Cosmic Rays Investigation by the PAMELA experiment

Beatrice Panico
INFN Naples
on behalf of PAMELA collaboration

INFN
Istituto Nazionale di Fisica Nucleare

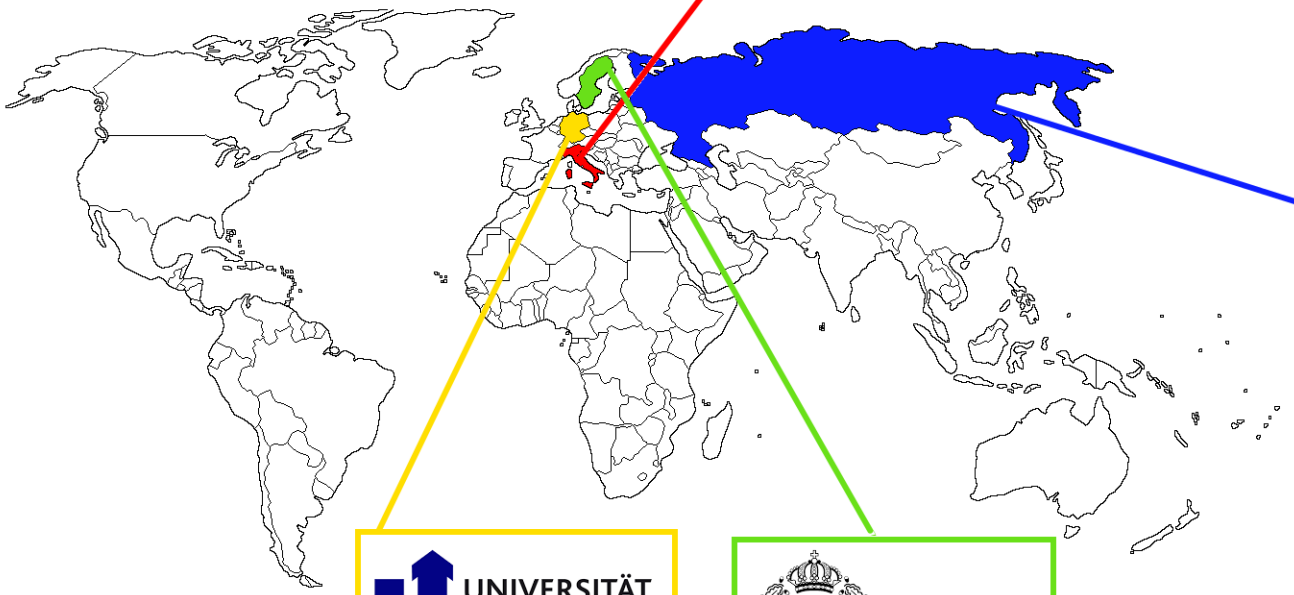
The PAMELA experiment

Payload for **A**ntimatter/**M**atter **E**xploration and **L**ight-nuclei **A**strophysics

- ✓ Search for antimatter: help solving the cosmological problem about the existence of the **apparent asymmetry between matter and antimatter**;
- ✓ Search for signatures of exotic processes **connected to the Dark Matter problem**;
- ✓ Study of cosmic-ray propagation, providing **new high precision data about CR primary and secondary fluxes**, to constrain on current acceleration and diffusion models of cosmic rays in the Galaxy
- ✓ Study solar physics and solar modulation, **investigating the heliosphere**
- ✓ Study terrestrial magnetosphere and **Earth magnetosphere**

The PAMELA collaboration

Naples Bari Florence Frascati Rome Trieste CNR, Florence



Germany

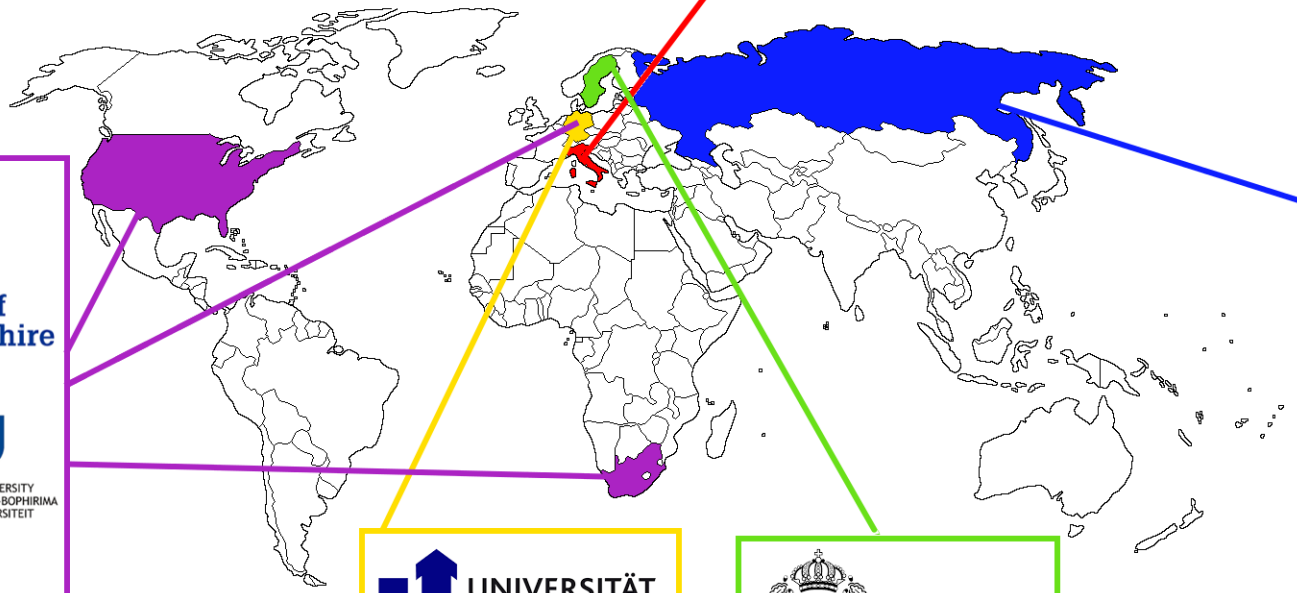
Sweden

Moscow

St. Petersburg

The PAMELA collaboration

Naples Bari Florence Frascati Rome Trieste CNR, Florence



External collaboration

Germany

Sweden

Moscow

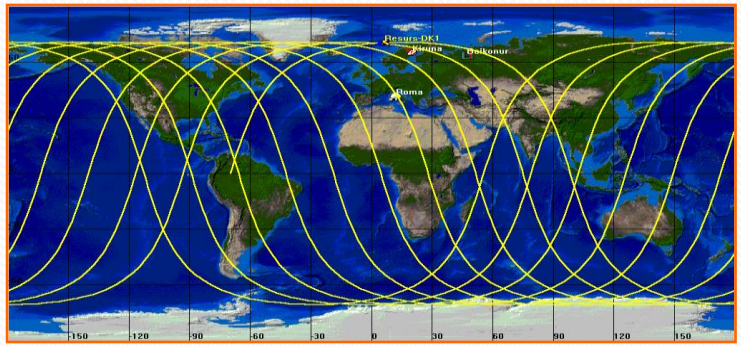
St. Petersburg

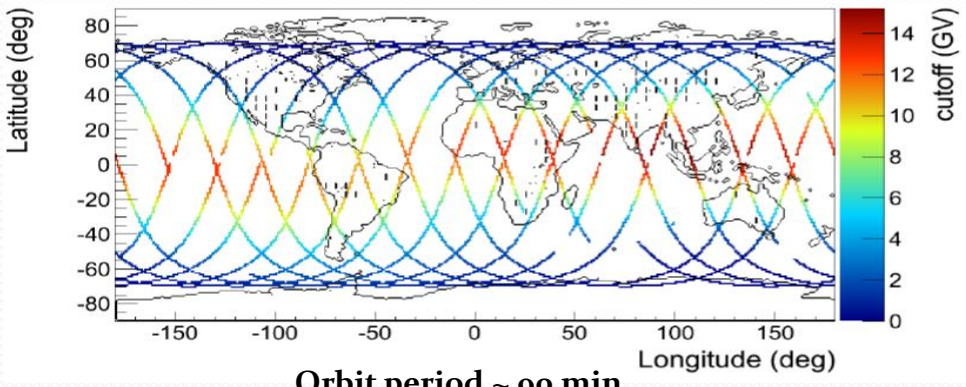
Launch: 15th June 2006, 0800 UTC

The PAMELA experiment

Resurs-DKI - multi-spectral imaging of Earth's surface
PAMELA is mounted inside a pressurized container of the Resurs DK-1 spacecraft

- Launched on 15th June 2006
- In nearly continuous data-taking mode since January 2016 when downlink operation were terminated





Orbit period ~ 90 min

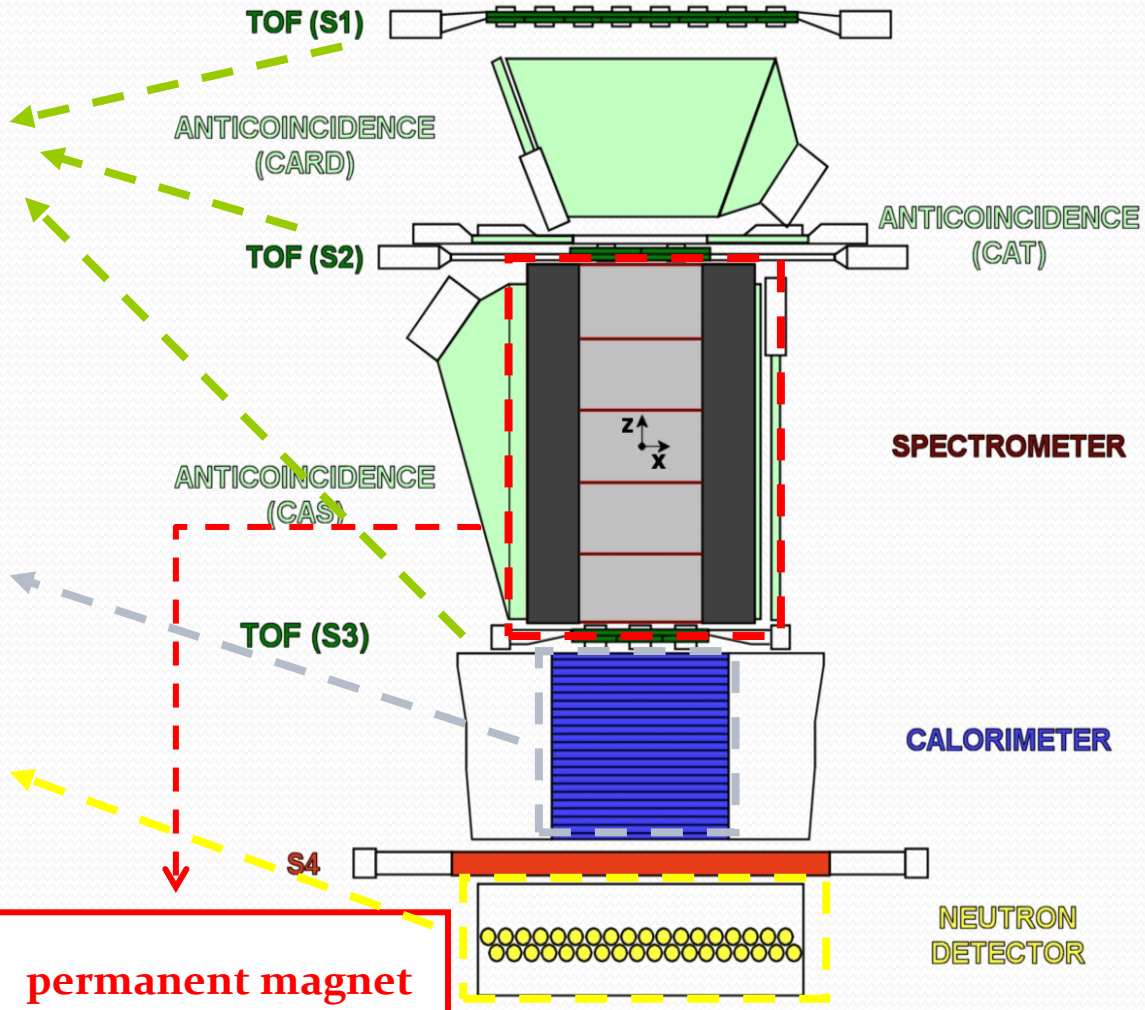
- ✔ Quasi polar and elliptical orbit
- ✔ Inclination ~ 70°
- ✔ Altitude ~ 300 - 600 km
- ✔ From 2010 circular orbit

The PAMELA experiment

Time-Of-Flight
plastic scintillators + PMT:
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX

Electromagnetic calorimeter
W/Si sampling (16.3 Xo, 0.6 λI)
- Discrimination e+ / p, anti-p / e^- (shower topology)
- Direct E measurement for e^-

Neutron detector
36 He^3 counters :
- High-energy e/h discrimination



Spectrometer
microstrip silicon tracking system + permanent magnet
It provides:
- ***Magnetic rigidity*** → R = pc/Ze
- ***Charge sign***
- ***Charge value from dE/dx***

GF: 21.6 cm² sr
Massa: 470 kg
Dimensioni: 130 x 70 x 70 cm³
Power Budget: 360 W

PAMELA overall results

- **Results span 4 decades in energy and 13 in flux**

Contents lists available at ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

The PAMELA Mission: Heralding a new era in precision cosmic ray physics

O. Adriani [a,b], G.C. Barbarino [c,d], G.A. Bazilevskaya [e], R. Bellotti [f,g], M. Boezio [h], E.A. Bogomolov [i], M. Bongi [a,b], V. Bonvicini [h], S. Bottai [b], A. Bruno [f,g], F. Cafagna [g], D. Campana [d], R. Carbone [d,h], P. Carlson [j,k], M. Casolino [i], G. Castellini [m], M.P. De Pascale [i,n,1], C. De Santis [i,n], N. De Simone [i], V. Di Felice [i], V. Formato [h,o], A.M. Galper [p], U. Giaccari [d], A.V. Karelin [p], M.D. Kheymits [p], S.V. Koldashov [p], S. Koldobskiy [p], S.Yu. Krut'kov [i], A.N. Kvashnin [e], A. Leonov [p], V. Malakhov [p], L. Marcelli [n], M. Martucci [n,q], A.G. Mayorov [p], W. Menn [r], V.V. Mikhailov [p], E. Mocchiutti [h], A. Monaco [f,g], N. Mori [a,b], R. Munini [h,j,k,o], N. Nikonov [i,l,n], G. Osteria [d], P. Papini [b], M. Pearce [j,k], P. Picozza [i,n,*], C. Pizzolotto [h,s,t], M. Ricci [q], S.B. Ricciarini [b,m], L. Rossetto [j,k], R. Sarkar [h], M. Simon [r], R. Sparvoli [i,n], P. Spillantini [a,b], Y.I. Stozhkov [e], A. Vacchi [h], E. Vannuccini [b], G.I. Vasilyev [i], S.A. Voronov [p], J. Wu [j,k,u], Y.T. Yurkin [p], G. Zampa [h], N. Zampa [h], V.G. Zverev [p]

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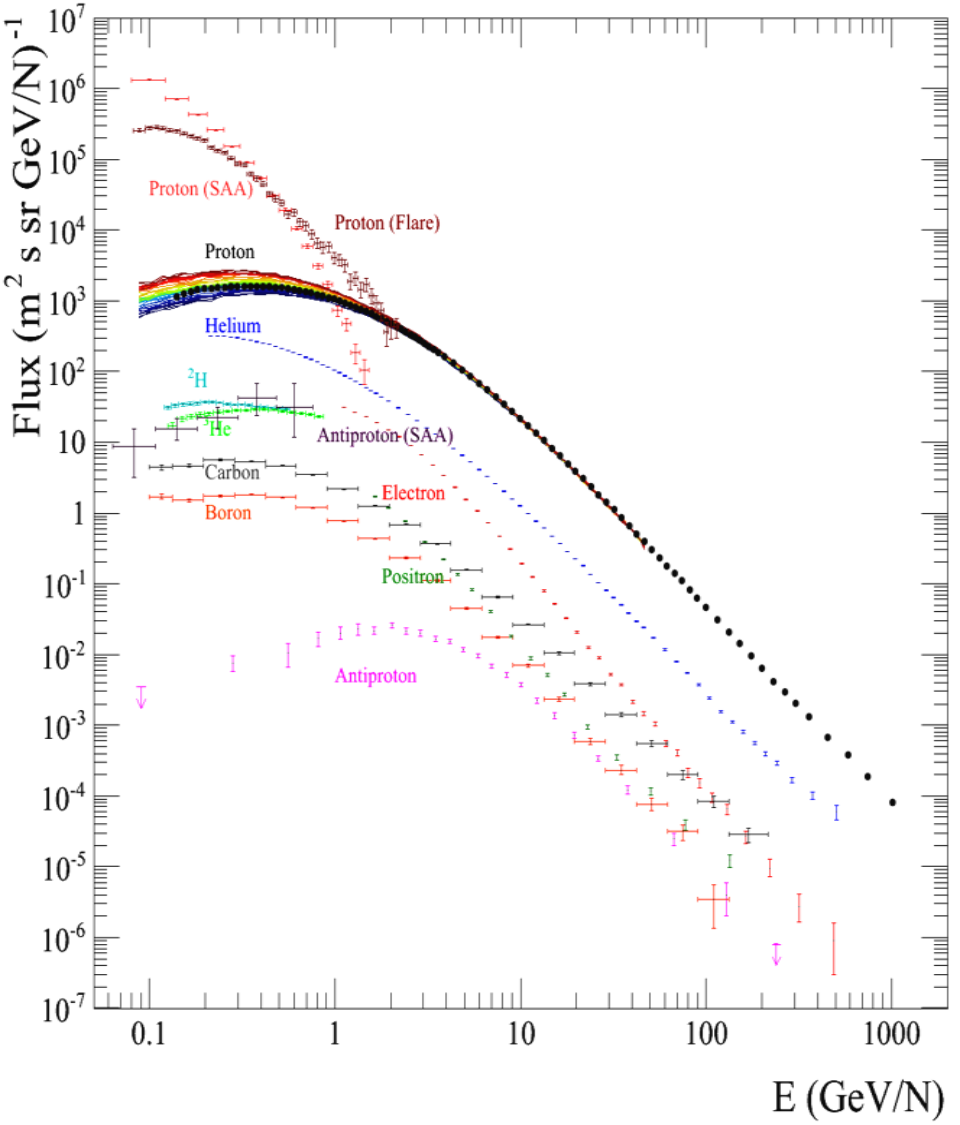
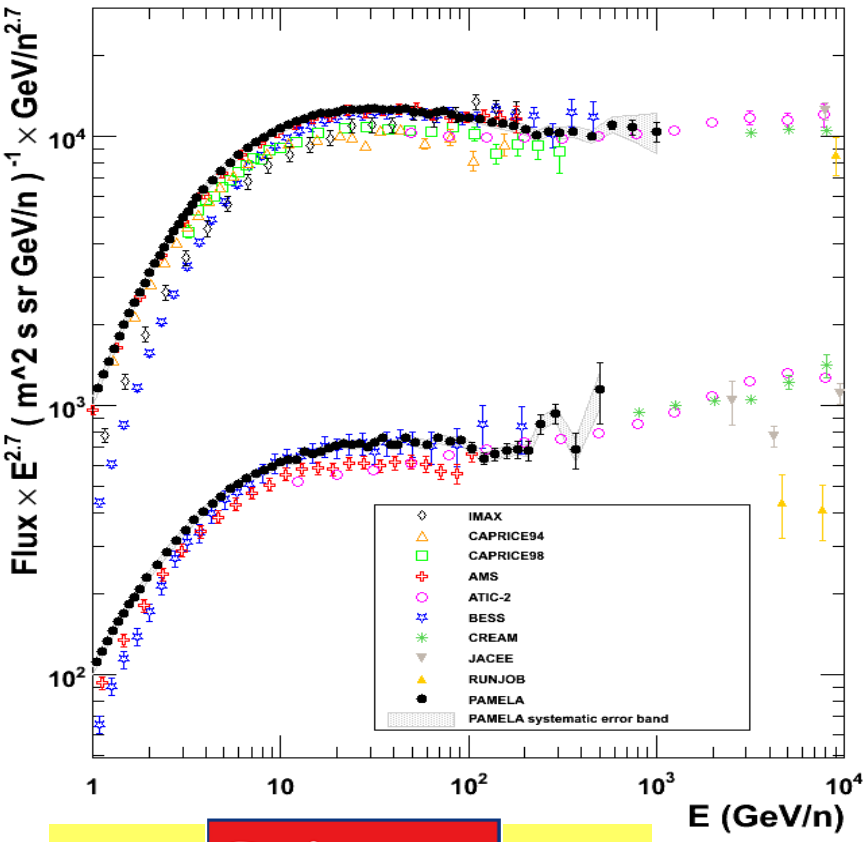


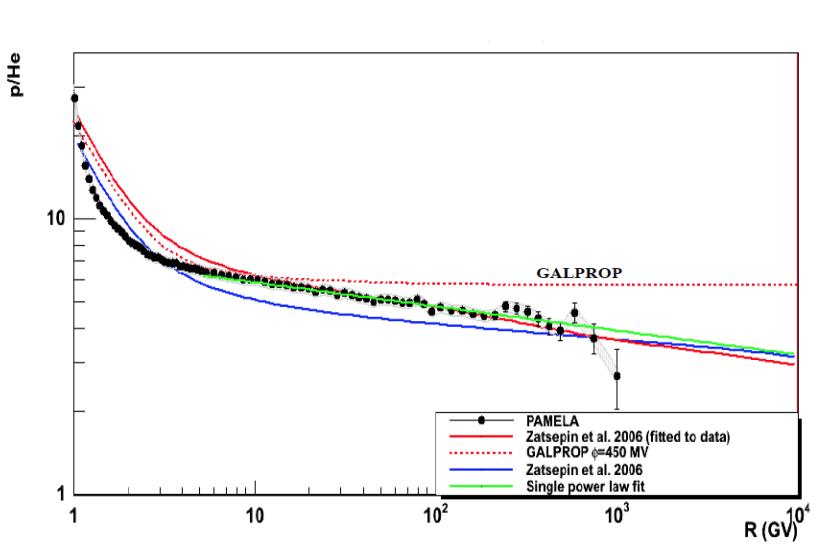
PAMELA overall results

- ✓ Absolute Fluxes of primary Cosmic Rays

Protons and Helium Nuclei Spectra & H/He ratio



- First high-statistics and high-precision measurement over three decades in energy
- Deviations from single power law (SPL):
  - Spectra gradually soften in the range 30÷230 GV
  - Spectral hardening @ R~235GV $\Delta\gamma \sim 0.2 \div 0.3$
    SPL is rejected at 98% CL

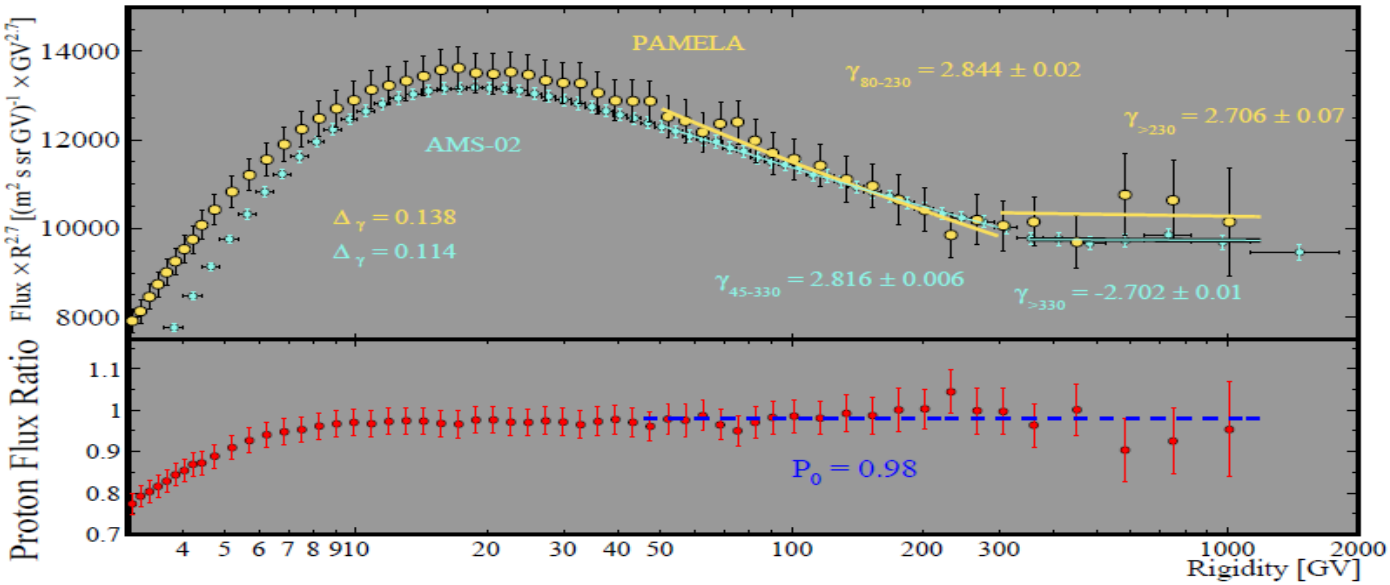


Clear evidence of different H and He slopes above ~ 10 GV

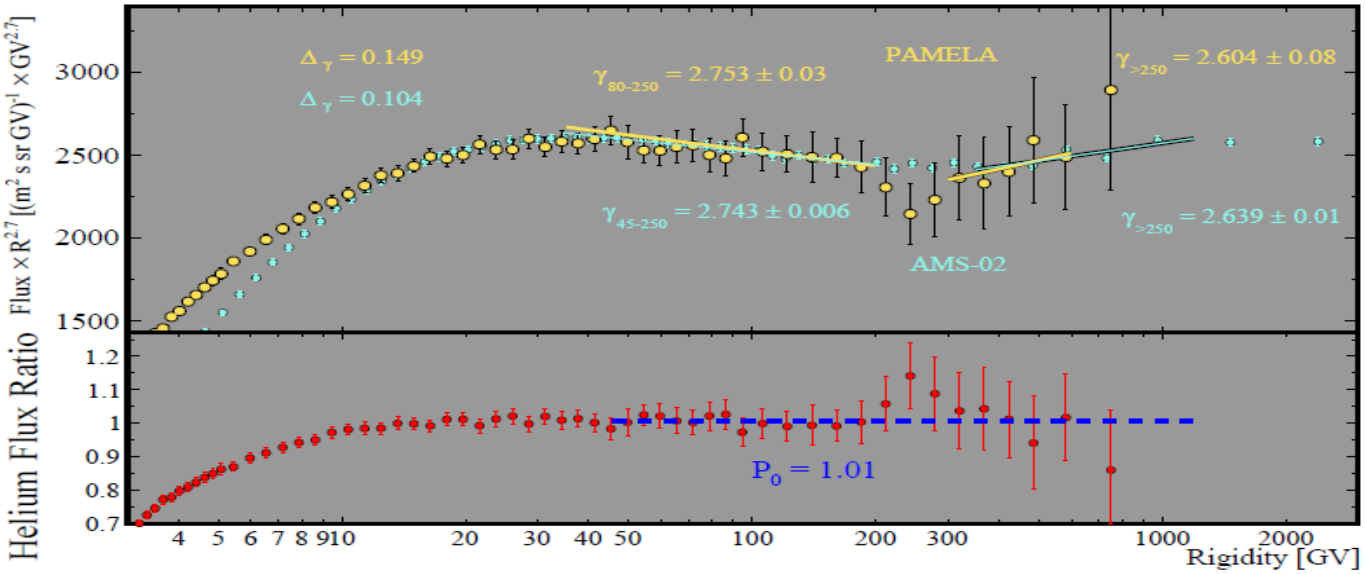
Science AAAS

O. Adriani et al. 2011, *PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra*

Result confirmed by AMS-02!

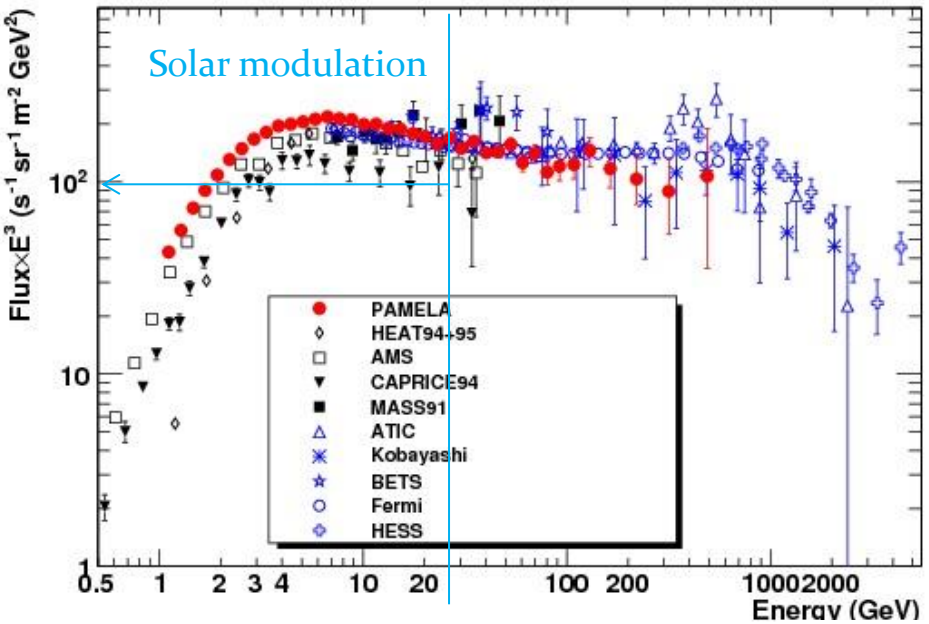


O. Adriani et al., Phys. Rep. 544 (2014) 323 ; M. Aguilar et al., PRL 114 (2015) 171103



O. Adriani et al., Science 332 (2011) 6025 ; M. Aguilar et al., PRL 115, (2015) 211101

PAMELA Results: Electrons



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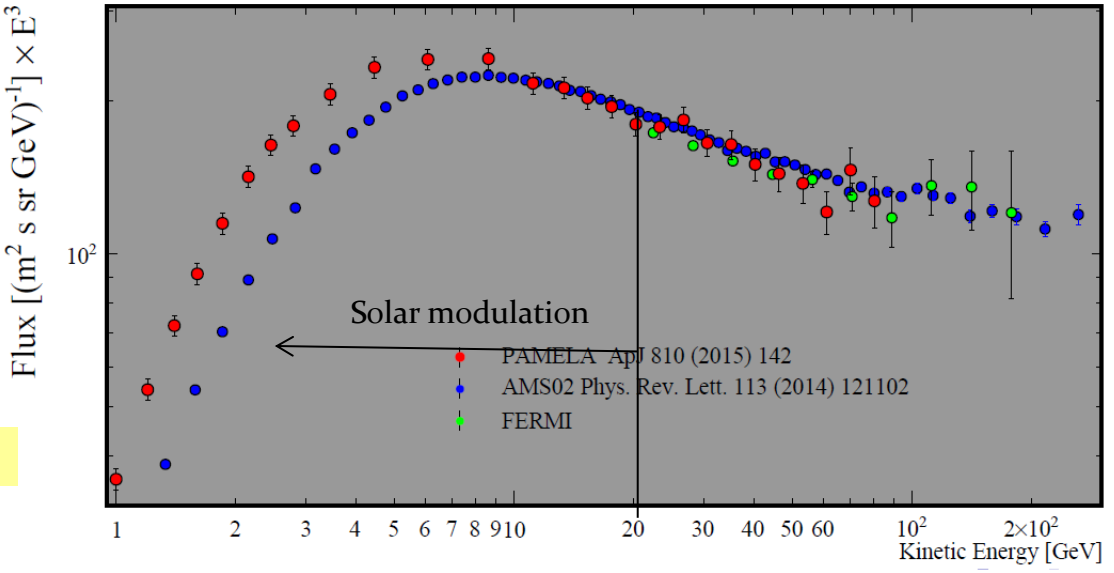
Featured in Physics Editors' Suggestion

Cosmic-Ray Electron Flux Measured by the PAMELA Experiment between 1 and 625 GeV

O. Adriani *et al.*
Phys. Rev. Lett. **106**, 201101 – Published 19 May 2011

Physics See Synopsis: Tantalizing cosmic-ray electrons



O. Adriani et al., ApJ 810 (2015) 142

PAMELA overall results

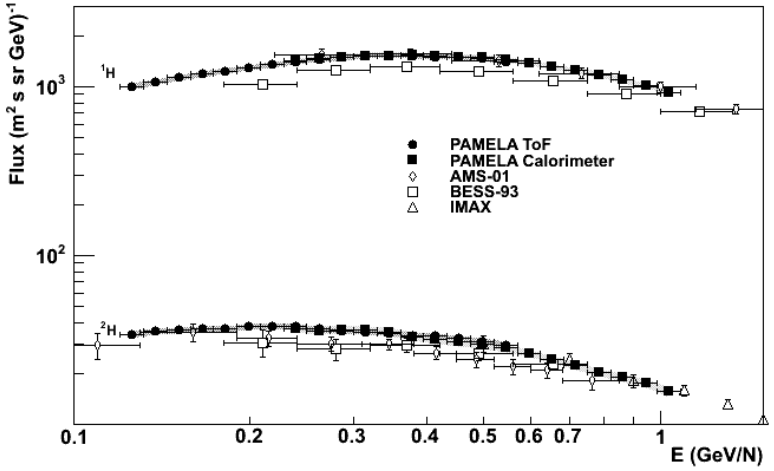
- ✓ Absolute Fluxes of primary Cosmic Rays
- ✓ Light Nuclei and Isotopes

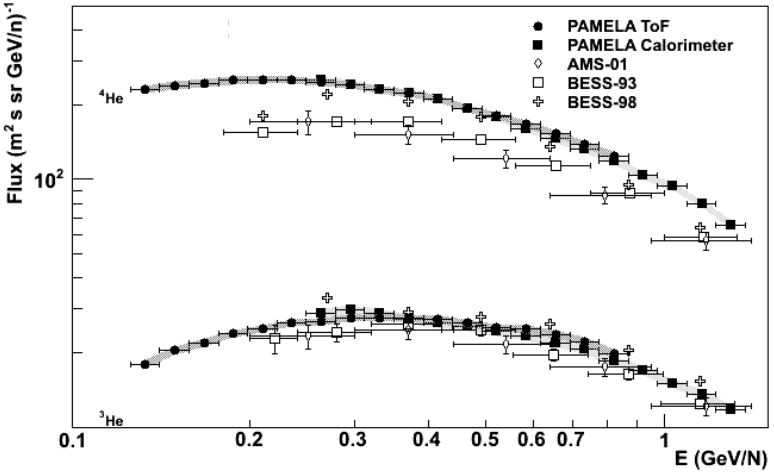
PAMELA Results: Secondary cosmic rays

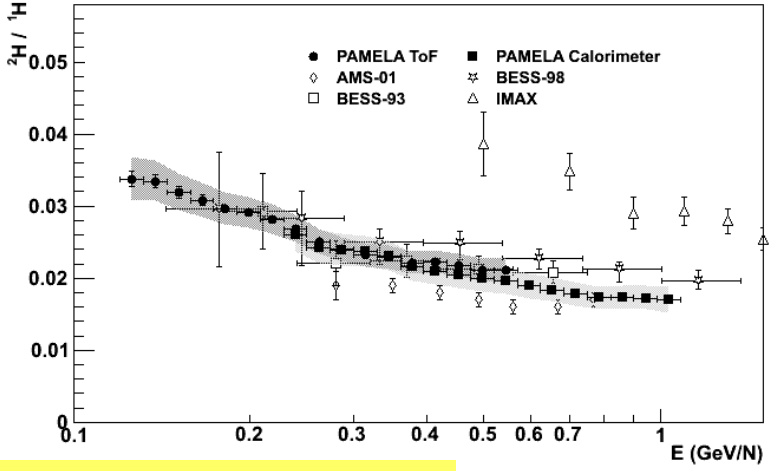
Light Nuclei and Isotopes

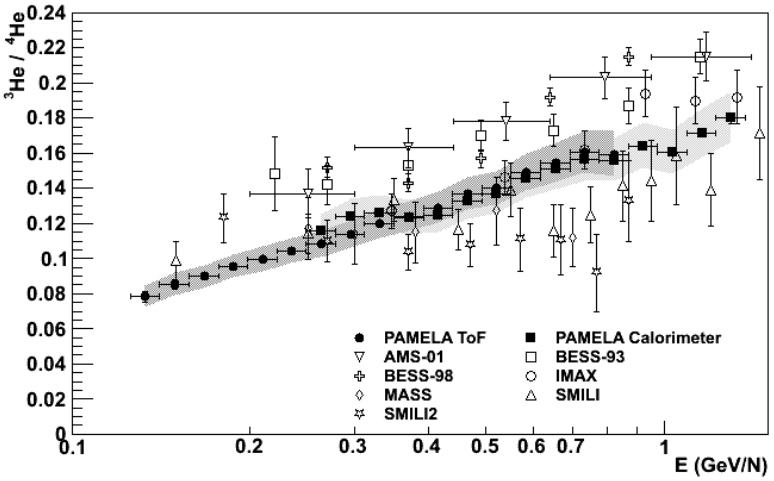
- Tuning of cosmic-ray propagation models with measurements of secondary/primary flux ratio
- $^{2}H/^{1}H$ and $^{3}He/^{4}He$ are complimentary to B/C measurements in constraining propagation models (Coste et al., A&A 539 (2012) A88)
- Antiparticles (antiprotons, positrons), secondaries from homogeneously distributed interstellar matter (light nuclei)

Hydrogen and helium isotopes









O. Adriani et al., ApJ 770 (2013) 2
O. Adriani et al., ApJ 818 (2016) 68

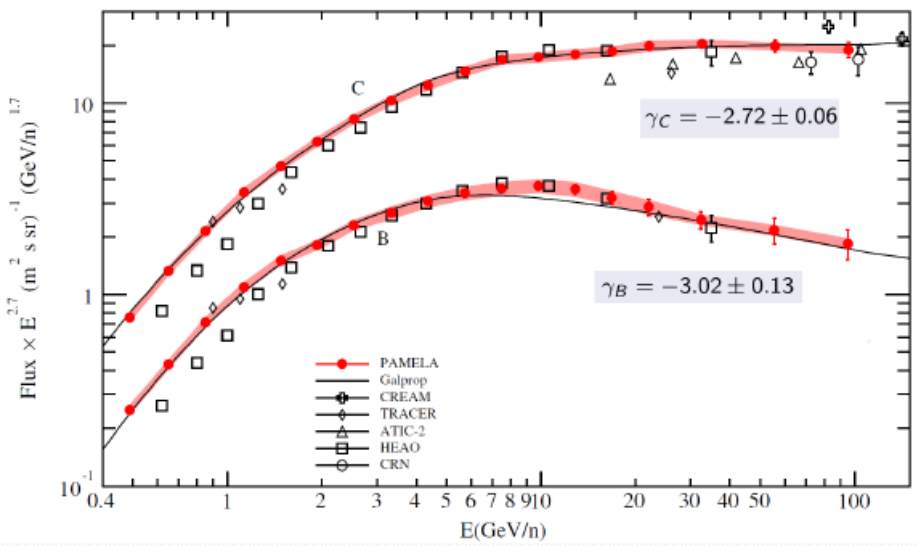
Boron and carbon fluxes and B/C

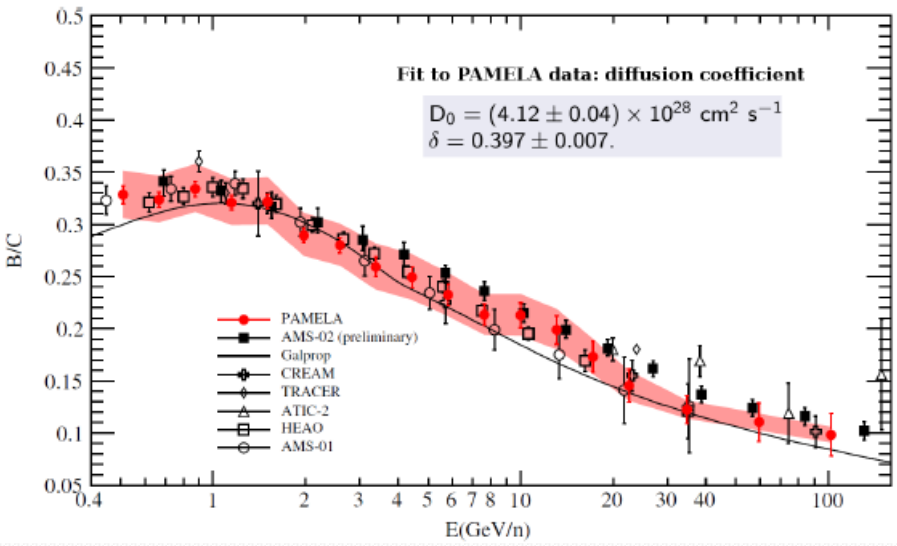
Boron and Carbon

- Flux measure from 2 to 260 GV;
- Different spectral shape;

B/C ratio

- Standard tool for studying propagation models;
- B/C ∝ diffusion coefficient, $K = D_0 E^{-\delta}$;



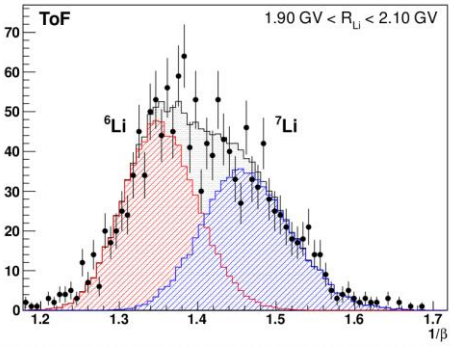


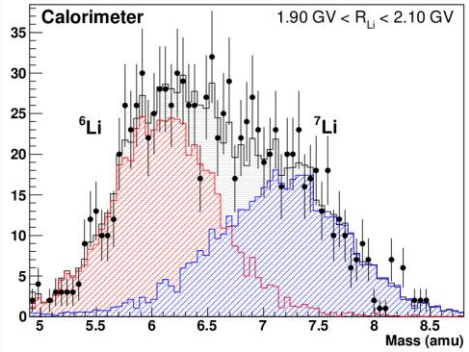
Adriani et al., ApJ 791 (2014), 93

Lithium and Beryllium Isotopes

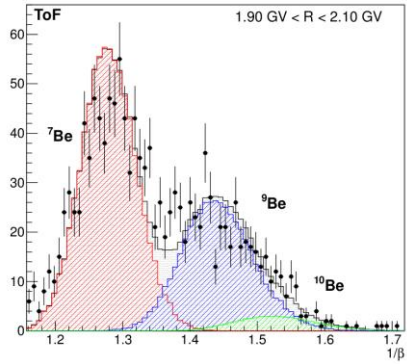
β (ToF) vs. Rigidity or Multiple dE/dx (Calorimeter) vs. rigidity

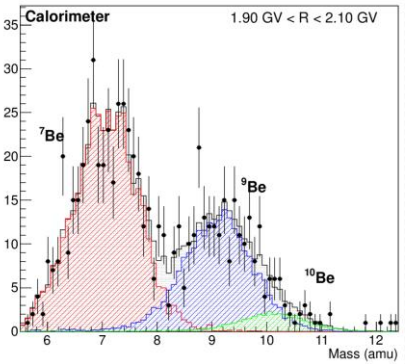
Lithium



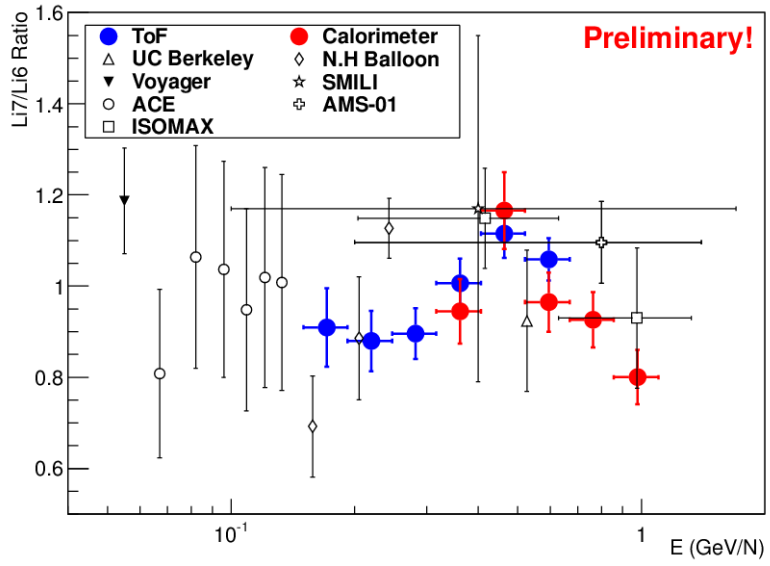


Beryllium

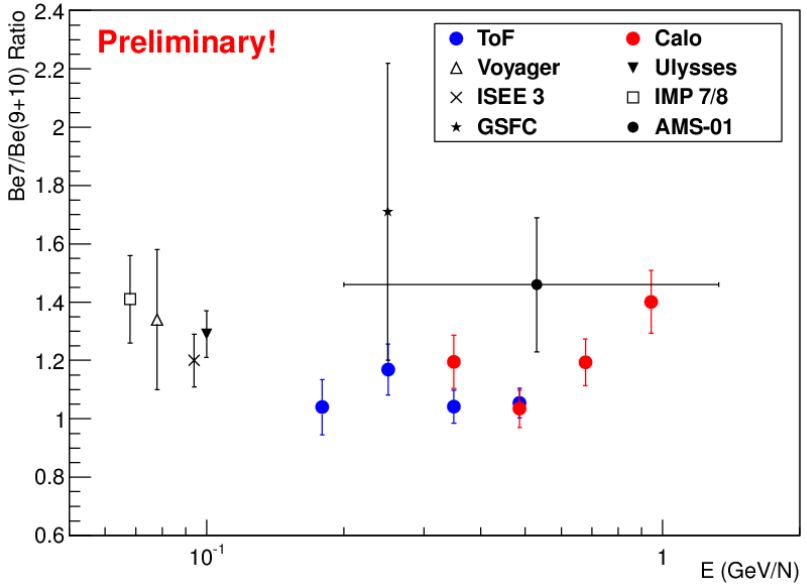




Ratio ^{7}Li / ^{6}Li



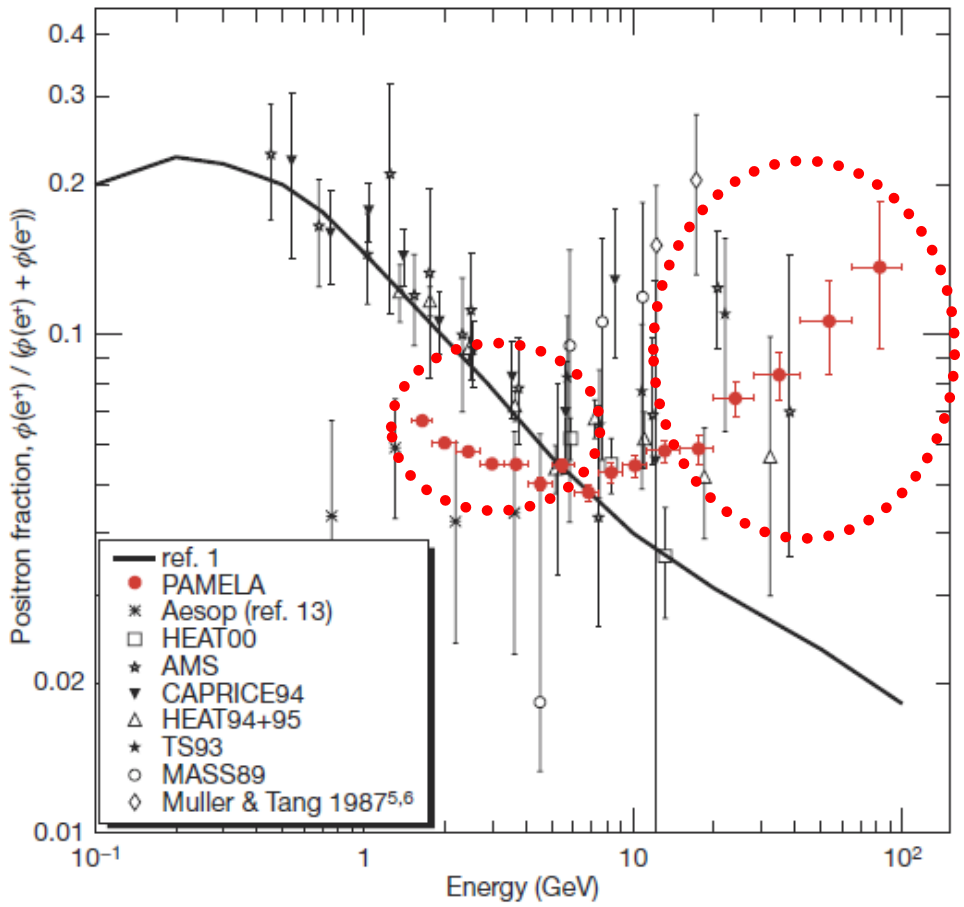
^{7}Be / (^{9}Be + ^{10}Be)



PAMELA overall results

- ✓ Absolute Fluxes of primary Cosmic Rays
- ✓ Light Nuclei and Isotopes
- ✓ Antiparticles

PAMELA Results: Positrons

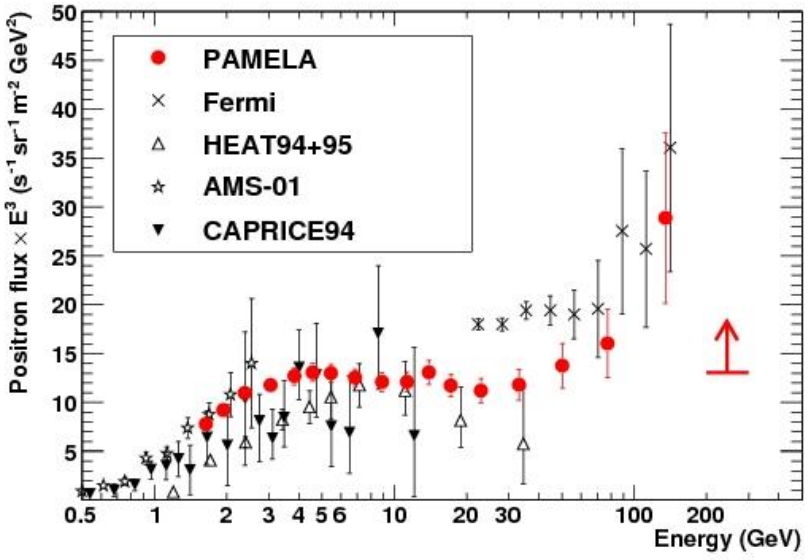


nature
International weekly journal of science
Vol 458|2 April 2009|doi:10.1038/nature07942 nature

LETTERS

An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

O. Adriani[1,2], G. C. Barbarino[3,4], G. A. Bazilevskaya[5], R. Bellotti[6,7], M. Boezio[8], E. A. Bogomolov[9], L. Bonechi[1,2], M. Bongi[2], V. Bonvicini[8], S. Bottai[2], A. Bruno[6,7], F. Cafagna[7], D. Campana[4], P. Carlson[10], M. Casolino[11], G. Castellini[12], M. P. De Pascale[11,13], G. De Rosa[4], N. De Simone[11,13], V. Di Felice[11,13], A. M. Galper[14], L. Grishantseva[14], P. Hofverberg[10], S. V. Koldashov[14], S. Y. Krutkov[9], A. N. Kvashnin[5], A. Leonov[14], V. Malvezzi[11], L. Marcelli[11], W. Menn[15], V. V. Mikhailov[14], E. Mocchiutti[8], S. Orsi[10,11], G. Osteria[4], P. Papini[2], M. Pearce[16], P. Picozza[11,13], M. Ricci[17], S. B. Ricciarini[2], M. Simon[15], R. Sparvoli[11,13], P. Spillantini[1,2], Y. I. Stozhkov[5], A. Vacchi[8], E. Vannuccini[2], G. Vasilyev[9], S. A. Voronov[14], Y. T. Yurkin[14], G. Zampa[8], N. Zampa[8] & V. G. Zverev[14]



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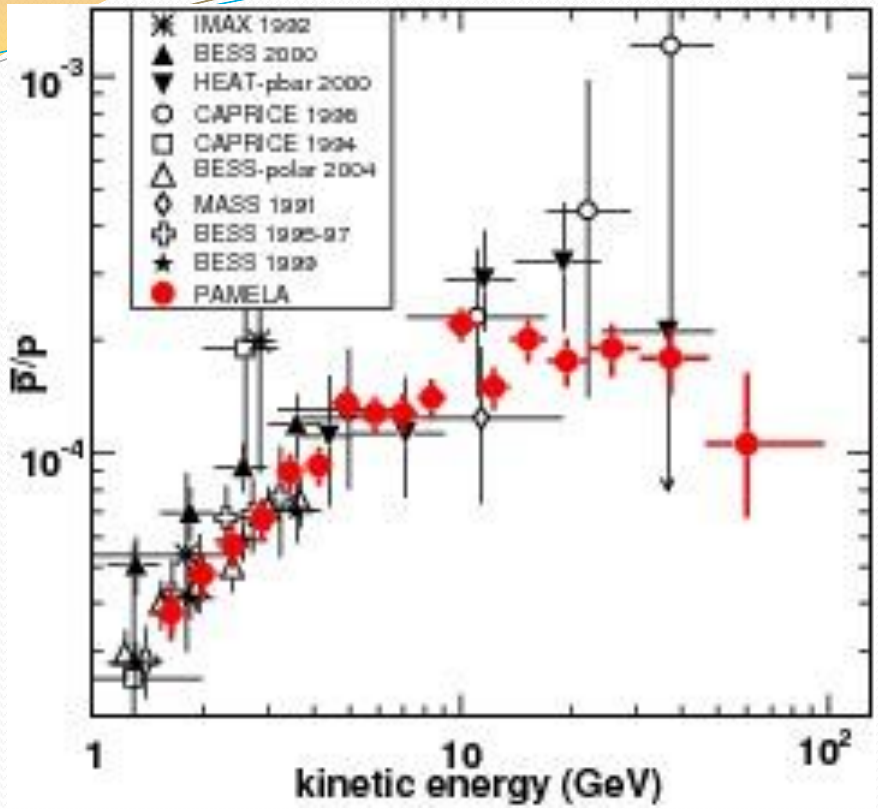
Cosmic-Ray Positron Energy Spectrum Measured by PAMELA

O. Adriani *et al.*
Phys. Rev. Lett. **111**, 081102 – Published 19 August 2013

Physics See Synopsis: A Long, Hard Look at Cosmic-Ray Positrons

PAMELA Results: Antiprotons



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PAMELA Results on the Cosmic-Ray Antiproton Flux from 60 MeV to 180 GeV in Kinetic Energy

O. Adriani *et al.*
Phys. Rev. Lett. **105**, 121101 – Published 13 September 2010

PHYSICS See Synopsis: Uncertain sources

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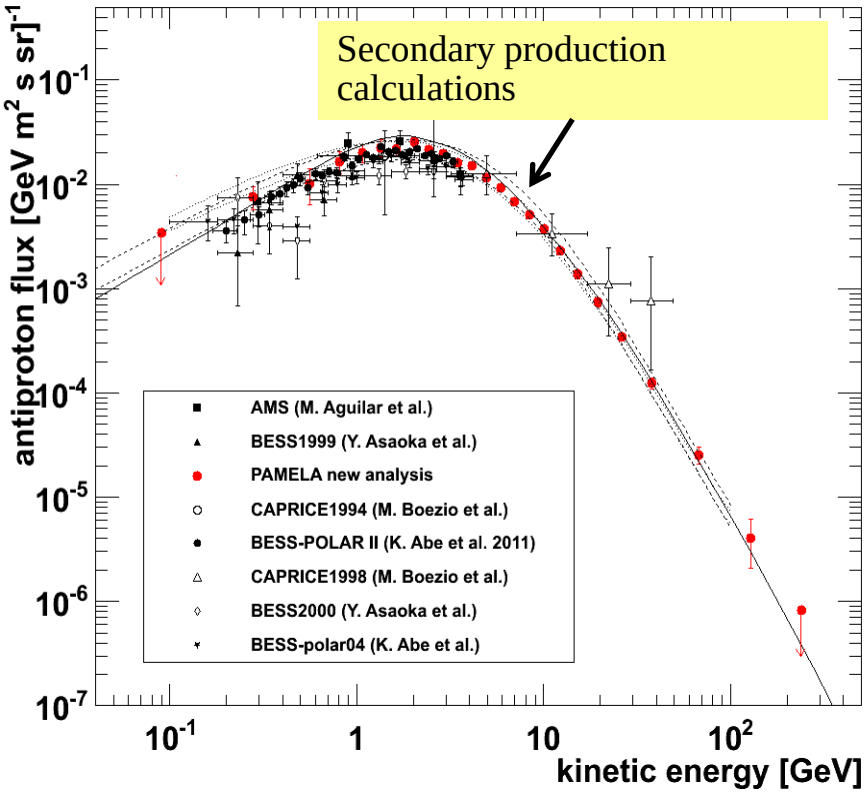
New Measurement of the Antiproton-to-Proton Flux Ratio up to 100 GeV in the Cosmic Radiation

O. Adriani *et al.* (PAMELA Collaboration)
Phys. Rev. Lett. **102**, 051101 – Published 2 February 2009

PHYSICS See Viewpoint: Debating the source of a rare particle



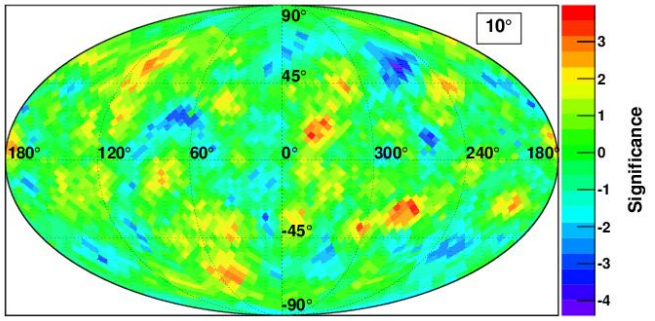
PAMELA overall results

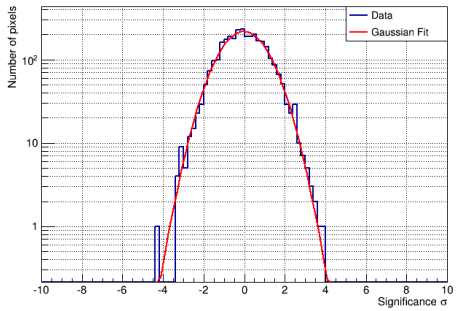
- ✓ Absolute Fluxes of primary Cosmic Rays
- ✓ Light Nuclei and Isotopes
- ✓ Antiparticles
- ✓ Anisotropies

PAMELA Results: CRE Anisotropy

Positrons - R > 10 GV

Significance map for *backtraced* positrons
Background: Protons
Angular scale 10°

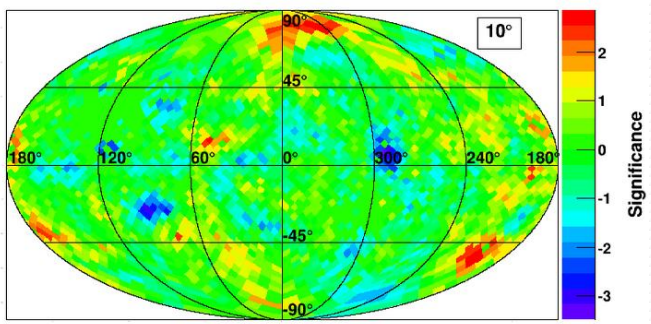


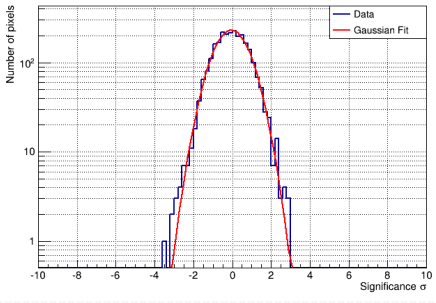


Histogram of calculated significance

Electrons R > 10 GV

Significance map for *backtraced* electrons
Background: Monte Carlo simulations
Angular scale 10°

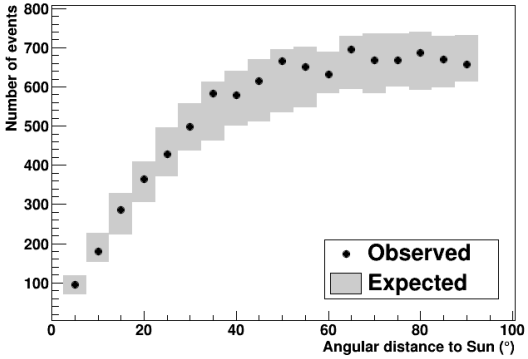




Histogram of calculated significance

O. Adriani et al., ApJ 811 (2015) 21

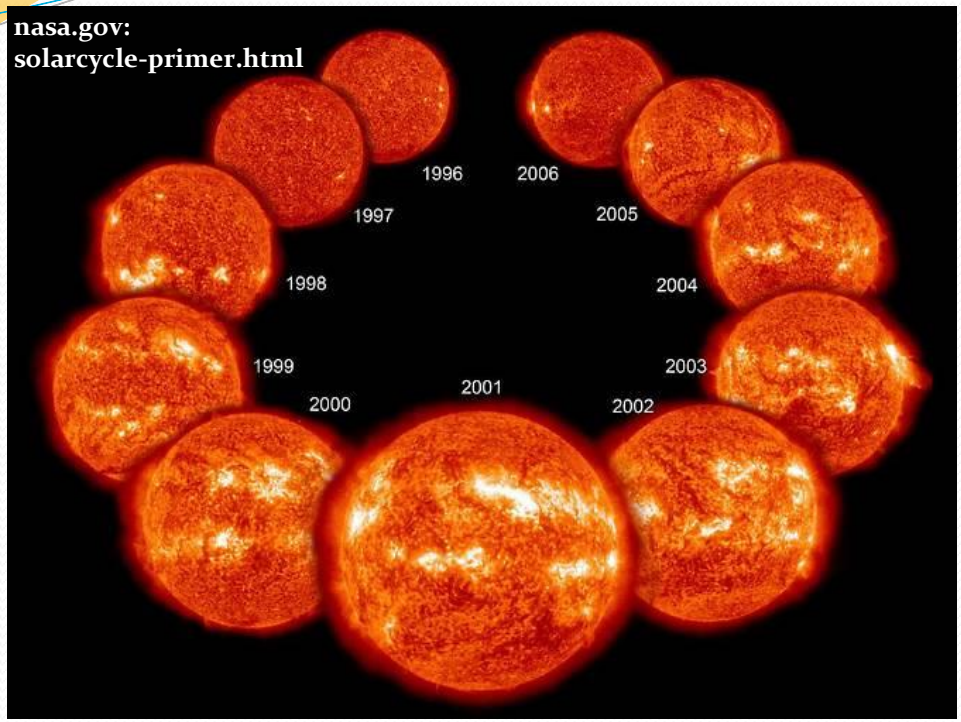
Number of events as a function of the angular distance from the Sun direction

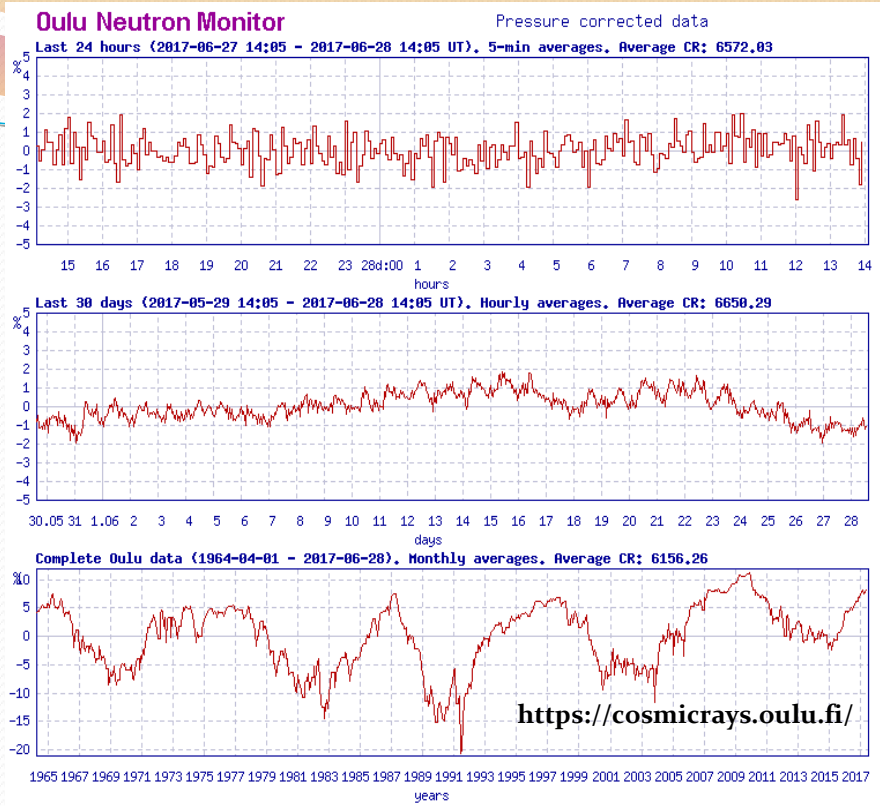


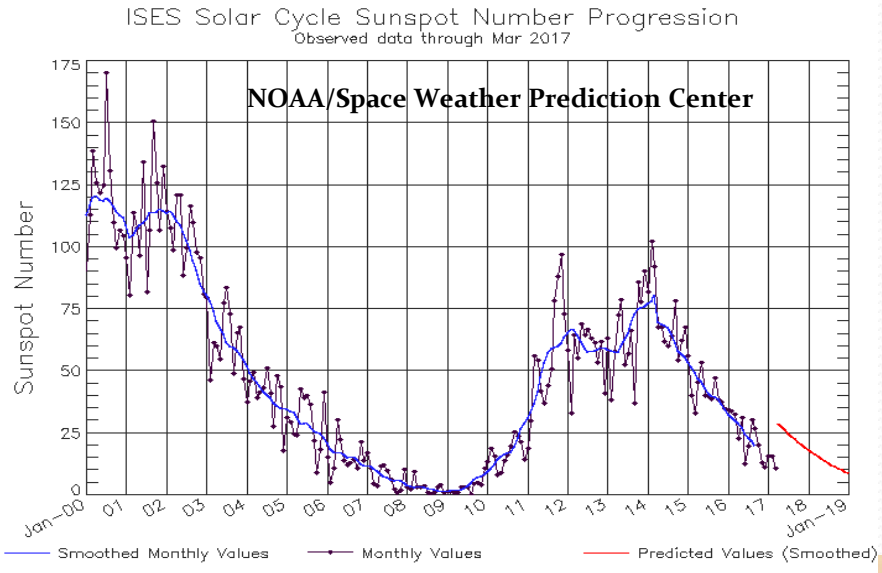
PAMELA overall results

- ✓ Absolute Fluxes of primary Cosmic Rays
- ✓ Light Nuclei and Isotopes
- ✓ Antiparticles
- ✓ Anisotropies
- ✓ Solar events, solar modulation

The solar modulation



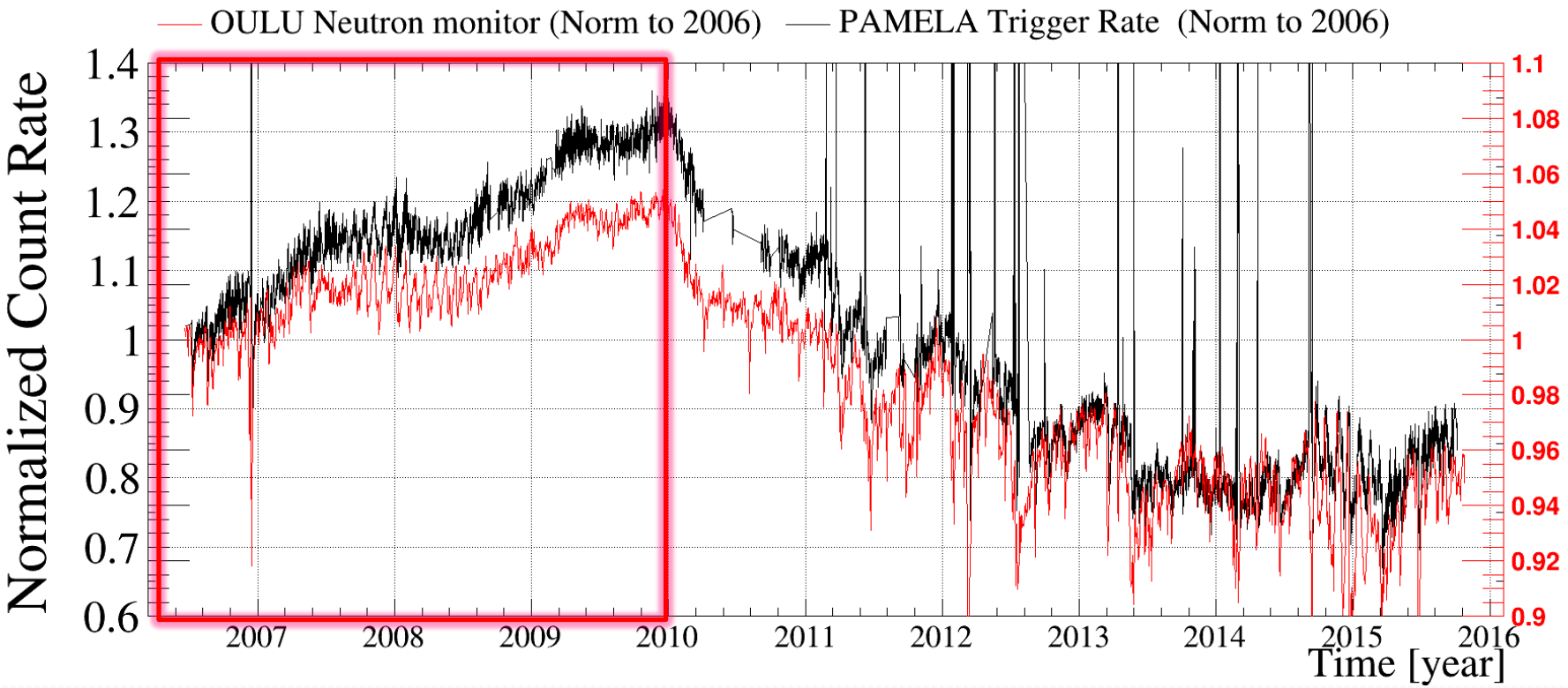




SOLAR CYCLE

- Solar activity rises and falls over an 11 year cycle
- Can be shorter/longer
- Different events during the cycle
- Activity correlates with Sunspot Number

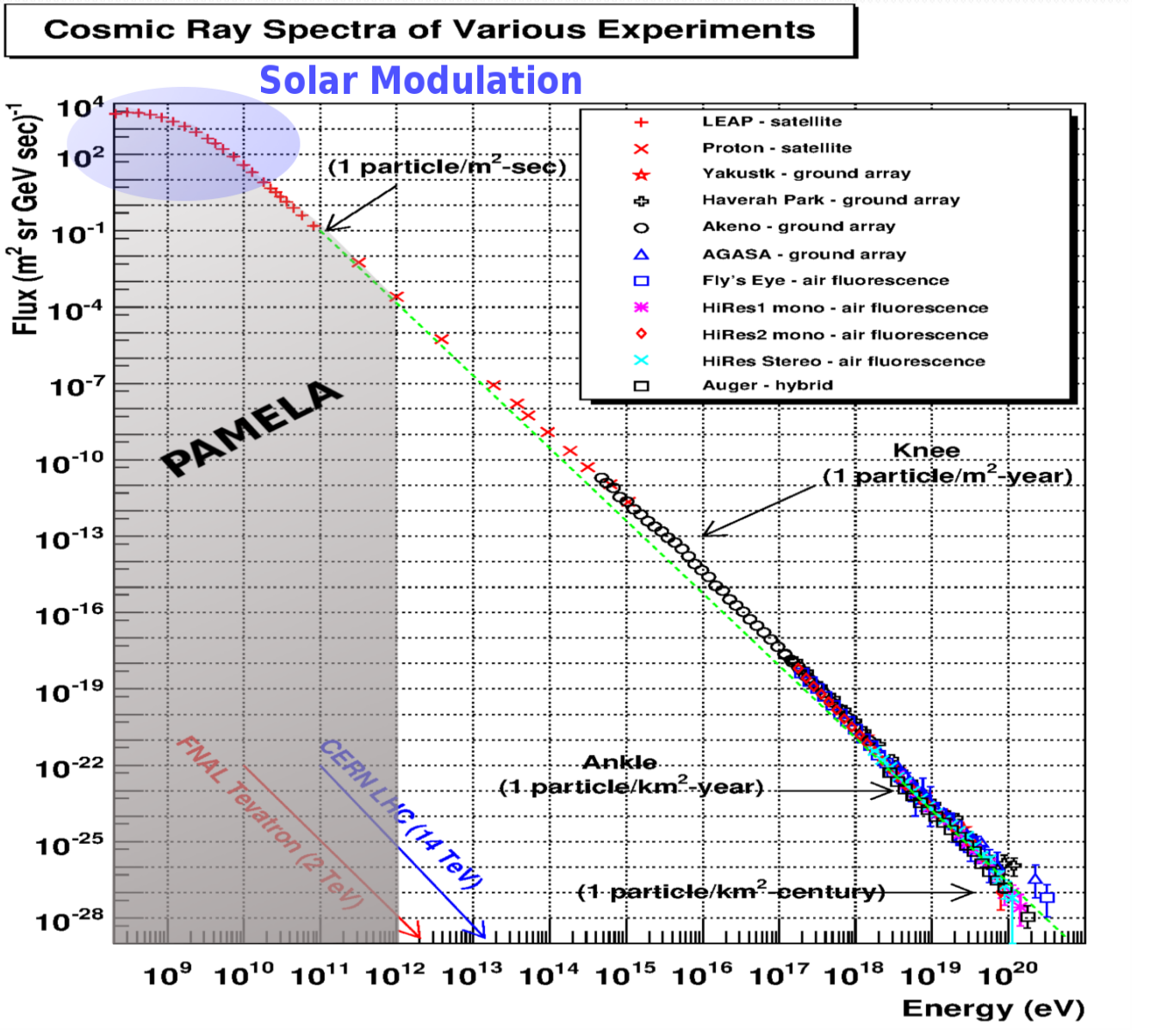
Heliospheric conditions during PAMELA observations



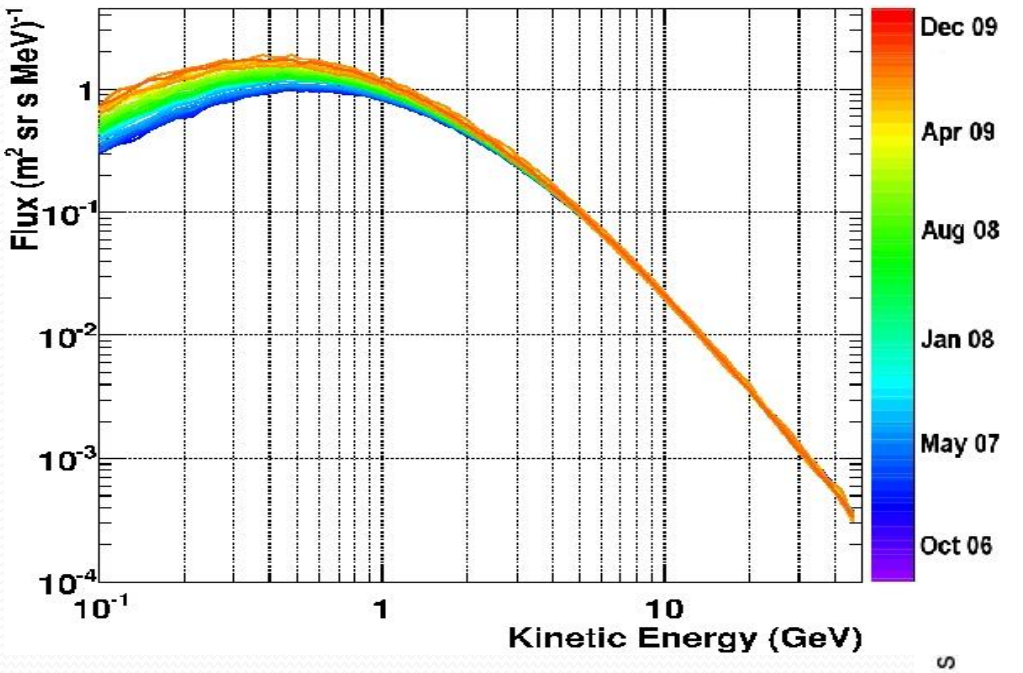
Neutron Monitor counts data from
http://cosmicrays.oulu.fi/

PAMELA observations covers ~ one solar cycle

The PAMELA experiment

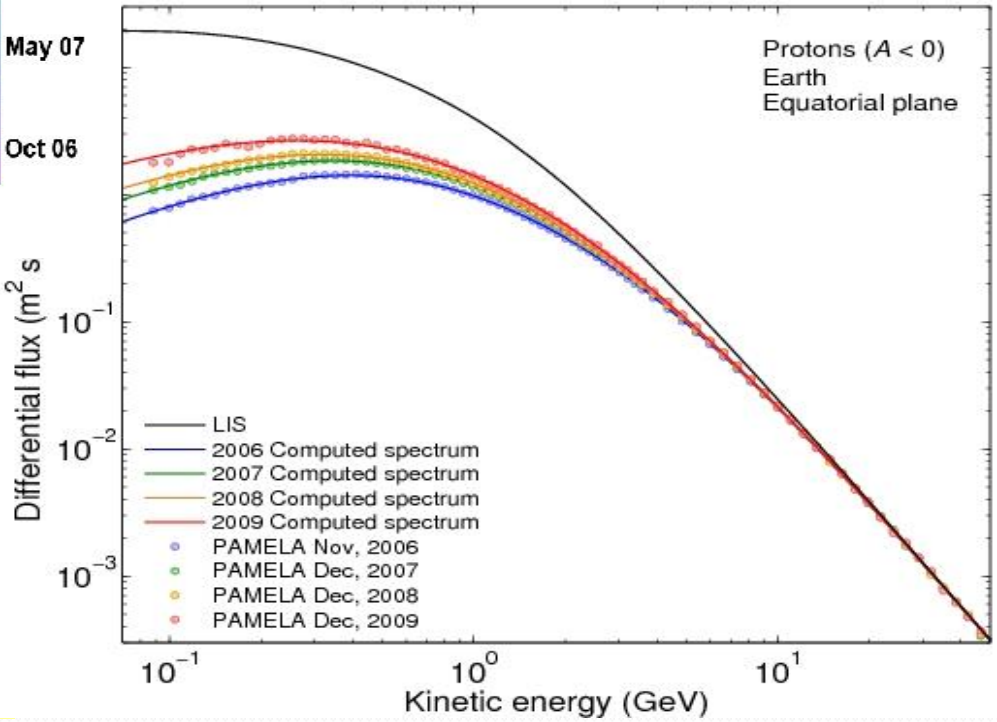


Time dependence of the proton flux



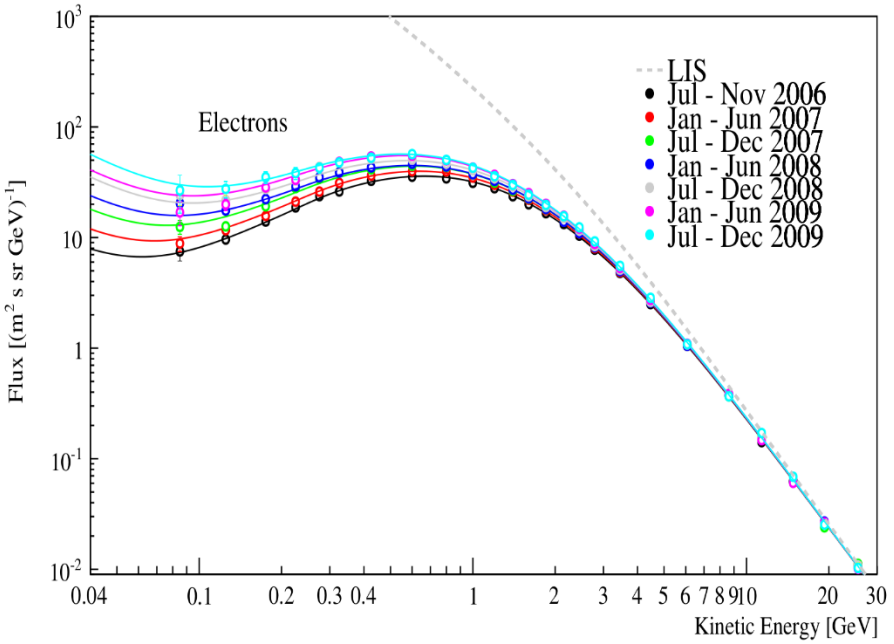
Evolution of the proton energy spectrum from July 2006 to December 2009

The PAMELA proton spectra over four months compared with the computed spectra



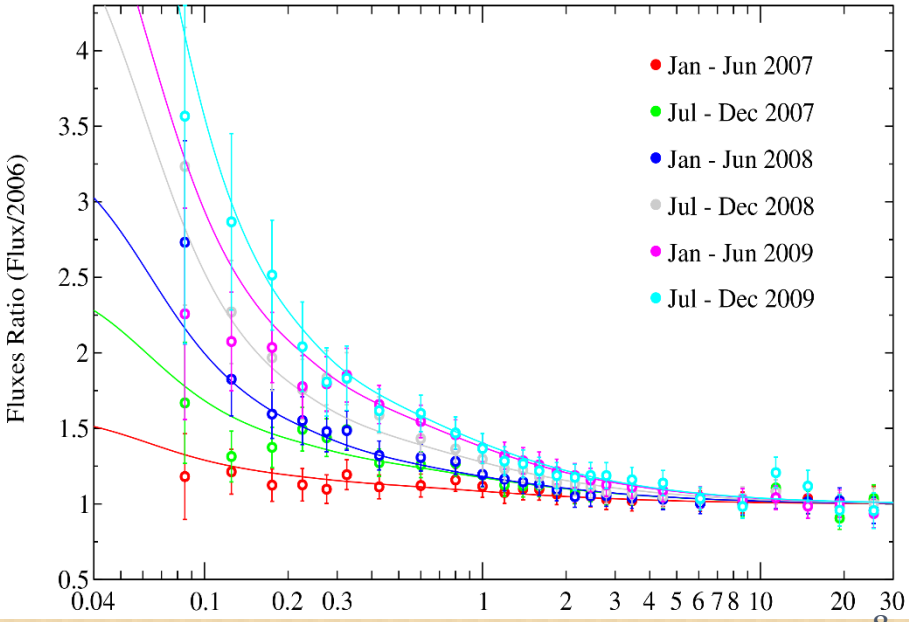
O. Adriani et al., ApJ 765 (2013) 91;
M. S. Potgieter et al., Solar Phys. 289 (2014) 391

Time dependence of the electron flux



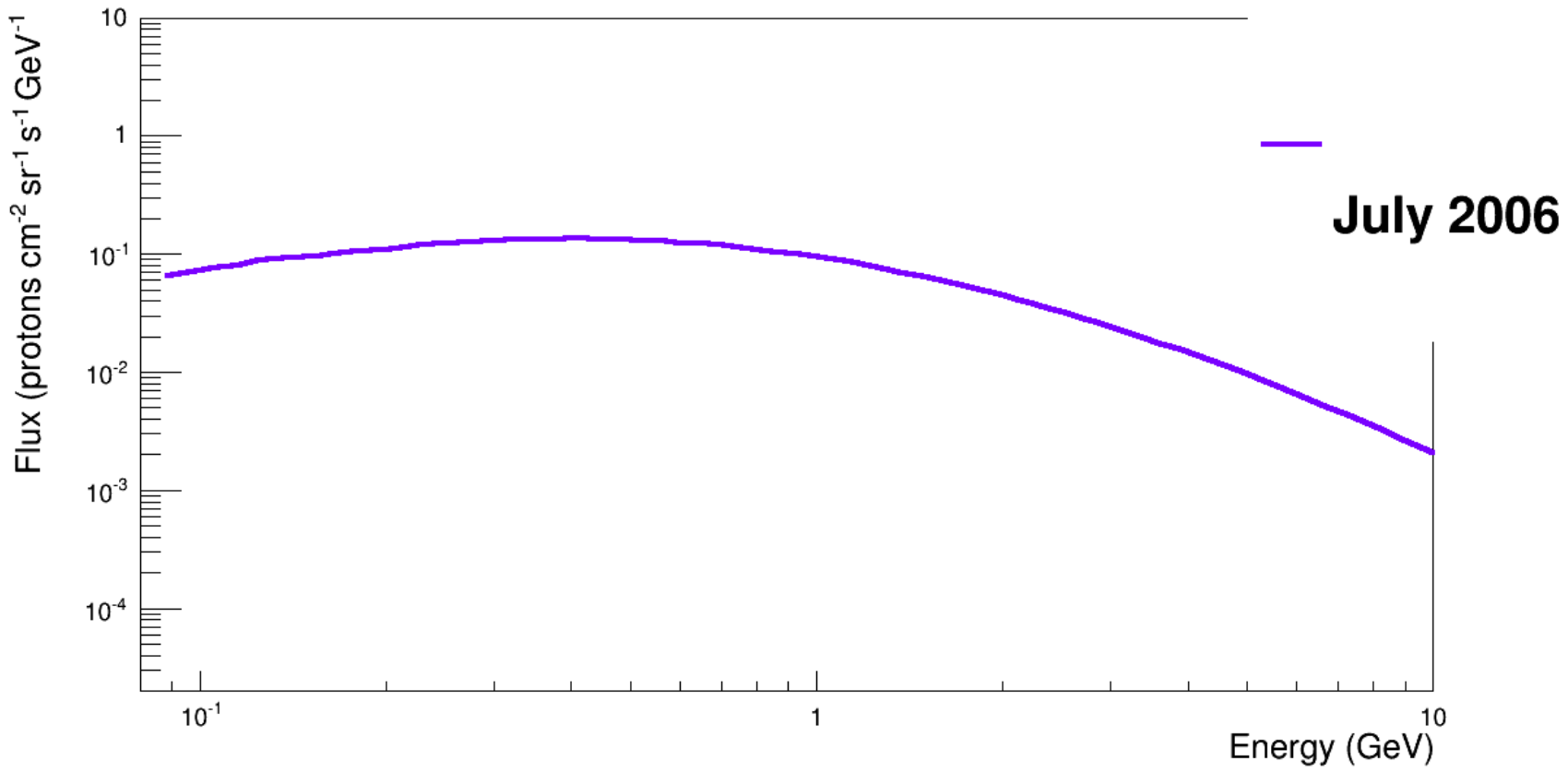
Evolution of the electron (e^-) energy spectrum from July 2006 to December 2009

The ratios between the measured e^- fluxes from January 2007 till December 2009 and the measured fluxes for the period July-November 2006 with the corresponding computed spectra.

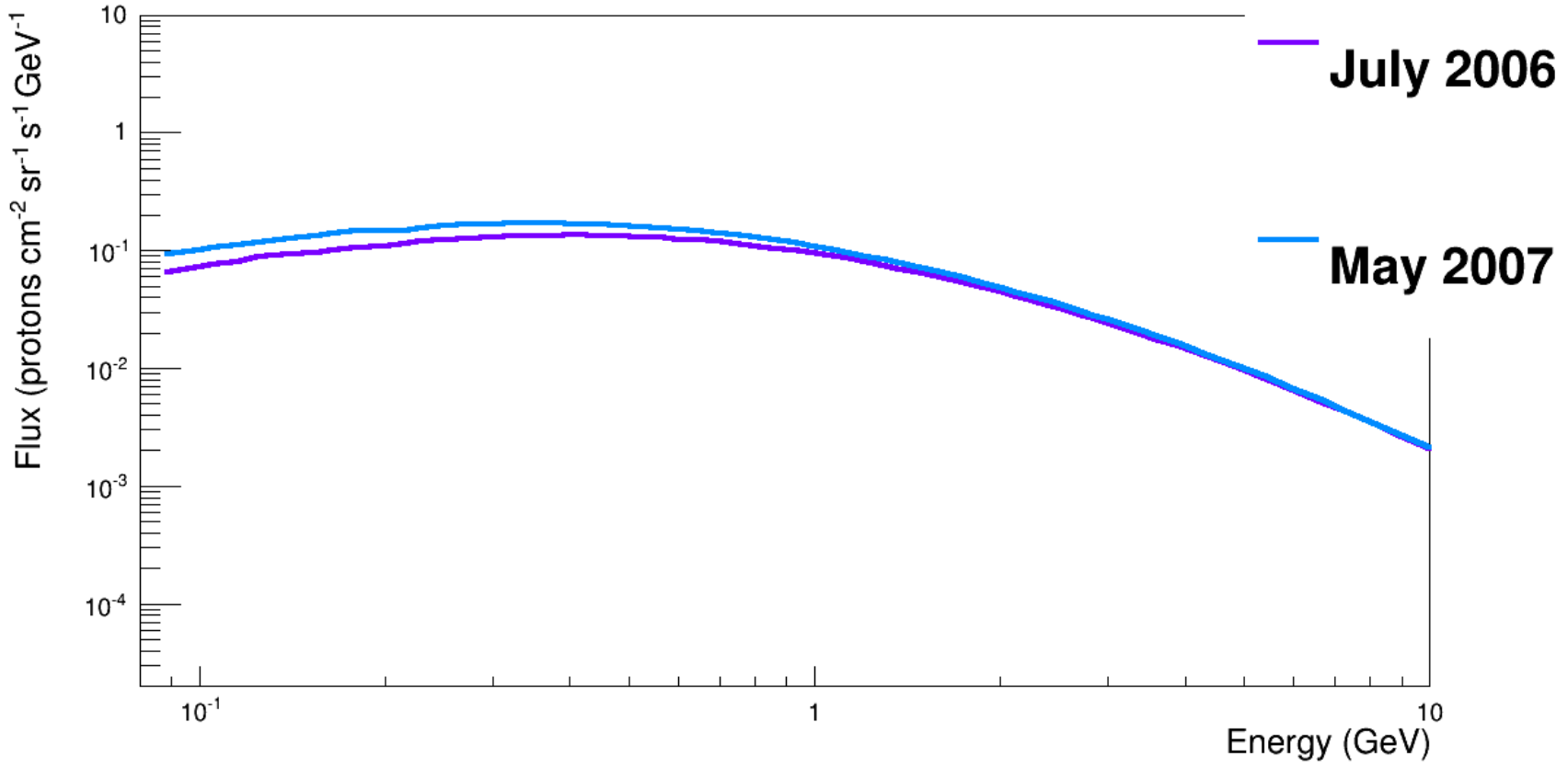


O. Adriani et al., ApJ 810 (2015) 142;
M. S. Potgieter et al., 810 (2015) 2, 141

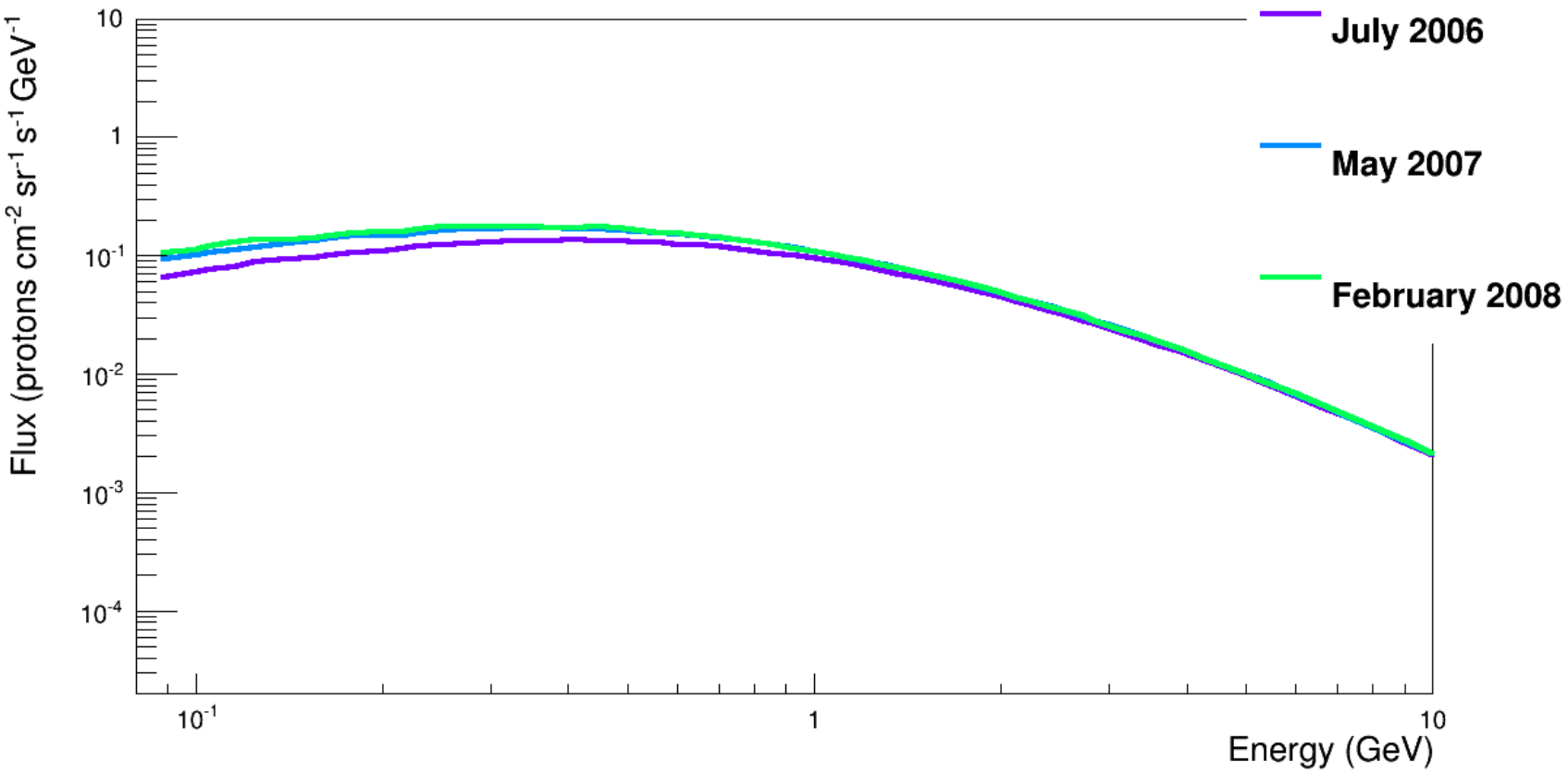
Time dependence of the proton flux



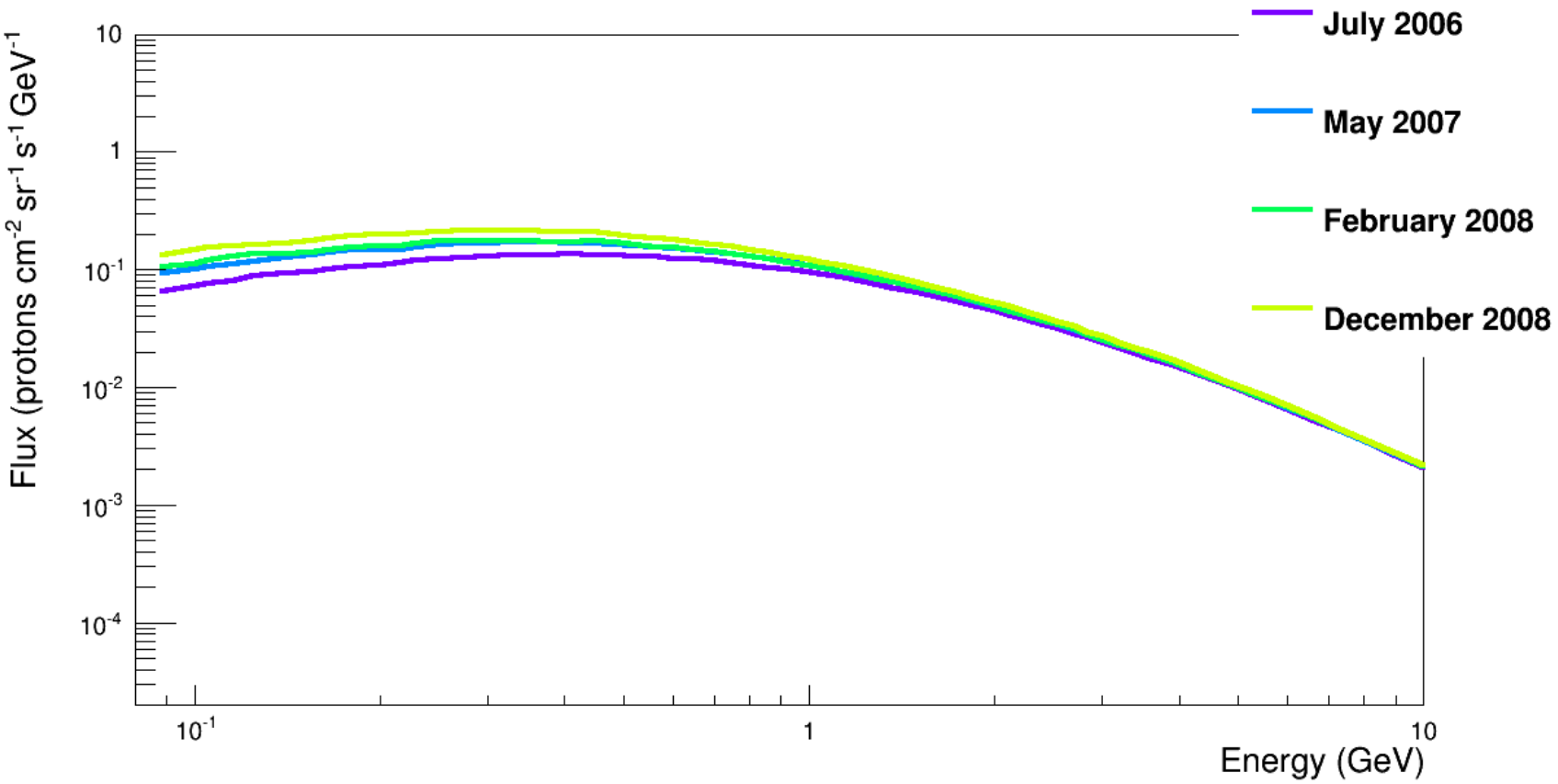
Time dependence of the proton flux



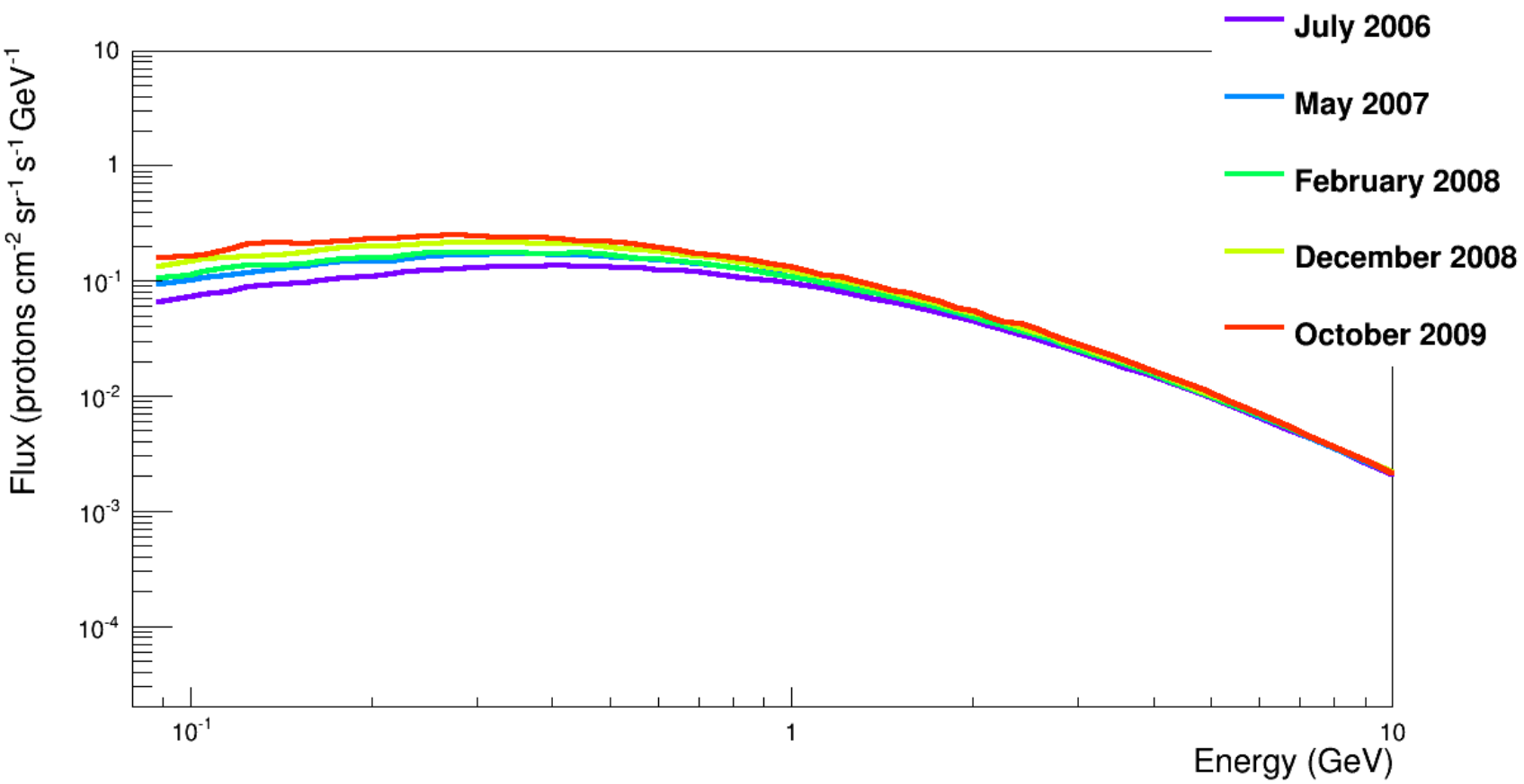
Time dependence of the proton flux



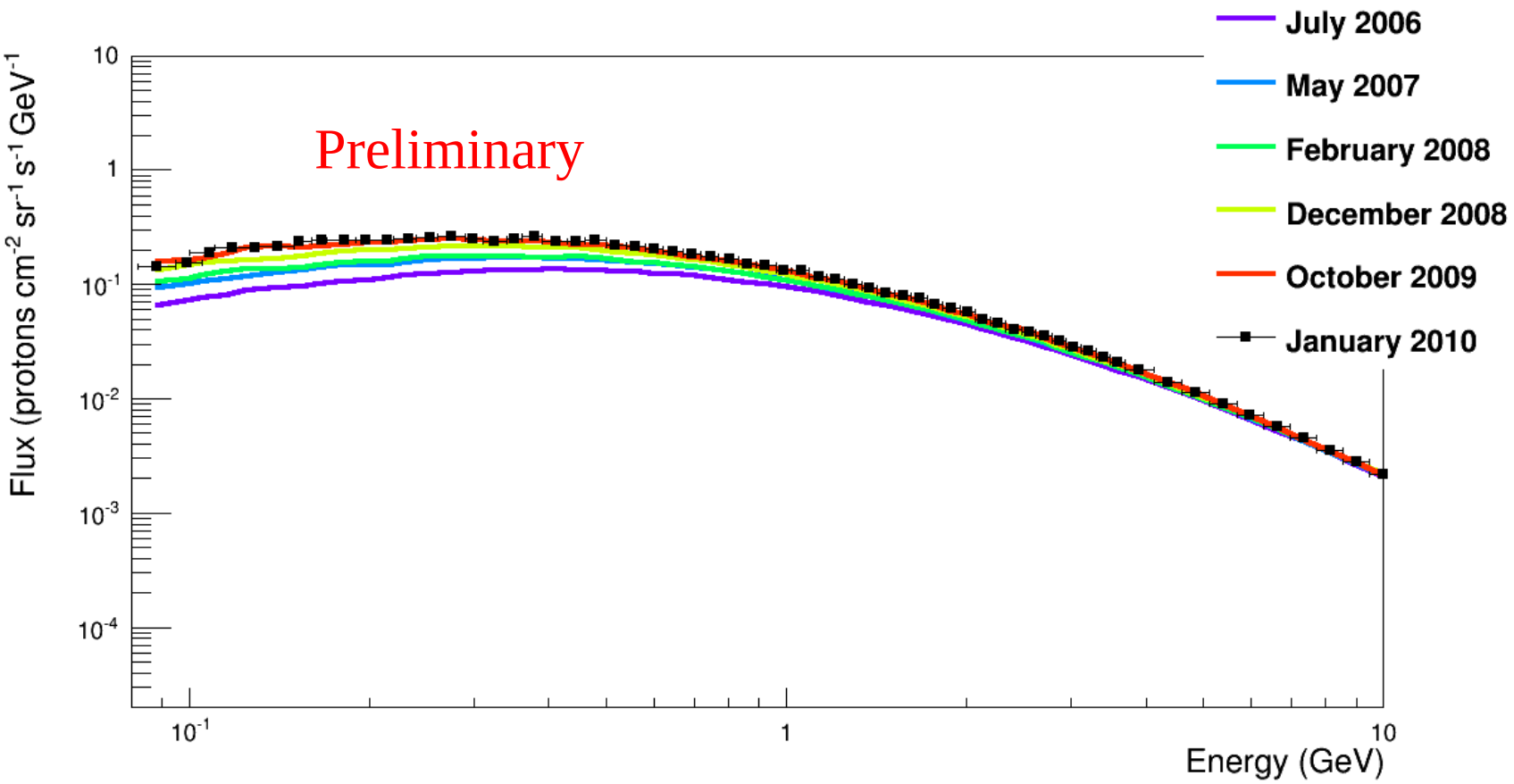
Time dependence of the proton flux



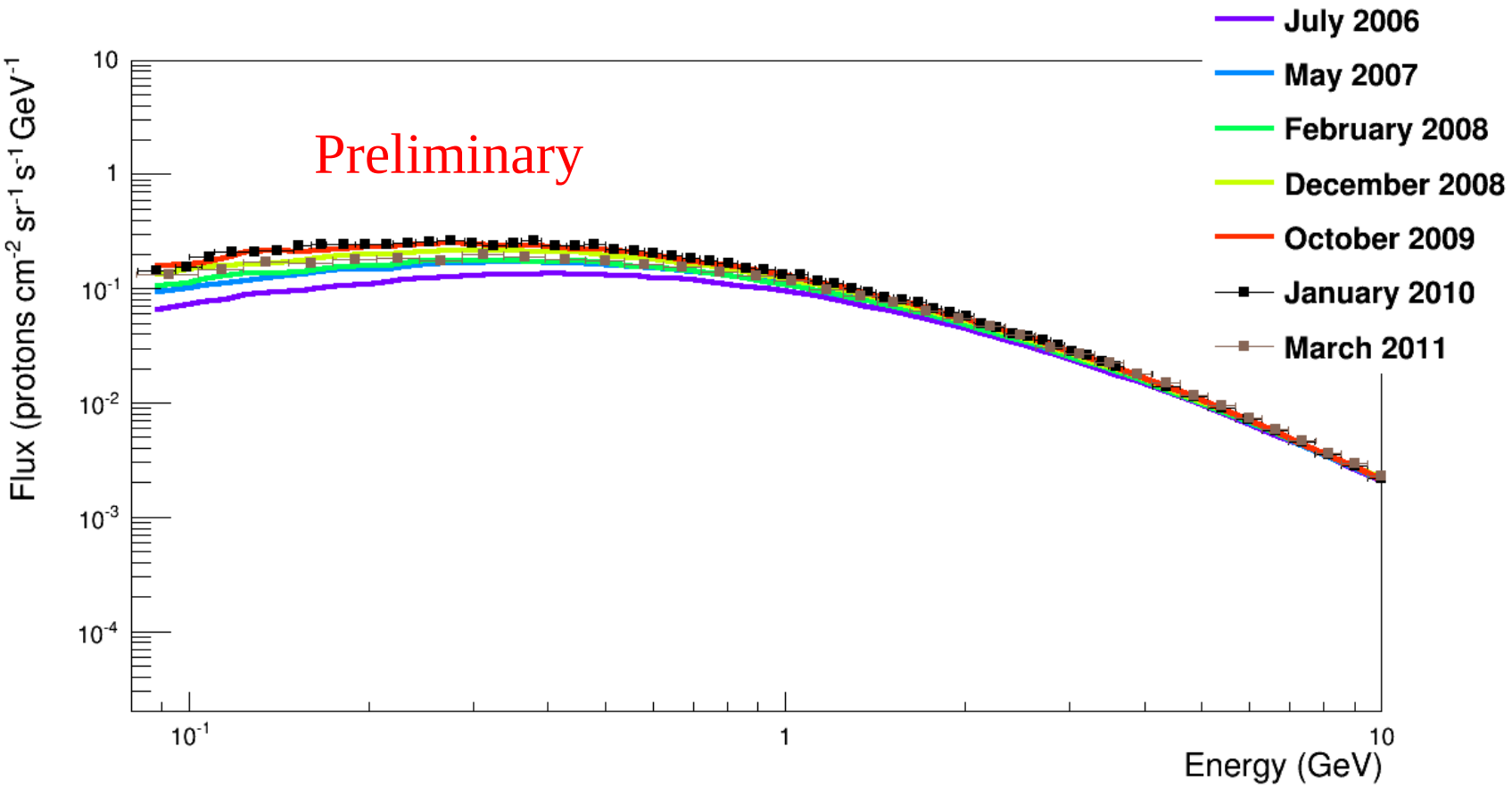
Time dependence of the proton flux



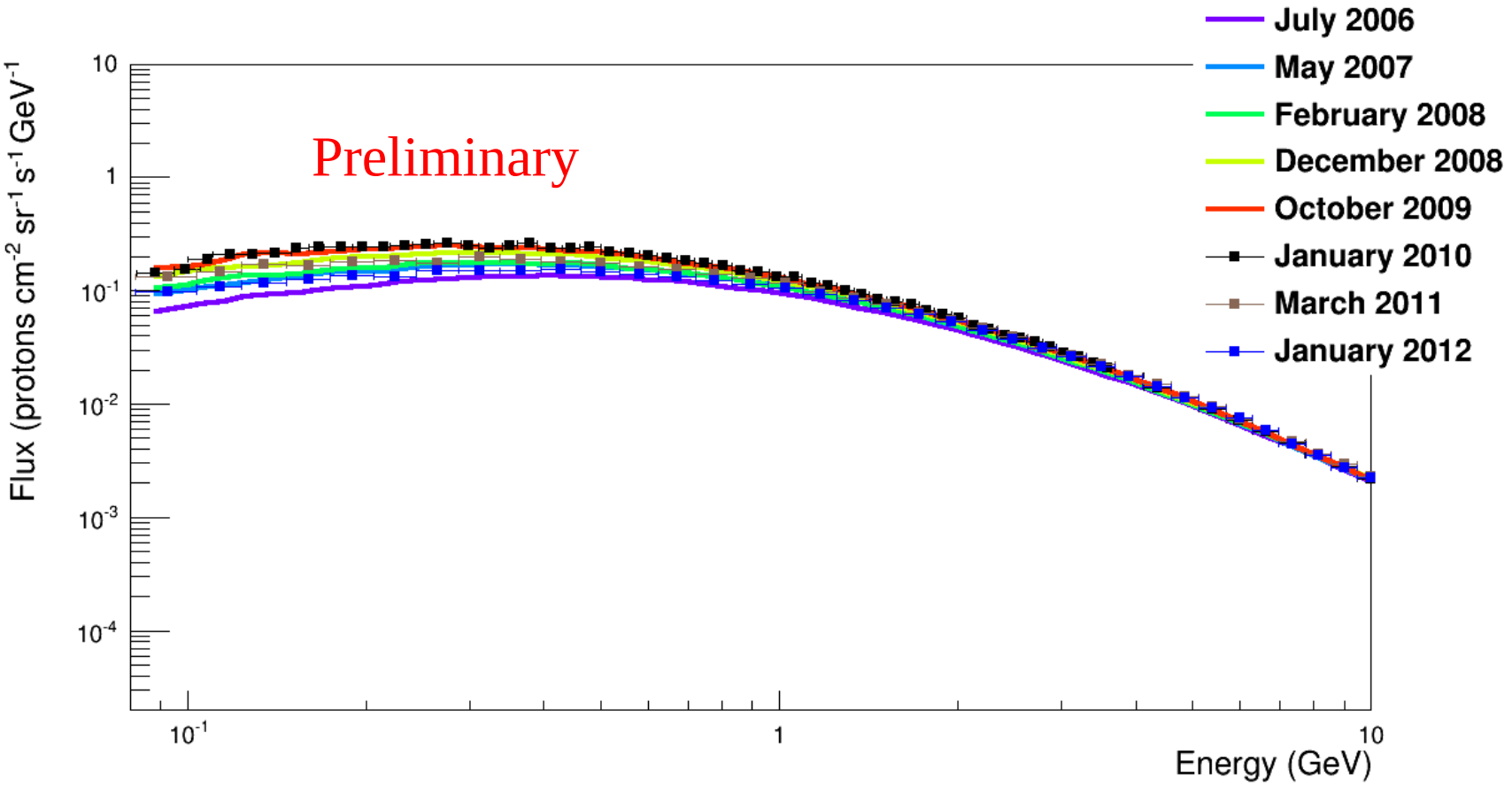
Time dependence of the proton flux



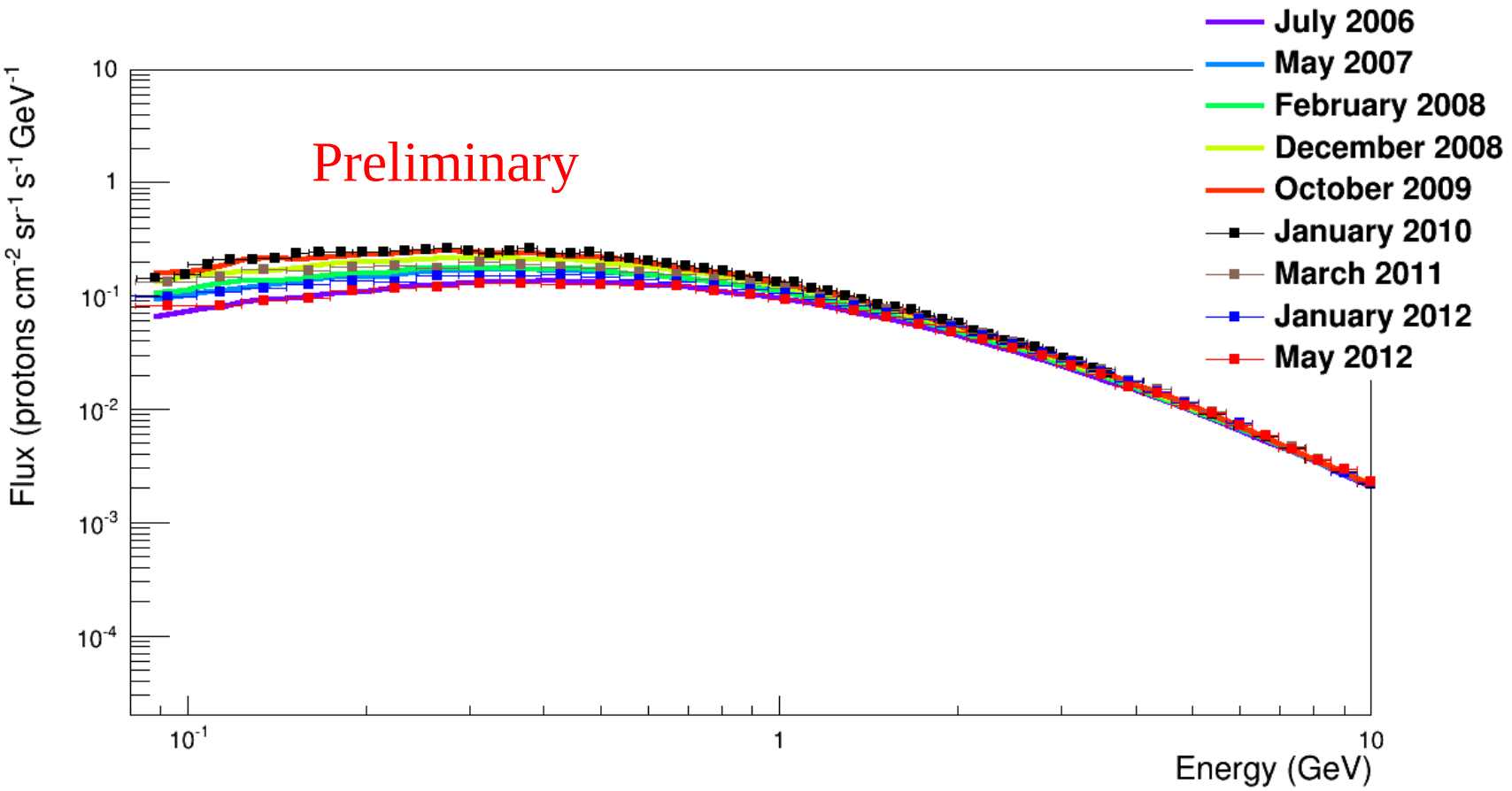
Time dependence of the proton flux



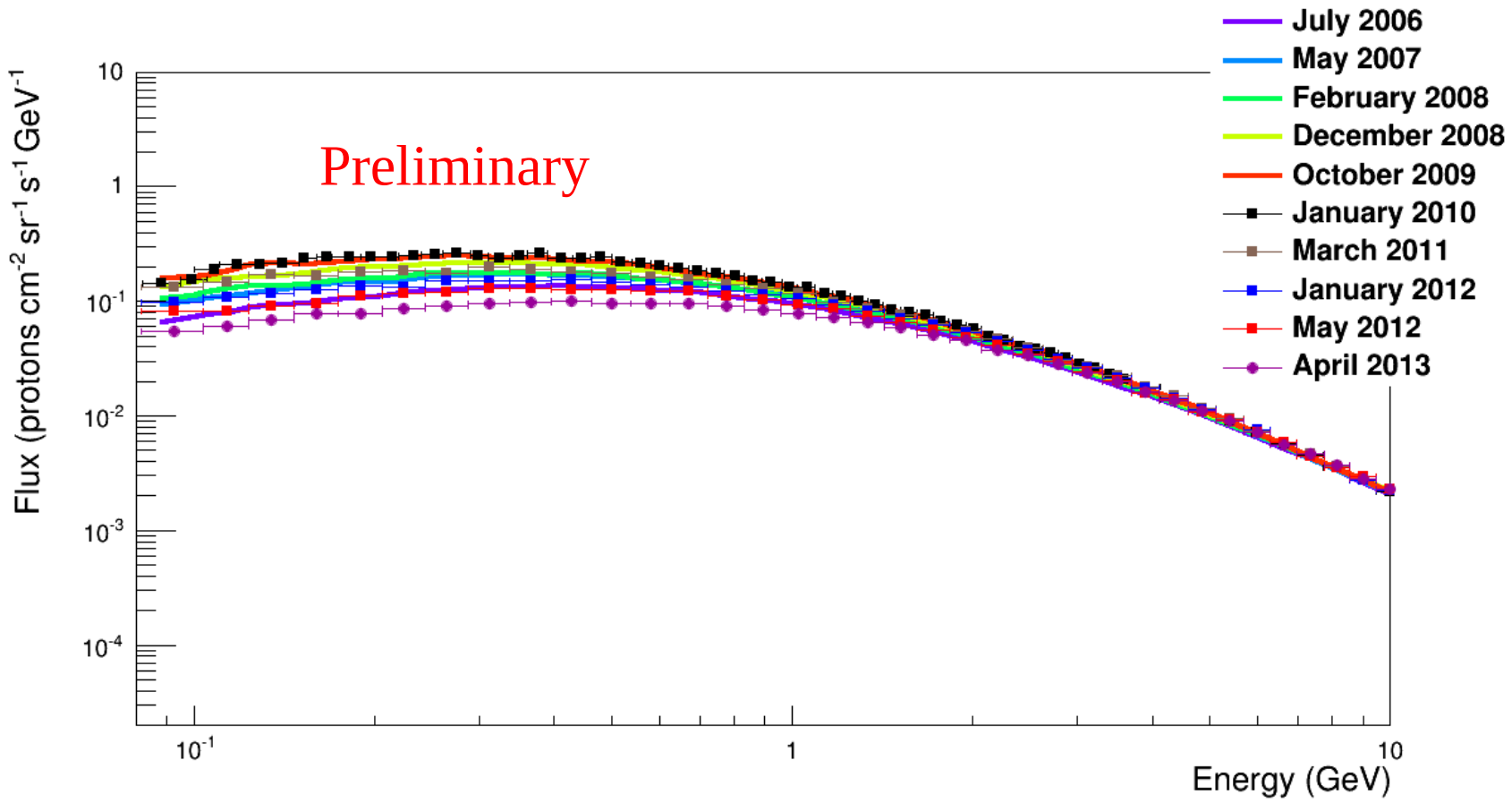
Time dependence of the proton flux



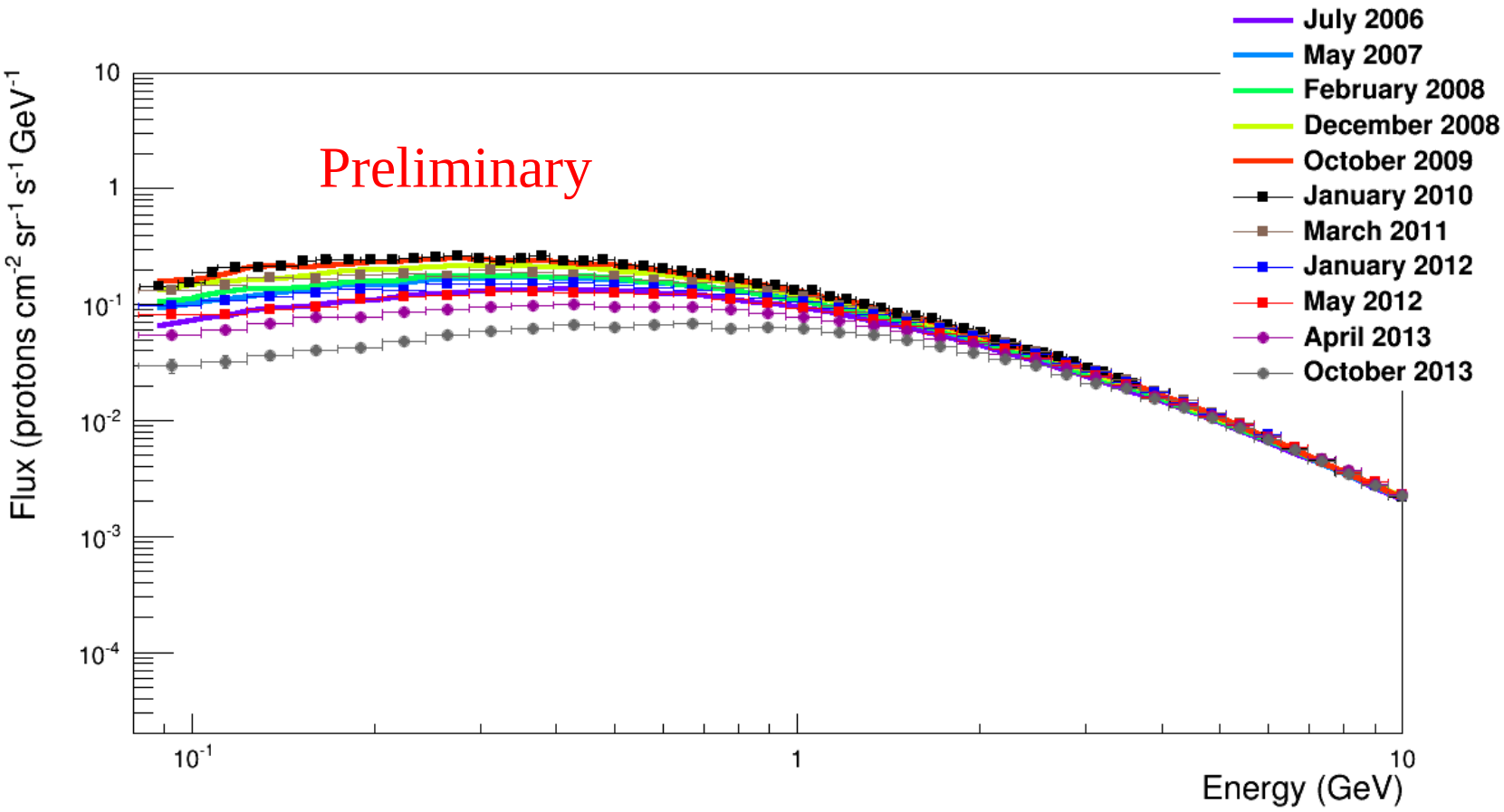
Time dependence of the proton flux



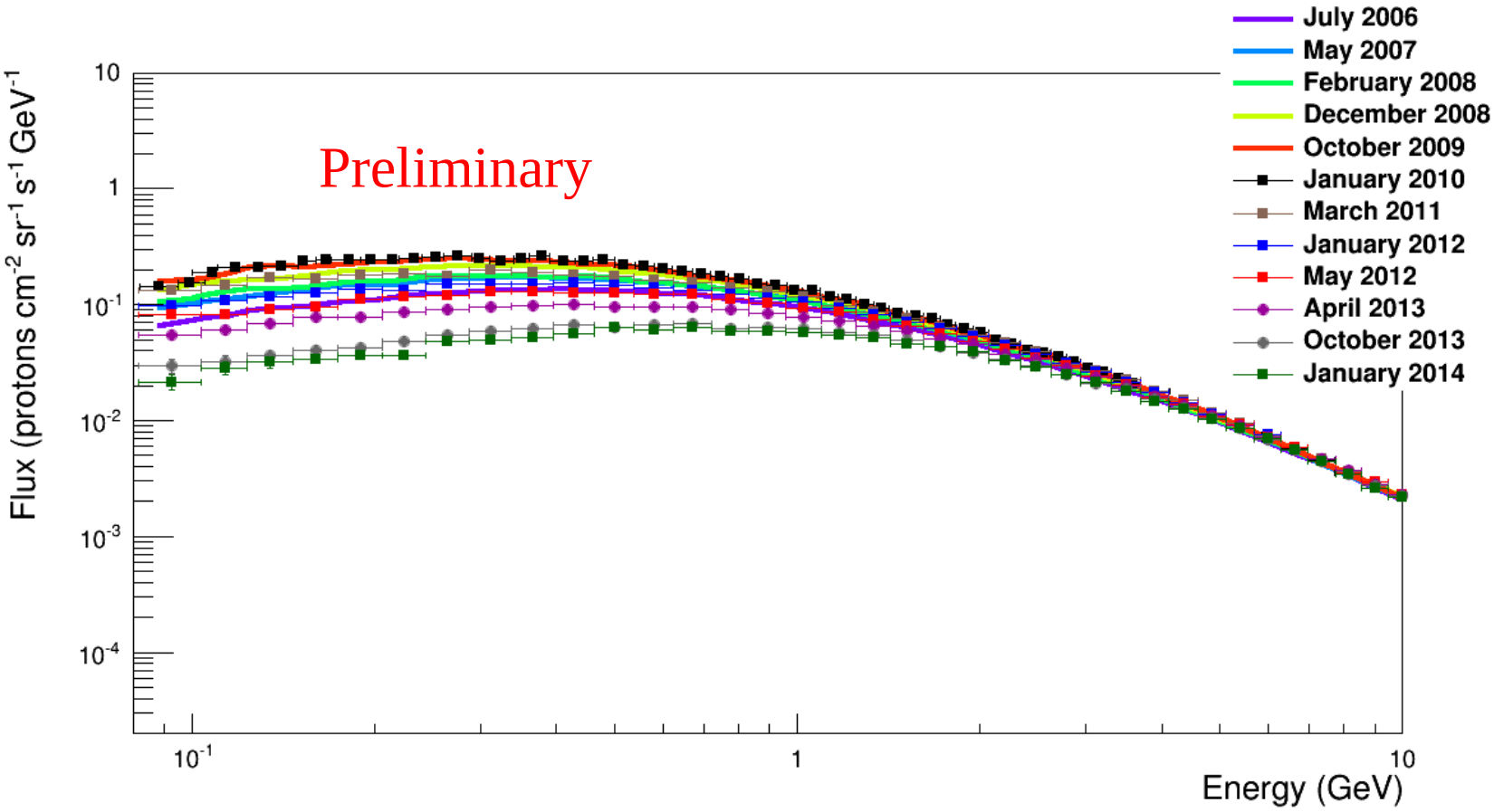
Time dependence of the proton flux



Time dependence of the proton flux

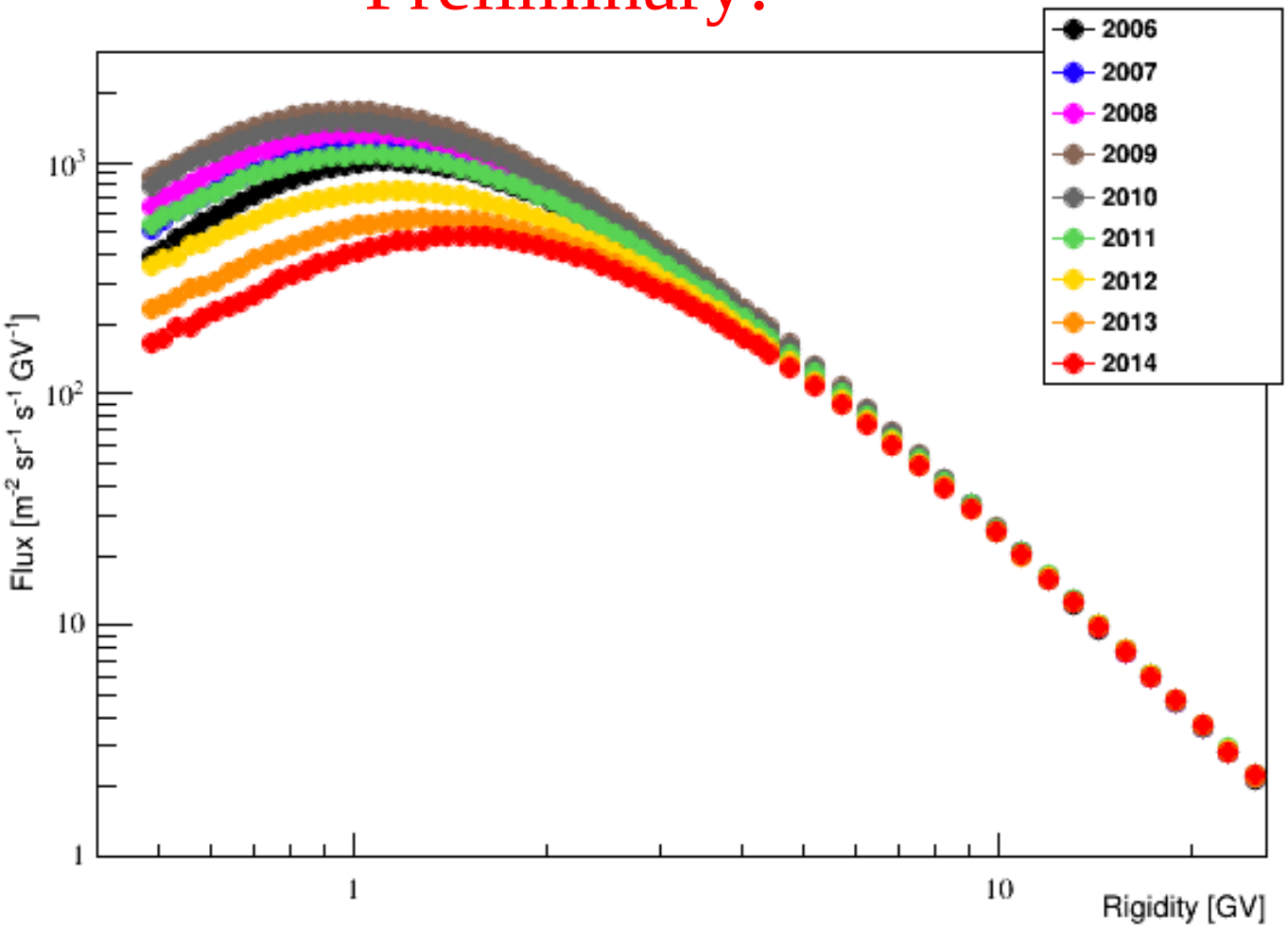


Time dependence of the proton flux

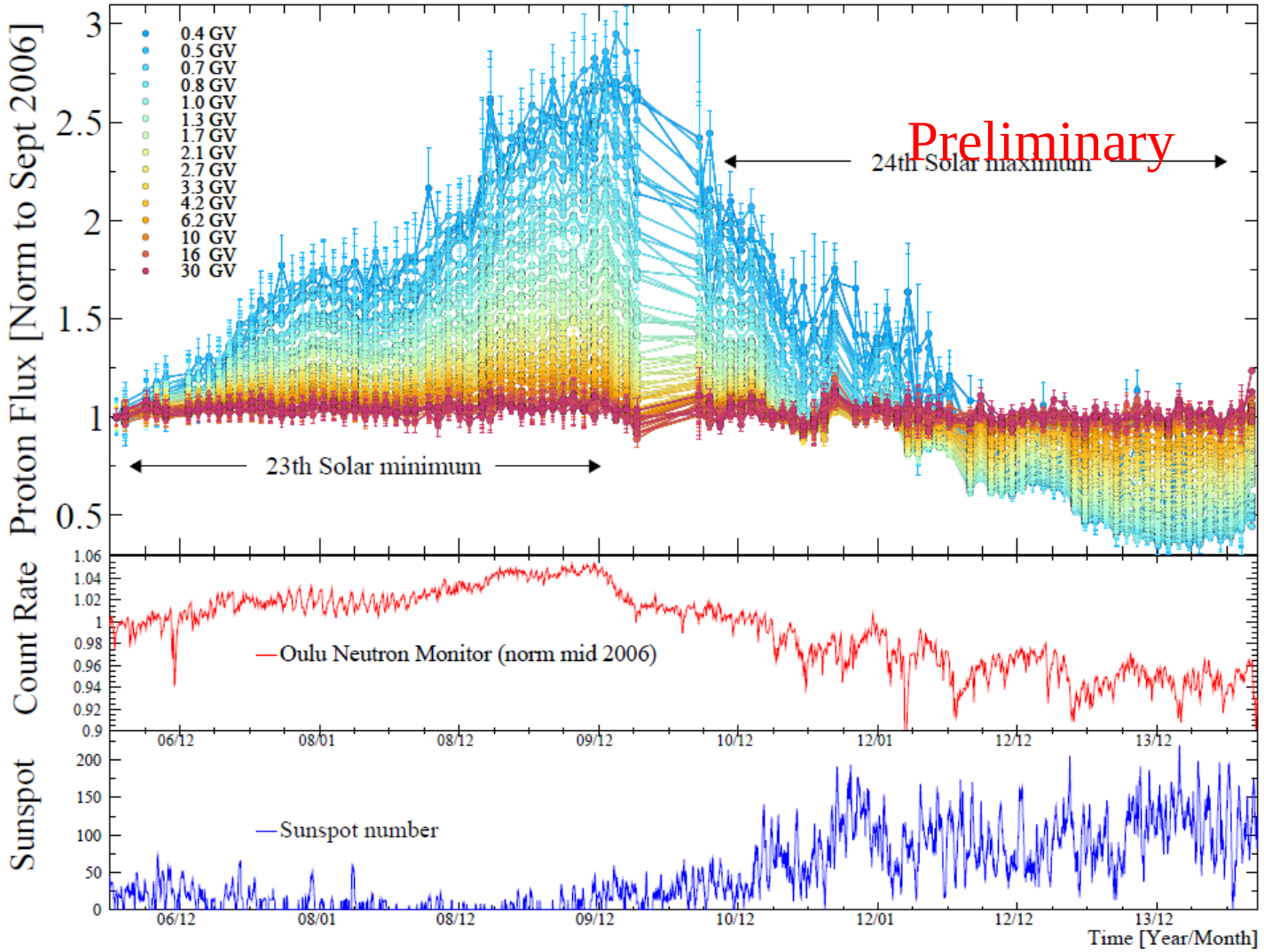


Time dependence of the proton flux

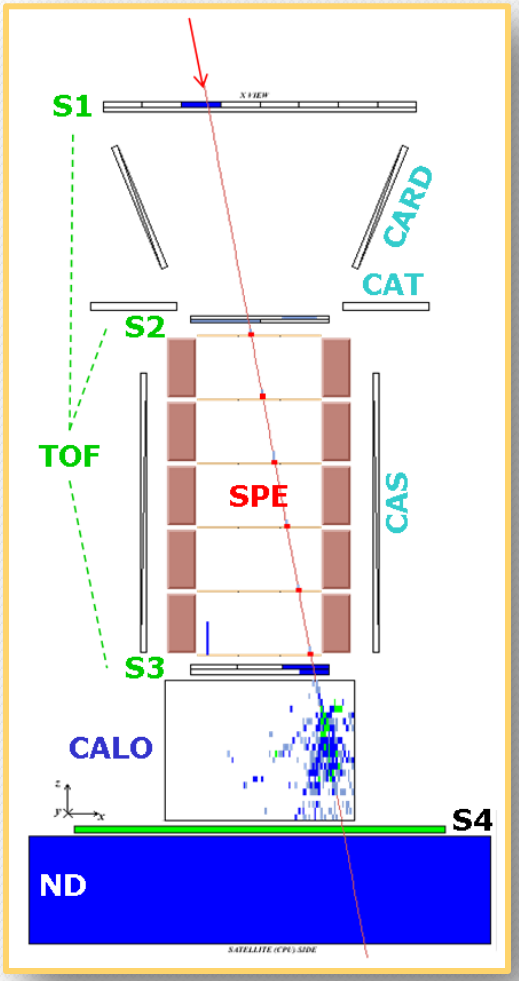
Preliminary!



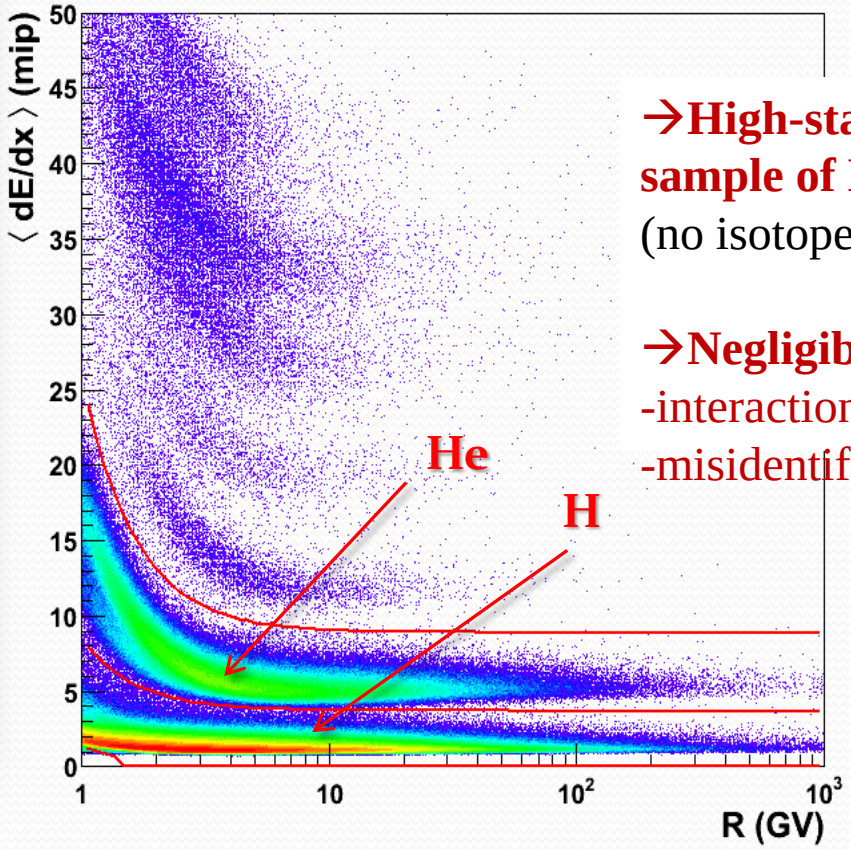
Time dependence of the proton flux



H/He selection



- Single good-quality track in the spectrometer
  → Particle rigidity (R = pc/Ze)
- Downward-going (velocity: β>0) & positive-curvature (R>0) trajectory
  → Positive-charge particle from above
- Clean pattern through the apparatus
  → Not an interaction product above or in the tracking system
- Energy deposits in the tracking system consistent with H and He nuclei

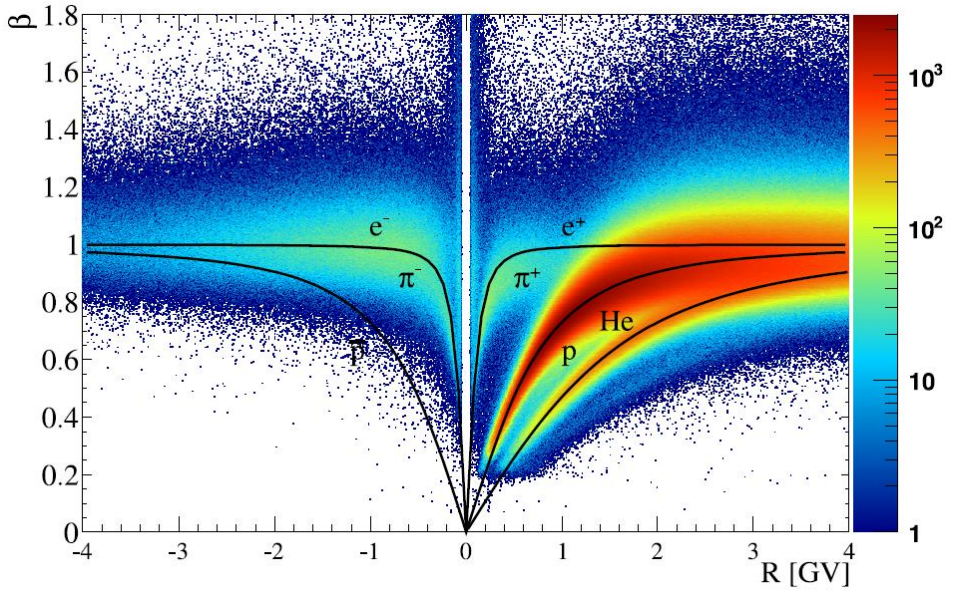


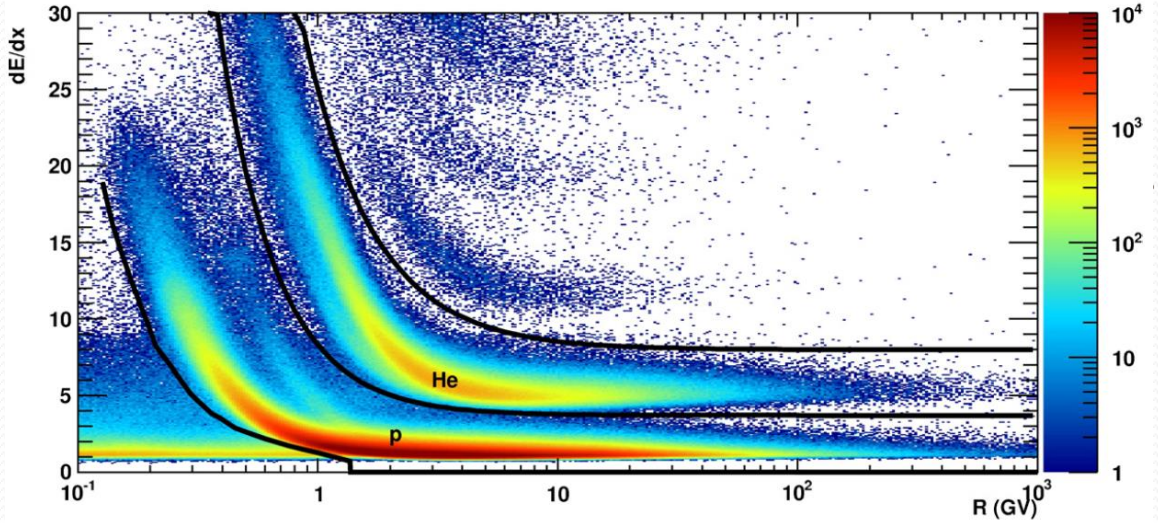
→High-statistic (~10^8) sample of H and He
(no isotope separation)

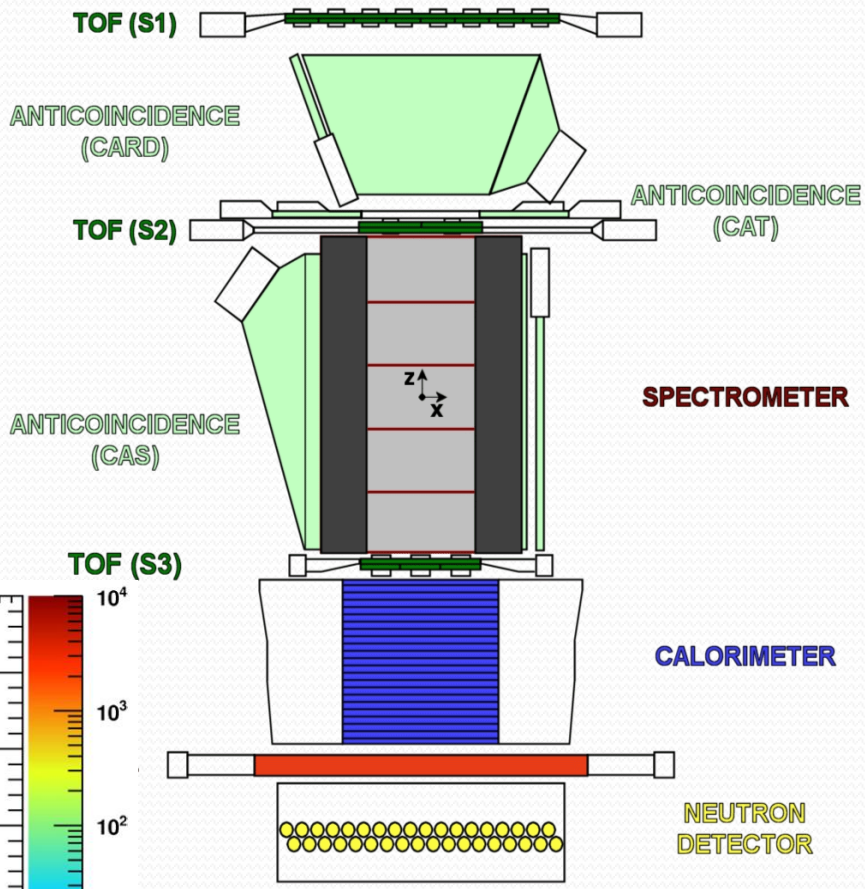
→Negligible bk of
-interaction products
-misidentified particles

PAMELA data

DATASET: From 2006 to 2014



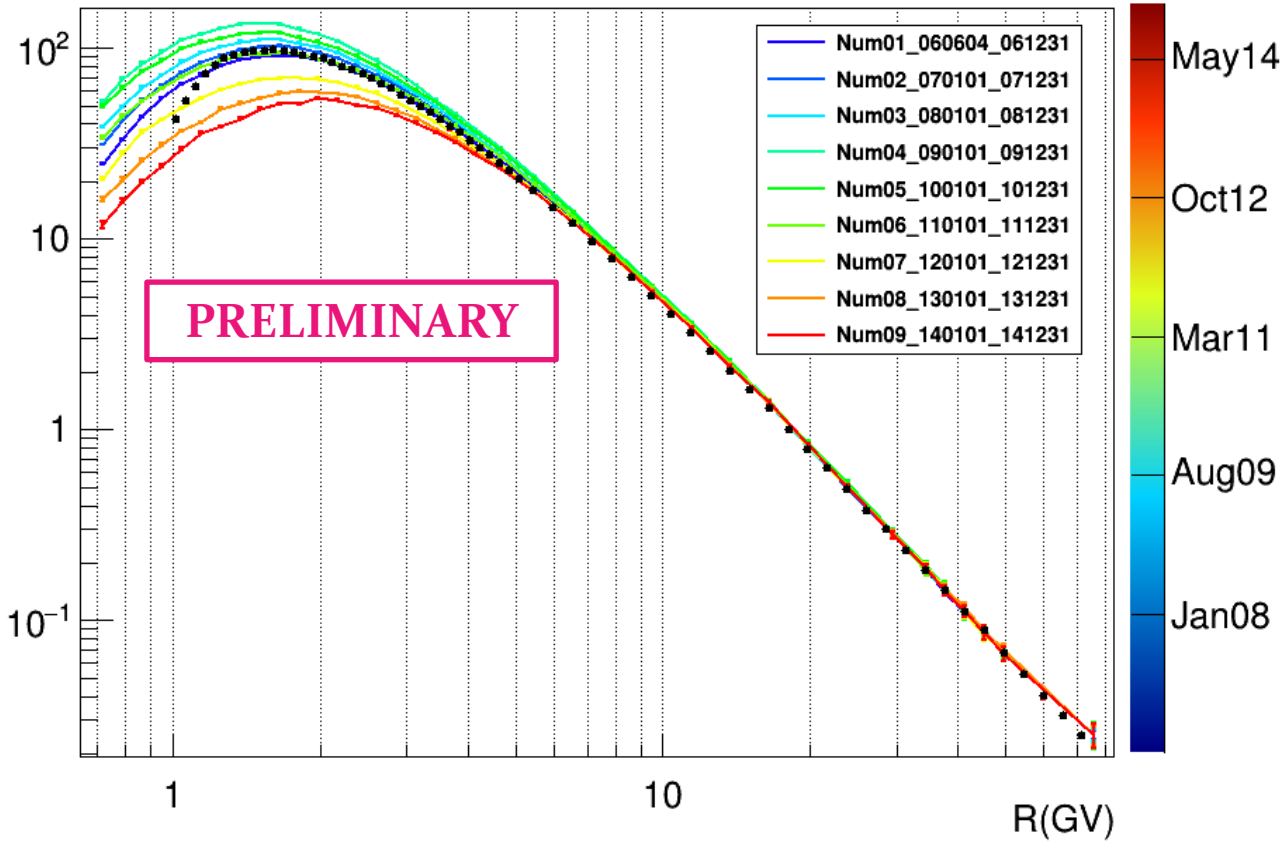




He Fluxes

Evolution of the helium energy spectrum from July 2006 to September 2014

- Acceptance 0.15
- Black Dots: Science
- Temporal period : 1 year
- Extended up to 2014



Summary and conclusions

- **PAMELA has been in orbit and studying cosmic rays for almost 9 years.**
- Antiproton energy spectrum and ratio → Measured up to ~300 GeV.
- High energy positron fraction (>10 GeV) → Measured up to ~300 GeV.
- H and He absolute fluxes → Measured up to ~1.2 TV.
- H and He isotope ratio
- Electron and positron absolute flux
- B/C ratio and absolute fluxes up to 100 GeV/n.
- CREs Anisotropies
- Solar physics: measurement of modulated fluxes and solar-flare particle spectra.
- Physics of the magnetosphere: first measurement of trapped antiproton flux and detailed measurement of trapped proton flux.
- Other studies and forthcoming results: *Primary and secondary-nuclei abundance (up to Oxygen), Solar modulation (long-term flux variation and charge-dependent effects), Solar events: several new events under study.*