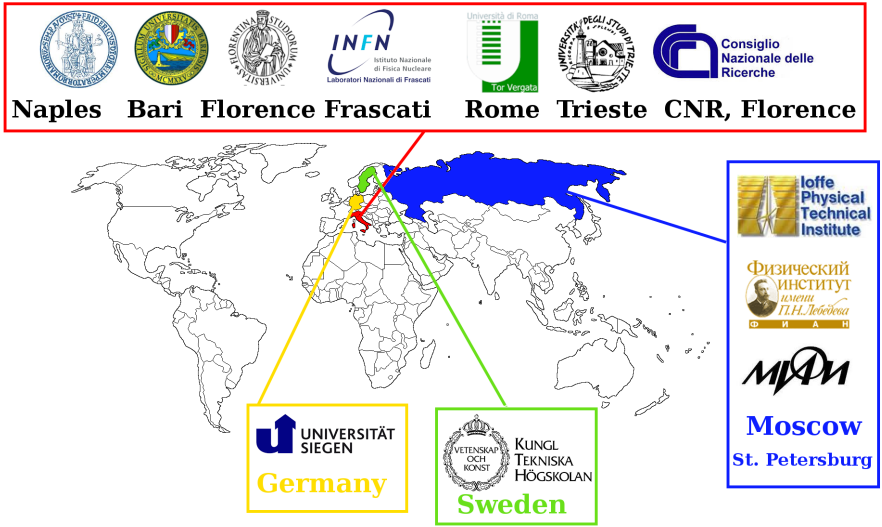
Cosmic ray PAMELA measurements deep inside the heliosphere

Valeria Di Felice

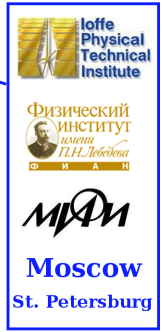
INFN Rome Tor Vergata and ASI Science Data Center

XXV European Cosmic Ray Symposium, 4 - 9 September 2016, Torino

PAMELA COLLABORATION



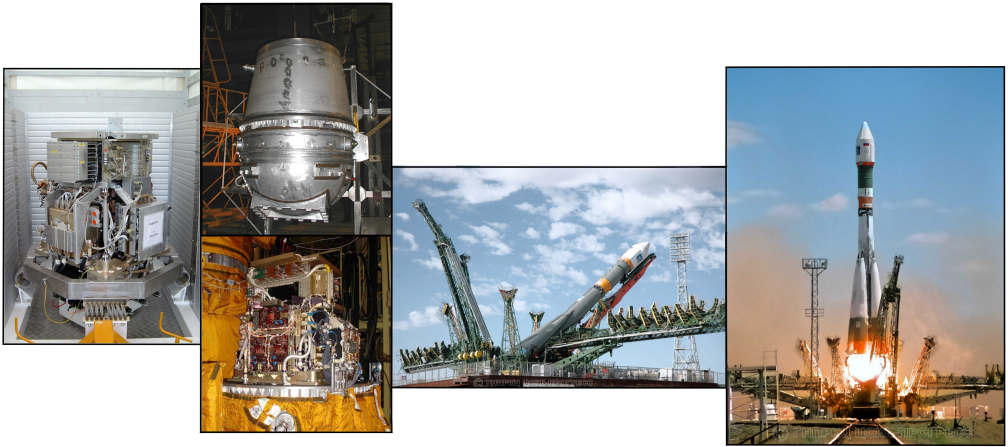
PAMELA COLLABORATION AND EXTERNAL COLLABORATION



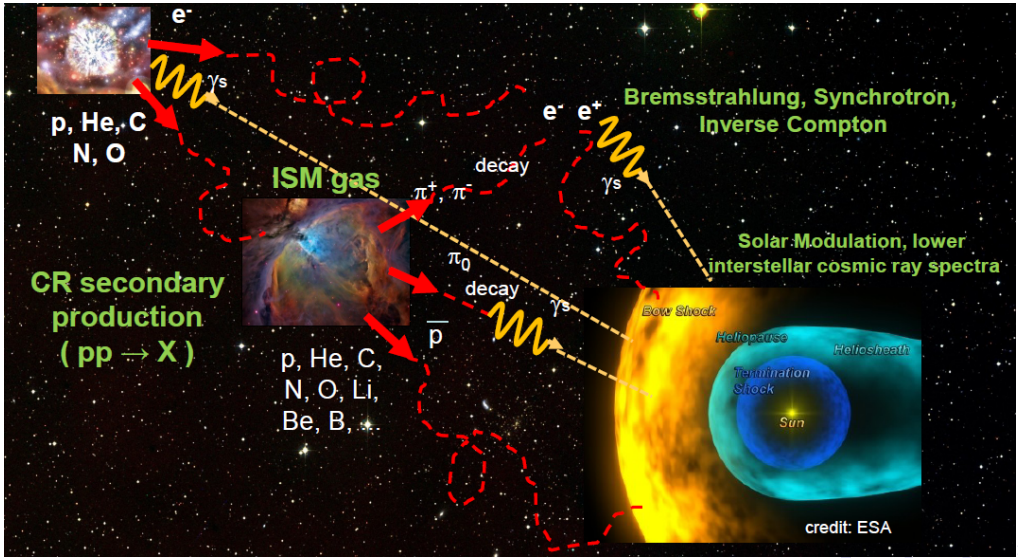
10 years of PAMELA

Launched on 15th June 2006. Recently celebrated 10 years in flight!

Space-borne experiment for the precise measure of the matter and antimatter component in cosmic rays.



Cosmic ray propagation



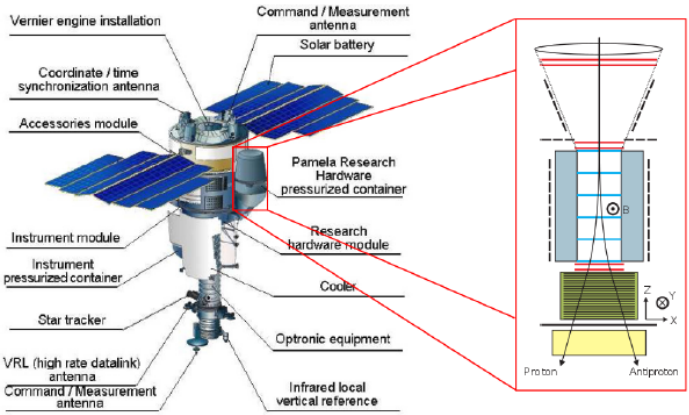
The PAMELA instrument

PAMELA

- Resurs DK1 satellite, high quality camera;
- Quasi-polar elliptical orbit 70 degree inclination 350/610 km.
- Circular from 2010 at 600 km.

Main goals

- Direct detection of CRs in space;
- Precise measurement of (anti)particles;
- Solar modulation, solar physics.



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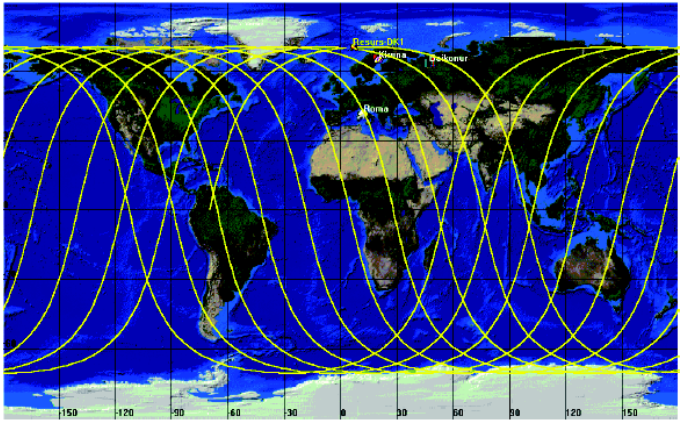

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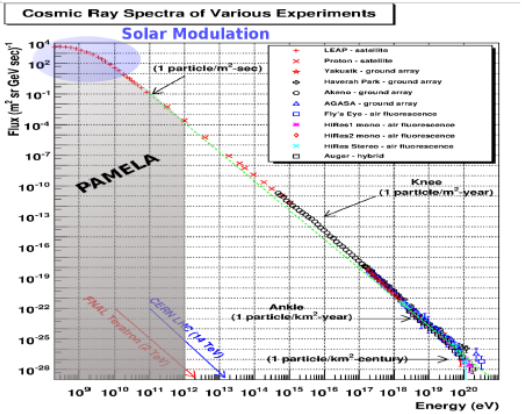
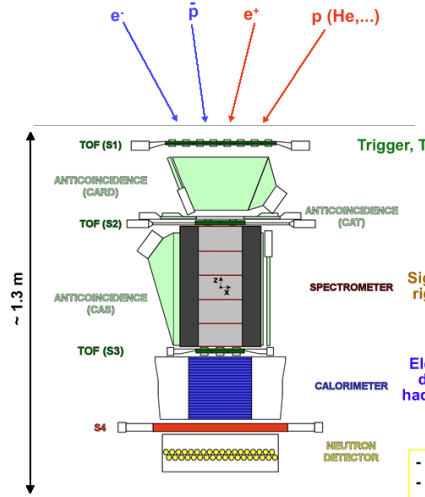


The PAMELA instrument



Trigger, ToF, dE/dx

- S1, S2, S3; double layers, x-y
- plastic scintillator (8mm)
- ToF resolution ~300 ps (S1-3 ToF >3 ns)
- lepton-hadron separation < 1 GeV/c
- S1.S2.S3 (low rate) / S2.S3 (high rate)

Sign of charge, rigidity, dE/dx

- Permanent magnet, 0.43 T
- 21.5 cm^2 sr
- 6 planes double-sided silicon strip detectors (300 μm)
- 3 μm resolution in bending view → MDR ~800 GV (6 plane) ~500 GV (5 plane)

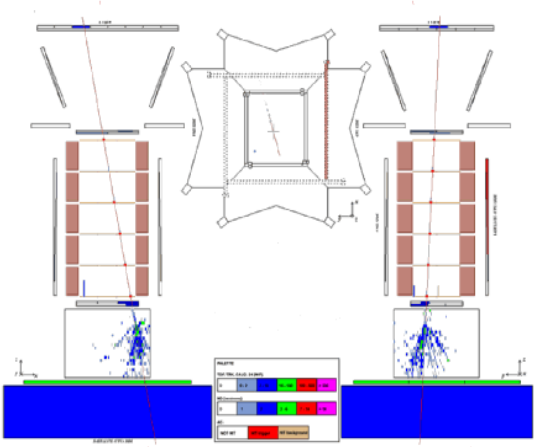
Electron energy, dE/dx, lepton-hadron separation

- 44 Si-x / W / Si-y planes (380)
- 16.3 X0 / 0.6 L
- dE/E ~5.5 % (10 - 300 GeV)
- Self trigger > 300 GeV / 600 cm^2 sr

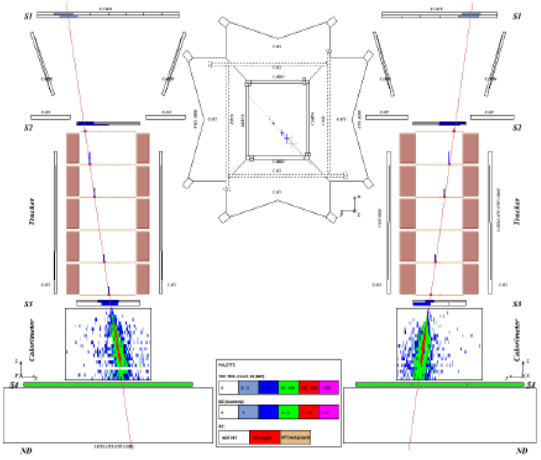
- 36 ^{3}He counters
- ^{3}He(n,p)T; E_p = 780 keV
- 1 cm thick poly + Cd moderator
- 200 μs collection

The PAMELA instrument

Interacting proton 16 GV



Positron 92 GV



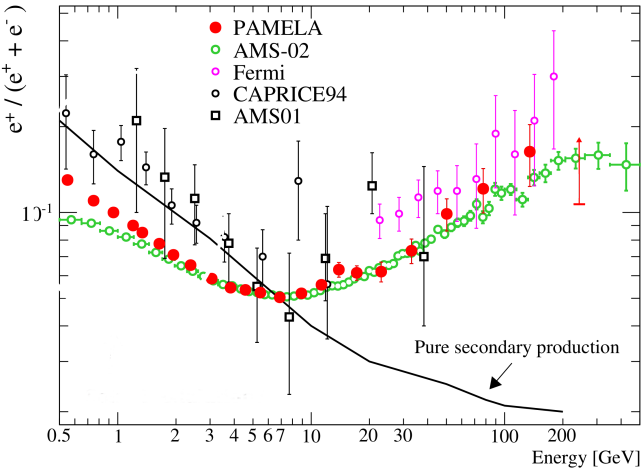
Positron fraction results

- **High energy**: evidence of positron excess above 10 GeV with respect to pure secondary production;
- **Low energy**: *charge-dependent solar modulation*. A clear understanding of the constraints related to charge-sign dependent solar modulation and how it changes with time (solar activity) is crucially important.

O. Adriani et al., Nature 458 (2009) 607

O. Adriani et al., AP 34 (2010) 1

O. Adriani et al., PRL 111 (2013) 081102



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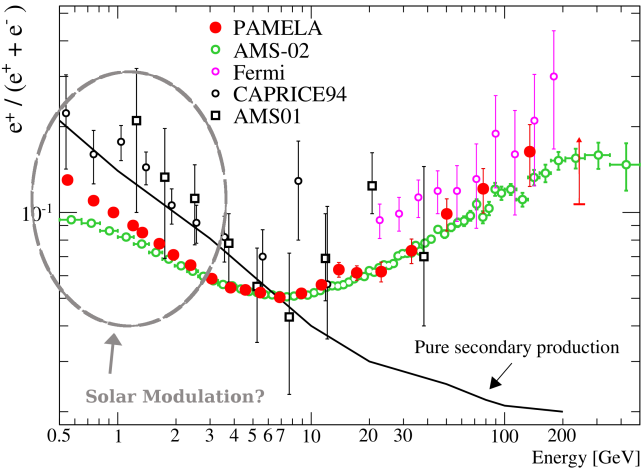
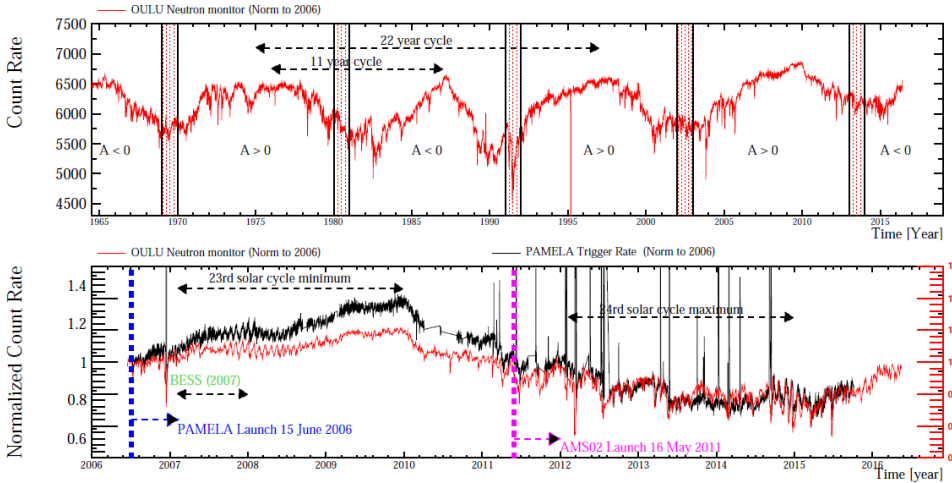
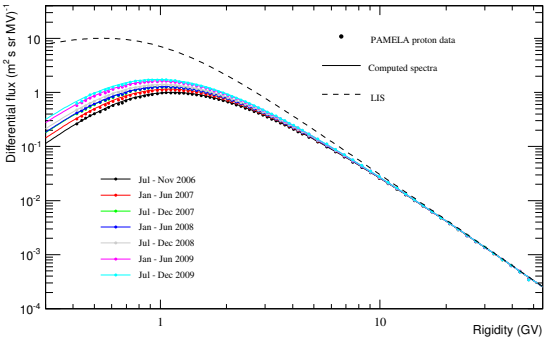


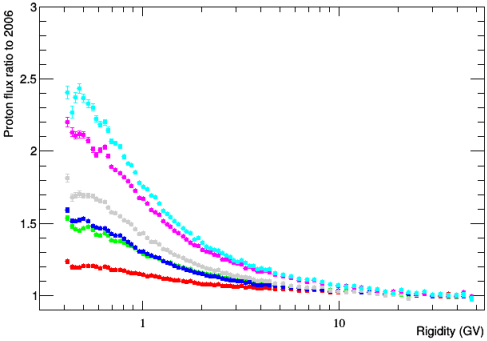
Solar Activity and Cosmic Rays



Galactic protons during solar minimum

Low energy (down to 80 MeV) **proton** **fluxes increase** at low energy as the **solar activity decreases**, from 2006 to 2009.



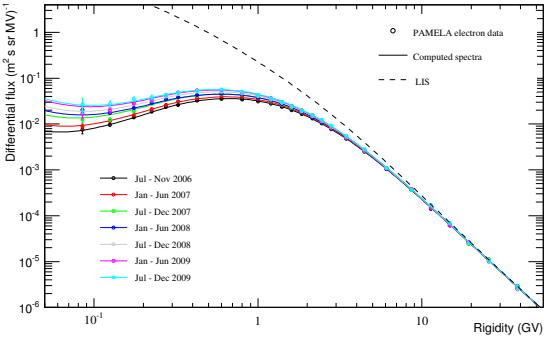


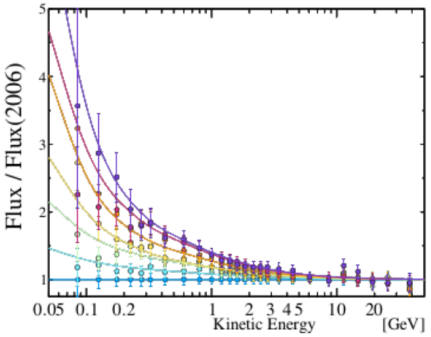
CR solar modulation significantly modifies the local interstellar cosmic ray spectra in intensity and shape, a process that depends on the **species of particles'**, their **energy**, **sign of charge**, and **solar activity**, both in terms of space, where in the heliosphere they are observed, and in time, when during a solar cycles they are measured.

Adriani et al., ApJ 765, 2 (2013)
Potgieter, M.S. et al. Sol Phys (2014) 289: 391

Galactic electrons during solar minimum

Low energy (down to 70 MeV) **electron fluxes increase** at low energy as the **solar activity decreases**, from 2006 to 2009.





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

See Munini R. talk on Monday 5th

Galactic positrons during solar minimum

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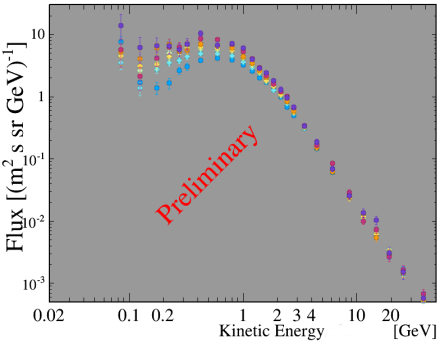
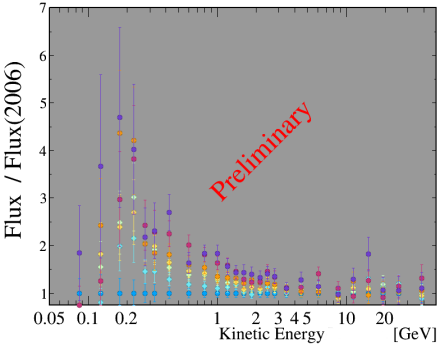




See Munini R. talk on Monday 5th

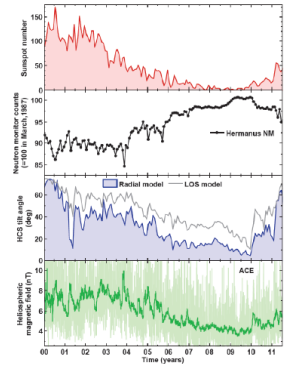
Modeling

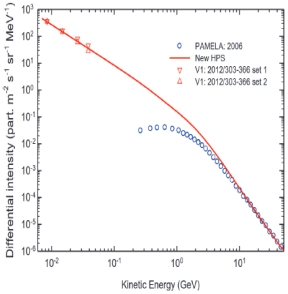
$$\underbrace{\frac{\partial f}{\partial t}}_{a} = \underbrace{-\mathbf{V}\cdot\nabla f}_{b} + \underbrace{\nabla\cdot(\mathbf{K}_s\cdot\nabla f)}_{c} - \underbrace{\langle \mathbf{v_D}\rangle\cdot\nabla f}_{d} + \underbrace{\frac{1}{3}(\nabla\cdot\mathbf{V})\frac{\partial f}{\partial \ln p}}_{e} + \underbrace{Q(\mathbf{x},p,t)}_{f}$$

(a) $f(\mathbf{x},p,t)$, omnidirectional function distribution of CRs; **(b)** convection with solar wind $\mathbf{V}$; **(c)** diffusion by magnetic field irregularities; **(d)** drift, curvature and gradient in magnetic field; **(e)** adiabatic energy losses; **(f)** local sources (Jovian electrons);

Model input parameters:

- Geometry and physical boundaries of the Heliosphere
- Solar activity parameters (time-varying)
- Input Local Interstellar Spectrum (LIS)





Potgieter, M. S., AdSpR, 53, 1415 (2014)

Modeling results

$$\underbrace{\frac{\partial f}{\partial t}}_{a} = -\underbrace{\mathbf{V}\cdot\nabla f}_{b} + \underbrace{\nabla\cdot(\mathbf{K}_s\cdot\nabla f)}_{c} - \underbrace{\langle \mathbf{v_D}\rangle\cdot\nabla f}_{d} + \underbrace{\frac{1}{3}(\nabla\cdot\mathbf{V})\frac{\partial f}{\partial \ln p}}_{e} + \underbrace{Q(\mathbf{x},p,t)}_{f}$$

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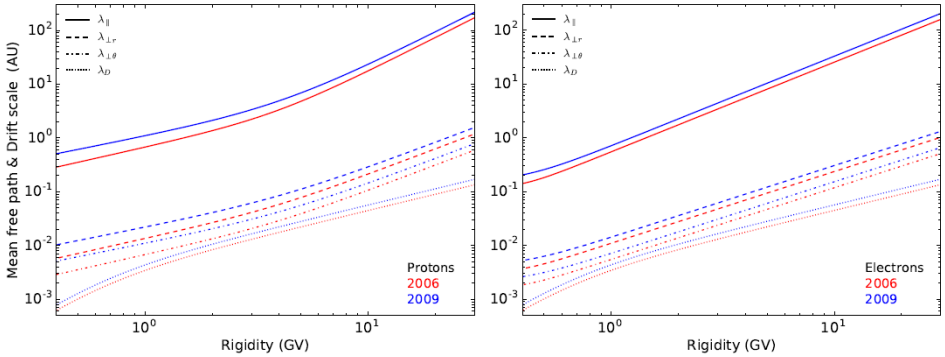

Charge sign dependent modulation - solar minimum

$$\underbrace{\frac{\partial f}{\partial t}}_{a} = \underbrace{-\mathbf{V}\cdot\nabla f}_{b} + \underbrace{\nabla\cdot(\mathbf{K}_s\cdot\nabla f)}_{c} - \underbrace{\langle \mathbf{v_D}\rangle\cdot\nabla f}_{d} + \underbrace{\frac{1}{3}(\nabla\cdot\mathbf{V})\frac{\partial f}{\partial \ln p}}_{e} + \underbrace{Q(\mathbf{x},p,t)}_{f}$$

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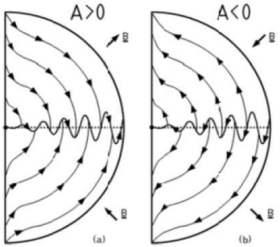
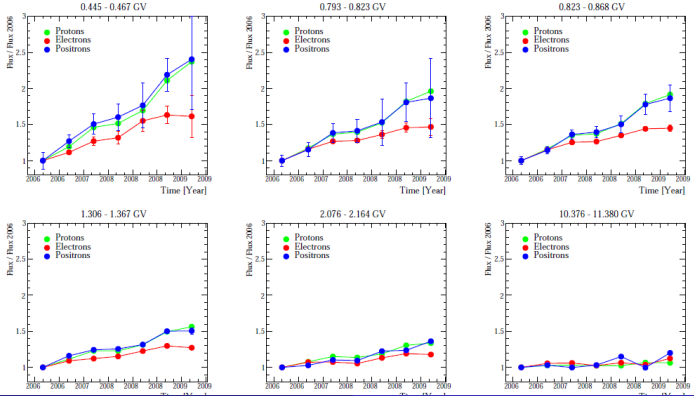


Positive particle

drift pattern

preliminary e^+ data

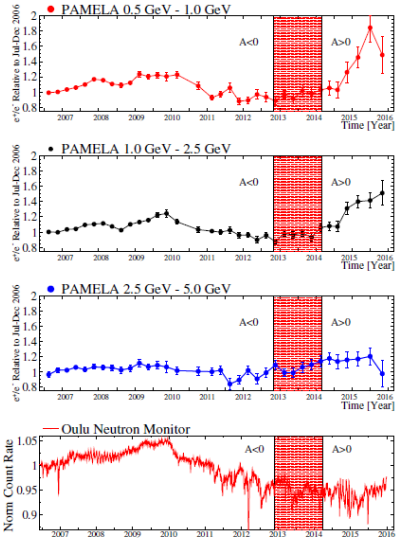


Reversal of the Sun magnetic field polarity

positron to electron ratio measurement:

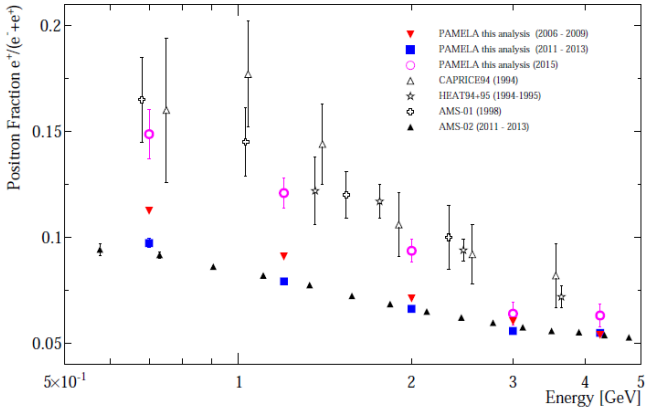
- Polarity reversal change global drift pattern for positive and negative particles;
- During the 24th solar cycle this took place between November 2012 and March 2014 (16 months apart);
- After few months the new condition "propagate" through the heliosphere and positron starts to increase abruptly.

O. Adriani et al., Phys. Rev. Lett. 116, (2016), 241105

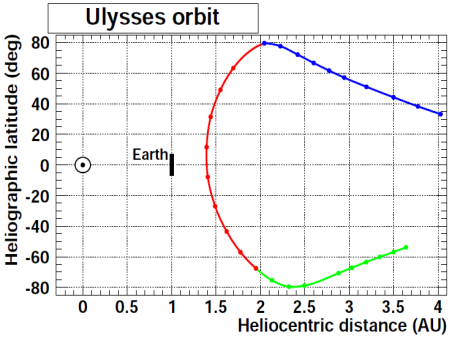


Positron fraction at low energy

- Low energy "tension" between experiments explained with charge-sign dependence;
- Positron fraction in 2015 approaches previous measure obtained in A > 0 epochs.

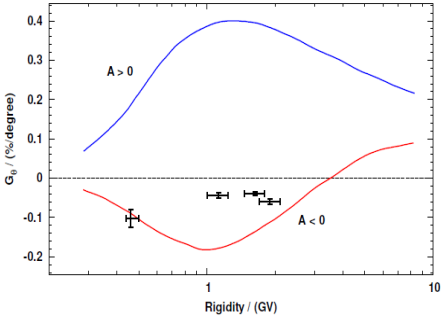


Spatial effects



J. Gieseler and B. Heber, A&A, 589 (2016) A32

De Simone et al, ASTRA, 7, 425 (2011)

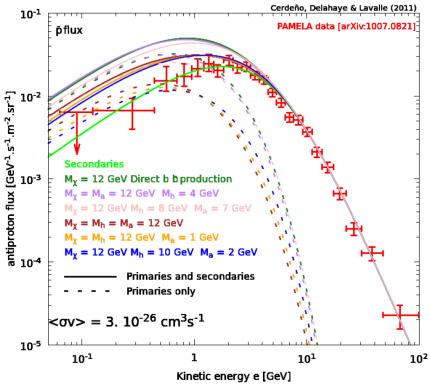


Radial and latitudinal gradients: proton intensity variation with distance found to be:

- radial: positive (increase of particle intensity with radial distance from the Sun)
- latitudinal: negative (higher fluxes in helio-equatorial regions respect to polar ones, as expected for positive particles in $A < 0$ polarity epochs)

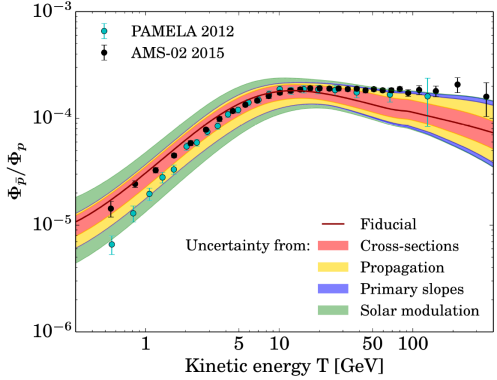
Antiproton and low energy indirect DM searches

Antiproton flux predictions for a 12 GeV WIMP annihilating into different mass combinations of an intermediate two-boson state which further decays into quarks.



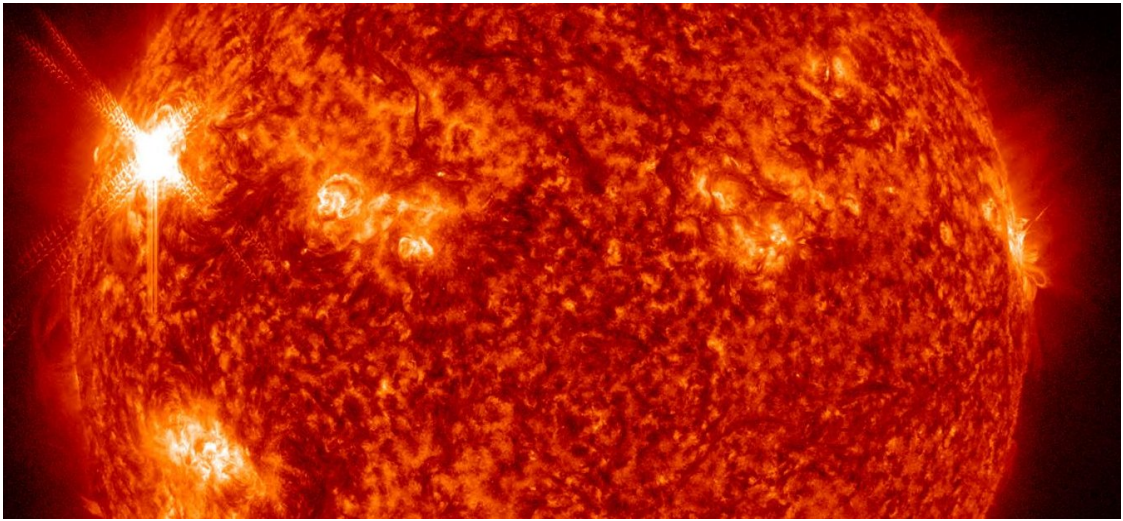
D. G. Cerdeno, T. Delahaye, J. Lavalle, Nucl. Phys. B 854 (2012) 738

Antiproton to proton ratio from recent experimental results and model-related uncertainties



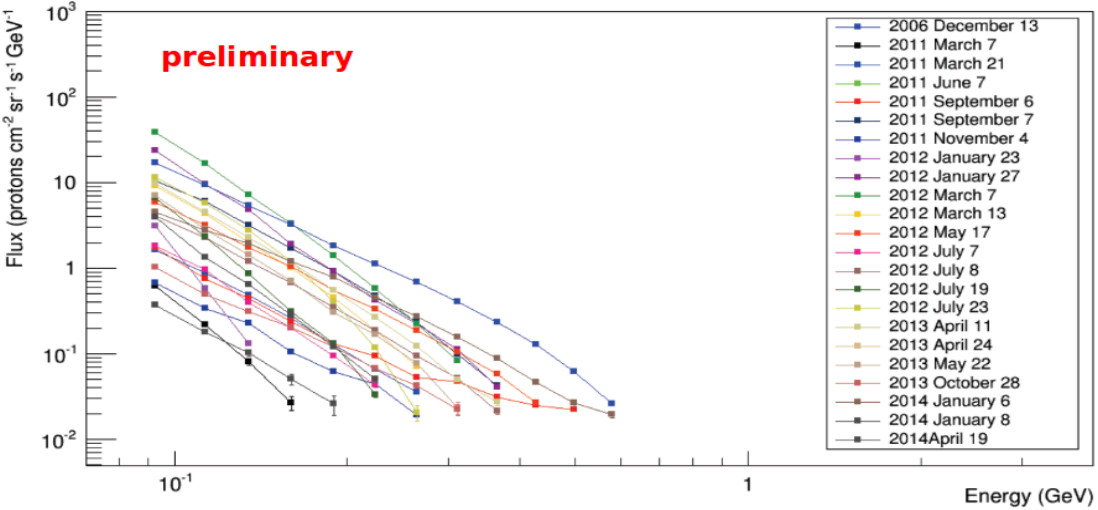
G. Giesen et al., JCAP 1509 (2015) 023, arXiv:1504:04276

Solar particle events



NASA/SDO

Solar particle events

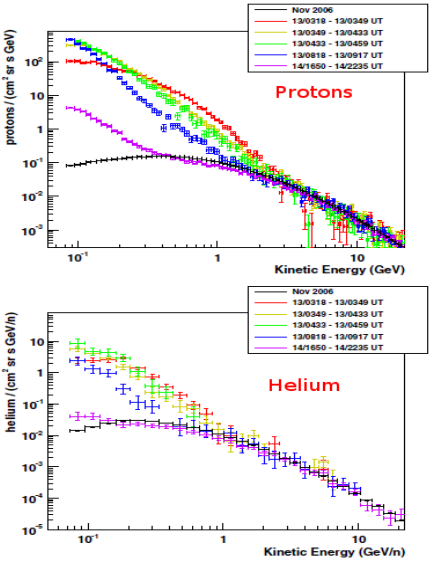


SEP on 2006 Dec 13^{th}

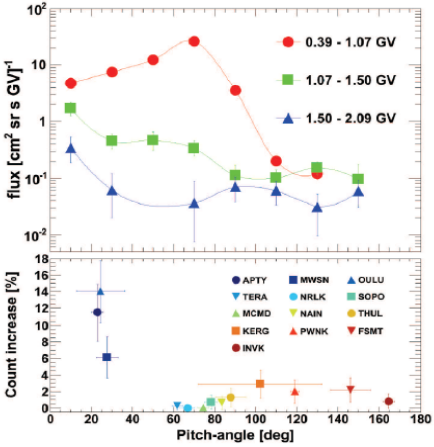
Complete information about SEP events:

- wide energy measurement interval, bridging the low energy data by other space based instruments and the GLE data by the worldwide network of neutron monitors (NMs);
- sensitivity to particle composition (protons, He nuclei...)
- possibility to reconstruct the angular distribution.

Adriani O. et al., ApJ 742:102 (2011)



SEP on 2012 May 17^{th}



Two proton components (different pitch angle distribution)

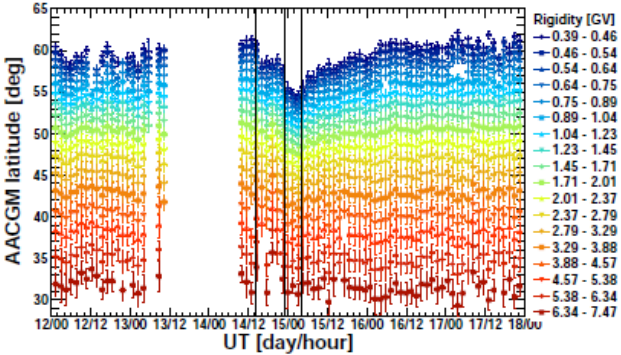
- Low rigidity ($\sim<$ 1 GV): confined to pitch angle $\sim$ 90, significant scattering
- High rigidity (1-3 GV): consistently with NMs, particles are field aligned, beam width $\sim 40 - 60$ (not scattered)

Bruno A. et al.,J. Phys.: Conf. Ser. 675 032006 (2016)

See Bruno A. talk on Wednesday 7^{th}

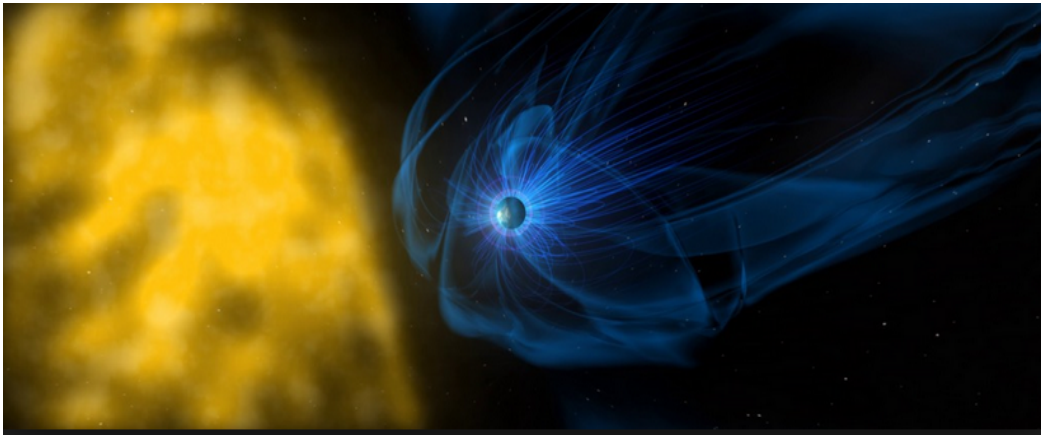
Latitudinal cutoff variation effect

Time profile of the geomagnetic cutoff latitudes measured by PAMELA for different rigidity bins, during the 14 Dec 2006 geomagnetic storm.



O. Adriani et al, SpaceWeather 14 (2016) 210, featured as a Research Spotlight on https://Eos.org

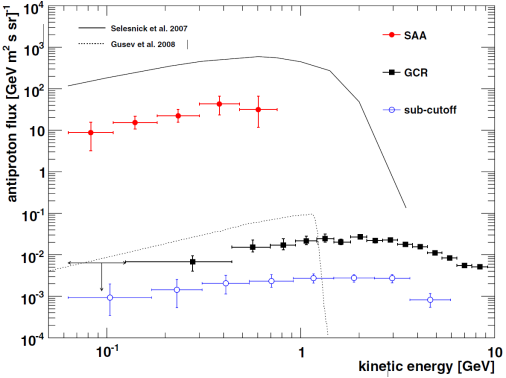
The effect of Earth Magnetosphere



svs.gsfc.nasa.gov

Geomagnetic trapped particles (South Atlantic Anomaly)

Discovery of **geomagnetic trapped antiproton**, flux exceeds by 3 order of magnitude the galactic component!

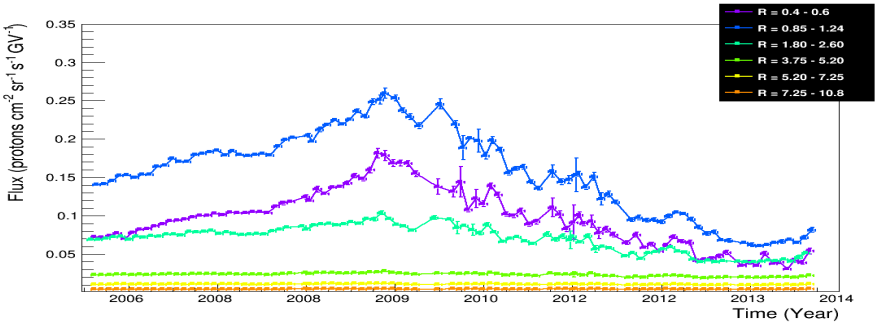


O. Adriani et al., ApJL 737 (2011), L29

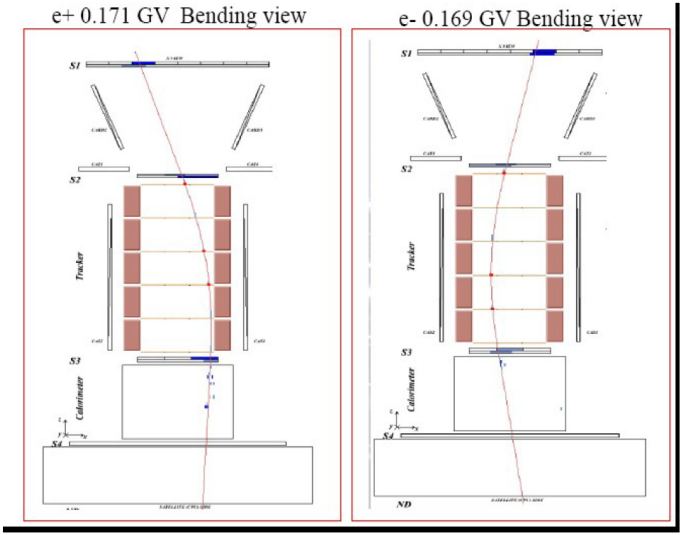
Conclusions and perspective

- **PAMELA has been in orbit and studying cosmic rays since 10 years**;
- PAMELA obtain a **huge amount of results measuring CR spectra with unprecedented precision** and opening the way of **high precision CR physics**;
- PAMELA resulted to be an excellent instrument for **heliospheric, solar and magnetospheric** physics studies.
- **Other studies and forthcoming results**: Solar modulation (long-term flux variation), Solar events: several new events under study
- published PAMELA data are available at the ASI Science Data Center *http://tools.asdc.asi.it/cosmicRays.jsp*

Preliminary proton fluxes at several rigidities

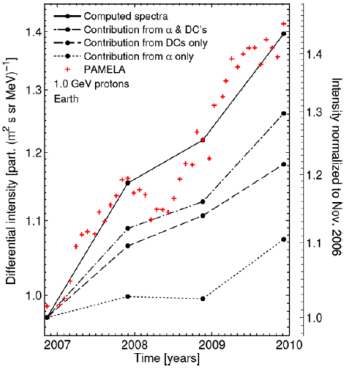


Spares

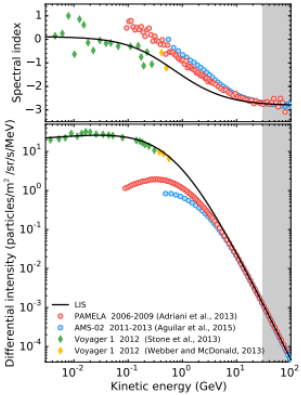

e+ 0.171 GV Bending view
e- 0.169 GV Bending view
S1
S2
S3
S4
Tracker
Calorimeter
ND

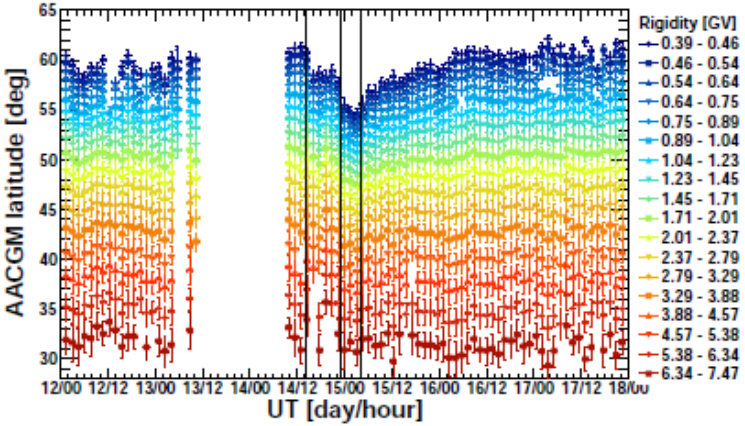
$$\underbrace{\frac{\partial f}{\partial t}}_{a} = \underbrace{-\mathbf{V}\cdot\nabla f}_{b} + \underbrace{\nabla\cdot(\mathbf{K}_s\cdot\nabla f)}_{c} - \underbrace{\langle \mathbf{v_D}\rangle\cdot\nabla f}_{d} + \underbrace{\frac{1}{3}(\nabla\cdot\mathbf{V})\frac{\partial f}{\partial \ln p}}_{e} + \underbrace{Q(\mathbf{x},p,t)}_{f}$$

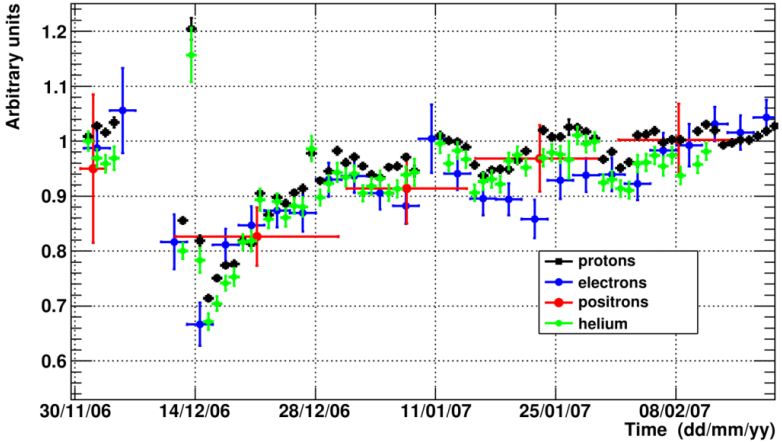
(a) $f(\mathbf{x},p,t)$, omnidirectional function distribution of CRs; **(b)** convection with solar wind $\mathbf{V}$; **(c)** diffusion by magnetic field irregularities; **(d)** drift, curvature and gradient in magnetic field; **(e)** adiabatic energy losses; **(f)** local sources (Jovian electrons);



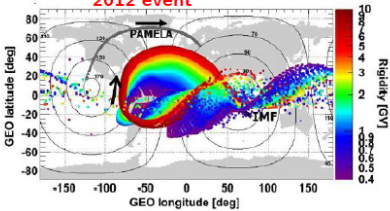
Computed and measured differential intensity for 1.0 GeV protons as a function of time, from November 2006 to December 2009.


Spectral index
1
0
−1
−2
−3
Differential intensity (particles/m^2 /sr/s/MeV)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
LIS
PAMELA 2006-2009 (Adriani et al., 2013)
AMS-02 2011-2013 (Aguilar et al., 2015)
Voyager 1 2012 (Stone et al., 2013)
Voyager 1 2012 (Webber and McDonald, 2013)
10^{-2}
10^{-1}
10^0
10^1
10^2
Kinetic energy (GeV)


AACGM latitude [deg]
65
60
55
50
45
40
35
30
12/00 12/12 13/00 13/12 14/00 14/12 15/00 15/12 16/00 16/12 17/00 17/12 18/00
UT [day/hour]
Rigidity [GV]
0.39 - 0.46
0.46 - 0.54
0.54 - 0.64
0.64 - 0.75
0.75 - 0.89
0.89 - 1.04
1.04 - 1.23
1.23 - 1.45
1.45 - 1.71
1.71 - 2.01
2.01 - 2.37
2.37 - 2.79
2.79 - 3.29
3.29 - 3.88
3.88 - 4.57
4.57 - 5.38
5.38 - 6.34
6.34 - 7.47

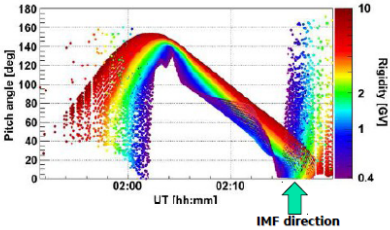

Arbitrary units
1.2
1.1
1
0.9
0.8
0.7
0.6
protons
electrons
positrons
helium
30/11/06
14/12/06
28/12/06
11/01/07
25/01/07
08/02/07
Time (dd/mm/yy)

First polar pass (01:58-02:20 UT) who registered **the May 17, 2012 event**



As PAMELA is moving eastward, observed asymptotic directions rapidly vary performing a (clockwise) loop over the region above Brazil.

The color codes refer to the particle rigidity



Distributions of asymptotic directions as a function of UT and pitch-angle

the color codes refer to the particle pitch-angle wrt the IMF

PAMELA is looking at the IMF direction at ~2:06 UT

Bruno et al., "The May 17, 2012 solar event: Back-tracing analysis and flux reconstruction with PAMELA", *Journal of Physics: Conference Series* 675.3 (2016).

Summary of PAMELA results

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

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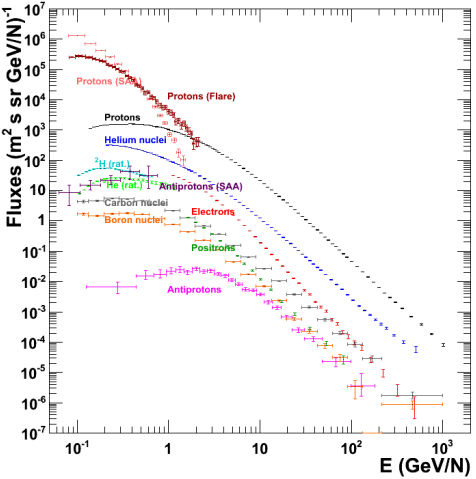
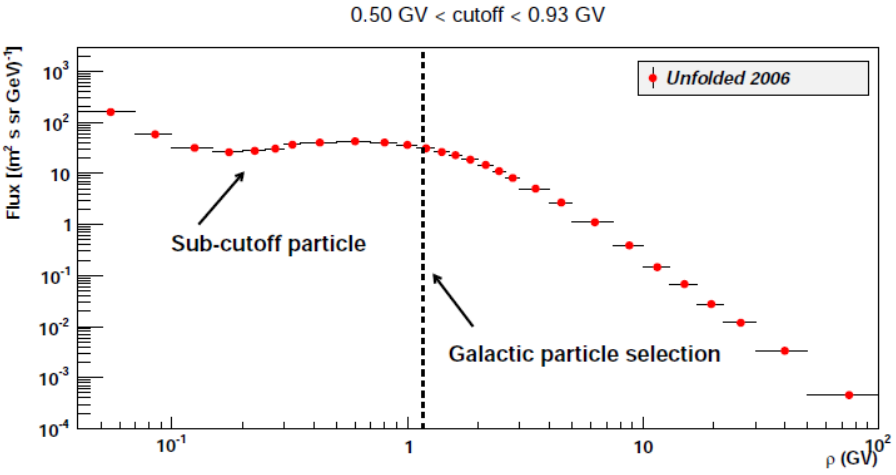
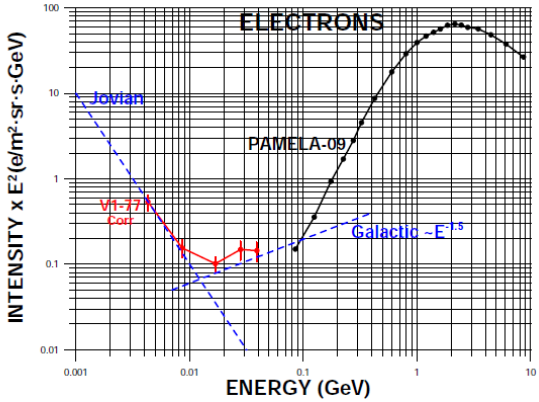
data available at the ASI Science Data Center
http://tools.asdc.asi.it/cosmicRays.jsp




0.50 GV < cutoff < 0.93 GV
Unfolded 2006
Sub-cutoff particle
Galactic particle selection
Flux [(m² s sr GeV)⁻¹]
ρ (GV)

- Data taken in period of solar minimum but with opposite polarity;
- Data agree at a level of 30%.



1. **Antiproton**: spectrum and ratio up to 300 GeV. No significant deviations from secondary production expectations.
2. **Positron fraction**: measured up to 300 GeV. Increases significantly (and unexpectedly) with energy. Primary source?
3. **Positron flux**: consistent with a new primary source.
4. **Anisotropy studies**: no evidence of anisotropy.
5. $\bar{He}/He$ **ratio**: broader energy range ever achieved.
6. **H and He absolute fluxes**: up to 1.2 TV. Complex spectral structures observed (hardening at 200 GV).
7. **H and He isotope fluxes**: and ratio $\rightarrow$ most complete measurements so far.
8. **Electron (e^-) absolute flux**: up to 600 GeV. Not inconsistent with an additional electron component.
9. **B/C ratio and absolute fluxes**: up to 100 GeV/n.
10. **Solar physics**: measurement of modulated fluxes and solar-flare particle spectra
11. **Physics of the magnetosphere**: first measurement of trapped antiproton flux and detailed measurement of trapped proton flux.