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

# LYMAN LINE DECREMENT DURING SOLAR FLARES

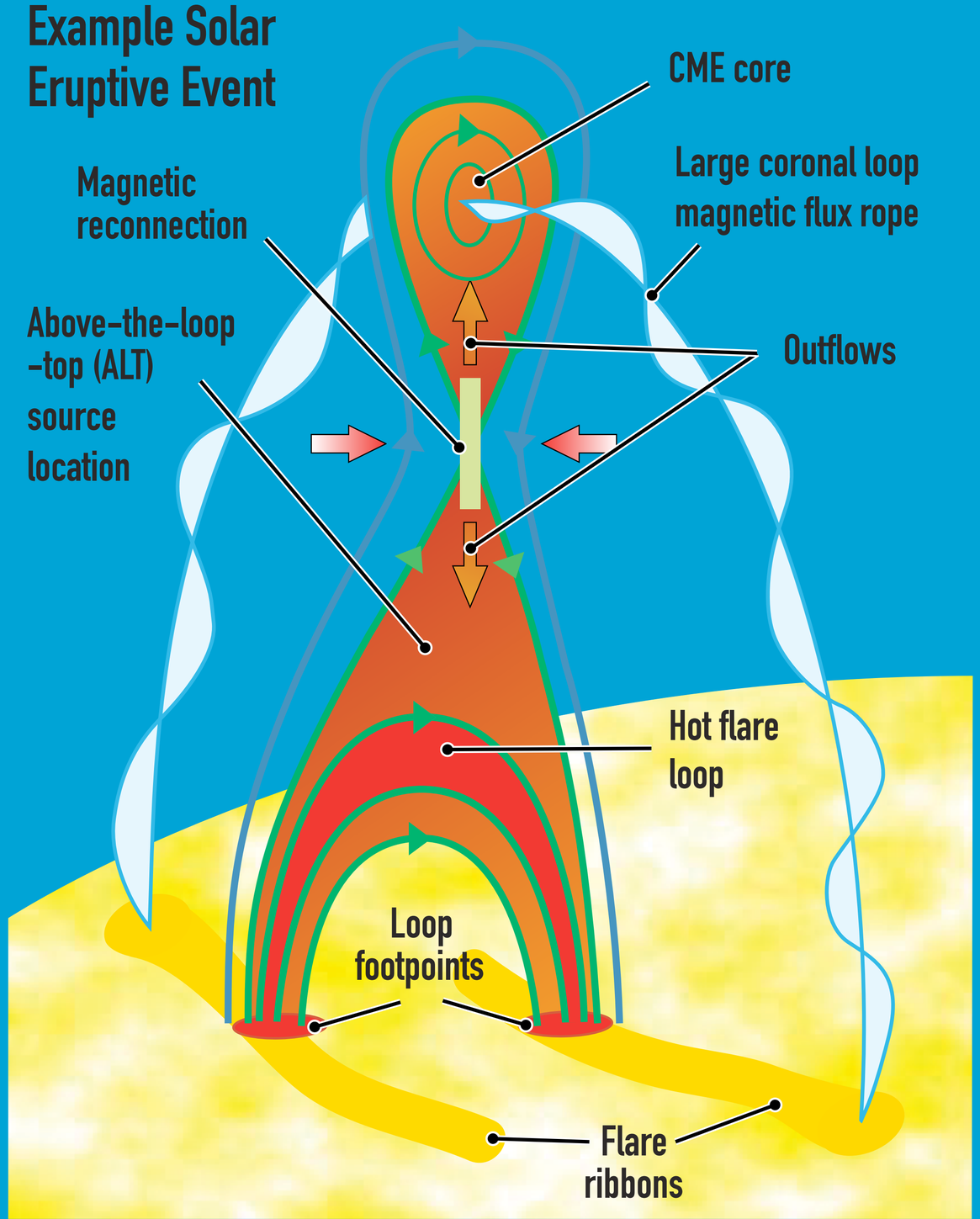
*A Model-data comparison between RHD models and Solar Orbiter SPICE observations*

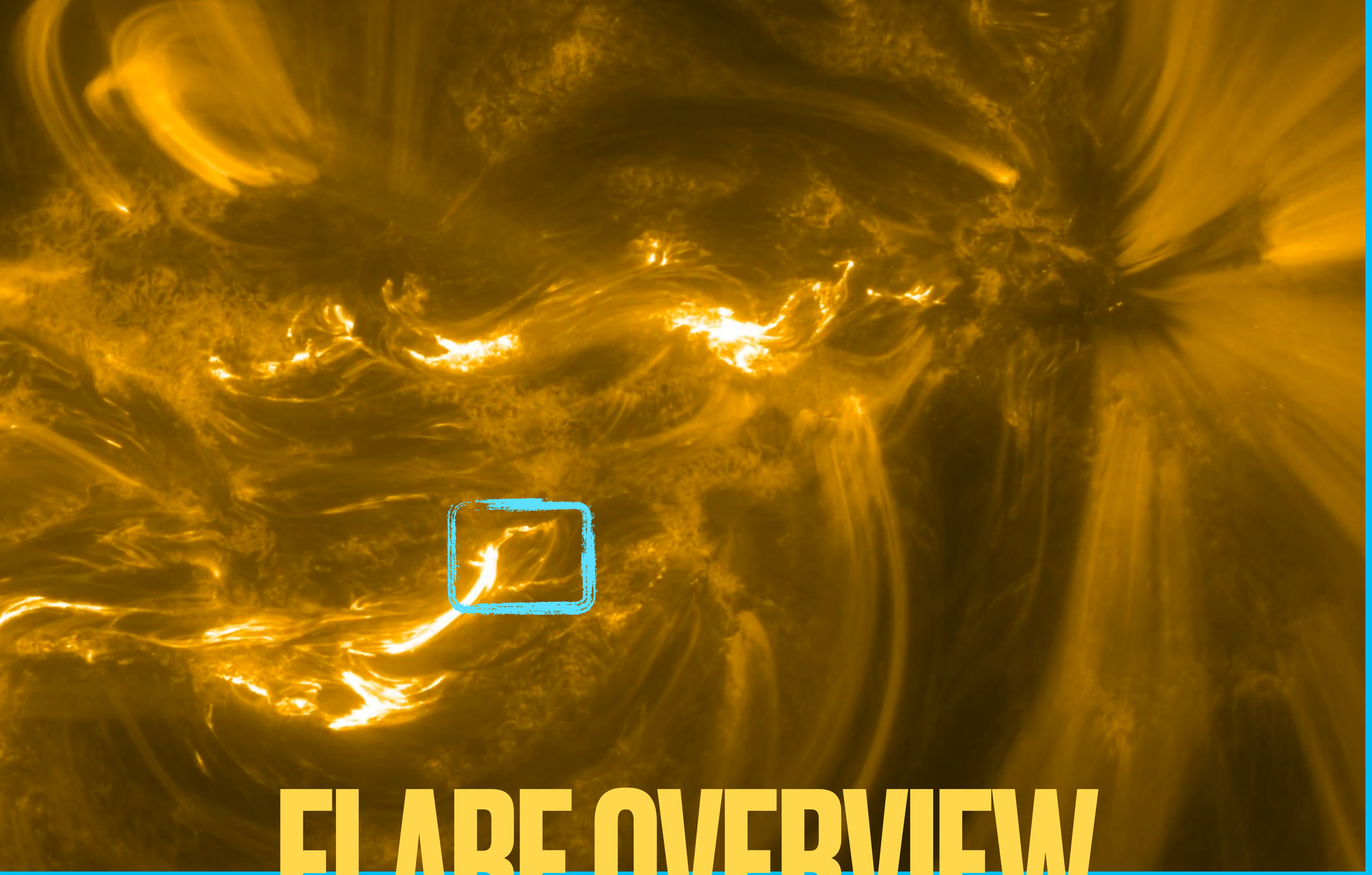
# OUTLINE

- 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;
  - ➡Lyβ / Lyγ 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 Lyβ and Lyγ 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





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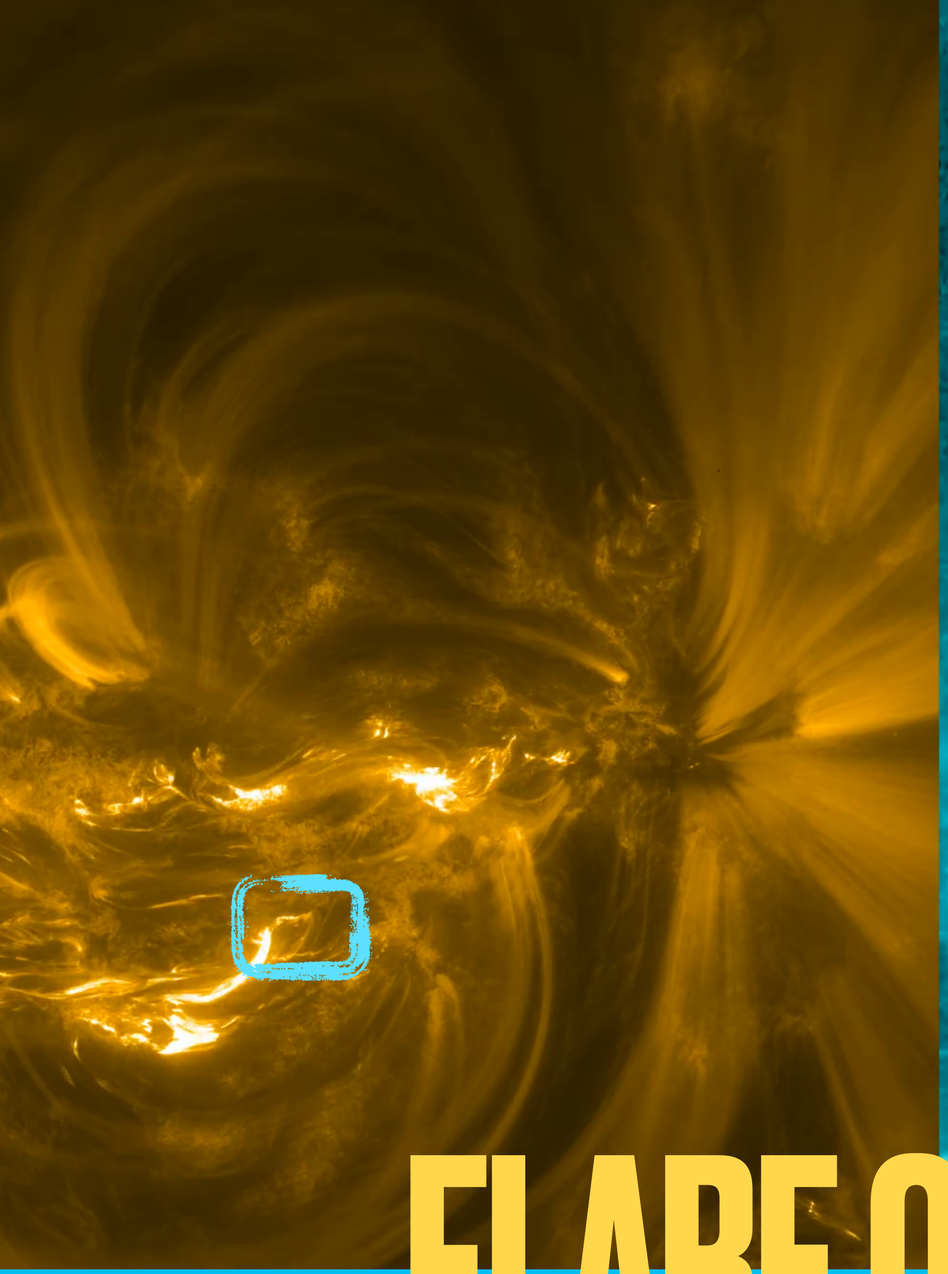

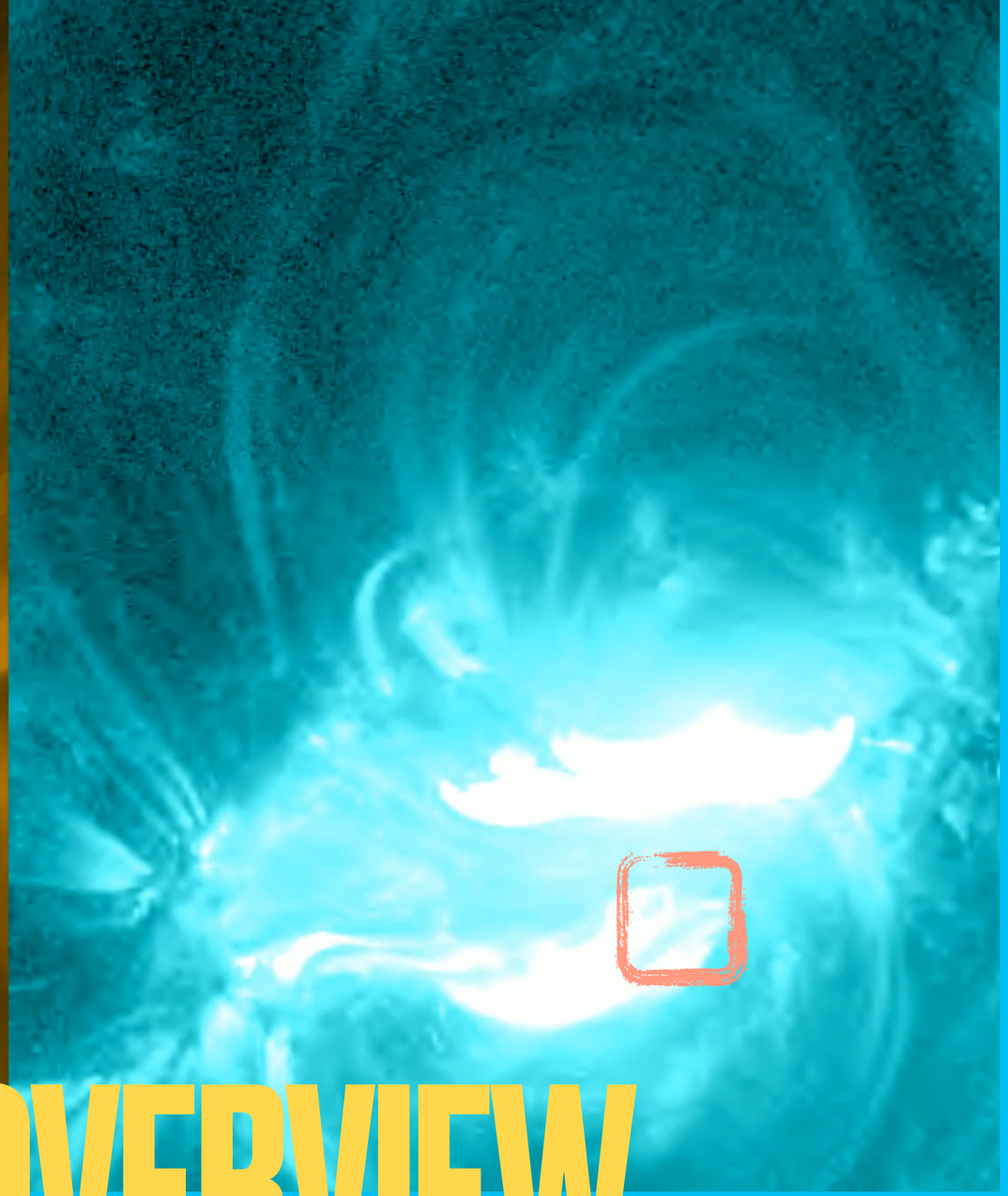

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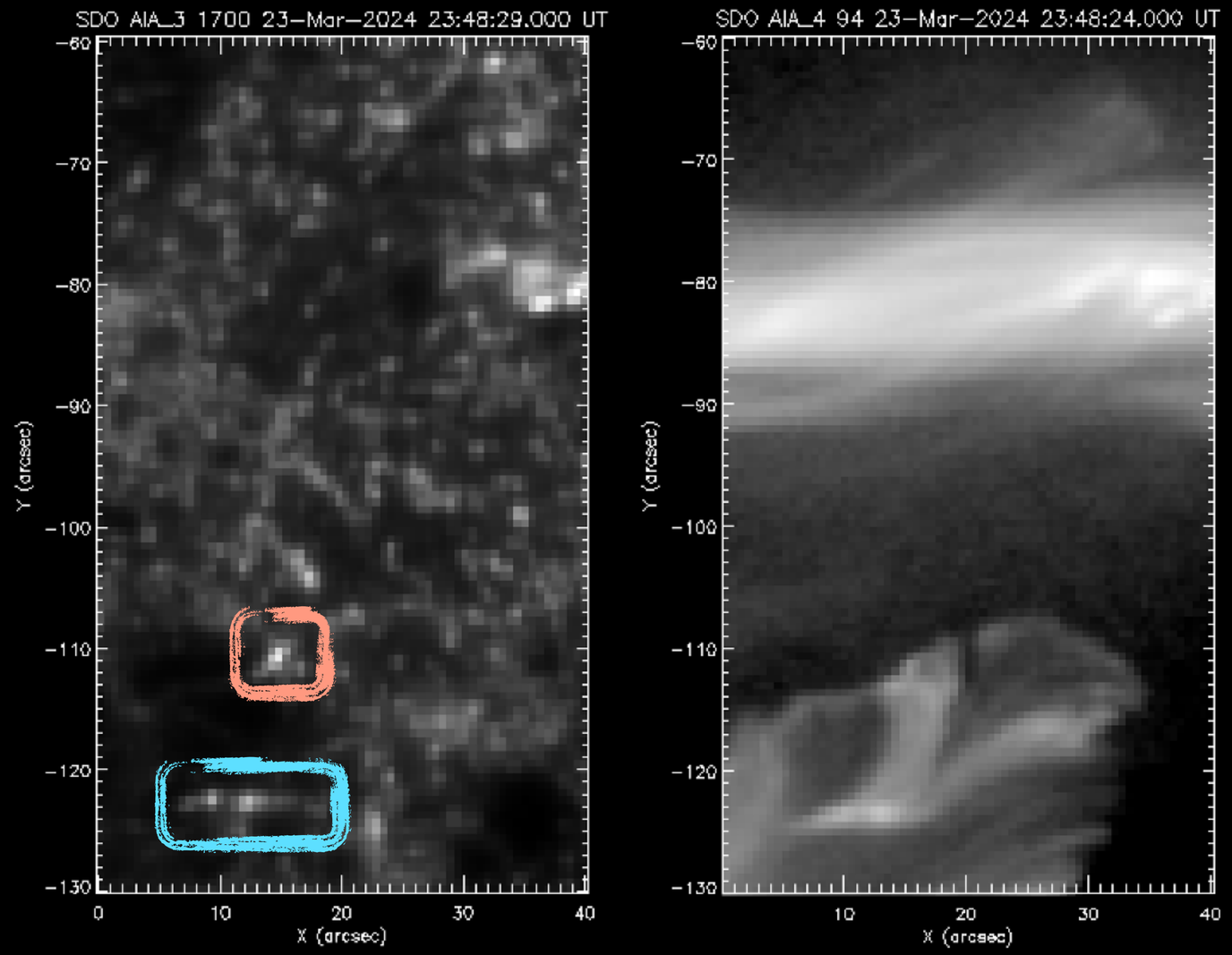


Intense compact source.

Weaker extended ribbon

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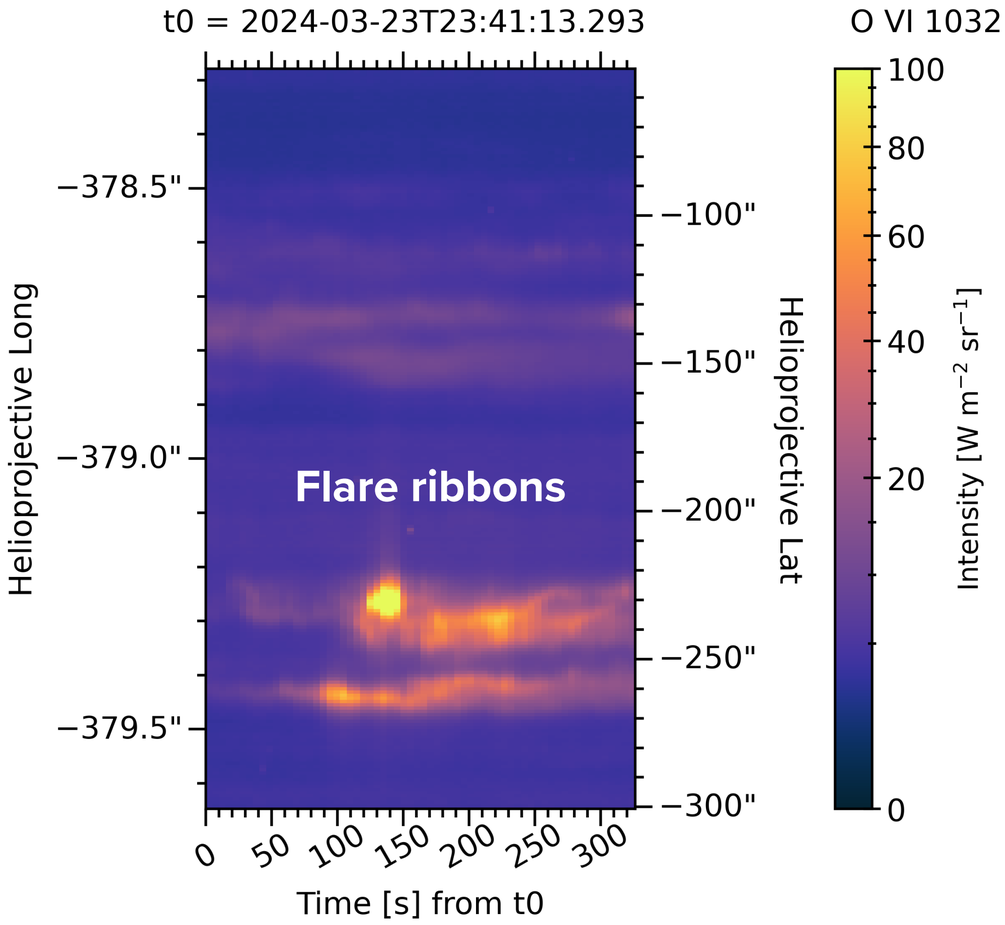


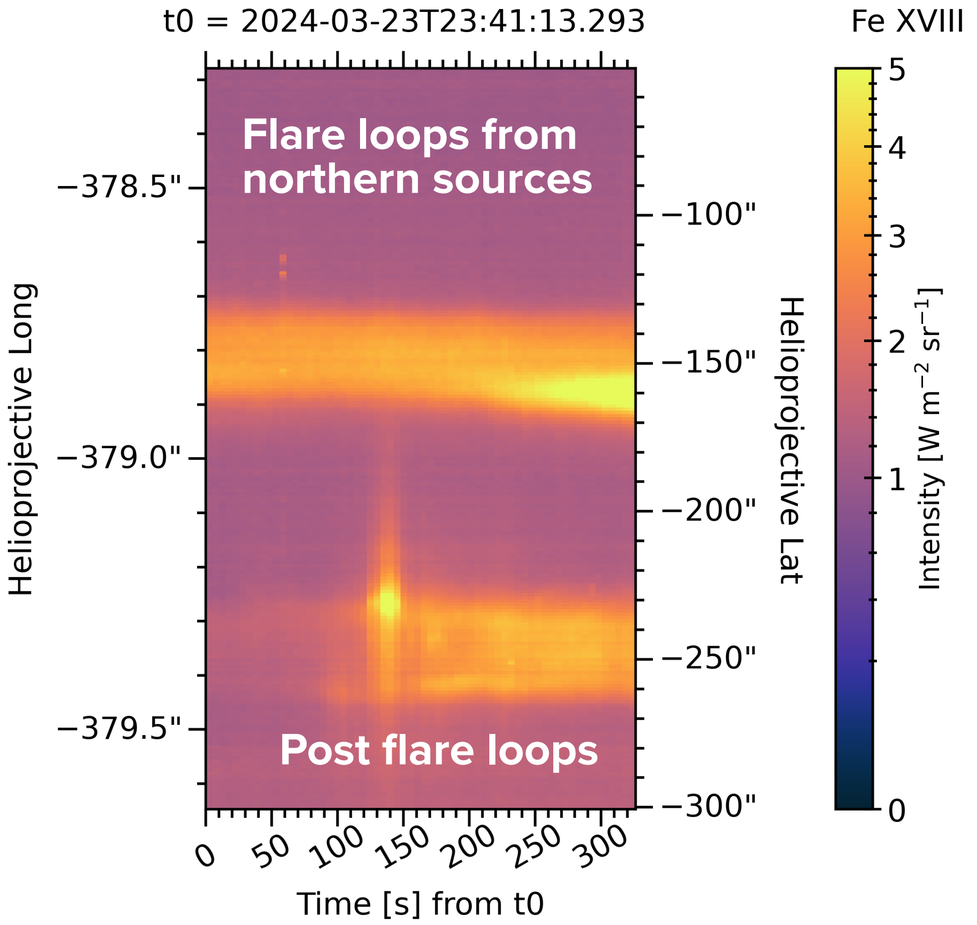


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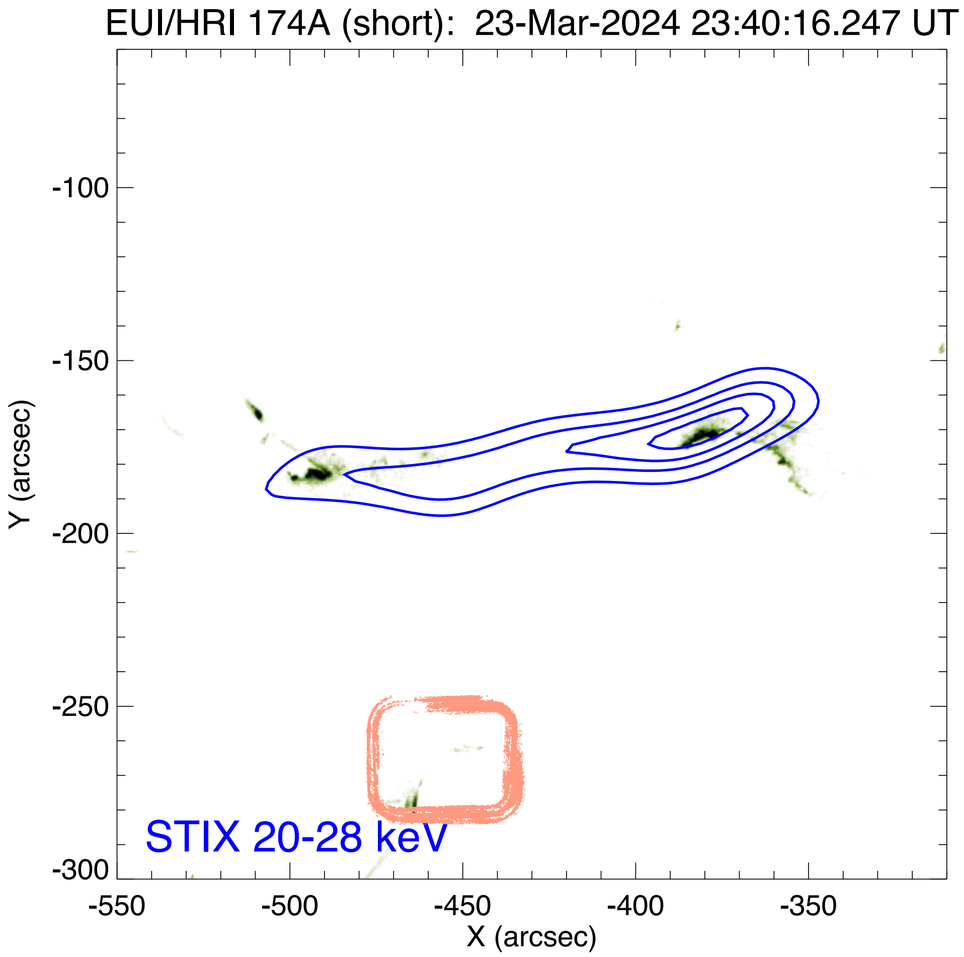
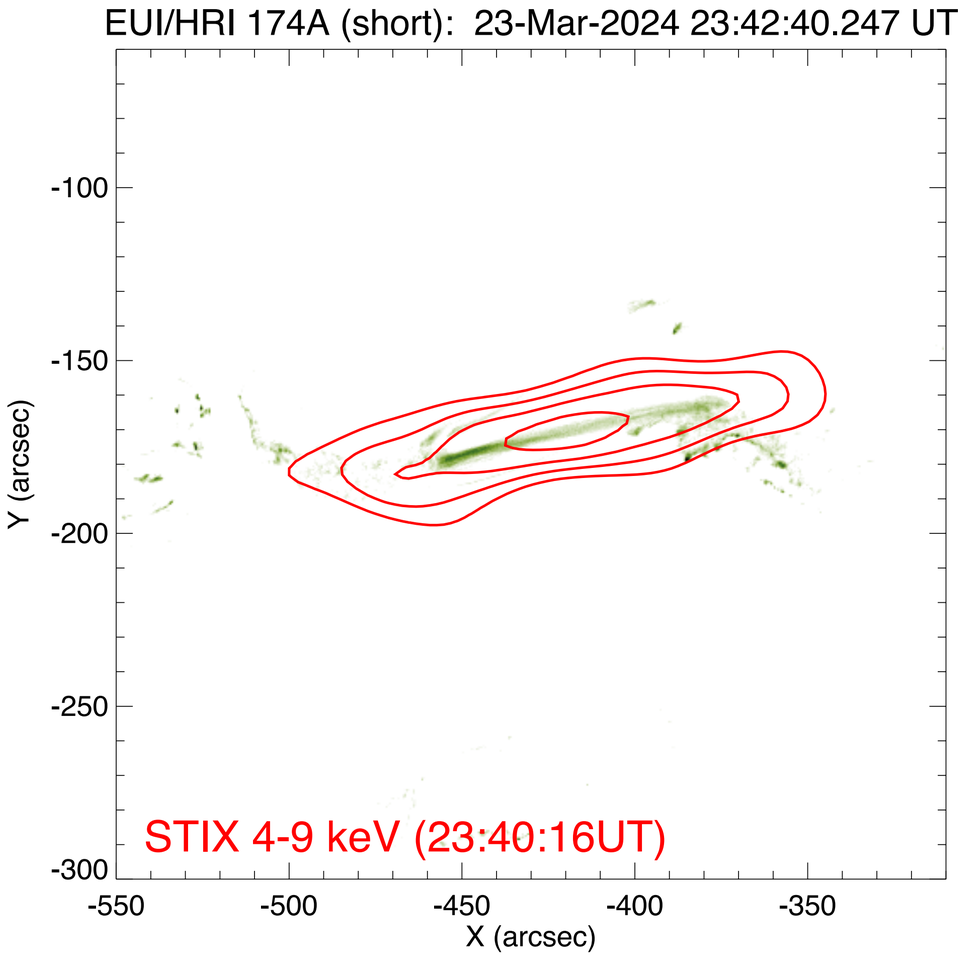
* STIX Imaging by Säm Krucker and Dan Ryan

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

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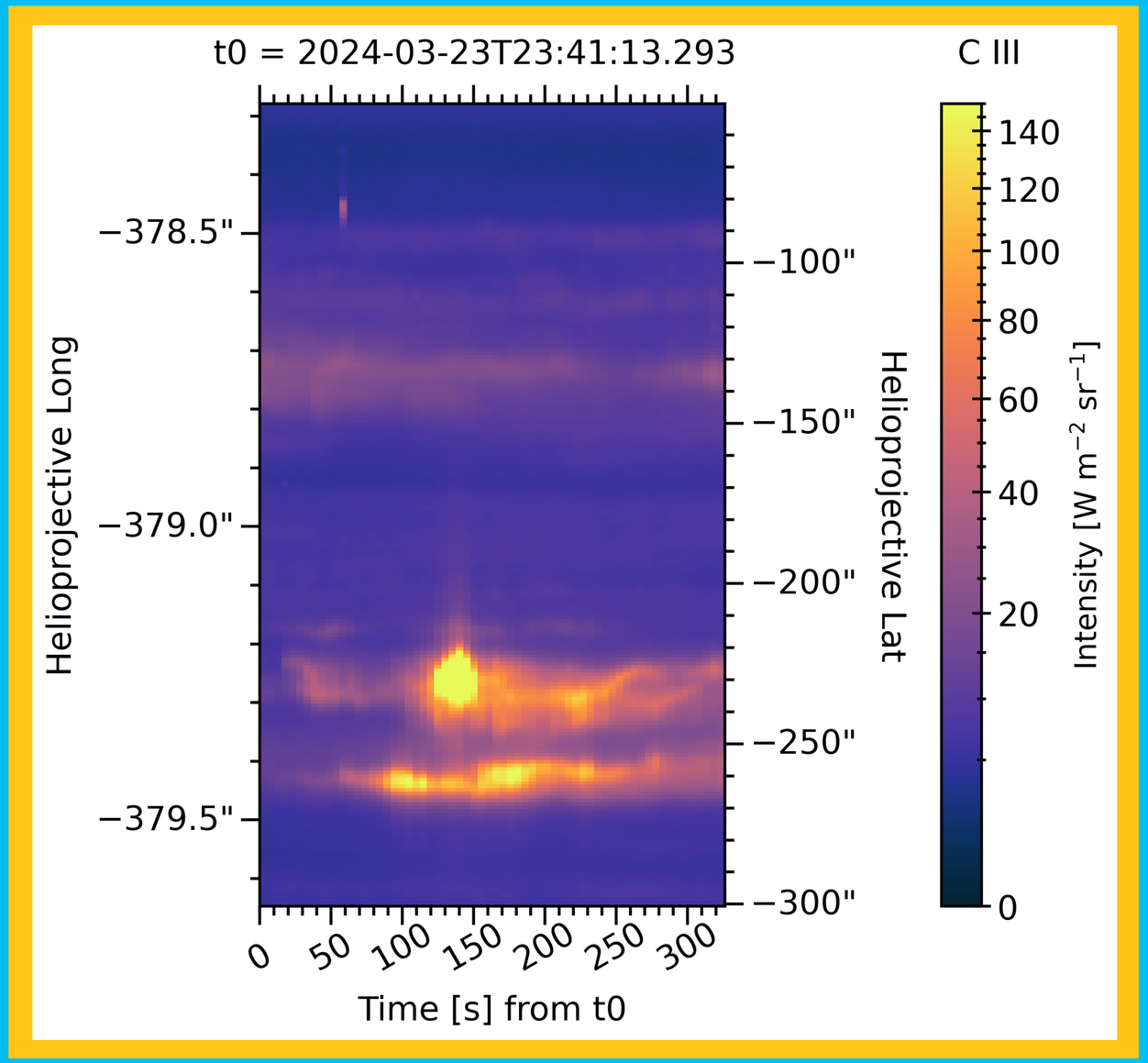
# OVERVIEW OF THE SPICE OBSERVATIONS

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

# SPECTRAL LINE LIST

- Many spectral lines were observed
  - **C III ~97.7nm**
  - Fe XVIII ~97.5nm
  - Fe XX ~72.1nm
  - Lyγ & Lyβ
  - Ne VIII ~77.0nm
  - N IV ~76.5nm
  - O II ~72.0nm
  - O III ~70.3nm
  - O VI ~103.2nm & ~103.7nm
  - … maybe SIII 101.2 — 101.6nm
- Covers a decent temperature range at 5s — one of highest cadence flare datasets.



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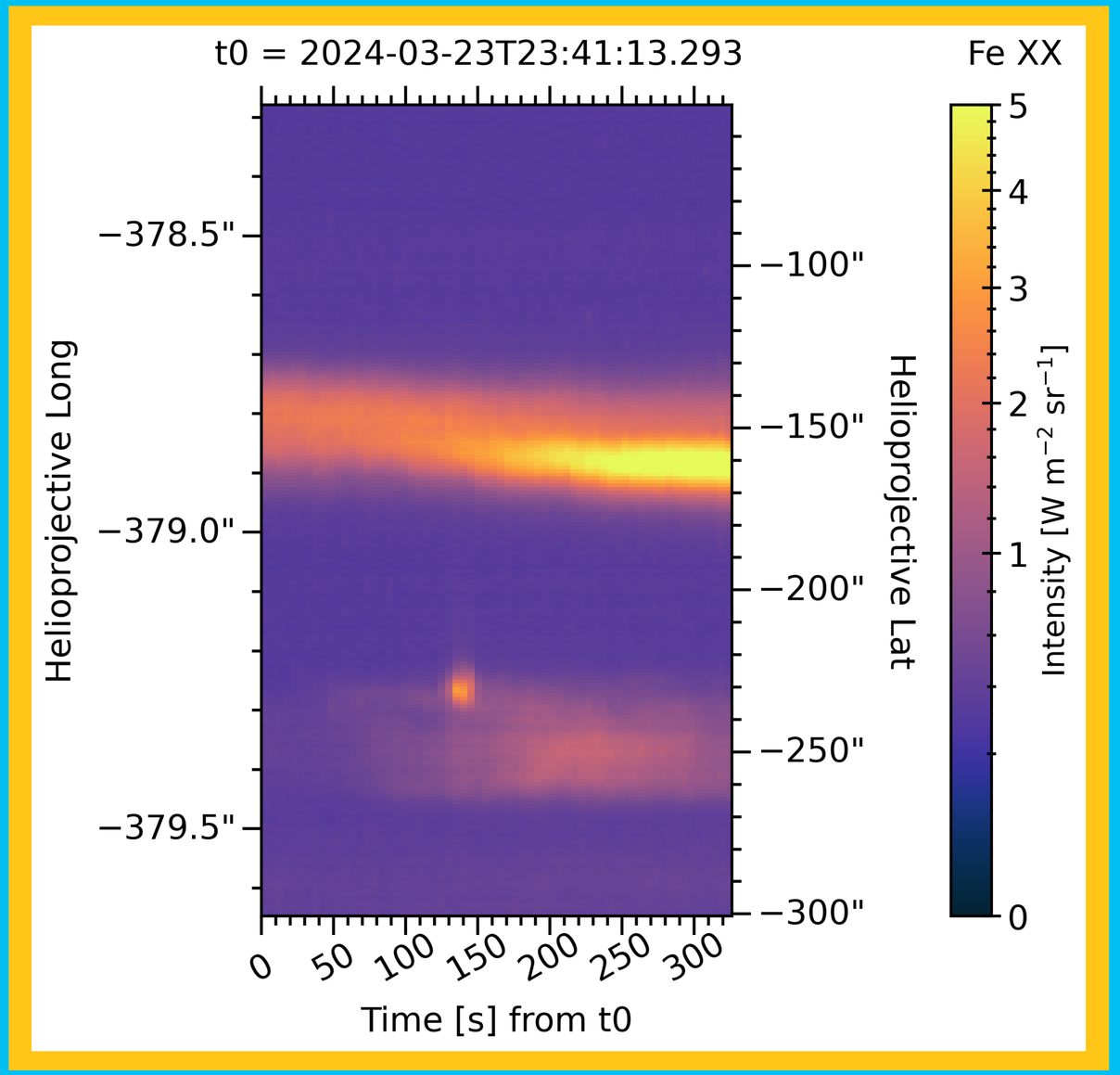

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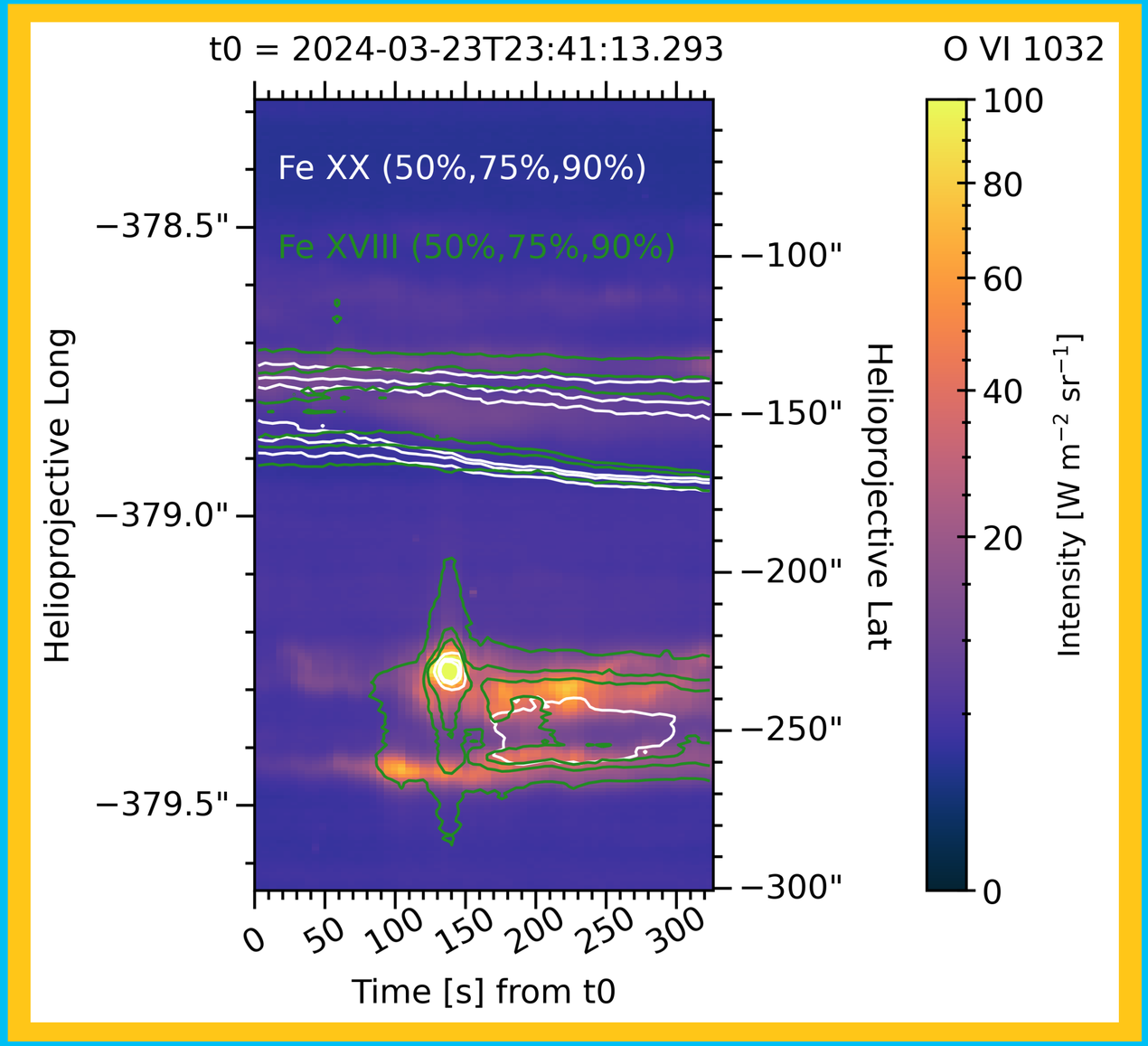

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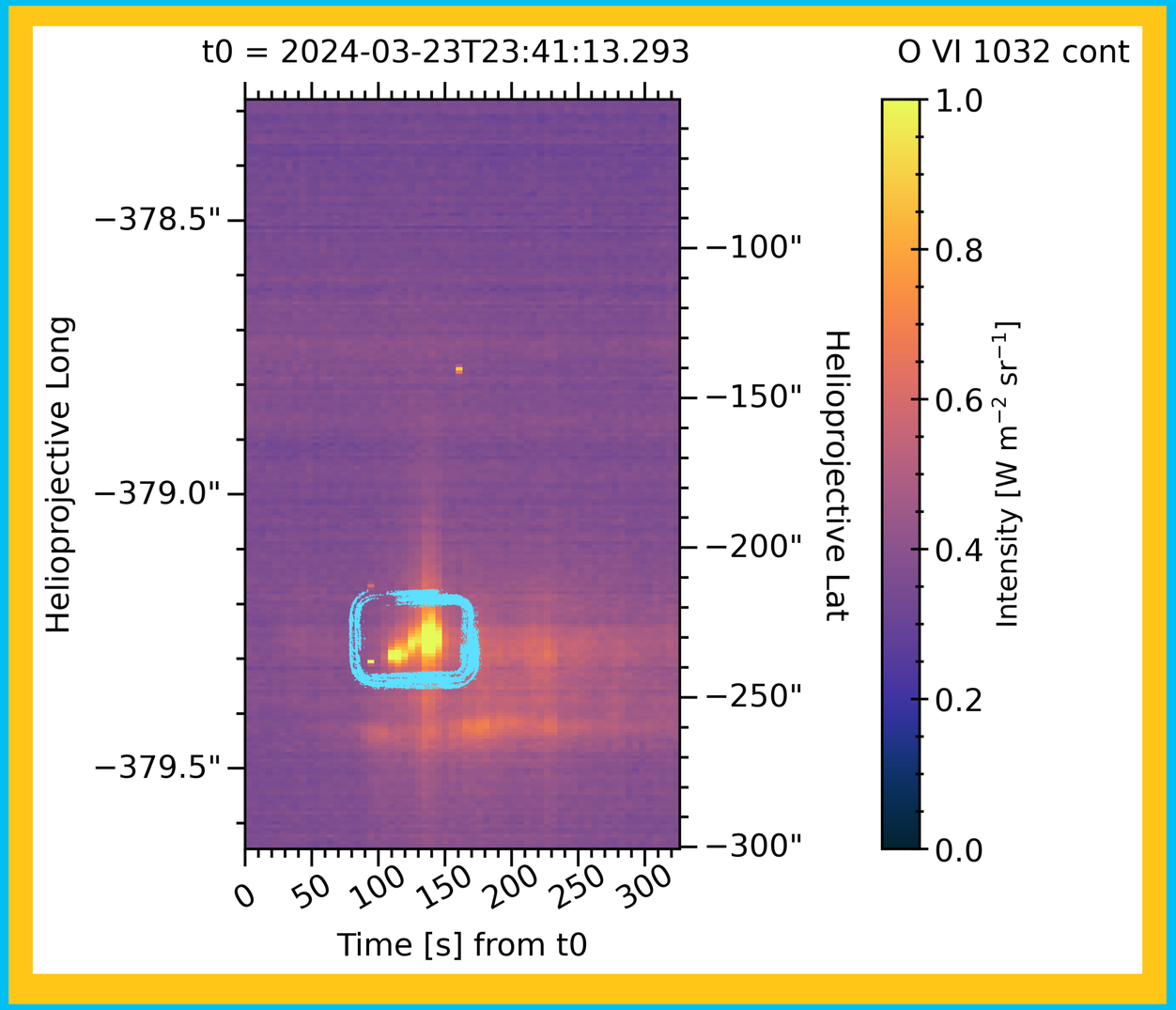
**Continuum brightens a little earlier in some locations!**



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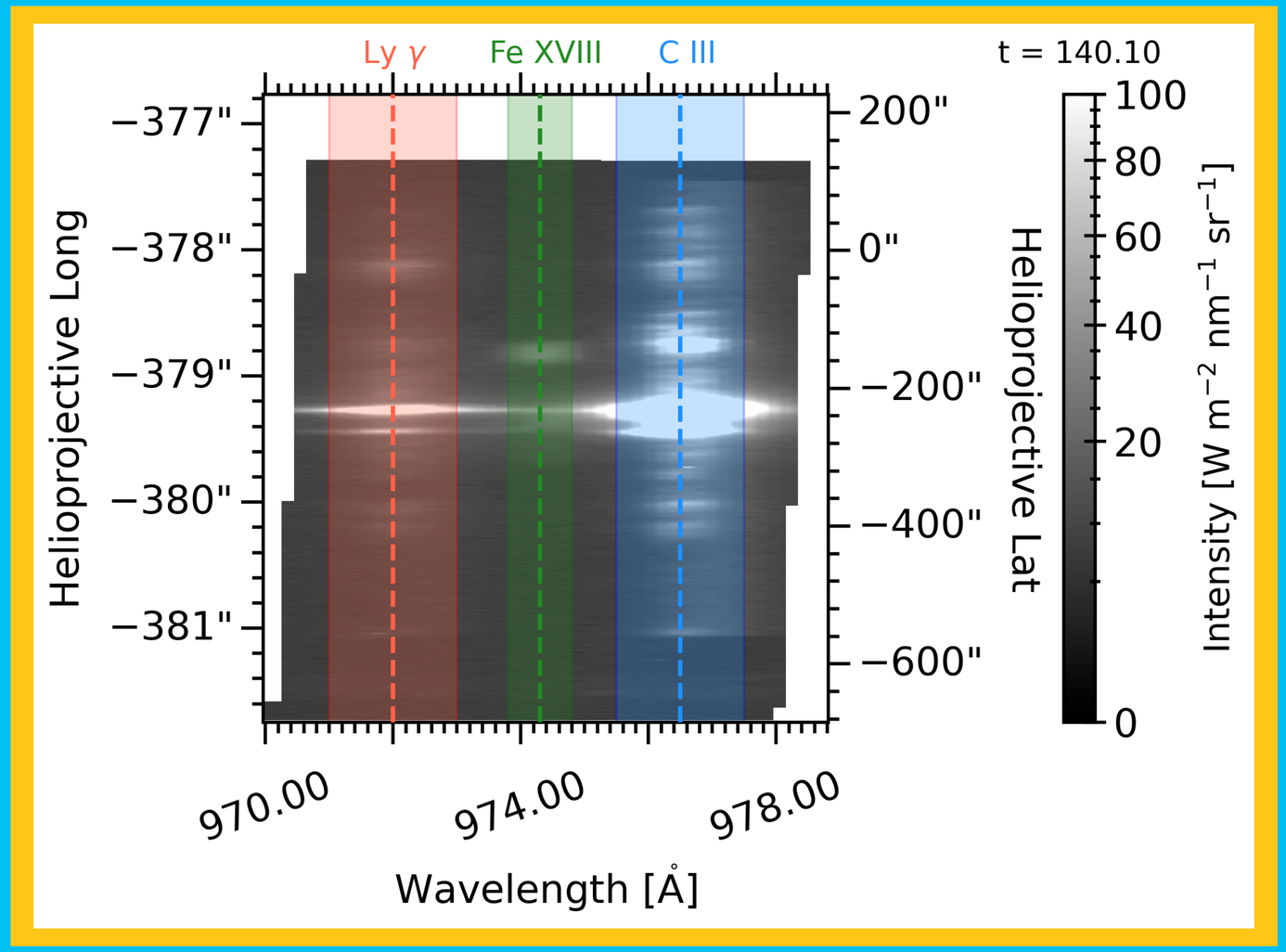

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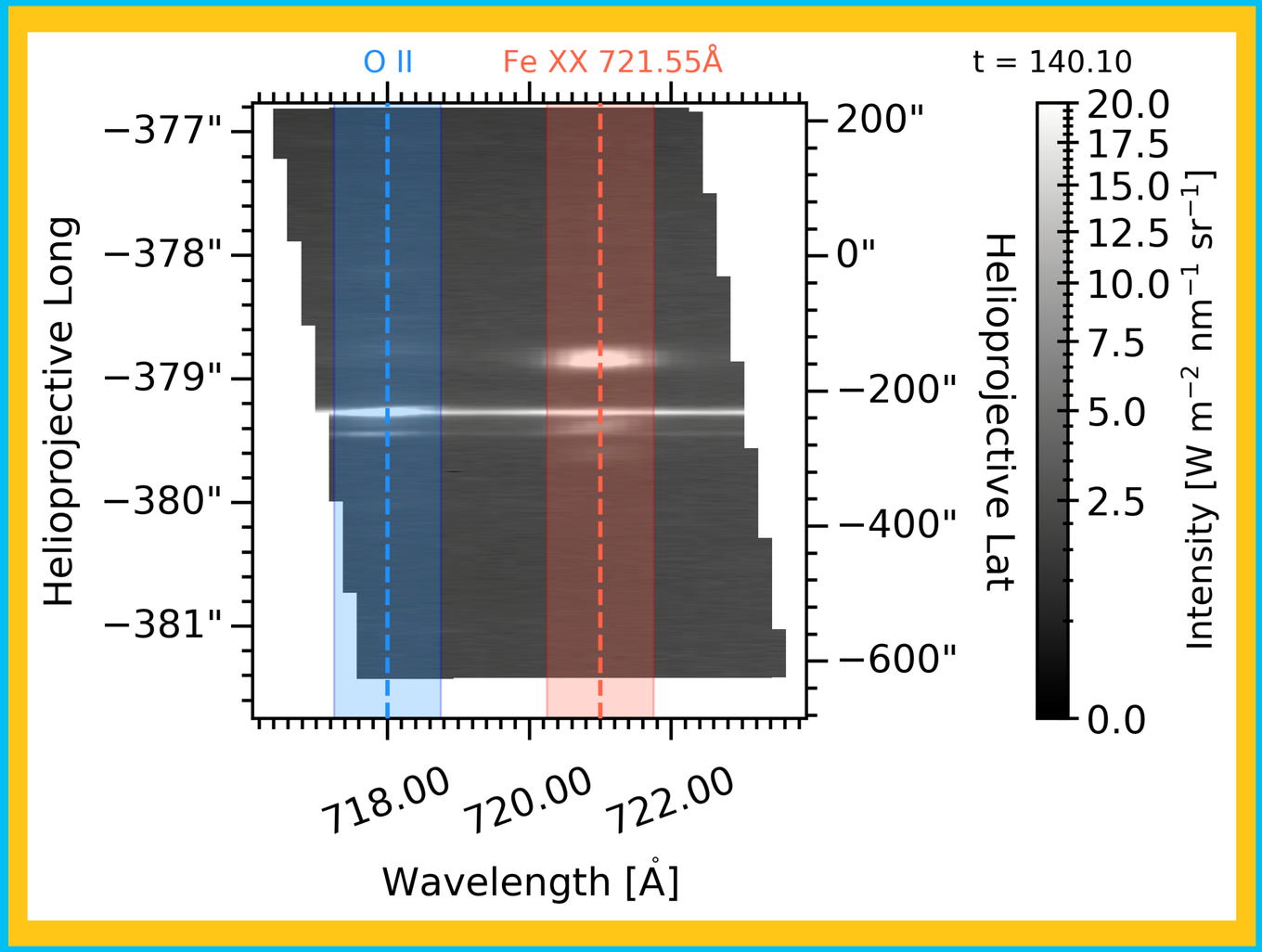
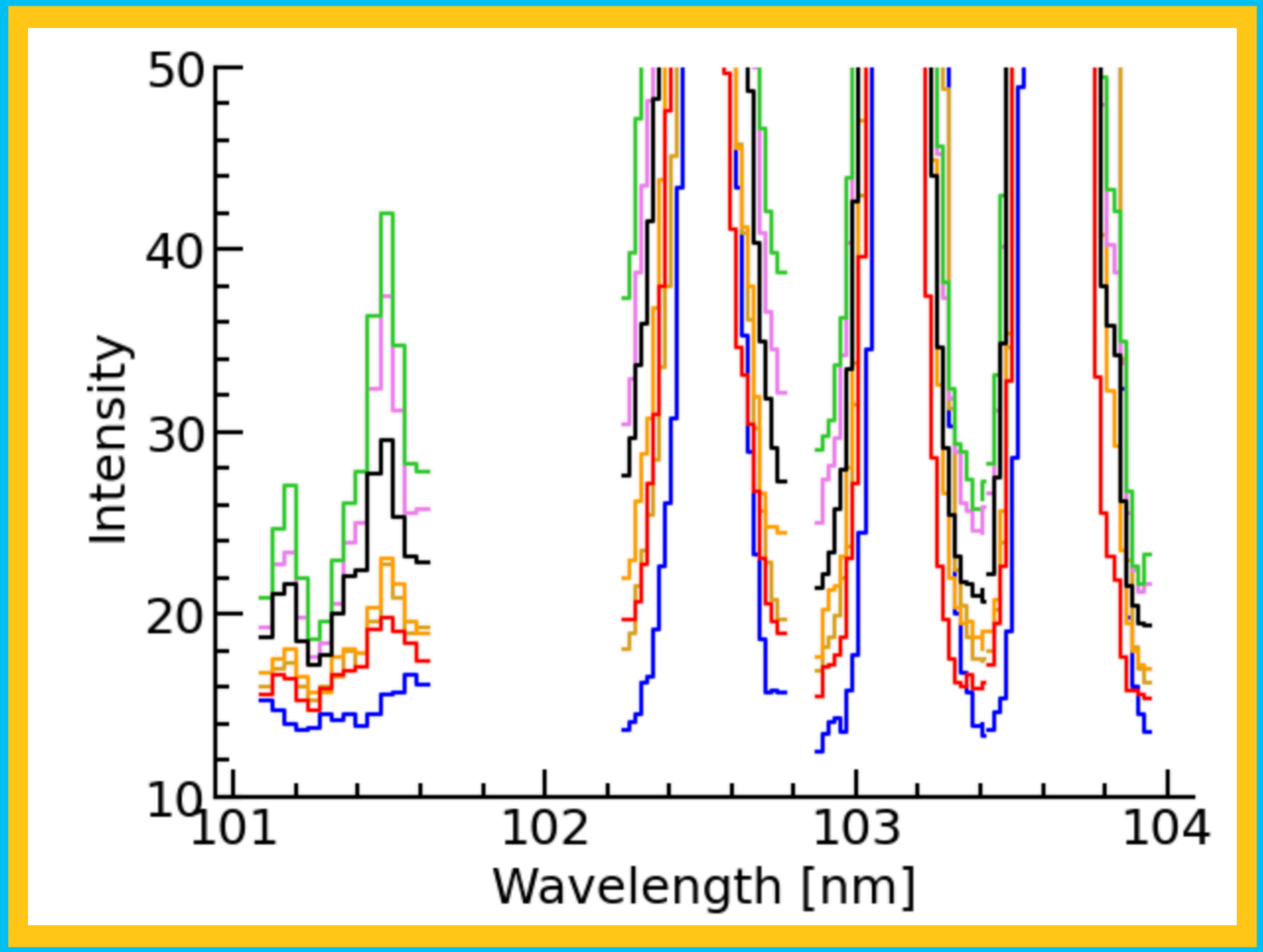


# ORRALL-ZIRKER EFFECT?

- 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 Lyβ & 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 Lyβ compared to blue.**




**S III + continuum** **Lyβ** **O VI** **O VI**

# 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.

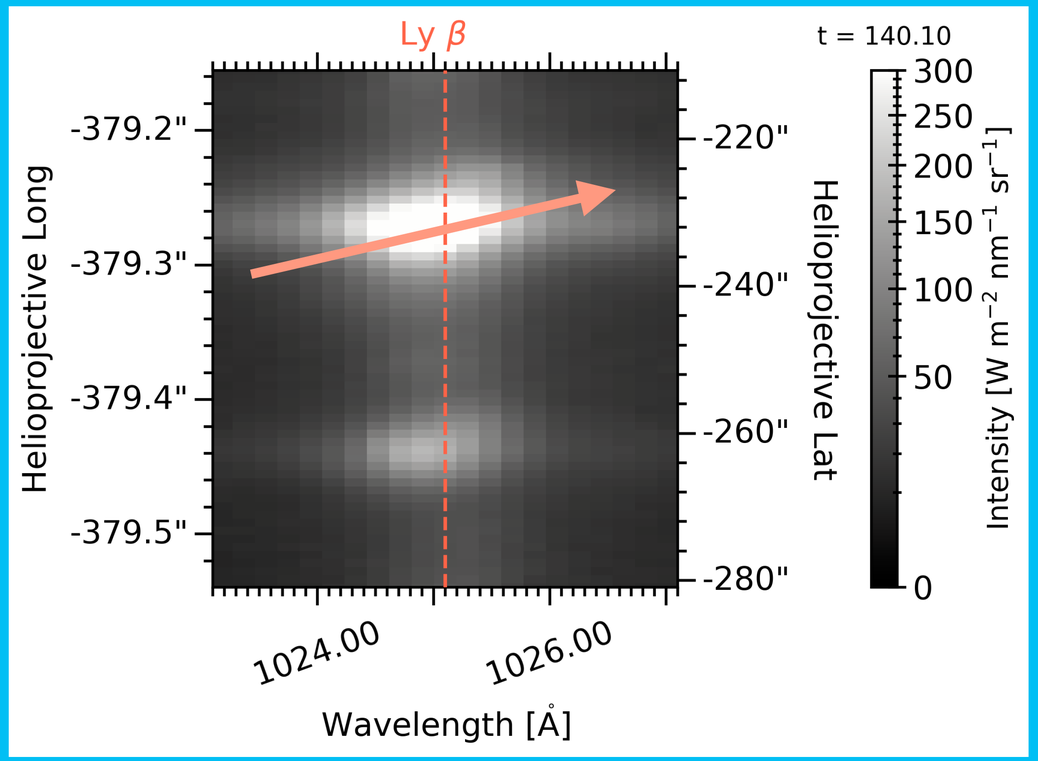
AN EASIER, BUT POTENTIALLY STILL POWERFUL, METRIC IS THE LYMAN DECREMENT.

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**

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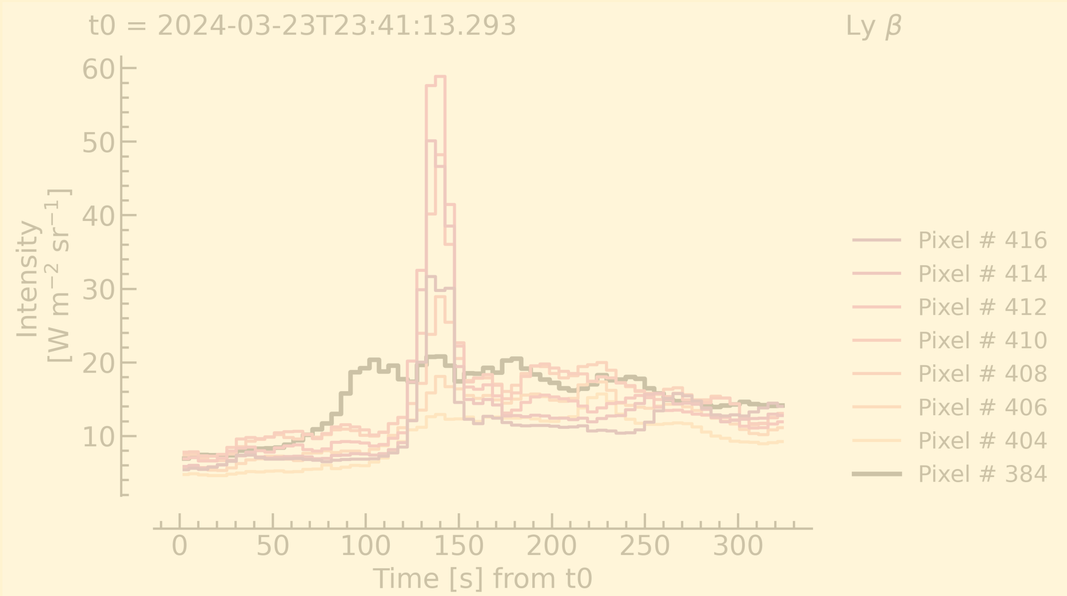
**No continuum subtraction yet either.**

# 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.

Lyγ and other lines show same.

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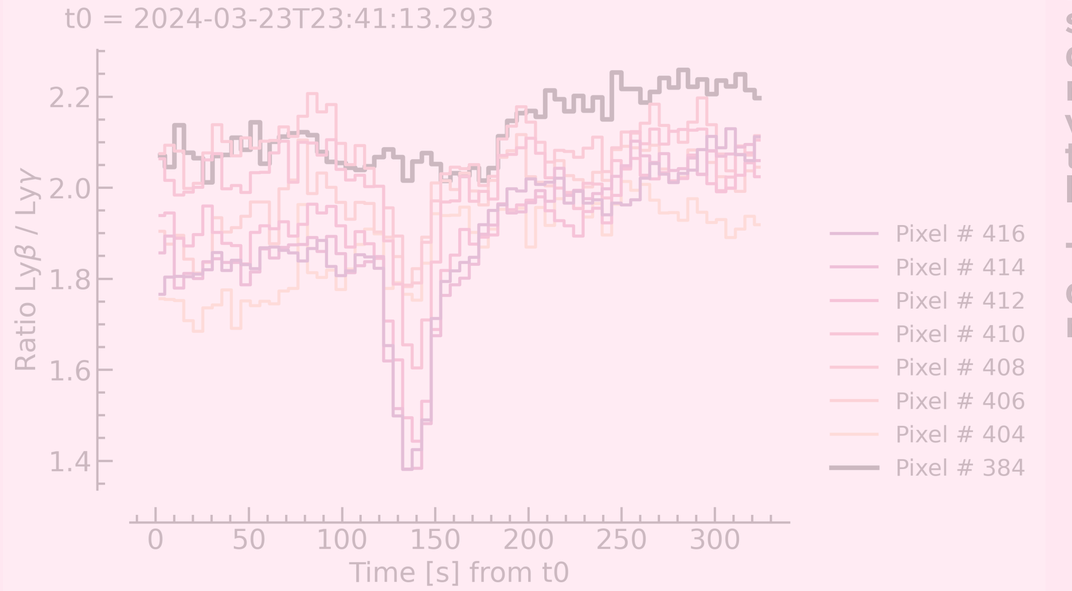


In the impulsive flare source the ratio decreases before returning to pre-flare values *faster* that the intensity of the line.

The lower source doesn't really show a meaningful change.

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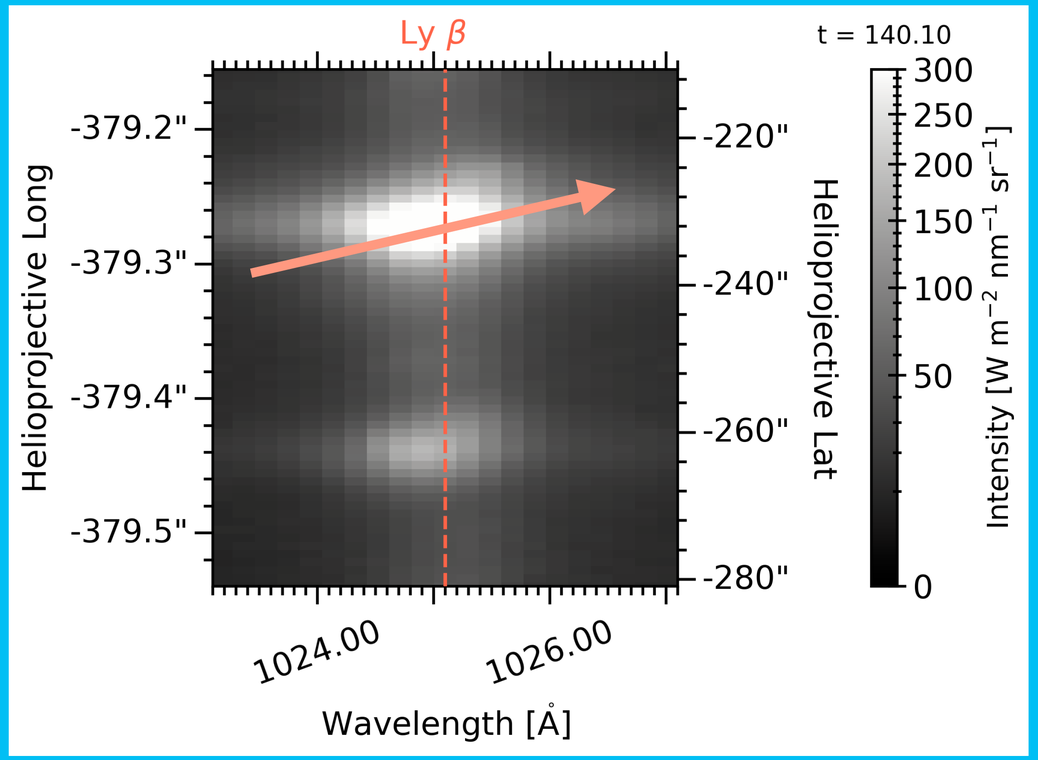


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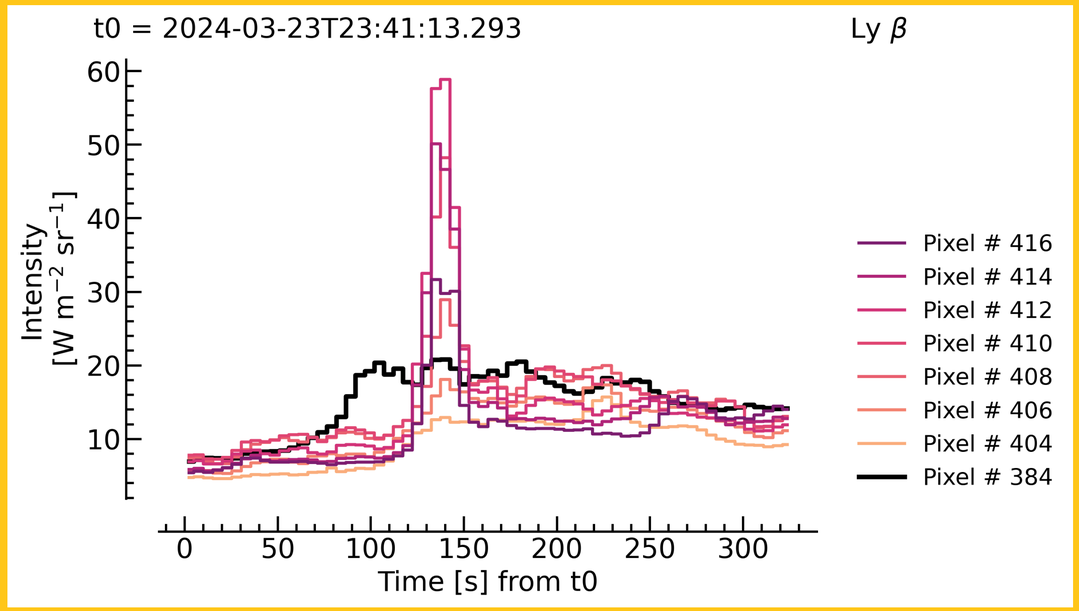


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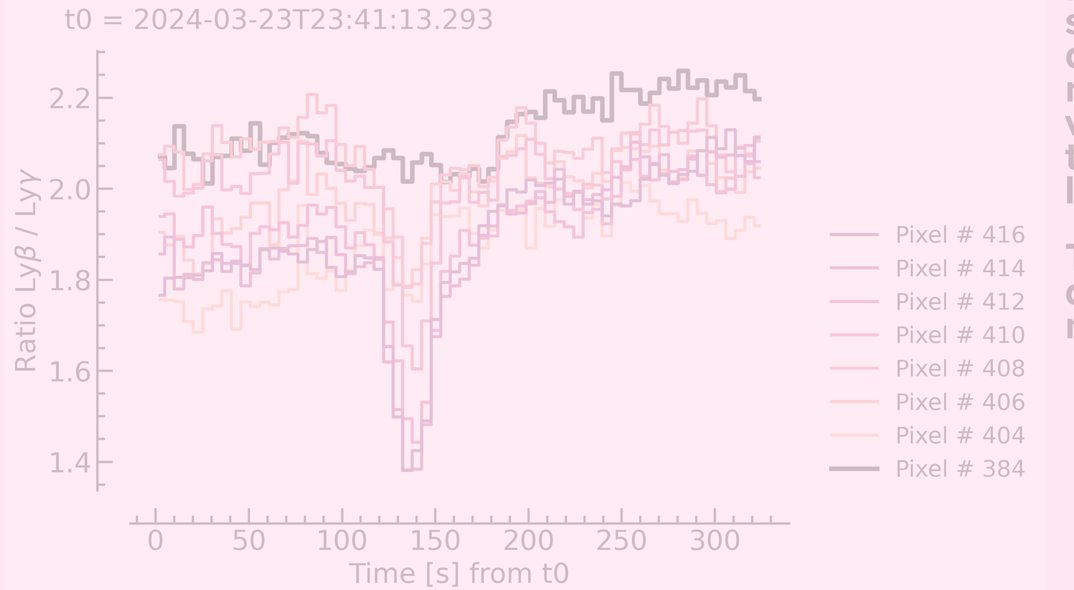


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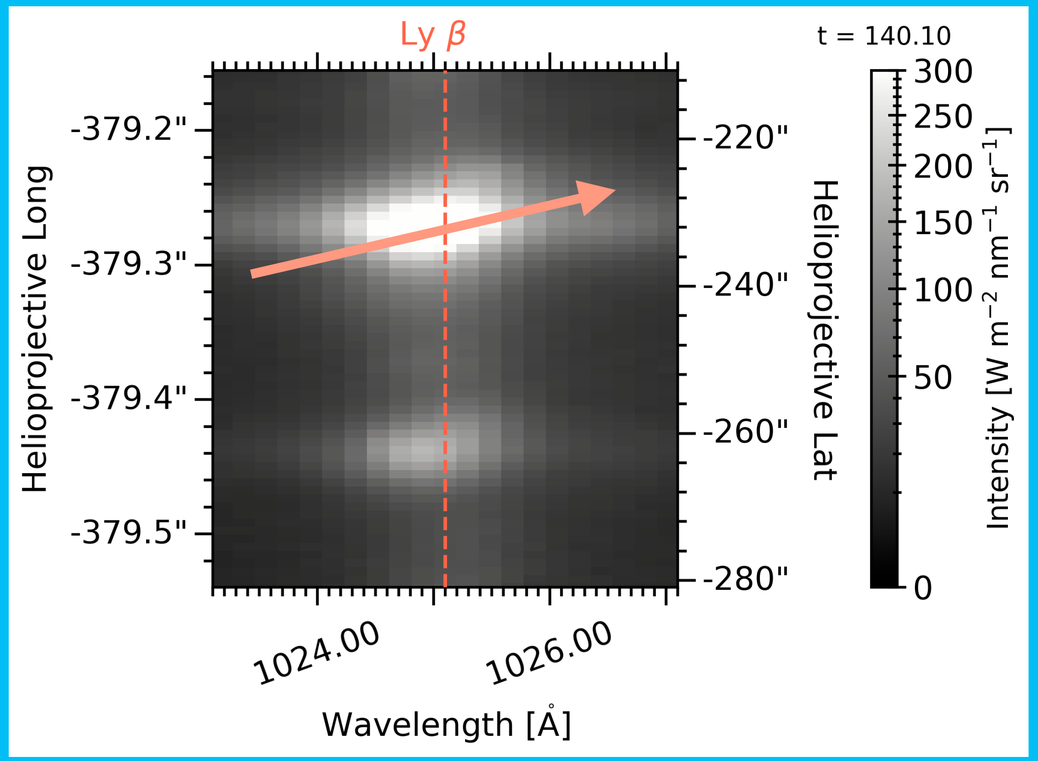


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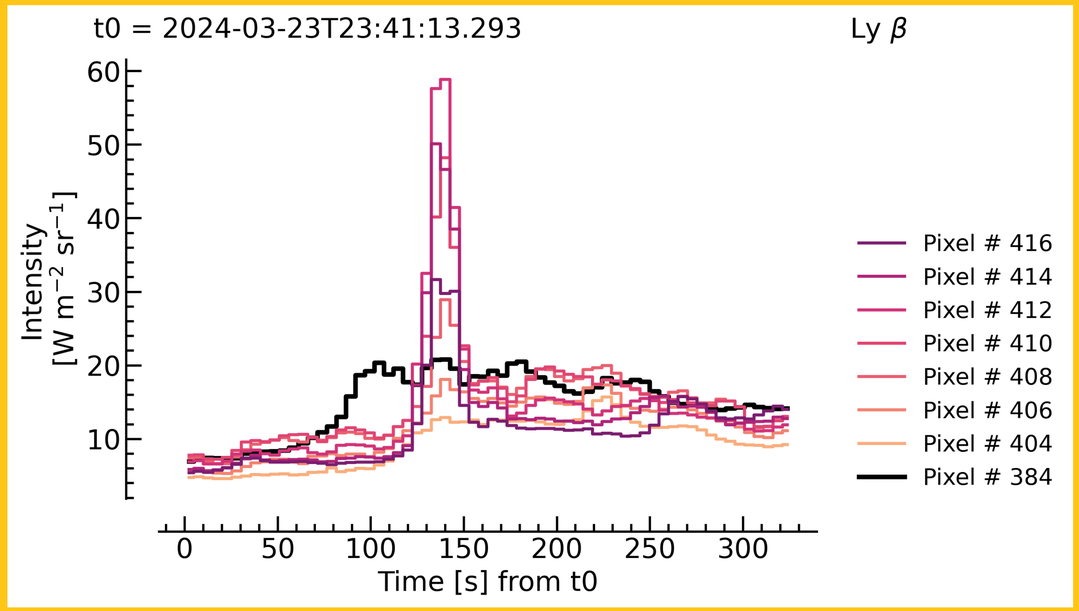


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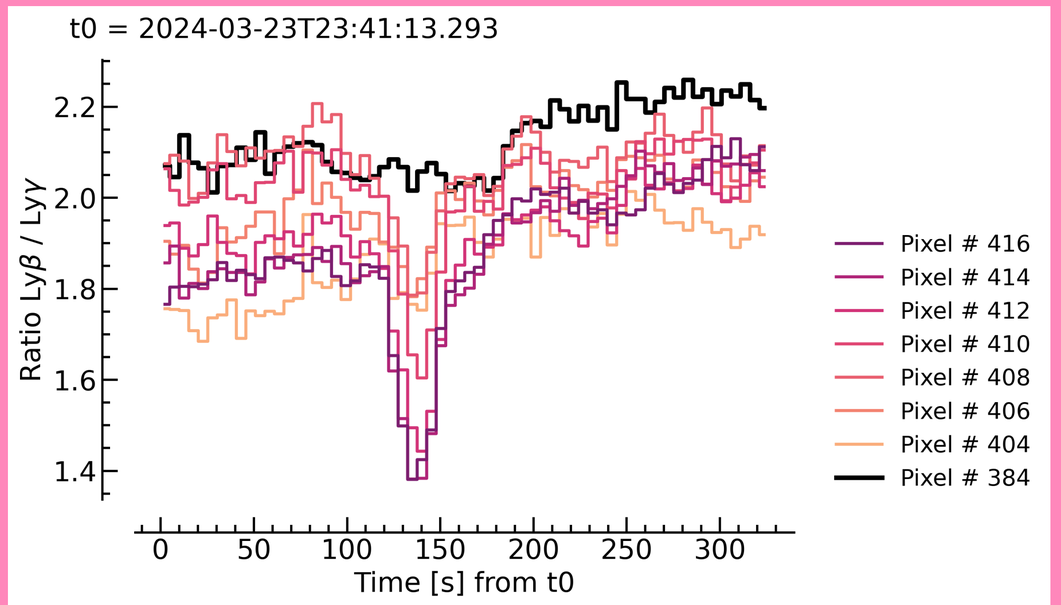


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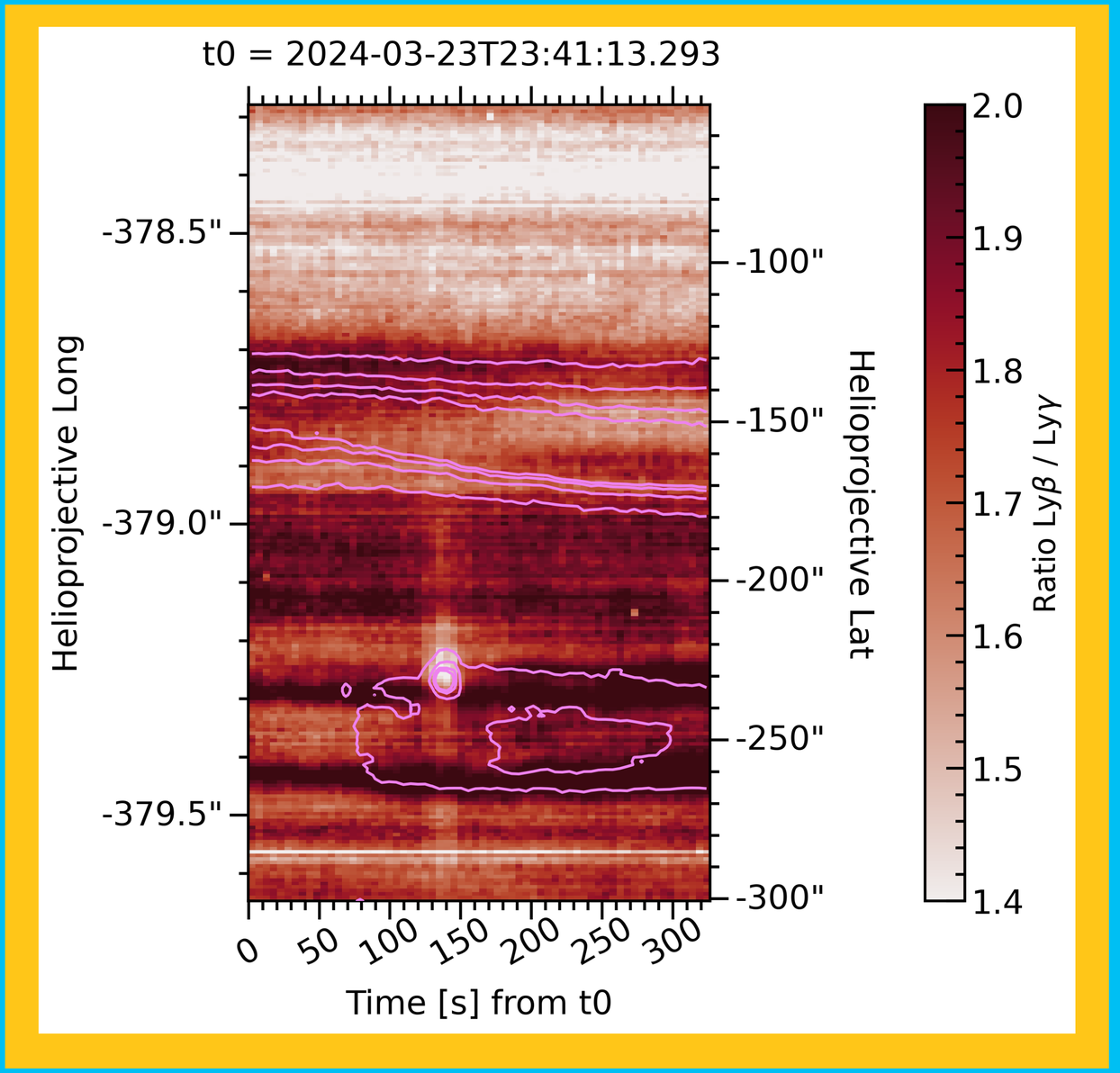
# LYMAN DECREMENT MAP

- 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.

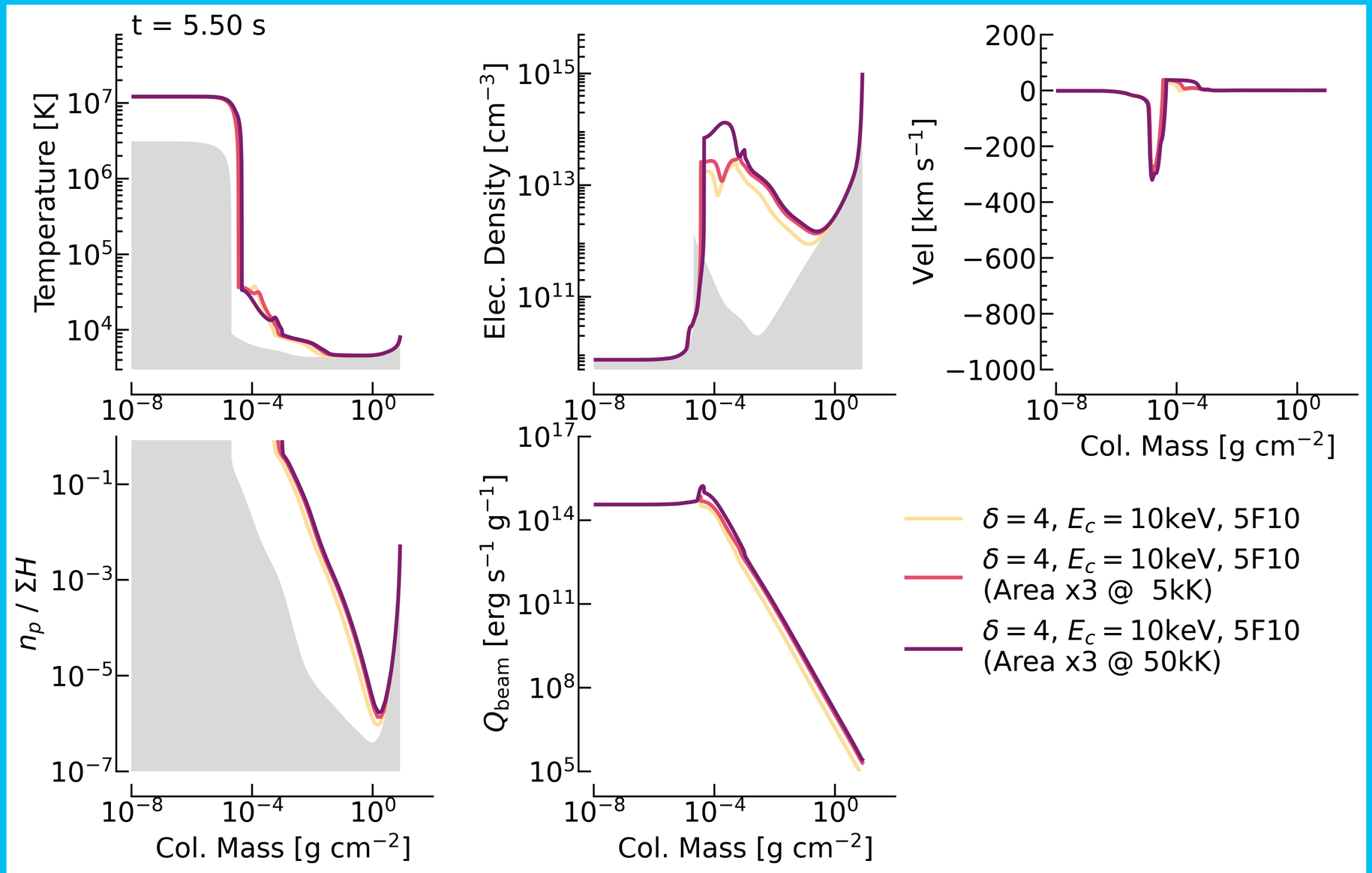
Contours are Fe XX



# 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..**



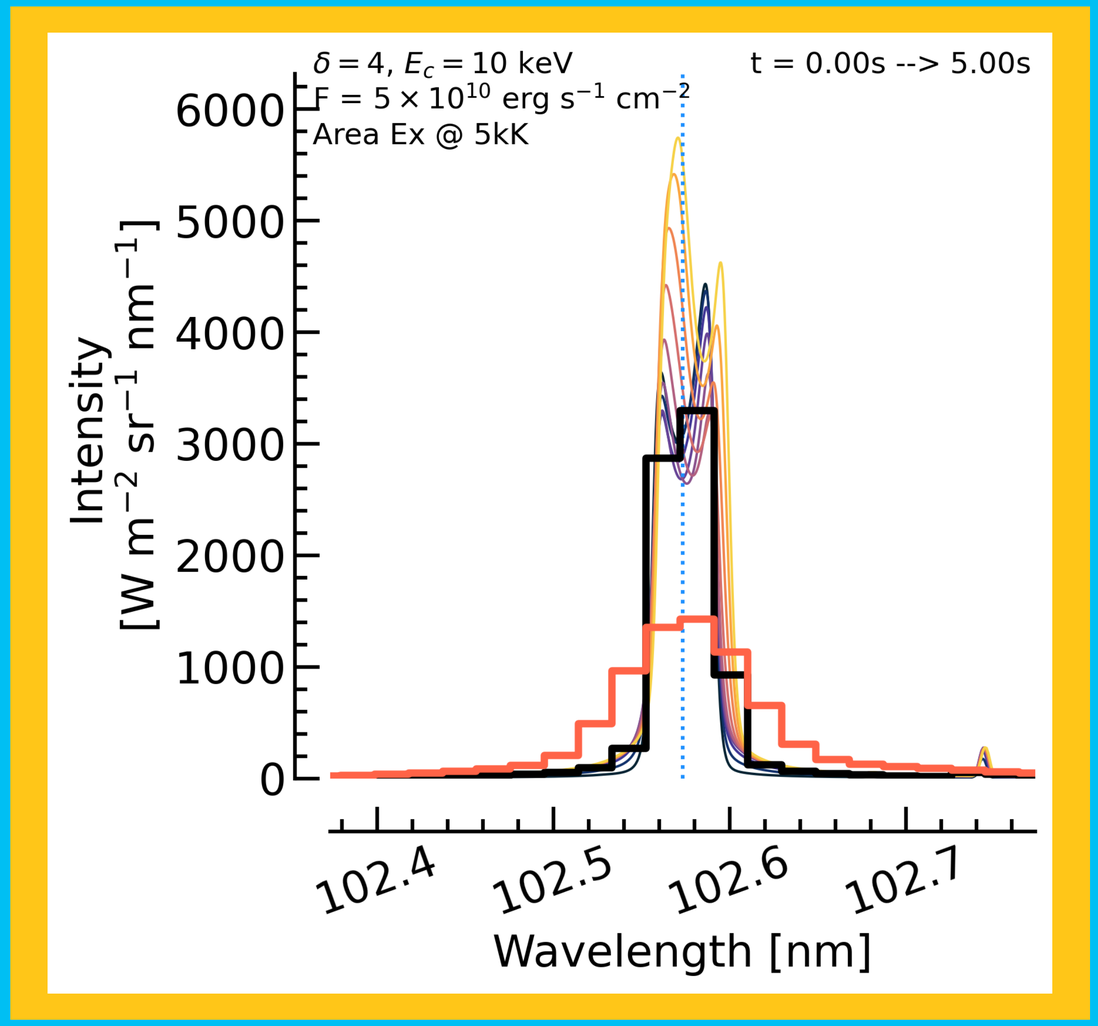
# MODEL -> SYNTHETIC SPICE

- 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.

**Coloured lines are spectra appearing in this exposure.**

**Black is the SPICE spectra, without PSF.**

**Red is with PSF applied (see later).**



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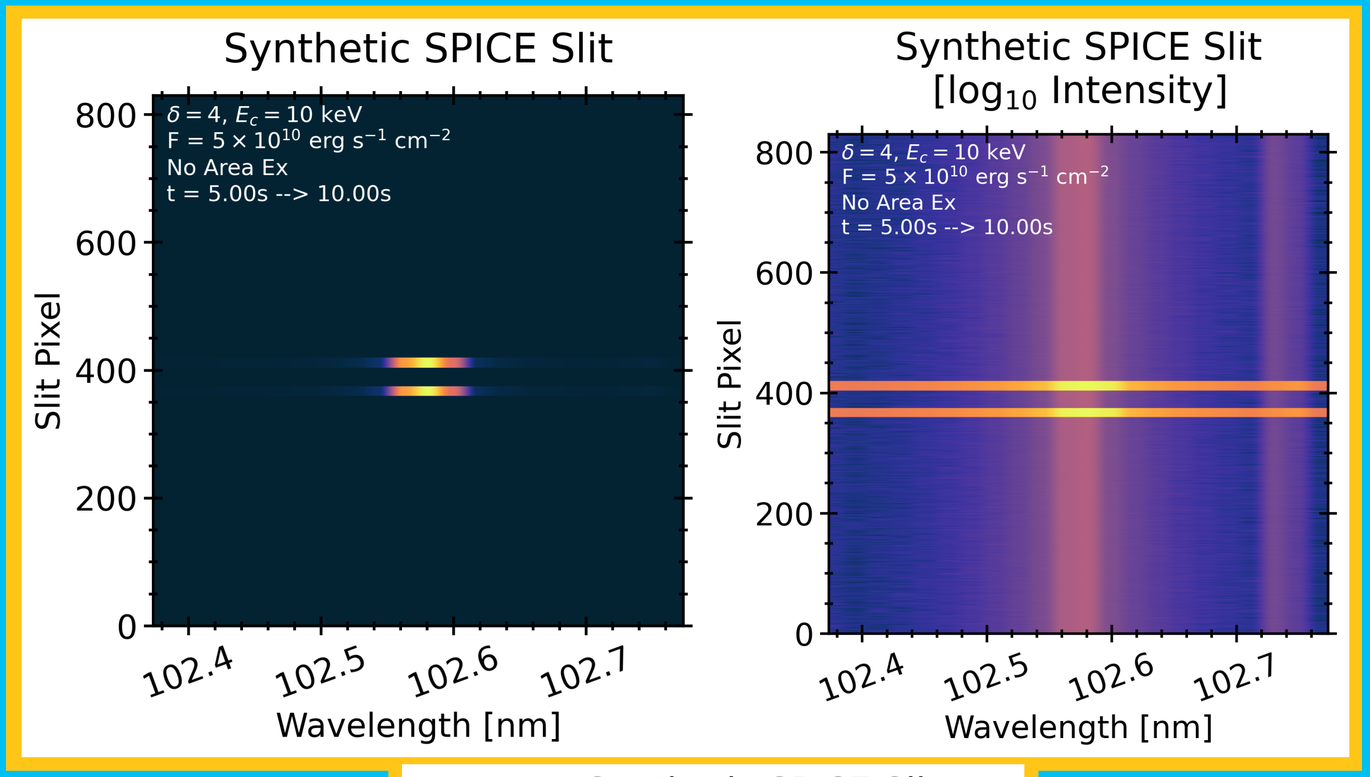


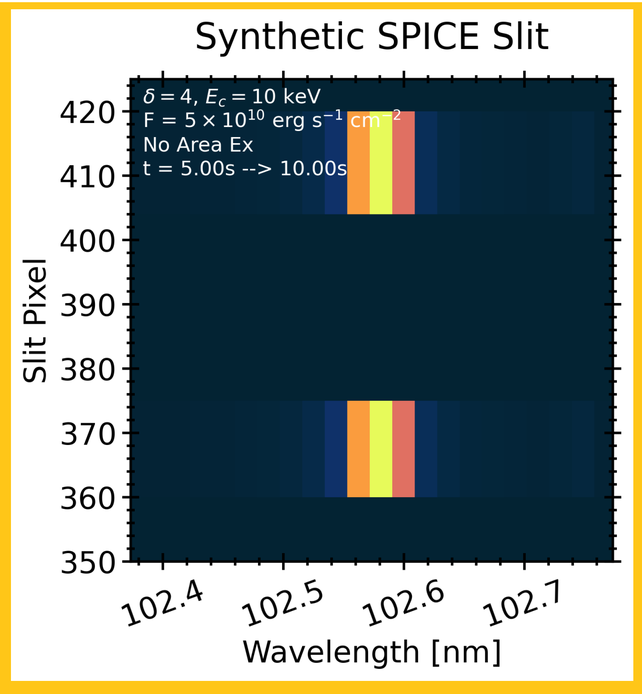

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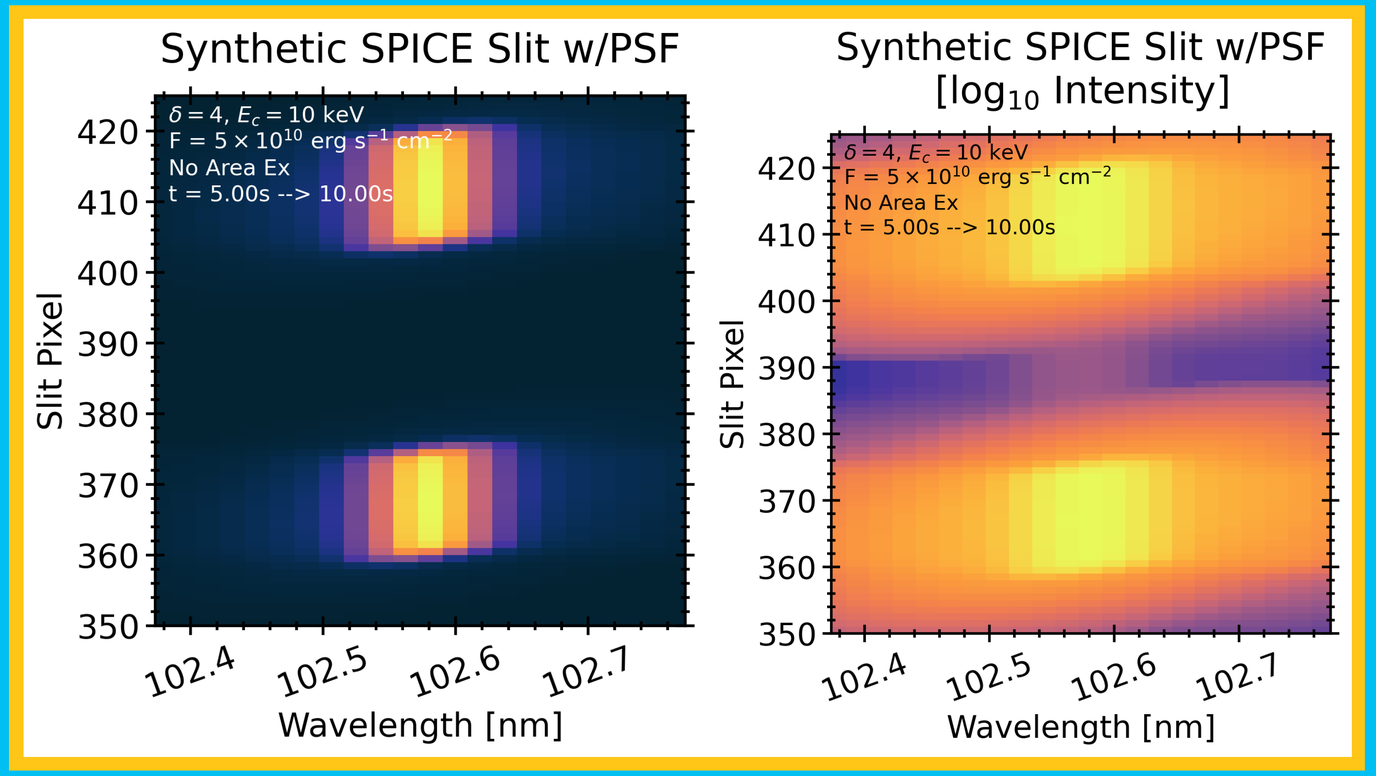

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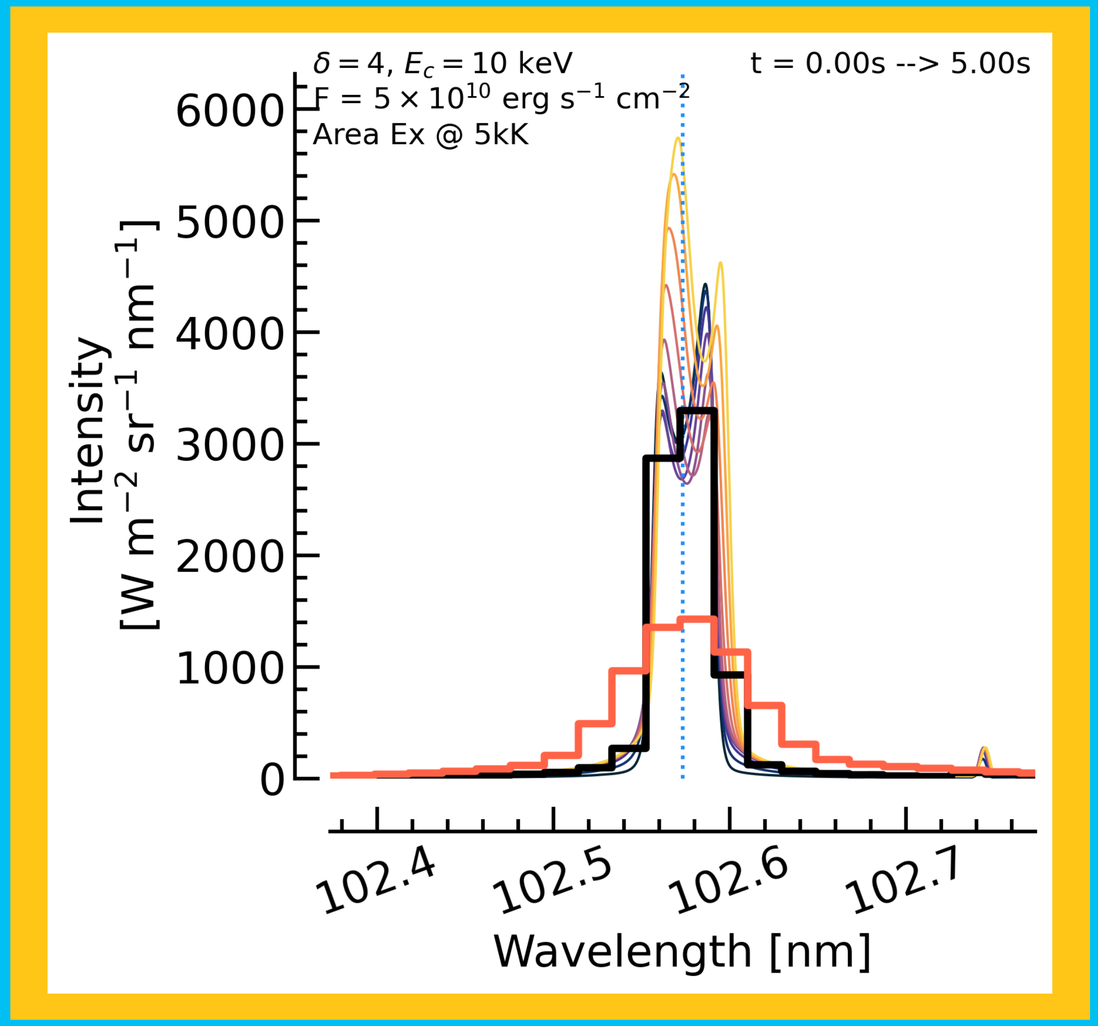

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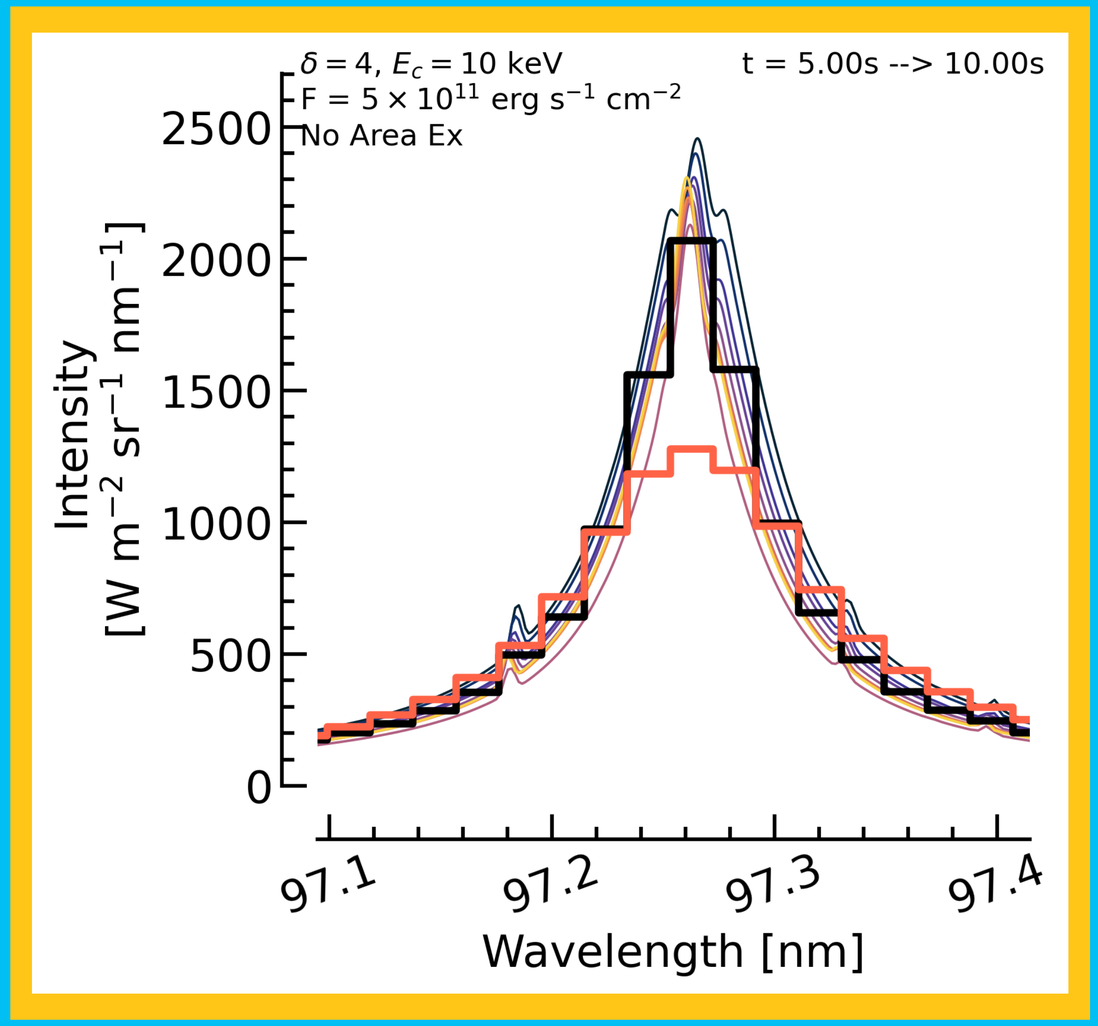
**Coloured lines are spectra appearing in this exposure.**

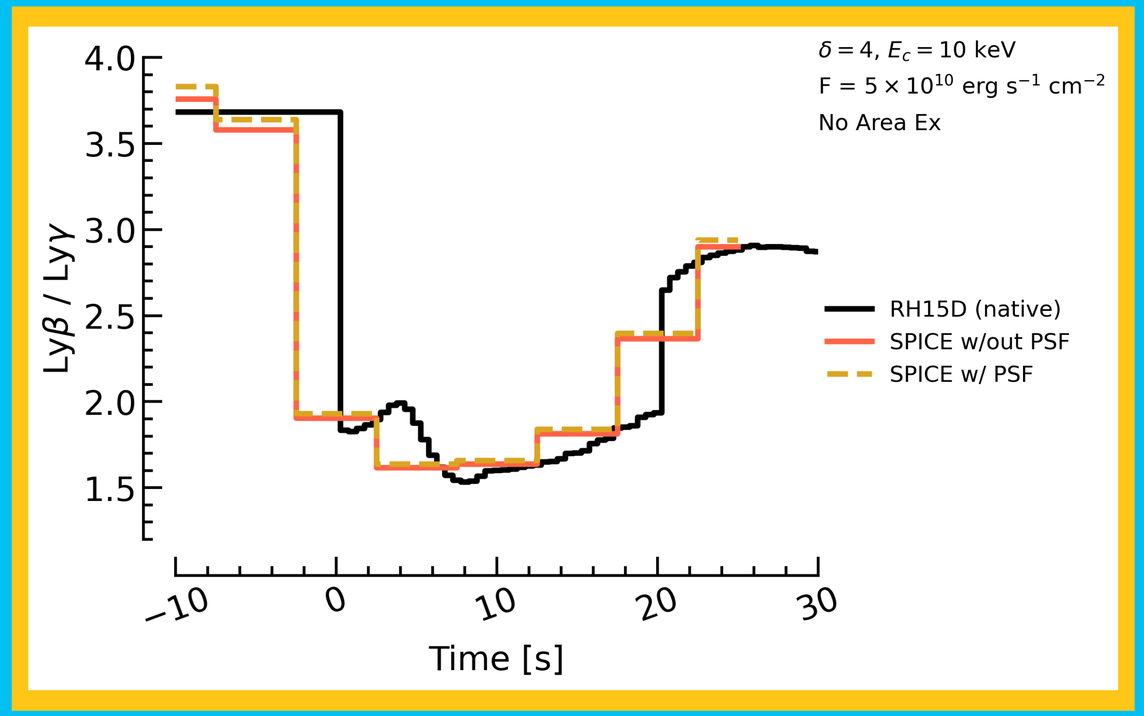
**Black is the SPICE spectra, without PSF.**

**Red is with PSF applied (see later).**



# MODELLED LYMAN DECREMENT

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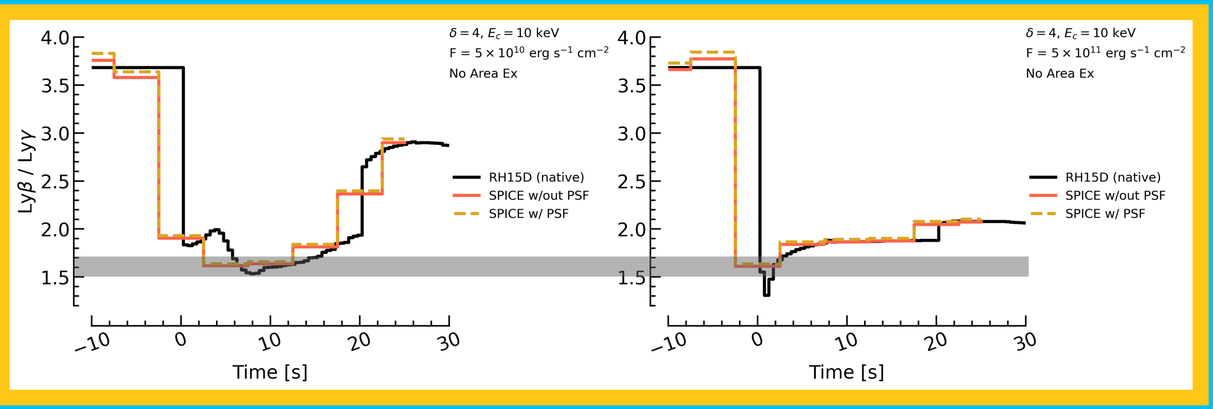
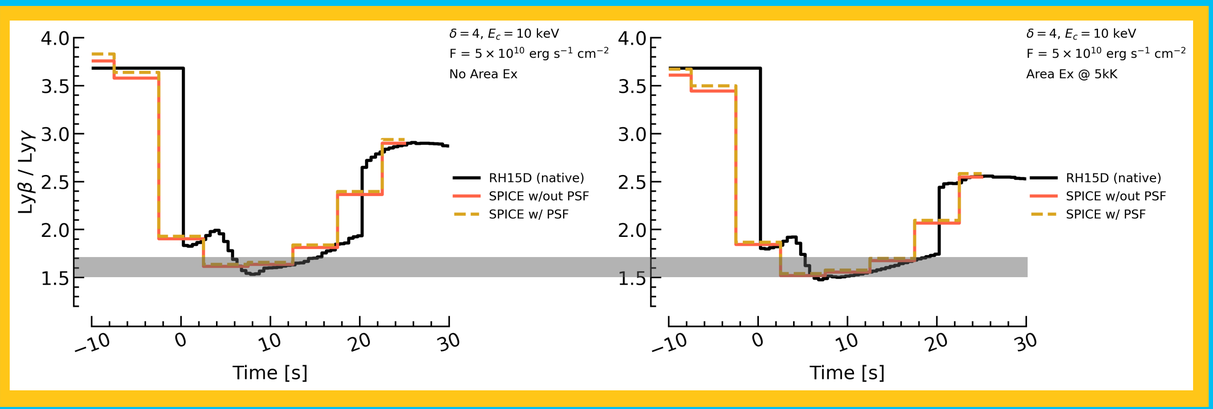
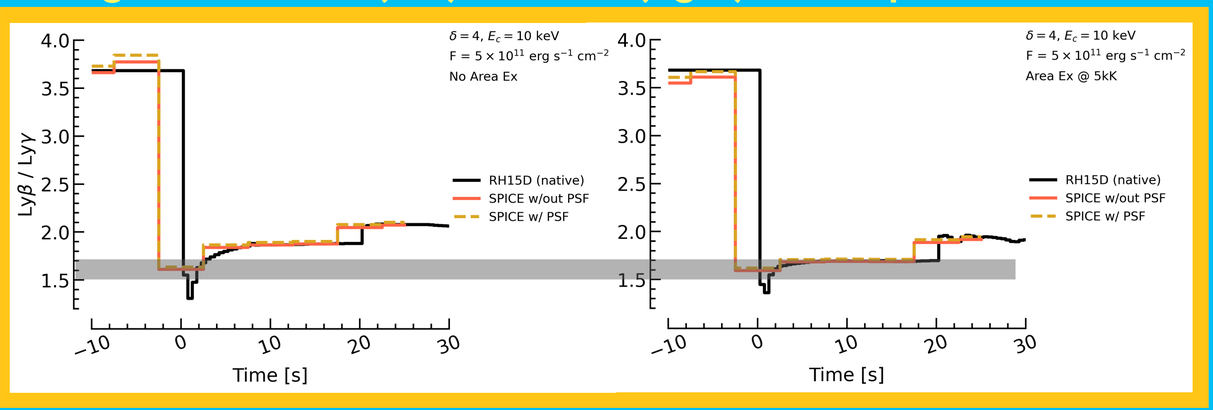
## Moderate flare (left) and strong flare (right), both w/out area expansion




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

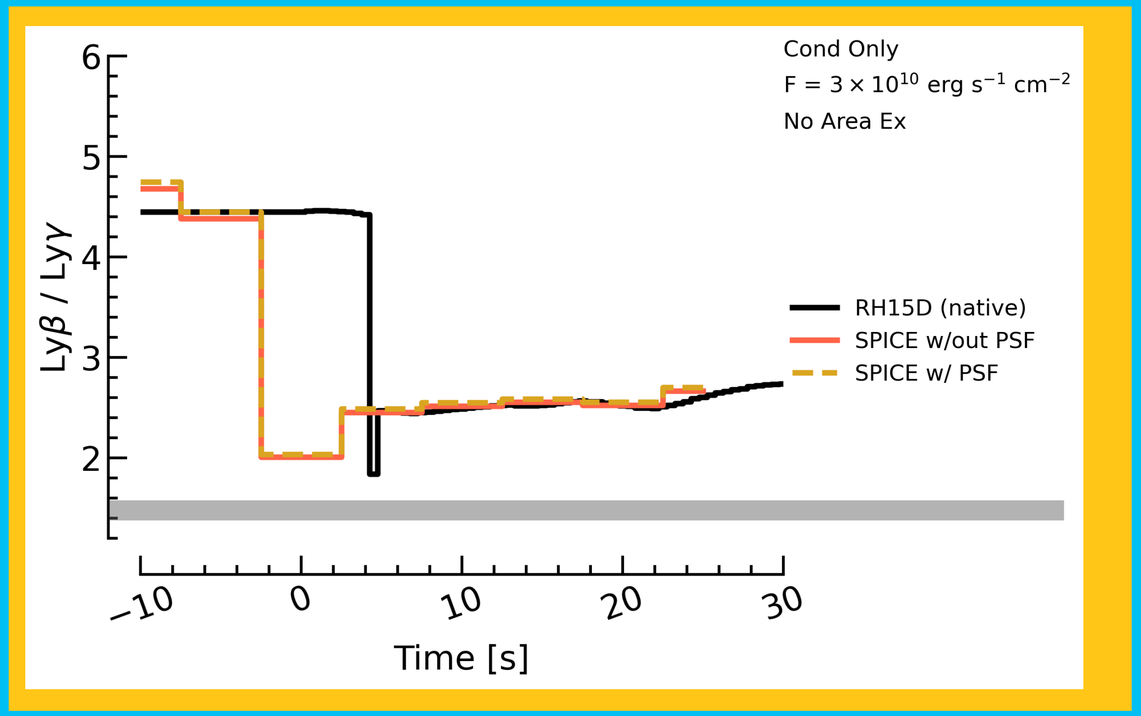



## Strong flare without (left) and with (right) area expansion

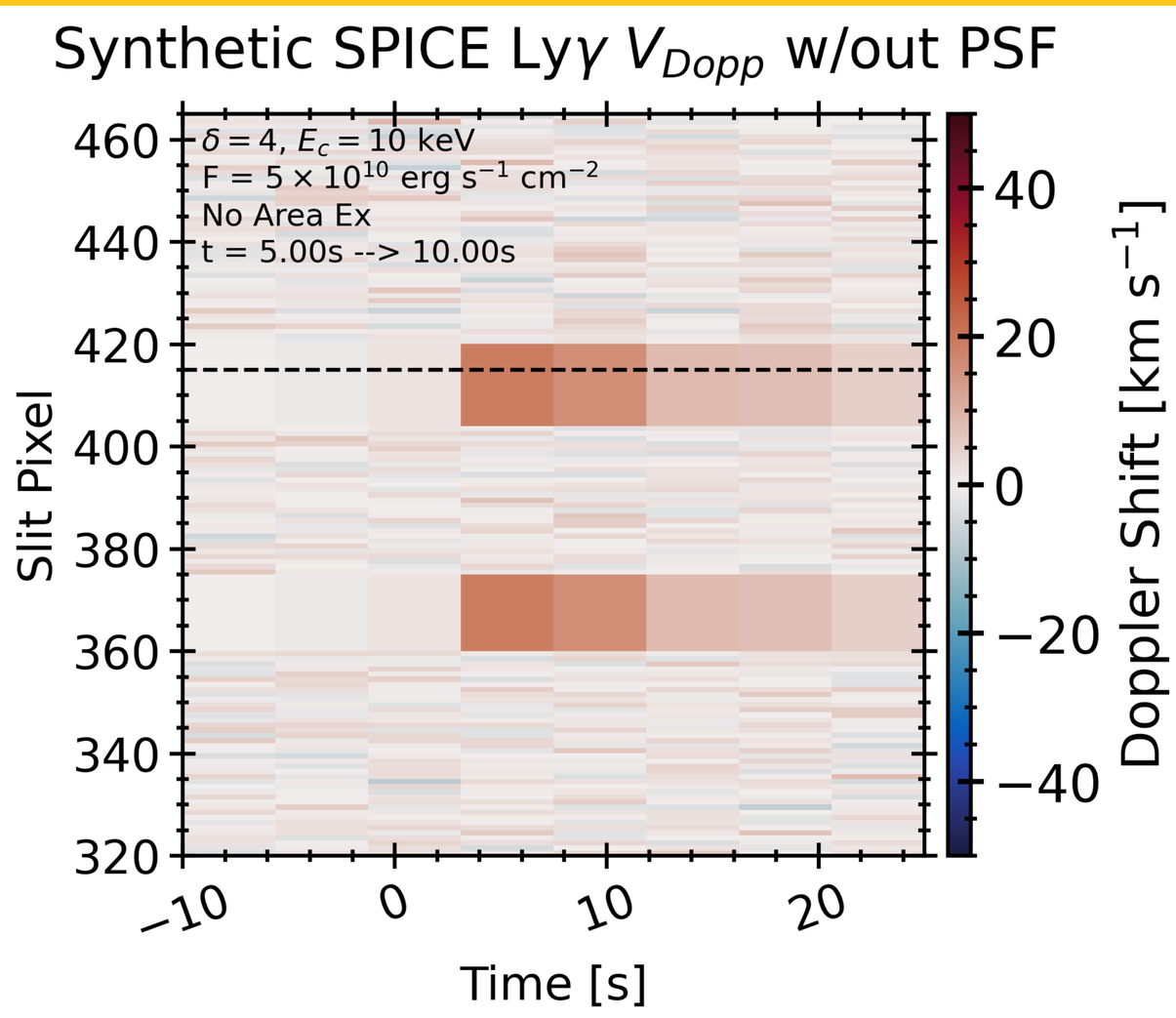


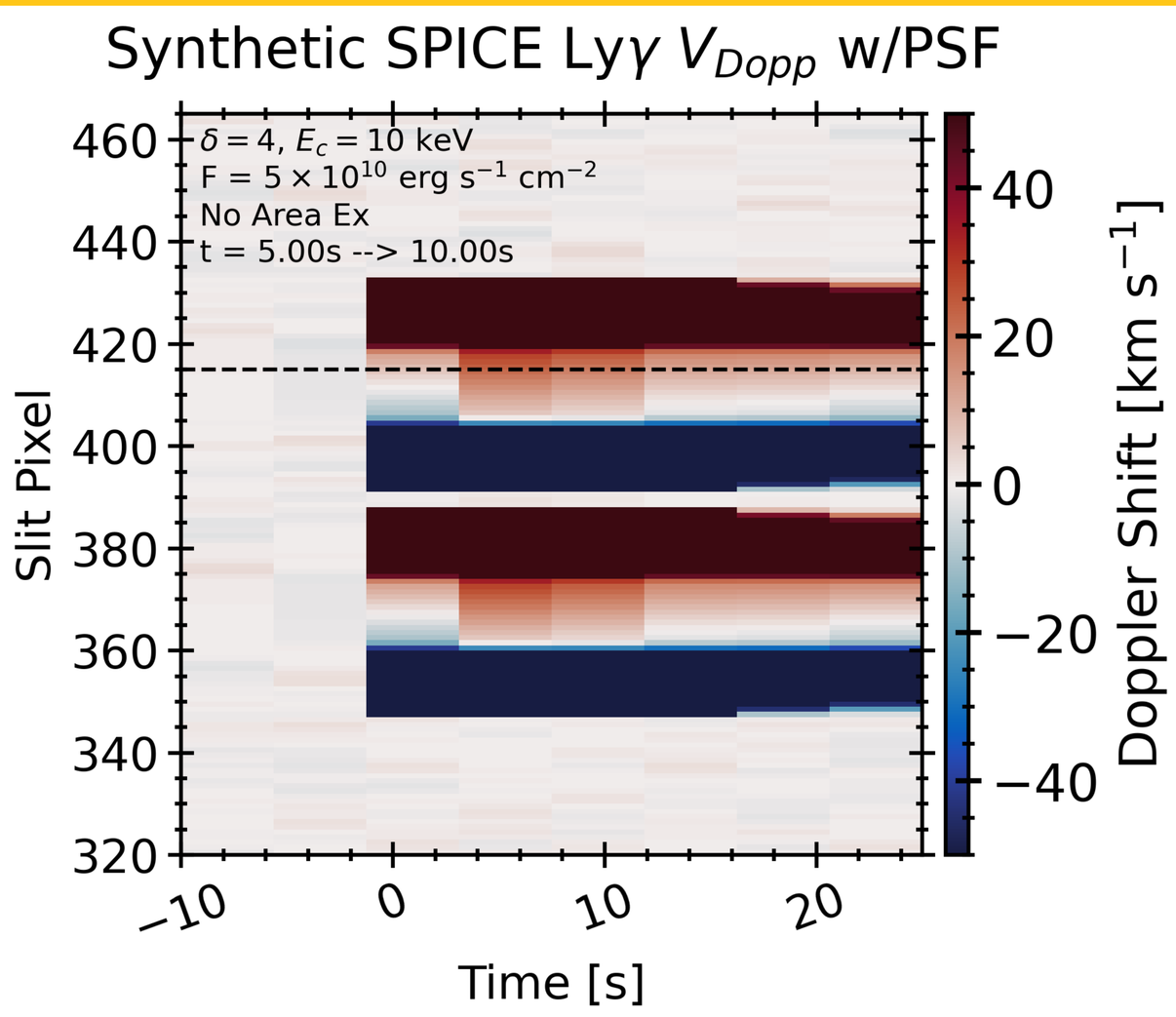
# MODELLED LYMAN DECREMENT

- 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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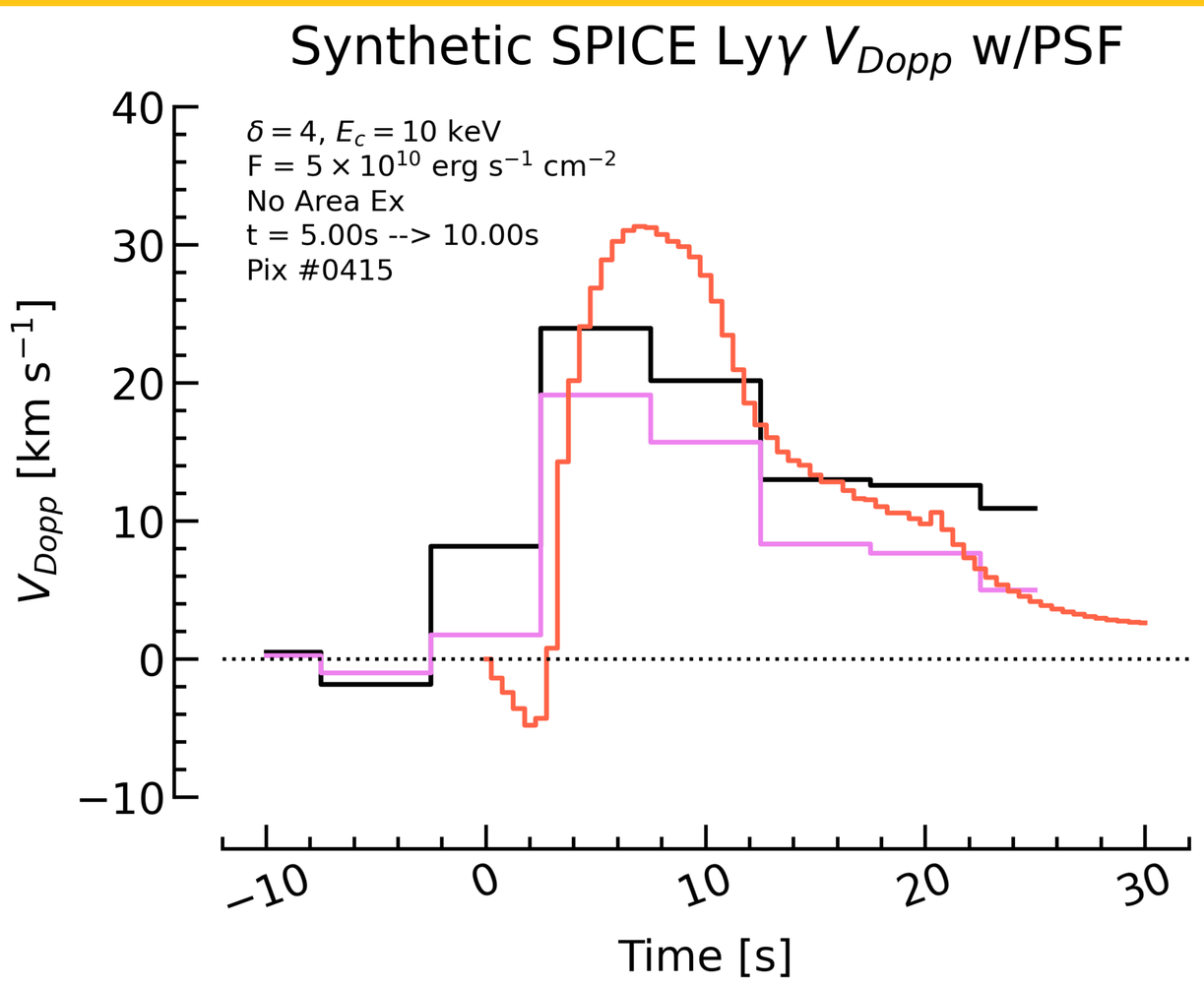
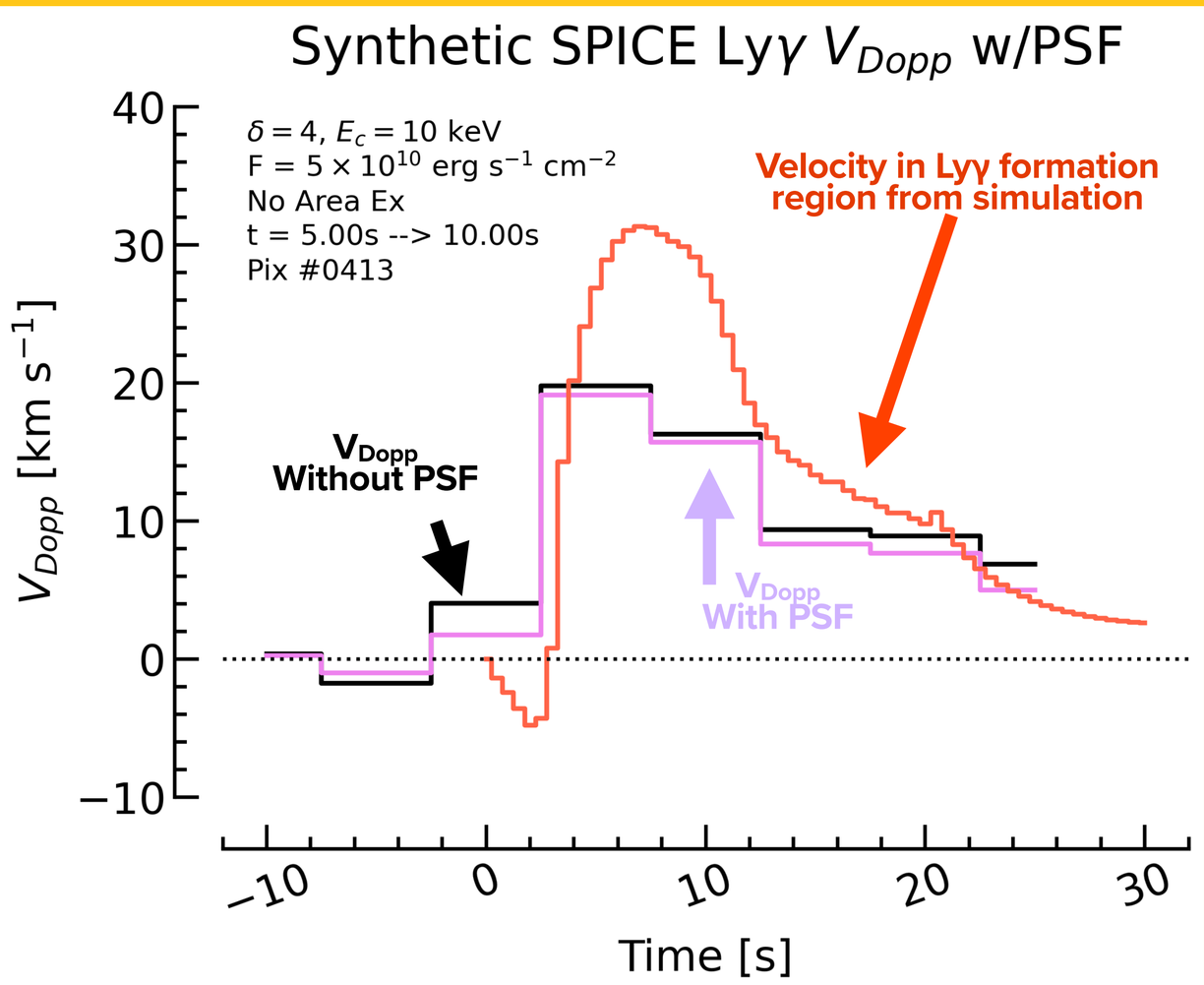



Pixel from edge of flare source




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;
  - ➡Lyβ / Lyγ 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 Lyβ and Lyγ 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!