Multiproxy reconstructions of the energy spectra for extreme solar particle events

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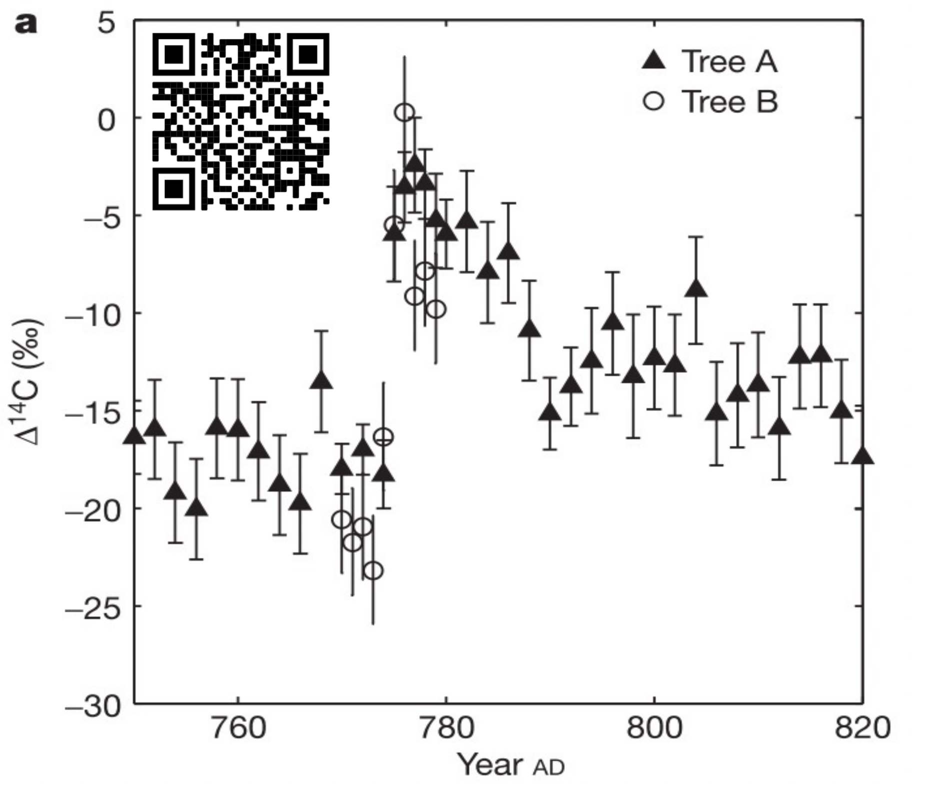
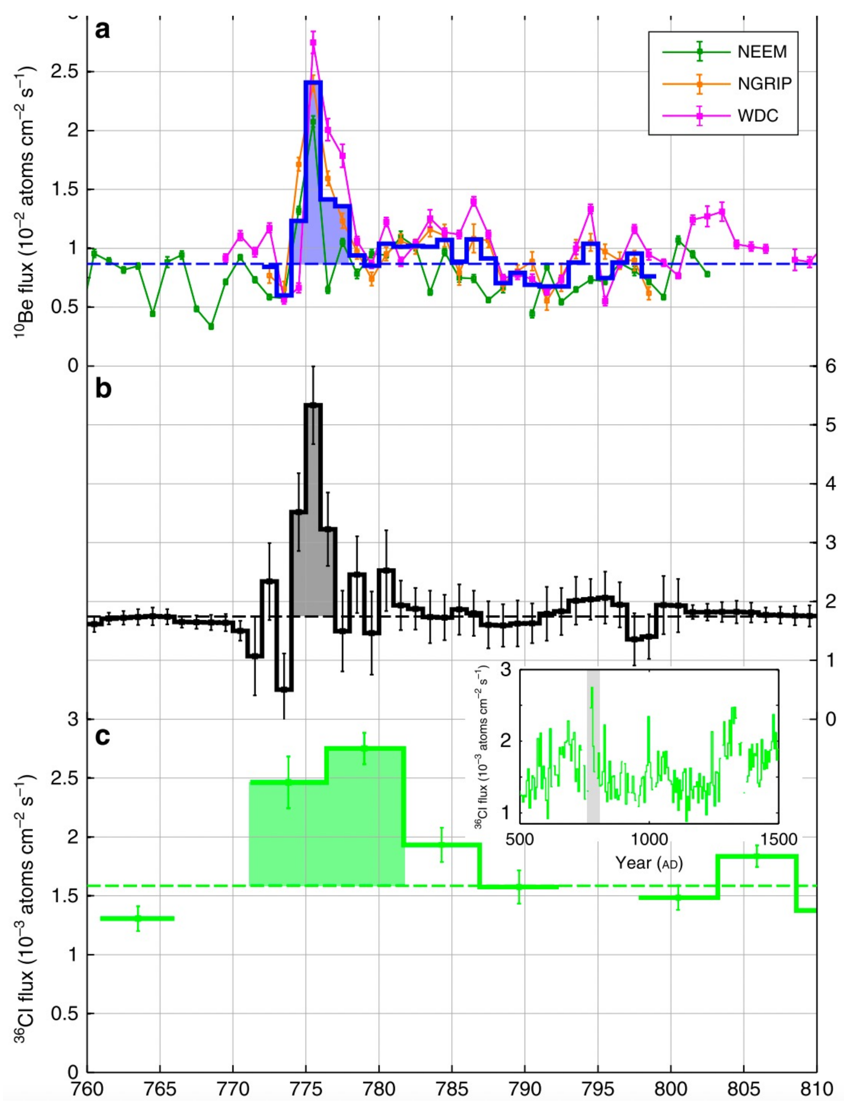
The first extreme solar particle event (ESPE) was found in 2012 by Miyake et al. in tree rings as a tremendous increase of cosmogenic (produced by cosmic rays) ^{14}C concentration during a short period of time around 774/775 AD.



Measured radiocarbon content and comparison with IntCal98 for event 774/775 AD. Picture from Miyake et al. 2012.

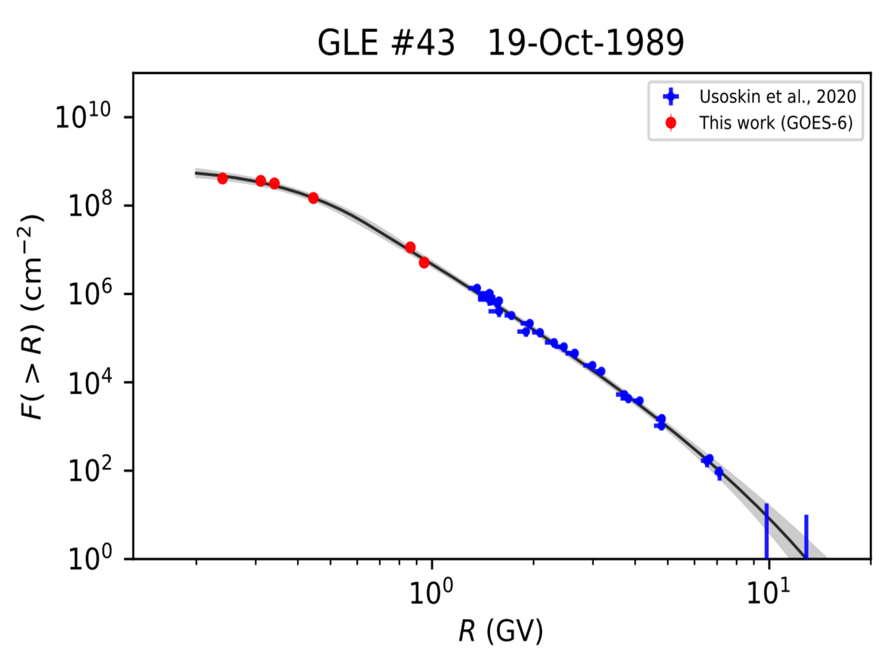


The AD 774/5 event in view of 10Be, 14C and 36Cl. Picture from Mekhaldi et al. 2015.

Several hypotheses about the origin of such events were proposed first, but it was shown soon [Usoskin et al., 2013] that it was caused by a huge solar particle event, by order(s) of magnitude higher than the most powerful modern ones. Since then, several similarly strong ESPEs have been found over the past millennia. In 2015 the ESPE signal in 774/775 AD was independently confirmed in 10Be and 36Cl.

The most powerful solar energetic particle (SEP) events are GLEs (ground-level enhancements) when secondary-particle atmospheric showers produced by SEPs can be detected by neutron monitors (NM). GLEs are characterized by a significant flux of SEPs with energies greater than 300 – 400 MeV. 73 GLE events occurred during the last 80 years. The most recent GLE #73 was registered on 28 Oct 2021 (see details in a talk by A. Mishev, 25 Jul 5.30 PM SH session). The NM data for GLE events are stored in International GLE database by the University of Oulu.

Recently, SEP fluences for 58 most powerful GLE events were reconstructed, combined with the low-energy data from GOES satellites and other sources, and fitted with the modified Band function spectral form (Koldobskiy et al. 2021 – details are given in a talk by Koldobskiy, 26 Jul 4.00 PM SH session).



Example of the fitting of the modified Band function to the data points or GLE #43, 19-Oct-1989 Picture from Koldobskiy et al. 2021.

There were a few attempts of ESPE fluence spectral form reconstructions in the past, mainly based on the ratios of cosmogenic isotope peak factors (i.e., the ratio of SEP signal to GCR signal) $^{10}Be/^{36}Cl$ and SEP fluences for GLE events F30/F200. However, the method itself is based on old calculations and therefore should be significantly revised.

In this work, we have reconstructed the SEP fluence for four multi-proxy-registered ESPEs. Cosmogenic-isotope signals reconstructed by different teams and reconstructions of the Earth's magnetic field (M) and solar modulation potential (φ) during the ESPEs are summarized in the following table:

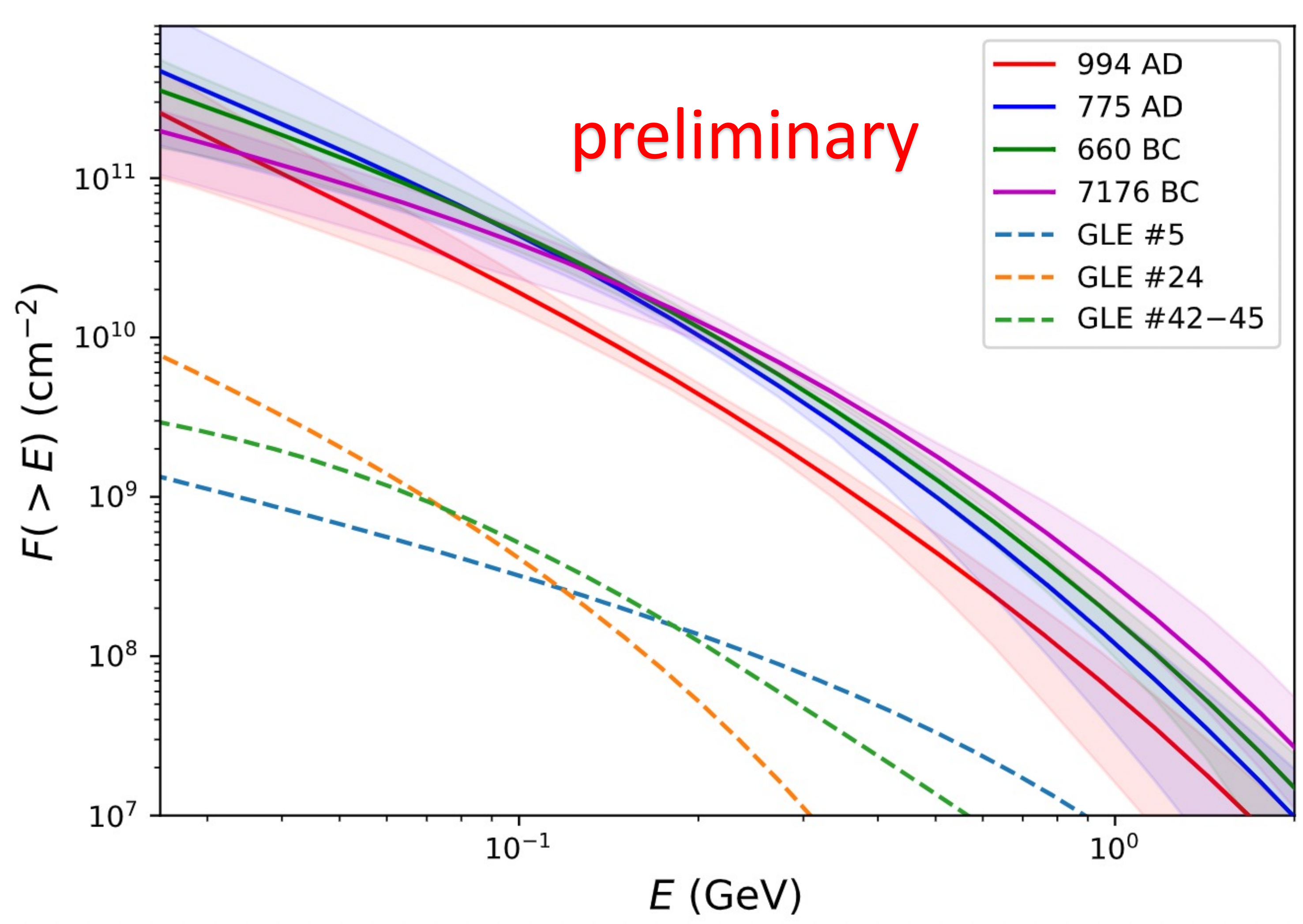
Event	M_K	M_P	ϕ, MV	Data	Type	^{10}Be	^{36}Cl	^{14}C
994AD	10.3 ± 0.4	9 ± 0.5	412 ± 40	M15	peak	1.2 ± 0.2	2.6 ± 0.3	2.4 ± 0.7
				M15	prod	$(3.9 \pm 0.5) \cdot 10^5$	$(1.3 \pm 0.1) \cdot 10^5$	$(1.2 \pm 0.4) \cdot 10^7$
				B18	peak			1.8 ± 0.4
				B18	prod			$(1.0 \pm 0.1) \cdot 10^6$
				B22	prod			$(1.2 \pm 0.1) \cdot 10^7$
775AD	10.7 ± 0.4	9.3 ± 0.5	690 ± 50	M15	peak	3.4 ± 0.3	6.3 ± 0.4	3.9 ± 0.7
				M15	prod		$(3.2 \pm 0.2) \cdot 10^5$	$(2.2 \pm 0.4) \cdot 10^7$
				B18	peak			3.2 ± 0.2
				B18	prod			$(1.9 \pm 0.1) \cdot 10^6$
				M21	peak	3.0 ± 0.2		
				B22	prod			$(2.2 \pm 0.1) \cdot 10^6$
660BC	11.4 ± 0.6	9 ± 0.4	390 ± 50	O19	peak	3.7 ± 1.2	6.4 ± 1.4	
				S19	prod			$(1.4 \pm 0.1) \cdot 10^7$
				B22	prod			$(1.6 \pm 0.2) \cdot 10^7$
				P22	peak	2.5 ± 0.9		
7176BC	8.7 ± 1.7	7.5 ± 0.4	550 ± 100	P22	peak	3.7 ± 0.4	6.1 ± 1.2	4.5 ± 0.5
				B22	prod			$(2.4 \pm 0.1) \cdot 10^6$

Our hypothesis was that ESPE integral flux (fluence) can be represented as the GLE fluence scaled by a constant factor.
For each ESPE, we consequently considered each of the GLE fluences (from Koldobskiy et al. 2021) and calculated the expected production of ^{14}C or deposition of ^{10}Be and ^{36}Cl in polar regions, considering the uncertainties of the GLE fluence, Earth's magnetic field and solar modulation potential during the ESPE.
Next, we simultaneously fitted multi-proxy data with the modelled GLE data and calculated the χ^2-statistics and the value of the scaling factor κ:

$$\chi_j^2 = \sum_i \left(\frac{\kappa_j \cdot S_{\mathrm{GLE},i,j} - S_{\mathrm{ESPE},i}}{\sigma_{\mathrm{ESPE},i}} \right)^2$$

$$\kappa_j = \frac{\sum S_{\mathrm{GLE},i,j} \cdot S_{\mathrm{ESPE},i}/\sigma^2_{\mathrm{ESPE},i}}{\sum S^2_{\mathrm{GLE},i,j}/\sigma^2_{\mathrm{ESPE},i}}$$

For each ESPE we considered 1000 realizations of each GLE (in total we got 58000 realizations of χ^2, κ and fluence F for each ESPE). Next, we selected only "good" fits, requiring $\chi^2 < 5.99$ and $\kappa < 3500$. For these realizations, we calculated the ensemble median and corresponding 68% confidence intervals. Results of the ESPE fluence reconstruction and their comparison with GLE events fluence are shown here:



New multi-proxy reconstructions show that ESPE fluences are about two orders of magnitude higher than fluences of directly observed GLEs. These results are in good agreement with a recently published method of single-proxy ESPE fluence reconstruction (Koldobskiy et al. 2022).