ICRR, 6/7/2011

Energy spectrum of proton and helium measured by PAMELA and acceleration of cosmic rays in the galaxy

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RIKEN, ASI, Japan

INFN & University of Roma Tor Vergata

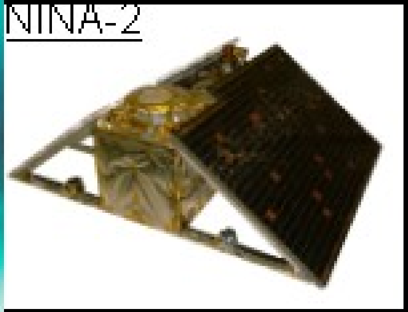
on behalf of the PAMELA collaboration

Past, present and future experiment

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

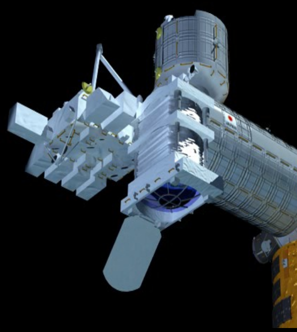
NINA-1

NINA-2



PAMELA

JEM-EUSO



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

9 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 …

NINA-1 | NINA-2 | LAZIO-SIRAD

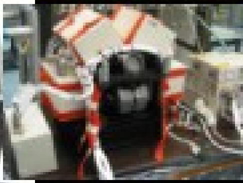
SILEYE-1 | SILEYE-2 | SILEYE-3 | ALTEA

SILEYE-1

SILEYE-2

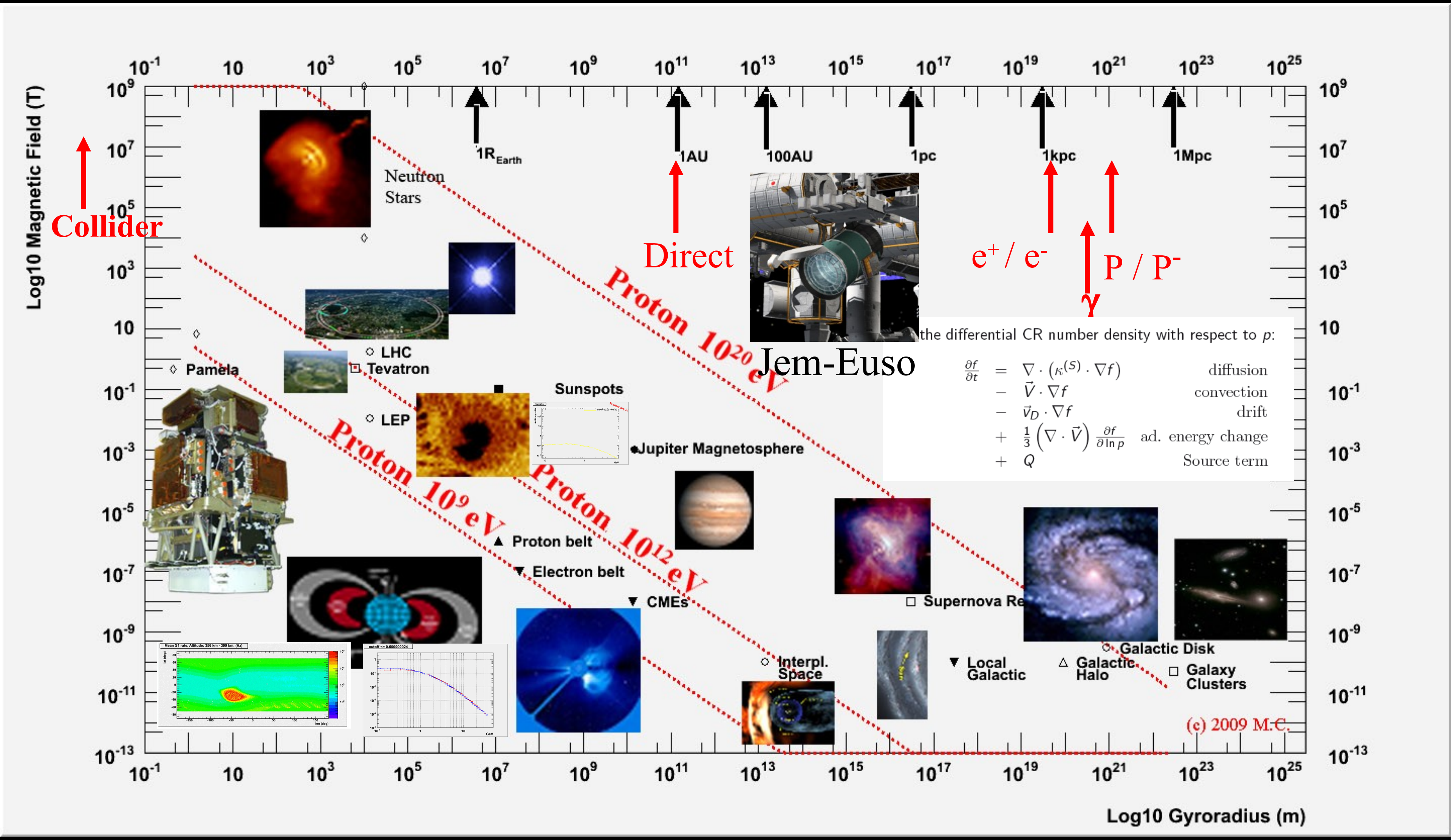
SILEYE-3/ ALTEINO:

LAZIO-SIRAD

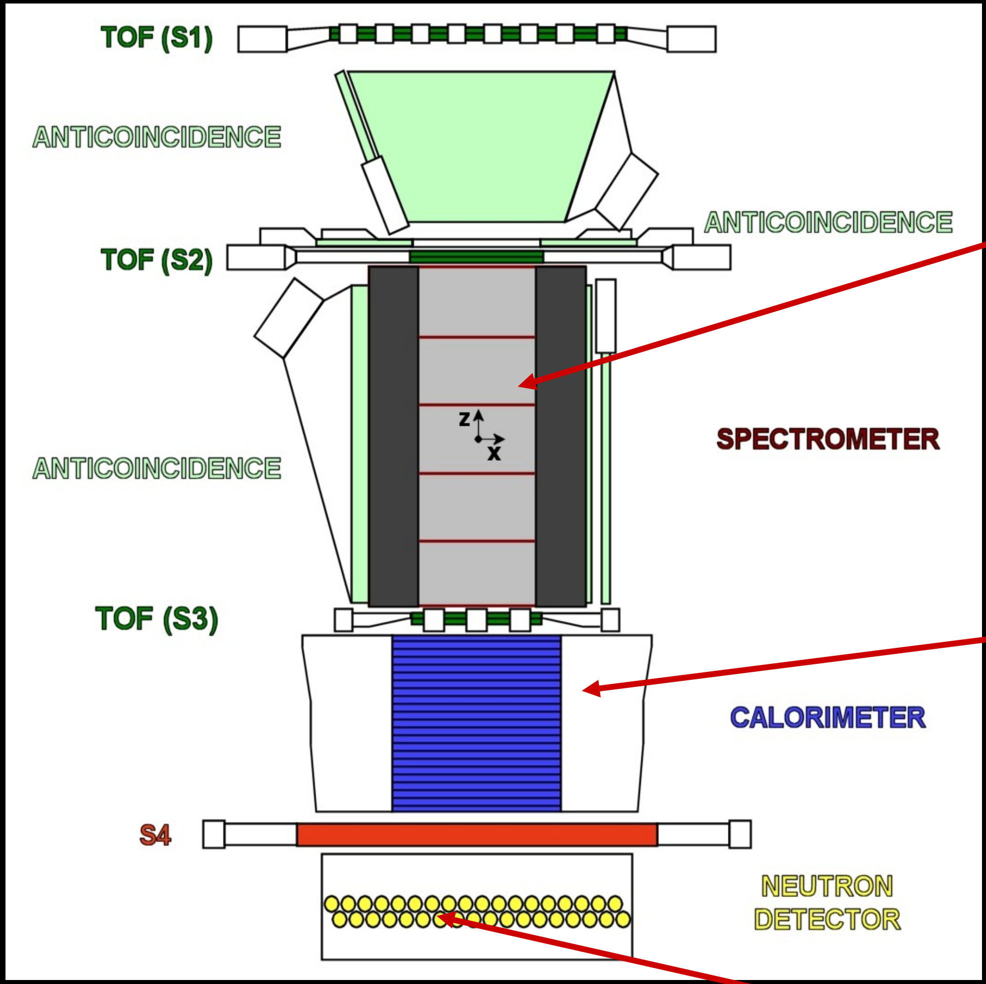


SILEYE-4/ALTEA

Pamela Physics objectives in the Hillas Plot



The PAMELA apparatus



Spatial Resolution

- ≅ 2.8 μm bending view
- ≅ 13.1 μm non-bending view

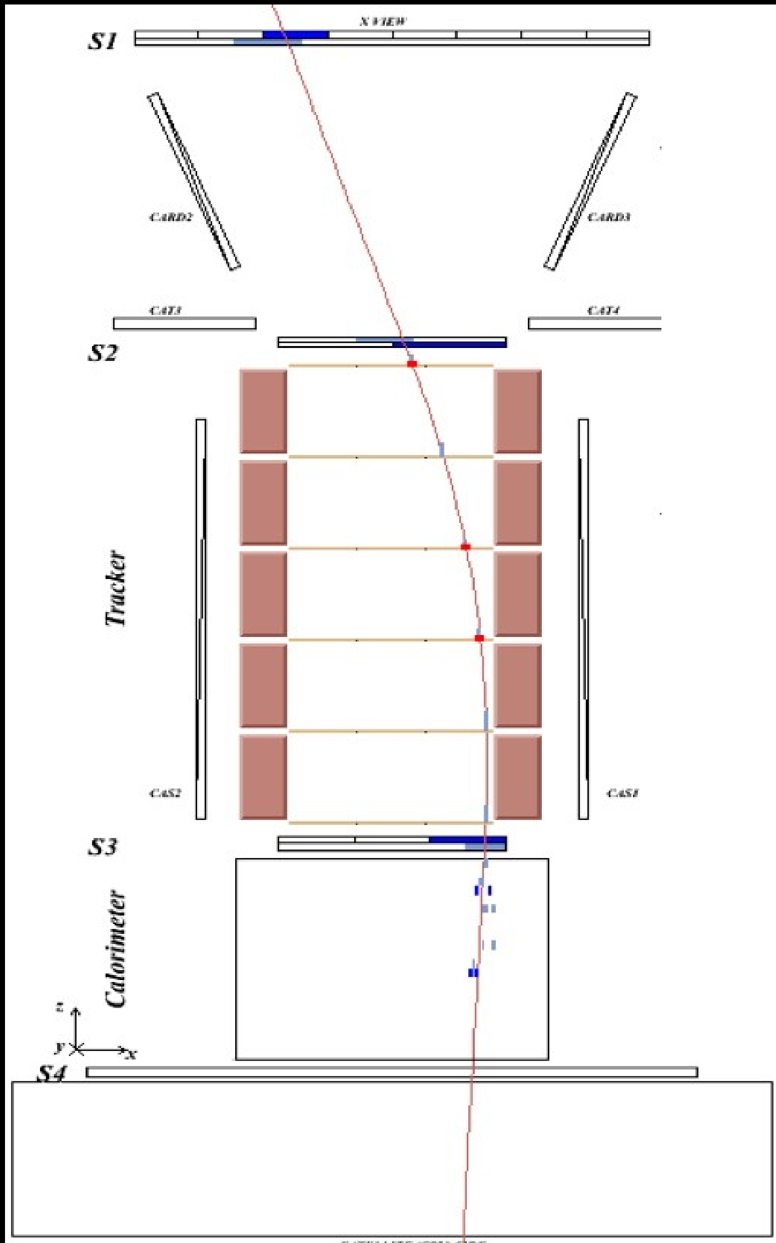
MDR from test beam data ≅ 1 TV

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

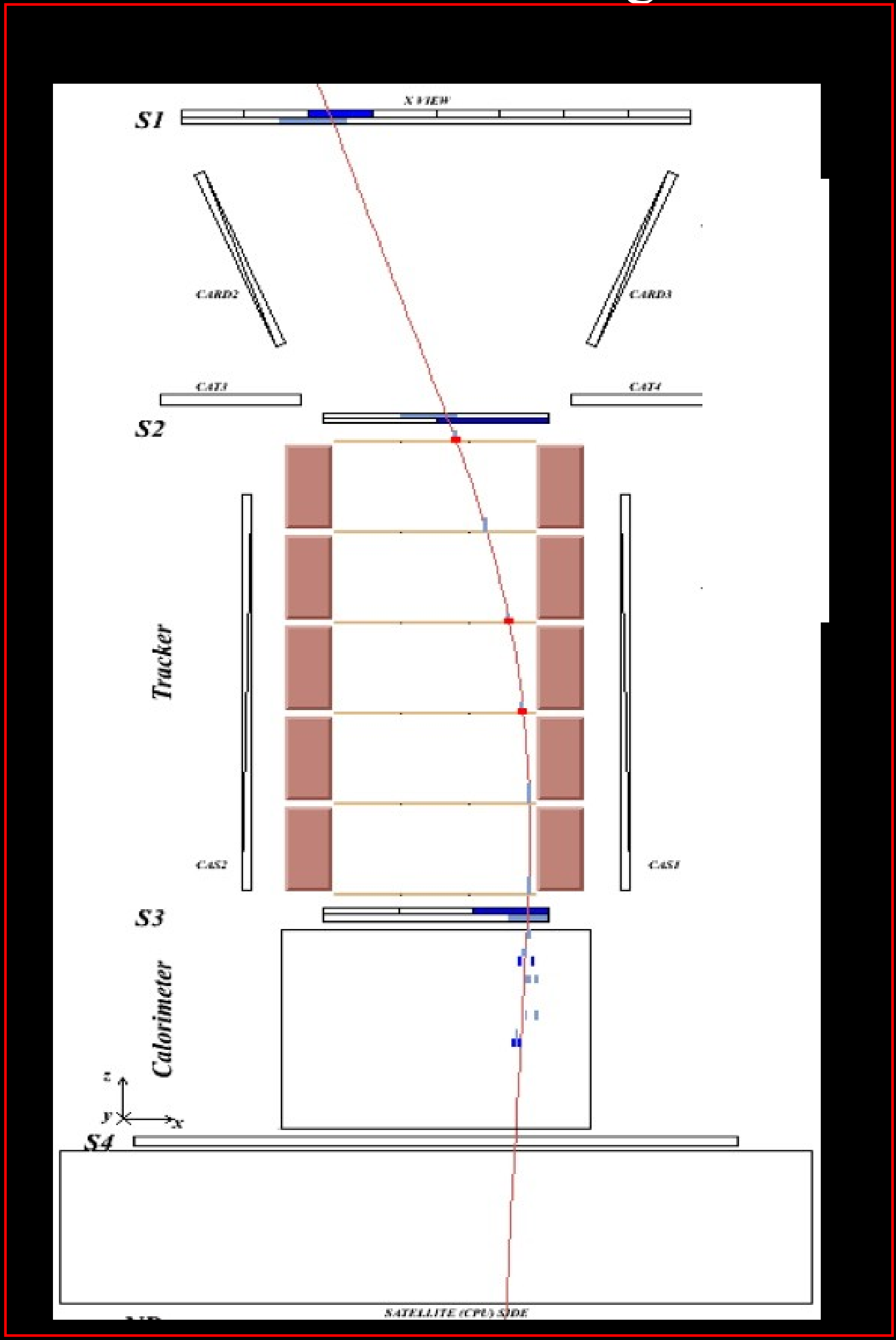


PHYSICAL QUANTITIES MEASURED BY PAMELA

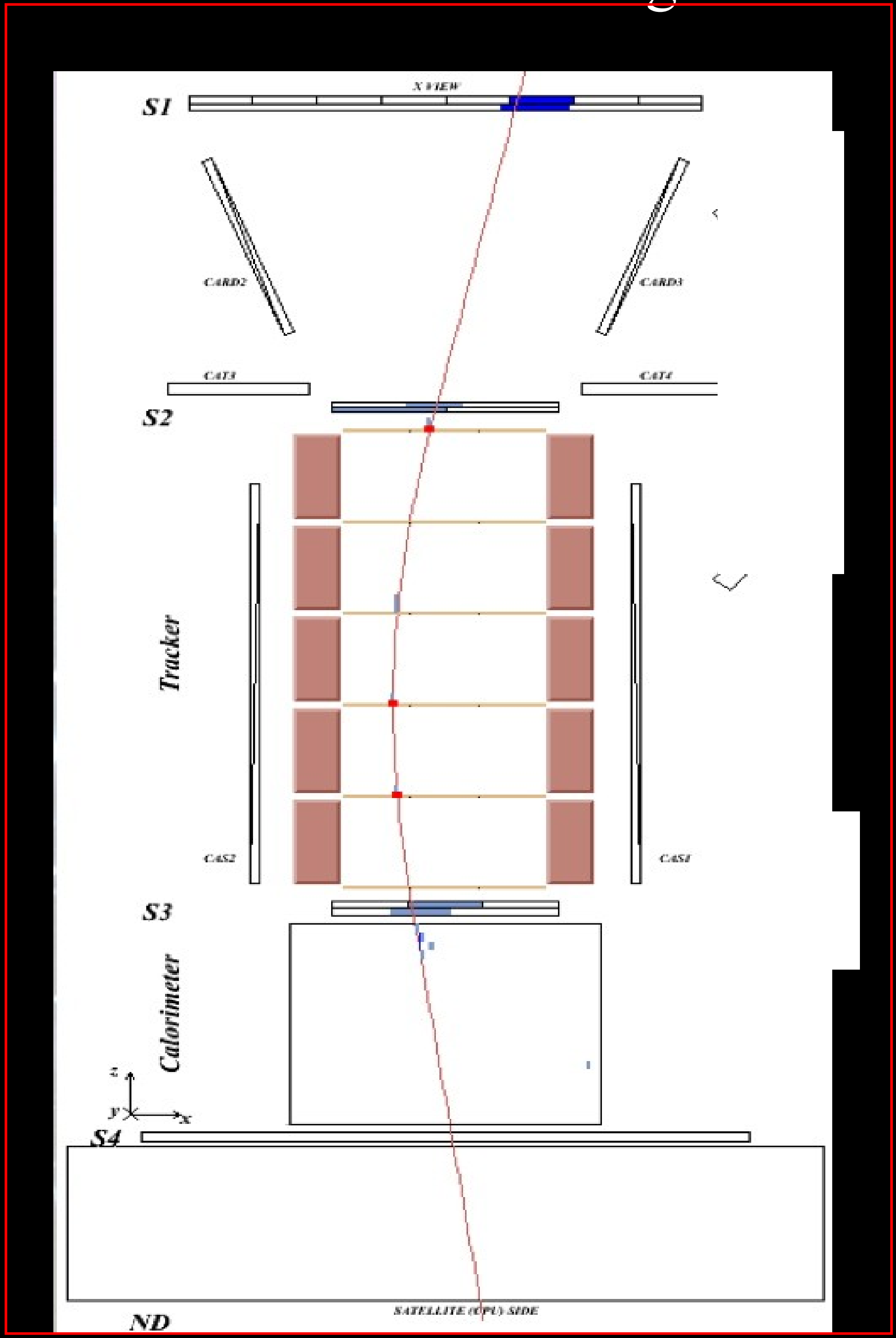
1. DEDX (scintillators, tracker, calo)
   → Z of the particle
2. DEFLECTION = 1/Rigidity
   → Impulse (4-6 planes)
3. Time of flight = 1/Beta (12 betas)
4. Shower (No, Hadronic, Electromagnetic)
   → lepton/hadron
5. Number of neutrons
   → lepton/hadron

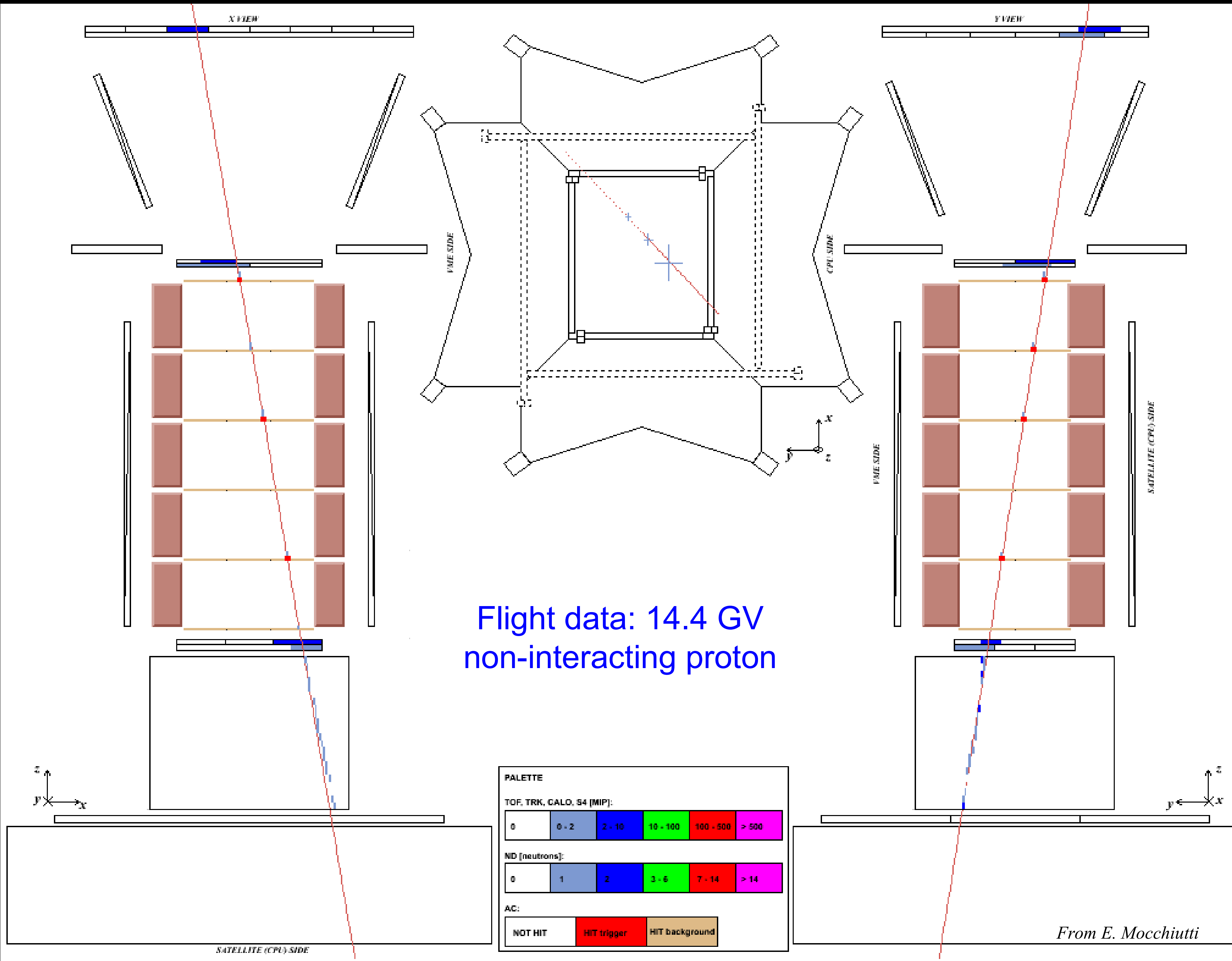
5% to 10% precision

e+ 0.171 GV Bending view

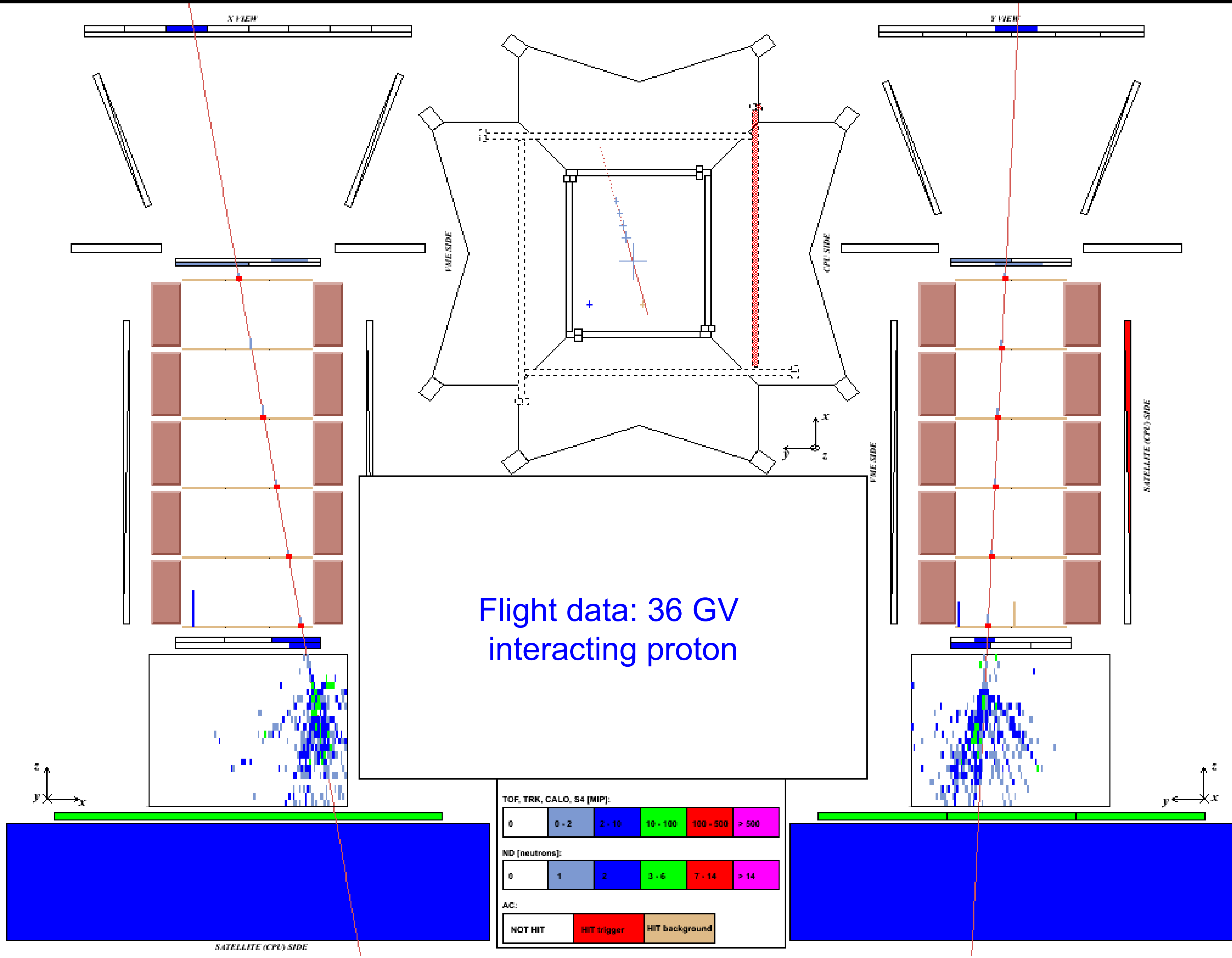


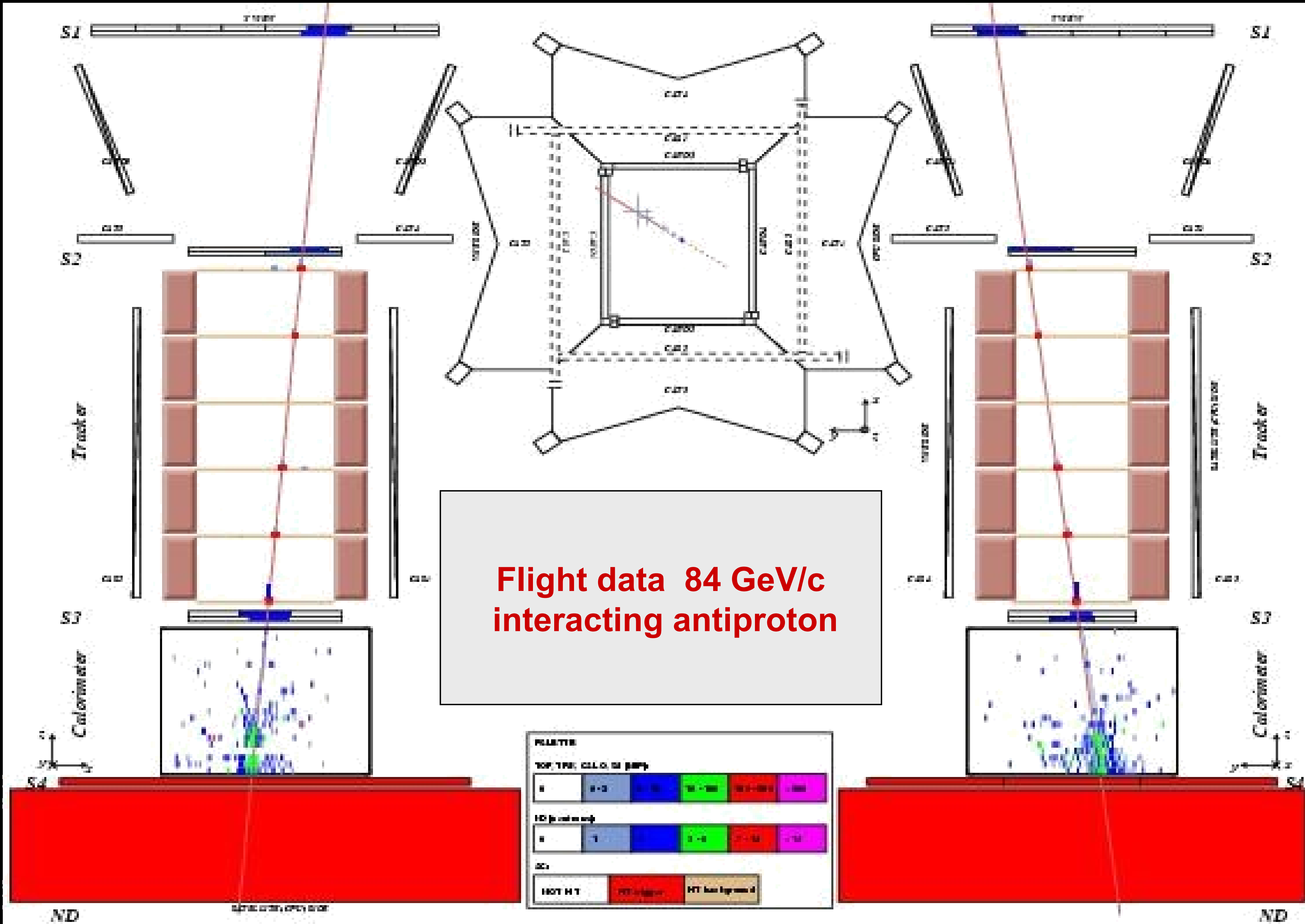
e- 0.169 GV Bending view



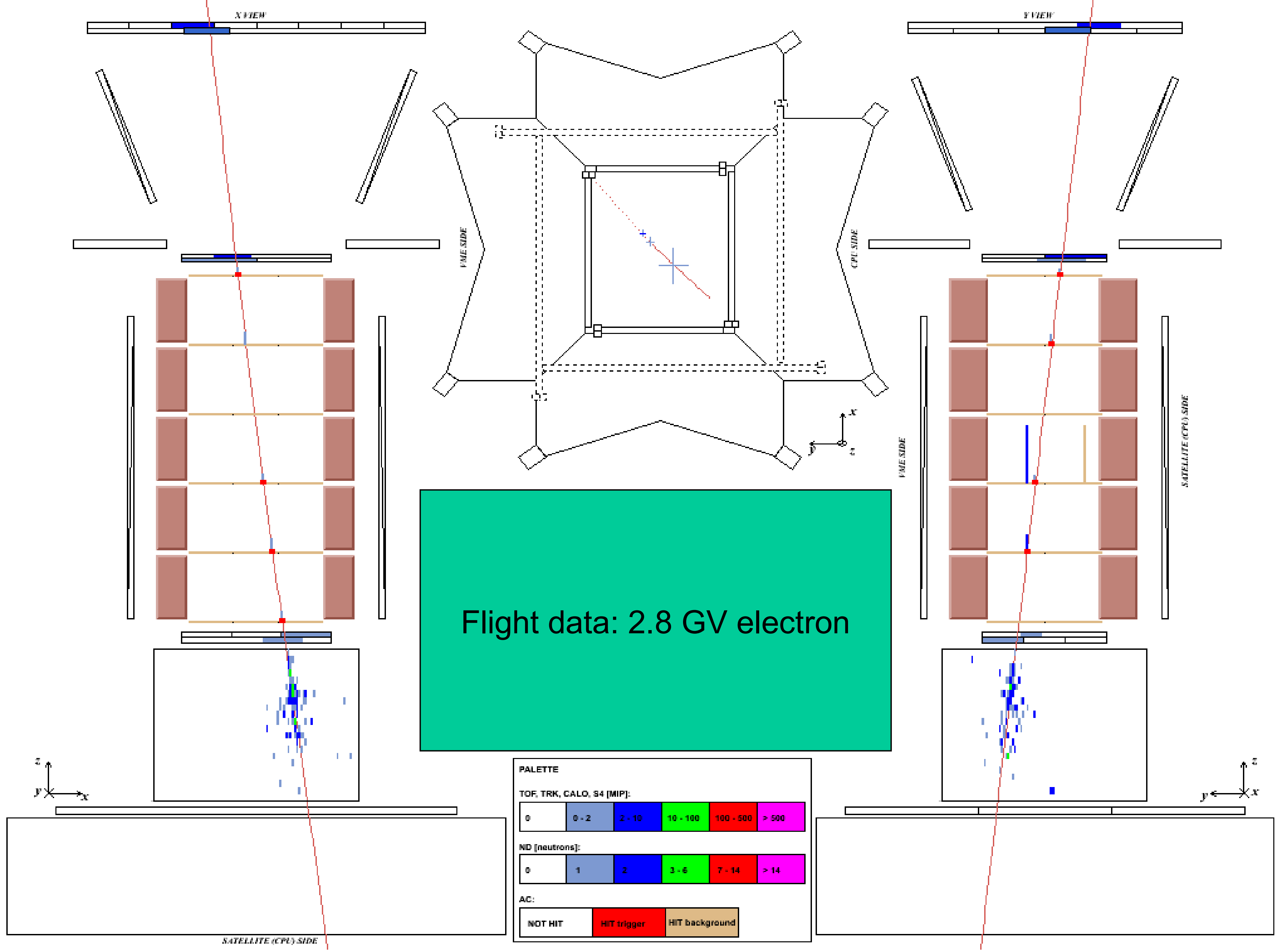

X VIEW
Y VIEW
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
Flight data: 14.4 GV
non-interacting proton
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background
From E. Mocchiutti

Flight data: 36 GV interacting proton

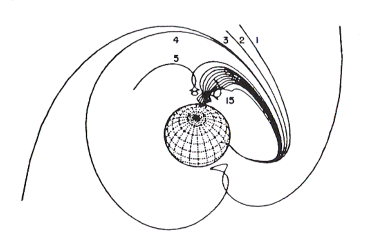


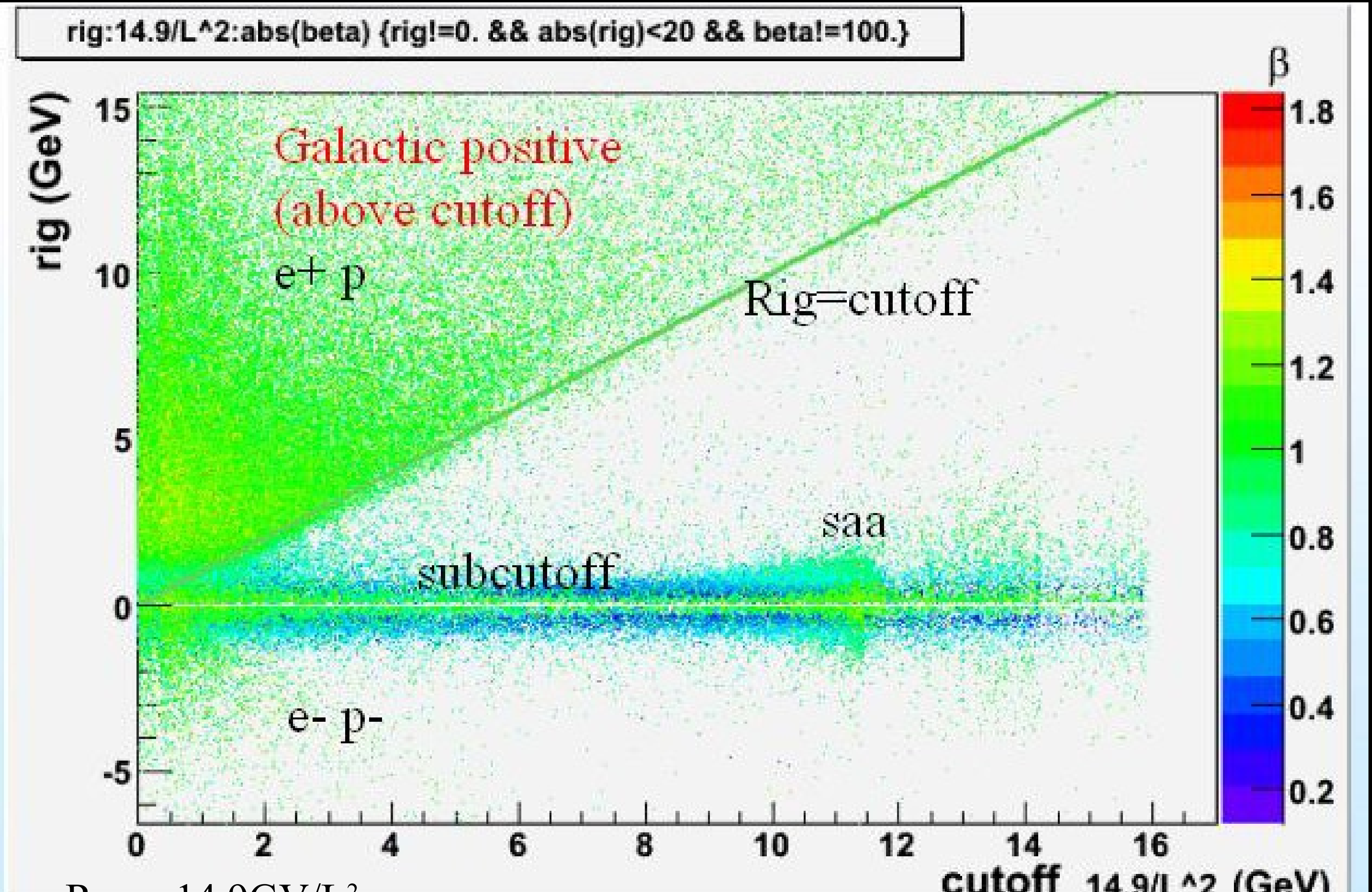


Flight data 84 GeV/c interacting antiproton


X VIEW
Y VIEW
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
Flight data: 2.8 GV electron
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background

Selection of galactic component according to geomagnetic cutoff





R_{cutoff}=14.9GV/L^2

Particle selection criteria

- 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

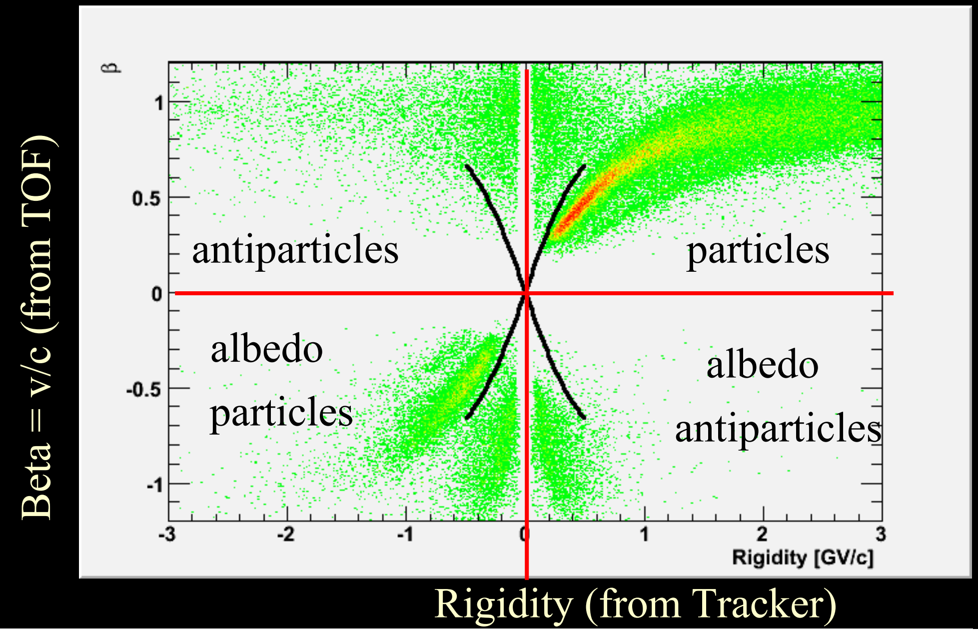
Fitted, single track

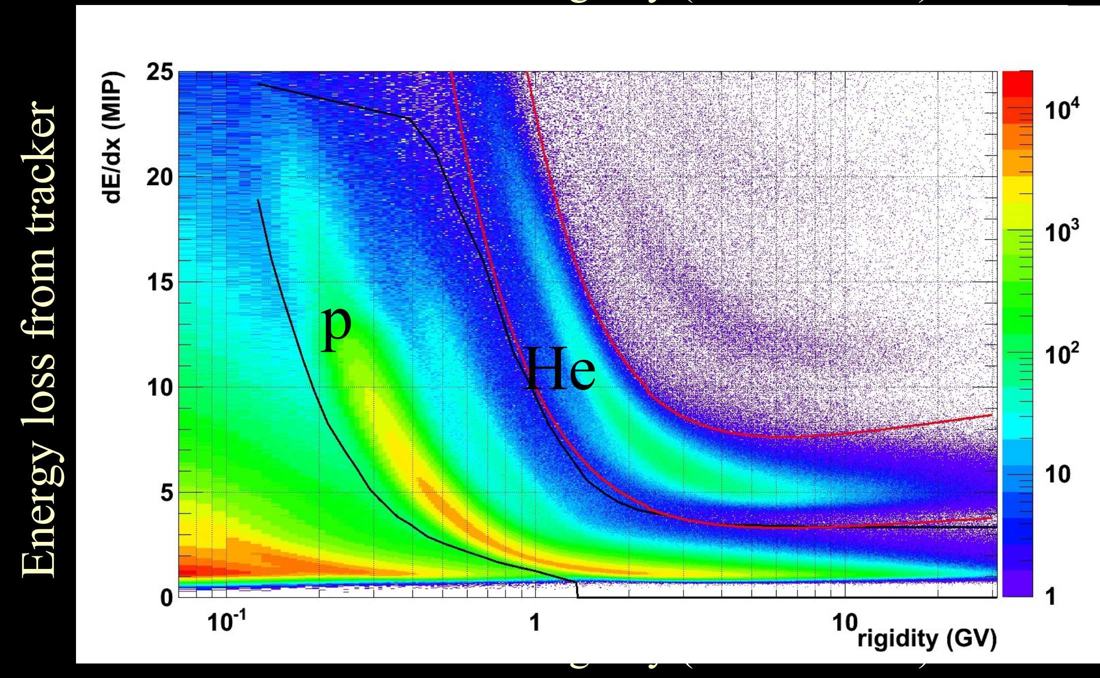
High lever arm, Nx

Rigidity R>0

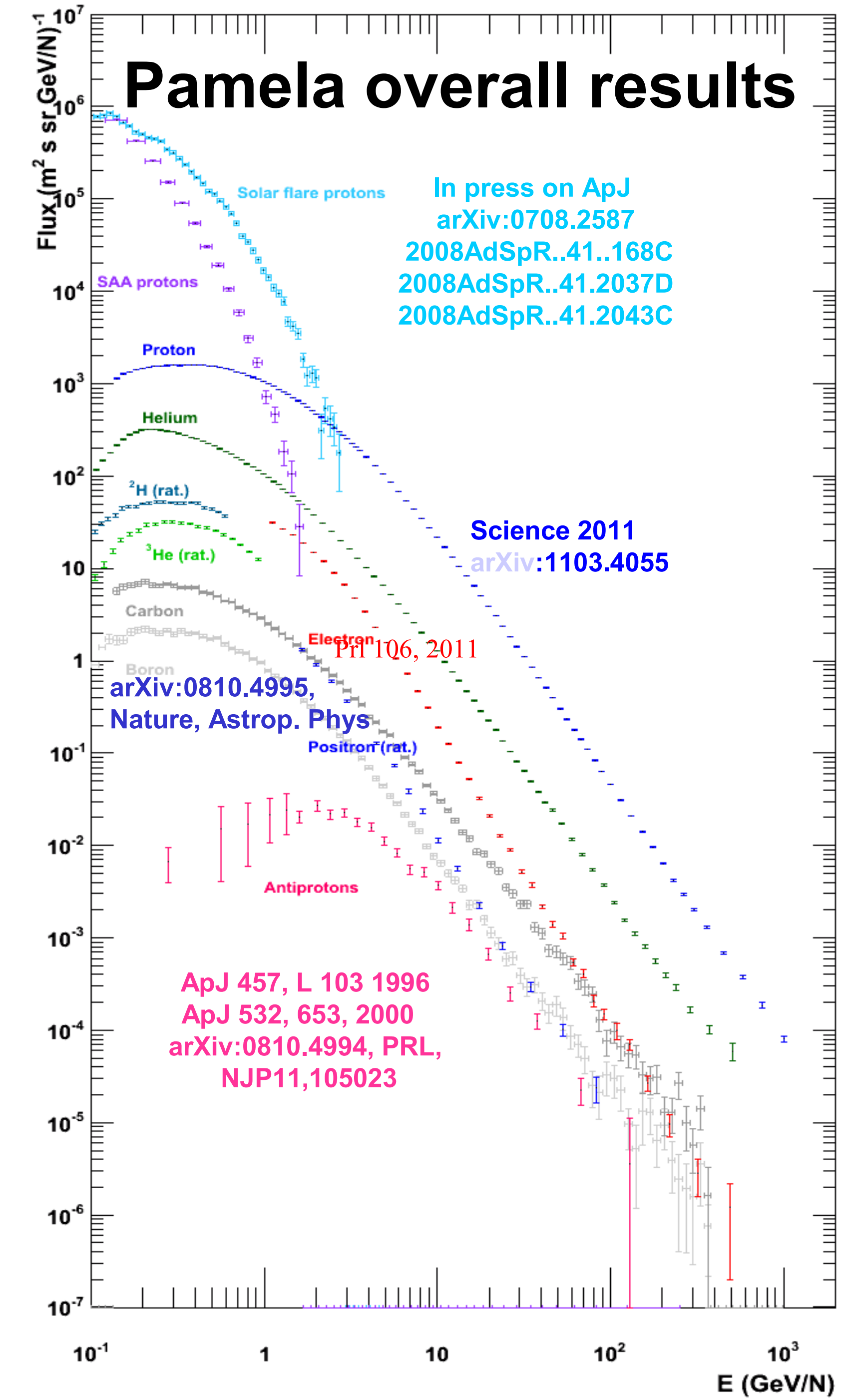
Beta>.2

No anti





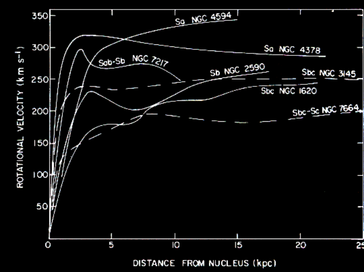
High precision charged cosmic ray measurement in Low Earth Orbit

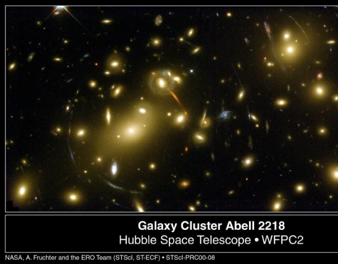


Dark Matter Searches

•Cosmology

Detection, not identification





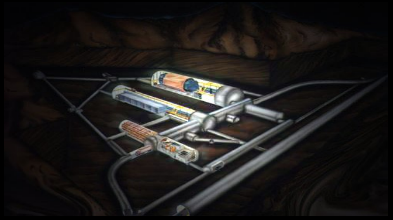
1E 0657-56 - Bullet Cluster

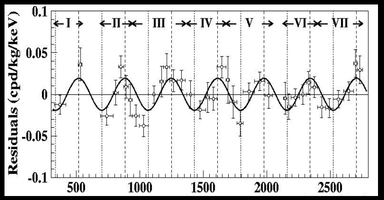
•LHC Search

Supersymmetry, not necessarily DM

•Direct Detection

Local structure and nature

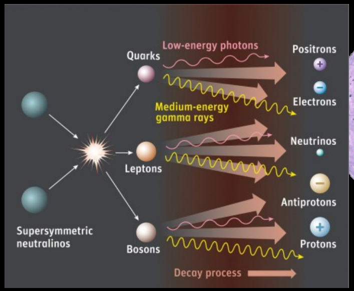


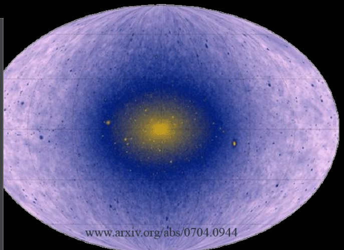


DAMA

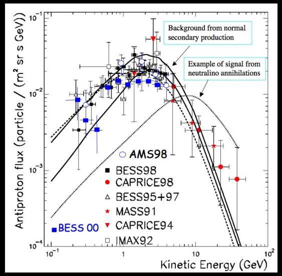
•Indirect Detection

Various galactic scales

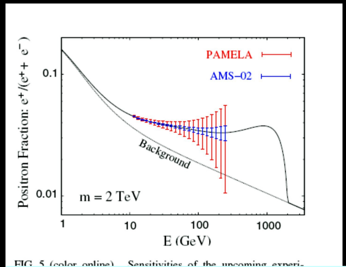




γ: Galactic centre

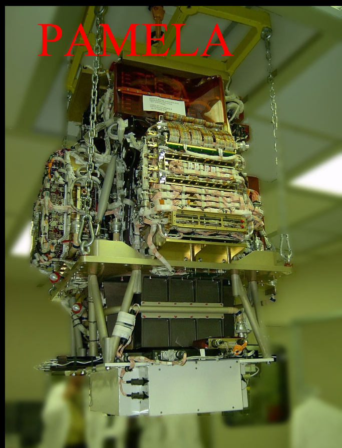


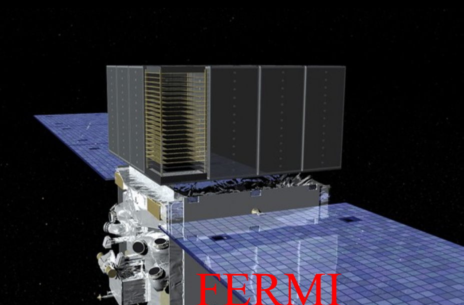
Antiprotons: Galactic average

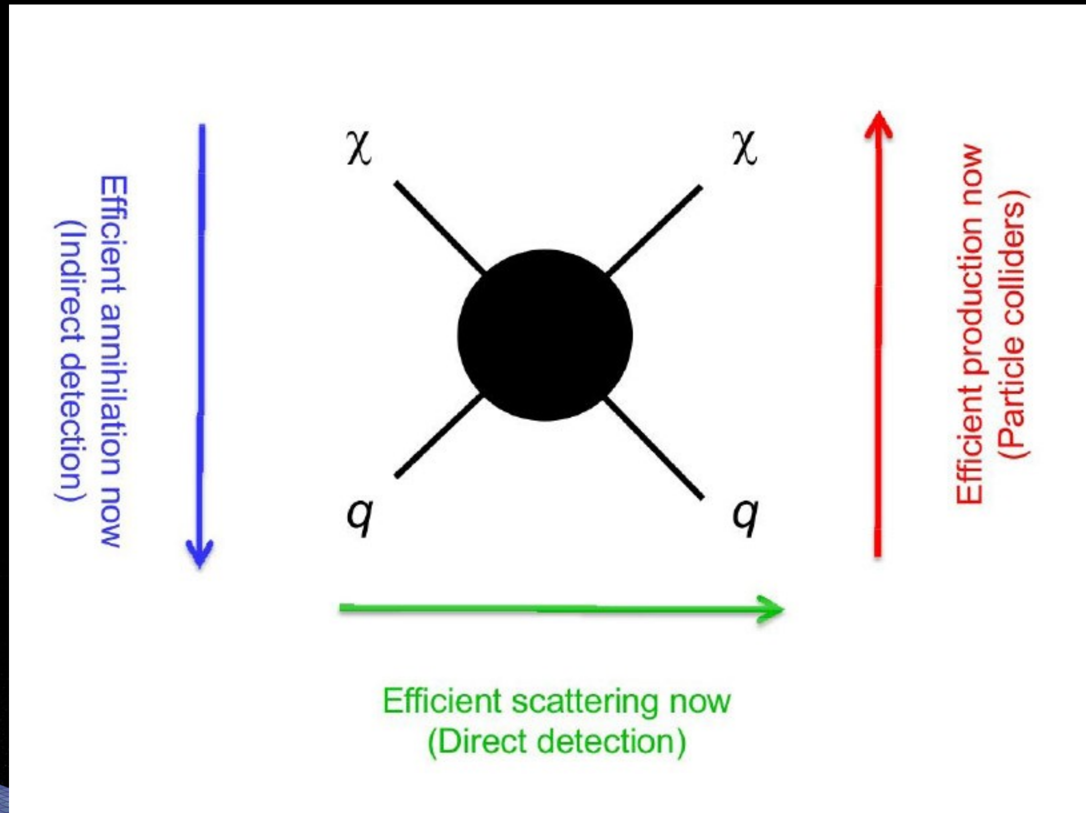


positrons: Local galactic 1kpc

Different approaches to search for Dark Matter







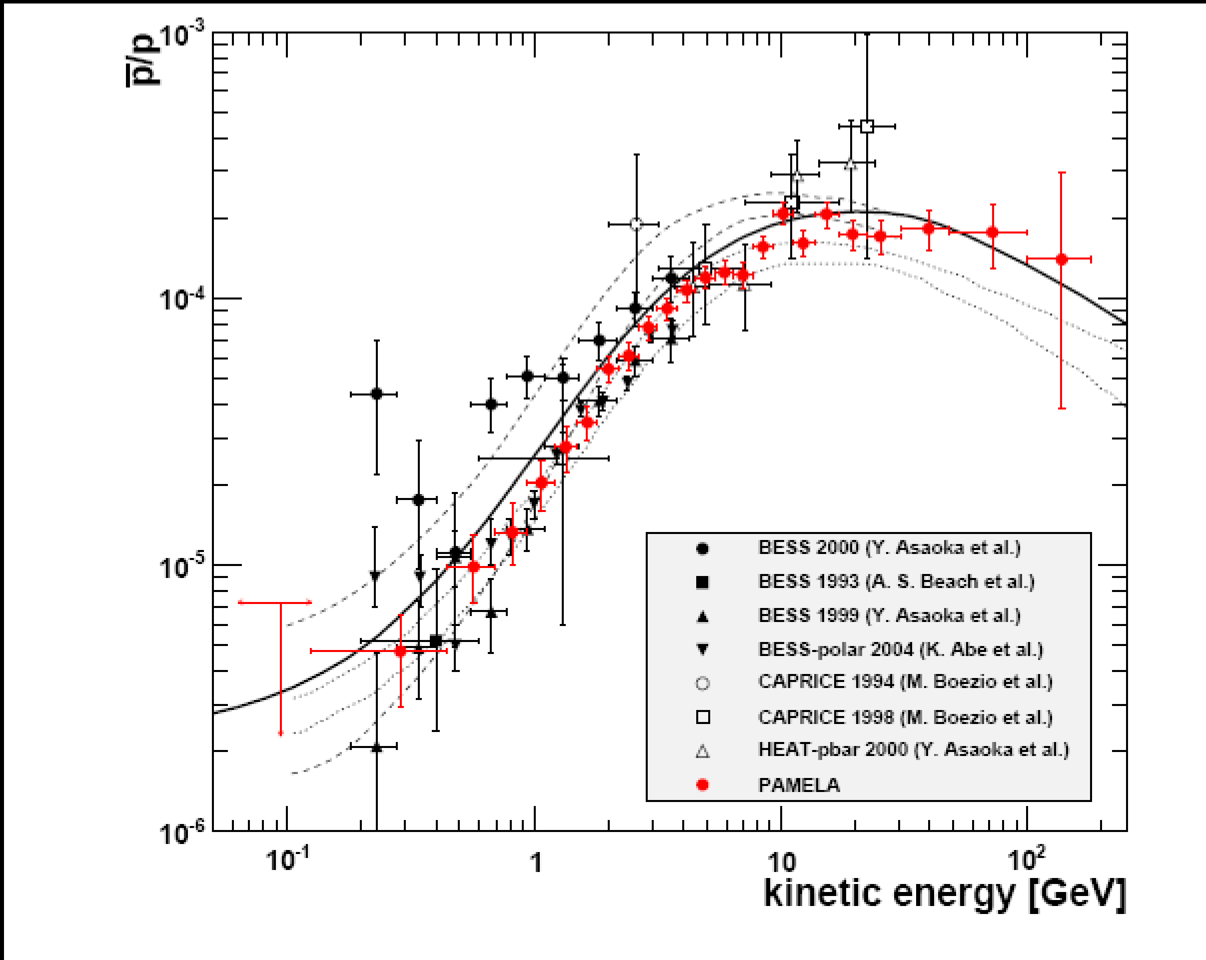
Adapted from P. Lipari

Antiproton/proton ratio

Confirms charge dependent solar modulation
Consistent with models (galprop, donato…) at high energy

PRL. 105, 121101, September 13,2010)

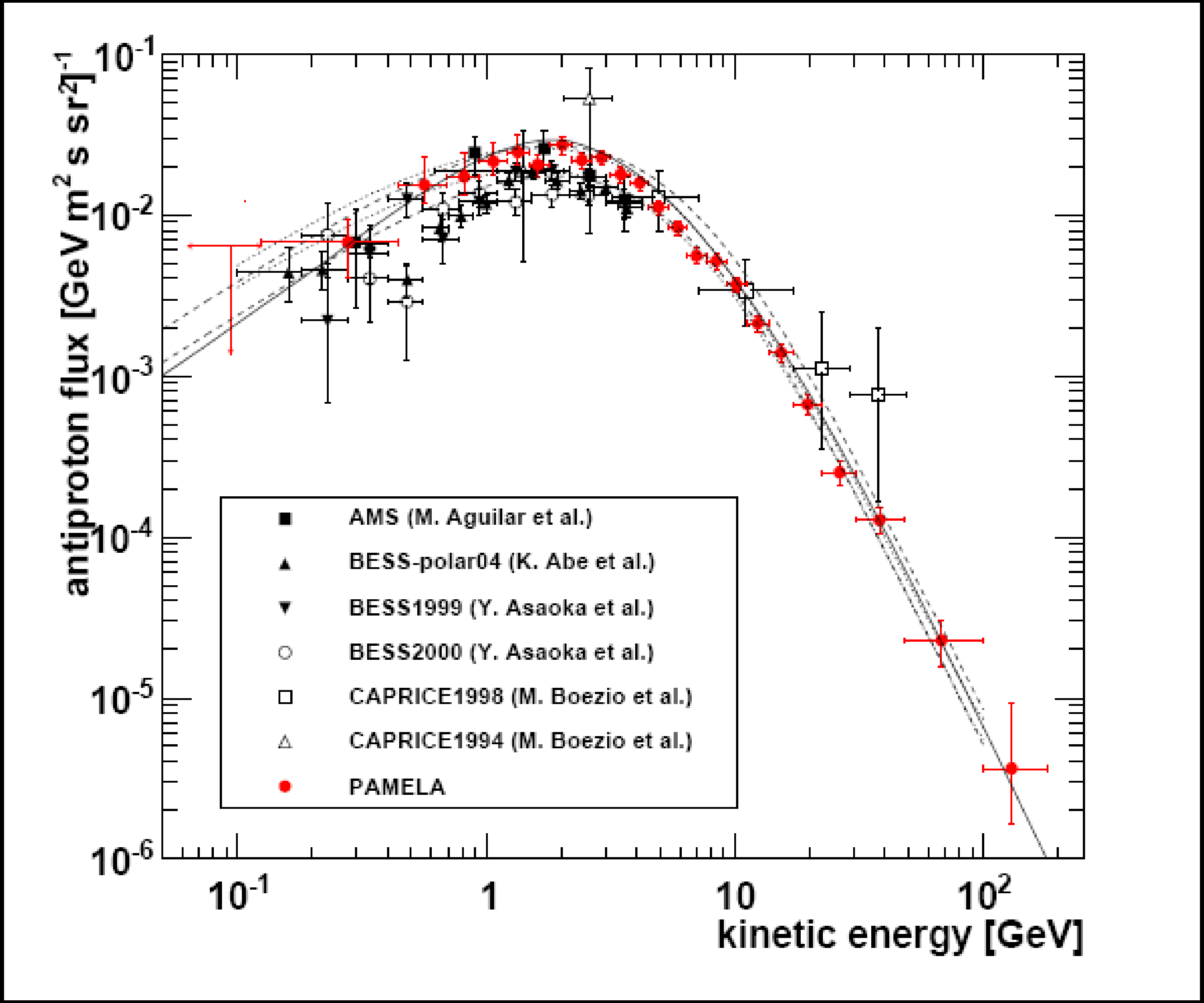
PRL 102:051101,2009



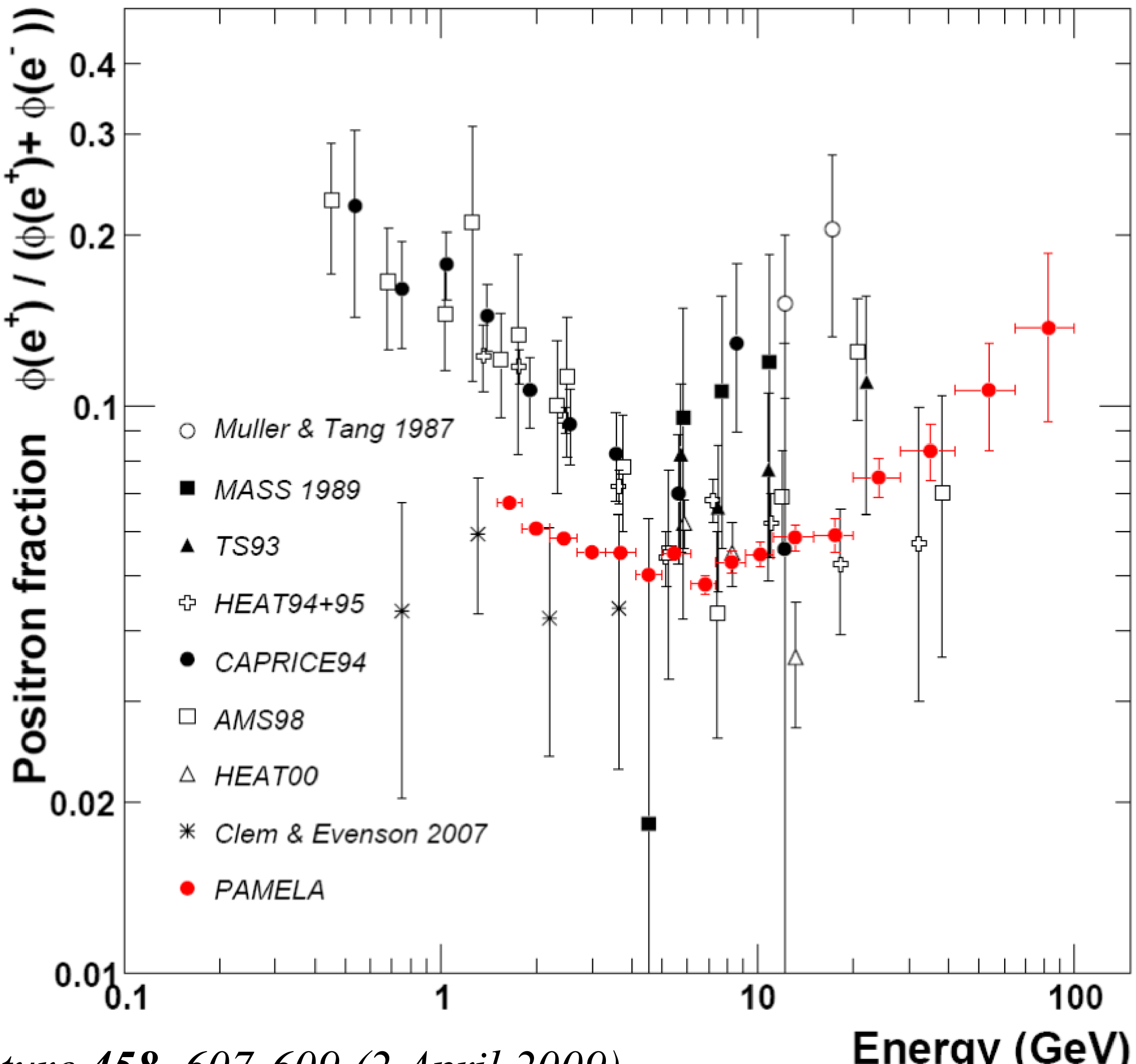
Antiproton absolute flux

PRL. 105, 121101, September 13,2010)

PRL 102:051101,2009

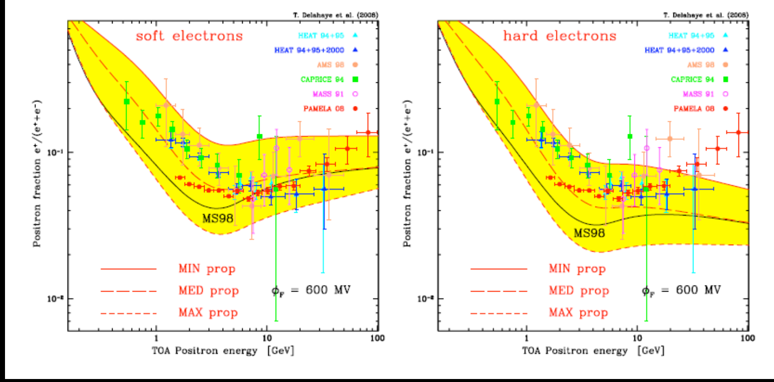


Pamela positron fraction



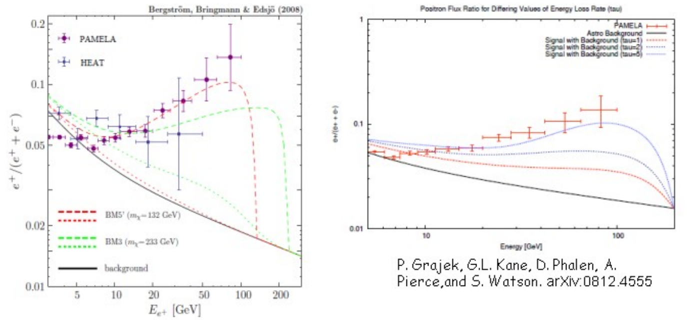
Nature ***458***, *607-609 (2 April 2009)*

Secondary production



Dark Matter Decay

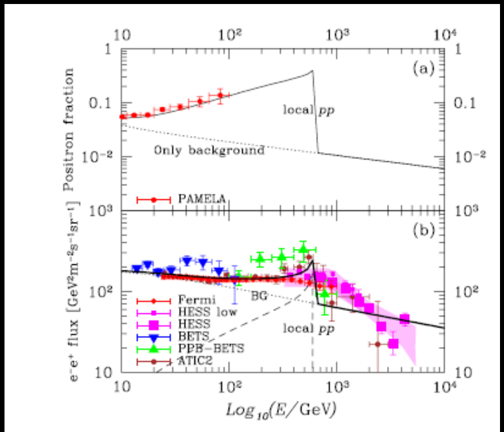
2. Example of DM solution: SUSY with internal bremsstrahlung and large boost factors, or Winos with unusual propagation parameters can give the right spectrum:

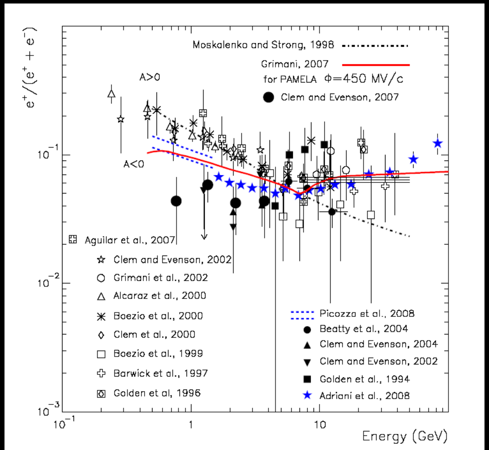


P. Grajek, G.L. Kane, D. Phalen, A. Pierce, and S. Watson. arXiv:0812.4555

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

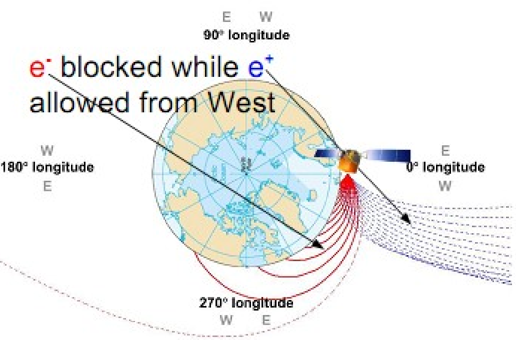
Astrophysical sources, SNR…

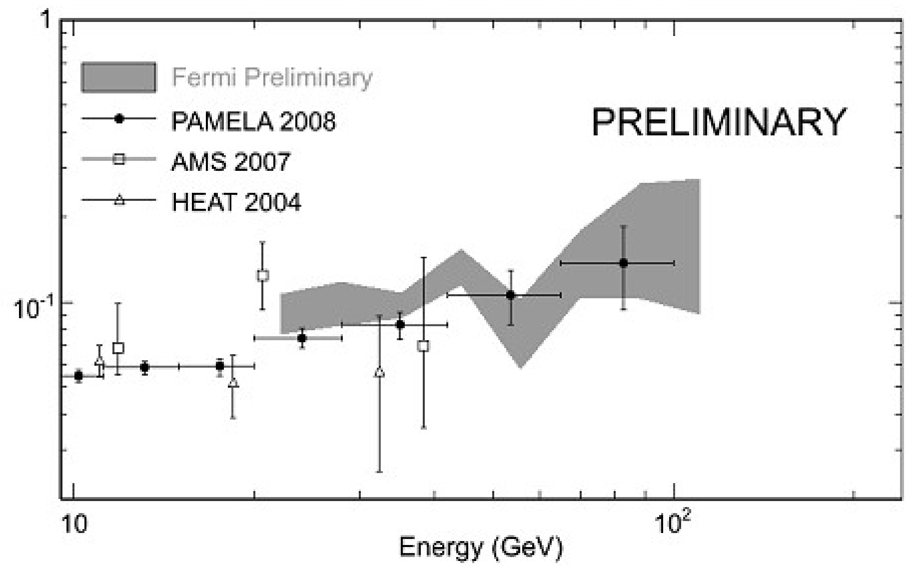




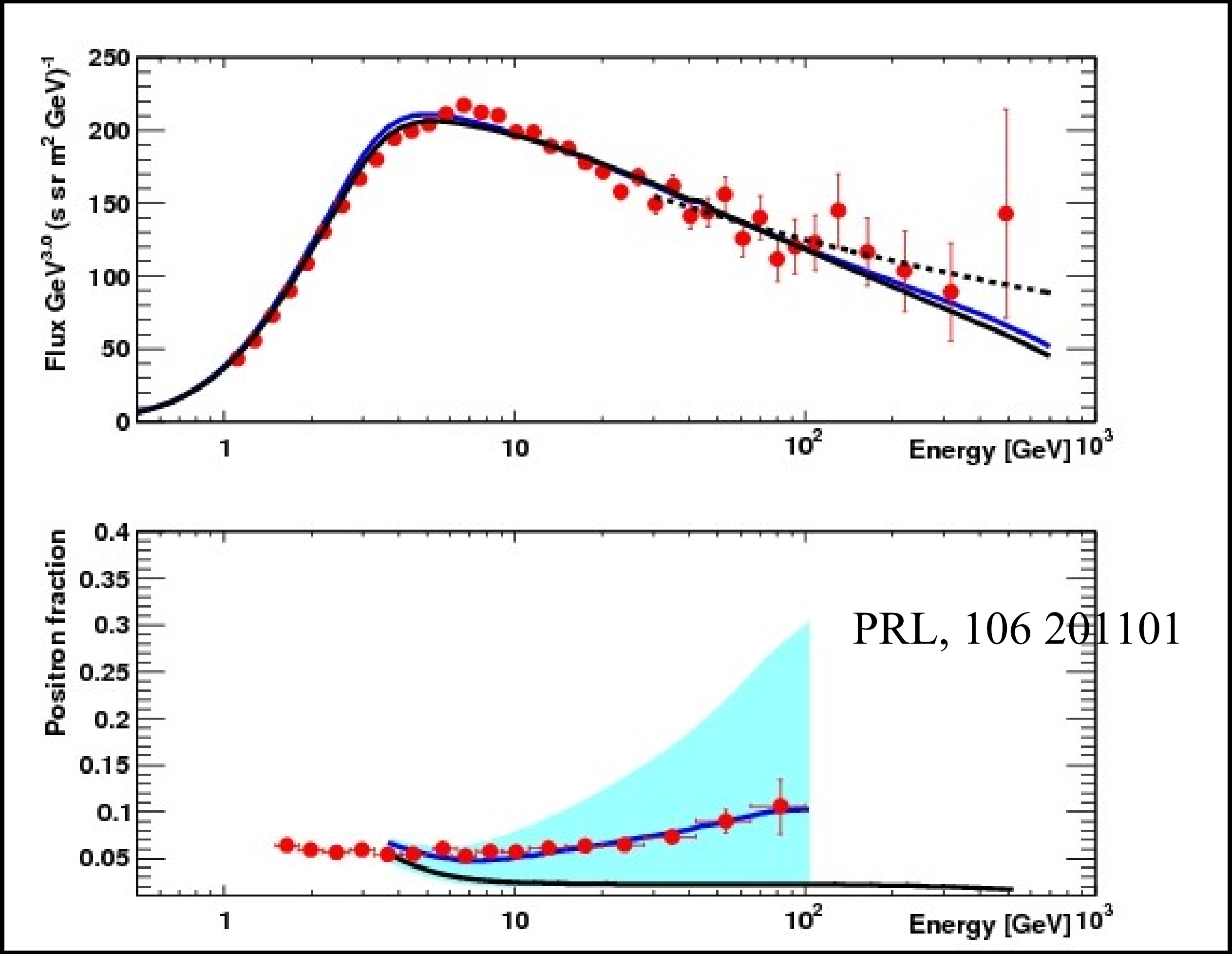
From Fermi Symposium

- **The Fermi-LAT has measured the cosmic-ray positron and electron spectra separately, between 20 – 130 GeV, using the Earth's magnetic field as a charge discriminator**
- **The two independent methods of background subtraction, Fit-Based and MC-Based, produce consistent results**
- **The observed positron fraction is consistent with the one measured by PAMELA**



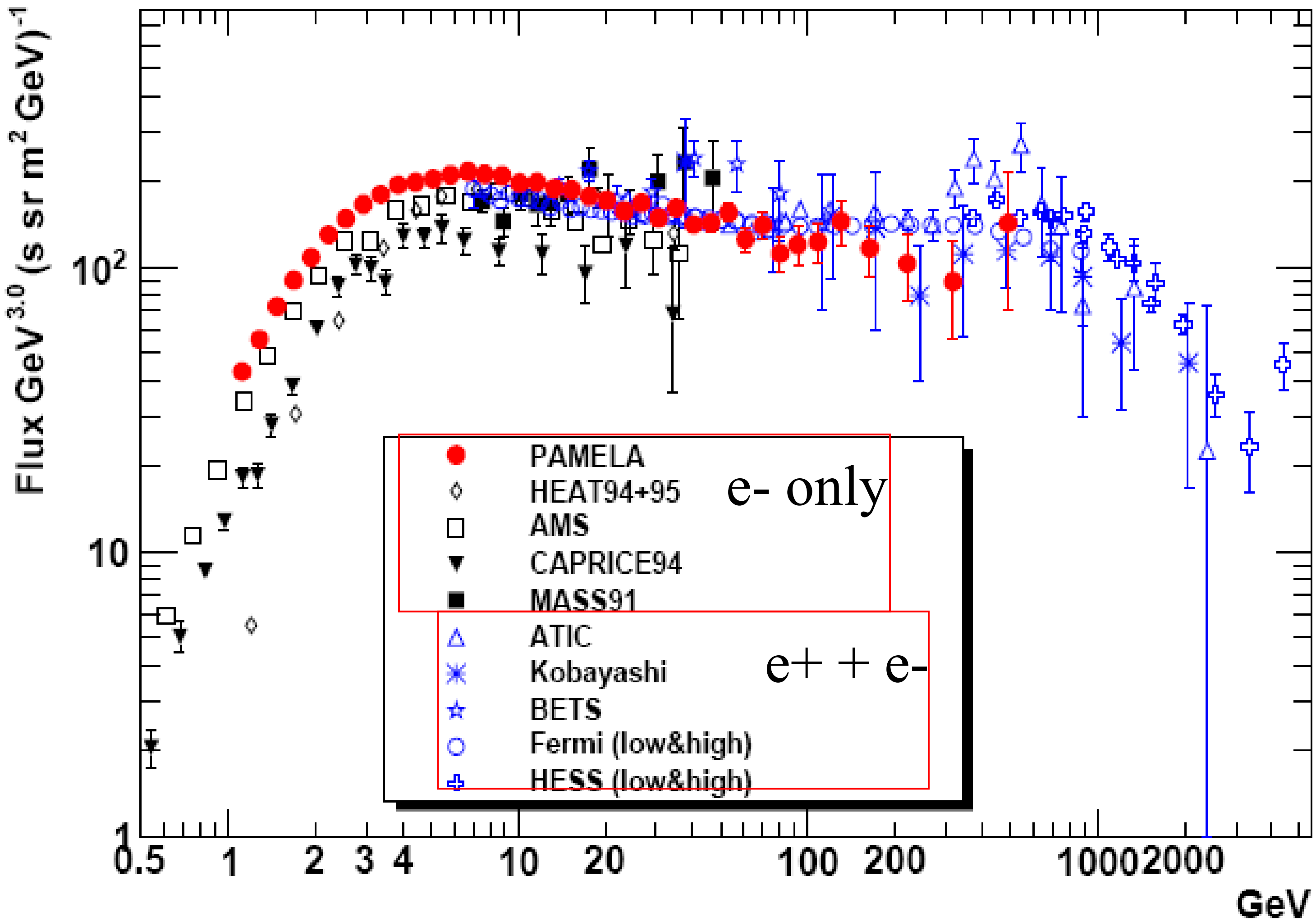


PAMELA e- spectrum



Solid line GALPROP calculation for a diffusion reacceleration model; the dotted line is a single power-law fit to the data above 30 GeV; the dashed-dotted line is a GALPROP calculation including a component from additional cosmic-ray electron sources. Bottom: the PAMELA positron fraction [28] compared with the previous GALPROP calculations with no (solid line) and with additional e− and e+ components (dashed-dotted line).

Electron spectrum



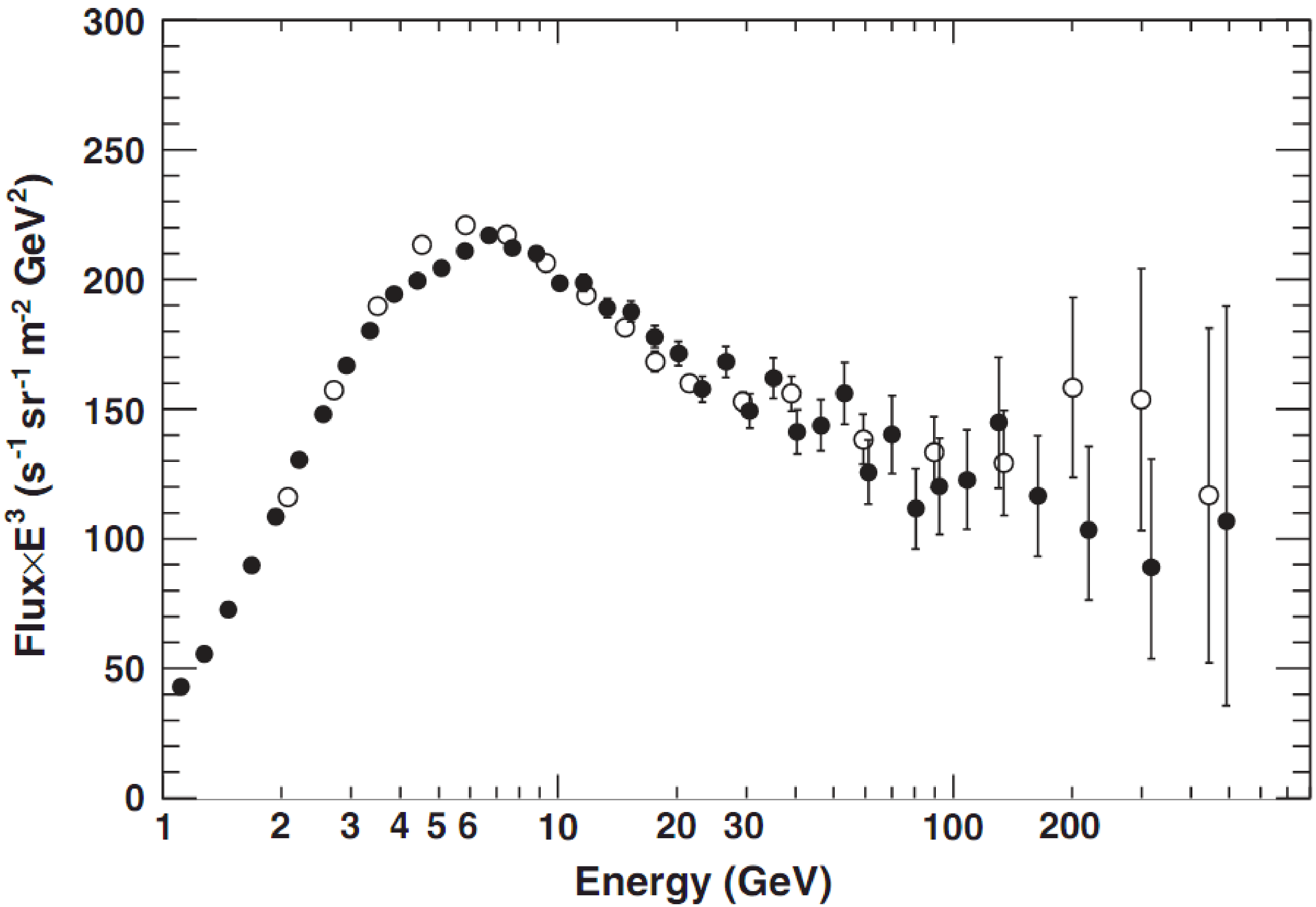


FIG. 1. The negatively charged electron spectrum measured by PAMELA with two independent approaches: energy derived from the rigidity (full circles); energy derived from the calorimeter information (open circles). The error bars are statistical only.

Debate on the origin of cosmic rays is still open

- Experimental evidence of Supernova acceleration is mounting
  - HESS TeV emision from SNR RX J1713.7-3946 → hadronic inter. Of cr. E>10^14eV *F. Aharonian, et al., Astron. Astrophys. 464, 235 (2007)*.
  - X-ray measurements of the same SNR → evidence that protons and nuclei can be accelerated E>10^15 eV in young SNR *Uchiyama, et al., Nature 449, 576 (2007)*.
  - AGILE: diffuse gamma-ray (100 MeV – 1 GeV) SNR IC 443 outer shock → hadronic acceleration *M. Tavani, et al., ApJL 710, L151 (2010)*.
  - Fermi: Shell of SNR W44 have → decay of pi0 produced in the interaction of hadrons accelerated in the shock region with the interstellar medium *A. Abdo, et al., Science 327, 1103 (2010)*.
  - Starburst galaxies (SG), where the SN rate in the galactic center is much higher than in our own, the density of cosmic rays in TeV gamma-rays (H.E.S.S infers cosmic rays density in SG NGC 253 three orders of magnitude higher than in our galaxy *F. Acero, et al., Science 326, 1080 (2009)*.
  - VERITAS: SG M82 cosmic rays density is reported to be 500 times higher than in the Milky Way *VERITAS Collaboration, et al., Nature 462, 770 (2009)*

However, supernova-only model has been challenged many times

- Multiple origin of cosmic rays:
  - SN explosions of various sizes in either the interstellar medium or in a pre-existing stellar wind, WR stars *P. L. Biermann, Space Science Reviews 74, 385 (1995); L. Biermann, Astron. Astrophys. 271, 649 (1993)*
- Nova stars and explosions in superbubbles, *V. I. Zatsepin, N. V. Sokolskaya, Astron. Astrophys. 458, 1 (2006))*
- Different acceleration processes such as nonlinear shock acceleration
  - *D. C. Ellison, International Cosmic Ray Conference (1993),* vol. 2 of International Cosmic Ray Conference, pp. 219
  - DSA, diffusive shock acceleration, *V. I. Zatsepin, N. V. Sokolskaya, Astron. Astrophys. 458, 1 (2006).*
  - M. Ahlers, P. Mertsch, S. Sarkar, Physical Review D 80, 123017 (2009).

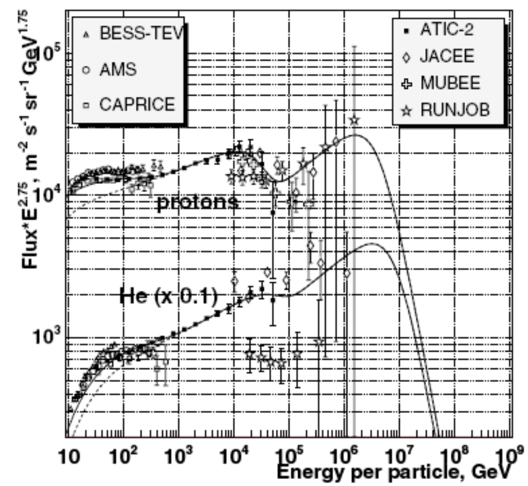
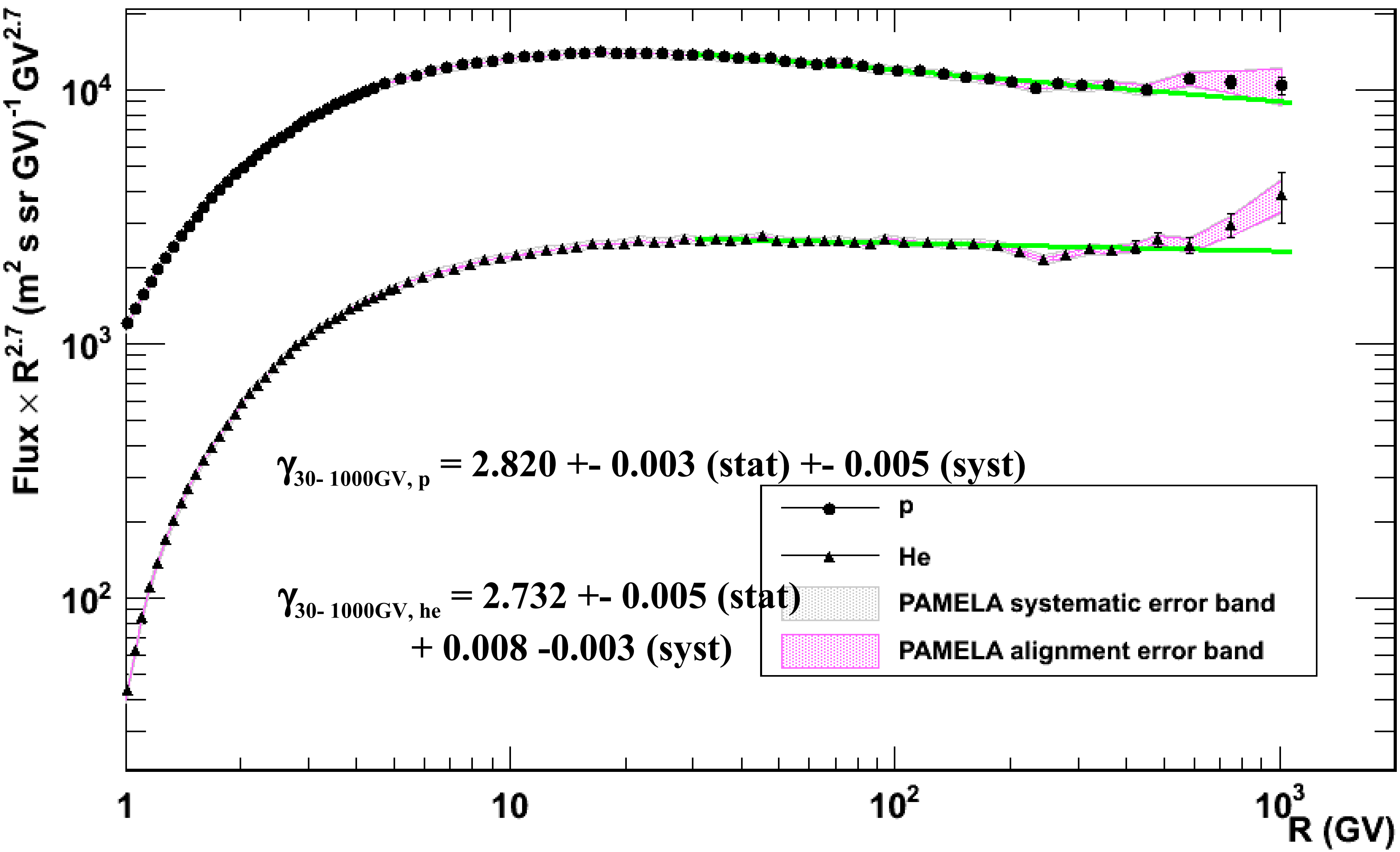


Fig. 1. Proton and He spectra. Dashed lines are described in Sect. 3, solid lines are described in Sect. 5.

Wolfendale et al, (ICRC 2009) one source cause of knee

Pamela galactic p and he

2006-2008



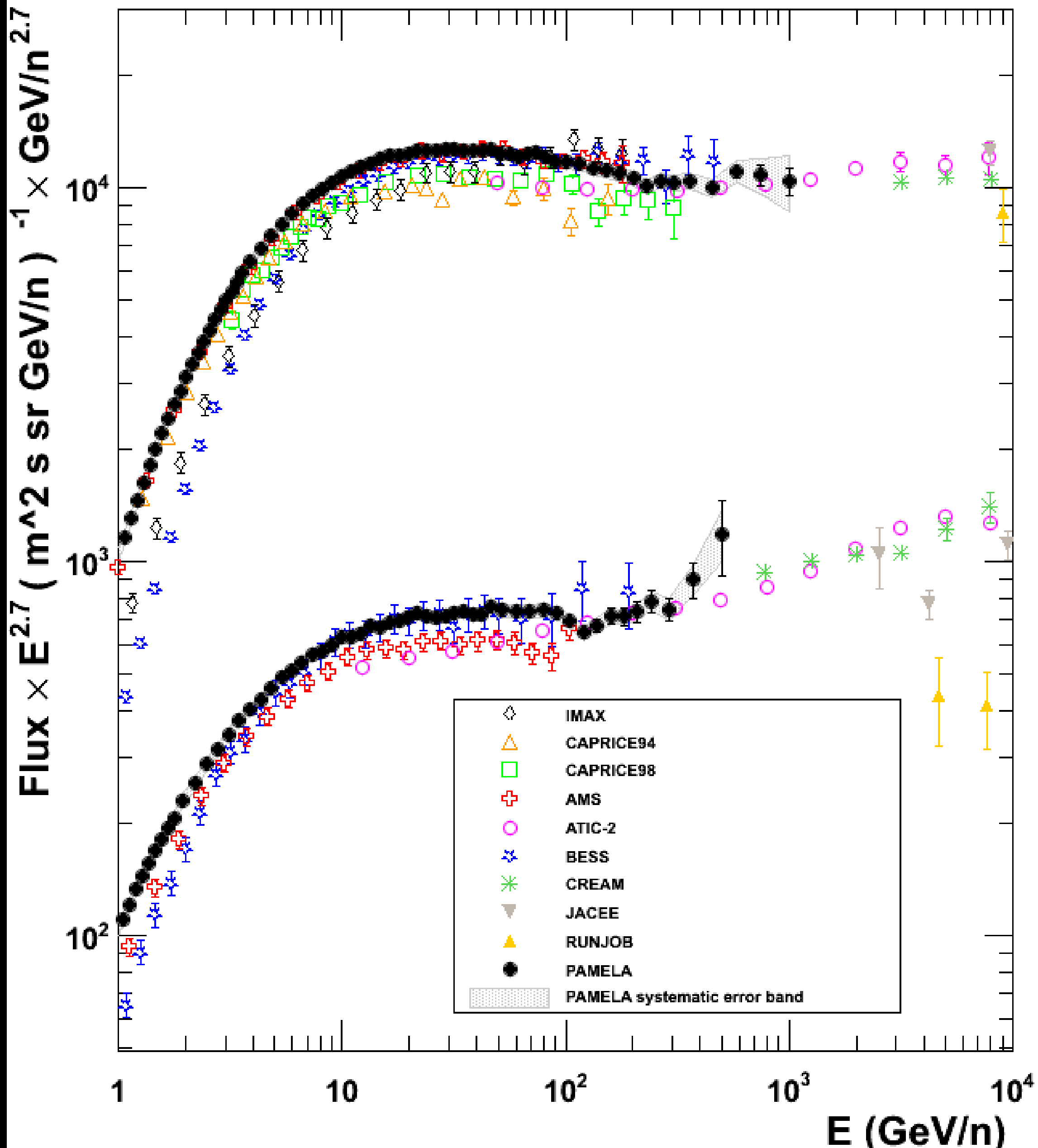
Comparison with previous experiments

Note the different (lower) values for the spectral indexes in kinetic energy:

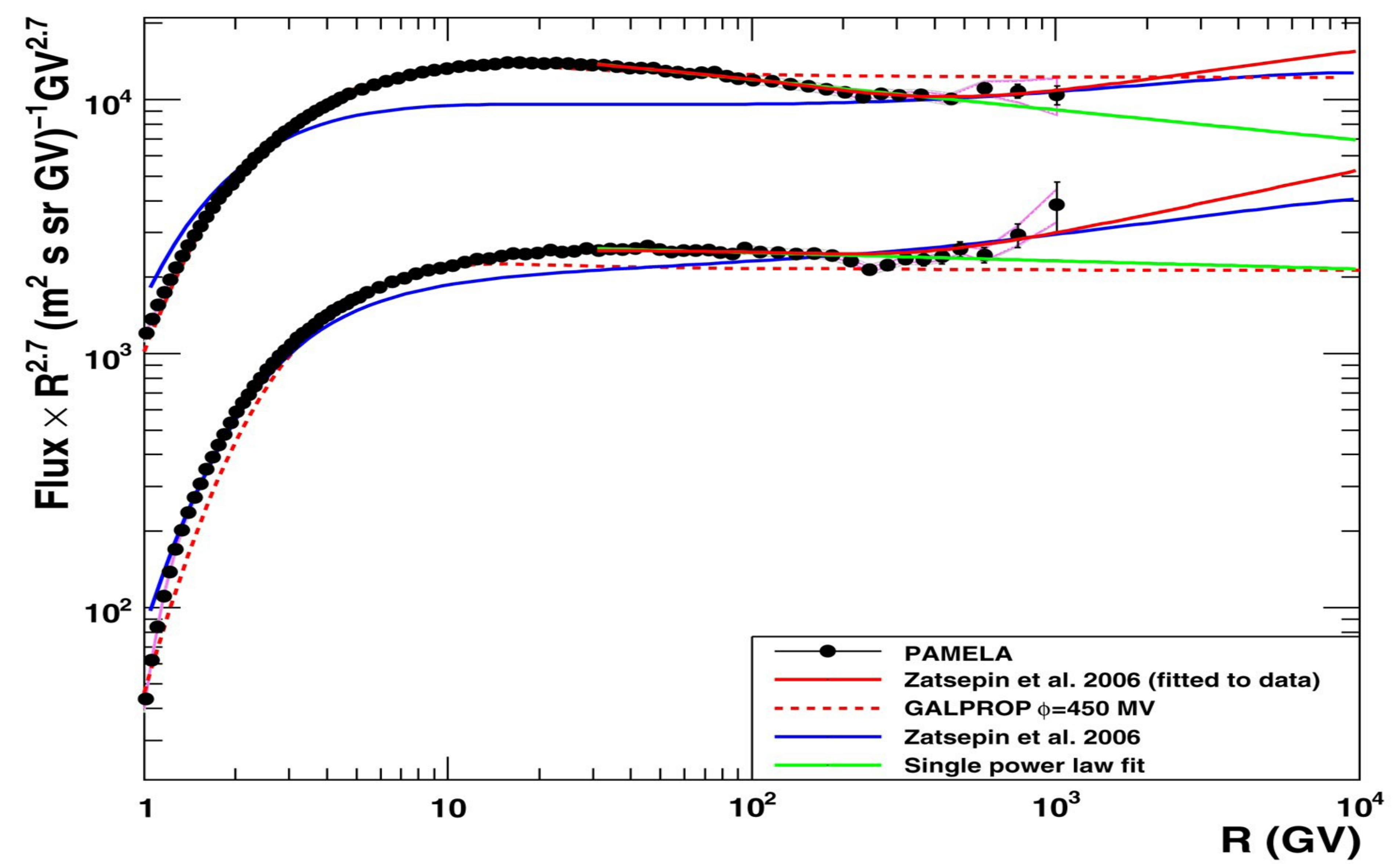
$\gamma_{30\text{-}1000\,\mathrm{GeV},\,p} = 2.782 \pm 0.003\ (\mathrm{stat}) \pm 0.004\ (\mathrm{syst})$

$\gamma_{15\text{-}600\,\mathrm{GeV/n},\,he} = 2.71 \pm 0.01\ (\mathrm{stat}) \pm 0.007\ (\mathrm{syst})$

$$\gamma_T = \frac{dlog(\phi_T)}{logT} = (\gamma_R - 1)\frac{T^2 + Tmc^2}{T^2 + 2Tmc^2} + \frac{T}{T + mc^2}$$



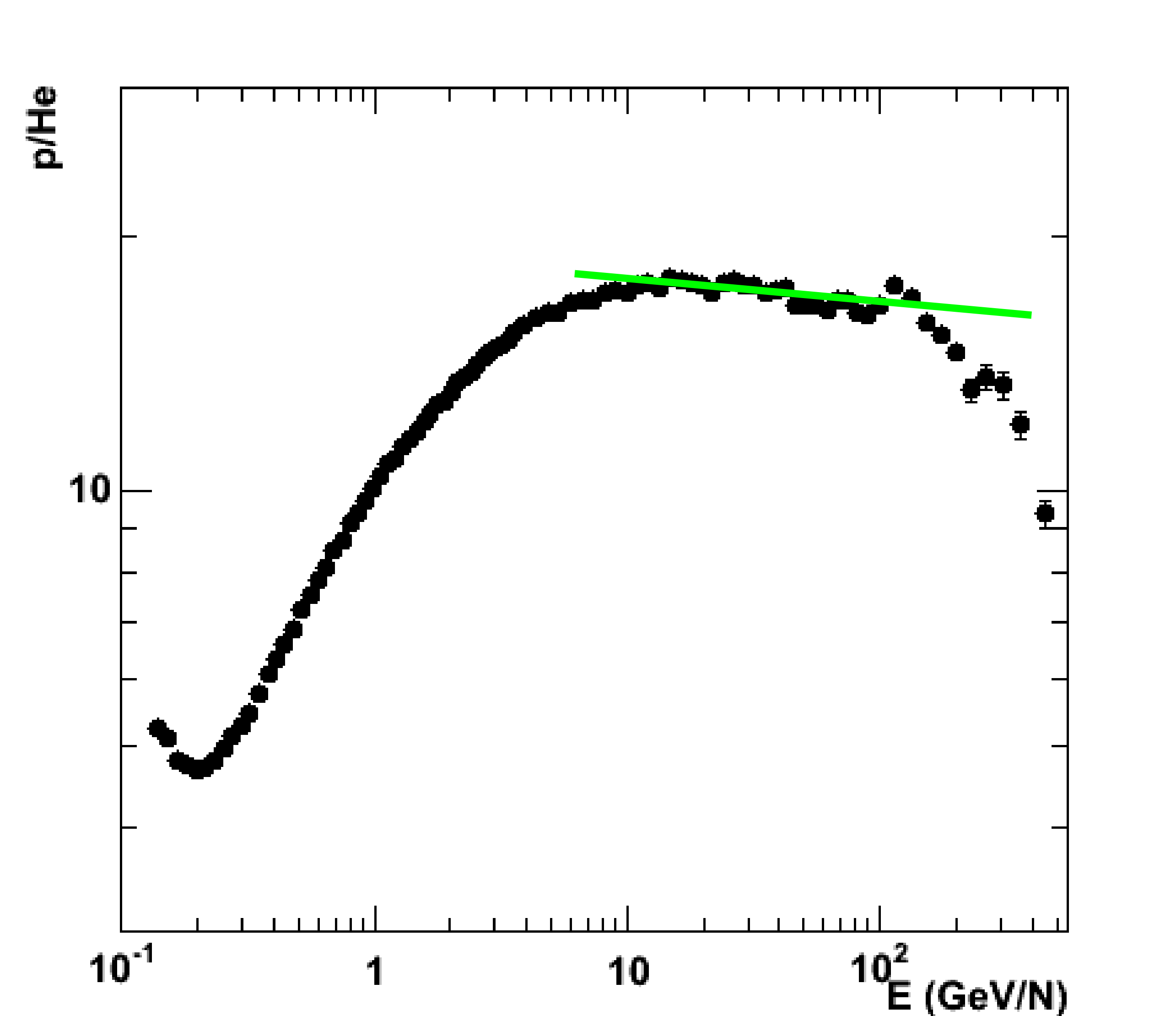
Fitting p and He spectra

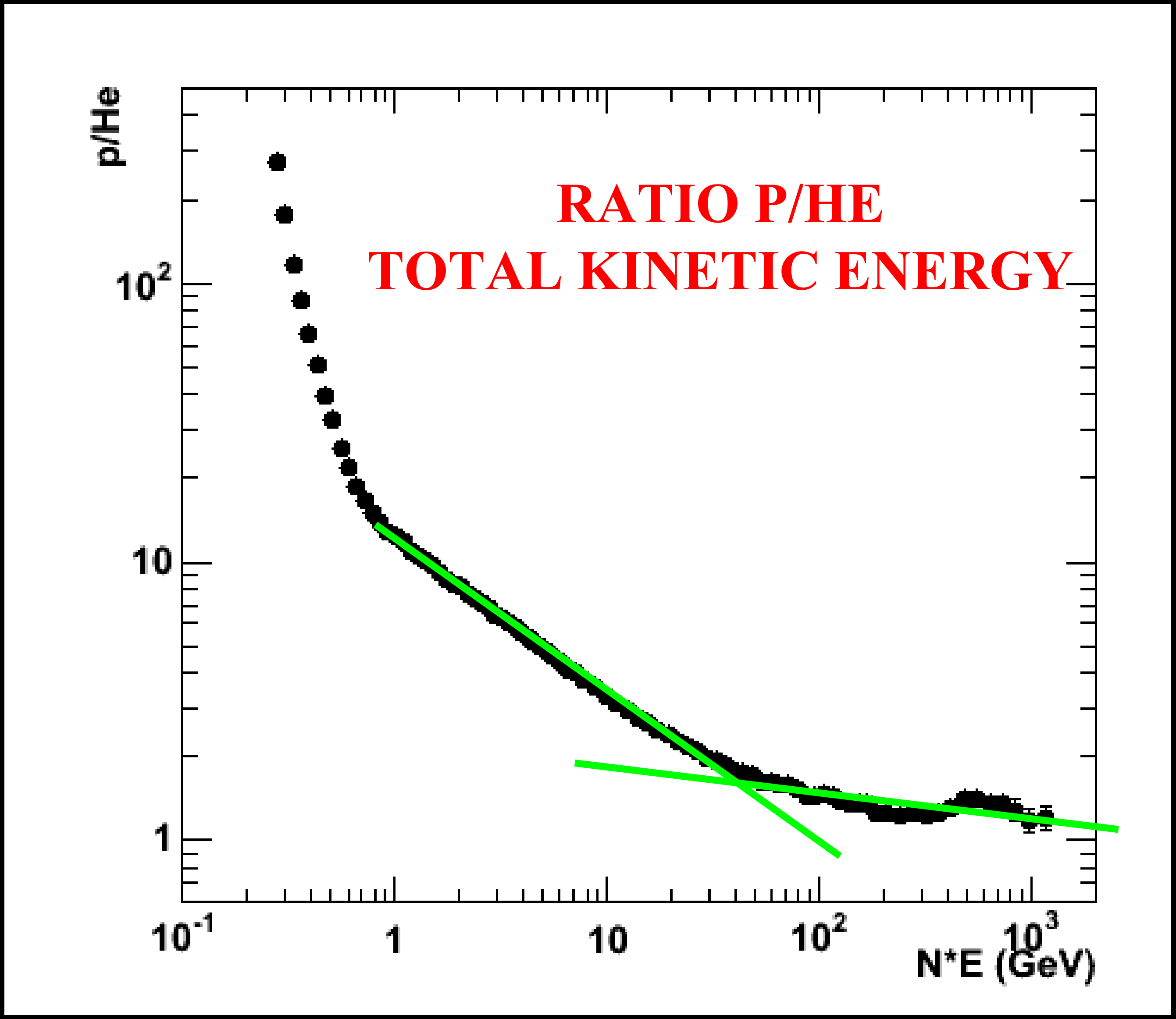


P/HE RATIO: KINETIC ENERGY/NUCLEON

Ratio has lower systematic

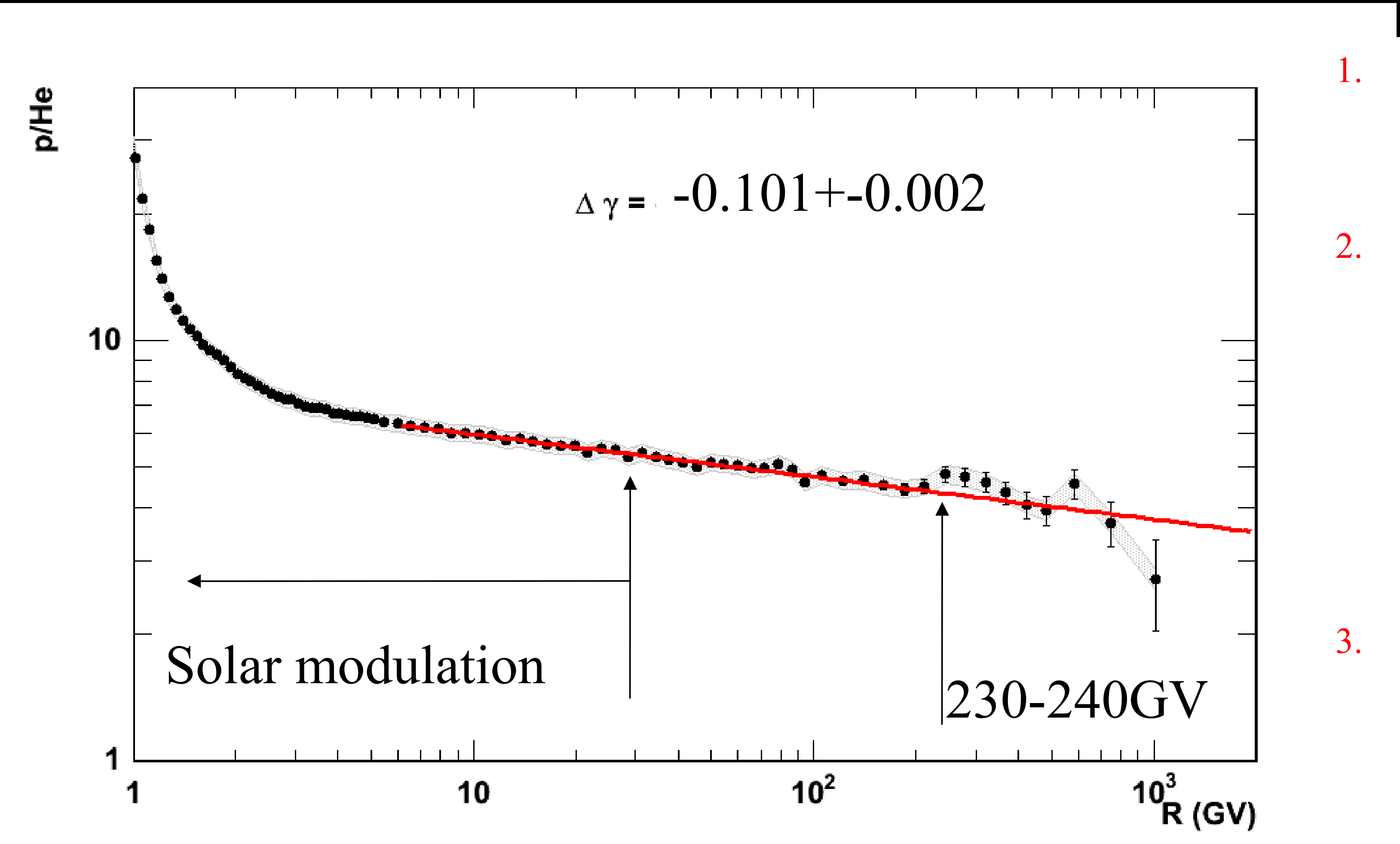
Less dependent from solar modulation





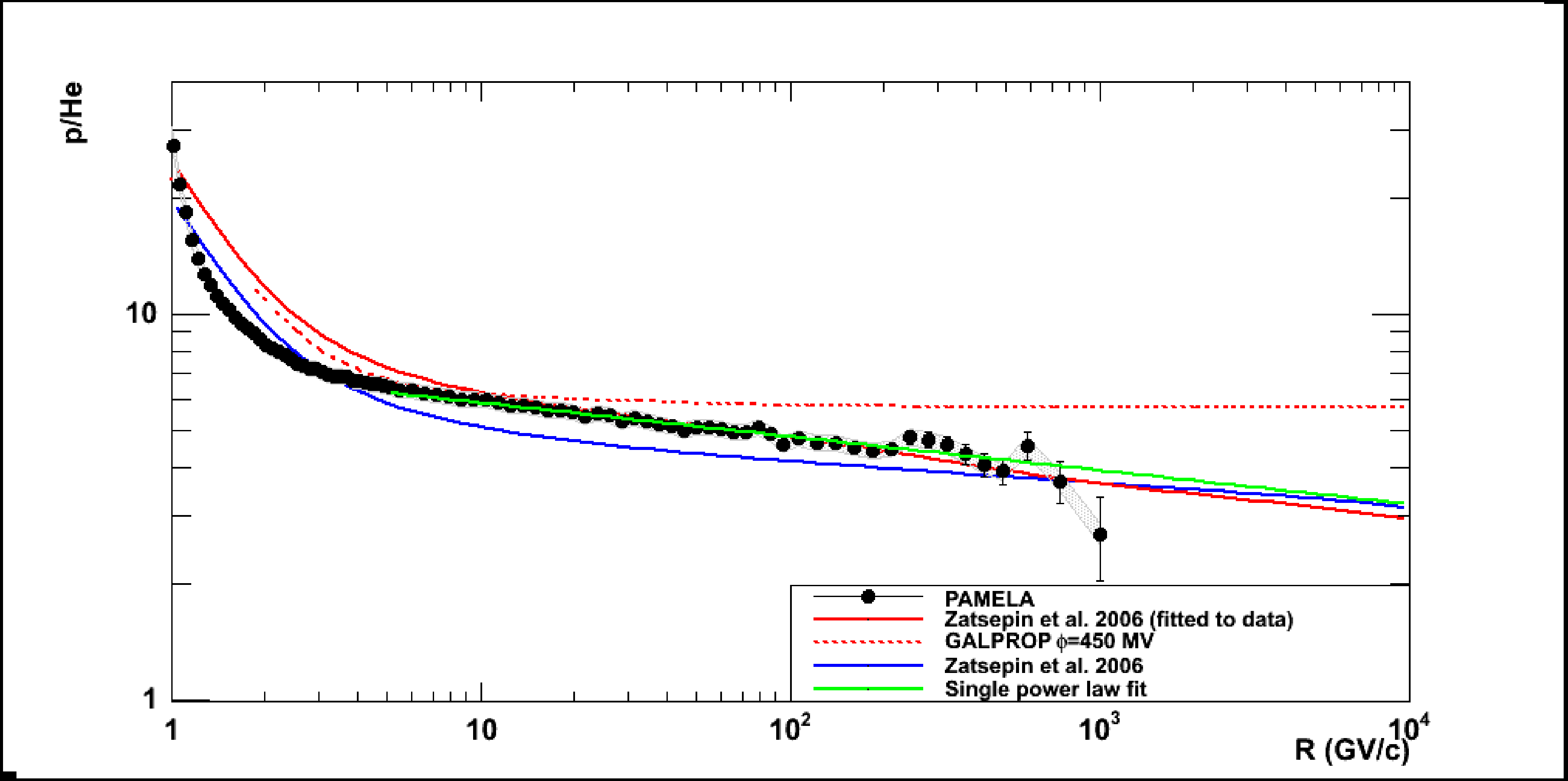
RATIO P/HE
TOTAL KINETIC ENERGY
p/He
10^2
10
1
10^{-1}
1
10
10^2
10^3
N*E (GeV)

Ratio P/He: Rigidity

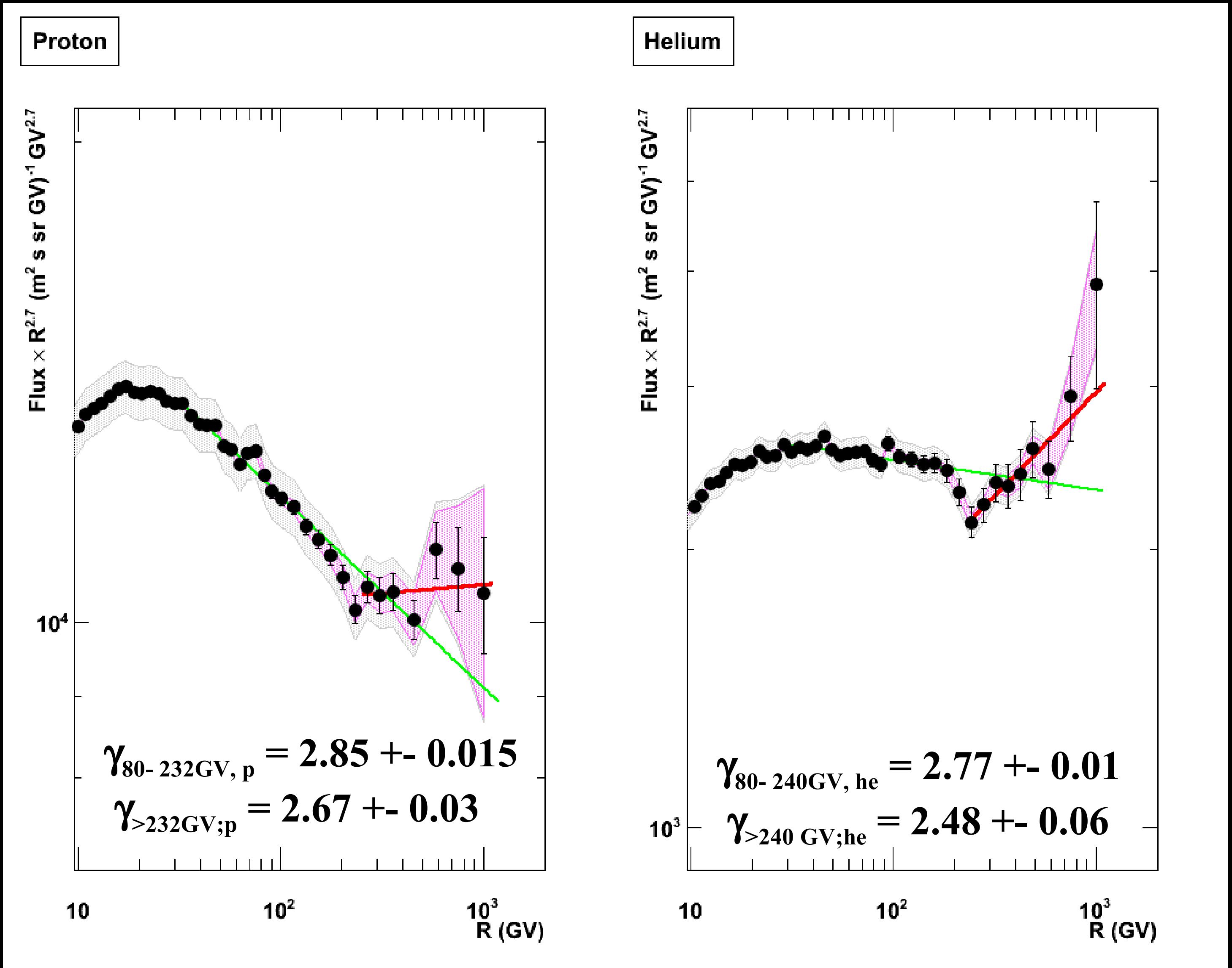


1. Acceleration is a rigidity dependent effect
2. The ratio decreases→ More He at high energies → Acceleration mechanisms or sources are different
3. Measurement valid also below the (low) solar modulation

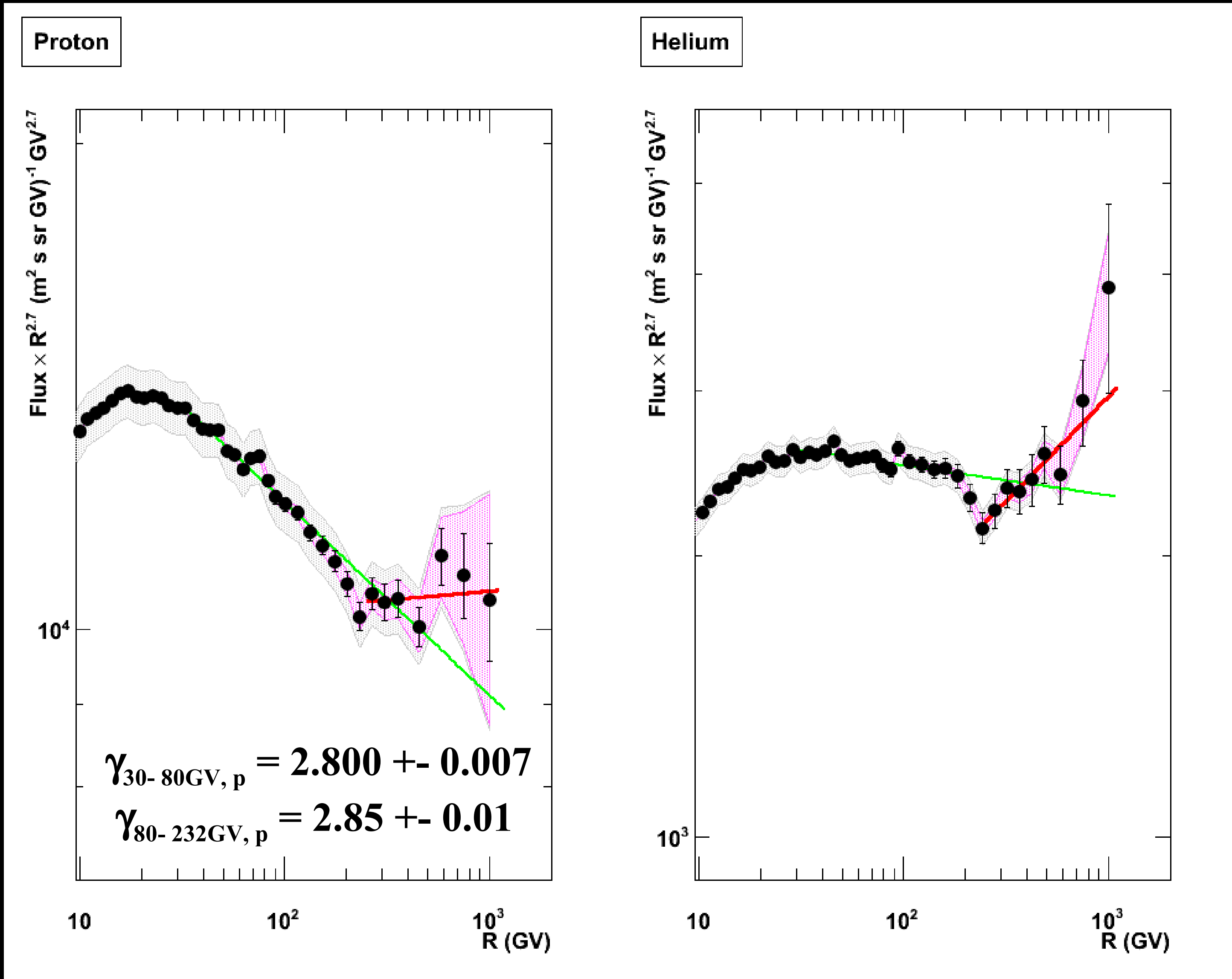
Fitting the p/he ratio



Deviations from the power law: >230-240 GV



Deviations from the power law: a) 30-240 GV



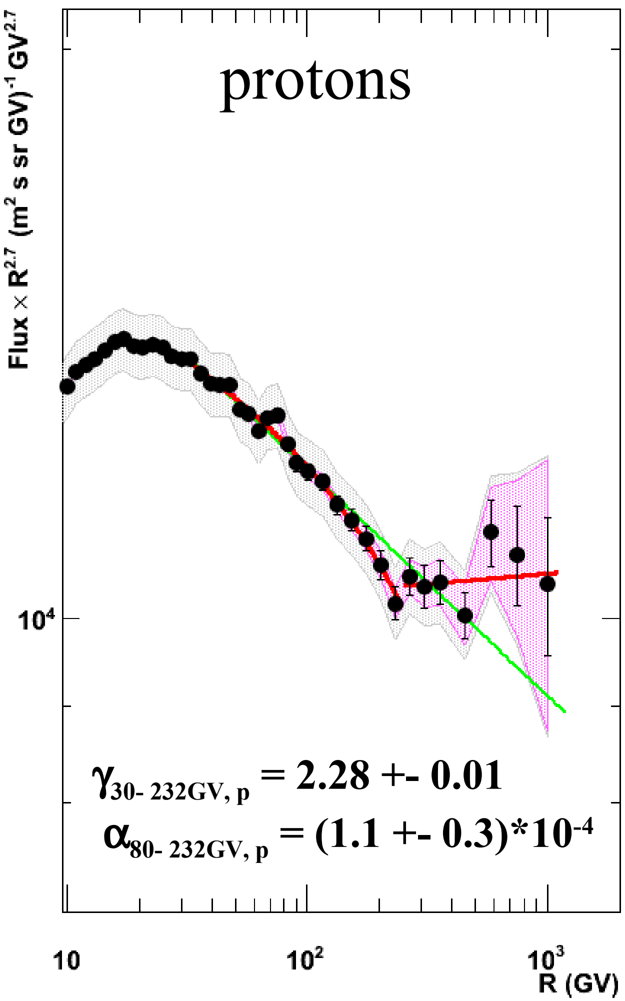
1. Additional source(s) above 240 GV
2. Fisher and T student test reject single power law to better than 99.7 CL

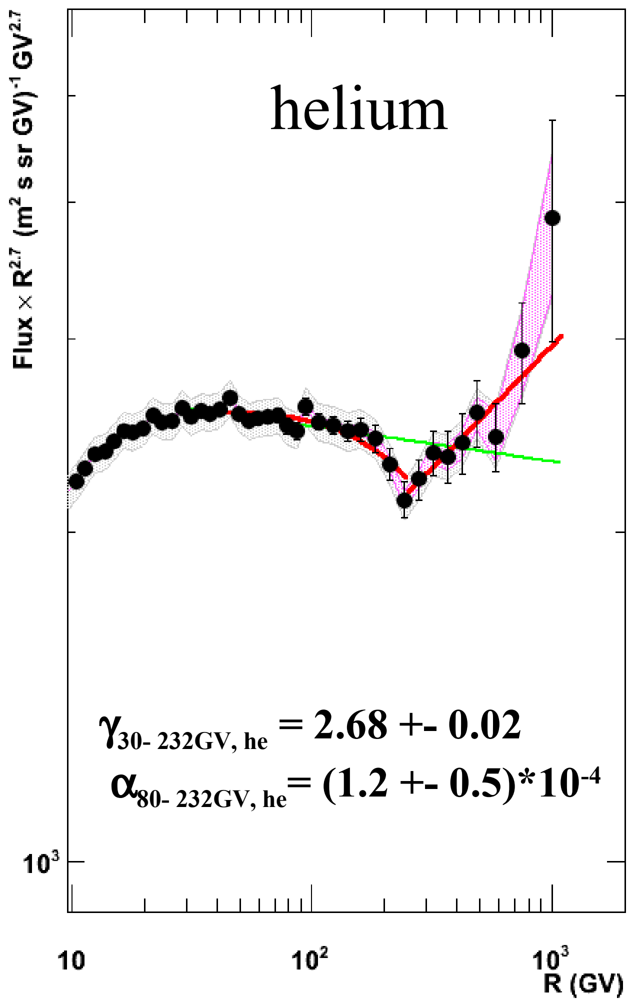
Deviations from the power law: b) 30-240 GV

$$\Phi = A * R^{-\Gamma} = A * R^{-\gamma-\alpha\frac{R-R_0}{R_0}}$$

Heli

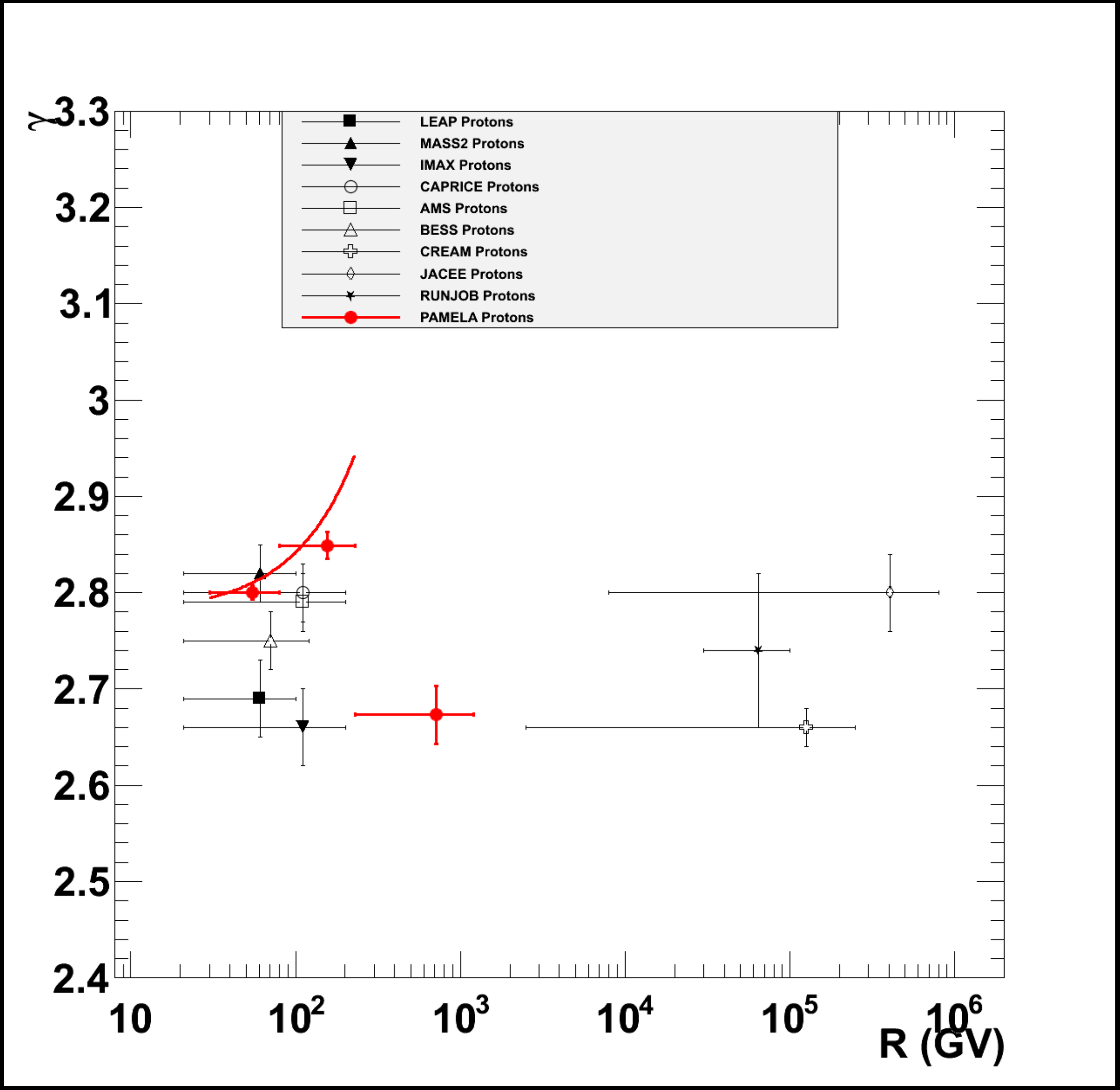
$$\gamma_R(R) = \frac{dlog(\Phi_R)}{dlog(R)} = -\gamma_0 + \alpha(1 - \frac{R}{R_0}(logR + 1))$$



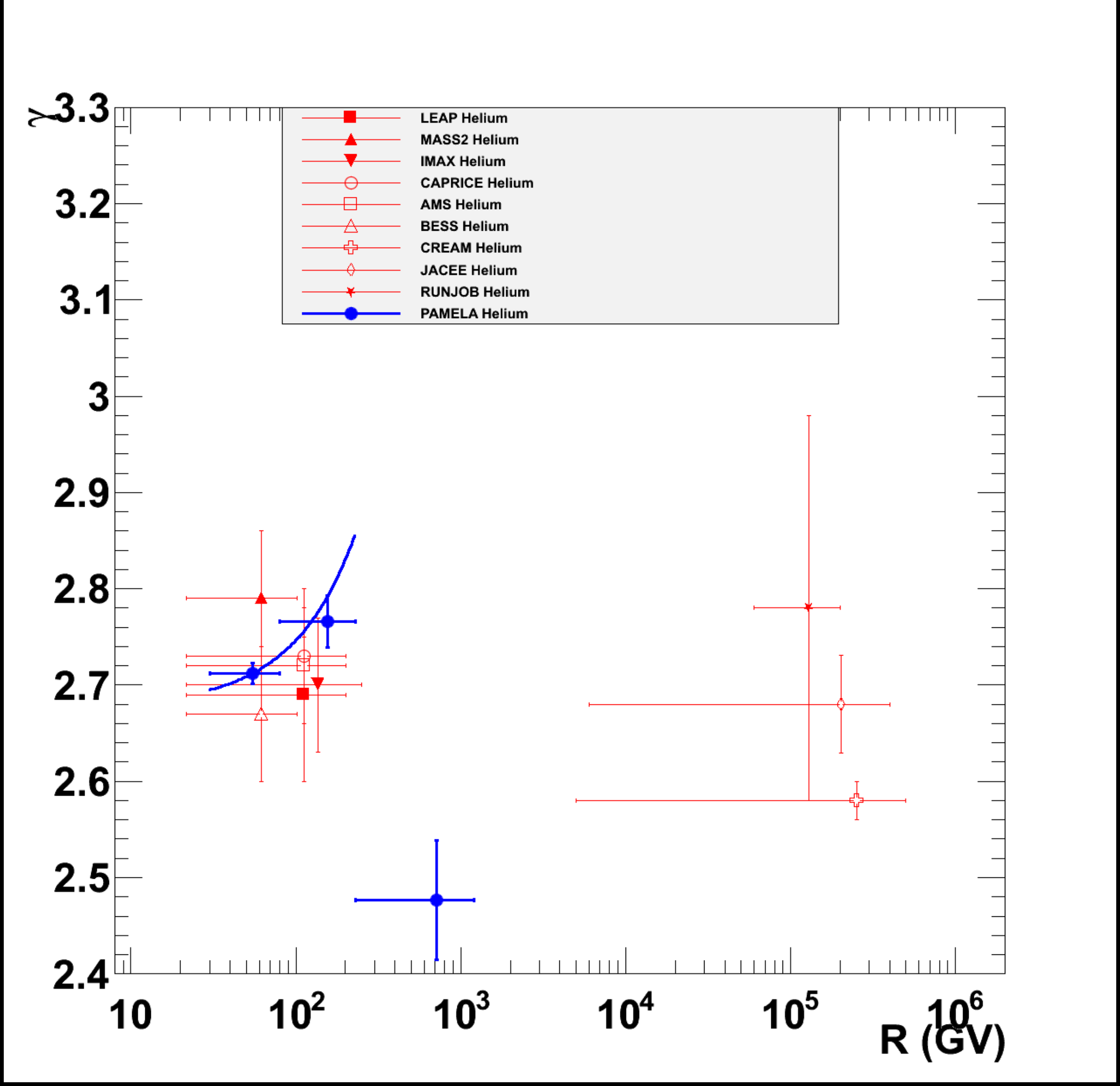


- The spectrum softens at 30-240 GV
- Single power law is also ruled out at lower rigidities

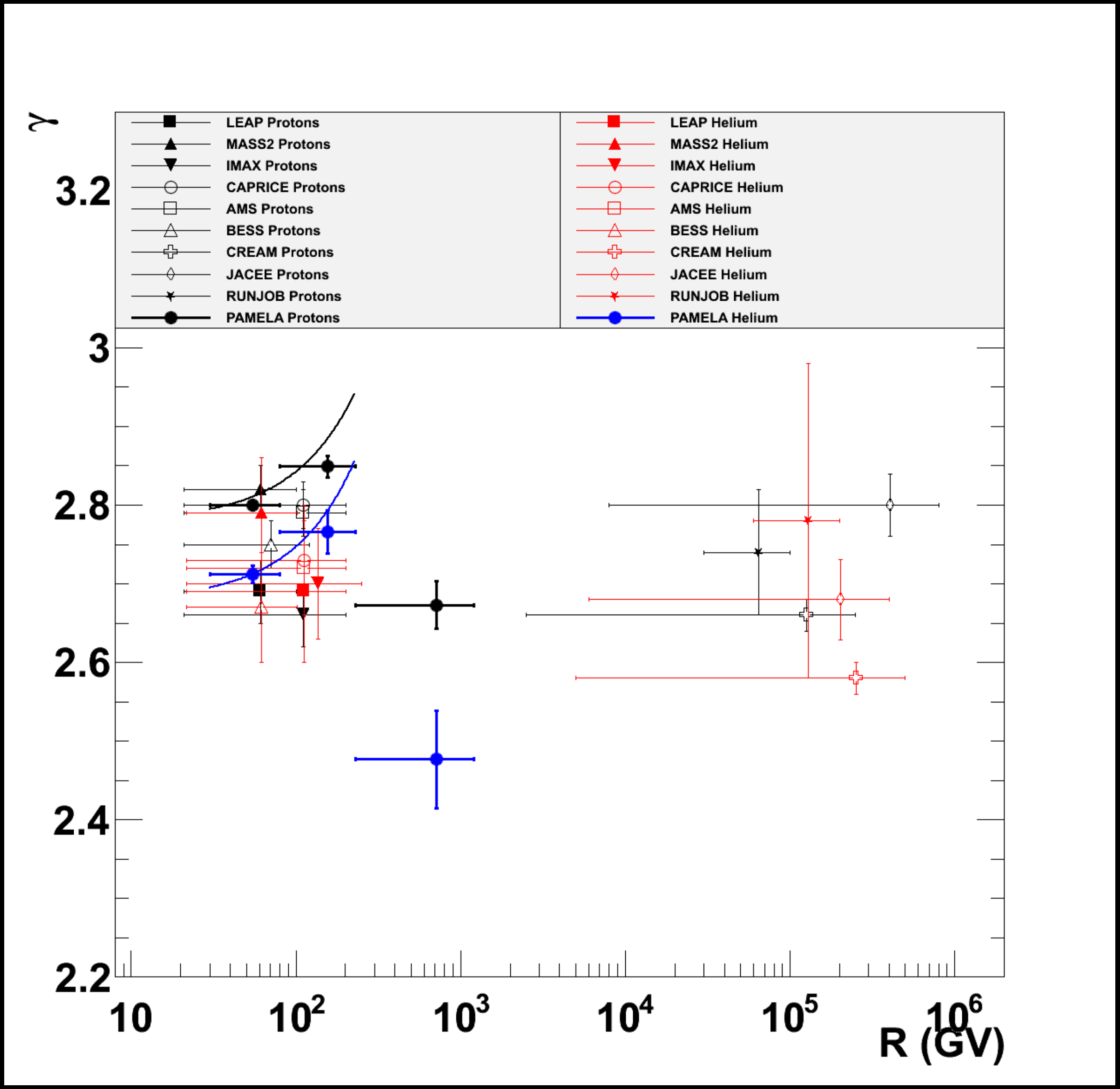
Proton spectral indexes



Helium spectral indexes



Proton and helium comparison



At higher energies:
CREAM balloon data

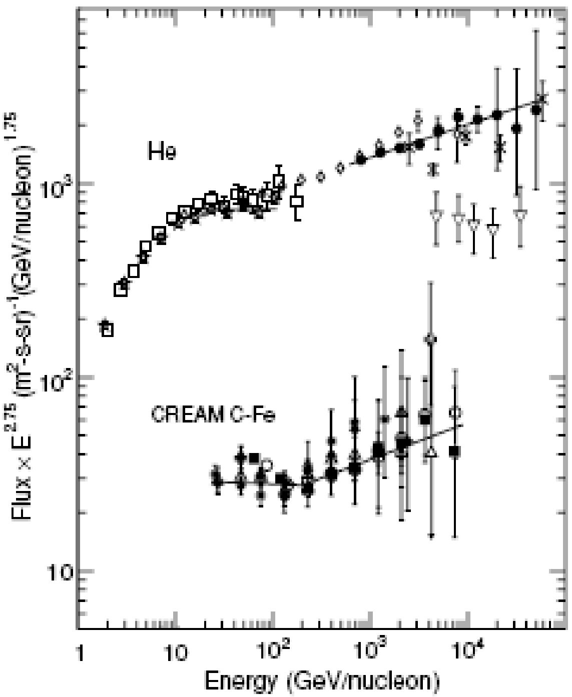


Figure 5. Broken power-law fit to helium and heavier nuclei data. The lines for helium represent a power-law fit to AMS (open stars) and CREAM (filled circles) data, respectively. Also shown are helium data from other experiments: BESS (open squares), ATIC-2 (open diamonds), JACEE (X), and RUNJOB (open inverted triangles). Some of the overlapping BESS and AMS data points are not shown to achieve better clarity. The lines for C-Fe data represent a broken power-law fit to the CREAM heavy nuclei data: carbon (open circles), oxygen (filled squares), neon (open crosses), magnesium (open triangles), silicon (filled diamonds), and iron (asterisks).

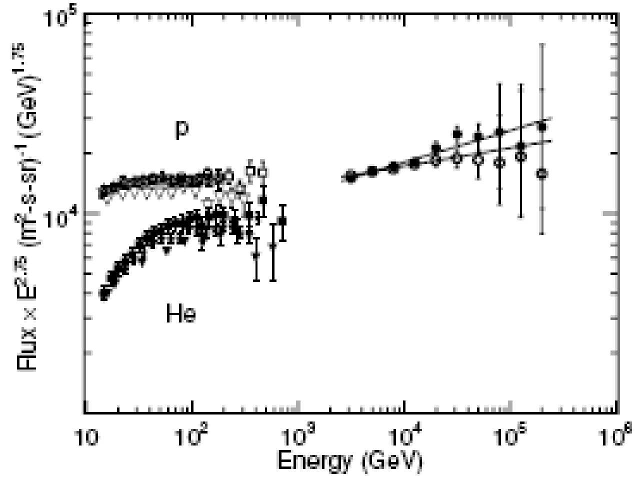


Figure 3. Measured energy spectra of cosmic-ray protons and helium nuclei. The CREAM-I spectra are compared with selected previous measurements (Alcaraz et al. 2000; Haino et al. 2004; Boezio et al. 2003) using open symbols for protons and filled symbols for helium: CREAM (circles), AMS (stars), BESS (squares), CAPRICE (inverted triangles). The error bars represent one standard deviation, which is not visible when smaller than the symbol size. The lines represent power-law fits to the CREAM data.

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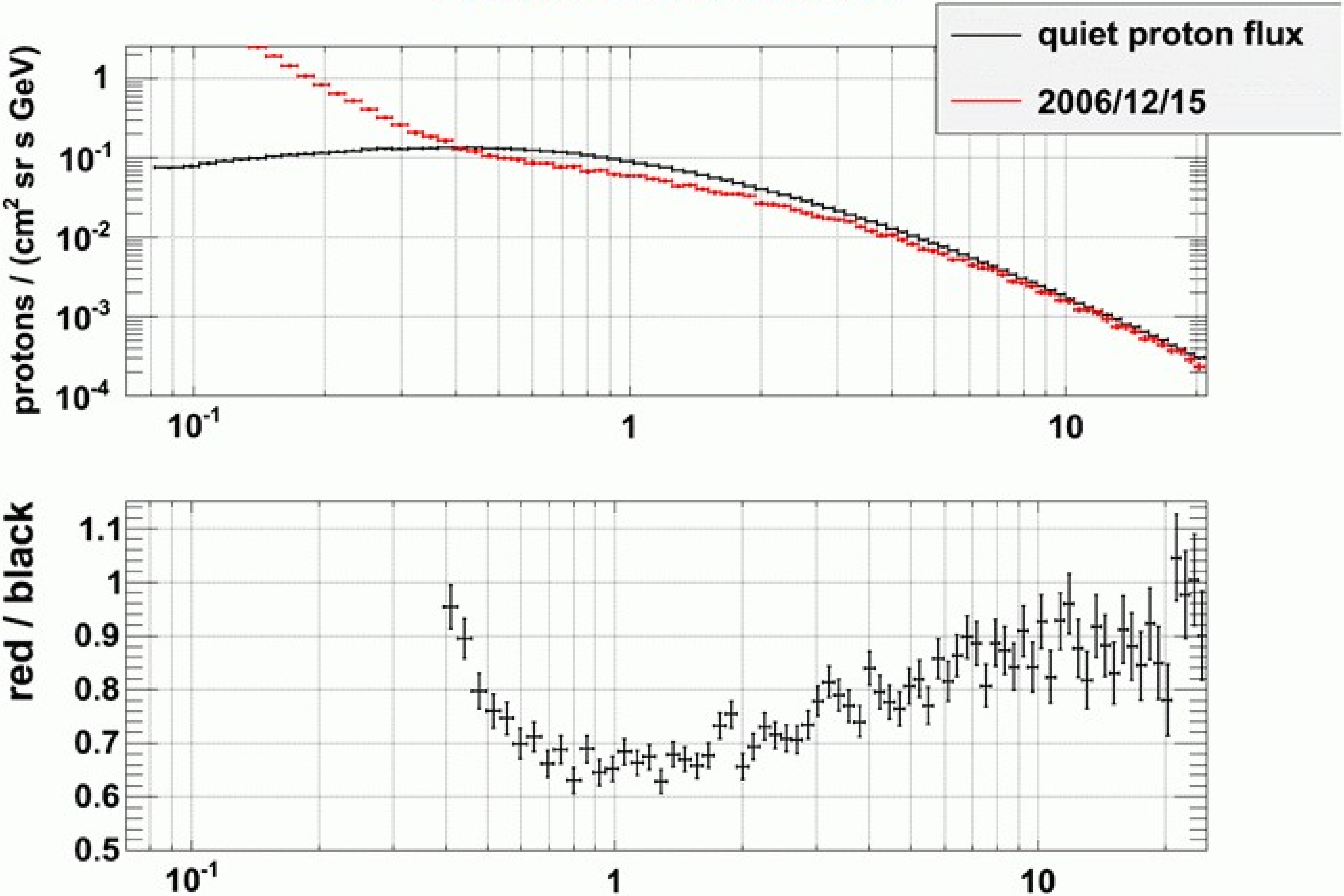
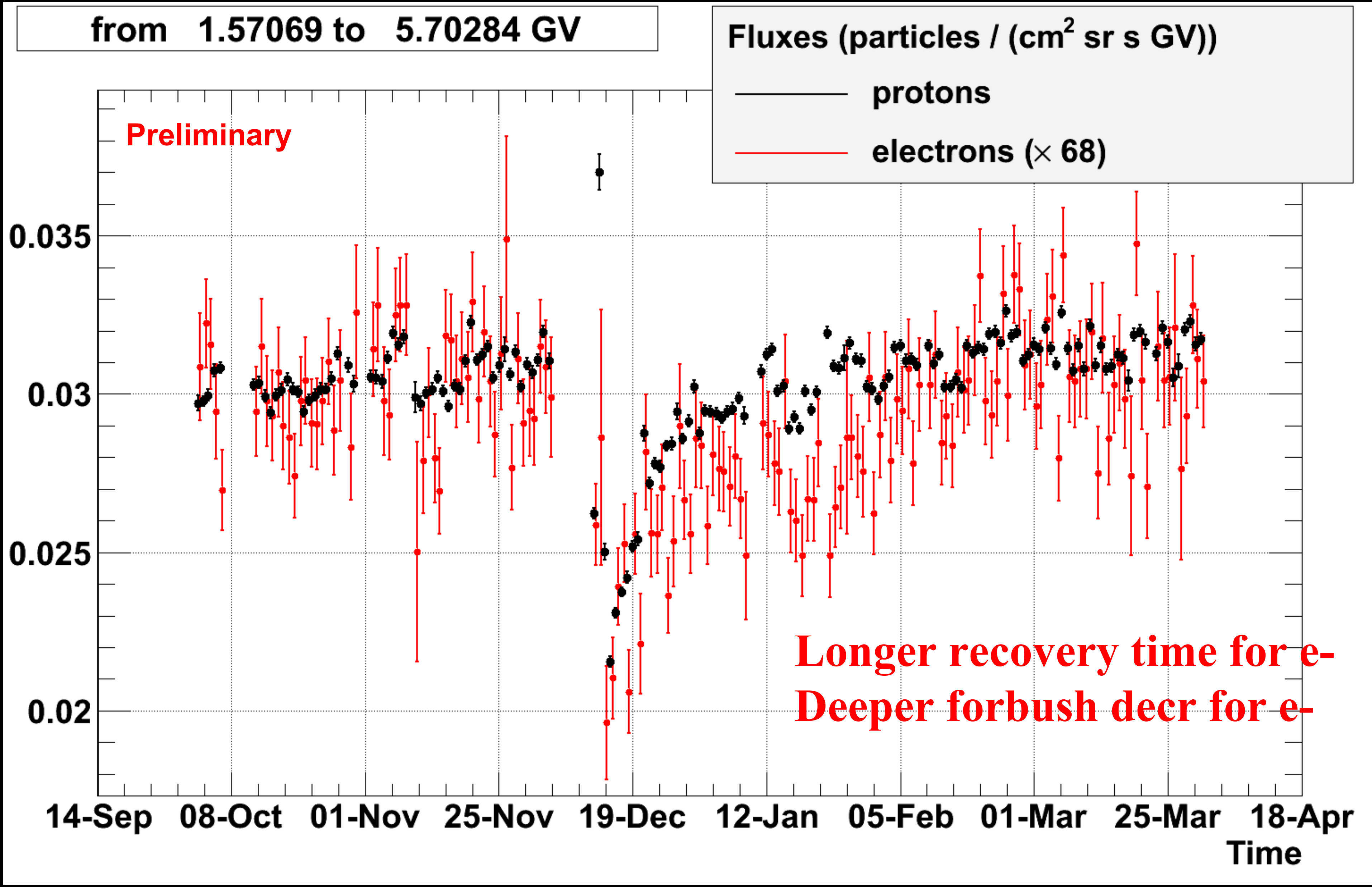
200 GeV/n: Indirect p, He

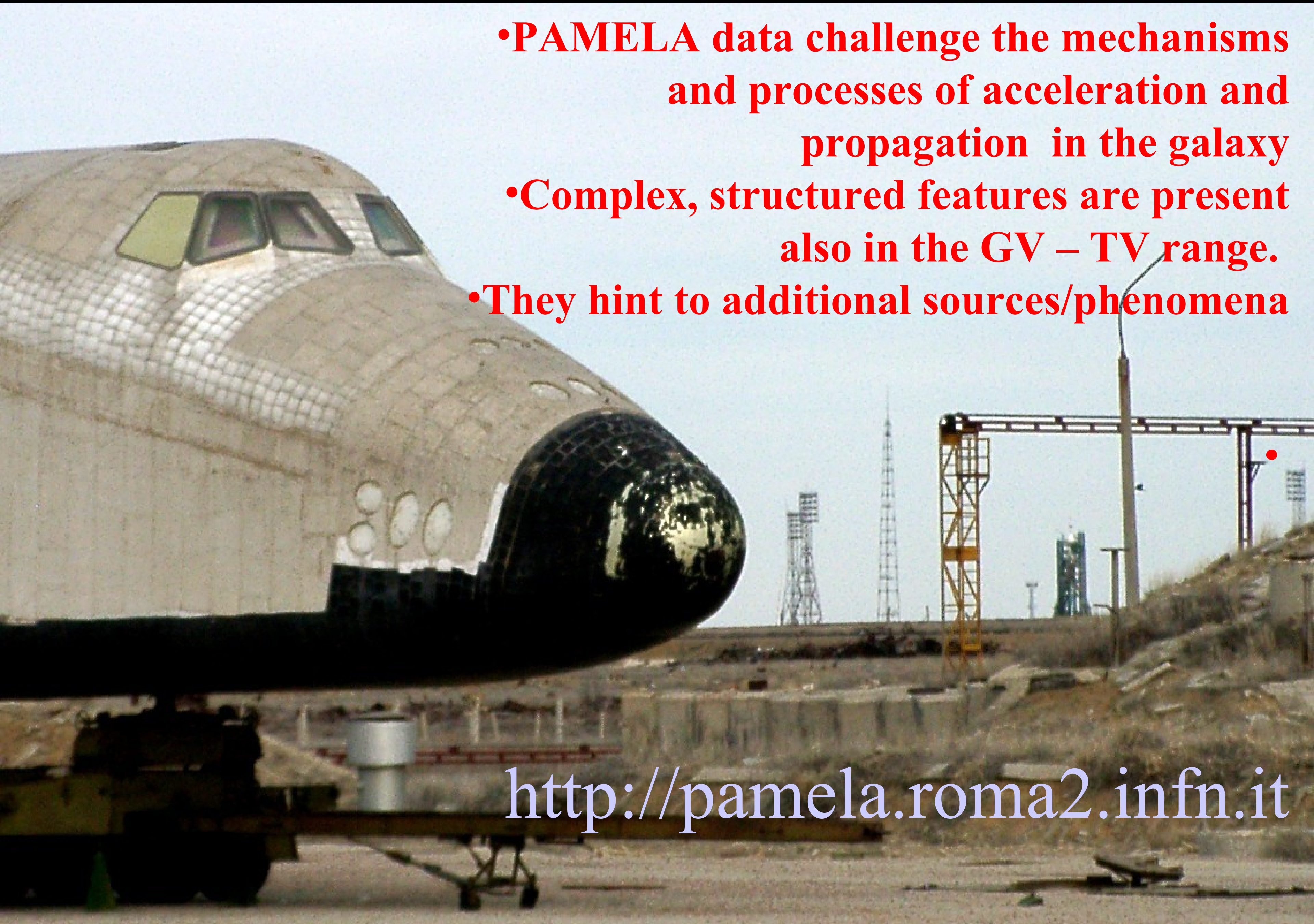
Direct C-Fe

Forbush decrease



Forbush decrease: comparison with e-





- **PAMELA data challenge the mechanisms and processes of acceleration and propagation in the galaxy**
- **Complex, structured features are present also in the GV – TV range.**
- **They hint to additional sources/phenomena**

http://pamela.roma2.infn.it

PAMELA has survived five years up to now, under discussion a possible extension

Most of the collaboration in Italy is part of the JEM-EUSO experiment (Picozza, PI of Pamela is now PI of JEM-EUSO)

Current work involves calibration tests of JE detector module in TA site in Utah.