What do we know about extreme solar events?

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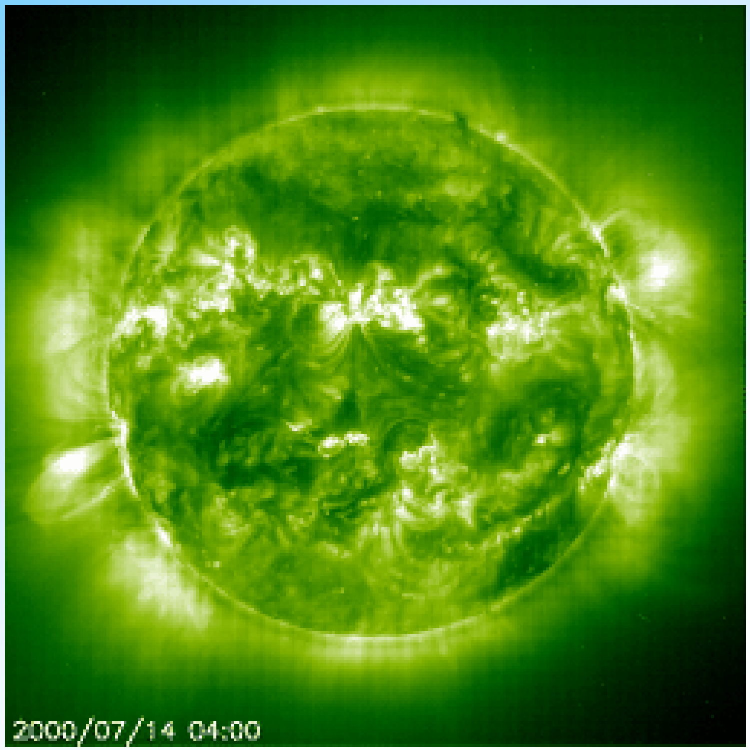
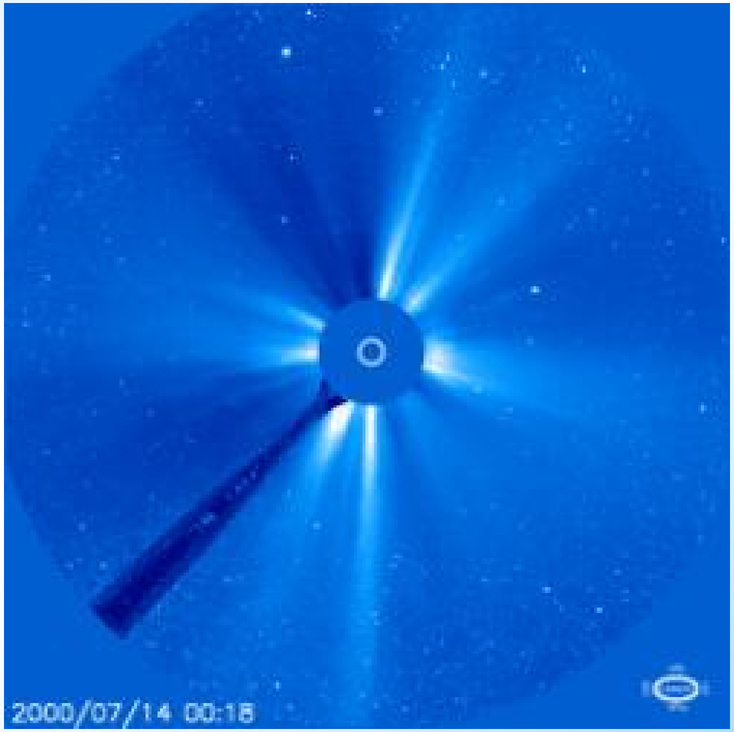
Solar flares and energetic particles





EIT 195 Å

LASCO C3

SOHO (Credit NASA)

Carrington flare

01-Sep-1859 :

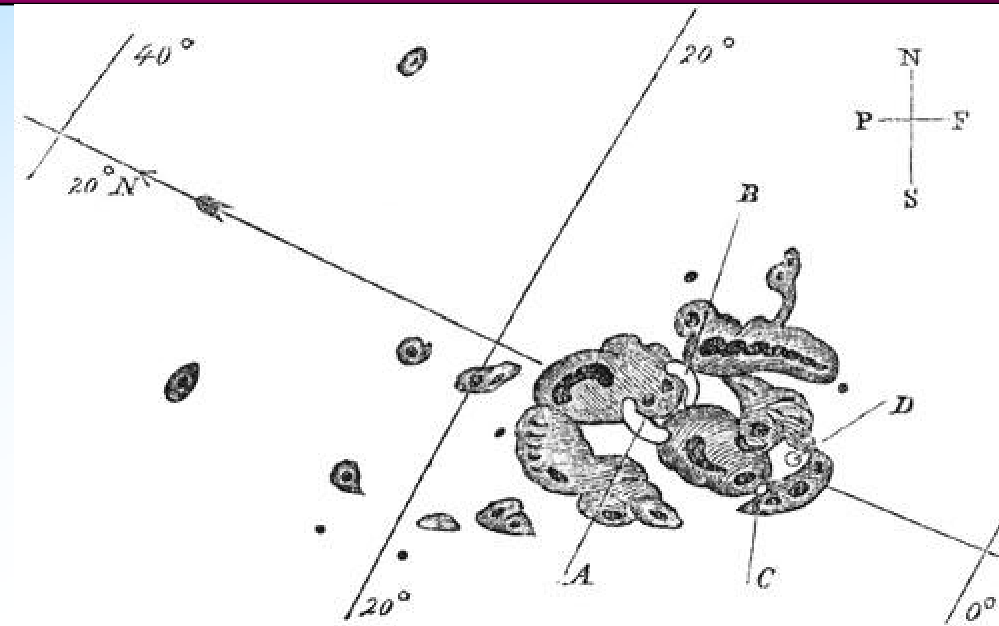
Richard Carrington and Richard Hodgson observed a white-light flash on the Sun

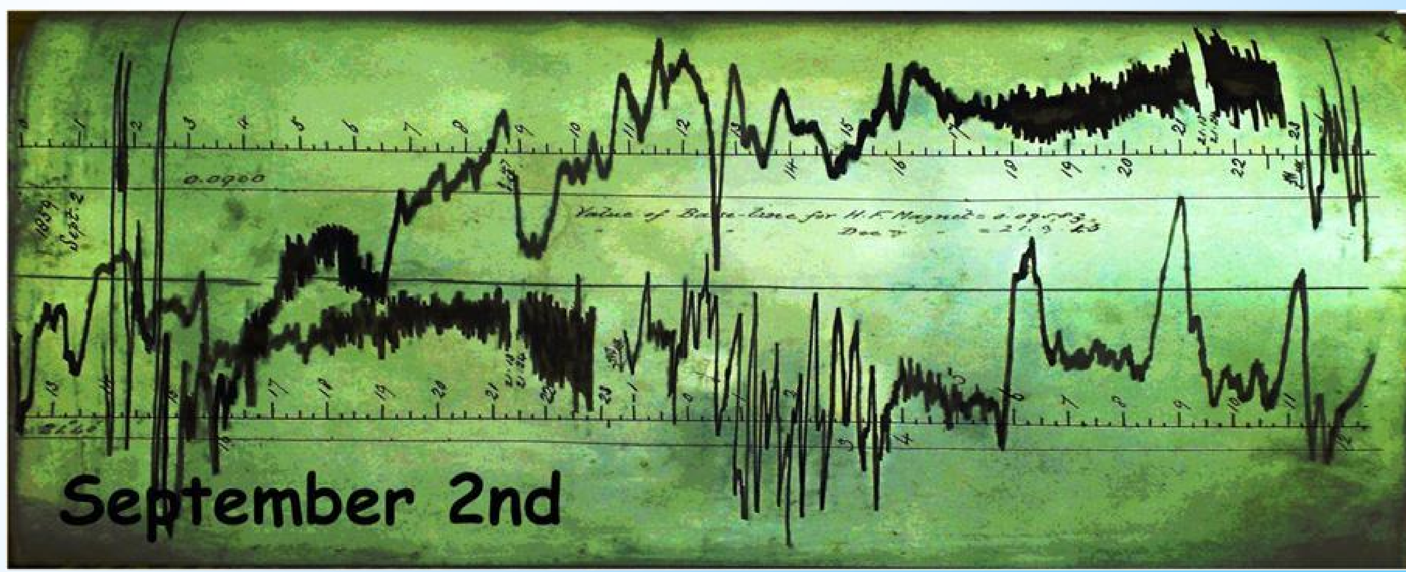
02-Sep-1859:

The strongest ever geomagnetic storm, telegraph lines melted

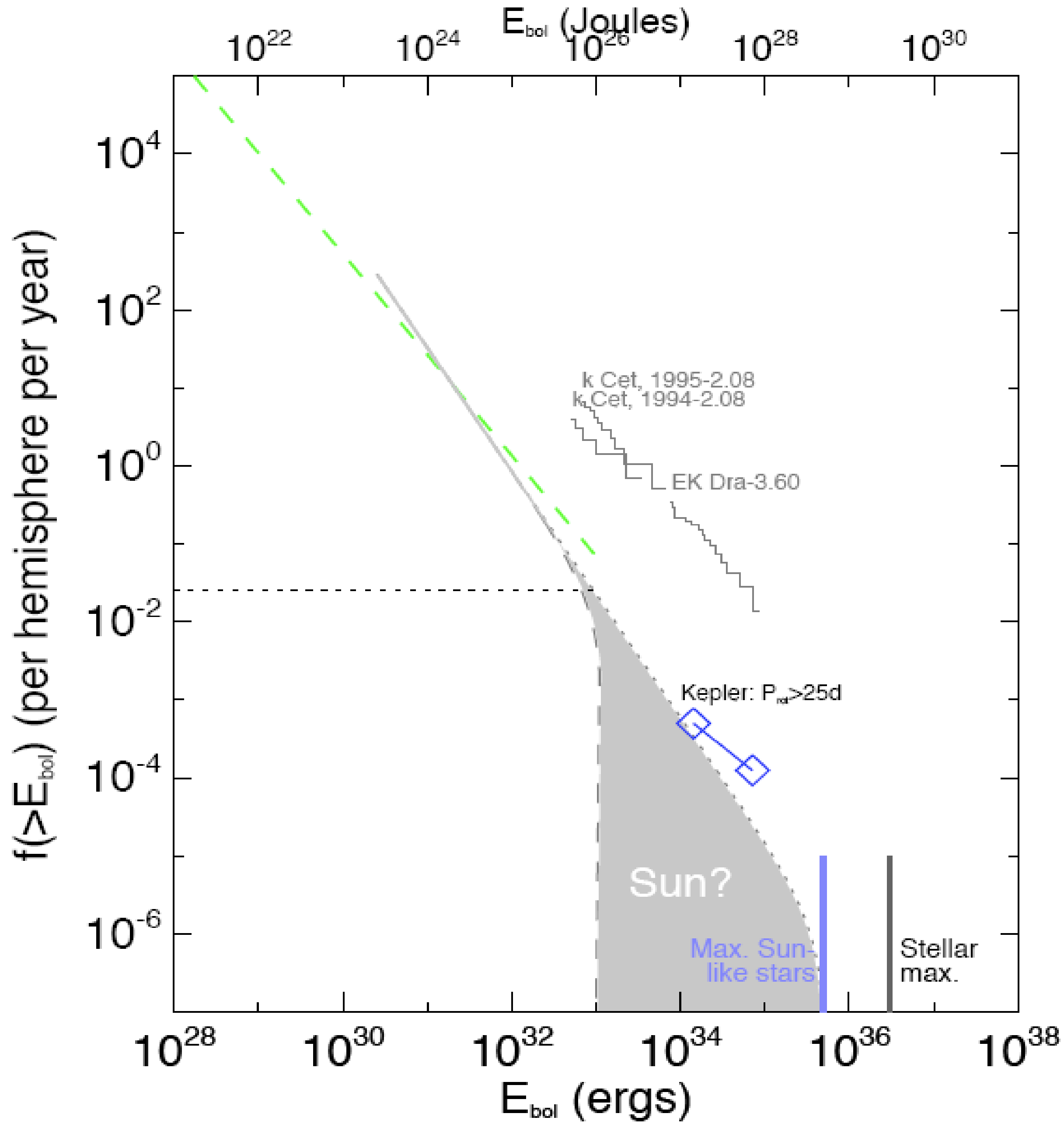
If nowadays:

Telecommunication and navigation systems would be in danger, electric power grids, gas/oil pipes, etc.



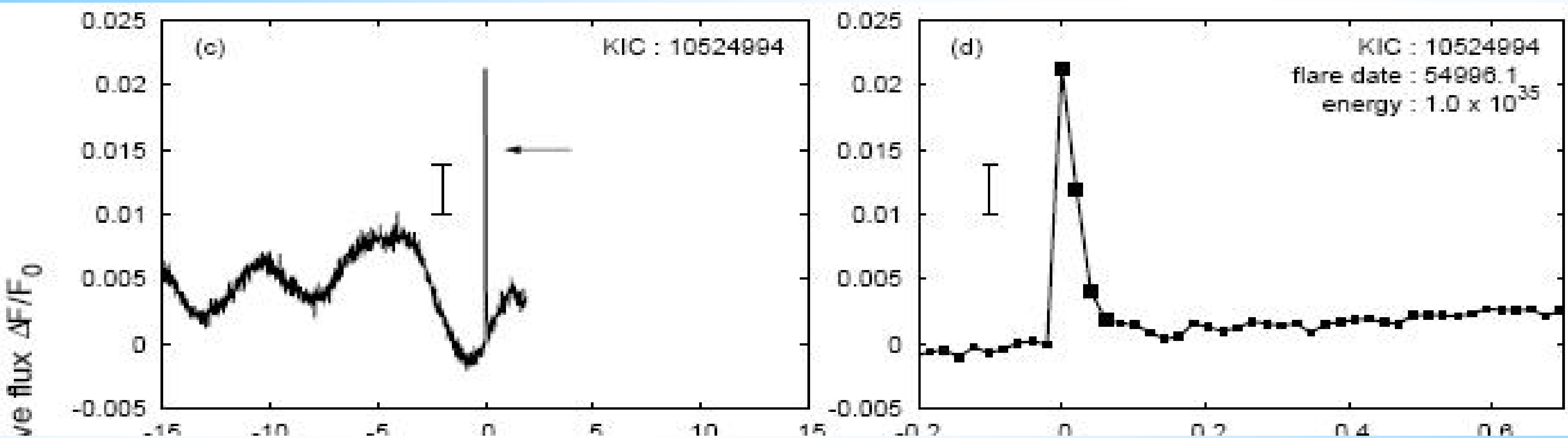


OPDF of solar flares



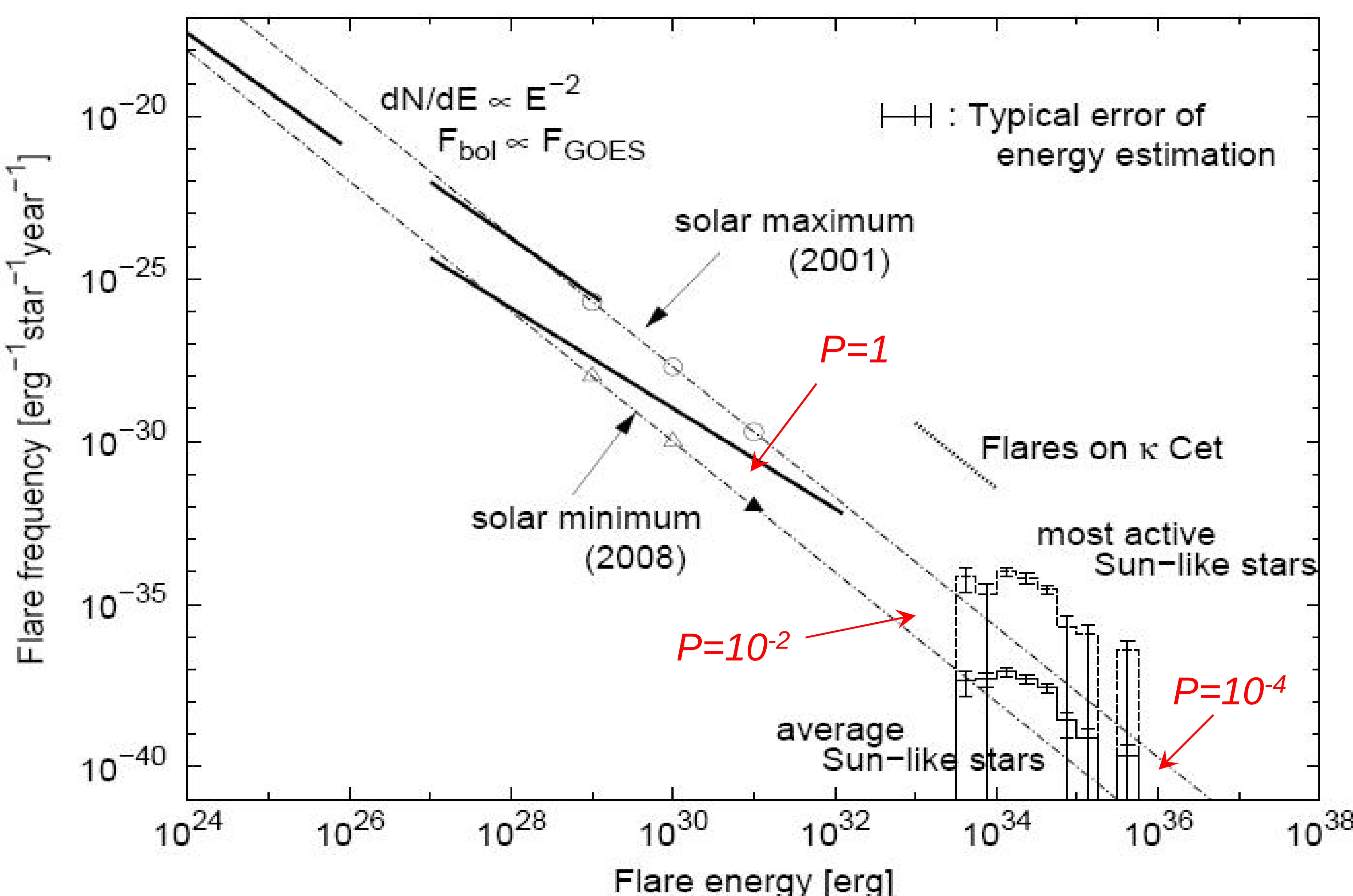
Schrijver & Beer, EOS, 2014

Stellar superflares



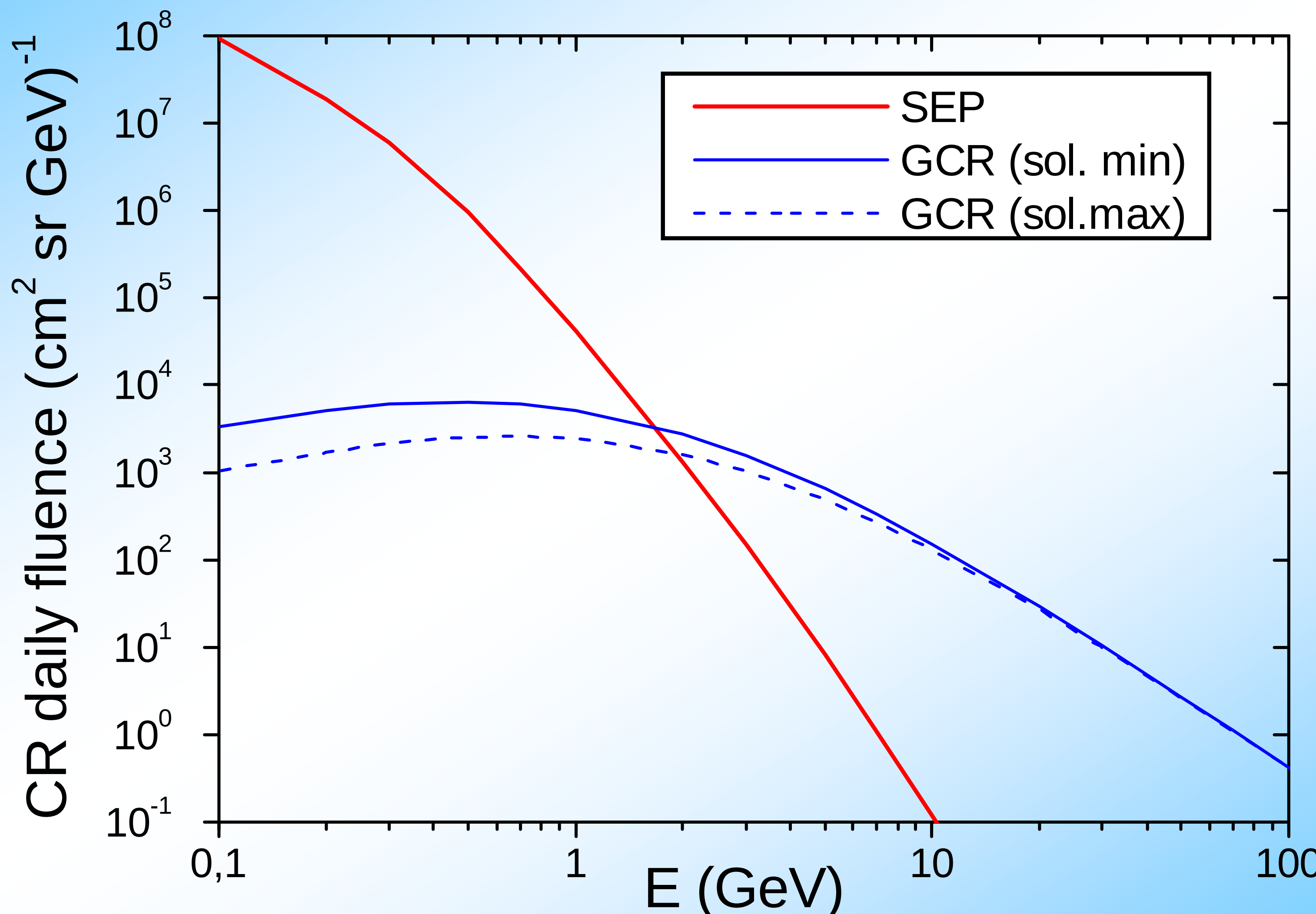
Shibayama et al., ApJS, 2013

OPDF of solar flares



Shibayama et al., ApJS, 2013

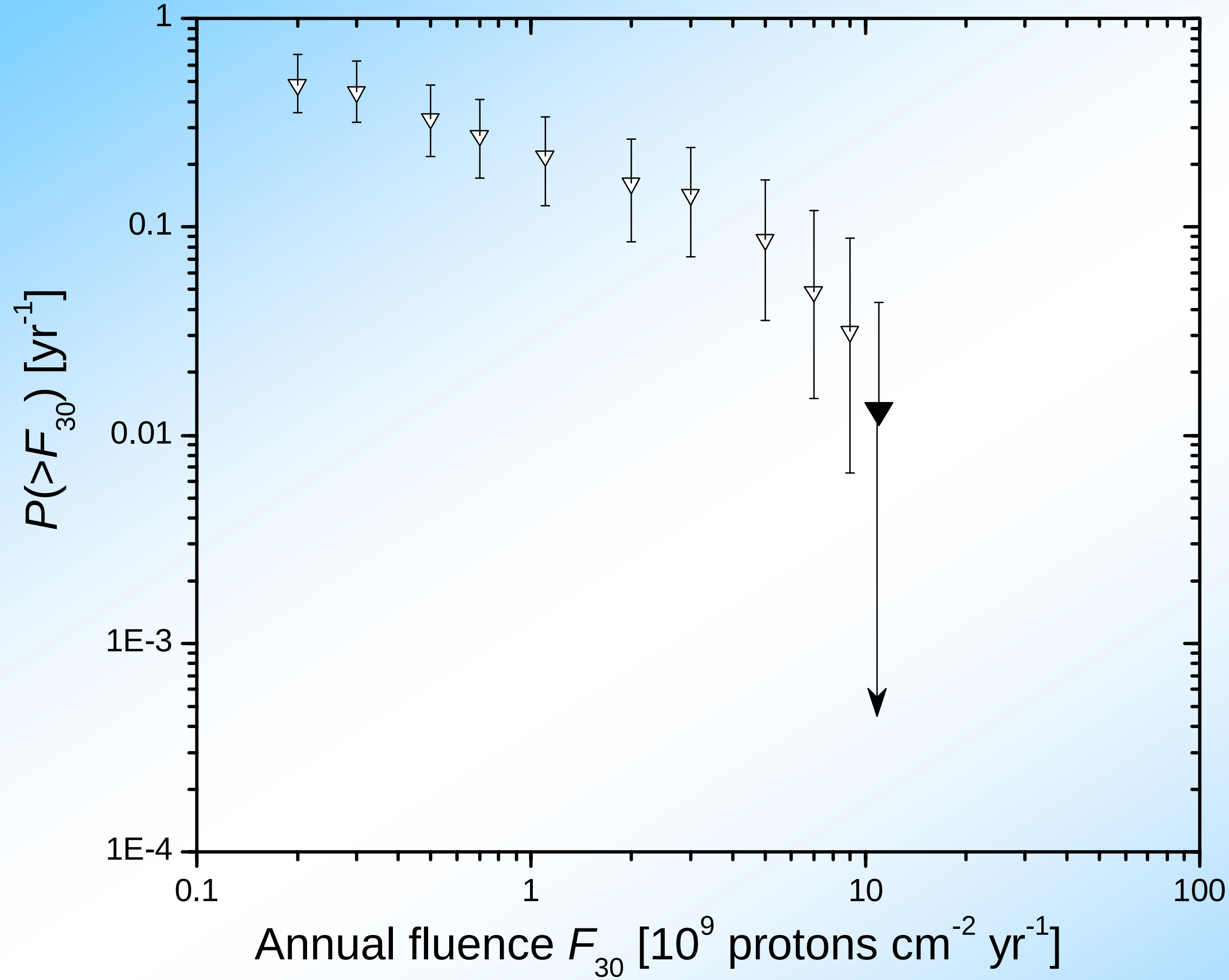
SEP vs GCR



CR daily fluence (cm2 sr GeV)-1
10-1
100
101
102
103
104
105
106
107
108
0,1
1
10
100
E (GeV)
SEP
GCR (sol. min)
GCR (sol.max)

Direct data: since 1950s

SPE: space era



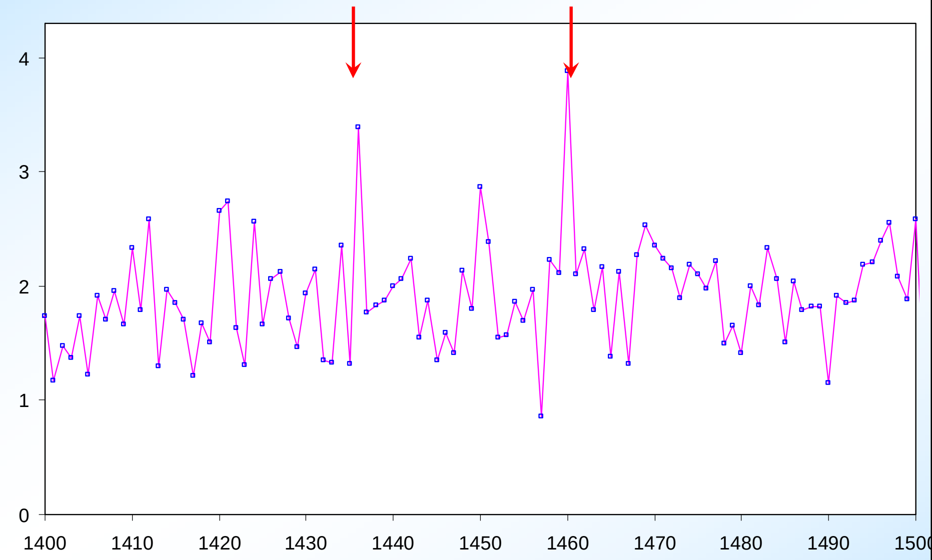
Shea & Smart (1990, 2012), Reedy (2012):
No events with $F_{30} > 10^{10}$ cm^{-2} since 1956.

Cosmogenic radionuclides

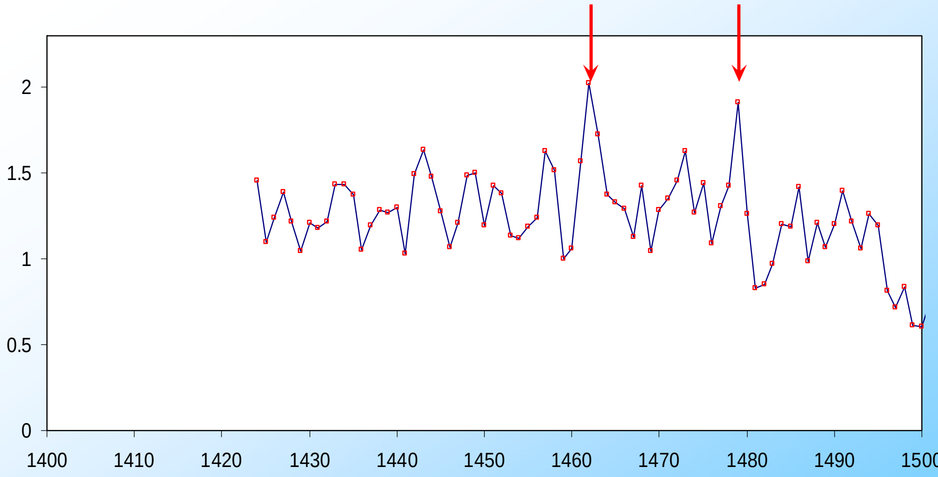
^{14}C and ^{10}Be: last 11 millennia

Potential signature in annual ^{10}Be

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



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



<u>**Cross-check performed**</u>

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)

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

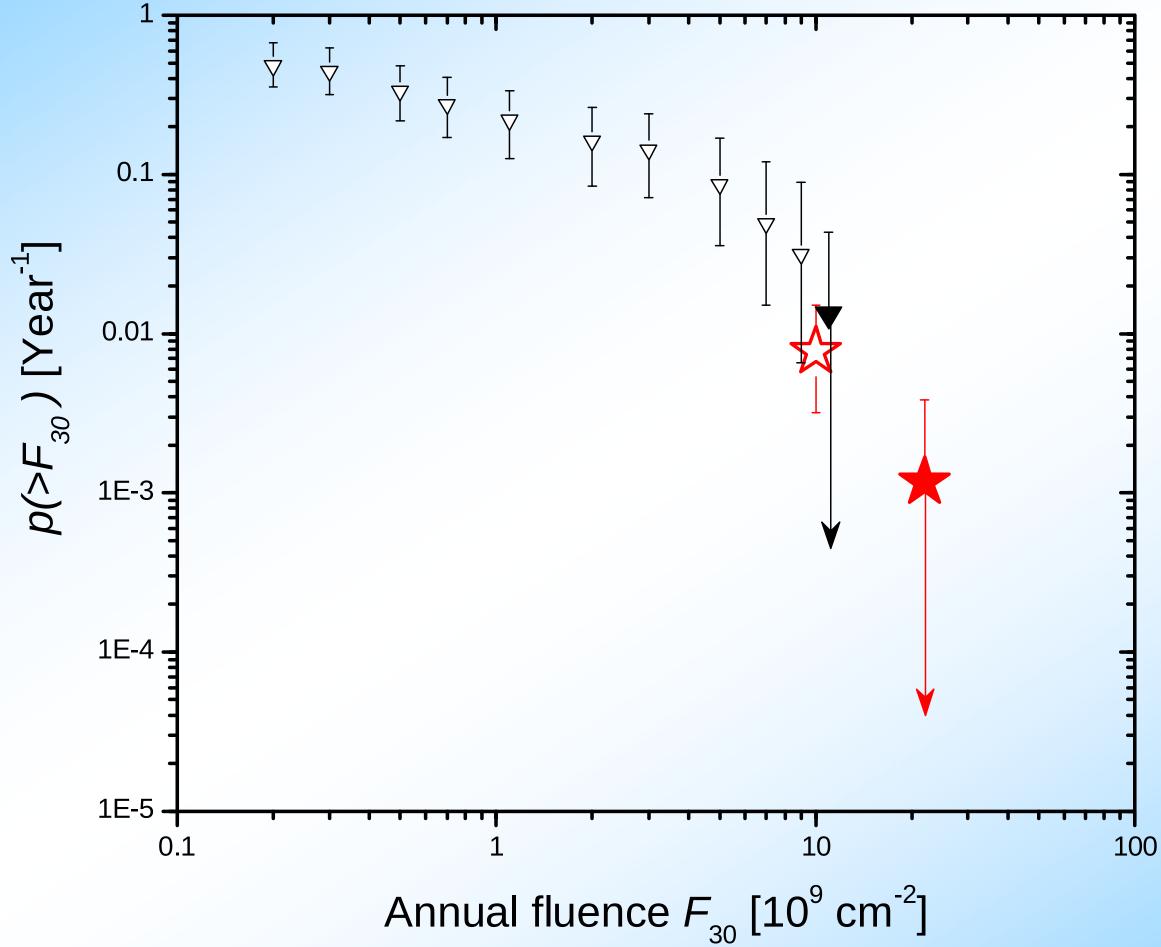
* **no events** with $F_{30}>2*10^{10}$ cm^{-2} over 600 years

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

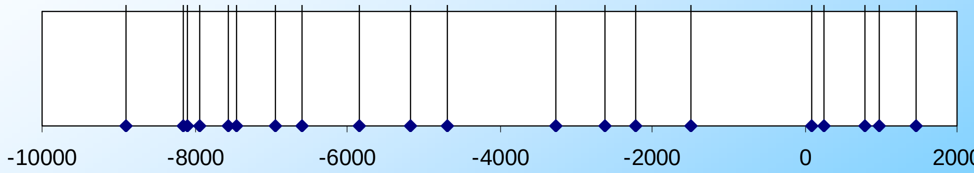
8910 BC	IntCal09	$2.0*10^{10}$
8155 BC	IntCal09	$1.3*10^{10}$
8085 BC	IntCal09	$1.5*10^{10}$
7930 BC	IntCal09	$1.3*10^{10}$
7570 BC	IntCal09	$2.0*10^{10}$
7455 BC	IntCal09	$1.5*10^{10}$
6940 BC	IntCal09	$1.1*10^{10}$
6585 BC	IntCal09	$1.7*10^{10}$
5835 BC	IntCal09	$1.5*10^{10}$
5165 BC	GRIP	$2.4*10^{10}$
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:

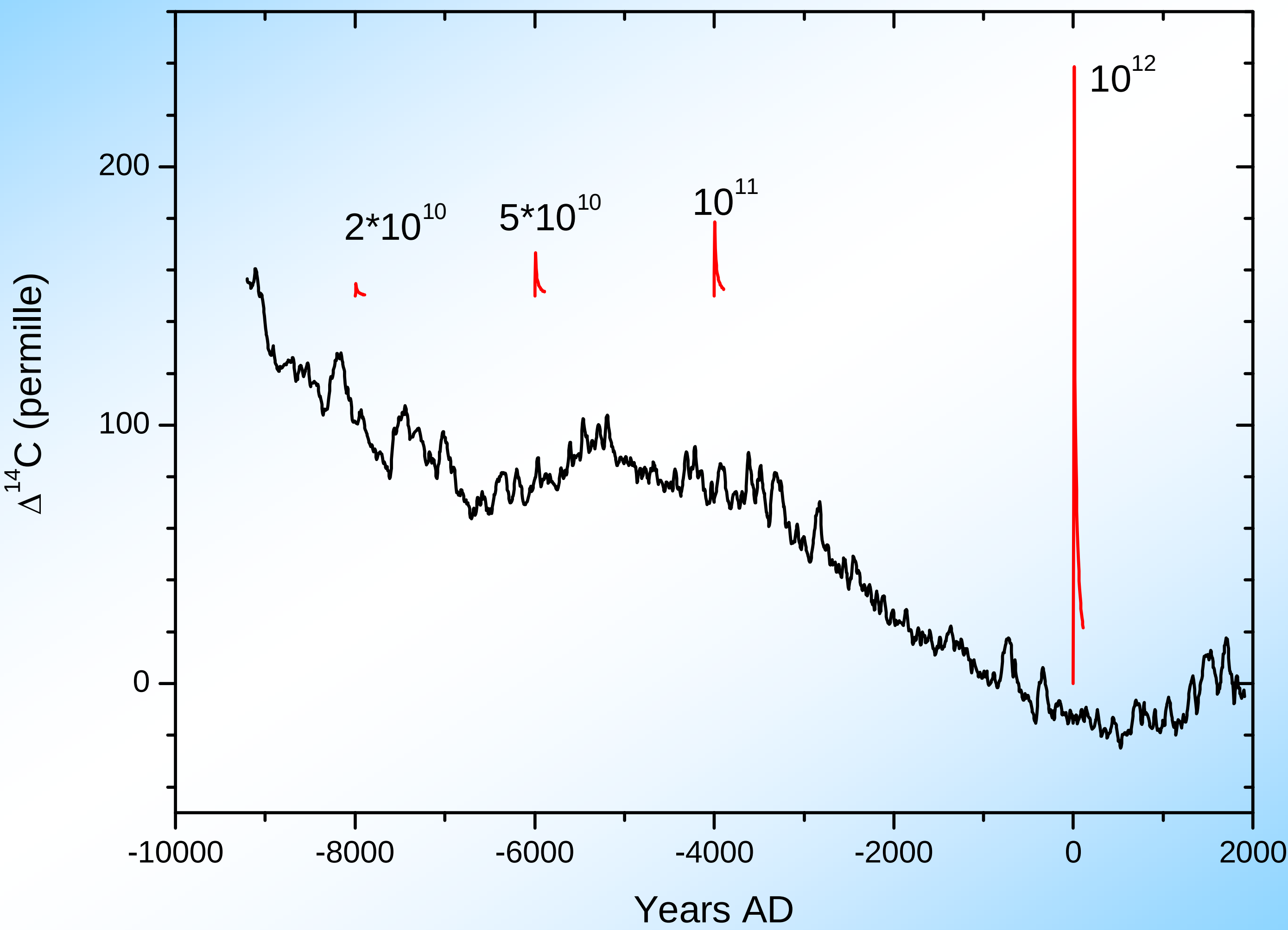
19 events $F_{30}=(1\text{-}3)*10^{10}$ cm^{-2}

1 event $F_{30}=(4\text{-}5)*10^{10}$ cm^{-2}

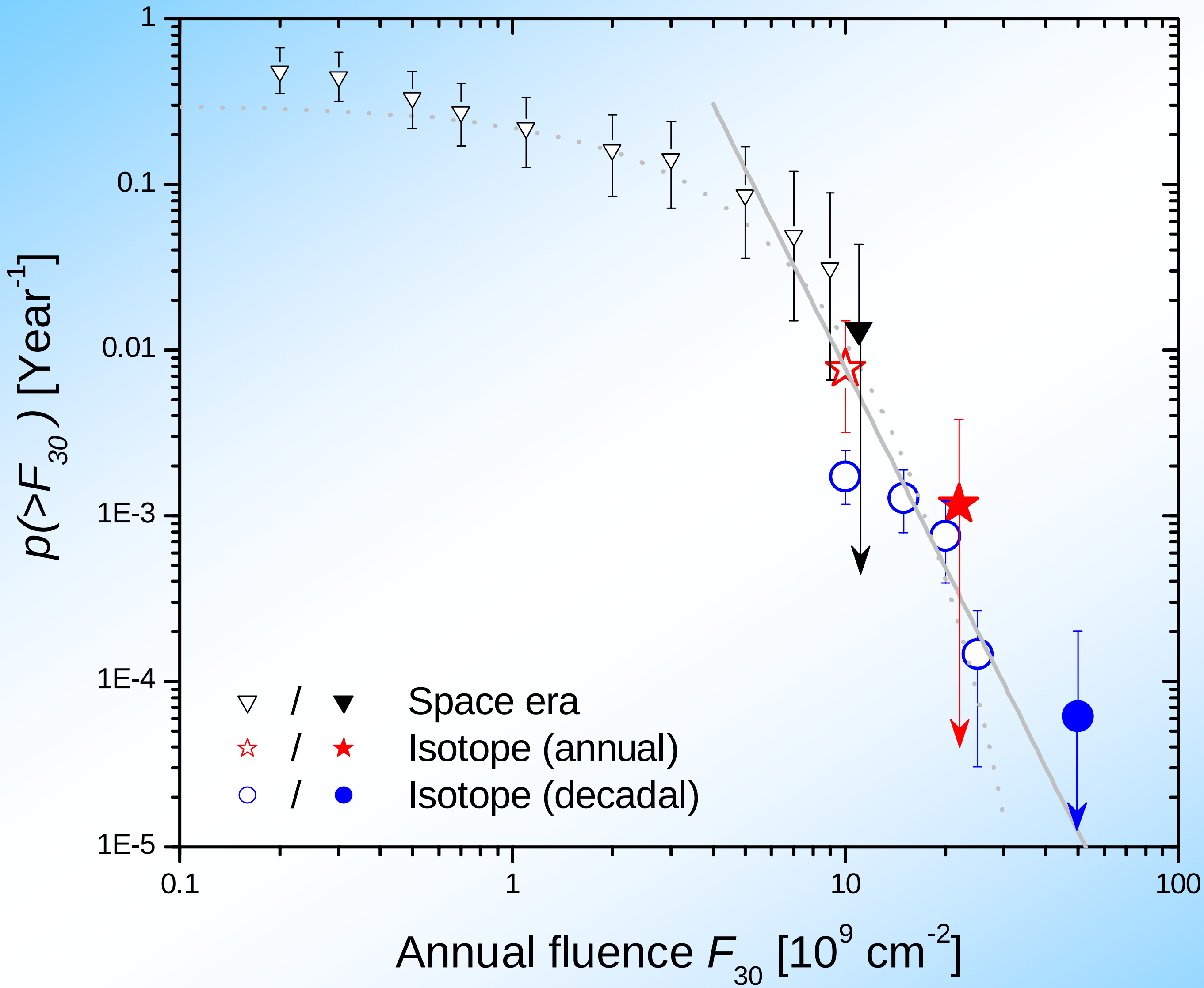
no events with $F_{30}>5*10^{10}$ cm^{-2}



Events to look for in Δ14C



SPEs: all data

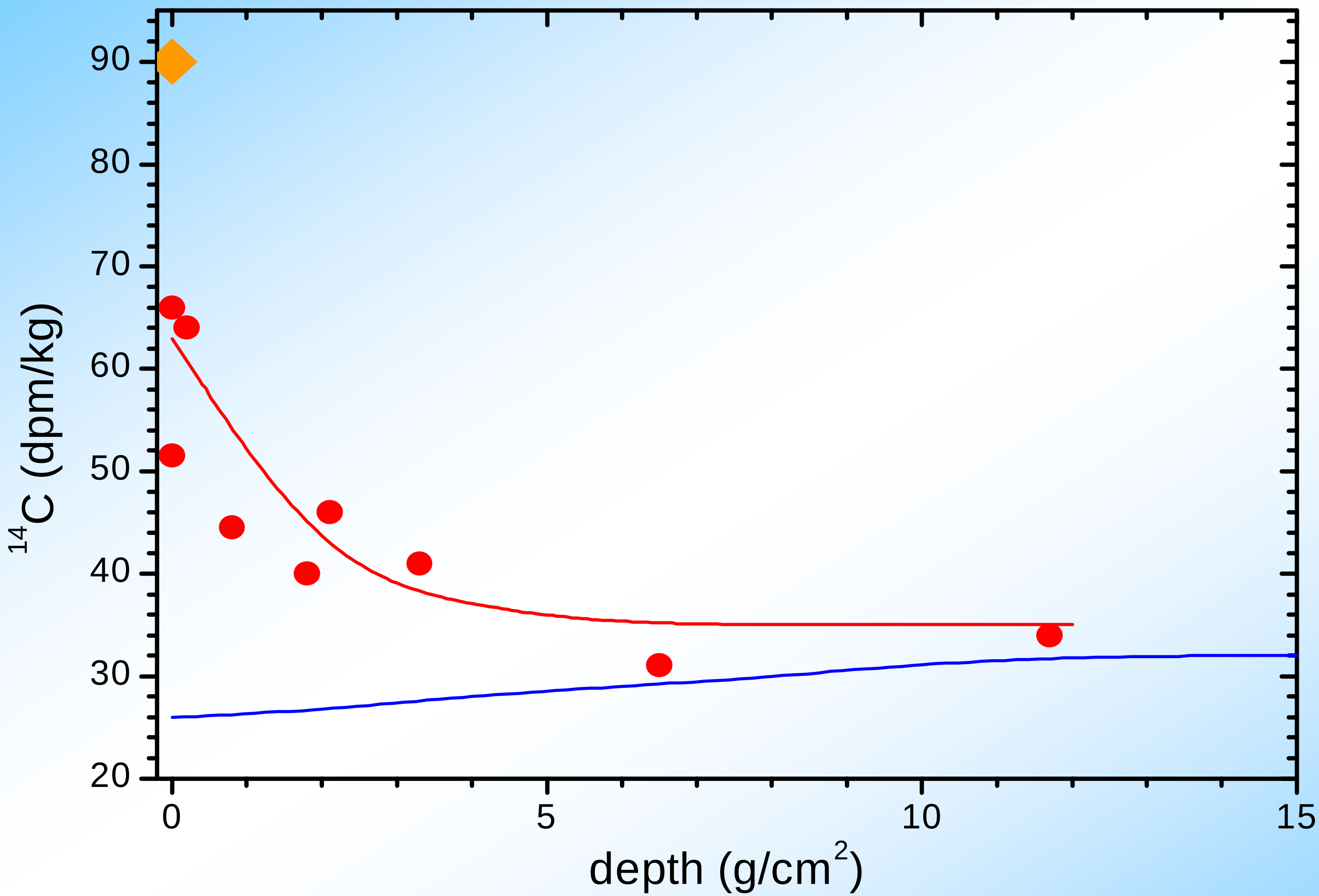


Subconclusions

- **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÷5)*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}.
- The greatest event was ca. 775 AD F_{30}~5*10^{10} cm^{-2}.
- On average, extreme SPEs contribute about 10% to the total SEP flux.
- Practical limits are: F_{30}≈1, 2÷3, and 5*10^{10} cm^{-2} for the occurrence probability ≈ 10^{-2}, 10^{-3} and 10^{-4} $year^{-1}$, respectively.

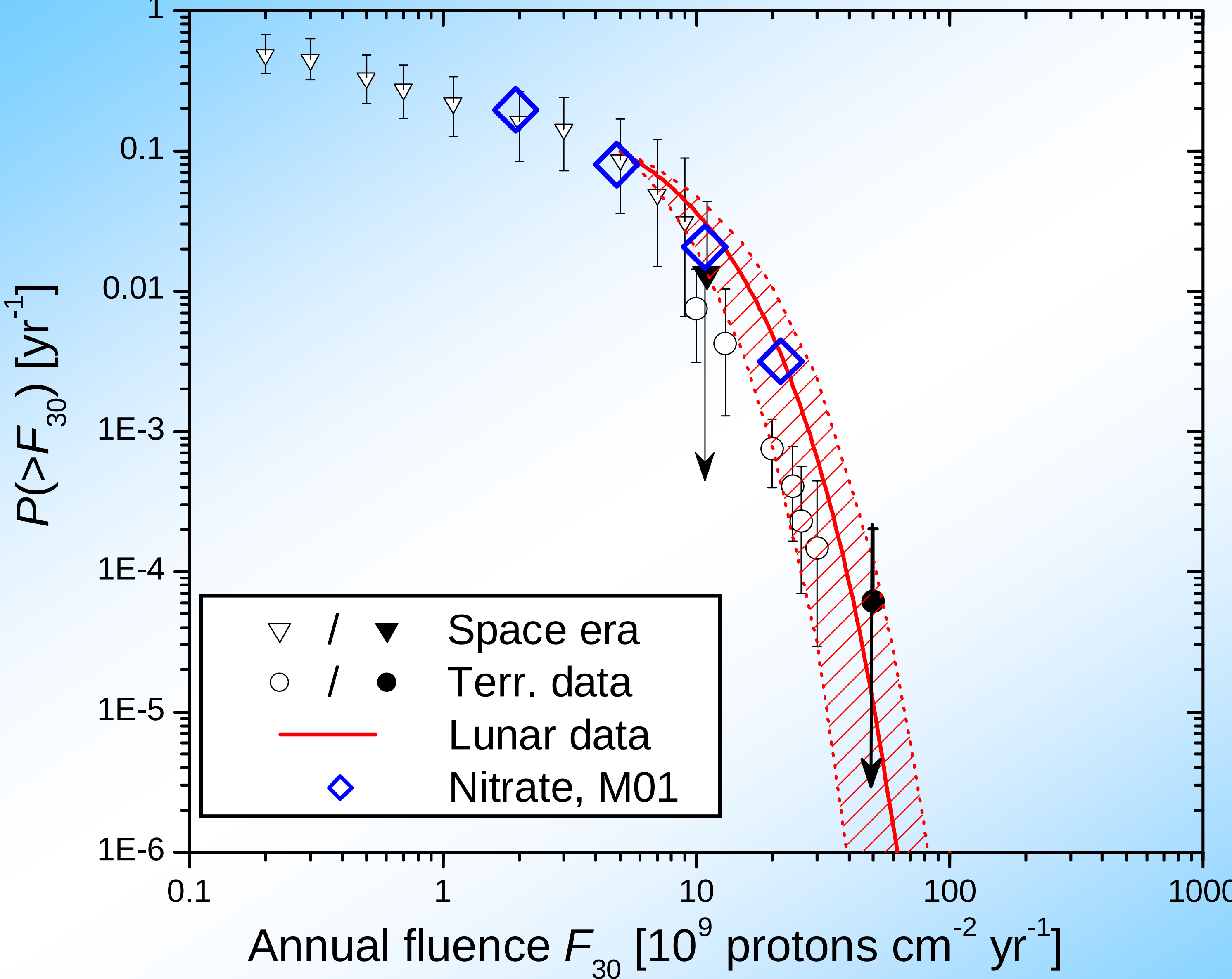
Cosmogenic radionuclides in lunar rocks: 1 Myr

Lunar/meteoritic samples



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

Final result



Kovaltsov & Usoskin, Sol.Phys, 2014

Summary

- Solar flares: based on large ensemble but short time statistics: **continuous OPDF**?

- SEP events: based on long-term proxy data: **A strong roll-off for $F_{30}>10^9$ protons/cm^2/yr**
  - The OP of a $F_{30}>10^{11}$ p/cm^2/yr event is $<10^{-6}$ yr^{-1}.

THANK YOU !