Upper limit for solar flare energies

Karel Schrijver

Lockheed Martin Advanced Technology Center

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.

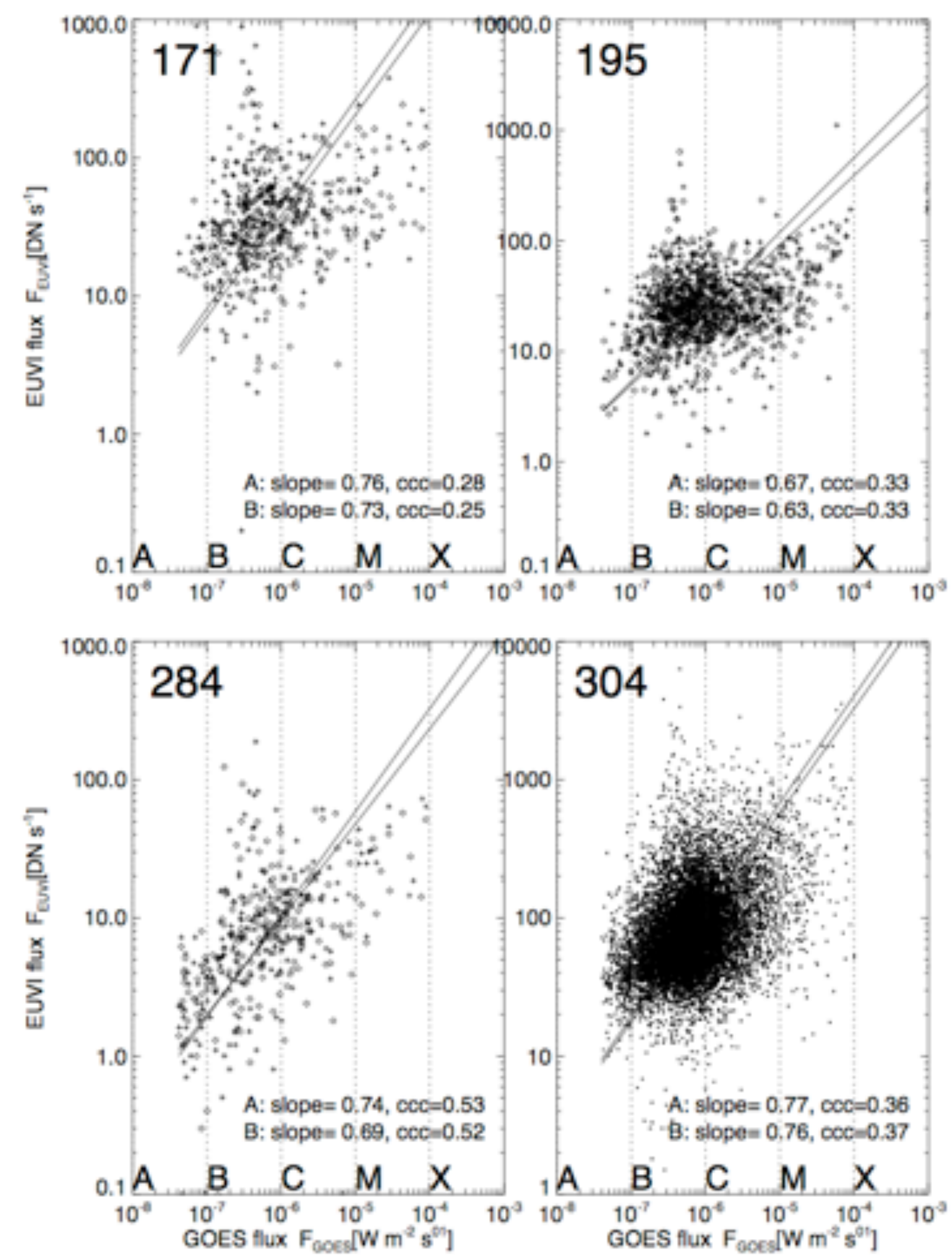
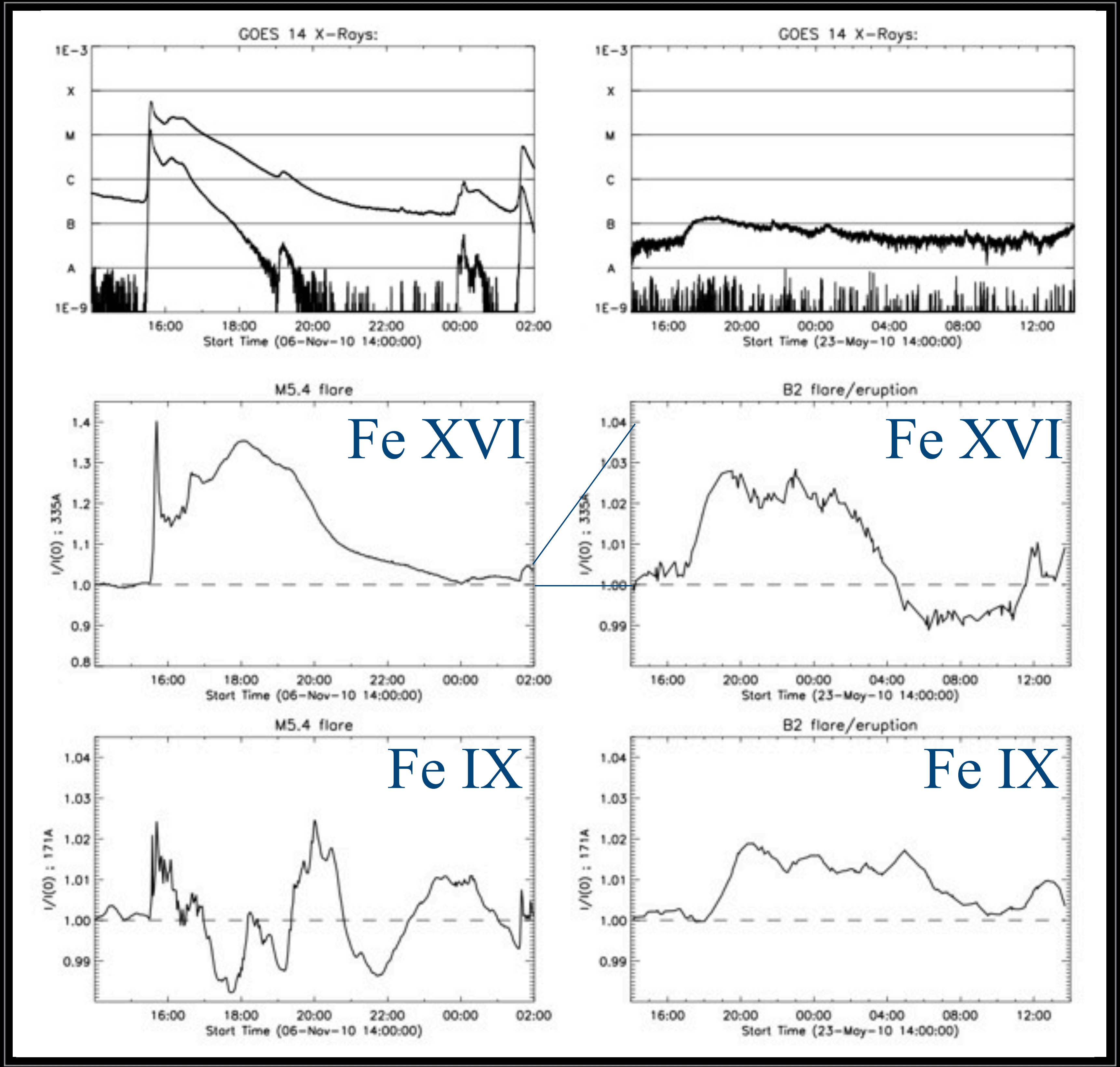


Figure 7. Scatterplot of EUVI fluxes (171, 195, 284, 304 Å) versus the GOES flux of all events simultaneously detected with EUVI and GOES. The data from spacecraft STEREO/A are indicated with cross symbols, from STEREO/B with diamond symbols. Separate fits and linear regression fits for both spacecraft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

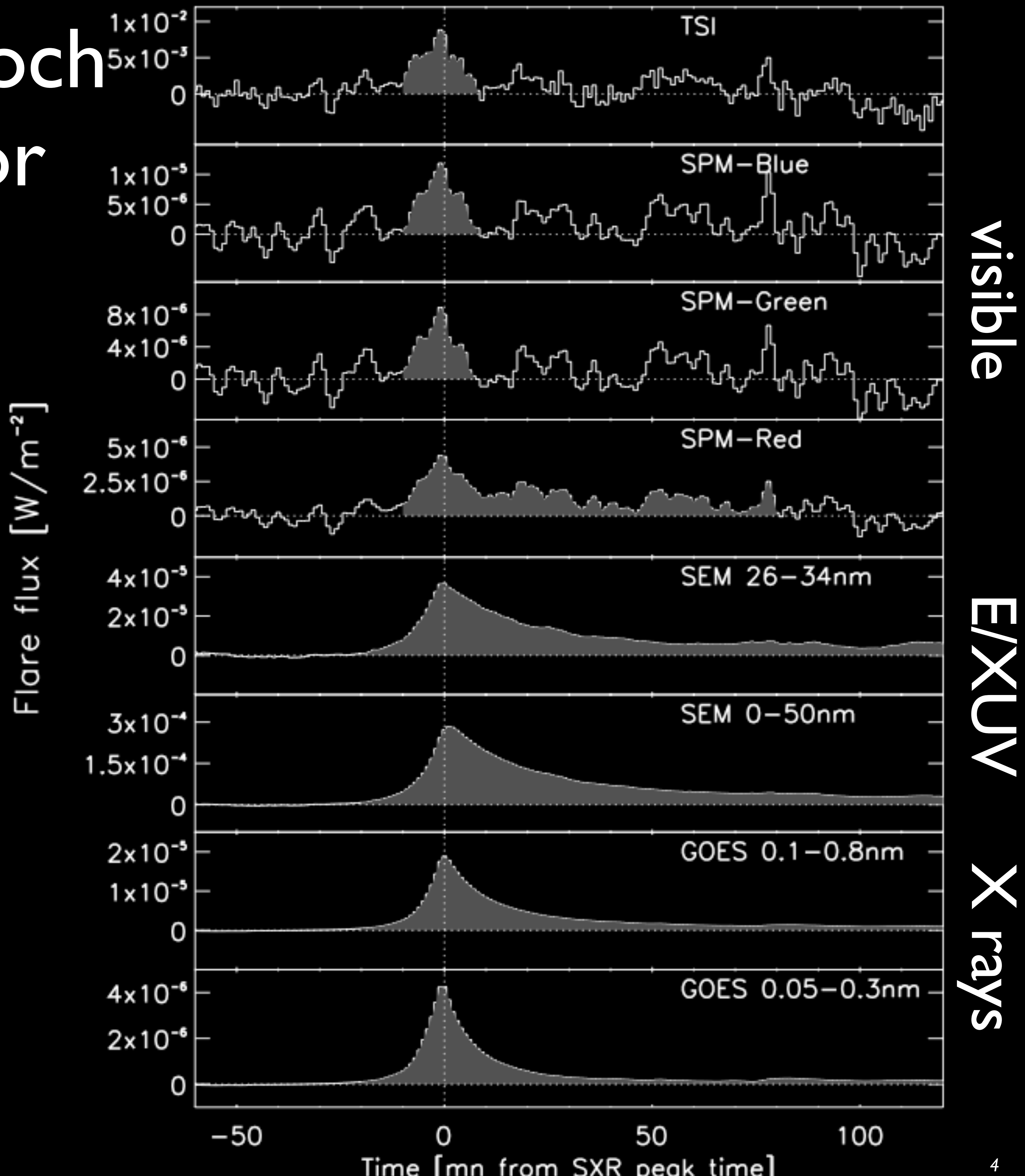
Aschwanden et al. (2013, SPh, subm.)

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.*



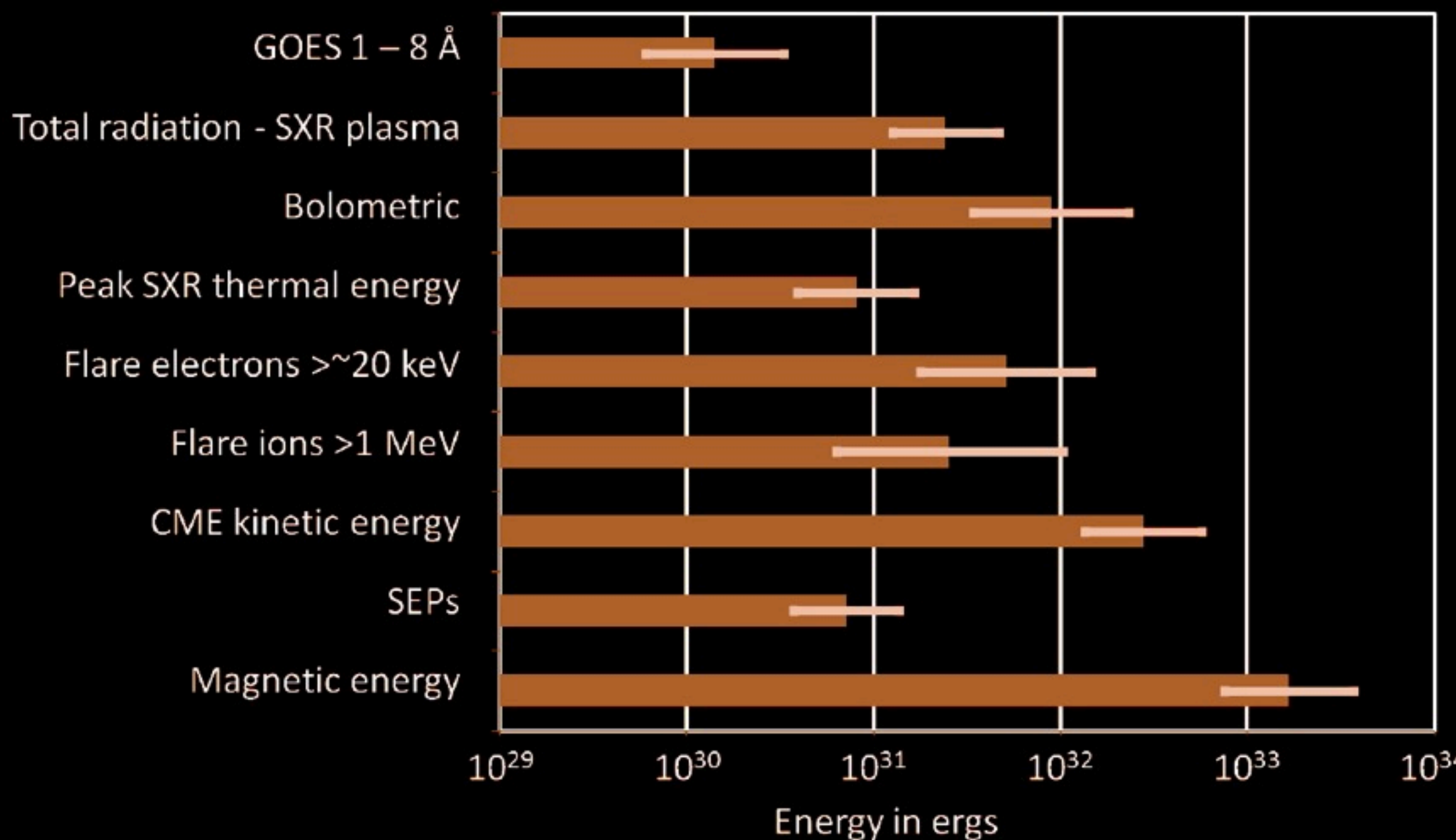
Superposed-epoch light curves for solar flares



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

From Kretzschmar (2011)

Flare energy: mostly WL and kinetic



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

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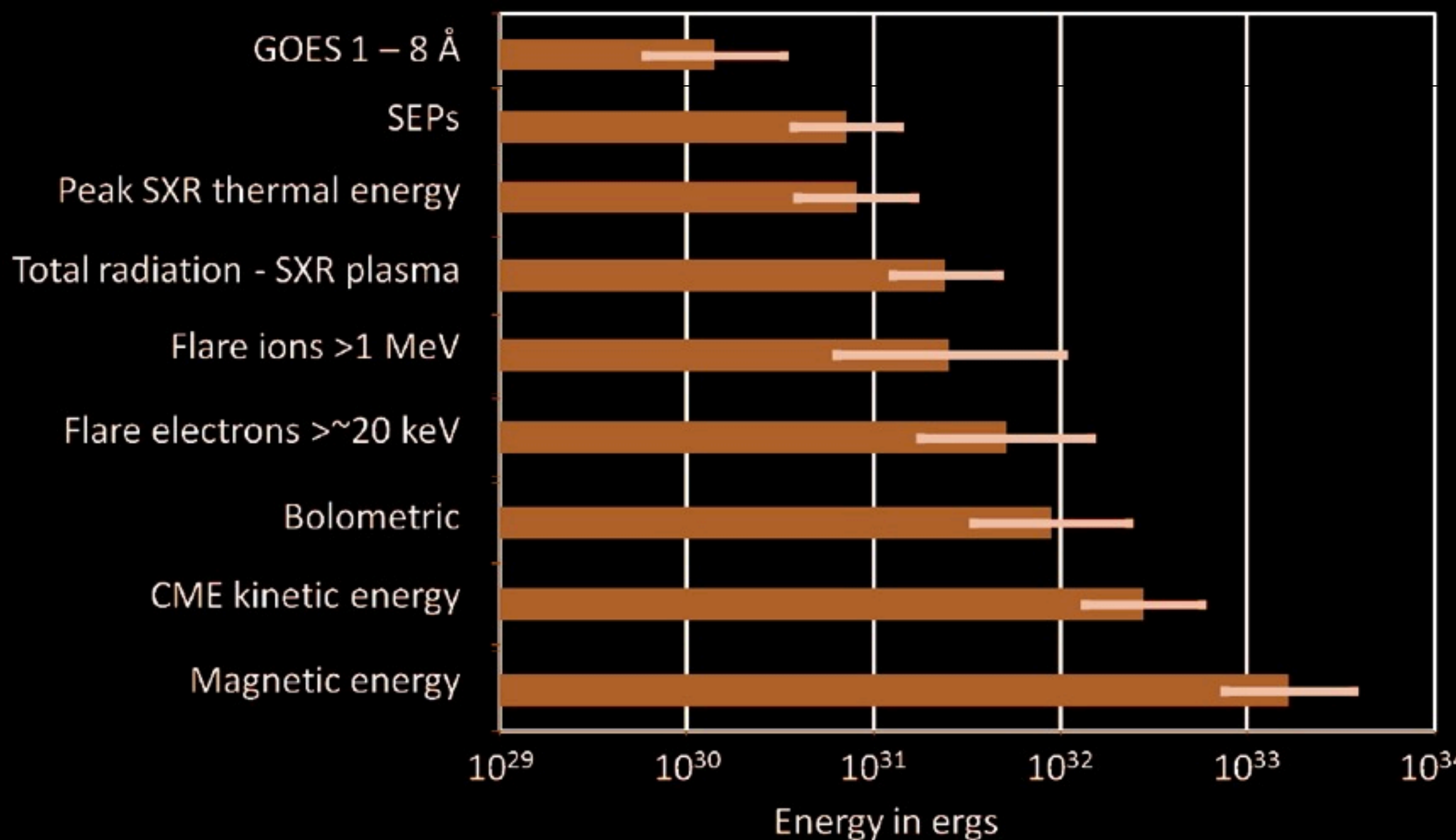
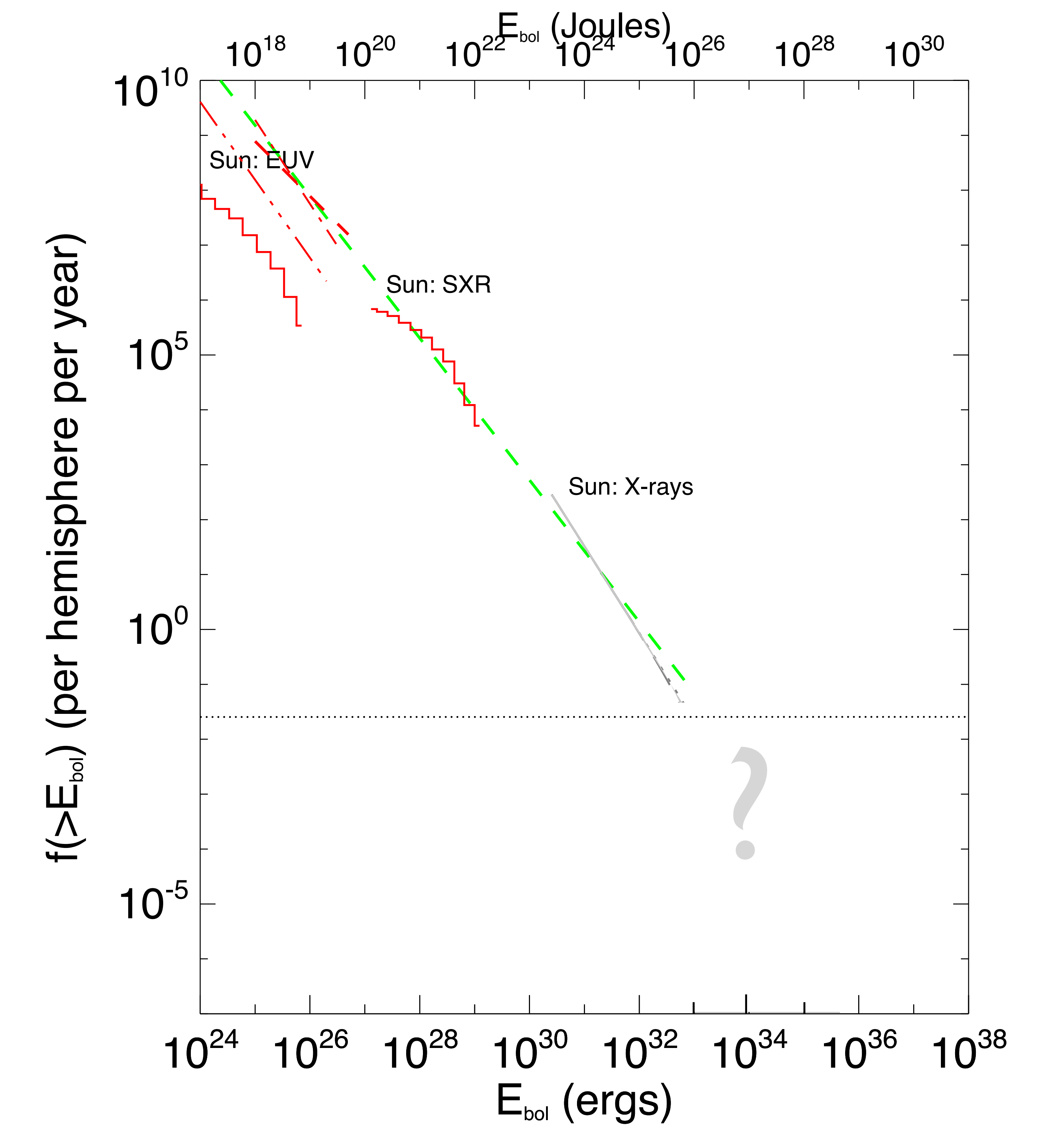


From Emslie et al. (2012): values for X3, X3, X4, X7, X8, X10 flares.

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)?

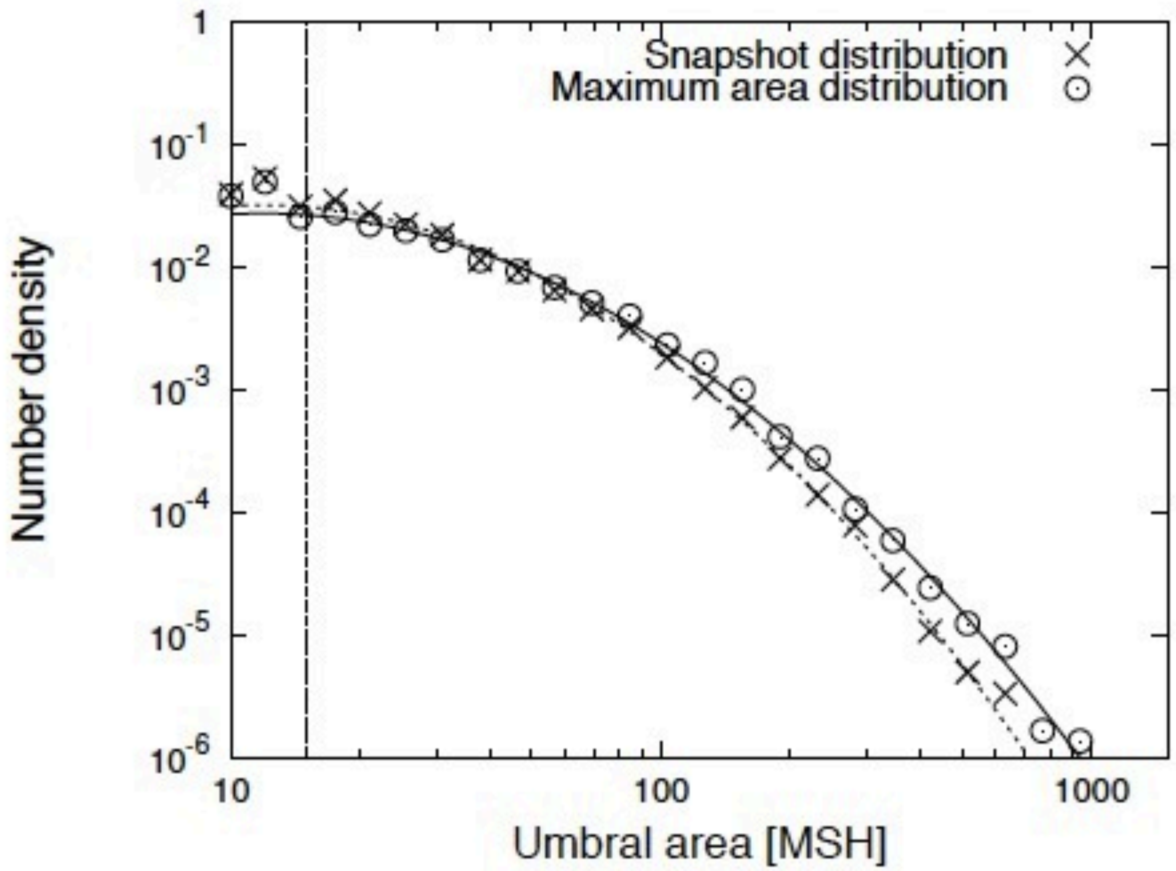


Fig. 1. Size distribution function of umbral areas obtained from the maximum development method (*circles*) and snapshot method (*crosses*). The log-normal fits are overplotted (*solid line:* Fit to maximum area distribution, *dotted line:* Fit to snapshot distribution). The vertical line indicates the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

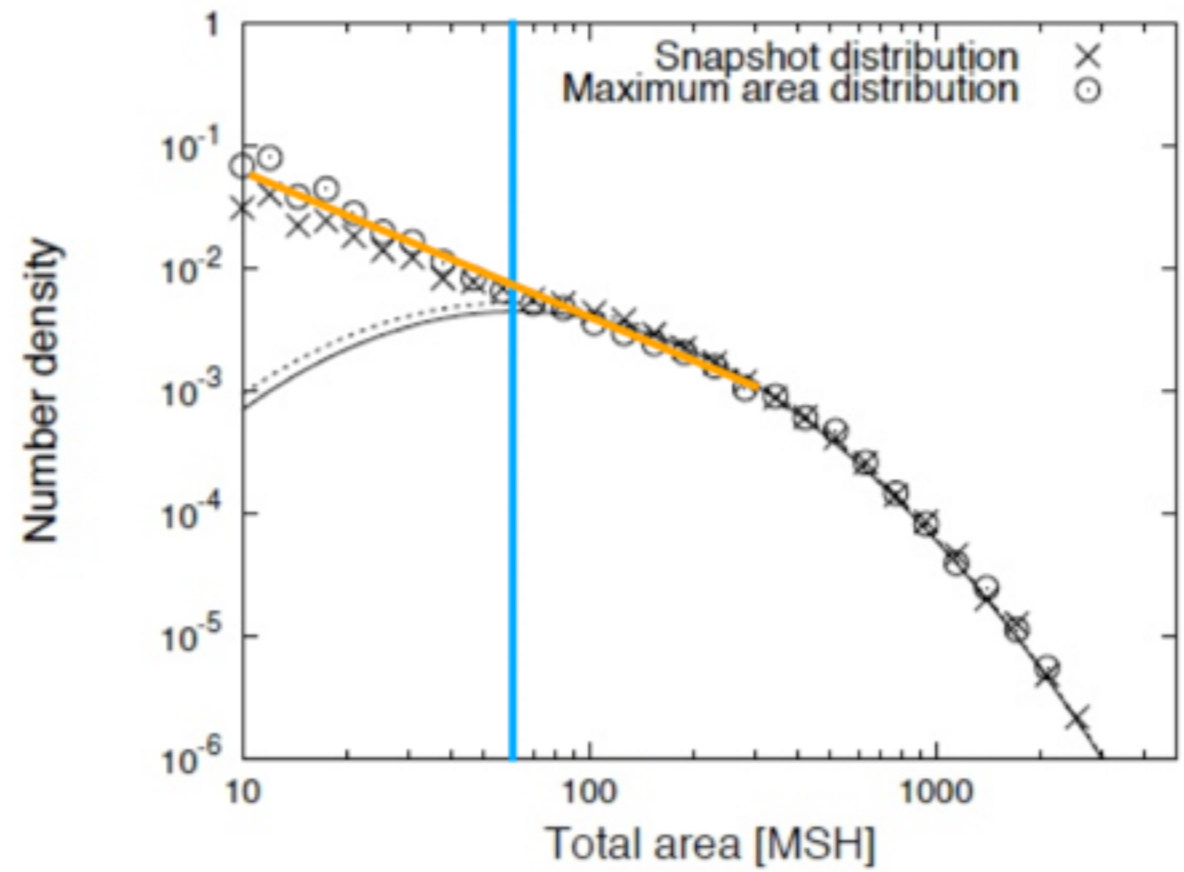
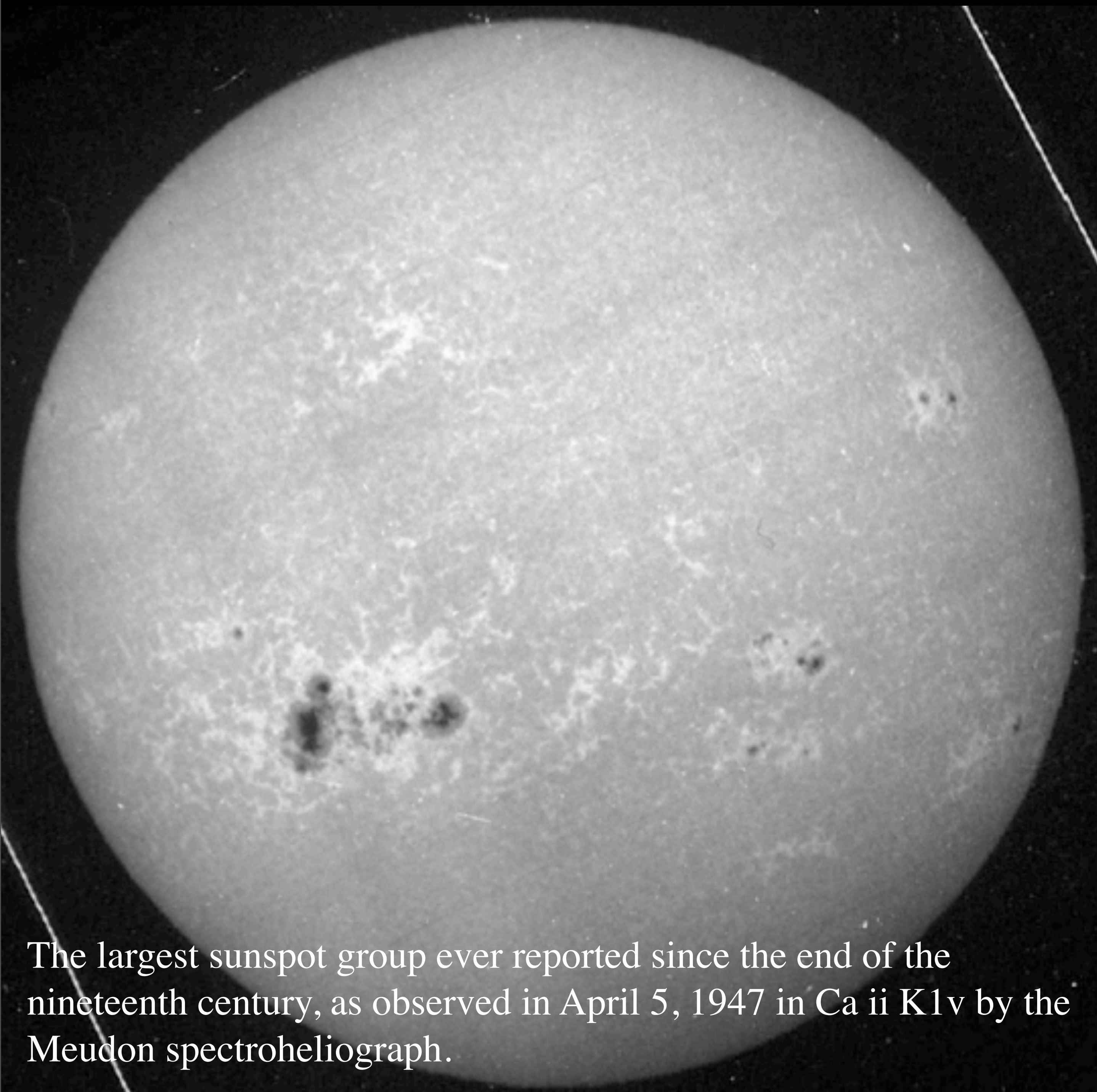


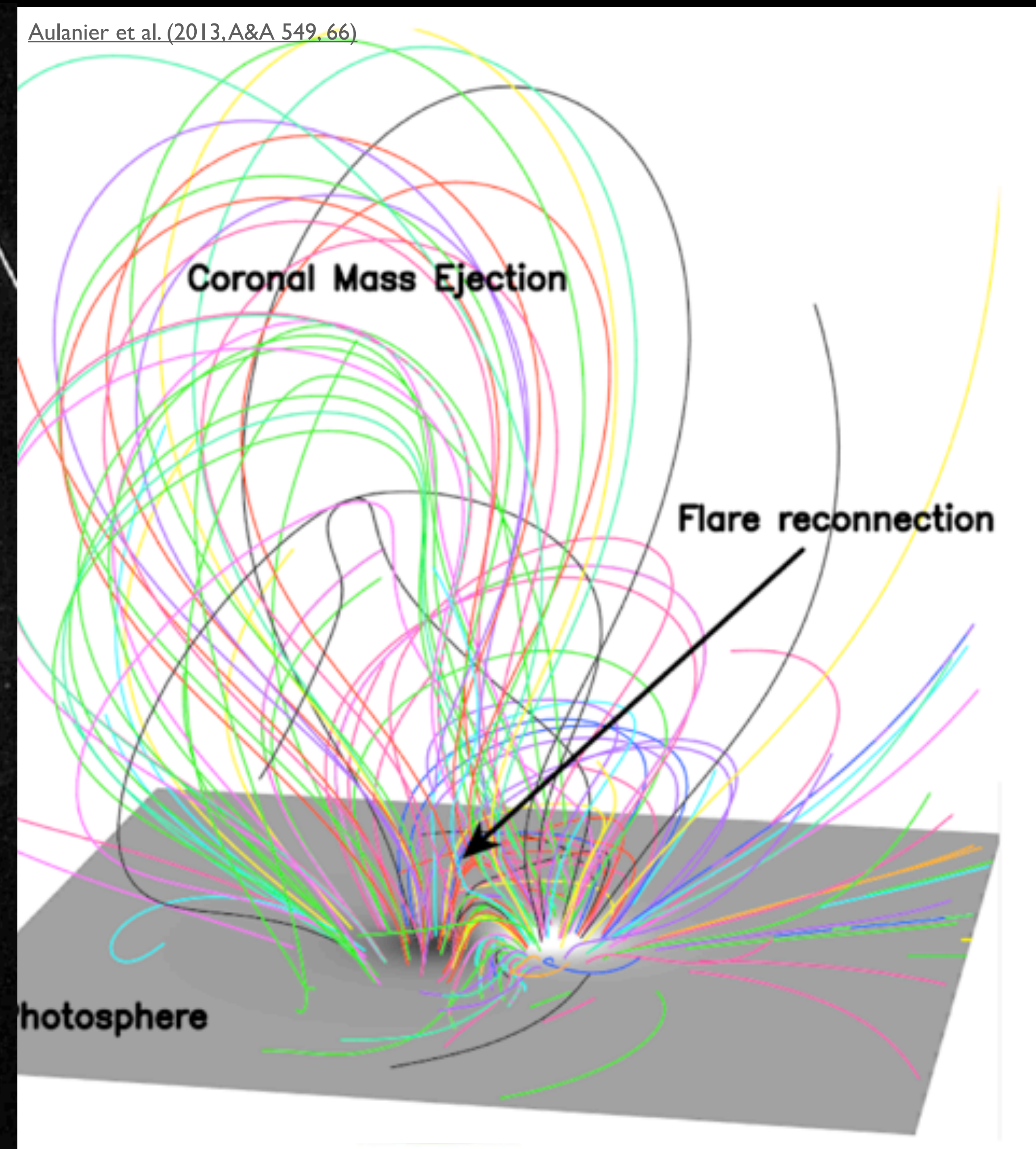
Fig. 2. Size distribution function of the total spot group areas (umbra+penumbra) obtained from the maximum development method (*circles*) and the snapshot method (*crosses*). Overplotted are the log-normal fits for $A >$ 60 MSH (*solid line*: Maximum development method, *dotted line*: Snapshot method).

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

Powering superflares



The largest sunspot group ever reported since the end of the nineteenth century, as observed in April 5, 1947 in Ca ii K1v by the Meudon spectroheliograph.



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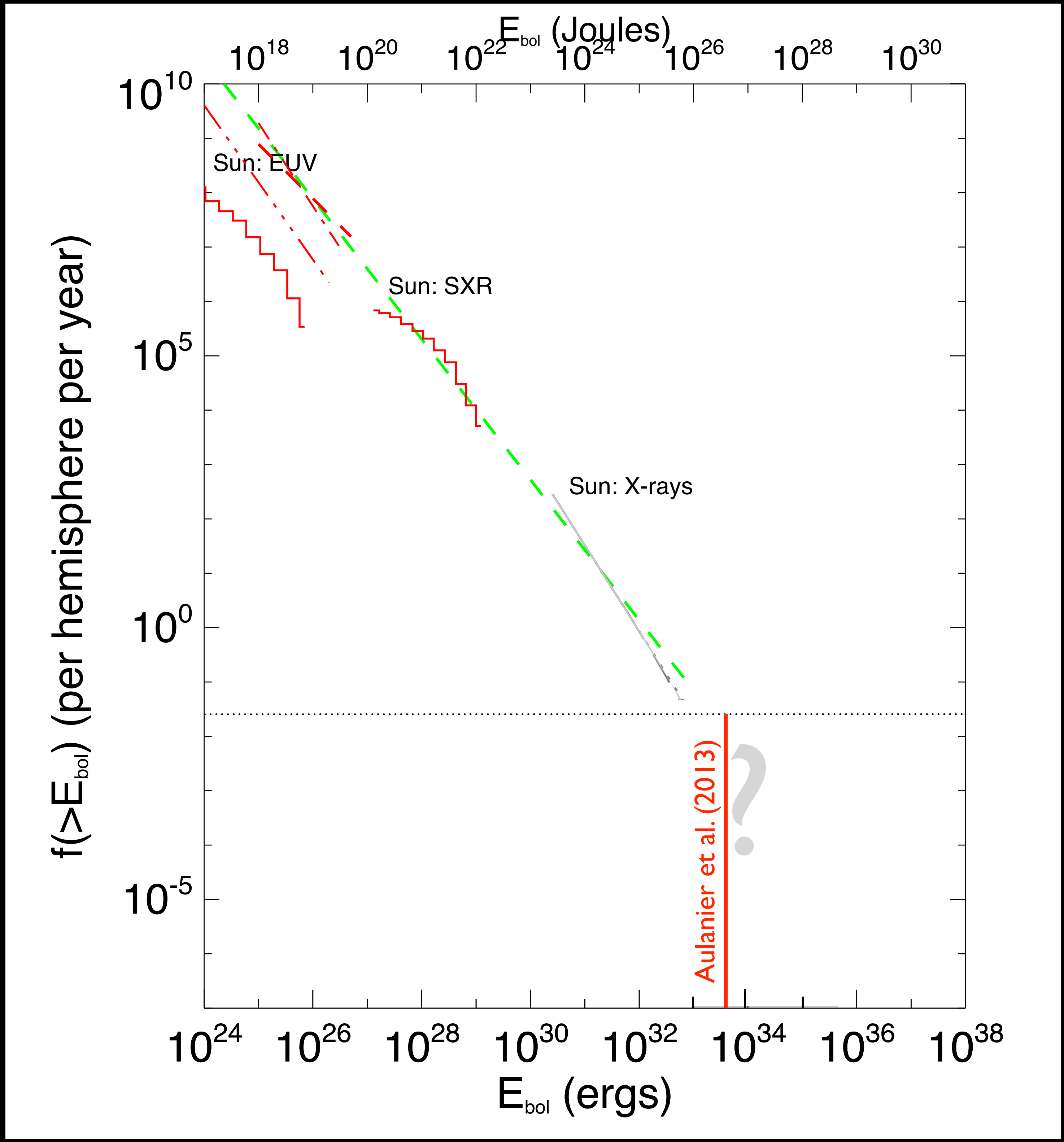
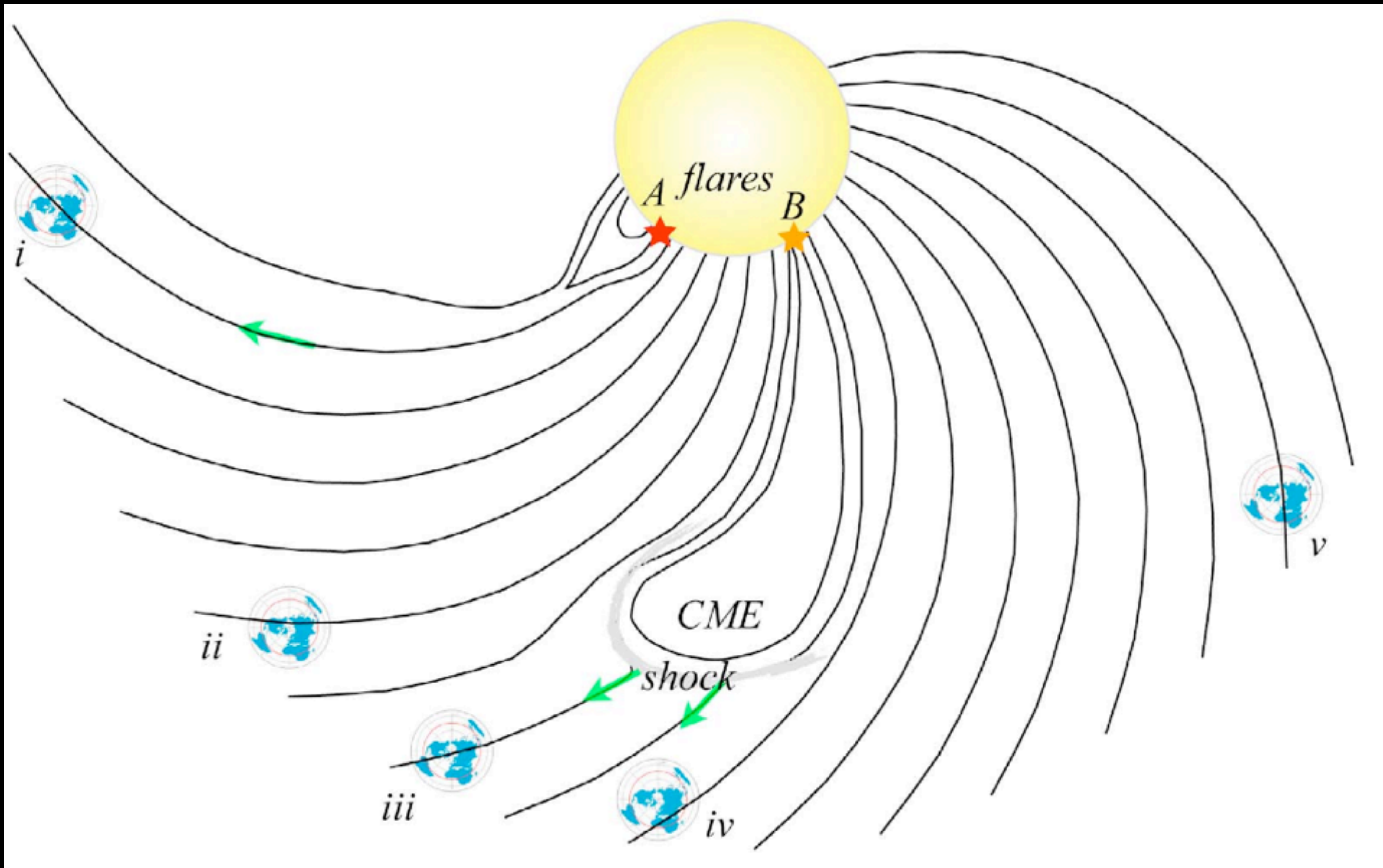
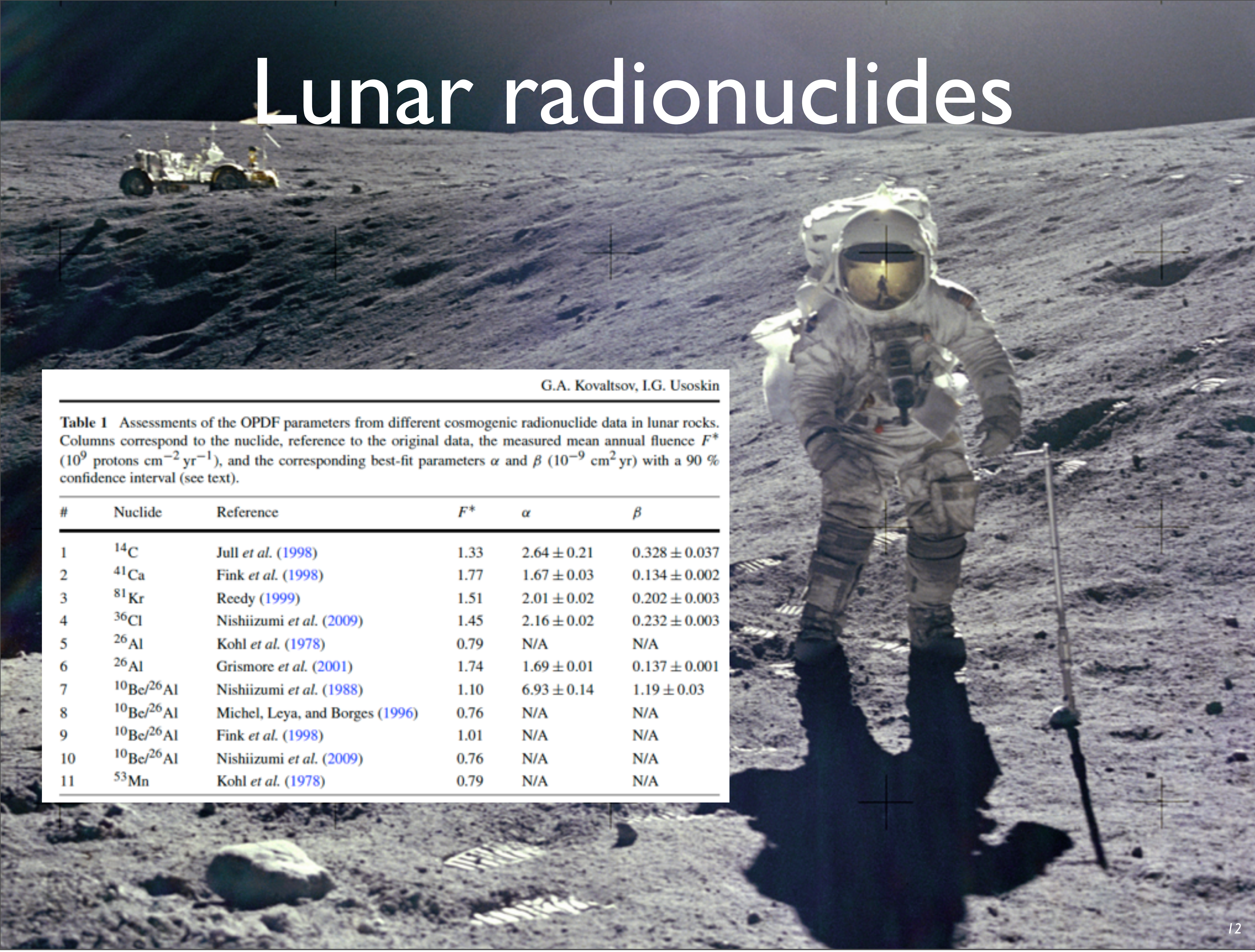


Studying flares by proxies?



Lunar radionuclides

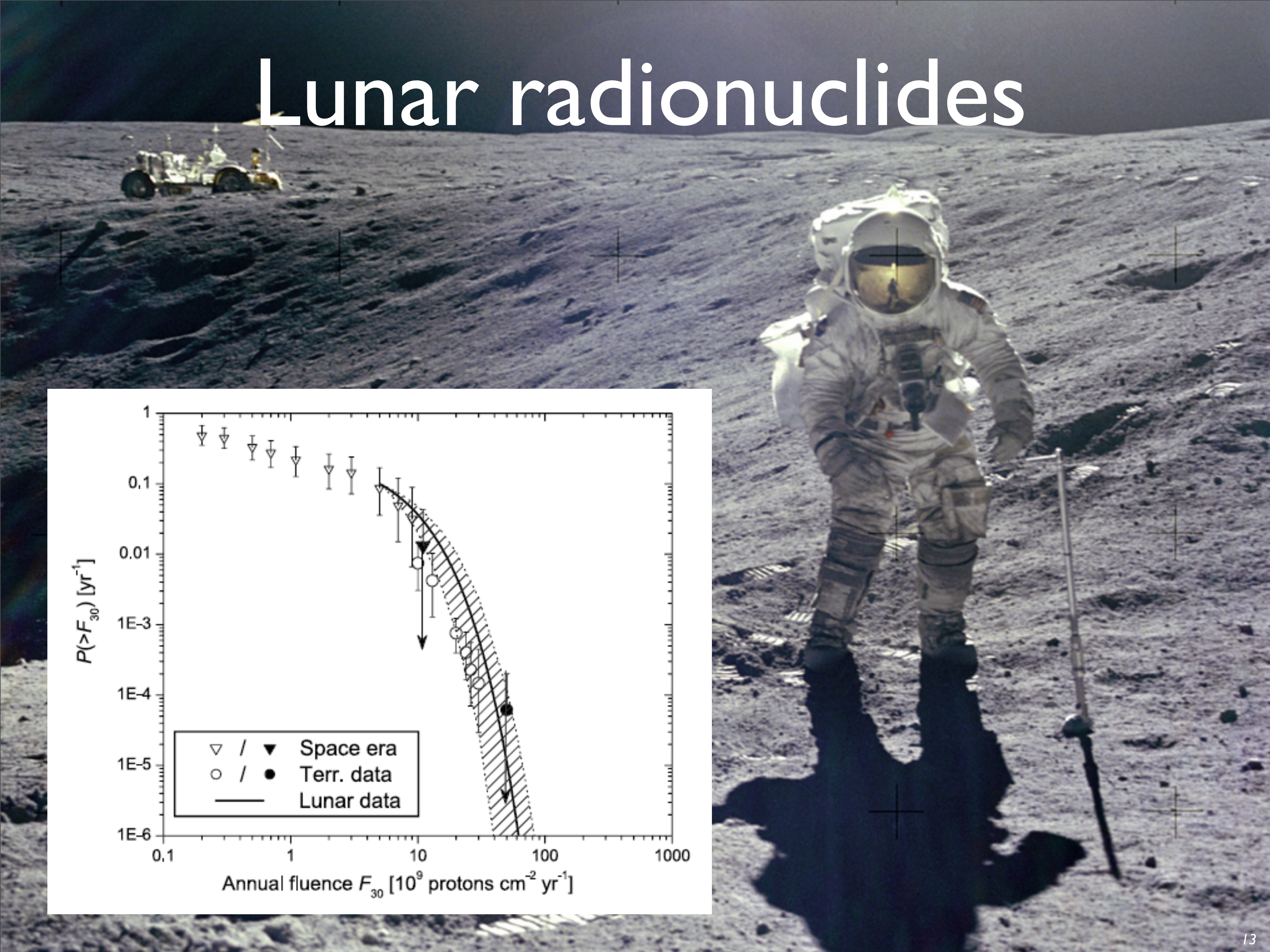


G.A. Kovaltsov, I.G. Usoskin

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).

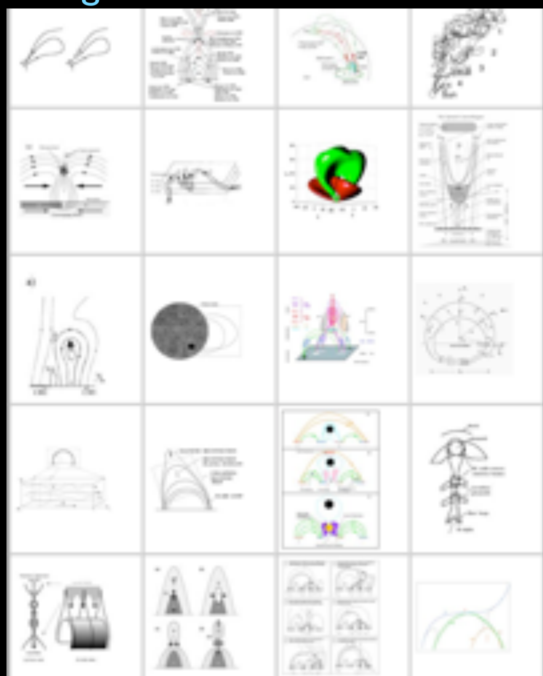
#	Nuclide	Reference	F^*	α	β
1	^{14}C	Jull *et al.* (1998)	1.33	2.64 ± 0.21	0.328 ± 0.037
2	^{41}Ca	Fink *et al.* (1998)	1.77	1.67 ± 0.03	0.134 ± 0.002
3	^{81}Kr	Reedy (1999)	1.51	2.01 ± 0.02	0.202 ± 0.003
4	^{36}Cl	Nishiizumi *et al.* (2009)	1.45	2.16 ± 0.02	0.232 ± 0.003
5	^{26}Al	Kohl *et al.* (1978)	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

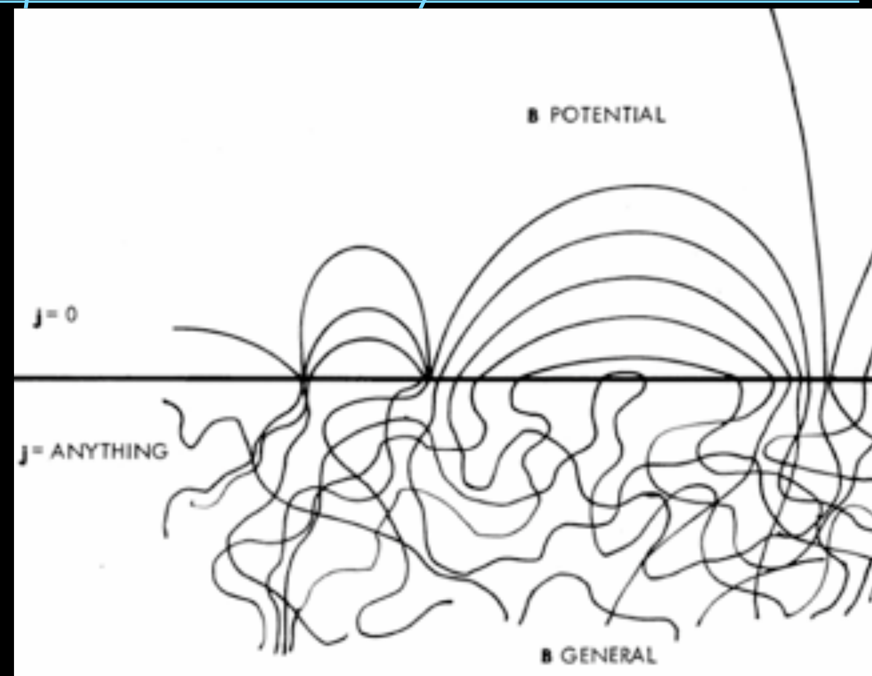
Lunar radionuclides

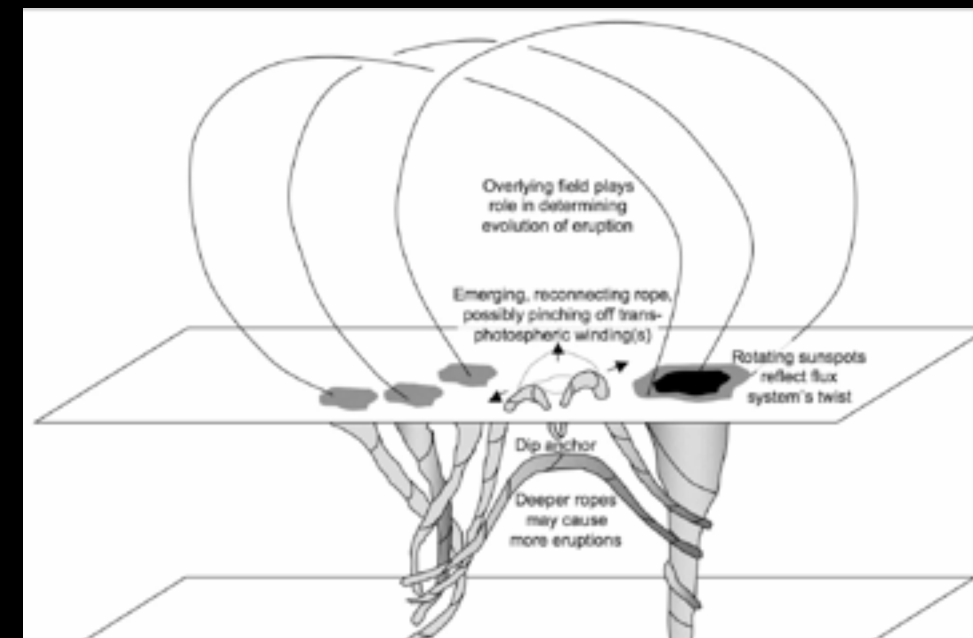


Solar-stellar flaring

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

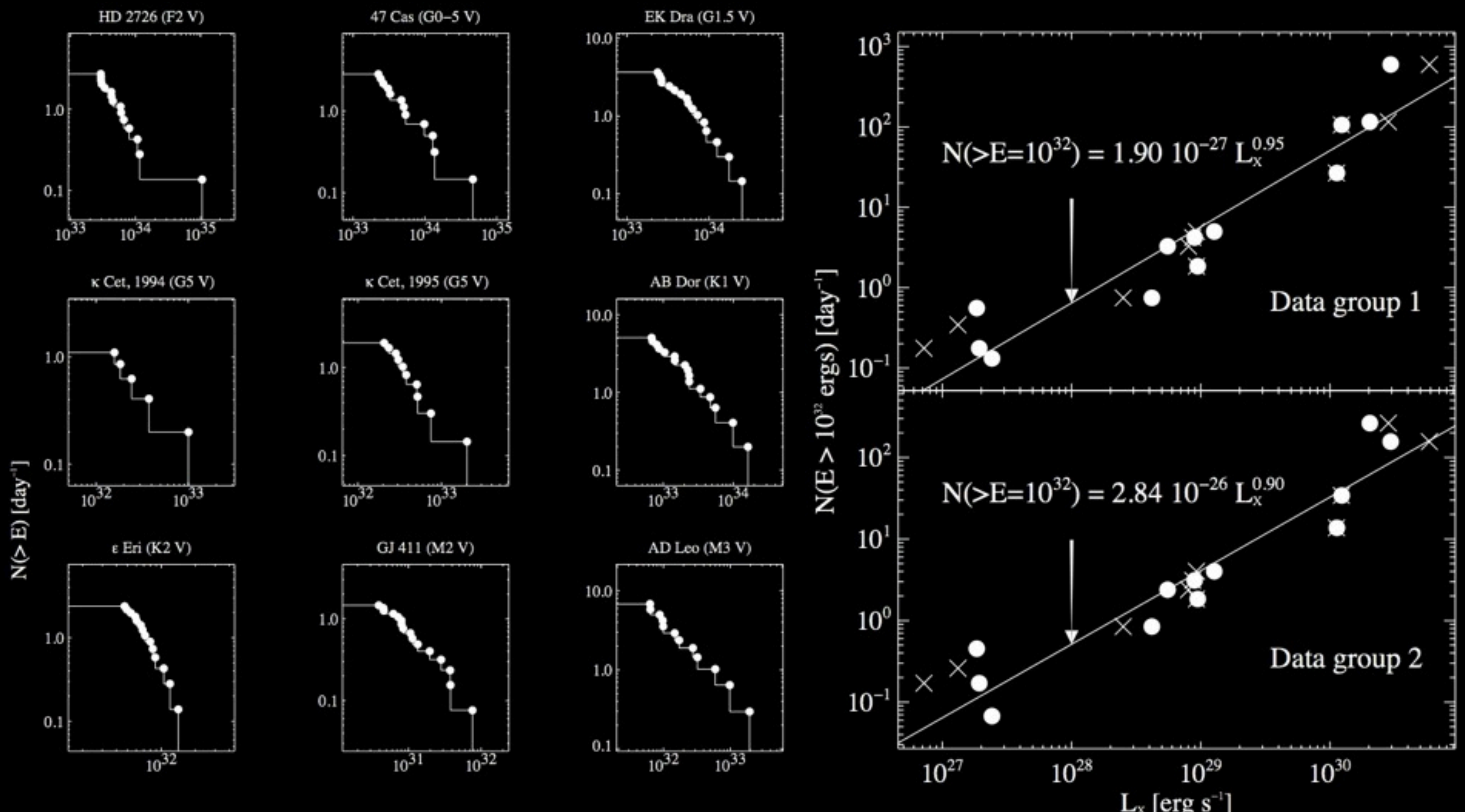
Solar-stellar comparison possible for infrequent largest solar flares, generally with non-overlapping wavelength ranges.

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

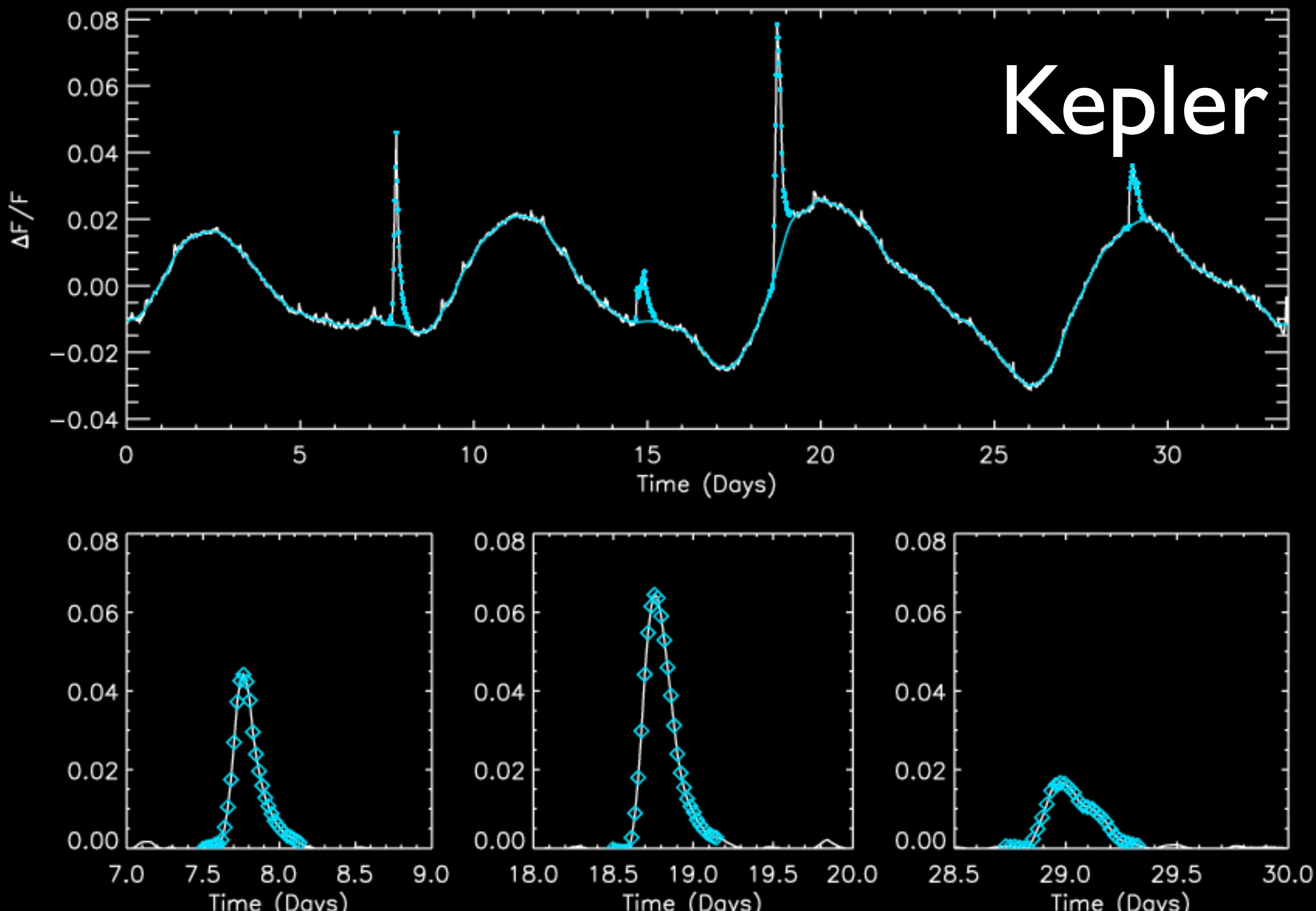
Courtesy: Rachel Osten

Stellar flares: XUV



Audard et al. (2000)

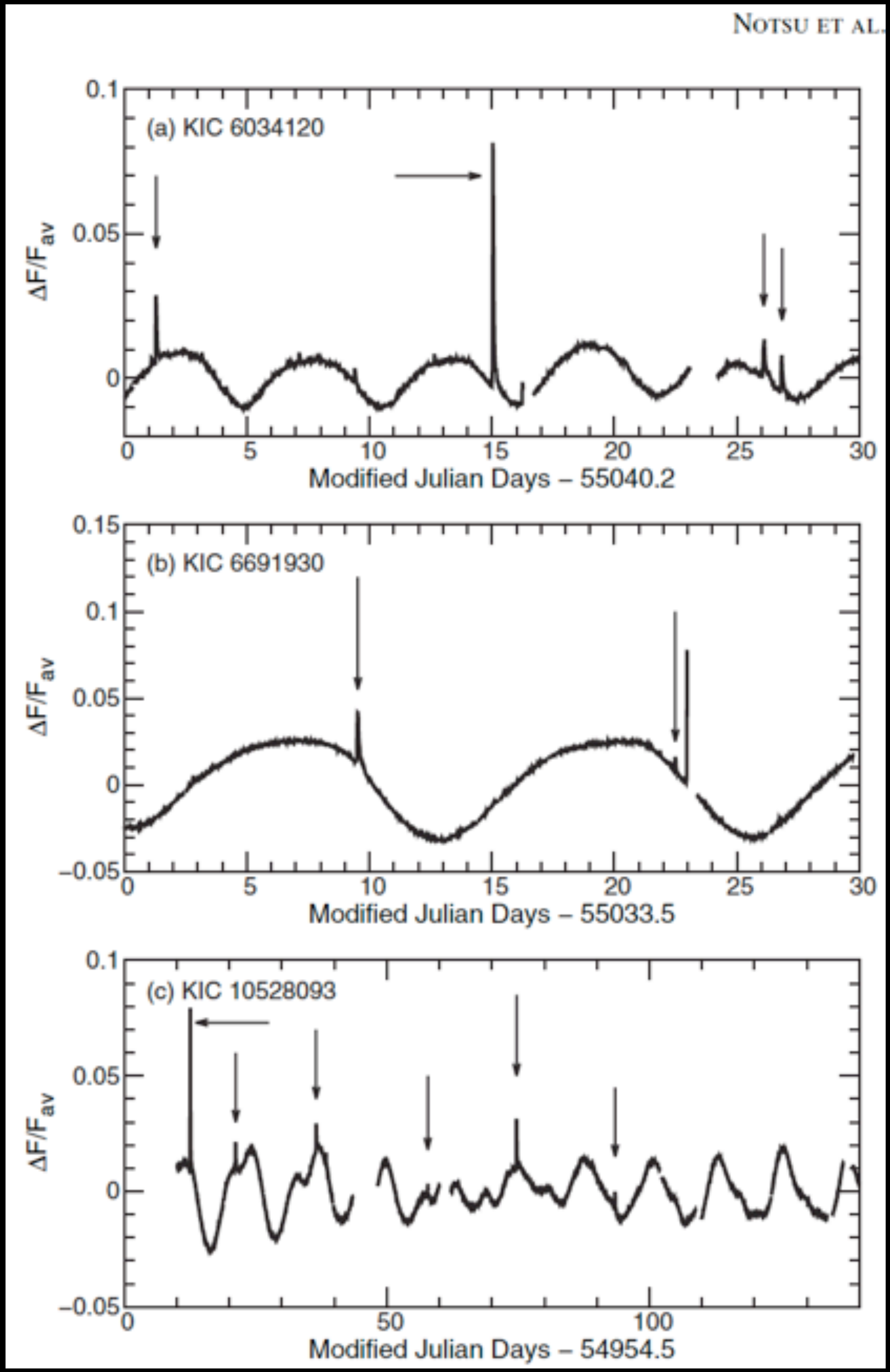
Visible-light flaring on stars



Walkowicz et al. (2011)

(b) Detail of subtracted light curve for an example flaring K dwarf.

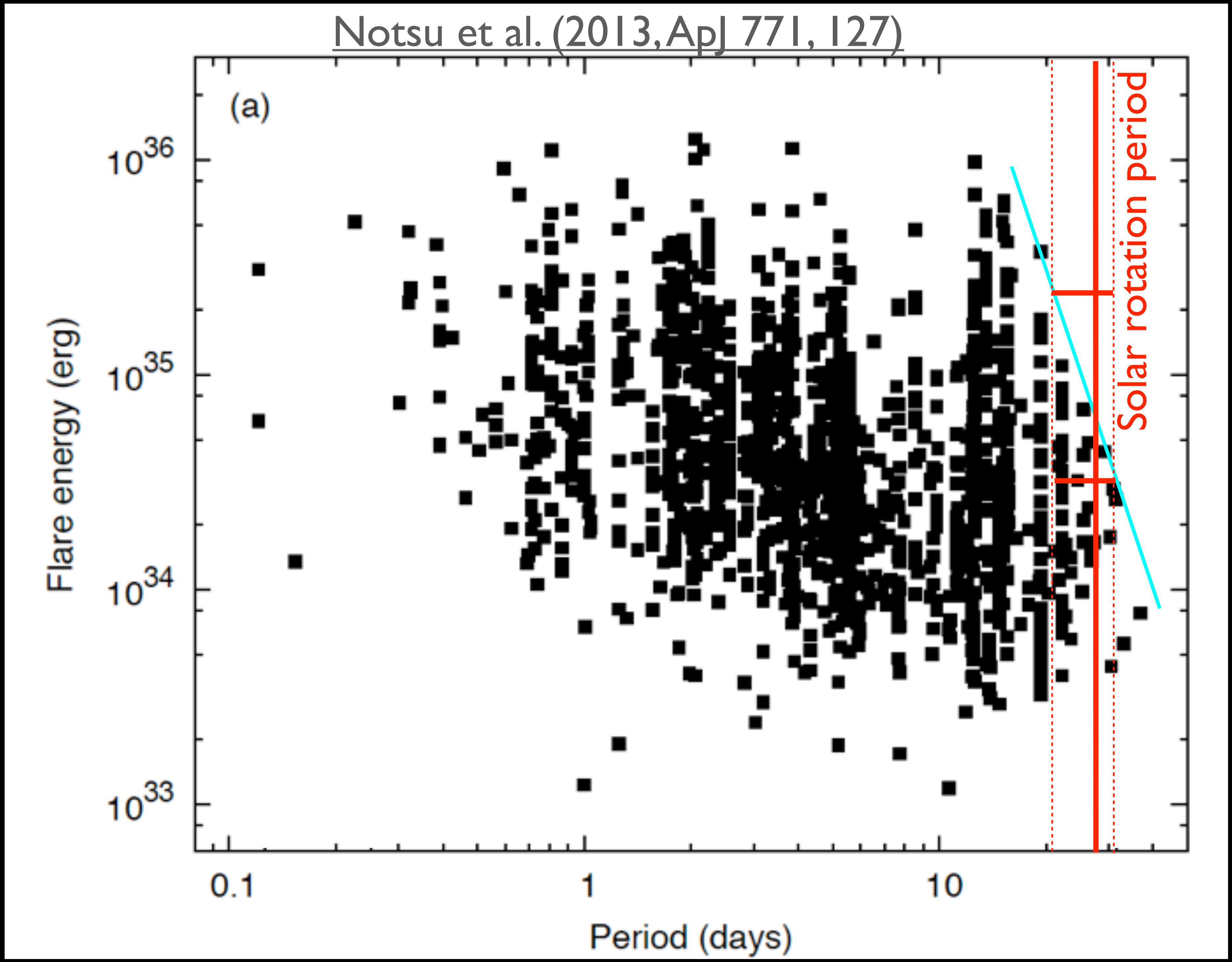
Visible-light flaring on stars

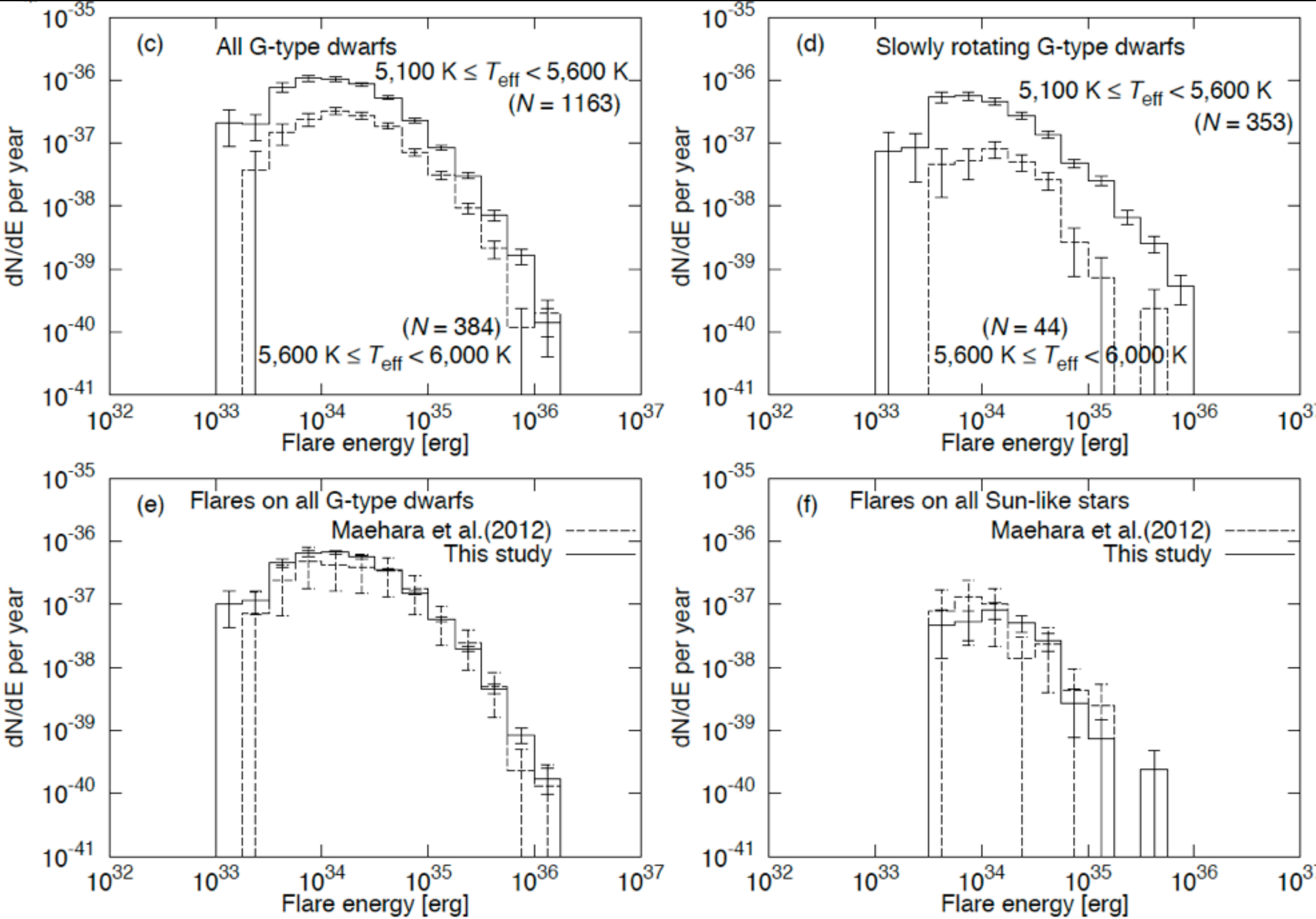


Kepler

Notsu et al. (2013)

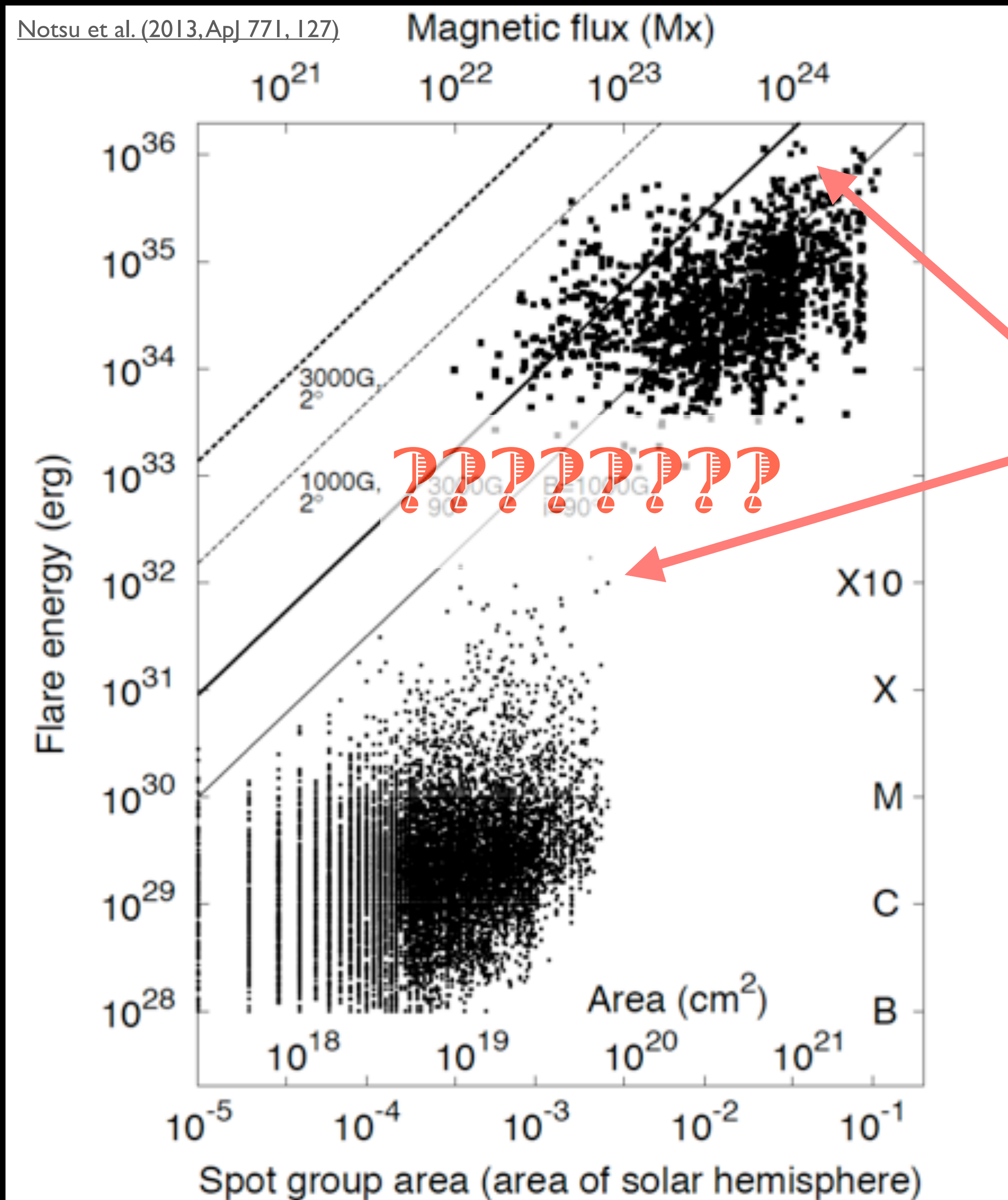
Visible-light flaring on stars
Kepler data

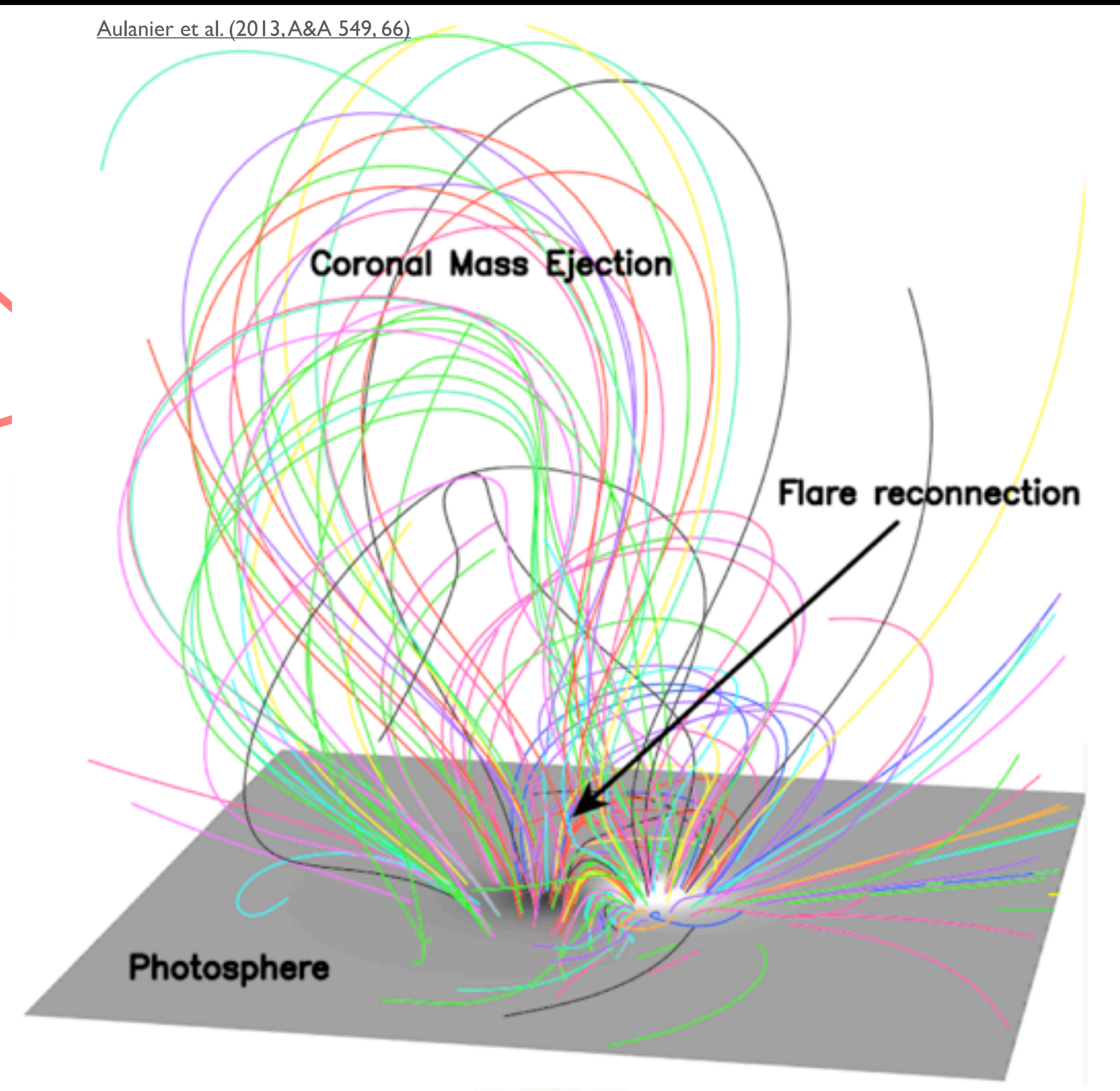




(c) All G-type dwarfs
5,100 K ≤ T_{eff} < 5,600 K
(N = 1163)
(N = 384)
5,600 K ≤ T_{eff} < 6,000 K
(d) Slowly rotating G-type dwarfs
5,100 K ≤ T_{eff} < 5,600 K
(N = 353)
(N = 44)
5,600 K ≤ T_{eff} < 6,000 K
(e) Flares on all G-type dwarfs
Maehara et al.(2012)
This study
(f) Flares on all Sun-like stars
Maehara et al.(2012)
This study
dN/dE per year
Flare energy [erg]

Powering superflares



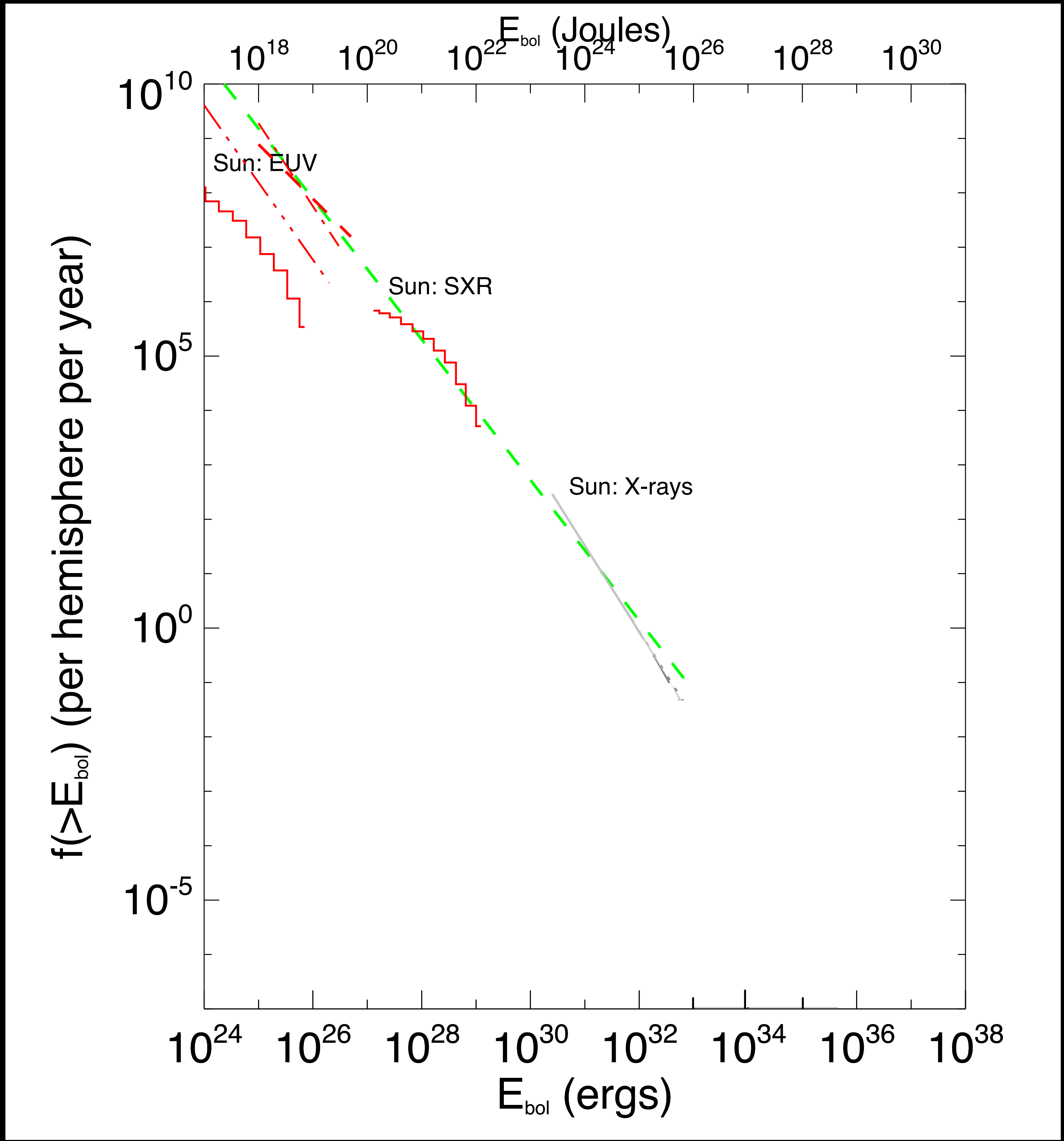


Are ‘Kepler flares’ ‘flares’?

Potential issues causing misinterpretation:

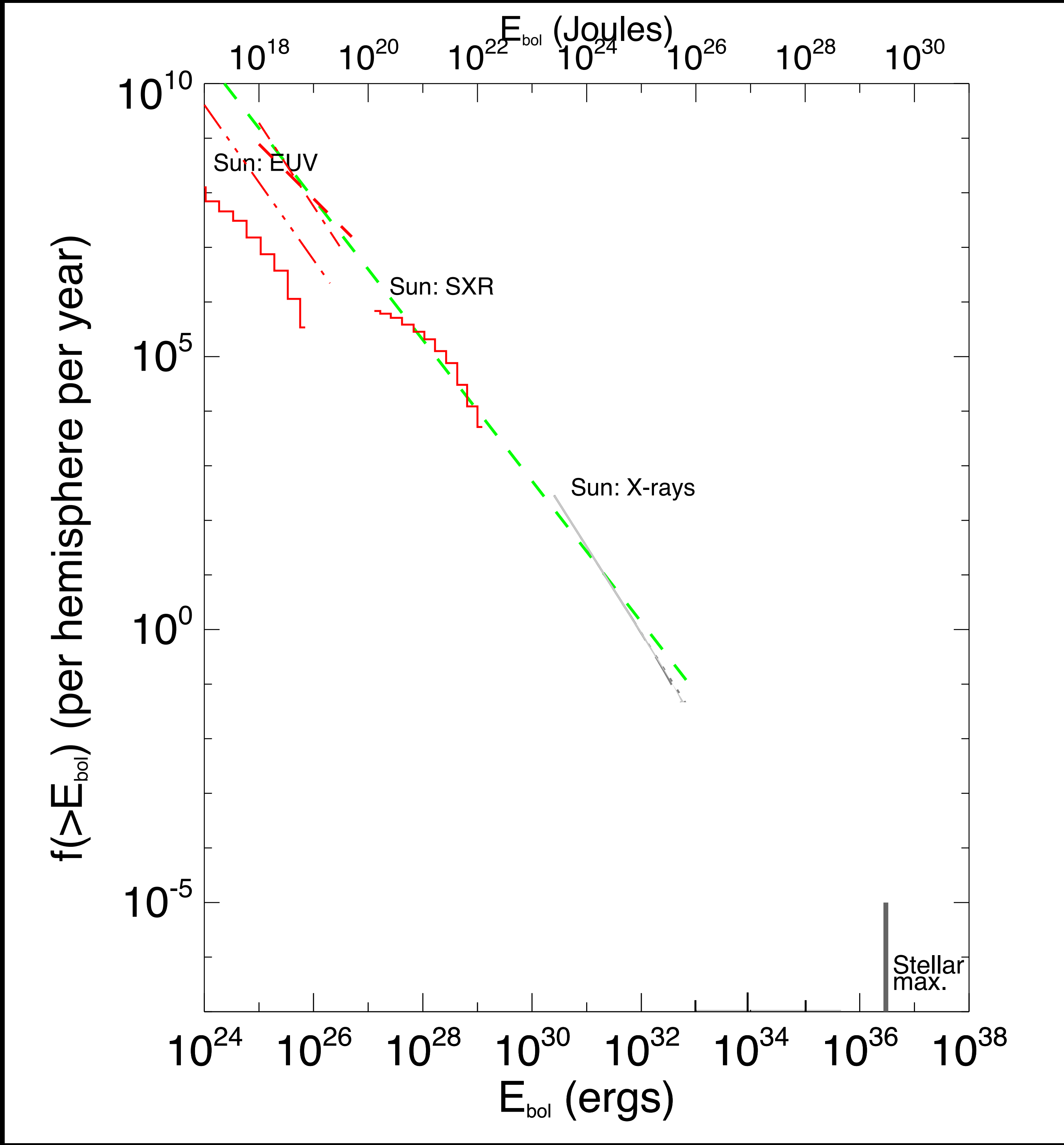
- Particle hits.
- Source misidentification: binary system, source confusion, period error (Notsu et al. (2013): “in some cases simply taking the highest peak can lead to choose spurious peaks at long timescales.”), ... (not likely comet impacts: C/2011 N3 ~10^{11}g & W3 ~10^{12}g at 600 km/s: 2 10^{26} - 2 10^{27} ergs)
- Calibration problem given unknown source spectrum
- Multiple events: percolation/sympathy
- Very strong dependence on rotation/age
- Low-statistics of solar events
- ...

Extreme solar flares



Extreme solar flares

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



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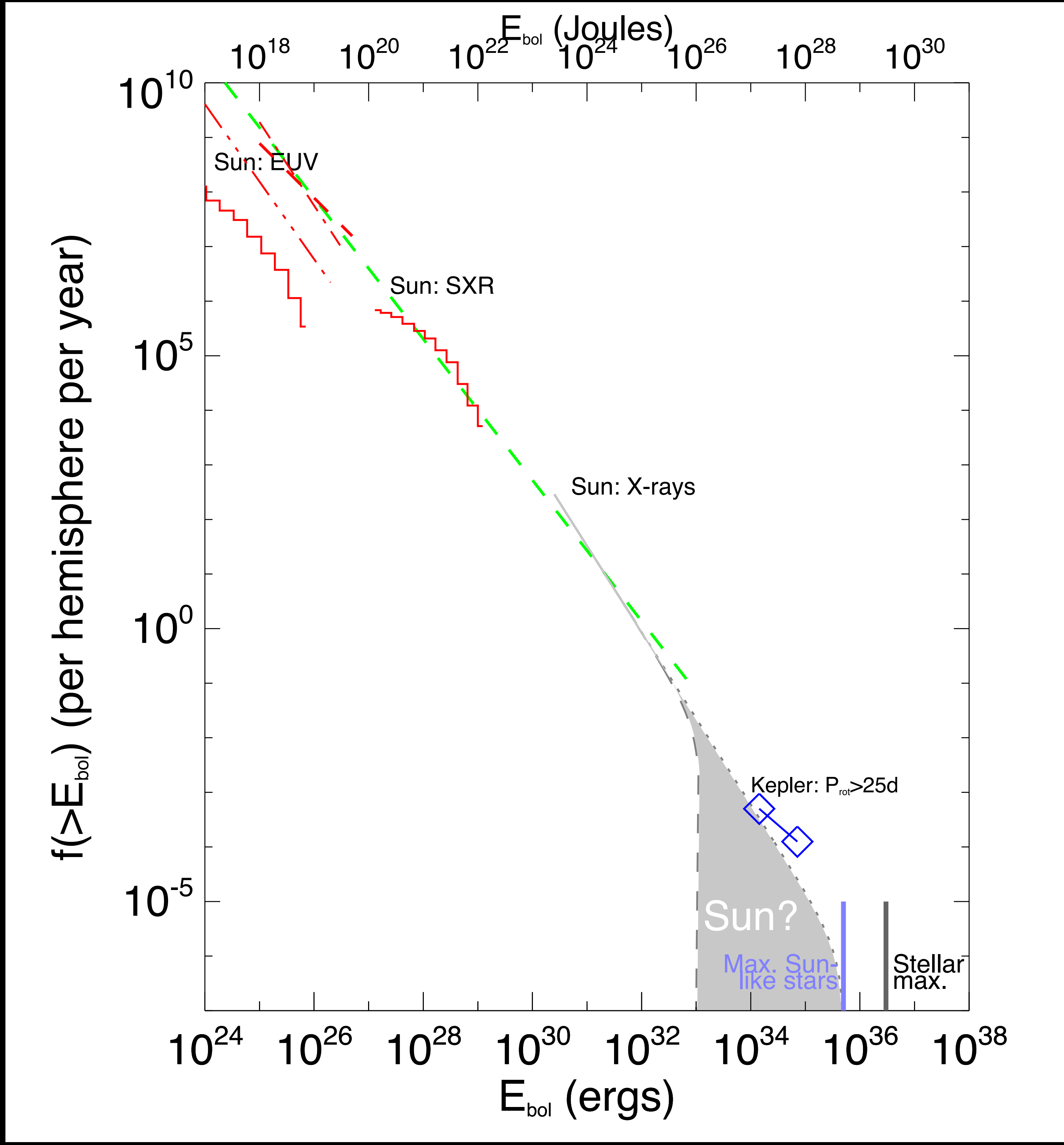
Kepler observations suggest continuation up to at least ~5 10^{35} ergs.



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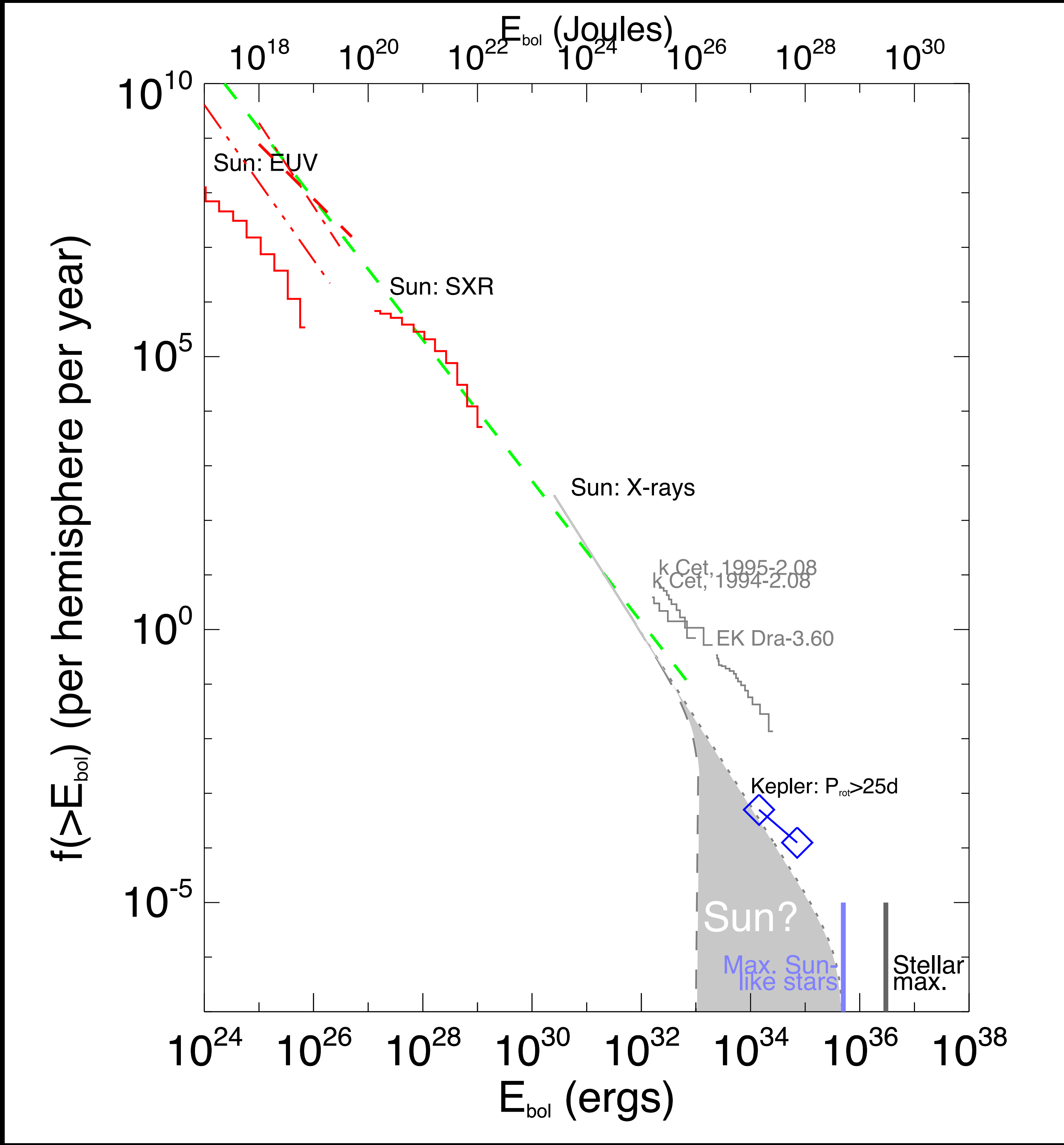
But the frequency scaling with more active stars fails.



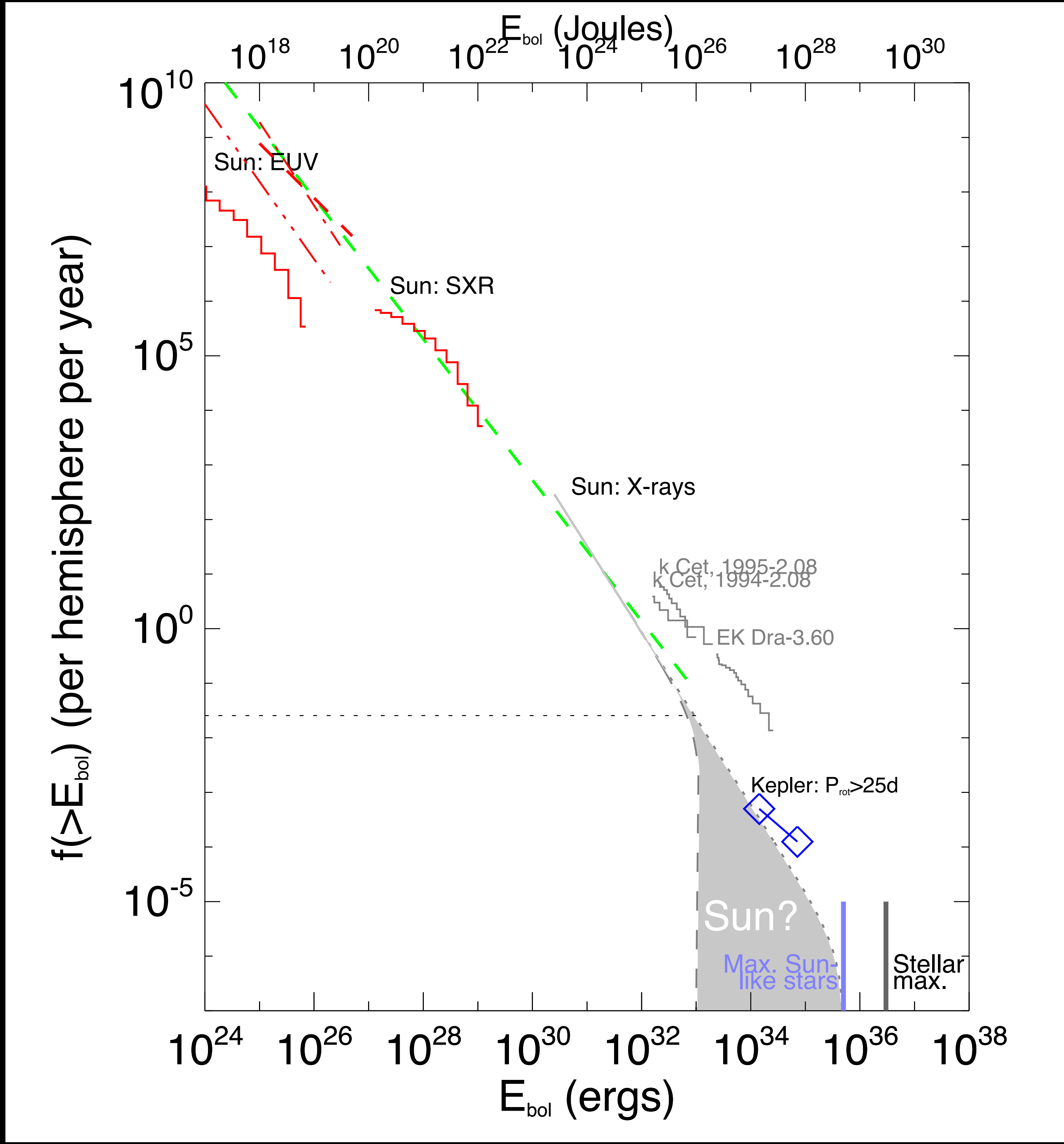
Extreme solar flares

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

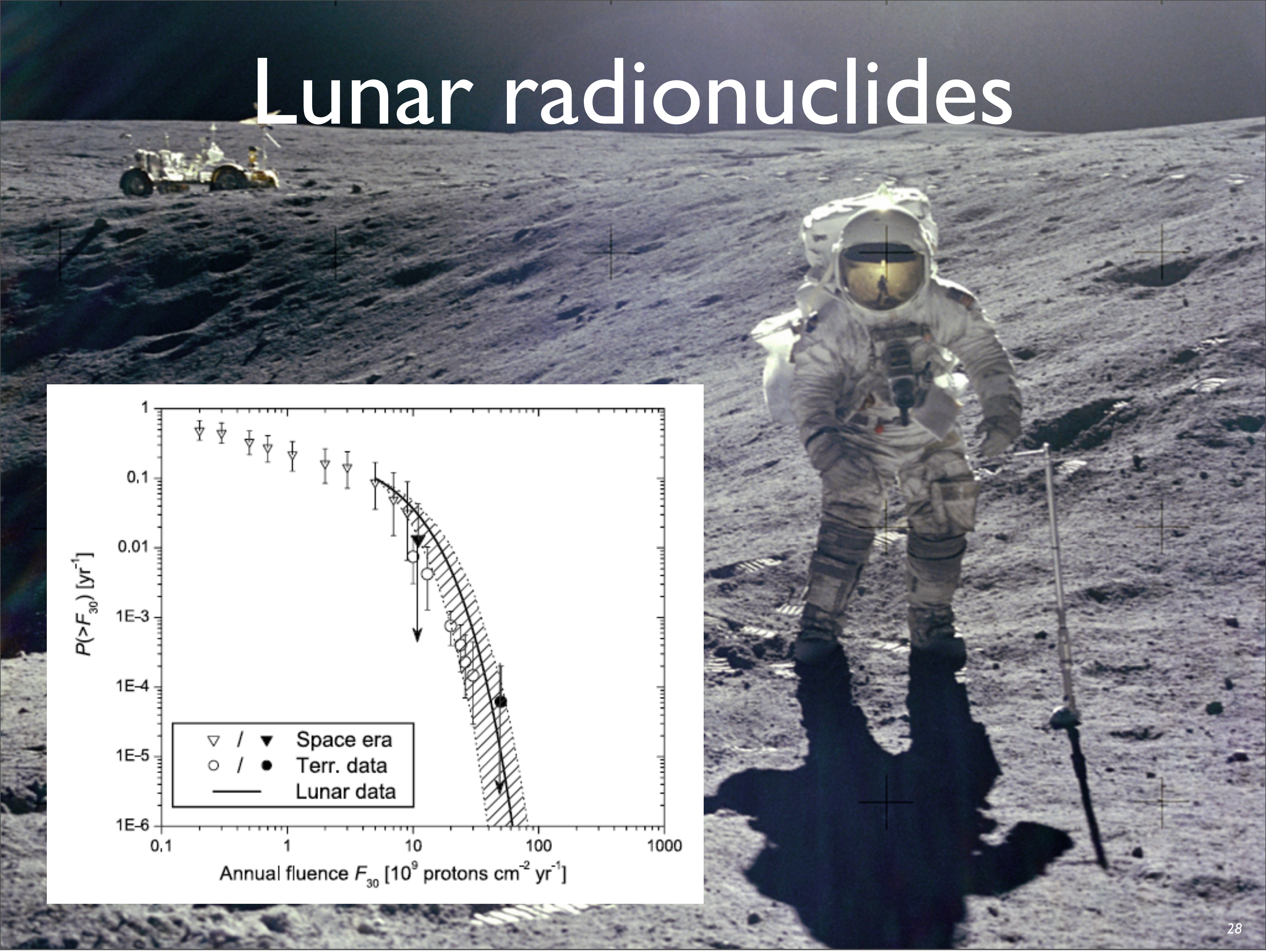
Kepler observations suggest continuation up to at least ~5 10^{35} ergs.

But the frequency scaling with more active stars fails.

Need to add more stellar observing time, improve understanding of energy distributions, and wait ...



Lunar radionuclides



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The largest imaginable magnetic storm

Vytenis M. Vasyliūnas

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.**

Available online 27 May 2010

Keywords:
Extreme magnetic storm
Dst index
Inflation of geomagnetic field

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.

The worst space weather

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 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.

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

The worst space weather

Stellar observations essential to establish largest possible flare from the Sun.

Radio-nuclide studies of lunar rocks and terrestrial ice and biosphere records need to be re-analyzed and extended in time and increased in S/N.

Models are needed to know the worst possible SEP and geomagnetic storm.

And, yes, it can get worse than we have seen to date ...