Carrington Events

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- History
- What is a Carrington Event?
- (What is any event?)
- Tree rings and stellar flares
- Will an extreme event smite us?

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Who was Carrington?

Cliver & Keer 2013

- An English advanced amateur, independently wealthy (b. 1826)
- He was *not* Lord Carrington, and not related to him
- He left no picture we know of, but his effects on MNRAS are clear

Precise sunspot measurements

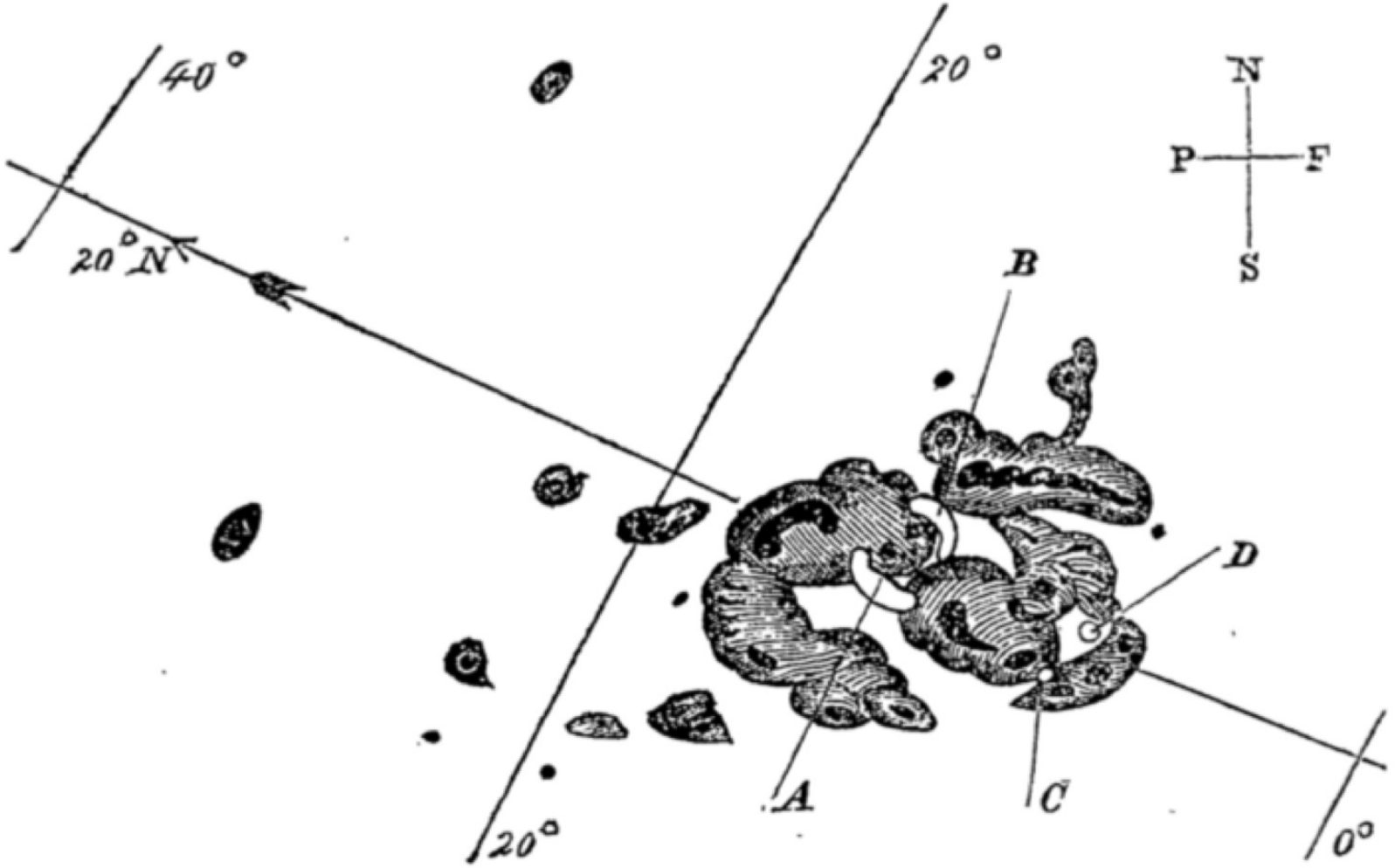
Prosser 2019

- Carrington made exact sketches via projection onto a screen of a “pale distemper of straw”

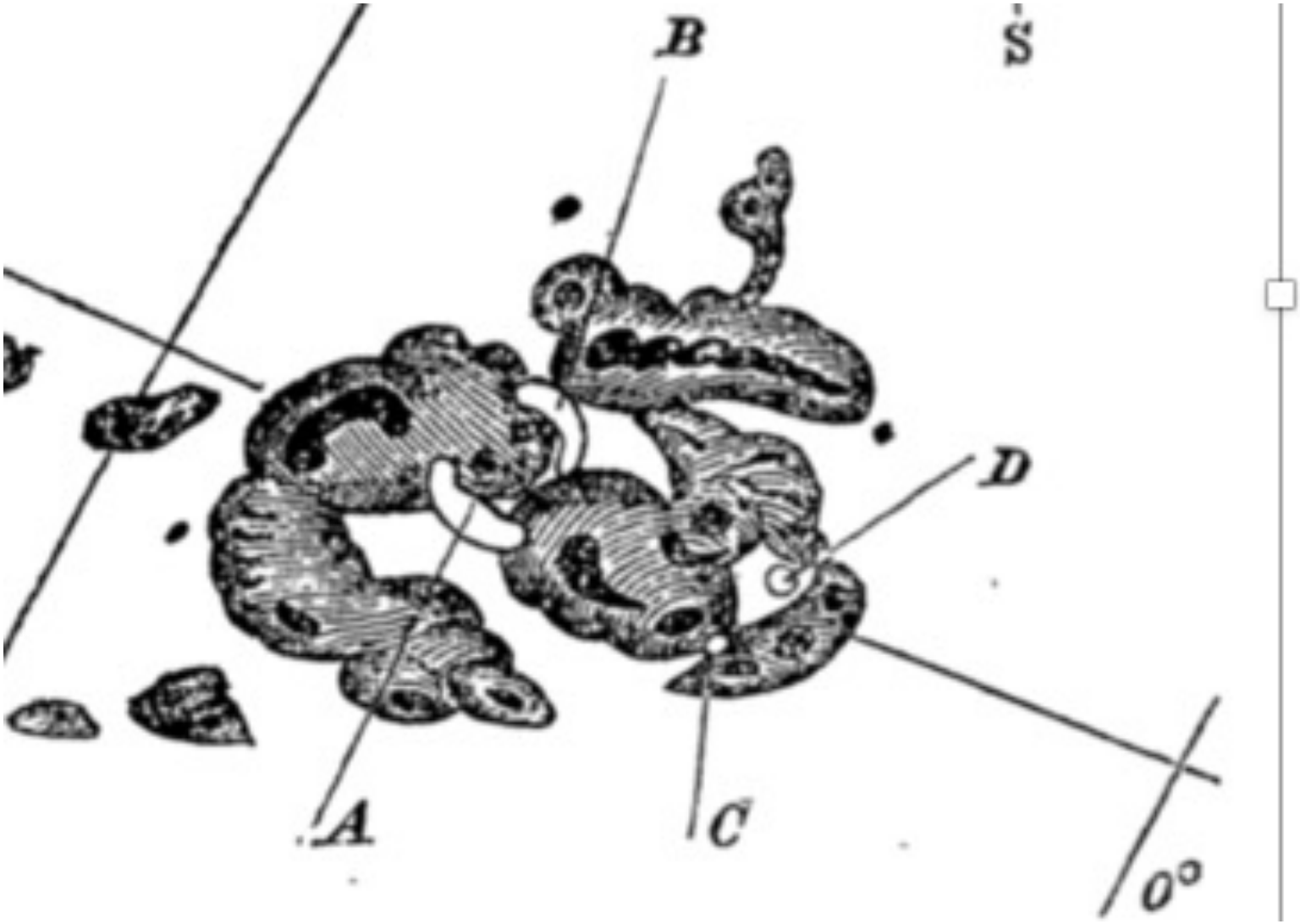
- He also used timing for precise definition of the geometry

- On this huge spot group in 1859, he had just finished his measurements when the flare popped off

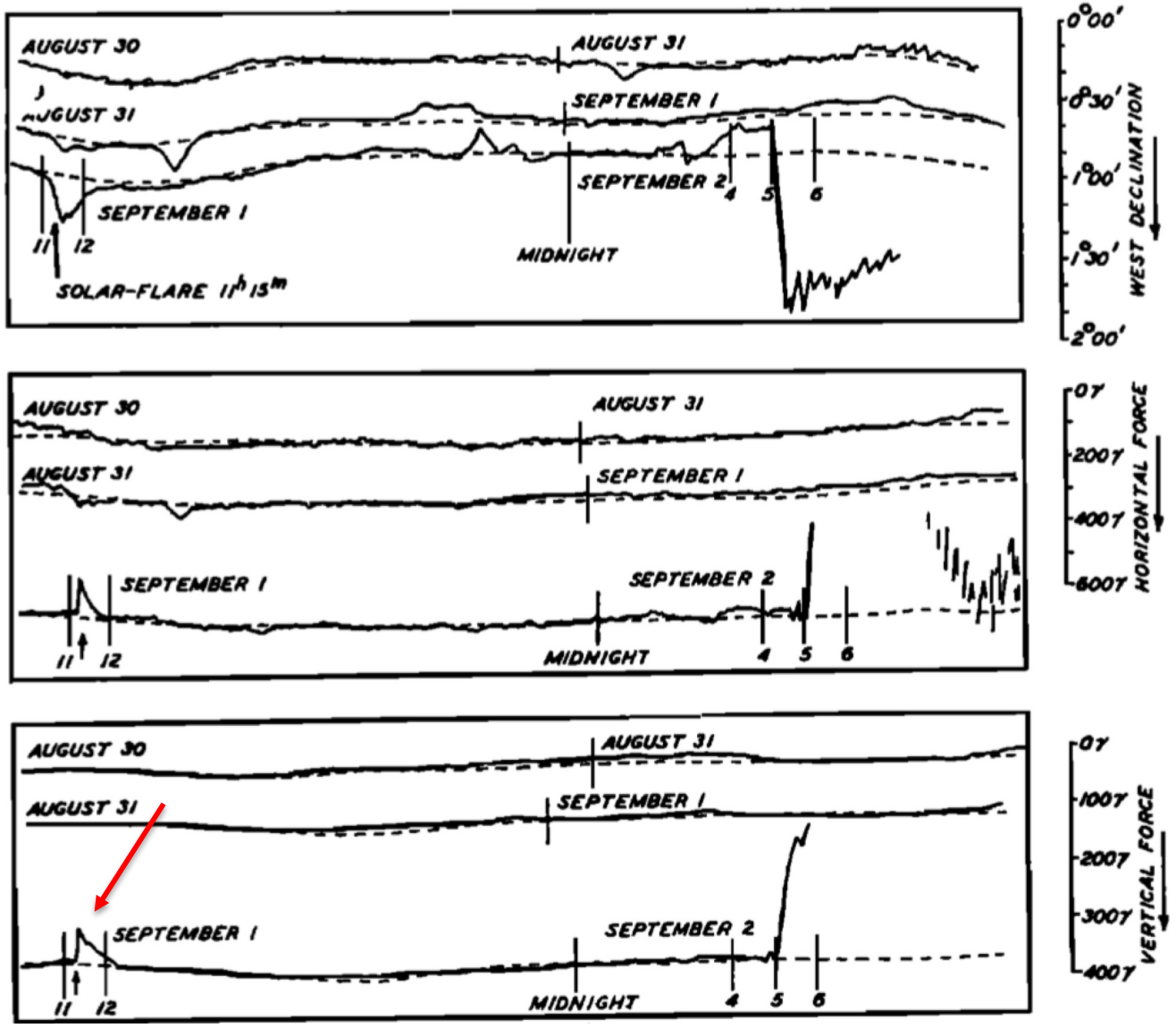
The Flare



The Flare



The Consequences

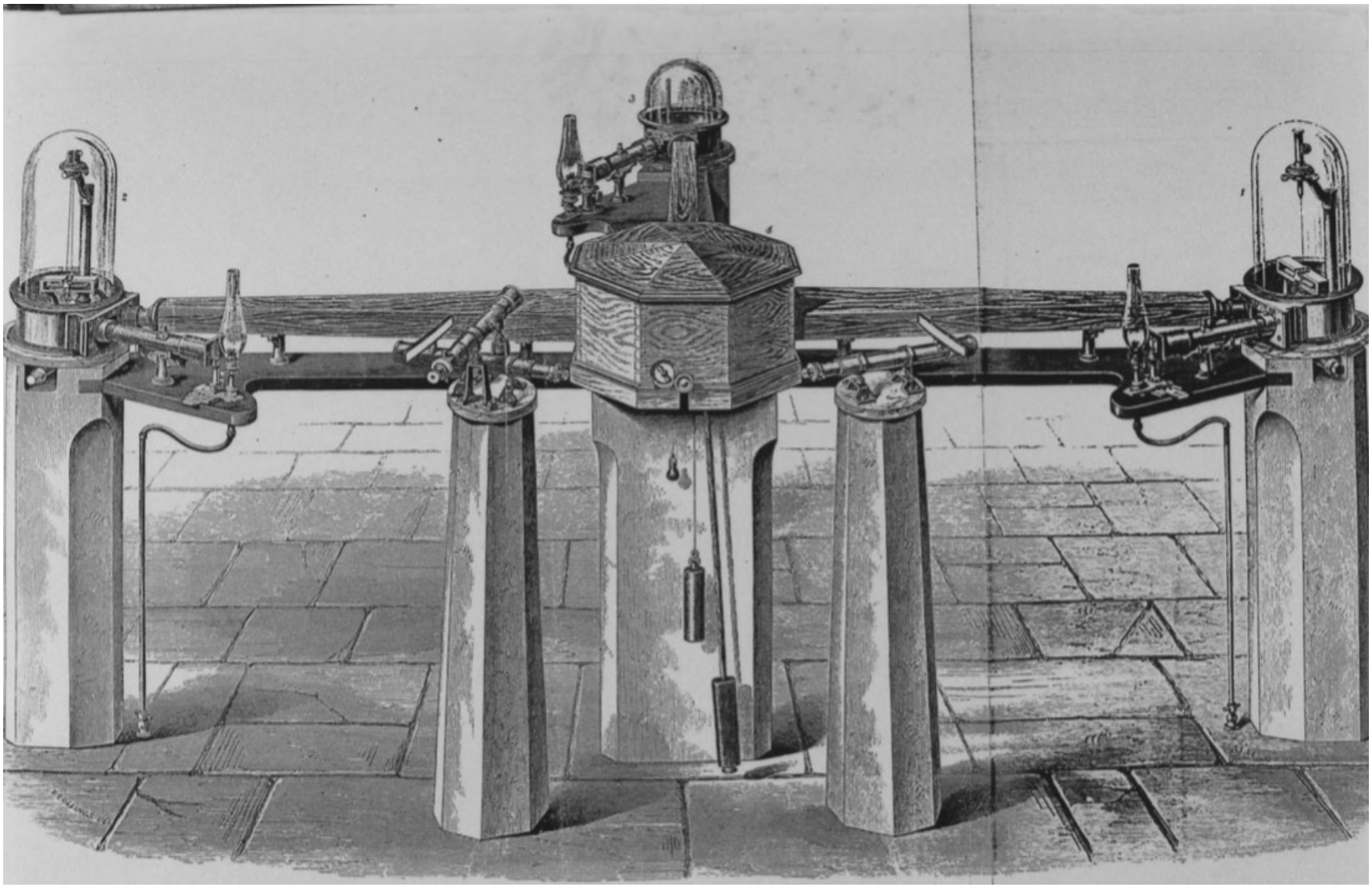


- The diurnal pattern
- The "crochet," aka "Solar Flare Effect"
- The storm sudden commencement
- A superstorm:
  - Dst -900 nT
  - Aurora in Havana

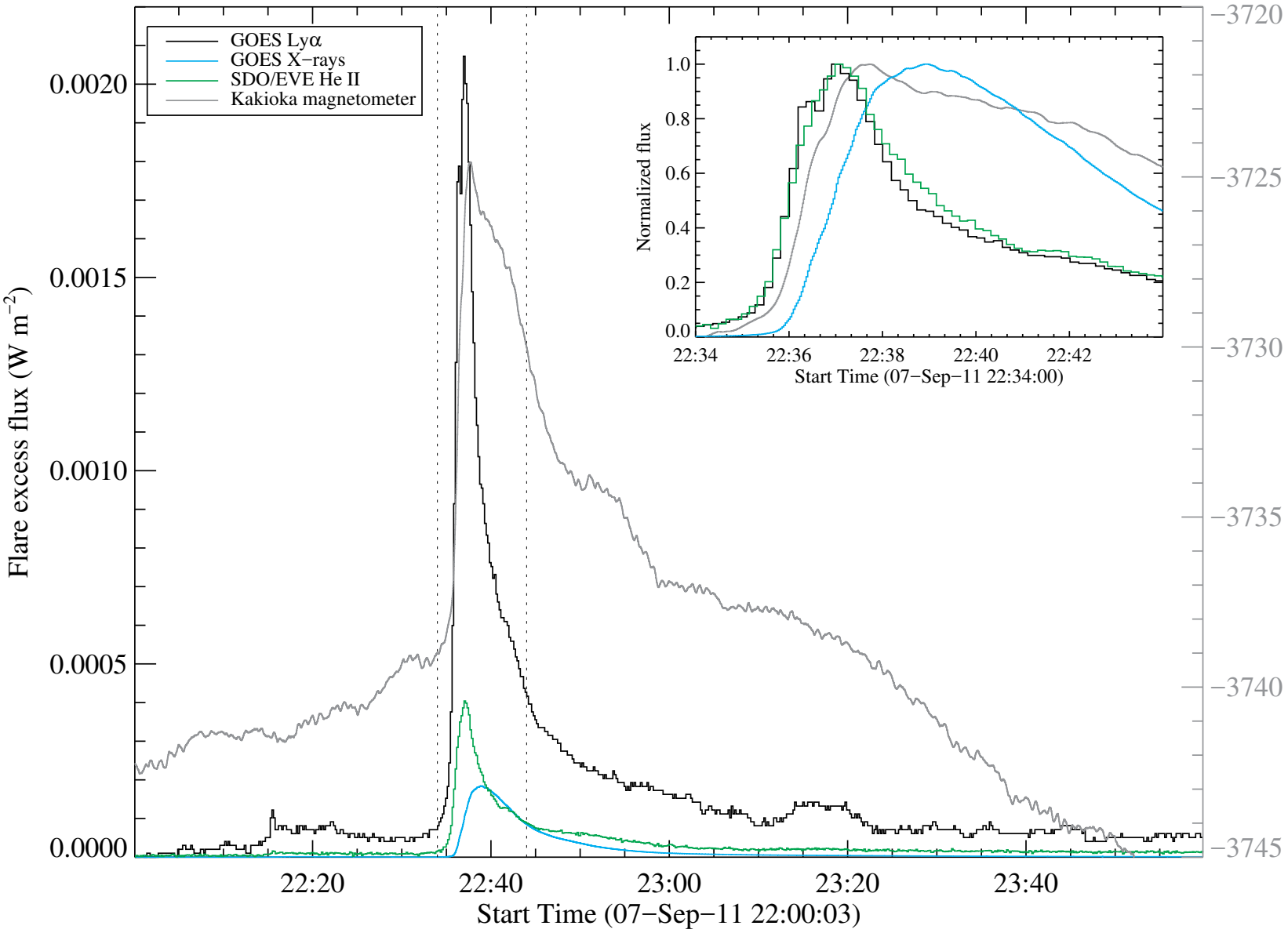
Credit E. Loomis for following up with The terrestrial effects (Shea & Smart 2006)

Balfour Stewart, 1860

A self-recording magnetograph



A modern crochet



Milligan et al. 2020
Laura Hayes?

How important?

The Carrington event was among the top few events, or perhaps top, in:

- Crochet (SFE) amplitude
- Storm magnitude (Dst)
- Auroral extent in latitude
- Sun -> Earth ICME travel brevity

So… how energetic was the flare itself?

- Carrington's own sketch and description
- the crochet as a proxy

A simple energy estimate

- Flare intensity: roughly double the quiet photosphere
- Flare area: 100 MSH (~0.01% of solar disk)
- Flare duration: 300 s

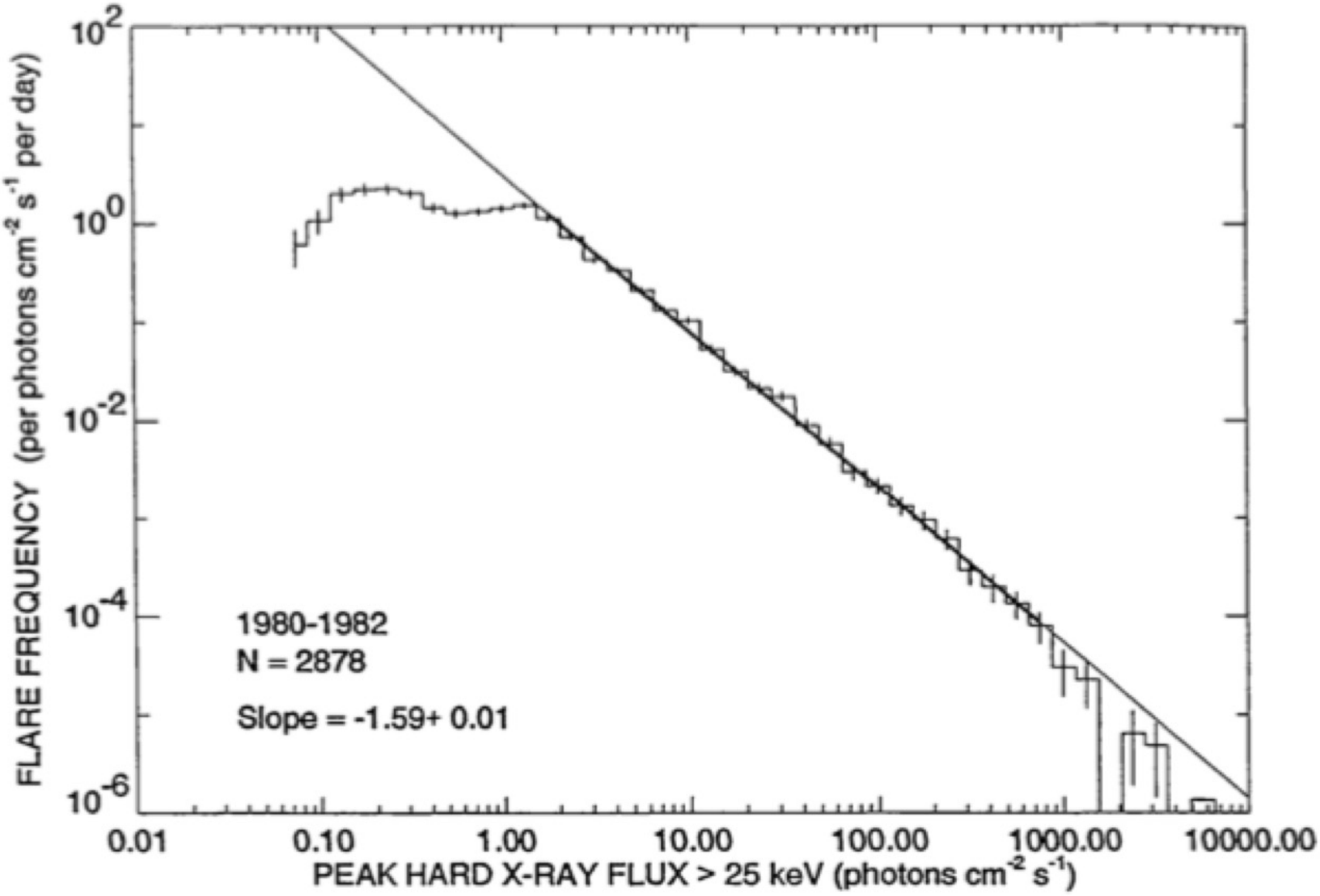
This compounds to 2.5×10^{32} erg

- ICME mass guessed at 10^{16} g: also 2.5×10^{32} erg

Total event energy 5×10^{32} erg

Carrington could have made this estimate, but the physics was far in the future. Also, the erg had not yet been invented (1873).

The power law



Crosby et al. 1993

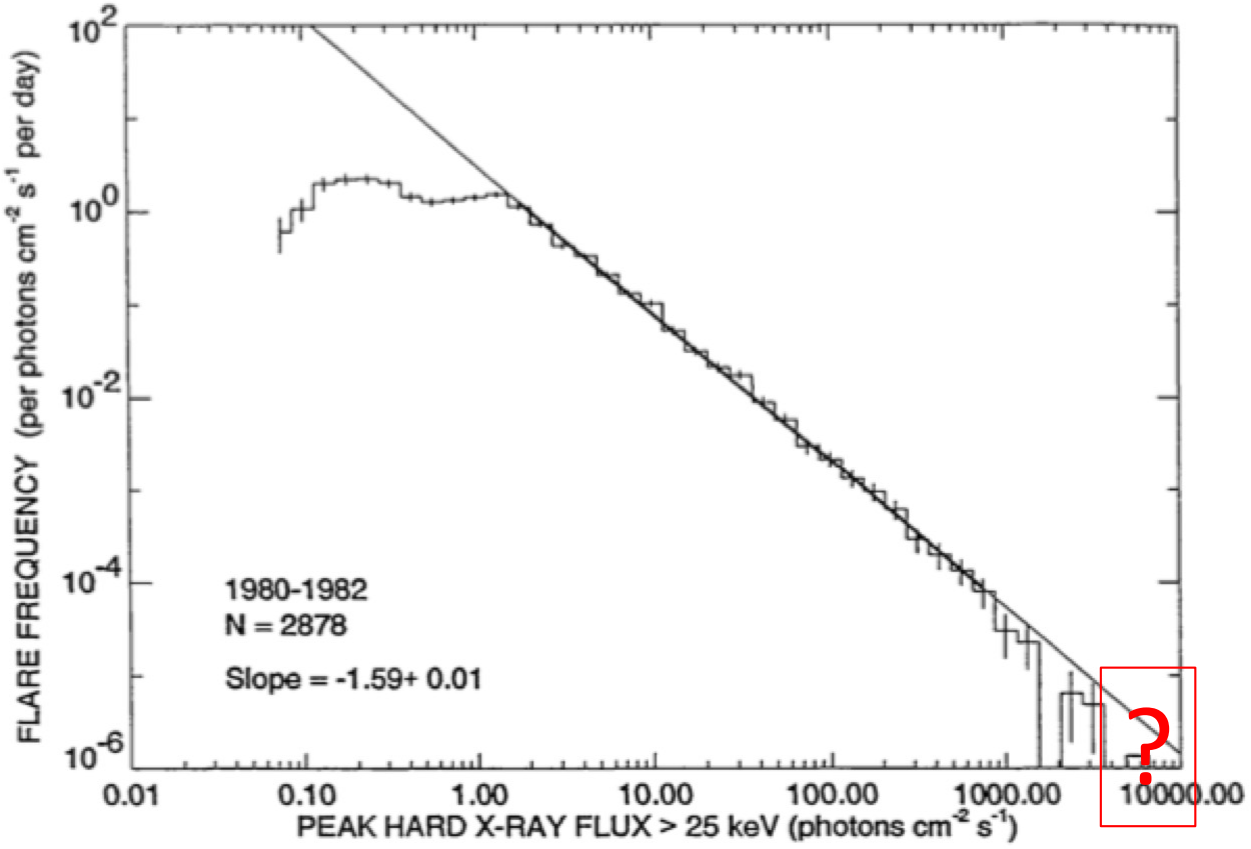
Power laws generally

- These very commonly describe the occurrence distributions of natural phenomena
  - Earthquakes
  - Nile floods
  - City populations
  - Word frequencies in the Bible *etc. etc*.

- Based on this law, we can easily estimate the probability of a future Carrington-class event (e.g. Love 2012)

- But what if something else is possible? A “Dragon-King” may lurk in the dimly lit corner. This would not follow the same physics as the power-law events do

The power law



?

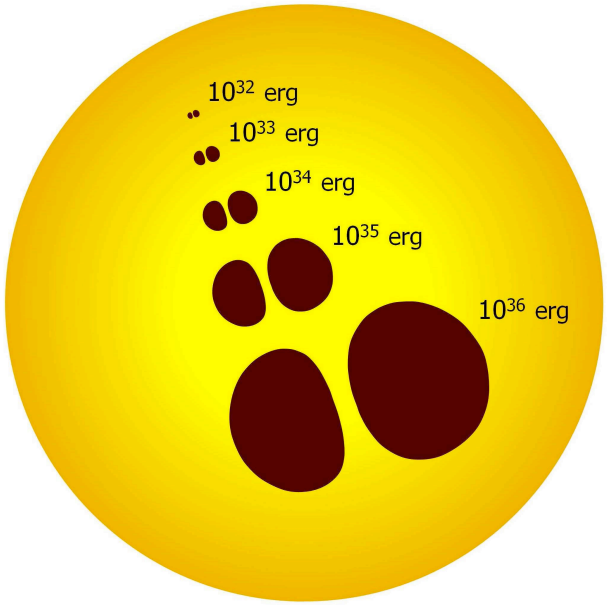
Dragon-King

Crosby et al. 1993

All considerations point to ~X45 for the Carrington event (~5 x 10^{32} erg)

Initial Conclusion

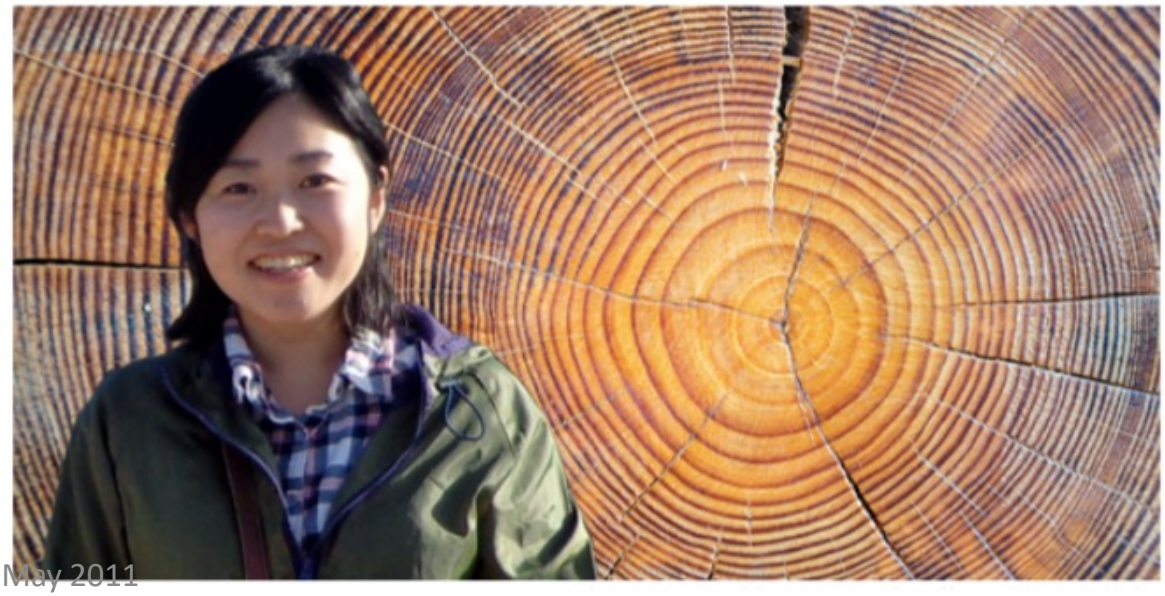
- We can define a Carrington Event as a flare/CME/storm at the top of the scale
- The archetype Carrington event itself was not superlative and a similar one would probably not be disastrous



State of the art in theory, Aulanier et al. 2013. In essence, "Give me a big enough sunspot, and I will give you a superflare!"

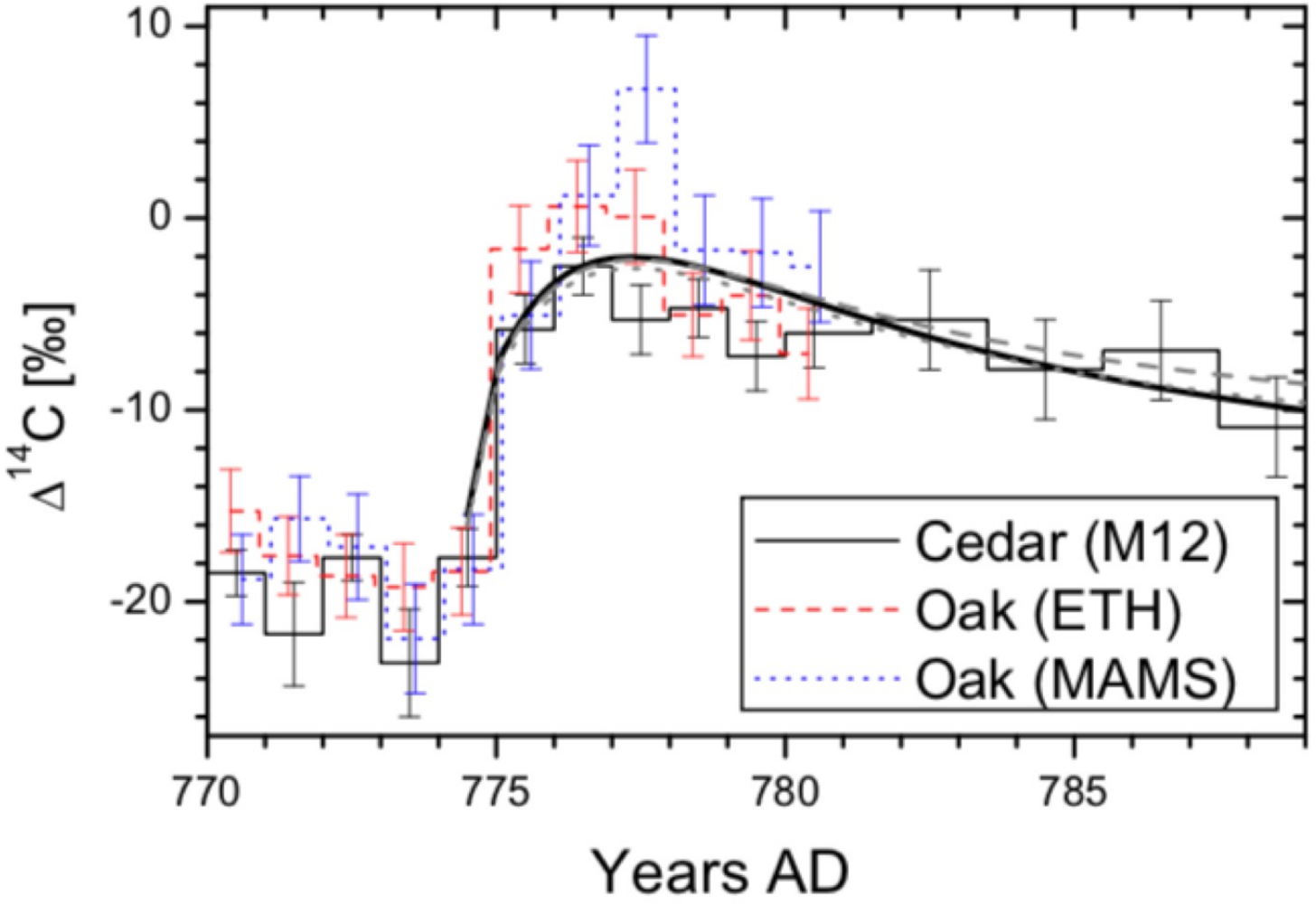
Two new discoveries about extreme events

- Three radionuclide events in the Holocene (Miyake et al. 2012, 2013; O'Hare et al. 2019), the first in ~775 AD
- *Kepler* observation of "superflares" on slowly-rotating "solar-type" stars (Maehara et al. 2012)



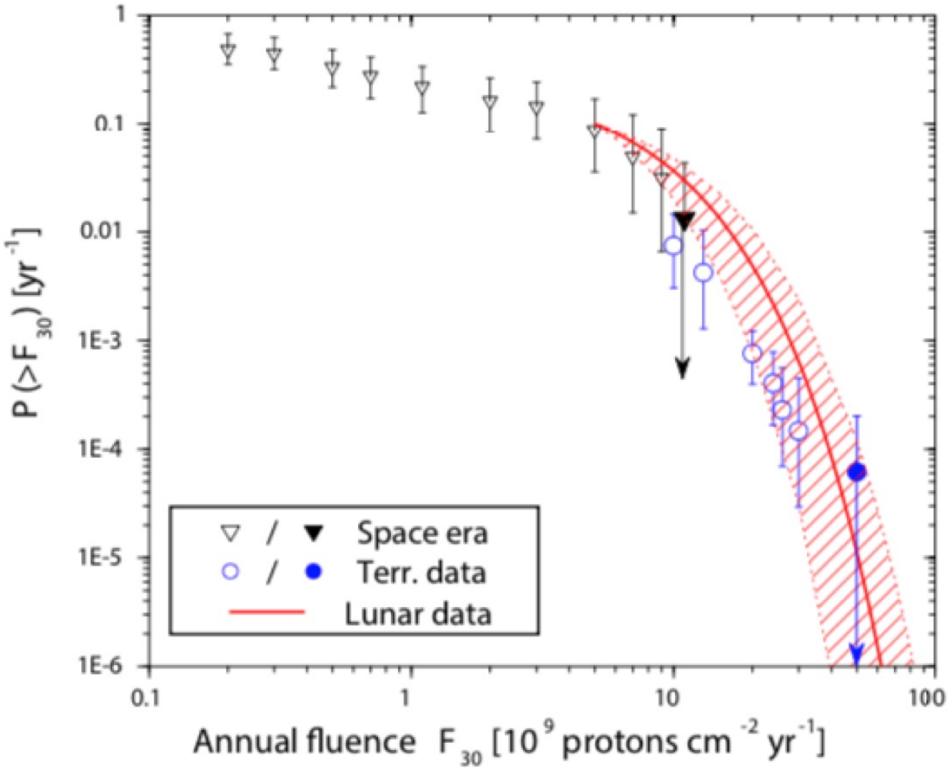
Then (2012, not 775) graduate student Fusa Miyake

AD 775 Solar (?!) Event

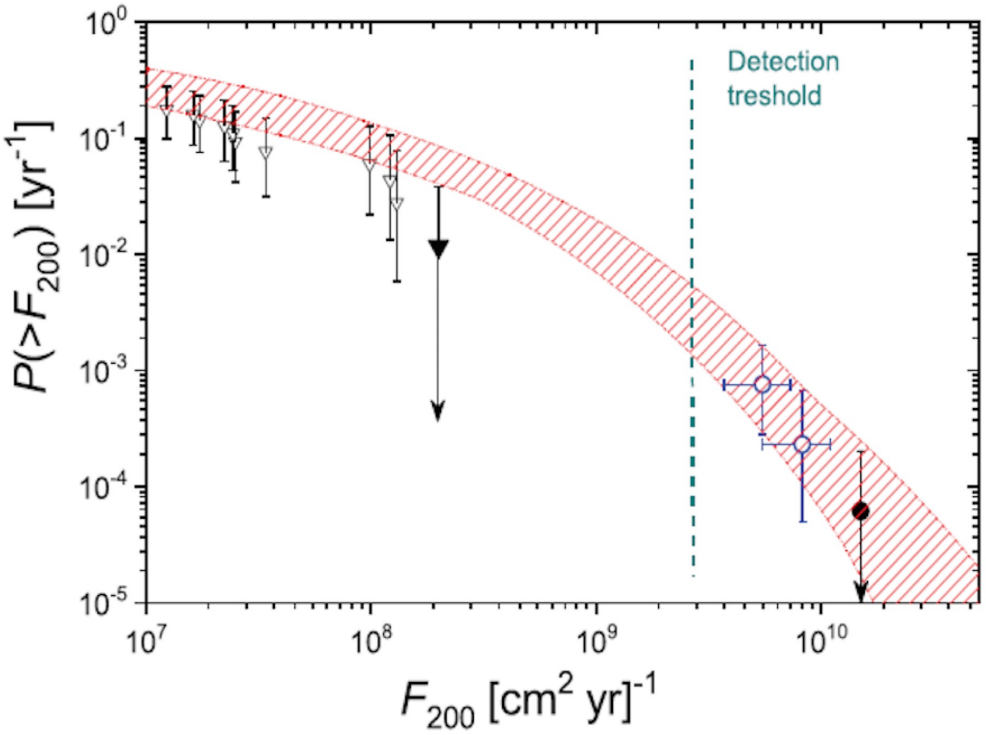


Kovaltsov-Usoskin 2013

SEPs as event proxies



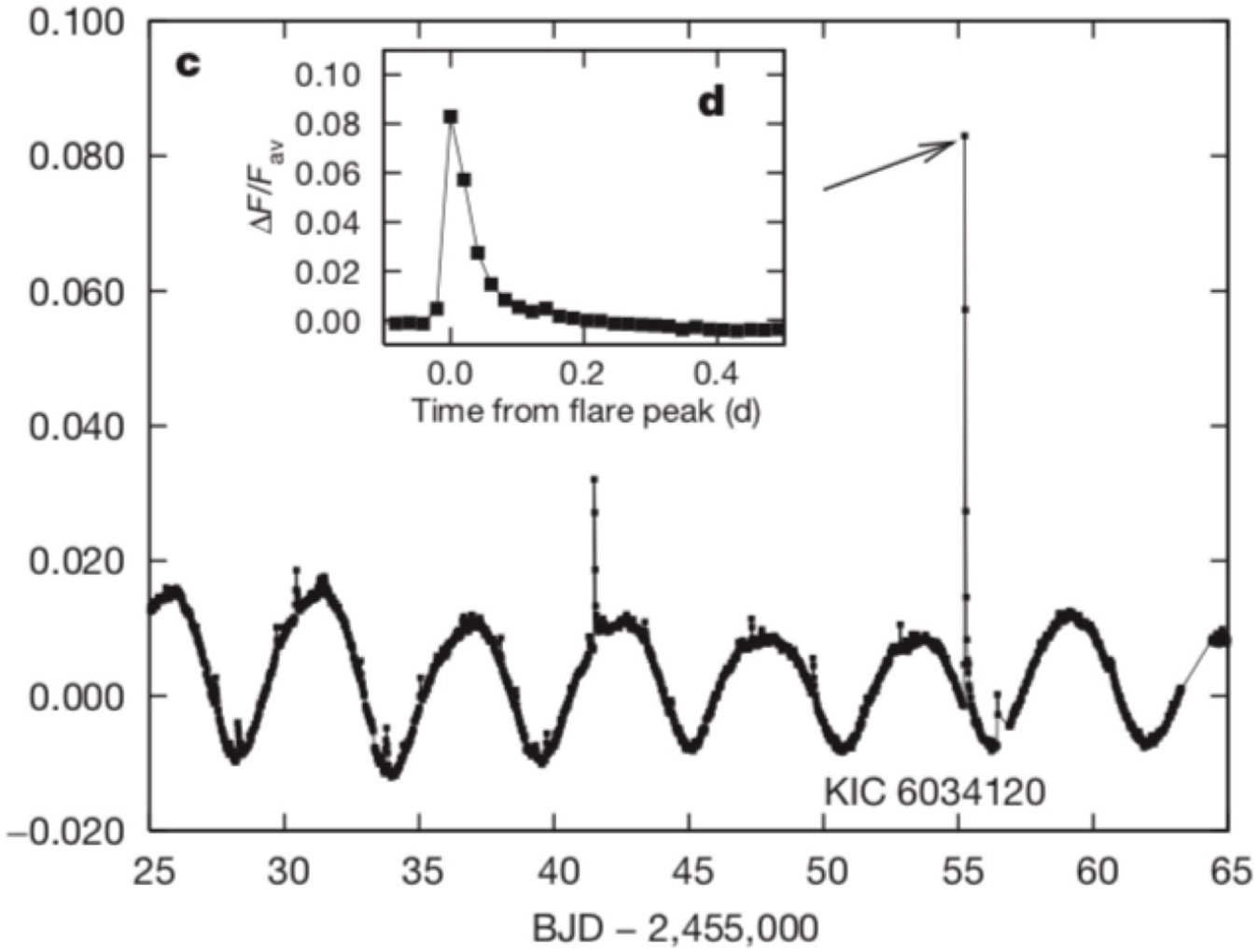
Kovaltsov-Usoskin 2013
cf. Lingenfelter-Hudson 1980



Miyake et al. 2020

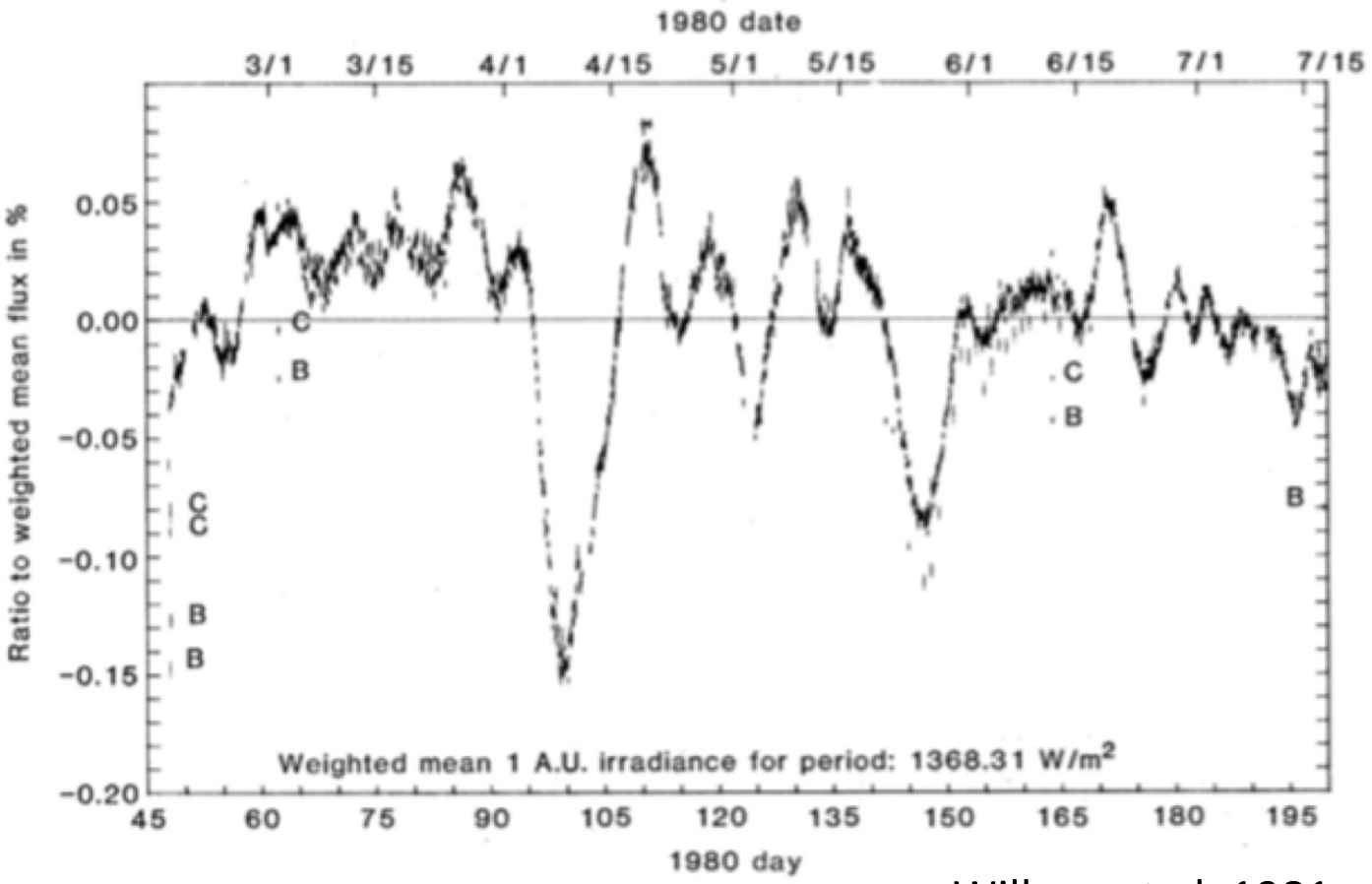
The observed flare power law in energy must have a break (Hudson 1991)

Kepler Stellar Photometry



Maehara et al. 2012

TSI Solar Photometry



Willson et al. 1981

Solar variability is facula-dominated on solar-cycle time scales

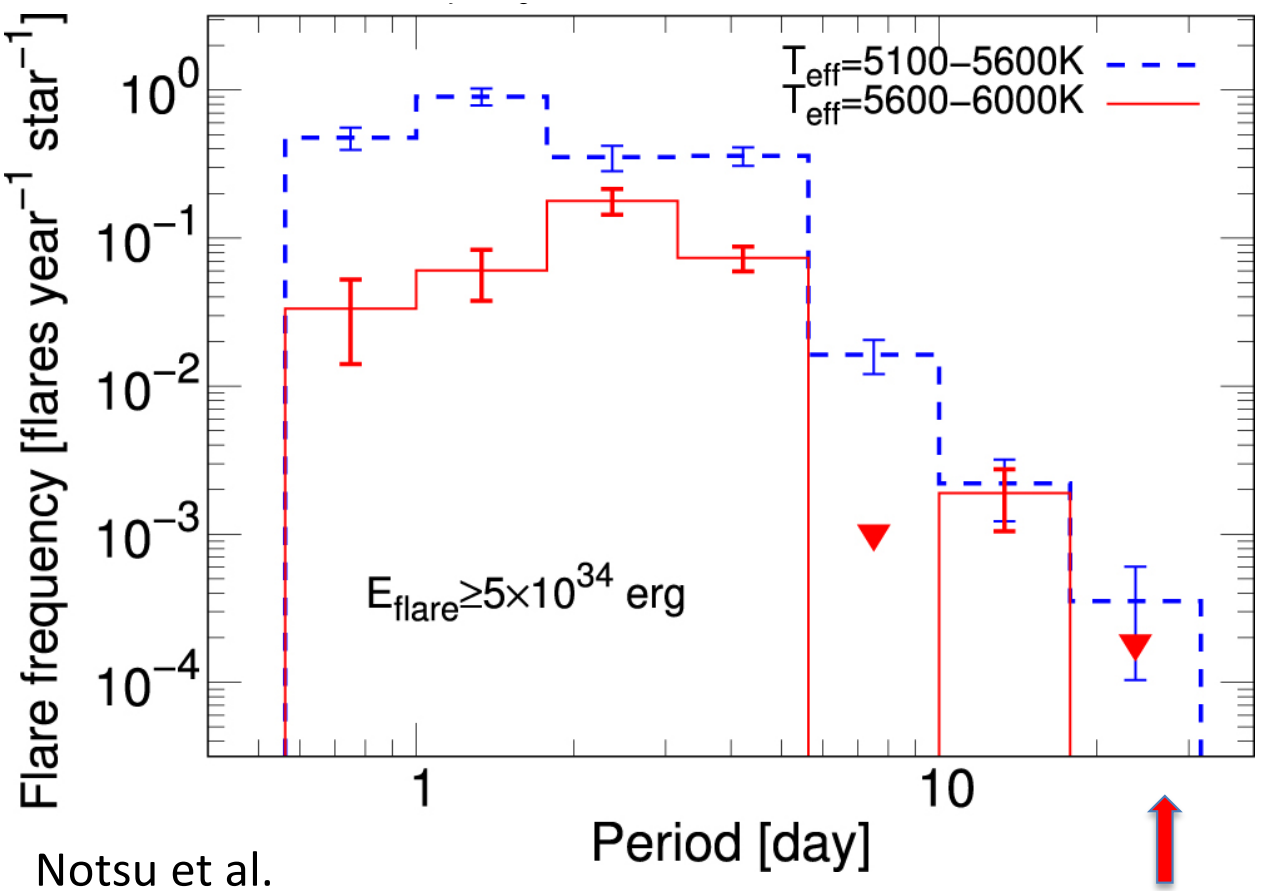
Flariness vs Dippiness

Flariness vs. dippiness

The solar TSI exhibits low-level (of order 50 ppm per 2-min sample) fluctuations due to convection and p-mode oscillation, and pronounced dips due to one-off sunspot transits – *dippiness*. Flares only marginally exceed these fluctuations. The *Kepler* timeseries for most superflare stars do not show dips, but instead have persistent quasi-sinusoidal variability at large amplitude (percents), plus the striking flare excesses – *flariness*.

- The Kepler "solar type" stars are not at all like the Sun in this property
- Sunspot/facular dominance of activity properties varies across the stellar types

Kepler Observations Misunderstood?



The Holocene

Solar period

Notsu et al. 2019

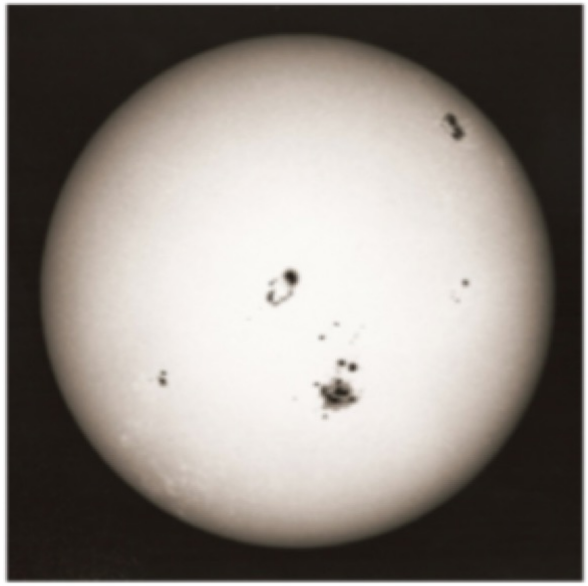
- **Superflare occurrence depends strongly on rotation period**
- **There are actually no statistics here!**

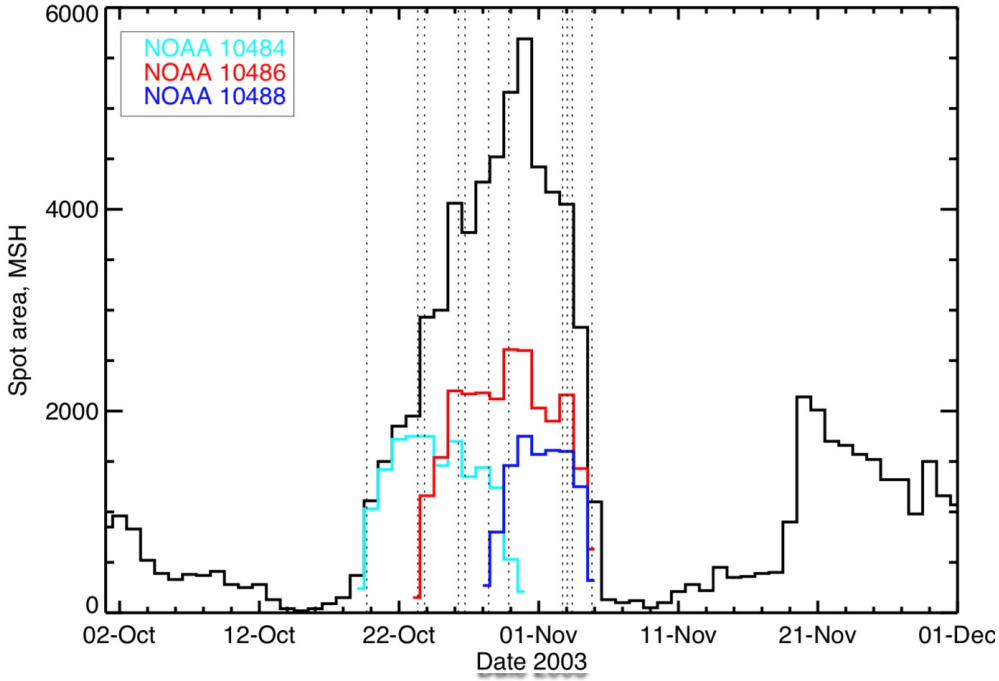
What have we learned from the tree rings and the Kepler events?

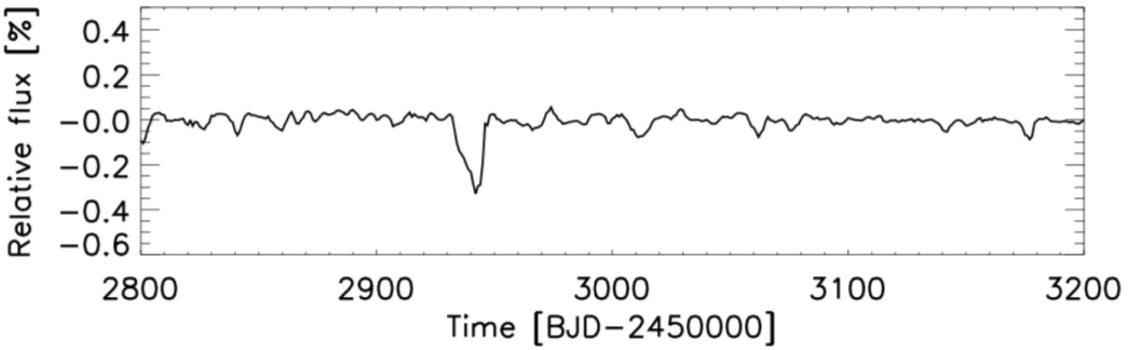
- The tree-ring events appear to have had much greater SEPs fluences than even SOL1956-02-23
- The Kepler events don't suggest a reasonable basis for extrapolation to the solar case

- The meaning of "event" must be extended to compound events
- We should look to stellar CMEs to understand the tree-ring link better

TSI Solar Photometry



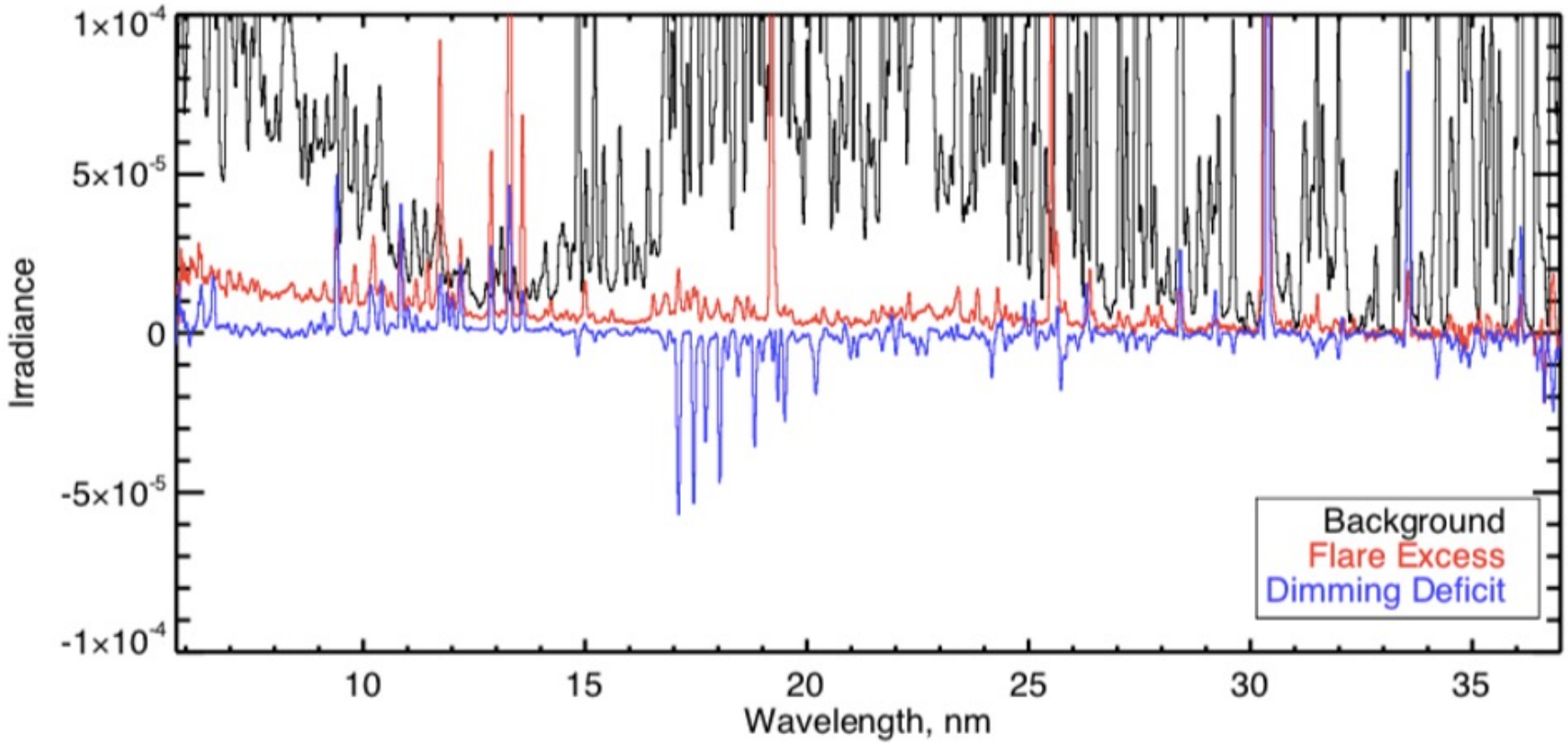




Isik et al. 2020

- **These events together match the Carrington spot and flare magnitudes pretty well – the famous 2003 "Halloween events"**

CME detection via EUV dimming



SDO/EVE spectroscopy readily detects solar mass ejections (Mason et al. 2016)

CMEs on stars

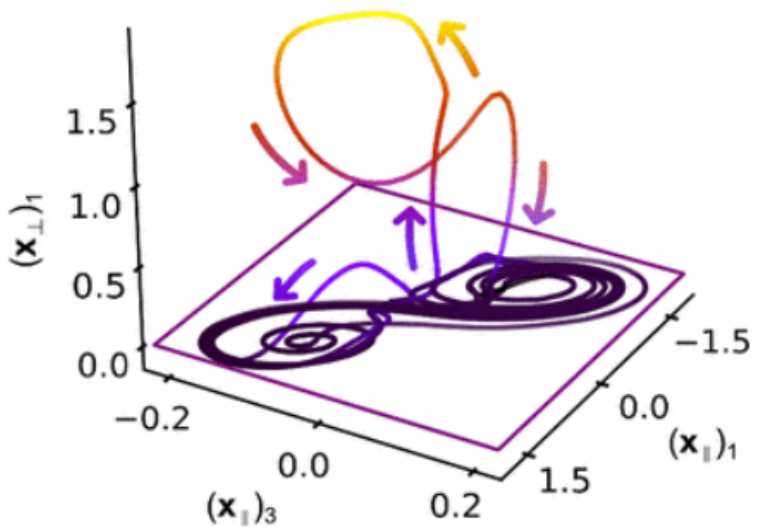
- There are many stars close enough to observe in the EUV.
- A dedicated stellar EUV instrument, doing what EVE does, would be very fruitful, for example just staring at Prox Cen

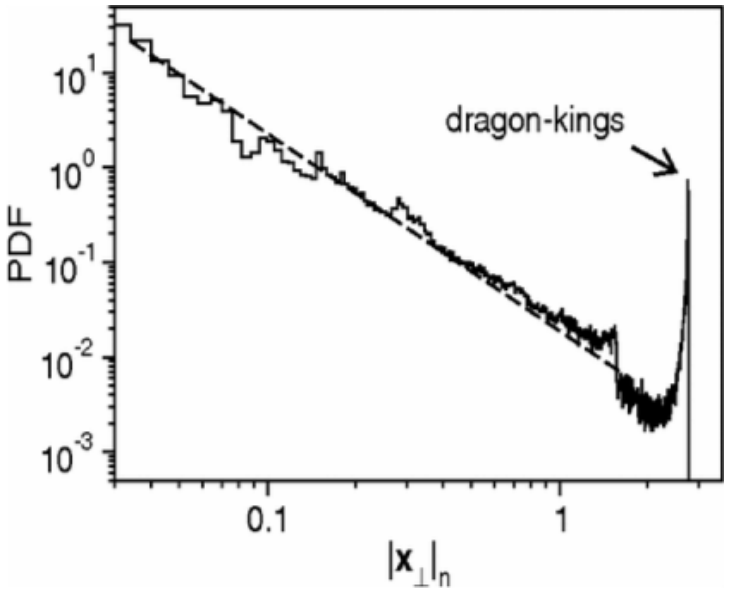
- The problem is SNR. Large aperture is needed to resolve event timescales. Veronig *et al*. (2021) provide some credible examples of stellar dimming events

Coupled oscillators “bubbling”

Sornette’s Dragon-King hypothesis

Poincaré and the theory of dynamical systems





19^{th} Century Natural Disasters

- The Carrington event: 10^{17} g in the heliosphere – a few singed beards
- The Tambora eruption: 10^{17} g in the stratosphere – countless fatalities

Conclusions

- We can define a ”Carrington event” as major flare/CME/storm of the greatest magnitude
- The archetype Carrington event(s) itself was not superlative and a similar occurrence would probably not be disastrous
- No new physics needed

- But… do the radioisotopes hint at a Dragon-King risk outside our extrapolations?
  - We must study these extreme events
  - We must be prudent about risk