Solar Extreme Events

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1) Nature of solar irradiance variability
2) The quandary of the “superflare” stars
3) The tree-ring evidence
4) Assessment

The emphasis in this talk is on the astrophysics, rather than geoeffectiveness

Solar Irradiance Variations

Table 1 Identified variability mechanisms for solar total irradiance

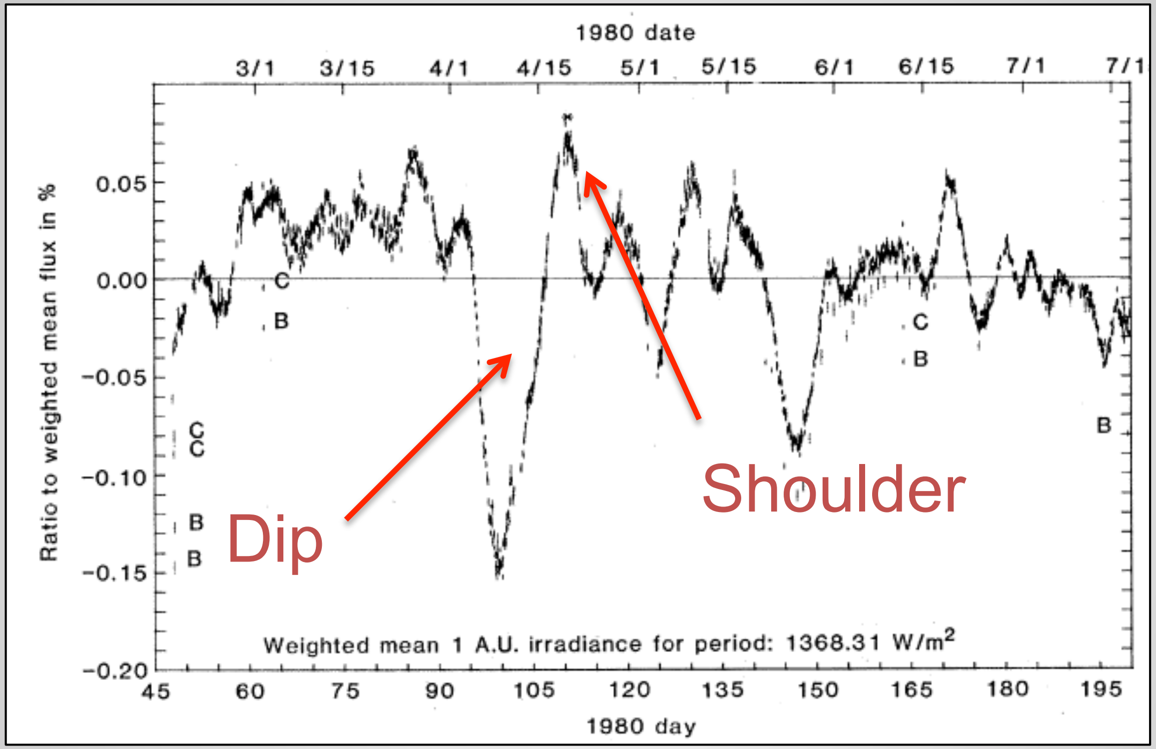
Mechanism	Time scale	Amplitude	Reference
Oscillations	5 min	Few ppm	Woodard & Hudson 1983
Granulation	Tens of min	Tens of ppm	Hudson & Woodard 1983
Sunspots	Few days	<0.2% peak-to-peak	Willson et al. 1981
Faculae	Tens of days	<0.1% peak-to-peak	Willson et al. 1981
Rotation	27 days	Variable	Fröhlich 1984
Active Network	11 yr	~0.1% peak-to-peak	Foukal & Lean 1988

Hudson, 1988

Plus (to be up-to-date):

Flares	Few min	Few hundred ppm	Woods et al. 2004
Secular	Cycle	150 ppm	Froehlich 2009
'Flicker'	Tens of min	Tens of ppm	Bastien et al. 2013 (Harvey 1985)

Sunspot TSI dips



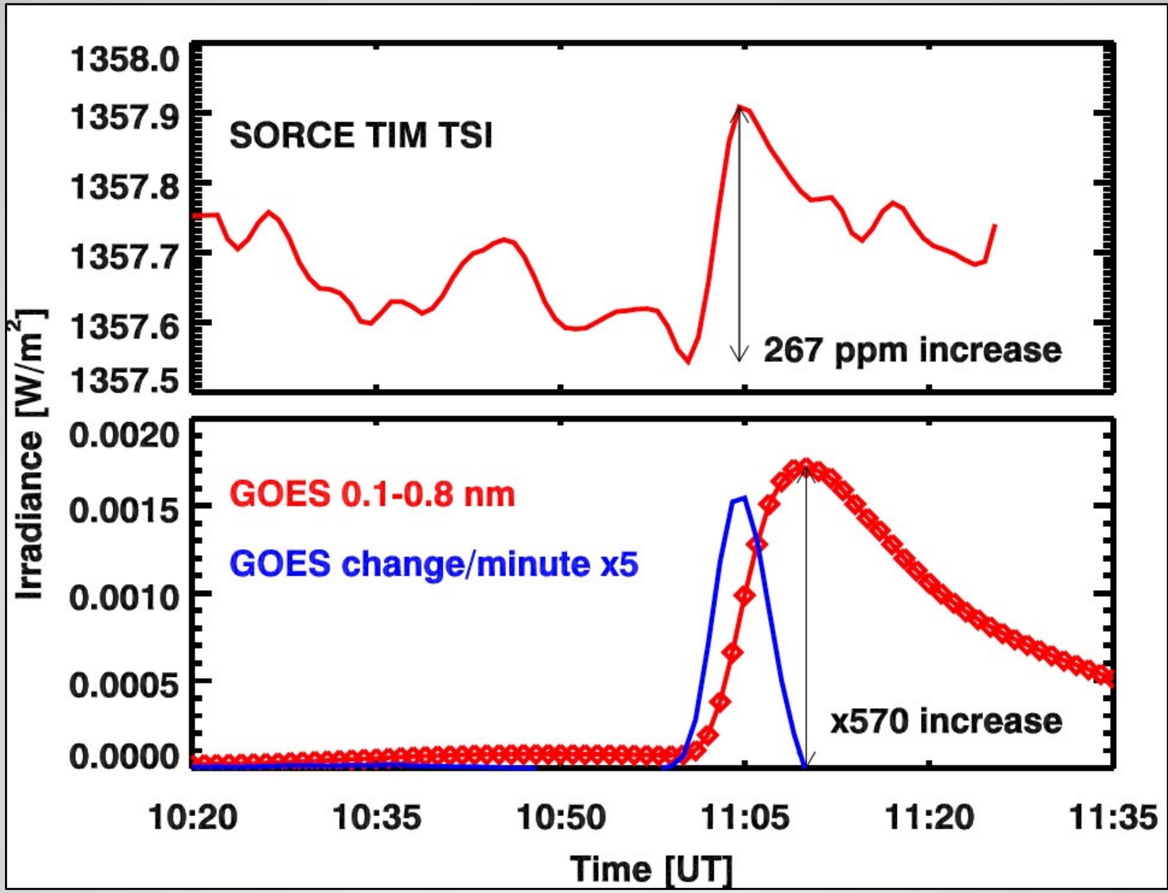
Willson et al. 1981

Sunspot "dips" last for about ¼ rotation and often have facular "shoulders"

Spots and faculae

- Sunspots are darker than their faculae are bright, especially early in their life.
- An individual dip lasts for about ¼ rotation, since the projected spot area is foreshortened.
- Facular excesses persist, and may dominate at the limb passages.

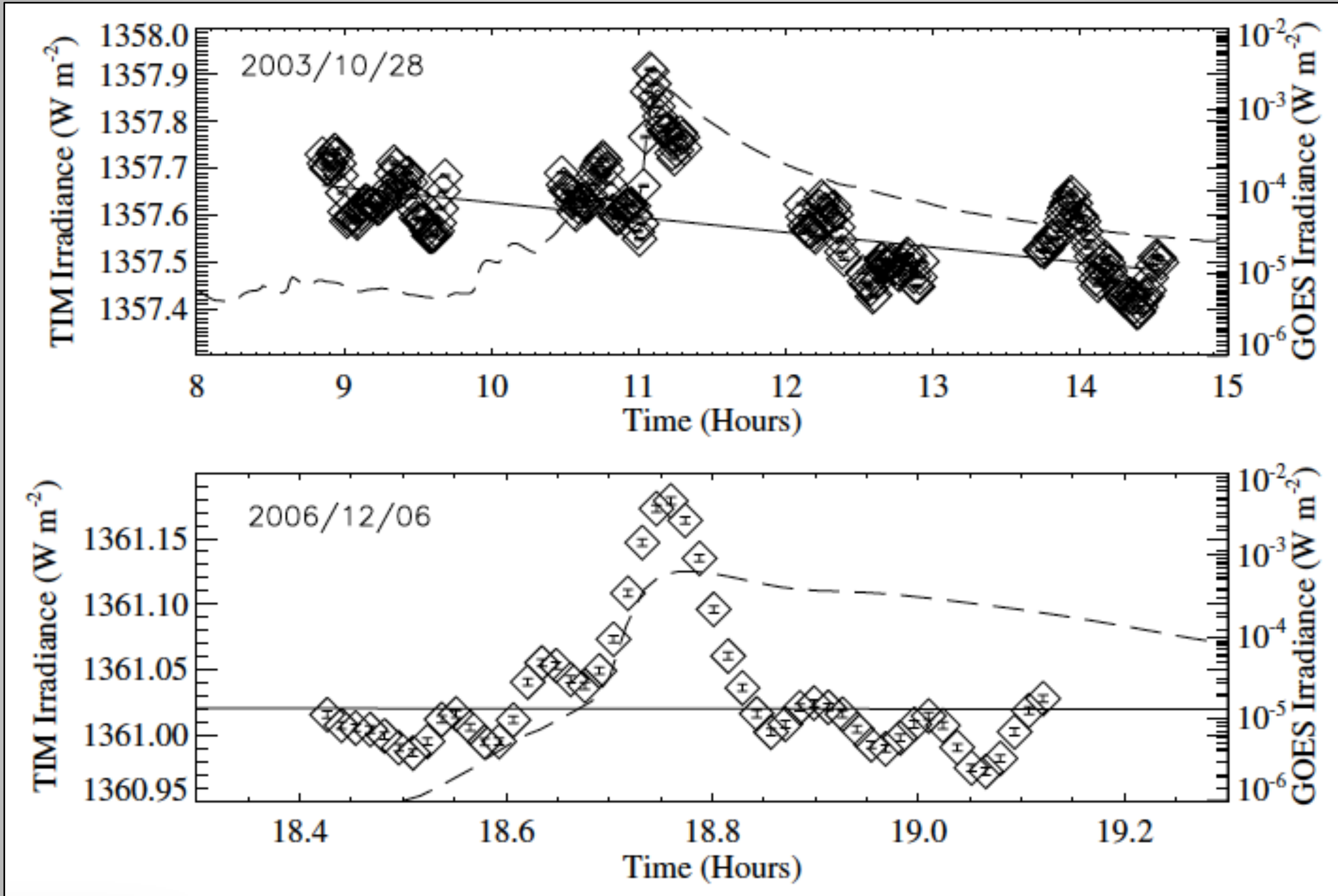
Flares in the TSI



Woods et al. 2004

• Note the clear association with the impulsive phase (cf. Kretzschmar, 2011): flare radiation is inherently *nonthermal.*

Flares in the TSI



Moore et al. 2014

Solar mini-superflares

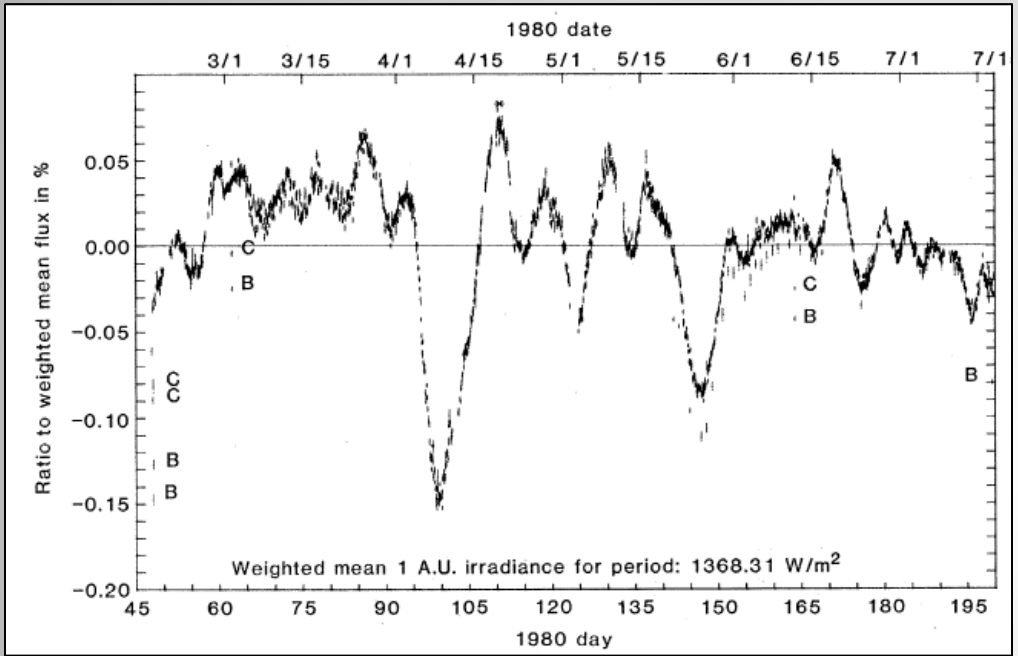
- Only two really credible TSI events thus far, in a time series of about 1/3 century.
- The TSI signatures closely match the impulsive phase: white-light flare, hard X-rays etc.
- Uncertainty in relation to Kepler superflare energy estimates.

  - Alternative flare paradigms?

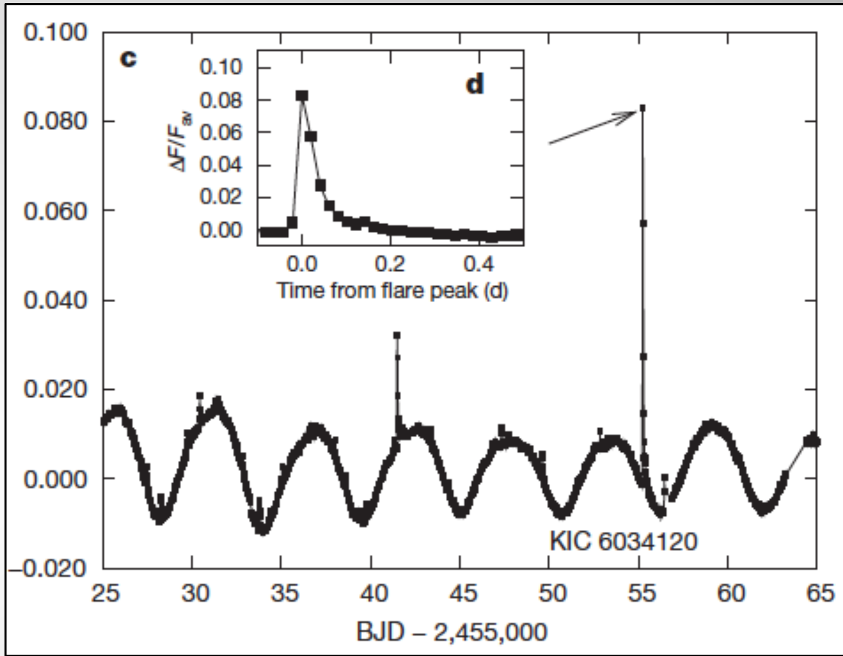
Increasing TSI flare sensitivity

- The limit at present comes from the background variability due to convection and p-modes.
- Most of this can be compensated and removed by comparison with images (J. Harvey idea).
- Lack of high time resolution severely limits our sensitivity for Sun-as-a-star flare observations.

Solar-stellar quandary



Willson et al. 1971



Maehara et al. 2012

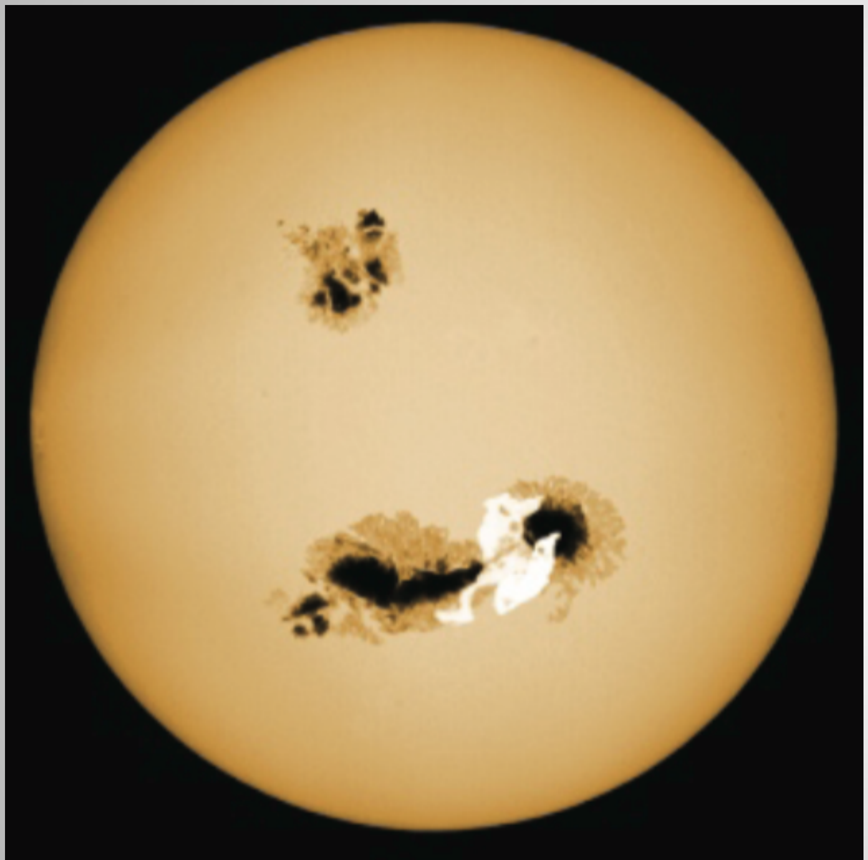
- Faculae are important for solar variability, but *not* for Kepler "superflare" stellar quiescent variations
- There are toy models to explain this, but a lot of unknowns get glossed over

Solar-stellar quandary

• The Sun has short-term weak chaotic variability, *with dips.*
• These Kepler stars have nearly sinusoidal variations, *with flares.*

These light curves could not be more different; where's the paradigm?

The Kepler "superflares"

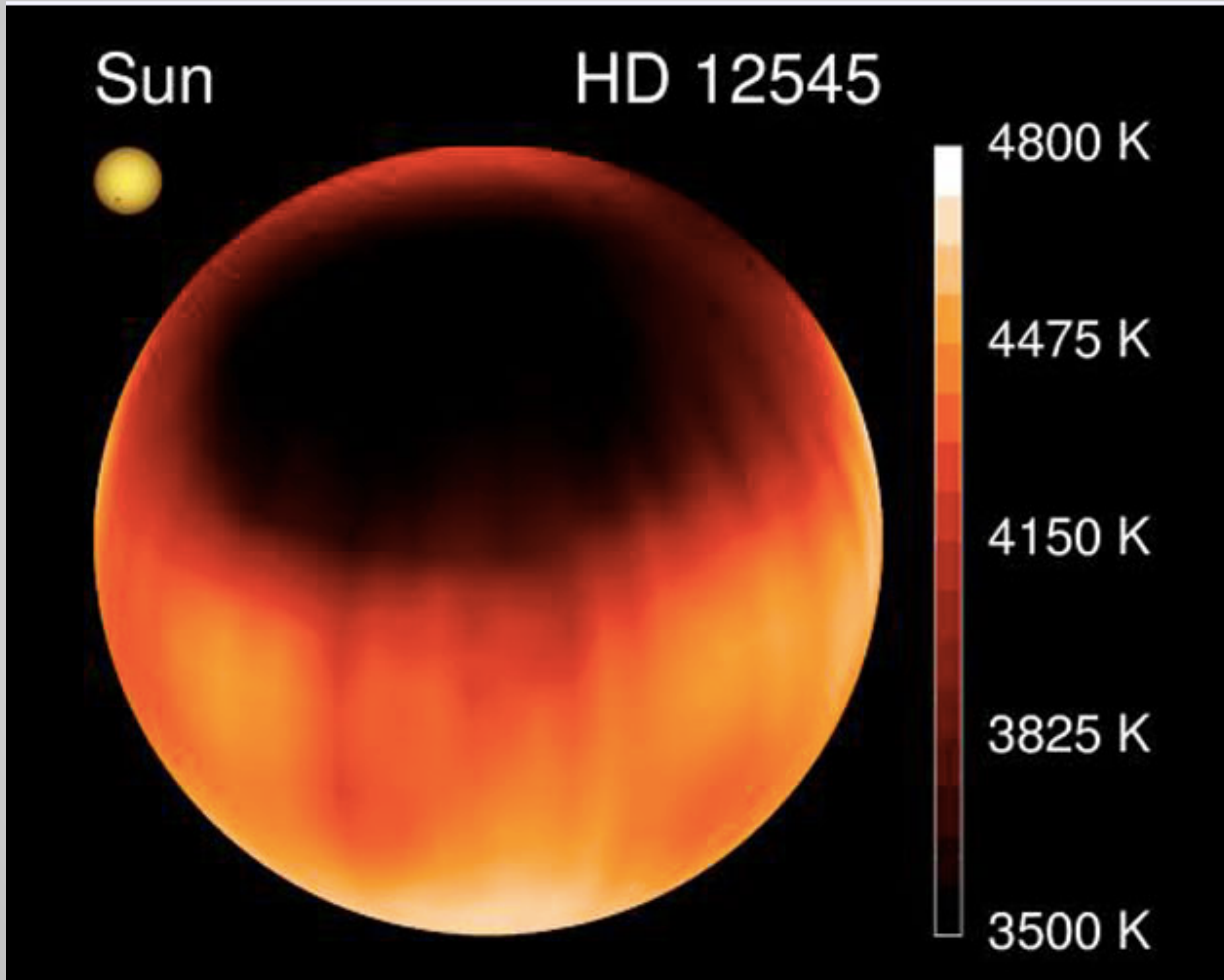


JAXA

• Where are the faculae? The smooth variations suggest that their behavior is very different from the solar case.

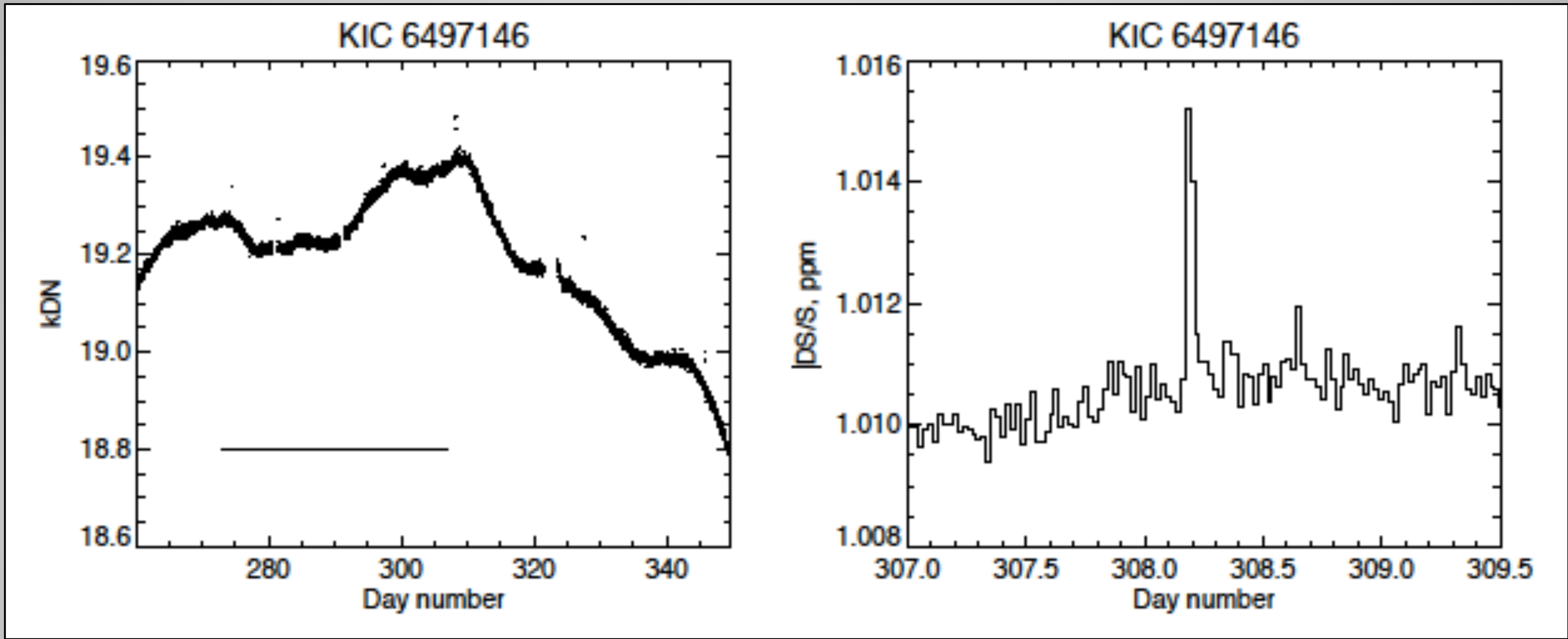
• Stellar modelers tend to ignore the methodology developed for solar TSI.

A Pole-on View – no dips?



An RS CVn star with a huge "spot": APOD 2003-11-02

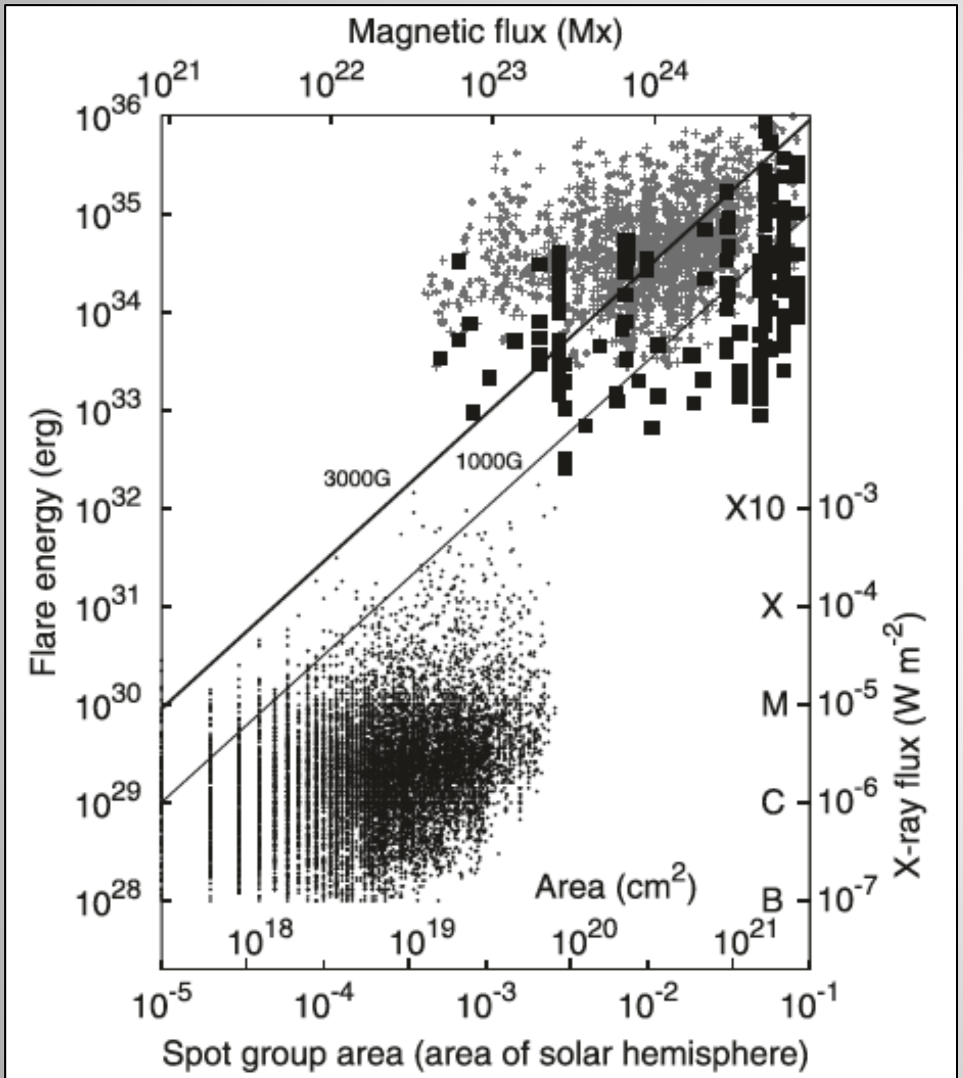
The case of Kepler-438b



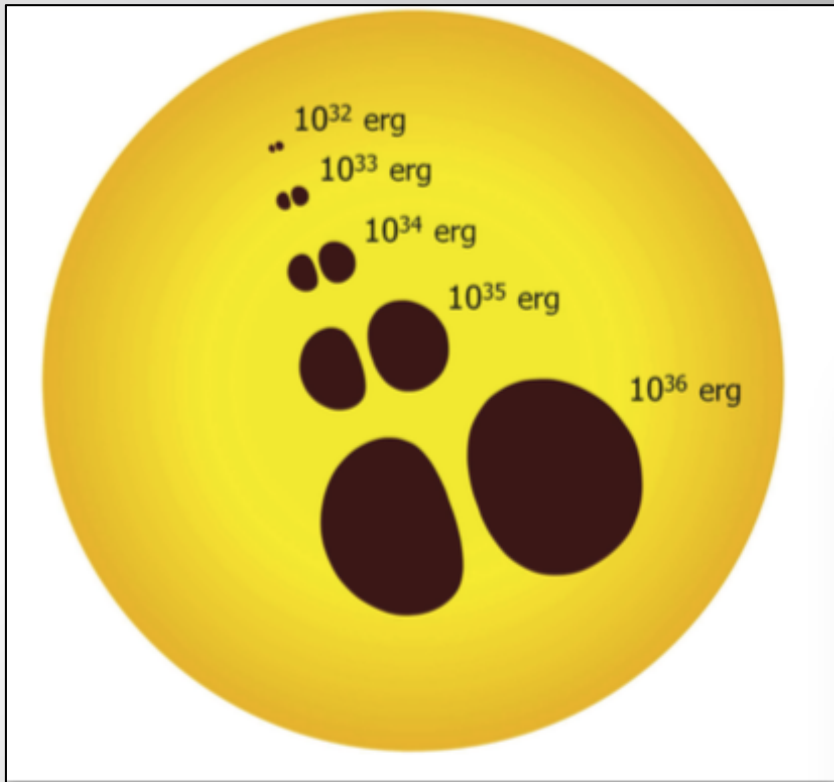
Armstrong et al. 2015

KIC00649146 is an M dwarf with planets *and* superflares. There is no evidence for solar-like "dips" in its lightcurve. The detection of planets suggests that we see this star in its equatorial plane.

The Kepler "superflares"



Maehara et al. 2015



Aulanier et al. 2014

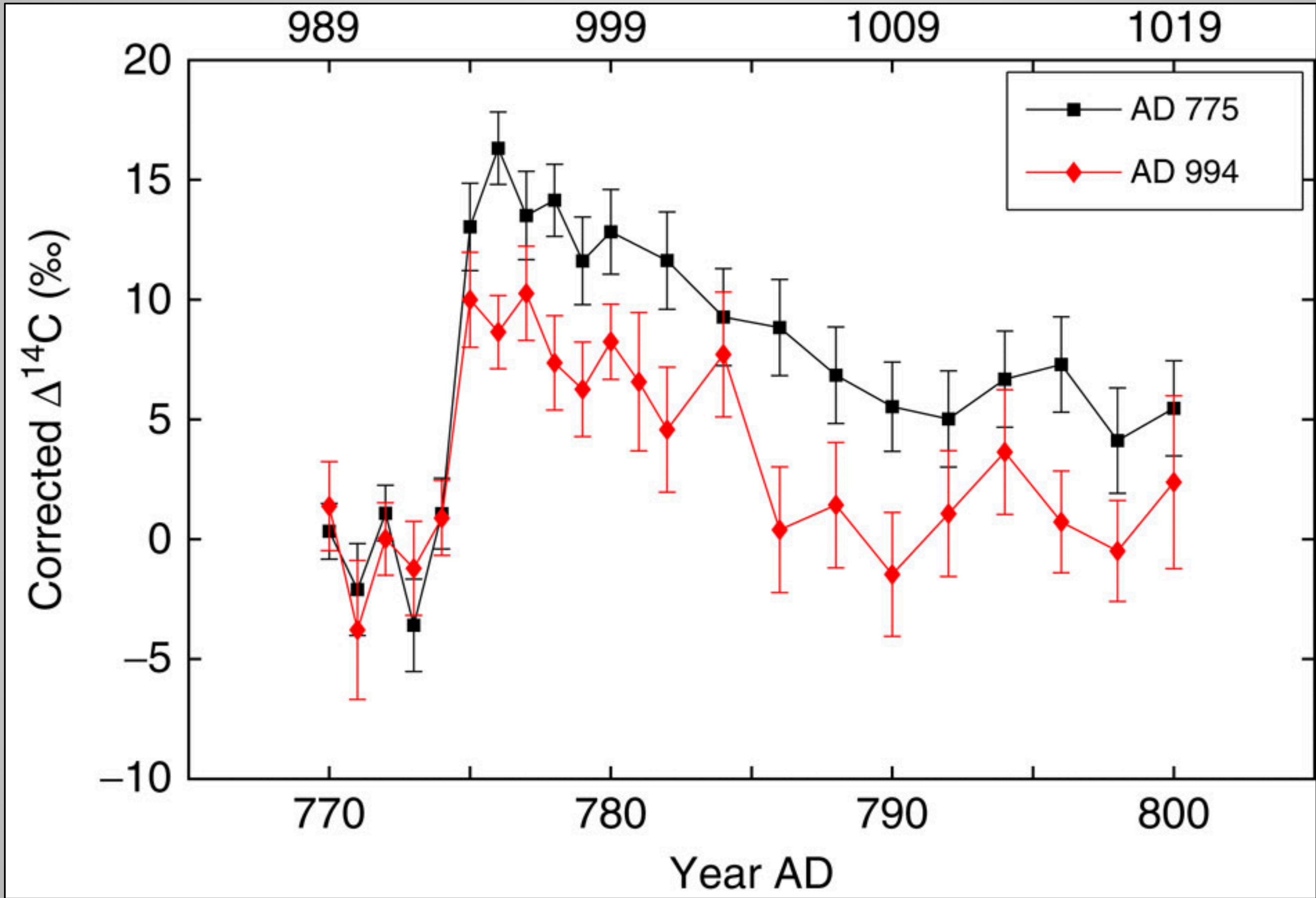
"Give me a big spot, and I can give you a big flare."

Radiodendrochronology

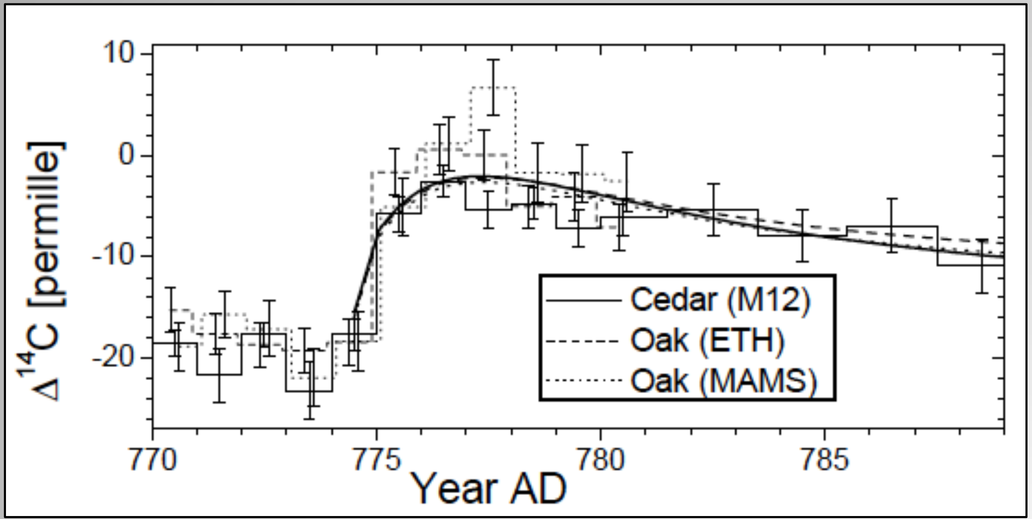
Some *Sugi* (cedar), perhaps at Yakushima, Japan

Nagoya graduate student Fusa Miyake

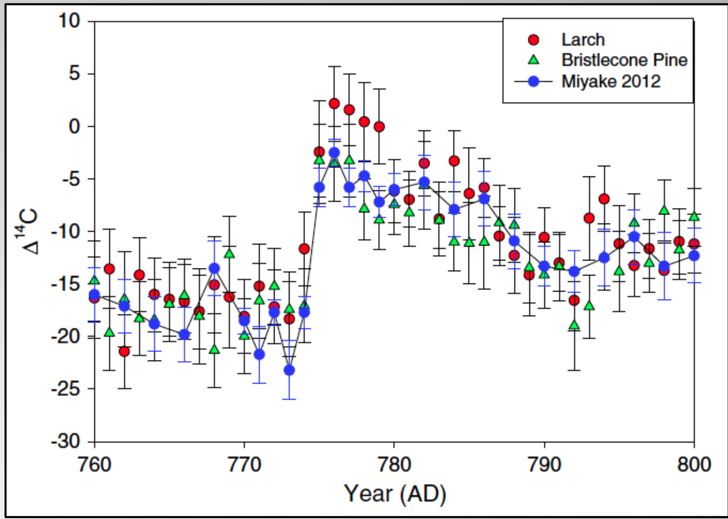
Extreme events in tree rings



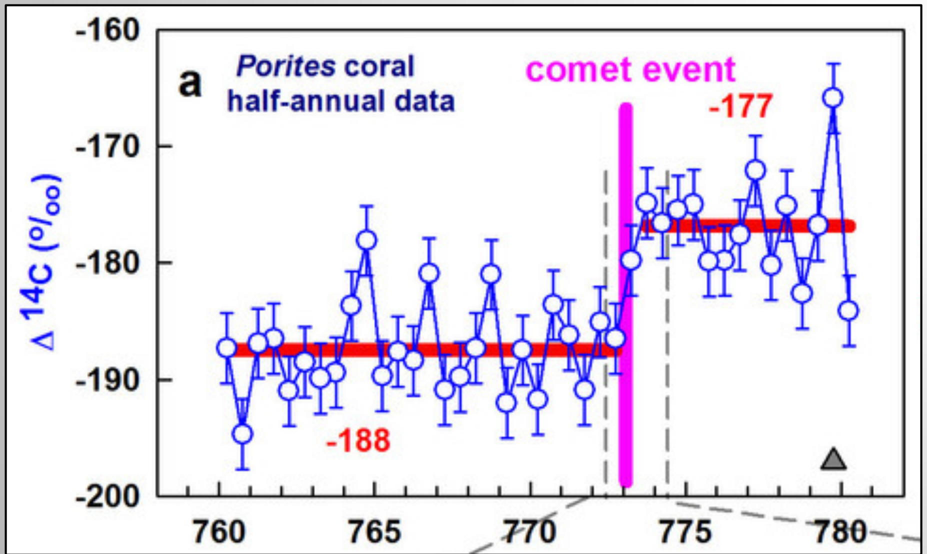
Miyake et al. 2013



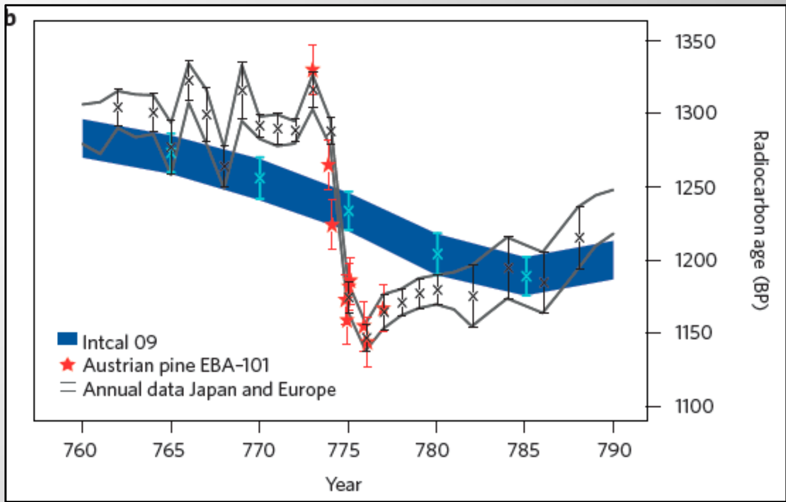
Usoskin & Kovaltsev 2013



Jull et al. 2014



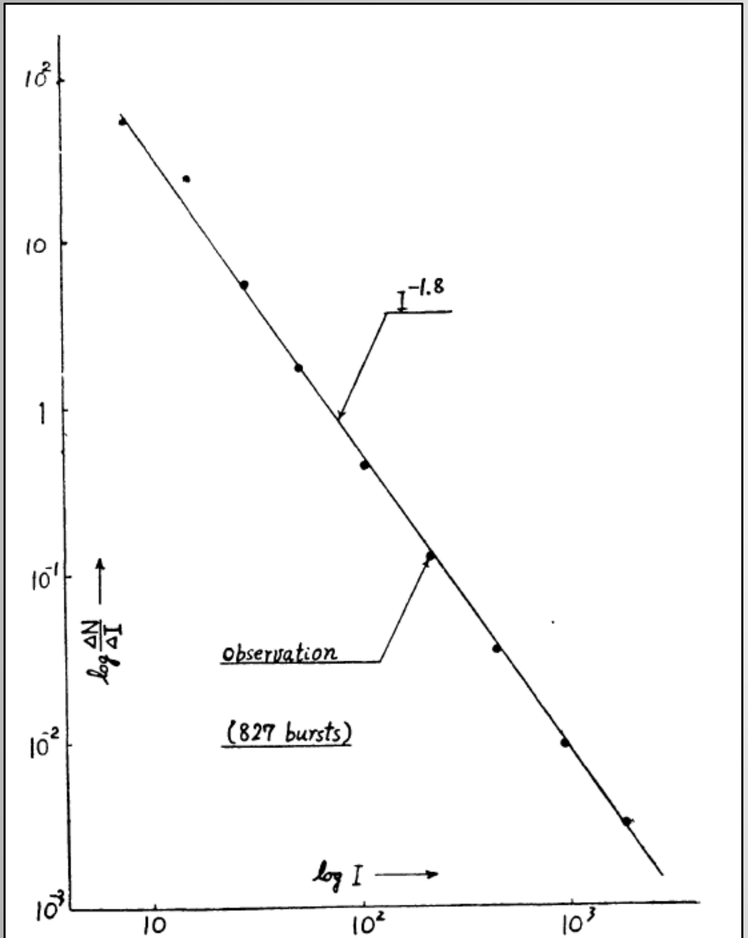
Liu et al. 2014

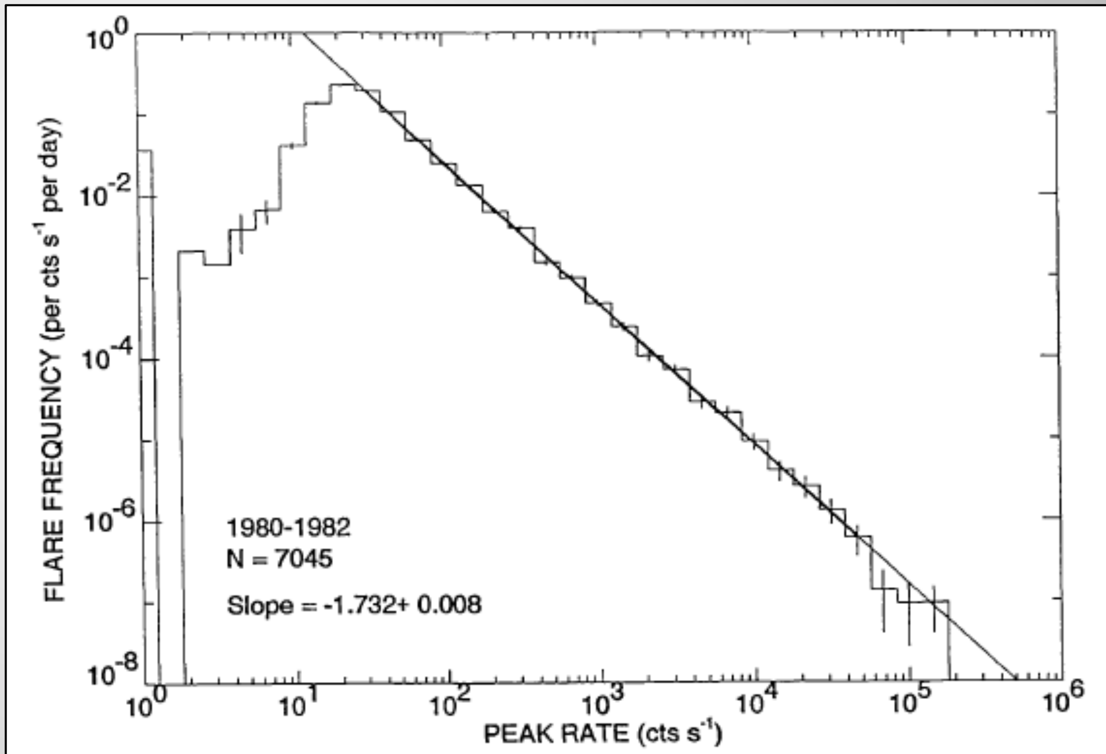


Büntgen et al. 2014

The problem of the power law:

a *break* *is required*





Akabane, 1956

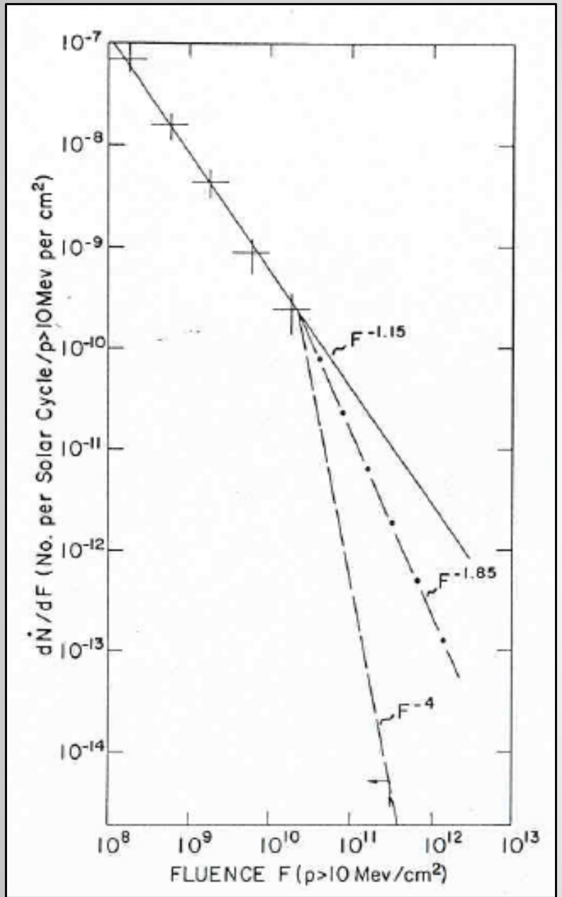
Crosby et al., 1993

Why is a break required?

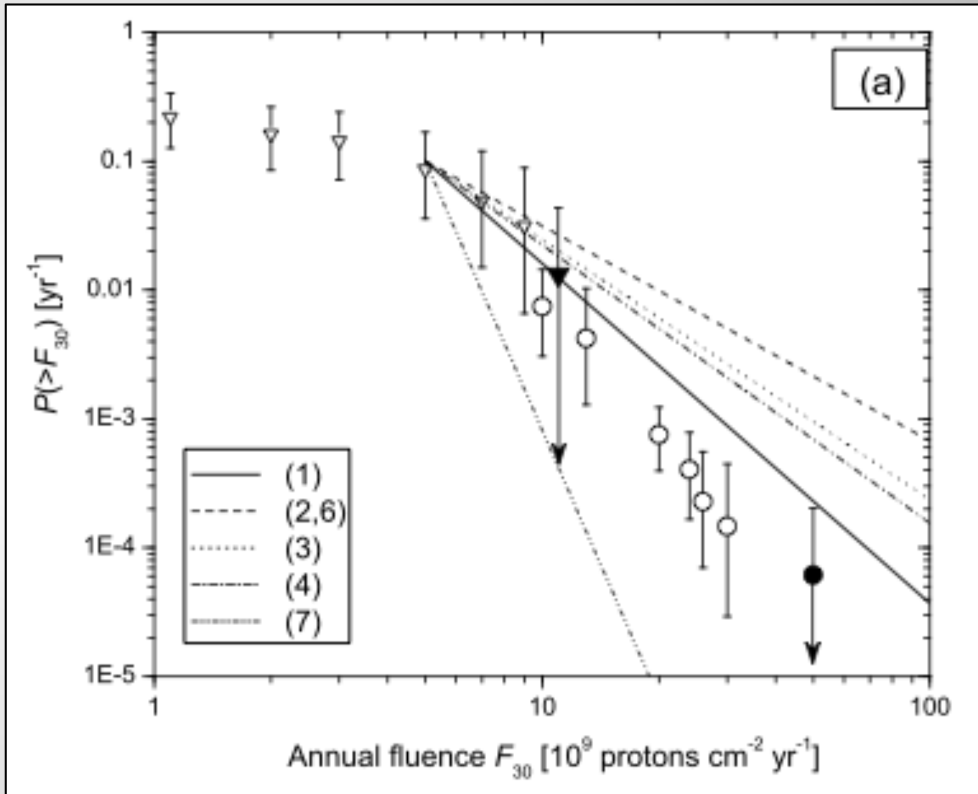
• The power-law index is so flat (<2) that the total energy would diverge without a break (Collura et al. 1988; Hudson 1991).

• Remark: the index is so flat that *nanoflares* may be irrelevant.

Can we see the break in SEPs?



Lingenfelter & Hudson 1980



Kovaltsov & Usoskin 2014

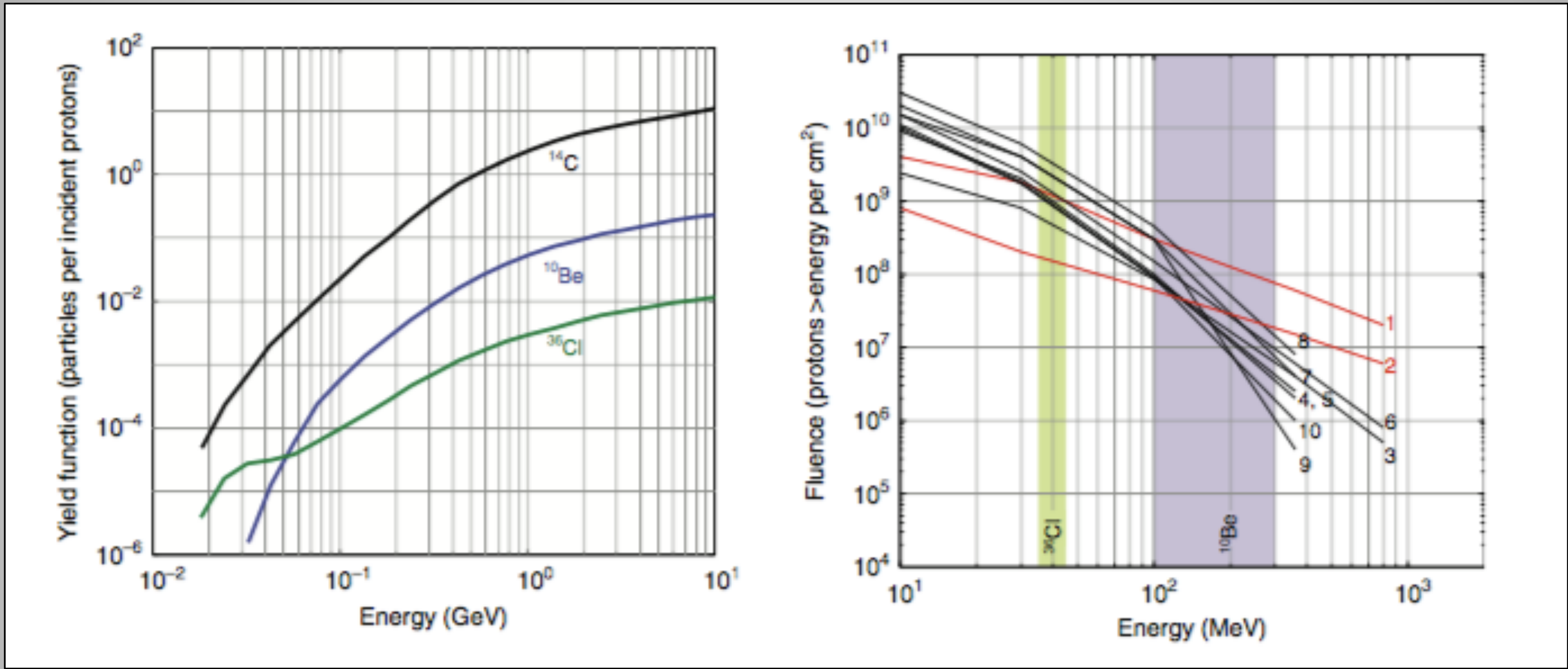
How do we interpret the break?

- The relationship between SEP fluence and event energy is very complicated:
  - Geometry (cf. July 2012 non-event)
  - Acceleration physics (saturation)
  - CME on/off problem (AR12192)

The breaking news

- Radiosotopic fingerprints from isotope patterns (Mekhaldi et al. 2015) are available.
- This fingerprint points towards the Sun as a cause (particles, rather than photons).
- The key distinction in detectability appears to be in the SEP spectral distribution.

The fingerprint



The events in red (right panel) are the two SPEs for which hard spectra occurred in the historical era: SOL1956-02-23 and SOL2005-01-20. These match the tree-ring requirements for the prehistorical events.

Assessment

- Can we predict extreme events? - No
- Can we predict extreme events statistically? - Maybe
- Should our prior include (a) superflares on Kepler stars, or (b) tree rings?- Tree rings
- See J. Love, "Credible occurrence probabilities for extreme geophysical events…" (GRL 2012): the Bayesian "credibility" intervals are

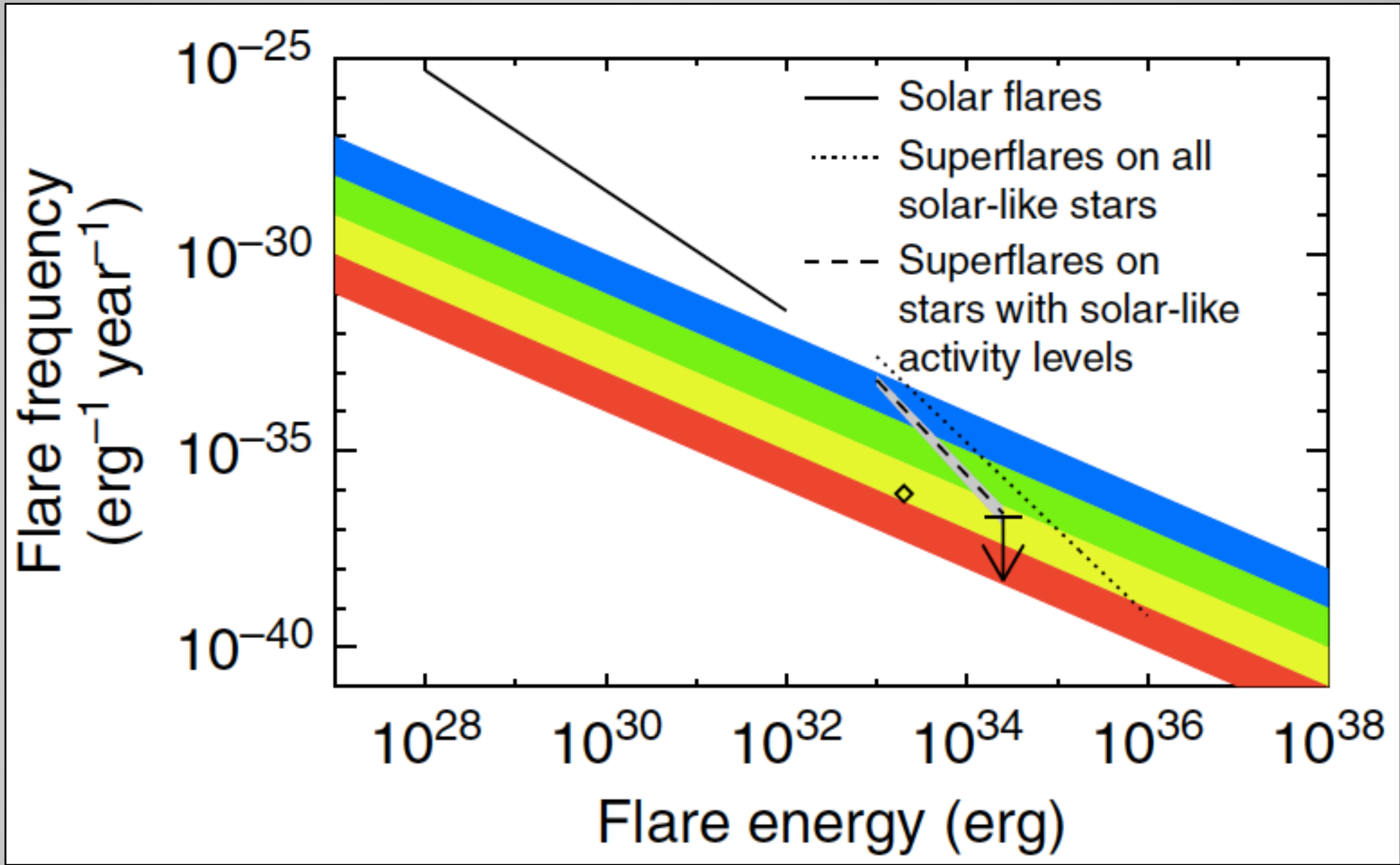
$$C_z(\lambda|k) = [(\sqrt{k} - z/2)^2, (\sqrt{k} + z/2)^2]$$

Evaluation

$$C_z(\lambda|k) = [(\sqrt{k} - z/2)^2, (\sqrt{k} + z/2)^2]$$

- For a Carrington-class event, Love's formula gives a 68.3% interval of [0.016, 0.137] events per decade.
- He says "The 10-yr recurrence probability for a Carrington event is somewhere between vanishingly unlikely and surprisingly likely."
- I think the main point is that the confidence interval has a width approaching a factor of 10.

Long-term distribution functions



Karoff et al. 2016

Solar flares: 1980-1989 (Crosby et al. 1993)
Dotted line: Shibayama et al. 2013
Rainbow: one flare per unit time (year… millennium)

Extreme events

- The Kepler superflares and the radiosotope events suggest that more energetic solar flares might occur.
- The weight of evidence for the tree-ring radiosotopes now implicates the Sun.
- To locate the break for solar flares, we need TSI observations at *higher time resolution.*