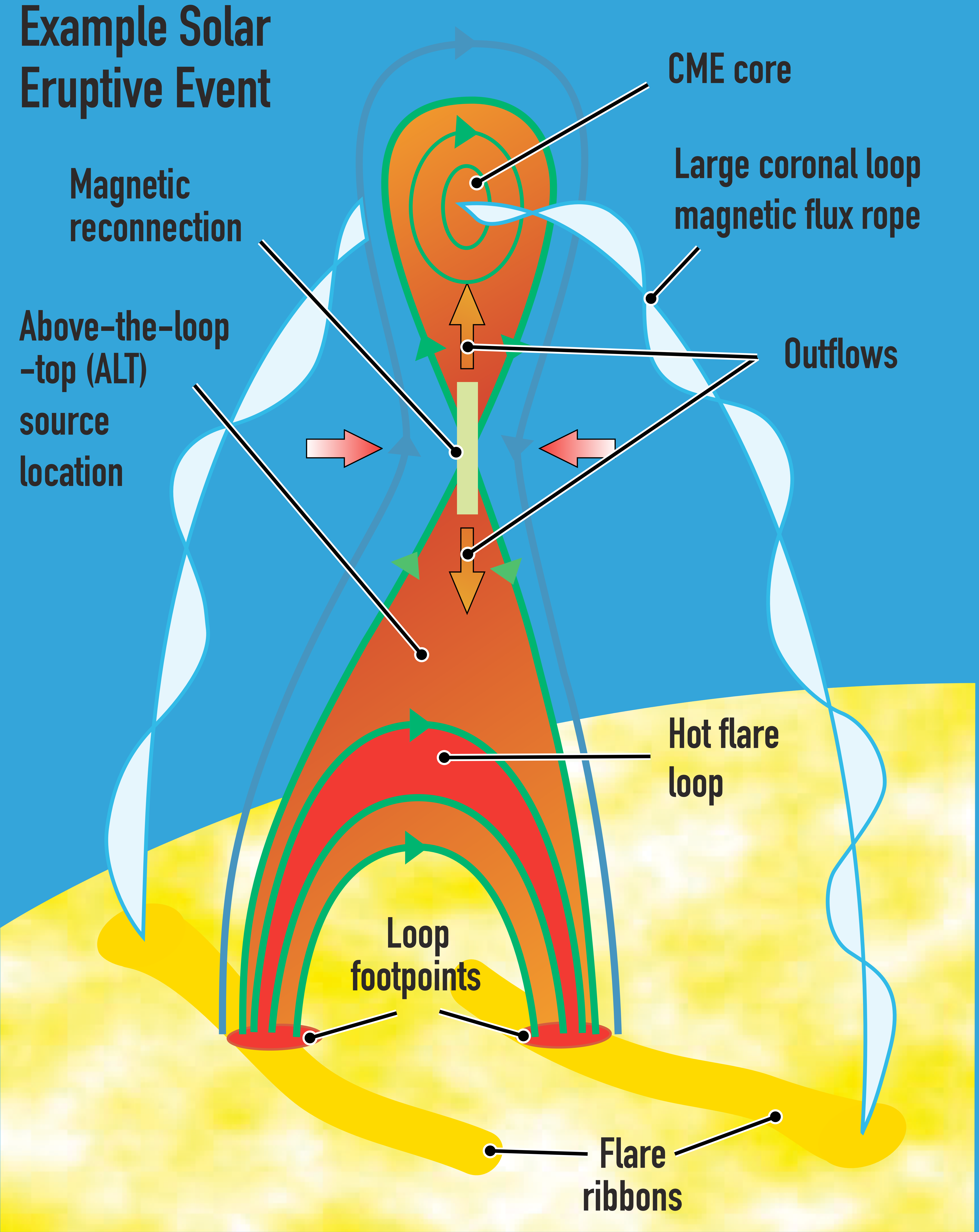
GRAHAM KERR (NASA/GSFC & CUA)

WHITE LIGHT SOLAR FLARES:
CONSTRAINING FLARE ENERGY TRANSPORT MODELS WITH THE OPTICAL & NUV CONTINUUM



SOLAR FLARES - STANDARD MODEL

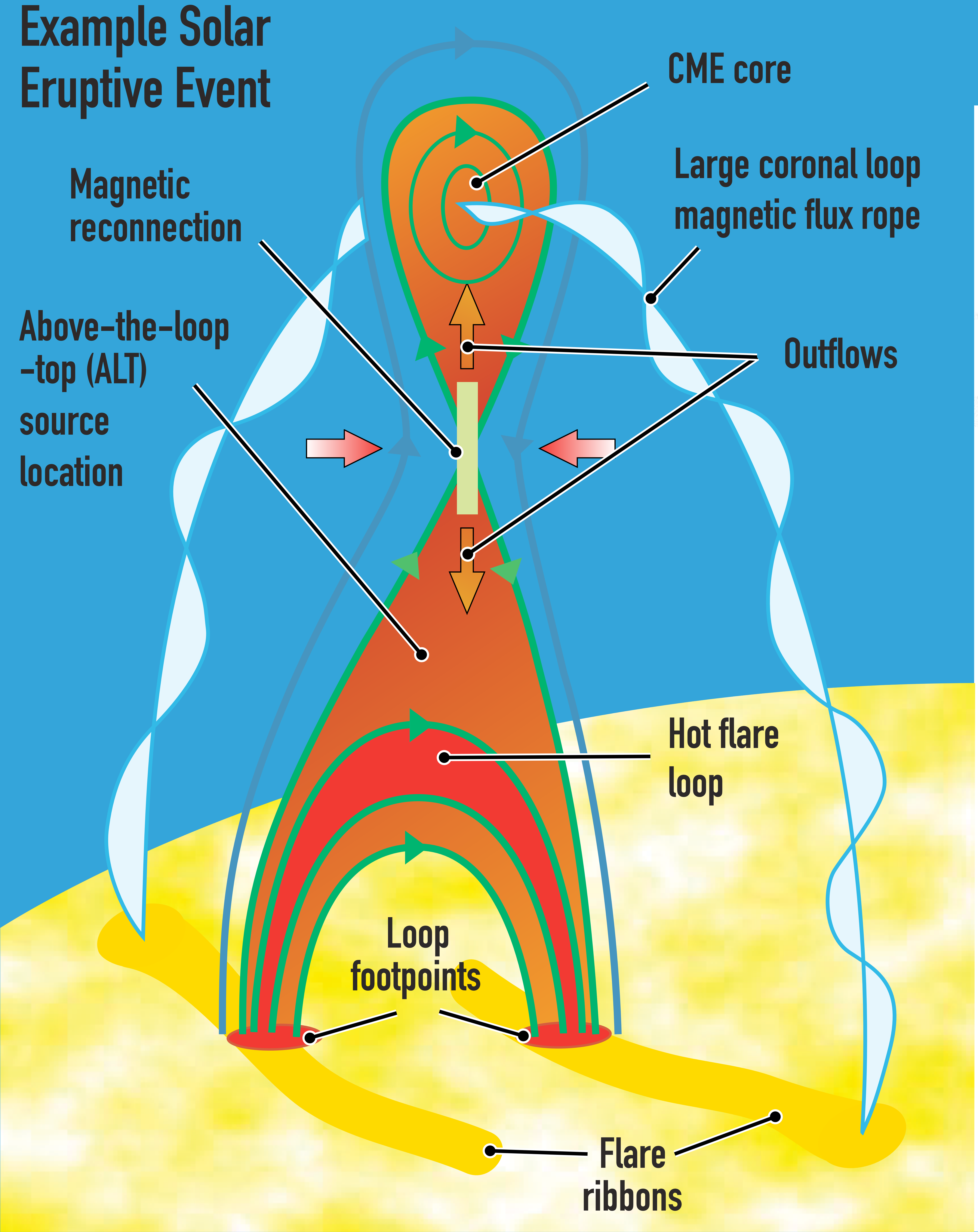
Transient, yet dramatic energy release in the solar atmosphere that, together with CMEs, drive space weather.

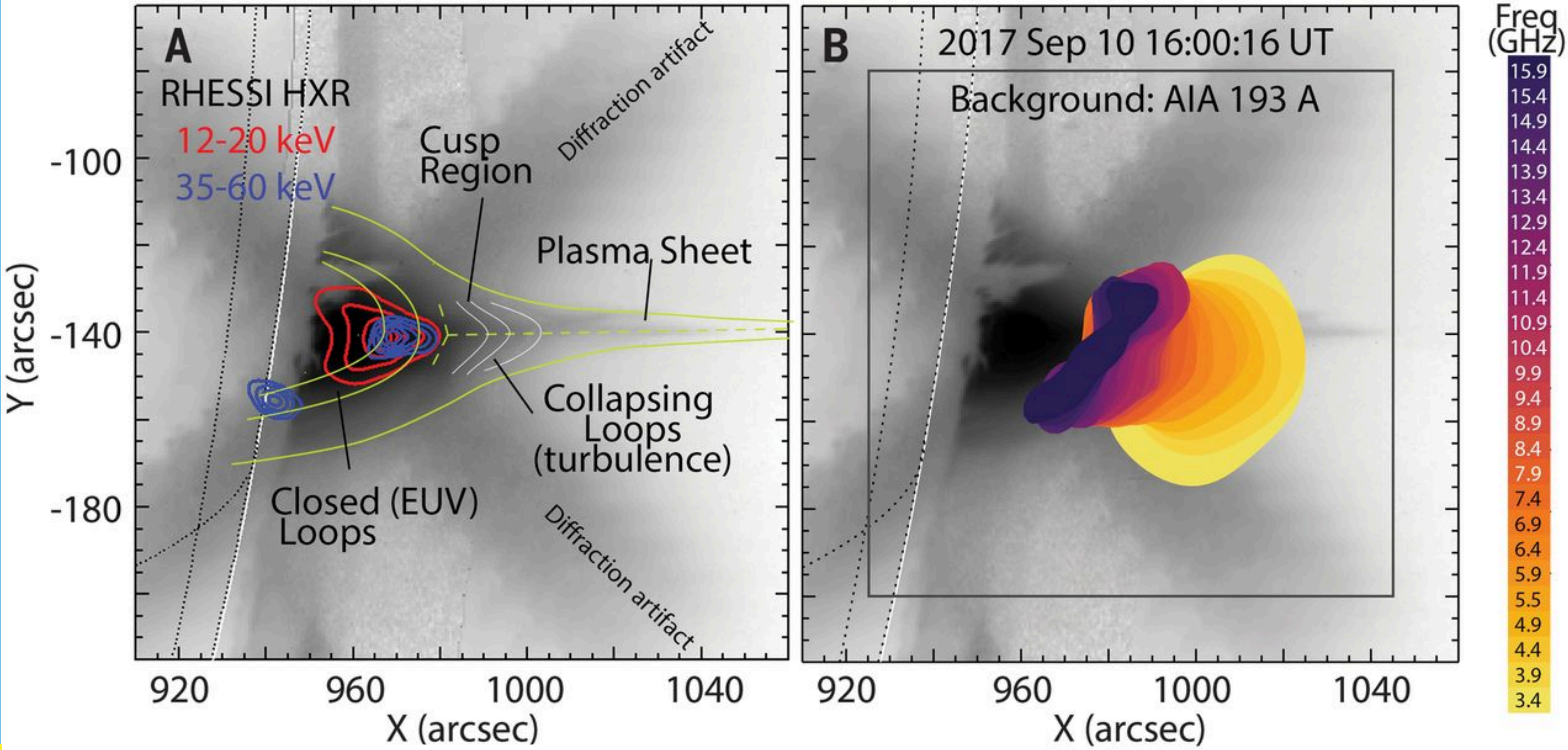
Magnetic reconnection liberates signifiant amounts of energy ($>10^{32}$ ergs) in the corona, causing in situ heating and accelerating particles out of the thermal background (usually we just talk about electrons but very likely protons and other ions are also accelerated).

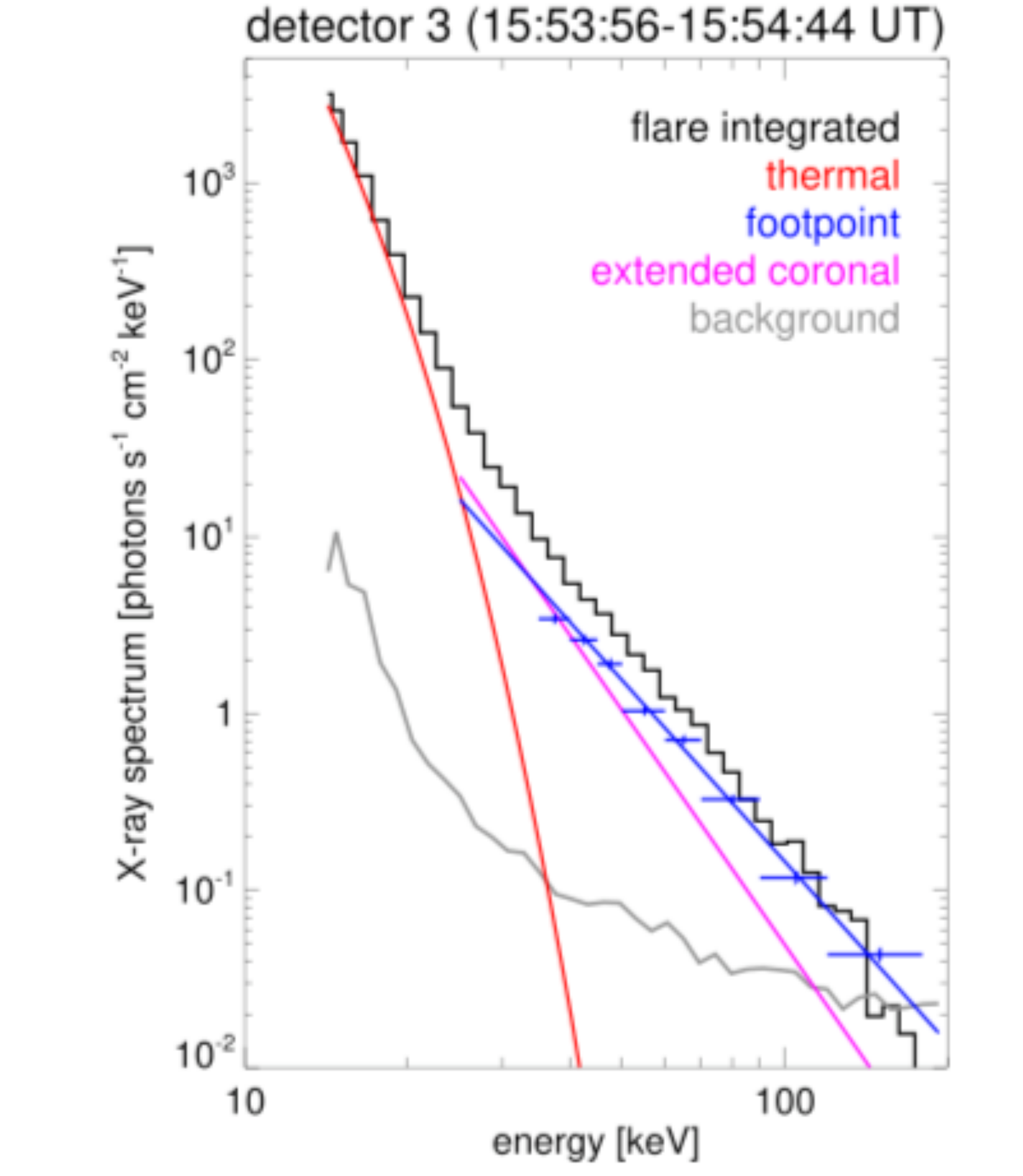
These non-thermal particles are ducted along the magnetic field lines to the lower atmosphere (transition region and corona), where they undergo Coulomb collisions.

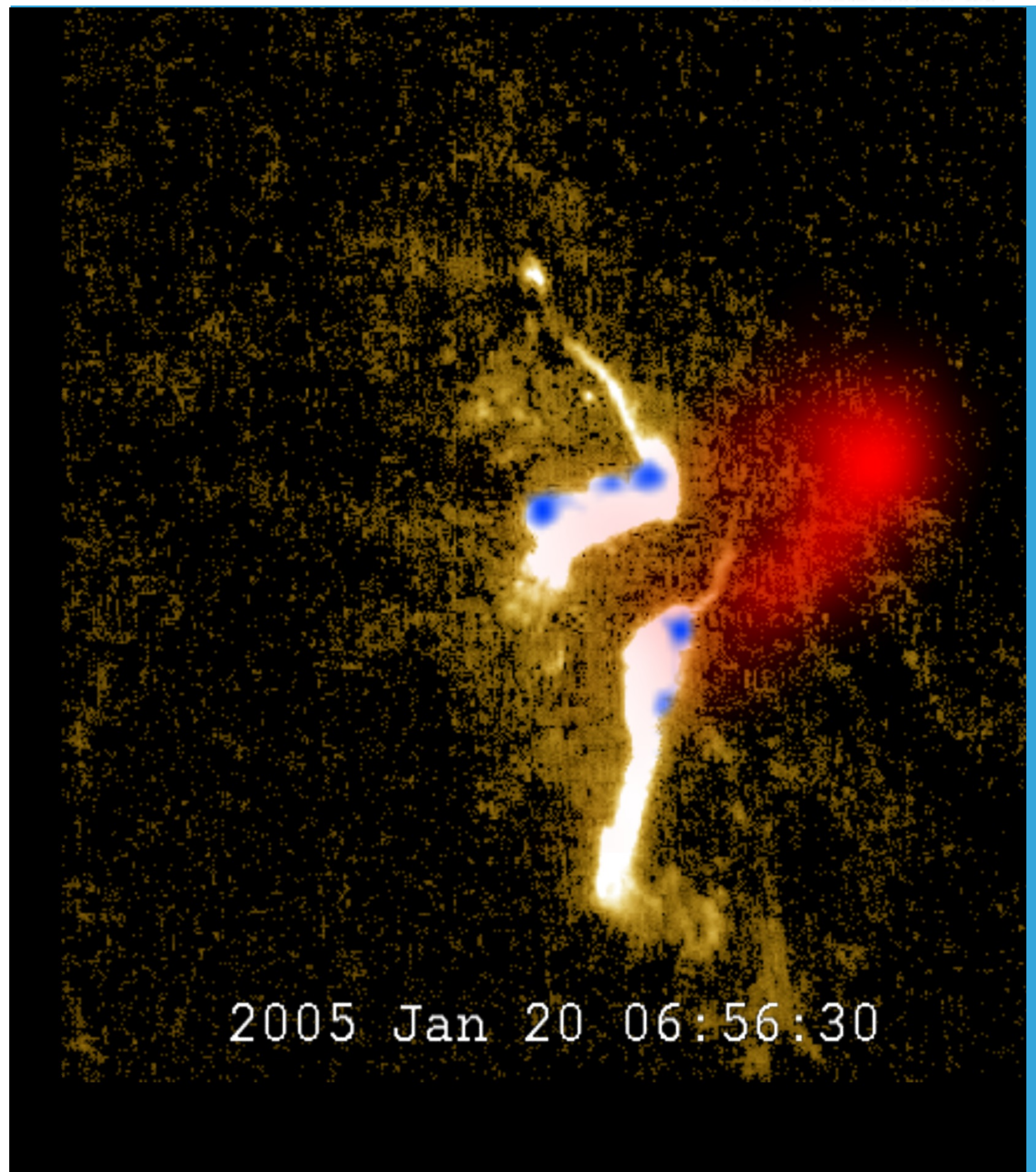
Intense plasma heating and and ionisation results in a broadband enhancement to the solar radiative output and mass flows.

SOLAR FLARES – OBSERVATIONS



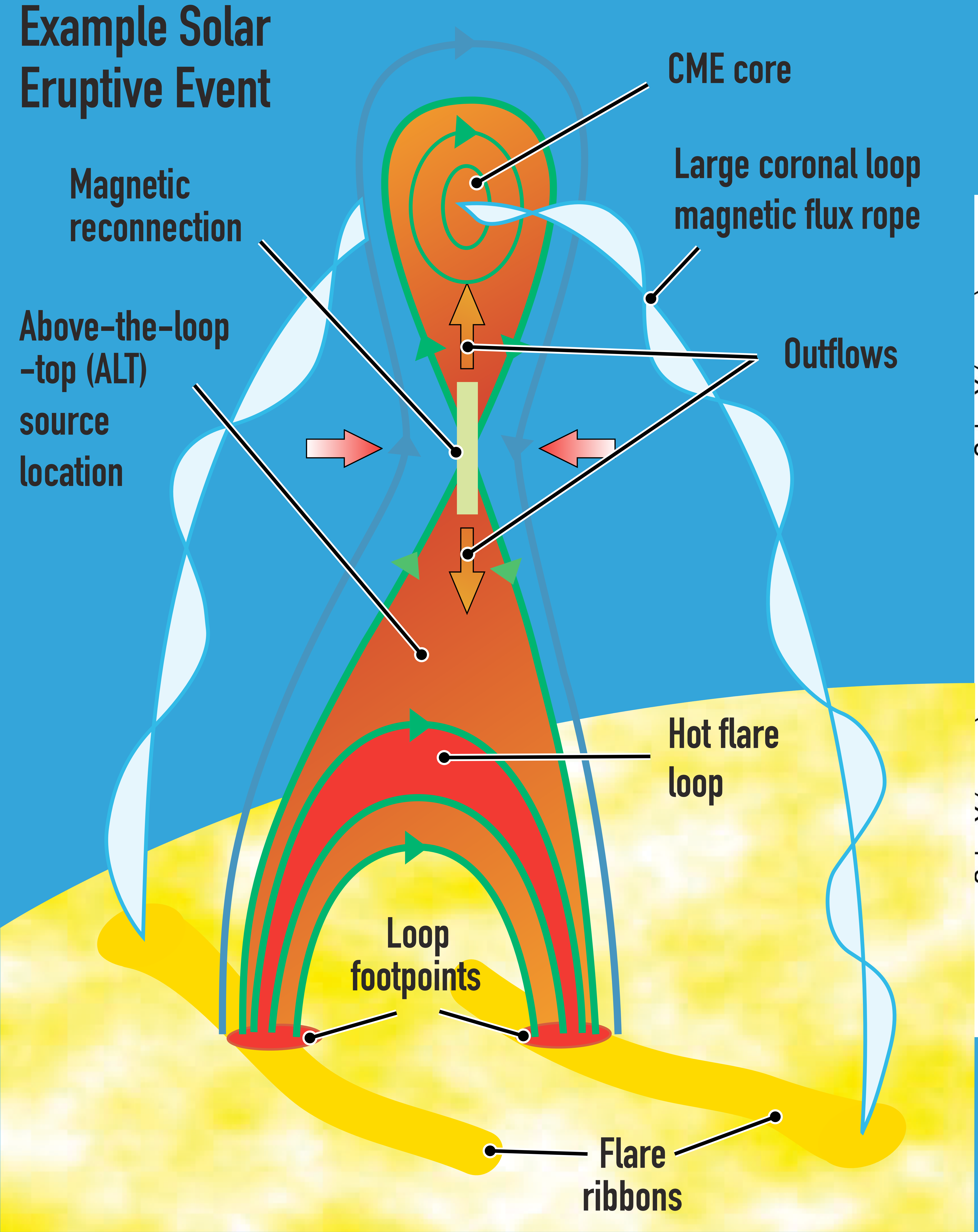


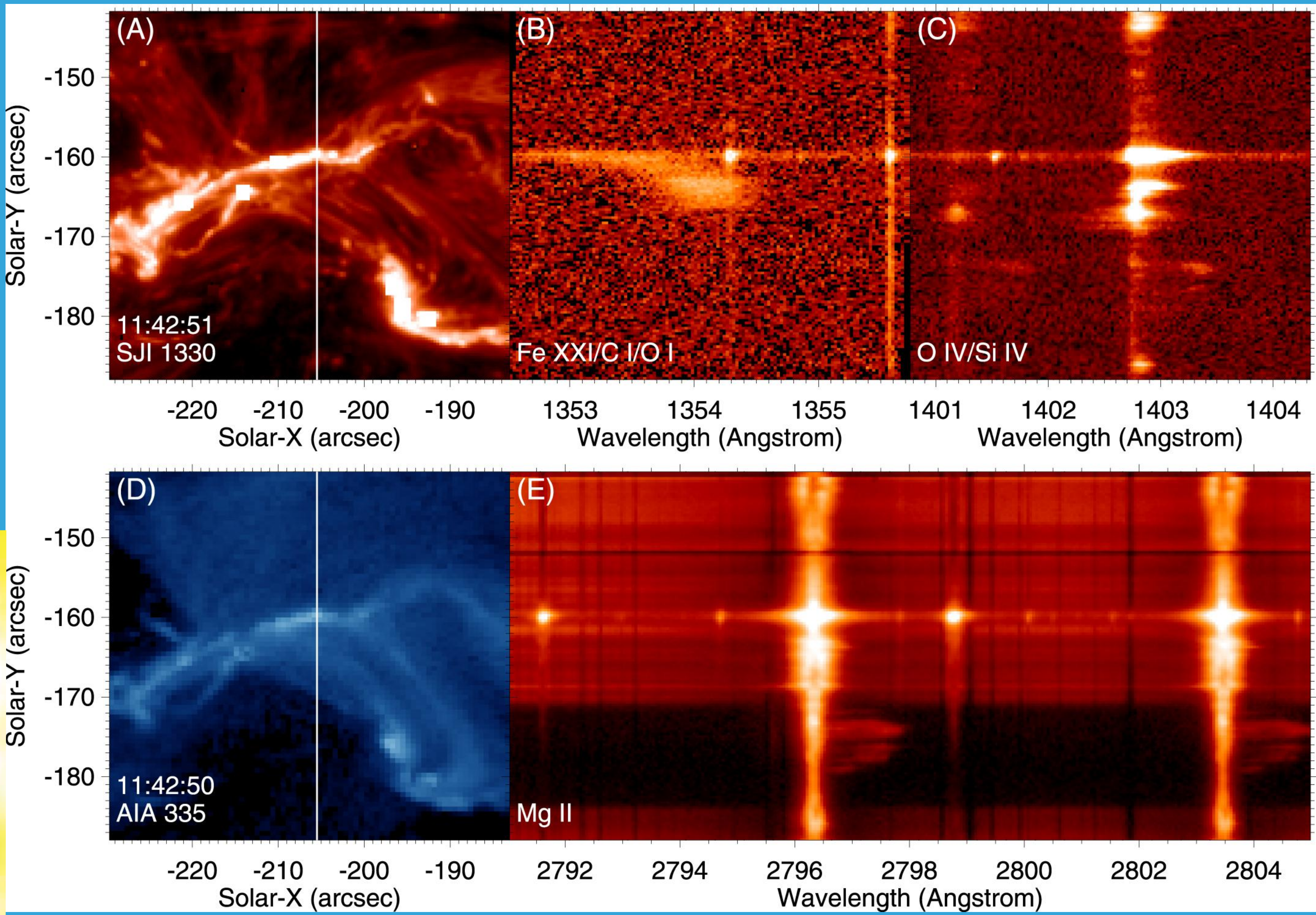


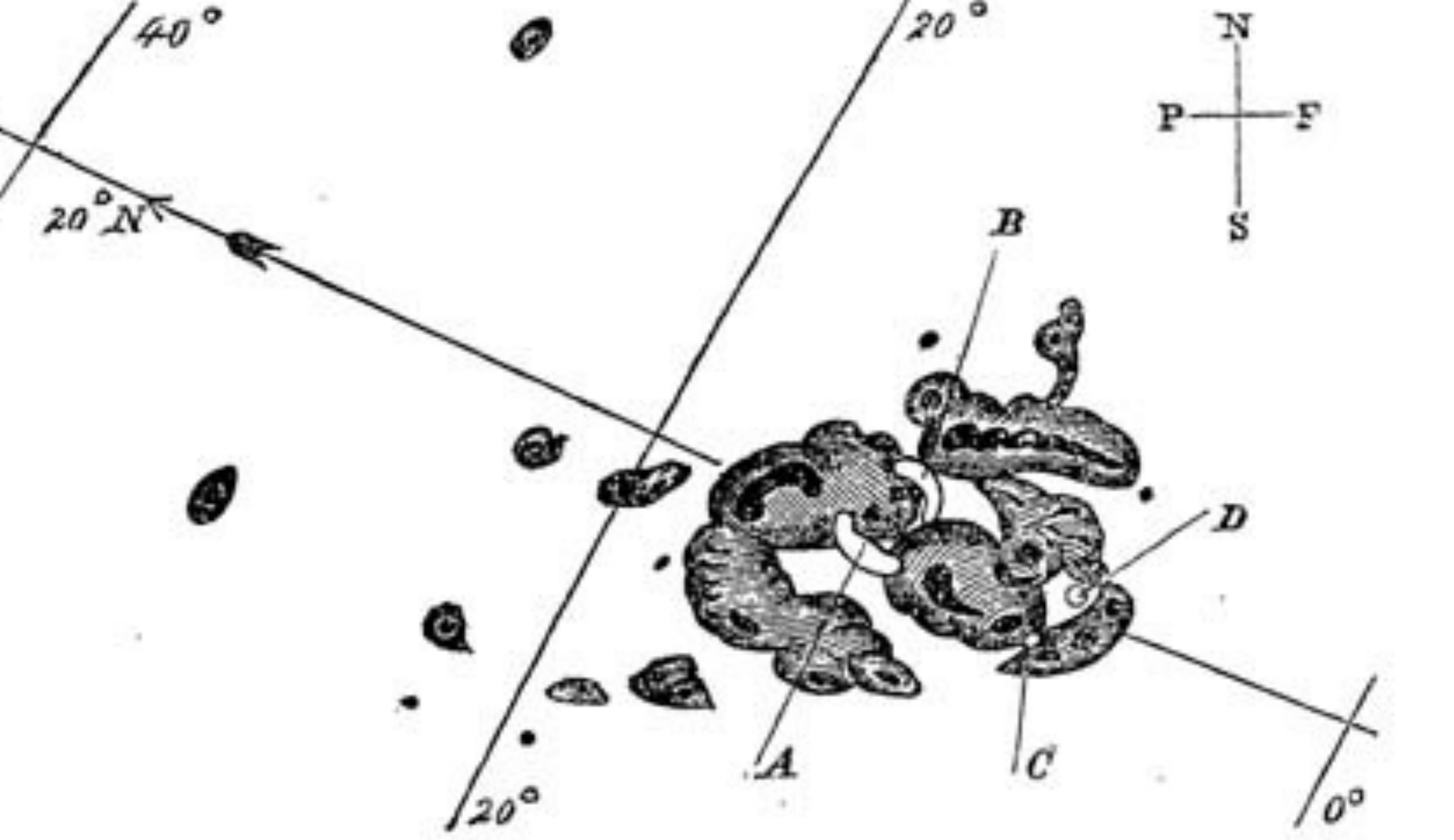


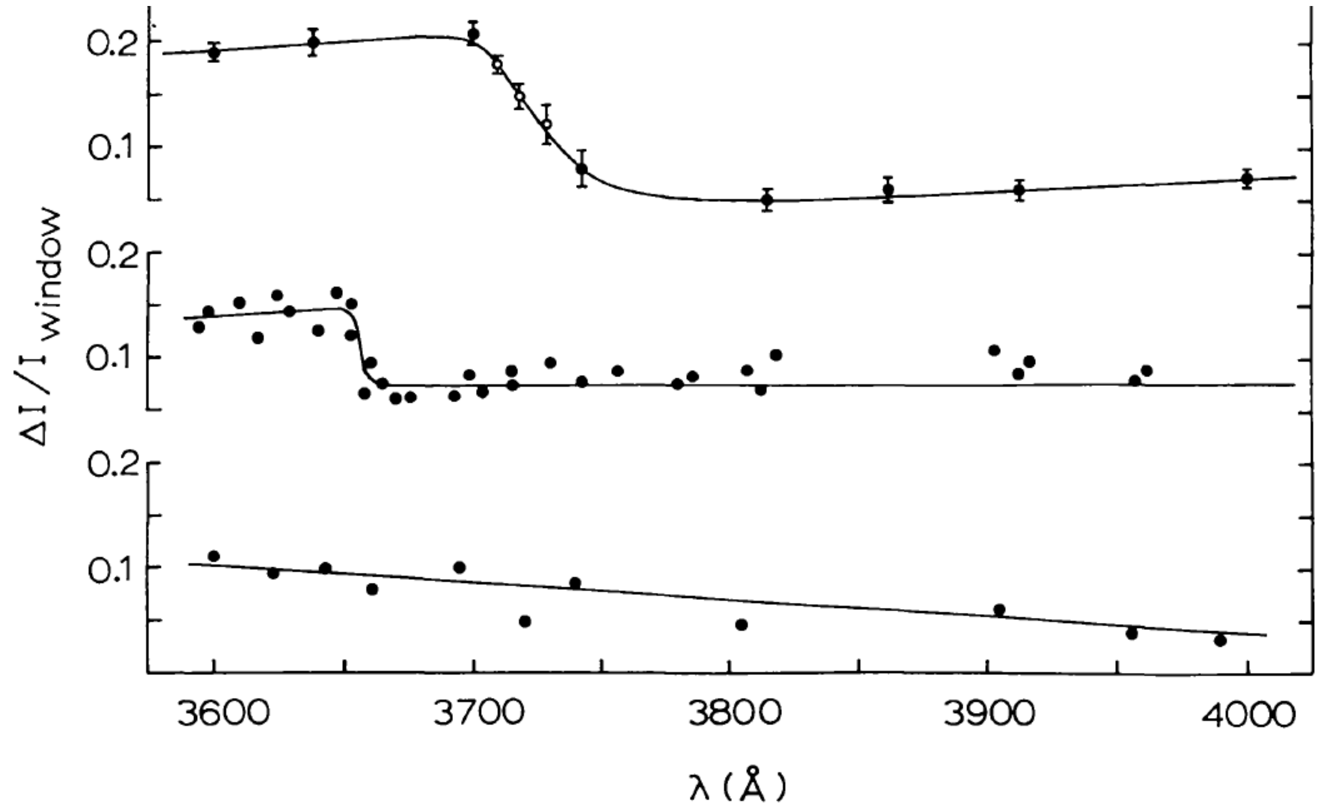
X-ray obs can be used to derive non-thermal electron distributions (which are then used to drive flare models.

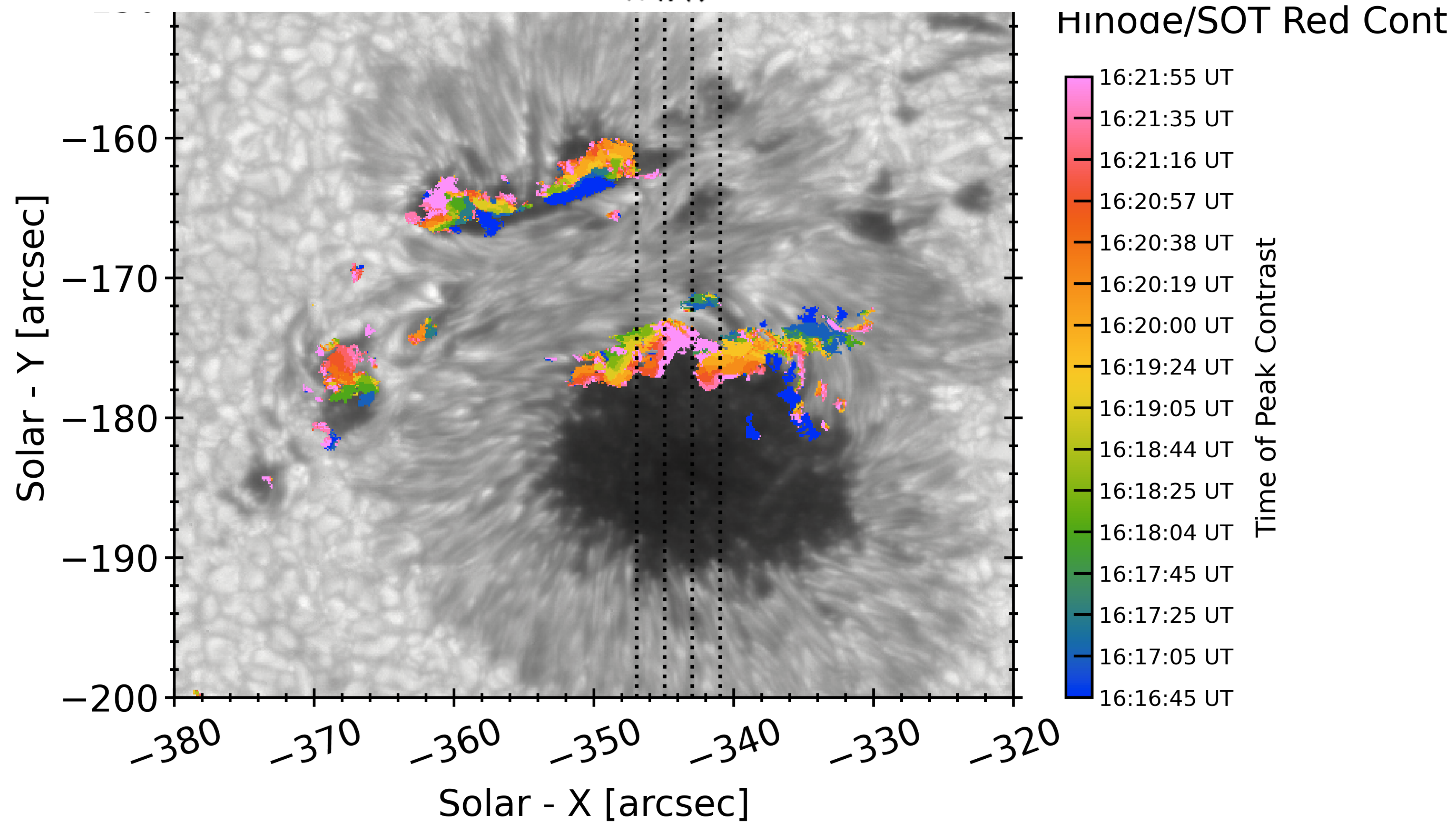
SOLAR FLARES – OBSERVATIONS











WHITE LIGHT SOLAR FLARES (WLFS)

WLFs are enhancements to the optical continuum, and can represent the ultimate fate of a significant fraction of flare energy.

Contrasts of only a few percent to a few tens of percent over the quiet photospheric emission — makes detections difficult.

Perceived as very rare events – 'big flare syndrome' – but have been observed down to C-class flares. In a recent study of 101 M or X class flares roughly half were WLFs.

Ambiguity in terms of emission mechanisms, but this is a crucial problem to solve due to the strong constraints WLF emission mechanisms place on energy transport mechanisms.

WLF EMISSION MECHANISMS

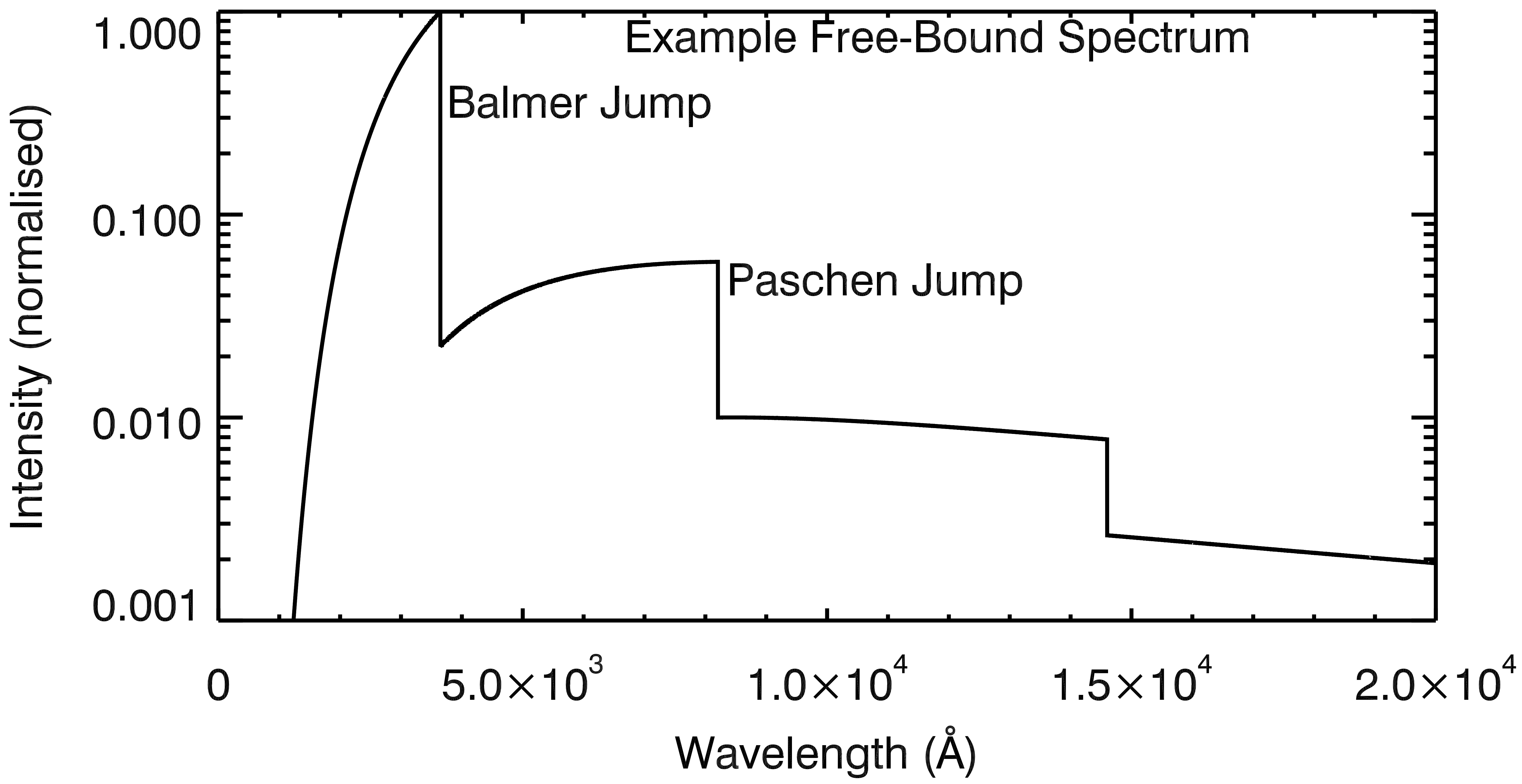
Photospheric Origin

- Electron beams cannot reach the photosphere. Some other agent is required. **Radiative backwarming** is a commonly proposed method.
- Energy input following a flare heats a very dense region, raising the temperature, electron density and H^- density (H + two electrons).
- This can either be the **photosphere** (traditional explanation) **or heating somewhere sufficient to raise the height of the τ = 1 surface** (which becomes the 'flare' photosphere).
- **WLF emission would be optically thick, consistent with that from a blackbody at temperature T ~ few x 10^3 K** (attenuated by some amount depending on the opacity structure and thickness of the emitting layer).

Chromospheric Origin

- Electron precipitation causes a **high degree of ionisation and heating** in a local region of the chromosphere.
- **Hydrogen recombinations occur leading to free-bound radiation, also known as recombination radiation** (proton + electron -> neutral H). Sensitive to electron density.
- WLFs would originate from an optically thin layer in the mid-upper chromosphere.
- They would exhibit features indicative of free-bound (recombination) spectra, such as **Balmer and Paschen edges/jumps** (which have been observed in some flares but not all).

WLF EMISSION MECHANISMS



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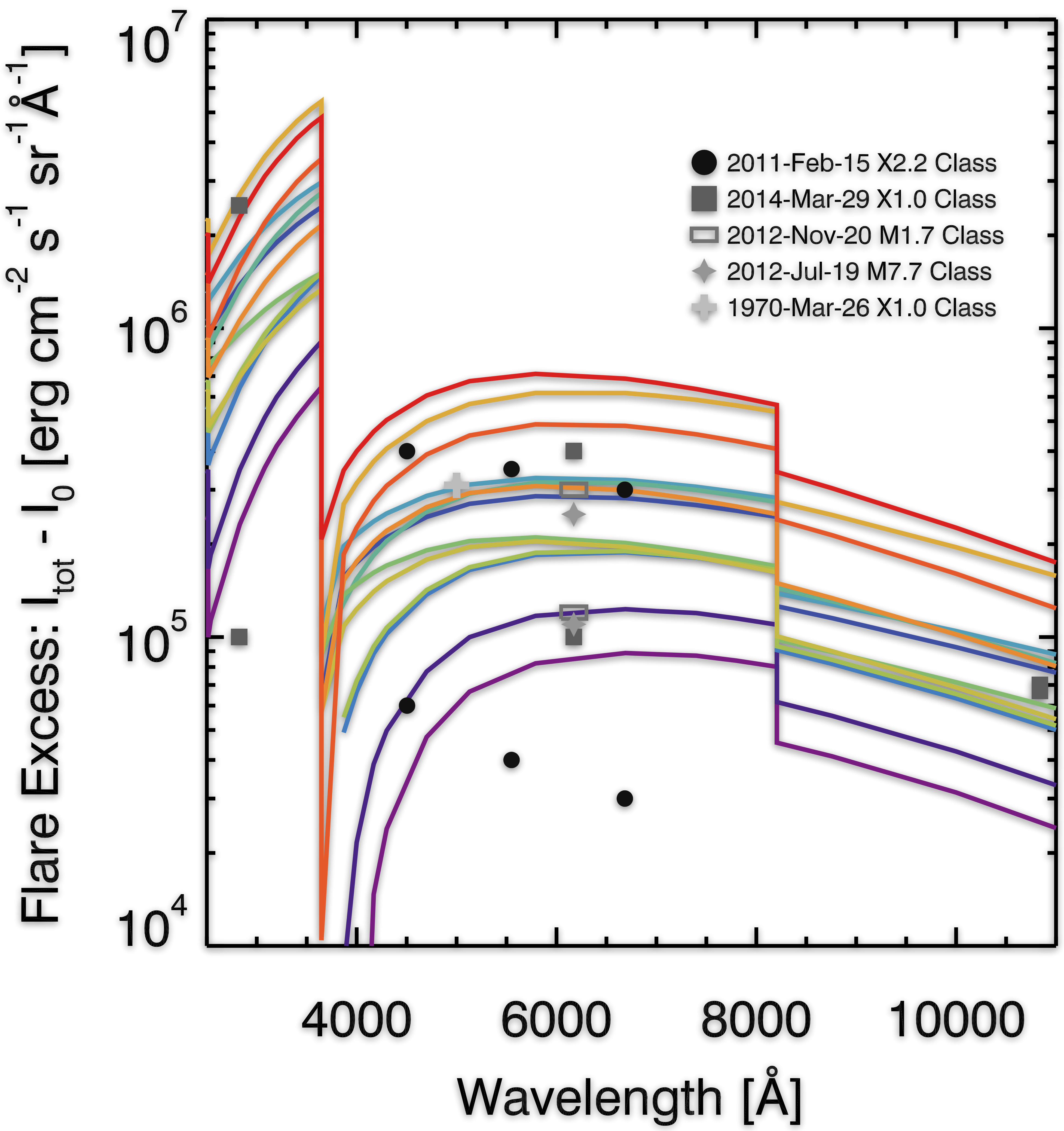
WLF MODELS

- Radiation hydrodynamics (RHD) flare modelling suggests that in strong flares the Balmer jump is always present.
- WLFs are the result, primarily, of optically thin hydrogen recombination radiation produced in the mid-upper flaring chromosphere.
- Plasma properties in the emitting volume are typically T~8-15kK and $n_e \sim 10^{12-14}$ cm^{-3}.
- Peak height of emission typically z ~ 800-1000km.
- Width (vertical extent) of the emitting region varies from a few x 10km to several hundred km.
- How well do models agree with this?

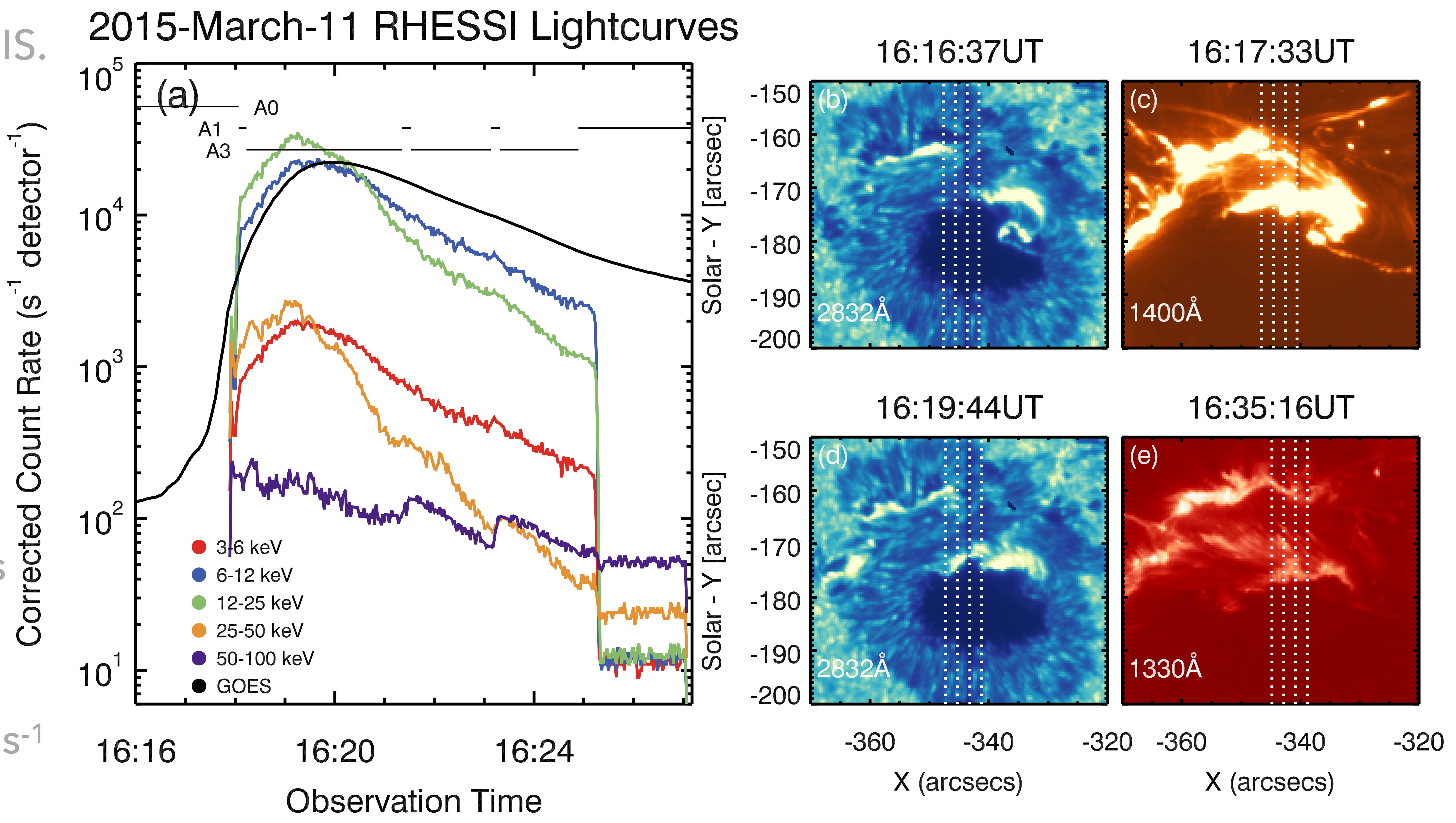
We need broadband spectroscopic observations to really answer this question.

For now we can use a combination of near-UV (NUV) observations from the interface Region Imaging Spectrograph (IRIS), and optical continuum observations from the Hinode/Solar Optical Telescope.



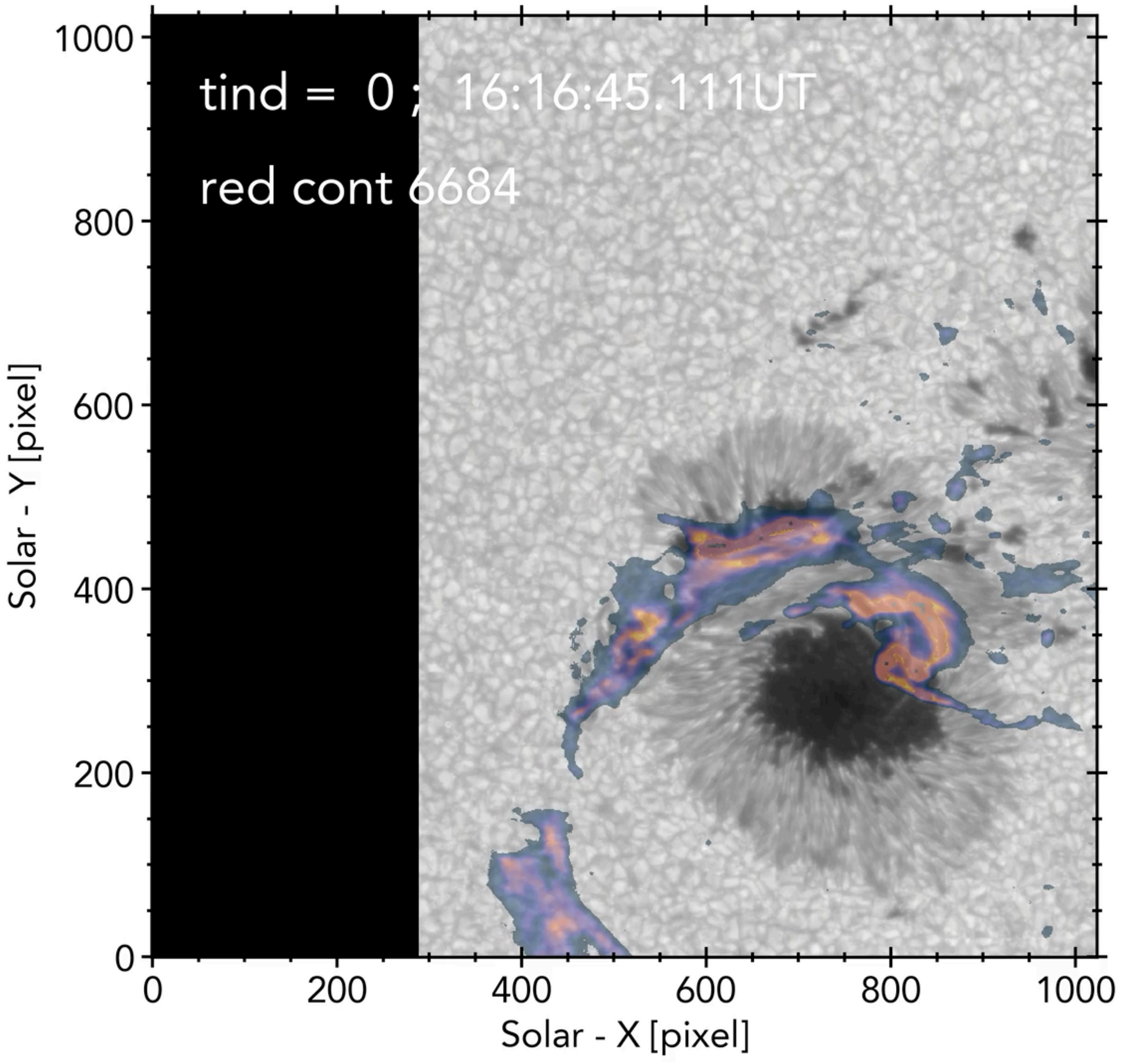
2015–MARCH–11 X CLASS FLARE

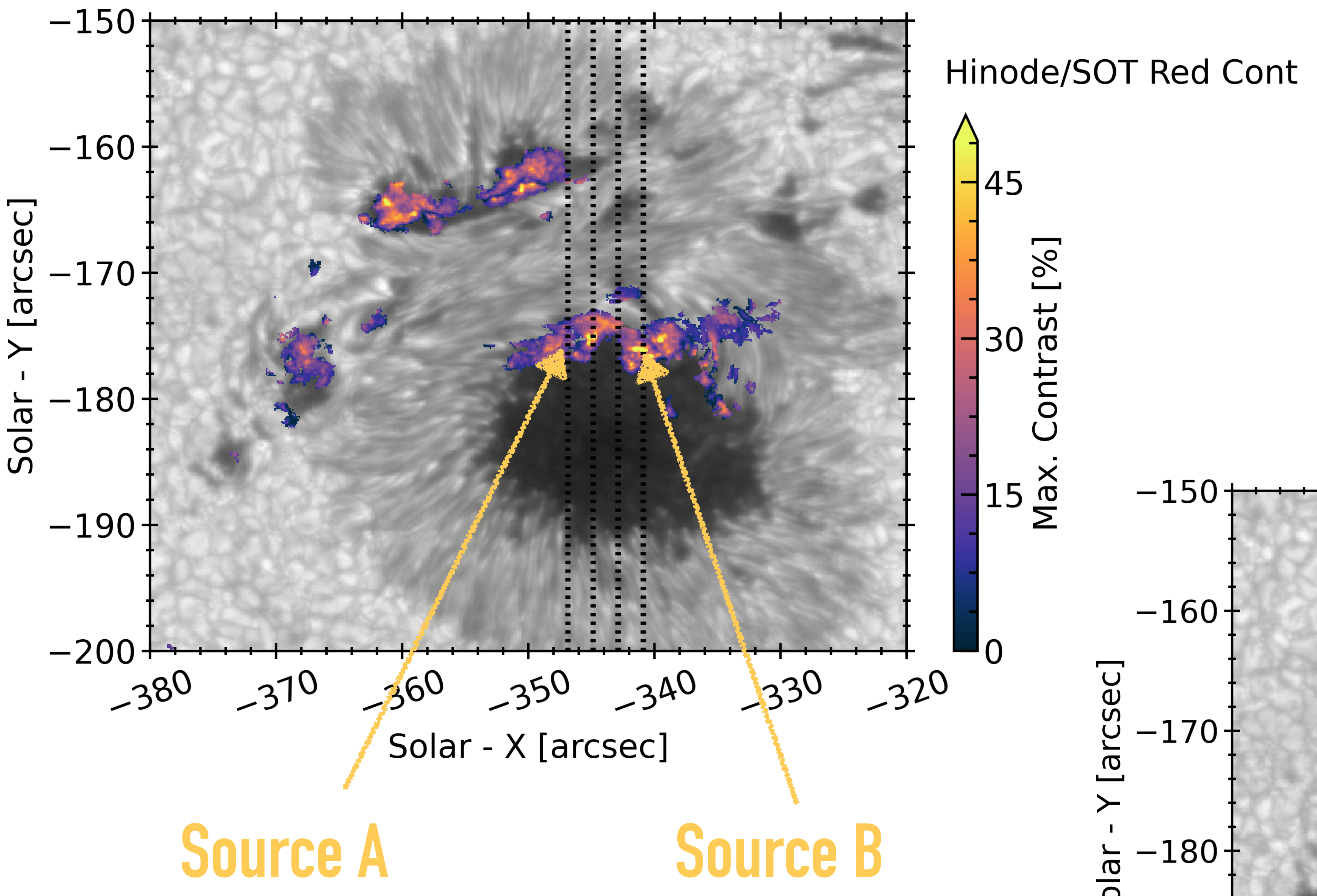
- X class flare, observed by both Hinode/SOT & IRIS.
- IRIS is a slit scanning spectrometer, providing near-UV spectral observations along 4 vertical slices of the flare (repeat cadence is ~20s). Pixel scale is 0.33”pix^{-1}.
- Hinode/SOT is a narrowband imager, providing three optical (4504Å, 5550Å, 6684Å) continuum passbands, with a cadence of ~20s. Pixel scale is ~0.109”pix^{-1}.
- To convert the Hinode data from count rate (DN s^{-1} px^{-1}) to physical units I compared disk centre observations from the day prior to the disk centre intensity from the Brault and Neckel FTS Spectral Atlas, averaged over the SOT passbands (weighted by the filter transmission curves).



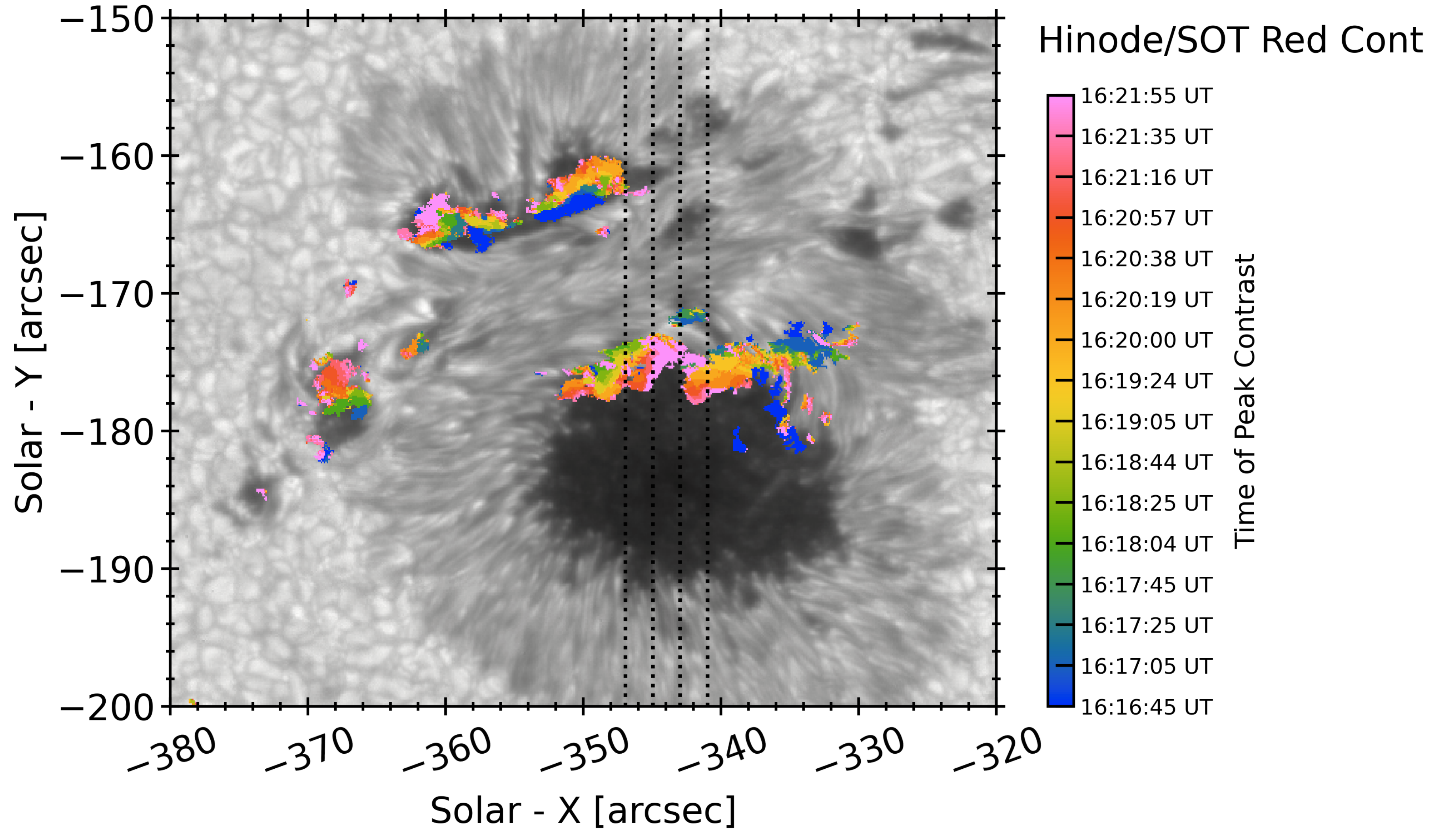
HINODE/SOT OBSERVATIONS

- Aligned all data via cross correlating sunspot and pores.
- Masked using Ca II H line observations (also from SOT)
- Reduced noise by subtracting a log unsharp mask of the image.
- Running difference of those images was used to identify the most likely WLF sources.
- Those sources were used as seeds in a region growing algorithm to identify weaker sources.



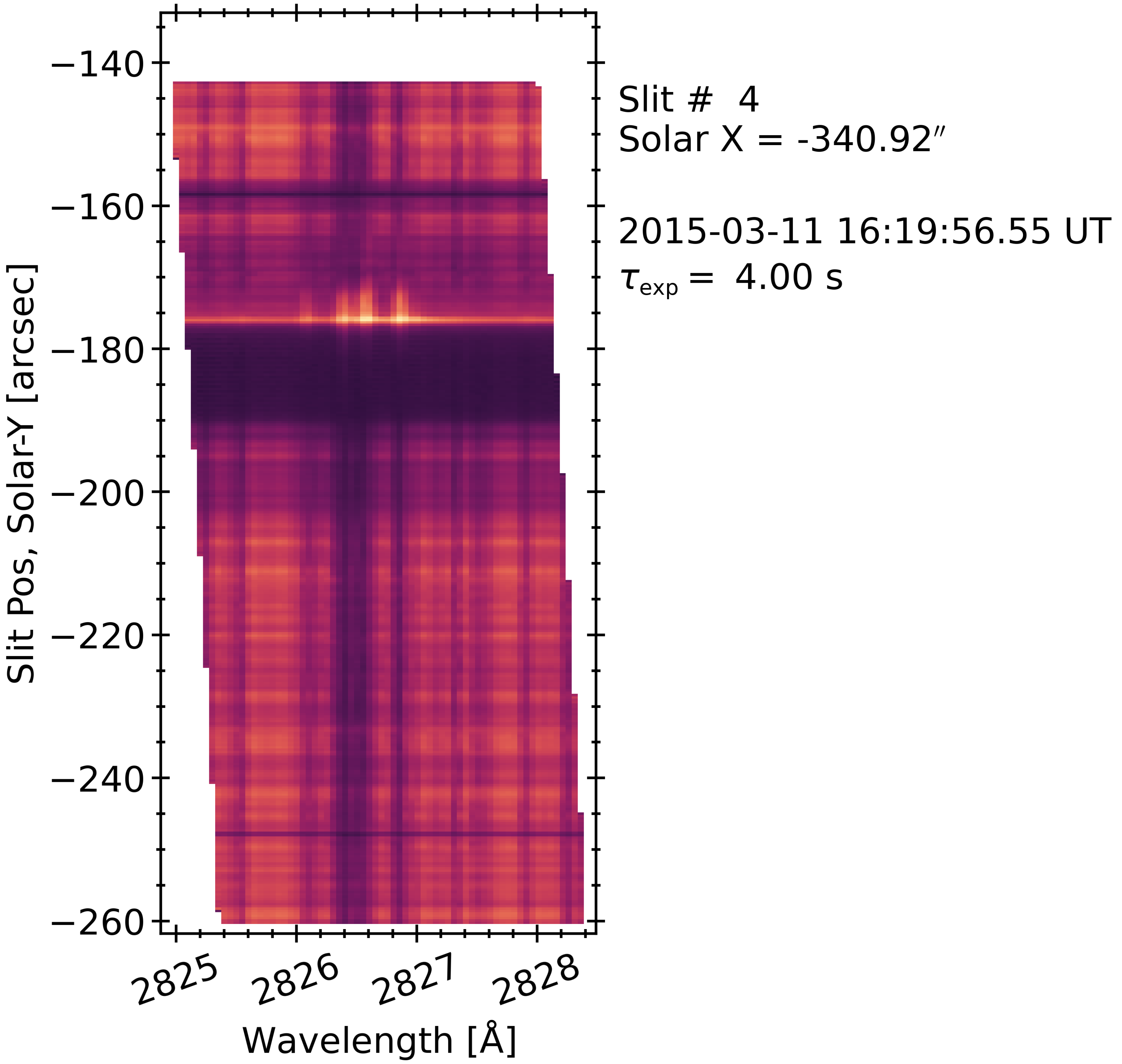


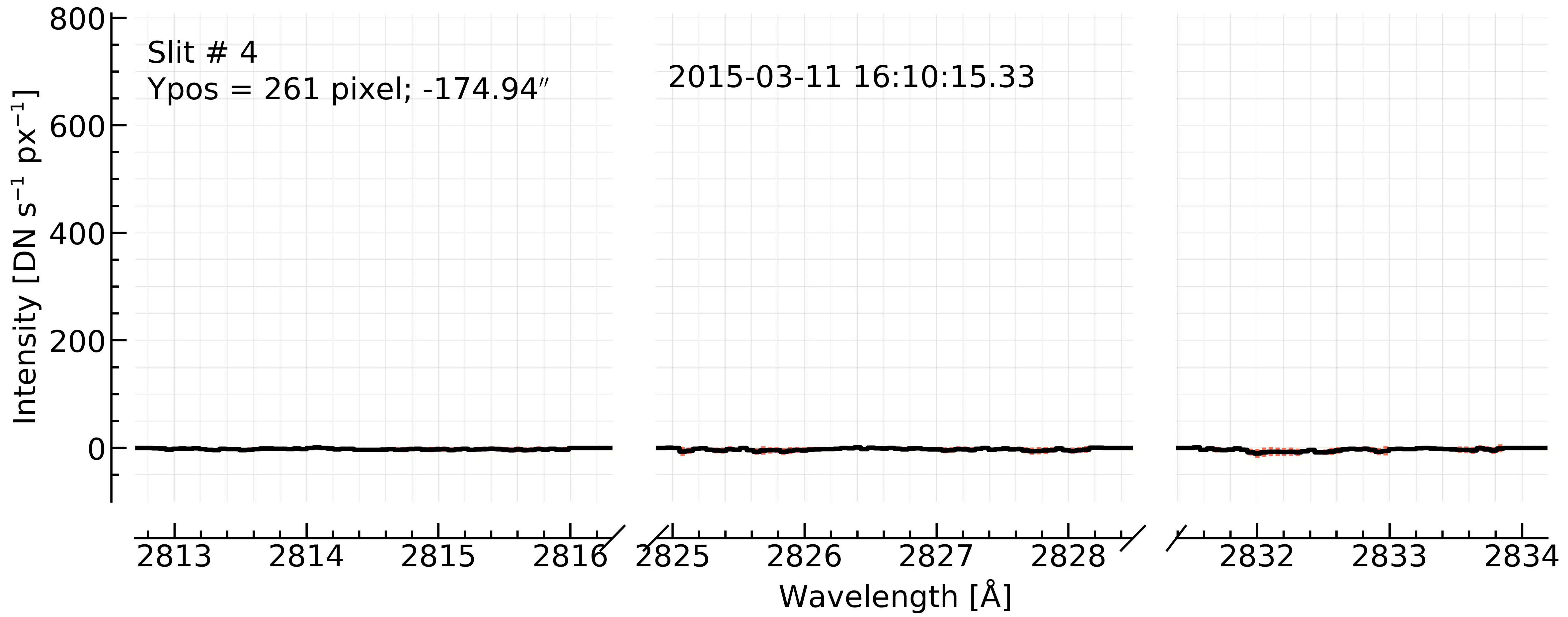
Black dashed lines are the locations of the IRIS slit.

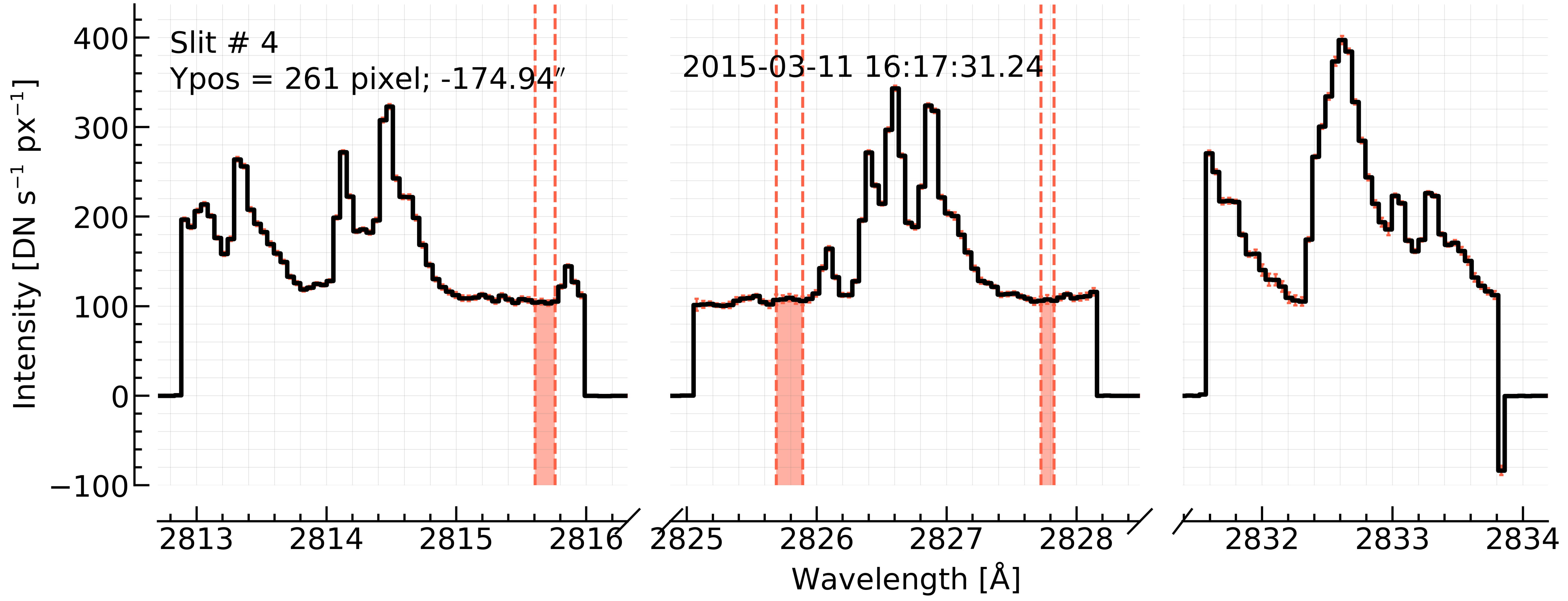


IRIS OBSERVATIONS

- Identified line-free portions of the spectrum, and averaged the intensity over that small range.

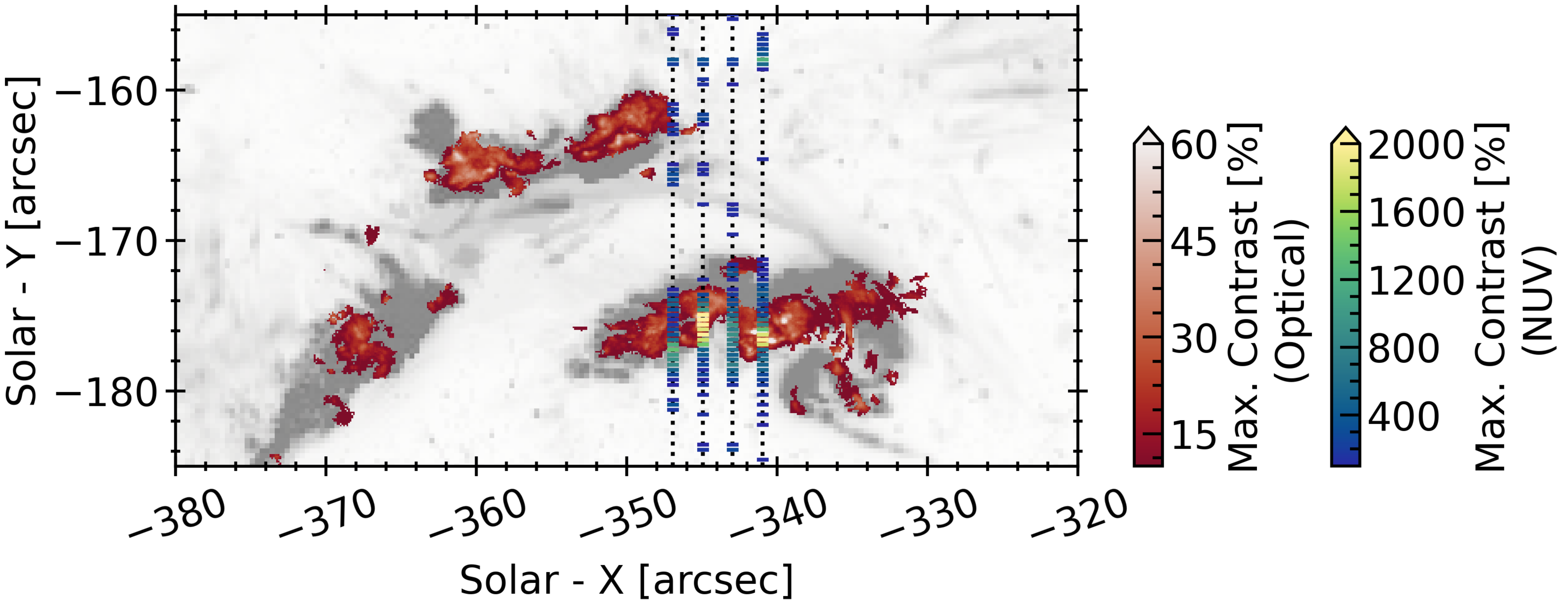


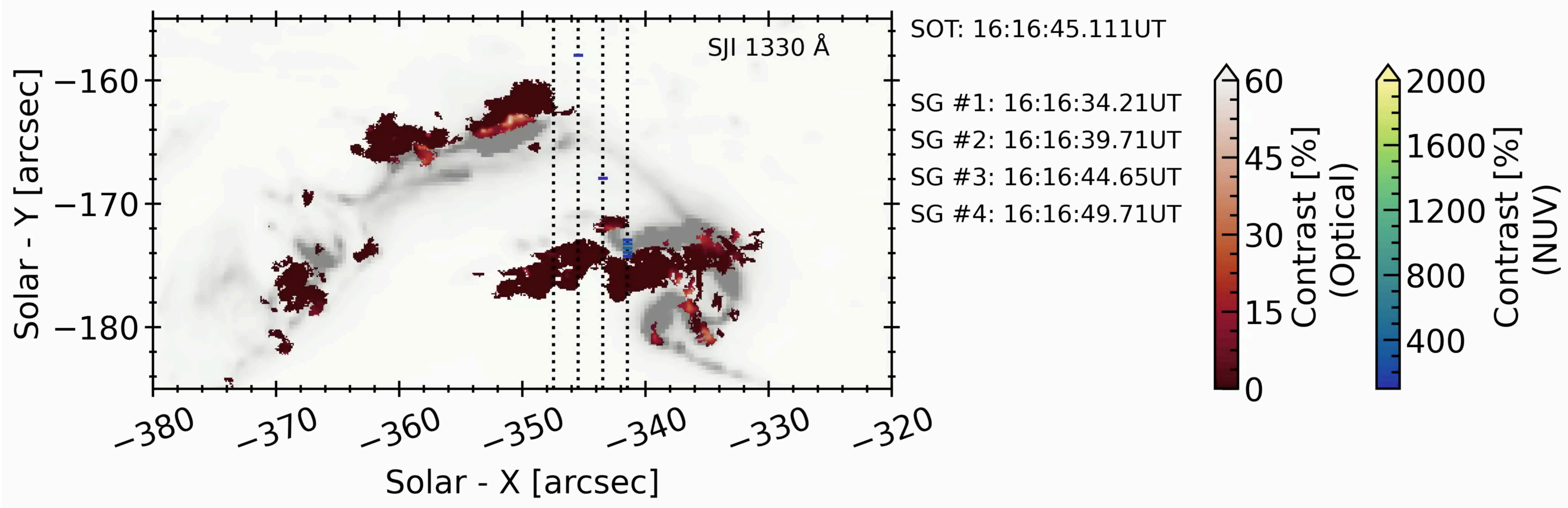




COMBINED OBSERVATIONS

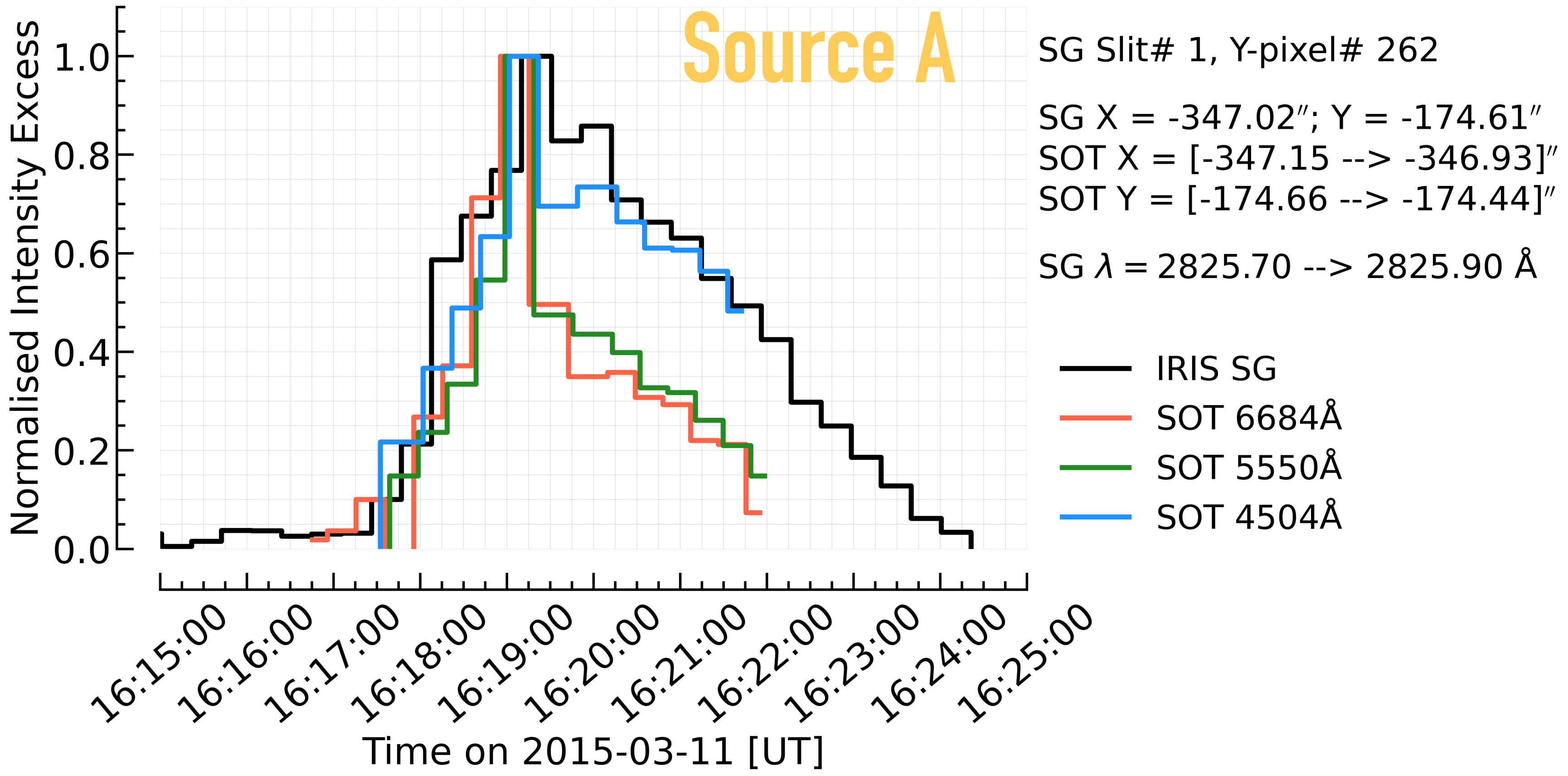
- Aligned IRIS data using fiducial marks to remove a drift over time.
- Rescaled IRIS Slit Jaw Imager 2832A data to SOT pixel size, cross-correlated using sunspot features (excluding portions that flared).
- Optical continuum enhancements and NUV continuum enhancements are largely co-spatial, but there are NUV sources with no optical counterpart. Some of those are flare-like (impulsive, with slower decay), but others are just variations in NUV intensity.
- NUV contrast is very much larger than optical (it's hard to outshine the photosphere).

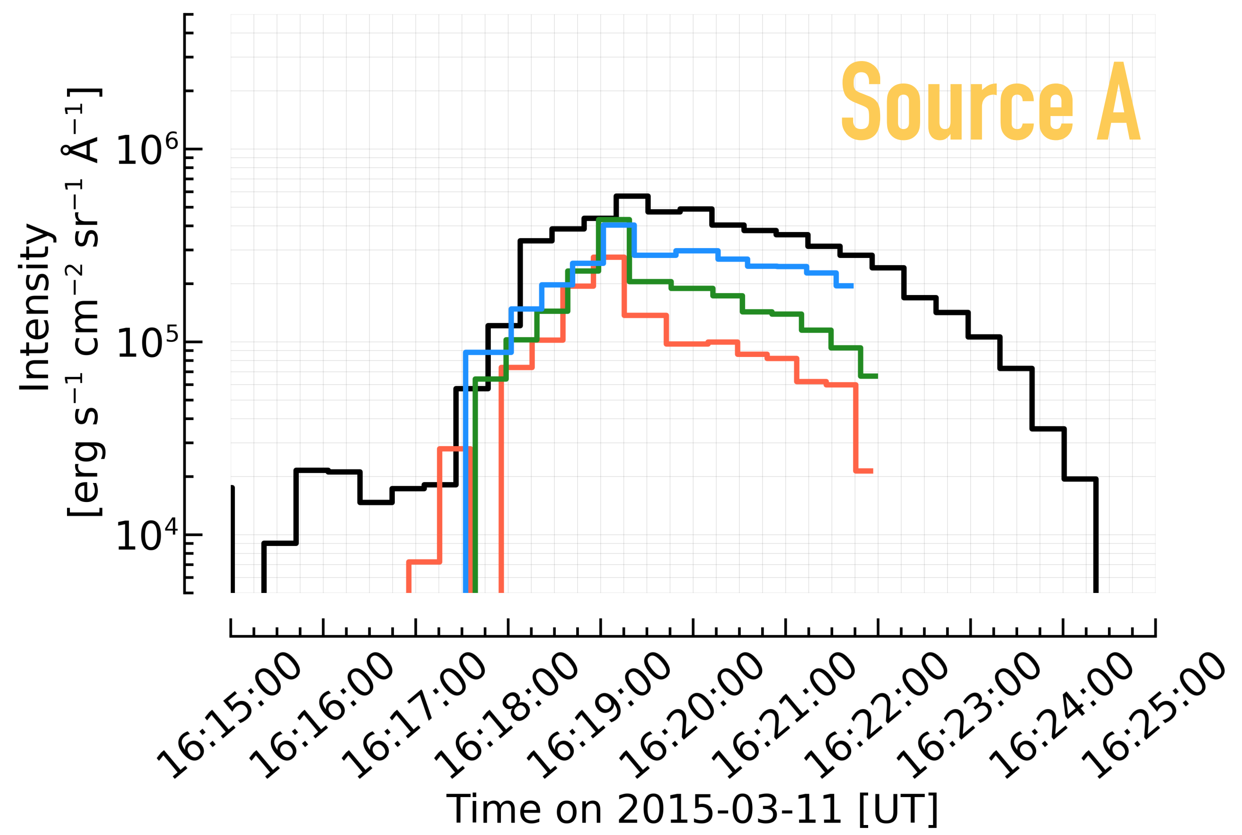


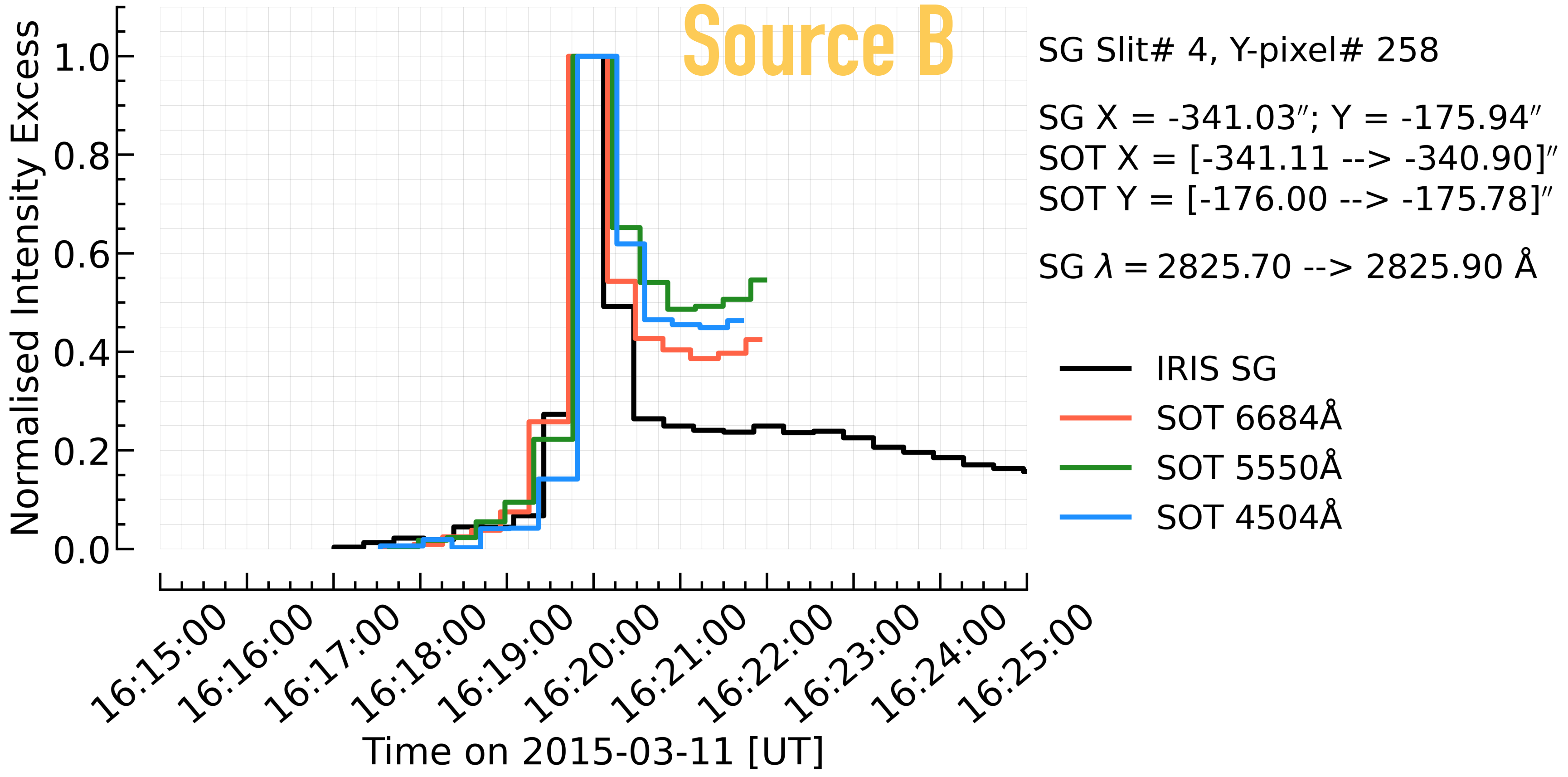


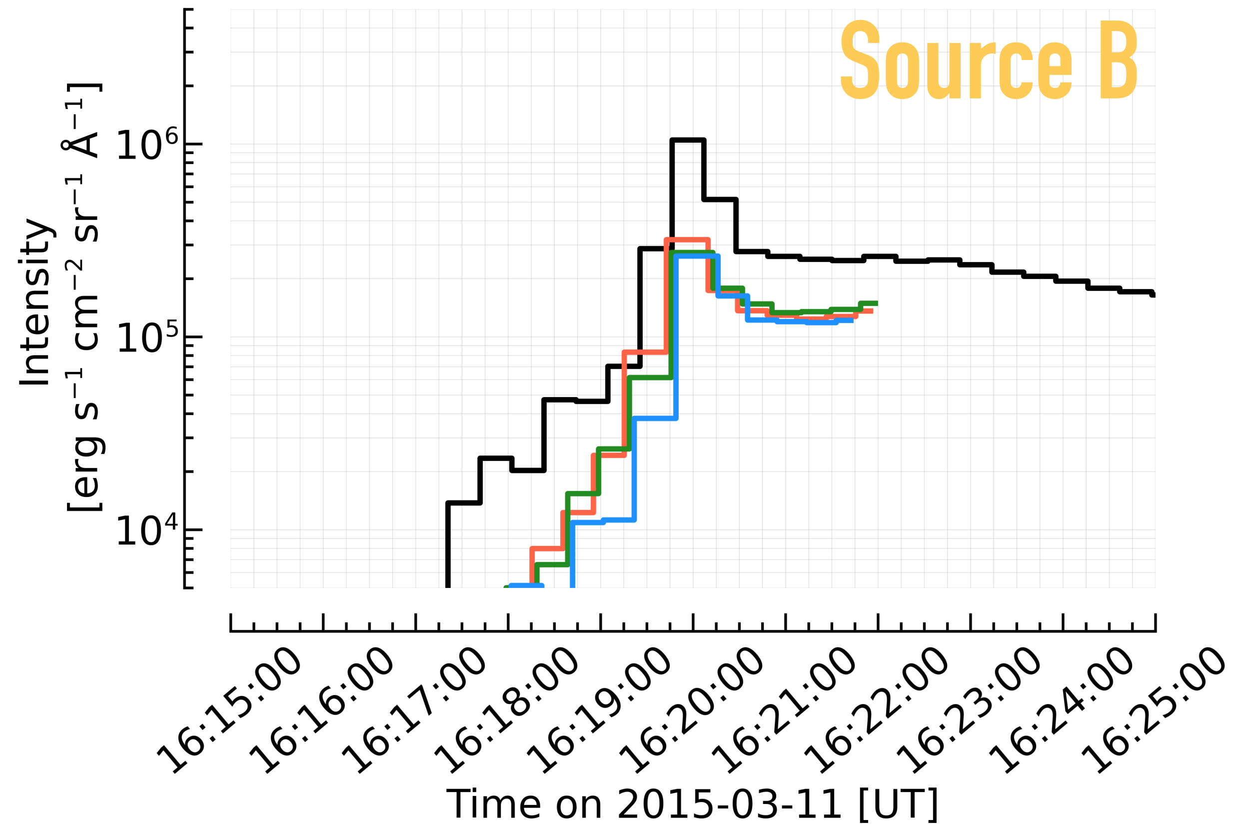
COMBINED OBSERVATIONS

- Selected two sources, from slit #1, and slit #4.
- The SOT data were averaged over [3x3] pixels to be more similar to the IRIS plate scale.
- Shown opposite are the normalised lightcurves, and the intensity excess.
- The IRIS background was the average of the same source over a 15 min period before the flare
- The SOT background for each pixel was the average of [3x3] pixels around the pixel in question. For SOT we only have a limited time range, so the pre-flare was taken to be the first frame in the sequence (not ideal).



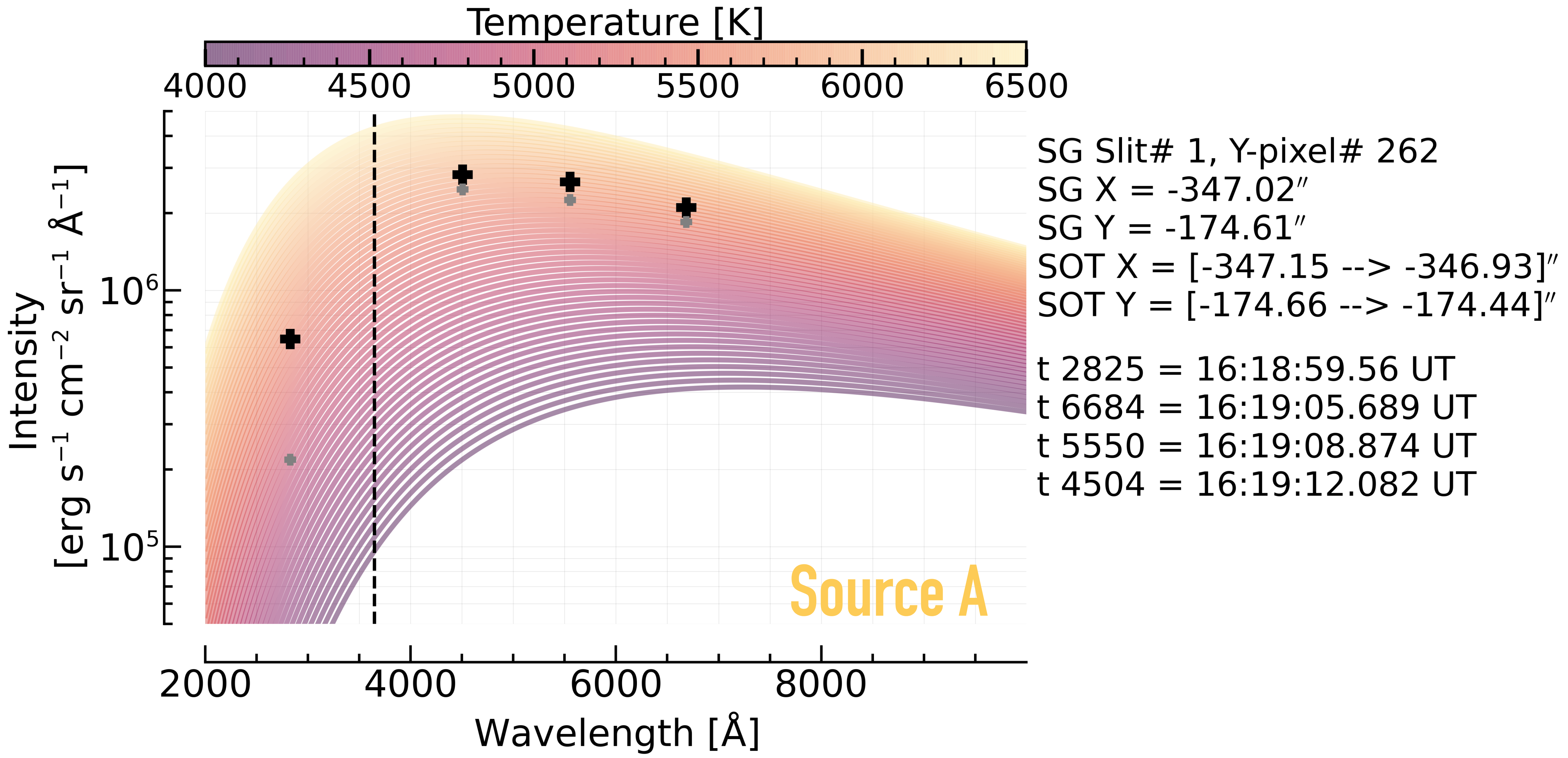


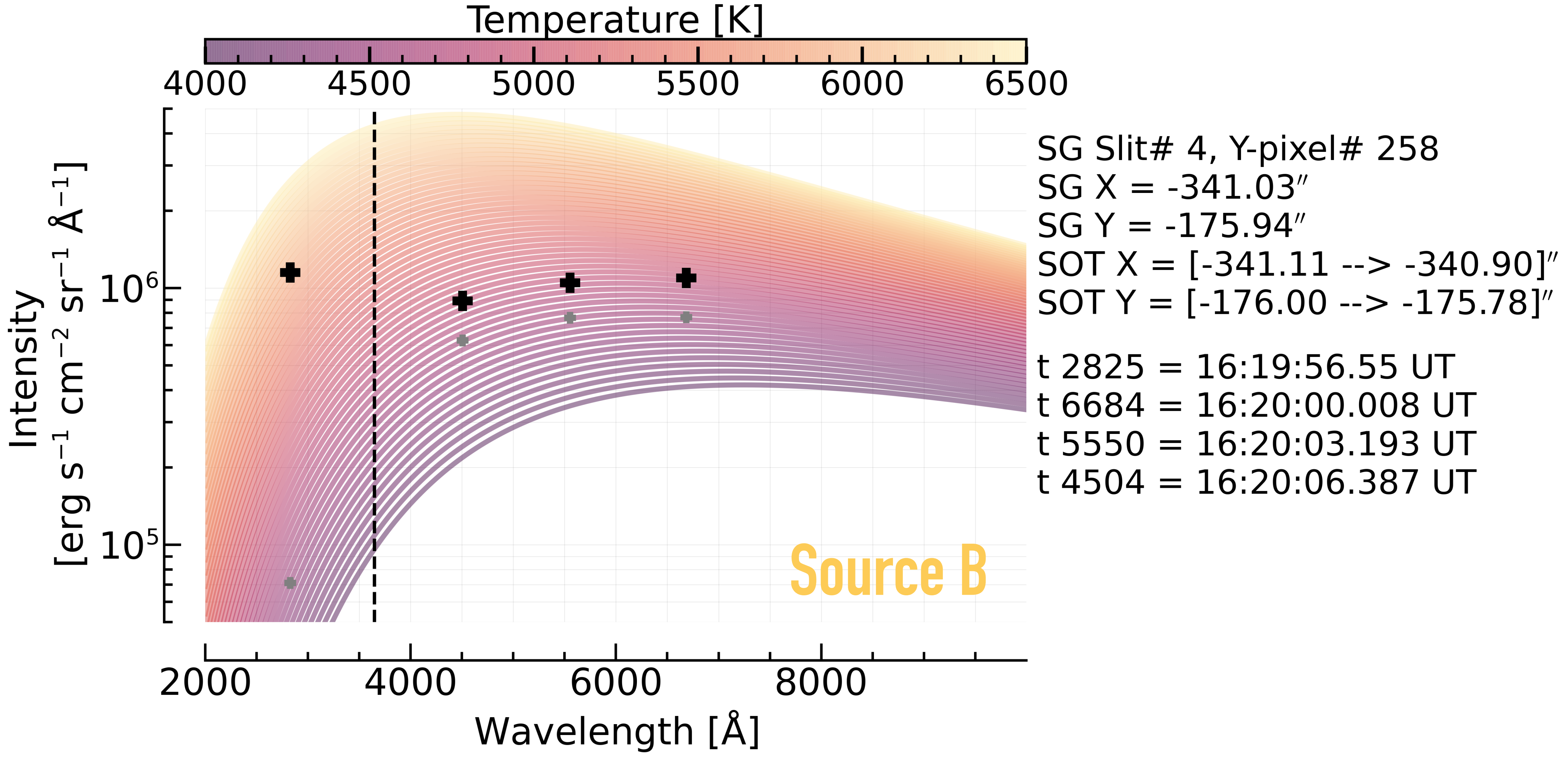




COMBINED OBSERVATIONS

- Very clear Balmer jump in Source B, but more ambiguous in Source A.
- The spectral shape of the sources also look different.
- Comparing the flare excess intensities and the ratio of NUV to optical can help us understand differences in different locations of the flare, and if our models are able to reproduce these properties.



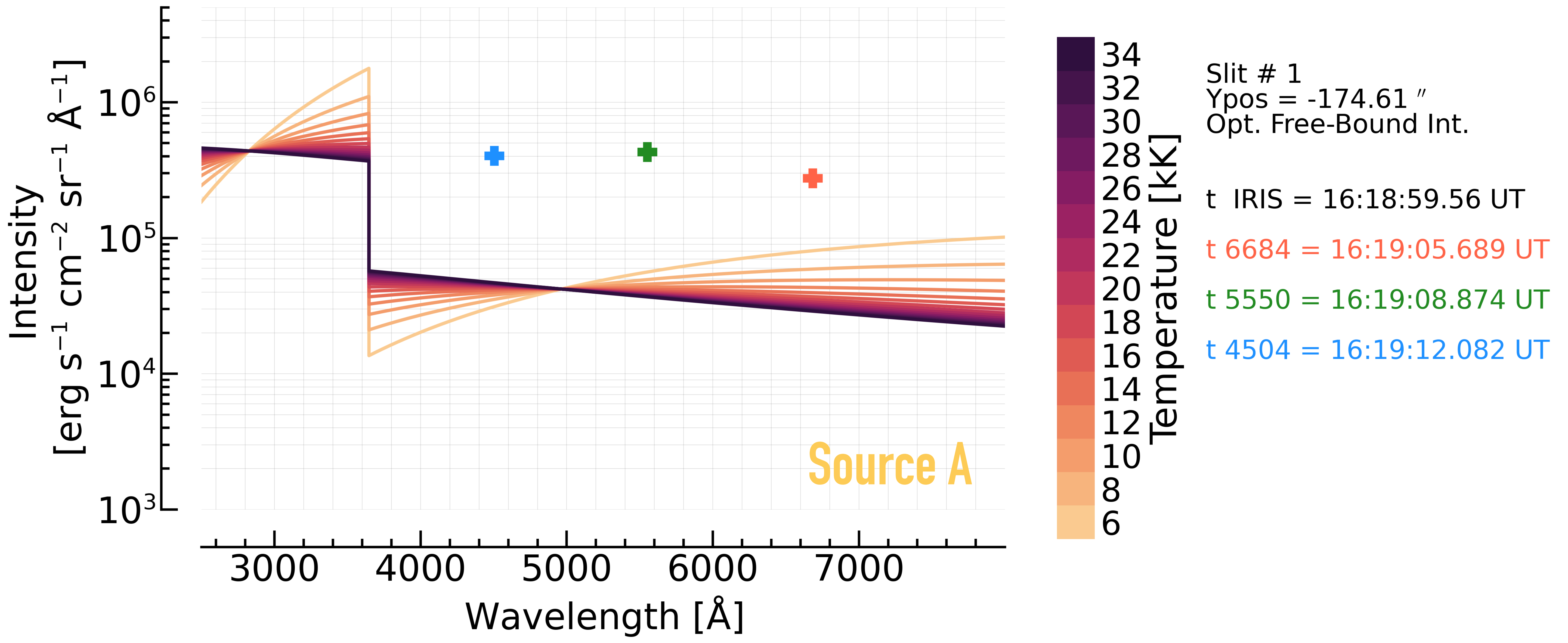


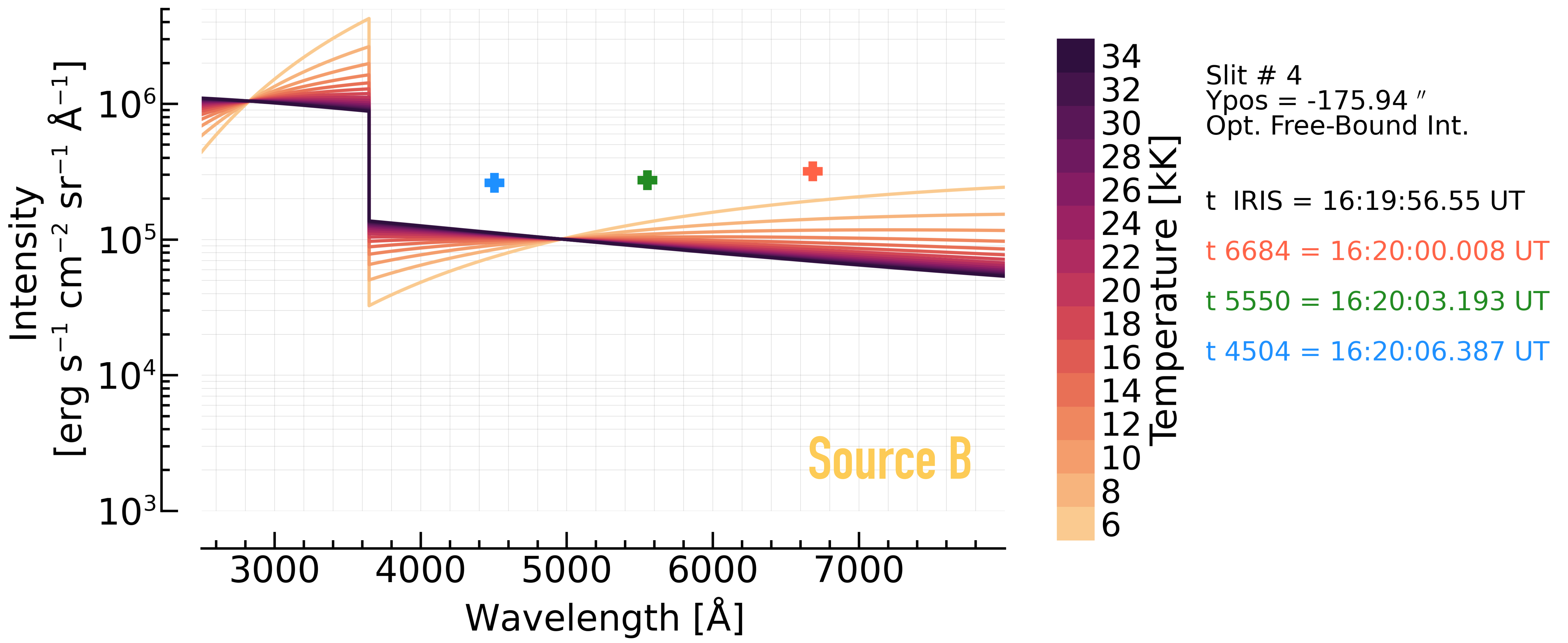
Blackbody curves are shown for context.

Grey markers are pre-flare

OPTICALLY THIN MODEL OF FLARE EXCESS

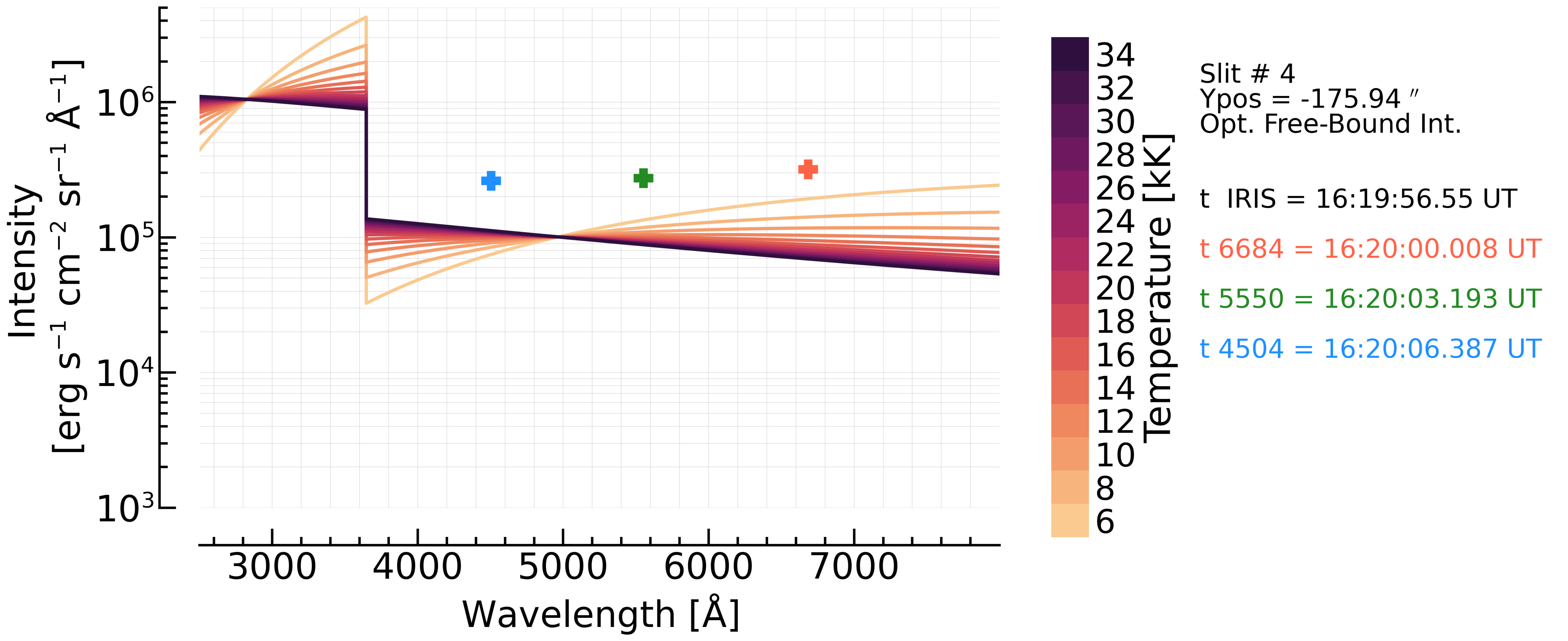
- Assuming a slab that is L thick, of constant temperature T and electron density n_e, in the chromosphere (that is optically thin) then the H recombination radiation is proportional to T, n_e^2L.
- Using the observed excess intensity in the NUV, the allowed values of n_e^2L was tabulated for a range of T = [6-34] kK.
- Using those, the resulting excess intensity in the optical from that slab can be estimated.
- While crude, this toy model can at least illustrate that Comparing the observed excess intensities shows that in both sources there is more emission than would be expected from recombination radiation alone.
- Next step is to compare to simulation predictions (though they suggest a smaller optical/NUV ratio than observed.

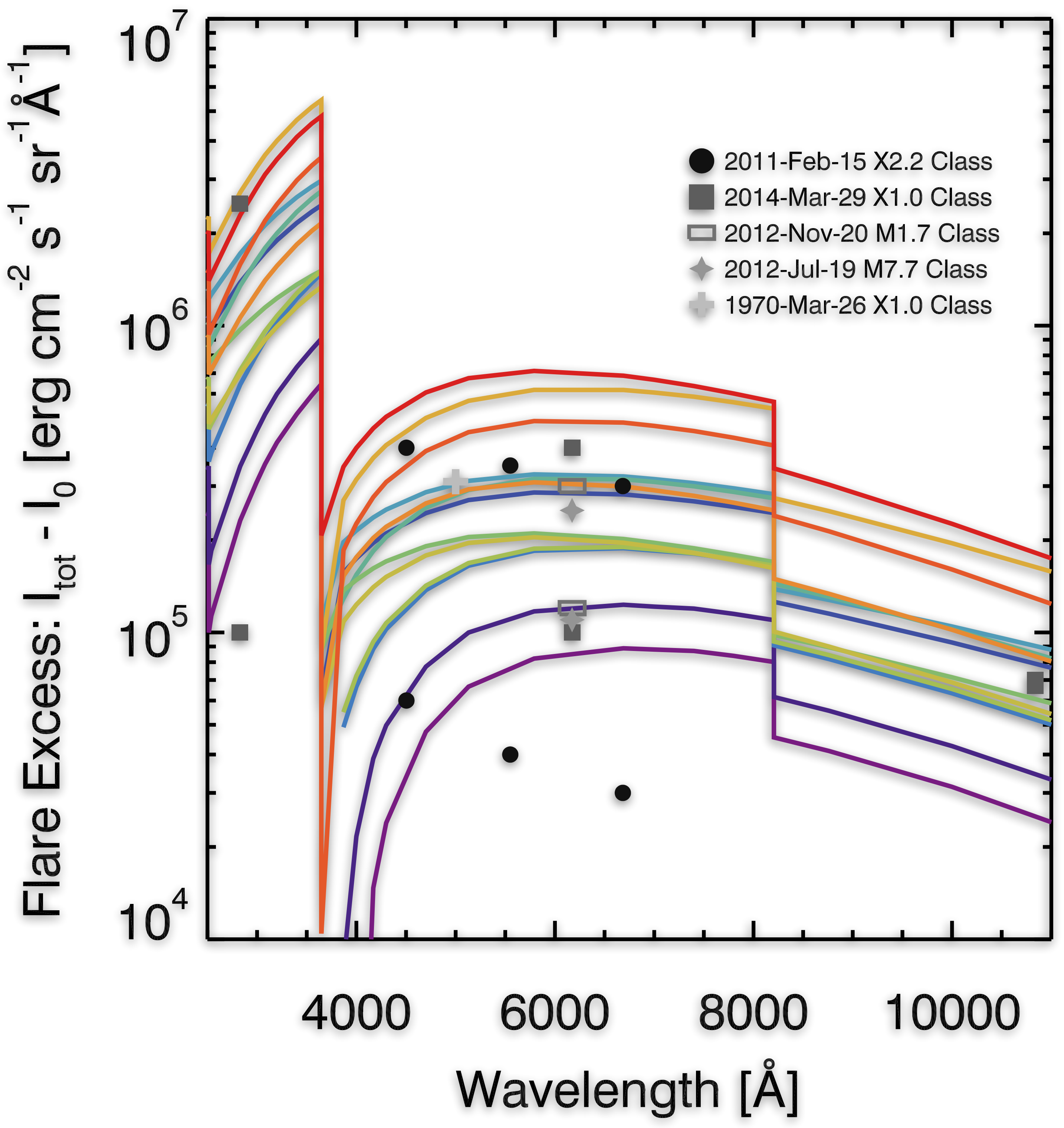




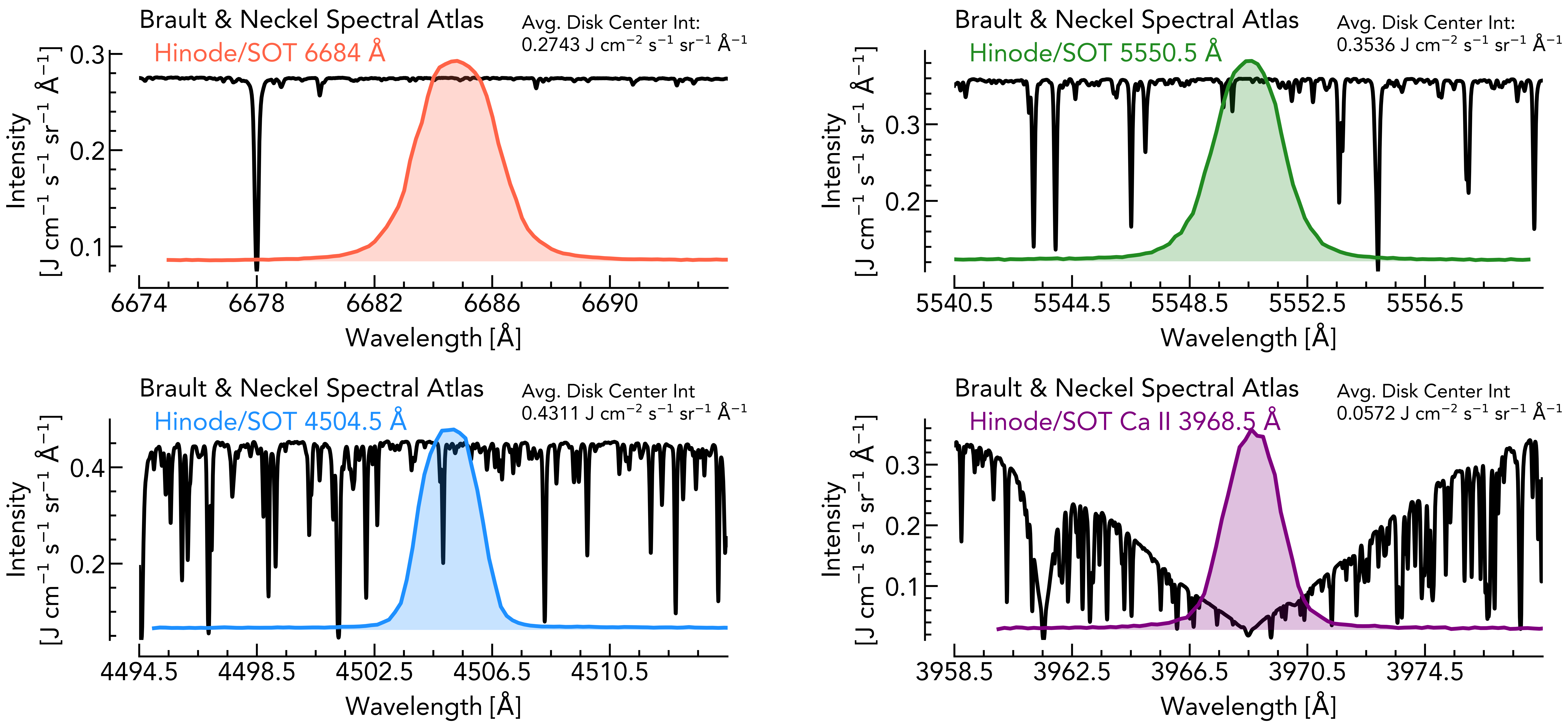
Conclusions

- Rare observation of a solar flare in both NUV and optical emission.
- There are co-spatial optical and NUV continuum emission, but some NUV sources without detectable optical source (models predict co-spatial).
- Preliminary analysis suggests that the spectral distribution varies in different sources (umbra vs penumbra?), and that the optical to NUV ratio is too high to be from H recombination alone.
- Does this mean we are missing ingredients in the flare models (e.g. heating at lower depths)?





Extra Slides


Brault & Neckel Spectral Atlas
Hinode/SOT 6684 Å
Avg. Disk Center Int:
0.2743 J cm^{-2} s^{-1} sr^{-1} Å^{-1}
Intensity [J cm^{-1} s^{-1} sr^{-1} Å^{-1}]
0.1
0.2
0.3
6674
6678
6682
6686
6690
Wavelength [Å]
Brault & Neckel Spectral Atlas
Hinode/SOT 5550.5 Å
Avg. Disk Center Int:
0.3536 J cm^{-2} s^{-1} sr^{-1} Å^{-1}
Intensity [J cm^{-1} s^{-1} sr^{-1} Å^{-1}]
0.2
0.3
5540.5
5544.5
5548.5
5552.5
5556.5
Wavelength [Å]
Brault & Neckel Spectral Atlas
Hinode/SOT 4504.5 Å
Avg. Disk Center Int
0.4311 J cm^{-2} s^{-1} sr^{-1} Å^{-1}
Intensity [J cm^{-1} s^{-1} sr^{-1} Å^{-1}]
0.2
0.4
4494.5
4498.5
4502.5
4506.5
4510.5
Wavelength [Å]
Brault & Neckel Spectral Atlas
Hinode/SOT Ca II 3968.5 Å
Avg. Disk Center Int
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Intensity [J cm^{-1} s^{-1} sr^{-1} Å^{-1}]
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0.2
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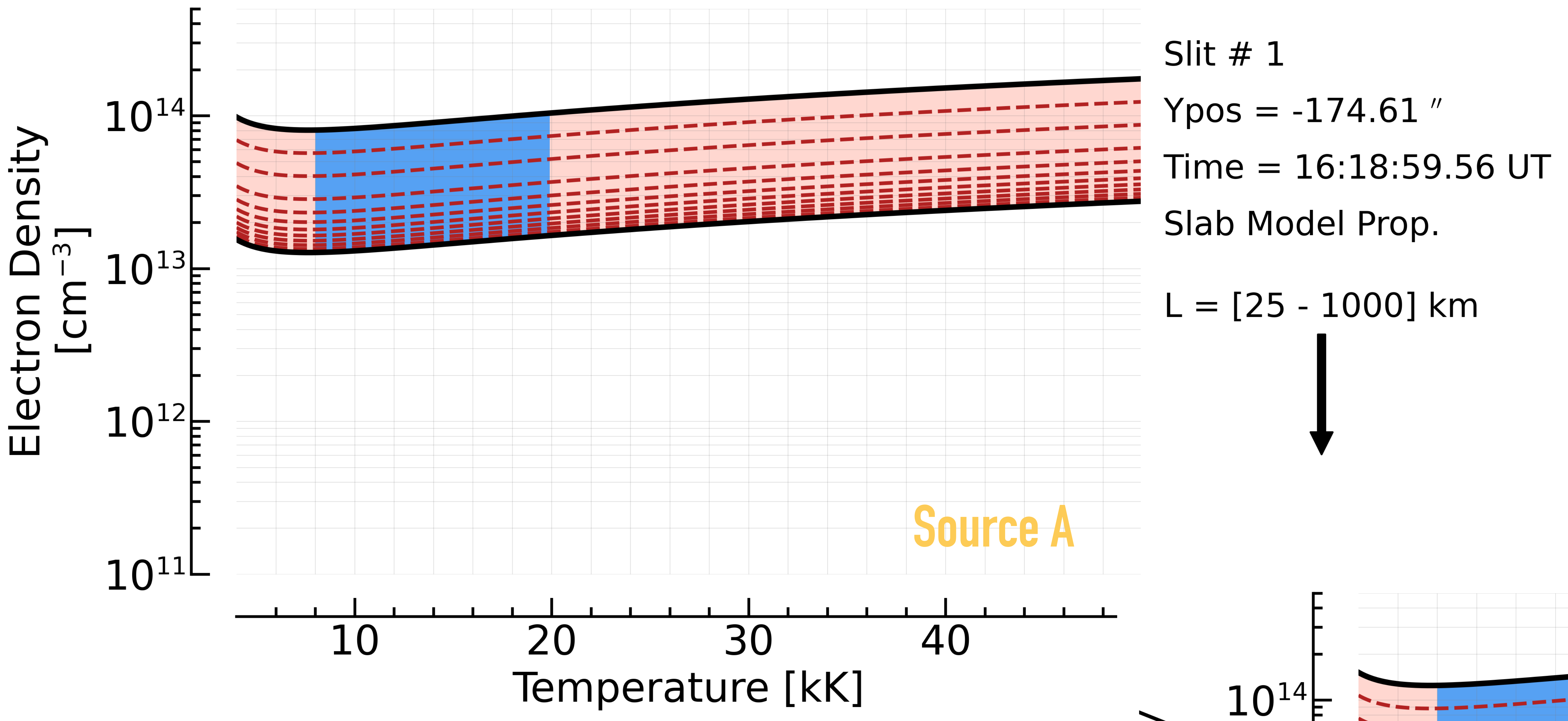
3958.5
3962.5
3966.5
3970.5
3974.5
Wavelength [Å]


Electron Density [cm^{-3}]
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10^{13}
10^{12}
10^{11}
10
20
30
40
Temperature [kK]
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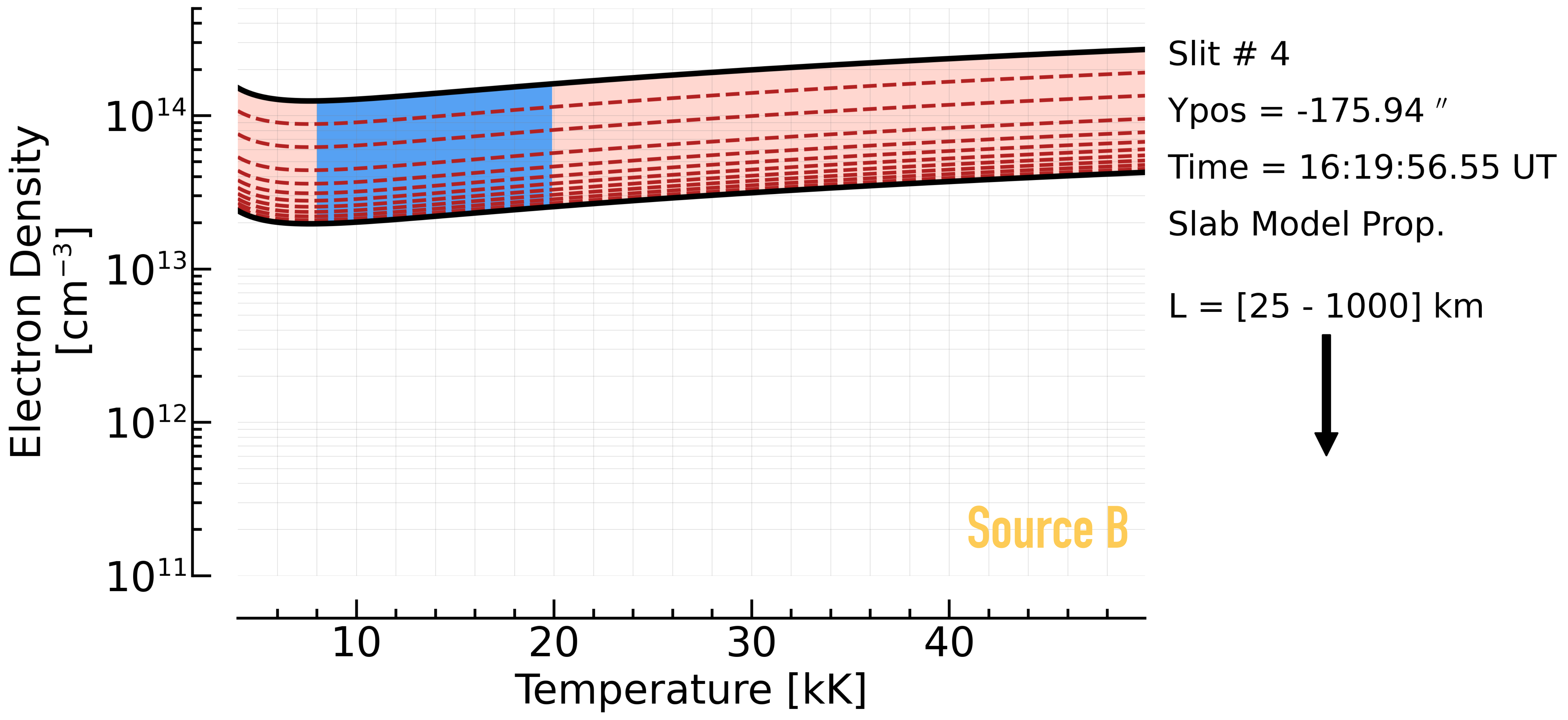
L = [25 - 1000] km


Electron Density [cm^{-3}]
10^{14}
10^{13}
10^{12}
10^{11}
10
20
30
40
Temperature [kK]
Source B
Slit # 4
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Slab Model Prop.
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