Solar Energetic Particles (SEP) & PAMELA

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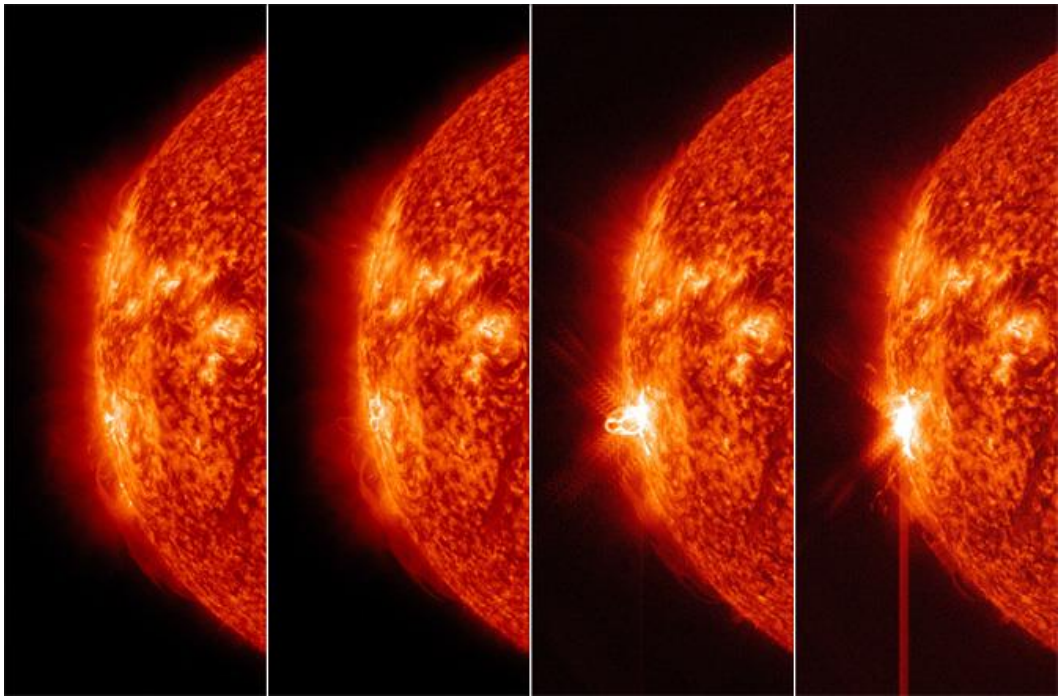
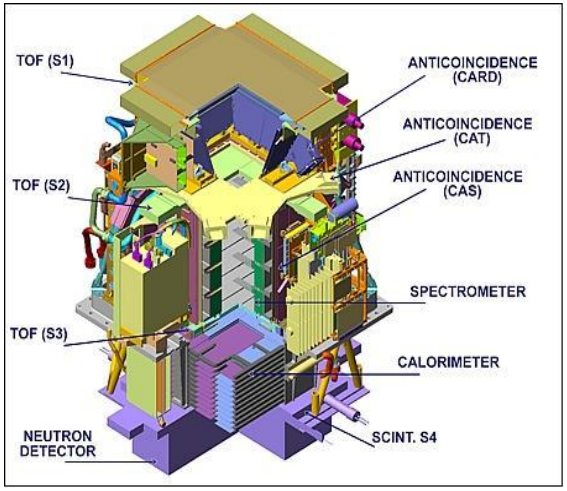


PAMELA instrument



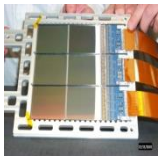
GF: 21.5 cm² sr
Mass: 470 kg
Size: 130x70x70 cm³
Power Budget: 360W

Anti-p	80 MV - 190 GV	$O(10^4)$
e^+	50 MV - 300 GV	$O(10^5)$
e^-	up to 600 GV	$O(10^6)$
p	up to 1 TV	$O(10^8)$
He	up to 400 GV/n	$O(10^7)$
Li/Be/B/C)	up to 200 GV/n	$O(10^{4-5})$

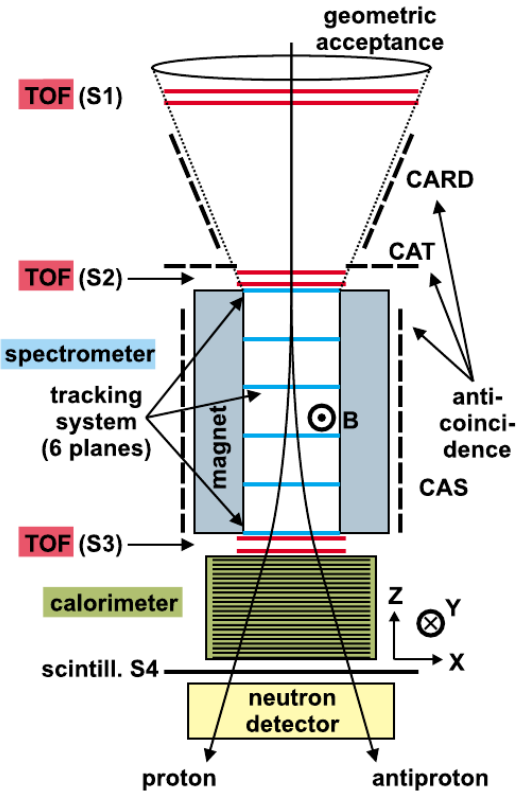
Time-Of-Flight
plastic scint.+ PMT:
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX.

Spectrometer
microstrip Si track sys
- *Rigidity → R = pc/Ze*
- *Charge sign*
- *Charge value from dE/dx*

+ permanent magnet

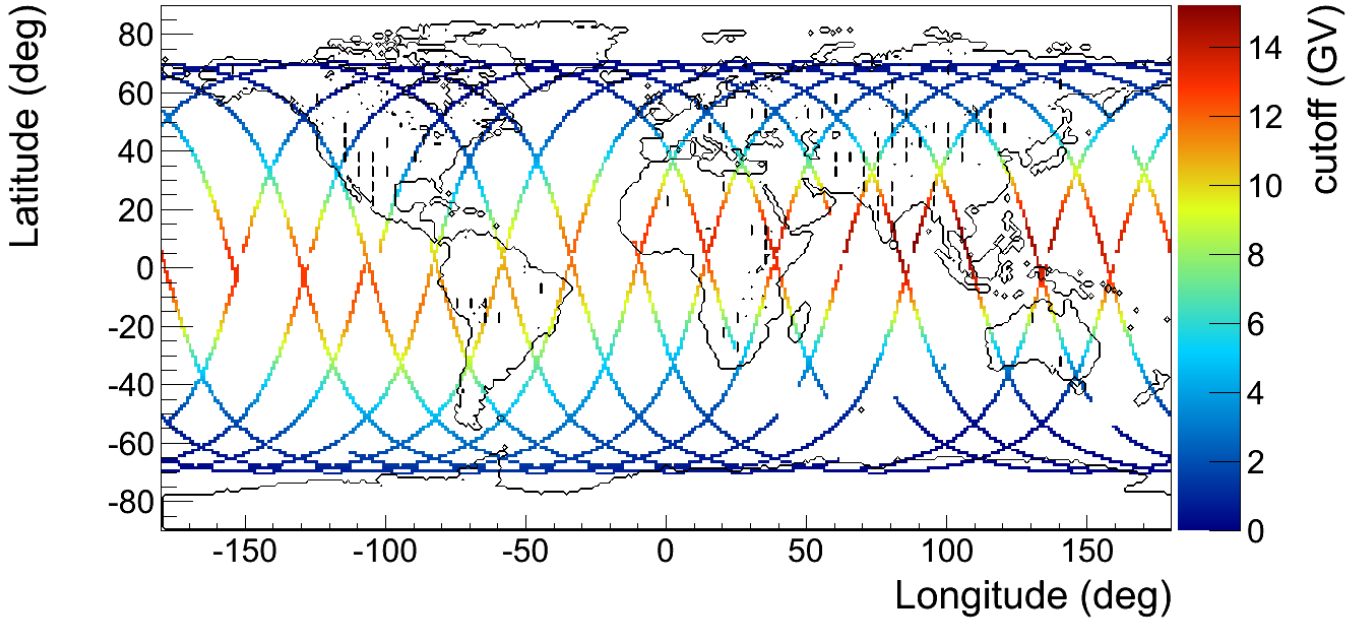


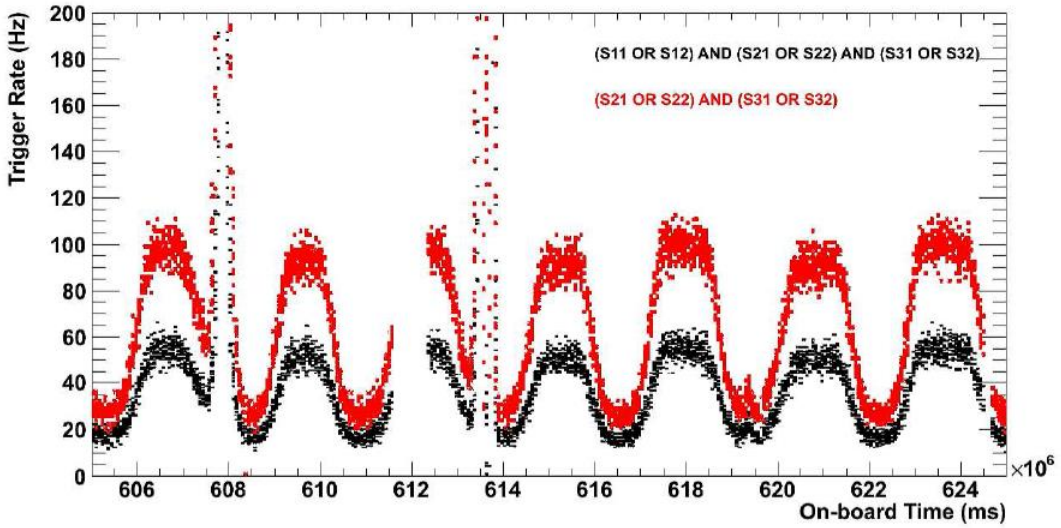
Electromag .calorimeter
W/Si samp (16.3 X_0, 0.6 λ_I)
-Discrimination e^+ / p,
anti-p / e^- (shower topology)
- Direct E measurement for e^-



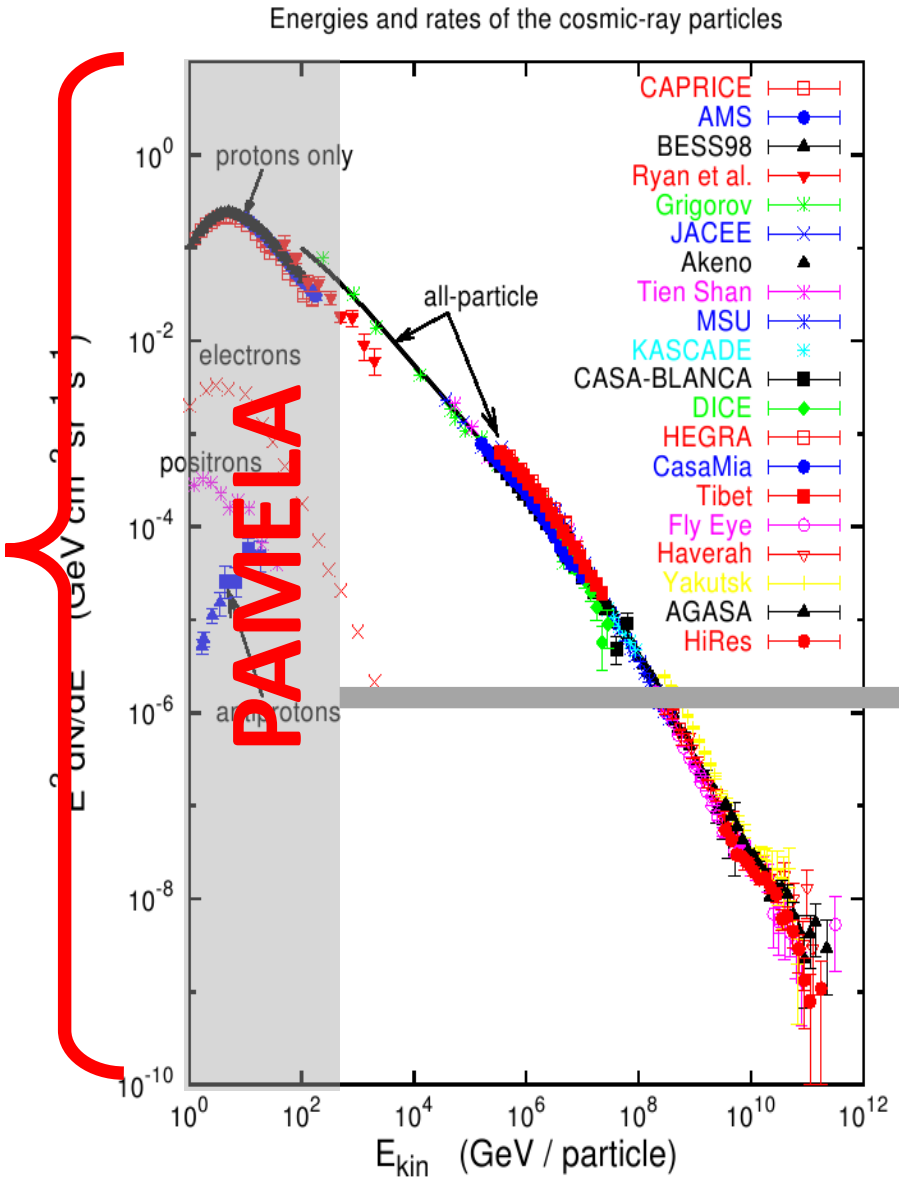
Neutron detector
^{3}He tubes + PMT:
- High-energy e/h discrimination

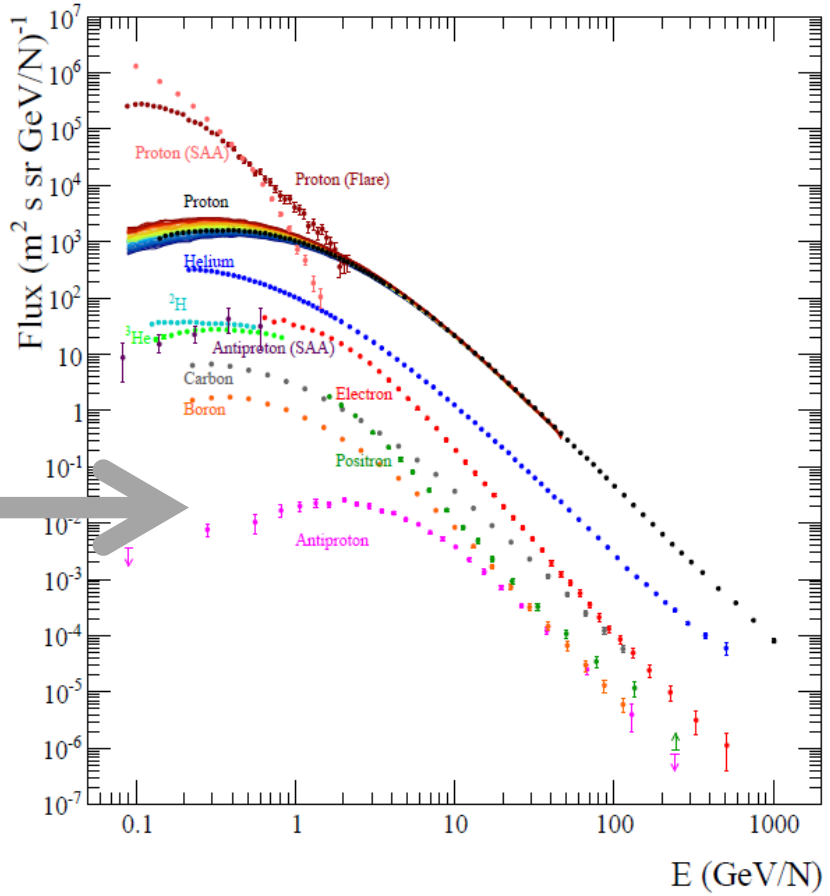
PAMELA orbit



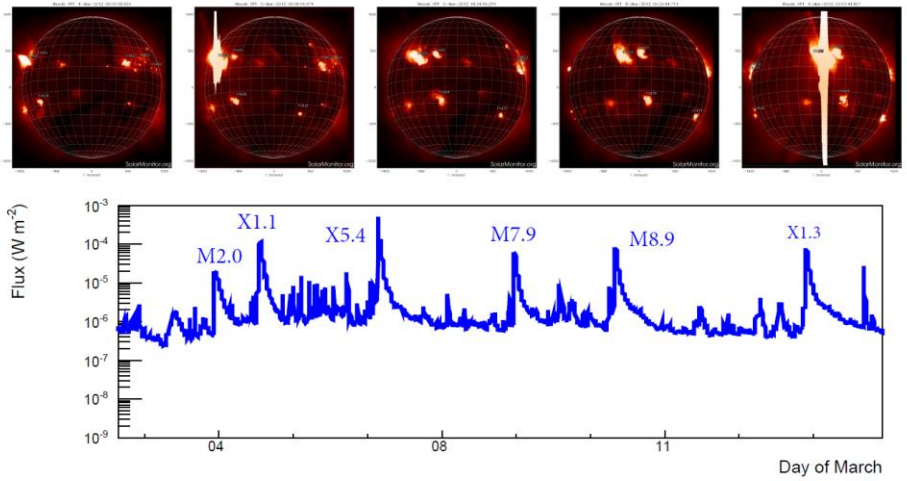


Cosmic rays studies





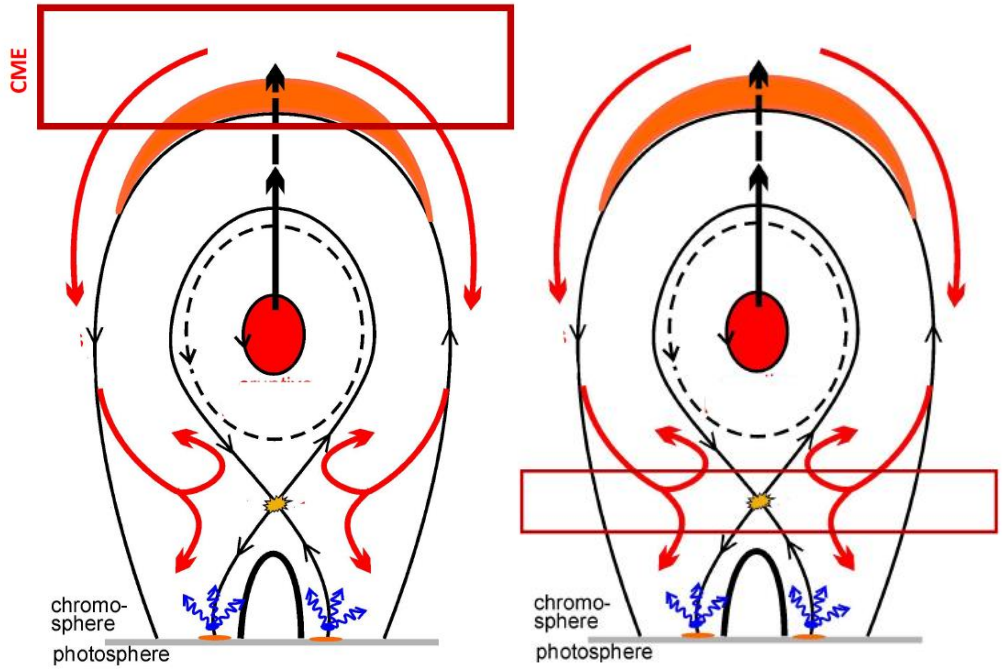
The origin of SEP



- SEPs are generated on the Sun during solar flares
- Particles are produced together with radiation (γ, radio, *X* etc)
- SEP change as solar flares change (position, energy etc)

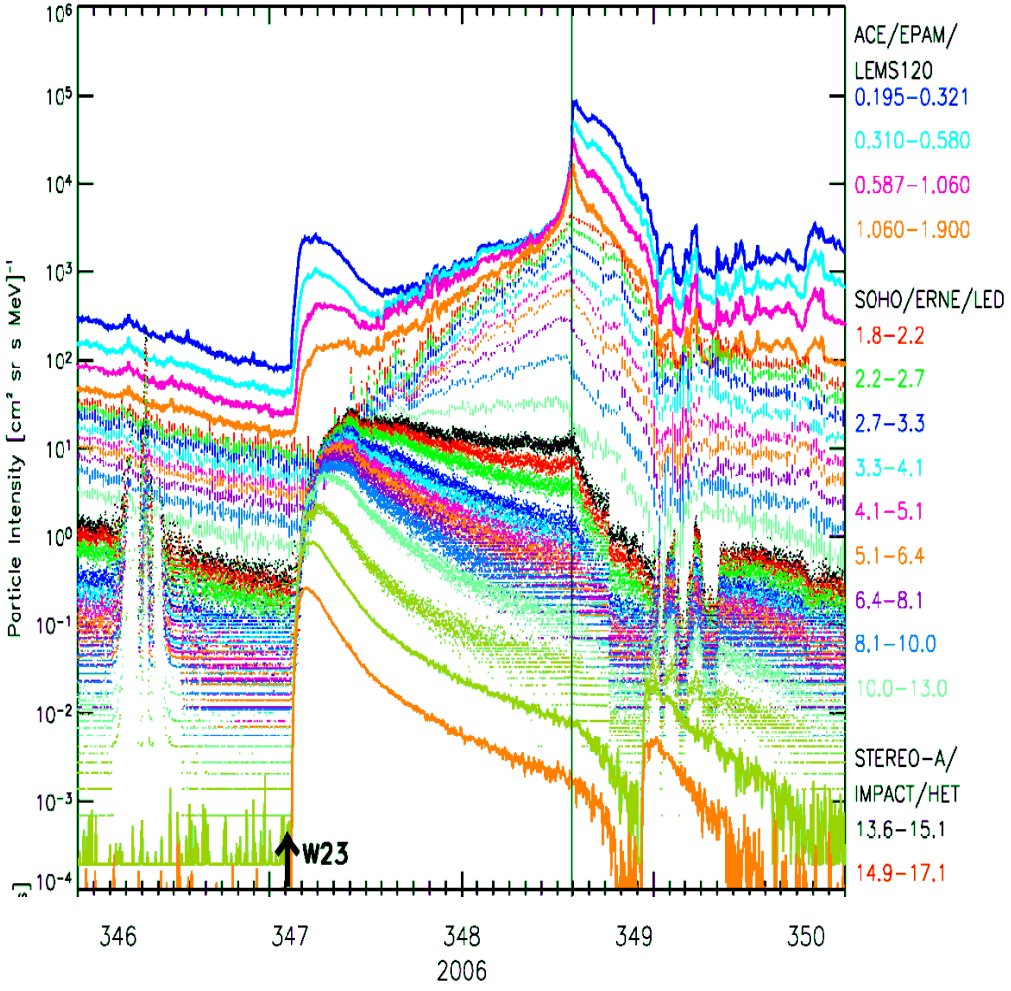
SEP are accelerated by different mechanisms

- **MAGNETIC RECONNECTION**: particle are accelerated in situ after rearrangement of the magnetic field lines
- **SHOCK**: particle are accelerated by the shock caused by Coronal Mass Ejections in space



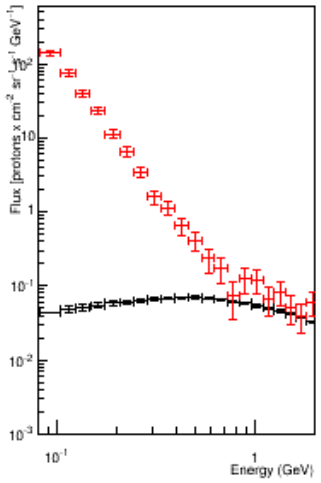
The origin of SEP

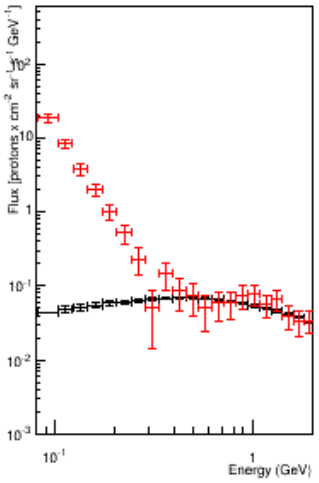
9 orders of magnitude



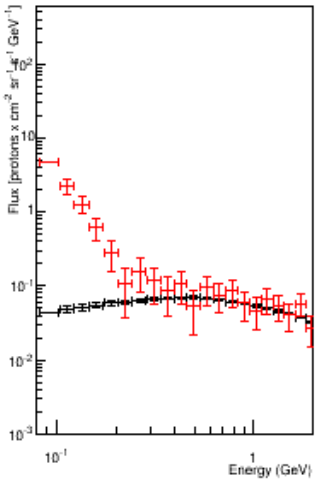
PAMELA study of SEPs

Maximum phase

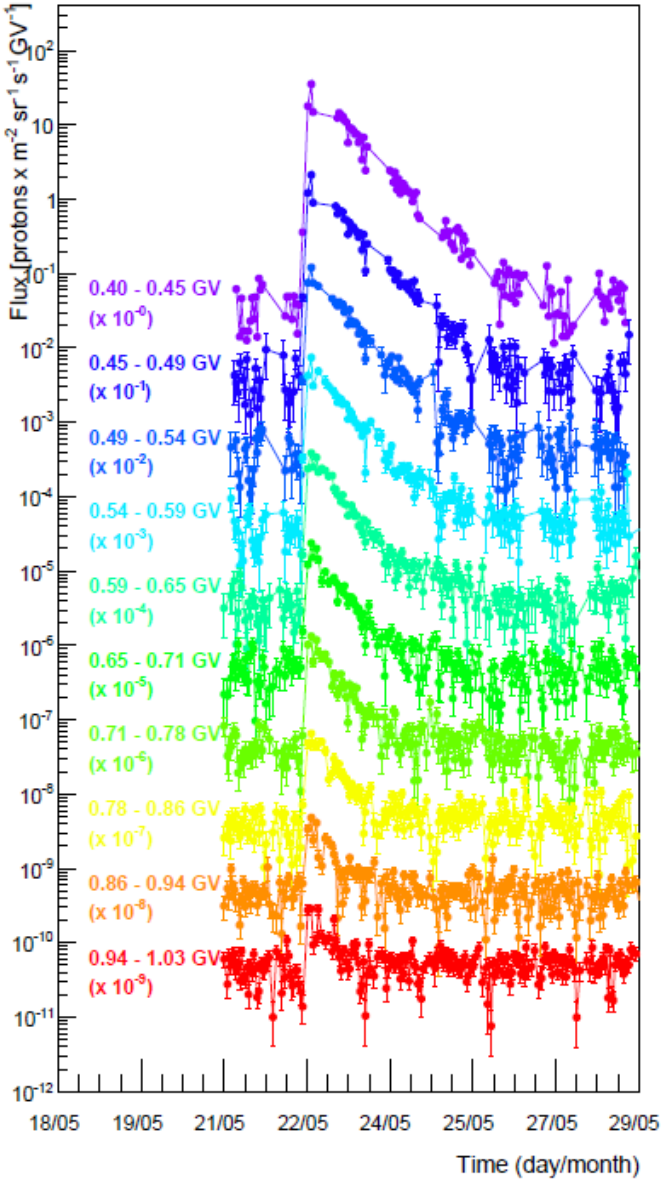




Descending phase

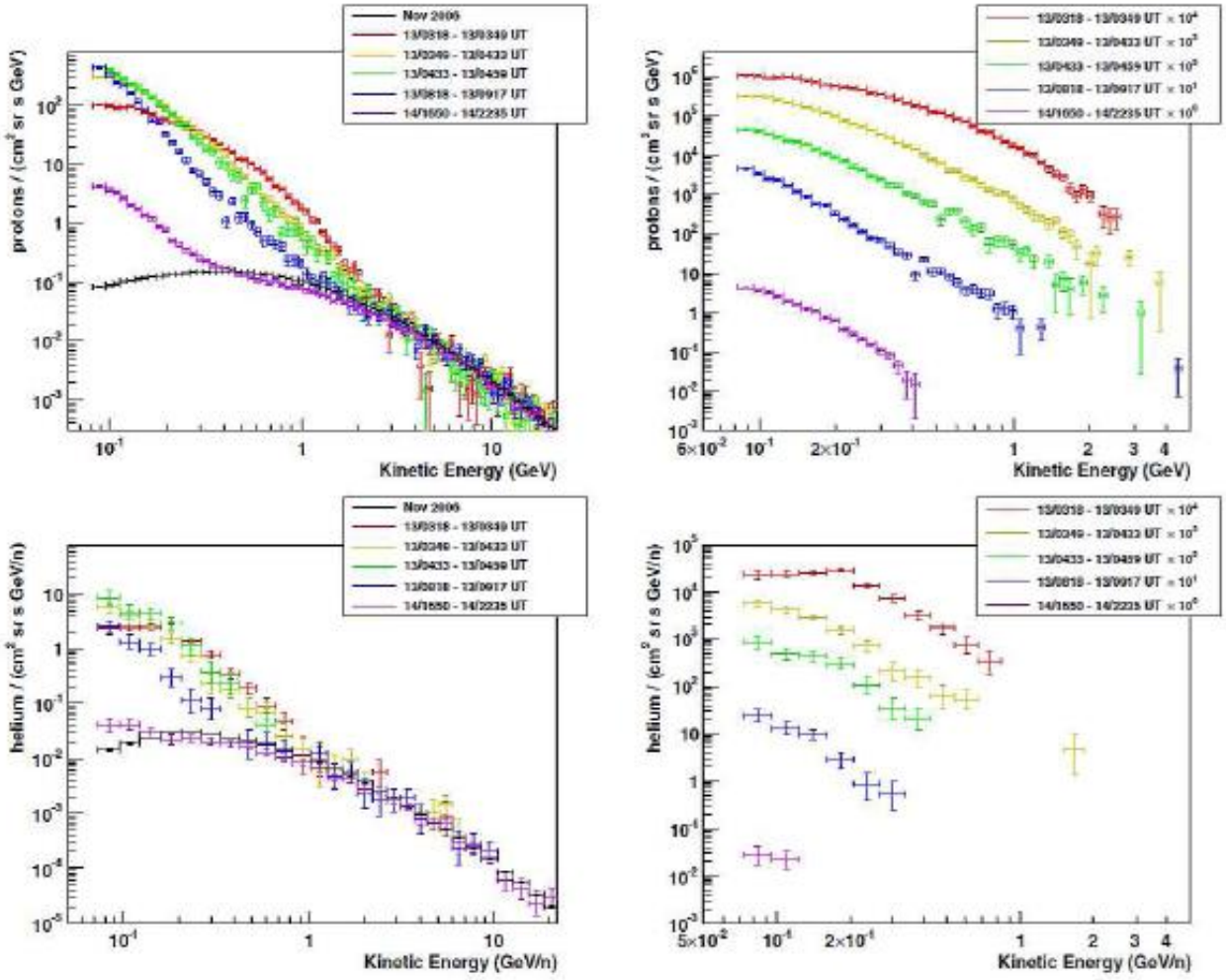


- PAMELA can measure SEPs from 80 MeV to approximately 2 GeV, filling the gap between other experiments like GOES, ACE and Neutron Monitors
- PAMELA high-latitude orbit allows the study of particle from the Sun in a very low cutoff rigidity
- PAMELA is able to perform very precise backtracing iteration to separate trapped particles from pure solar ones



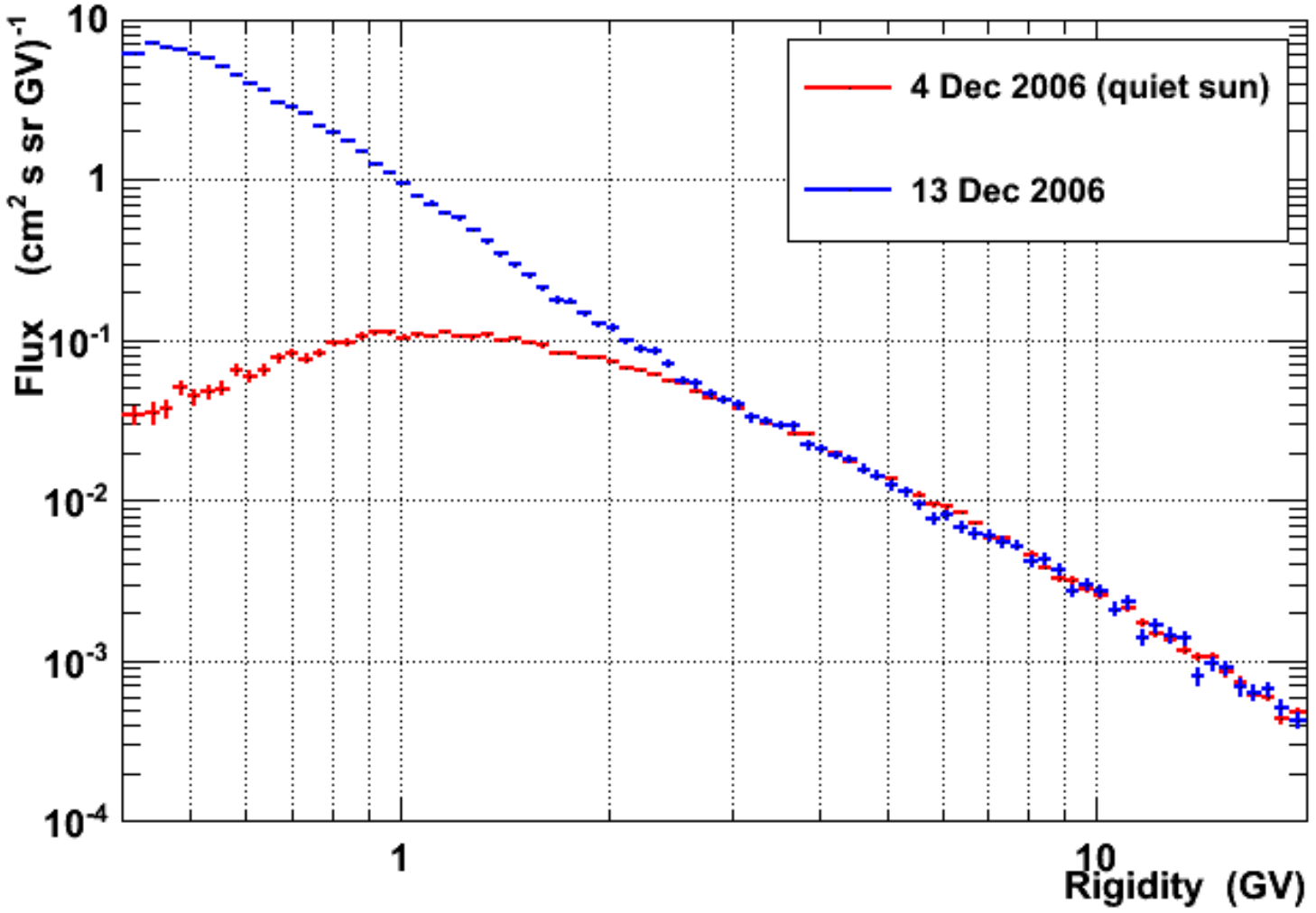
The origin of SEP

December 2006

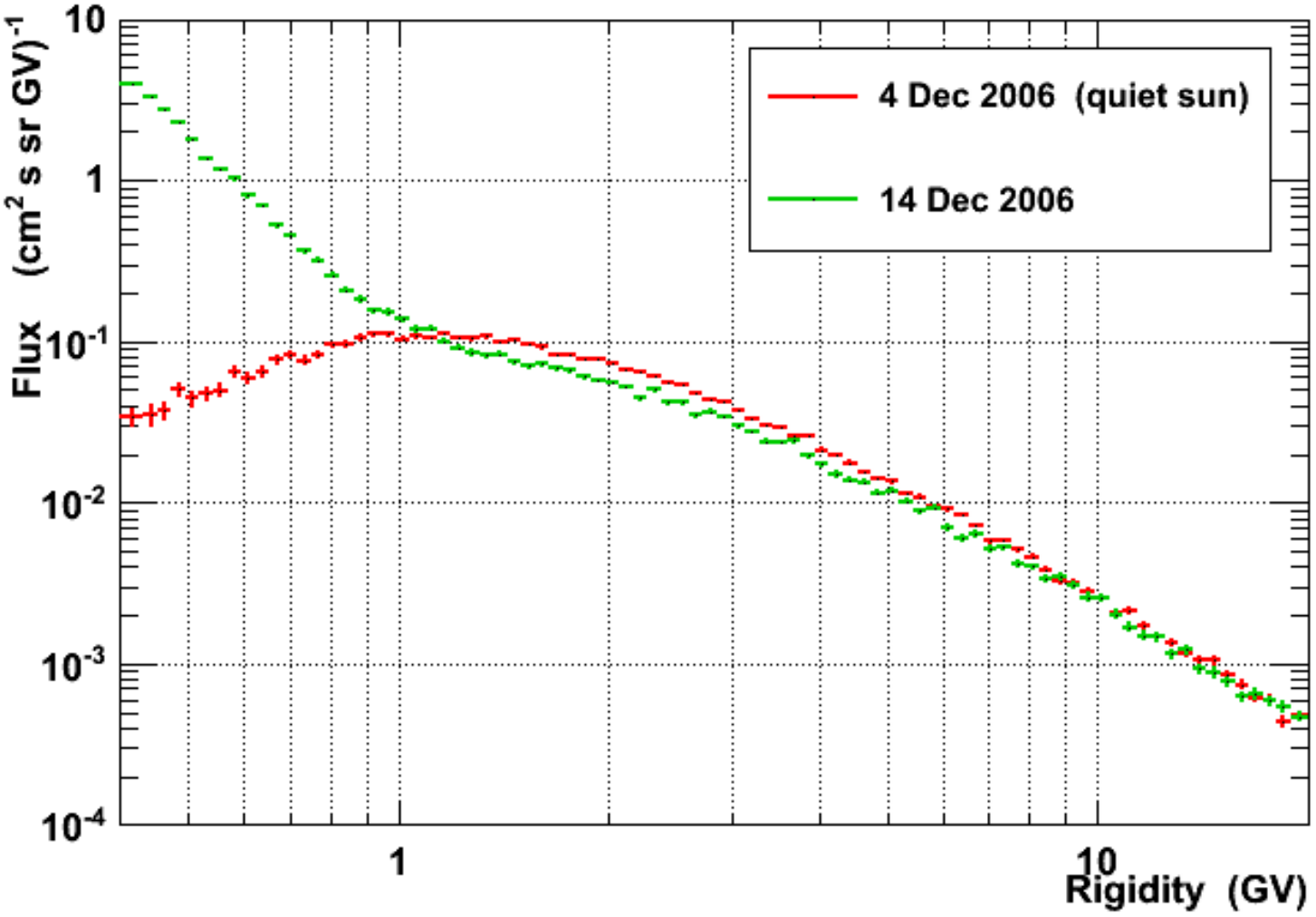


- High performance even under high rate of particles
- Particle sensitivity to discriminate solar proton from solar helium (if present)
- Fluxes evaluated in narrow time intervals to study sudden variation of solar fluxes

The Forbush effect



The Forbush effect



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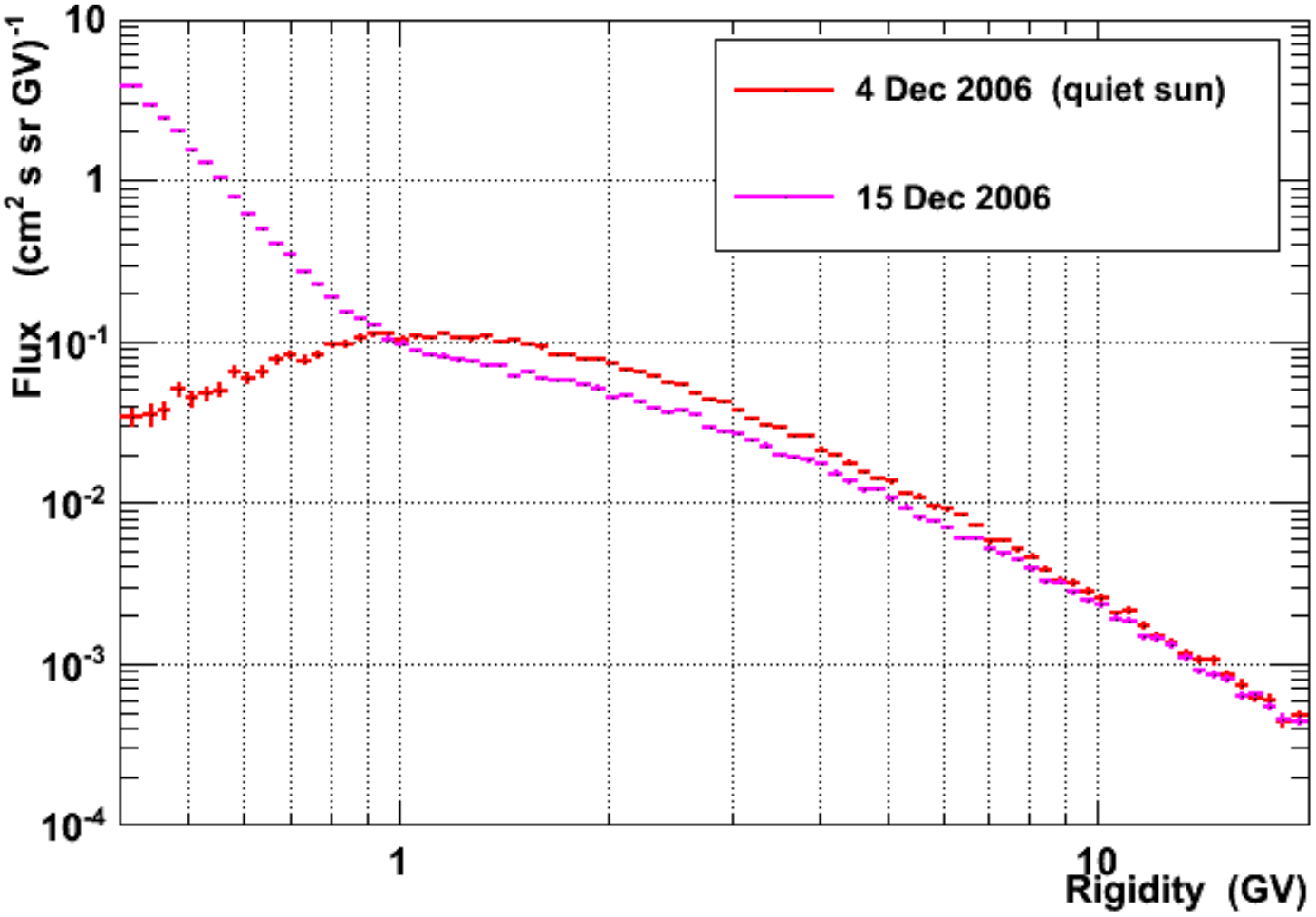


The Forbush effect

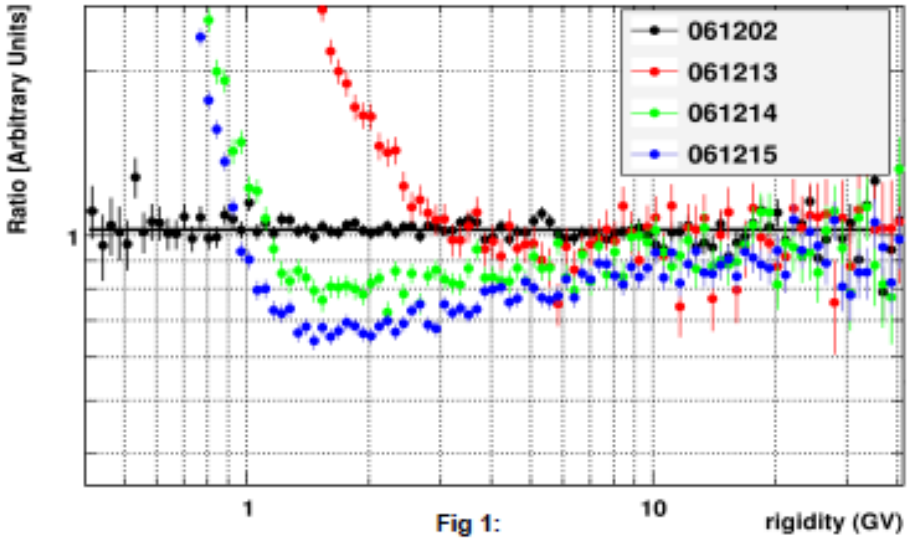
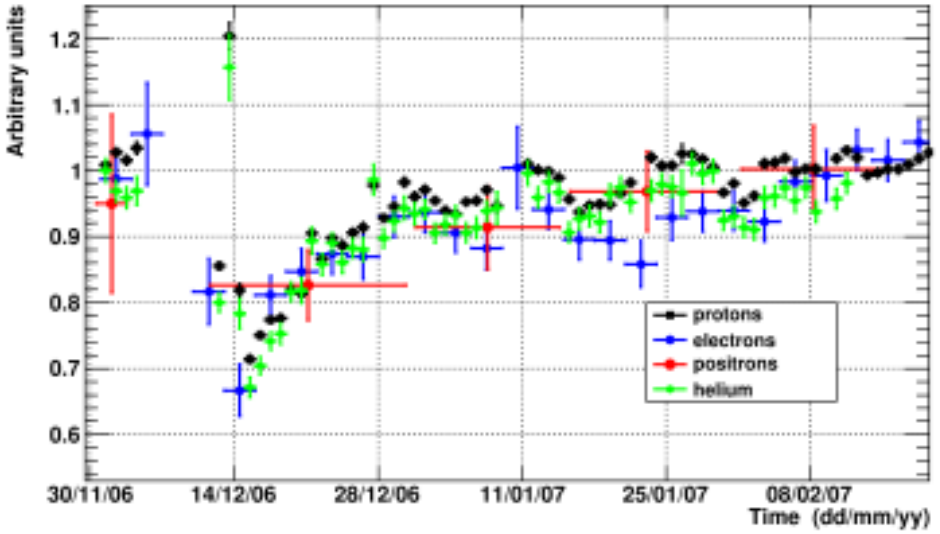


Fig 1:

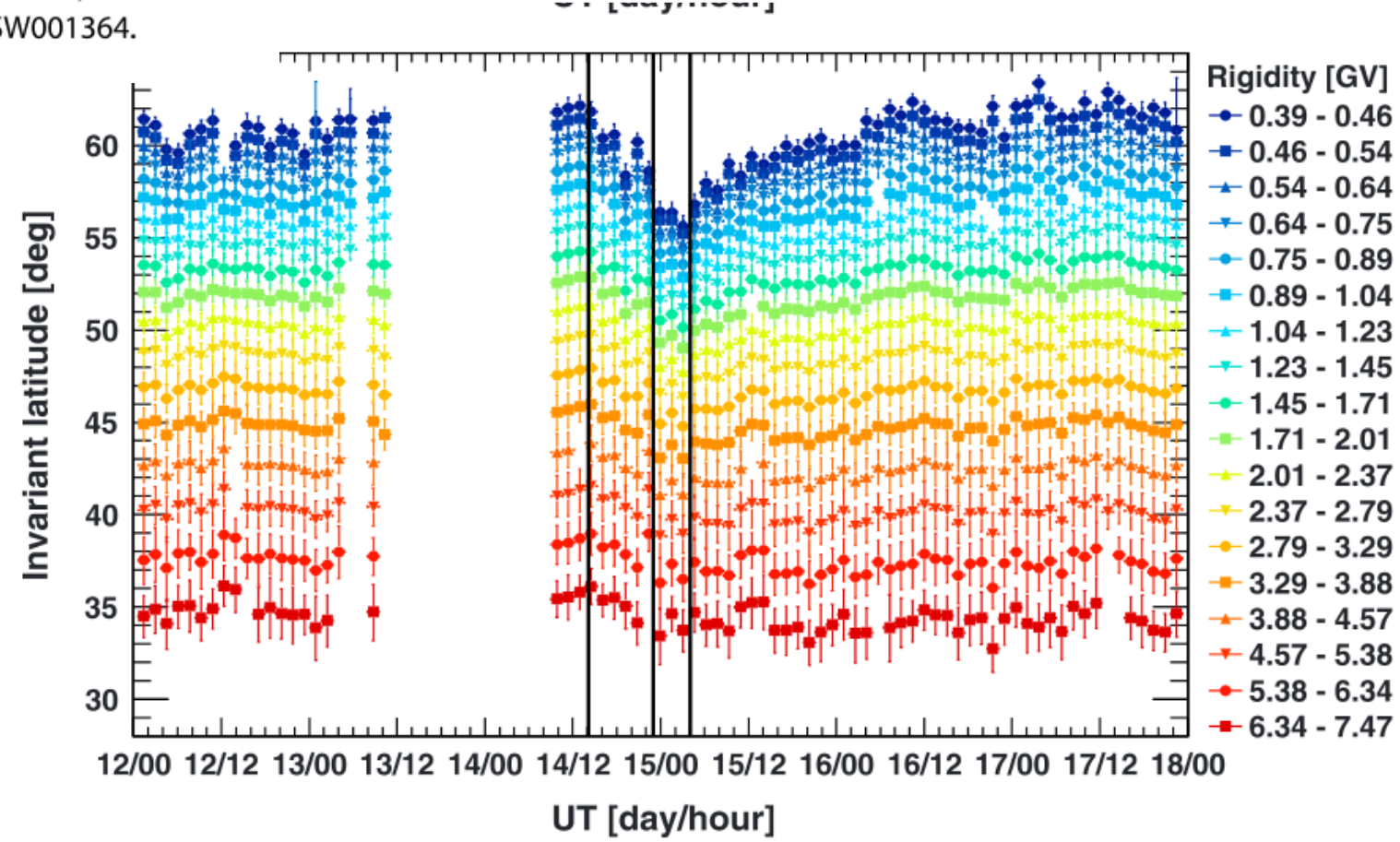
Comparison between daily proton fluxes normalized to quite sun condition for the 2006 December 13th event



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

Cutoff variations after December event

Adriani, O., et al. (2016), PAMELA's measurements of geomagnetic cutoff variations during the 14 December 2006 storm, *Space Weather*, *14*, doi:10.1002/2016SW001364.



Cutoff variations after December event

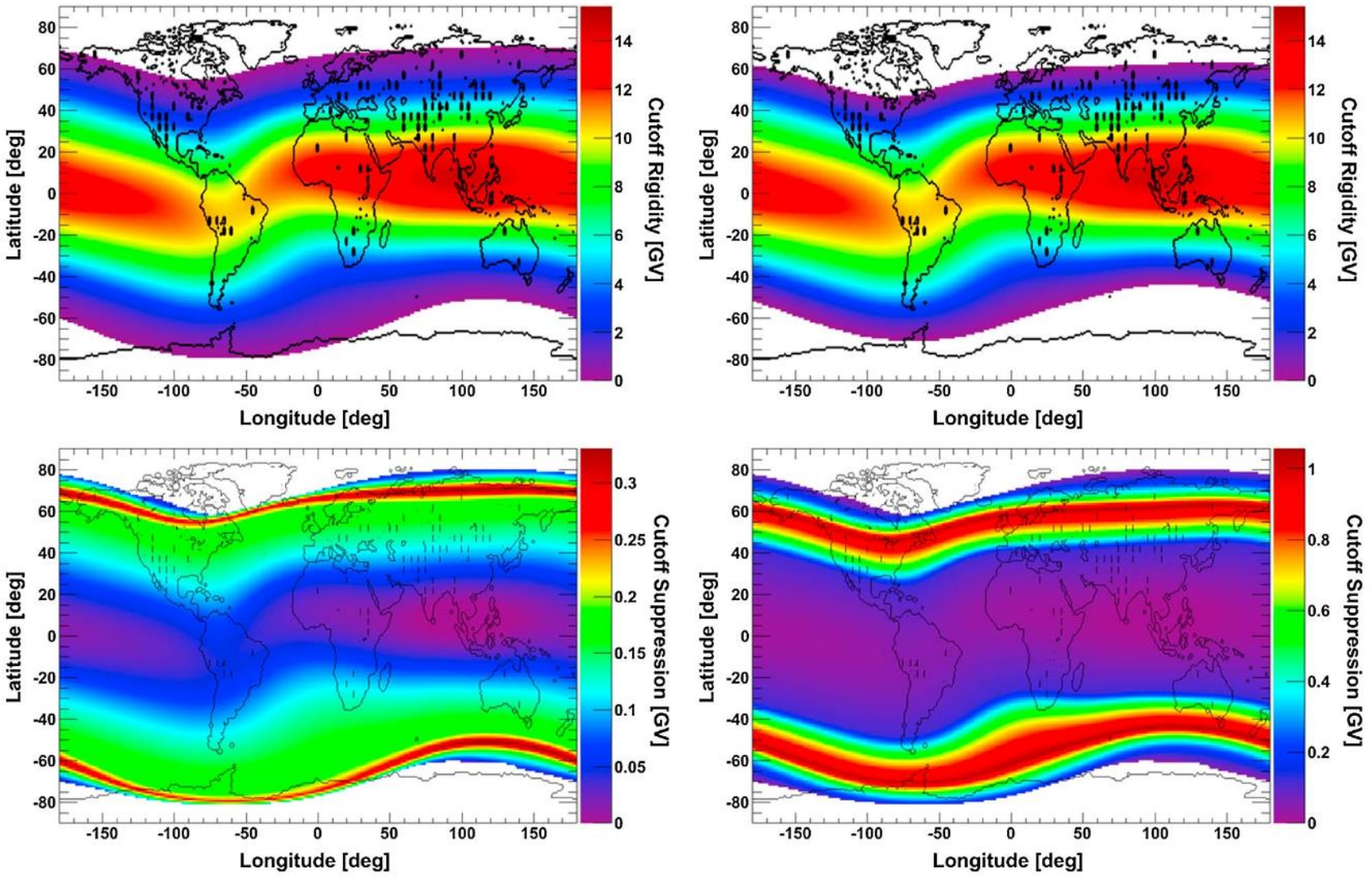


Figure 3. (top row) Cutoff rigidity maps evaluated (left) at the shock arrival and (right) at the time of maximum cutoff suppression. (bottom row) The corresponding cutoff decrease with respect to geomagnetically quiet conditions.

Satellite malfunctioning

The solar energetic particles are responsible for 3 classes of satellite anomalies:

SURFACE CHARGING

- electrons between 0 and 100 keV can contribute to an abnormal accumulation of charge on the surface of the satellite (NASA Handbook - 4002, 1999)

INTERNAL CHARGING

- Electrons with energies> 100 keV can penetrate through ~ 3 mm of aluminum shielding and cause abnormalities or charge buildup in the internal components of the satellite (NASA Handbook - 4002 , 1999)

SINGLE EVENTS UPSETS / BURNOUT / LATCHUP

- Protons with energies> 5 MeV can penetrate through ~ 3 mm aluminum shielding and cause temporary or permanent damage to the onboard electronics after the passage of the particle itself in the various components

Ground effects

- A **geomagnetic storm** is caused by the interaction of the particles and / or magnetic bubbles with the ionosphere and magnetosphere of the Earth

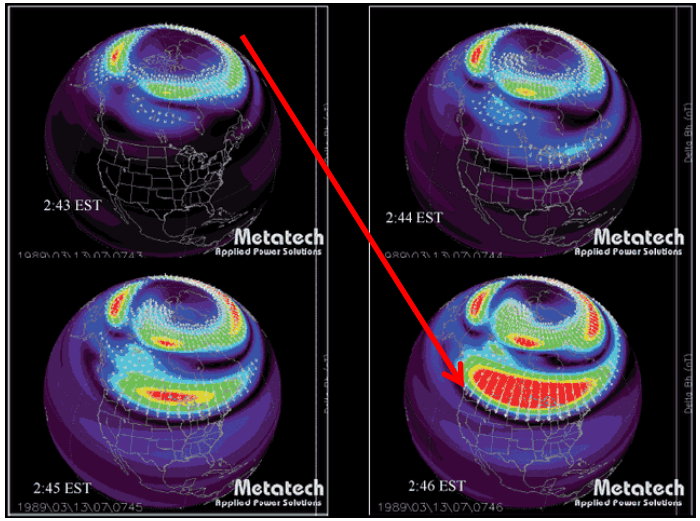
- A geomagnetic storm media can last **24-48 hours**

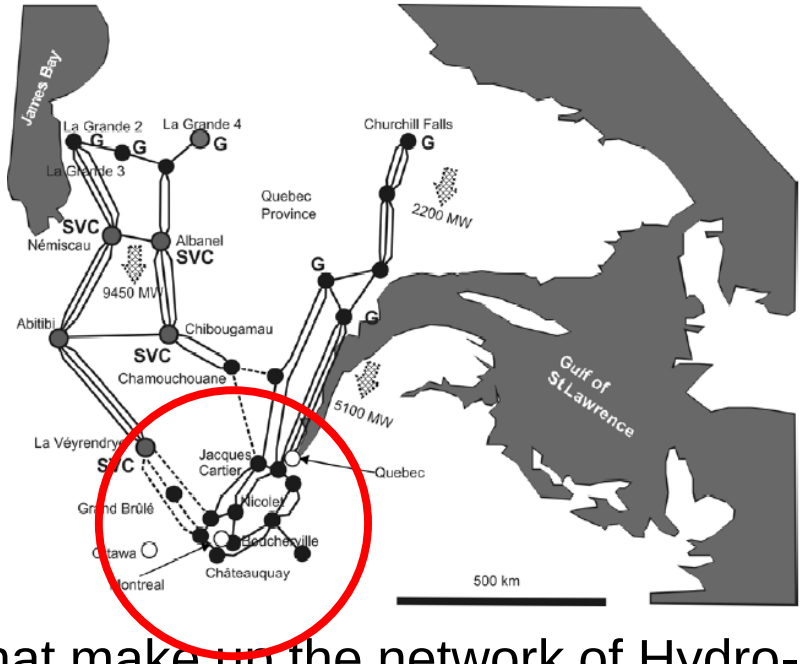
- Geomagnetic storms cause wide variations in the currents in the ionosphere which produce **geomagnetic induced currents (GIC)** in conductor systems operating on the surface of the Earth.

- **Electrical networks of transmission and underground piping are common examples of such conductor systems.**

THE EVENTS OF 1989: THE HYDROELECTRIC STATION OF QUEBEC

Increased low latitude particles> 700%





- On March 13, 1989 17 stations that make up the network of Hydro-Quebec (Canada) **have stopped working within 1 minute**

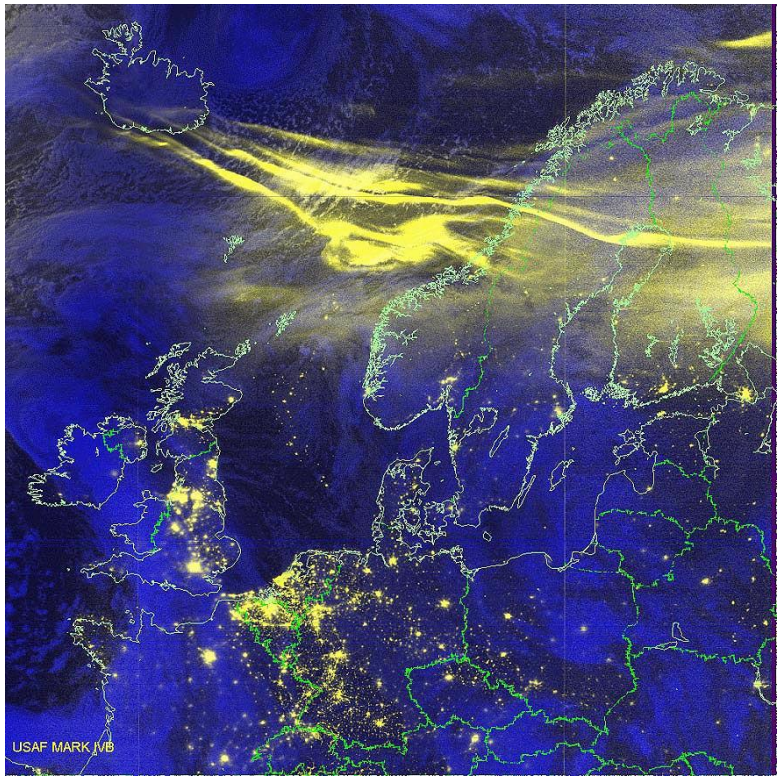
- The blackout affected **842,000 people**, causing damage amounting to $ **670,000**

- The cause is found in the **solar event happened the previous day**, which created induced currents that have interfered with power lines that connect the individual stations with the main generators, disconnecting the whole system

THE EVENTS OF 1989: THE POWER PLANT IN NEW JERSEY

- Again on March 13, 1989, the **main generator of the Public Service Electric and Gas Company of New Jersey (12 million dollars) has stopped working.**
- **The following blackout affected 110,000 people for six weeks** (installation time and full-scale operation of the replacement generator).
- The GIC also caused the partial melting of the insulation panels and damaged beyond repair welding joints
- The generator was repaired after two years and **the company has incurred huge losses.**

THE EVENT OF 2003: THE POWER GRID OF MALMO



CME with energy about 3.5×10^{30} erg

↓

10 000 000 times bigger than the whole energy consumed by the Earth in 2014

↓

10 000 times bigger than the energy released by the earthquake in 2004

- In the night between October 31 and November 1, 2003, a solar event of extreme durability and power caused power outages in Malmo power grid in Sweden, **causing a blackout that lasted more than 50 minutes, affecting about 500,000 people only in the area**
- **Repercussion in the Swedish transport (controlled by that power grid)**
- 15 transformers also damaged in South Africa: **estimated $ 1.7 million damage**