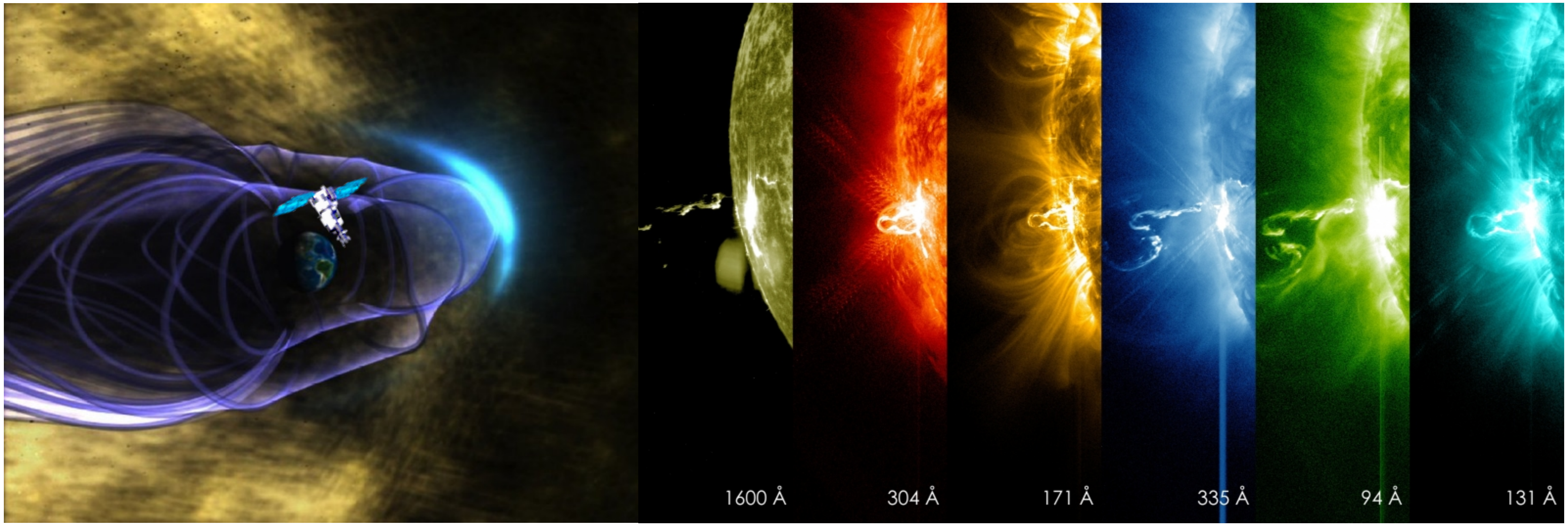

SOLAR ENERGETIC PARTICLE EVENTS OBSERVED BY THE PAMELA MISSION

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on behalf of the PAMELA collaboration

IRENE Space Radiation Modelling and Data Analysis Workshop 2019
29-31 May 2019, Sykia, Greece

Motivation

- Two class scenario of SEP origin
  - **Impulsive events**: related to flares, short duration, small intensity, Type III bursts, ^{3}He e- Fe enriched, …
  - **Gradual events**: related to CME-driven shocks, long duration, large intensity, Type II bursts, …

- Recent studies have shown that SEP events are, in general, originated by a **mixture of impulsive and gradual processes**, and the event evolution depends on their relative importance and on the **magnetic connection to Earth**
  - albeit there is still no consensus about the details of the individual mechanisms

- However, the characterization of **high energy (>100 MeV) SEP fluxes** is still affected by large uncertainties, in part due to the relatively low observations in this range

Motivation

- The most energetic SEP events induce atmospheric showers whose secondary products are measured by ground-based detectors (e.g. NMs) during the so-called **Ground Level Enhancements (GLEs)**
    - However, ground-based observations rely on a number of assumption (CR interactions with terrestrial magnetosphere and atmosphere) —> large uncertainties
- Aside from the relevant Space Weather implications, GLEs are of particular interest since they represent SEP acceleration at its most efficient. The HE protons of GLE events can reach 1 AU with minimal interplanetary scattering. Thus, their spectra provide **important constraints on SEP origin**.
- For example, in the scenario of **diffusive shock acceleration (DSA)**, high energy cutoffs (or ``roll-overs") may reflect changes in the acceleration efficiency resulting from <u>the finite lifetime and the finite size of the shock</u>:
    - three-dimensionality of the shock front (curvature), limited acceleration time scales, and/or vanishing power in the magnetic field wave spectrum (causing the diffusion coefficient to increase rapidly with the heliocentric distance), each contributing to releasing particles from the shock and terminating acceleration.

Motivation

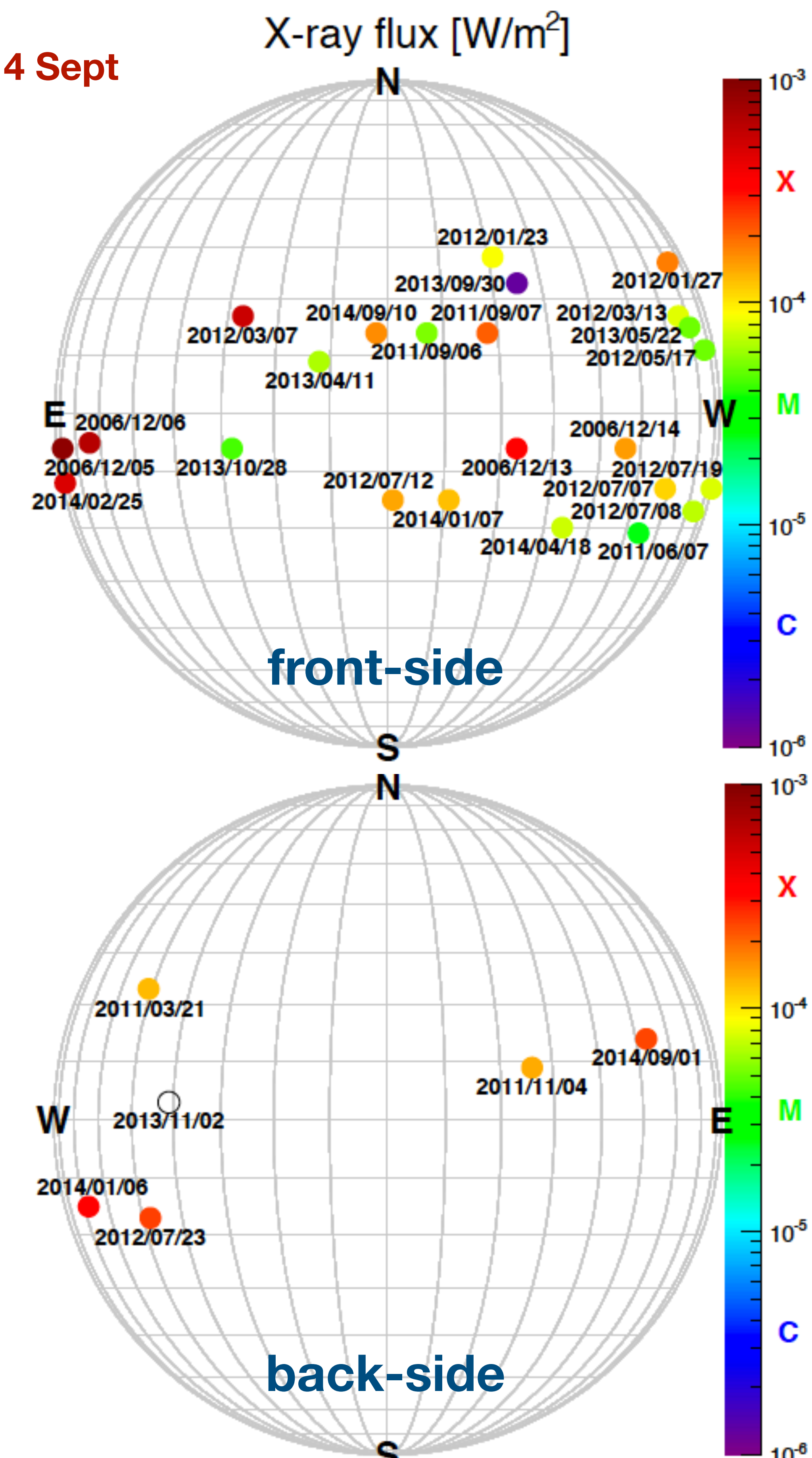
- Thanks to its unique observational capabilities, the **PAMELA** mission provides accurate and detailed SEP measurements in a wide energy range (>80 MeV)
    - including energy spectra, pitch-angle distributions and particle composition (H, He, …)
- significantly improving the characterization of most energetic SEP events and allowing the investigation of the relationship between GLE and non-GLE events
- In particular, PAMELA can detect for the first time with good sensitivity the roll-over in the high energy spectra predicted by diffusive shock acceleration theory, enabling a more complete and clearer view of SEP origin and transport.

PAMELA data set

Major SEP events observed by PAMELA between 2006 July and 2014 Sept

	SEP Event	Flare			CME		
#	Onset time	Onset time	Class	Location	1^{st}-app. time	V_{sky}	Width
1	2006 12/05, 15:00	12/05, 10:19	X9.0	S06E79	...	...	...
2	2006 12/06, 23:15	12/06, 18:29	X6.5	S05E64	12/06, 20:12	...	H
3	2006 12/13, 02:55	12/13, 02:14	X3.4	S06W23	12/13, 02:54	1774	H
4	2006 12/14, 22:55	12/14, 21:07	X1.5	S06W46	12/14, 22:30	1042	H
5	2011 03/21, 03:30	03/21, 02:11[a]	$\lesssim$X1.3[a]	N23W129[a]	03/21, 02:24	1341	H
6	2011 06/07, 07:00	06/07, 06:16	M2.5	S21W54	06/07, 06:49	1255	H
7	2011 09/06, 02:30	09/06, 01:35	M5.3	N14W07	09/06, 02:24	782	H
8	2011 09/06, 23:35	09/06, 22:12	X2.1	N14W18	09/06, 23:05	575	H
9	2011 11/04, 00:15	11/03, 22:45[b]	$\lesssim$X1.4[b]	N09E154[b]	11/03, 23:30	991	H
10	2012 01/23, 04:20	01/23, 03:38	M8.7	N28W21	01/23, 04:00	2175	H
11	2012 01/27, 18:40	01/27, 17:37	X1.7	N27W71	01/27, 18:27	2508	H
12	2012 03/07, 01:40	03/07, 00:02	X5.4	N17E27	03/07, 00:24	2684	H
13	2012 03/13, 17:50	03/13, 17:12	M7.9	N17W66	03/13, 17:36	1884	H
14	2012 05/17, 01:50	05/17, 01:25	M5.1	N11W76	05/17, 01:48	1582	H
15	2012 07/07, 00:05	07/06, 23:01	X1.1	S13W59	07/06, 23:24	1828	H
16	2012 07/08, 17:45	07/08, 16:23	M6.9	S17W74	07/08, 16:54	1497	157
17	2012 07/12, 17:15	07/12, 15:37	X1.4	S15W01	07/12, 16:48	885	H
18	2012 07/19, 06:25	07/19, 04:17	M7.7	S13W88	07/19, 05:24	1631	H
19	2012 07/23, 06:30?	07/23, 02:31[c]	$\lesssim$X2.5[c]	S17W132[c]	07/23, 02:36	2003	H
20	2013 04/11, 08:00	04/11, 06:55	M6.5	N09E12	04/11, 07:24	861	H
21	2013 05/22, 13:50	05/22, 13:08	M5.0	N15W70	05/22, 13:25	1466	H
22	2013 09/30, 02:15	09/29, 21:43	C1.3	N17W29	09/29, 15:36	1179	H
23	2013 10/28, 17:55	10/28, 15:07	M4.4	S06E28	10/28, 15:36	812	H
24	2013 11/02, 07:25	11/02, 04:00	...	N03W139	11/02, 04:48	828	H
25	2014 01/06, 08:05	01/06, 07:30[d]	$\lesssim$X3.5[e]	S15W112[e]	01/06, 08:00	1402	H
26	2014 01/07, 19:20	01/07, 18:04	X1.2	S15W11	01/07, 18:24	1830	H
27	2014 02/25, 03:00	02/25, 00:39	X4.9	S12E82	02/25, 01:25	2147	H
28	2014 04/18, 13:30	04/18, 12:31	M7.3	S20W34	04/18, 13:25	1203	H
29	2014 09/01, 17:00	09/01, 10:54[f]	$\lesssim$X2.4[e]	N14E127[e]	09/01, 11:12	1901	H
30	2014 09/10, 19:45	09/10, 17:21	X1.6	N14E02	09/10, 18:00	1267	H

References— (*a*) Rouillard et al. (2012), (*b*) Mewaldt et al. (2013), (*c*) Nitta et al. (2013), (*d*) Thakur et al. (2014), (*e*) Ackermann et al. (2017), (*f*) Plotnikov et al. (2017).



Data analysis

- Proton intensities evaluated with a **48-min time resolution** (=spacecraft semi-orbits).

- The effective "**duty cycle**" is rigidity dependent due to geomagnetic effects, and lower energy particles can be measured only at higher magnetic latitudes

- To discard trapped/albedo particles and avoid magnetospheric effects, interplanetary CR fluxes are conservatively estimated by selecting protons with rigidity 1.3 times higher than the local Stormer vertical cutoff

- The data gaps due to cutoff and low detection efficiency effects are corrected by exploiting the GOES data, previously calibrated by using PAMELA data (Bruno 2017).

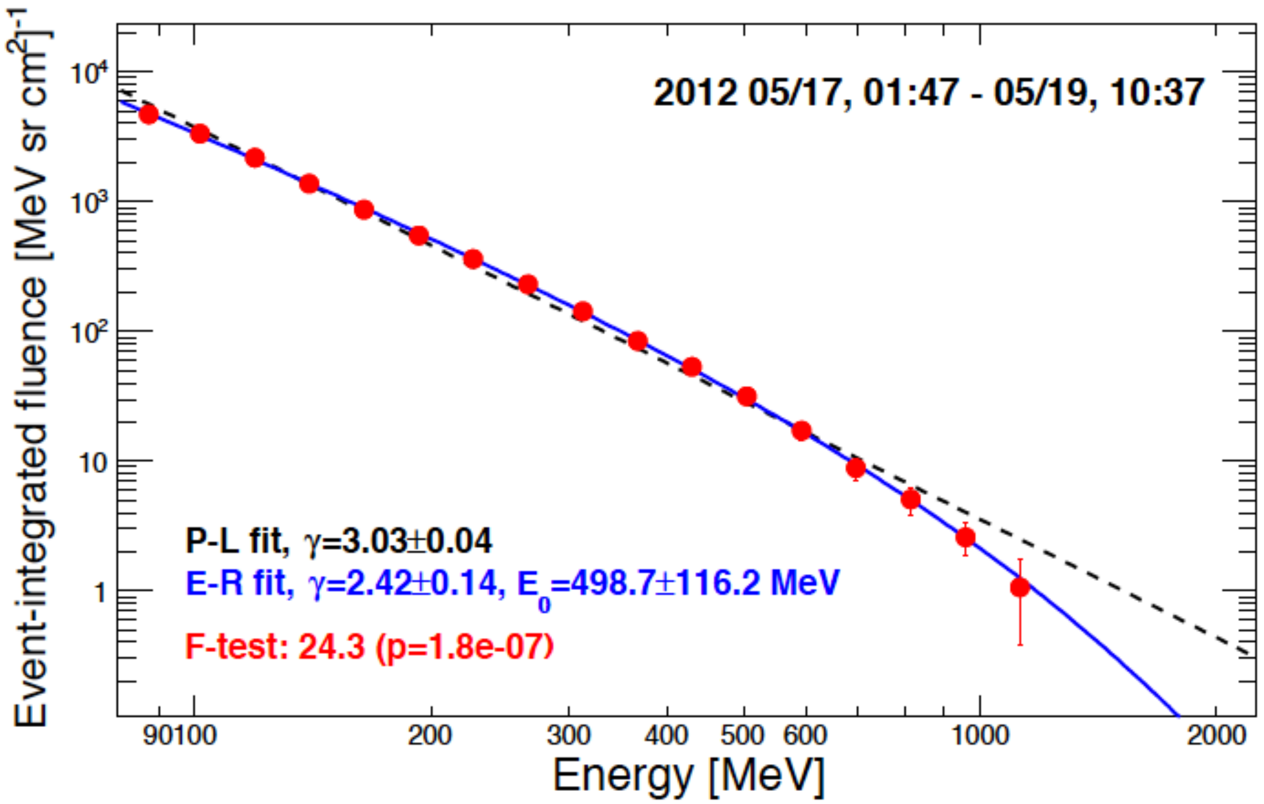
- The time dependent **GCR background** is subtracted for each semi-orbit, and computed by extrapolating to lower energies the fit of the measured spectrum performed above the maximum SEP energy up to 100 GeV, based on the force-field model

- **Pitch angle anisotropies** with respect to the local IMF direction are accounted for by estimating the instrument "asymptotic" exposure along the satellite orbit, based on an accurate trajectory tracing analysis

- **Event-integrated fluences** are evaluated using the flux intensities from the various semi-orbits that register a signal during the SEP event duration interval

$$\Phi_{sep}(E) = \int_T F_{sep}(E)dt \simeq \sum_{i=1}^{n} [F_{sep,i}(E) \times \Delta t_i] = \frac{T}{n} \times \sum_{i=1}^{n} F_{sep,i}(E)$$

Spectral fits



- Accounting for a possible roll-over in the high energy SEP spectra, event-integrated fluences are fitted by using a functional form based on **Ellison & Ramaty (1985)**, consisting of a power-law spectrum modulated by an exponential:

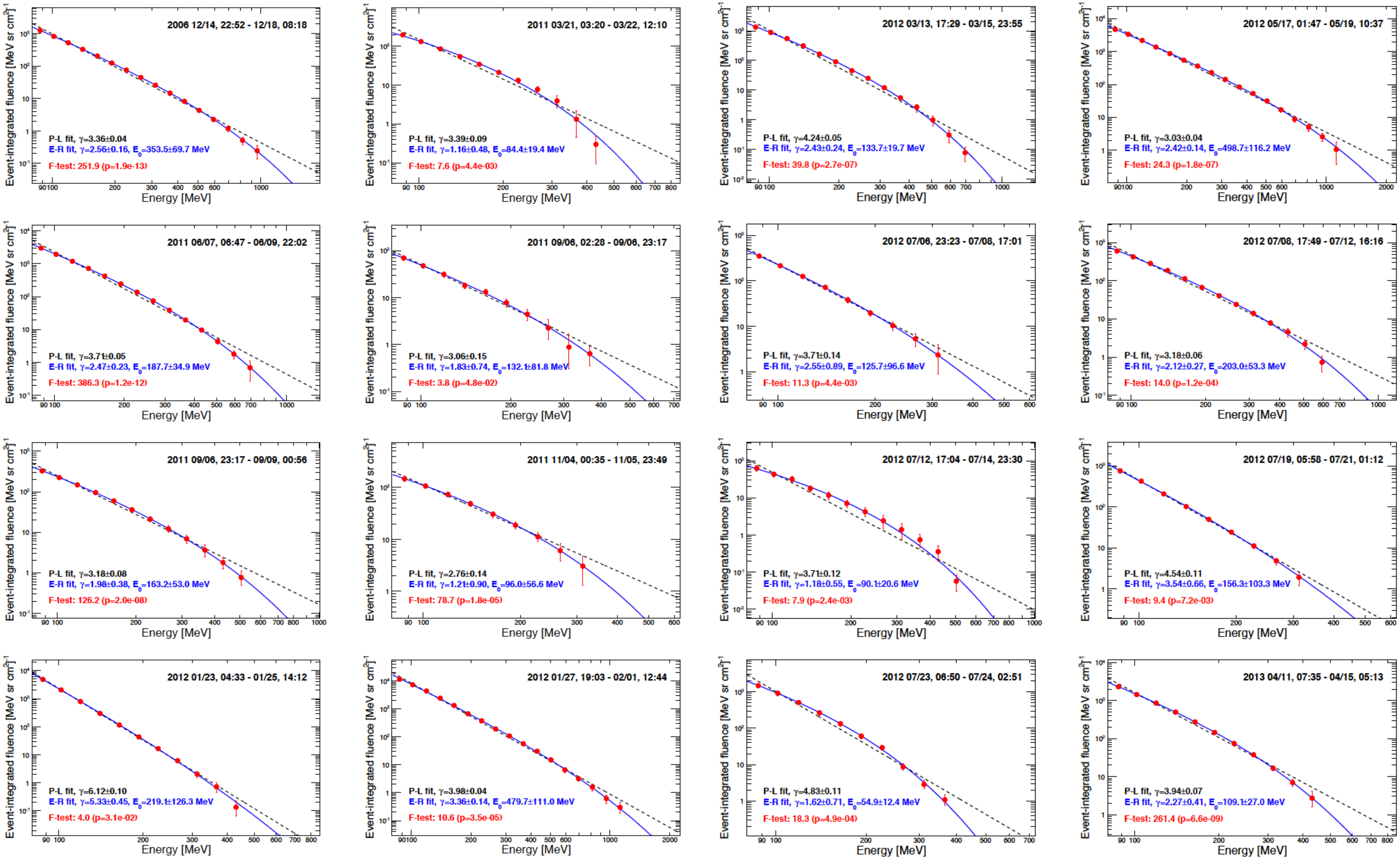
$$\Phi_{sep}(E) = A \times (E/E_s)^{-\gamma} \times e^{-E/E_0}$$

where $\mathbf{E_0}$ is the roll-over energy and the scaling energy **Es** is fixed to the PAMELA energy threshold (80MeV)

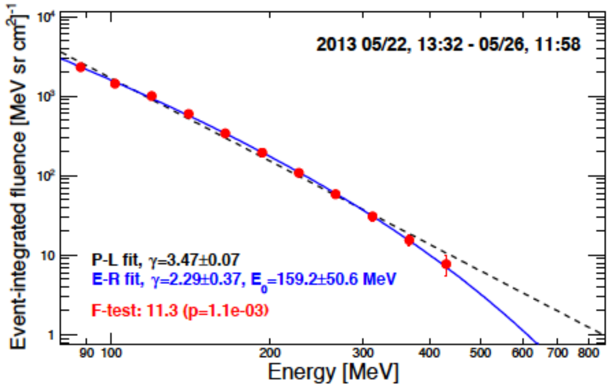
- F-test used to compare the E-R and the simple power-law models.

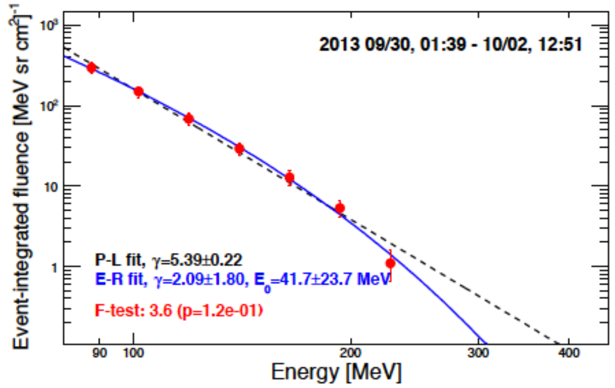
- In the simplest scenario and in terms of diffusive shock acceleration, the slope of the power-law is related to the Mach number and the compression ratio, which govern the efficiency for shock acceleration, while the cutoff energy is a reflection of the loss mechanisms (finite extension and lifetime of the shock)

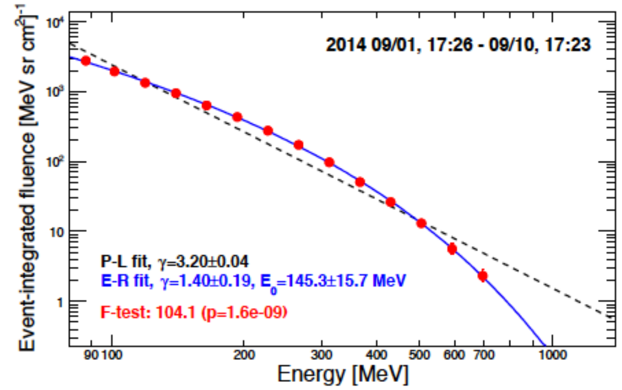
Spectral fits

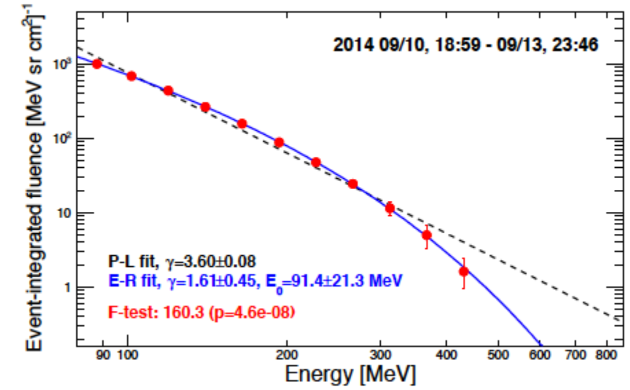


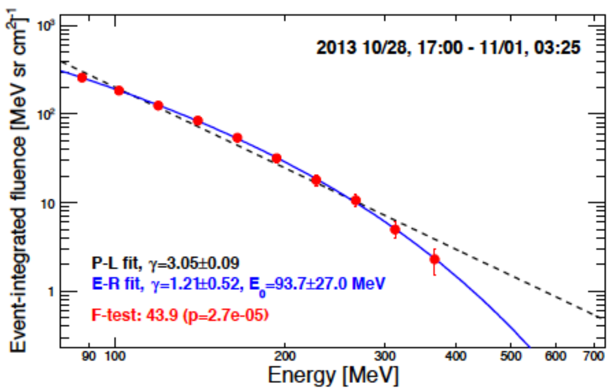
Spectral fits

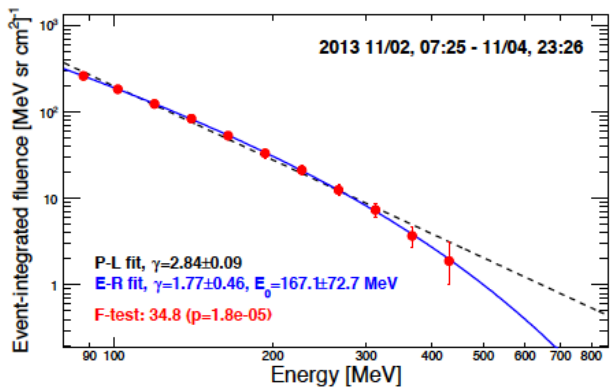


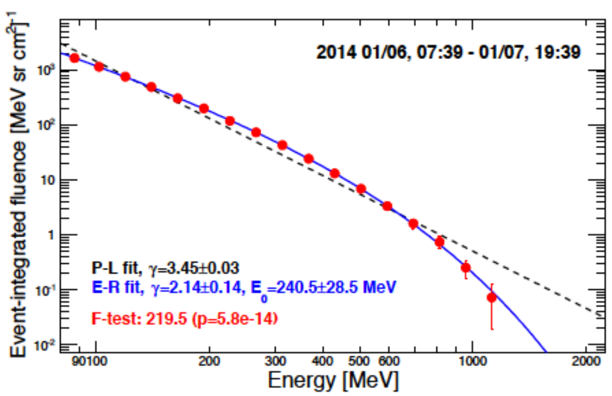


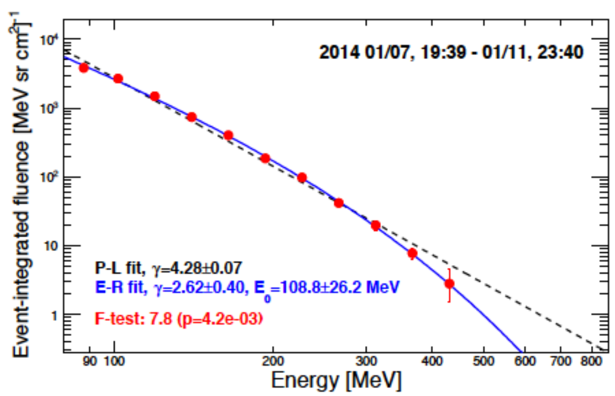


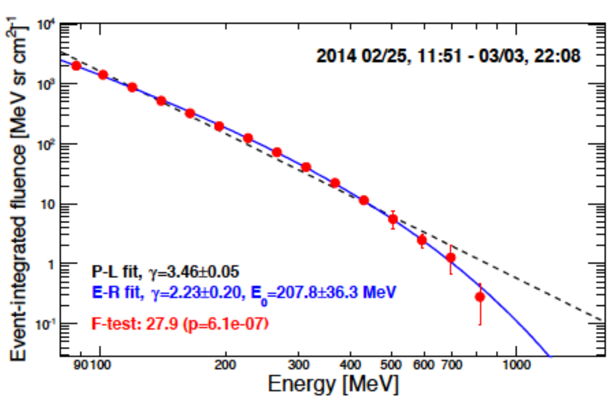


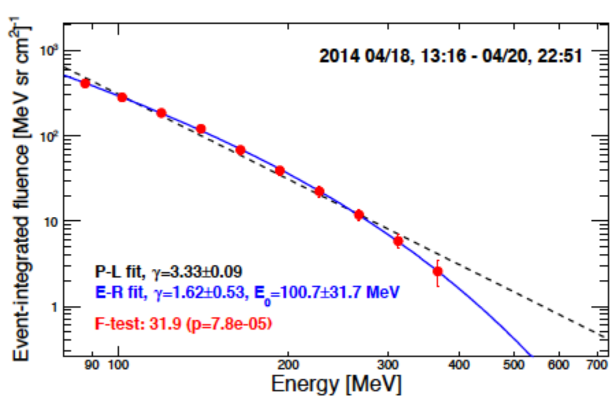




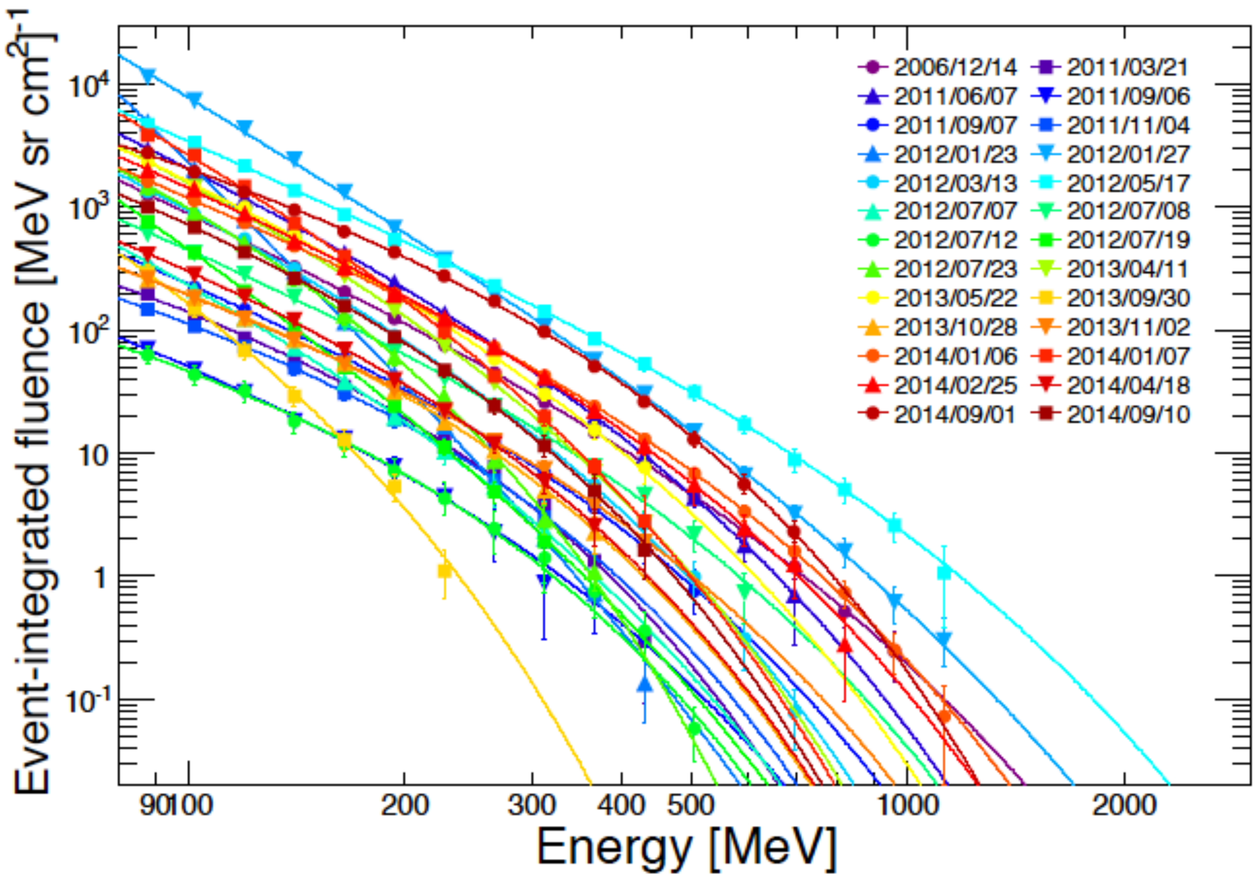


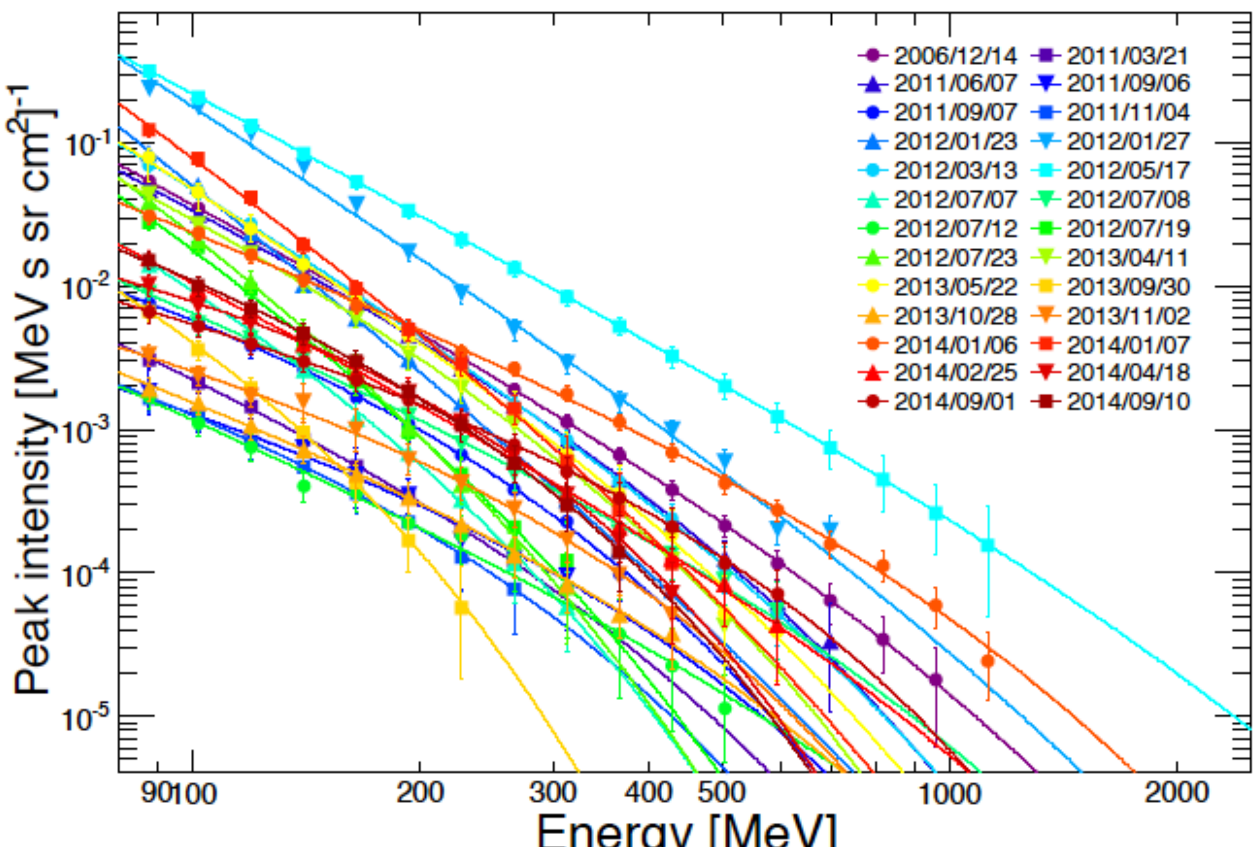






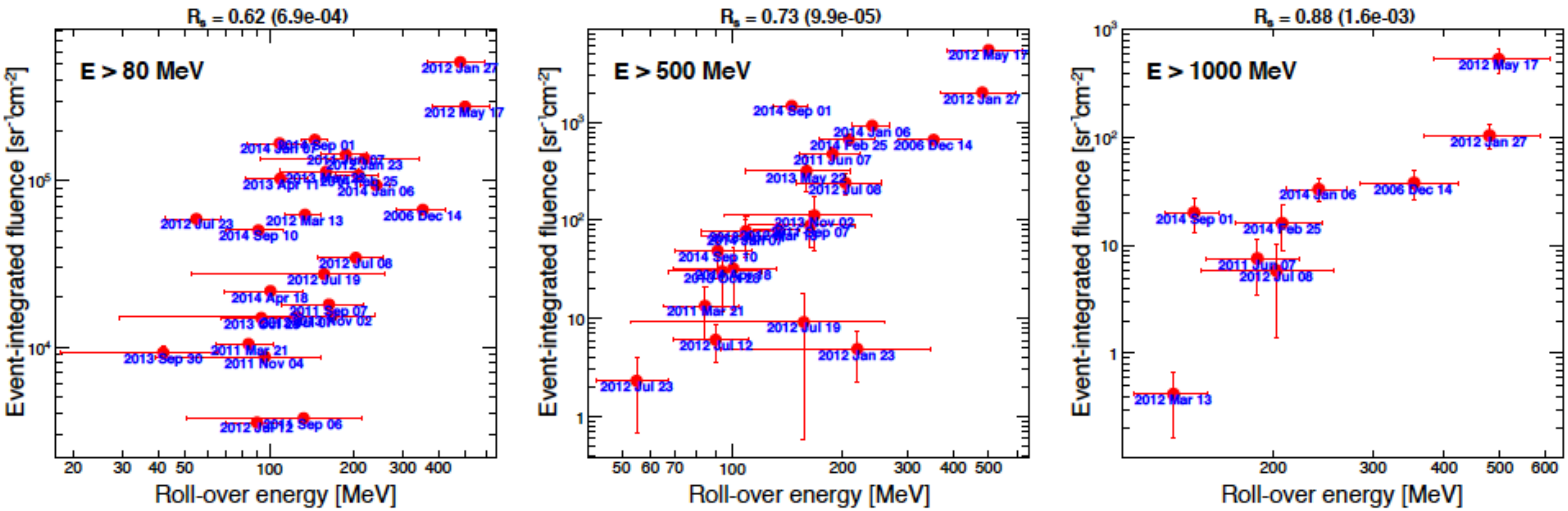
PAMELA results and DSA theory





- PAMELA data as a whole span about five and four orders of magnitude in fluences and peak intensities, respectively.
- Results are consistent with DSA theory predictions
  - **High energy spectral roll-overs arising from shock limited extension and/or limited lifetime**
  - Transient acceleration process with time- and space-limited operations, i.e. quasi-spherical CME shocks of limited extent which restrict the duration of acceleration at high energy, where the limits arise from the limited time the shock is strong and the divergent geometry.
- **No qualitative differences in the spectra of all measured events**

PAMELA results and DSA theory



- Measured fluences are well correlated with the roll-over energies, with **the most energetic events exhibiting the highest cutoffs**; the correlation improves with increasing proton energy.

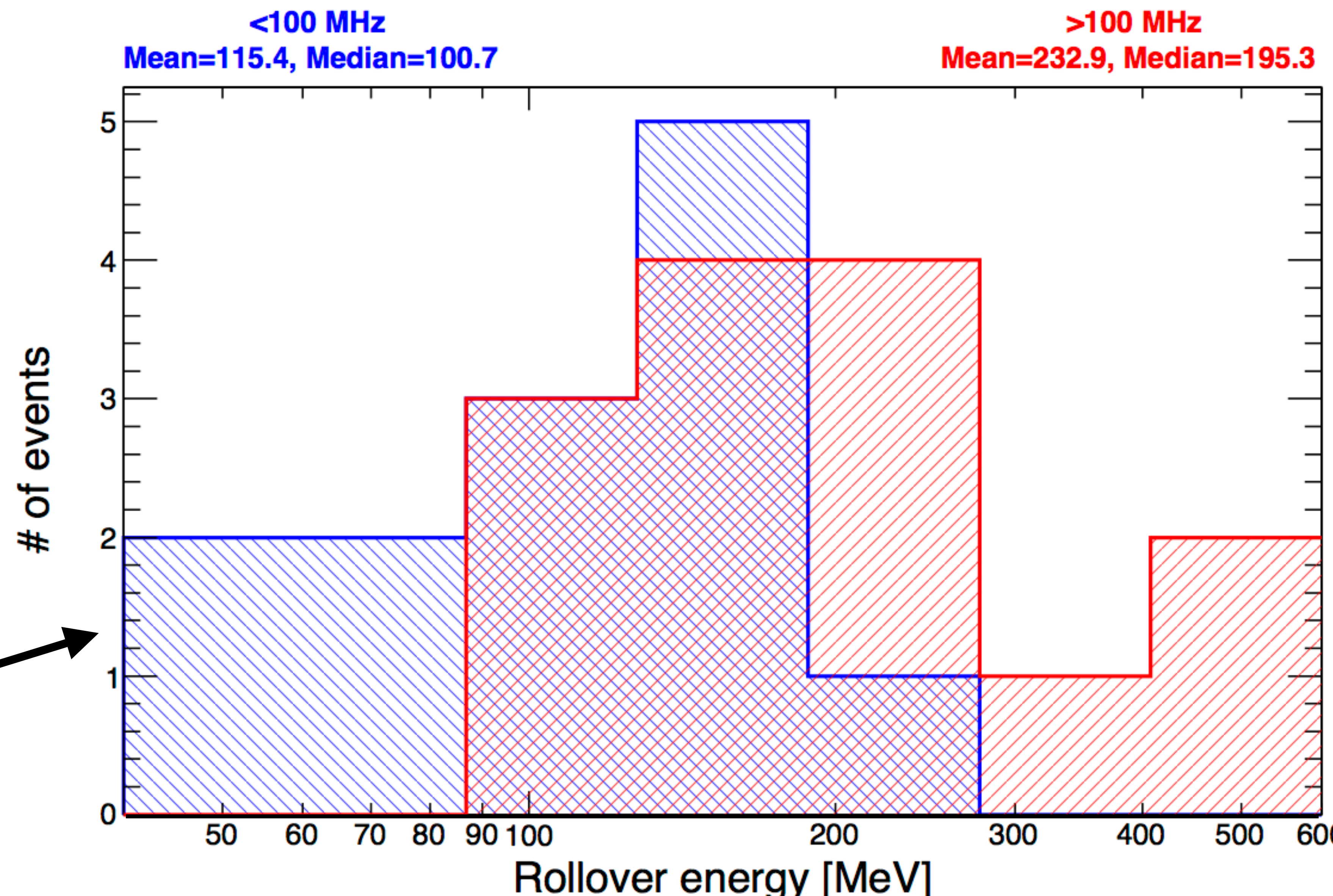
- The more efficient the shock acceleration is, the greater the overall intensity of the particle event and the hardness of the spectrum.

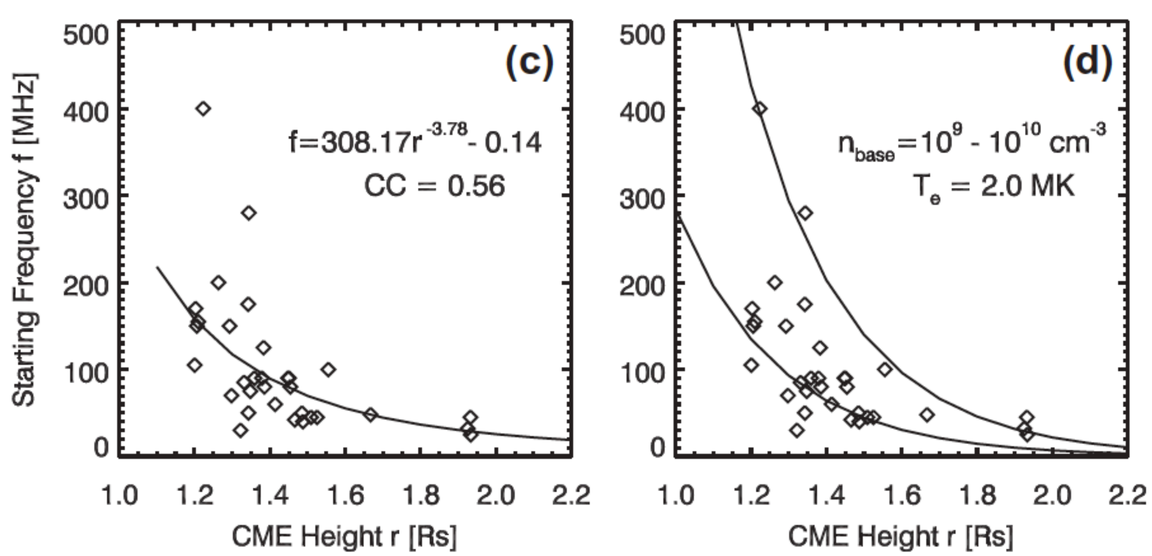
Spectral roll-over and Type II radio emission

All PAMELA event are associated with **long duration Type II and Type III radio bursts**

In particular, Type II emission extends from decameter-hectometric (DH) to metric (m) wavelengths

PAMELA events subdivided into two samples based on the **starting frequency of the metric Type II radio emission**



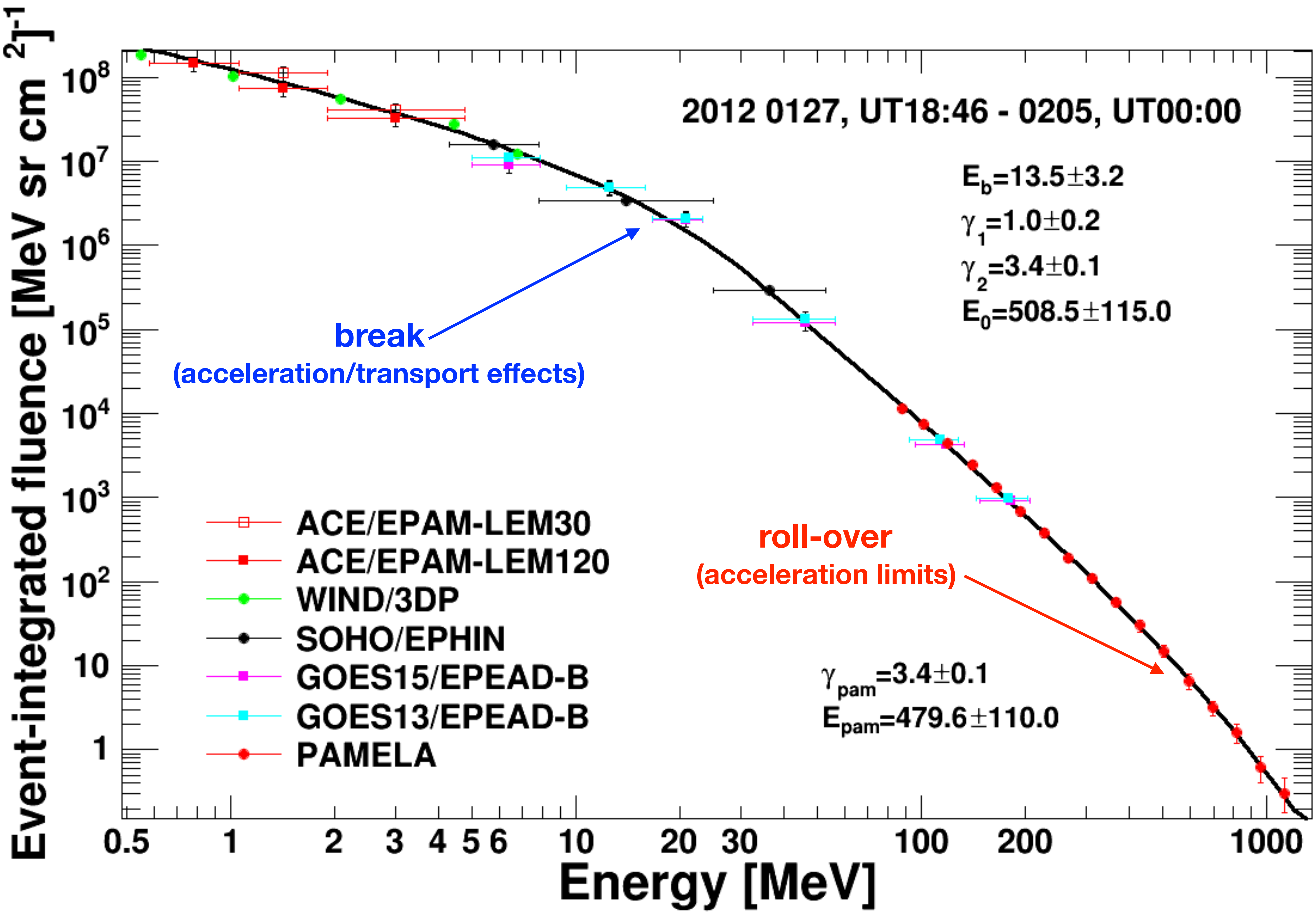


Gopalswamy et al. 2013

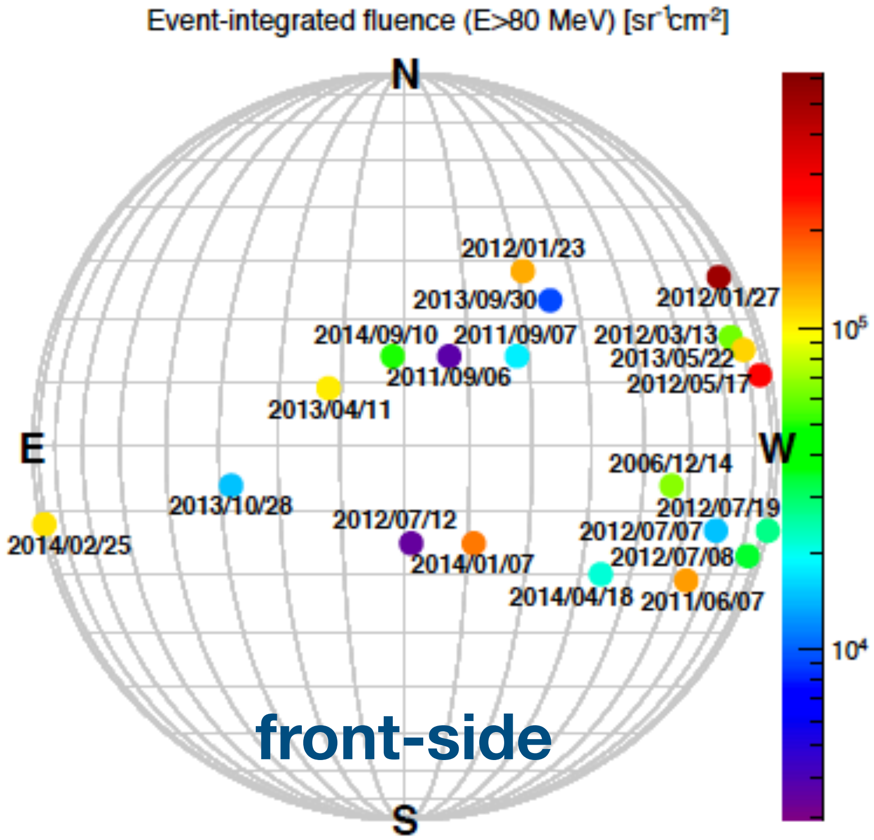
On average, higher roll-over energies are associated with higher starting frequencies

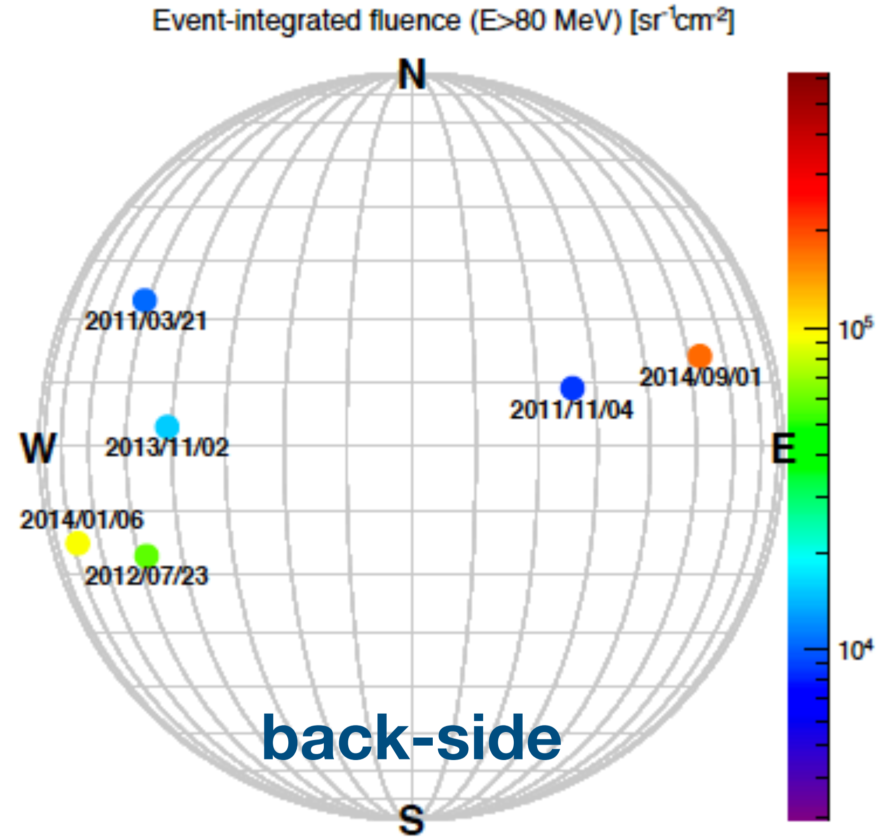
→ **lower shock formation heights**

Overall SEP spectra (>500 keV)

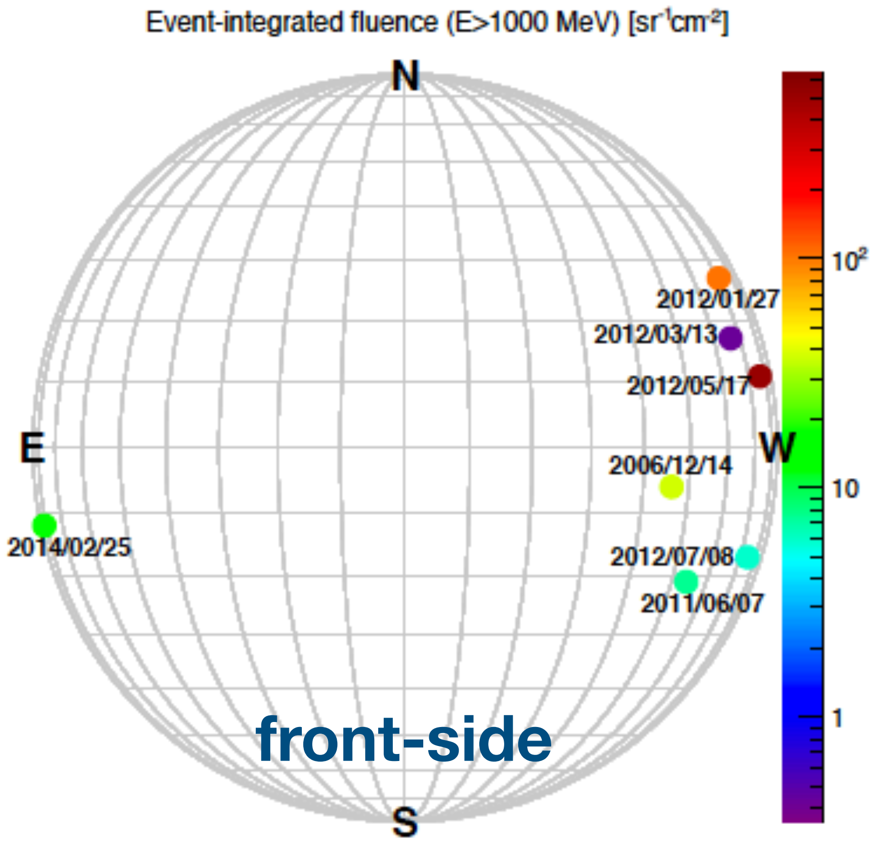


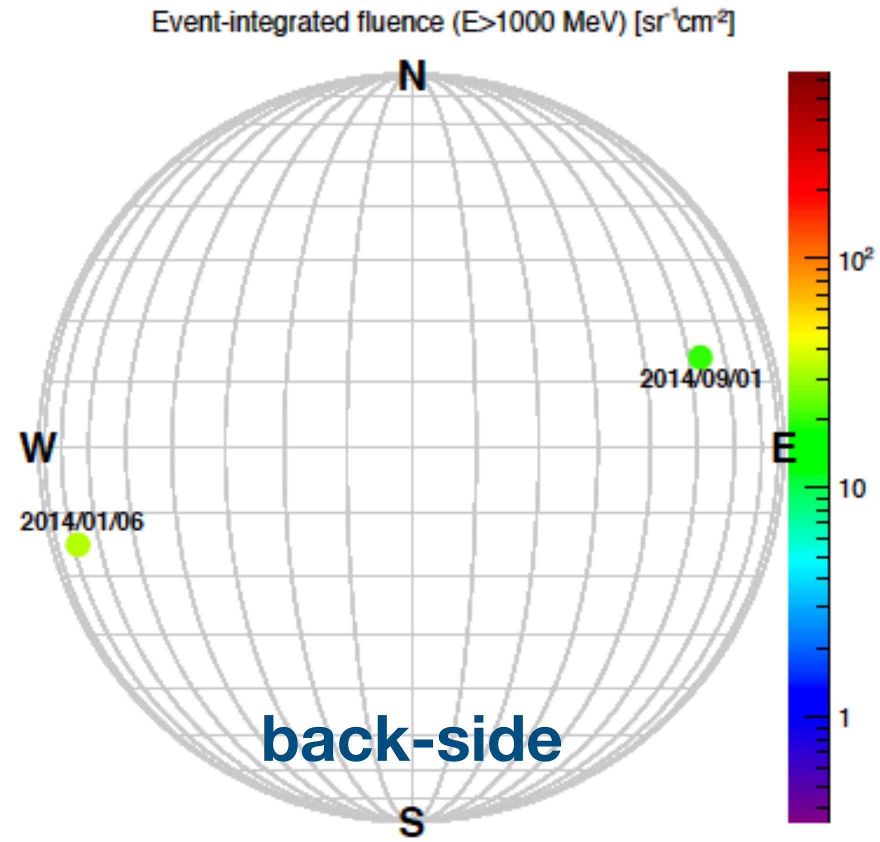
Event-integrated fluence vs source heliographic location





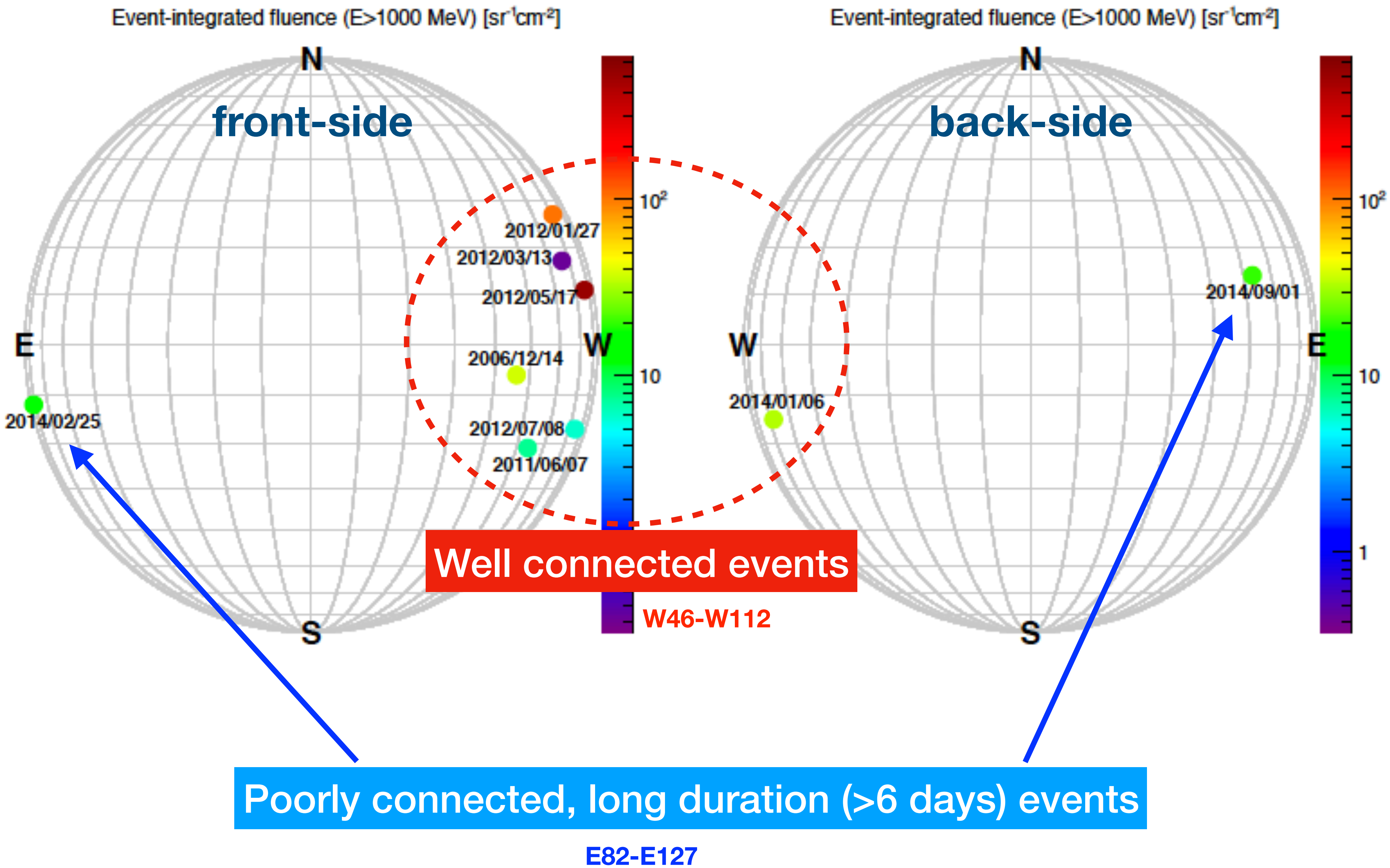
>80 MeV





>1000 MeV

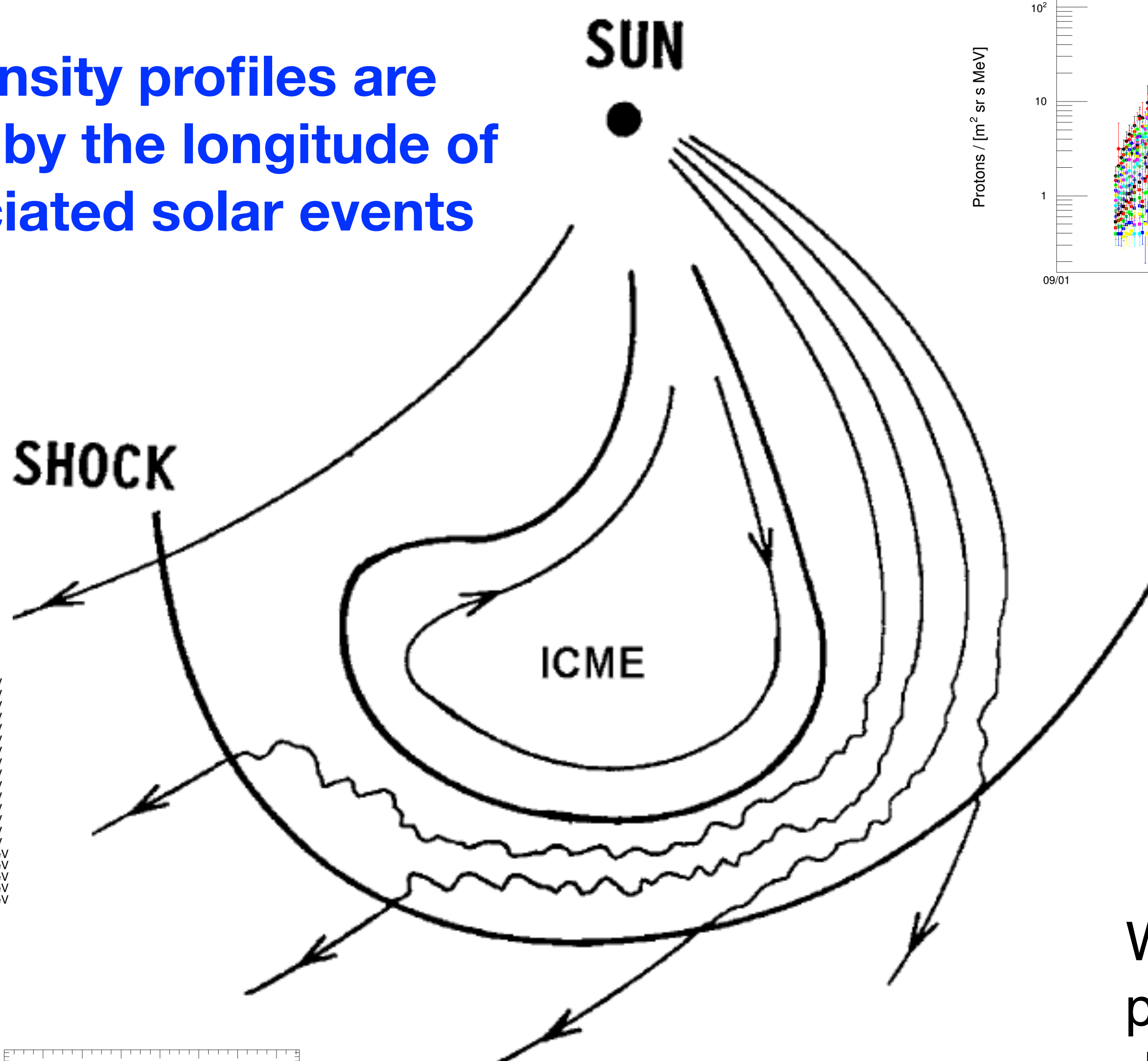
High energy SEP events (>1000 MeV)

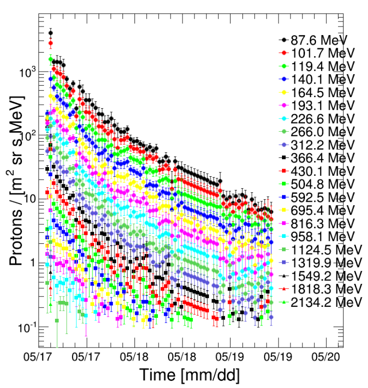


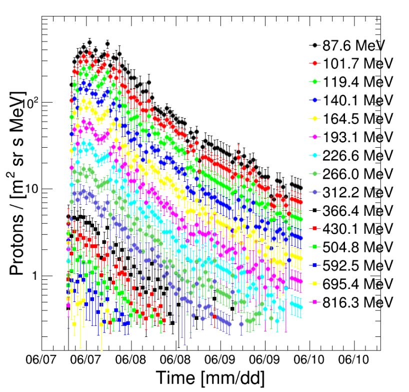
PAMELA results demonstrate that poorly connected events can contribute significantly to the SEP fluence detected near the Earth

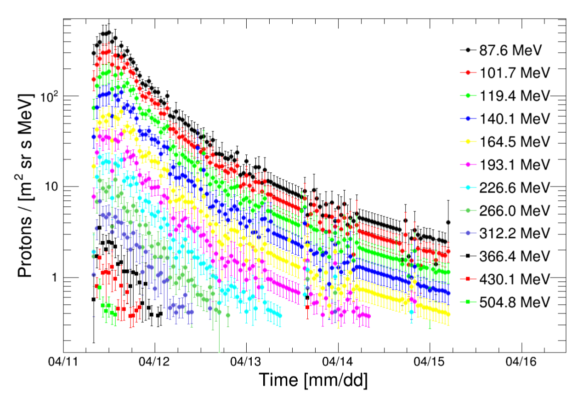
SEP time profiles and magnetic connection

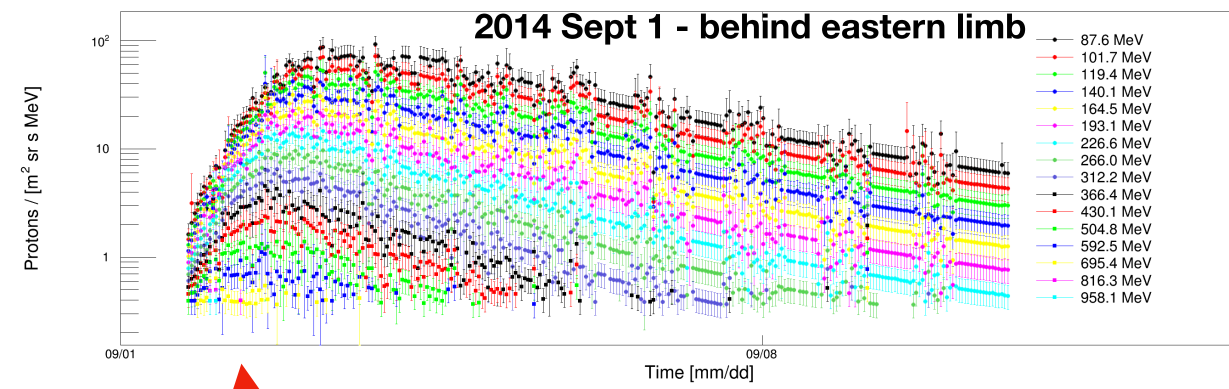
The intensity profiles are organized by the longitude of the associated solar events

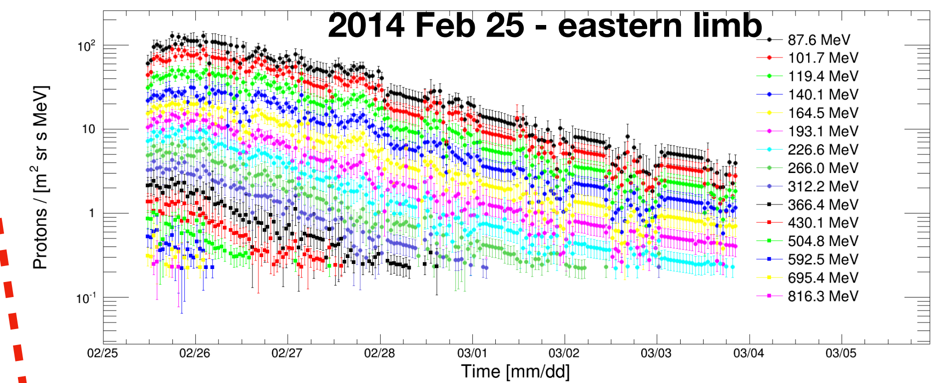












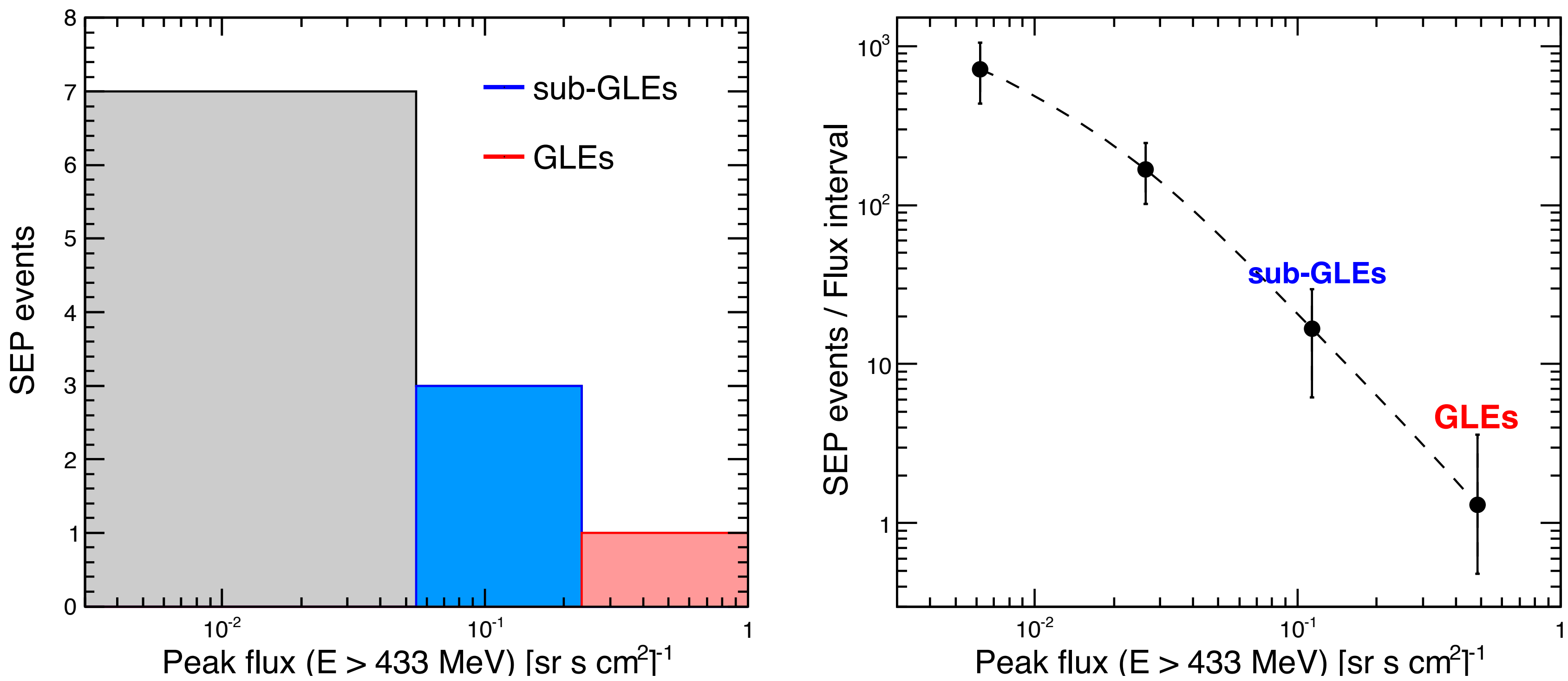
When high energy particles from poorly connected events are detected at Earth, they tend to be in **long duration**, relatively weak, SEP events, where processes such as cross field diffusion and co-rotation with the Sun delay their arrival and extend their duration at Earth.

GLE and sub-GLE events

- **GLEs:** at least two independent NMs – including a near sea level station – registered a simultaneous statistically significant increase related to the SEP arrival
- **sub-GLEs:** SEP events registered only by South Pole NMs

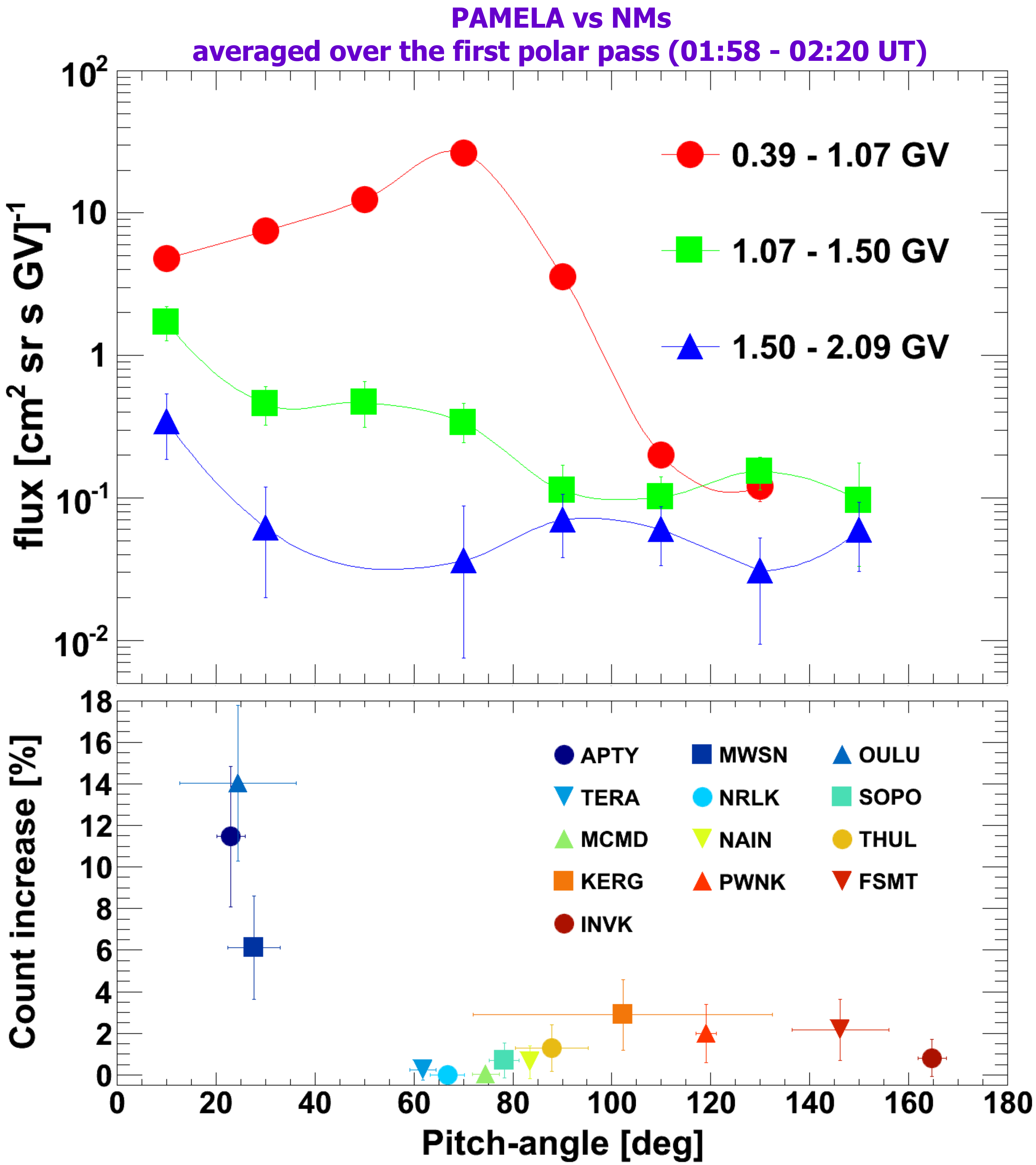
Several concomitant factors may contribute to the SEP variability and to the rarity of the GLE events, such as the associated CME kinetic energy, the shock morphology and evolution, the ambient conditions, the magnetic connection to Earth and the interplanetary transport.

- **2012 May 17 GLE**: good both longitudinal and latitudinal magnetic connection to Earth
- **2014 Jan 6 sub-GLE**: good latitudinal connection, but relatively poor longitudinal connection
- **2012 Jan 27 sub-GLE**: good longitudinal connection, but relatively poor latitudinal connection
- **2006 Dec 14 (potential) sub-GLE**: includes a contribution from the previous large event (Dec 13 GLE), flux intensities suppressed by Forbush decrease effects (magnetic cloud on Dec 14),



Several other events above the NM threshold (1 GV or 433 MeV), exhibiting relatively lower intensities. The occurrence rate of SEP events of a given peak flux is inversely related to the intensity itself

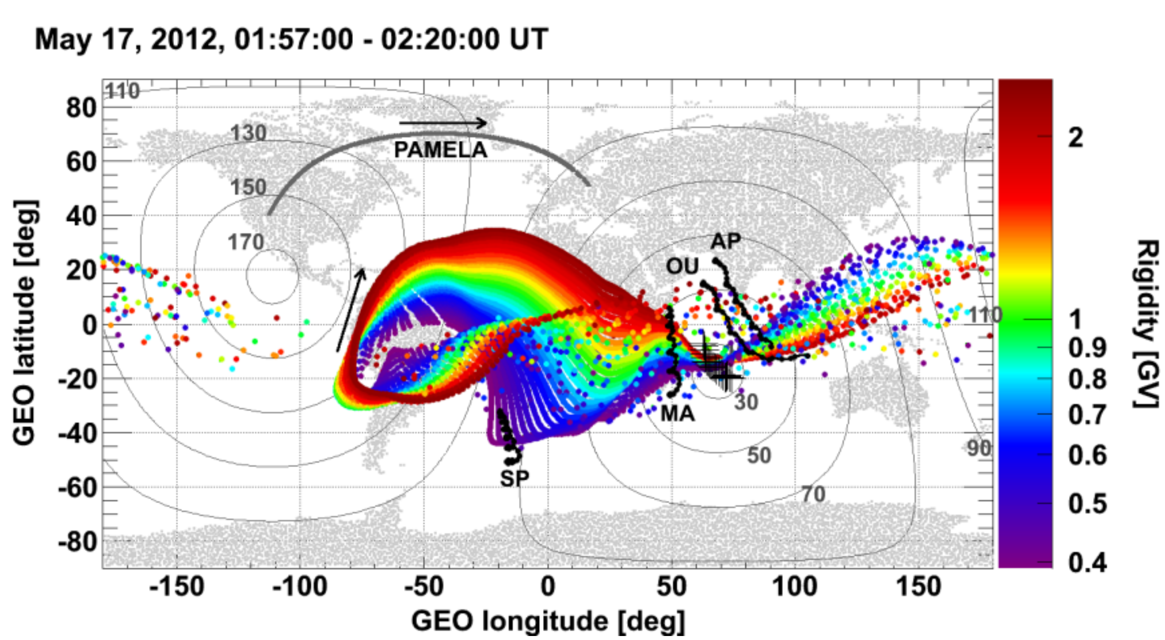
SEP anisotropies: the 2012 May 17 GLE event



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.

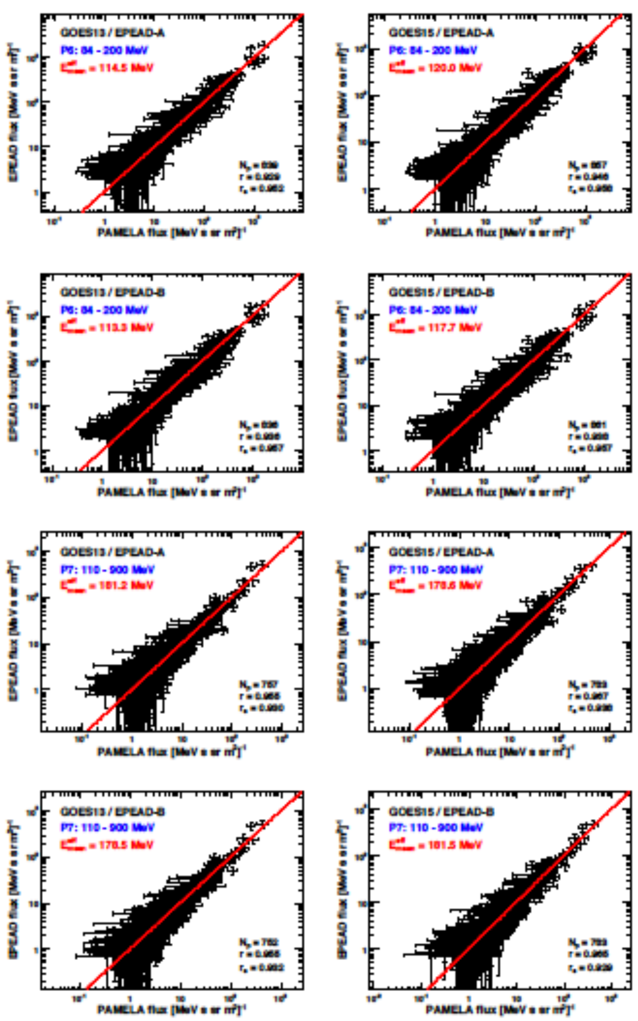
At rigidities >1 GV, corresponding to NM data, the particles are mostly field aligned.



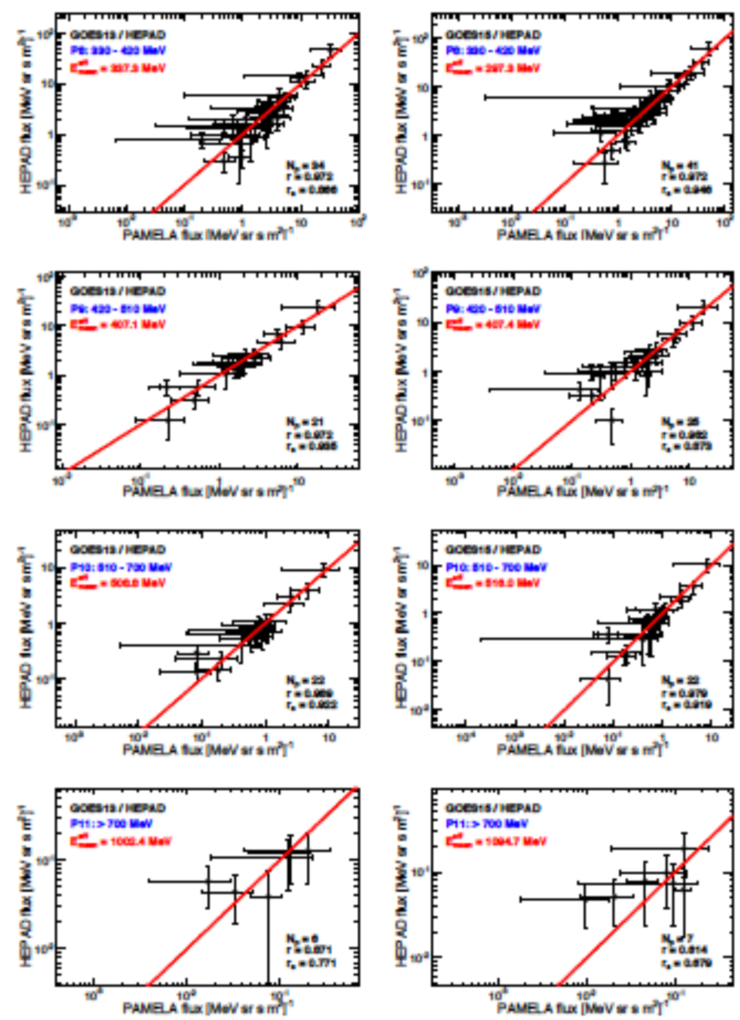
Adriani et al., ApJ, 801:L3, 2015

Calibration of GOES-13/15 proton detectors

Bruno, Space Weather, 15, 2017

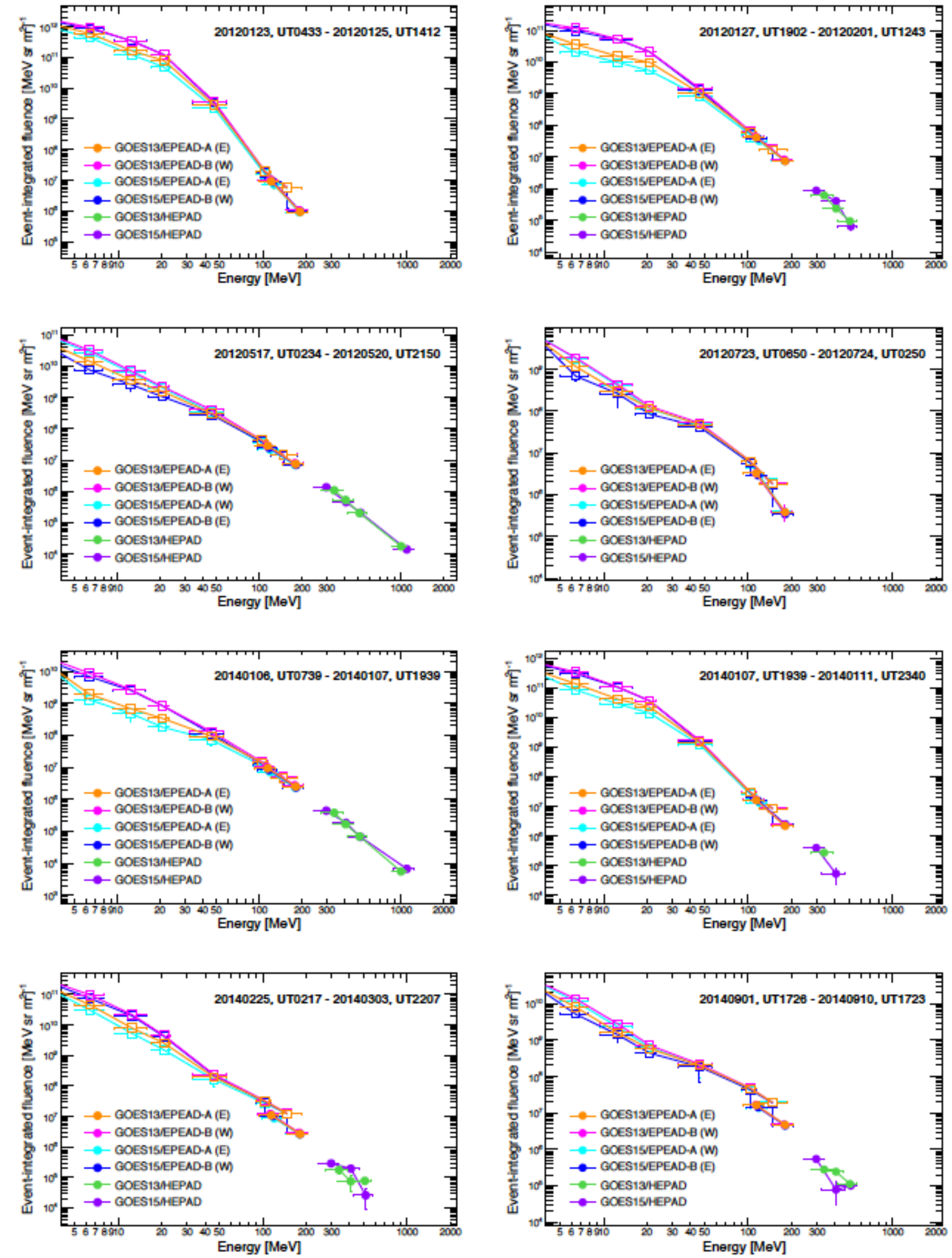


EPEAD sensors



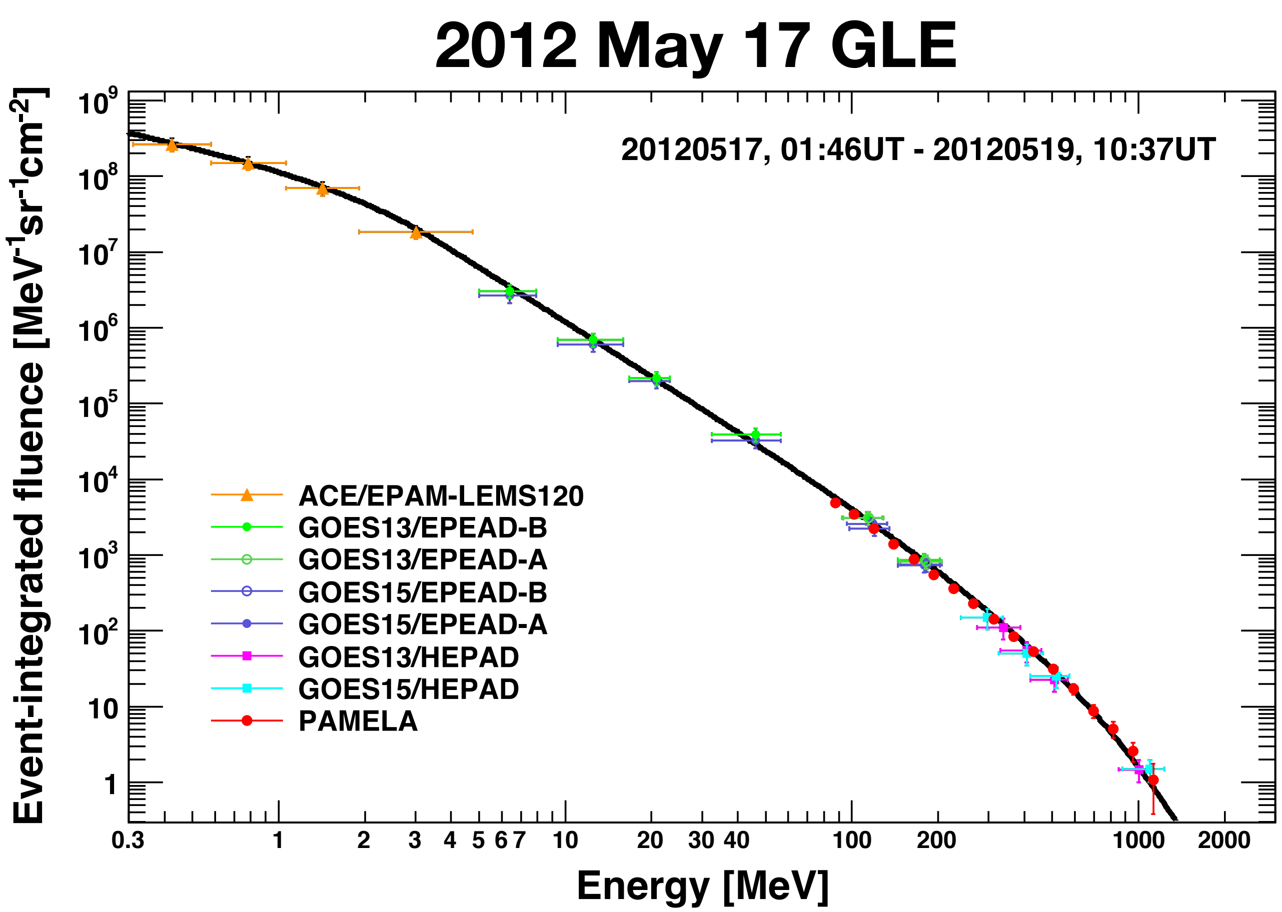
HEPAD sensors

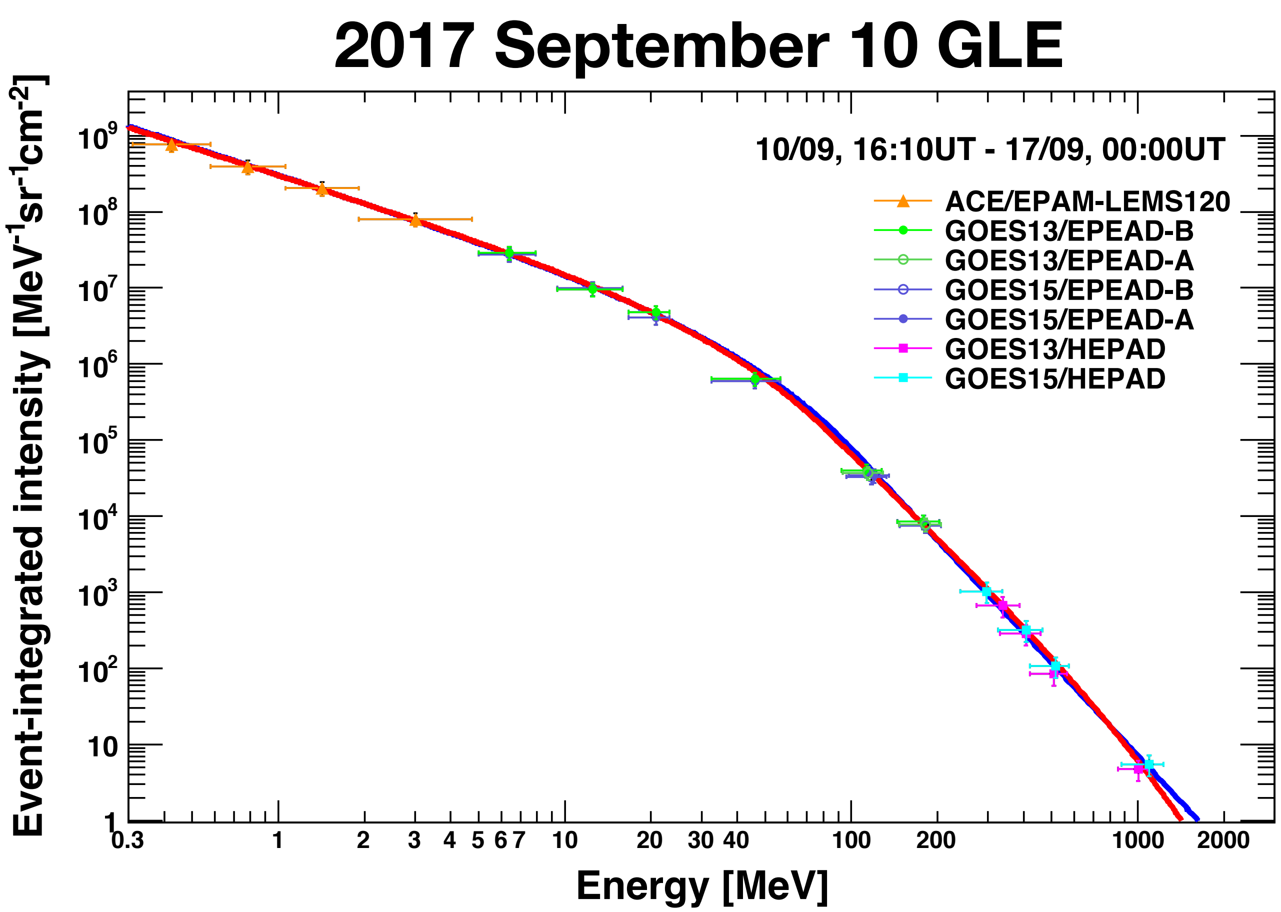
the high quality data measurements from the PAMELA mission were used to calibrate the **high energy (>80 MeV) proton channels (P6—P11) of the EPEAD and the HEPAD sensors onboard the GOES-13 and -15**, bringing the measured spectral intensities in-line with those registered by PAMELA. Suggested corrections significantly reduce the uncertainties on the response of GOES detectors, thus improving the reliability of the spectroscopic observations of SEP events.



Calibrated fluence spectra

Spectral results for the 2017 September events





The new calibrated GOES/EPEAD-HEPAD data enable a more precise measurement of the SEP energy spectra for the time period after PAMELA (e.g. 2017 September) or for the intervals when PAMELA was off (e.g. 2011 August)

Conclusions

- Thanks to its unique observational capabilities, the PAMELA satellite-borne experiment can investigate for the first time SEP events over a **wide energy region (>80 MeV) encompassing the low energy observations by in-situ spacecraft and GLE observations made by the ground-based NM network**.
  - We analyzed the 26 major SEP events registered by PAMELA between 2006 December and 2014 September, including one GLE and potentially three sub-GLEs. PAMELA results enable a more complete and clearer picture of SEPs that offers the possibility of constraining models of particle acceleration to high energies.
- **Consistent with the diffusive shock acceleration theory**, the measured SEP spectra are well reproduced by a power-law modulated by an exponential cutoff attributed to particles escaping the shock region during acceleration.
  - However, transport processes must also contribute to the spectral variability, and further work is required to explore the relative influences of acceleration and transport on SEP spectra at the highest energies.
- Furthermore, PAMELA observations shed new light to the long lasting question concerning the **differences between GLE and non-GLE events**. Based on the intensity and the position of the SEP sources, the event size distribution and the spectral shapes, we did not find any reason for considering the GLEs as a separate class; they rather represent the most energetic subset of the SEP global distribution.
  - Potential limits for the peak fluxes of GLE and sub-GLE events based on space measurements are provided for the first time.

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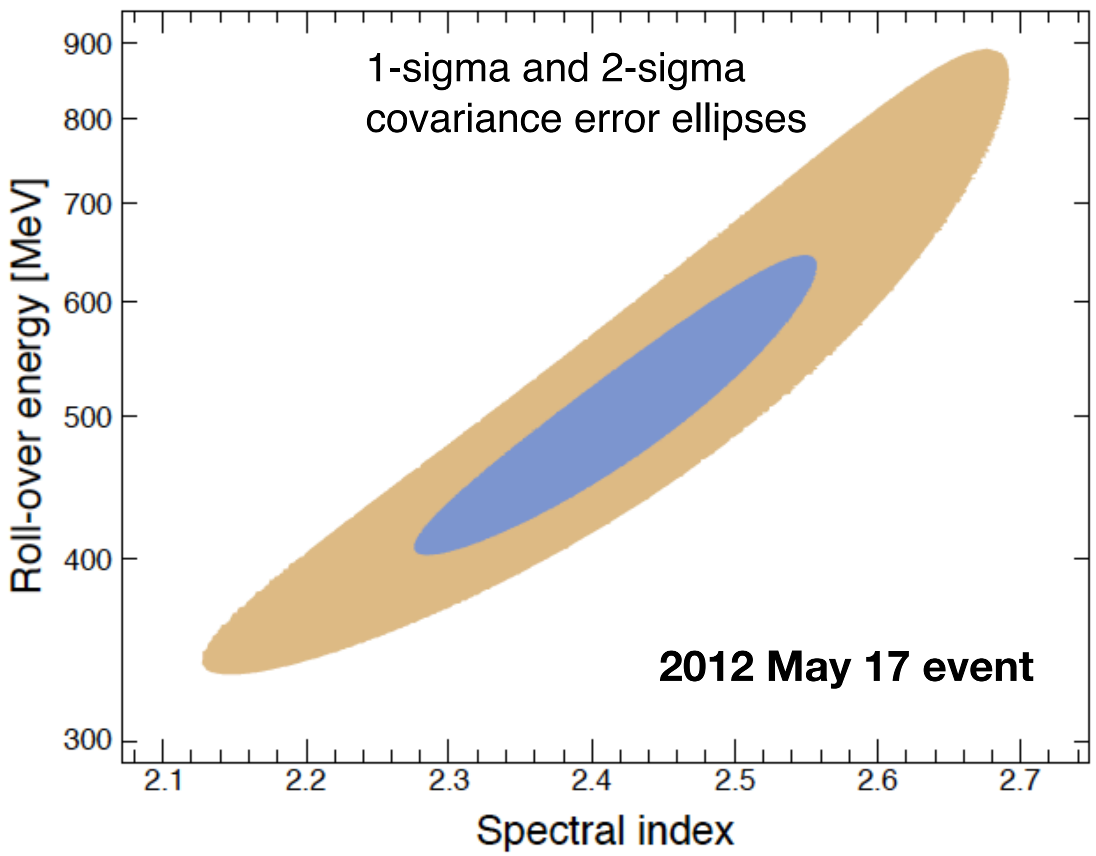
- **Spares slides**

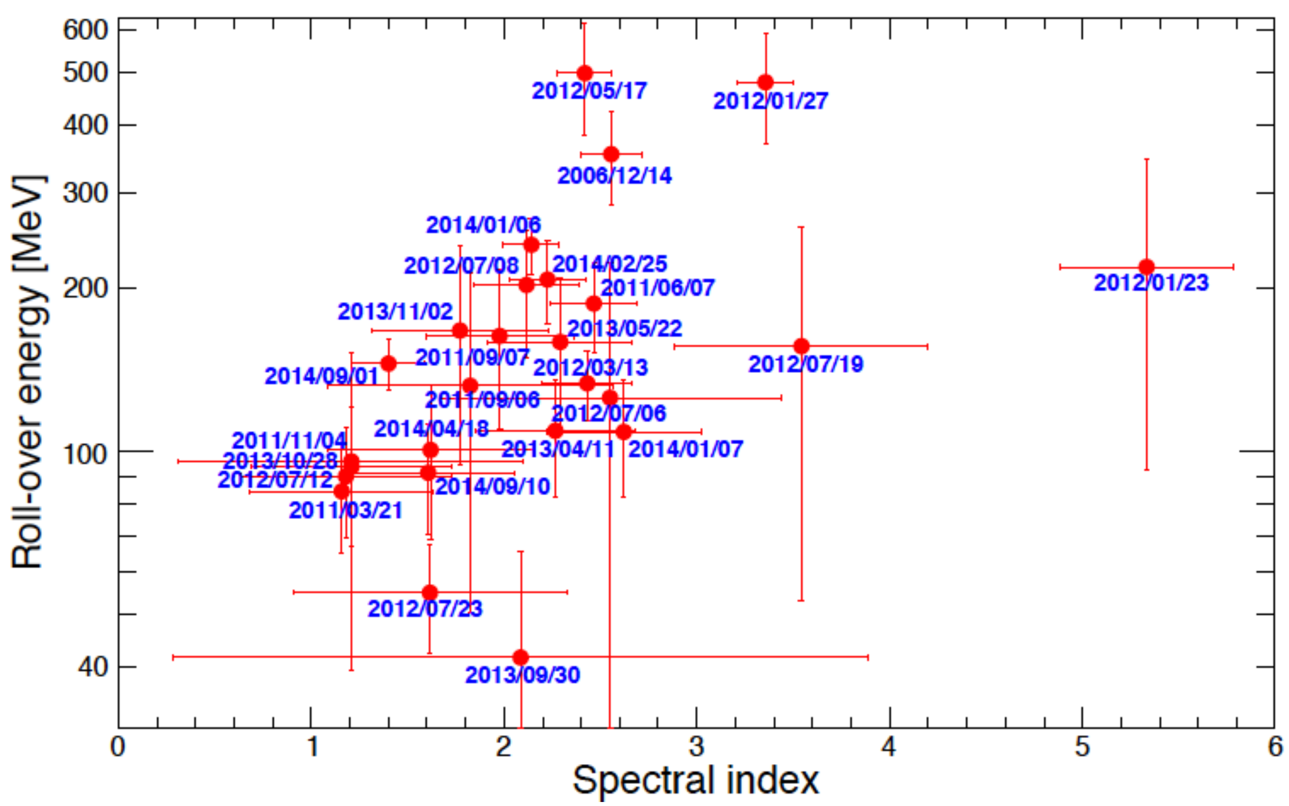
Spectral fits: cross-correlations



In fitting spectra, a cross correlation between the power-law index and the roll-over energy is unavoidable, affecting parameter uncertainties.

The roll-over energy increases with growing spectral index.

The reason for this is that when attempting an E-R fit to a given spectrum, if a steeper power law (larger spectral index) is chosen, the best fit is obtained when the greater fall off at higher energies in the power law is compensated by a larger roll-over energy.



Roll-over energy vs spectral index global distribution. An overall trend can be noticed, with higher roll-over energies associated with larger spectral indices.

The global positive correlation between roll-over energy and power law index may be a manifestation of the effect illustrated in the figure above;

further statistical investigation is necessary to infer more physical meaning to the trend.

Long Duration Gamma-Ray Flares (LDGRFs)

- Delayed and prolonged gamma-ray (>100 MeV) emission after the flare impulsive phase

- Identified with the Compton Gamma-Ray Observatory (CGRO), the Solar Maximum Mission (SMM), and now Fermi.

- The highest energy emission has generally been attributed to pion production from the interaction of high-energy ions (>300 MeV protons and >200 MeV alphas) with the ambient matter,
    - suggesting that particle acceleration occurs over large volumes extending high in the corona, either from **stochastic acceleration within large coronal loops** or from **back precipitation from coronal mass ejection (CME) driven shocks**.

- Typically, LDGRFs are associated with CMEs and large solar energetic particle (SEP) events, with energies often exceeding those of ground level enhancements (GLEs, >500 MeV).
    - Any direct connection between energetic GLE-type particles observed in space and the accelerated ion population producing the high-energy gamma-ray emission is unclear

- It is possible to test these models by a making direct comparison between the properties of the accelerated ion population at the flare derived from the observations of Fermi/LAT with the derived properties of SEPs observed by PAMELA in the energy range corresponding to the pion-related emission observed with Fermi.

- For 14 SEP events we compare the two populations – SEPs in space and the interacting particles at the Sun – and discuss the implications in terms of potential sources of the LDGRFs

Comparing LDGRFs and SEP events

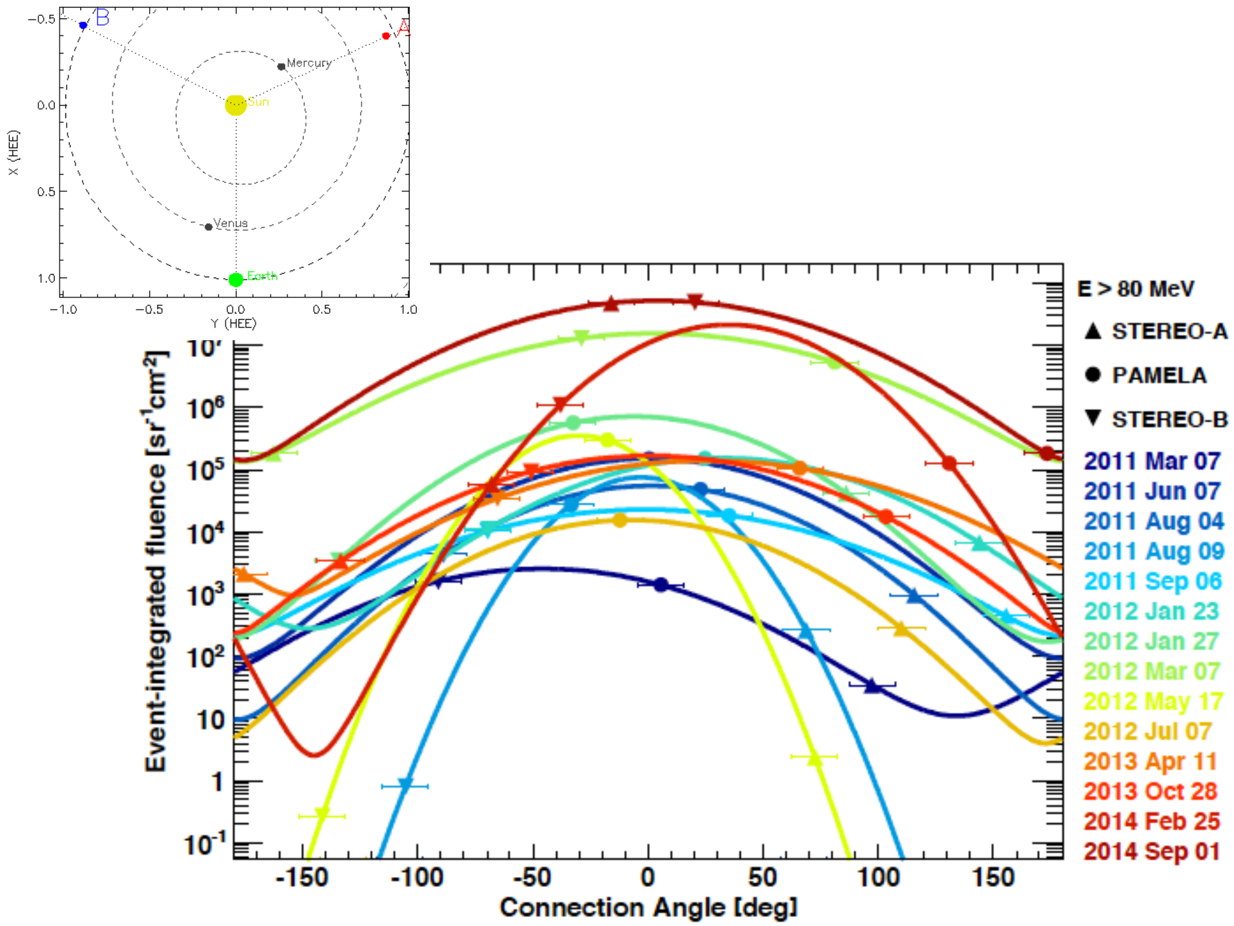


Figure 5. Longitudinal extent of SEP events determined from the fits (Equation 4) of the event-integrated intensities (>80 MeV) measured by PAMELA and STEREO-A/B, as a function of the longitudinal difference (connection angle) between the spacecraft magnetic footpoints at 30 R_s and the location of the parent flare.

de Nolfo et al. 2019, accepted for publication in ApJ

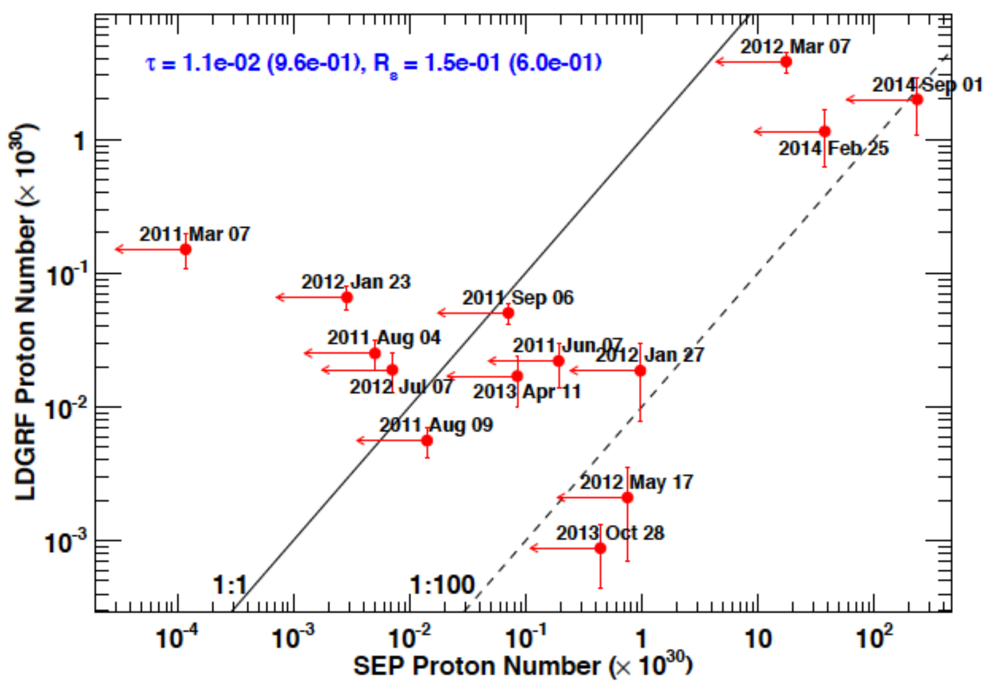


Figure 7. Number of protons deduced from *Fermi*/LAT (Share et al. 2018) compared with number of protons determined from PAMELA and STEREO-A/B. The solid and the dashed lines mark the one-to-one and the one-to-hundred correspondences, respectively. The Kendall's τ and the Spearman rank (R_s) correlation coefficients are also reported, along with corresponding p-values.

- We calculate the total number of >500 MeV protons at 1 AU, N_{SEP}, taking advantage of the PAMELA and STEREO data with the aid of transport simulations, and compare it with the number of high-energy protons at the Sun, N_{LDGRF}, as deduced from Fermi/LAT data.

- The two proton numbers are poorly correlated, with their ratio spanning more than five orders of magnitude, suggesting that **the back precipitation of shock-acceleration particles is unlikely the source of the LDGRF emission**.