

**GRAHAM S. KERR** (CATHOLIC UNIV. OF AMERICA / NASA GSFC)

# LYMAN LINE DECREMENT DURING SOLAR FLARES

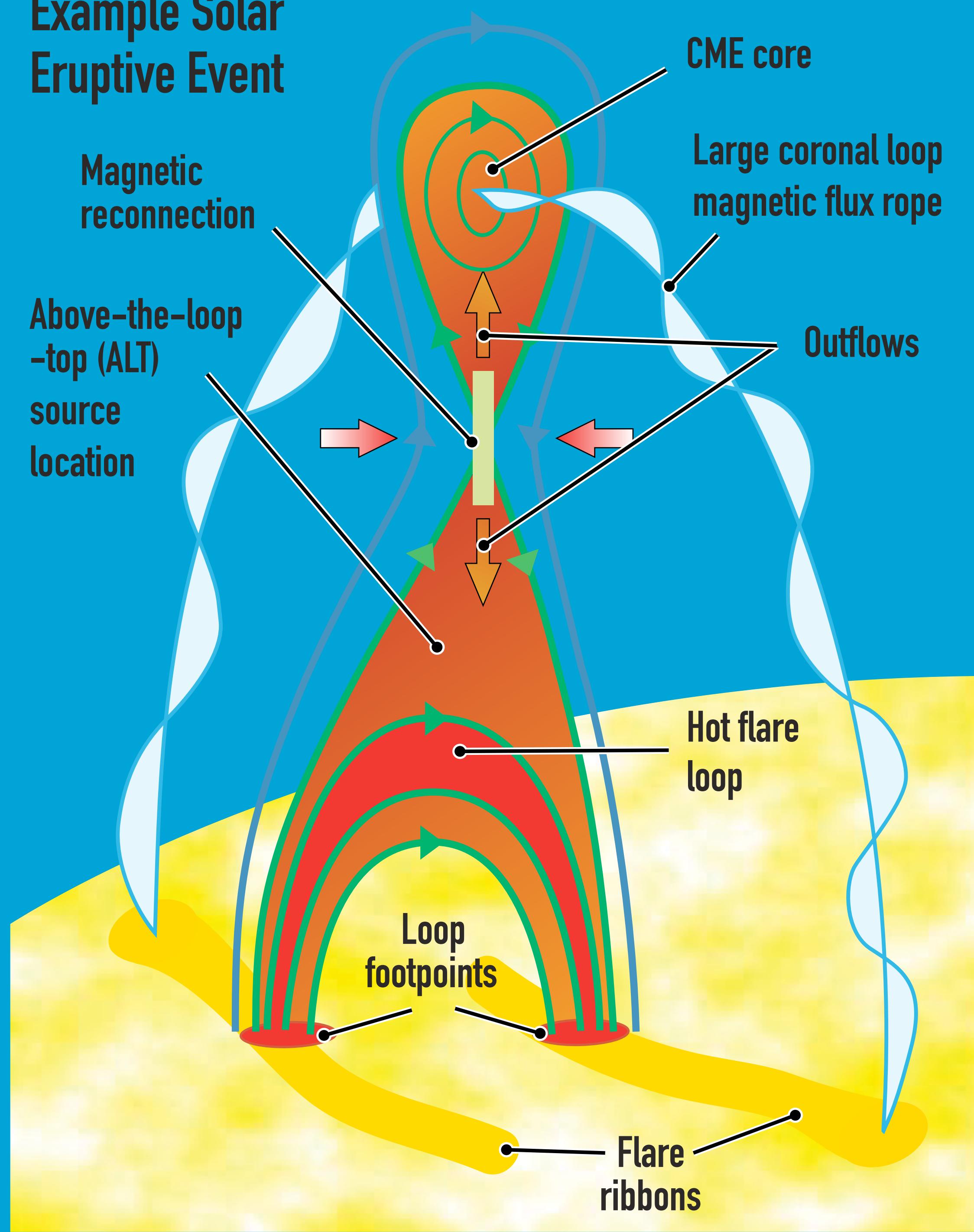
*A Model-data comparison between RHD models and Solar Orbiter SPICE observations*

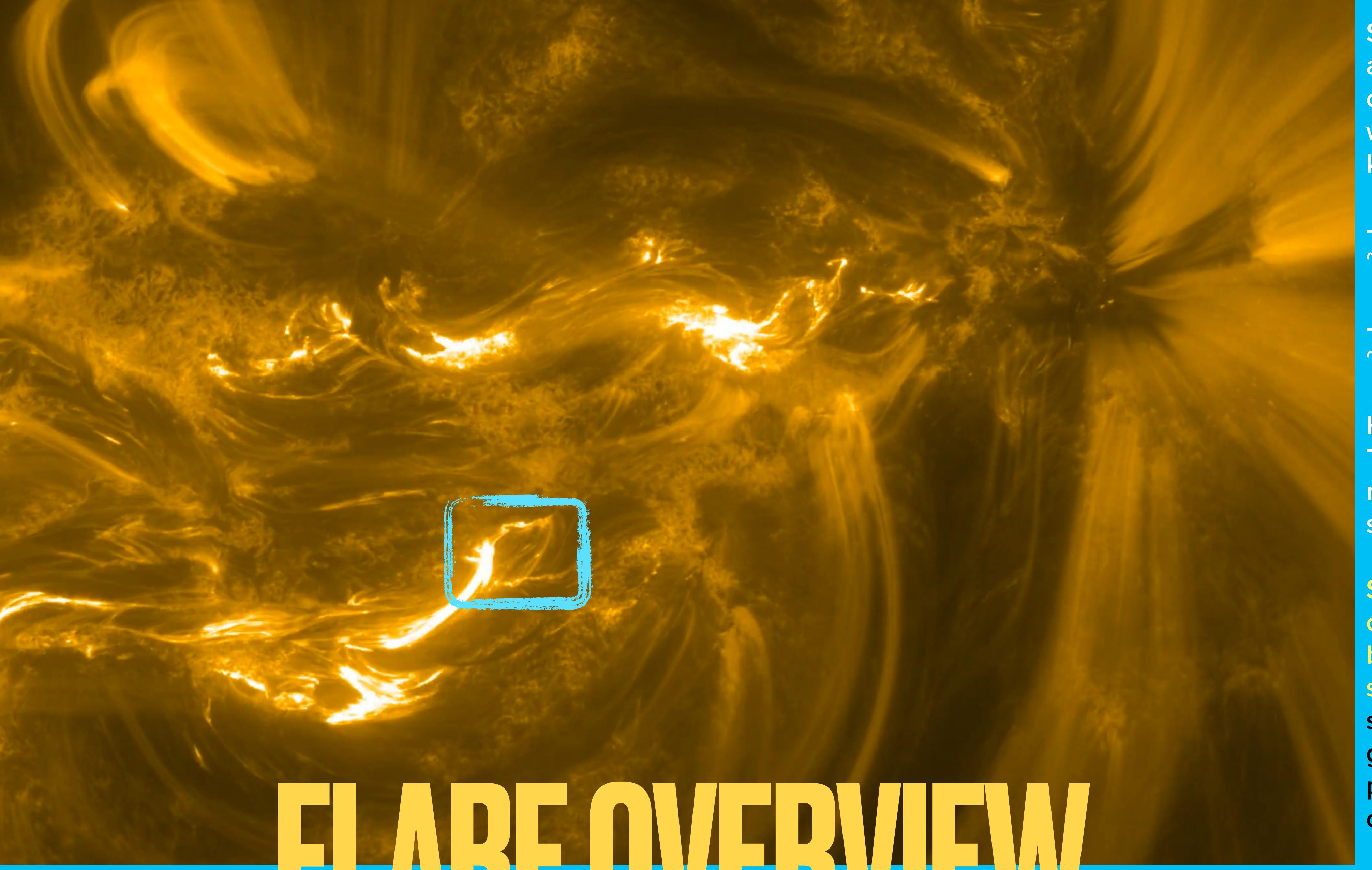
# OUTLINE

- Overview of SPICE observations of the 23rd March 2024 23:46UT M2.5 flare.
- Preliminary observational analysis:
  - ➔ No obvious Orrall-Zirker effect;
  - ➔ High cadence observations of a compact source;
  - ➔ Ly $\beta$  / Ly $\gamma$  ratio shows transient decrease;
- Preliminary RHD modelling of the event:
  - ➔ 12 electron beam simulations — heating upper chromosphere, or lower atmosphere, two different flare strengths;
  - ➔ 1 thermal conduction only simulation;
  - ➔ Synthesized Ly $\beta$  and Ly $\gamma$  lines, and studied formation properties;
  - ➔ Produced synthetic SPICE slit, including PSF;
  - ➔ Lyman decrement consistent with observations only in electron beam scenario, but observations miss structure in lightcurves;
  - ➔ Doppler motions strongly affected by PSF, but a slice through middle of source is sufficiently free of artifacts

Main takeaway — really nice high cadence observations of the EUV flare spectrum, but could go to higher cadence!

# Example Solar Eruptive Event





# FLARE OVERVIEW

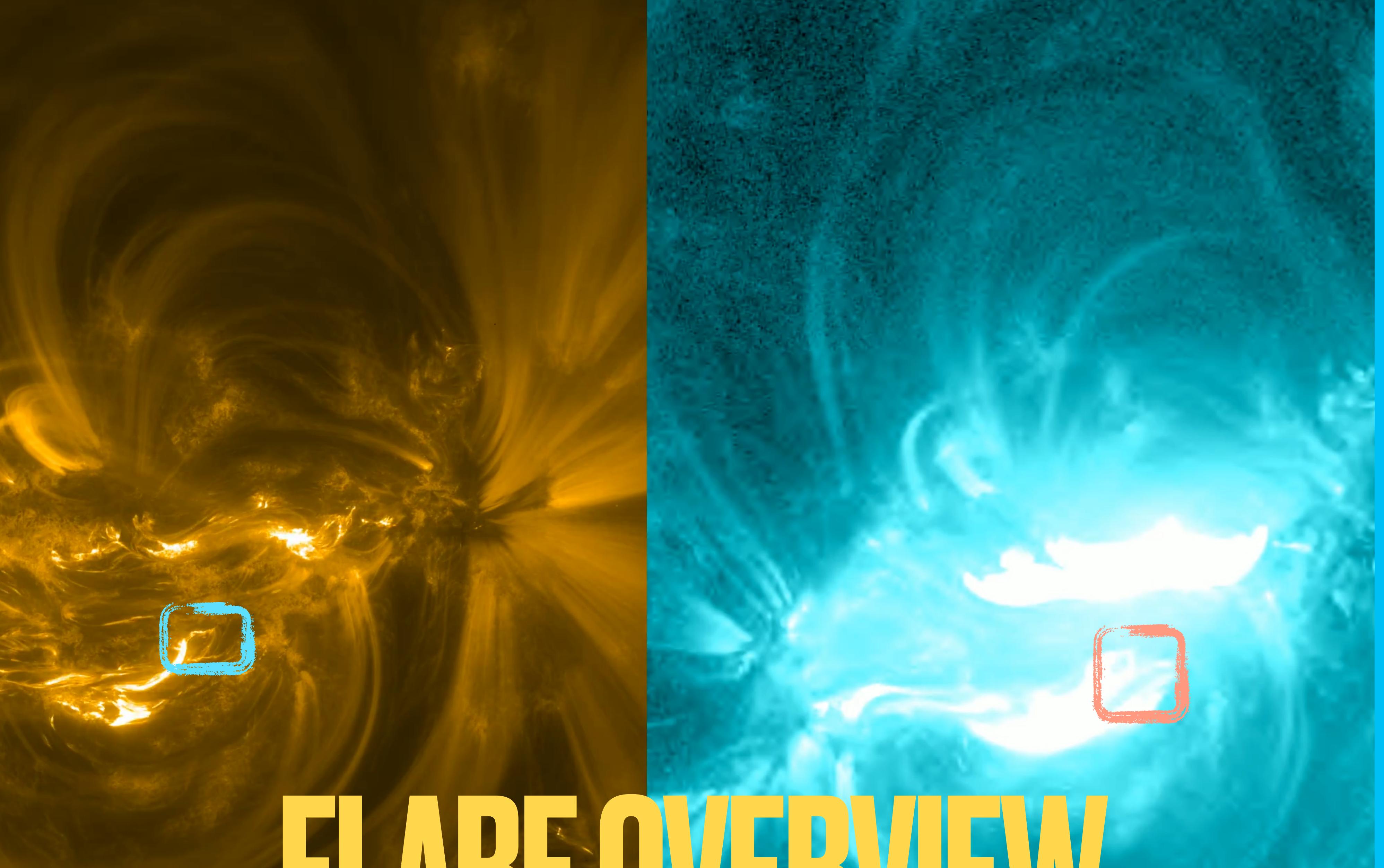
SPICE observed a series of sit-and-stare observations with 5s cadence during the major flare watch. So far there are two known events:

- M2.5 class 23rd March 2024  
~23:46UT

- C9 class 24th March 2024  
~01:00UT

Here I focus on the first event. This was a complex event with multiple ribbons and loop systems.

SPICE observed was a compact but intense brightening between larger sets of flare ribbons. The box shows a tentative, educated guess at where SPICE slit was positioned but need proper co-alignment.



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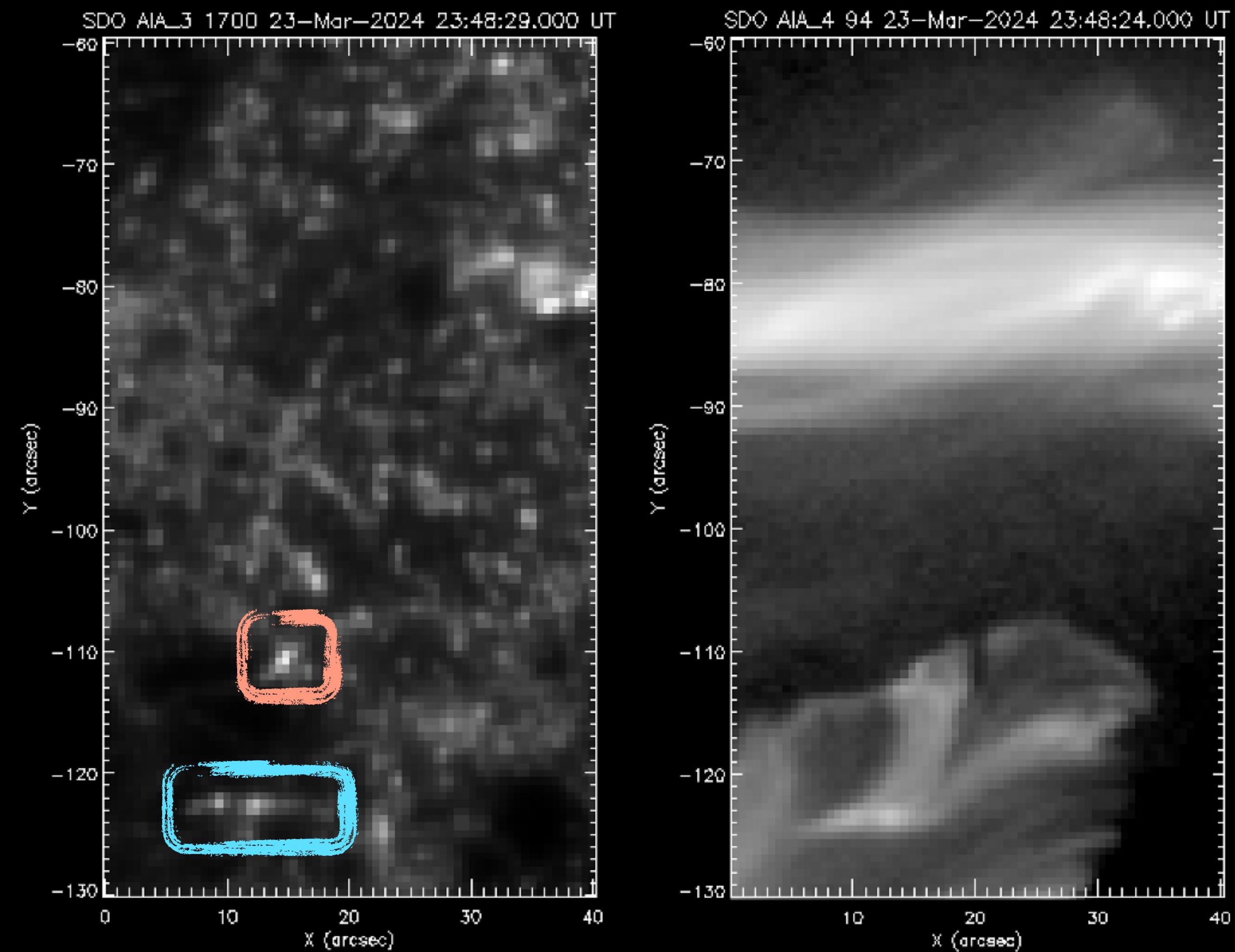
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\* Adapted from slide provided by P. Young



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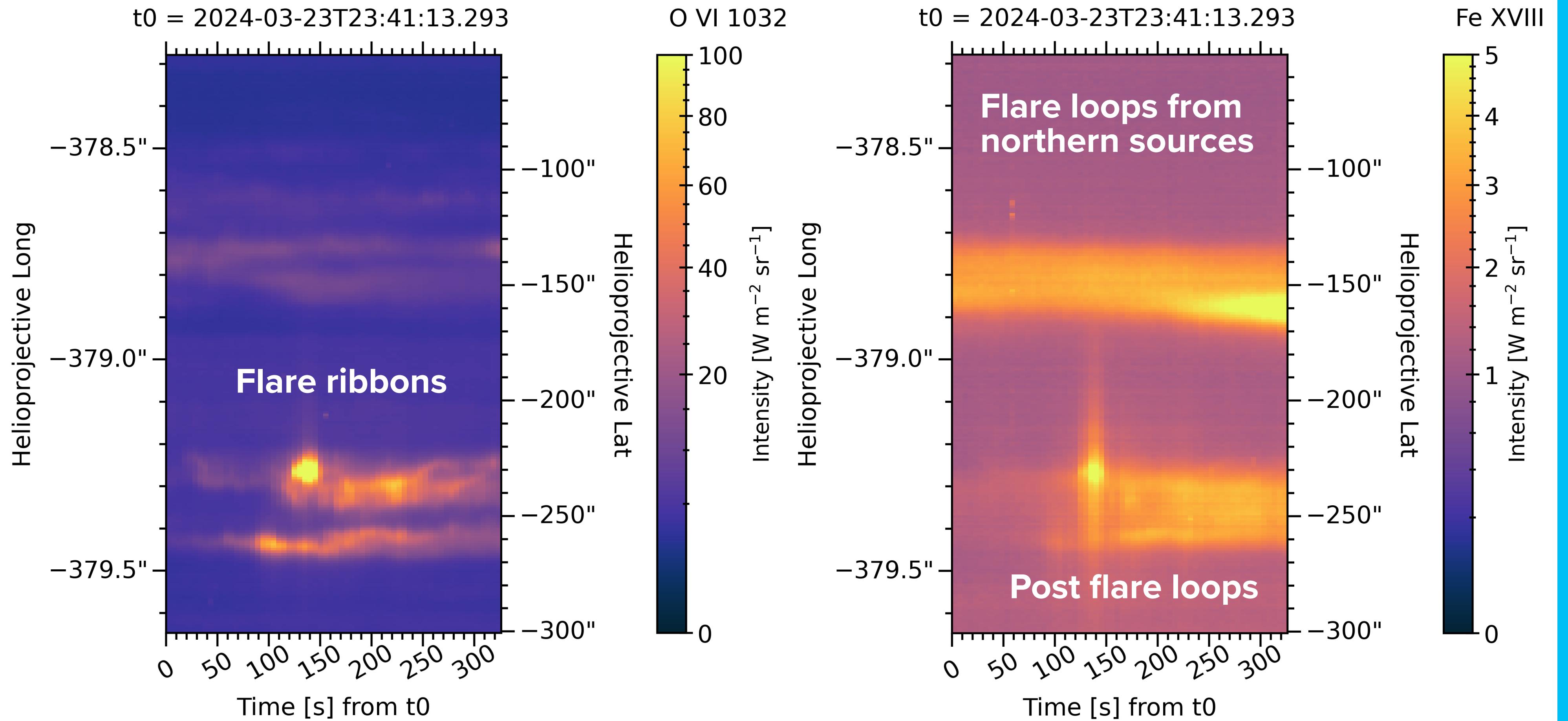
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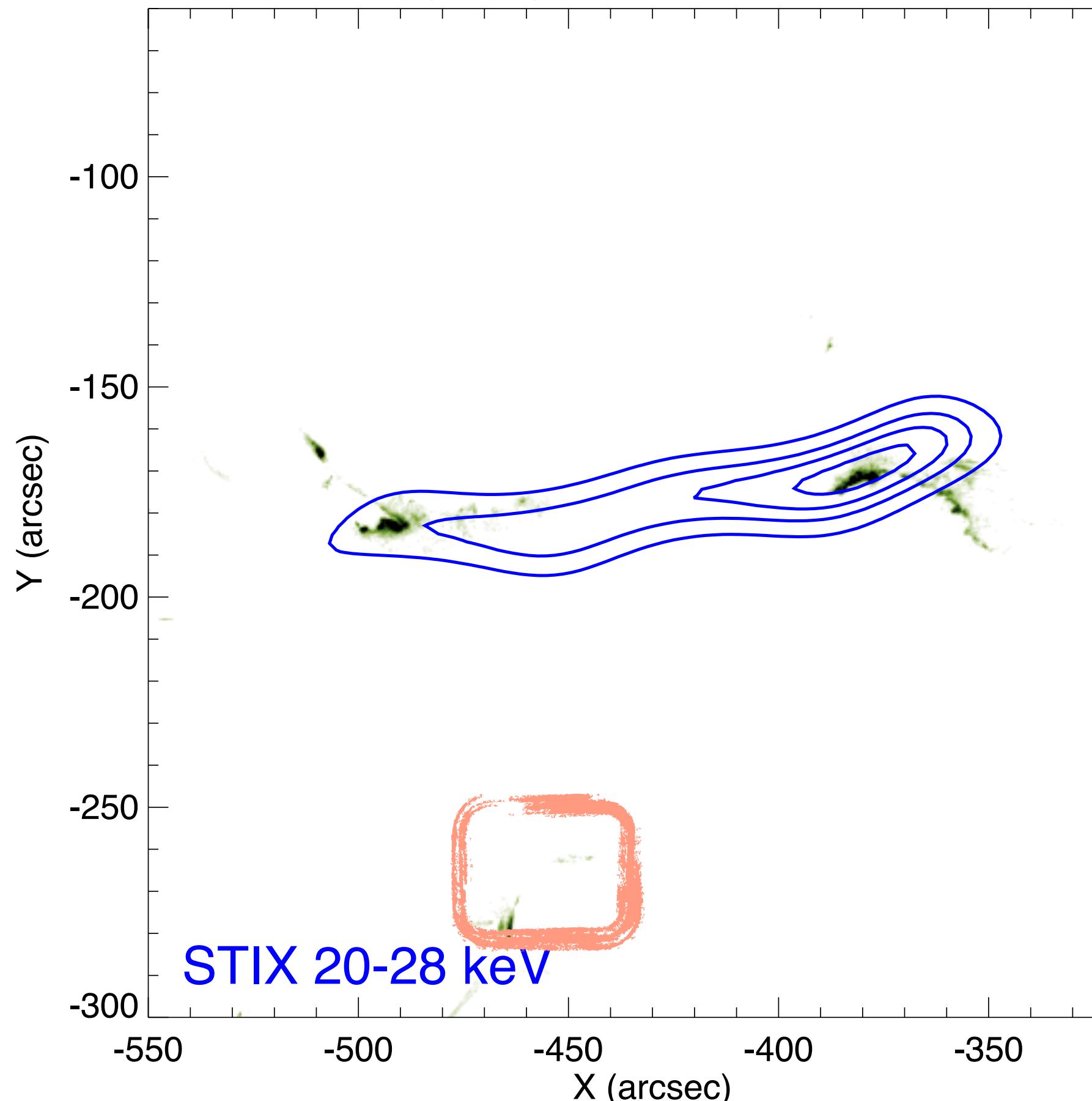
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\* STIX Imaging by Säm Krucker and Dan Ryan

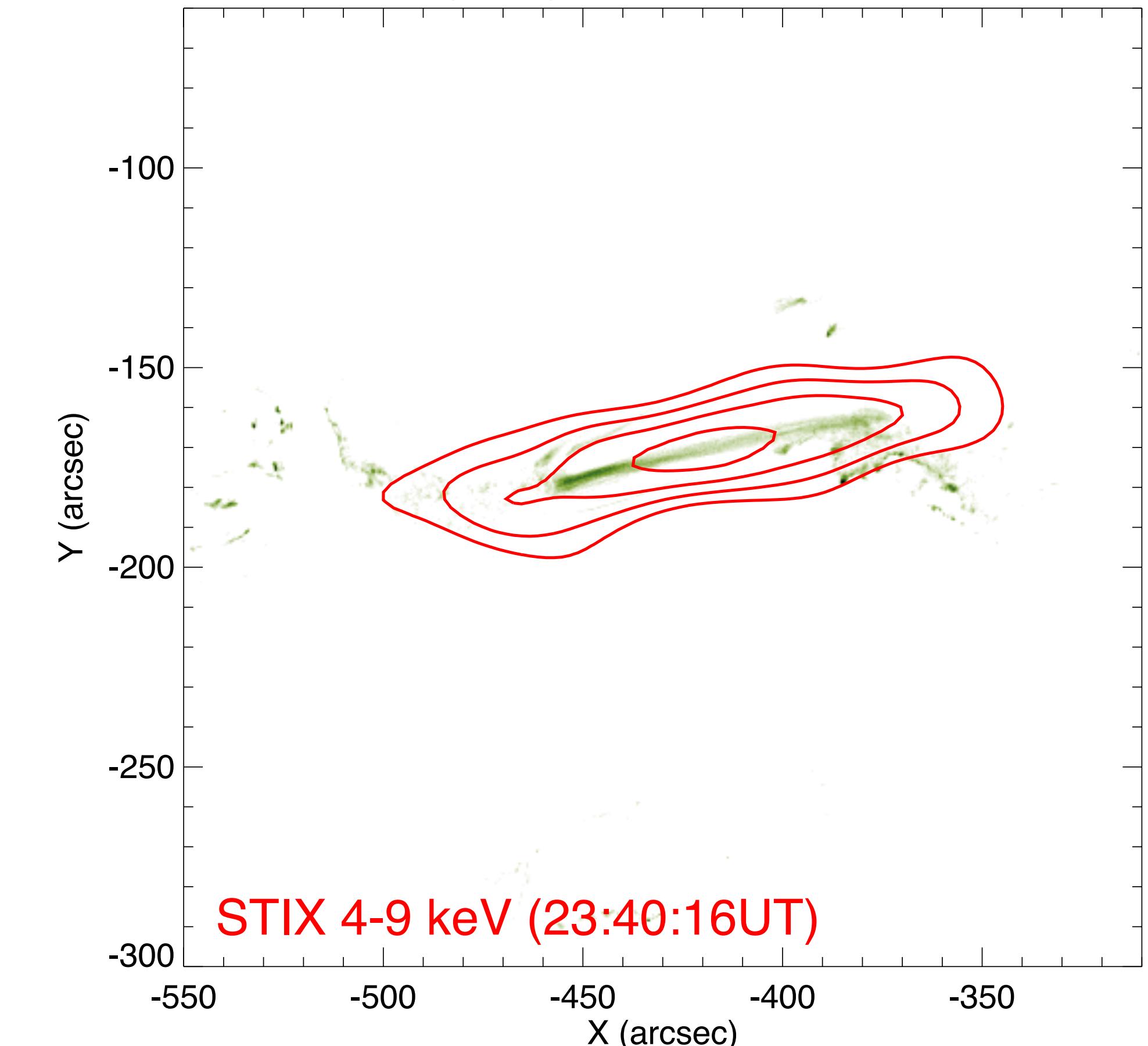
Dominant X-ray sources are to north of SPICE source, but needs proper co-alignment (STIX co-aligned with HRI in images below).

EUI/HRI 174A (short): 23-Mar-2024 23:40:16.247 UT



STIX 20-28 keV

EUI/HRI 174A (short): 23-Mar-2024 23:42:40.247 UT



STIX 4-9 keV (23:40:16UT)

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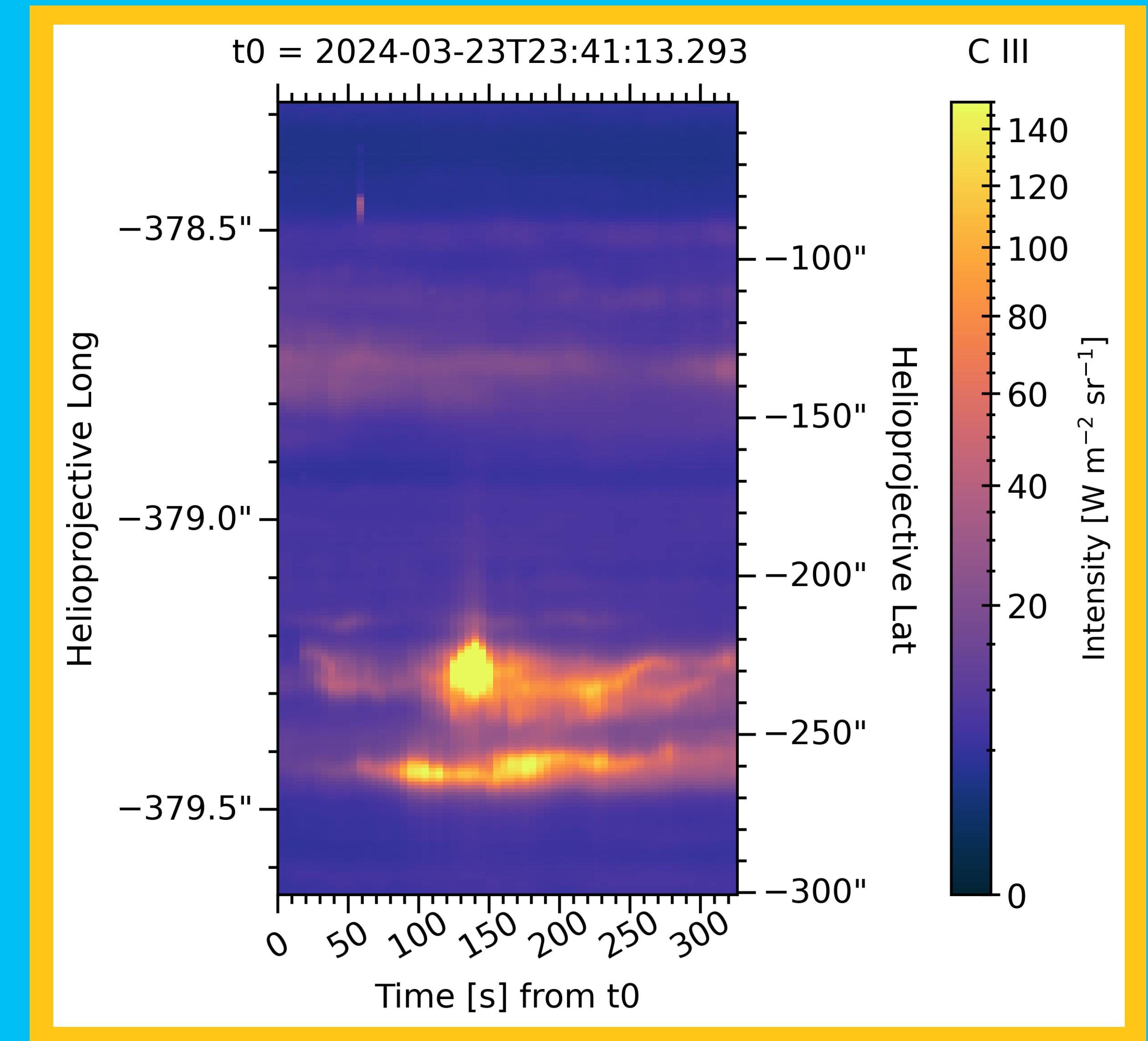
# FLARE OVERVIEW

# **OVERVIEW OF THE SPICE OBSERVATIONS**

**23RD MARCH 2024 23:46UT M2.5 CLASS FLARE**

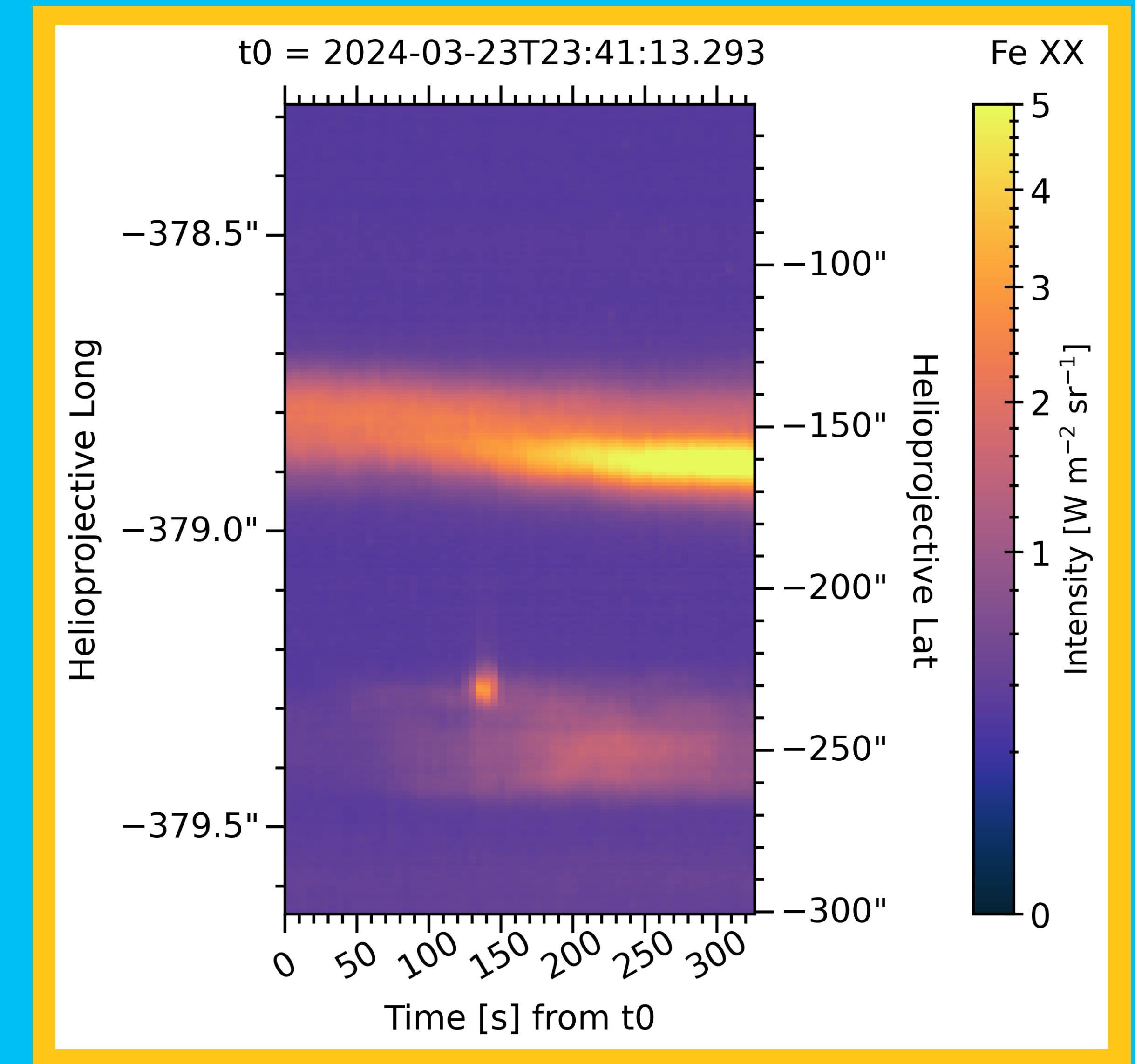
# SPECTRAL LINE LIST

- Many spectral lines were observed
  - ◆ C III  $\sim$ 97.7nm
  - ◆ Fe XVIII  $\sim$ 97.5nm
  - ◆ Fe XX  $\sim$ 72.1nm
  - ◆ Ly $\gamma$  & Ly $\beta$
  - ◆ Ne VIII  $\sim$ 77.0nm
  - ◆ N IV  $\sim$ 76.5nm
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  - ◆ O III  $\sim$ 70.3nm
  - ◆ O VI  $\sim$ 103.2nm &  $\sim$ 103.7nm
  - ◆ ... maybe S III 101.2 – 101.6nm
- Covers a decent temperature range at 5s — one of highest cadence flare datasets.



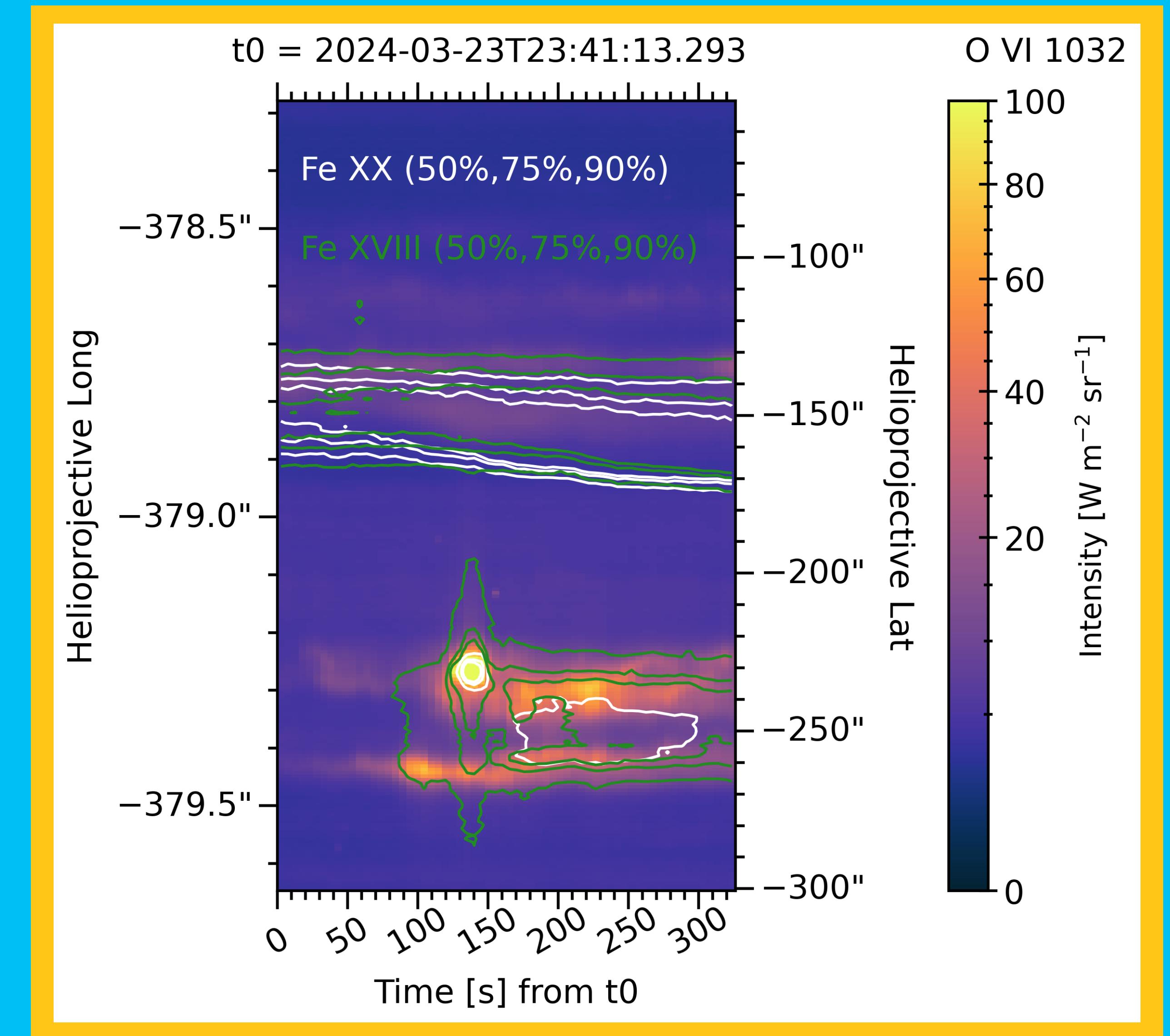
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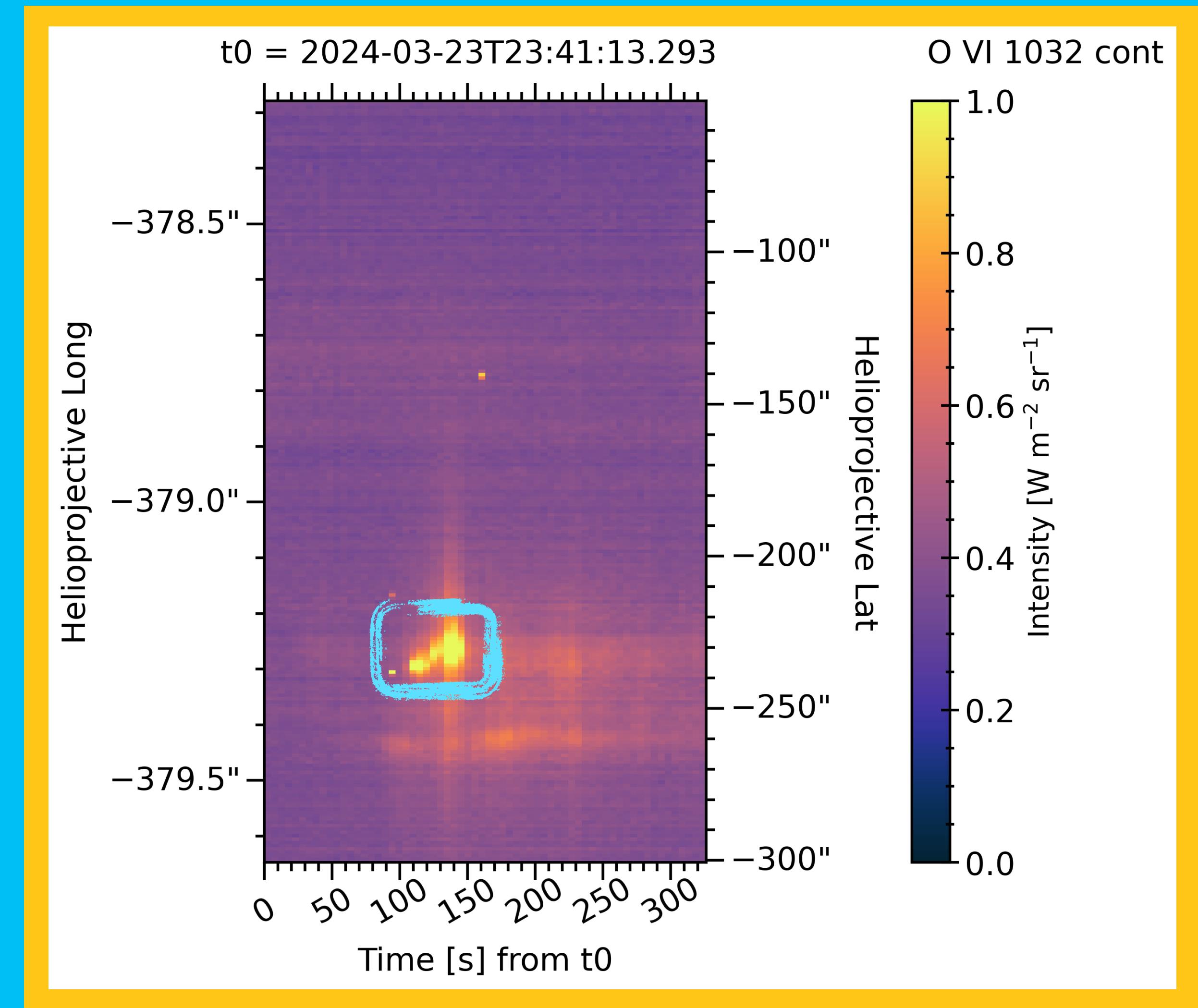
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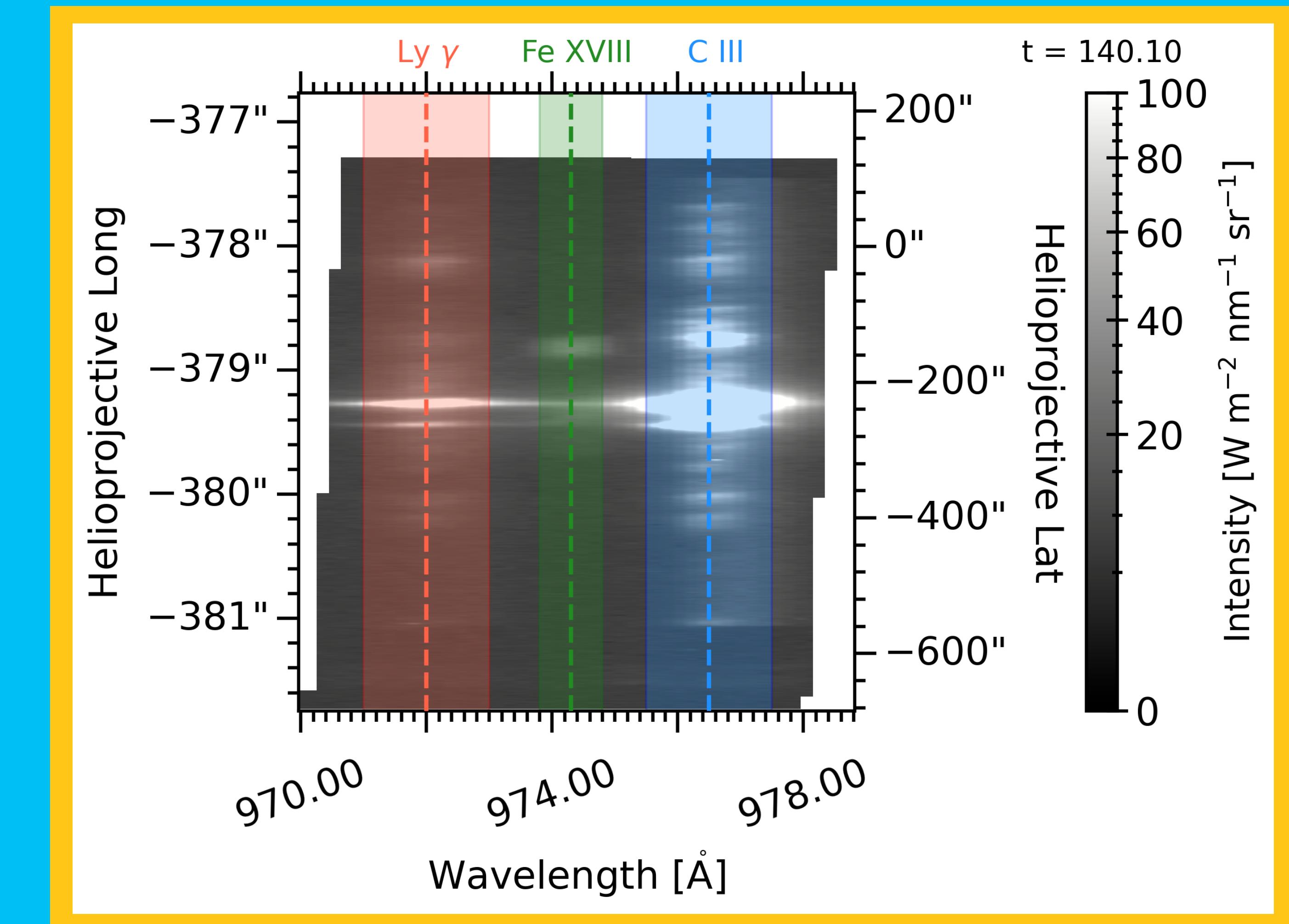
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Continuum brightens a little earlier in some locations!



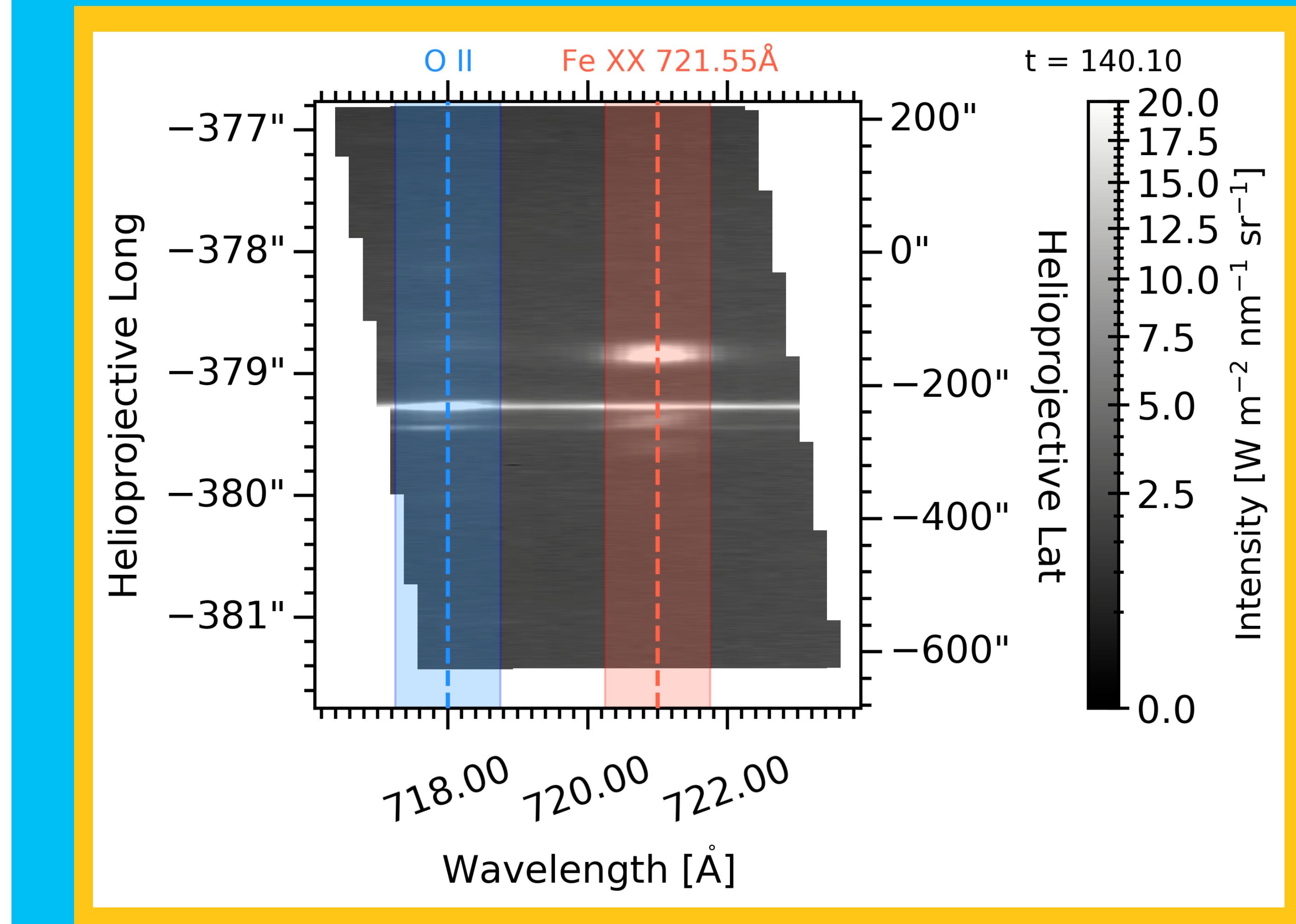
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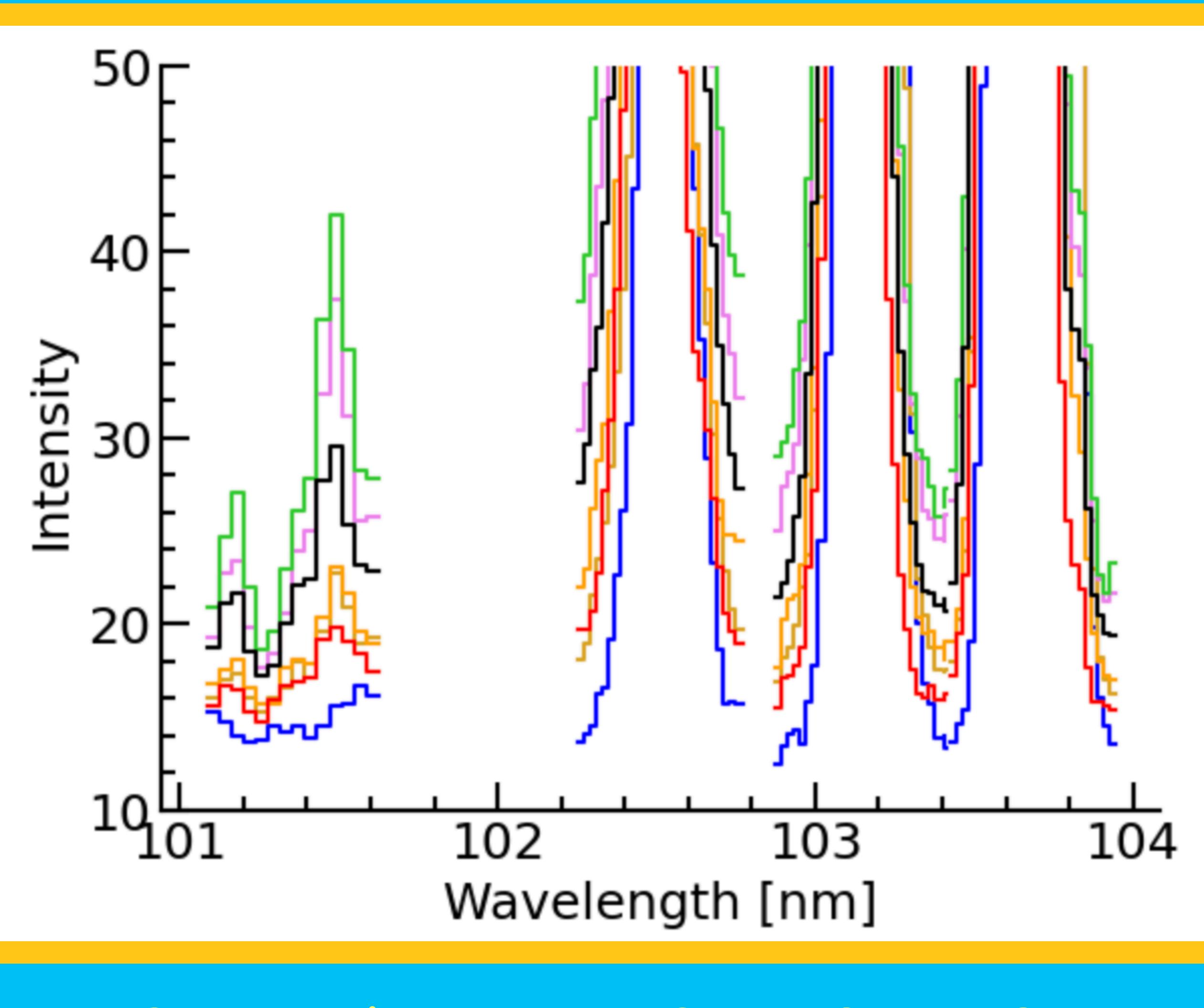
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# ORRALL-ZIRKER EFFECT?

- Preliminary answer: **Not yet**
- ◆ See Kerr et al 2023 ApJ 945 for details.
- ◆ In brief, a potential diagnostic of accelerated protons, in which charge exchange results in enhanced continuum near Ly $\beta$  & O VI.
- ◆ Simulations predict **very** transient effect... **perhaps 5s cadence is insufficient and we should push to 1s** (... if doable?).

No clear enhancement of continuum on red side of Ly $\beta$  compared to blue.



# **LYMAN LINE DECREMENT**

**23RD MARCH 2024 23:46UT M2.5 CLASS FLARE**

**DUE TO SPICE PSF, COMPARING DOPPLER SHIFTS AND LINE WIDTHS TO MODELS IS NOT STRAIGHTFORWARD.**

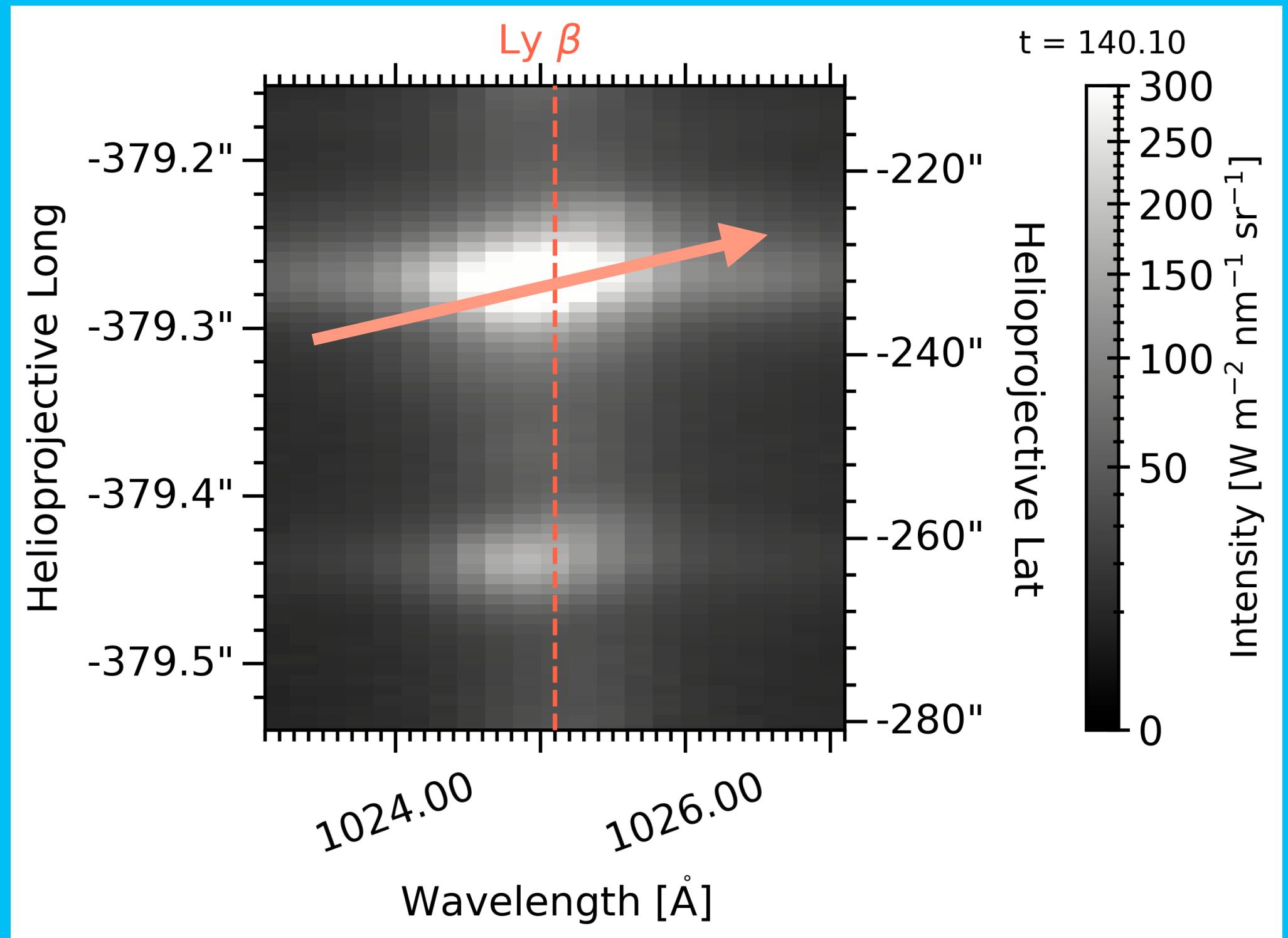
**AN EASIER, BUT POTENTIALLY STILL POWERFUL, METRIC IS THE LYMAN DECREMENT.**

**THIS CAN INFORM US ABOUT THE ATMOSPHERIC STRATIFICATION AND POTENTIALLY NONTHERMAL PROCESSES.**

# EFFECTS OF THE PSF

The tilted PSF means that inferring line widths or Doppler Shifts is non-trivial.

Need to remove PSF effects, but that takes time, so initially Lets do something simpler (i.e. line intensity ratios).



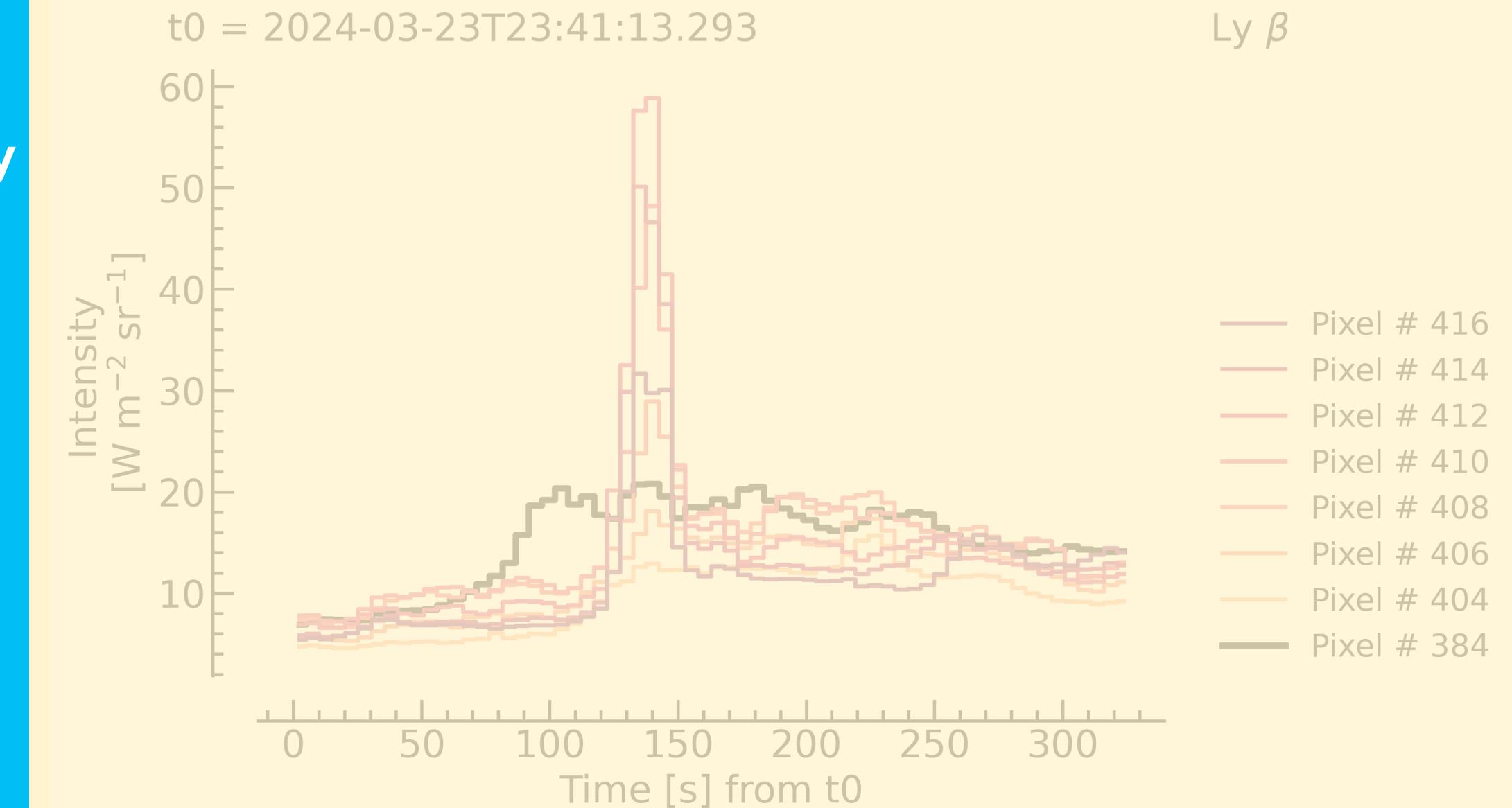
Since the lines are clipped, and start having blends I select

$$\begin{aligned}\text{Ly}\beta &+/- 0.20\text{nm} \\ \text{Ly}\gamma &+/- 0.16\text{nm}\end{aligned}$$

I haven't calibrated wavelength range properly yet — just using a close-enough guess for now.

No continuum subtraction yet either.

# INTENSITY INCREASE IS VERY TRANSIENT

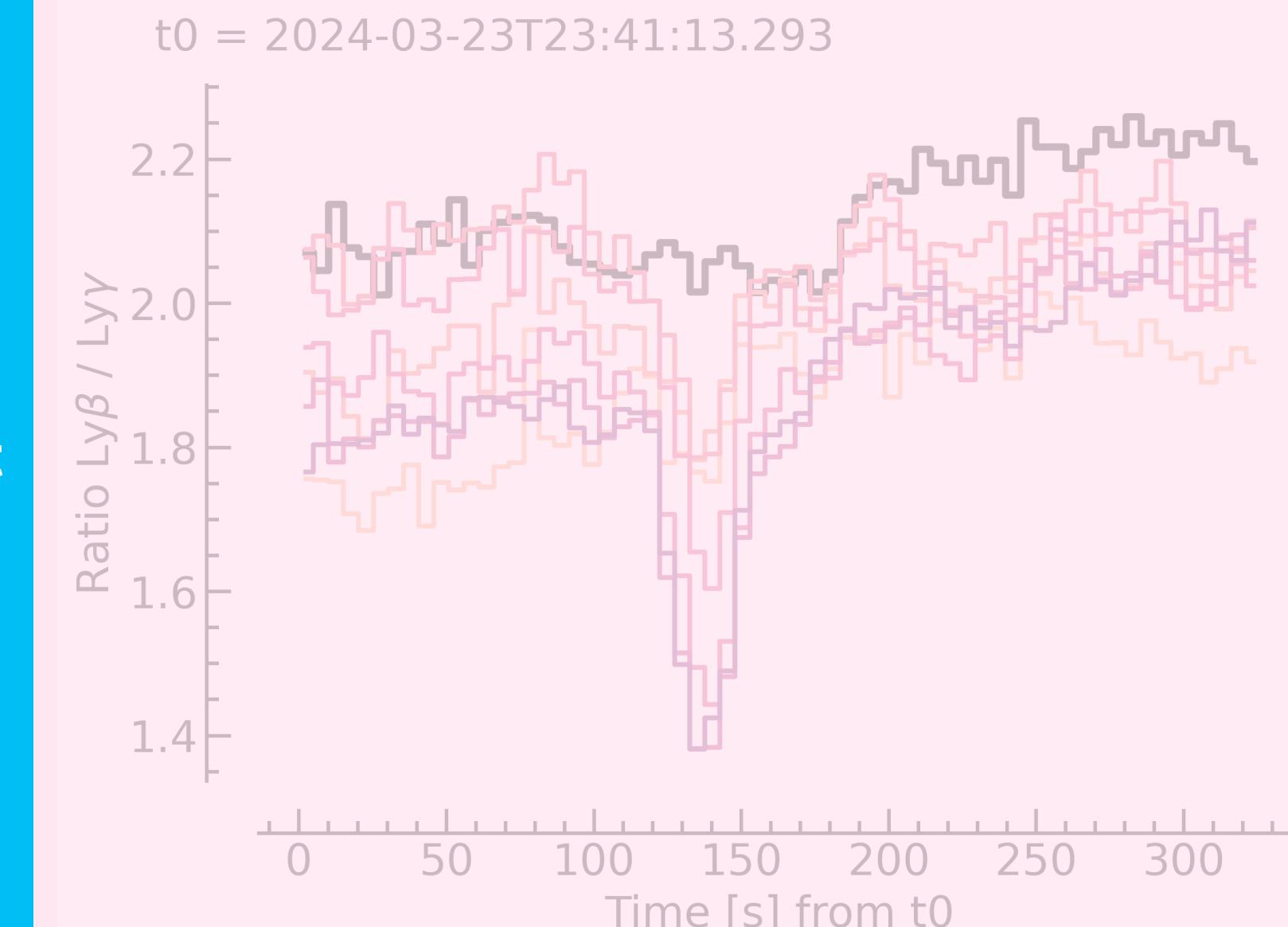


Upper source much more intense, with a transient (~30s) peak followed by slower decay to background.

Lower source (black curve) is much weaker and with less impulsive emission.

Ly $\gamma$  and other lines show same.

# LYMAN DECREMENT IN UPPER VS LOWER SOURCE



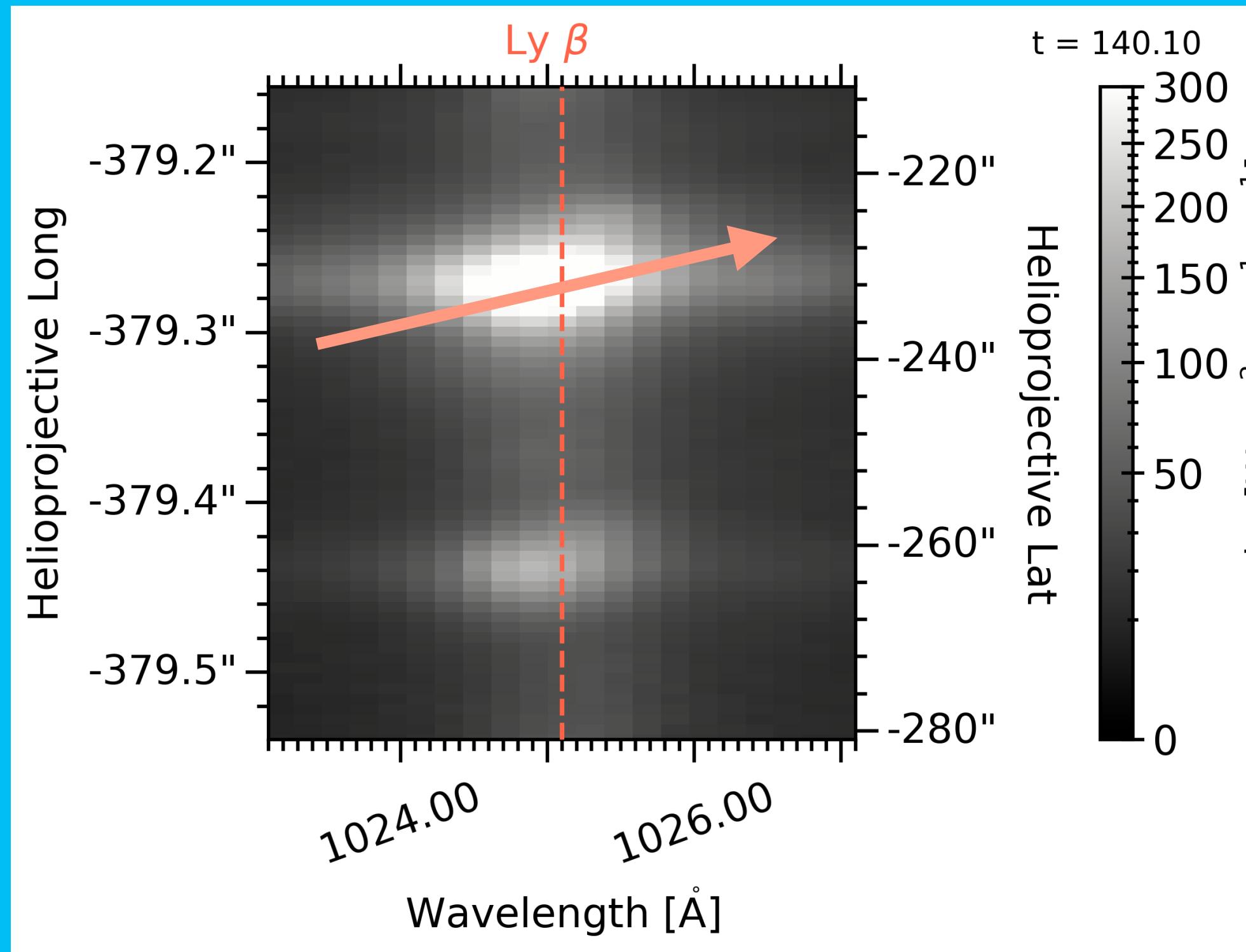
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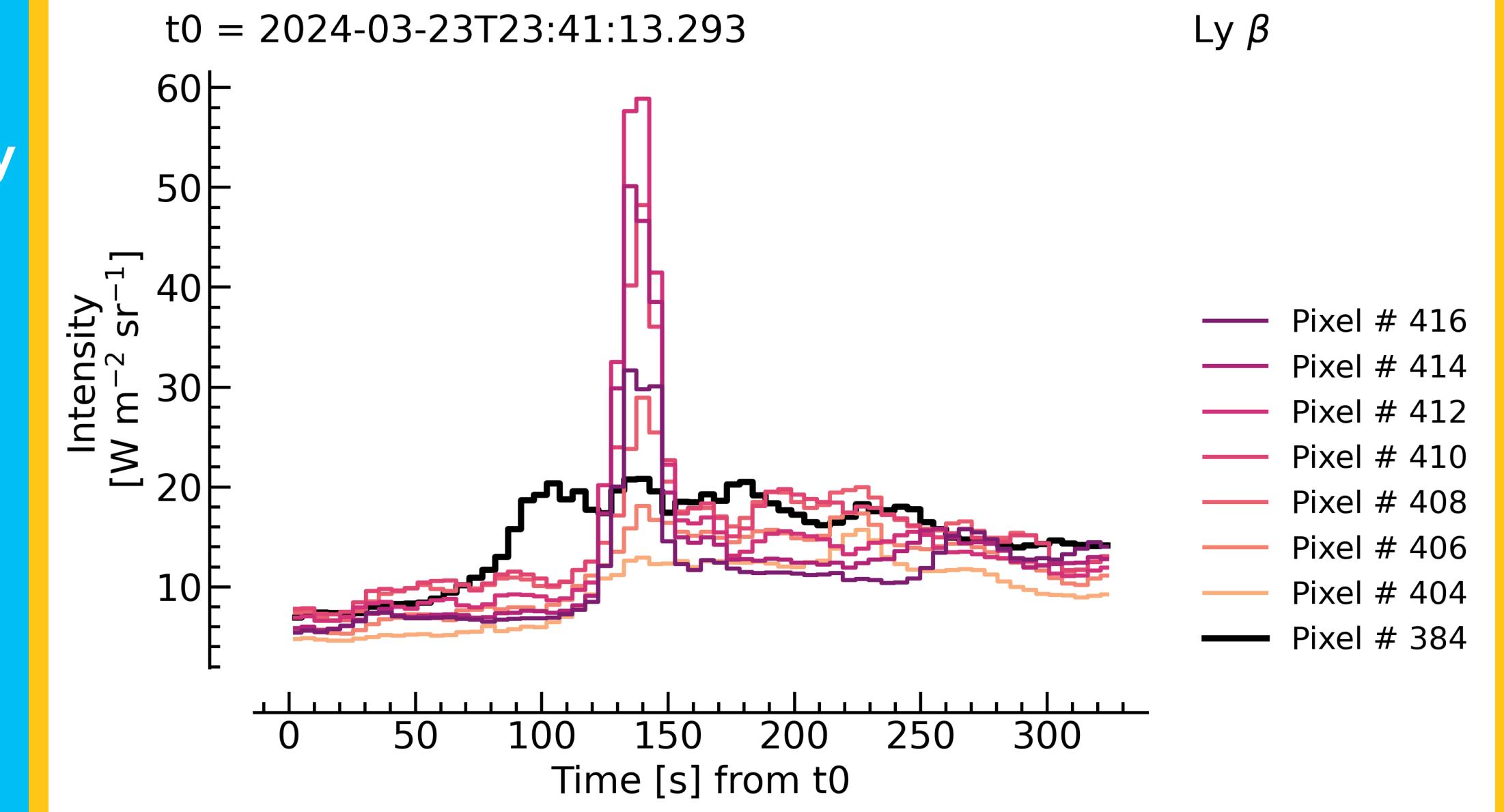
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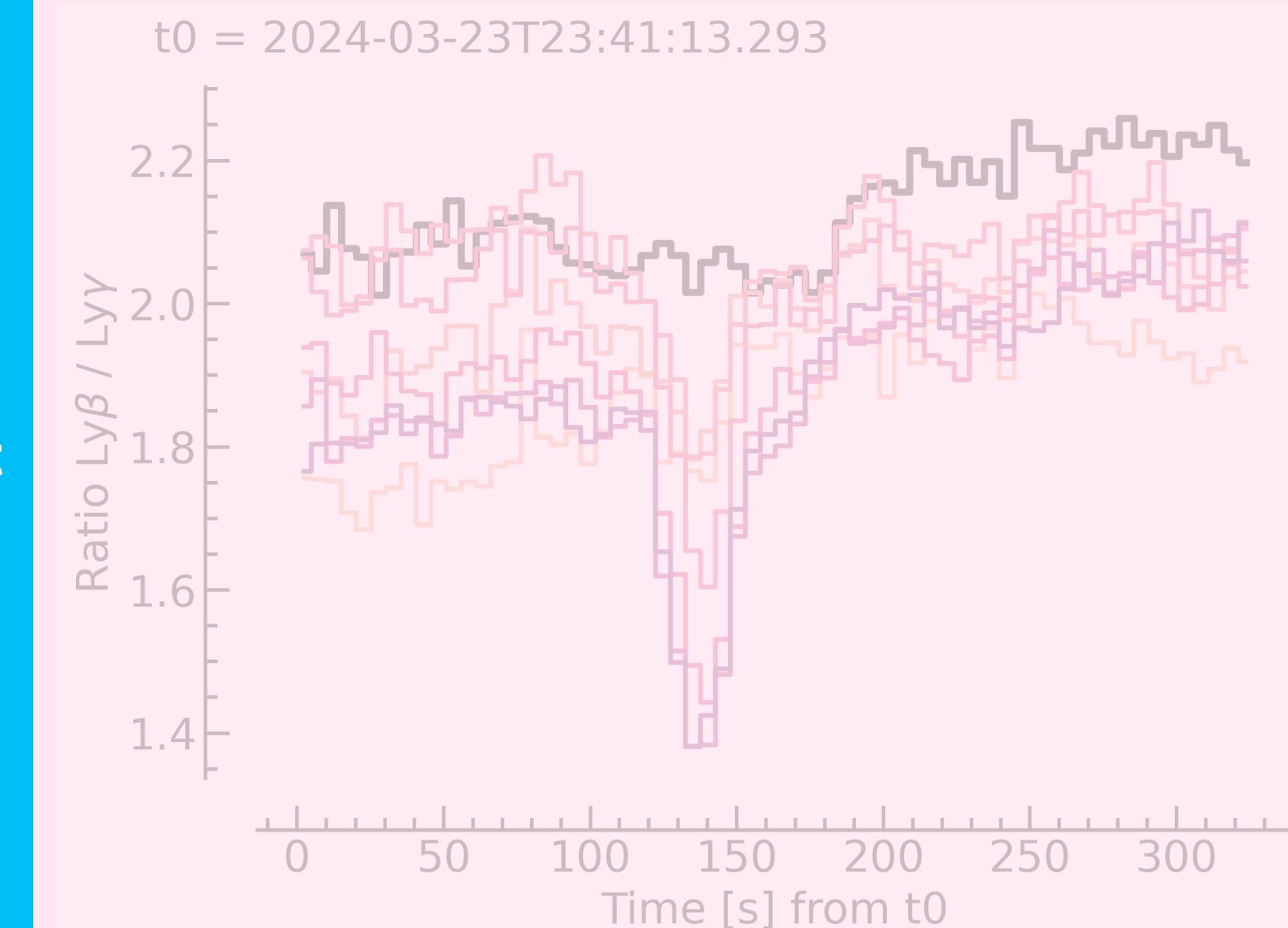


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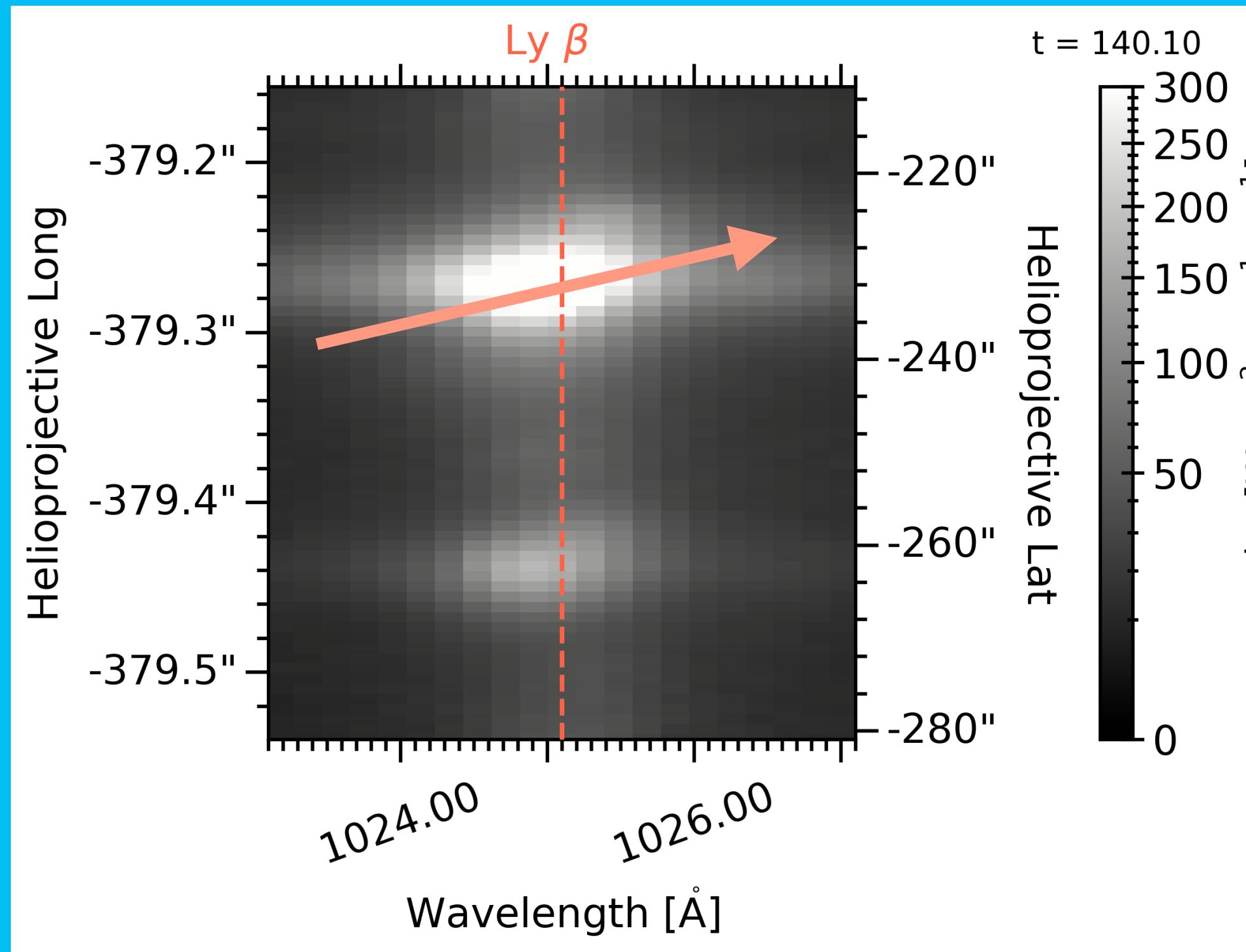
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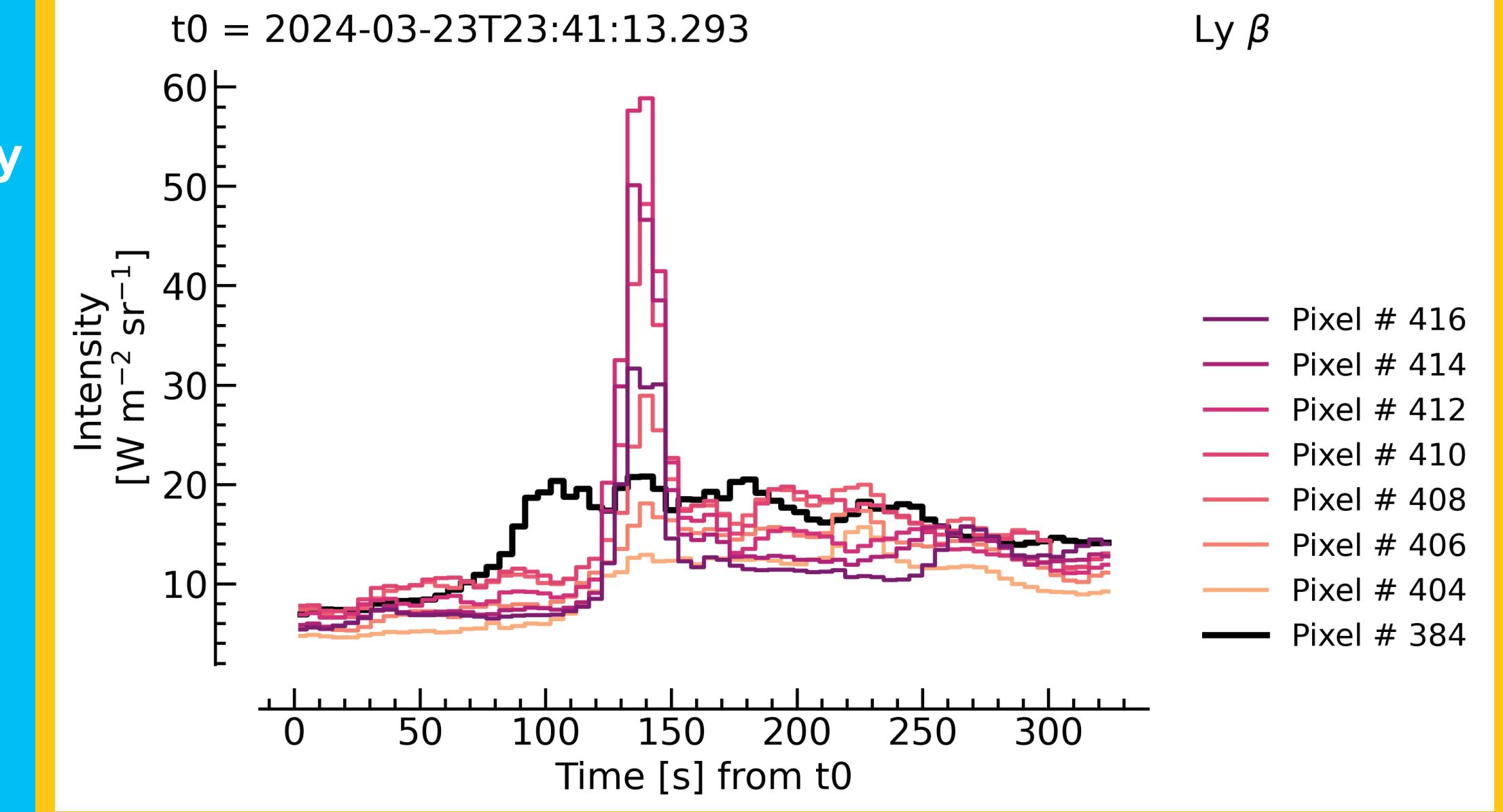
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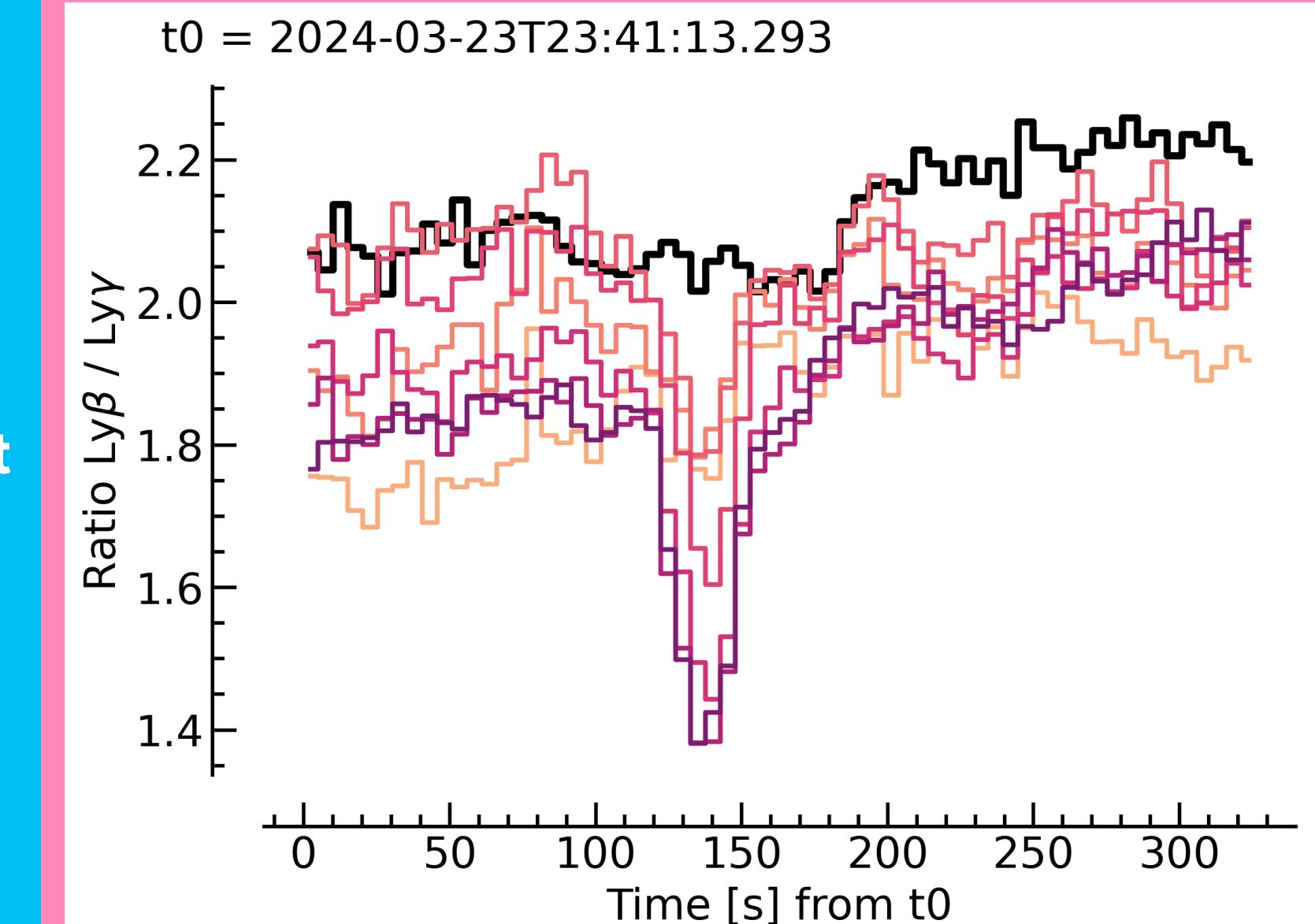


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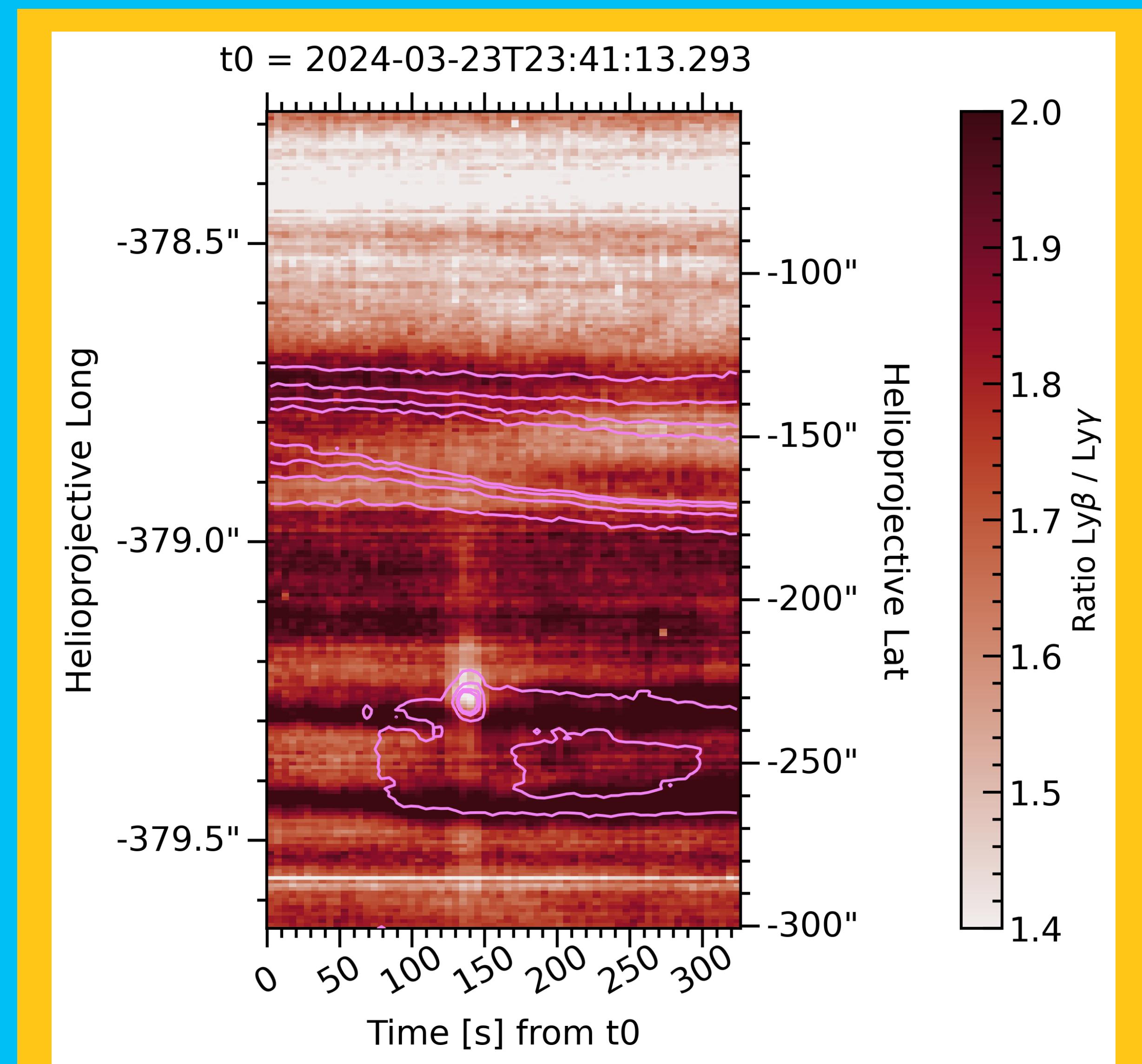
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# LYMAN DECREMENT MAP

- Map shows transient decrease of ratio. and rapid return to pre-flare, in upper source.
- Lower source doesn't really vary.
- Note that in upper portion of field-of-view (away from the flare region) the ratio is lower. So, the ratio tells us about the relative change during the flare, but a low ratio doesn't just occur in flares.

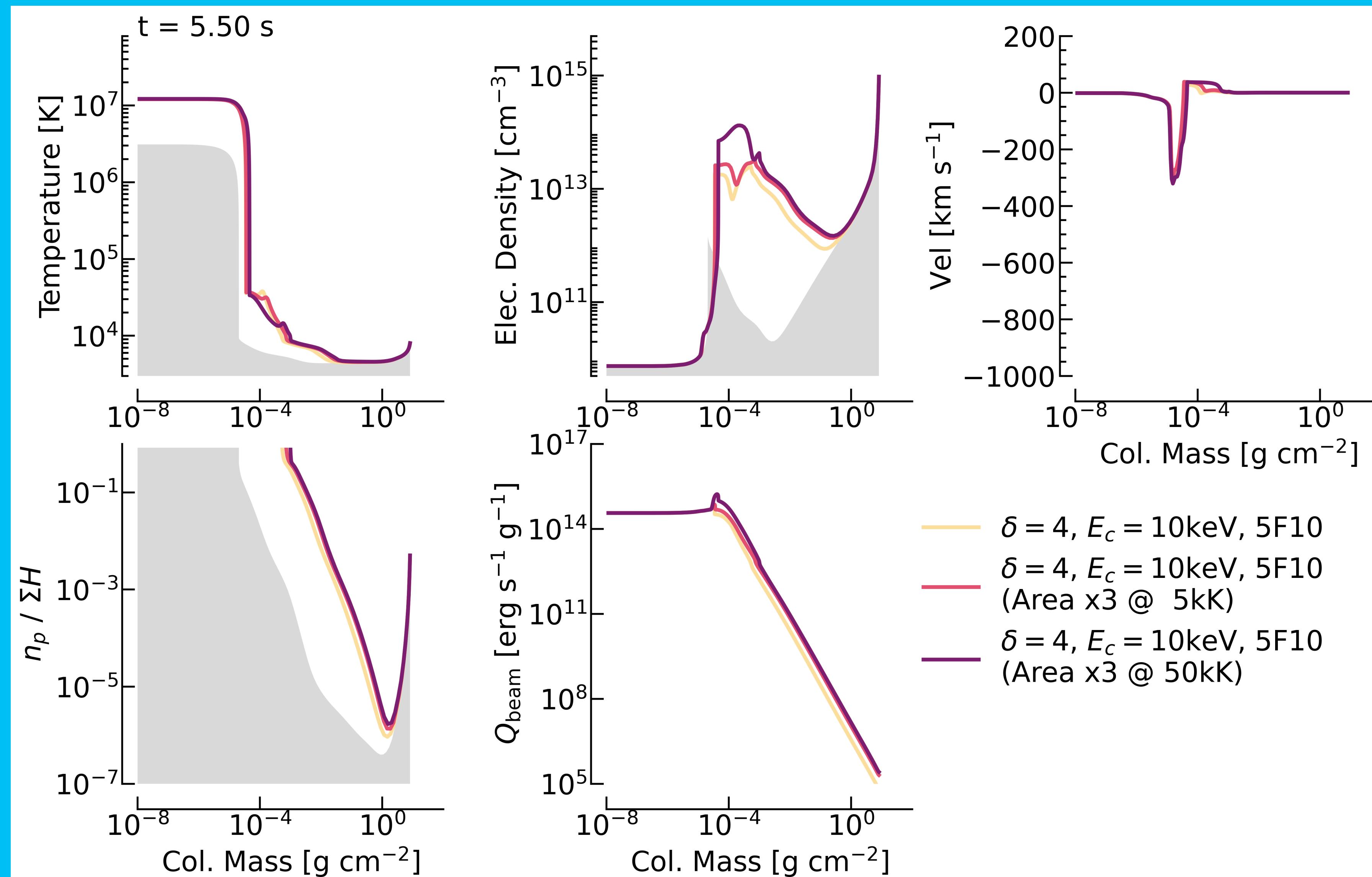
Contours are Fe XX



# **COMPARING TO RHD MODELS**

**RADYN FLARE SIMULATIONS PROCESSED THROUGH RH15D TO GET FULL LYMAN PROFILES  
(USES H NON-EQUIL POPS & INCLUDES PRD AND BLENDS)**

RAN SEVERAL LOOP MODELS, INCLUDING AREA EXPANSION. NOT GOING TO DISCUSS THE VARIOUS DIFFERENCES IN DETAIL HERE, BUT I VARIES BOTH THE ENERGY INPUT AND AREA EXPANSION..



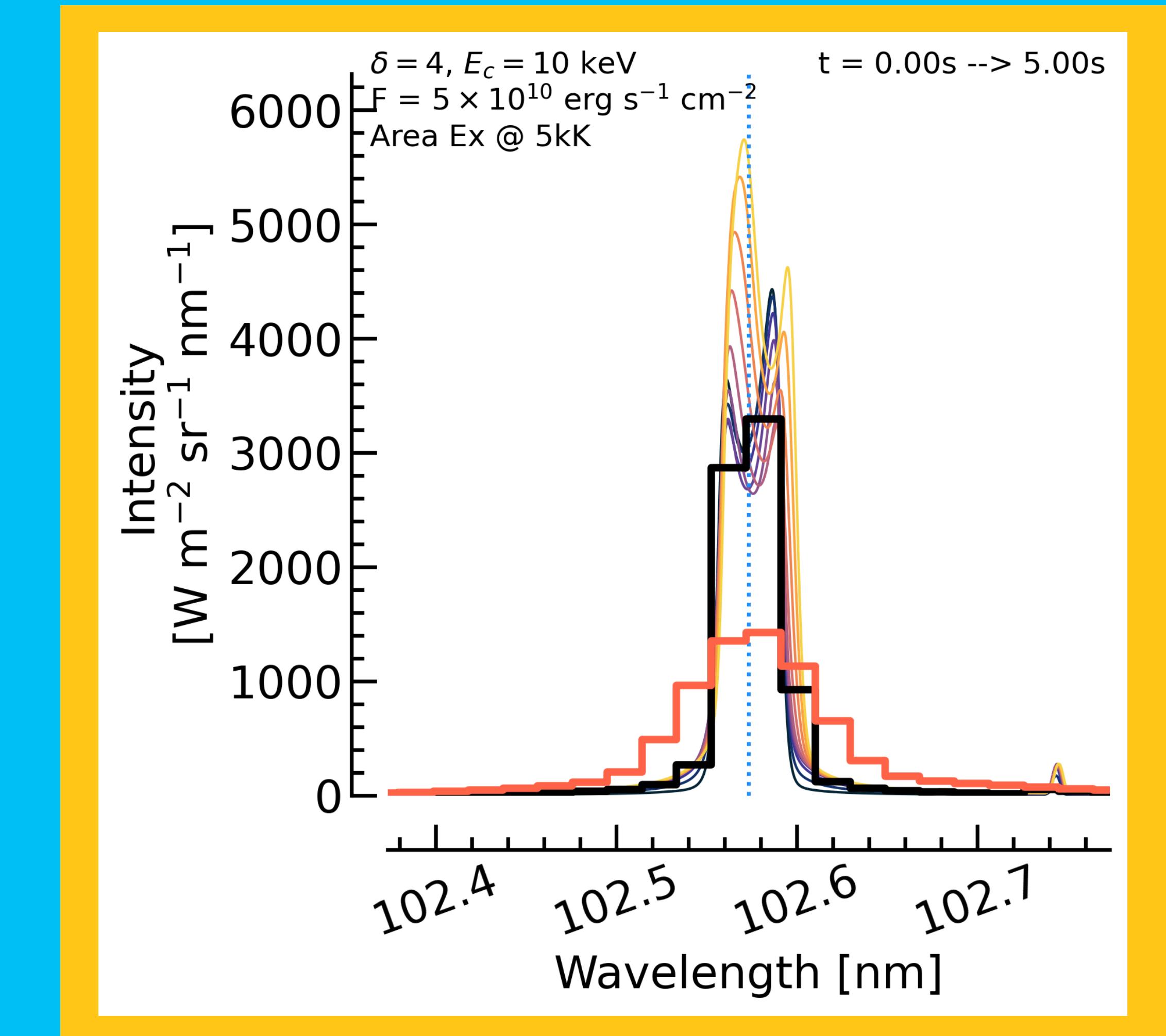
Coloured lines are spectra appearing in this exposure.

Black is the SPICE spectra, without PSF.

Red is with PSF applied (see later).

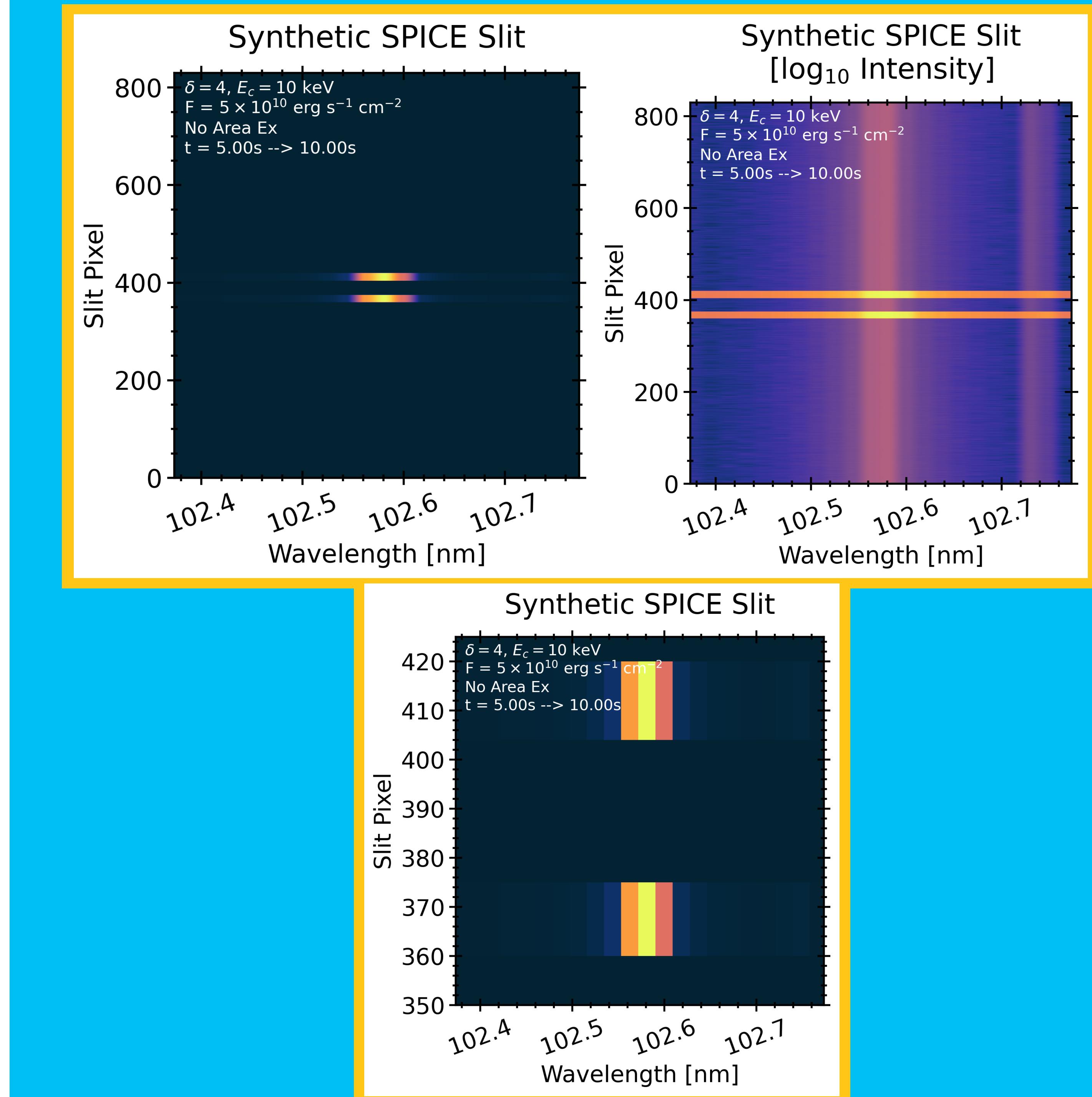
# MODEL → SYNTHETIC SPICE

- Model output was converted to a synthetic SPICE flare by:
  - ◆ Recasting to SPICE plate scale;
  - ◆ Converted to photon number;
  - ◆ Folding through SPICE effective area;
  - ◆ Summed through exposure time and readout time;
  - ◆ Added Poisson noise;
  - ◆ Converted back to physical units.



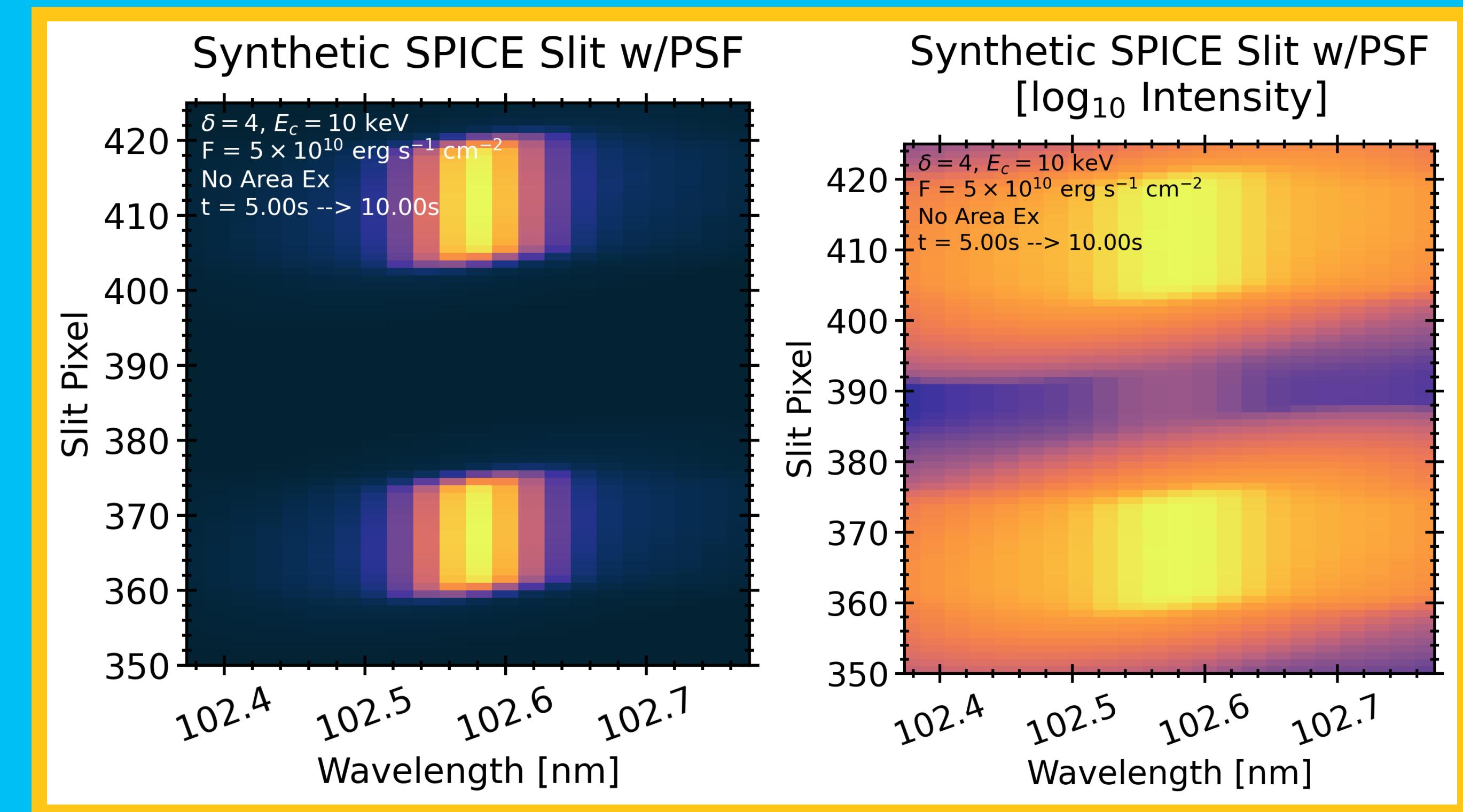
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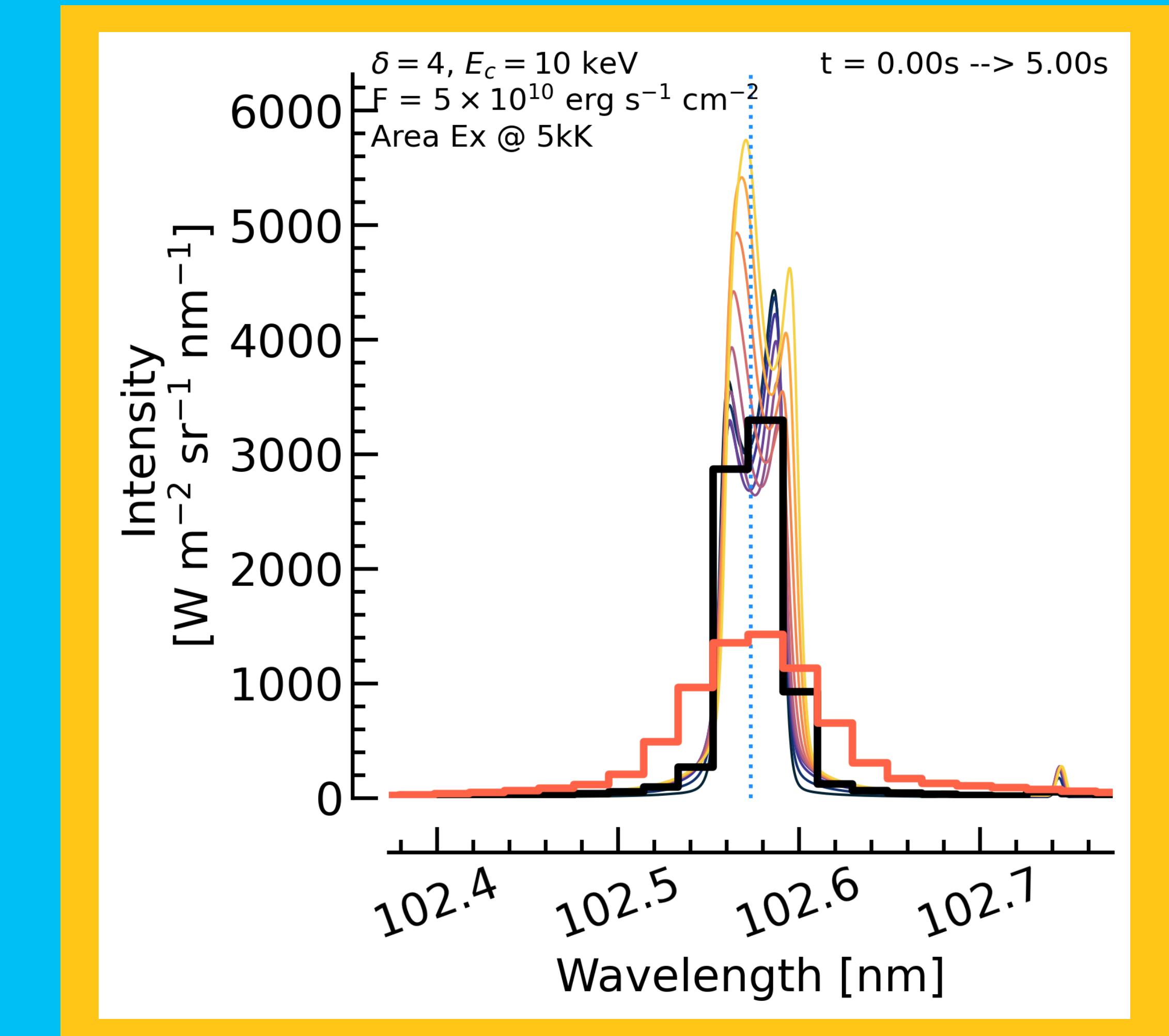
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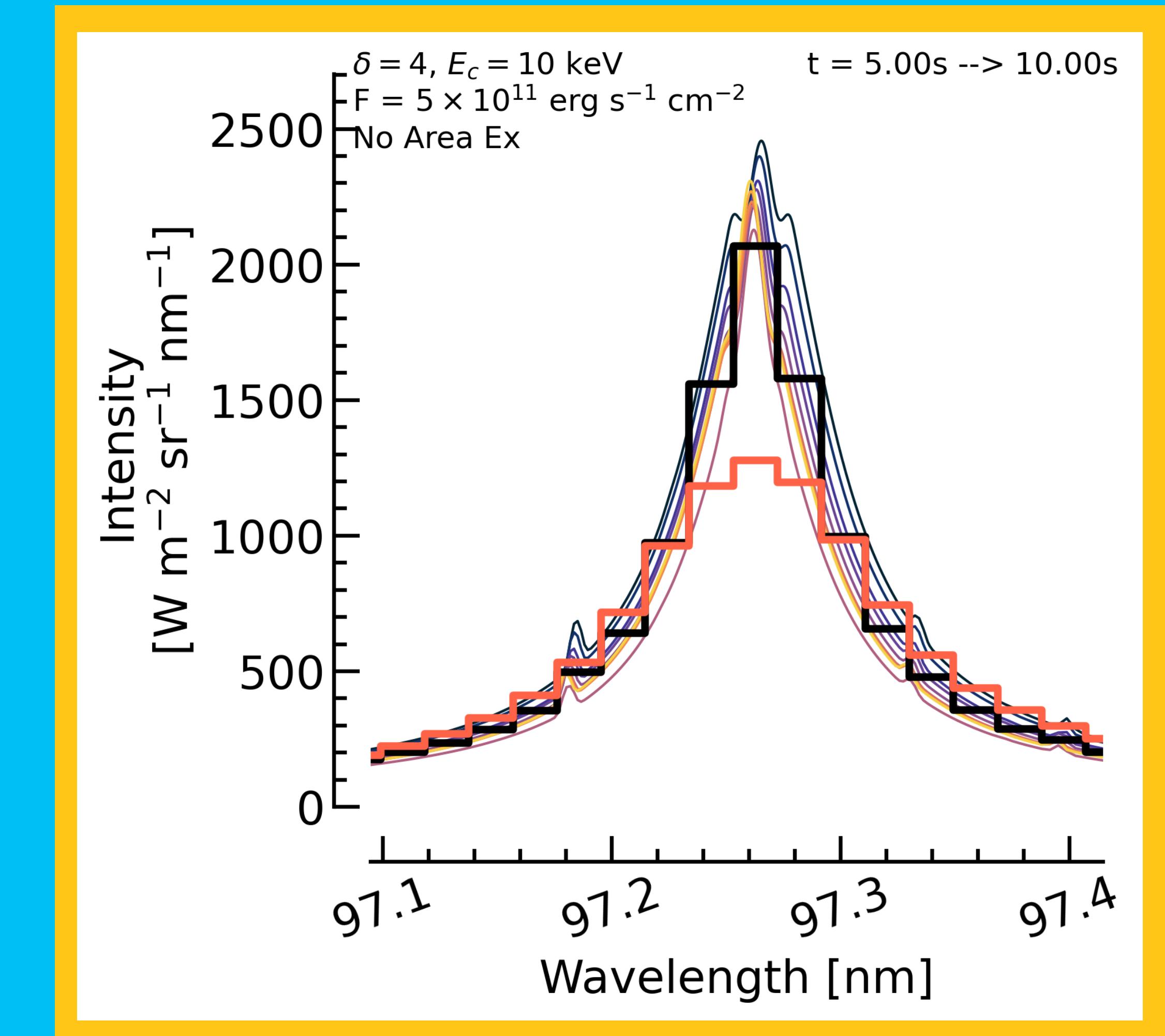
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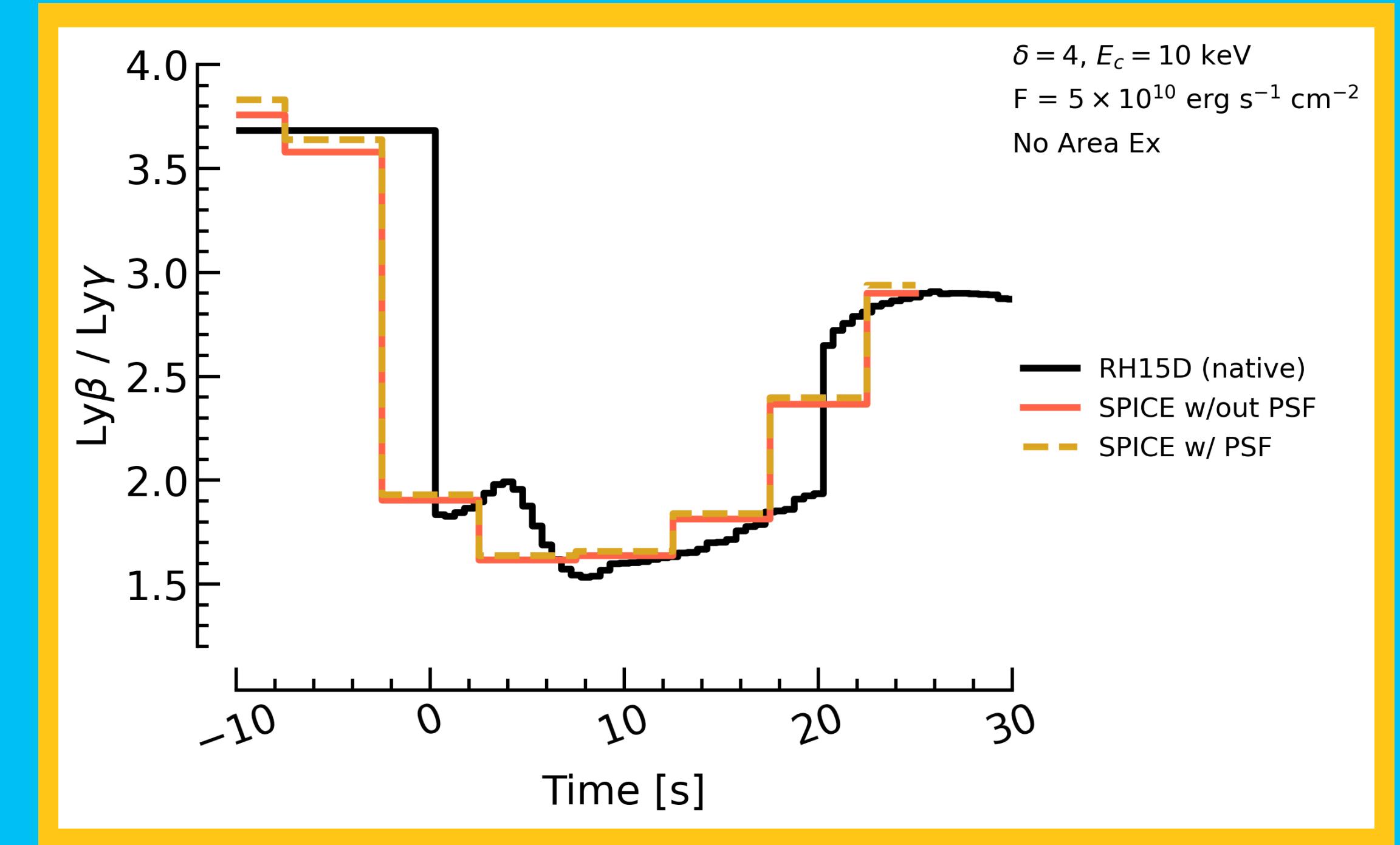
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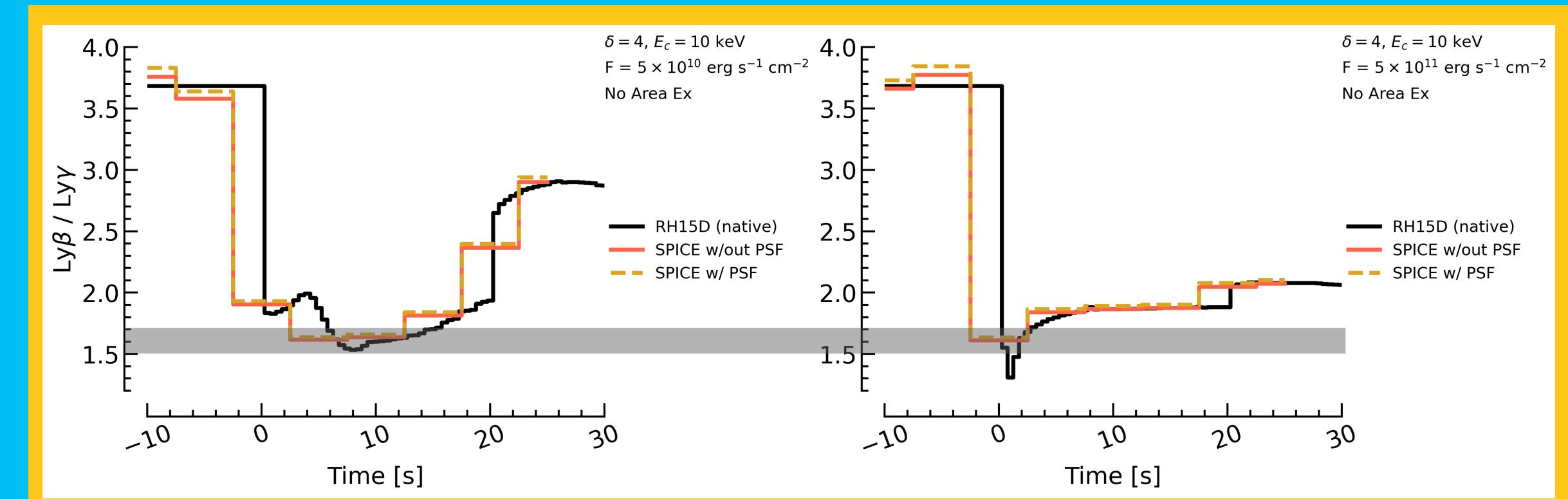
- Electron beam models produce Lyman decrements that are mostly consistent with observations!
- They are transient, and have similar values.
- Importantly, the pre-flare ratio is too high in our models, indicating that the pre-flare atmosphere isn't ideal.
- Can track atmospheric properties to see what this might mean... early indications suggest the lines form closer together and at similar temperature/electron density.



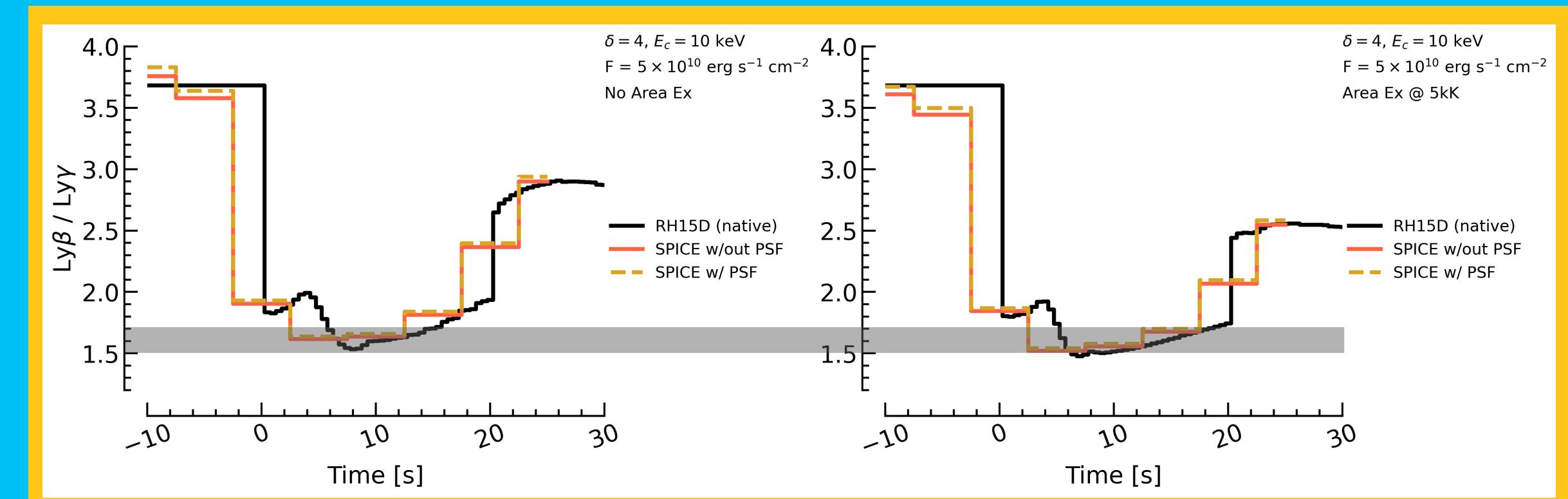
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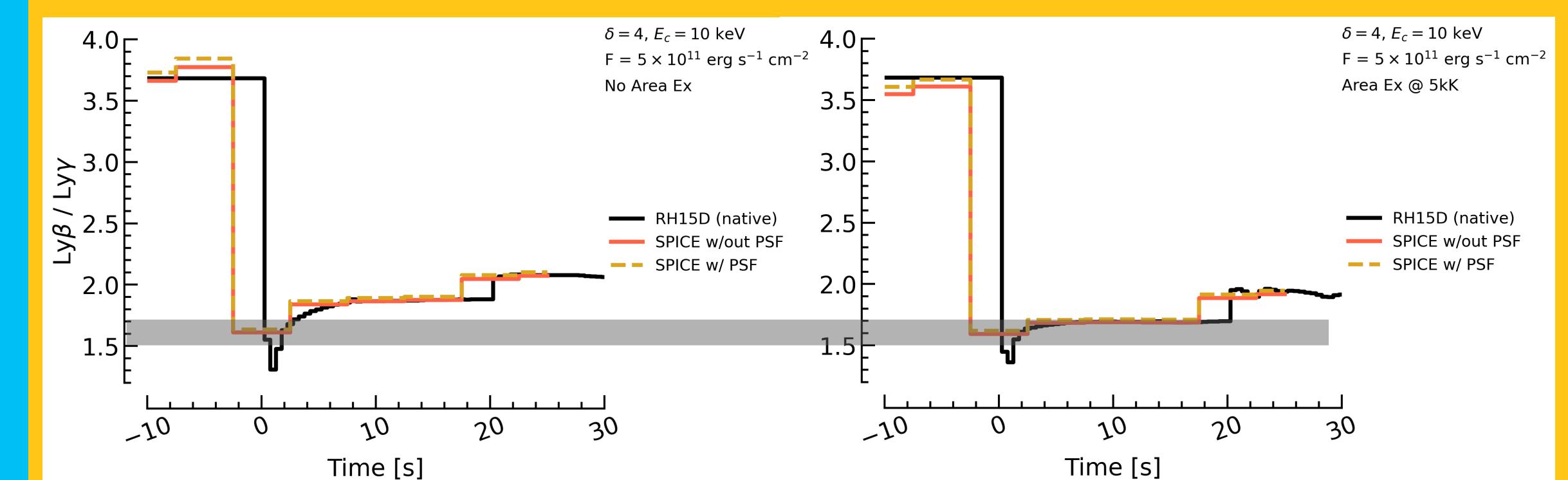
Moderate flare (left) and strong flare (right), both w/out area expansion



Moderate flare without (left) and with (right) area expansion

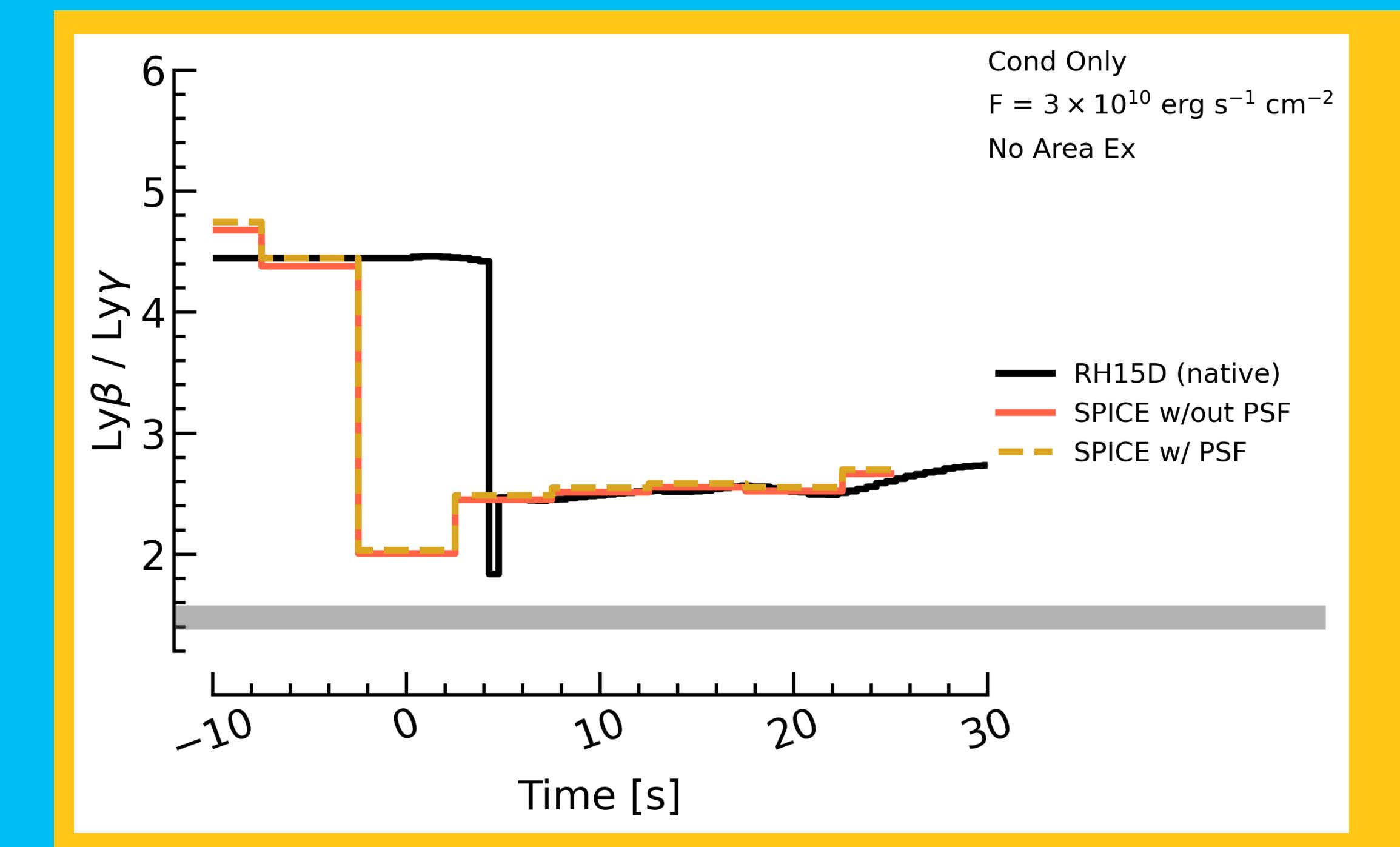


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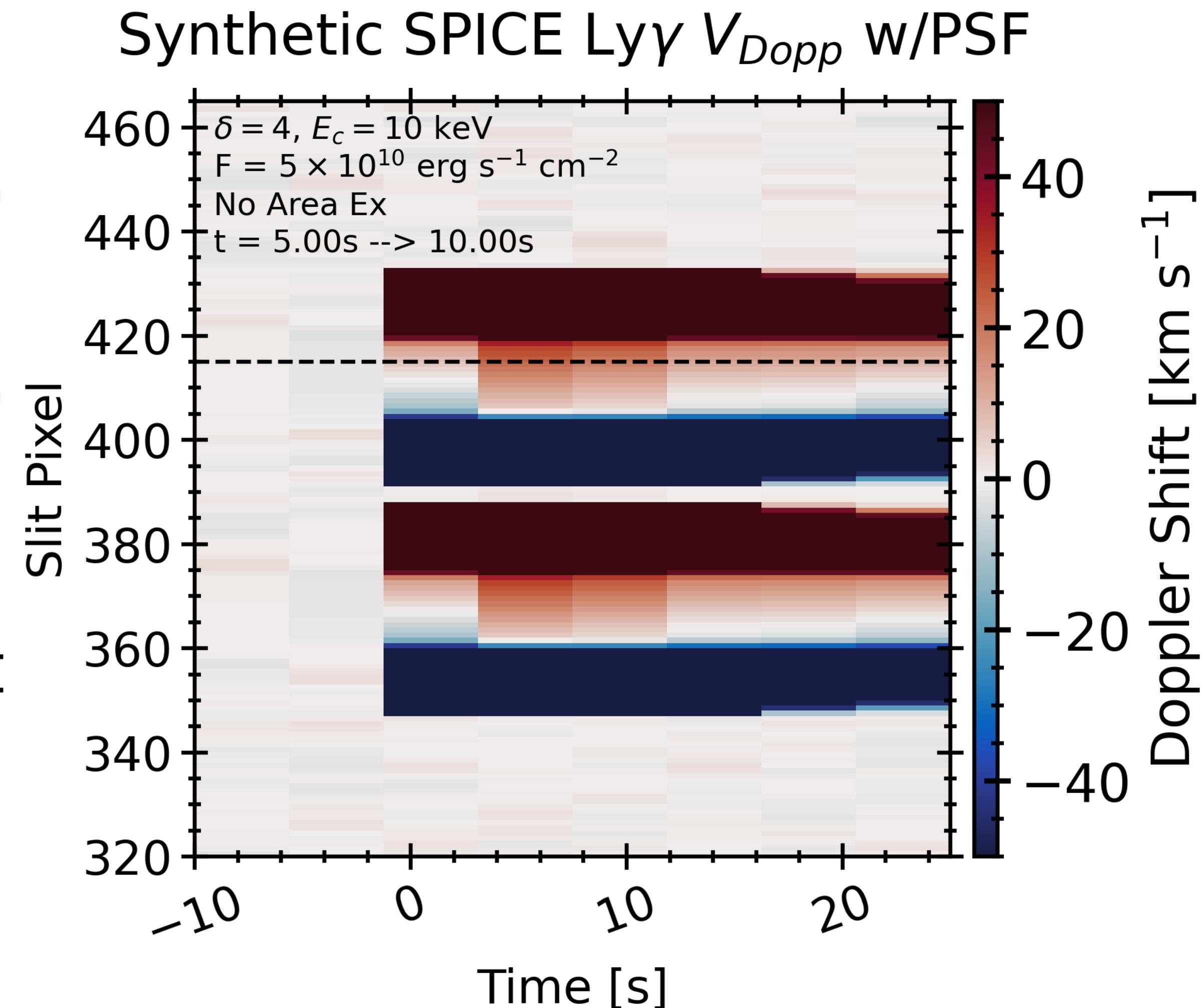
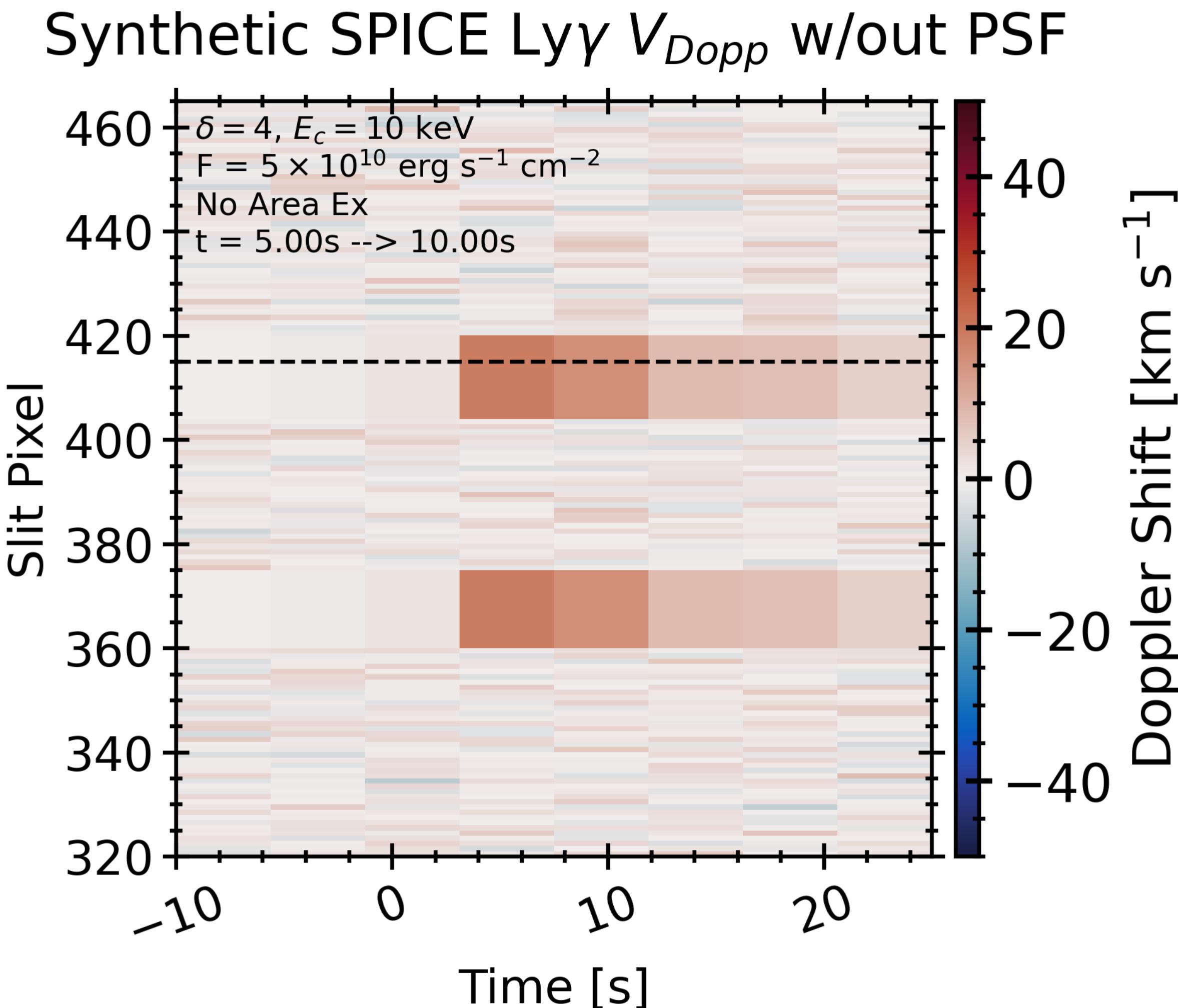


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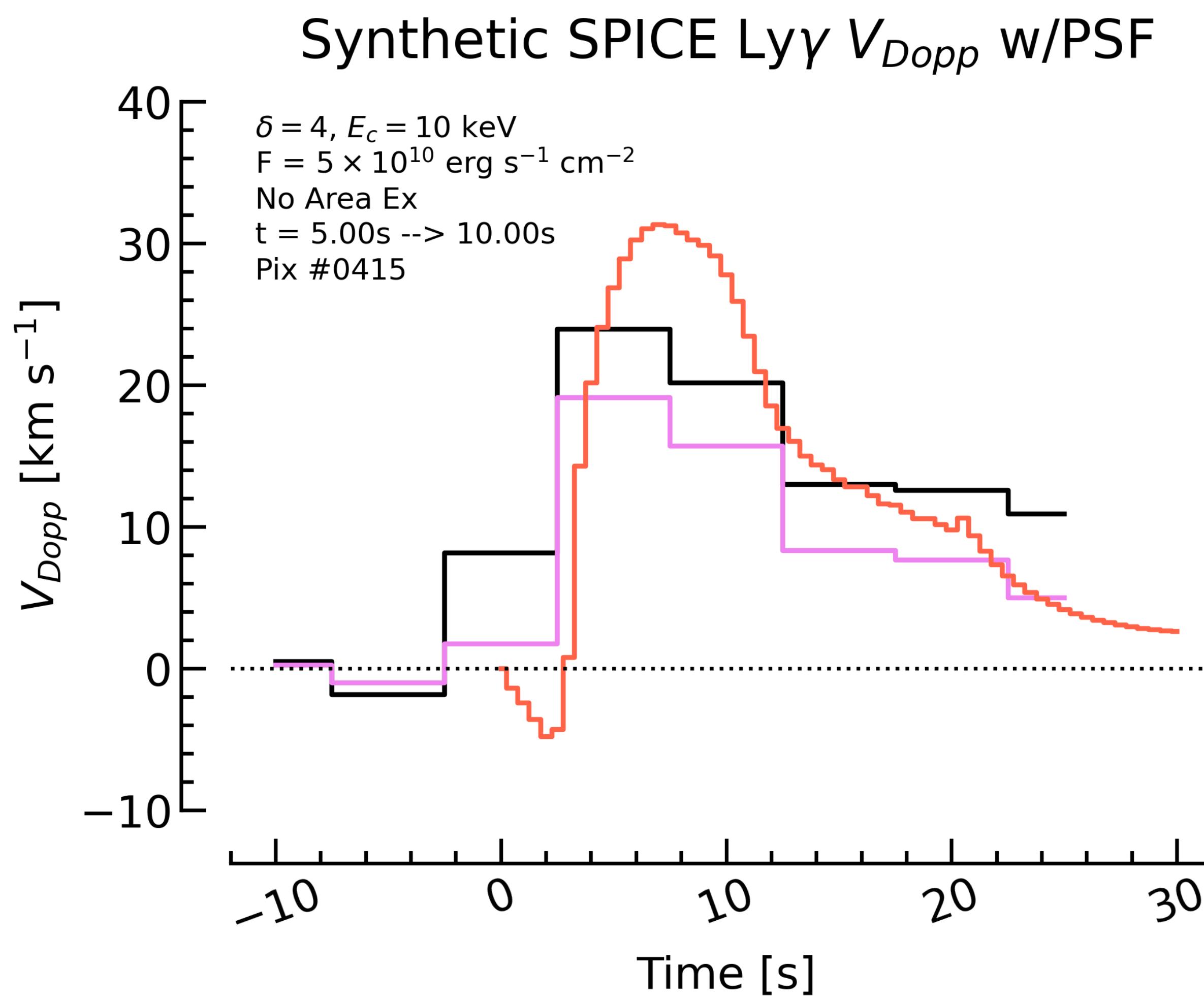
- Thermal conduction models *do not* show a deep enough decrease in the ratio.
- Perhaps this means that the stronger ribbon is primarily non thermal electron-beam driven and the lower is not.
- Could be related to lack of non thermal collisional excitation ... more work needed.



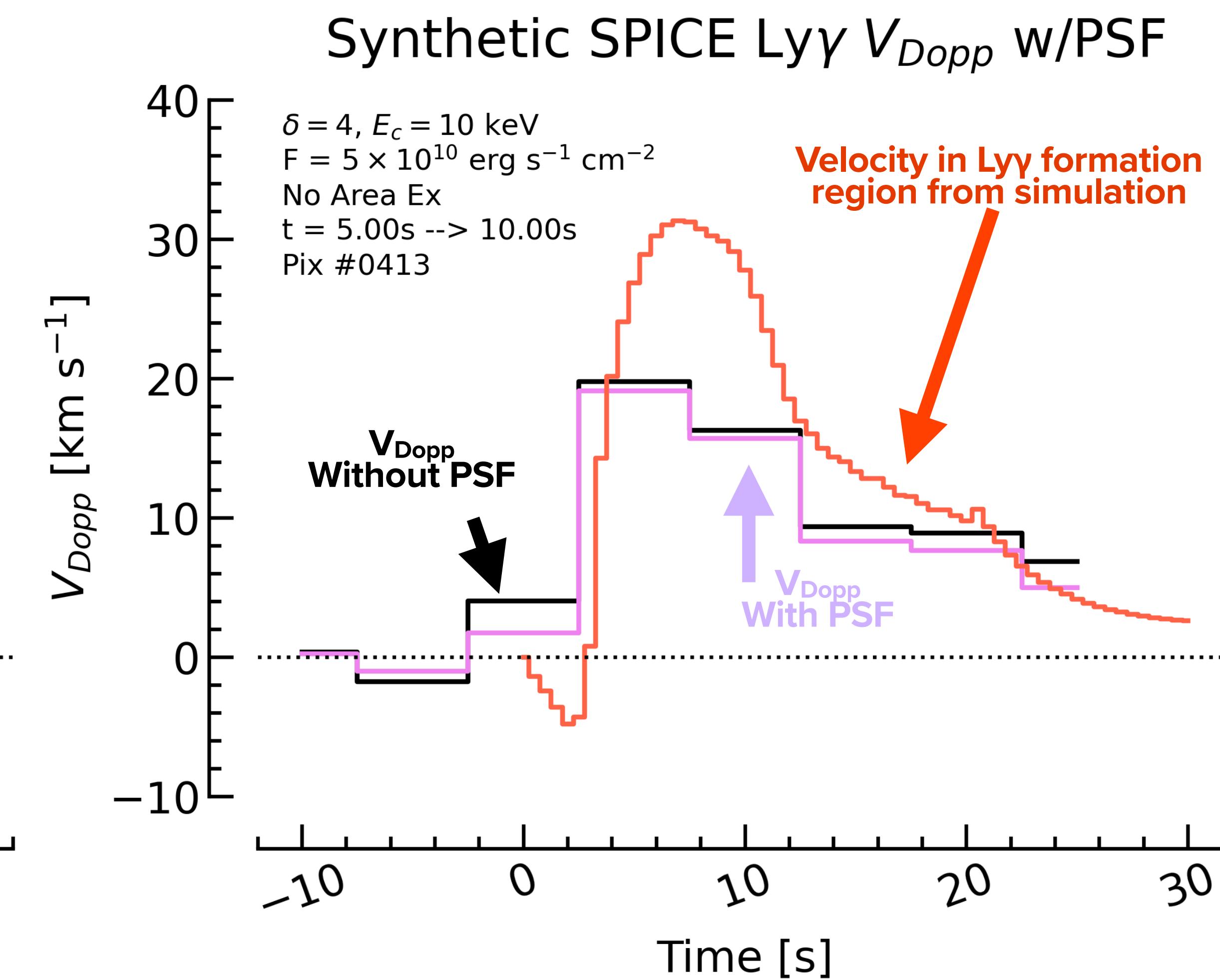
# THE PSF AFFECTS THE DOPPLER MOTIONS A LOT! ... ONLY CENTRAL PORTION OF SOURCE IS UNAFFECTED.



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Pixel from edge of flare source



Pixel from middle of flare source

# SUMMARY

- Overview of SPICE observations of the 23rd March 2024 23:46UT M2.5 flare.
- Preliminary observational analysis:
  - ➔ No obvious Orrall-Zirker effect;
  - ➔ High cadence observations of a compact source;
  - ➔ Ly $\beta$  / Ly $\gamma$  ratio shows transient decrease;
- Preliminary RHD modelling of the event:
  - ➔ 12 electron beam simulations — heating upper chromosphere, or lower atmosphere, two different flare strengths;
  - ➔ 1 thermal conduction only simulation;
  - ➔ Synthesized Ly $\beta$  and Ly $\gamma$  lines, and studied formation properties;
  - ➔ Produced synthetic SPICE slit, including PSF;
  - ➔ Lyman decrement consistent with observations only in electron beam scenario, but observations miss structure in lightcurves;
  - ➔ Doppler motions strongly affected by PSF, but a slice through middle of source is sufficiently free of artifacts

Main takeaway — really nice high cadence observations of the EUV flare spectrum, but could go to higher cadence!