INFN Istituto Nazionale di Fisica Nucleare

Università di Roma Tor Vergata

PAMELA a Payload for Antimatter Matter Exploration and Light–nuclei Astrophysics

Capabilities of the Space Instrument PAMELA for Solar Research

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ON BEHALF OF THE PAMELA COLLABORATION

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11th European Spaceweather Week, 17-21 November 2014 Liege, Belgium

ESWW

PAMELA COLLABORATION

Italy

Bari Florence Frascati Naples Rome Trieste

USA

New Mexico

New Hampshire

Russia

Moscow
St. Petersburg

Germany

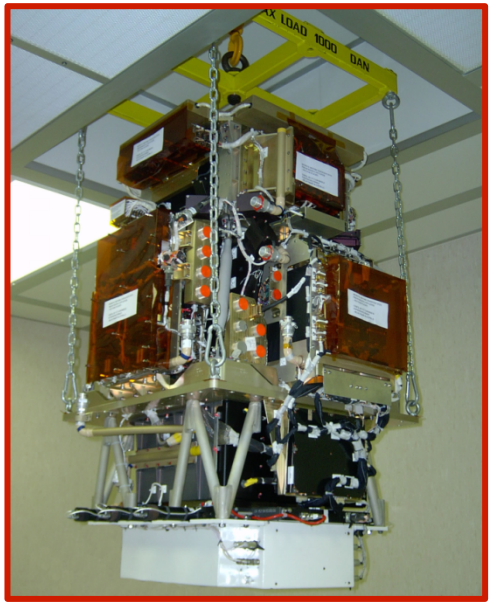
Siegen

Sweden

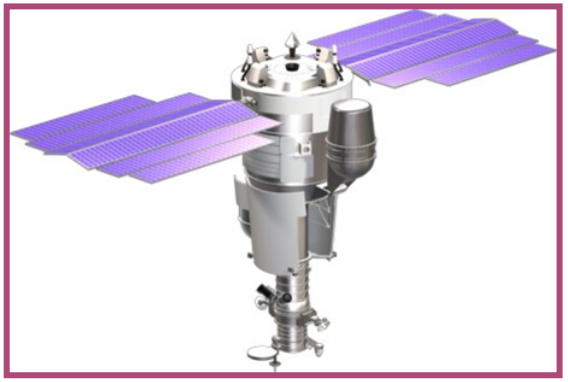
KTH, Stockholm

PAMELA MISSION

- **Direct** detection of CRs in space
- Main focus on **antiparticles** (antiprotons and positrons)



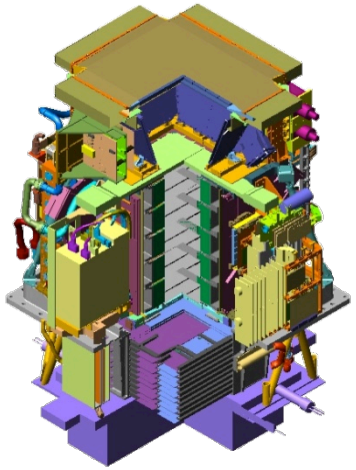
- PAMELA on board of Russian satellite **Resurs DK1**
- Orbital parameters:
  - inclination ~70° (⇒ low energy)
  - altitude ~ 360-600 km (elliptical) – now 500 km (circular)



→ **Launched on 15th June 2006**

→ **PAMELA in continuous data-taking mode since then!**

PAMELA INSTRUMENT

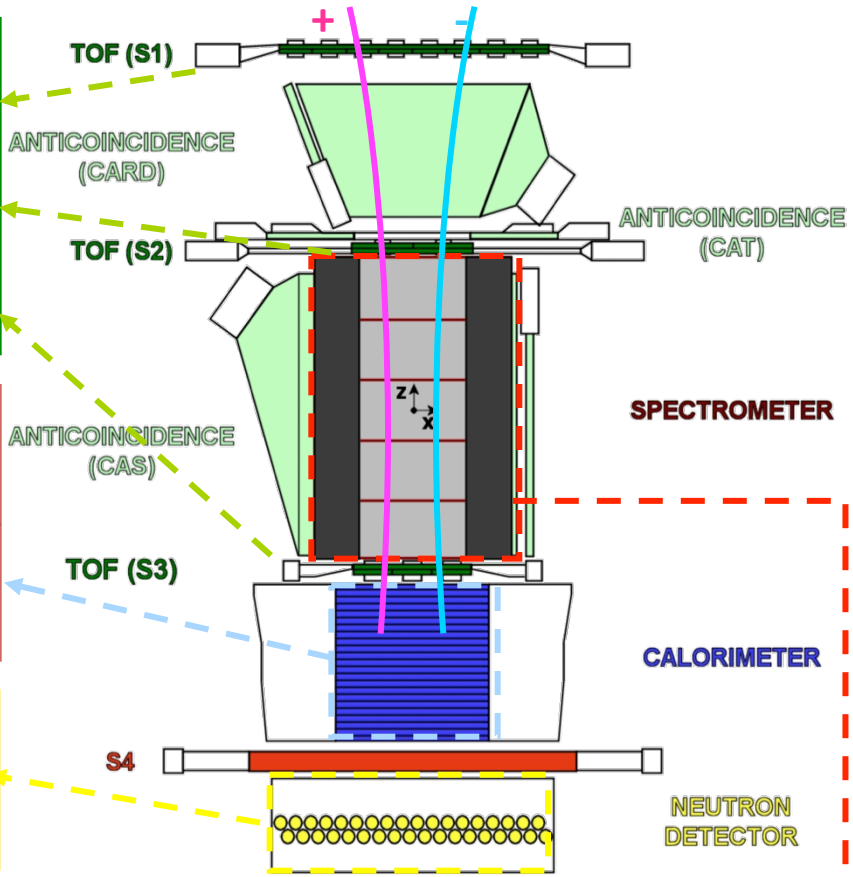


GF: 21.5 cm^2 sr
Mass: 470 kg
Size: 130x70x70 cm^3
Power Budget: 360W

Time-Of-Flight
plastic scintillators + PMT
- Trigger
- Albedo rejection
- Mass identification up to 1 GeV
- Z identification from *dE/dx*

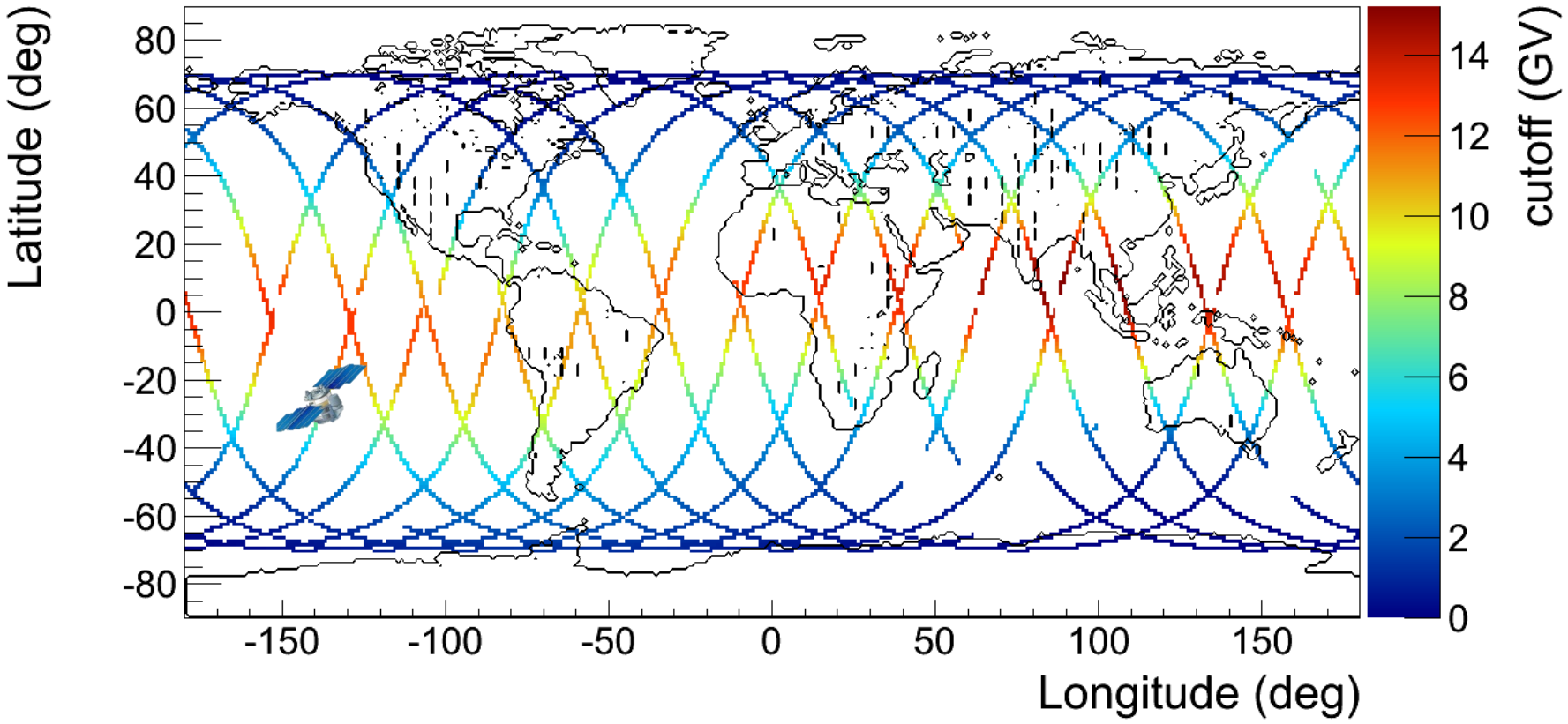
Electromagnetic calorimeter
W/Si sampling (16.3 X0, 0.6 λI)
- Discrimination e^+ / p, anti-p / e^-
- Direct E measurement for e^-

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



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

PAMELA ORBIT



Semi-polar orbit (70°) outside the atmosphere

1) **Different trigger configuration → optimal response to higher rates during Solar Particle Events**
2) **Collecting solar particles down to 80 MeV and up to several GeVs → ideal for Ground Level Enhancement studies**
3) **Over 30 polar passes every day → good capabilities in catching the onset of an event**

PAMELA published results

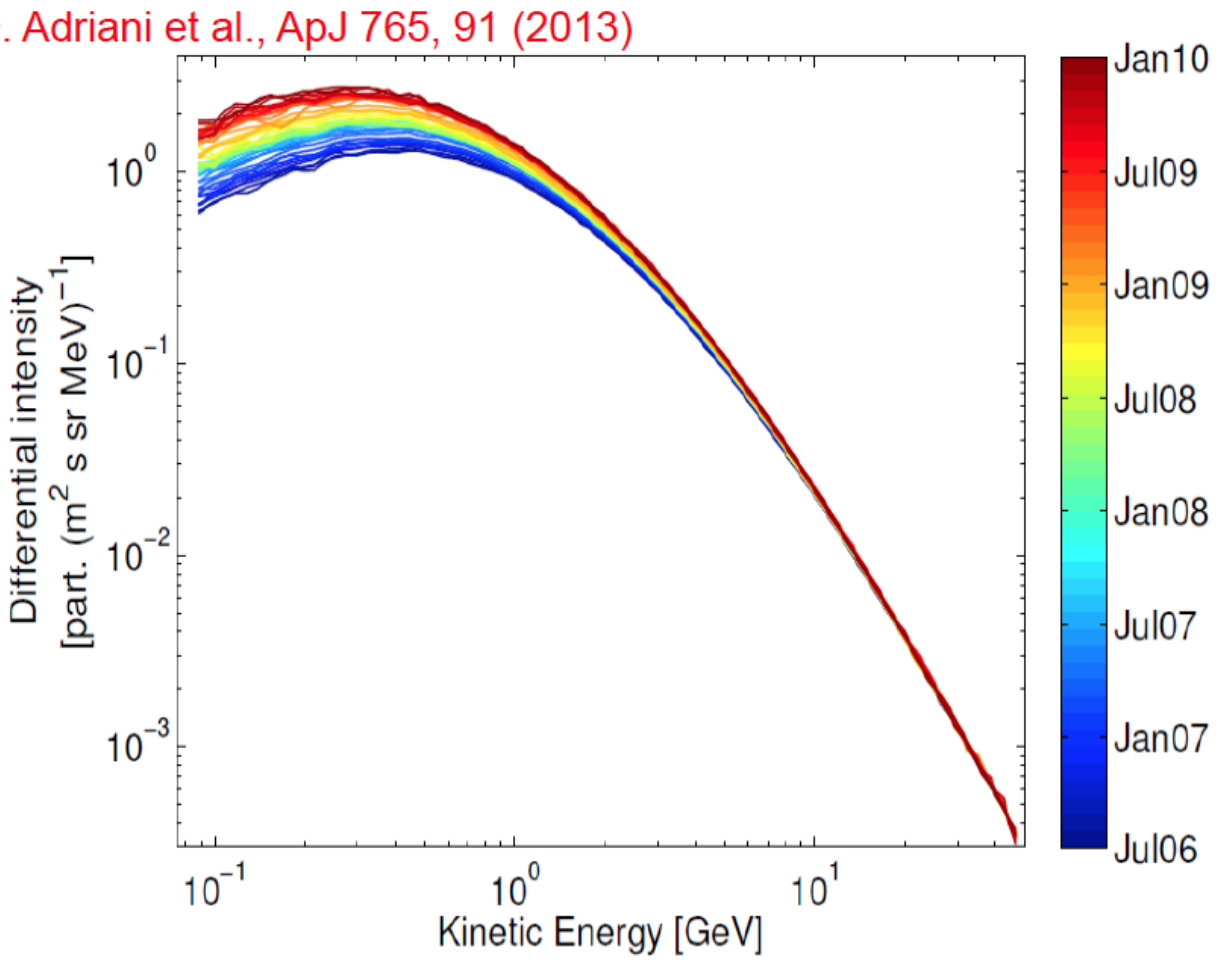
- **Antiproton flux + antiproton/proton ratio** (100 MeV-200 GeV)
- **Positron flux + positron/electron ratio** (100 MeV-200 GeV)
- **Electron flux** (1 – 500 GeV)
- **Proton and helium flux** (1 GeV – 1.2 TeV)
- **B/C ratio** (500 MeV – 100 GeV)
- **H and He isotope flux**
- **AntiHe/He**
- **Proton flux vs. time** – solar modulation
- **Trapped antiproton flux**
- **SEP data** (13 December 2006 event)

PAMELA SOLAR MODULATION STUDIES

SOLAR MODULATION : PROTON SPECTRA

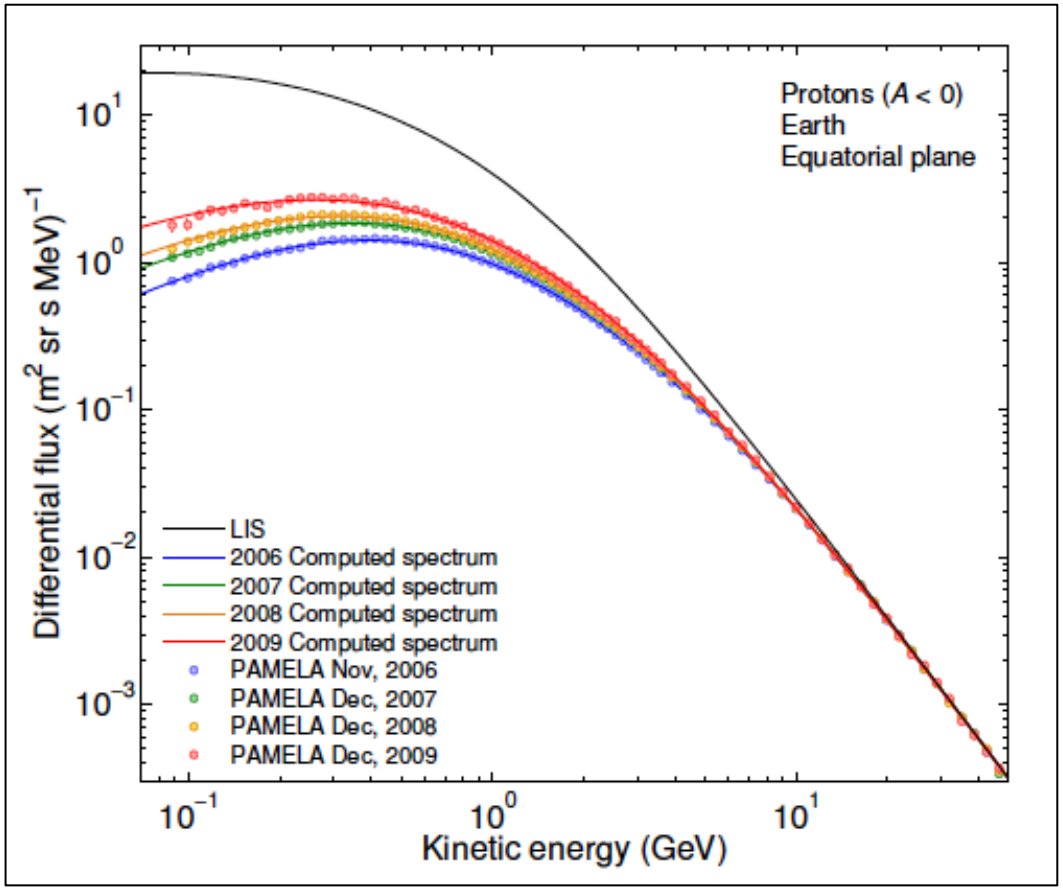
The **evolution of the proton energy spectrum** as particle intensities approached the period of **minimum solar activity**, from **July 2006 (violet), to December 2009 (red)**.

The region between the blue and red curves indicates the **spread in proton fluxes during this time.**



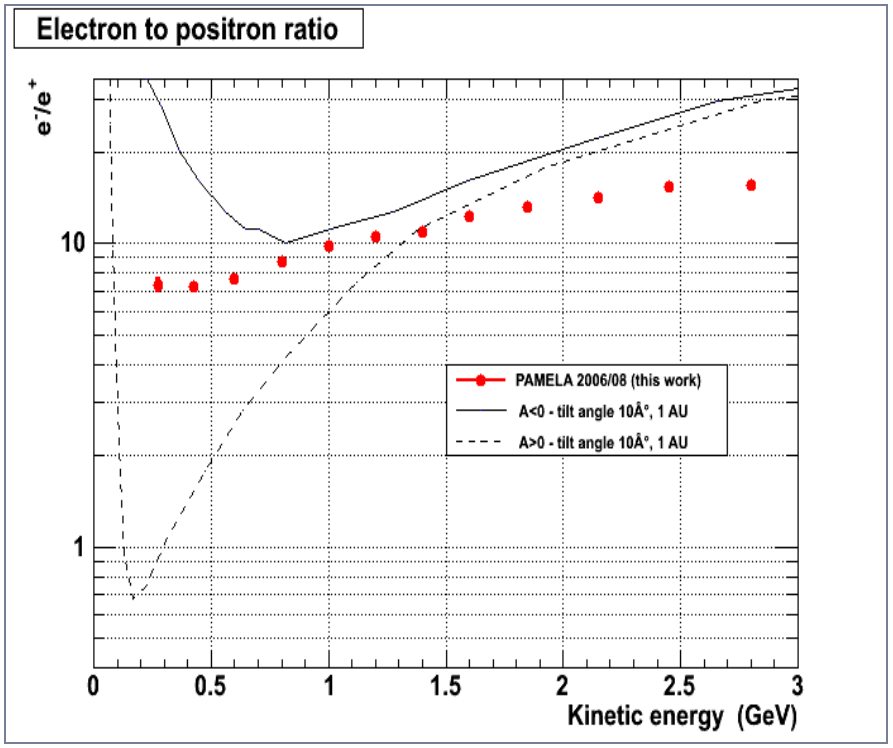
SOLAR MODULATION : LIS SPECTRA

LIS based on that by Langner and Potgieter, modified at high energies to match PAMELA data

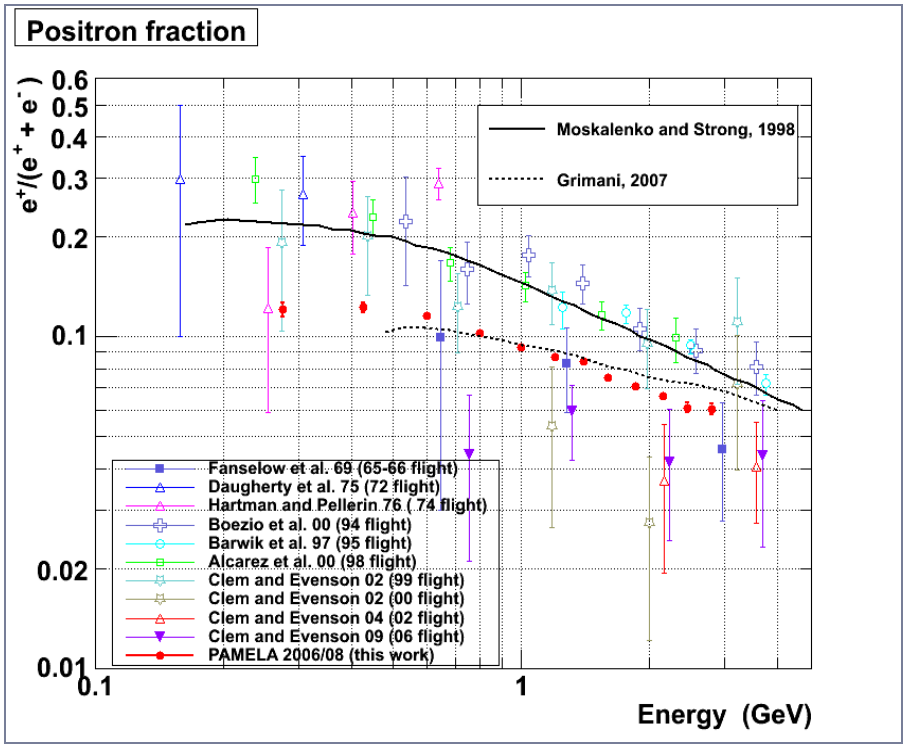


CHARGE DEPENDENT SOLAR MODULATION

PAMELA POSITRON FRACTION @ low energy



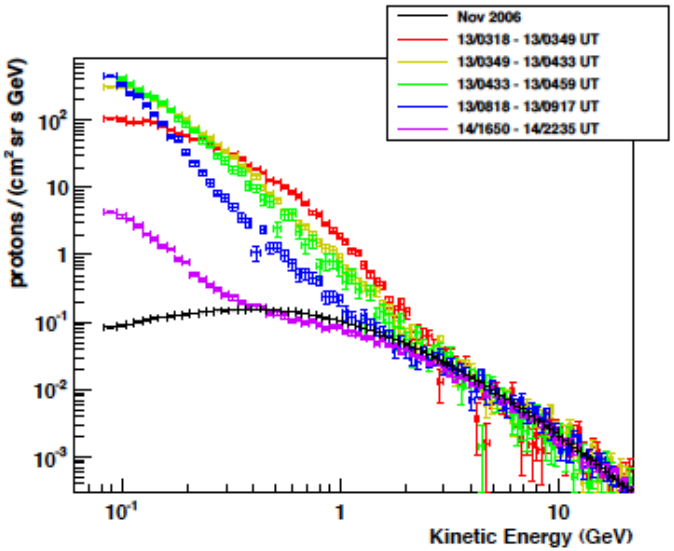
PAMELA ELECTRON to POSITRON RATIO @ low energy

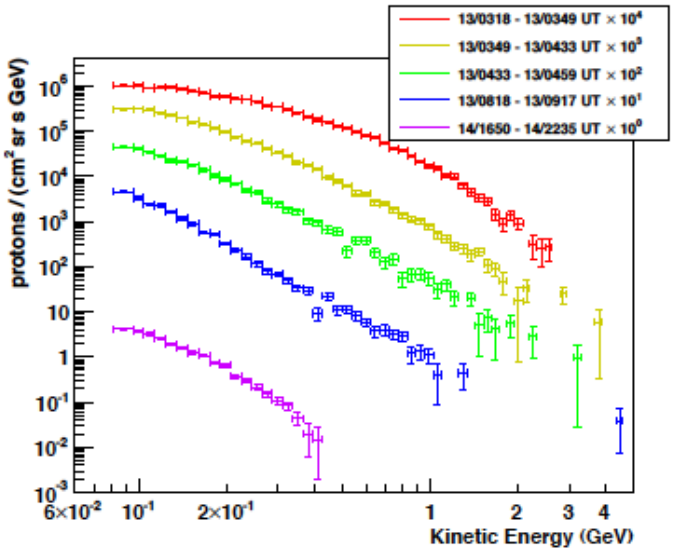


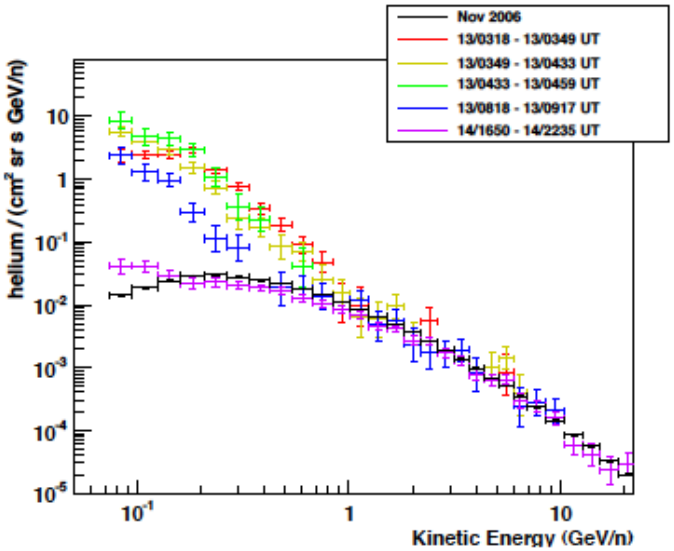
PRELIMINARY

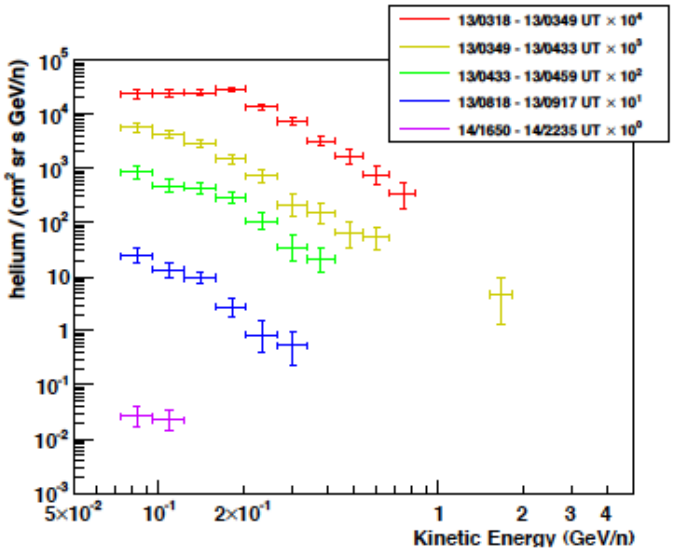
PAMELA SEP STUDIES

SEP from Dec. 13, 2006



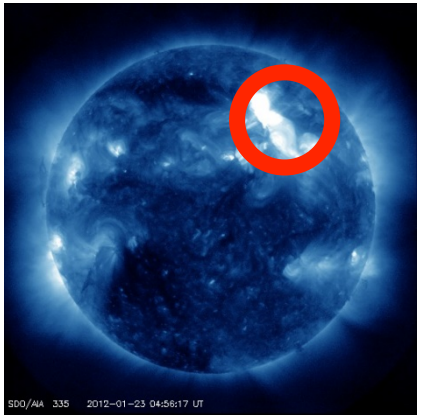






Adriani et al. - *ApJ 742 102, 2011*

EVENTS UNDER STUDY 1/2

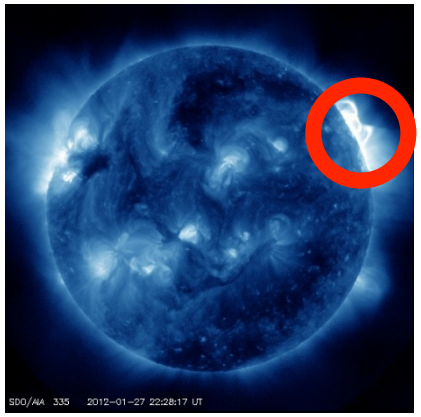


M8.7

01/23/2012

0359 UTC

AR1402



X1.7

01/27/2012

1833 UTC

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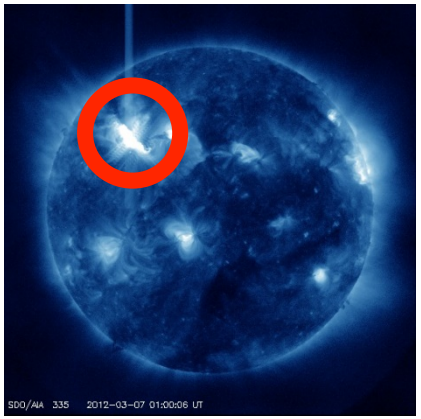

X5.4

03/07/2012

0024 UTC

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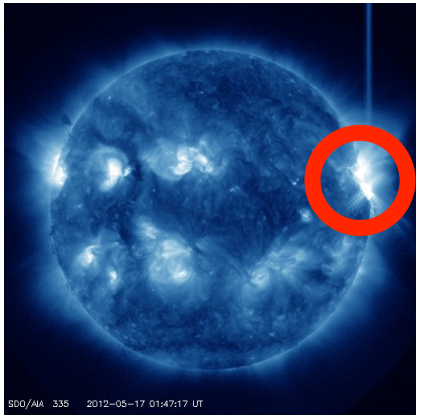

M5.1

05/17/2012

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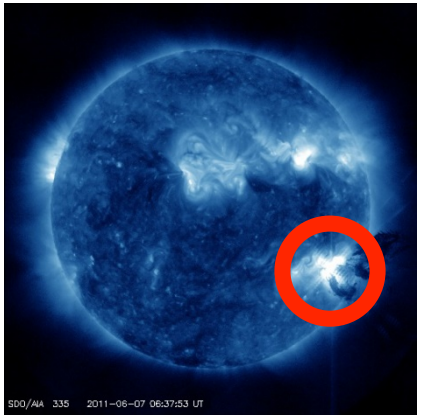
AR1476

EVENTS UNDER STUDY 2/2



M2.0

06/07/2011

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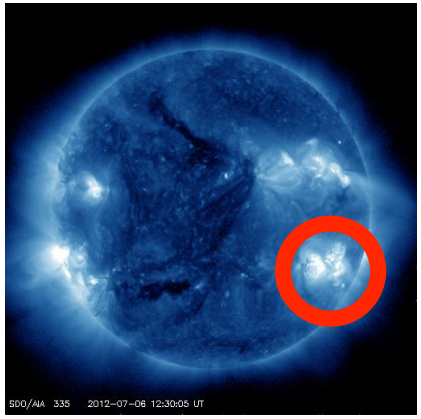
AR1227

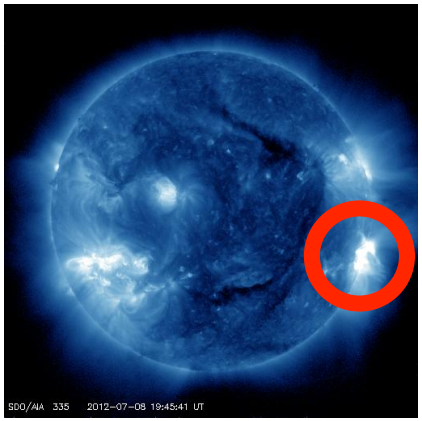


M2.6

07/07/2012

1103 UTC

AR1515



M6.9

07/08/2012

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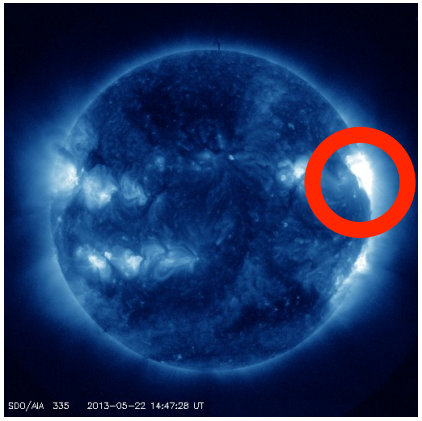


M5.0

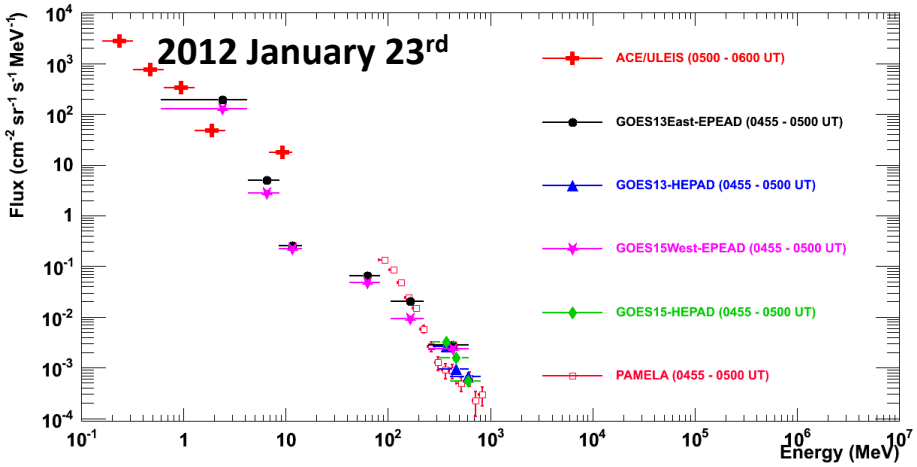
05/22/2013

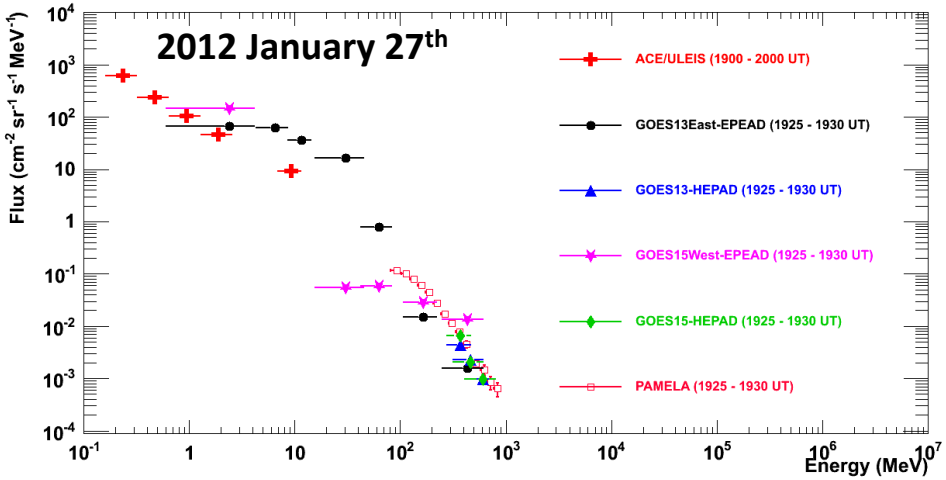
1332 UTC

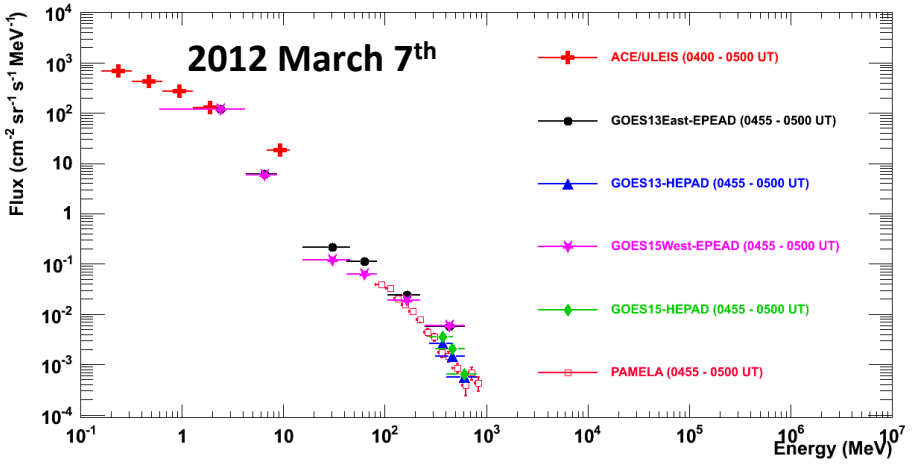
AR1745

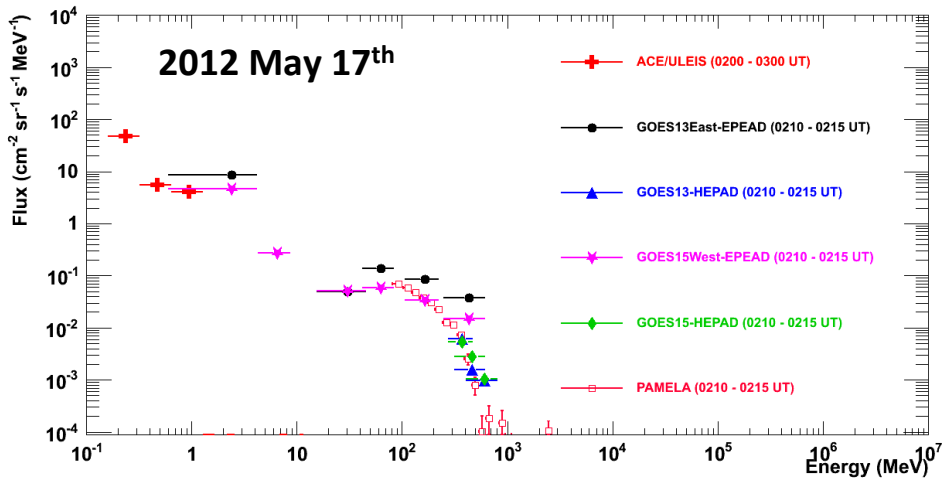
COMPLETING THE SPECTRUM

PAMELA bridges the gap below ACE, GOES and many others and above the Neutron Monitors to obtain a complete spectrum









ACCELERATION MECHANISMS

- **PAMELA can measure energy (or rigidity) spectra with very high precision (up to several hundreds of Gev) AND in a very narrow time window → well-suited for acceleration and propagation mechanisms**

- **Time averaged spectra (on a proper time window) measured by PAMELA can be fitted to extract parameter information and decide which mechanism better fits the data points**

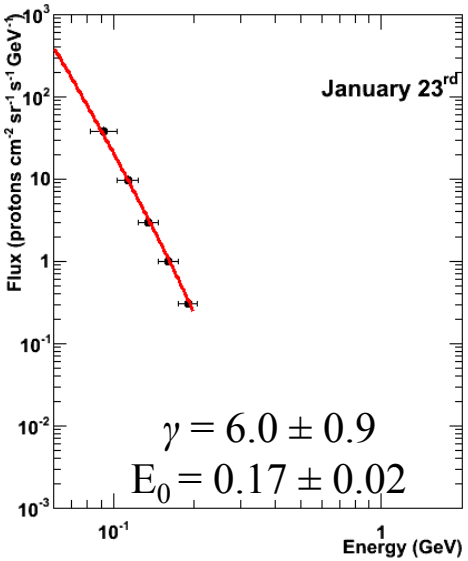
1. DIFFUSIVE SHOCK ACCELERATION

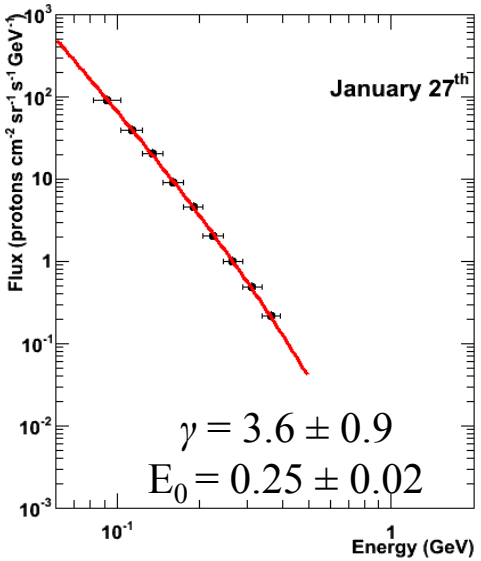
$$\Phi_p = AE^{-\gamma}e^{-\frac{E}{E_0}}$$

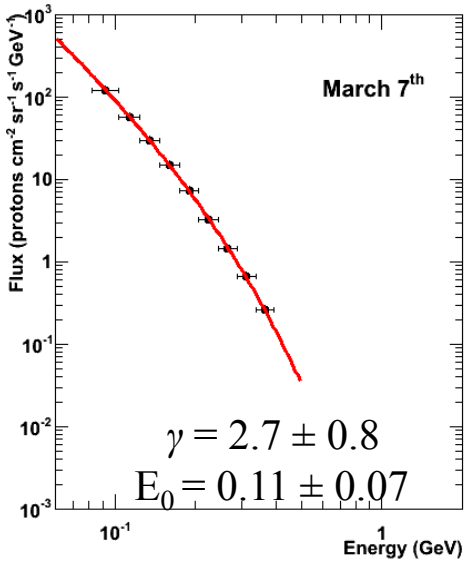
2. STOCHASTIC ACCELERATION

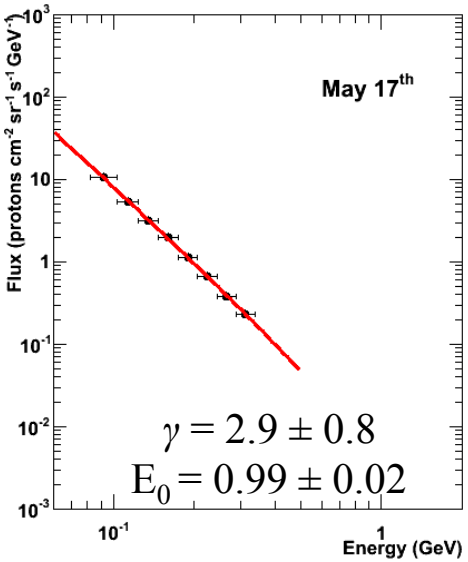
$$\Phi_p = ARK_2\left(\frac{R}{c\alpha T}\right)^{\frac{1}{2}}$$

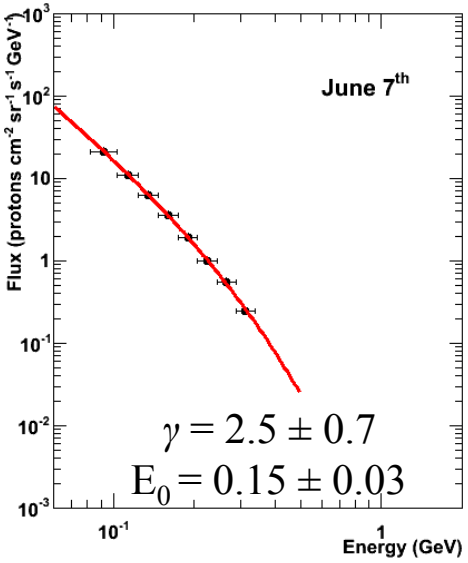
$$\Phi_p = AE^{-\gamma} e^{-\frac{E}{E_0}}$$

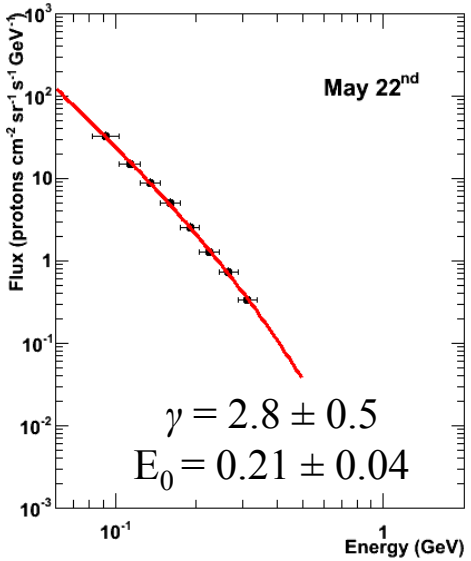




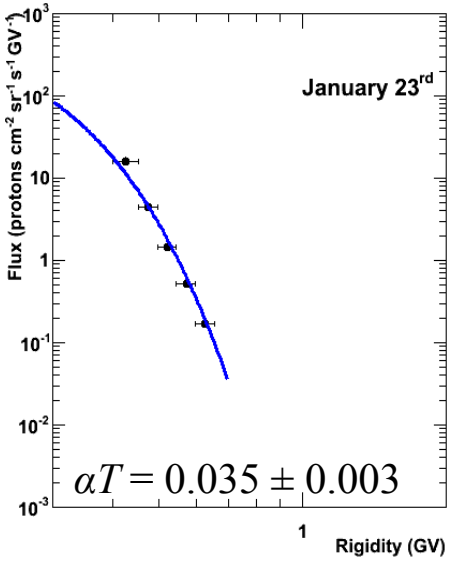


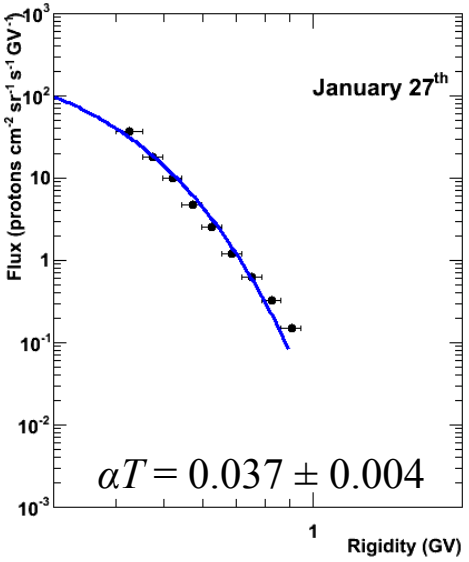


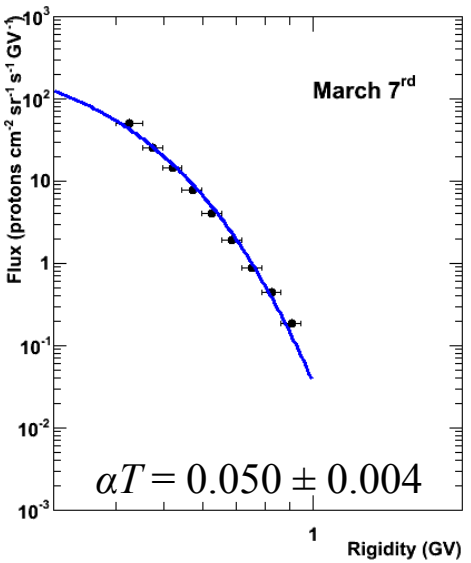


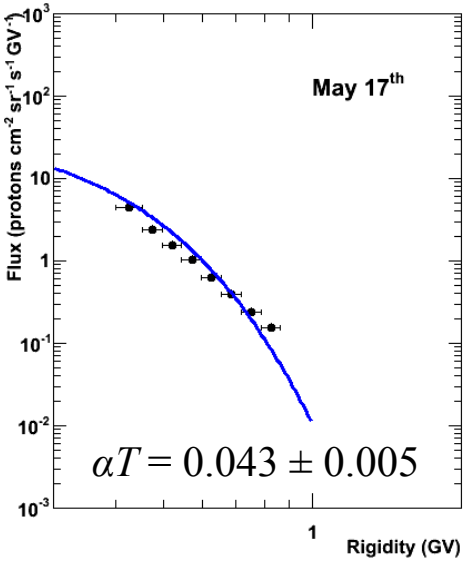


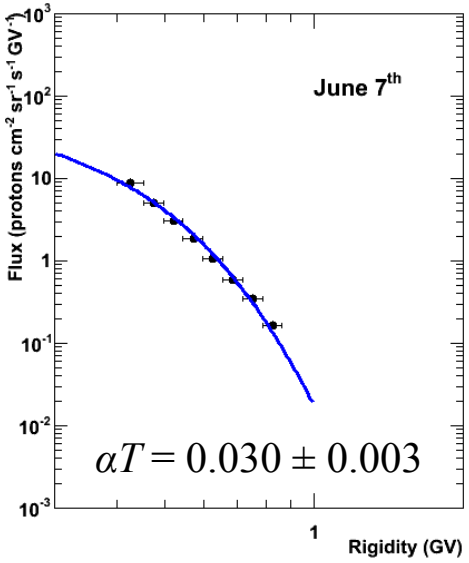
$$\Phi_p = ARK_2 \left(\frac{R}{c\alpha T} \right)^{\frac{1}{2}}$$

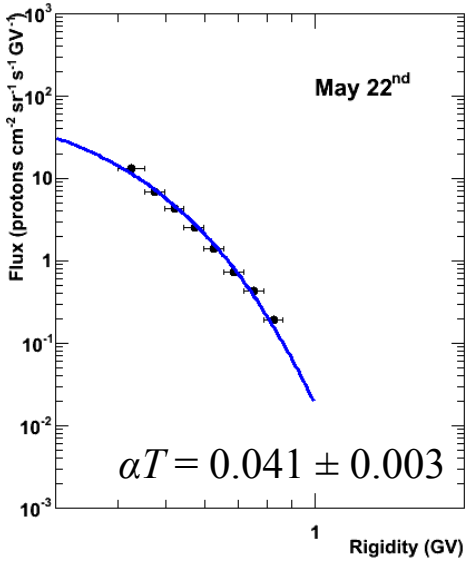












FORBUSH DECREASE STUDY

PAMELA studied also Forbush decrease (up to about 30 GV) for different particles

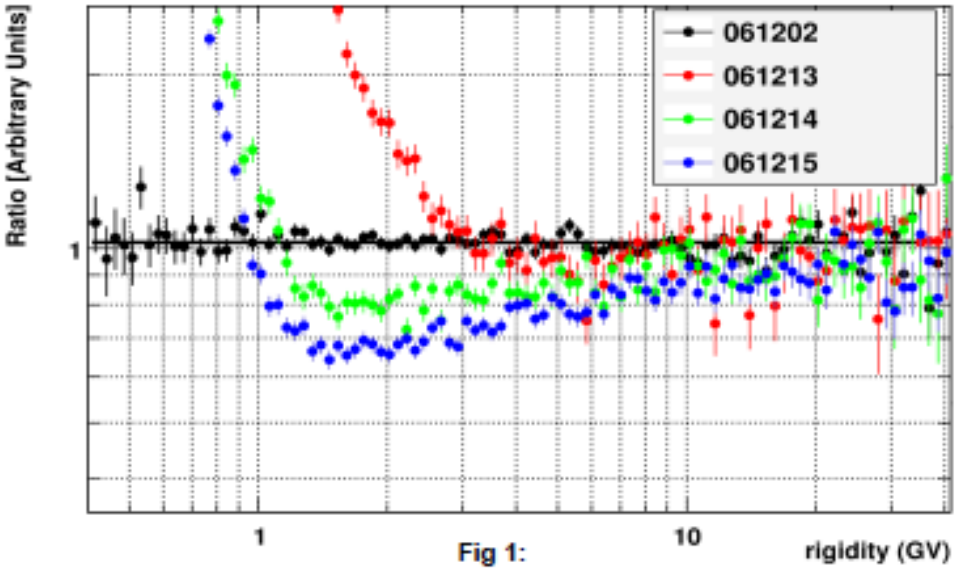
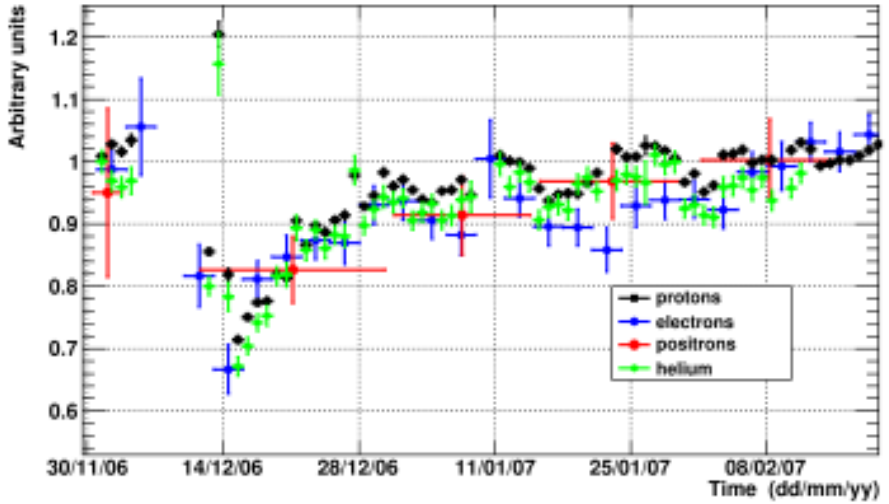


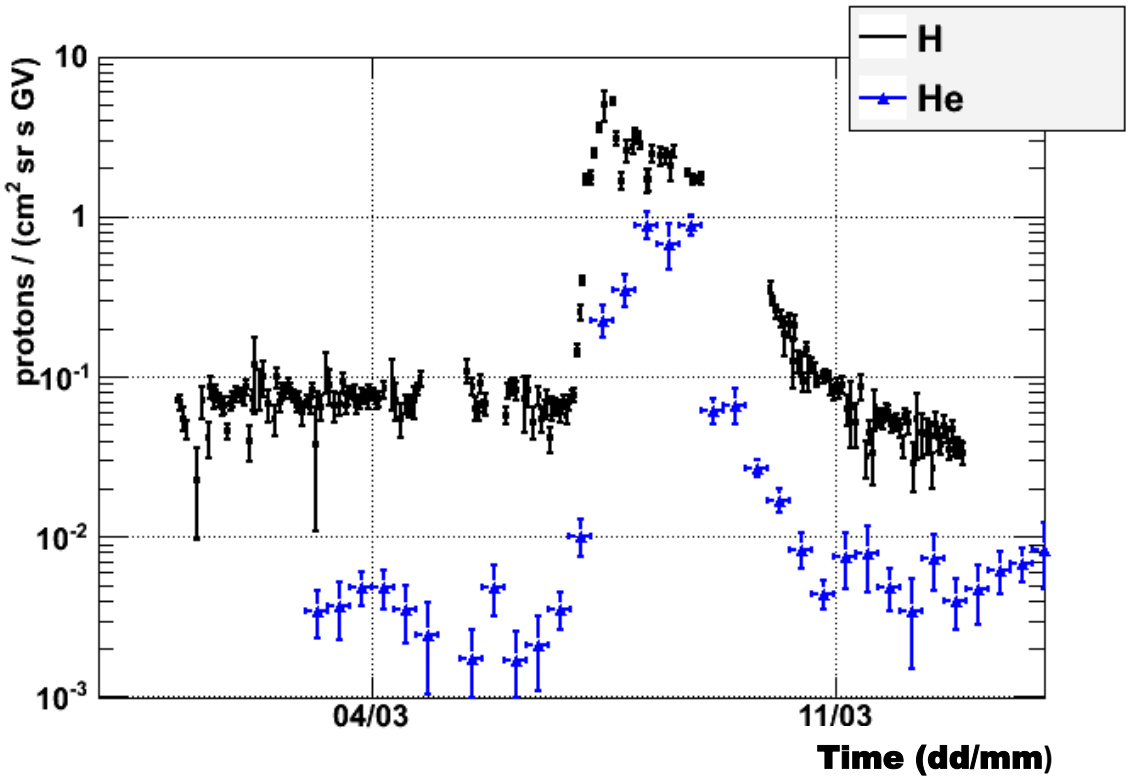
Fig 1:

Comparison between daily proton fluxes normalized to quite sun condition for the 2006 December 13th event



Time dependence of rigidity range between 1.57 GV and 5.70 GV of the flux normalized to quiet sun.

HELIUM/PROTON COMPARISON



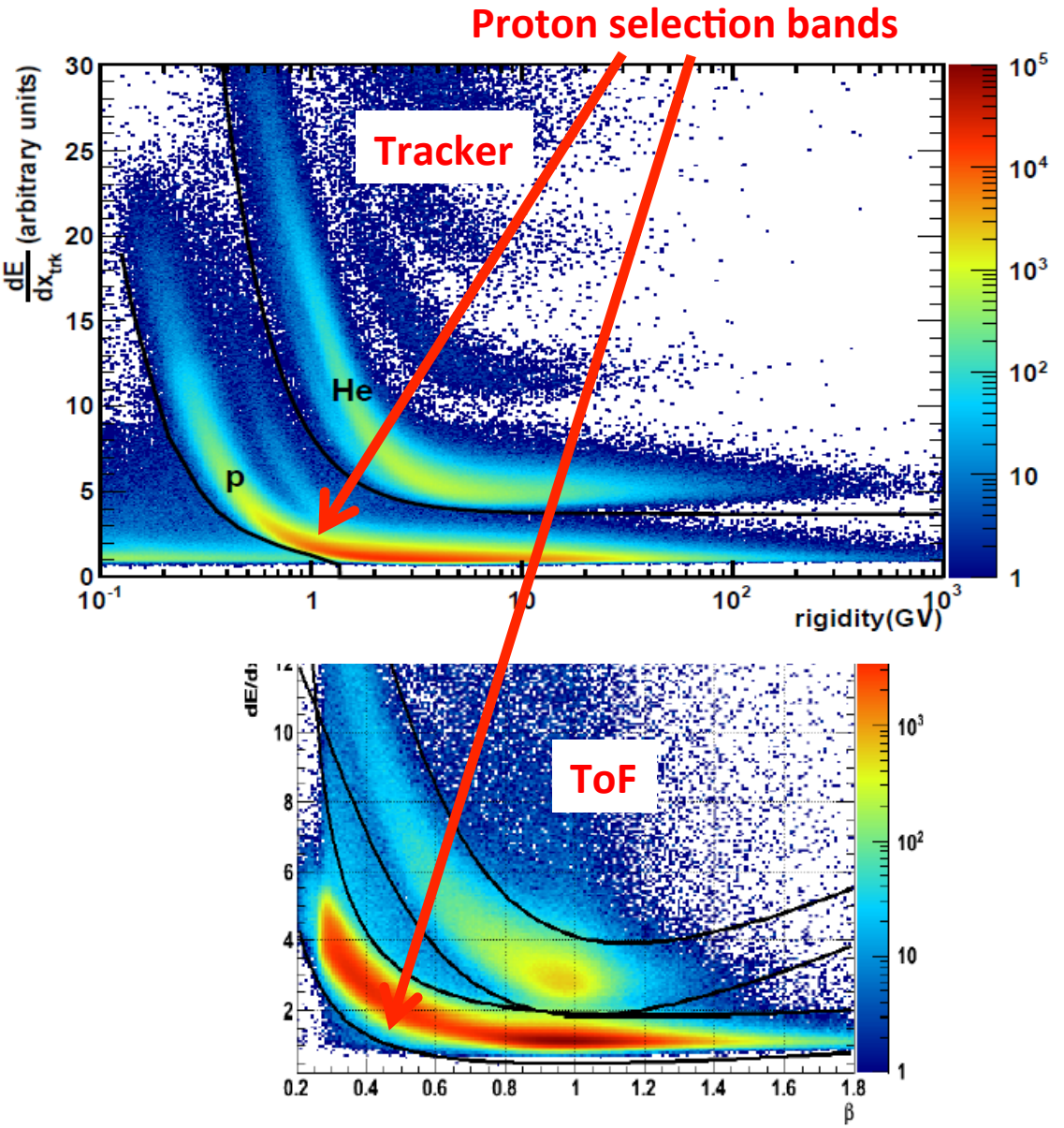
Comparing proton & Helium measurements

- **Helium spectra measured from 0.7 GV**
- **Z identification allows good separation between samples**
- **Different behaviour during solar events?**

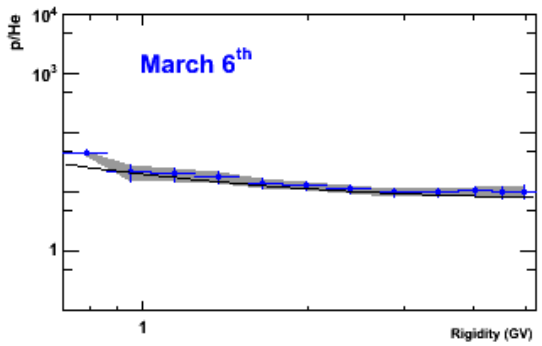
Study of charge/mass dependence of acceleration mechanisms

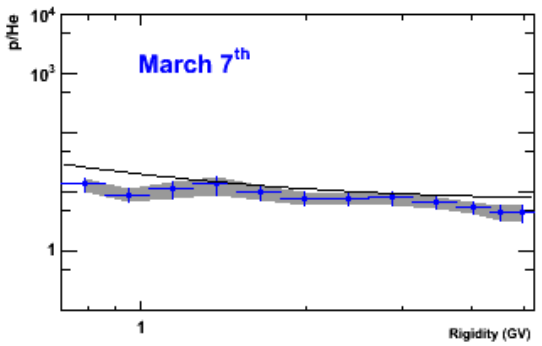
Particle Selection for SEP's events

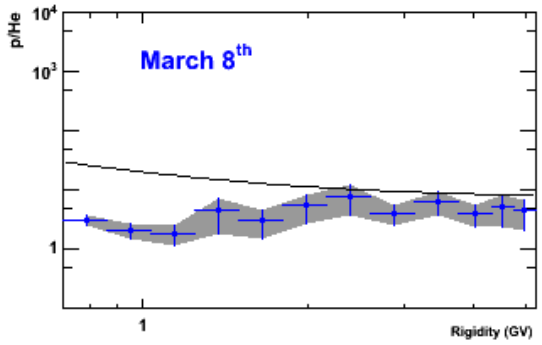
- *Both tracker silicon layers and TOF scintillatiing layer perform excellent charge separation.*
- *No possibility to confuse the two species, due to charge consistency requests.*

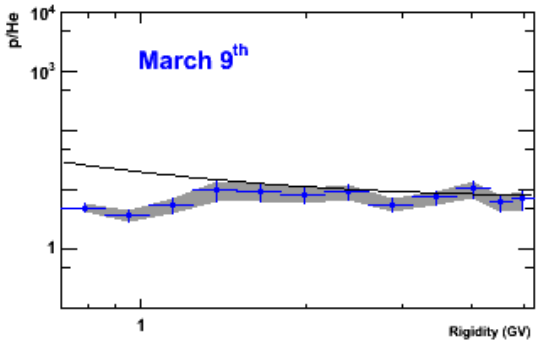


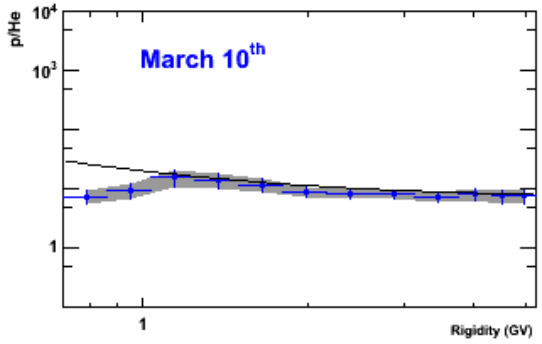
HELIUM ENHANCEMENT

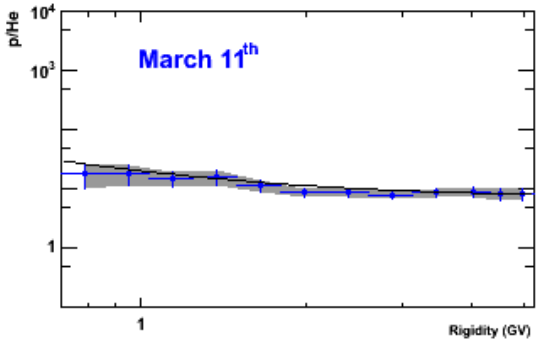










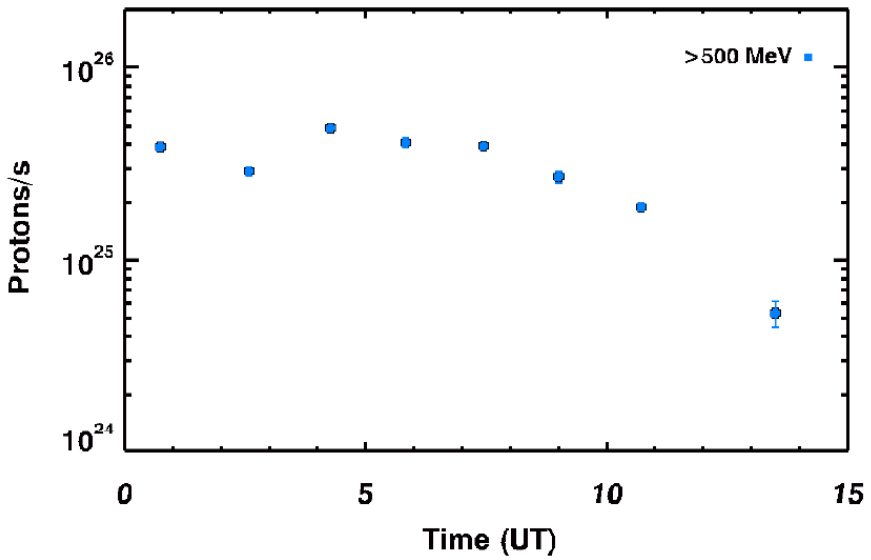


p/He ratio during the 2012 March 7th event

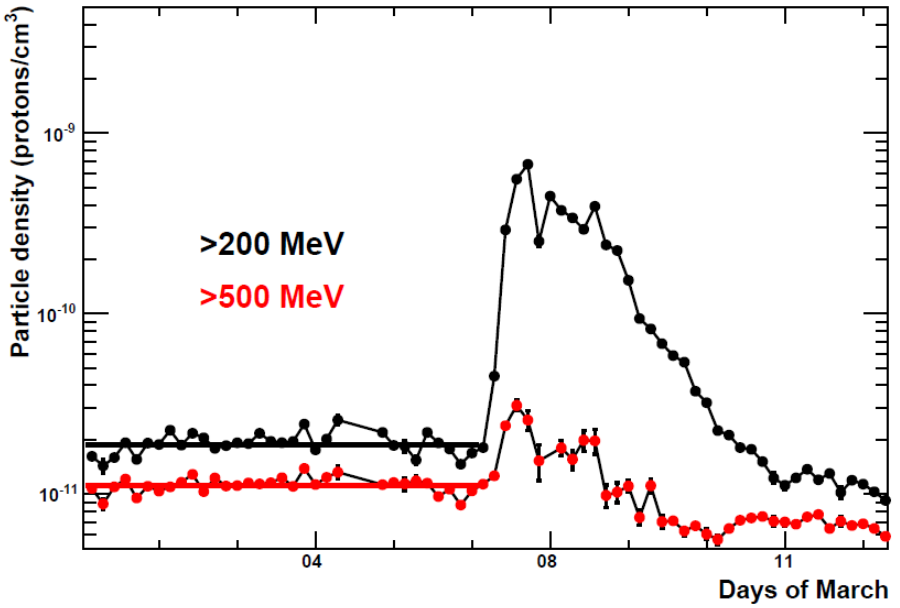
- **The Helium enhancement (He/p > 15%) has been associated with large flare**
- **The ratio decreases respect to the quiet Sun condition**
- **The ratio tends to become normal again after 5 days**

COMPARING POPULATION SUN-EARTH

- We compare the derived accelerated ion population at the Sun (obtained by Fermi γ measurement) with the ion population directly measured in space by PAMELA



Derived accelerated proton fluence (> 500 MeV) based on from a standard γ-ray production model

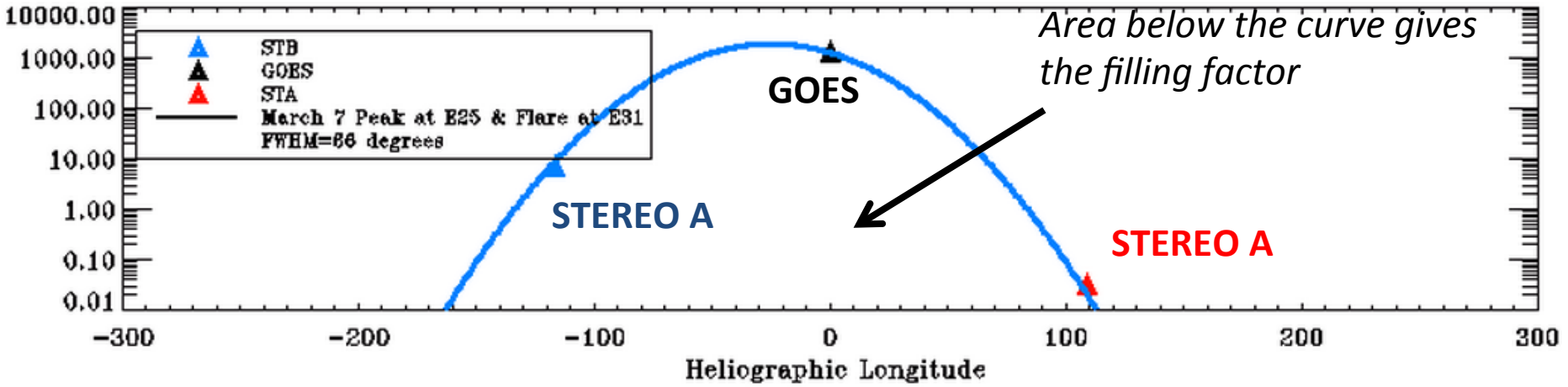


Particle density measured by PAMELA (> 200 & > 500 MeV)

COMPARING POPULATION SUN-EARTH

PAMELA offers for the first time a unique opportunity to observe high-energy SEPs with ion energies that are known to produce the high-energy gamma-ray emission observed by FERMI/LAT, enabling the possibility to determine a connection, if any, between particles at the Sun and those in space.

- **A multi-point observations of GOES, STEREO A & STEREO B (> 10 MeV) is used to obtain a filling factor and calculate the differential number of particles (dN_p) and then obtain a volume-integrated density (N_p)**



COMPARING POPULATION SUN-EARTH

X-Ray Flare	Class	Location	CME Km/s	Fermi > 200 MeV	Fermi > 500 MeV	PAMELA > 200 MeV	PAMELA > 500 MeV	Ratio @ 500 MeV
7 March 2012	X5.4/X1.3	N18E31	1785	2.6×10^{31}	1.5×10^{30}	7.2×10^{29}	8.0×10^{28}	15

Results of the deduced number of accelerated ions at the Sun and measured by PAMELA

The total number of protons (> 500 MeV) is 15 × the protons measured by PAMELA (for the 7 March 2012 event)

1. Populations are unrelated?

2. Ions at the Sun are accelerated by stochastic acceleration at the Sun and do not escape?

3. Protons measured in space accelerated by a separate mechanism (CME shock?)

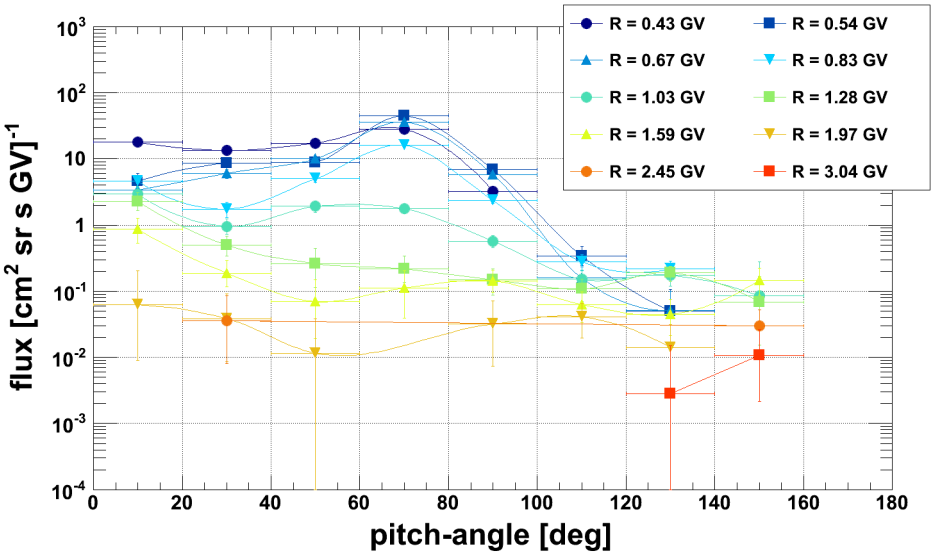
ANISOTROPY STUDIES

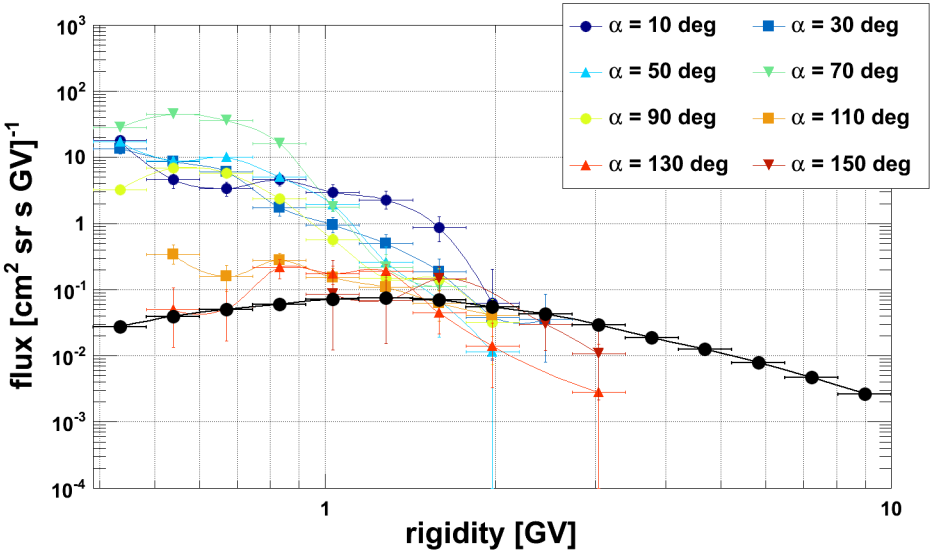
- PAMELA innovative aspects include **the possibility of measuring the pitch-angle distributions,** essential for the interpretation of solar events.

- A key ingredient is the use of back-tracing techniques, based on a realistic description of the magnetosphere, in order to **reconstruct particle trajectories, identify asymptotic arrival directions and thus reconstruct the pitch angles.**

- PAMELA data can be **combined with data from NMs and other satellite-based detectors,** in order to model the directional distribution of solar events, estimating the role of local transport phenomena.

THE ANISOTROPY OF 2012 MAY 17th





Flux distribution as a function of pitch-angle in 10 bins of rigidity. The galactic background (estimated during a similar orbit of May 16th) is subtracted

Flux distribution as a function of rigidity in 10 bins of pitch-angle. The galactic background (estimated during a similar orbit of May 16th) is subtracted

THE ANISOTROPY OF 2012 MAY 17th

- Observations from PAMELA during the 2012 May 17 SEP event **exhibit differential anisotropies and thus transport features over the instrument rigidity range.**

- SEP protons exhibit two distinct pitch angle distributions**; a low-energy population that extends to 90°** and **a high energy population that is beamed at high energies (> 1 GeV), consistent with neutron monitor observations.**

- In order to explain a low-energy SEP population that exhibits significant scattering or redistribution **accompanied by** a high energy population that reaches the Earth unhindered by dispersive transport effects, **it is possible to postulate that the scattering or redistribution takes place locally.**

- This could be the first definitive observations of **the effects of solar energetic particle transport within the Earth's magnetosheath.**

SEARCH FOR SOLAR NEUTRONS 1/2

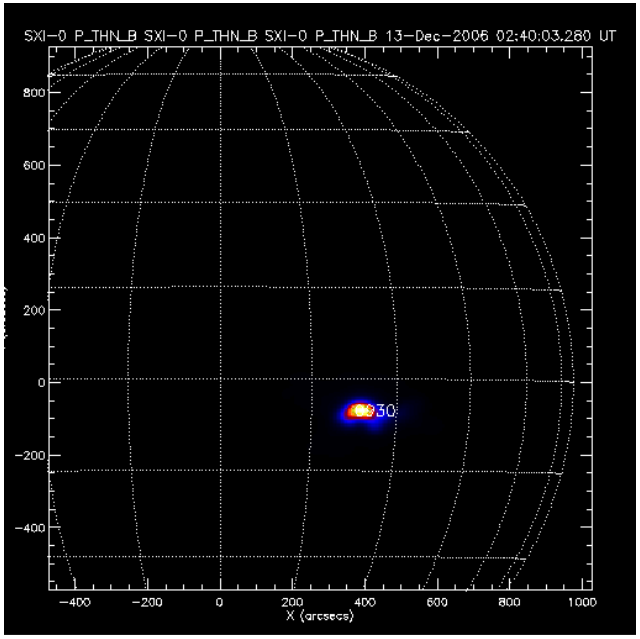
Solar neutrons can be produced by any solar event.

PAMELA Neutron Detector (ND) is sensitive to neutrons fluxes coming from Sun.

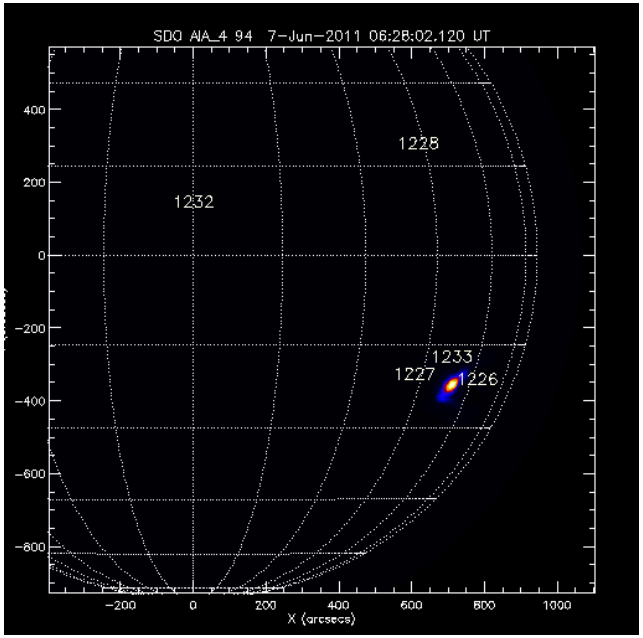
Search of ND counts increasing after SEP event in comparison with counts during 1 orbit before the event.

Two events under study:

December 13rd 2006

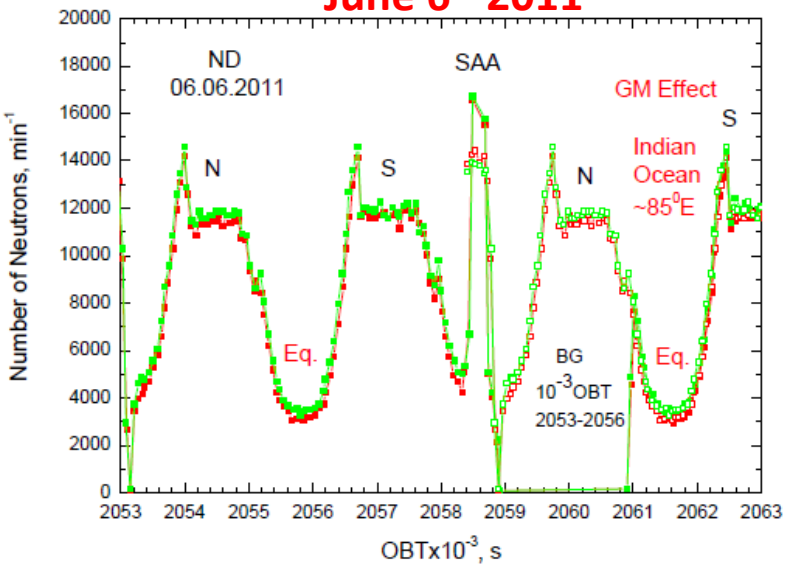


June 7th 2011

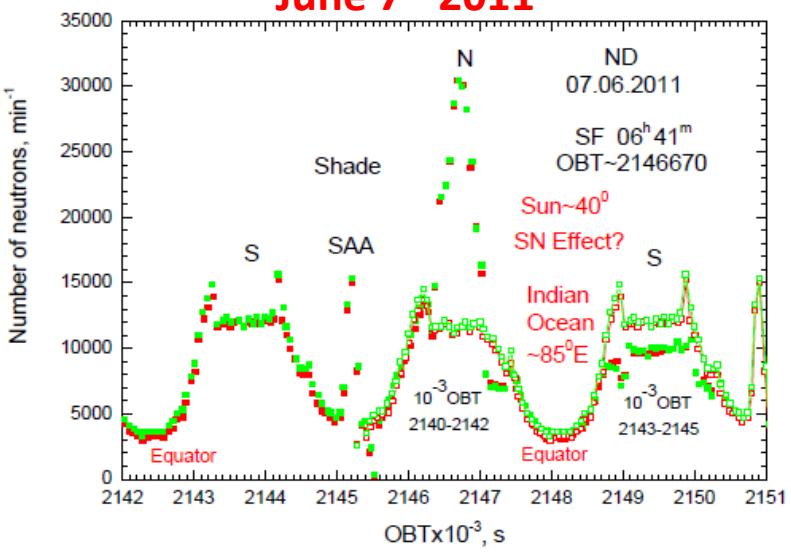


SEARCH FOR SOLAR NEUTRONS 2/2

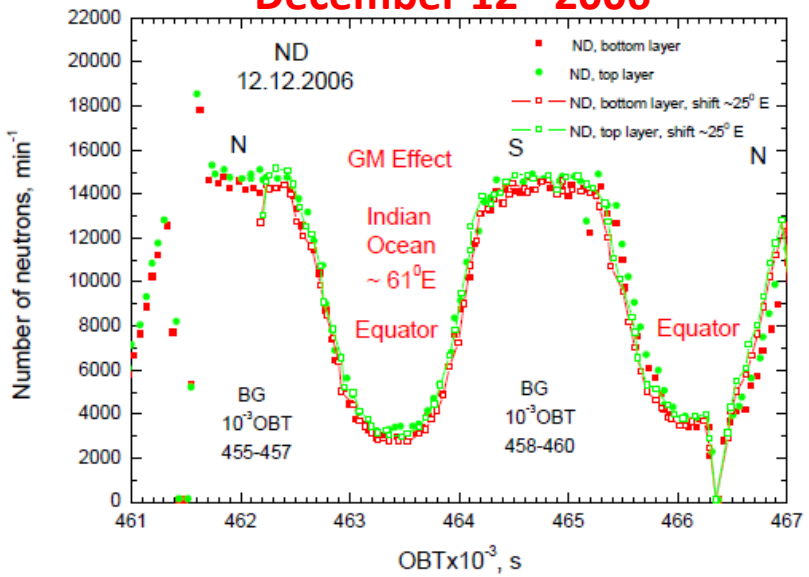
June 6th 2011



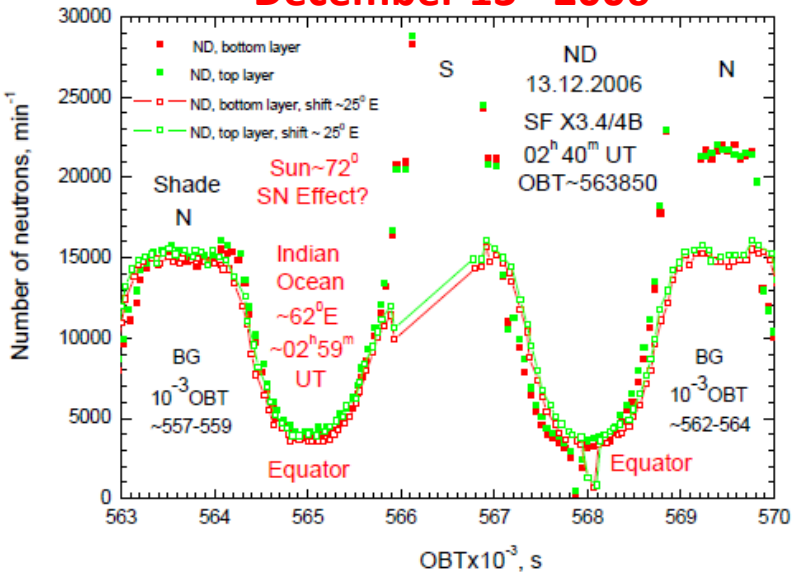
June 7th 2011



December 12th 2006

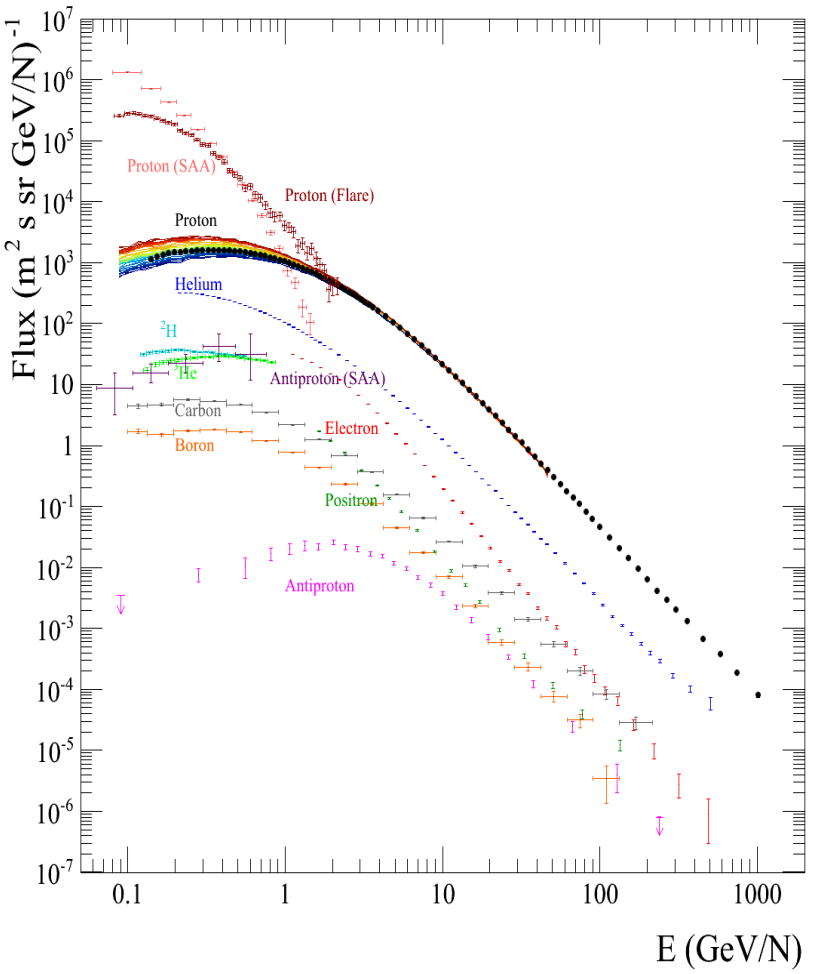


December 13rd 2006



PAMELA OVERALL RESULTS

Results span 4 decades in energy and 13 in fluxes !



PAMELA data public and available at http://tools.asdc.asi.it/cosmicRays.jsp (ASI data Centre)

CONCLUSIONS (1)

- PAMELA has been in orbit and studying cosmic rays for more than 8 years. Its operation time will continue until 2015.

- Though conceived primarily for high energy cosmic ray studies, **PAMELA has unique features suitable for solar research, and has already provided valuable data.**

- One article about the 13 Dec. 2006 SEP event already published. A new article *"How the Earth's Magnetosheath effects Solar Energetic Particles*" (with US theoreticians) just submitted to Science.

CONCLUSIONS (2)

- Since several years, PAMELA started **collaborations with solar physicists all over the world**: North-West Univ. (South-Africa) for solar modulation, Univ. of Kiel for gradients in heliosphere, GSCF, NMSU, NHU (Usa) for SEP analysis with NM, FERMI collaboration for joint analysis.

- PAMELA is collaborating especially with solar and radiation groups of **Univ. of Tor Vergata (Rome),** IAPS/ INAF (Rome) and Kapodistrian University of Athens (Greece) **groups for joint analysis.** See our poster

Multiplatform observations of the Earth's particle radiation environment during the 17 May 2012 SEP event *(Laurenza M. et al., Poster 8.02).*

PAMELA on PHYSICS REPORTS

"The PAMELA Space Mission: Heralding a New Era in Precision Cosmic Ray Physics"

Physics Reports 544 (2014), pp. 323-370

Summarizes published and unpublished (but final) PAMELA results.