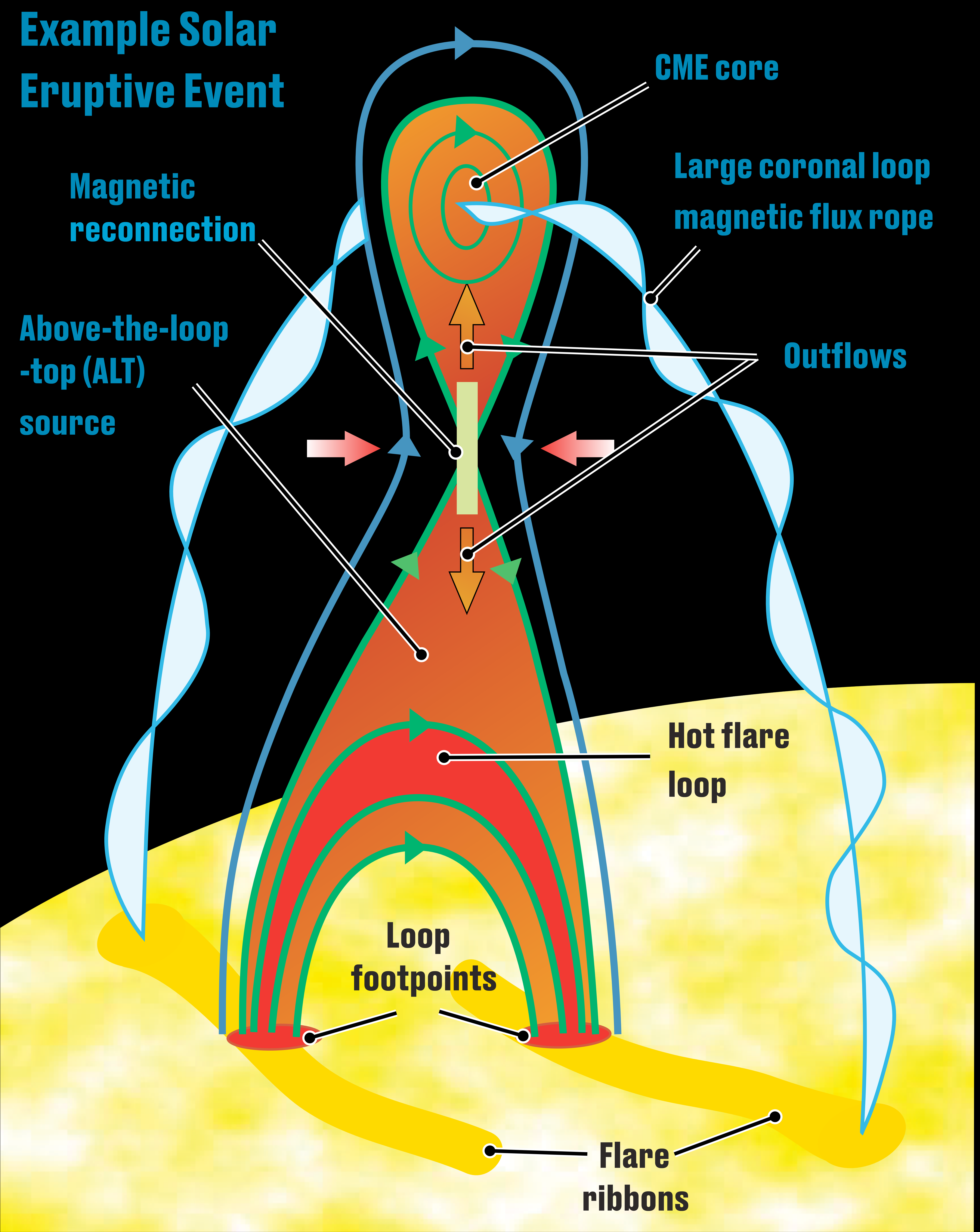
**GRAHAM S. KERR** (CATHOLIC UNIV. OF AMERICA / NASA GSFC)

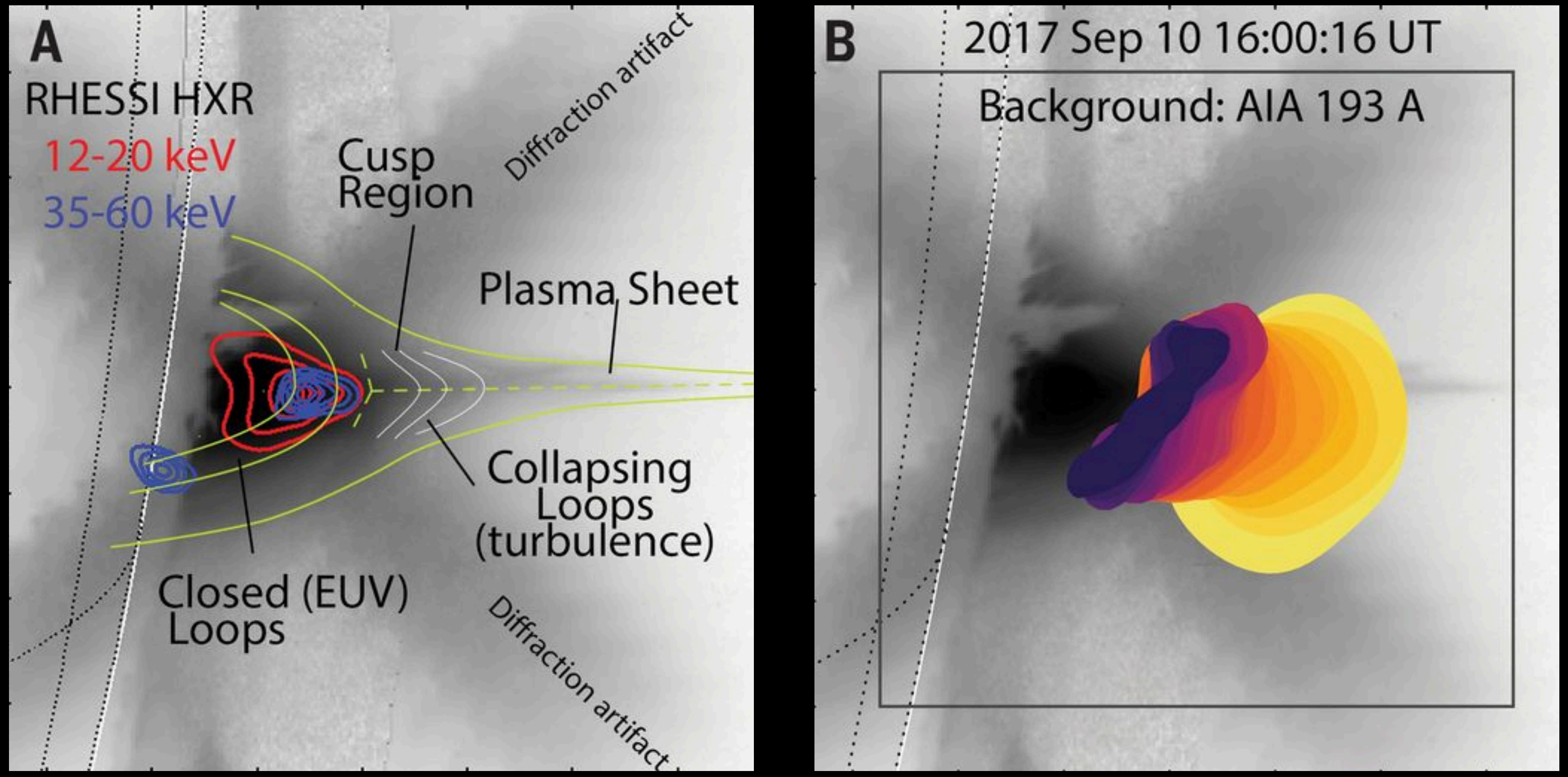
DAN RYAN, SÄM KRUCKER, ANDREW INGLIS, JOEL ALLRED, LAURA HAYES, TERRY KUCERA, JEFF BROSIUS, PETER YOUNG, JOE PLOWMAN + SPICE, STIX AND EUI TEAMS

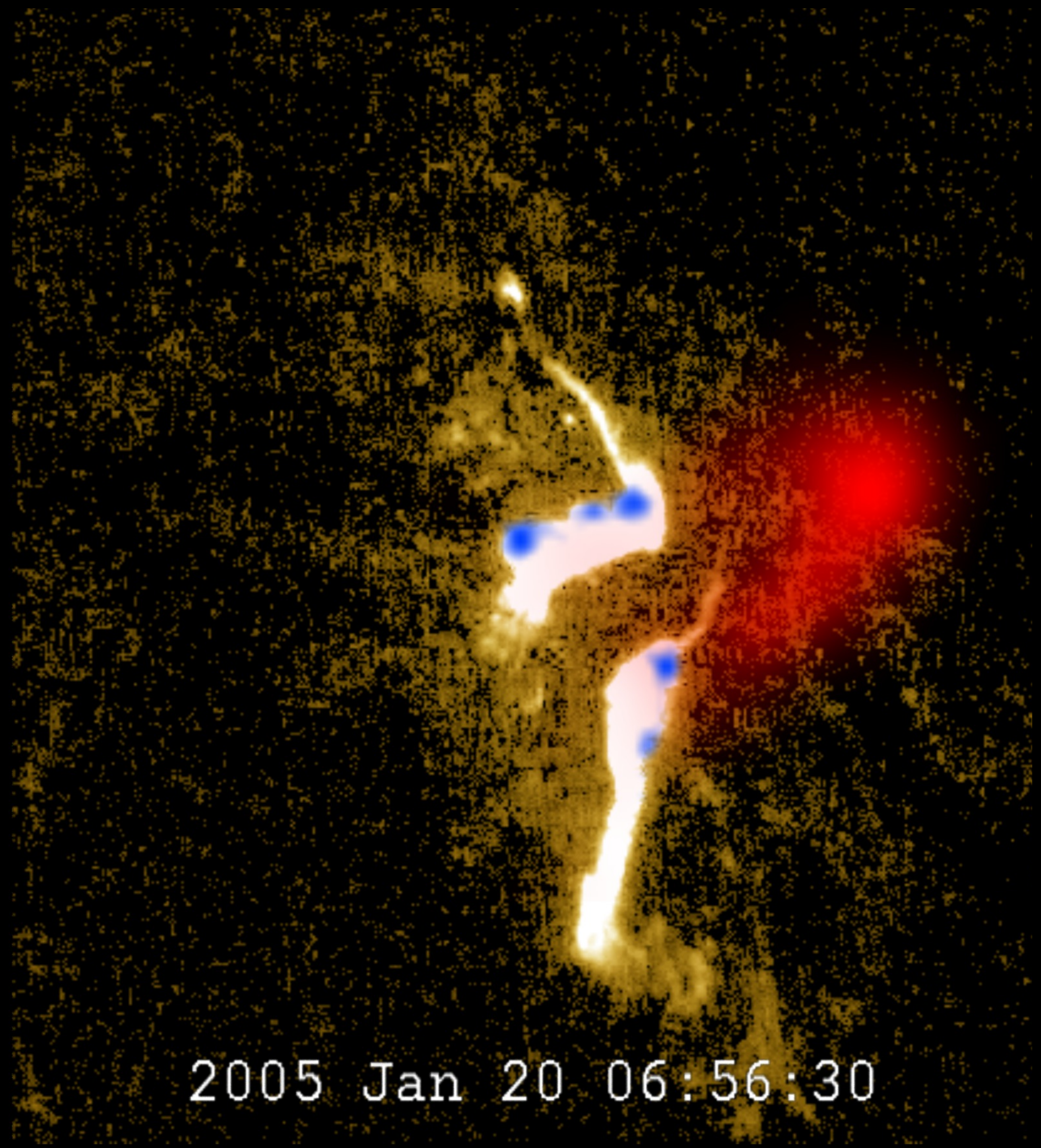
# SOLAR ORBITER'S MAJOR FLARE CAMPAIGN

*First high-cadence flare results from SPICE*


IRIS
SDO


Example Solar
Eruptive Event
CME core
Magnetic
reconnection
Large coronal loop
magnetic flux rope
Above-the-loop
-top (ALT)
source
Outflows
Hot flare
loop
Loop
footpoints
Flare
ribbons


A
RHESSI HXR
12-20 keV
35-60 keV
Cusp
Region
Diffraction artifact
Plasma Sheet
Collapsing
Loops
(turbulence)
Closed (EUV)
Loops
Diffraction artifact
B
2017 Sep 10 16:00:16 UT
Background: AIA 193 A


2005 Jan 20 06:56:30

**STIX** – Non-thermal electron imaging spectroscopy.

**EUI** – High-cadence, short-exposure, saturation free EUV imaging.

**SPICE** – High-cadence spectroscopy spanning 10kK - 10MK.

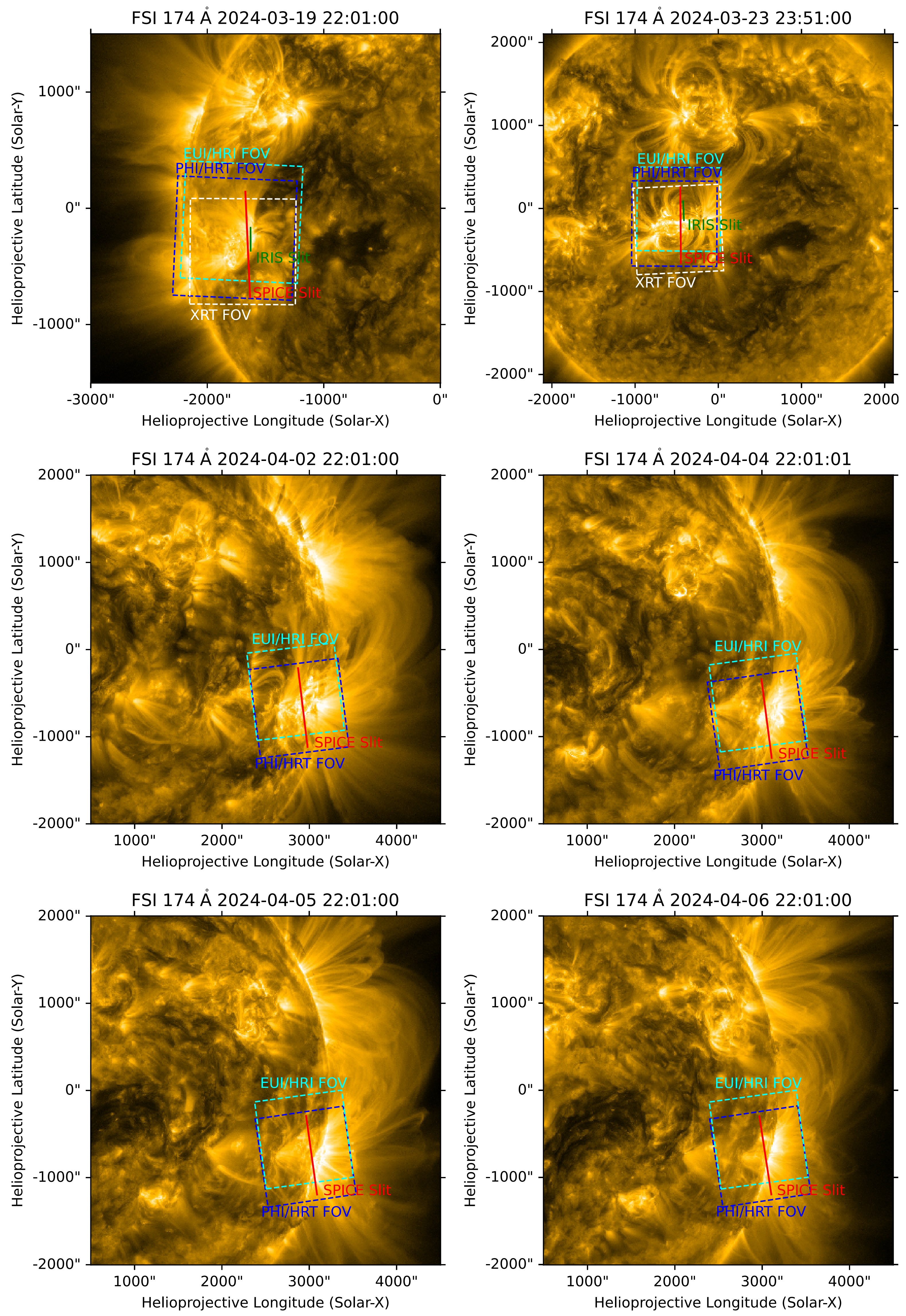
# SOLAR ORBITER MAJOR FLARE WATCH

**Science Goals:**

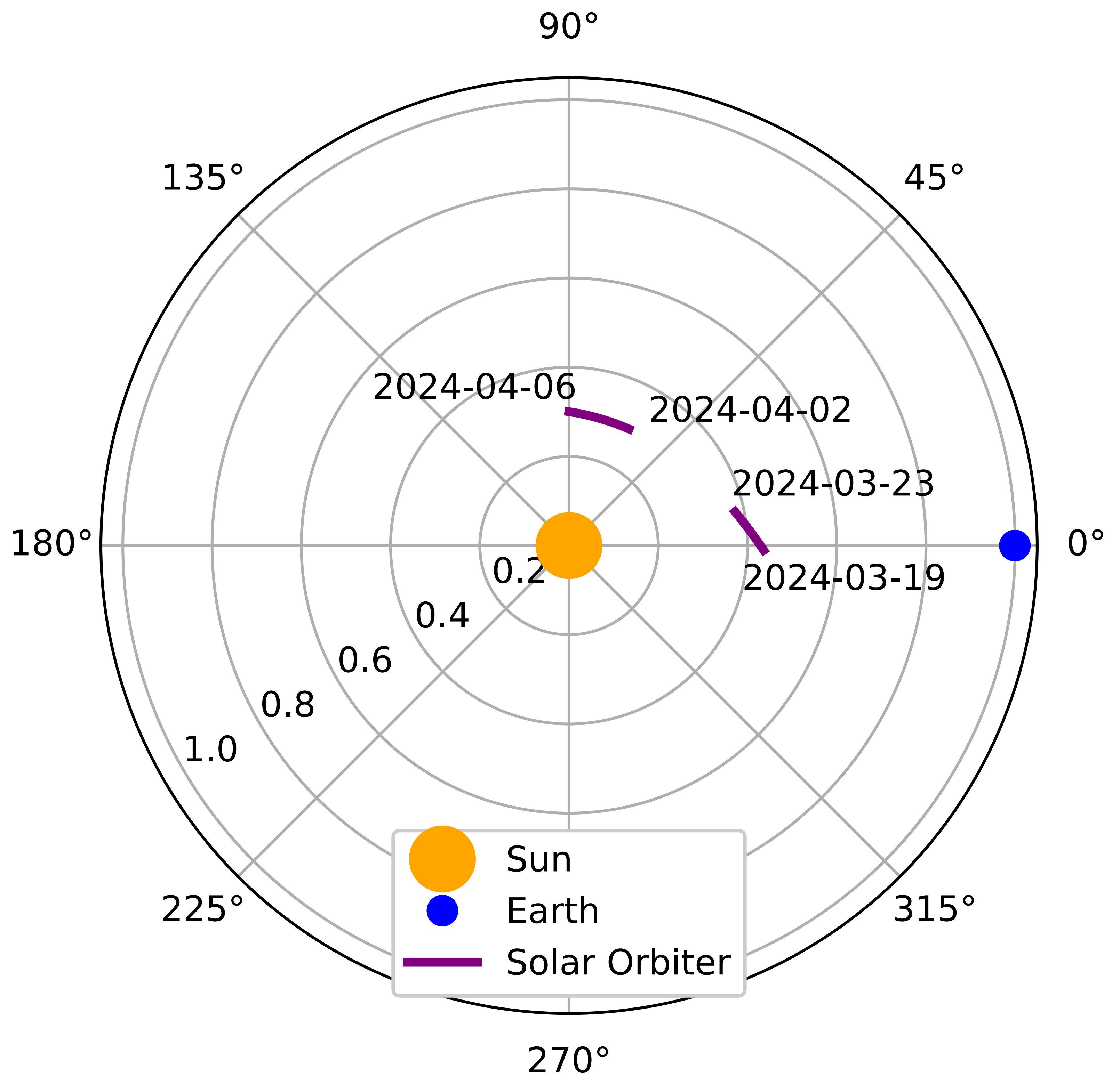
(1) Probe the spatial evolution of flare plasma on timescales relevant to impulsive flare energy release.

(2) Identify flare-accelerated ions via the Orrall-Zirker effect.

(3) Explore the 3D geometry of flare sources and their evolution with time.




# RYAN et aL 2025, in prep

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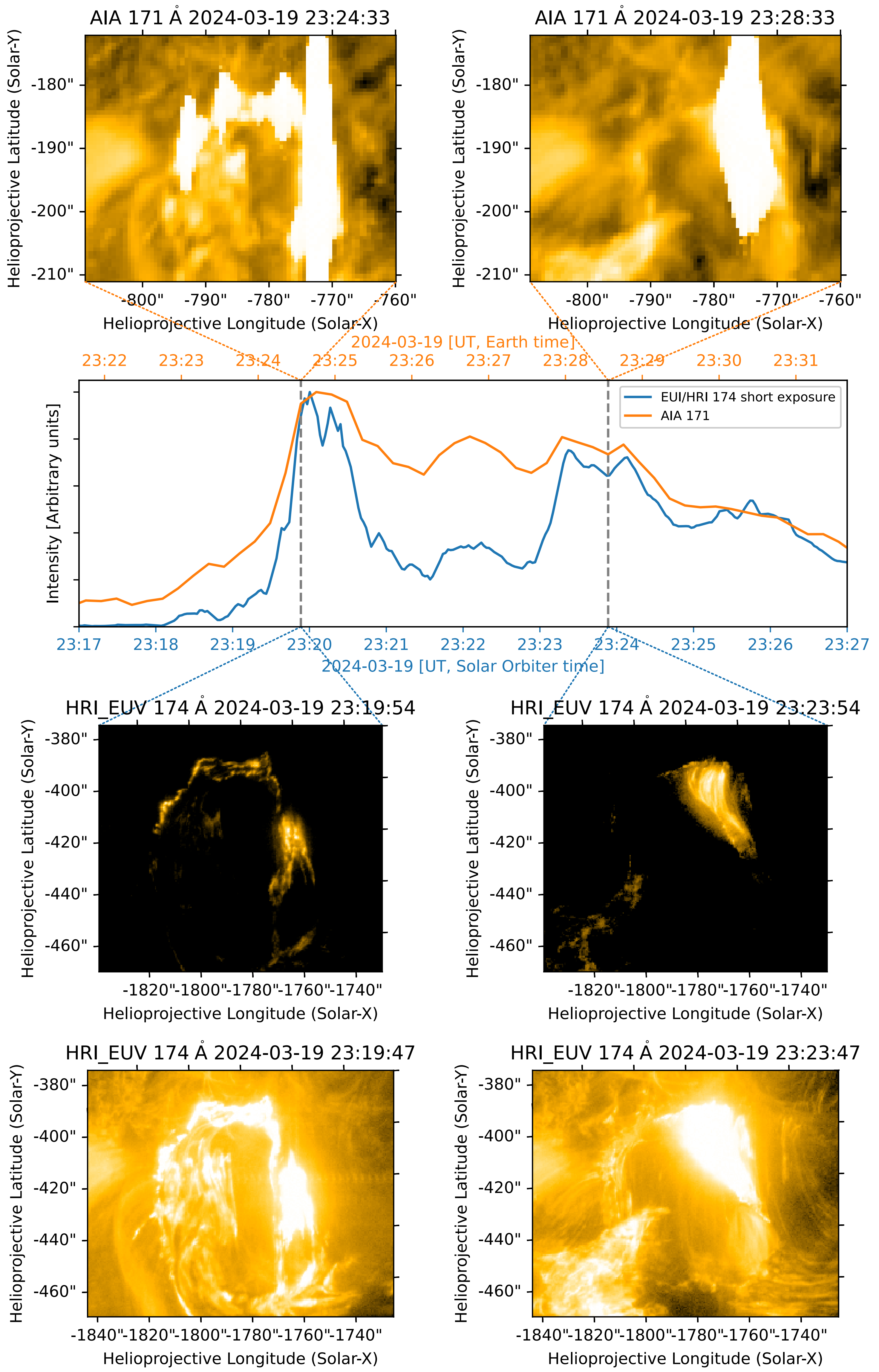
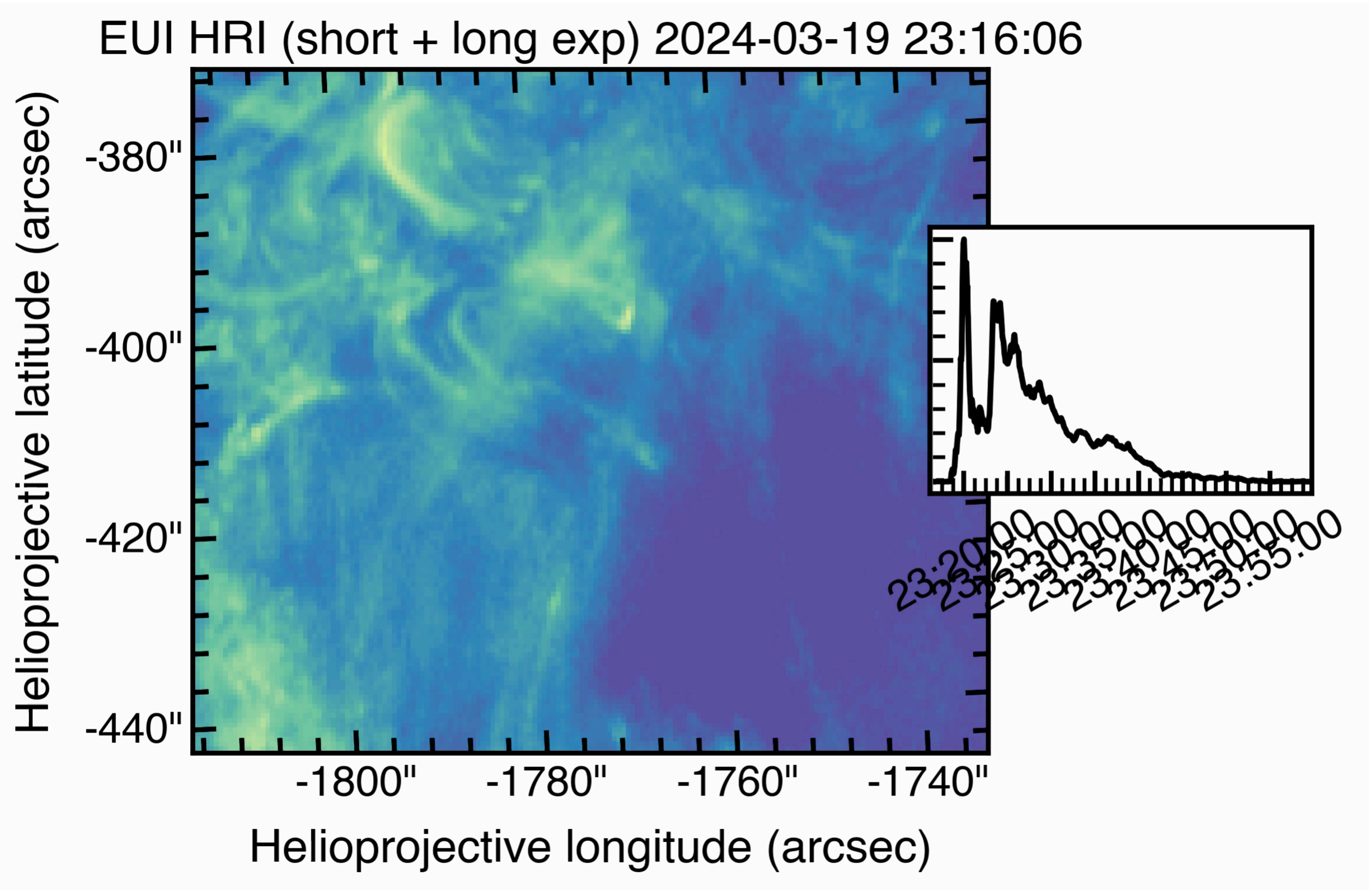
# SOLAR ORBITER MAJOR FLARE WATCH




# RYAN et aL 2025, in prep

# HAYES et aL 2025, in prep

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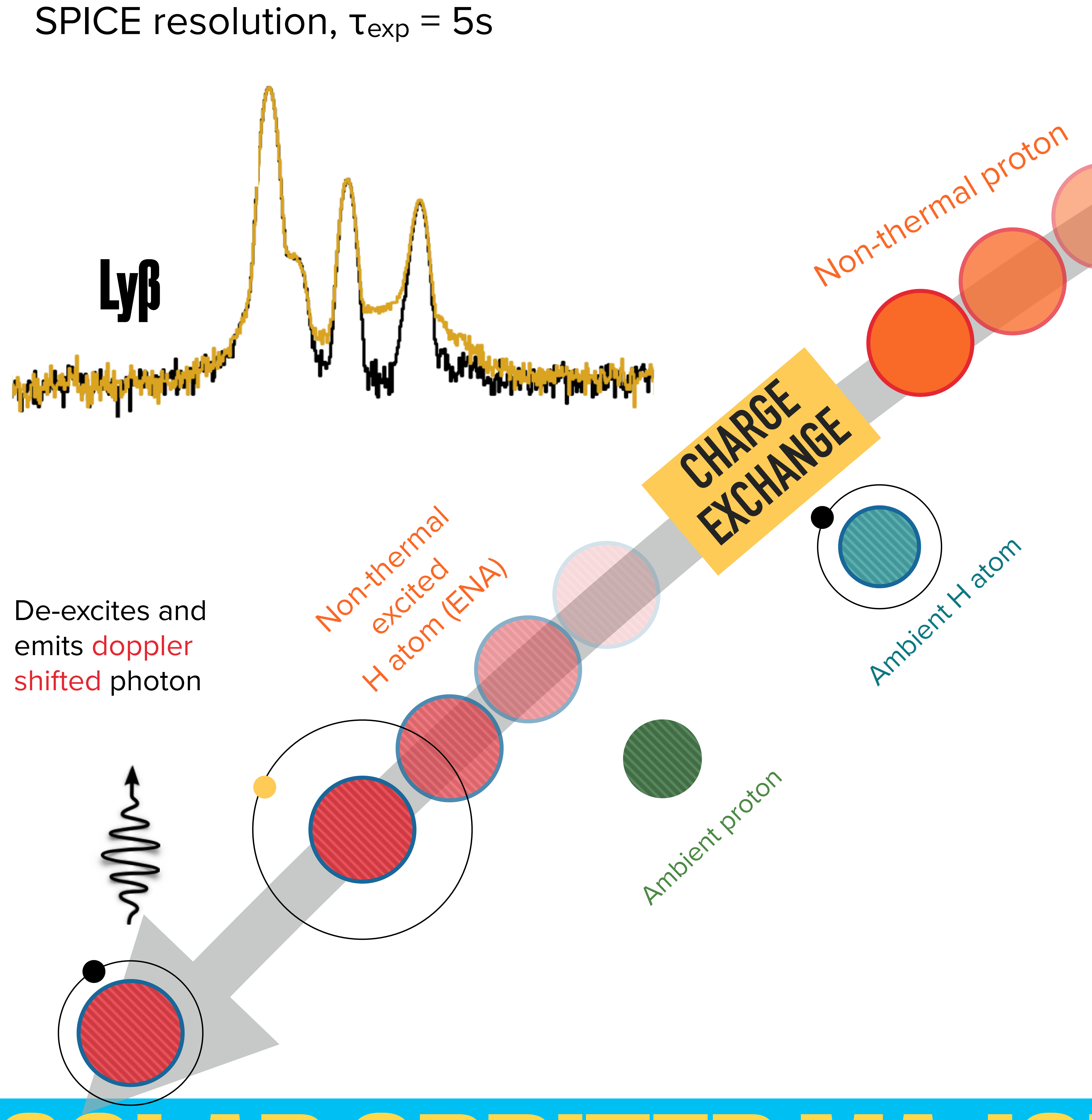
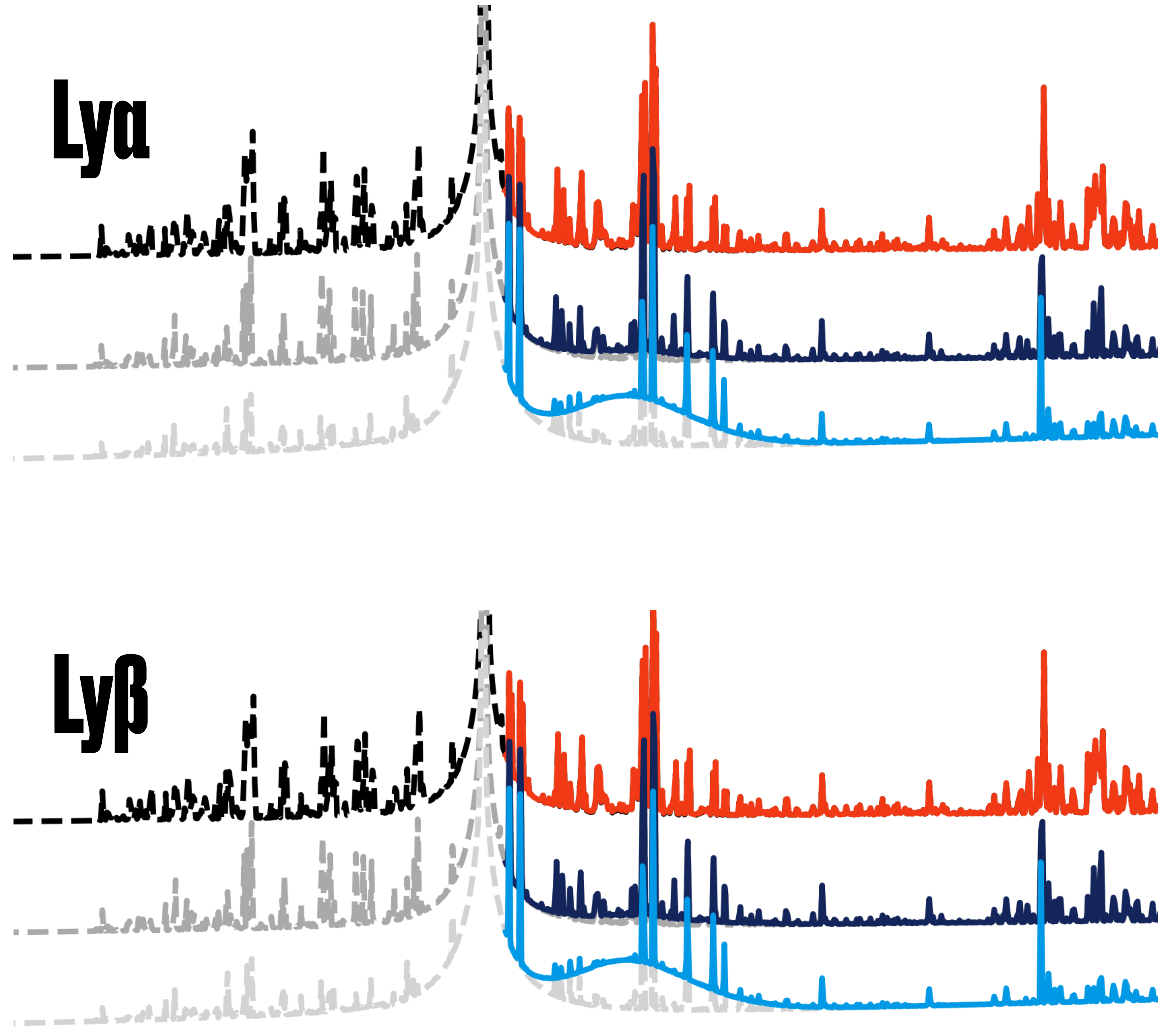



See also:
Canfield and Chang 1985 ApJ 295
Fang et al 1995 A&A 297
Brosius et al 1995 ApJ 441
Brosius et al 1999 ApJ 514
Hudson et al 2012 ApJ 752
Kerr et al 2023, ApJ 945




# SOLAR ORBITER MAJOR FLARE WATCH

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(1) Probe the spatial evolution of flare plasma on timescales relevant to impulsive flare energy release.

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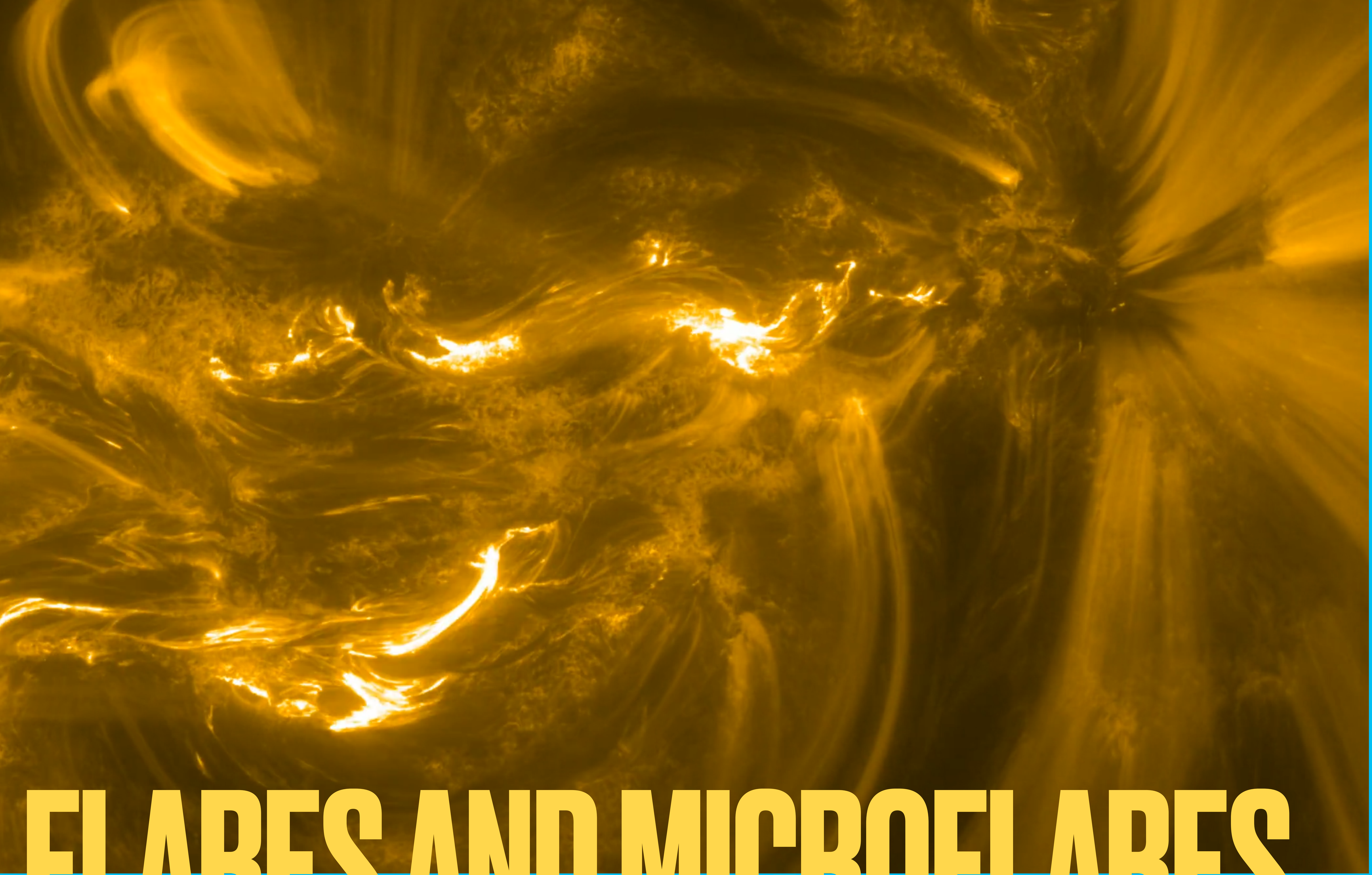
PERIHELION 5 MAJOR FLARE WATCH
23/24 MARCH 2024
EUI HRI-EUV 174 2024-03-23T23:05:18.374 | D☉: 0.3814au
AIA 131 2024-03-23T23:04:30.622 | D☉: 0.9969au


OCTOBER 15 2024 MAJOR FLARE WATCH
HOT-OFF-THE-PRESSES (NOT SCIENCE READY YET)
2024-10-15T18:10:53.243

# FLARES OBSERVED BY SPICE



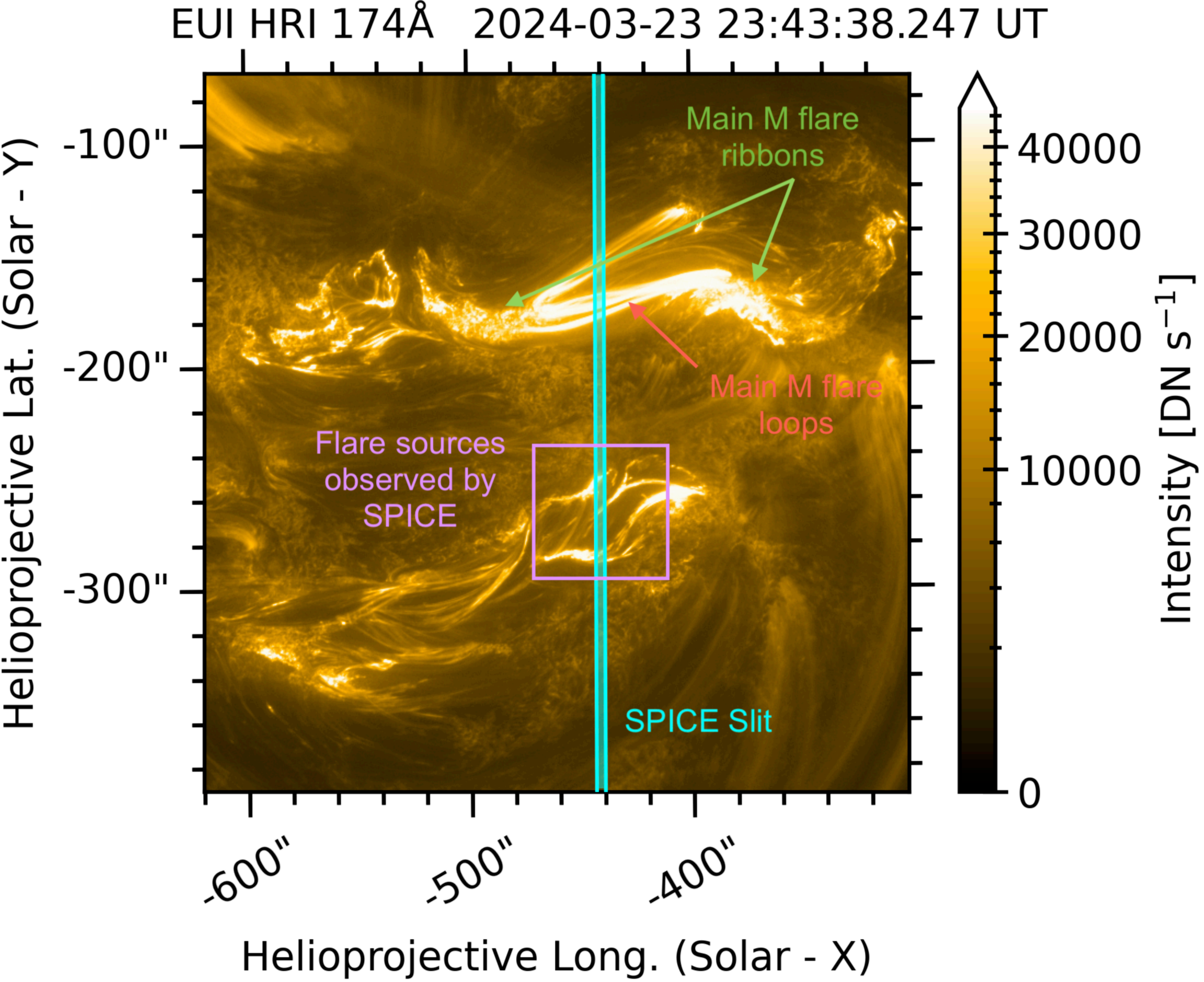
# FLARES AND MICROFLARES

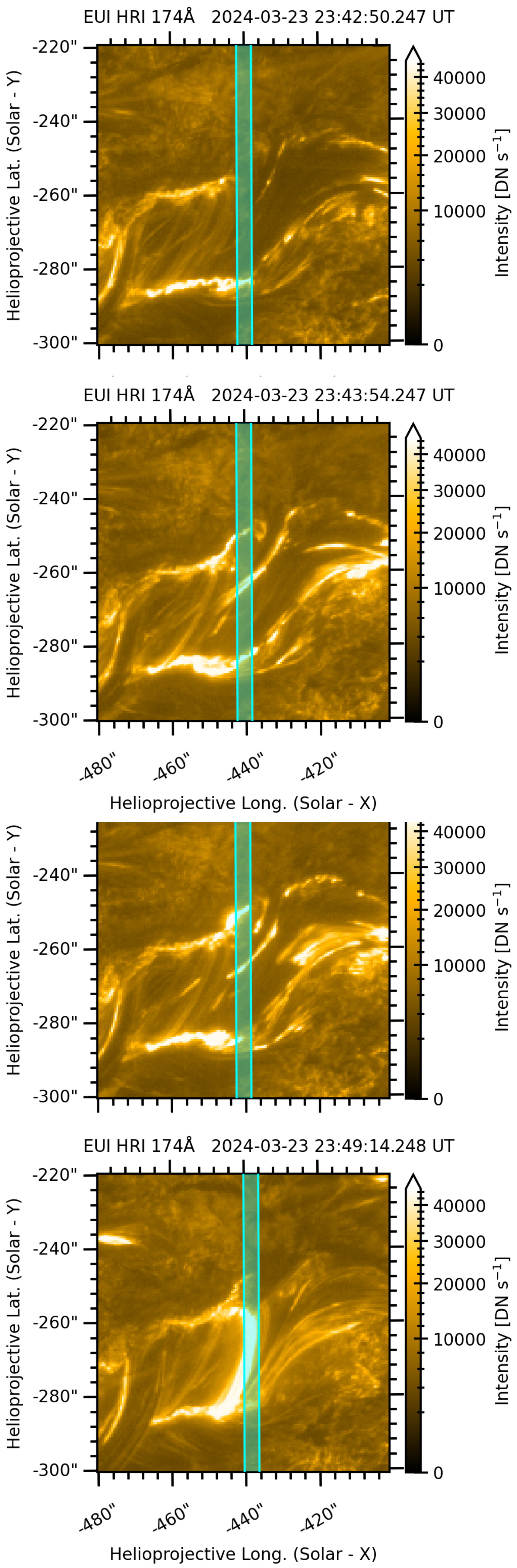
SPICE observed a series of sit-and-stare observations with 5s cadence during the spring 2024 major flare watch. So far there are two known events:

- 23rd March 2024 ~23:43UT

- 24th March 2024 ~01:43UT

Both flaring regions were complicated, with a large amount of activity.




# FLARE #1 OVERVIEW

SPICE observed a series of sit-and-stare observations with 5s cadence during the spring 2024 major flare watch. So far there are two known events:

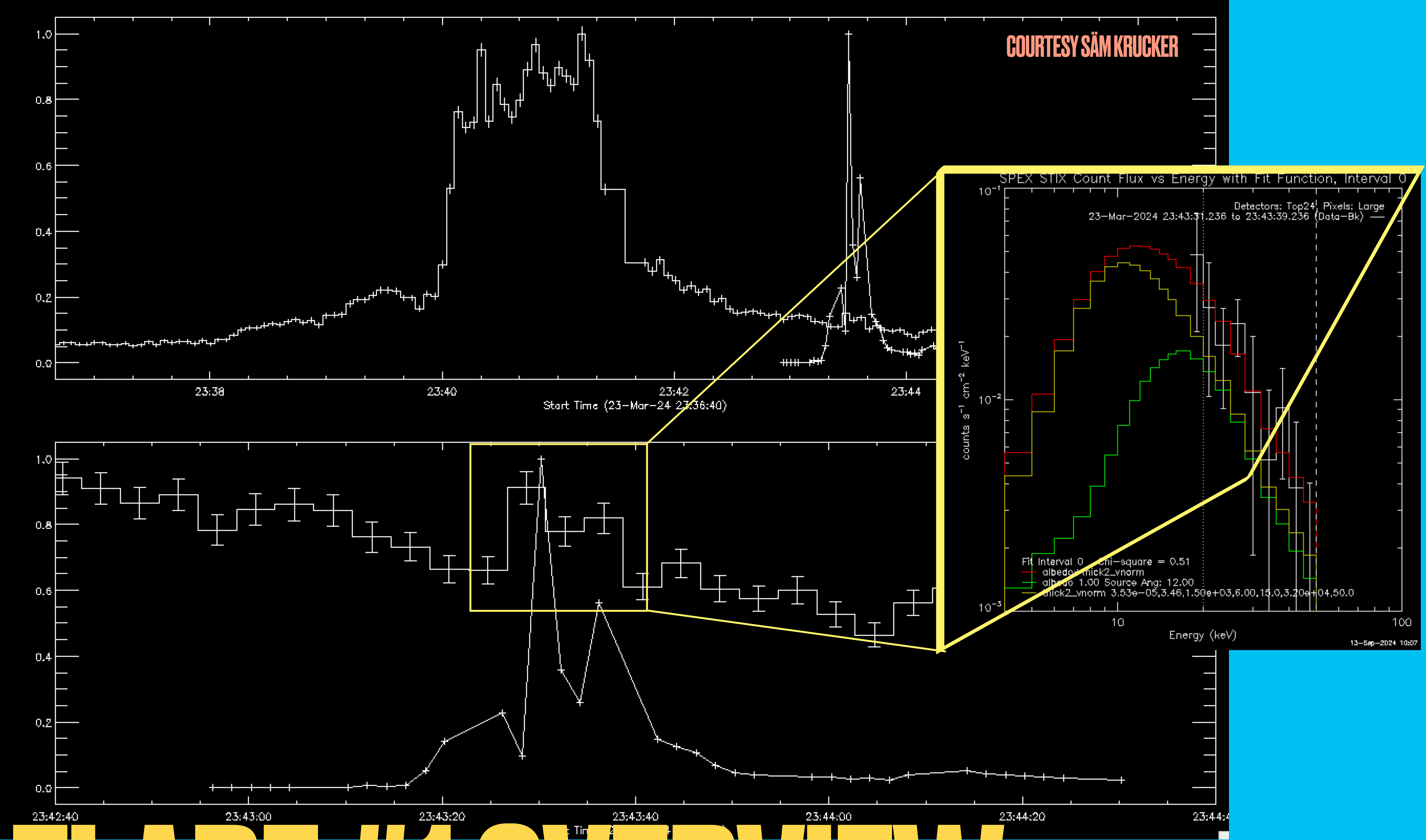
- 23rd March 2024 ~23:43UT (Flare #1)

- 24th March 2024 ~01:43UT (Flare #2)

**Flare #1:** SPICE observed a compact but intense brightening between larger sets of flare ribbons. Possibly a hard microflare (Battaglia et al 2024).

Two sources (strong and weak ribbons) caught by SPICE slit.

STIX observations show a small increase in HXRs at time of EUI / SPICE brightenings.

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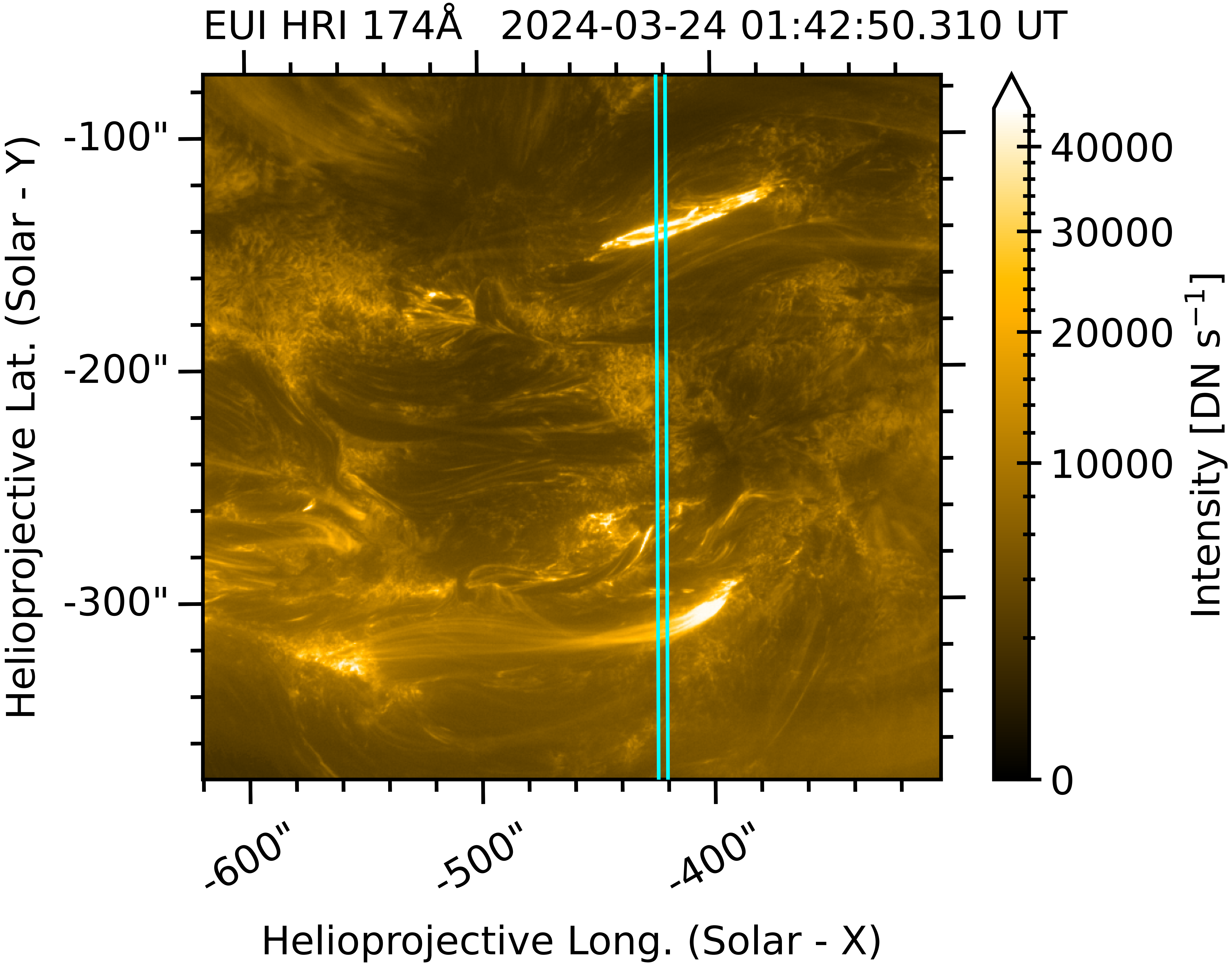
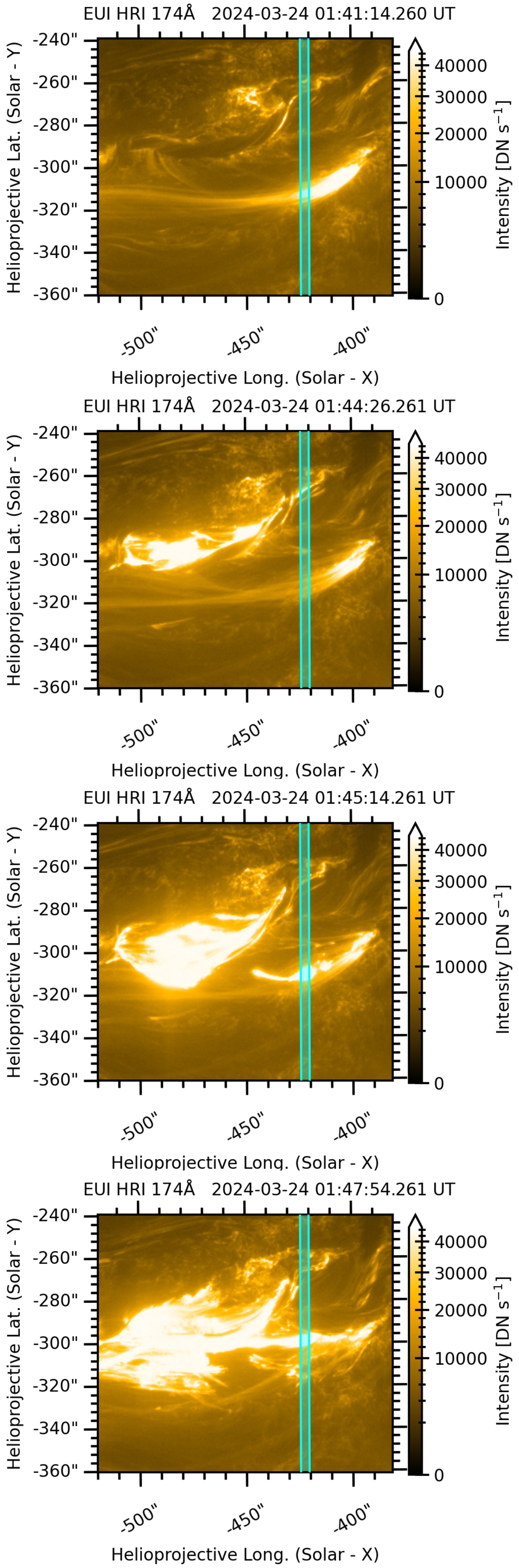



# FLARE #2 OVERVIEW




SPICE observed a series of sit-and-stare observations with 5s cadence during the spring 2024 major flare watch. So far there are two known events:

- 23rd March 2024 ~23:43UT (Flare #1)

- 24th March 2024 ~01:43UT (Flare #2)

**Flare #2**

Two sources from bouts of flare activity.

One ('other source') was a mix of footpoint and loop emission in north part of the field of view..

The second was a ribbon source adjacent within an M class flare, in south part of the field of view.

# OVERVIEW OF THE SPICE FLARE OBSERVATIONS

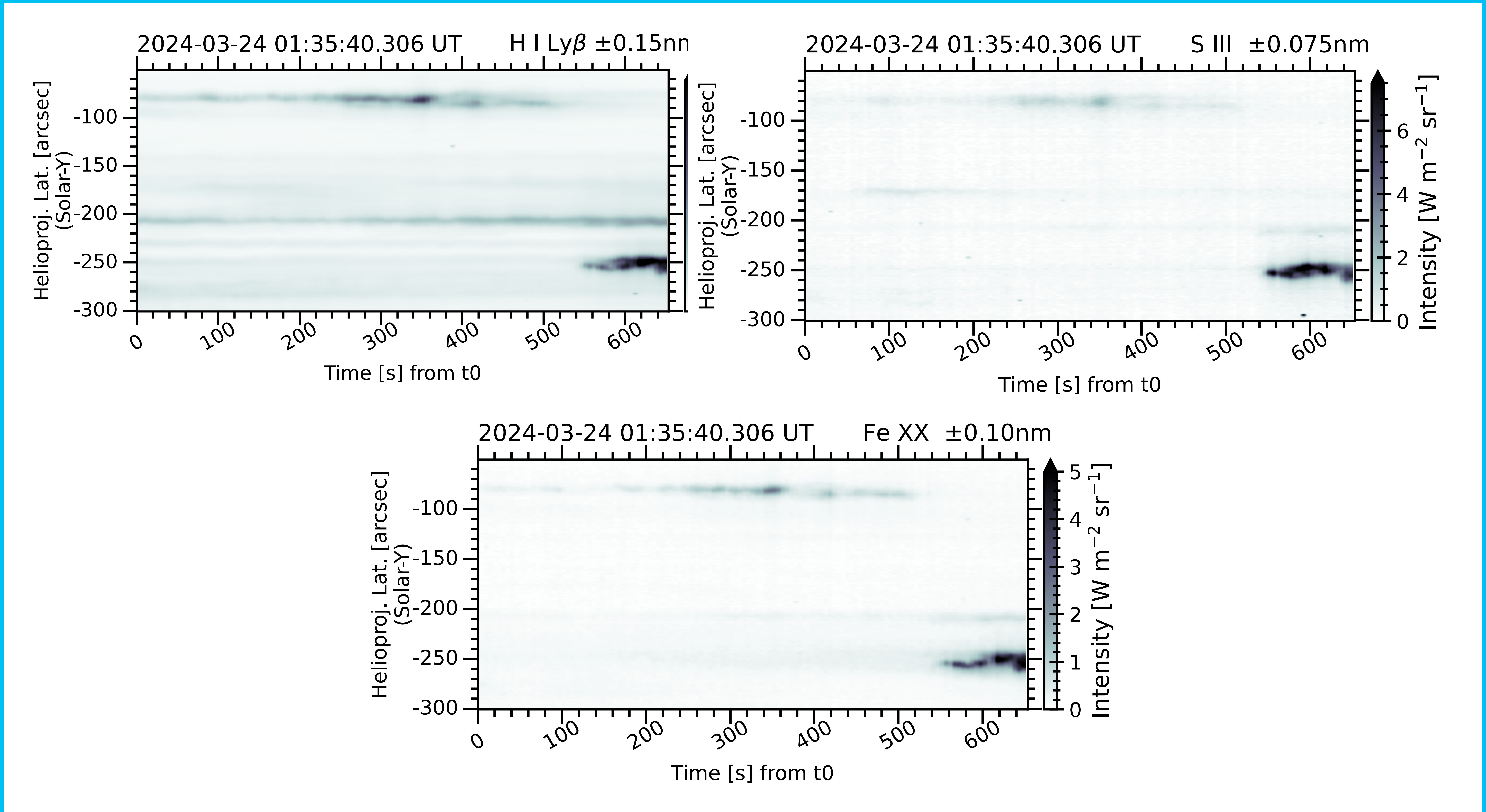
# SPECTRAL LINE LIST

- Many spectral lines were observed, covering logT = 4-7
- 5.1s cadence observations of chromosphere, transition region, and coronal response to the flares.
- Aim #1 was to search for signs of non-thermal protons, but no evidence yet (see Kerr et al 2023; Orrall & Zirker 1976).
- Aim #2 was to obtain high-cadence plasma response to flare energy injection.

| Window ID | Ion | $\lambda$ [nm] | Form. Temperature $\log T$ [K] | Spectral Binning | $\delta\lambda$ [nm] |
|---|---|---|---|---|---|
| O III 703 / Mg IX 706 (Merged) | O III[a] | 70.385 | 4.90 | 2 | 0.0195034 |
| | Mg IX | 70.606 | 6.00 | 2 | 0.0195034 |
| Fe XX 721 + O II (Merged) | O II | 71.850 | 4.45 | 2 | 0.0195034 |
| | Fe XX | 72.156 | 7.00 | 2 | 0.0195034 |
| N IV 765 - Peak | N IV | 76.515 | 5.15 | 2 | 0.0195034 |
| Ne VIII 770 - Peak | Ne VIII | 77.043 | 5.80 | 2 | 0.0195034 |
| Ly-g-CIII group (Merged) | H I Ly$\gamma$ | 97.254 | ~4.0 | 2 | 0.0192460 |
| | Fe XVIII | 97.486 | 6.85 | 2 | 0.0192460 |
| | C III | 97.702 | 4.85 | 2 | 0.0192460 |
| Ly beta blue continuum (Merged ) | S III[b] | 101.249 | 4.70 | 4 | 0.0384920 |
| | S III[b,c] | 101.550 | 4.70 | 4 | 0.0384920 |
| | S III[b,c] | 101.578 | 4.70 | 4 | 0.0384920 |
| Ly Beta 1025 (Merged) | H I Ly$\beta$ | 102.572 | ~4.0 | 2 | 0.0192460 |
| O VI 1032 (Merged) | O VI | 103.191 | 5.45 | 2 | 0.0192460 |
| O VI 1037 (Merged) | C II | 103.634 | 4.39 | 2 | 0.0192460 |
| | O VI | 103.761 | 5.45 | 2 | 0.0192460 |

# SPACETIME MAPS OF FLARE #1

# SPACETIME MAPS OF FLARE #2

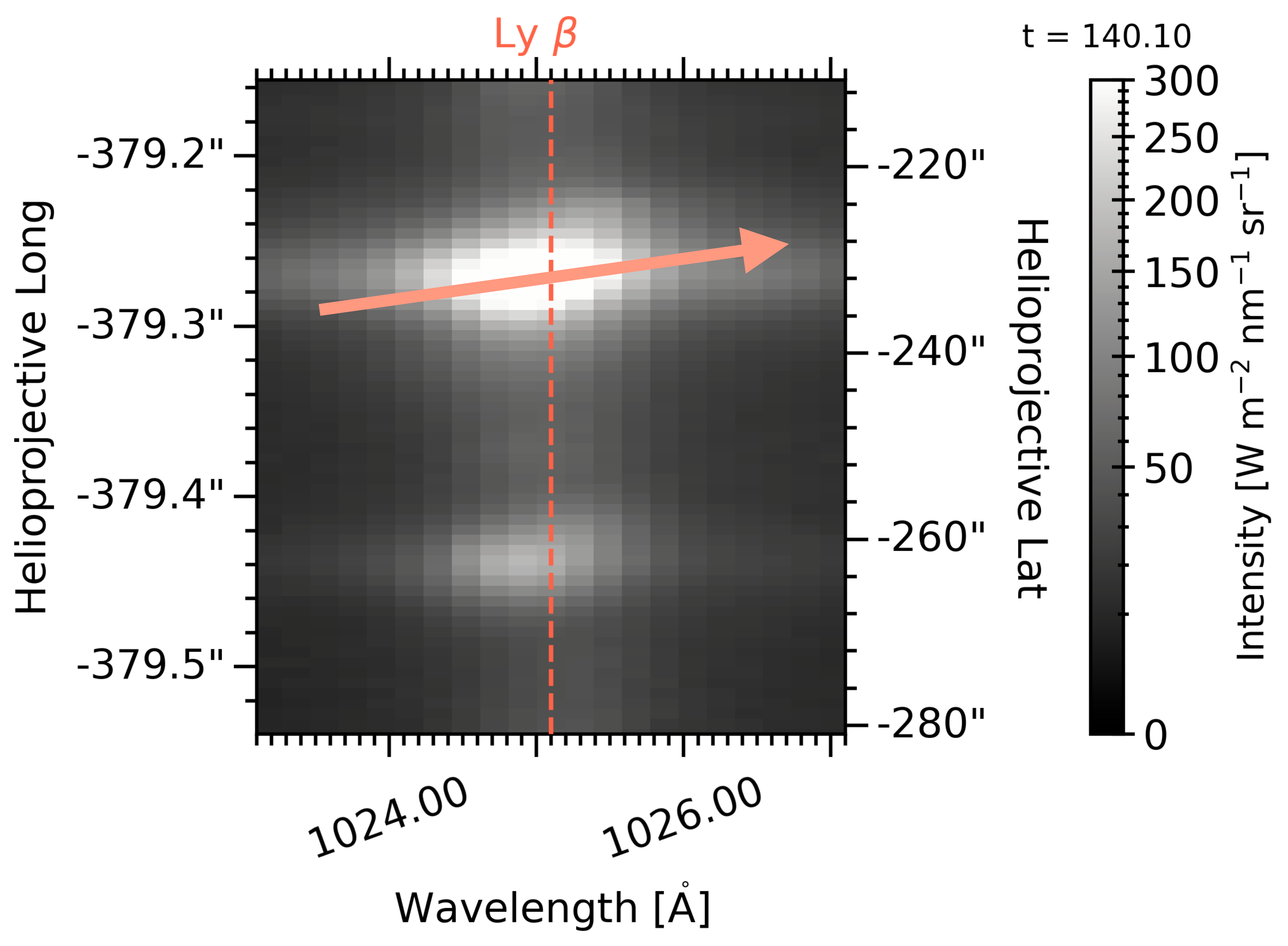


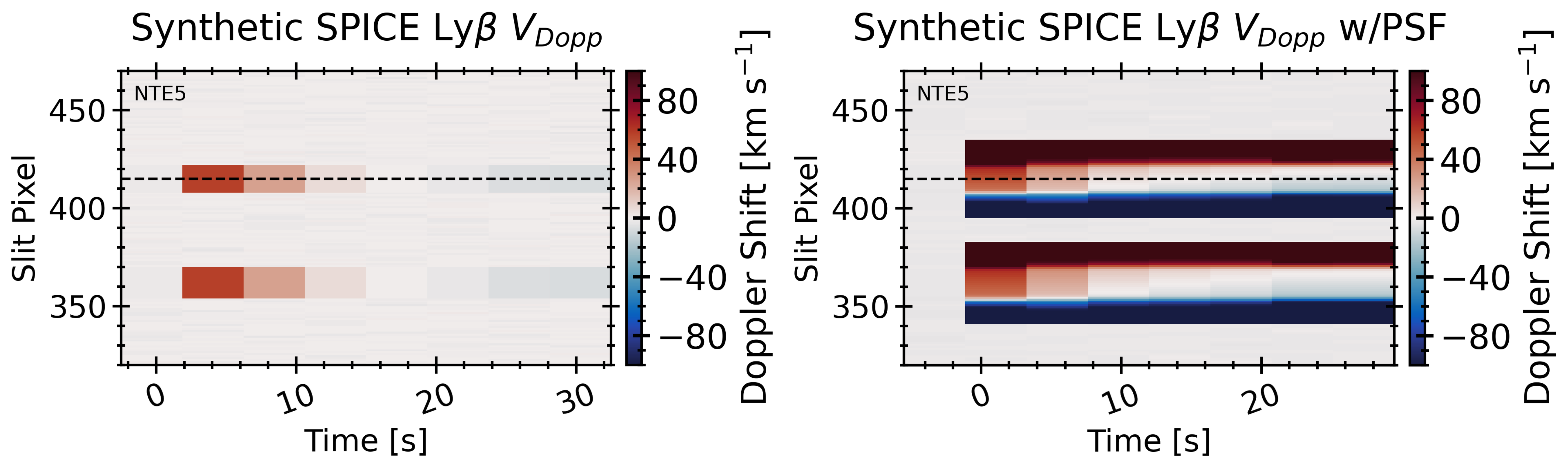
# LYMAN LINE DECREMENT

DUE TO SPICE'S 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 NON-THERMAL PROCESSES.

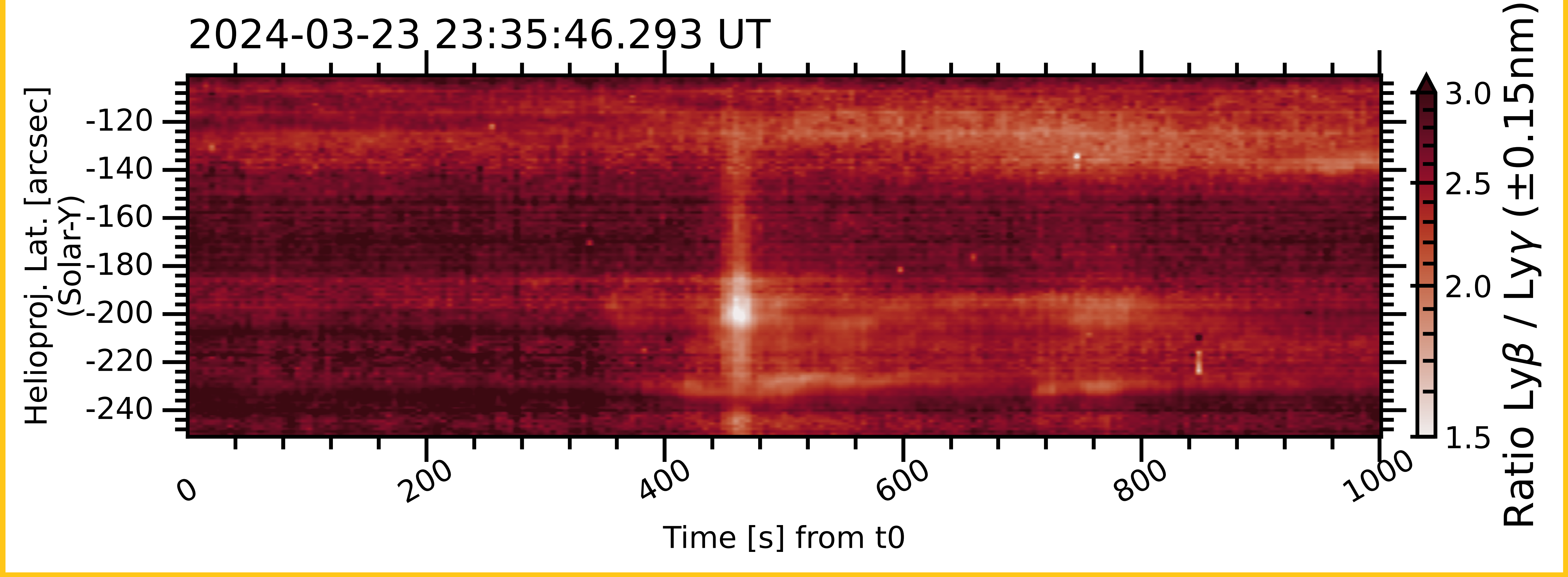


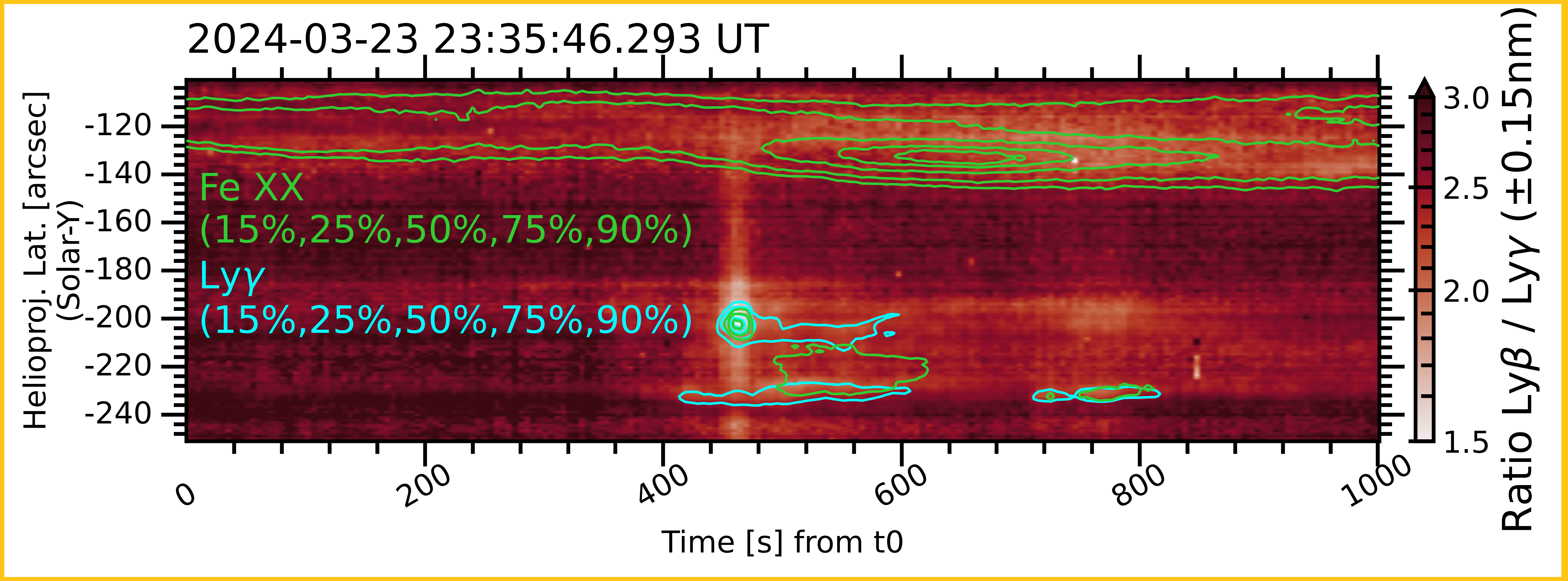



**FLARE #1**

# LYMAN DECREMENT MAP

- There are transient decrease of ratio and rapid return to pre-flare, in stronger ribbon source.
- Weaker ribbon source doesn't really vary shows a more gradual and more modest decrease.

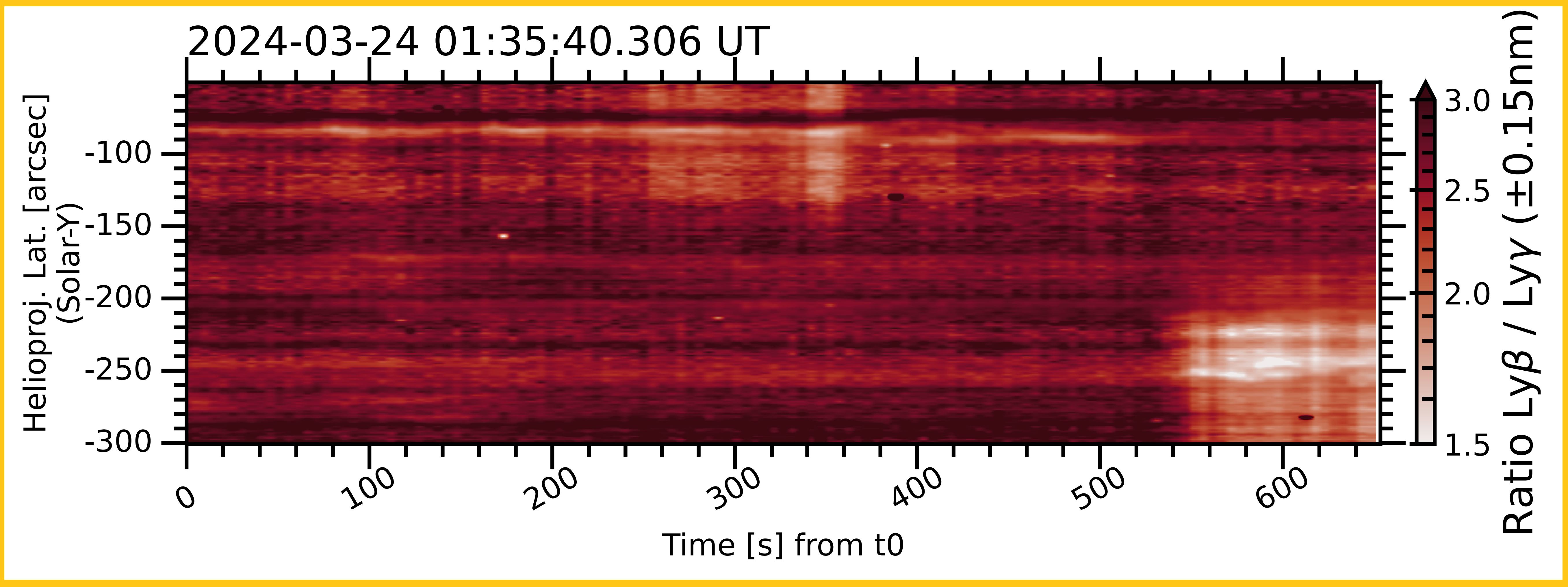


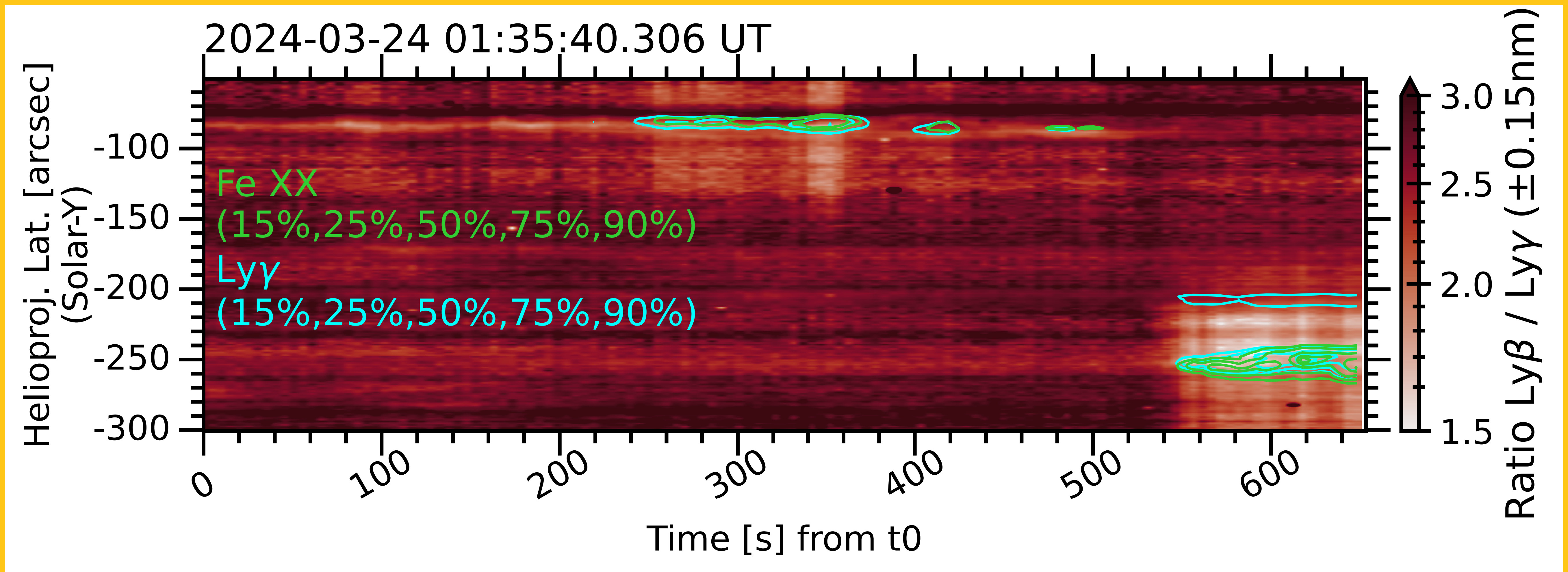



## FLARE #2

# LYMAN DECREMENT MAP

- Ribbon source in south shows large decrease, but more longer lived — this source was less compact than in Flare #1 so possibly a mixing of multiple footpoints.
- The other source in the north shows a few transient decreases.

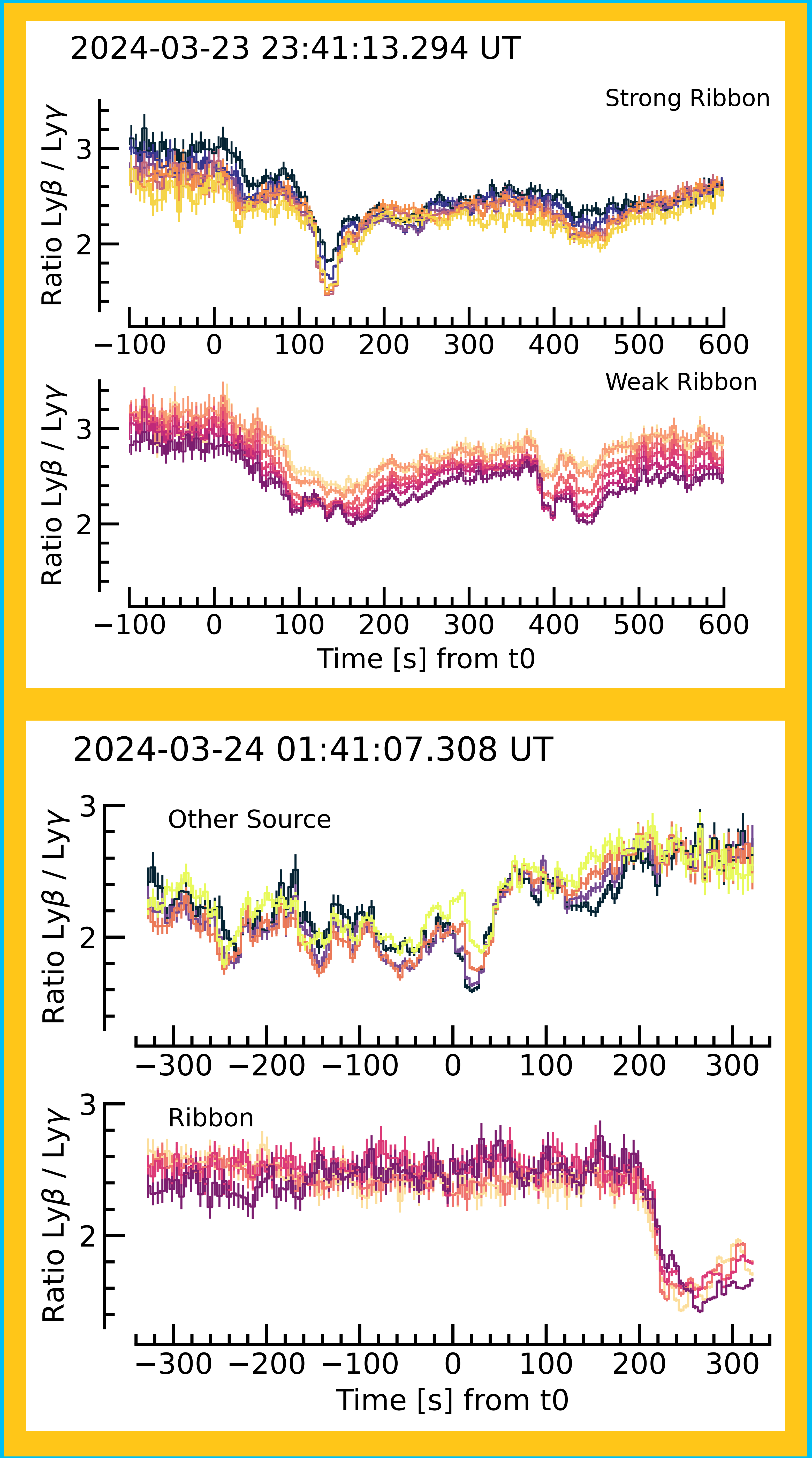


# LYMAN DECREMENT LIGHTCURVES

- Seems to three different behaviors:

1. Transient, impulsive decrease to Rβγ < 2
2. Gradual, longer-lived decrease to Rβγ > 2.
3. Impulsive decease to Rβγ < 2, but longer-lived.

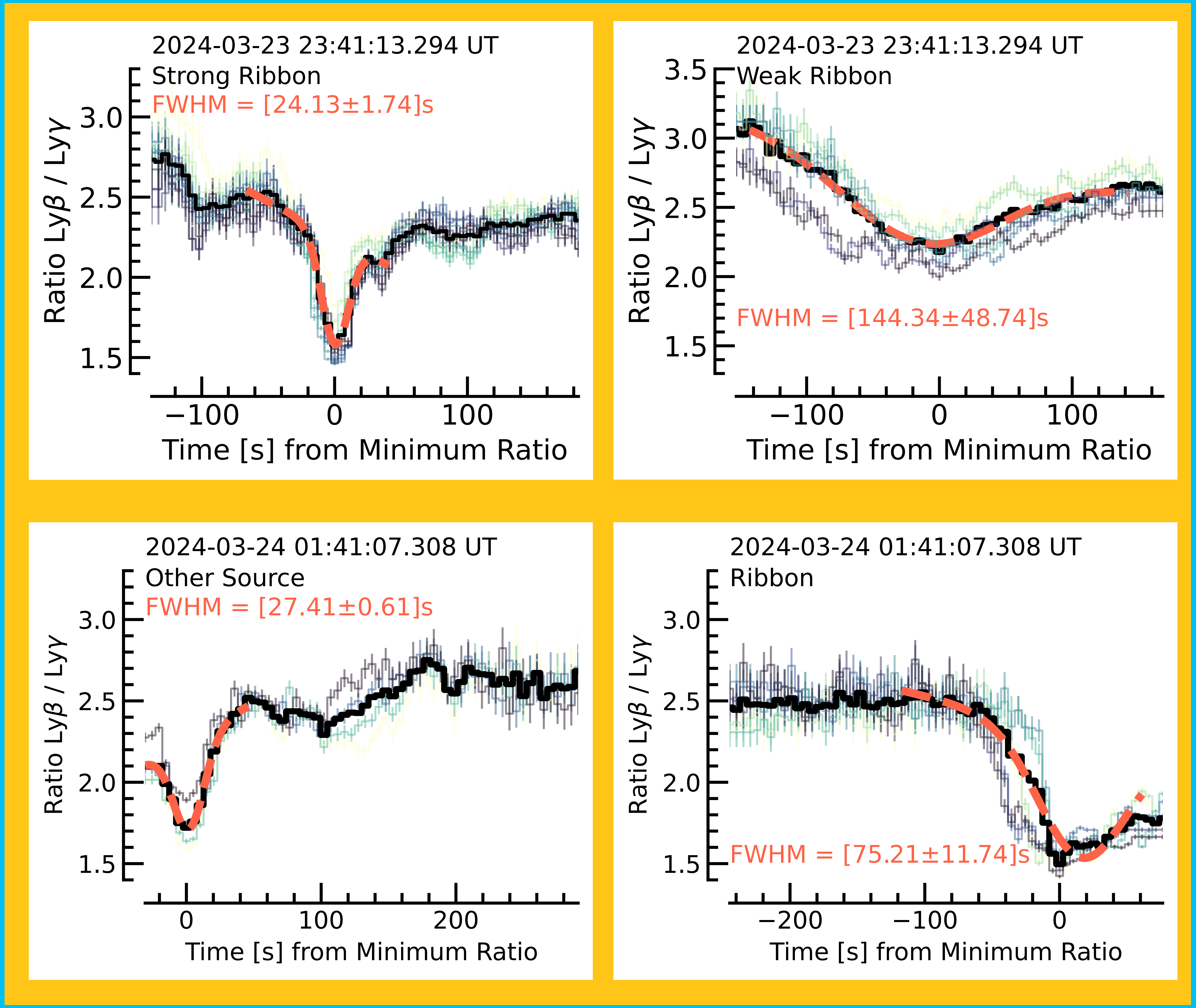


# LYMAN DECREMENT LIGHTCURVES

- Seems to three different behaviors:

  1. Transient, impulsive decrease to $R_{\beta\gamma} < 2$
  2. Gradual, longer-lived decrease to $R_{\beta\gamma} > 2$.
  3. Impulsive decease to $R_{\beta\gamma} < 2$, but longer-lived.

- Superposing the lightcurves shows the different lifetimes.



# COMPARING TO RHD MODELS

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

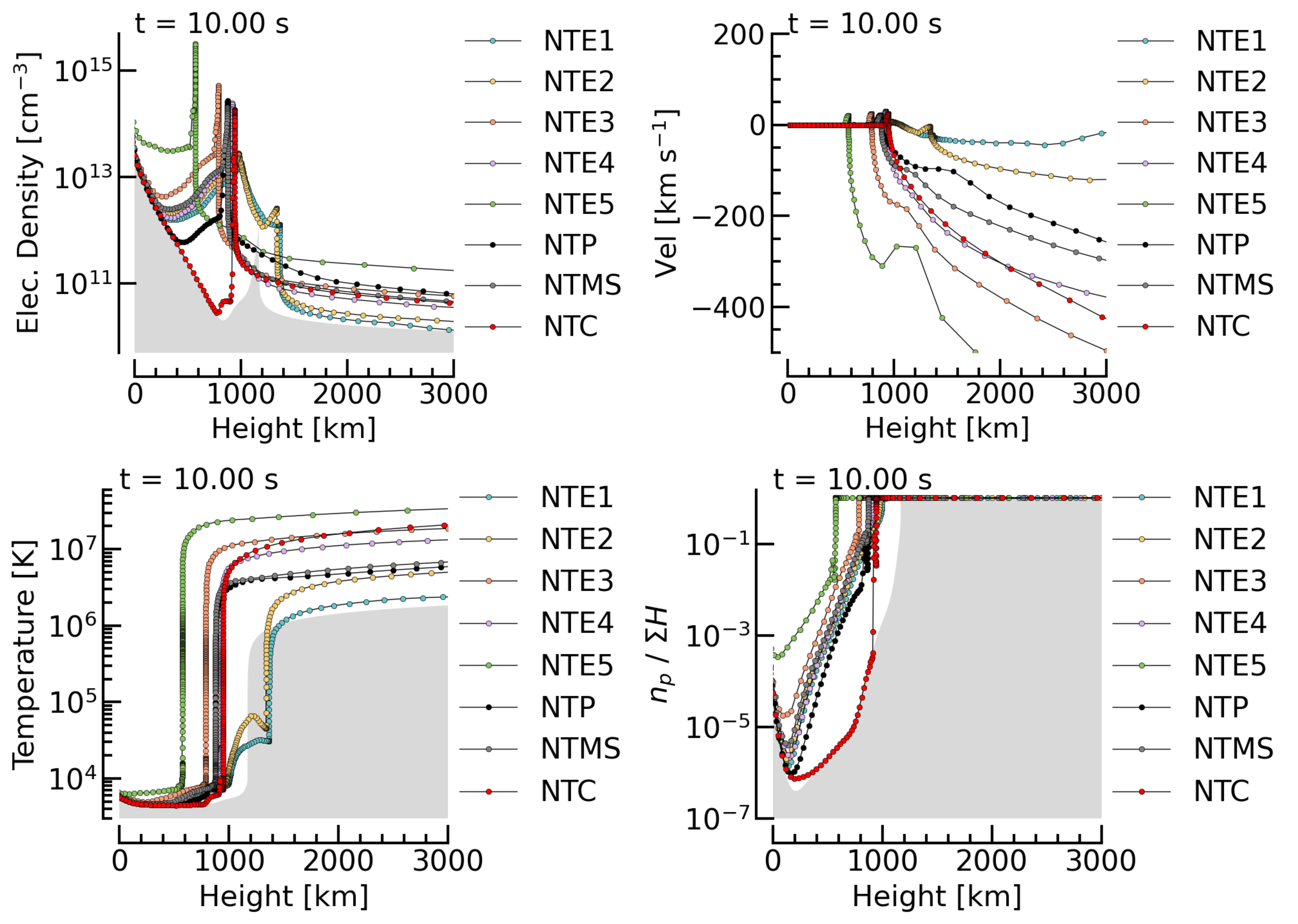
# MODEL PARAMETERS

- Hypothesis: SPICE is sampling different parts of flare ribbons, so energy flux density or physical processes are different.
- To determine what Rβγ can tell us about either the energy flux density injected to the lower atmosphere, or the mechanism by which it was injected a series of RADYN simulations were produced.
  - Non-thermal electron driven flares (NTE);
  - Non-thermal proton driven flares (NTP);
  - Multi-species particle distributions (NTMS);
  - *In-situ* coronal heating

| Label | Mechanism | Flux Density, $F$ [erg s$^{-1}$ cm$^{-2}$] | Injection Duration [s] | Fluence, $F_{total}$ [erg cm$^{-2}$] | $\delta$ | $E_c$ [keV] |
|---|---|---|---|---|---|---|
| NTE1 | Nonthermal electrons | $4.4 \times 10^9$ | 20 | $8.8 \times 10^{10}$ | 3.5 | 20 |
| NTE2 | Nonthermal electrons | $1.6 \times 10^{10}$ | 20 | $3.2 \times 10^{11}$ | 3.5 | 15 |
| NTE3 | Nonthermal electrons | $1.0 \times 10^{11}$ | 20 | $2.0 \times 10^{12}$ | 3.5 | 10 |
| NTE4 | Nonthermal electrons | $5.0 \times 10^{10}$ | 20 | $1.0 \times 10^{12}$ | 4.0 | 10 |
| NTE5 | Nonthermal electrons | $5.0 \times 10^{11}$ | 20 | $1.0 \times 10^{13}$ | 4.0 | 10 |
| NTP | Nonthermal protons | $1.6 \times 10^{10}$ | 20 | $3.2 \times 10^{11}$ | 3.5 | 50 |
| NTMS | Nonthermal protons + | $1.0 \times 10^{10}$ | 20 | $2.0 \times 10^{11}$ | 3.5 | 50 |
| | Nonthermal electrons | $1.6 \times 10^{10}$ | 20 | $3.2 \times 10^{11}$ | 3.5 | 15 |
| TC | *In-Situ* ('direct') Heating | $3.0 \times 10^{10}$ | 20 | $6.0 \times 10^{11}$ | - | - |

**NTE1-3 and electron part of NTMS guided by STIX**

# ATMOSPHERIC EVOLUTION



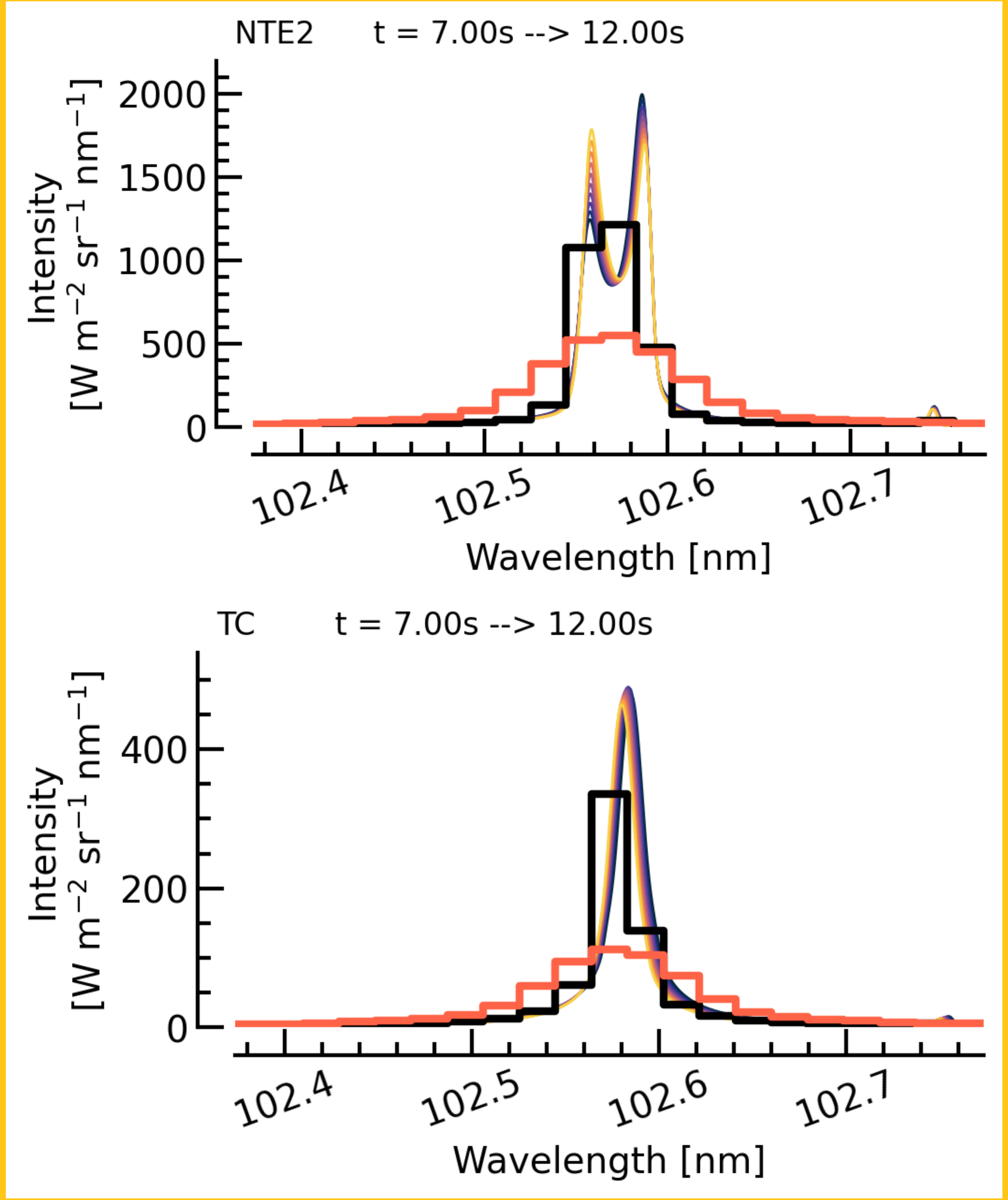
# MODEL -> SYNTHETIC SPICE

- 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.**

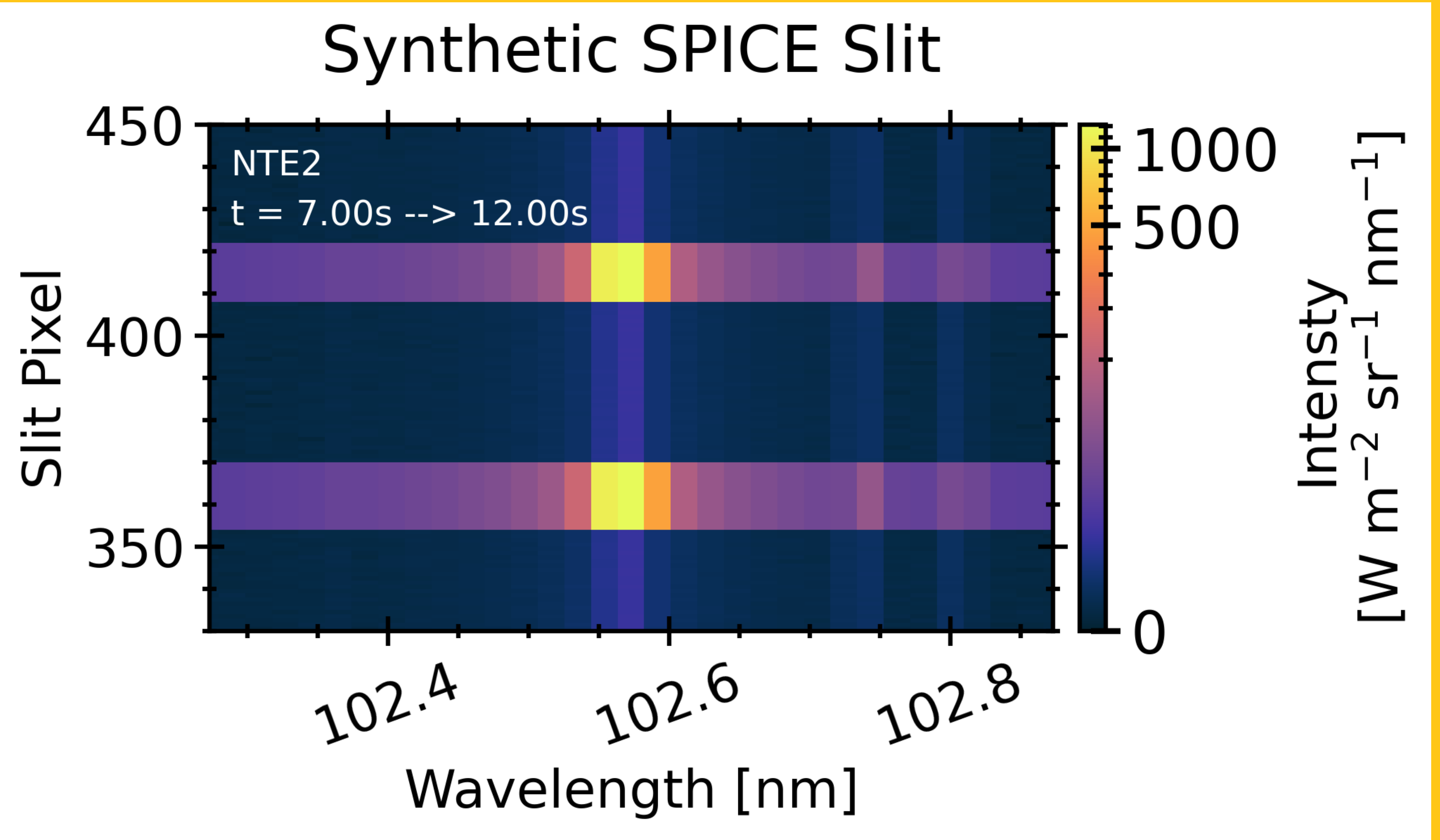
**Black is the SPICE spectra, without PSF.**

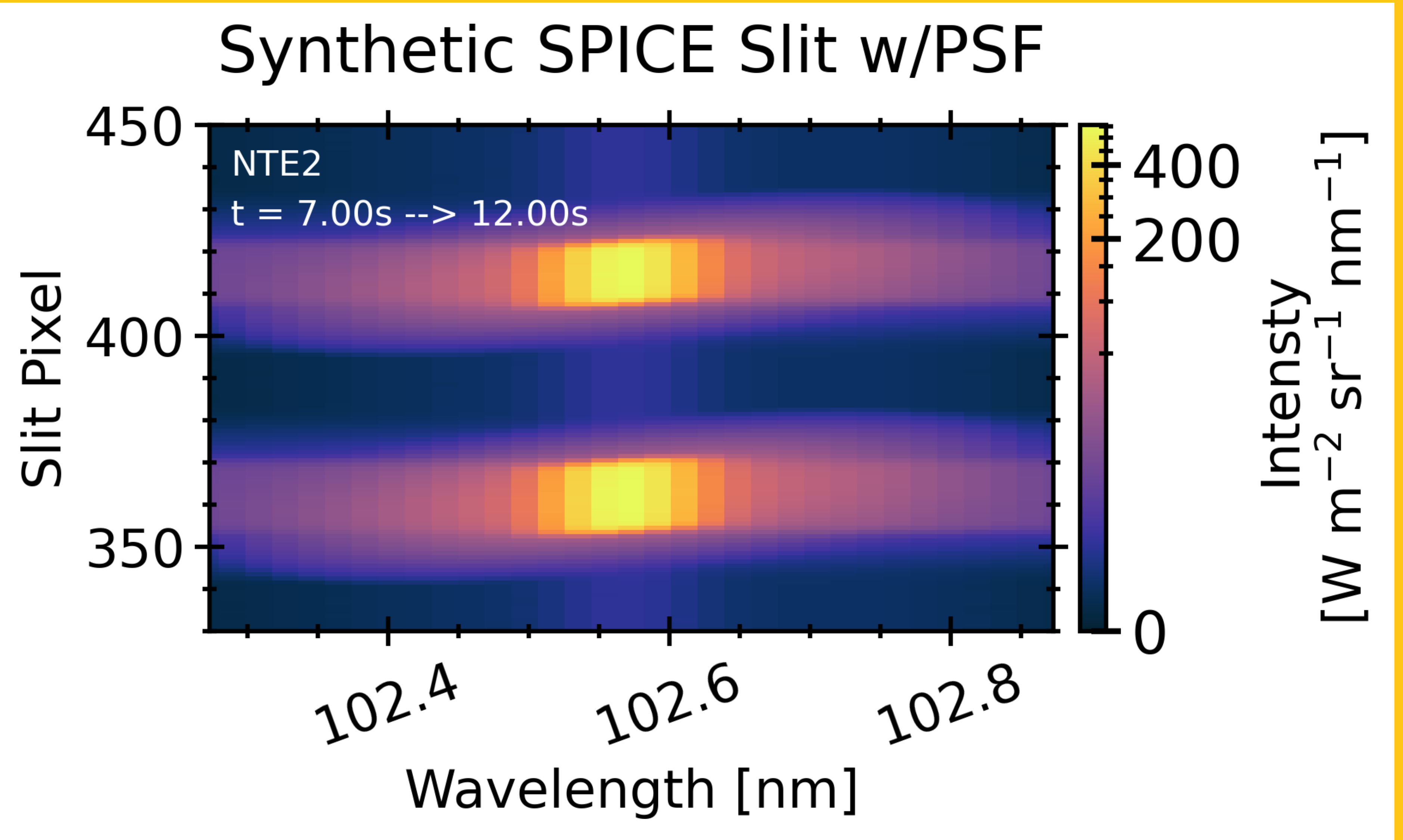
**Red is with PSF applied (see later).**



# MODEL -> SYNTHETIC SPICE

- An artificial sit-and-stare observation was created, very ad-hoc for now (can be more creative in future, e.g. different simulations for each ribbon etc.,). Wavelength and spatial dimensions guided by observations.
- This was passed through Joe Plowman's SHARPPEST tools to apply a titled PSF.



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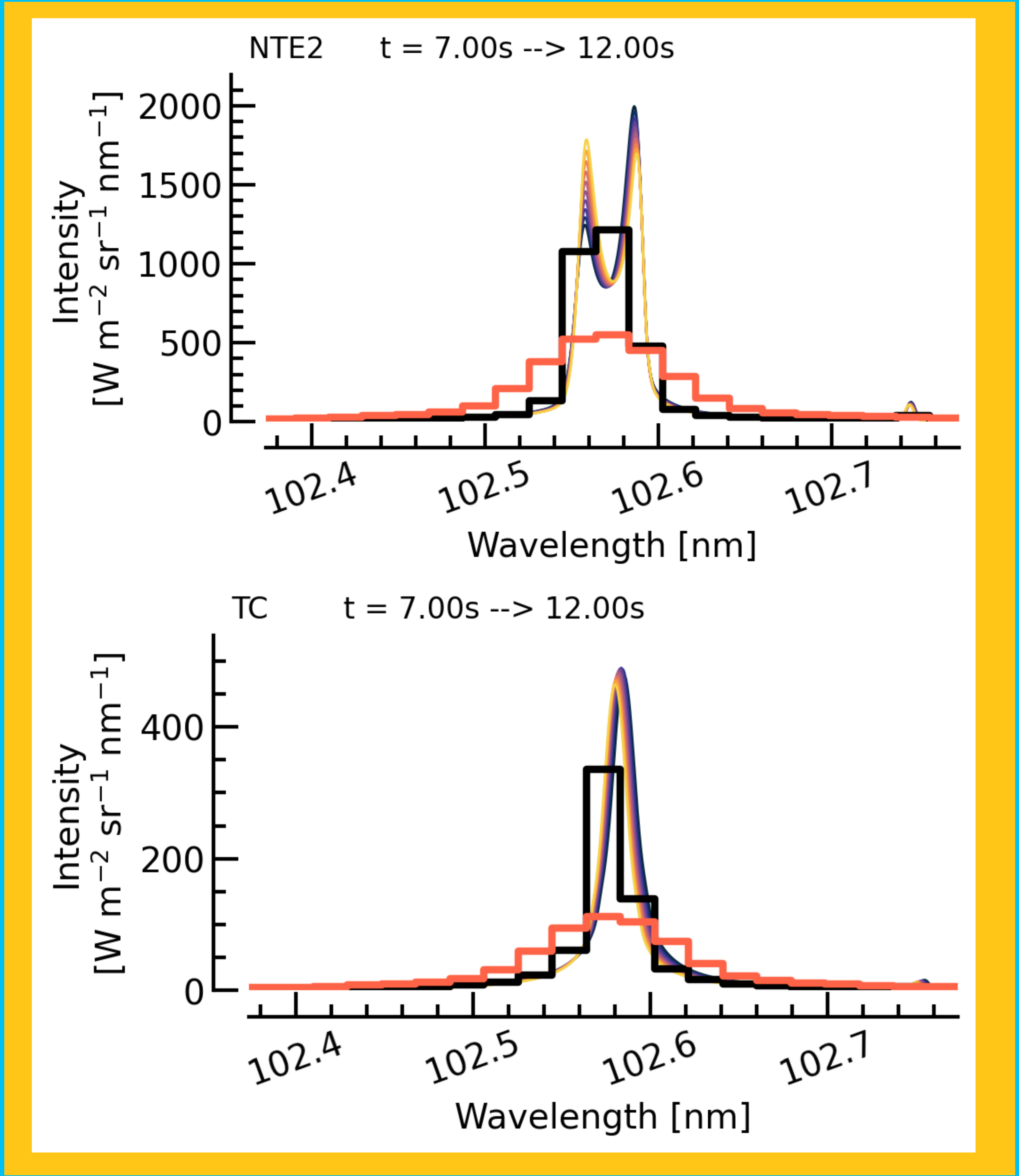
  - ✦ Converted to photon number;
  - ✦ Folding through SPICE effective area;
  - ✦ Summed through exposure time and readout time;
  - ✦ Added Poisson noise;
  - ✦ Converted back to physical units.
- PSF (red) results in a broader profile with weaker core.

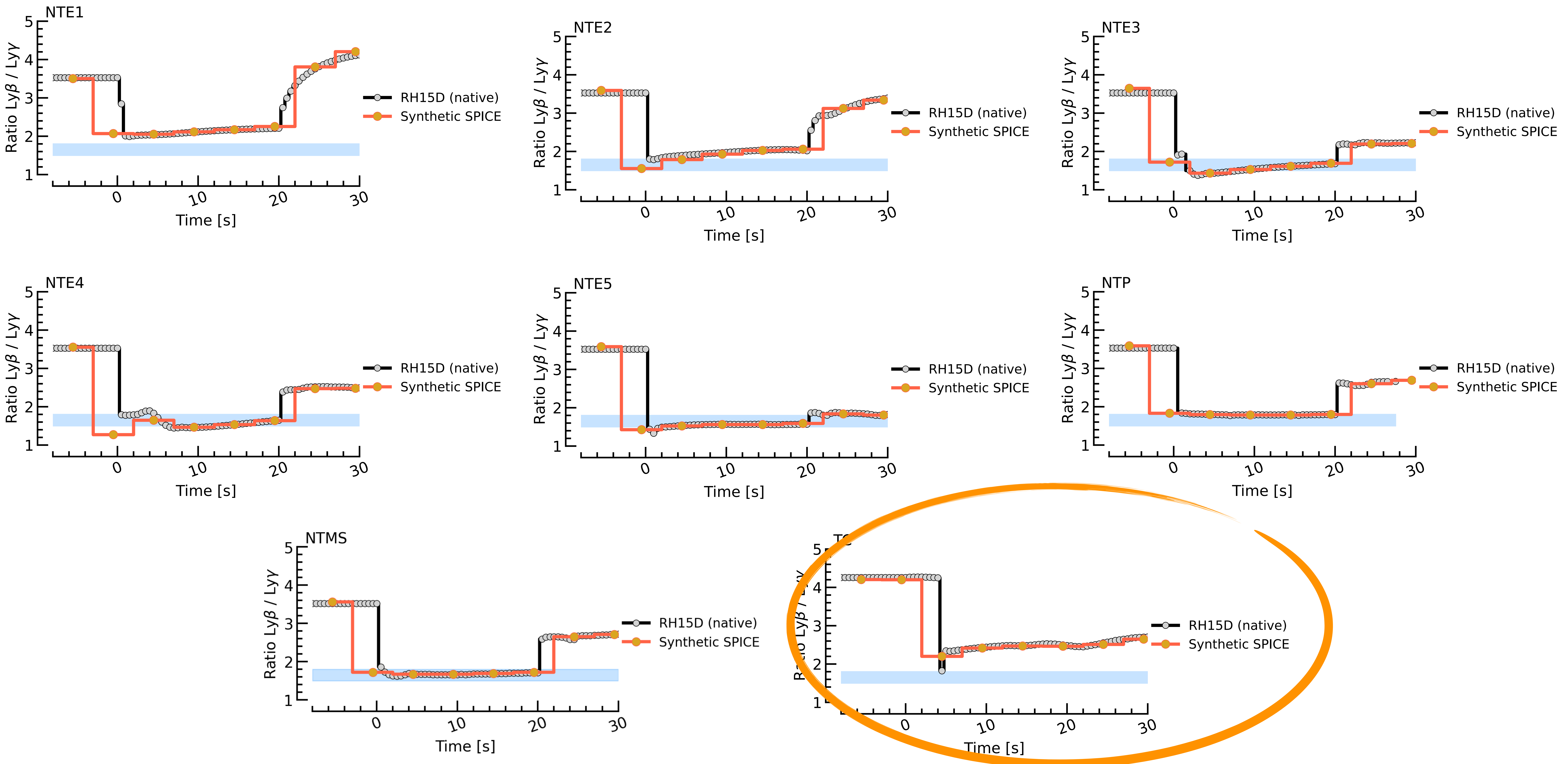
**Coloured lines are spectra appearing in this exposure.**

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

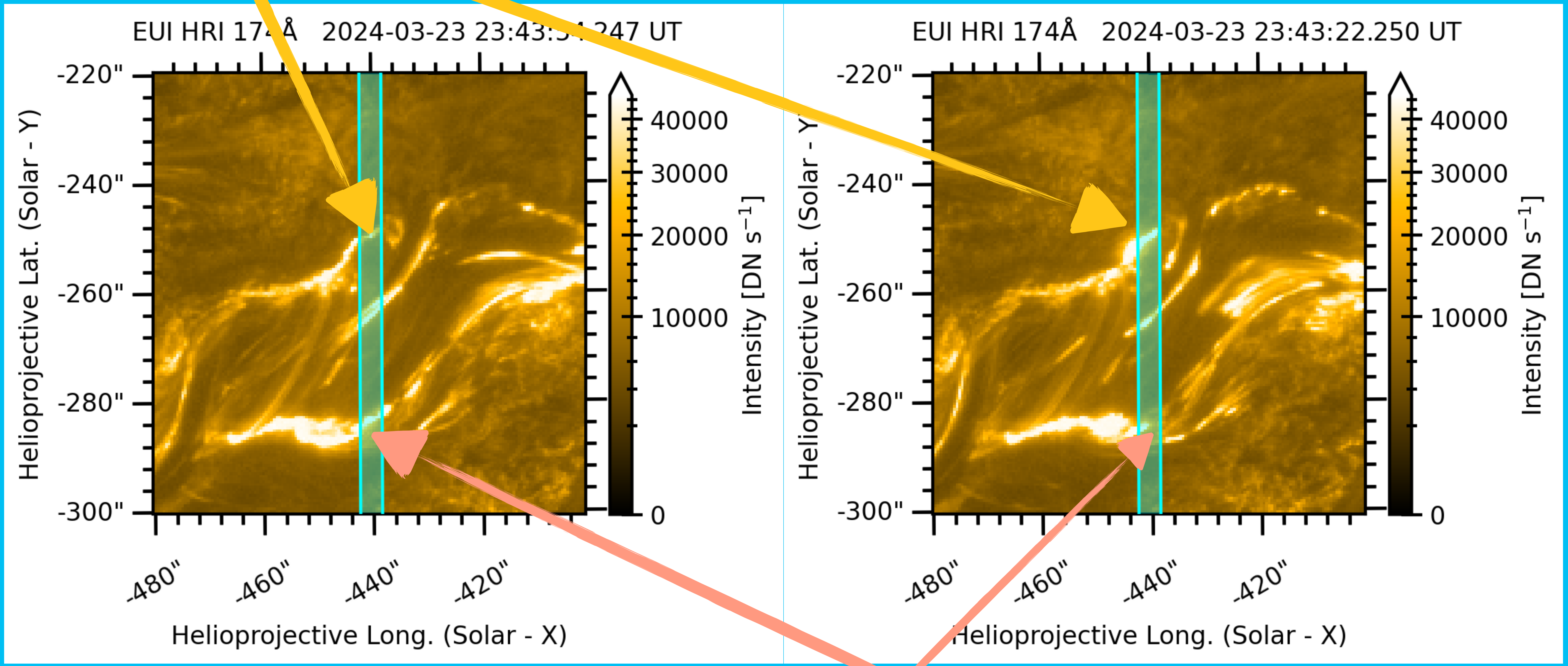
**Red is with PSF applied**



# LYMAN DECREMENT IN FLARE MODELS



Consistent with particle beam precipitation

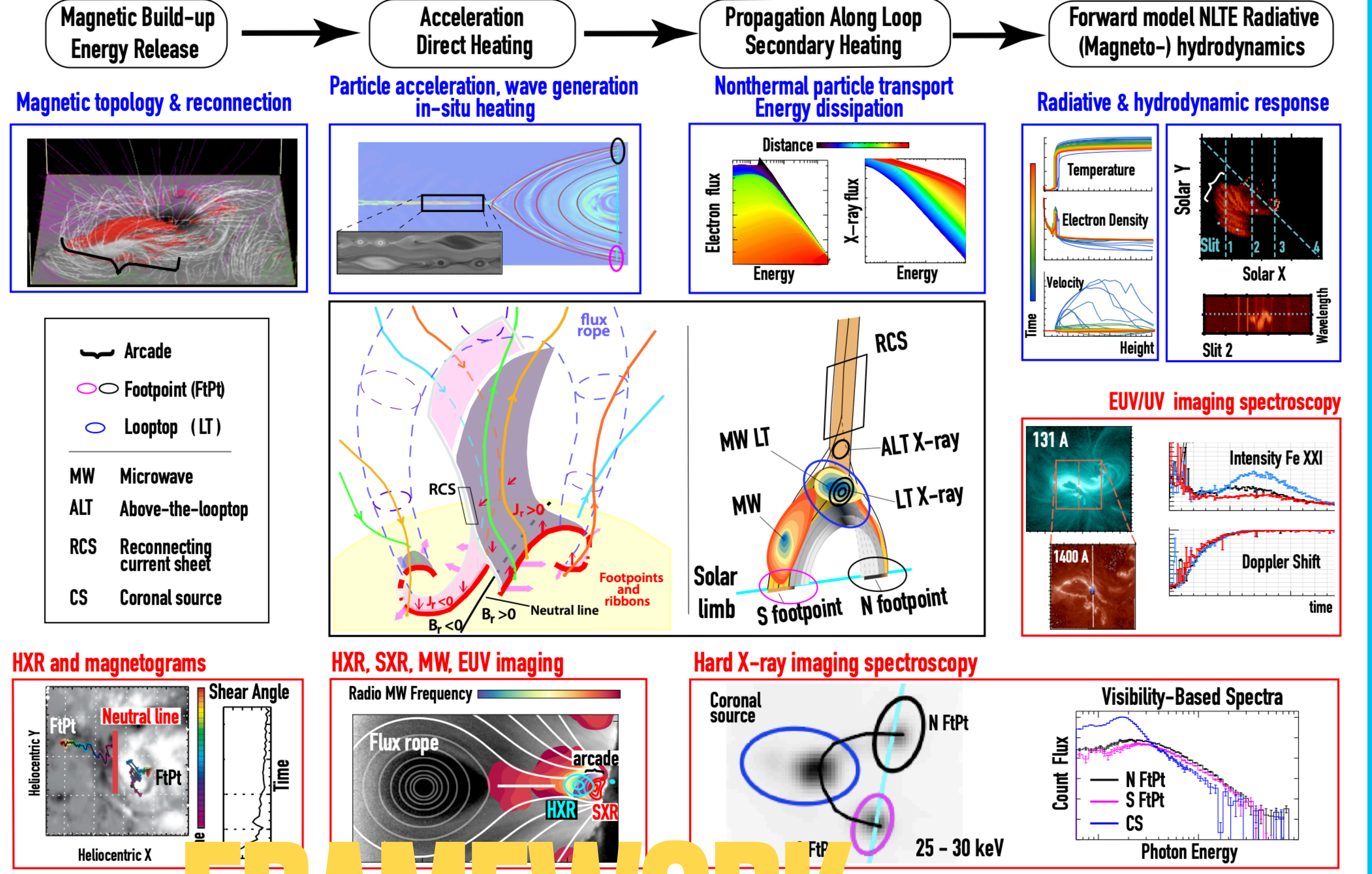



Consistent with heat flux from hot corona

# NEXT STEPS IN SOLAR FLARE MODELING

**LINKING MODELS TO PRODUCE END-TO-END SIMULATIONS OF SOLAR FLARES**

Joel Allred, Joel Dahlin, Rick DeVore, Silvina Guidoni, Judy Karpen, Graham Kerr, Marc Swisdak, & Valeriy Tenishev

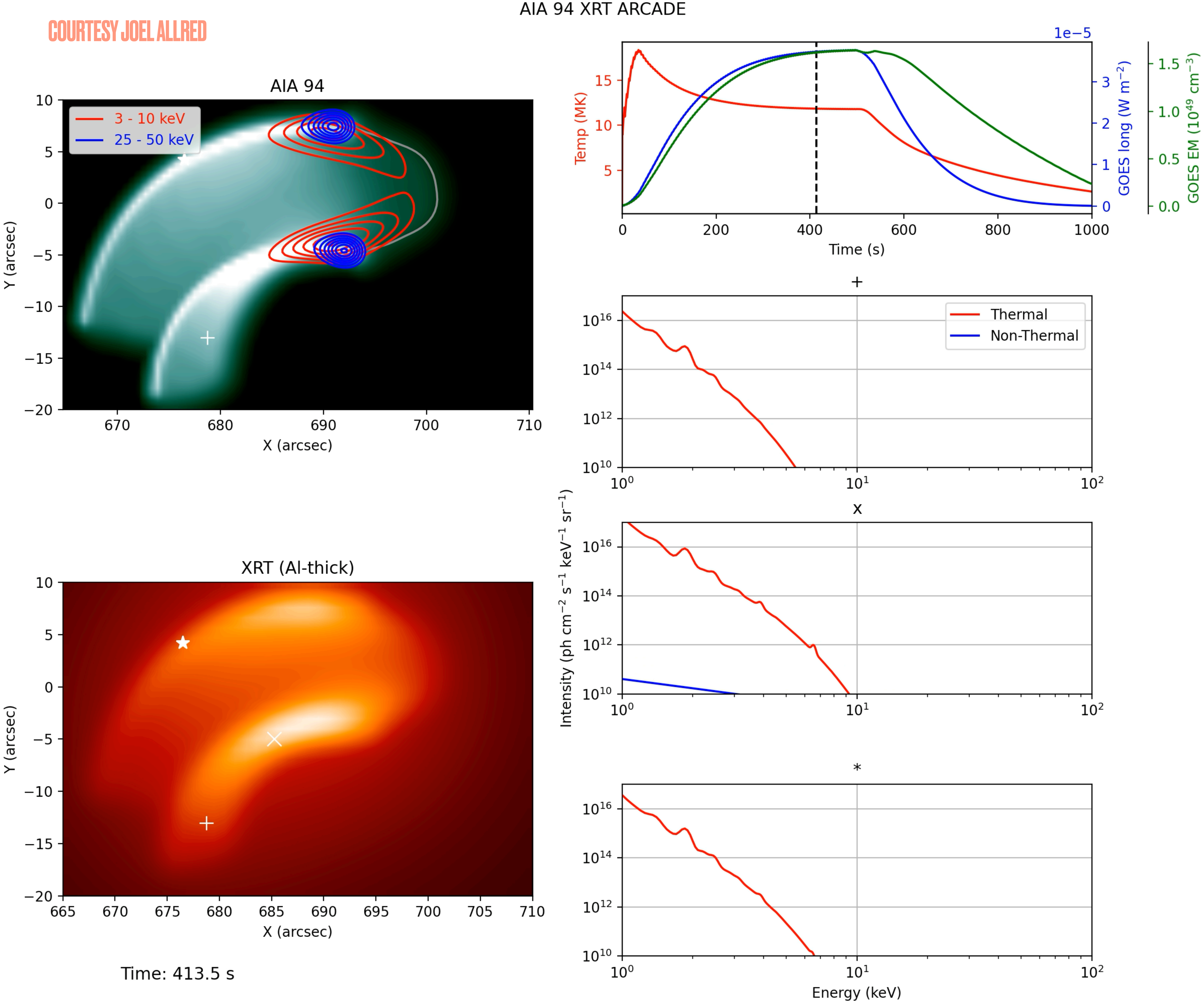



# FRAMEWORK

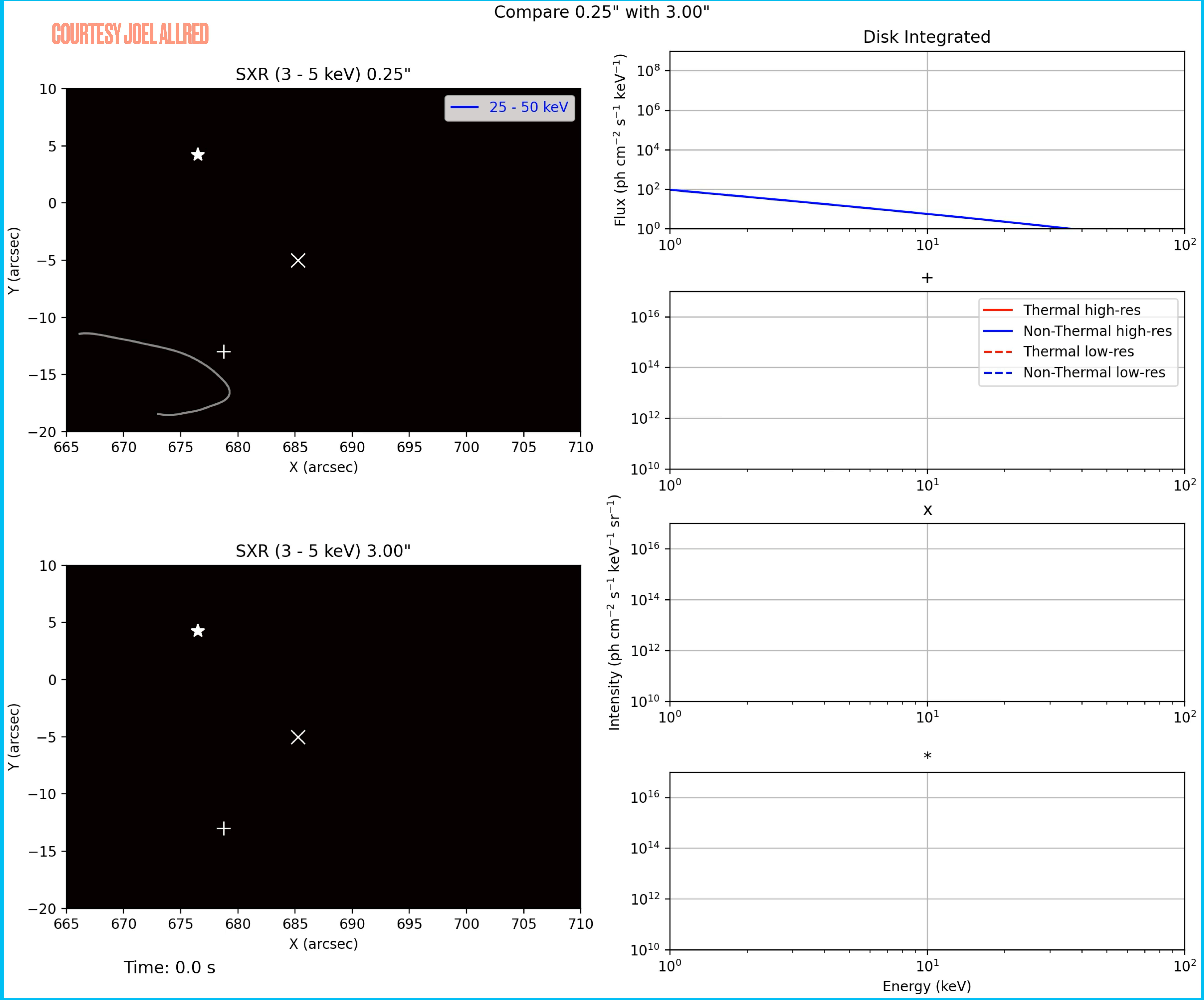
Flares cross vast array of scales, from MHD to kinetic… 10 orders of magntiude!

**Modelling all of the important physical processes involved, at the relevant spatial and temporal scales, is a severe challenge.**

**Here we link models, in one direction, with the output of one driving the the next model: energy build up all the way through to chromospheric response.**



AIA 94 XRT ARCADE
COURTESY JOEL ALLRED
AIA 94
3 - 10 keV
25 - 50 keV
Y (arcsec)
X (arcsec)
XRT (Al-thick)
Time: 413.5 s
Temp (MK)
GOES long (W m$^{-2}$)
GOES EM ($10^{49}$ cm$^{-3}$)
1e−5
Time (s)
Thermal
Non-Thermal
Intensity (ph cm$^{-2}$ s$^{-1}$ keV$^{-1}$ sr$^{-1}$)
Energy (keV)


Compare 0.25" with 3.00"
COURTESY JOEL ALLRED
SXR (3 - 5 keV) 0.25"
25 - 50 keV
Y (arcsec)
X (arcsec)
SXR (3 - 5 keV) 3.00"
Y (arcsec)
X (arcsec)
Time: 0.0 s
Disk Integrated
Flux (ph cm$^{-2}$ s$^{-1}$ keV$^{-1}$)
+
Thermal high-res
Non-Thermal high-res
Thermal low-res
Non-Thermal low-res
x
*
Intensity (ph cm$^{-2}$ s$^{-1}$ keV$^{-1}$ sr$^{-1}$)
Energy (keV)

# SUMMARY

- Observational analysis:
  - ➡No obvious Orrall-Zirker effect;
  - ➡High cadence observations of a compact source;
  - ➡Lyβ / Lyγ ratio can show a strong, impulsive and transient decrease or a gradual, long-lived, modest decrease;
- RHD modelling of the event:
  - ➡ 5 electron beam simulations, 1 proton beam simulation, 1 multi-species beam simulation, 1 thermal conduction-only simulation;
  - ➡ Synthesized Lyβ and Lyγ lines, and studied formation properties;
  - ➡ Produced synthetic SPICE slit, including PSF;
  - ➡Strong and transient Lyman decrement decrease consistent with observations only in particle beam scenario.
  - ➡Doppler motions strongly affected by PSF, but a slice through middle of source is sufficiently free of artifacts.
- Next steps:
  - ➡Further study of plasma evolution in the flare.
  - ➡Work on further constraints of energy flux density (Andrea's hard microflare study should be useful!)
  - ➡Hints of very fast downflows, but need to deal with PSF and analyze properly.
  - ➡Apply RADYN_Arcade framework to the Major Flare Watch observations.