# New reconstruction of the event-integrated spectra for GLE events

**Sergey Koldobskiy,** **Osku Raukunen, Rami Vainio, Gennady Kovaltsov and Ilya Usoskin**

# Outline

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

Based on:

*Solar Physics (2018) 293:110*

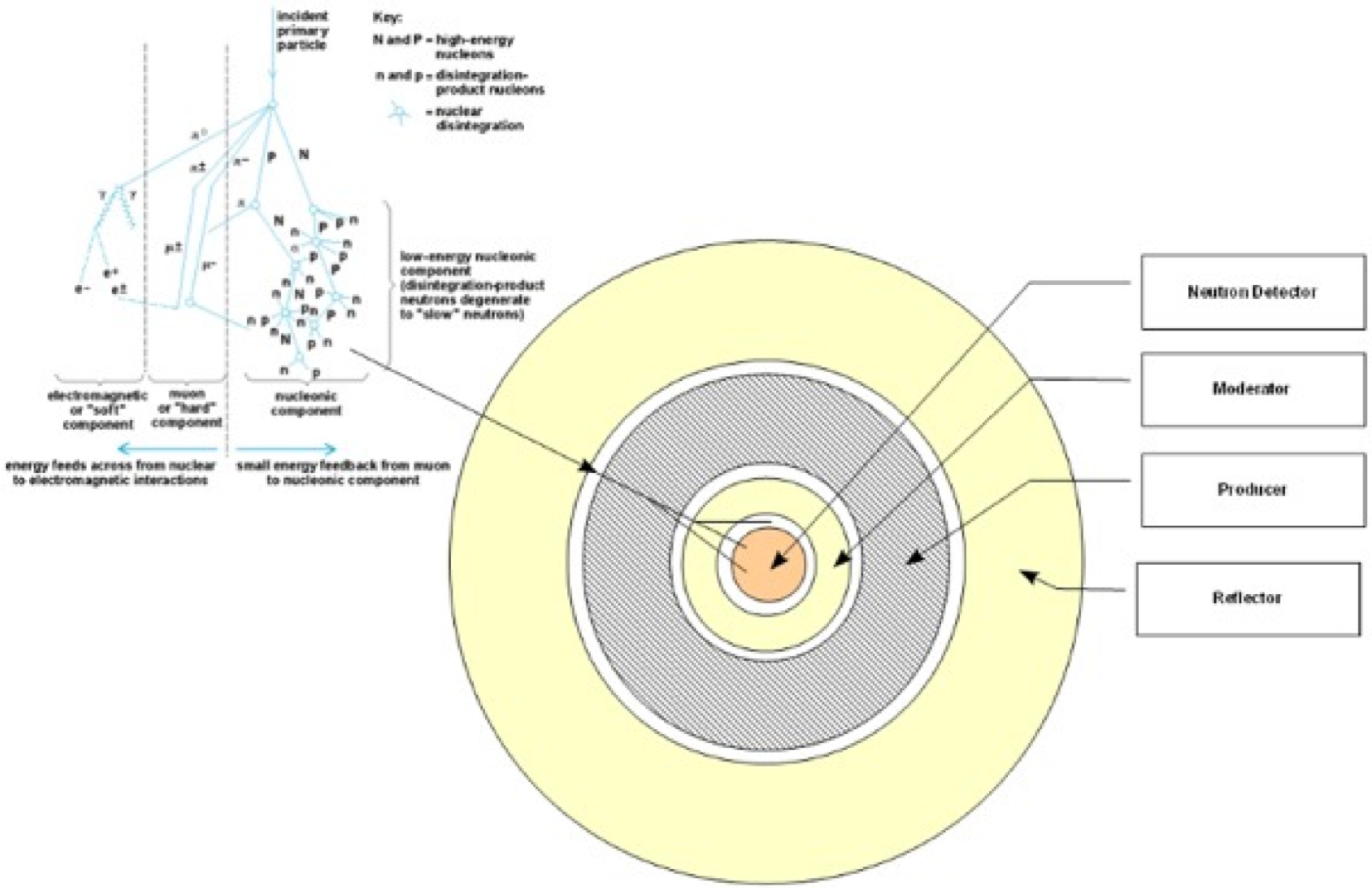
*Solar Physics (2019) 294:94*

*A&A (2020) 640 A17*

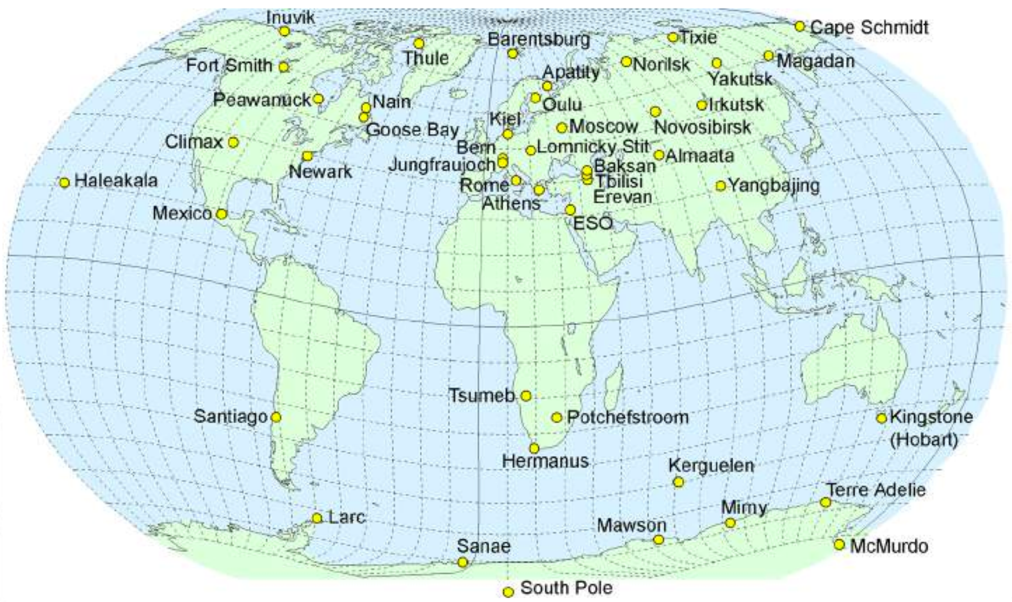
*A&A (2021) 647 A132*

# Neutron Monitors (NM)

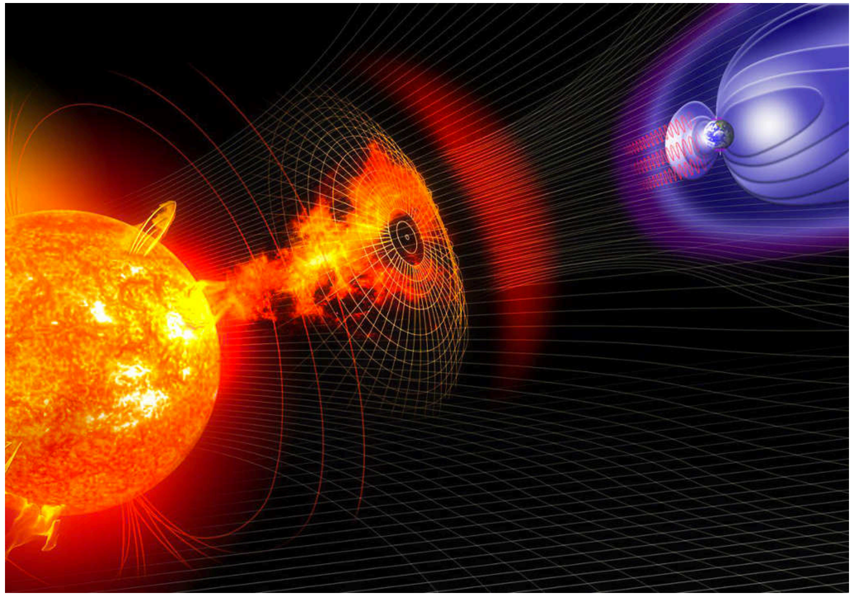
The scheme of the atmospheric shower and its registration in NM




NM network



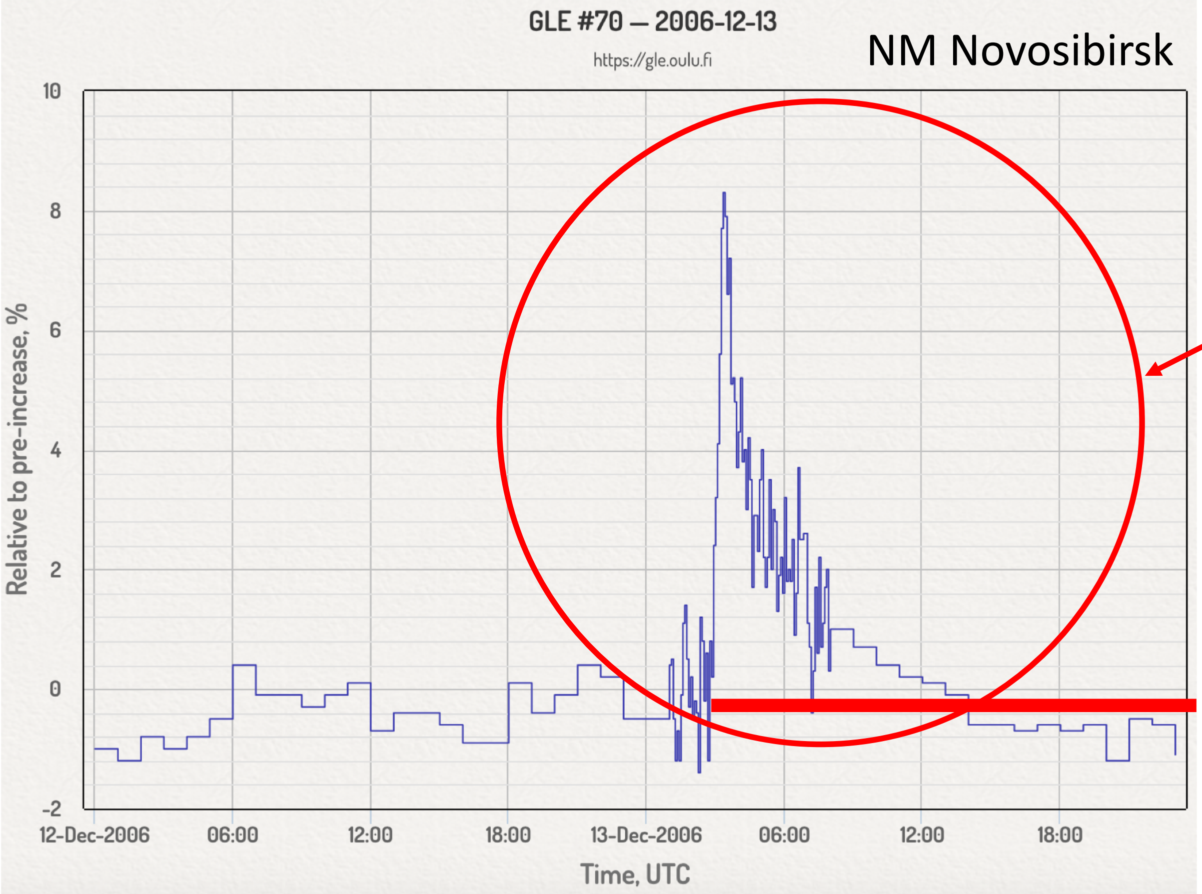
# GLE integral increase



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]**

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

Example of GLE registration by NM

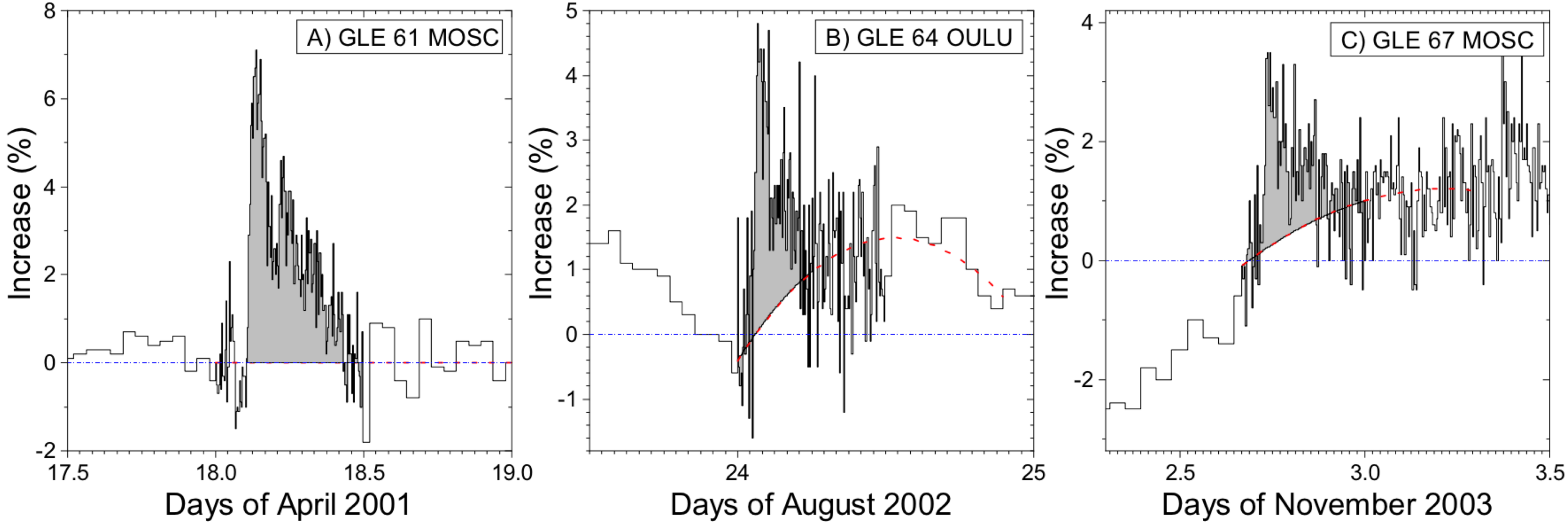



GLE signal

GCR pre-increase level

# Major IGLED update: time-dependent GCR background

Examples of different GCR backgrounds (stable, diurnal variation, recovery phase of the Forbush decrease)



# The $R_{eff}$ method

The 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.

Solar Phys (2018) 293:110
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]**

$F(>R_{eff}) = K_{eff} N_{GLE}$,

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

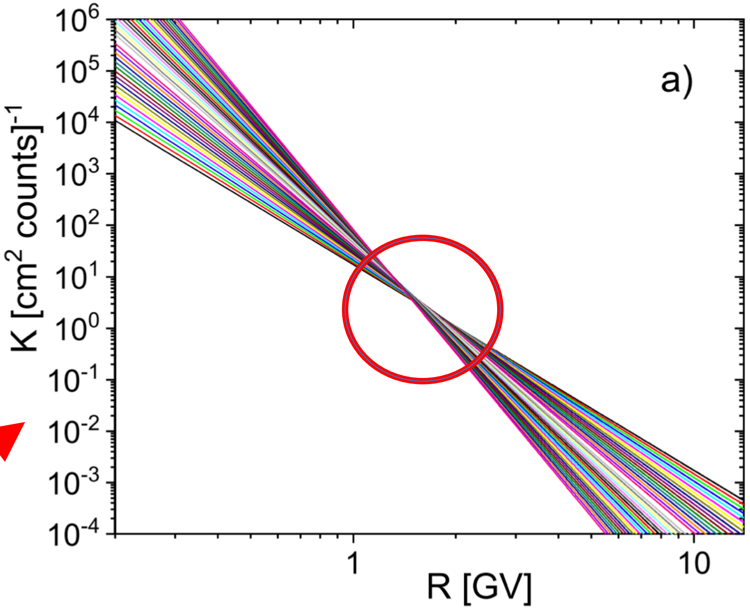
$K_{eff} = F(>R_{eff}) / N_{GLE}$ and $K_{eff}$ for given R must be constant irrespectively from the SEP fluence function

*We have tested this method using simple power-law, modified power-law, power-law with an exponential cutoff, for example, for simple power-law:*

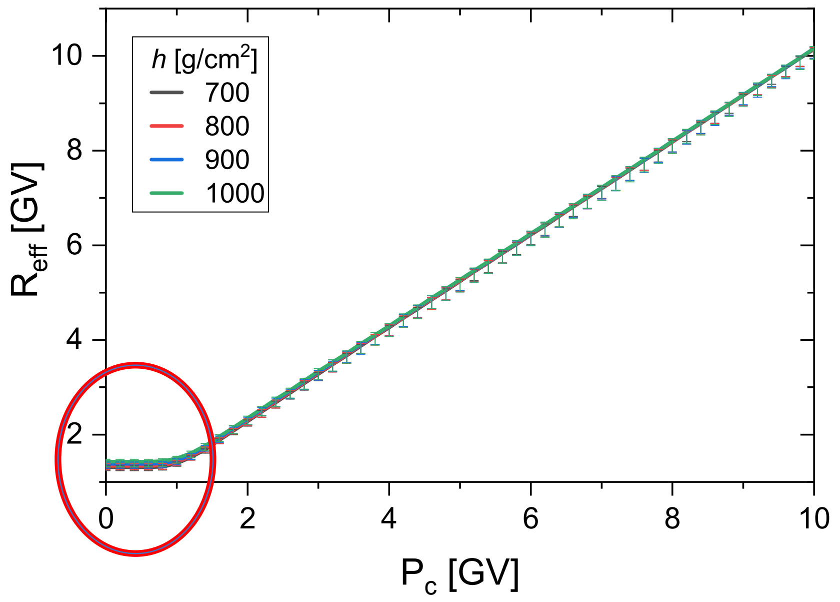
$$F(>R) = F_0 R^{-\gamma}$$

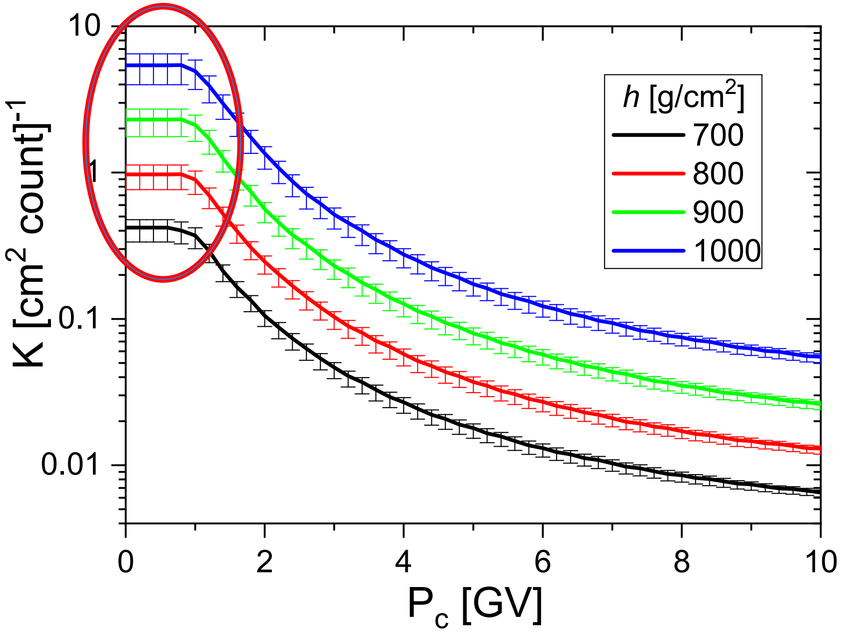
*and therefore*

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



# $R_{eff}$ 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 are shaped by two different processes: the atmospheric cutoff (particles must possess sufficient energy of several hundred MeV to initiate an atmospheric cascade reaching the ground) and the geomagnetic cutoff (particles must have enough 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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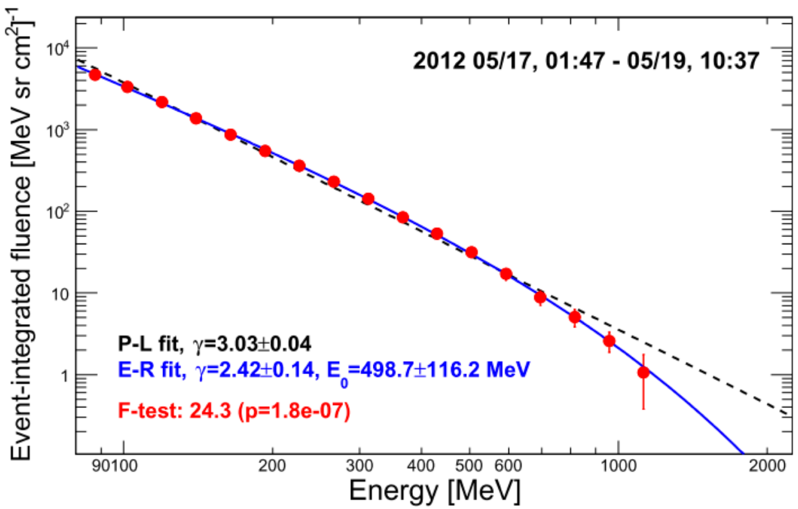
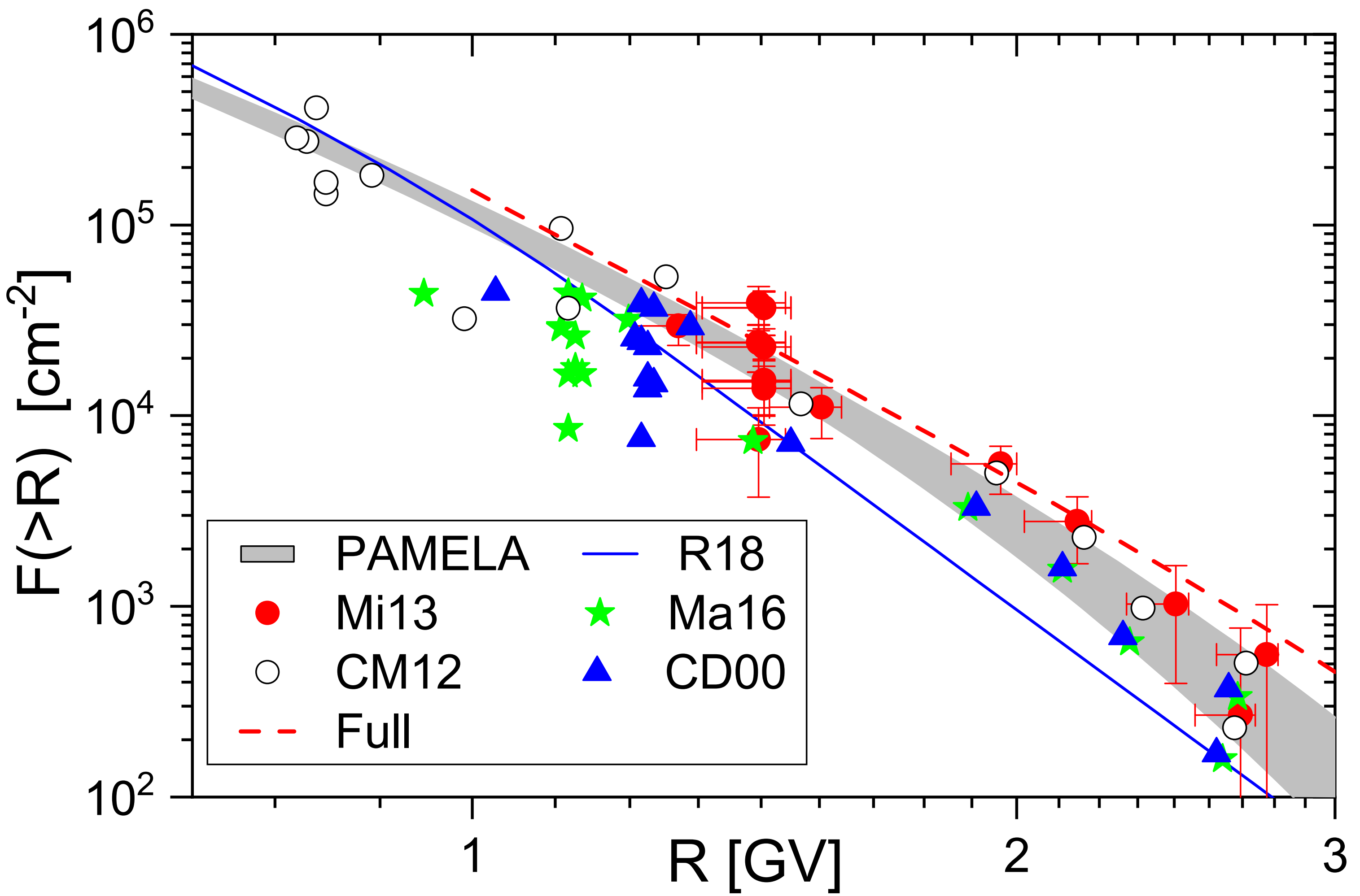
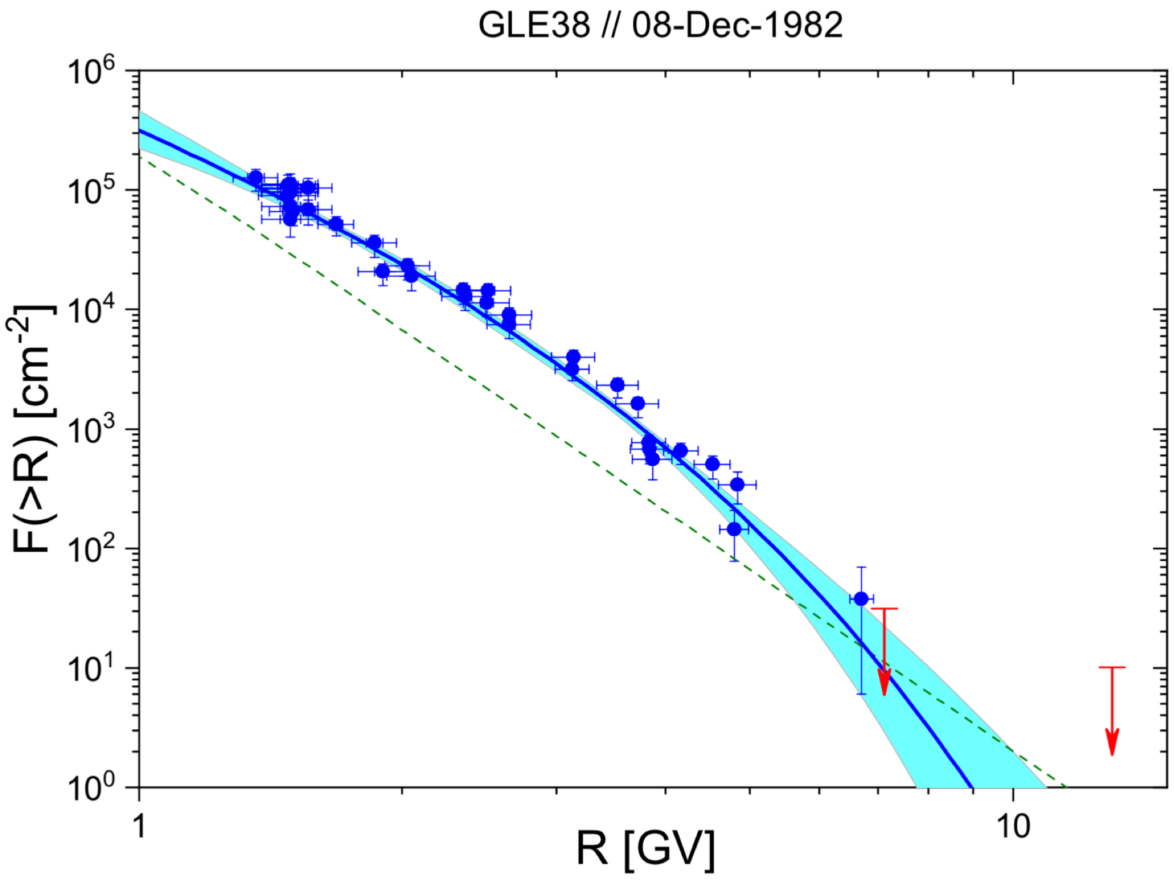



PAMELA direct measurements are in better agreement with CM12 and Mi13 yield function. CD00 and Ma16 YF possibly overestimate the NM response in low-energy region.

This conclusion agrees with findings of NM YF validation made with the use of AMS-02 proton and helium monthly data.

GLE71 (17-May-2012)

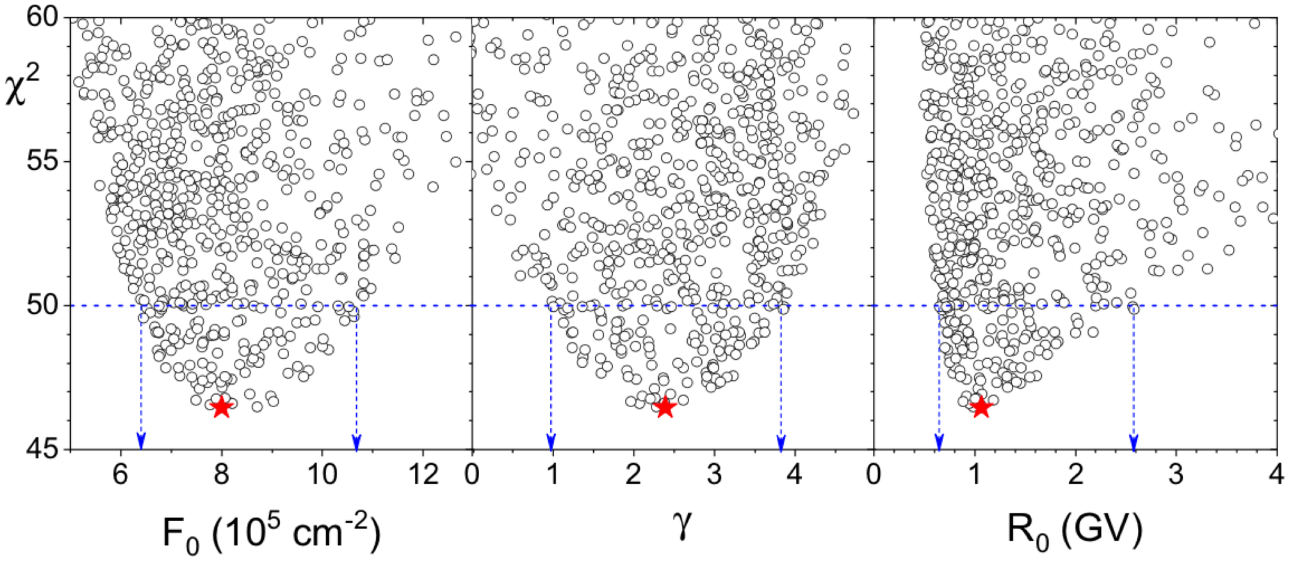





58 strongest GLE events were analyzed, and NM-based integral flux points were reconstructed and fitted with power-law with exponential cutoff:

| GLE number | Date | $J_0$ [cm$^{-2}$] | $\sigma J^+$ | $\sigma J^-$ | $\gamma$ | $\sigma_\gamma^+$ | $\sigma_\gamma^-$ | $R_0$ [GV] | $\sigma_{R0}^+$ | $\sigma_{R0}^-$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 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 |

Uncertainties were assessed using Monte-Carlo simulations:



# Low energy SEP measurements

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

For years >1989 we collaborated with the Turku team to produce several fluence points from GOES data using the method described in:

J. Space Weather Space Clim. 2020, **10**, 24

https://doi.org/10.1051/swsc/2020024

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**Very high energy proton peak flux model**

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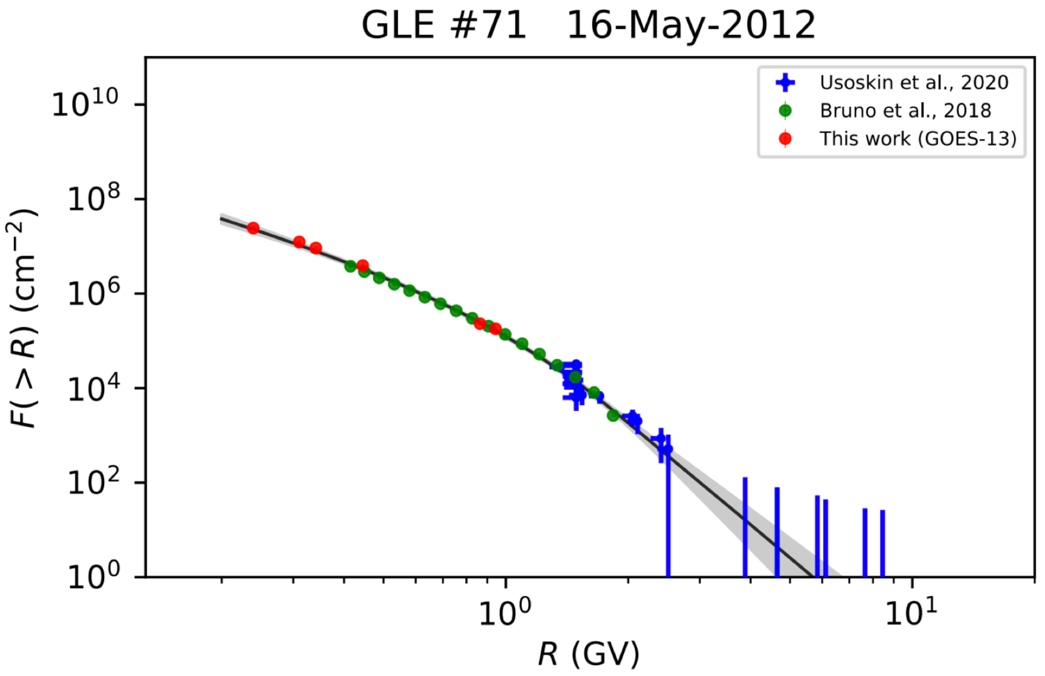
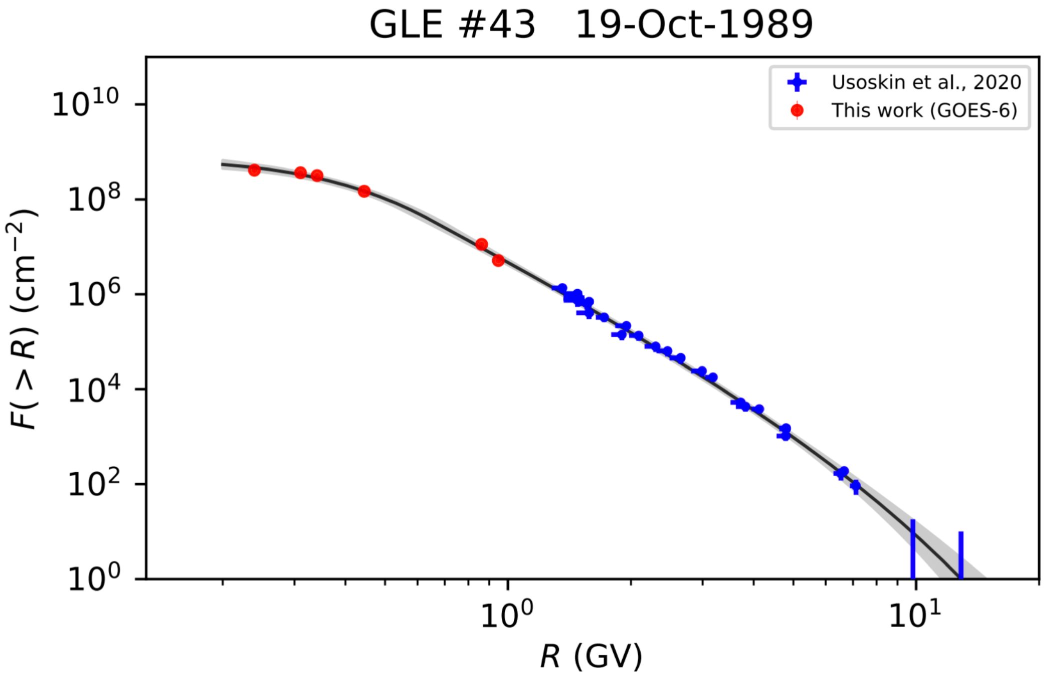
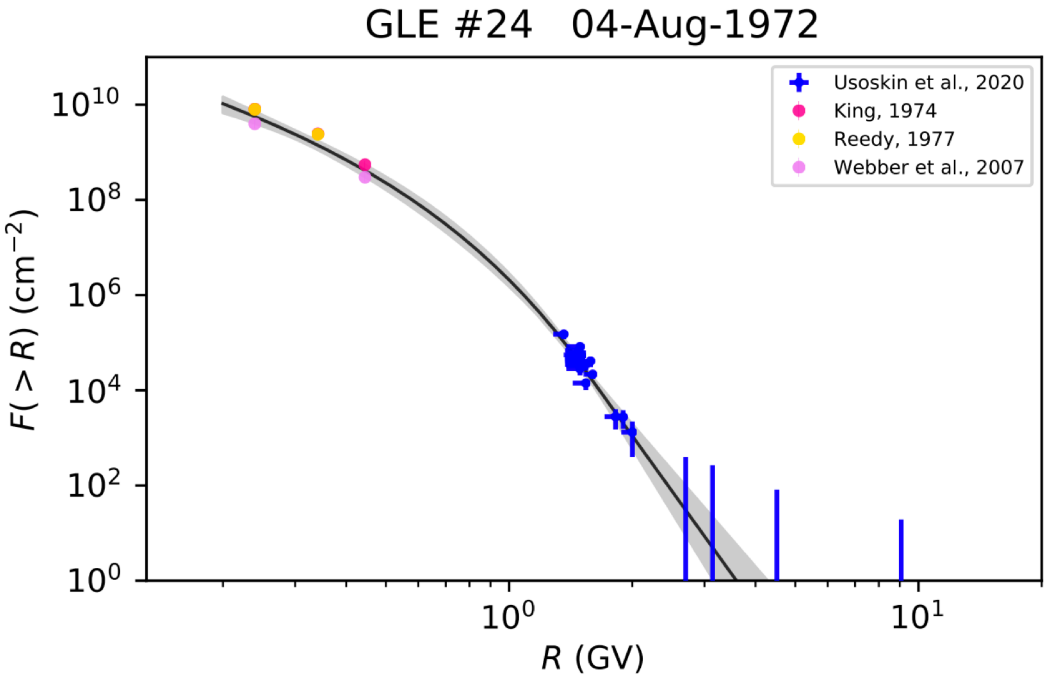
We fitted SEP fluences in the wide energy range from 30 MeV to several GeVs using Modified Band function:

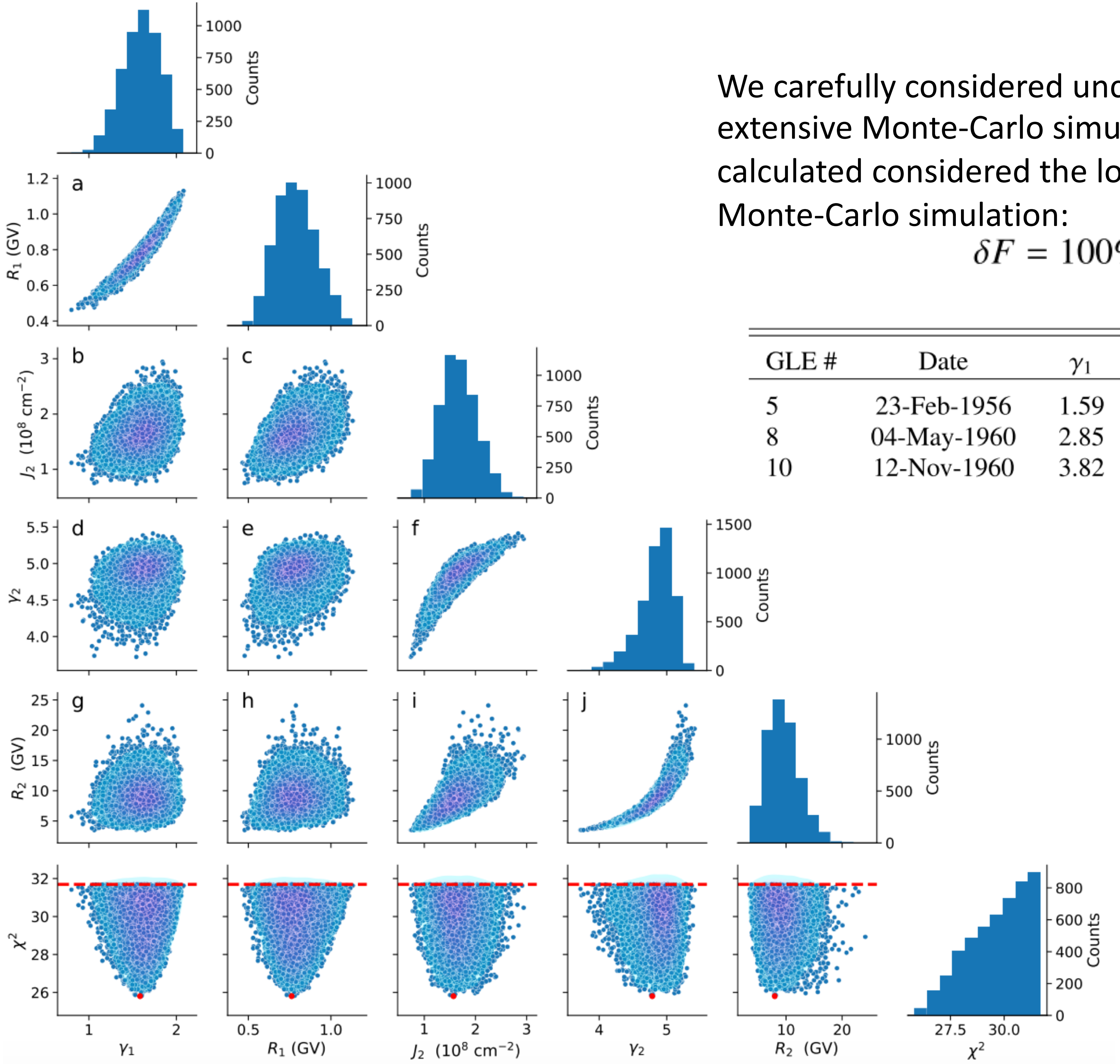
$$F(R) = J_1 \left( \frac{R}{1\,\mathrm{GV}} \right)^{-\gamma_1} \exp\left( -\frac{R}{R_1} \right) \quad \text{if } R < R_\mathrm{b},$$

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






We carefully considered uncertainties of the produced result using extensive Monte-Carlo simulations. The total uncertainty of the fluence was calculated considered the lowest and highest fluences produced during Monte-Carlo simulation:

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

| GLE # | Date | $\gamma_1$ | $R_1$, GV | $J_2$, cm$^{-2}$ | $\gamma_2$ | $R_2$, GV | $R_{\rm b}$, GV | Δ, % |
|---|---|---|---|---|---|---|---|---|
| 5 | 23-Feb-1956 | 1.59 | 0.770 | $1.63 \times 10^8$ | 4.84 | 8.614 | 2.748 | 21.0 |
| 8 | 04-May-1960 | 2.85 | −1.276 | $9.43 \times 10^5$ | −1.36 | 0.507 | 1.528 | 33.8 |
| 10 | 12-Nov-1960 | 3.82 | 6.244 | $2.71 \times 10^7$ | 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.