# Solar energetic particles measured by PAMELA


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**on behalf of the PAMELA collaboration**



**Space Radiation and Plasma Monitoring Workshop, 13-14 May 2014**

**European Space Research and Technology Centre (ESTEC)**

# The PAMELA collaboration

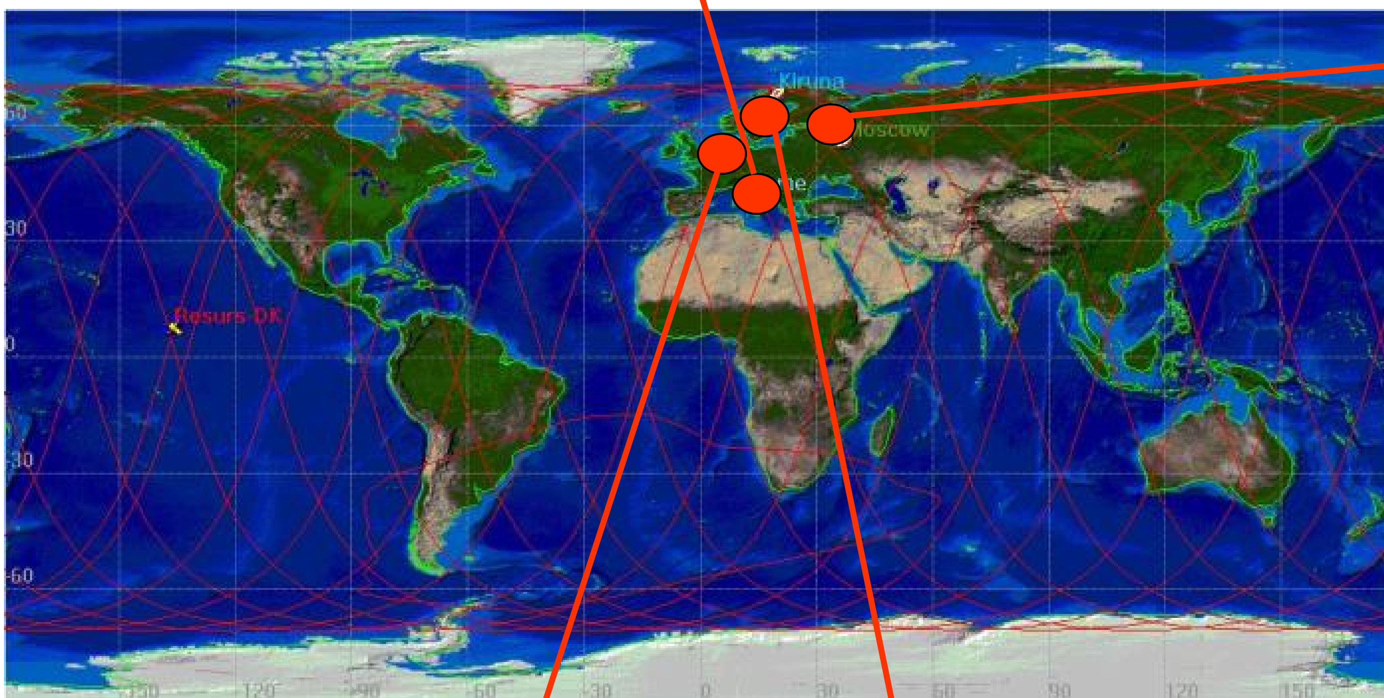
Italy: Bari, Florence, Frascati, Naples, Rome, Trieste, CNR, Florence

Russia:

Ioffe Physico-Technical Institute

Moscow

St. Petersburg

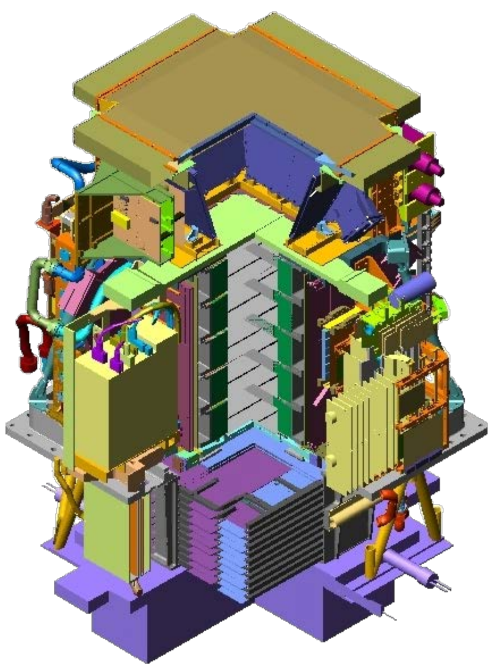



Germany: Siegen

Sweden: KTH, Stockholm

# The PAMELA apparatus

**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

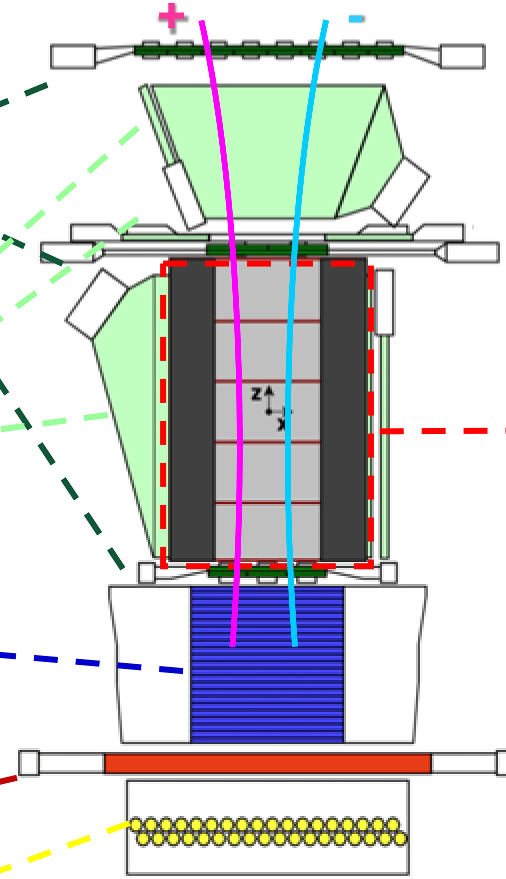
**Time-Of-Flight**
plastic scintillators + PMT
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX.

**Anticoincidence shield**
plastic scintillators + PMT

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

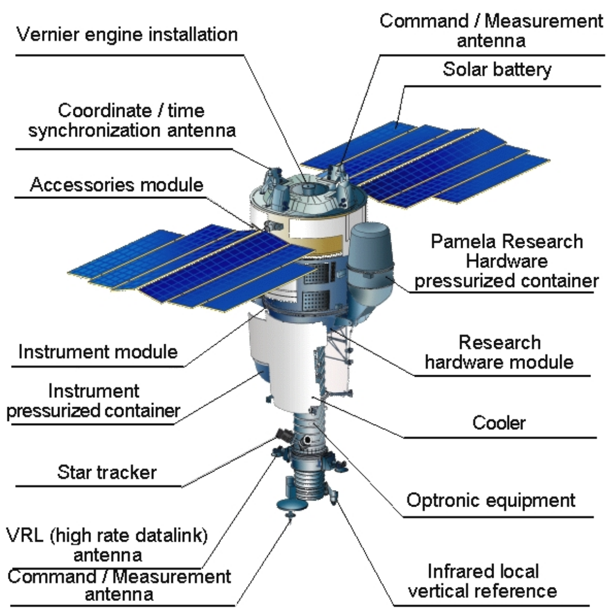
**Bottom scintillator** (+PMT)

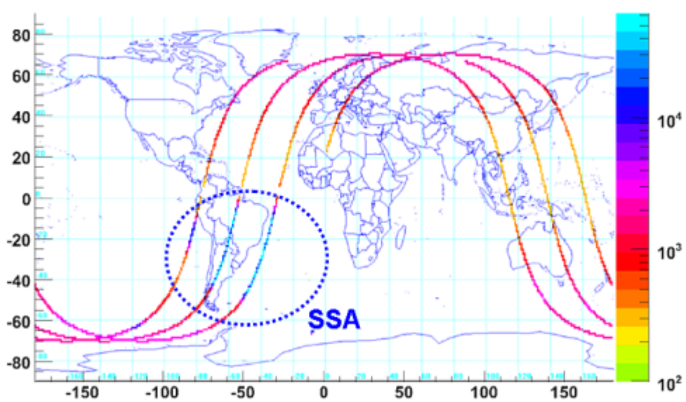
**Neutron detector**
$^3$He counters
- High-energy e/h discrimination




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

# The Resurs-DK1 satellite




- Mass: ~6.7 tons
- Height: 7.4 m
- Solar array span: ~14 m
- Average power (per day): 2000 W (PAMELA 360 W)

- Semi-polar (70° inclination) and elliptical (350÷610 km altitude) orbit
- Orbital period: 96 min

- ✓ 3-axis stabilized
- ✓ Orientation calculated by onboard processor with accuracy <1°
- ✓ Angular velocity stabilization accuracy: 0.005 degree/s

❖ **in orbit since June 15th 2006**

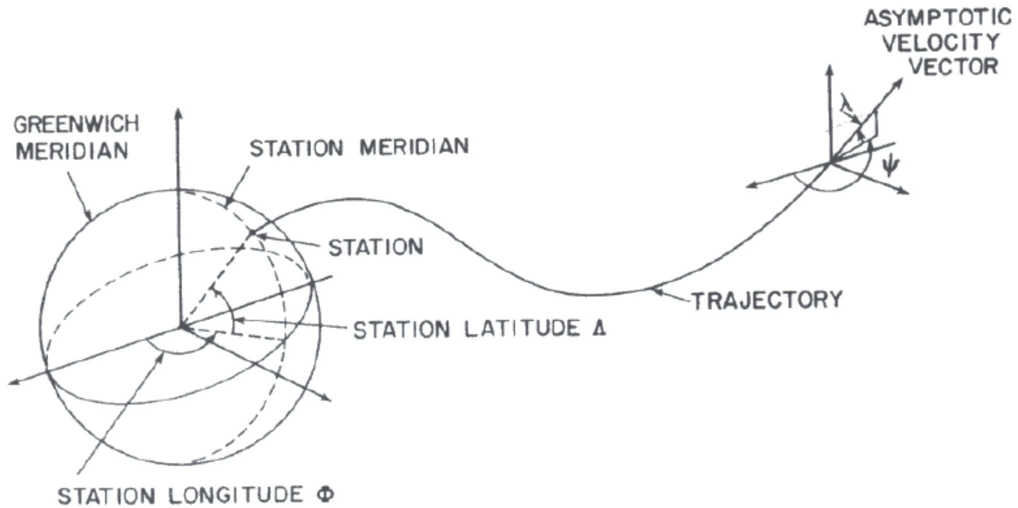
# PAMELA and SEPs

Multi-wavelength and multi-point observations now available (SDO, SOHO, STEREO, ACE, RHESSI, FERMI, etc) make this a critical time to analyze high-energy SEPs.

Advantages of PAMELA:

- 1. Wide energy range
  - inclusive of the gap region between high energy data from ground-based detectors and low energy observations from spacecrafts.
- 2. Sensitive to composition of SEPs
- 3. Potential to contribute significantly to constraining the injection time-scales.
- 4. Discovery potential to observe positron and concomitant neutrons

# SEPs and geomagnetic back-tracing




- In order to analyze anisotropies related to the solar flare, we need to account for the effect of the geomagnetic field on particle propagation.

- Generally (neutron monitors) one is interested in particle "asymptotic directions", i.e. the directions of approach before they encountered the magnetosphere.

- ✓ To determine asymptotic directions, particle trajectories are numerically traced backward through a model magnetosphere until they cross the magnetopause.

- ★ The calculation also allows to evaluate geomagnetic cutoff rigidities and to separate protons of interplanetary and atmospheric (trapped & albedo particles) origin.

# Geomagnetic back-tracing

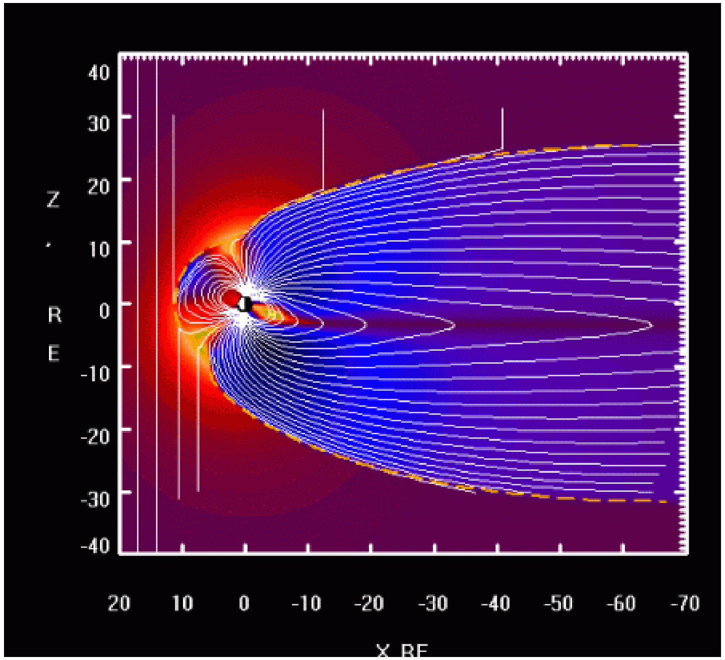
- Based on Smart & Shea (2000, 2005) code
  - Runge-Kutta integration of motion equations

- Uses the *"International Radiation Belt Environment Modeling"* (IRBEM) library (Boscher et al. 2012)

- Realistic description of the geomagnetic field:
  - internal sources: IGRF-11 model
  - external sources: Tsyganenko models
  - IMF and Solar Wind parameters:
    - high-resolution (5-min) OMNIWeb data

✓ Already used in the analysis of under-cutoff protons
(see my presentation: *"Geomagnetically trapped and albedo protons measured by PAMELA"*)

# The Tsyganenko models




http://geo.phys.spbu.ru/~tsyganenko/modeling.html

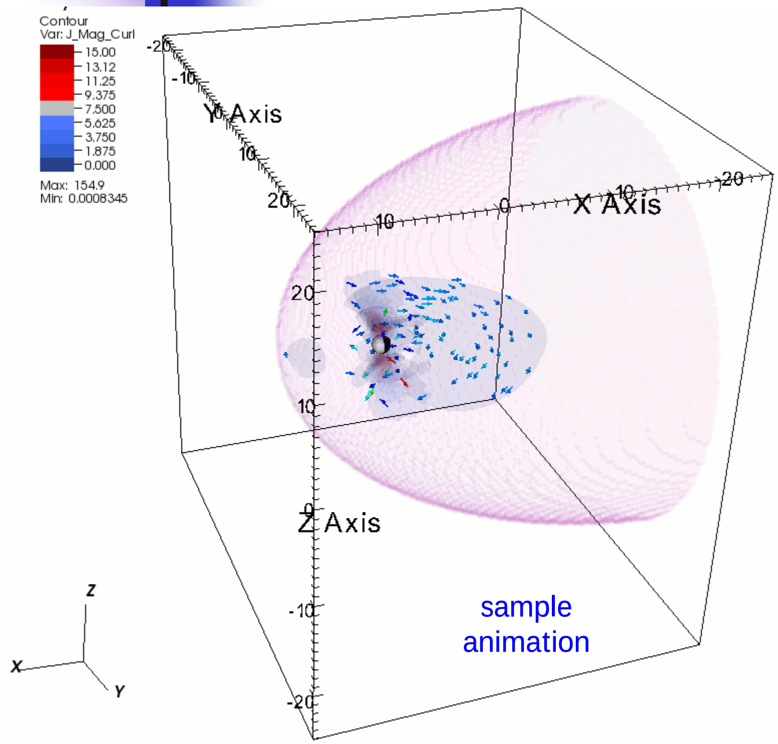
Semi-empirical best-fit representations for the geomagnetic field, including the contributions from external magnetospheric sources:

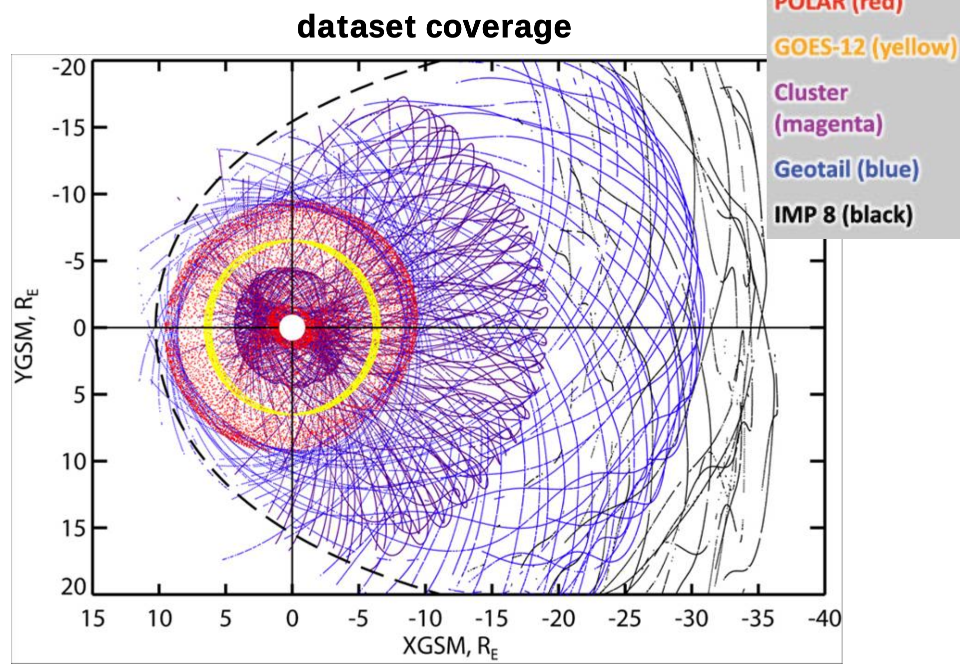
- ring current, magnetotail current system, magnetopause currents and large-scale system of field-aligned currents.

Latest versions (Tsyganenko & Sitnov, 2005; 2007) provide a <u>dynamical description of the storm-time geomagnetic field</u> in the inner magnetosphere

- based on 5-min resolution OMNIWeb data

# The TS07D model




**For more details:** http://geomag_field.jhuapl.edu/model/

In this analysis we used the **TS07D** model (Tsyganenko & Sitnov 2007):

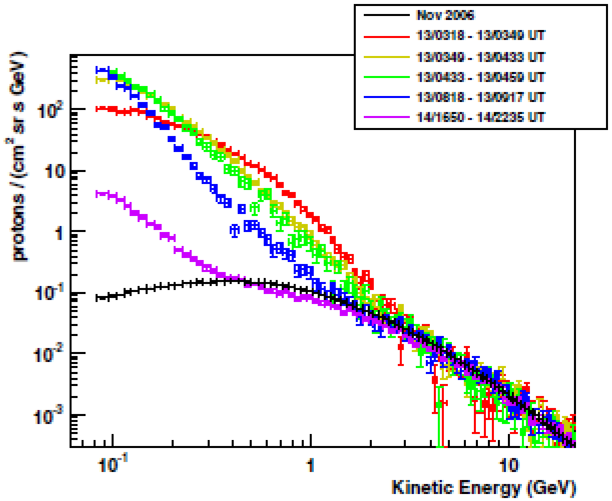
- High-resolution: large (~$10^6$ points) dataset based on recent (1995-2005) spacecraft measurements (Cluster, Polar, Geotail, IMP-8, GOES 8-12).
- Coverage: < 30-35 $R_E$ (previous version TS05 is limited to $X_{GSE} \geq -15\ R_E$)
- More flexible and strongly superior to all past empirical models in reconstructing distribution of storm-scale currents.

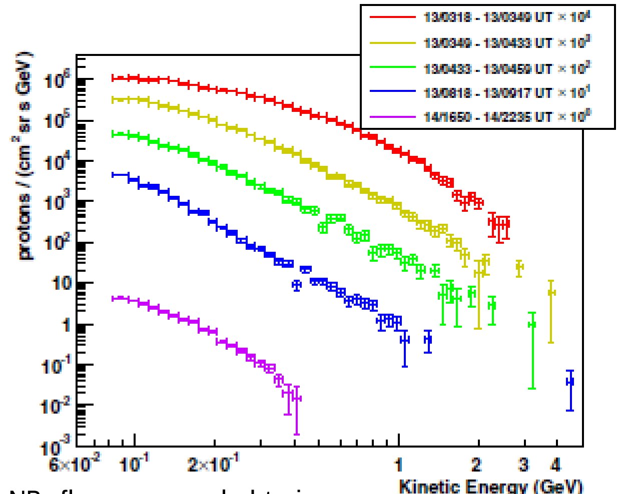
# Results

## Sample event: December 13, 2006

# The December 13, 2006 event

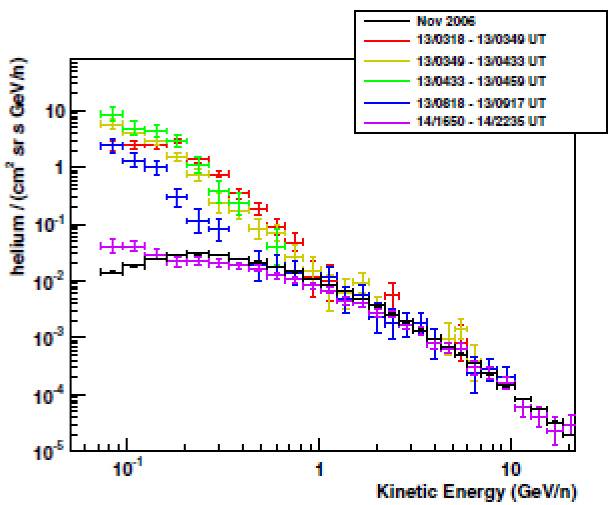
**protons**

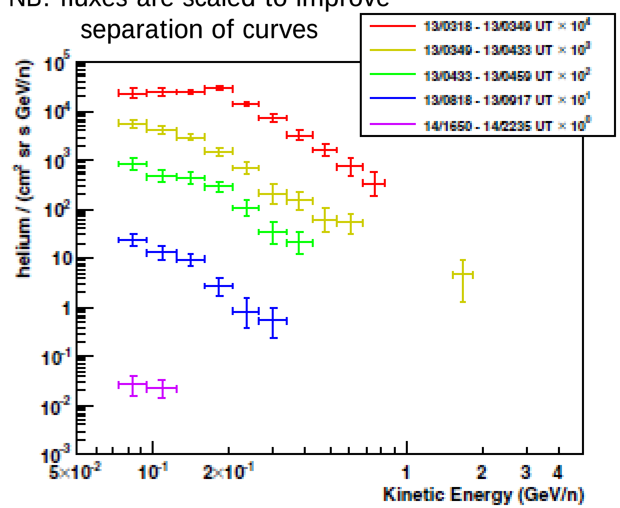



NB: fluxes are scaled to improve separation of curves

**Helium**



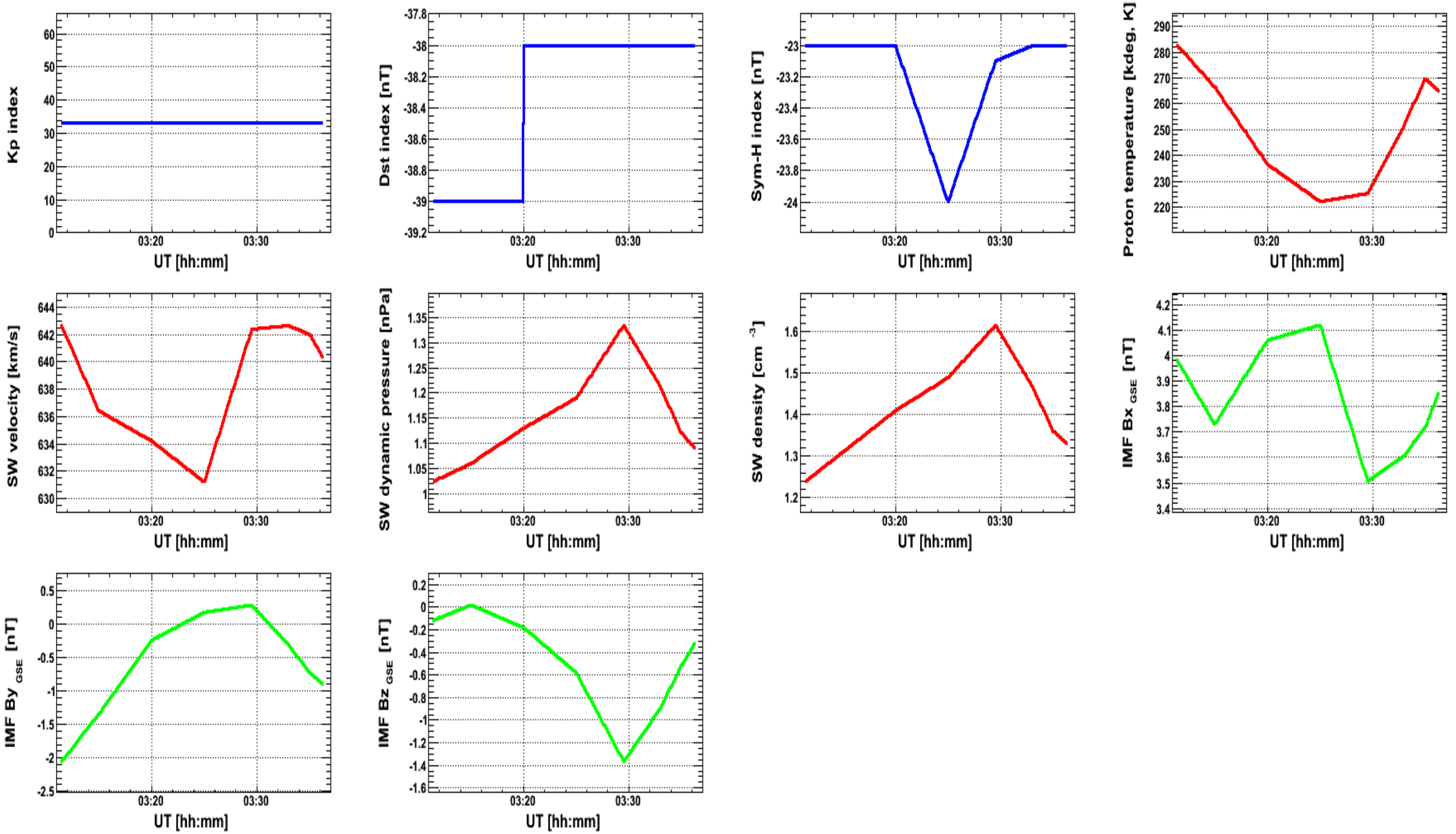




Adriani, O., et al., "*Observations of the 2006 December 13 and 14 Solar Particle Events in the 80 MeV/n - 3 GeV/n Range from Space with the PAMELA Detector*", ApJ 742 102 2011.

# The December 13, 2006 event

## IMF and SW parameters

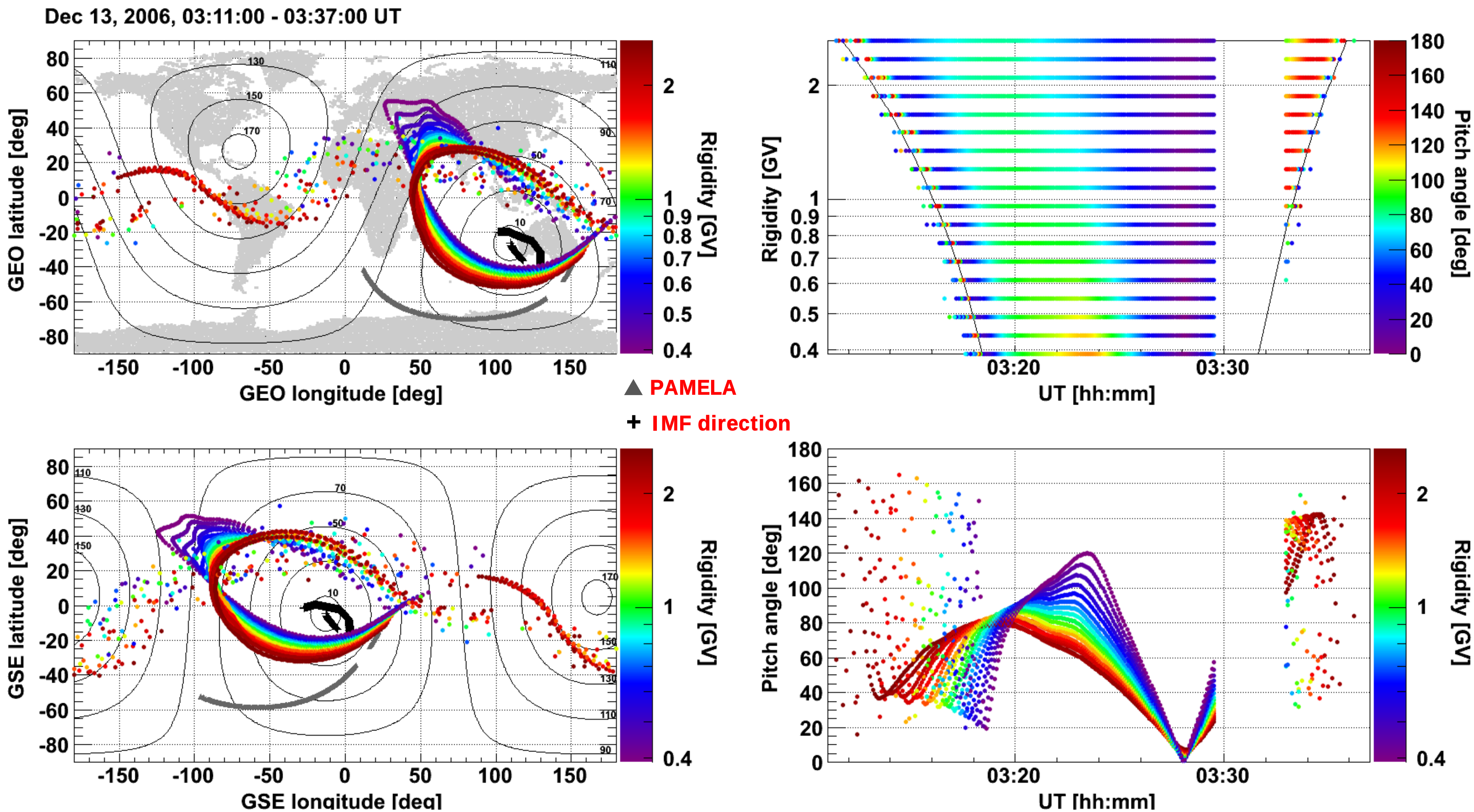
**time interval: 03:11 – 03:37 UT**



# The December 13, 2006 event

## PAMELA vertical asymptotic directions

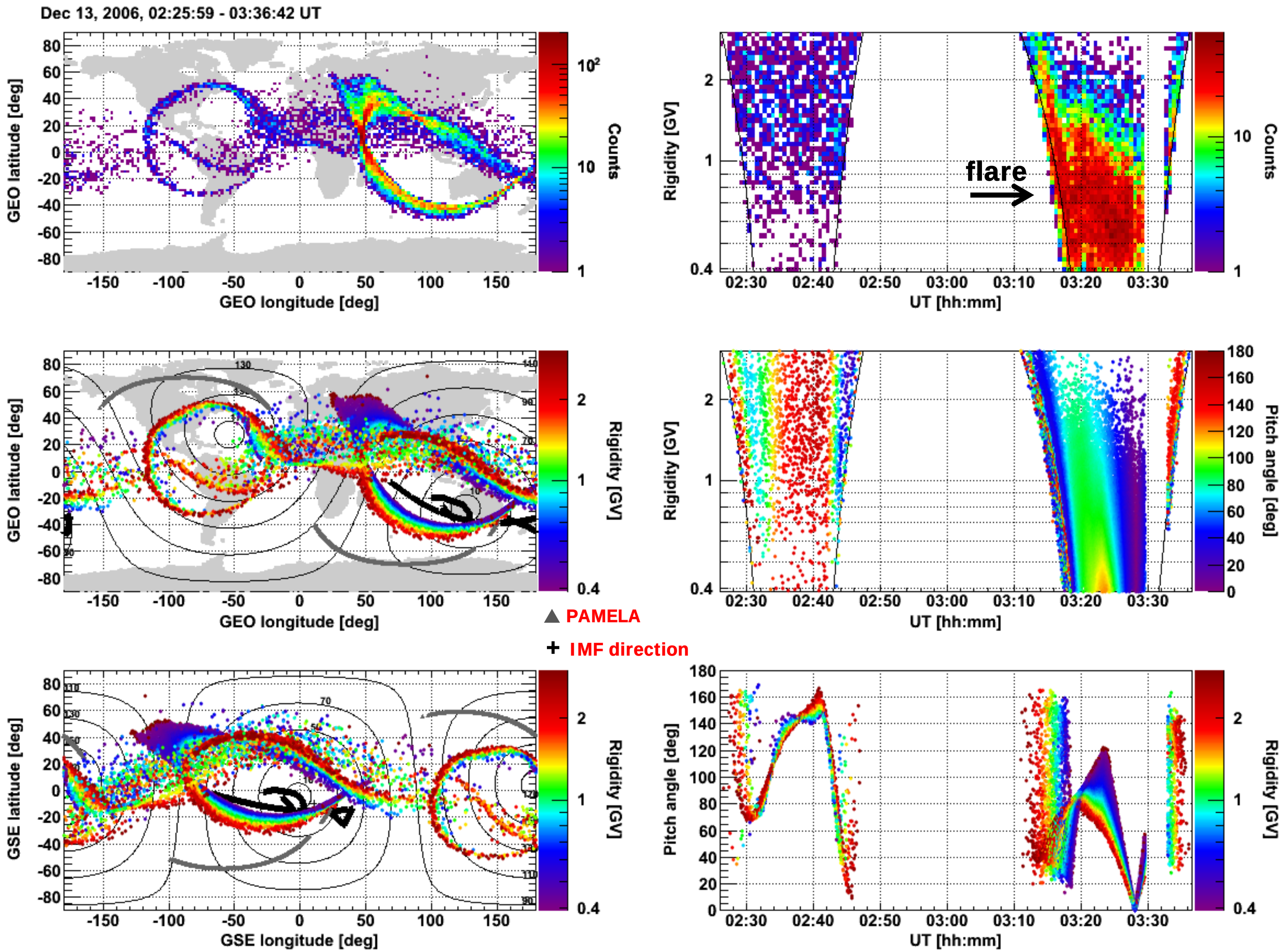
**Evaluated for 18 rigidity values between 0.39 - 2.5 GV**




GSE frame: X = Earth-Sun line, Z = Ecliptic North Pole

# The December 13, 2006 event

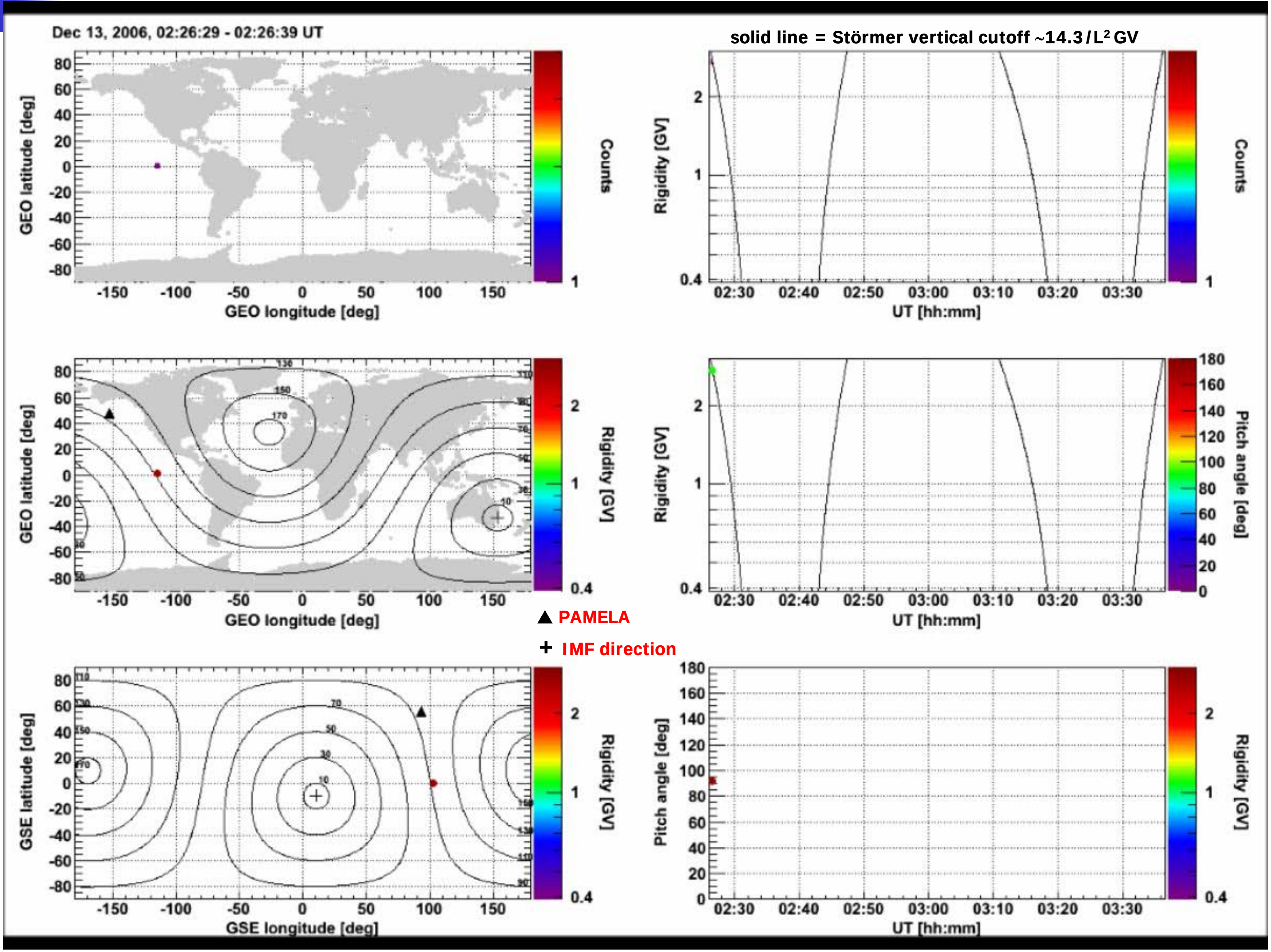
## proton back-tracing




GSE frame: X = Earth-Sun line, Z = Ecliptic North Pole

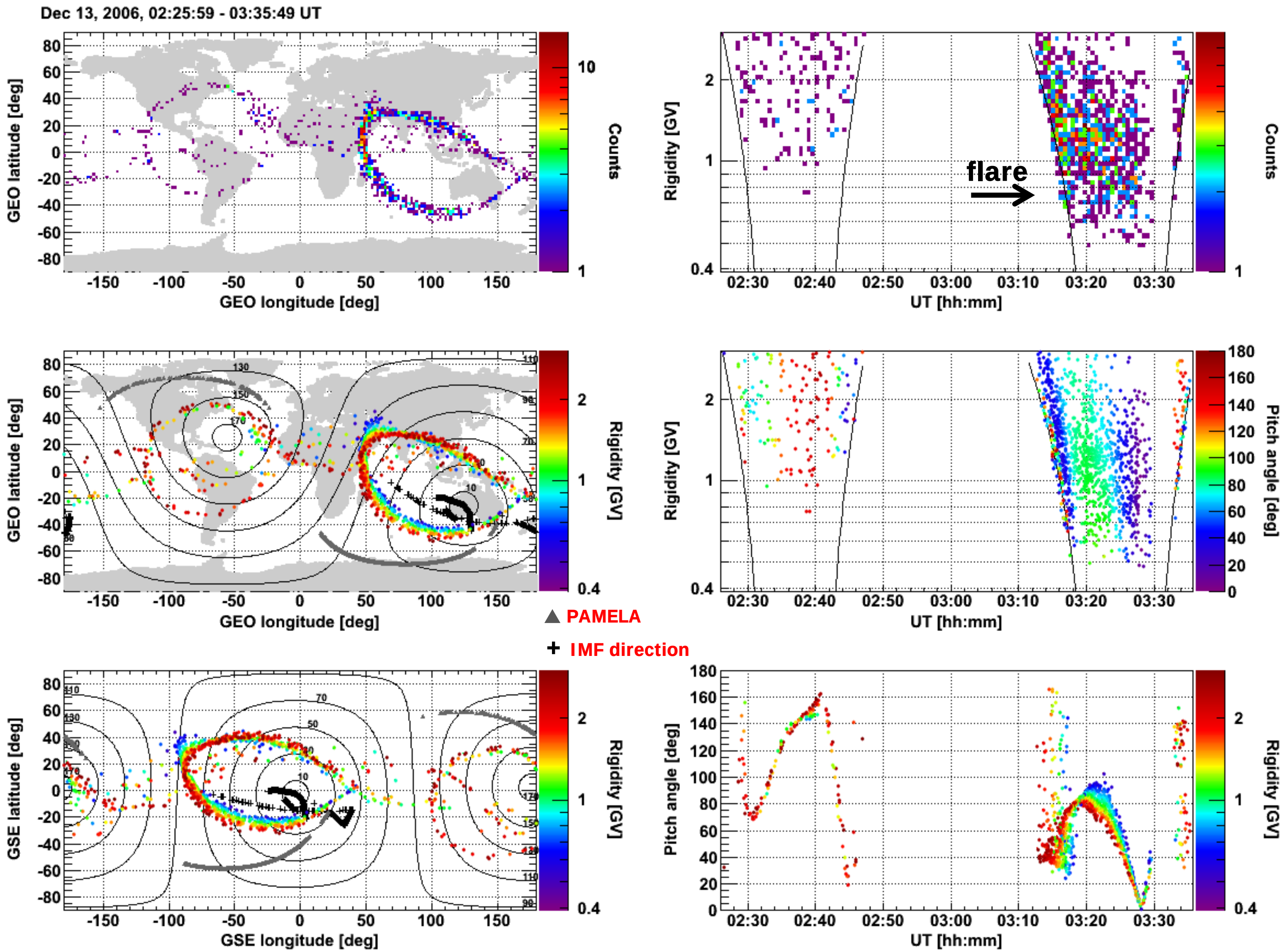
# The December 13, 2006 event

## proton back-tracing: animation

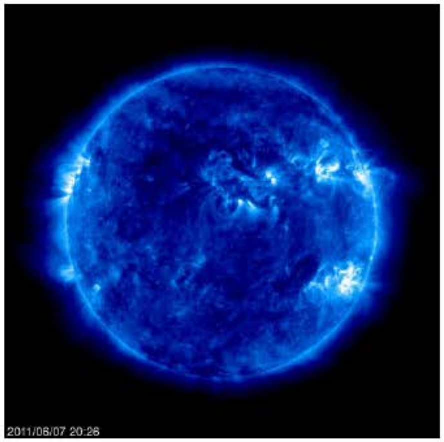


# The December 13, 2006 event

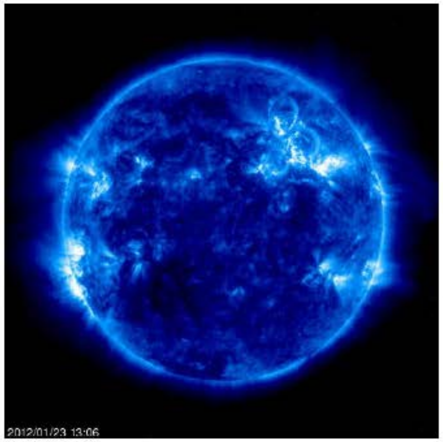
## Helium back-tracing



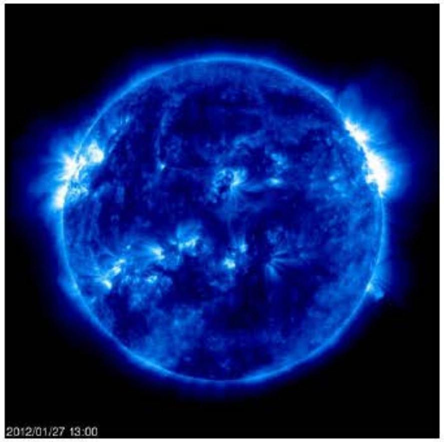
# Major SEP events under study



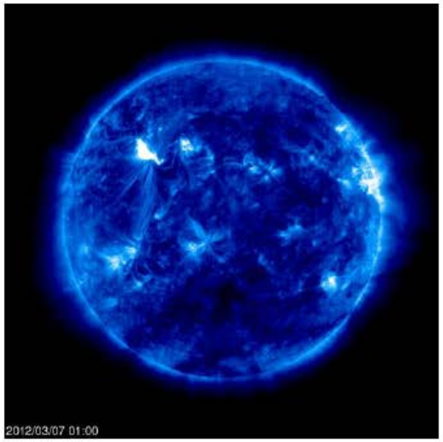
2011 June 07 (M2)



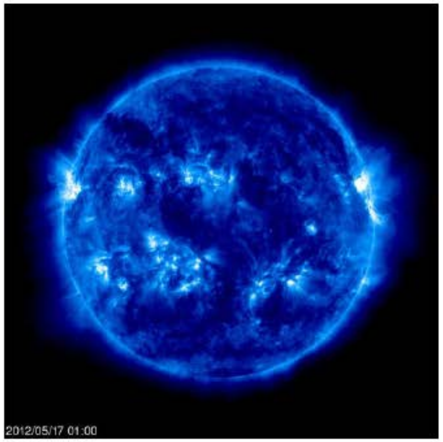
2012 January 23(M8)



2012 January 27 (X1)



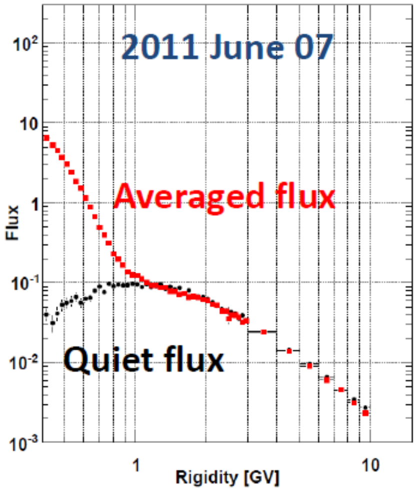
2012 March 07 (X5)

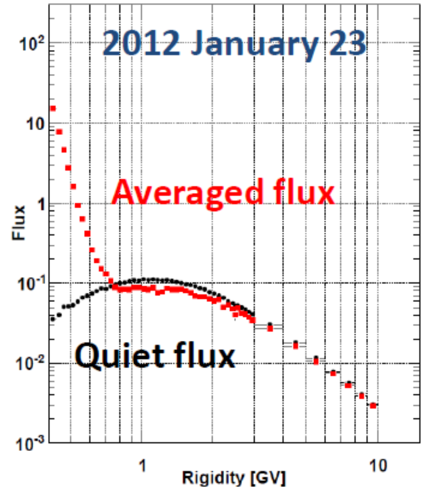


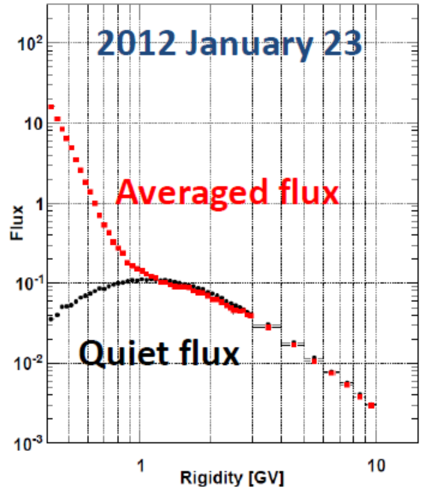
**2012 May 17 (M5)**

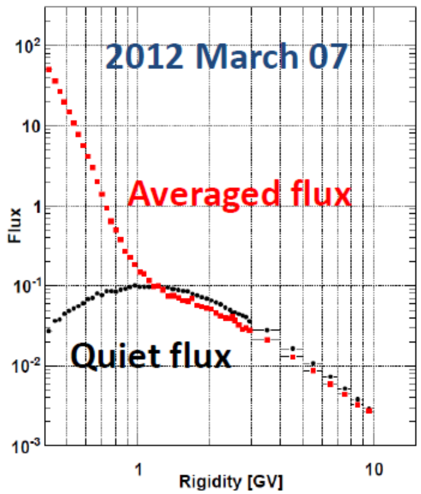
# Major SEP events under study

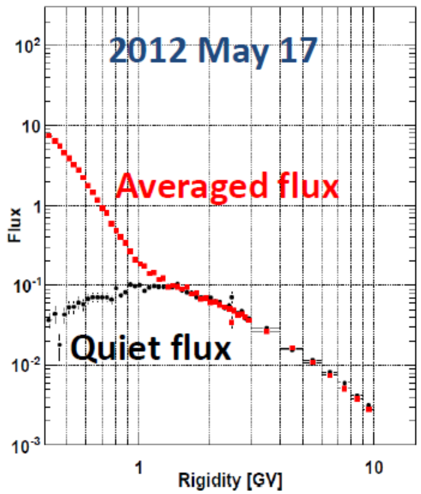
**arbitrary units (preliminary!!!)**



# Combined back-tracing analysis

- The unique data of PAMELA can be combined with other solar contextual data to form a complete picture of the evolving SEP event and to identify connections, if any, with the low-energy SEP component.

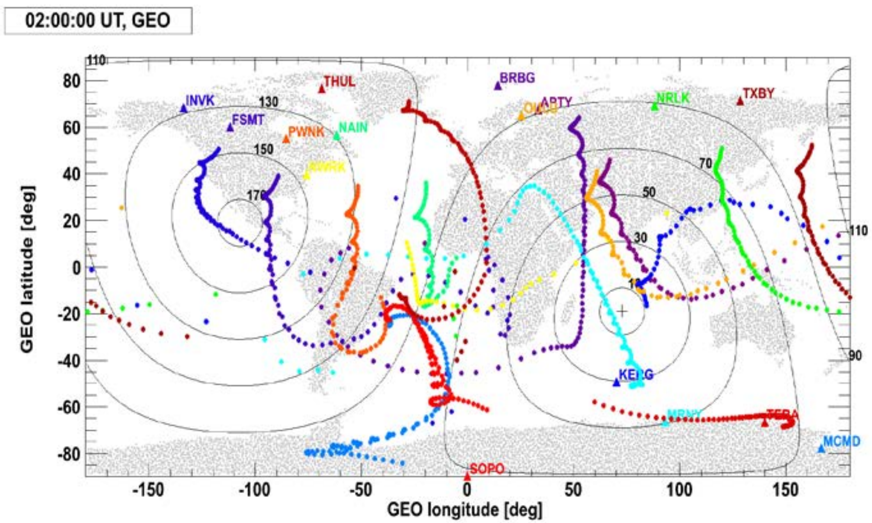
- The highest energy SEPs, the so-called **Ground Level Enhancements (GLEs)**, offer a unique opportunity to study the signatures of acceleration relatively unhindered by the effects of transport.

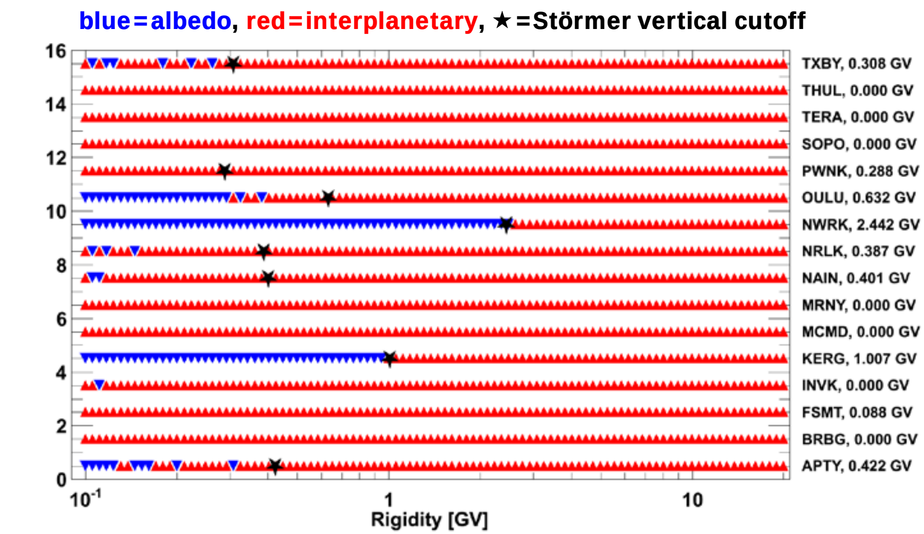
- The shape and morphology of GLEs can be evaluated through extensive modeling of the response of the world-wide network of Neutron Monitors (NMs) located at widely differing locations and altitudes, in combination with PAMELA data.
  - Each NM provides the particle intensity as a function of time observed at a given geographic location.
  - <u>The back-tracing analysis was applied to 16 NM stations</u>.
  - NM asymptotic directions evaluated in the rigidity range: 0.1÷20 GV

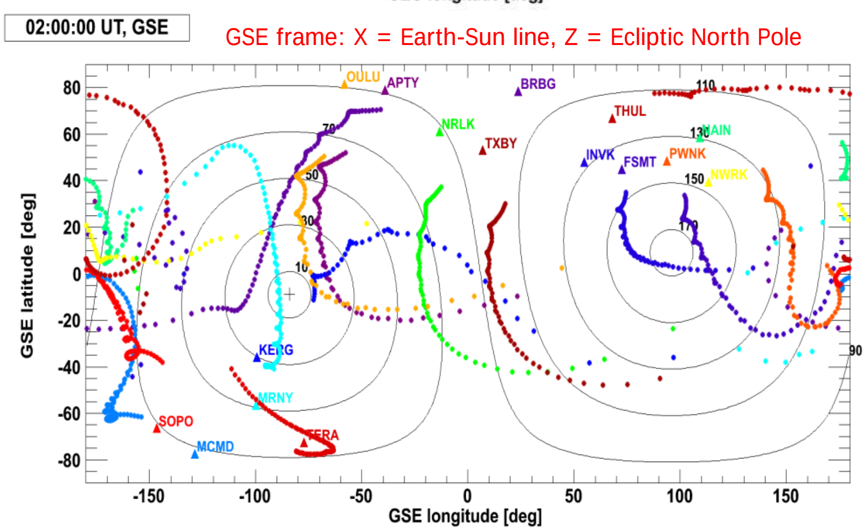
# Neutron monitors

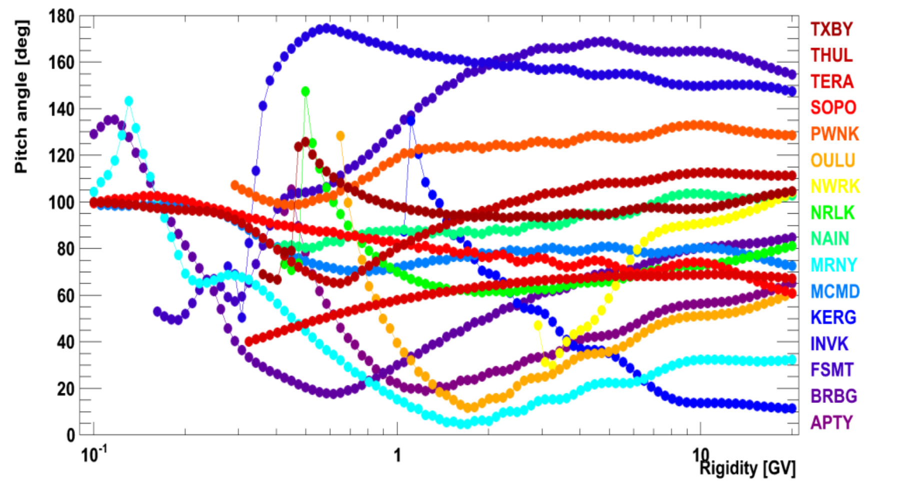
## vertical asymptotic directions

**December 13, 2006, 03:00 UT**



# Conclusions

- PAMELA innovative aspects include the possibility of measuring the pitch-angle distribution and, consequently, the extent of particle scattering at high energies.

- In particular, the analysis of the anisotropy of the event prompt phase can put important constraints on particle transport and enable a clearer view of the processes governing acceleration at the Sun.

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

- Using both ground- and satellite-based detectors, the directional distribution of incoming events can be modeled to determine the omnidirectional density and weighted anisotropy.

- The work is in progress. Next steps include:
  - application of the back-tracing study to all SEPs registered by PAMELA (2006-2014)
  - reconstution of energetic spectra as a function of time pitch-angle