# OCCURRENCE OF EXTREME SEP EVENTS ON DIFFERENT TIME SCALES


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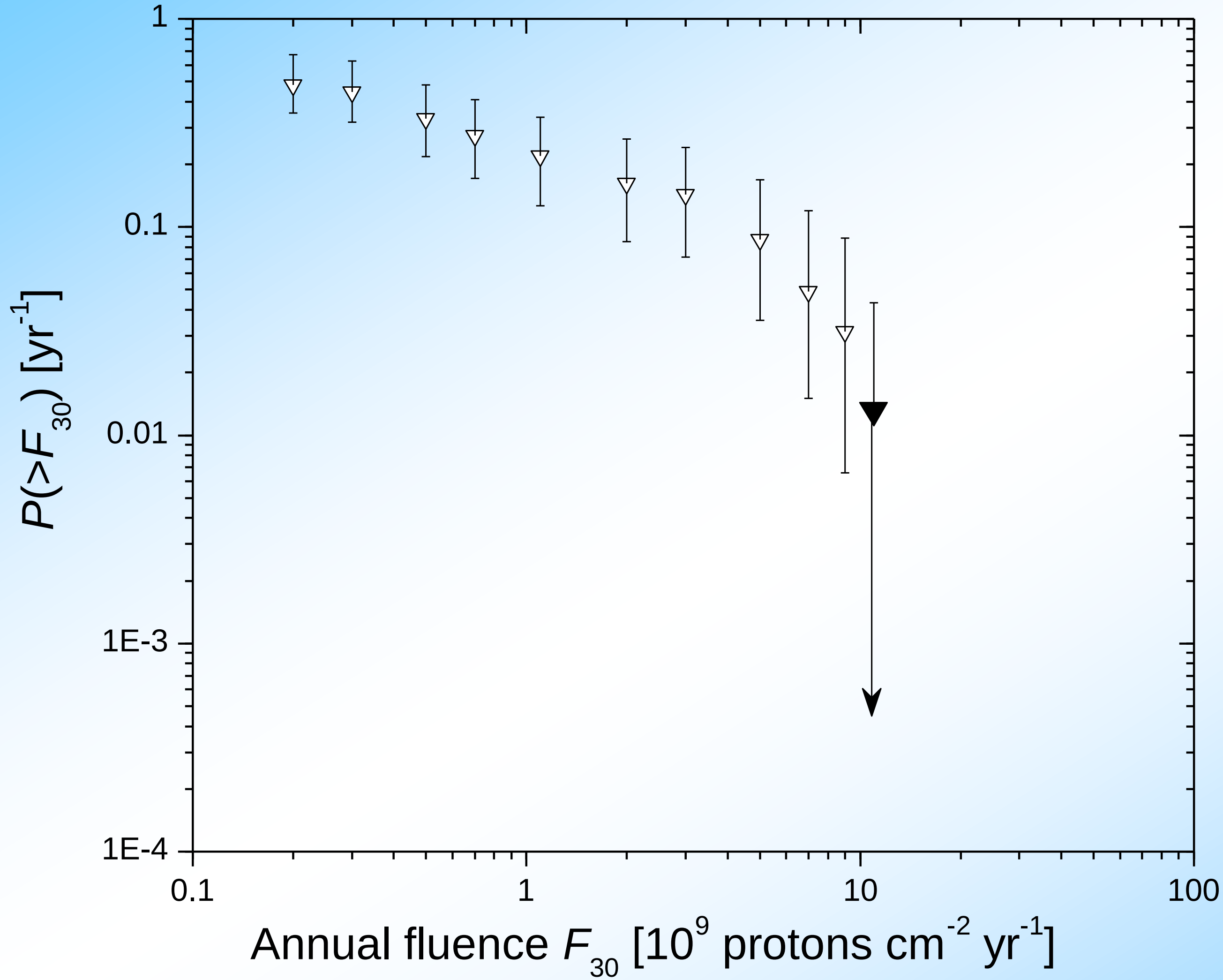
# Direct data: since 1950s

# SPE: space era



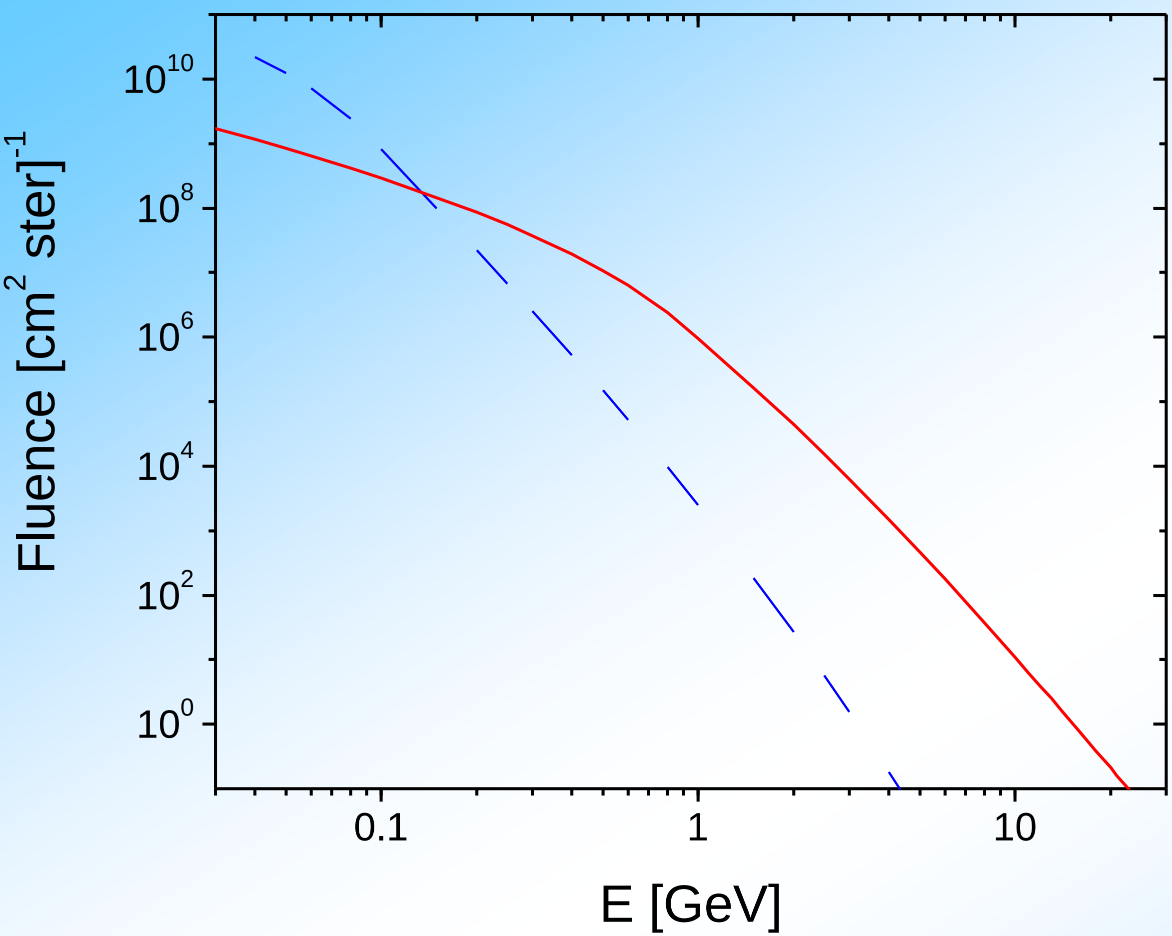

Shea & Smart (1990, 2012), Reedy (2012):
No events with $F_{30} > 10^{10}$ $cm^{-2}$ since 1956.

# Cosmogenic radionuclides: last 11 millennia

# Data series used

- ***IntCal09*** $\Delta^{14}C$ global series: 11000 BC – 1900 AD, 5-yr time resolution (Reimer et al. 2009).
- ***SB93*** $\Delta^{14}C$ global annual series: 1511 – 1900 AD (Stuiver & Braziunas 1993).
- ***Dye3*** $^{10}Be$ Greenland annual series: 1424–1985 AD (Beer et al. 1990).
- ***NGRIP*** $^{10}Be$ Greenland annual series: 1389–1994 AD (Berggren et al. 2009).
- ***SP*** $^{10}Be$ South Pole Antarctic series: 850–1950 AD, quasi-decadal (Raisbeck et al. 1990; Bard et al. 1997).
- ***DF*** $^{10}Be$ Dome Fuji Antarctic series: 695–1880 AD, quasi-decadal (Horiuchi et al. 2008).
- ***GRIP*** $^{10}Be$ Greenland series: 7380 BC–1640 AD, quasi-decadal (Yiou et al. 1997; Vonmoos et al. 2006).
- $^{14}C$ (Miyake et al., 2012, 2013)

# SPE scenaria




**SPE56:**

23-Feb-1956 – hard spectrum

NM: 4000% at Leeds NM

$F_{30}$ = $10^9$ cm$^{-2}$ (Shea & Smart, 1990)

$Q_{10Be}$ = 7.5*$10^4$ at/cm$^2$ (intermediate mixing)

$Q_{14C}$ = 2.9*$10^6$ at/cm$^2$ (global)

**SPE72:**

04-Aug-1972 – soft spectrum

NM: 10% at Oulu NM

$F_{30}$ = 5*$10^9$ cm$^{-2}$.

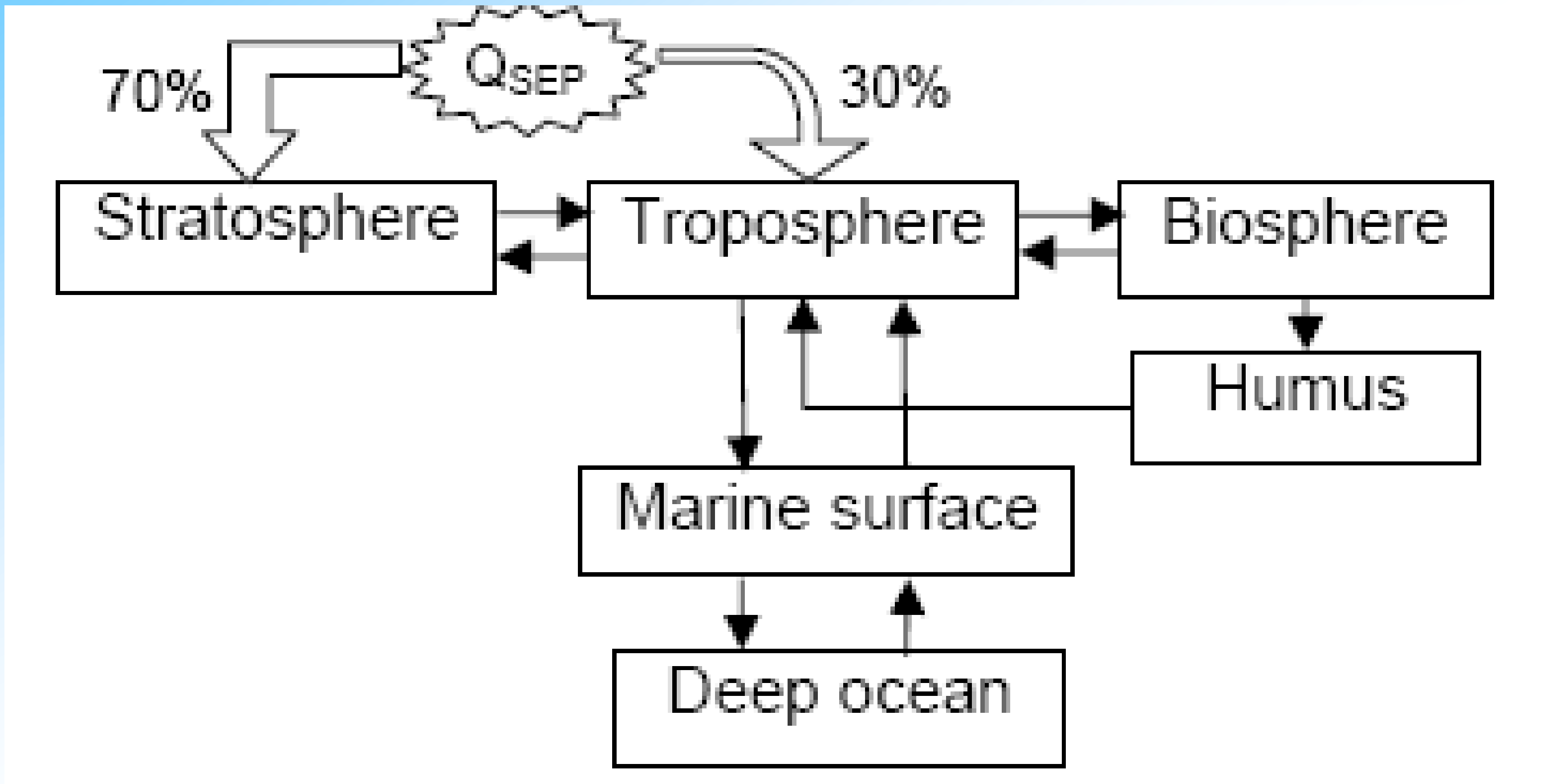
$Q_{10Be}$ = 1.1*$10^4$ at/cm$^2$ (intermediate mixing)

$Q_{14C}$ = 3.1*$10^5$ at/cm$^2$ (global)

$^{14}C$ / $^{10}Be$ → $F_{200}$, not $F_{30}$, conversion is a matter of spectrum. Soft-spectrum event may be missing in the cosmogenic nuclide data.

The same isotope signal requires 40X greater $F_{30}$ in SPE72 than in SPE56,

# Carbon cycle



# 775 AD: model vs. data

SEP → production → $Q_{14C}$

(Kovaltsov et al., 2012)

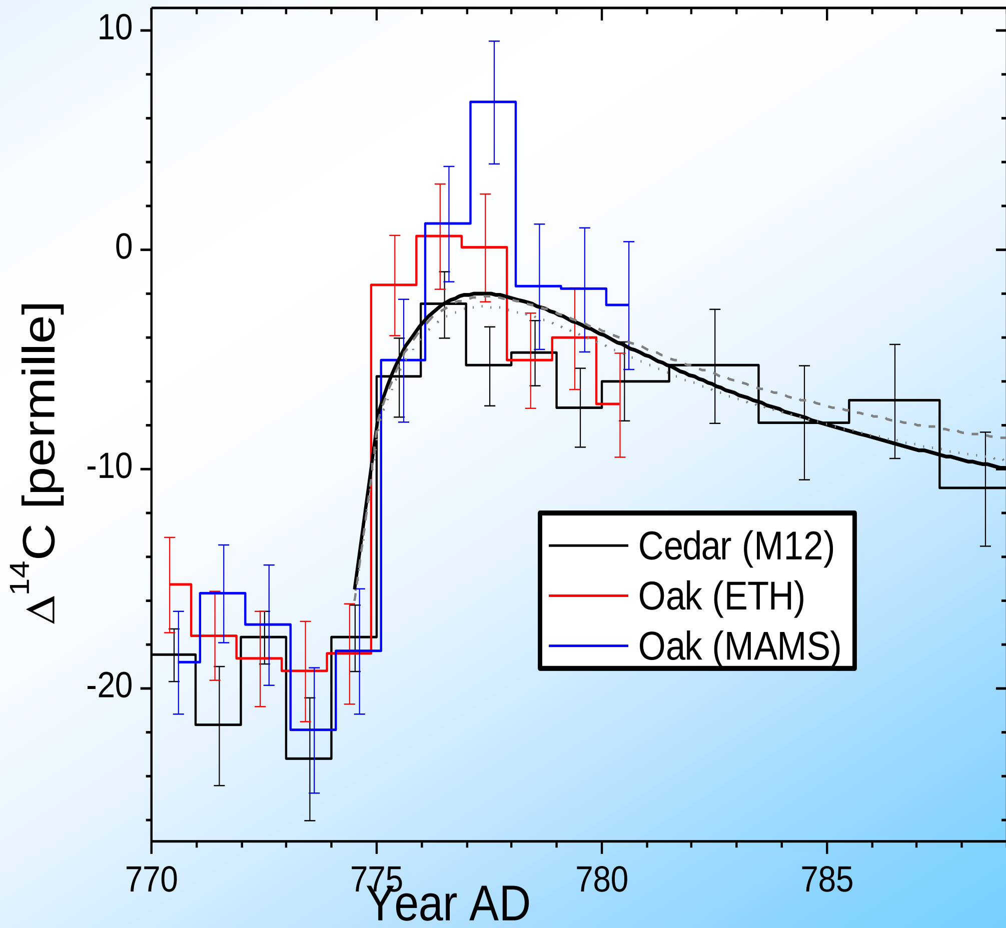
Q → carbon cycle → $\Delta^{14}C$

5-box model (Damon & Peristykh, 2004)

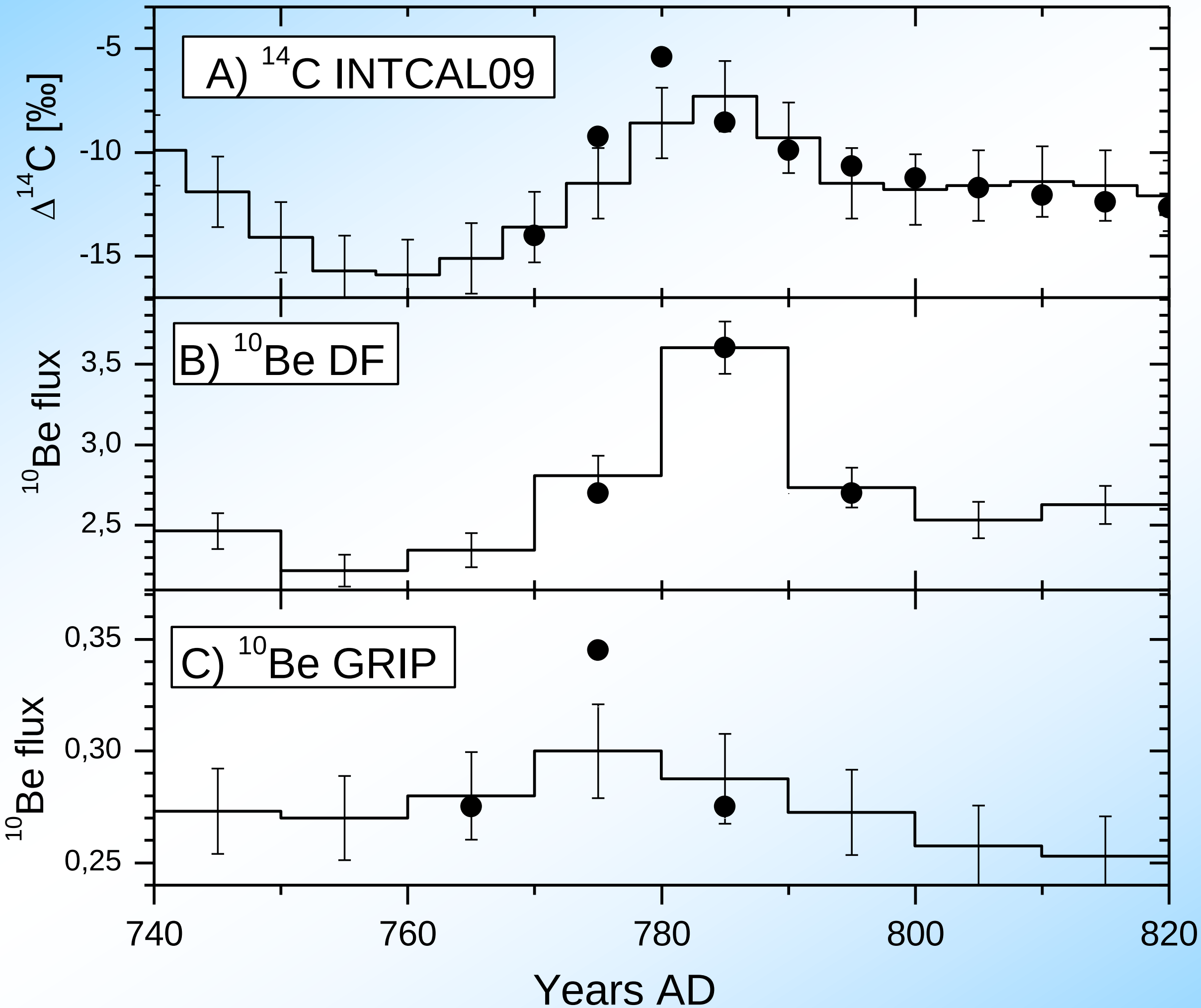
Response for SPE56 is:

Peak – 0.2-0.35 ‰ (errors ~2 ‰),
FWHM~20-30 yrs, rise time 0-10 yrs.

Fit of 45 SPE56 ($F_{30}$=4.5*$10^{10}$ $cm^{-2}$) →



# 775 AD – other data



# Candidates from annual series (600 yrs)

| | | | |
|---|---|---|---|
| • 1460-1462: | NGRIP | $F_{30}$= | $1.5*10^{10}$ $cm^{-2}$ |
| | Dye3 | | $1*10^{10}$ |
| • 1505 | Dye3 | | $1.3*10^{10}$ |
| • 1719 | NGRIP | | $1*10^{10}$ |
| • 1810 | NGRIP | | $1*10^{10}$ |

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* **4 events** with $F_{30}=1\text{-}1.5*10^{10}$ $cm^{-2}$ over 600 years

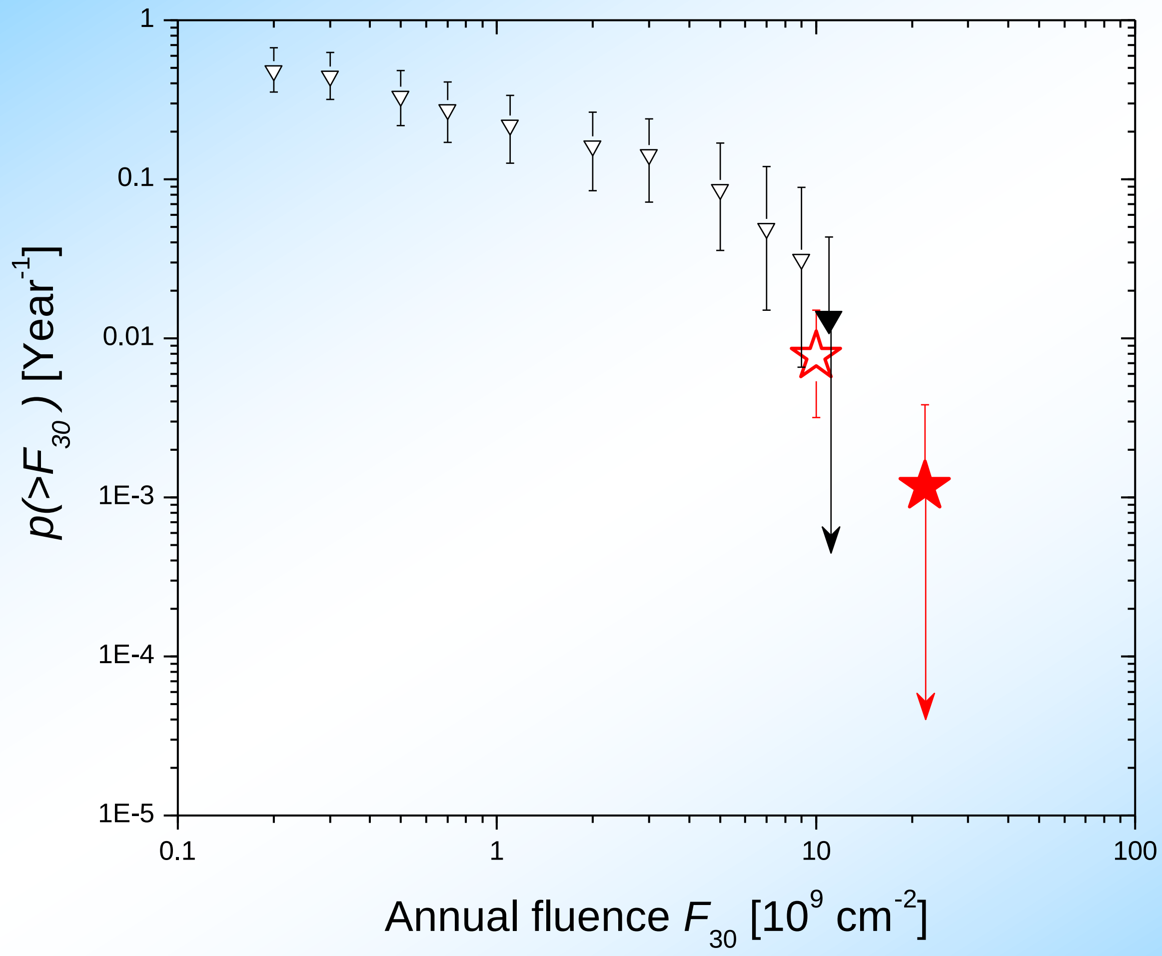
* **no events** with $F_{30}>2*10^{10}$ $cm^{-2}$ over 600 years

Thus:

$p=0.0077(^{+0.0073}_{-0.0045})$ $yr^{-1}$ – 1/130 yr for $F_{30}<2*10^{10}$ (NB: not 4/600=1/150 yr !)

$p=0 – 0.0027$ $yr^{-1}$ – rarer than 1/400 yr for $F_{30}>2*10^{10}$   (median 1/850 $yr^{-1}$)

# SPEs: 600 years of data



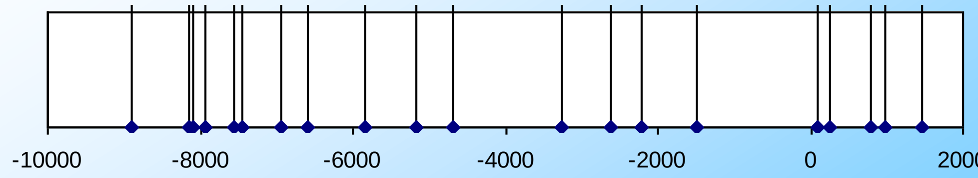
# Candidates from rougher series

| | | |
|---|---|---|
| 8910 BC | IntCal09 | $2.0*10^{10}$ |
| 8155 BC | IntCal09 | $1.3*10^{10}$ |
| 8085 BC | IntCal09 | $1.5*10^{10}$ |
| 7930 BC | IntCal09 | $1.3*10^{10}$ |
| 7570 BC | IntCal09 | $2.0*10^{10}$ |
| 7455 BC | IntCal09 | $1.5*10^{10}$ |
| 6940 BC | IntCal09 | $1.1*10^{10}$ |
| 6585 BC | IntCal09 | $1.7*10^{10}$ |
| 5835 BC | IntCal09 | $1.5*10^{10}$ |
| 5165 BC | GRIP | $2.4*10^{10}$ |
| 4680 BC | IntCal09 | $1.6*10^{10}$ |
| 3260 BC | IntCal09 | $2.4*10^{10}$ |
| 2615 BC | IntCal09 | $1.2*10^{10}$ |
| 2225 BC | IntCal09 | $1.2*10^{10}$ |
| 1485 BC | IntCal09 | $2.0*10^{10}$ |
| 95 AD | GRIP | $2.6*10^{10}$ |
| 265 AD | IntCal09 | $2.0*10^{10}$ |
| 780 AD | IntCal09/DF | $2\text{-}5*10^{10}$ |
| 990 AD | M13 | $2.5*10^{10}$ |
| 1455 AD | SP | $7.0*10^{10}$ overestimate?? |

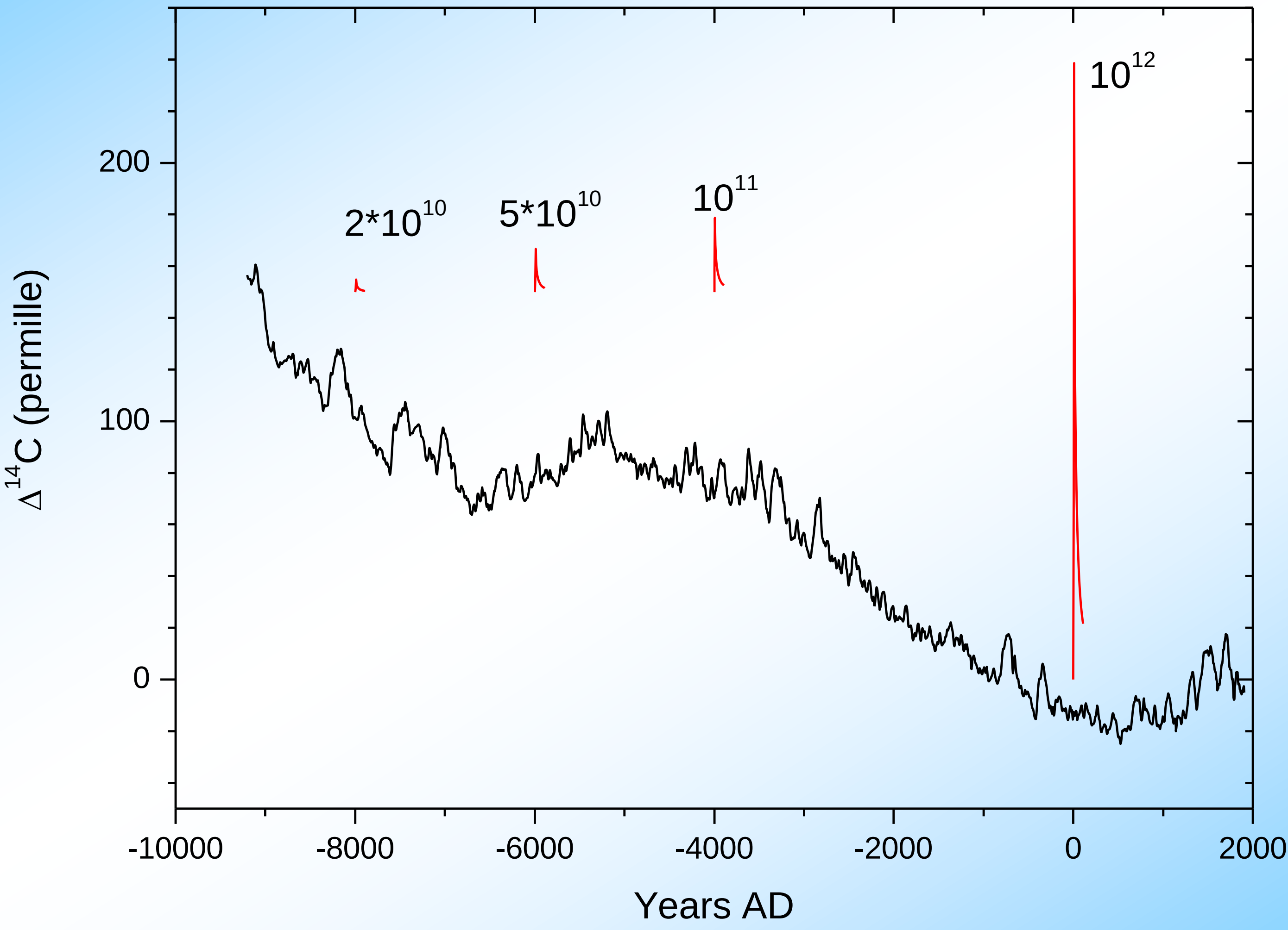
Statistics for 11400 years:

20 events $F_{30}=(1\text{-}3)*10^{10}$ cm$^{-2}$

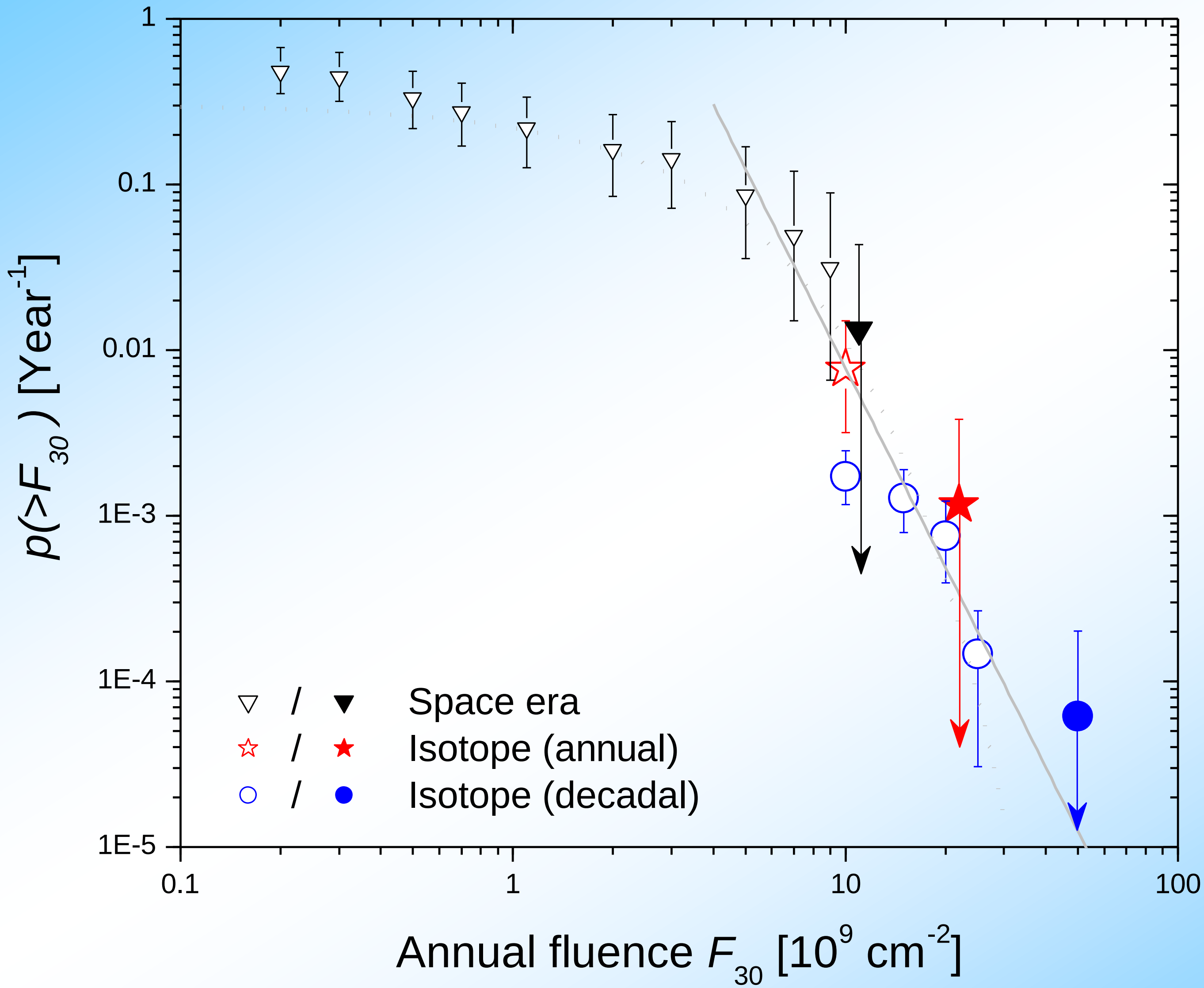
no events with $F_{30}>5*10^{10}$ cm$^{-2}$



# Events to look for in Δ¹⁴C



# SPEs: all data



# Subconclusions

- **Four** potential candidates with $F_{30}$=(1÷1:5)*$10^{10}$ $cm^{-2}$ and no events with $F_{30}>2*10^{10}$ $cm^{-2}$ identified since 1400 AD in the annually resolved $^{10}Be$ data.

- For the Holocene, **20** SPEs with $F_{30}$=(1÷3)*$10^{10}$ $cm^{-2}$ are found in the $^{14}C$ and $^{10}Be$ data and clearly no event with $F_{30}>5*10^{10}$ $cm^{-2}$.

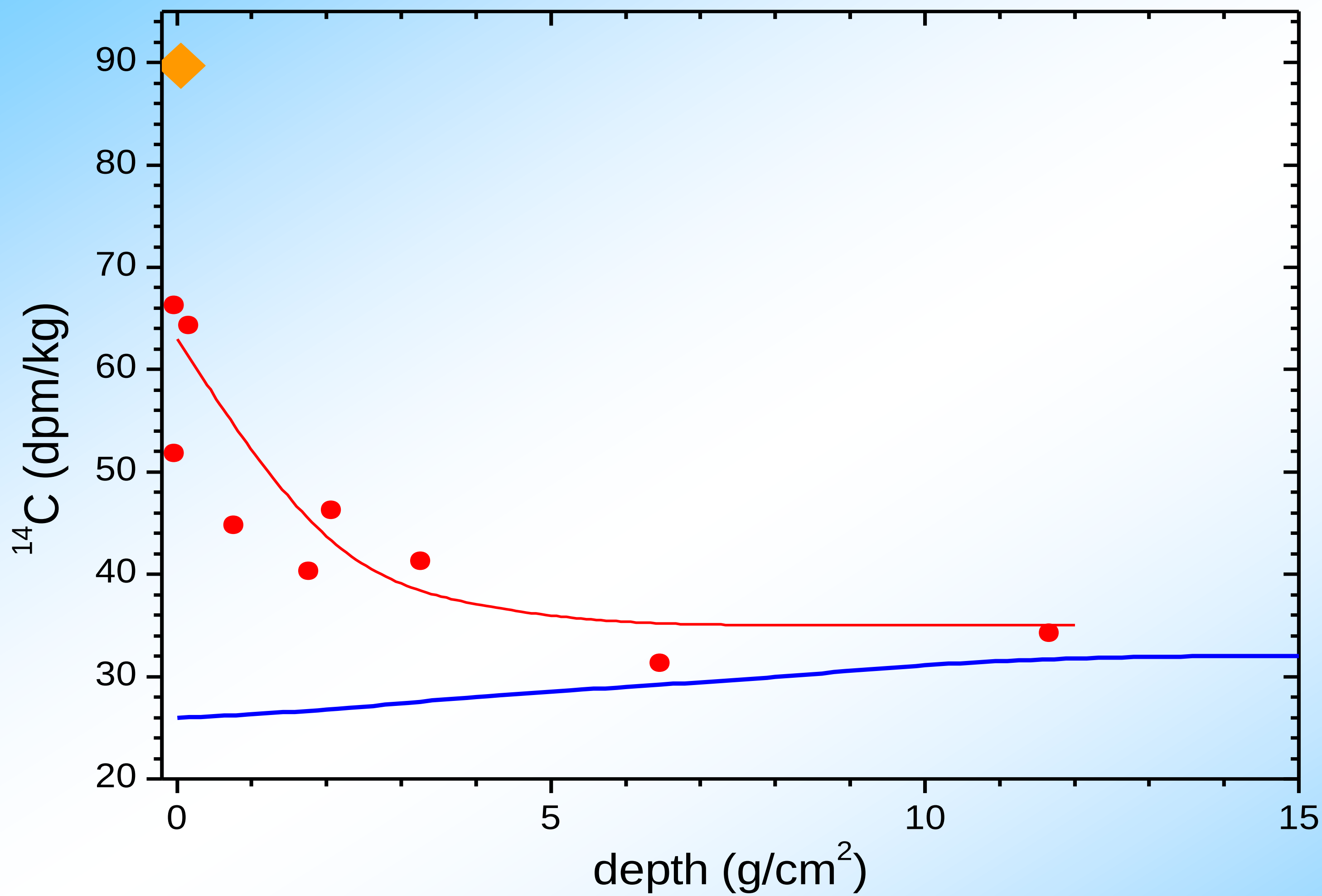
- On average, extreme SPEs contribute about 10% to the total SEP flux.

- Practical limits are: $F_{30}\approx 1$, 2÷3, and $5*10^{10}$ $cm^{-2}$ for the occurrence probability ≈ $10^{-2}$, $10^{-3}$ and $10^{-4}$ $year^{-1}$, respectively.

- BUT: uncertainty of conversion $F_{200} \rightarrow F_{30}$

# Cosmogenic radionuclides in lunar rocks: 1 Myr

# Lunar/meteoritic samples




$^{14}$C activity in a lunar sample 68815 (Jull et al., 1998).

# Lunar rock data

Table 1. Assessments of the parameters of OPDF from different cosmogenic radionuclide data in lunar rocks. Columns correspond to the nuclide, reference to the original data, the measured mean annual fluence $F^*$ ($10^9$ protons/cm$^2$/yr), and the corresponding best-fit parameters $\alpha$ and $\beta$ ($10^{-9}$ cm$^2$ yr) with the 90% confidence intervals (see text).

| # | Nuclide | Reference | $F^*$ | $\alpha$ | $\beta$ |
|---|---|---|---|---|---|
| 1 | $^{14}C$ | (Jull *et al.*, 1998) | 1.33 | $2.64 \pm 0.21$ | $0.328 \pm 0.037$ |
| 2 | $^{41}Ca$ | (Fink *et al.*, 1998) | 1.77 | $1.67 \pm 0.03$ | $0.134 \pm 0.002$ |
| 3 | $^{81}Kr$ | (Reedy, 1999) | 1.51 | $2.01 \pm 0.02$ | $0.202 \pm 0.003$ |
| 4 | $^{36}Cl$ | (Nishiizumi *et al.*, 2009) | 1.45 | $2.16 \pm 0.02$ | $0.232 \pm 0.003$ |
| 5 | $^{26}Al$ | (Kohl *et al.*, 1978) | 0.79 | N/A | N/A |
| 6 | $^{26}Al$ | (Grismore *et al.*, 2001) | 1.74 | $1.69 \pm 0.01$ | $0.137 \pm 0.001$ |
| 7 | $^{10}Be/^{26}Al$ | (Nishiizumi *et al.*, 1988) | 1.10 | $6.93 \pm 0.14$ | $1.19 \pm 0.03$ |
| 8 | $^{10}Be/^{26}Al$ | (Michel, Leya, and Borges, 1996) | 0.76 | N/A | N/A |
| 9 | $^{10}Be/^{26}Al$ | (Fink *et al.*, 1998) | 1.01 | N/A | N/A |
| 10 | $^{10}Be/^{26}Al$ | (Nishiizumi *et al.*, 2009) | 0.76 | N/A | N/A |
| 11 | $^{53}Mn$ | (Kohl *et al.*, 1978) | 0.79 | N/A | N/A |

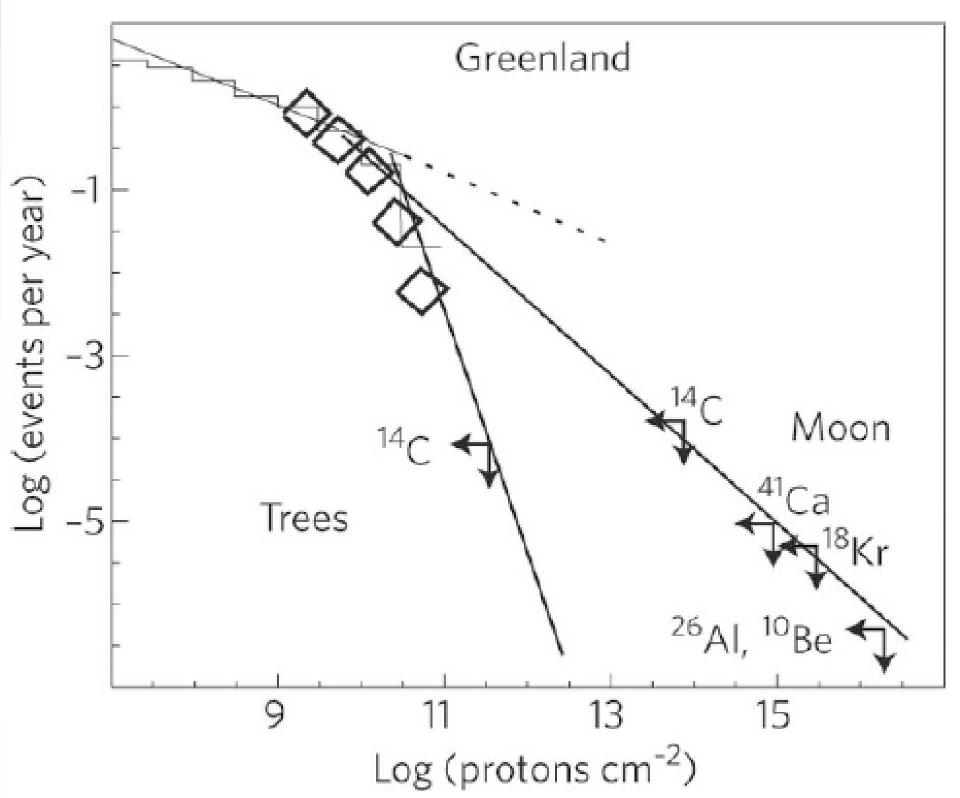
Fluence is averaged over the isotope's life time (production-vs-decay balance) – no time resolution.

# Earlier estimate

$^{14}C$:

P~$10^{-4}$ $yr^{-1}$ = 1/$\tau$ (~6 kyr),

$F_{30}$~$10^{13}$ p/$cm^2$/yr = $10^9 * \tau$




By definition, α=1.

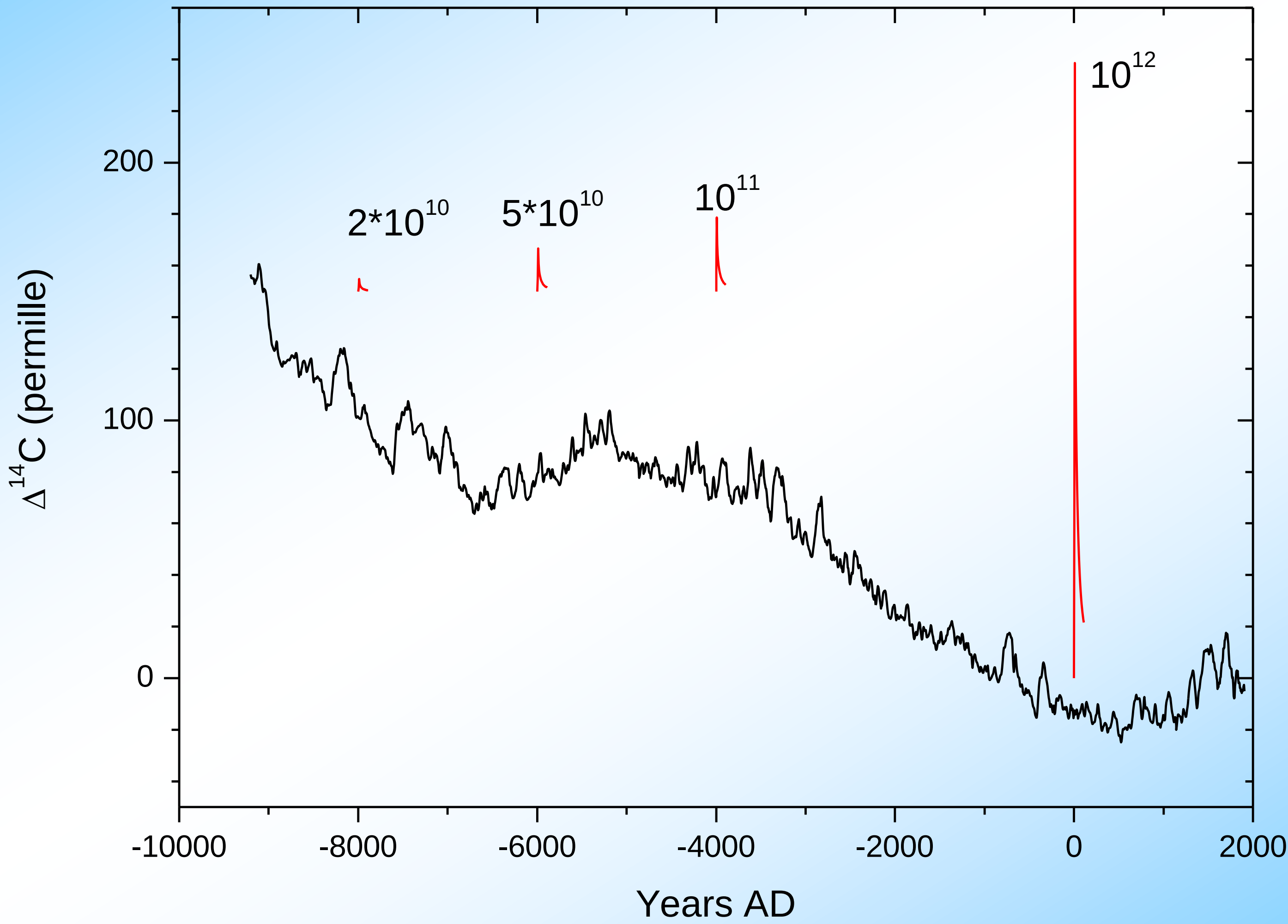
Reedy (1996):

assumption was made that all of that nuclide was made by one huge SPE at one half-life of that radionuclide ago. These four limits define a line that drops

Inconsistency:

an event in $^{14}C$ (6 kyr) _must_ leave record in $^{41}Ca$ (~100 kyr), etc.

# Events to look for in $\Delta^{14}C$



# Some formalism

$$\langle F\rangle = \int_0^{F_0} F\cdot p(F)\cdot dF + \int_{F_0}^{\infty} F\cdot p(F)\cdot dF = \langle F_1\rangle + \langle F_2\rangle,$$

Low-fluence events High-fluence events

For 1955-2007, <F>=1.1*$10^9$ /cm$^2$/yr

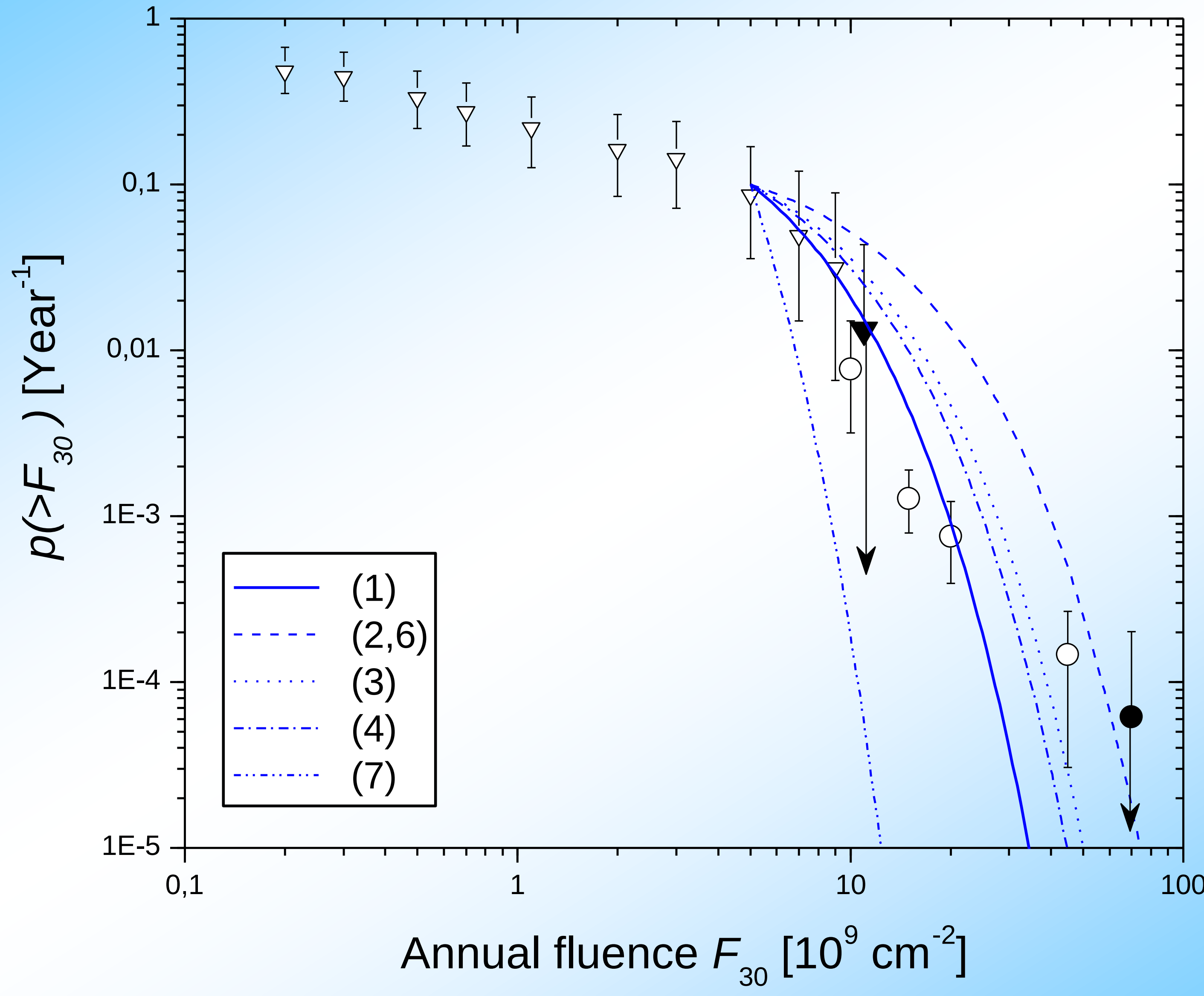
$P_o$=0.1 yr$^{-1}$, $F_o$=0.52*$10^9$ /cm$^2$/yr ~1/2<F>

$p=dP/dF$

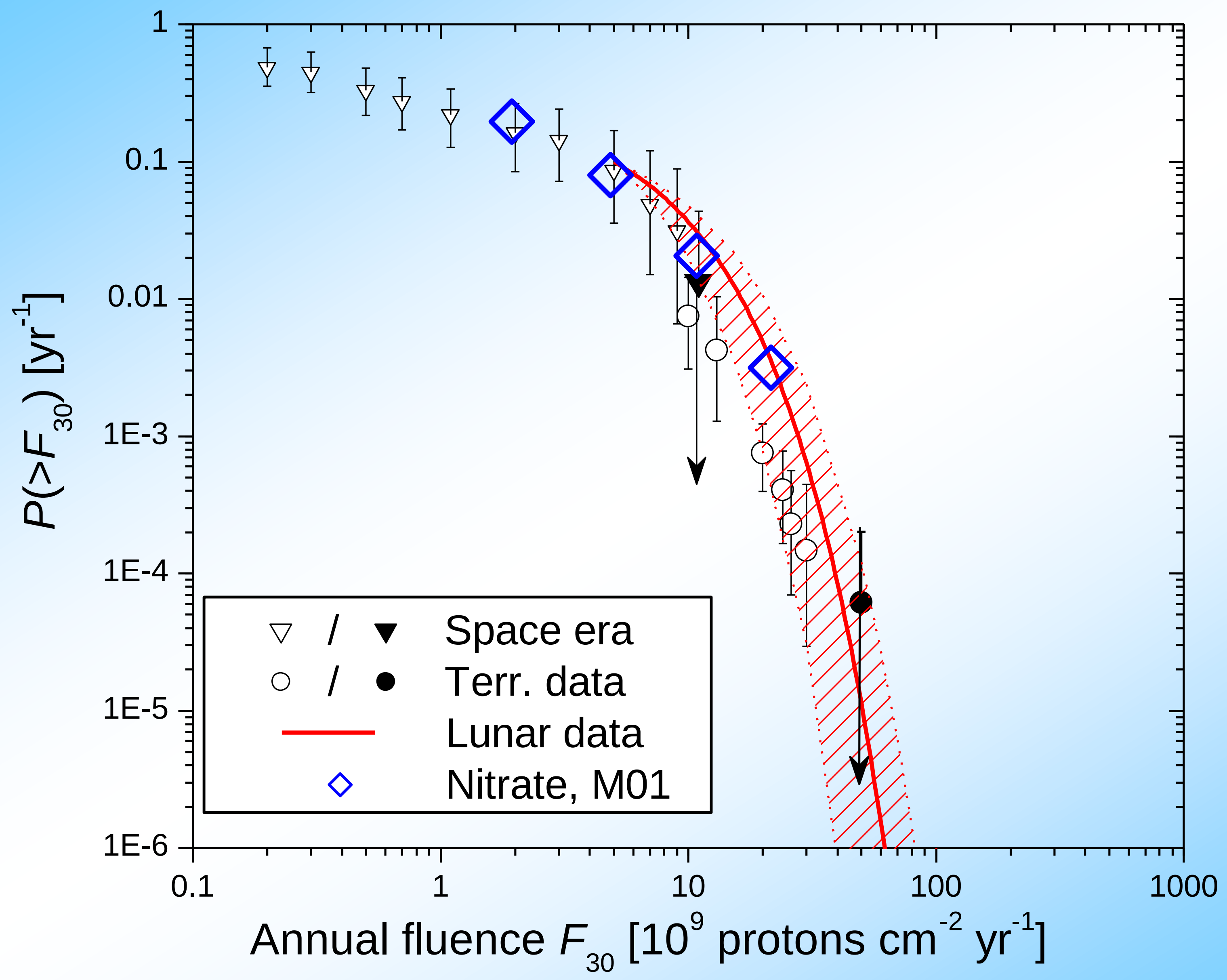
$P=P_o*(F/F_o)^{-\alpha}$ → power law

$P=P_o*\exp(\beta(F_o-F))$ → exponential

# Exponential OPDF



# Final result



# Summary on lunar rock-based SEP assessments

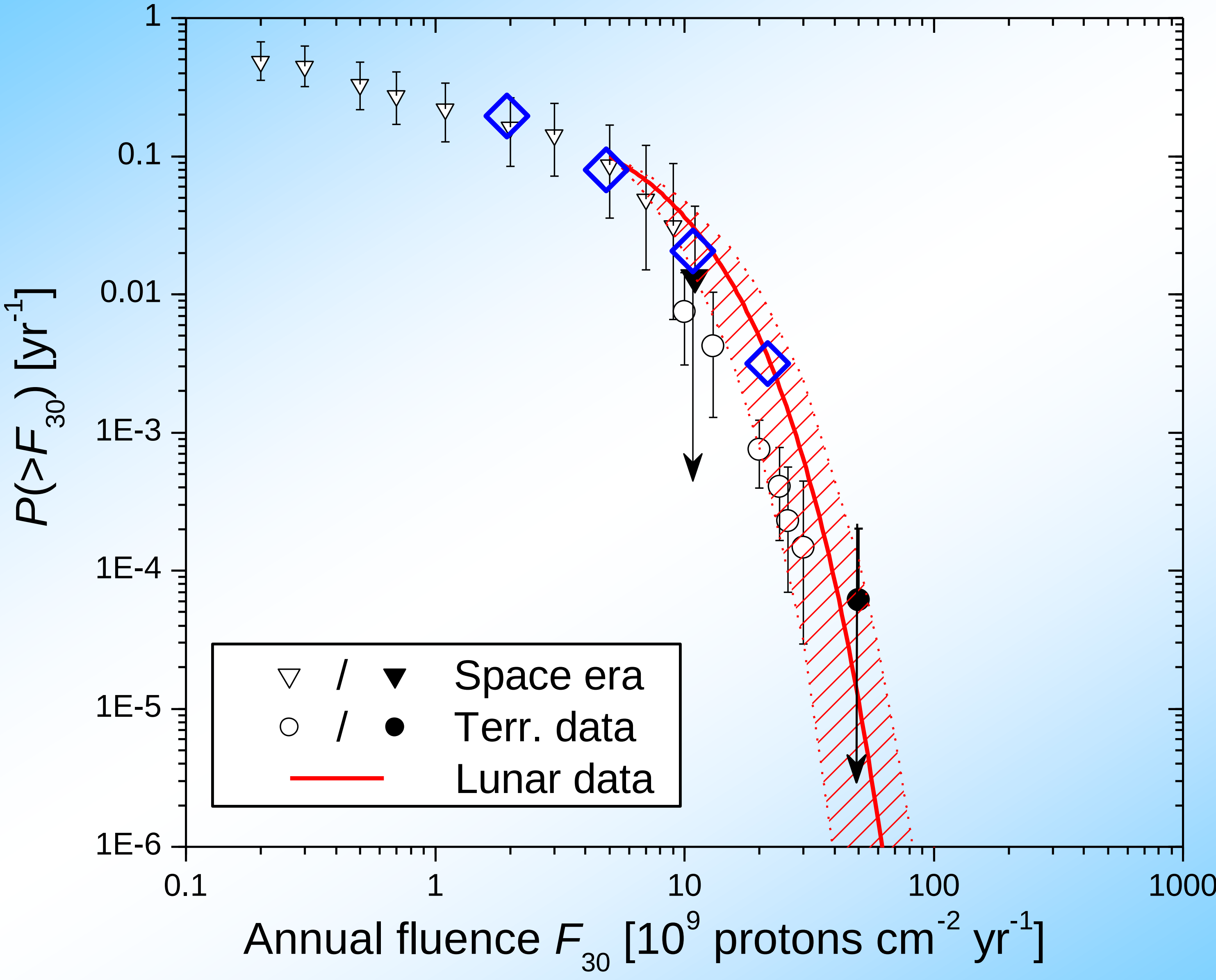
- Earlier estimates based on unrealistic assumptions (all $F_{30}$ caused by a single event occurred at half-life time ago) → too high fluxes.

- A more realistic assumption → consistent with other independent data (terrestrial cosmogenic isotopes and ”direct” observations).

- A strong roll-off is proposed for $F_{30}>10^9$ protons/cm$^2$/yr on average.

- The OP of a $F_{30}>10^{11}$ p/cm$^2$/yr event is $<10^{-6}$ yr$^{-1}$.

# Final result



# THANK YOU !

# SPE in $^{14}C$

SEP → production → $Q_{14C}$

(Kovaltsov et al., 2012)

Q → carbon cycle → $\Delta^{14}C$

5-box model (Damon & Peristykh, 2004)

Response for SPE56 is:

Peak – 0.2-0.35 ‰ (errors ~2 ‰),
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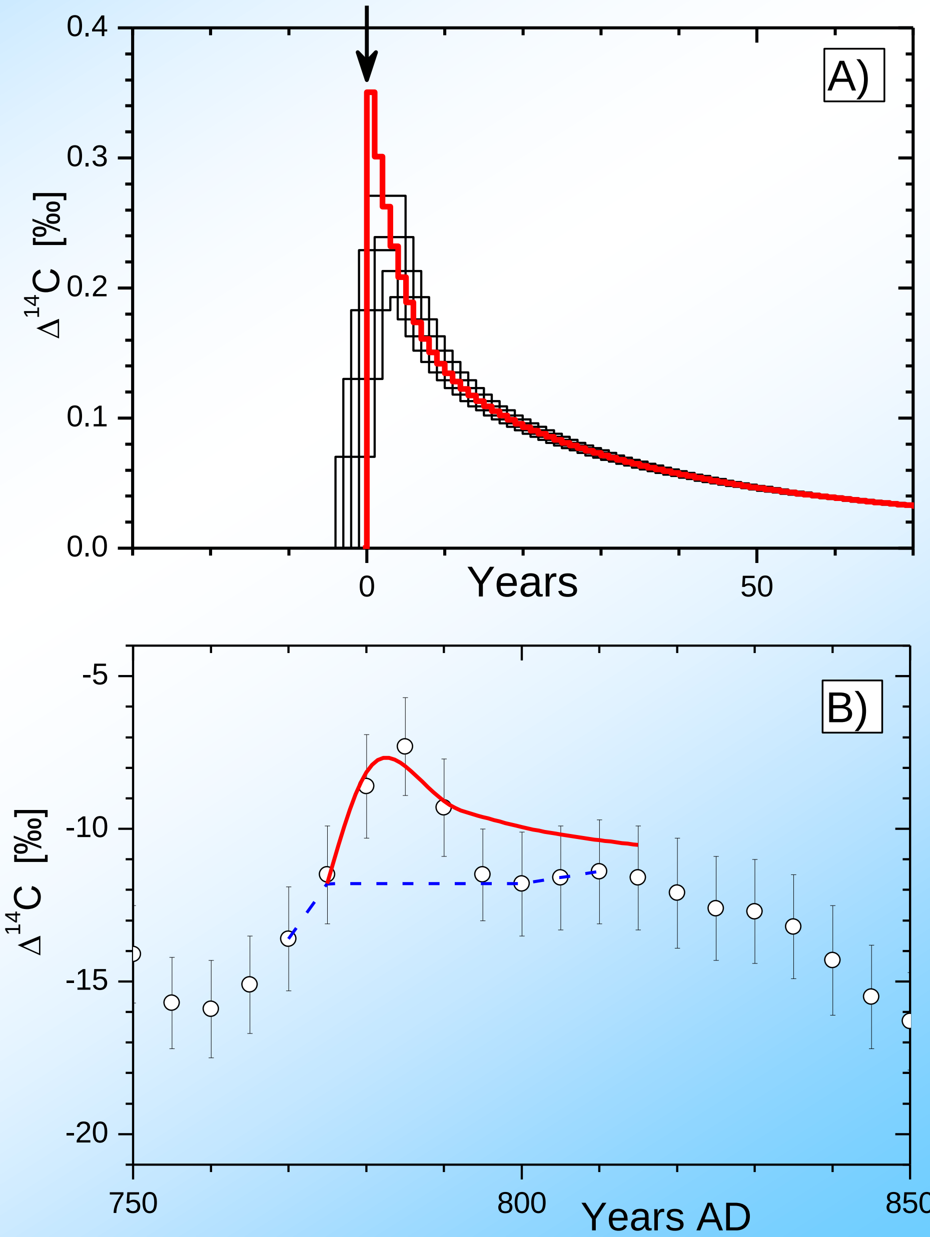
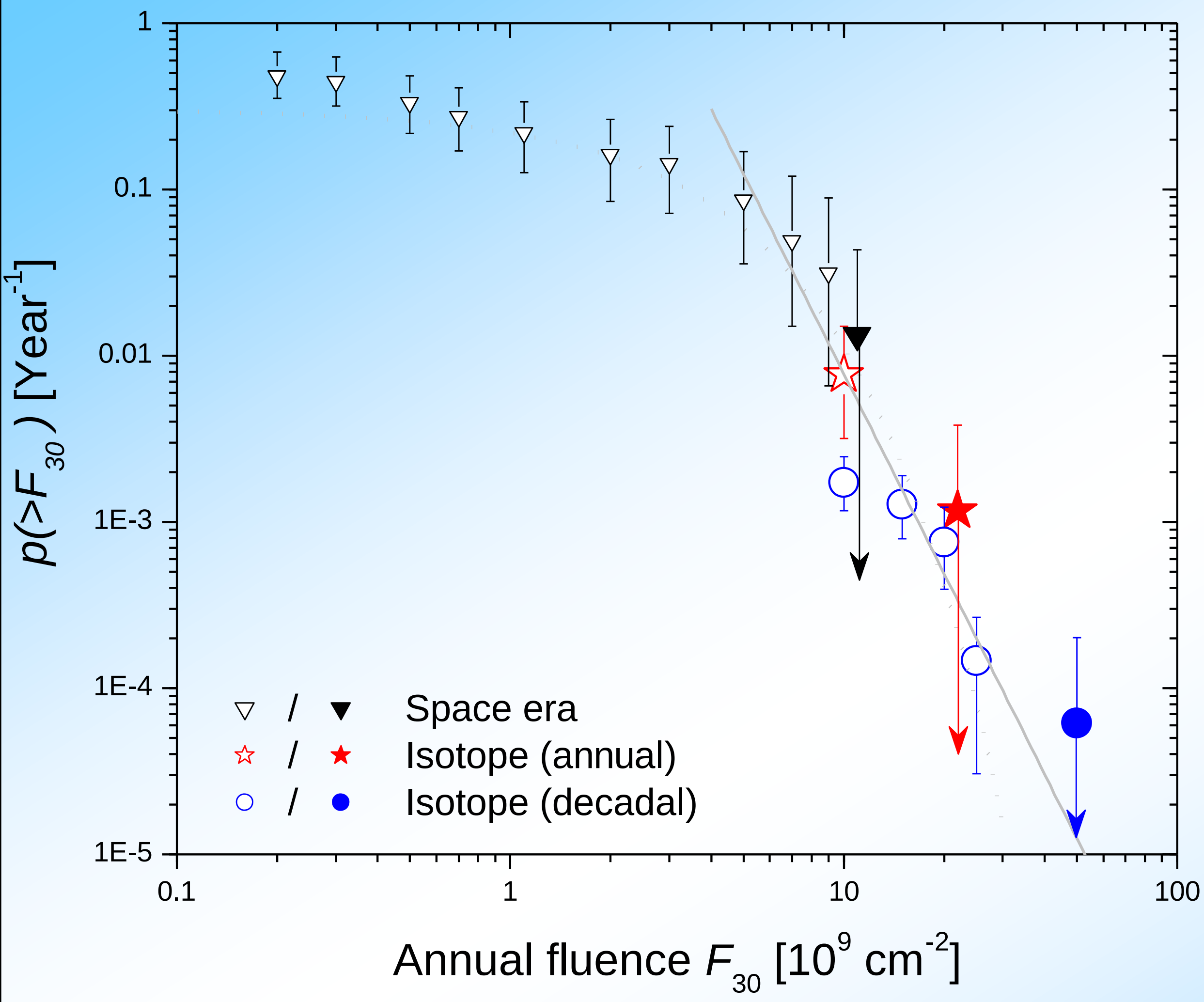
Fit of 24 SPE56 ($F_{30}=2.4*10^{10}$ cm$^{-2}$) →



# Lunar rocks




$f'_{30}$~35 cm$^{-2}$ s$^{-1}$ for Space era

(Shea & Smart, 2002; Reedy, 2012)

Fitting tail > 7*10$^9$ cm$^{-2}$:

~exp(-0.33*10$^{-9}$*F$_{30}$) or ~F$_{30}$$^{-4}$

$f''_{30}$~3.2-3.5 cm$^{-2}$ s$^{-1}$ for extreme SPEs

→

$f_{30}=f'+f''$=38-39 cm$^{-2}$ s$^{-1}$

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Lunar rocks:

$F_{30}$=21-56 (~40) cm$^{-2}$ s$^{-1}$

*Totally consistent*

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SPE72 scenario:

$f''_{30}$~110-130 cm$^{-2}$ s$^{-1}$ →

$f_{30}$~150 cm$^{-2}$ s$^{-1}$ - *inconsistent*

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**_Extreme SPEs should have hard spectra!_**

# Lunar rock data

**Table 1.** Assessments of the parameters of OPDF from different cosmogenic radionuclide data in lunar rocks. Columns correspond to the nuclide, reference to the original data, the measured mean annual fluence $F^*$ ($10^9$ protons/cm$^2$/yr), and the corresponding best-fit parameters $\alpha$ and $\beta$ ($10^{-9}$ cm$^2$ yr) with the 90% confidence intervals (see text).

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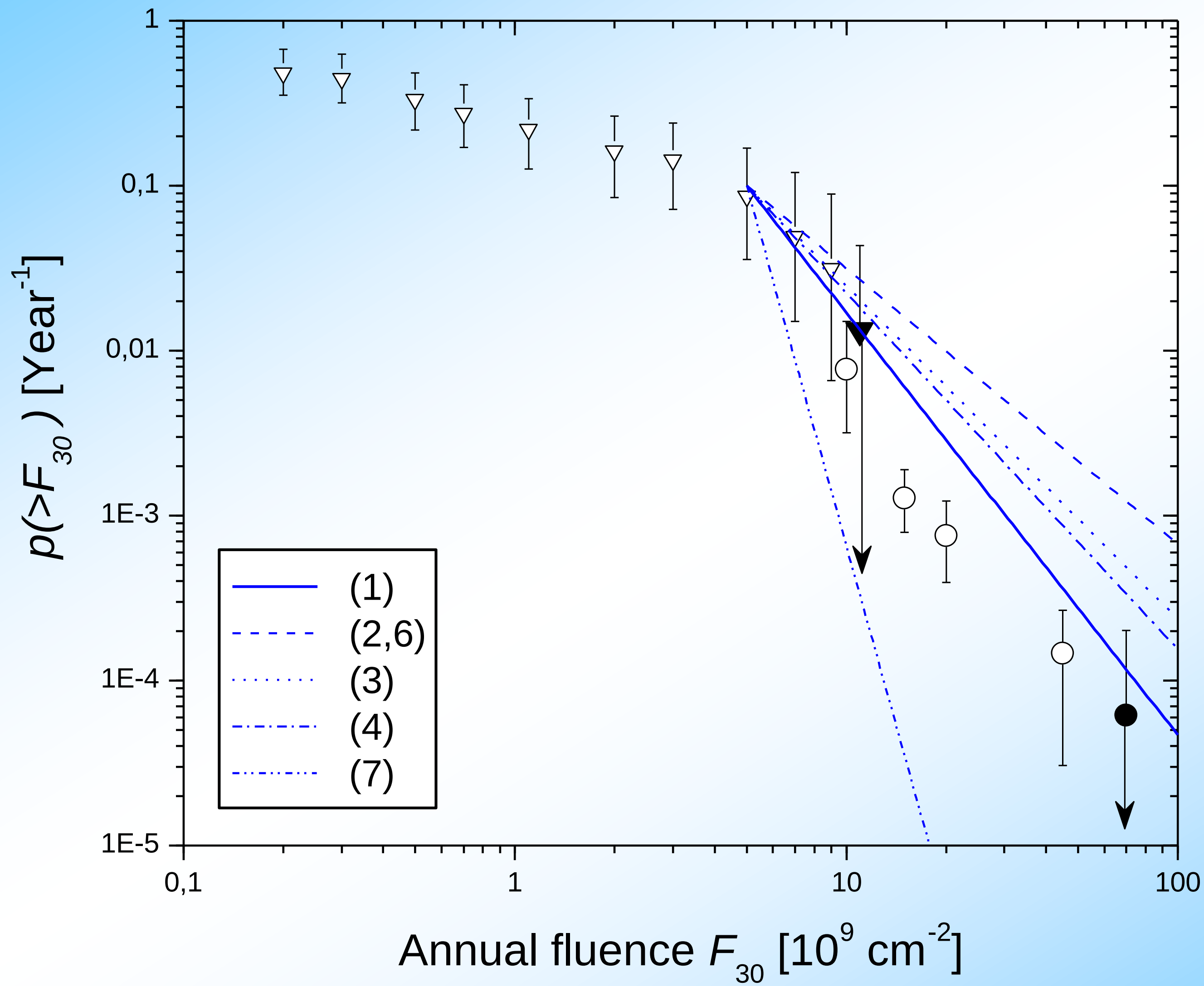
# Power-law OPDF



# Some formalism

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For 1955-2007, $<F>=1.1*10^9$ /cm$^2$/yr

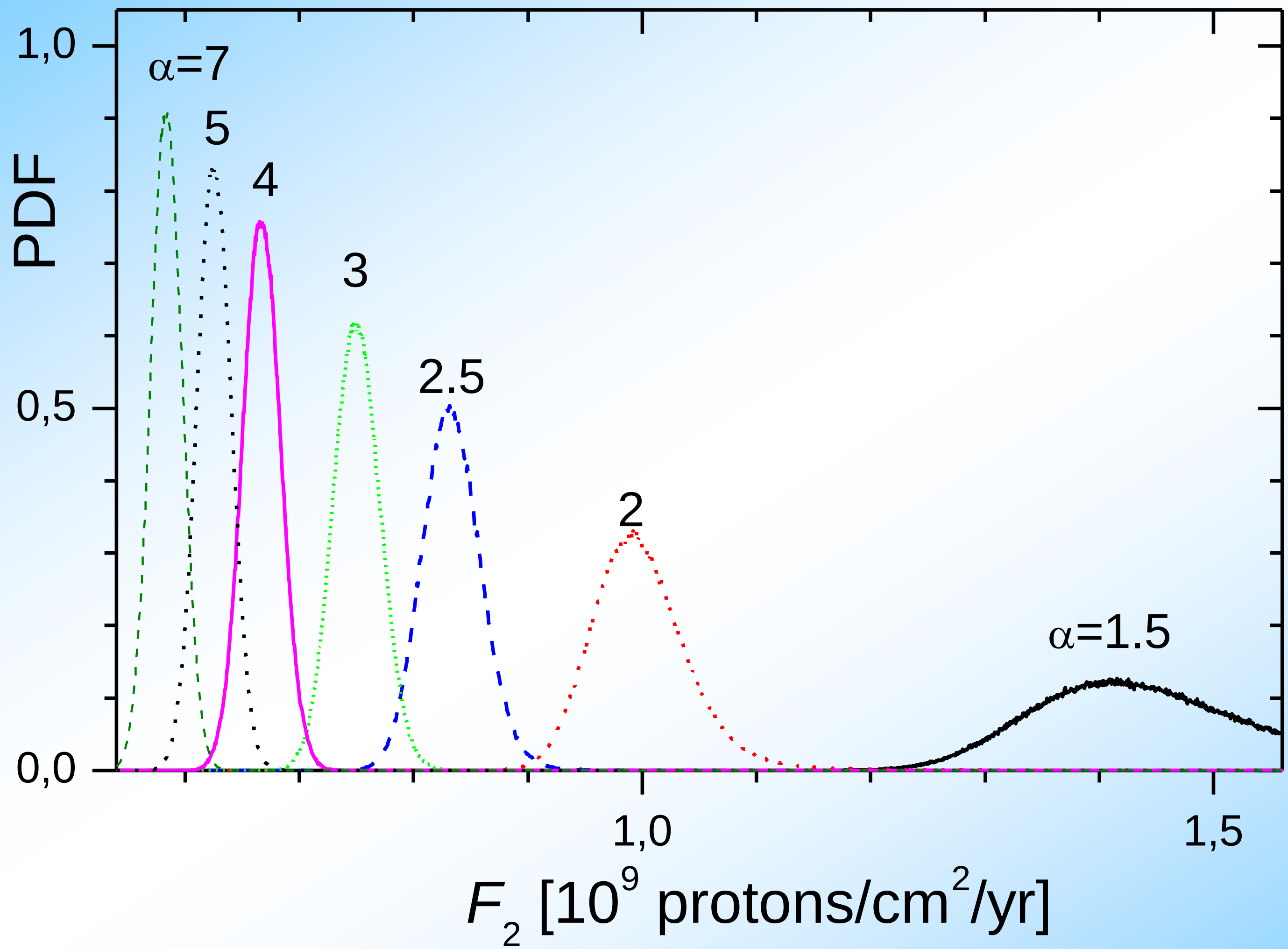
$P_o=0.1$ yr$^{-1}$, $F_o=0.52*10^9$ /cm$^2$/yr

$p=dP/dF$

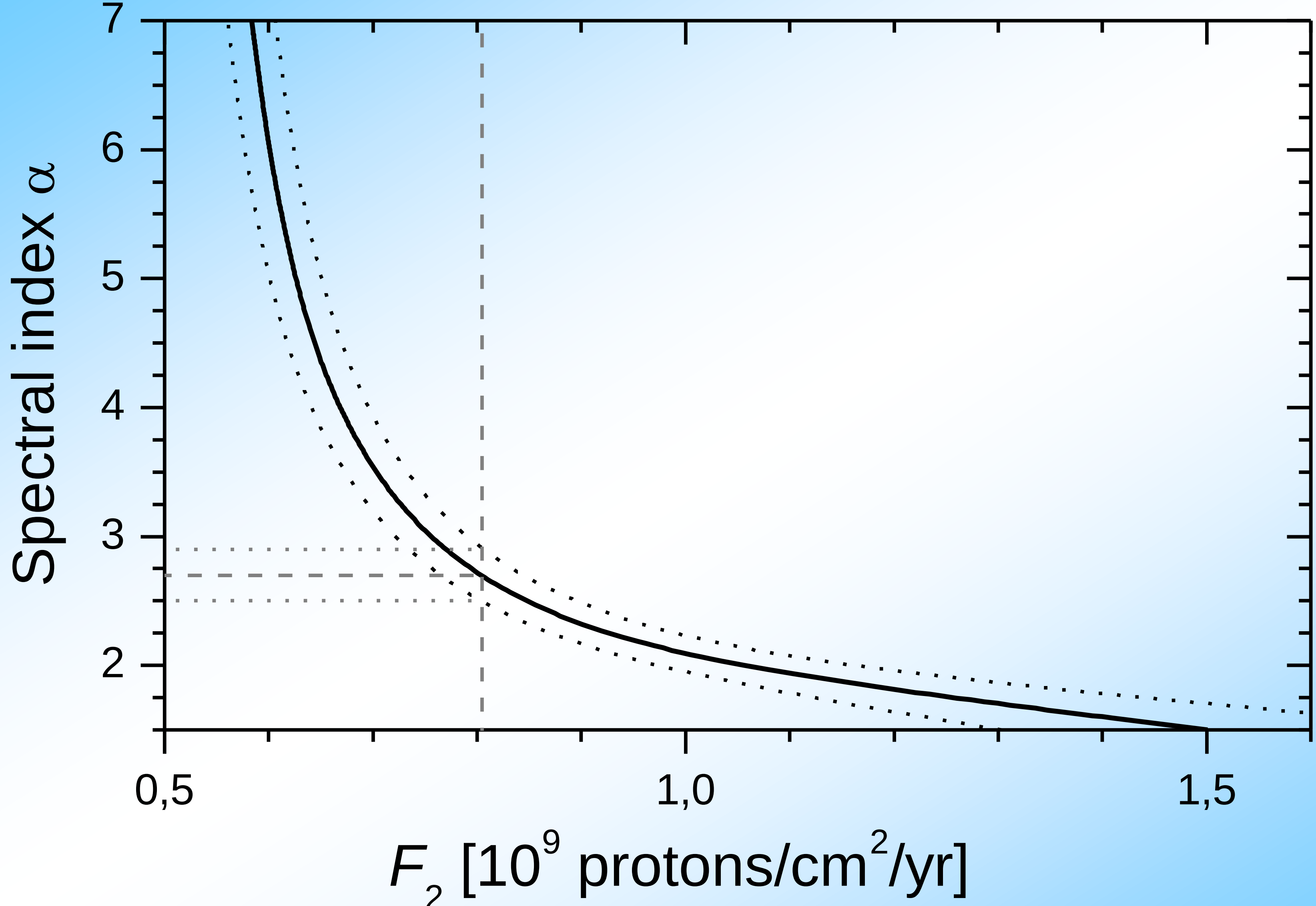
$P=Po*(F/Fo)^{-\alpha}$ → power law

$P=Po*exp(\beta(Fo-F))$ → exponential

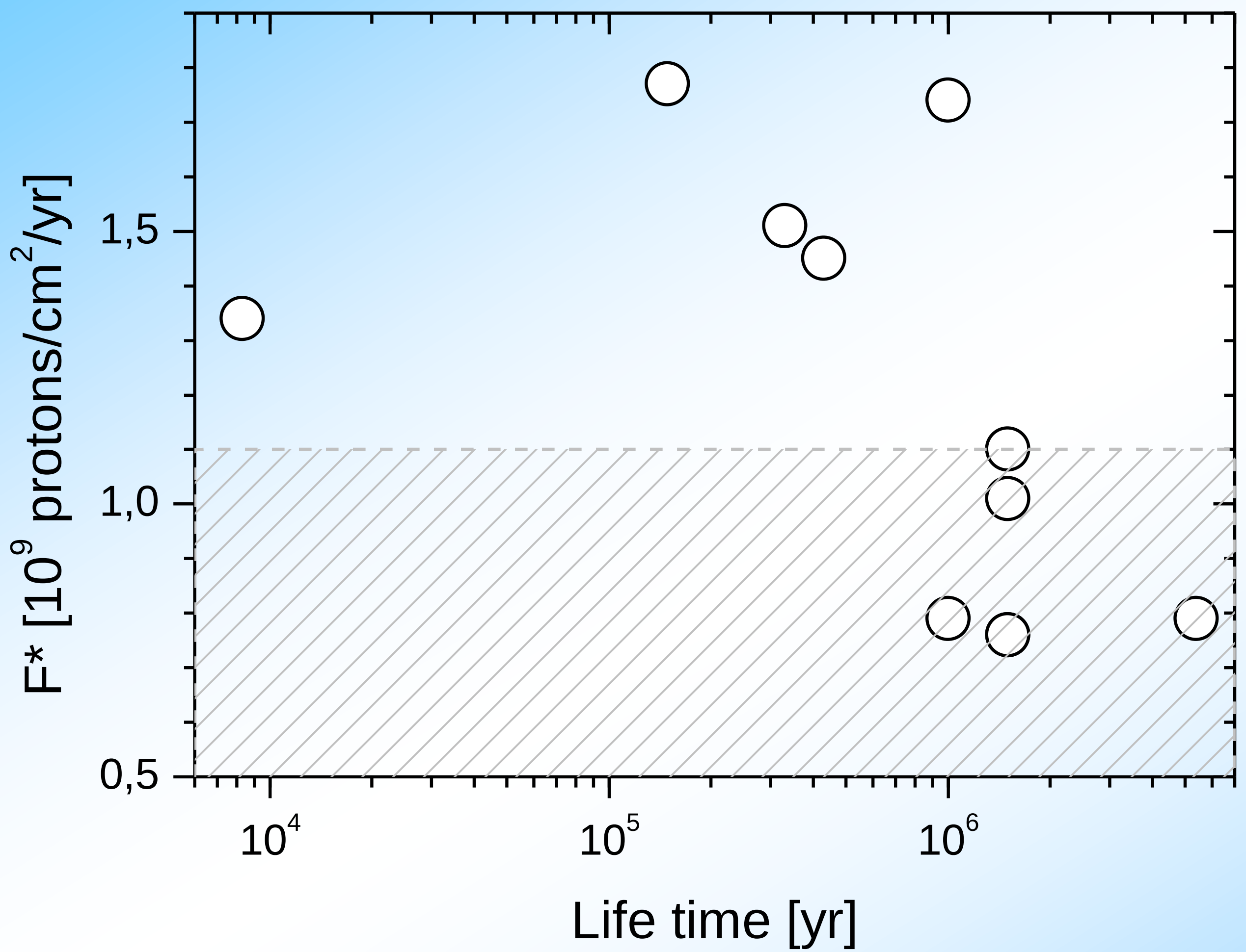
# PDF vs. F2



# Calibration curve



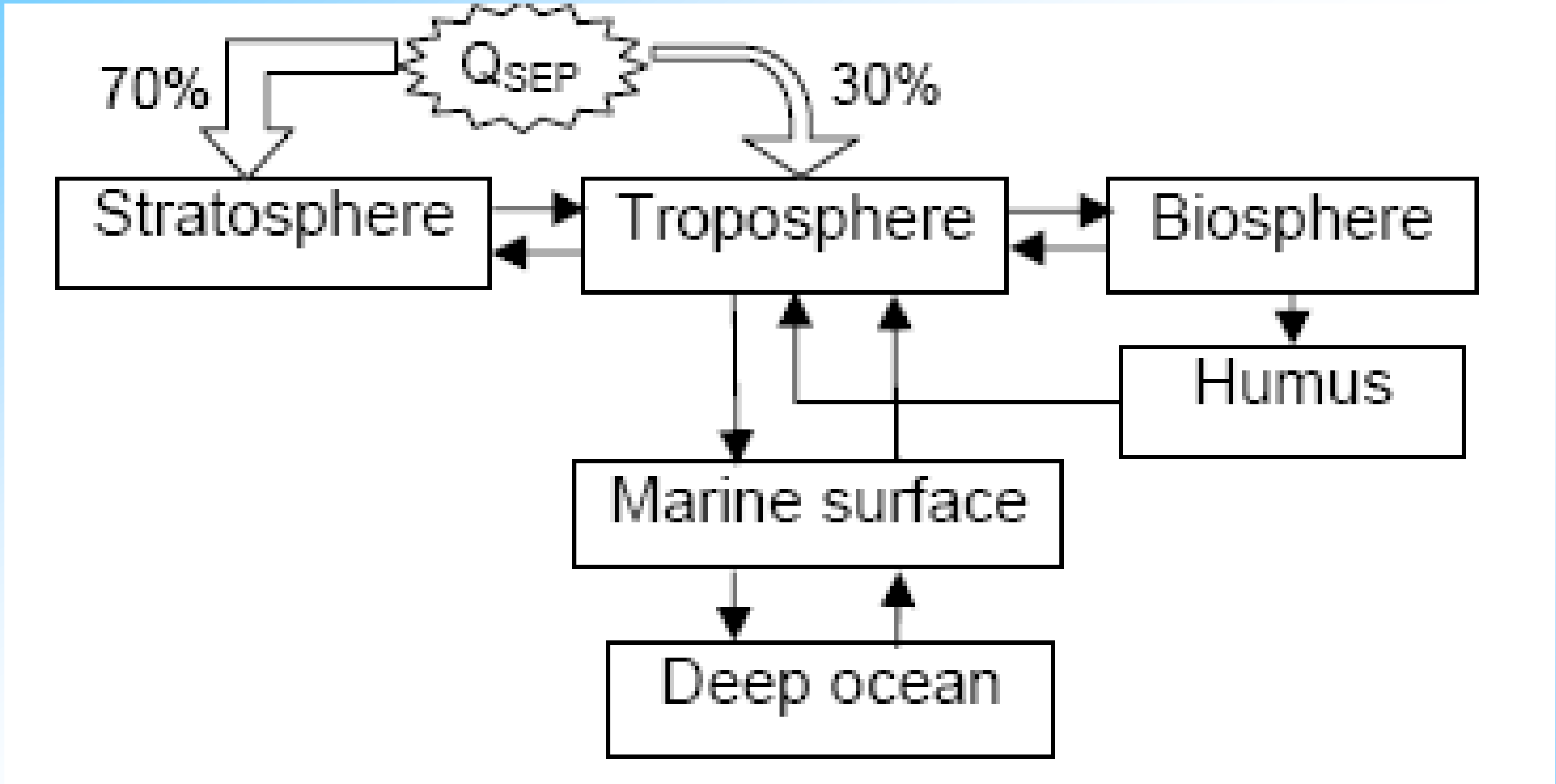
# Lunar rock data




**Such a situation is impossible!**

Even switching SEP off does not help → neglect long-living isotopes.

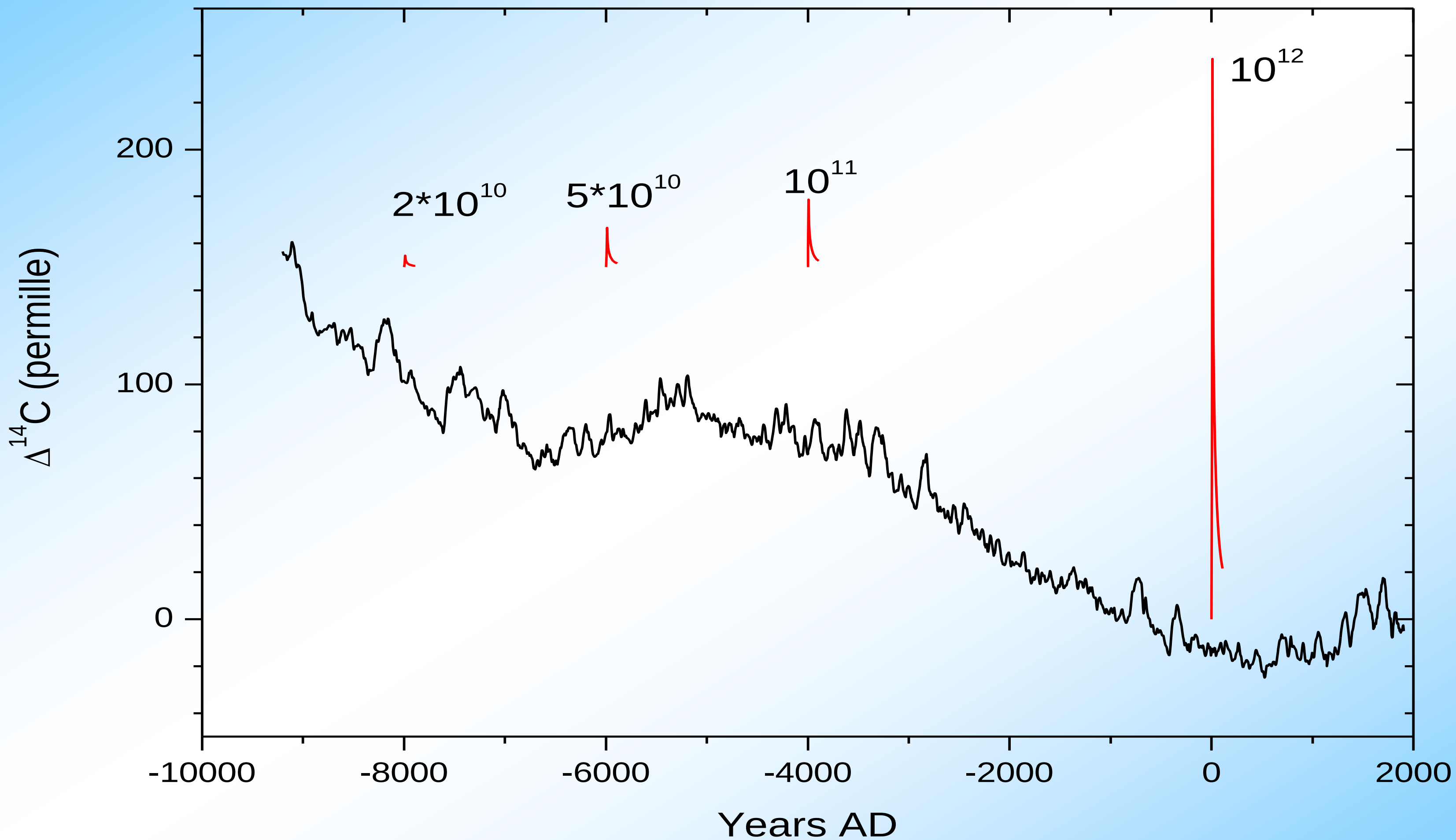
# Scheme



70%
$Q_{SEP}$
30%
Stratosphere
Troposphere
Biosphere
Humus
Marine surface
Deep ocean

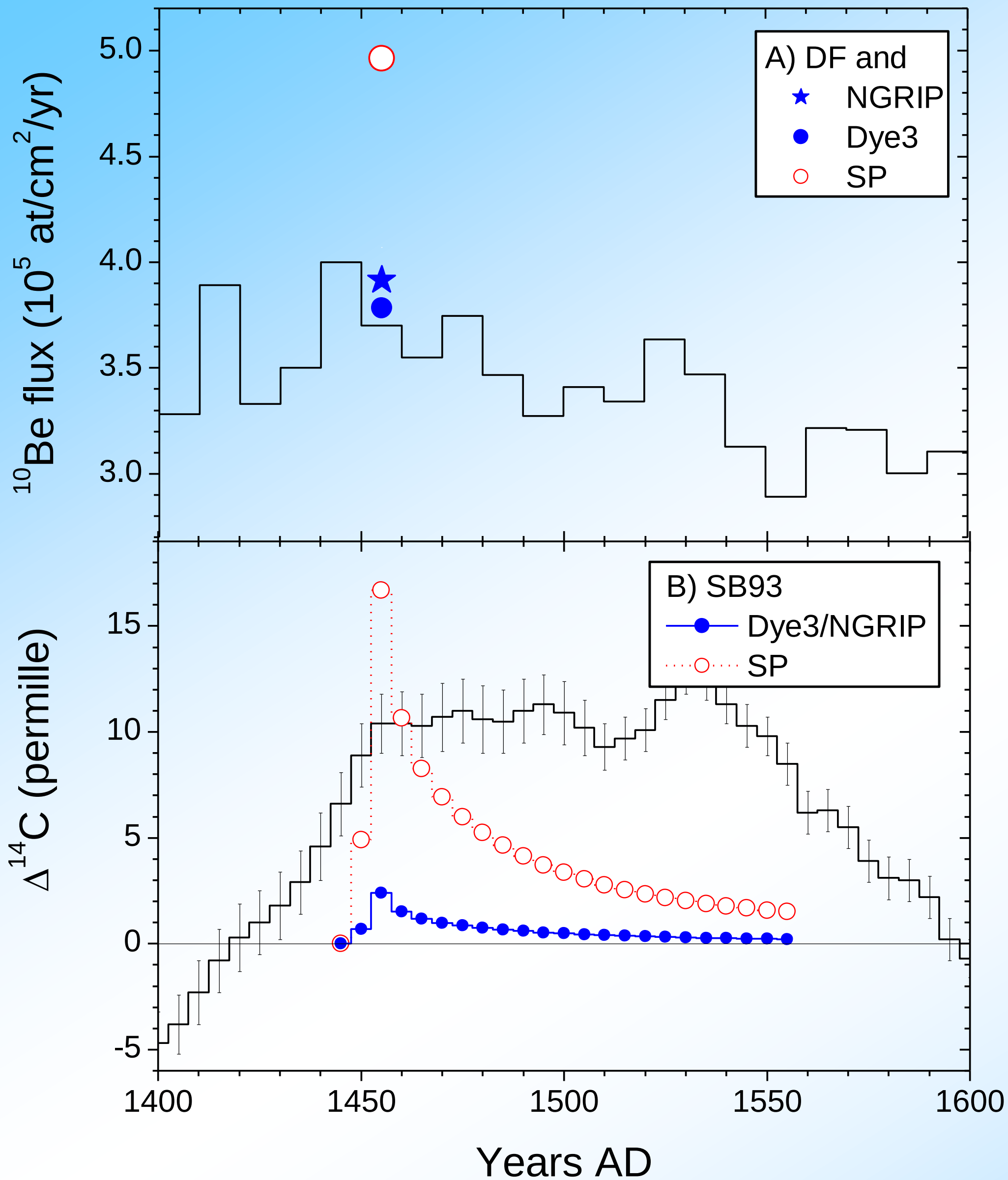
# Lunar rock vs. $\Delta^{14}C$

Lunar rock-based limit: Half of the fluence – by one SPE **BUT**:
$^{14}$C-LR based estimate *f*~42 $cm^{-2}s^{-1}$ (Jull et al.), for non-extreme SPEs *f*~35 $cm^{-2}s^{-1}$ => for extreme SPE *f*~7 $cm^{-2}s^{-1}$ => total $F_{30}$ fluence ~2*$10^{12}$ $cm^{-2}$ over Holocene => max ~$10^{12}$ $cm^{-2}$.




Lunar rocks: A few $F_{30}=10^{13}$ events over Holocene – must be seen in $\Delta^{14}C$ series.

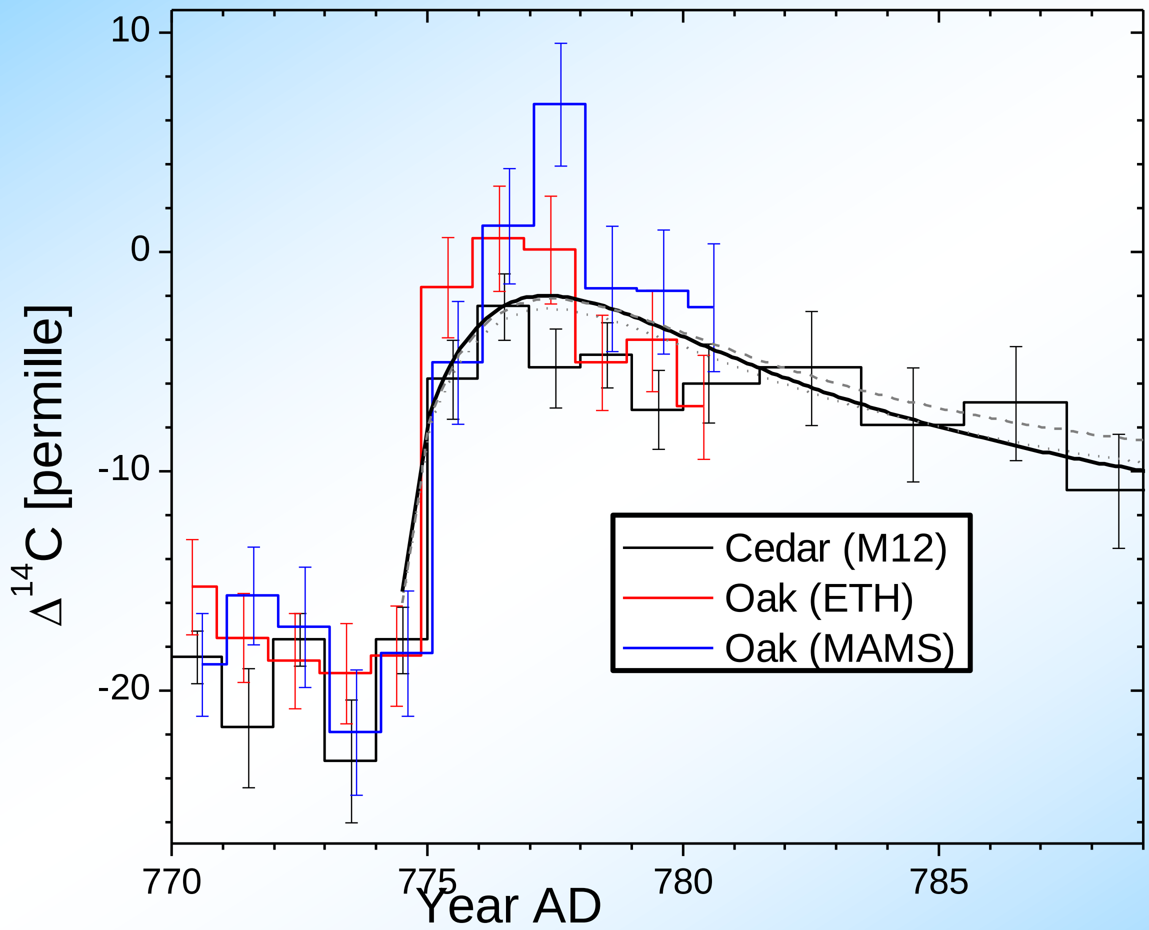
# Specific event of ca. 1460 AD



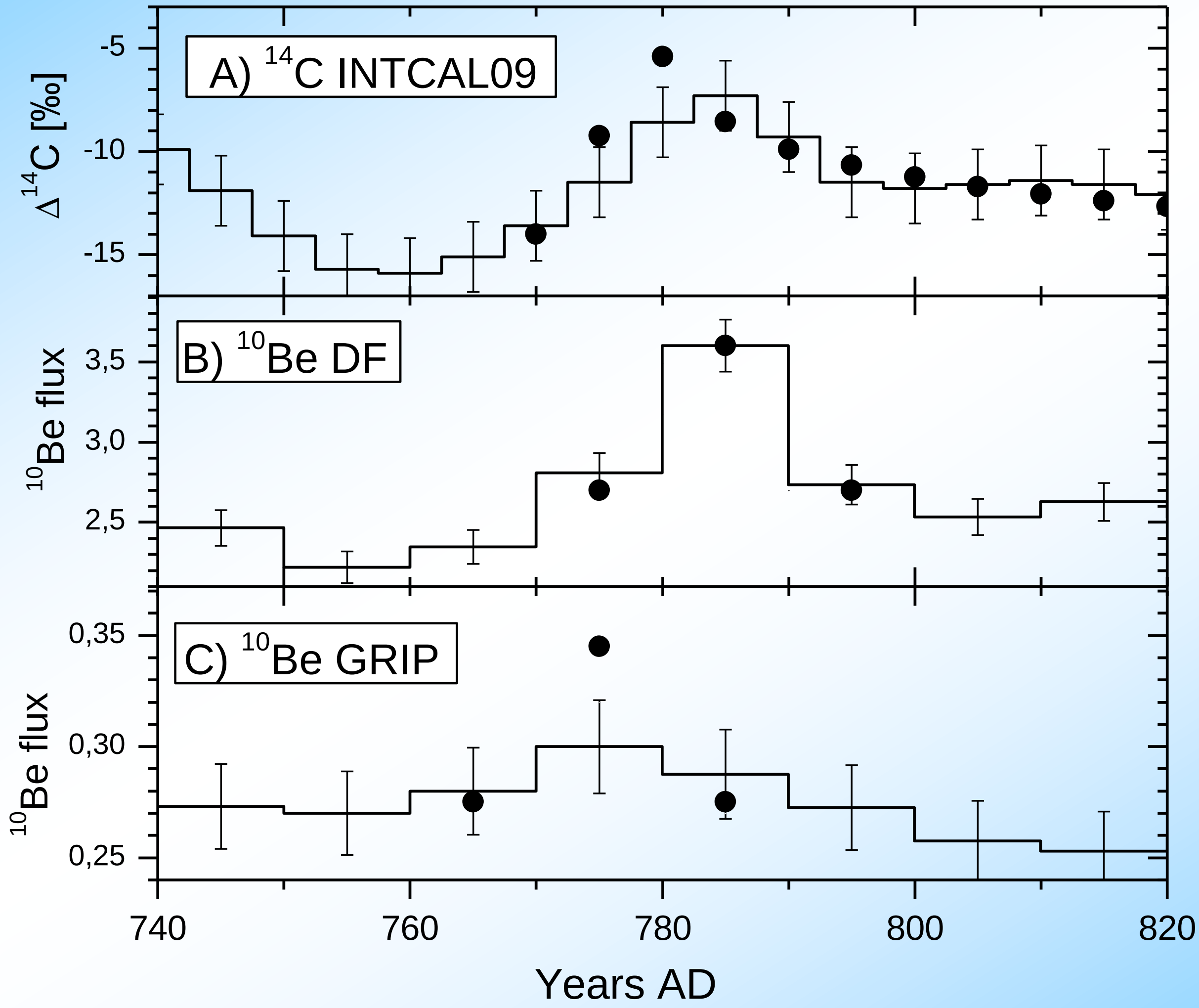

NGRIP/Dye3 signal ($F_{30}$=(1-1.5)*$10^{10}$ cm$^{-2}$) is consitent with DF and SB93 (no signal),

SP-implied signal ($F_{30}$=7*$10^{10}$ cm$^{-2}$) – too high

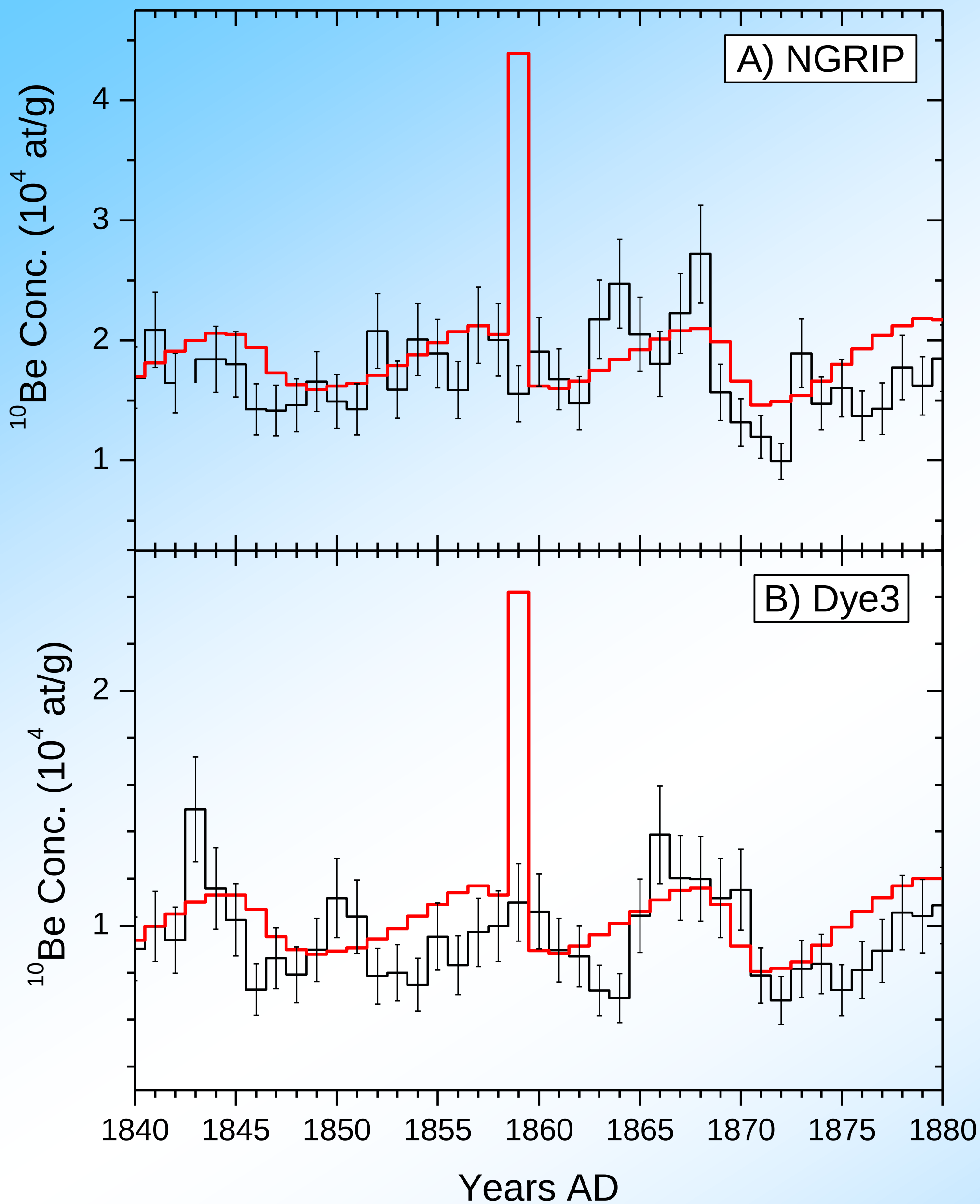
# 775 AD: model vs. data



# 780 AD – other data



# Carrington event 1859




Carrington event 1859:

$F_{30}$=1.8*$10^{10}$ $cm^{-2}$ (McCracken et al., 2001).

\+

GCR (from Alanko-Huotari et al., 2007)

\+

$^{10}$Be production model (Kovaltsov & Usoskin, 2010)

→

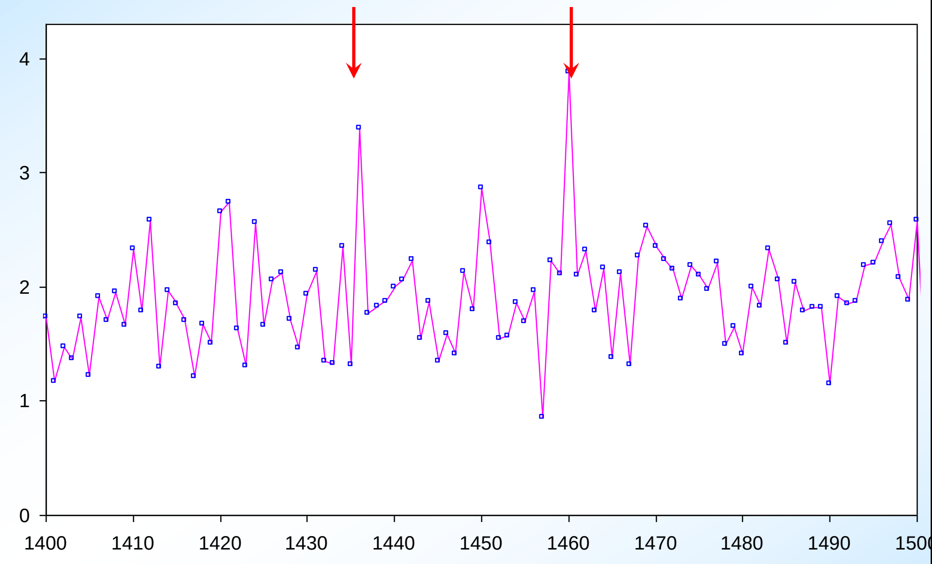
modelled $^{10}$Be response.

The expected peak is ~10 σ too high =>

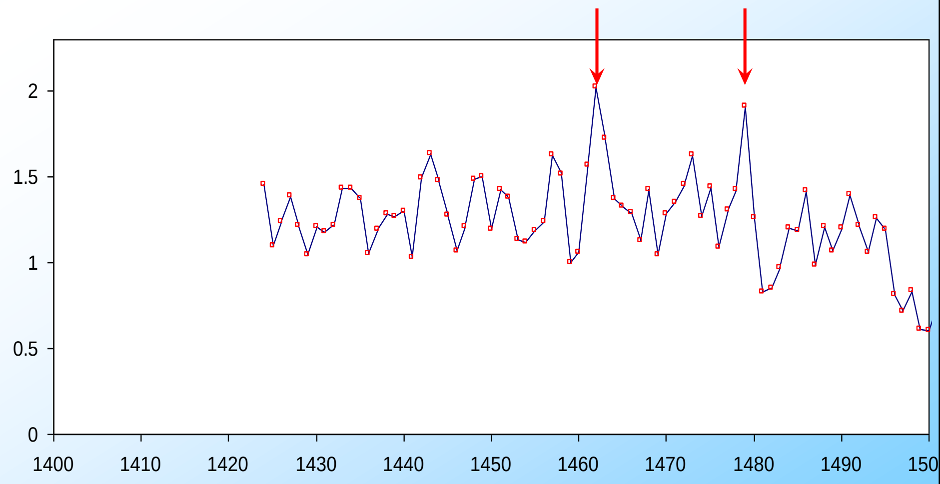
Should be <5*$10^9$ $cm^{-2}$.

# Potential signature in annual $^{10}Be$

- ***NGRIP*** series: peaks > $1.3 \times 10^4$ at/g
  1436, 1460, 1650, 1719, 1810, 1816, 1965




- ***Dye3*** series: peaks > $0.6 \times 10^4$ at/g
  1462, 1479, 1505, 1512, 1603




- ***SB93*** series: no peaks identified

Cross-check performed

# SPEs: all data