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PAMELA measurements of proton and helium nuclei and cosmic ray acceleration in the galaxy

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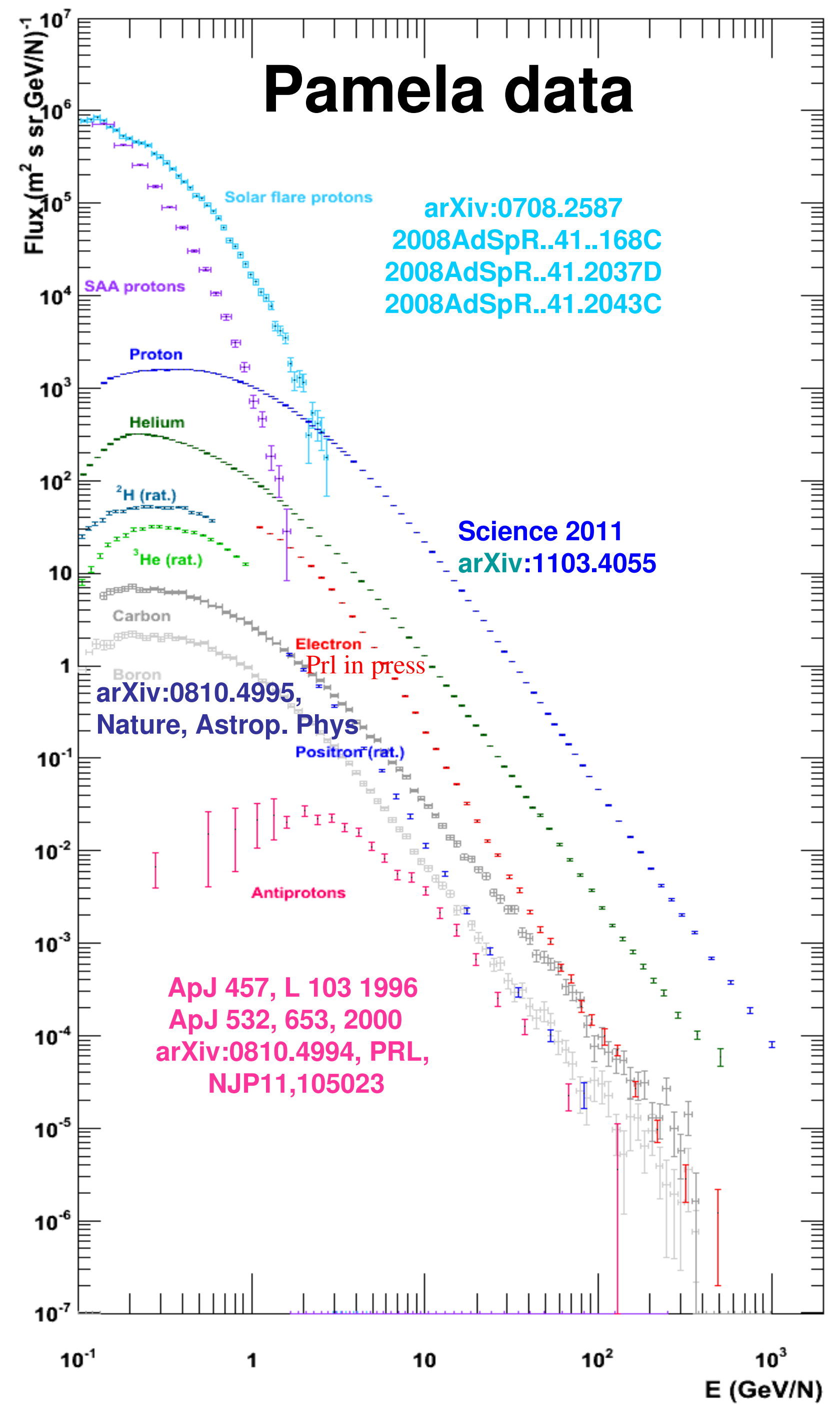
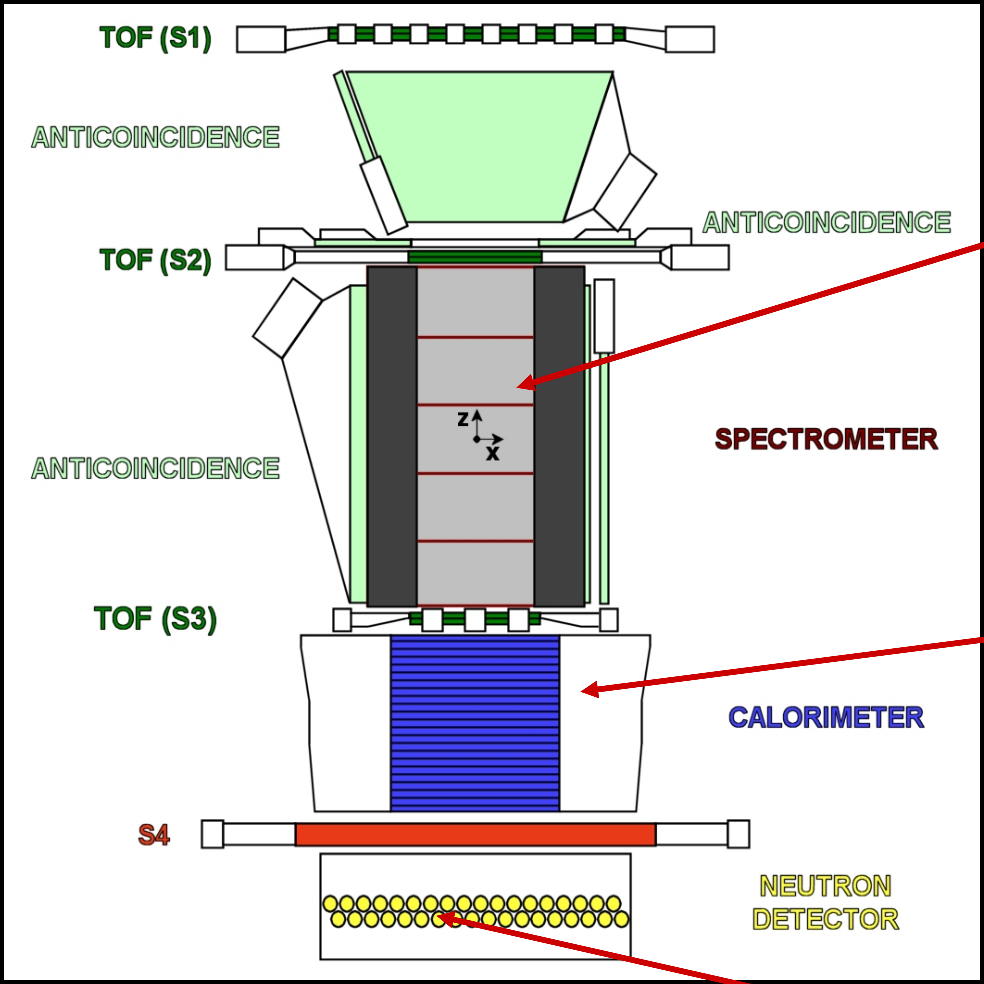
RIKEN
Tor Vergata

High precision charged cosmic ray measurement in Low Earth Orbit



The PAMELA apparatus



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

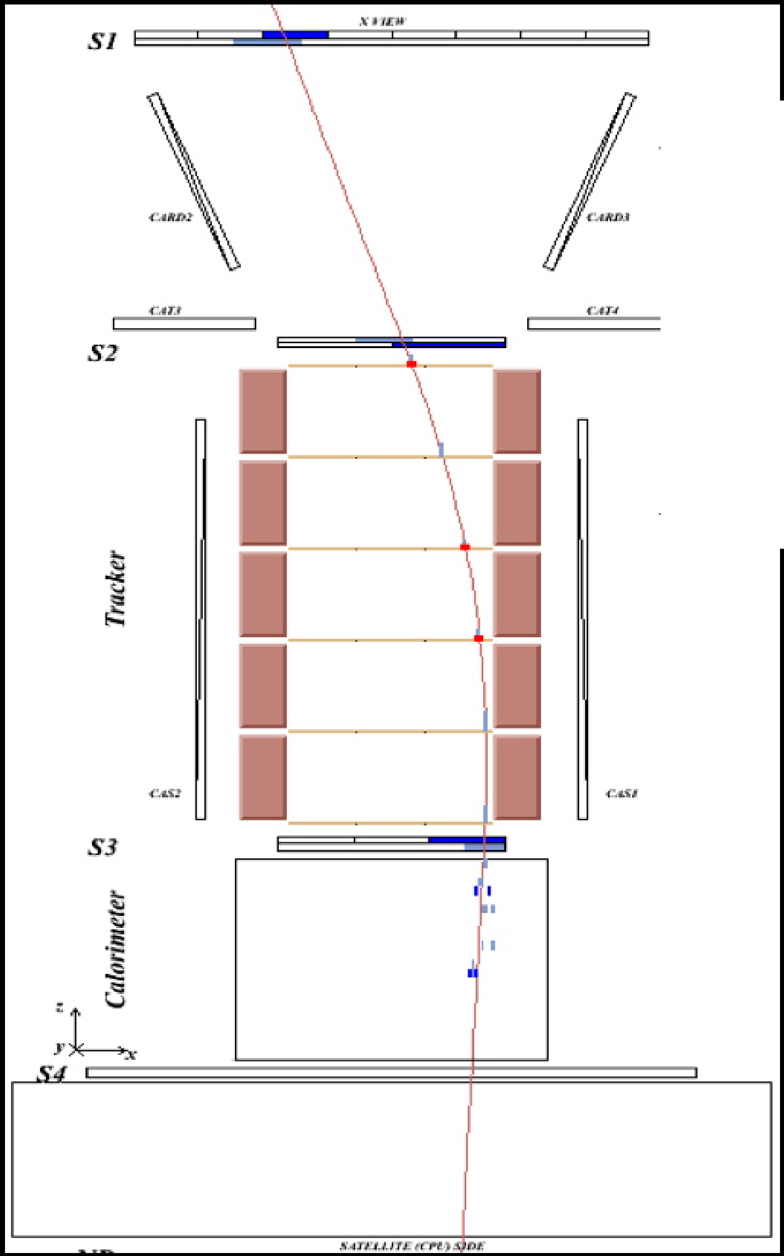
MDR from test beam data ≅ 1 TV

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

ND p/e separation capabilities >10 above 10 GeV/c, increasing with energy

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

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

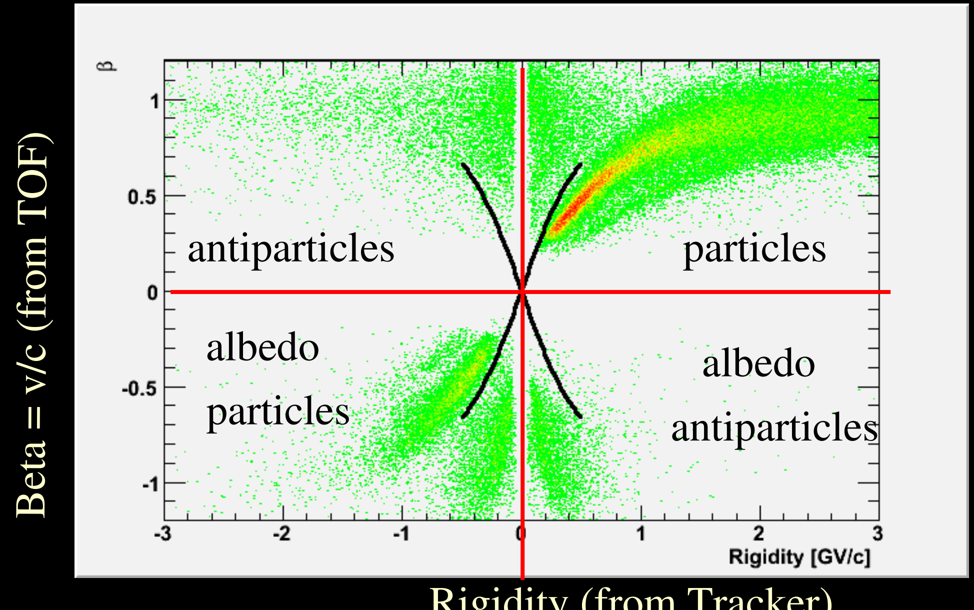
5% to 10% precision

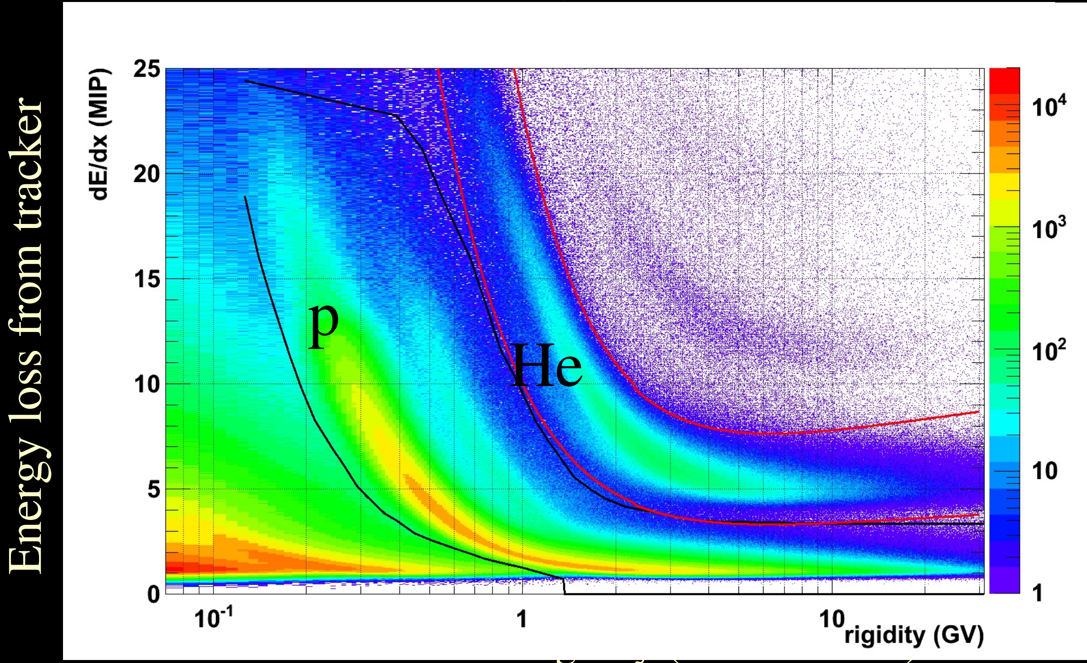
Proton and Helium Absolute flux

- 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.

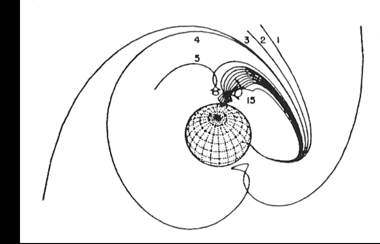
Selection criteria

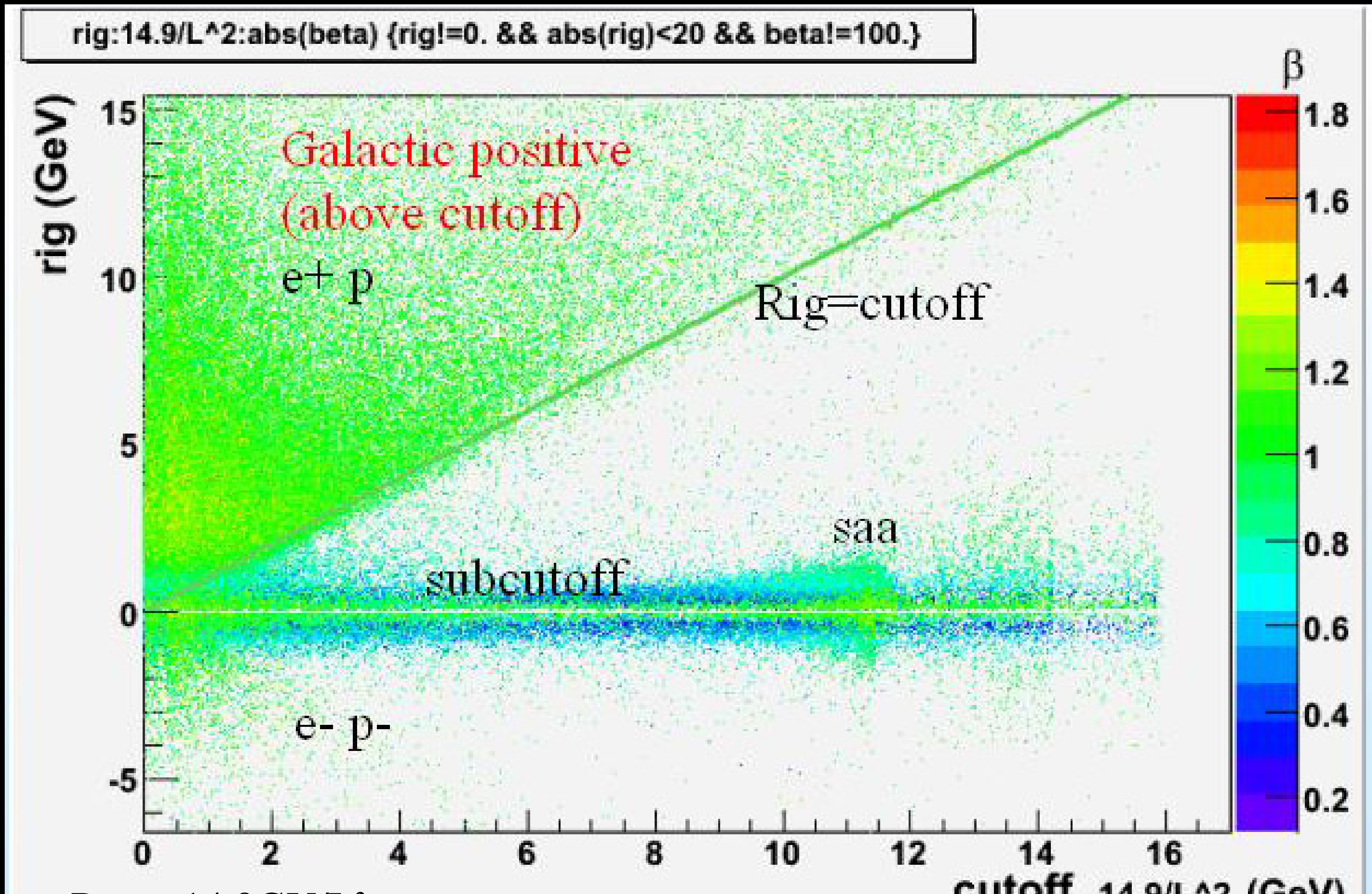
Fitted, single track
High lever arm, Nx
Rigidity R>0
Beta>.2
No anti





Selection of galactic component according to geomagnetic cutoff





$R_{cutoff}=14.9GV/L^2$

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*

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).

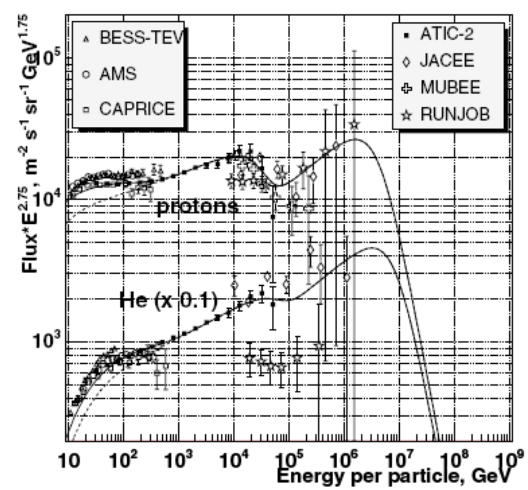
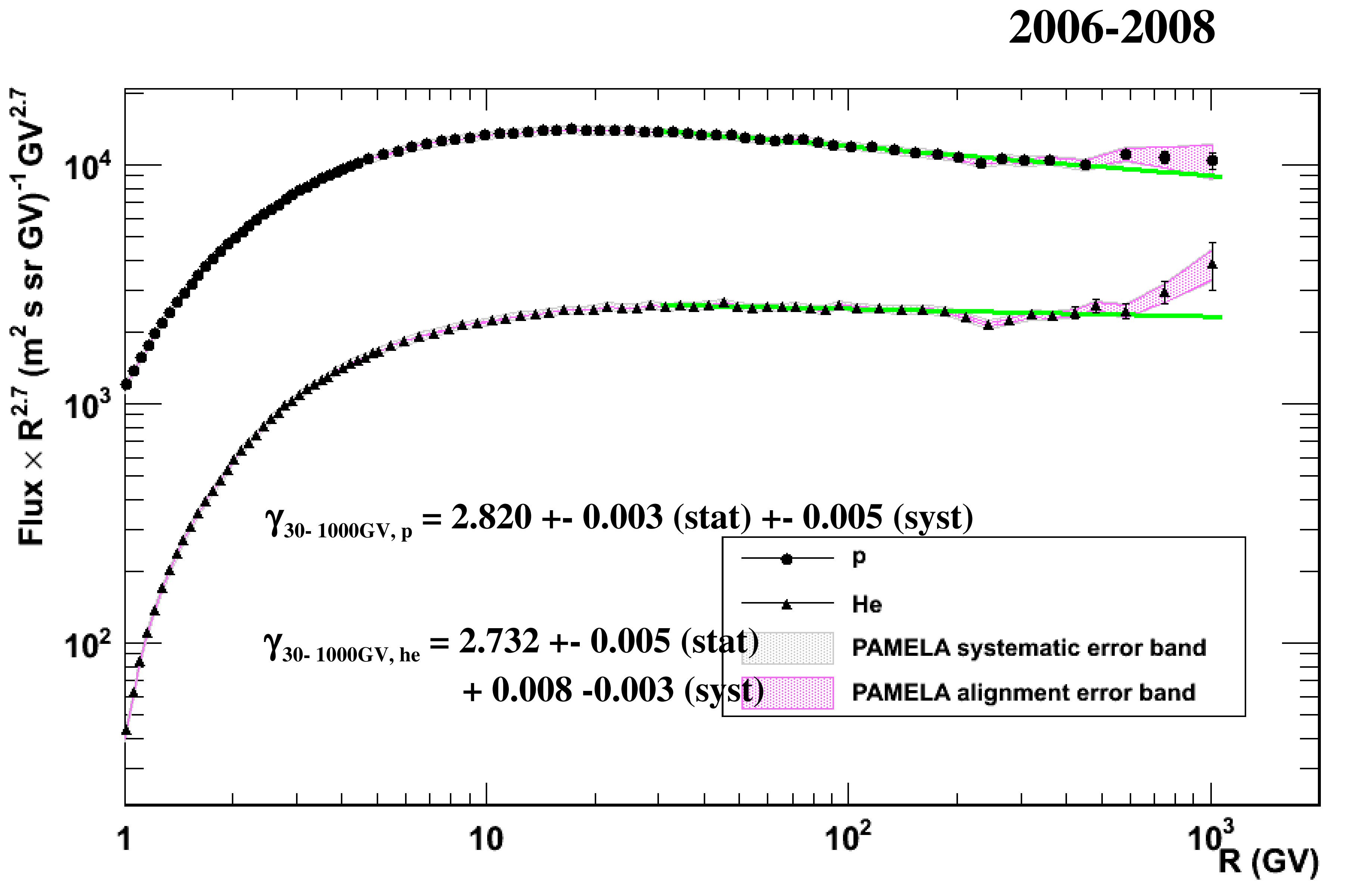


Fig. 1. Proton and He spectra. Dashed lines are described in Sect. 3, solid lines are described in Sect. 5.

Pamela galactic p and he



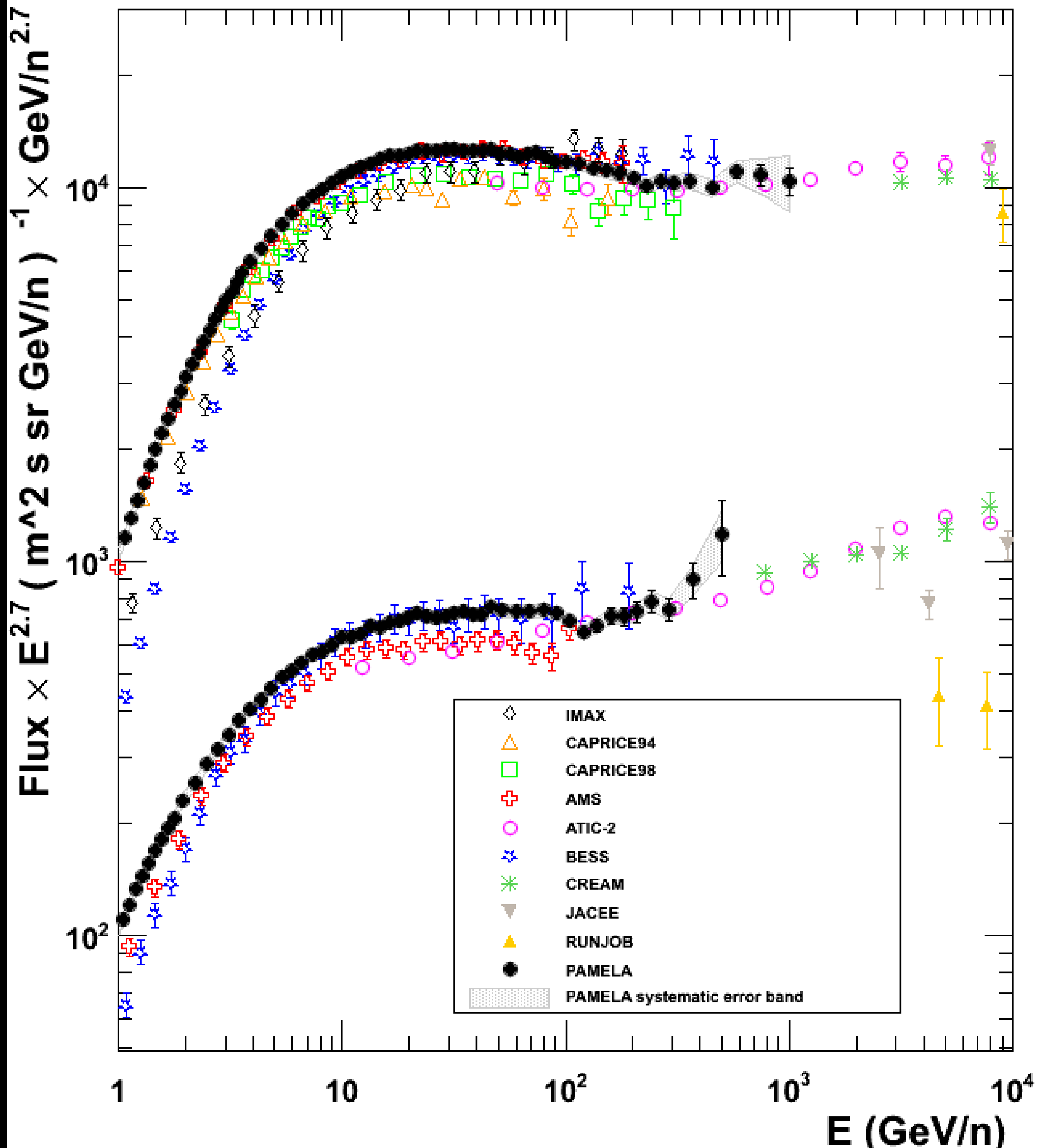
Comparison with previous experiments

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

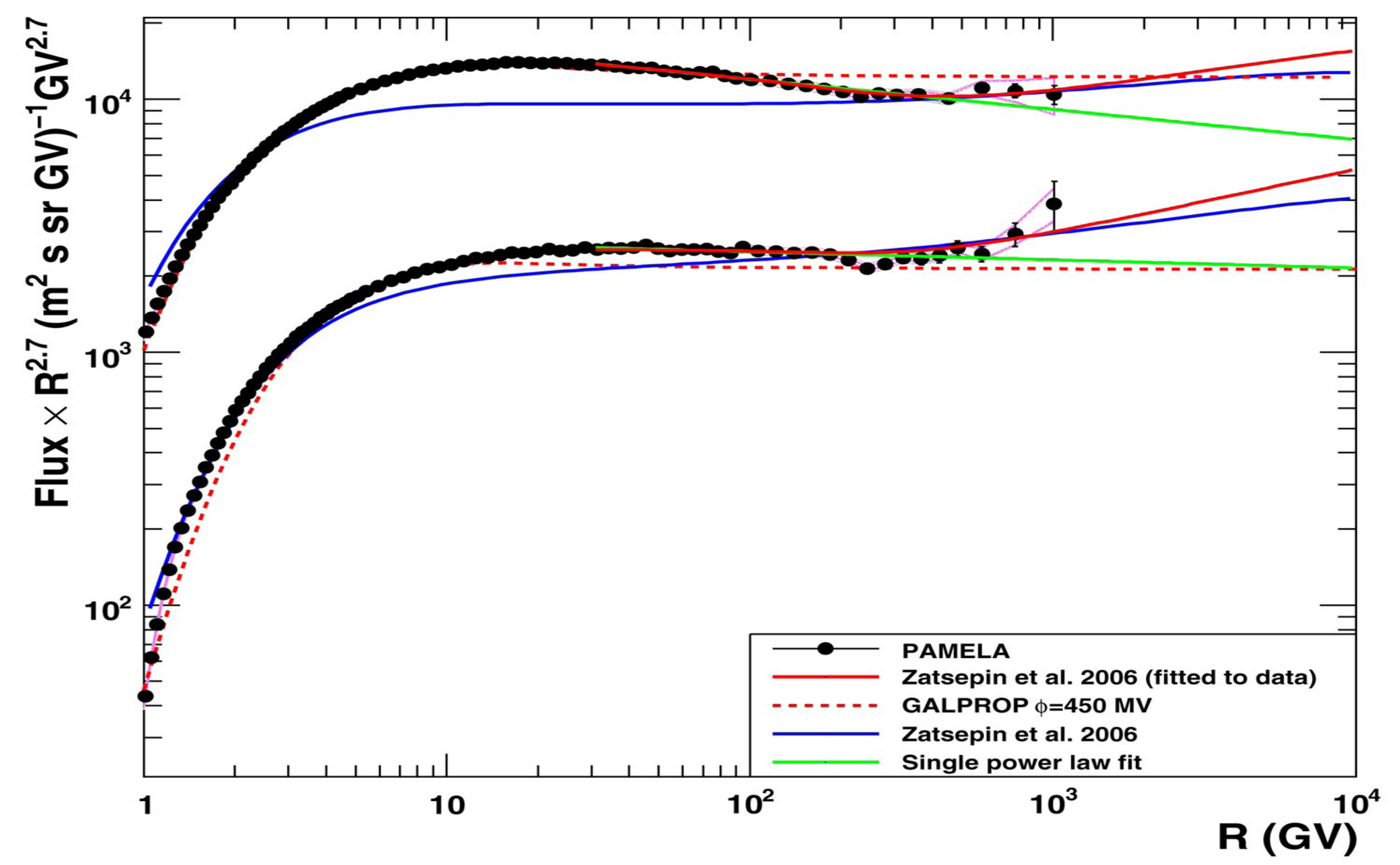
$\gamma_{30-1000GeV, p}$ = 2.782 +- 0.003 (stat) +- 0.004 (syst)

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

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



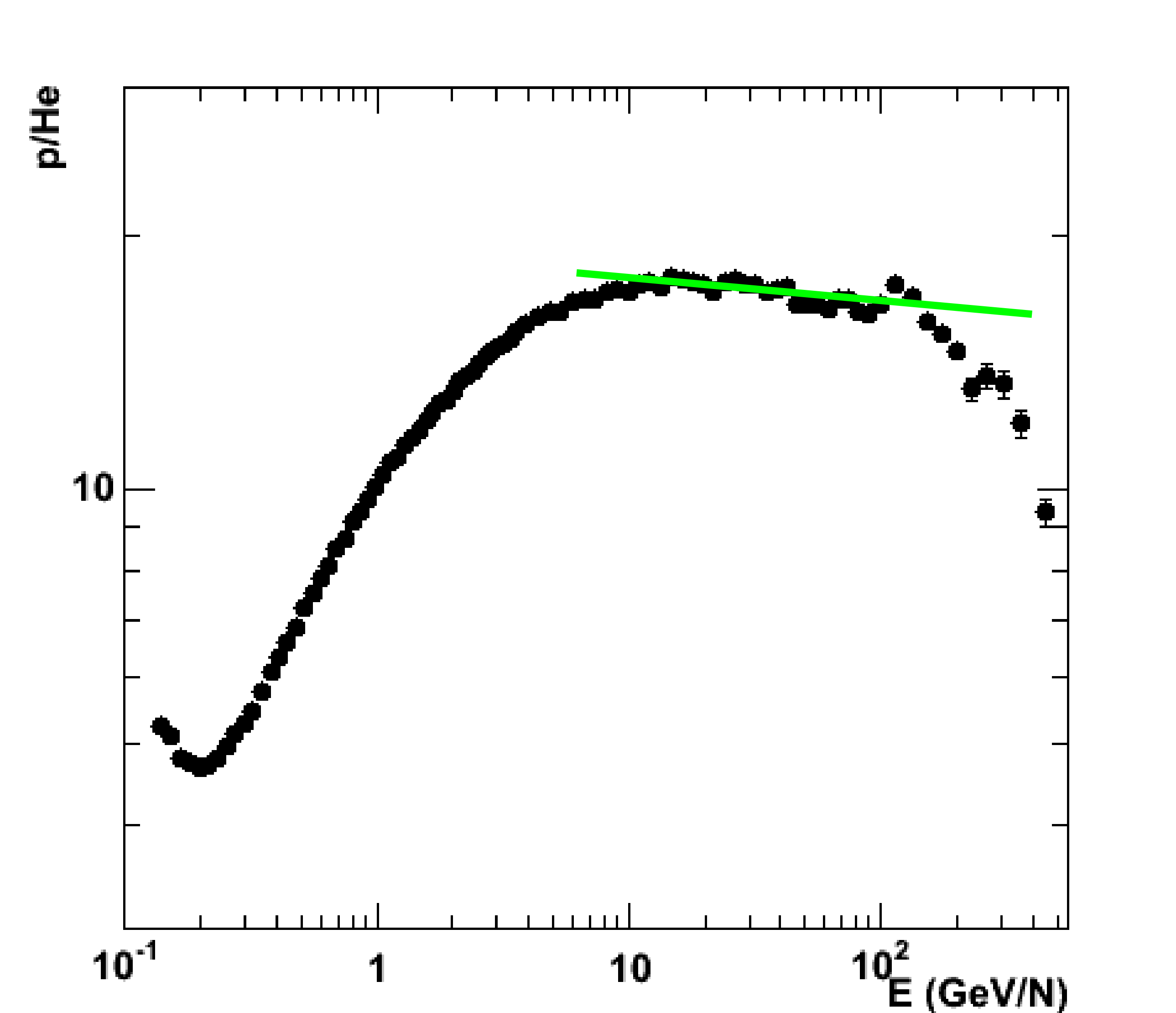
Fitting p and He spectra

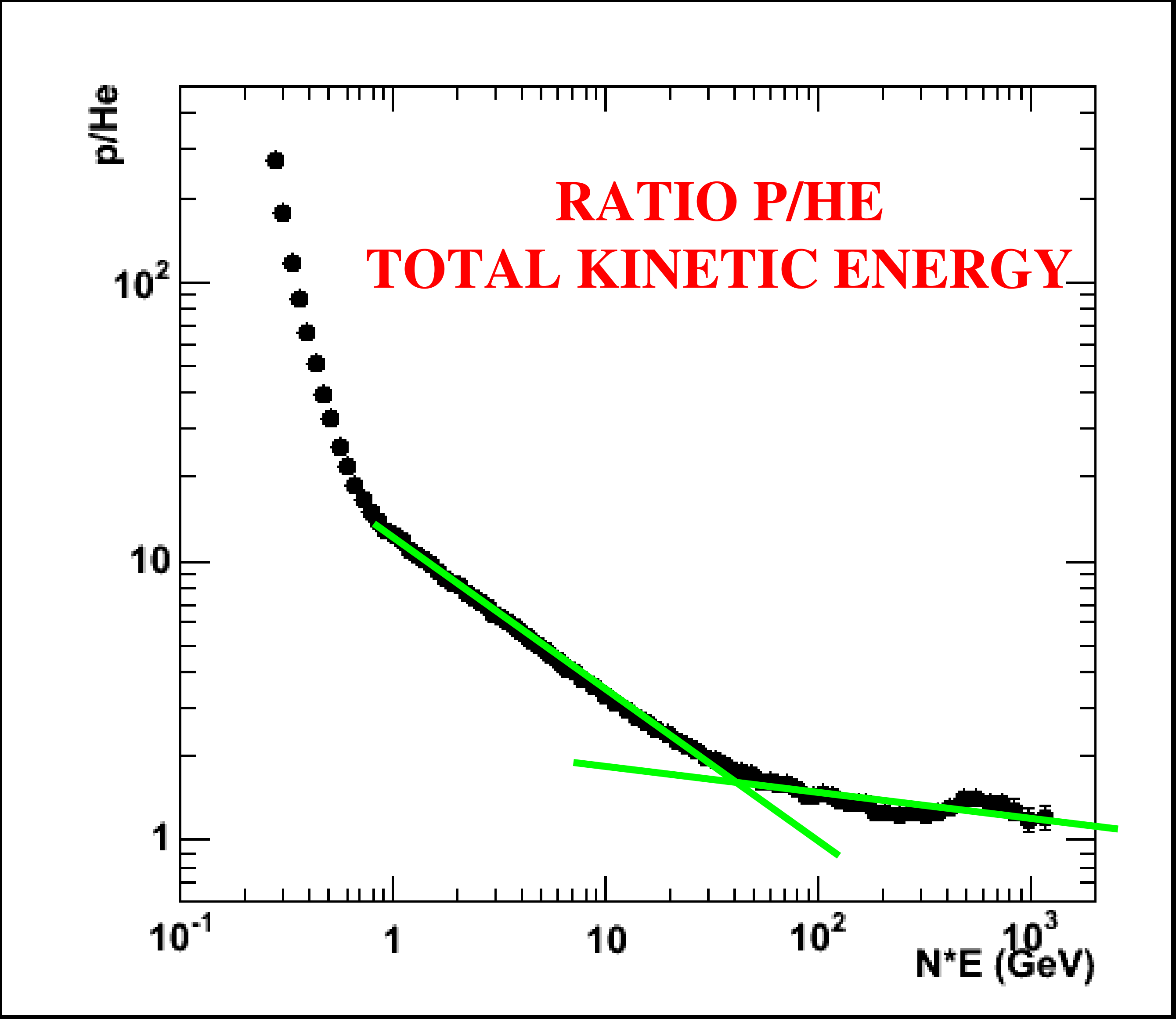


P/HE RATIO: KINETIC ENERGY/NUCLEON

Ratio has lower systematic

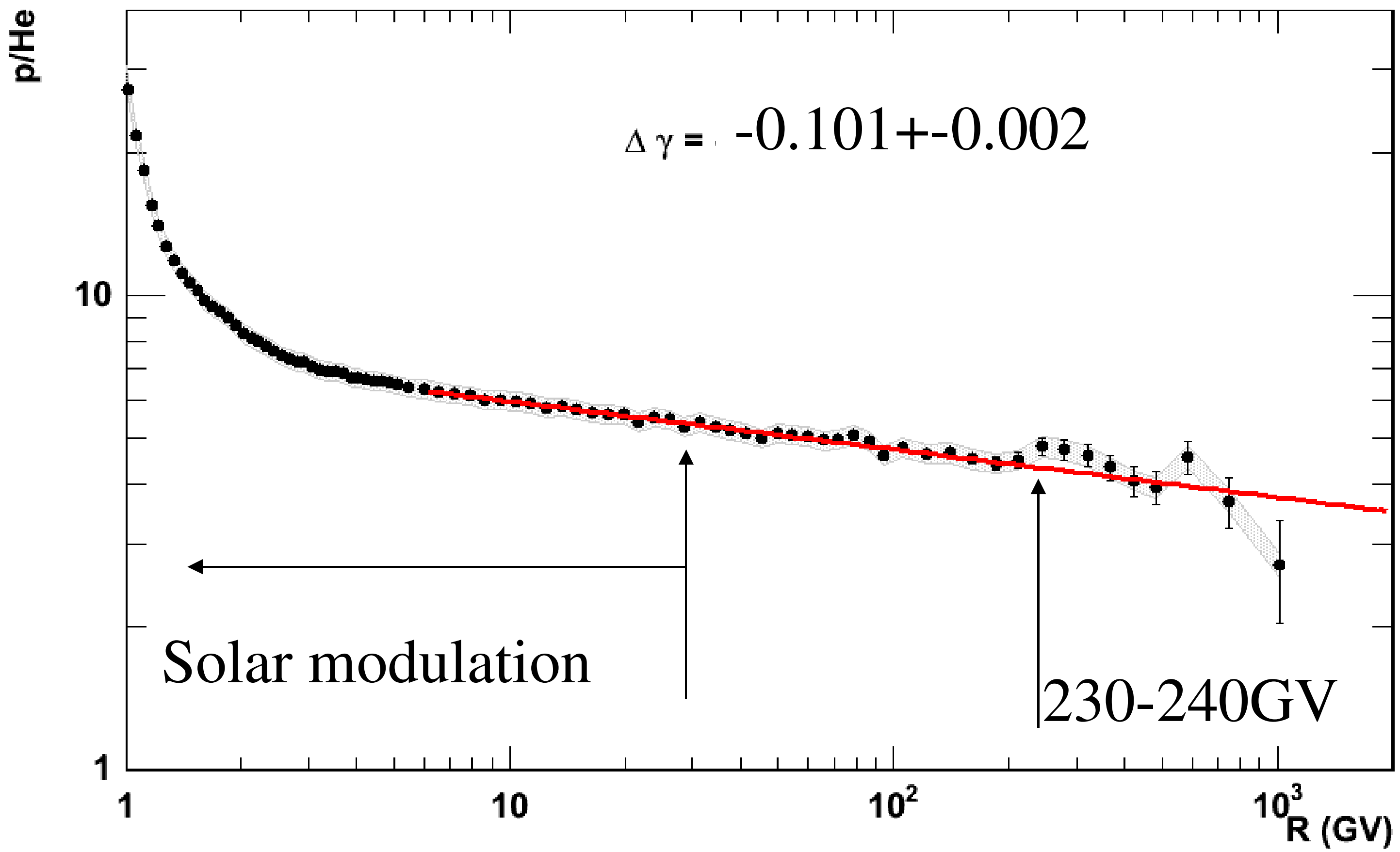
Less dependent from solar modulation





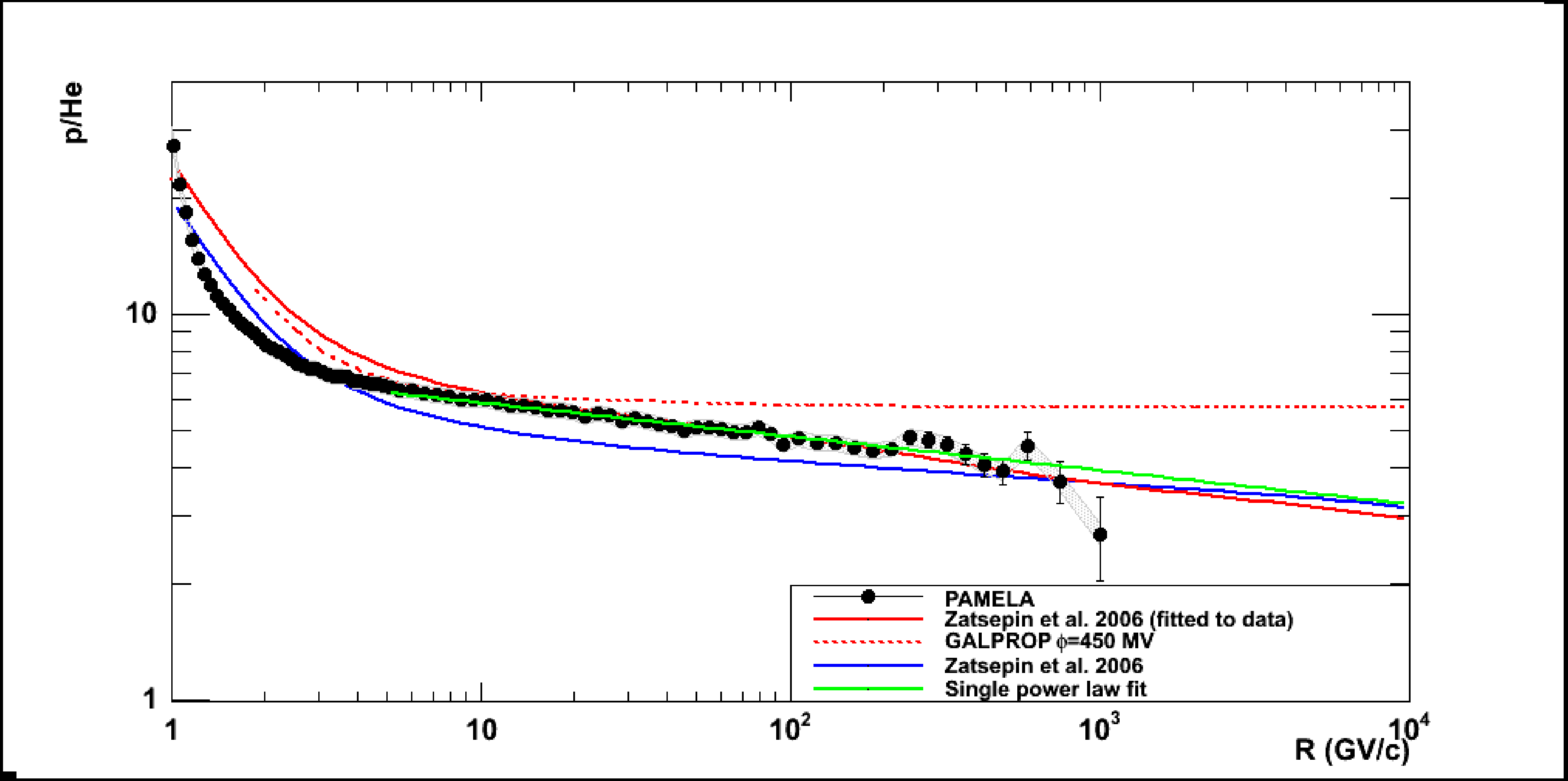
RATIO P/HE
TOTAL KINETIC ENERGY
p/He
10^2
10
1
10^{-1}
1
10
10^2
10^3
N*E (GeV)

Ratio P/He: Rigidity

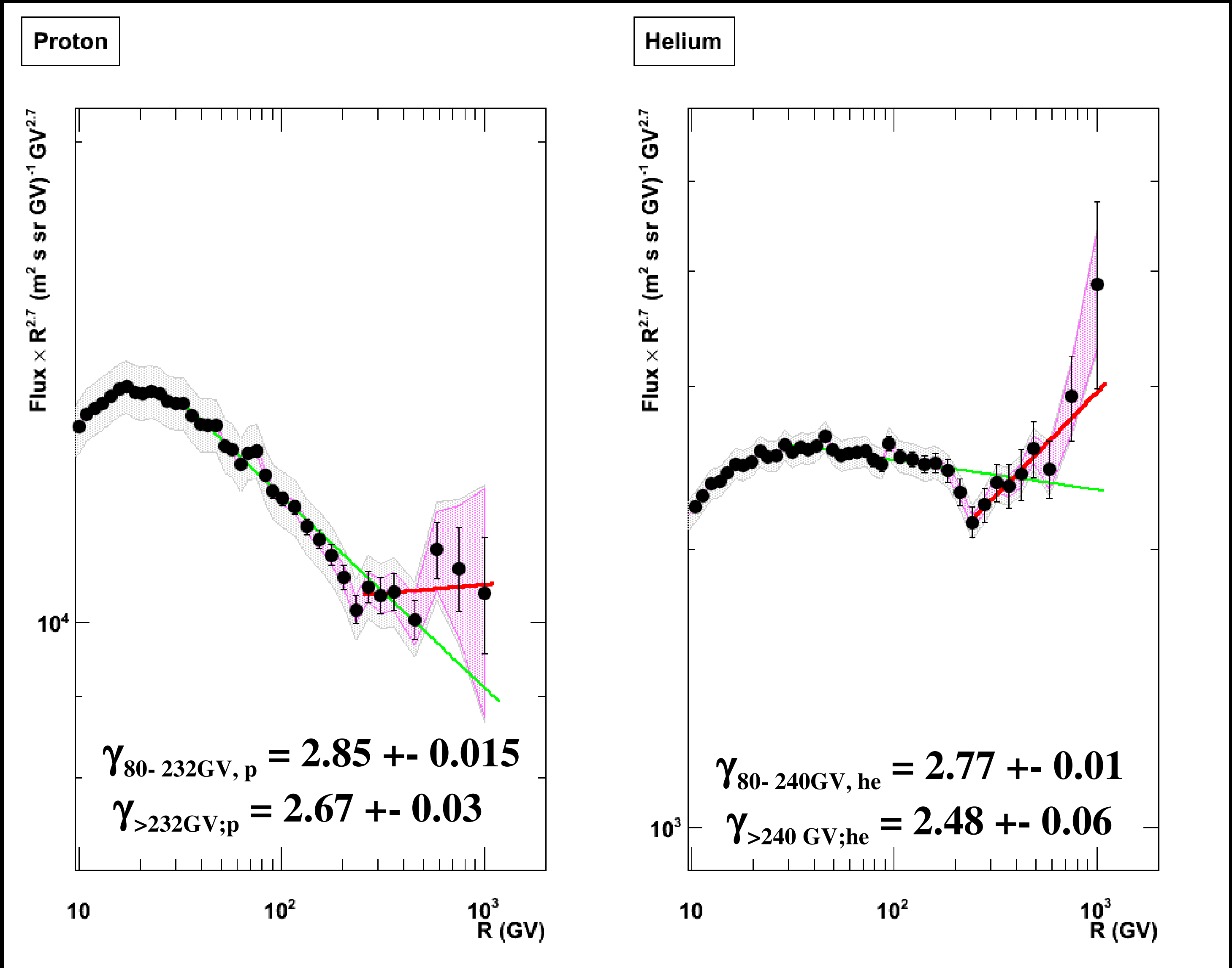


- Acceleration is a rigidity dependent effect
- The ratio decreases→ More He at high energies → Acceleration mechanisms or sources are different
- Measurement valid also below the (low) solar modulation

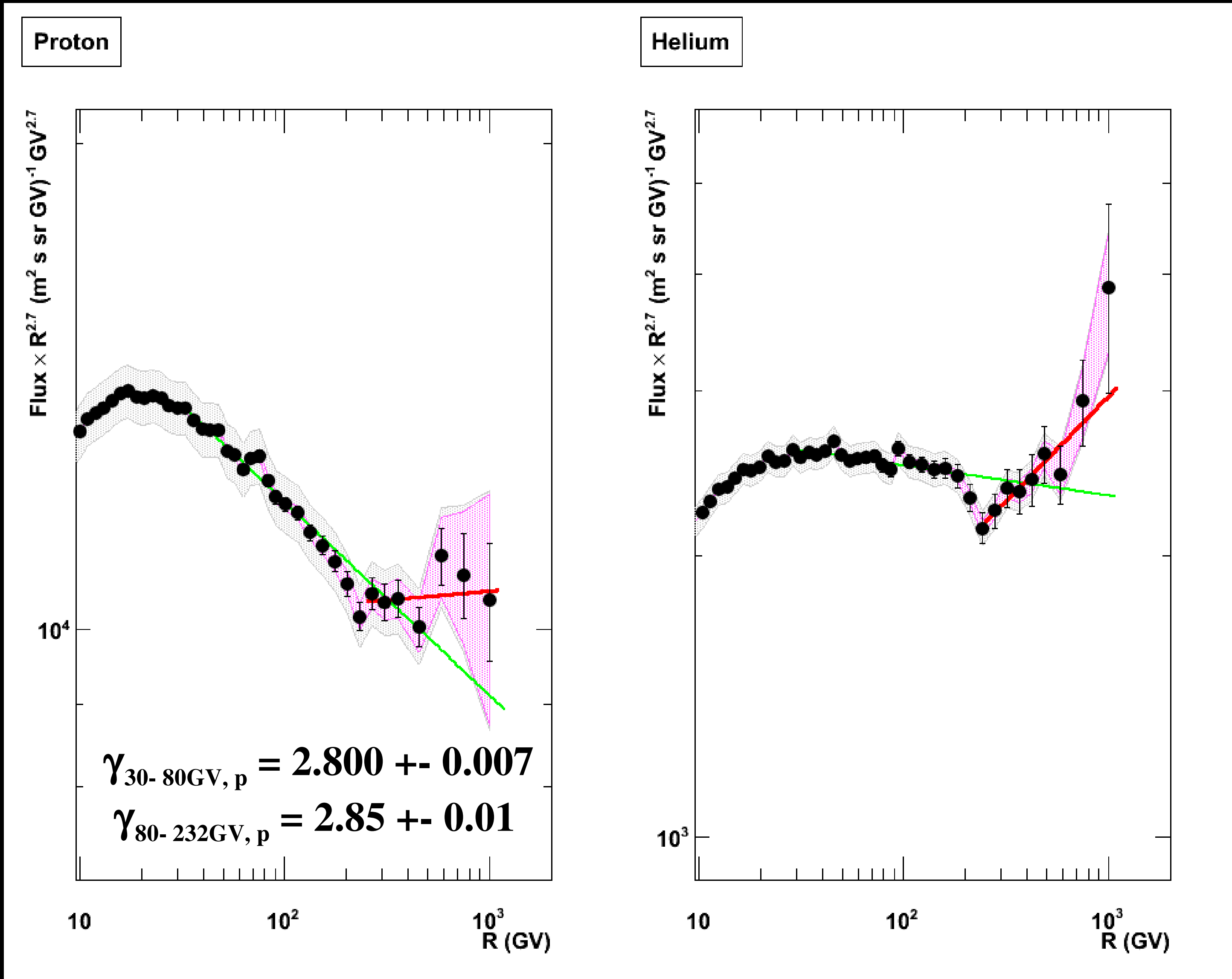
Fitting the p/he ratio



Deviations from the power law: >230-240 GV



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

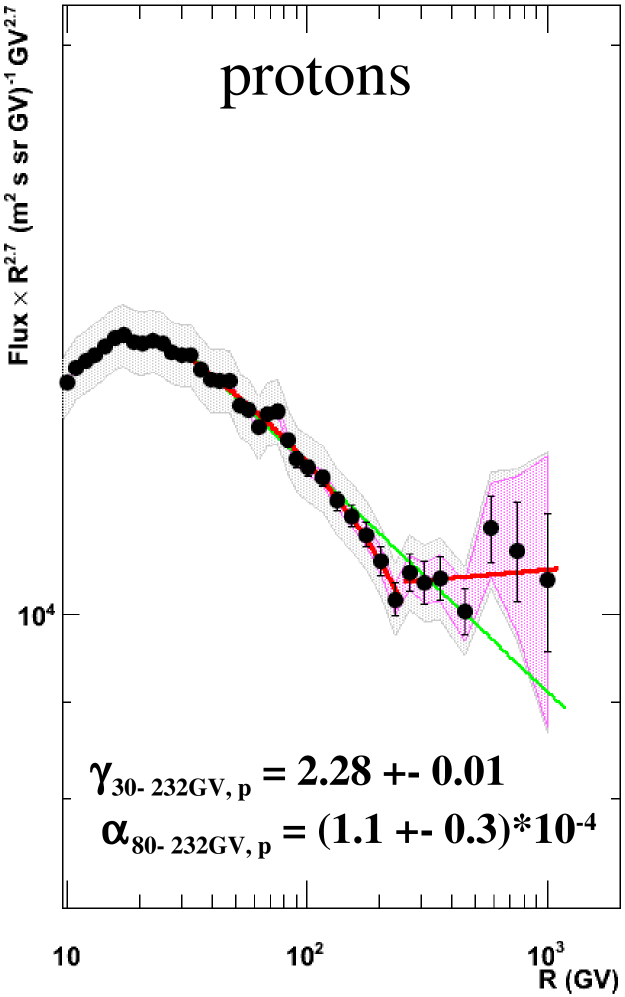


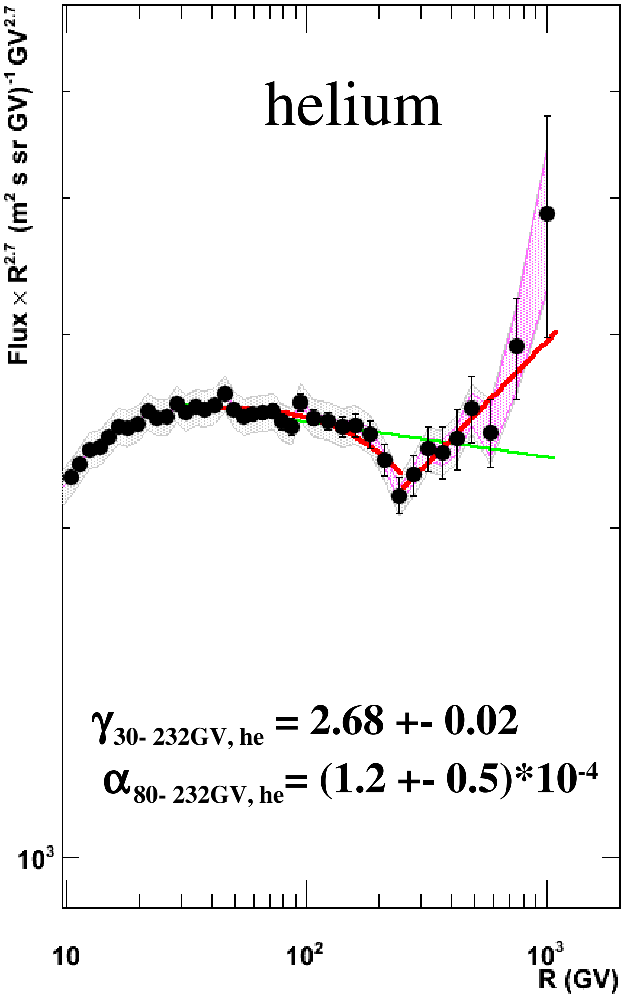
1. Additional source(s) above 240 GV
2. Fisher and T student test reject single power law to better than 99.7 CL

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

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

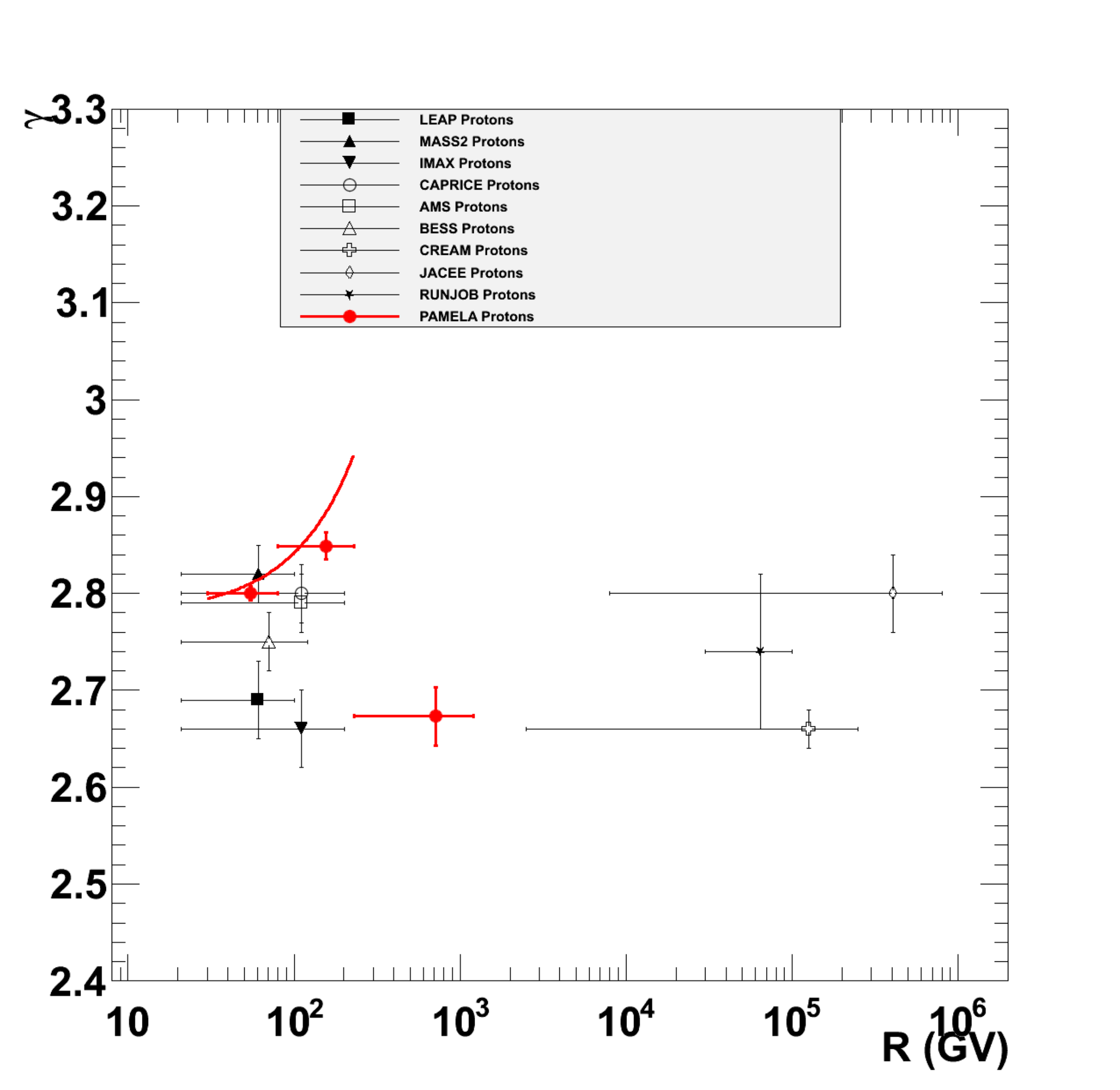
$$\gamma_R(R) = \frac{dlog(\Phi_R)}{dlog(R)} = -\gamma_0 + \alpha(1 - \frac{R}{R_0}(logR + 1))$$



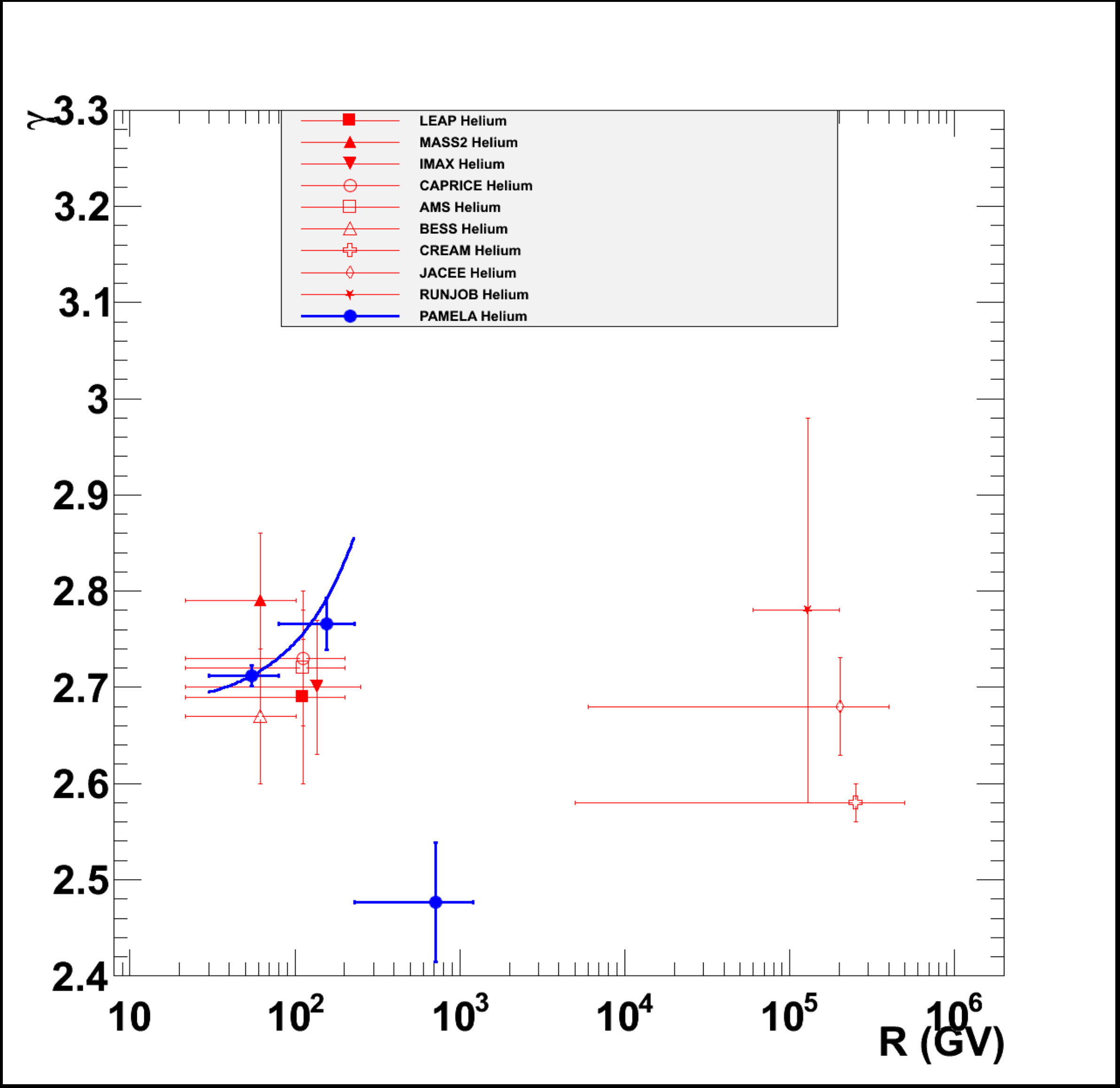


- The spectrum softens at 30-240 GV
- Single power law is also ruled out at lower rigidities

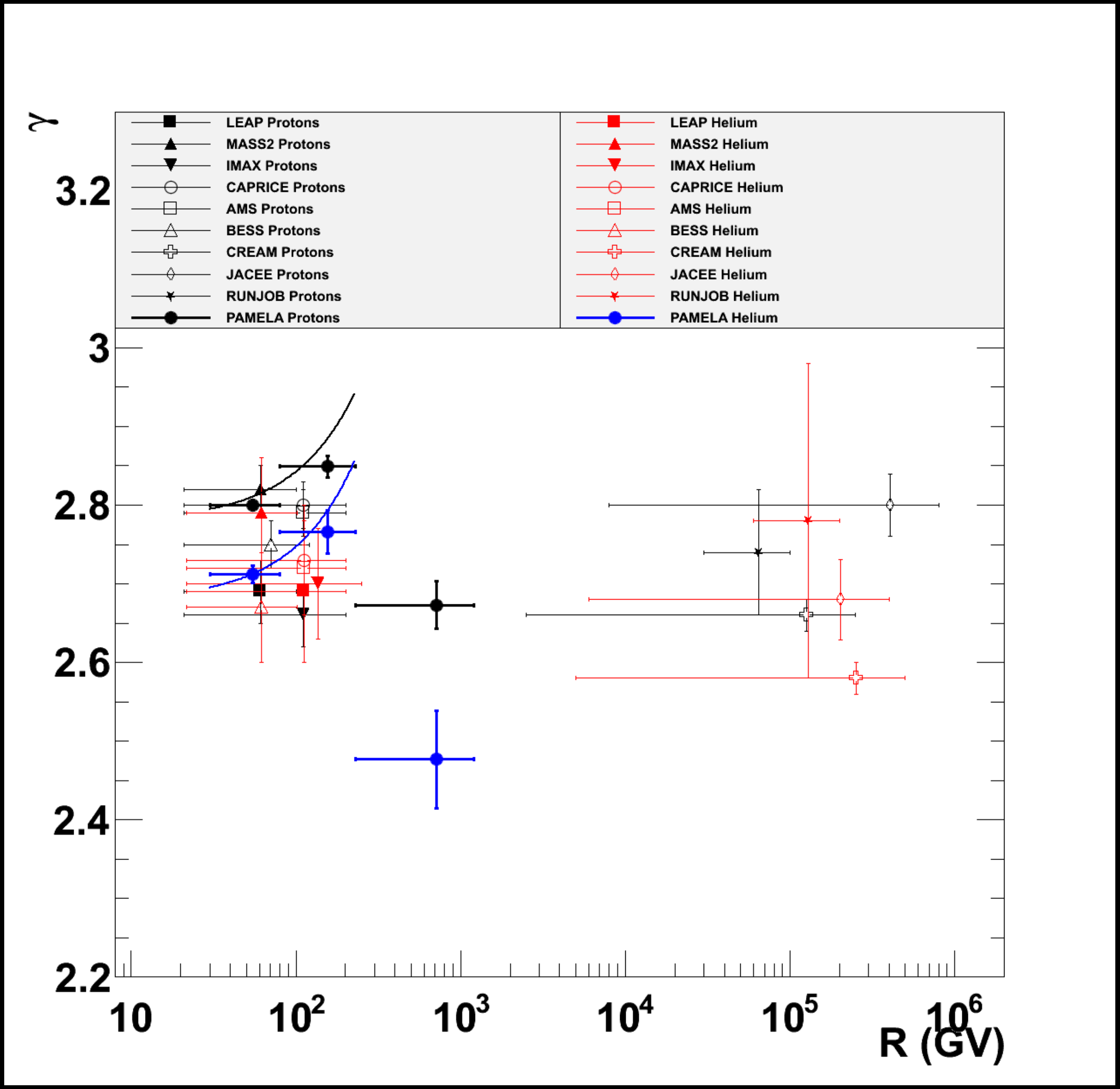
Proton spectral indexes



Helium spectral indexes



Proton and helium comparison



At higher energies: CREAM balloon data

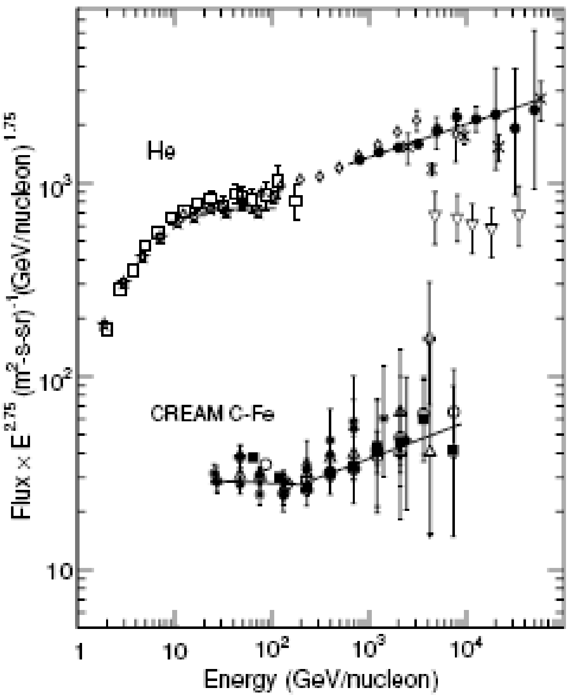


Figure 5. Broken power-law fit to helium and heavier nuclei data. The lines for helium represent a power-law fit to AMS (open stars) and CREAM (filled circles) data, respectively. Also shown are helium data from other experiments: BESS (open squares), ATIC-2 (open diamonds), JACEE (X), and RUNJOB (open 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).

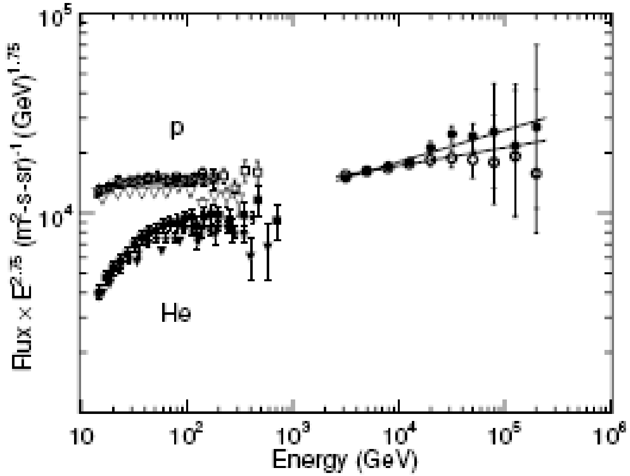


Figure 3. Measured energy spectra of cosmic-ray protons and helium nuclei. The CREAM-I spectra are compared with selected previous measurements (Alcaraz et al. 2000; Haino et al. 2004; Boezio et al. 2003) using open symbols for protons and filled symbols for helium: CREAM (circles), AMS (stars), BESS (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.

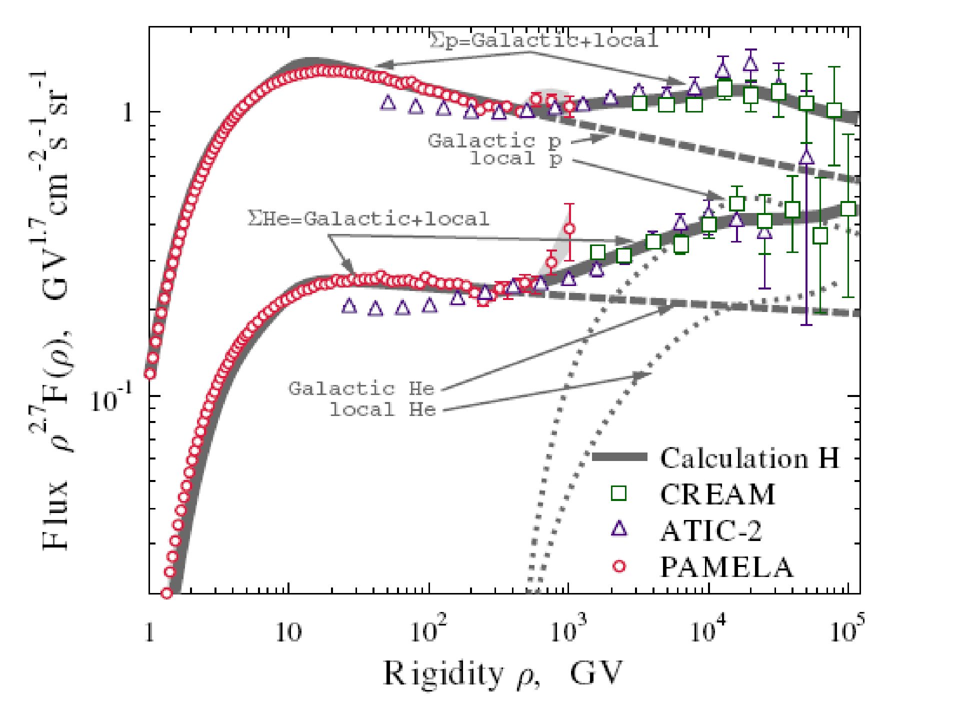
ApJL 2010

200 GeV/n (PAMELA at 120 GeV/n)

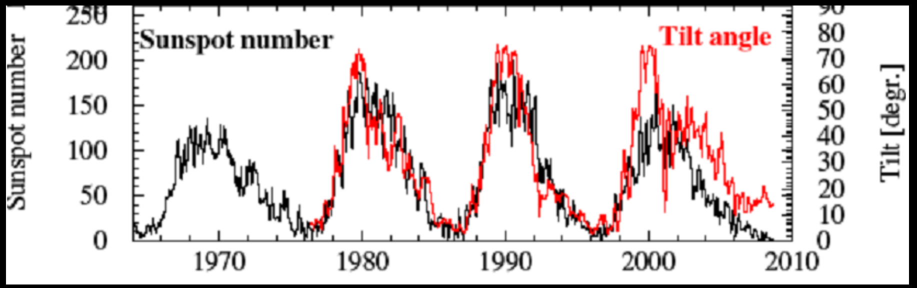
Indirect p, He Direct C-Fe

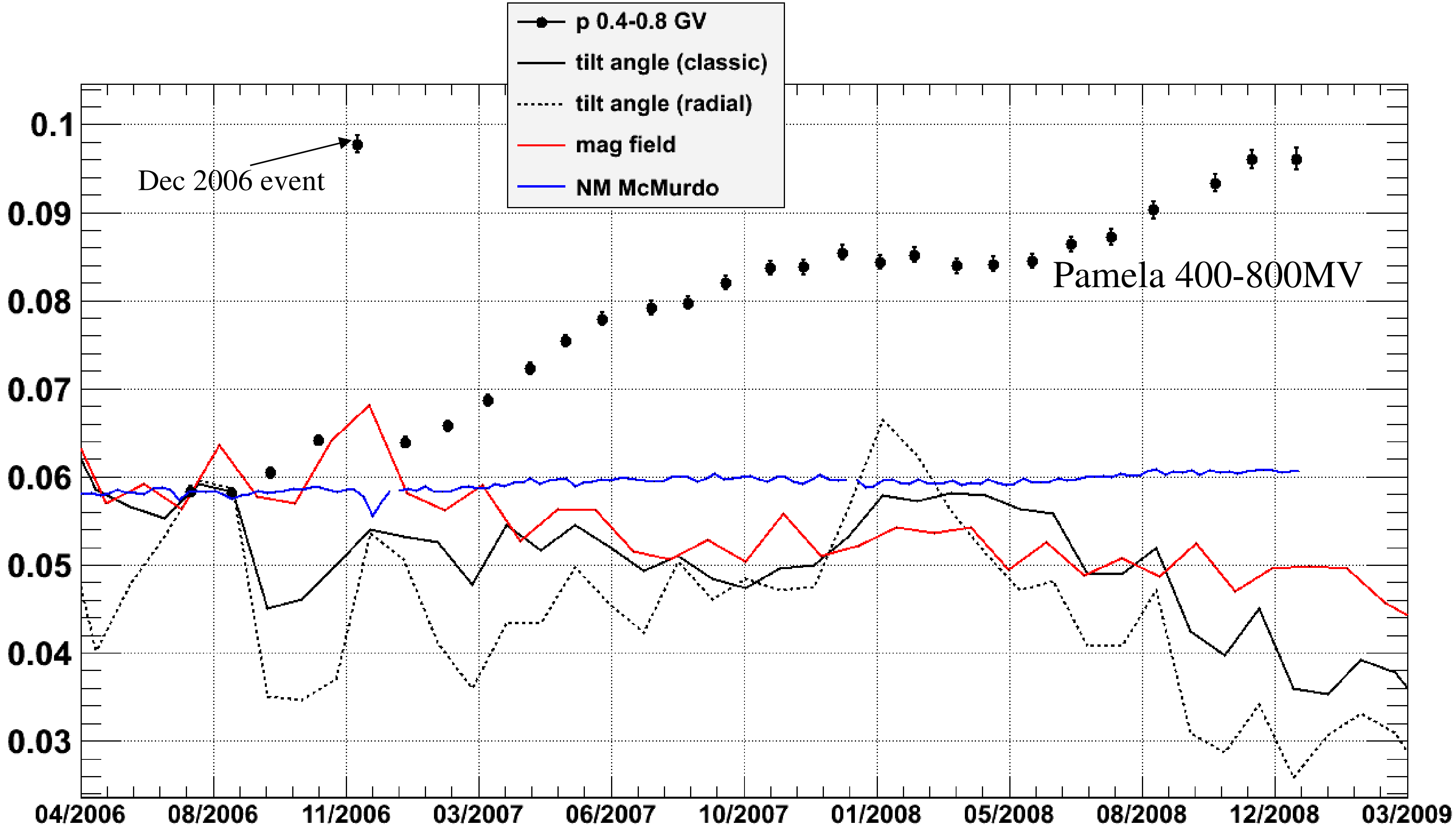
Various hyopotesis

- Additional Source *Wolfendale 2011*
- Spallation *Blasi & Amato 2011*
- Weak local component (+ others) *Vladimirov, Johanesson, Moskalenko 2011*

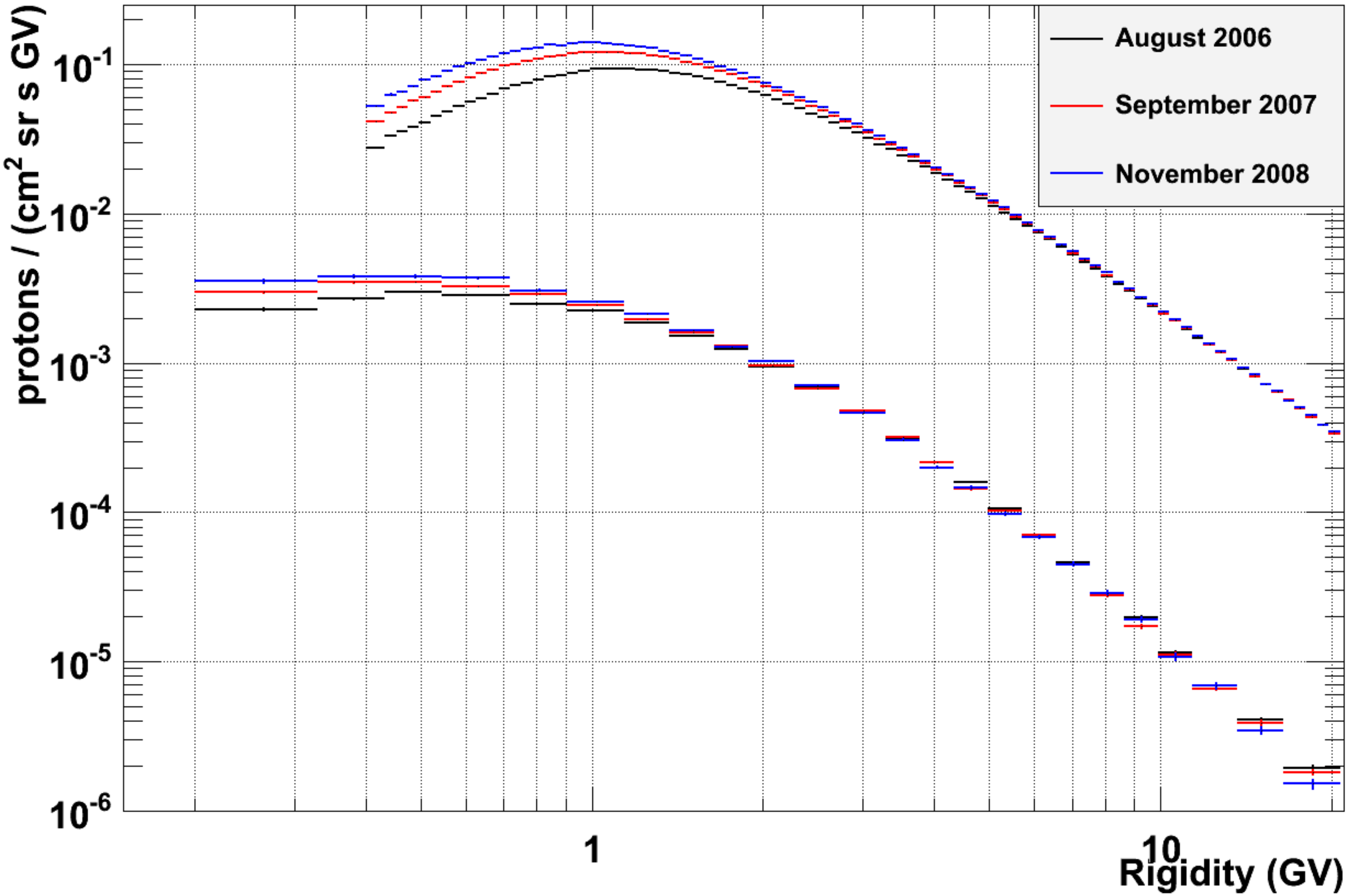


Time evolution of Pamela low energy proton flux





Solar modulation: P and e



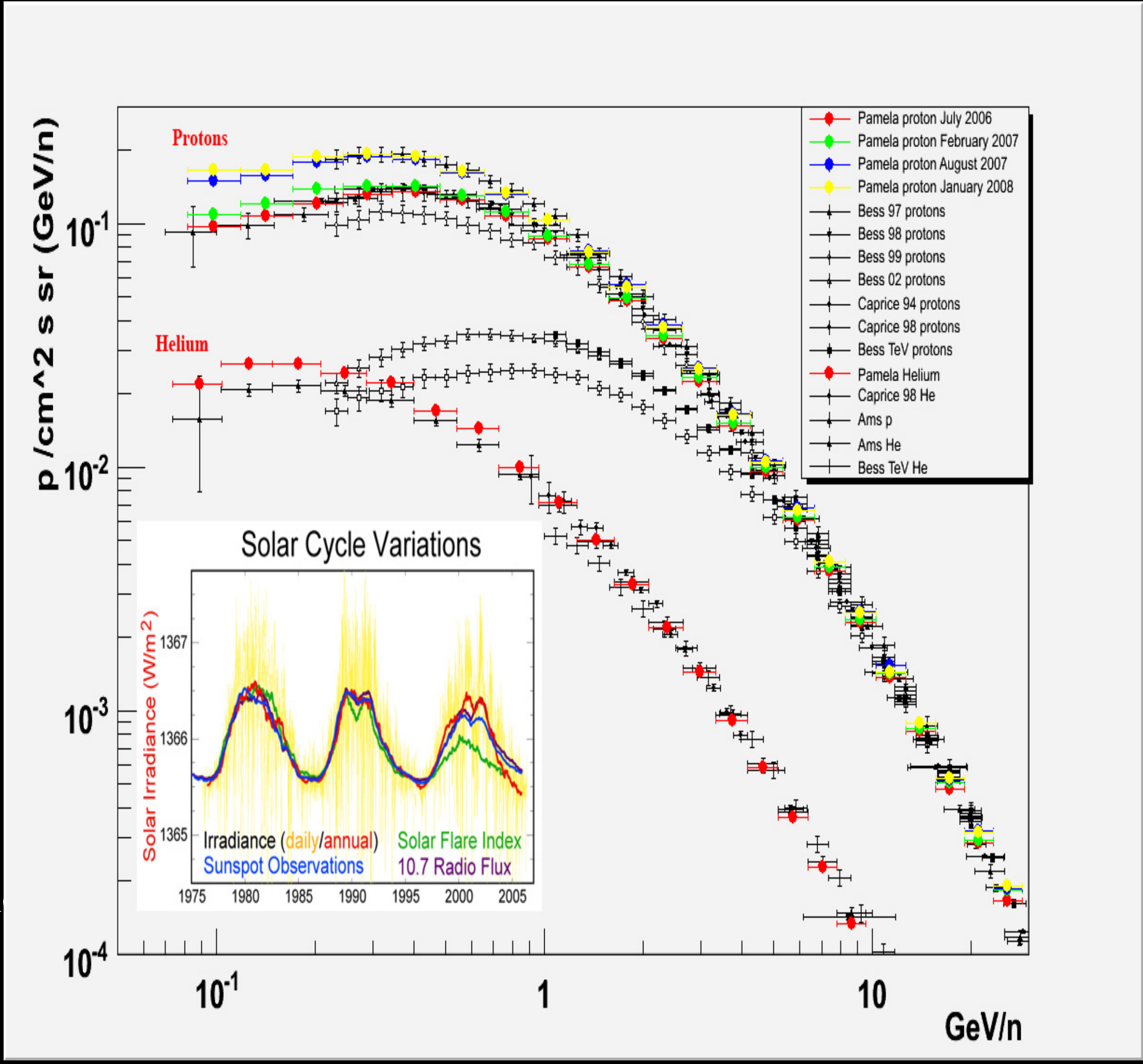
Solar modulation at minimum of solar cycle XXIII years 2006-2008

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

p/(cm² s sr GV)

Spectral index

2.76 ±0.01



Solar modulation parameter

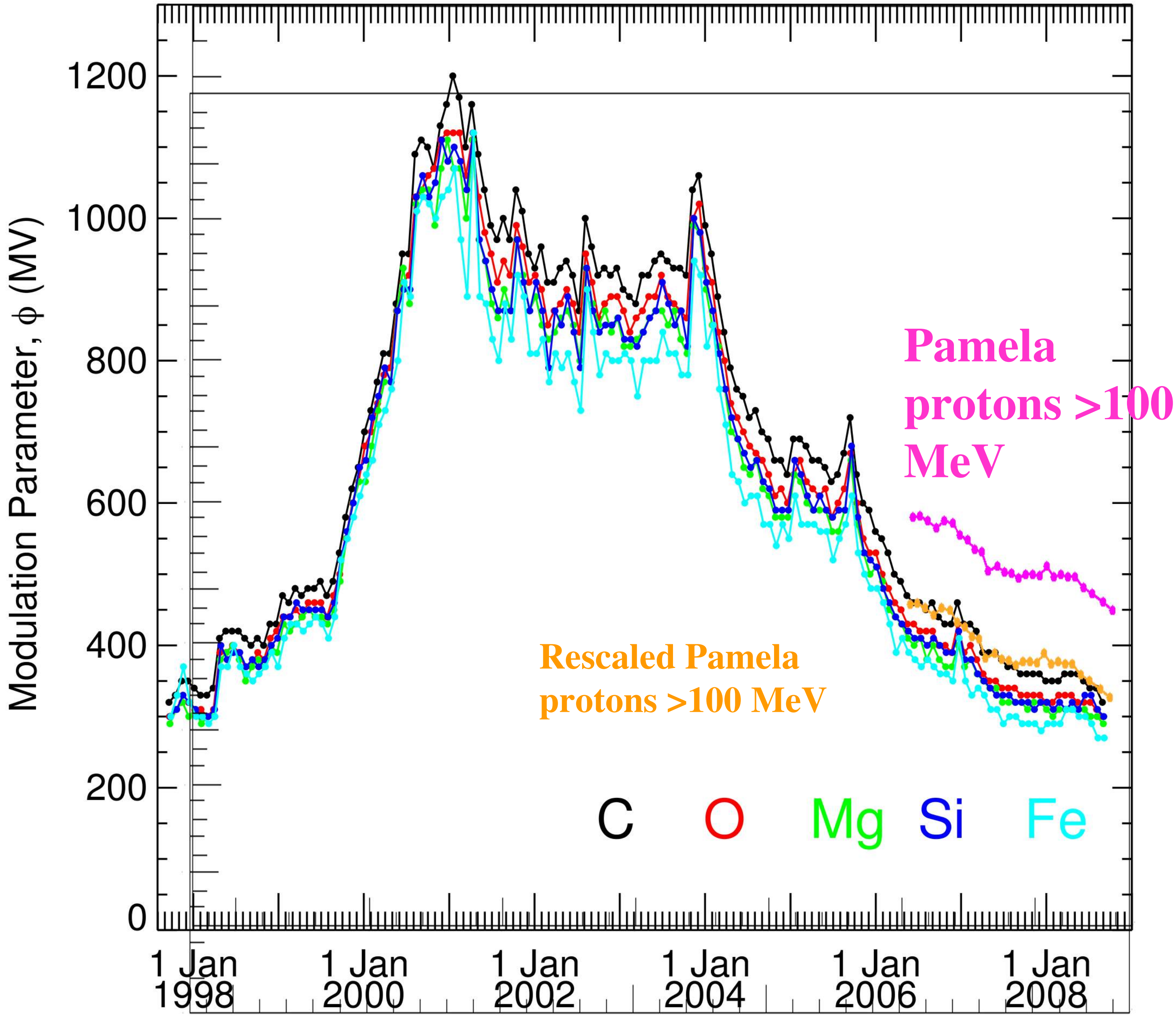
ϕ(GV)

JUL06 5.81-01 ± 2e-03

DEC07 5.00-01 ± 2-03

dec08 4.82-01 ± 3-03

But Spherical approximation is n
sufficient for charge dependent
solar modulation



Modulation Parameter, φ (MV)
1200
1000
800
600
400
200
0
1 Jan 1998
1 Jan 2000
1 Jan 2002
1 Jan 2004
1 Jan 2006
1 Jan 2008
Pamela protons >100 MeV
Rescaled Pamela protons >100 MeV
C
O
Mg
Si
Fe

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

http://pamela.roma2.infn.it