EXTREME SOLAR EVENTS

The distribution of flare energies for the Sun and Sun-like stars

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Eric Wolff

Chameleon behavior of solar storms

- GOES class provides a very uncertain measure of the energy in a solar coronal storm event.
- Example: large scatter in event peak brightness as function of wavelength.

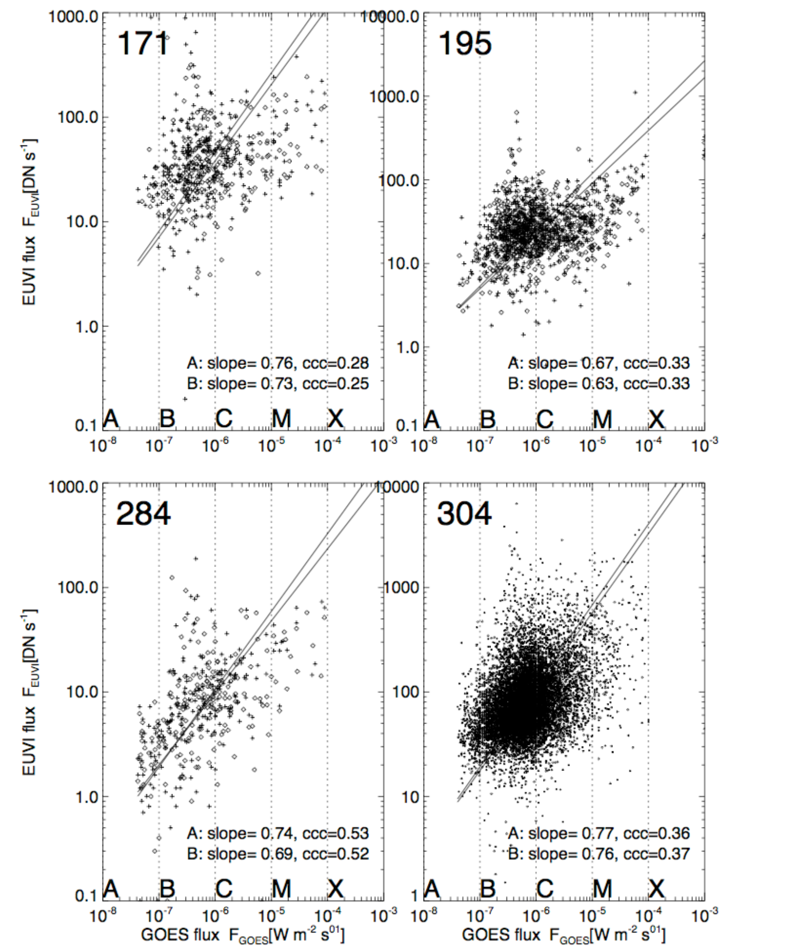
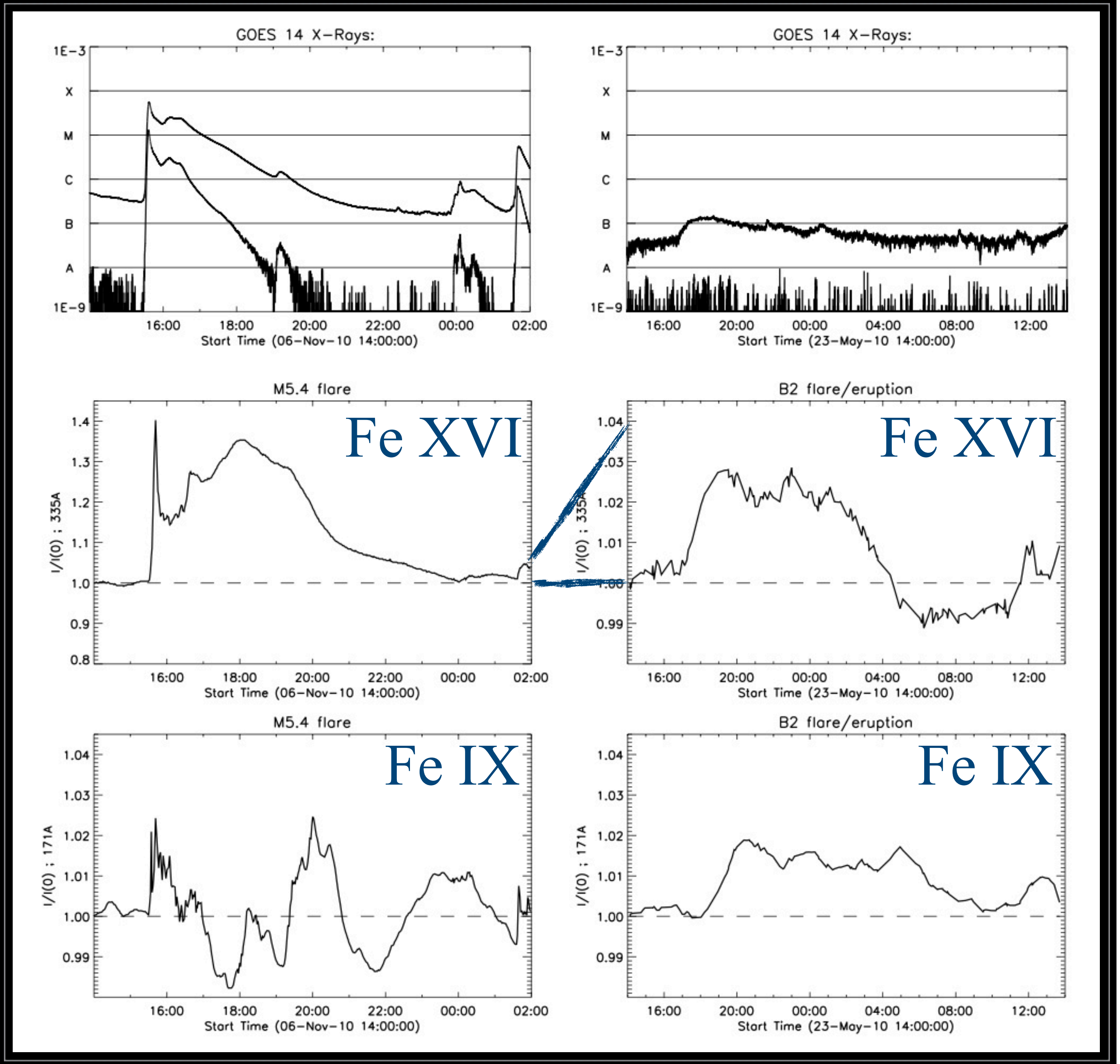


Figure 7. Scatterplot of EUVI fluxes (171, 195, 284, 304 Å) versus the GOES flux of all events simultaneously detected with EUVI and GOES. The data from spacecraft STEREO/A are indicated with cross symbols, from STEREO/B with diamond symbols. Separate fits and linear regression fits for both spacecraft are indicated.

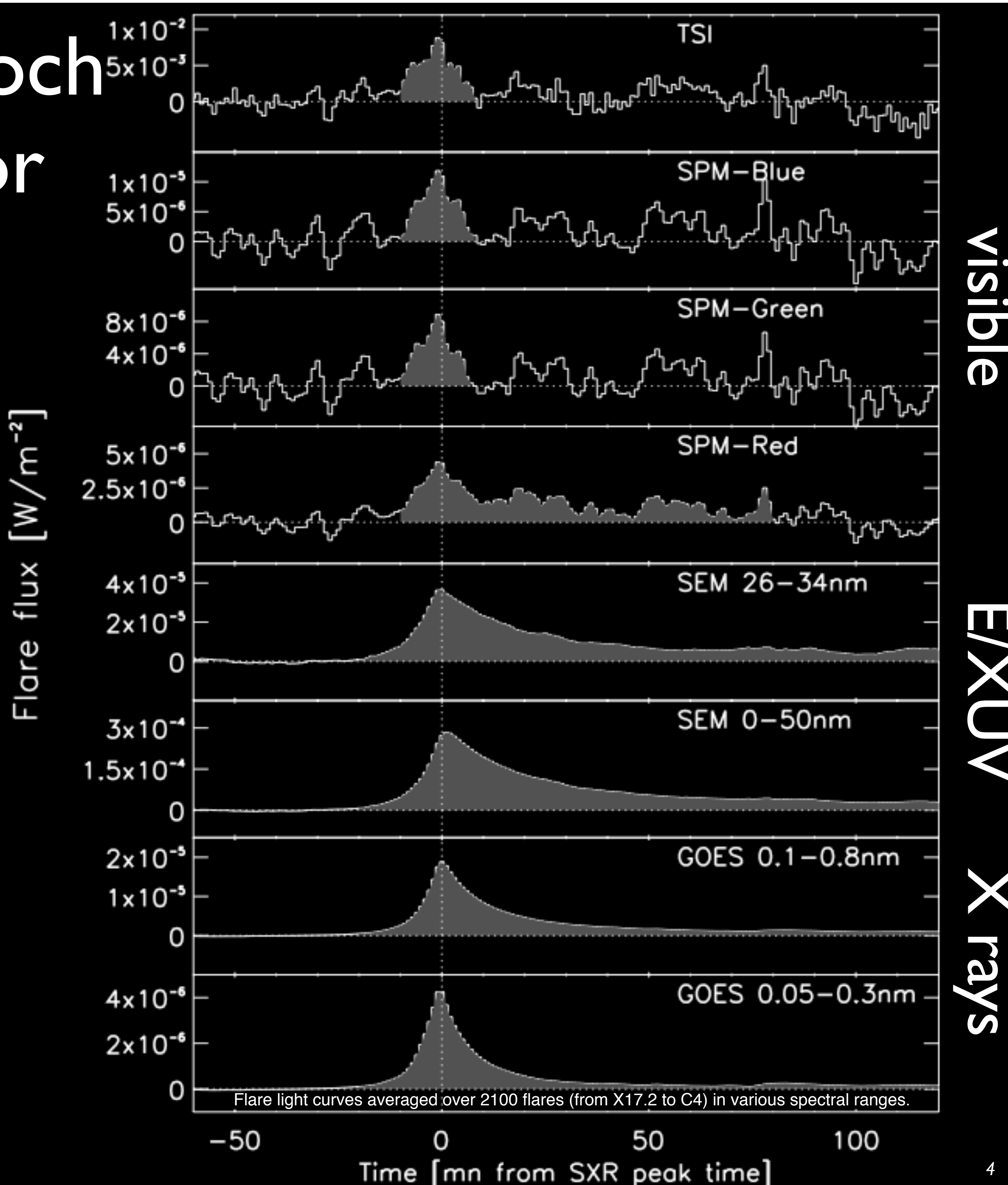
Aschwanden et al. (2014, SPh)

Chameleon behavior of solar storms

- GOES class provides a very uncertain measure of the energy in a solar coronal storm event.
- Example: GOES classes for an active-region flare and quiet-Sun filament eruption *differ by factor of ~250 for comparable 'bolometric' energies in the X-ray/(E) UV domain.*



Superposed-epoch light curves for solar flares

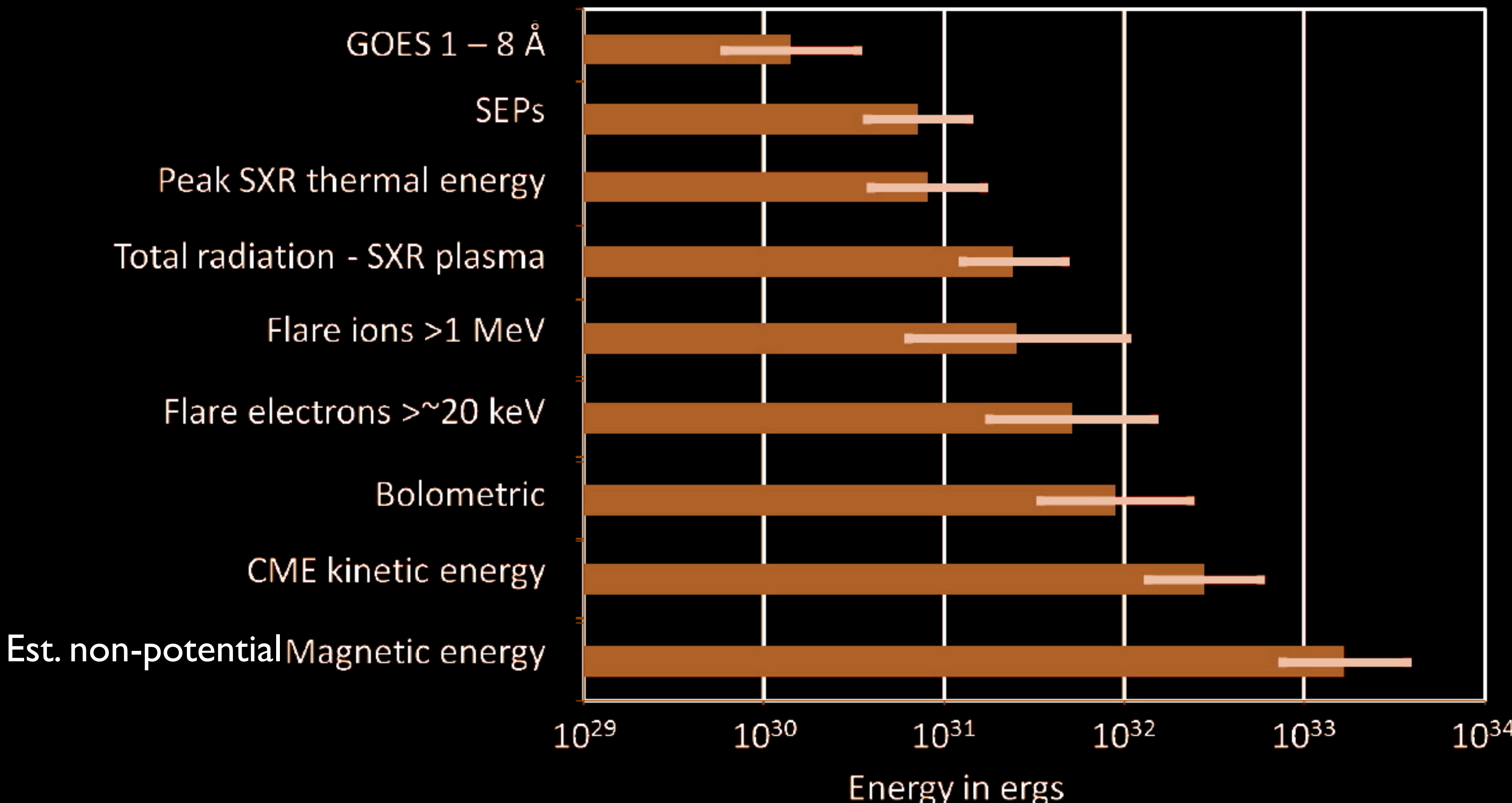


Flare light curves averaged over 2100 flares (from X17.2 to C4) in various spectral ranges.

The bulk of the energy is emitted where it is hardest to measure!

From Kretzschmar (2011)

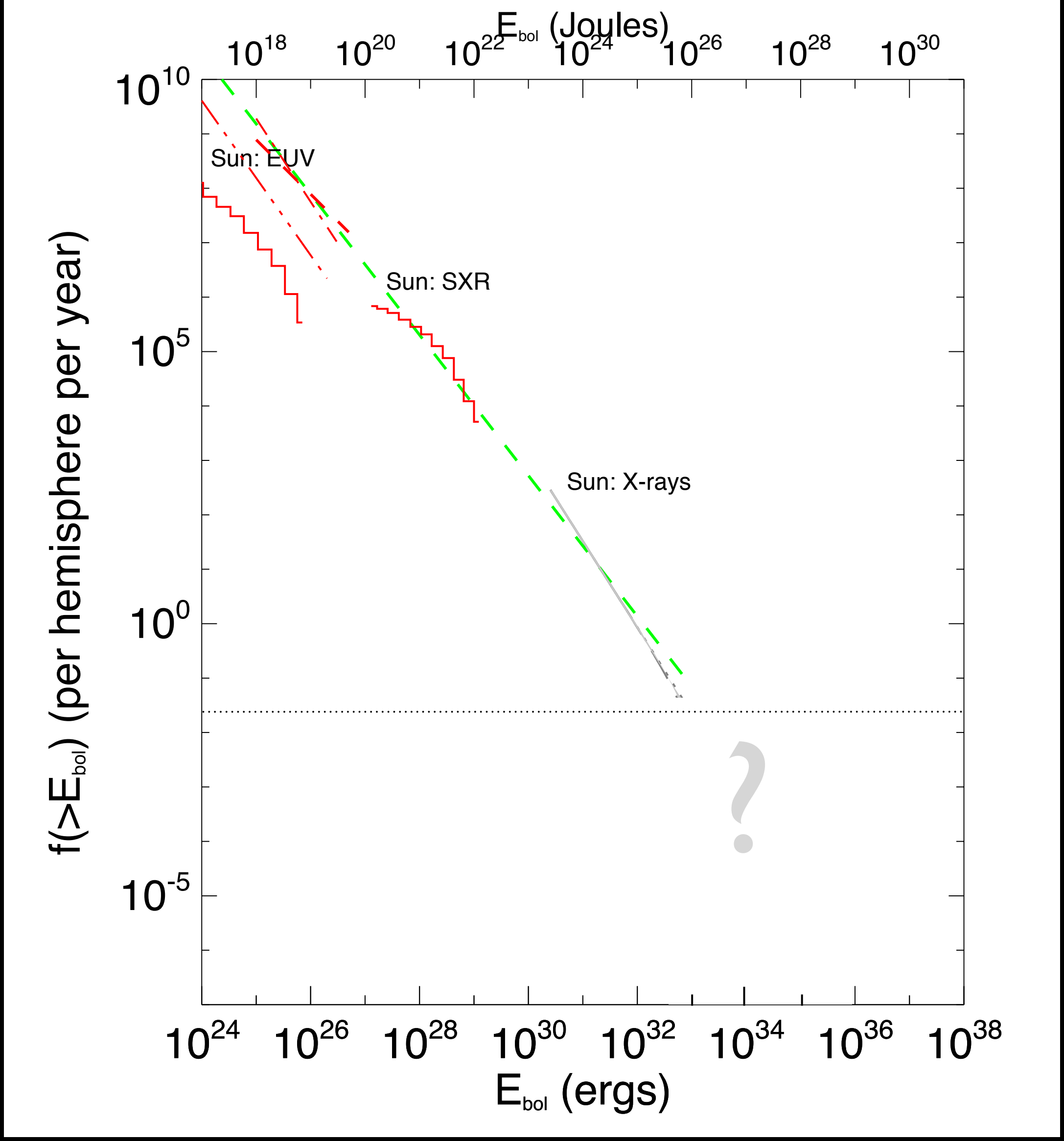
Flare energy: mostly WL and kinetic



Modified after Emslie et al. (2012): values for X3, X3, X4, X7, X8, X10 flares.

Solar flare statistics

Combining solar EUV to X-ray data for 39 years of GOES monitoring of solar activity, combined with ~2 decades of EUV observing.



Observed spot group areas: no cutoff (yet)?

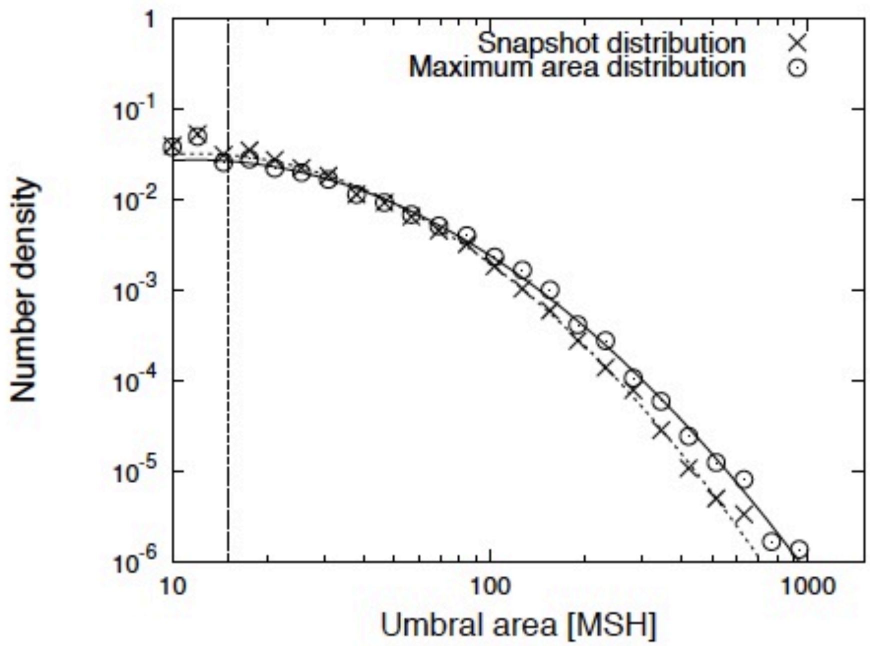


Fig. 1. Size distribution function of umbral areas obtained from the maximum development method (*circles*) and snapshot method (*crosses*). The log-normal fits are overplotted (*solid line:* Fit to maximum area distribution, *dotted line:* Fit to snapshot distribution). The vertical line indicates the smallest umbral area considered for the fits.

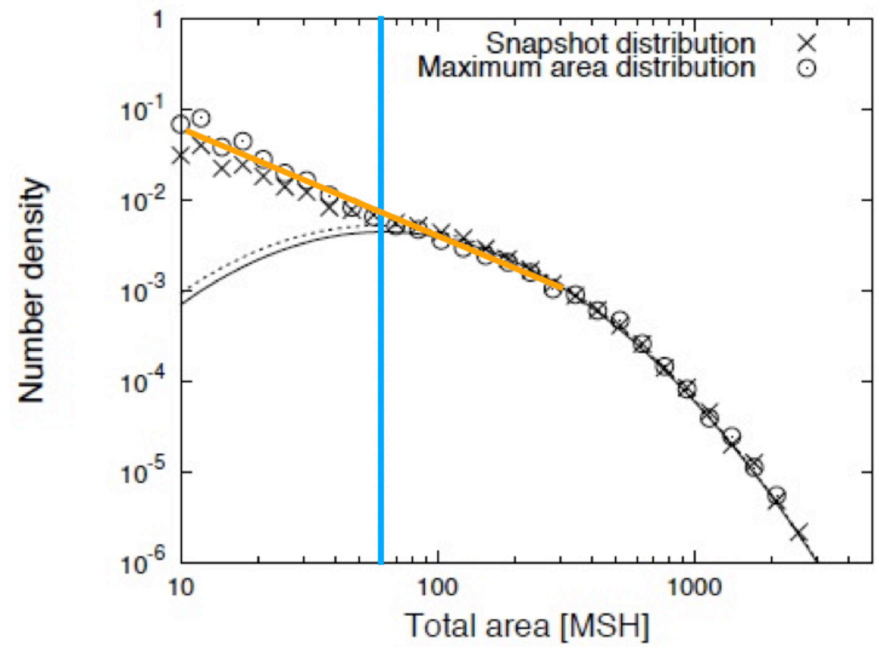
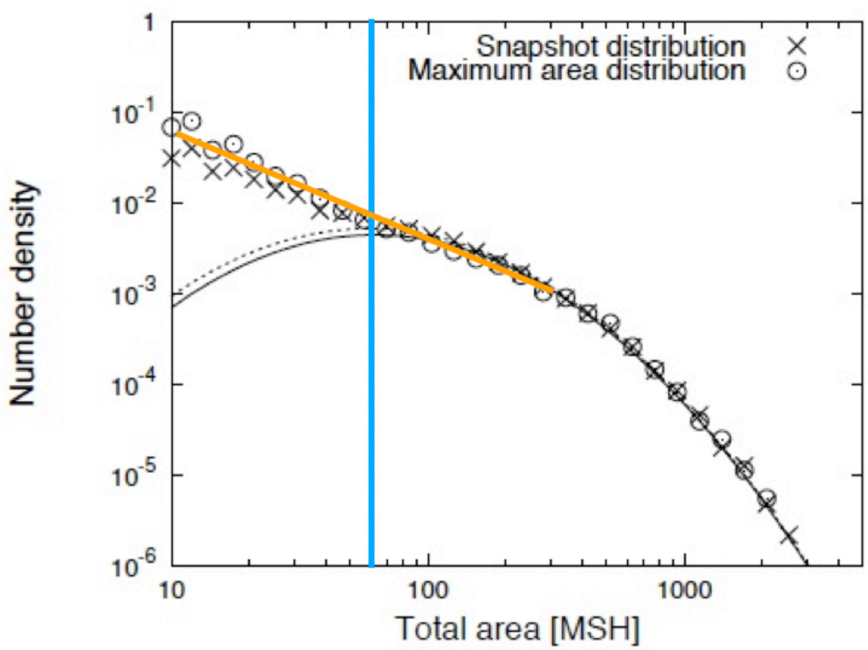


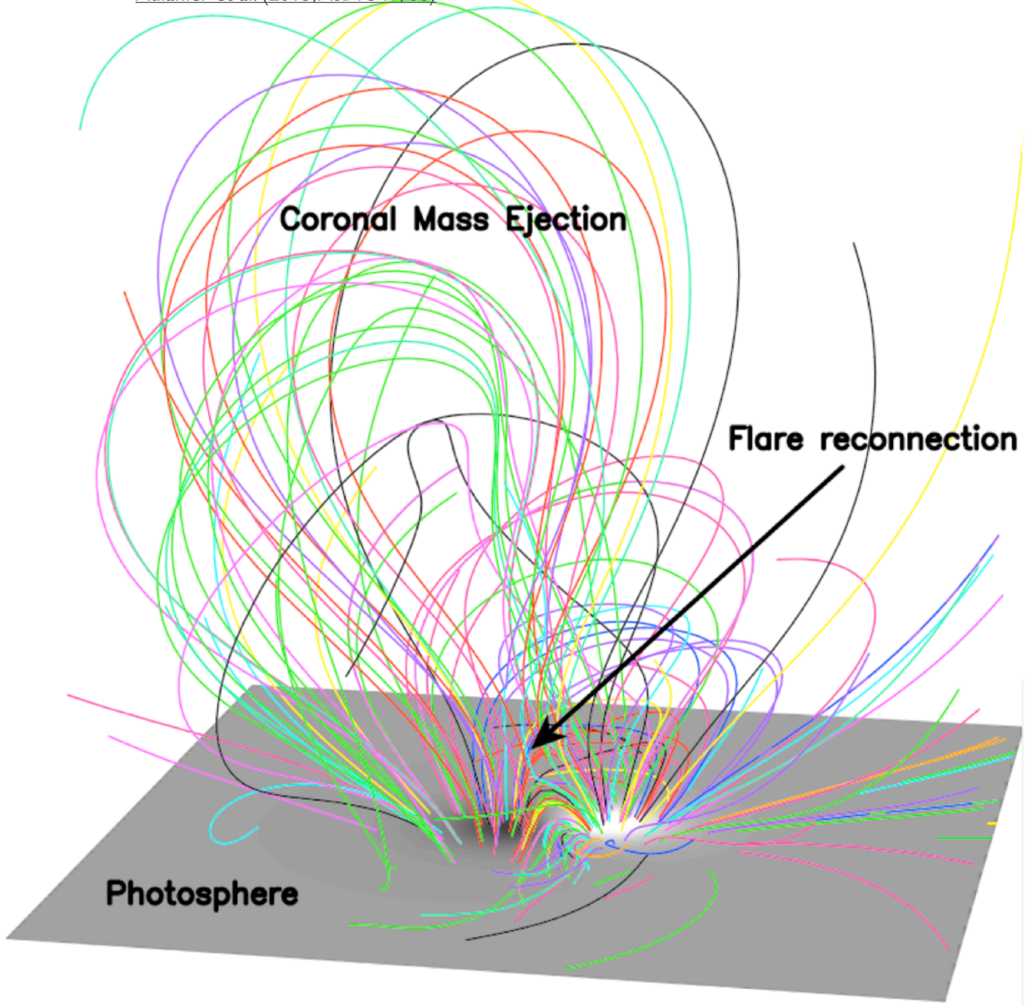
Fig. 2. Size distribution function of the total spot group areas (umbra+penumbra) obtained from the maximum development method (*circles*) and the snapshot method (*crosses*). Overplotted are the log-normal fits for $A >$ 60 MSH (*solid line*: Maximum development method, *dotted line*: Snapshot method).

"On the size distribution of sunspot groups in the Greenwich sunspot record 1874-1976", Baumann & Solanki (2005).

Powering superflares



Aulanier et al. (2013, A&A 549, 66)



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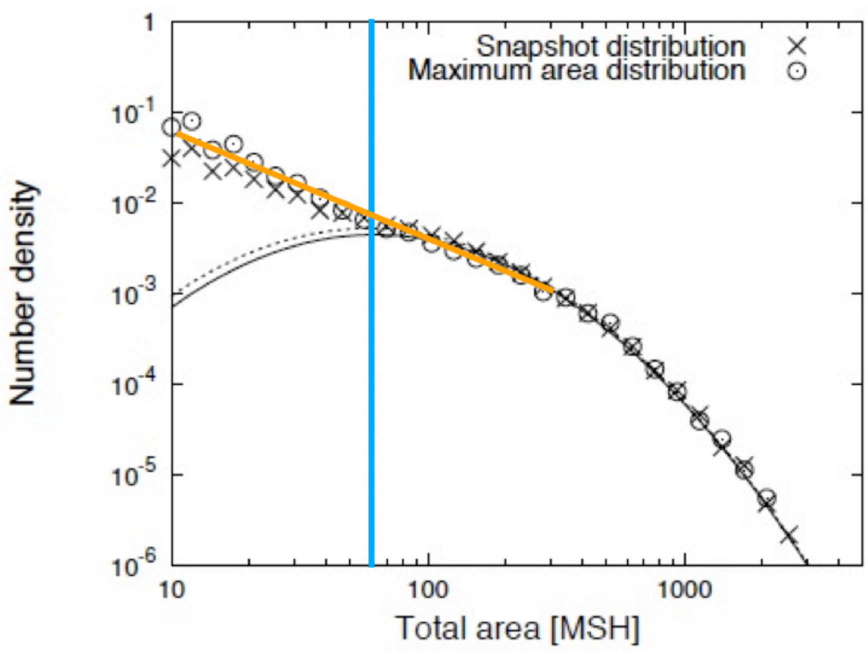

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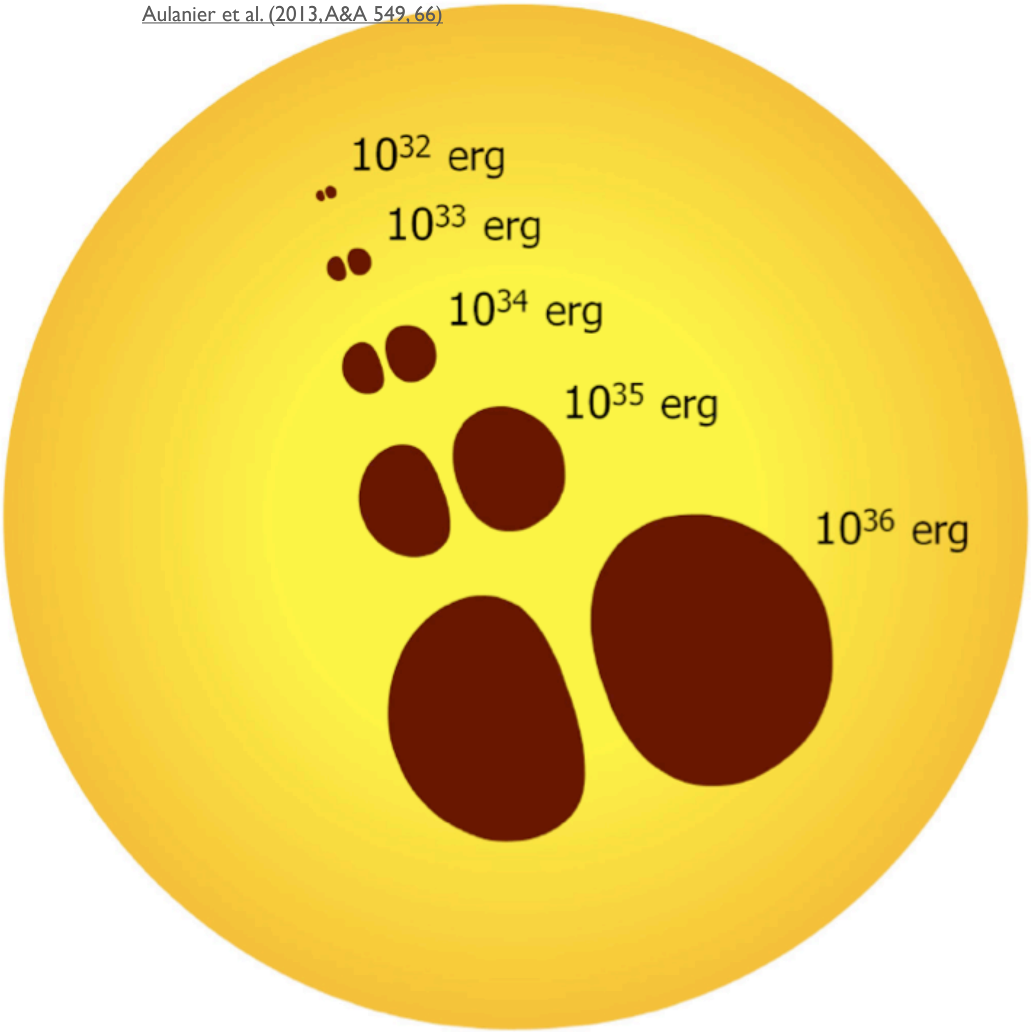

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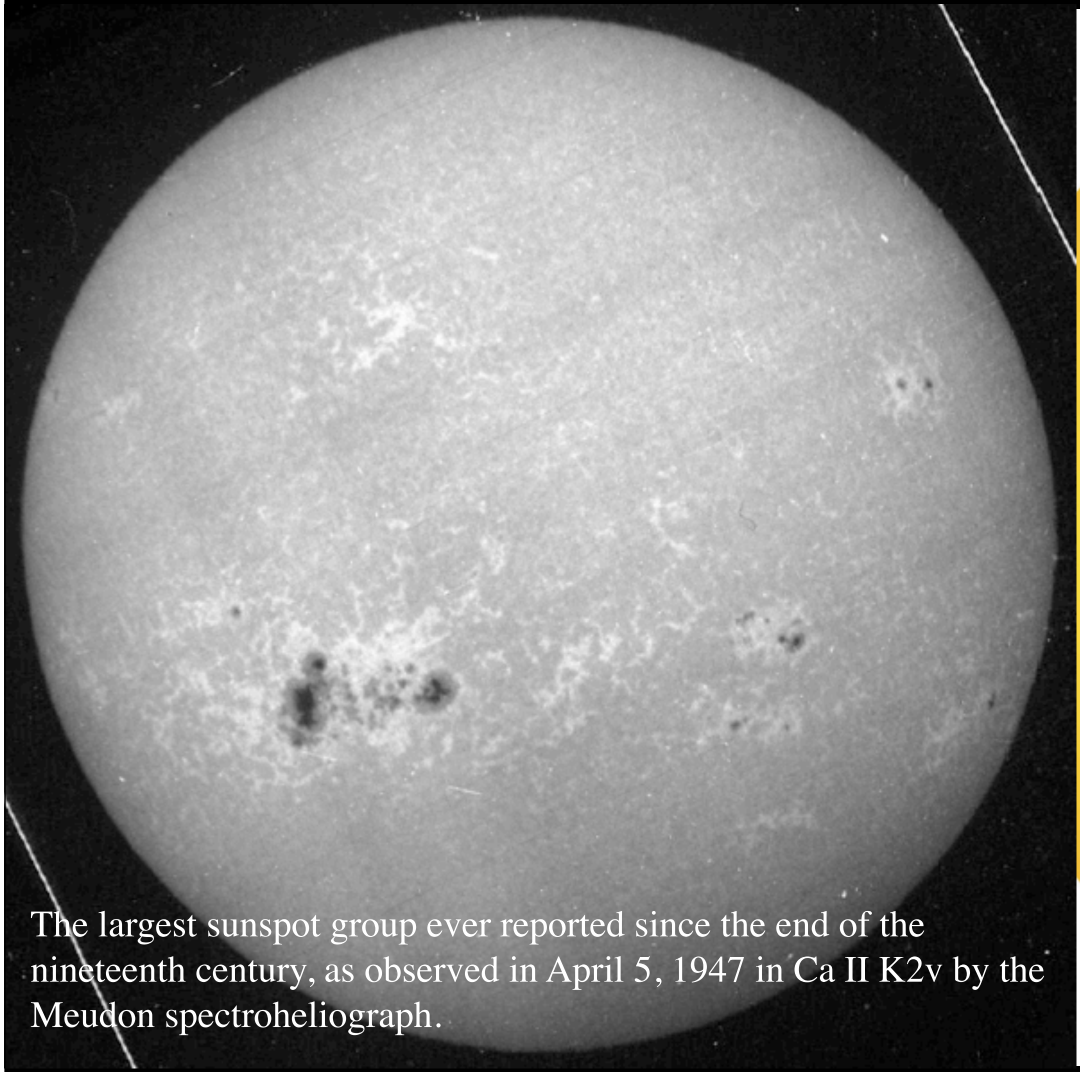
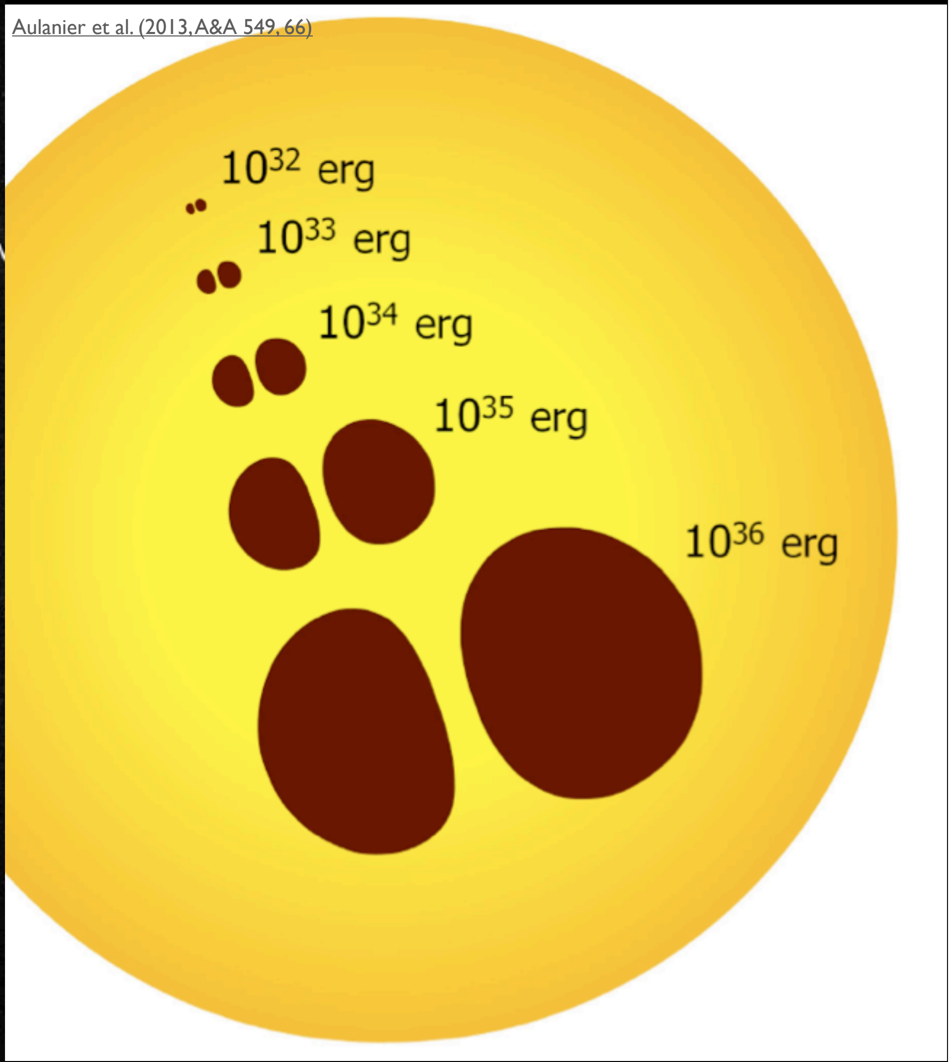


The largest sunspot group ever reported since the end of the nineteenth century, as observed in April 5, 1947 in Ca II K2v by the Meudon spectroheliograph.

Aulanier et al. (2013, A&A 549, 66)



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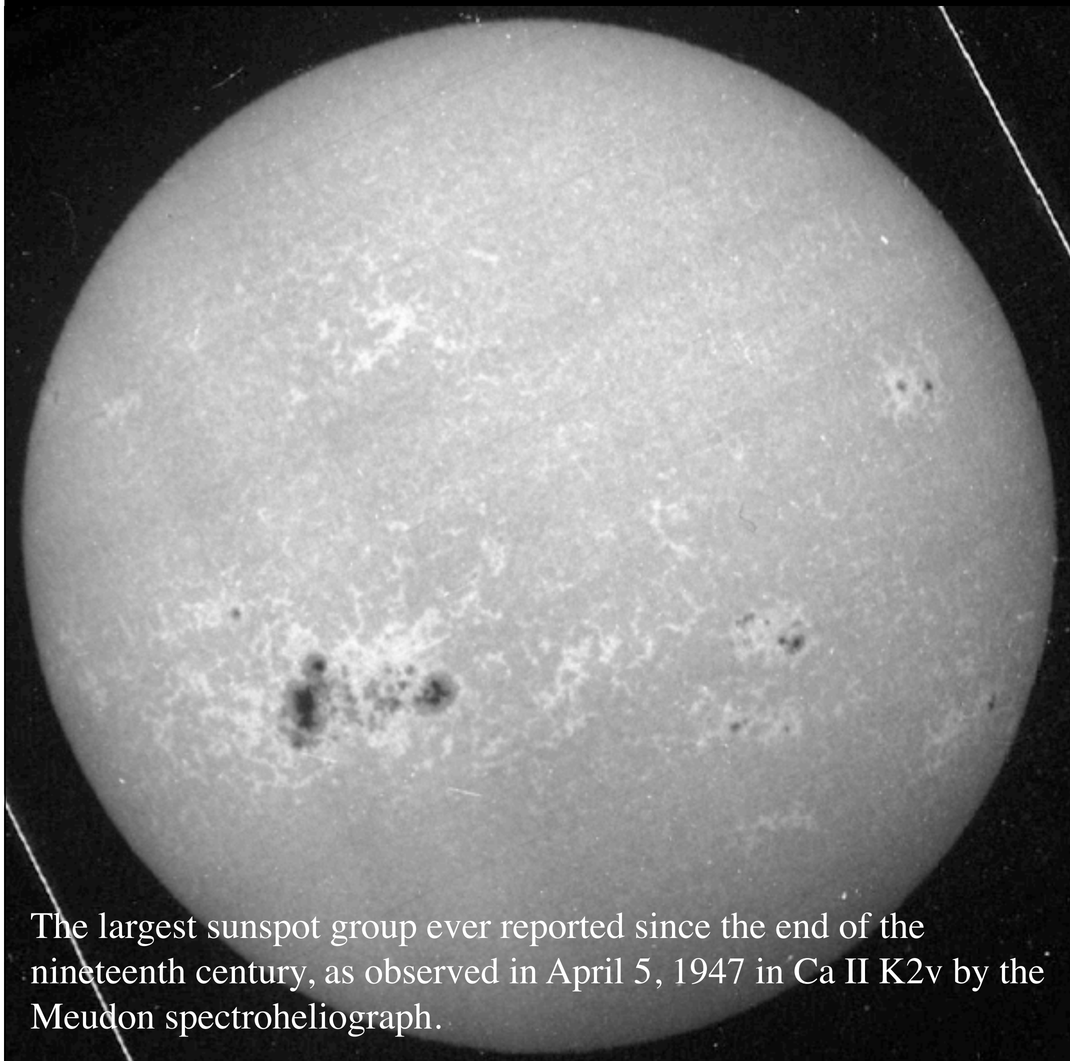

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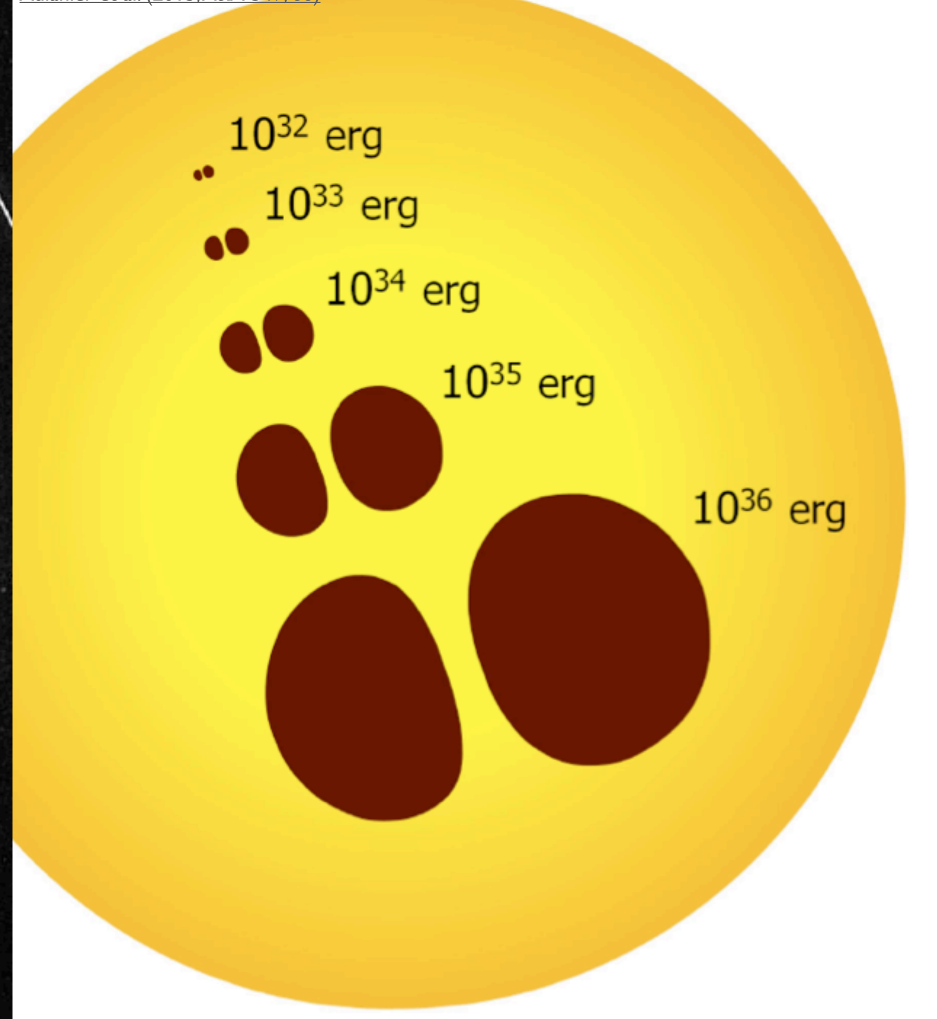

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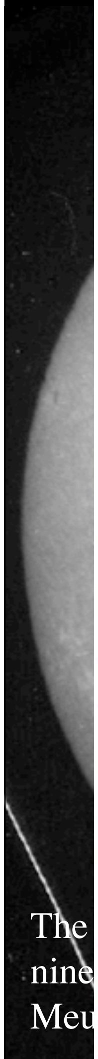
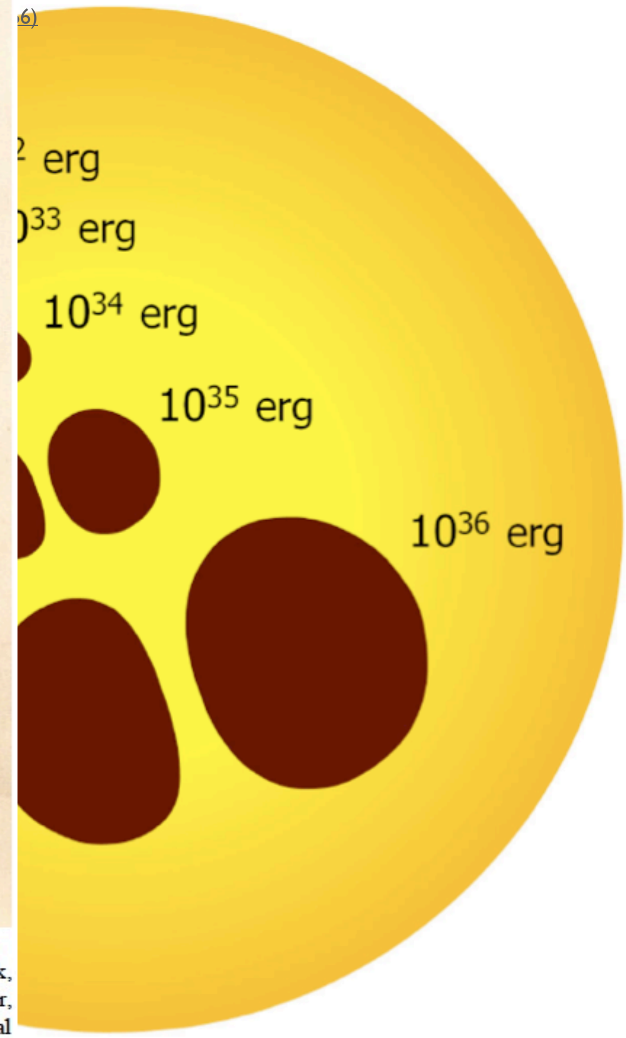


The
nine
Meu

Fig. 1. The earliest known drawing of sunspots, which appears in *The Chronicle of John of Worcester* (Darlington et al., 1995; McGurk, 1998). This drawing shows the apparent positions and sizes of two sunspots that were observed on AD 1128 December 8 from Worcester, England. Part of the surrounding Latin text describes the two sunspots and also presents historical information that enables this medieval sunspot observation to be precisely dated. A translation of the relevant part of the Latin text is presented in Sect. 2.



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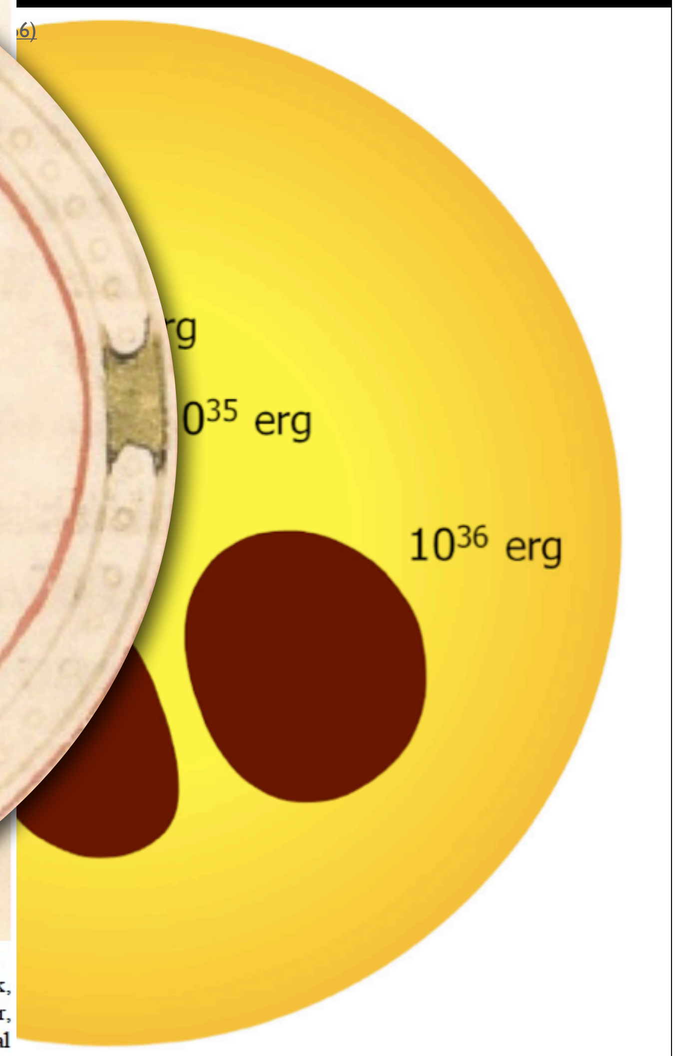

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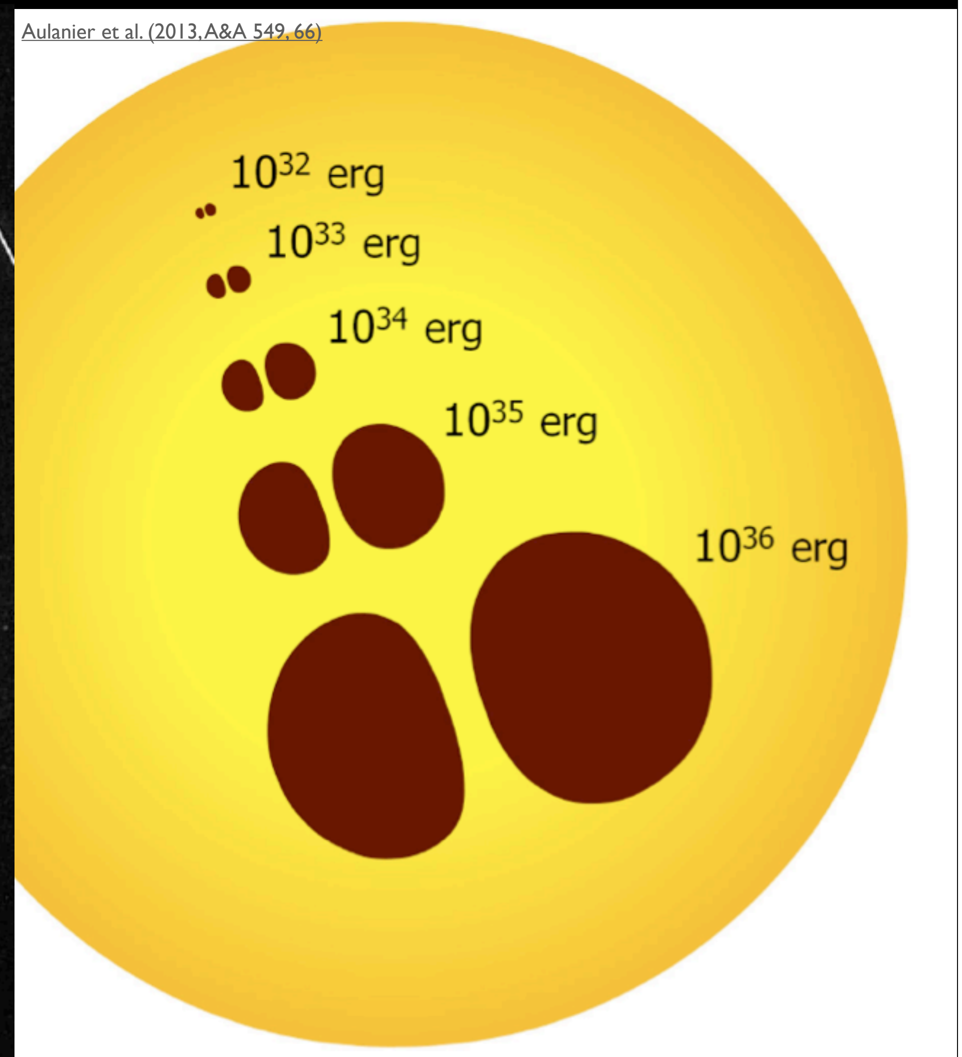
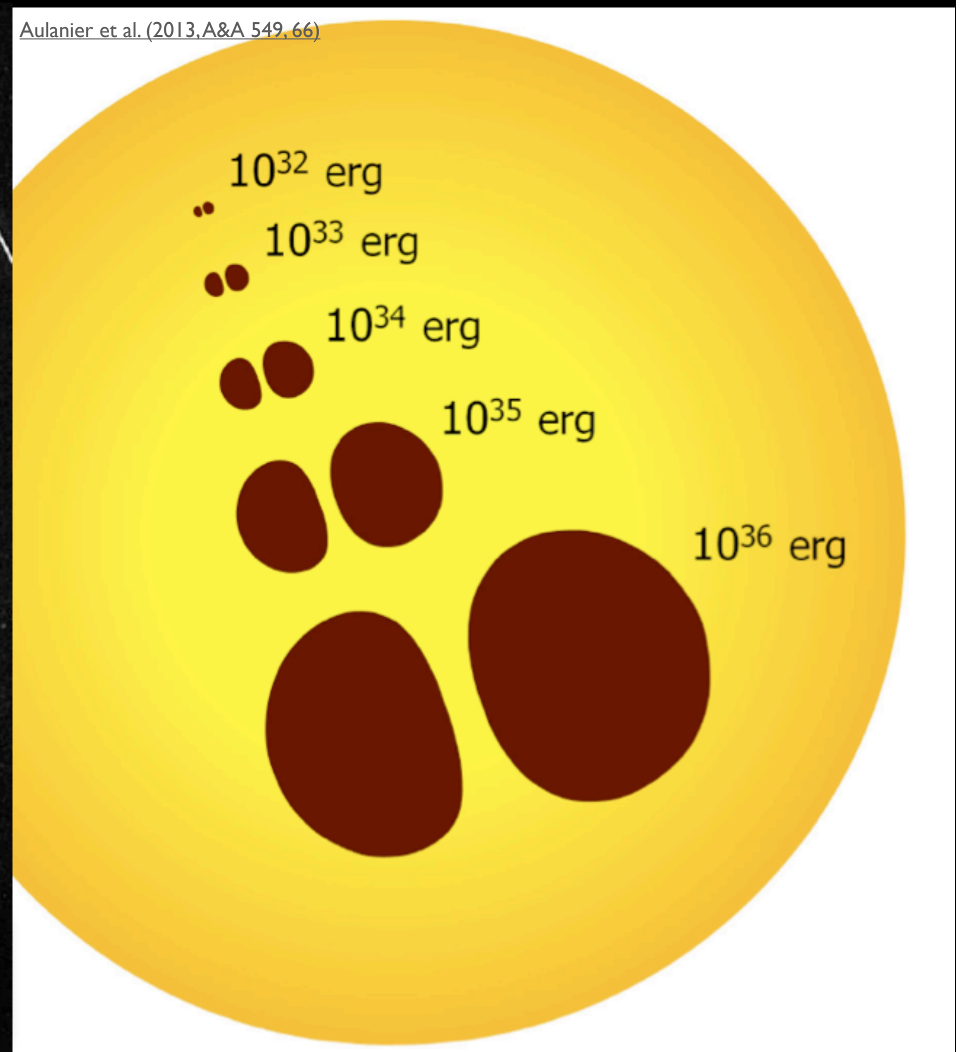


Powering superflares

Sunspots on 1128/12/08,
by John, of Worcester



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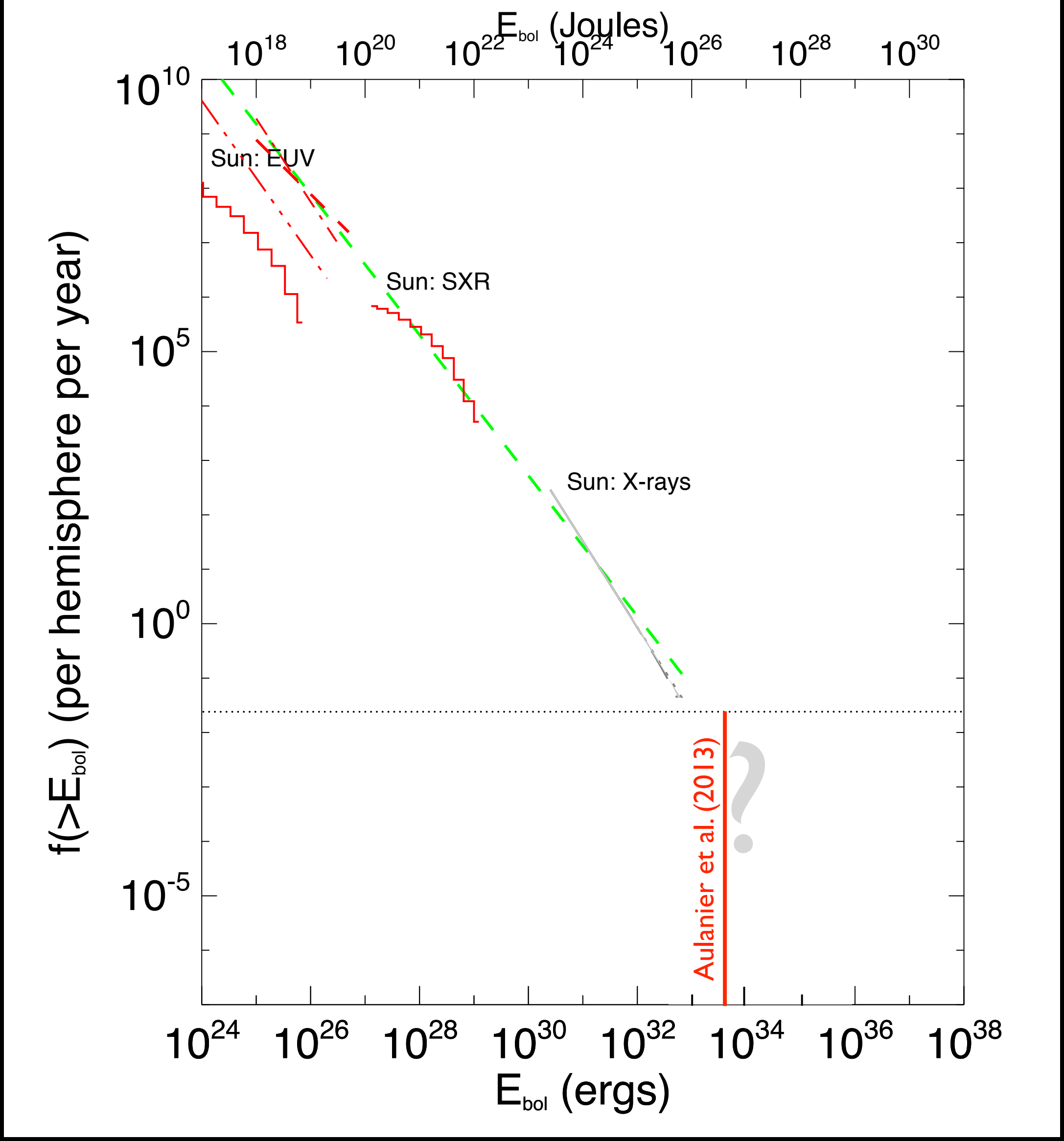
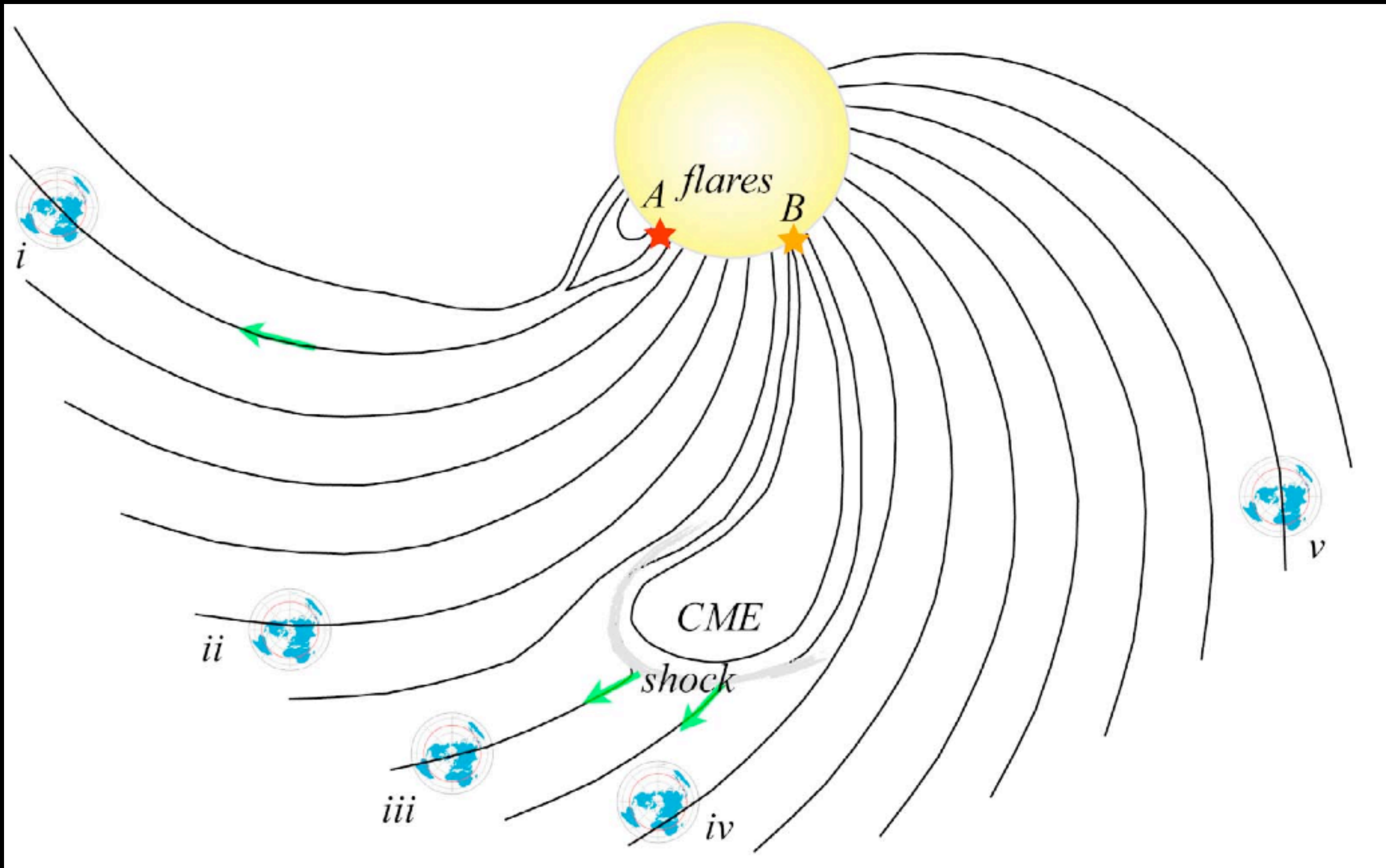
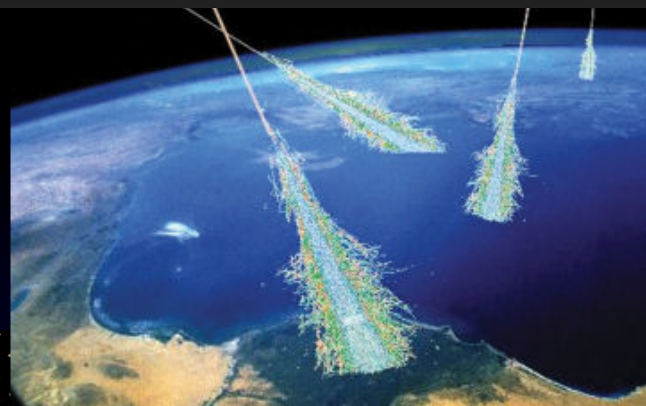


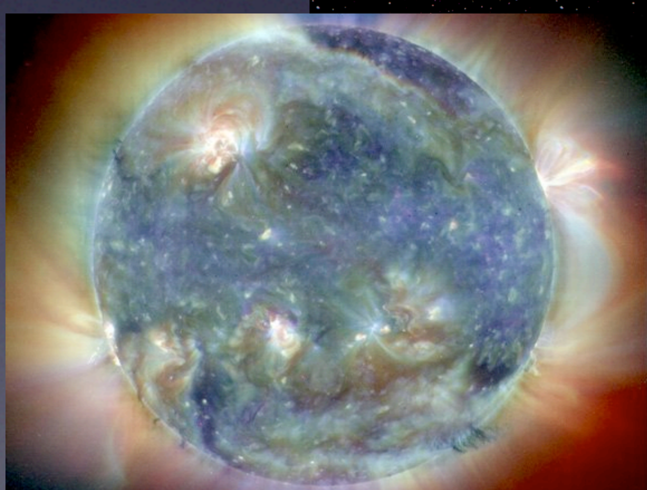
Studying flares by proxies?



Pre-historic* records of solar activity

**Before ~1950*





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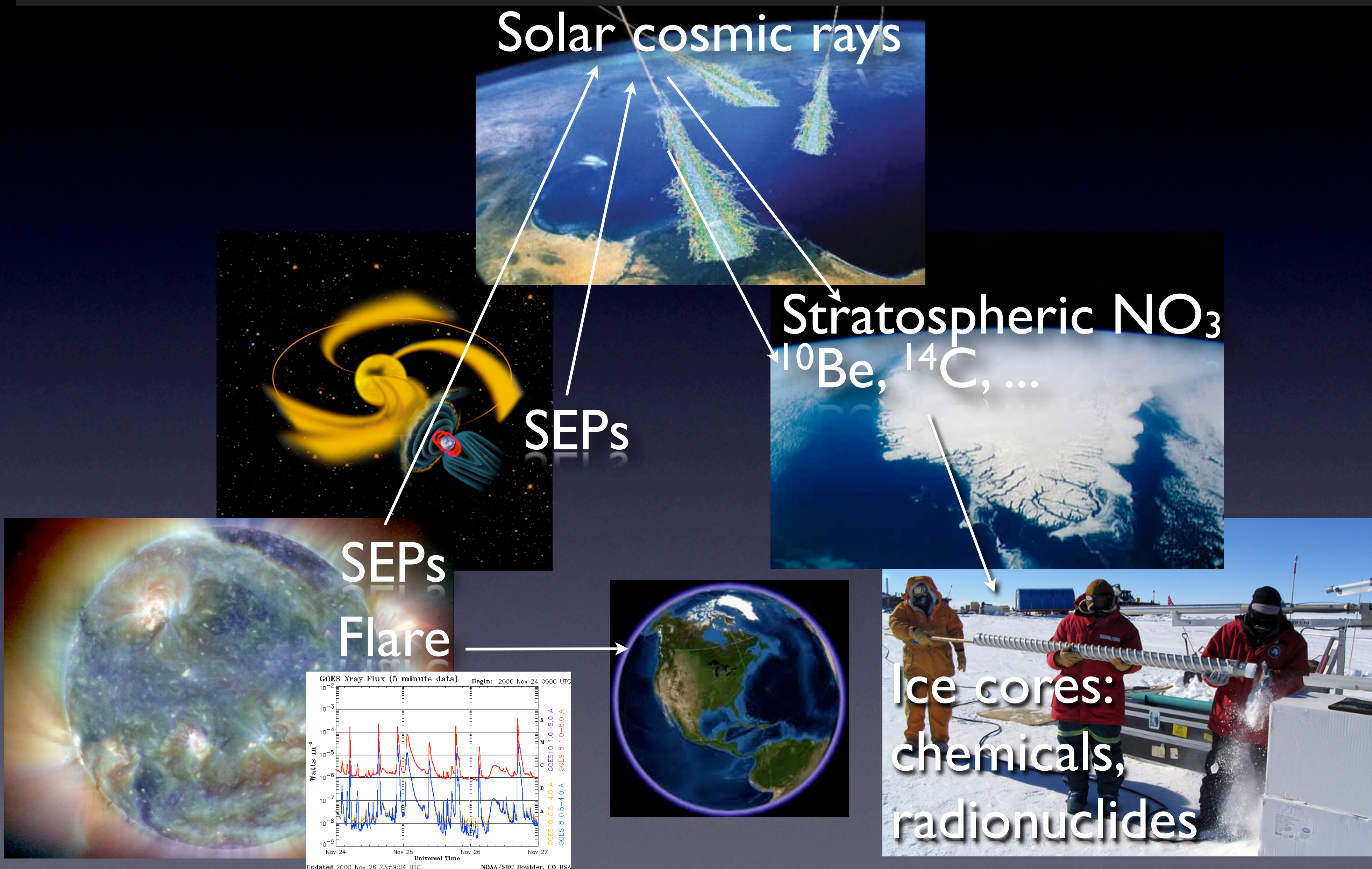
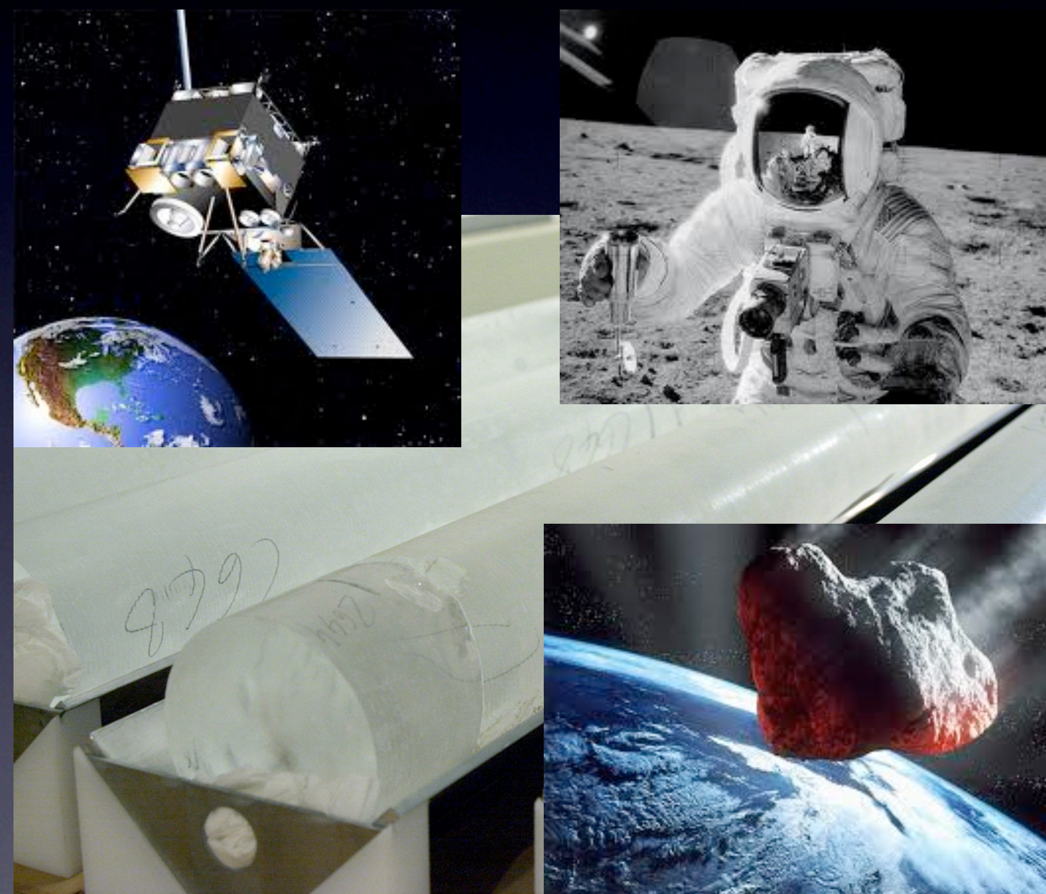


Solar energetic particles (SEPs)

SEP statistic can be obtained from:

- Spacecraft particle instruments and ground-based neutron monitors;
- Chemical signatures (NO_3 in ice)
- Radionuclides in biosphere, ice, rocks (Earth, Moon), meteorites.



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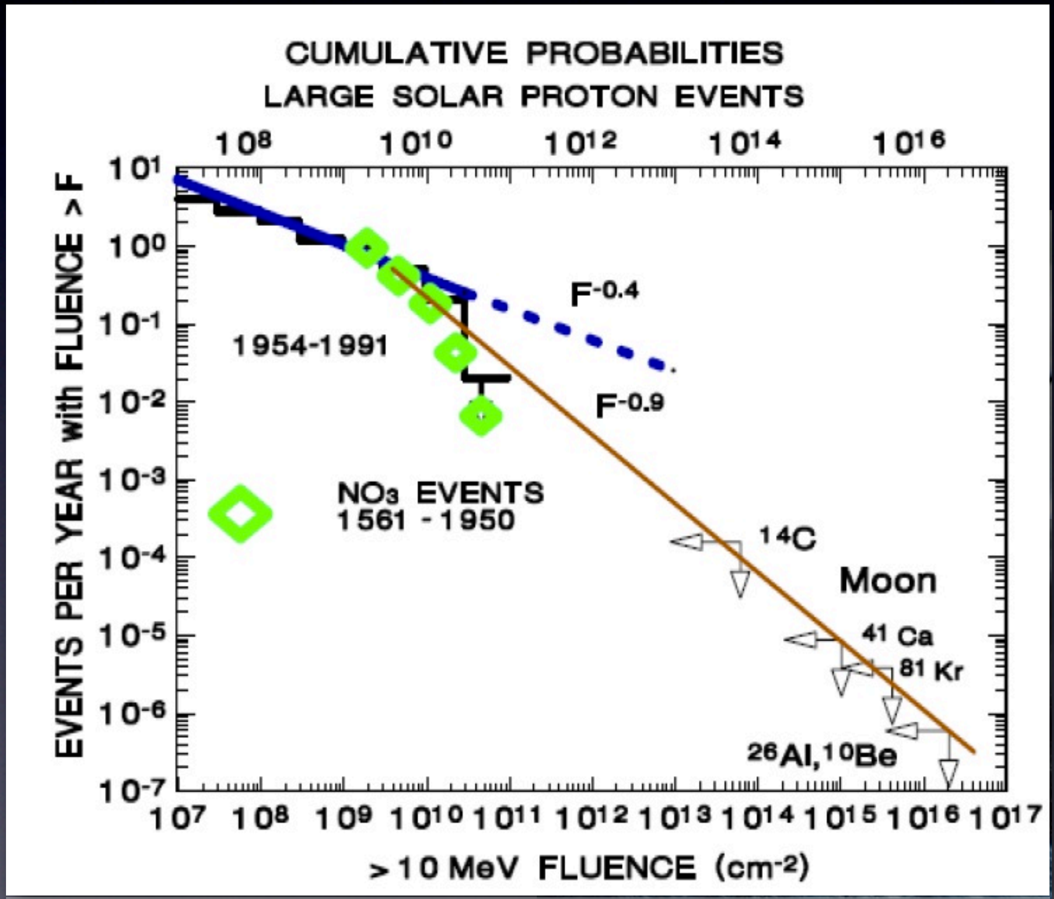

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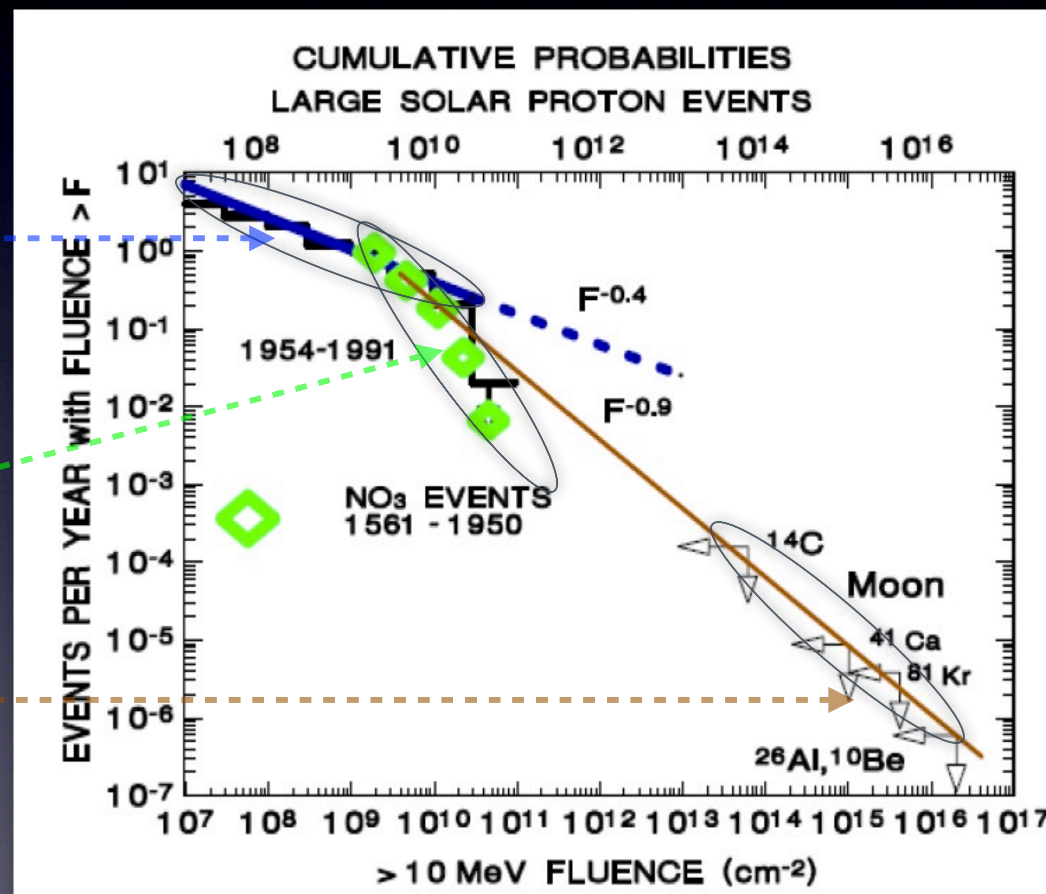

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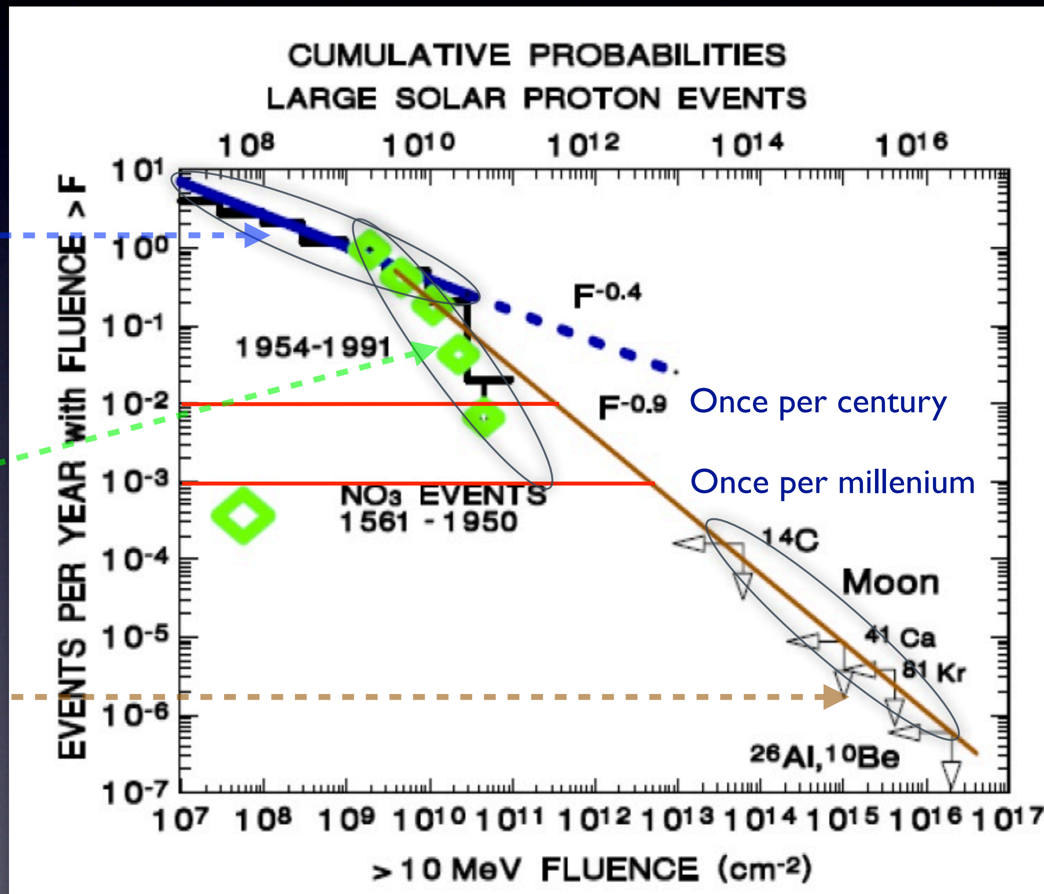
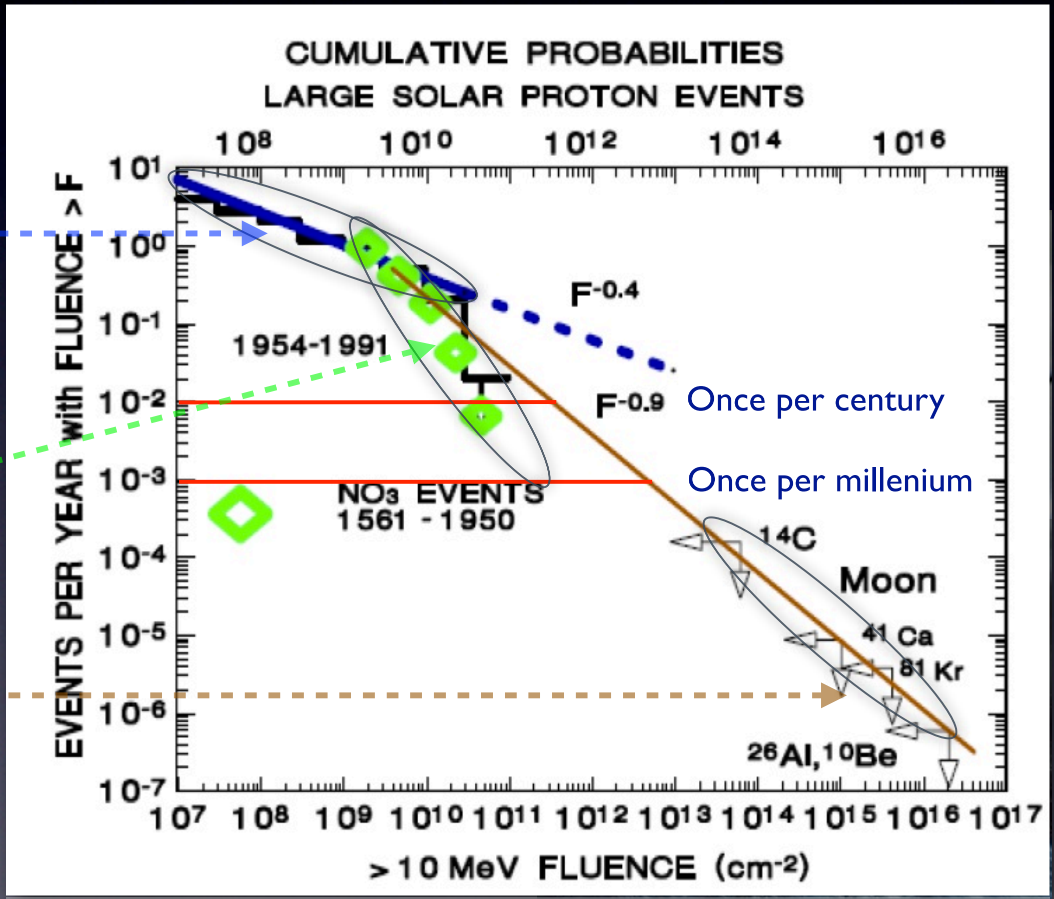


Solar energetic particles (SEPs)

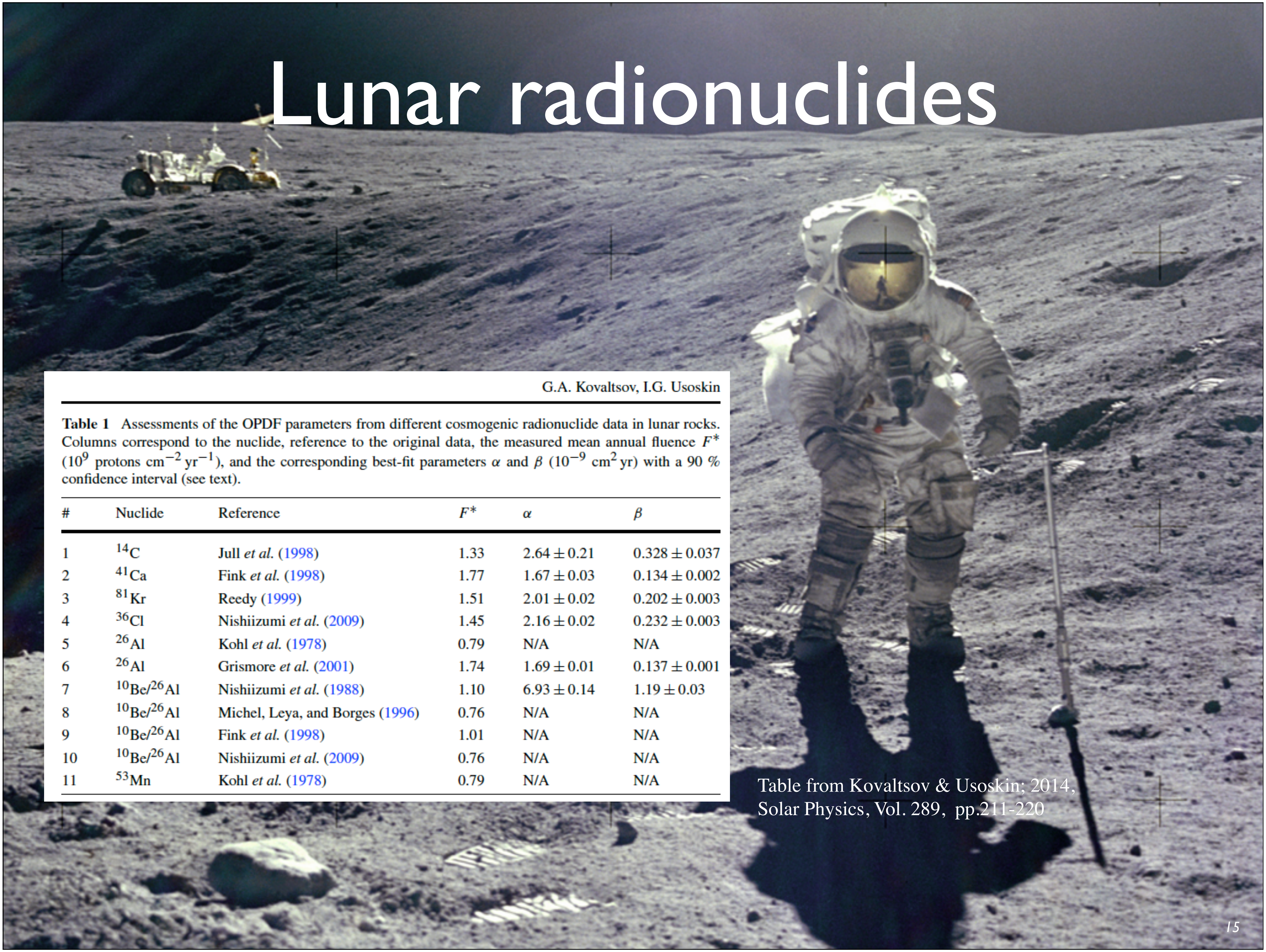
SEP statistic can be obtained from:

- Spacecraft particle instruments and ground-based neutron monitors;
  Records since ~1950s; too short
- Chemical signatures (NO_3 in ice)
  atmospheric chemists & glaciologists argued that pathways are improbable and that there is too much source confusion
- Radionuclides in biosphere, ice, rocks (Earth, Moon), meteorites.

Lunar rocks & meteorites: cumulative dose only. Biosphere: washes out signal. Ice: limited resolution (~3y) on background of galactic cosmic rays.



Lunar radionuclides



G.A. Kovaltsov, I.G. Usoskin

Table 1 Assessments of the OPDF parameters 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^{-1}), and the corresponding best-fit parameters α and β (10^{-9} cm^2 yr) with a 90 % confidence interval (see text).

#	Nuclide	Reference	F^*	α	β
1	^{14}C	Jull *et al.* (1998)	1.33	2.64 ± 0.21	0.328 ± 0.037
2	^{41}Ca	Fink *et al.* (1998)	1.77	1.67 ± 0.03	0.134 ± 0.002
3	^{81}Kr	Reedy (1999)	1.51	2.01 ± 0.02	0.202 ± 0.003
4	^{36}Cl	Nishiizumi *et al.* (2009)	1.45	2.16 ± 0.02	0.232 ± 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 ± 0.01	0.137 ± 0.001
7	^{10}Be/^{26}Al	Nishiizumi *et al.* (1988)	1.10	6.93 ± 0.14	1.19 ± 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

Table from Kovaltsov & Usoskin; 2014,
Solar Physics, Vol. 289, pp.211-220

Lunar & terrestrial radionuclides

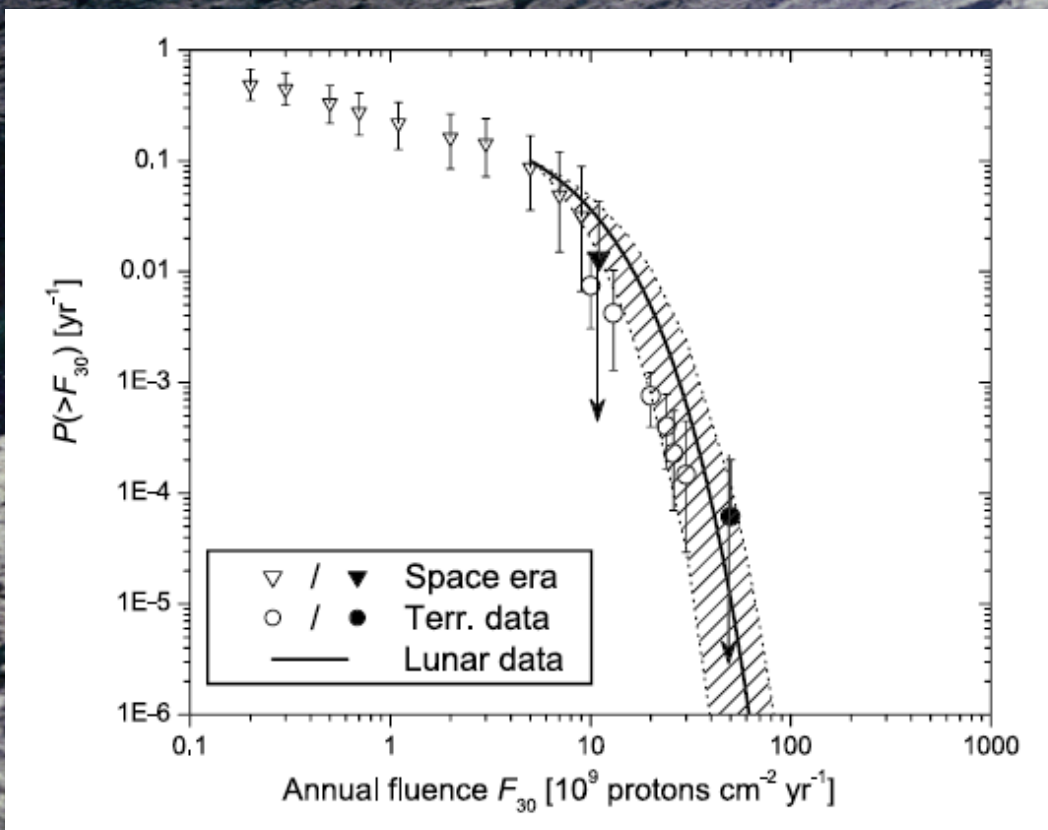
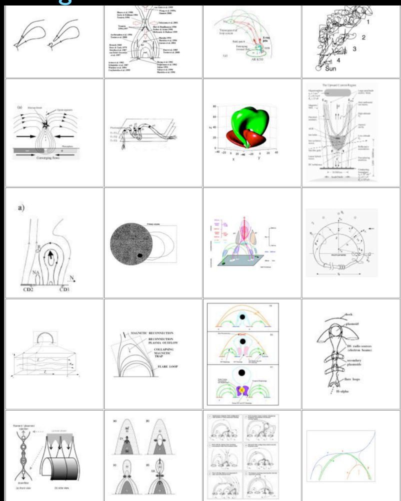
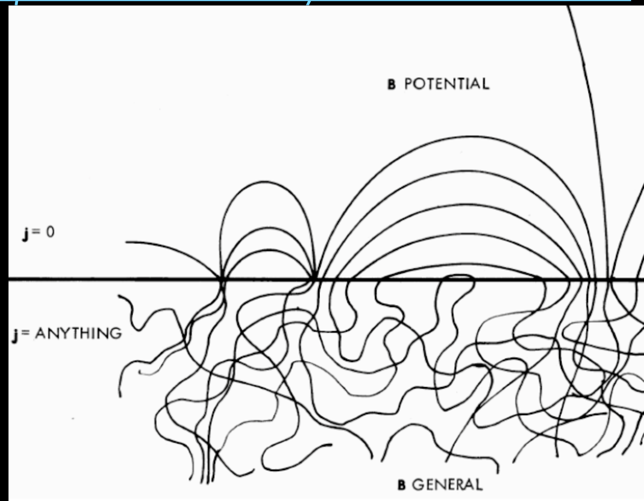


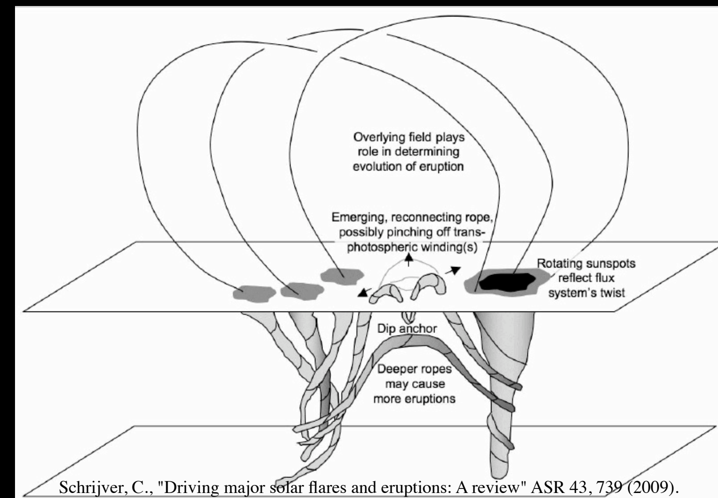
Figure from Kovaltsov & Usoskin; 2014,
Solar Physics, Vol. 289, pp.211-220

Solar-stellar flaring

Hugh Hudson's cartoon archive: http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons/







Schrijver, C., "Driving major solar flares and eruptions: A review" ASR 43, 739 (2009).

Flare:

- definition/stellar: a sudden, temporary brightening
- conceptually/solar: a conversion of EM field energy into kinetic energy, resulting in photons + associated phenomena

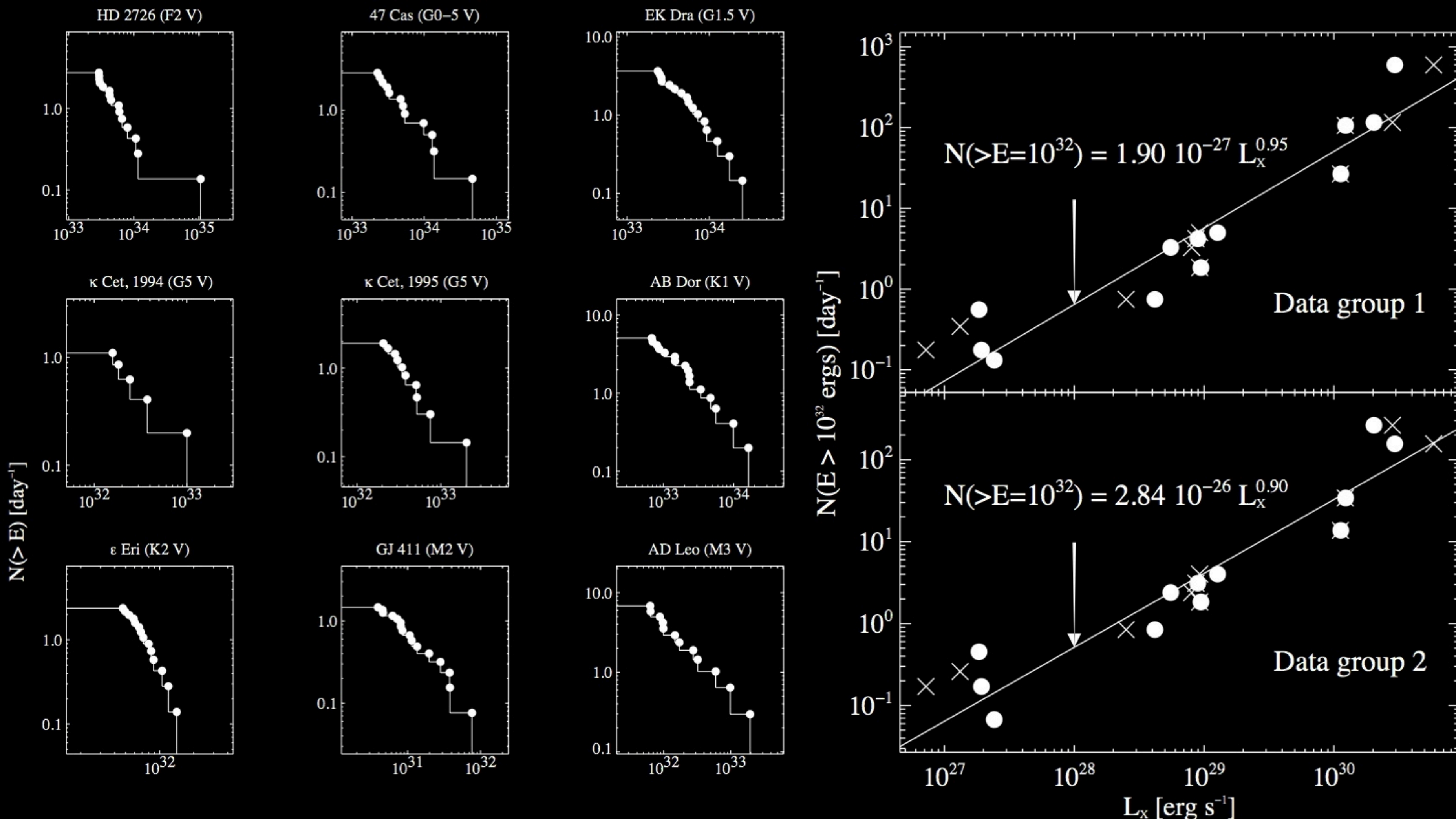
Solar-stellar comparison possible for infrequent largest solar flares, generally with non-overlapping wavelength ranges.

Multi-Wavelength Stellar Flare Studies

λ range	instruments	info
radio (mm-50 cm)	ALMA, EVLA, ATCA, MERLIN, LOFAR, GMRT	flux, polarization: gyrosynchrotron, coherent emission
optical (3000-7000 A)	spectra, photometry	white light flares
UV 900-3000 A	IUE, HST, FUSE, GALEX	chromosphere, TR: flux, redshift, density
EUV 80-350 A	EUVE, Chandra/LETGS	corona: density, temperature, EM
SXR 1.8-30 A	ASCA, RXTE, BeppoSAX, Chandra, XMM-Newton, Swift	corona: temp., EM, abundance densities
HXR 10-100 keV	Swift, BeppoSAX	corona: thermal/ nonthermal

Courtesy: Rachel Osten

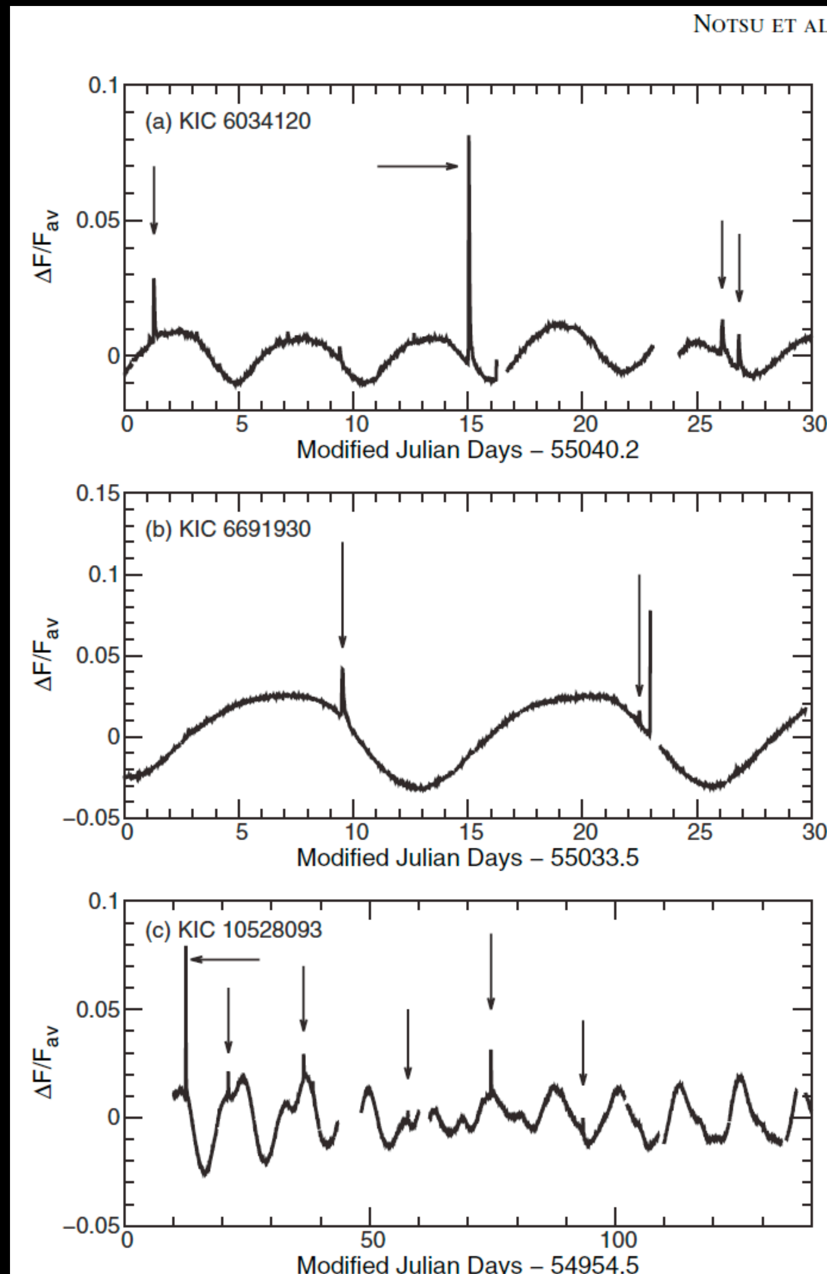
Stellar flares: XUV



Audard et al. (2000)

Visible-light flaring on stars

Kepler light curves

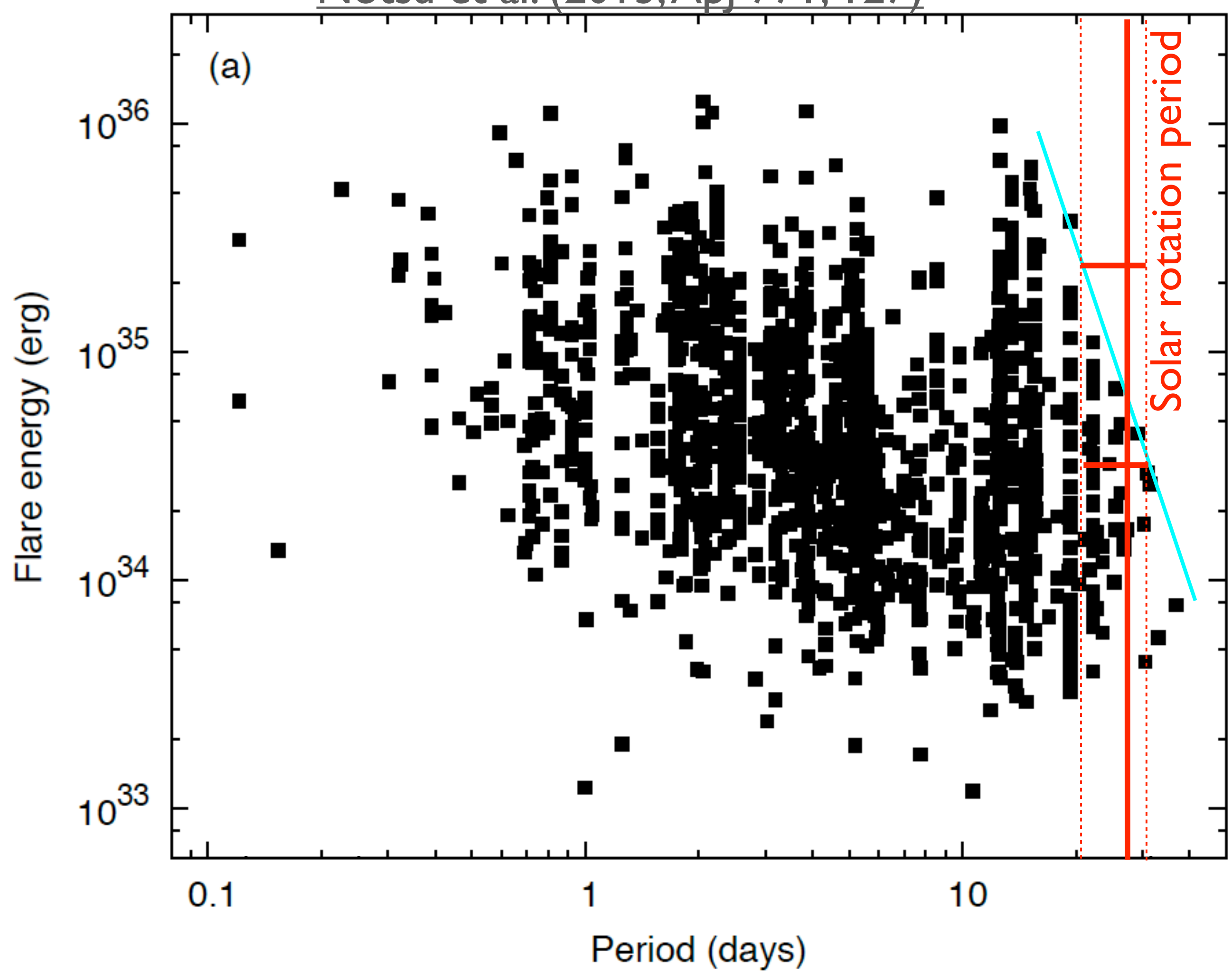


Notsu et al. (2013)

Added note: with 4 arcsec/pixel, source confusion is likely in some cases. Kitze et al. (2014) find evidence for one such case, but not for the slowly-rotating stars shown in later diagrams (and in Schrijver and Beer, 2014).

Visible-light flaring on stars
Kepler data

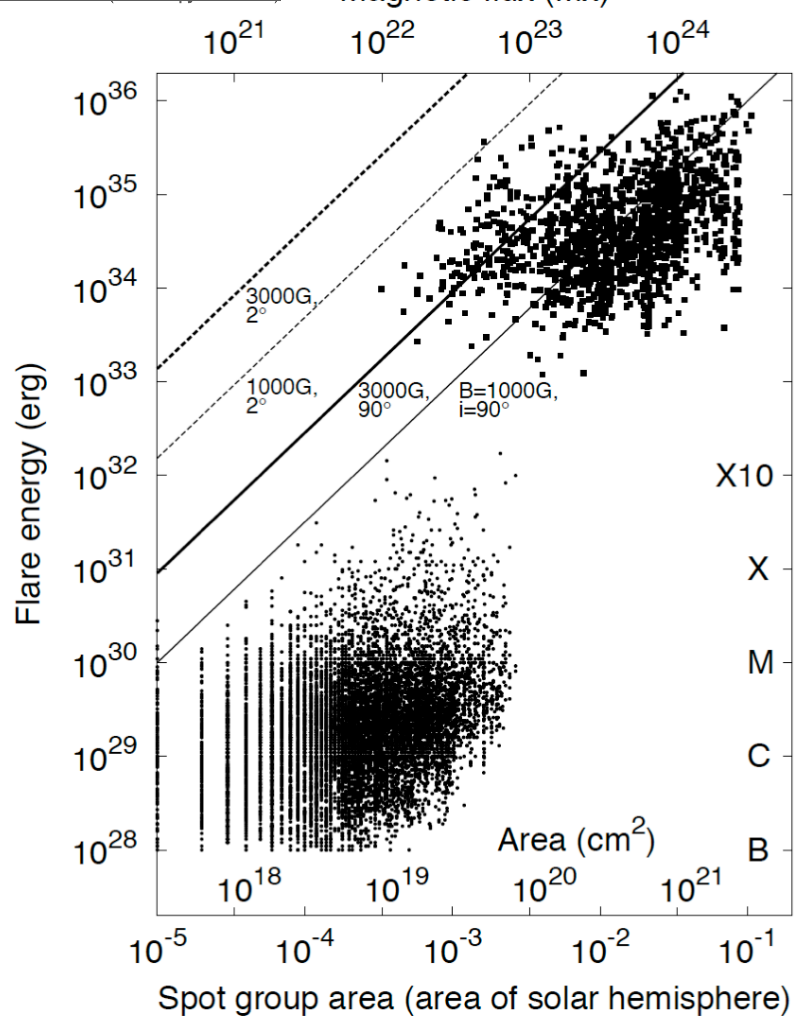
Notsu et al. (2013, ApJ 771, 127)



See Nogami et al. (2014; arXiv) on spectroscopic studies of two superflaring Sun-like stars.

Powering superflares

Notsu et al. (2013, ApJ 771, 127)



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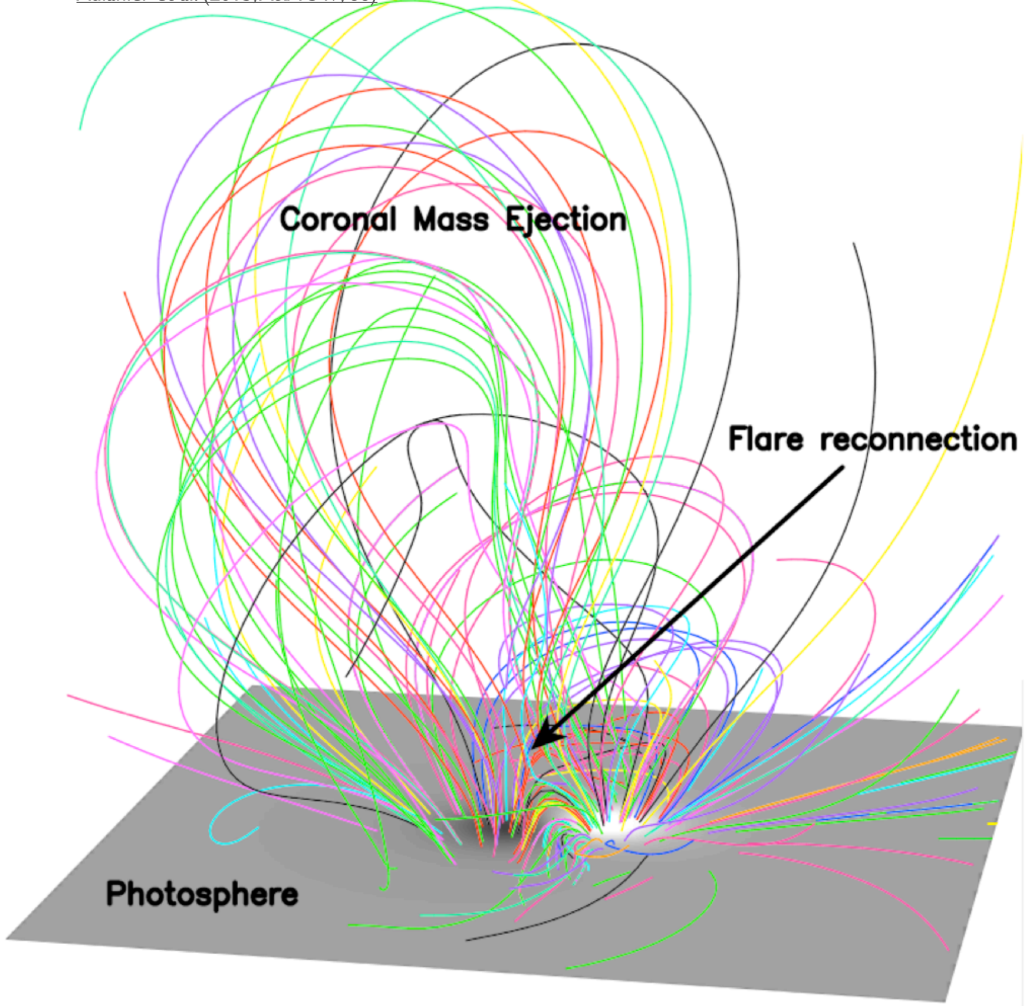

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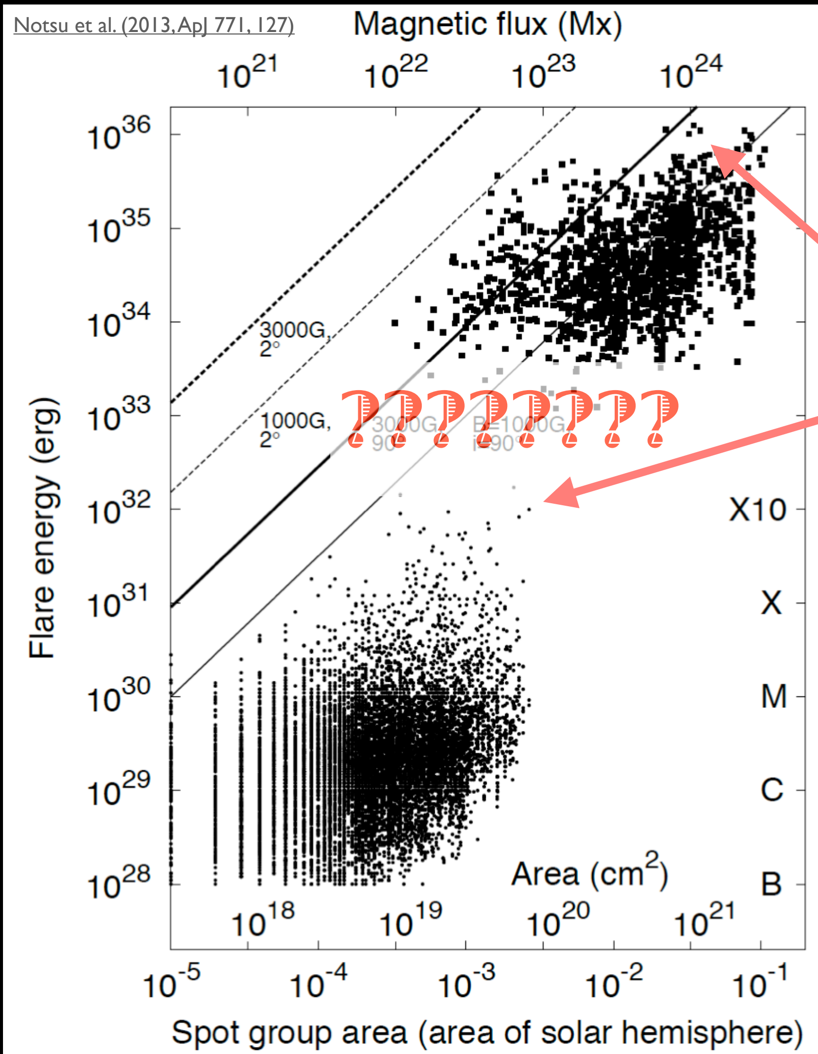
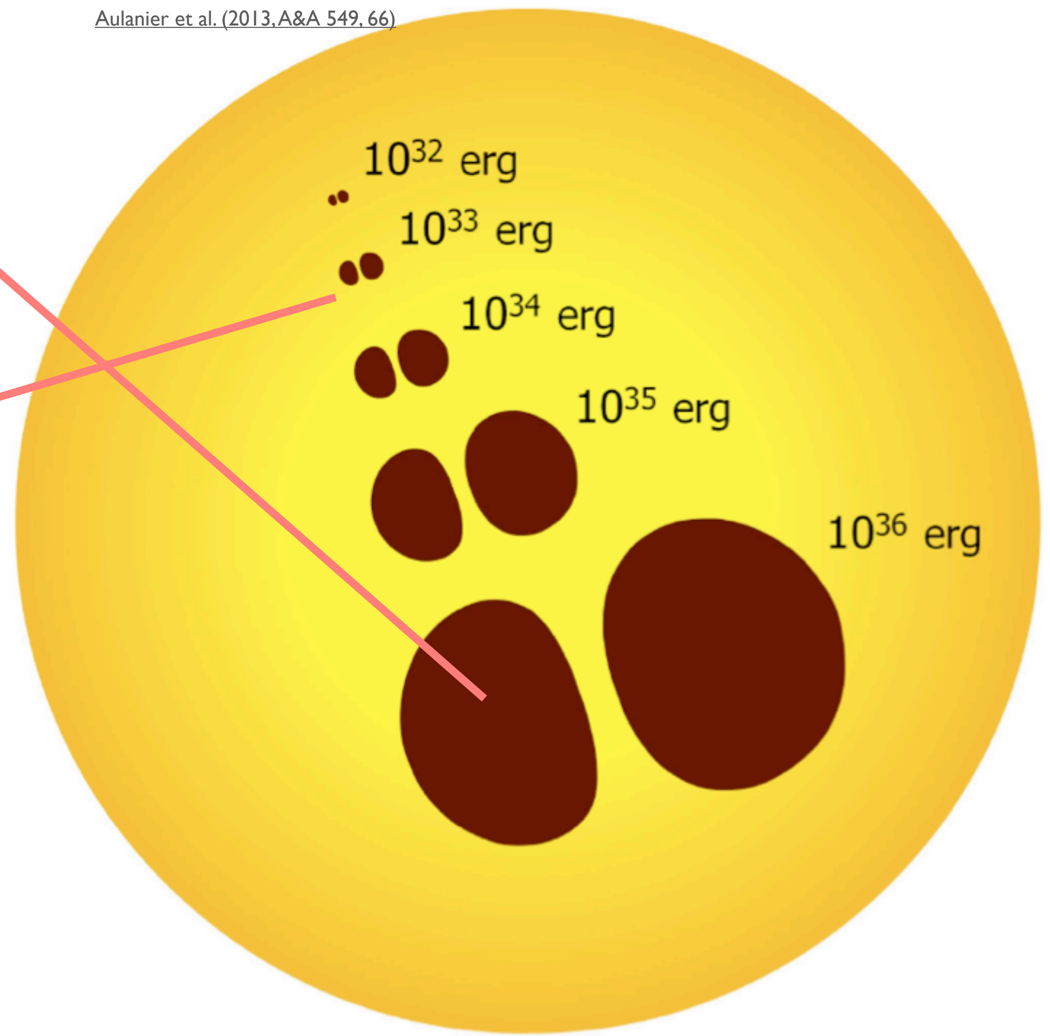
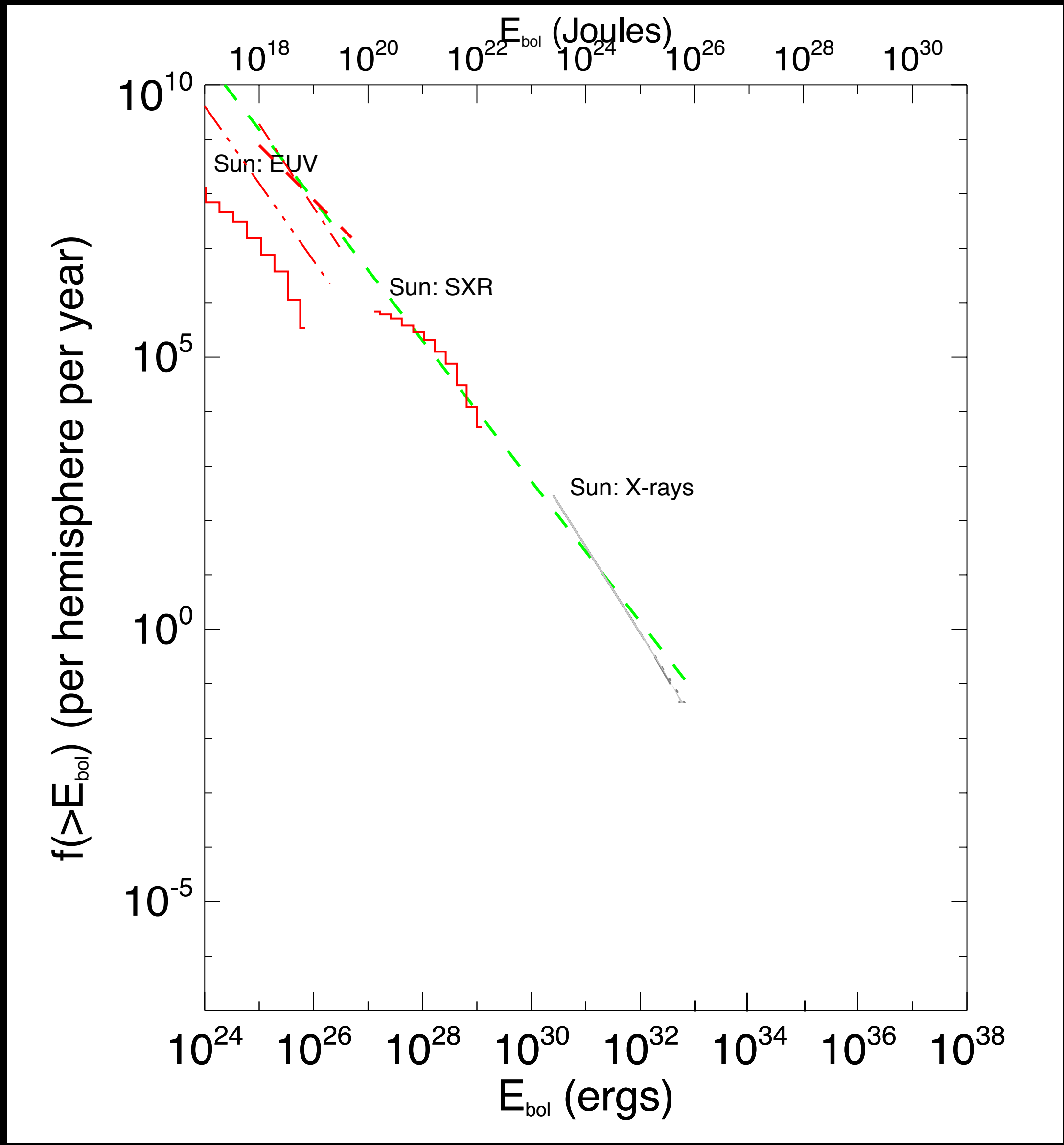


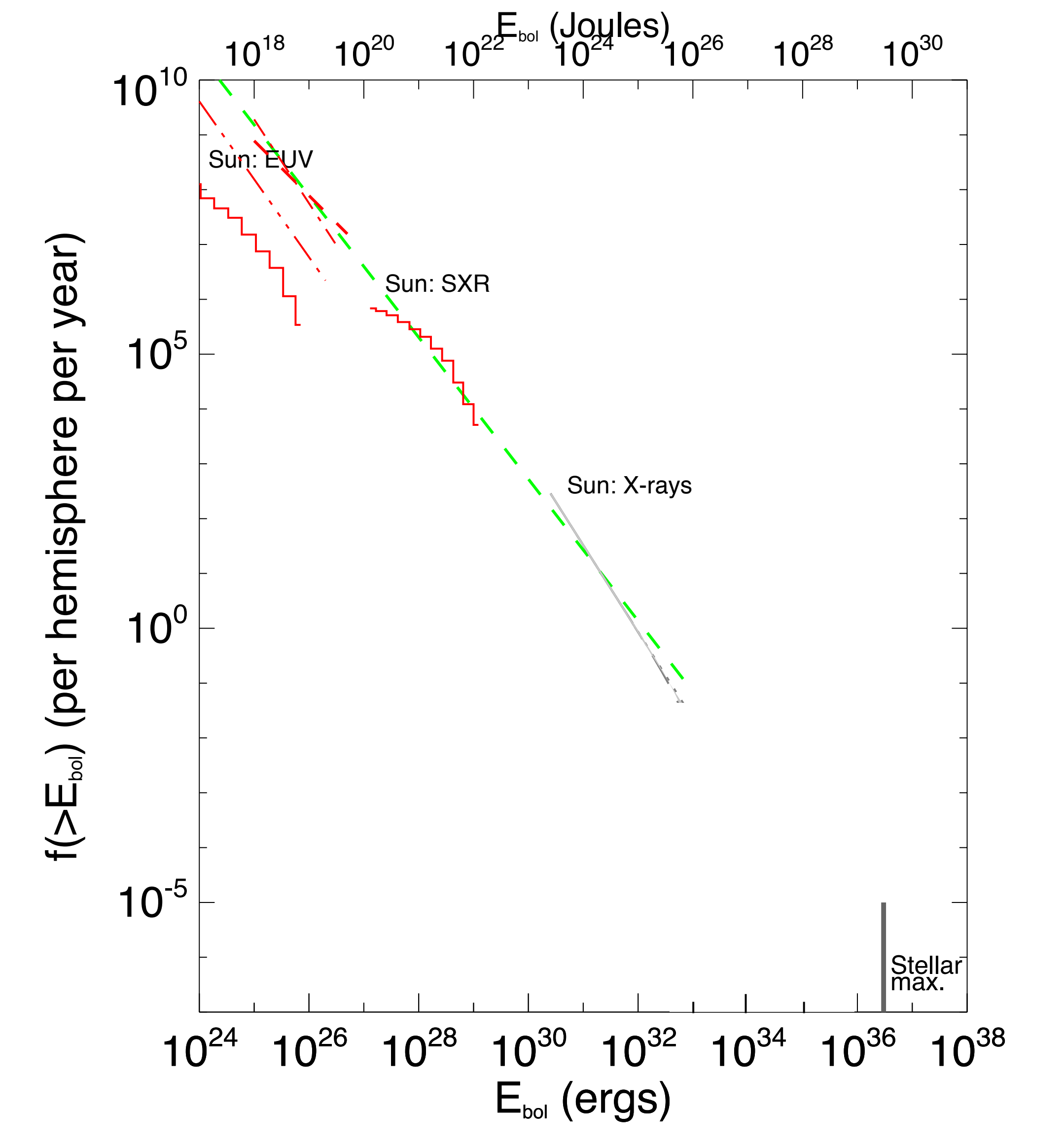


Extreme solar flares



Extreme solar flares

Maximum for cool stars in general: ~3 10^{36} ergs.



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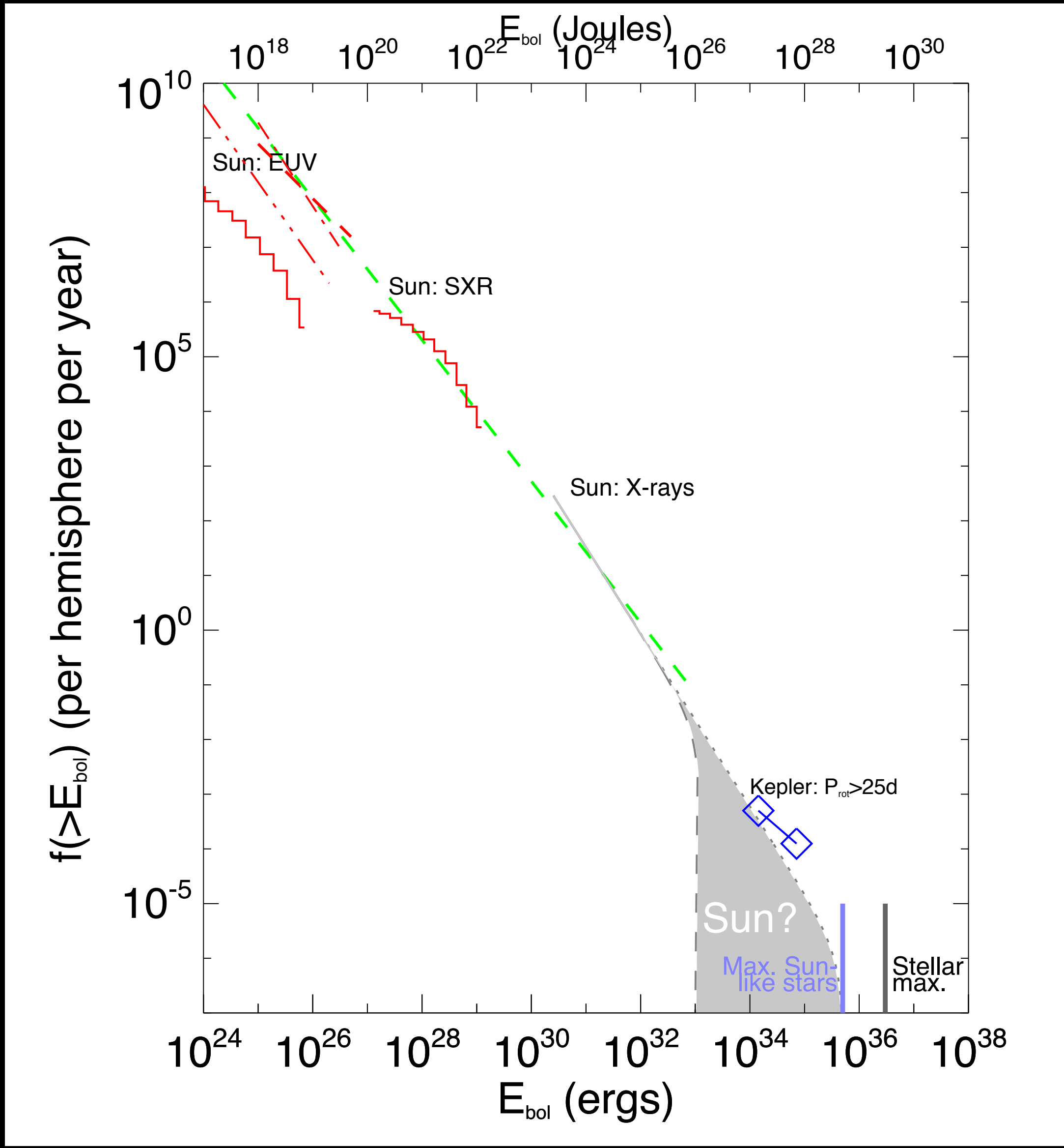

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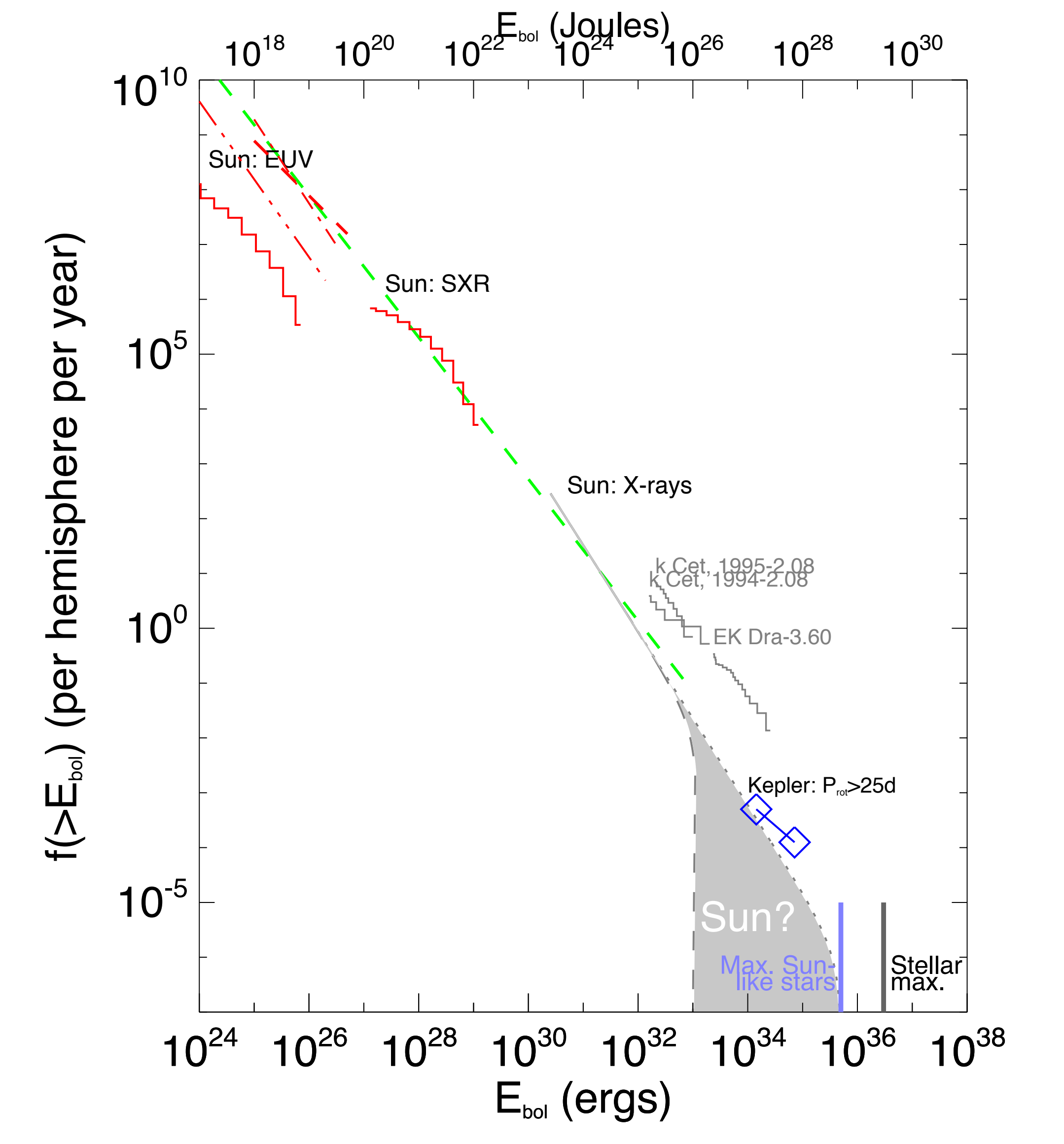

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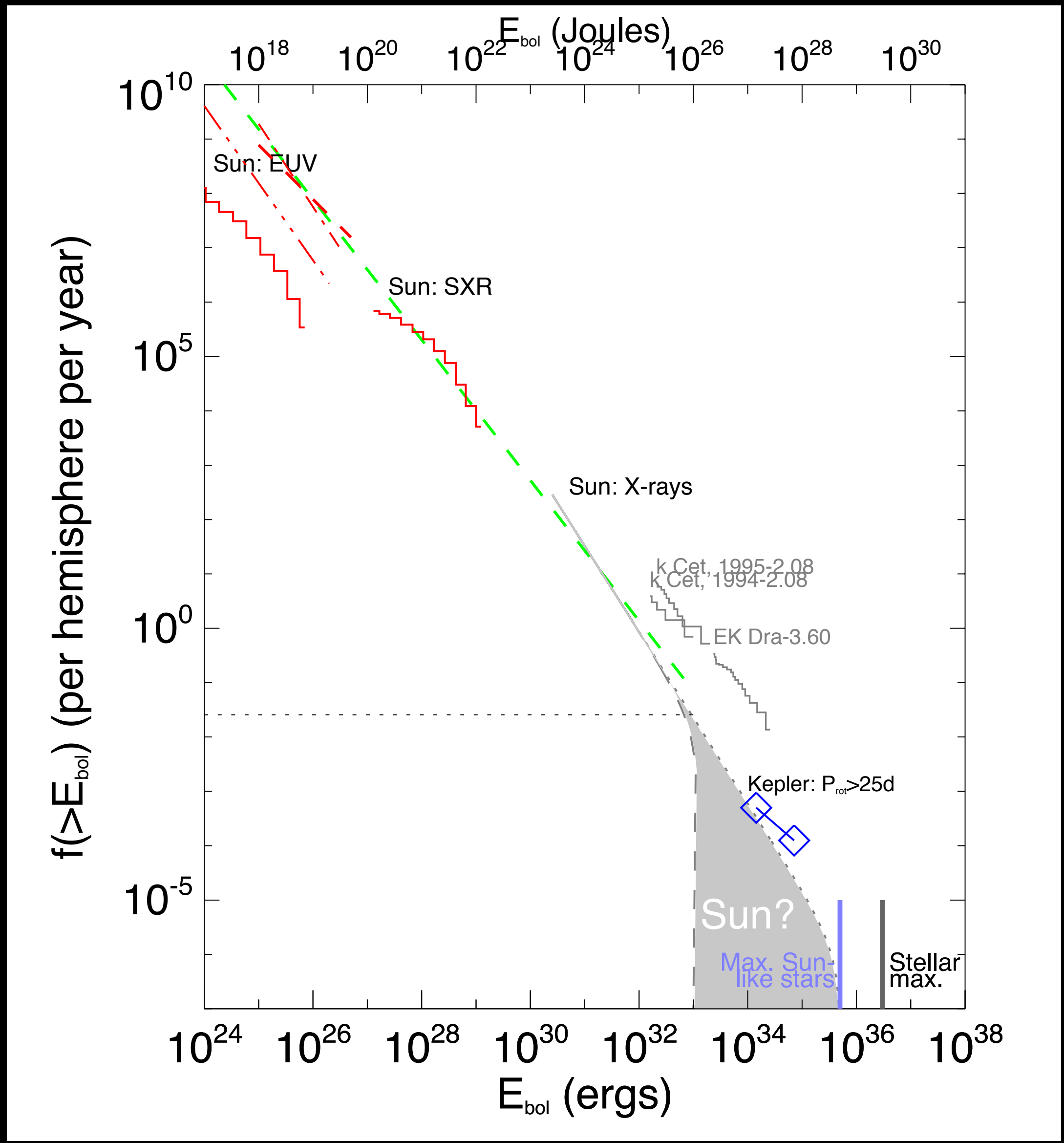

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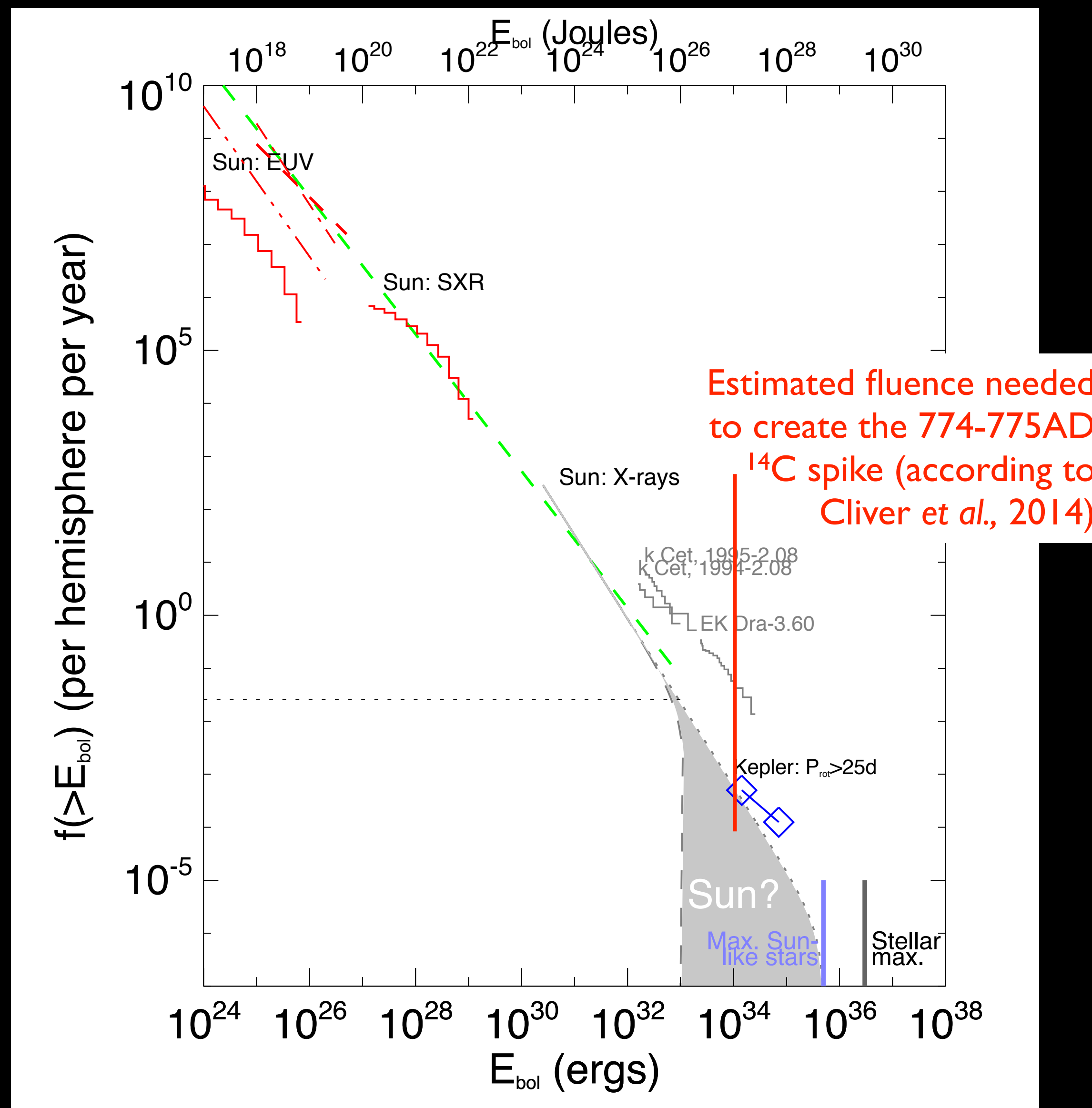

Lunar radionuclides

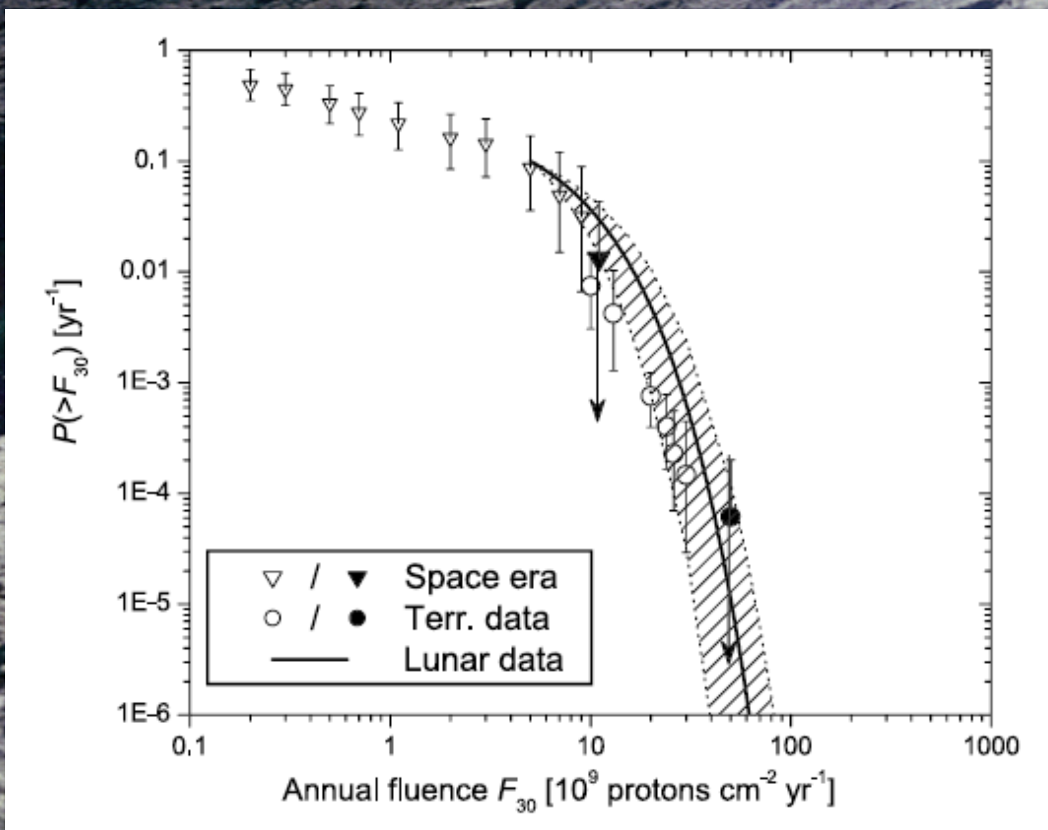

Figure from Kovaltsov & Usoskin; 2014, Solar Physics, Vol. 289, pp.211-220

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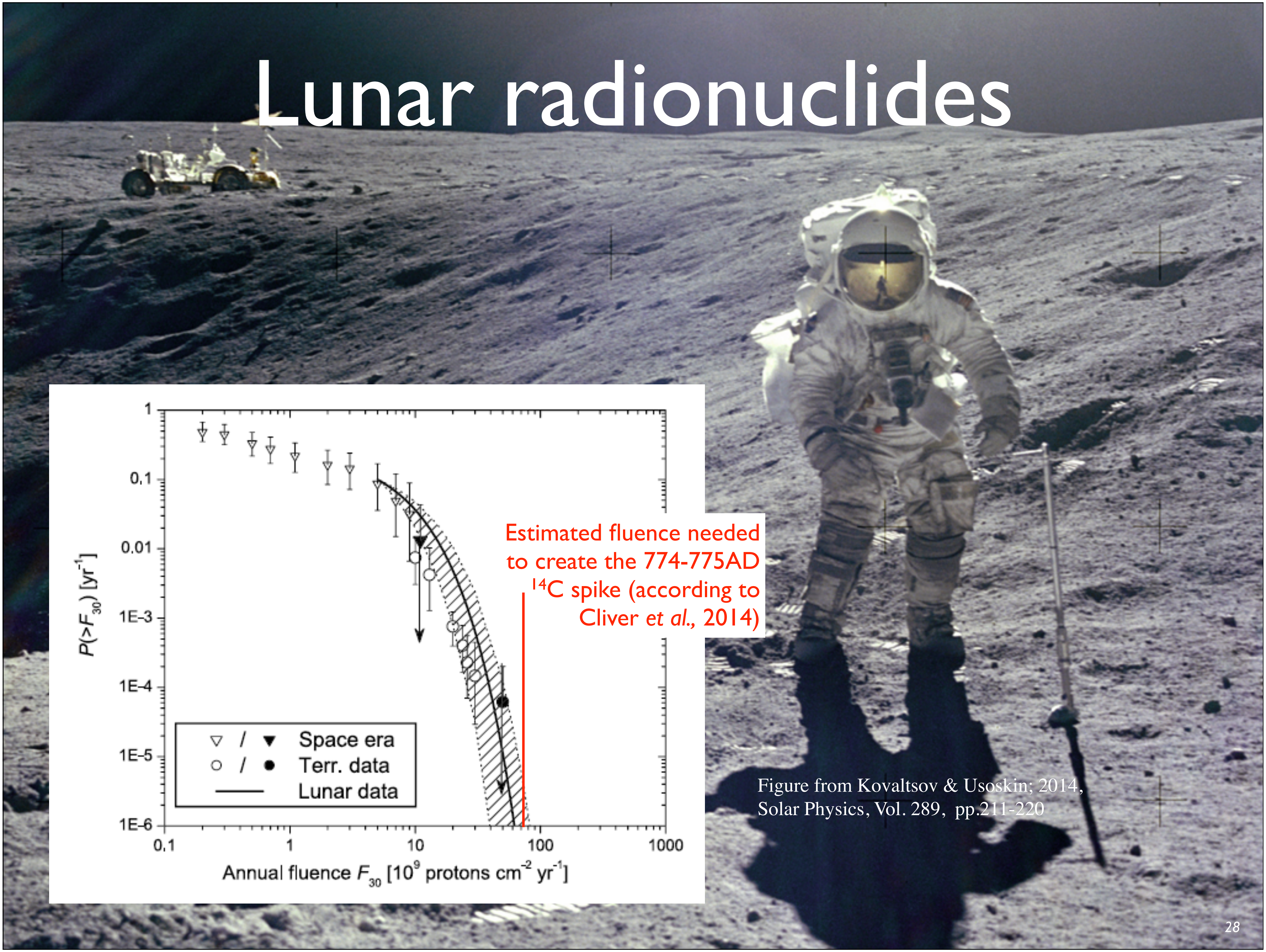
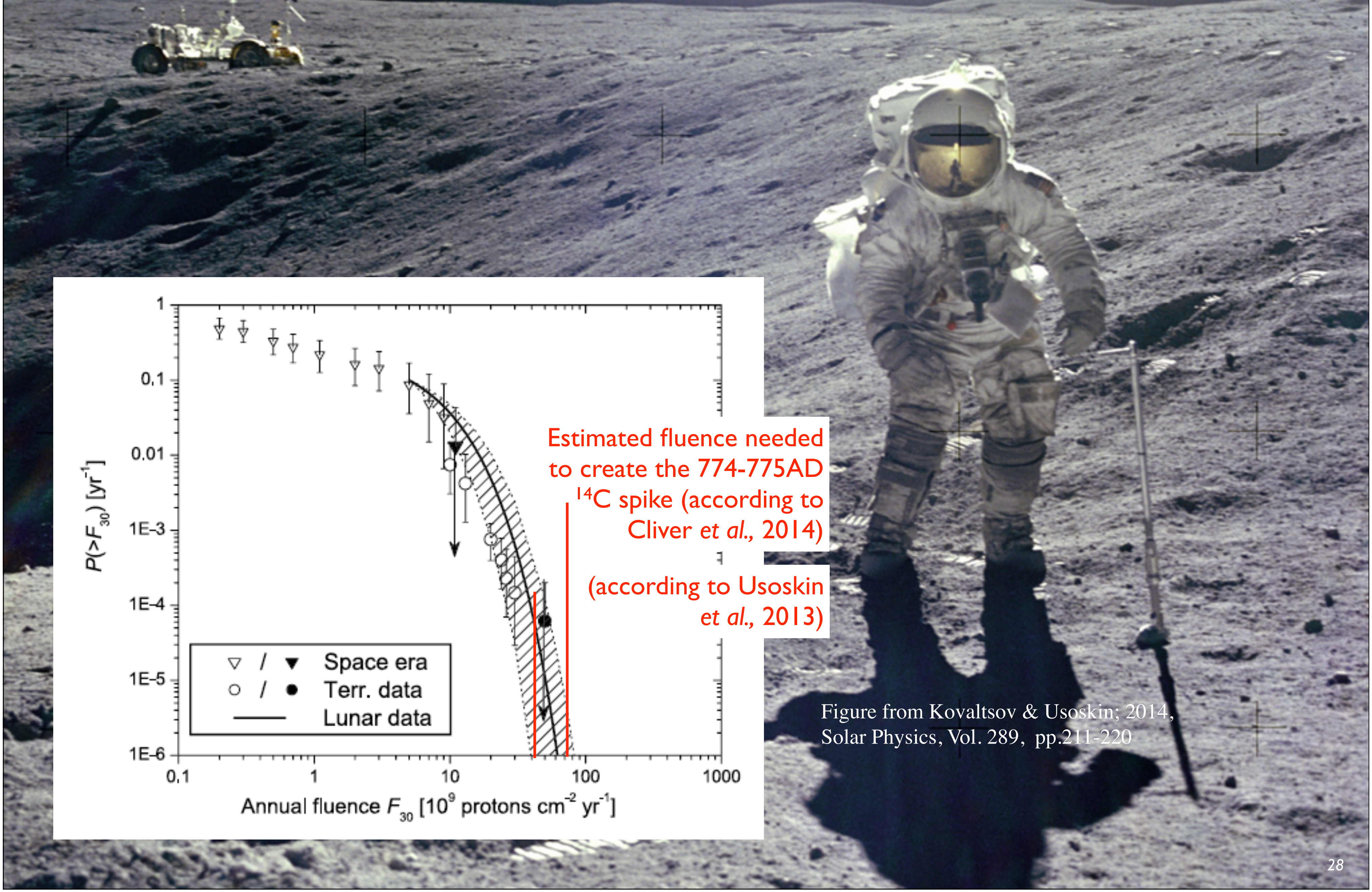


Estimated fluence needed to create the 774-775AD ^{14}C spike (according to Cliver *et al.*, 2014)

Figure from Kovaltsov & Usoskin; 2014, Solar Physics, Vol. 289, pp.211-220

Lunar radionuclides



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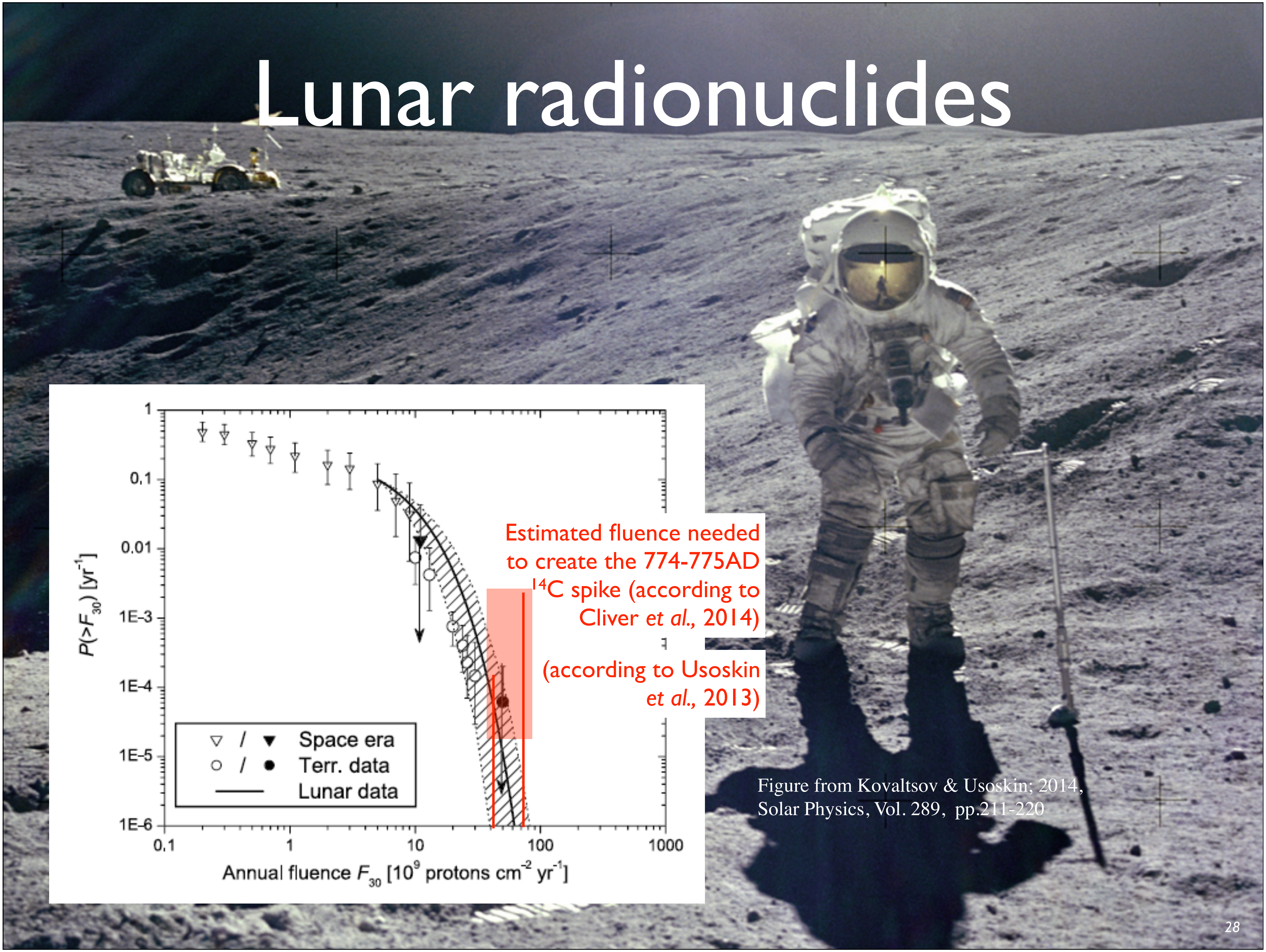

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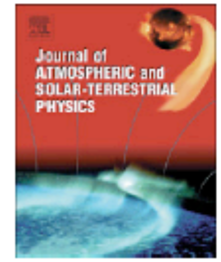

The largest imaginable magnetic storm

Vytenis M. Vasyliūnas

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A R T I C L E I N F O

Available online 27 May 2010

Keywords:
Extreme magnetic storm
Dst index
Inflation of geomagnetic field

A B S T R A C T

The size of a magnetic storm is measured by the maximum depression of the horizontal magnetic field at the Earth's equator. The largest depression that could possibly occur can be estimated by noting that the geomagnetic field is inflated by plasma pressure in the magnetosphere that is enhanced above the effective pressure the of the surrounding medium (magnetosheath and magnetotail), and that this pressure enhancement results largely from adiabatic compression as plasma is transported inward into dipolar flux tubes of decreasing volume. A rough but reasonable upper limit can then be estimated by setting the effective plasma pressure equal to the magnetic pressure of the dipole field at the equator of each flux tube, and applying the Dessler–Parker–Sckopke theorem. The upper limit thus obtained for the (negative) value of the *Dst* index is $-Dst \sim 2500$ nT; for comparison, the largest depression yet observed is estimated as $-Dst \sim 1760$ nT.

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The worst space weather

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Stellar data reveal that some space weather can be much more severe than what we have recently experienced:

- Solar flares may reach energies up to 100-300 times above those observed in the past four decades.

Lunar and terrestrial radionuclide and geomagnetic storm theory suggest that different types of extreme space weather do not serve as mutual proxies:

- Energetic particle storm intensities likely saturate at a few times the space-age maximum.
- Geomagnetic storms may never exceed twice the strength of the powerful 1859 Carrington event *[if focusing on Dst – but is that the right thing to do?]*.

All these potential extremes exceed the levels to which modern technologies, connected in a network of growing complexity, have been exposed.

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Stellar observations are essential to establish the largest possible flare from the Sun ... but can we be confident that stars are “Sun-like”?

Radio-nuclide studies of lunar rocks and terrestrial ice and biosphere records need to be re-analyzed and extended in time and increased in signal-to-noise contrast ... but how do ‘extreme’ SEP events map to extreme flares?

Models are needed to know the worst possible geomagnetic storm ... or are there other ways to establish extreme GMD limits?

But the bottom line is: yes, it can get worse than we have experienced to date! Can we set an upper limit, or merely a smooth frequency distribution?

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