Solar Extreme Events in the Past

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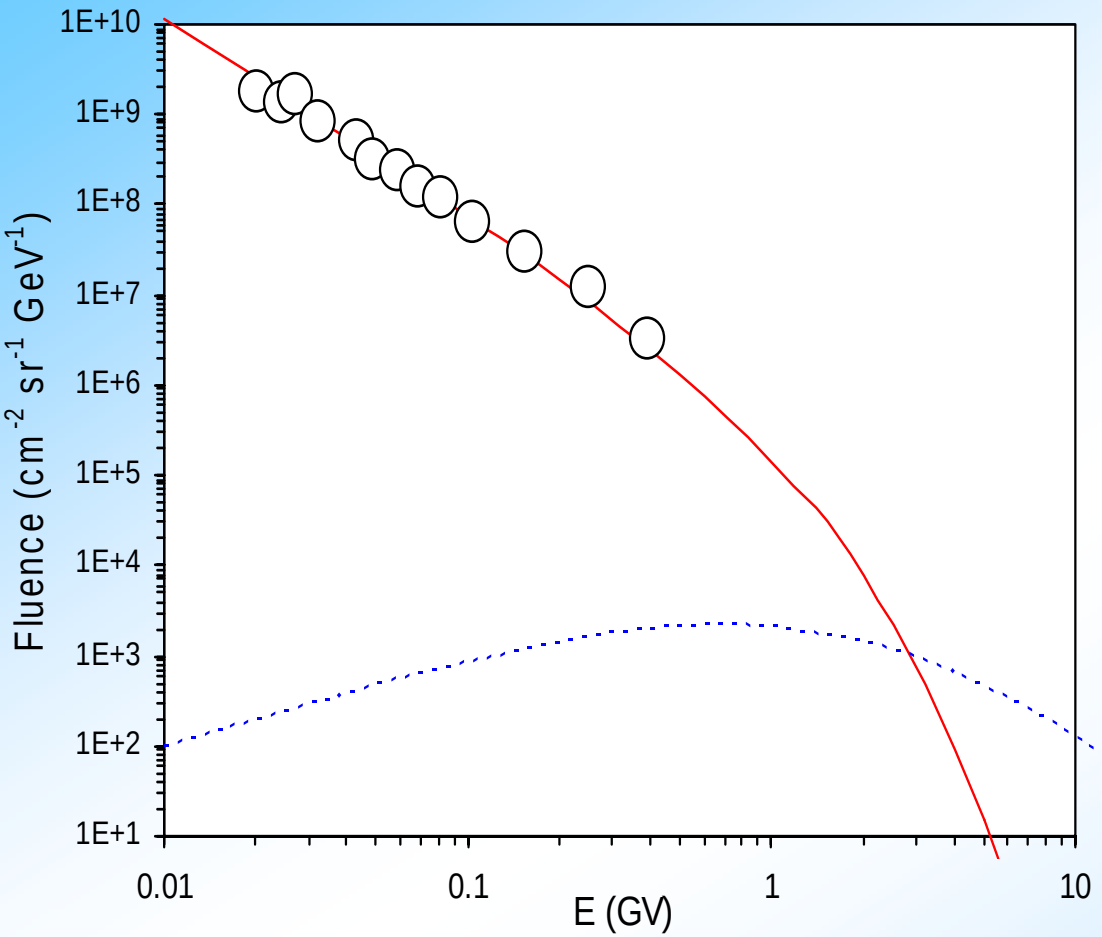
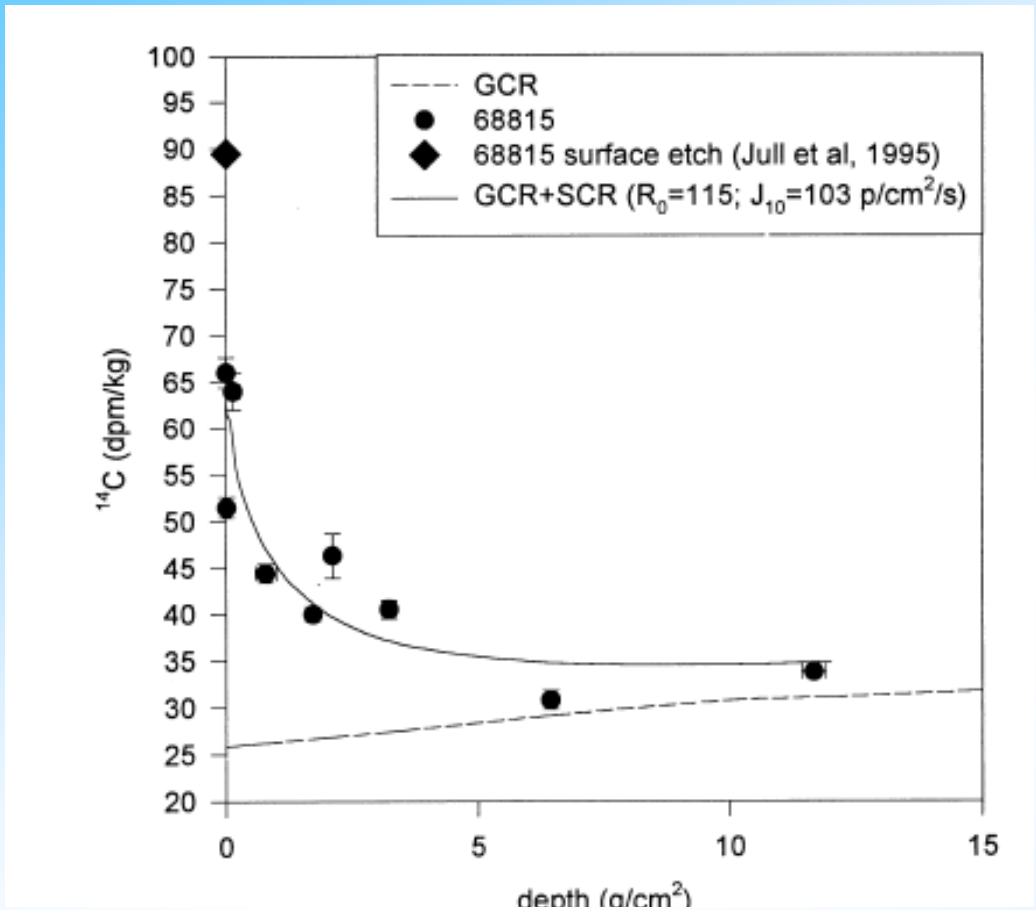
SCR vs GCR



Daily fluence of SCR and GCR for 20/01/2005 (dots – GOES data).

How can one seperate them?

Lunar soil – a spectrometer



Lunar soil acts as a natural spectrometer – deeper layers correspond to more energetic GCR, while upper layers to GCR+SCR (Jull et al., GCA, 1998).

Only time integration is possible.

Meteorites – can be time stamped, but upper layer are destroyed.

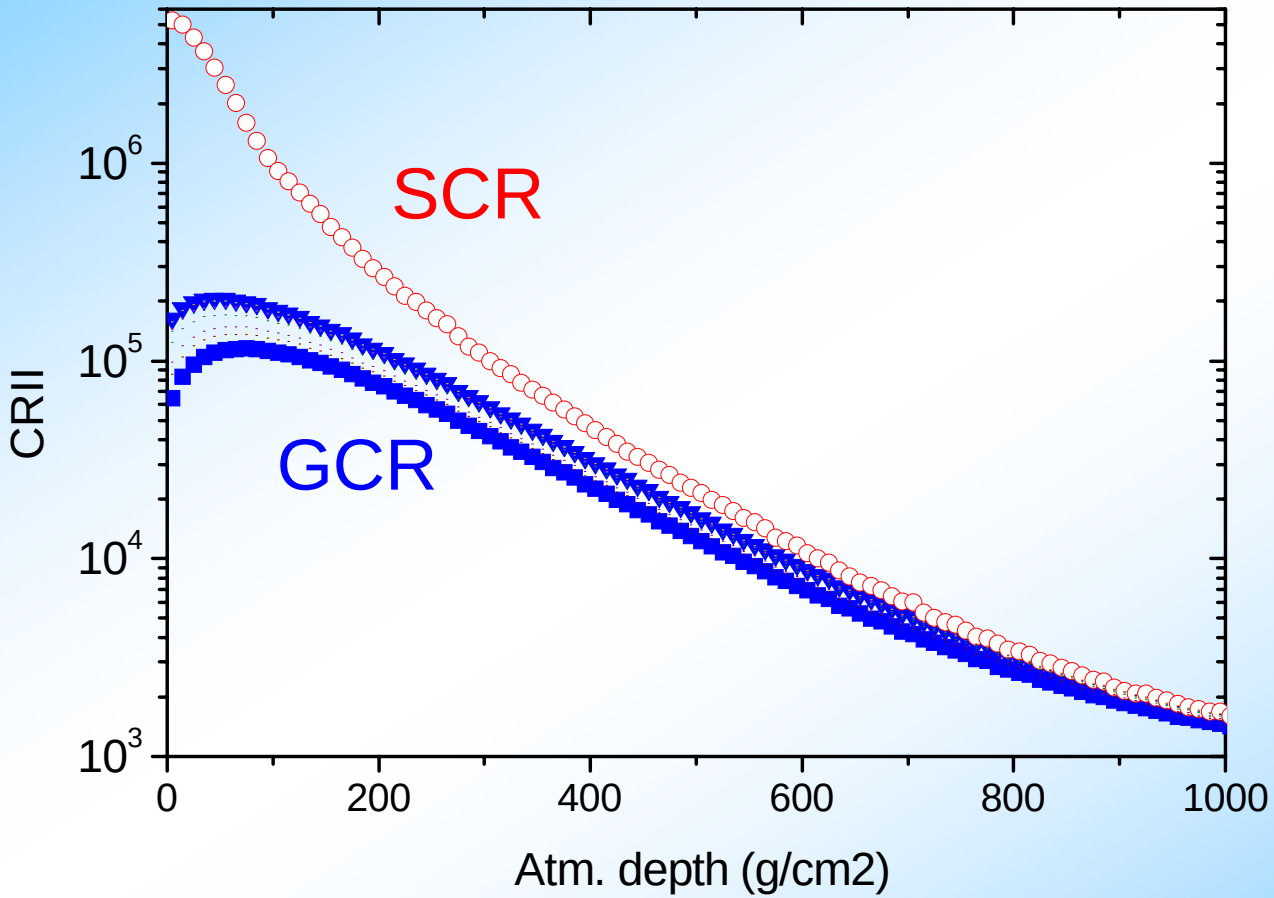
Lunar samples: Long-term averages

Table 6. Solar-proton spectral parameters and 4π integral fluxes (p/cm^2/s) above 4 energies (in MeV) determined from spacecraft data (SEL, IMP-8, and SPME) and lunar samples using different isotopes

Time range	Data source	Reference	R_0 (MV)	E > 10	E > 30	E > 60	E > 100
1954–1964	^{22}Na, ^{55}Fe	Reedy (1977)	100	378	136	59	26
10^4 yr	^{14}C	This work	110–115	103	42	17	7
10^5 yr	^{41}Ca[1]	Klein et al. (1990)	70	120	28	7	1.5
		Fink et al. (1998)	80	200	56	16	4
3′ 10^5 yr	^{81}Kr[1]	Reedy and Marti (1991)	~85	—	—	14	4
5′ 10^5 yr	^{36}Cl[1]	Nishiizumi et al. (1995)	~75	100	26	7	2
10^6 yr	^{26}Al[2]	Kohl et al. (1978)	100	70	25	9	3
10^6 yr	^{10}Be, ^{26}Al[2]	Nishiizumi et al. (1995)	75	100	26	7	2
	^{10}Be, ^{26}Al	Michel et al. (1996)	125	55	24	11	5
		Fink et al. (1998)	100	89	32	12	4
2′ 10^6 yr	^{10}Be, ^{26}Al[2]	Nishiizumi et al. (1998)	>70	—	~35	~8	~2
5′ 10^7 yr	^{53}Mn	Kohl et al. (1978)	100	70	25	9	3
~2′ 10^6 yr[3]	^{21,22}Ne, ^{38}Ar	Rao et al. (1994)	80–90	58–87	~22	~7	~2

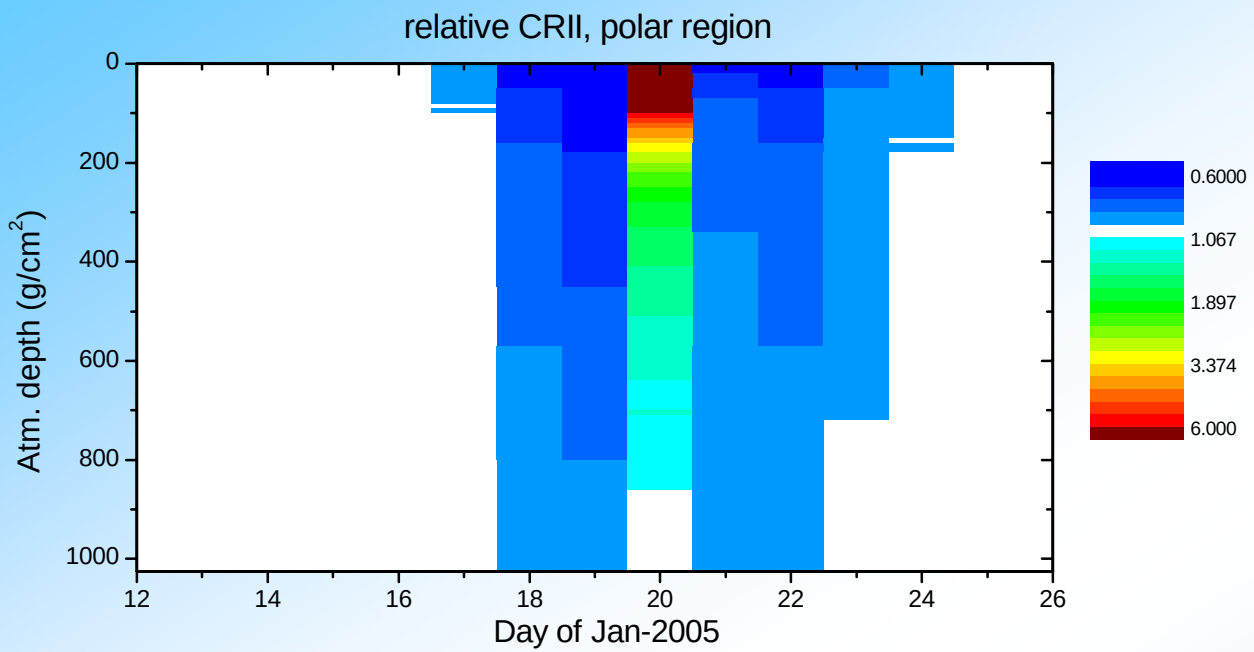
Jull et al., GCA, 1998

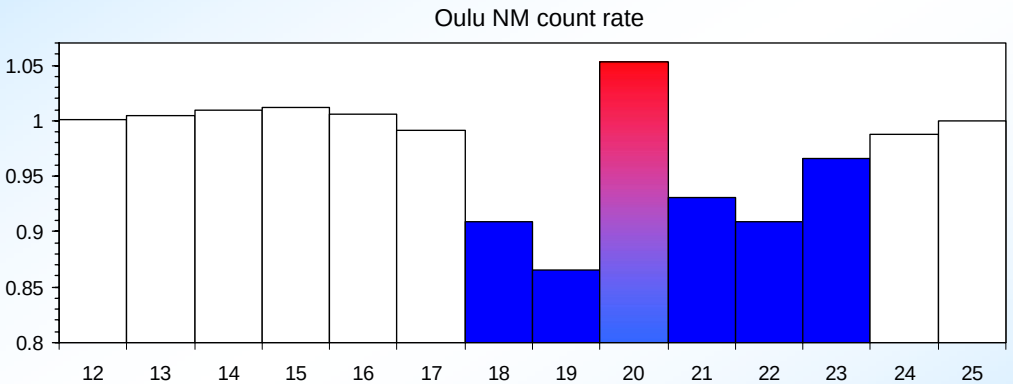
Atmosphere as a spectrometer



CRII in the polar atmosphere for 20/01/2005 (computed by Usoskin & Kovaltsov, 2006)

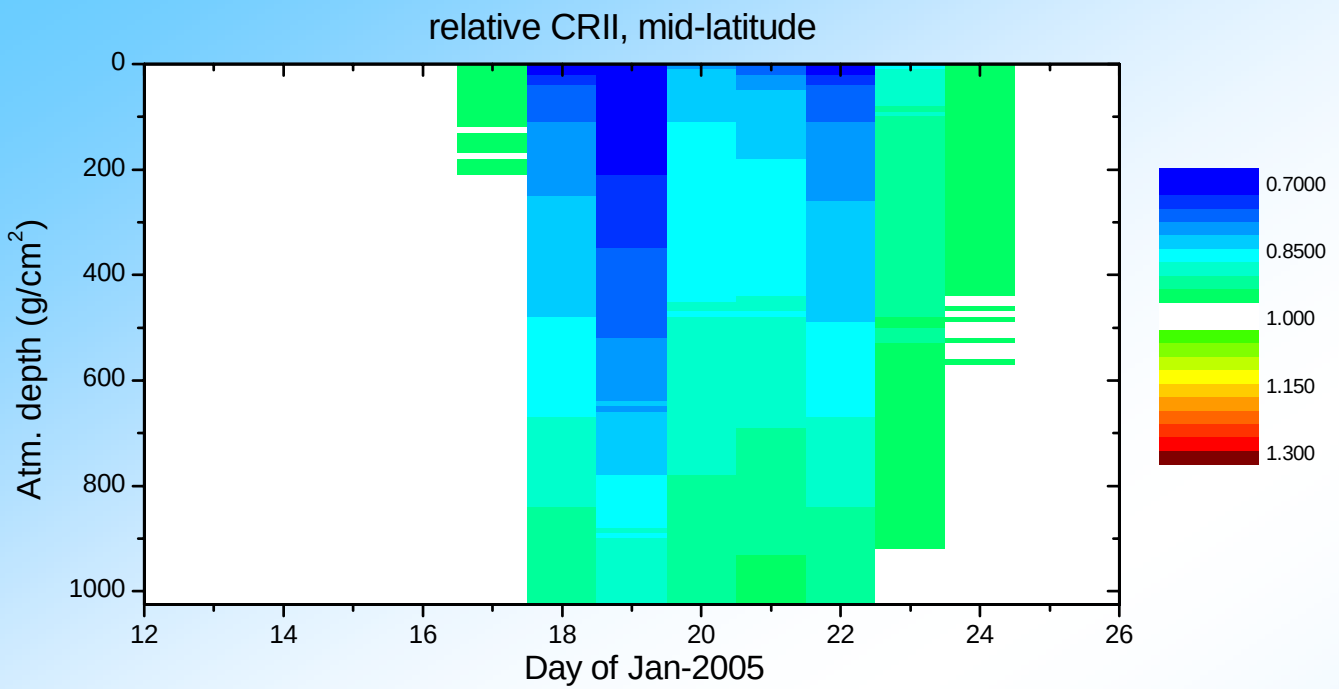
Severe SPE+FD, polar region

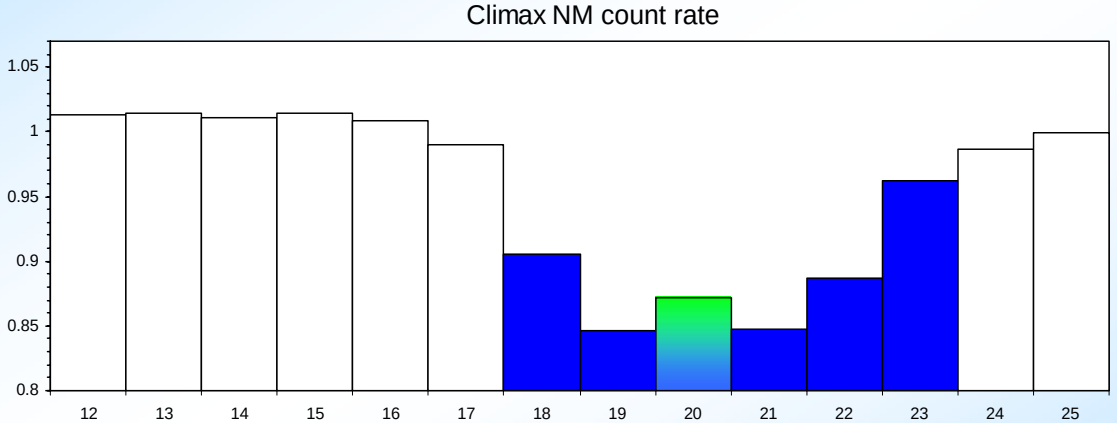




CRII and cosmic rays in the polar region in January 2005, normalized to the quite pre-event period.

Severe SPE+FD, mid-latitude region





The same as before but for mid-latitudes (Pc=3 GV).

Nitrates – a proxy for SCR

- "Odd nitrogen" NO*x* (e.g., N, NO, NO2, NO3, 2N2 O5, BrONO2, ClONO2, HO2NO2, and HNO3) is produced in the polar stratosphere by cosmic rays (e.g., *Jackman et al*. [1990, 1993], *Vitt et al*. [2000]).

- In the polar stratosphere SCR play a crucial role.

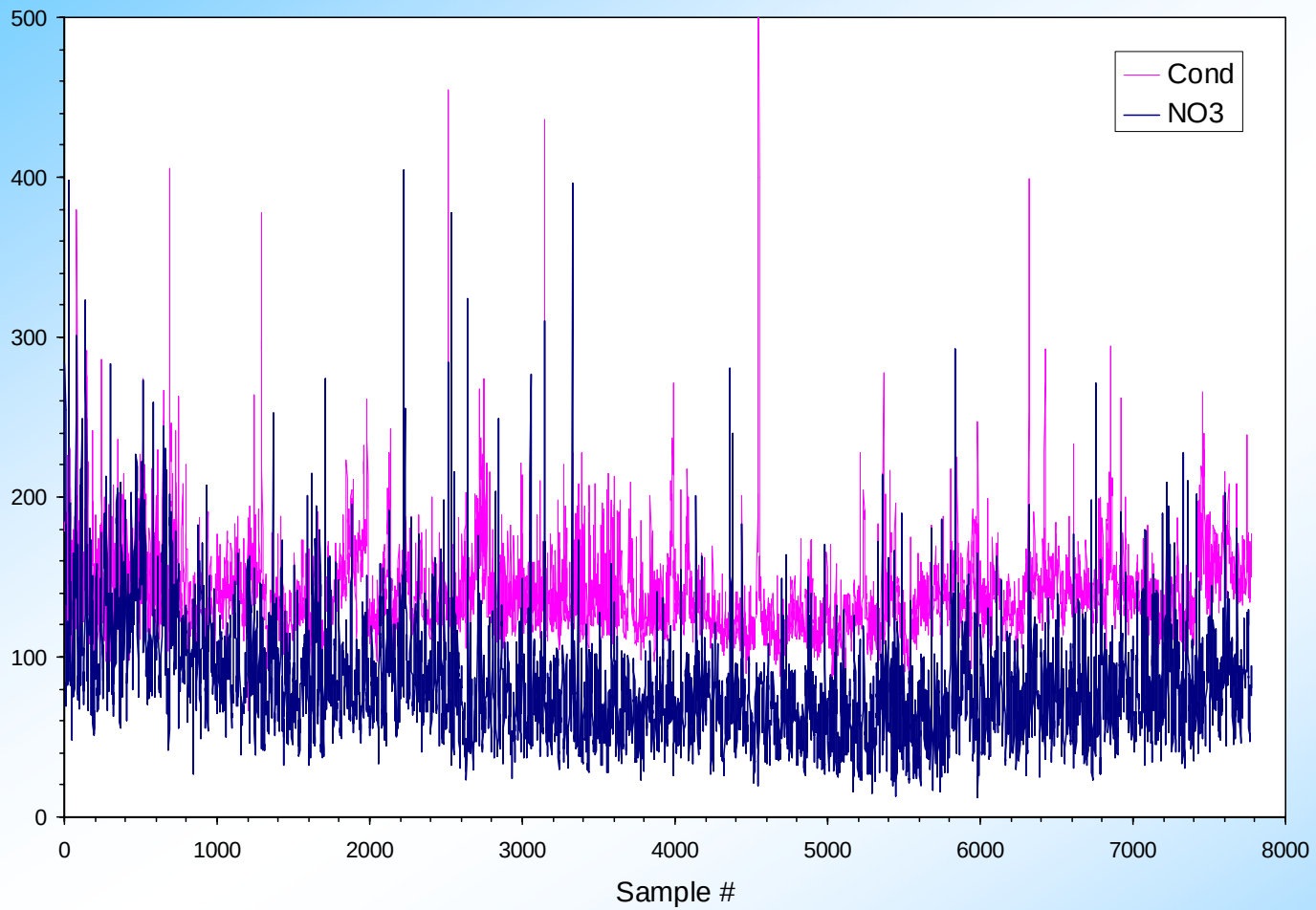
- This "odd nitrogen" → nitrates that can precipitate and be kep in ice/firn.

- Thus, record of nitrates in polar ice – a proxy for SCR flux.

- High time resolution → individual SEE (groups of SEE)

Works by Dreschhoff & Zeller; Shea, Mccracken et al.

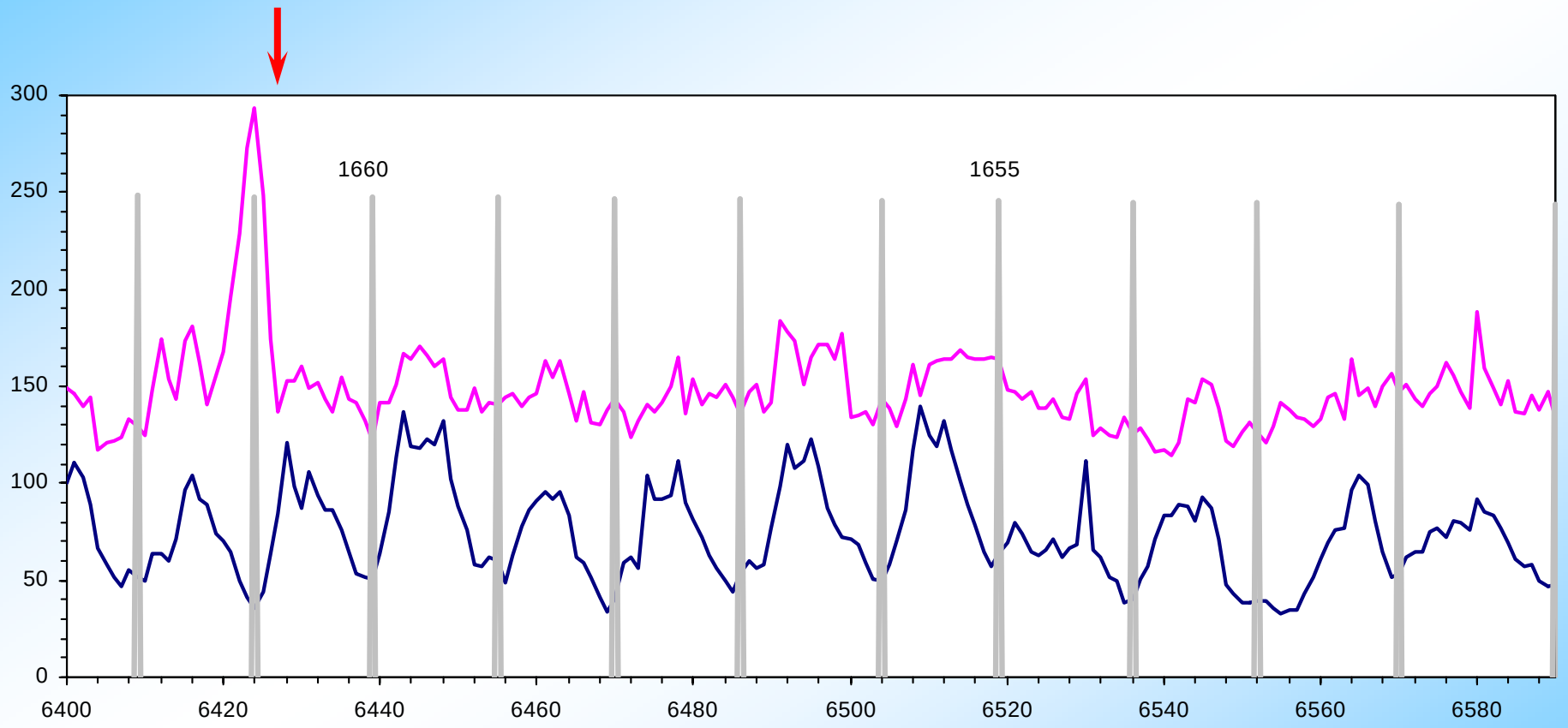
Nitrate data



Nitrate data in Greenland ice (1576-1992) – Dreschhoff & Zeller (1990, 1994), Zeller & Dreschhoff (1995)

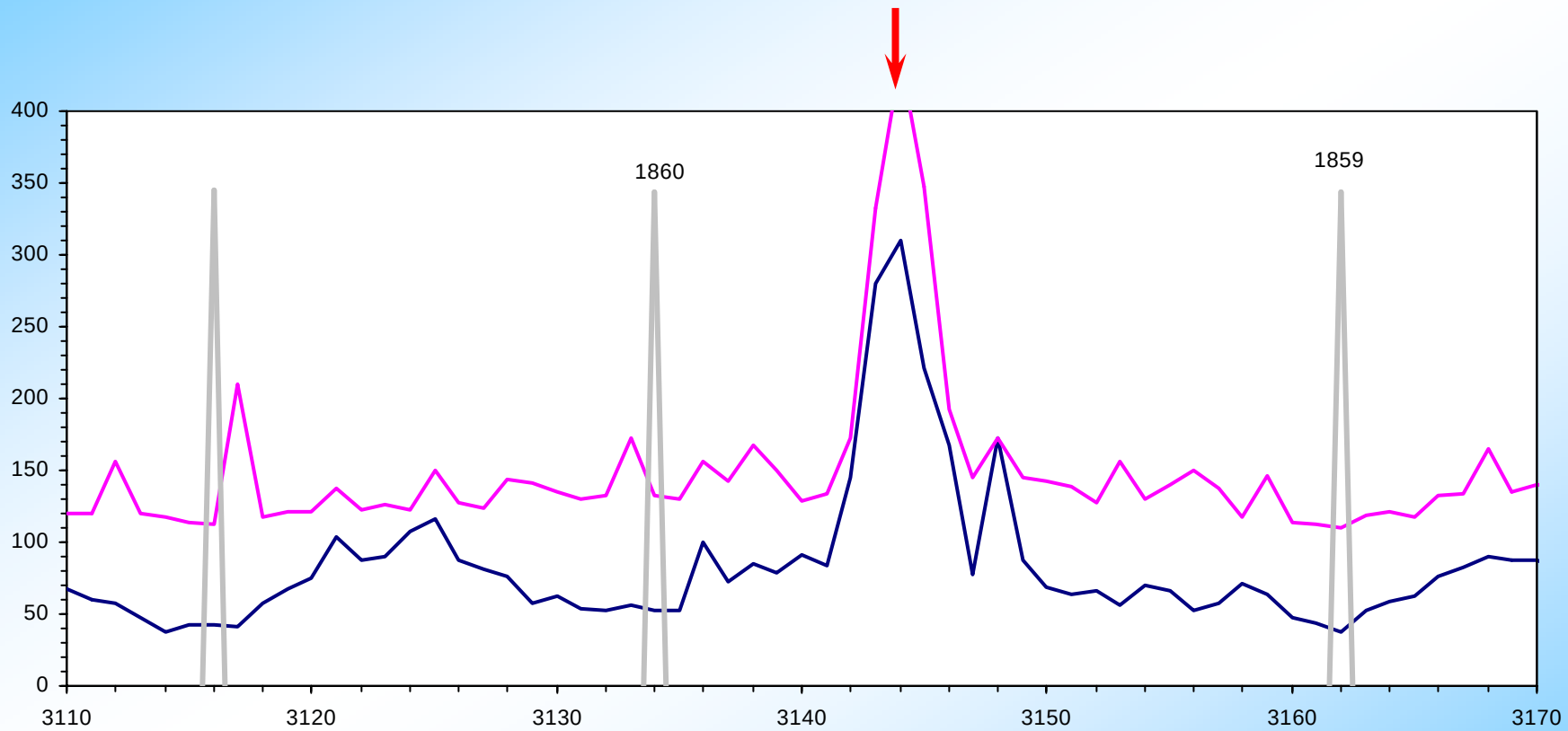
Nitrate series timing

Katla Volcano, Iceland, 03/11/1660

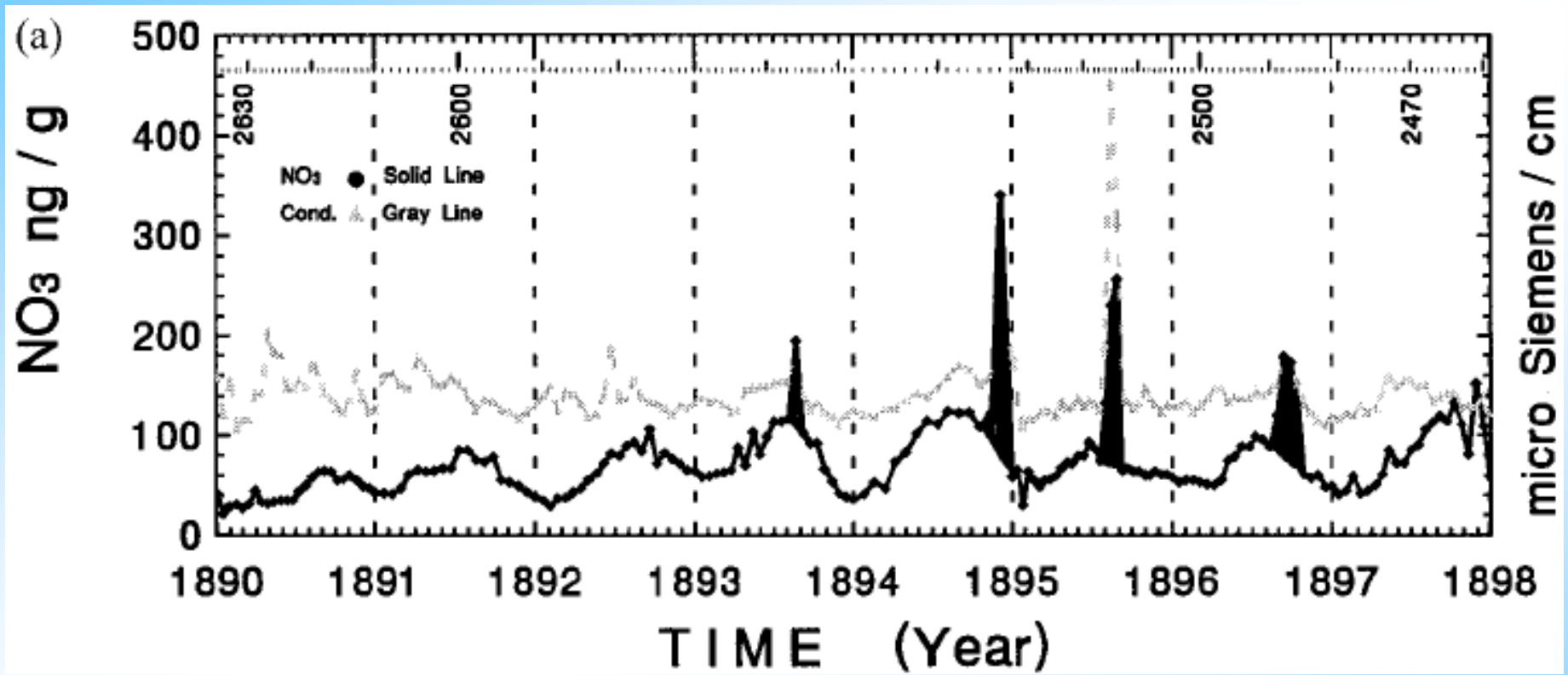


SEE in nitrate series

Carrington flare 01/09/1859



Some SEE in 19-th centuries



McCracken et al., 2001

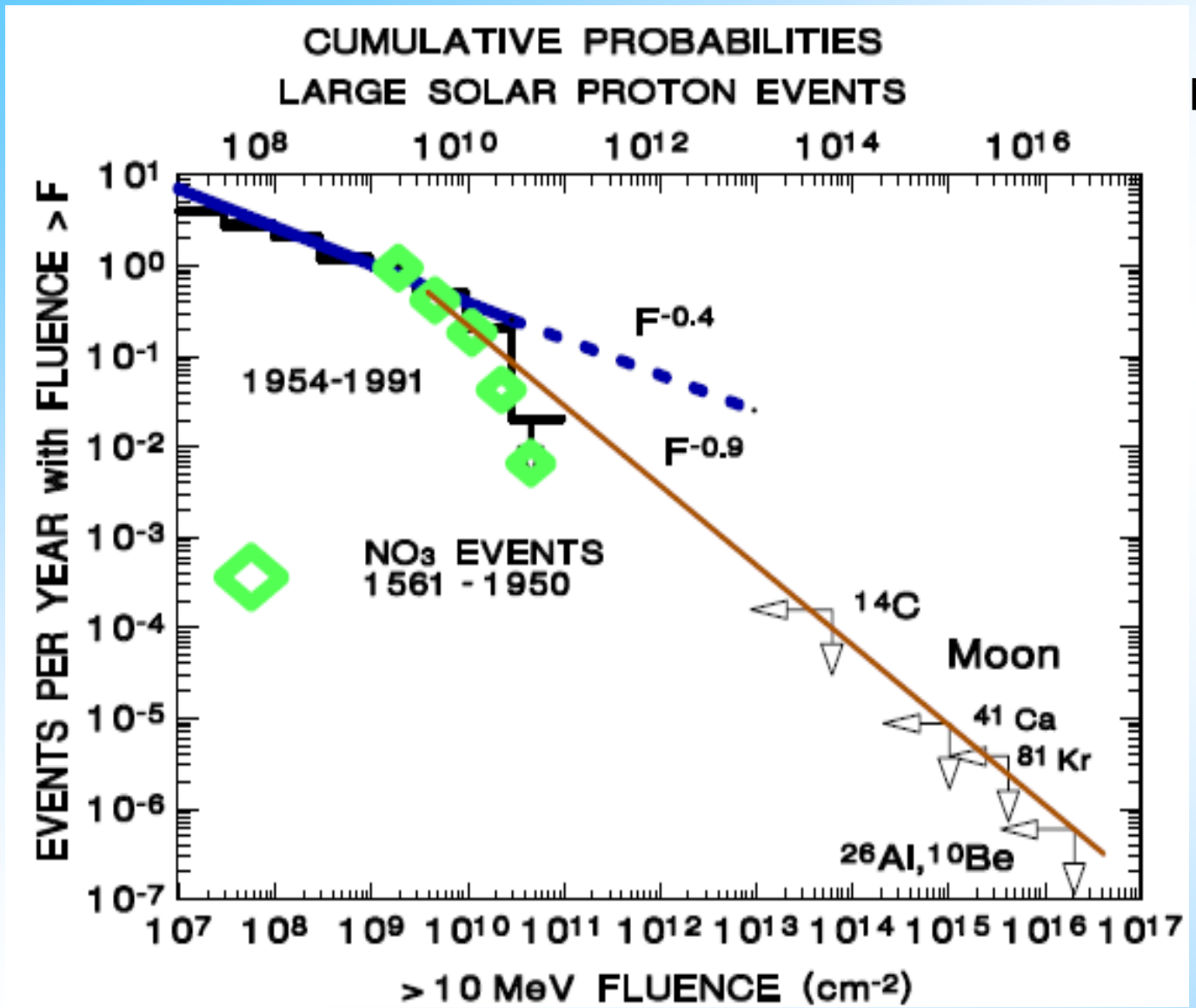
List of nitrate-defined SEEs

Table 1. Impulsive Nitrate Events (>30 MeV Proton Fluence $>2 \times 10^9$ cm^{-2}) in the Interval 1561–1950

Year	Nitrate Concentration, ng g^{-1}	>30 MeV Proton Fluence,[a] $\times 10^9$ cm^{-2}
1562	80	2.0
1564	94	2.3
1570	194	4.8
1574	99	2.5
1578	86	2.2
1582	119	3.0
1587	92	2.3
1596	118	2.9
1599	118	2.9
1603	209	5.2
1604	90	2.3
1605	284	7.1
1608	136	3.4
1610	187	4.7
1610	116	2.9
1612	108	2.7
1616	159	4.0
1619	319	8.0
1620	83	2.1
1621	89	2.2
1635	113	2.8
1637	246	6.1
1639	170	4.3
1647	208	5.2
1667	164	4.1
1682	112	2.8
1700	234	5.8
1701	111	2.8
1706	129	3.2
1710	188	4.7
1719	298	7.4
1727	252	6.3
1730	102	2.6
1755	216	5.4
1763	156	3.9
1774	180	4.5
1789	118	3.0
1793	219	5.5
1794	146	3.7
1805	141	3.5
1807	118	3.0
1813	255	6.4
1822	131	3.3
1849	101	2.5
1851	373	9.3
1859	115	2.9
1859	751	18.8
1864	280	7.0
1866	88	2.2
1868	93	2.3
1878	201	5.0
1879	141	3.5
1885	104	2.6
1886	149	3.7
1889	178	4.5
1893	93	2.3
1894	301	7.7
1895	444	11.1
1896	322	8.0
1897	125	3.1
1908	113	2.8
1909	132	3.3
1913	158	4.0
1919	96	2.4
1928	83	2.1
1929	187	4.7
1934	111	2.8
1936	94	2.4
1942	145	3.0
1944	138	3.4

70 events identified by McCracken et al., 2001

Probability of SEE to occur



McCracken et al., 2001

SEE in cosmogenic isotopes

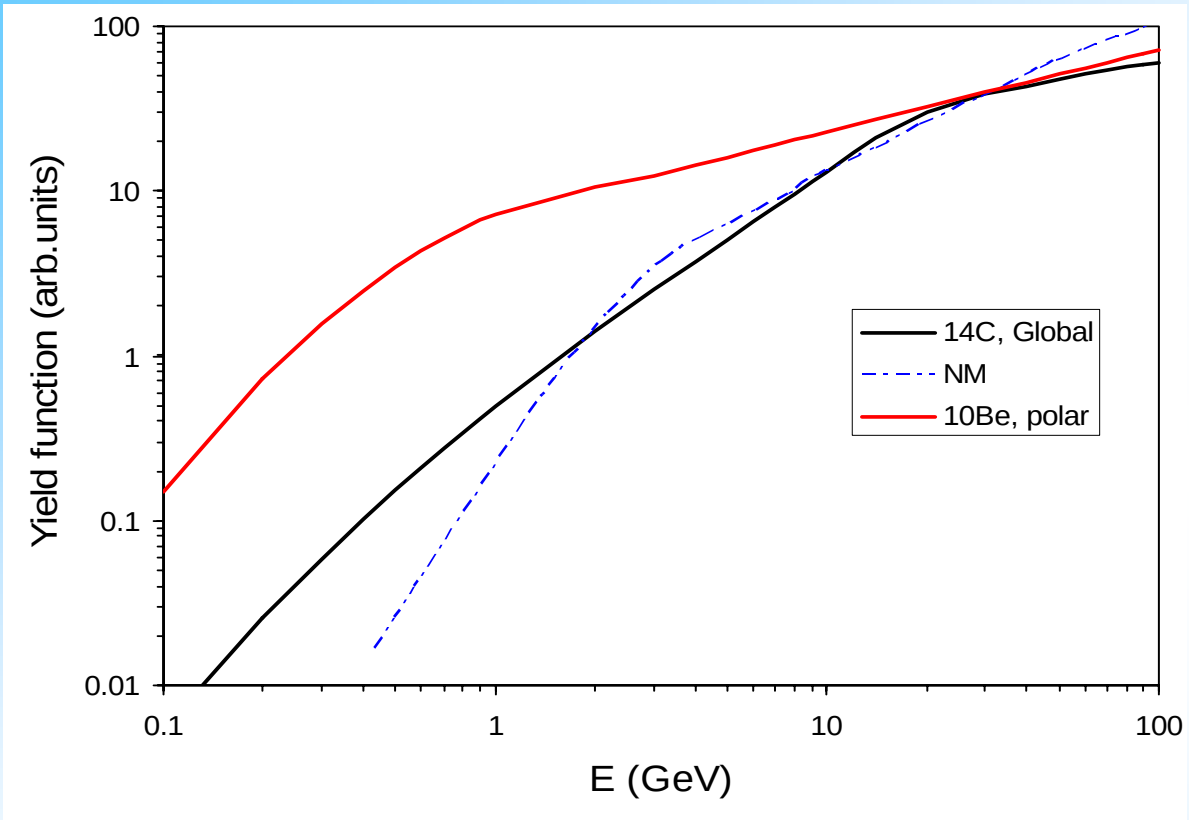
Cosmogenic isotopes are produced by CR in the Earth's atmosphere.
Usually only GCR are considered. What about SCR?

This question has been discussed since long but the results are controversal for ^{14}C.

General agreement is that strong SEP events can be detectable in ^{10}Be signal, but there is a need for quantitative evaluation of the effect.

A thorough quantitative study of a possible SCR signal in terrestrial comsogenic isotope data has been performed recently (Usoskin et al., GRL, 33(8), L08107 2006).

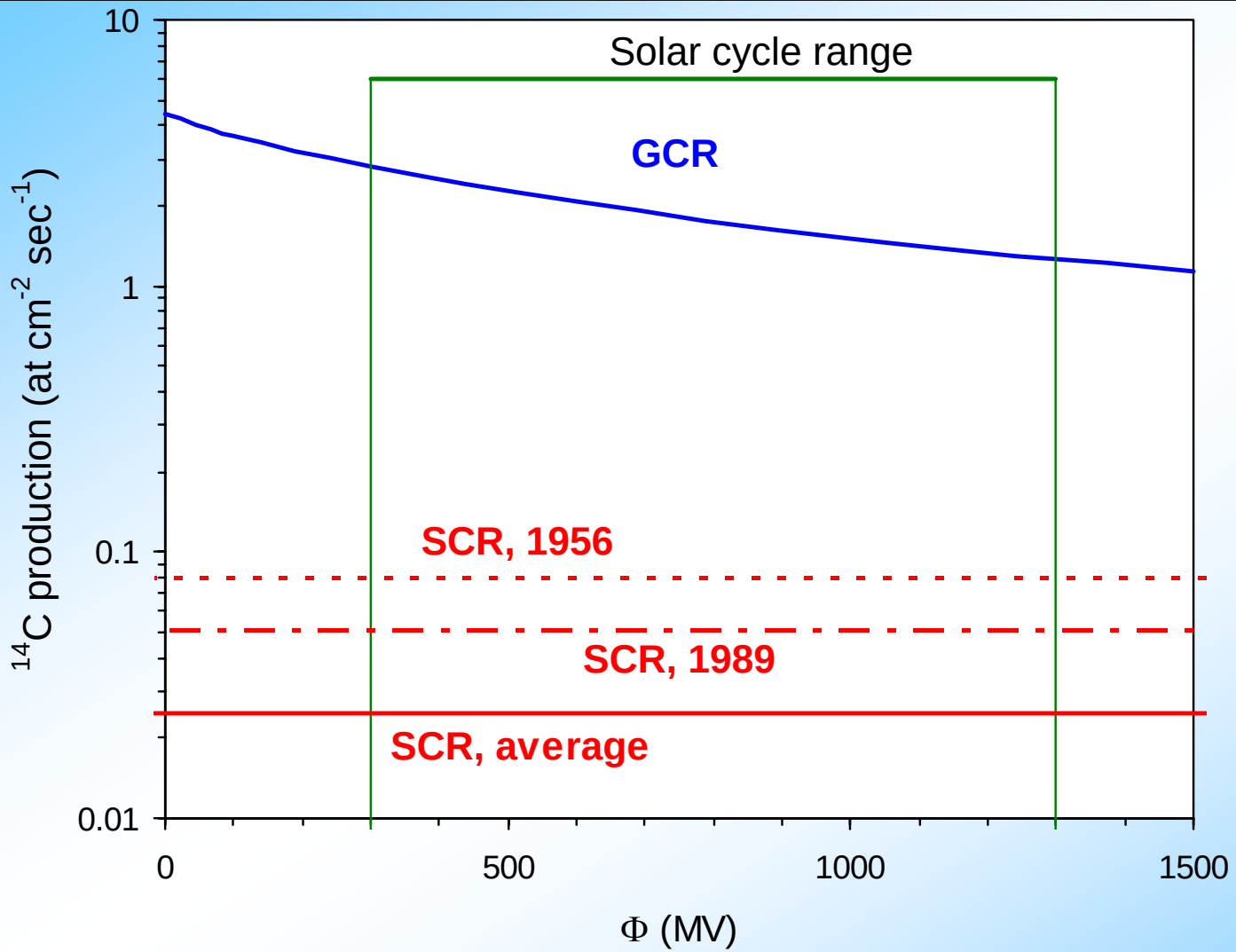
Isotope production



Differential yield functions:
global ^{14}C (Castagnoli & Lal, 1980); ^{10}Be polar (Webber & Higbie, 2003); polar NM (Clem & Dorman, 1999).

^{14}C is close to NMs (no net SCR signal in annual NM data since 1951), also the attenuation due to the carbon cycle → **no SCR signal is expected in ^{14}C**

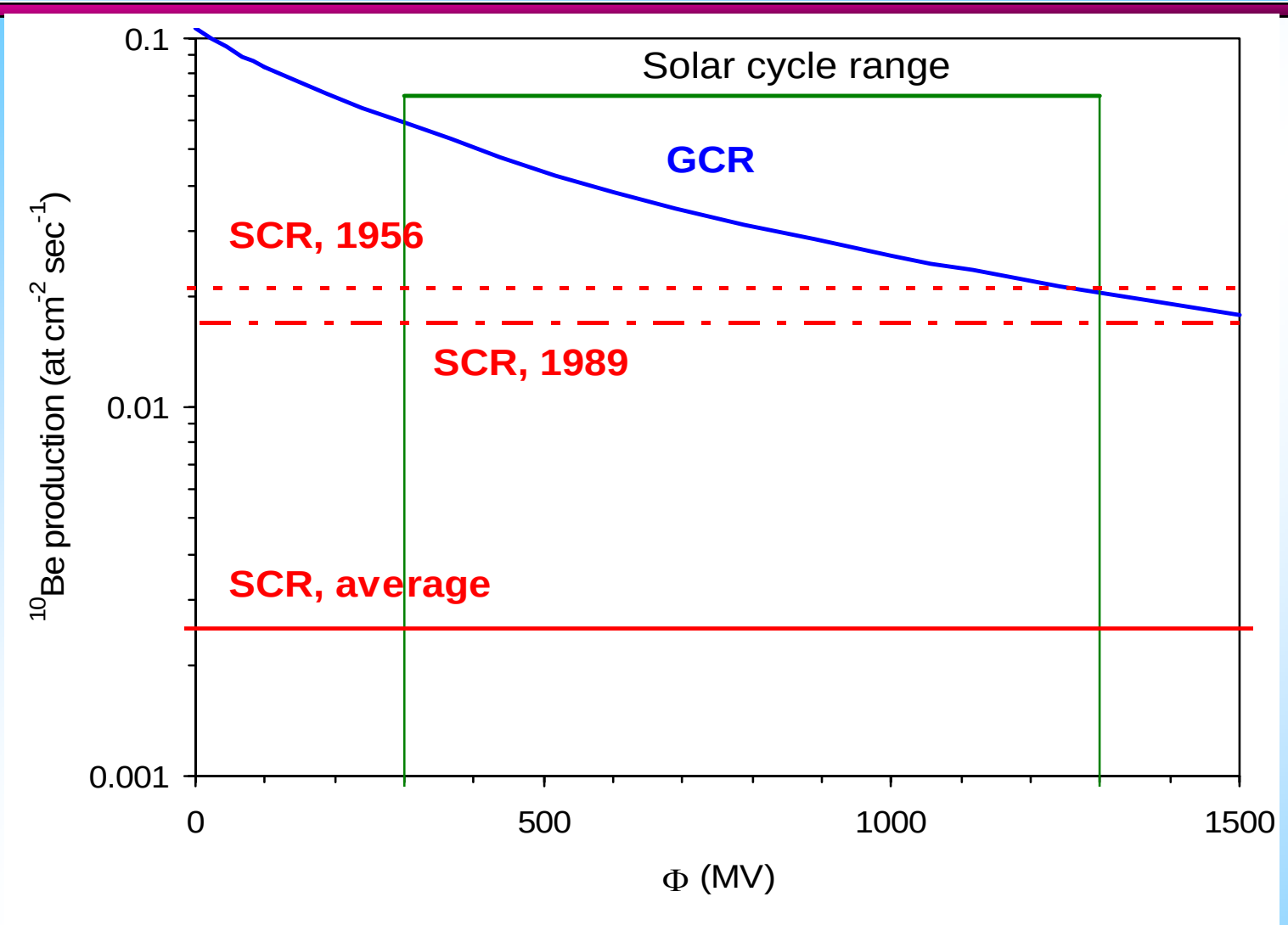
^{14}C global production by GCR and SCR



Annual production of ^{14}C in the Earth atmosphere by ***GCR*** and ***SCR.***

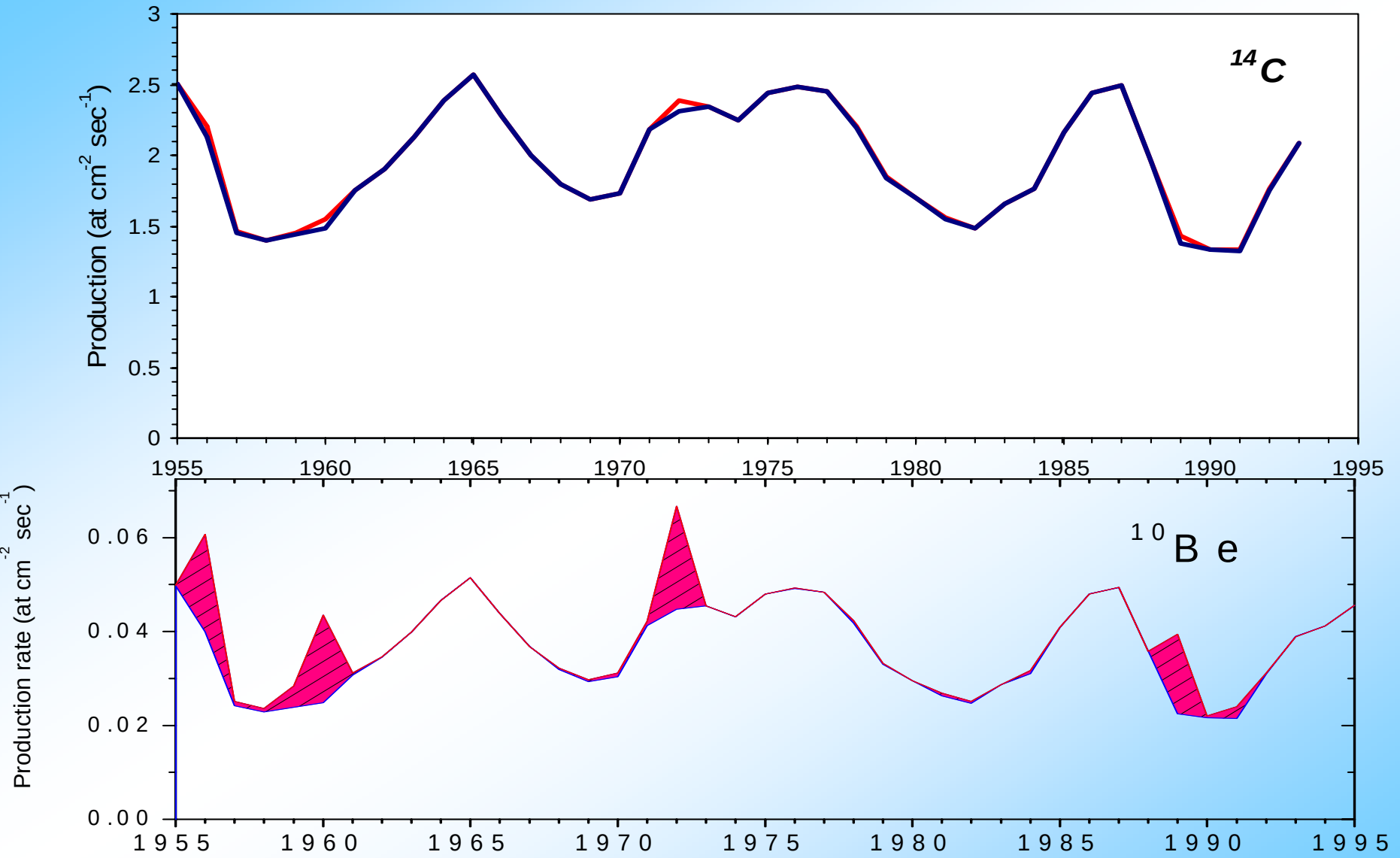
SCR are hardly detectable in ^{14}C data.

^{10}Be polar production by GCR and SCR

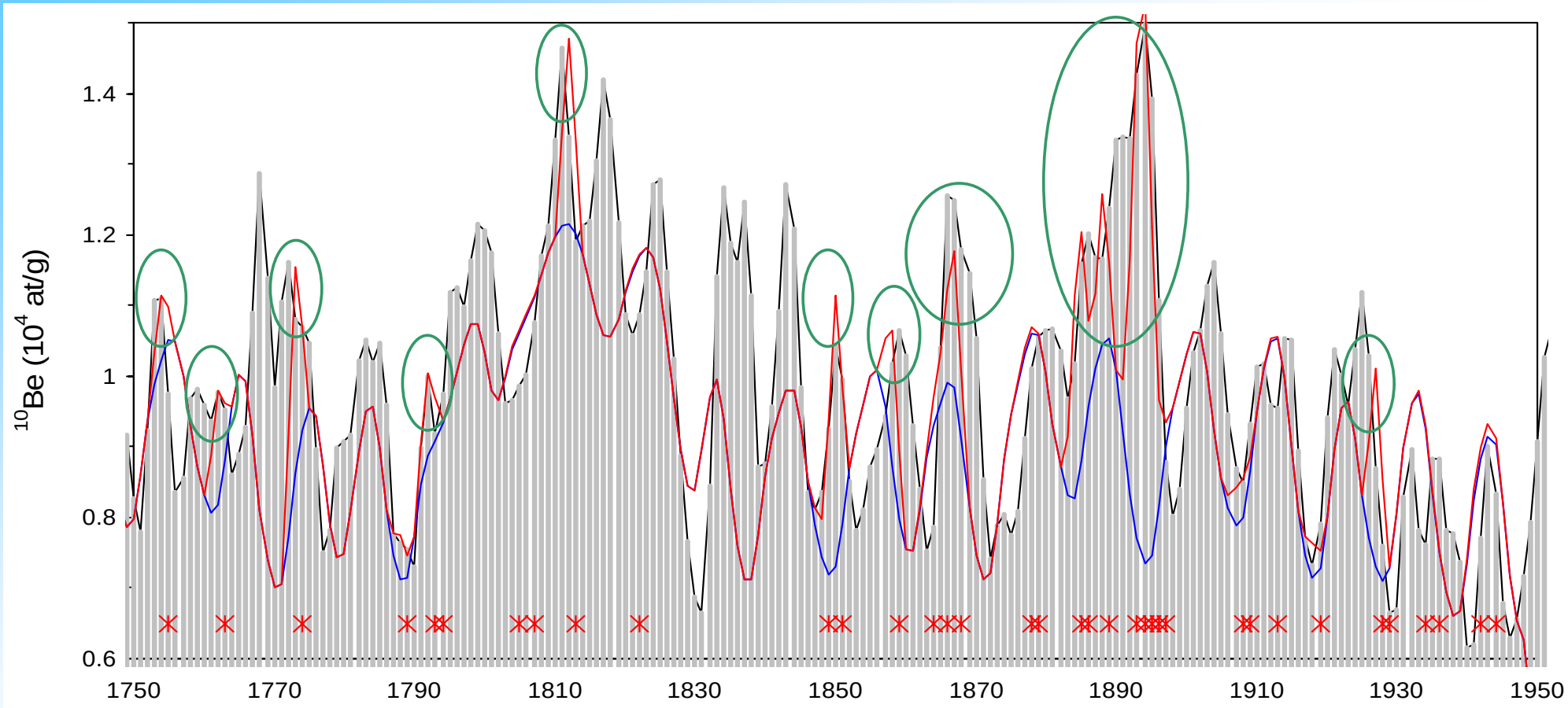


Major SEE can be observed by ^{10}Be data.

Modelled production



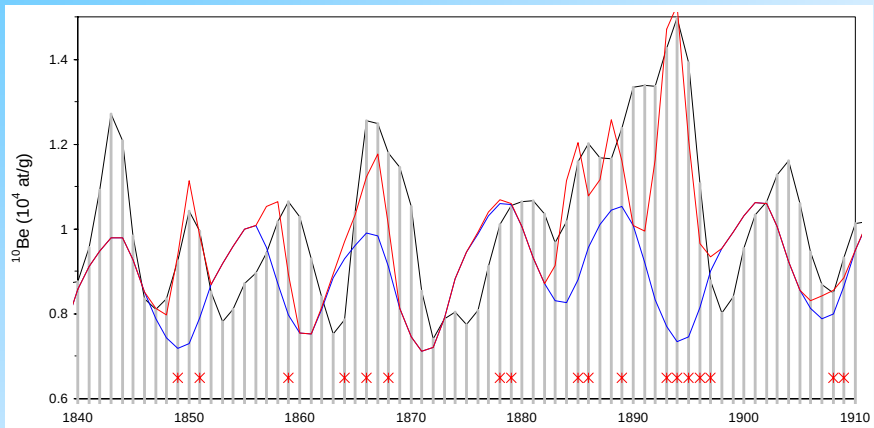
Measured and modelled ^{10}Be

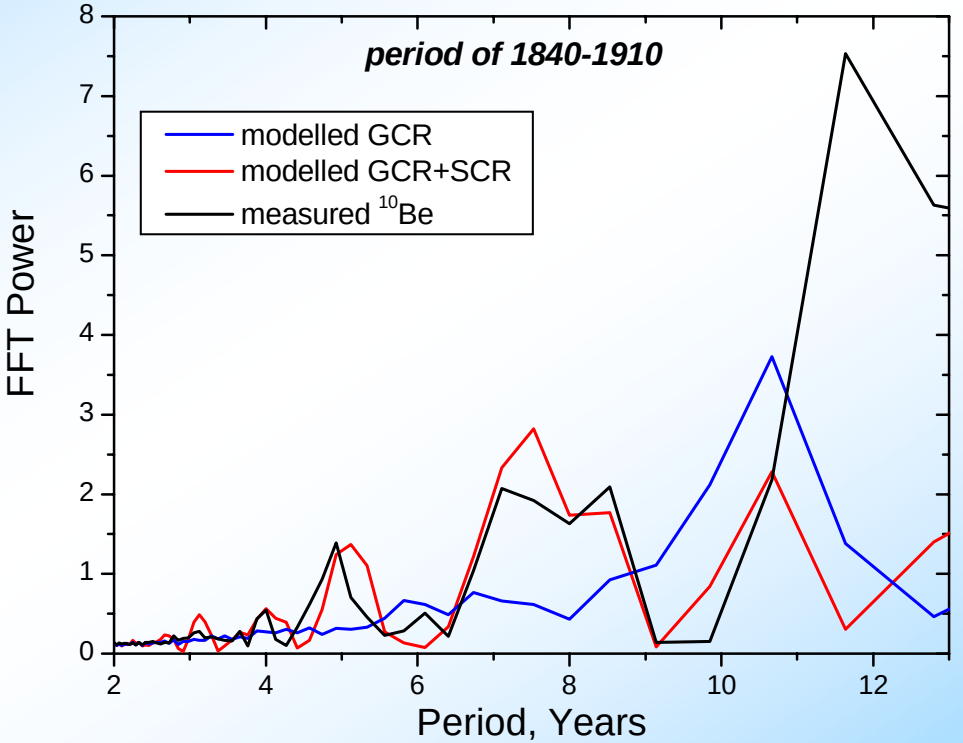


1-2-1 smoothed **measured** (Greenland Dye-3, Beer et al., 1990) and modelled polar ^{10}Be: ***GCR*** (Usoskin et al., 2006) and ***SCR+GCR***. Dates of nitrate-based SEEs are shown by * (McCracken et al., 2001).

Not all SEP events ←→ peaks in ^{10}Be.

5.5-year intermittent periodicity



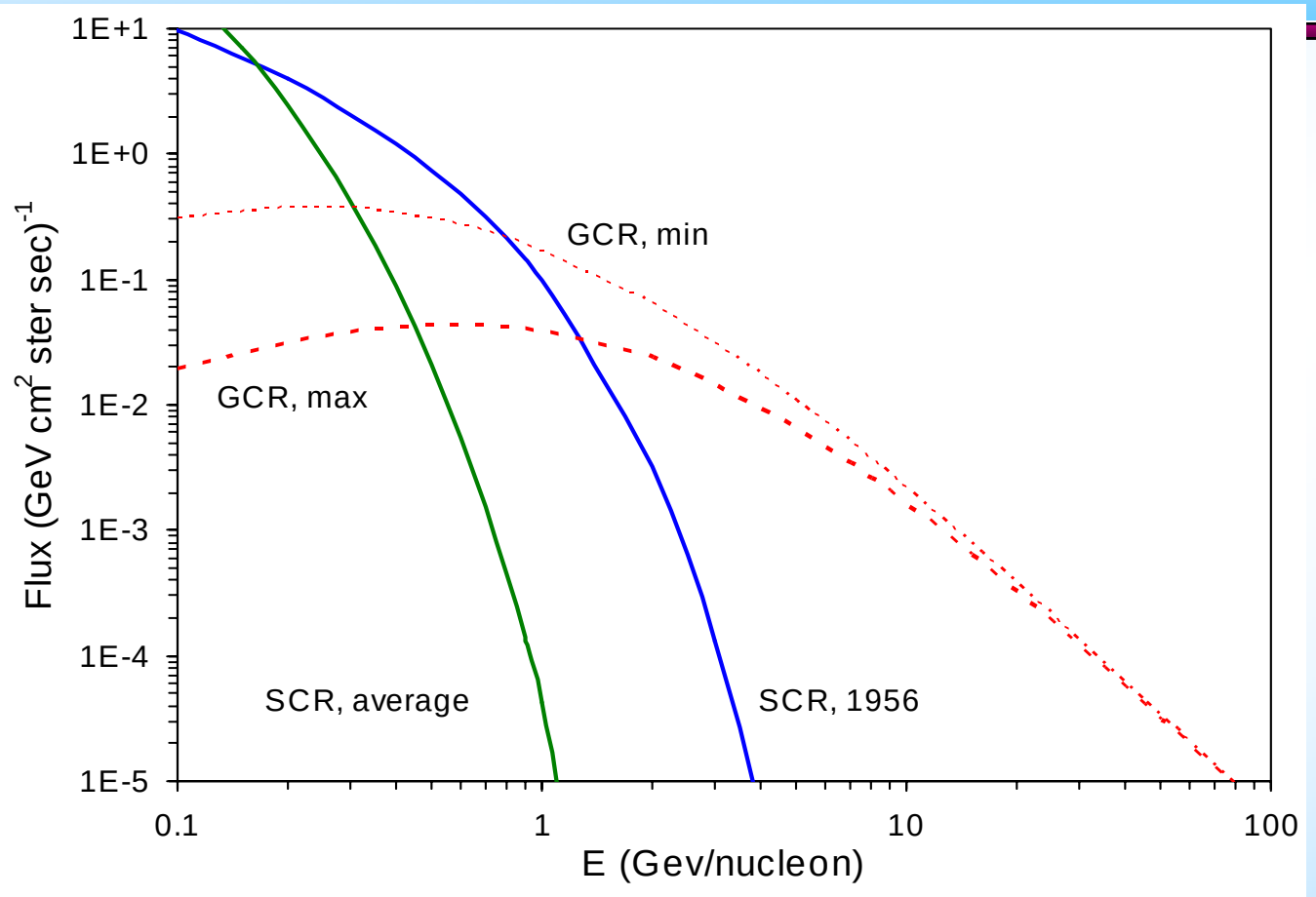


Conclusions

- Long-term averages of the SCR flux can be estimates using *lunar samples*. The result indicate that the present level of solar activity is much higher than the average.
- 70 candidates for major SEEs ($F_{30}>10^9$) have been identified in 1561-1950 using *nitrate data* in polar ice.
- SCR may significantly contribute into the polar ^{10}Be production. Ten episodes in ^{10}Be data have been identified during 1750-1950, which can hold a signature of severe SEP events. The combination of GCR and SCR may be responsible for a 5.5-year periodicity in ^{10}Be series found during some periods. Cosmogenic isotopes can miss SEE if they accompanied by strong FD.
- A thorough study of the ^{10}Be data combined with the data on nitrates in polar ice may allow for an estimate of very strong SEP events in the past.
- ^{14}C does not provide a suitable tool to study SCR in the past and its production rate represents solely variations of GCR due to solar modulation.


THANK YOU !

Energy spectra



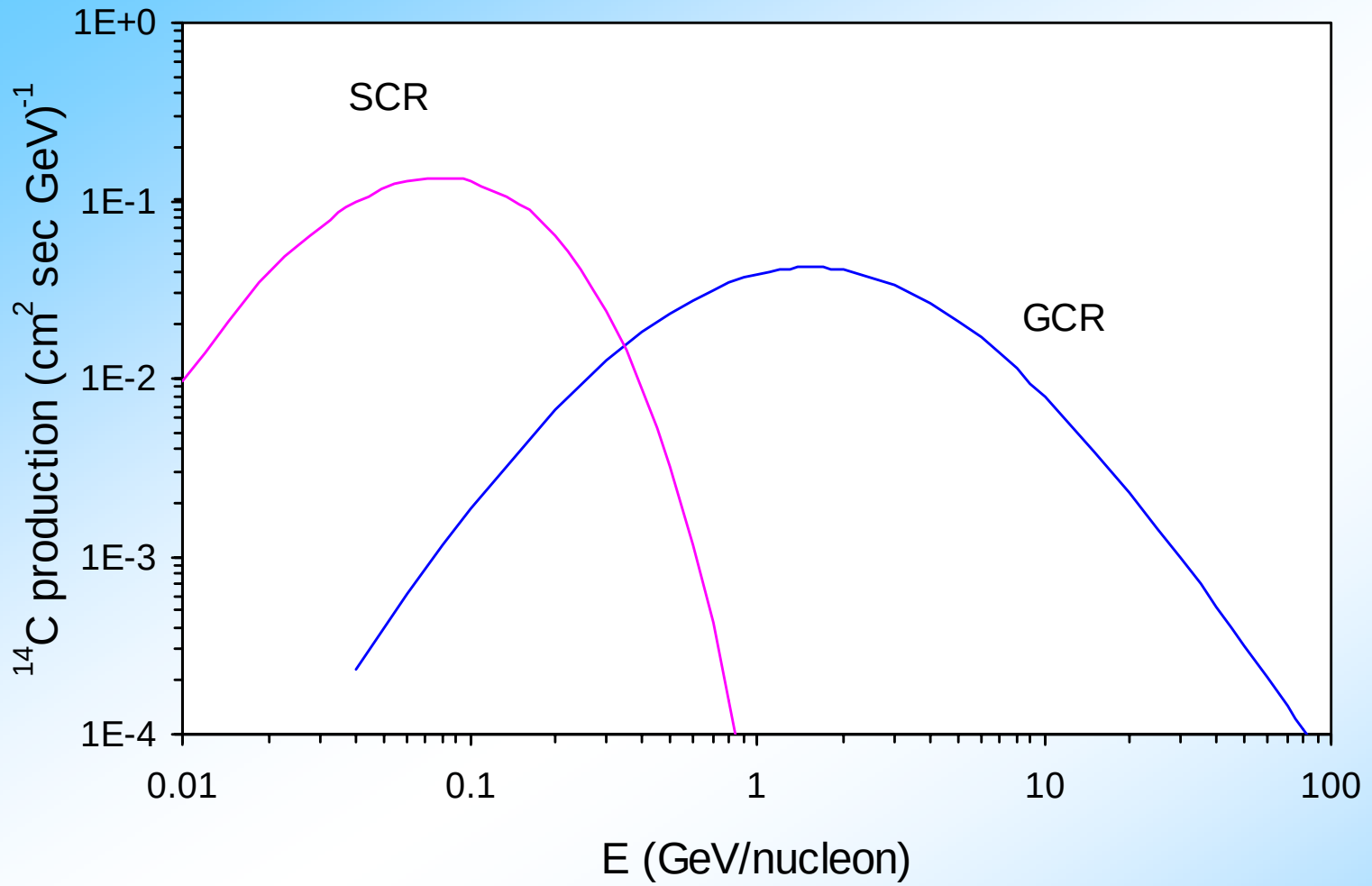
Differential energy spectra of cosmic rays: GCR for solar maximum and minimum, SCR for the year 1956, and SCR averaged over last solar cycles.

SCR spectrum is parametrized through the characteristic exponent over rigidity:

$$J_{SCR}(P)=J_o * \exp(-P/P_o)$$

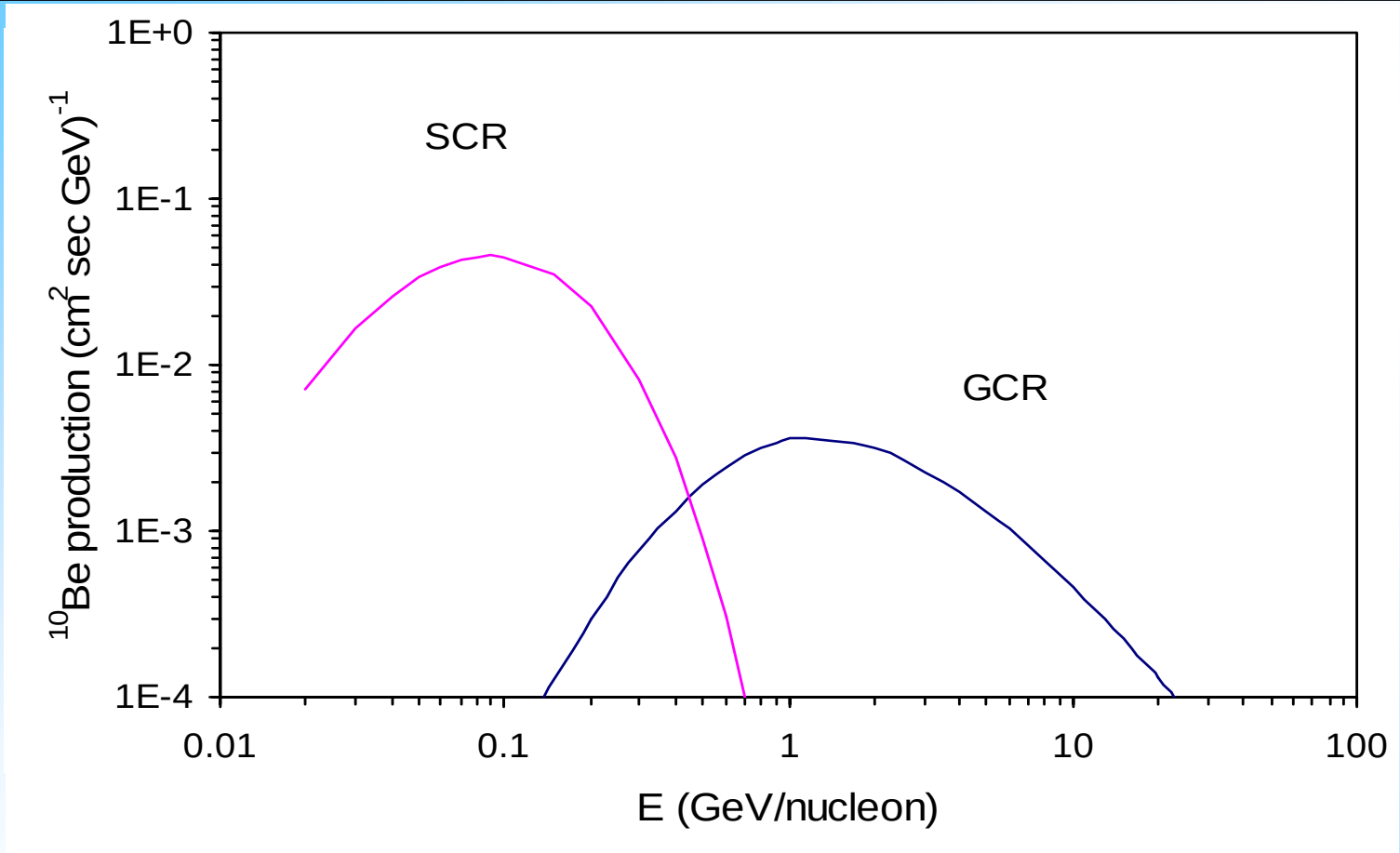
Typical values of P_o are within the range of 50-350 MV.

^{14}C production by GCR and SCR



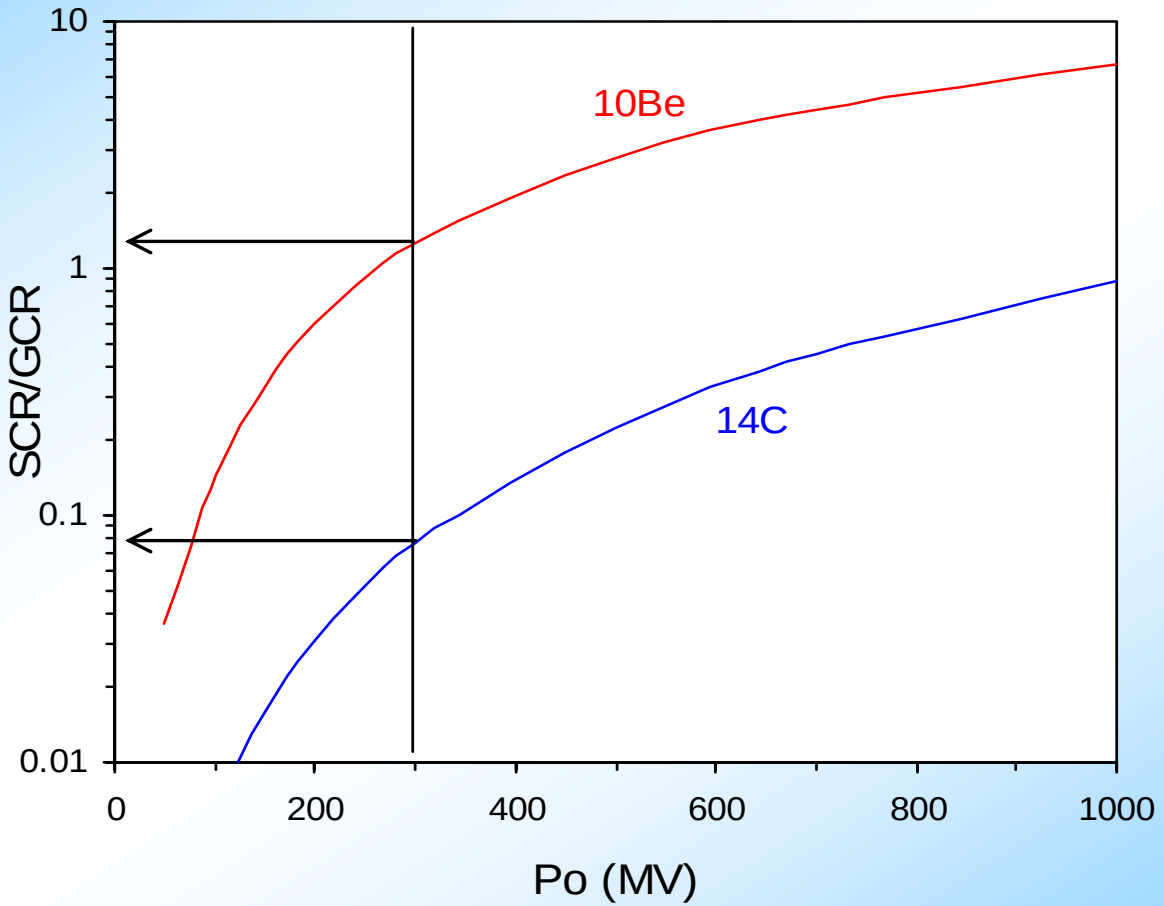
Differential production functions of global ^{14}C by **GCR** (solar maximum) and **SCR** (average for the last cycles).

^{10}Be production



Differential production of polar ^{10}Be by GCR (solar maximum) and SCR (average for the last cycles).

SCR-produced isotopes



Ratio of SCR-to-GCR signal in cosmogenic isotopes for F(>30 MeV)=10^9 cm^{-2}.

^{14}C during cycle No.13

- According to ***^{10}Be*** and polar ***nitrates*** data, the strongest SCR signal was during solar cycle ***No.13*** (1889-1901).

- Caluclations suggest for detectable SCR production of ***^{14}C***:
  - mean annual ***^{14}C*** production due to SCR during 1890-1900 is ~0.24 (at cm $^{-2}$ sec^{-1}):
    - 10% of the GCR-produced ***^{14}C***
    - 10 times the average SCR production during last cycles;
  - In 1895, ***^{14}C*** production would be ~1 (at cm $^{-2}$ sec^{-1}) → ~40% of the GCR-production.

- This period (cycle 13) was claimed to be the only period with a possible contribution of SCR (Peristykh & Damon, 1998; Konstantinov et al., 1992).

- We know of no other SEP candidates during the last 200 years to produce an essential amount of ^{14}C.

Nitrate series timing: seasonal cycle