New reconstruction of the event-integrated spectra for GLE events

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Outline

1. Motivation.
2. The new R_{eff} method (“bow-tie”).
3. Reconstruction of SEP fluences (high- and low-energy).
4. Conclusion

Based on:

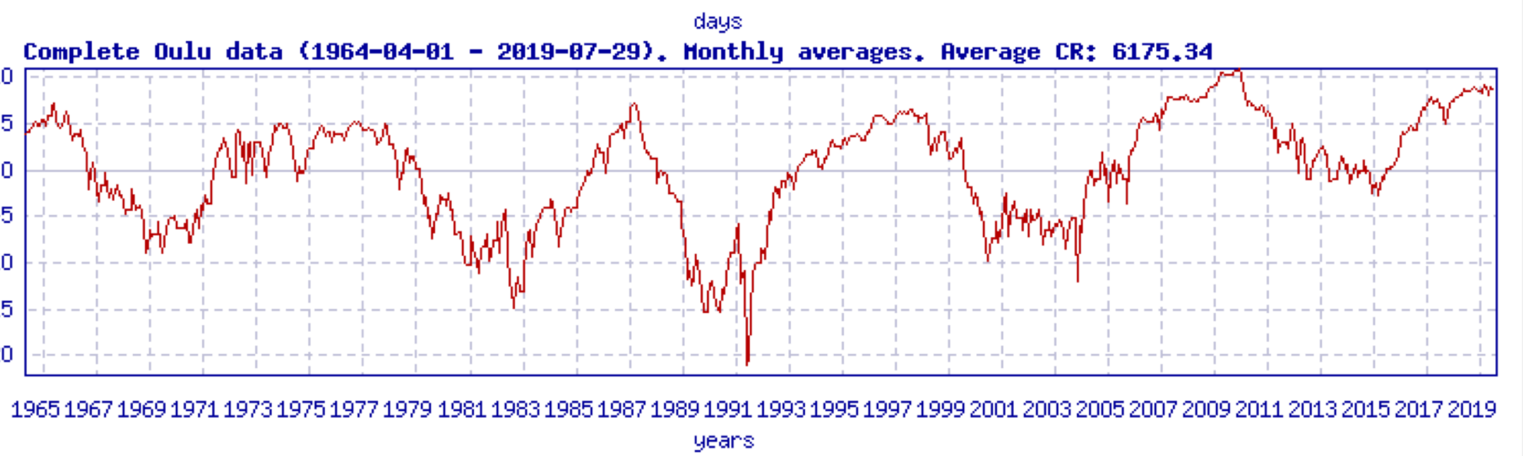
Solar Physics (2018) 293:110

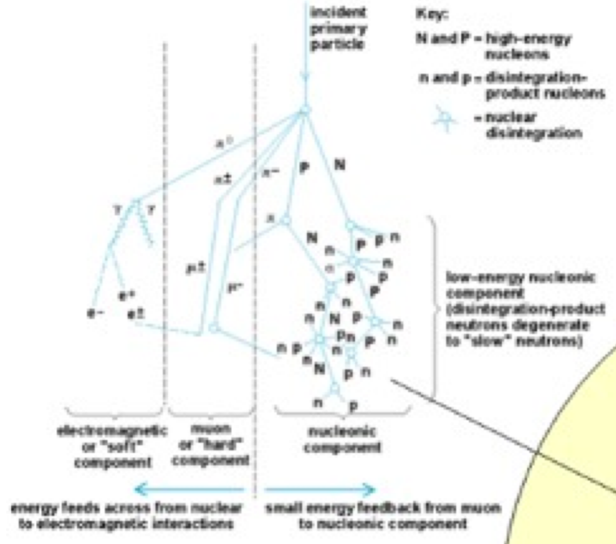
Solar Physics (2019) 294:94

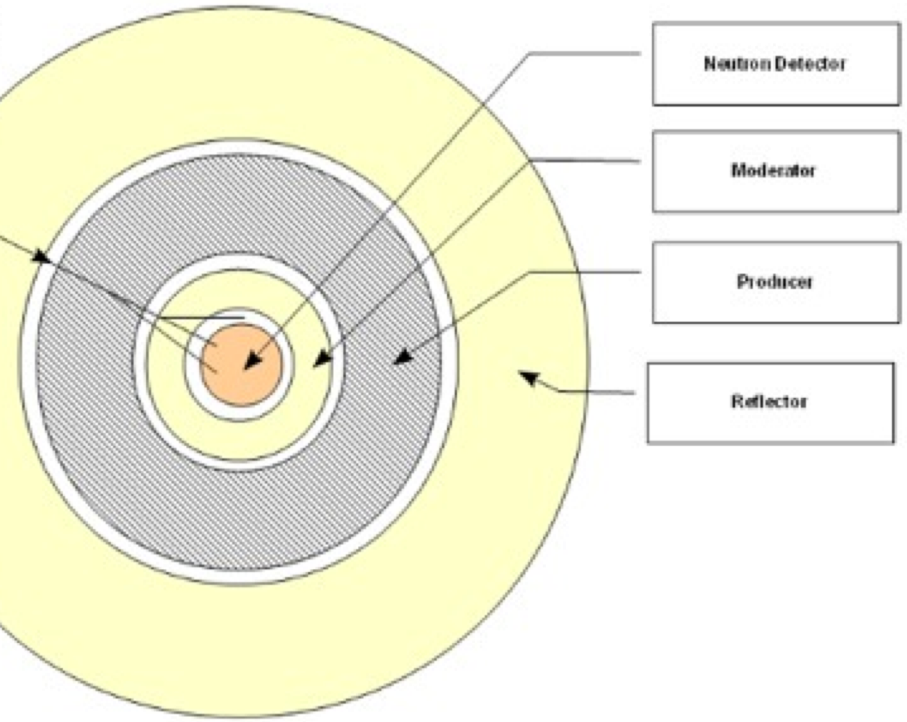
A&A (2020) 640 A17

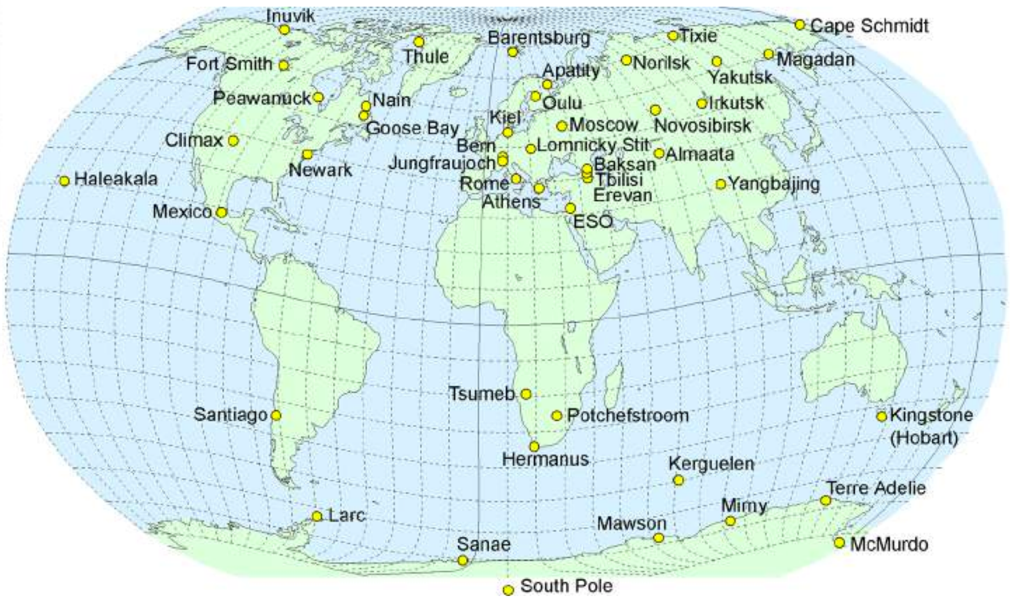
A&A (2021) 647 A132

Neutron Monitors

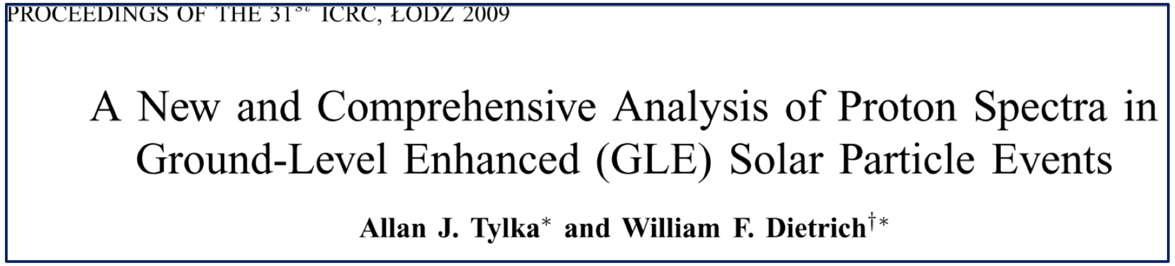








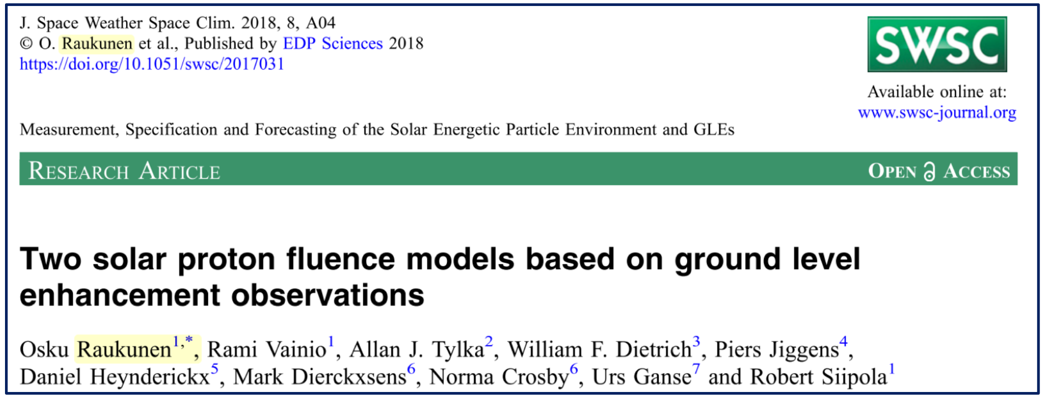
Overview on recent results



PROCEEDINGS OF THE 31st ICRC, ŁODZ 2009

A New and Comprehensive Analysis of Proton Spectra in Ground-Level Enhanced (GLE) Solar Particle Events

Allan J. Tylka[*] and William F. Dietrich[†*]



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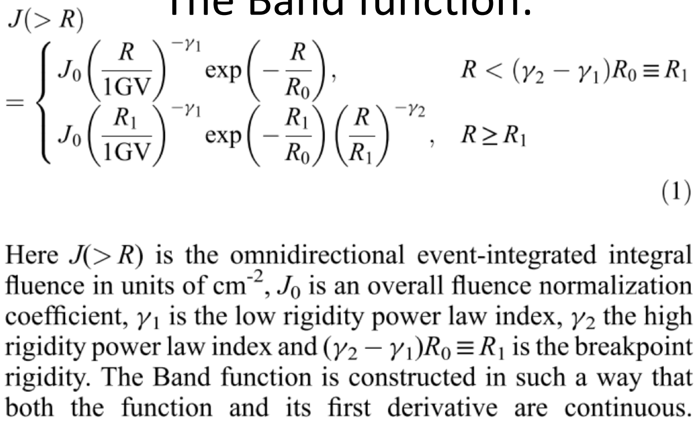
Measurement, Specification and Forecasting of the Solar Energetic Particle Environment and GLEs

RESEARCH ARTICLE — OPEN ACCESS

Two solar proton fluence models based on ground level enhancement observations

Osku Raukunen[1,*], Rami Vainio[1], Allan J. Tylka[2], William F. Dietrich[3], Piers Jiggens[4], Daniel Heynderickx[5], Mark Dierckxsens[6], Norma Crosby[6], Urs Ganse[7] and Robert Siipola[1]

The Band function:



$$J(>R) = \begin{cases} J_0\left(\frac{R}{1\,\mathrm{GV}}\right)^{-\gamma_1}\exp\left(-\frac{R}{R_0}\right), & R<(\gamma_2-\gamma_1)R_0\equiv R_1 \\ J_0\left(\frac{R_1}{1\,\mathrm{GV}}\right)^{-\gamma_1}\exp\left(-\frac{R_1}{R_0}\right)\left(\frac{R}{R_1}\right)^{-\gamma_2}, & R\geq R_1 \end{cases} \tag{1}$$

Here $J(>R)$ is the omnidirectional event-integrated integral fluence in units of cm^{-2}, J_0 is an overall fluence normalization coefficient, γ_1 is the low rigidity power law index, γ_2 the high rigidity power law index and $(\gamma_2-\gamma_1)R_0\equiv R_1$ is the breakpoint rigidity. The Band function is constructed in such a way that both the function and its first derivative are continuous.

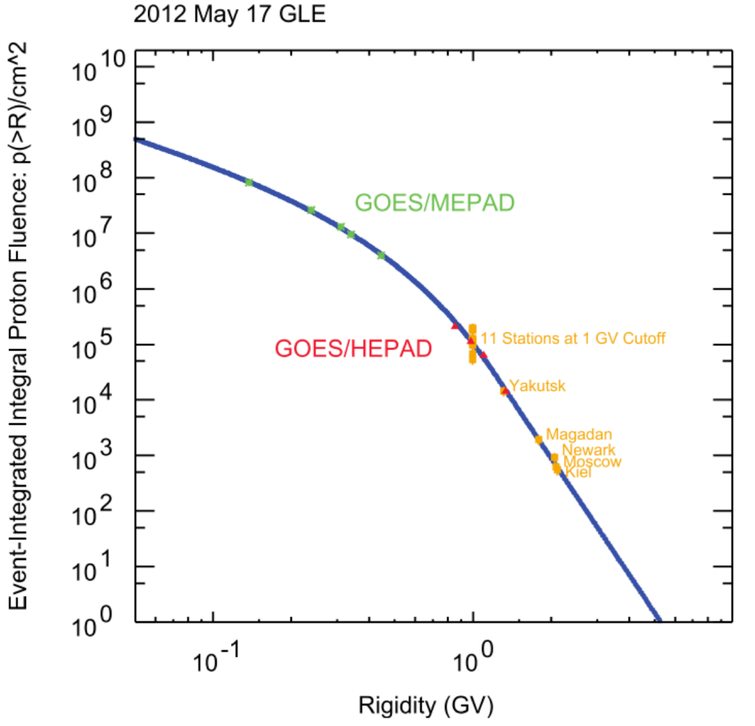


Fig. 1. Event-integrated proton fluence spectrum for GLE 71. NM observations are shown in orange, GOES/MEPAD in green, GOES/HEPAD in red and the Band-fit spectrum in blue.

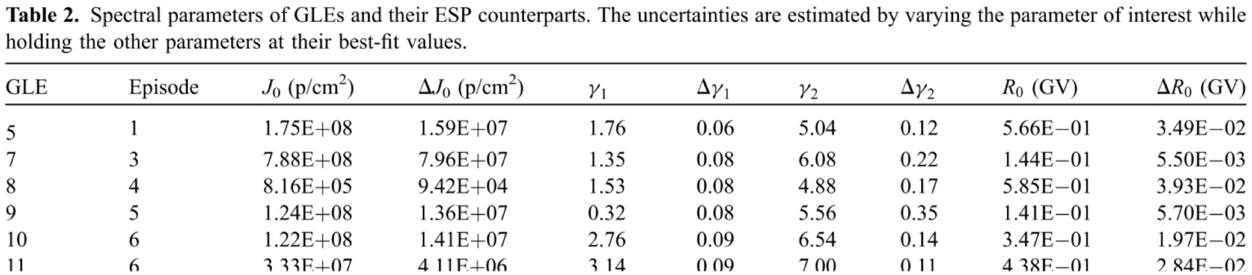


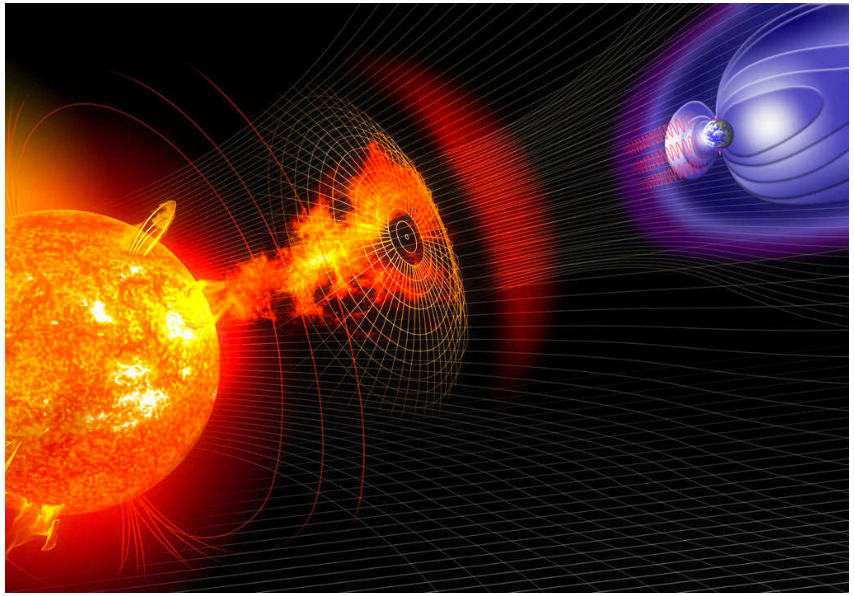
Table 2. Spectral parameters of GLEs and their ESP counterparts. The uncertainties are estimated by varying the parameter of interest while holding the other parameters at their best-fit values.

GLE	Episode	J_0 (p/cm^2)	ΔJ_0 (p/cm^2)	γ_1	$\Delta\gamma_1$	γ_2	$\Delta\gamma_2$	R_0 (GV)	ΔR_0 (GV)
5	1	1.75E+08	1.59E+07	1.76	0.06	5.04	0.12	5.66E−01	3.49E−02
7	3	7.88E+08	7.96E+07	1.35	0.08	6.08	0.22	1.44E−01	5.50E−03
8	4	8.16E+05	9.42E+04	1.53	0.08	4.88	0.17	5.85E−01	3.93E−02
9	5	1.24E+08	1.36E+07	0.32	0.08	5.56	0.35	1.41E−01	5.70E−03
10	6	1.22E+08	1.41E+07	2.76	0.09	6.54	0.14	3.47E−01	1.97E−02
11	6	3.33E+07	4.11E+06	3.14	0.09	7.00	0.11	4.38E−01	2.84E−02

Why are we decided to update calculations?

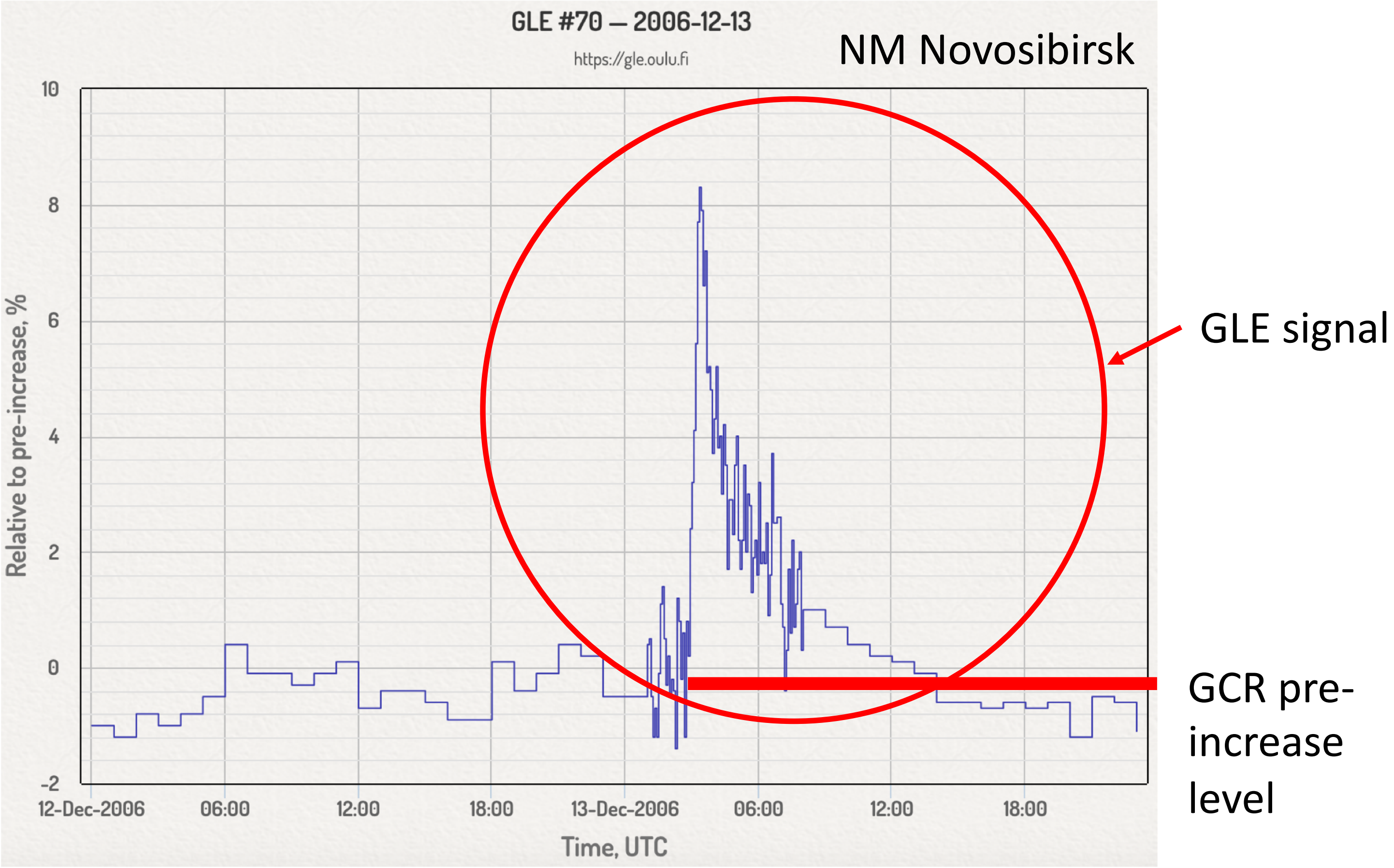
1. Method uses prescribed function and finds the best-fit parameters for it. What if is prescribed function is wrong? → Create the method of fluence assessment independent from the prescribed SEP function.
2. Reconstruction uses neutron monitor yield function by Clem and Dorman (SSR, 2000). Neutron monitor yield function validation using AMS-02 data showed that this yield function possibly overestimates the low-energy particles response in neutron monitor together with Ma16 yield function and Mi13 and CM12 shows better performance during validation. → Use Mi20 yield function (altitude-dependent!)

GLE integral increase



From the International GLE database (IGLED, *gle.oulu.fi*) we have calculated relative integral increases from SEP during GLE events in the units of relative units of **[% * hour]**

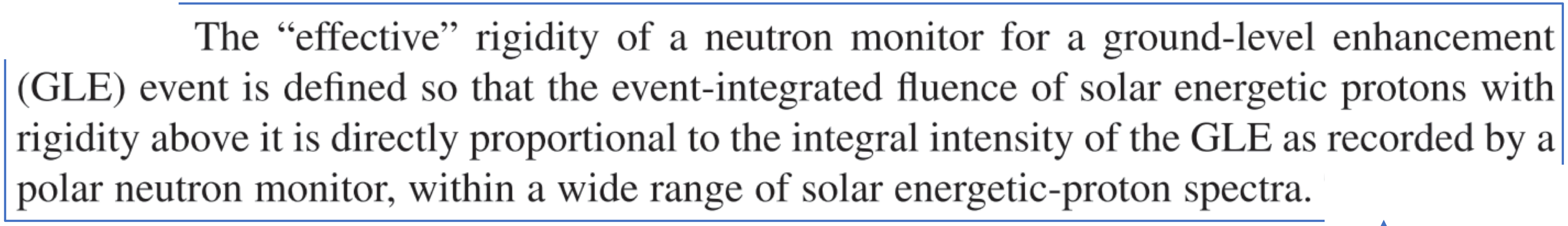
$$N_{GLE} = X * N_{GCR}$$



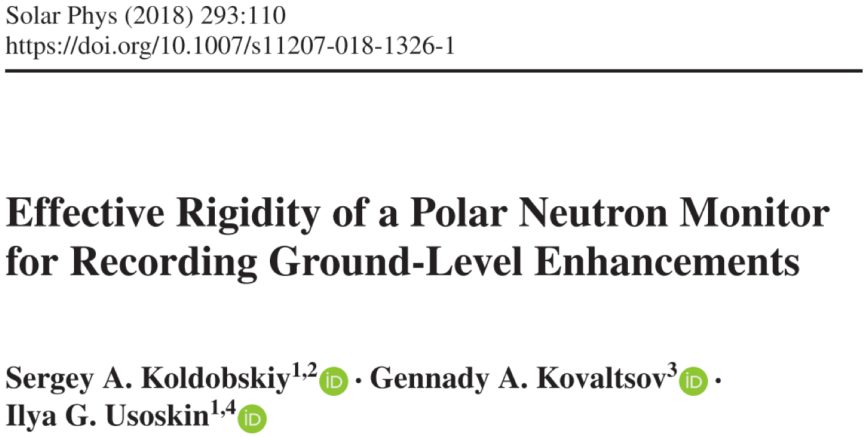
GCR pre-increase level

The R_{eff} method

Let me start from definition:



The "effective" rigidity of a neutron monitor for a ground-level enhancement (GLE) event is defined so that the event-integrated fluence of solar energetic protons with rigidity above it is directly proportional to the integral intensity of the GLE as recorded by a polar neutron monitor, within a wide range of solar energetic-proton spectra.



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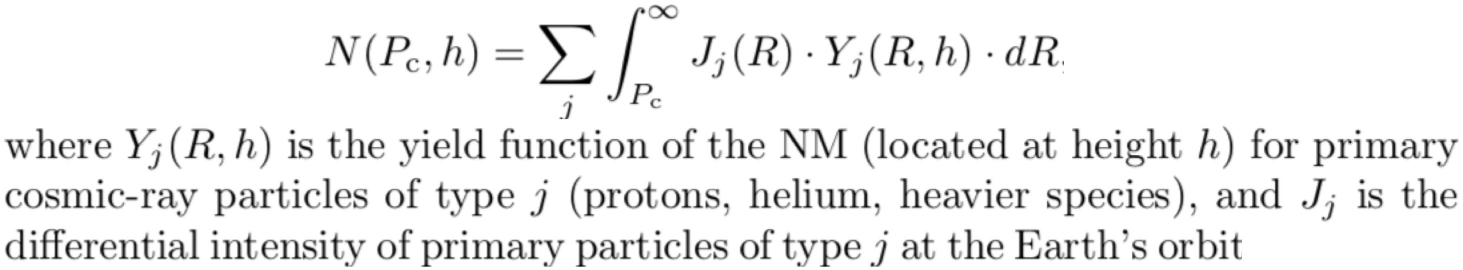
https://doi.org/10.1007/s11207-018-1326-1

Effective Rigidity of a Polar Neutron Monitor for Recording Ground-Level Enhancements

Sergey A. Koldobskiy[1,2] · Gennady A. Kovaltsov[3] · Ilya G. Usoskin[1,4]

$F(>R_{\text{eff}}) = K_{\text{eff}}\, N_{\text{GLE}}$,
where K_{eff} is (nearly) constant in the entire range of realistic GLE proton spectra and N_{GLE} is an integral NM response to GLE protons.

Theoretical NM response can be calculated as:



$$N(P_c, h) = \sum_j \int_{P_c}^{\infty} J_j(R) \cdot Y_j(R, h) \cdot dR,$$

where $Y_j(R, h)$ is the yield function of the NM (located at height h) for primary cosmic-ray particles of type j (protons, helium, heavier species), and J_j is the differential intensity of primary particles of type j at the Earth's orbit

Here we used NM yield function by Mishev et al. (2013, 2020)

The R_{eff} method

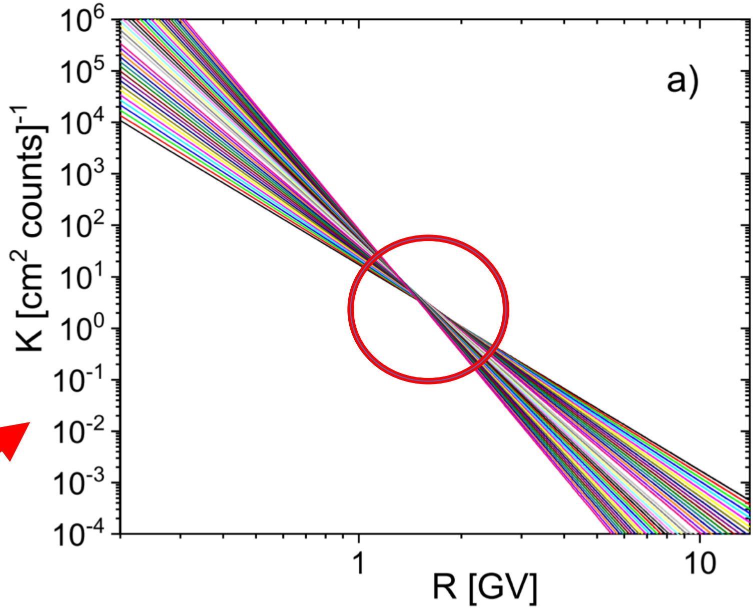
$K_{\mathrm{eff}} = F(>R_{\mathrm{eff}}) / N_{\mathrm{GLE}}$ and K_{eff} for given R must be constant irrespectively from the SEP fluence function

First we have tested this method using simple power-law:

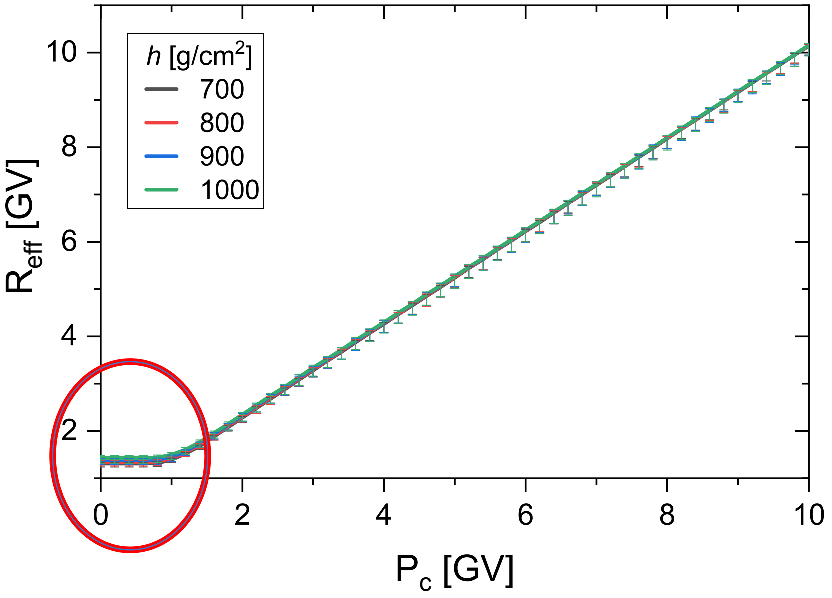
$$F(>R)=F_0R^{-\gamma}$$

and

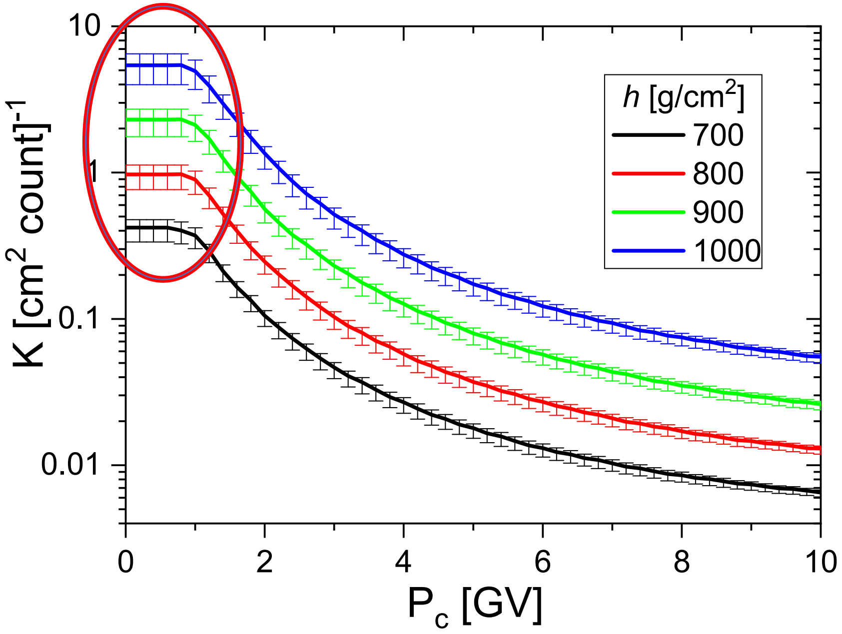
$$K_{eff}(R) = \frac{F(>R)}{\int_{P_c}^{\infty} \frac{dF(R)}{dR} Y(R)dR}$$



R_{eff} and K_{eff} as functions of P_c and h



Effective rigidity R_{eff} is very close to the geomagnetic rigidity cutoff P_c for low- and mid-latitude locations ($P_c >$ 3 GV) but saturates at 1.3–1.5 GV (depending on the atmospheric depth) for high-latitude sites.



The value of the K_{eff} varies with the geomagnetic cutoff depicting a shoulder at high-latitude locations and a nearly exponential decrease with P_c for low- and mid-latitudes.

These relations is shaped by two different processes, viz. the atmospheric cutoff (particles must possess sufficient energy of a several hundred MeV to initiate an atmospheric cascade reaching the ground) and the geomagnetic cutoff (particles must possess sufficient rigidity to be able to enter the atmosphere). While the geomagnetic cutoff dominates at low- and mid-latitudes, the atmospheric cutoff becomes crucial at high latitudes.

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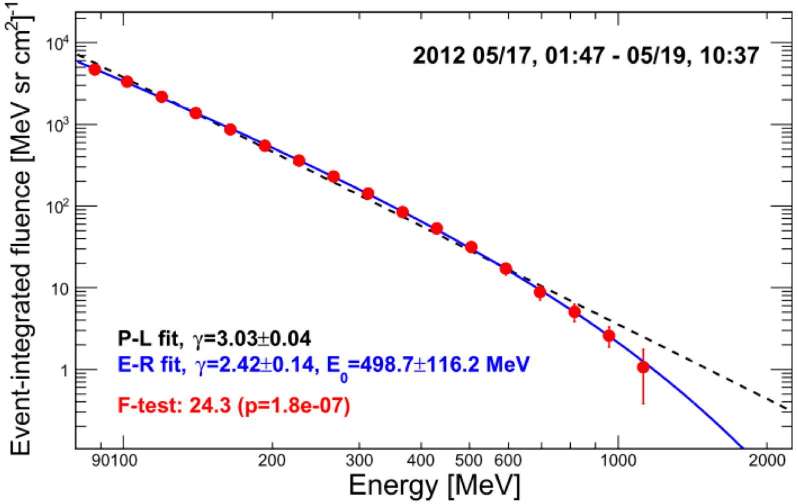
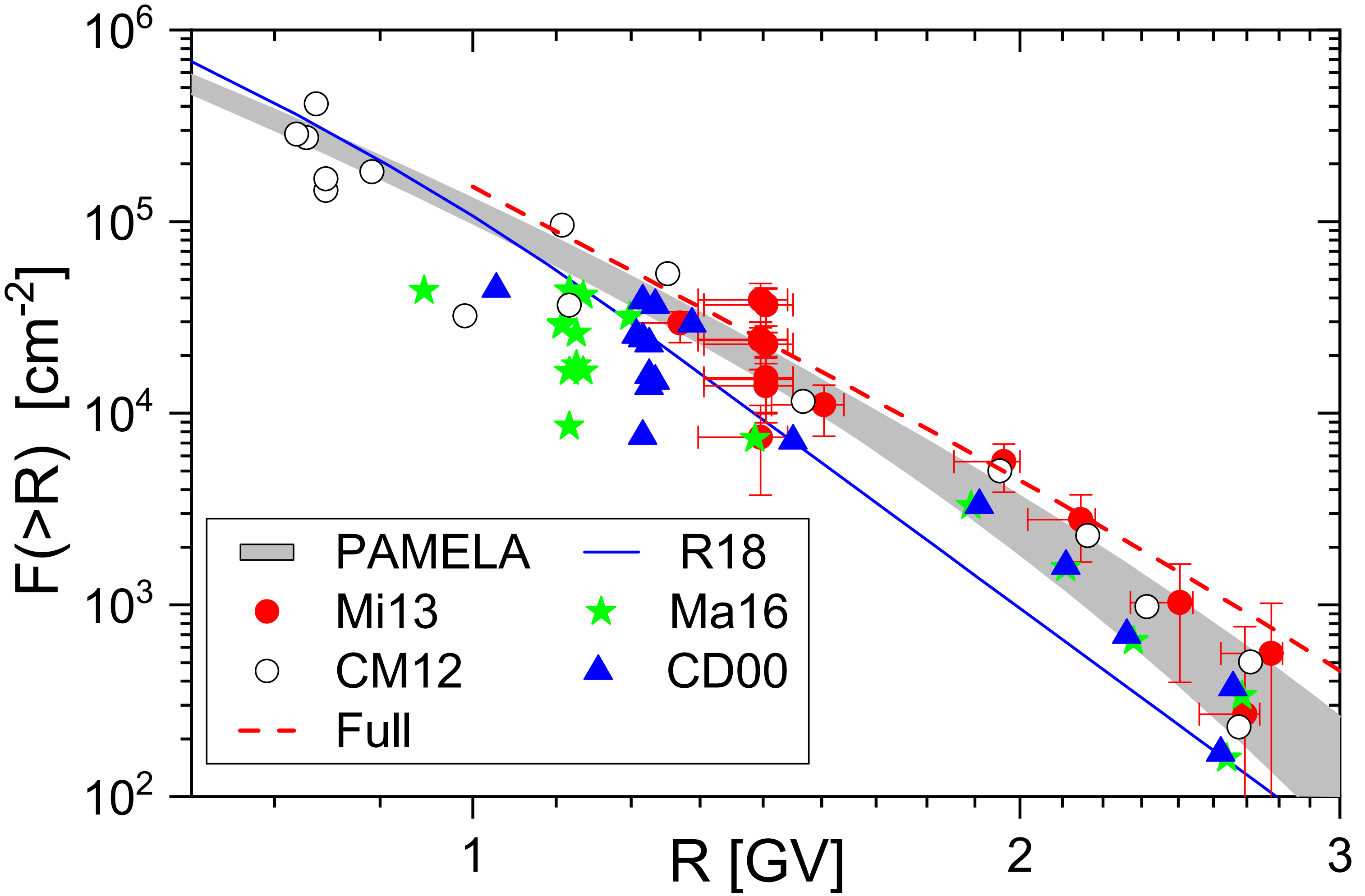


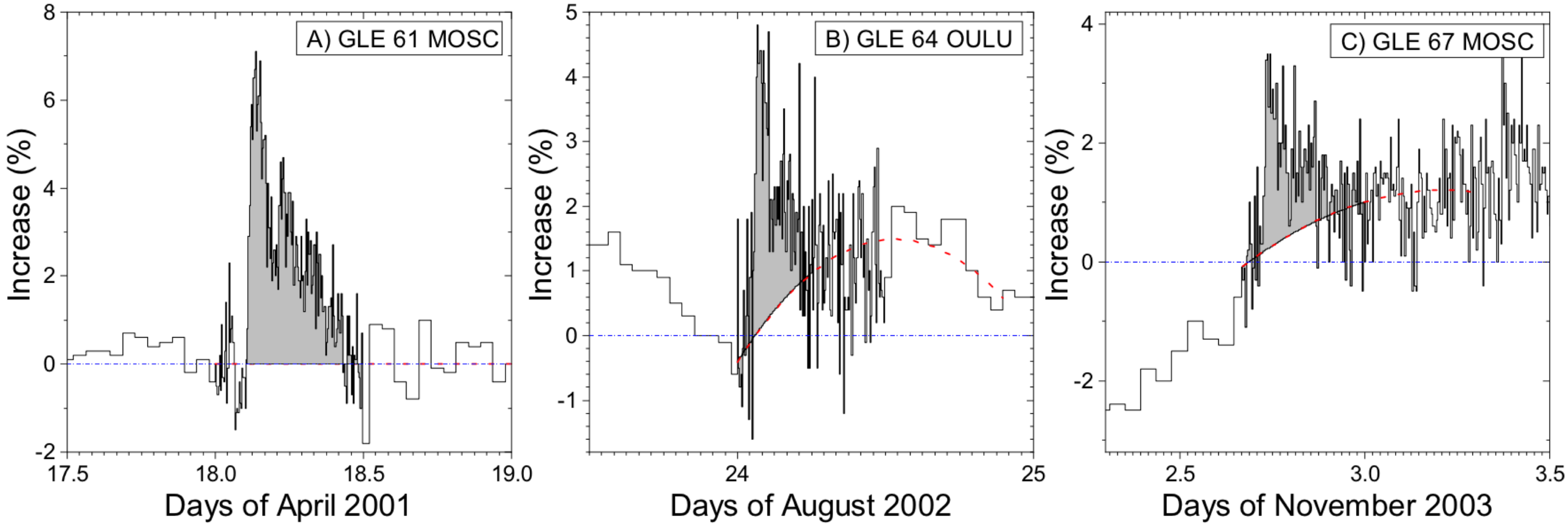
PAMELA direct measurements are in better agreement with CM12 and Mi13 yield function, CD00 and Ma16 YF possibly overestimate the NM response in low-energy region.

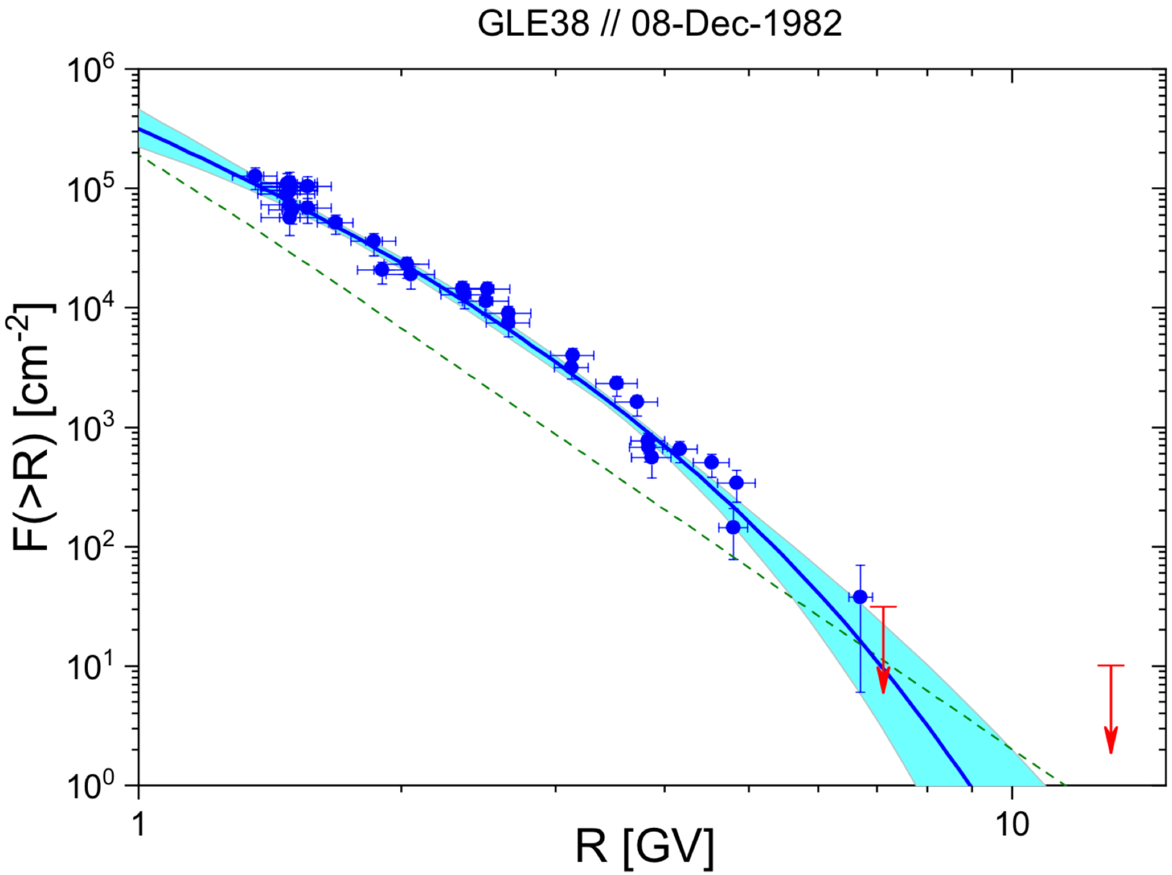
This conclusion is in agreement with conclusions of NM YF validation made with use of AMS-02 proton and helium monthly data.

GLE71 (17-May-2012)

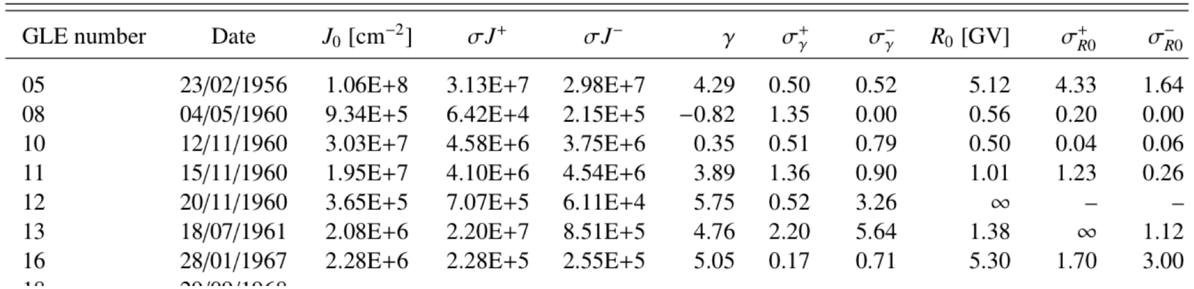


Major IGLED update: time-depedent GCR background

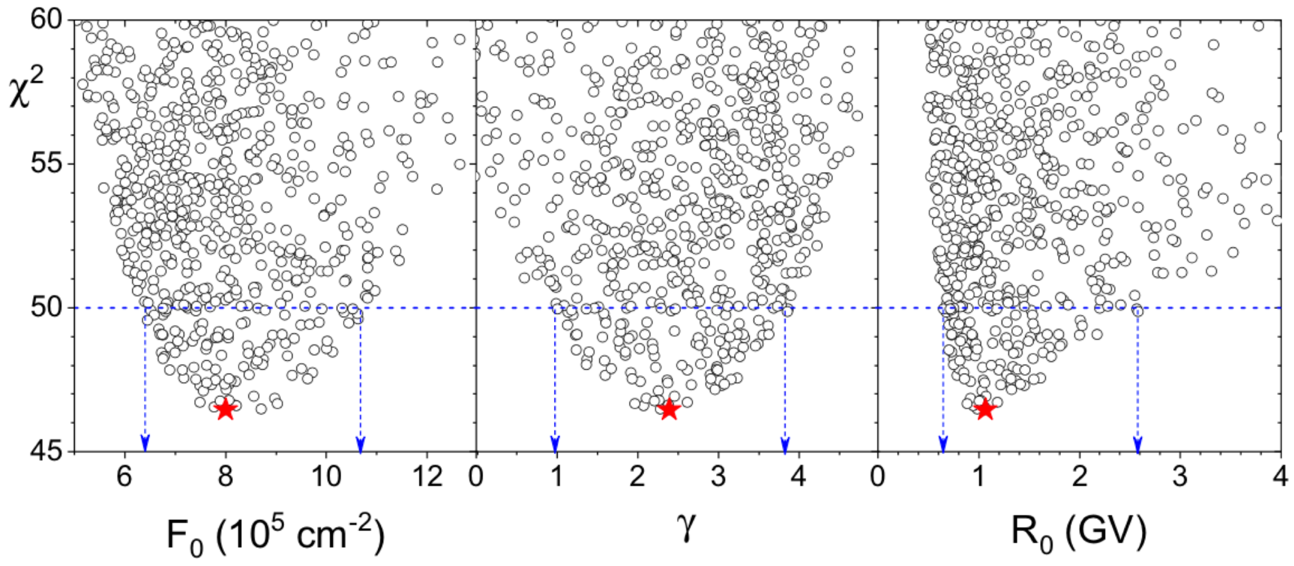




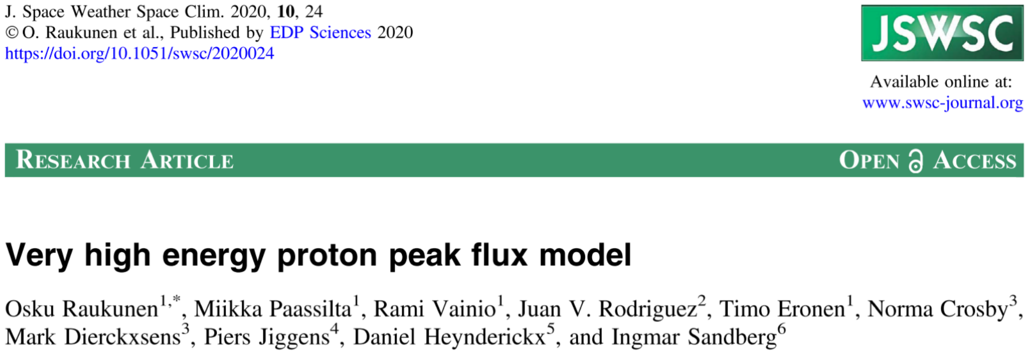
58 strongest GLE evets were analyzed, and NM-based integral flux points were reconstructed.



GLE number	Date	J_0 [cm^{-2}]	σJ^+	σJ^-	γ	σ_γ^+	σ_γ^-	R_0 [GV]	σ_{R0}^+	σ_{R0}^-
05	23/02/1956	1.06E+8	3.13E+7	2.98E+7	4.29	0.50	0.52	5.12	4.33	1.64
08	04/05/1960	9.34E+5	6.42E+4	2.15E+5	−0.82	1.35	0.00	0.56	0.20	0.00
10	12/11/1960	3.03E+7	4.58E+6	3.75E+6	0.35	0.51	0.79	0.50	0.04	0.06
11	15/11/1960	1.95E+7	4.10E+6	4.54E+6	3.89	1.36	0.90	1.01	1.23	0.26
12	20/11/1960	3.65E+5	7.07E+5	6.11E+4	5.75	0.52	3.26	∞	–	–
13	18/07/1961	2.08E+6	2.20E+7	8.51E+5	4.76	2.20	5.64	1.38	∞	1.12
16	28/01/1967	2.28E+6	2.28E+5	2.55E+5	5.05	0.17	0.71	5.30	1.70	3.00



Low energy SEP measurements



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RESEARCH ARTICLE — OPEN ACCESS

Very high energy proton peak flux model

Osku Raukunen[1,*], Miikka Paassilta[1], Rami Vainio[1], Juan V. Rodriguez[2], Timo Eronen[1], Norma Crosby[3], Mark Dierckxsens[3], Piers Jiggens[4], Daniel Heynderickx[5], and Ingmar Sandberg[6]

For years before 1989, we used fluences from several sources based on different spacecraft and experiments (King 1974; Reedy 1977; Goswami et al. 1988; Feynman & Gabriel 1990; Jun et al. 2007; Webber et al. 2007).

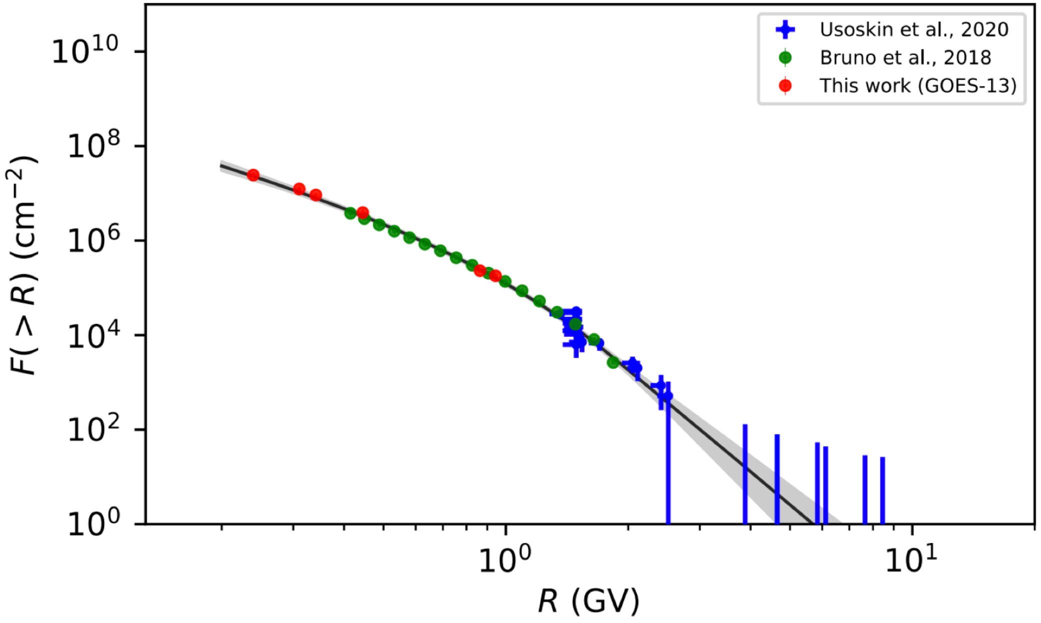
PAMELA measurements for GLE #71

Modified Band function:

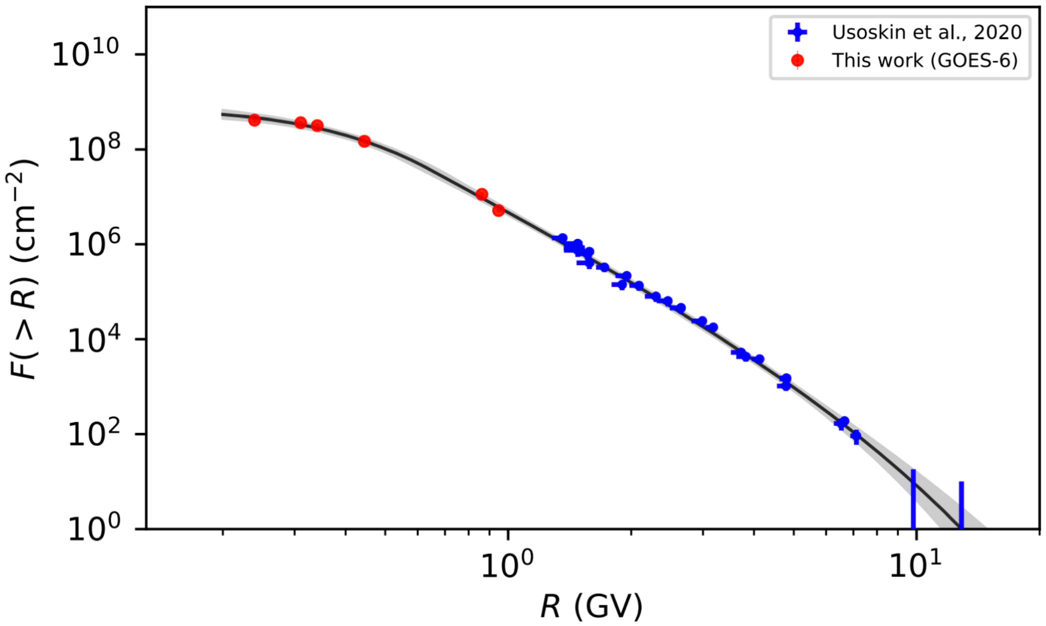
$$F(R) = J_1 \left(\frac{R}{1\,\mathrm{GV}}\right)^{-\gamma_1} \exp\left(-\frac{R}{R_1}\right) \quad \text{if } R < R_\mathrm{b},$$

$$F(R) = J_2 \left(\frac{R}{1\,\mathrm{GV}}\right)^{-\gamma_2} \exp\left(-\frac{R}{R_2}\right) \quad \text{if } R \geq R_\mathrm{b},$$

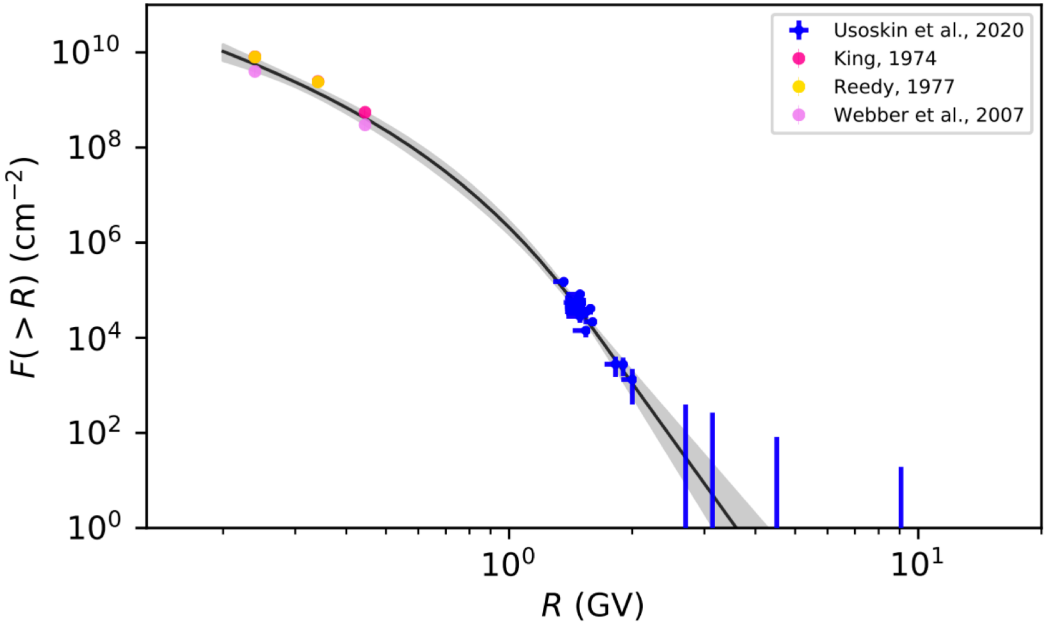
GLE #71 16-May-2012

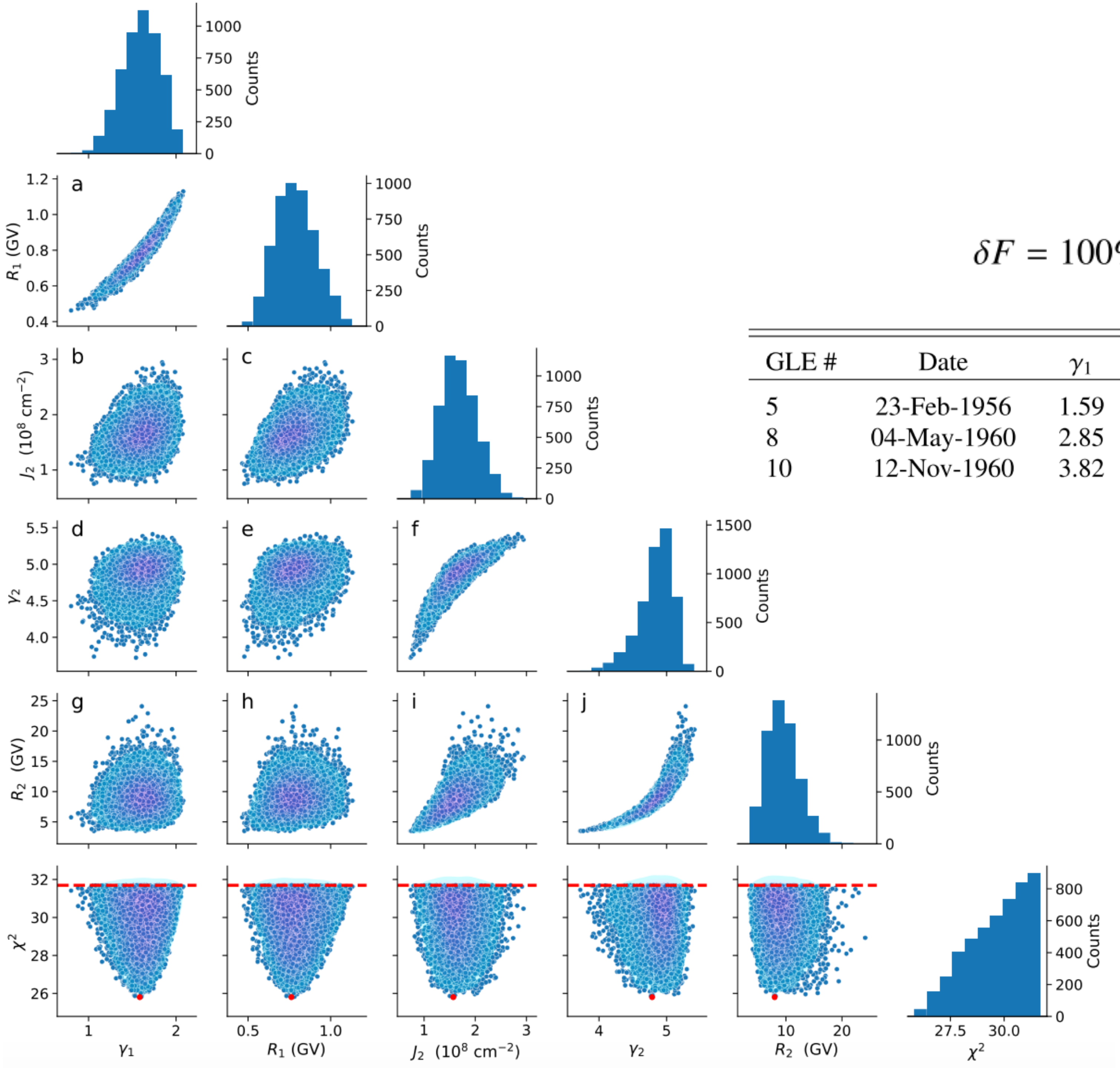


GLE #43 19-Oct-1989



GLE #24 04-Aug-1972





$$\delta F = 100\% \times \left\langle \frac{F_{\rm up}(R) - F_{\rm low}(R)}{F_{\rm up}(R) + F_{\rm low}(R)} \right\rangle_{R_{\rm s}<R<R_{\rm n}},$$

GLE #	Date	γ_1	R_1, GV	J_2, cm^{-2}	γ_2	R_2, GV	$R_{\rm b}$, GV	Δ, %
5	23-Feb-1956	1.59	0.770	1.63×10^8	4.84	8.614	2.748	21.0
8	04-May-1960	2.85	−1.276	9.43×10^5	−1.36	0.507	1.528	33.8
10	12-Nov-1960	3.82	6.244	2.71×10^7	0.01	0.483	1.995	17.0

Conclusion

- “Bow-tie” method of fluence reconstruction was applied to NM data, that allowed us to reconstruct SEP integral fluxes for 58 strongest GLE events;
- Detrended GLE data allowed to identify Sep signal more precisely (in particular, for weak events);
- We used GOES satellites data to obtain SEP fluences for period 1989–2017;
- For years before 1989 we used all available low-energy data;
- NM and satellite points were fitted with modified Band function, parameter uncertainties were carefully evaluated;
- New reconstruction of the strongest SEP events particle fluence create new basis for different applications, including the production of cosmogenic isotopes and assessment of radiation doses.