

Title: Searching for Dark Matter with Cosmic Antiparticles: the PAMELA Experiment

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Abstract: New results on the antiproton-to-proton and positron-to-all electron ratios over a wide energy range (1 – 100 GeV) have been obtained by the PAMELA mission. These data are mainly interpreted in terms of dark matter annihilation or pulsar contribution. The instrument PAMELA, in orbit since June 15th, 2006 on board the Russian satellite Resurs DK1, is daily delivering to ground 16 Gigabytes of data. The apparatus is designed to study charged particles in the cosmic radiation, with a particular focus on antiparticles for searching antimatter and signals of dark matter annihilation. A combination of a magnetic spectrometer and different detectors allows antiparticles to be reliably identified from a large background of other charged particles. This talk reviews the design of the apparatus and illustrates the most recent scientific results obtained by PAMELA, together to some of the recent theoretical interpretations. In particular new data on antiprotons, protons, positrons, electrons absolute fluxes will be presented.

Searching for Dark Matter with Cosmic Antiparticles: the PAMELA Experiment



Piergiorgio Picozza
INFN and University of Rome Tor Vergata

New Lights on Dark Matter

Perimeter Institute
June 11 -13, 2009

PAMELA

Payload for Antimatter Matter Exploration
and Light Nuclei Astrophysics



PAMELA Collaboration

Italy:



Bari



Florence



Frascati



Naples



Rome



Trieste



CNR, Florence

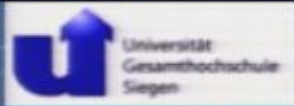


Russia:



Moscow
St. Petersburg

Germany:



Siegen

Sweden:



KTH

PAMELA Launch 15 June 2006

Bajkonur Cosmodrome
(Kazakhstan)



Pirsa: 09060032



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The Physics of PAMELA

Search for antihelium (primordial antimatter)

Search for dark matter annihilation

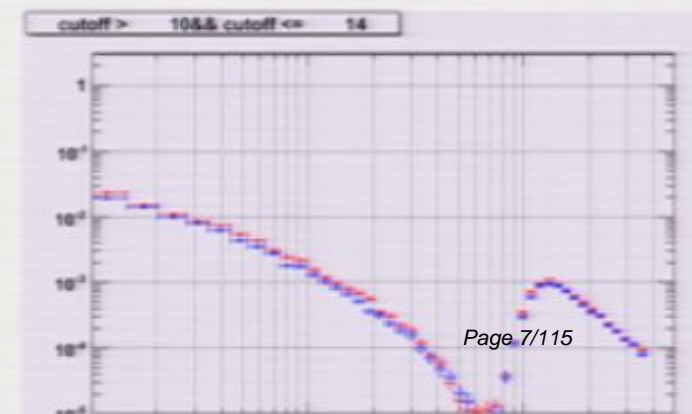
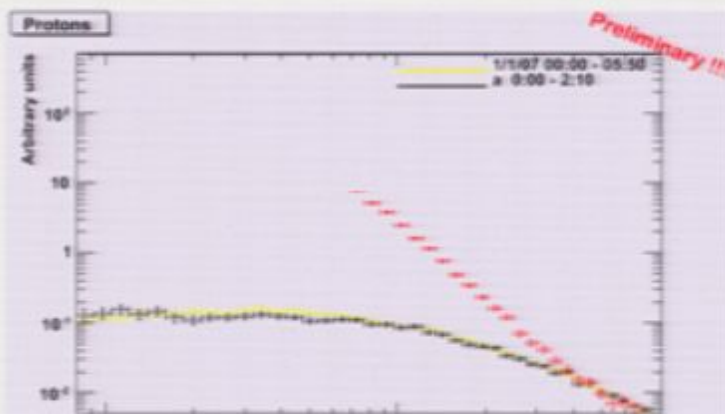
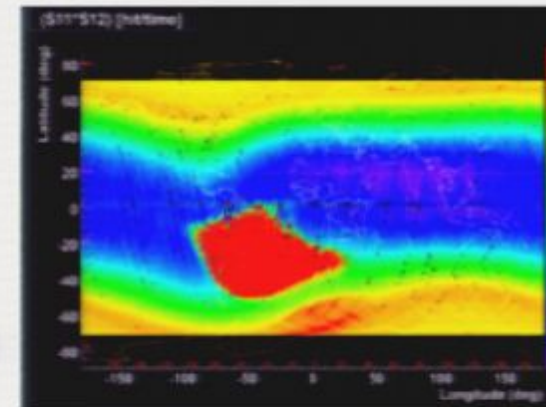
Search for new Matter in the Universe (Strangelets?)

Study of cosmic-ray propagation

Study of solar physics and solar modulation

Study of terrestrial magnetosphere

Study of high energy electron spectrum (local sources?)



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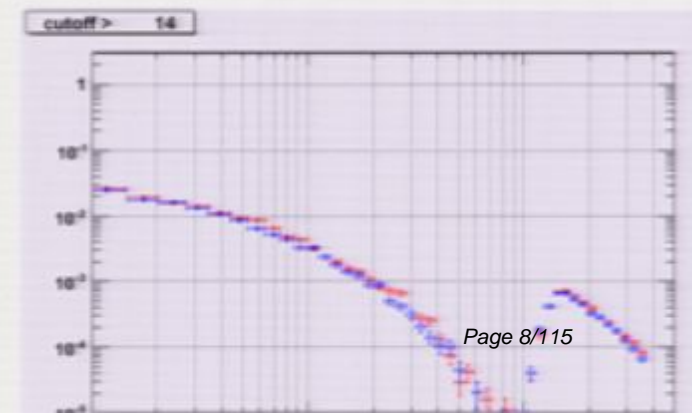
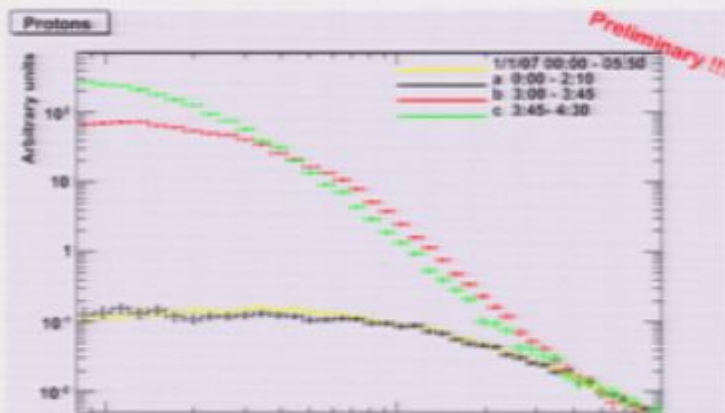
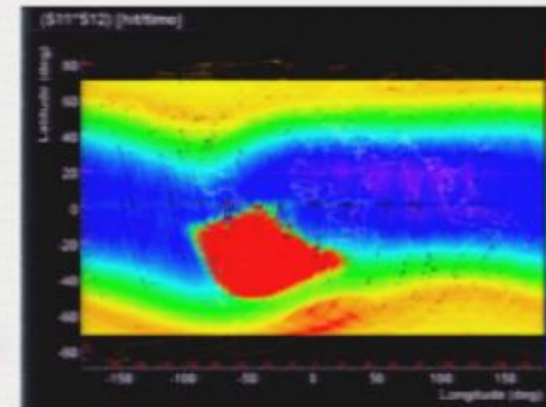
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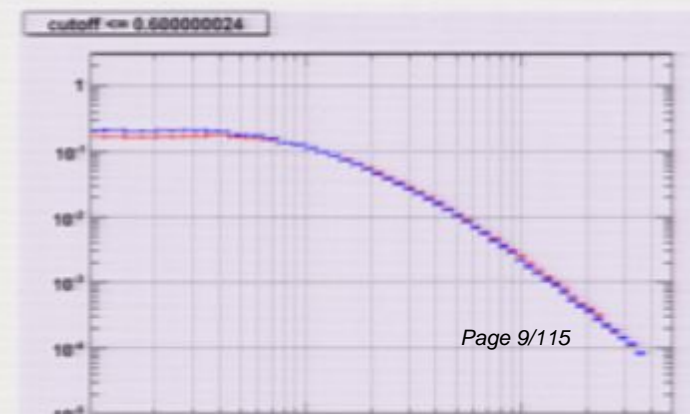
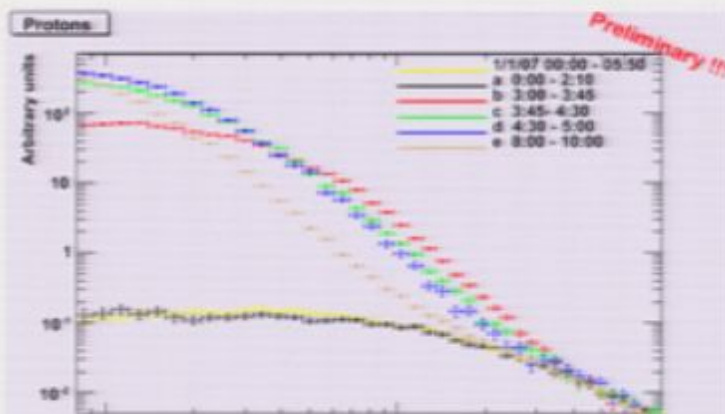
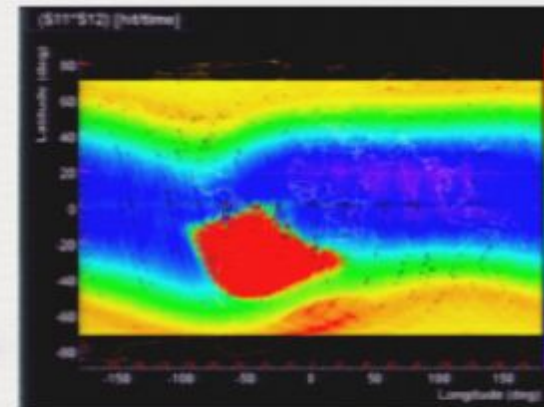
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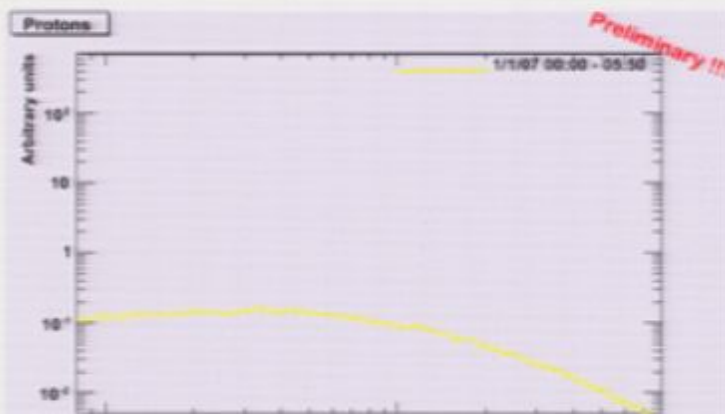
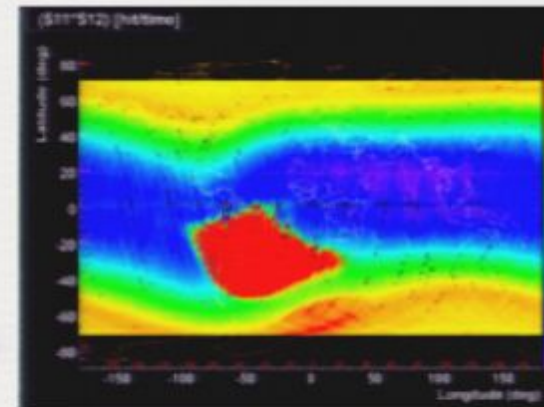
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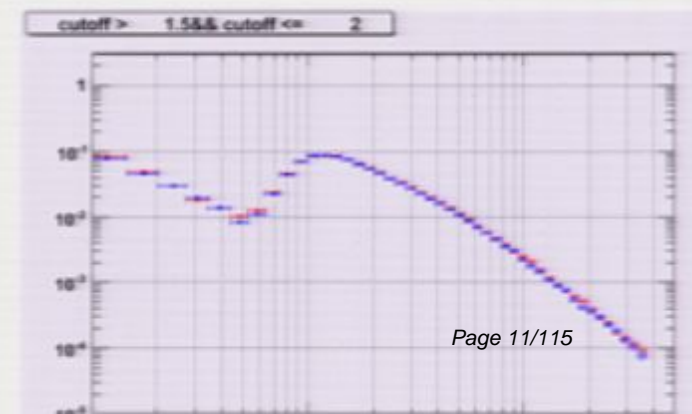
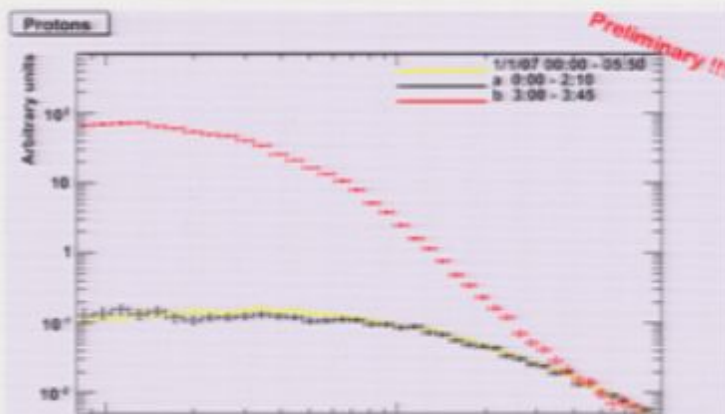
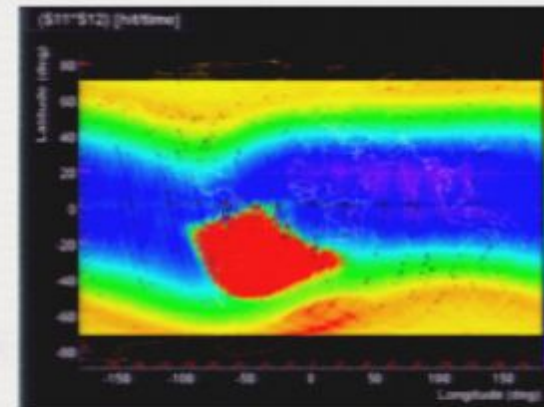
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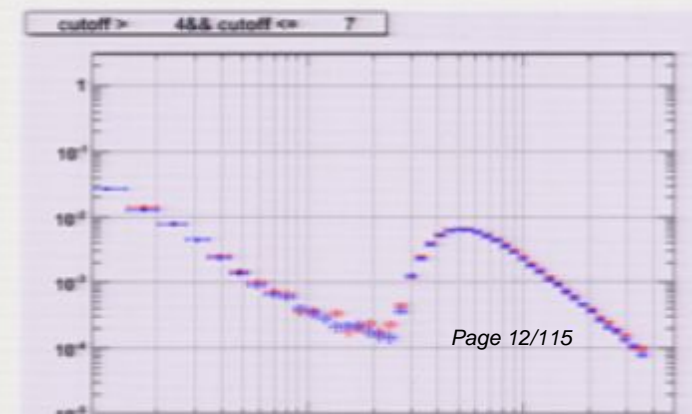
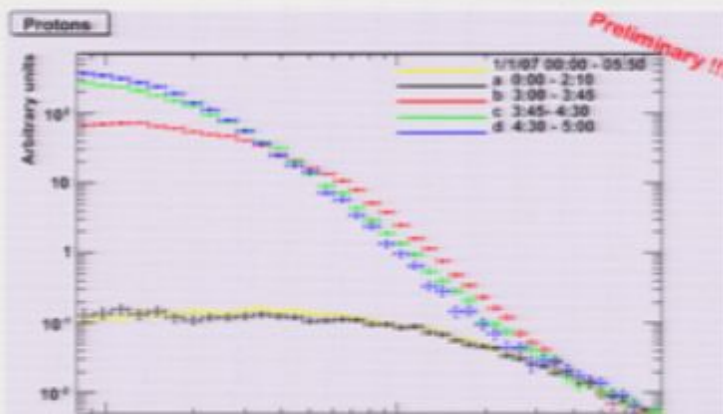
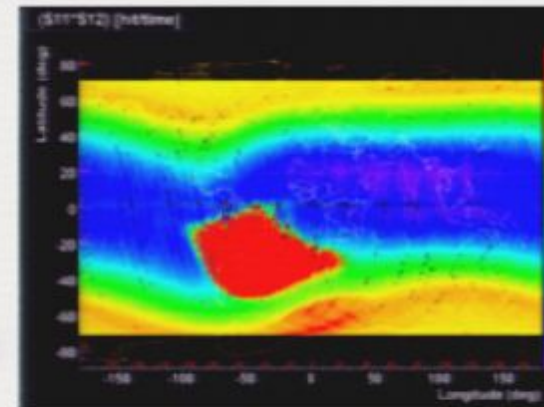
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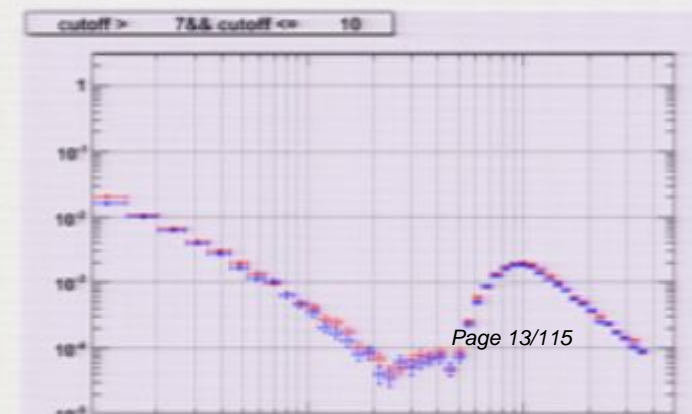
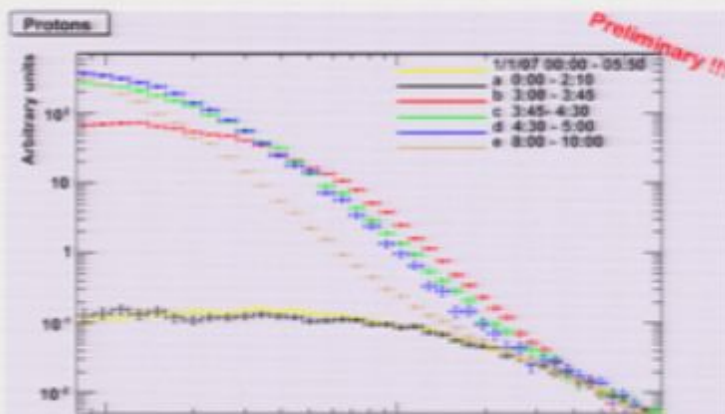
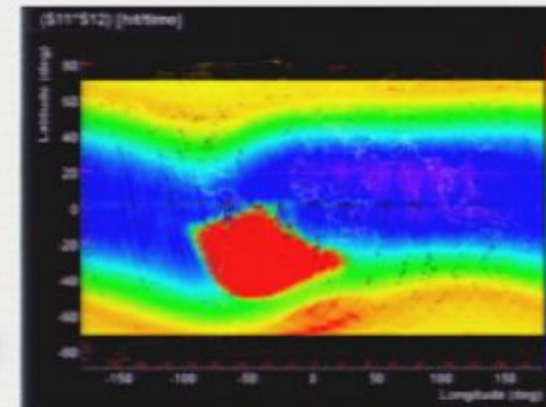
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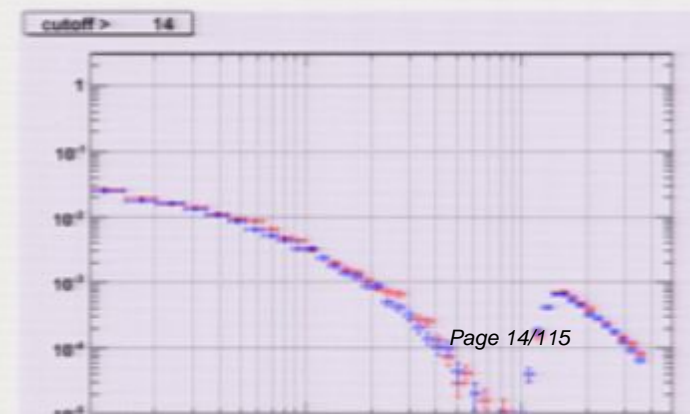
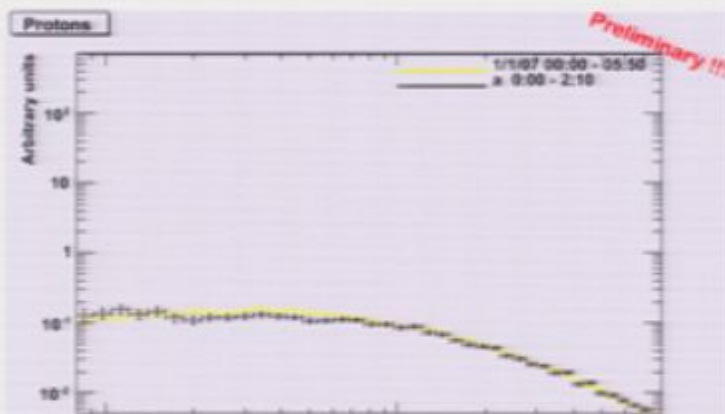
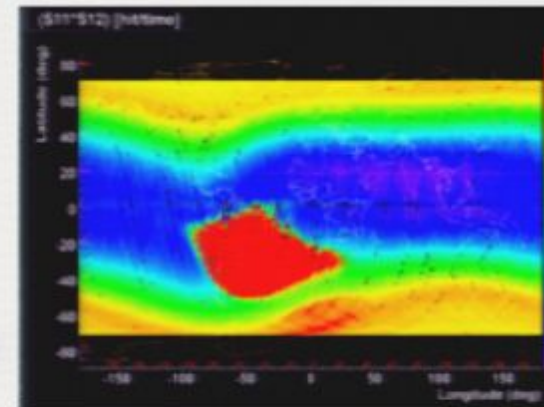
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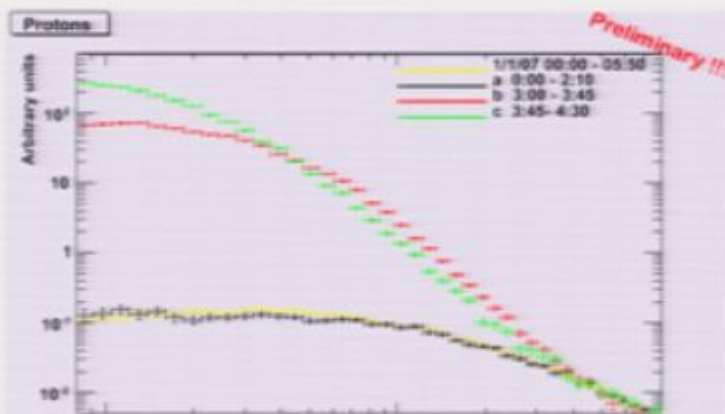
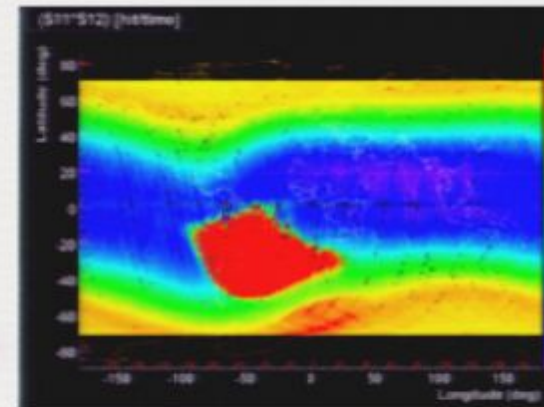
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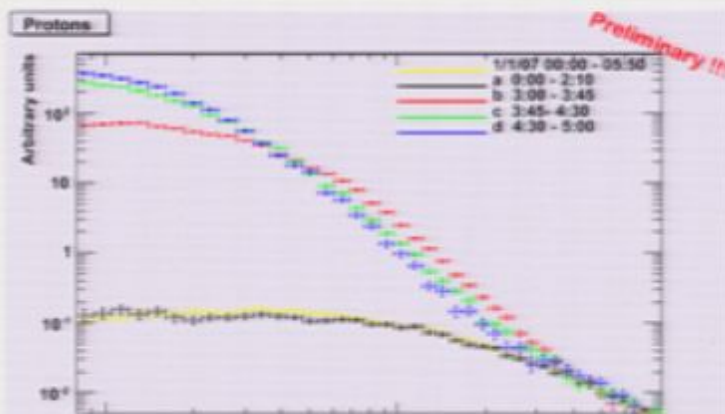
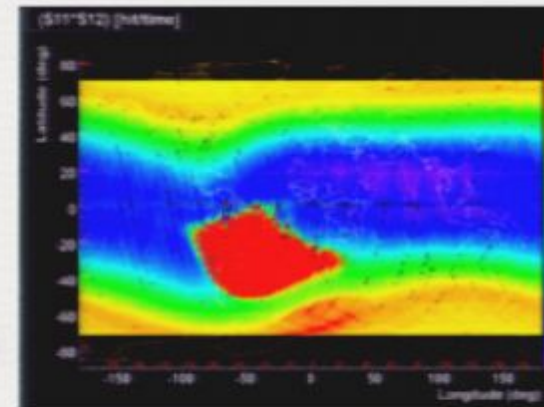
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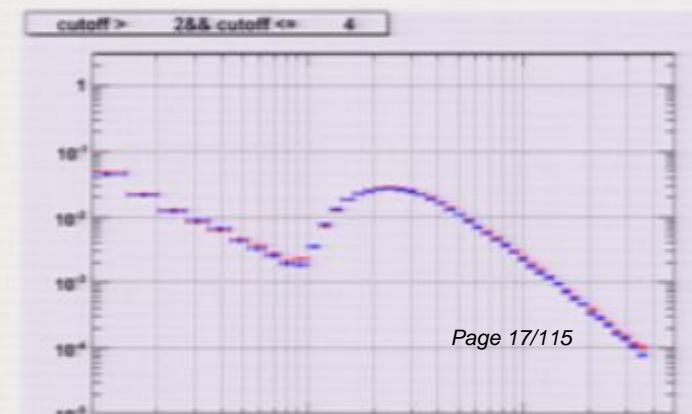
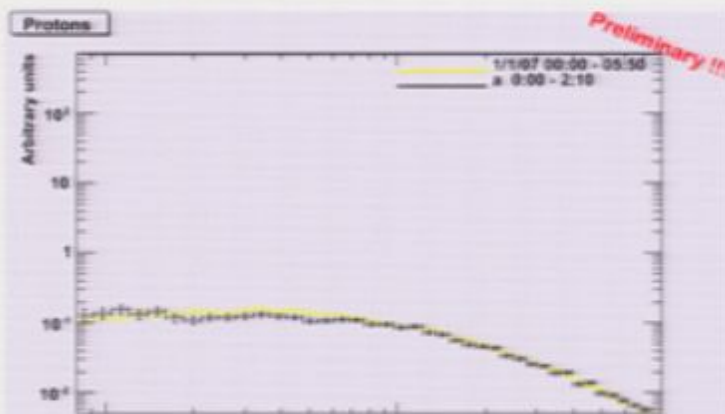
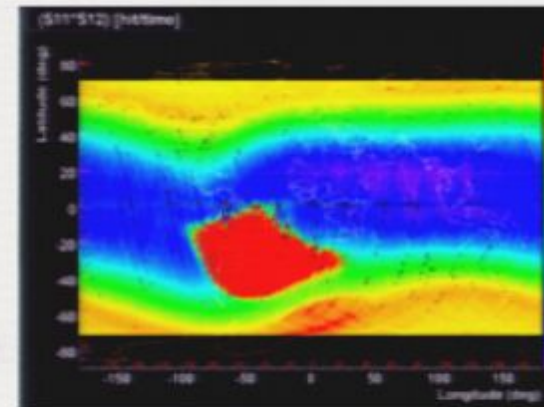
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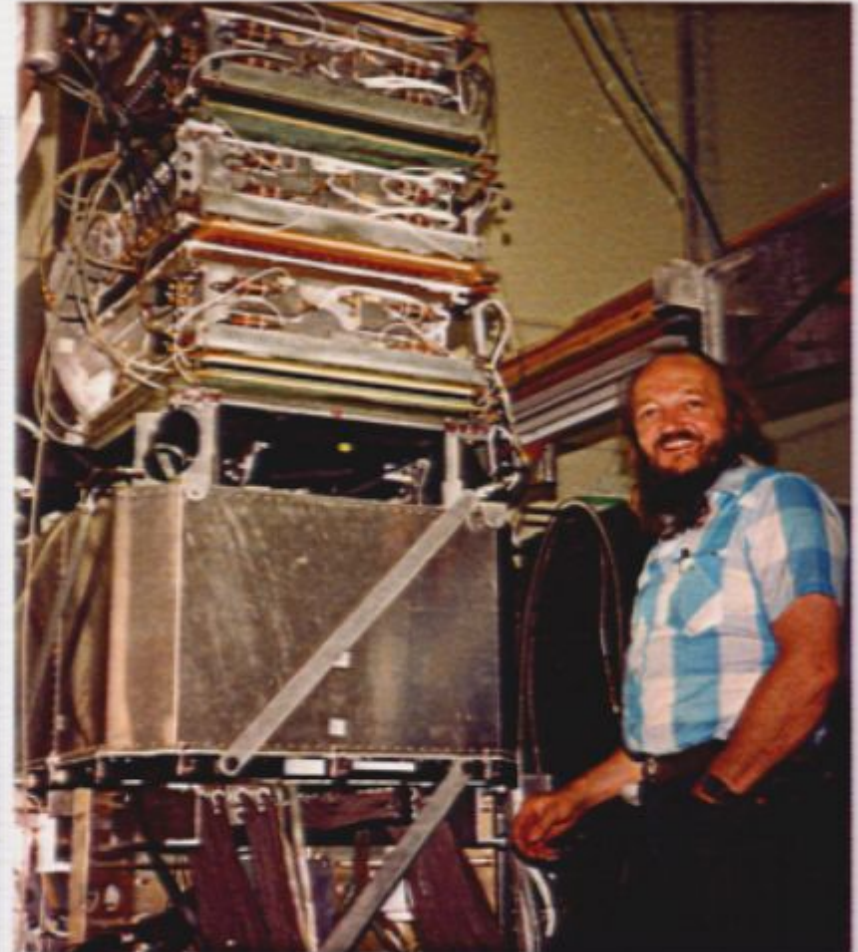
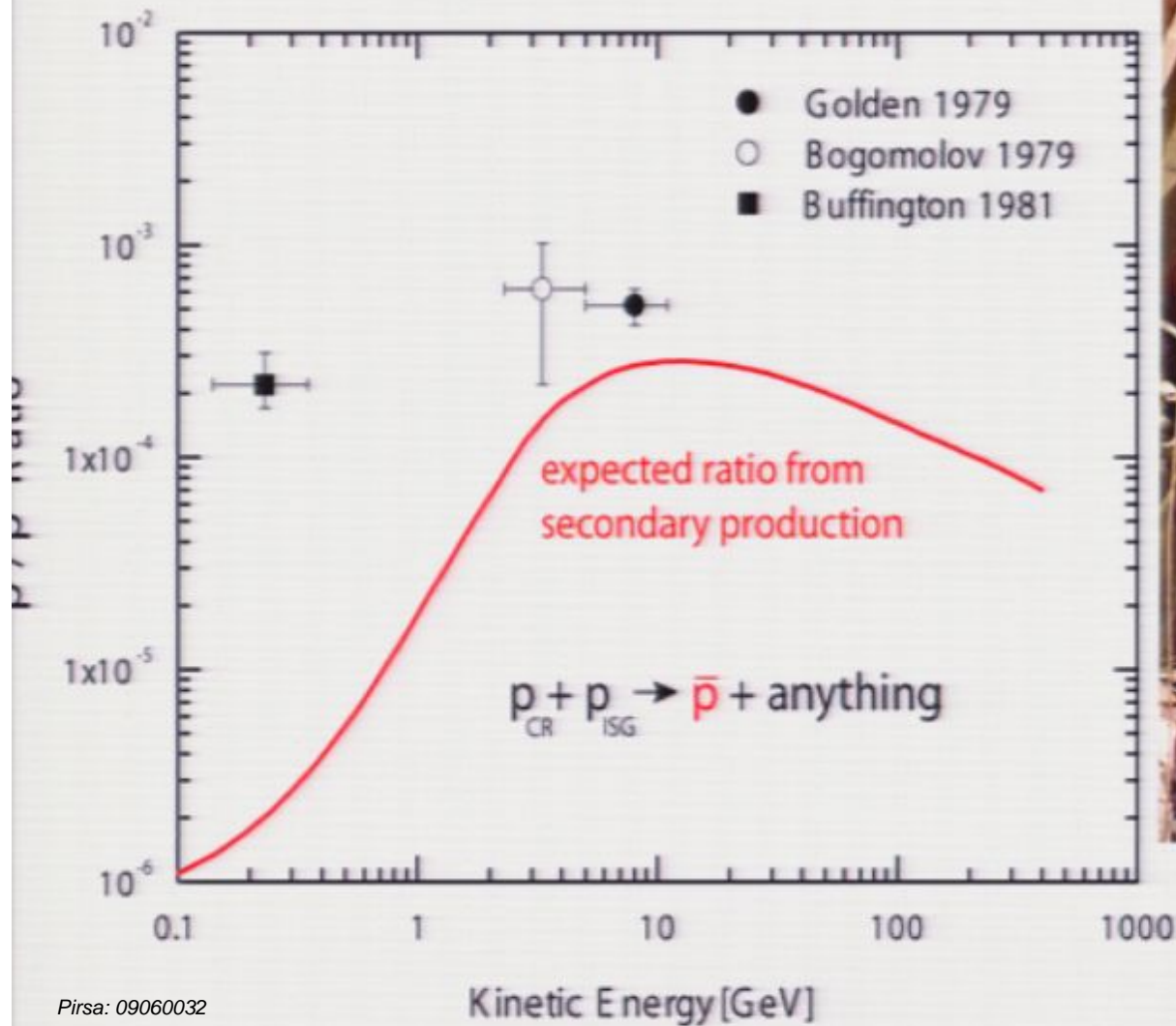
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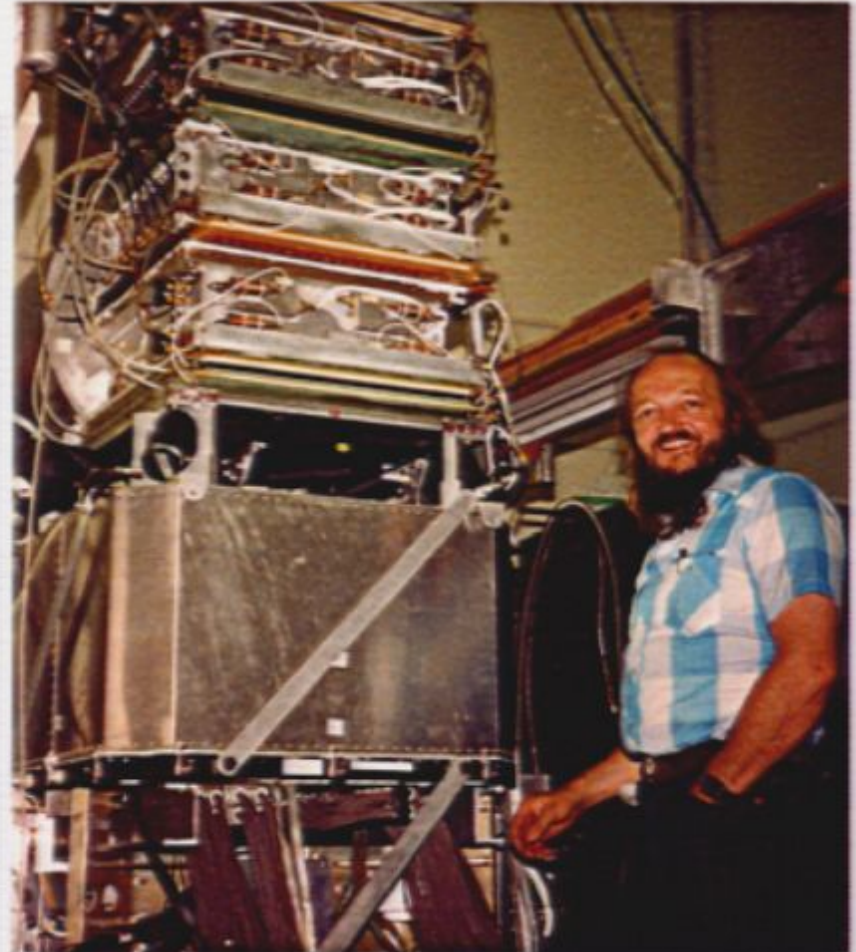
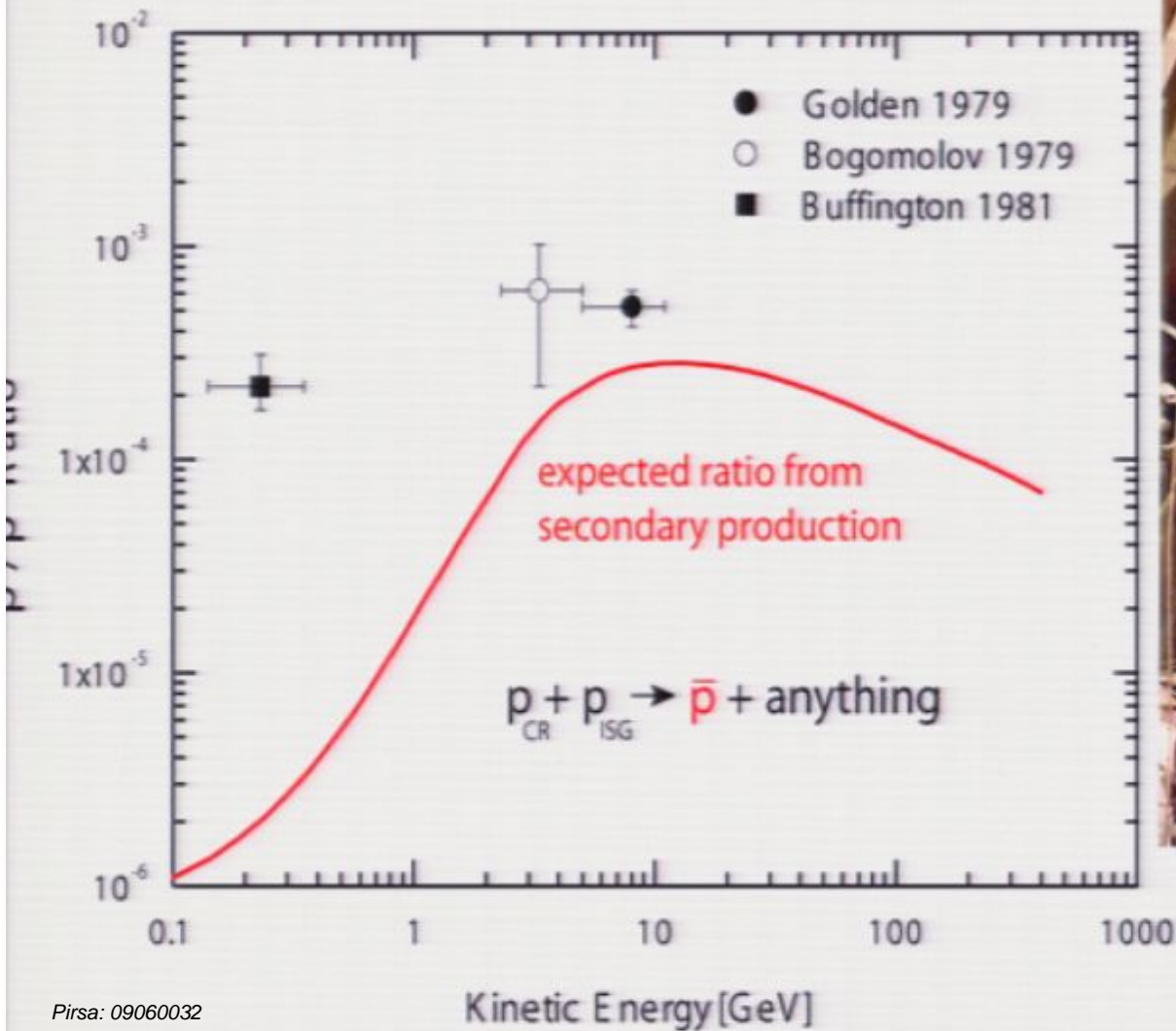


The first historical measurements on galactic antiprotons



Robert L. Golden

The first historical measurements on galactic antiprotons



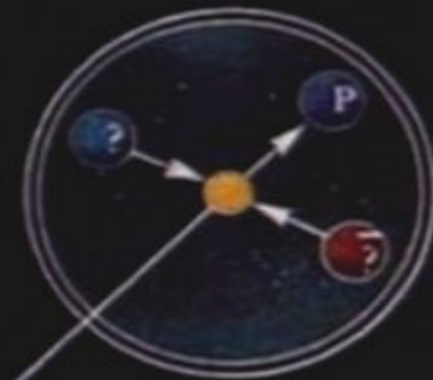
Robert L. Golden

ANTIMATTER

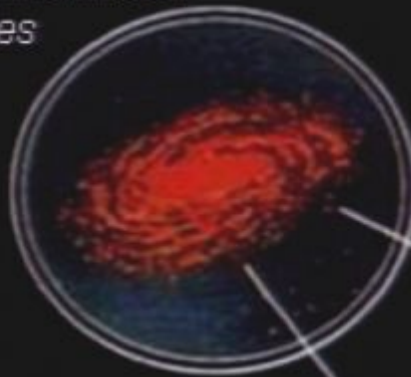
Collision of High Energy Cosmic Rays with the Interstellar Gas



Annihilation of Exotic Particles



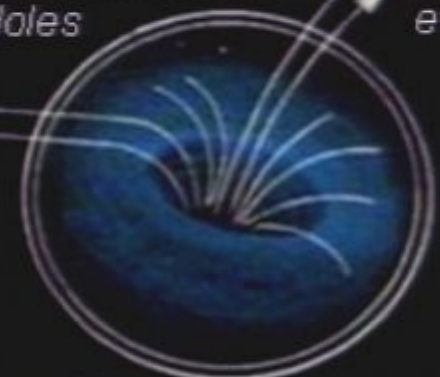
Cosmic Rays Leaking Out of Antimatter Galaxies



Antimatter Lumps In the Milky Way



Evaporation of Primordial Black Holes



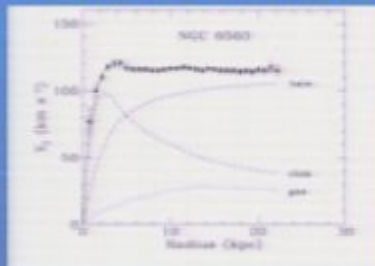
Pulsar's magnetospheres



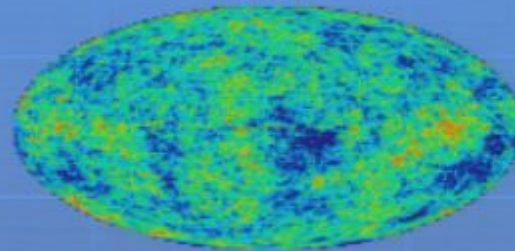
Dark Matter

Evidence for the existence of an unseen, “*dark*”, component in the energy density of the Universe comes from several independent observations at different length scales:

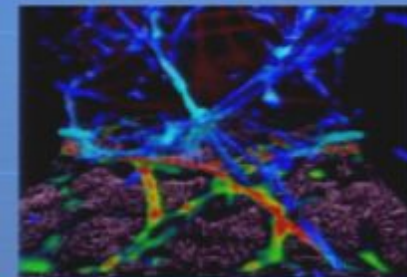
Rotation curves of galaxies



CMB



Large Scale Structure



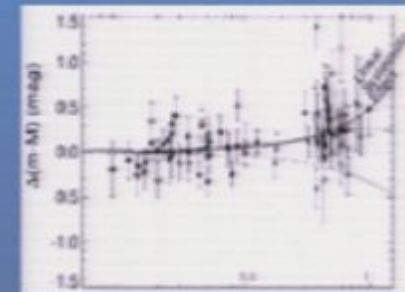
Galaxy clusters



Lensing



SN Ia



Bertone, Hooper & Silk, [hep-ph/0404175](https://arxiv.org/abs/hep-ph/0404175). Bergstrom, [hep-ph/0002126](https://arxiv.org/abs/hep-ph/0002126). Jungman et al, [hep-ph/9506380](https://arxiv.org/abs/hep-ph/9506380)

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
~10⁶²%??*



THE “*WIMP MIRACLE*”

Table 1. Properties of various Dark Matter Candidates

Bergstrom

| Type | Particle Spin | Approximate Mass Scale |
|---------------------|---------------|-------------------------------|
| Axion | 0 | μeV - meV |
| Inert Higgs Doublet | 0 | 50 GeV |
| Sterile Neutrino | 1/2 | keV |
| Neutralino | 1/2 | 10 GeV - 10 TeV |
| Kaluza-Klein UED | 1 | TeV |

Many possibilities, but WIMPs are singled out by an exceptional “coincidence”: **parameters of the STANDARD MODELS of PARTICLE PHYSICS and COSMOLOGY** conspire to provide a viable cold DM candidate at the **ELECTROWEAK SCALE**

The SUSY Particle Spectrum

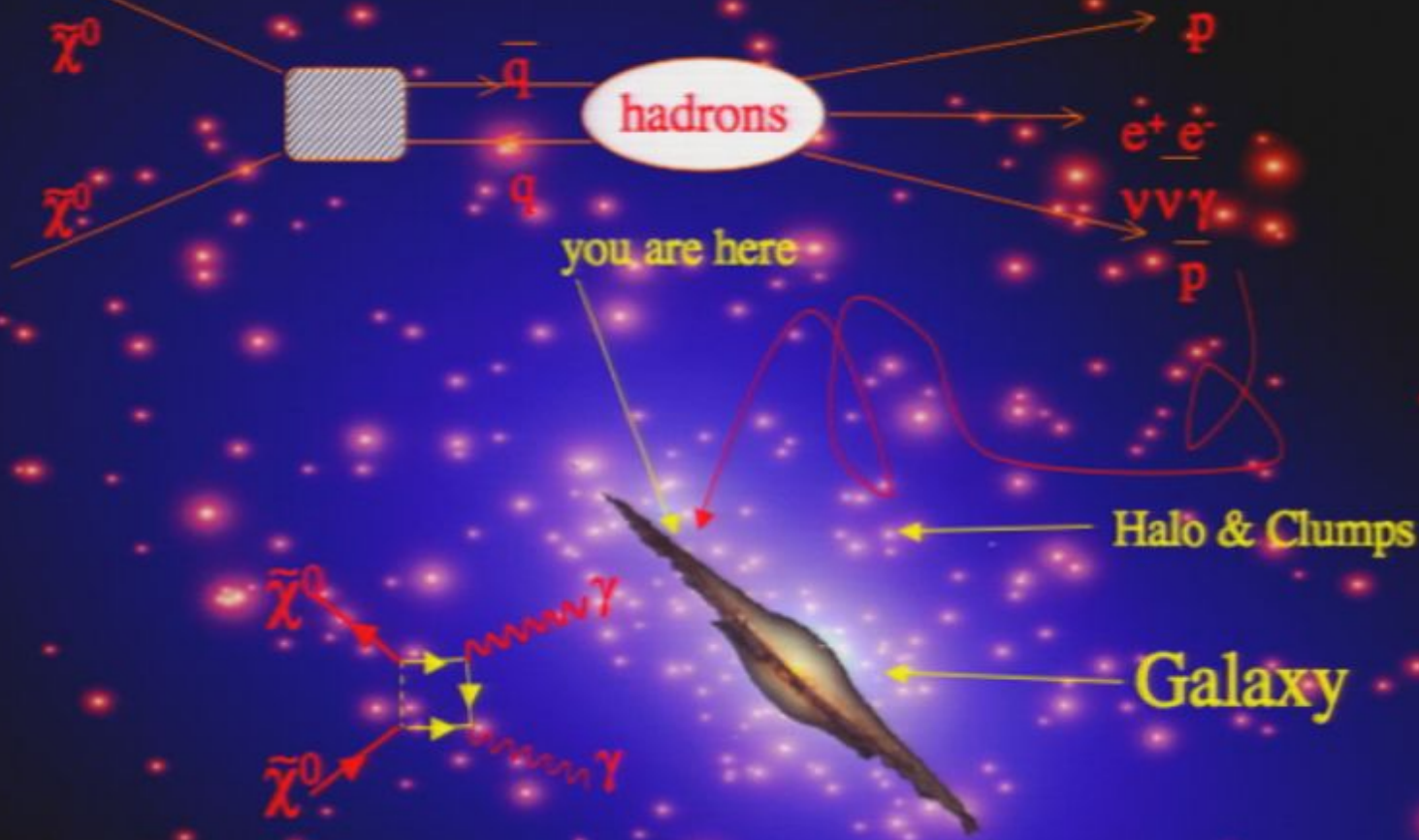
Standard Model

| 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 | γ | 1 | neutralinos | $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$ | 1/2 |
| Z boson | Z | 1 | | | |
| light Higgs | h | 0 | | | |
| heavy Higgs | H | 0 | | | |
| pseudoscalar Higgs | A | 0 | charginos | $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$ | 1/2 |
| W boson | W^\pm | 1 | | | |
| charged Higgs | H^\pm | 1 | gluino | \tilde{g} | 1/2 |
| gluon | g | 1 | gravitino | \tilde{G} | 3/2 |
| graviton | G | 2 | | | |

'LSP'
(usually)

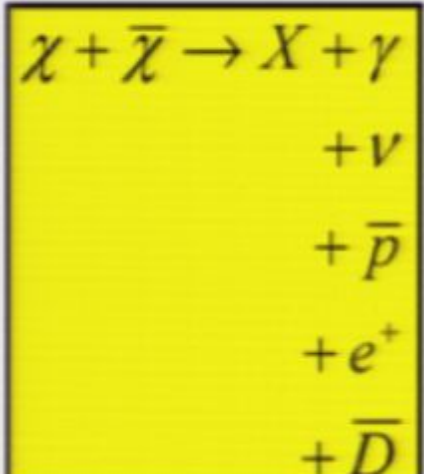
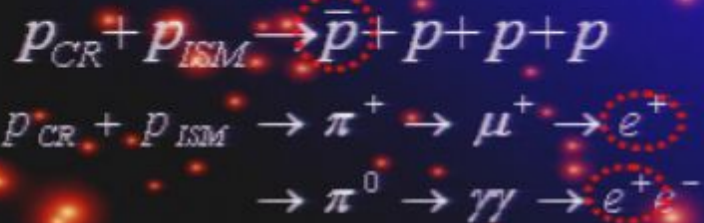
$$\chi = N_1 \tilde{\gamma} + N_2 \tilde{Z}^0 + N_3 \tilde{H}_1^0 + N_4 \tilde{H}_2^0; \sum_{i=1}^4 |N_i|^2 = 1$$

Signal (supersymmetry)...



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

... and background



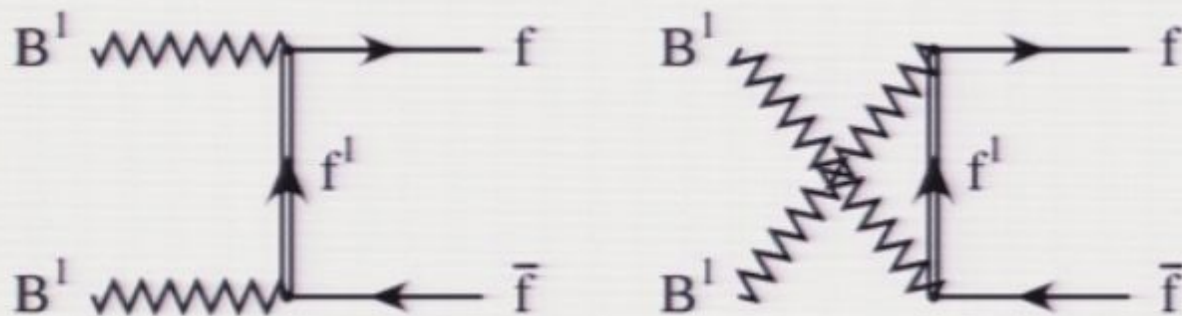
(GLAST-FERMI AMS-02)
 (AMANDA / IceCube)
PAMELA
 (and Bess, AMS et

Neutralino Annihilations

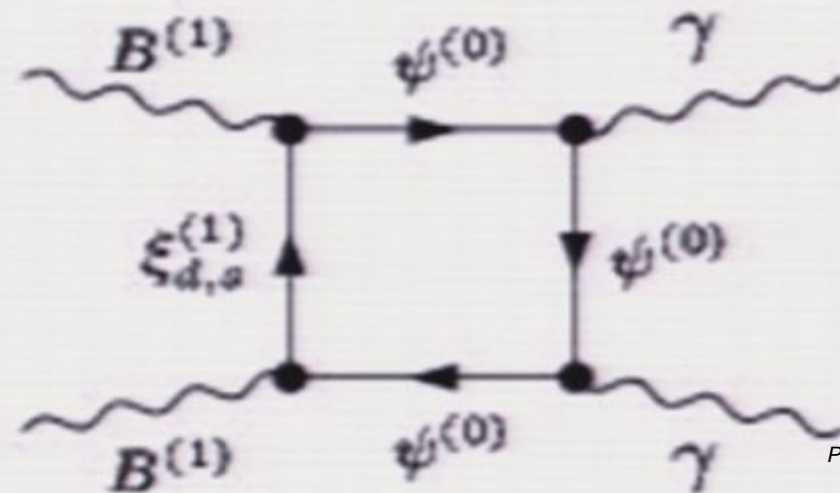
Another possible scenario: KK Dark Matter

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

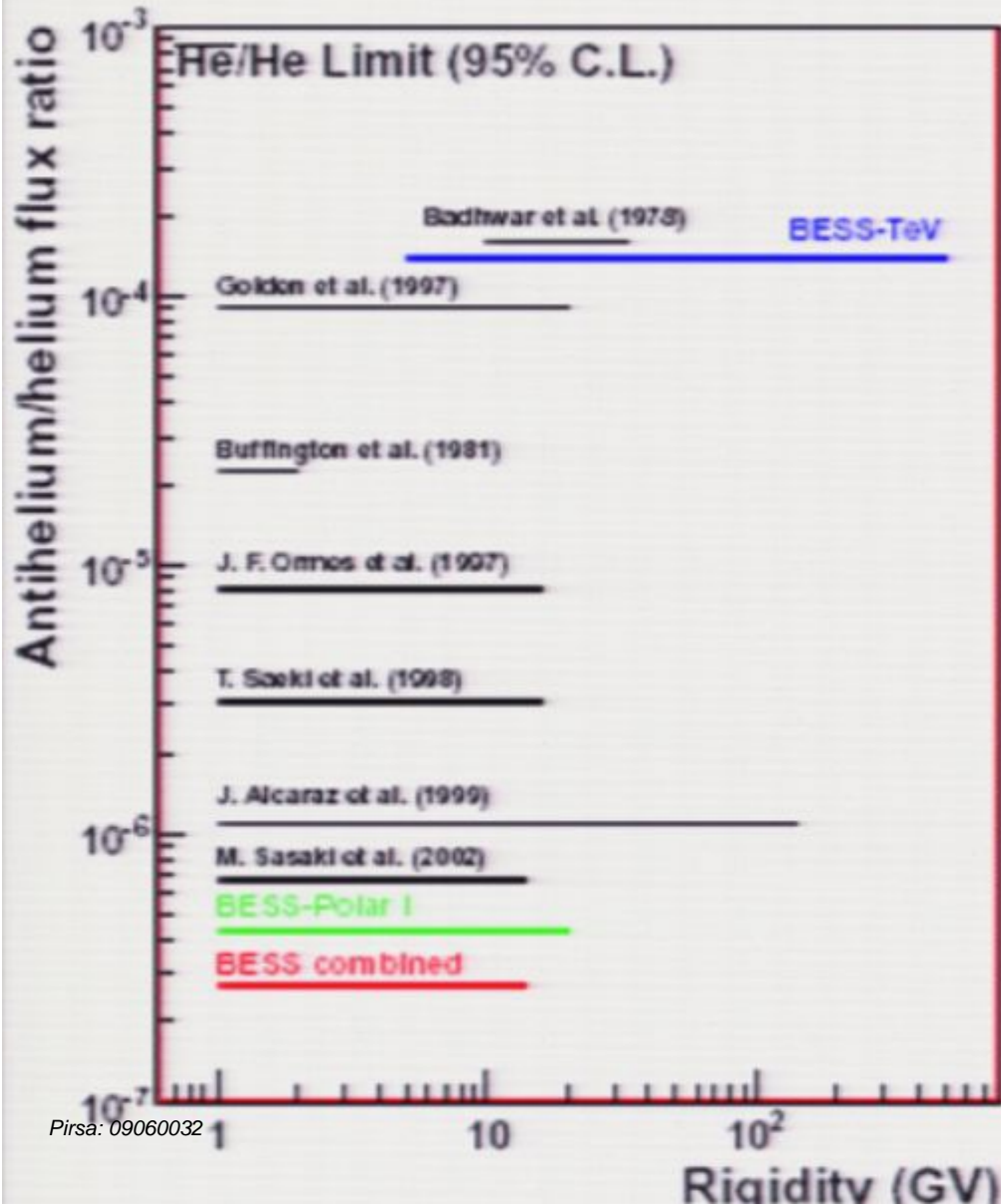
Bosonic Dark Matter:
fermionic final states
no longer helicity
suppressed.
 e^+e^- final states
directly produced.



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



Antimatter



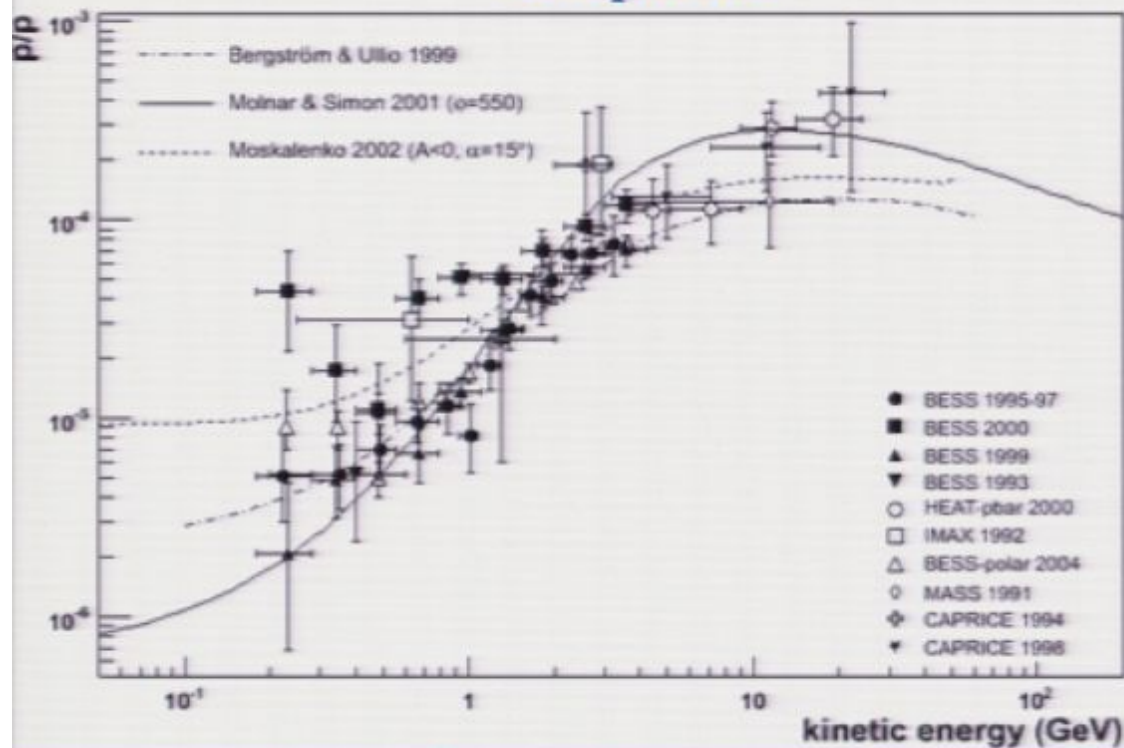
"We must regard it rather an accident that the Earth and presumably the whole Solar System contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about"

P. Dirac, Nobel lecture (1933)

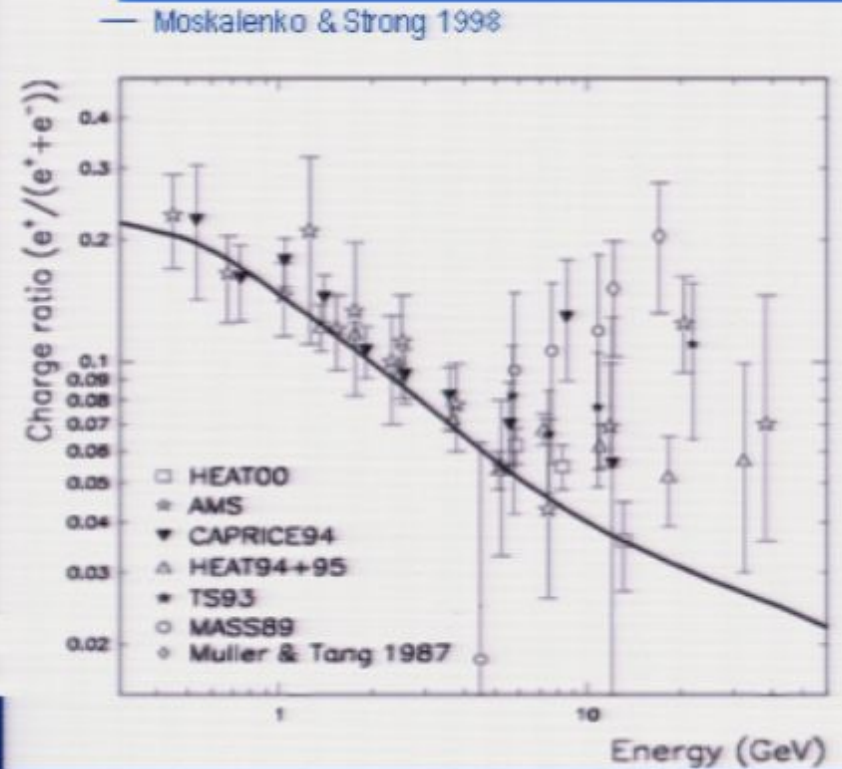
Cosmic Ray Antimatter

Present status

Antiprotons



Positrons

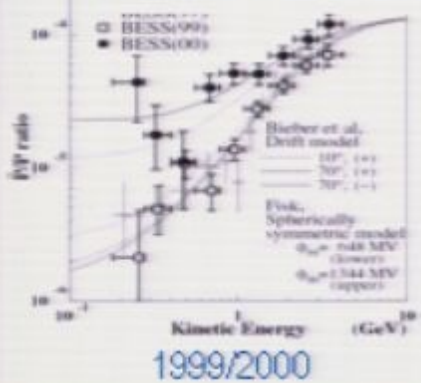


Cosmic Ray Antimatter

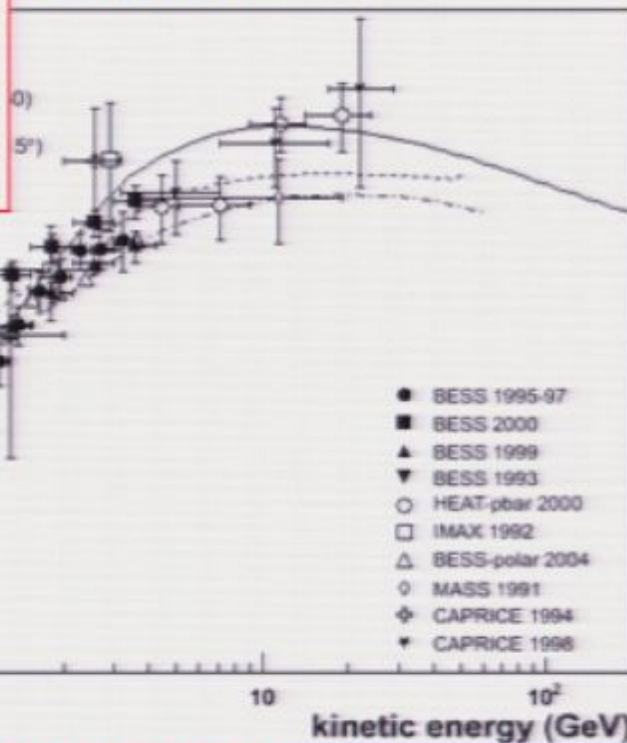
Present status

Charge-dependent solar modulation

Asaoka Y. Et al. 2002

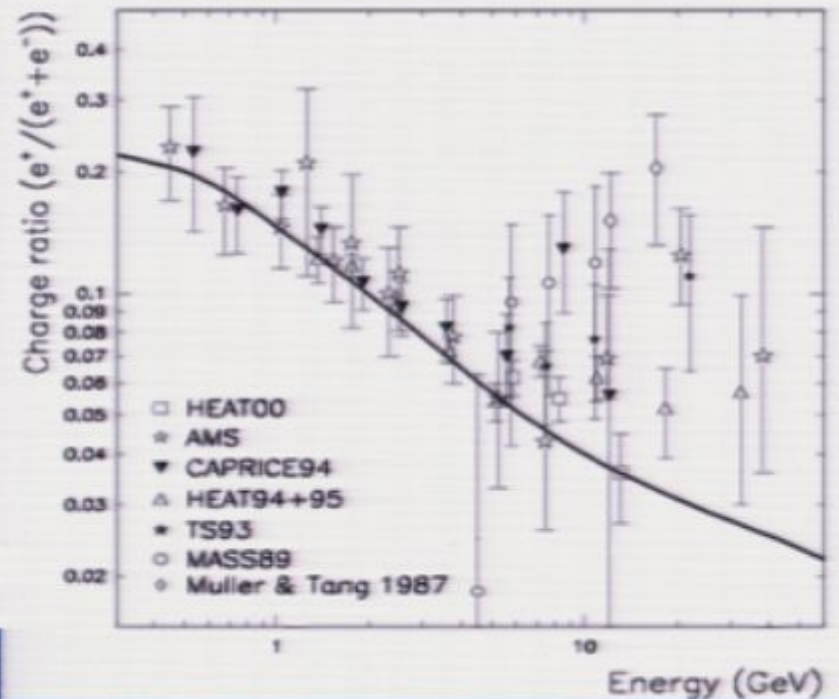


Antiprotons



Positrons

Moskalenko & Strong 1998



CR + ISM \rightarrow **p-bar** + ...

kinematic threshold:

5.6 GeV for the reaction

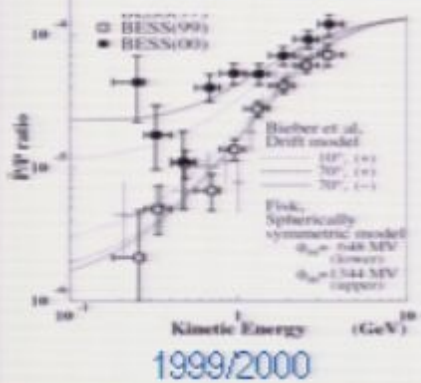
$pp \rightarrow \bar{p}ppp$

Cosmic Ray Antimatter

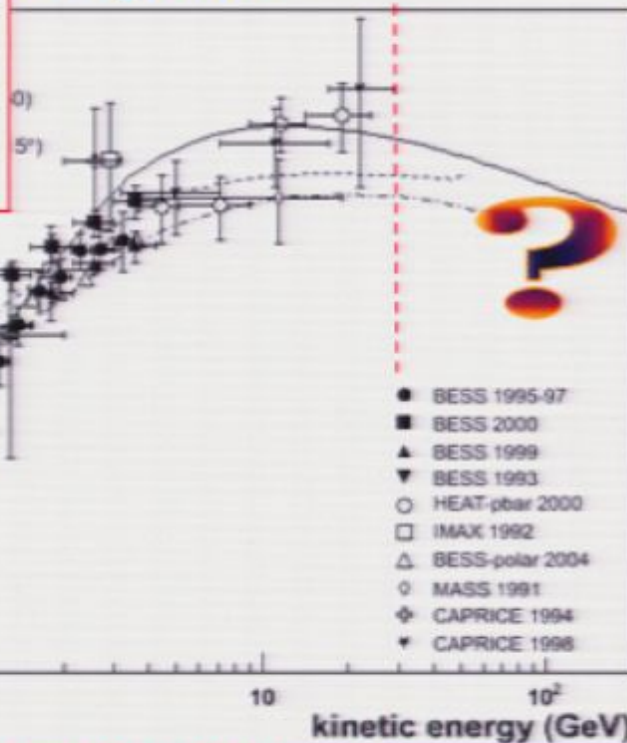
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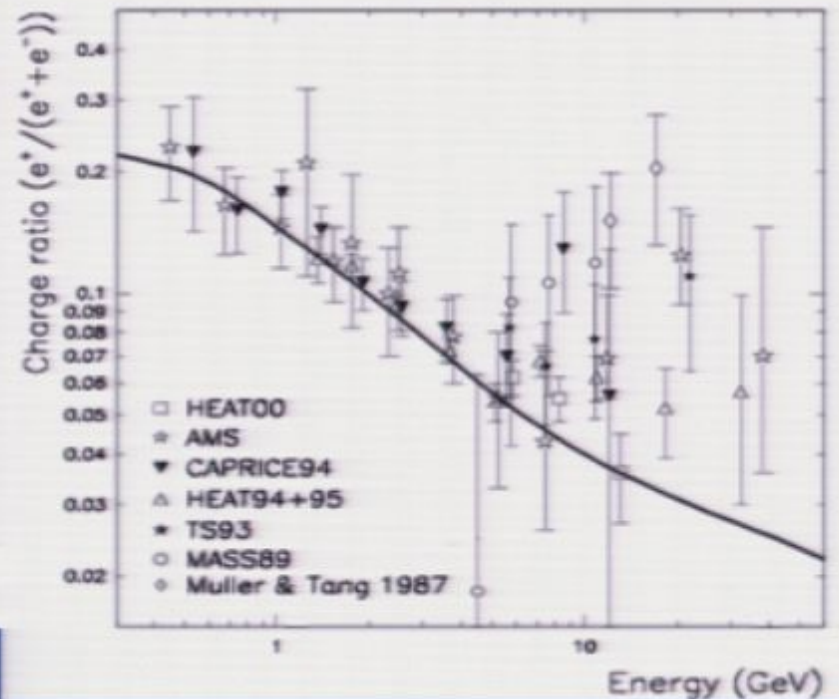


Antiprotons



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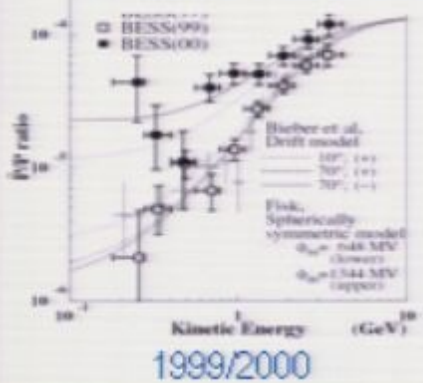
$pp \rightarrow \bar{p}ppp$

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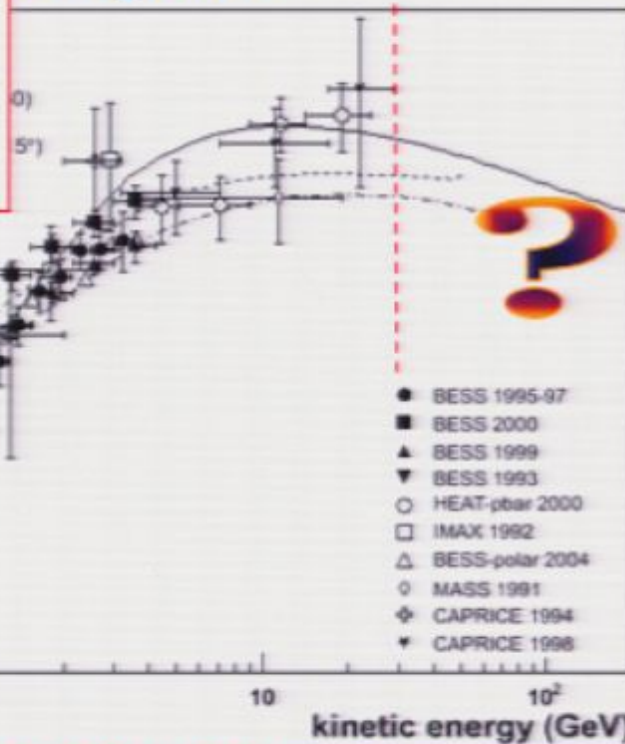
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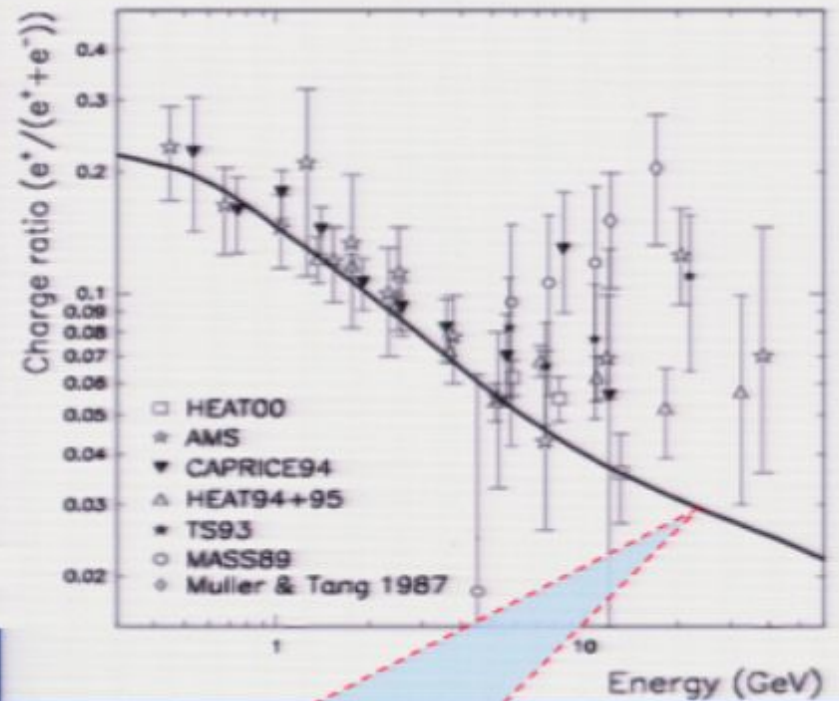


Antiprotons



Positrons

Moskalenko & Strong 1998



CR + ISM \rightarrow **p-bar** + ...

kinematic threshold:

5.6 GeV for the reaction

$pp \rightarrow \bar{p}ppp$

CR + ISM $\rightarrow \pi^\pm + x \rightarrow \mu^\pm + x \rightarrow e^\pm + x$

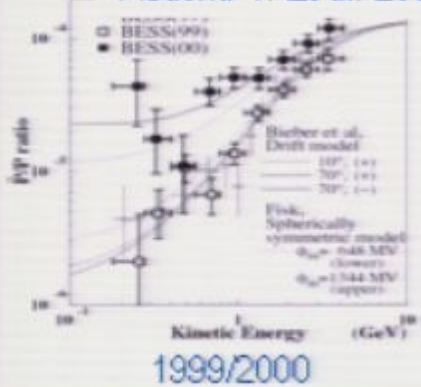
CR + ISM $\rightarrow \pi^0 + x \rightarrow \gamma \rightarrow e^\pm$

Cosmic Ray Antimatter

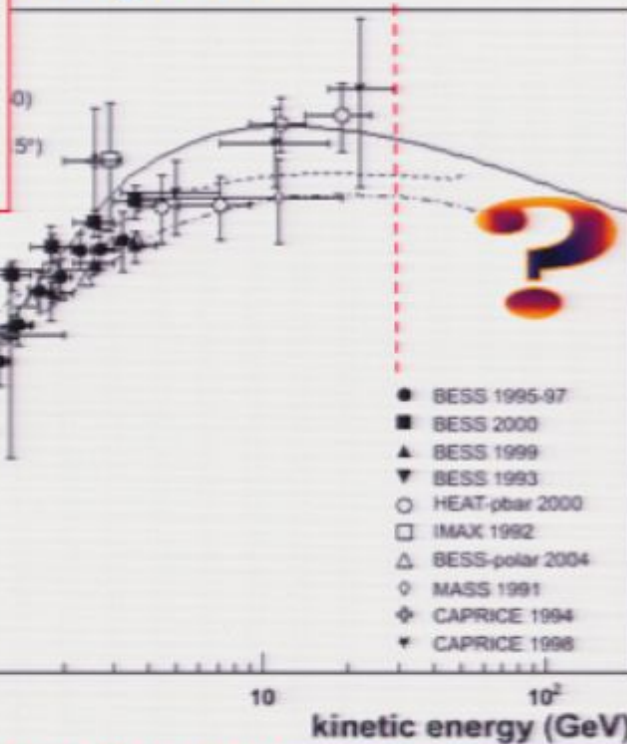
Present status

Charge-dependent solar modulation

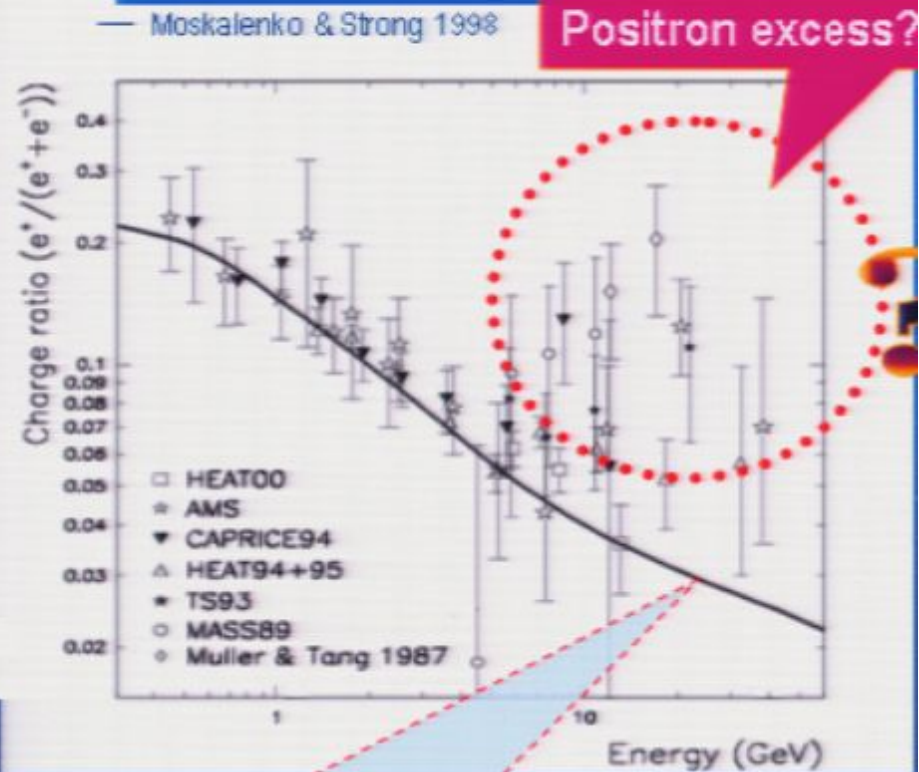
Asaoka Y. Et al. 2002



Antiprotons



Positrons



CR + ISM \rightarrow **p-bar** + ...

kinematic threshold:

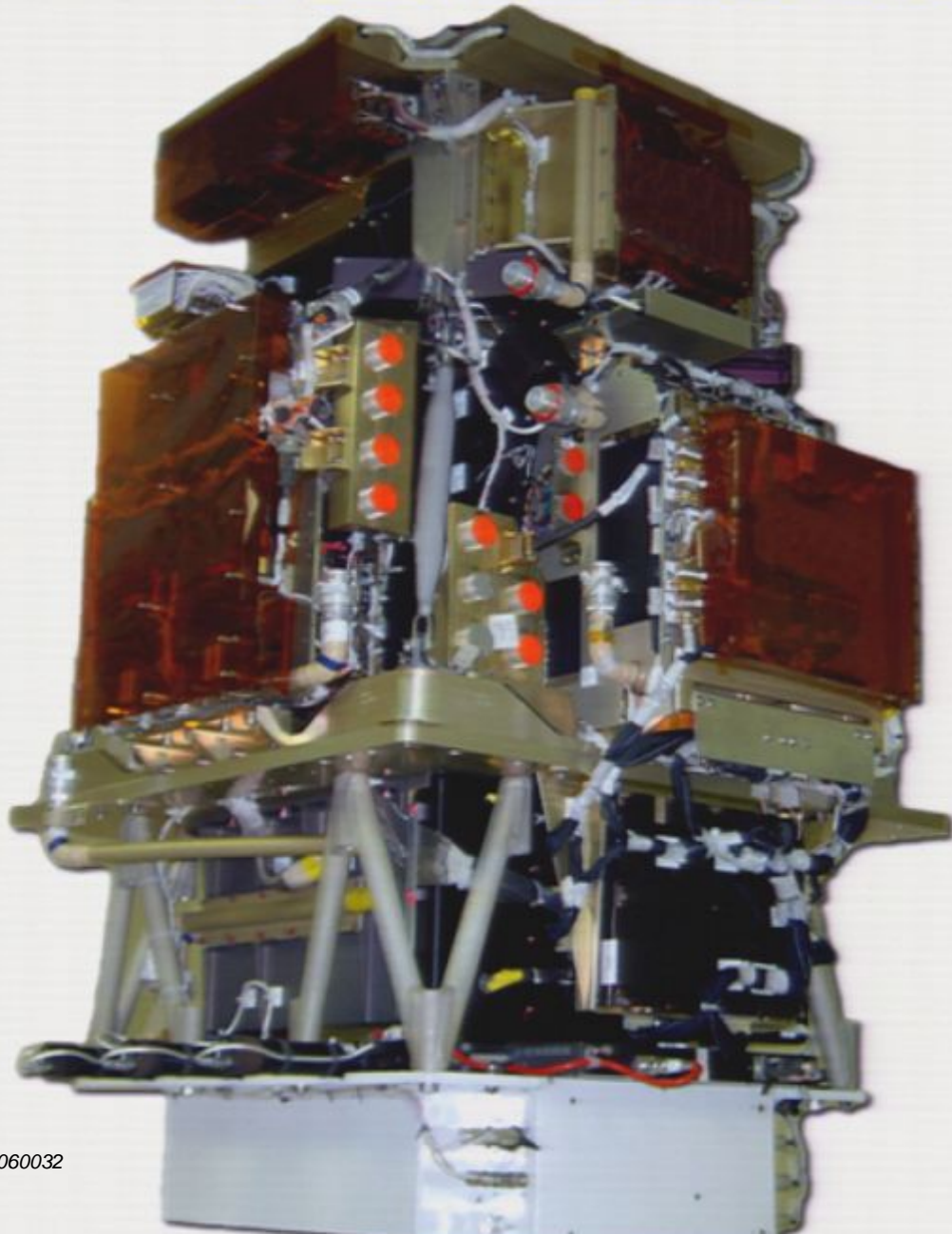
5.6 GeV for the reaction

$pp \rightarrow \bar{p}ppp$

CR + ISM $\rightarrow \pi^\pm + x \rightarrow \mu^\pm + x \rightarrow e^\pm + x$

CR + ISM $\rightarrow \pi^0 + x \rightarrow \gamma \rightarrow e^\pm$

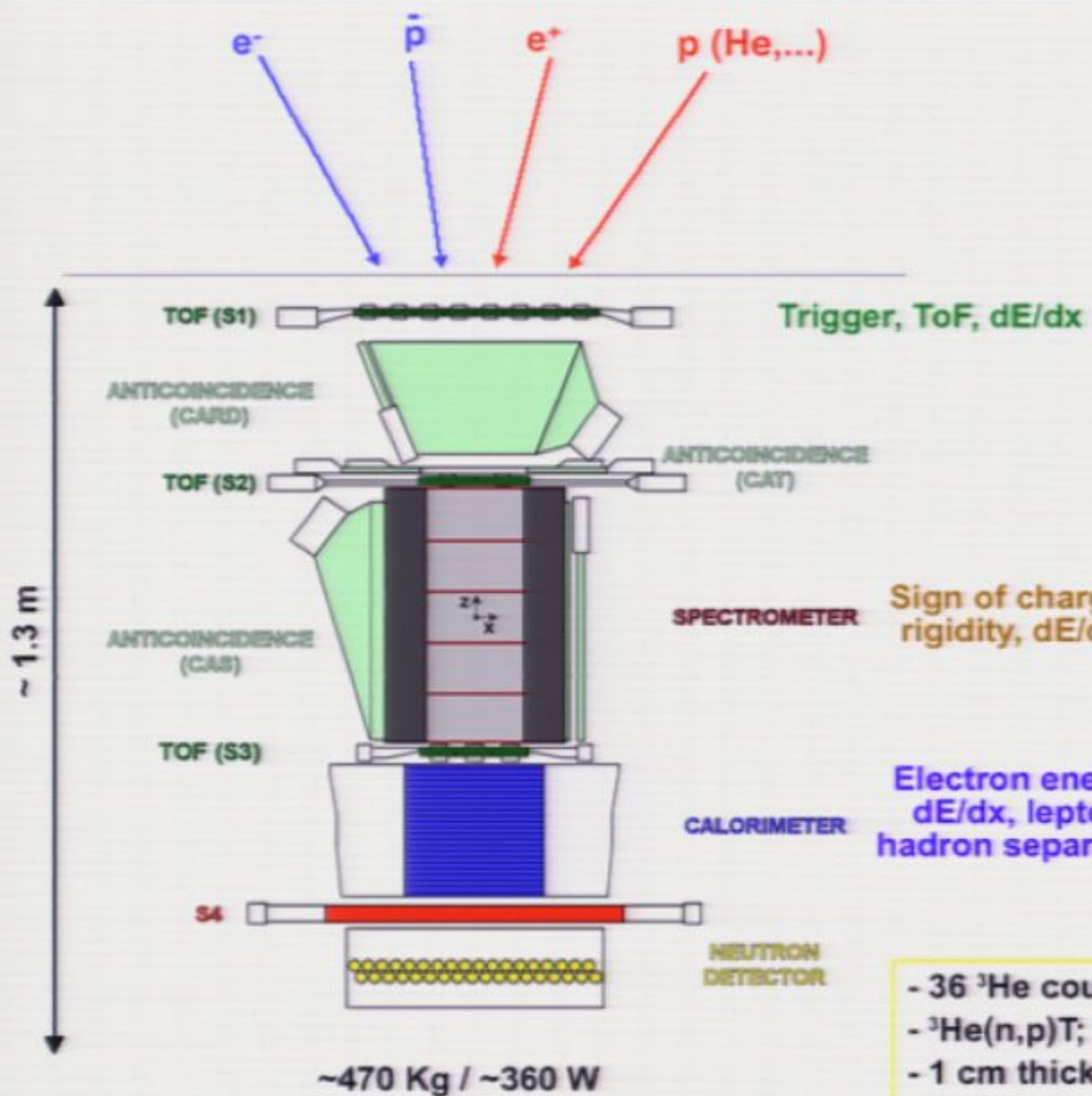
PAMELA Instrument



GF ~21.5 cm²sr

Mass: 470 kg

Size: 130x70x70 cm³



- 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)

- Permanent magnet, 0.43 T
- 21.5 cm² sr
- 6 planes double-sided silicon strip detectors (300 μm)
- 3 μm resolution in bending view → MD
- ~800 GV (6 plane) ~500 GV (5 plane)

- 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 cm² sr

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

Design Performances

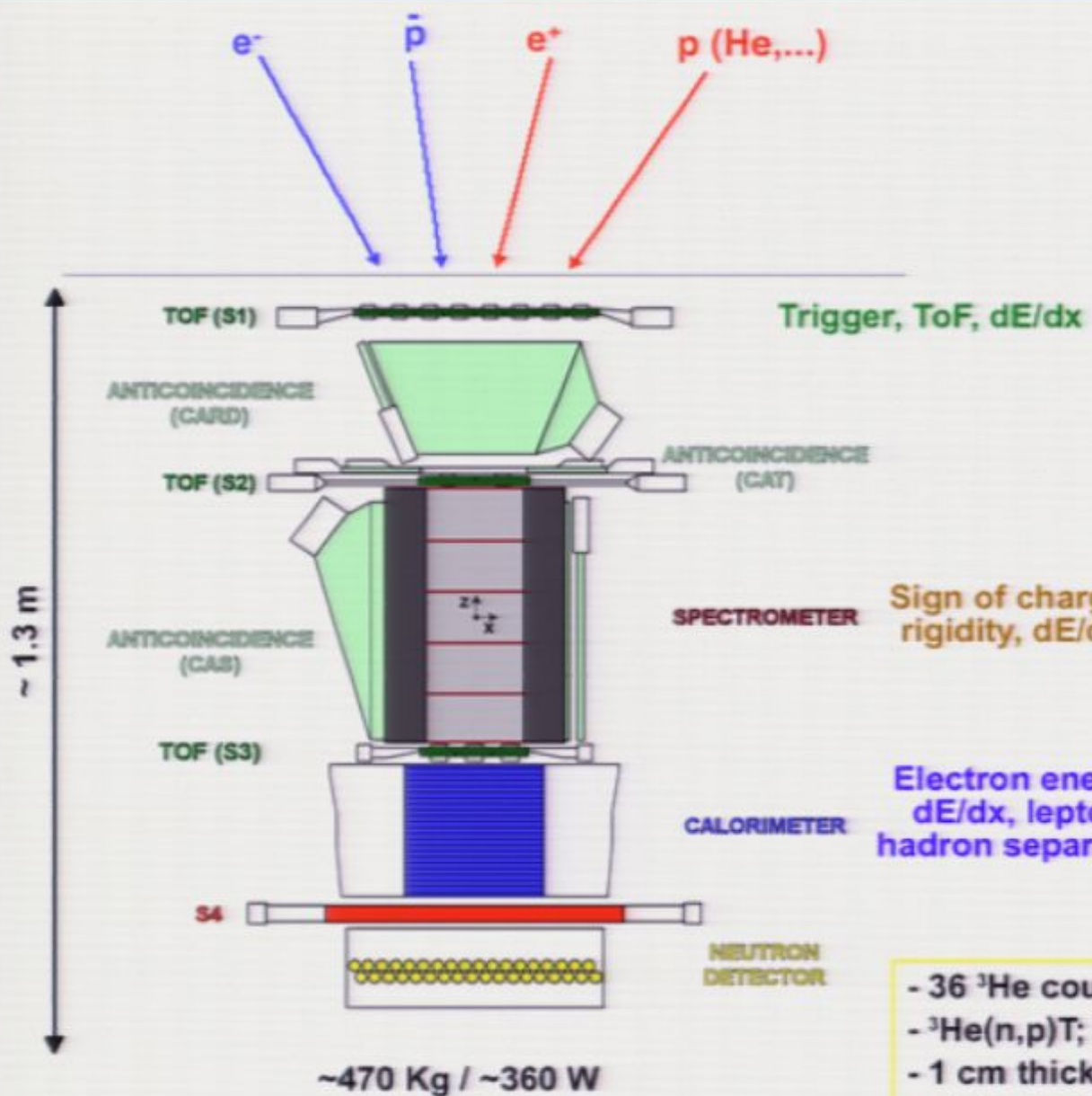
Energy range

| | |
|--------------------------|---|
| ■ 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 3×10^{-8} in $\overline{\text{He}}/\text{He}$ |

→ Simultaneous measurement of many cosmic-ray species

→ New energy range

→ Unprecedented statistics



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Design Performances

Energy range

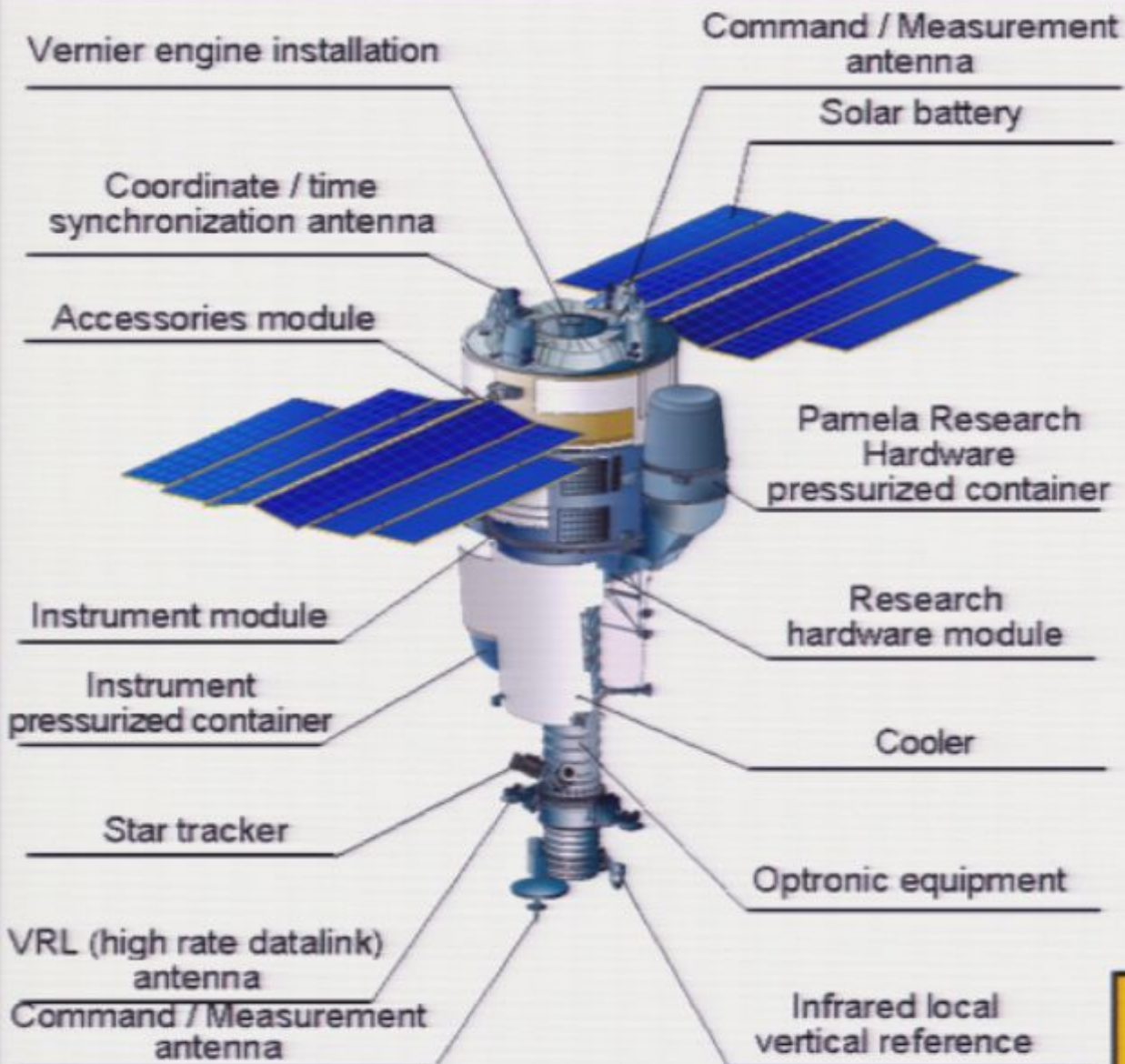
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→ New energy range

→ Unprecedented statistics

Resurs-DK1 satellite

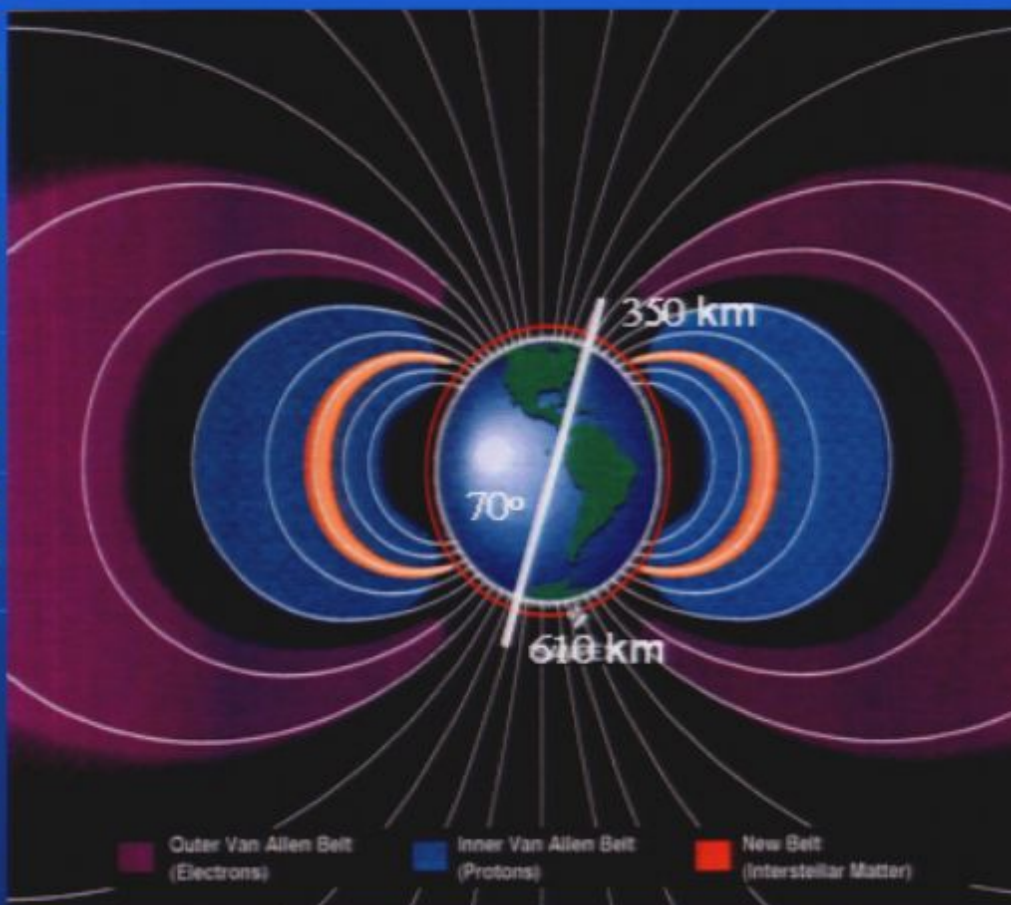
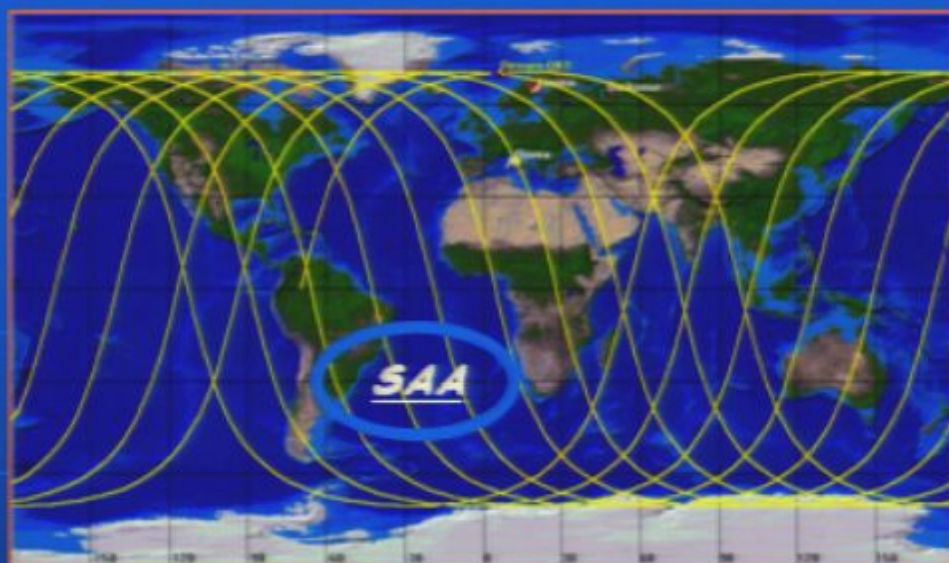


Pirsa: 09060032

- **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 m²

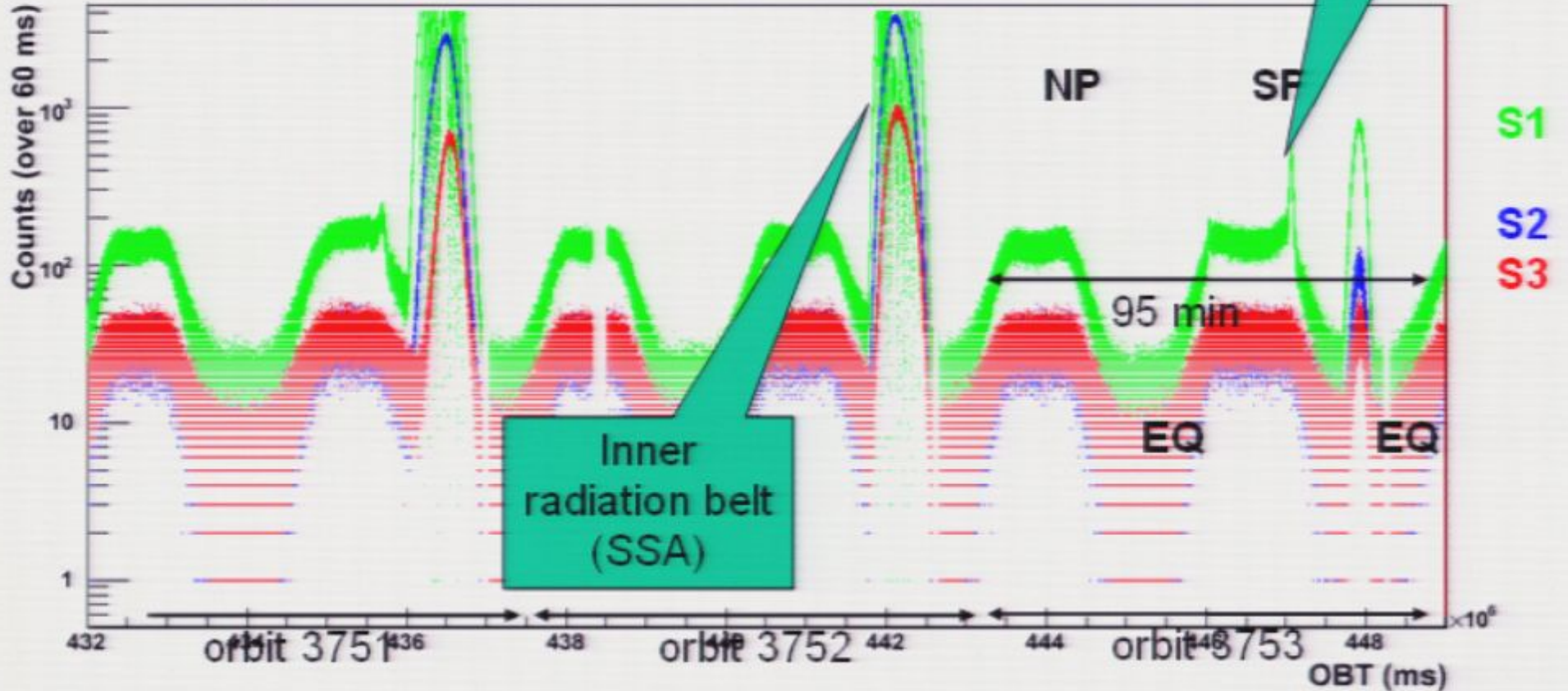
Orbit Characteristics

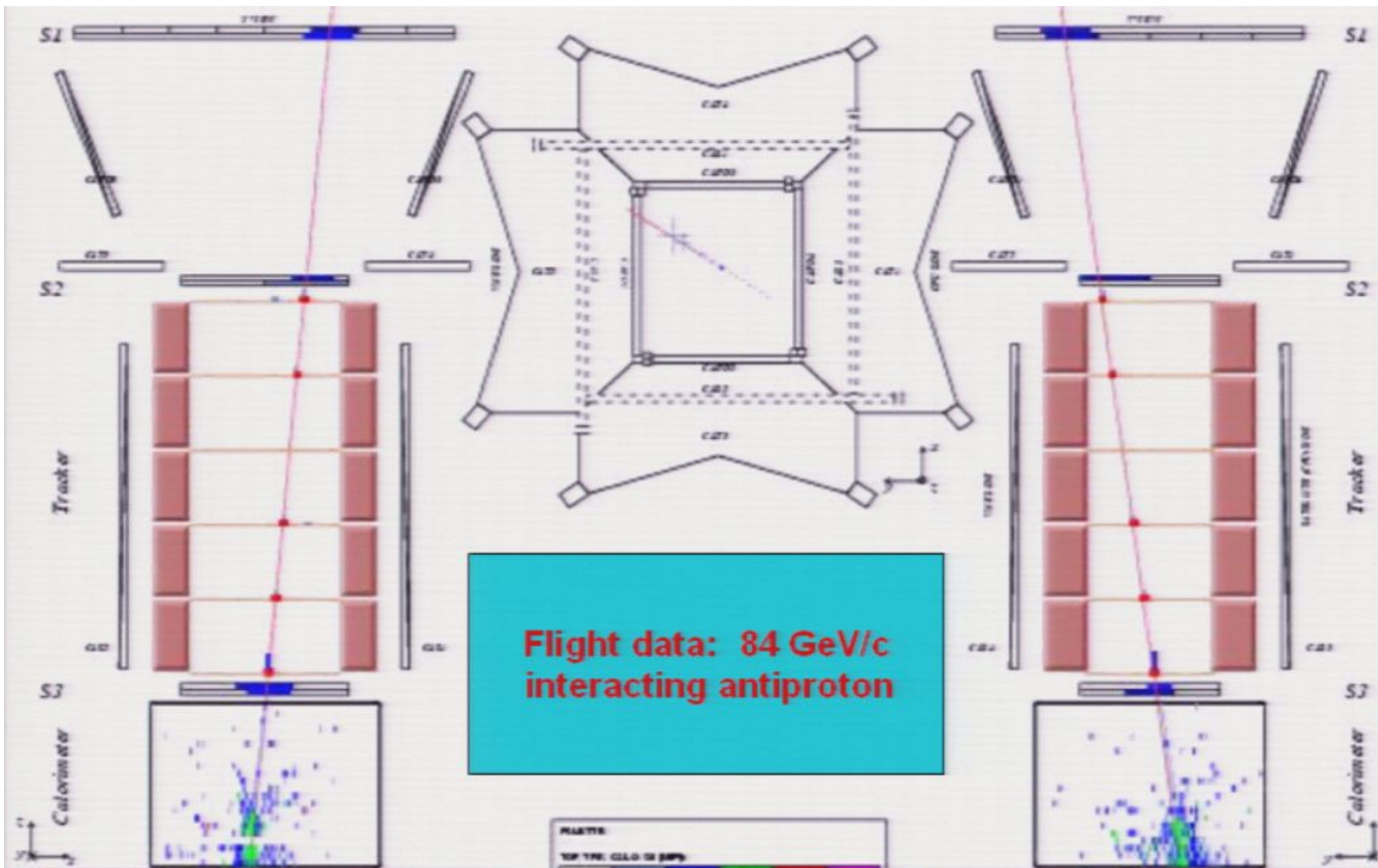


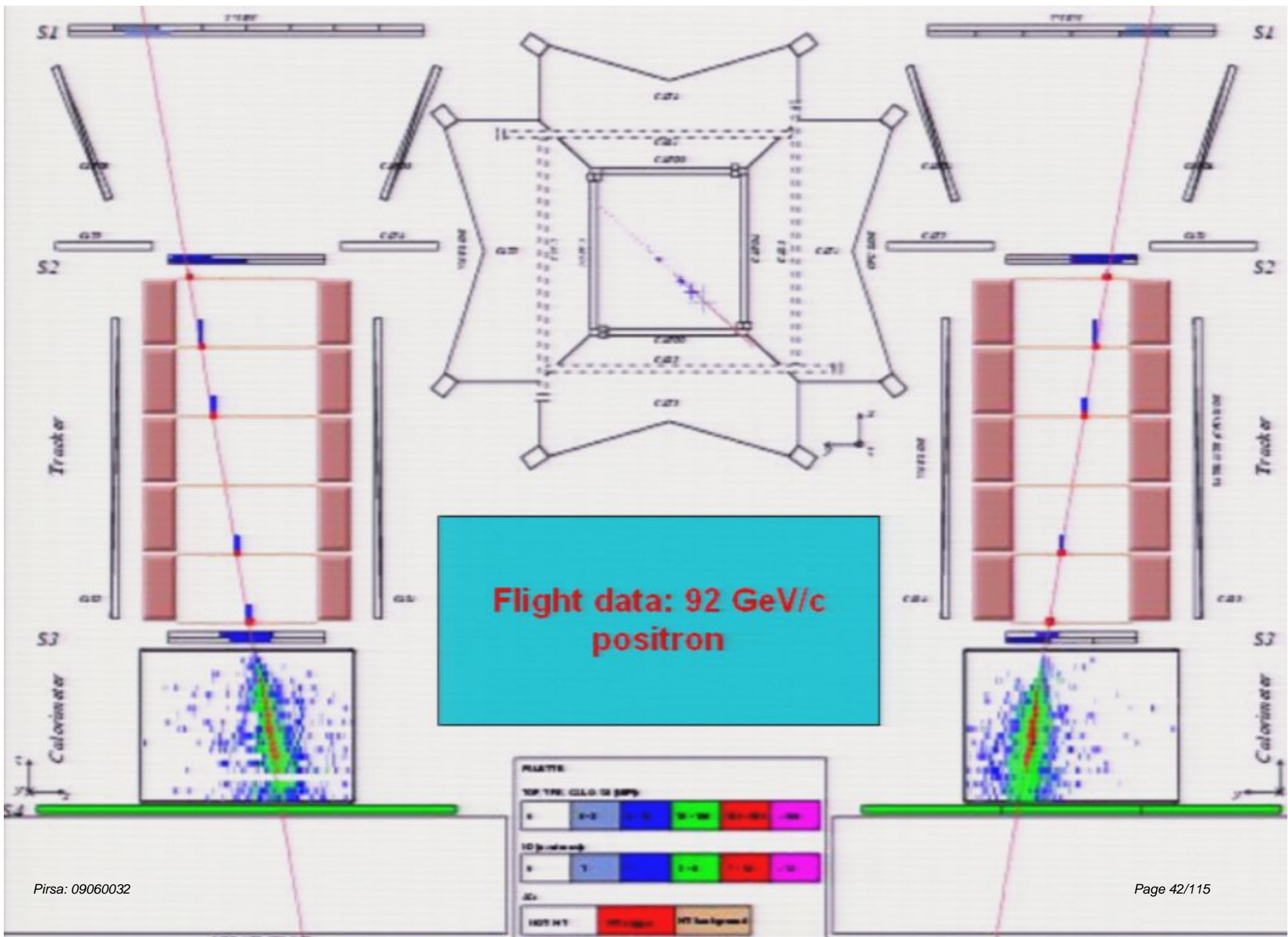
- Low-earth elliptical orbit
- 350 – 610 km
- Quasi-polar (70° inclination)
- SAA crossed
- 16 Gigabytes transmitted daily to Ground-NTsOMZ Moscow

PAMELA Orbit

Download @orbit 3754 – 15/02/2007 07:35:00 MWT







**Flight data: 92 GeV/c
positron**

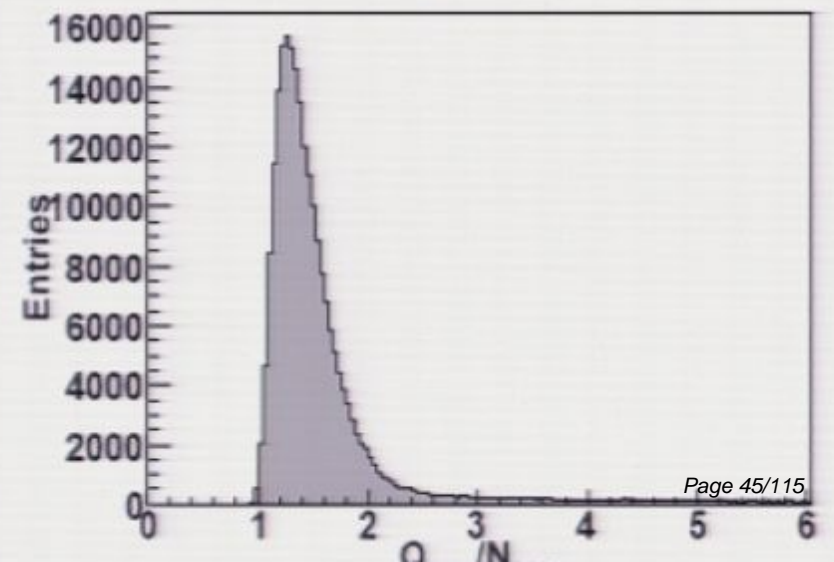
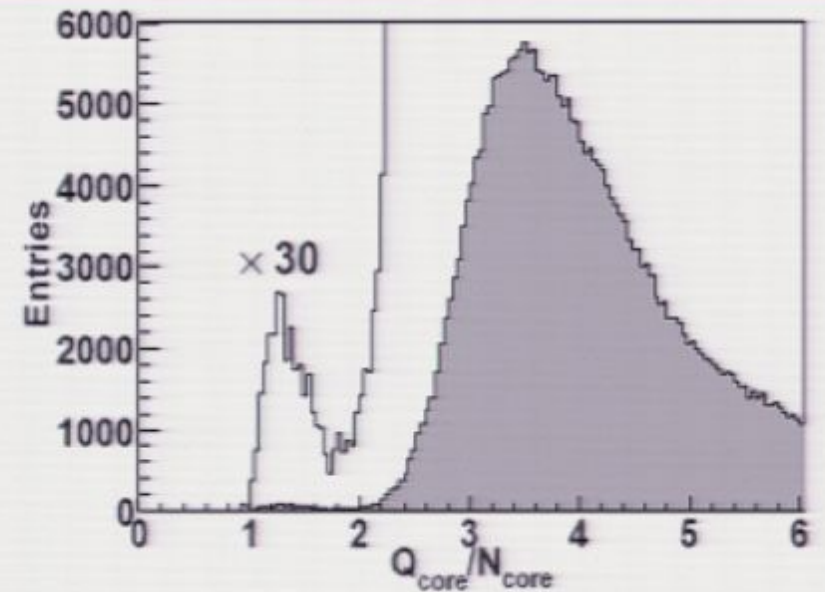
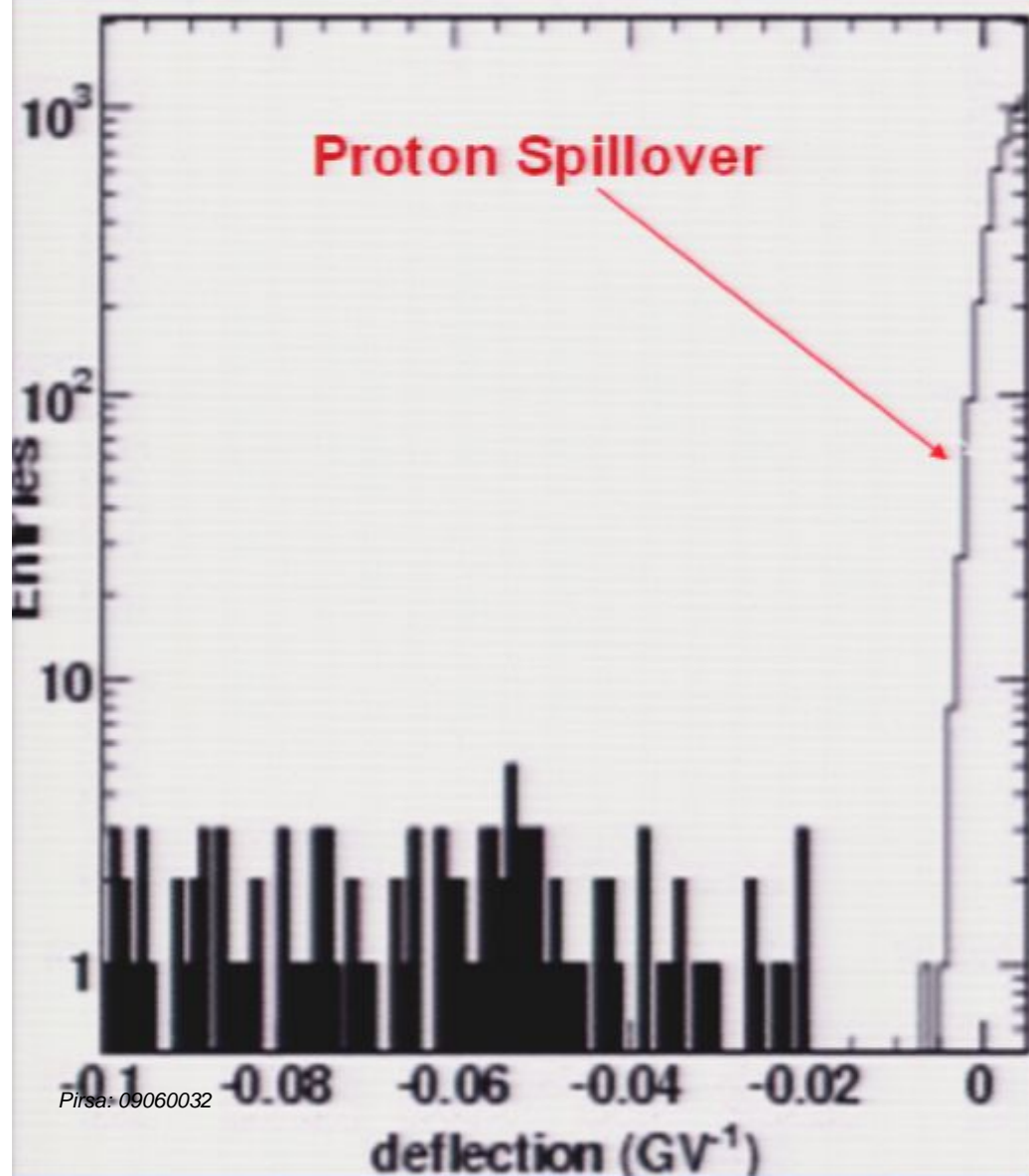
| PLATE: | | | | | |
|----------------------|-----|-----------------|-----|---------------|------|
| TOP TRK: CLG 10 (MP) | | | | | |
| S | 1-2 | 3-4 | 5-6 | 7-8 | 9-10 |
| ID (to be used) | | | | | |
| S | 1 | 2-3 | 4-5 | 6-7 | 8-9 |
| ID: | | | | | |
| NOT HT | | HT (to be used) | | HT background | |

PAMELA Status

- **Today 1093 days in flight**
- **data taking $\sim 73\%$ live-time**
- **>13 TBytes of raw data downlinked**
- **> 10^9 triggers recorded and under analysis**

Antiprotons

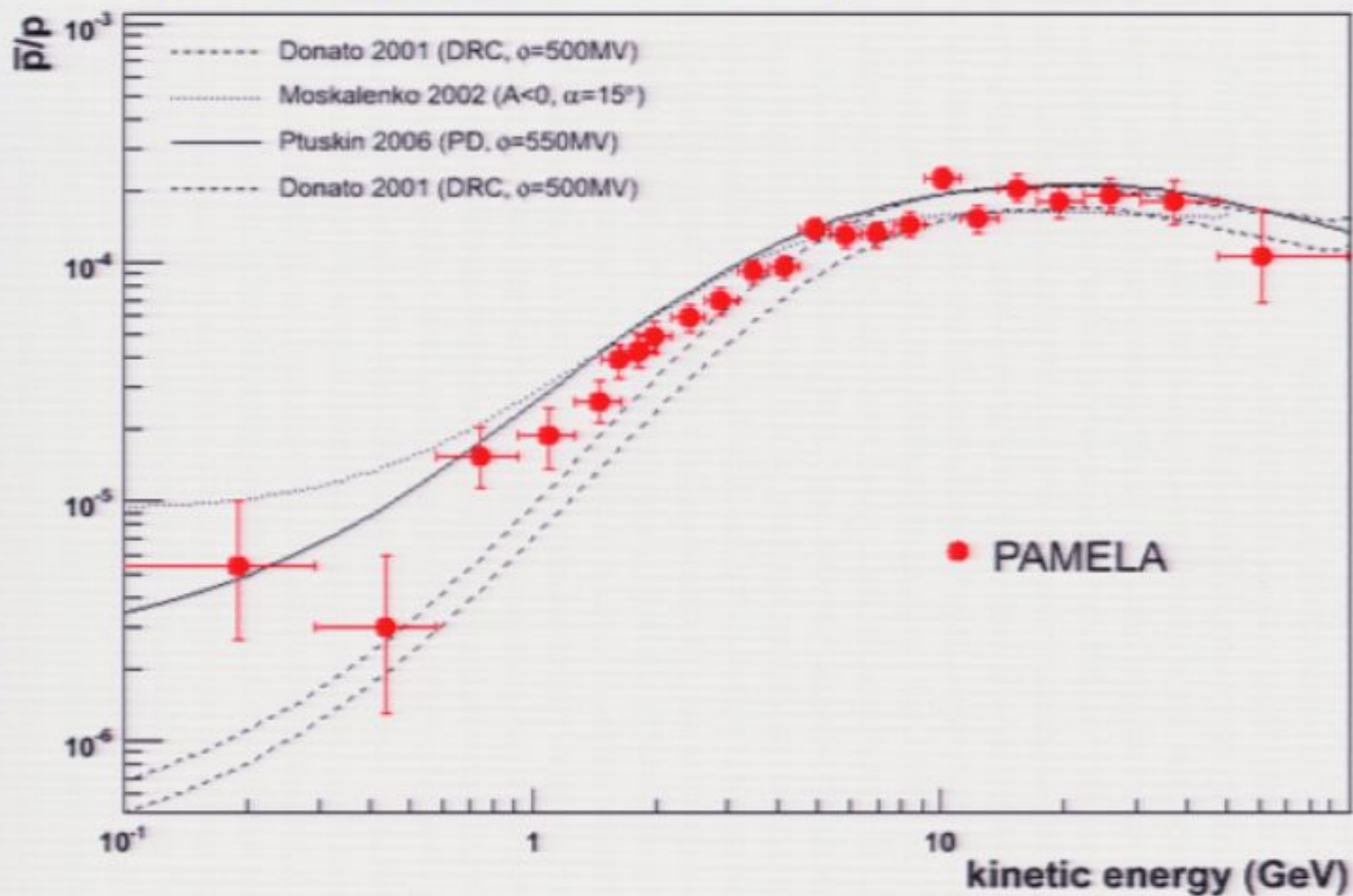
PAMELA antiproton selection



Antiproton to proton ratio

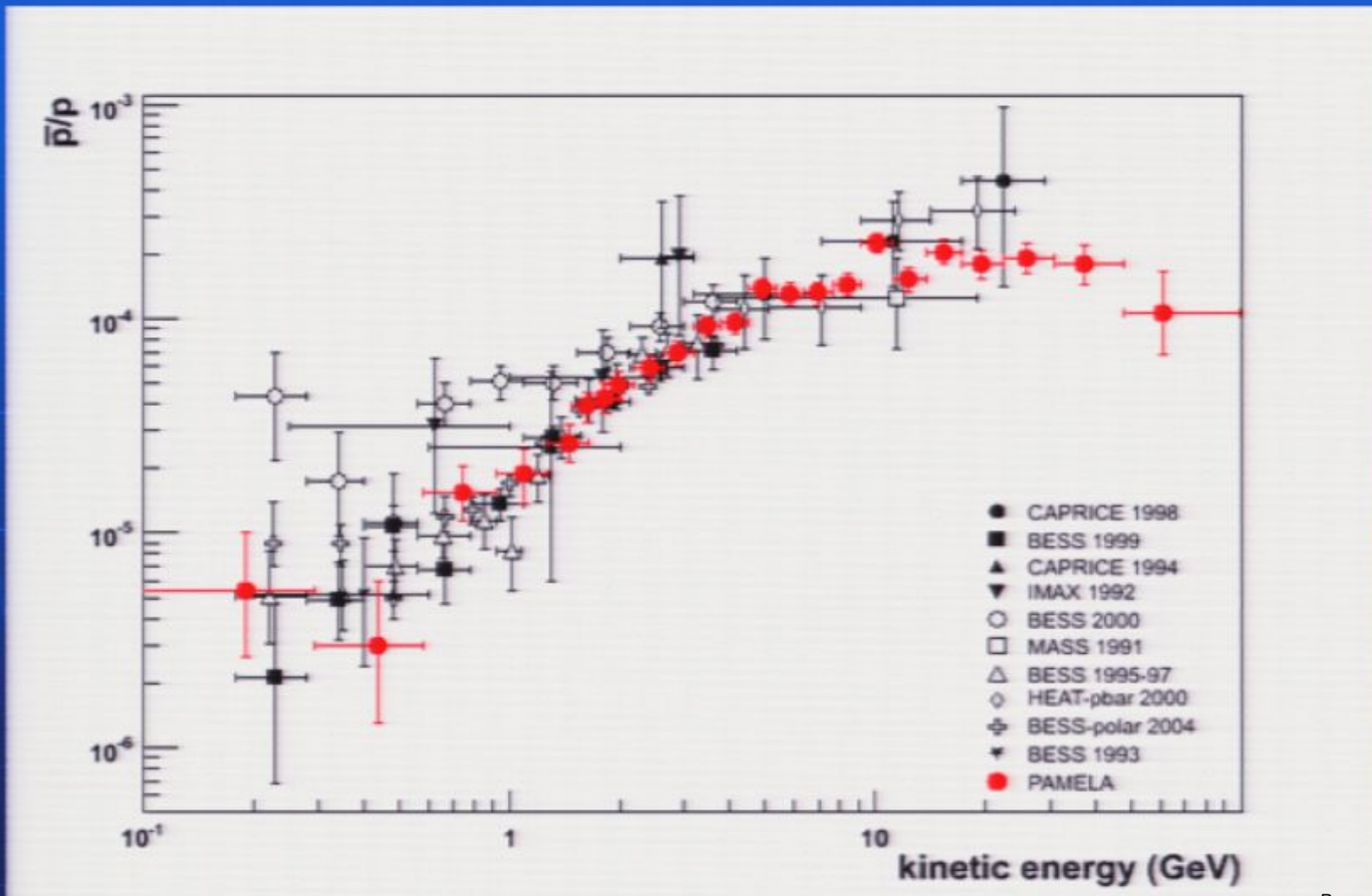
PRL 102, 051101 (2009)

Secondary Production Models

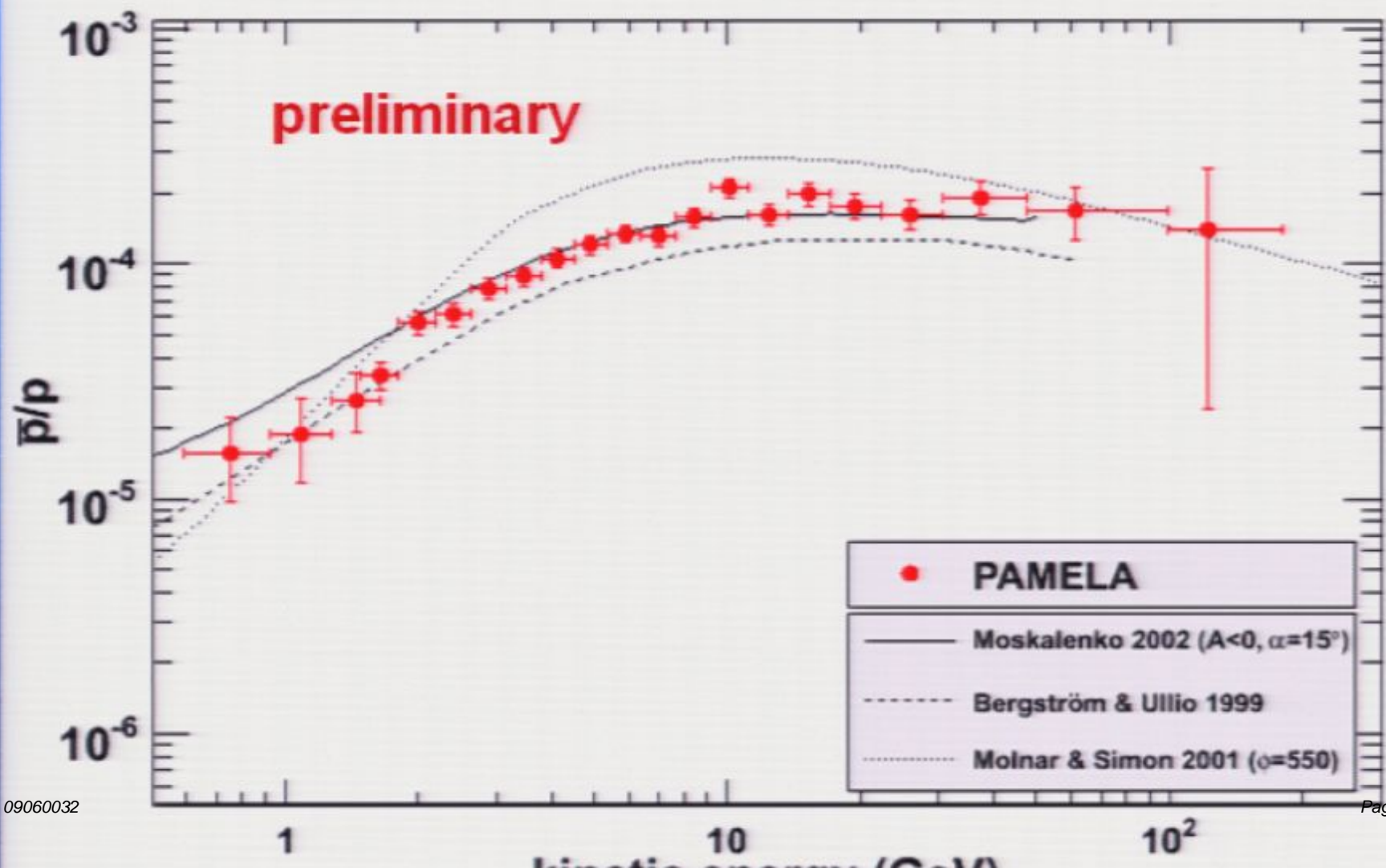


Antiproton to proton ratio

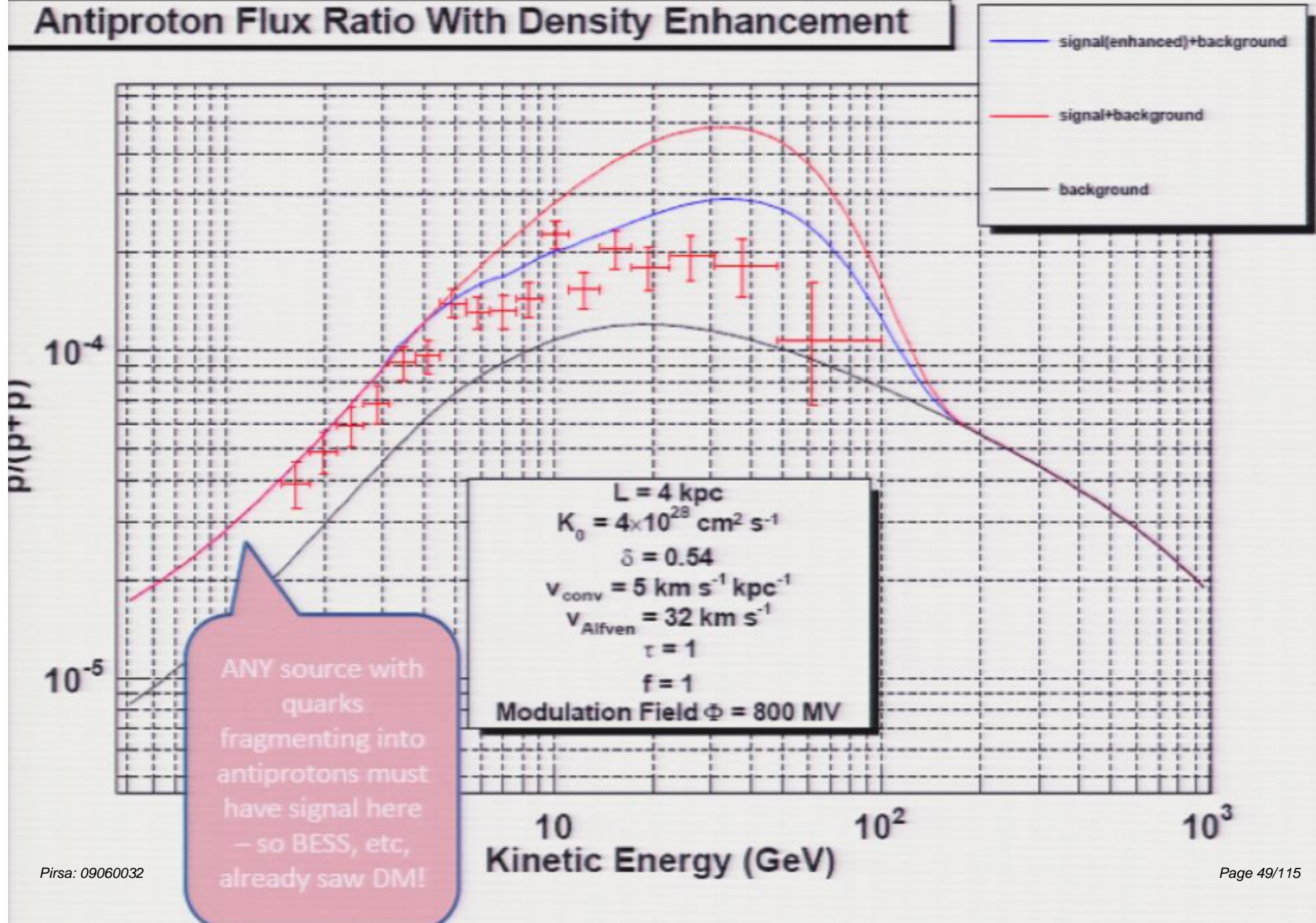
PRL 102, 051101 (2009)

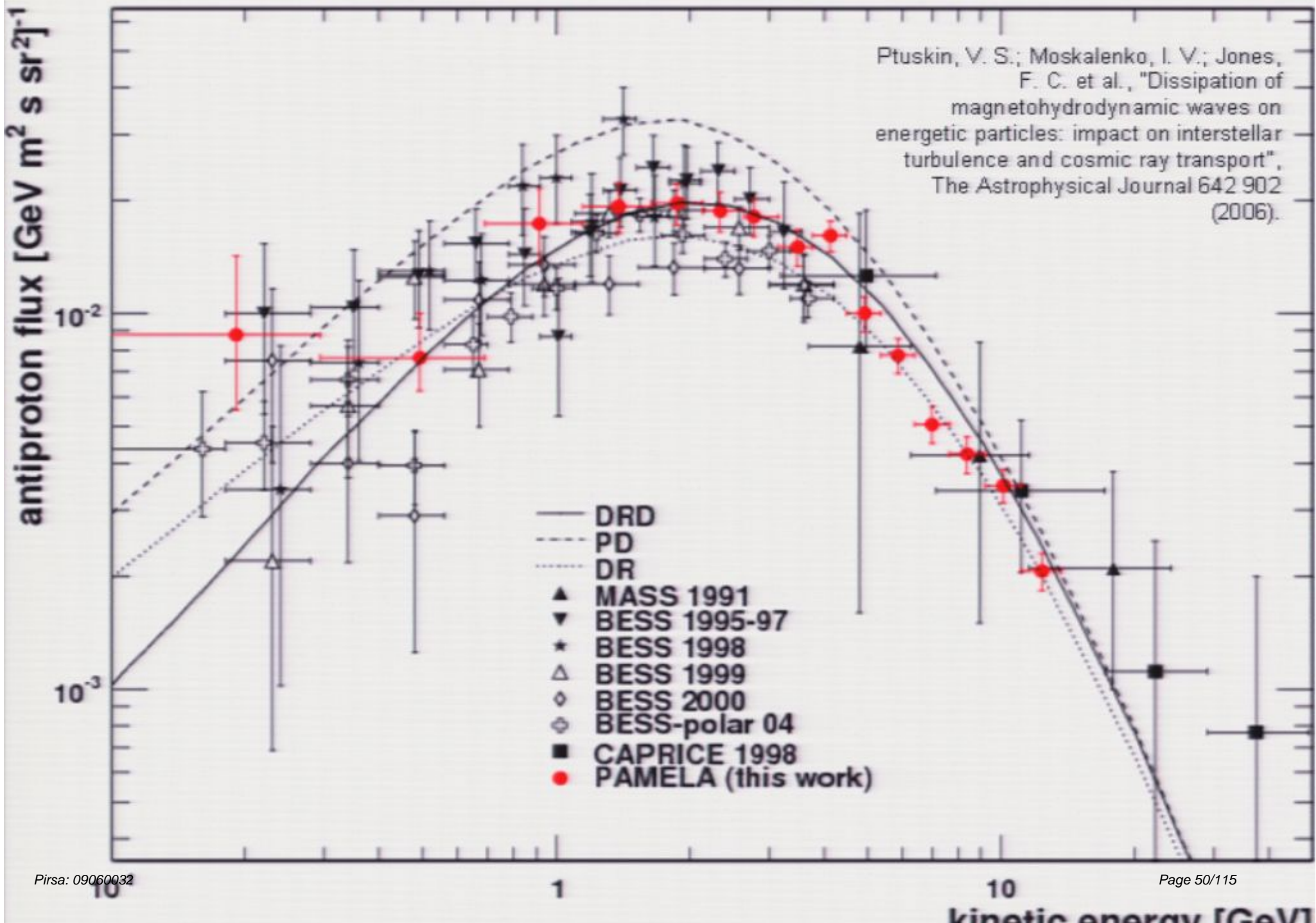


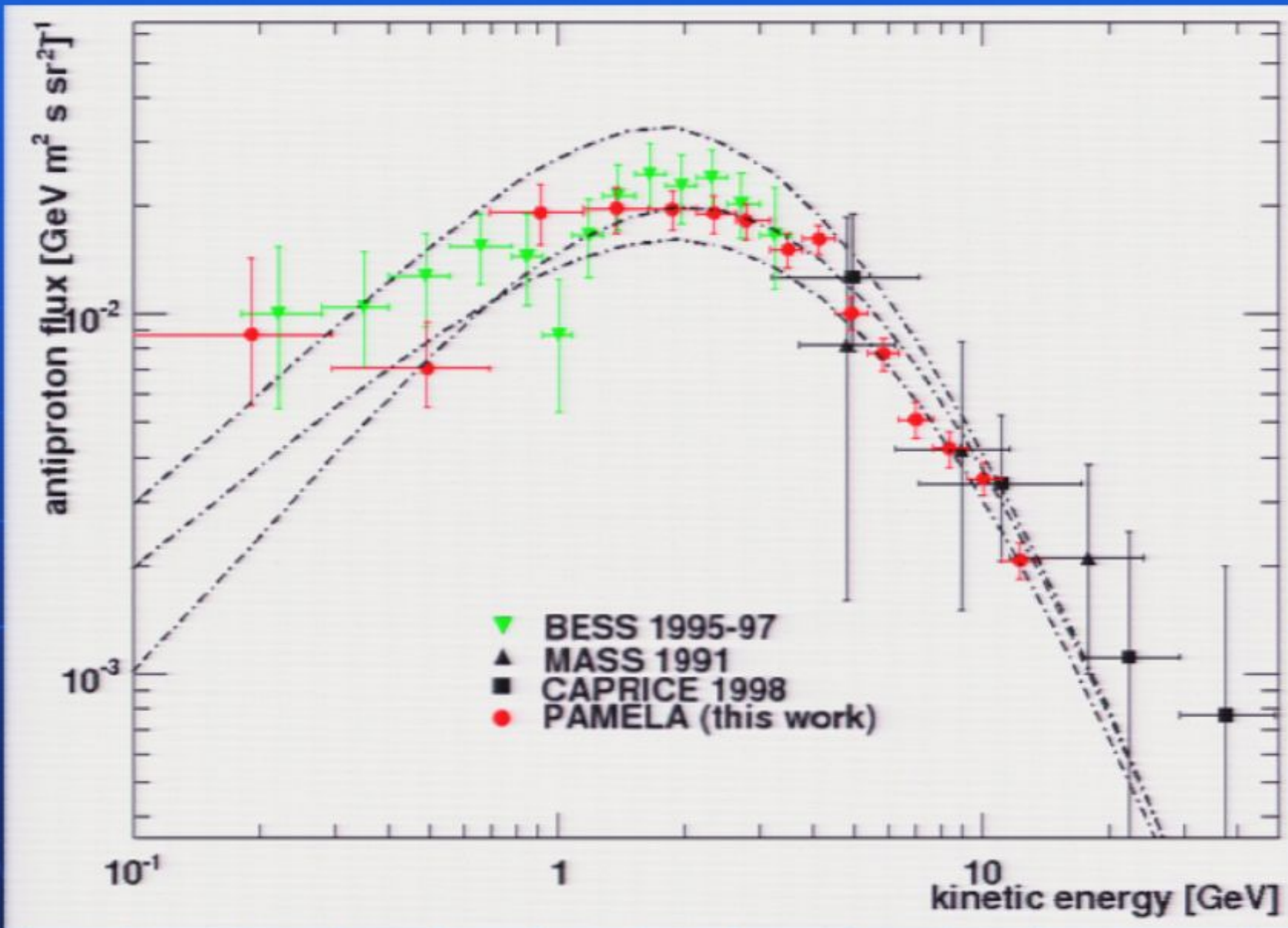
Antiproton to proton ratio



Antiproton Flux Ratio With Density Enhancement



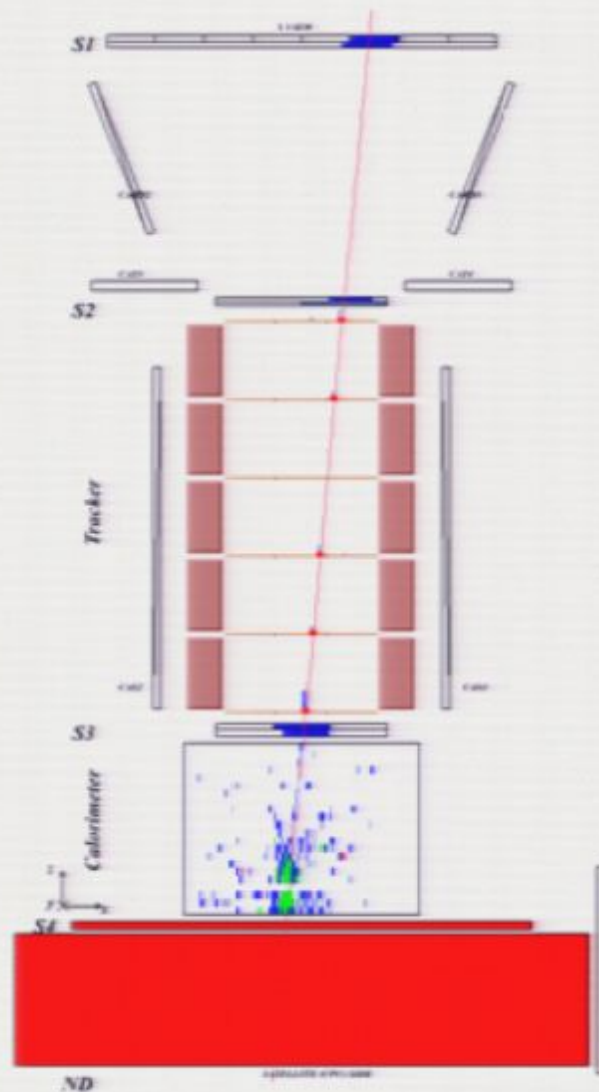




Positrons

- The Analysis has been done using only flight data
- Beam tests and MC simulations only for cross-checks

Proton / positron selection

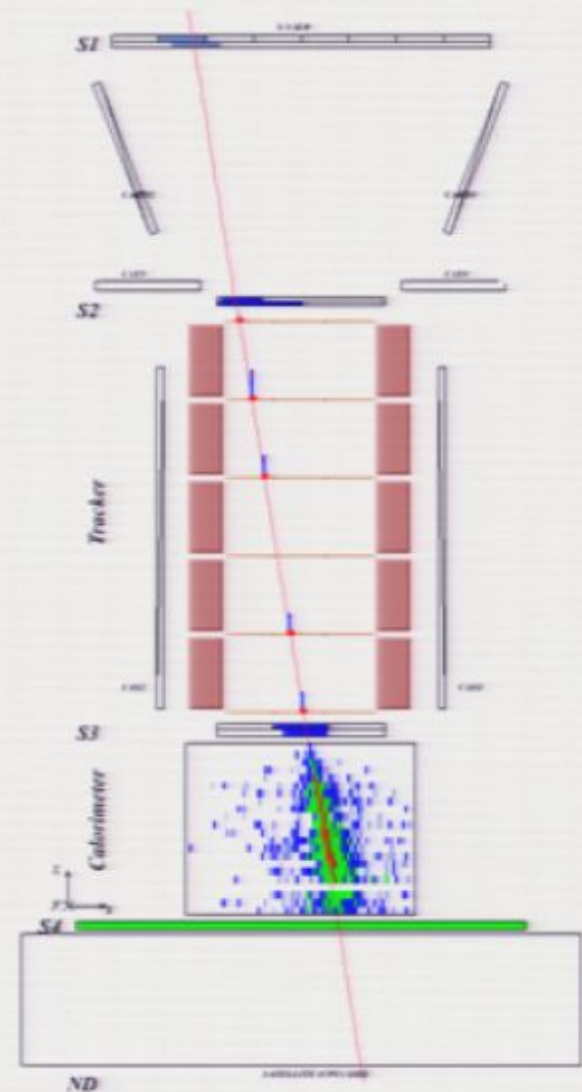


Time-of-flight:
trigger, albedo
rejection, mass
determination (up
to 1 GeV)

Bending in
spectrometer:
sign of charge

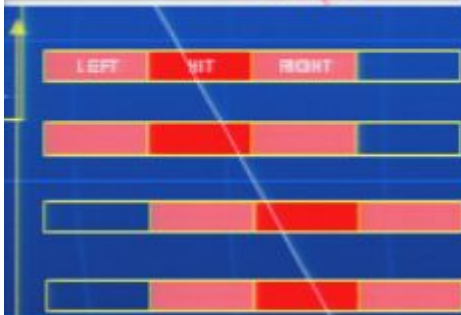
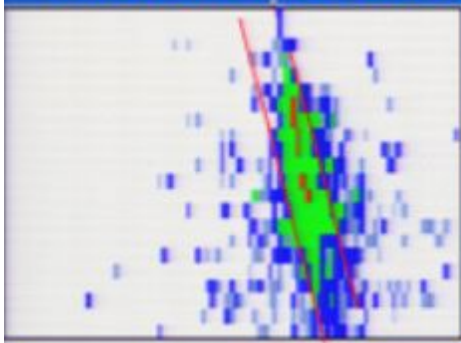
Ionisation energy
loss (dE/dx):
magnitude of charge

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



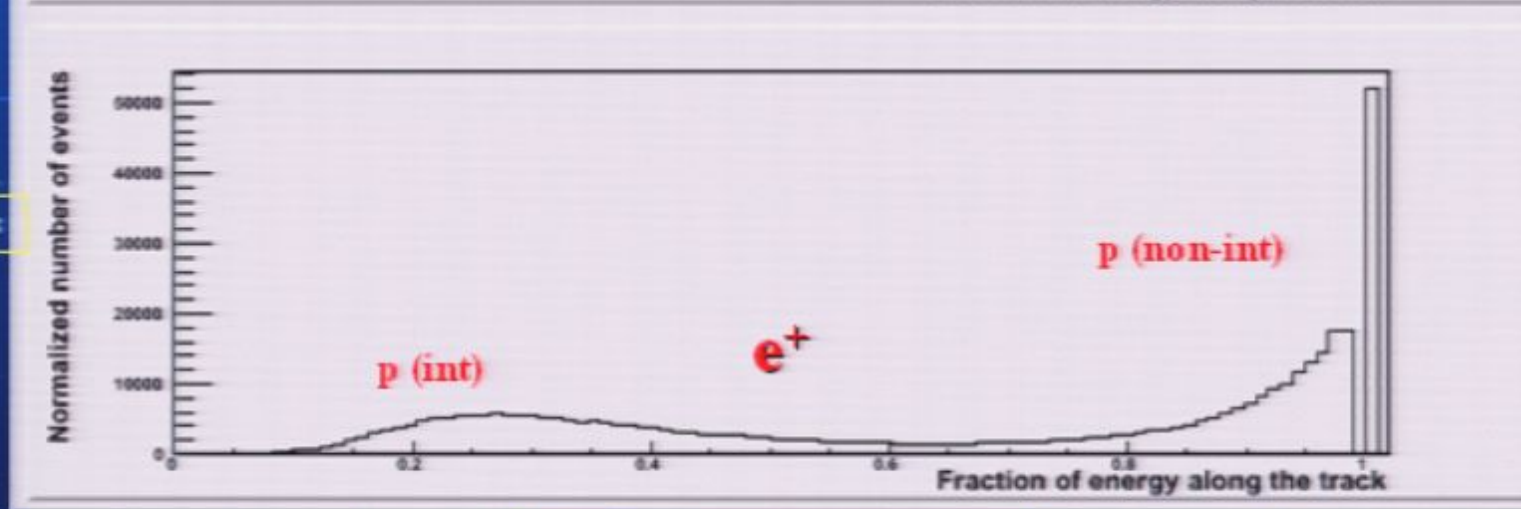
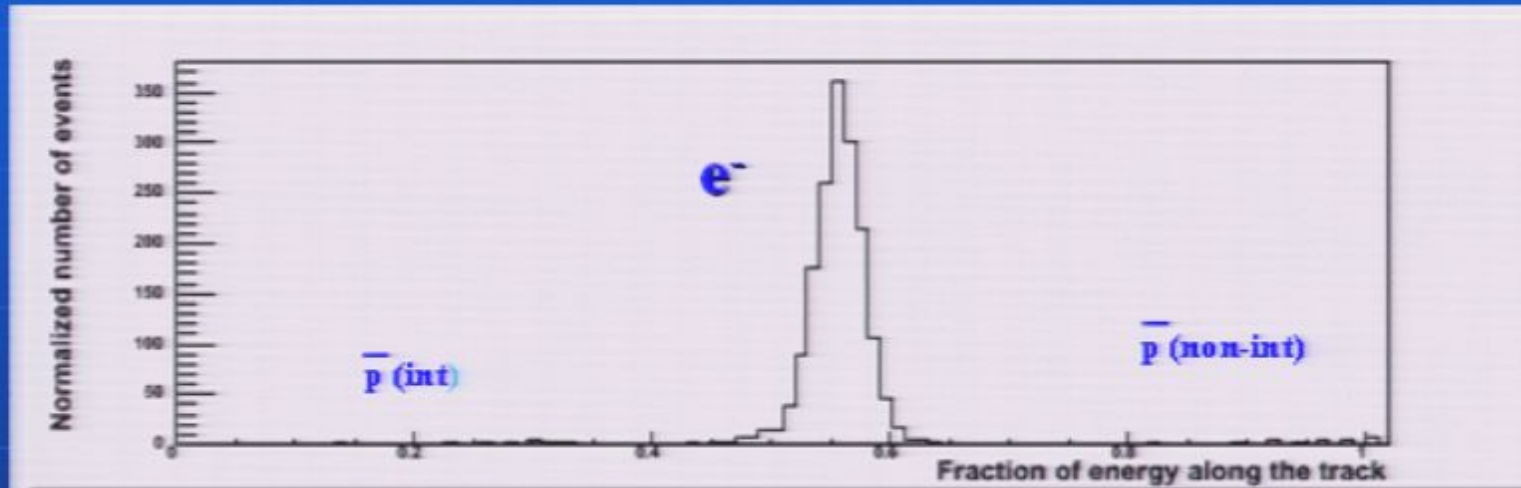
Positron selection with calorimeter

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



strips

$0.6 R_M$

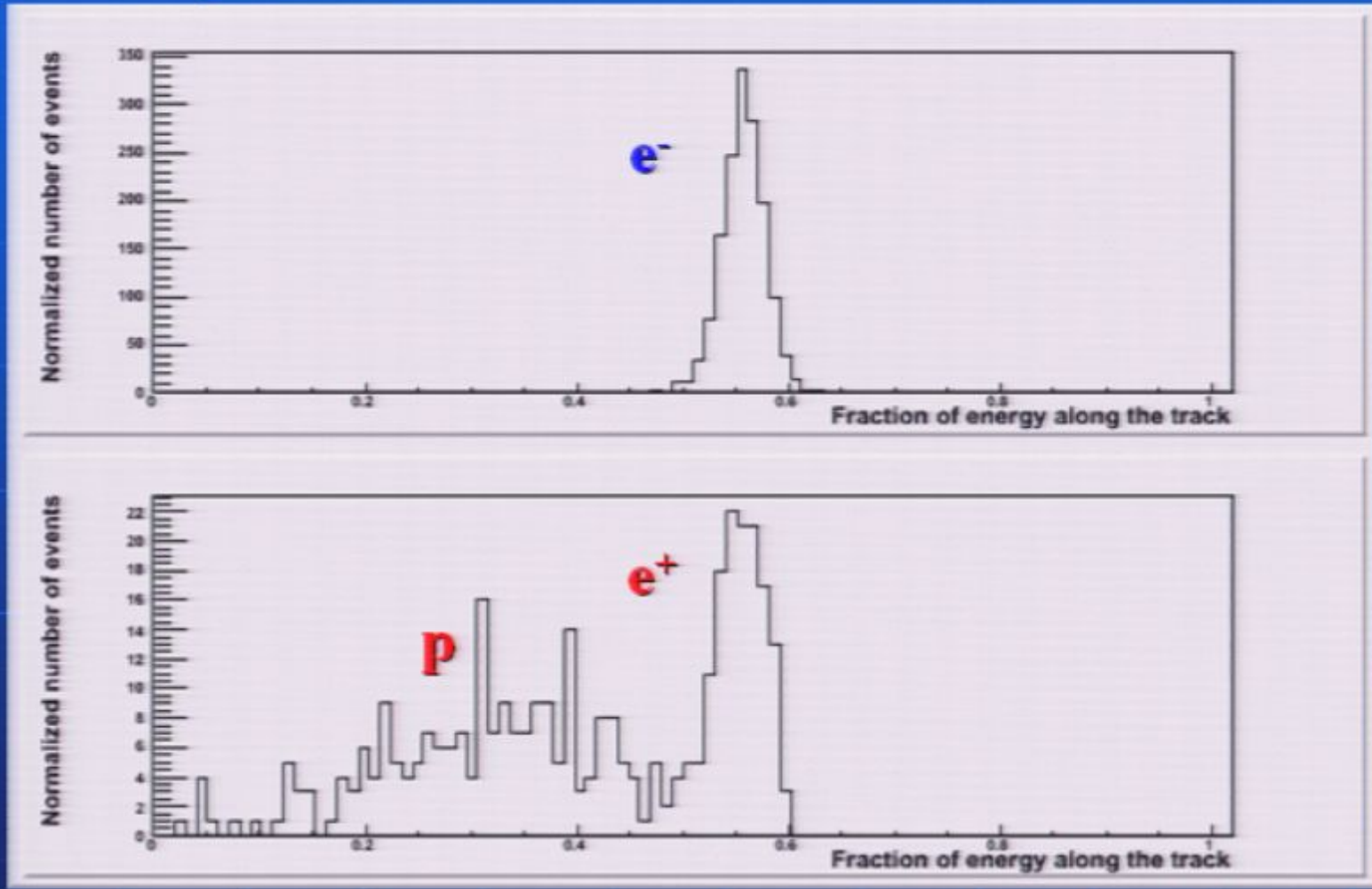


for em showers
100% of E contained
1.4 R

Rigidity: 20-30 GV

Positron selection with calorimeter

Rigidity: 20-30 GV



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

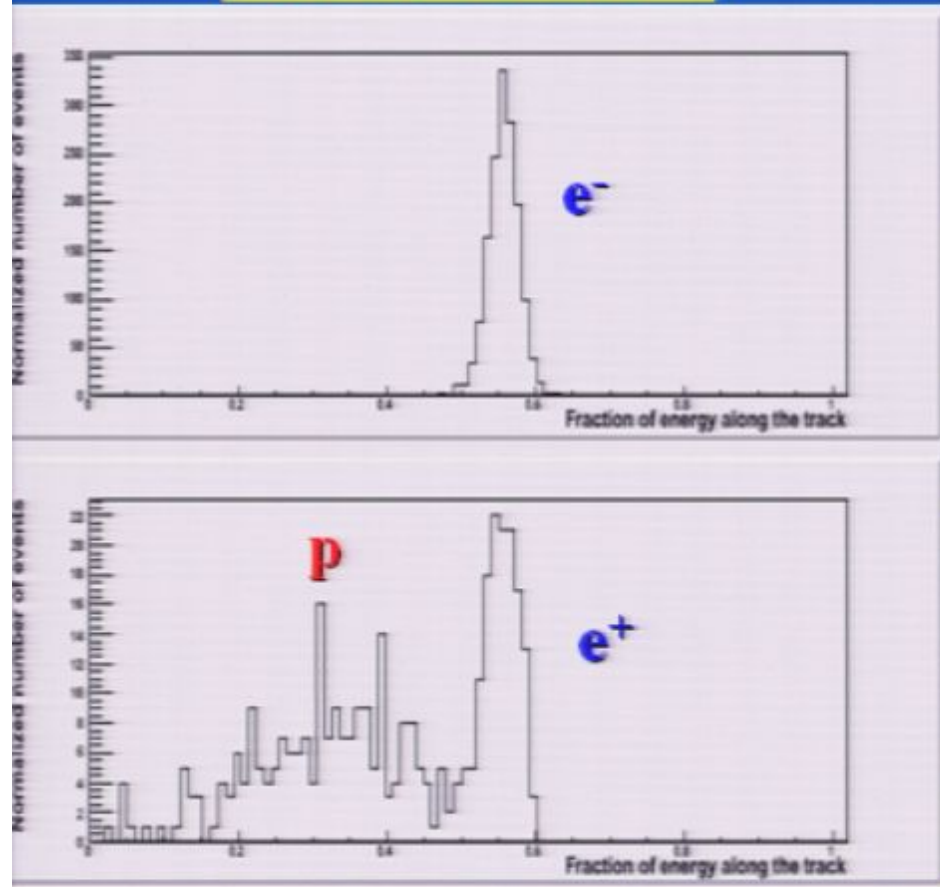
+

Energy-momentum match
Starting point of shower

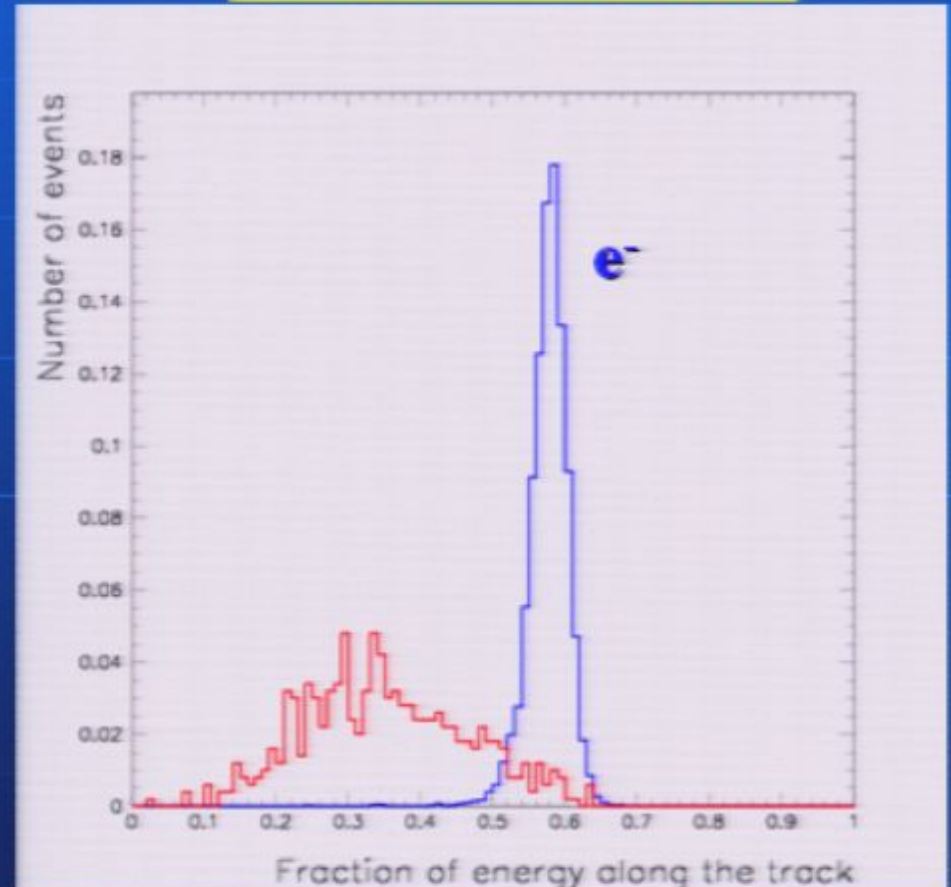
Positron selection with calorimeter

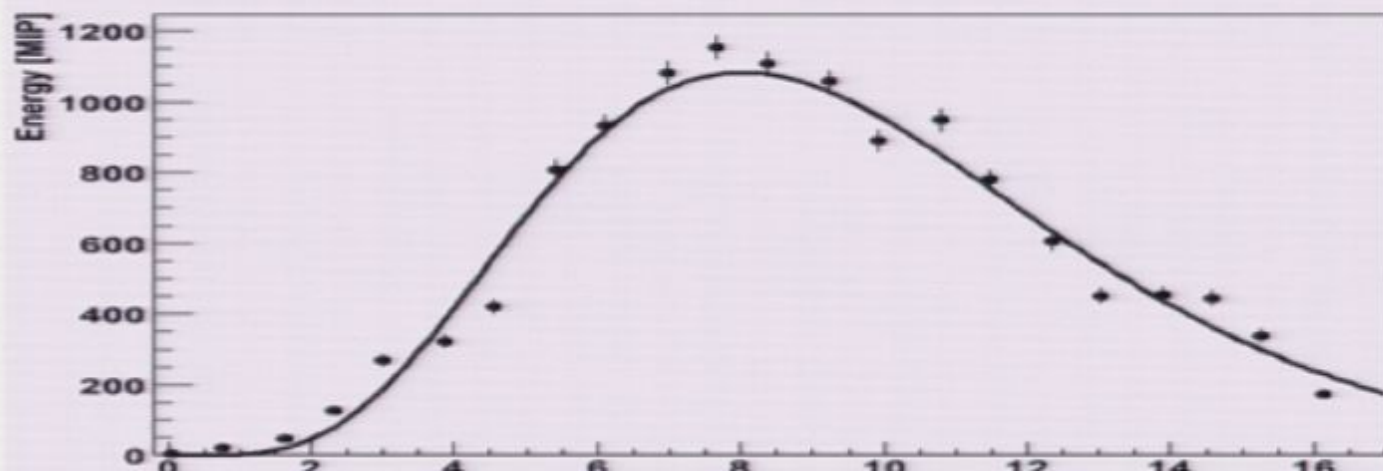
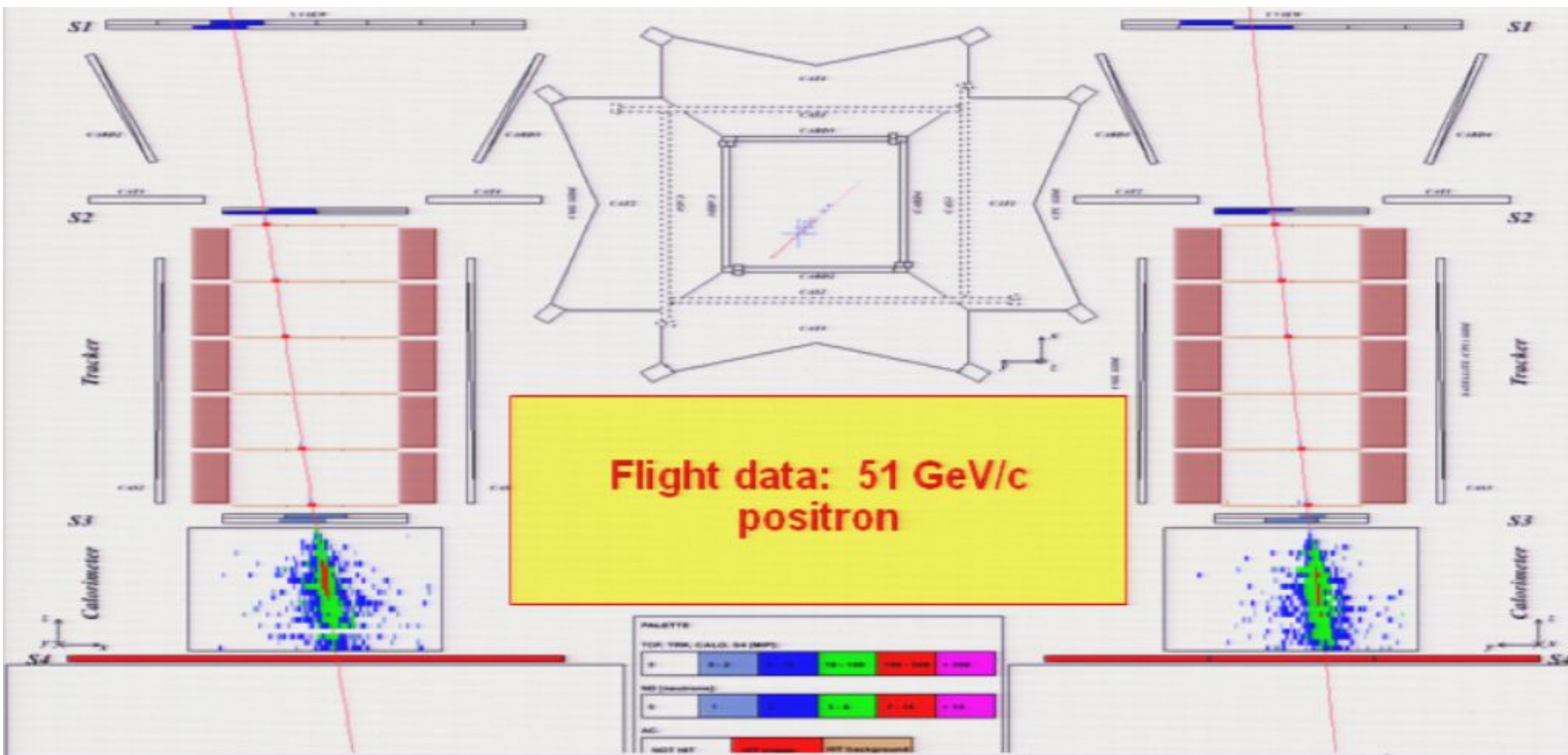
Fraction of charge released along the calorimeter track
(left, hit, right)

Flight data:
rigidity: 20-30 GV



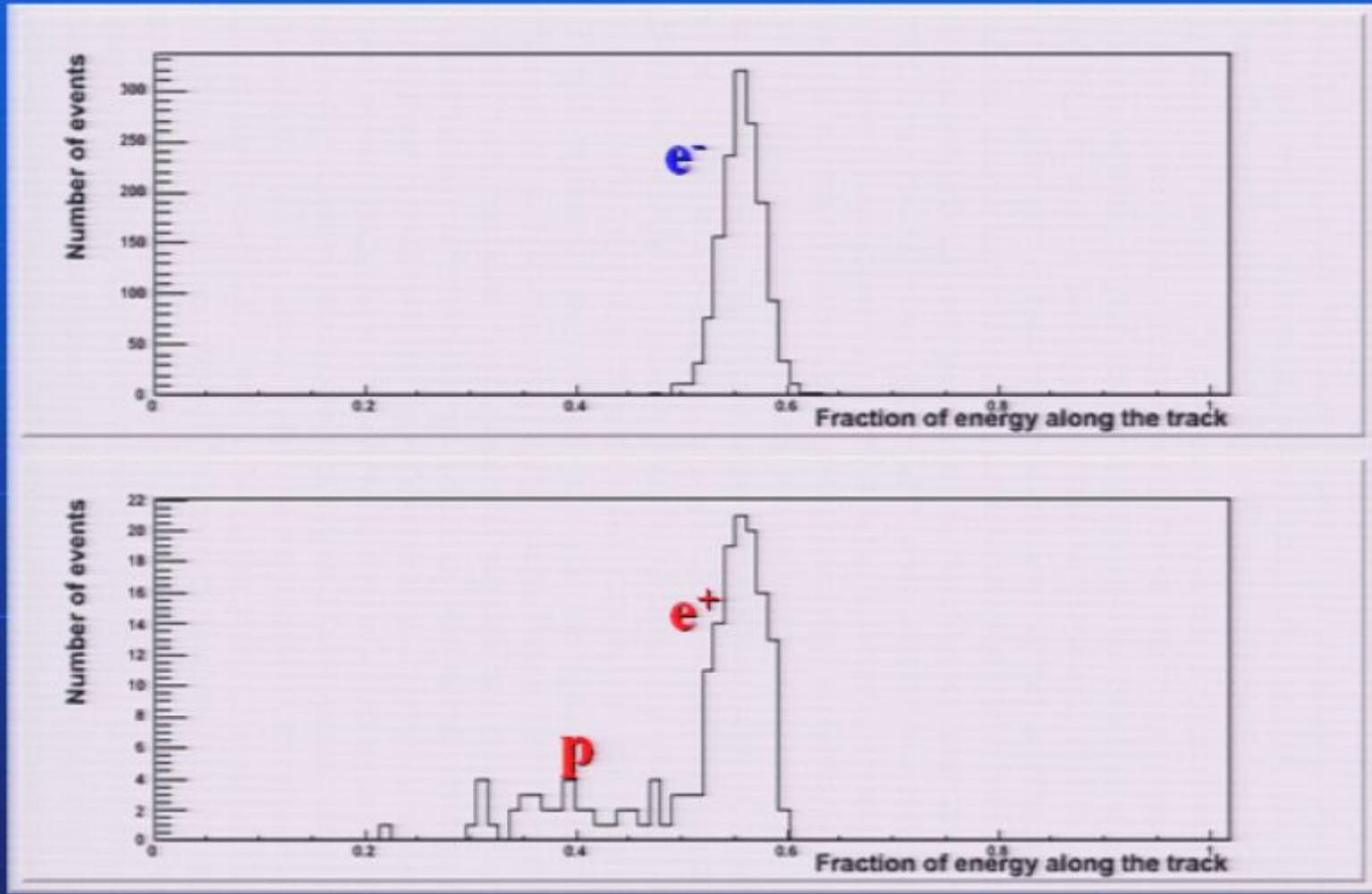
Test beam data
Momentum: 50 GeV/c





Positron selection with calorimeter

Rigidity: 20-30 GV



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

+

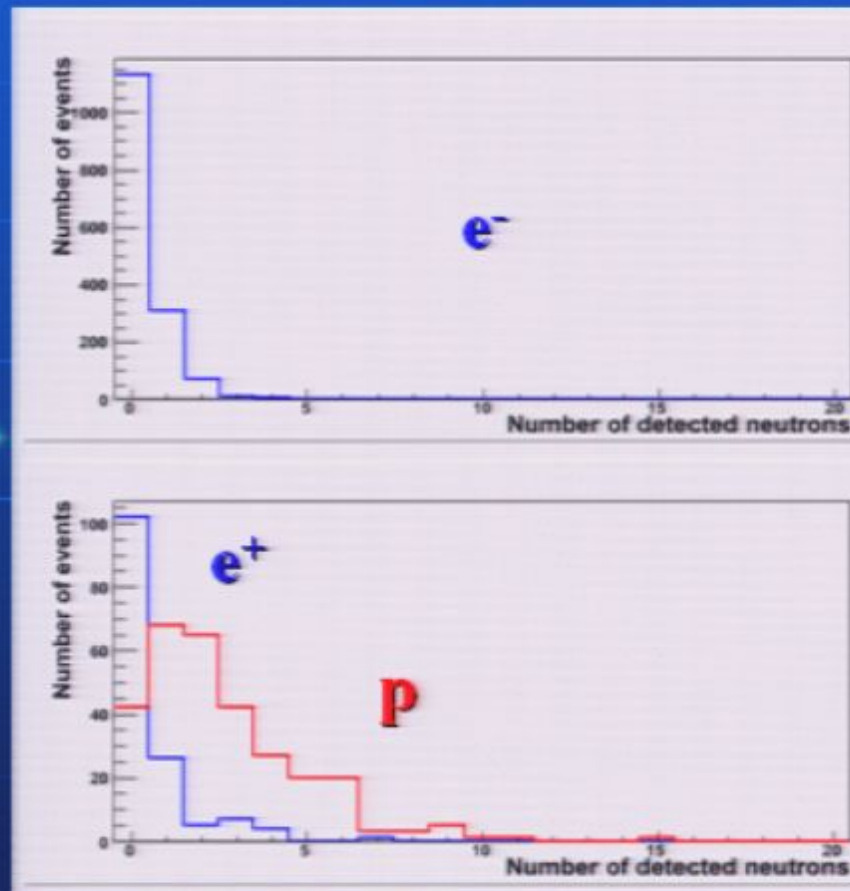
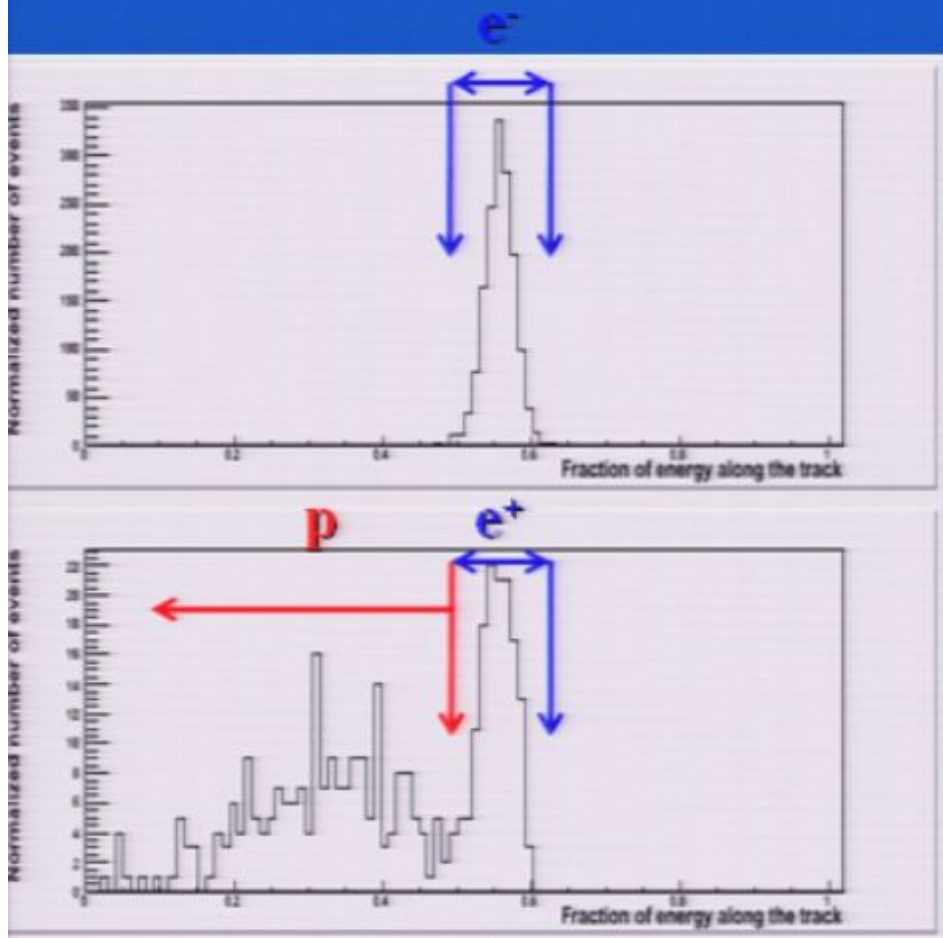
- Energy-momentum match
- Starting point of shower
- Longitudinal profile

Positron selection

Rigidity: 20-30 GV

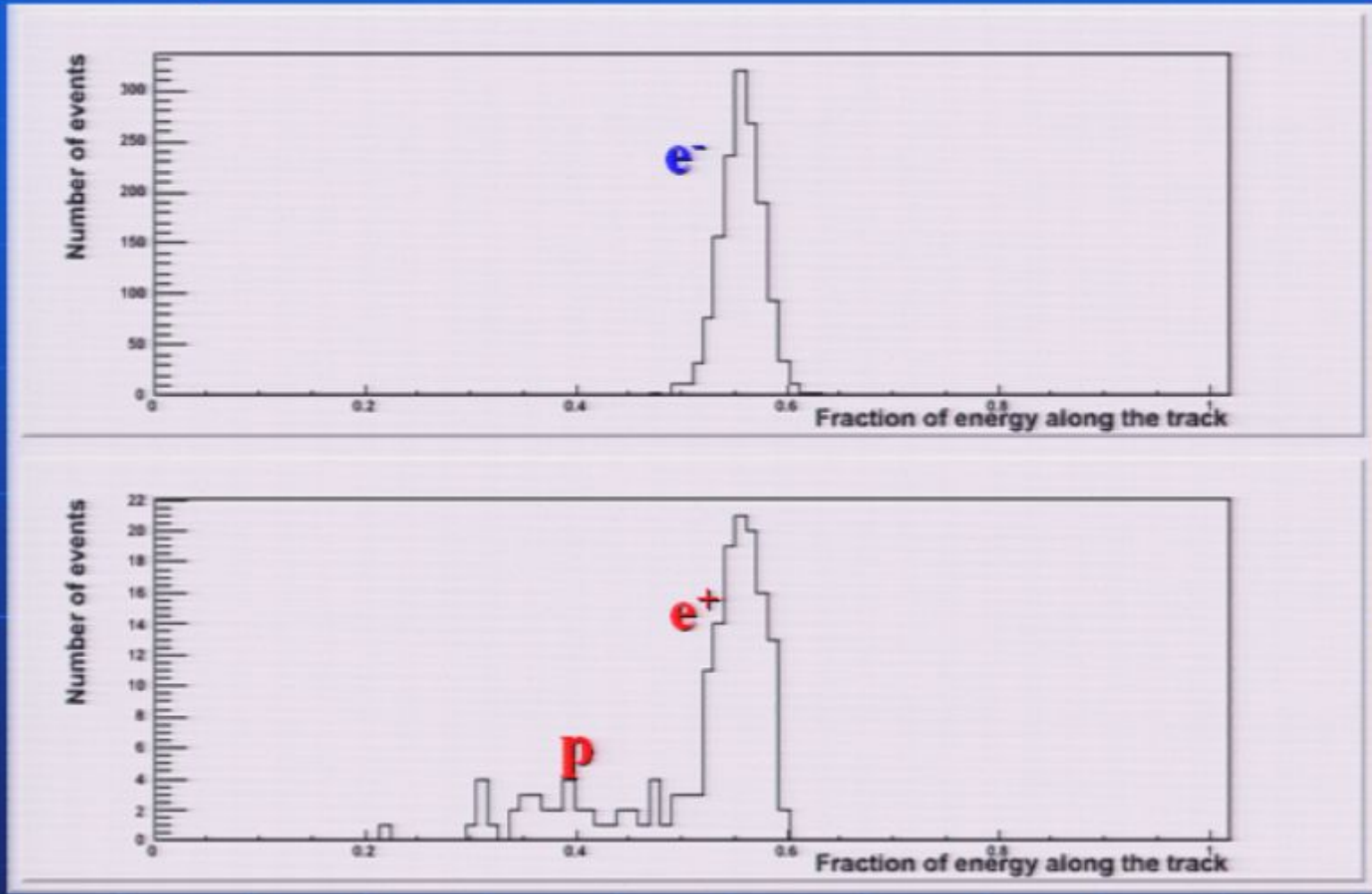
Fraction of charge released along the calorimeter track (left, hit, right)

Neutrons detected by ND



Positron selection with calorimeter

Rigidity: 20-30 GV



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

+

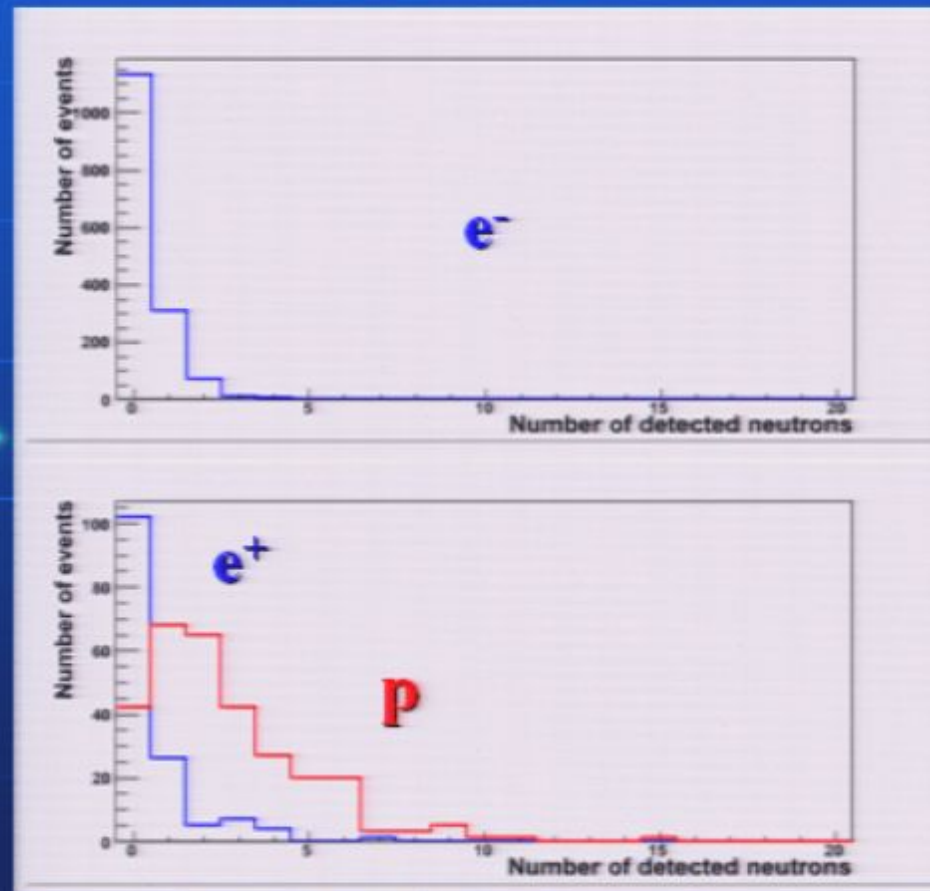
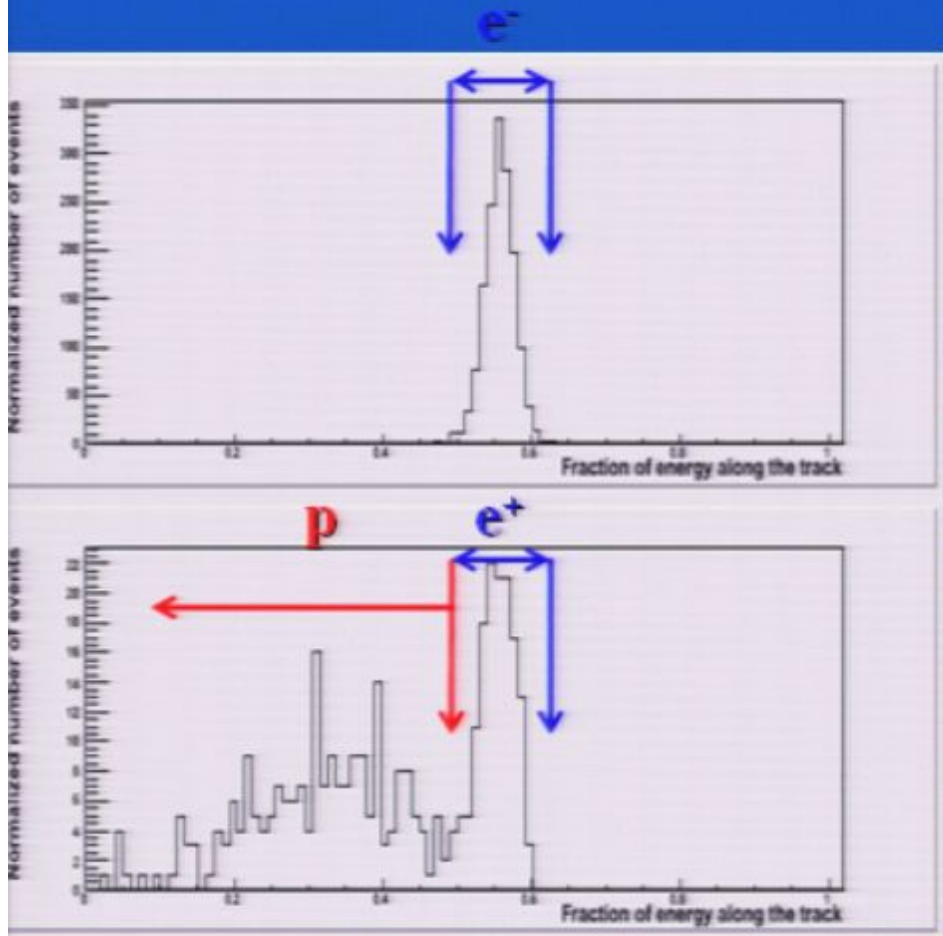
- Energy-momentum match
- Starting point of shower
- Longitudinal profile

Positron selection

Rigidity: 20-30 GV

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

Neutrons detected by ND



The “pre-sampler” method

CALORIMETER: 22 W planes: 16.3 X_0



The “pre-sampler” method

CALORIMETER: 22 W planes: $16.3 X_0$

2 W planes: $\approx 1.5 X_0$

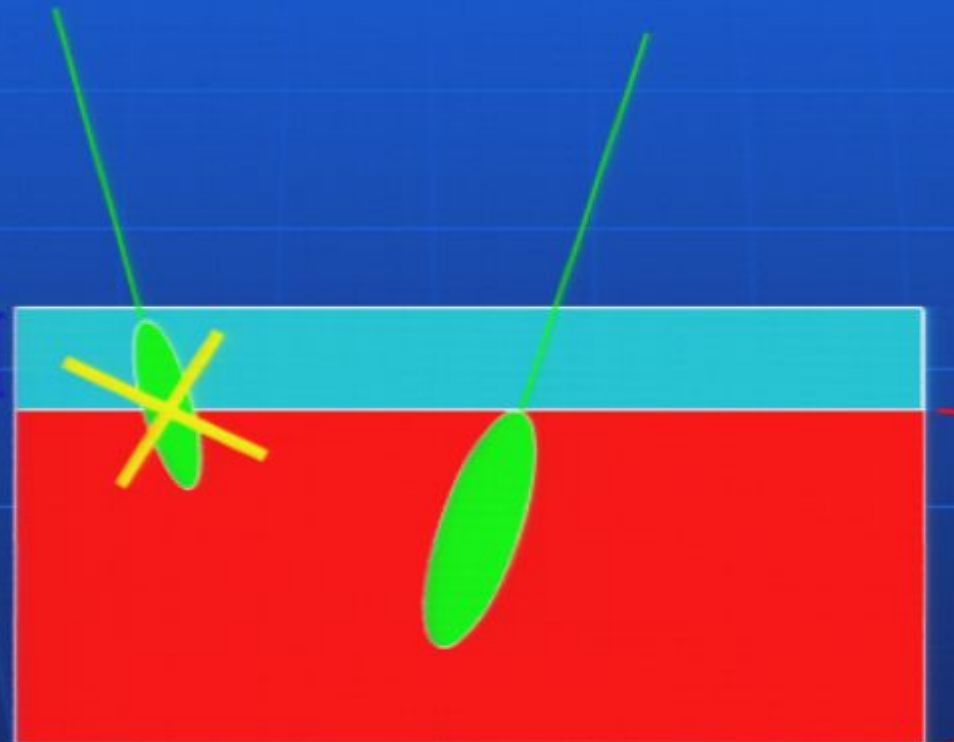


20 W planes: $\approx 15 X_0$

The “pre-sampler” method

CALORIMETER: 22 W planes: $16.3 X_0$

2 W planes: $\approx 1.5 X_0$



20 W planes: $\approx 15 X_0$

The “pre-sampler” method

POSITRON SELECTION



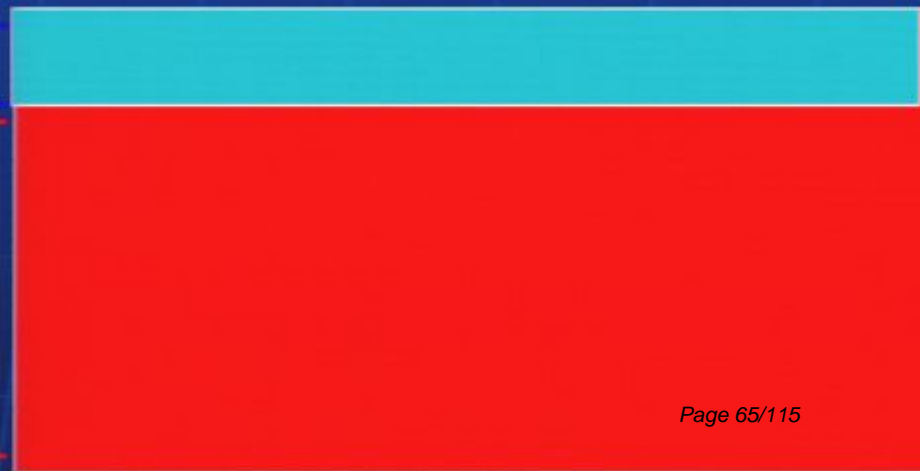
20 W planes: $\approx 15 X_0$

2 W planes: $\approx 1.5 X_0$

PROTON SELECTION

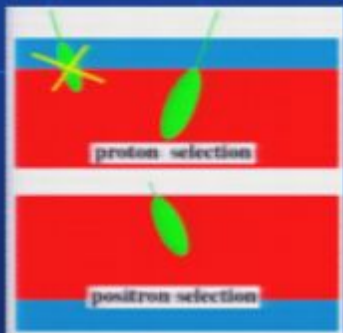
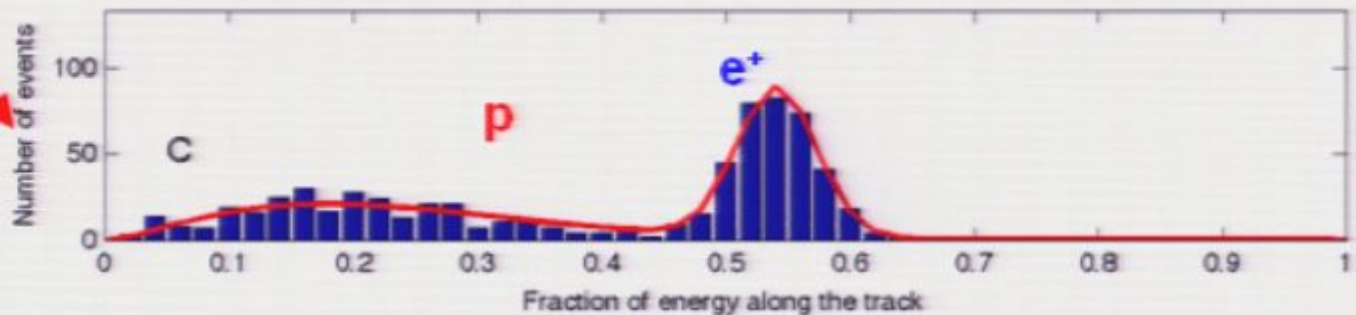
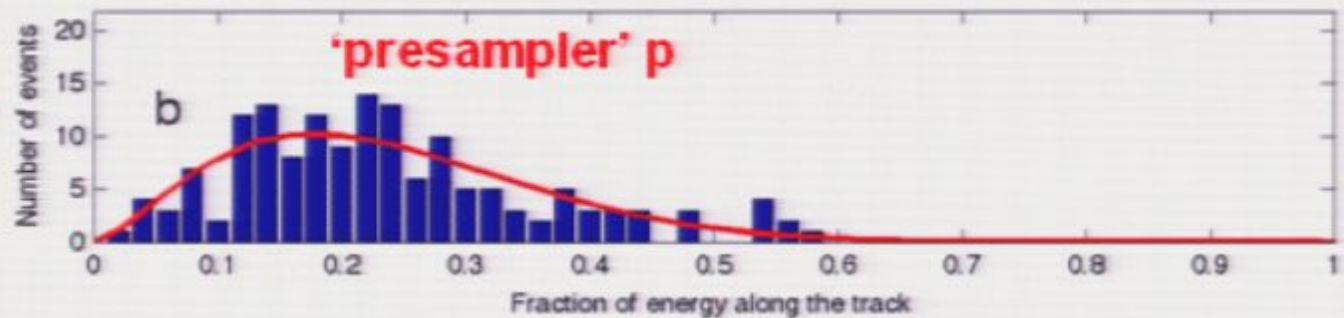
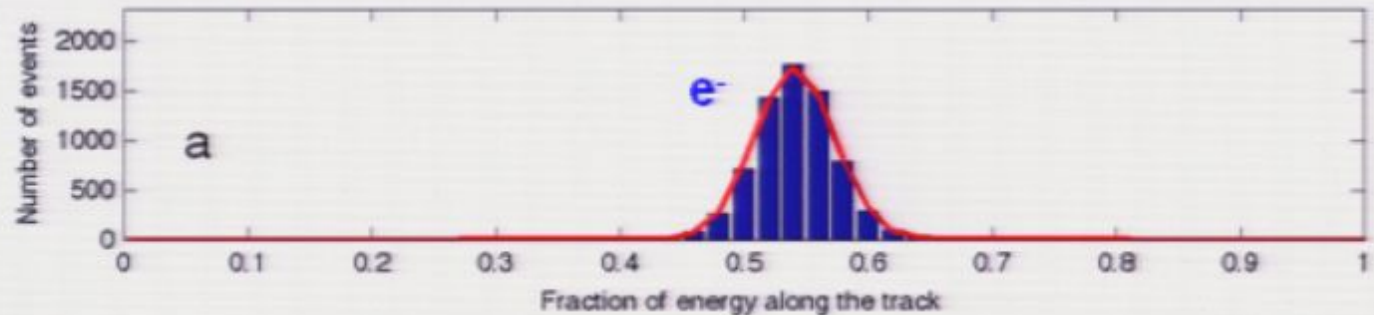
2 W planes: $\approx 1.5 X_0$

20 W planes: $\approx 15 X_0$



e^+ background estimation from data

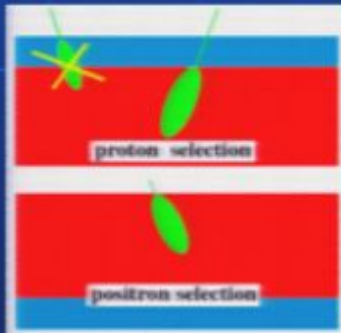
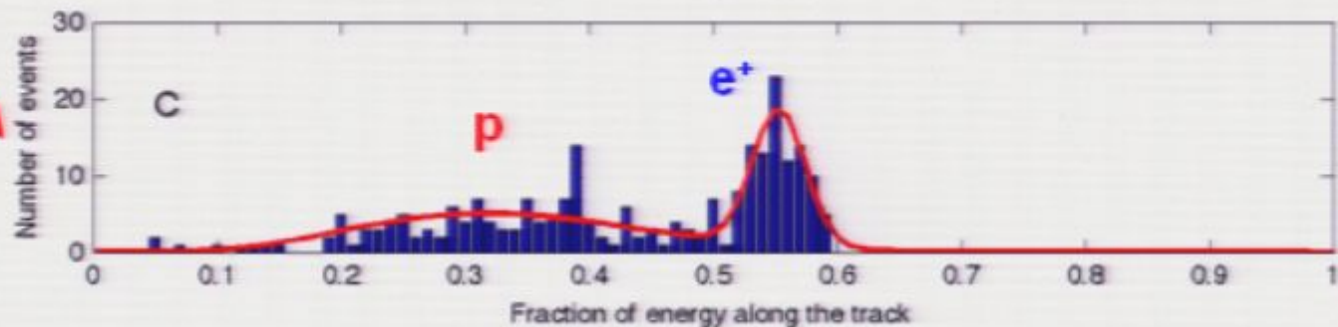
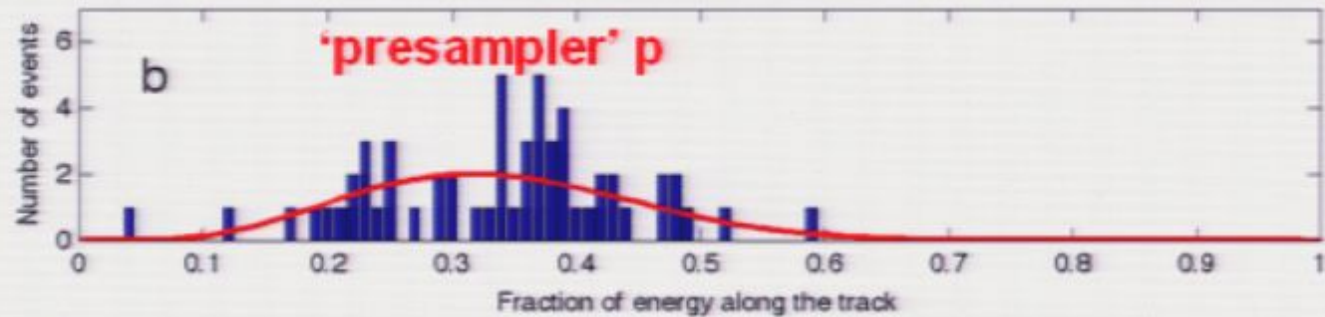
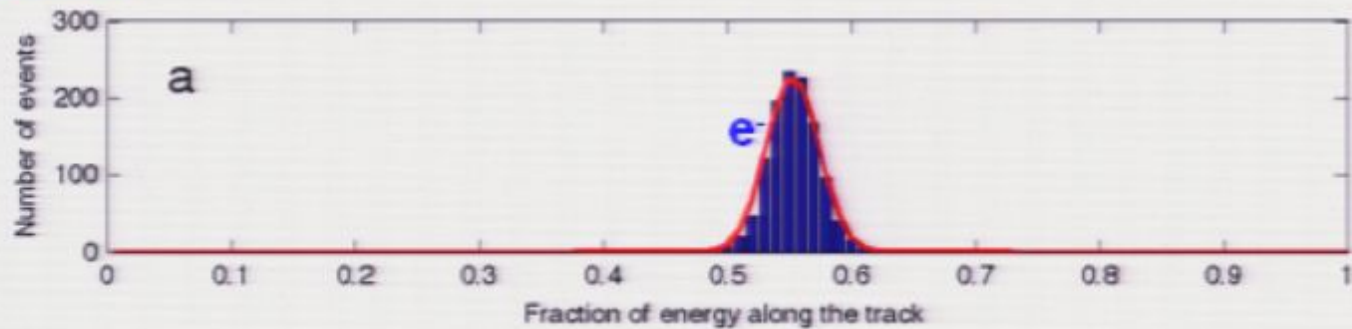
Rigidity: 20-28 GV



- Energy-momentum match
- Starting point of shower

e^+ background estimation from data

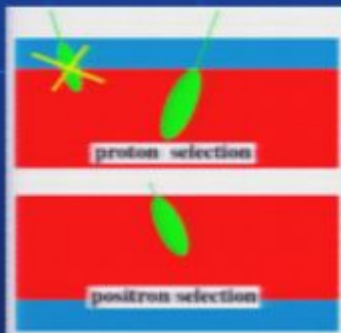
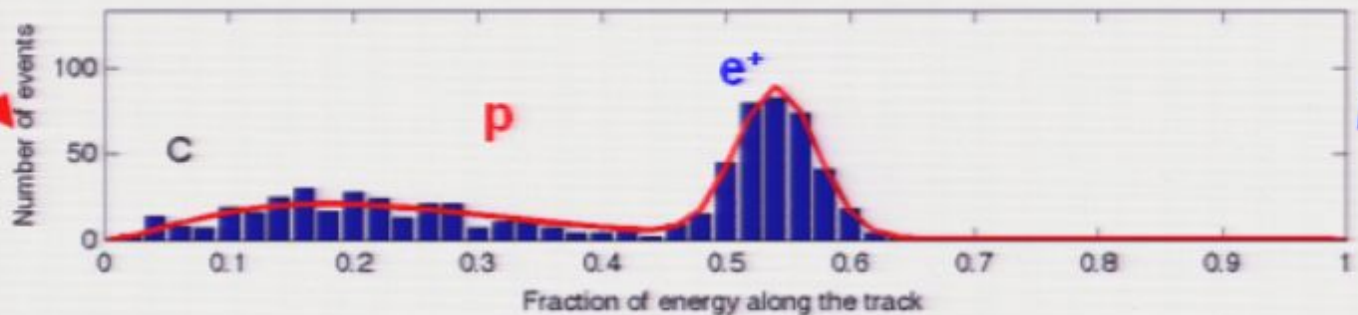
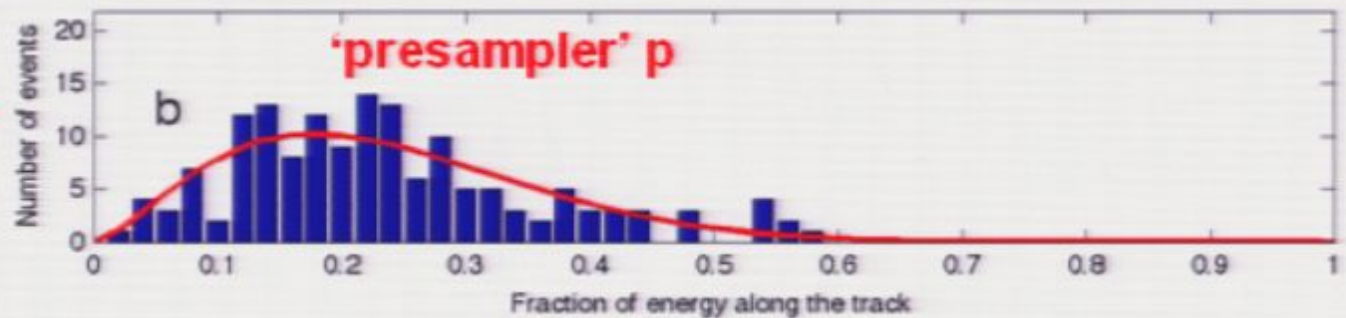
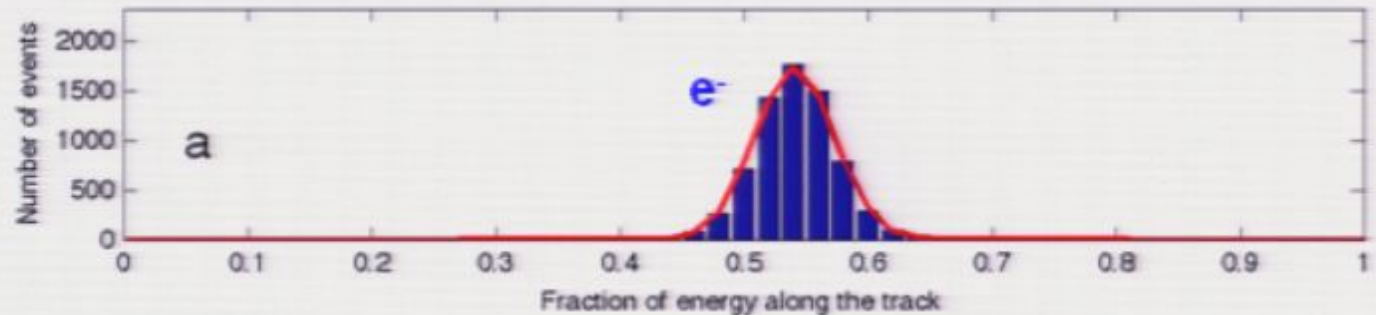
Rigidity: 6.1-7.4 GV



- Energy-momentum match
- Starting point of shower

e^+ background estimation from data

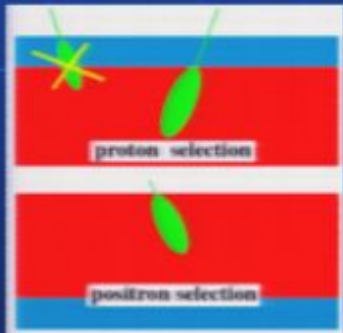
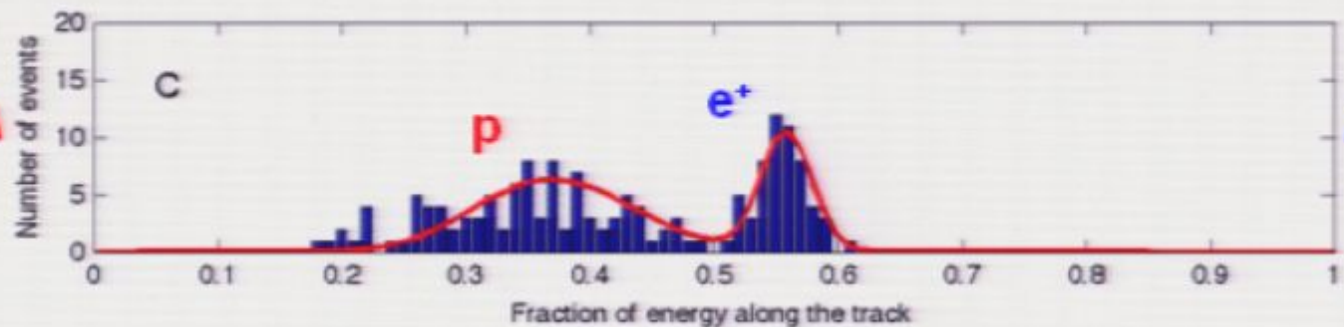
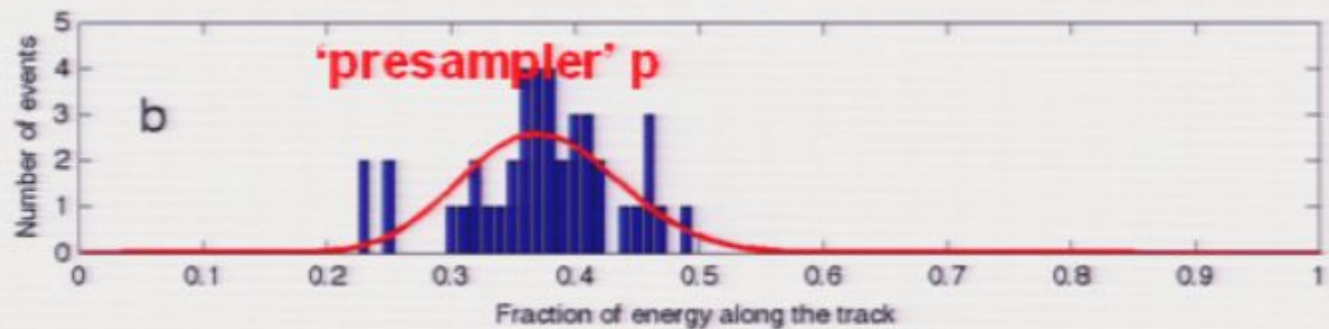
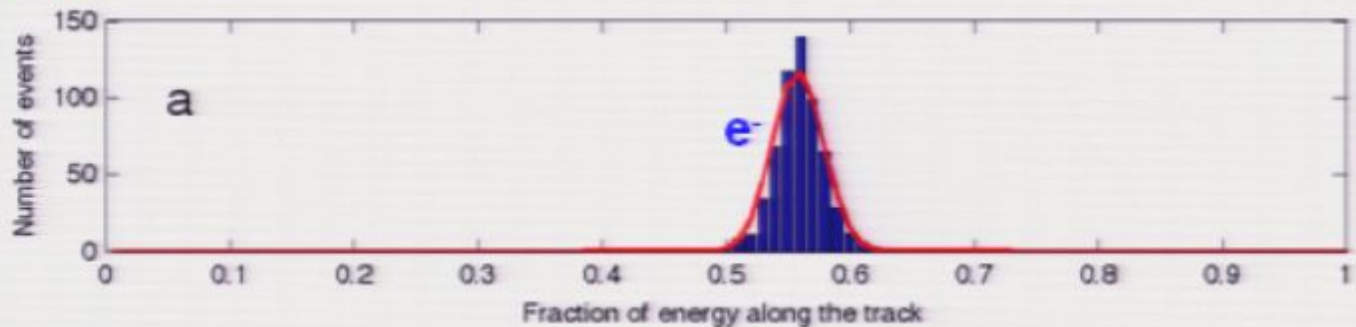
Rigidity: 20-28 GV



- Energy-momentum match
- Starting point of shower

e^+ background estimation from data

Rigidity: 28-42 GV

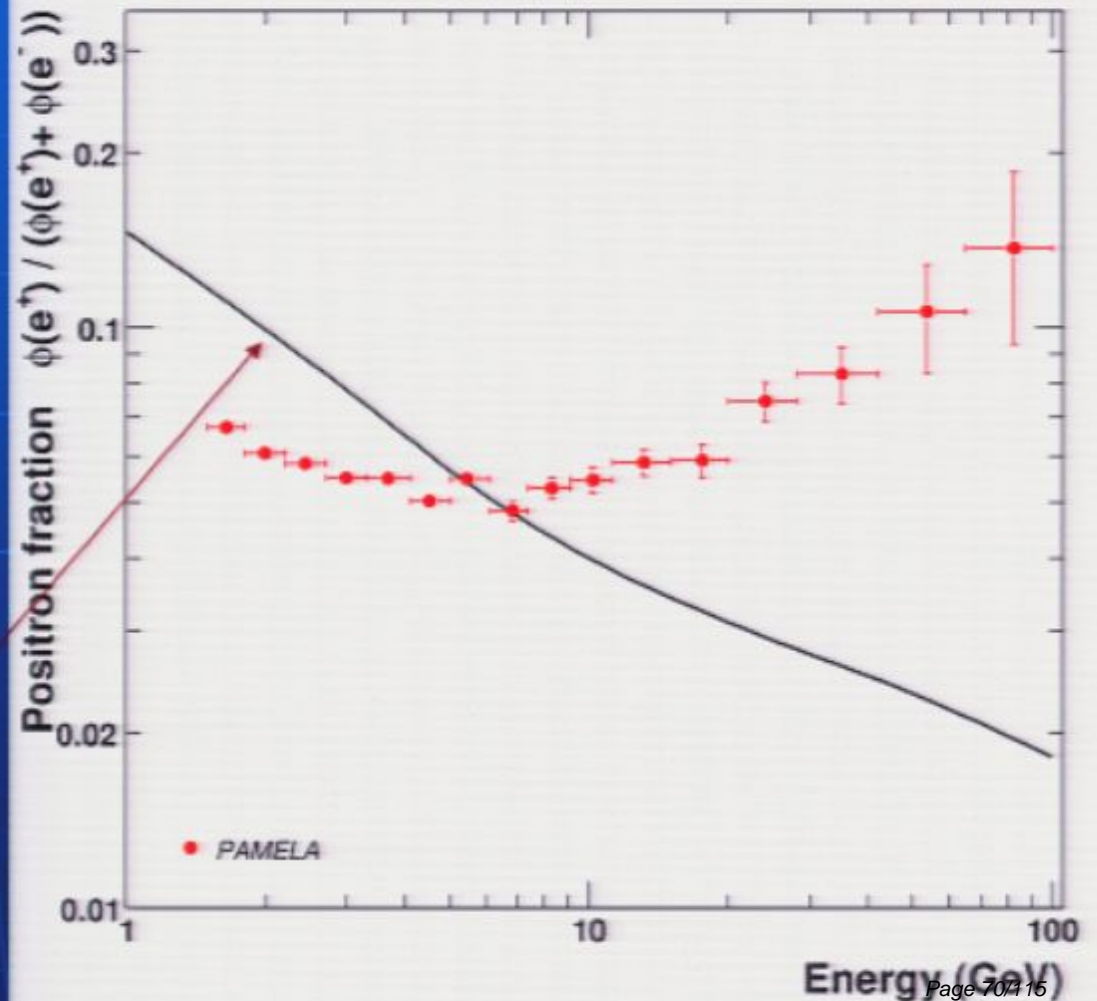


- Energy-momentum match
- Starting point of shower

Positron to all electron ratio

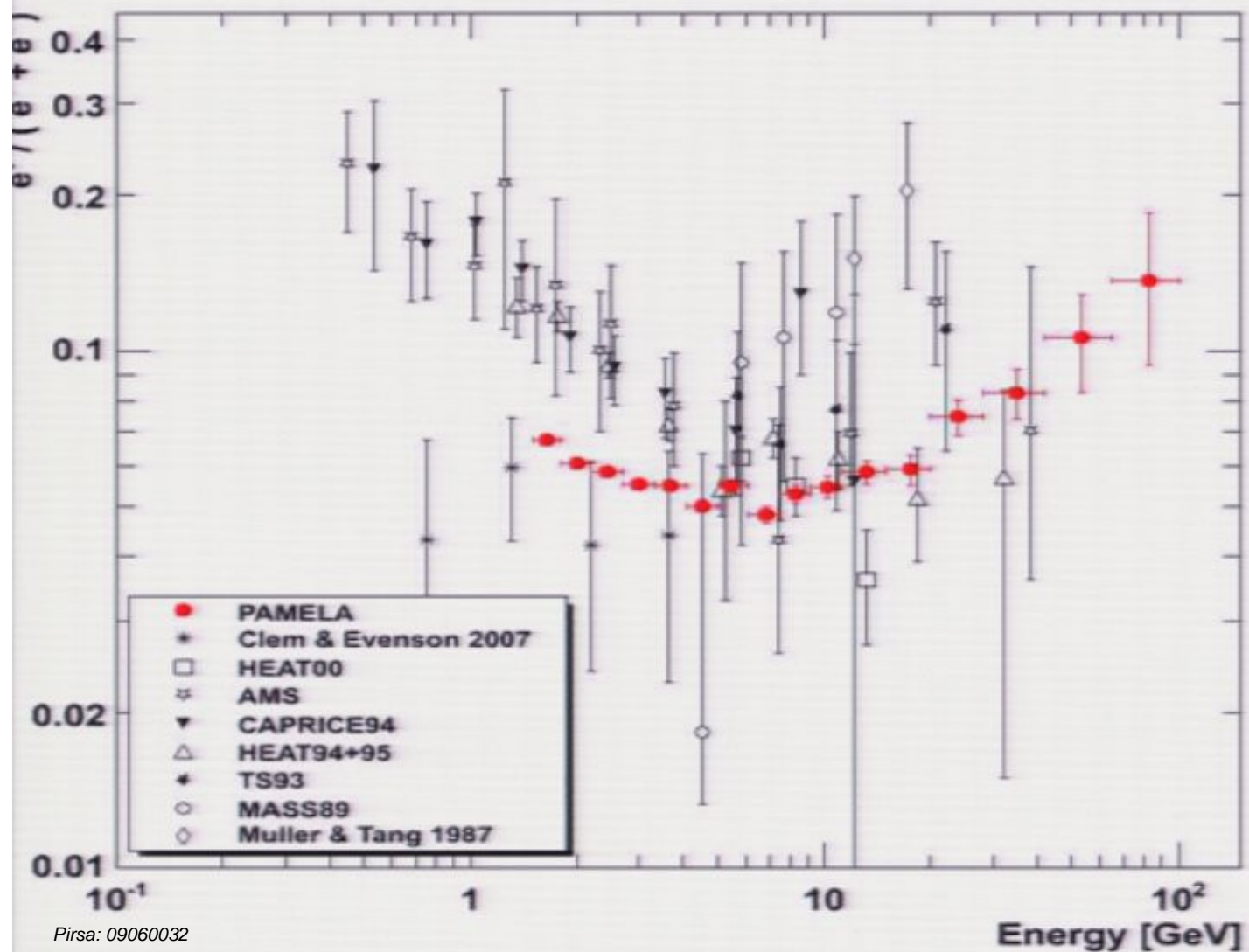
Nature 458, 697, 2009

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

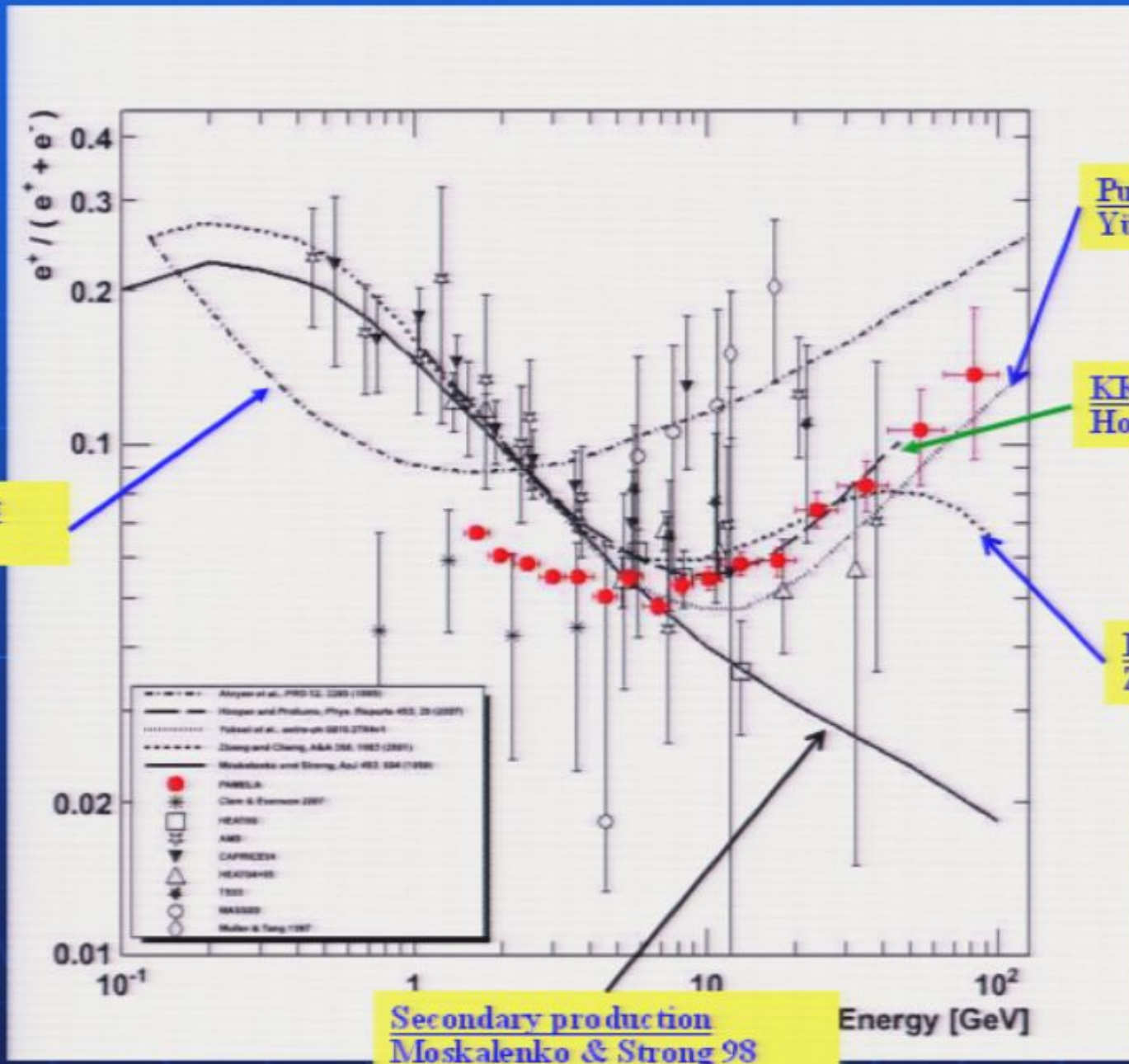


Secondary production
Moskalenko & Strong 98

Positron to all electron ratio

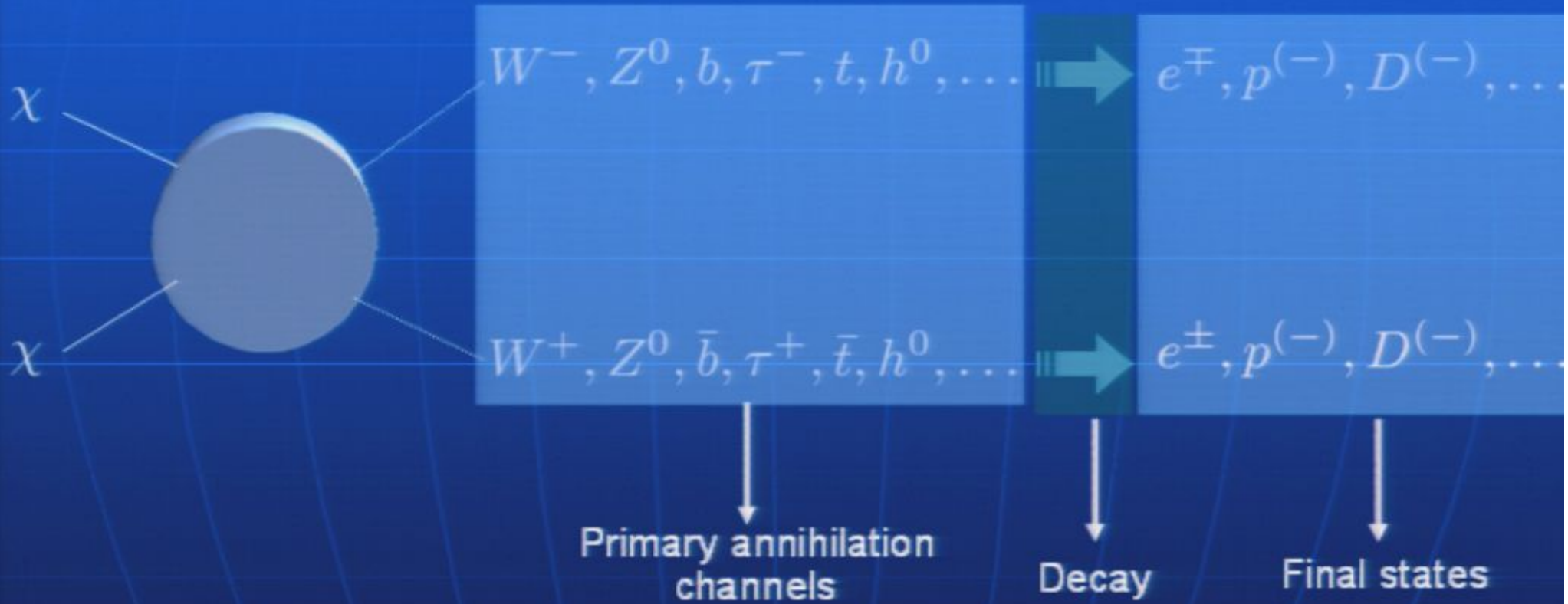


PAMELA Positron Fraction



DM annihilations

DM particles are stable. They can annihilate in pairs.



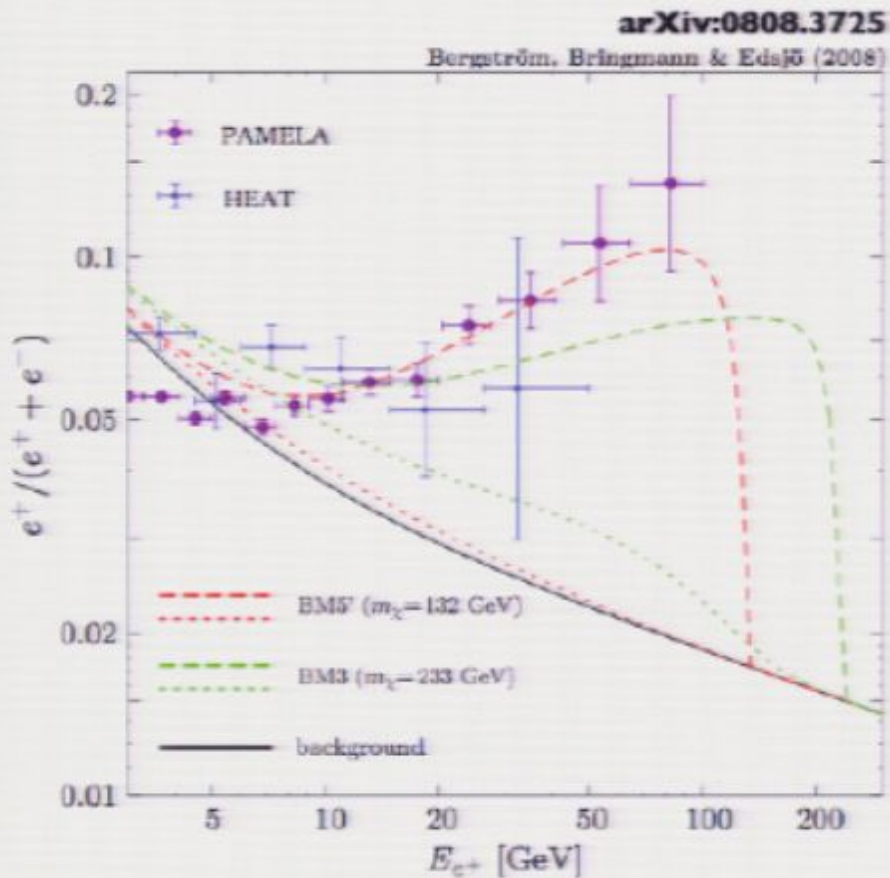
flux $\propto n^2 \sigma_{\text{annihilation}}$
 astro&
 particle

reference cross section:

$$\sigma_{\text{ref}} = 3 \times 10^{-26} \text{ cm}^2$$

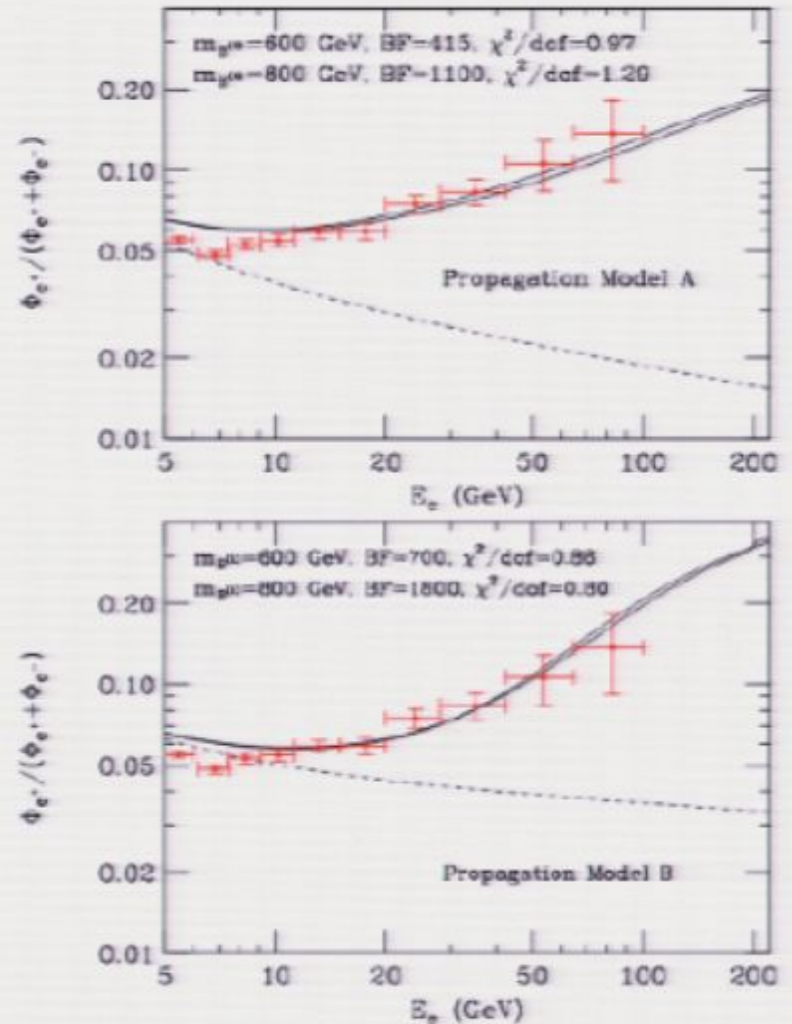
$$\sigma \equiv \langle \sigma v \rangle$$

Example: Dark Matter



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

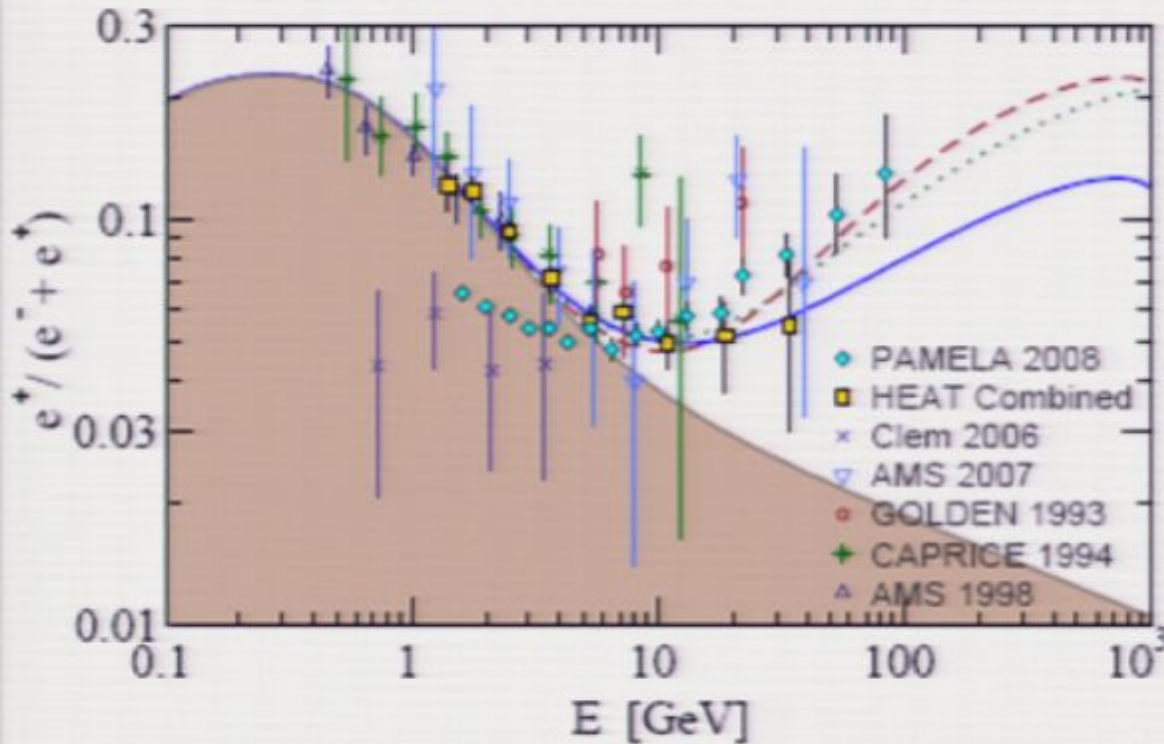
S. Profumo Astro-ph 0812-4457

The rotating magnetic field of the pulsars strips e^- that are accelerated at the polar cap or at the outer gap and 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.

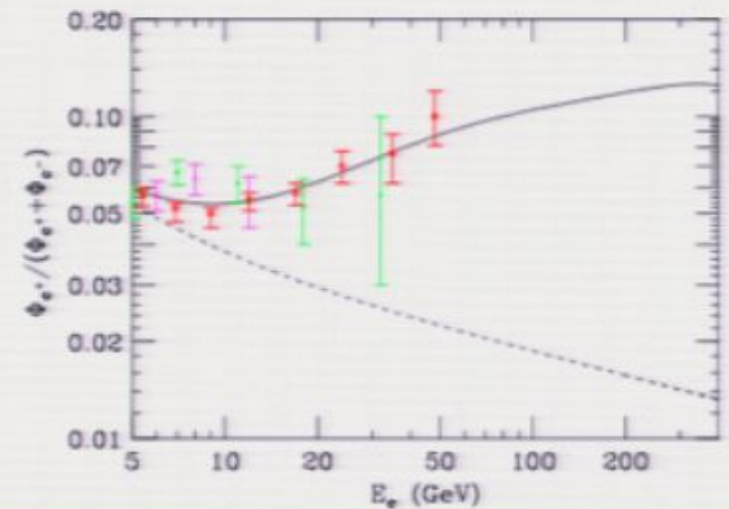
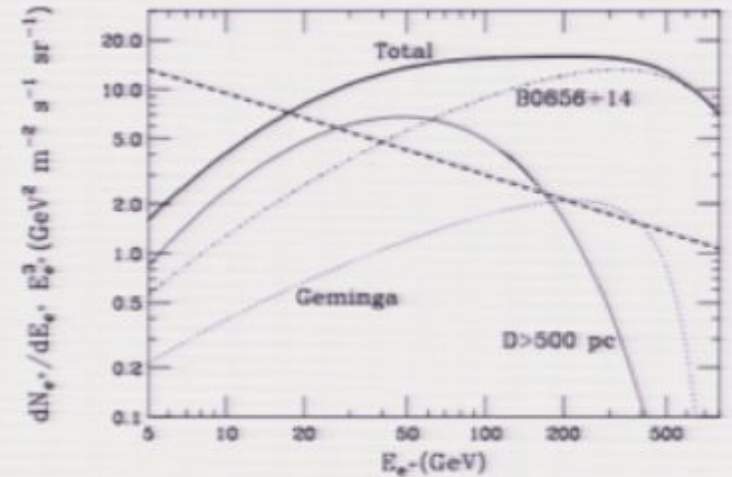
$$E_{tot} \simeq 10^{46} \text{ eV}$$

- 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

Interaction of high energy gamma-rays with star-light

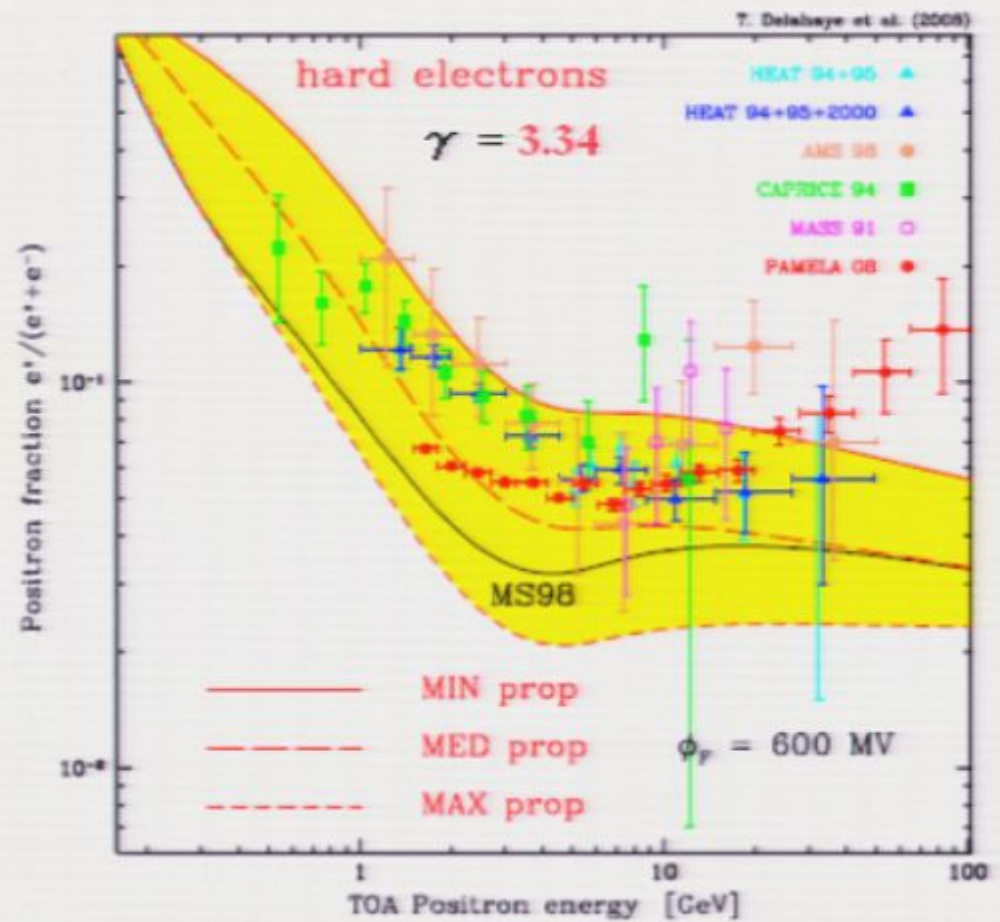
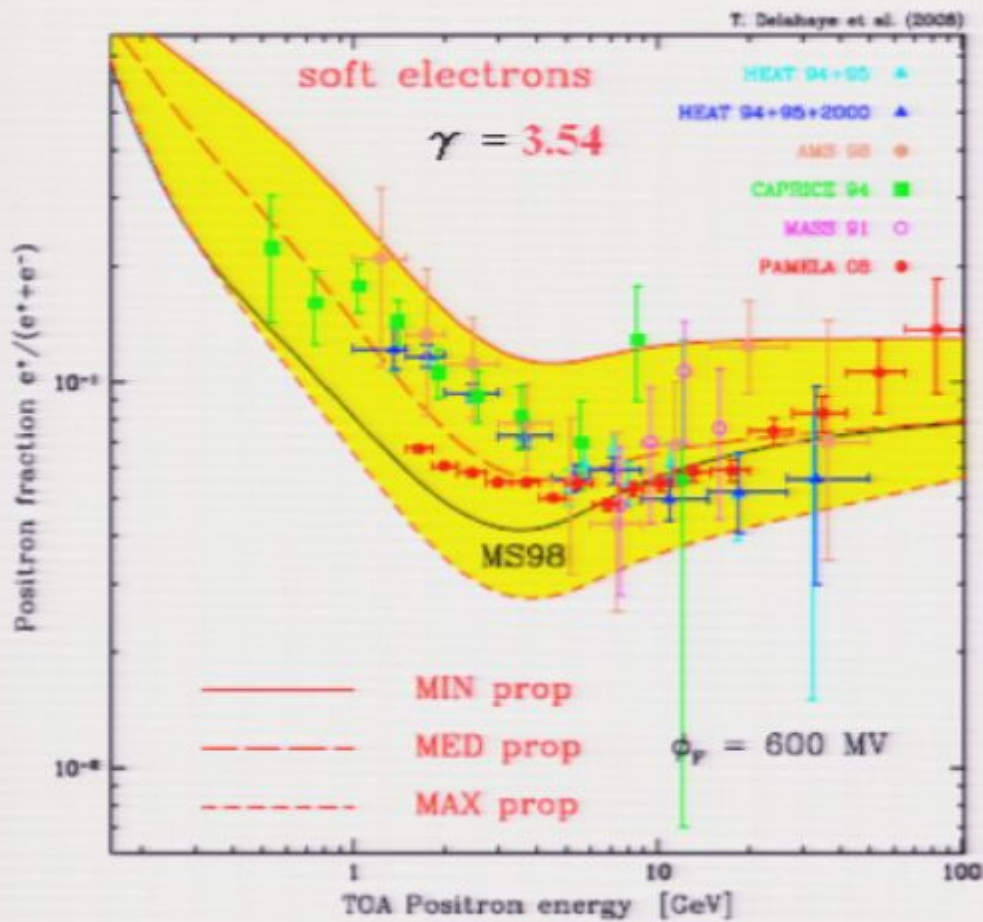
F A Aharonian and A M Atoyan

J. Phys. G: Nucl. Part. Phys. 17 (1991) 1769-1778.

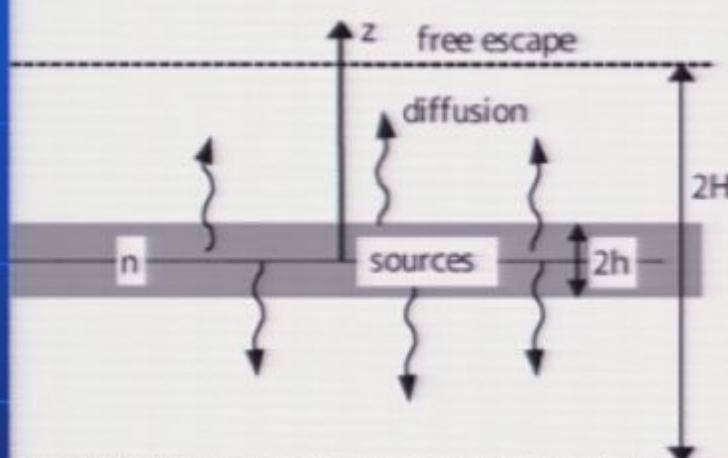
After discovery of TeV binaries like LS5039 and LSI 61 by HESS/Magic/VERITAS in which the powerful production of high and very high energy gamma-rays is accompanied by their absorption (which leads to the modulation of the gamma-ray signal), it is clear that these objects are also sources of electron-positron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

Suggestion from Aharonian

Standard Positron Fraction Theoretical Uncertainties



Cosmic Rays Propagation in the Galaxy

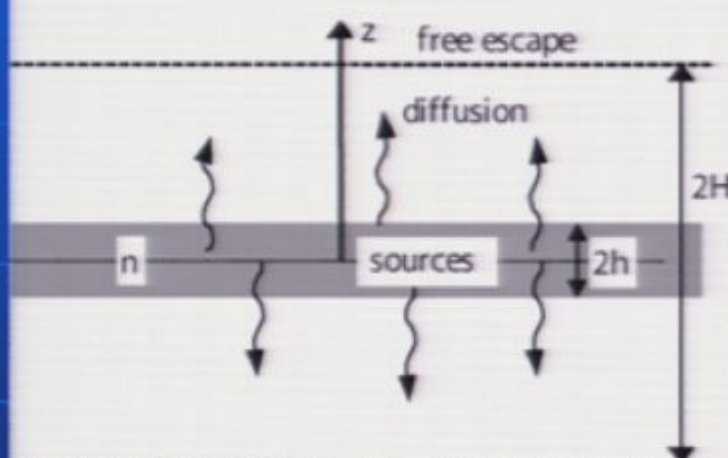


$$\frac{\partial N_i(E, z, t)}{\partial t} = \underbrace{D(E) \cdot \frac{\partial^2}{\partial z^2} N_i(E, z, t)}_{\text{diffusion}} - \underbrace{N_i(E, z, t) \left\{ \frac{1}{\tau_i^{\text{int}}(E, z)} + \frac{1}{\gamma(E) \tau_i^{\text{dec}}} \right\}}_{\text{interaction and decay}}$$

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

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

Cosmic Rays Propagation in the Galaxy



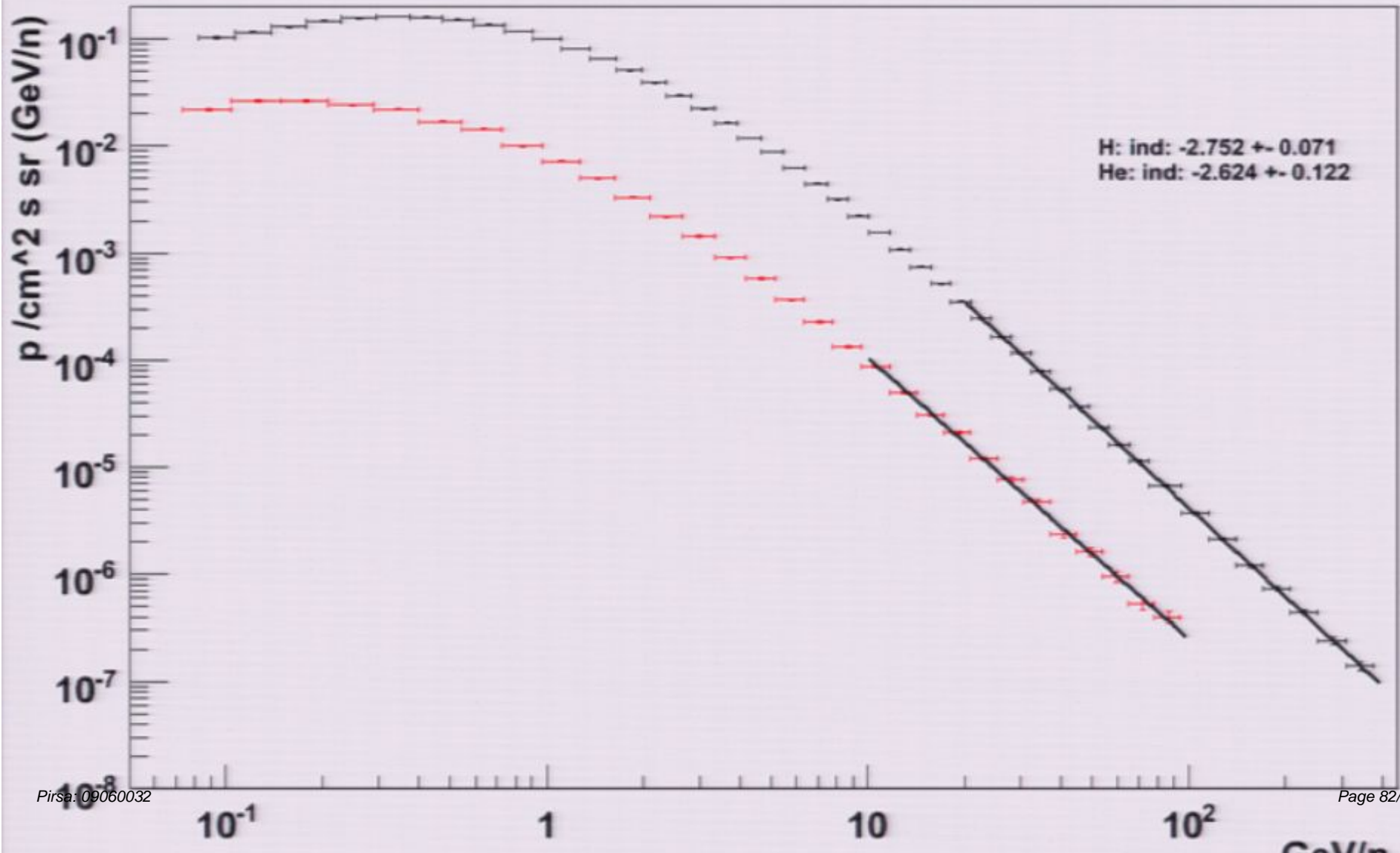
$$\frac{\partial N_i(E, z, t)}{\partial t} = \underbrace{D(E) \cdot \frac{\partial^2}{\partial z^2} N_i(E, z, t)}_{\text{diffusion}} - \underbrace{N_i(E, z, t) \left\{ \frac{1}{\tau_i^{\text{int}}(E, z)} + \frac{1}{\gamma(E) \tau_i^{\text{dec}}} \right\}}_{\text{interaction and decay}}$$

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

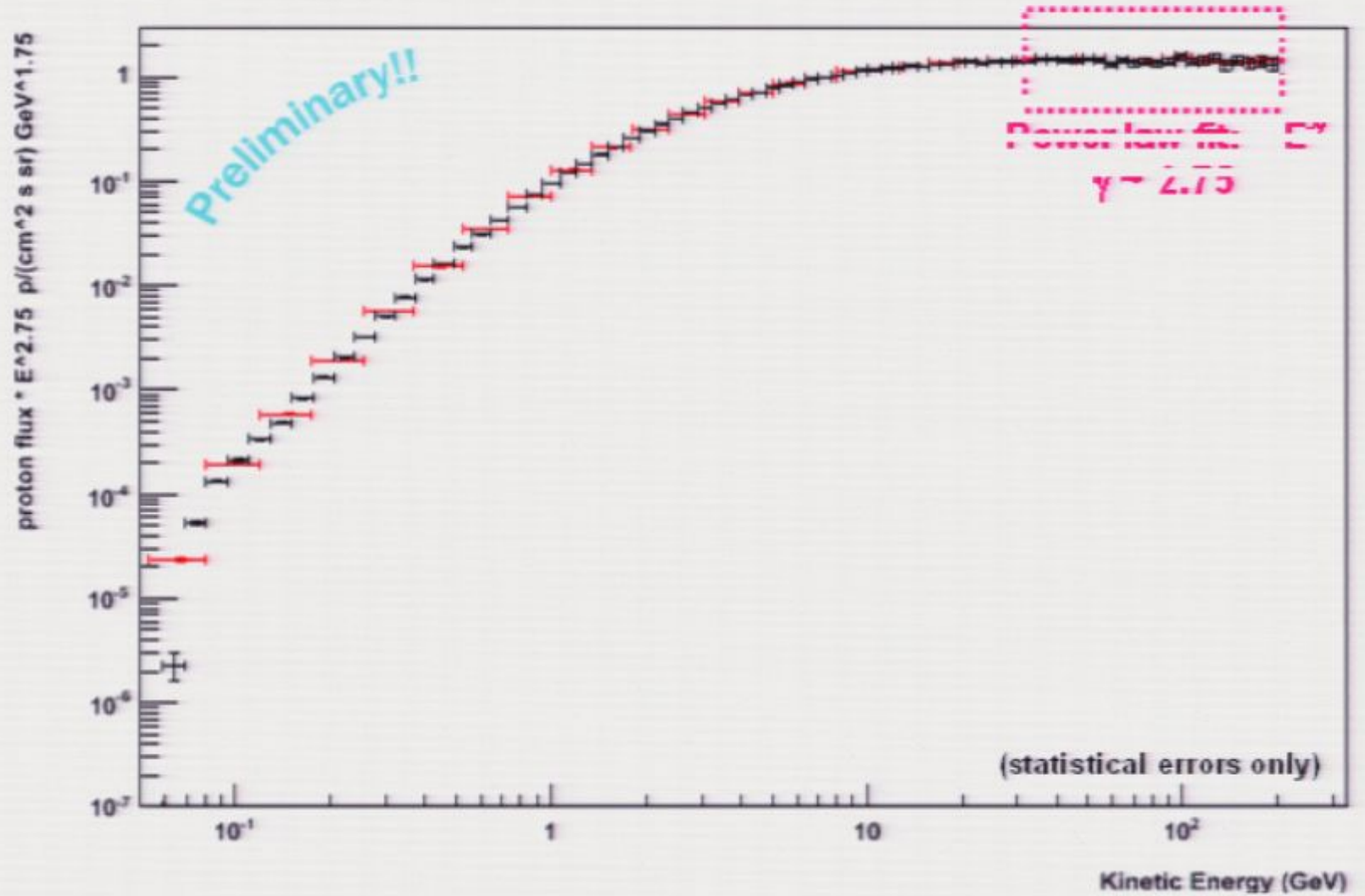
$$- \underbrace{\frac{\partial}{\partial E} \left\{ \left\langle \frac{\partial E}{\partial t} \right\rangle \cdot N_i(E, z, t) \right\} + \frac{1}{2} \frac{\partial^2}{\partial E^2} \left\{ \left\langle \frac{\Delta E^2}{\Delta t} \right\rangle \cdot N_i(E, z, t) \right\}}_{\text{energy changing processes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

Proton and Helium spectra, July 2006

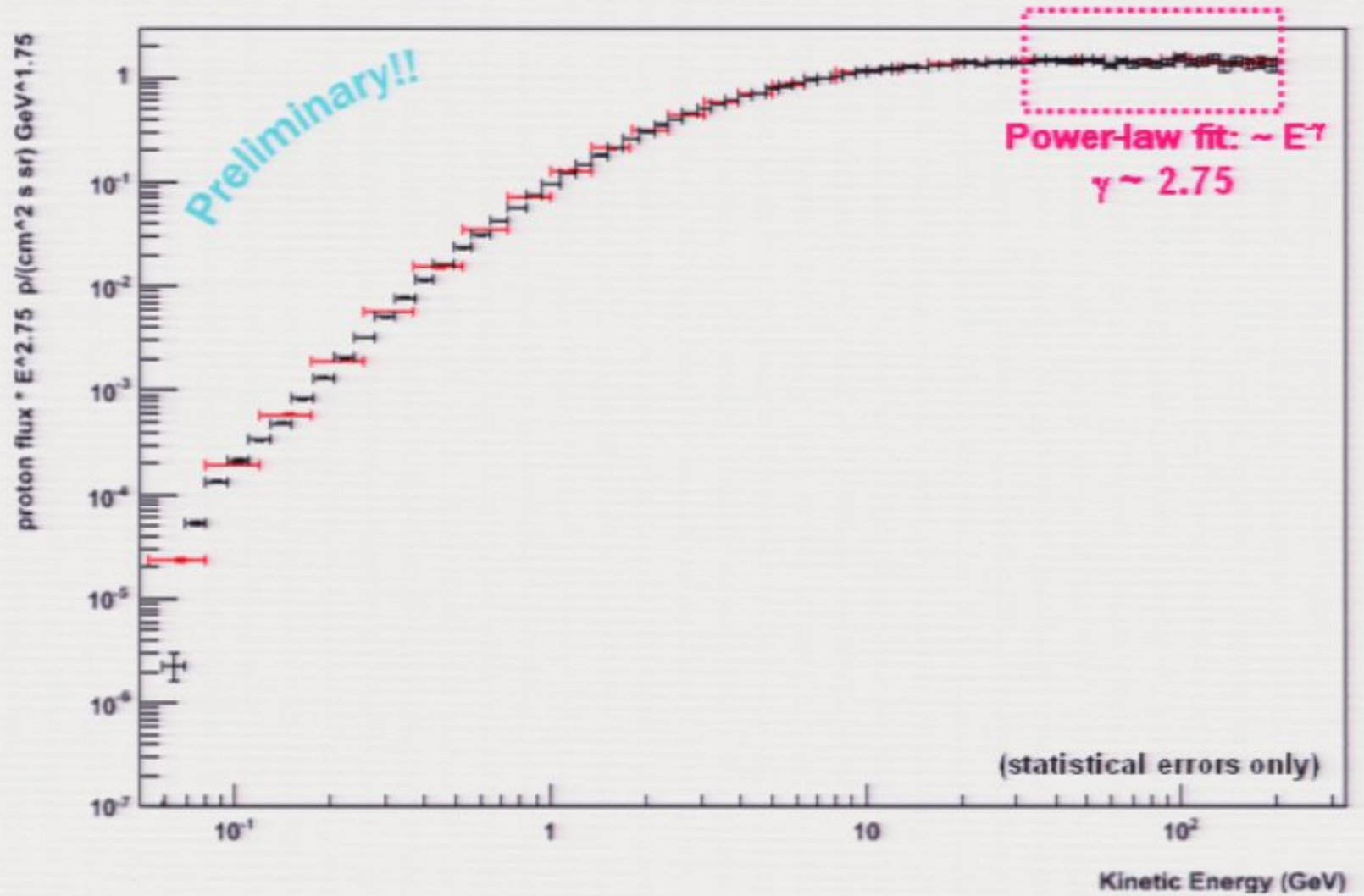
preliminary



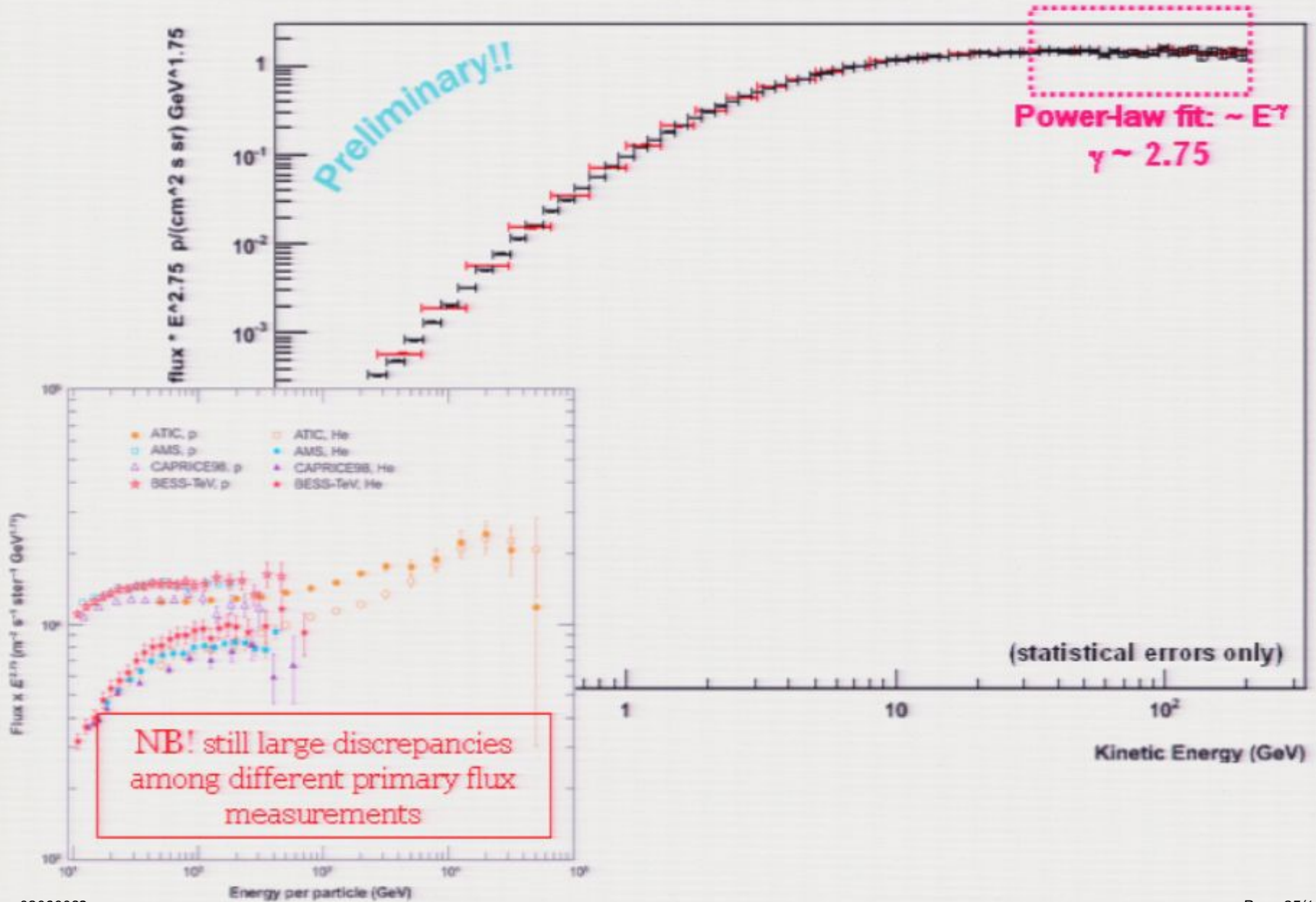
Proton flux



Proton flux



Proton flux



Nuclei identification

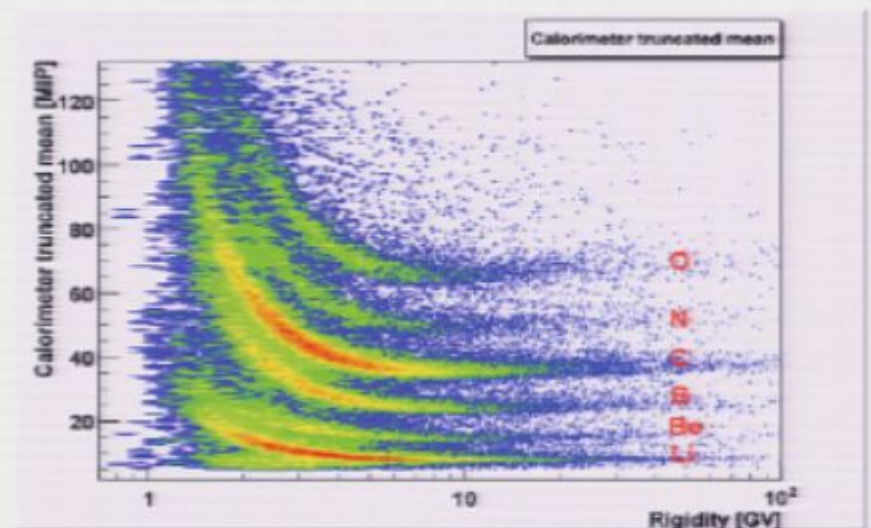
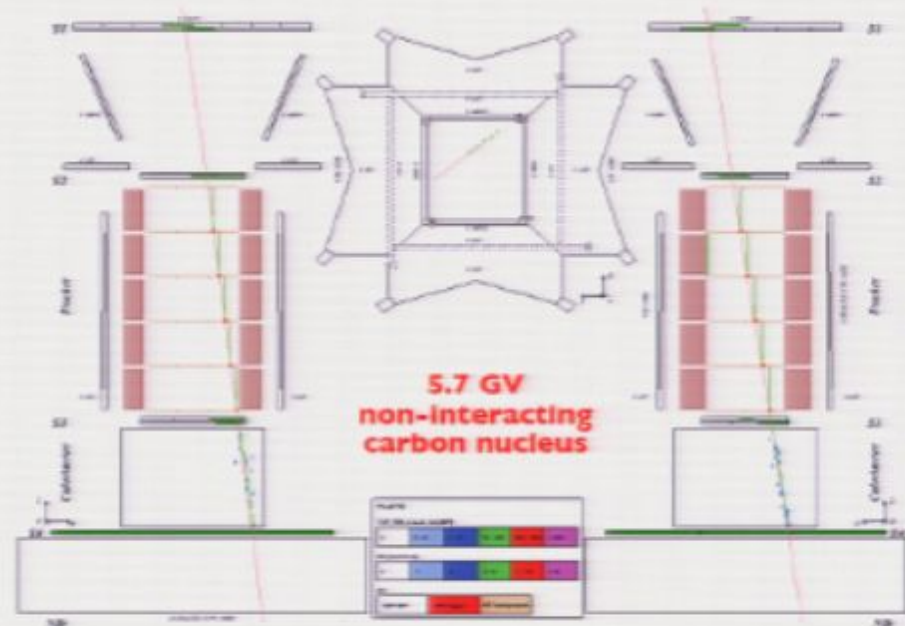
- Important input to secondary production + propagation models

- Secondary to primary ratios:

- B / C
- Be / C
- Li / C

- Helium and hydrogen isotopes:

- $^3\text{He} / ^4\text{He}$
- d / He



Truncated mean of multiple measurements in different silicon planes

Light nuclei

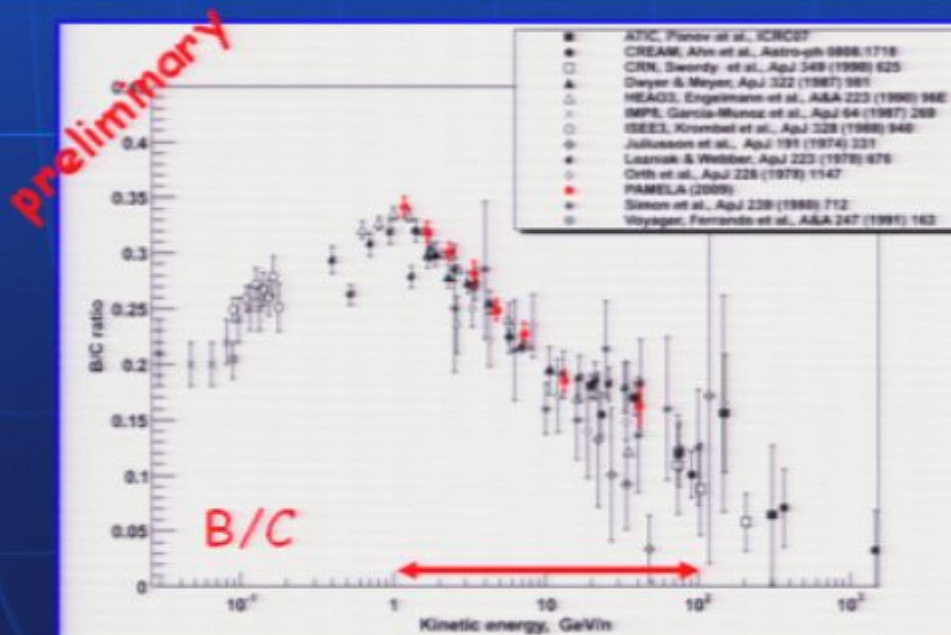
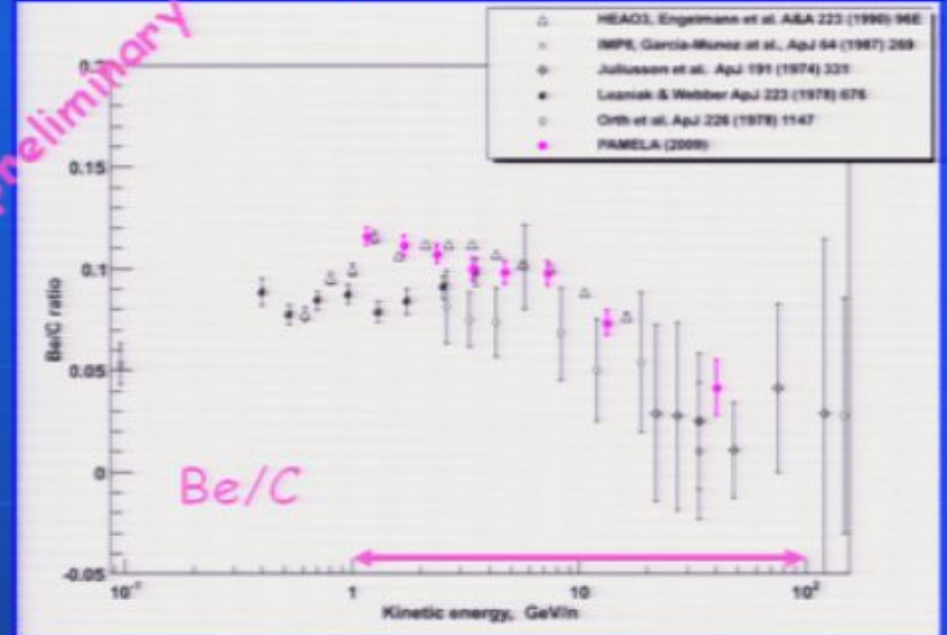
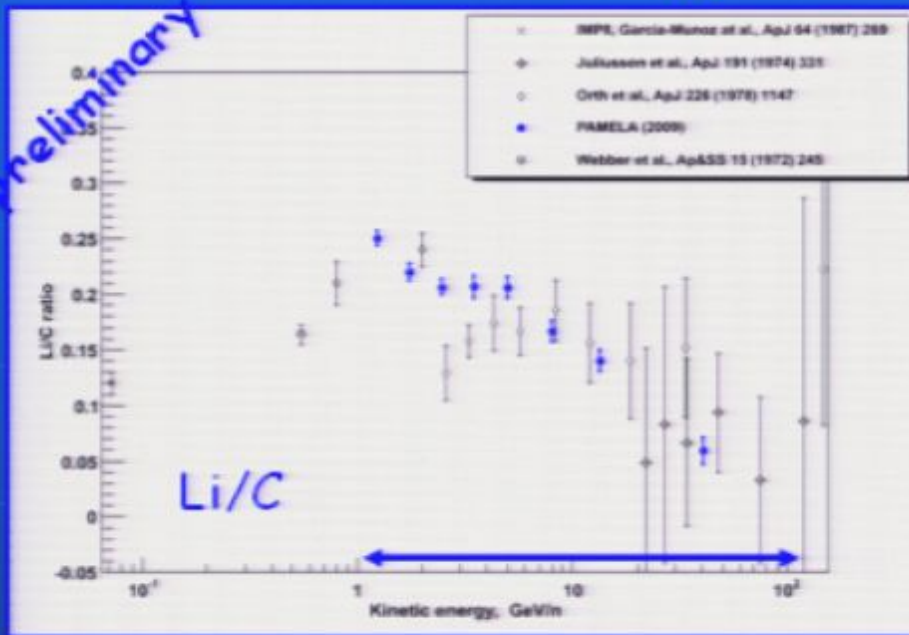
Statistics collected until December 2008:

- ❖ 120.000 **C nuclei**
- ❖ 45.000 **B nuclei**
- ❖ 16.000 **Be nuclei**
- ❖ 30.000 **Li nuclei**

between 200 MeV/n and 100 GeV/n, with quite stringent selection cuts (30% efficiency and 0.01% contamination among species).

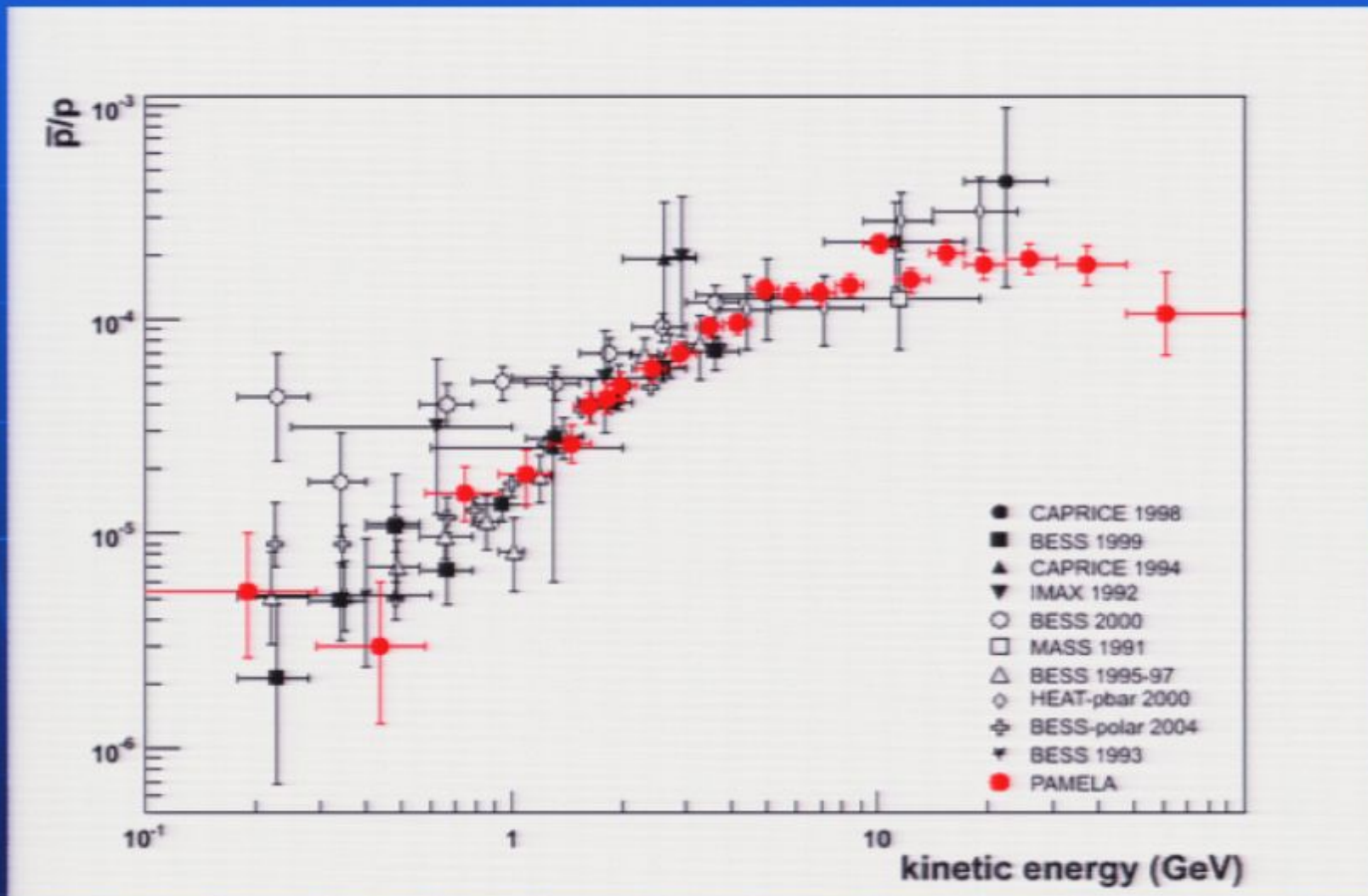
Secondary/Primary ratios in progress !

PAMELA preliminary results

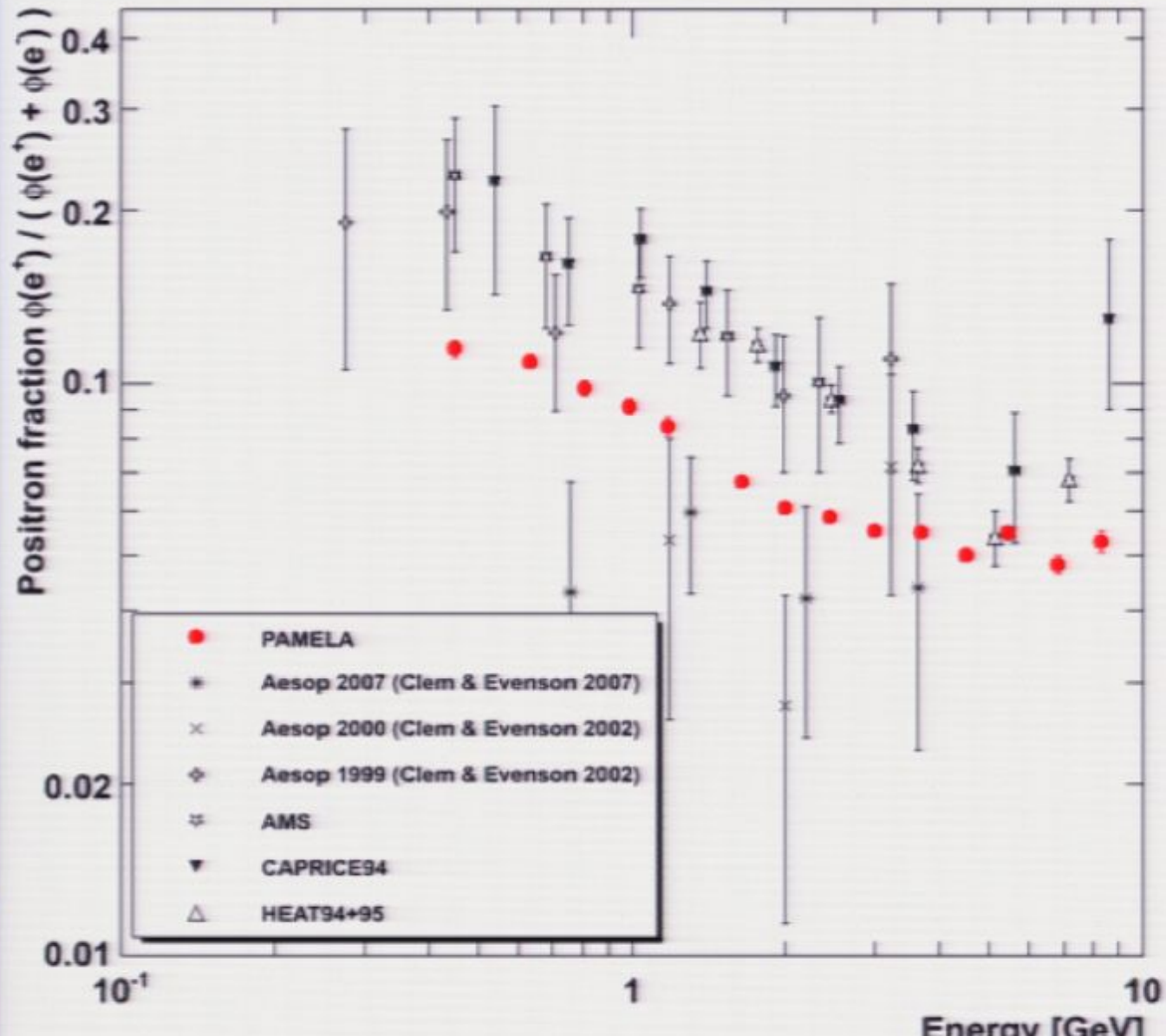


Antiproton to proton ratio

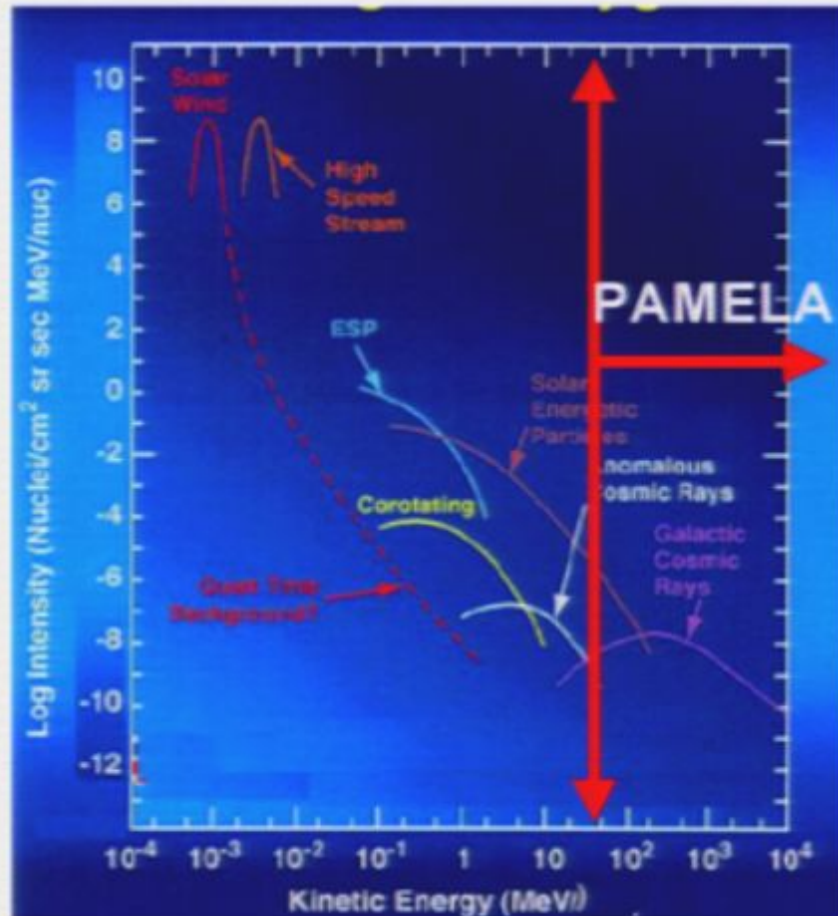
PRL 102, 051101 (2009)



Positron Fraction



Solar Physics with PAMELA



- Solar Modulation effects
- High energy component of Solar Proton Events (from 80 MeV to 10 GeV)
- High energy component of electrons and positrons in Solar Proton Events (from 50 MeV)
- Nuclear composition of Gradual and Impulsive events
- ³He and ⁴He isotopic composition

Solar Modulation of galactic cosmic rays

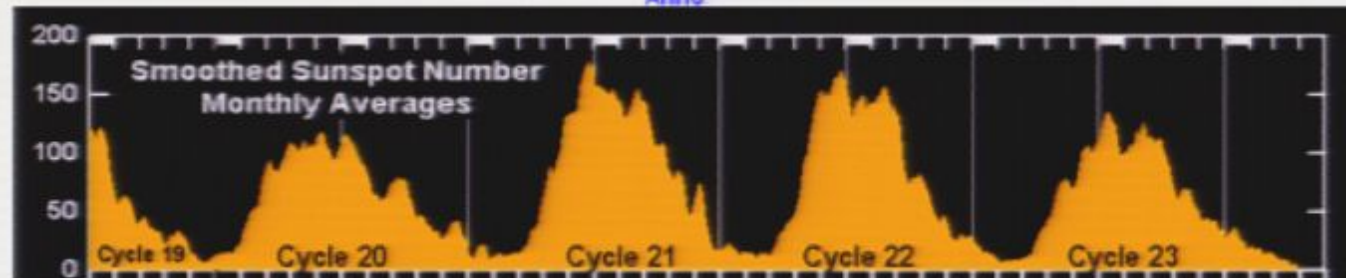
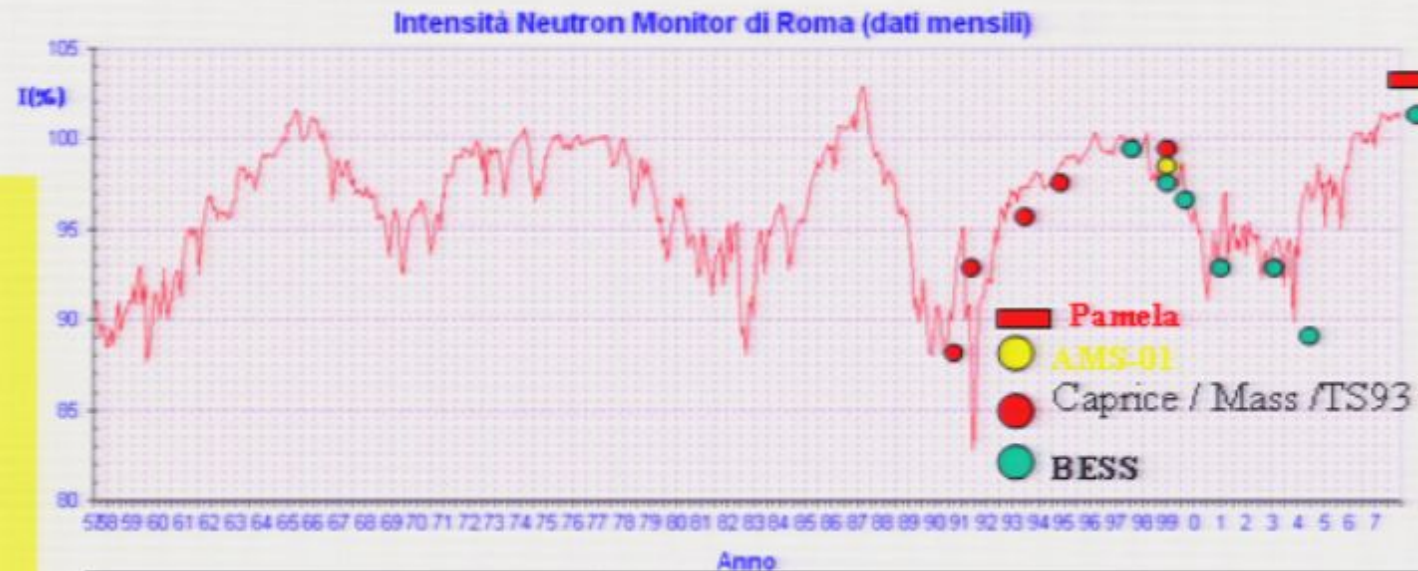
Study of charge sign dependent effects

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

J.W. Bieber, *et al.* *Physical Review Letters*, 84, 674, 1999.

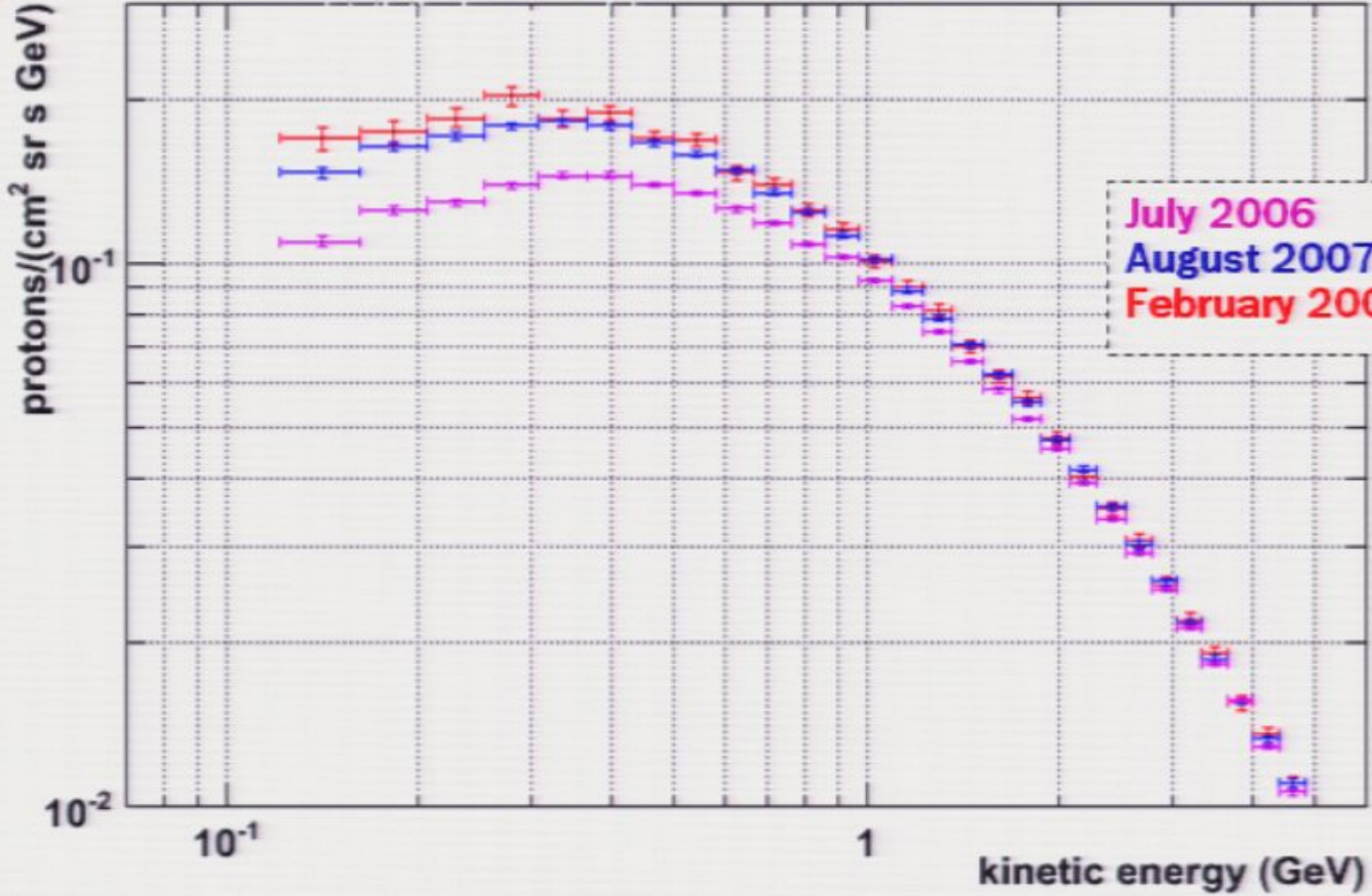
Clem *et al.* 30th ICRC 2007

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



Preliminary

Solar modulation



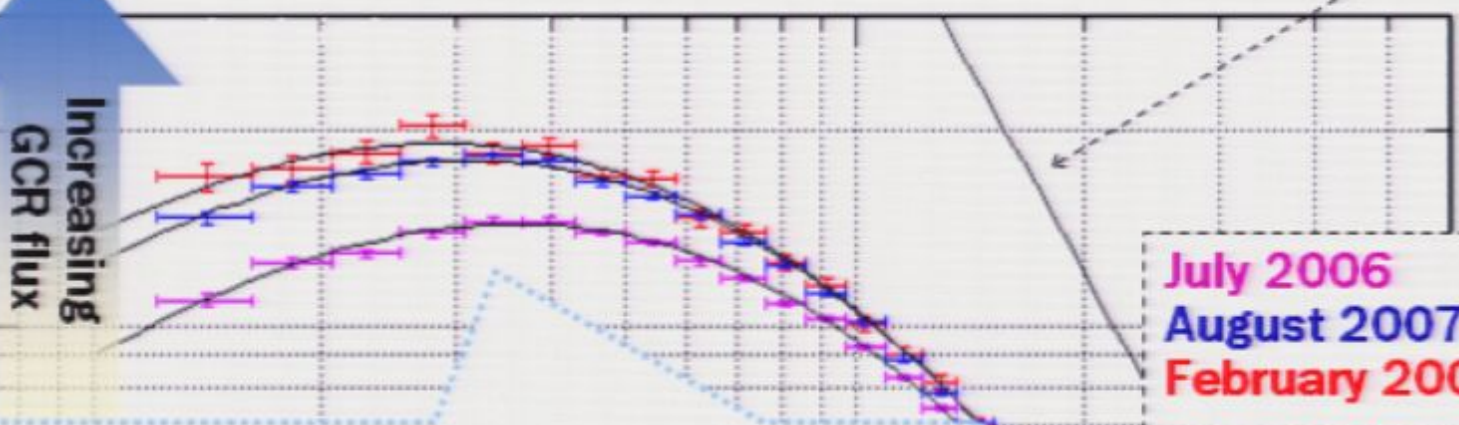
July 2006
August 2007
February 2008

Solar modulation

preliminary

Interstellar spectrum

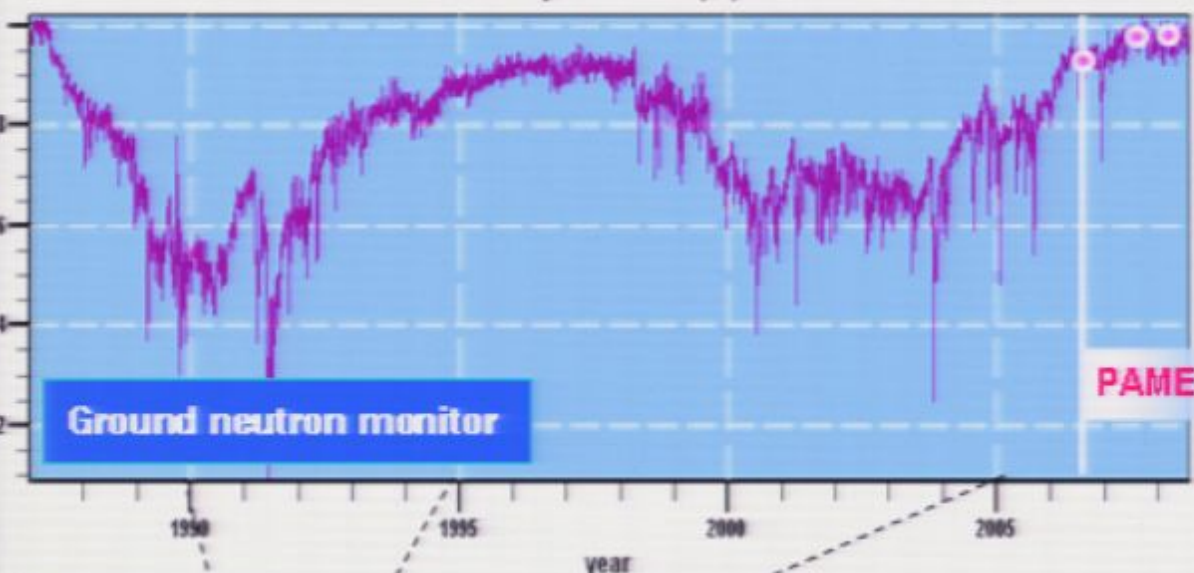
$\text{ons}/\text{cm}^2 \text{ sr s GeV}$
 10^{-1}



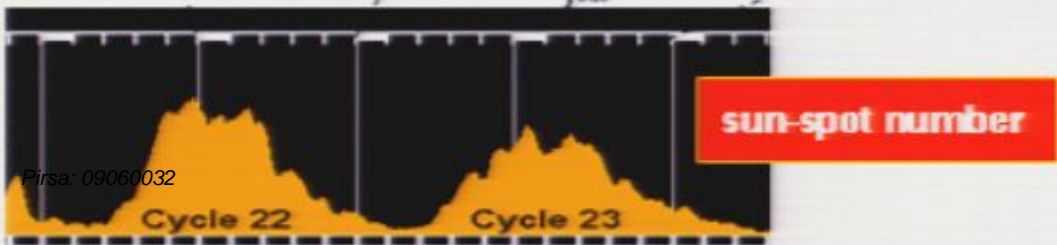
Decreasing solar activity

July 2006
August 2007
February 2008

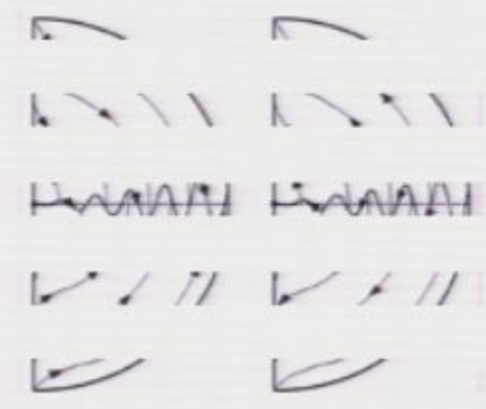
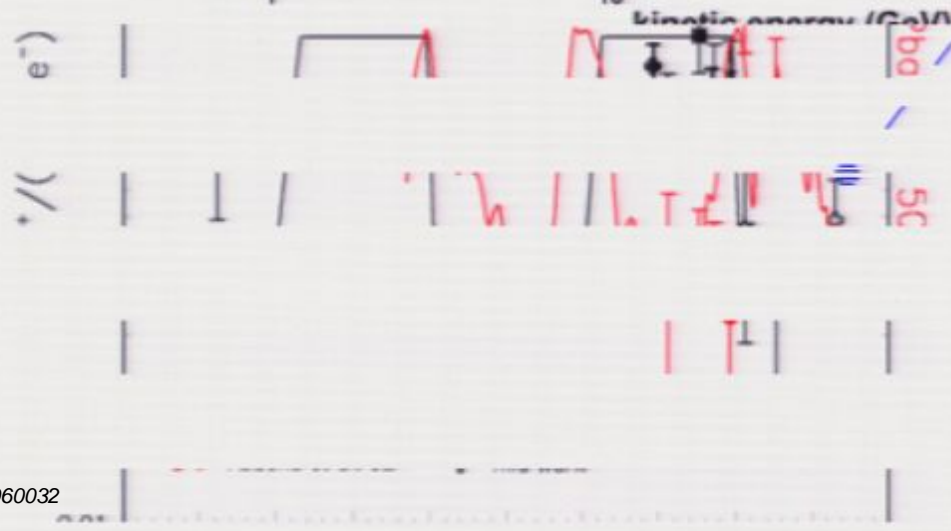
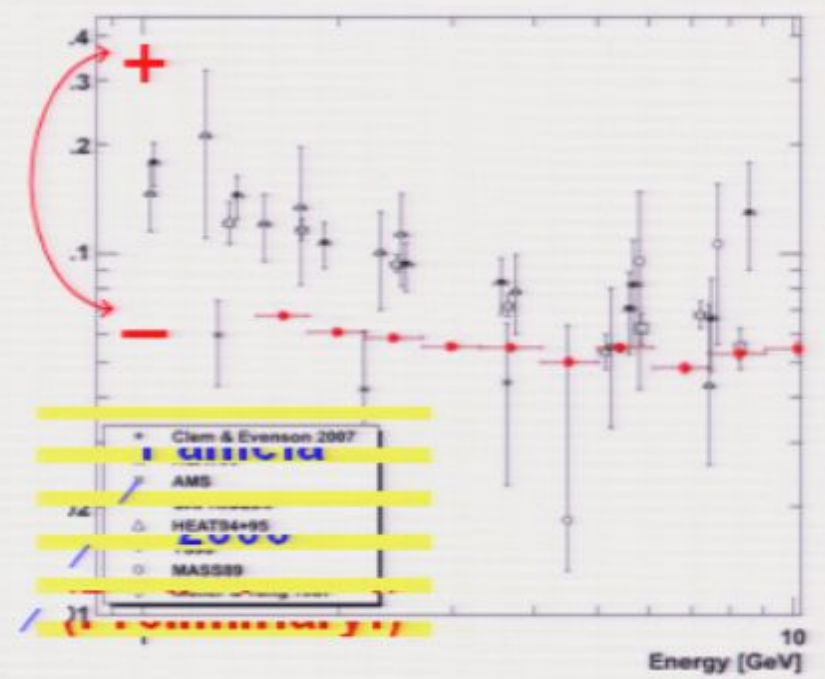
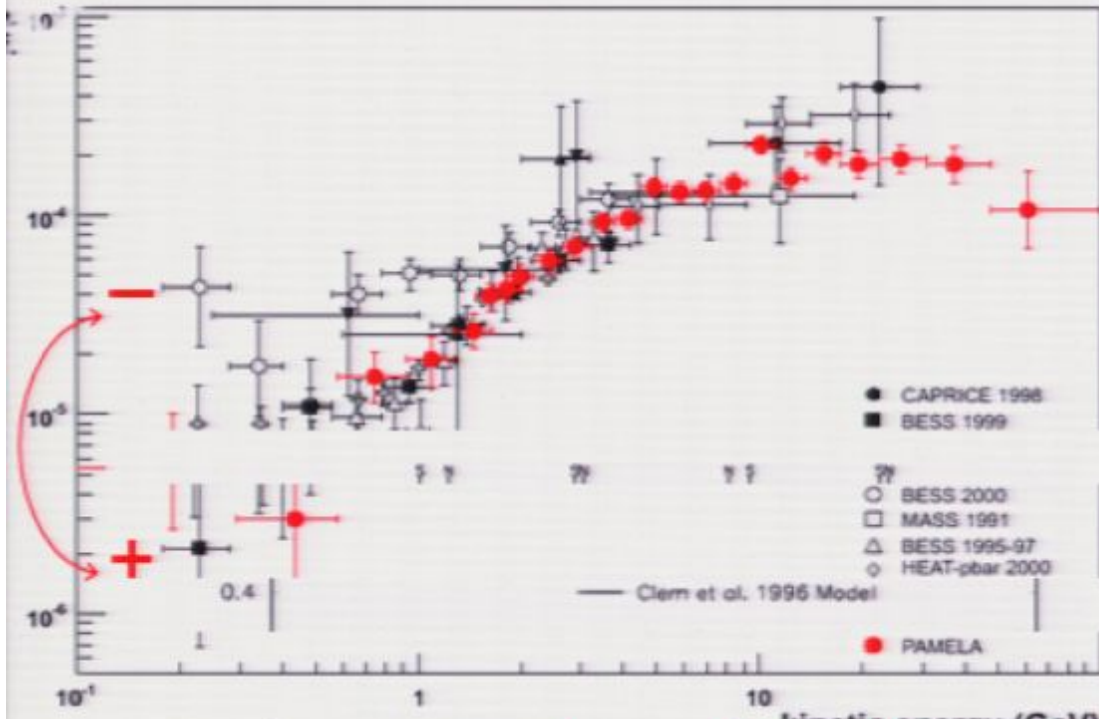
Cosmic rays variations(%)



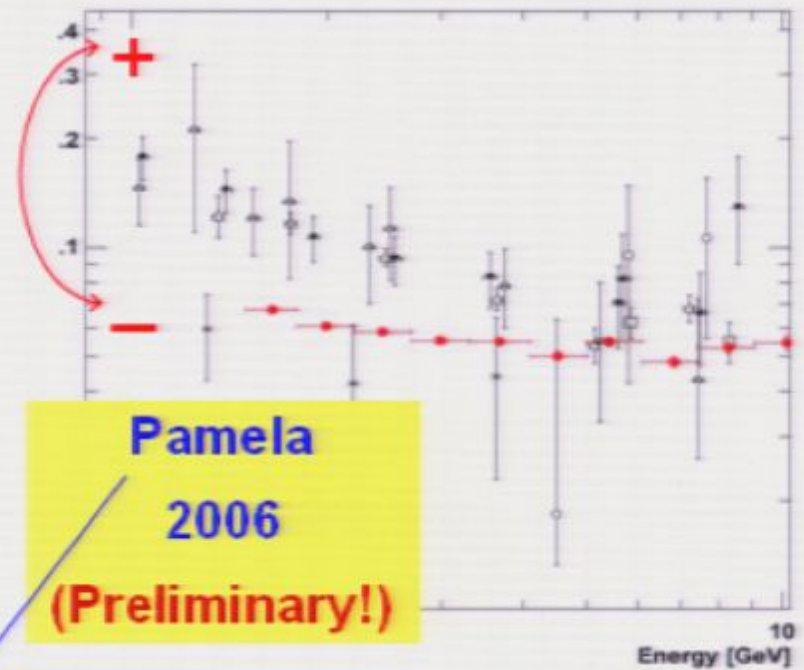
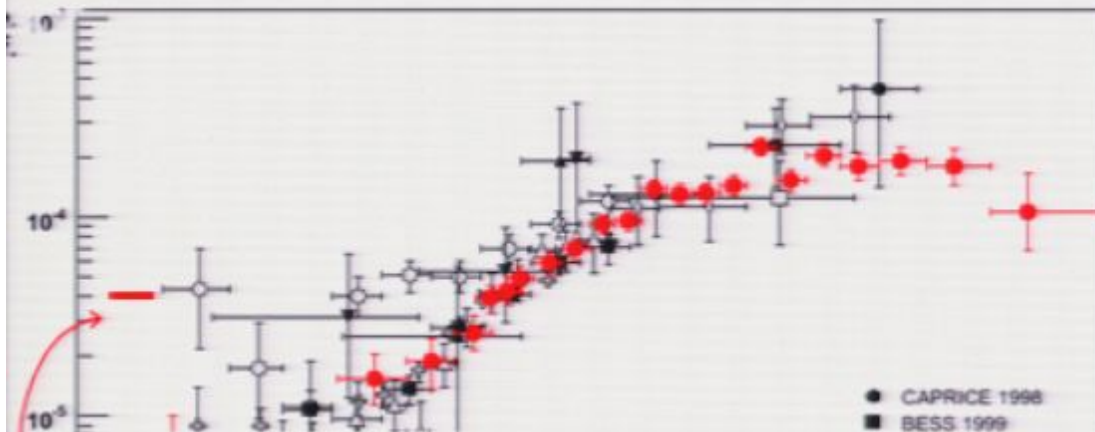
kinetic energy (GeV)



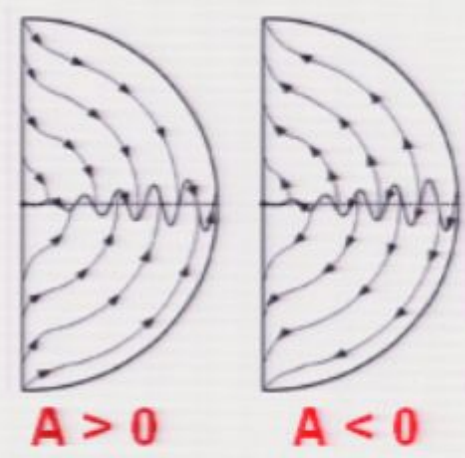
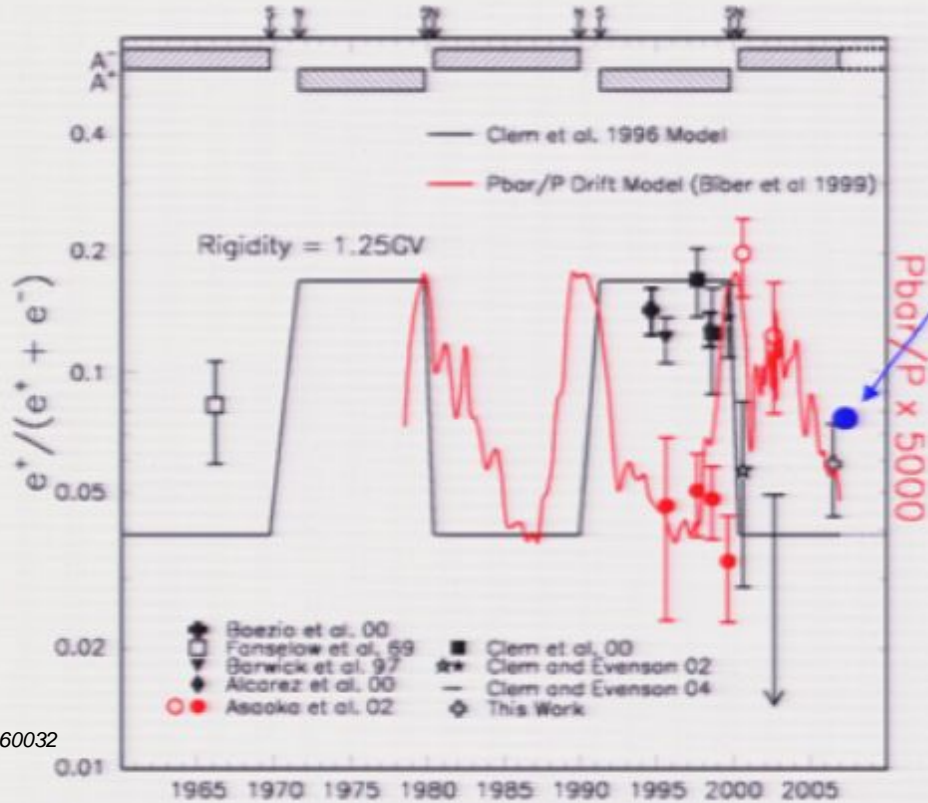
Charge dependent solar modulation



Charge dependent solar modulation

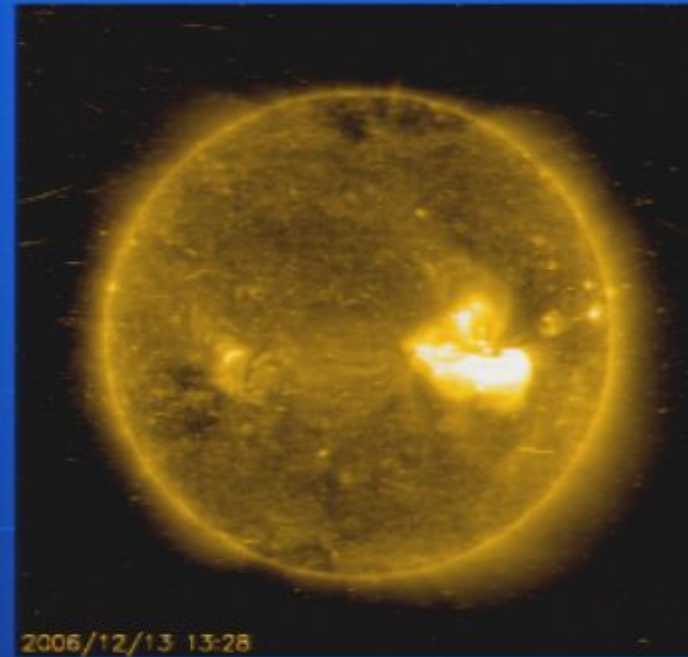
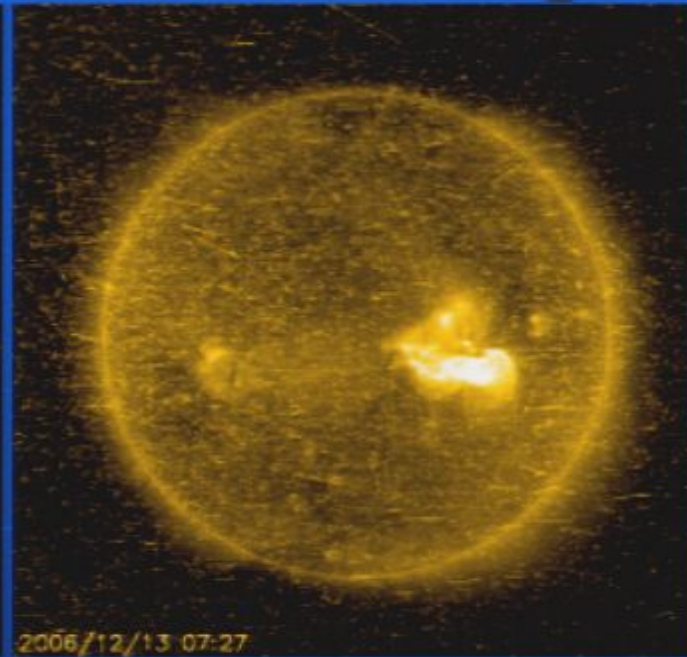
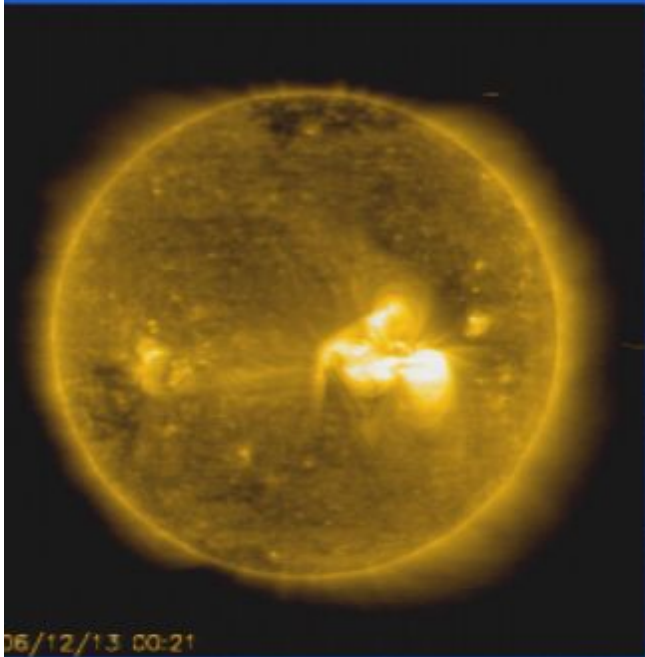


Pamela
2006
(Preliminary!)

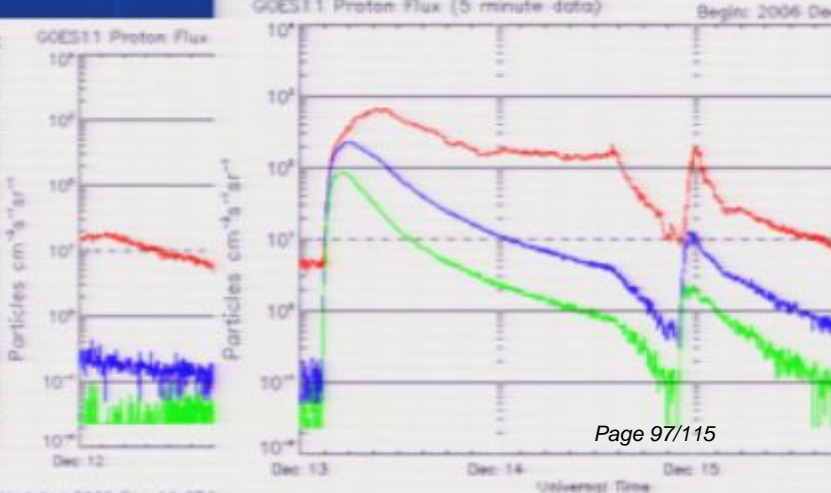
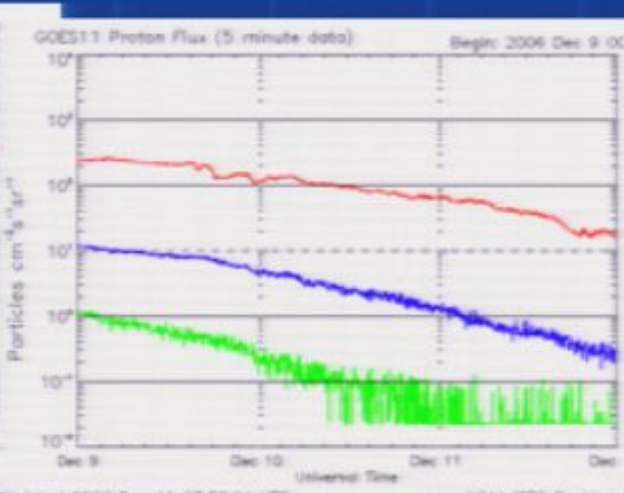
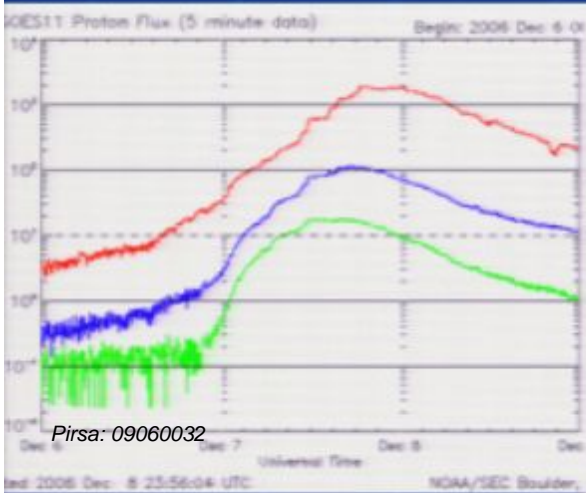


Positive particles

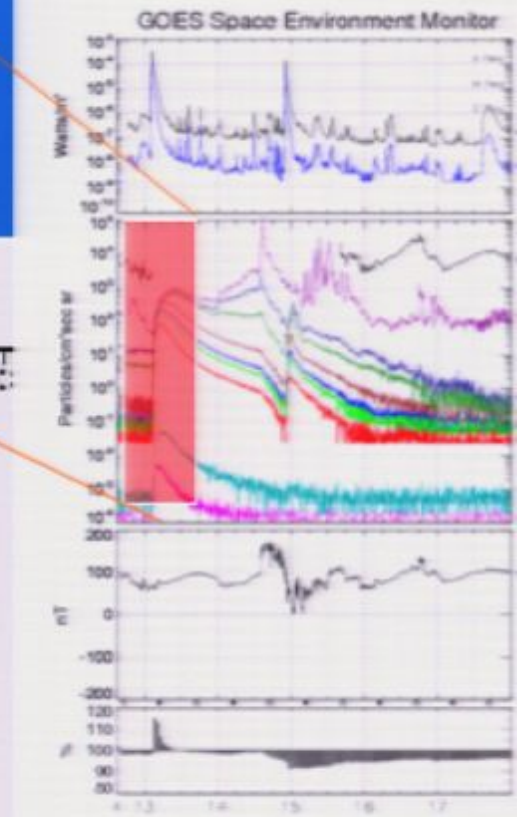
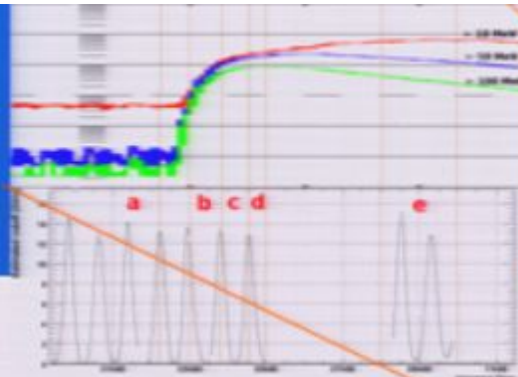
December 2006 Solar particle events



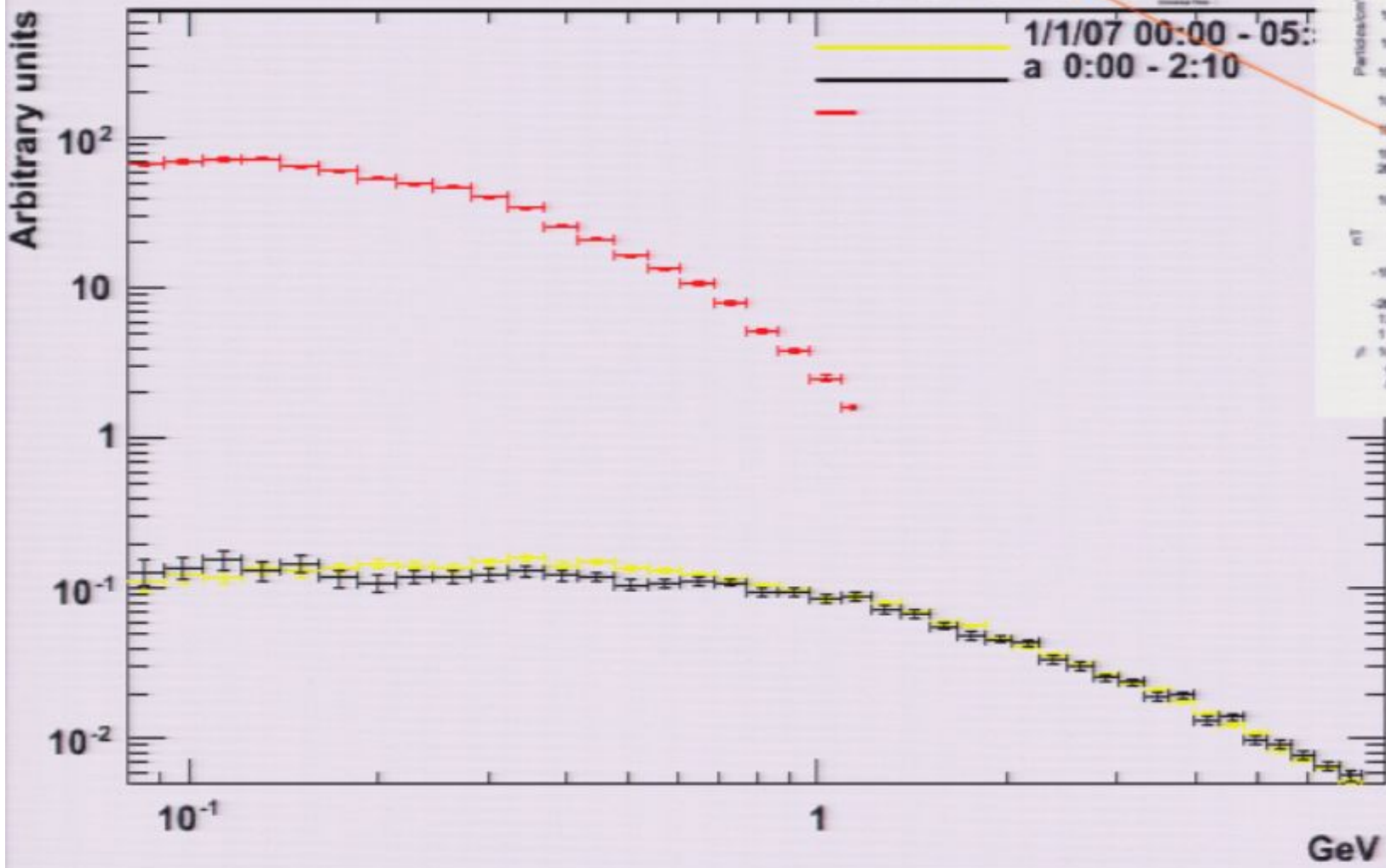
Dec 13th largest CME since 2003, anomalous at sol min X3.4 solar flare



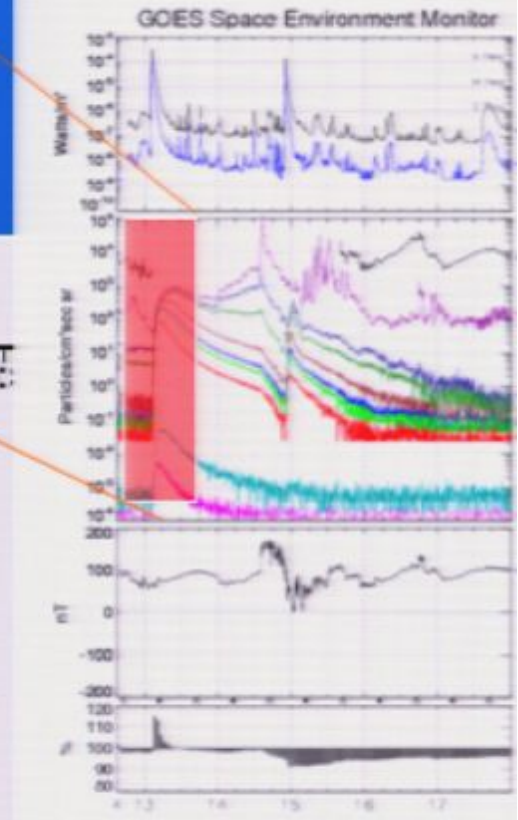
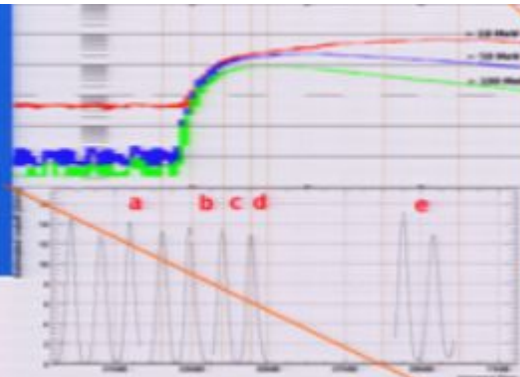
December 13th 2006 event



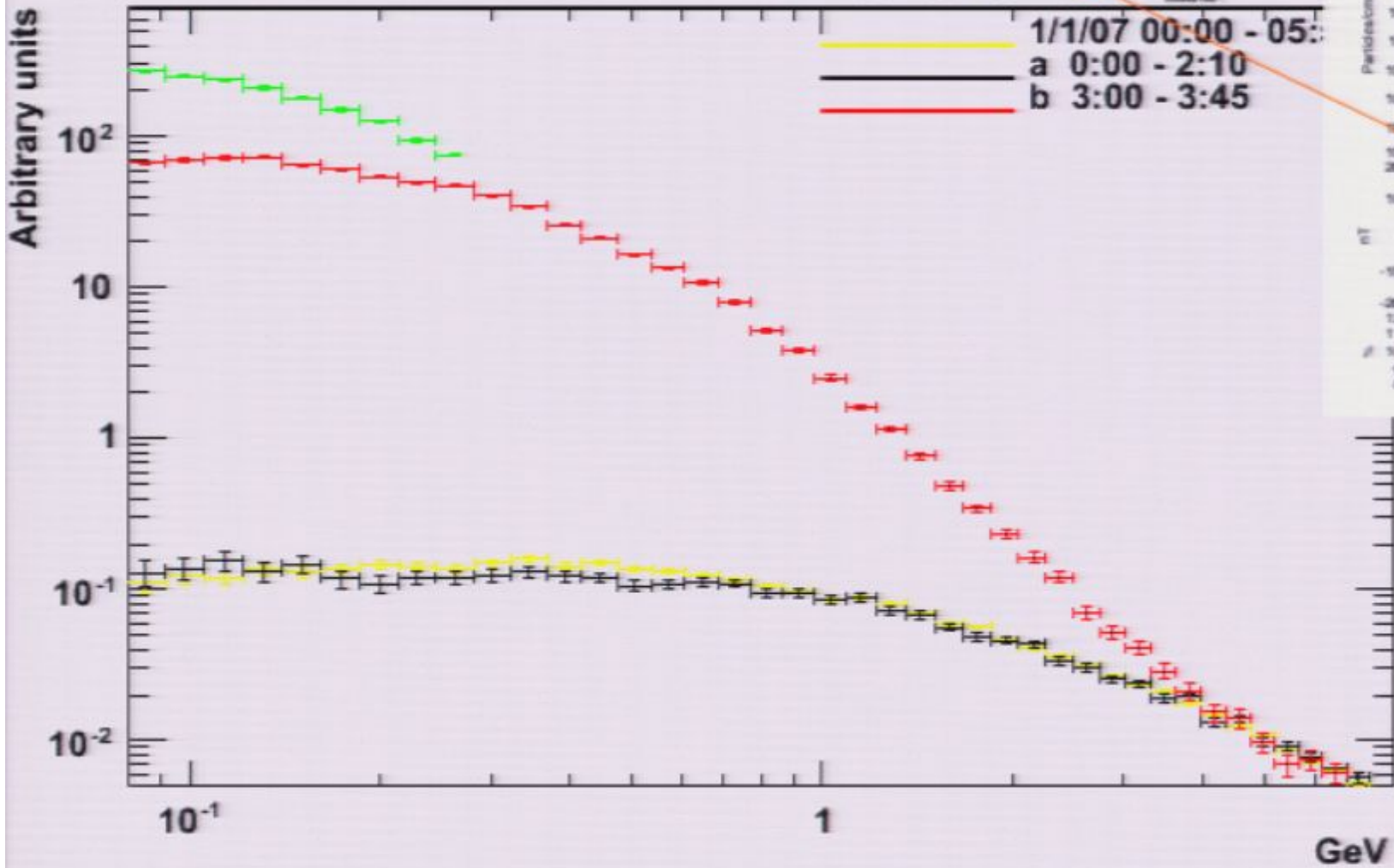
Protons



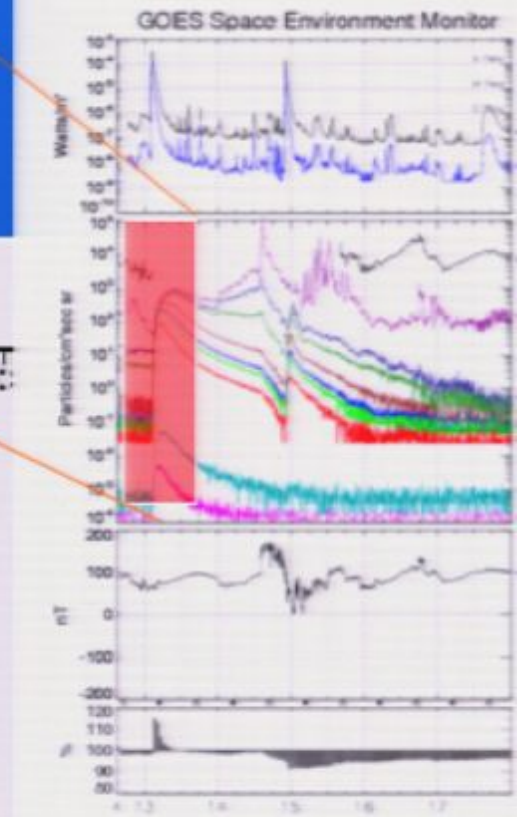
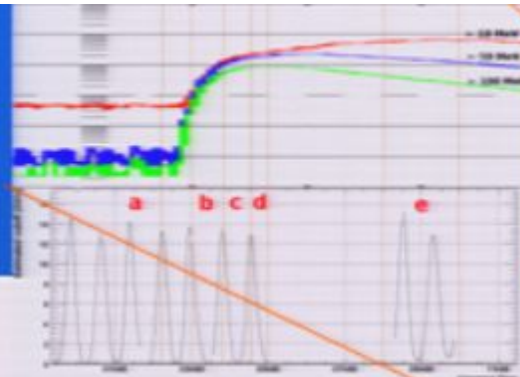
December 13th 2006 event



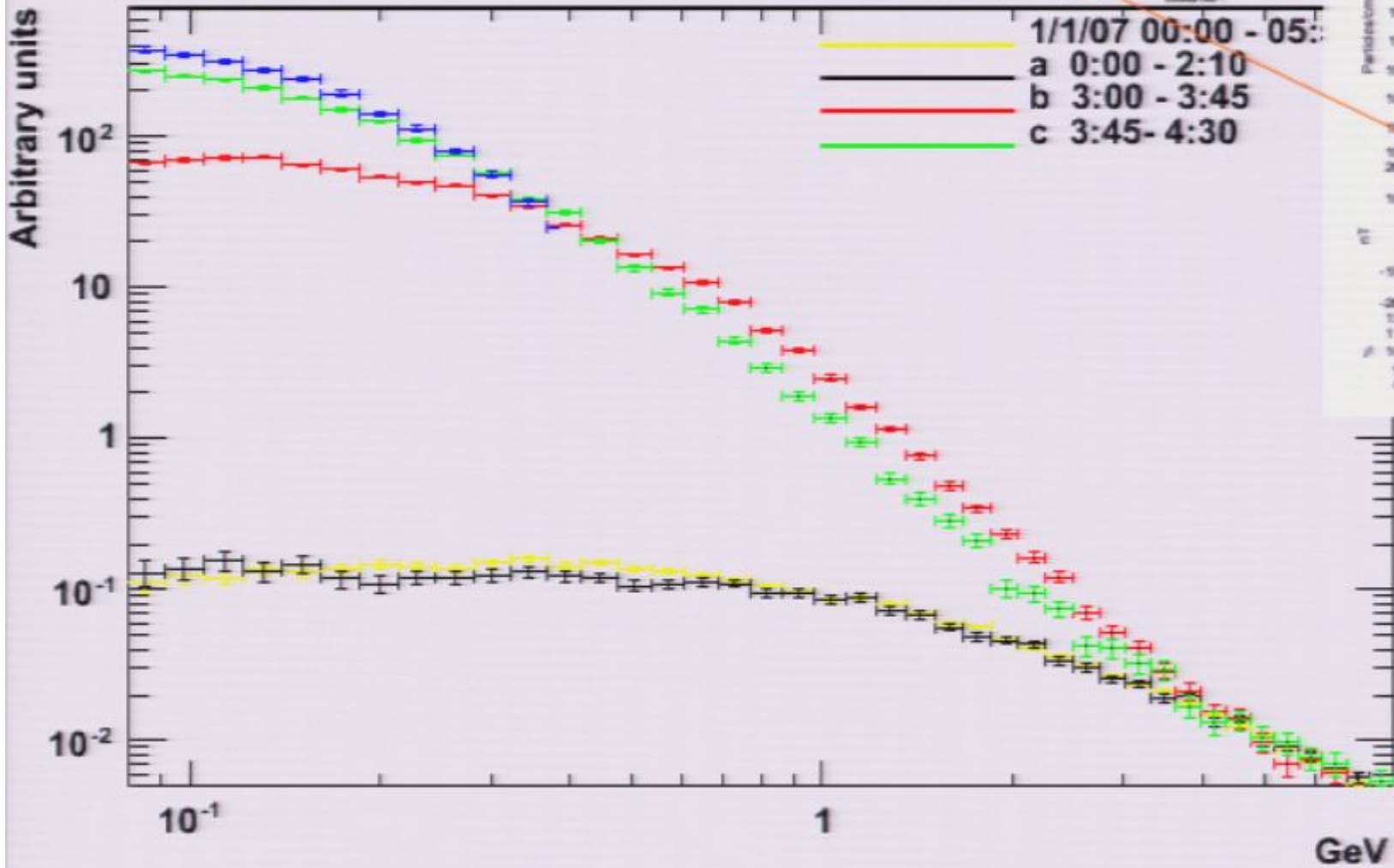
Protons



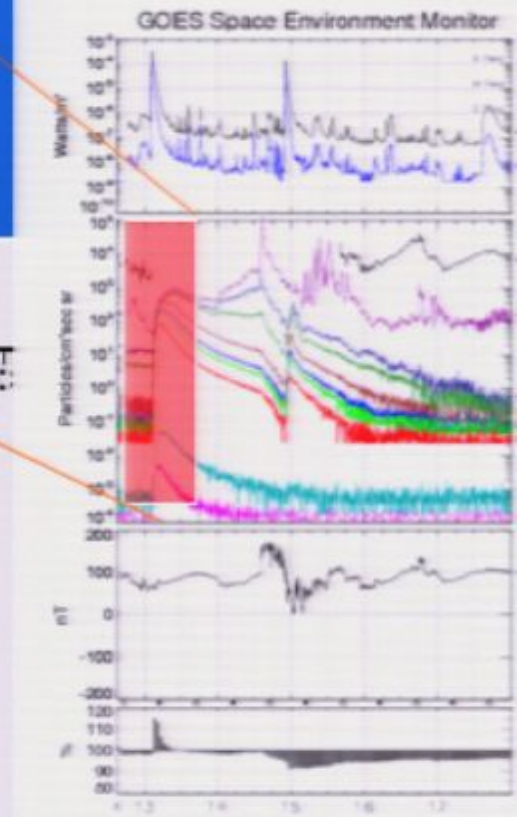
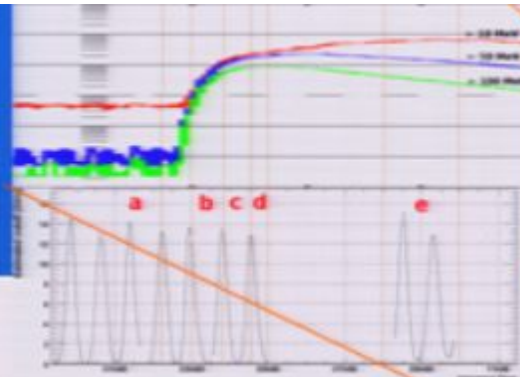
December 13th 2006 event



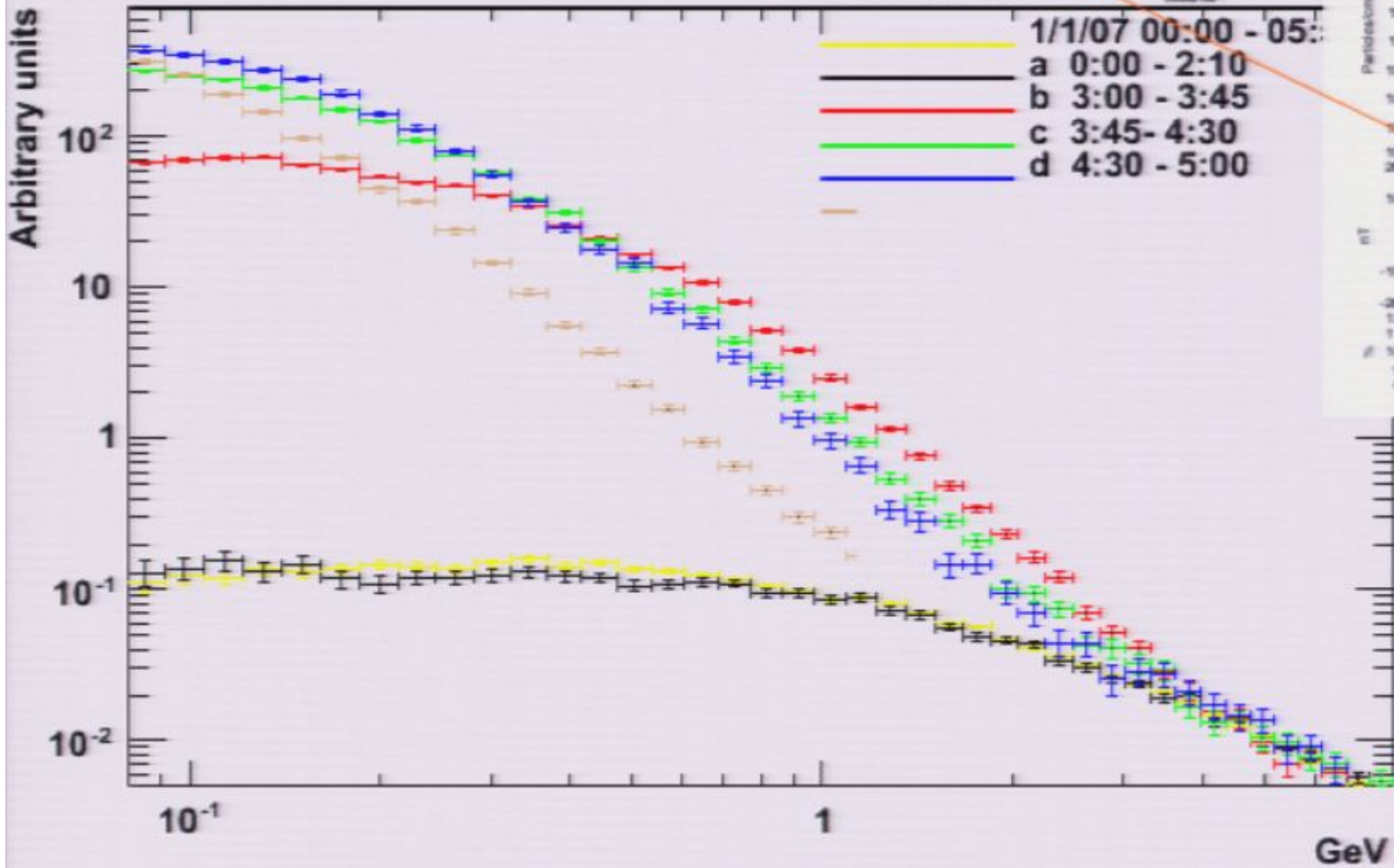
Protons



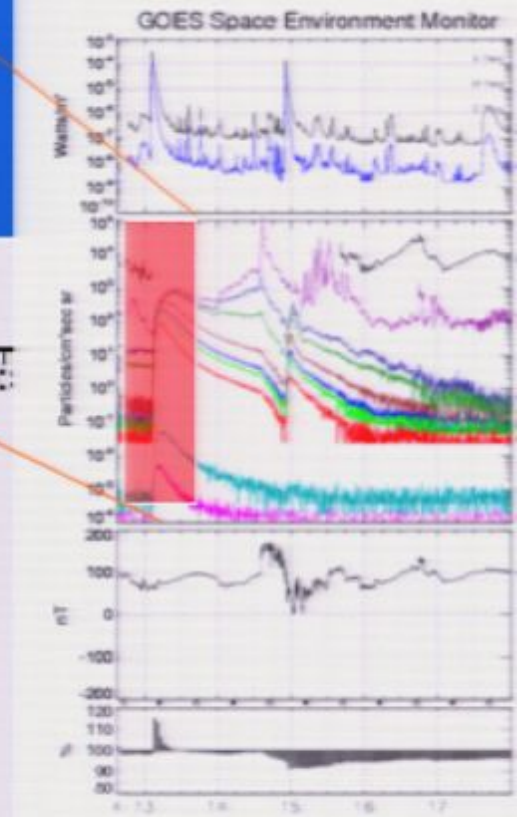
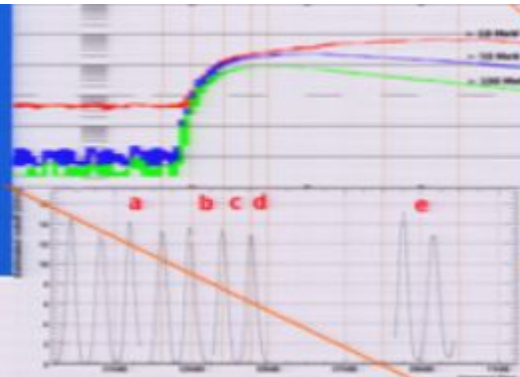
December 13th 2006 event



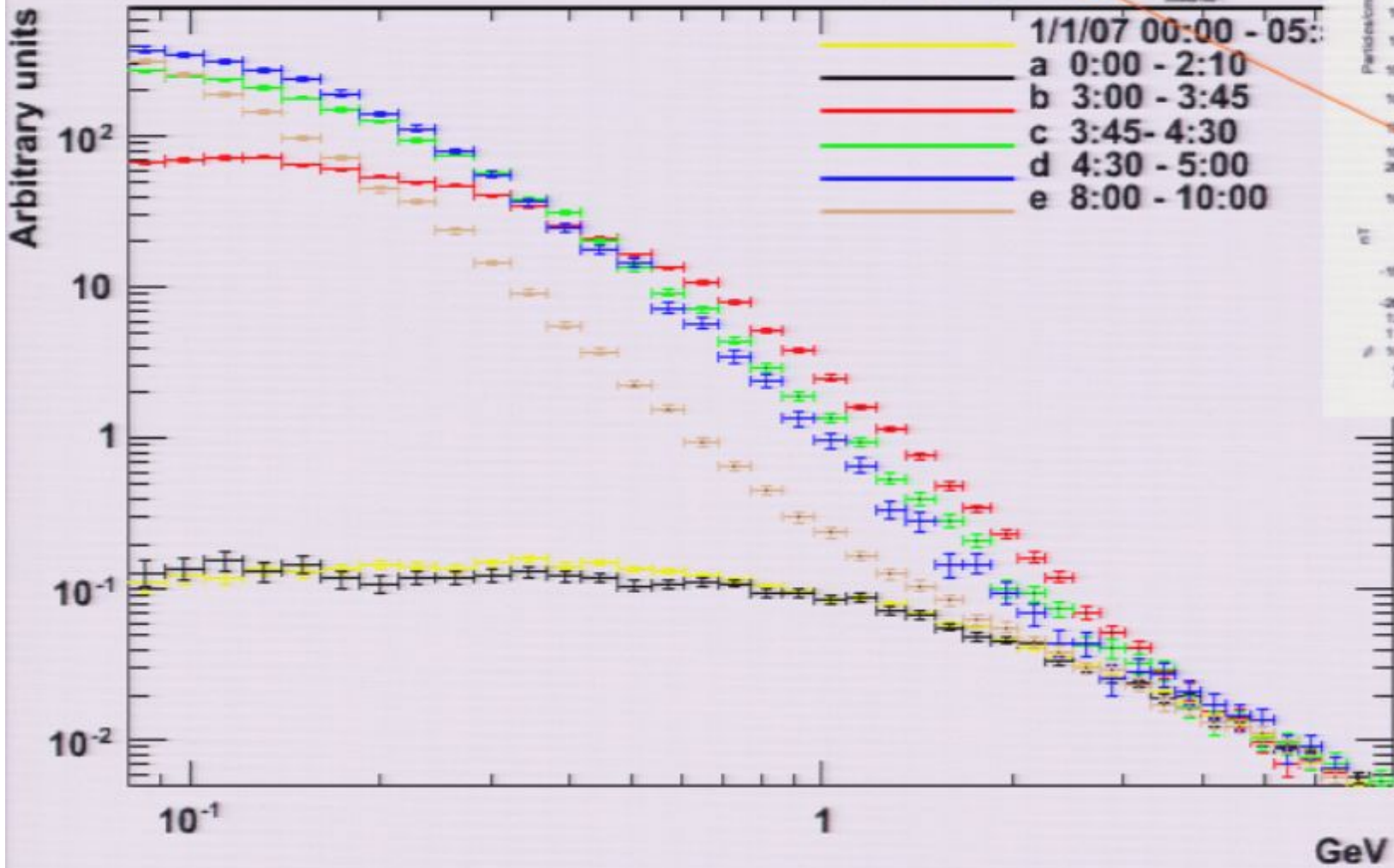
Protons



December 13th 2006 event

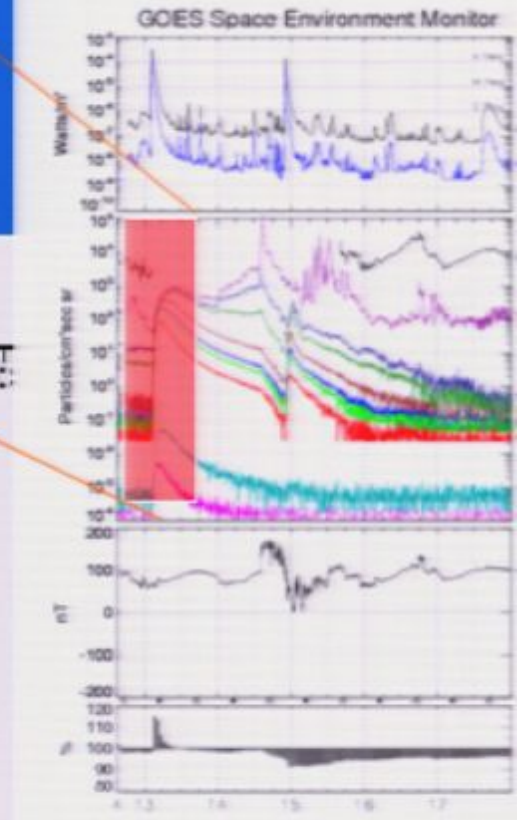
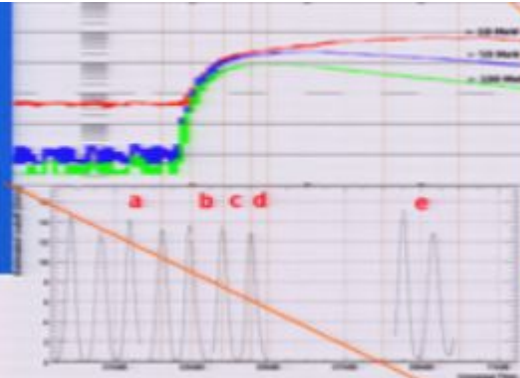
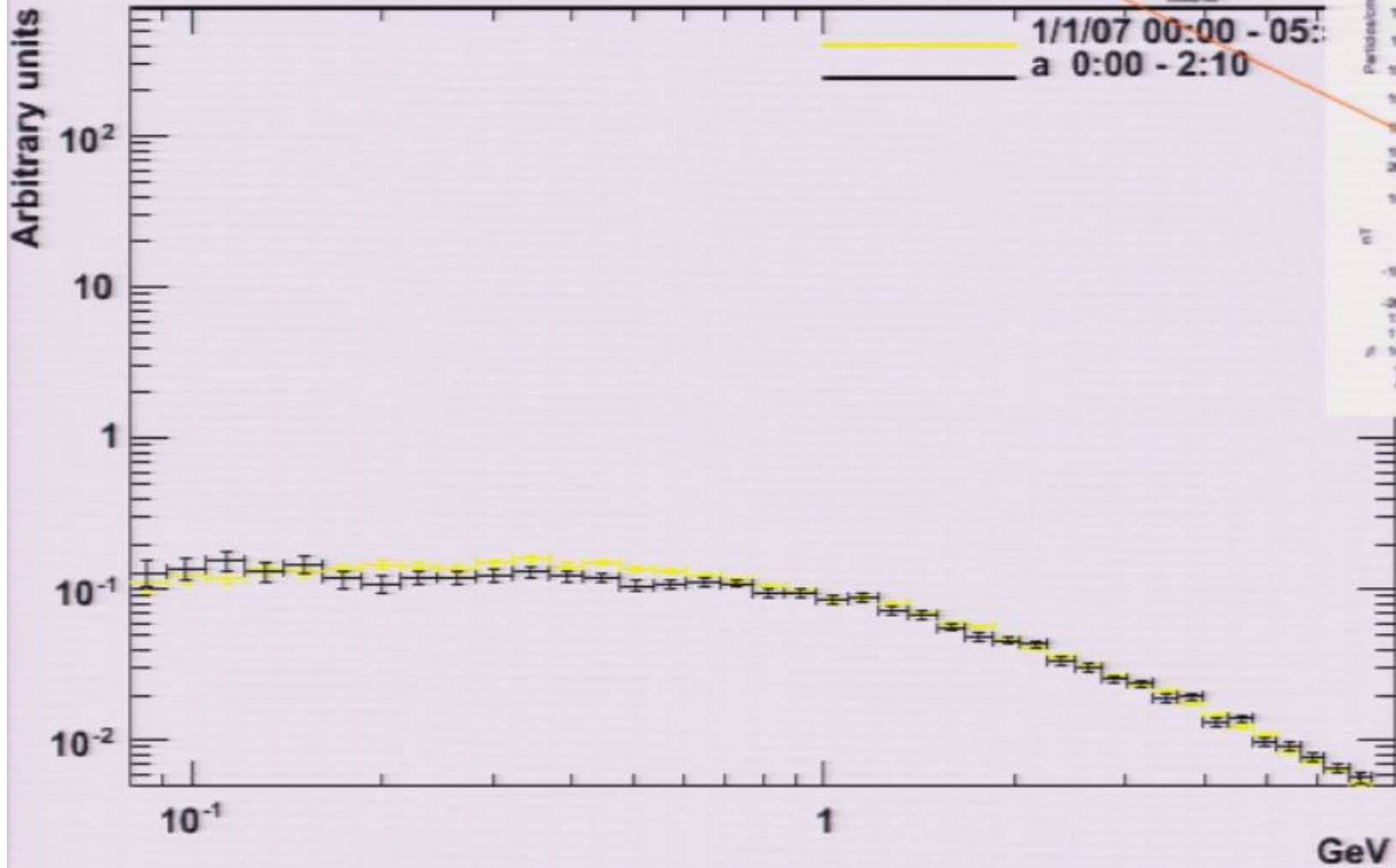


Protons

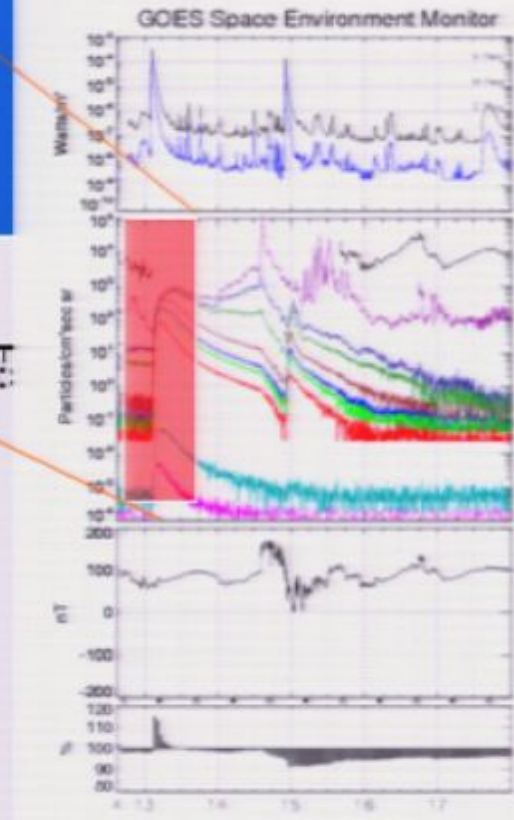
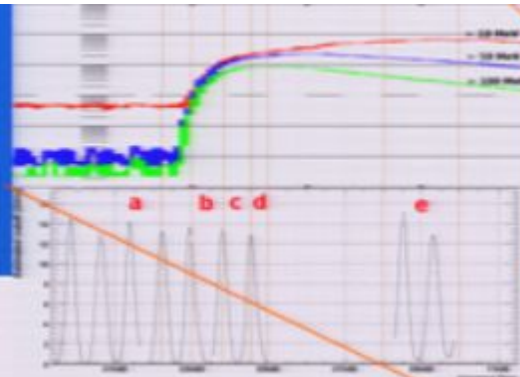


December 13th 2006 event

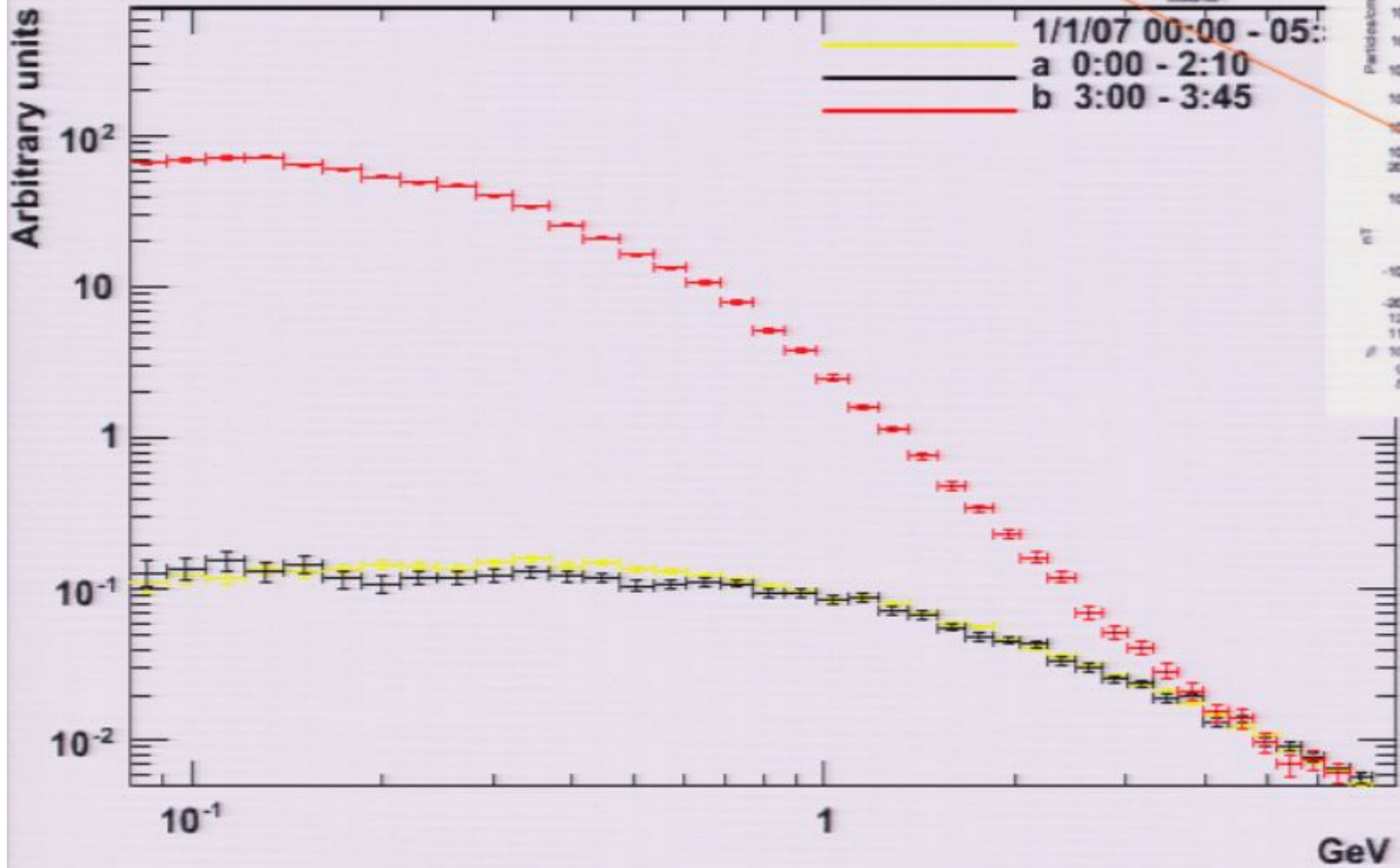
Protons



December 13th 2006 event

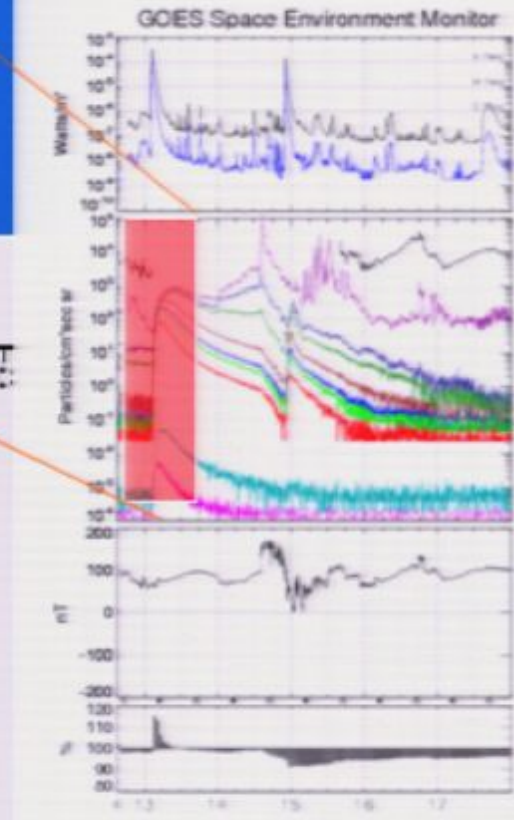
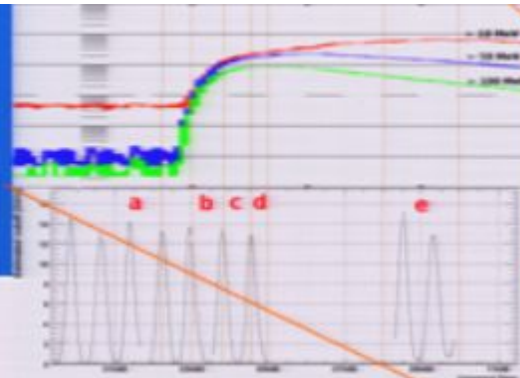
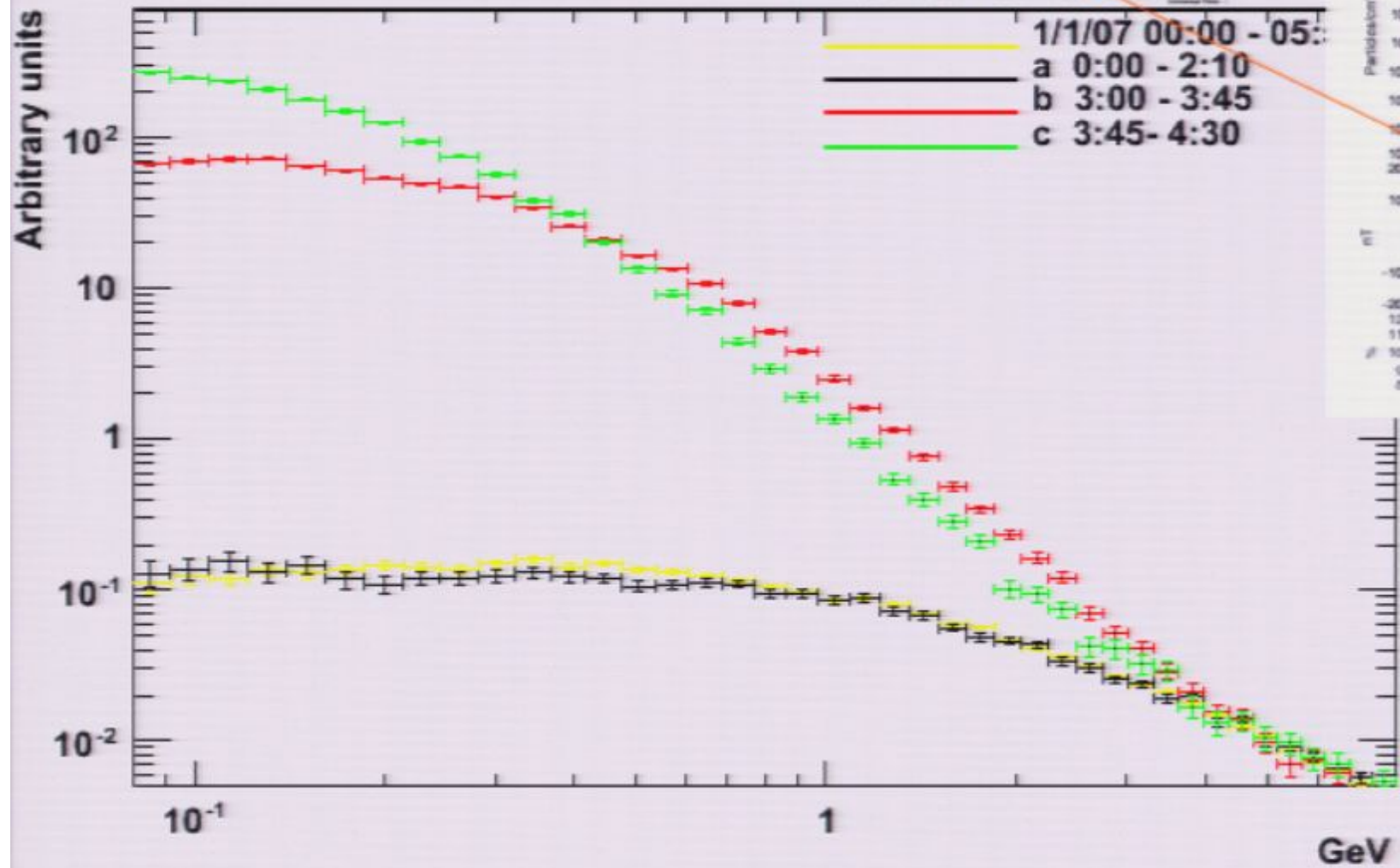


Protons

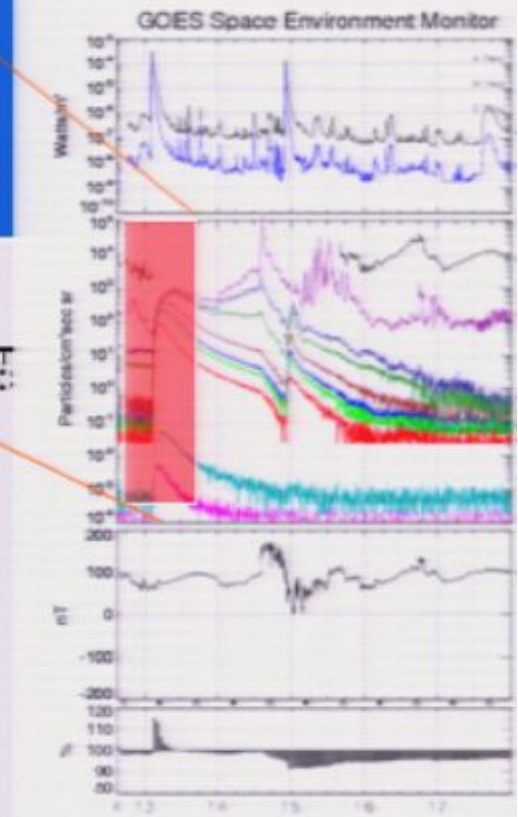
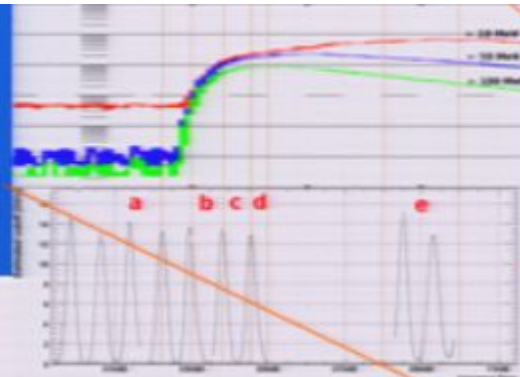


December 13th 2006 event

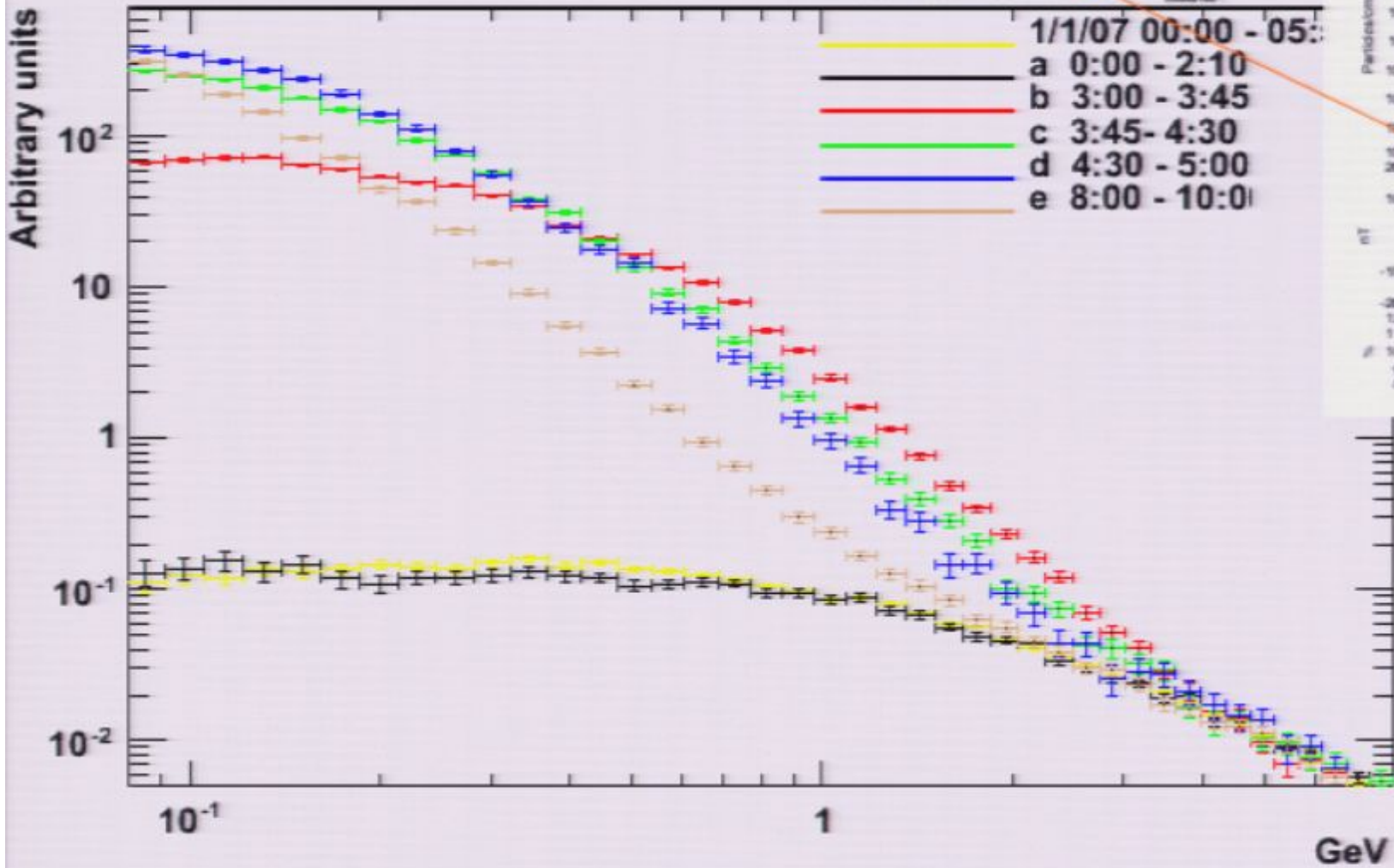
Protons



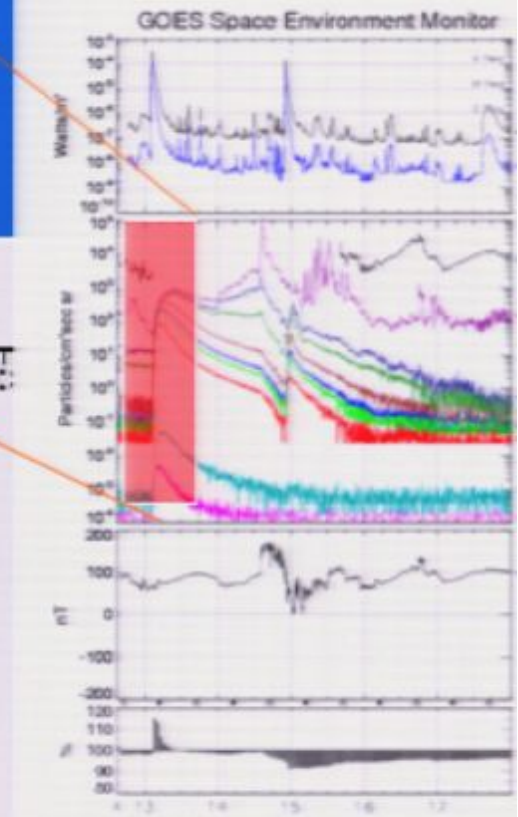
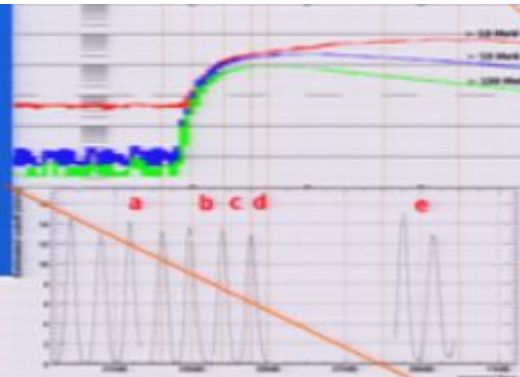
December 13th 2006 event



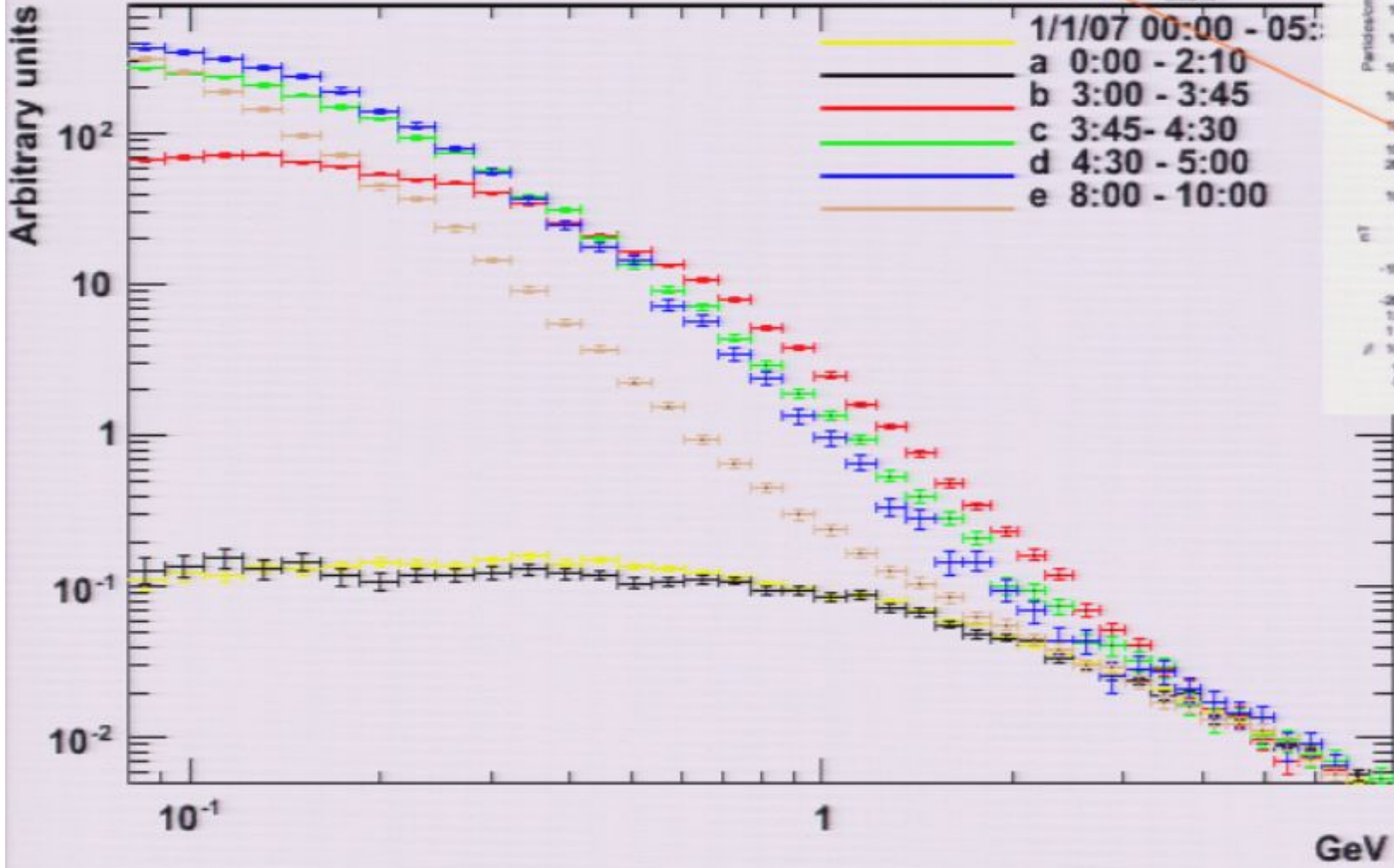
Protons



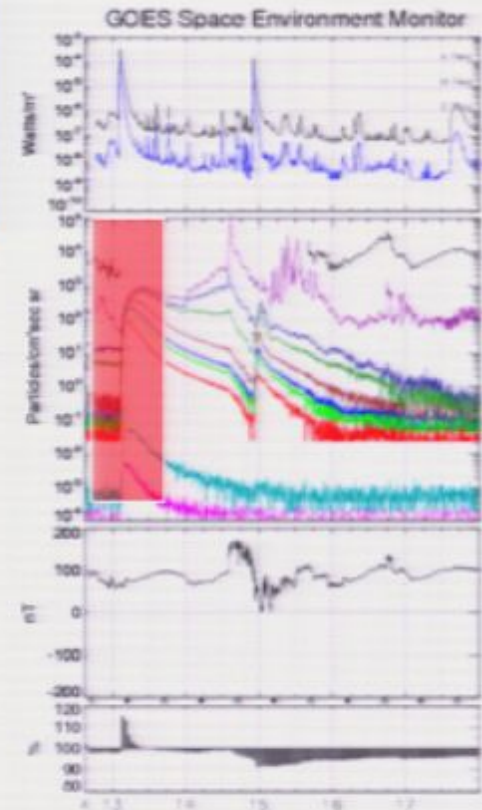
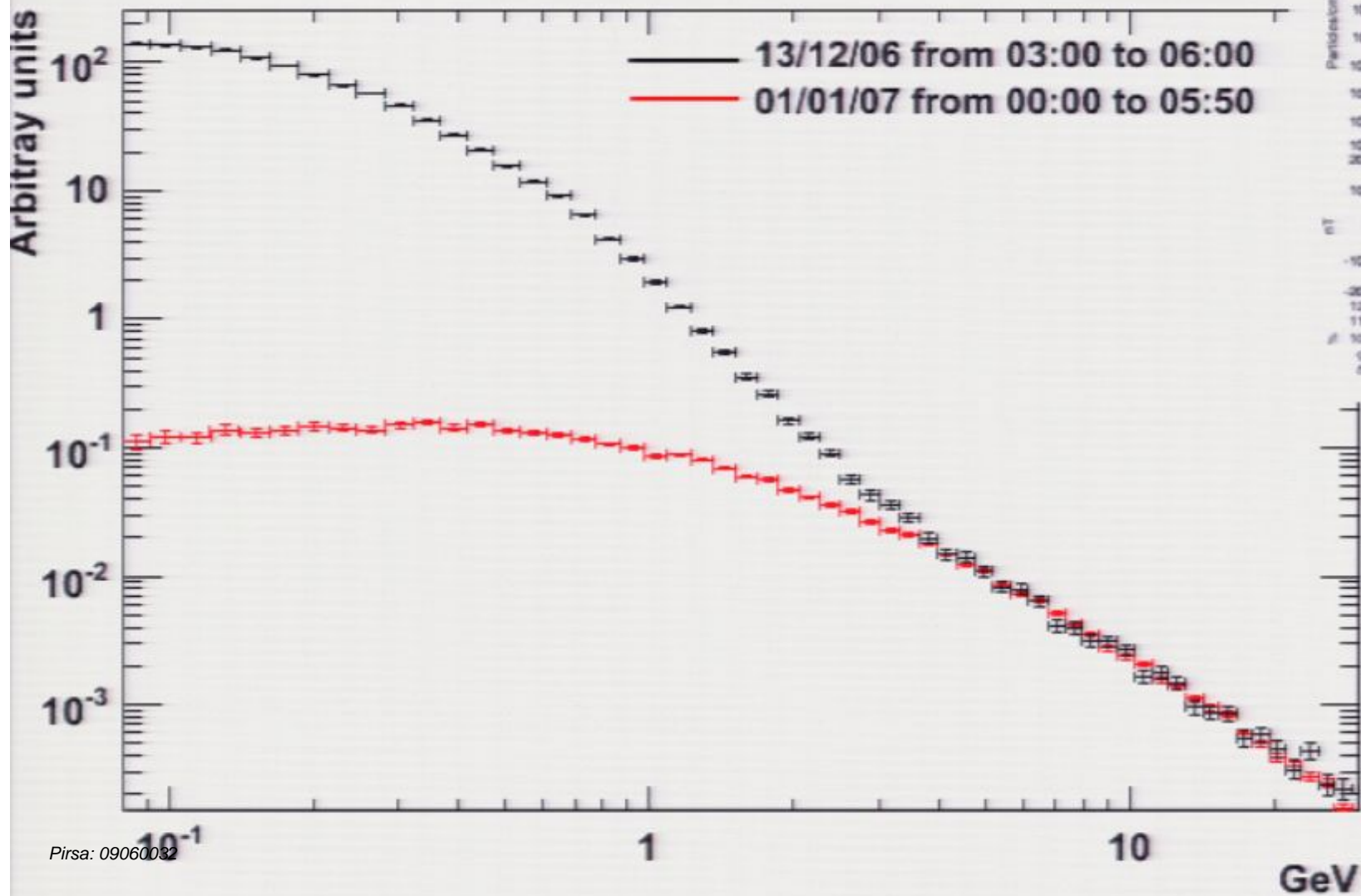
December 13th 2006 event



Protons

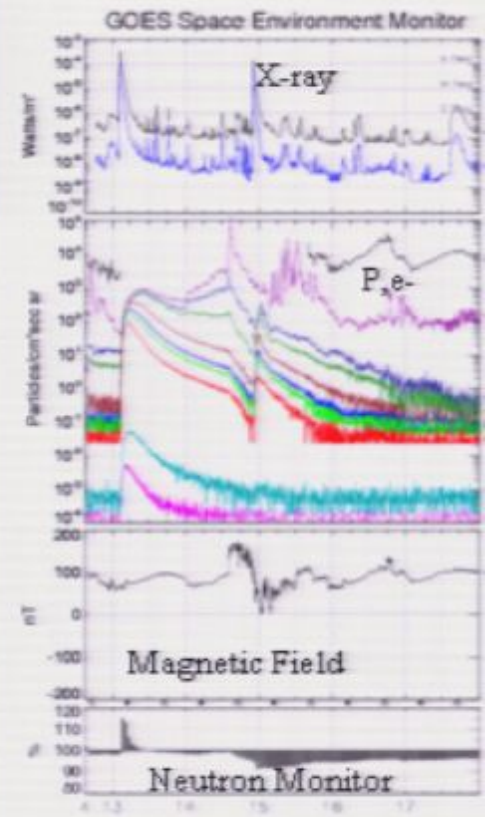
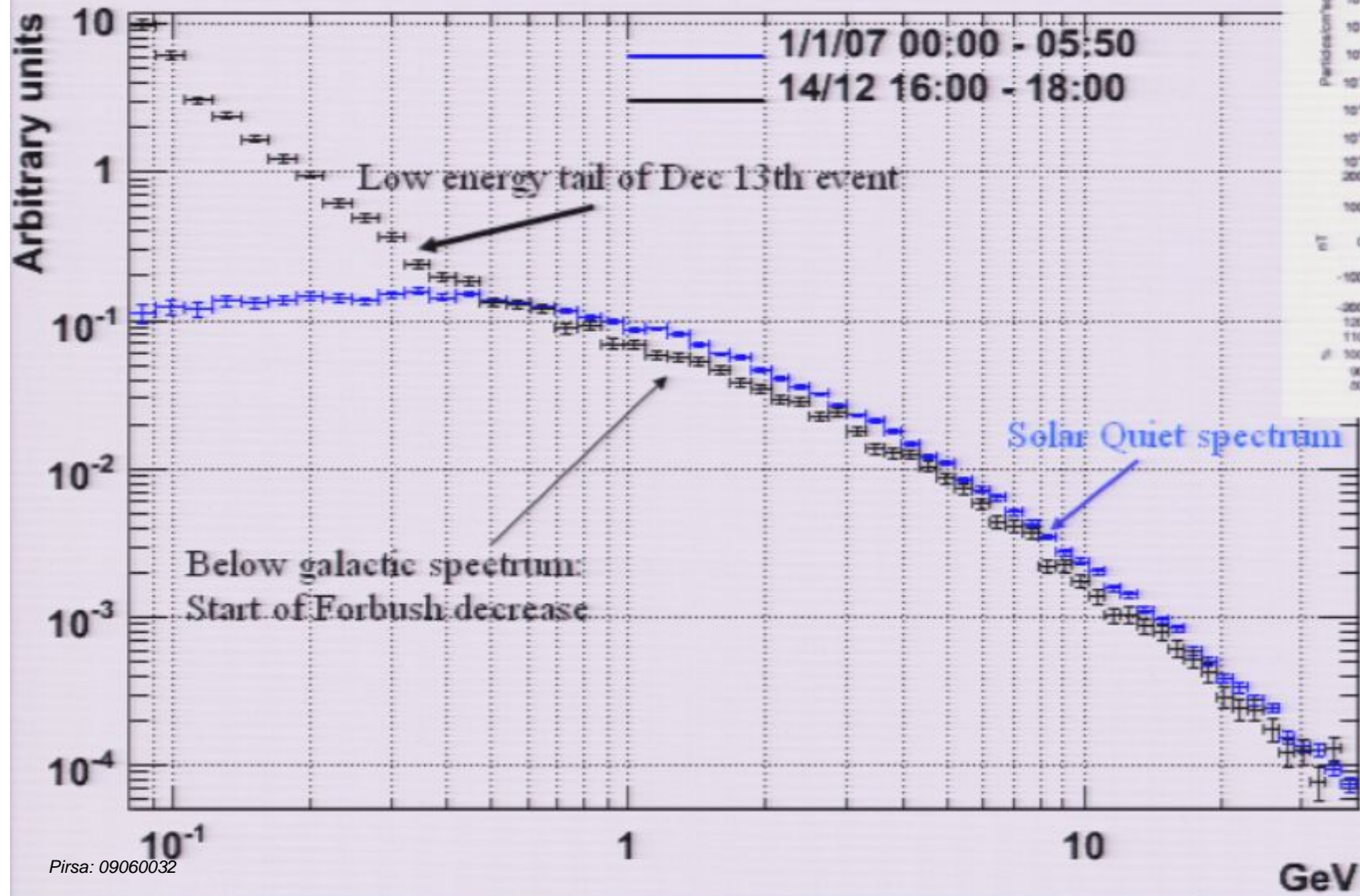


December 13th 2006 He differential spectrum



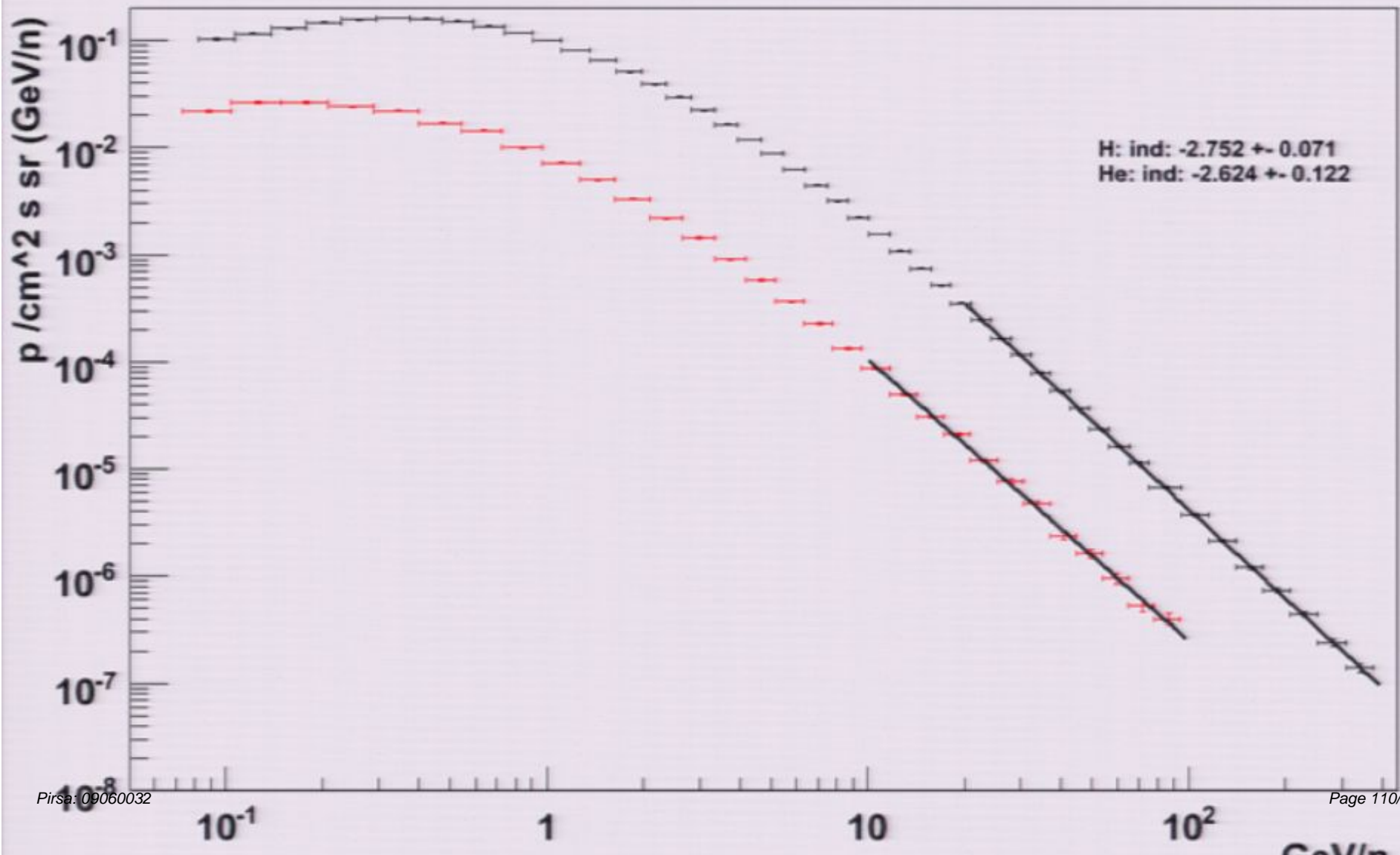
December 14th 2006 event

Protons



Proton and Helium spectra, July 2006

preliminary

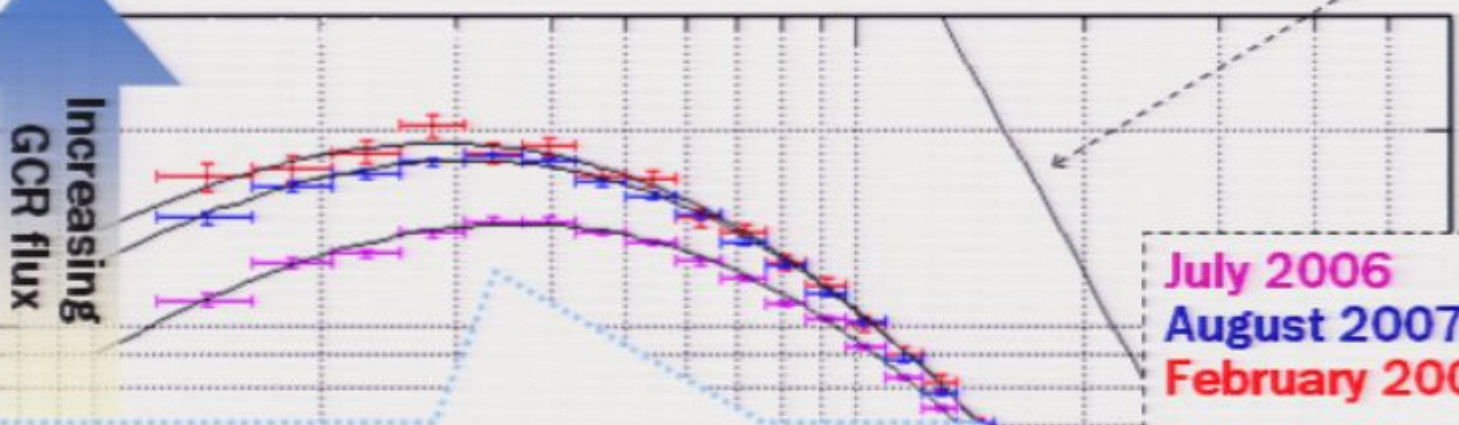


Solar modulation

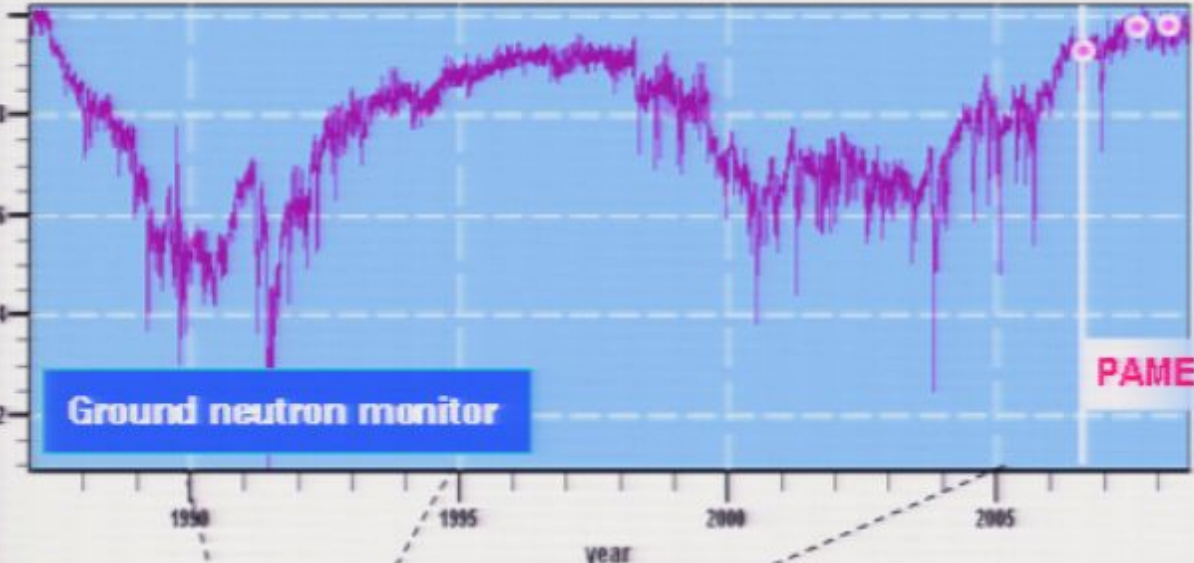
preliminary

Interstellar spectrum

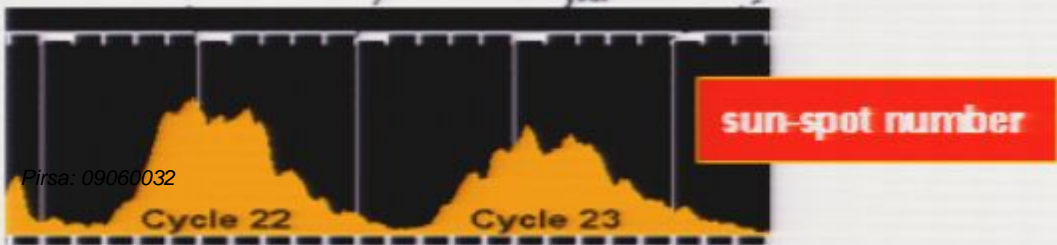
$\text{ons}/\text{cm}^2 \text{ sr s GeV}$
 10^{-1}



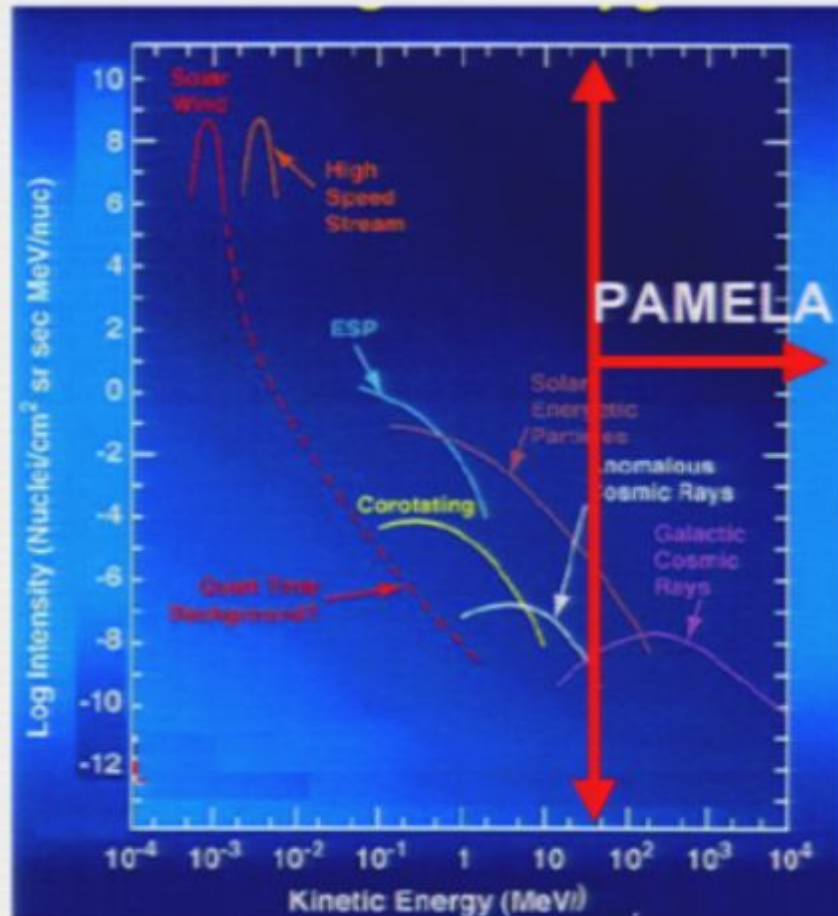
Cosmic rays variations(%)



kinetic energy (GeV)

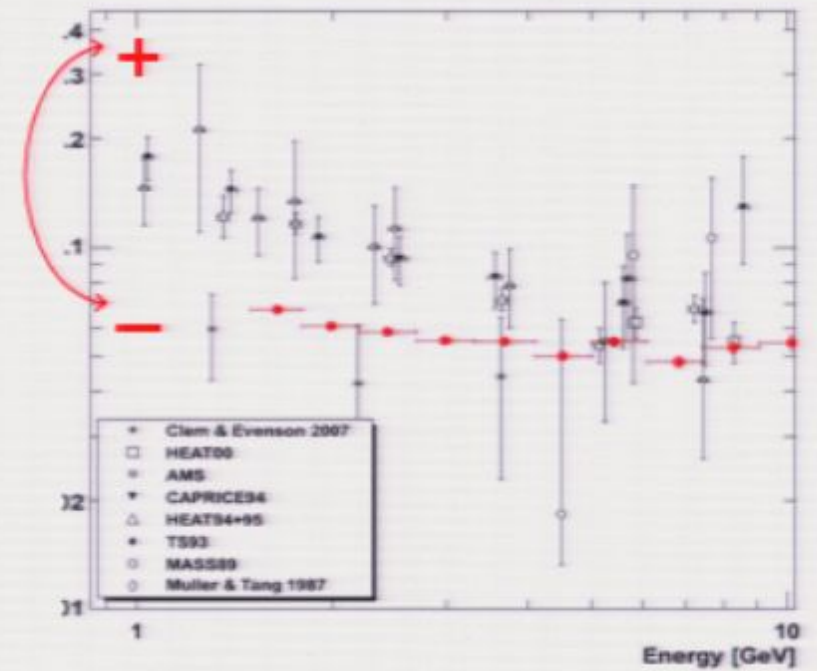
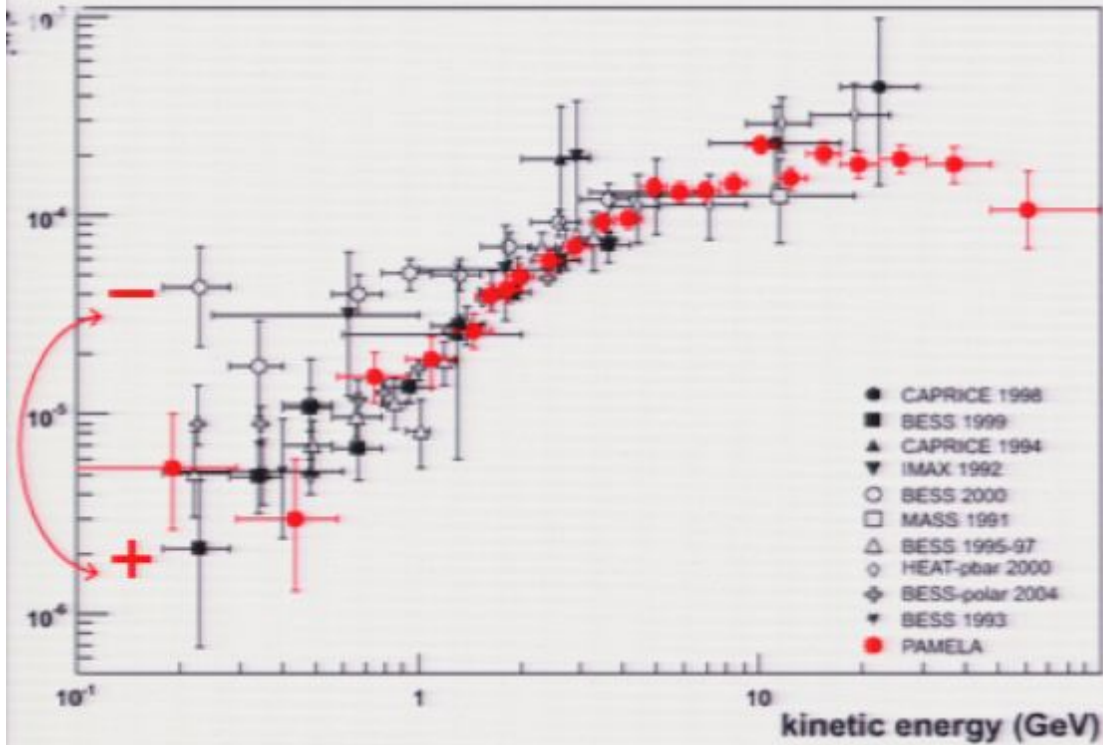


Solar Physics with PAMELA

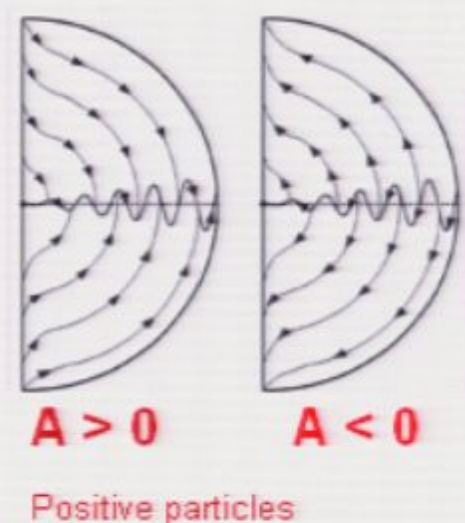
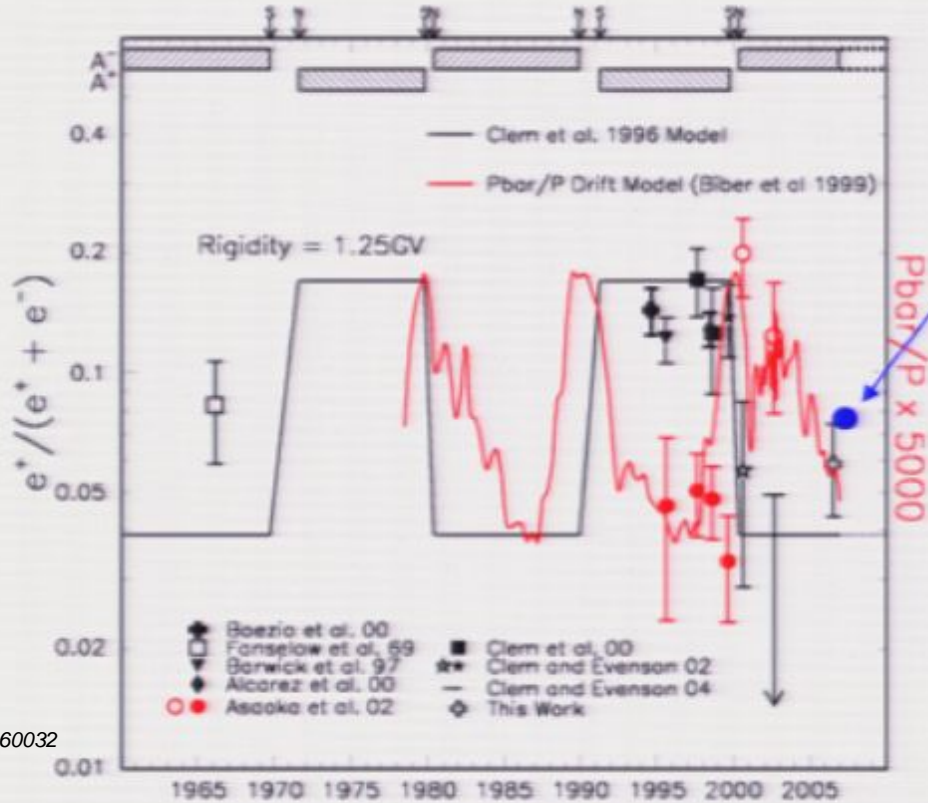
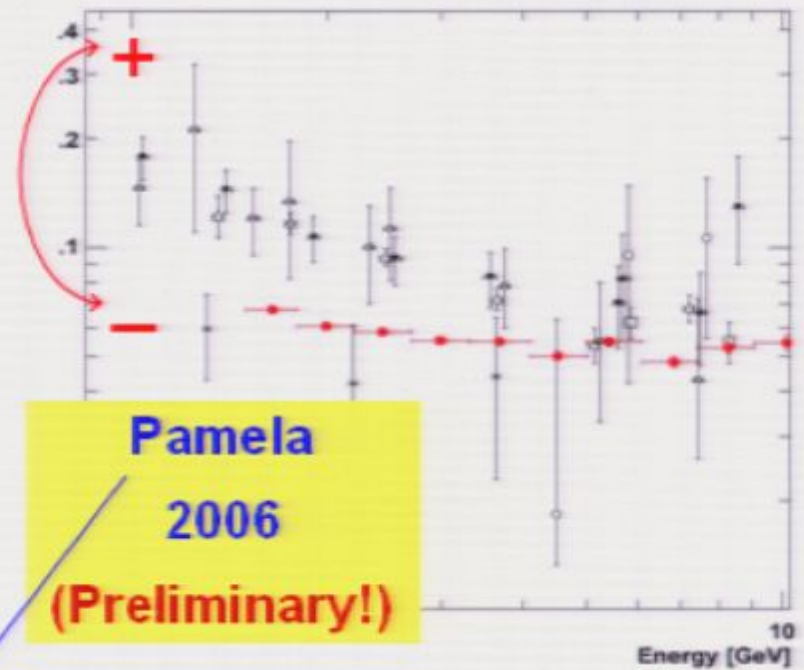
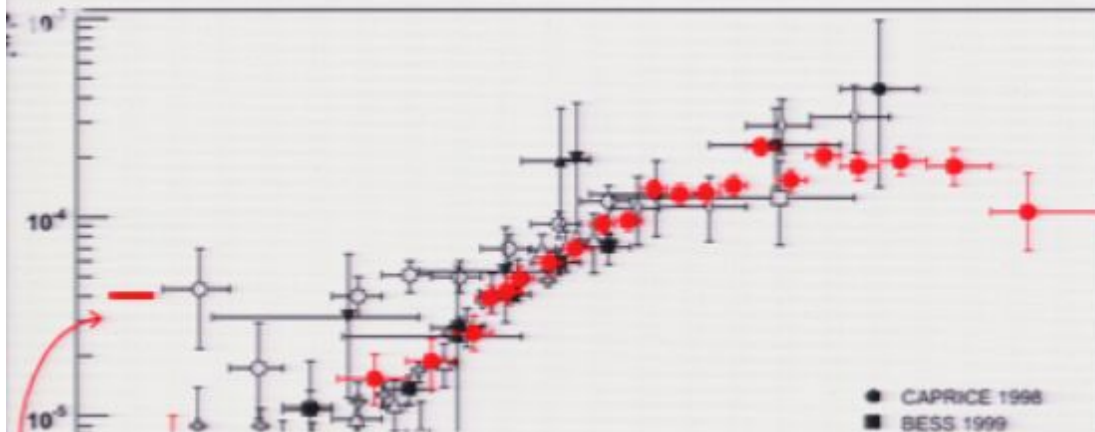


- Solar Modulation effects
- High energy component of Solar Proton Events (from 80 MeV to 10 GeV)
- High energy component of electrons and positrons in Solar Proton Events (from 50 MeV)
- Nuclear composition of Gradual and Impulsive events
- ^3He and ^4He isotopic composition

Charge dependent solar modulation



Charge dependent solar modulation



Charge dependent solar modulation

