From the Sun to the Stars

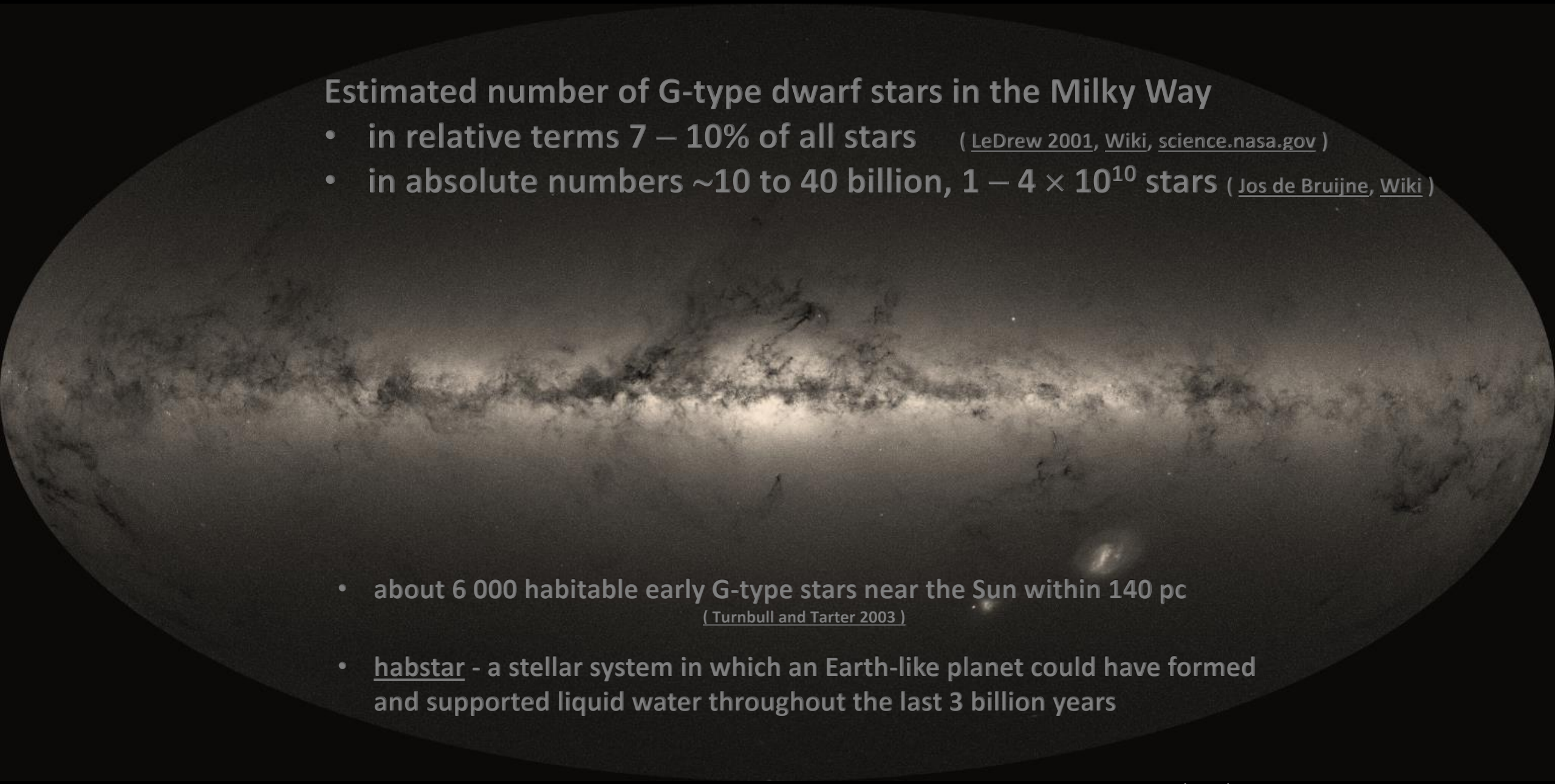
Synthesizing Sun-as-a-Star Observations of Flares



By ESA/Gaia/DPAC. Acknowledgement: A. Moitinho.

Estimated number of G-type dwarf stars in the Milky Way

- in relative terms 7 – 10% of all stars (LeDrew 2001, Wiki, science.nasa.gov)
- in absolute numbers ~10 to 40 billion, $1 - 4 \times 10^{10}$ stars (Jos de Bruijne, Wiki)



- about 6 000 habitable early G-type stars near the Sun within 140 pc
  (Turnbull and Tarter 2003)
- habstar - a stellar system in which an Earth-like planet could have formed and supported liquid water throughout the last 3 billion years

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Solar-Type Dwarfs and Flare Energy Input to Exoplanets

- G-type dwarf stars host an outer convective envelope coupled with differential rotation
- This enables an α–Ω magnetic dynamo, sustaining long-term magnetic activity
- Magnetic energy release manifests as:
  - Stellar flares
  - Coronal mass ejections

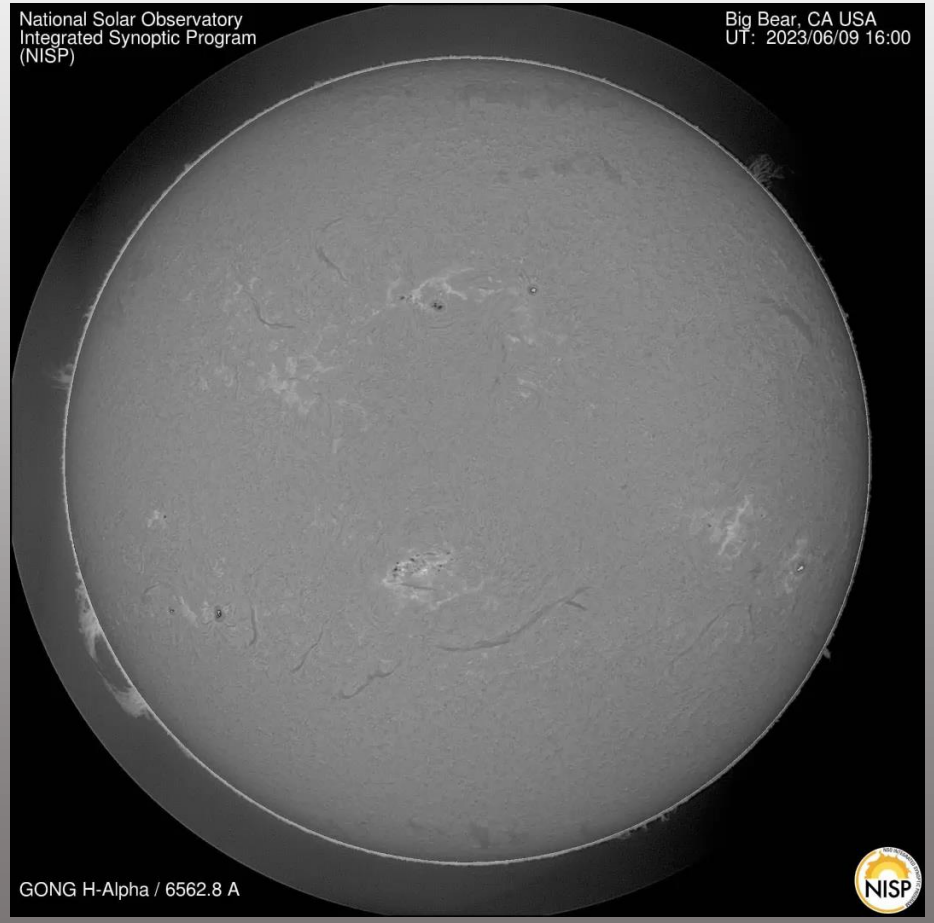
Key question

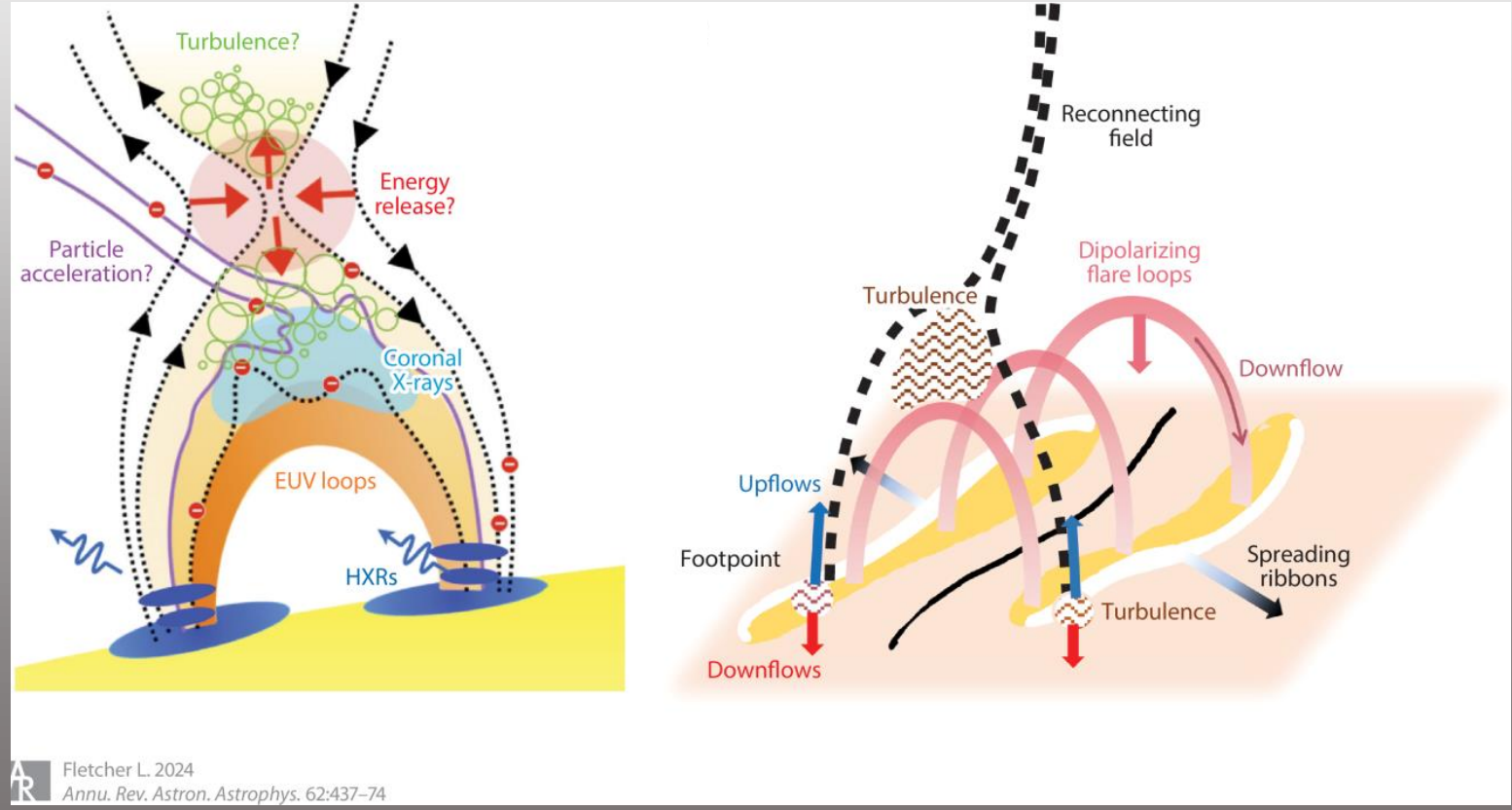
What is the excess radiative energy deposited in an exoplanetary atmosphere during a stellar flare?

Solar Flares in a Nutshell

- Magnetic energy is suddenly released from the coronal magnetic field
- Intense plasma heating occurs in a relatively small volume
- The eruption drives plasma expansion, flows, and particle acceleration
- Energized plasma radiates across the electromagnetic spectrum

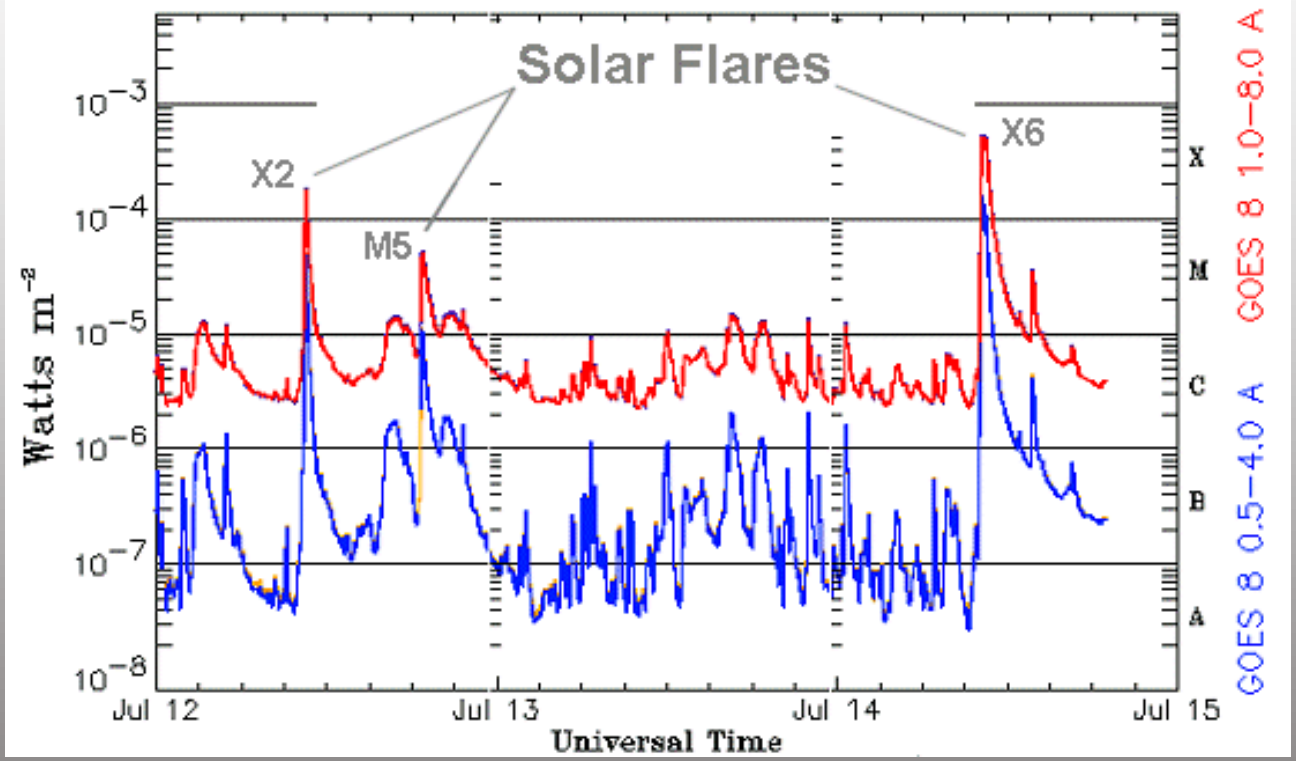
→ a multiwavelength spectacle





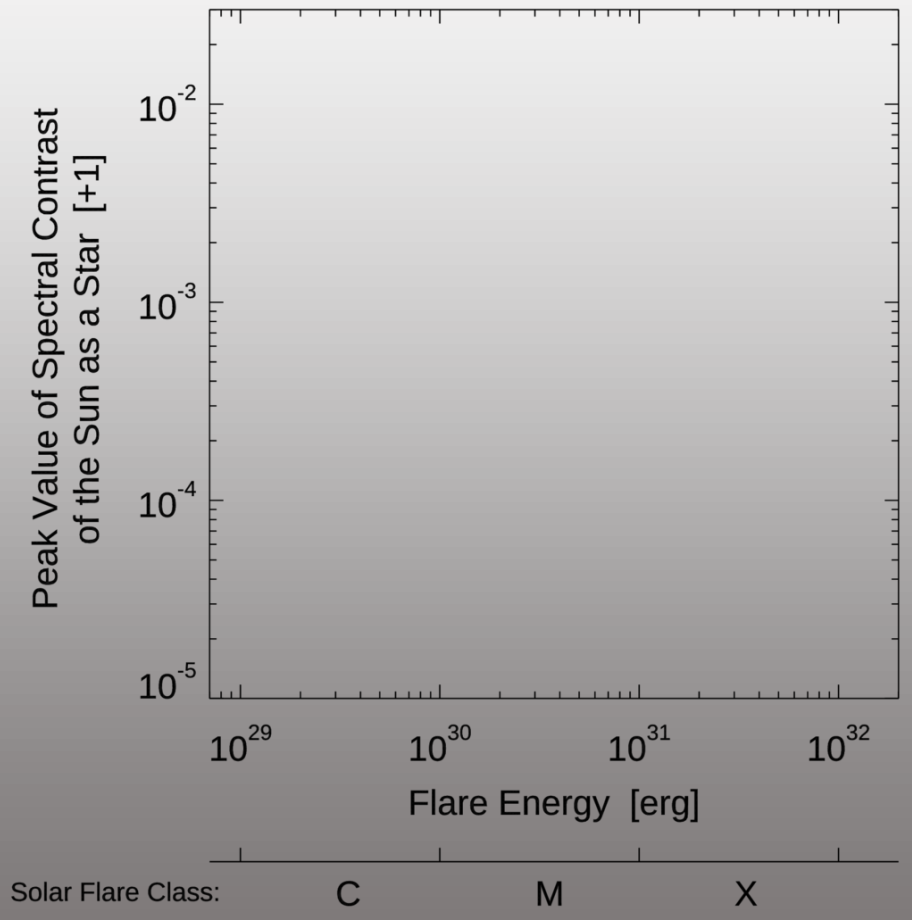
Solar Flares Classification

soft X-ray flux of the Sun as a star

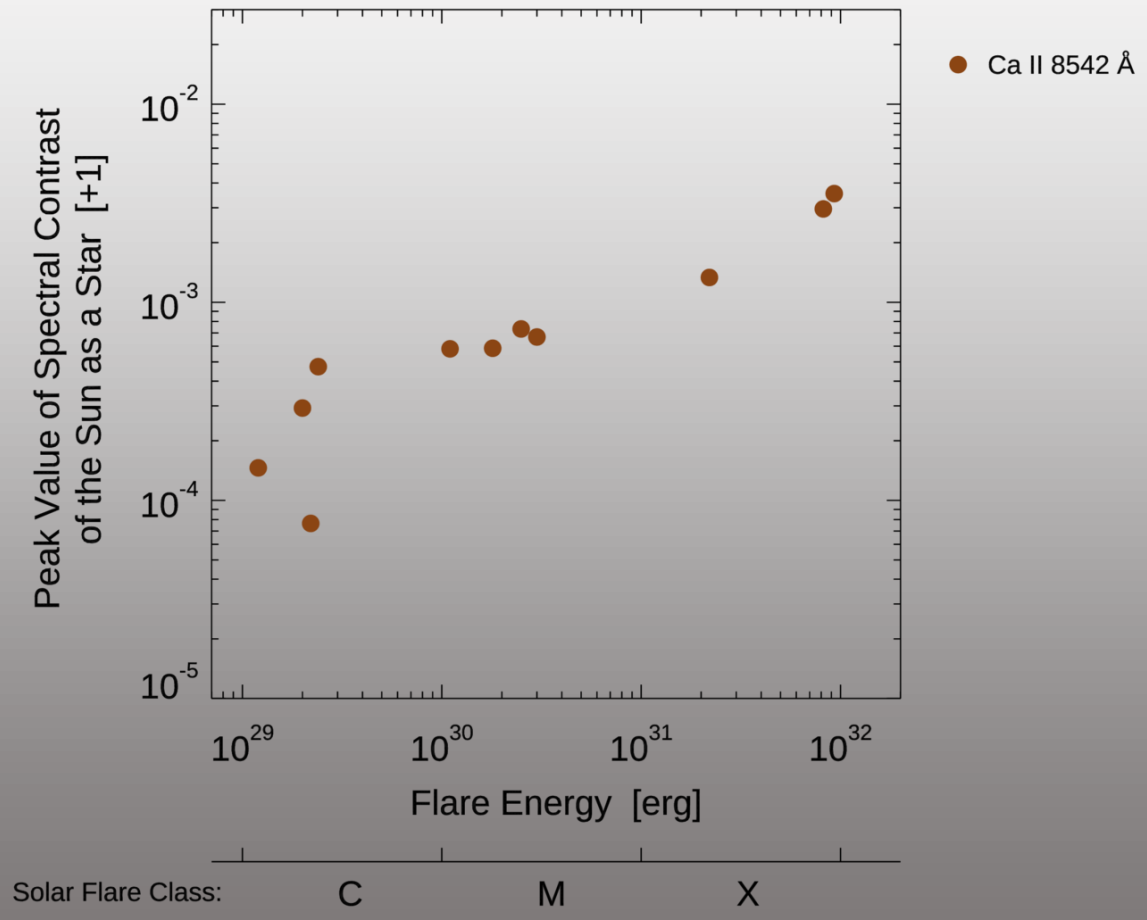


Flare class	Peak X-ray Flux in the 1–8 Å Band
B	$< 10^{-6}$ Wm^{-2}
C	$10^{-6} – 10^{-5}$ Wm^{-2}
Medium	$10^{-5} – 10^{-4}$ Wm^{-2}
eXtreme	$\geq 10^{-4}$ Wm^{-2}

GOES = Geostationary Operational Environmental Satellite


Peak Value of Spectral Contrast
of the Sun as a Star [+1]
10-2
10-3
10-4
10-5
1029
1030
1031
1032
Flare Energy [erg]
Solar Flare Class:
C
M
X

Scaling law of stellar flare energy. Really?



De Wilde et al. (2025)

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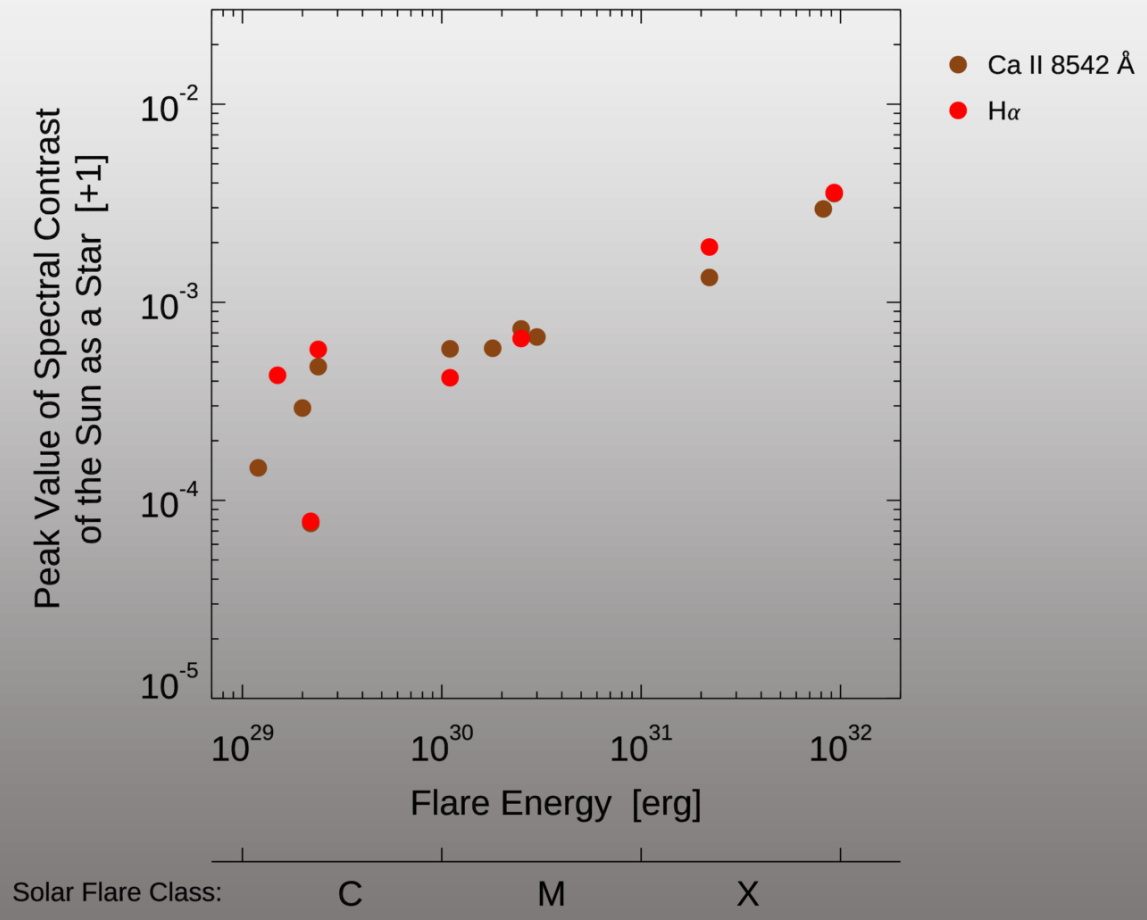

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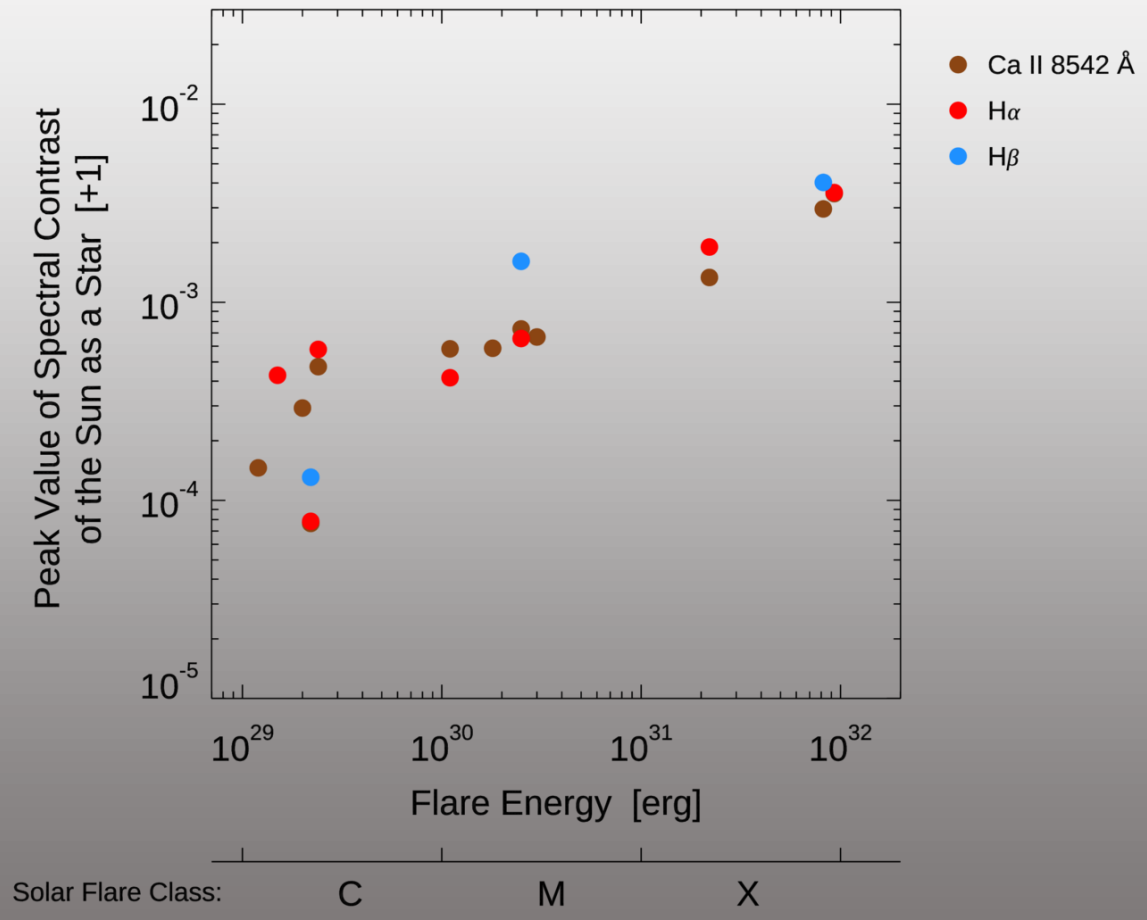

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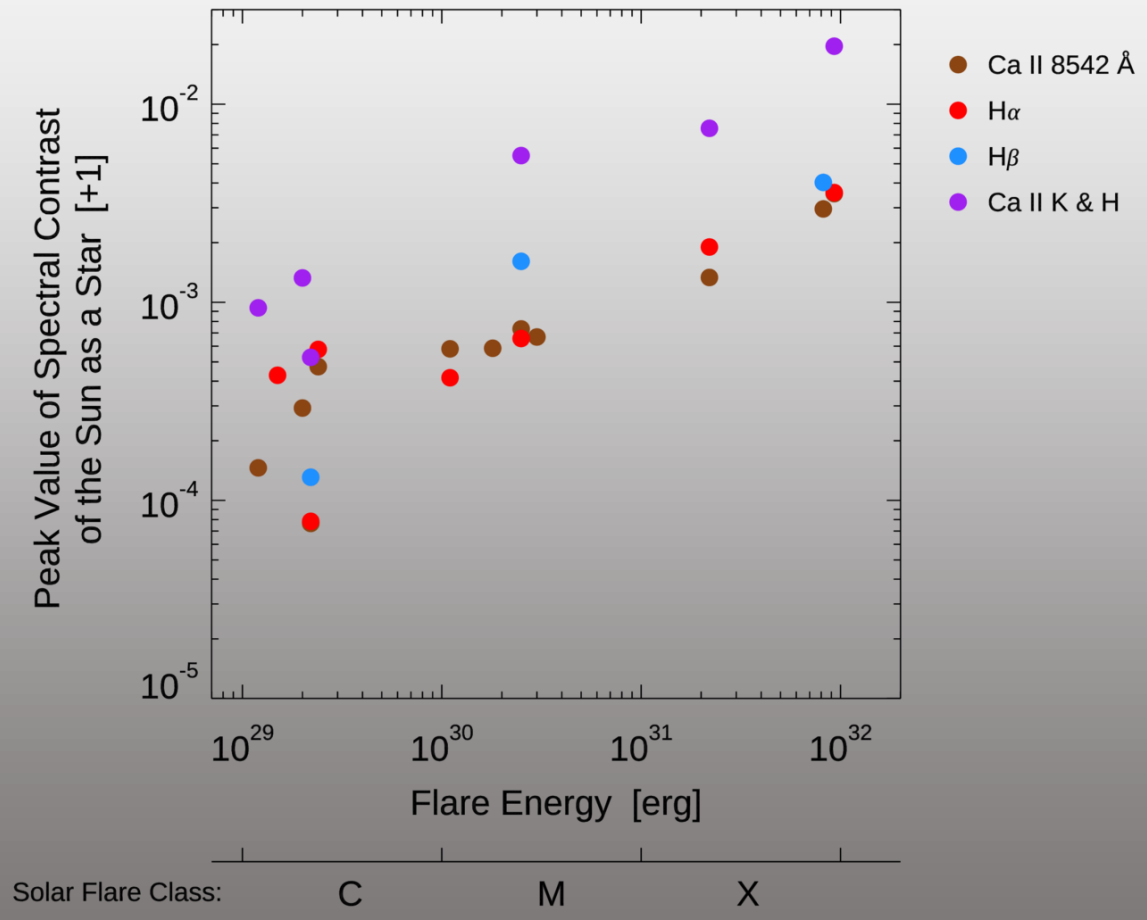

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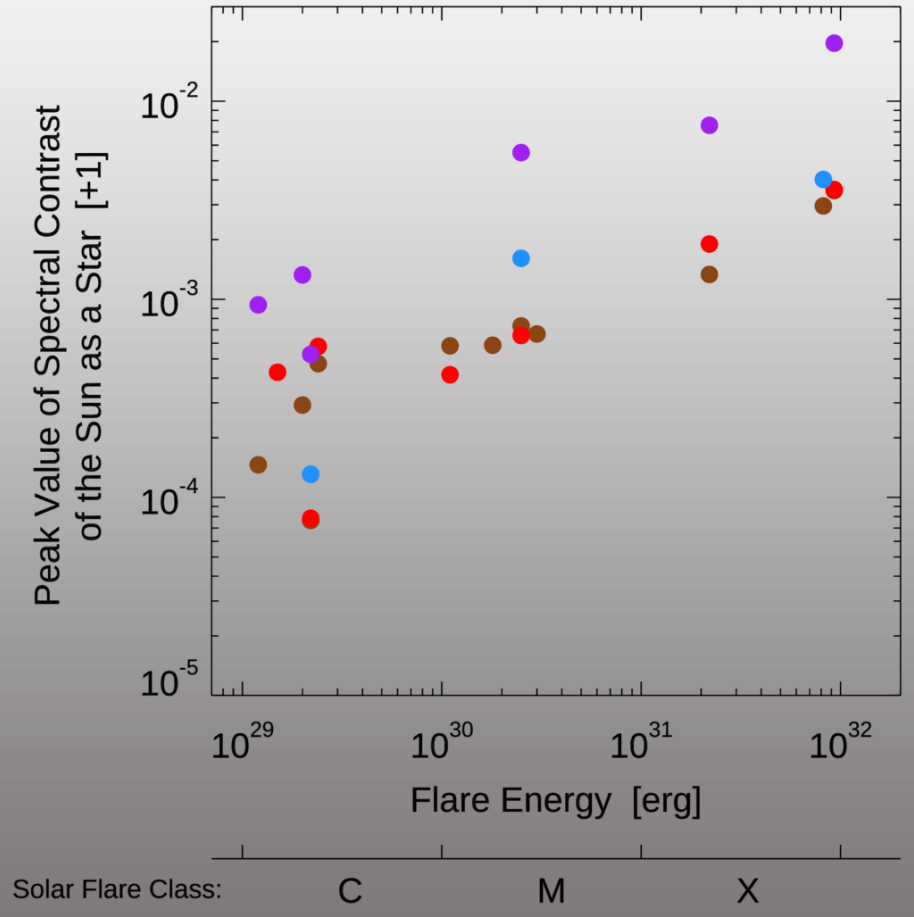


$$Spectral\ Contrast\ C_{\mathrm{peak}} \approx (Flare\ Energy)^{a}$$

Line	*R*	*b*	*a*
Ca II K	0.995	−15.5	0.430
Ca II 8542 Å	0.924	−16.6	0.443
Hα	0.847	−15.8	0.417
Overall fit	0.744	−19.7	0.547

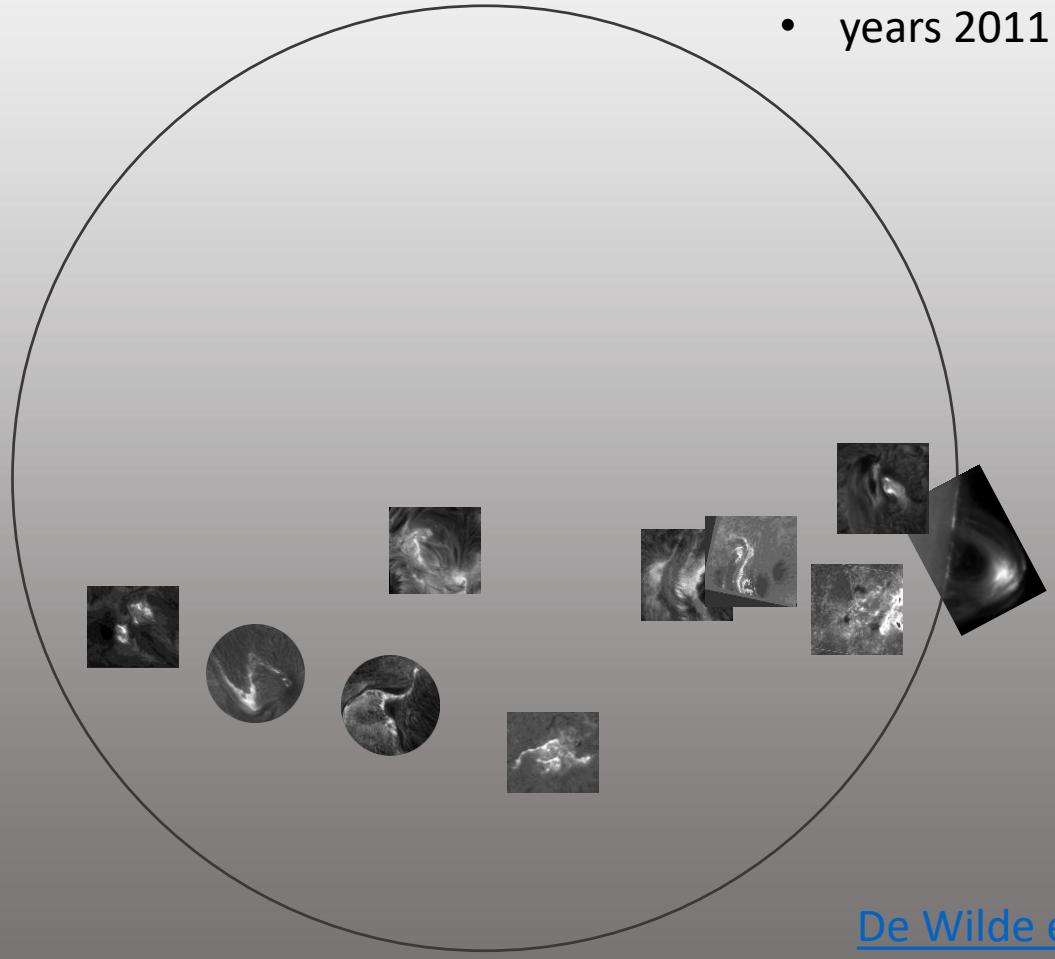
$$\log_{10} C_{\mathrm{peak}} \approx b + a \log_{10} E_{\mathrm{flare}}$$

$$C_{\mathrm{peak}} \approx E_{\mathrm{flare}}^{a} \approx \sqrt{E_{\mathrm{flare}}}$$

De Wilde et al. (2025)

Flare sample overview and locations

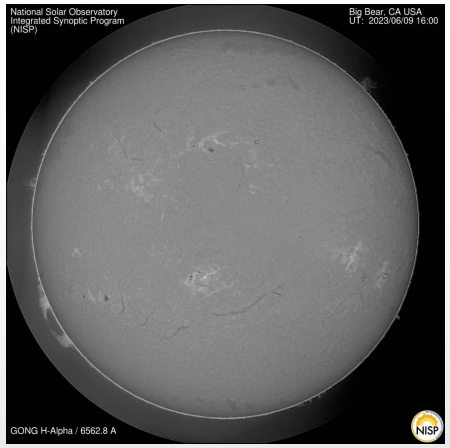
- 19 flares, classes X9.3 – C1.9, μ = 0.97 – 0.00
- Swedish 1-m Solar Telescope (La Palma)
- imaging spectroscopy of strong chromospheric lines from Ca II K & H to Ca II 8542 Å
- years 2011 – 2024







De Wilde et al. (2025)



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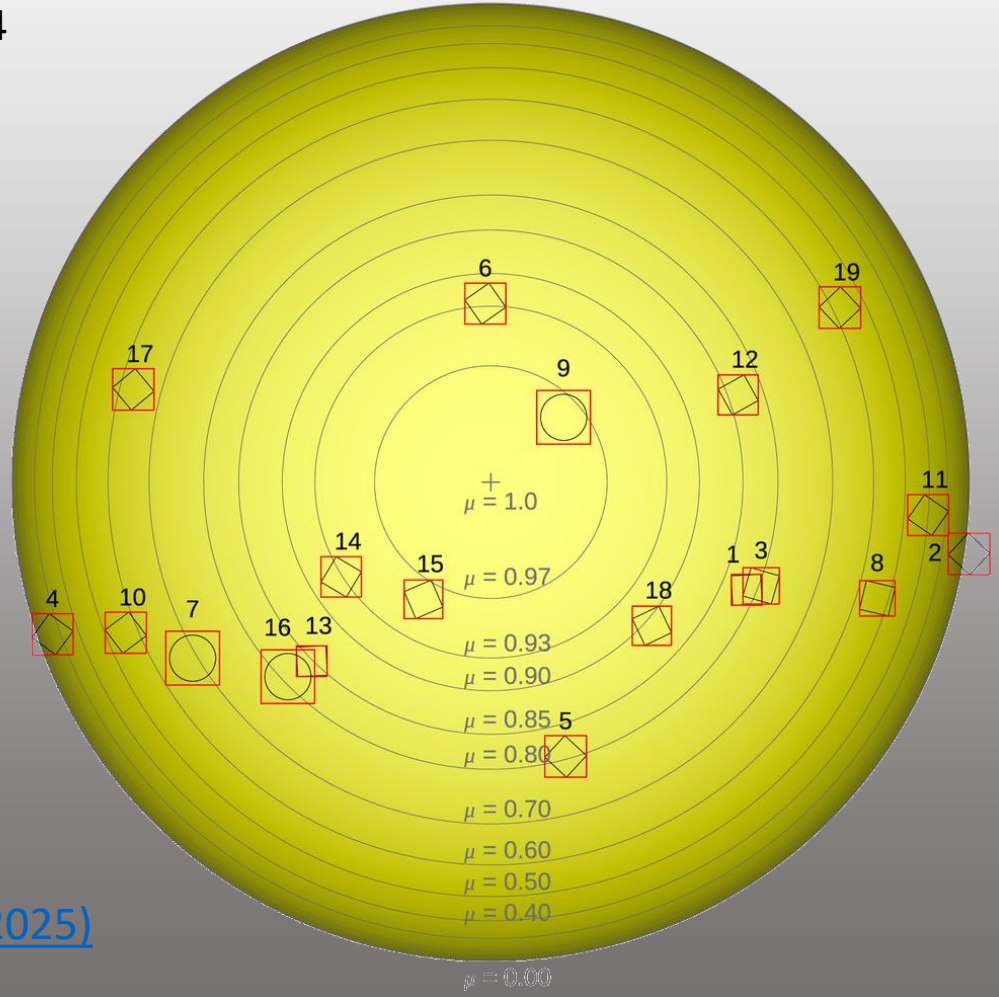
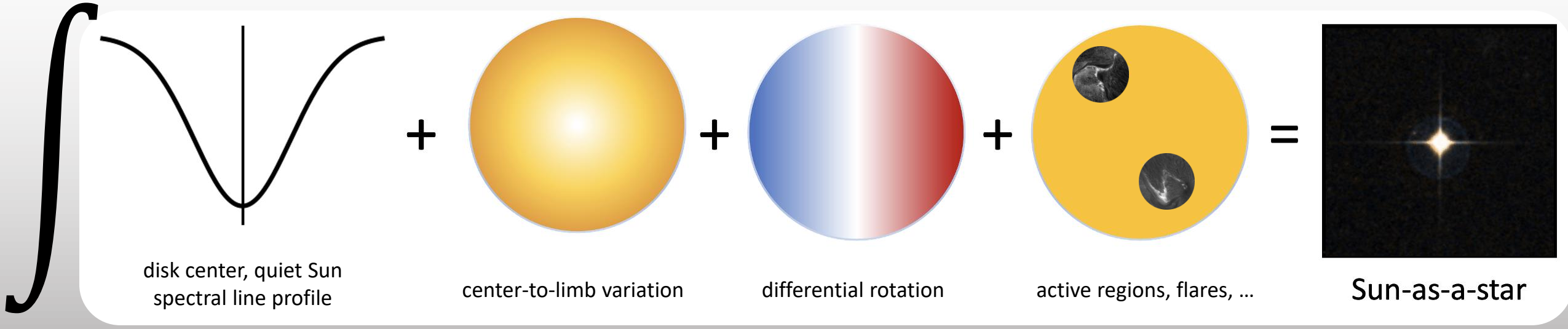


De Wilde et al. (2025)

Numerical Empirical Sun-as-a-Star Integrator NESSI



NESSI by [Pietrow & Pastor Yabar 2024] - Overview and Requirements

Purpose

- Converts high-resolution solar observations with a **partial field of view** into **Sun-as-a-star spectra**

Required Inputs

- Quiet-Sun spectral line profile at **disk center**
- Empirical **center-to-limb variation (CLV)** curves for each wavelength point
- **Differential rotation** velocity profile
- **Orientation of the solar rotation axis** relative to the observer

Code availability: https://github.com/apy-github/NESSI

Formal concepts

Contrast profile *C*(λ, t)

$$\Delta I_{\mathrm{FOV}}(\lambda, t) = \frac{O^{-1}}{A_{\mathrm{FOV}}} \int_{\mathrm{FOV}} I(x, y, \lambda, t) - I^{(\mathrm{N})}(x, y, \lambda)\, \mathrm{d}x\mathrm{d}y,$$

$$I_{\mathrm{FD}}(\lambda, t) = I_{\mathrm{FD}}^{(\mathrm{N})}(\lambda) + \Delta I_{\mathrm{FOV}}(\lambda, t).$$

$$C(\lambda, t) = I_{\mathrm{FD}}(\lambda, t) / I_{\mathrm{FD}}^{(\mathrm{N})}(\lambda).$$

De Wilde et al. (2025)

Formal concepts

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Differenced equivalent width δEW

$$\Delta S(\lambda, t) = \frac{\Delta I_{\mathrm{FOV}}(\lambda, t)}{I_{\mathrm{FD}}^{(\mathrm{N})}(\lambda_{\mathrm{cont}})}.$$

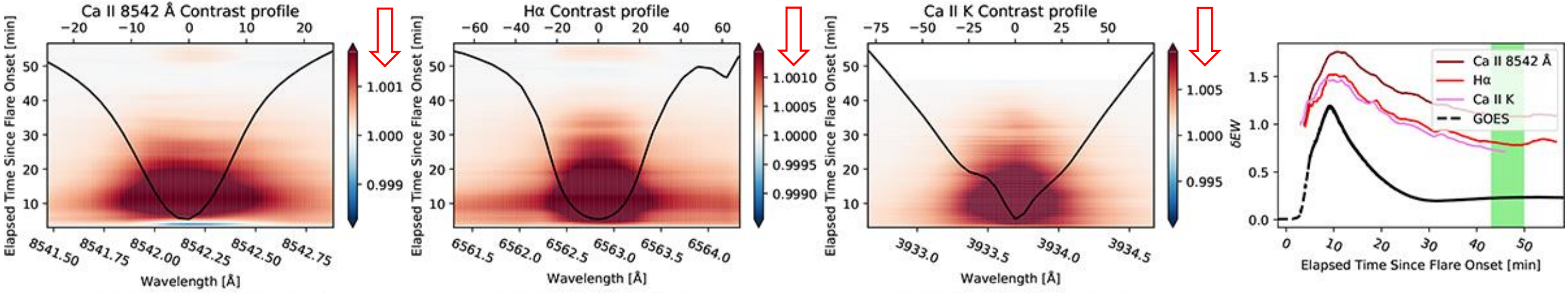
$$\Delta EW = \int_{\lambda_0 - \Delta\lambda}^{\lambda_0 + \Delta\lambda} \Delta S(\lambda, t)\, \mathrm{d}\lambda, \qquad \Delta\lambda = 0.5 \text{ Å}$$

Normalized equivalent width $\delta EW(t) = \Delta EW(t) \,/\, |\Delta EW(t_0)|$.

De Wilde et al. (2025)

X9.3 Flare (2017-09-06)

The strongest flare of past Solar Cycle 24



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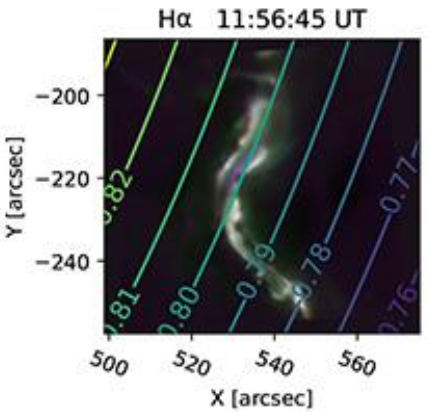
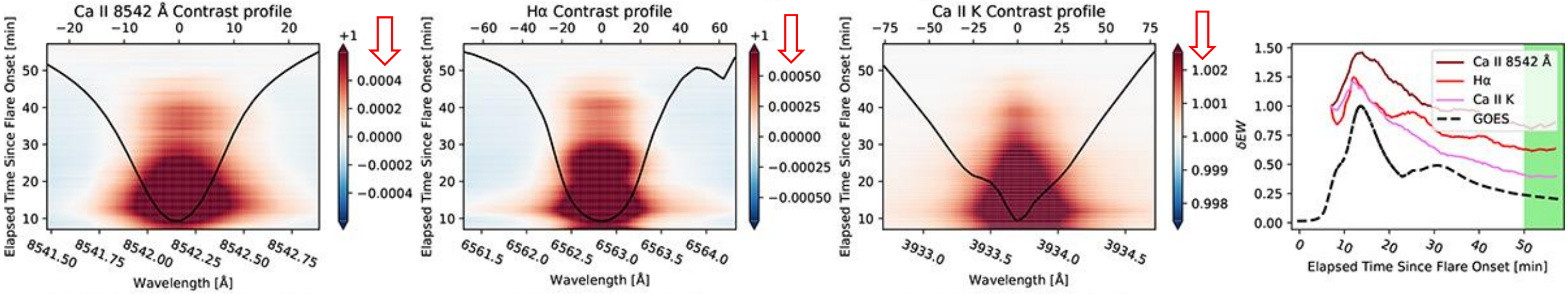


[De Wilde et al. (2025)]

X2.2 Flare (2017-09-06)



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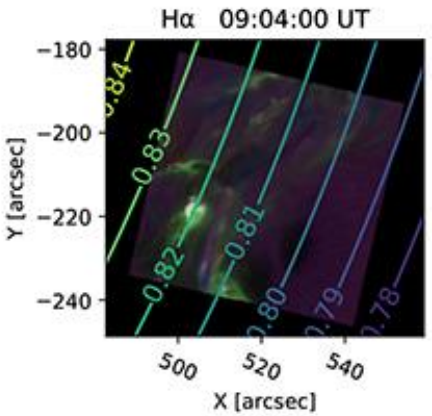


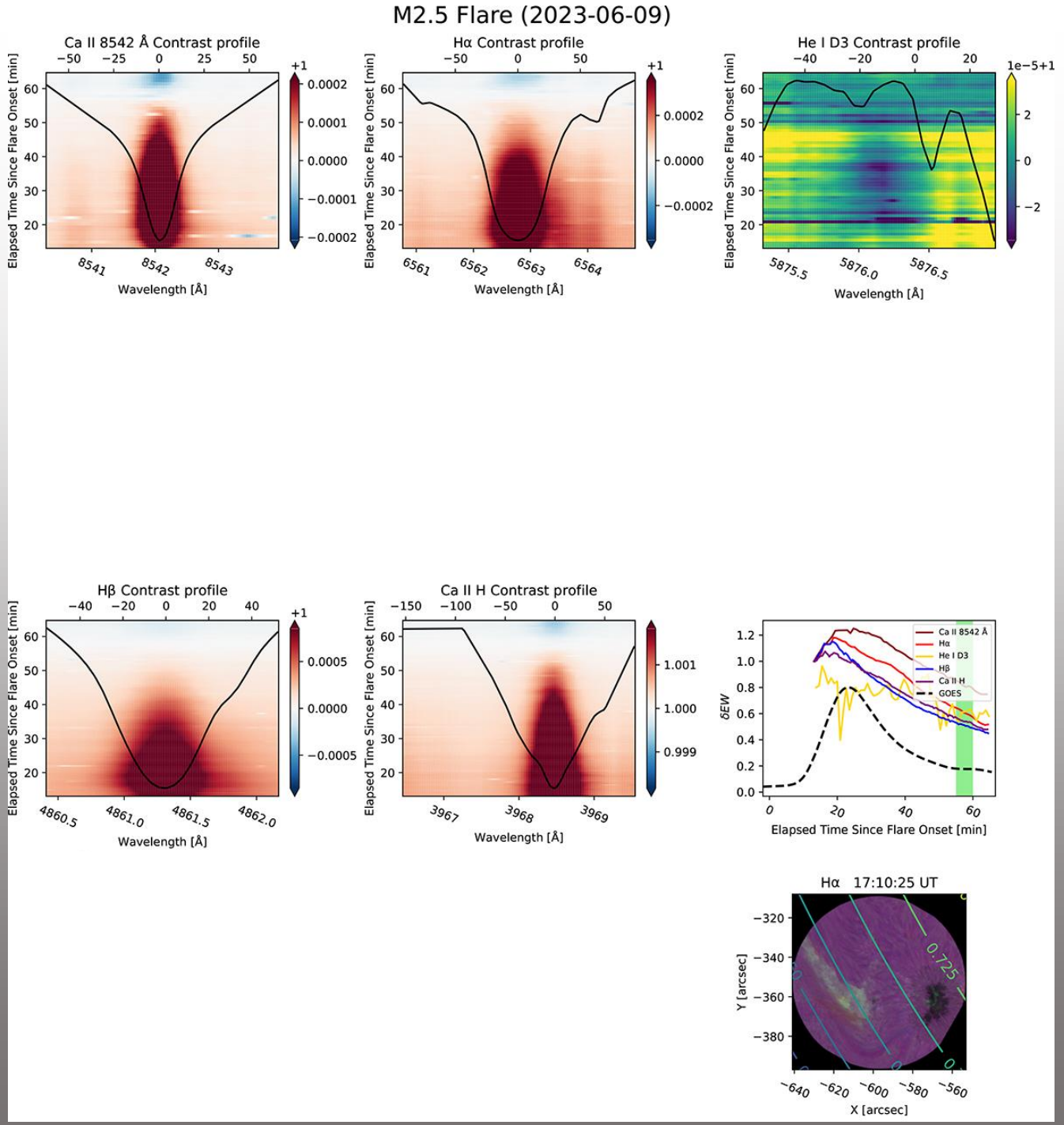
De Wilde et al. (2025)

Contrast profiles

Ca II 8542 Å, Hα, and He I D3

Contrast profiles

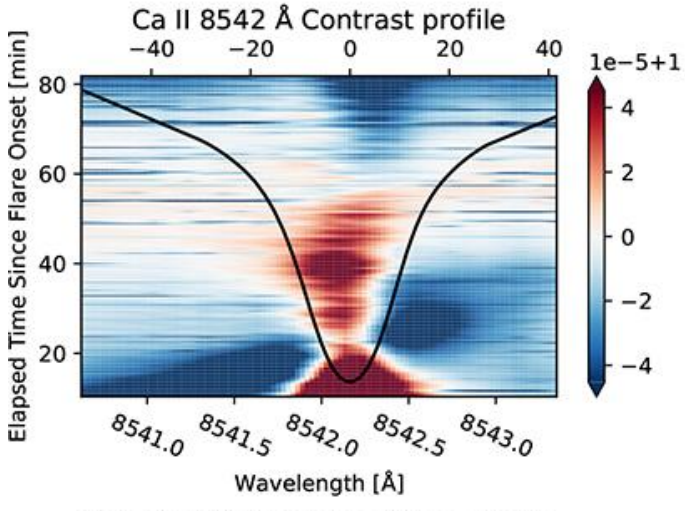
Hβ and Ca II H

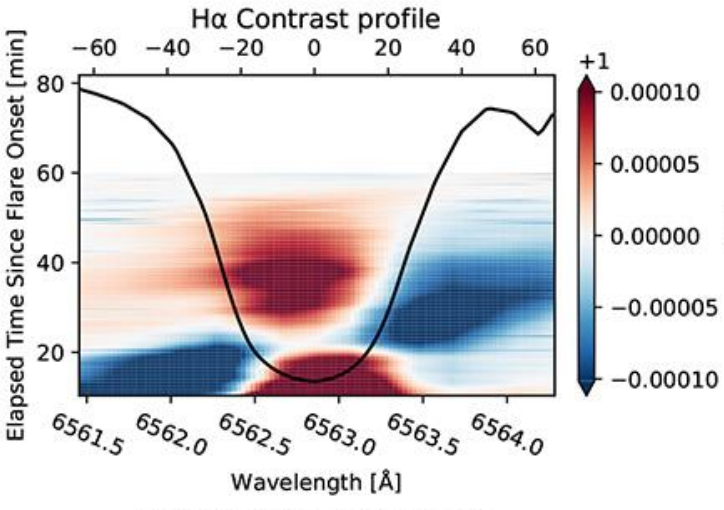


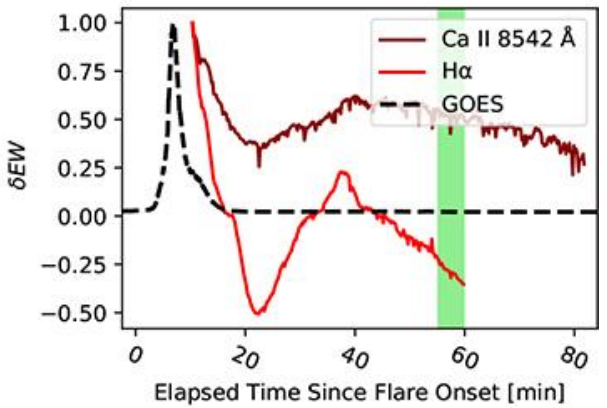
Normalized equivalent width

De Wilde et al. (2025)

C8.4 Flare (2016-05-14)







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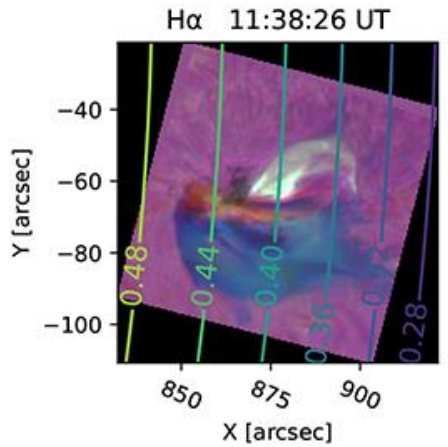
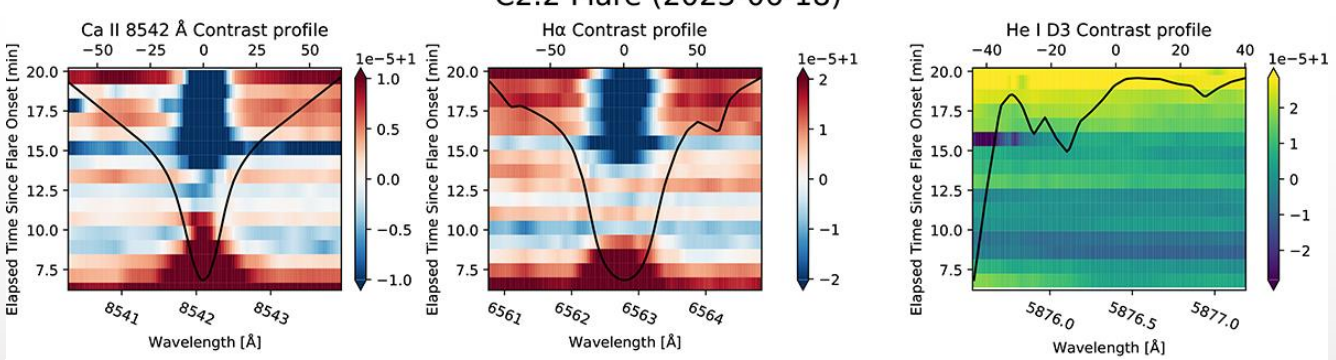


[De Wilde et al. (2025)]

Contrast profiles

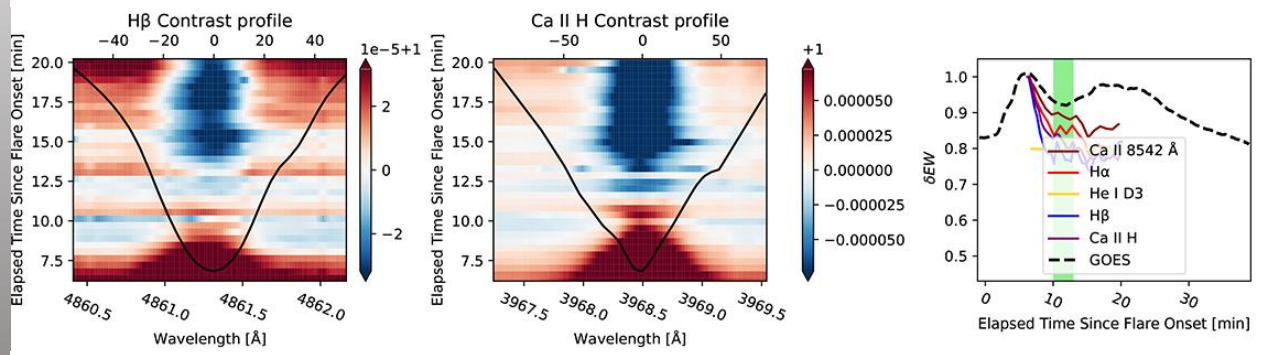
Ca II 8542 Å, Hα, and He I D3



The same analyses were applied to a sample of **19 flares** spanning classes **X9.3 to C1.9**.

Contrast profiles

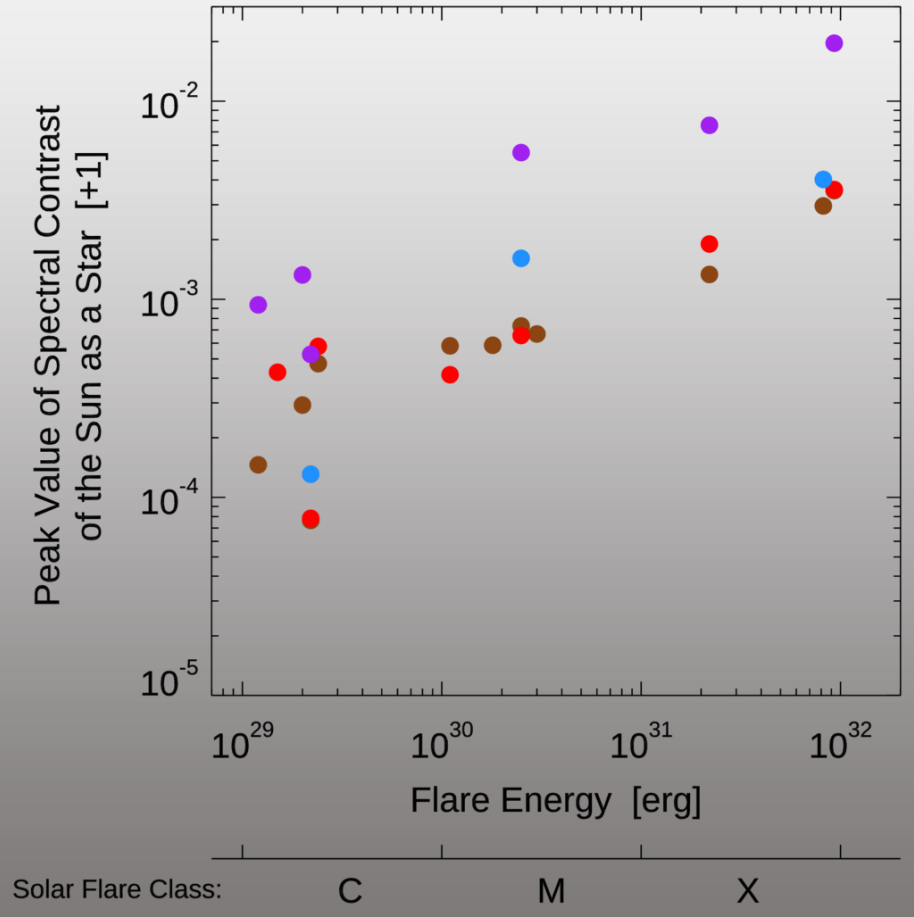
Hβ and Ca II H



Normalized equivalent width

[De Wilde et al. (2025)]

Empirical scaling law of stellar flare energy



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De Wilde et al. (2025)

Conclusion

Revealing patterns and laws crucially relies on the analysis of **large statistical data sets**.

Think big data.

De Wilde et al., 2025: Synthesizing Sun-as-a-star flare spectra from high-resolution solar observations

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The topic of “the Sun as a Star” in hindsight

The topic of "the Sun as a star" has seen a substantial revival in the context of exoplanet research and planetary habitability.

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