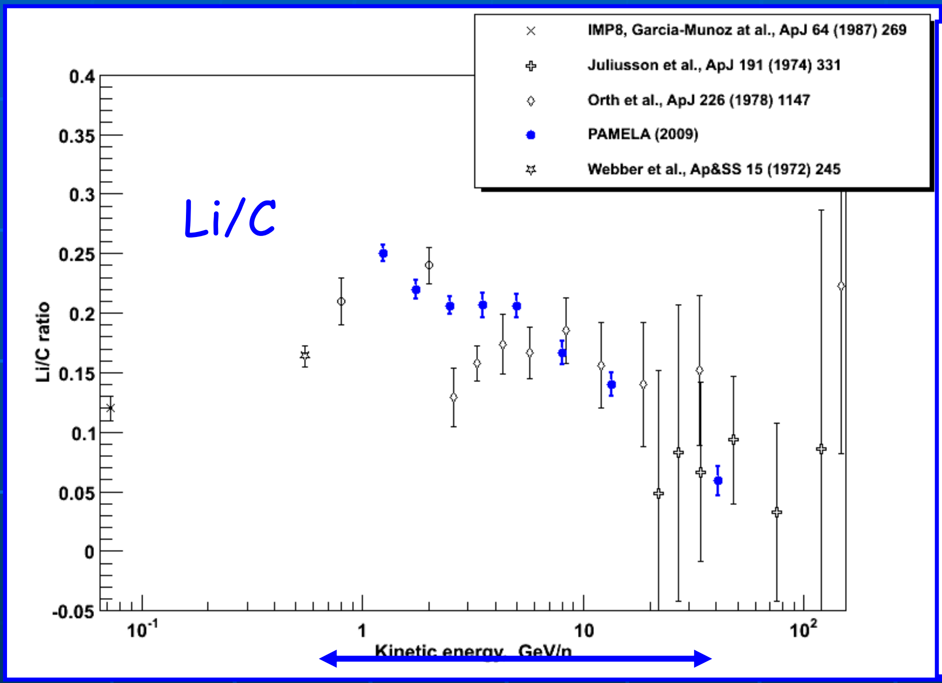
Truncated mean of multiple dE/dx measurements in different silicon planes

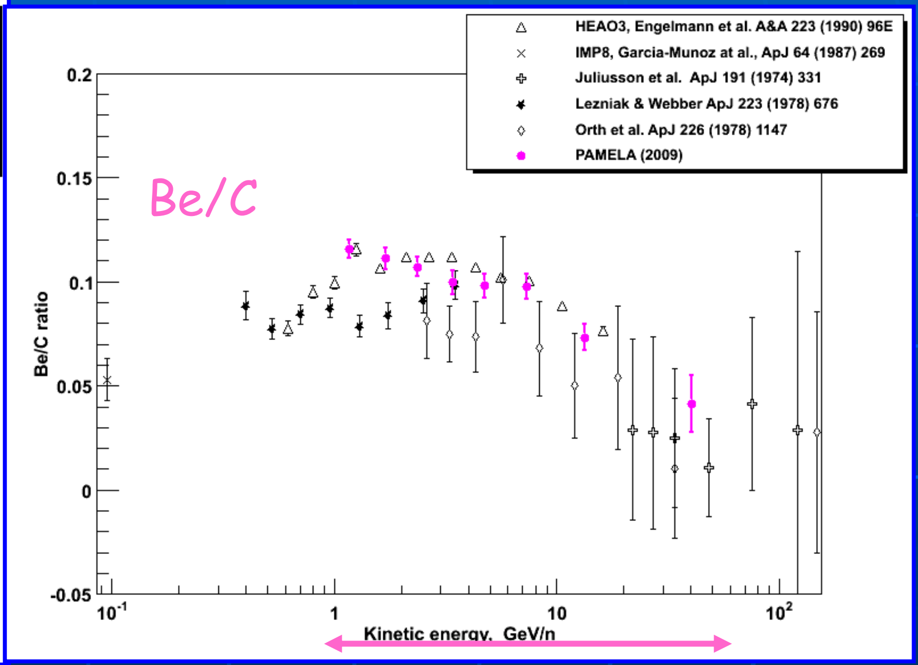
B/C



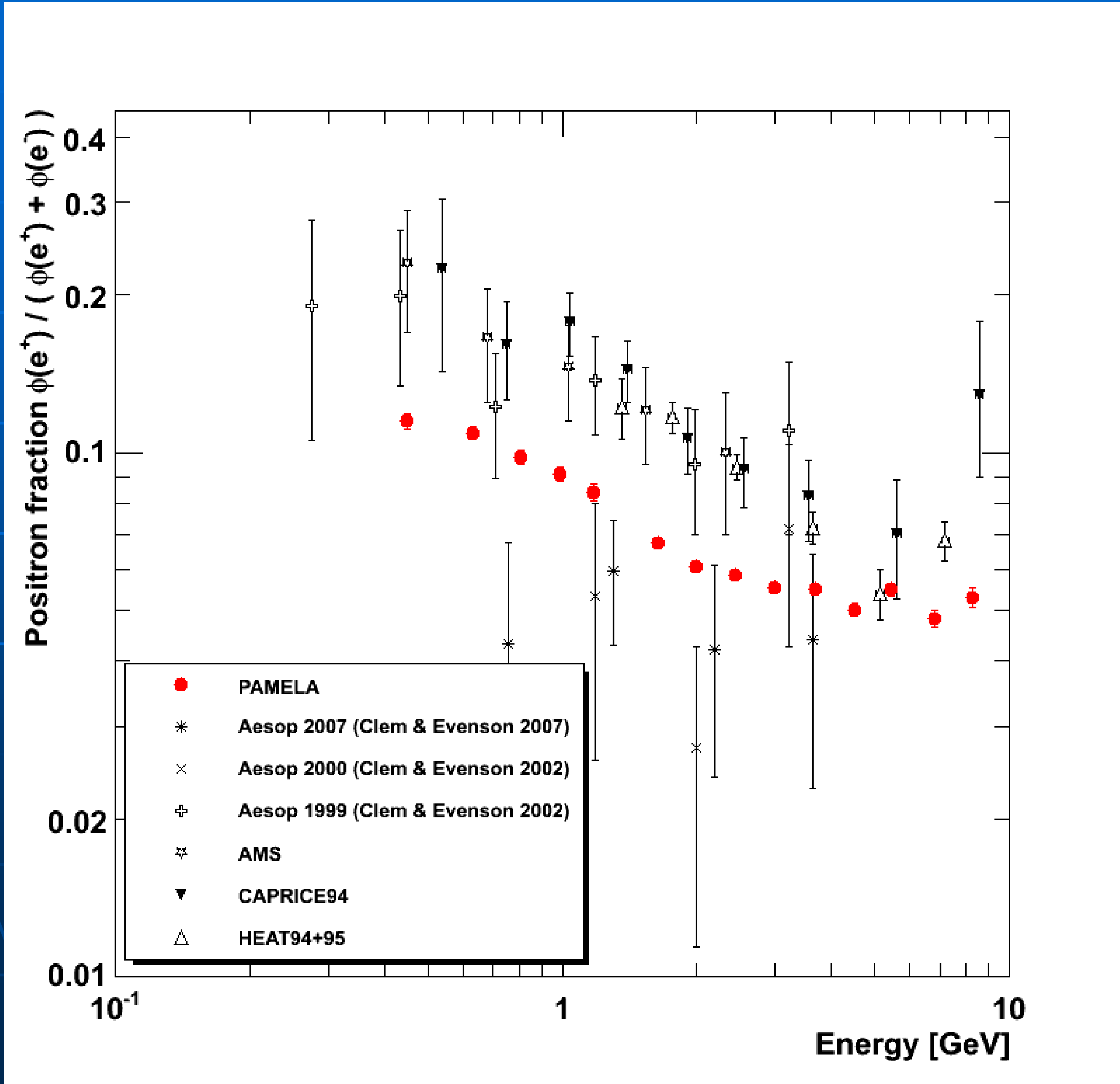
ATIC, Panov at al., ICRC07
CREAM, Ahn et al., Astro-ph 0808.1718
CRN, Swordy et al., ApJ 349 (1990) 625
Dwyer & Meyer, ApJ 322 (1987) 981
HEAO3, Engelmann et al., A&A 223 (1990) 96E
IMP8, Garcia-Munoz et al., ApJ 64 (1987) 269
ISEE3, Krombel et al., ApJ 328 (1988) 940
Juliusson et al., ApJ 191 (1974) 331
Lezniak & Webber, ApJ 223 (1978) 676
Orth et al., ApJ 226 (1978) 1147
PAMELA (2009)
Simon et al., ApJ 239 (1980) 712
Voyager, Ferrando et al., A&A 247 (1991) 163
Preliminary
B/C ratio
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
10^{-1}
1
10
10^2
10^3
Kinetic energy, GeV/n

PAMELA preliminary results





Positron Fraction



Solar Modulation of galactic cosmic rays

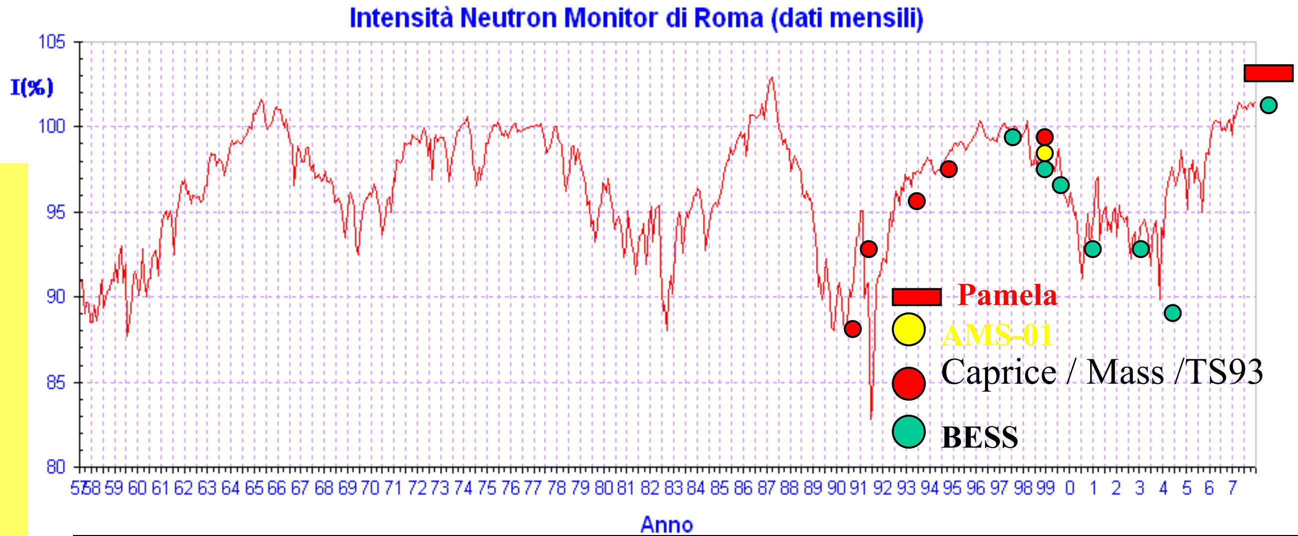
- **Study of charge sign dependent effects**

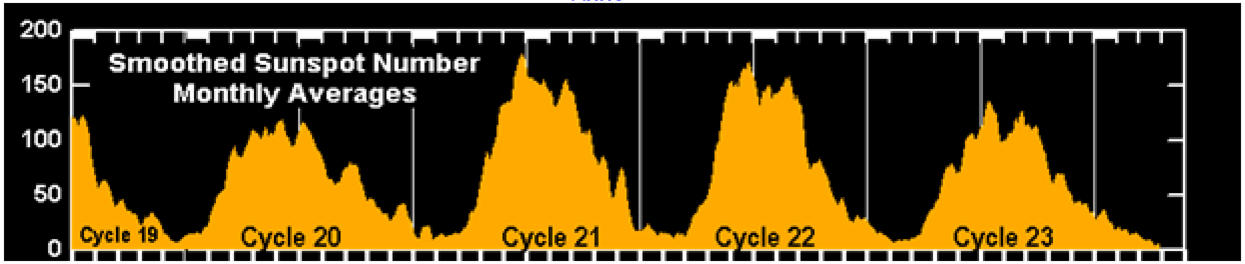
Asaoka Y. et al. 2002, Phys. Rev. Lett. 88, 051101),

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

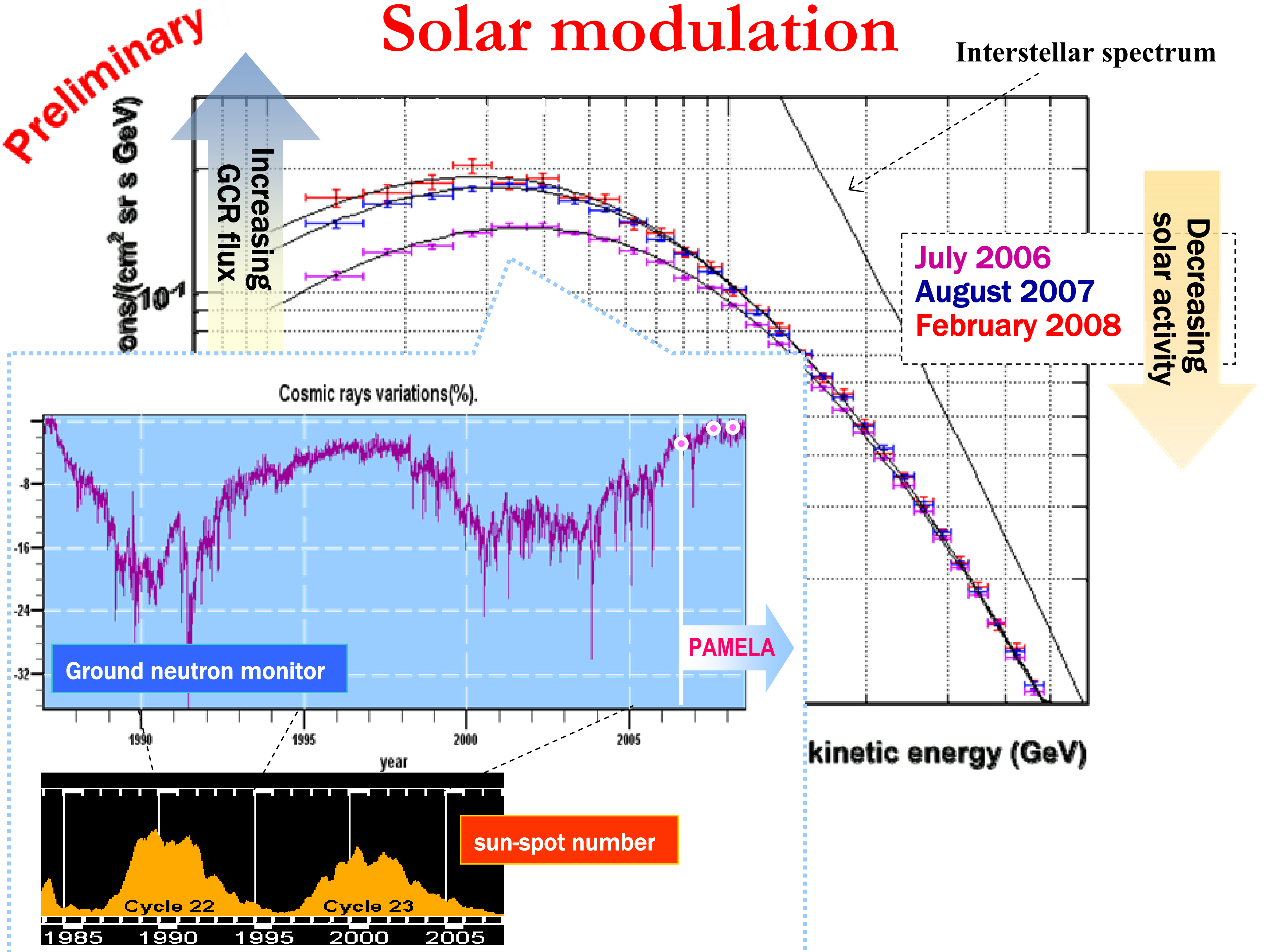
J. Clem et al. 30th ICRC 2007

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

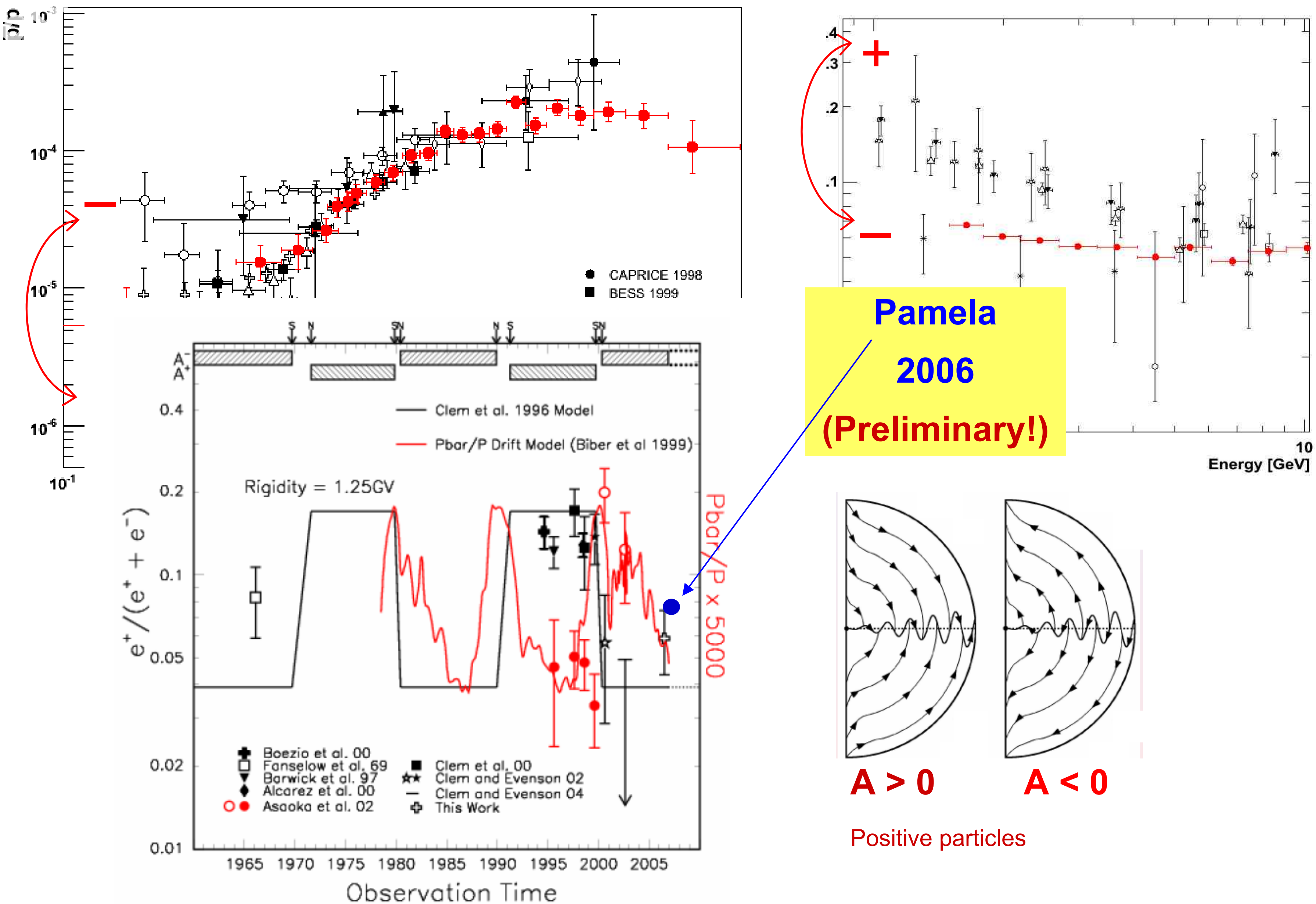




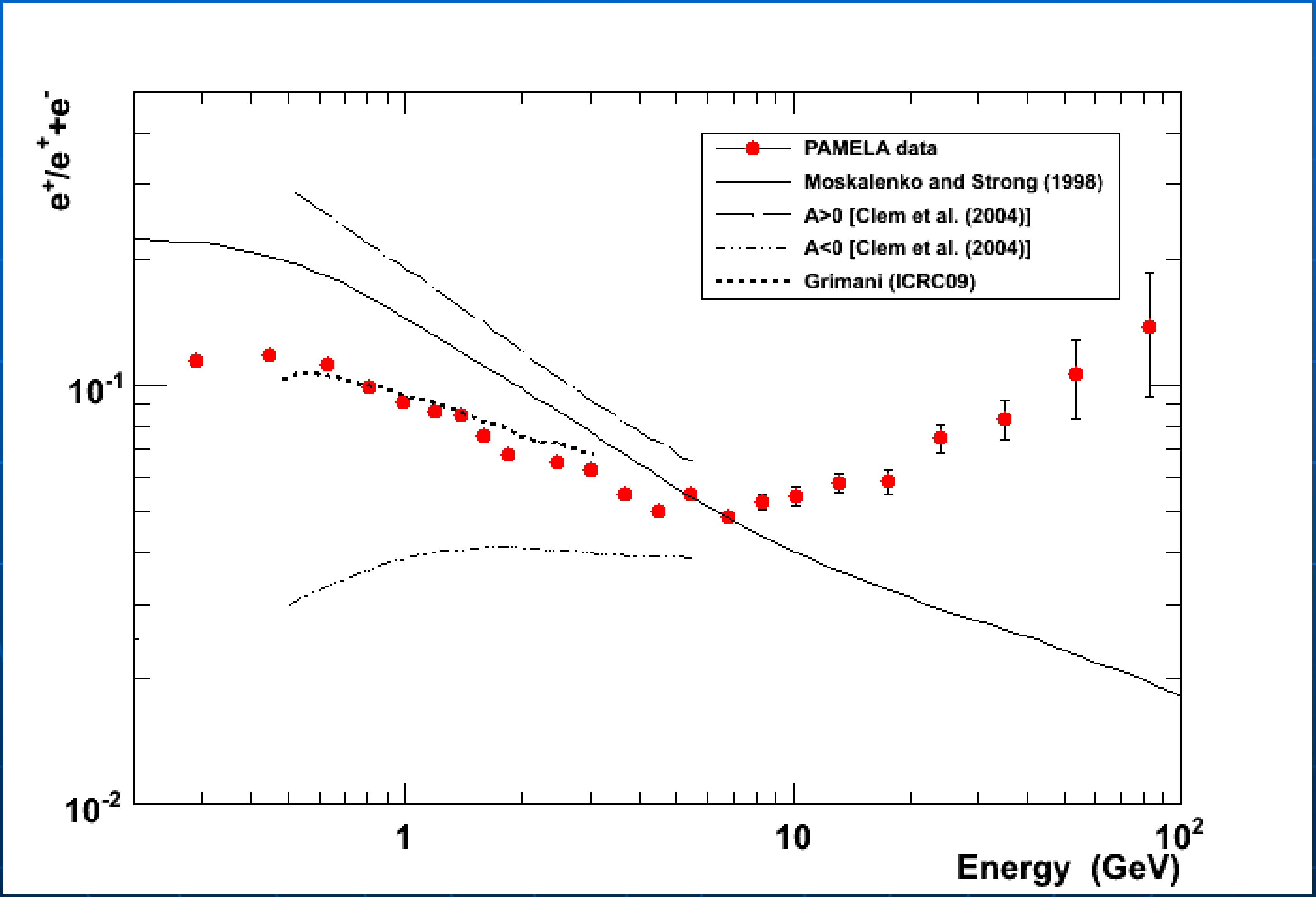
Solar modulation



Charge dependent solar modulation



Positron Fraction



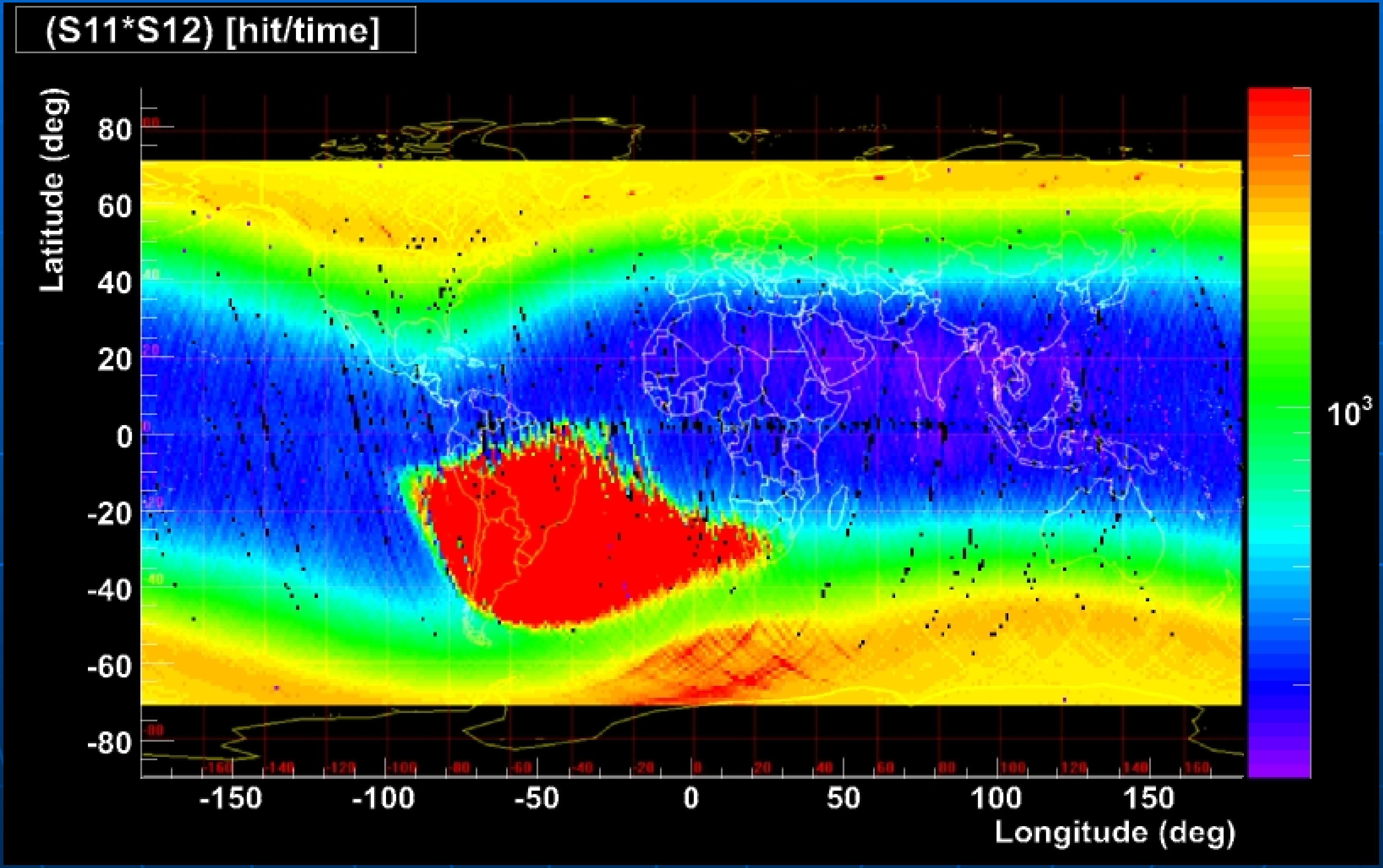
Radiation Belts

South Atlantic Anomaly

Secondary production from CR interaction with atmosphere

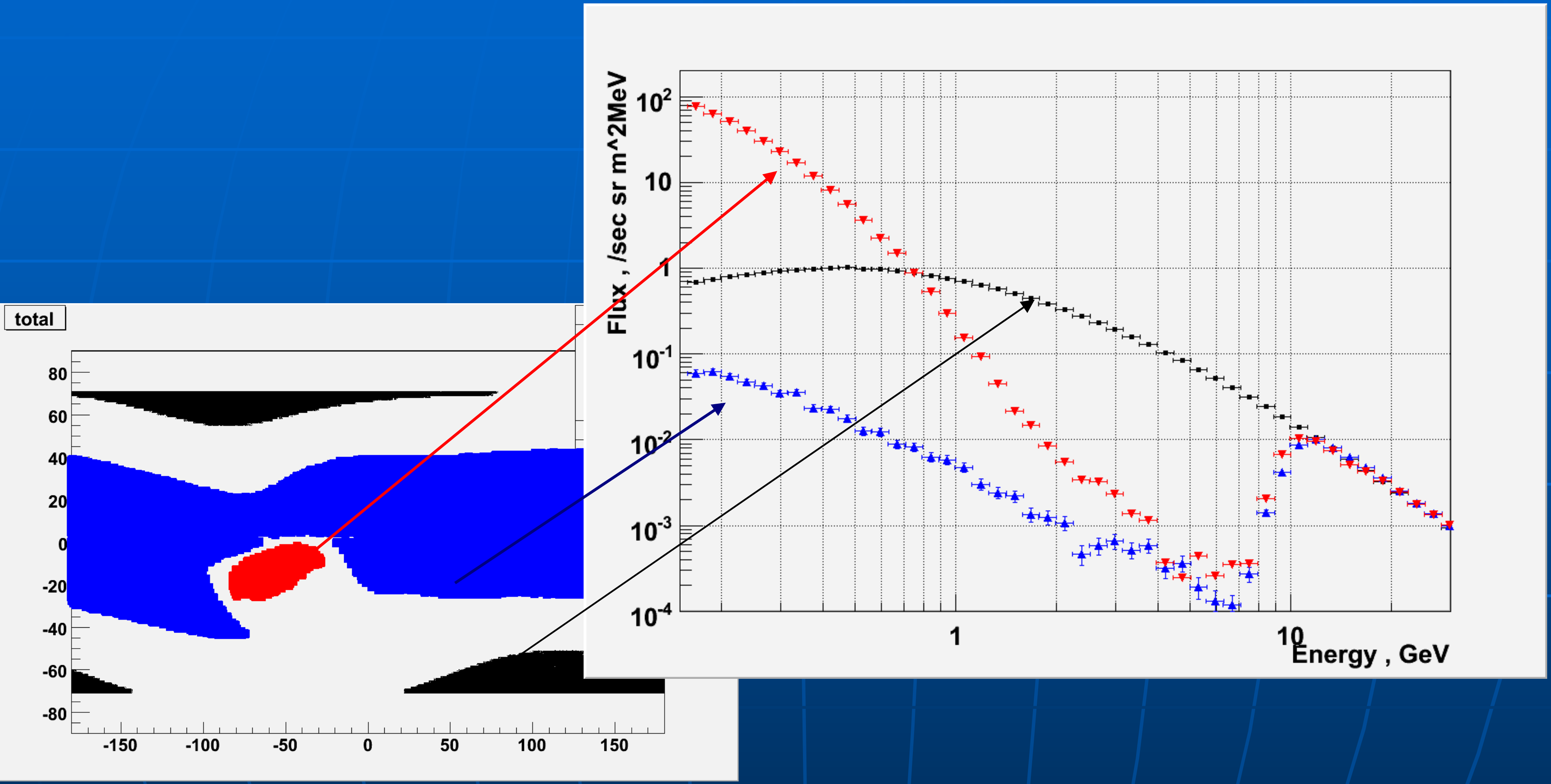
Study terrestrial magnetosphere

Pamela World Maps: 350 – 650 km alt



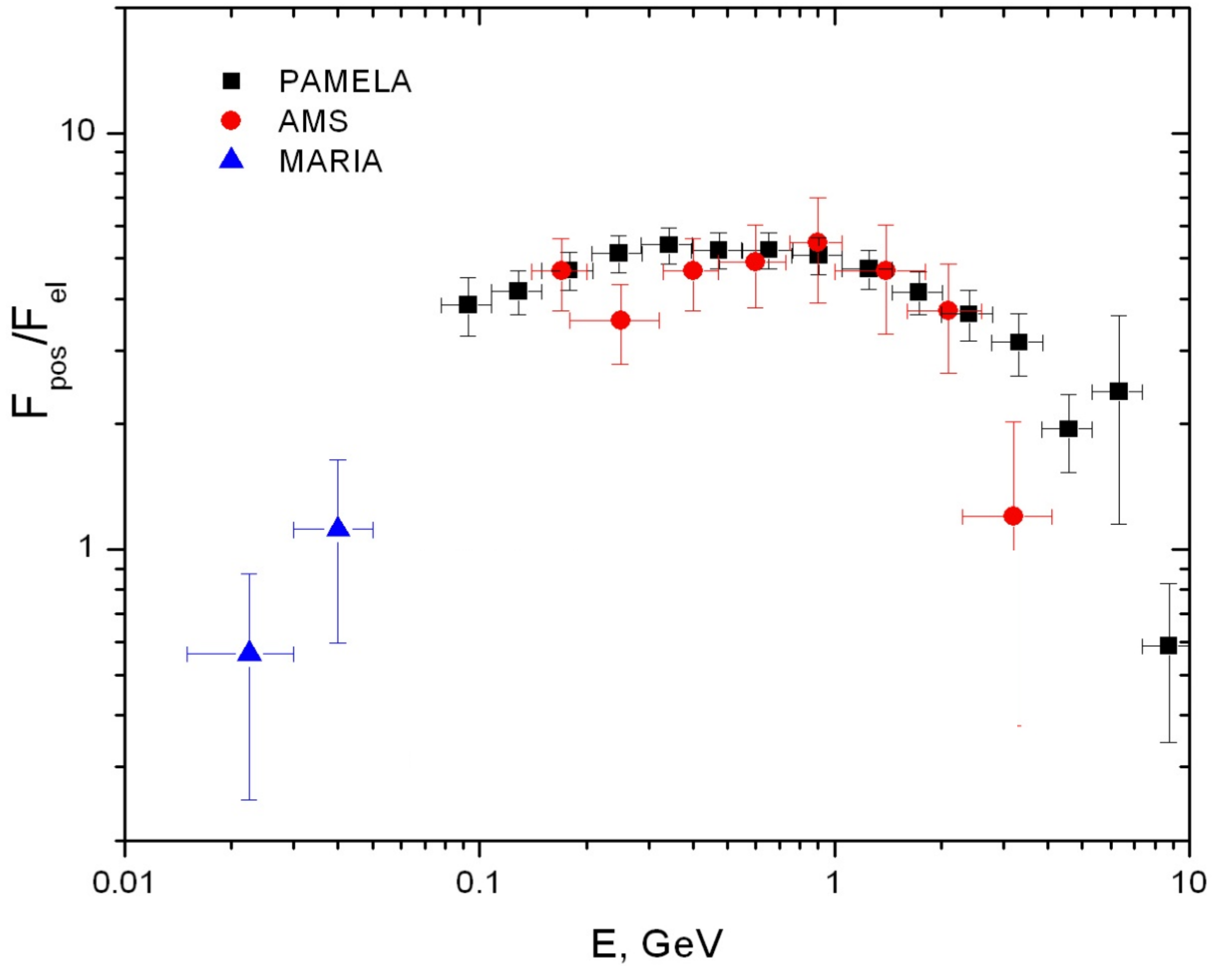
36 MeV p, 3.5 MeV e-

Proton spectrum in SAA, polar and equatorial regions

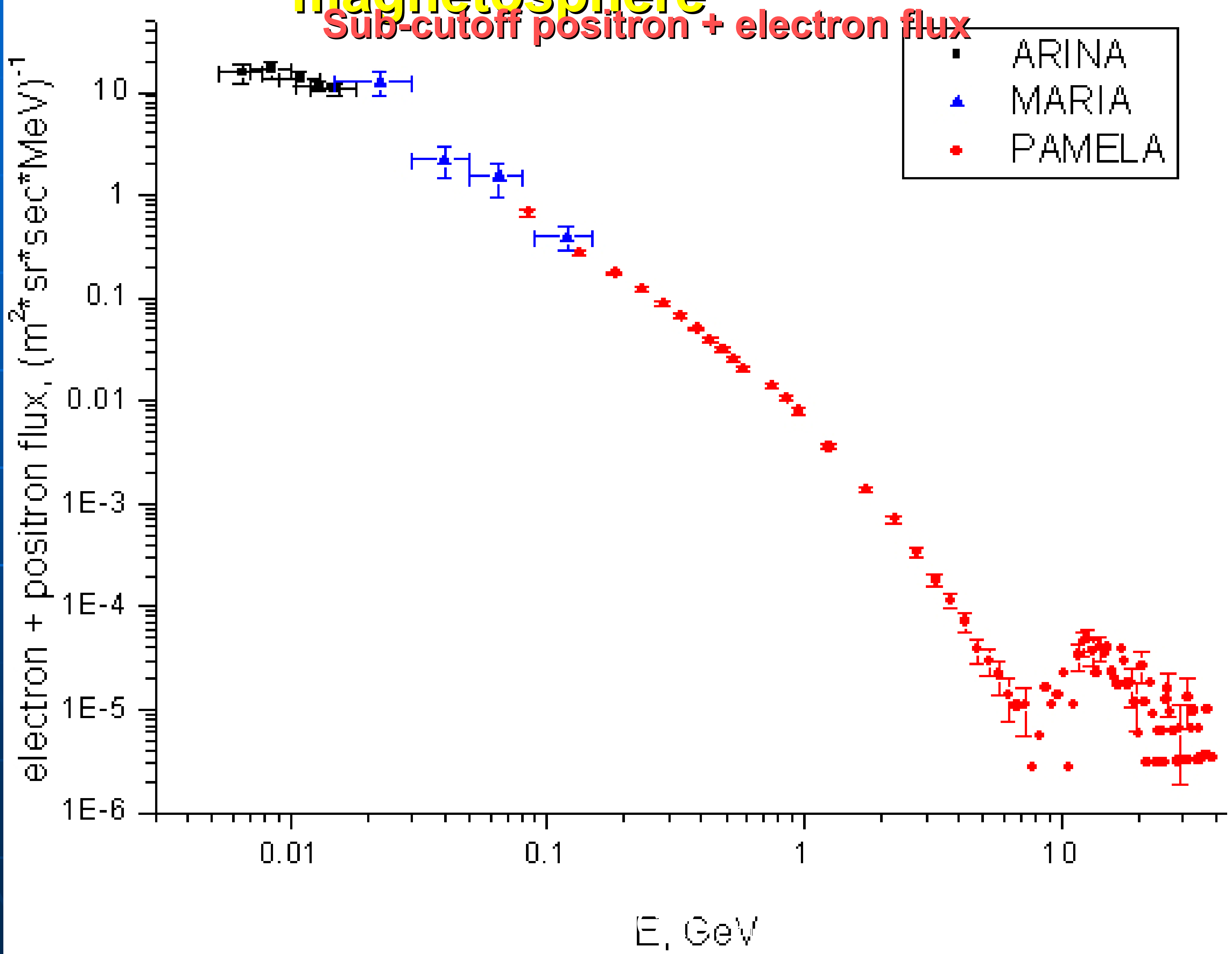


Study terrestrial magnetosphere

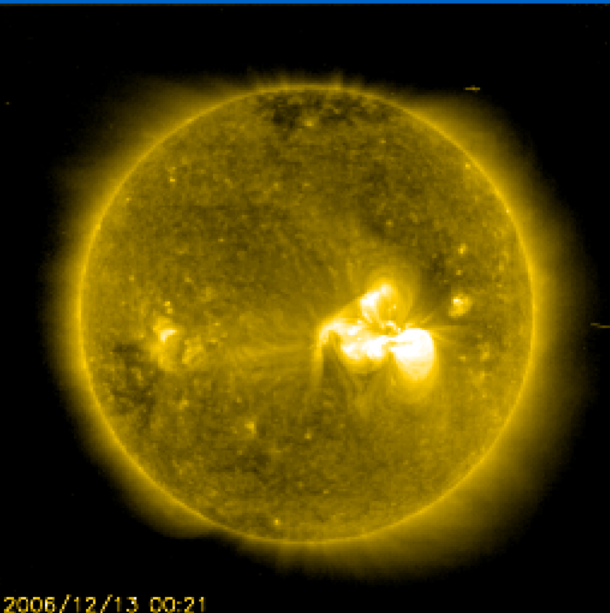
Ratio of sub-cutoff positron to electron fluxes

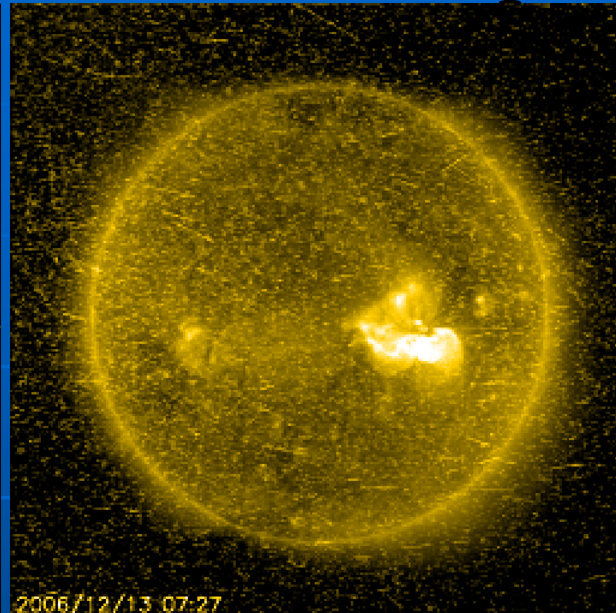


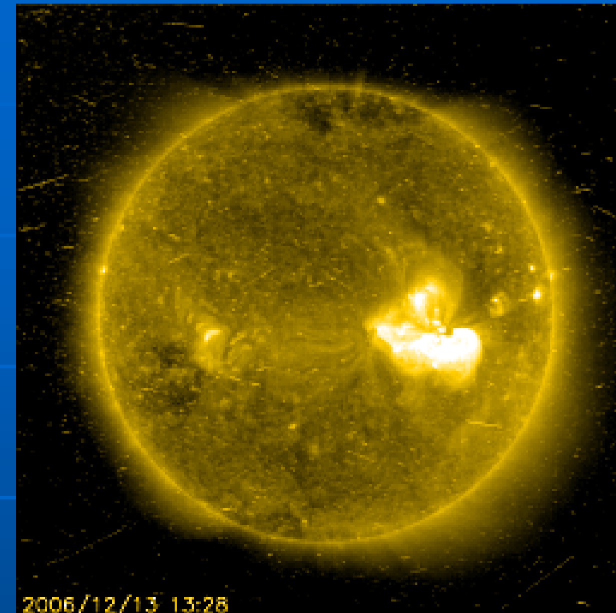
Study terrestrial magnetosphere



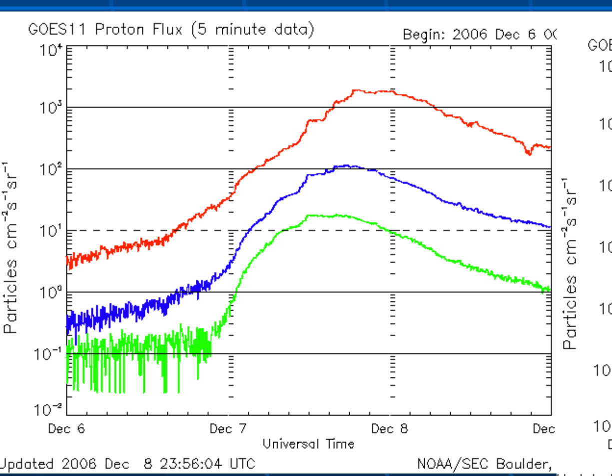
December 2006 Solar particle events

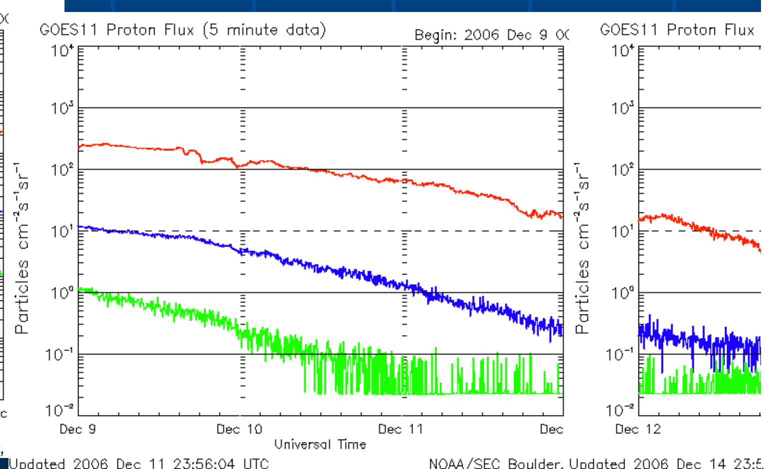


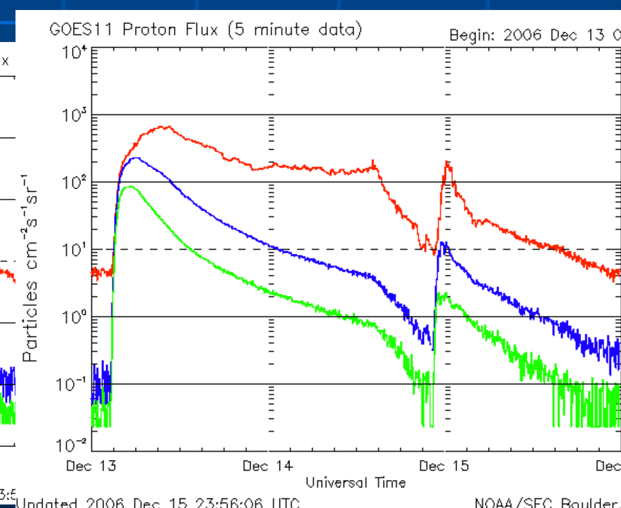




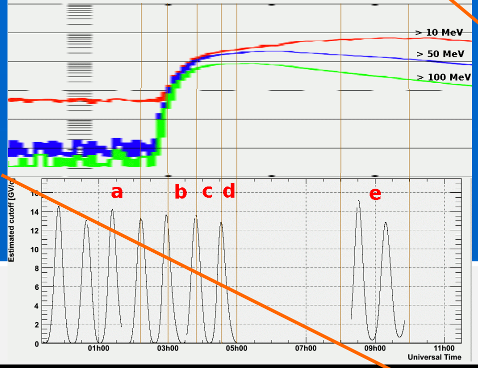
Dec 13th largest CME since 2003, anomalous at sol min

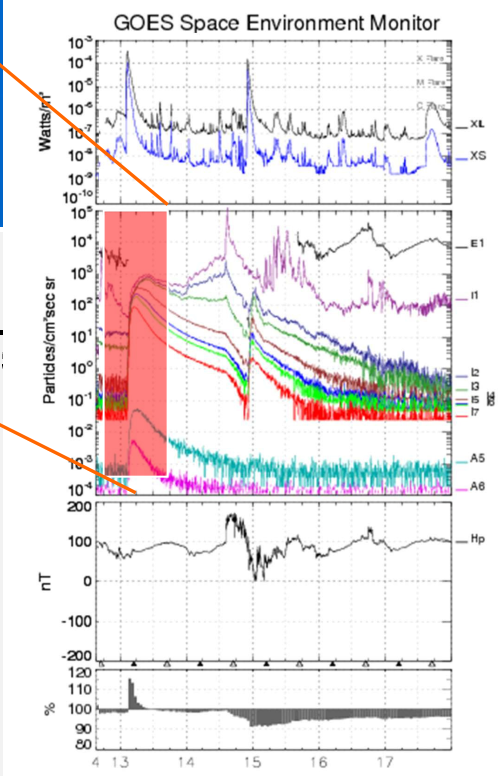


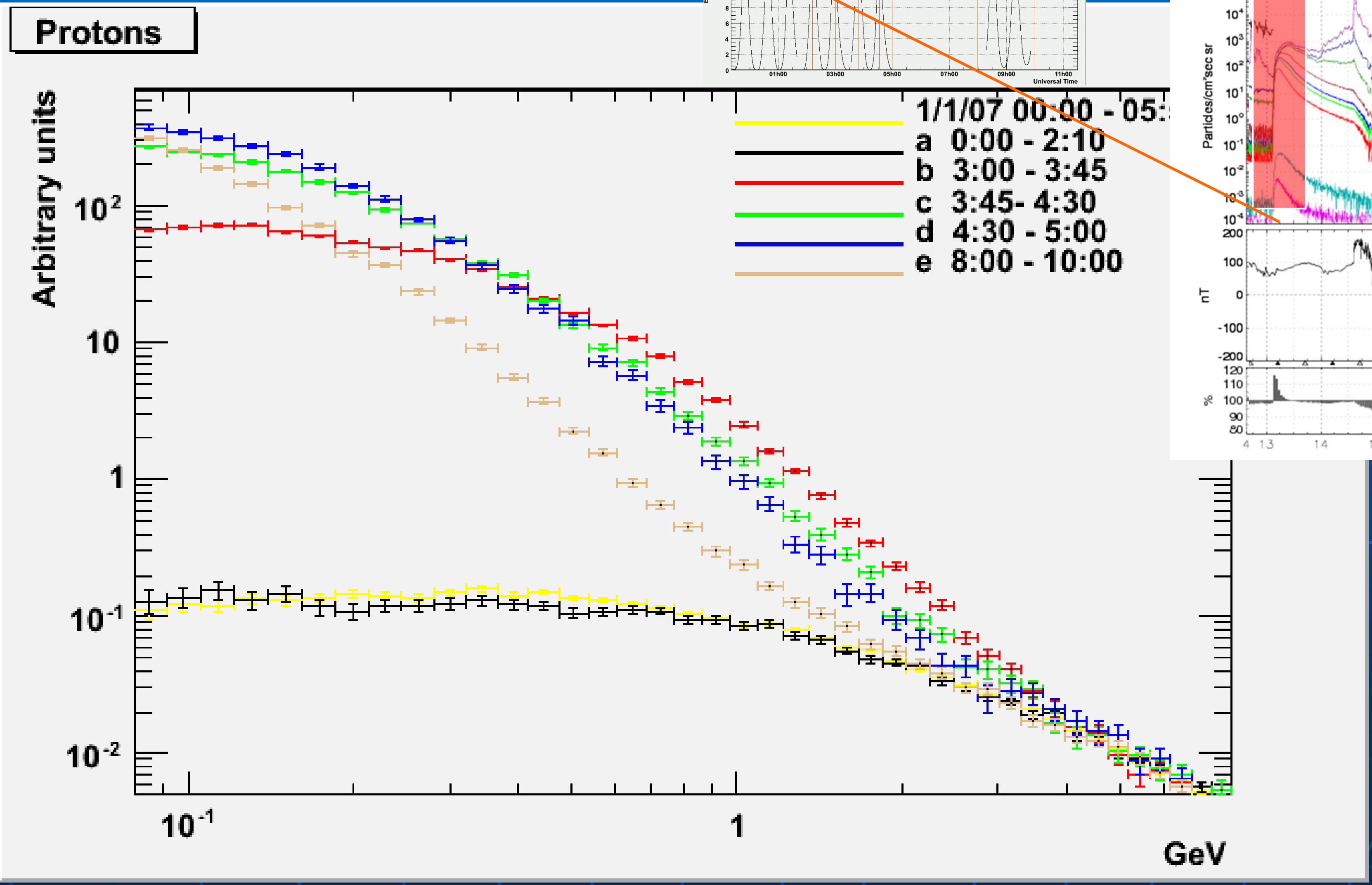




December 13th 2006 event

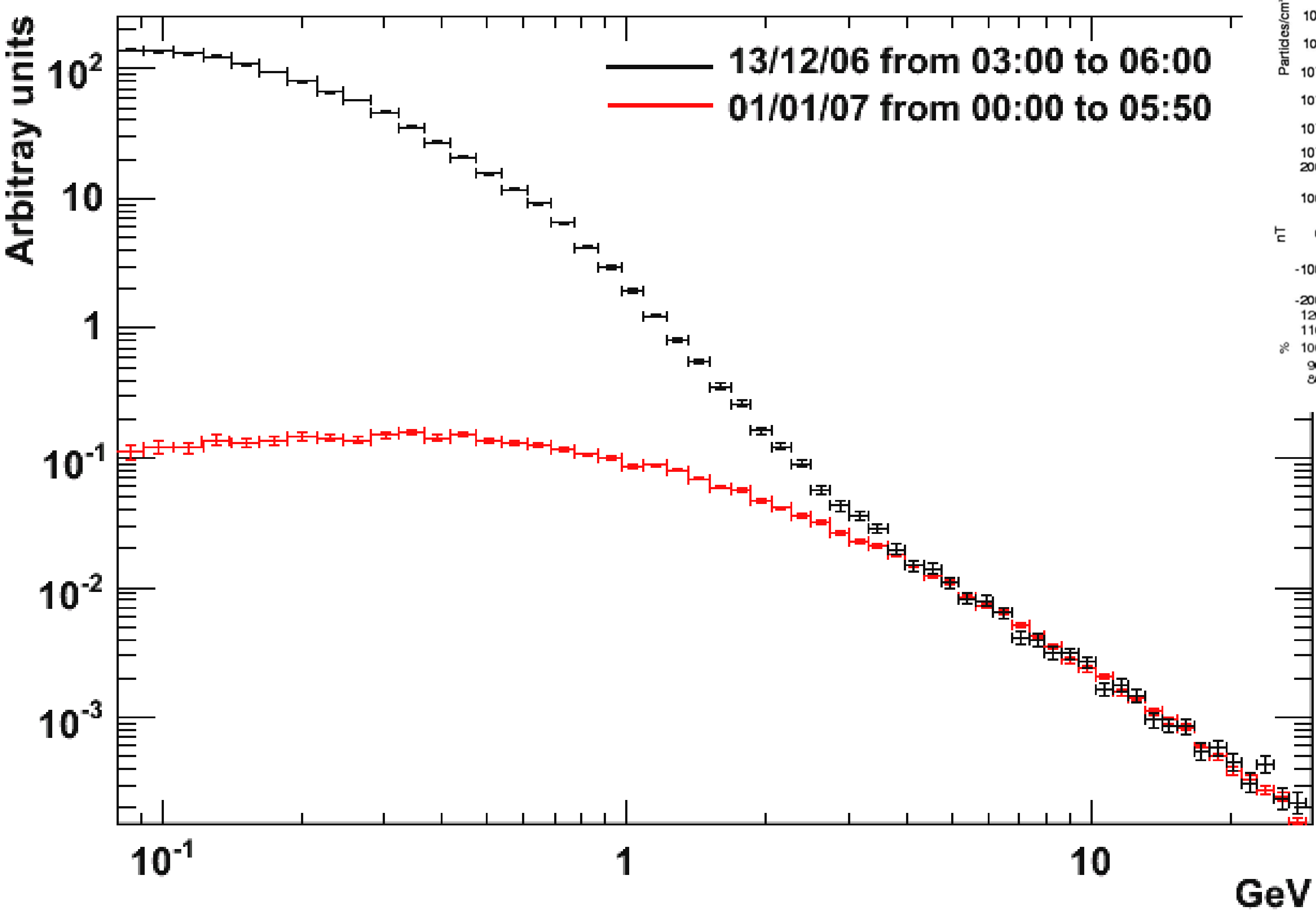


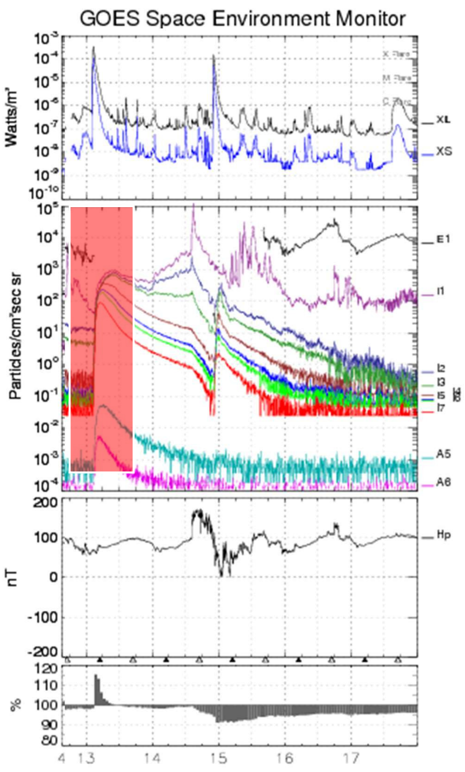




Preliminary!

December 13th 2006 He differential spectrum





Thanks!

http:// pamela.roma2.infn.it