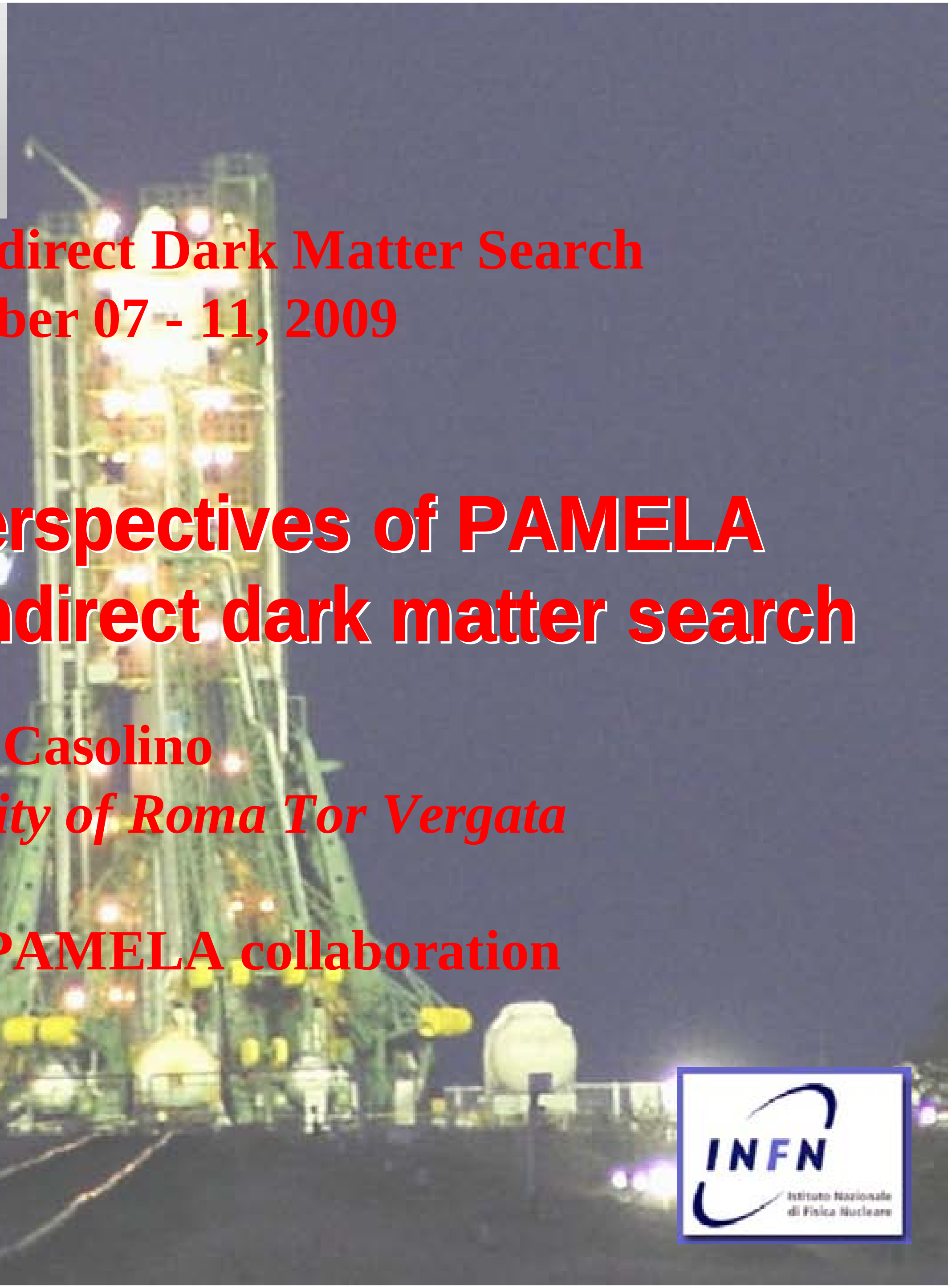


IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE
数物連携宇宙研究機構

Focus week on Indirect Dark Matter Search
December 07 - 11, 2009

Status and perspectives of PAMELA experiment for indirect dark matter search

M. Casolino
INFN & University of Roma Tor Vergata

on behalf of the PAMELA collaboration

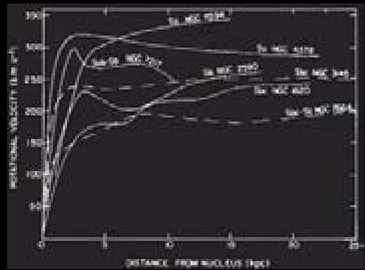
Tor Vergata

INFN Istituto Nazionale di Fisica Nucleare

Dark Matter Searches

•Cosmology

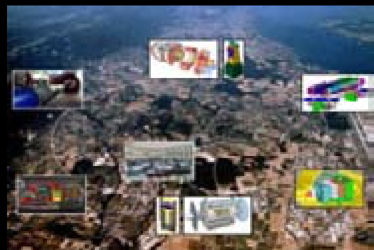
Detection, not identification



1E 0657-56 - Bullet Cluster

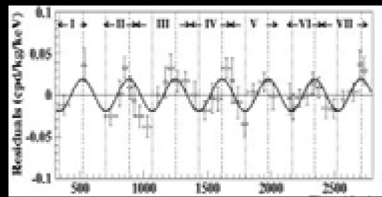
•LHC Search

Supersymmetry, not necessarily DM



•Direct Detection

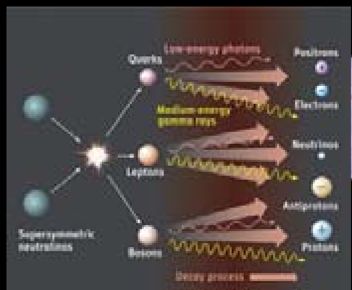
Local structure and nature

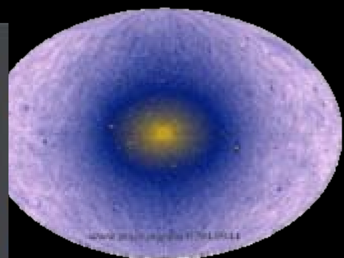


DAMA

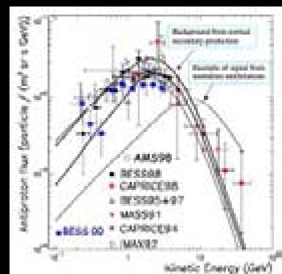
•Indirect Detection

Various galactic scales

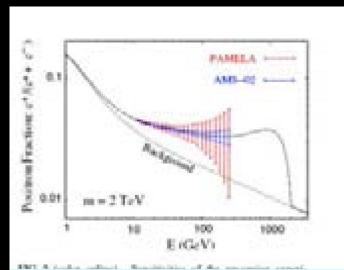




γ: Galactic centre



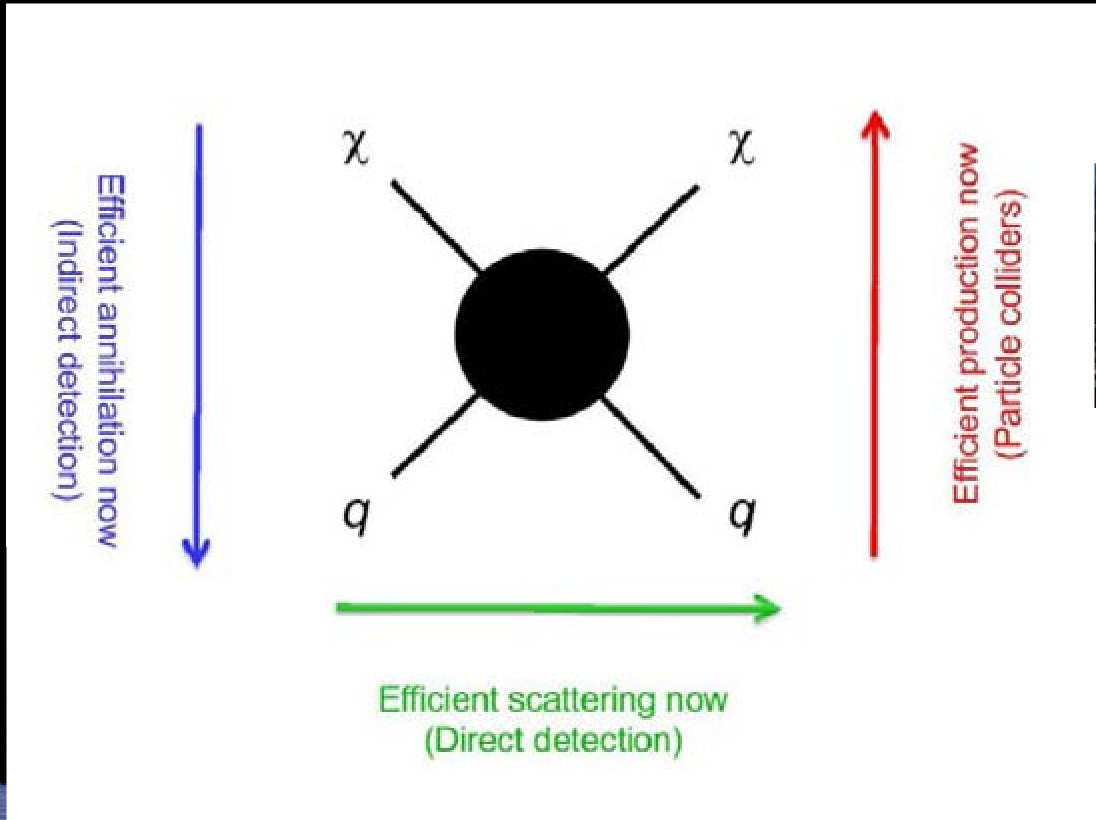
Antiprotons: Galactic average

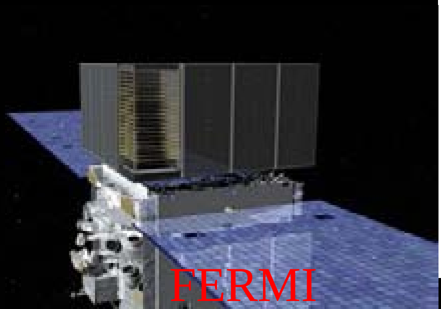


positrons: Local galactic 1kpc

M. Casolino, INFN & University Roma Tor Vergata

Different approaches to search for Dark Matter





Adapted from P. Lipari

Another problem:

Matter / Antimatter Asymmetry in the Universe

Sakharov conditions

1) Direct violation of barionic number

particle “X” decays breaking barion symmetry

2) CP violation

to avoid specular antiparticle decay

3) Non thermal equilibrium at a given time

To avoid barion compensation through inverse processes

Sakharov, A.D. 1967, J. of Exper. and Theo. Phys. Letters, 5, 24-28, “Violation of CP Invariance, C Asymmetry, and Baryon Asymmetry of the Universe”

Russian: Андре́й Дми́триевич Са́харов) (May 21, 1921 – December 14, 1989)

Matter – Antimatter domain separation?

- γ-ray ≈ 0.1 GeV from annihilation in boundary regions

- ***Current limit: separation above cluster of galaxy ($\geq$ 10 Mpc)***

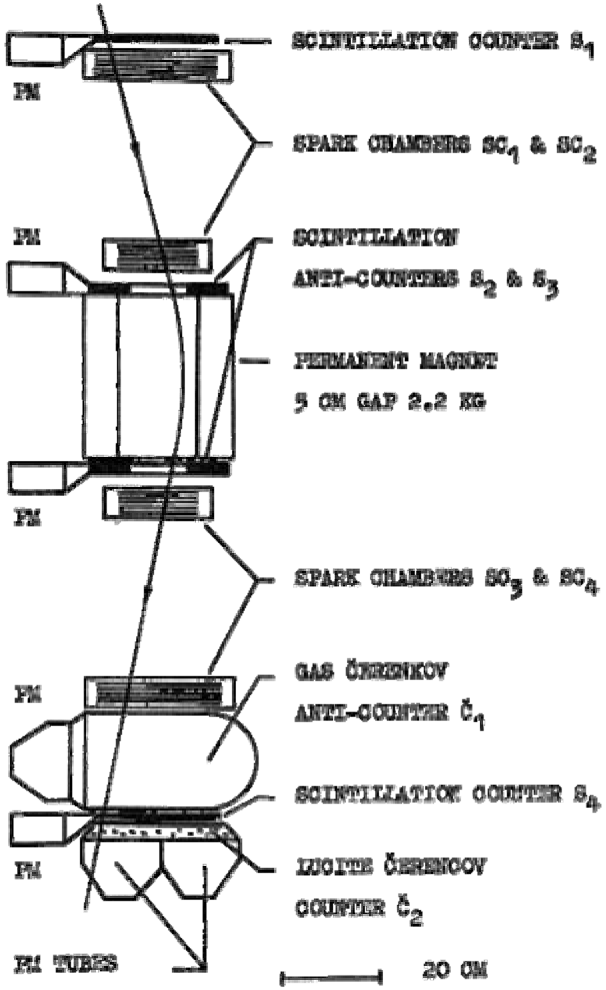
Steigman, G. 1976, Ann. Rev. Astron. Astrophys. 14, 339,
"Observational tests of antimatter cosmologies"

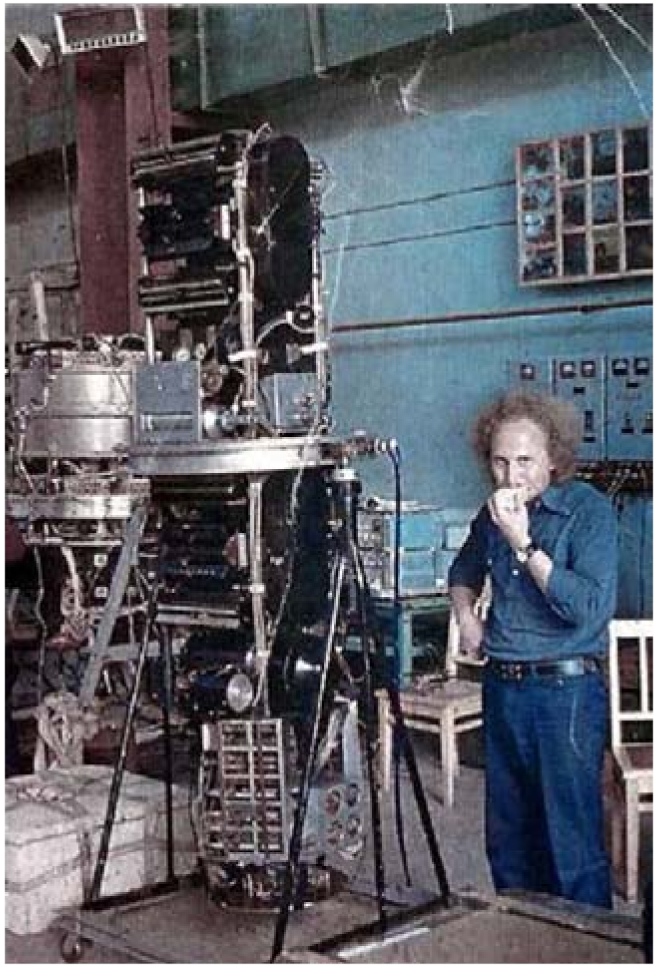
- Observable?
- Magnetic fields ?
- Survival probability?

Ahlen, S.P. et al. 1982, ApJ, 260, 20,
"Can we detect antimatter from other galaxies?"

M33

Discovery of antiprotons in cr, 1979





$\bar{p}/p$ ratio

6 x 10^{-4}

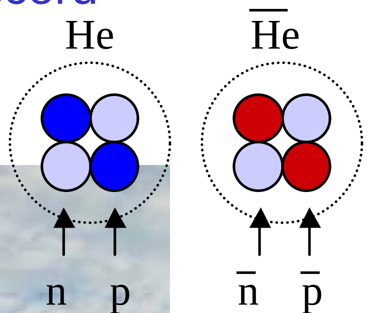
2-5 GeV

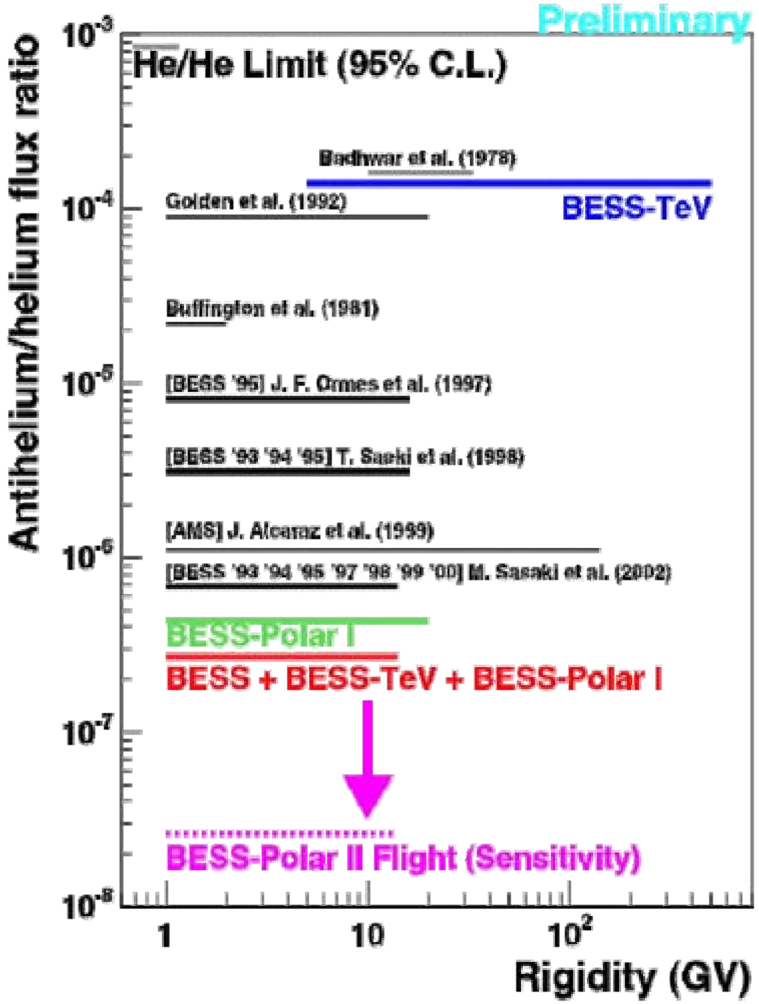
From
Robert E. Streitmatter

Bogomolov, E.A. et al. 1979, Proc. 16th ICRC, Kyoto, 1, 330,
"A Stratospheric Magnetic Spectrometer Investigation of the Singly Charged Component Spectra and Composition of the Primary and Secondary Cosmic Radiation"

Antihelium search

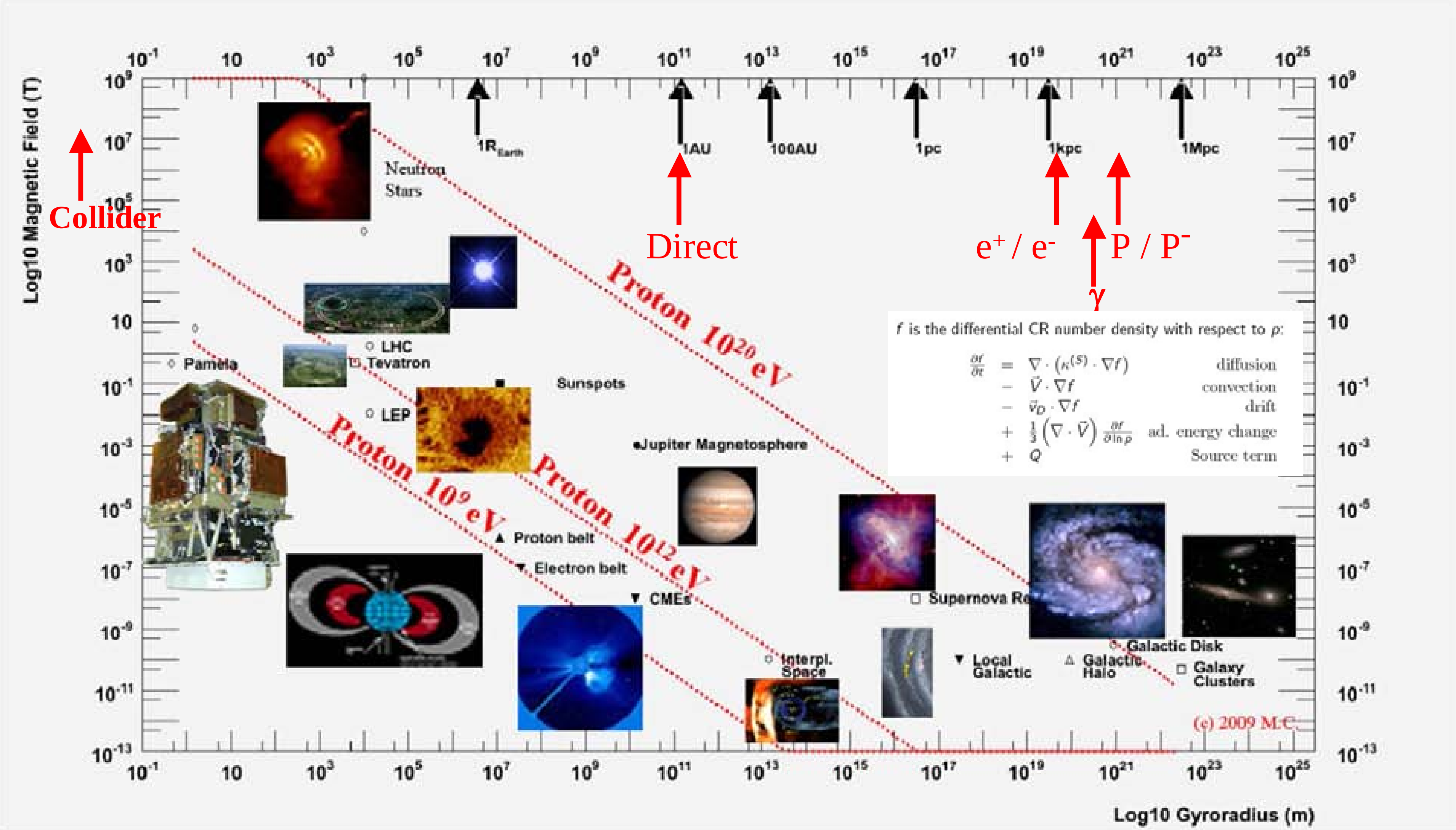
- Probability to produce antinuclei in cosmic rays is negligible. AntiHe could be produced in Big Bang.
- **Look in cosmic rays**
- **Up to now only upper limit**
- BESS has current world record





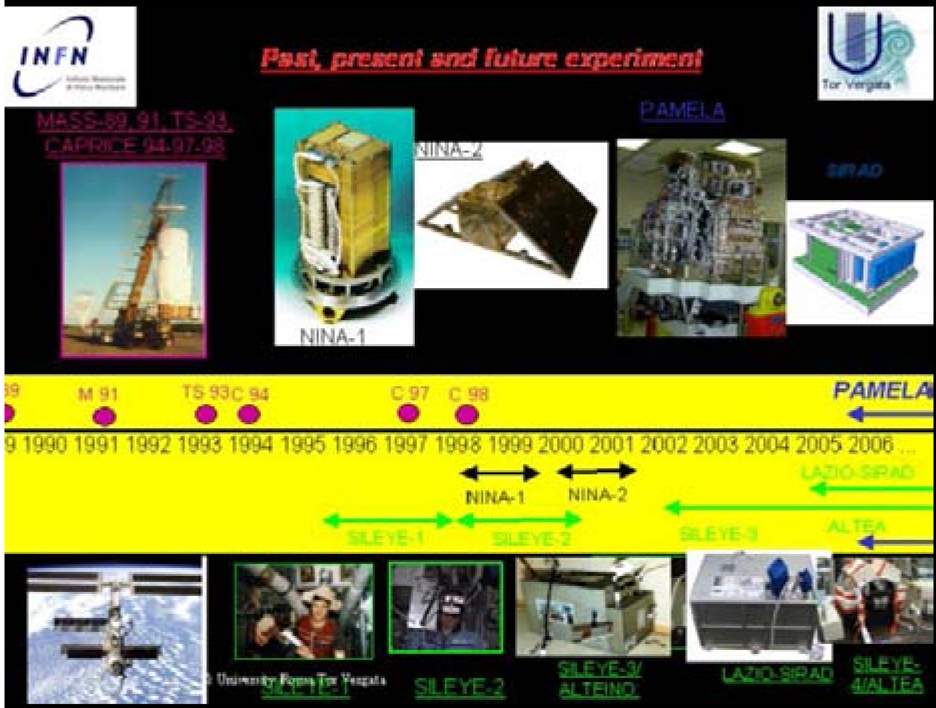
Ref.: M. Sasaki et al. at COSPAR-2006

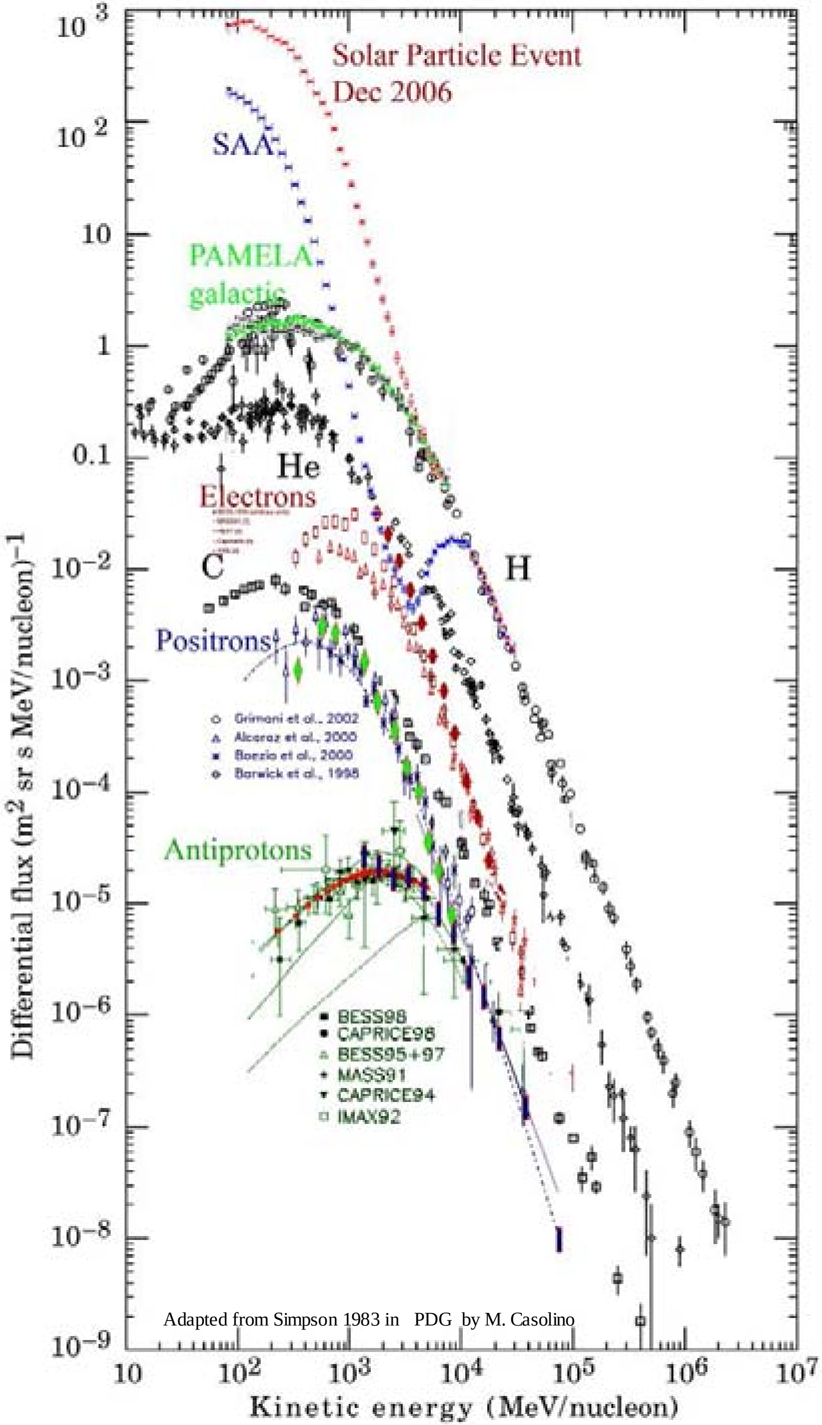
Pamela Physics objectives in the Hillas Plot



$$\frac{\partial f}{\partial t} = \nabla\cdot(\kappa^{(S)}\cdot\nabla f) - \vec{V}\cdot\nabla f - \vec{v}_D\cdot\nabla f + \frac{1}{3}(\nabla\cdot\vec{V})\frac{\partial f}{\partial \ln p} + Q$$

High precision charged cosmic ray measurement in Low Earth Orbit





M. Casolino, INFN & University Roma Tor Vergata

Time of Flight
(three scintillators, 6 planes, 48 phototubes)

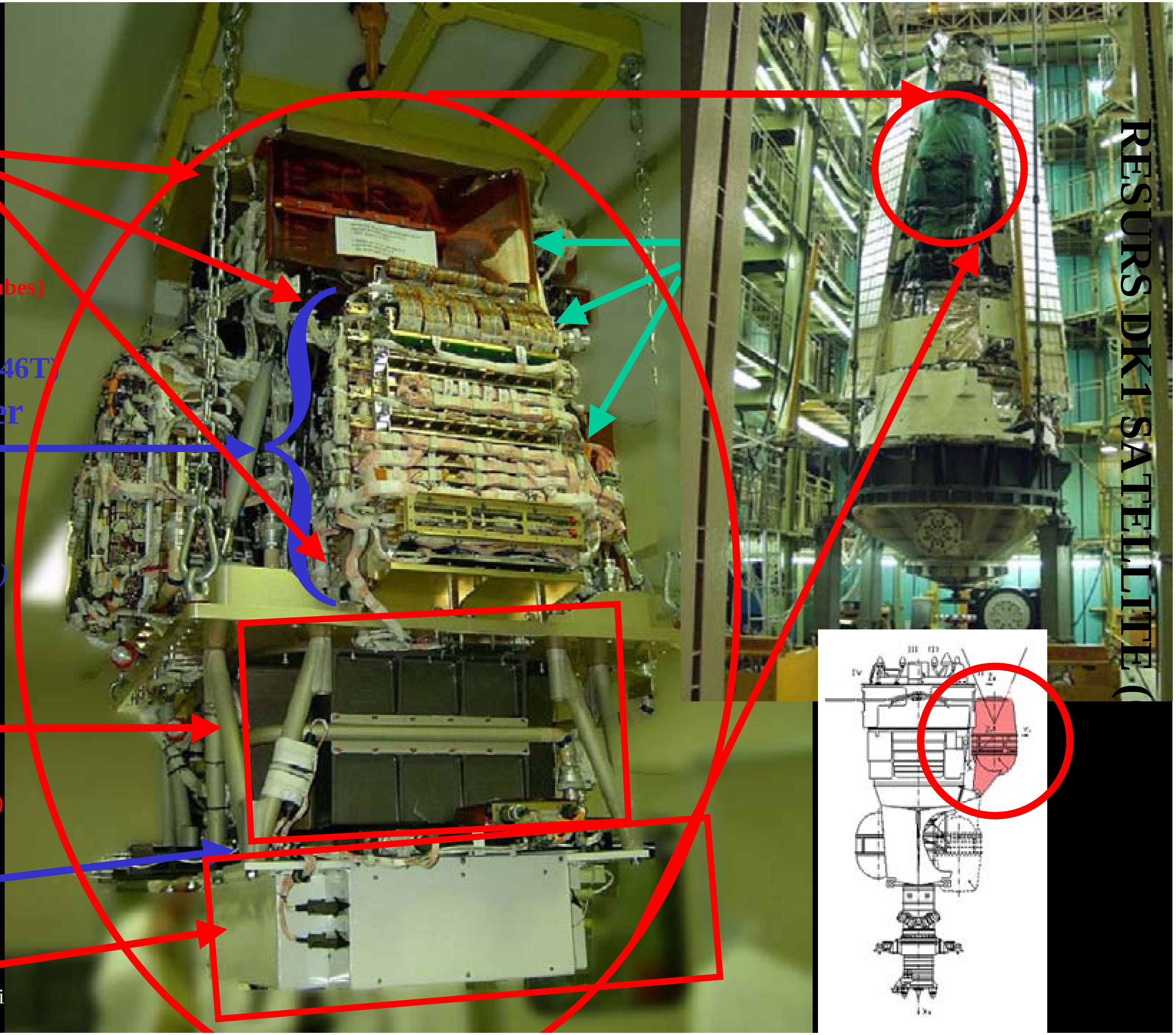
Magnetic (0.46T) Spectrometer Microstrip detector
(6 double sided microstrip planes)

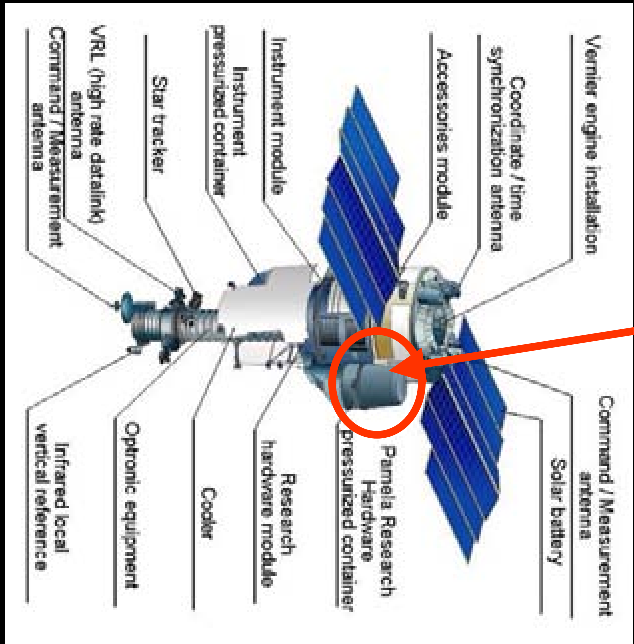
Silicon Tungsten Tracking Calorimeter
(44 planes of 96 strip)

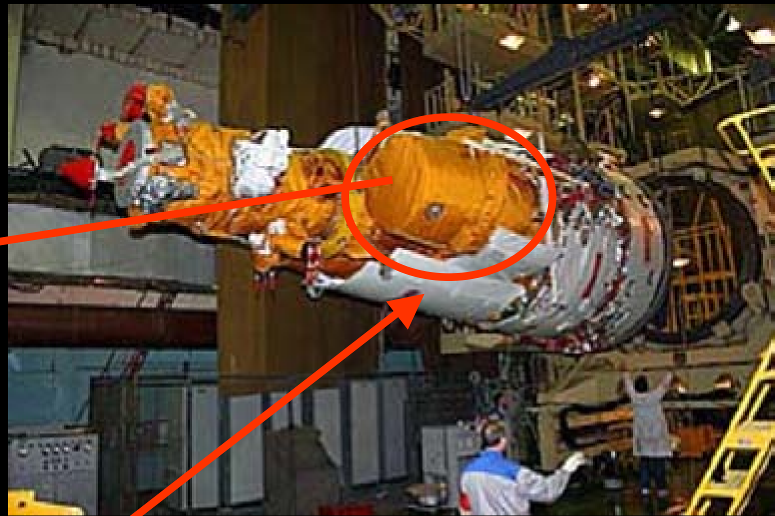
Shower Catcher Scintillator

Neutron Detector

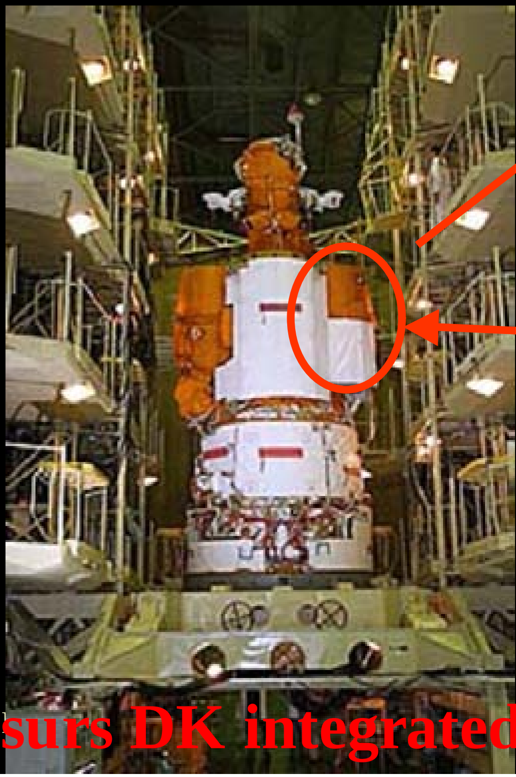
M. Casoli



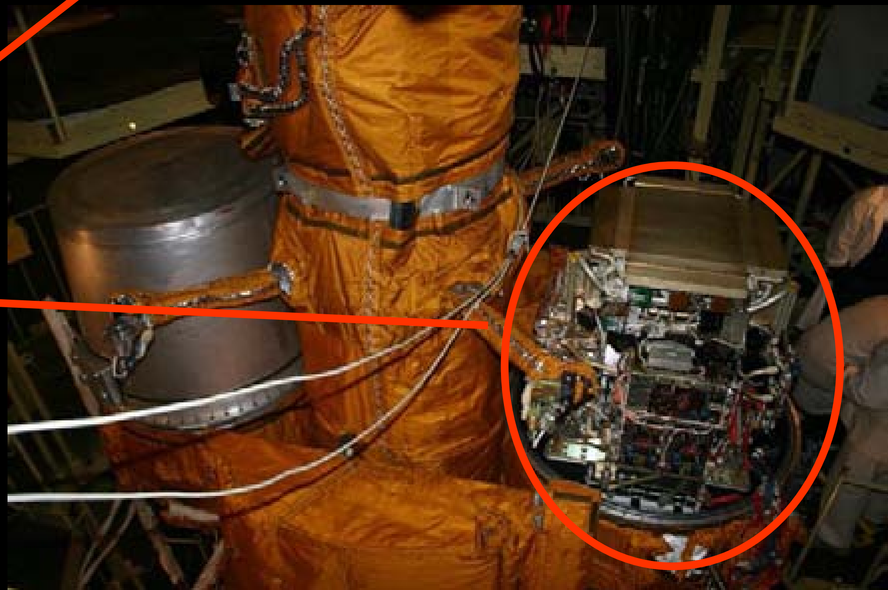




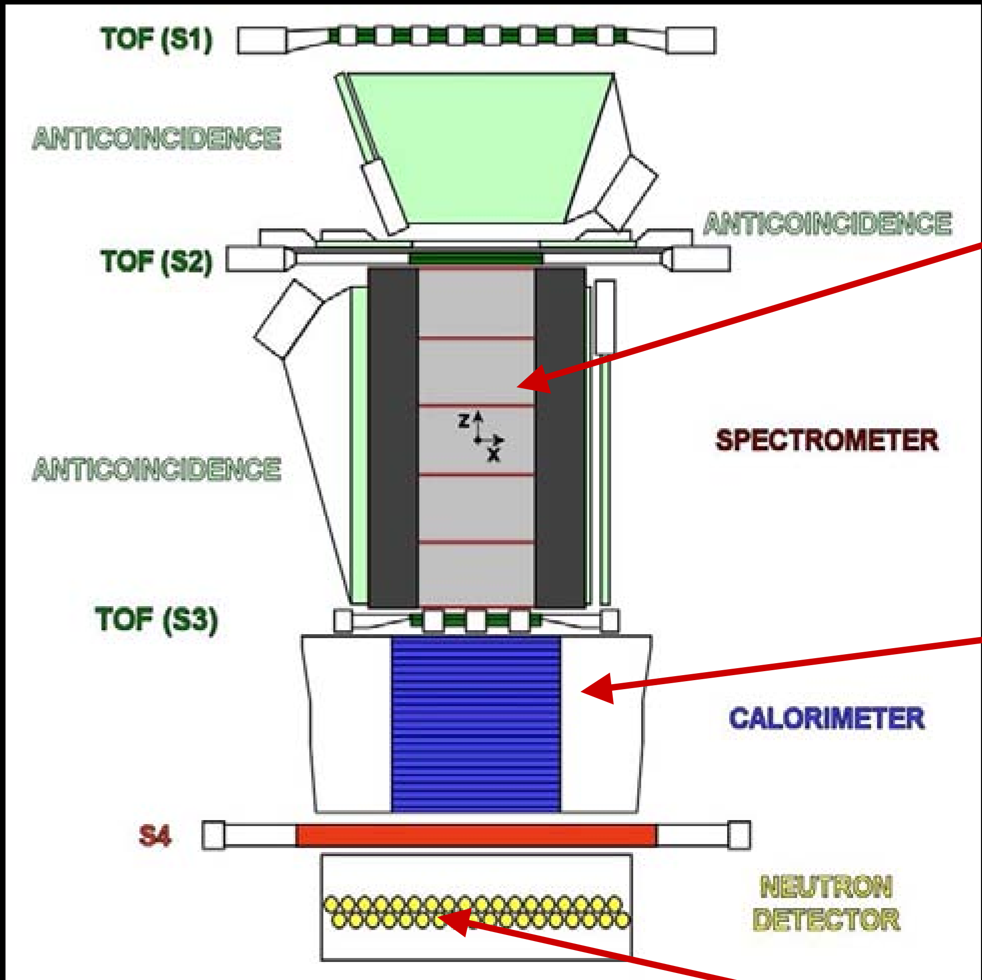
Coupling to Soyuz



Resurs DK integrated



Pamela during integration in Baikonur



Spatial Resolution

- $\cong$ 2.8 μm bending view
- $\cong$ 13.1 μm non-bending view

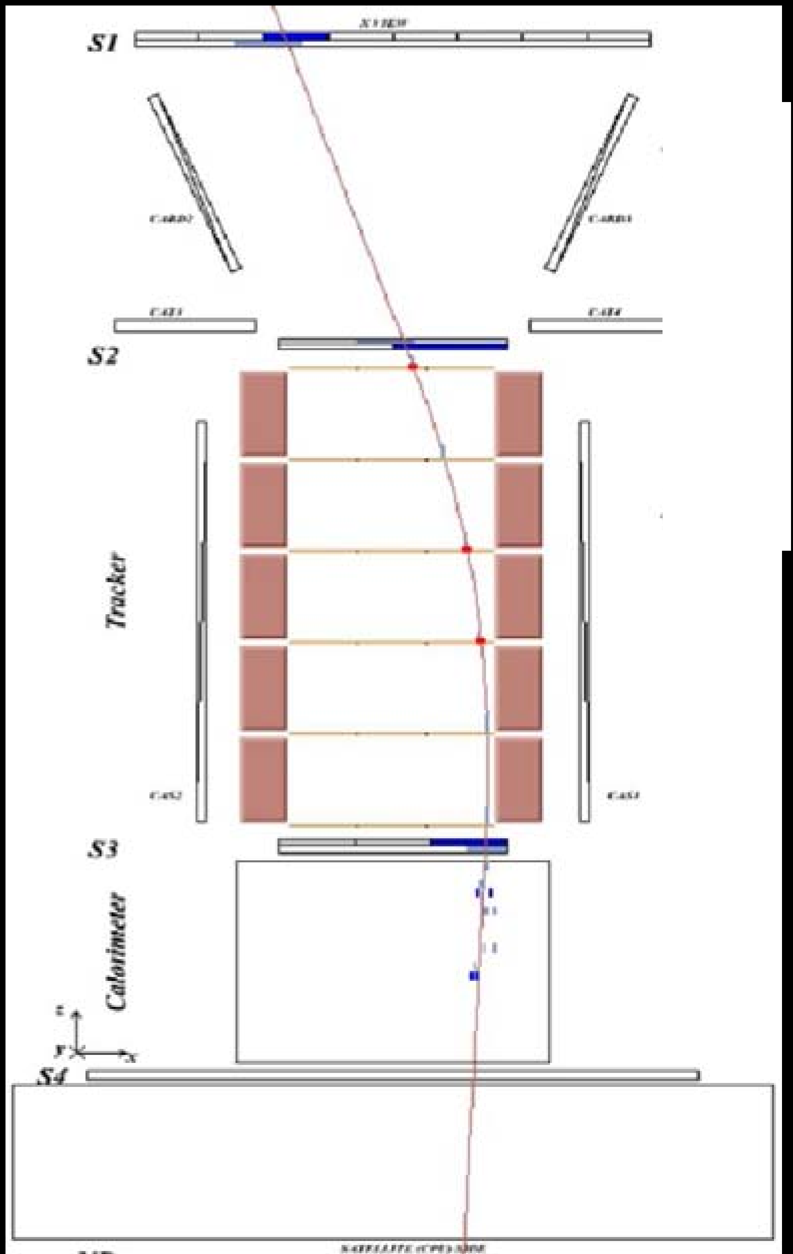
MDR from test beam data $\cong$ 1 TV

Calorimeter Performances:

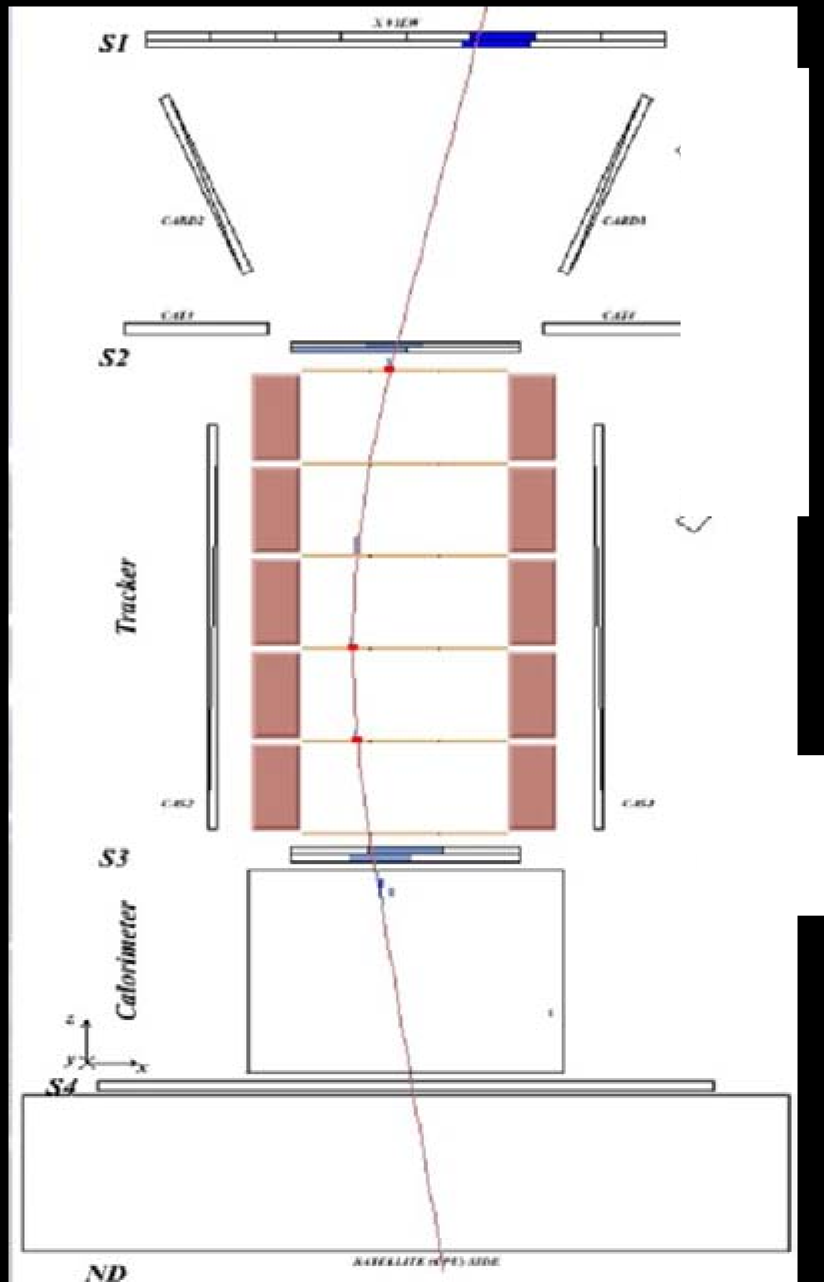
- $\bar{p}/e^+$ selection eff. ~ 90%
- p rejection factor ~ 10^5
- e^- rejection factor > 10^4

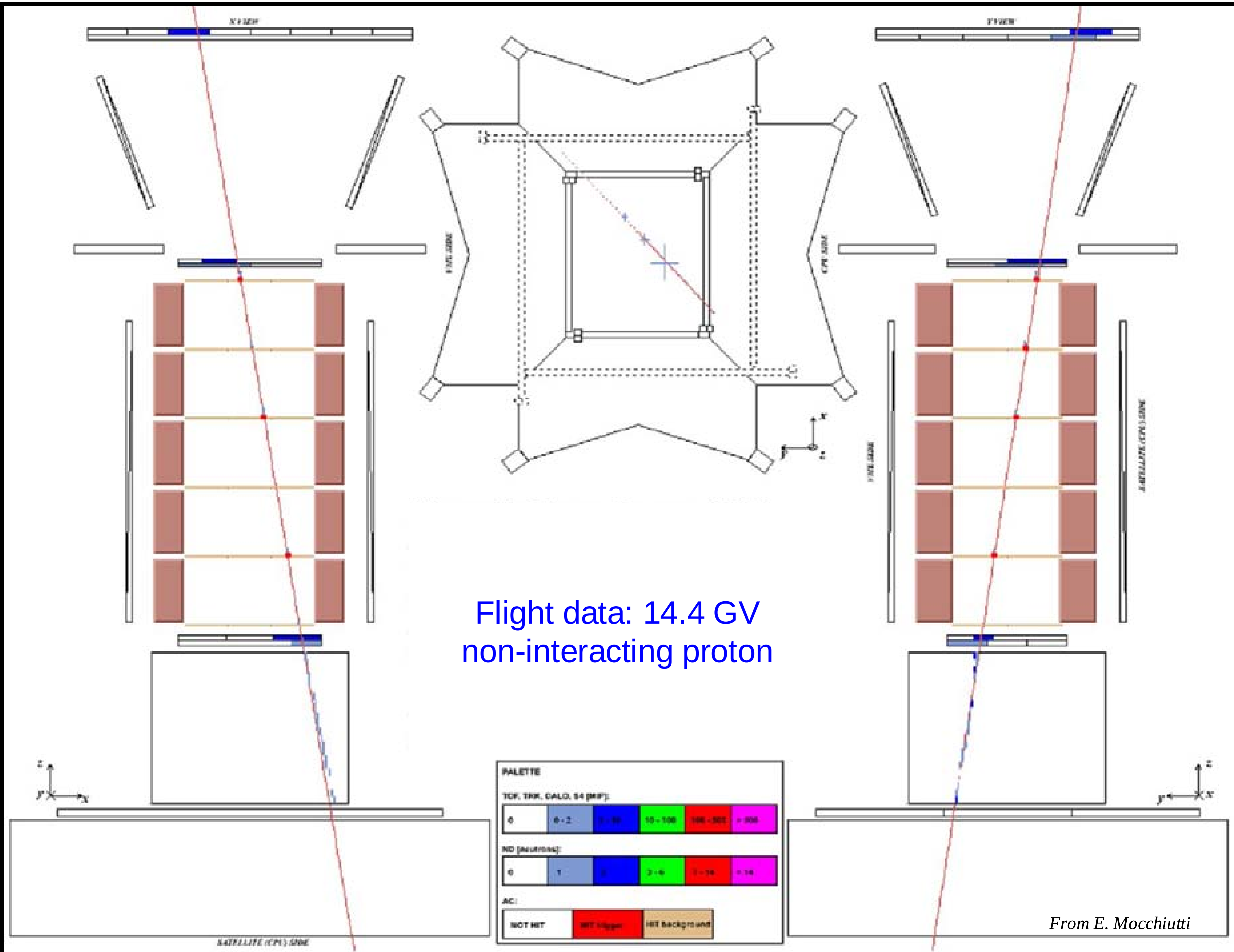
GF ~20.5 $cm^2 sr$
Mass: 470 kg
Size: 120x40x45 cm^3
Power Budget: 360 W

ND p/e separation capabilities >10 above 10 GeV/c, increasing with energy e+ 0.171 GV Bending view



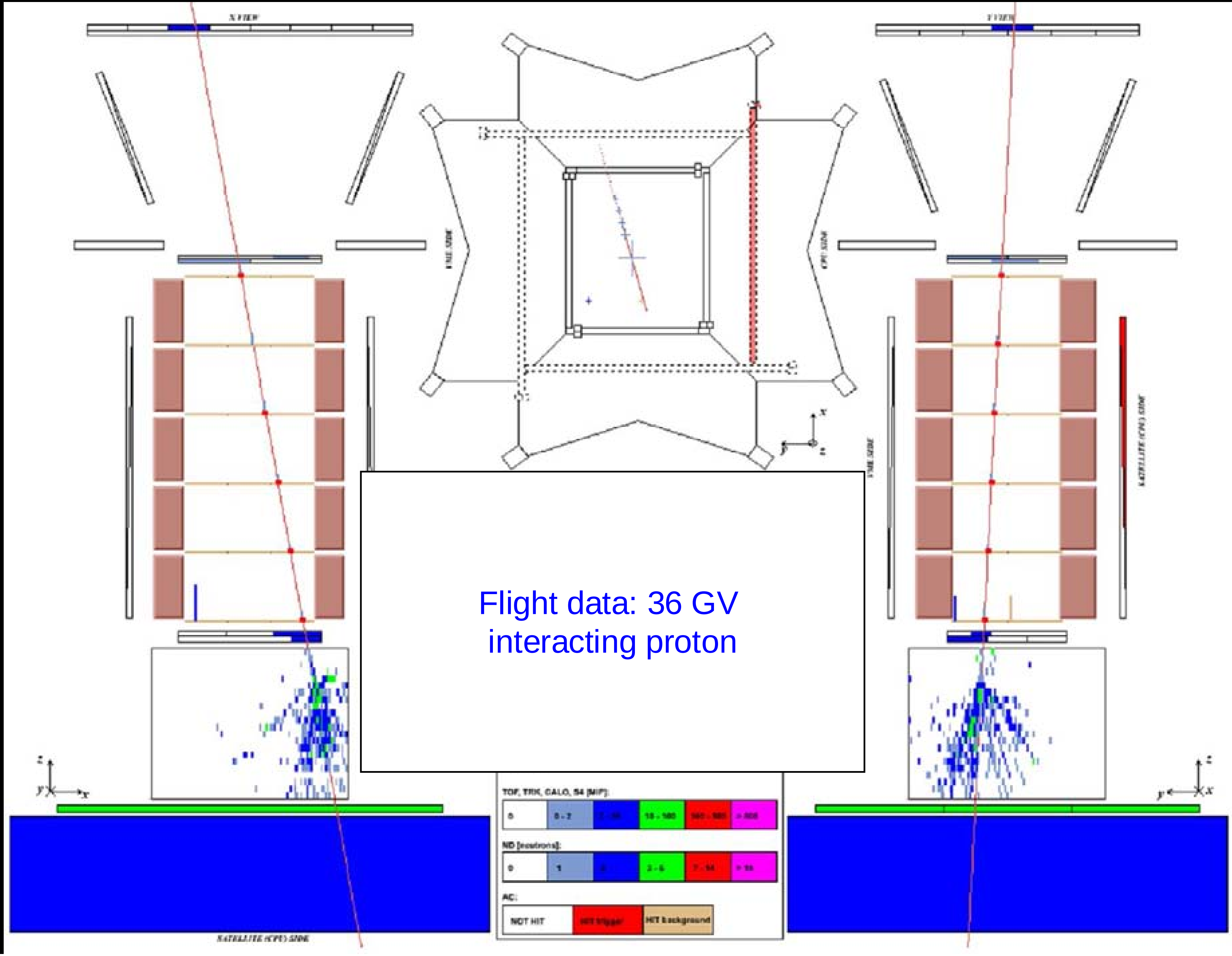
e- 0.169 GV Bending view



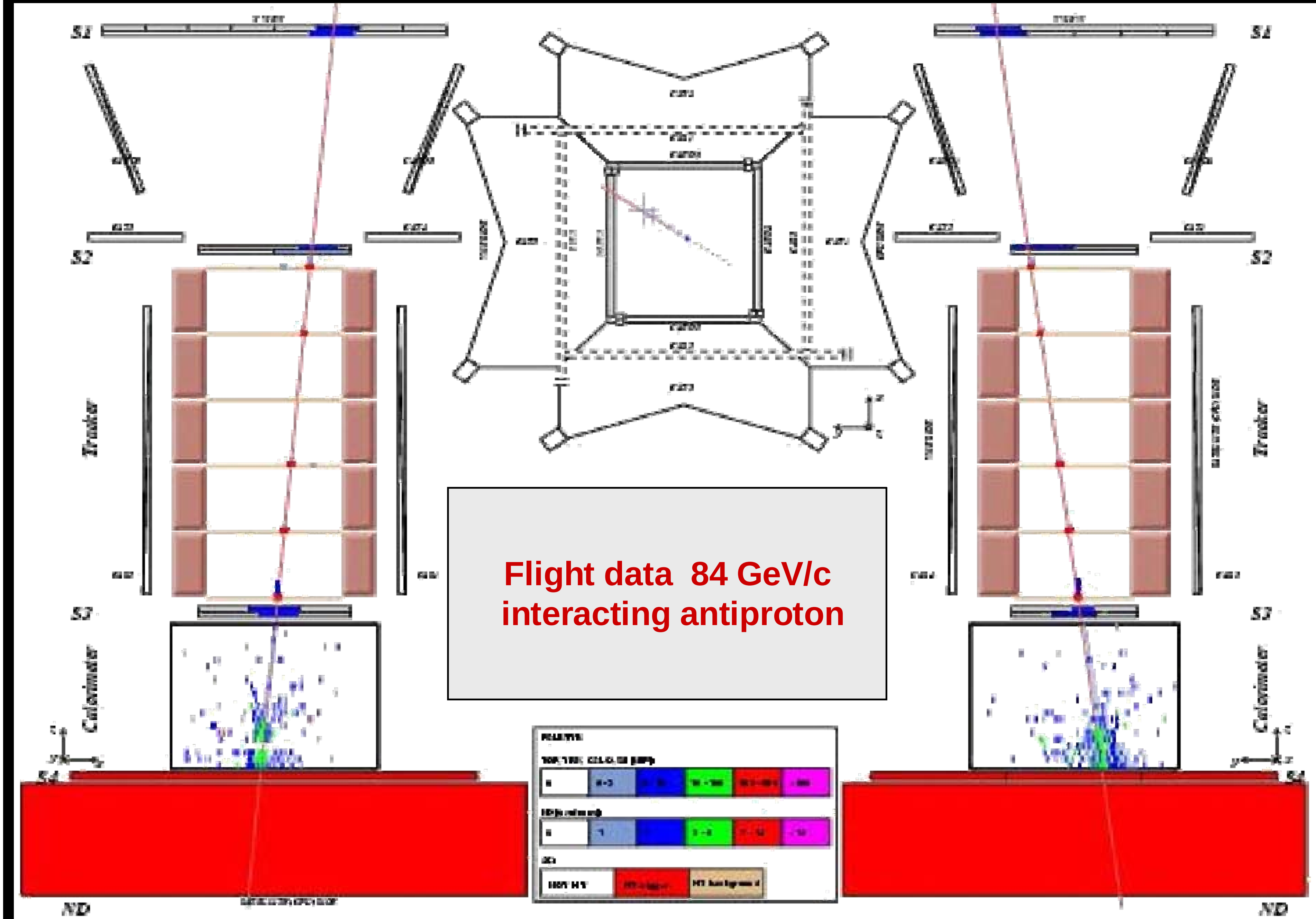


Flight data: 14.4 GV
non-interacting proton

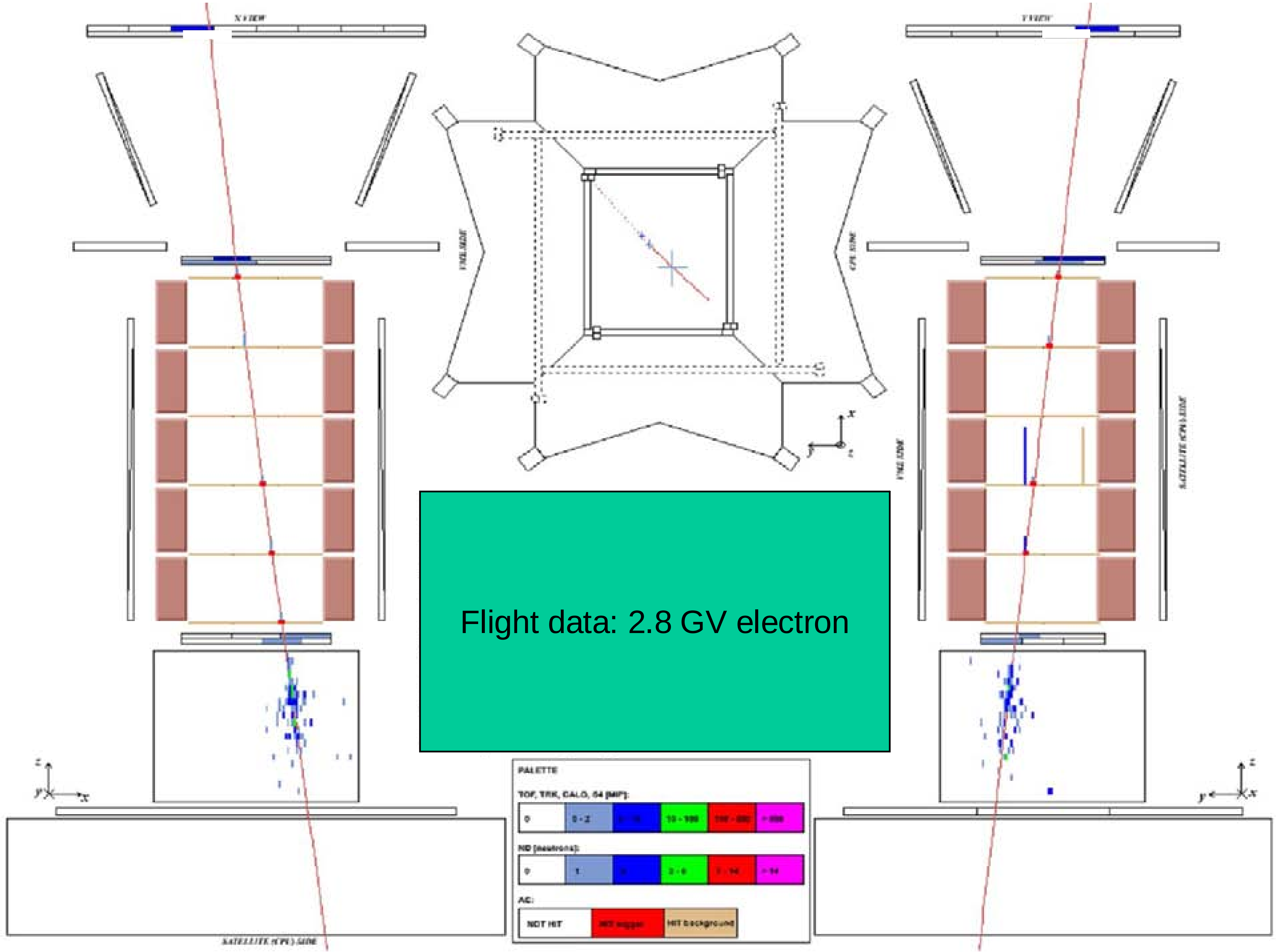
From E. Mocchiutti



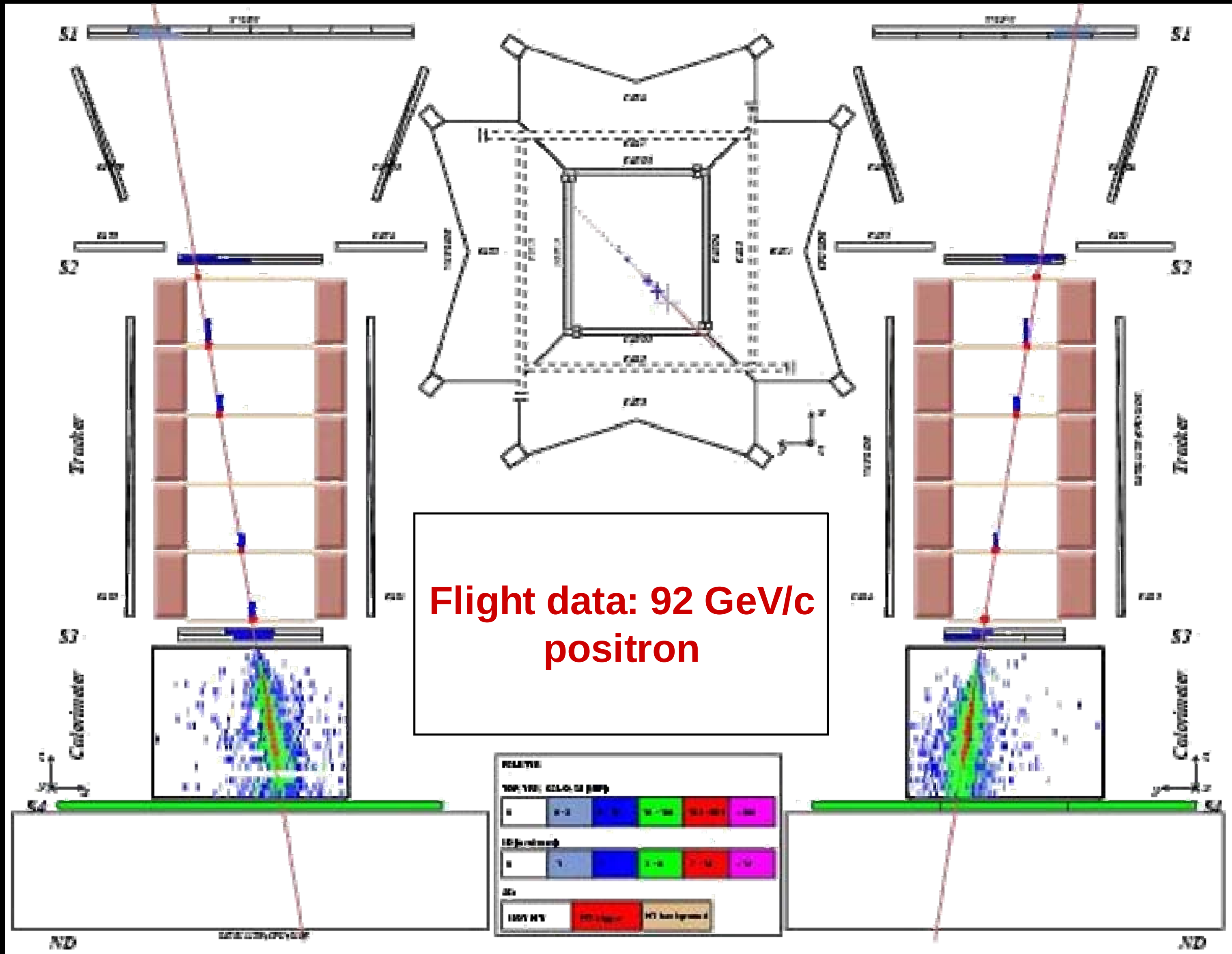
Flight data: 36 GV
interacting proton

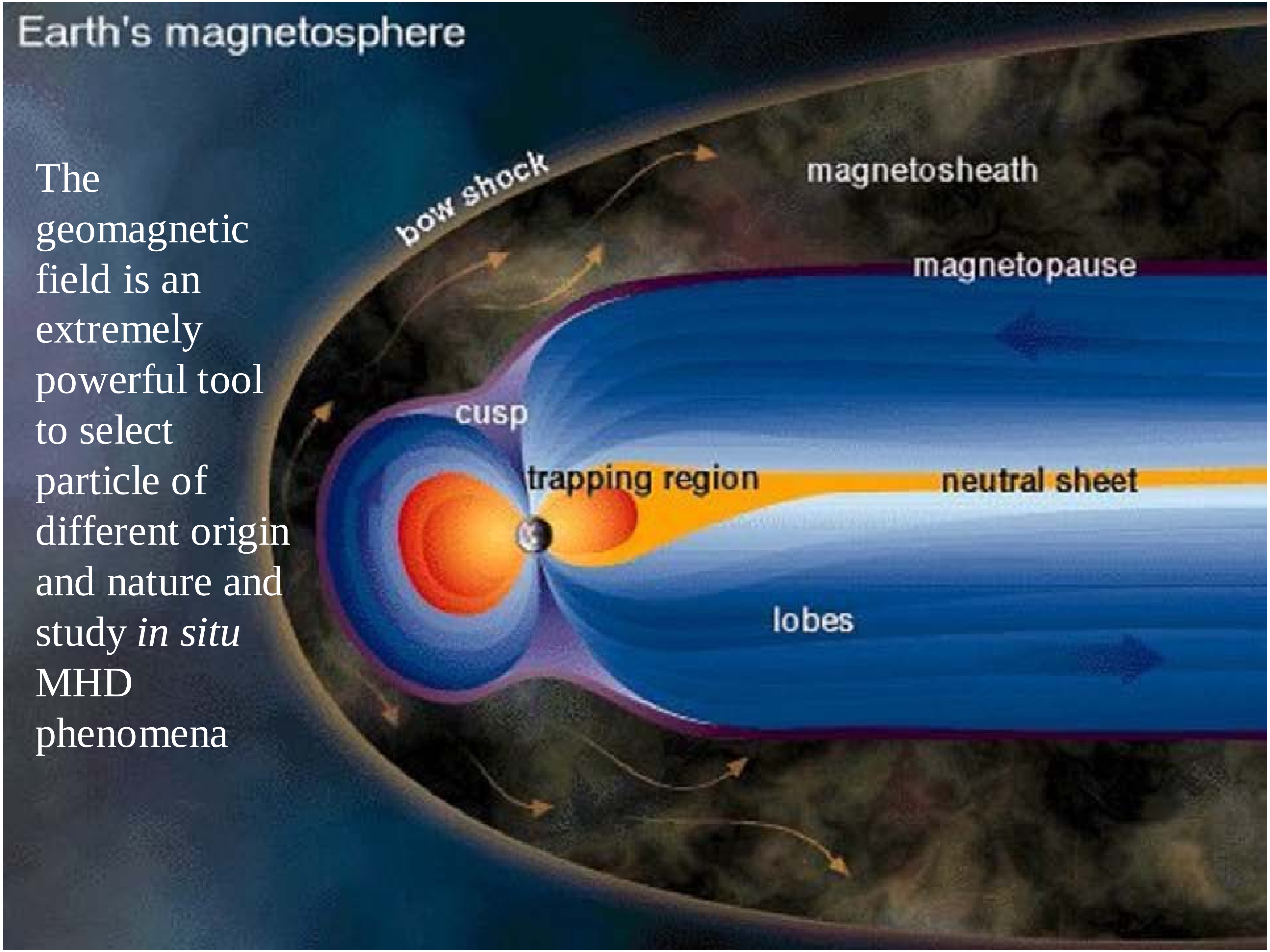


Flight data 84 GeV/c interacting antiproton



Flight data: 2.8 GV electron

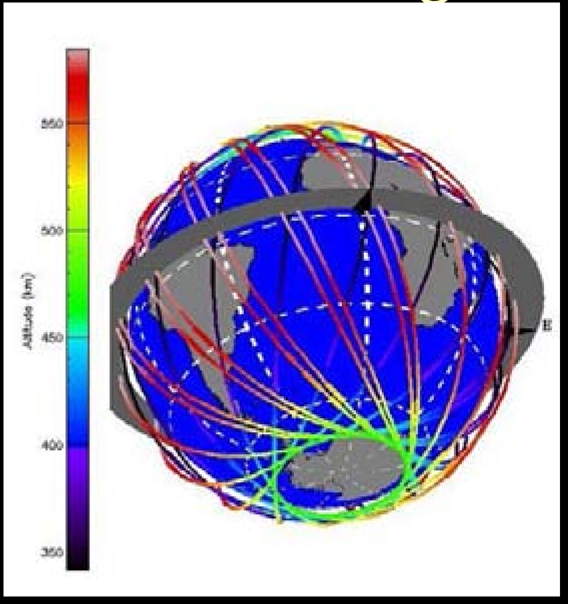

S1
S2
S3
S4
ND
Tracker
Calorimeter
Flight data: 92 GeV/c
positron

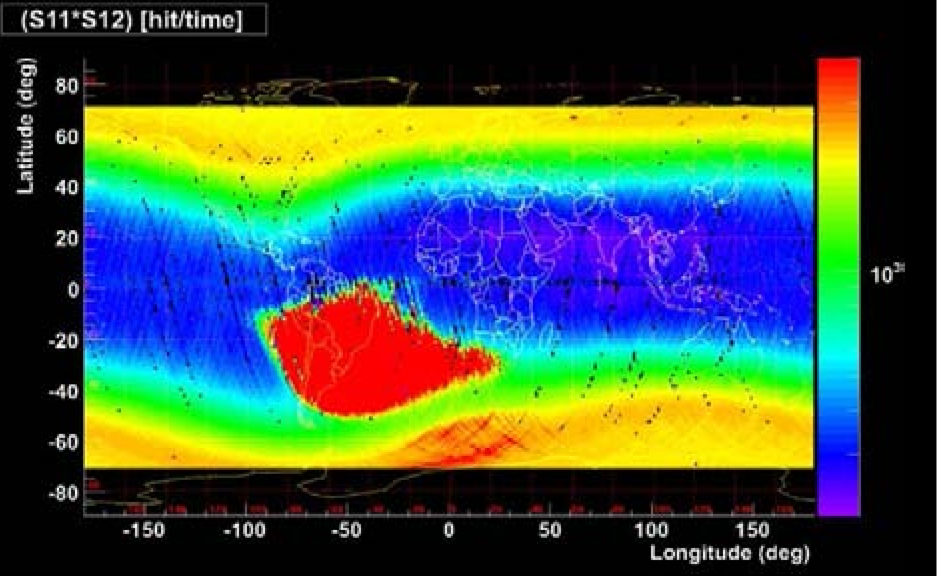


The geomagnetic field is an extremely powerful tool to select particle of different origin and nature and study *in situ* MHD phenomena

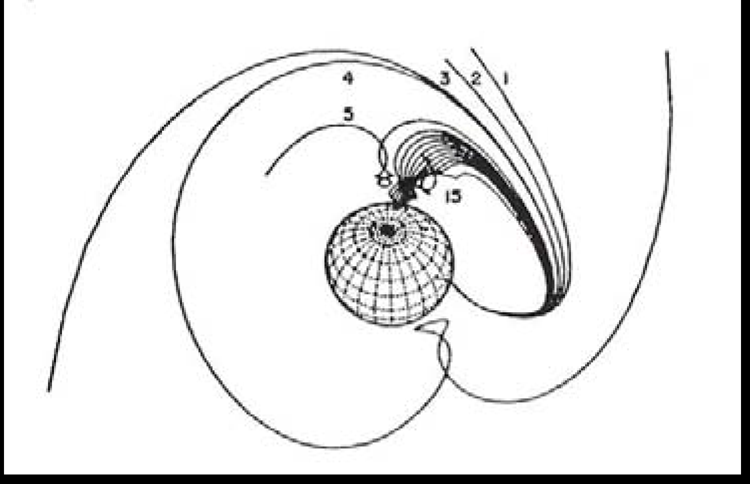

Pamela
Measurement of
the radiation belts
http://www.youtube.com/watch?v=OaoiPw5Pqbg
2008 M. Casolino
Google
Image NASA

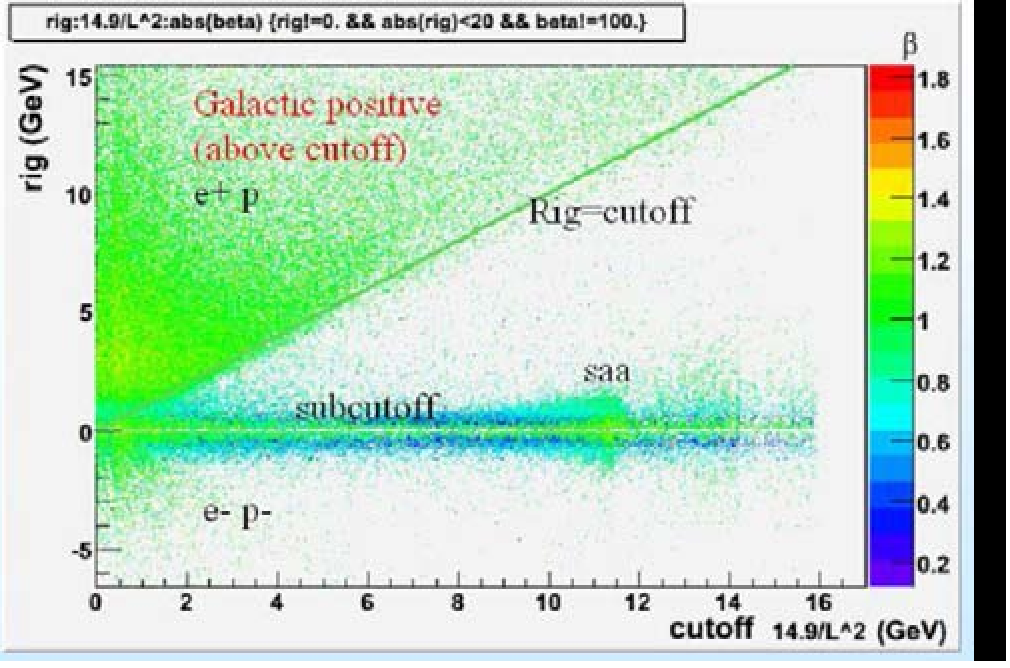
Selection of galactic component according to geomagnetic cutoff





R_{cutoff}=14.9GV/L^2





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Proton and Helium Absolute flux

- Montecarlo efficency for cuts
- Trigger efficiency
- Tracking efficiency
- Multiple Scattering
- Correction for energy loss in det
- Back scattering…
- Systematics under close investigation, currently about 1-2% uncertainty on abs flux.

Selection criteria

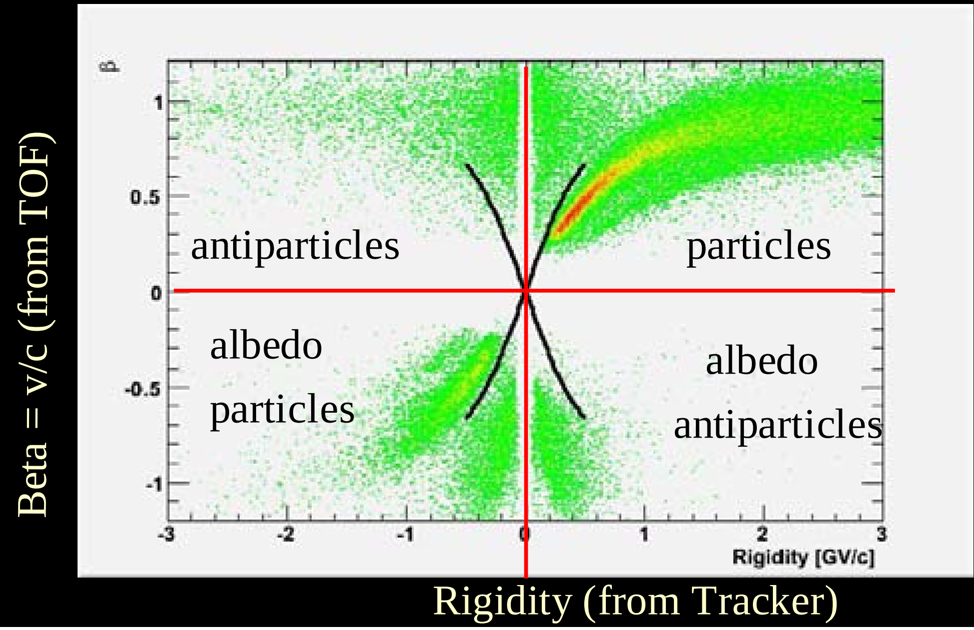
Fitted, single track

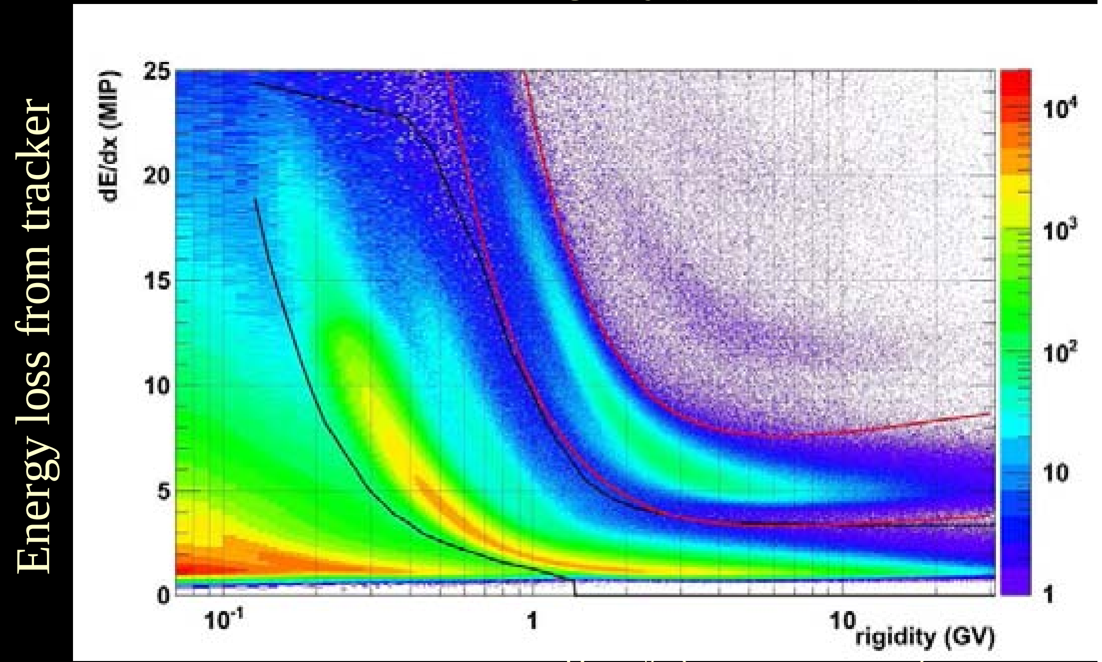
High lever arm, Nx

Rigidity R>0

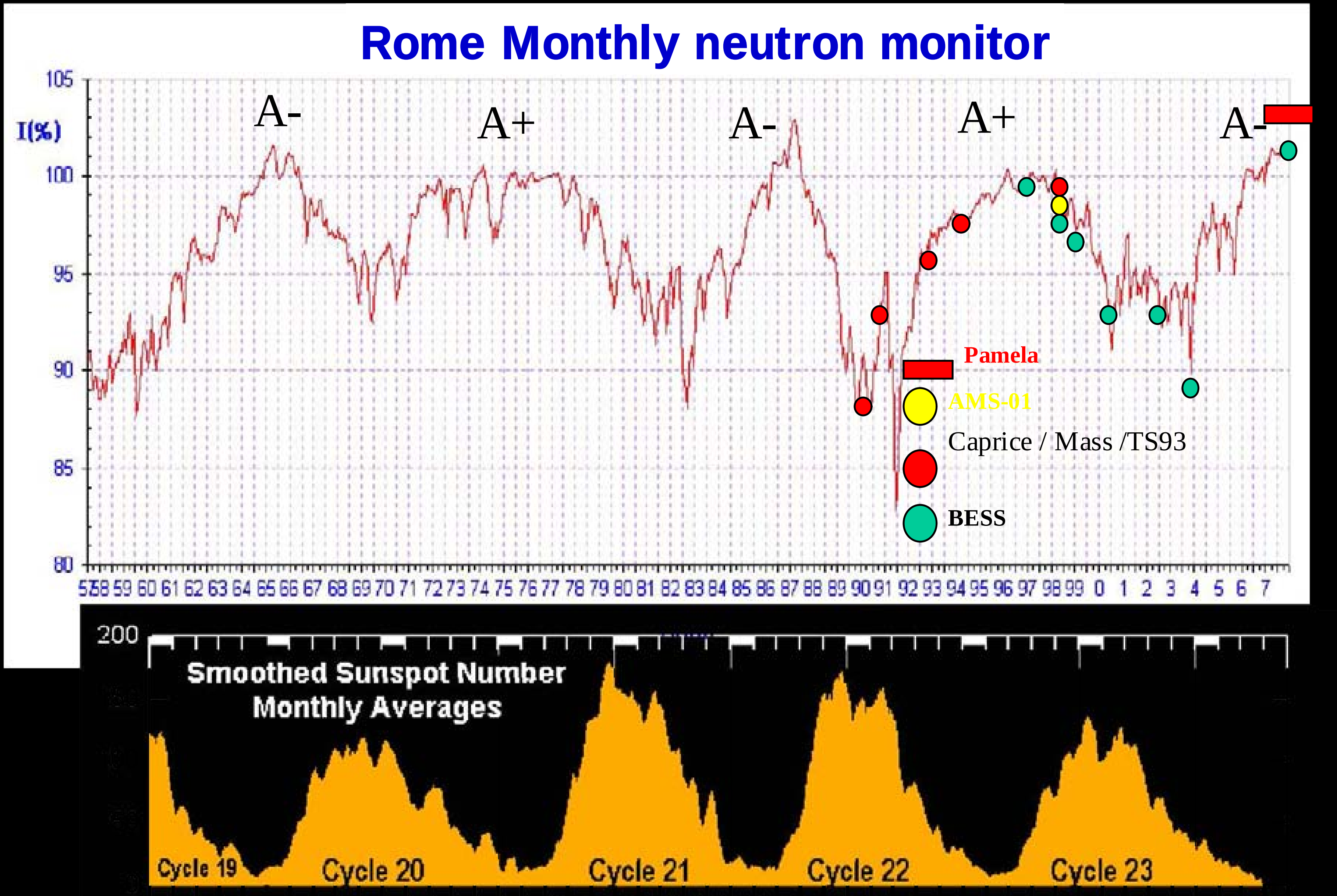
Beta>.2

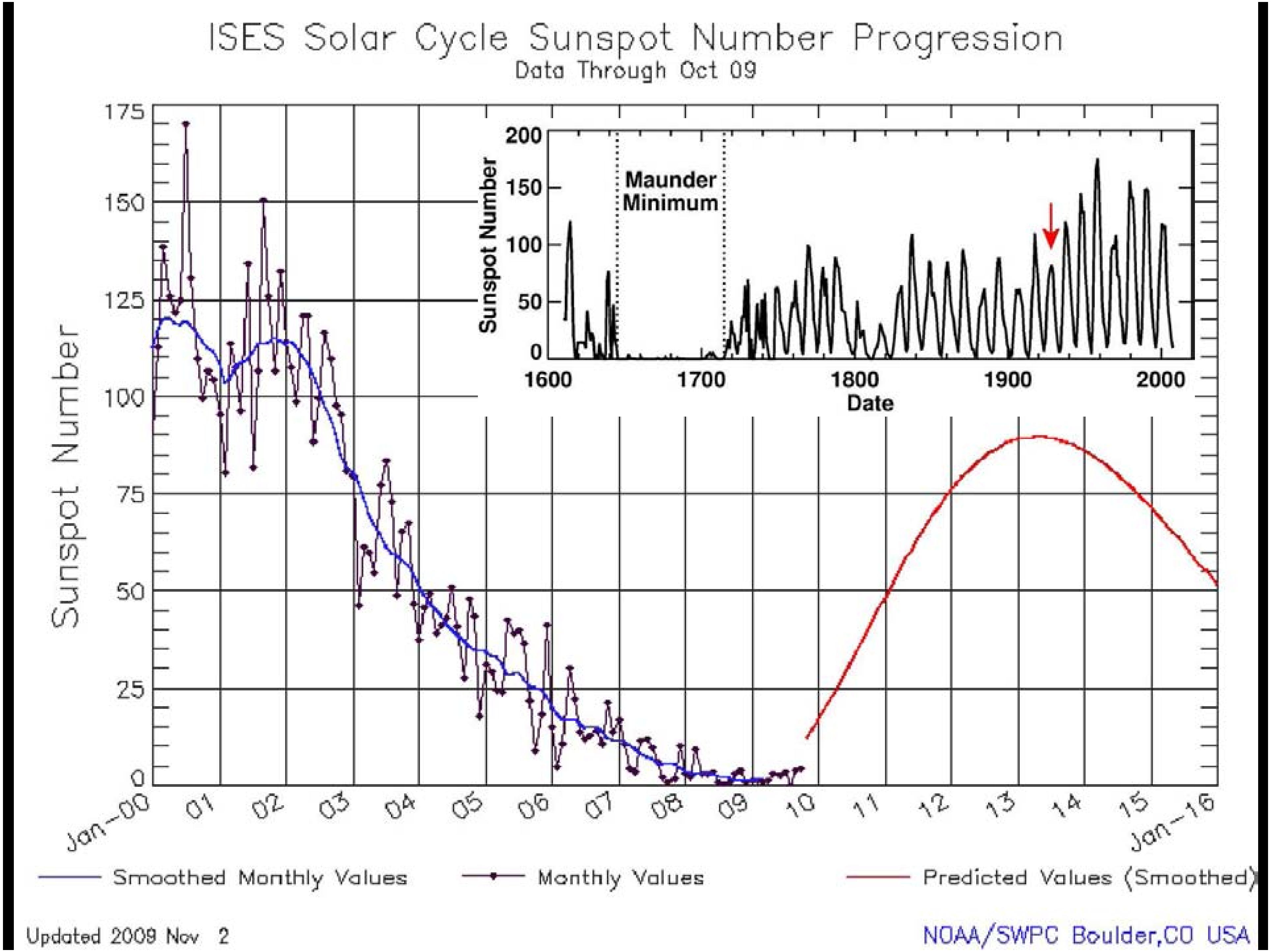
No anti



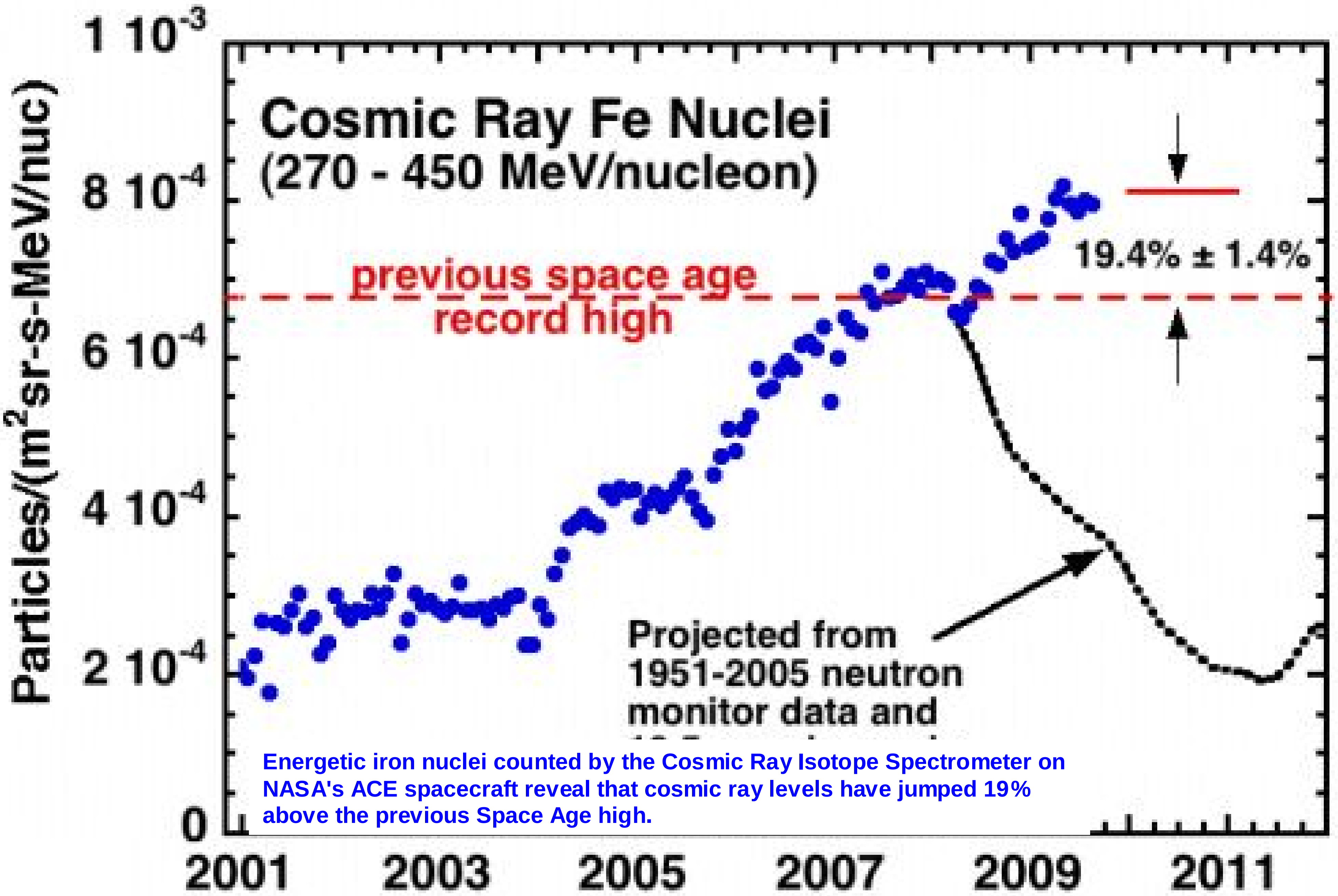


Solar modulation at minimum of solar cycle XXIII years 2006-2008



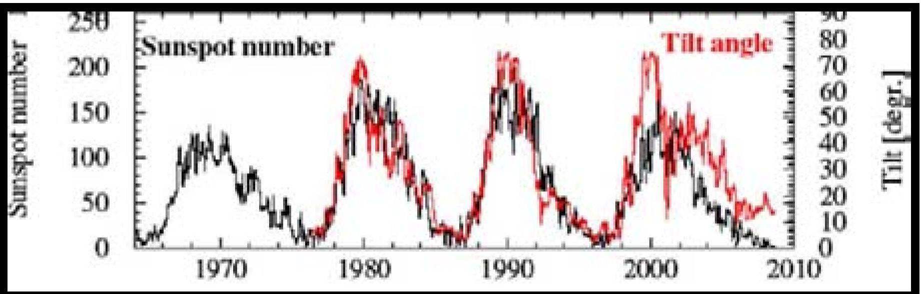

ISES Solar Cycle Sunspot Number Progression
Data Through Oct 09
Sunspot Number
175
150
125
100
75
50
25
0
Jan-00
01
02
03
04
05
06
07
08
09
10
11
12
13
14
15
Jan-16
Maunder Minimum
200
150
100
50
0
1600
1700
1800
1900
2000
Date
Smoothed Monthly Values
Monthly Values
Predicted Values (Smoothed)
Updated 2009 Nov 2
NOAA/SWPC Boulder,CO USA

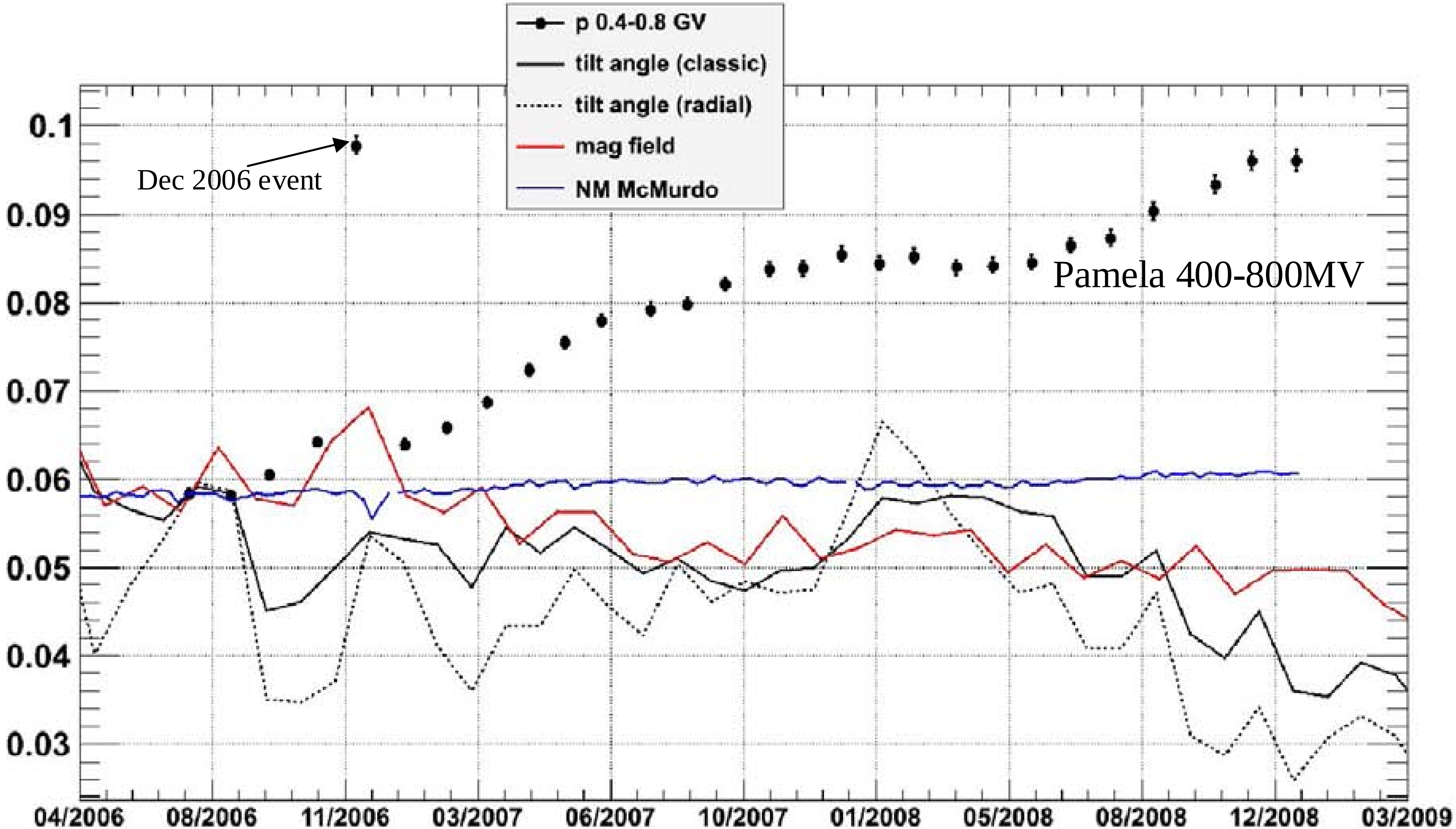
Low Solar Activity → high particle flux



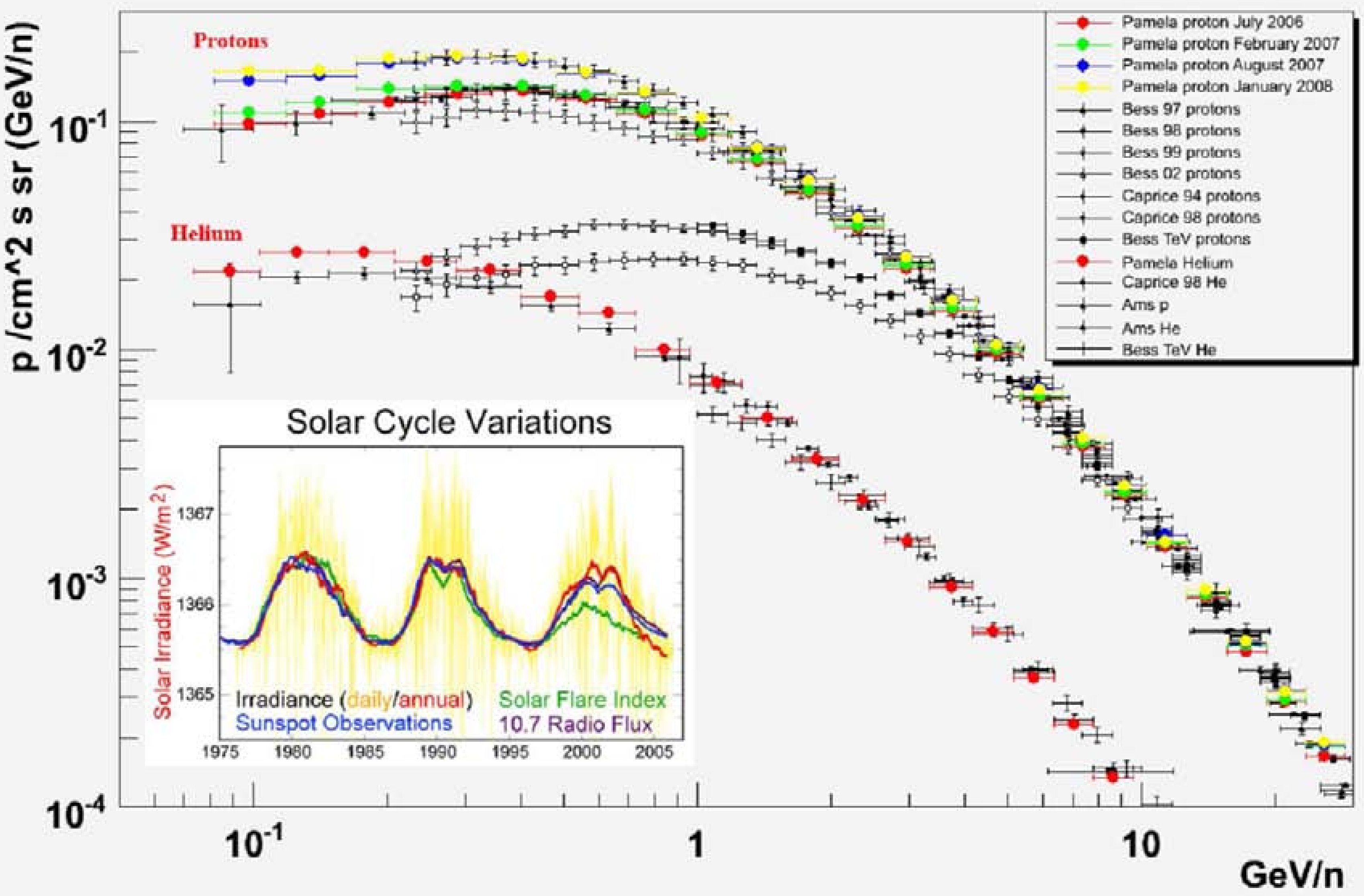
Energetic iron nuclei counted by the Cosmic Ray Isotope Spectrometer on NASA's ACE spacecraft reveal that cosmic ray levels have jumped 19% above the previous Space Age high.

Time evolution of Pamela low energy proton flux





Solar modulation is effective below 10 GeV



Solar modulation at minimum of solar cycle XXIII years 2006-2008

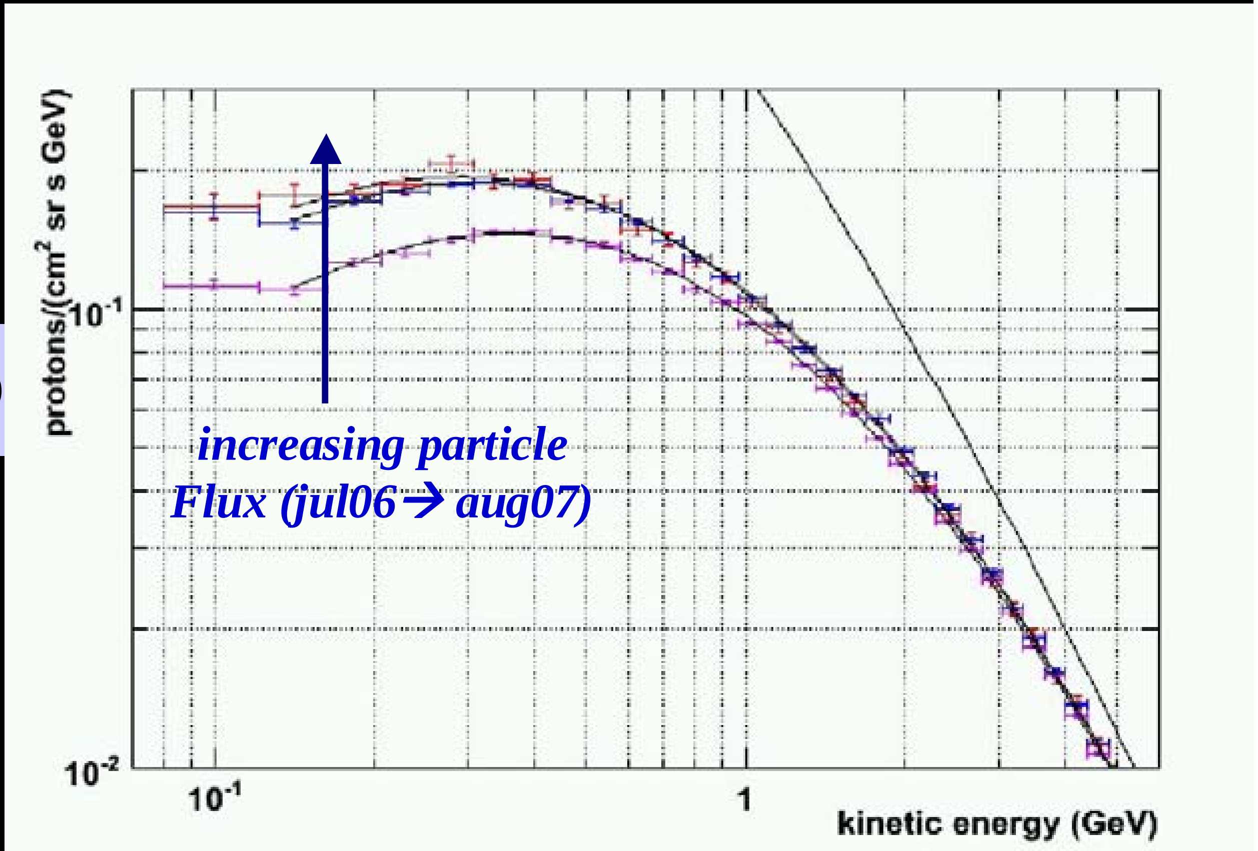
$F_{is} = 1.54\ \beta_{is}^{0.7}\ R_{is}^{-2.76}$

p/(cm² s sr GV)

Spectral index

2.76 ±0.01

$$J(r,E,t) = \frac{E^2 - E_0^{\ 2}}{(E^2 + \Phi(t))^2 - E_0^{\ 2}} J(\infty, E + \Phi(t))$$



Solar modulation parameter

ϕ(GV)

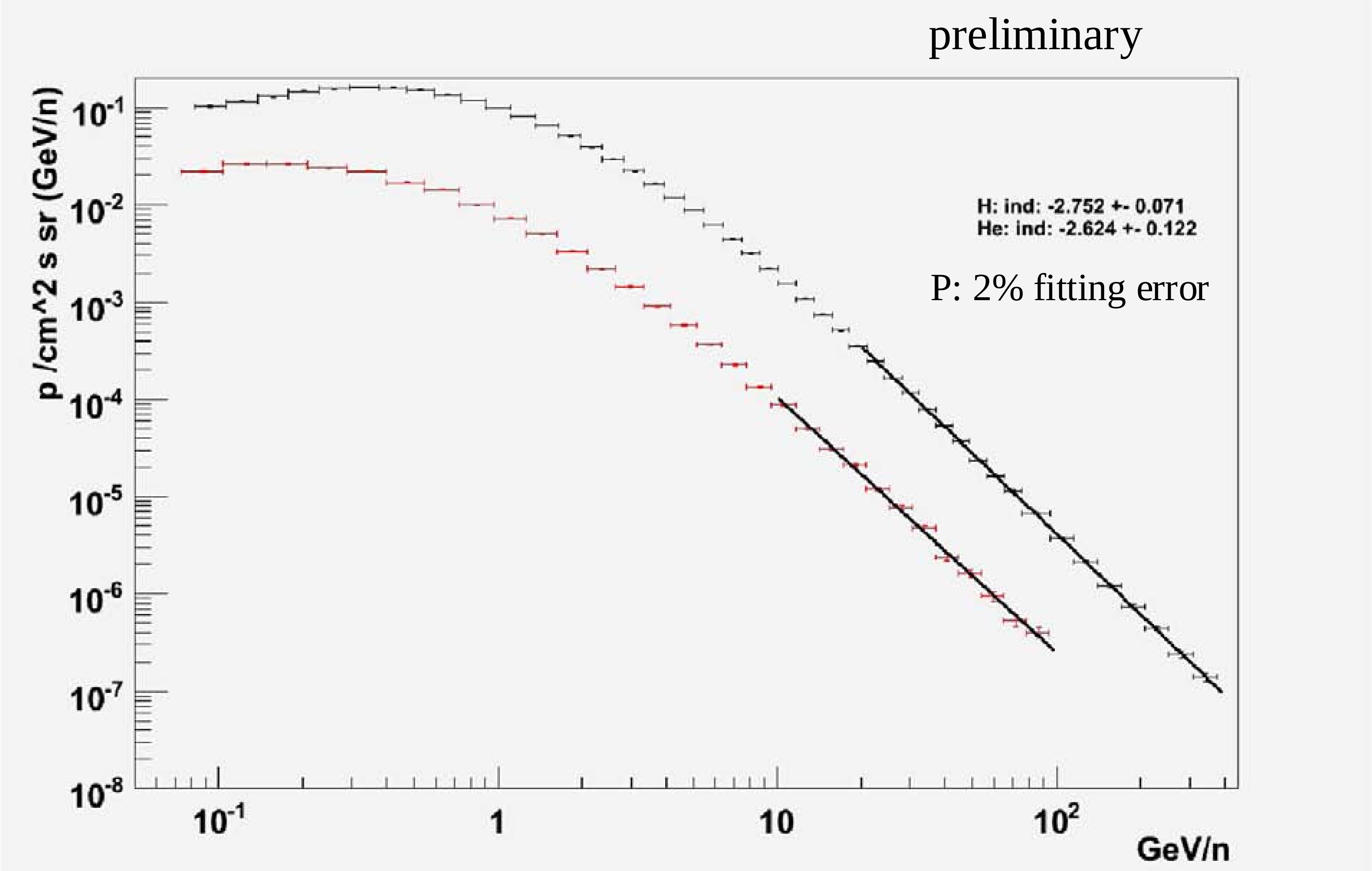
JUL06 5.01-01 ± 2e-03

JAN07 4.16-01 ± 2-03

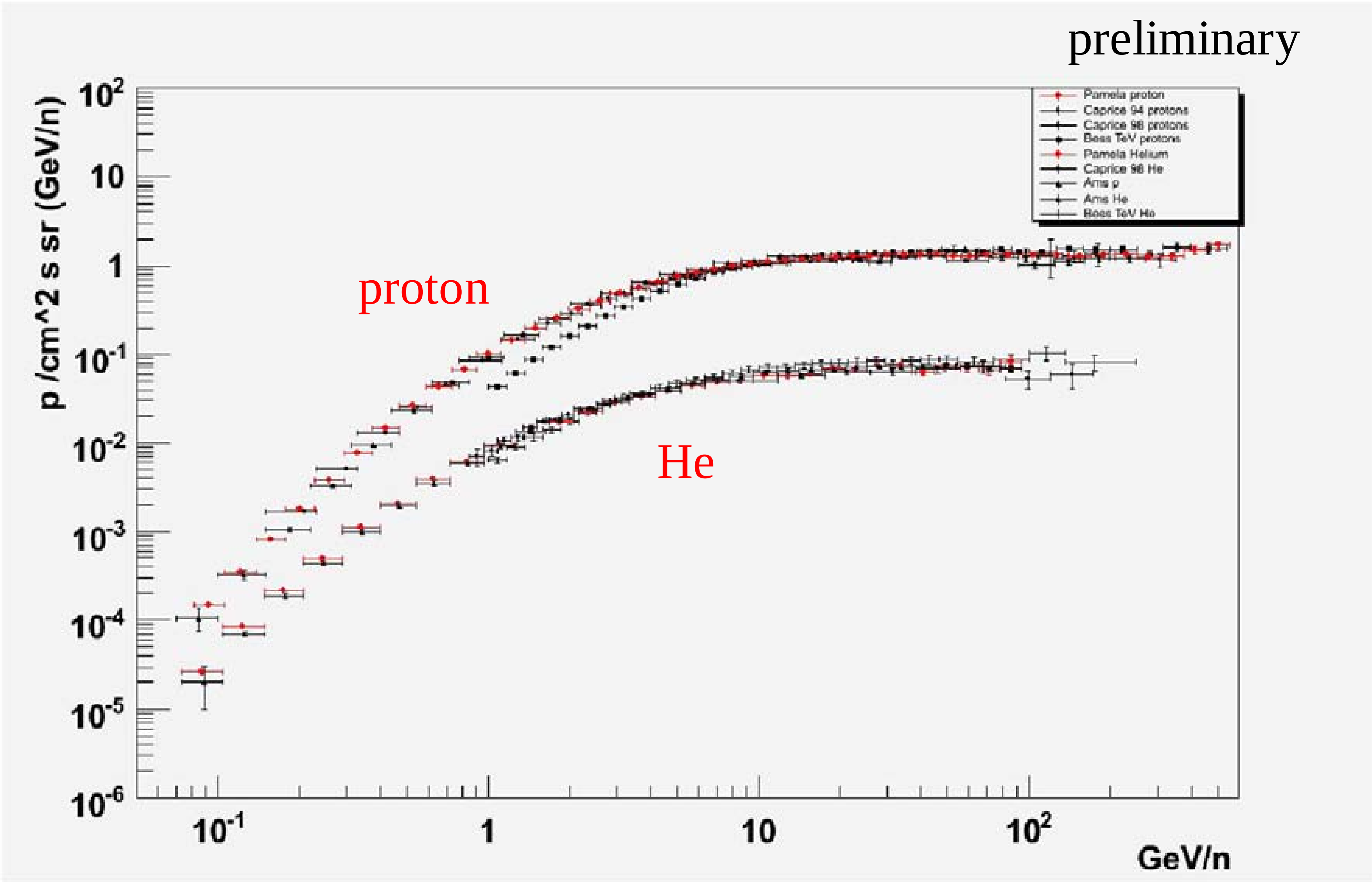
AUG07 4.02-01 ± 3-03

But Spherical approximation is not sufficient for charge dependent solar modulation

Proton and Helium spectra, kinetic energy, Jul 2006



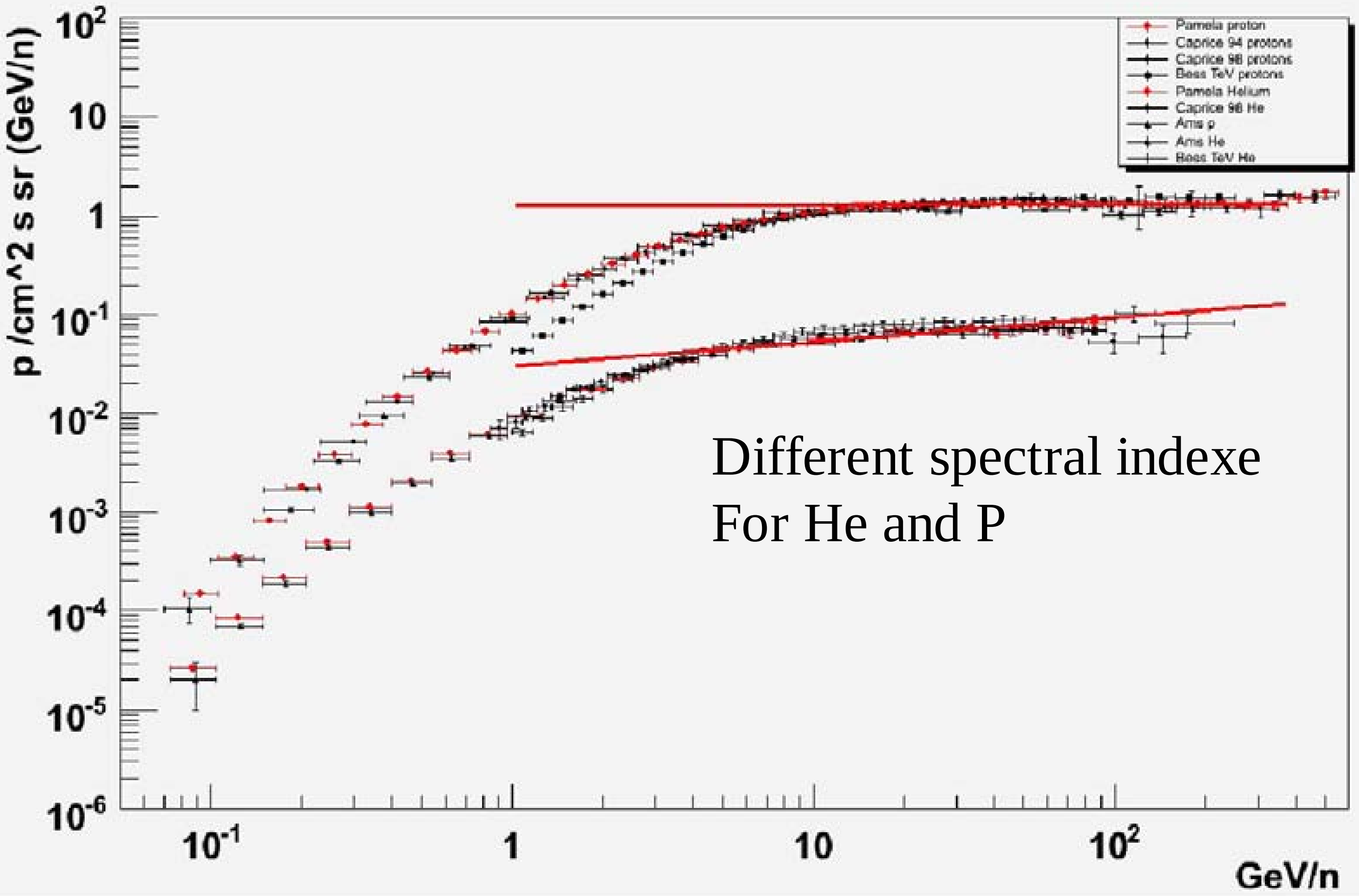
Comparison with other experiments

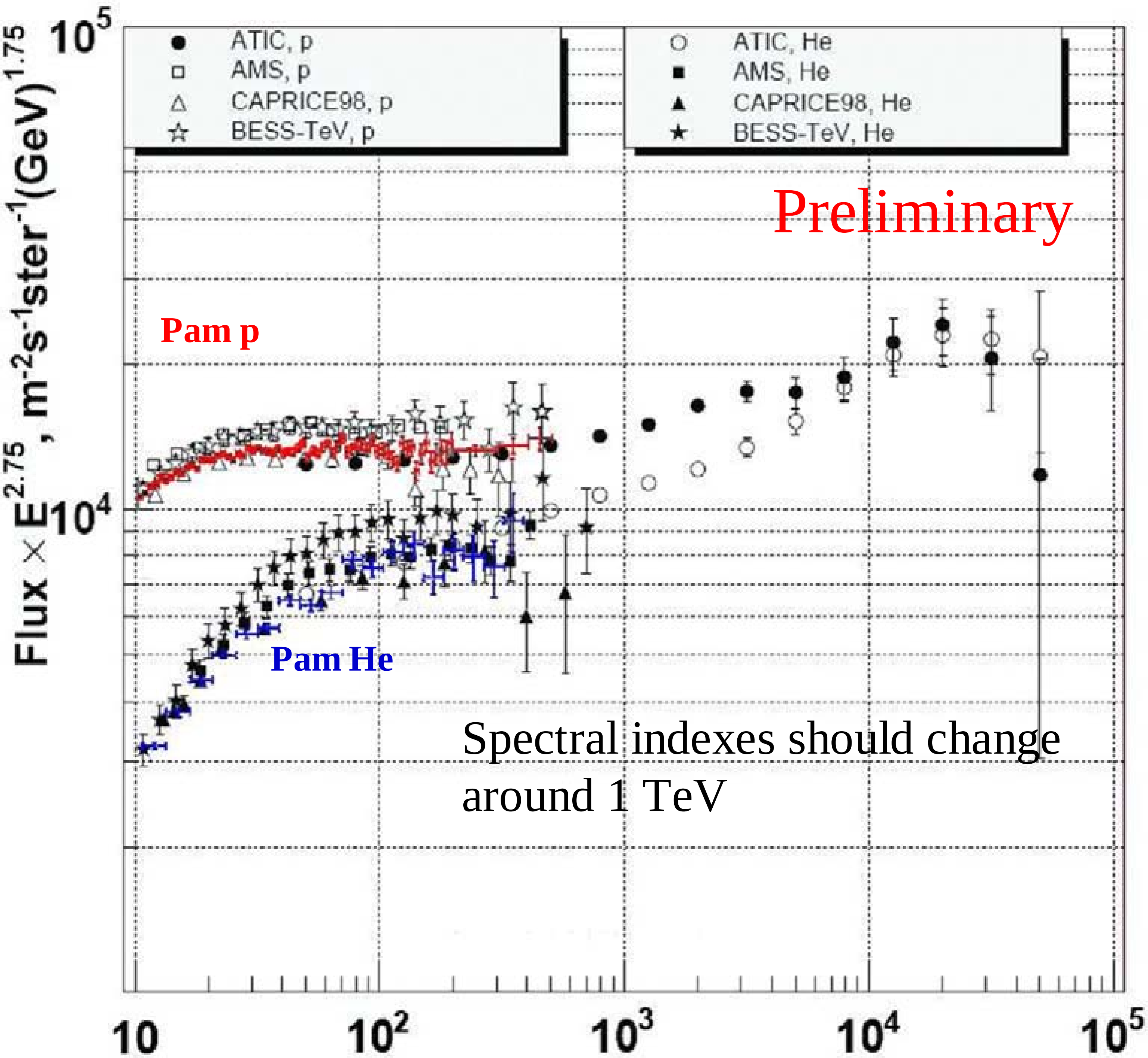


Comparison with other experiments

*E^275

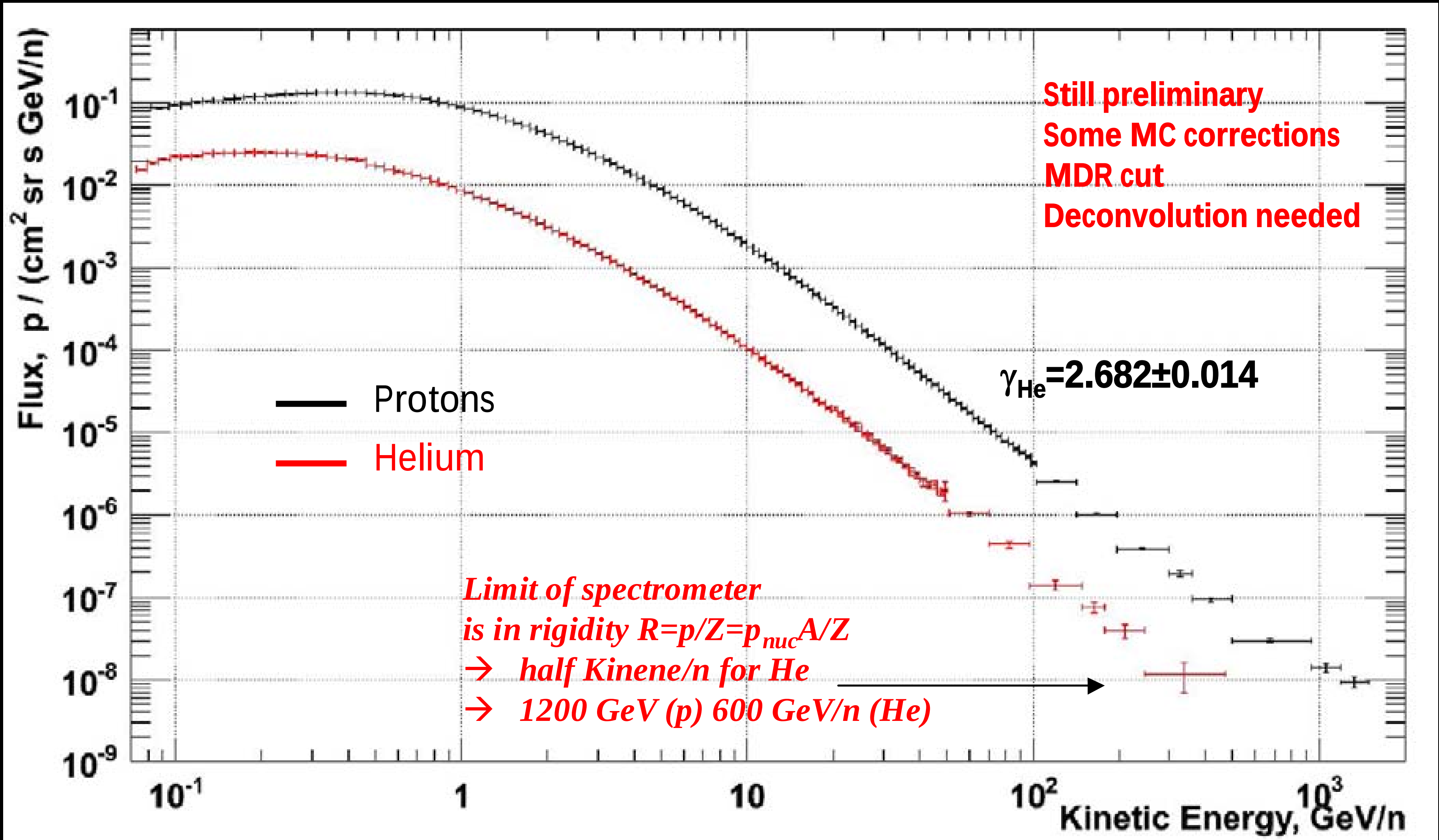
preliminary





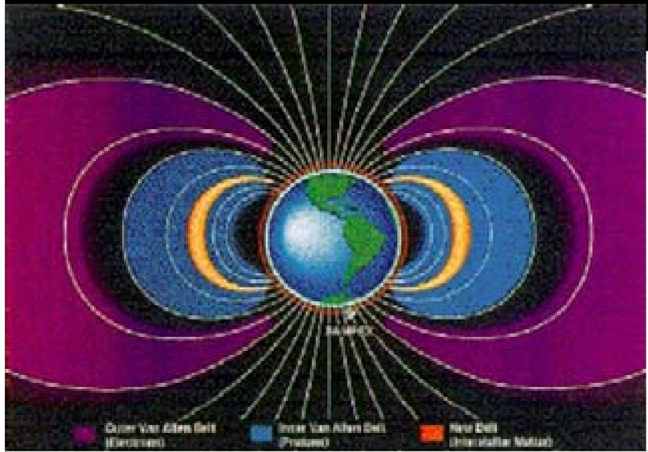
ATIC, p
AMS, p
CAPRICE98, p
BESS-TeV, p
ATIC, He
AMS, He
CAPRICE98, He
BESS-TeV, He
Preliminary
Pam p
Pam He
Spectral indexes should change around 1 TeV
Flux × E^2.75, m^-2 s^-1 ster^-1 (GeV)^1.75
10^5
10^4
10
10^2
10^3
10^4
10^5

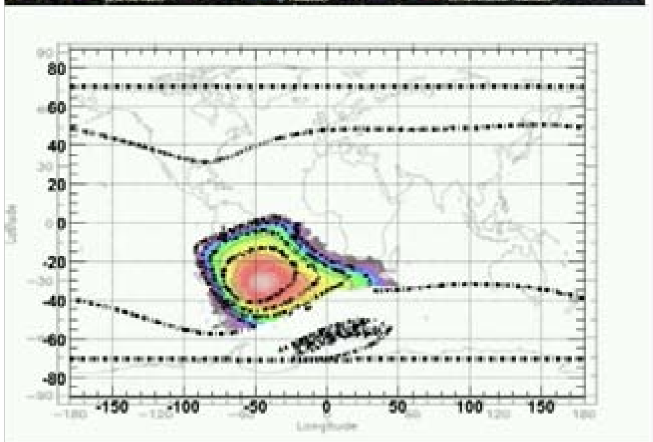
Preliminary results at high energy

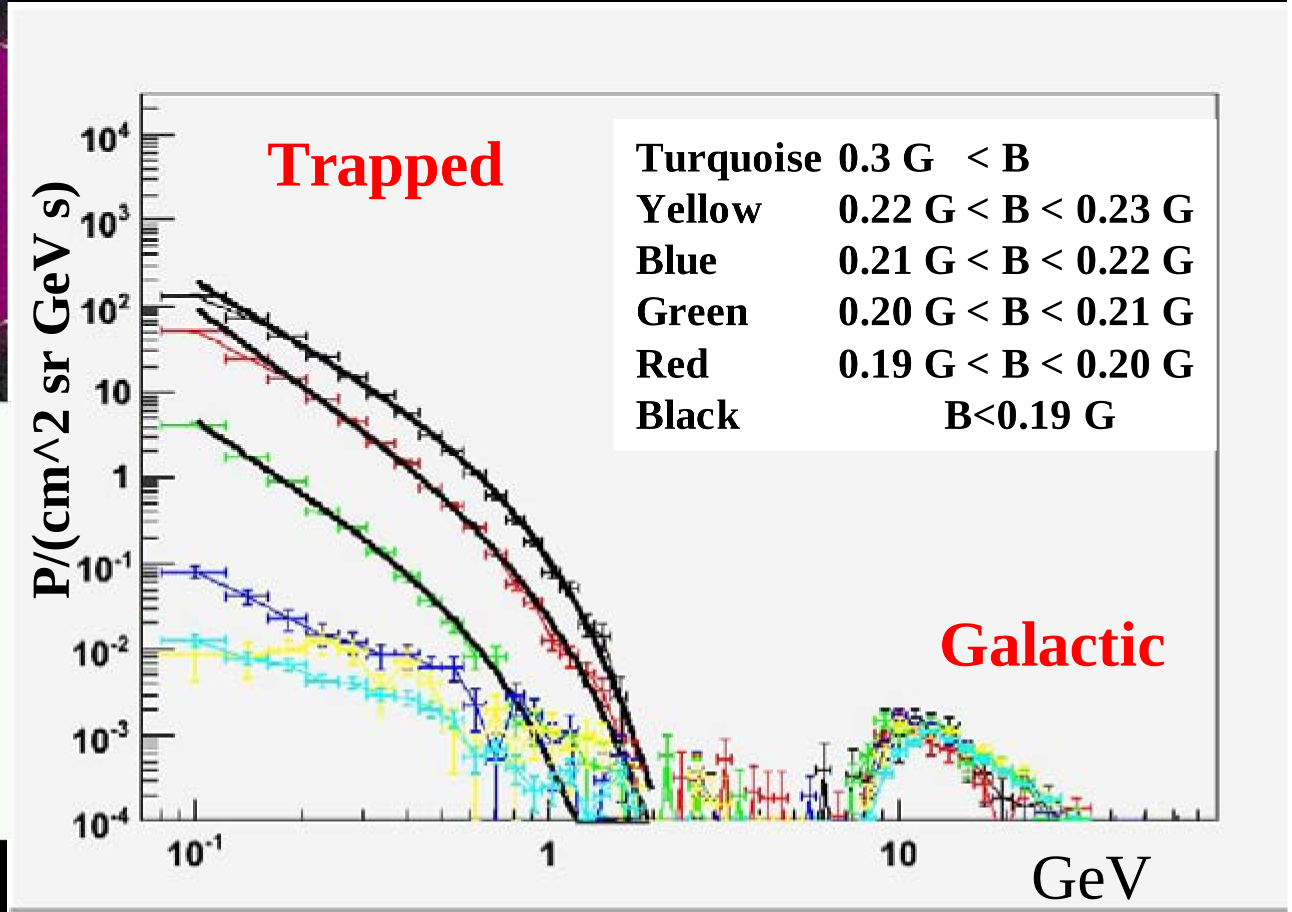


Trapped proton flux in the Van Allen belt (South Atlantic Anomaly)

Arxiv 0810.4980v1







Integral Pamela flux
(E>35 MeV)
(PSB97 plot by SPENVIS project, model by BIRA-IASB)

	A	γ_0	γ_1	χ^2/ndf
nero	0.11±0.01	6.0±0.4	3.1±0.5	7.1
rosso	(2.3±0.3) 10^{-2}	5.9±0.5	2.6±0.6	6.8
verde	(5±3) 10^{-4}	8.1±1.8	4.7±1.8	10.

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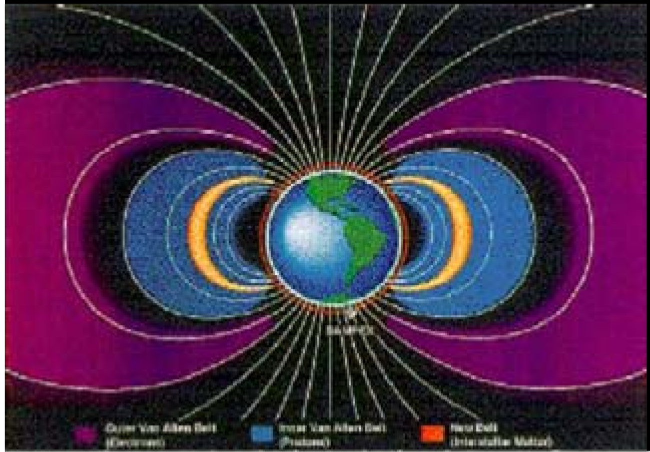
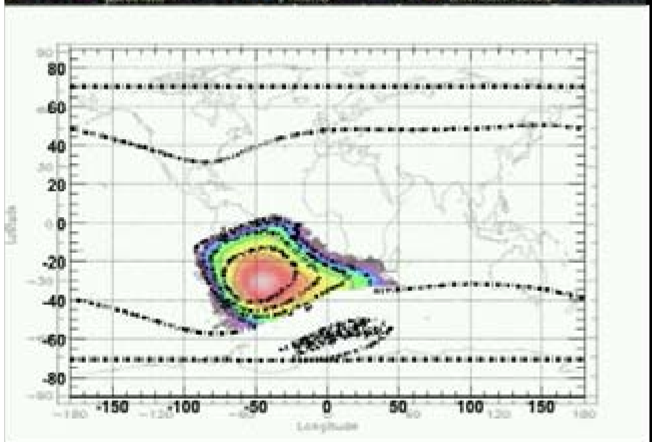
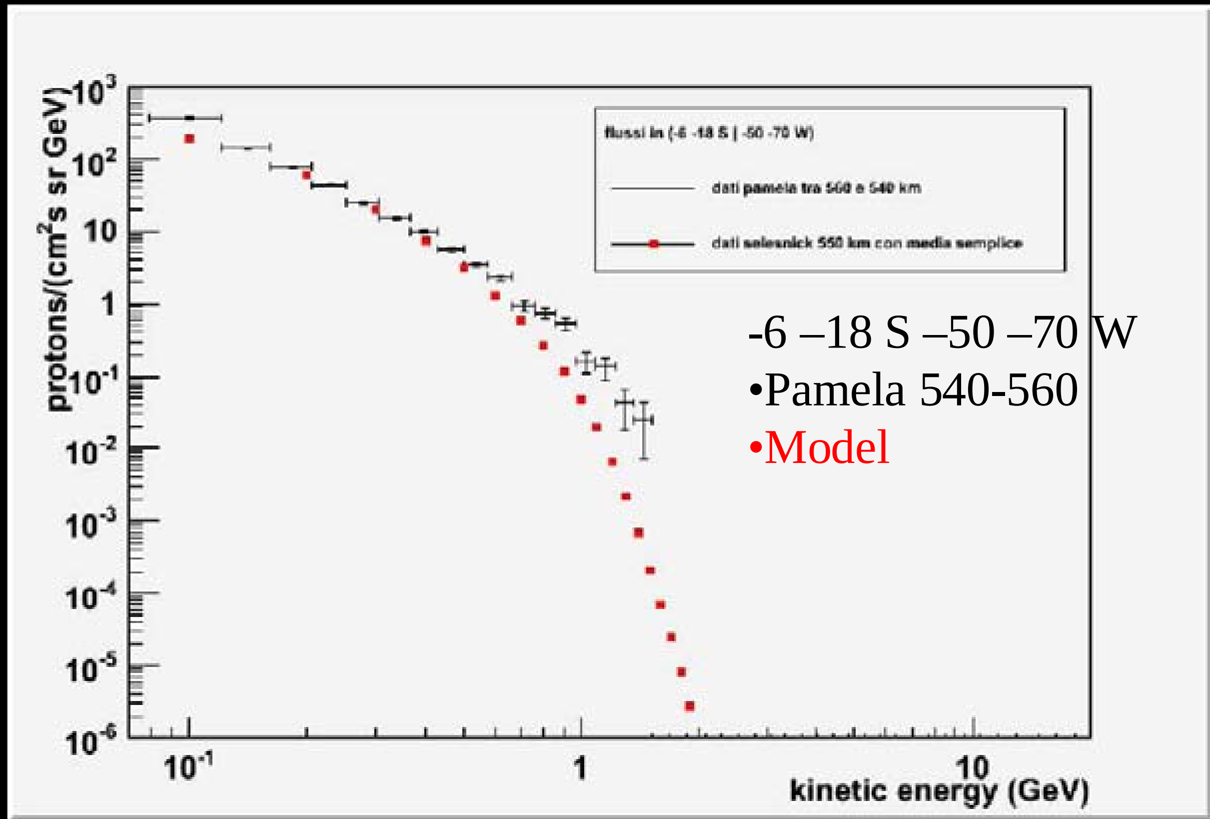
Trapped proton flux in the Van Allen belt
Comparison with models



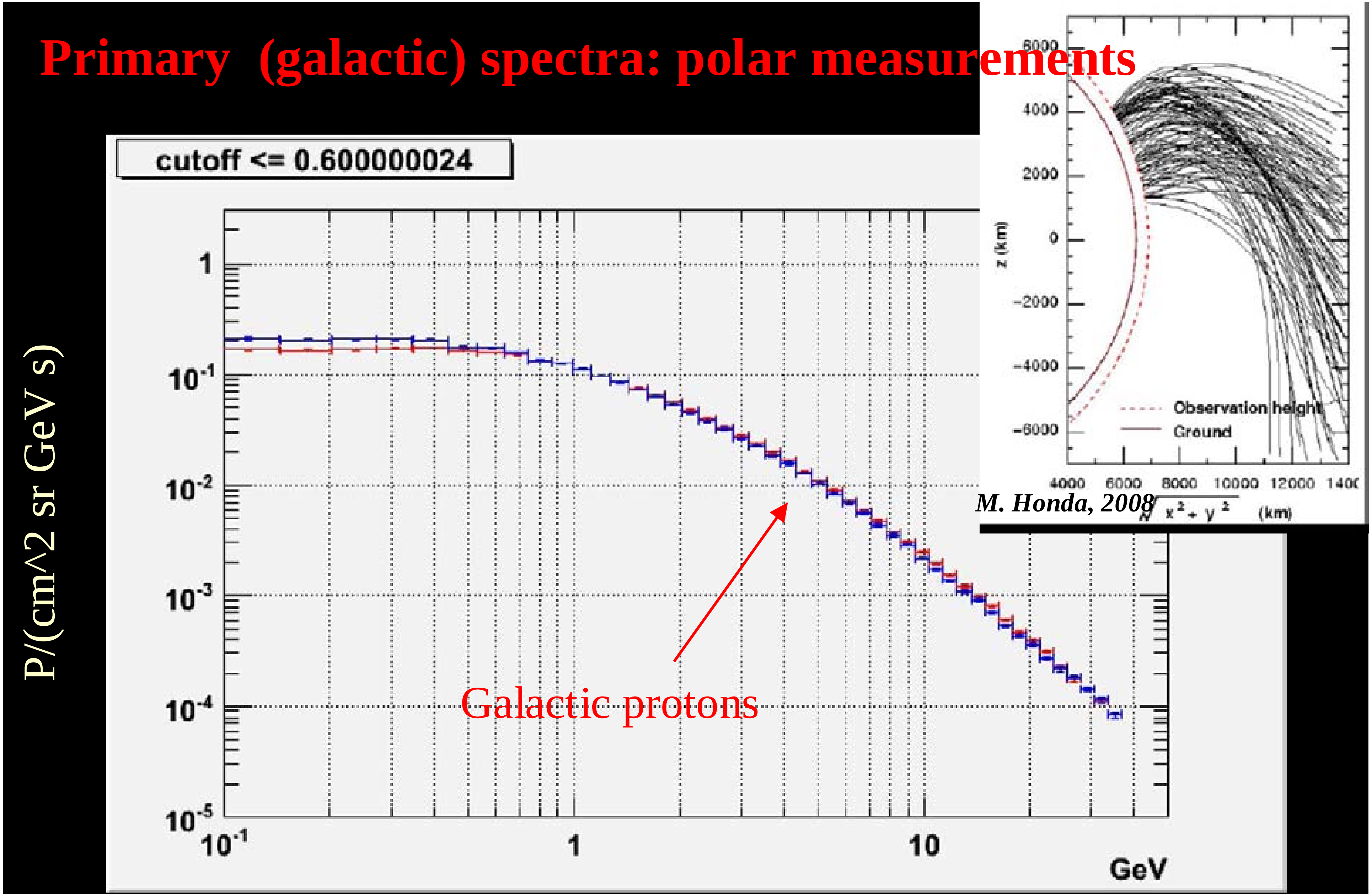




-6 –18 S –50 –70 W
- Pamela 540-560
- Model

R. S. Selesnick,1 M. D. Looper,1 and R. A. Mewaldt2
SPACE WEATHER, VOL. 5, S04003, doi:10.1029/2006SW000275, 2007

Primary (galactic) spectra: polar measurements

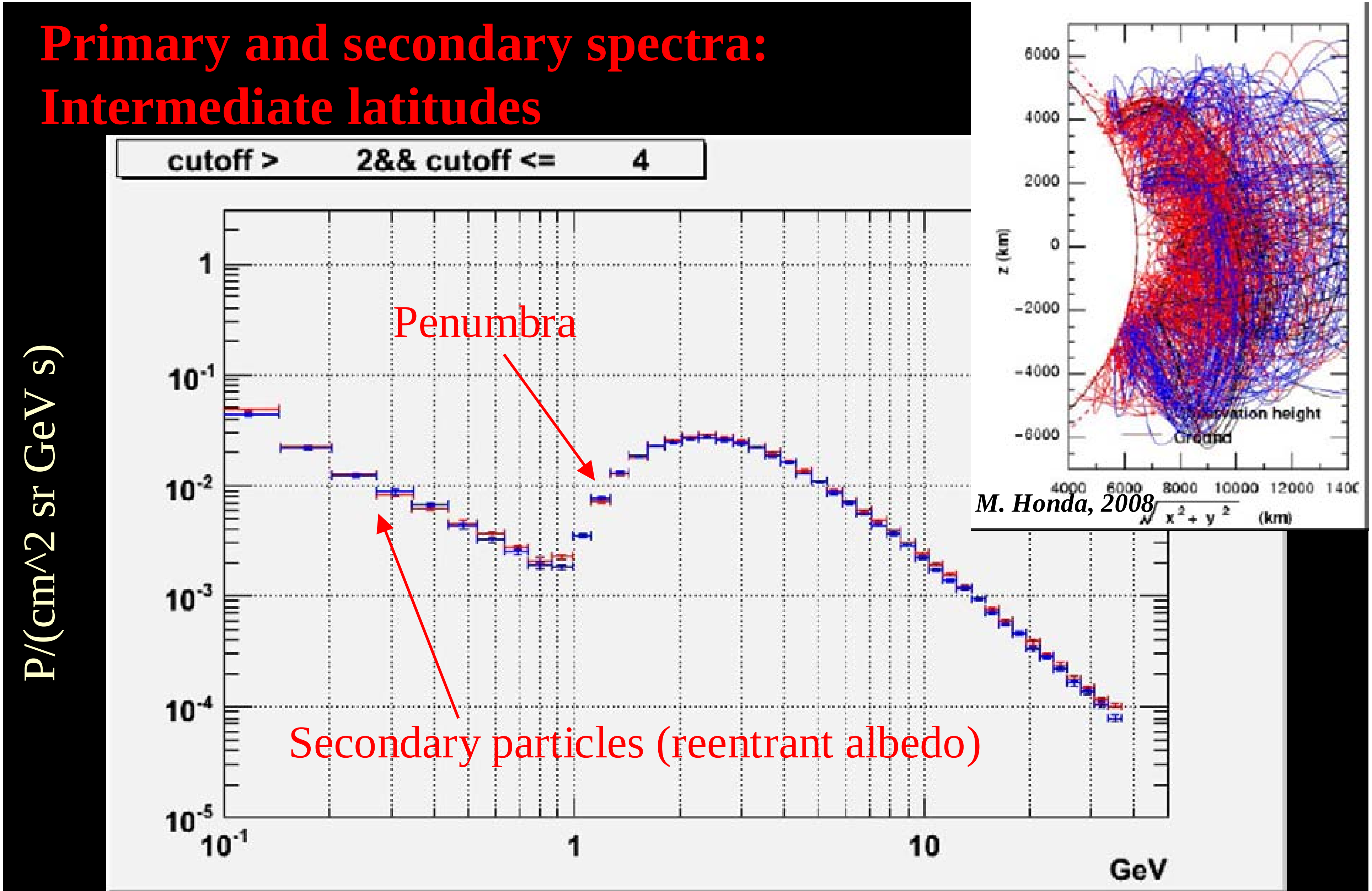


M. Honda, 2008

RED: JULY 2006

BLUE: AUGUST 2007

Primary and secondary spectra: Intermediate latitudes

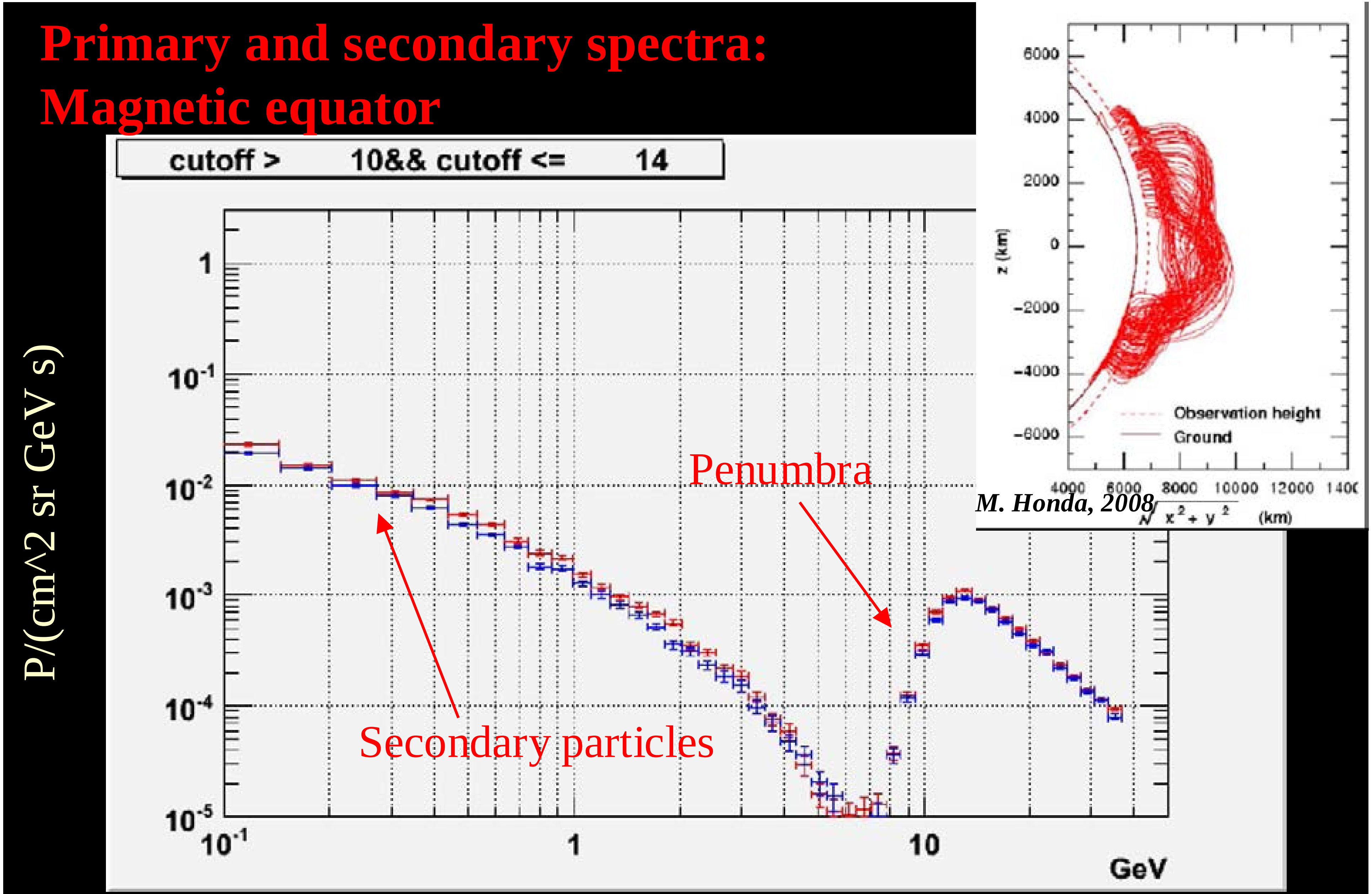


M. Honda, 2008

RED: JULY 2006

BLUE: AUGUST 2007

Primary and secondary spectra: Magnetic equator



RED: JULY 2006

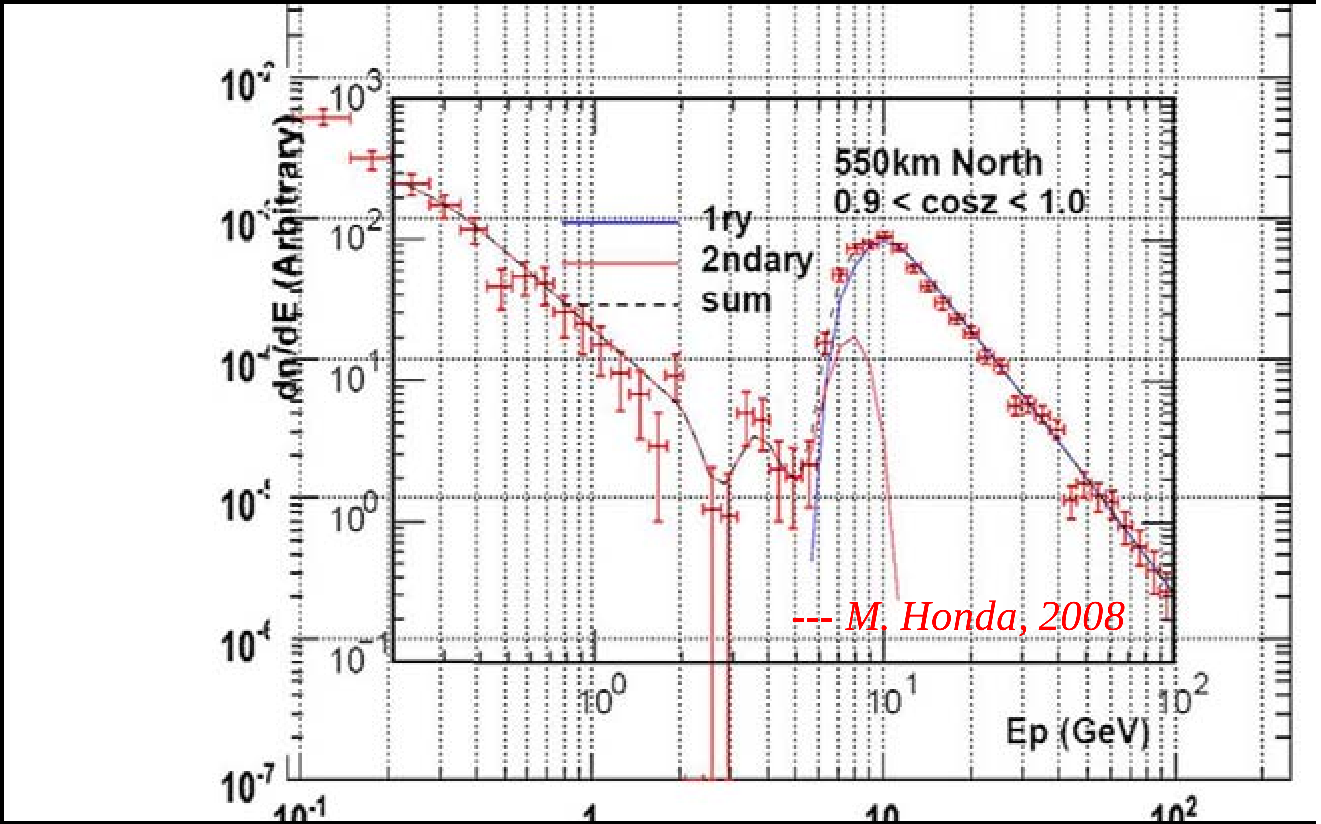
BLUE: AUGUST 2007

Secondary (reentrant albedo) proton flux at various cutoffs

→**Atmospheric neutrino contribution**

→**Astronaut dose on board International Space Station**

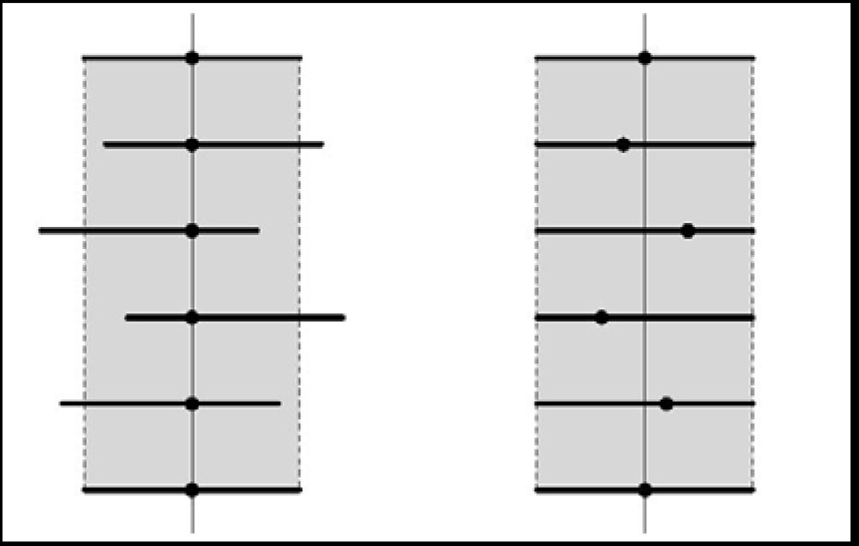
→**Indirect measurement of cross section in the atmosphere**



Arxiv 0810.4980v1

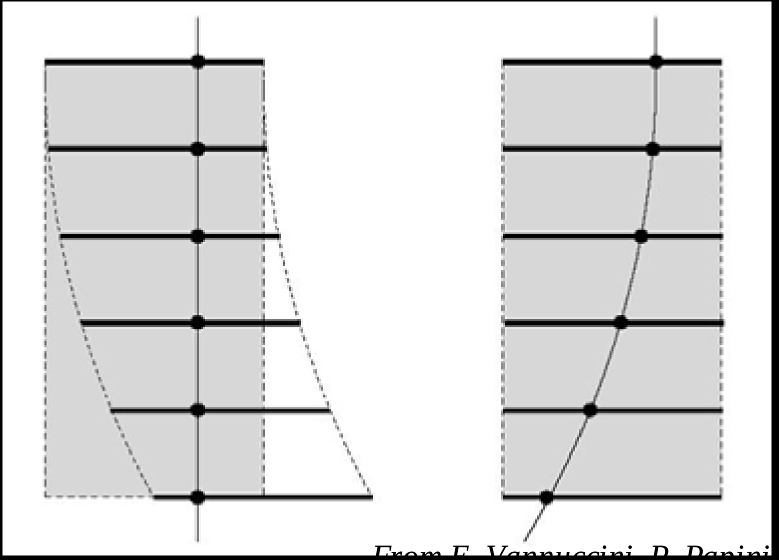
Alignment

Critical Issue: an antiparticle
Can be faked if alignment of the
detector is wrongly considered



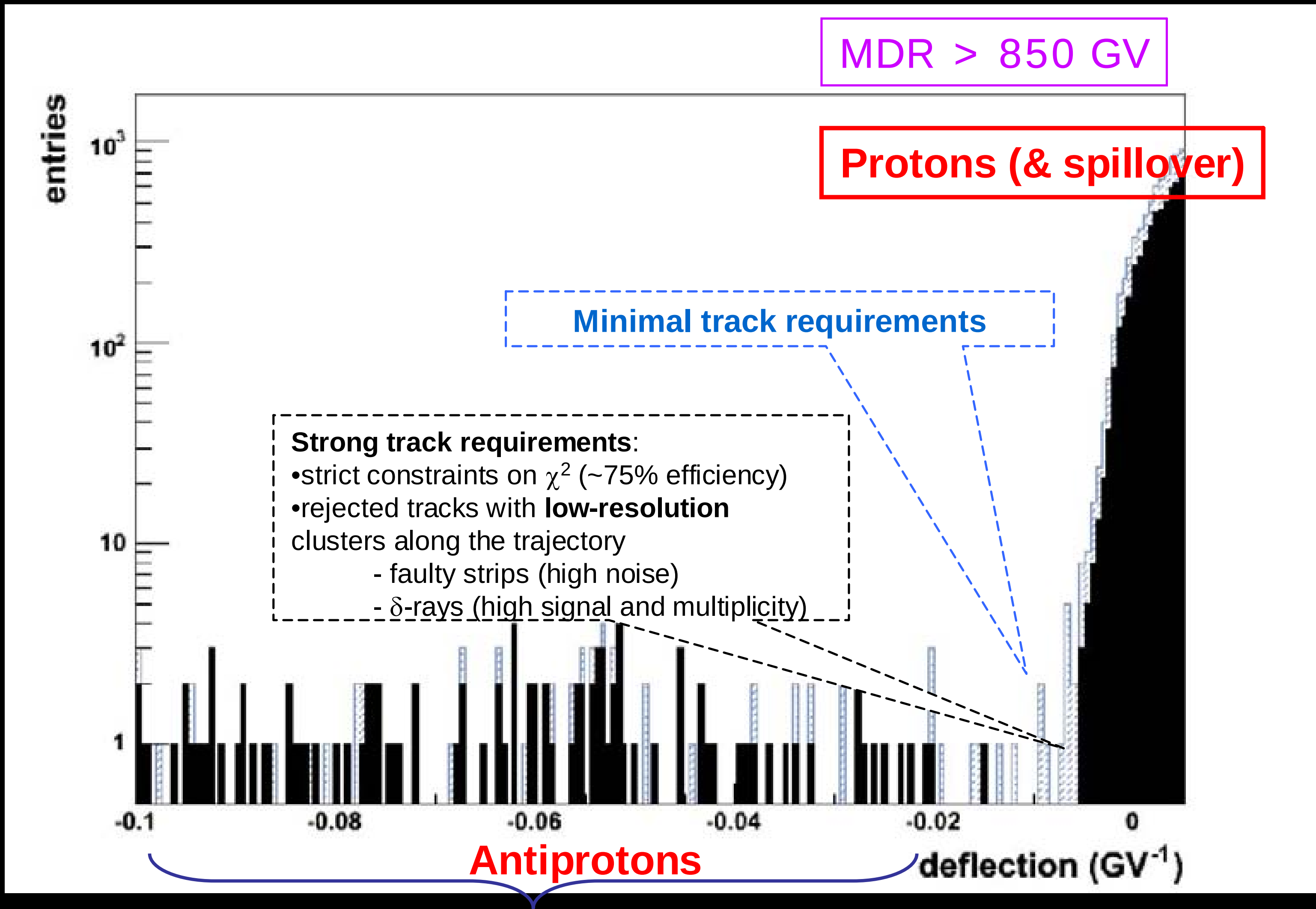
Incoherent misalignment
Correction with protons
2 steps: column alignment +
inter-column alignment

Coherent misalignment
Correction with electrons
(or electrons + positrons)
and comparison with
simulation



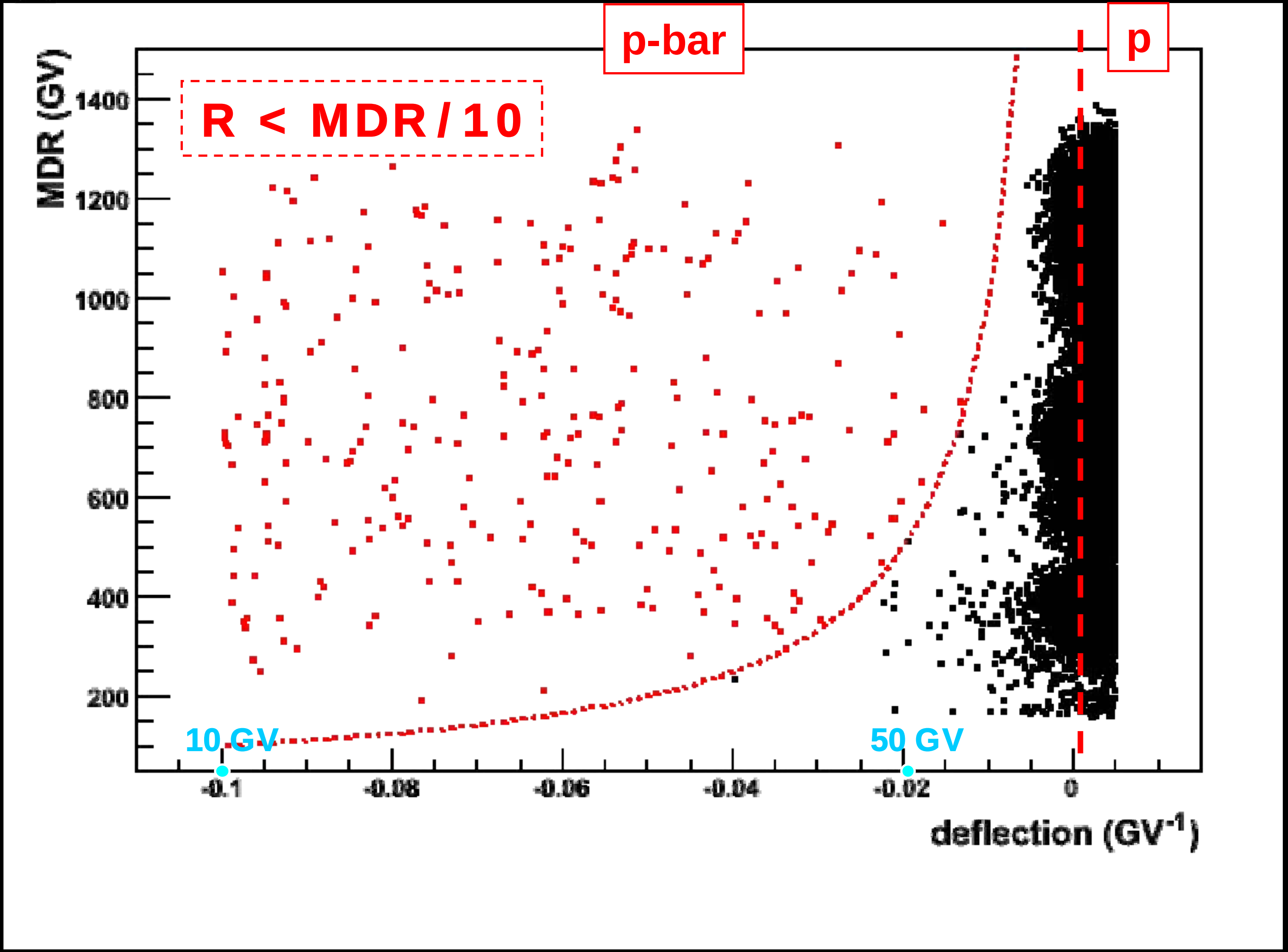
From E. Vannuccini, P. Papini

Proton spillover background



From O. Adriani ata

High-energy antiproton selection



From O. Adriani

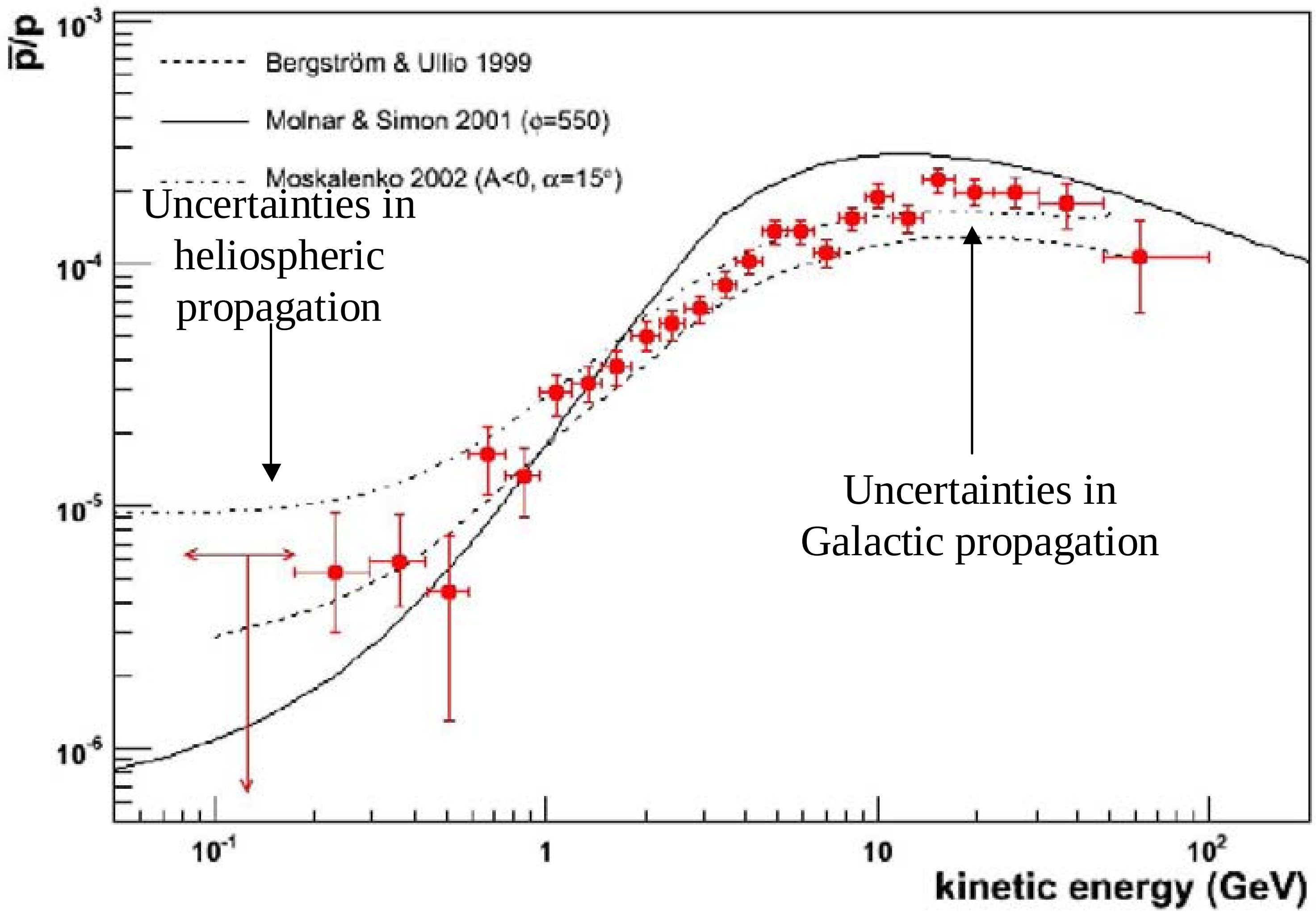
Antiproton ratio measured with Pamela: Comparison with theoretical models

Released data
1-100 GeV

Currently roughly 10 TB of data

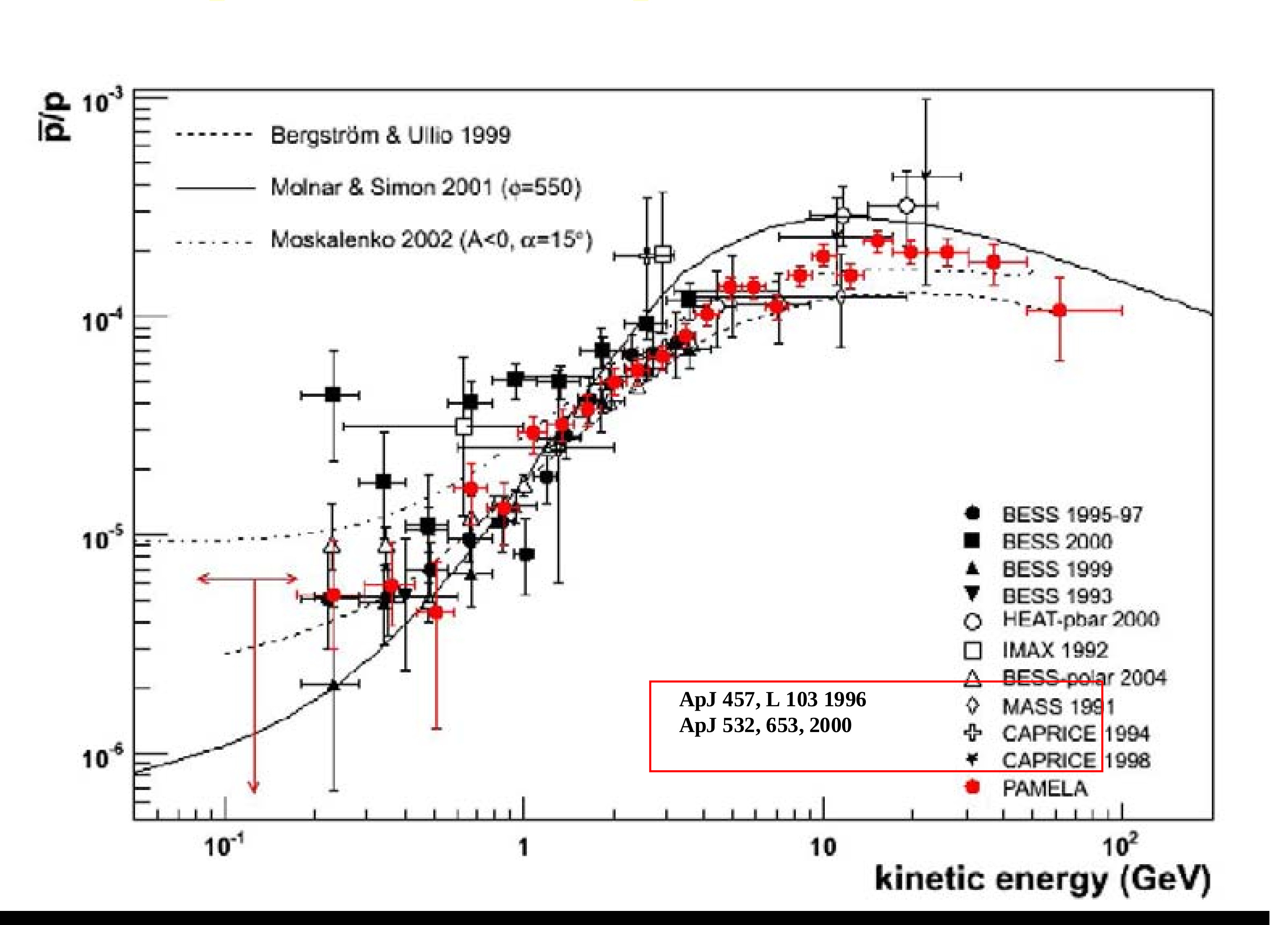
As of March '08
Out of 8.8 TB

- 10^7 p
- 800 p^-



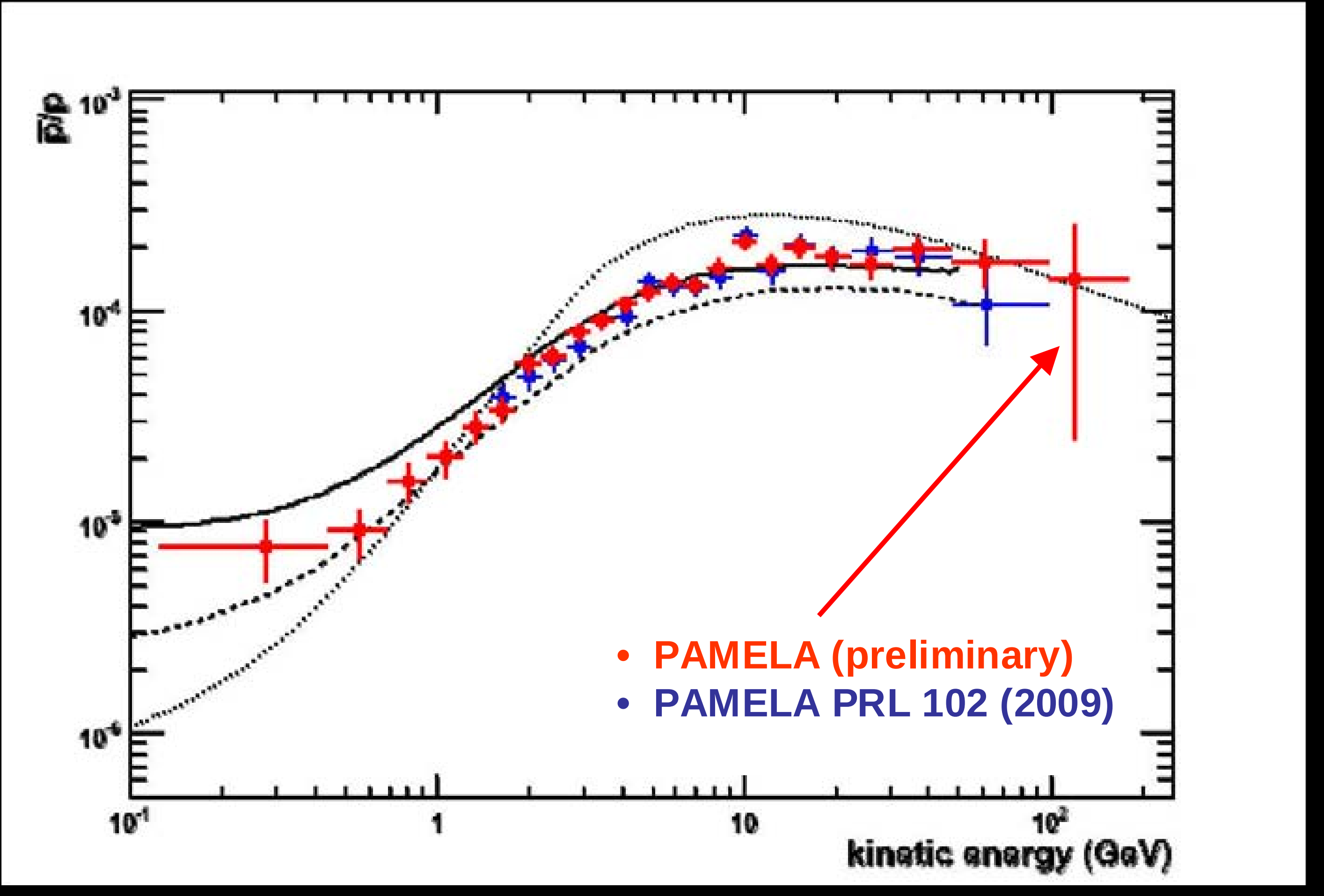
Antiproton ratio measured with Pamela: Comparison with experimental data

- Highest energy up to now
- Coherent with secondary production
- Uncertainties of Galactic Propagation
- Would favour Moskalenko 2002 (except highest energy)



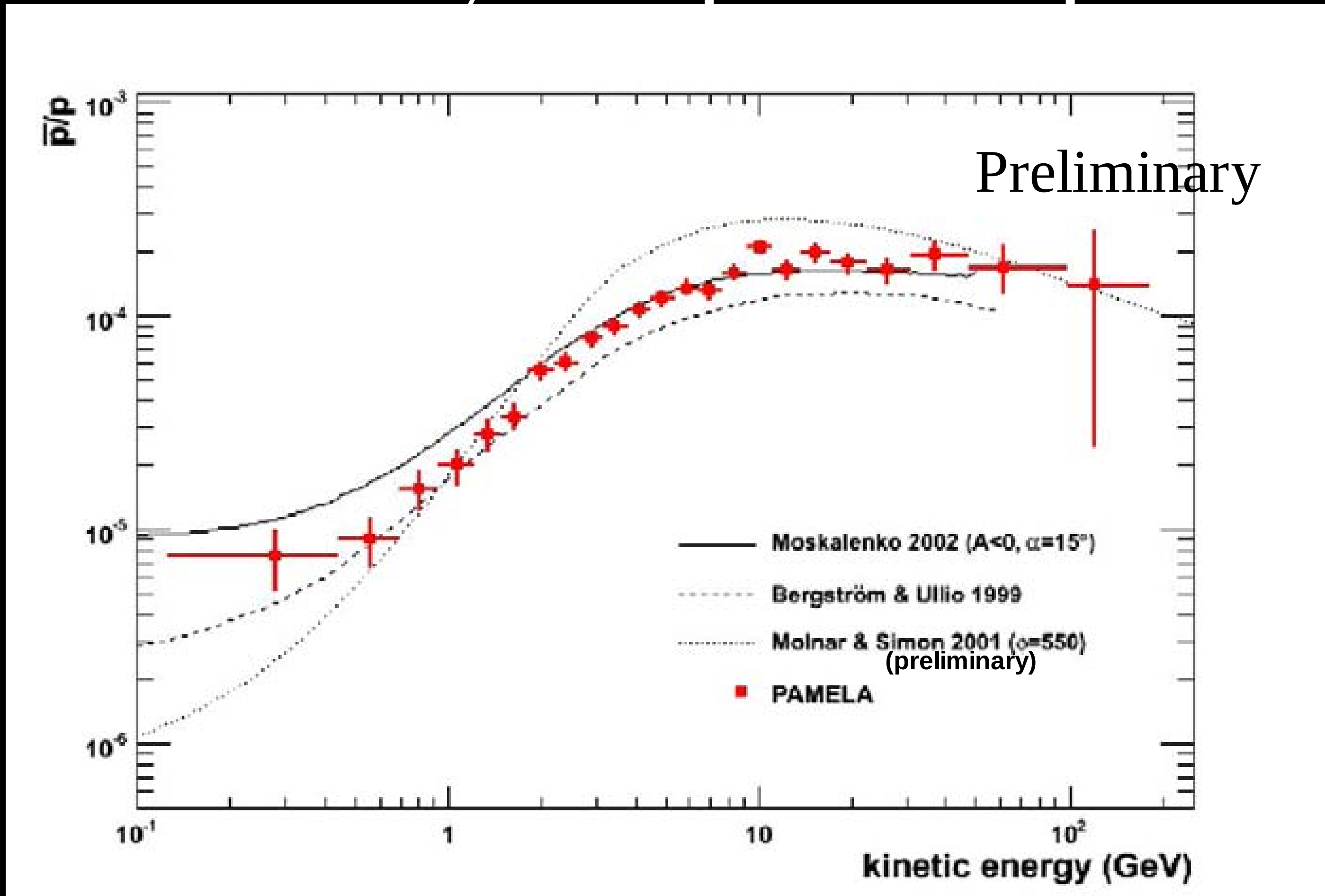
arXiv:0810.4994v1 [astro-ph] 28 Oct 2008 PRL

Antiproton ratio



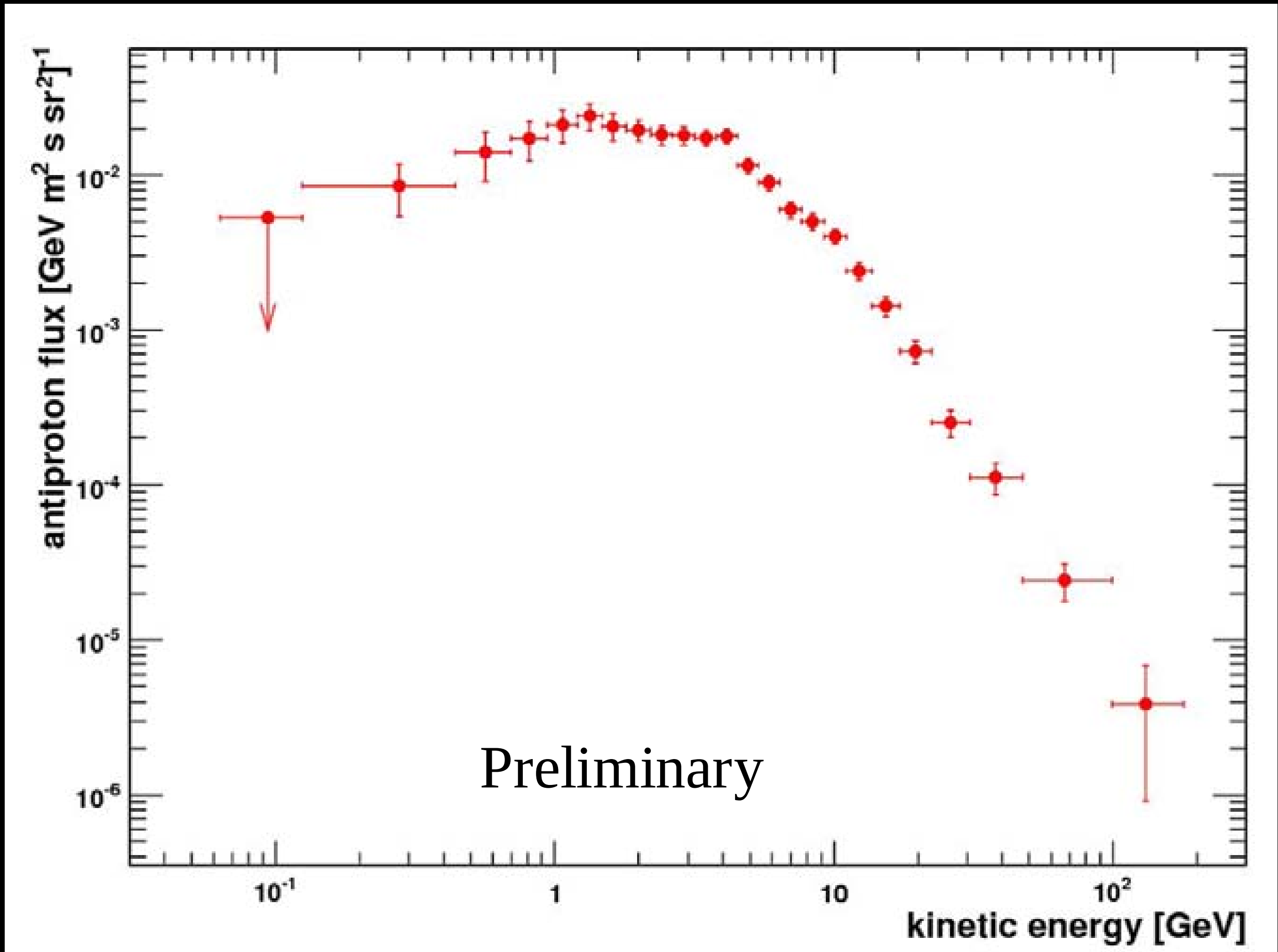
- New points consistent with old ones.

Preliminary antiproton spectrum



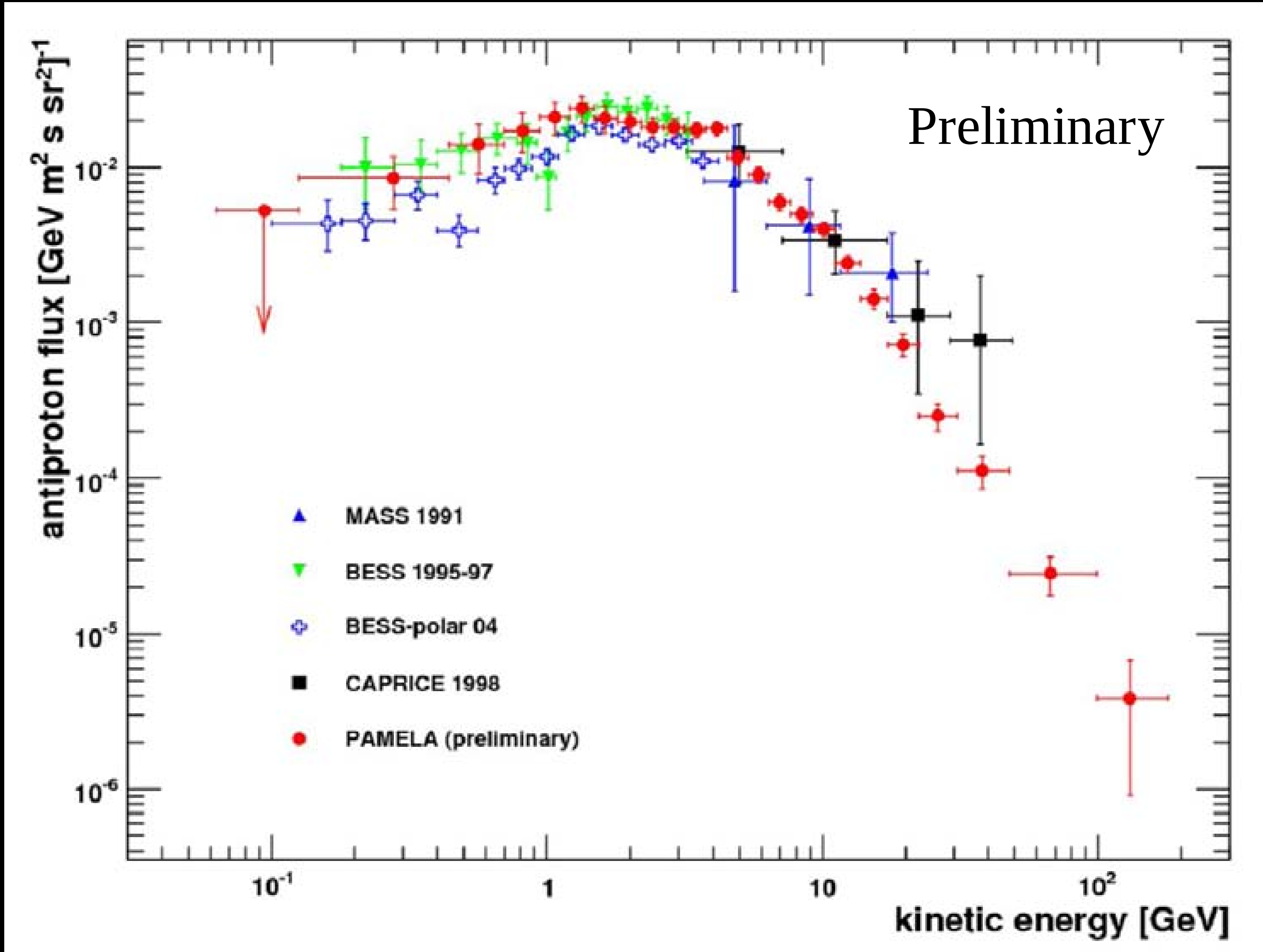
- highest bin: MDR > 6 · |R| is used to increase statistics..

Preliminary antiproton spectrum

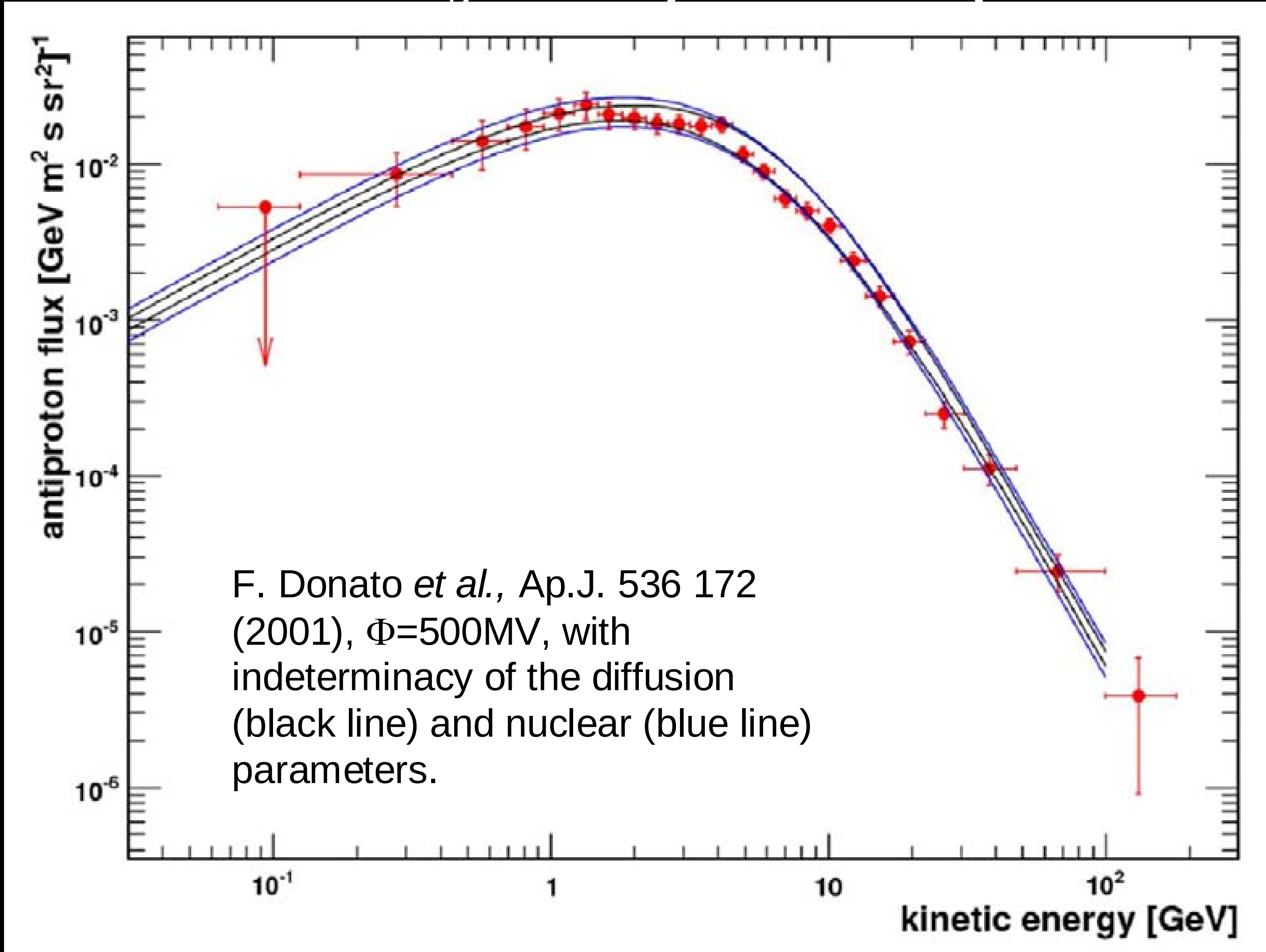


– Preliminary - Evaluation of systematics is under way.

Preliminary antiproton spectrum

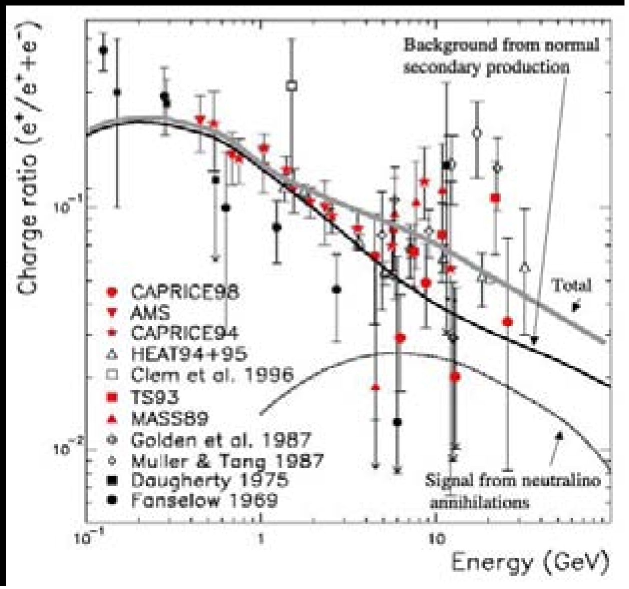


Preliminary antiproton spectrum



Positrons results

- Till August 30th about 20000 positrons from 200 MeV up to 200 GeV have been analyzed
- More than 15000 positrons over 1 GeV
- Other eight months data to be analyzed
- Selection criteria based on calorimeter
- Tuned and tested with
  - Montecarlo
  - Test Beam
  - In flight data
  - Cross-checked with Neutron Detector

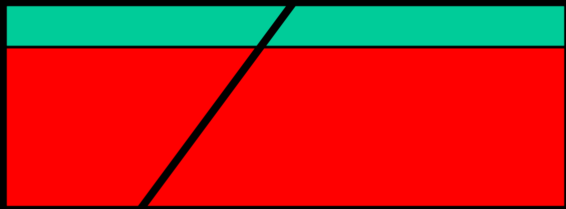


Preshower Technique to reduce systematics of proton contamination:

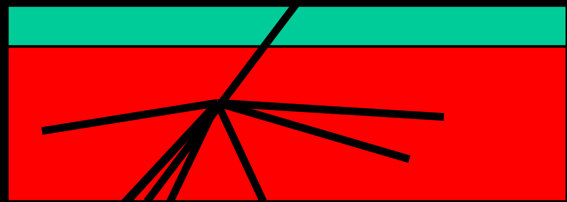
Optimize electromagnetic/hadronic shower discrimination, reduce systematics

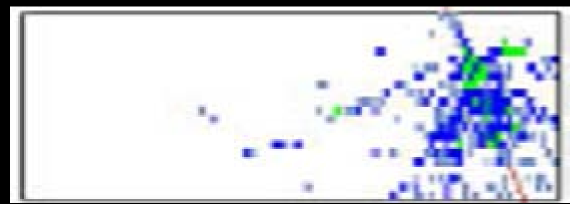
Protons:

- Non Interacting



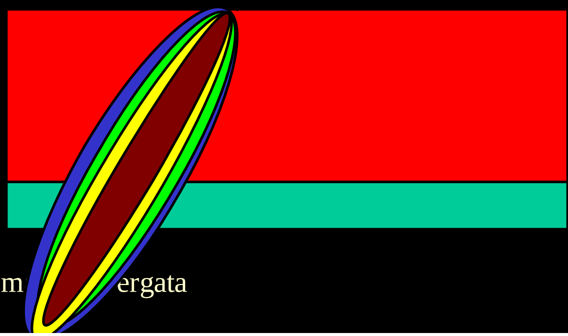
- Interacting

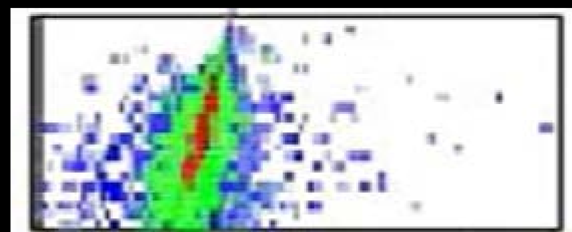




Electrons / Positrons

- Interacting (e.m.)

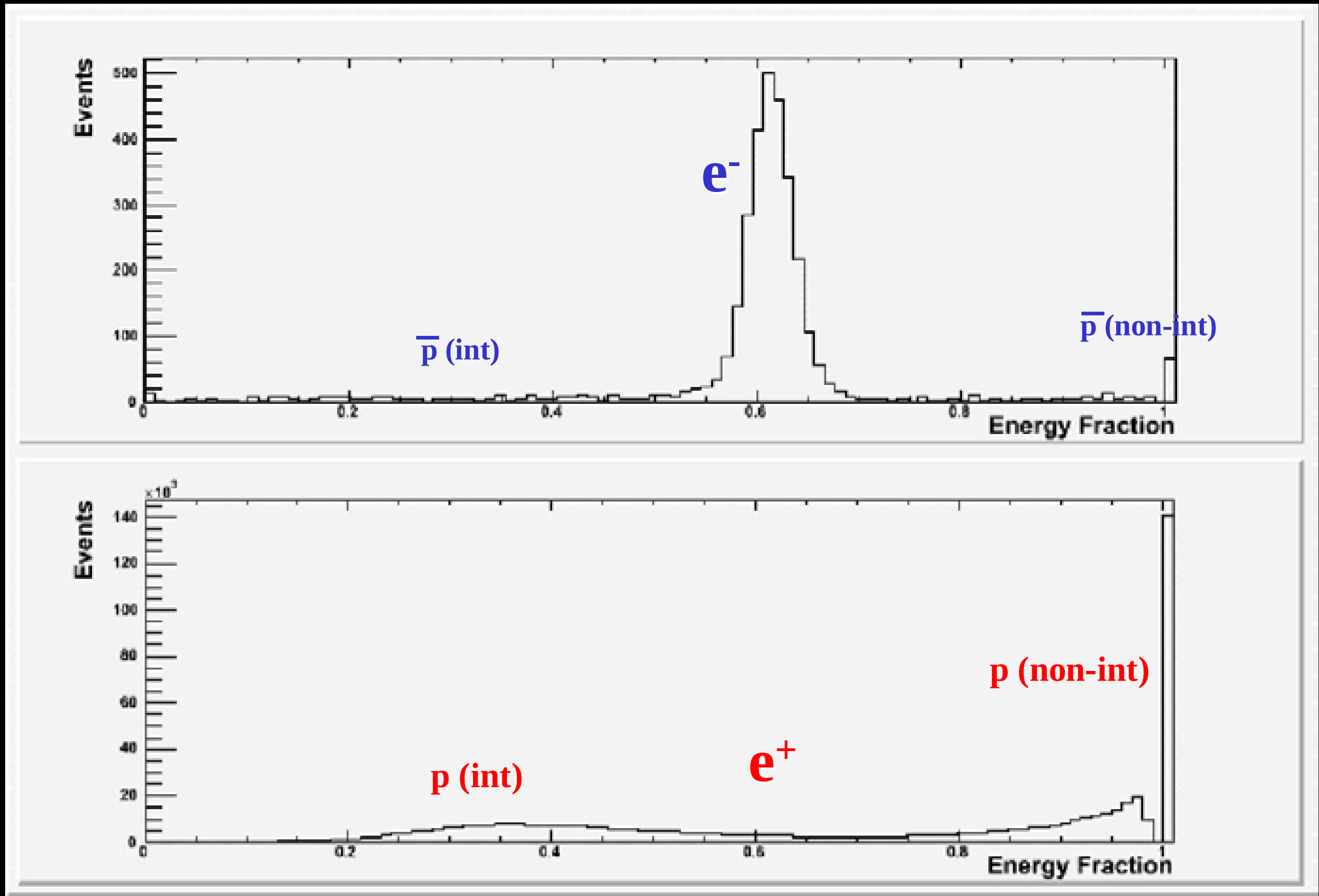




Recipe: M. Boezio, E. Mocchiutti

Positron selection with calorimeter (1)

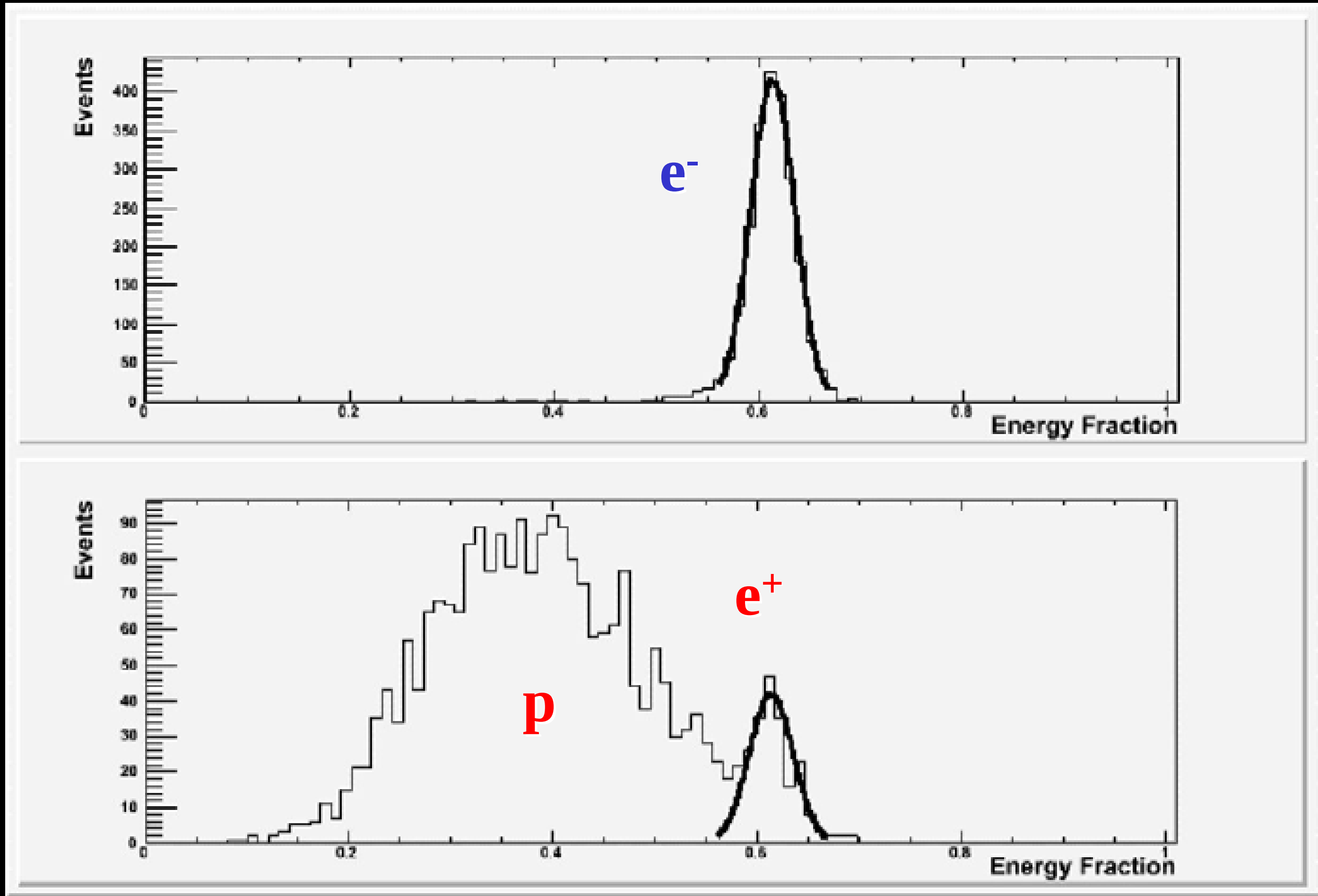
Rigidity: 20-30 GV



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

Positron selection with calorimeter (2)

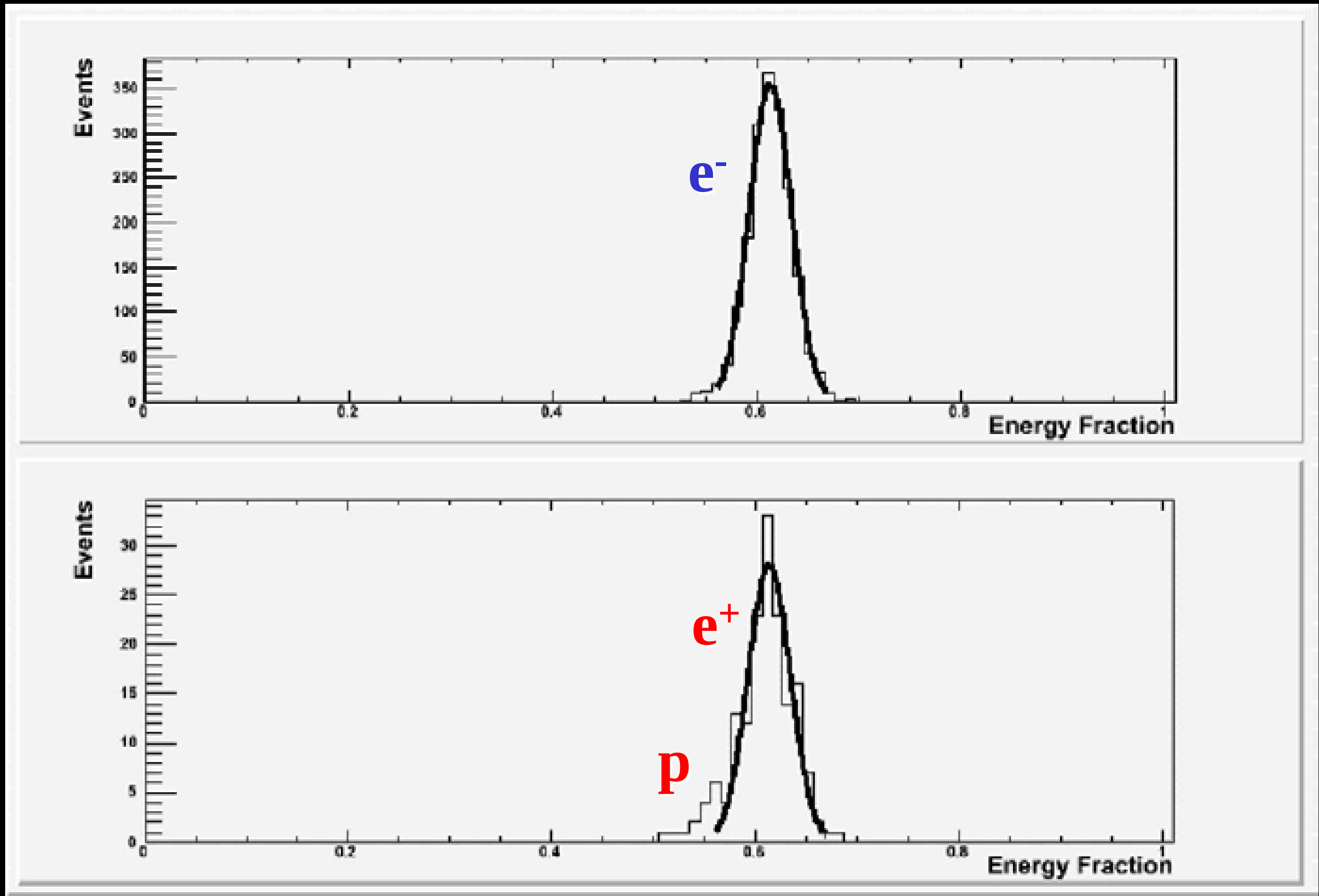
Rigidity: 20-30 GV



Fraction of charge released along the calorimeter track (left, hit, right) **+** **Energy-momentum match**

Positron selection with calorimeter (3)

Rigidity: 20-30 GV

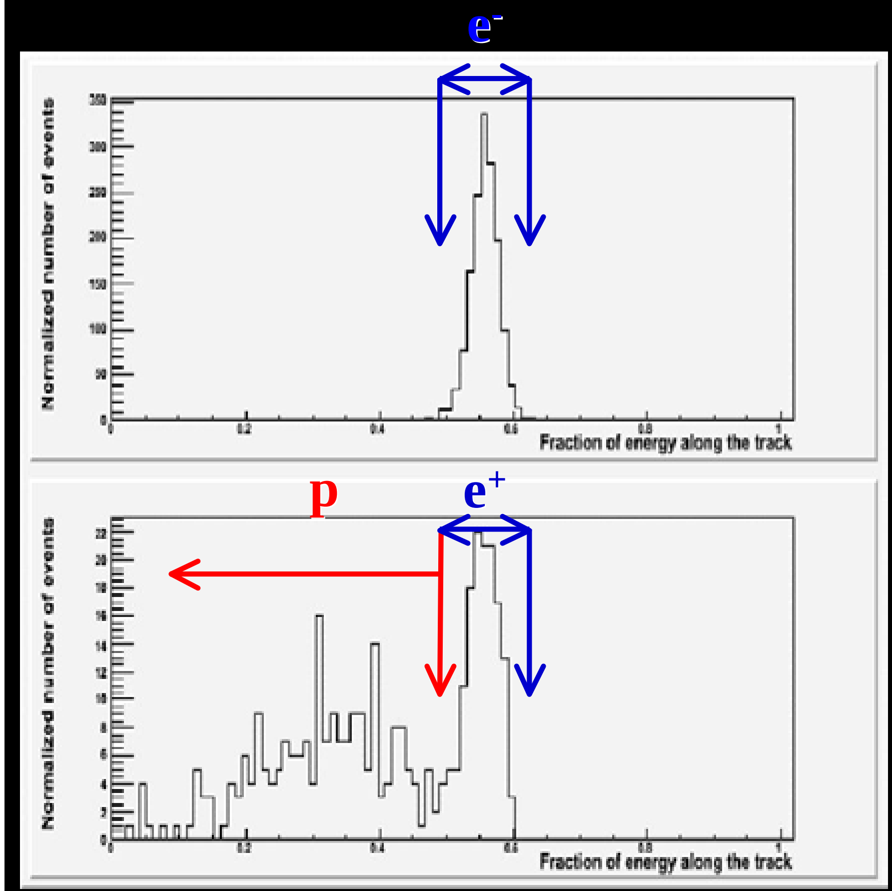


Fraction of charge released along the calorimeter track (left, hit, right) + **Energy-momentum match** +
- **Starting point of shower Longitudinal profile**

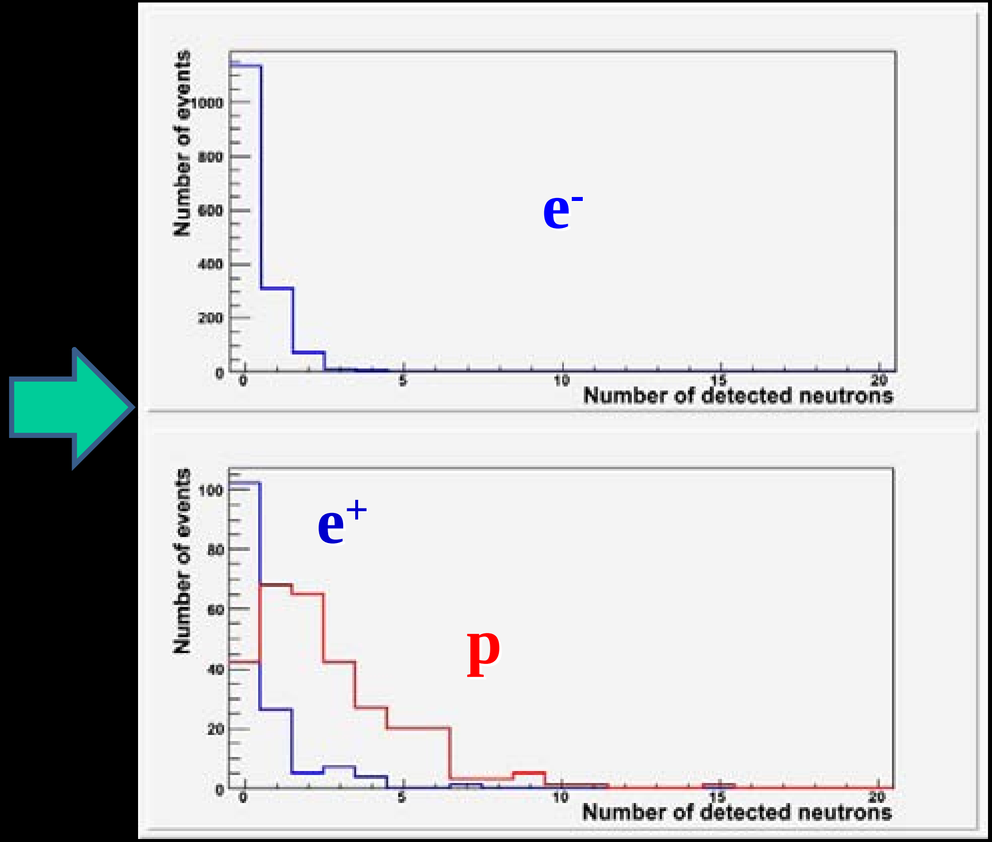
Positron selection (4)
Indipendent selection/check with ND

Rigidity: 20-30 GV

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



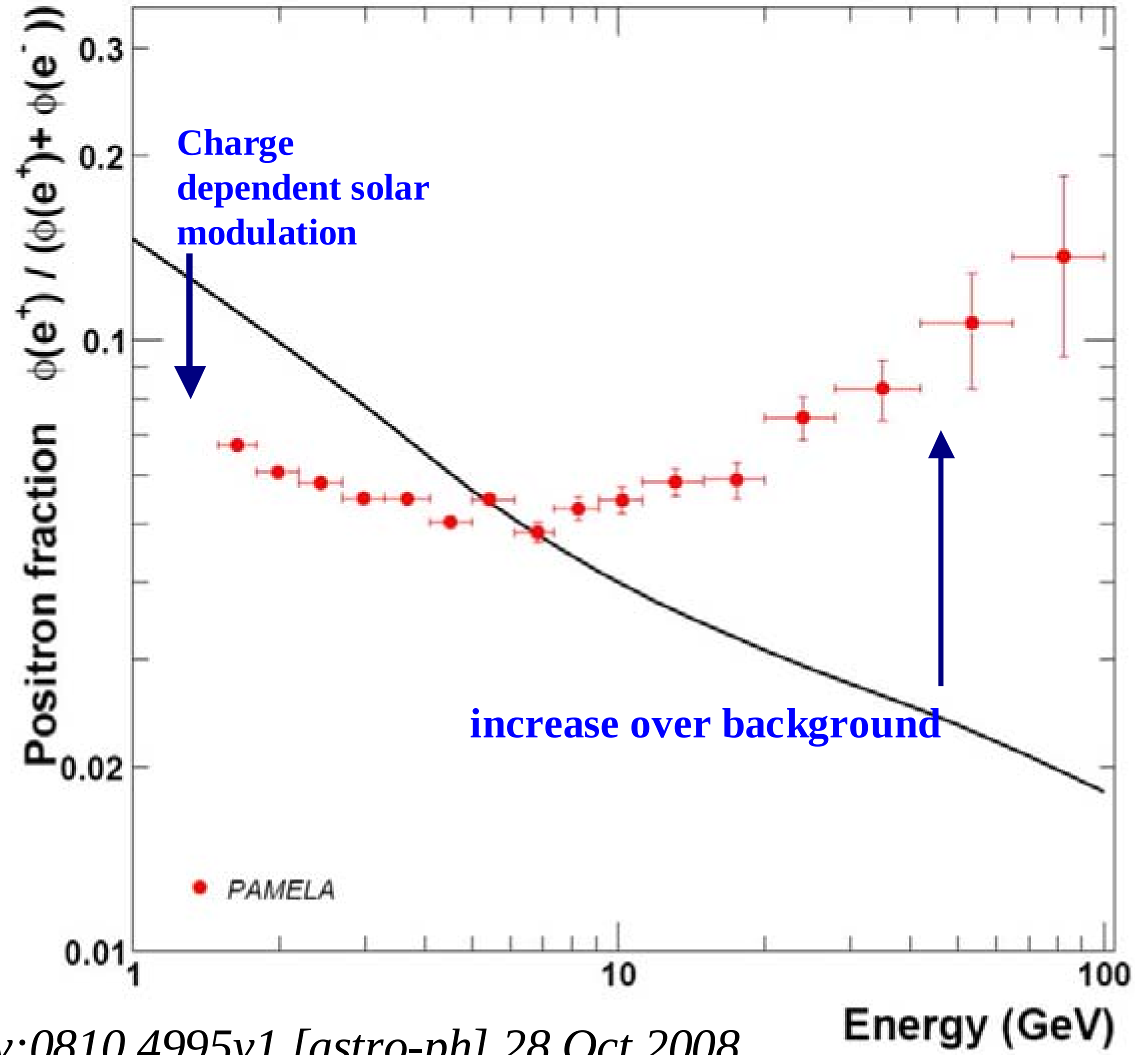
Neutrons detected by ND



Energy-momentum match
Starting point of shower

Pamela positron fraction

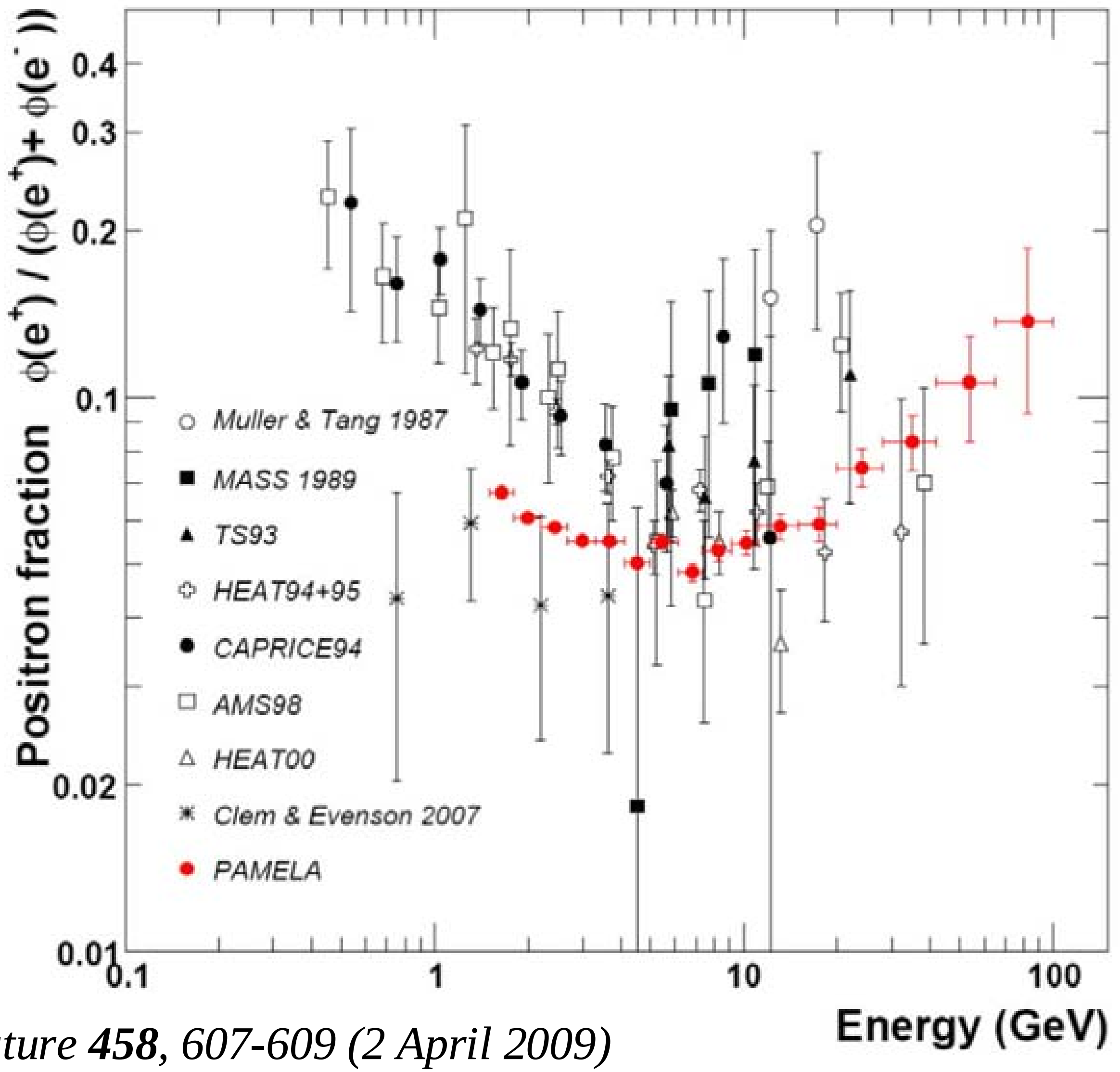
- July 2006 – February 2008 (~500 days)
- Collected triggers ~10^8
- Identified ~ 150 10^3 electrons and ~ 9 10^3 positrons between 1.5 and 100 GeV (180 positrons above 20 GeV



arXiv:0810.4995v1 [astro-ph] 28 Oct 2008

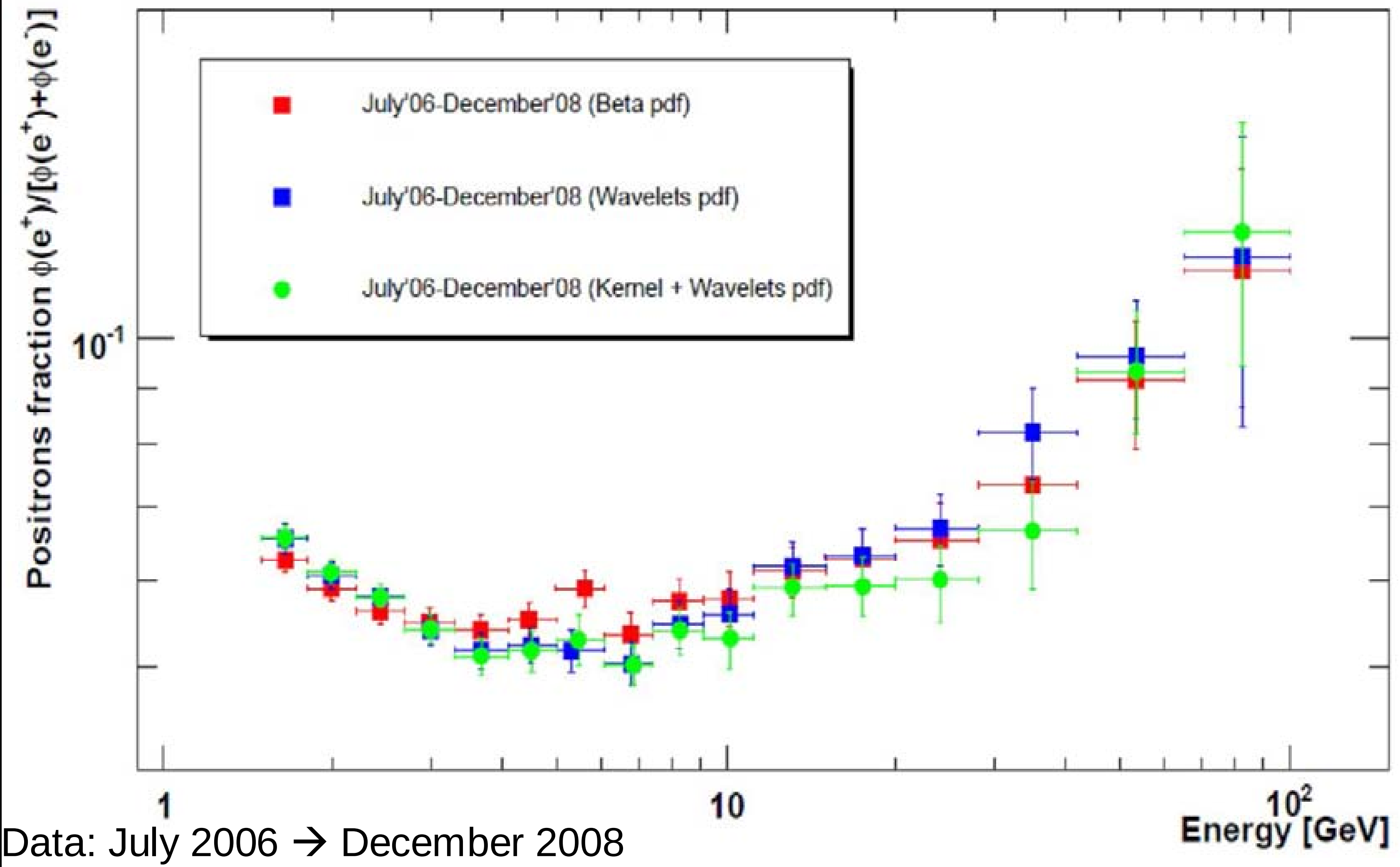
*Nature **458**, 607-609 (2 April 2009)*

Pamela positron fraction: comparison with other data



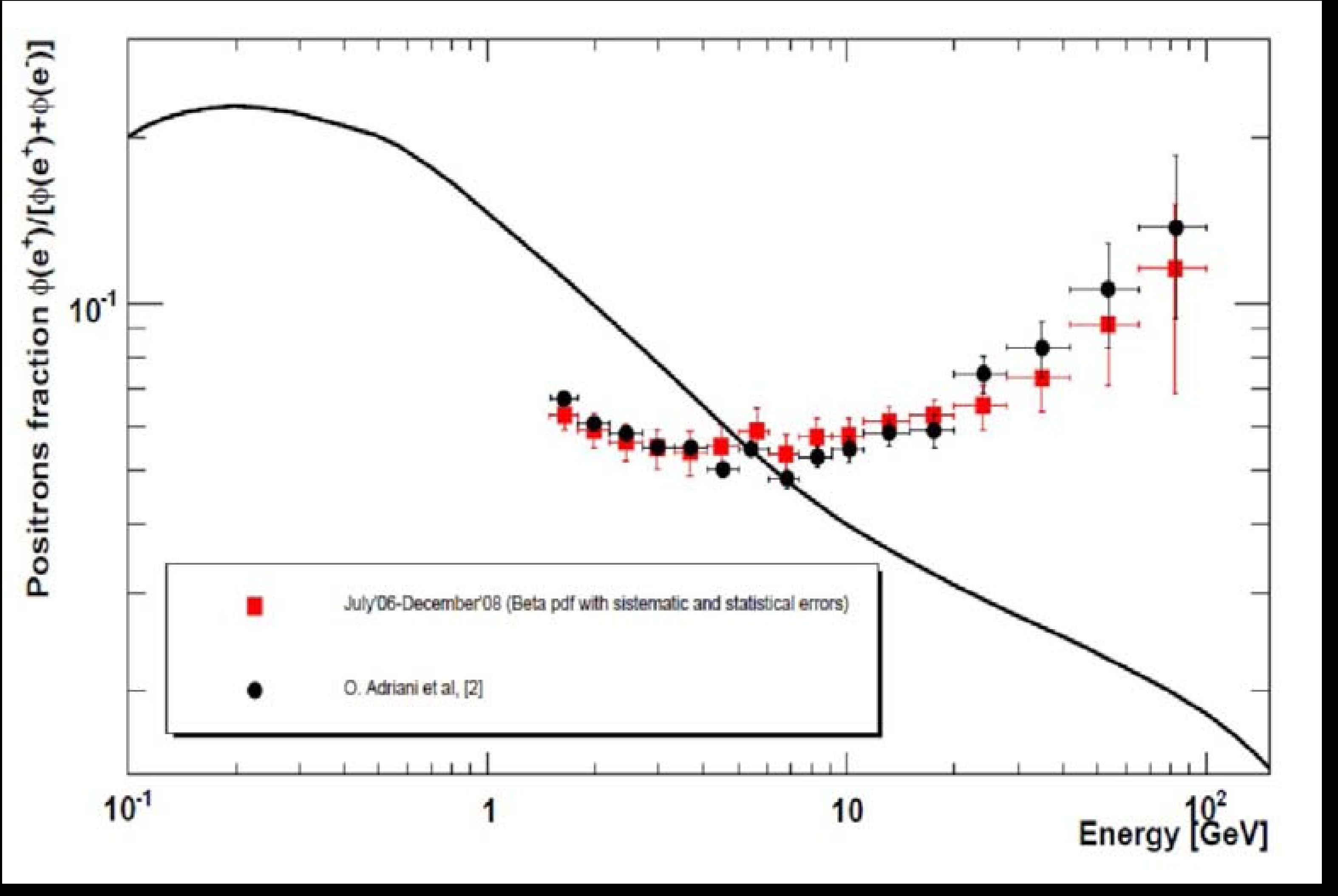
*Nature **458**, 607-609 (2 April 2009)*

Various approach to background subtraction



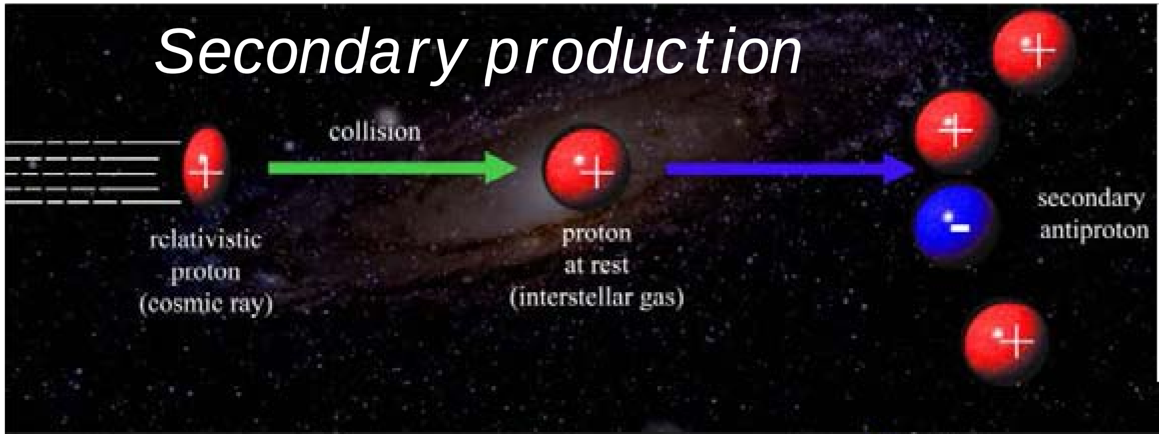
Data: July 2006 → December 2008

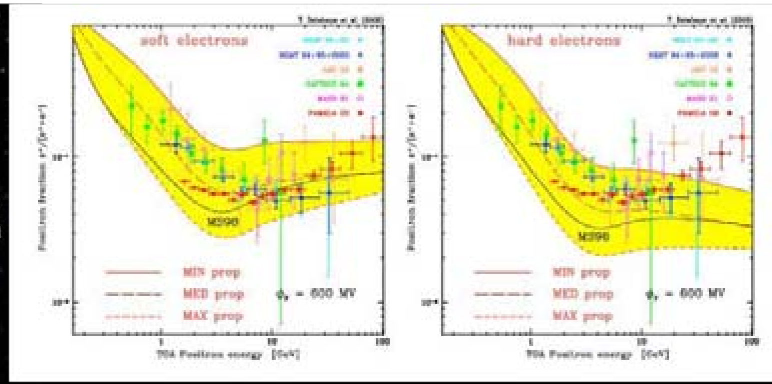
More positrons… data up to December 2008



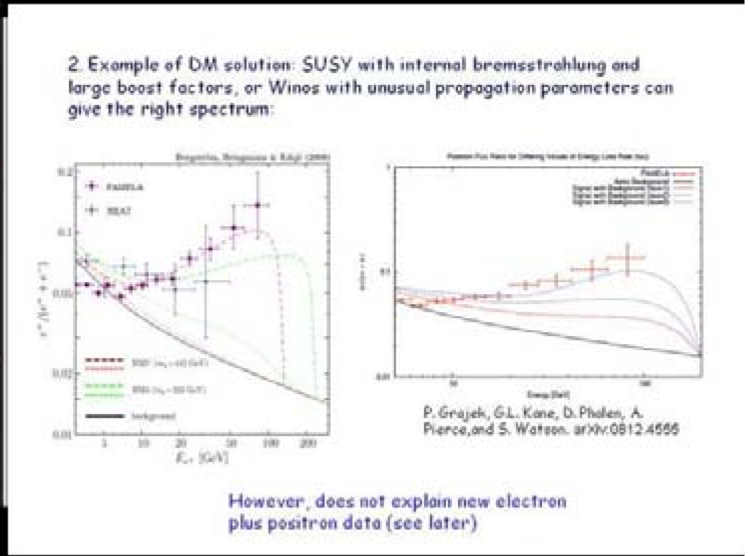
July 2006 → December 2008

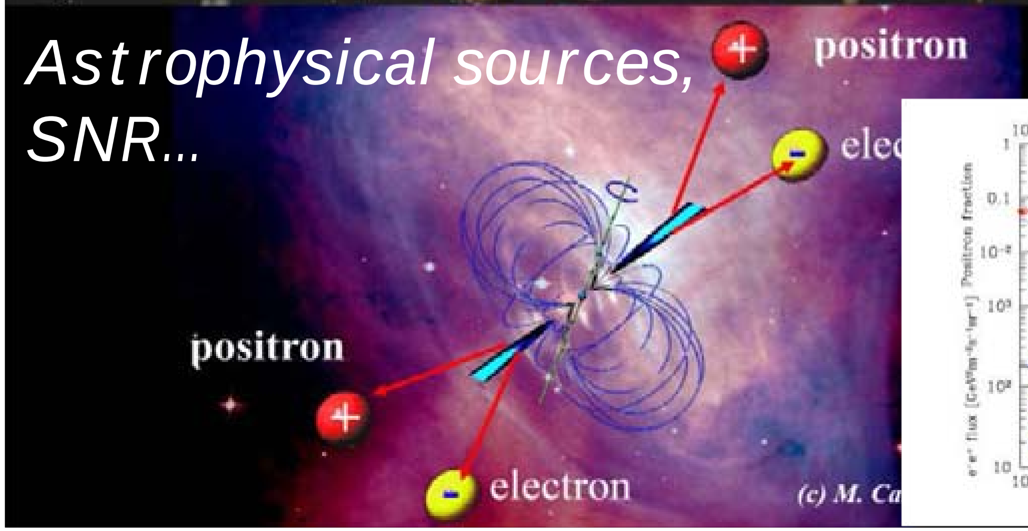
M. Casolino, INFN & University Roma Tor Vergata

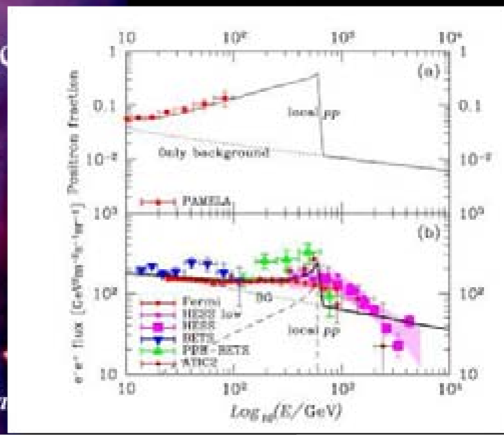

Secondary production
collision
relativistic proton (cosmic ray)
proton at rest (interstellar gas)
secondary antiproton

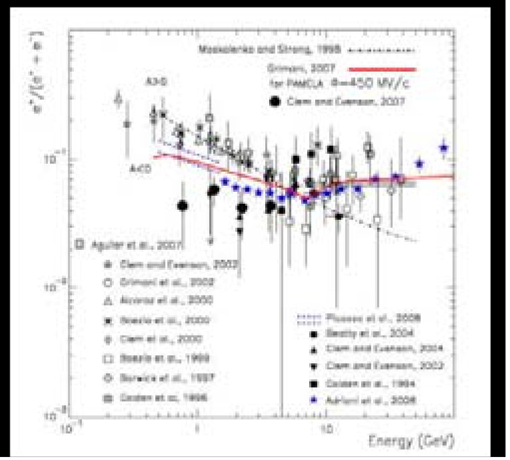

soft electrons
hard electrons
MIN prop
MED prop
MAX prop
TOA Positron energy [GeV]


Dark Matter Decay
quarks
annihilation
Dark Matter
leptons
bosoni
electrons
positrons
neutrinos
$\nu_e \nu_\tau \nu_\mu$
antiprotons
protons


2. Example of DM solution: SUSY with internal bremsstrahlung and large boost factors, or Winos with unusual propagation parameters can give the right spectrum:
P. Grajek, G.L. Kane, D. Phalen, A. Pierce, and S. Watson. arXiv:0812.4555
However, does not explain new electron plus positron data (see later)


Astrophysical sources, SNR...
positron
positron
electron
(c) M. Ca


local PP
Only background
PAMELA
Fermi
HESS low
HESS
BETS
PPB-BETS
ATIC2
Log$_{10}$(E/GeV)


Moskalenko and Strong, 1998
Energy (GeV)

EDSJO 2009

Pulsars	New SNRs mechanisms	Dark matter	?
Uncertainties			
• Acceleration model (polar cap, outer gap, ...) • Injection spectrum $E^{-\alpha}$? • Release into the ISM (when, how much?) • Source locations, ages, ...	• Environmental parameters at SNR (production mechanism) • Distance to closest source • Cut-off energies	• Particle physics model • Particle physics enhancement (Sommerfeld) • Substructure enhancement (halo model)	?
Tests			
• Anisotropy of flux • Fluctuations in spectrum • consistency checks (gamma, X-ray, ...)	• Antiproton fluxes • Secondary nuclei	• FSR & IC photons from galactic centre • Continuing positron rise • CMBR distortions	?

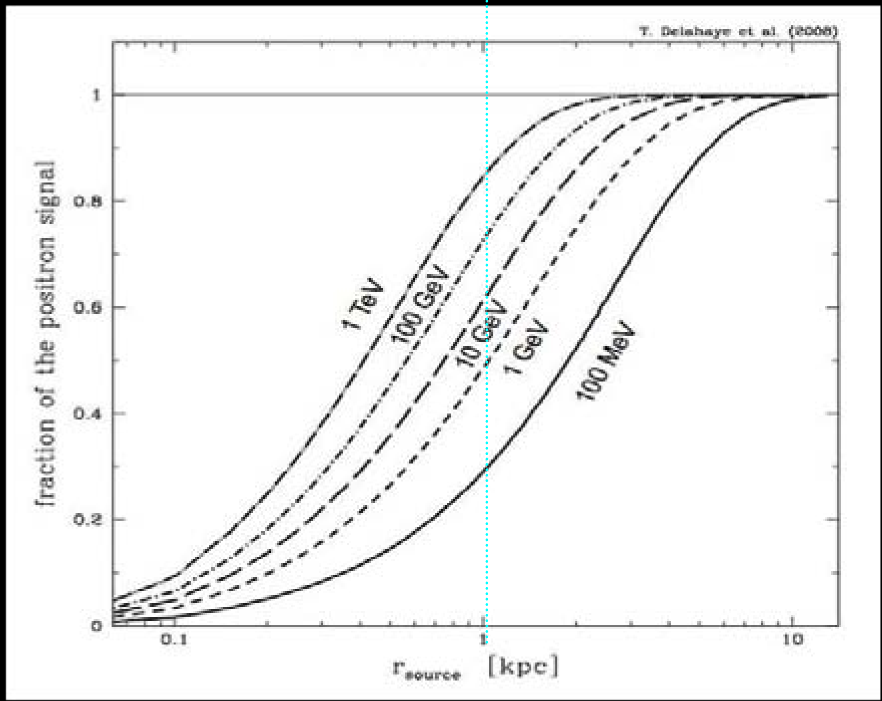
Positron origin

Where do positrons and electrons come from?

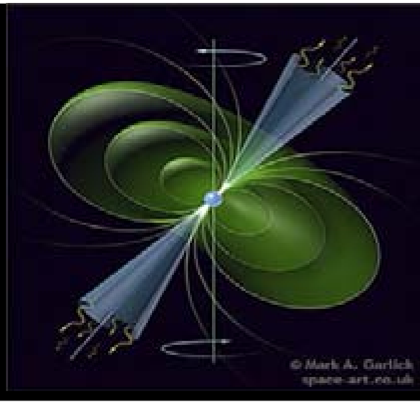
Mostly locally within 1 Kpc, due to the energy losses by Synchrotron Radiation and Inverse Compton
They sample the neighborhood of the galaxy
Protons and antiptotons the whole galaxy

Typical lifetime

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



Astrophysical Origin



Pulsars

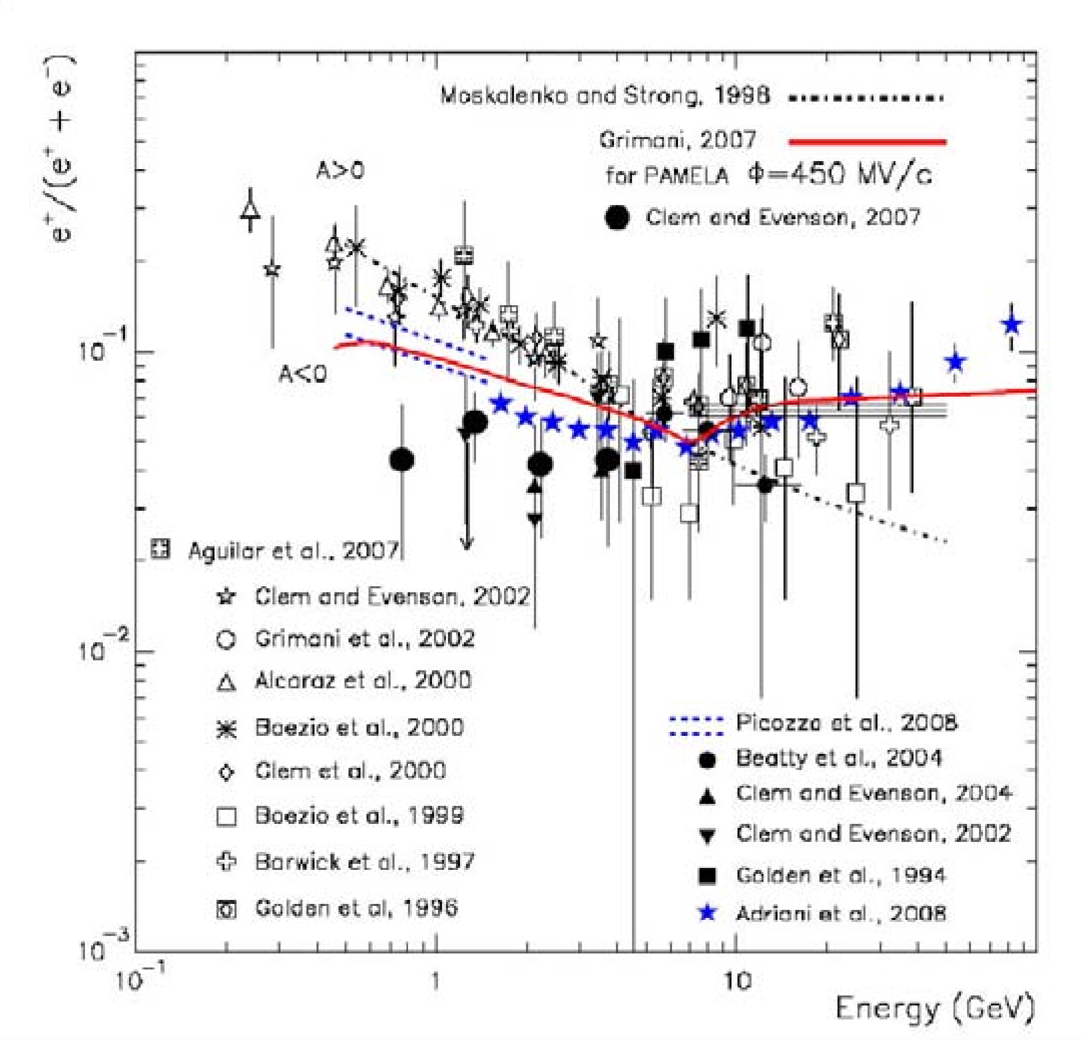
Must be young ($T<10^5$ yr) and nearby (<1 kpc). If not: too much diffusion, low energy, too low flux.

Injection flux:

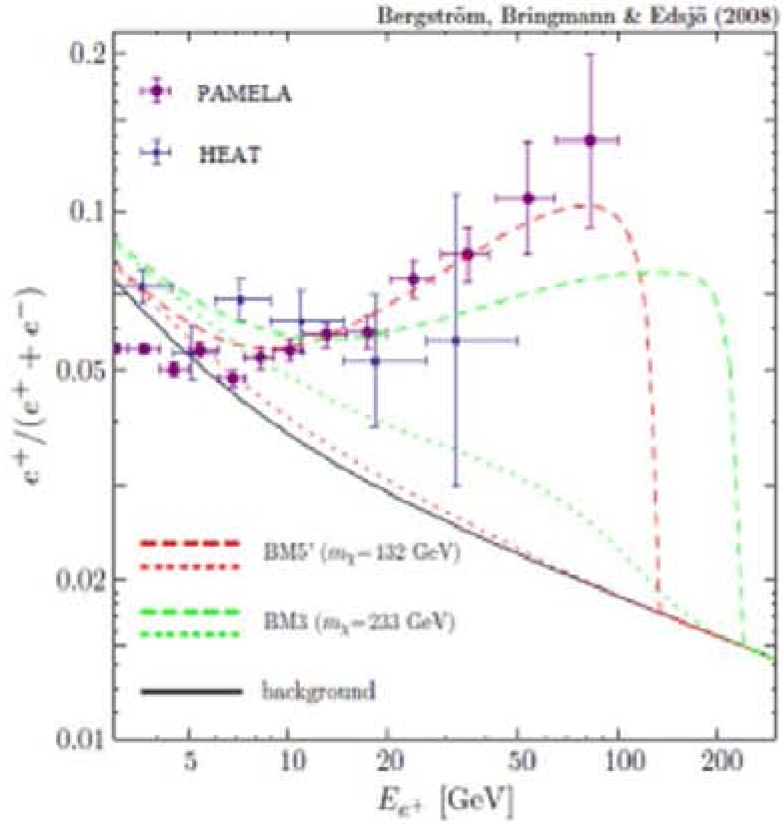
$$\Phi_{e\pm} \simeq E^{-p} \exp(E/E_c)$$

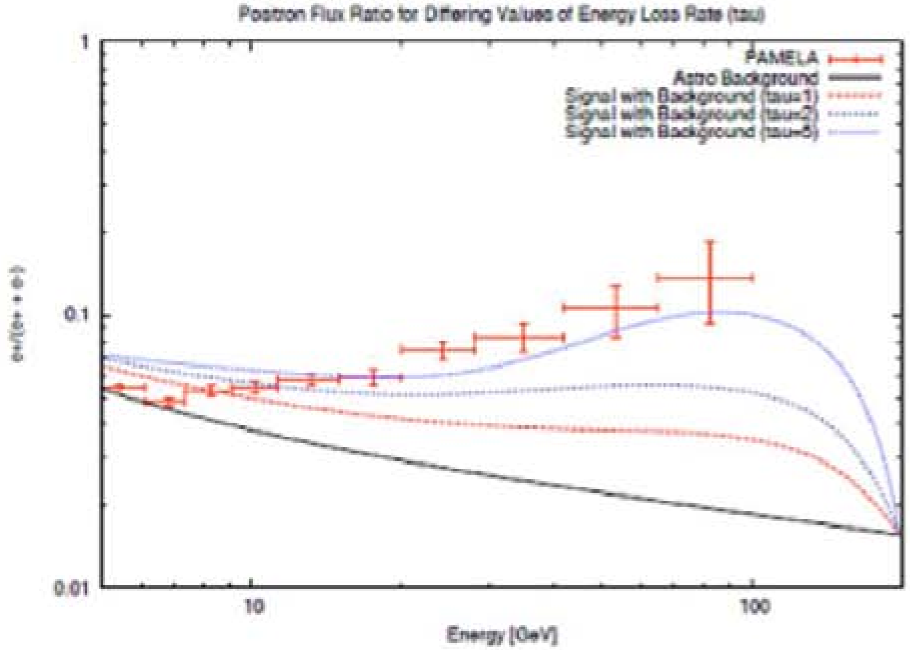
$$p \simeq 2$$

$$E_c \simeq 10 - 10^2\,\mathrm{TeV}$$



2. Example of DM solution: SUSY with internal bremsstrahlung and large boost factors, or Winos with unusual propagation parameters can give the right spectrum:



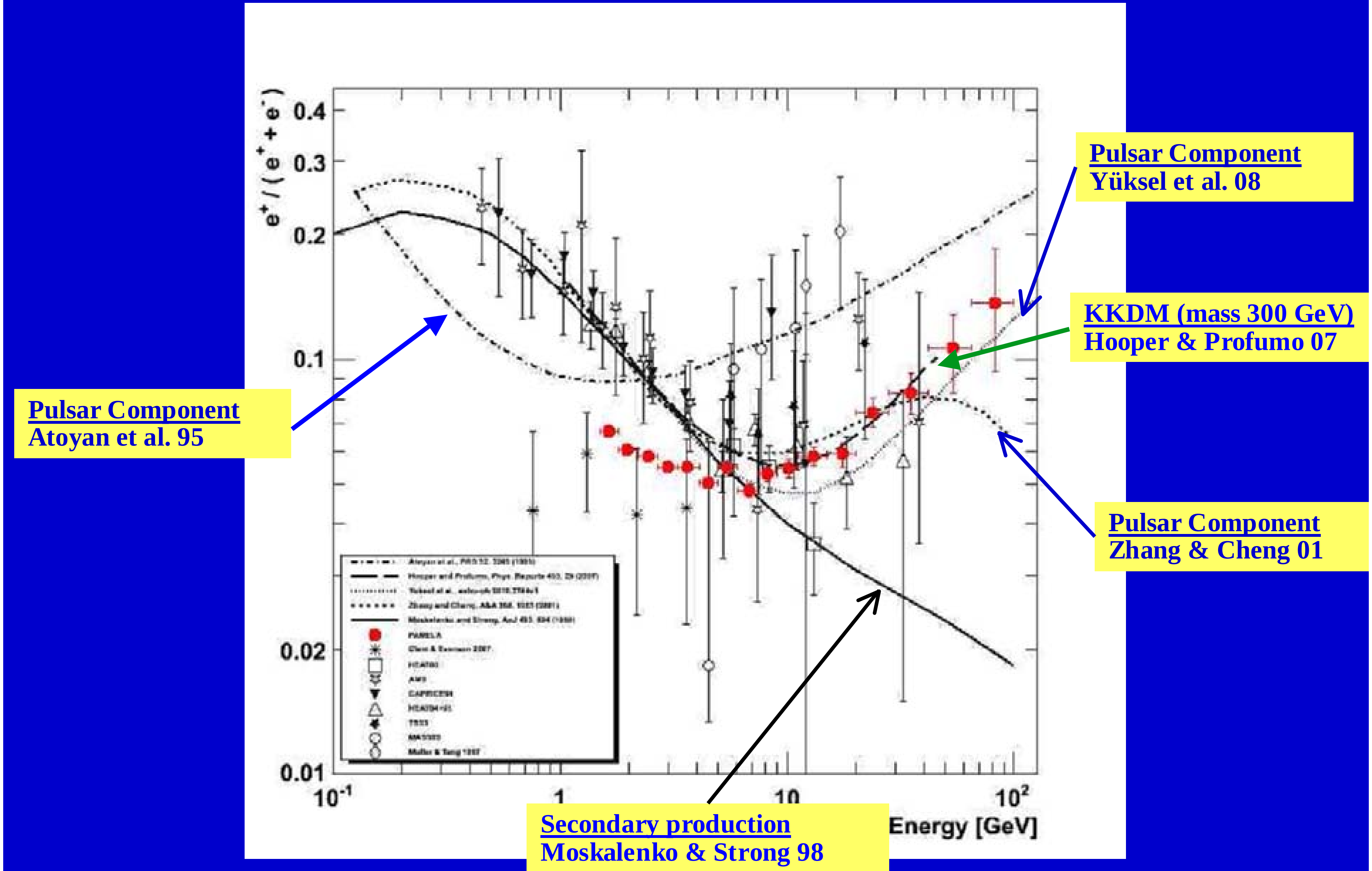


P. Grajek, G.L. Kane, D. Phalen, A. Pierce,and S. Watson. arXiv:0812.4555

Bergstrom 2009

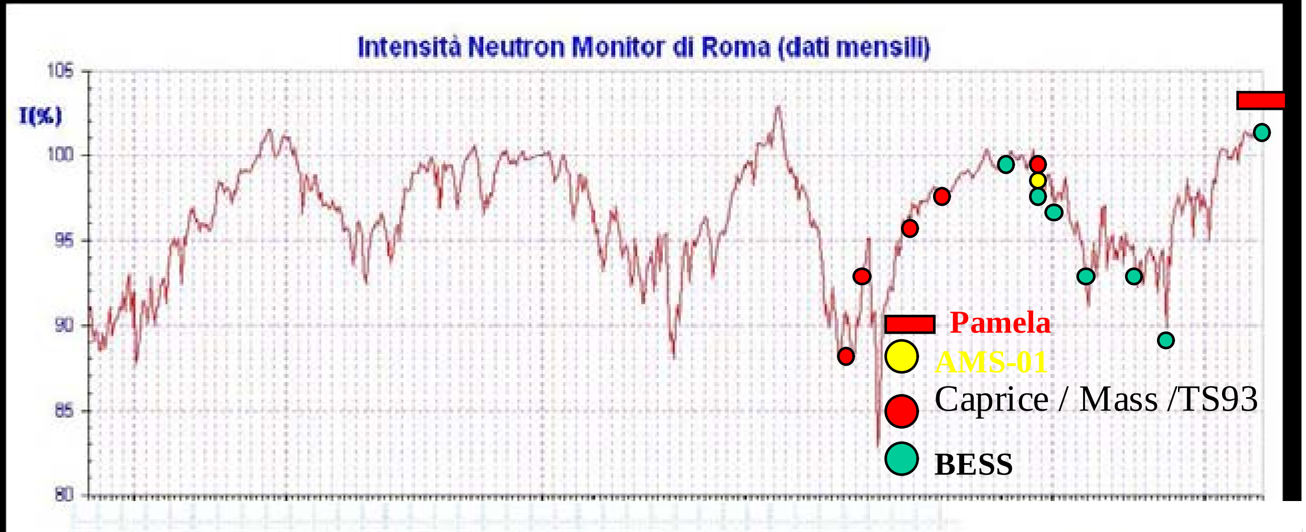
However, does not explain new electron plus positron data (see later)

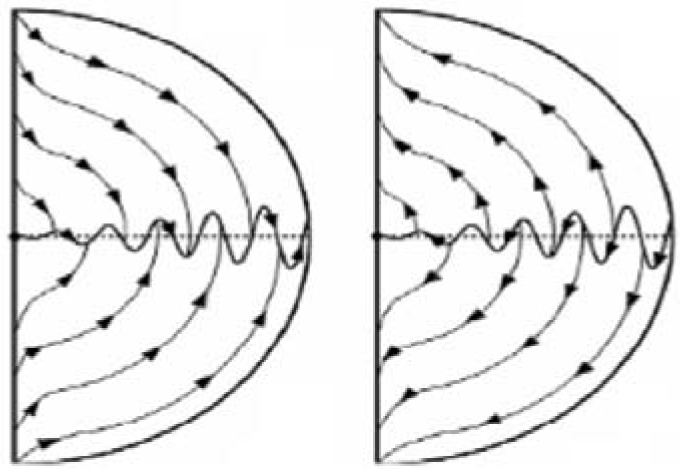
Positron fraction: comparison with models



Charge dependent solar modulation of low energy positrons

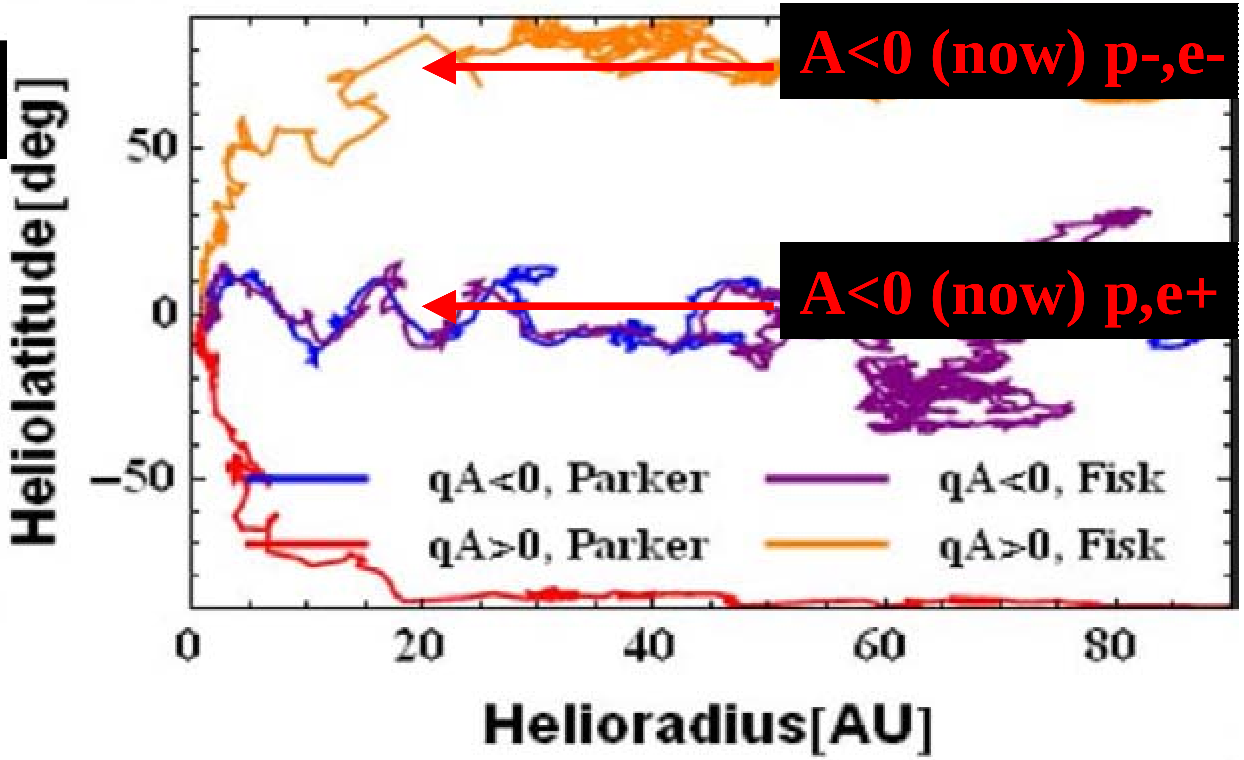
- Charge dependent solar modulation
- Separate qA>0 with qA<0 solar cycles
- Evident in the proton flux
- Observed in the antiproton channel by BESS
- Full 3D solution of the Parker equation – drift term depends on sign of the charge



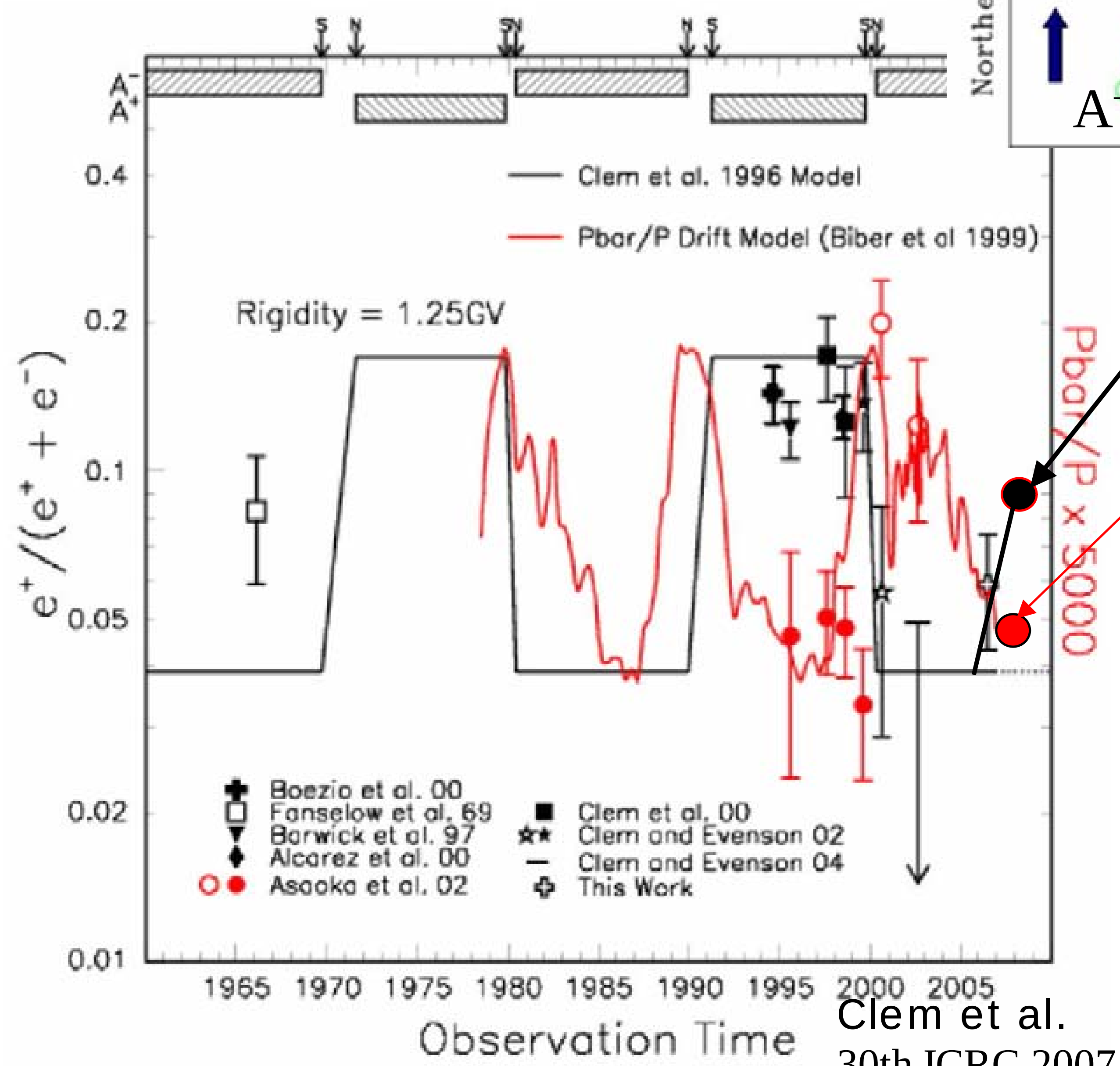


A > 0
Positive particles

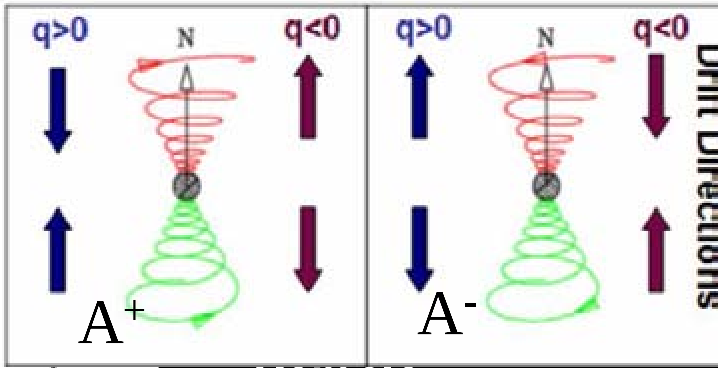
A < 0
Positive particles



Charge dependent solar modulation



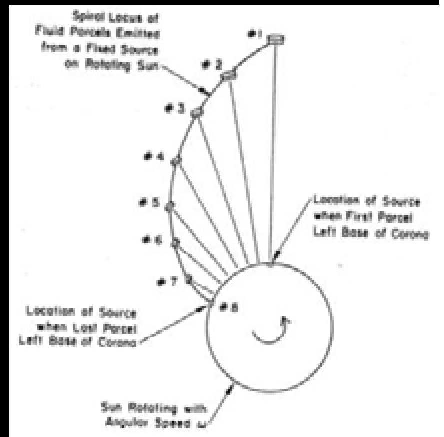
Clem et al.
30th ICRC 2007



Pamela

Pamela e+

Pamela p-



Fermi seems to exclude Egret excess

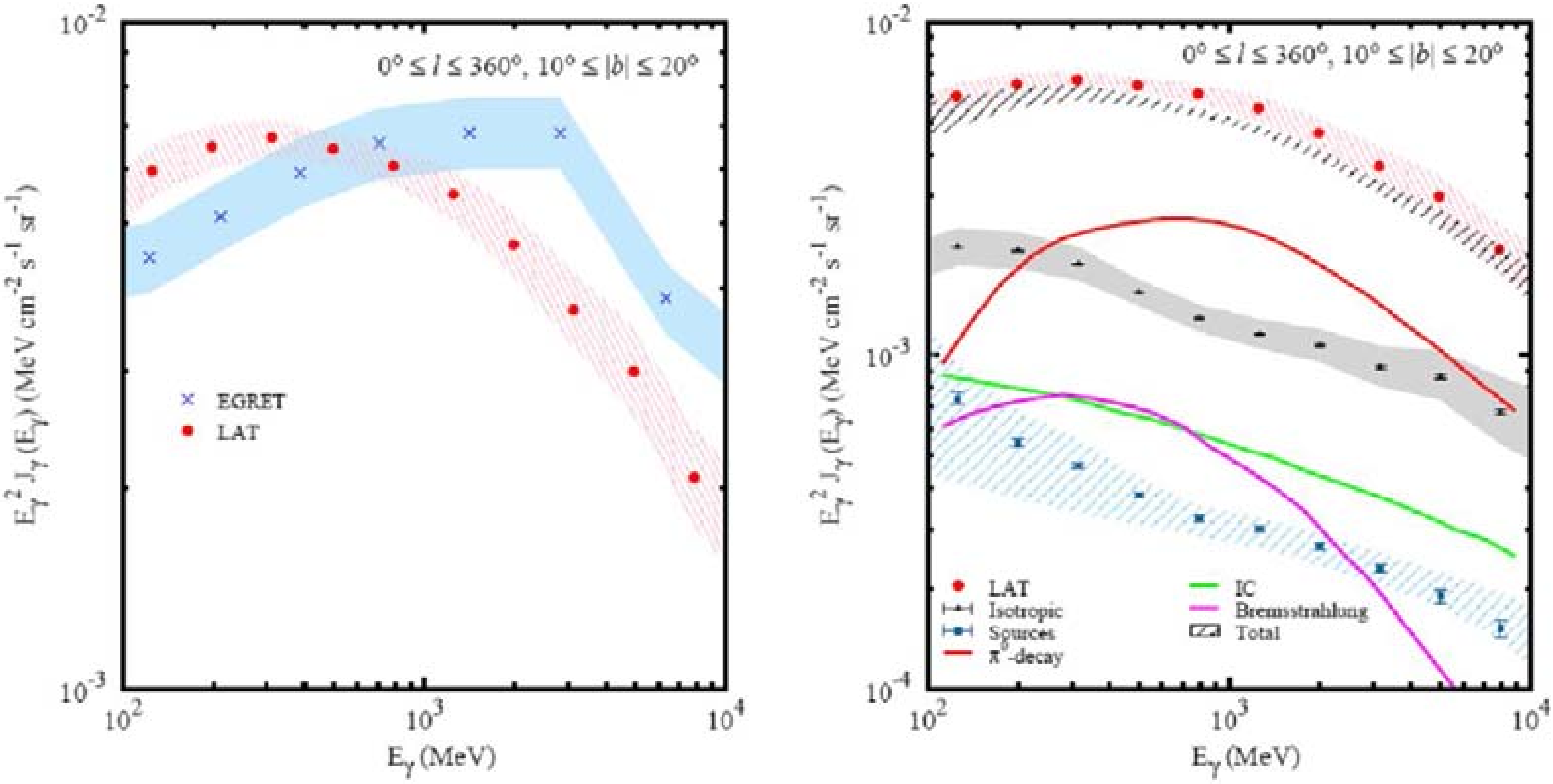


Fig. 1: *Left:* Preliminary diffuse emission intensity averaged over all Galactic longitudes for latitude range $10° \le |b| \le 20°$. Data points: LAT, red dots; EGRET, blue crosses. Systematic uncertainties: LAT, red; EGRET, blue. *Right:* Preliminary LAT data with model, source, and UIB components for same sky region. Model (lines): π^0-decay, red; Bremsstrahlung, magenta; IC, green. Shaded/hatched regions: isotropic, grey/solid; source, blue/hatched; total (model + UIB + source), black/hatched.

Porter, Icrc 2009

Fermi Haze
as IC counterpart of WMAP

Wmap haze in synchroton rad
Toward glactic center

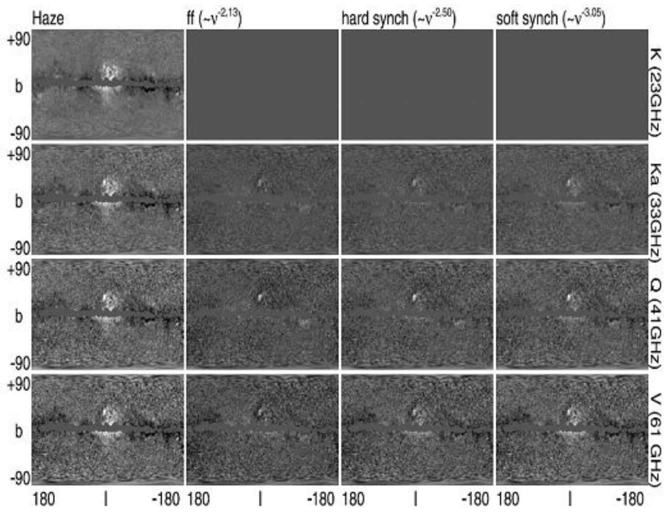


Fig. 5.—Haze is determined in 4 *WMAP* bands by subtracting CMB, soft synchrotron (Haslam et al. [1982] template), free-free (Hα template), and spinning dust. Using the K-band haze as a template, it is then subtracted from Ka, Q, and V bands assuming various power laws. A free-free spectrum fits most of the sky well, apart from the ζ Oph cloud $(l, b) = (5°, 25°)$. See § 3.3.

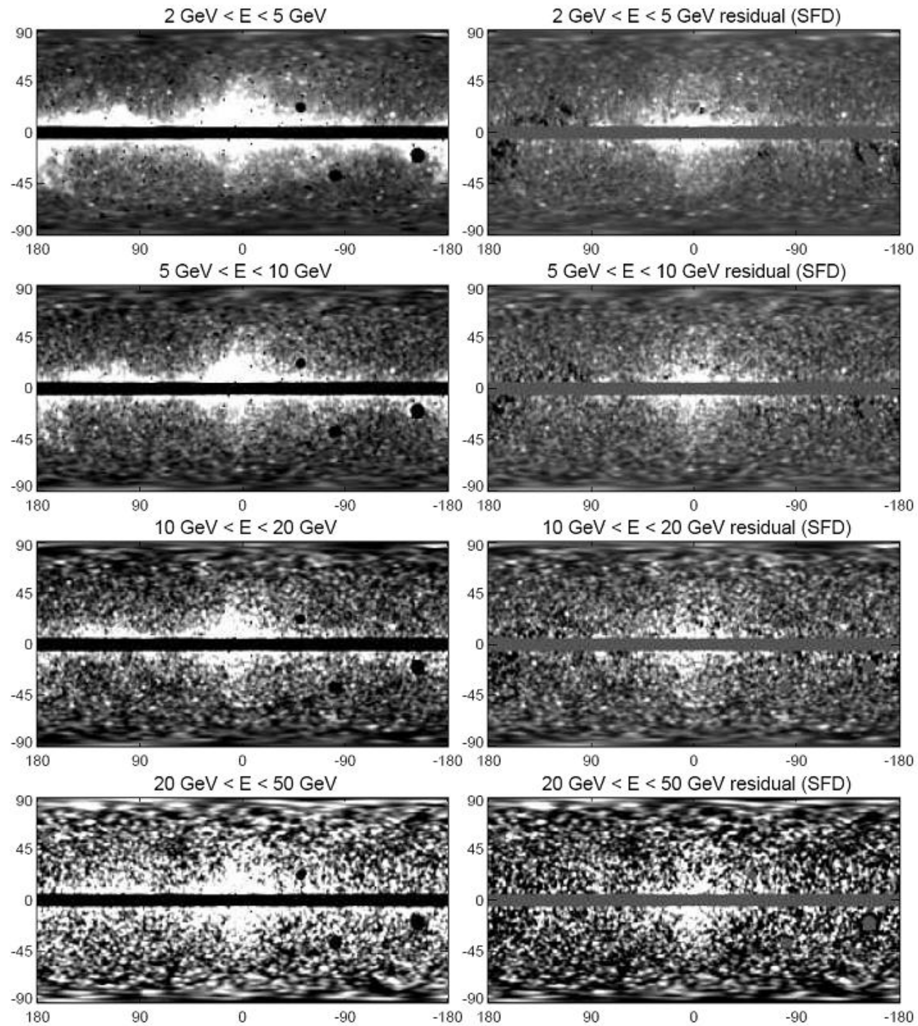


Fig. 3.— Residual maps after cross-correlating *Fermi* maps at various energies with the SFD dust map. The mask is described in §3.2. Cross-correlations are done over unmasked pixels and for $75 \leq \ell \leq 285$. Although the template removes much of the emission, there is a clear excess towards the Galactic center. This excess also includes a disky component which is likely due to ICS and bremsstrahlung from softer electrons (see Figure 5).

ApJ, 614:186–193,
2004 October 10

arXiv:0910.4583v1

Electrons and positrons are fashionable

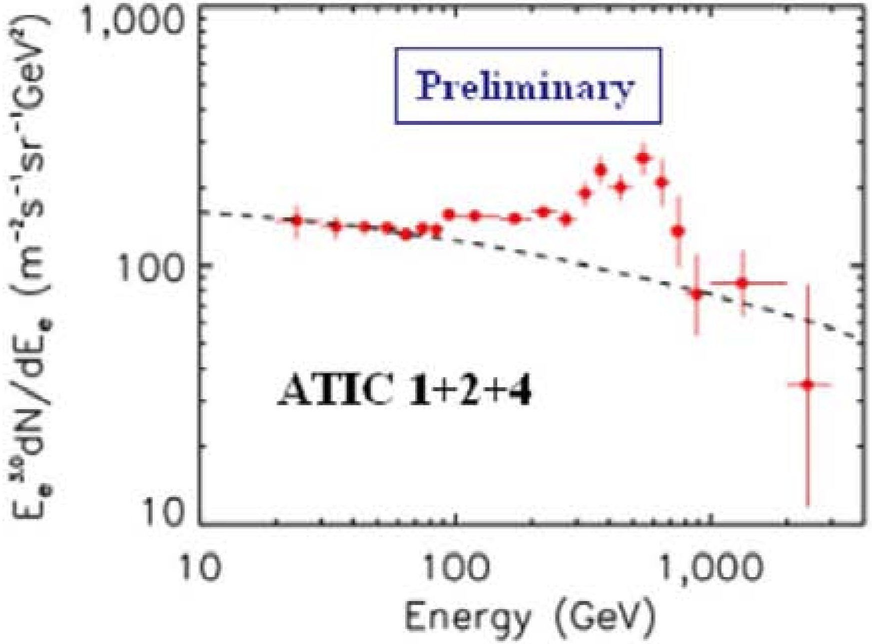
But there is disagreement on the $e^{+}+e^{-}$ spectrum

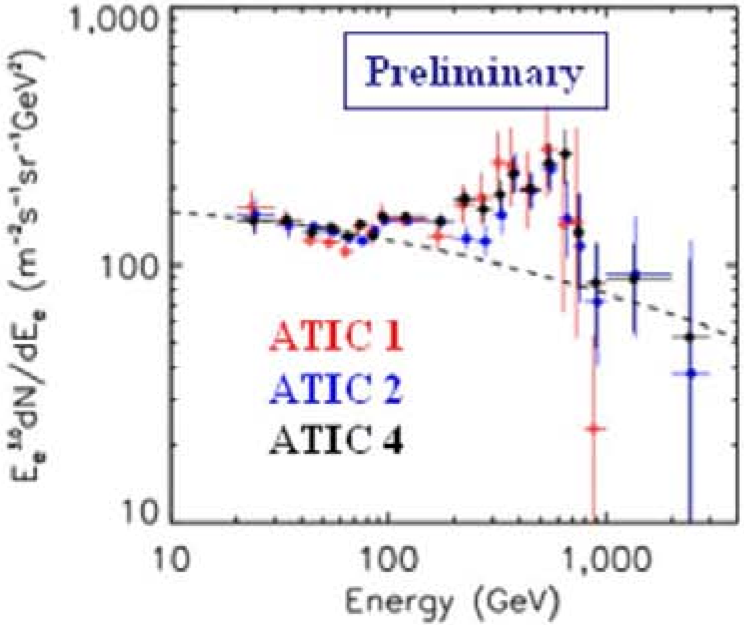
Atic: Balloon but deep detector

BGO calorimeter,
ATIC 1+2, 18.4 rl,
in 4 XY, planes,
ATIC 4, 22.9 rl,
in 5 XY planes,

Fermi: Large statistics (400 events in last bin) but shallow: **12.5 X_0**

All three ATIC flights are consistent



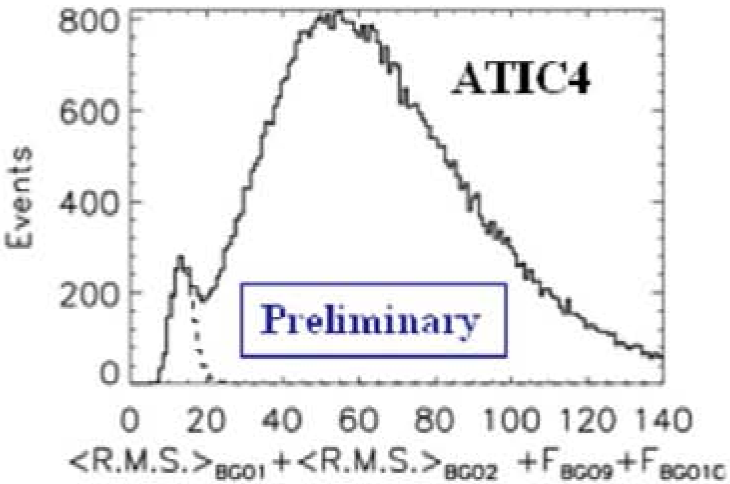


"Source on/source off" significance of bump for ATIC1+2 is about 3.8 sigma

ATIC-4 with 10 BGO layers has improved e , p separation. **(~4x lower background)**

"Bump" is seen in all three flights.

Significance for ATIC1+2+4 is 5.1 sigma

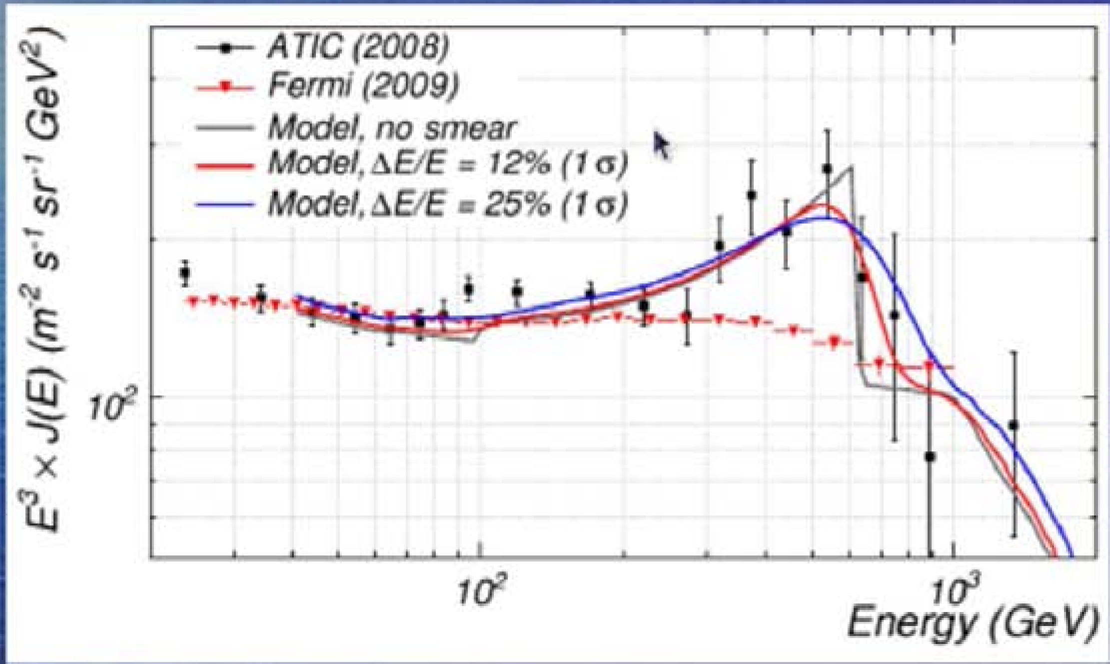


Joachim Isbert PAMELA 2009

And finally we want to check - could we miss "ATIC-like" spectral feature?

We validated the spectrum reconstruction by:

- *comparing the results for different path length subsets*
- *varying the electron selections*
- *simulating the LAT response to a spectrum with an "ATIC-like" feature:*

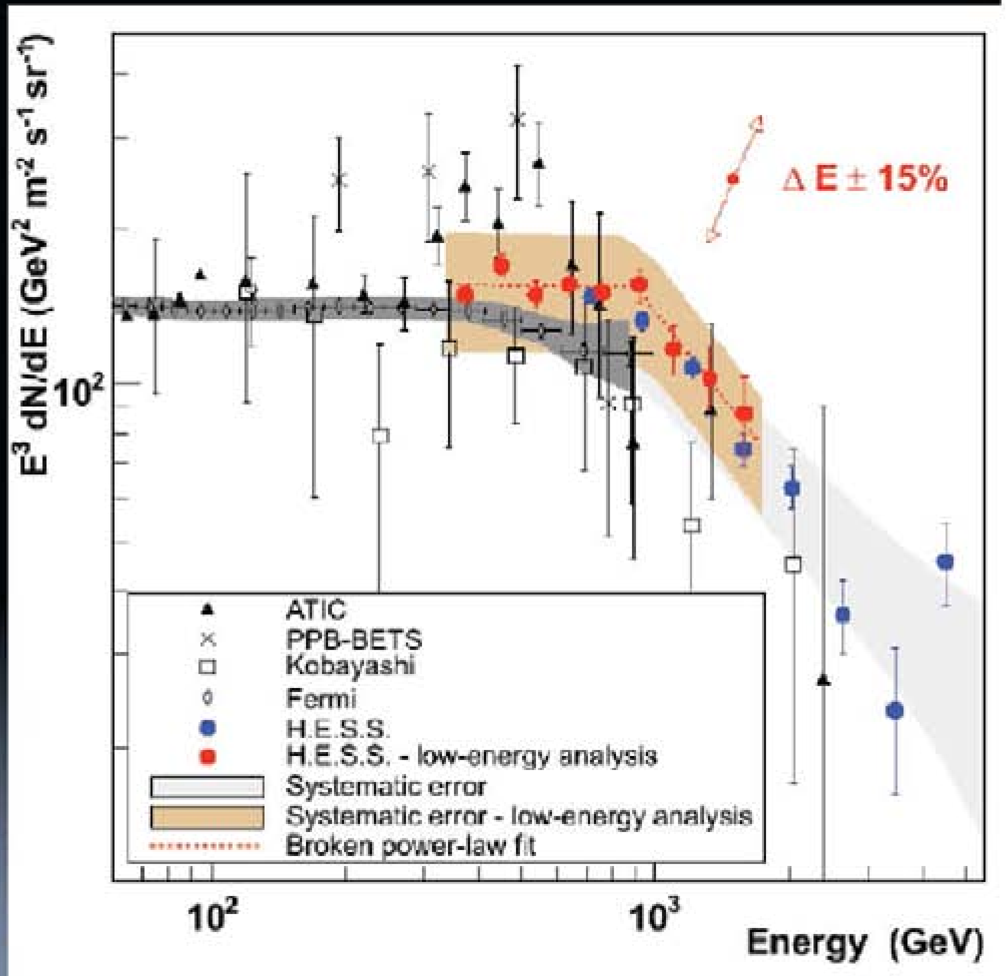


This demonstrates that the Fermi LAT would have been able to reveal "ATIC-like" spectral feature with high confidence if it were there. <u>Energy resolution is not an issue with such a wide feature</u>

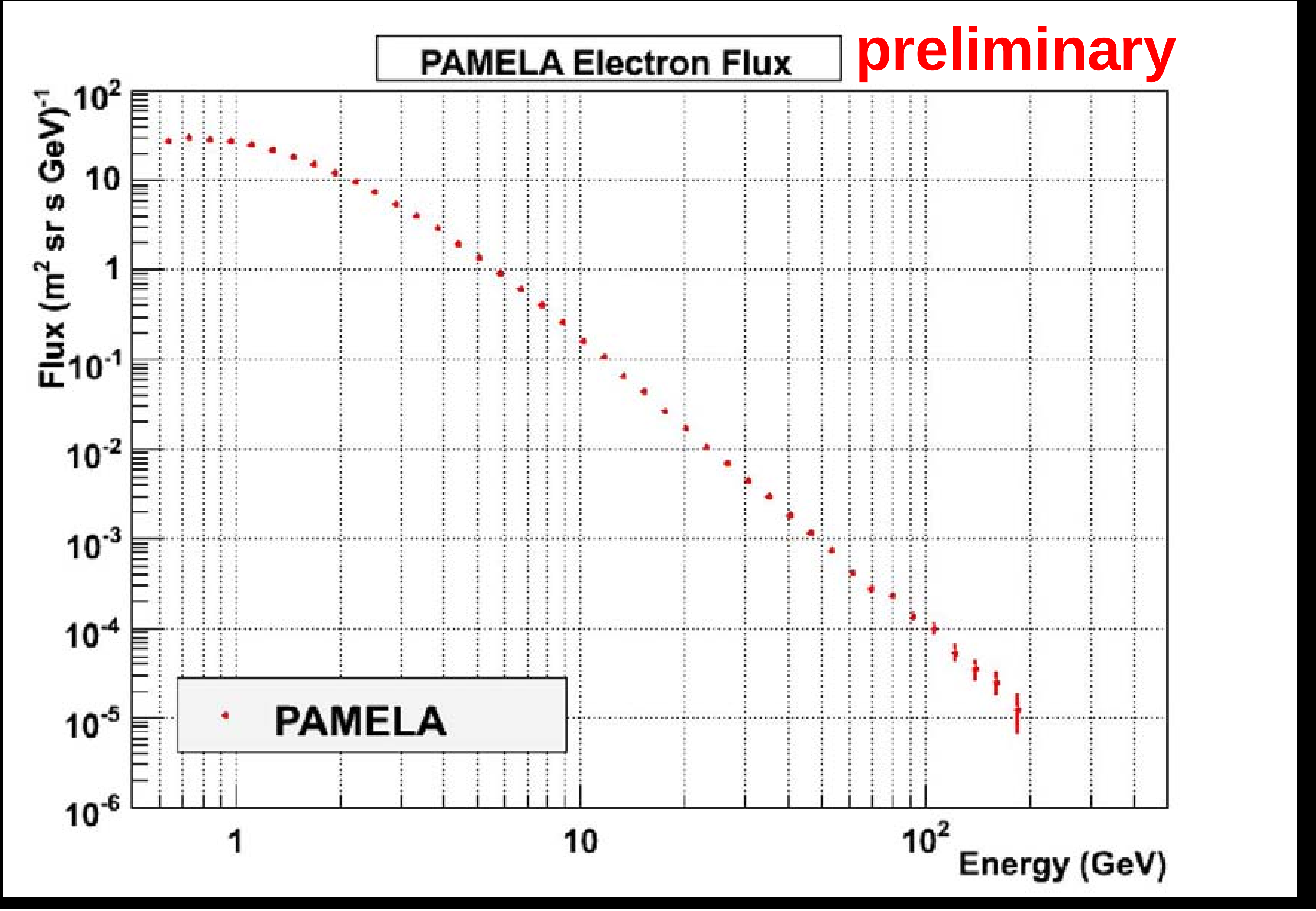
HESS electrons

Egberts, 2009

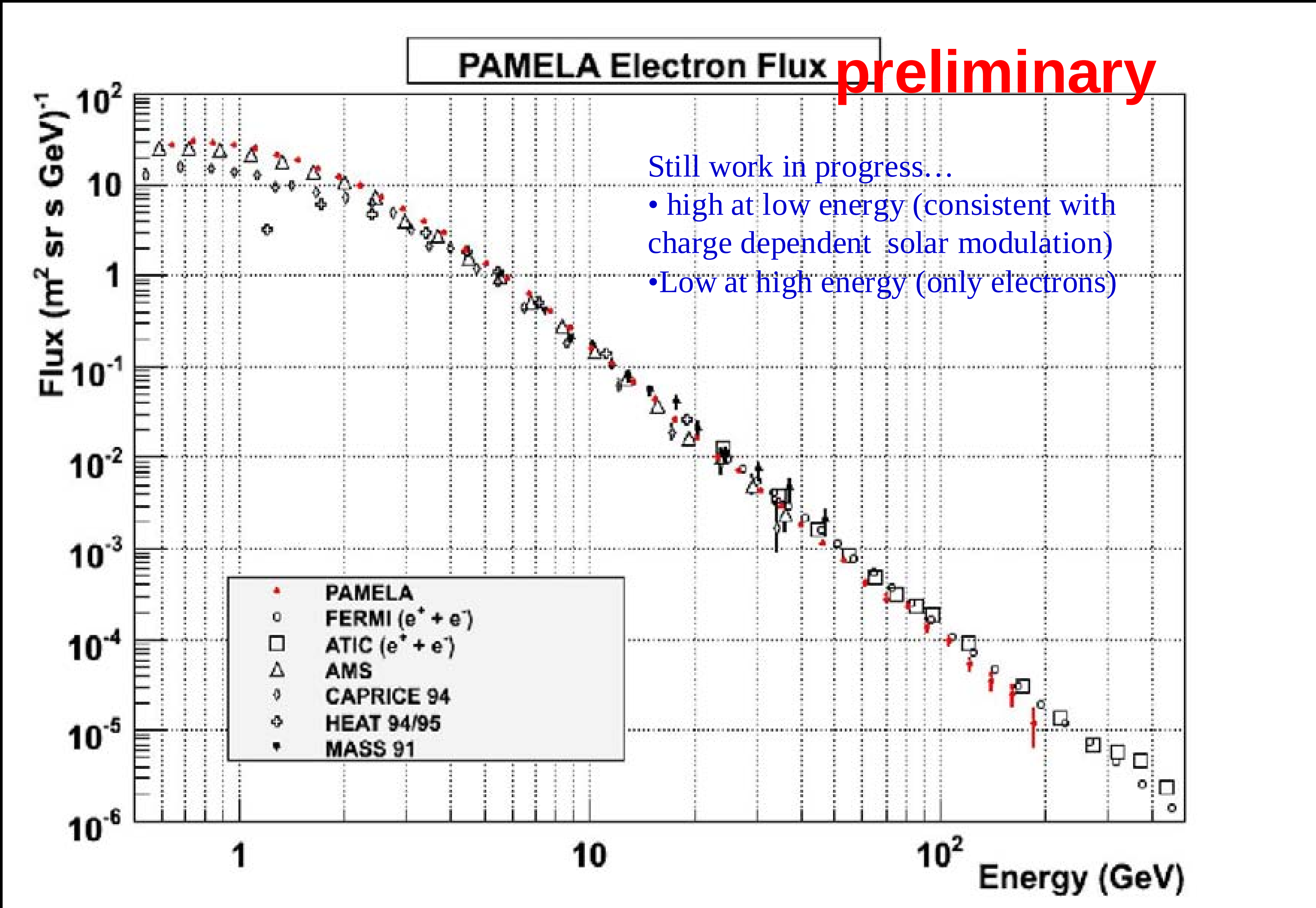
- Cuts:
  - impact distance < 100 m
  - image size in each camera > 80 photo electrons
  - Data set of 2004/2005
- Syst. uncertainty: atmospheric variations + model dependence of proton simulations (SIBYLL vs. QGSJET-II)
- Spectral index:
  $\Gamma_1 = 3.0 \pm 0.1(\text{stat}) \pm 0.3(\text{syst.})$
  $\Gamma_2 = 3.9 \pm 0.1(\text{stat}) \pm 0.3(\text{syst.})$

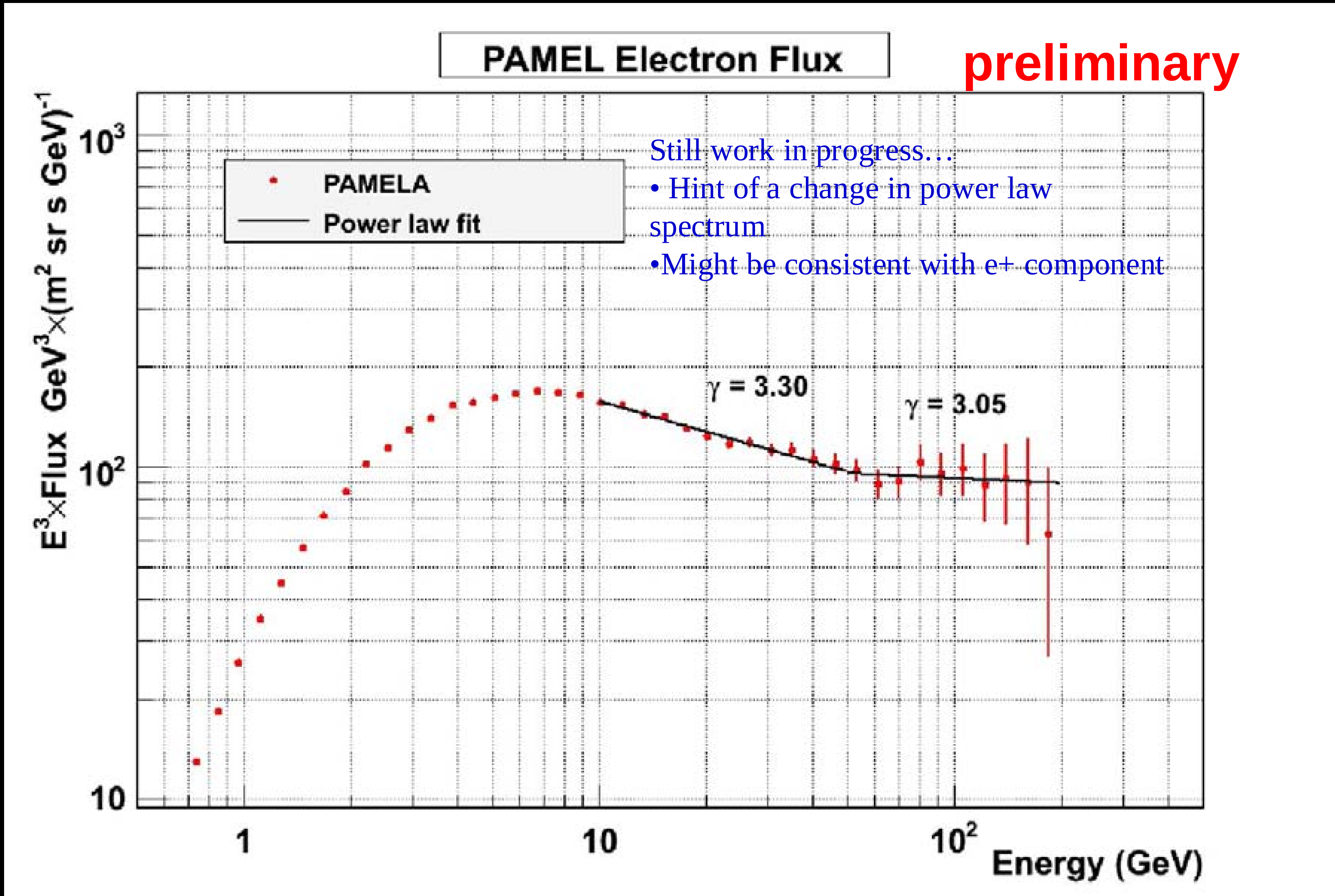


PAMELA electron flux



Comparison with other experiments



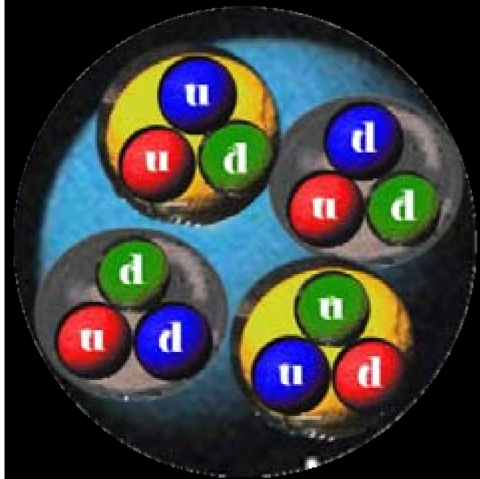


PAMEL Electron Flux
preliminary
Still work in progress…
• Hint of a change in power law spectrum
•Might be consistent with e+ component
PAMELA
Power law fit
γ = 3.30
γ = 3.05
E3×Flux GeV3×(m2 sr s GeV)-1
10
10^2
10^3
1
10
10^2
Energy (GeV)

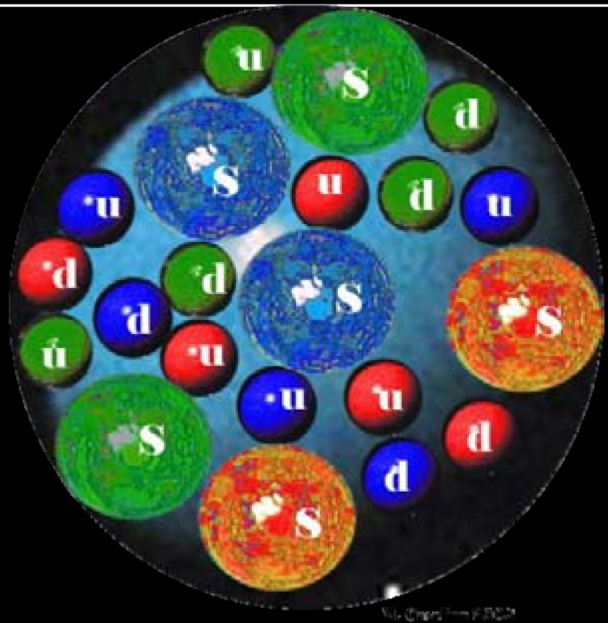
Search for exotic matter: Strangelets

(Lumps of Strange Quark Matter)

Roughly equal numbers of u,d,s quarks in a single ‘bag’ of cold hadronic matter.



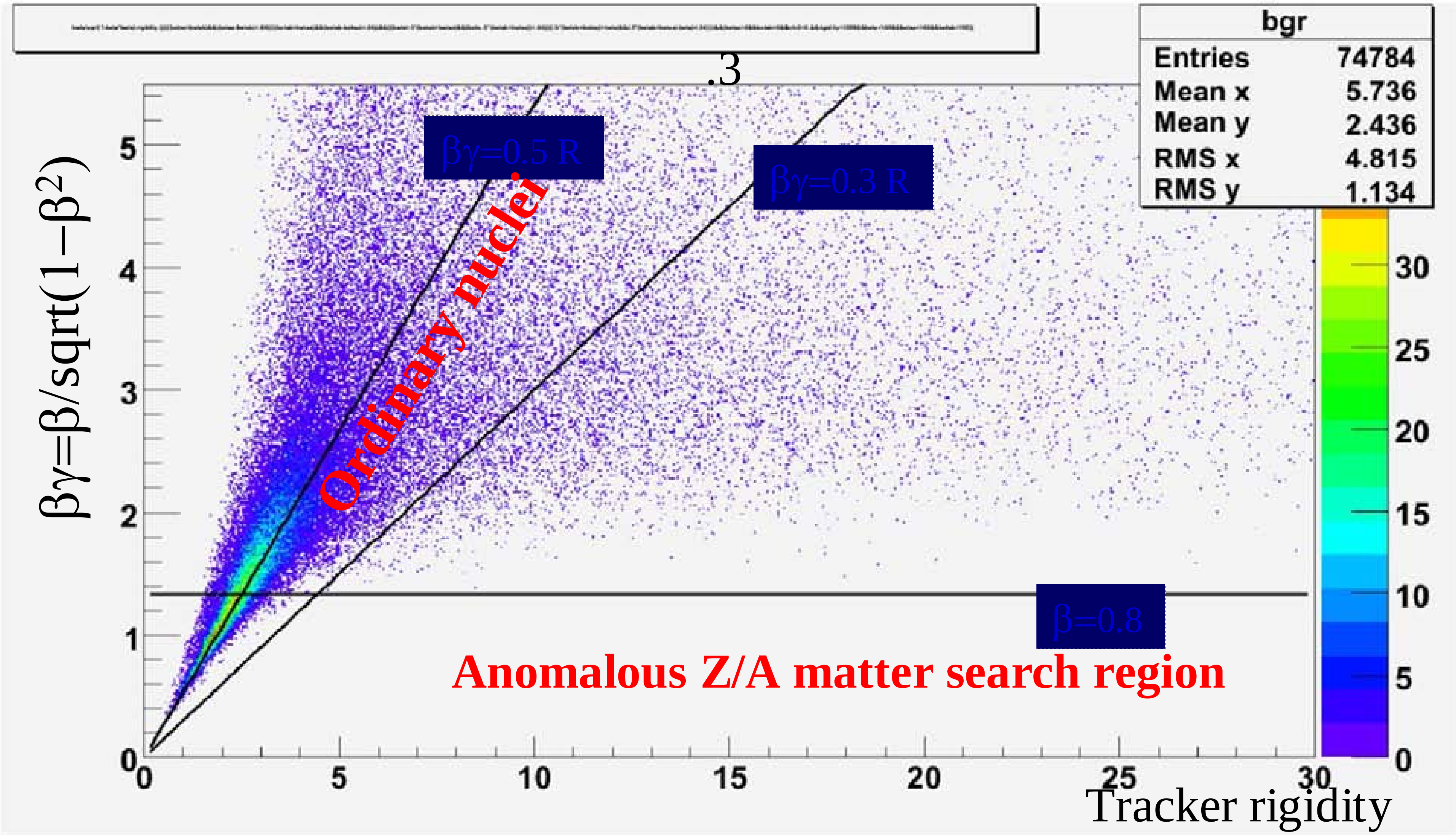
Z=2 A=4 (He)
Z/A=0.5



Z=2 A=7
Z/A=0.286

- u,d,s quark matter might be stable
- Not limited in A
- A=100, 1000….
- Z is almost zero due to cancellation of quark charge
- Could account for a (small) part of DM
- Also candidate of UHECR

Search for anomalous Z/A particles in cosmic radiation with PAMELA



•**Pamela is operating successfully in space**

•**Expected three years of operations – completed**
Extended other 2 years

•**Data received until now show good potential and fullfillment of scientific goals**

http://pamela.roma2.infn.it

http://www.casolino.it