PAMELA:

Measurements of Matter and Antimatter in Space

Nicola De Simone

INFN and University of Rome Tor Vergata

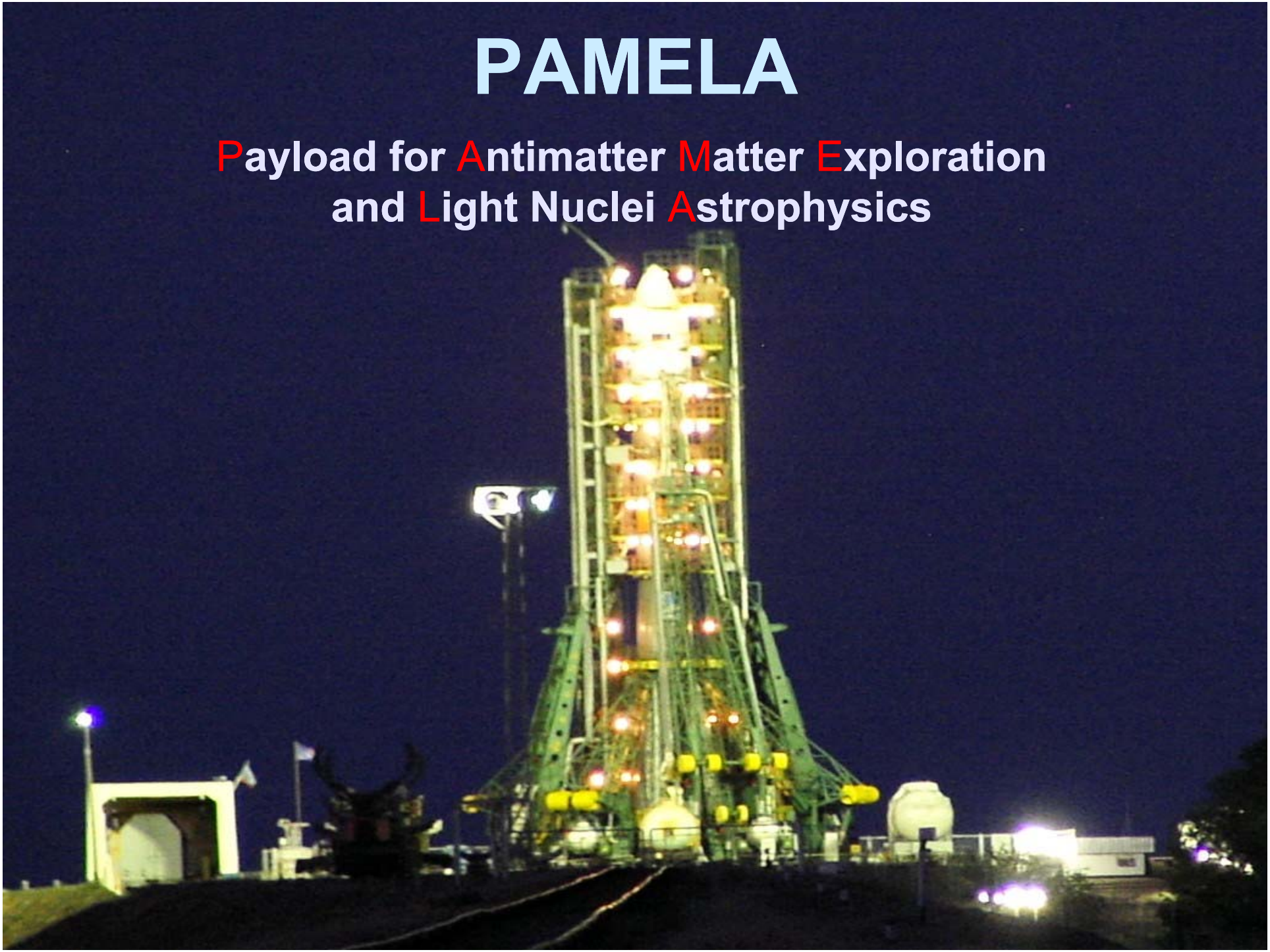
on behalf of the PAMELA Collaboration

8th SciNeGHE Workshop

Trieste, September 8 - 10, 2010

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

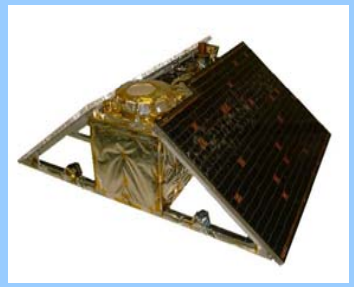
WiZard RIM Program

(Russian Italian Missions)

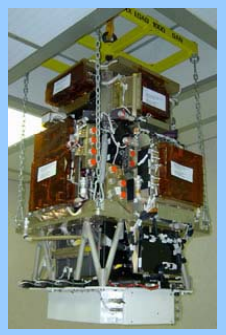
MASS-89, 91, TS-93, CAPRICE 94-97-98

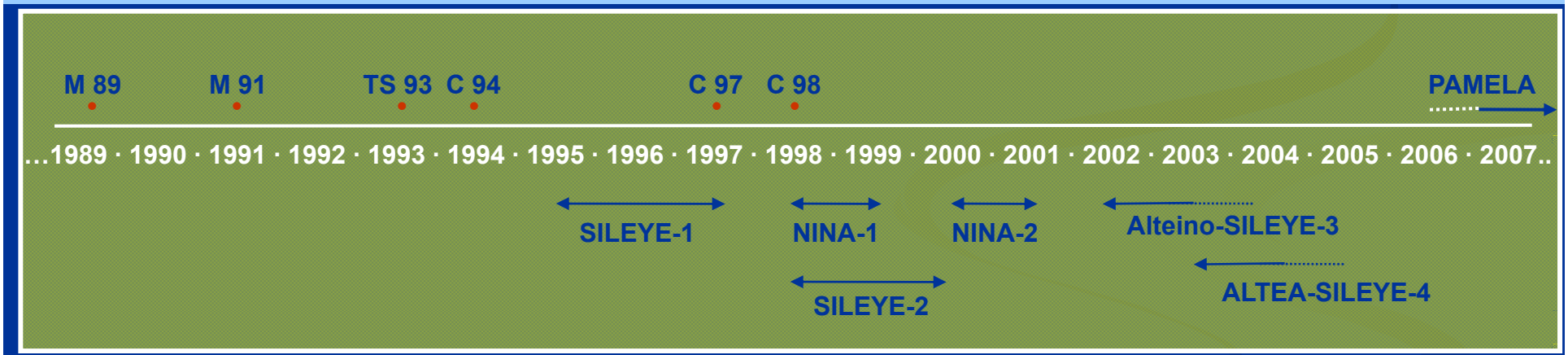
NINA-1

NINA-2



PAMELA





SILEYE-1

SILEYE-2

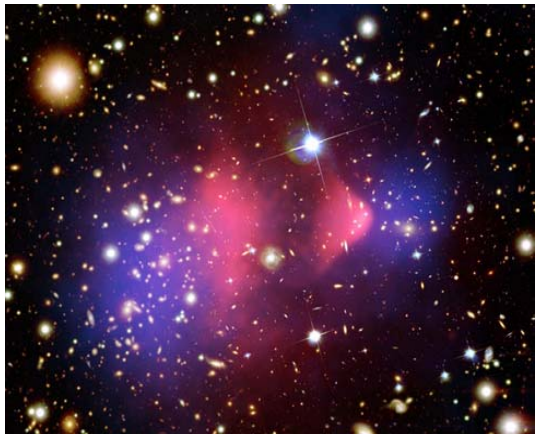
ALTEINO: SILEYE-3

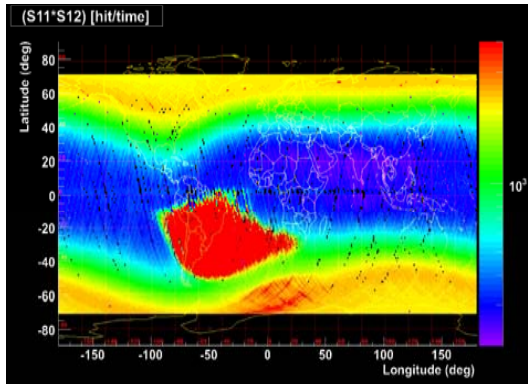
LAZIO SIRAD

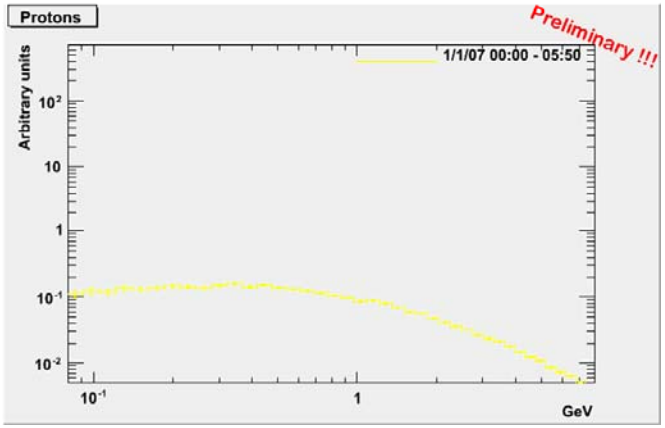
ALTEA: SILEYE-4

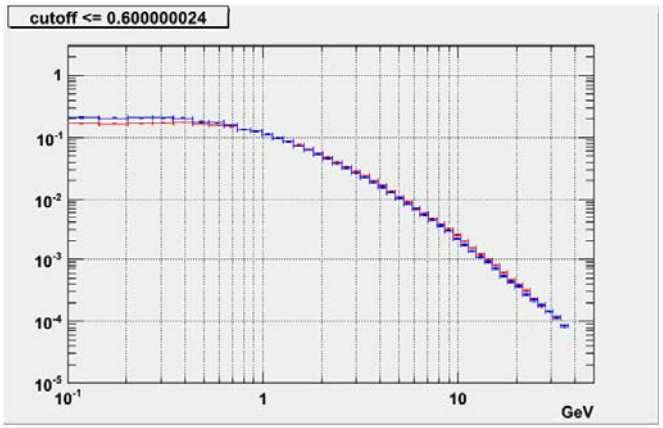
The Physics of PAMELA

- Search for dark matter annihilation
- Search for antihelium (primordial antimatter)
- Search for new matter in the Universe (strangelets?)
- Study of cosmic-ray propagation
- Study of solar physics and solar modulation
- Study of terrestrial magnetosphere

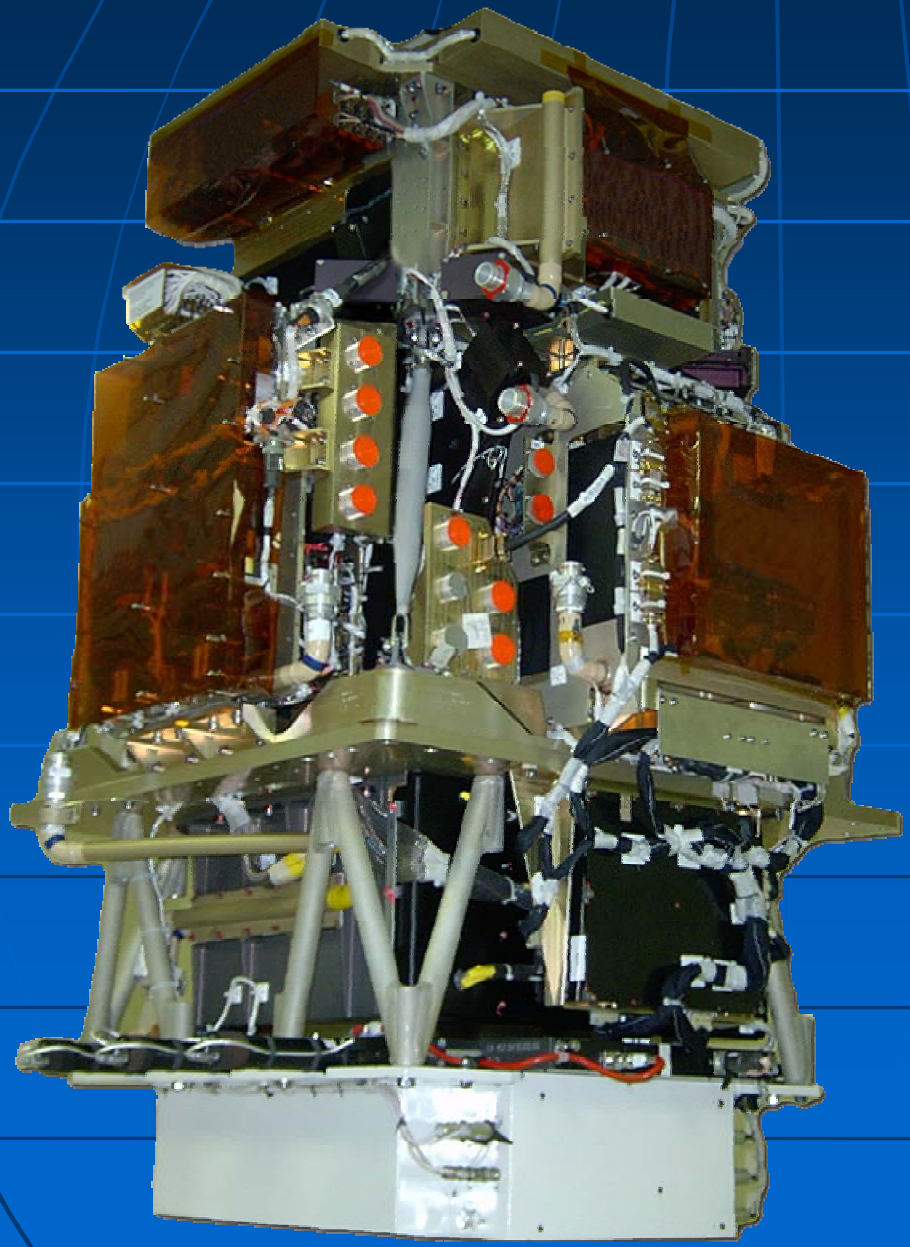








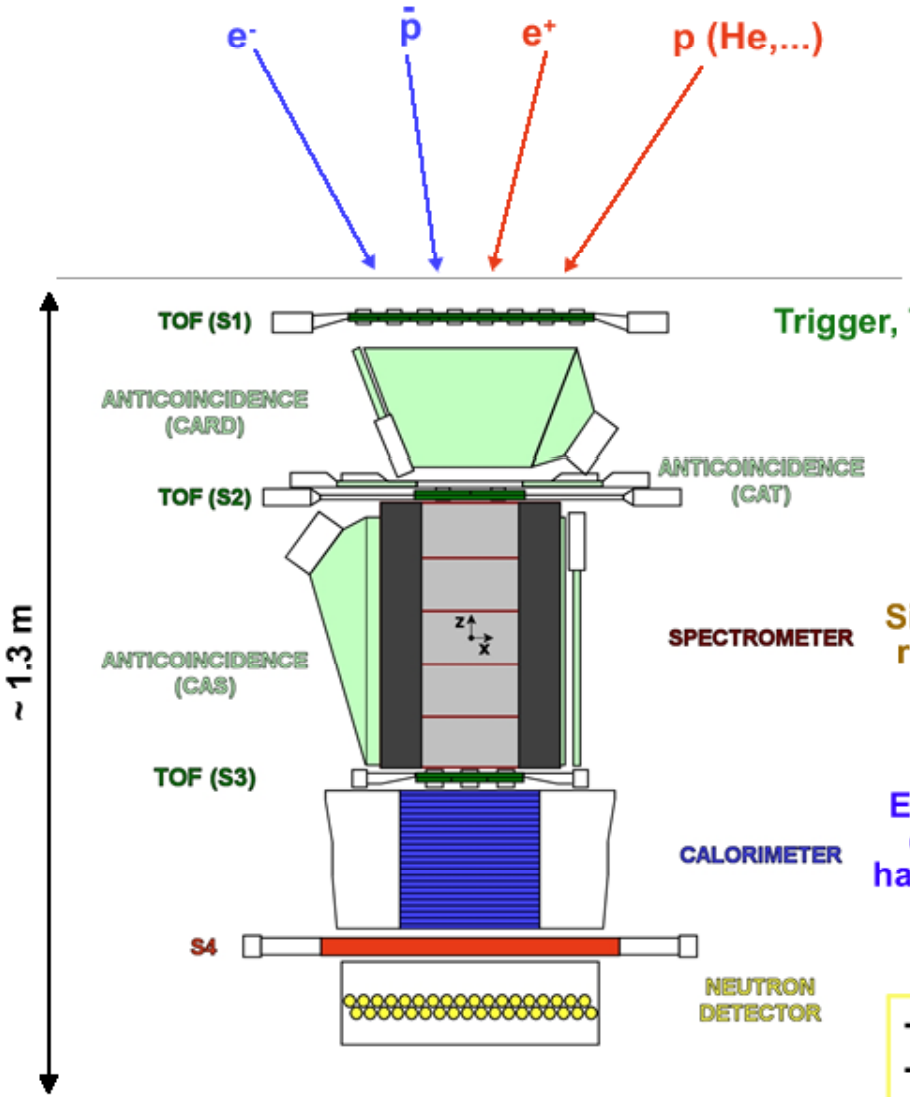
PAMELA Instrument



GF ~21.5 cm^2sr

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 ~1200 GV (6 planes)

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

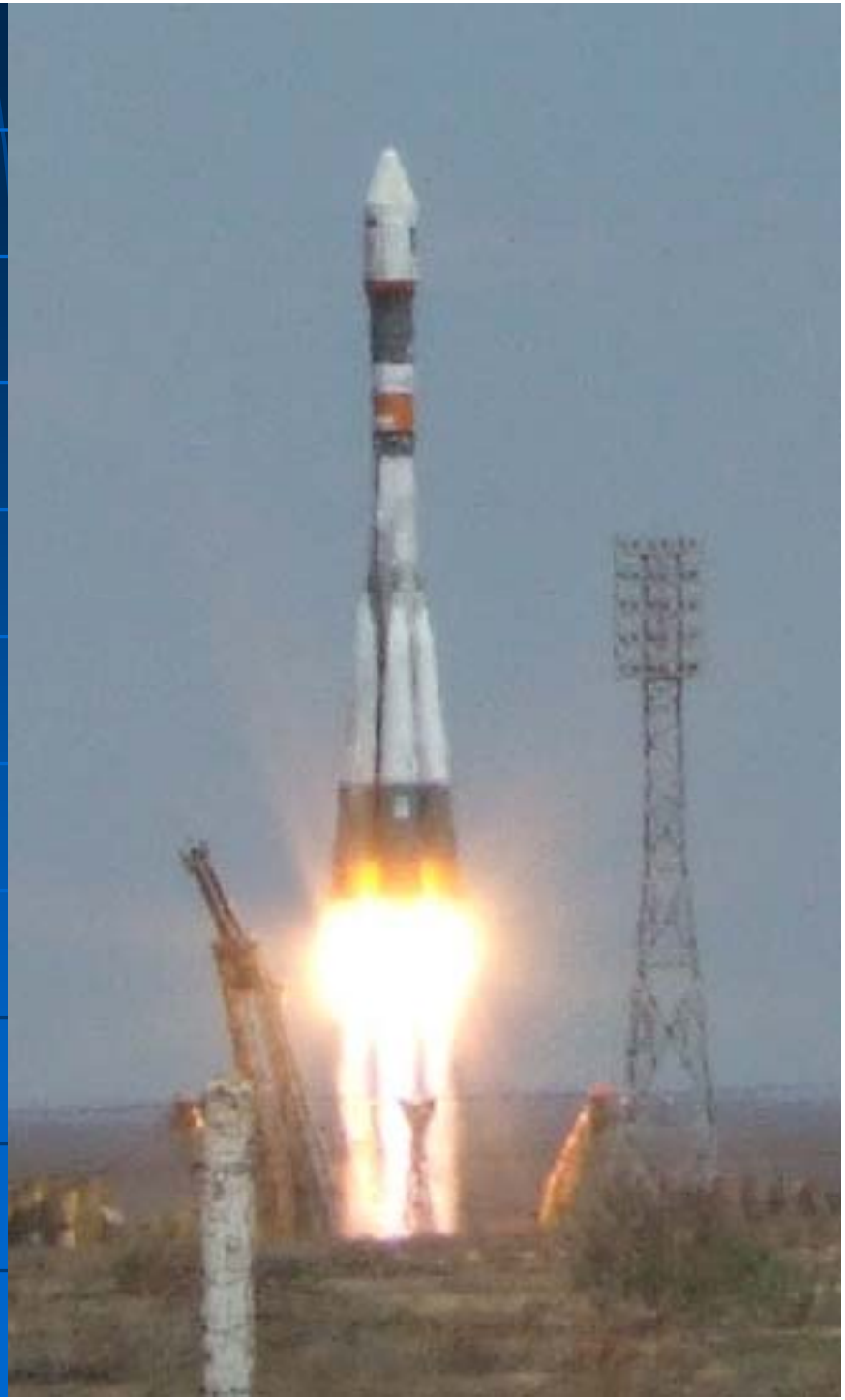
Design Performance

	Energy range
Antiprotons	80 MeV - 190 GeV
Positrons	50 MeV – 300 GeV
Electrons	up to 500 GeV
Protons	up to 1 TeV
Helium	up to 400 GeV/n
Electrons+positrons	up to 2 TeV (from calorimeter)
Light Nuclei (Li/Be/B/C)	up to 200 GeV/n
AntiNuclei search	sensitivity of 3×10^{-8} in $\overline{He}/He$

PAMELA

Launch 15/06/06

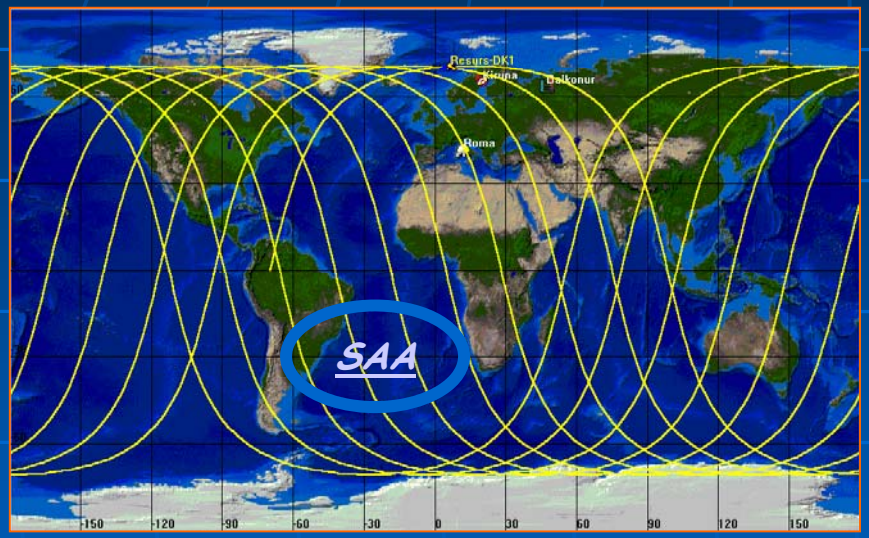
16 Gigabytes trasmitted daily to Ground NTsOMZ Moscow

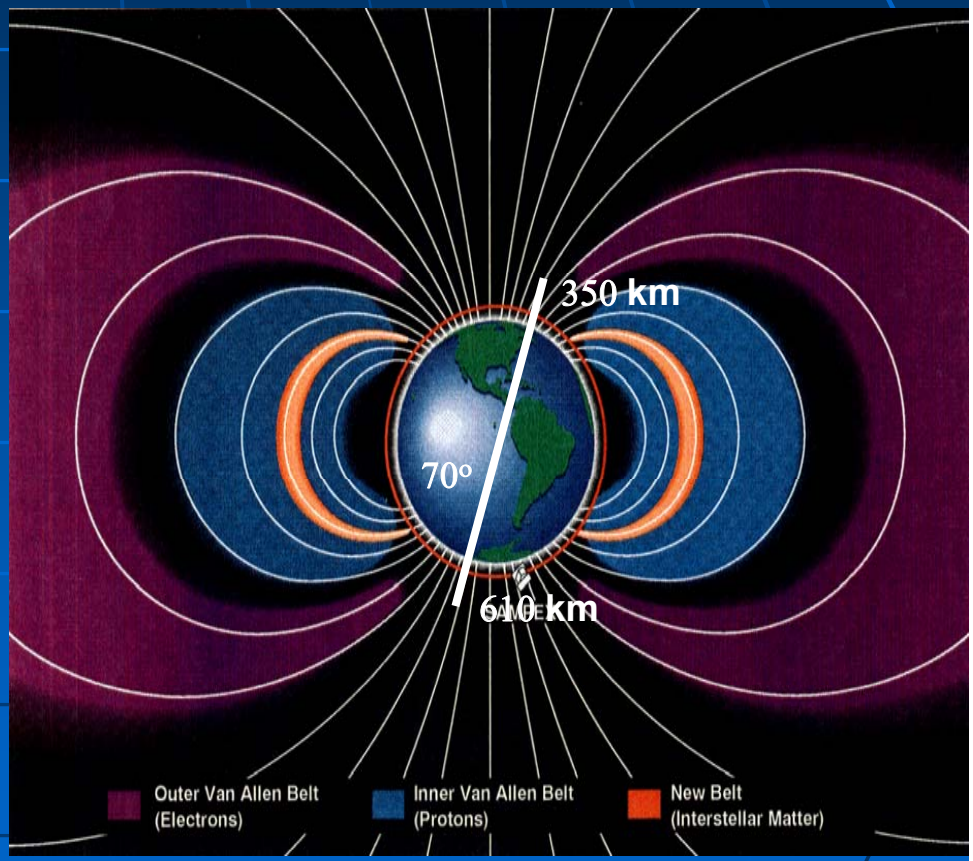


PAMELA Status

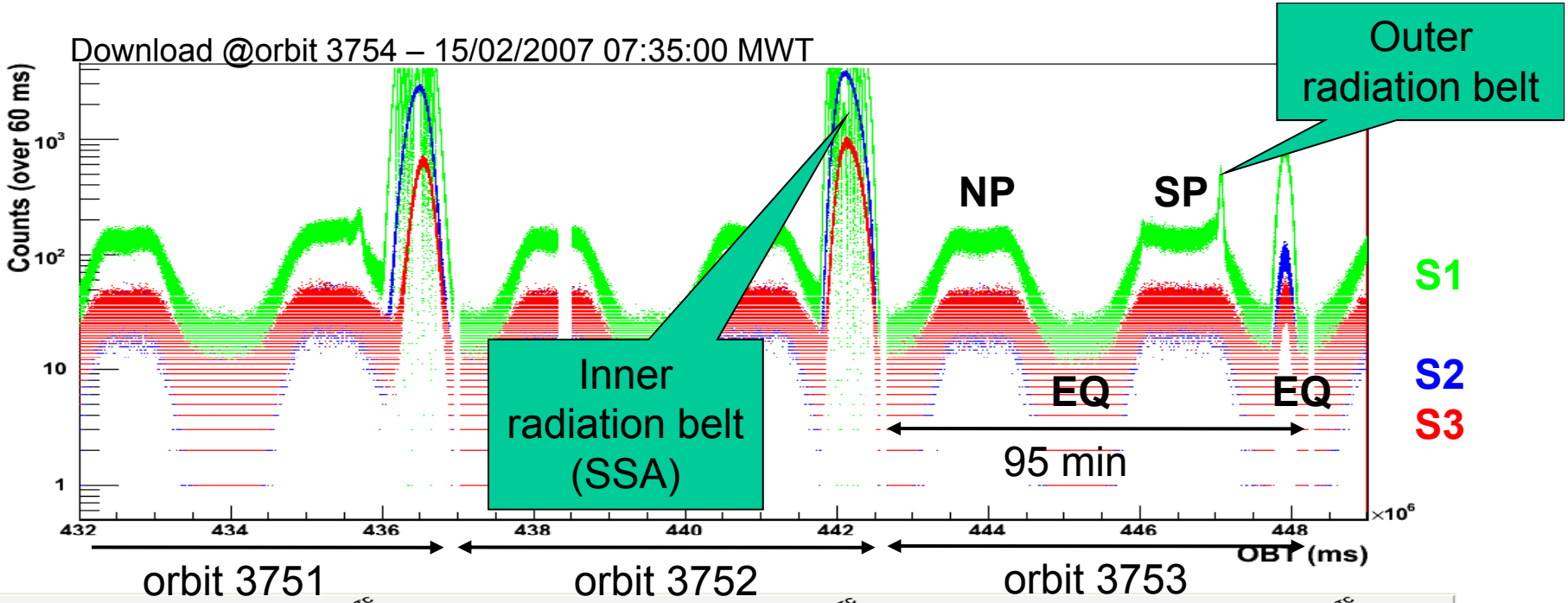
- Till now: 1550 days in flight
- ~20 TBytes of raw data downlinked
- $>2.10^9$ triggers recorded and under analysis

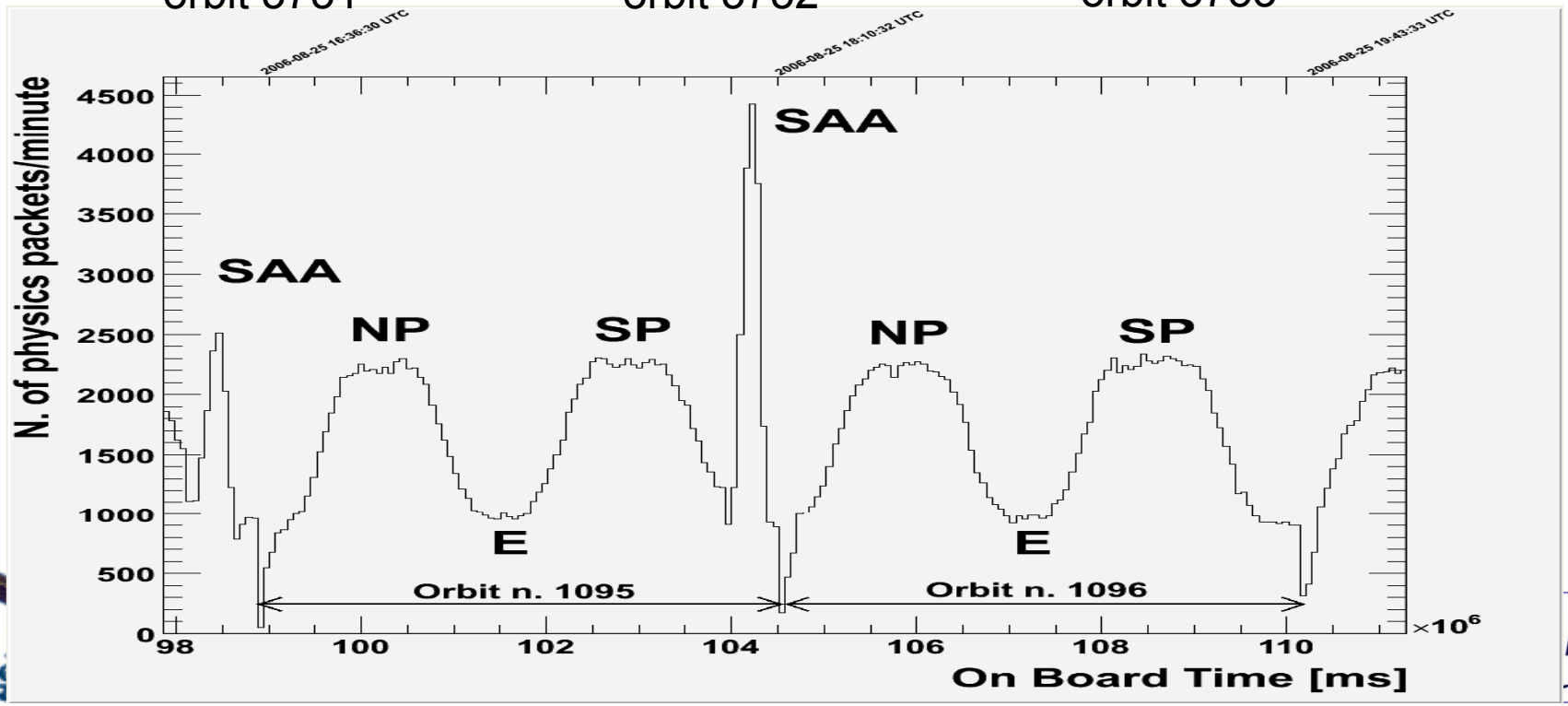
Orbit Characteristics



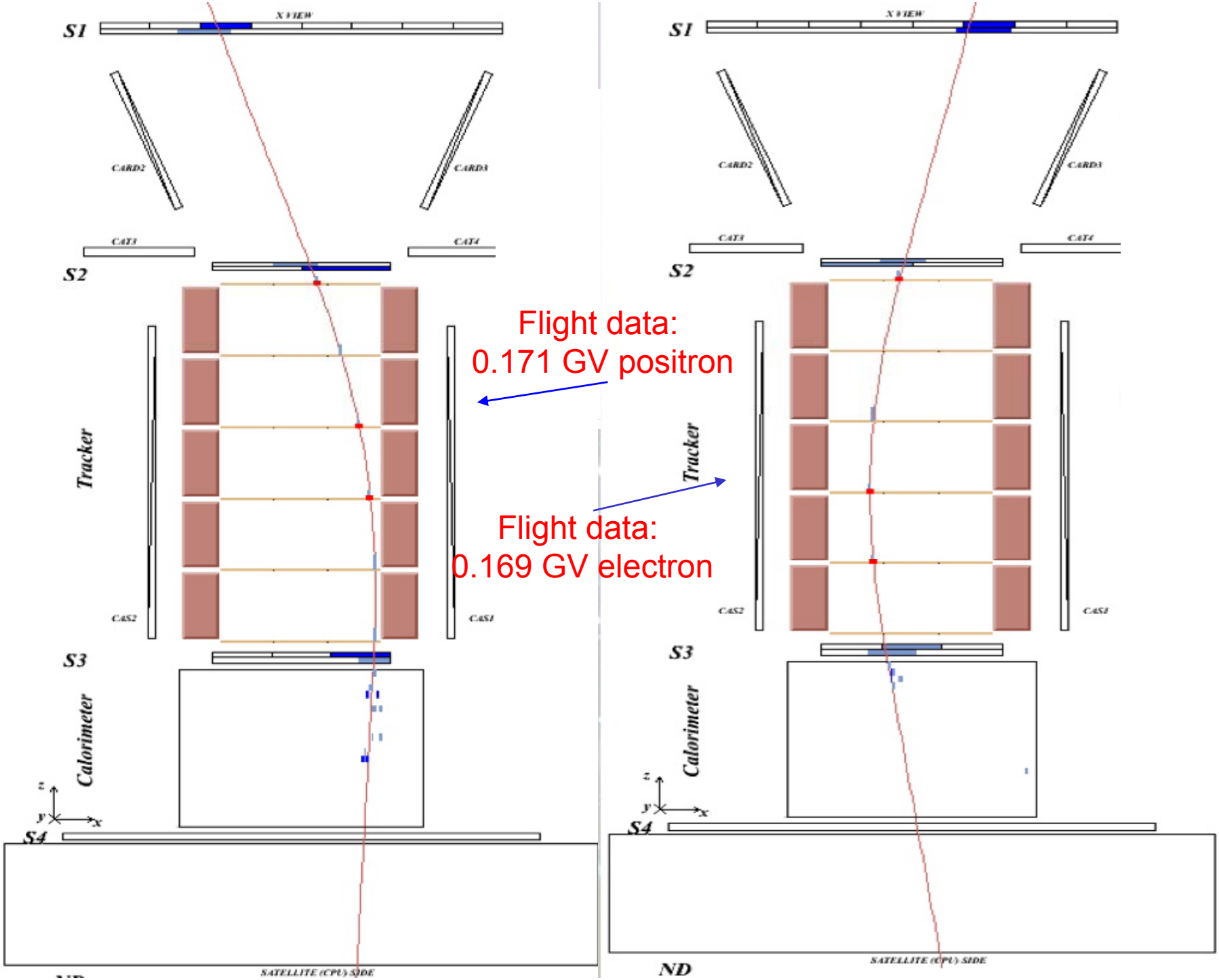


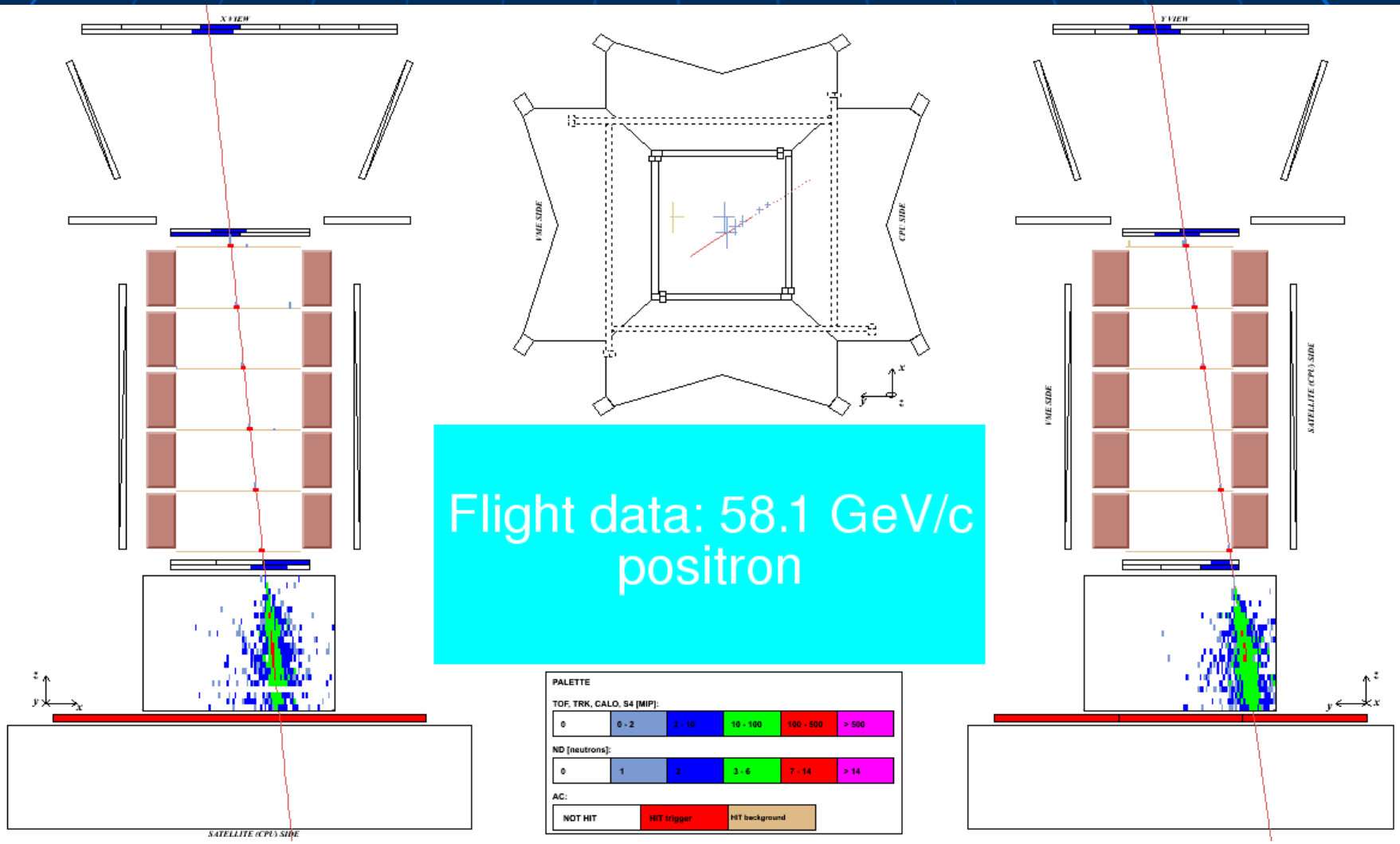
- Low-earth elliptical orbit
- 350 – 610 km
- Quasi-polar (70º inclination)
- SAA crossed


Download @orbit 3754 – 15/02/2007 07:35:00 MWT
Counts (over 60 ms)
Outer radiation belt
NP
SP
S1
S2
S3
Inner radiation belt (SSA)
EQ
EQ
95 min
OBT (ms)
orbit 3751
orbit 3752
orbit 3753

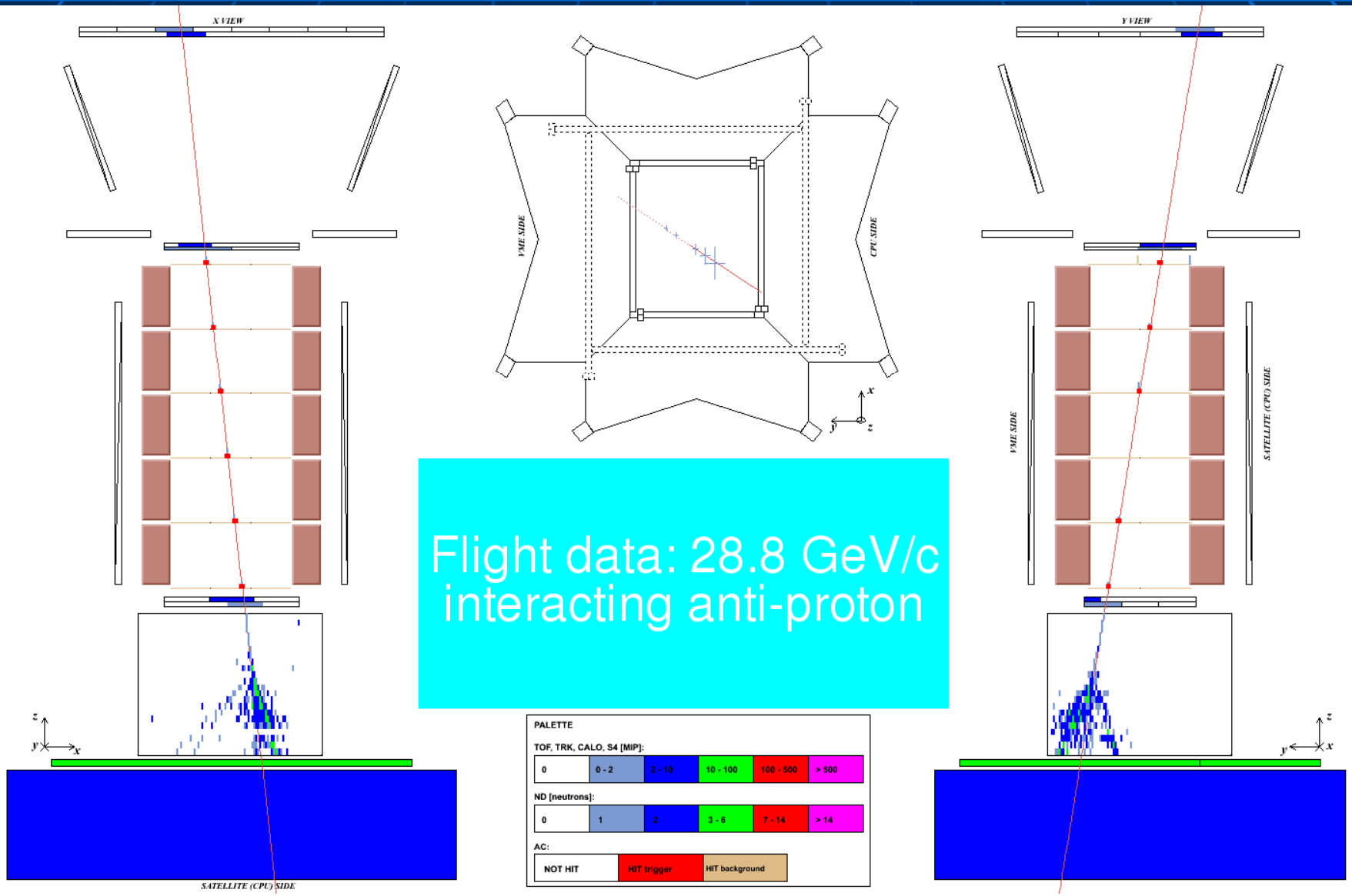

N. of physics packets/minute
SAA
SAA
NP
SP
NP
SP
E
E
Orbit n. 1095
Orbit n. 1096
On Board Time [ms]

Particle ID with PAMELA

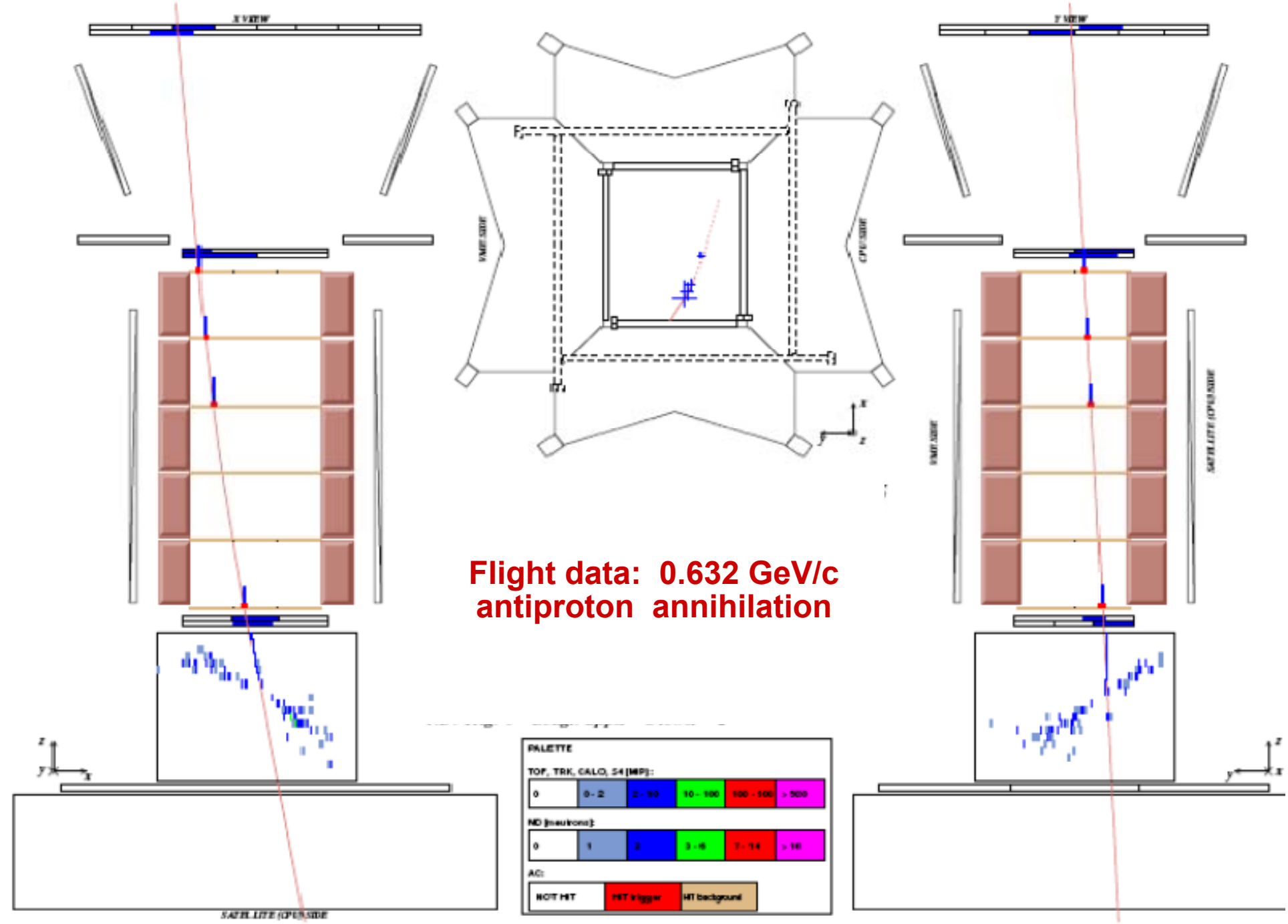

S1
X VIEW
CARD2
CARD3
CAT3
CAT4
S2
Tracker
CAS2
CAS1
S3
Calorimeter
S4
SATELLITE (CPU) SIDE
ND
Flight data:
0.171 GV positron
Flight data:
0.169 GV electron



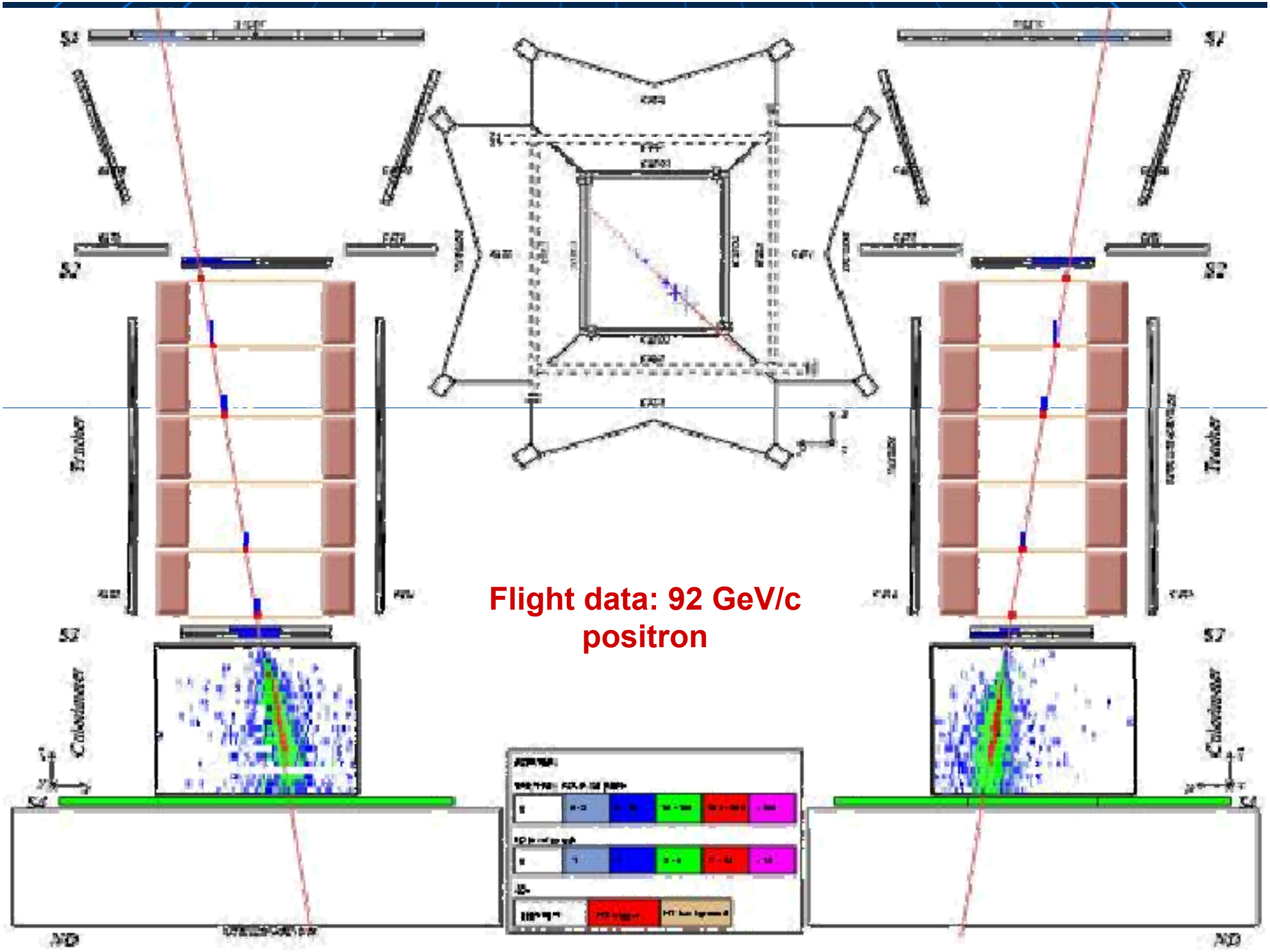
Flight data: 58.1 GeV/c positron



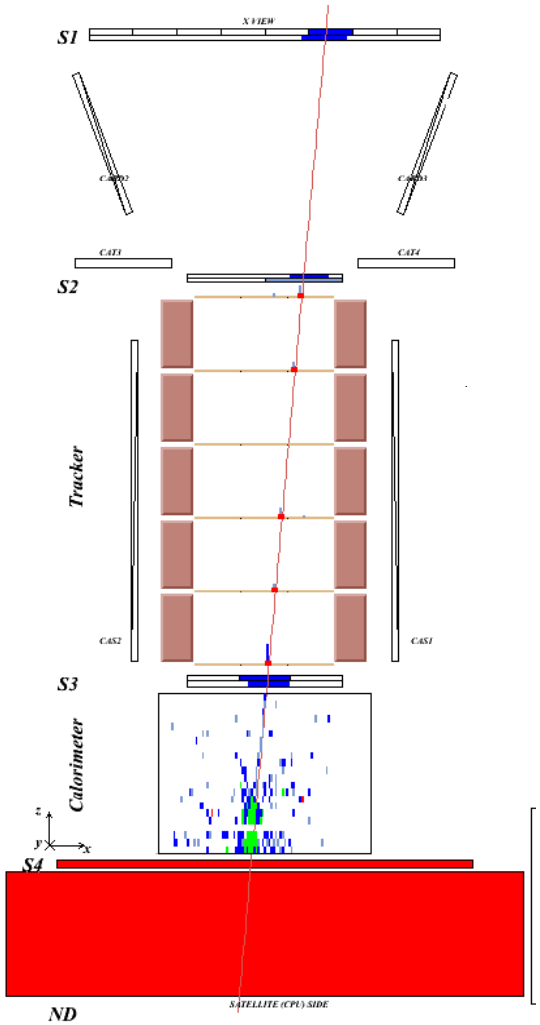
Flight data: 28.8 GeV/c interacting anti-proton



Flight data: 0.632 GeV/c antiproton annihilation


Flight data: 92 GeV/c
positron
Tracker
Tracker
Calorimeter
Calorimeter

Antiproton / Positron Identification



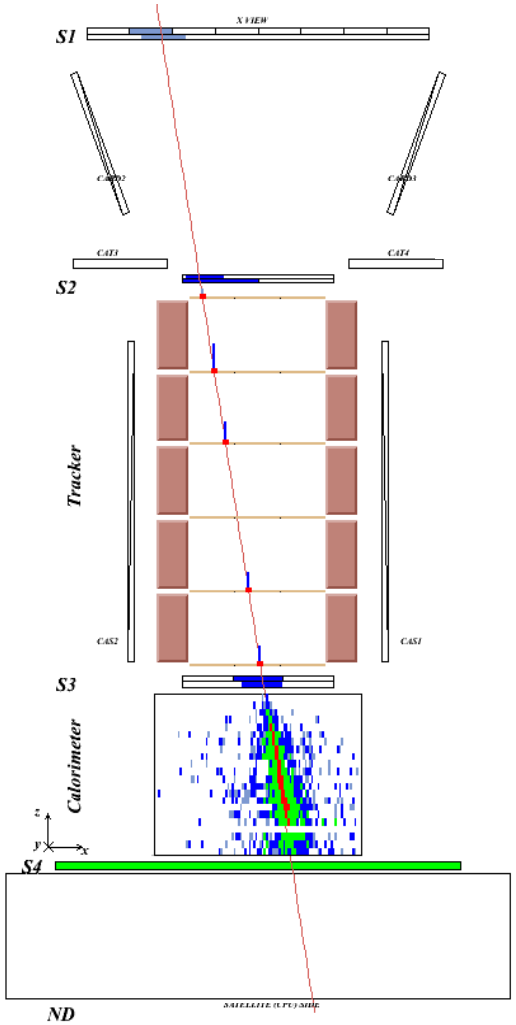
Antiproton
(NB: $e^-/\bar{p} \sim 10^2$)

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
(NB: $p/e^+ \sim 10^{3\text{-}4}$)

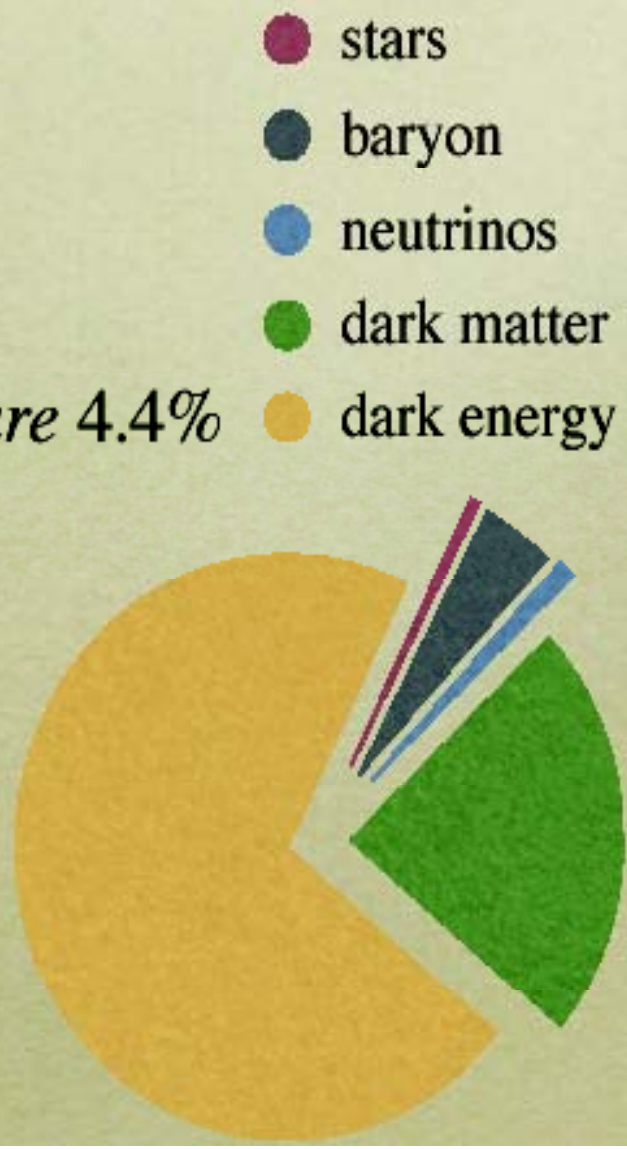
Antiparticles with PAMELA

THE UNIVERSE ENERGY BUDGET

- *Stars and galaxies are only* ~0.5%
- *Neutrinos are* ~0.1–1.5%
- *Rest of ordinary matter*

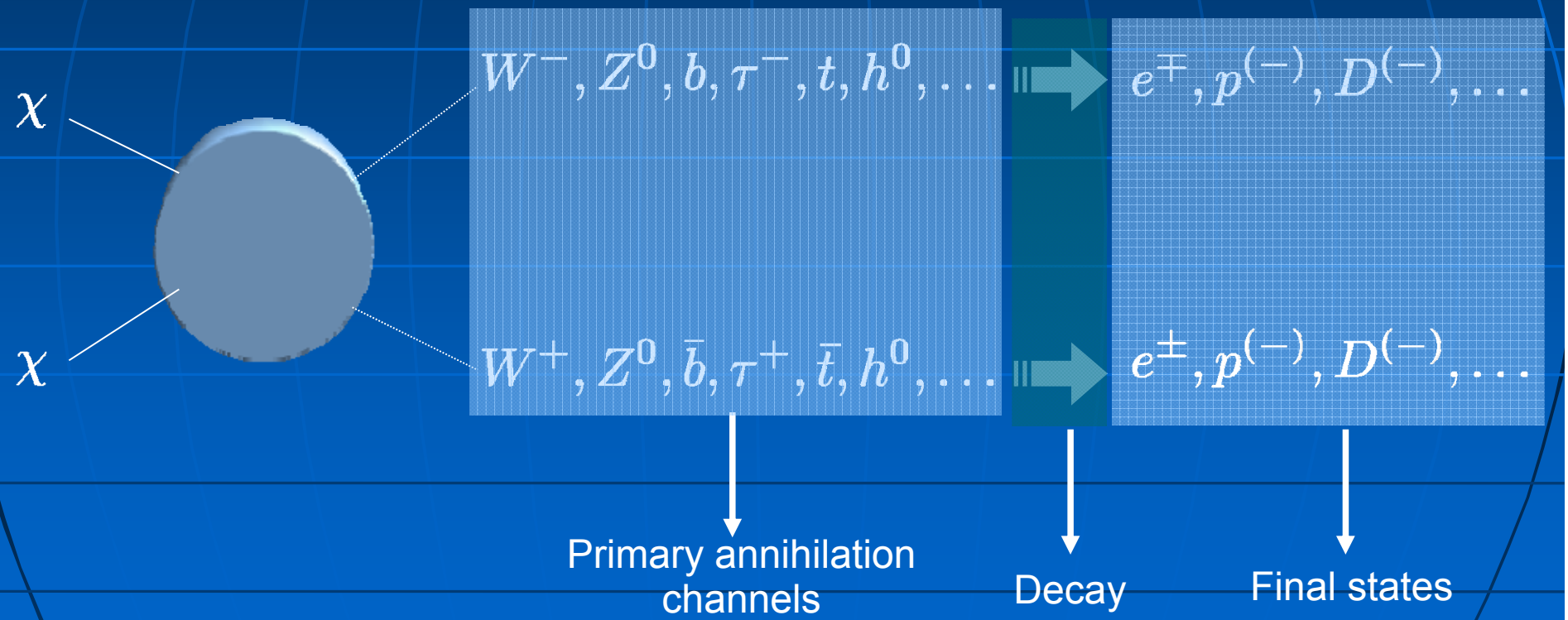
  (electrons, protons & neutrons) are 4.4%
- *Dark Matter* 23%
- *Dark Energy* 73%
- *Anti-Matter* 0%
- *Higgs Bose-Einstein condensate*

  ~10^{62}%??



DM annihilations

DM particles are stable. They can annihilate in pairs.



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

astro& cosmo

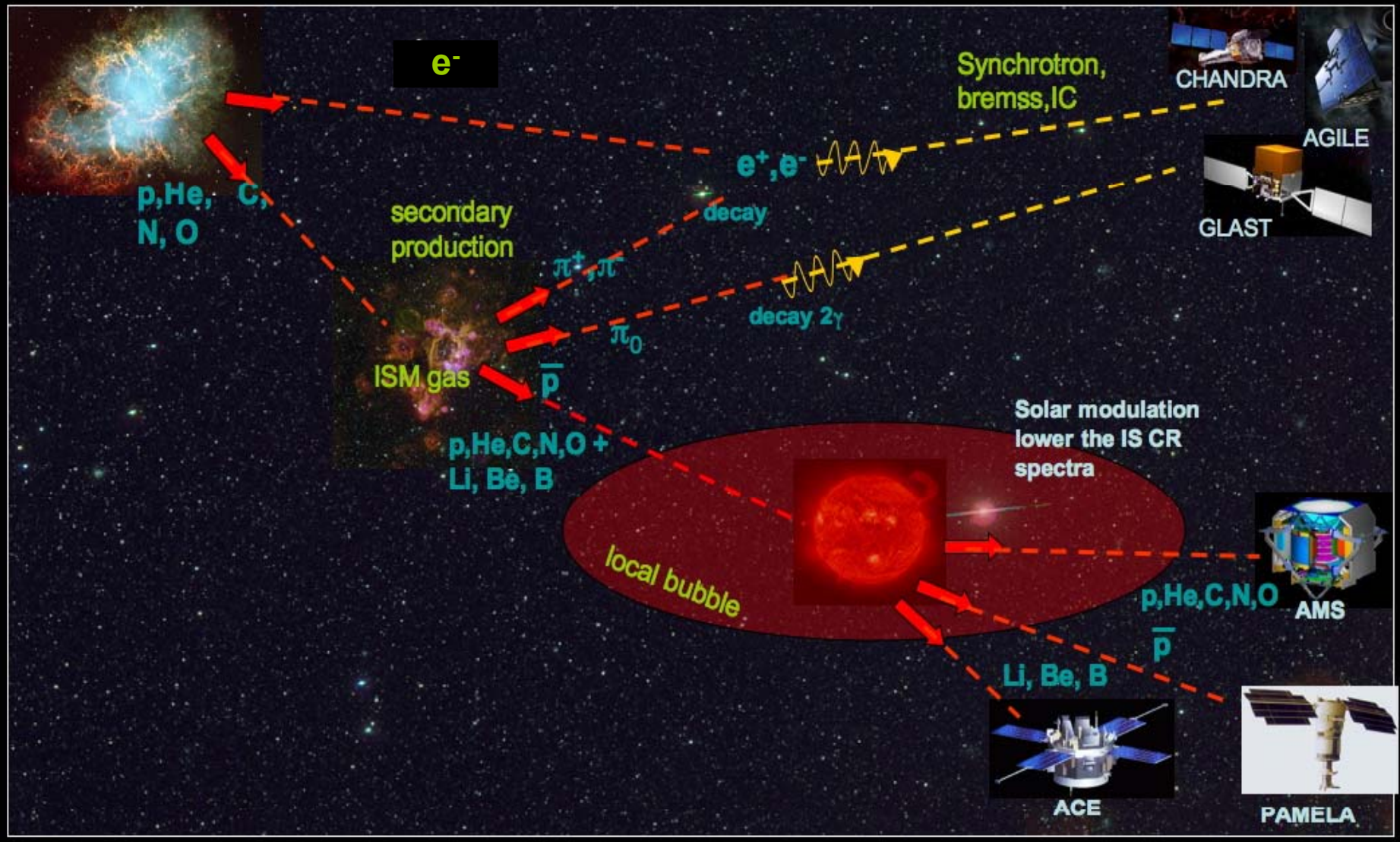
particle

reference cross section:

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

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

COSMIC RAYS PRODUCTION MECHANISMS



Antiparticle detection

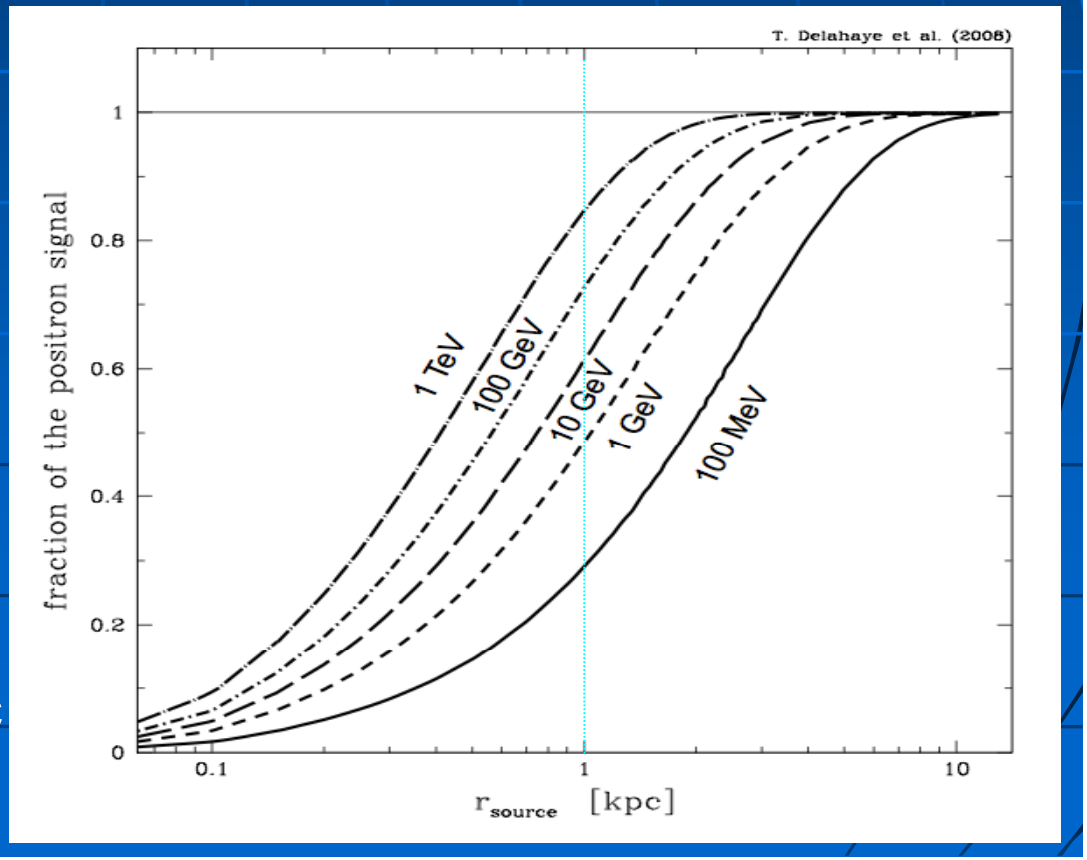
Where do positrons come from?

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

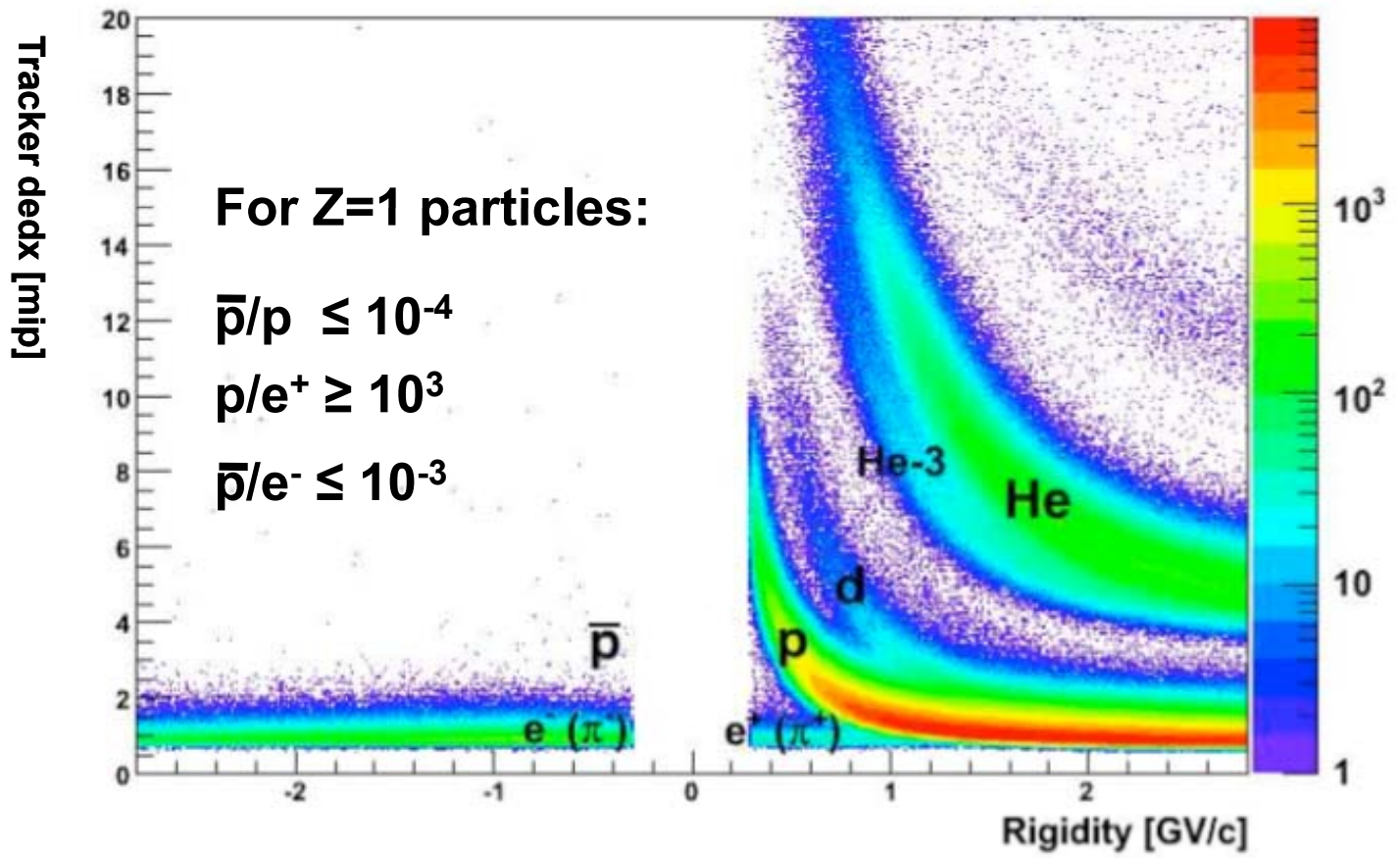
Typical lifetime

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

Antiprotons within 10 Kpc

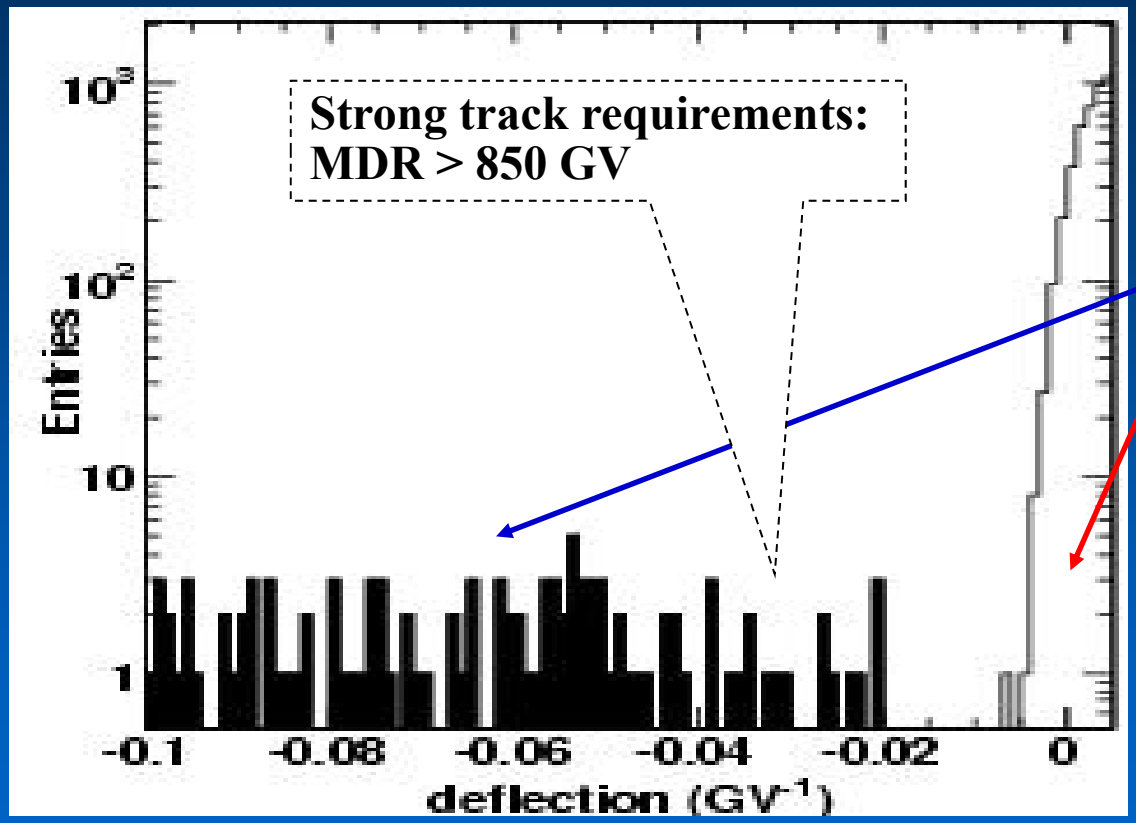


Searching for Antimatter
We have to identify the particles…



Particle identification results from the combination of measurements from the full instrument

Deflection spectrum of the remaining Protons and Antiprotons



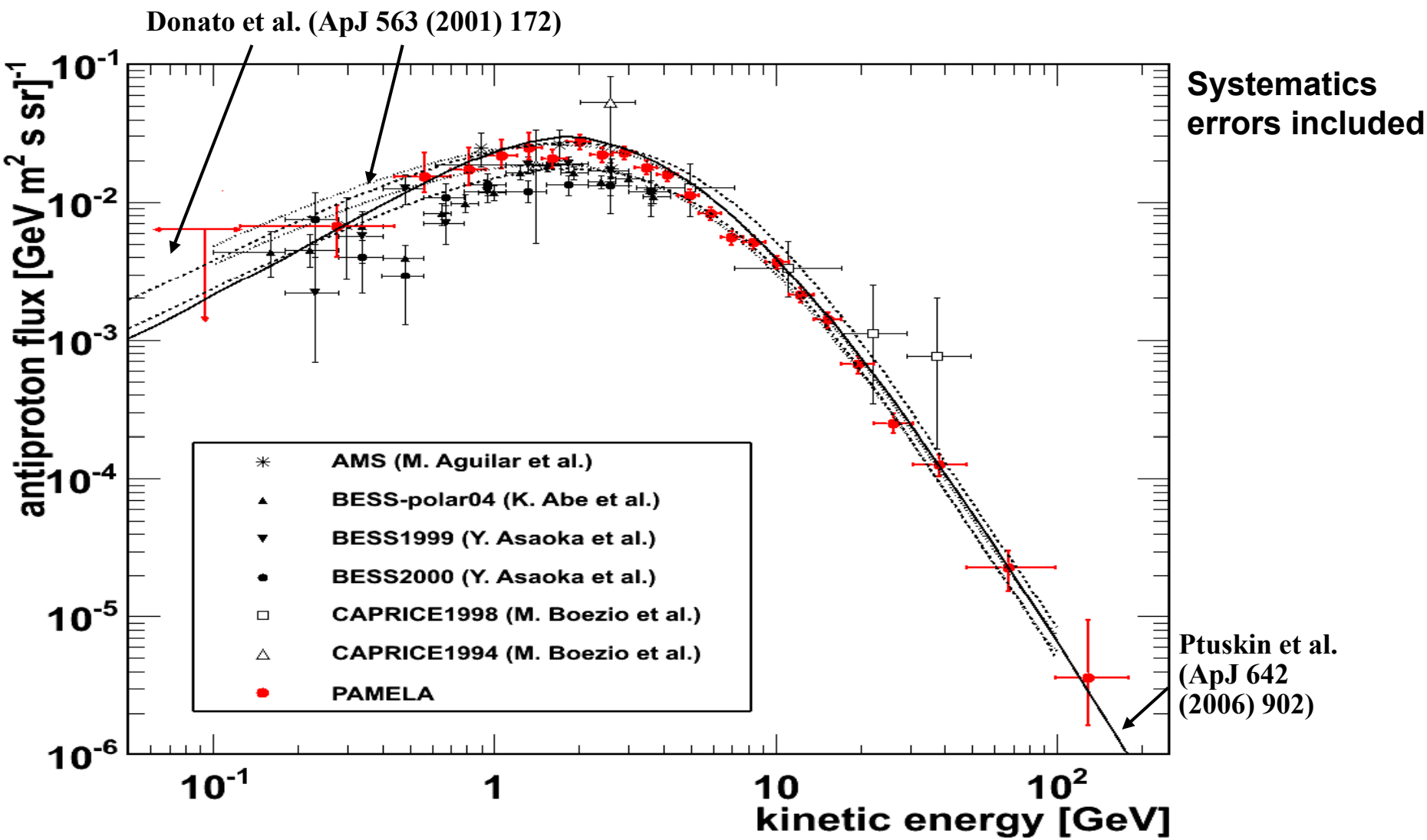
Tracker Identification

Antiprotons

Protons (& spillover)

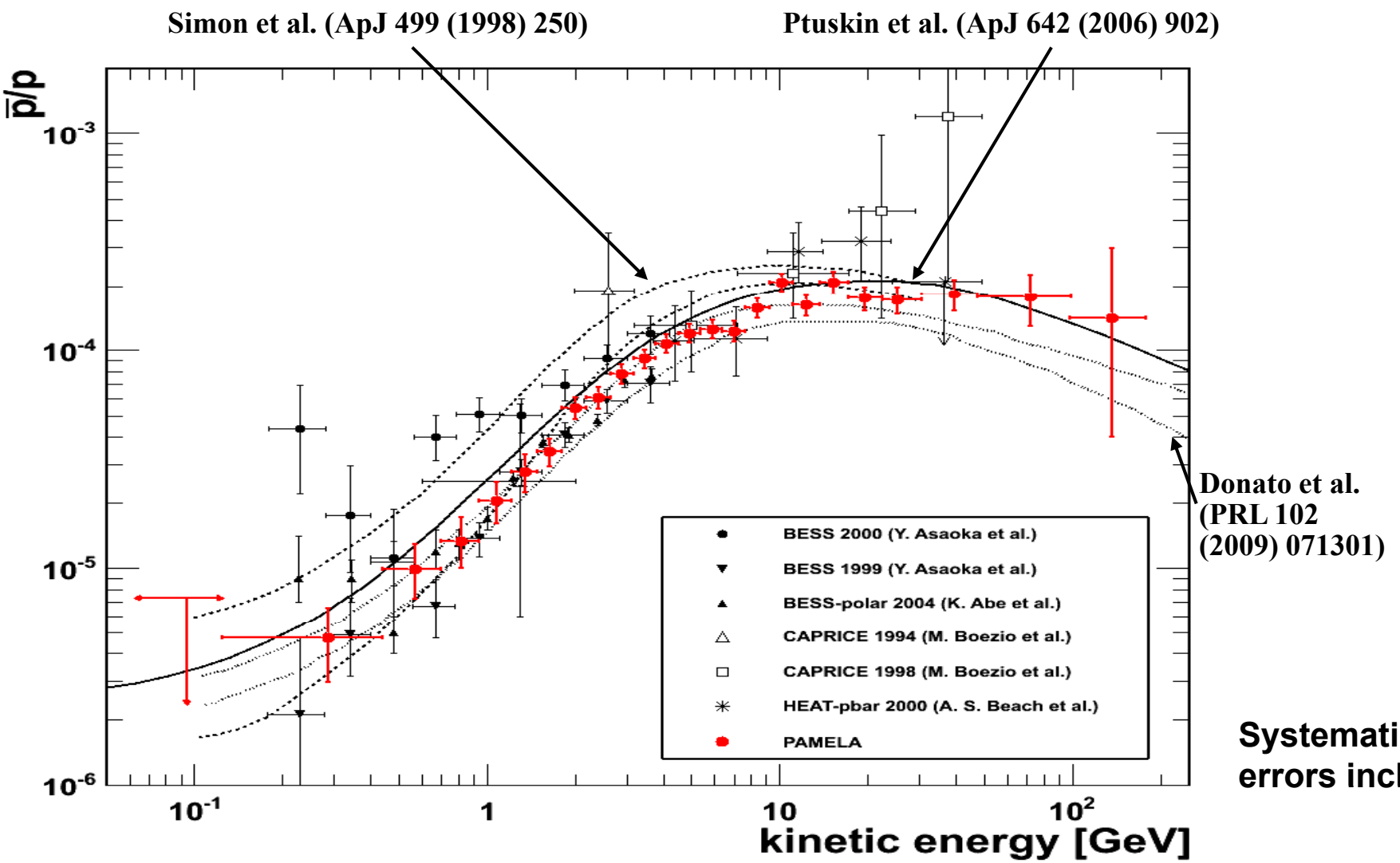
Deflection = 1/Rigidity

Antiproton Flux
(0.06 GeV - 180 GeV)



Adriani et al., astro-ph 1007.0821 PRL in press

Antiproton to proton ratio (0.06 GeV - 180 GeV)



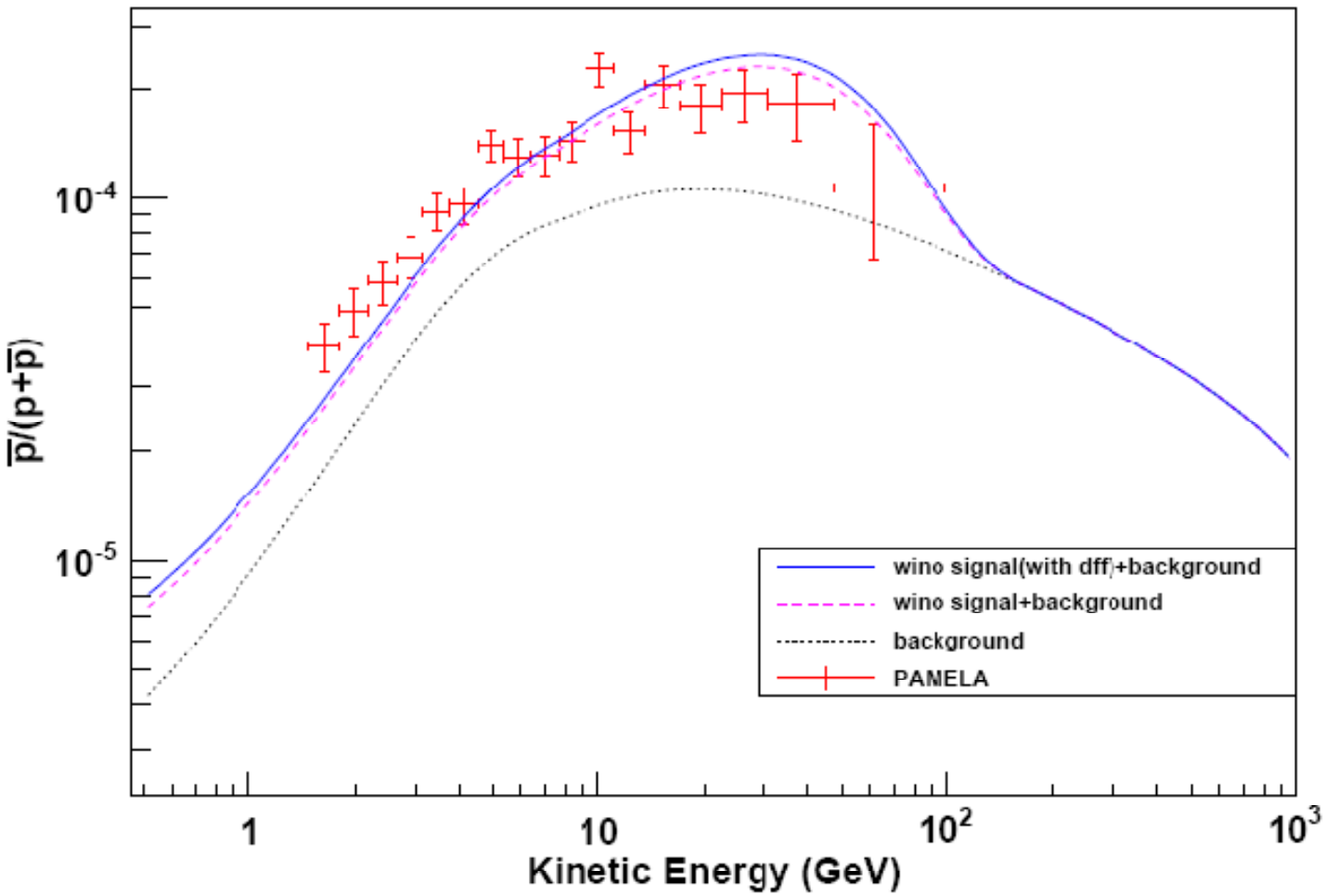
Systematics errors included

Adriani et al., astro-ph 1007.0821

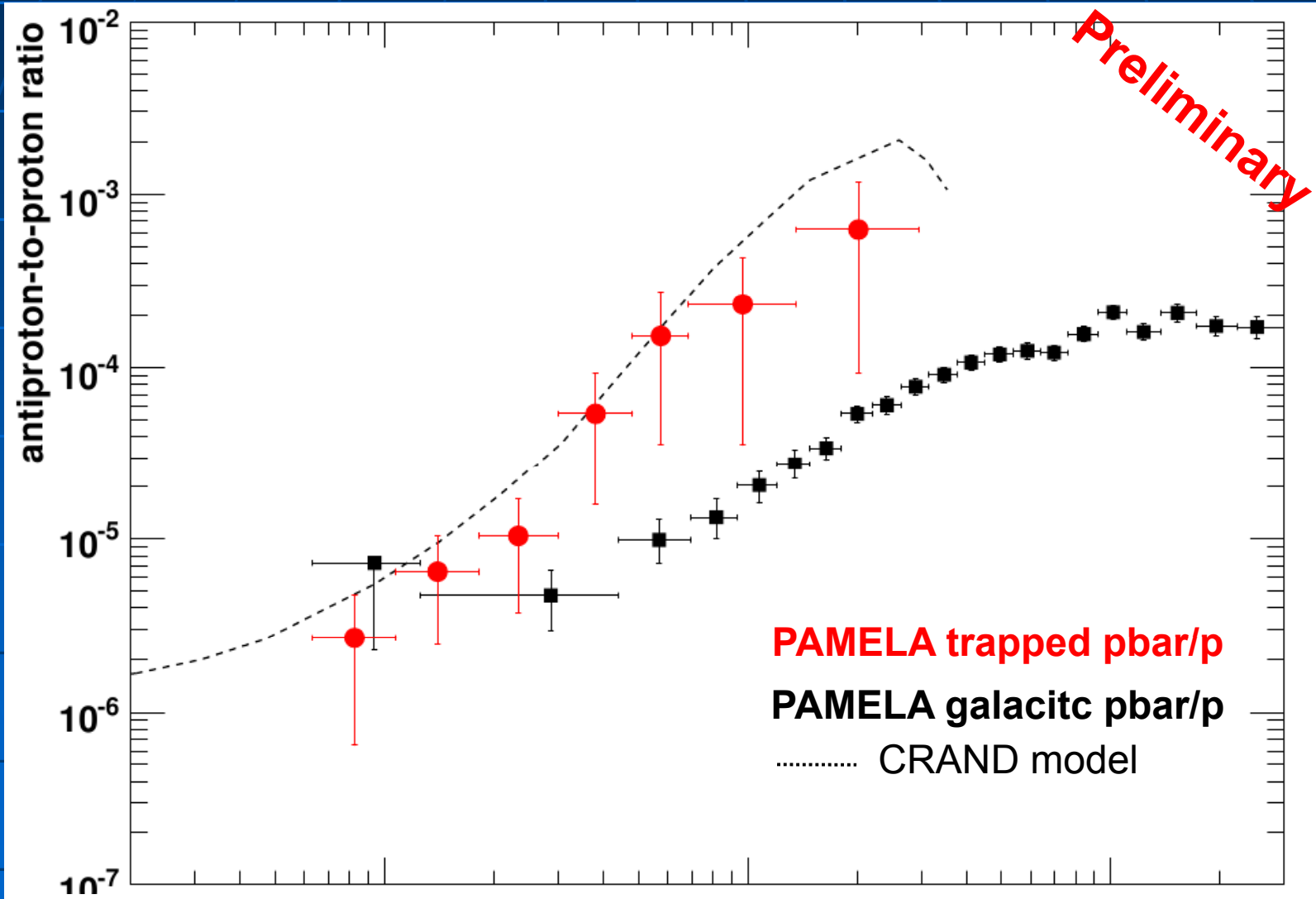
Wino Dark Matter in a non-thermal Universe

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

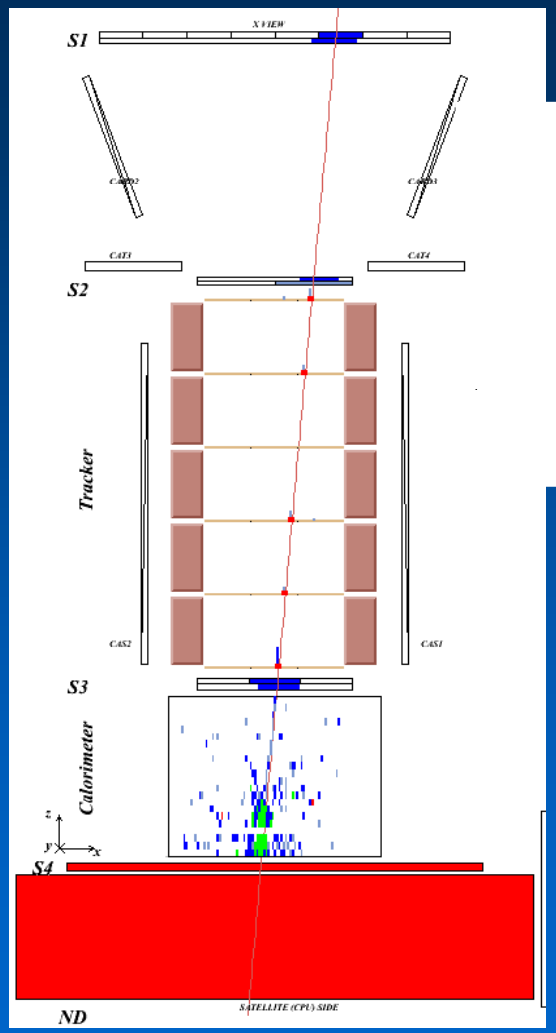
arXiv:0906.4765v3 [astro-ph.HE]



Trapped Antiprotons in the South Atlantic Anomaly



Proton / positron discrimination

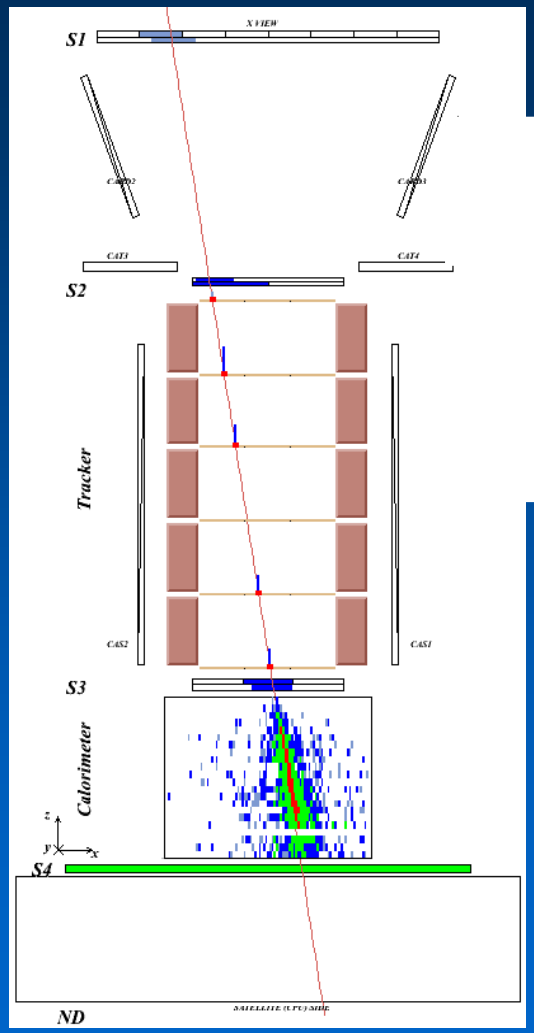


Time-of-flight:
trigger, albedo rejection, mass determination (up to 1 GeV)

Bending in spectromete:
sign of charge

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

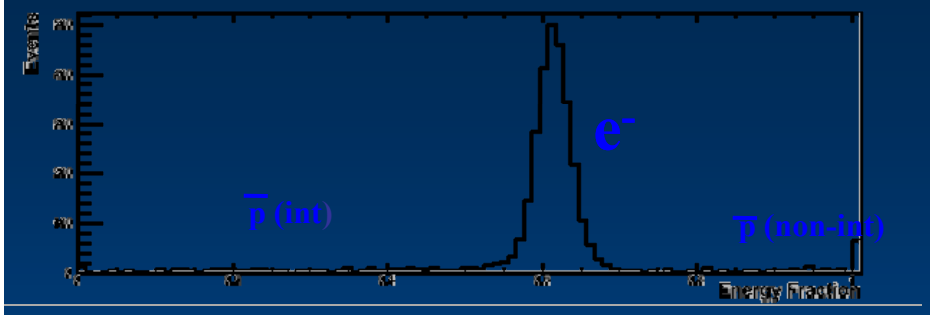
Interaction pattern in calorimeter:
electron-like or proton-like, electron energy

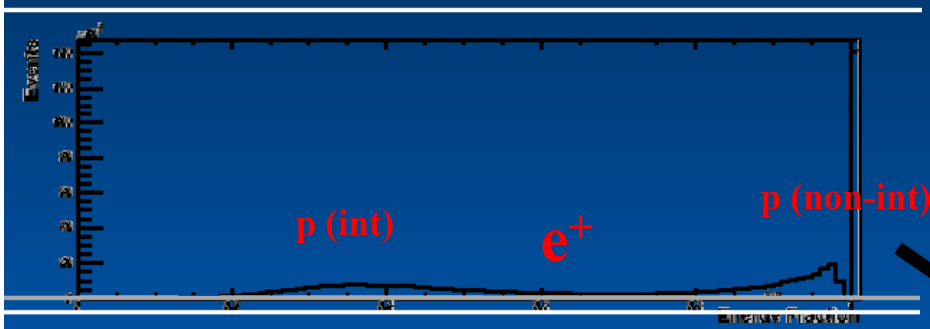


Proton

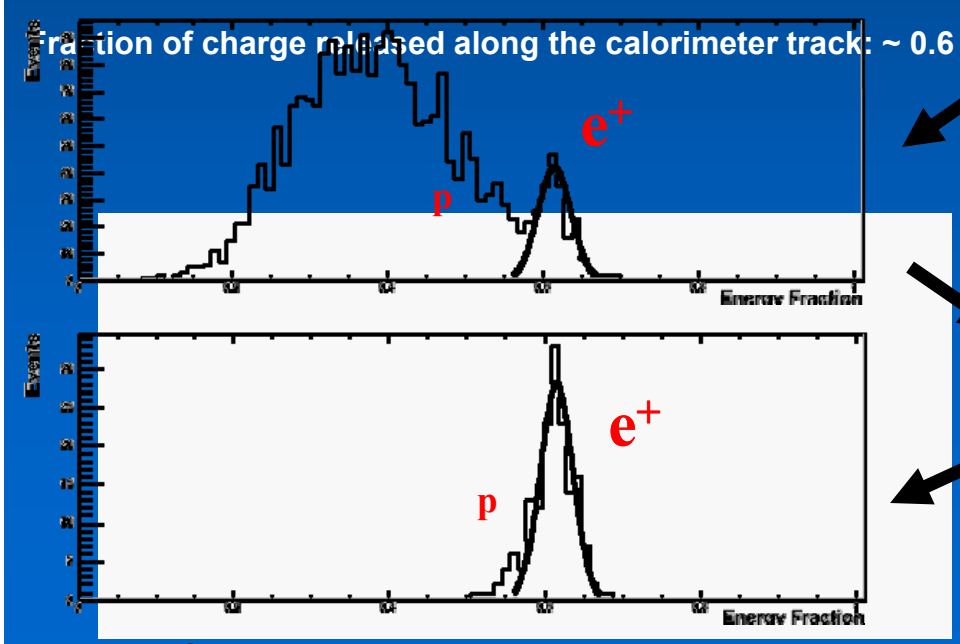
Positron

Positron Selection



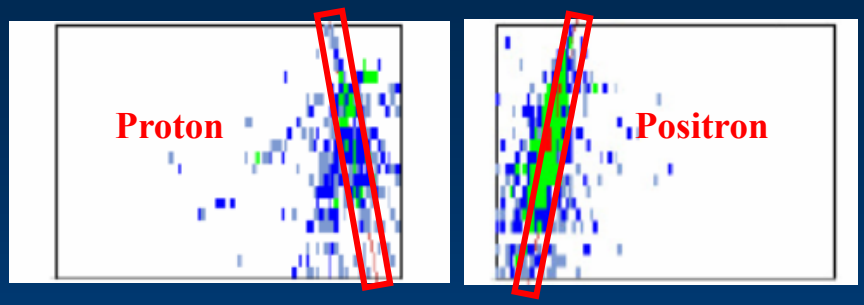


Fraction of charge released along the calorimeter track: ~ 0.6 R_m

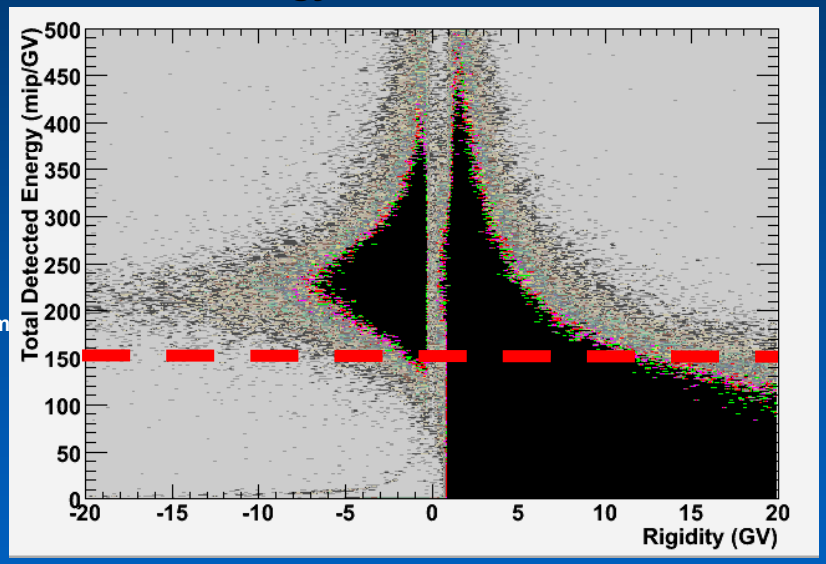


Fraction of charge released along the calorimeter track: ~ 0.6 R_m

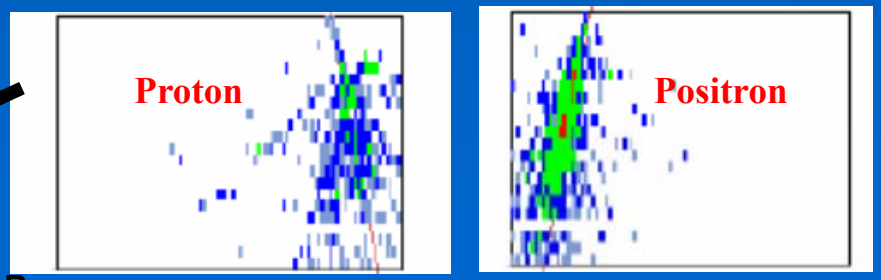
Fraction of charge released along the calorimeter track



Energy-Momentum Match

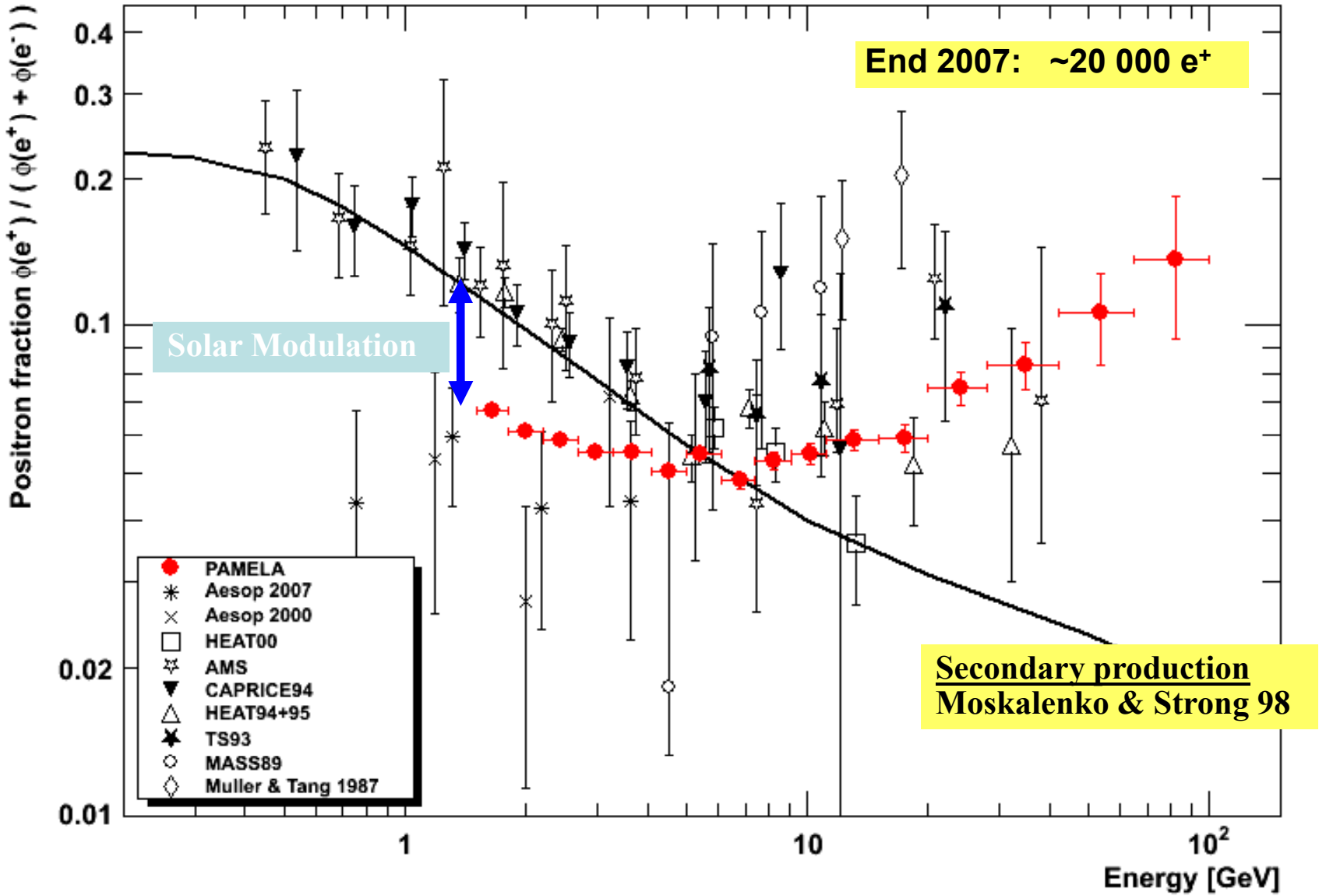


Cut on starting point, lateral & longitudinal profile



PAMELA Positron Fraction

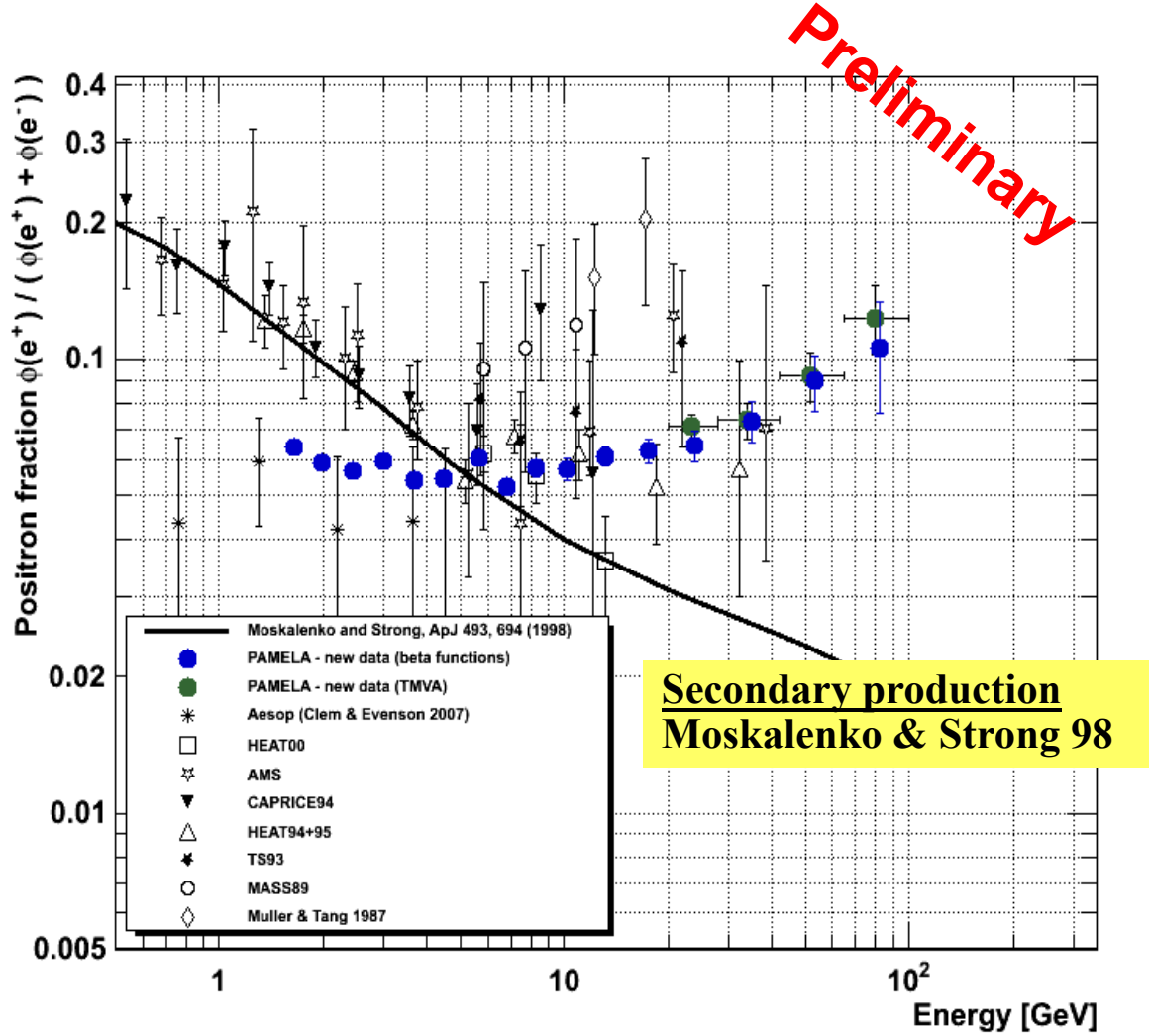
Nature 458 (2009) 607 - 2nd April 2009



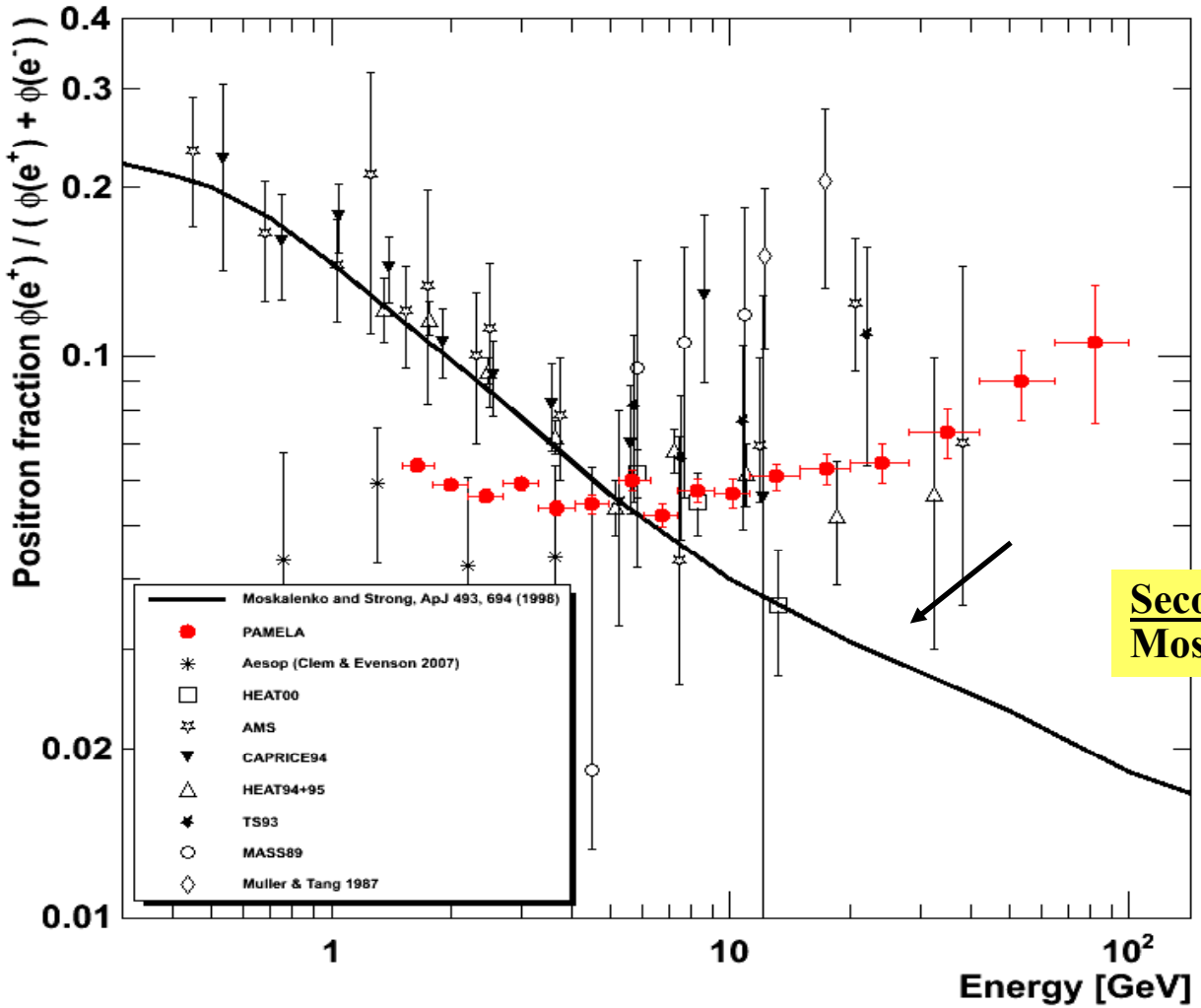
PAMELA Positron Fraction (2010)

- Neuronal network software: TMVA package from CERN
- Use more data 2006-2008

Statistics increase ~2.5 (factor 3 in the highest energy bin)



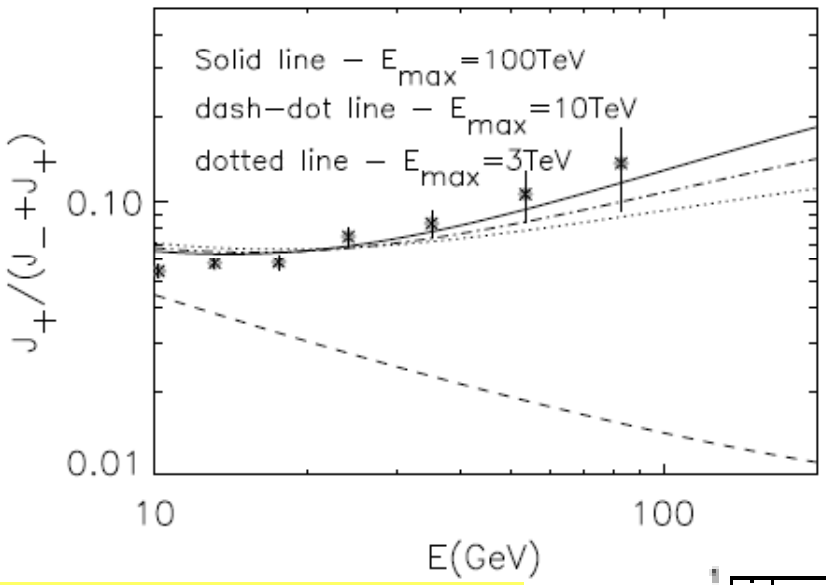
Positron to Electron Fraction

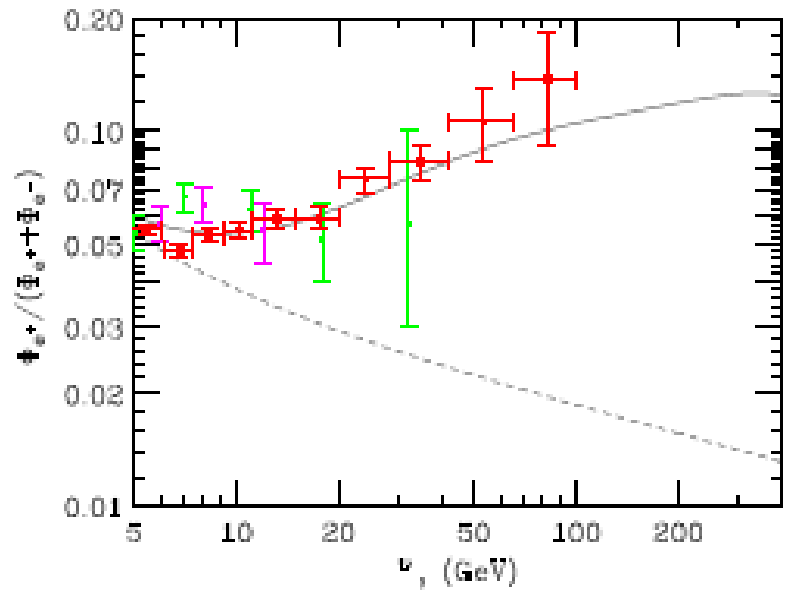


Secondary production
Moskalenko & Strong 98

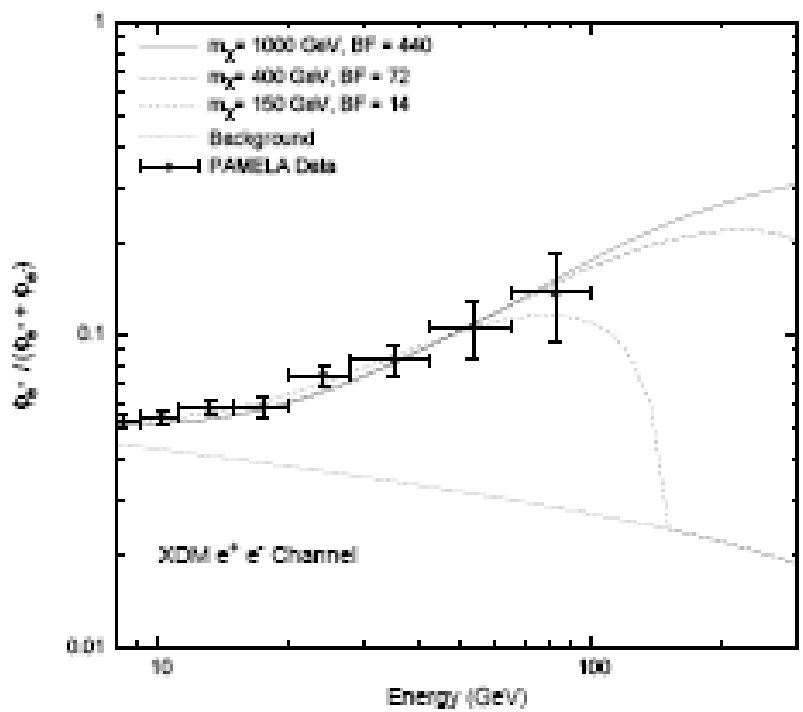
Adriani et al, Astropart. Phys. 34 (2010) 1
arXiv:1001.3522 [astro-ph.HE]

A Challenging Puzzle for CR Physics





P.Blasi, PRL 103 (2009) 051104; arXiv:0903.2794
Y. Fujita arXiv .0904.5298
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 pbar/p and B/C ratios.



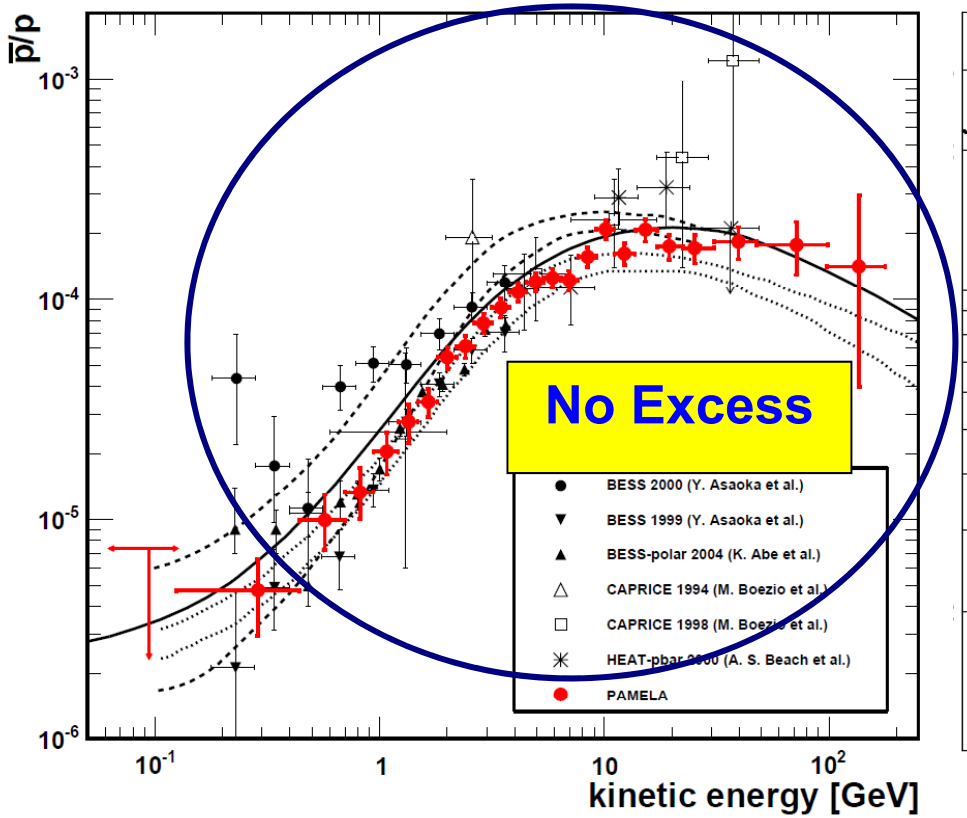
i, and P. Serpico, JCAP
Xiv:0810.1527
diffuse mature &nearby

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

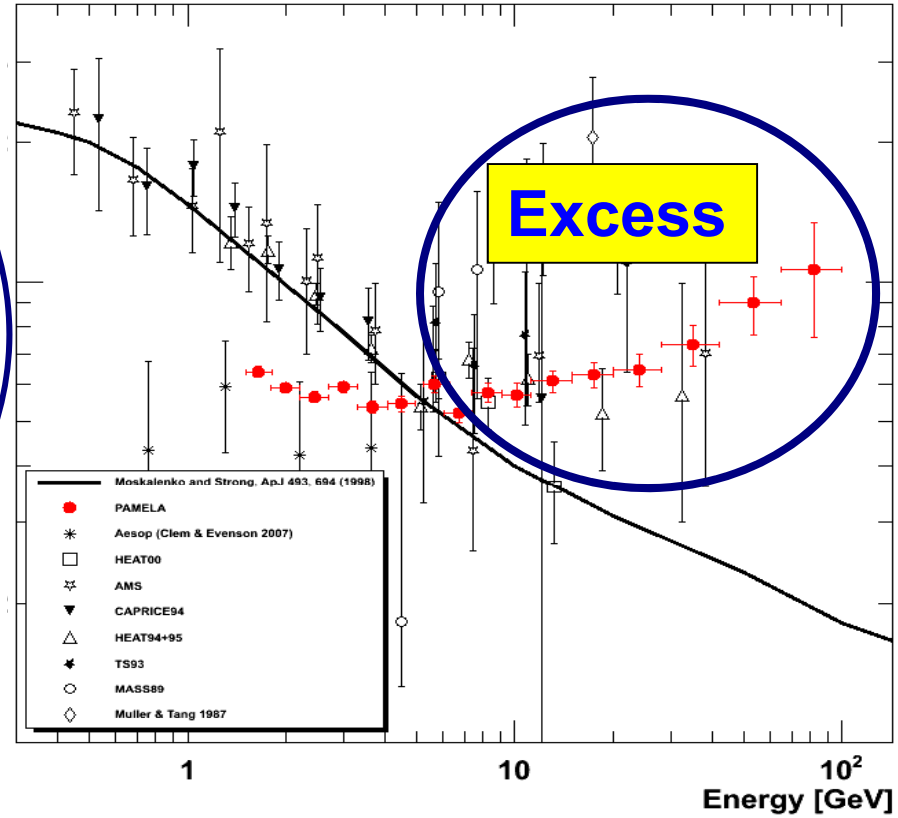
Dark Matter (and other) Interpretations

have to bring these two observations into a common theoretical framework

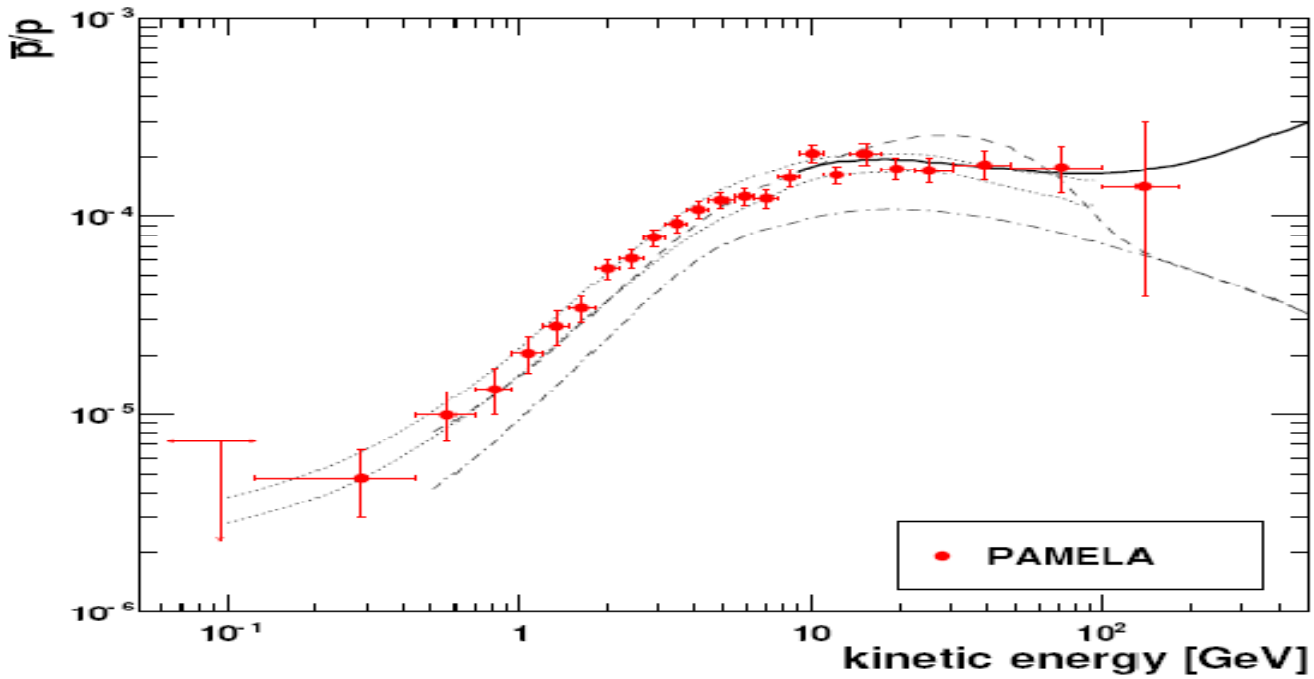
Antiprotons

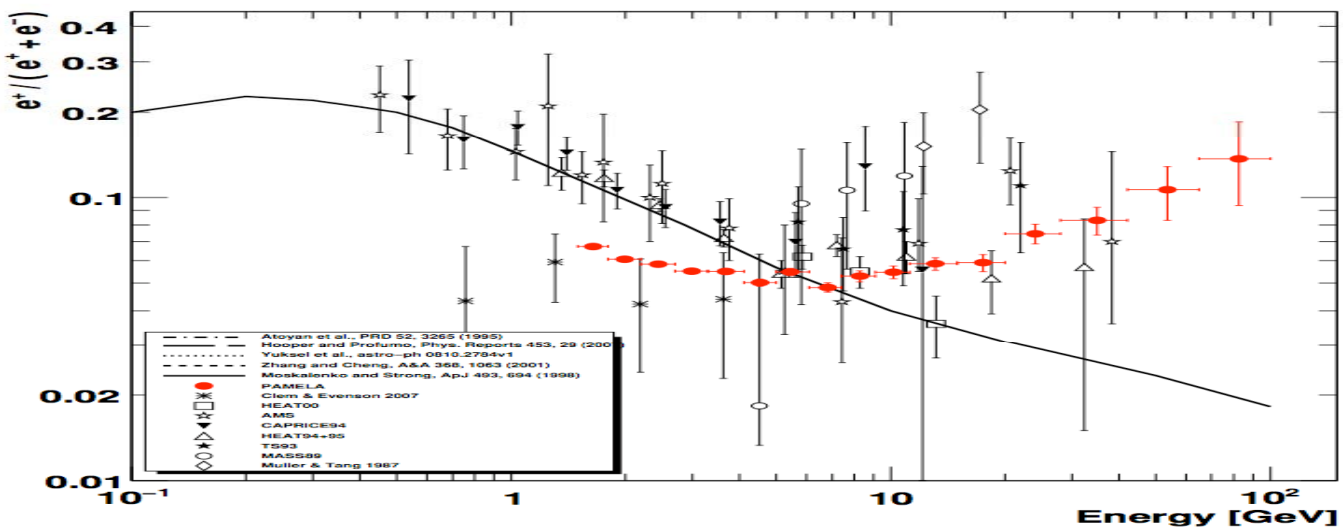


Positrons



A Challenging Puzzle for Dark Matter

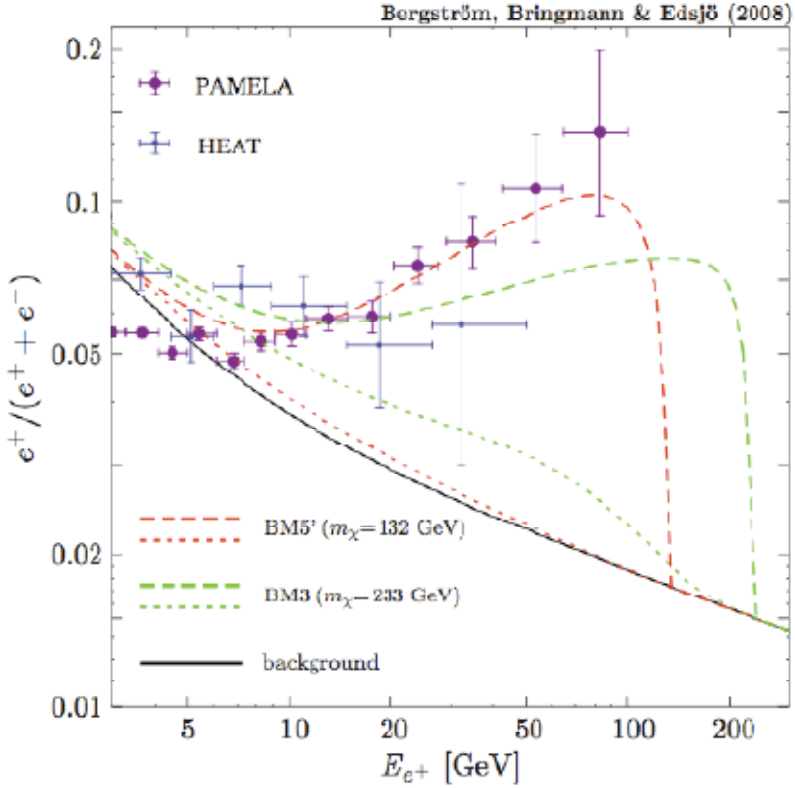




Example: Dark Matter

arXiv:0808.3725

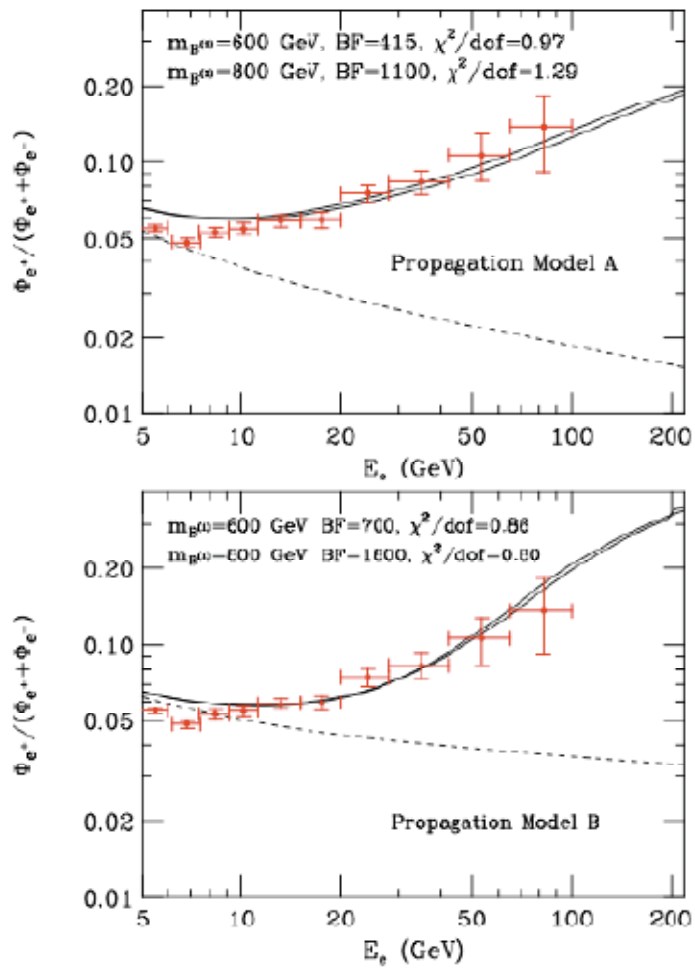
Bergström, Bringmann & Edsjö (2008)



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

Hooper and Zurek

arXiv:0902.0593v1

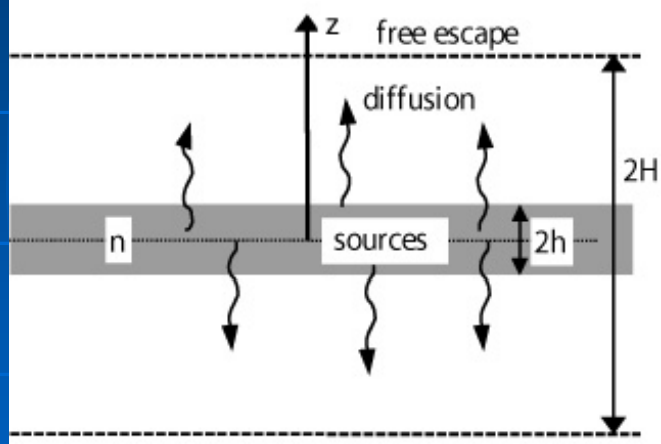


Kaluza-Klein dark matter

PAMELA Cosmic Ray Spectra

Cosmic Rays Propagation in the Galaxy

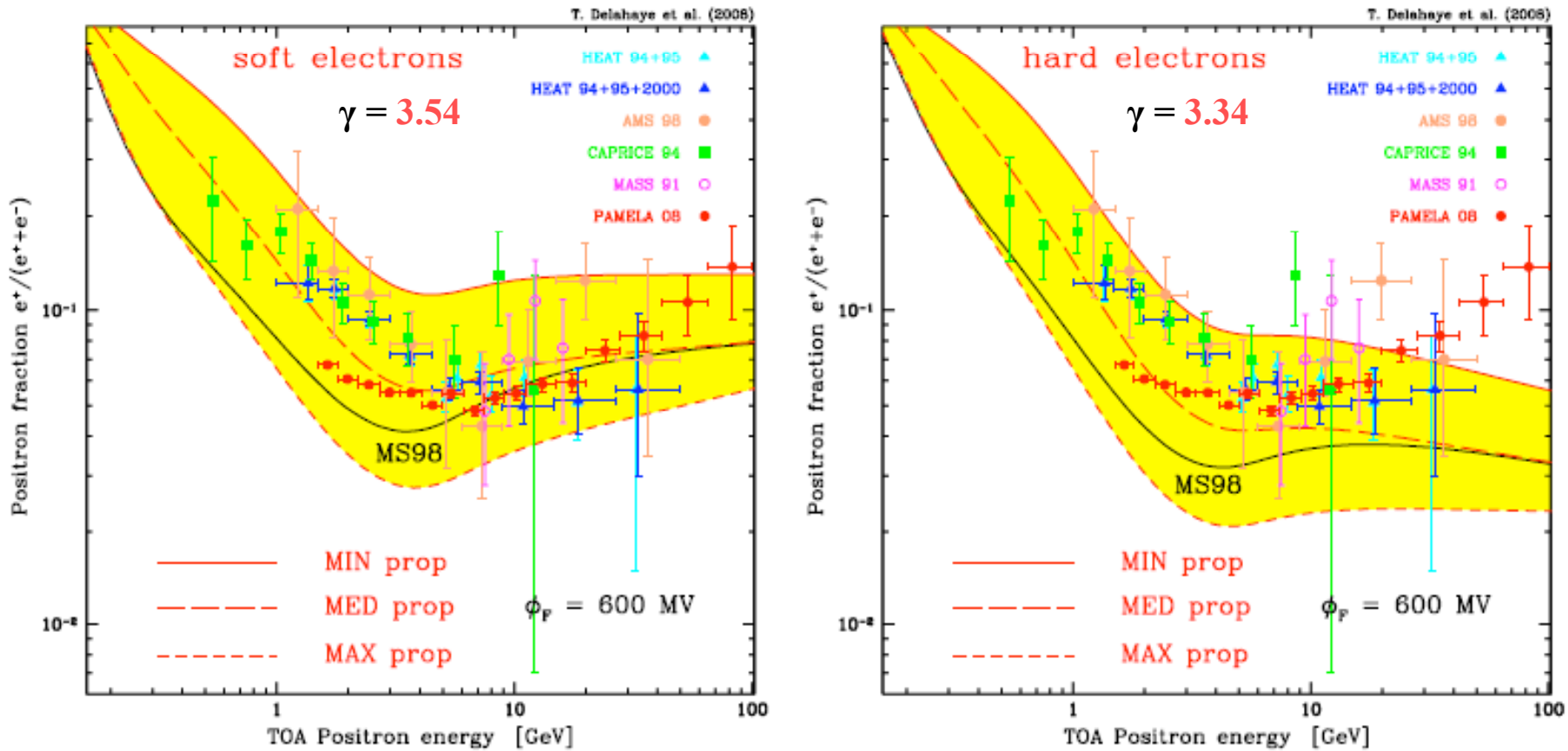
$$\frac{\partial N_i(E,z,t)}{\partial t} = \underbrace{D(E)\cdot\frac{\partial^2}{\partial z^2}N_i(E,z,t)}_{\text{diffusion}} - \underbrace{N_i(E,z,t)\left\{\frac{1}{\tau_i^{\text{int}}(E,z)} + \frac{1}{\gamma(E)\tau_i^{dec}}\right\}}_{\text{interaction and decay}}$$



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

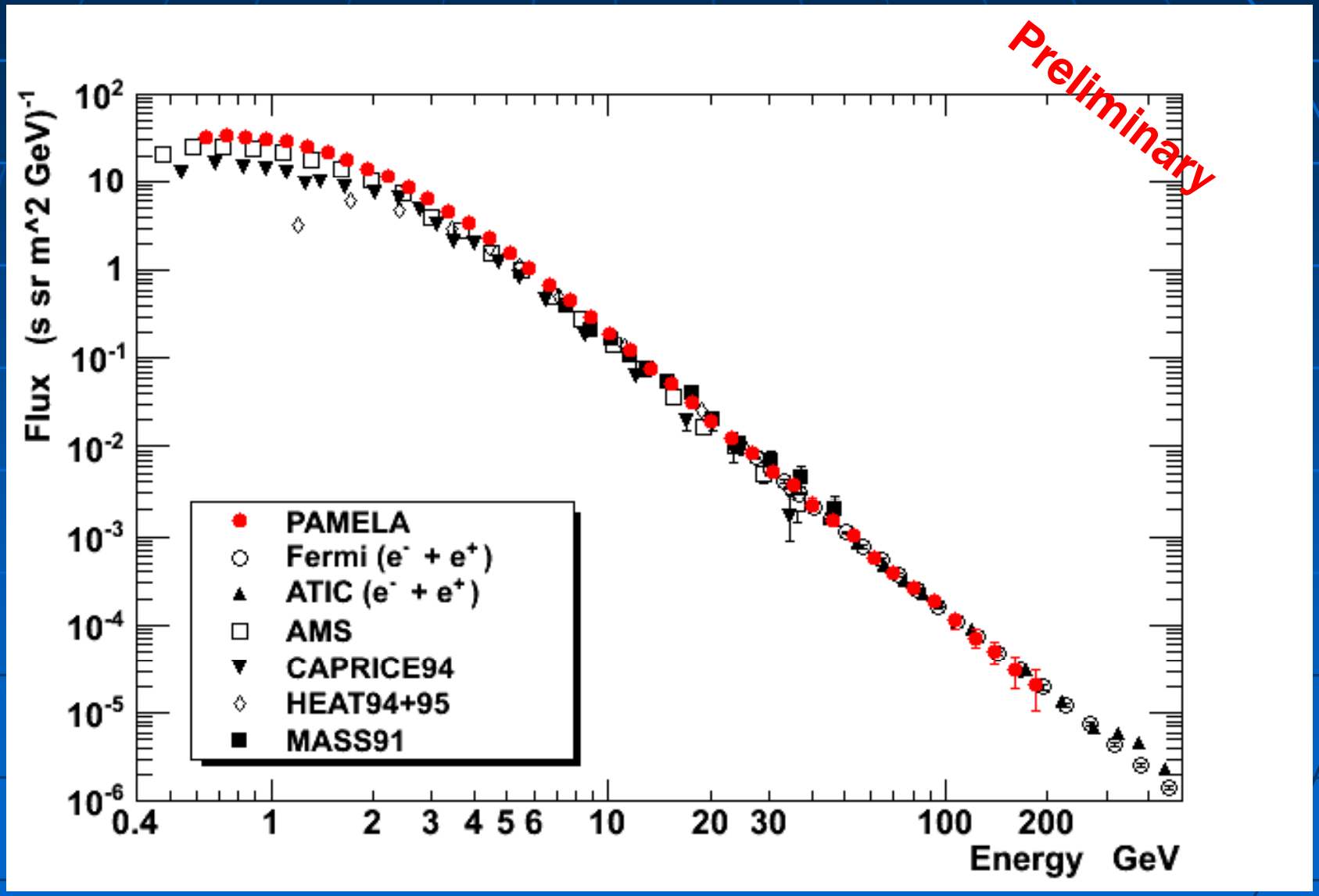
$$\underbrace{-\frac{\partial}{\partial E}\left\{\left\langle\frac{\partial E}{\partial t}\right\rangle\cdot N_i(E,z,t)\right\} + \frac{1}{2}\frac{\partial^2}{\partial E^2}\left\{\left\langle\frac{\Delta E^2}{\Delta t}\right\rangle\cdot N_i(E,z,t)\right\}}_{\text{energy changing processes (ionisation,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

Standard Positron Fraction
Theoretical Uncertainties



T. Delahaye et al., arXiv: 0809.5268v3

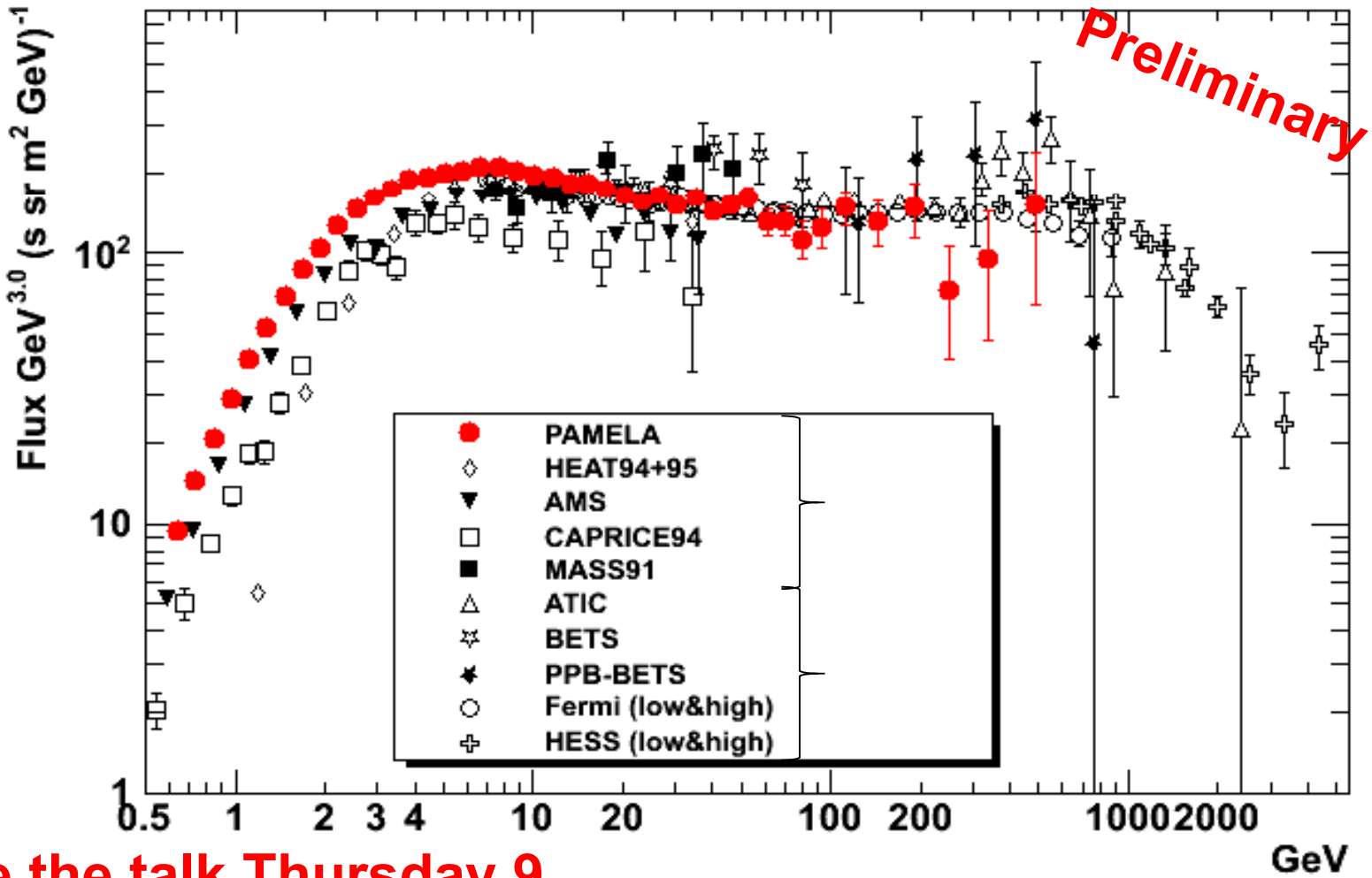
Electron (e^-) Spectrum



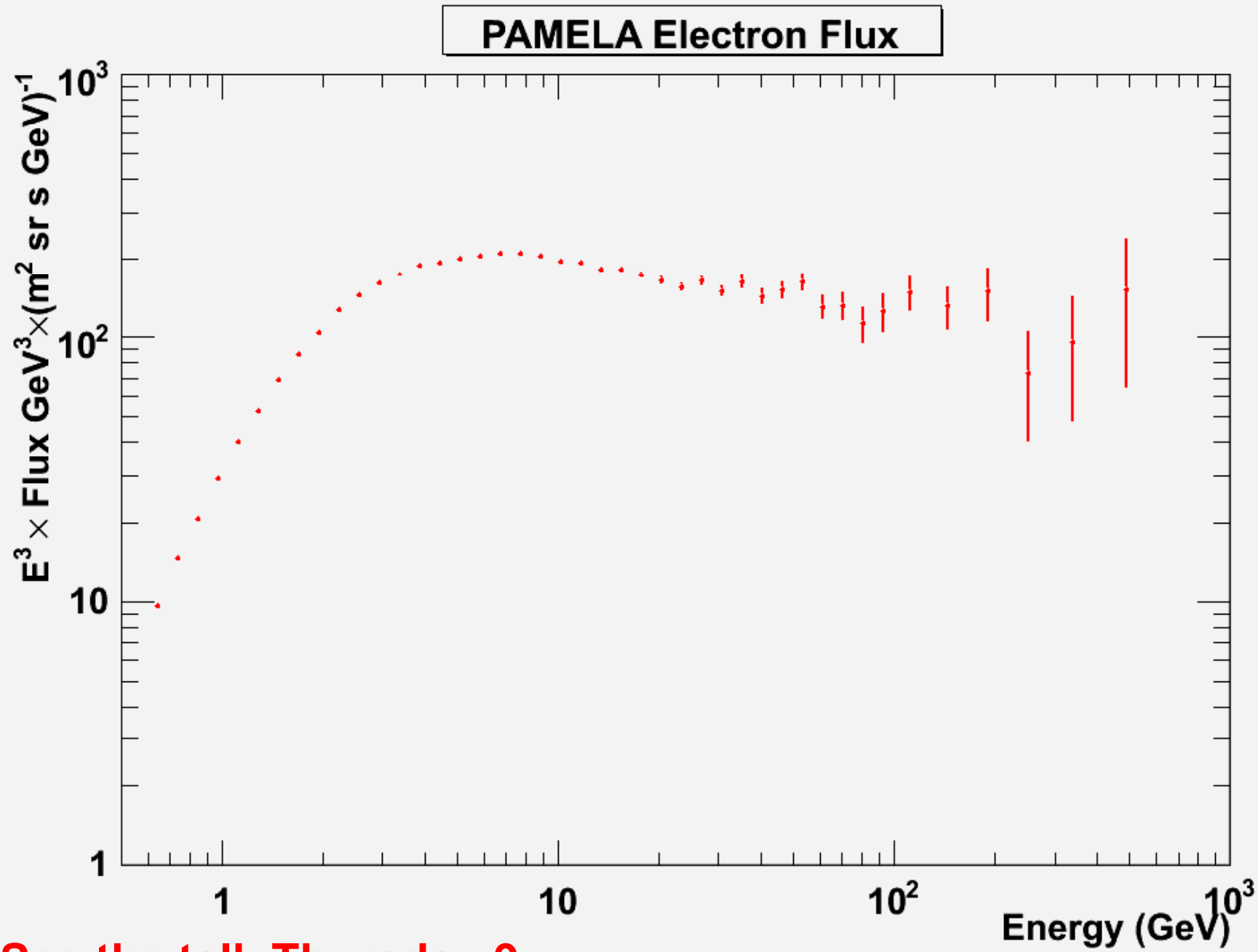
See the talk Thursday 9

PAMELA: Spectrometer & Calorimeter: e^-

- Spectrometer to select events with negative curvature
- Calorimeter to select electrons
- Spectrometer Rigidity → Energy



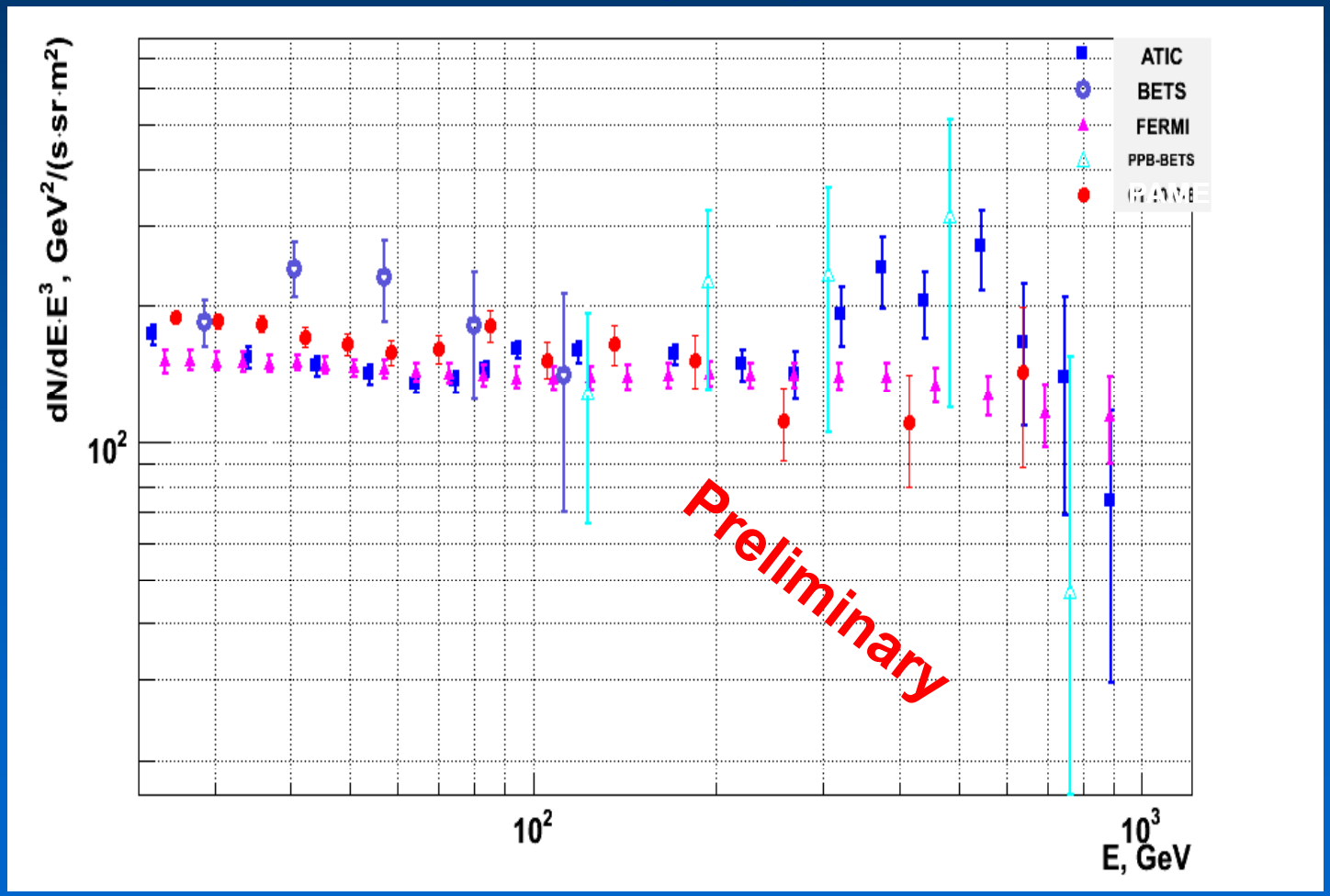
See the talk Thursday 9



See the talk Thursday 9

PAMELA: Only Calorimeter : $e^+ + e^-$

Use different topology of EM and hadronic showers in the calorimeter to select electrons (totally 21 parameters were used)

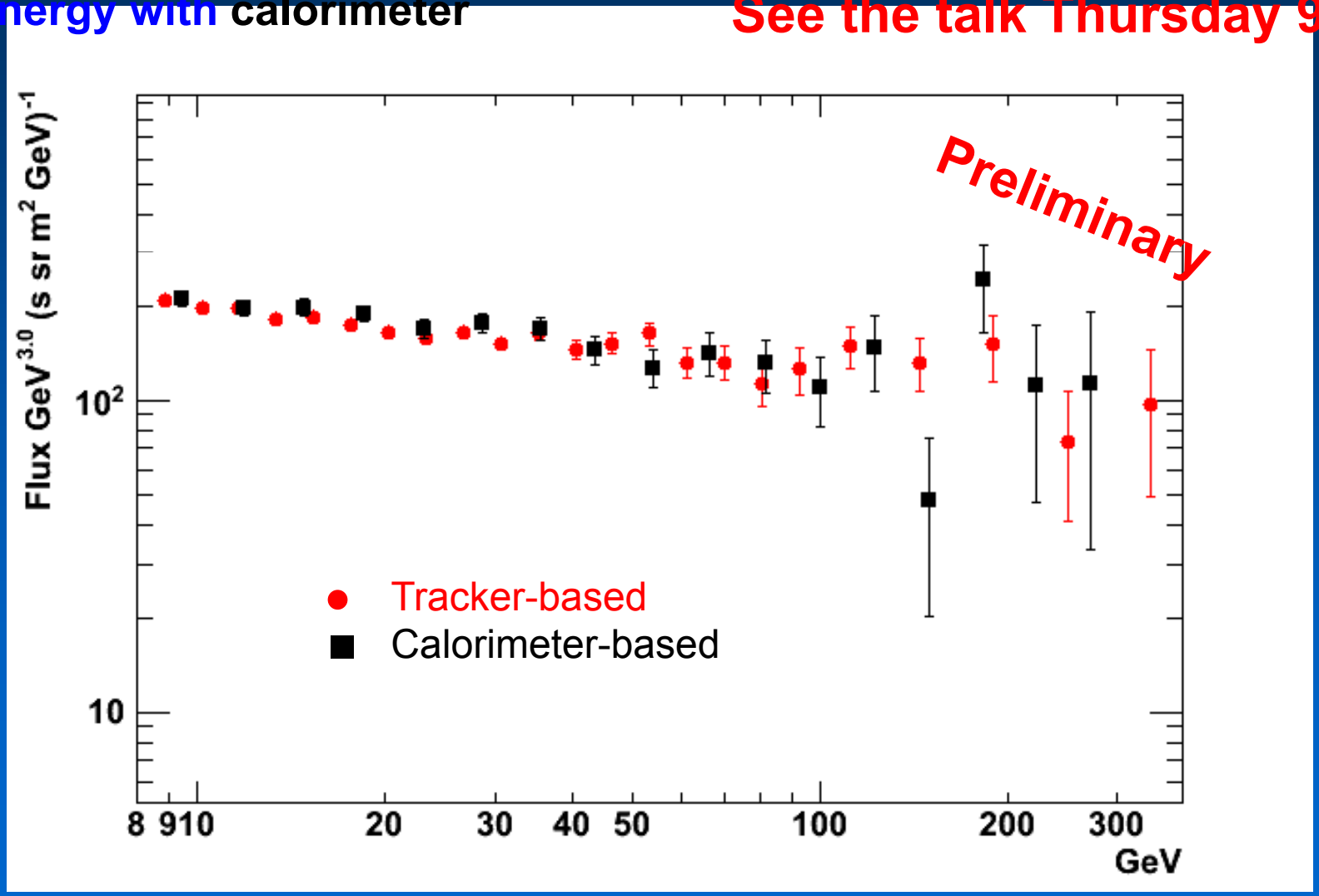


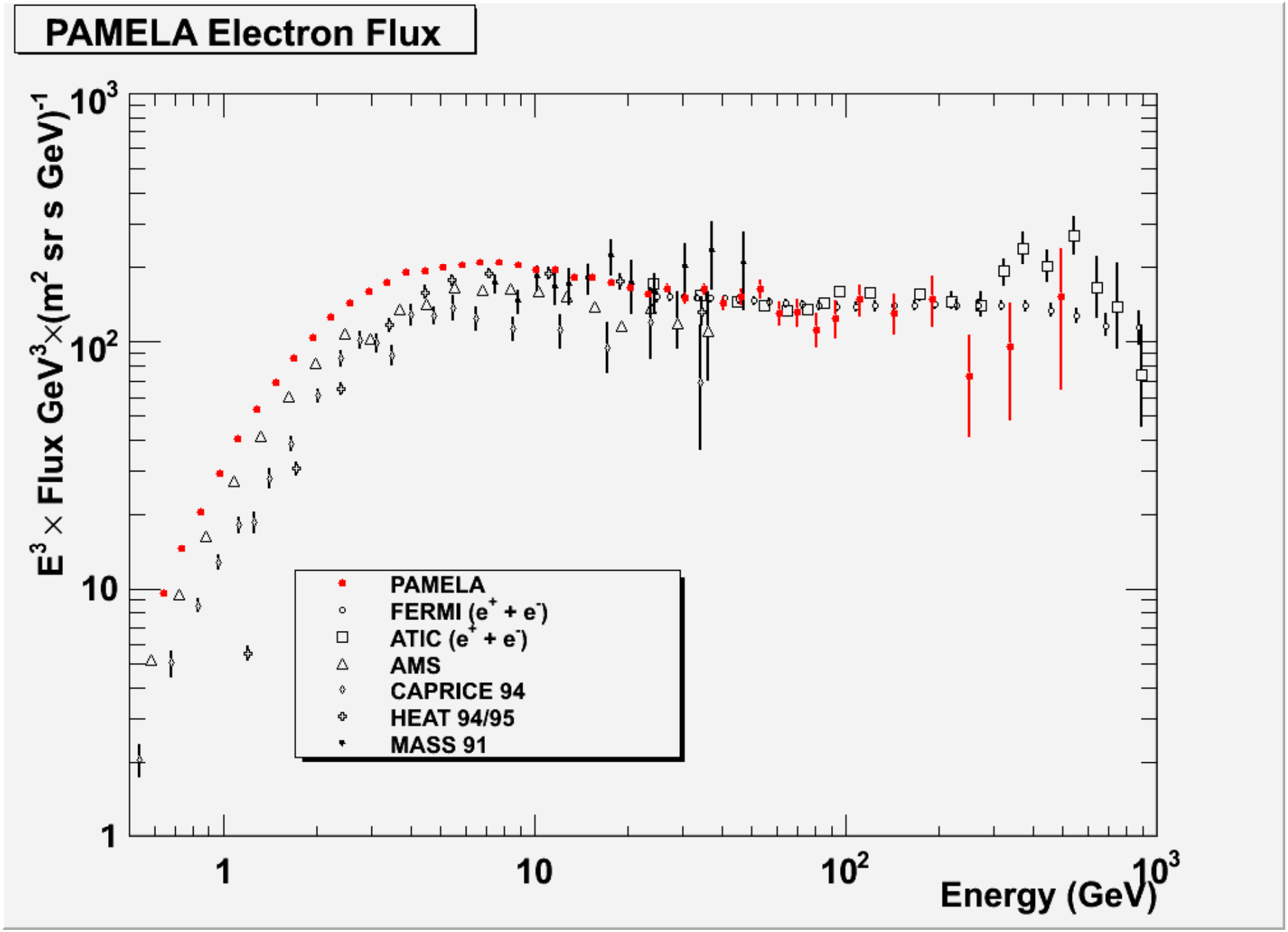
Electron spectrum, tracker based

PAMELA: Spectrometer & Calorimeter #2: e^-

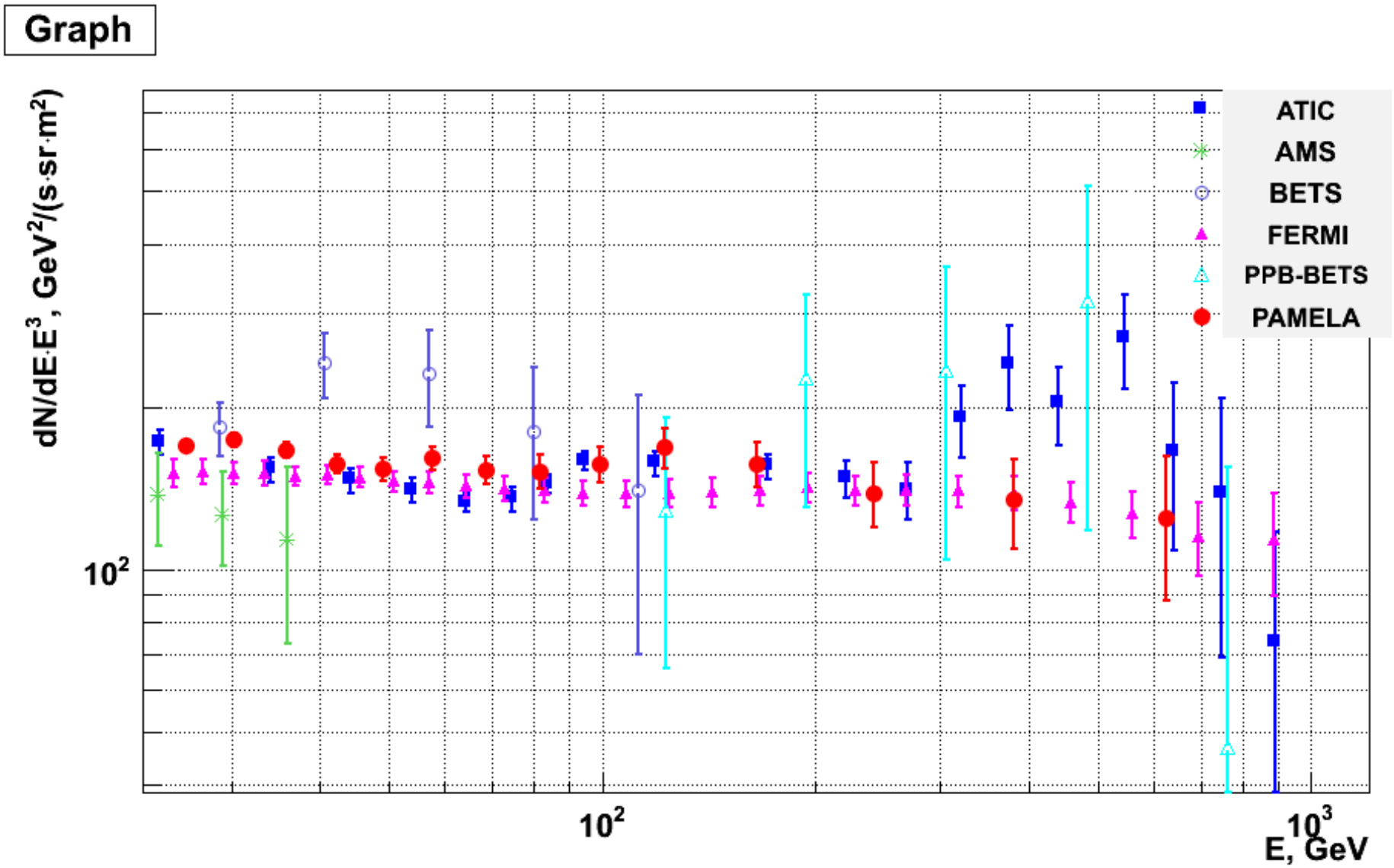
- Spectrometer to select events with negative curvature, loose cuts
- Calorimeter to select electrons, strong cuts
- Energy with calorimeter

See the talk Thursday 9

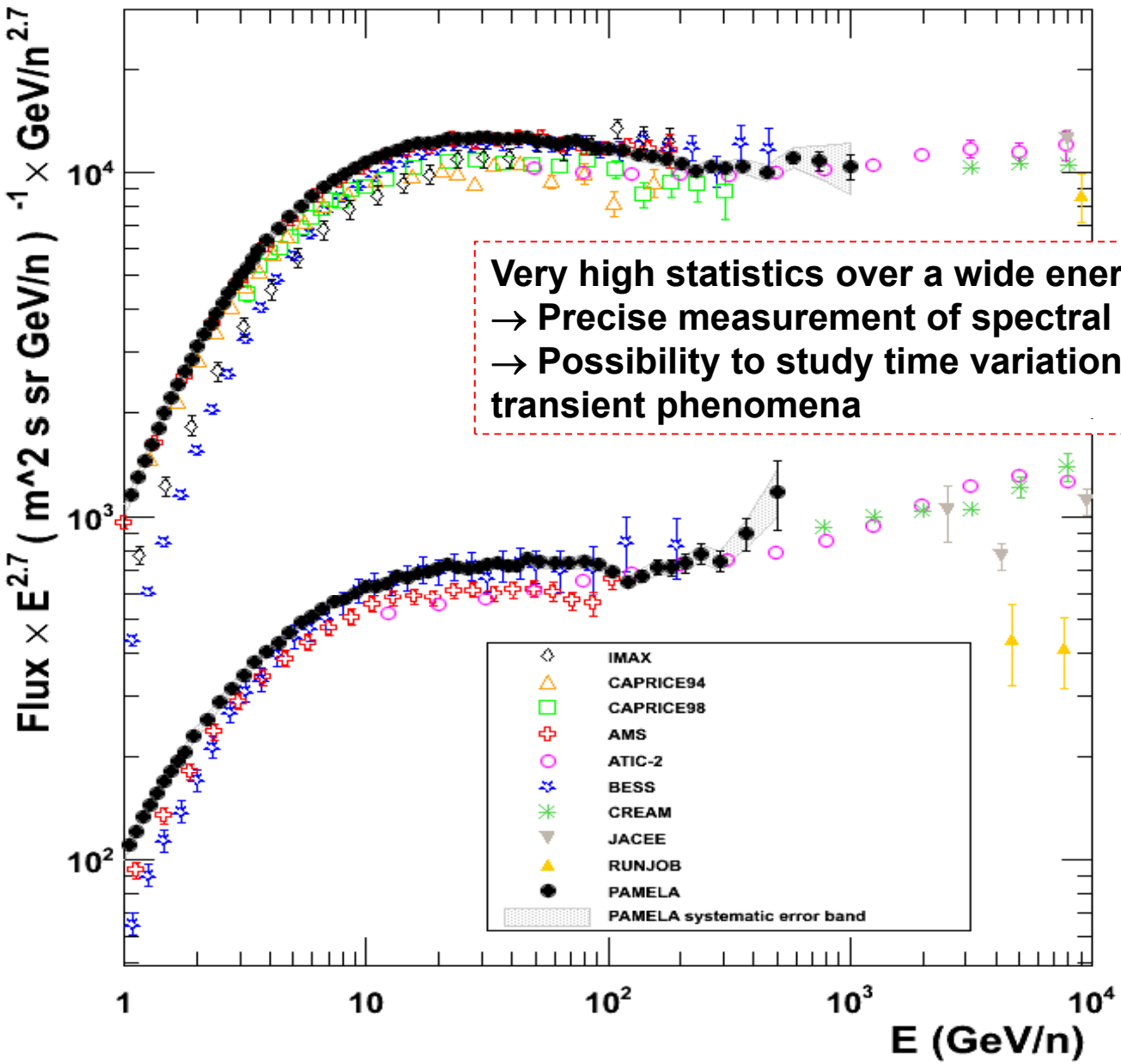



PAMELA Electron Flux
$E^3 \times$ Flux $GeV^3 \times (m^2\ sr\ s\ GeV)^{-1}$
10^3
10^2
10
1
1
10
10^2
10^3
Energy (GeV)
PAMELA
FERMI ($e^+ + e^-$)
ATIC ($e^+ + e^-$)
AMS
CAPRICE 94
HEAT 94/95
MASS 91

All electrons
PAMELA very preliminary



Proton and Helium spectra

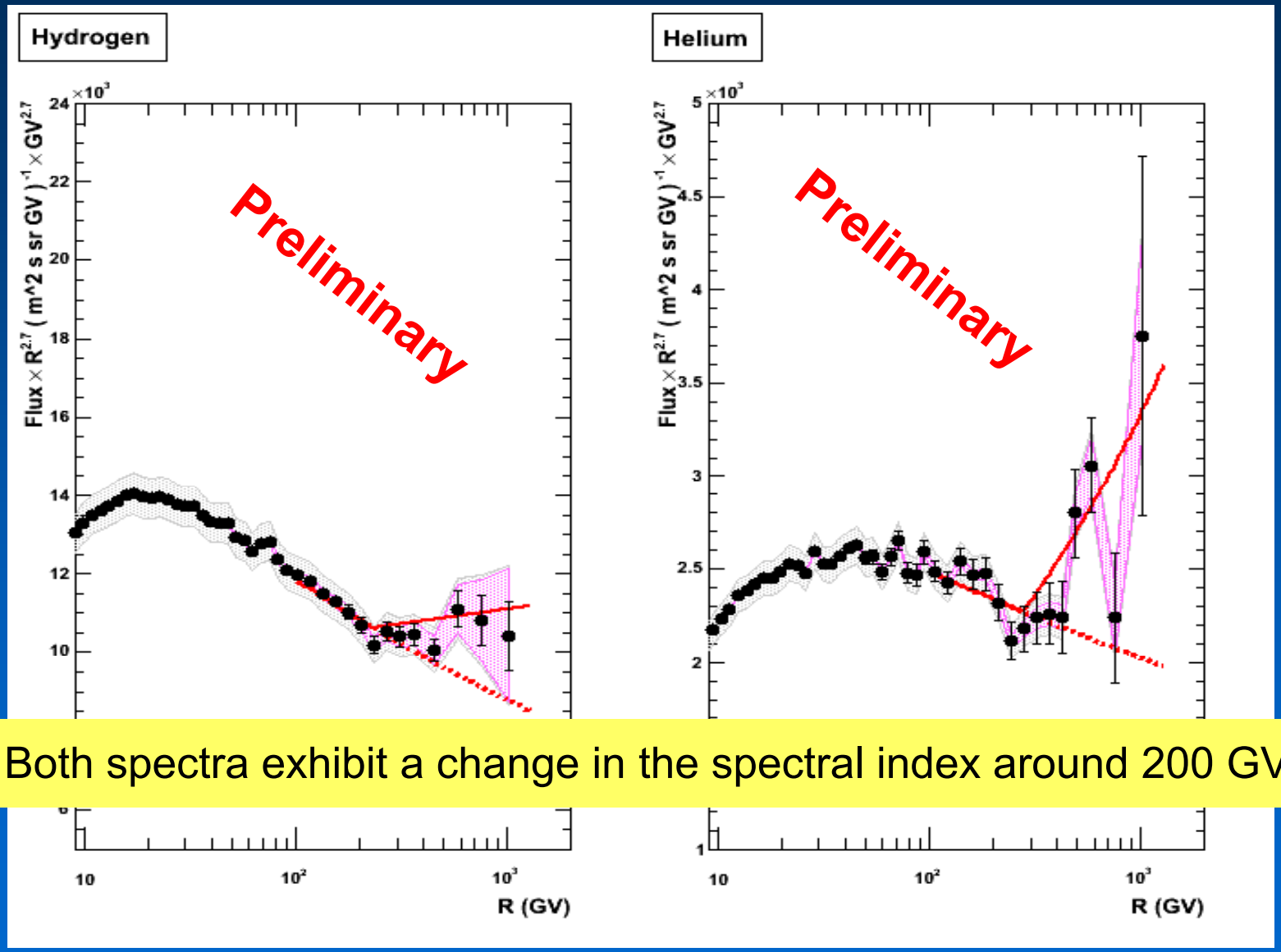


p

He

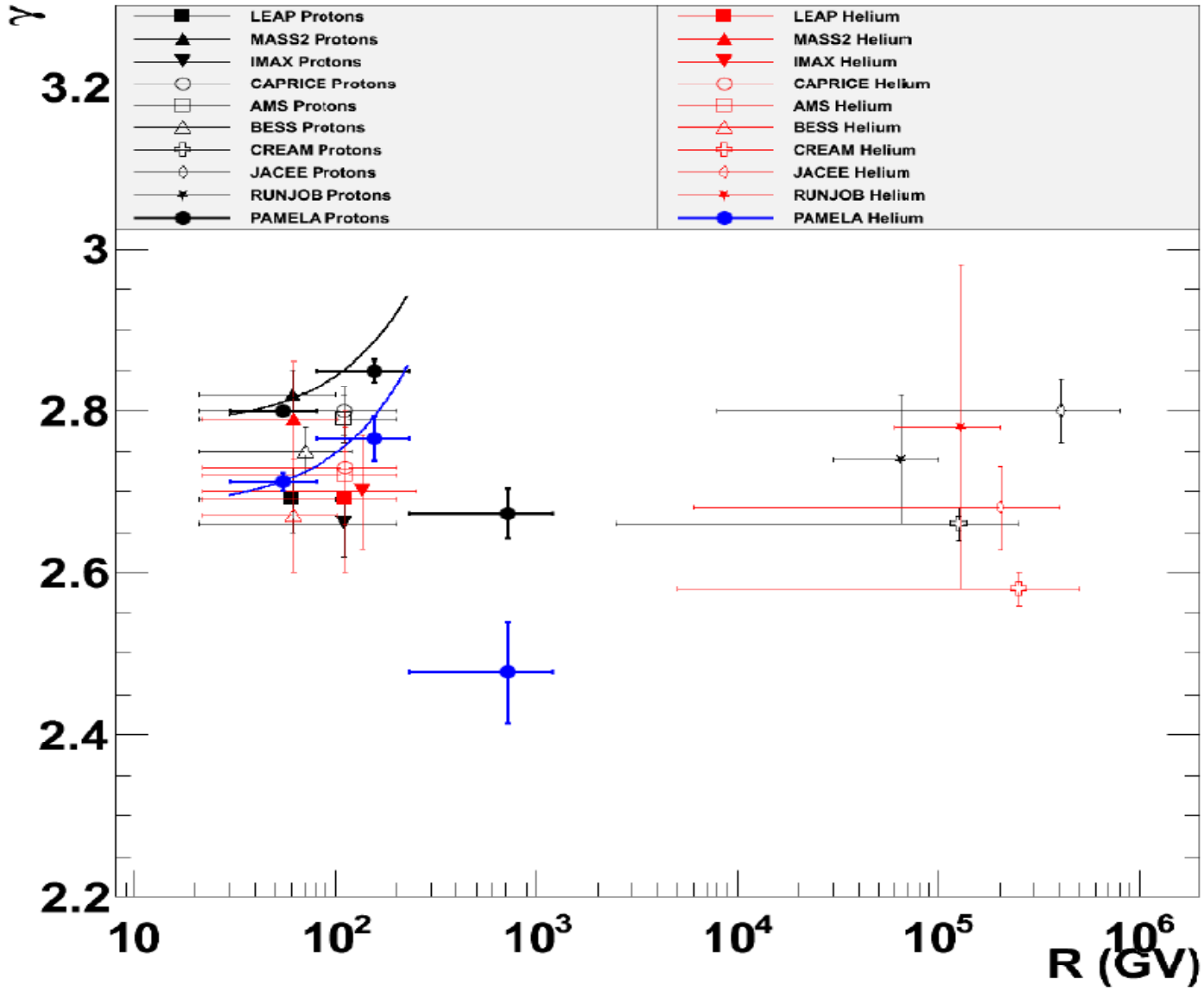
Very high statistics over a wide energy range
→ Precise measurement of spectral shape
→ Possibility to study time variations and transient phenomena

Proton and Helium Spectrum

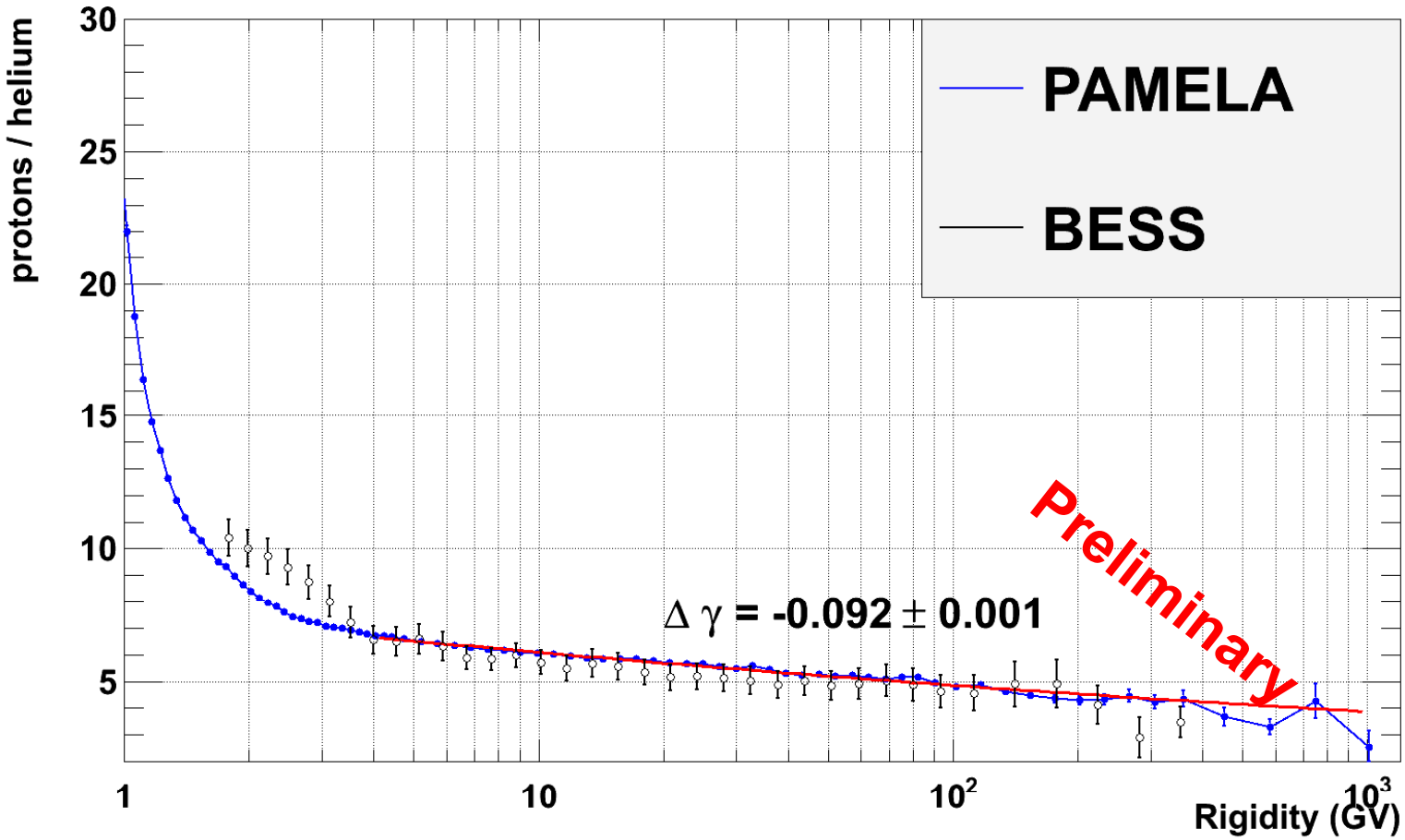


Both spectra exhibit a change in the spectral index around 200 GV.

γ index

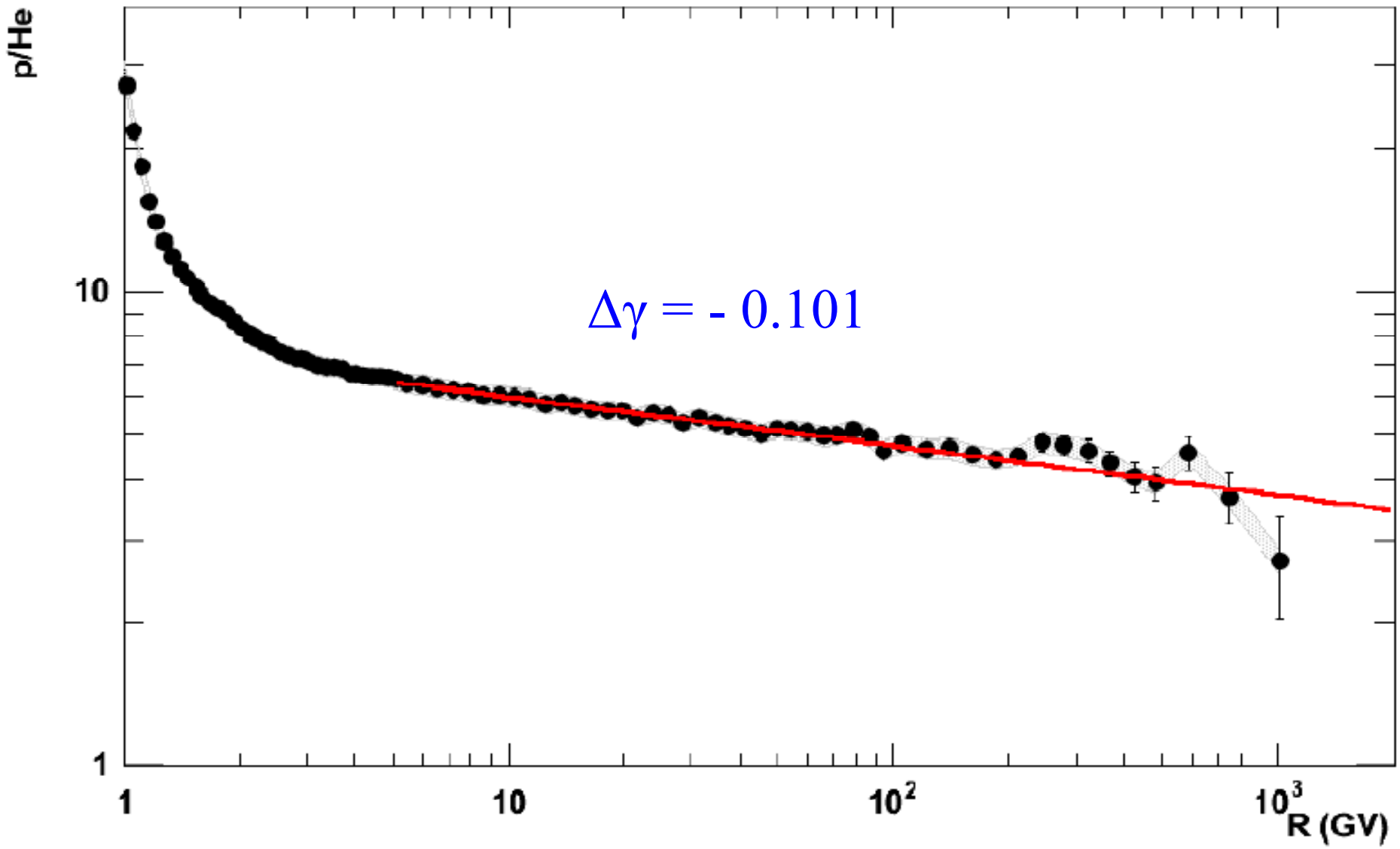

γ
LEAP Protons
MASS2 Protons
IMAX Protons
CAPRICE Protons
AMS Protons
BESS Protons
CREAM Protons
JACEE Protons
RUNJOB Protons
PAMELA Protons
LEAP Helium
MASS2 Helium
IMAX Helium
CAPRICE Helium
AMS Helium
BESS Helium
CREAM Helium
JACEE Helium
RUNJOB Helium
PAMELA Helium
3.2
3
2.8
2.6
2.4
2.2
10
10^2
10^3
10^4
10^5
10^6
R (GV)

Proton to Helium Ratio

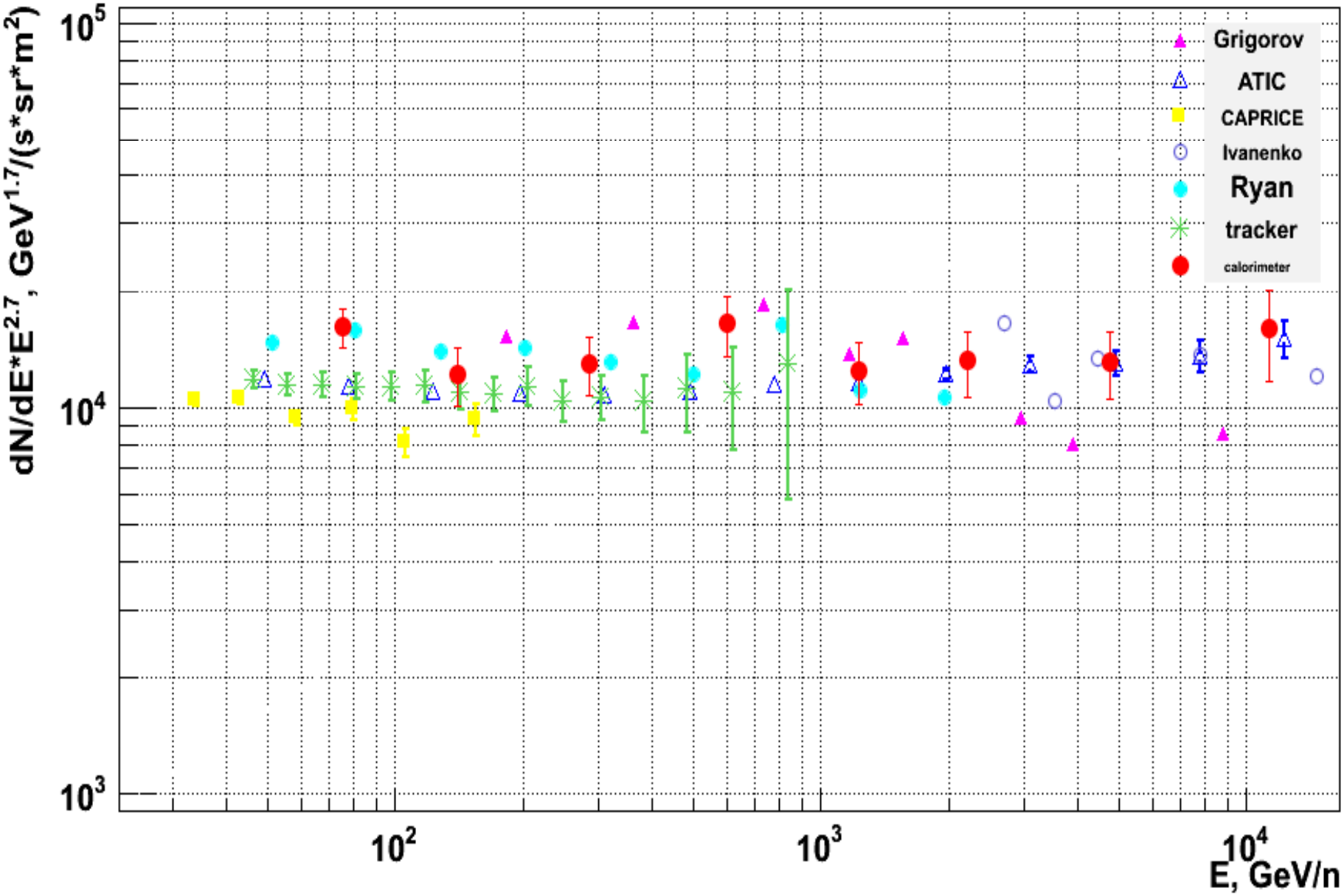


- Different injections mechanisms or sources for protons and helium ?
- No other source or mechanism which effects the ratio down to ~ 4 GV ?

Proton Helium ratio

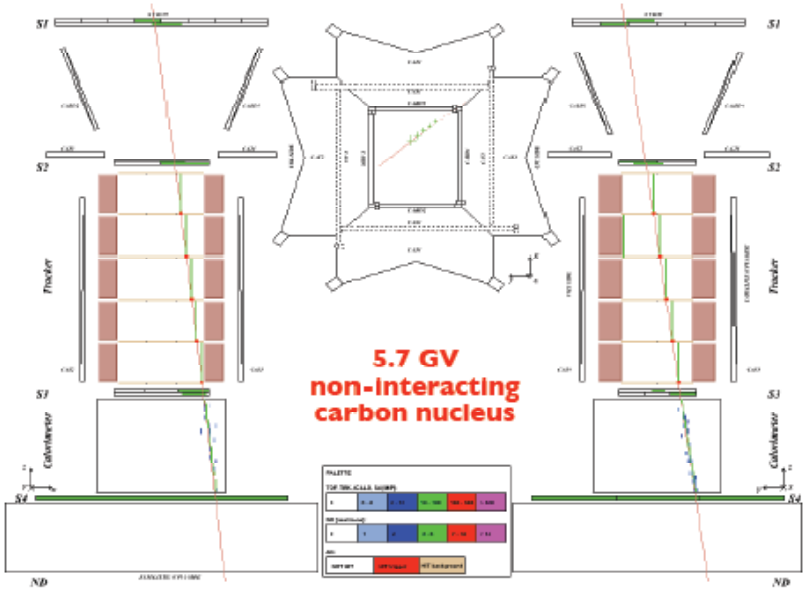


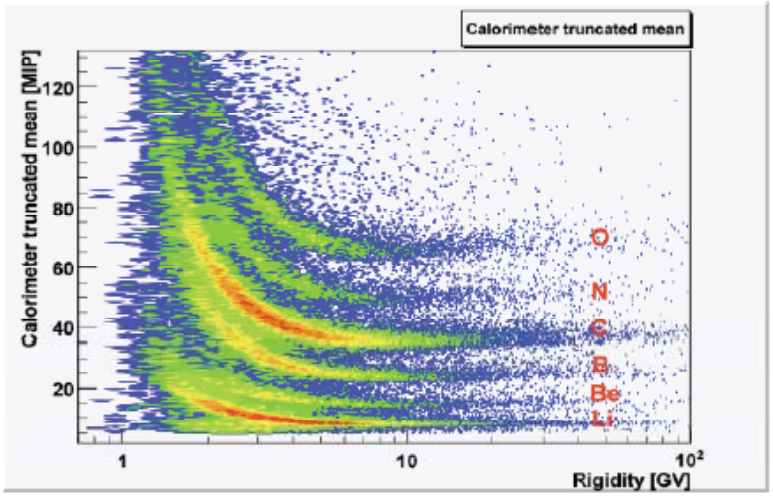
Proton flux


dN/dE*E^2.7, GeV^1.7/(s*sr*m^2)
10^5
10^4
10^3
10^2
10^3
10^4
E, GeV/n
Grigorov
ATIC
CAPRICE
Ivanenko
Ryan
tracker
calorimeter

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

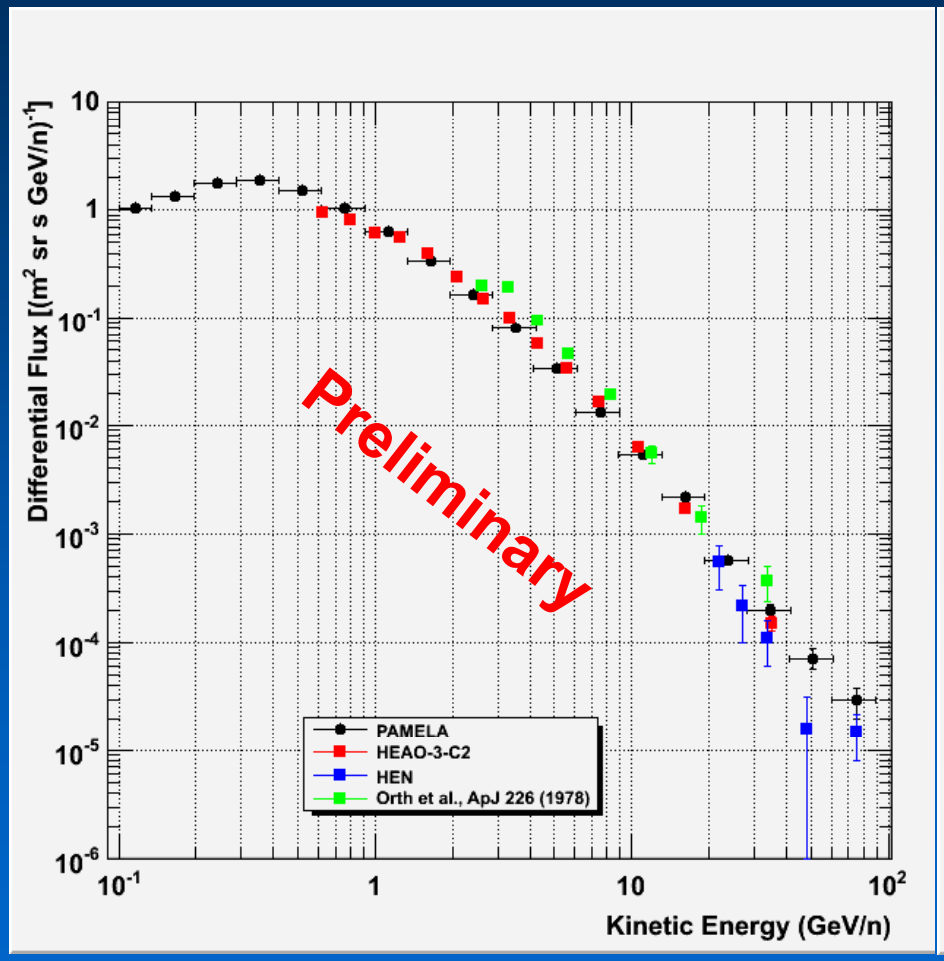




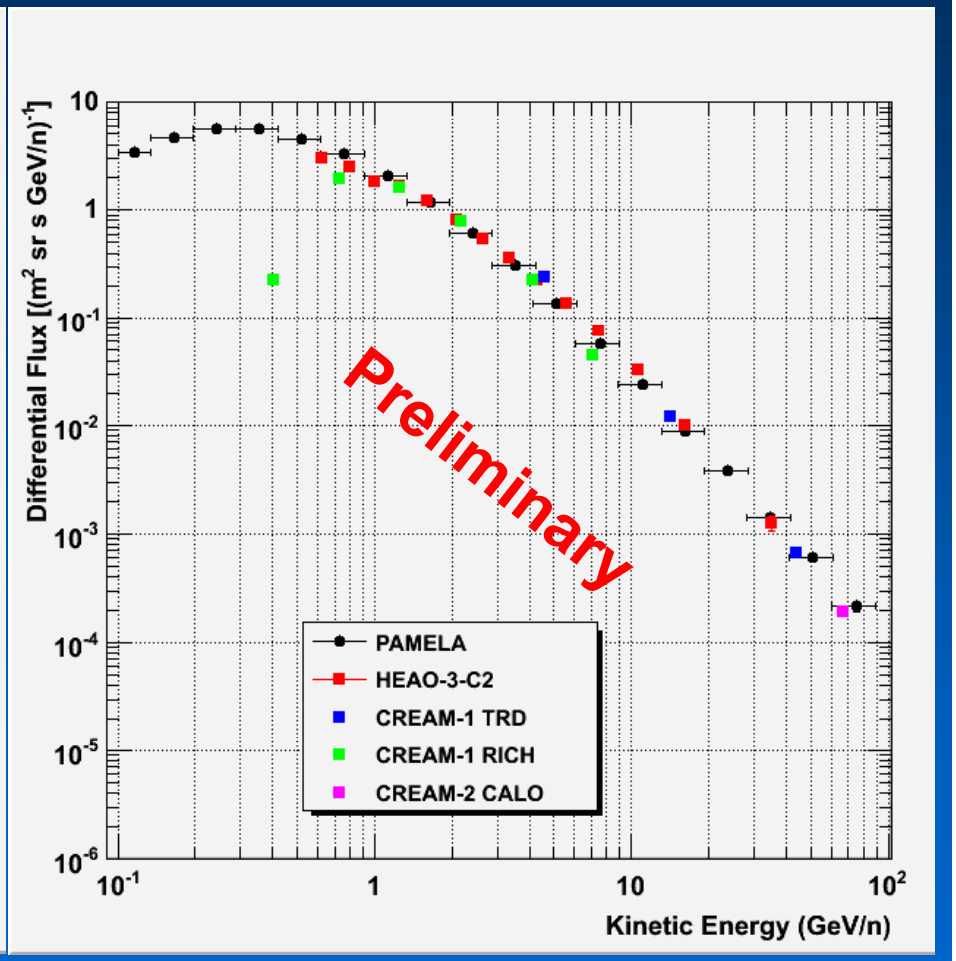
Truncated mean of multiple dE/dx measurements in different silicon planes

PAMELA Boron and Carbon Spectra

Boron

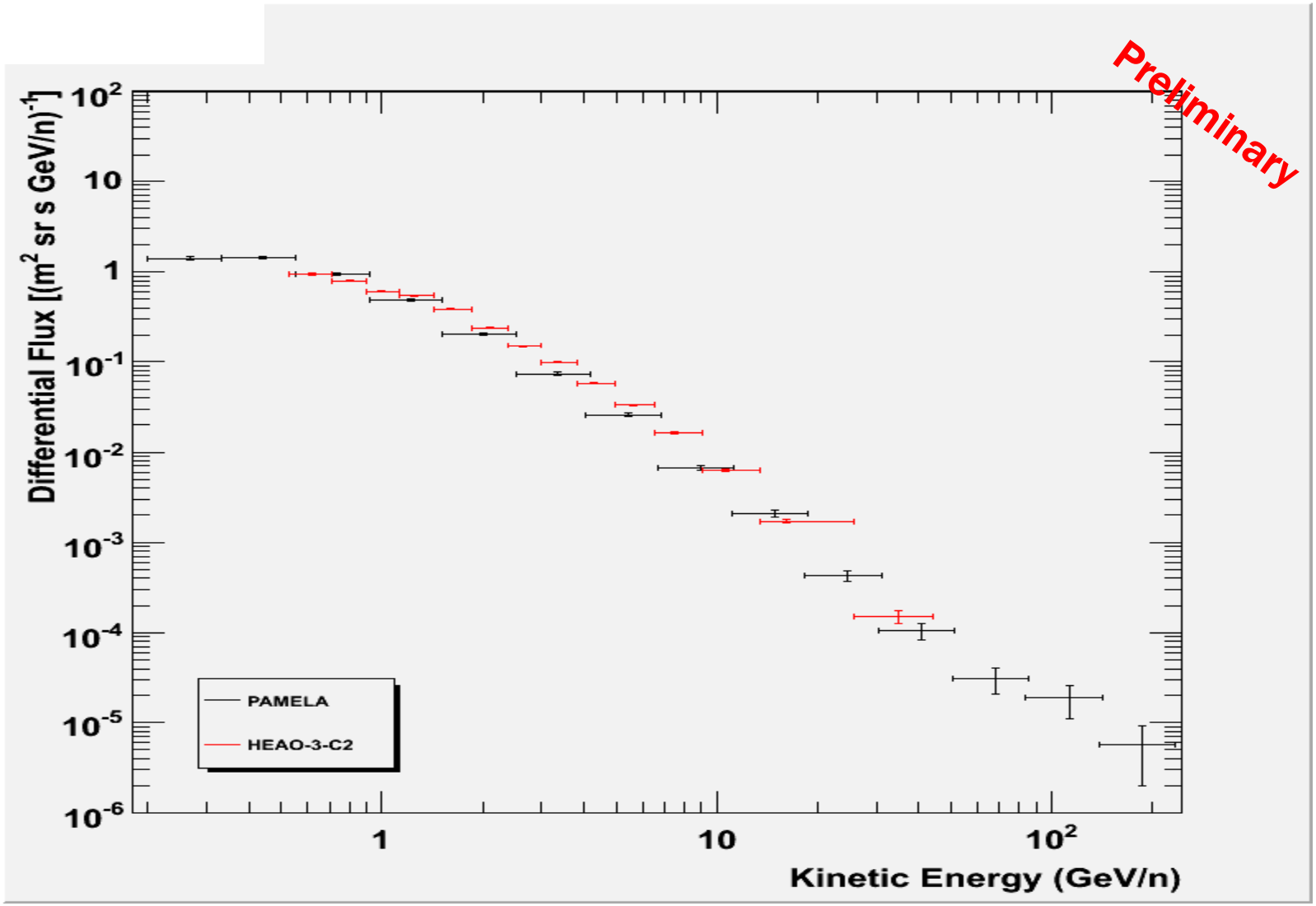


Carbon

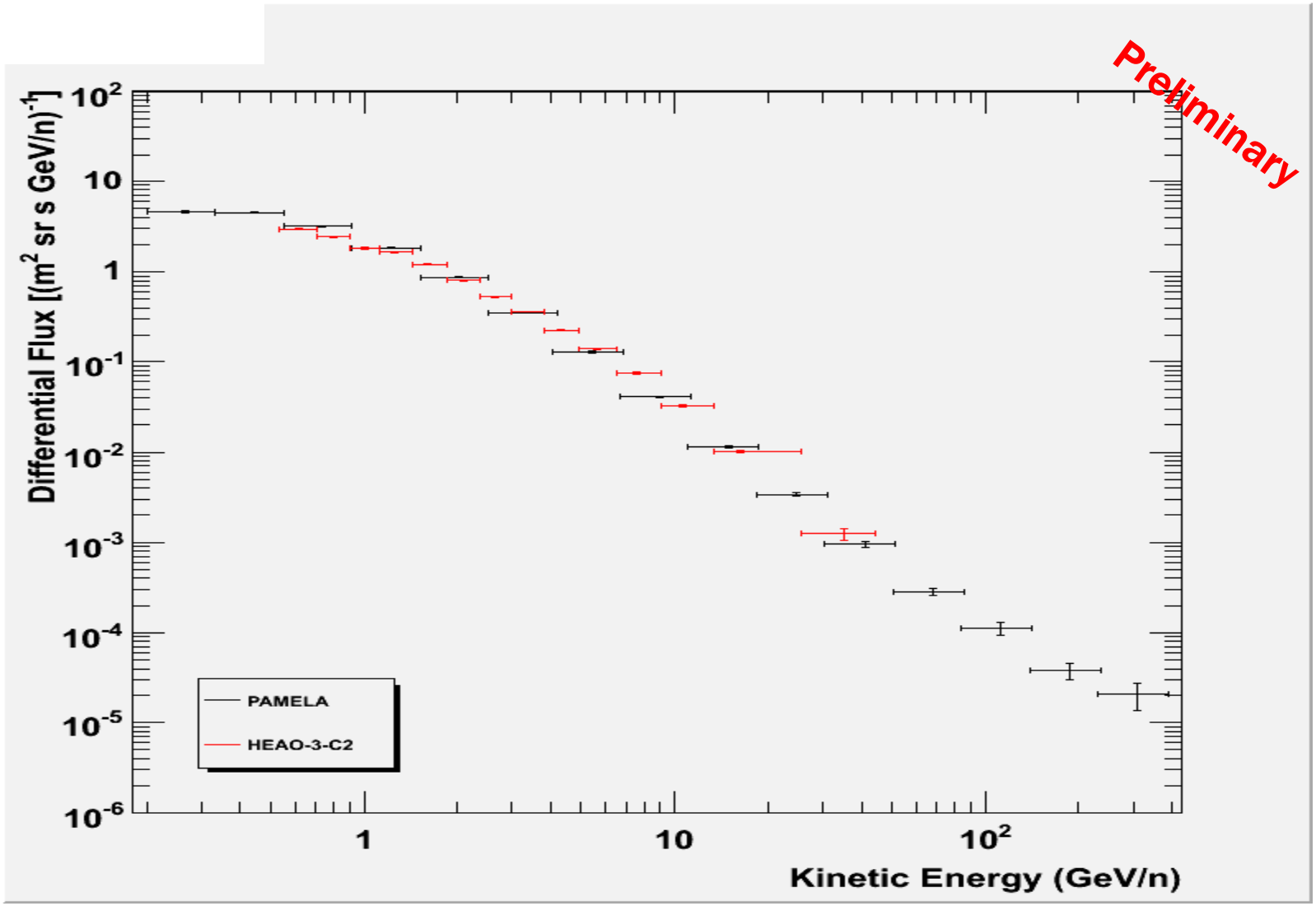


Light Nuclei Spectra and Ratios: Work in Progress…

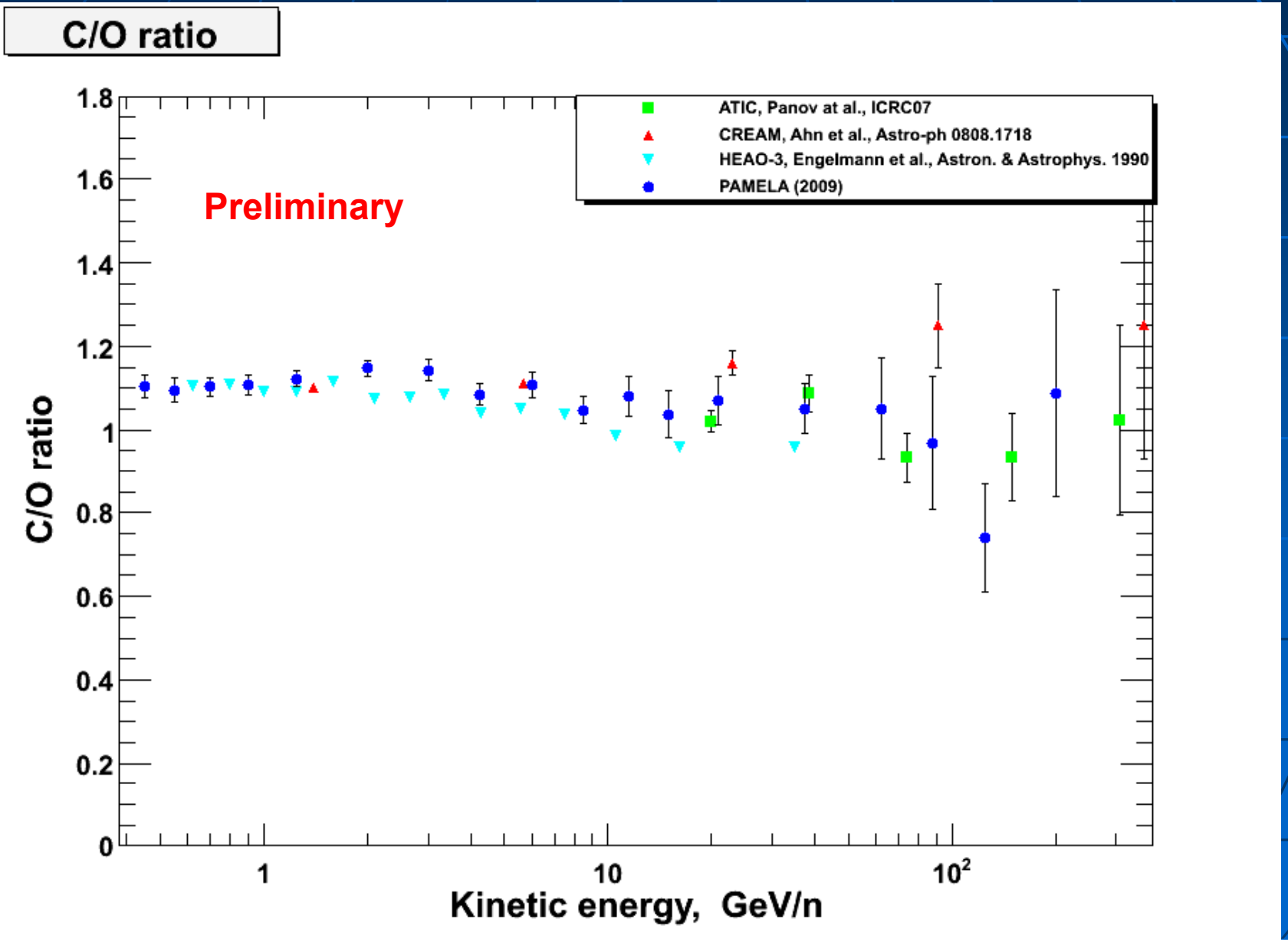
Boron Spectrum



Carbon Spectrum



C/O ratio


C/O ratio
ATIC, Panov at al., ICRC07
CREAM, Ahn et al., Astro-ph 0808.1718
HEAO-3, Engelmann et al., Astron. & Astrophys. 1990
PAMELA (2009)
Preliminary
C/O ratio
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
10
10^2
Kinetic energy, GeV/n

Solar Modulation of galactic cosmic rays

- **Study of charge sign dependent effects**

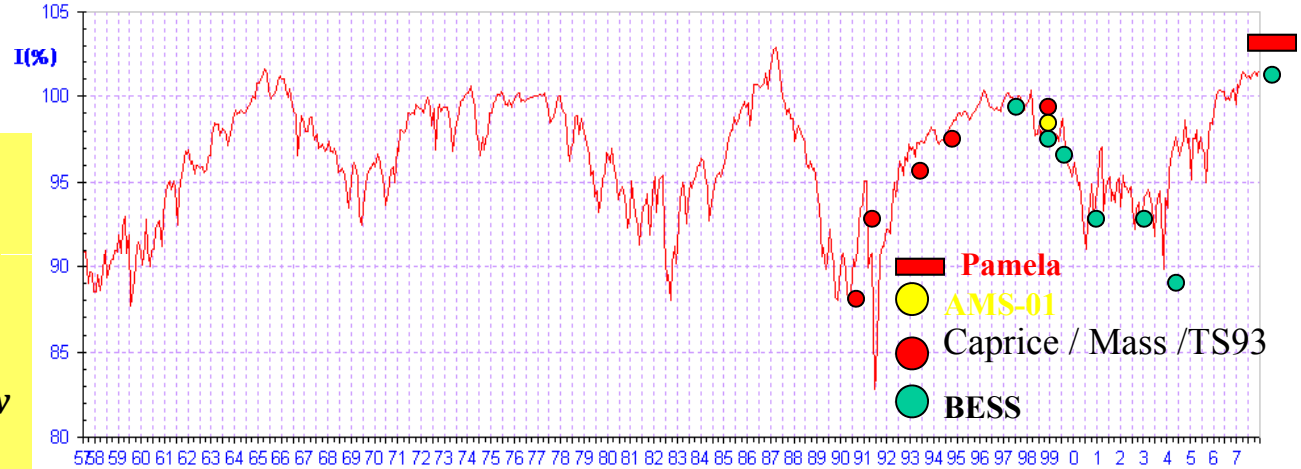
Asaoka Y. et al. 2002, Phys. Rev. Lett. 88, 051101),

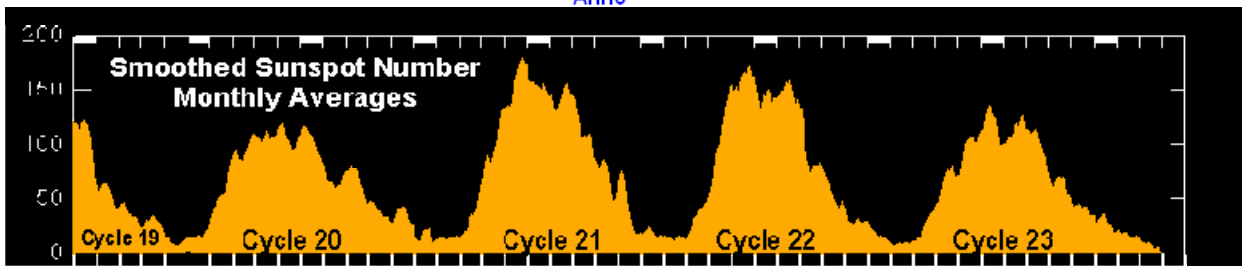
Bieber, J.W., et al. Physi-cal Review Letters, 84, 674, 1999.

J. Clem et al. 30th ICRC 2007

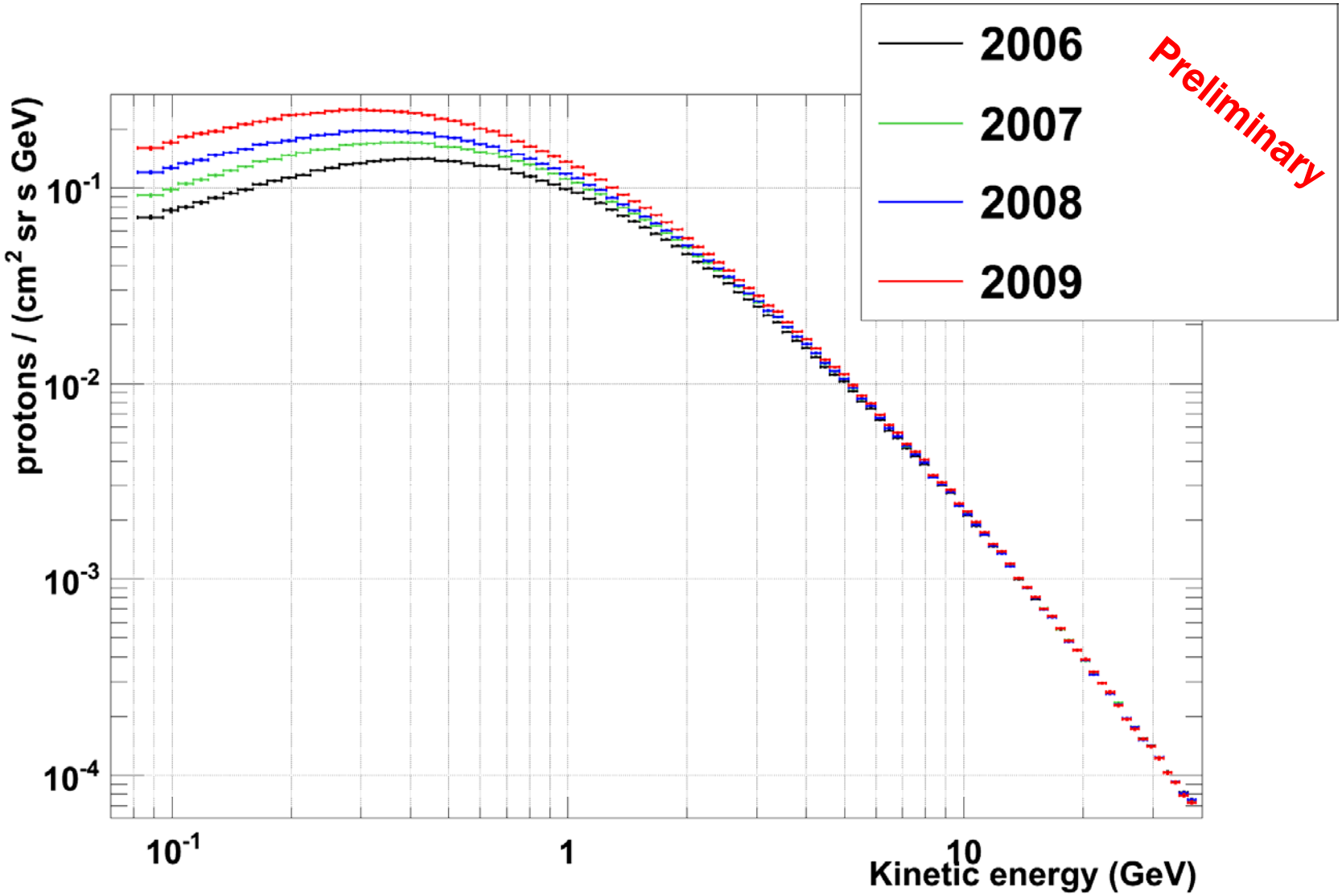
U.W. Langner, M.S. Potgieter, Advances in Space Research 34 (2004)

Rome Neutron Monitor count rates

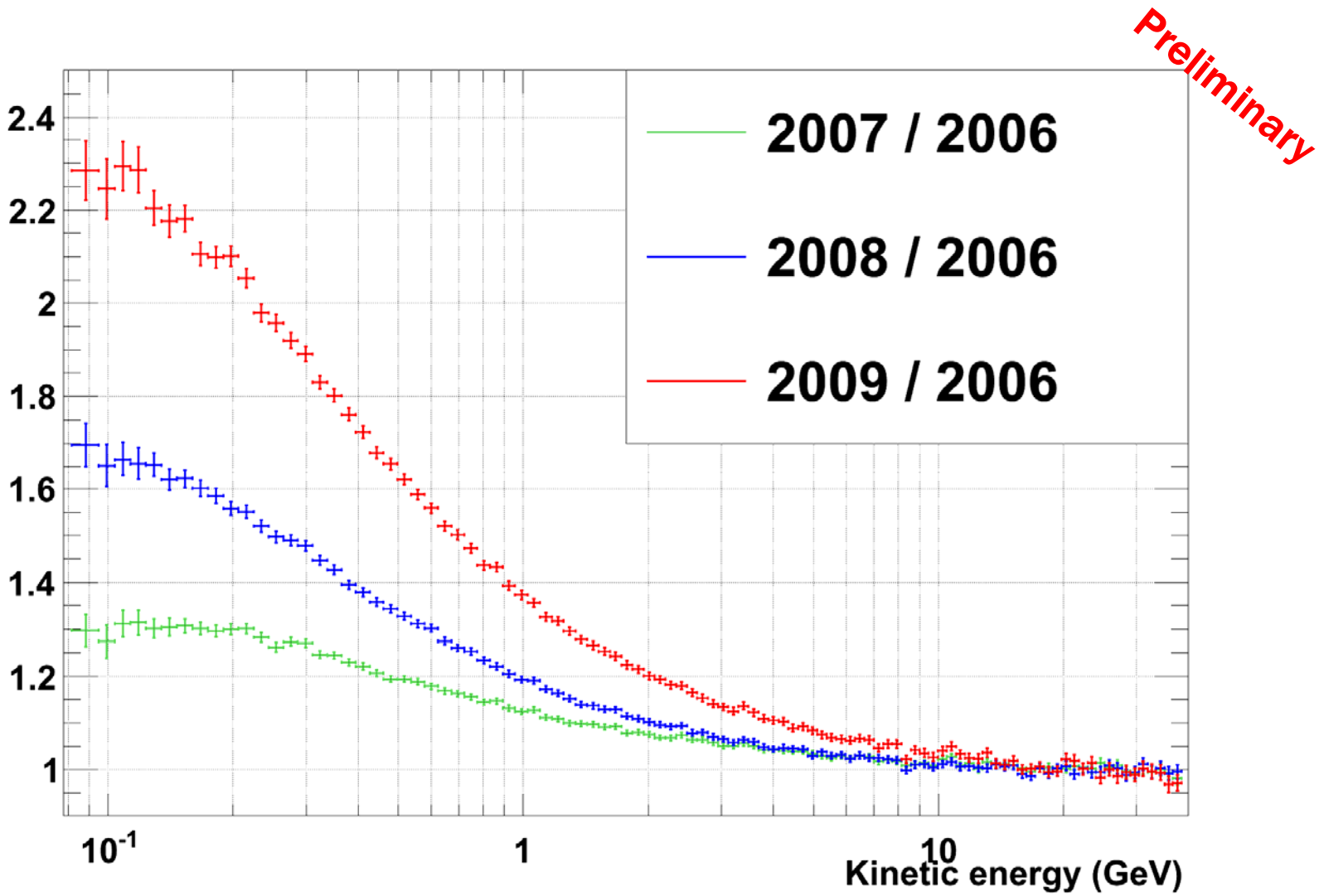




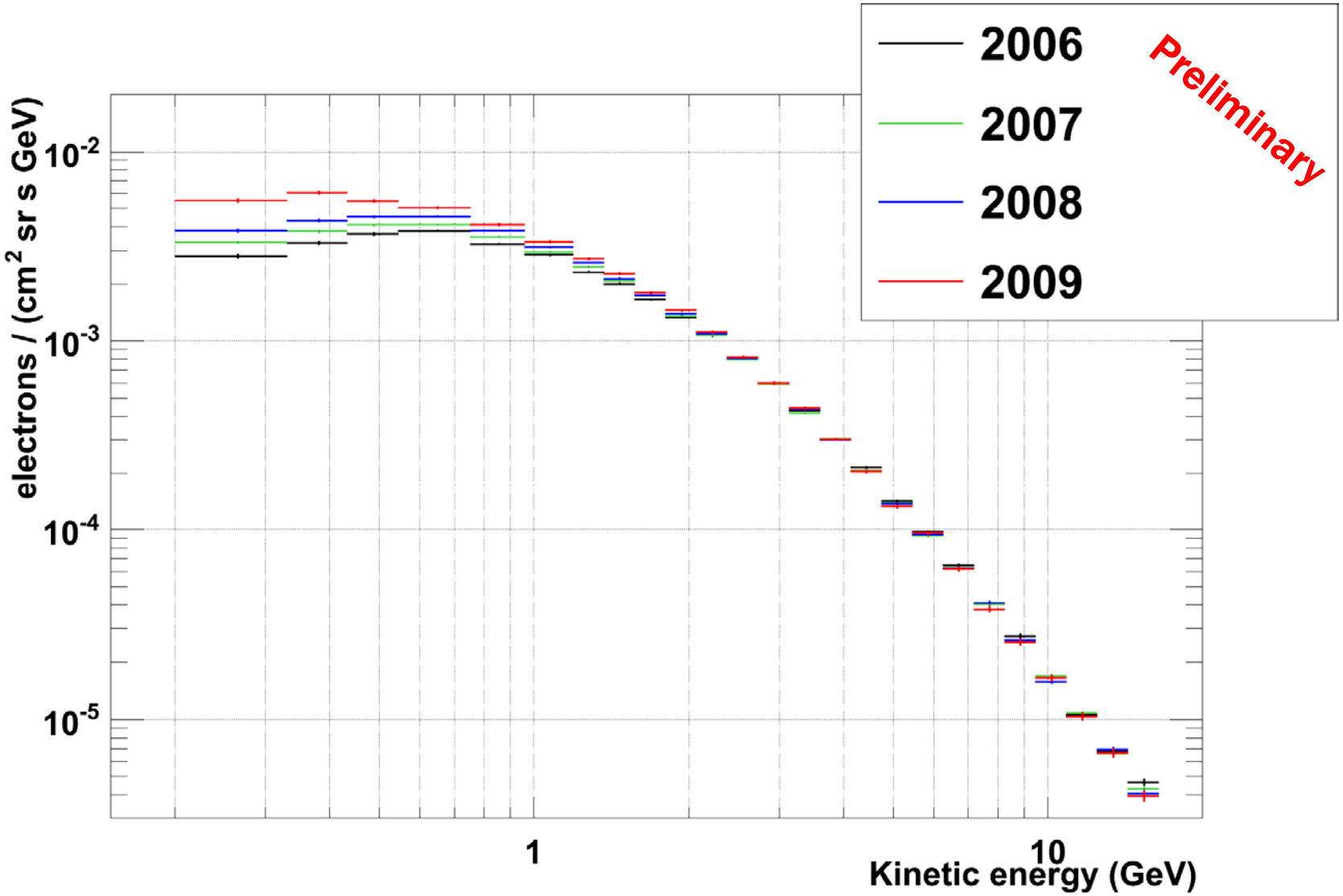
Time Dependence of PAMELA Proton Flux



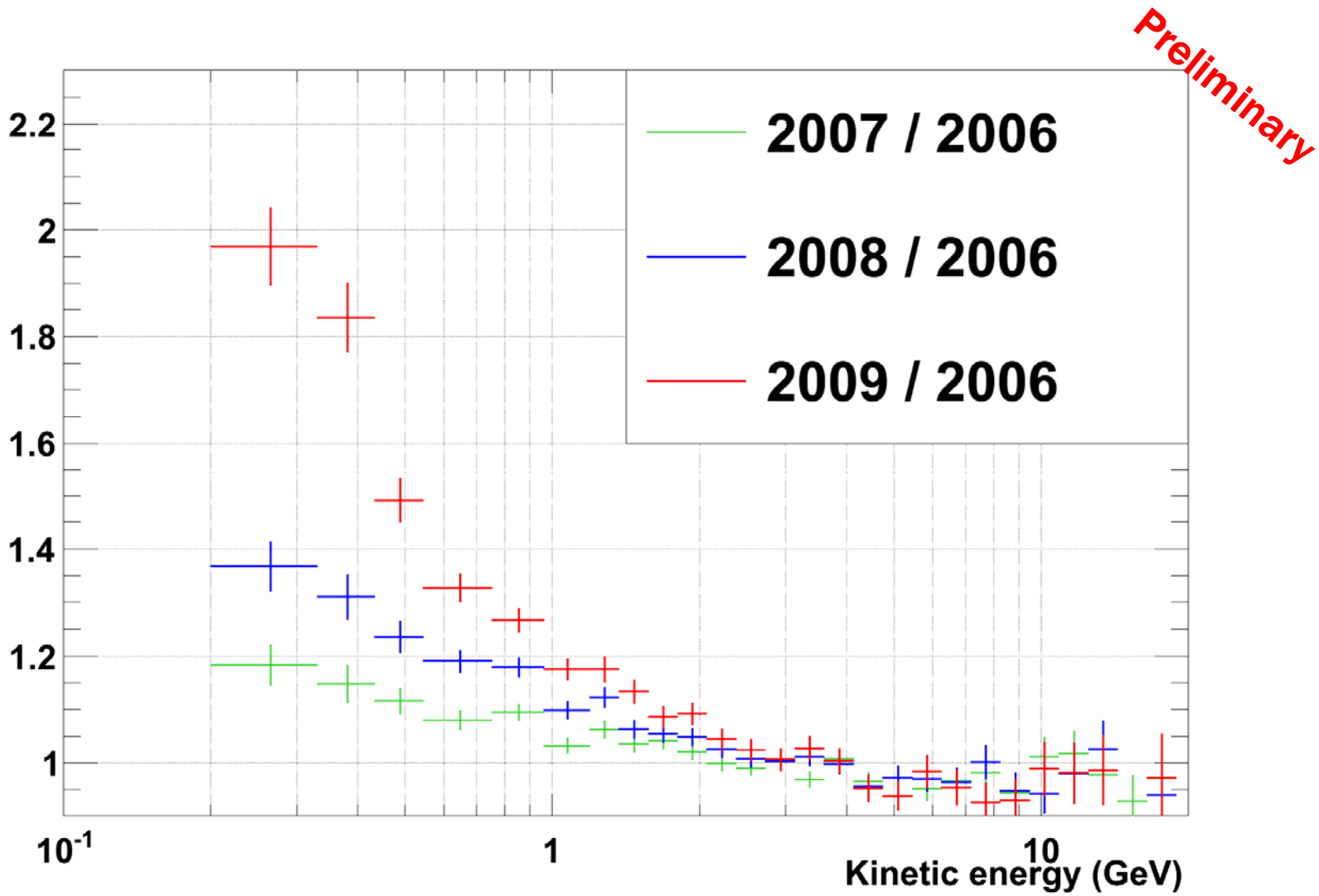
Time Dependence of PAMELA Proton Flux



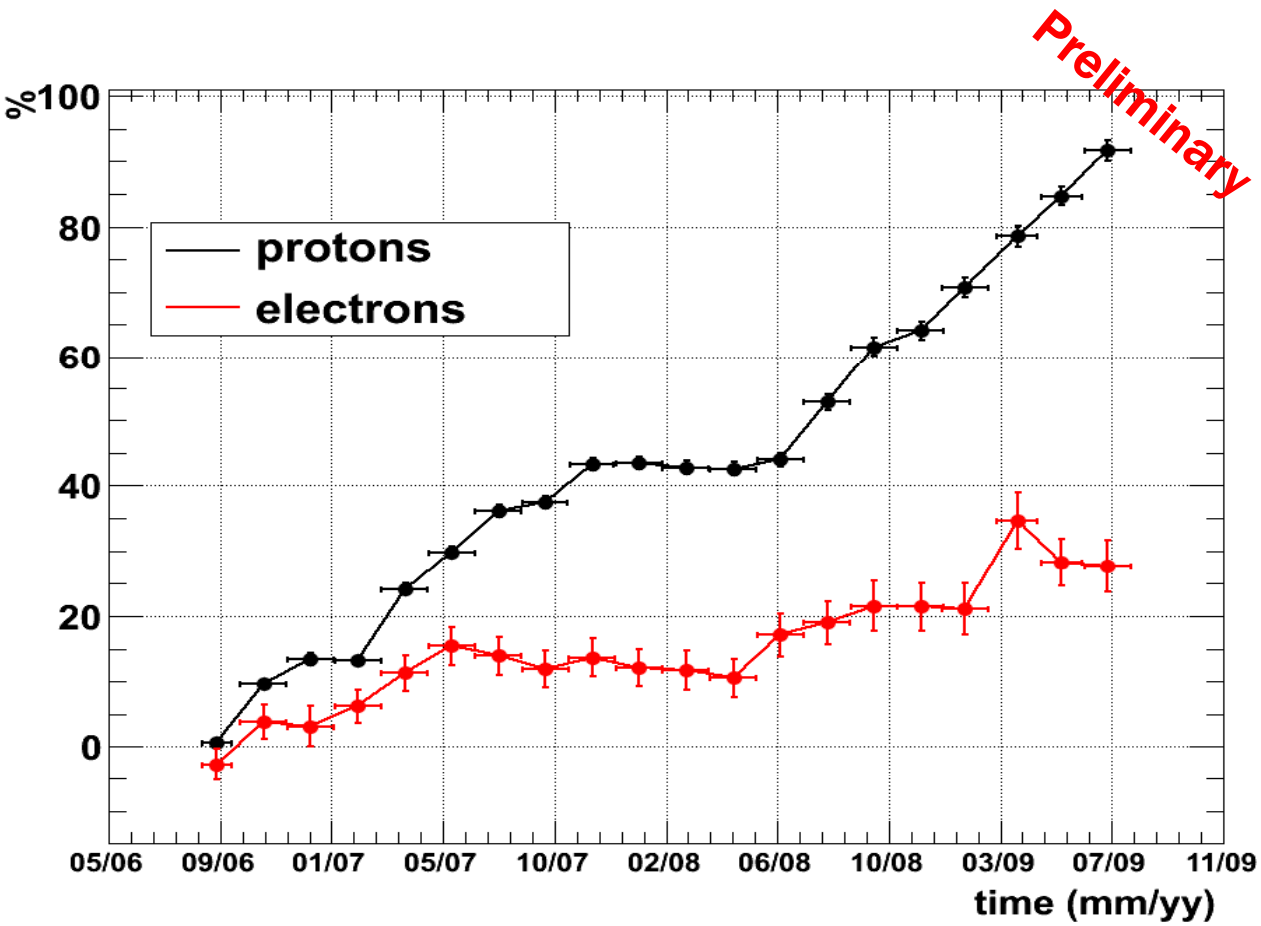
Time Dependence of PAMELA Electron (e^-) Flux



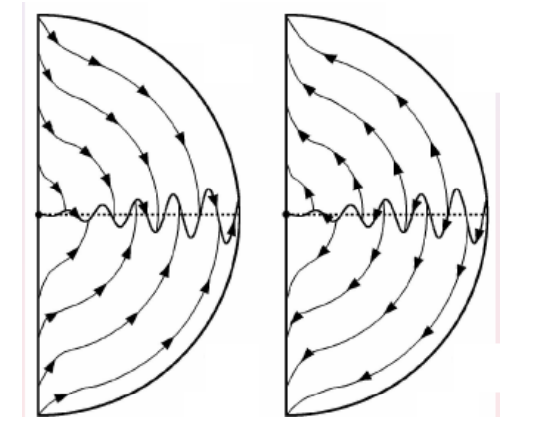
Time Dependence of PAMELA Electron (e^-) Flux



Time Dependence



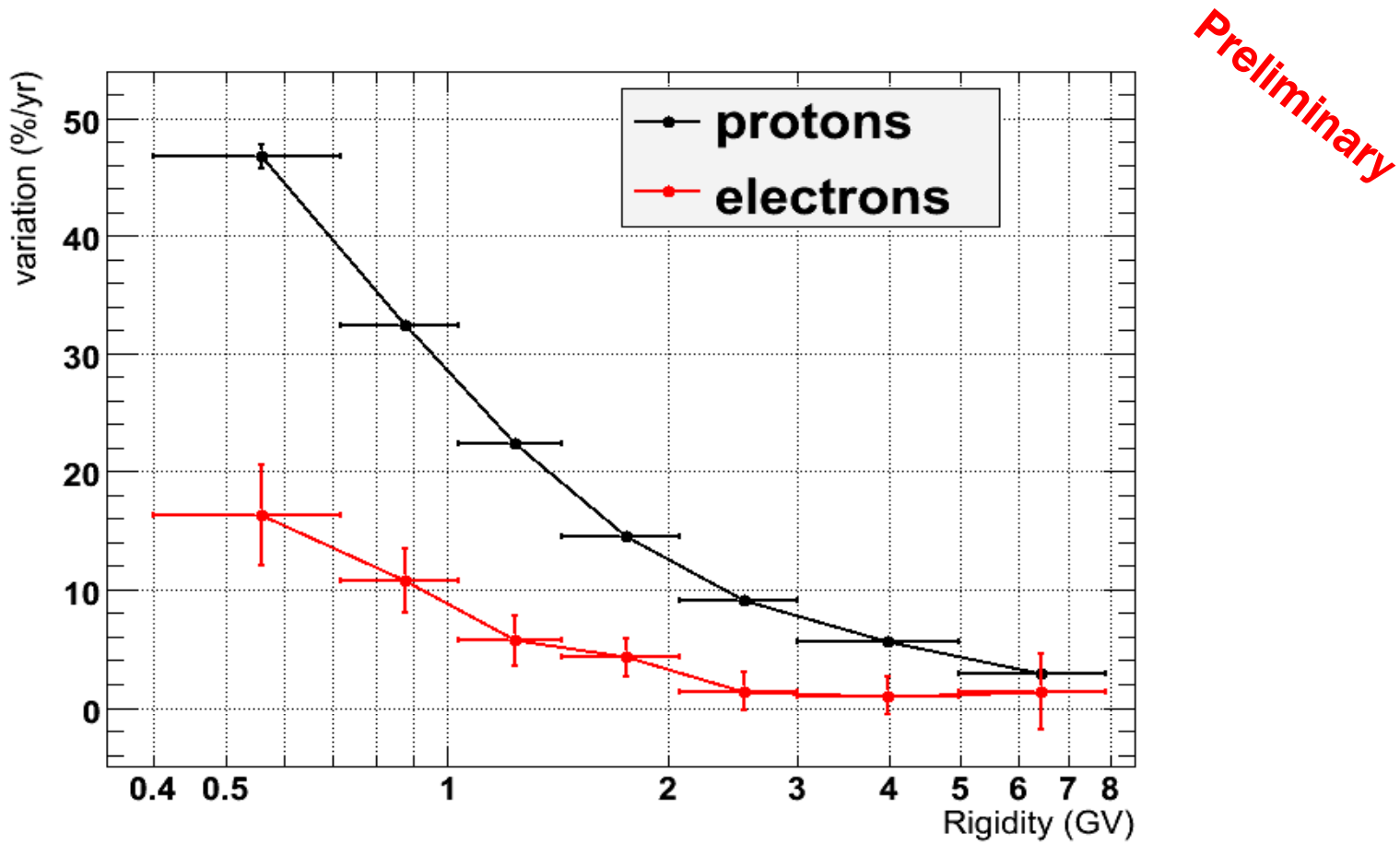
A < 0



Negative particles Positive particles

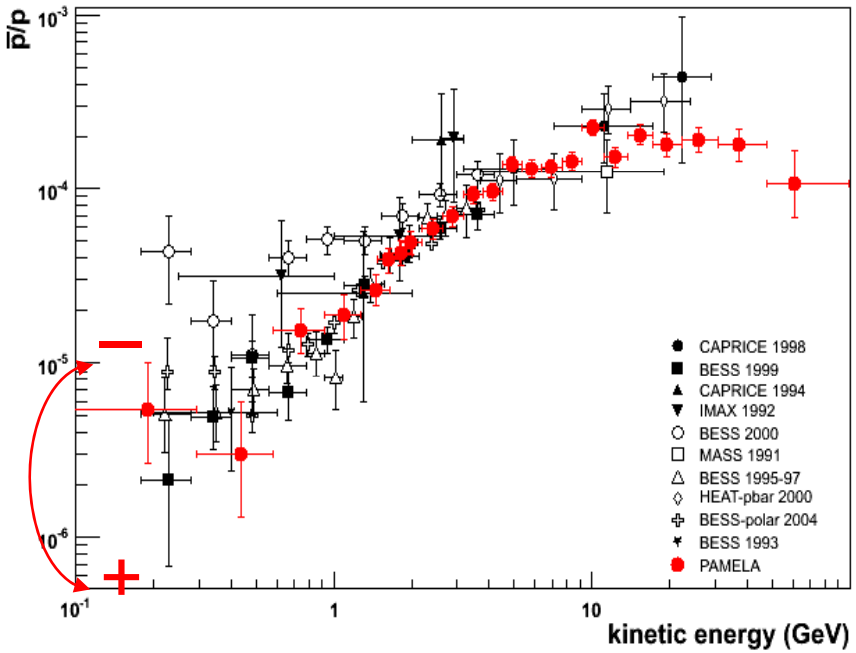
Flux variation as a function of time for rigidities between 0.72 and 1.04 GV

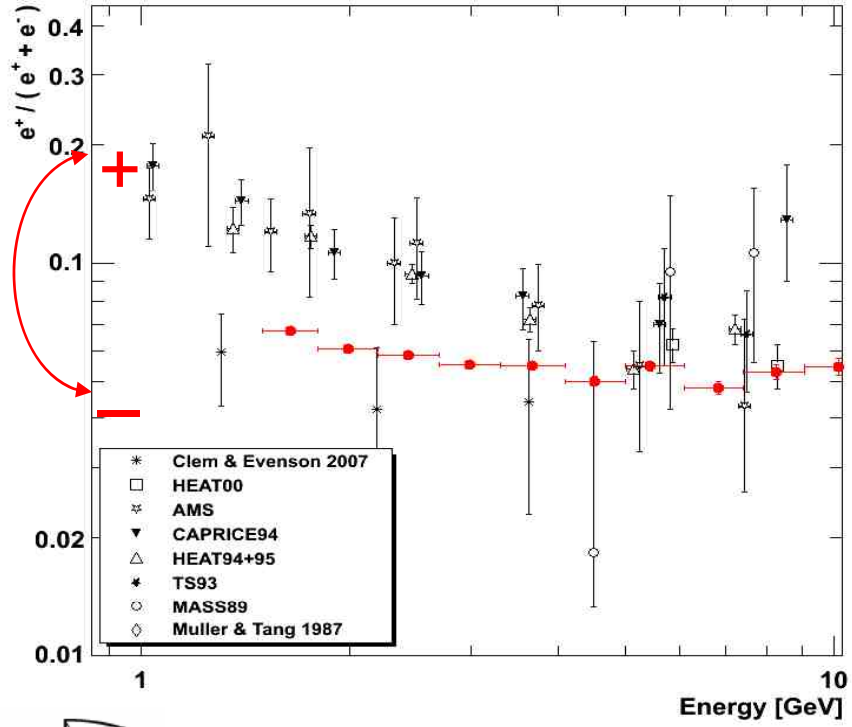
Time Dependence



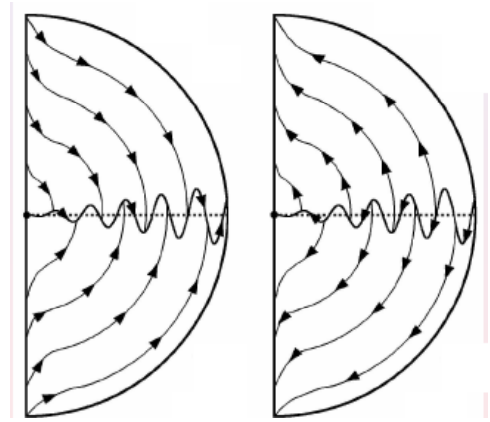
Increase of the flux measured by PAMELA from July 2006 to December 2008

Charge dependent solar modulation



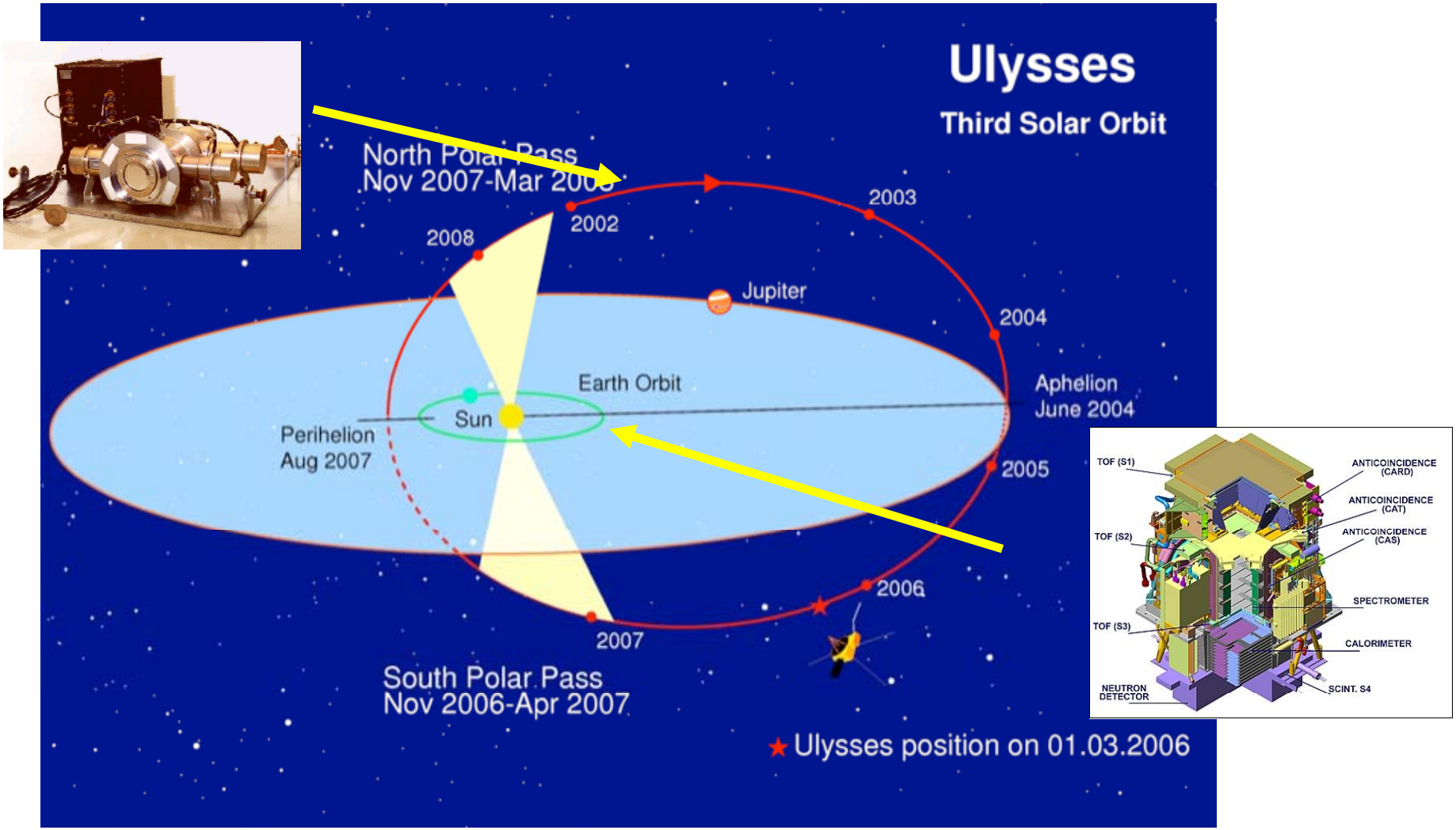


A < 0



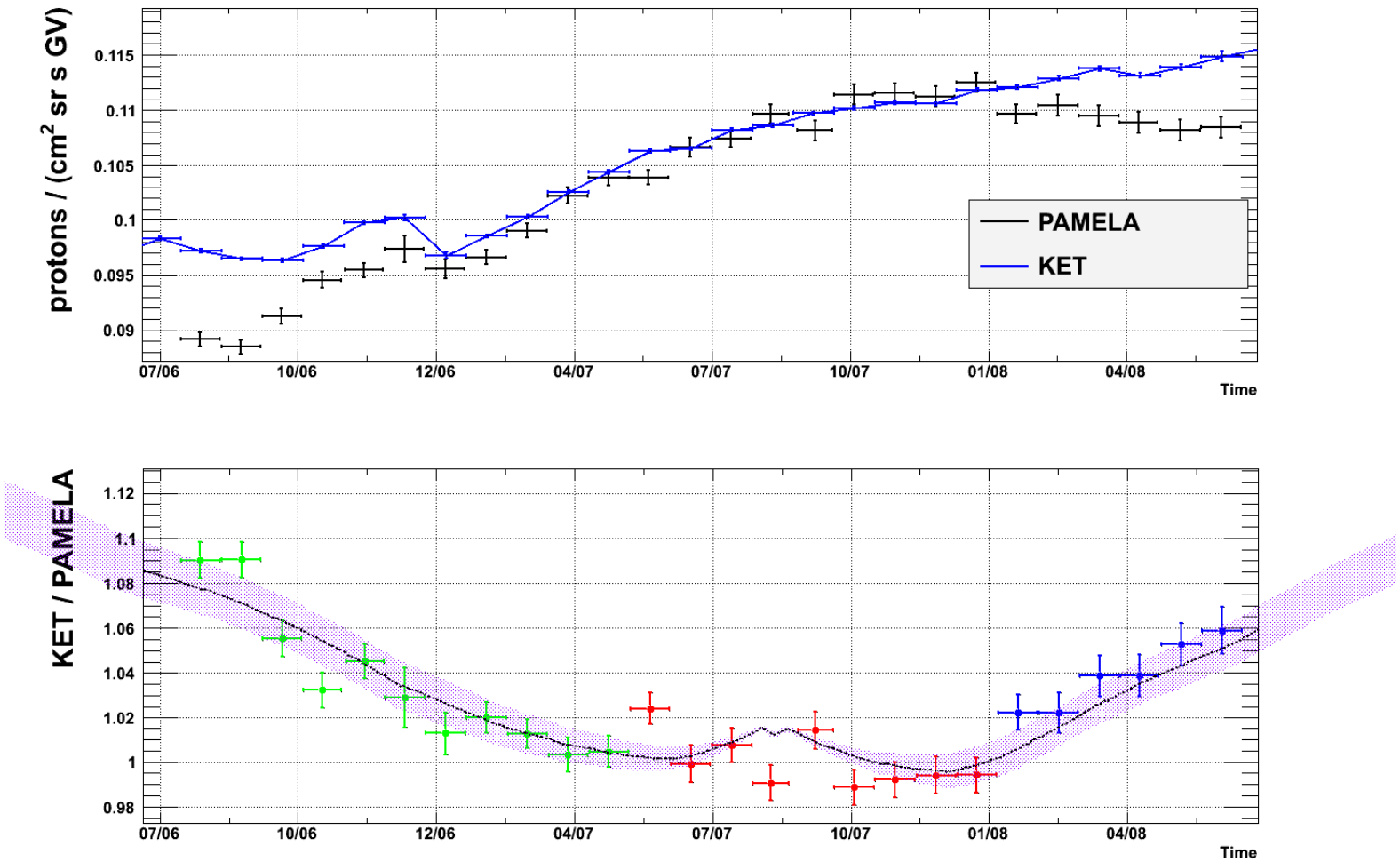
Negative particles **Positive particles**

Gradients in the Heliosphere, PAMELA & ULYSSES



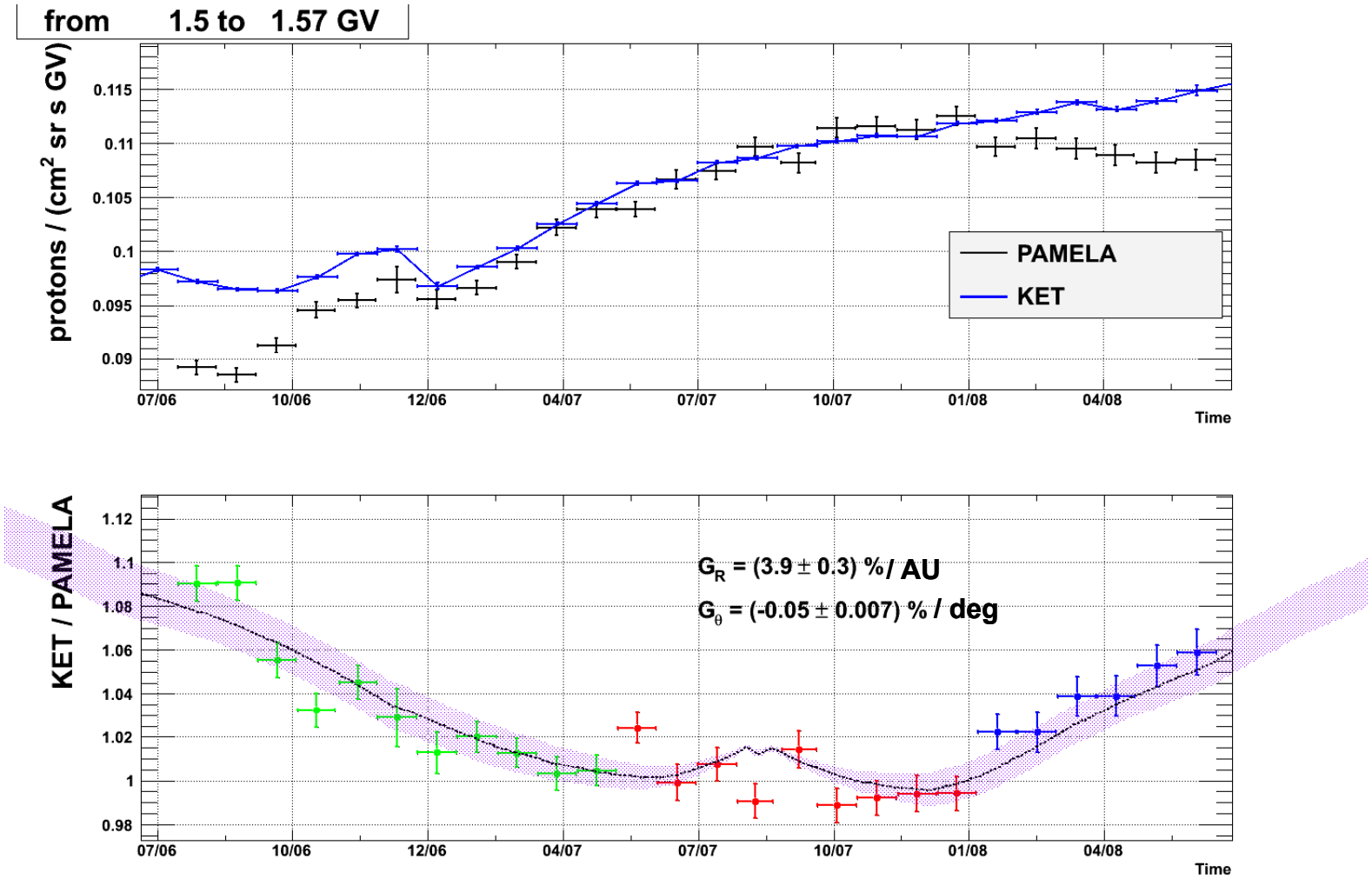
$$ln\left(\frac{I(t,R,\theta)}{I_{PAMELA}(t)}\right) = G_R R + G_\theta \theta$$

Gradients in the Heliosphere, PAMELA & ULYSSES



Comparison of the proton flux measured between 1.5 and 1.57GV by PAMELA and ULYSSES as a function of time

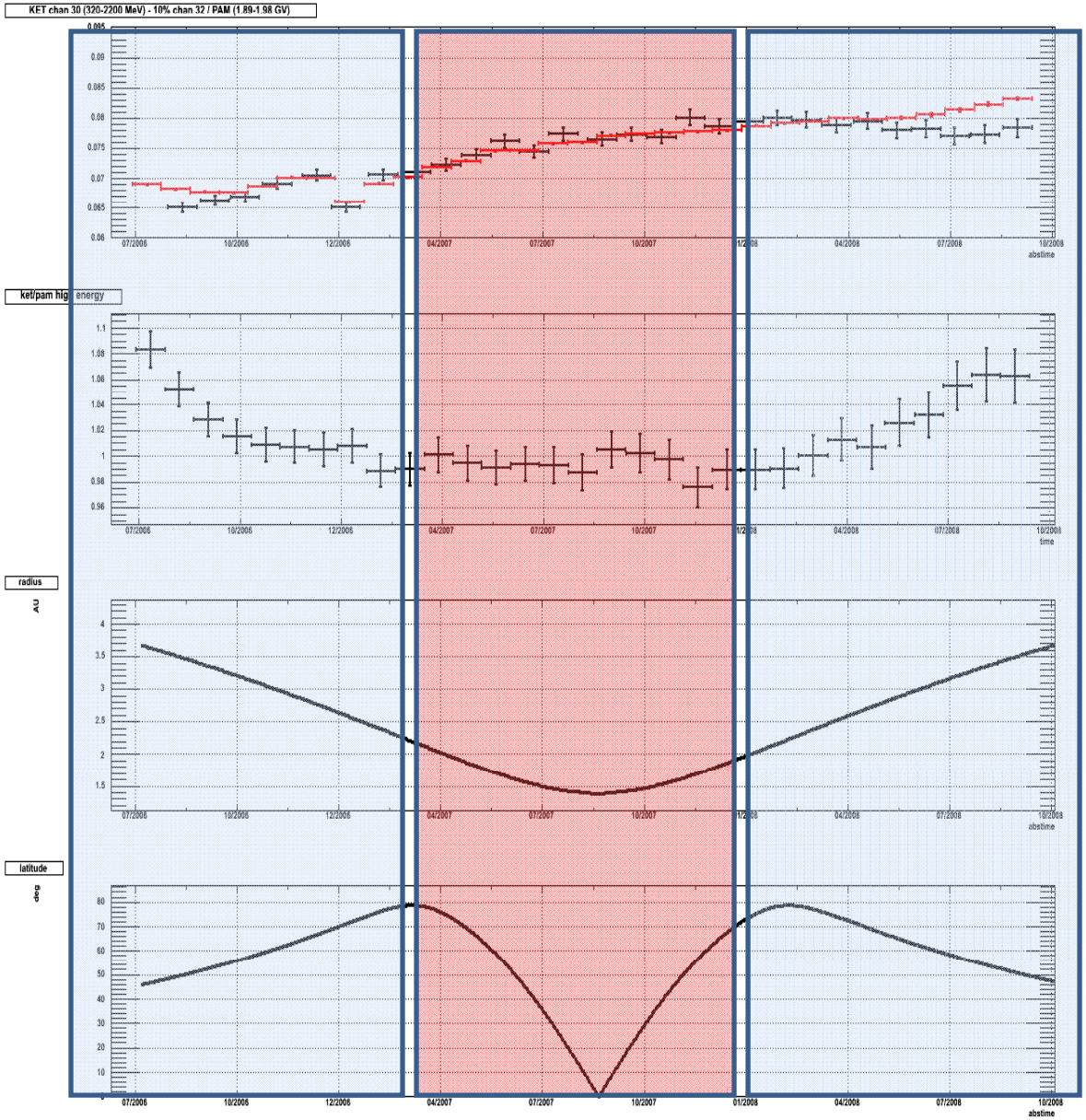
Gradients in the Heliosphere, PAMELA & ULYSSES



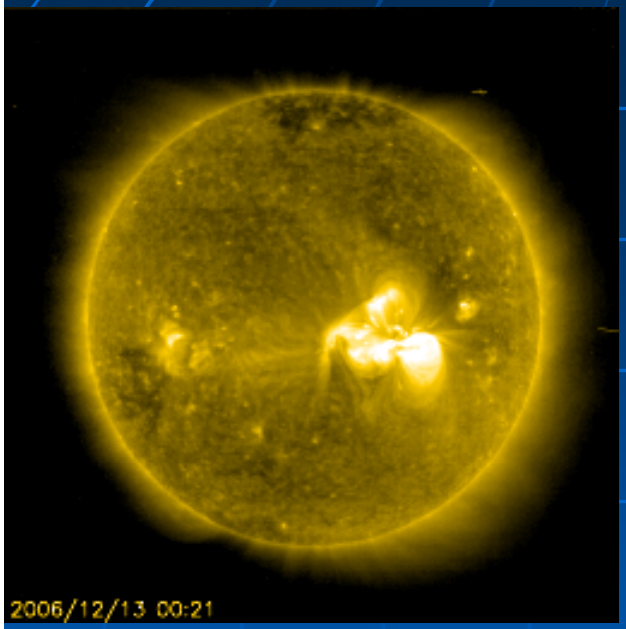
Comparison of the proton flux measured between 1.5 and 1.57 GV by PAMELA and ULYSSES as a function of time

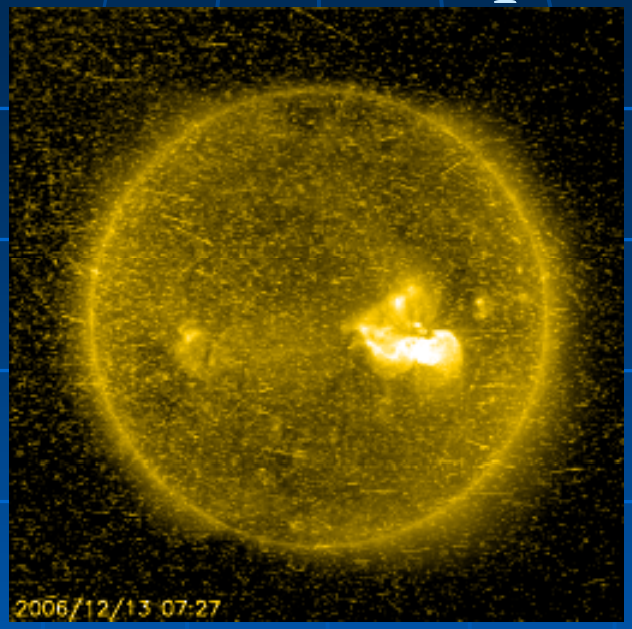
Gradients in the heliosphere, PAMELA & ULYSSES

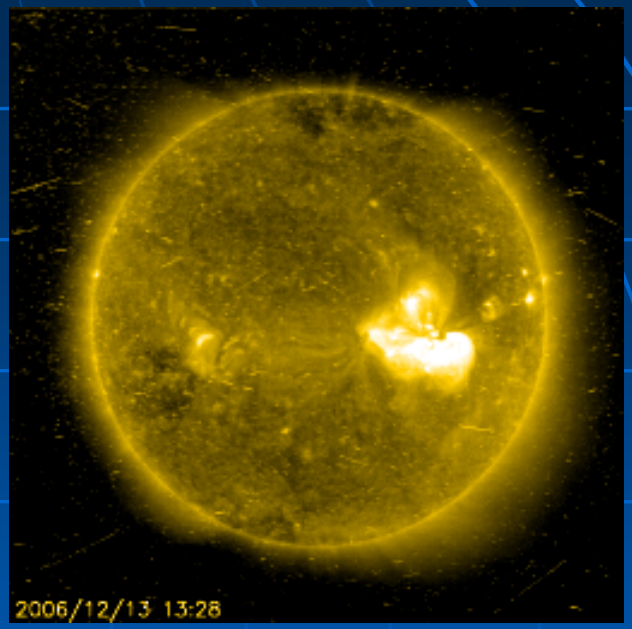
1. **Period: Radial distance decreases and absolute value of heliographic latitude increases, while intensity ratio decreases**
2. **Period: Radial distance and latitude first decrease and then increase, while intensity ratio is constant**
3. **Period: Radial distance increases and heliographic latitude decrease, while intensity ratio increases**



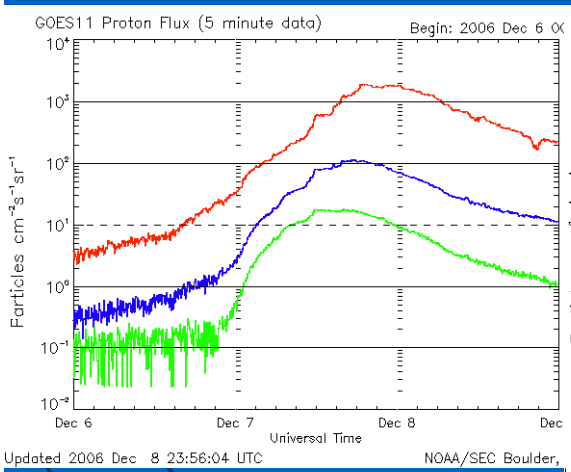
December 2006 Solar particle events

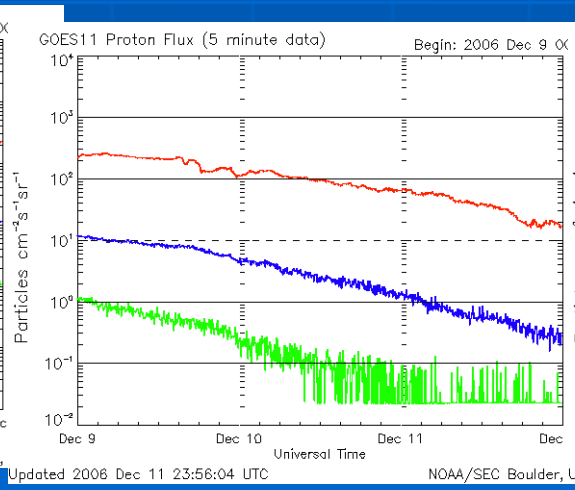


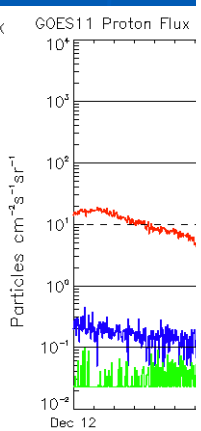


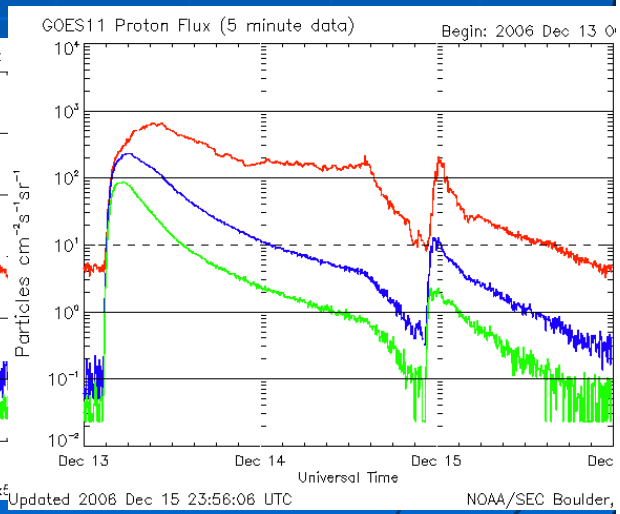


Dec 13th largest CME since 2003, anomalous at sol min X3.4 solar flare.



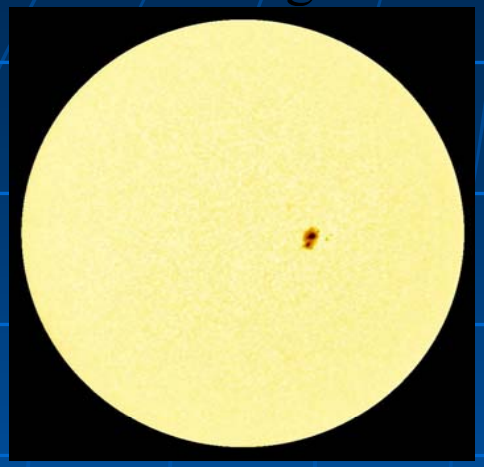






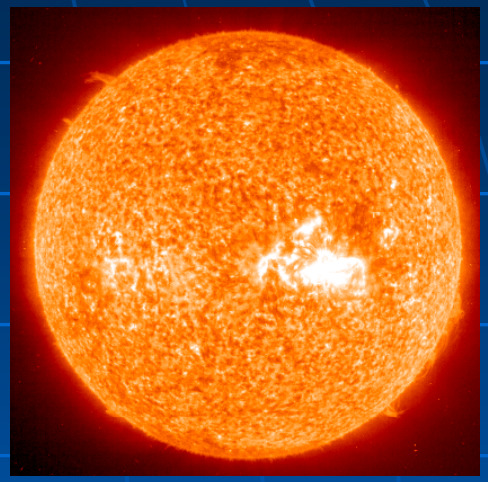
The Sun on December 13, 2006

White light

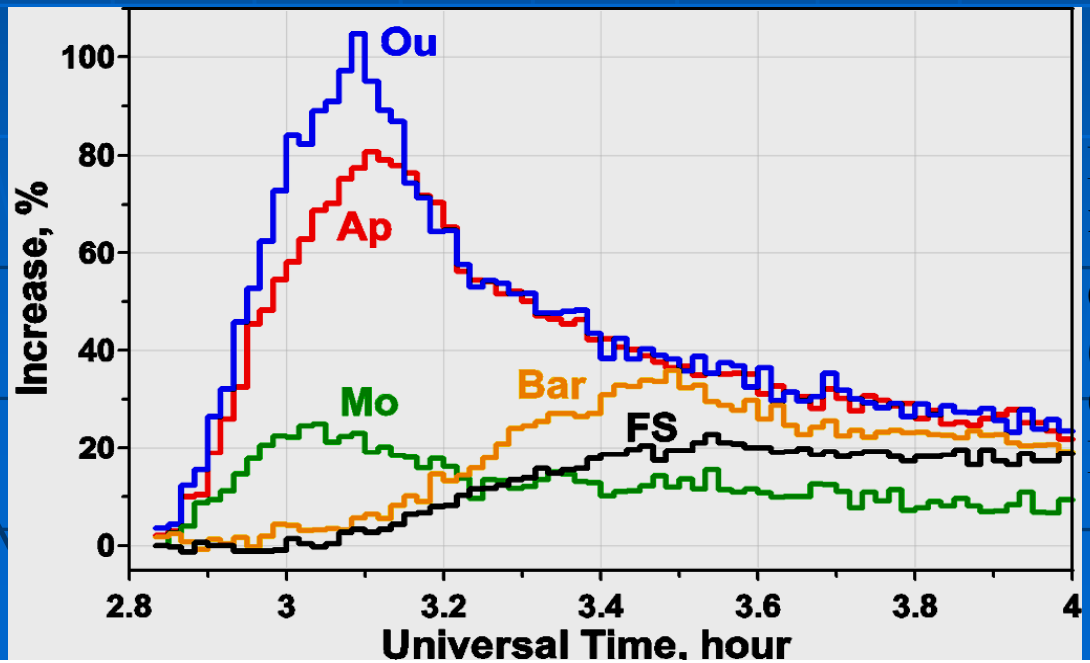


Active region AR10930

30 nm emission



Ground level effect of a solar flare X3.4/2B S06 W24 02.26 UT

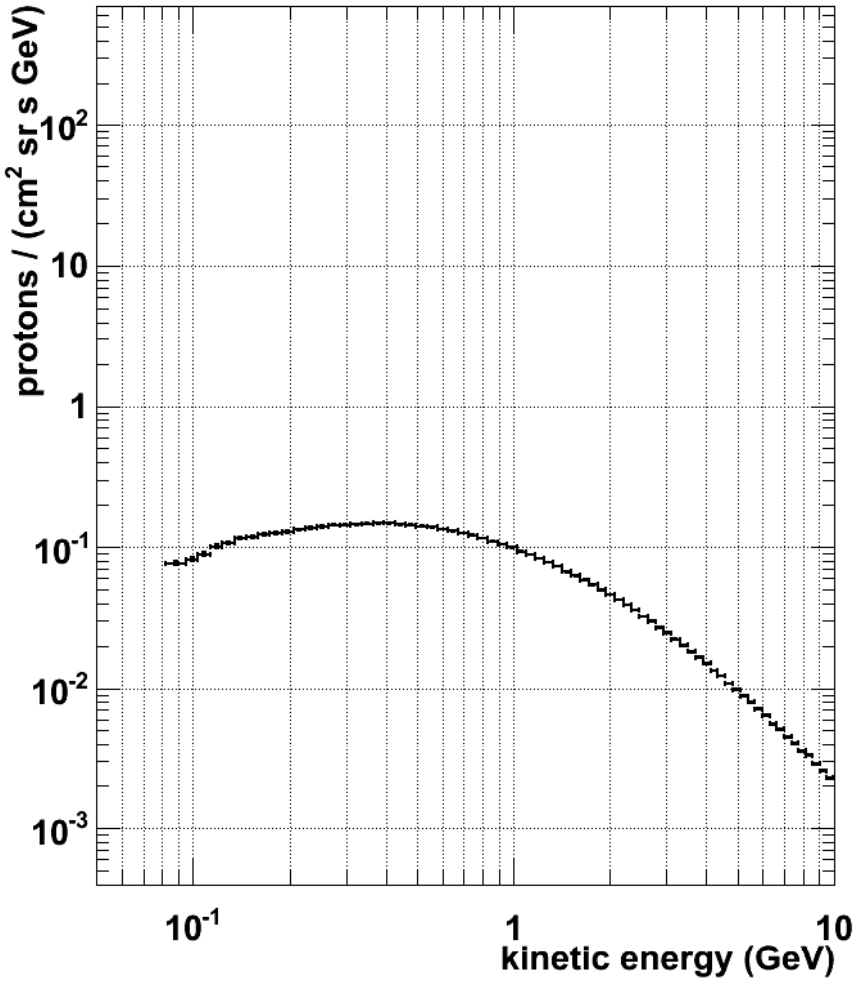


Enhancement profiles at neutron monitors:

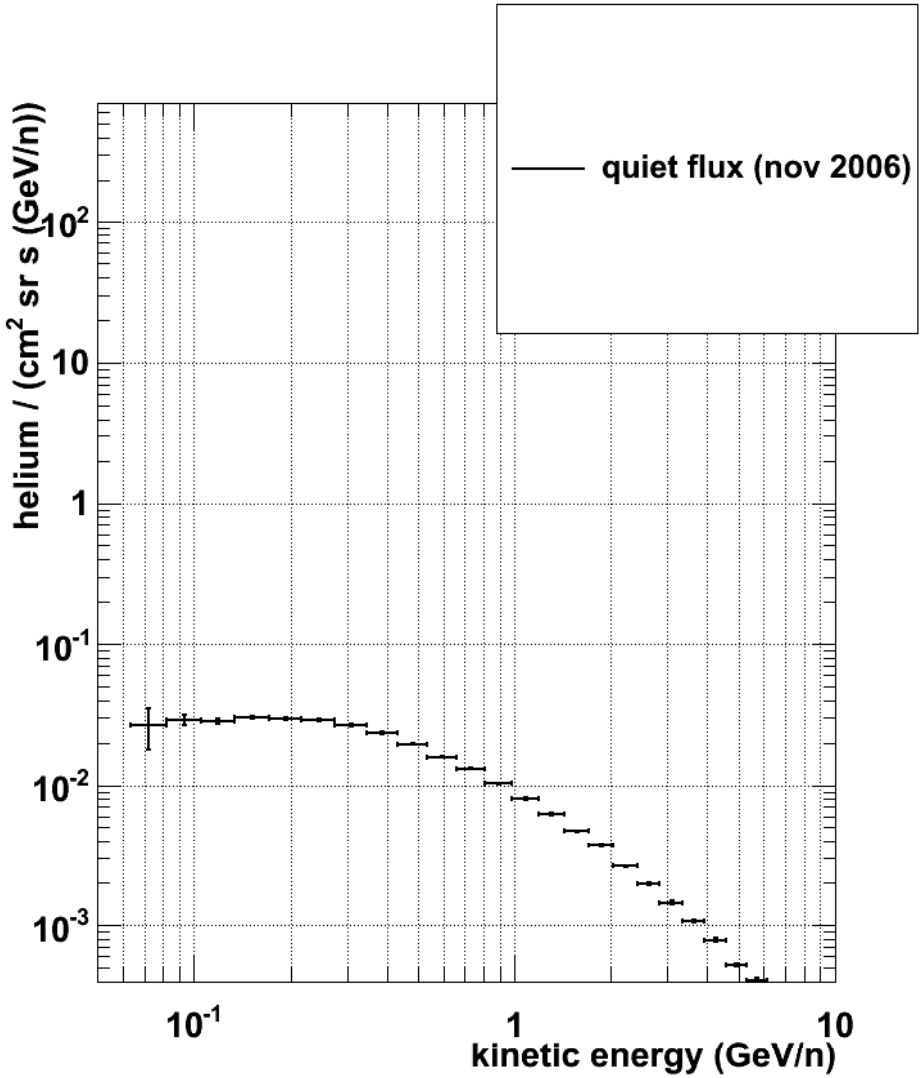
Oulu (Rc=0.77 GV), Apatity (Rc=0.60GV), Moscow (Rc=2.4 GV), , Barentsburg (Rc=0… GV), Fort Smith (Rc=0… GV),

December 13

Proton flux

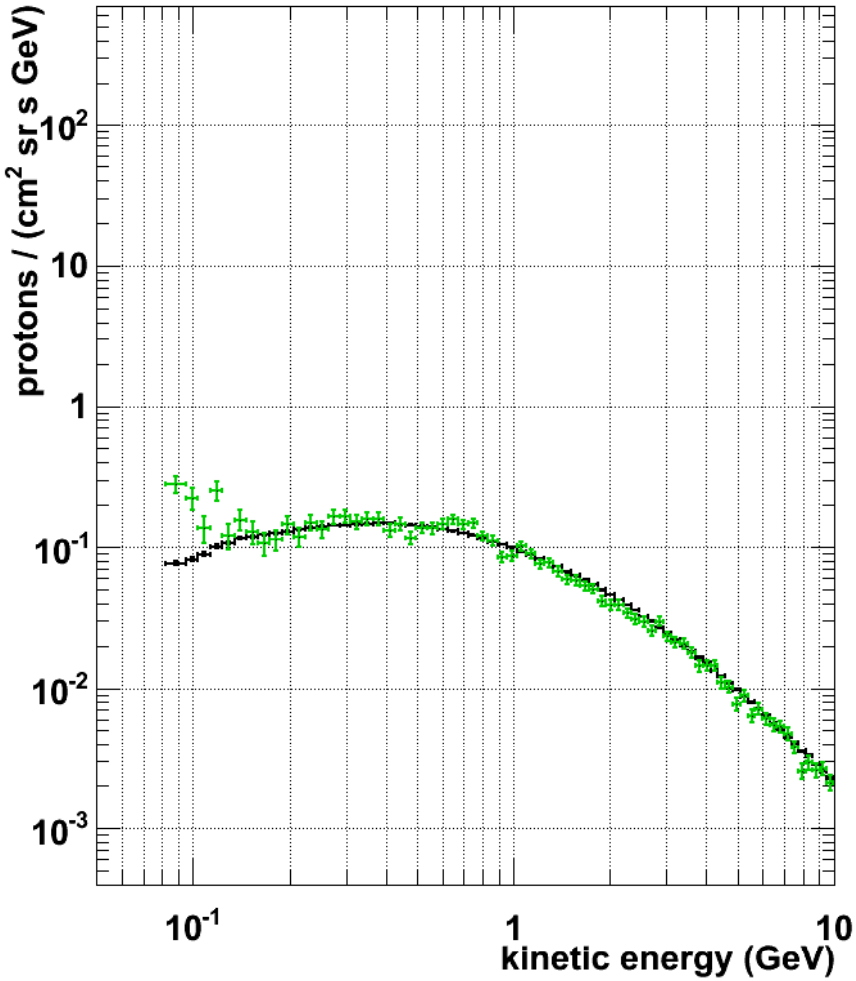


Helium flux



December 13

Proton flux



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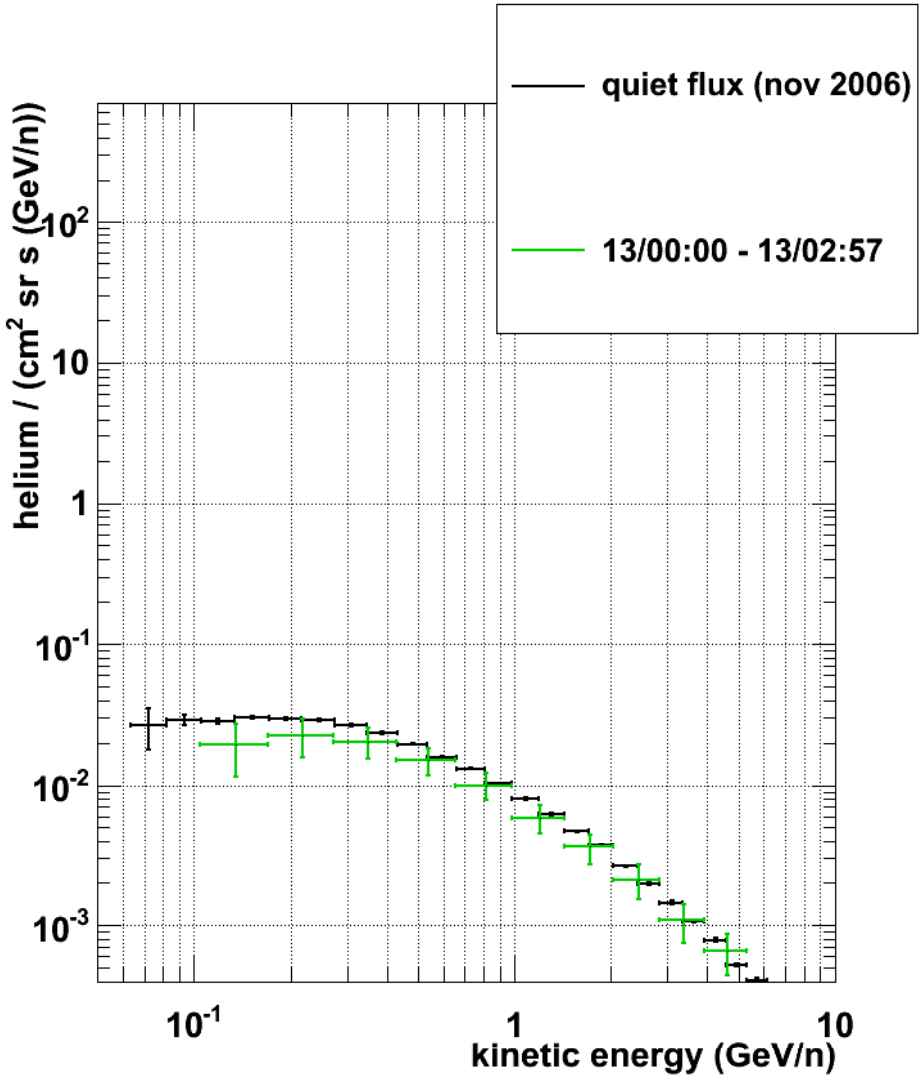
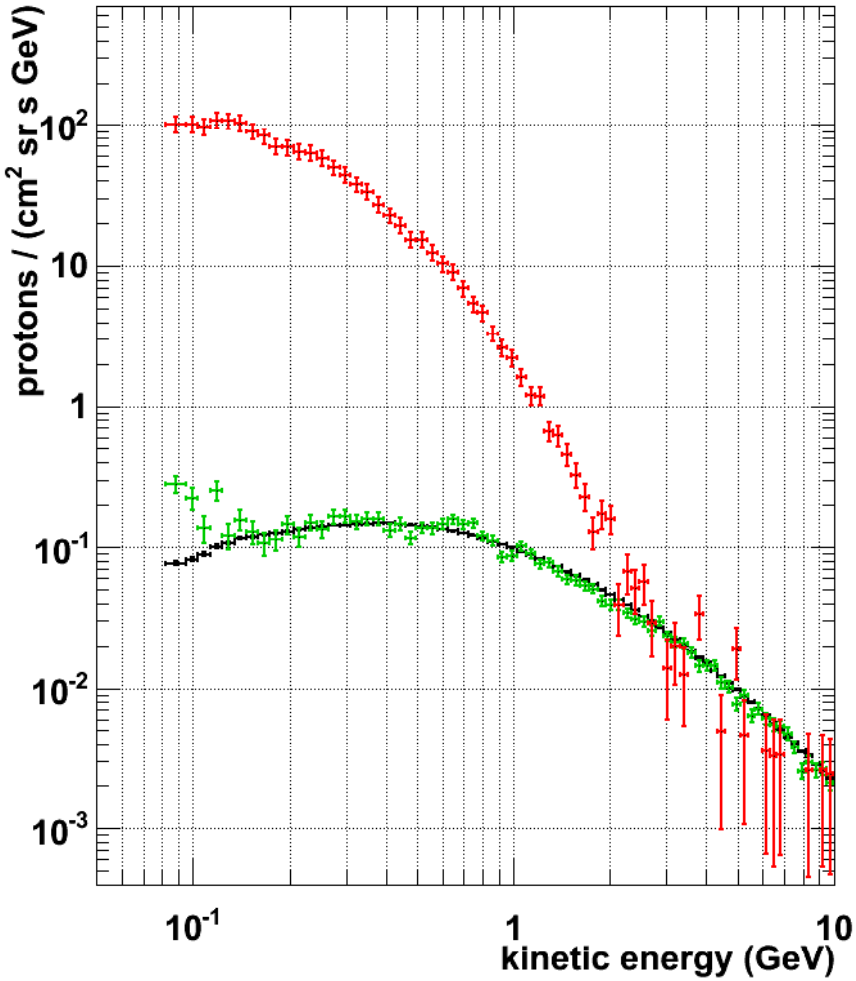
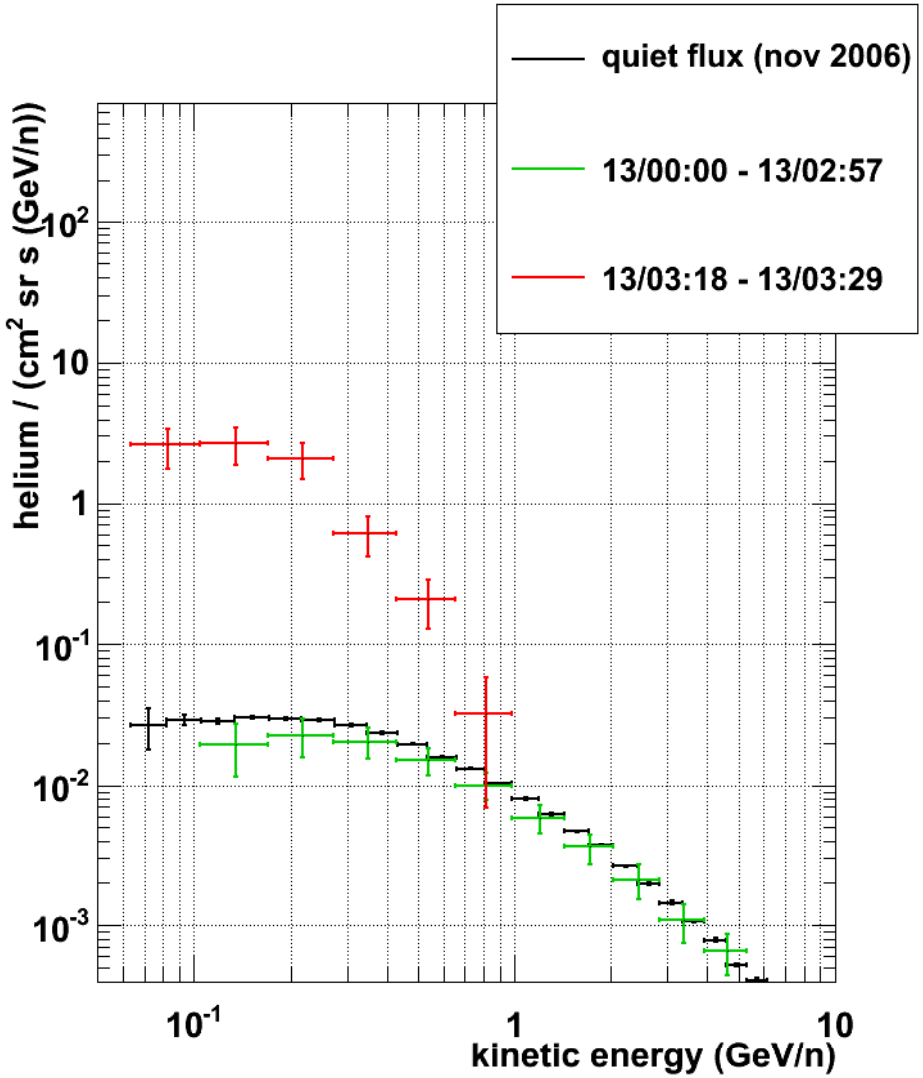


December 13

Proton flux

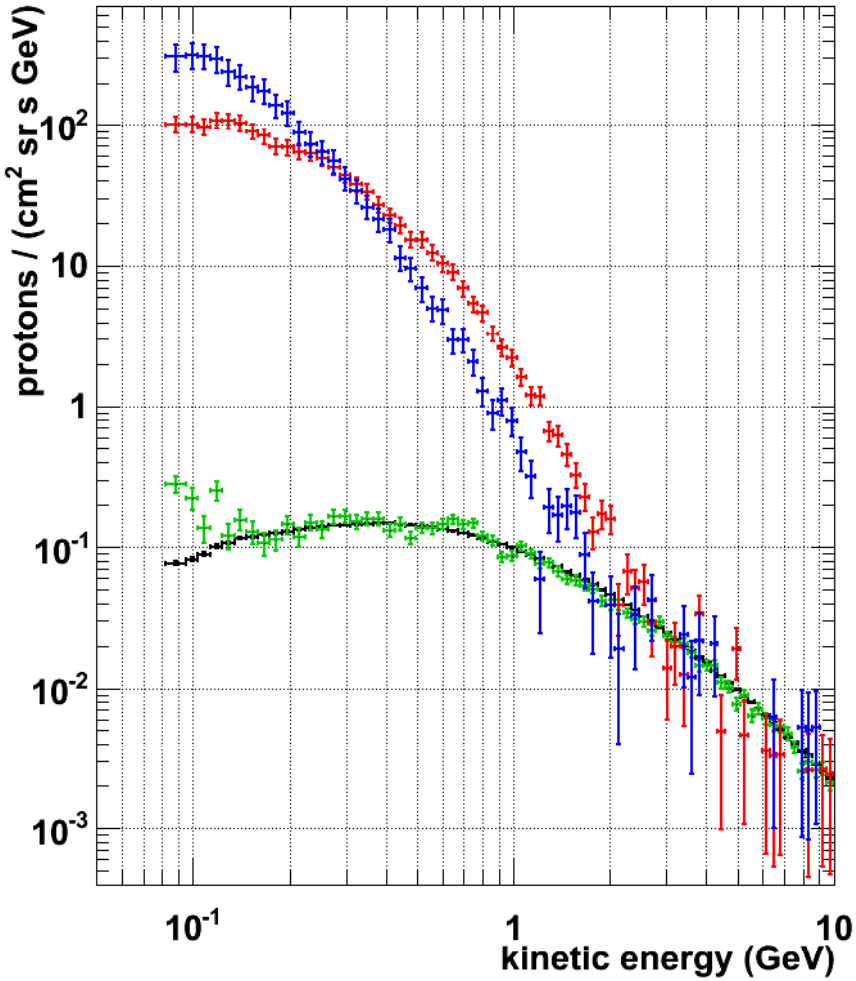


Helium flux

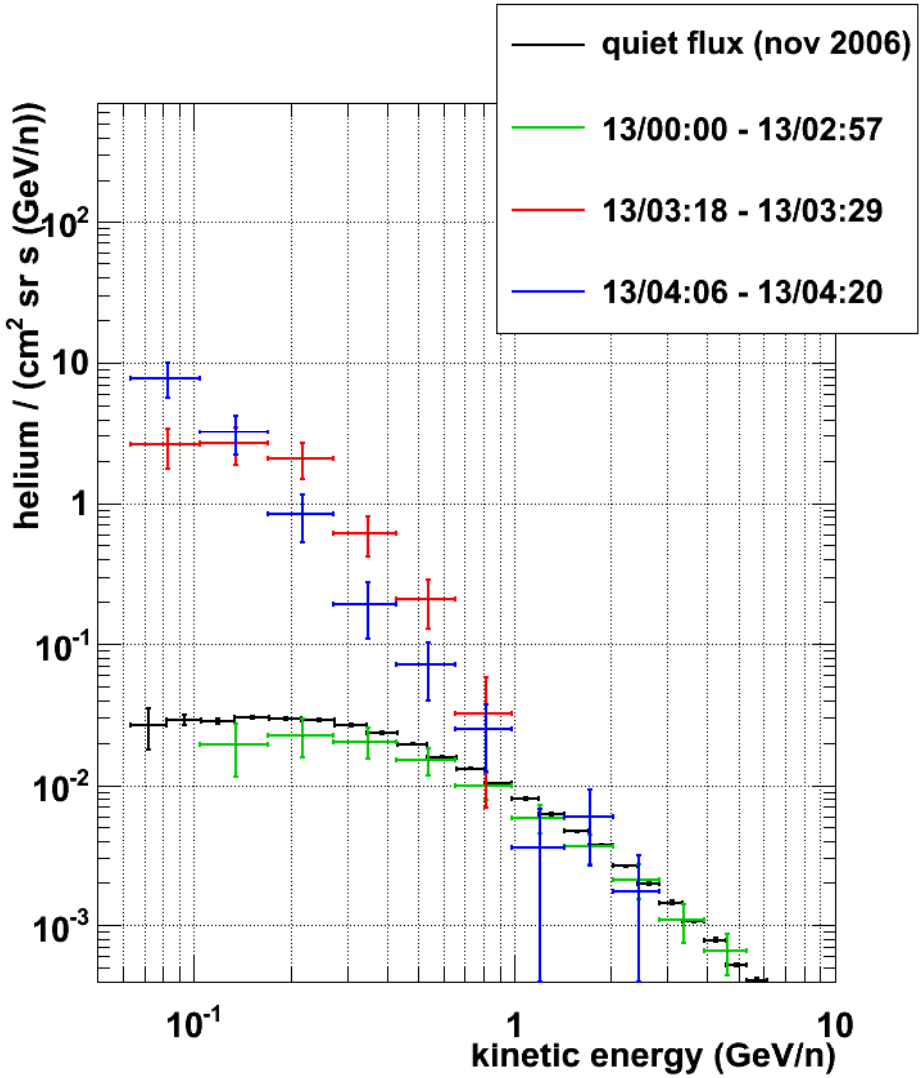


December 13

Proton flux

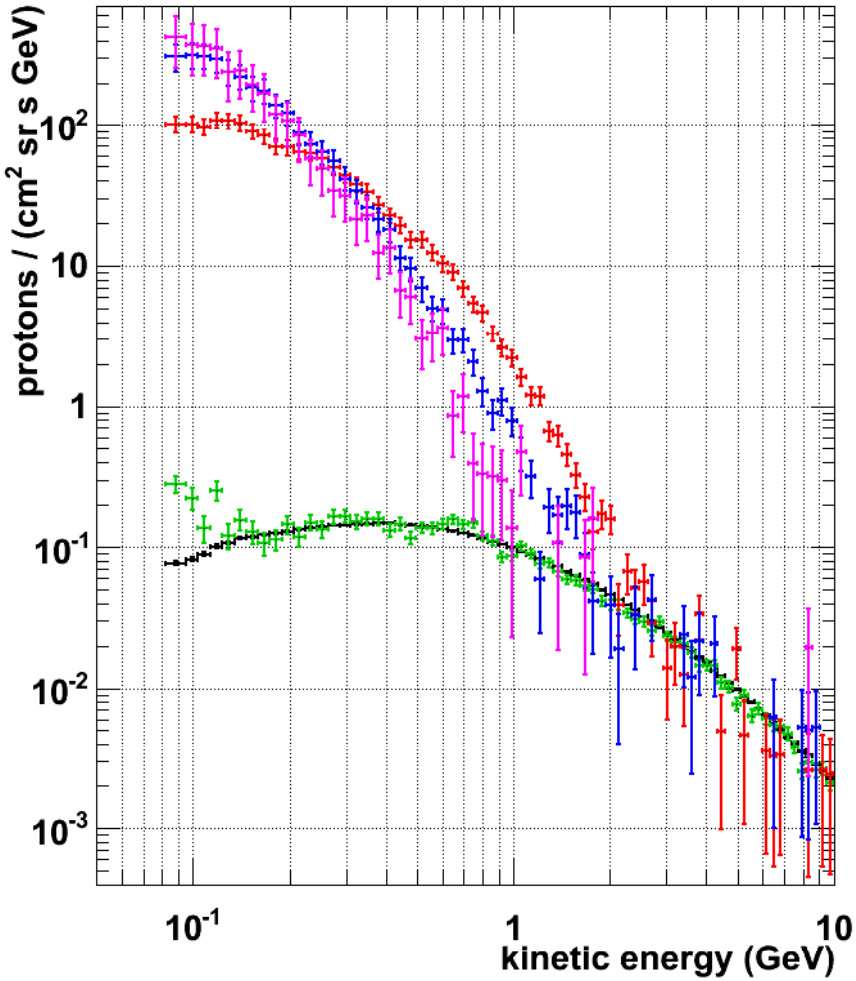


Helium flux



December 13

Proton flux



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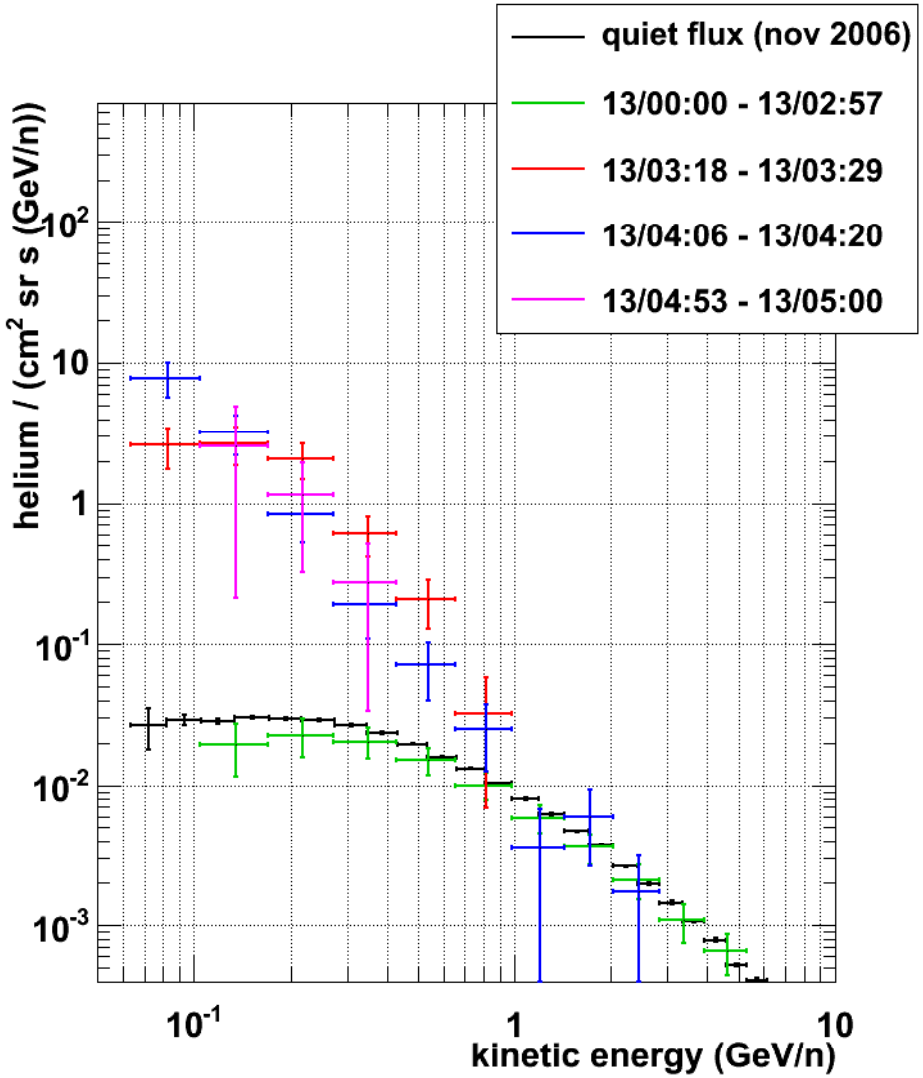
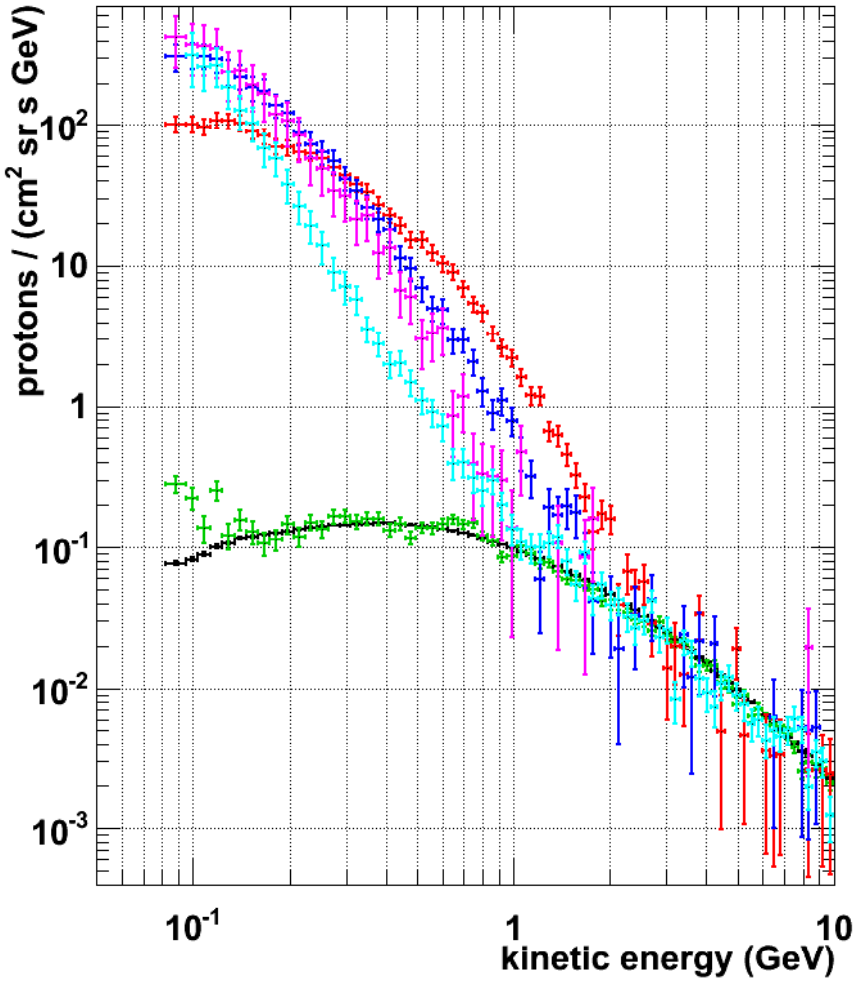
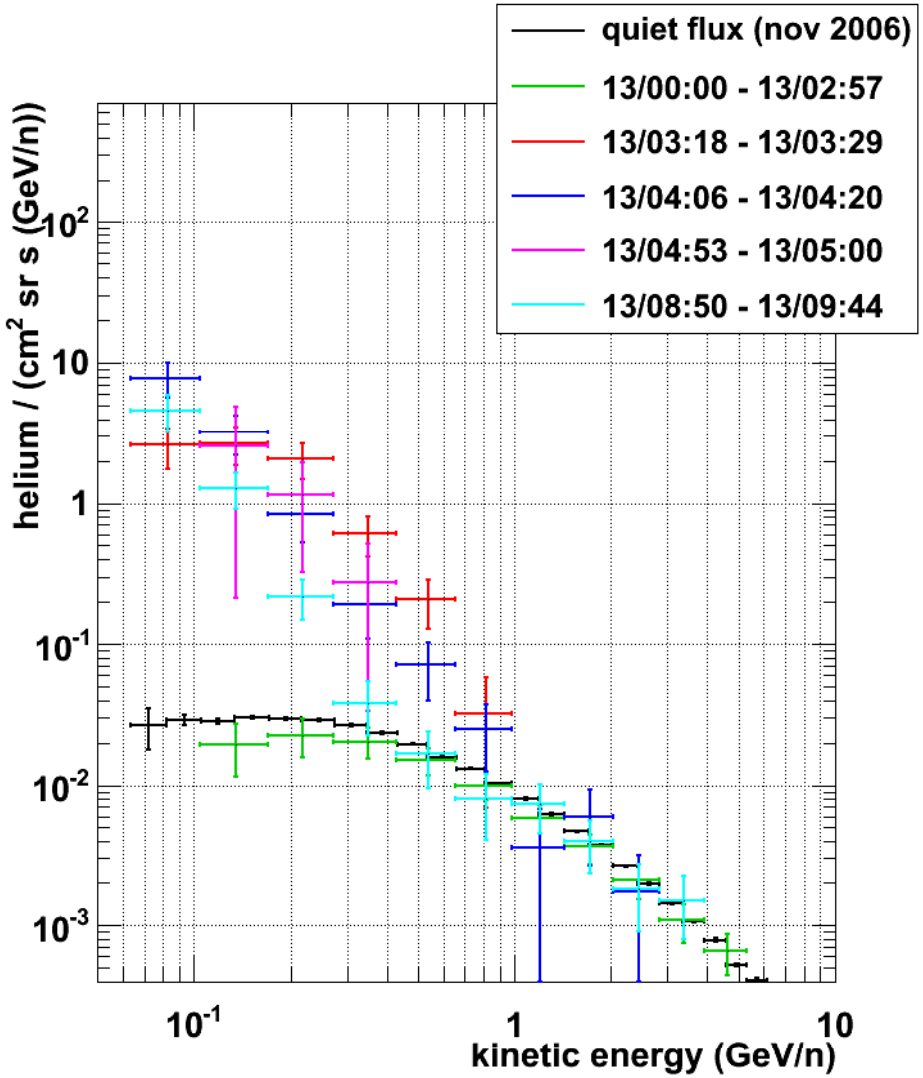


December 13

Proton flux

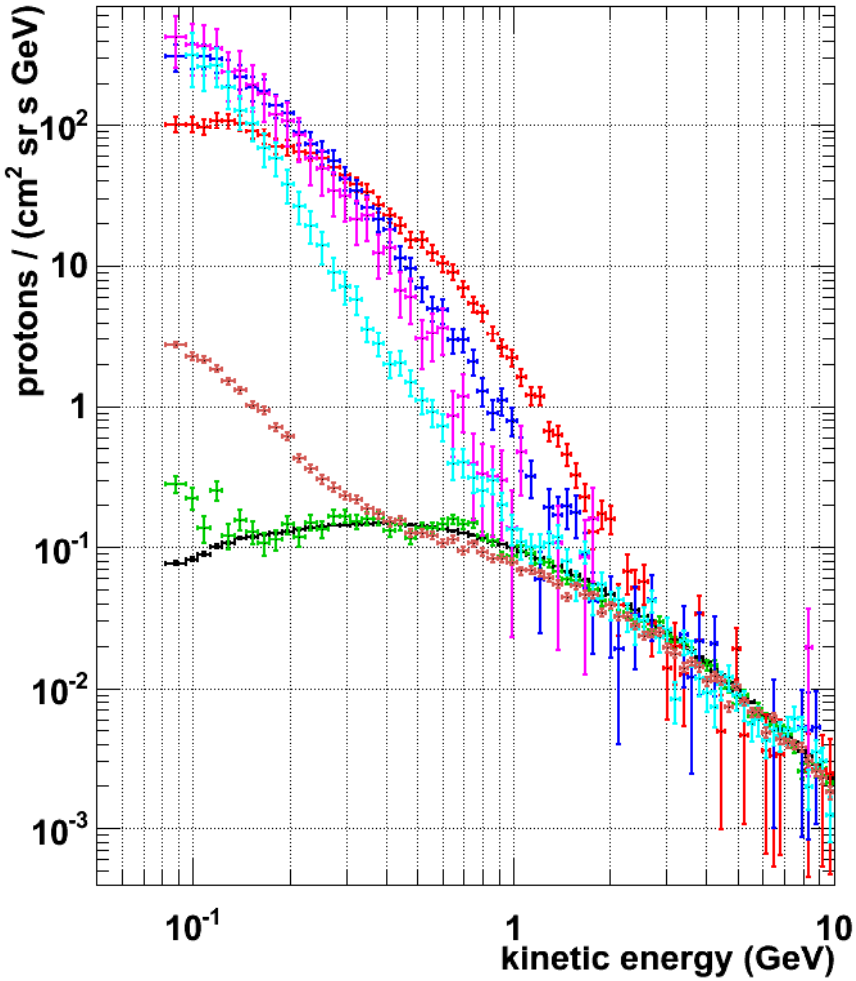


Helium flux



December 13

Proton flux



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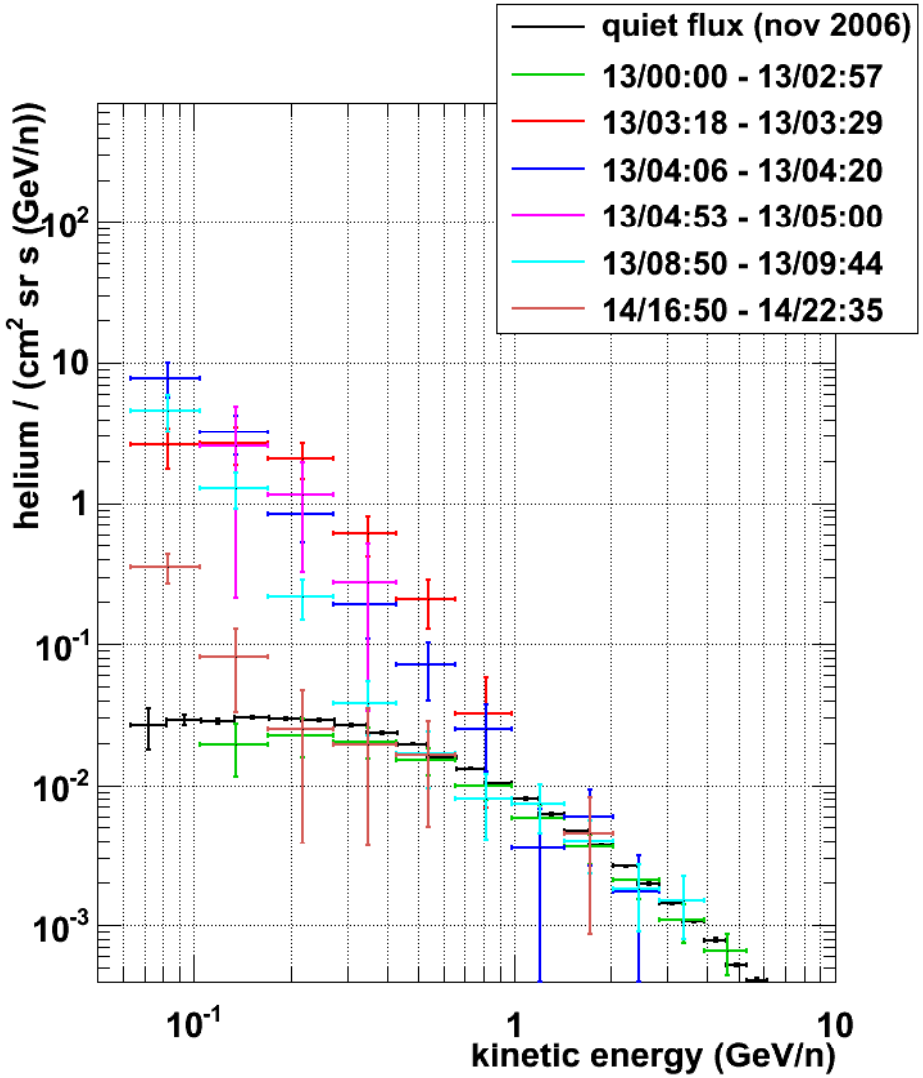
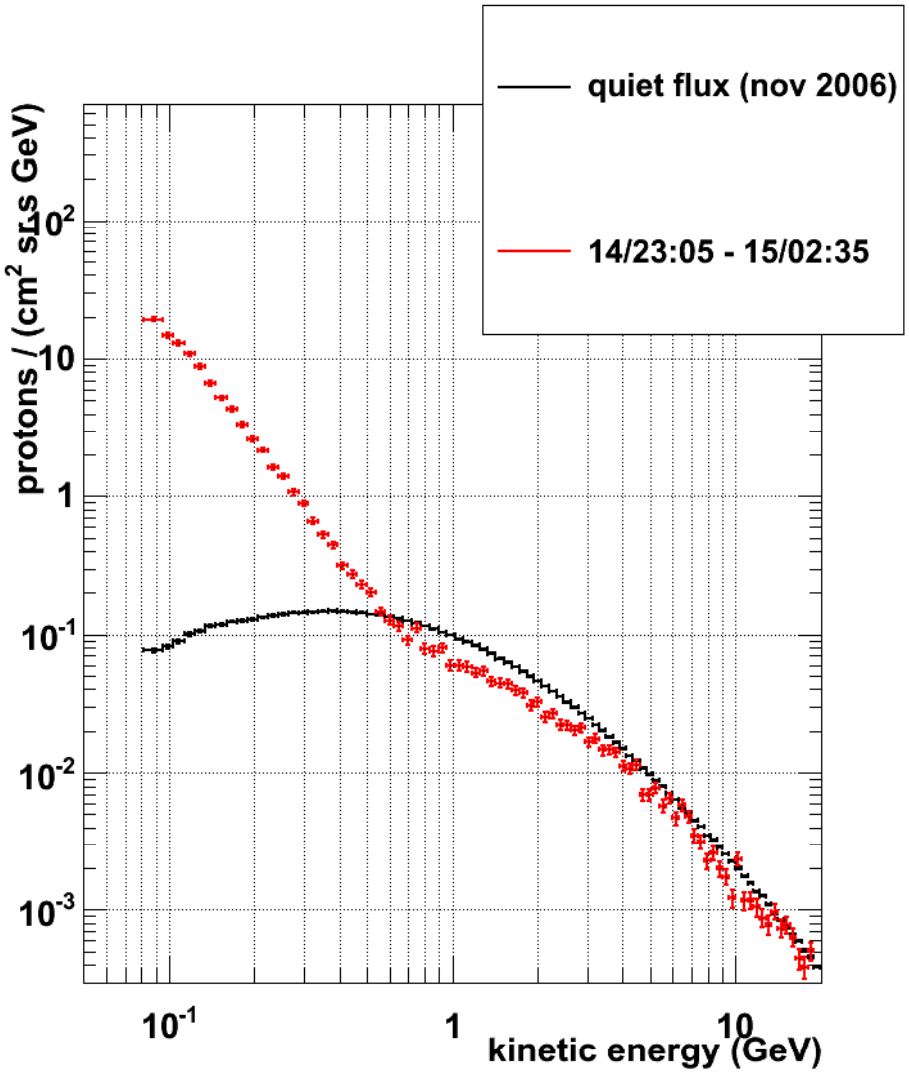
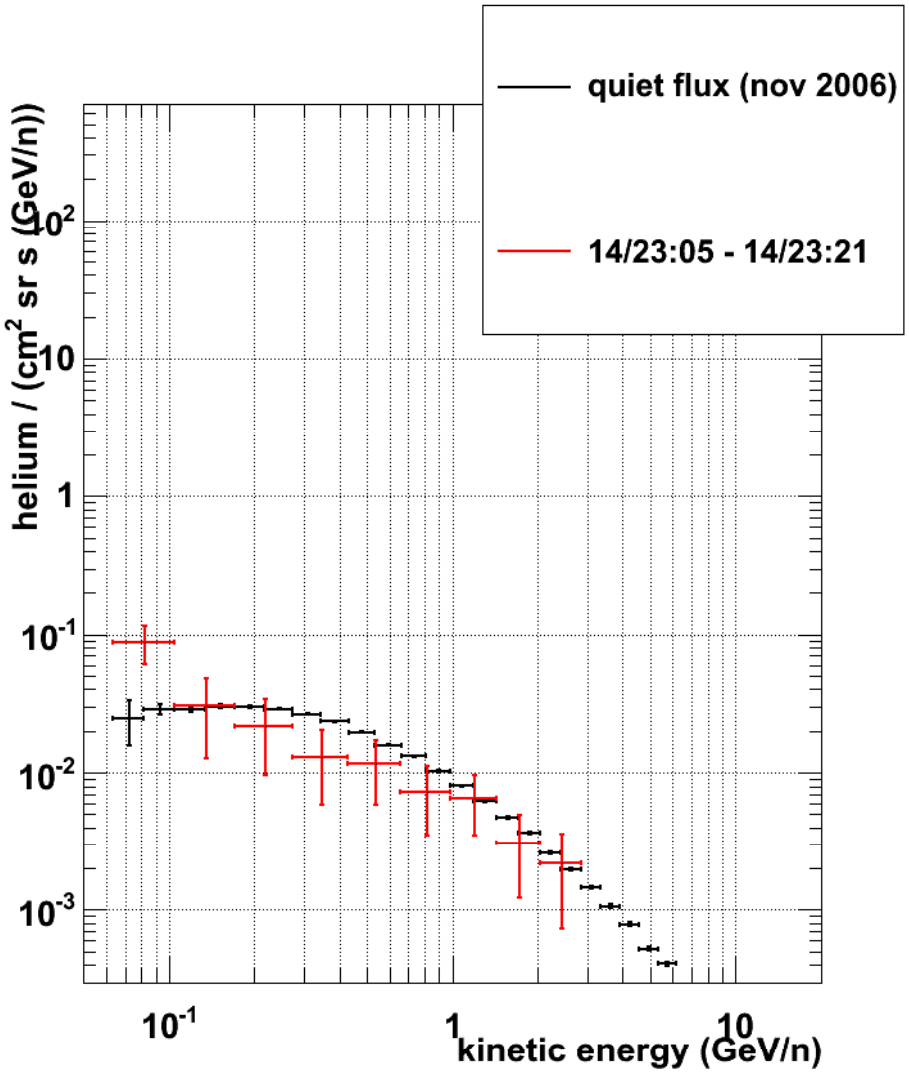


December 14

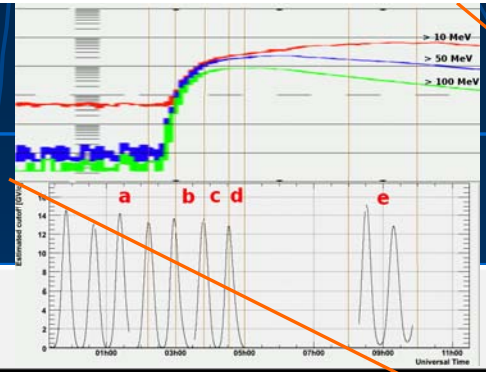
Proton flux

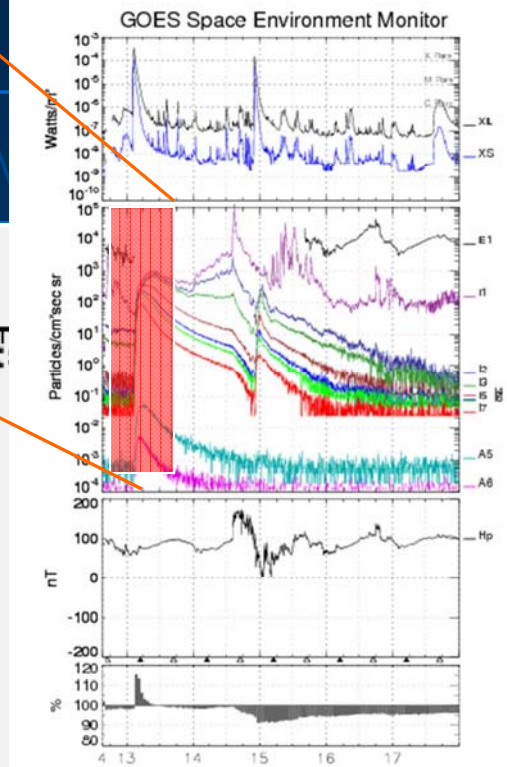


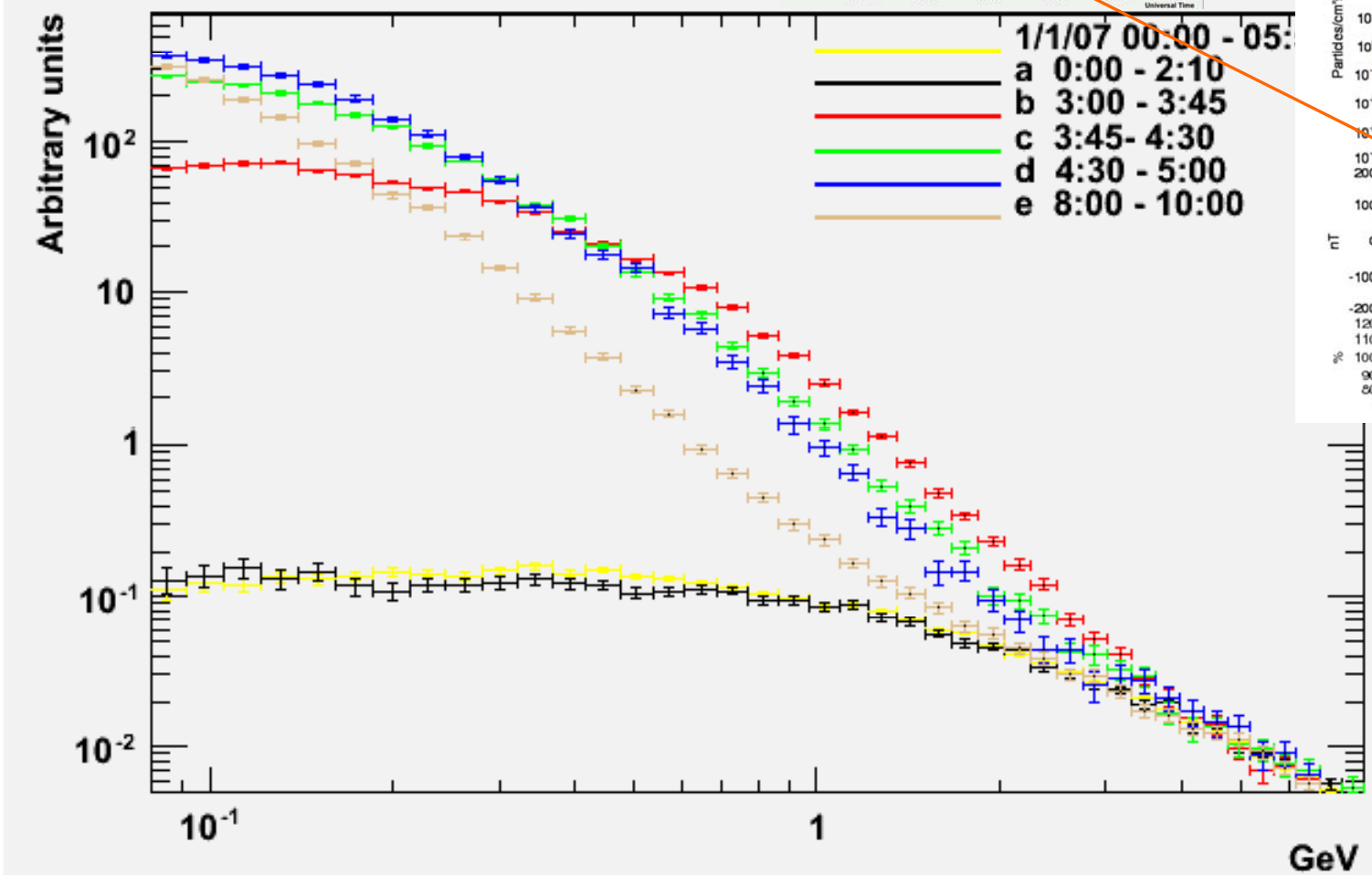
Helium flux



December 13th 2006 event

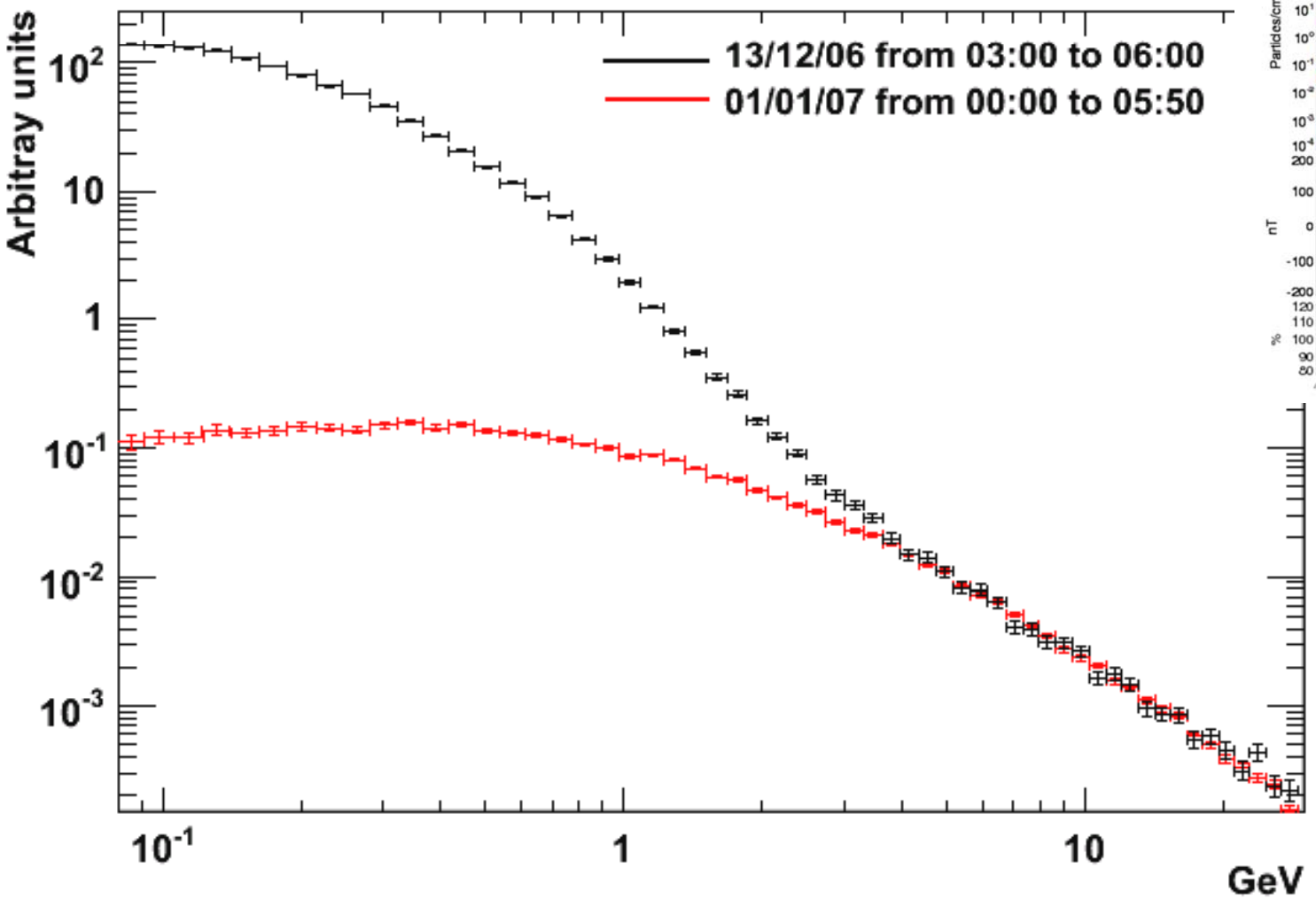


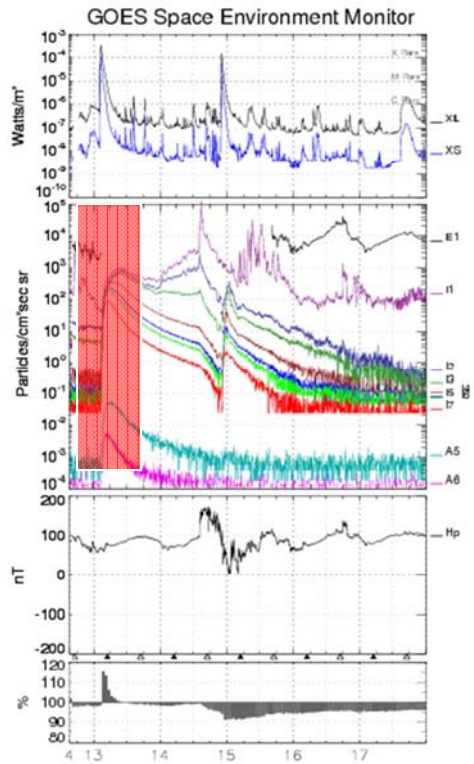




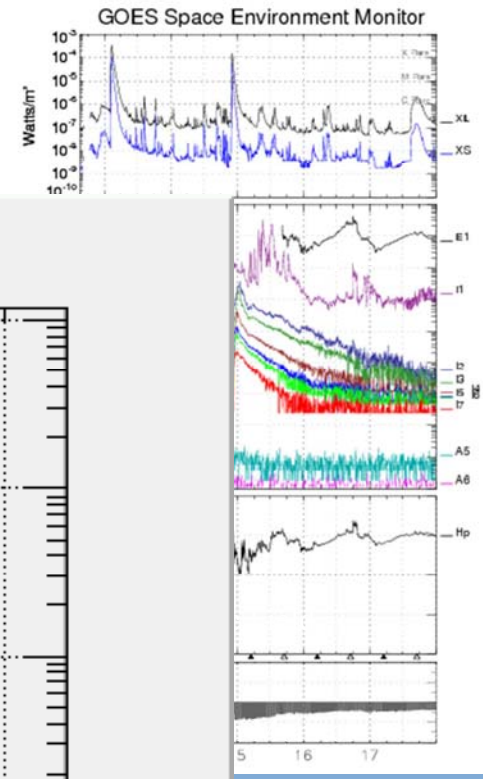
Preliminary!

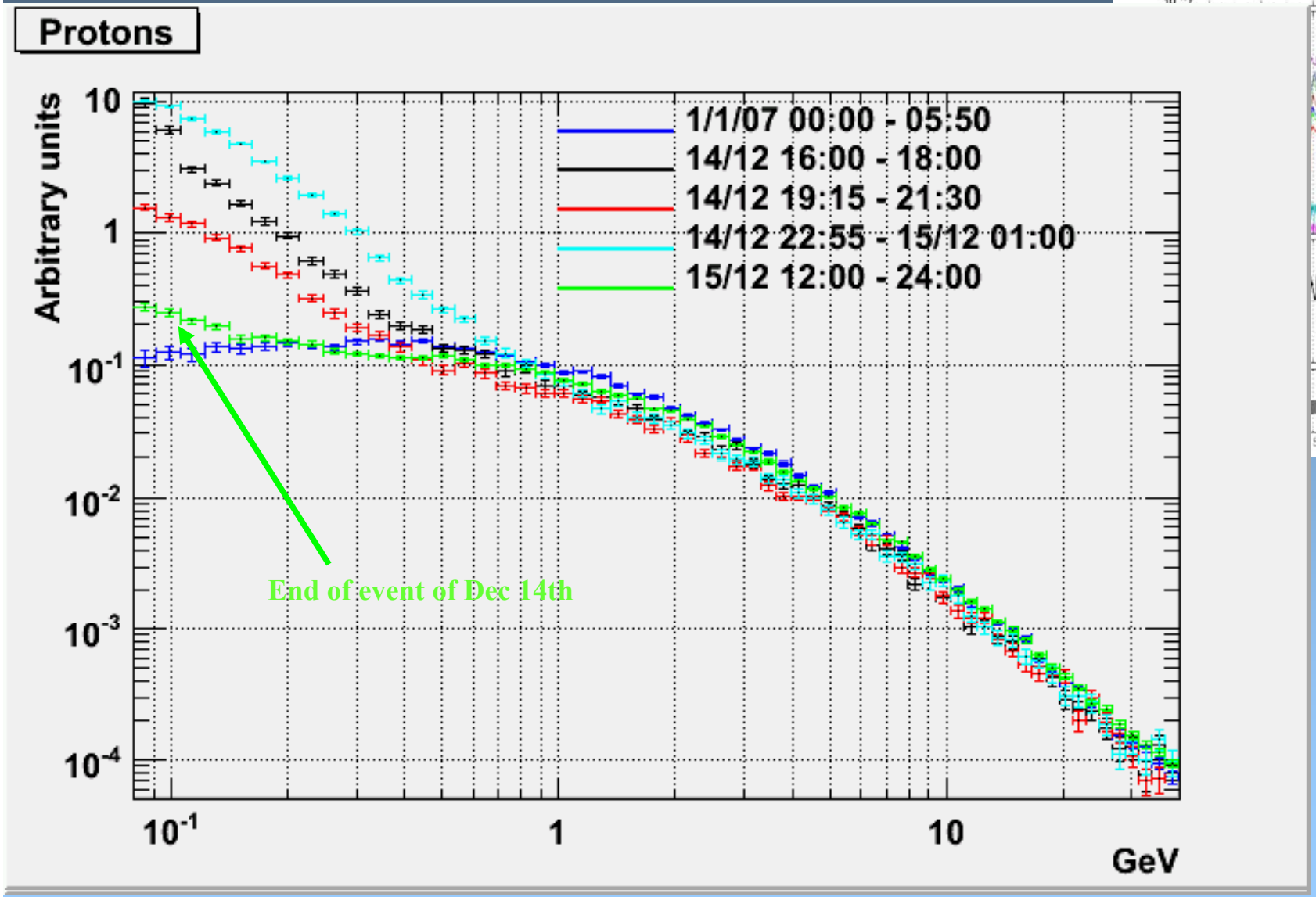
December 13th 2006 He differential spectrum





December 14th 2006 event





Preliminary!

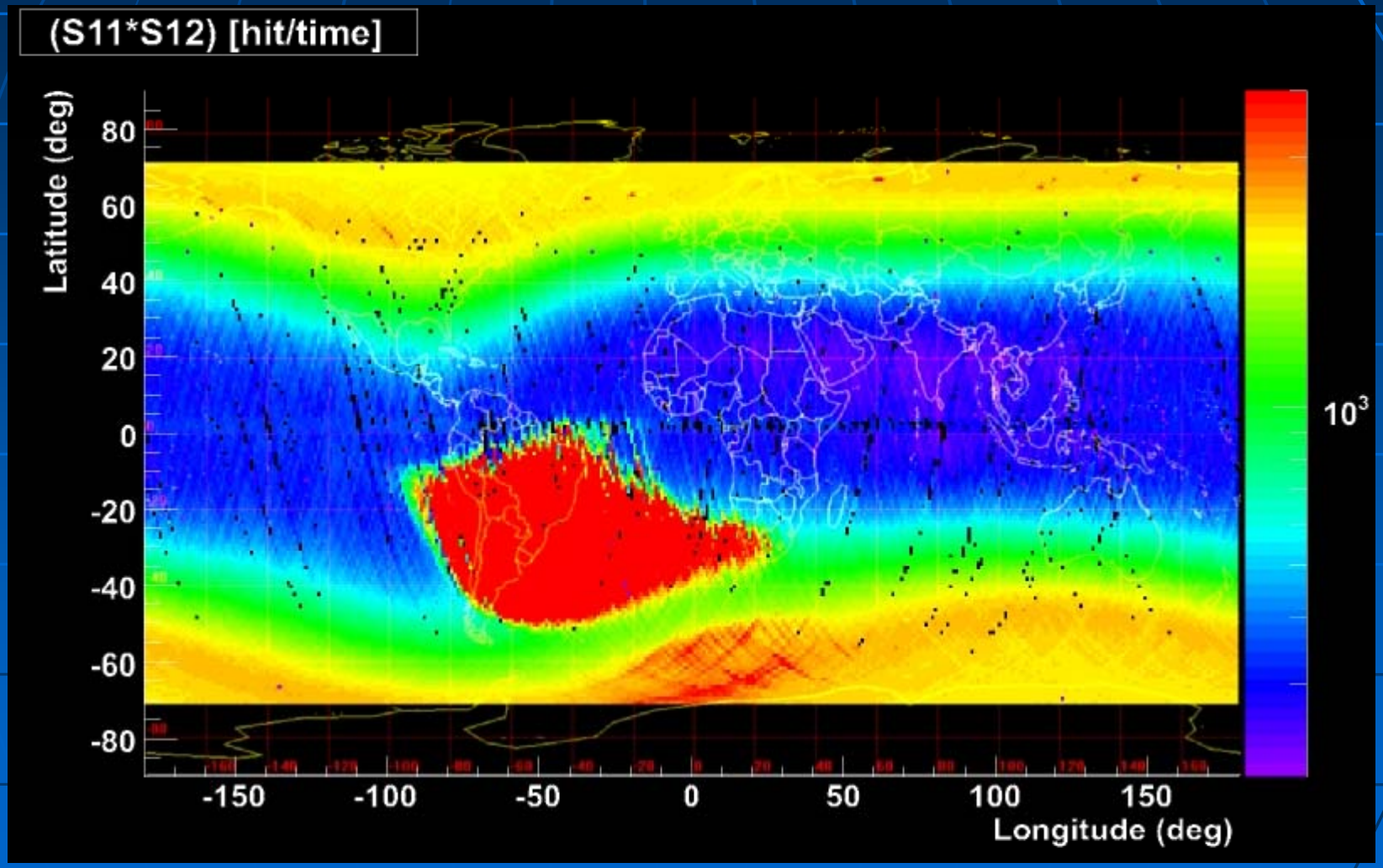
Radiation Belts

South Atlantic Anomaly

Secondary production from CR interaction with atmosphere

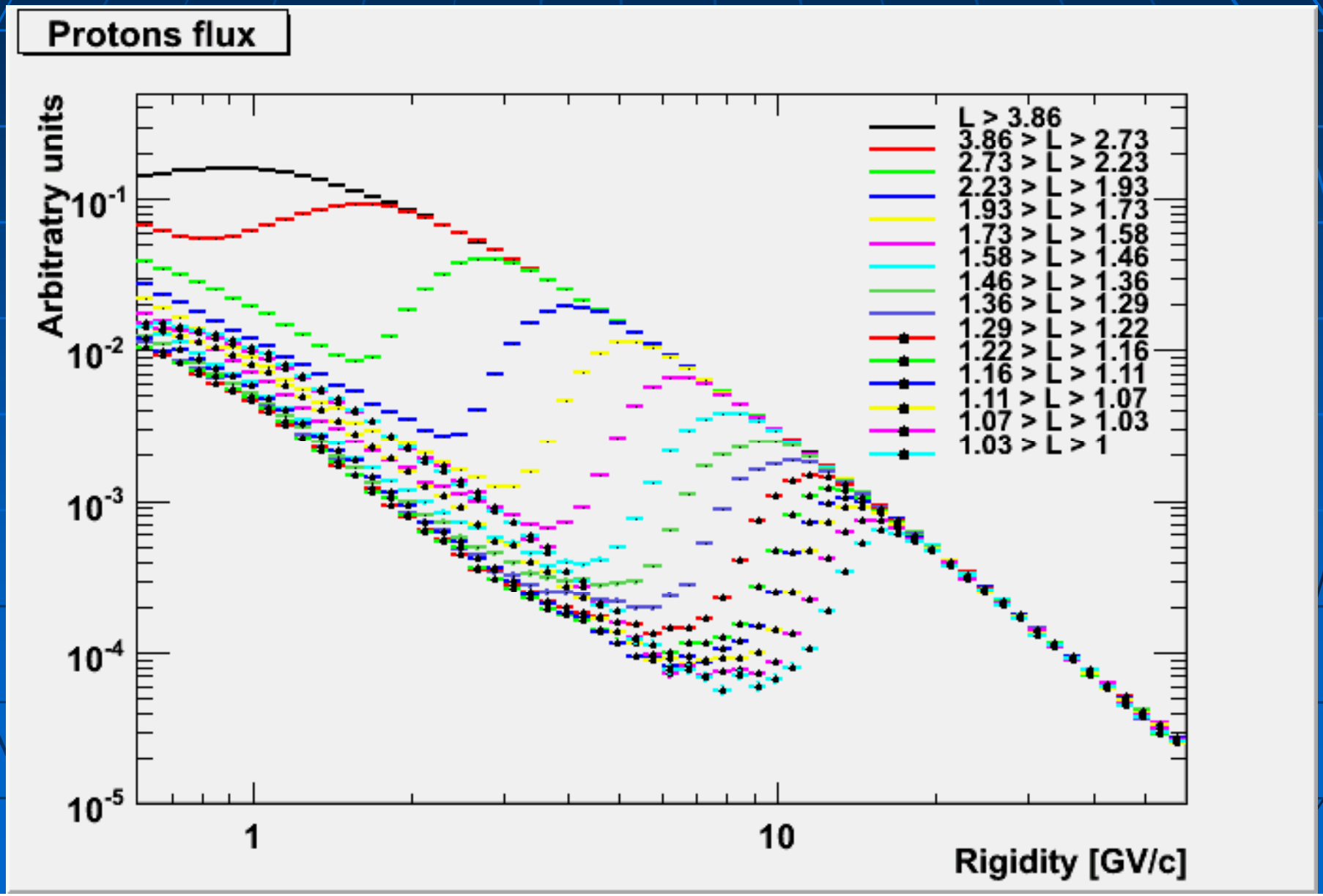
Study terrestrial magnetosphere

Pamela World Maps: 350 – 650 km alt

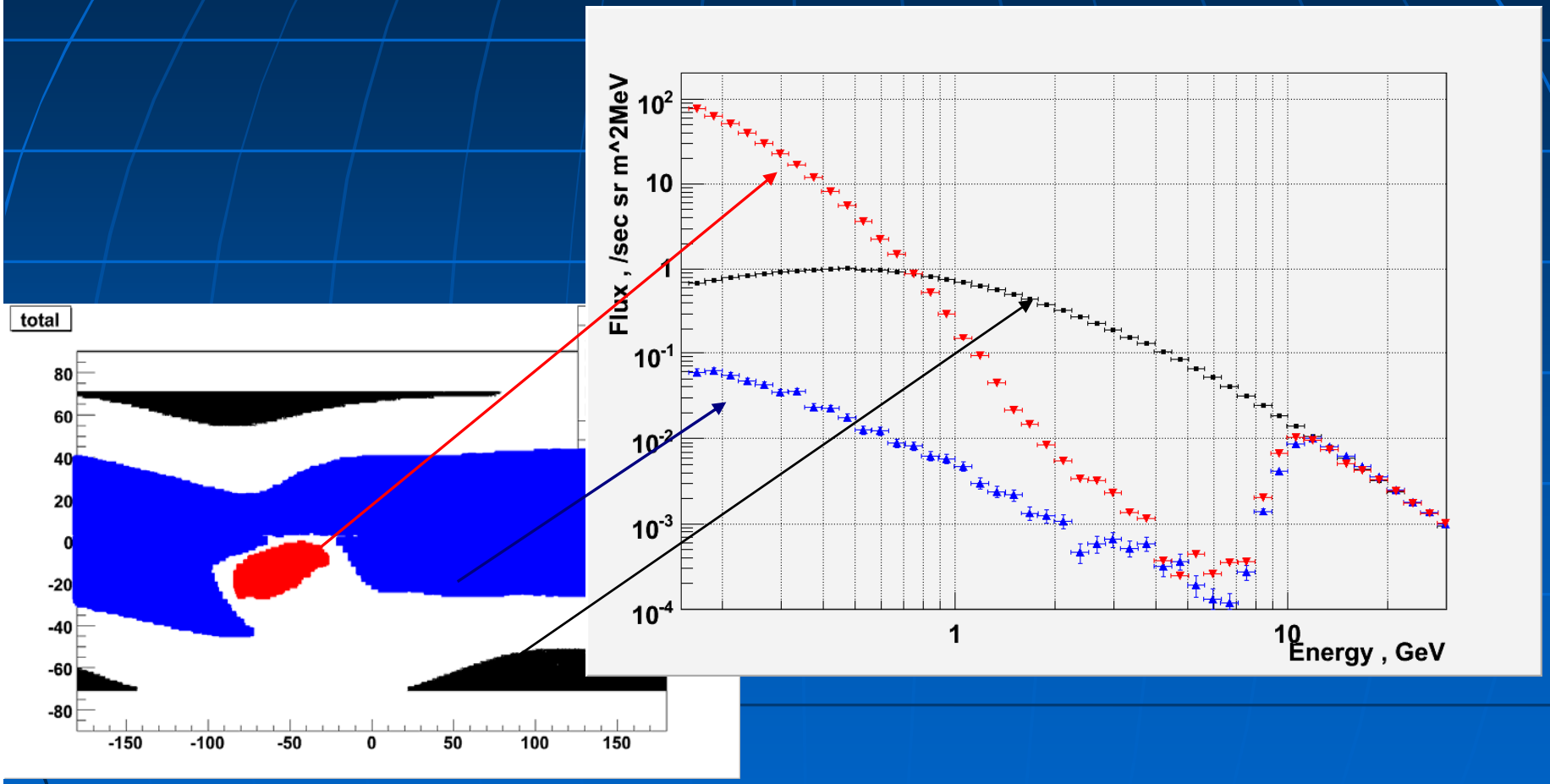


36 MeV p, 3.5 MeV e-

Subcutoff particles



n spectrum in SAA, polar and equatorial regions



Thanks!

http://pamela.roma2.infn.it

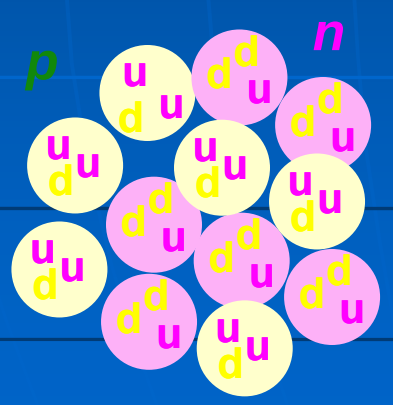
Other Objectives

Search for New Matter in the Universe:

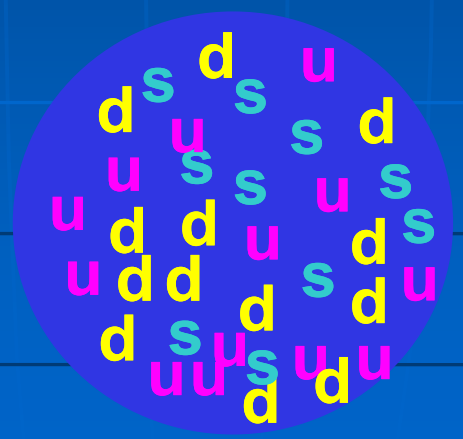
An example is the search for "strangelets".

There are six types of Quarks found in accelerators.
All matter on Earth is made out of only two types of quarks. "Strangelets" are new types of matter composed of three types of quarks which should exist in the cosmos.

Carbon Nucleus



Strangelet



i. **A stable, single "super nucleon" with three types of quarks**

ii. **"Neutron" stars may be one big strangelet**

AMS courtesy