Solar energetic particle events measured by the PAMELA mission

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on behalf of
the PAMELA collaboration

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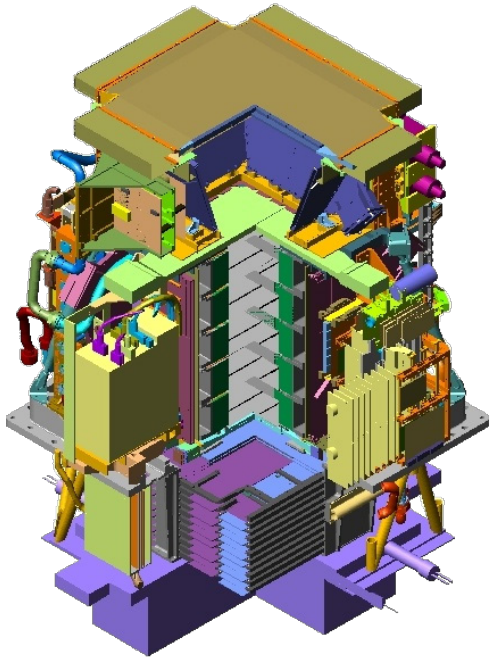
The PAMELA experiment

Main requirements → high-sensitivity particle identification and precise momentum measure



Size: 130x70x70 cm^3
GF: 21.5 cm^2 sr
Mass: 470 kg
Power Budget: 360W

Resurs DK-1 satellite:
Semi-polar (70° inclination) and elliptical (350÷610 km altitude) orbit

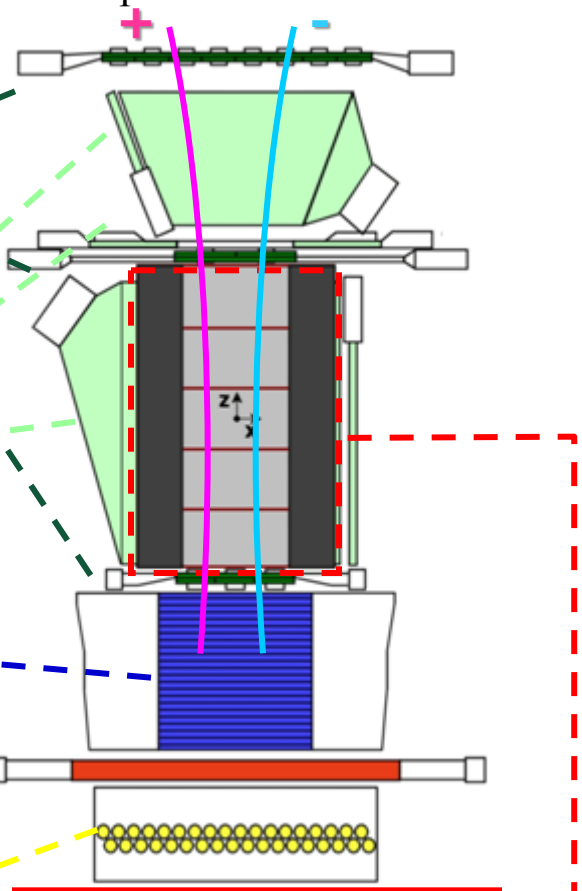
Time-Of-Flight
plastic scintillators + PMT
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX.

Anticoincidence shield
plastic scintillators + PMT

Electromagnetic calorimeter
W/Si sampling (16.3 X_0, 0.6 λI)
- Discrimination e+ / p, anti-p / e^- (shower topology)
- Direct E measurement for e^-

Bottom scintillator (+PMT)

Neutron detector
^{3}He counters
- High-energy e/h discrimination



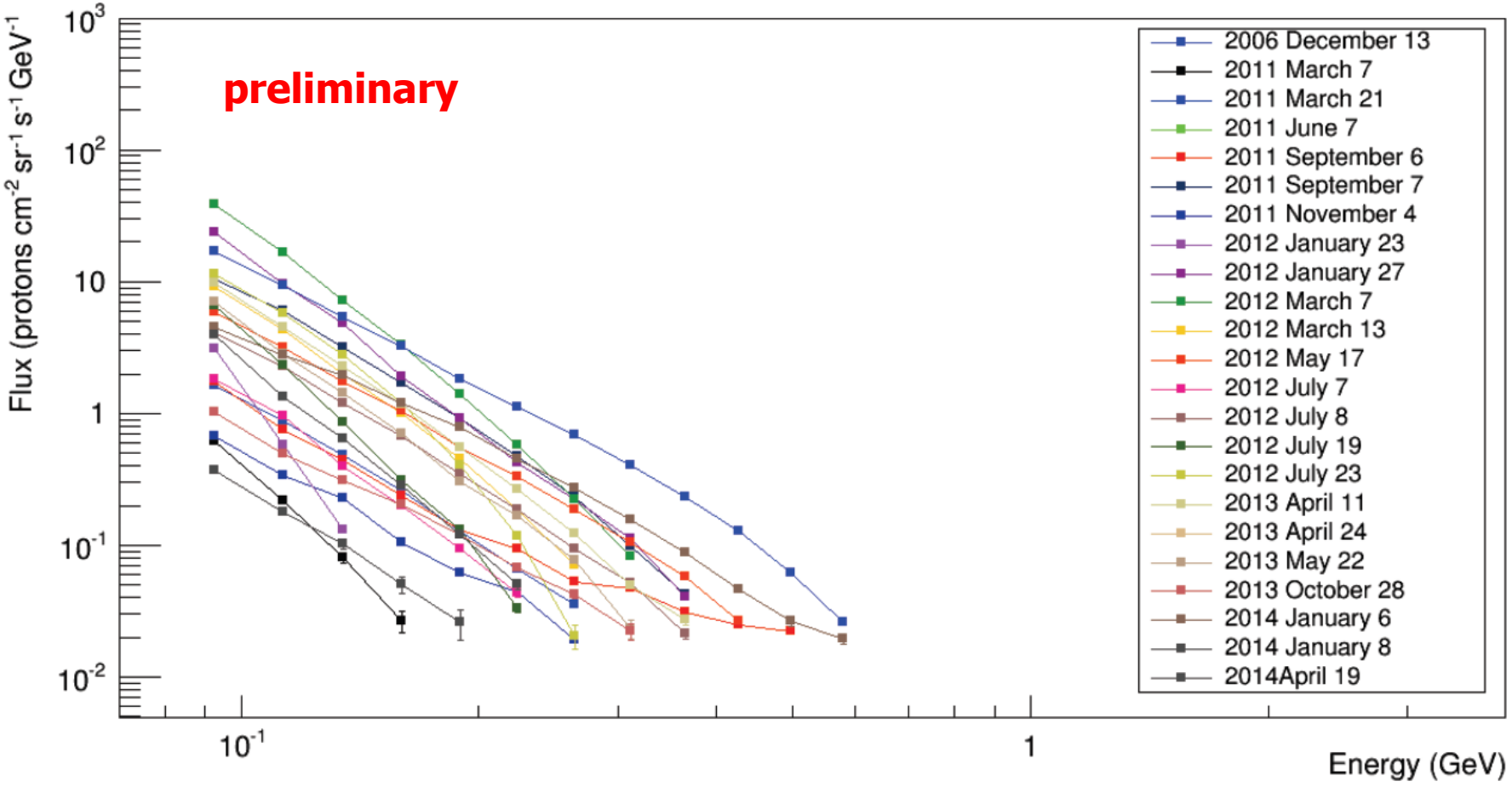
Spectrometer
microstrip silicon tracking system + permanent magnet
- Magnetic rigidity: R=pc/Ze
- Charge sign
- Charge value from dE/dx
- Particle direction

PAMELA's SEP measurements

- wide energy interval: ~80 MeV – several GeV
  - bridging the low energy data by other space-based instruments and the GLE data by the worldwide network of neutron monitors (NMs)
- sensitive to particle composition
  - protons, He nuclei, …
- possibility to reconstruct the angular distribution
  - investigation of flux anisotropies

→ complete view of SEP events !

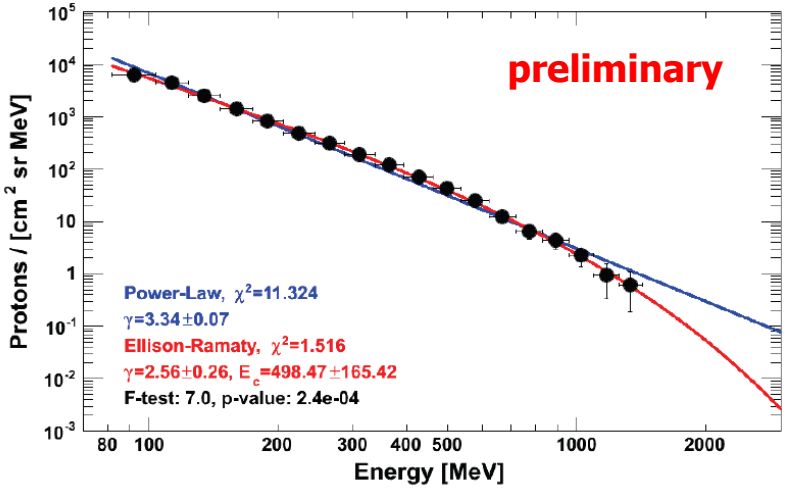
SEP energy spectra



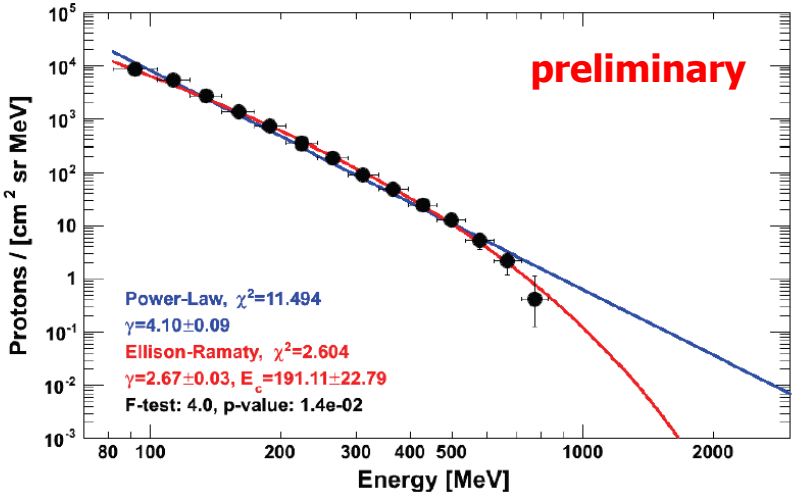
Observations of the energy spectra of high-energy SEPs provide important constraints on particle acceleration and transport.

Spectral fits

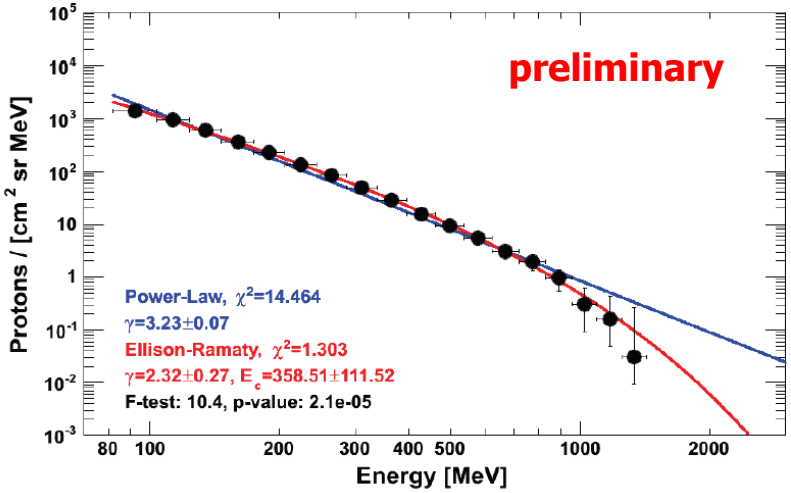
20120517, UT023448 -- 20120520, UT001341



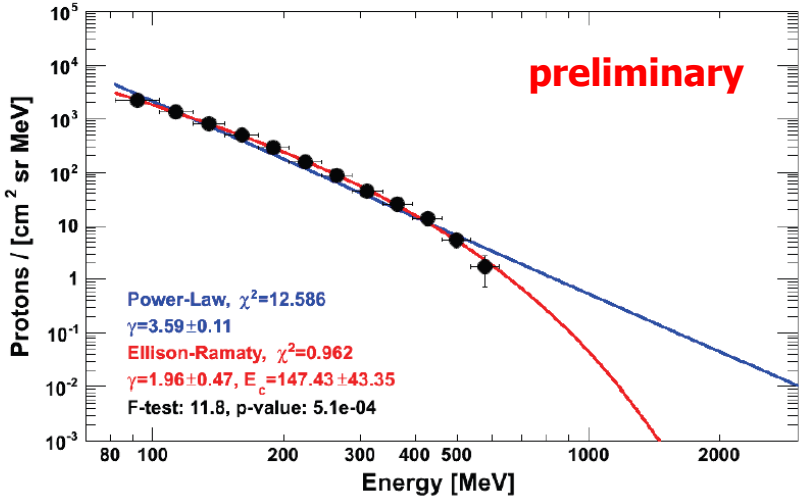
20120127, UT181431 -- 20120130, UT000724



20140106, UT083600 -- 20140107, UT122000

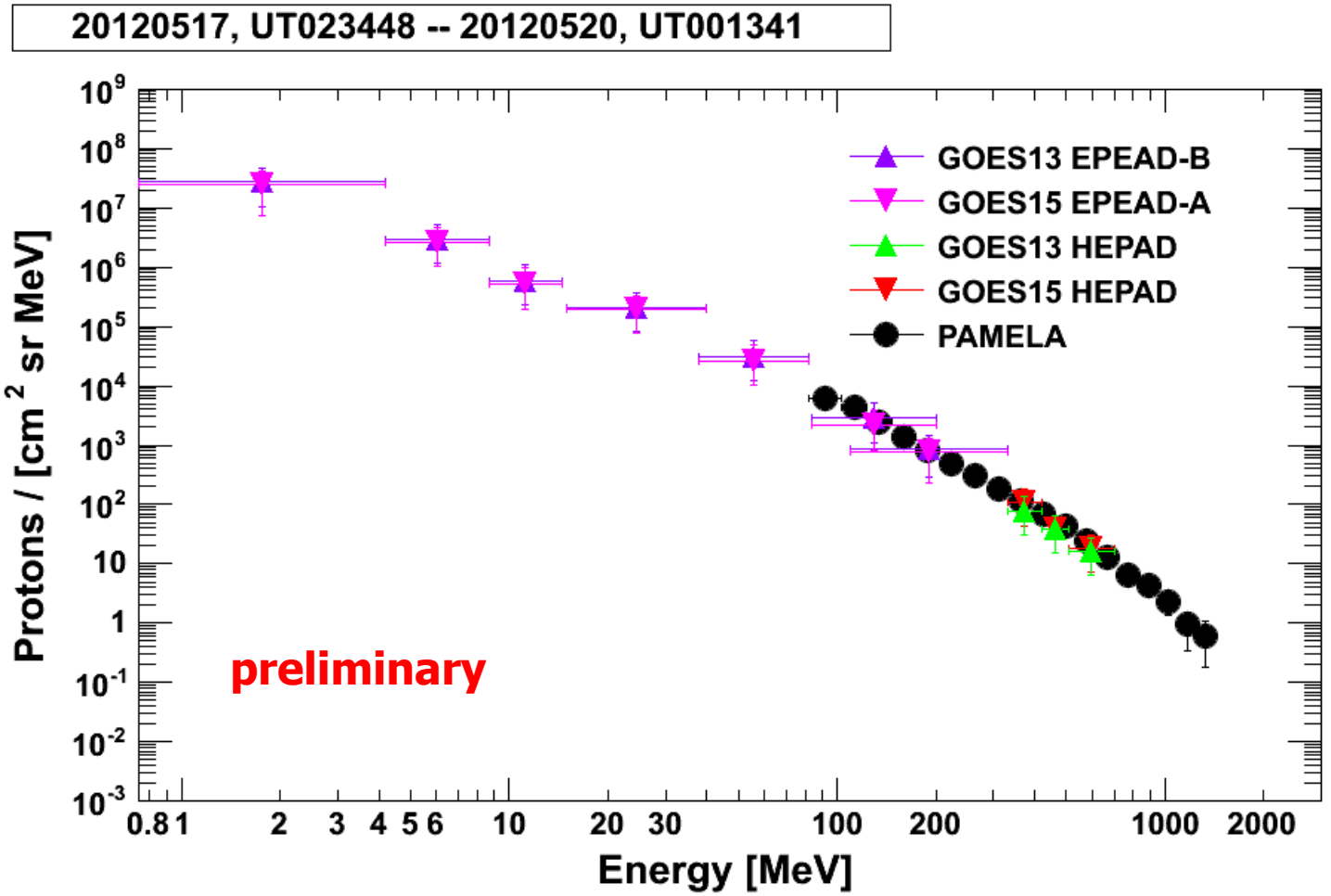


20140225, UT114830 -- 20140303, UT000209



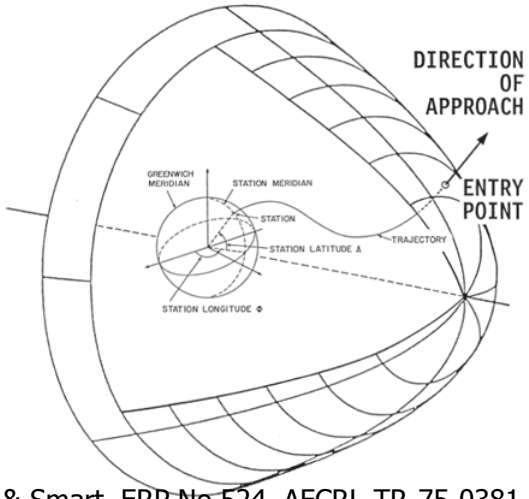
The high-energy cutoffs reflect changes in the SEP acceleration efficiency

Comparison with GOES

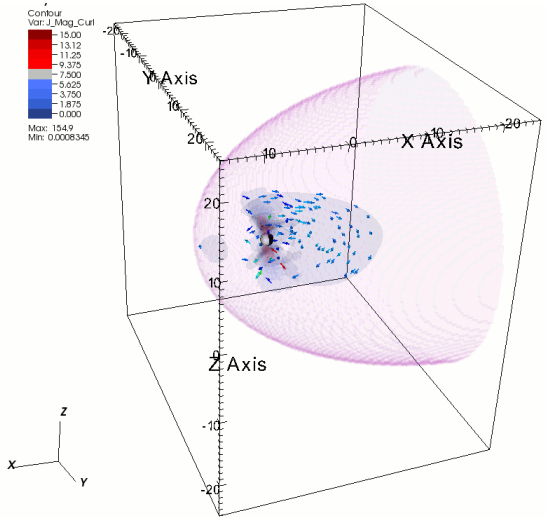


NB: GOES fluxes corrected for the GCR background and contaminations

Trajectory analysis



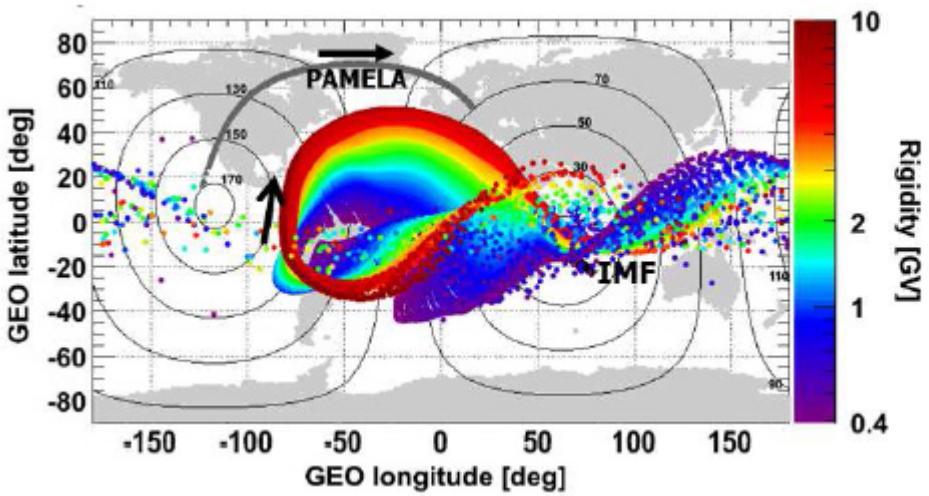
[Shea & Smart, ERP No 524, AFCRL-TR-75-0381, 1975]



- In order to measure SEP angular distributions and investigate the degree of anisotropy, it is necessary to account for the effect of the geomagnetic field on particle propagation.
- Typically (NMs) one is interested in particle arrival "**asymptotic directions**", i.e. the directions of approach before they enter the magnetosphere.
- To determine asymptotic directions, particle trajectories are reconstructed in a model magnetosphere by means of **numerical integration methods** (Smart & Shea 2005).
- Geomagnetic field models: IGRF11 + TS05/TS07D high-resolution dynamical models
- The trajectory analysis also allows to evaluate geomagnetic cutoff rigidities and to separate protons of interplanetary (GCRs & SEPs) and atmospheric (trapped & albedo) origin.

Asymptotic viewing directions

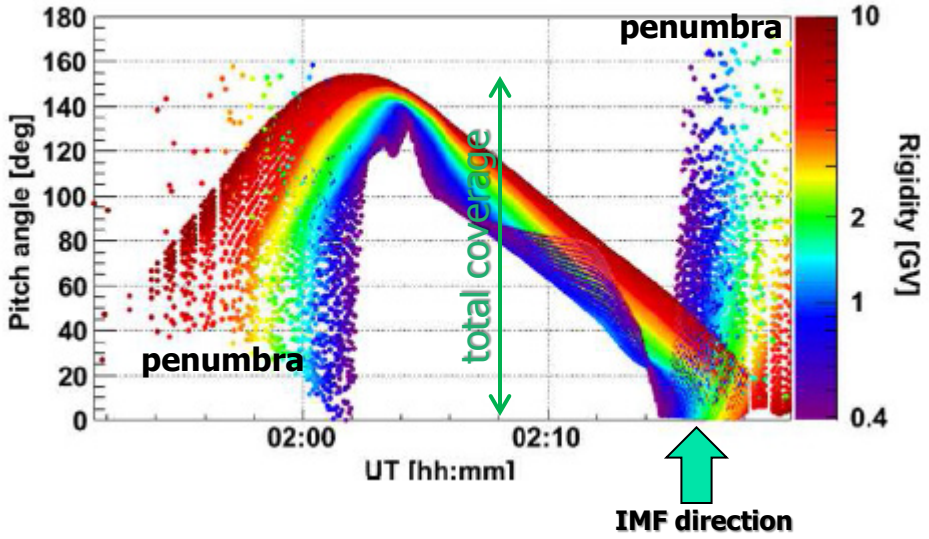
First polar pass (01:58-02:20 UT) who registered **the May 17, 2012 event**



PAMELA's asymptotic (vertical) directions of view in GEO coordinates.

- The color codes refer to the particle rigidity.
- The contour curves represent values of constant pitch angle with respect to the IMF.

As PAMELA was moving eastward, its asymptotic field of view rapidly varied performing a clockwise loop over the region above Brazil.



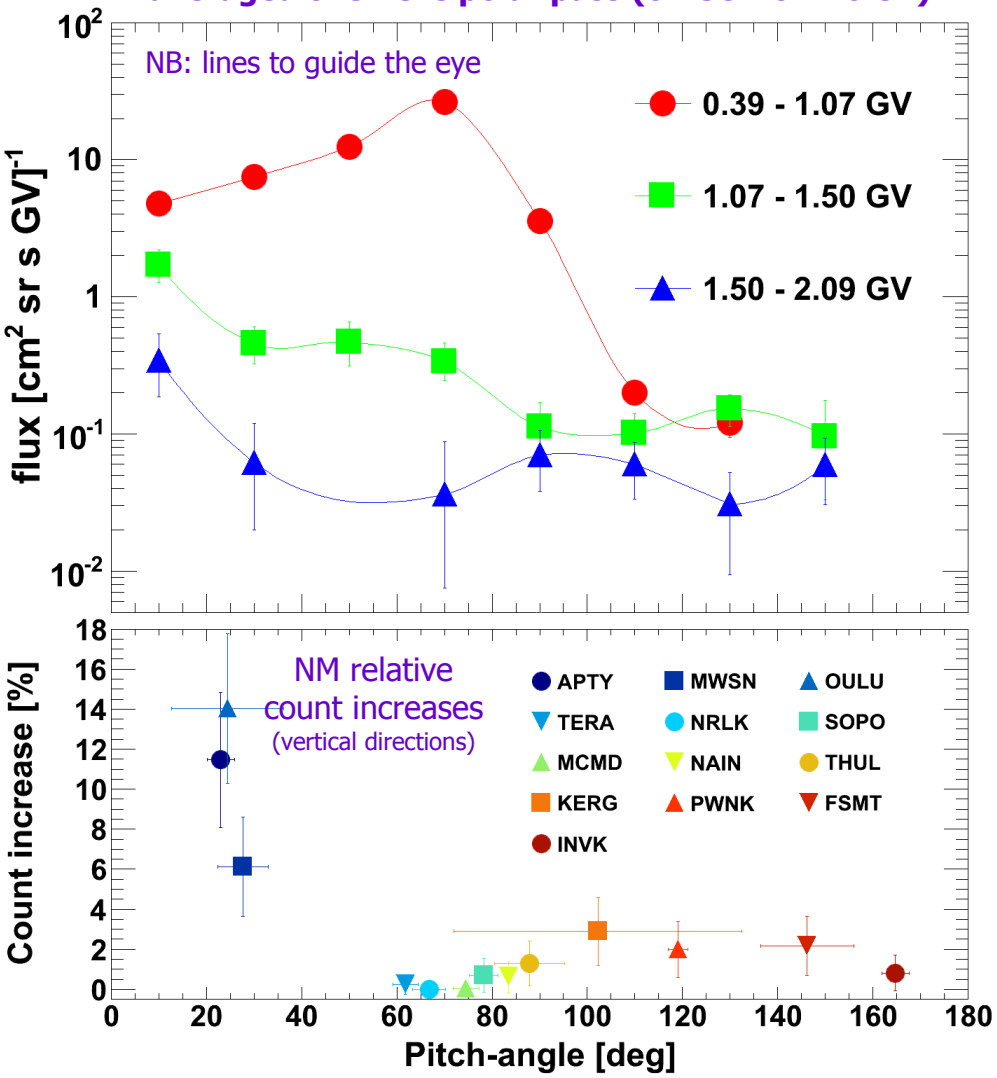
PAMELA's asymptotic directions as a function of time and pitch-angle.

Although the instantaneous pitch angle coverage is small, a large interval (0-150 deg) is covered during the whole polar pass.

PAMELA is looking at 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).

Pitch angle distribution



The May 17, 2012 event

PAMELA observes two populations simultaneously with very different pitch angle distributions:

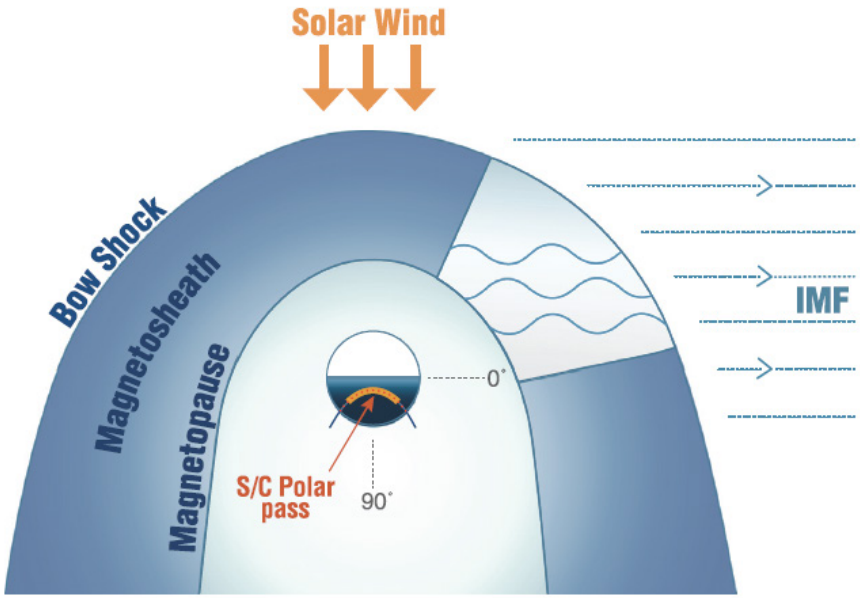
- a low-energy component (<1 GV)
  - confined to pitch angles <90°
  - and exhibiting signicant scattering or redistribution;
- and a high-energy component (>1.5 GV)
  - beamed with pitch angles <30°,
  - consistent with NM observations.
- The component with intermediate energies (1 - 1.5 GV) suggests a transition between the low and high energies.

At rigidities >1 GV, corresponding to NM data, the particles are mostly field aligned.

see: **Adriani et al., ApJ, 801:L3, 2015**

Pitch angle distribution

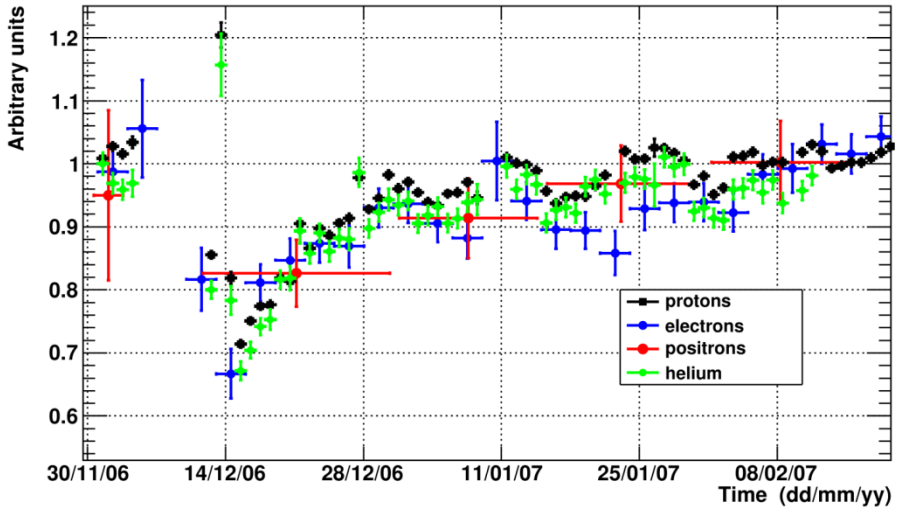
The May 17, 2012 event



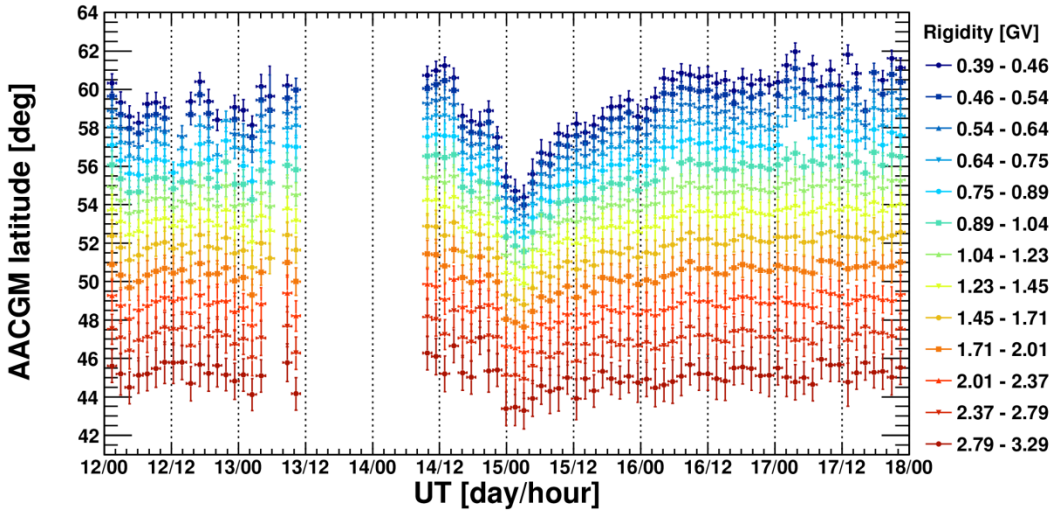
Adriani et al., ApJ, 801:L3, 2015

The presence of these simultaneous populations can be explained by postulating a local scattering/redistribution in the Earth's magnetosheath, with a major role played by the quasi-perpendicular IMF orientation

Related analysis



Time variations in the intensity (1.57 - 5.70 GV) of protons, He nuclei, electrons and positrons, during the **Forbush Decrease** event associated with the 13 Dec 2006 CME



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

Conclusions

- The PAMELA satellite-experiment is providing accurate SEP measurements between solar cycles 23 and 24 (>30 events), in a wide energy range (≥80 MeV),
  - bridging the gap between the current spacecraft observations and the energy range accessible by ground-based neutron monitors (GLE events).

- Its unique observational capabilities include the possibility of measuring the flux angular distribution and thus investigating possible SEP anisotropies.
  - based on advanced particle tracing techniques

- PAMELA's observations of the energy spectra of high-energy SEPs provide important constraints on particle acceleration and transport mechanisms, bringing vital new input that will advance our predictive capability for space weather modeling.