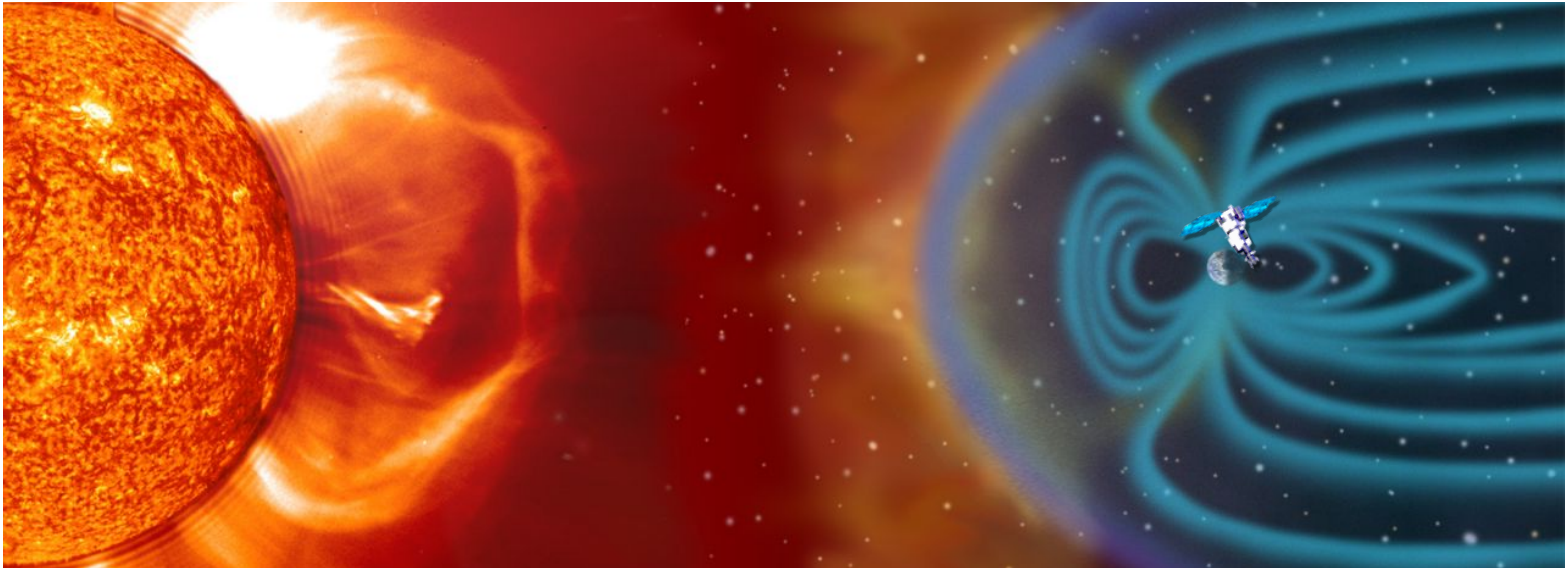

SOLAR ENERGETIC PARTICLE OBSERVATIONS WITH THE PAMELA EXPERIMENT

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on behalf of the PAMELA collaboration

Goddard Space Flight Center

36th International Cosmic-Ray Conference (ICRC2019)
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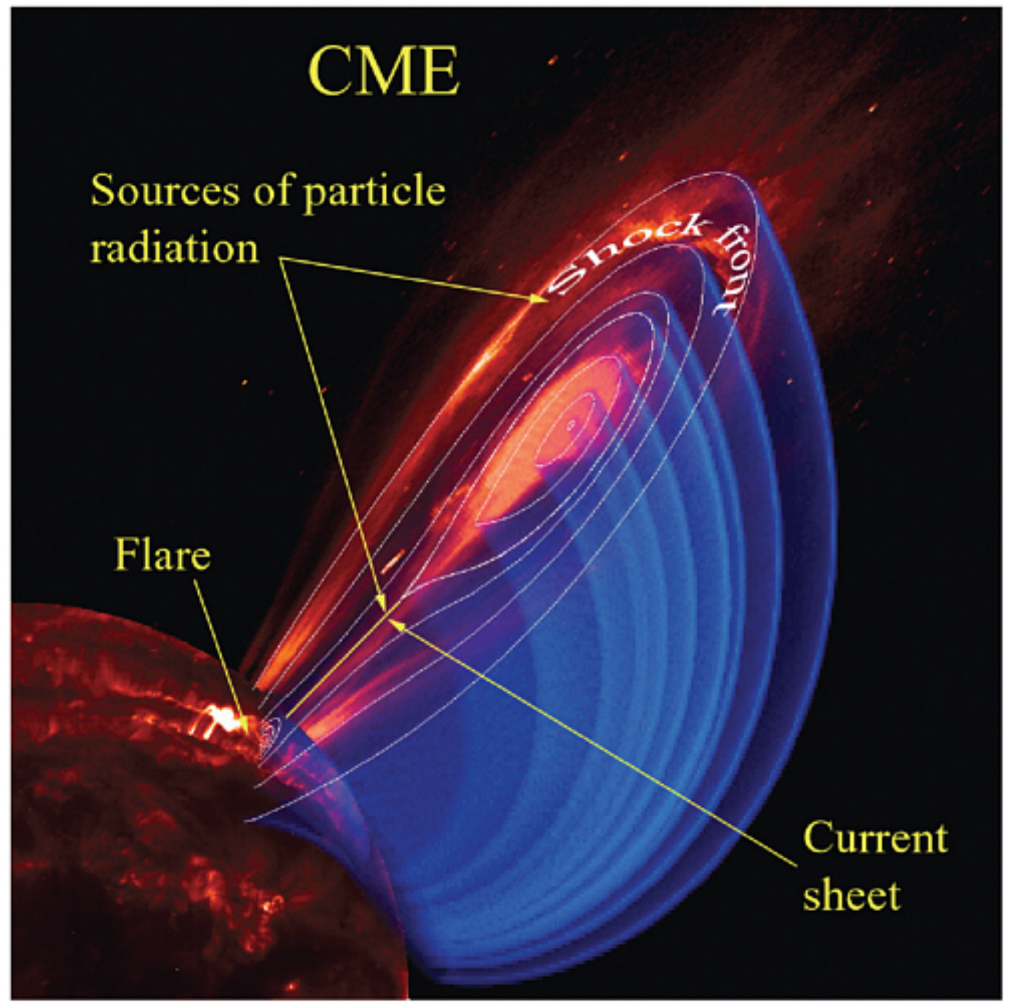
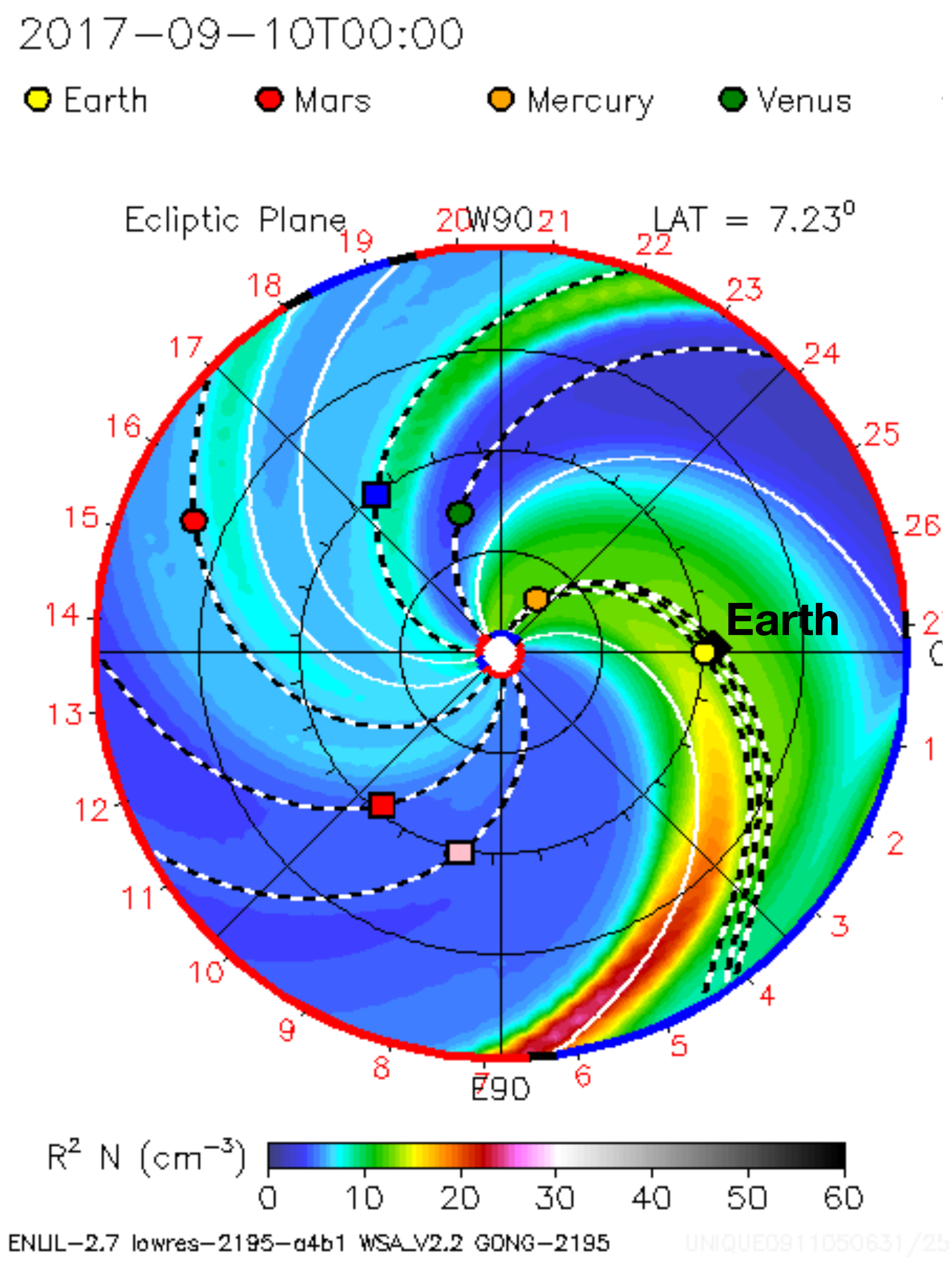
Origin of SEPs





- Two class scenario of SEP acceleration
  - **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
- While SEPs with energies below few hundred MeV have been extensively investigated by a number of missions (e.g. ACE, STEREO, WIND), the characterization of **higher-energy SEP** fluxes is still affected by large uncertainties, in part due to the relatively few observations in this range,
  - mostly relegated to *indirect* measurements (**GLEs**)

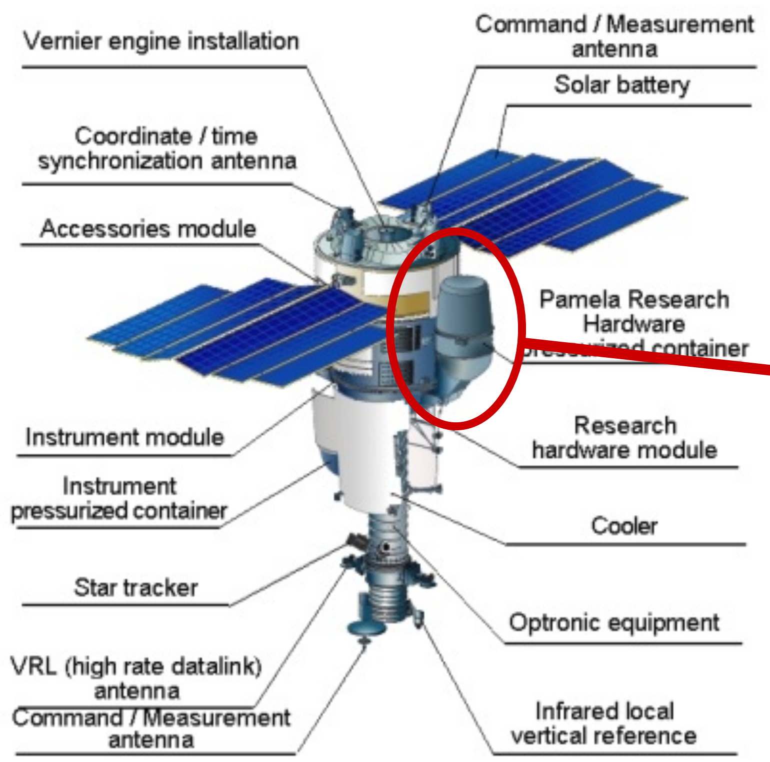
Ground Level Enhancements (GLEs)

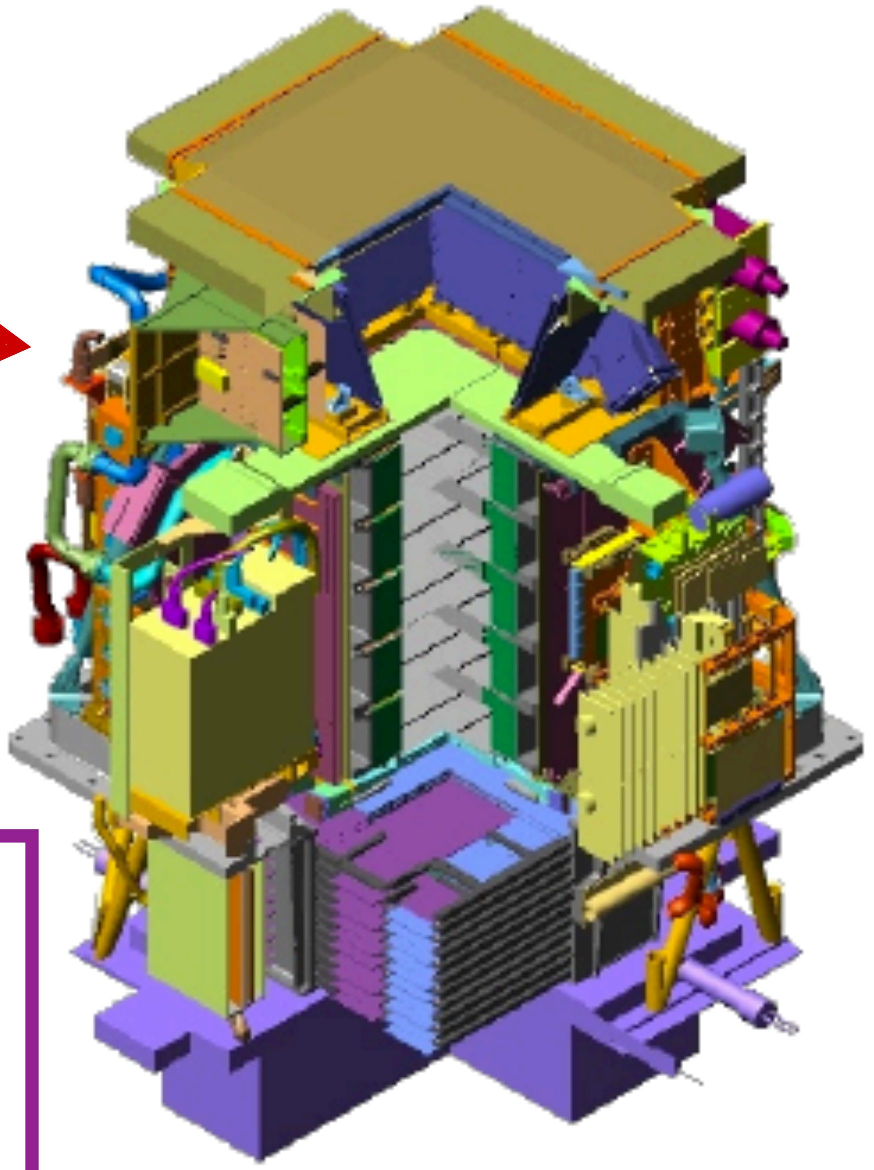
- The most energetic (≳500 MeV) SEP events induce atmospheric showers whose secondary products are measured by ground-based detectors, including the worldwide network of neutron monitors (NMs)
  - 72 GLEs since 1940s, **only 2 during solar cycle 24** → **rare events!**
  - However, *indirect* observations rely on a number of assumption (CR interactions with terrestrial magnetosphere and atmosphere) → **large uncertainties!**
- Aside from relevant *Space Weather* implications, GLEs are of particular interest since they represent **SEP acceleration at its most efficient**.
  - Furthermore, the ~GeV protons causing GLE events can reach 1 AU with minimal interplanetary scattering.
  - Thus, their spectra provide **important constraints on SEP origin**.

The PAMELA experiment

Payload for Antimatter-Matter Exploration and Light-nuclei Astrophysics

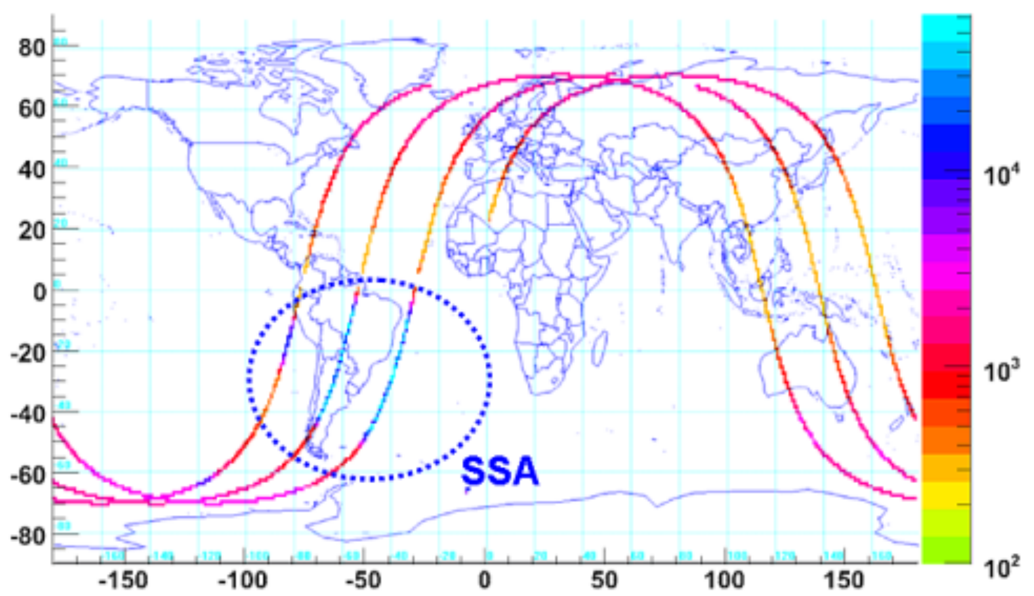
Main requirements → high-sensitivity particle identification and precise momentum measure





Resurs-DK1
semi-polar (70°inclination) & elliptical (350-610 km) orbit

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



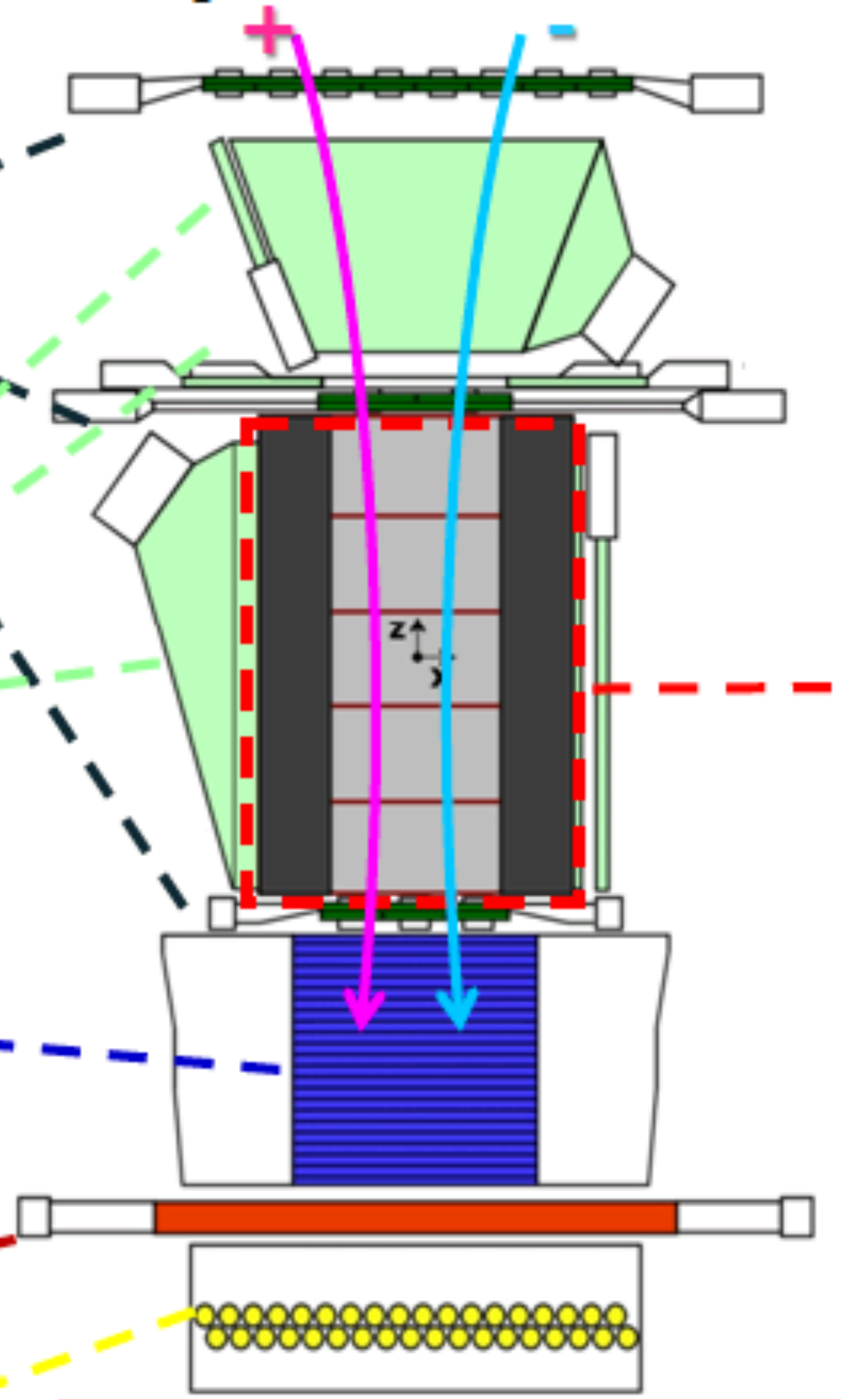
Time-Of-Flight
plastic scintillators + PMT
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX.

Anticoincidence shield
plastic scintillators + PMT

Electromagnetic calorimeter
W/Si sampling (16.3 X_0, 0.6 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



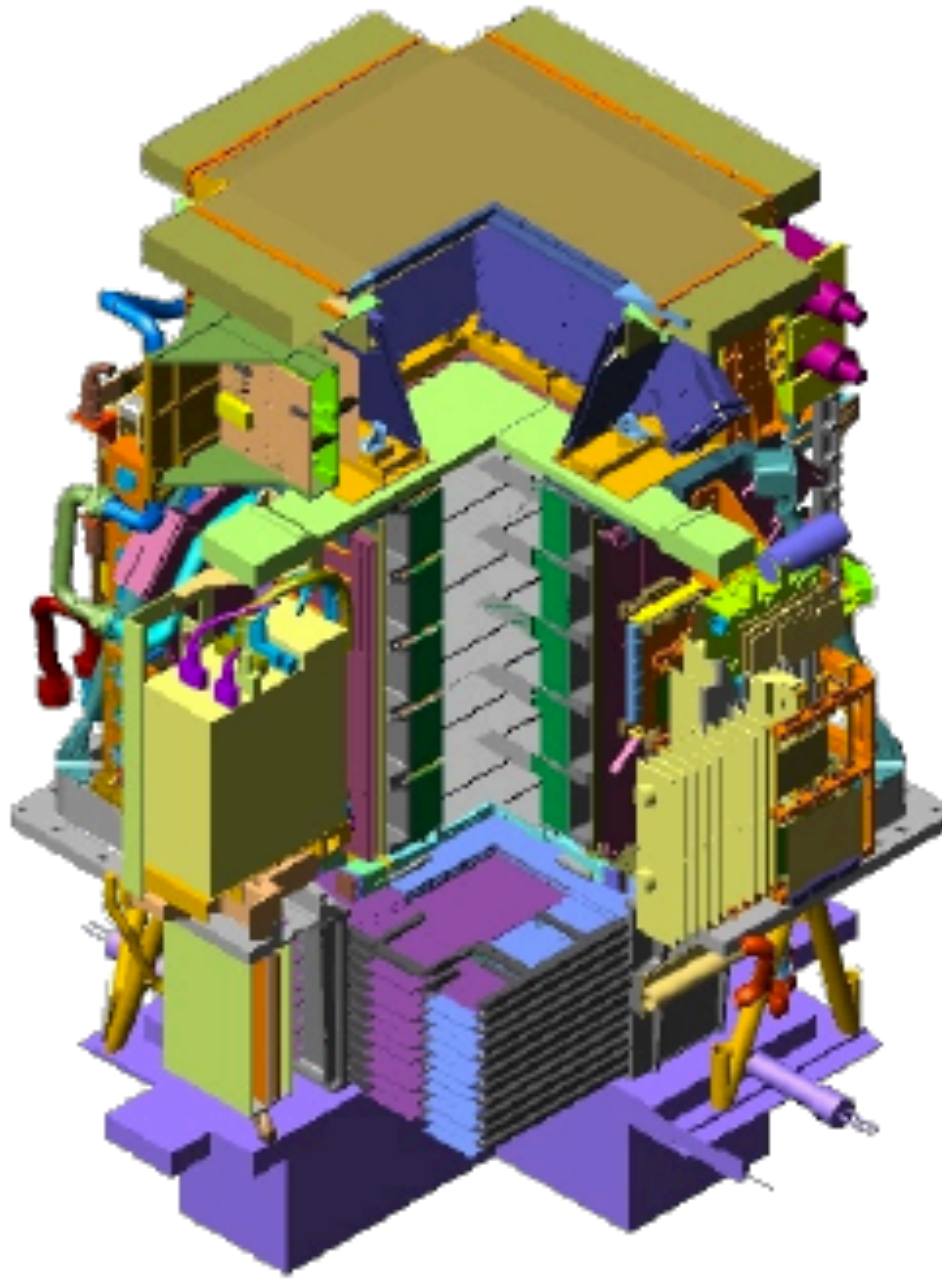
Spectrometer
microstrip silicon tracking system + permanent magnet
- Magnetic rigidity: R=pc/Ze
- Charge sign
- Charge value from dE/dx
- Particle direction

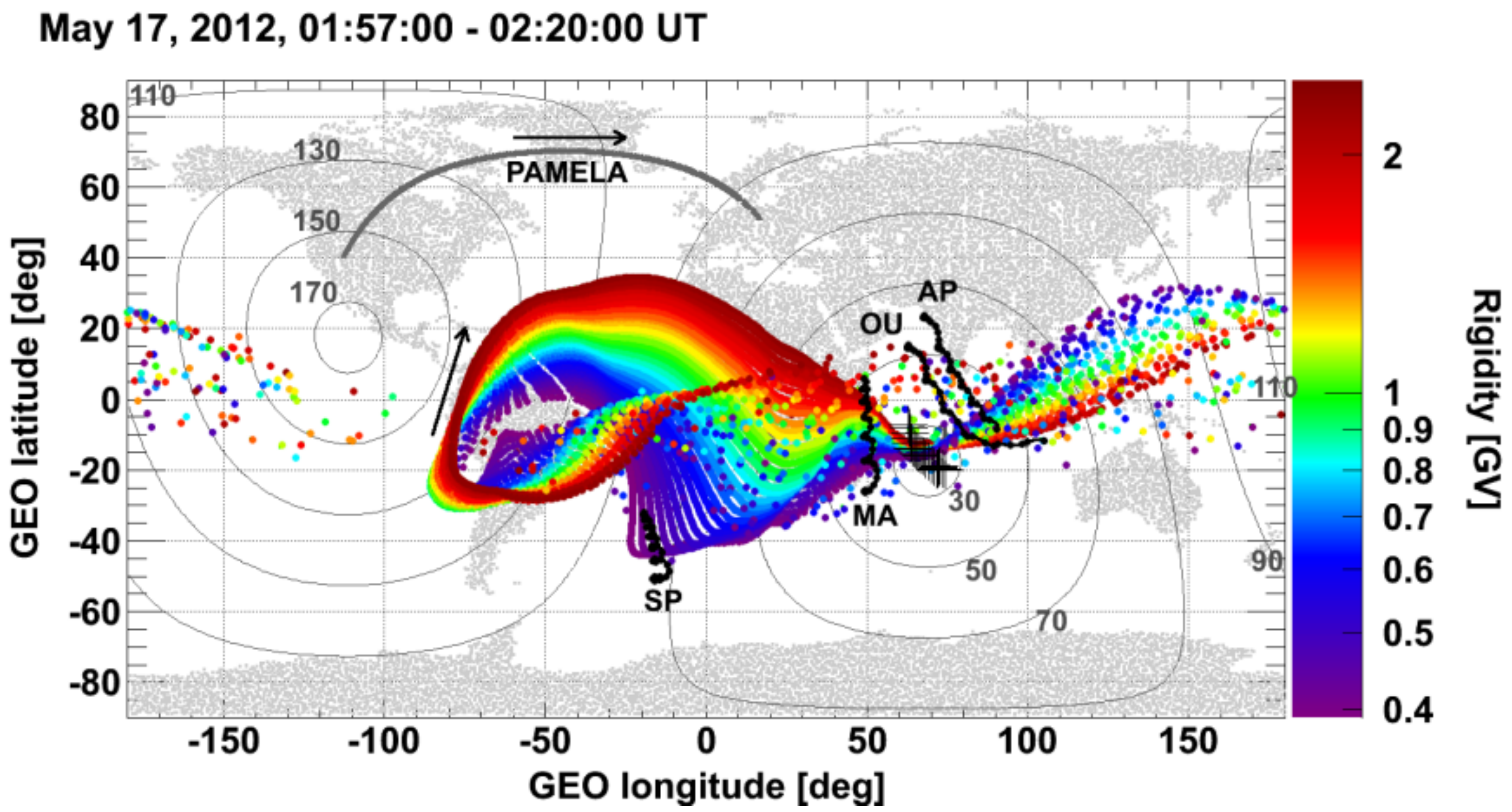
- **Research for Dark Matter indirect signatures**
- **Investigation of the CR origin and propagation mechanisms in the Galaxy, the heliosphere and the terrestrial magnetosphere**
- **Detailed measurement of the different particle populations (galactic, solar, geomagnetically trapped and albedo) in the near-Earth radiation environment**

Precise measurements of CR protons, electrons, their antiparticles and light nuclei between several tens of MeV and ~1 TeV

Almost 10 years of data taking (July 2006 - January 2016)

The PAMELA experiment





- Thanks to its unique observational capabilities, the PAMELA experiment has recently offered a unique opportunity to study SEPs with energies between **80 MeV and few GeV**,
  - including their energy spectra, composition (H, He) and pitch-angle distributions
- In particular, PAMELA has measured for the first time, with good accuracy, the spectral features at moderate and high energies,
  - significantly improving the characterization of most energetic SEP events, and allowing the investigation of the relationship between GLE and non-GLE events

PAMELA data set

All associated with **fast halo CMEs** (except 2012 Jul 8) and **≥M-class flares** (except 2013 Sept 29, filament eruption)

and accompanied by **long-duration type-II and type-III radio bursts**

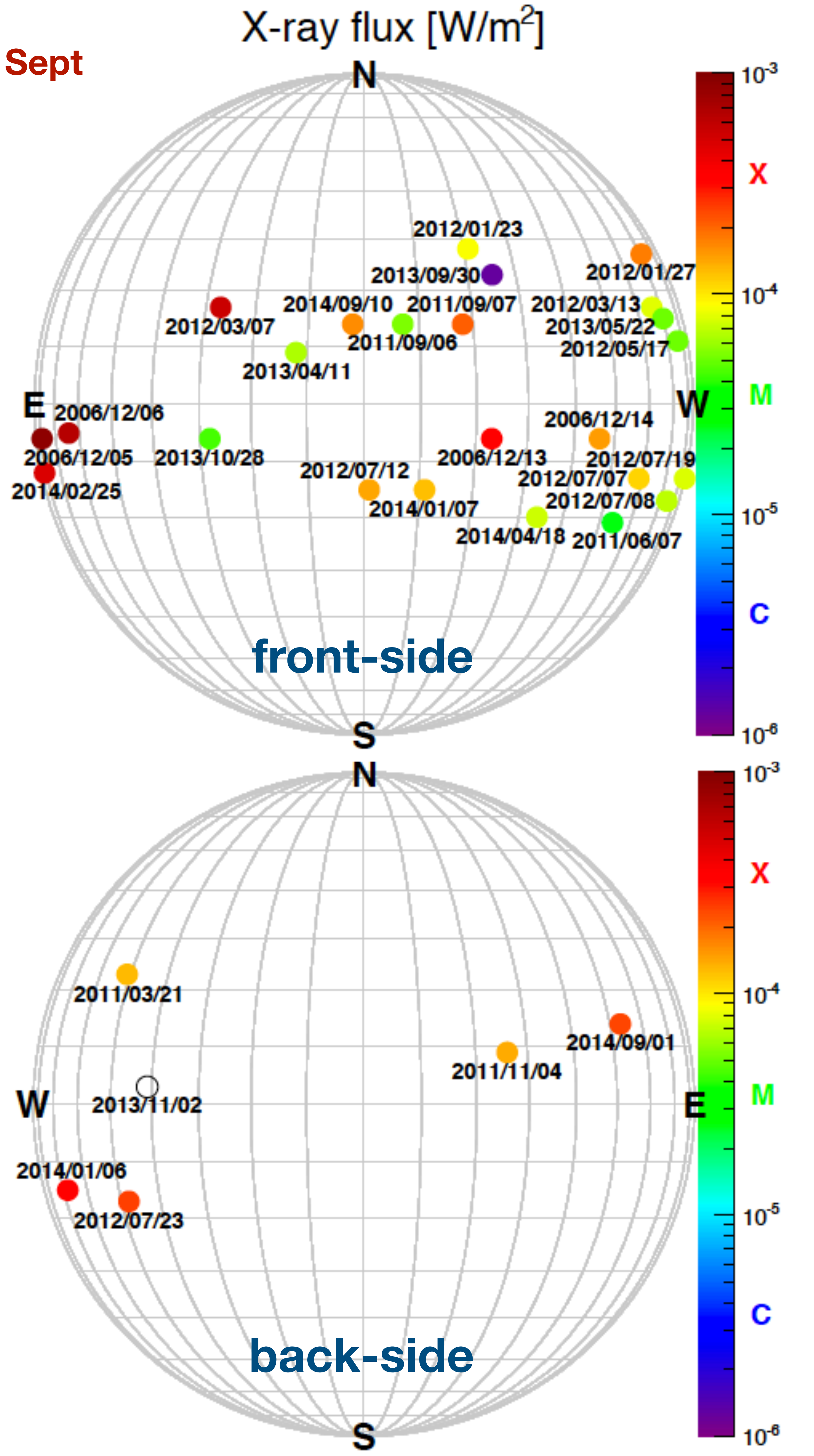
Six back-side eruptions

2 **GLE** events (2006 Dec 13 and 2012 May 17) and 3 sub-GLEs (2012 Jan 27, 2012 Mar 7, 2014 Jan 6)

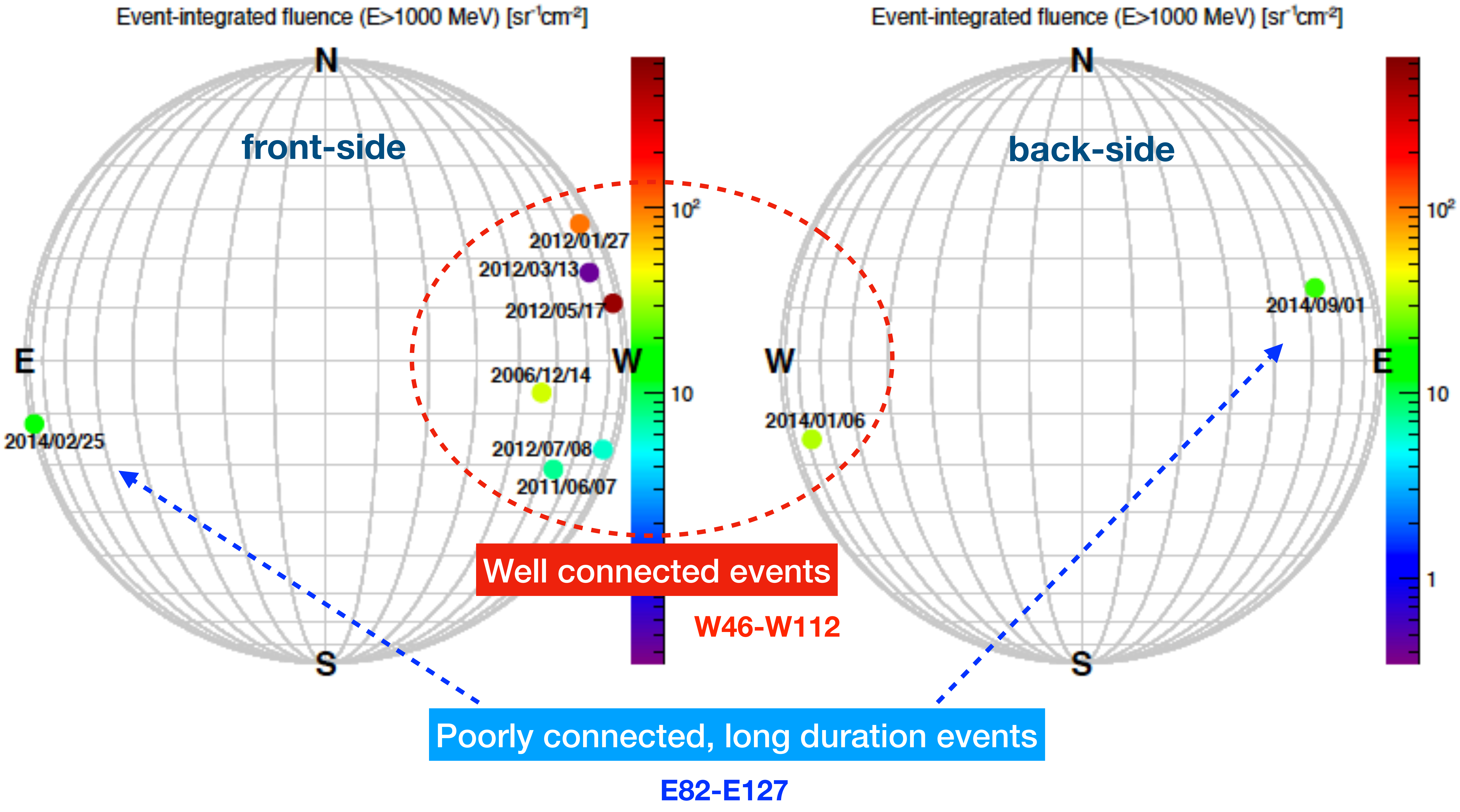
Major SEP events observed by PAMELA between 2006 July and 2014 Sept

	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).



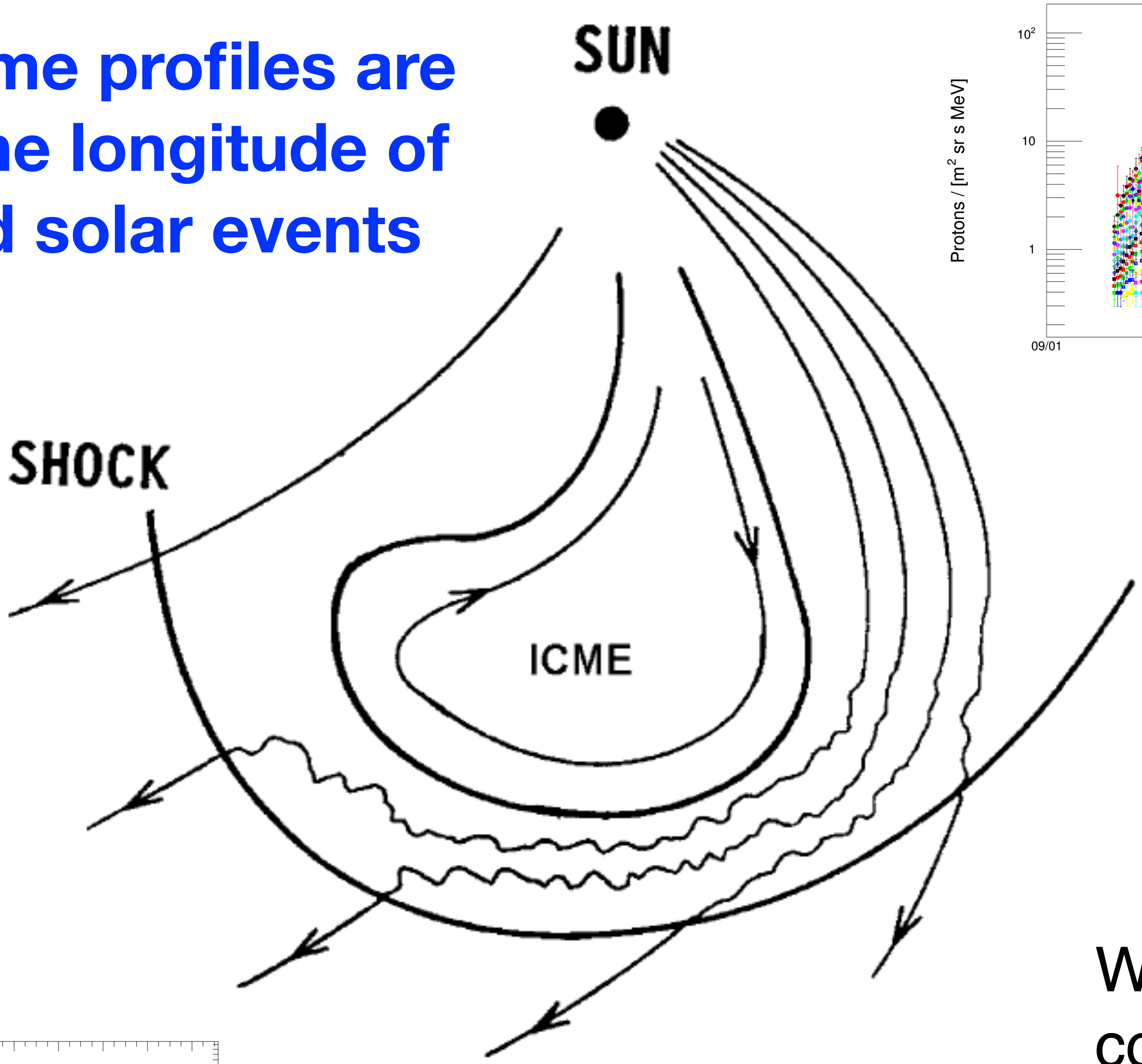
SEP events and magnetic connectivity

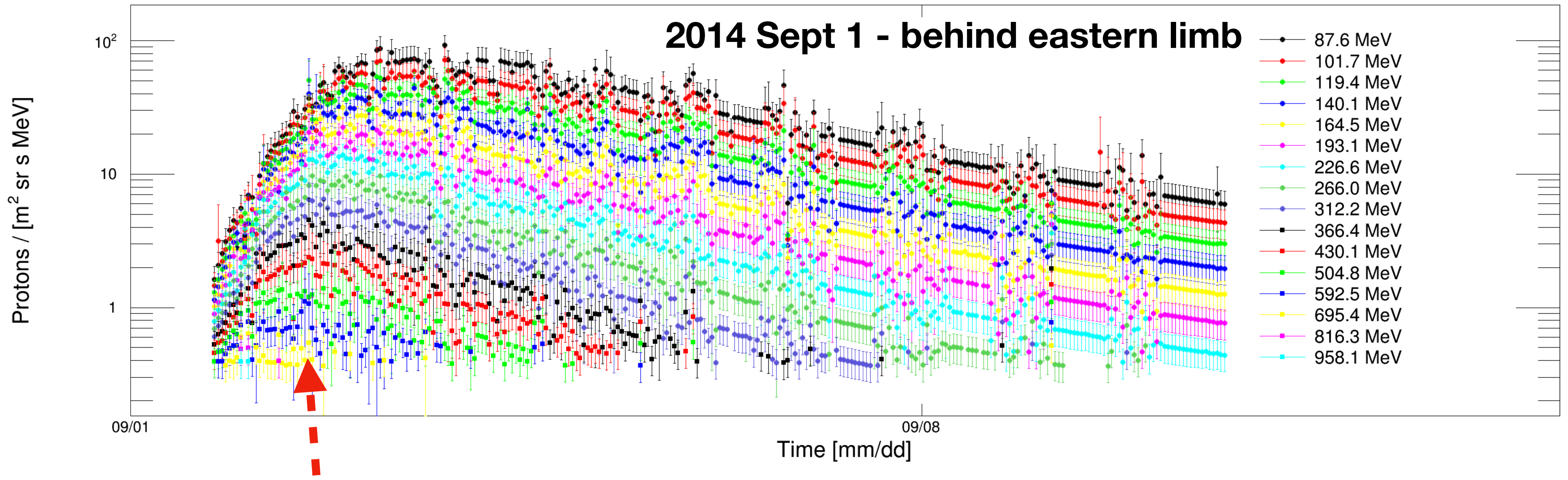


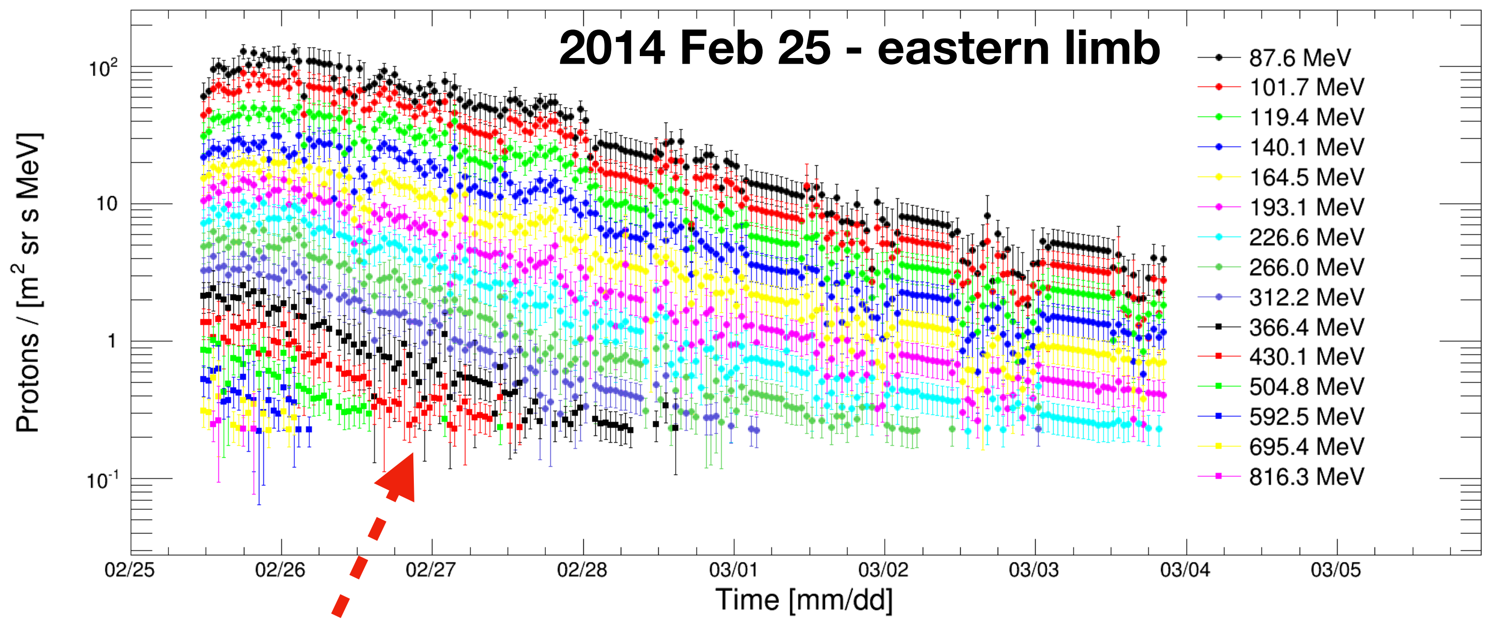
PAMELA results demonstrate that poorly connected events can contribute significantly to the high-energy SEP flux detected near the Earth

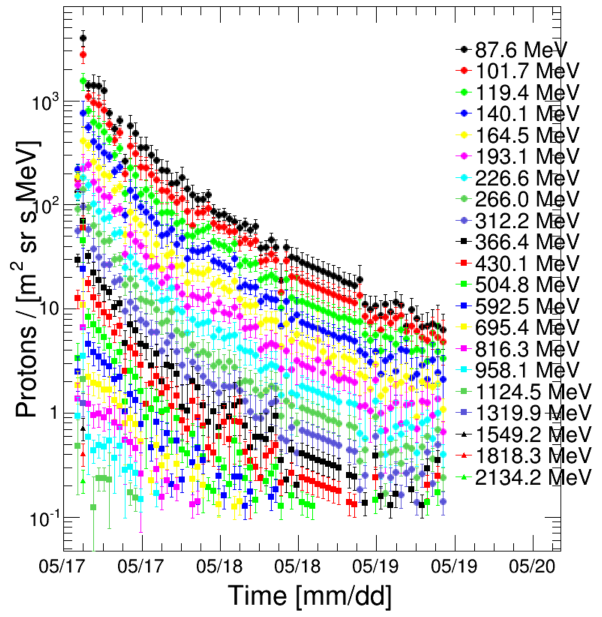
SEP events and magnetic connectivity

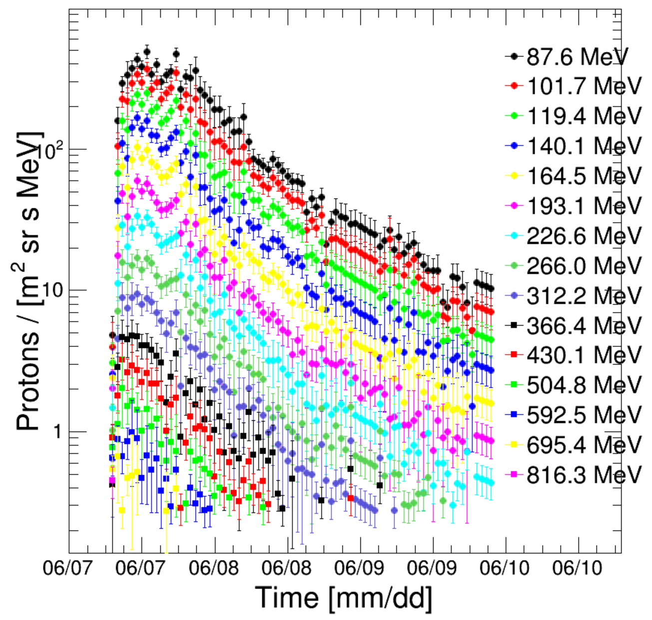
The intensity time profiles are organized by the longitude of the associated solar events

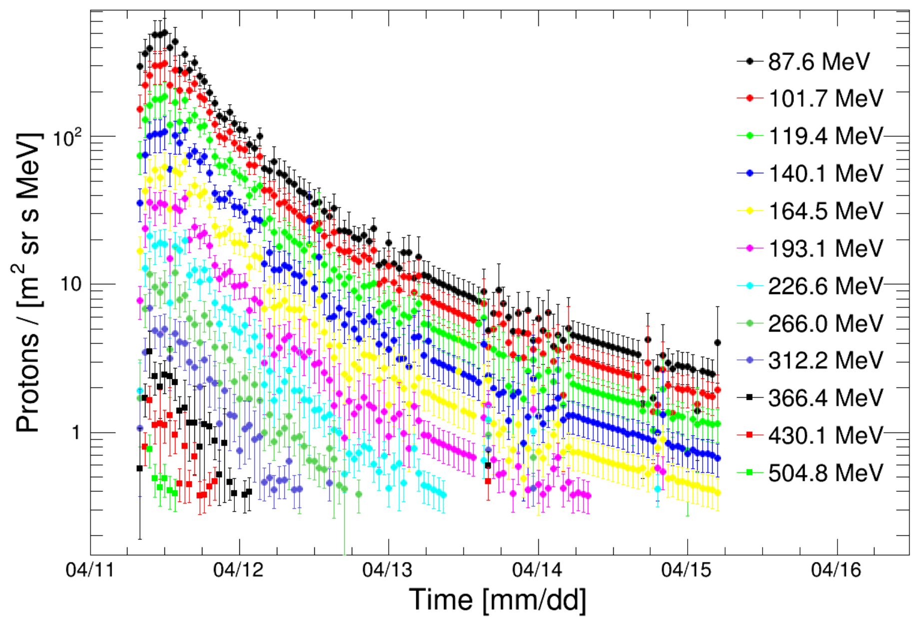






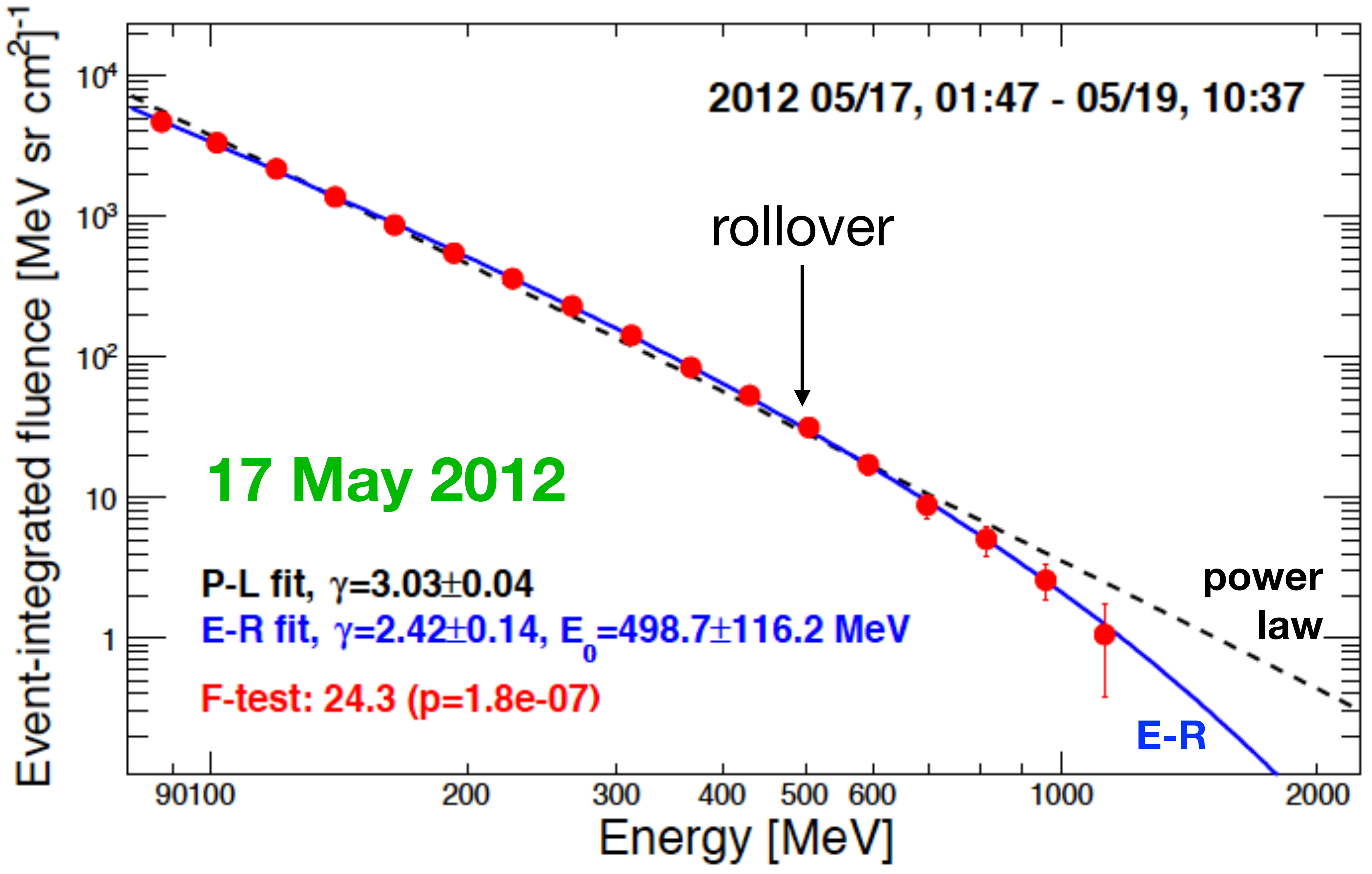






When high-energy particles from poorly connected events are detected at Earth, they tend to be in **long duration**, relatively weak, SEP events, where processes such as **cross field diffusion** and **co-rotation** with the Sun delay their arrival and extend their duration at Earth.

Spectral fits



- SEP event-integrated spectra were fitted by using a functional form based on **Ellison & Ramaty (1985)**, consisting of a power-law spectrum modulated by an exponential:

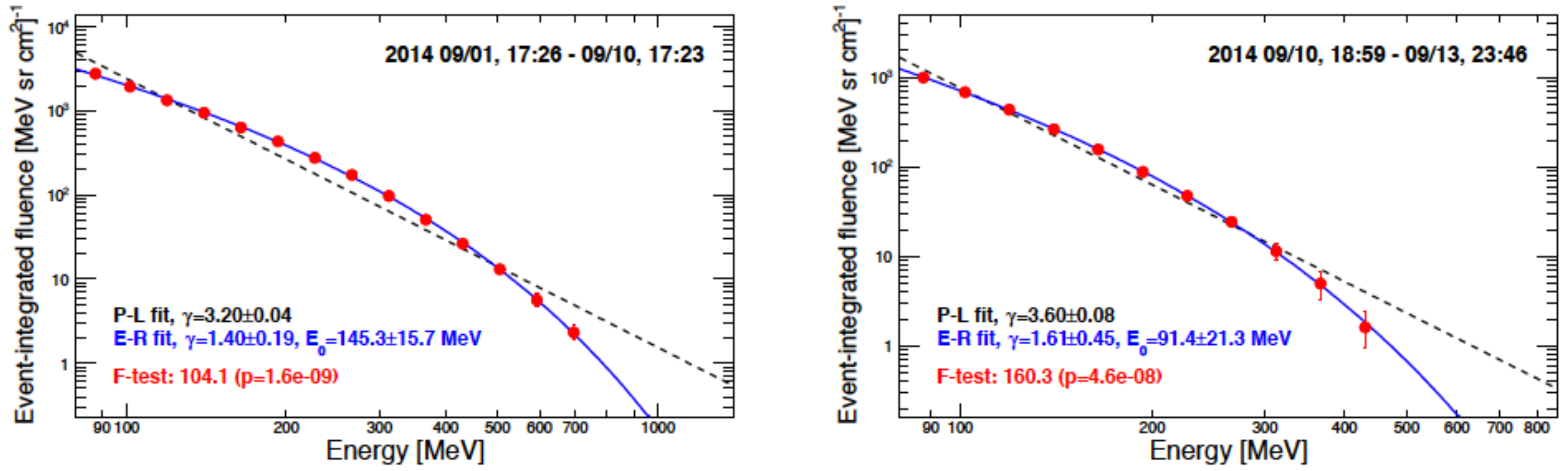
$$\Phi_{sep}(E) = A \times (E/E_s)^{-\gamma} \times e^{-E/E_0}$$

where E_0 is the rollover energy and the scaling energy E_s is fixed to the PAMELA energy threshold (80 MeV)

- In the simplest scenario (no transport effects) and in terms of **diffusive shock acceleration (DSA)**, 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) → NB: *a power-law extending to infinite energies is unphysical!*

Spectral fits

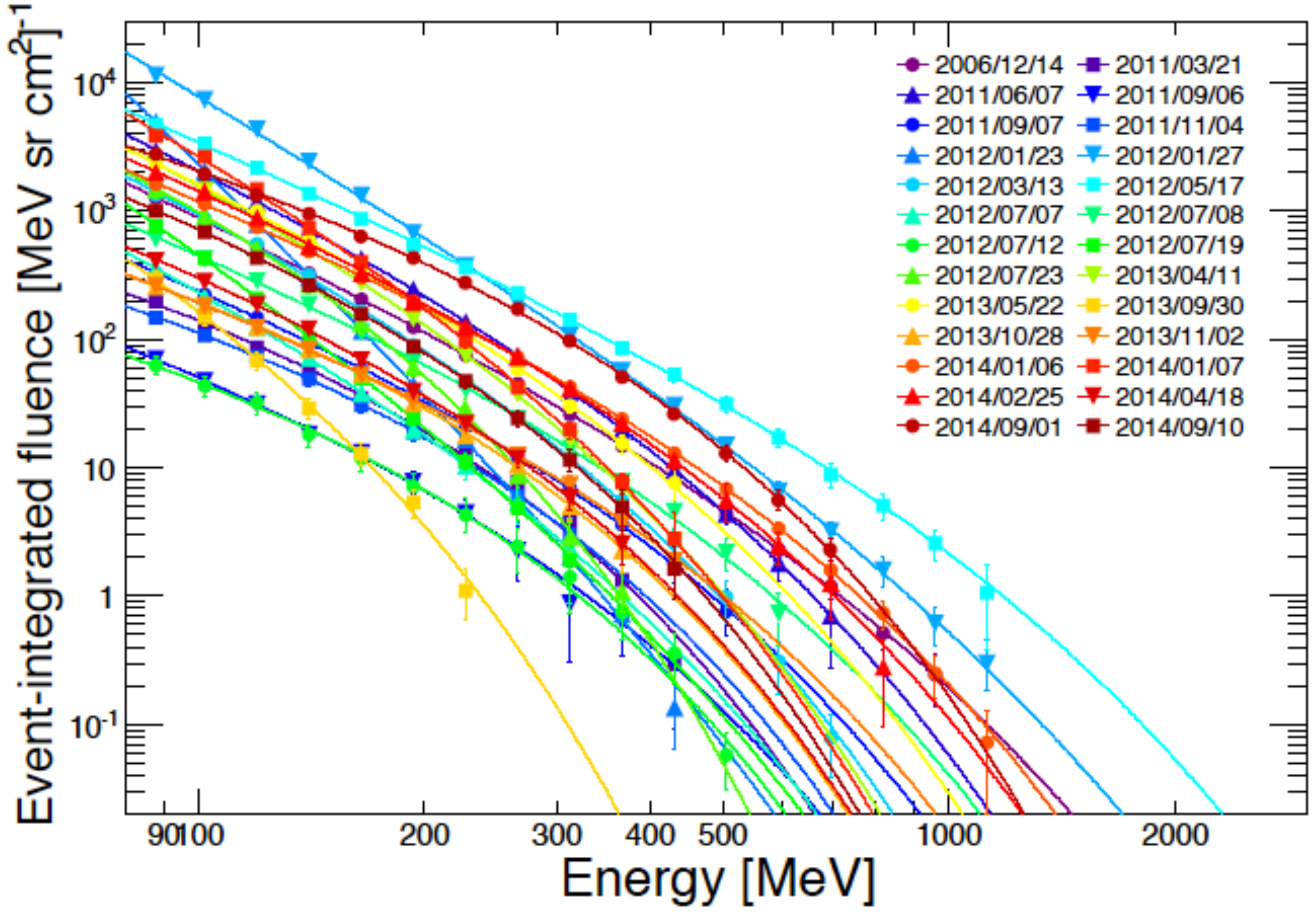
The power-law hypothesis is rejected in all the cases

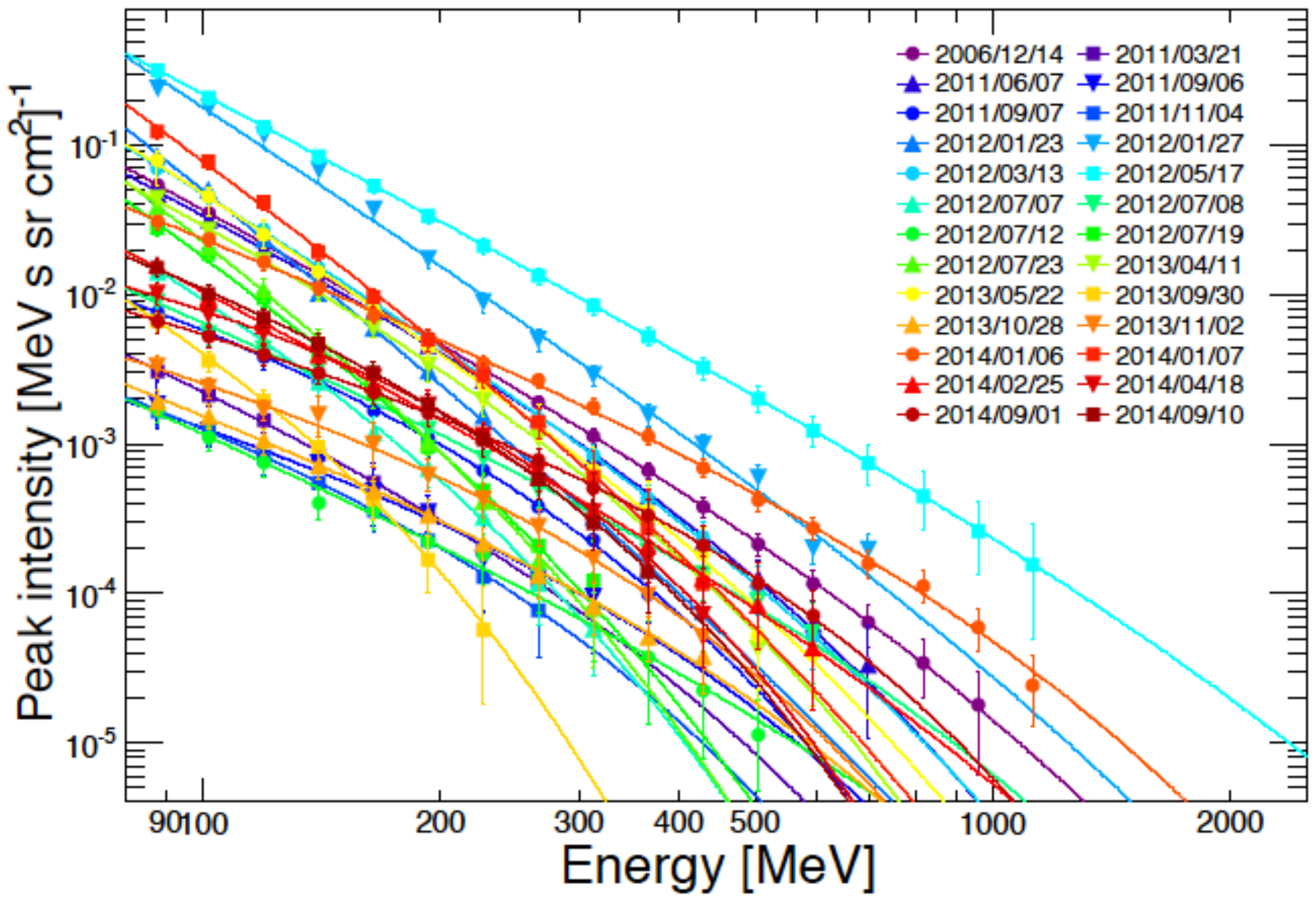


All the spectra are well reproduced by the E-R functional form

Bruno, A., *et al.* 2018, ApJ, 862:97

Spectral fits



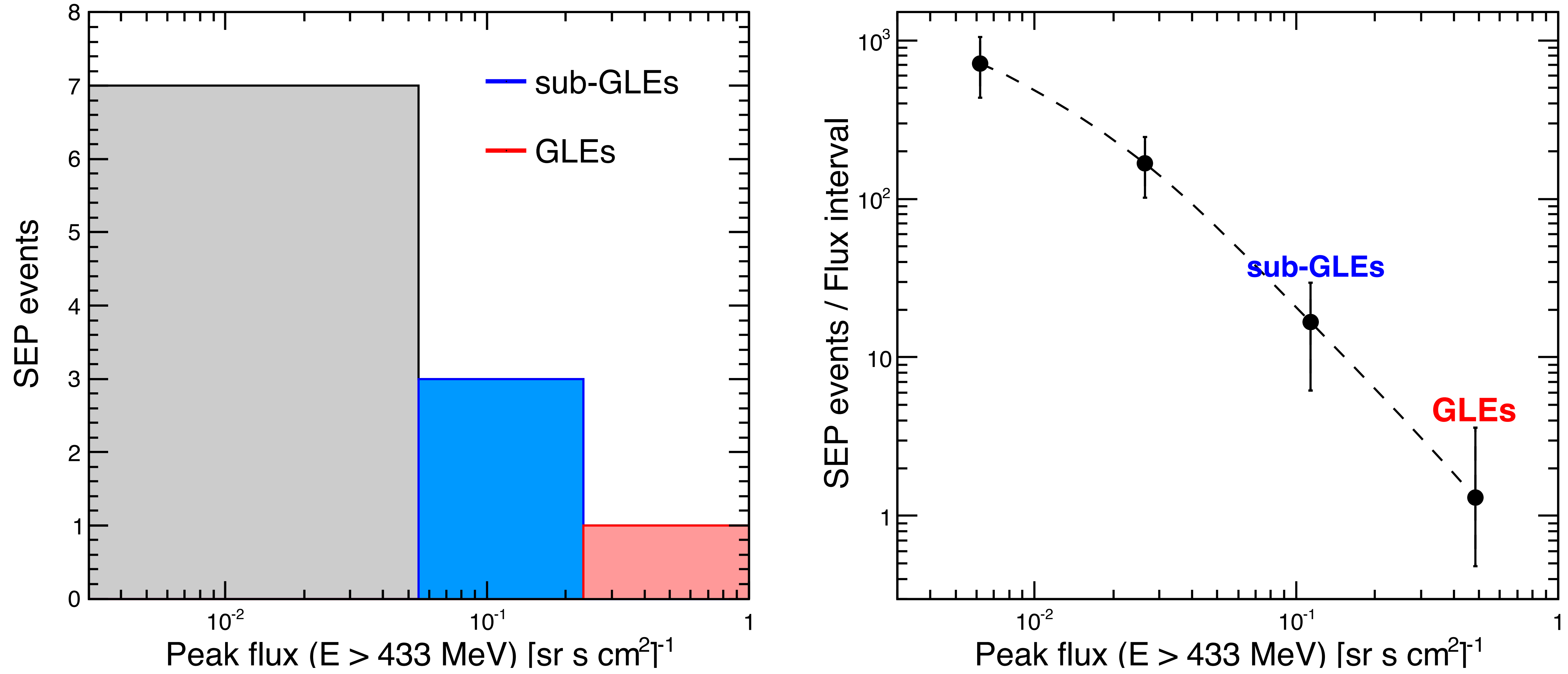


- PAMELA data as a whole span about five and four orders of magnitude in fluences and peak intensities, respectively.
  - **No qualitative differences in the spectra of all measured events (E-R functional form)**
- Results are consistent with **DSA** theory predictions (e.g. Ellison & Ramaty (1985), Lee & Ryan (1986), Lee (2005))
  - Particles can be scattered by magnetic turbulence back and forth across the shock multiple times, achieving efficient acceleration.
  - **High-energy spectral rollovers 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.

GLE vs non-GLE events

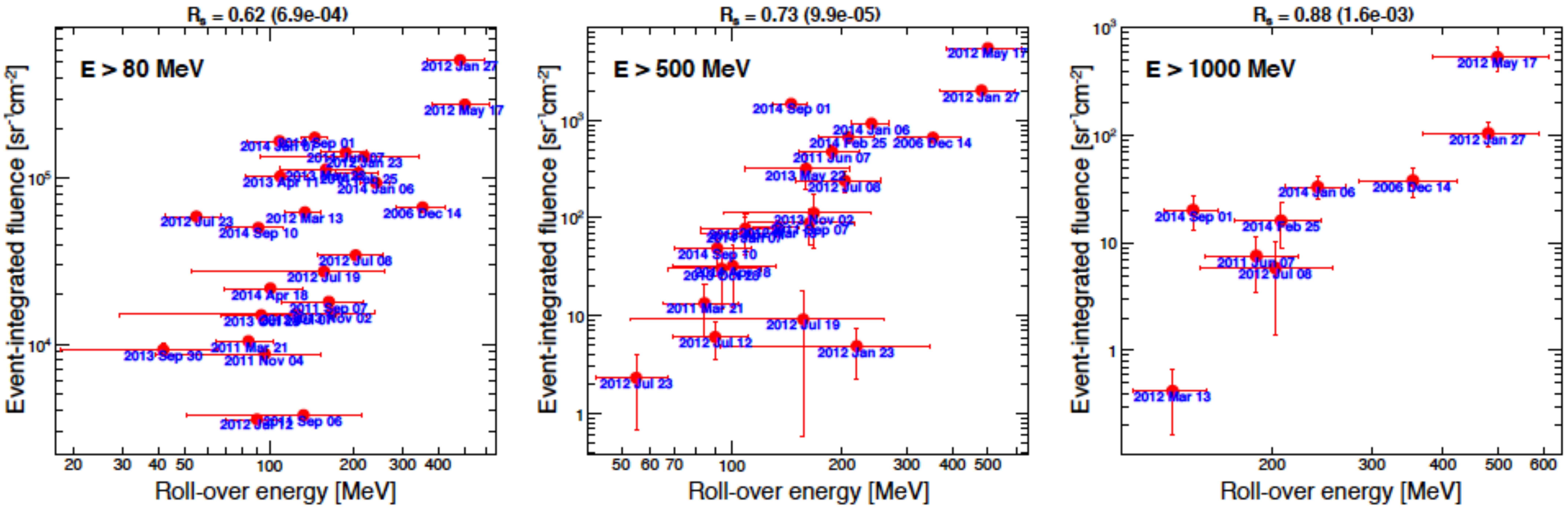
- ***GLEs**: at least two independent NMs – including a near sea level station – registered a simultaneous statistically significant increase related to the SEP arrival (threshold: 1 GV or ~433 MeV)*
- ***sub-GLEs**: SEP events registered only by the high-altitude South Pole NMs (threshold: ~300 MeV)*

Several concomitant factors may contribute to the SEP variability and to the rarity of the GLE events, such as the associated shock speed, morphology and evolution, the ambient conditions, the presence of seed particle populations, the magnetic connection to Earth and the interplanetary transport.



- The occurrence rate of SEP events of a given peak intensity is inversely related to the intensity itself.
- No qualitative distinction between the spectra of GLE and non-GLE events was observed, suggesting that GLEs are **not a separate class**, but rather are a subset of a continuous distribution of SEP events that are more intense at high energies (harder spectra)

PAMELA results and DSA theory



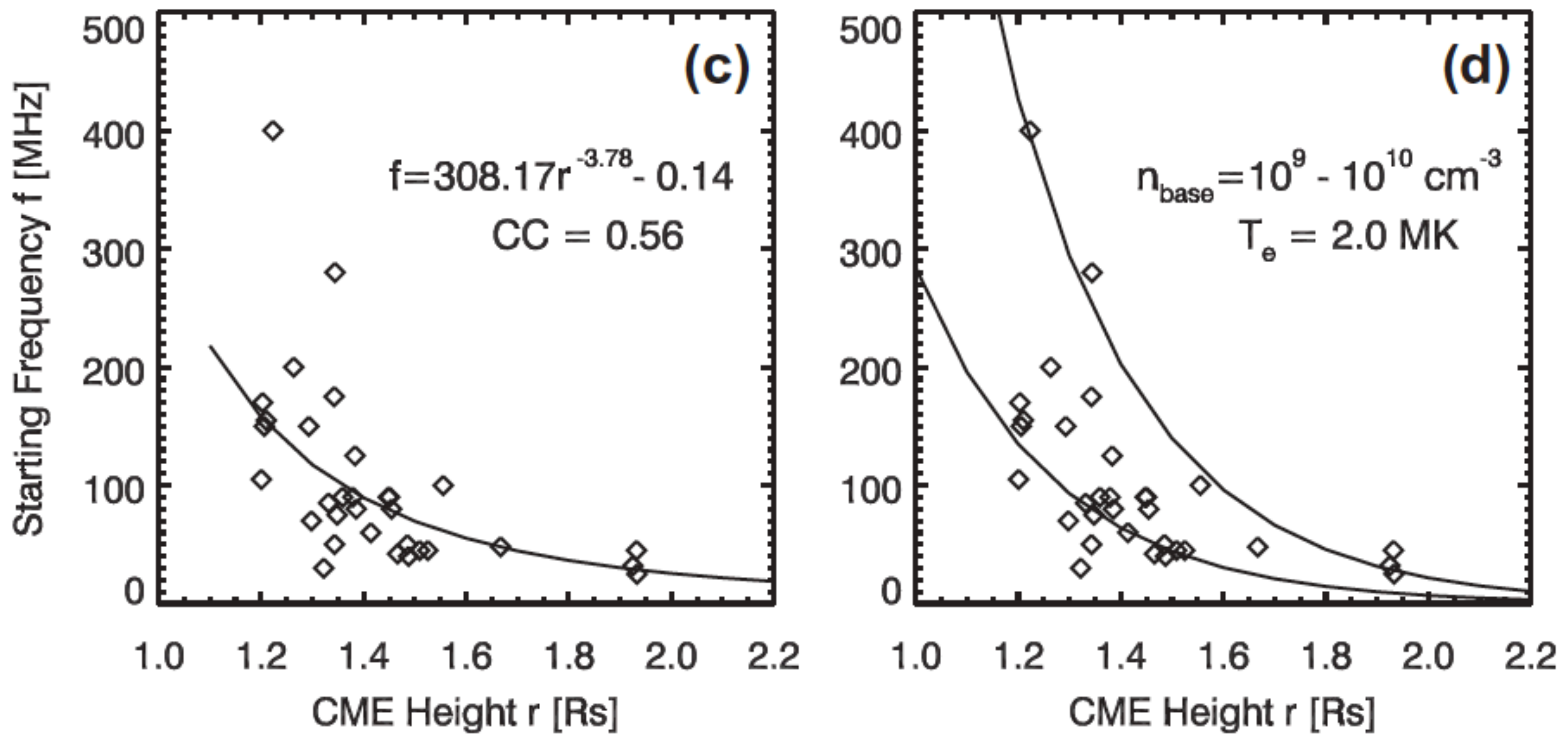
Measured fluences well correlated with rollover energies, with the spectra of the most energetic events exhibiting the highest cutoffs; the correlation improves with increasing proton energy.

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

SEP maximum energy

- It has been suggested that the **maximum particle energy** may be determined by several concomitant factors,
  - including the shock speed, geometry and age, the coronal magnetic field strength and configuration, and the presence of seed particle populations.
- Recent studies have shown that the most energetic particles originate **very close to the Sun (<2 Rs)**, where the magnetic field is stronger and thus the acceleration is more efficient
  - This is corroborated by observations of **type-II radio bursts** produced by electrons accelerated by shocks, which commence at higher frequencies for the most energetic particle events
- Since both the shock speed and the magnetic field strength decrease with increasing heliocentric distances, the maximum acceleration energy **reduces with time** as the shock propagates out into the interplanetary space
- As higher energy particles are expected to be accelerated closer to the shock nose, better magnetically connected events tend to have harder spectra

Spectral rollovers and type-II radio emission



- The starting frequency of the type-II bursts is correlated with the shock formation height (e.g., Gopalswamy *et al.* (2013))
- Higher frequencies are thus associated with smaller helio-distances (higher densities, more intense fields → **higher SEP max energies**)

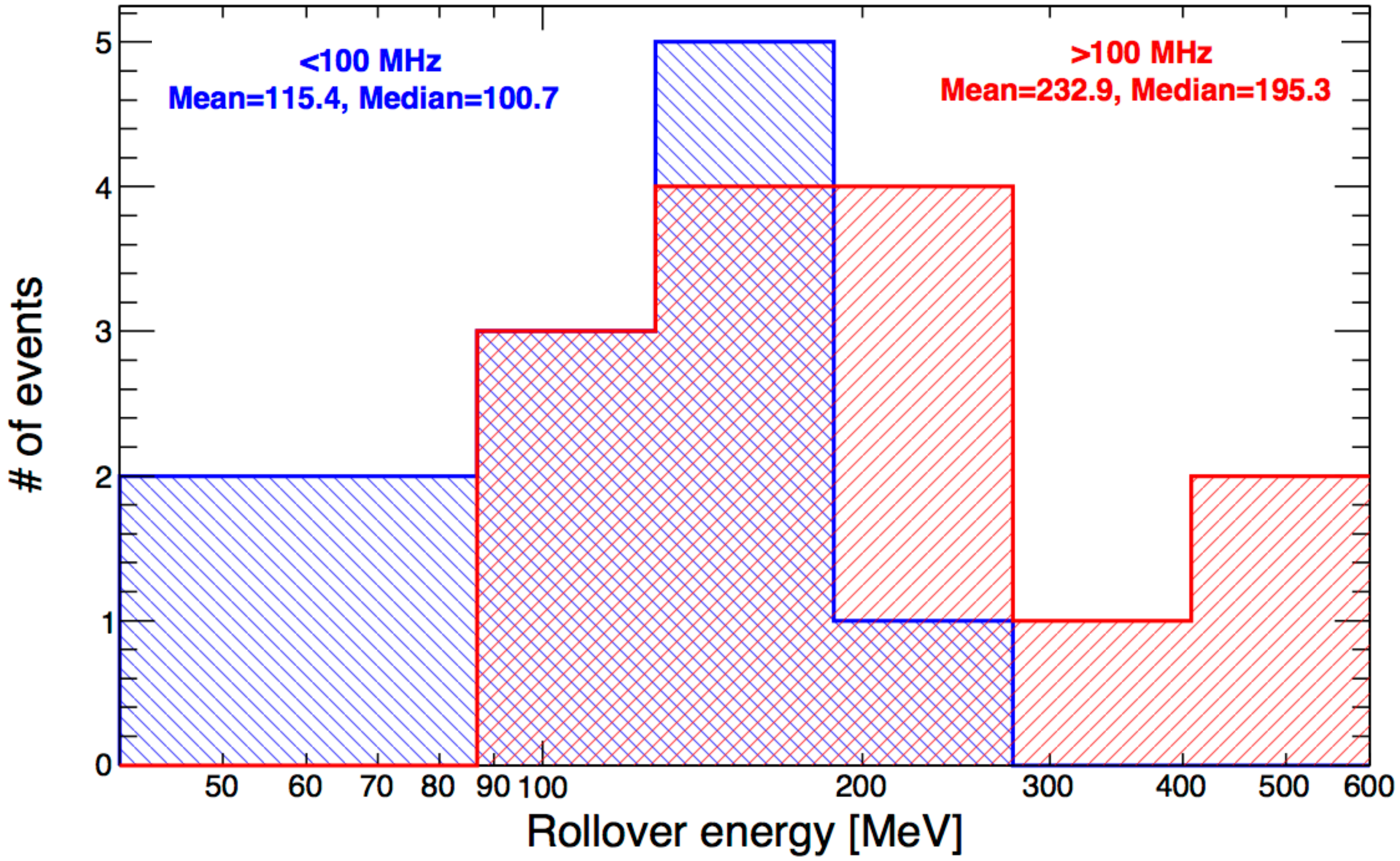
PAMELA events subdivided into two samples based on the **starting frequency of the type-II radio emission**

All PAMELA SEP event were associated with **long-duration type-II and type-III radio bursts**

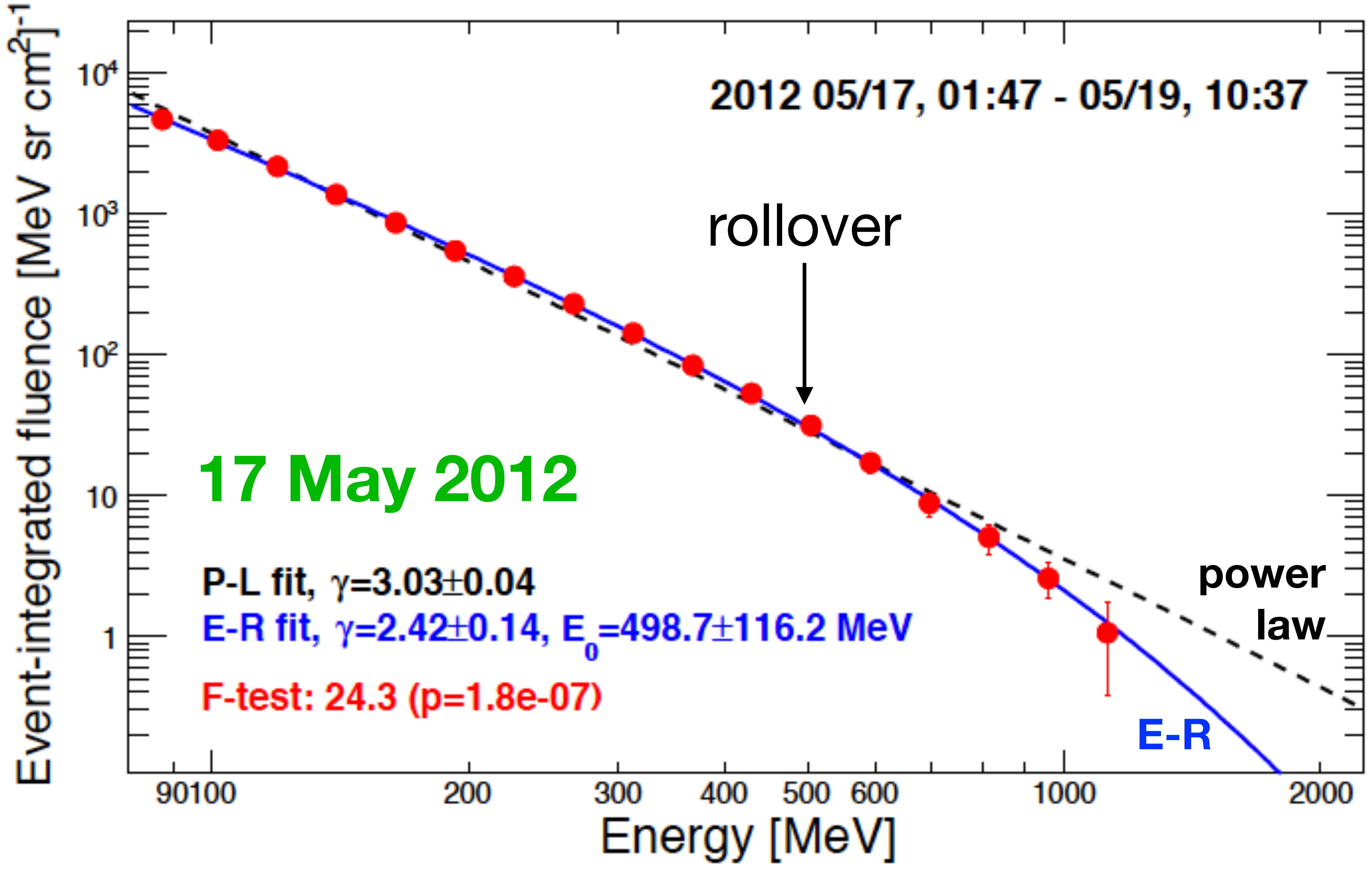
In particular, detected type-II emission extends from decameter-hectometric (DH) to metric (m) wavelengths

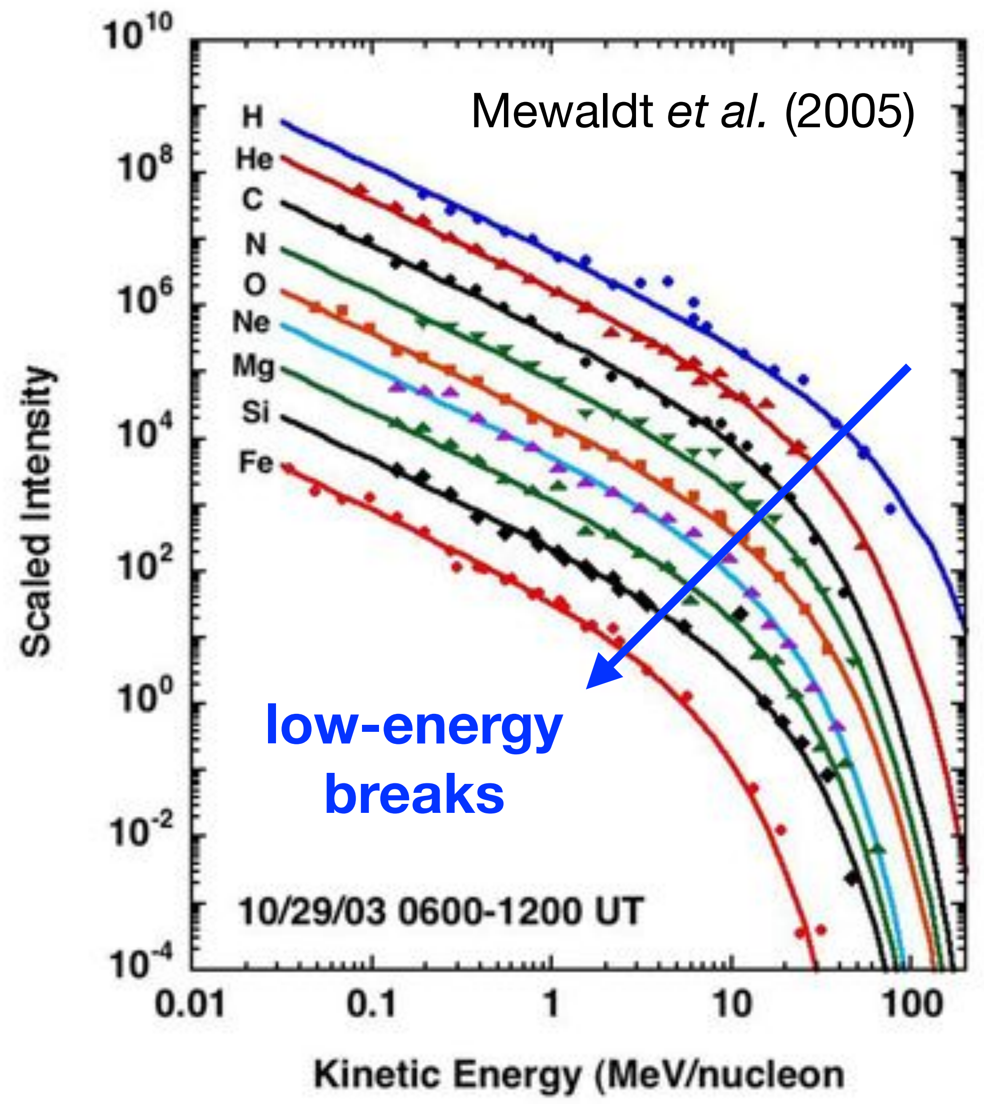
On average, higher rollover energy values are associated with higher type-II starting frequencies

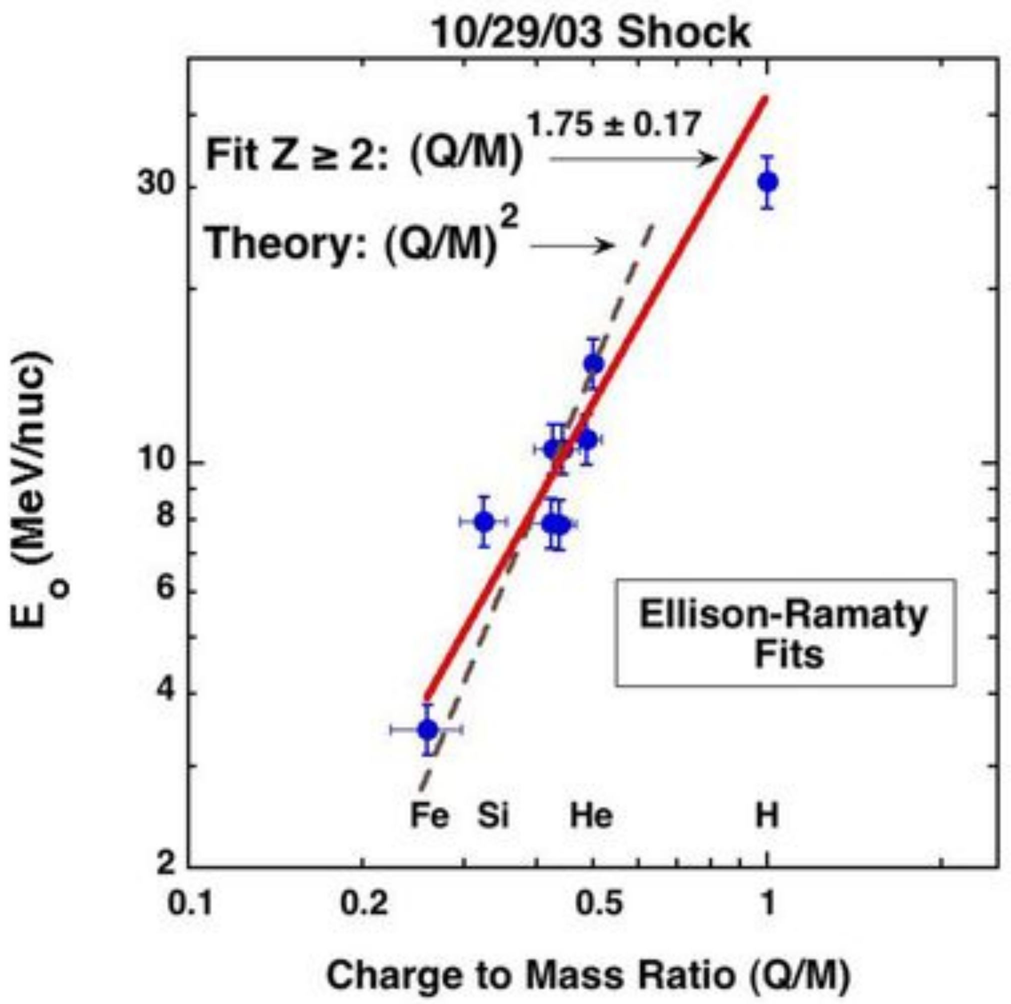
→ **lower shock formation heights**



Spectral rollovers and low-energy breaks





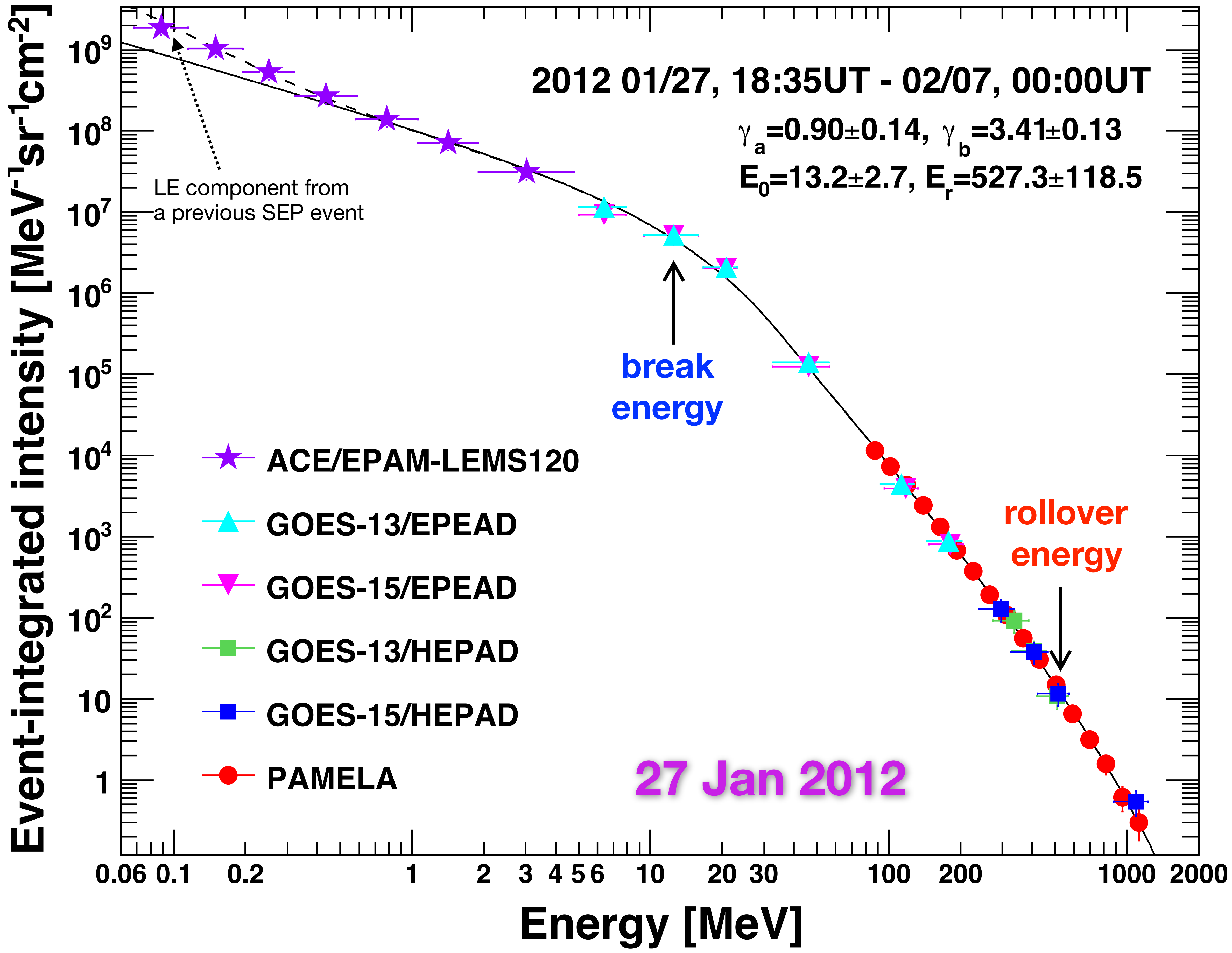


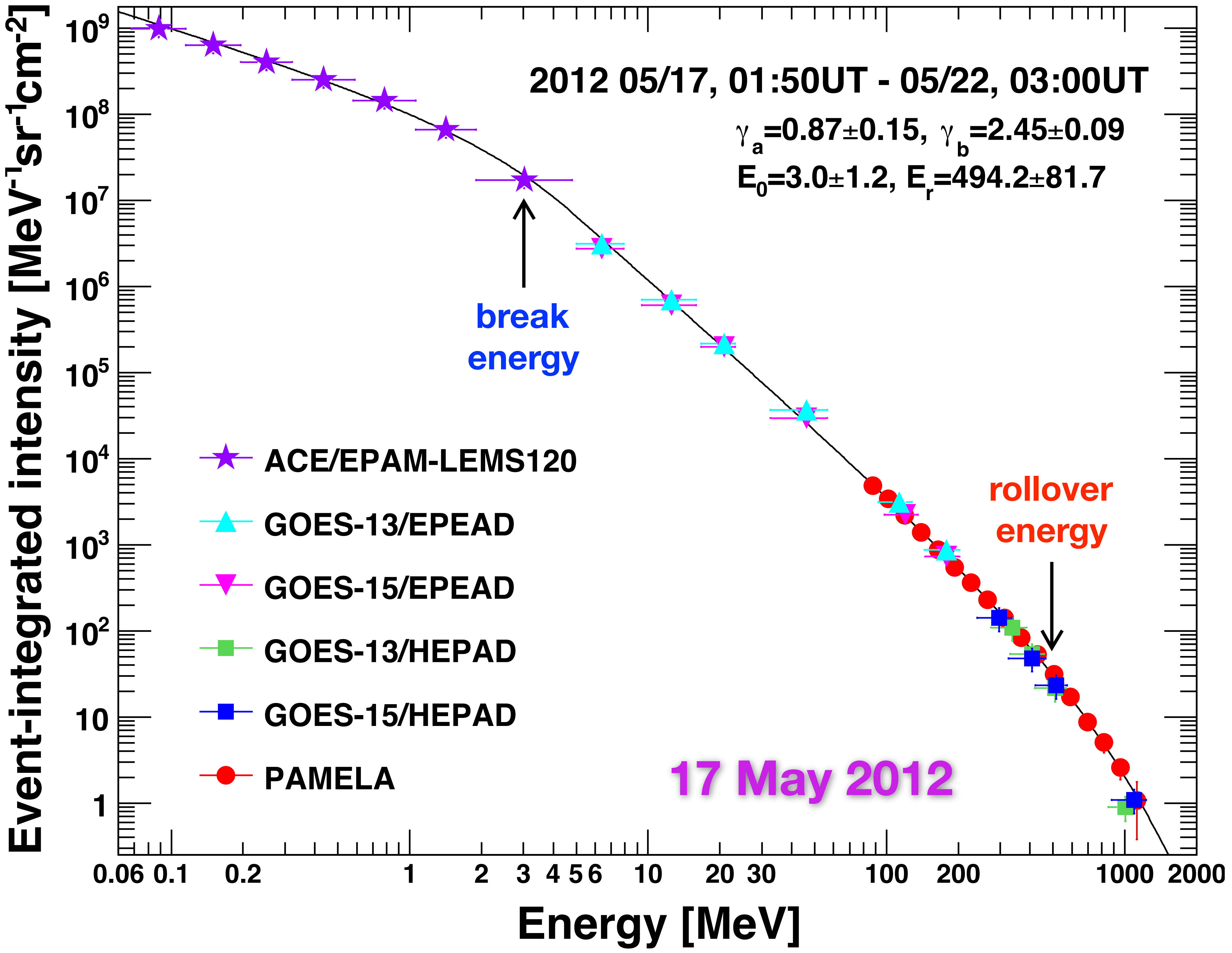
- In the scenario of DSA, the high-energy (several tens/hundreds of MeV) spectral rollovers reported for the first time by PAMELA are attributed to particles escaping the shock region during acceleration due to effects mostly related to the limited extension and lifetime of the shock
  - three-dimensionality 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.

- It should be emphasized that they represent a **distinct spectral feature with respect to the breaks previously reported at much lower energies (few/tens of MeV/n)** in the spectra of H-Fe nuclei (e.g., Mewaldt *et al.* (2005))

- While such low-energy spectral breaks, that decrease in energy with the ion charge-to-mass ratio, were predicted to originate from DSA at near-Sun, there are alternative interpretations based on interplanetary transport effects (e.g., Lee & Li (2005); Zhao *et al.* (2016))

SEP spectra in a wide energy range





E_r = rollover energy, E_0 = break energy

70 keV - few GeV event-integrated spectra based on combined ACE+GOES+PAMELA data

GOES-EPEAD/HEPAD data are based on the calibrations by Sandberg *et al.* (2014) and Bruno (2017) for proton energies below and above 80 MeV, respectively

Conclusions

- The PAMELA satellite-borne experiment has provided **first direct spectral measurements of SEP events over a wide energy region ranging from 80 MeV to few GeV**, bridging the low-energy observations by in-situ spacecraft and rare GLE detections made by the ground-based NM network.
  - Spectra of the 26 major SEP events between 2006 December and 2014 September.
  - Extension to other high-energy events in solar cycle 24 (e.g. 2017 September events) taking advantage of cross-calibrated GOES data
- PAMELA results significantly improve the characterization of most energetic SEP events
  - **Measured spectra exhibit a high-energy rollover that can be attributed to the limits of DSA**.
    - However, transport processes must also contribute to the spectral variability, and further work is required to explore the relative influences of acceleration and transport.
  - No qualitative distinction between the spectra of GLE and non-GLE events, suggesting that GLEs are not a separate class, but are a subset of a continuous distribution of SEP events that are more intense at high energies.
- The SEP spectra were reconstructed over a wide energy range by combining PAMELA, ACE and GOES observations, enabling the investigation of the relationship between low- and high-energy particles, and a clearer view of the SEP origin and propagation mechanisms (work in progress).

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- Bruno, A., *et al.* 2018, ***Solar Energetic Particle Events Observed by the PAMELA Mission***, ApJ, 862:97, doi: https://doi.org/10.3847/1538-4357/aacc26
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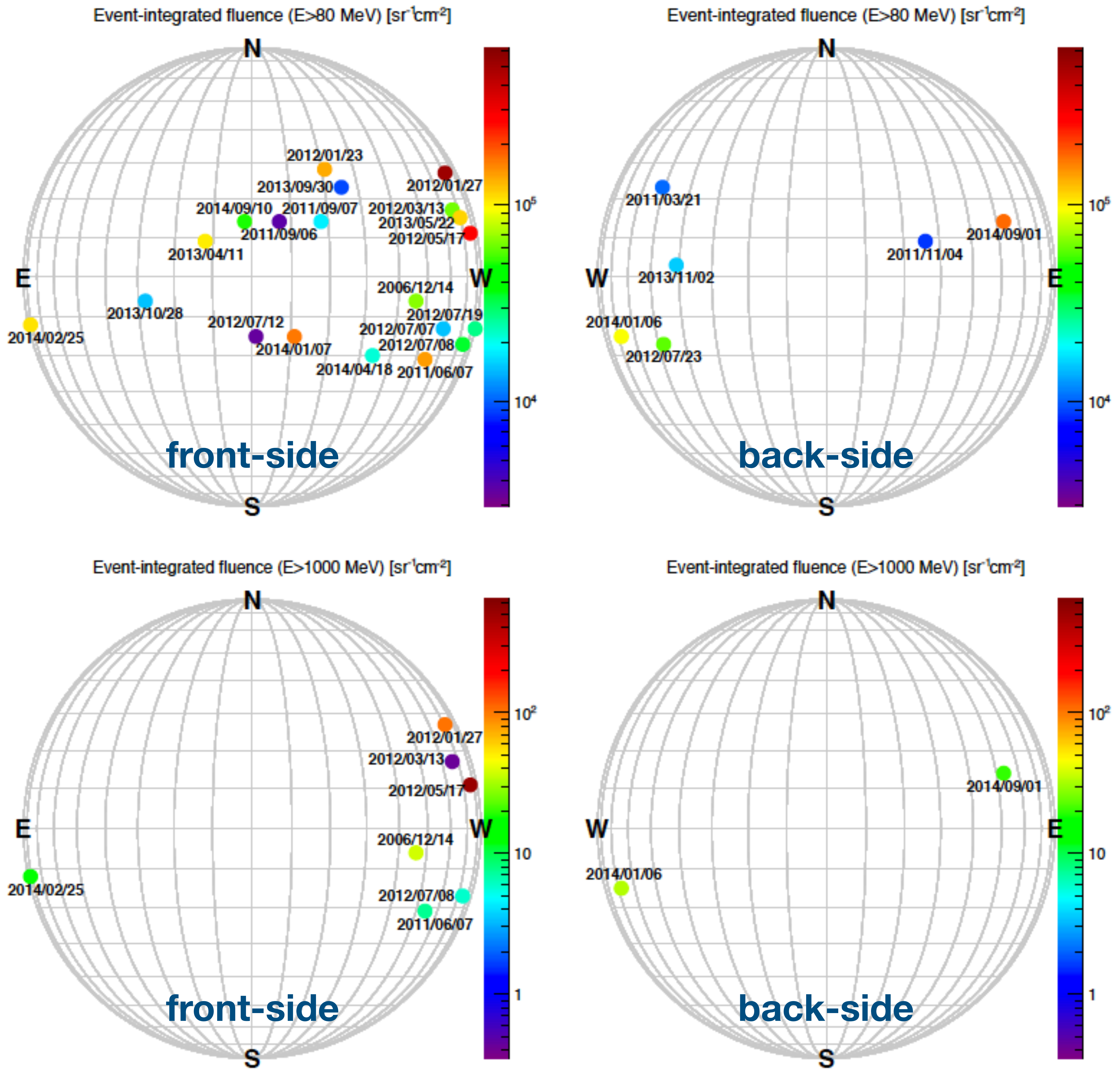
Spares slides

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

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

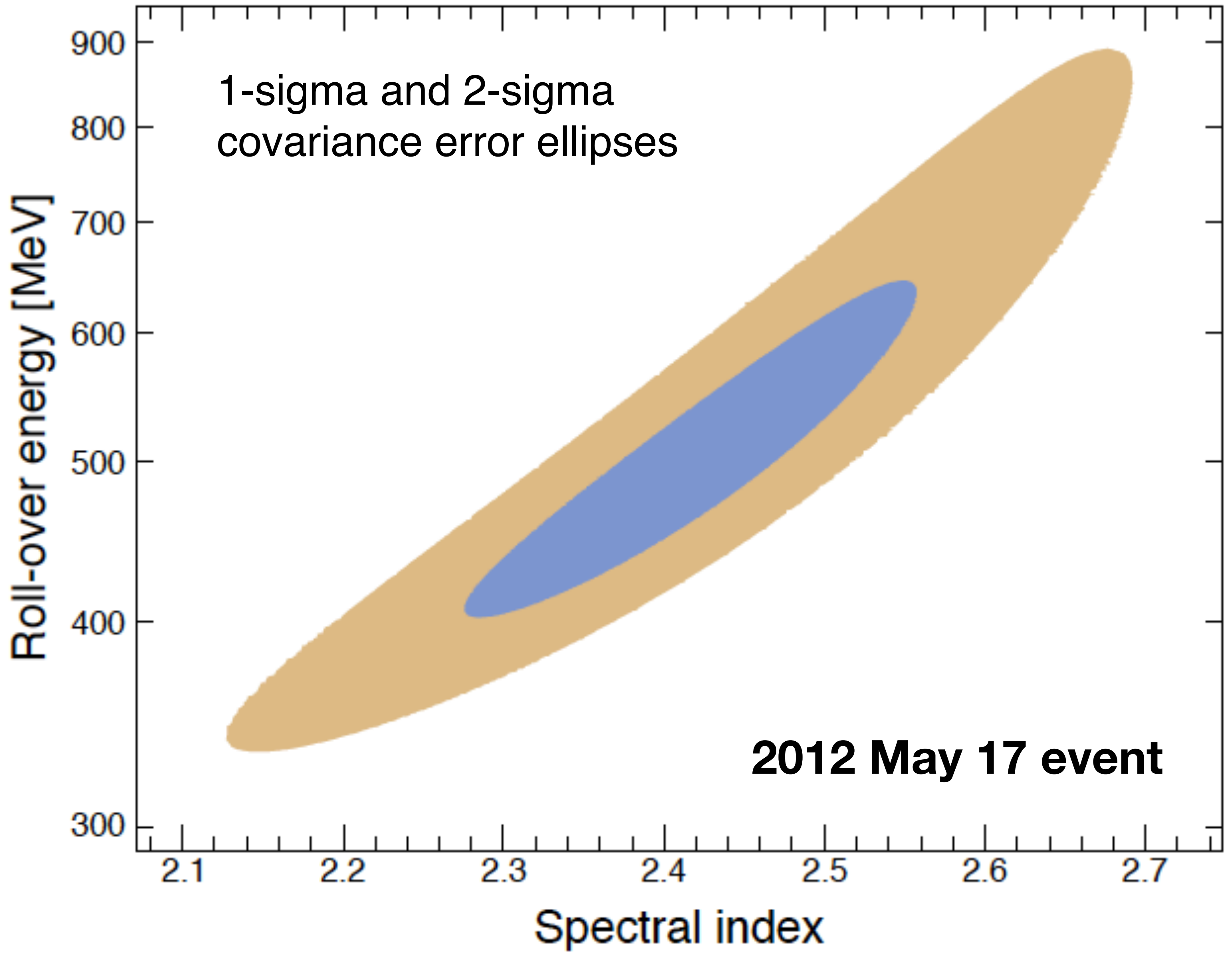
Event-integrated intensity vs source heliographic location



>80 MeV

>1000 MeV

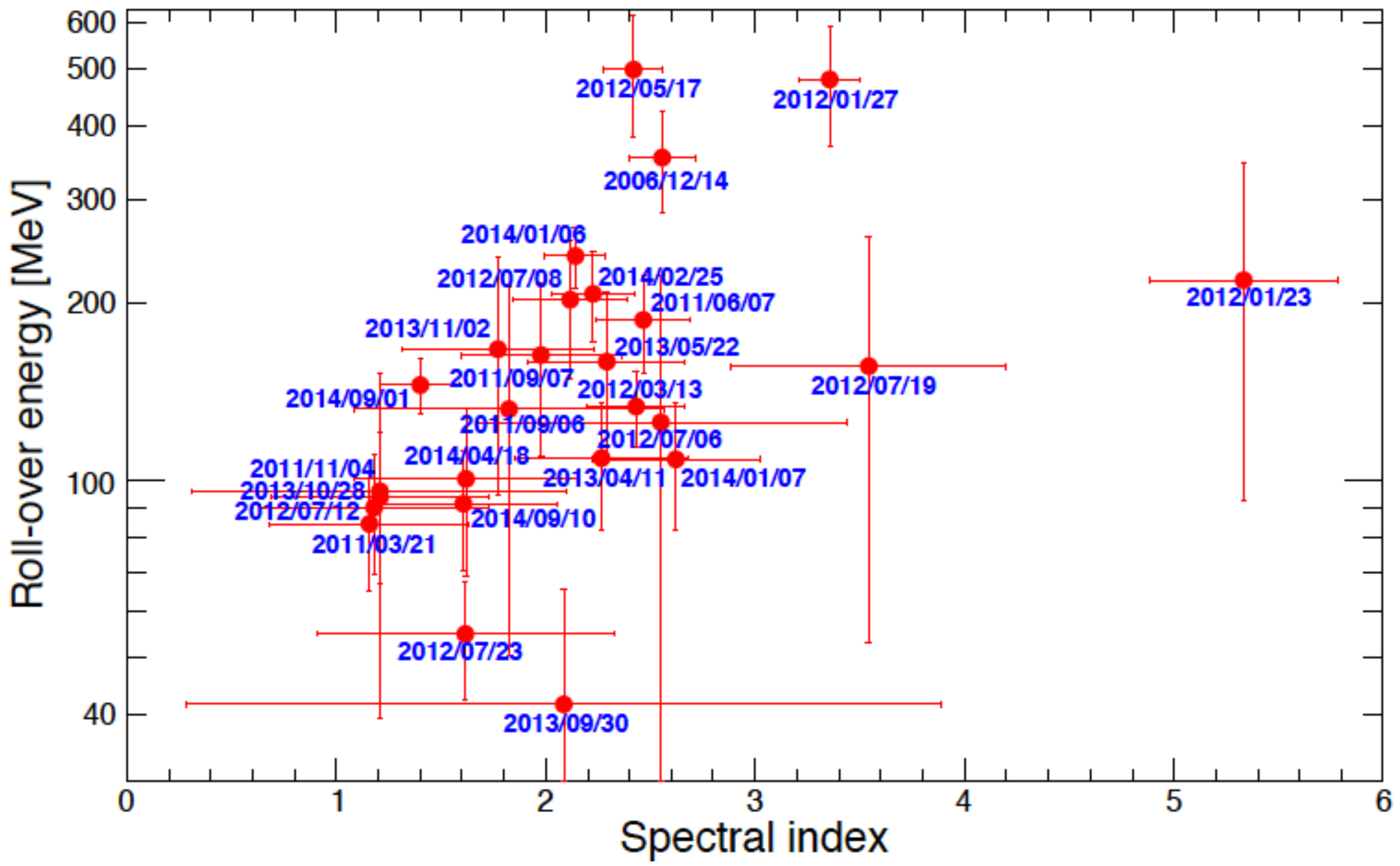
Spectral fits: cross-correlations



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

The rollover 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 rollover energy.



Rollover energy vs spectral index global distribution. An overall trend can be noticed, with higher rollover energies associated with larger spectral indices.

The global positive correlation between rollover 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.

Spectral fit in a wide energy range

- In general, spectral features observed at different energies may arise from particle acceleration in different locations (e.g., the flare region, corona or interplanetary space), so the spectral shapes may exhibit the **combined signatures of several dynamic processes** that may be complex to disentangle.
- Furthermore, the morphology and the evolution of SEP events are strongly influenced by the magnetic connection to sources, and by interplanetary transport effects and transient/corotating solar wind disturbances, which significantly complicate the interpretation of data.
- As a consequence, **it is challenging to model the SEP spectral shape over a wide energy range with a simple functional form**.
- An attempt to reproduce both the low-energy break and the high-energy rollover in the SEP spectra is provided by the ``combined'' function (see Bruno *et al.* (2019), Space Weather, 17, 419):

$$\Phi_{tot}(E) = \Phi_{Band}(E)\ exp(-E/E_r)$$

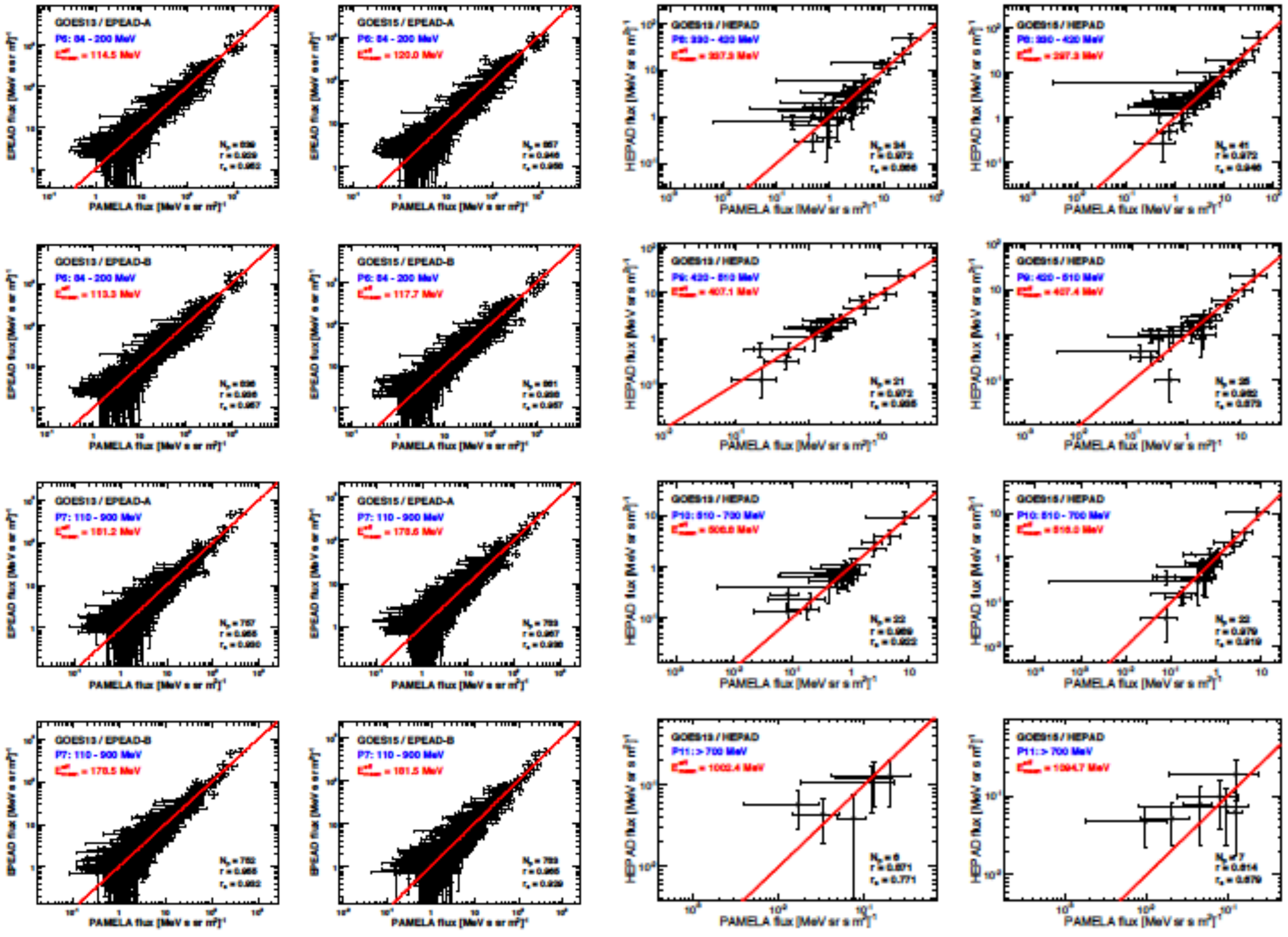
where:

$$\Phi_{Band}(E) = \begin{cases} A\ E^{-\gamma_a}\ exp(-E/E_0) & \text{for } E < (\gamma_b - \gamma_a)\ E_0, \\ A\ E^{-\gamma_b}\ [(\gamma_b - \gamma_a)\ E_0]^{(\gamma_b - \gamma_a)}\ exp(\gamma_a - \gamma_b) & \text{for } E > (\gamma_b - \gamma_a)\ E_0, \end{cases}$$

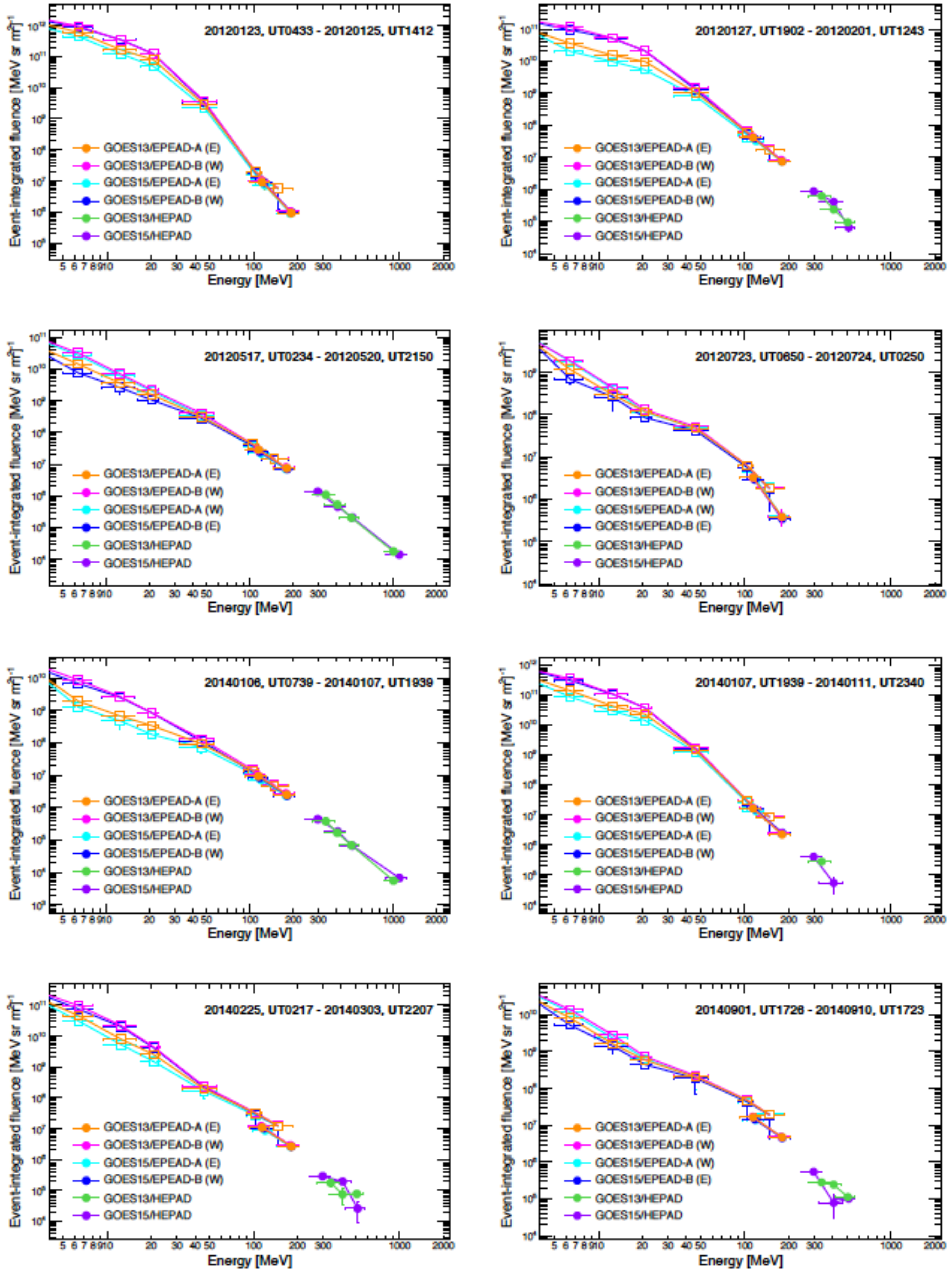
is the *Band function*, providing a smooth transition between two regions with different spectral index (γ_a, γ_b); E_r = rollover energy, E_0 = break energy.

Calibration of GOES-13/15 proton detectors

Bruno (2017), Space Weather, 15, 1191

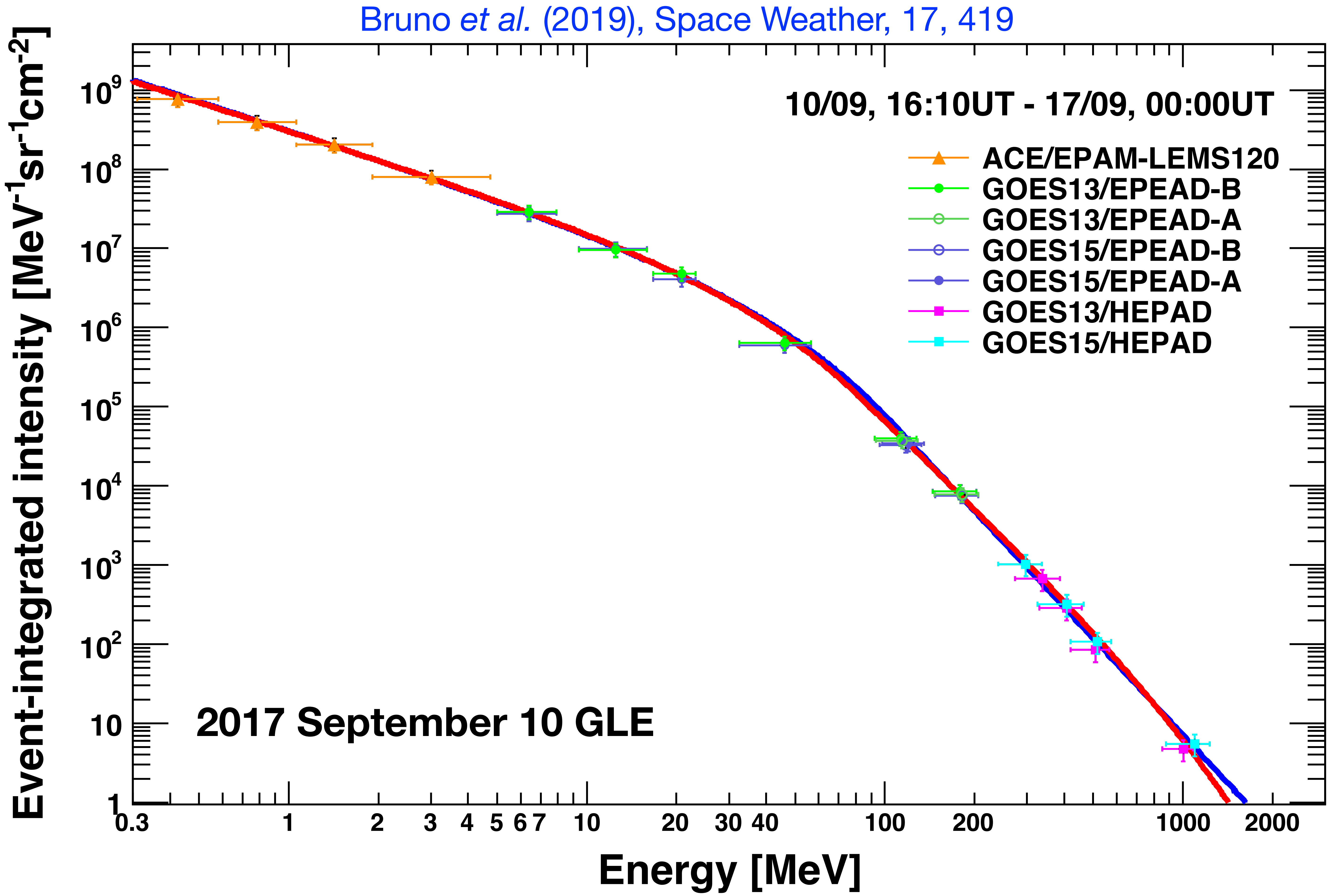


EPEAD sensors **HEPAD sensors**



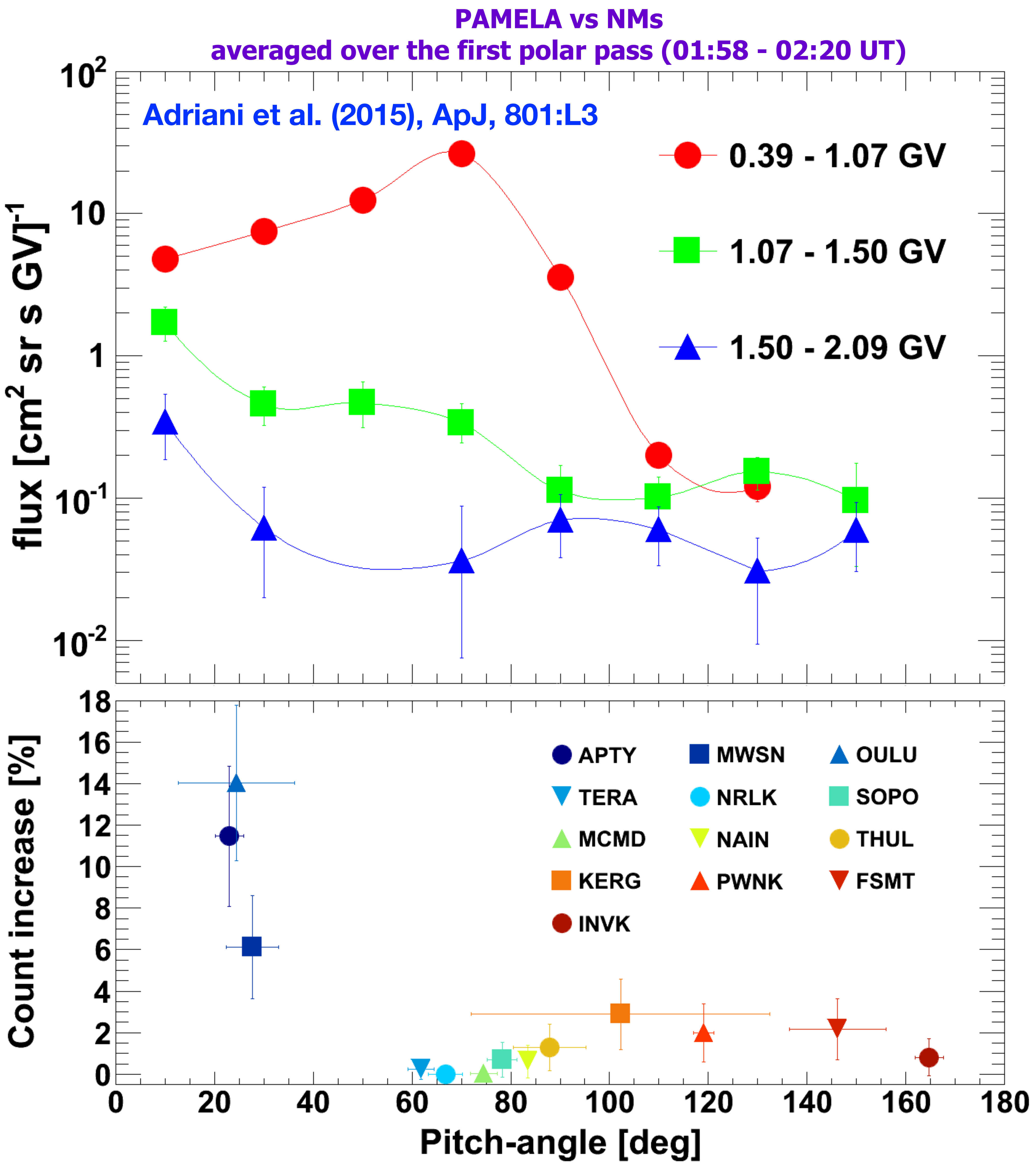
the high quality data measurements of PAMELA mission were used to calibrate the **high-energy (>80 MeV) proton channels (P6—P11) of the EPEAD and the HEPAD sensors onboard the GOES-13 and -15**, bringing the measured spectral intensities in-line with those registered by PAMELA. Suggested corrections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

Spectral results for the 2017 September 10 GLE event



The new calibrated GOES/EPEAD-HEPAD data enable a more precise measurement of the SEP energy spectra during the intervals when PAMELA was not acquiring data (e.g. 2011 August) or after the mission was terminated (e.g. the 2017 September events)

SEP pitch-angle distribution: the 2012 May 17 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.