Extreme Events in the Lower Solar Atmosphere

Hugh Hudson
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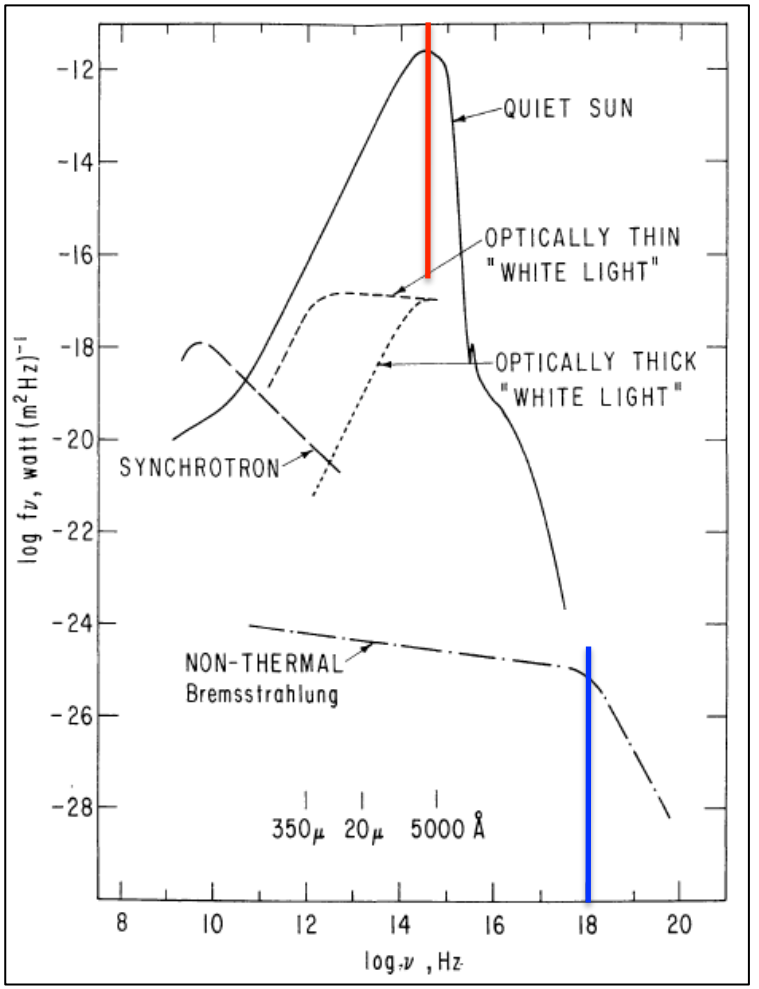
(i) Assess our knowledge of flare luminosity
(ii) Comment on significance of lower atmosphere

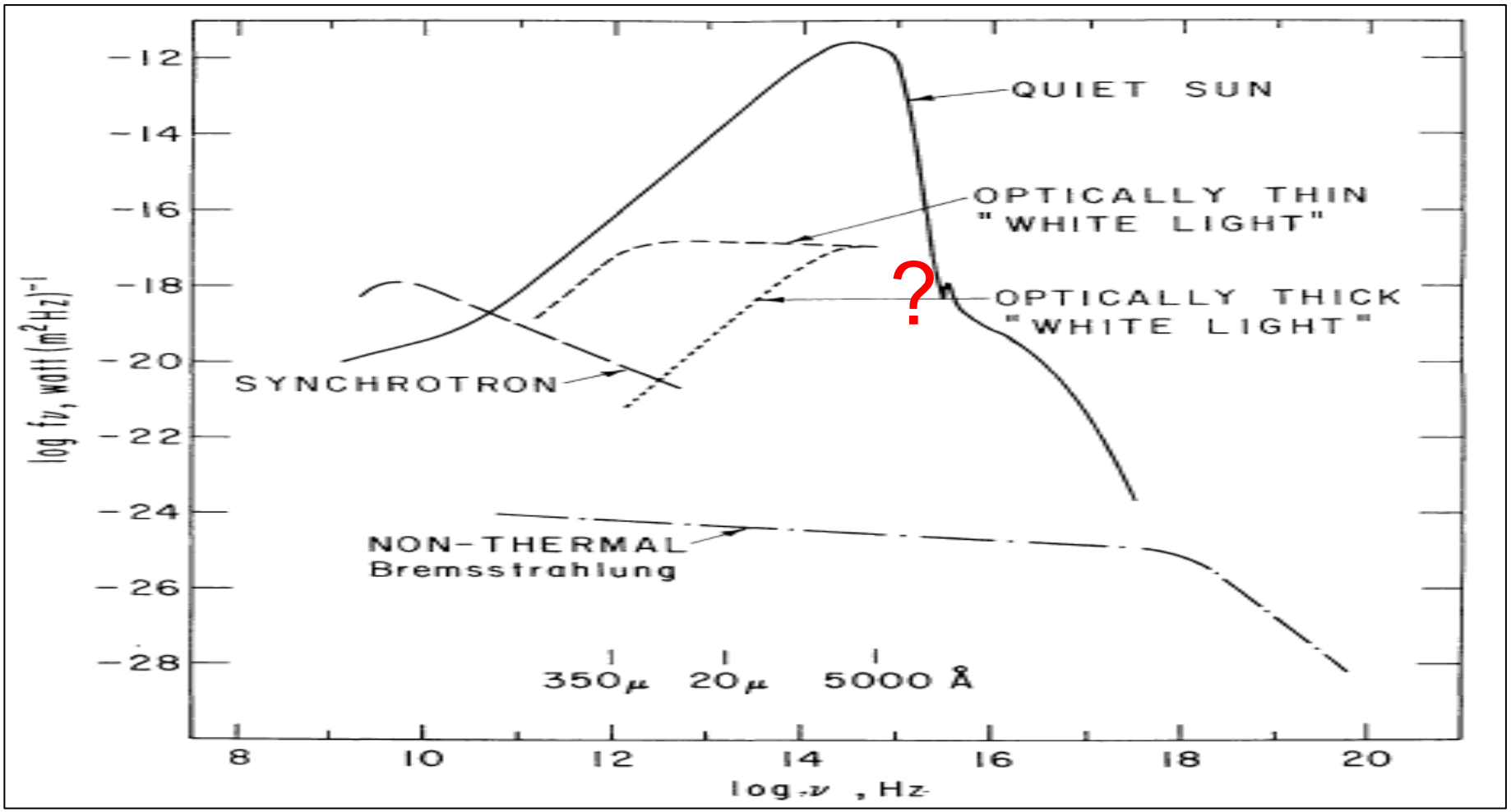
Proxies for flare energy

- Hα Importance (why Hα?)
  - S,1, 2, 3 reflect area
  - F, N, B reflect intensity
- GOES class
  - 1-8 A
  - 0.5-4 A

These proxies are used for convenience and are not easily calibrated!

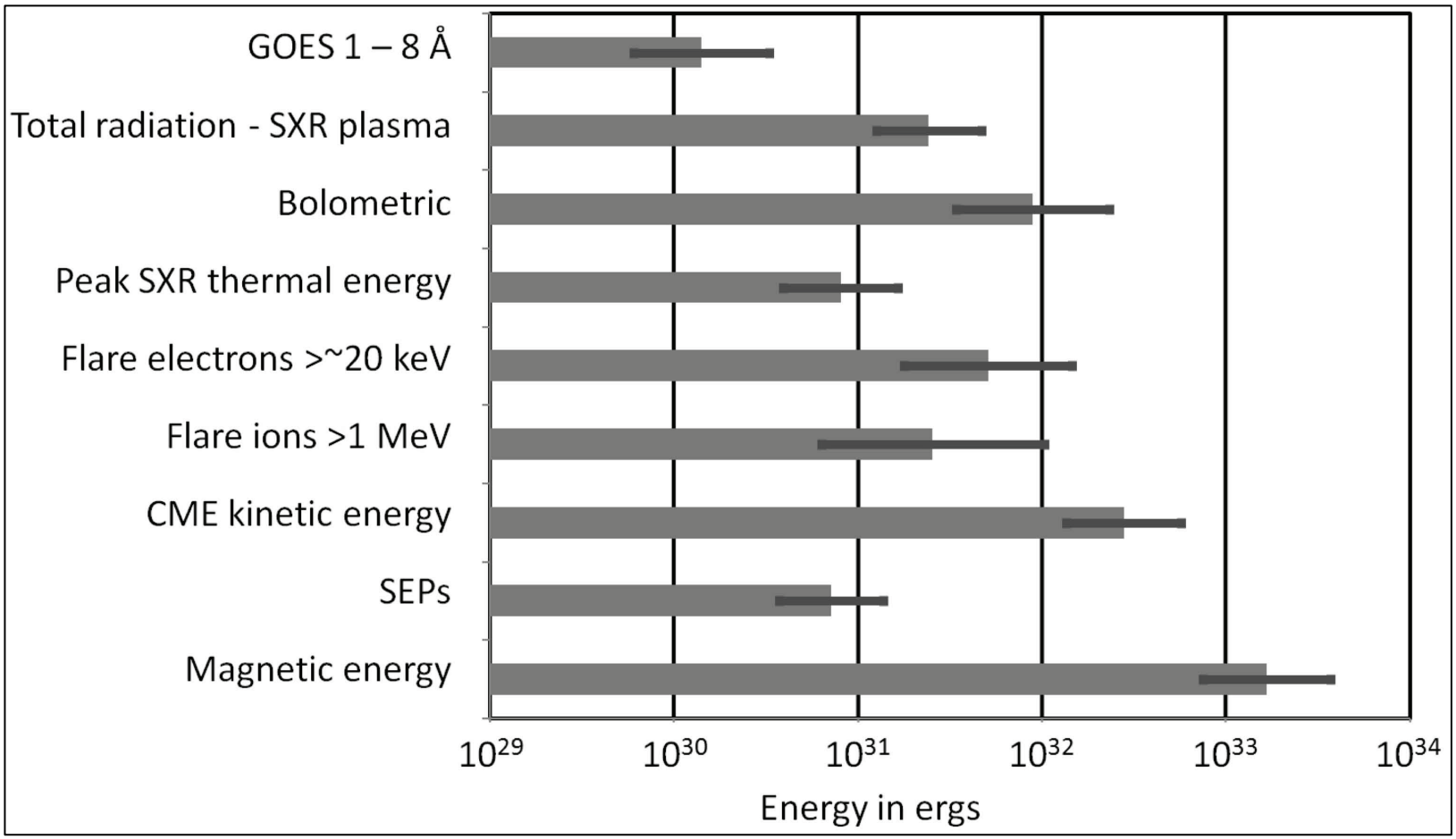


Ohki & Hudson 1975



- We don’t know much about the UV extension of the WL
- The bolometric measurements are marginal
- The Sun provides a very high background level
- Granulation, p-modes etc. interfere badly

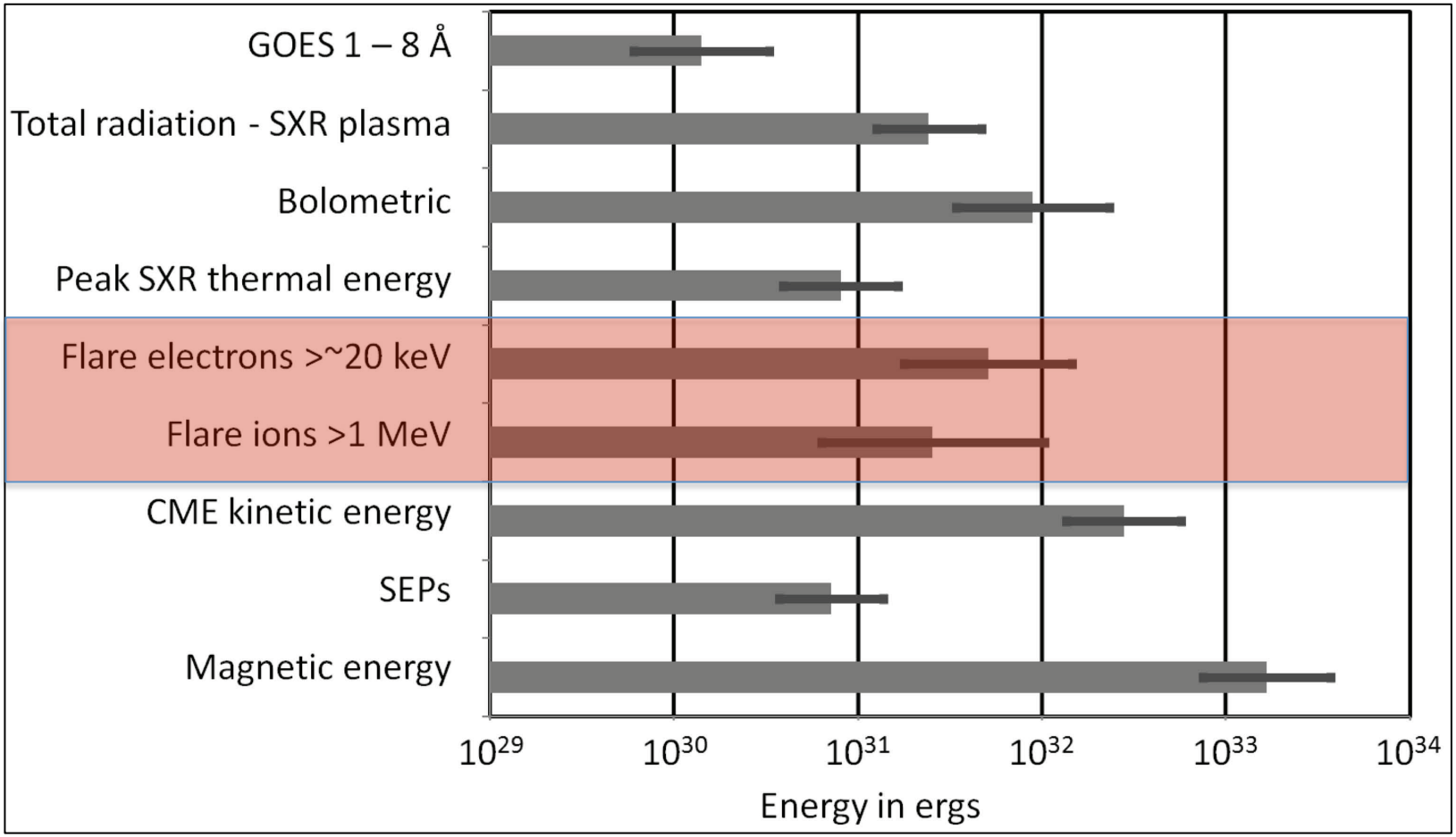
Energy partition (6-event sample)



Emslie et al. (2012)

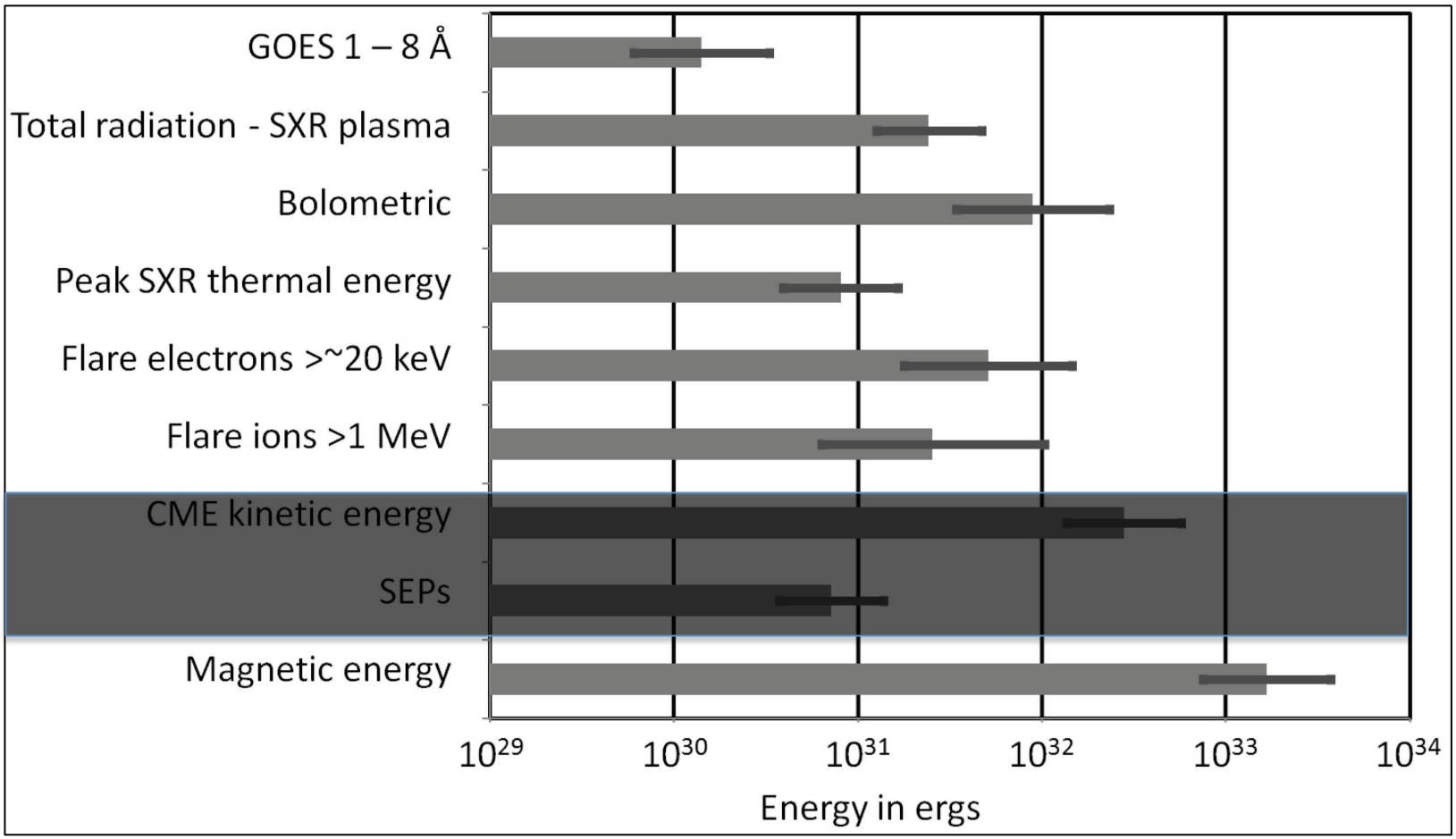
Primary forms of energy release –

*but where is "heating"?**

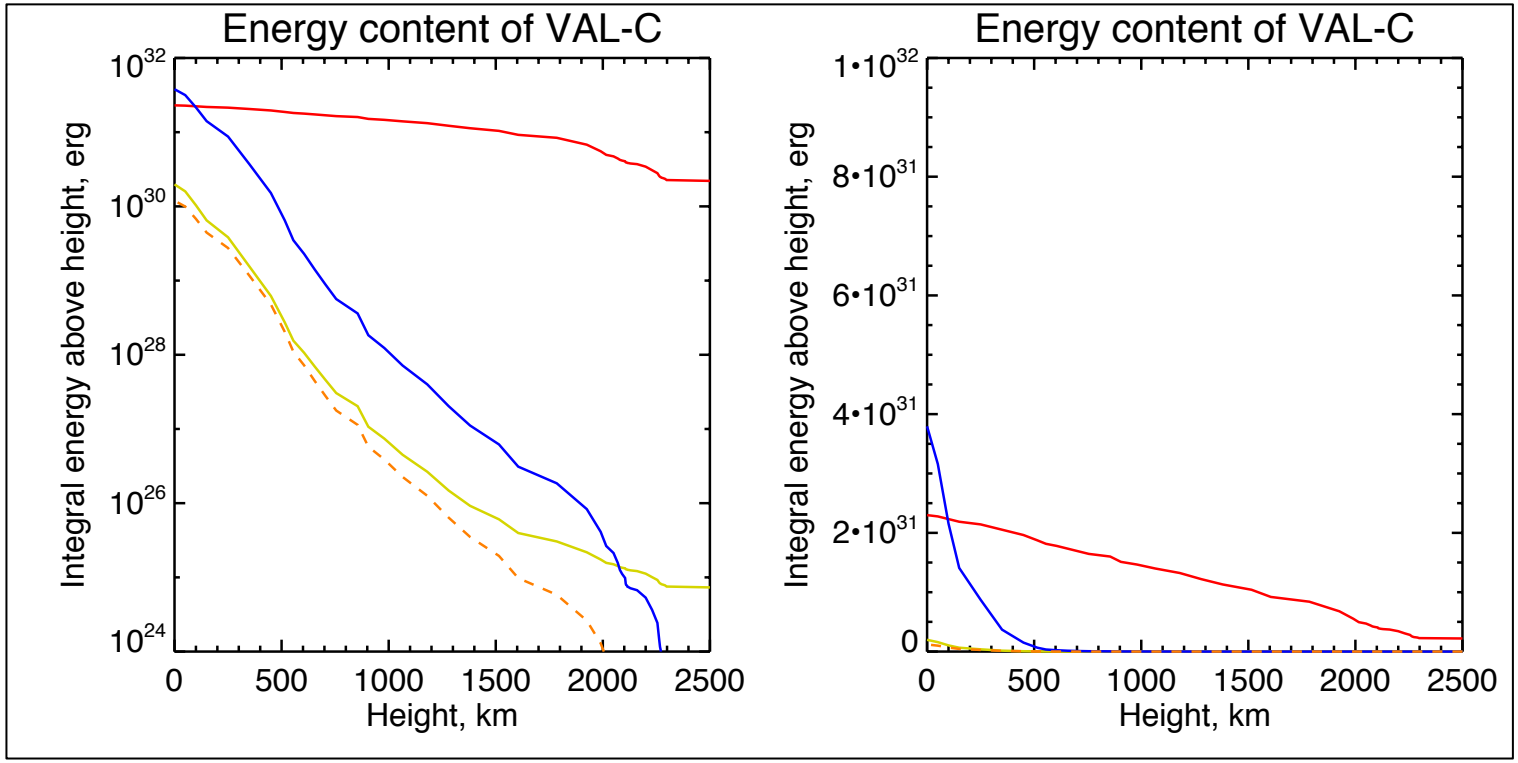


*"This demonstrates that direct heating from the energy release at the reconnection site can be an efficient process." – Chamberlin et al., 2012

Flares without CMEs



Energy sources



Cumulative energy content above height, in an area (10 Mm)^2 of the VAL-C model: Dashed, levitation by one scale height; blue, ionization; gold, thermal; red, magnetic at 1500 G

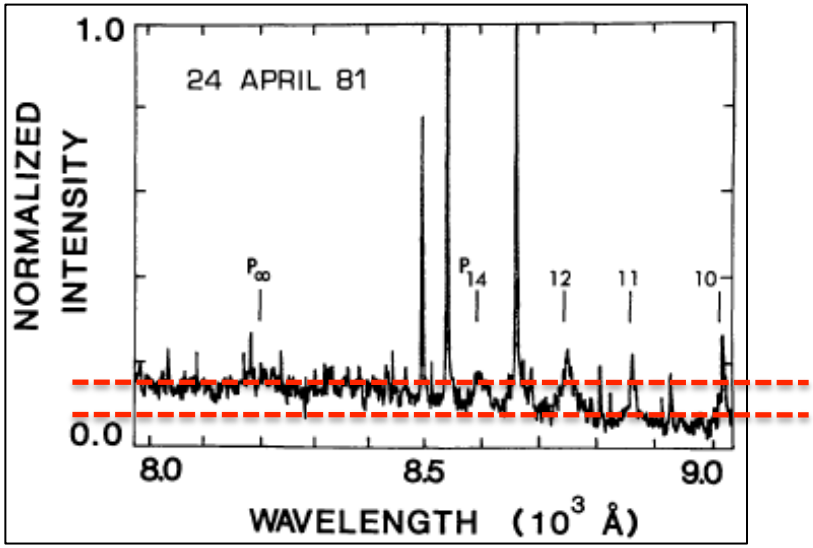
Hudson 2007, 2011

A seemingly inevitable conclusion:

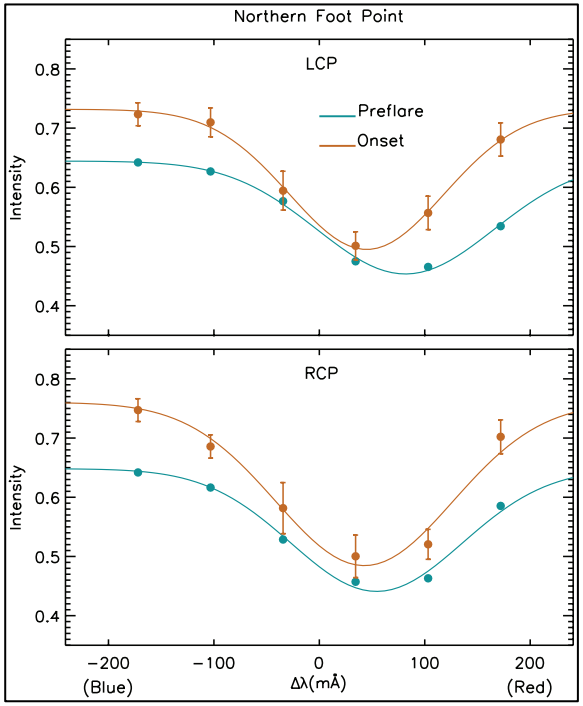
The excess energy for a flare, though radiated mainly from a compact volume in the lower atmosphere, must have gotten there from somewhere else

White-light flare spectra

- Truly *continuum*, or are there emission lines?
- If continuum, optically thick (~blackbody)?
- Or optically thin (recombination radiation)?
- What about the energy in the UV, and the Balmer jump?

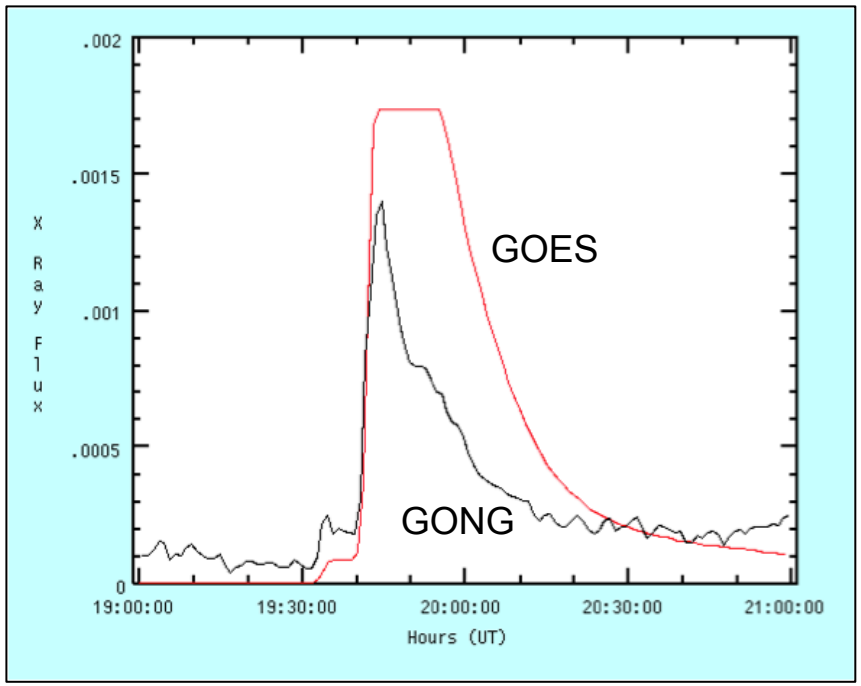


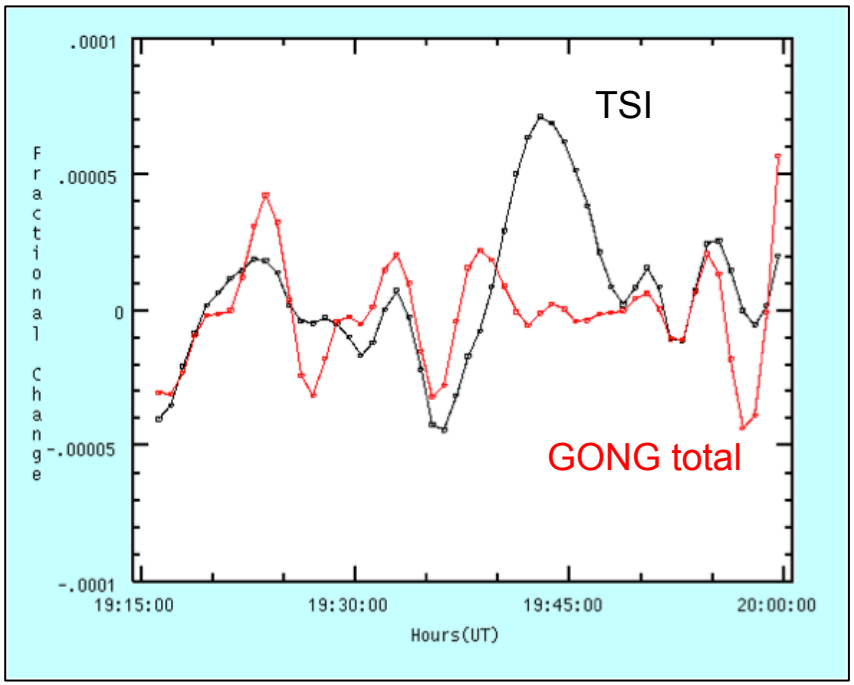
Paschen jump: Neidig-Wiborg 1984



HMI: Martinez-Oliveros et al, 2011

A “white-light prominence” – SOL2003-11-04





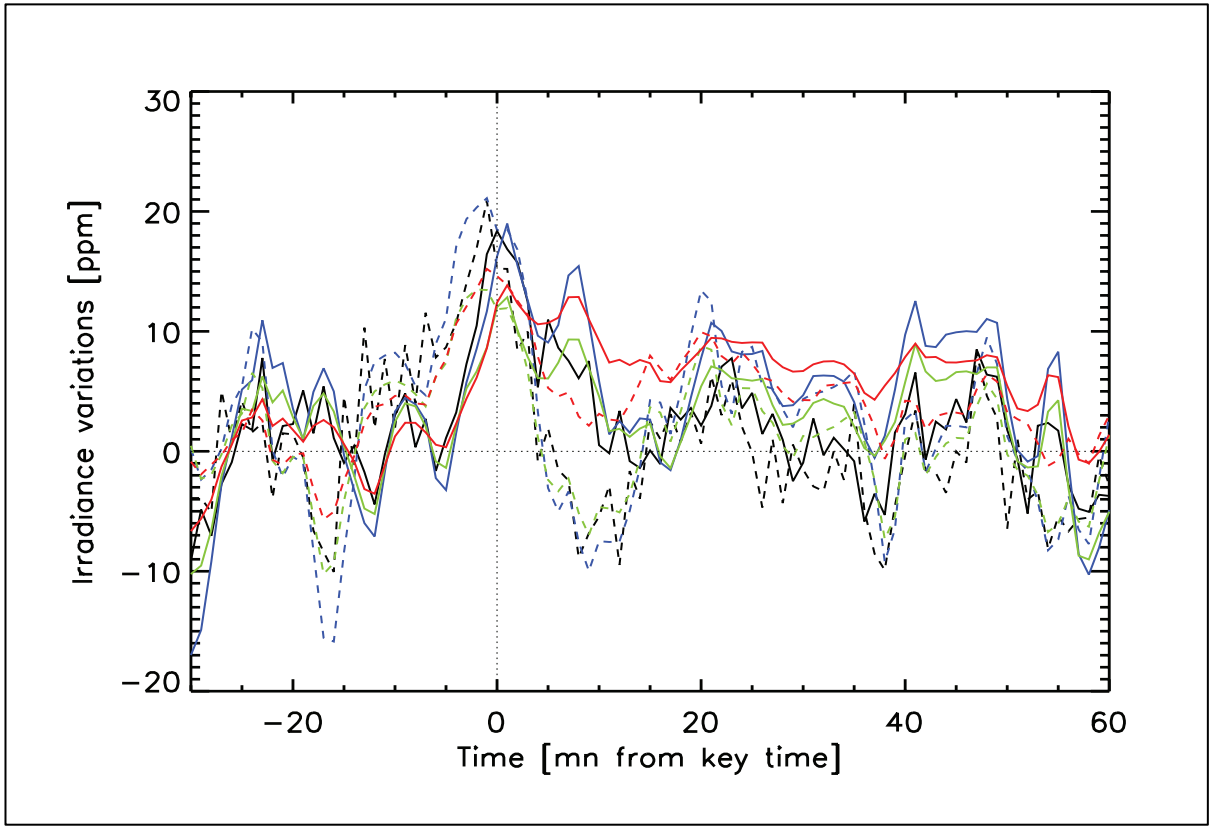
Harvey et al, 2004: 110 ppm
Woods et al., 2005: ~120 ppm
Emslie et al, 2012: 424 ppm

The Harvey analysis

- Harvey compared the TIM bolometric signal with the GONG image sums*
- The good correlations outside the time of the SOL2003-11-04 flare show how to subtract background
- A GONG survey using this technique would help compensate for the Sun's background problems

*Could also be done with MDI or HMI

Chree analysis



Kretzschmar, 2011

SOHO/VIRGO TSI, r, b, g
- dashed: key time GOES
- solid: key time dGOES/dt

Clear conclusions:

The bolometric output of a solar flare peaks in the impulsive phase, rather than in the GOES/Hα gradual phase

The bolometric measurements are very uncertain because of the presence of solar background fluctuations

Ancient history

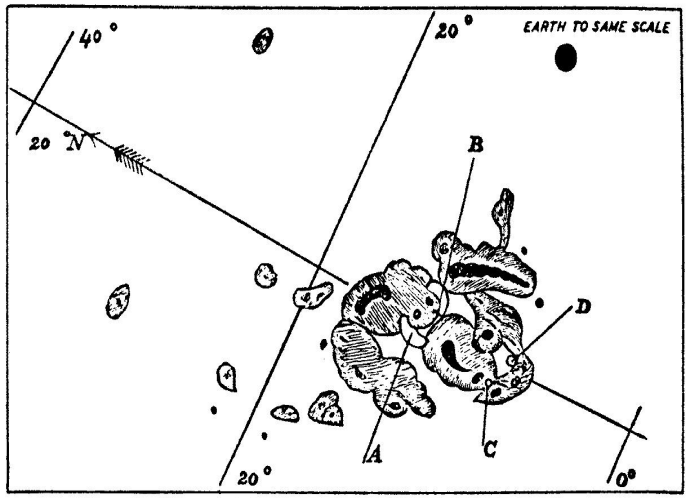


FIG. 36. Solar sketch, September 1, 1859, by R. C. Carrington

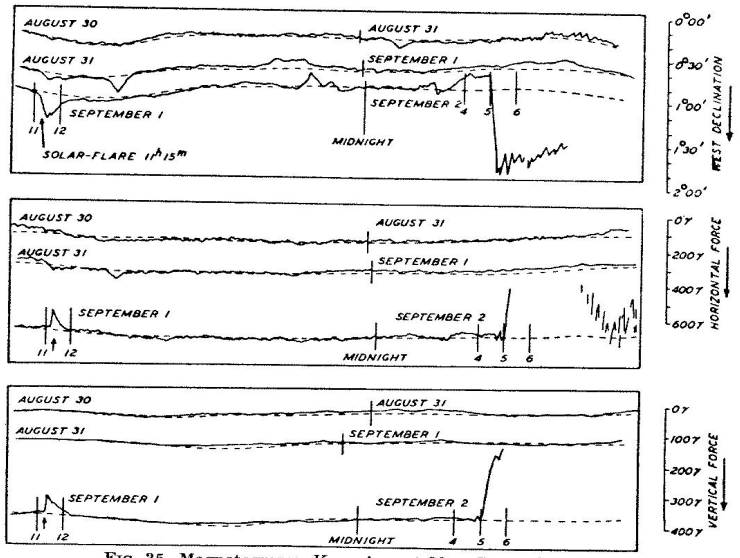


FIG. 35. Magnetograms, Kew, August 30 to September 2, 1859

Well-known graphic:

- White-light patches appeared
- The energy of the disturbance they reveal is very large
- Research in flare physics began (albeit slowly)

Less-well-known graphic:

- The ionosphere and magnetosphere can be seriously disturbed
- Röntgen and Heaviside
- "Space weather" is born (slower still)

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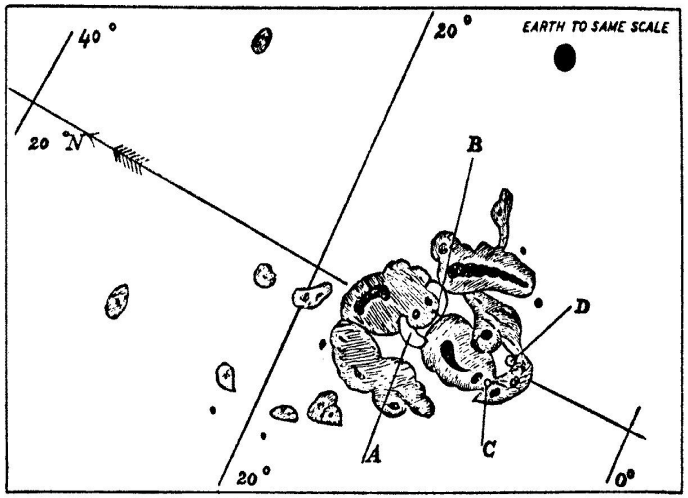

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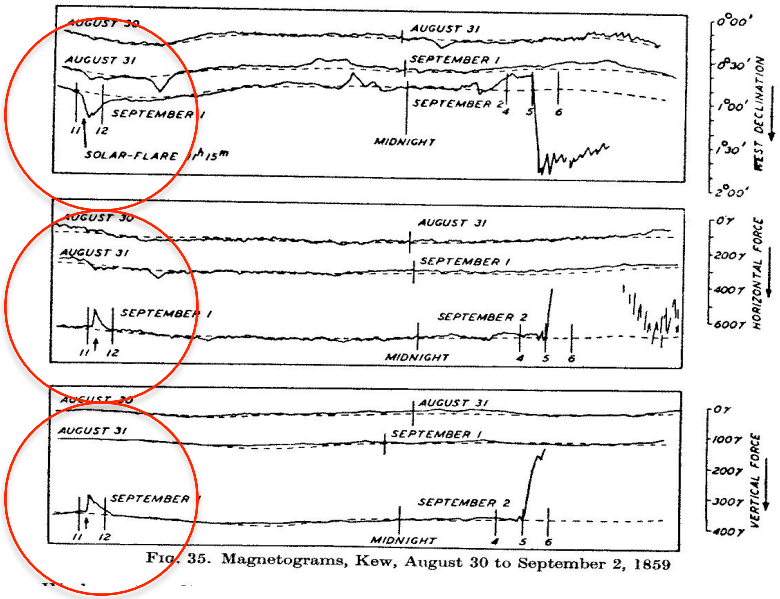

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More recent history

White-light flare occurrence:

- Neidig-Cliver catalog (1983; 57 events)
- Matthews et al. (2001; 28 *Yohkoh* events)
- SDO/HMI lists forthcoming (and GONG?)

White-light flare spectroscopy:

- Only a handful of good optical spectra
- A shocking ignorance of the UV spectrum
- Ground-based and IRIS data forthcoming

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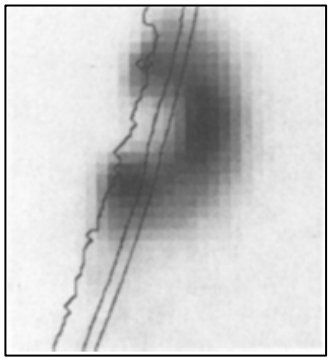
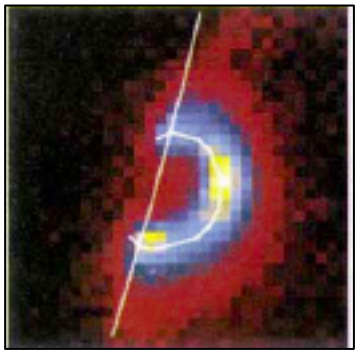
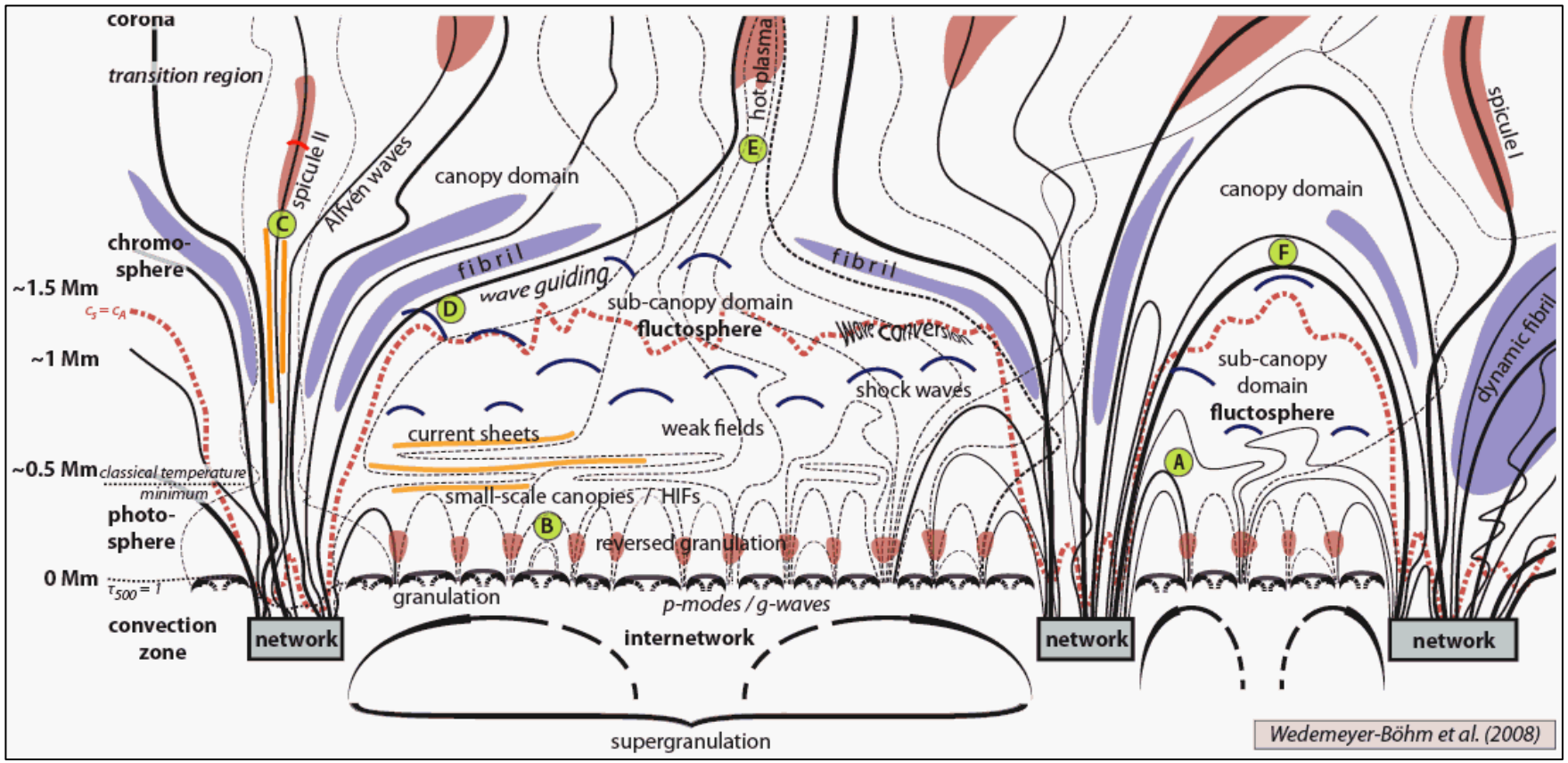


Hudson 1994: bright SXR footpoints, 4 citations (cf. McTiernan et al. 1993, with 58)

Masuda et al. 1994: coronal HXR source, 527 citations



Structure of the atmosphere

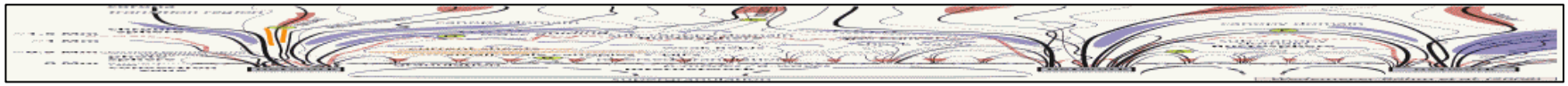


Wedemeyer-Böhm 2004

Corona
Transition region
Chromosphere
} Modeled in 1D “semi-empirical” style
Photosphere

Structure of the atmosphere

(at a roughly correct aspect ratio)



Role of the lower atmosphere

- In many cases, CME eruptions begin in compact sources in the low corona (Dere et al., 1997; Zarro et al., 1998)
- These cases include major geoeffective events associated with fast CMEs
- There is a tight relationship between the impulsive phase of the flare, and the acceleration phase of the CME – this suggests a common energy source, and we should track it down

“Mighty Oaks”

Significance of the lower solar atmosphere

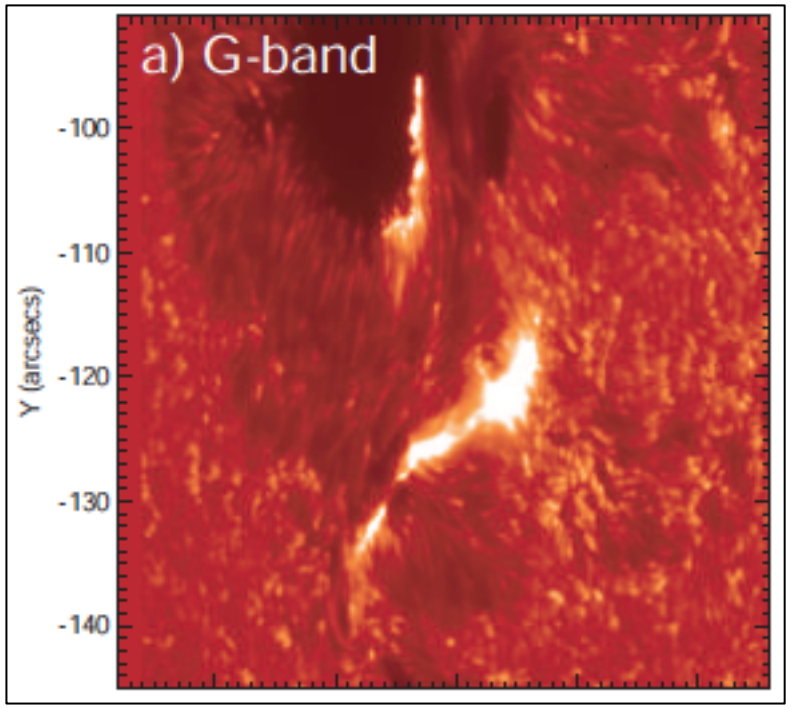
Observation: The chromosphere and photosphere dominate the flare luminosity

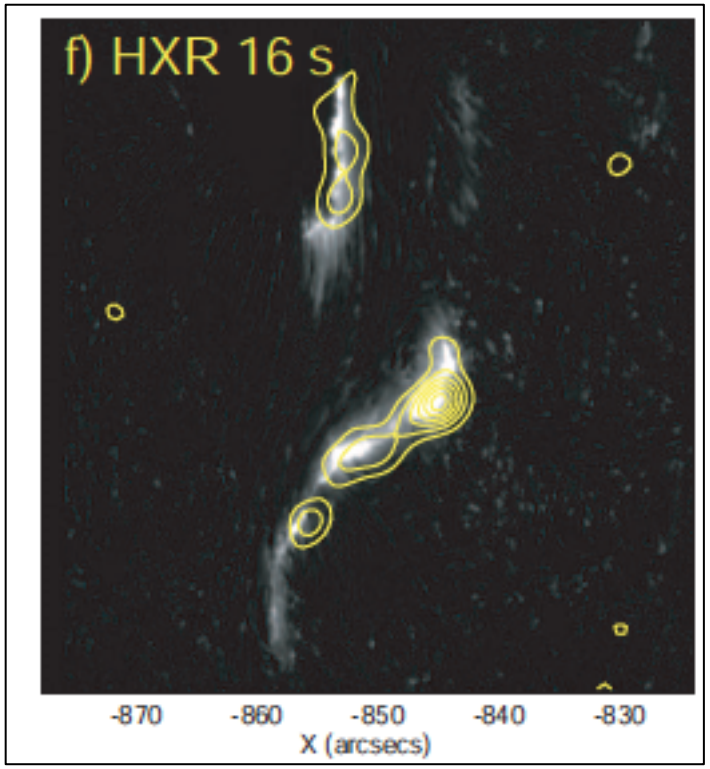
Physics: This domain separates regions with very different conditions:

- Densities drop suddenly
- Temperatures increase suddenly
- Collisionality drops precipitously
- Radiation decouples
- Plasma beta goes from high to low
- The fibril field becomes space-filling

Flare footpoint sources

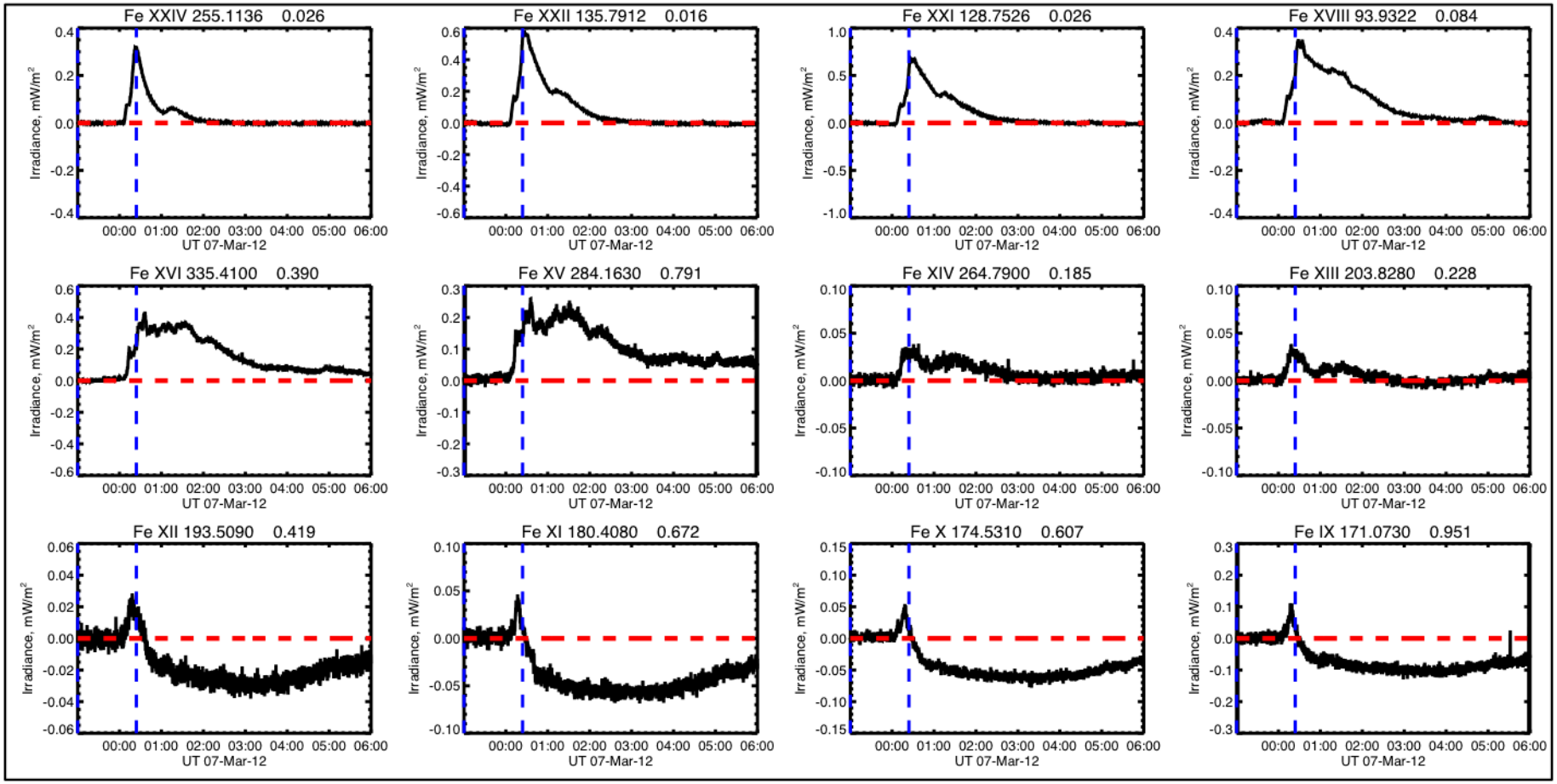
(RHESSI, white light)





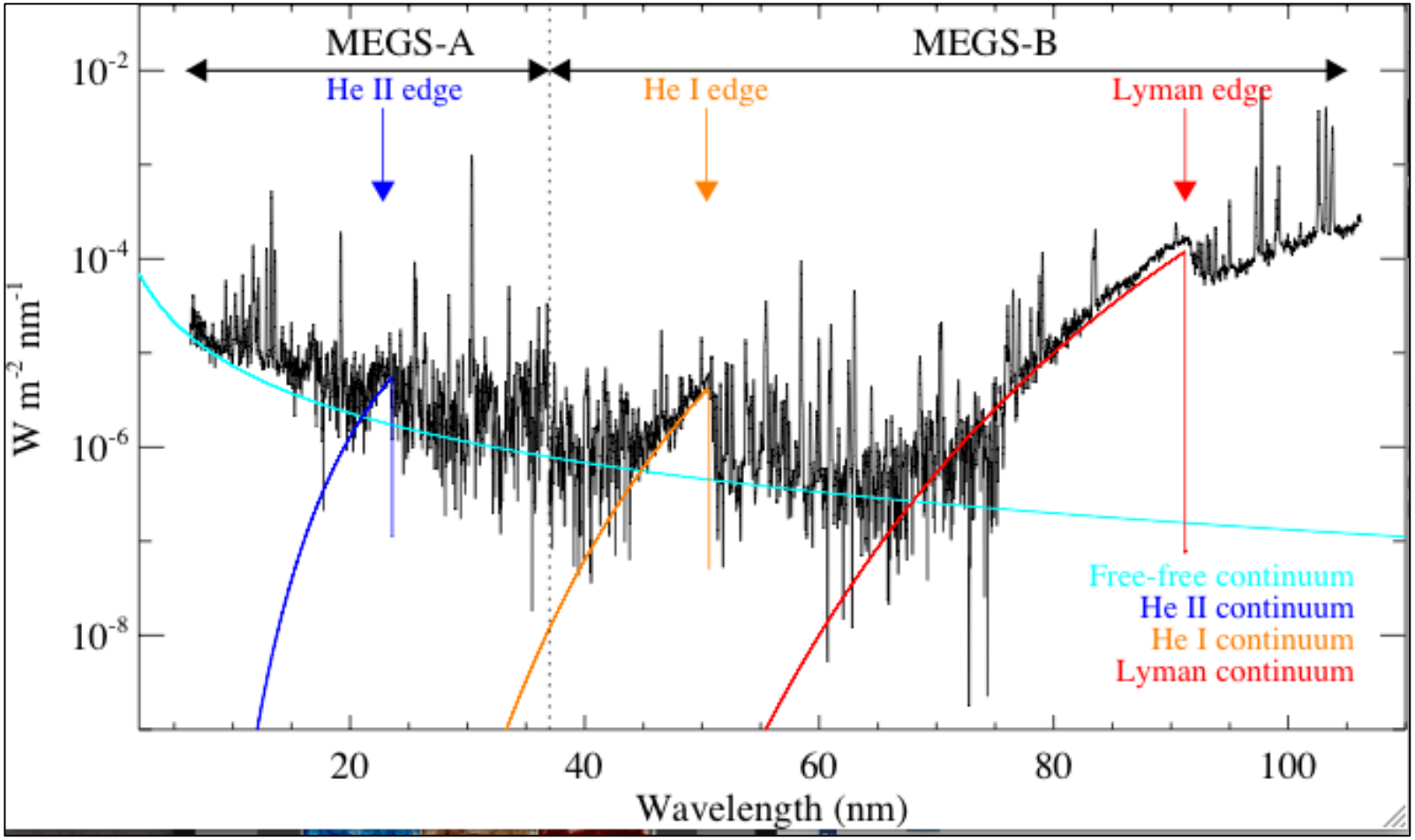
Krucker et al., 2011: very compact, very luminous sources in the lower atmosphere

Seeing the EUV as a stellar astronomer might



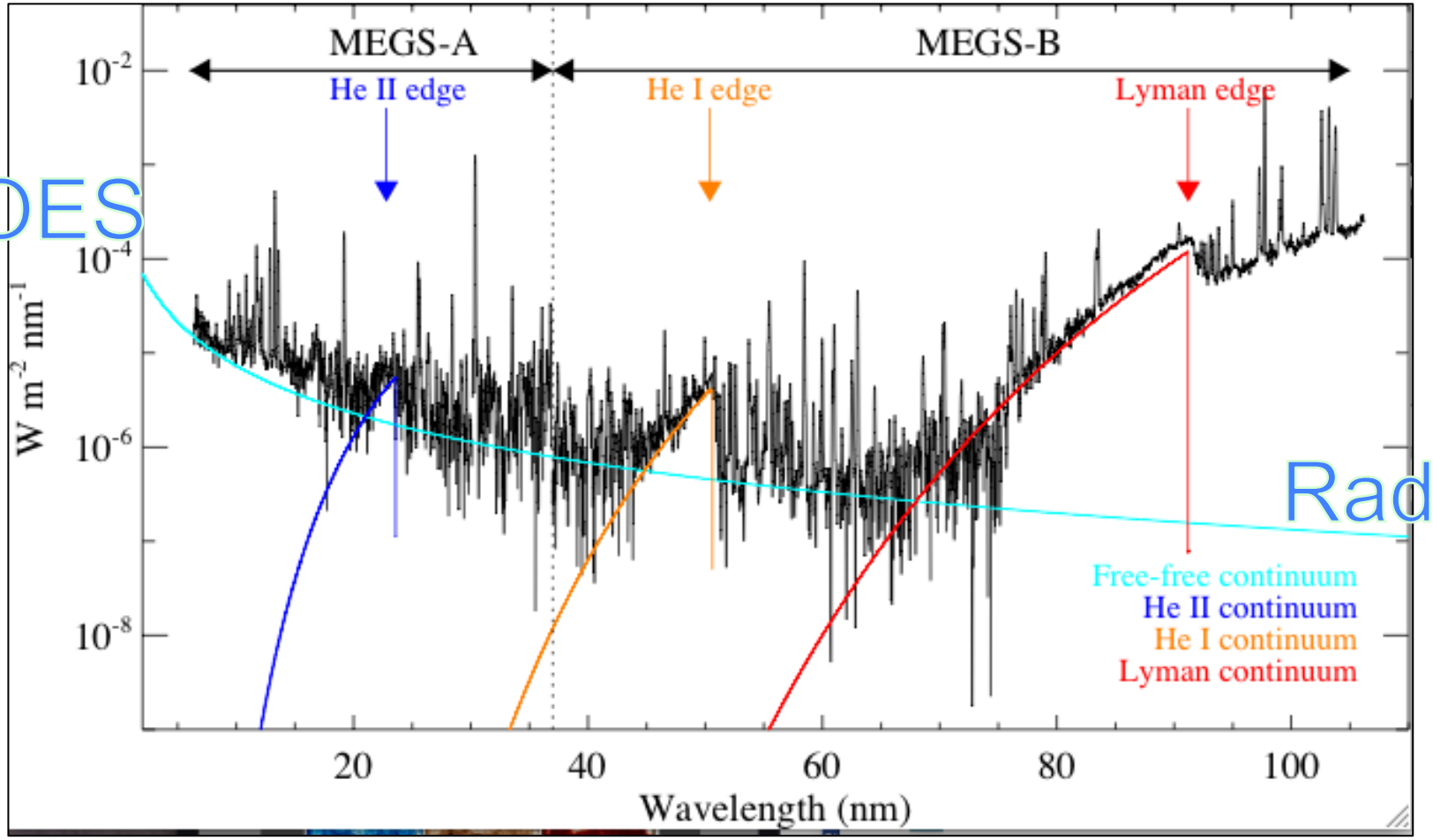
An SDO/EVE “Fe Cascade plot,” for SOL2012-03-07

More about EVE



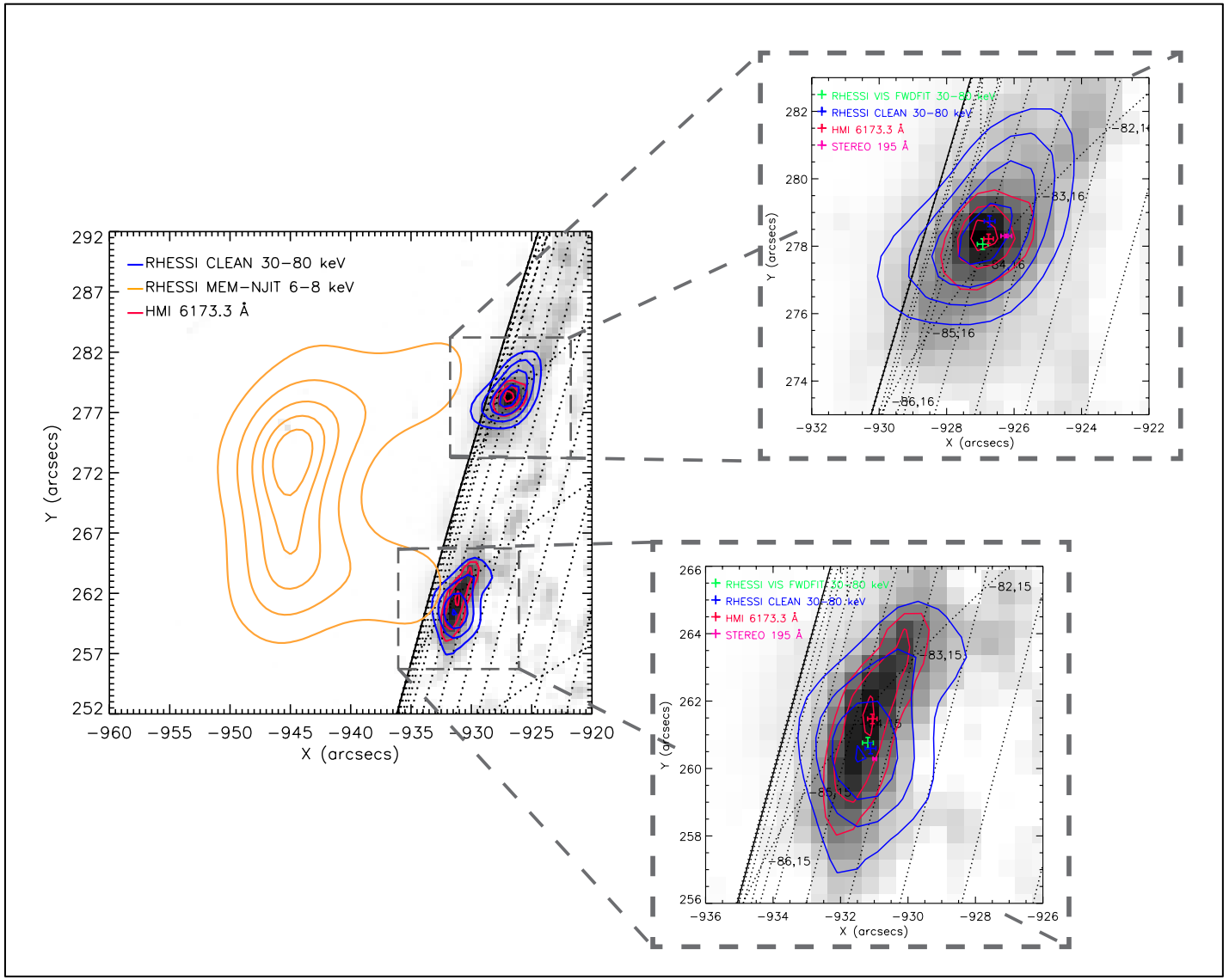
R. Milligan

More about EVE



R. Milligan

Height of flare sources



Martinez-Oliveros et al., 2012

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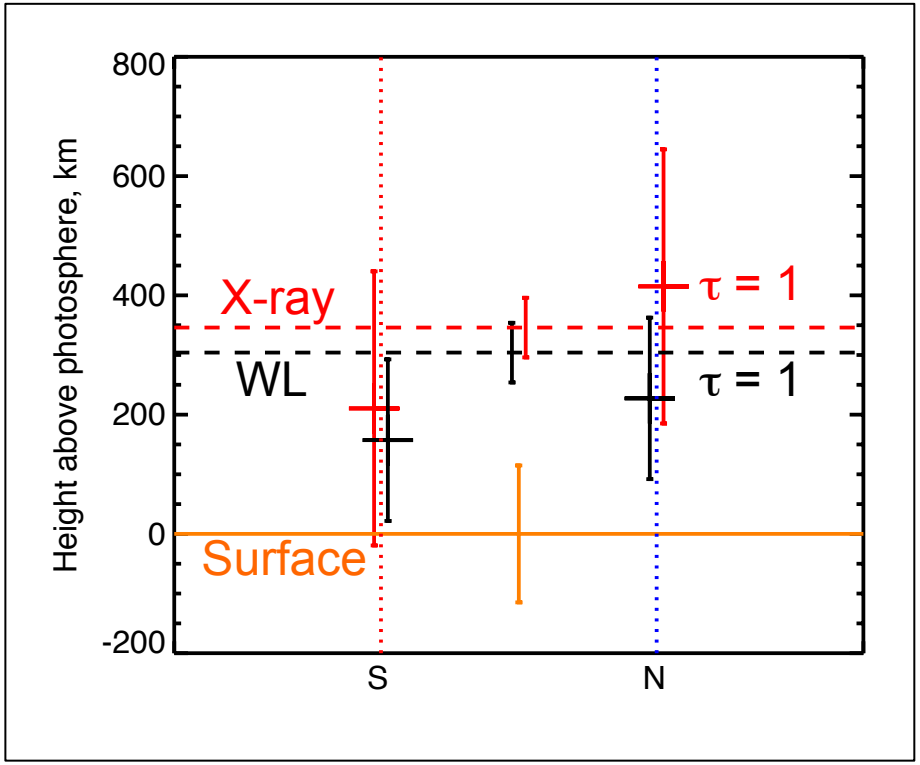

Martinez-Oliveros et al., 2012

- First height measurements of a WLF (RHESSI/HMI/STEREO): SOL2011-02-24
- The X-ray and WL sources lie at the very minimum altitude permissible by VAL-C
- The heights are significantly below the prediction of any thick-target model
- Thus far only one flare analyzed in this way

Conclusions

- Our characterization of flare luminosity is still quite primitive, with uncertainties of 0.5-1 dex most likely
- The impulsive phase of the flare (and the acceleration phase of the CME, if any) are energetically important
- The lower solar atmosphere contains a lot of flare physics, which is important both for flares and for CMEs
- Concern about inadequate knowledge of longer time scales in flare development, e.g. new Fermi results

Flare Spectral Energy Distribution