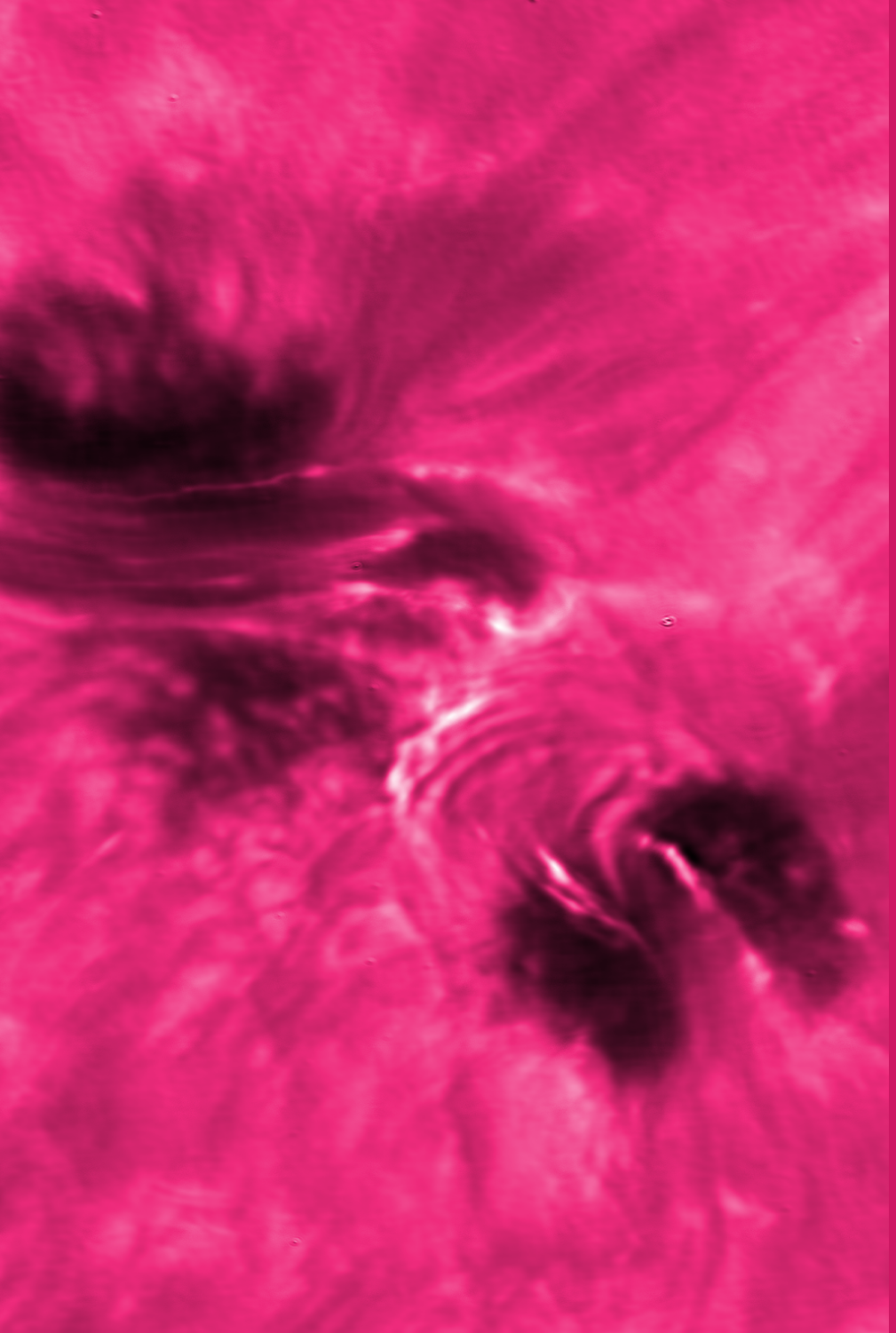


Clustering analysis of dynamical signatures and their evolution in high-resolution flare observations by DKIST

S. Riley[1, 2]

[1]Montana State University,
Department of Physics
[2]DKIST Ambassador

National Solar Observatory Seminar
2025 August 19

Outline

1. Introduction
   - Solar flares
   - Dynamical signatures
   - Science objectives
2. Analysis
   - k-means
3. 2022 Dec 27
   - Flare overview
   - Clustering results
   - Epoch-driven approach
4. 2023 May 05
   - Flare overview
   - Clustering results
   - Evolution-driven approach
5. Concluding remarks

Anatomy of solar flares

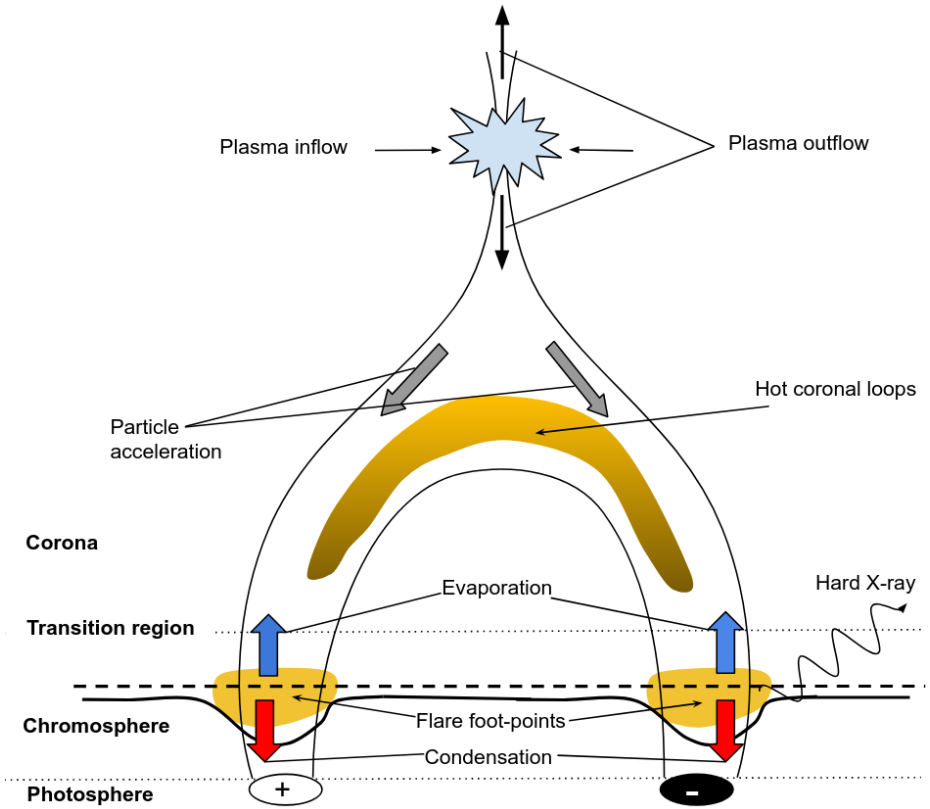
Standard flare model

(Carmichael, 1964; Sturrock, 1966; Hirayama, 1974; Kopp & Pneuman, 1976)

- Free magnetic energy is released
- Energy transported down along the magnetic field lines
- Drives condensation and evaporation

Open questions

1. What is the mechanism converting the energy?
2. How is the energy transported?



(Yadav et al., 2021)

Anatomy of solar flares

Energy transport from the corona to chromosphere

- **Non-thermal electrons**

  (Emslie et al., 2012)

- Thermal conduction

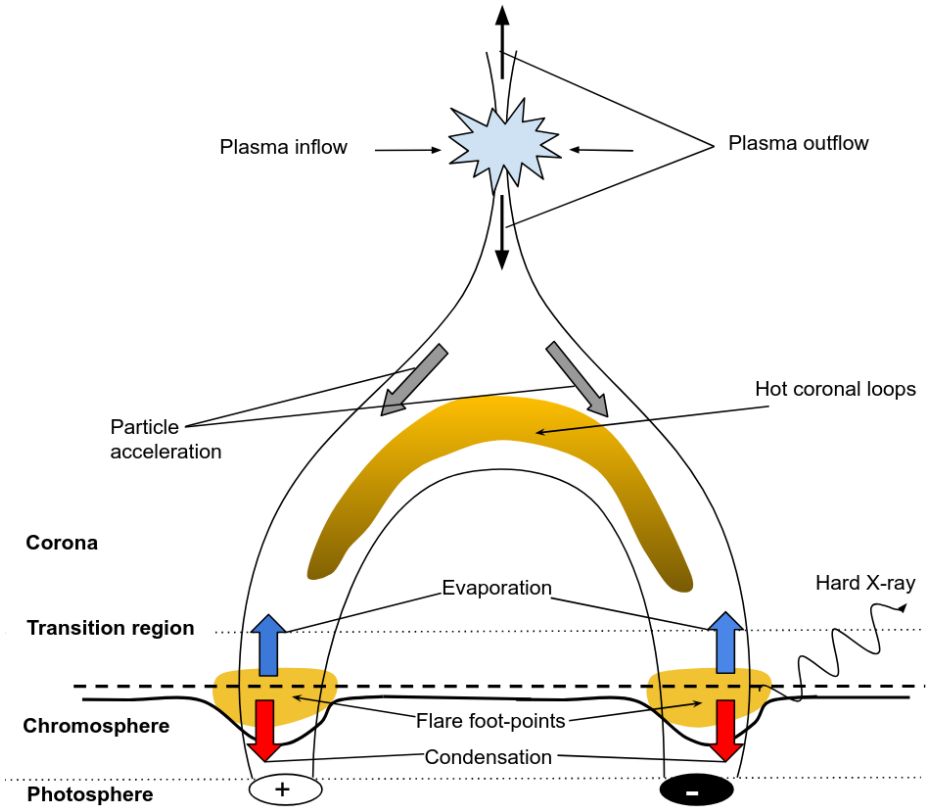
  (Gan et al., 1991; Longcope and Klimchuk, 2015)

- Waves

  (Flecther and Hudson, 2008; Reep and Russell, 2016)

- Ion beams

  (Vilmer et al., 2011)



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- We can't directly observe hard x-rays at high spatial resolutions.
- Flare loops are made of strains

Anatomy of solar flares

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A problem

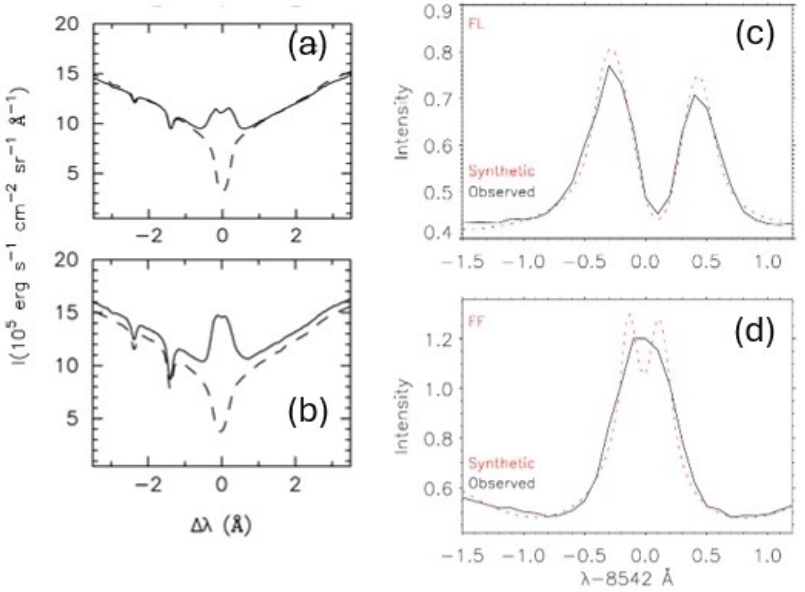
- We can't directly observe hard x-rays at high spatial resolutions.
- Flare loops are made of strains

The workaround

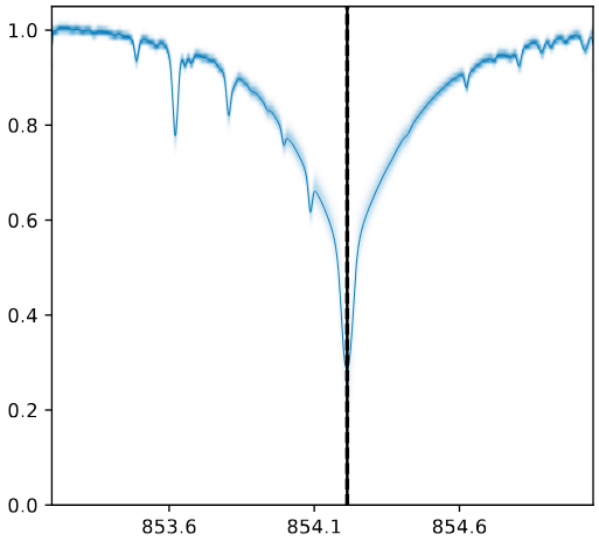
- Identify the signatures where we do have the spatial resolving power: the chromosphere.

Dynamical signatures

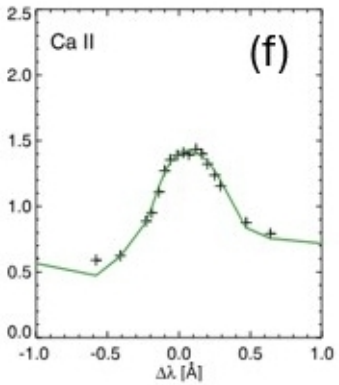
- Changes to the quiescent line profile
  - Line intensity
  - Line shift
  - Line width
  - Asymmetry

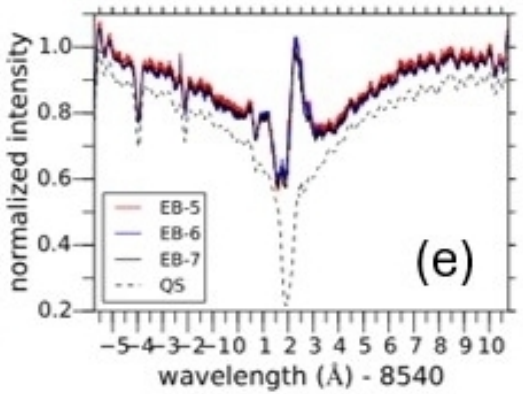


(Fang et al., 2006)



(Kuridze et al., 2017)



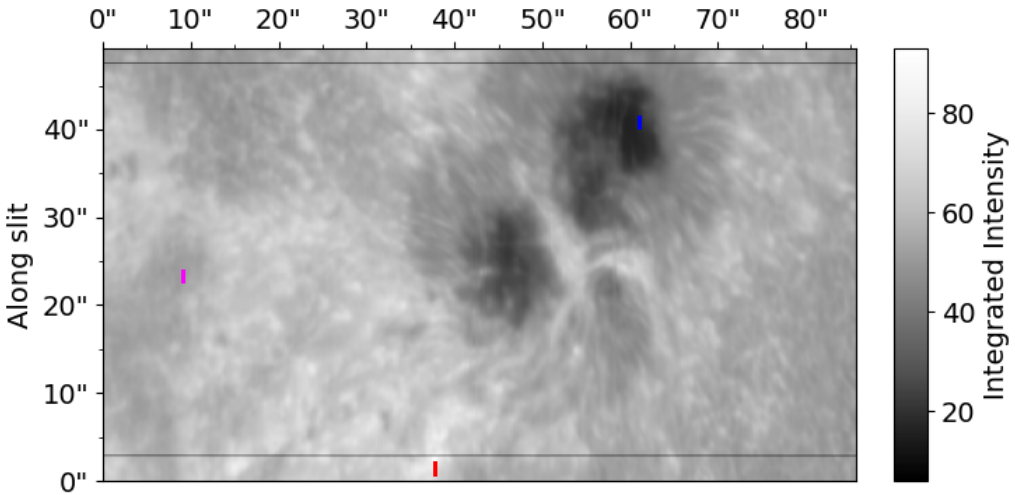


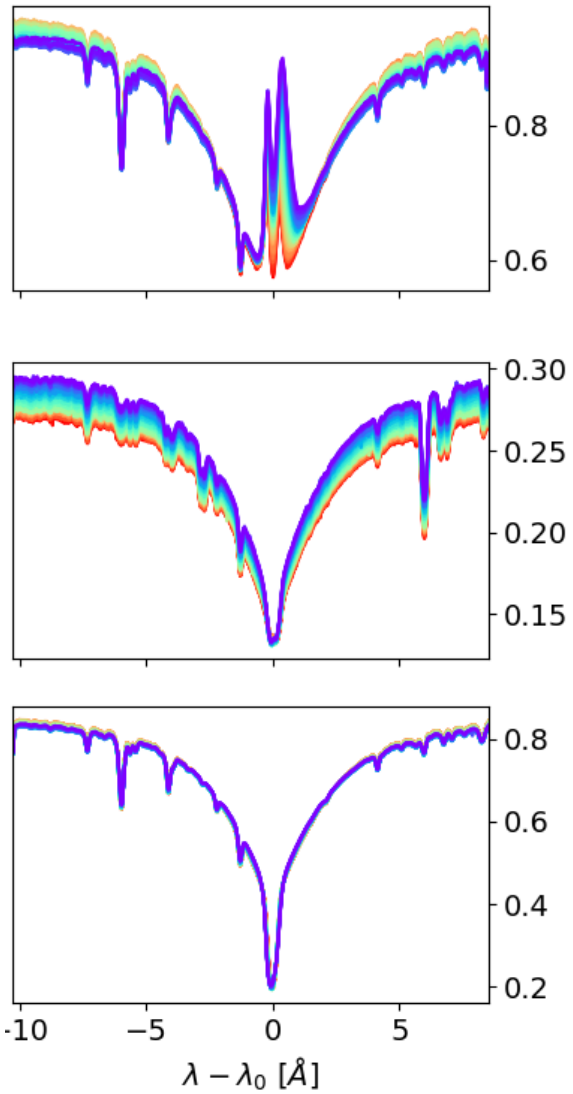
(Rezaei and Beck, 2015)

(Ferrente et al., 2024)

Dynamical signatures

- Changes to the quiescent line profile
  - Line intensity
  - Line shift
  - Line width
  - Asymmetry
- Spatial scales

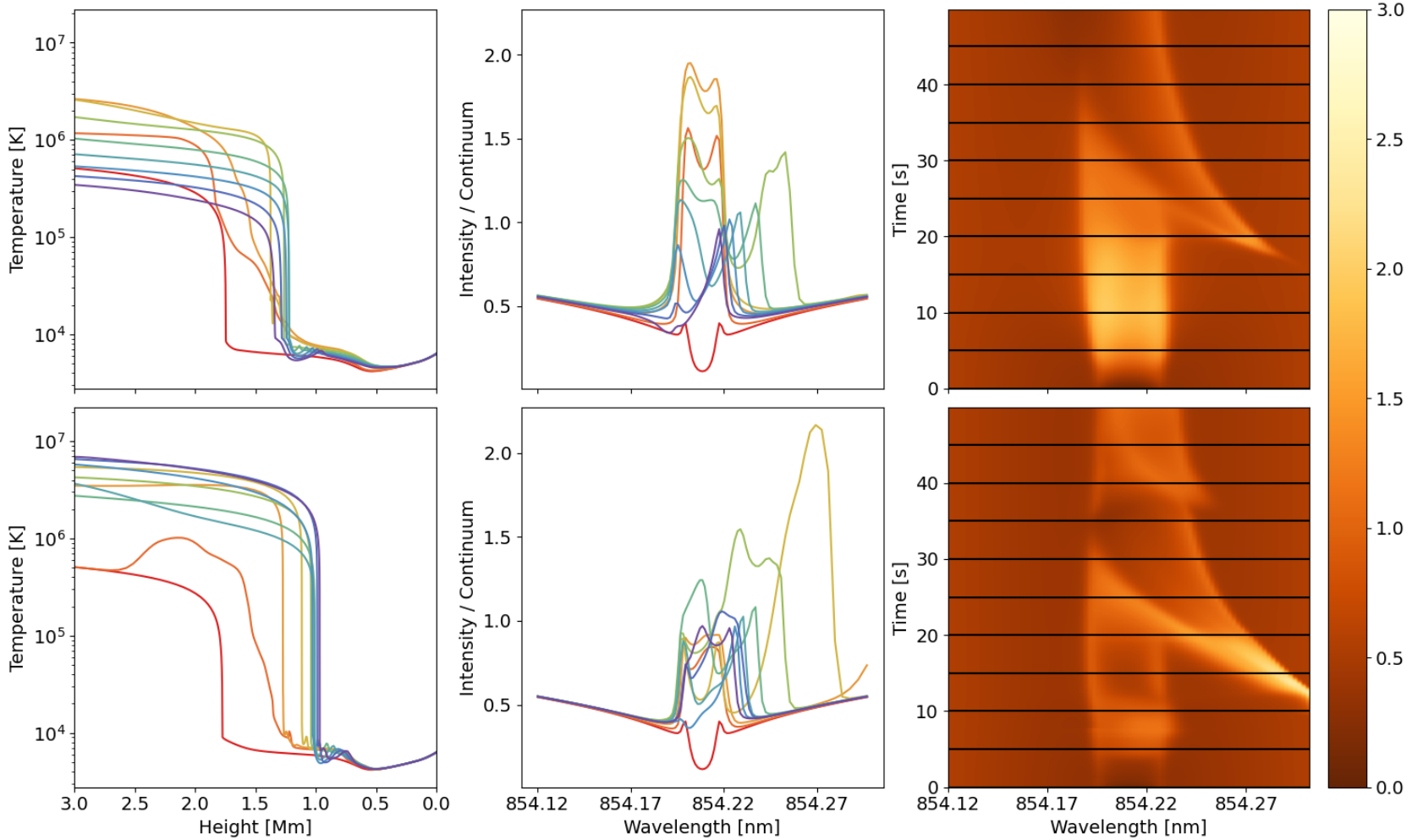




Introduction

Dynamical signatures

$F = 10^{10}\,\frac{\text{erg s}^{-1}}{\text{cm}^2}, \quad E_0 = 10\,\text{keV}, \quad \delta = 3$



$F = 10^{10}\,\frac{\text{erg s}^{-1}}{\text{cm}^2}, \quad E_0 = 10\,\text{keV}, \quad \delta = 8$

Driving questions

Q1 What **dynamical signatures** are associated with different evolutionary stages of individual heating events?

Q2 What are the **temporal-spatial scales** relevant to these signatures?

Q3 *What are the **physical mechanisms** behind these dynamical signatures?*

Analysis

Analysis objective

- To develop a method of characterizing large amounts of spectral data by the **dynamical signatures** and **evolution**

Analysis

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Finding the signatures

Clustering algorithm

- L_0 Intrinsic Layer
- L_1 Optimized Layer

Analysis

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Finding the signatures

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Describing the evolution

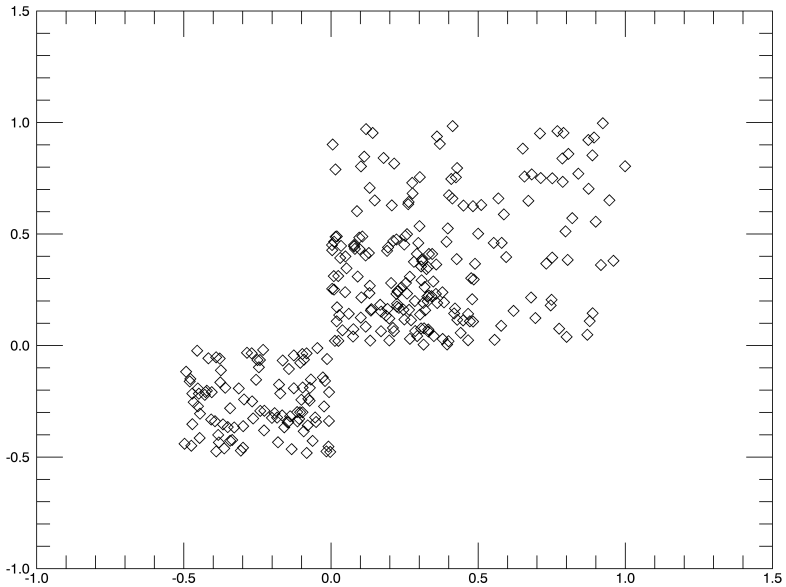
Epoch-driven approach

- Additional observations to define the heating history

Evolution-driven approach

- Heating history is provided by ViSP observations

Optimized layer



Goal: Minimize the "Within Cluster Distance"

Start: Initialize representatives $\mu_j^{(0)}$

For each iteration q,

$$c_i^{(q)} = \underset{1 \le j \le k}{\operatorname{argmin}} ||\mathbf{x}_i - \mu_j^{(q)}||^2$$

$$\mu_j^{(q+1)} = \frac{1}{n_j^{(q)}} \sum_{i=1}^{n_j^{(q)}} \delta_{c_i j} \mathbf{x}_i$$

Stop: $\sqrt{||\mu^{(q+1)} - \mu^{(q)}||^2} \le 10^{-6}$

Analysis

Optimized layer

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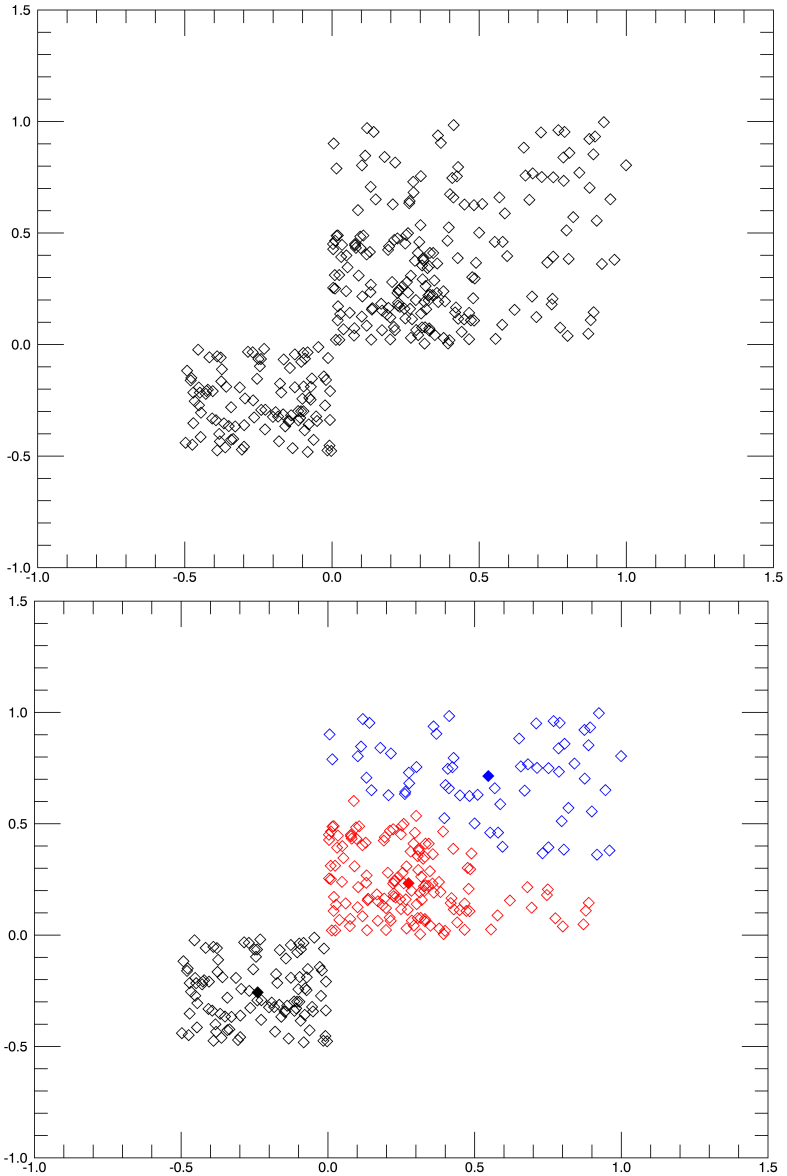

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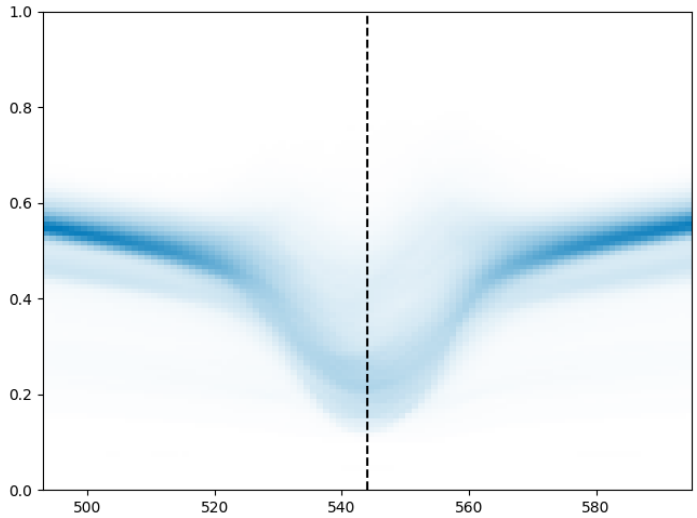
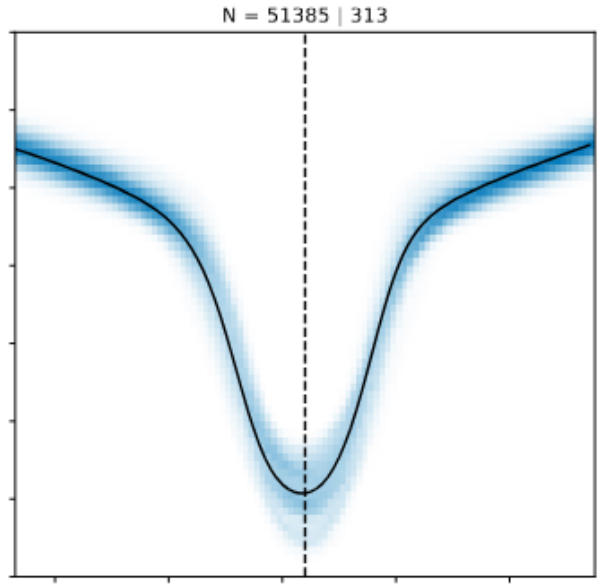
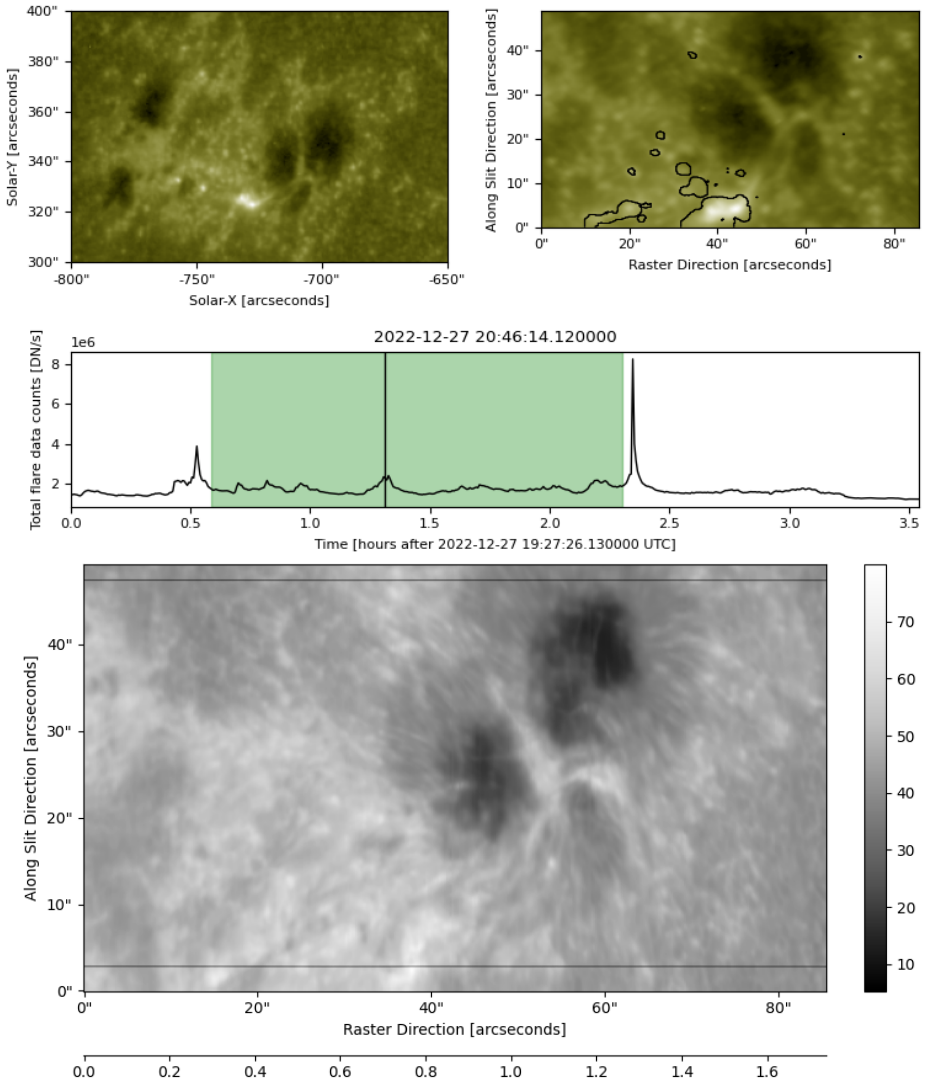




Flare overview

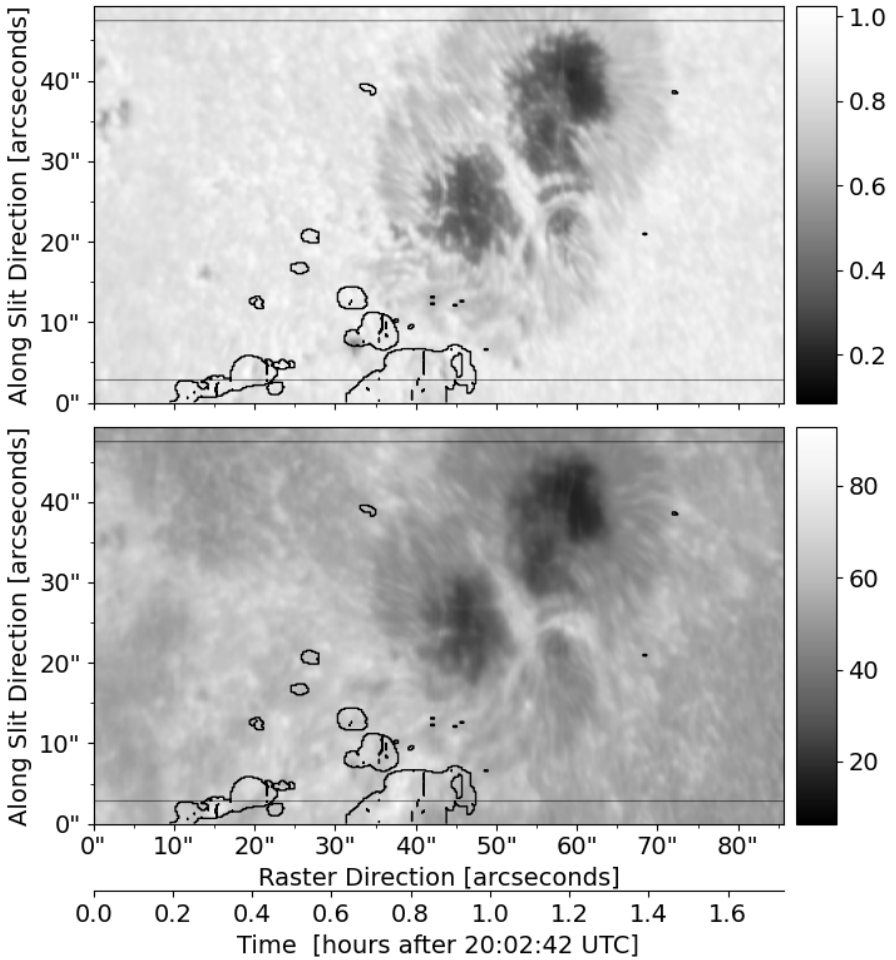
ViSP Observation Info

		Ca II λ8542
Observed	:	Ca II H Fe I
Slit Width	:	0.214”/pxl
Pxl Scale	:	0.0194”/pxl
FOV	:	85.6” $\times$ 49.5”
Step Cadence	:	15.67 s
Total time	:	1hr 45min

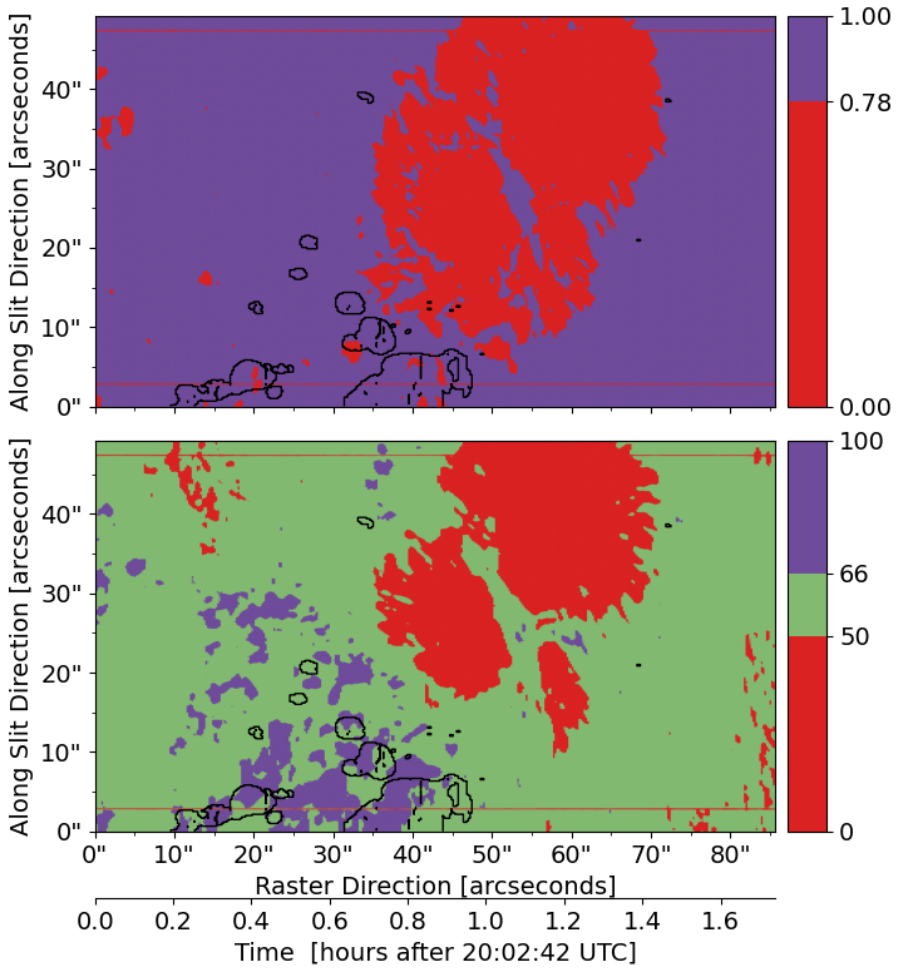


Clustering (Intrinsic layer)

Intensity maps

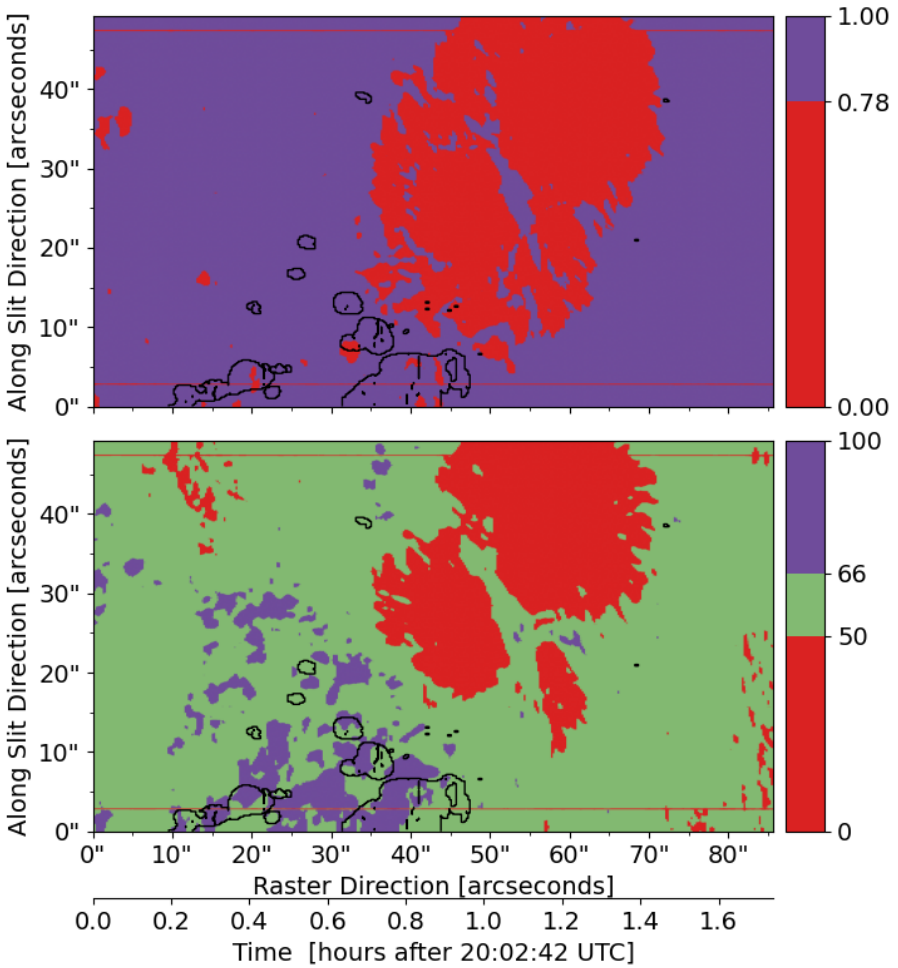


Intrinsic layer maps

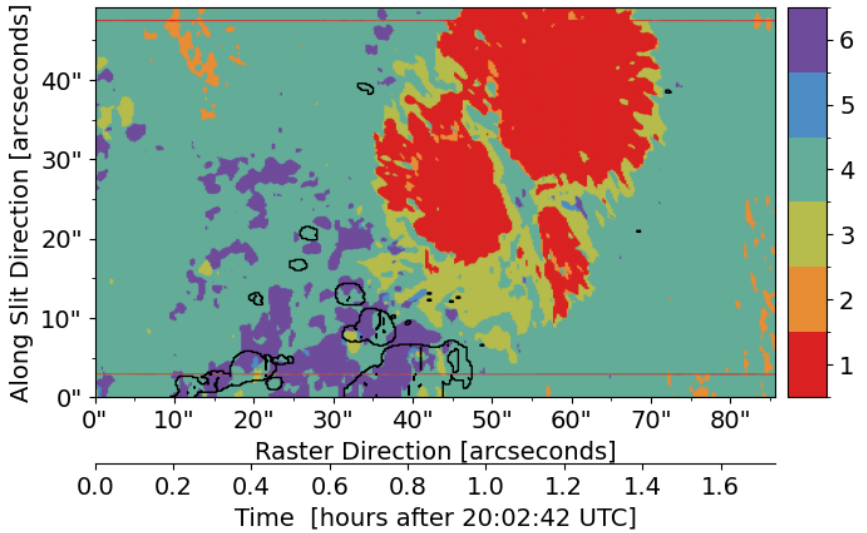


Clustering (Intrinsic layer)

Intrinsic layers

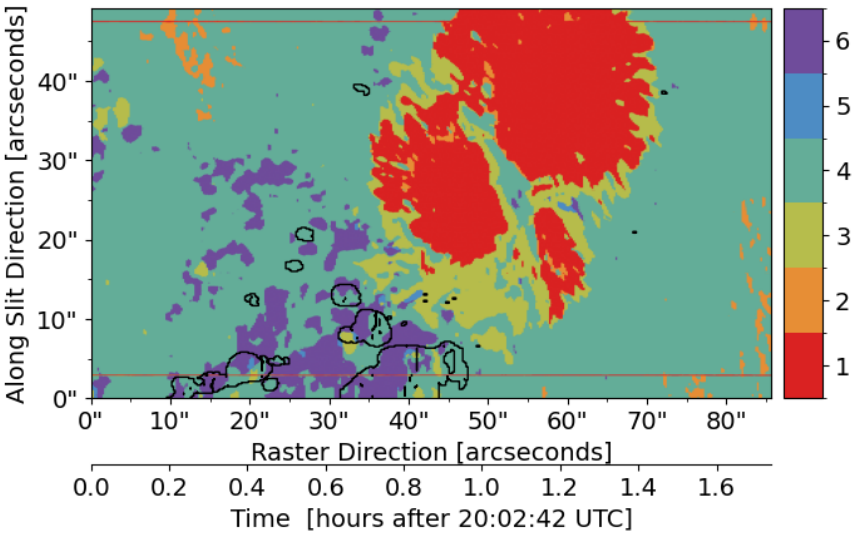


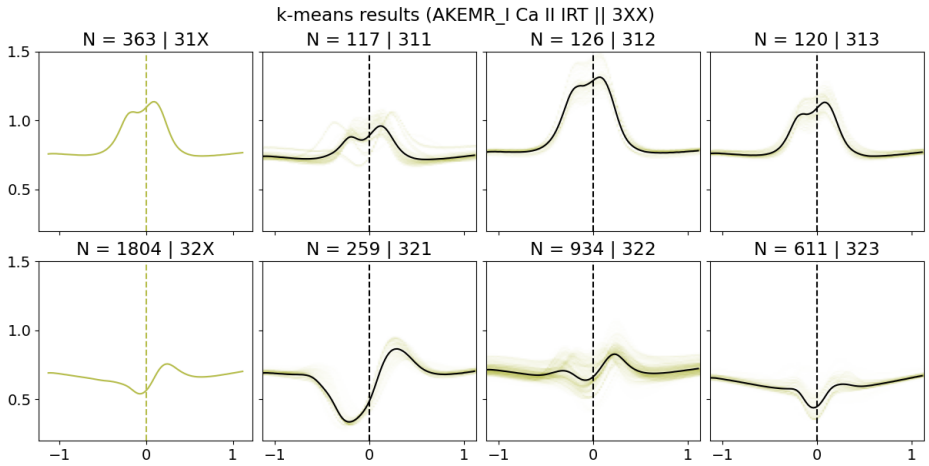
Coupled layer



2022 Dec 27

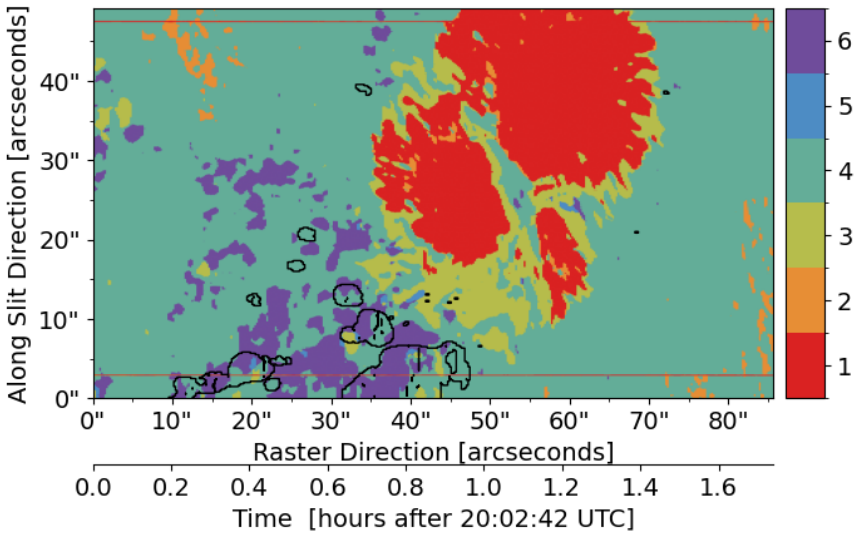
Clustering (Optimized layer)

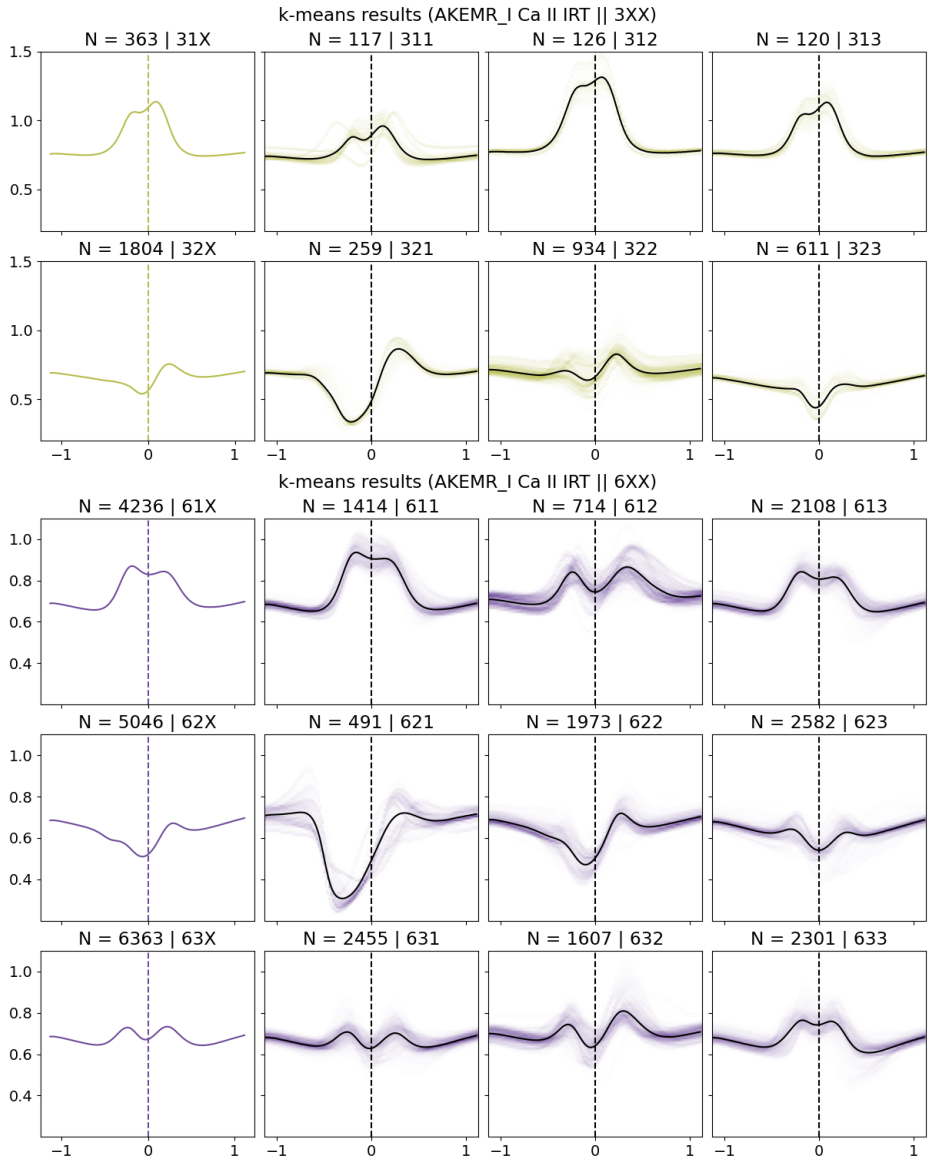




2022 Dec 27

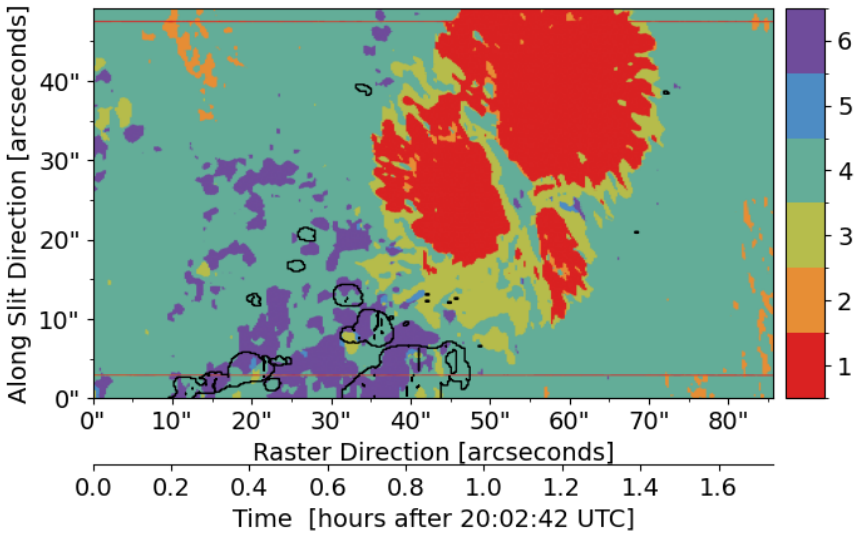
Clustering (Optimized layer)



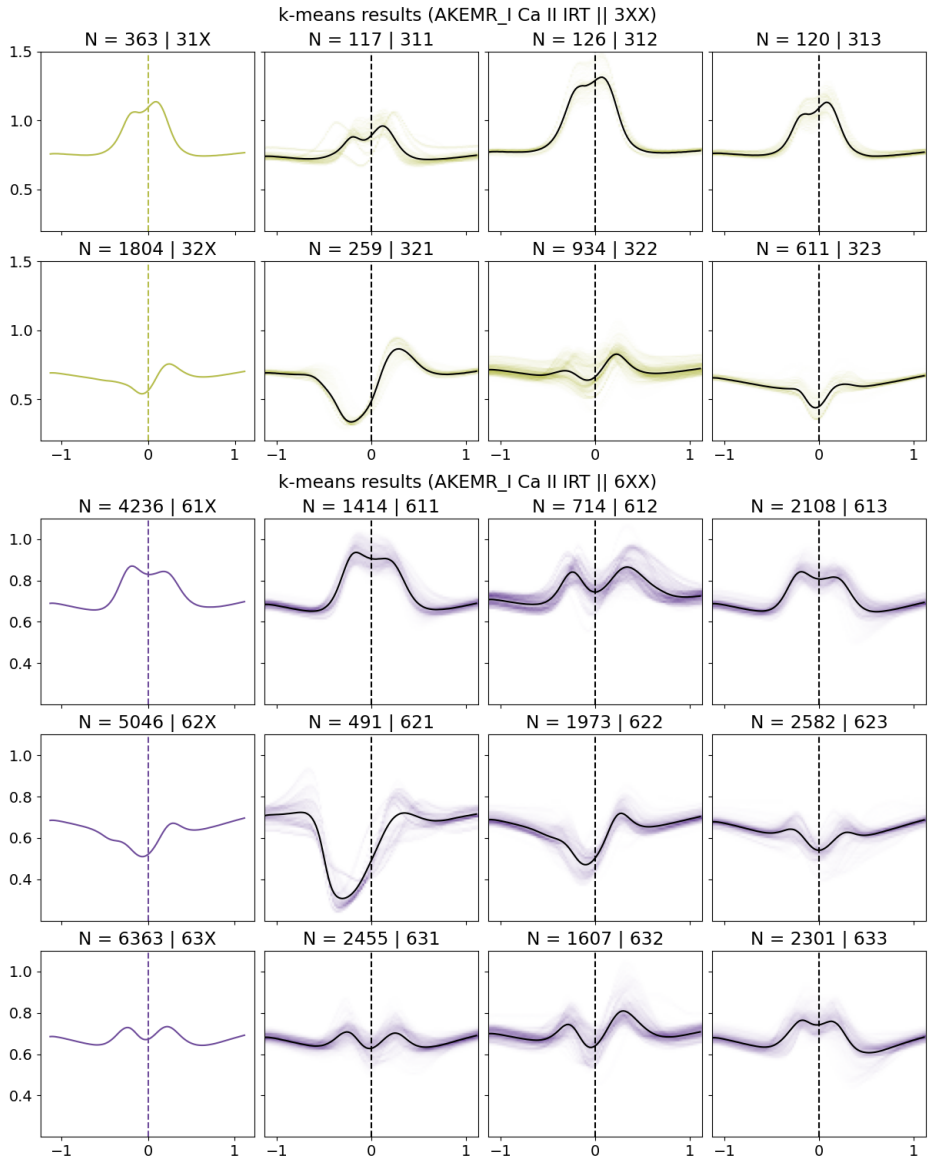


2022 Dec 27

Clustering (Optimized layer)



- Only snapshots. We can't directly obtain the evolution



Epoch-driven approach

Analysis objective

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Epoch-driven approach

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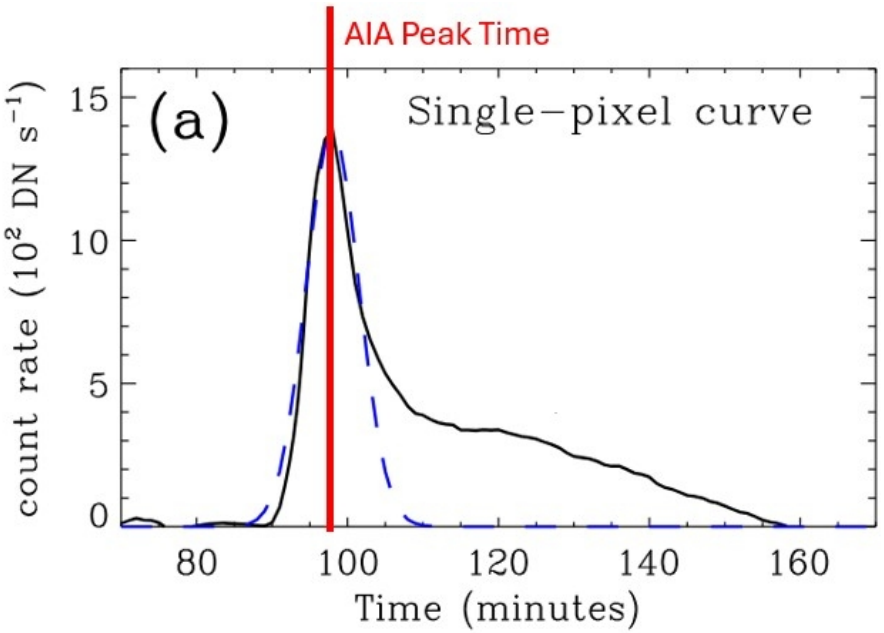
$\Delta t =$ ViSP Time $-$ AIA Peak Time

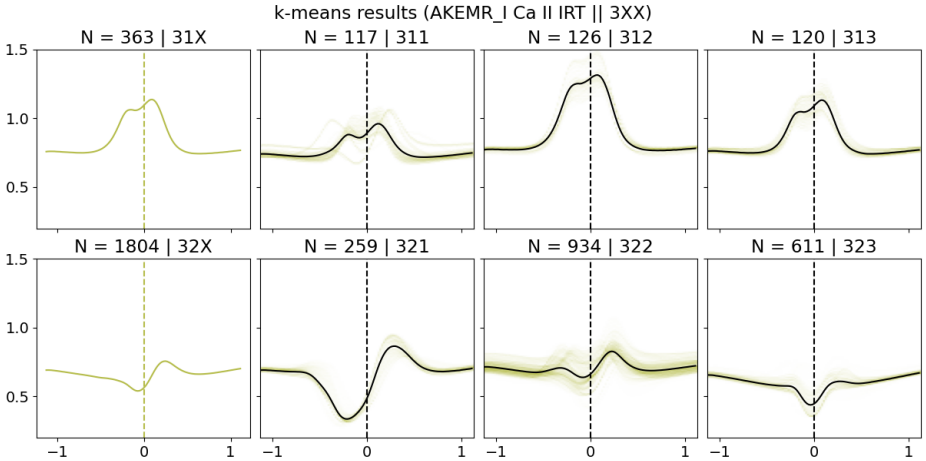
- $\Delta t < 0$ (Rise phase)
- $\Delta t > 0$ (Decay phase)

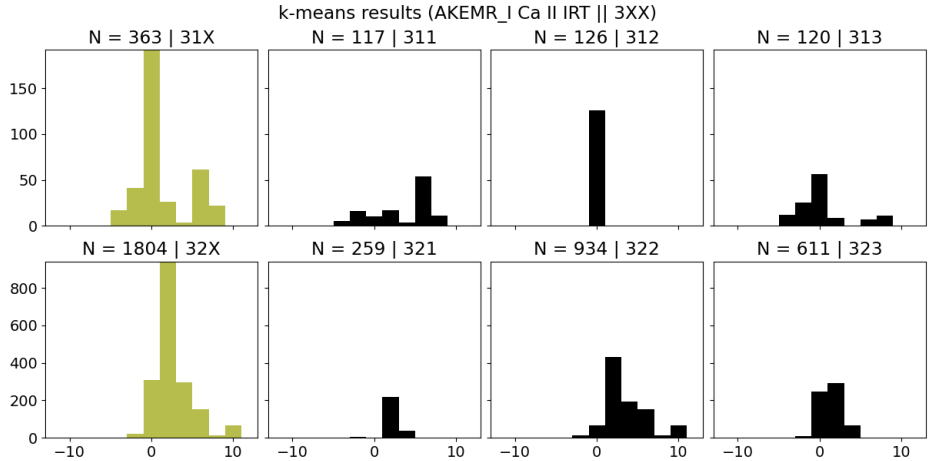


(Adapted from Zhu et al., 2018)

2022 Dec 27

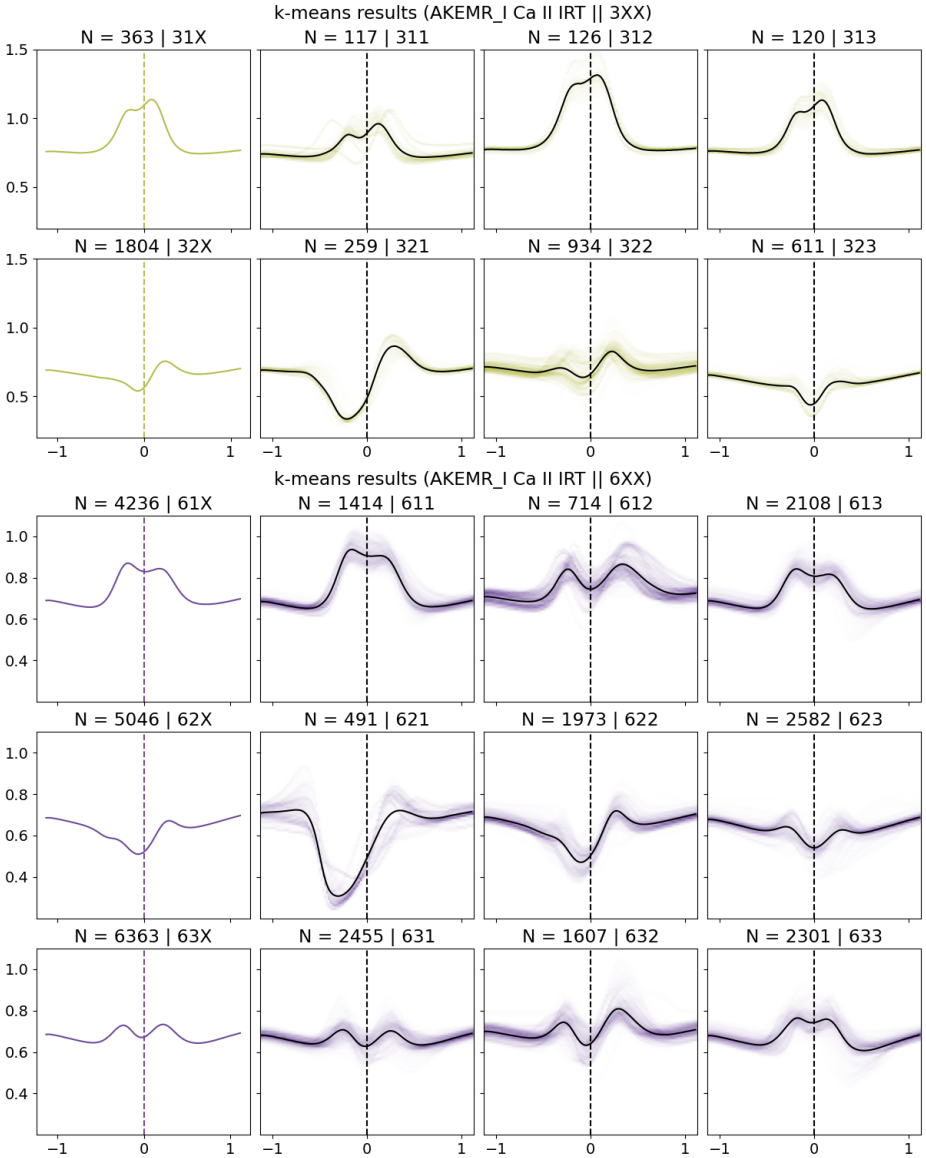
Epoch-driven approach

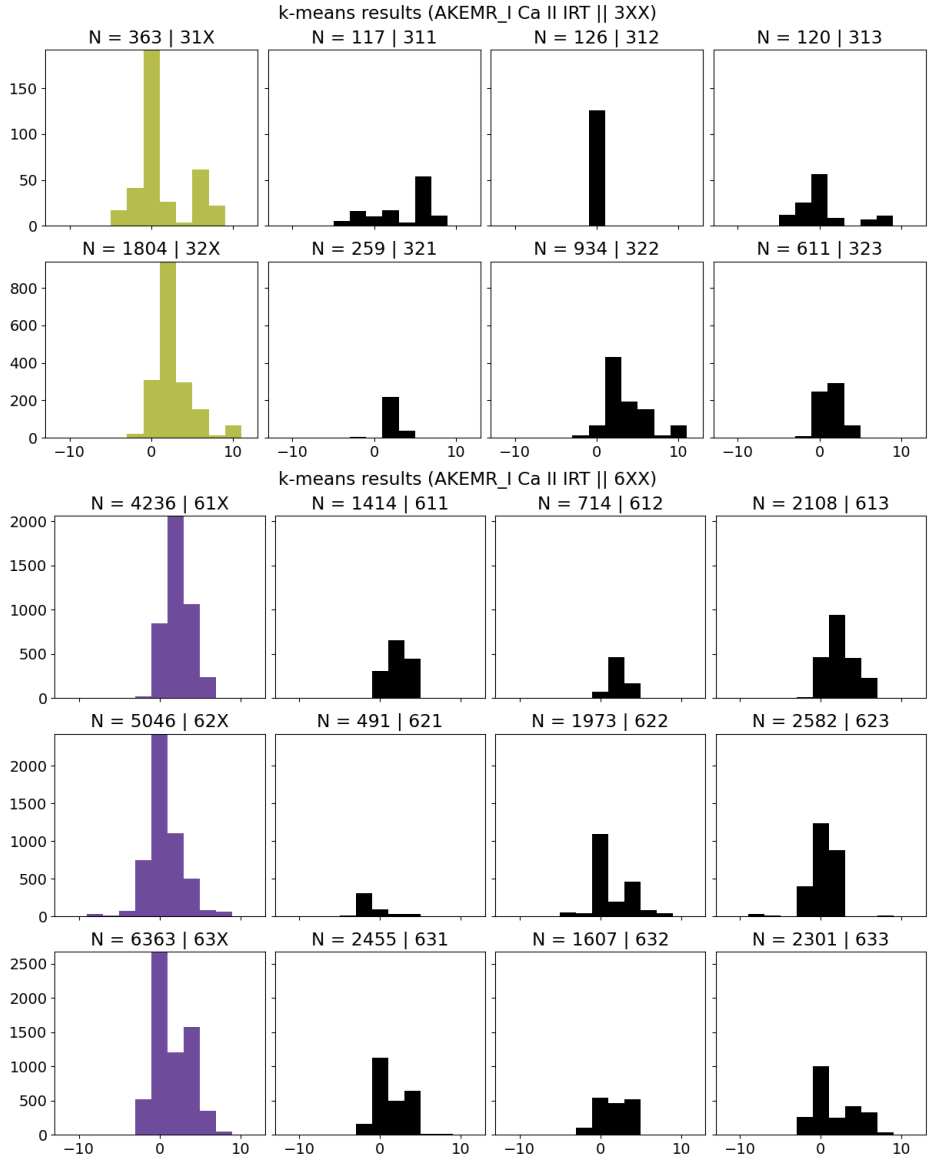




2022 Dec 27

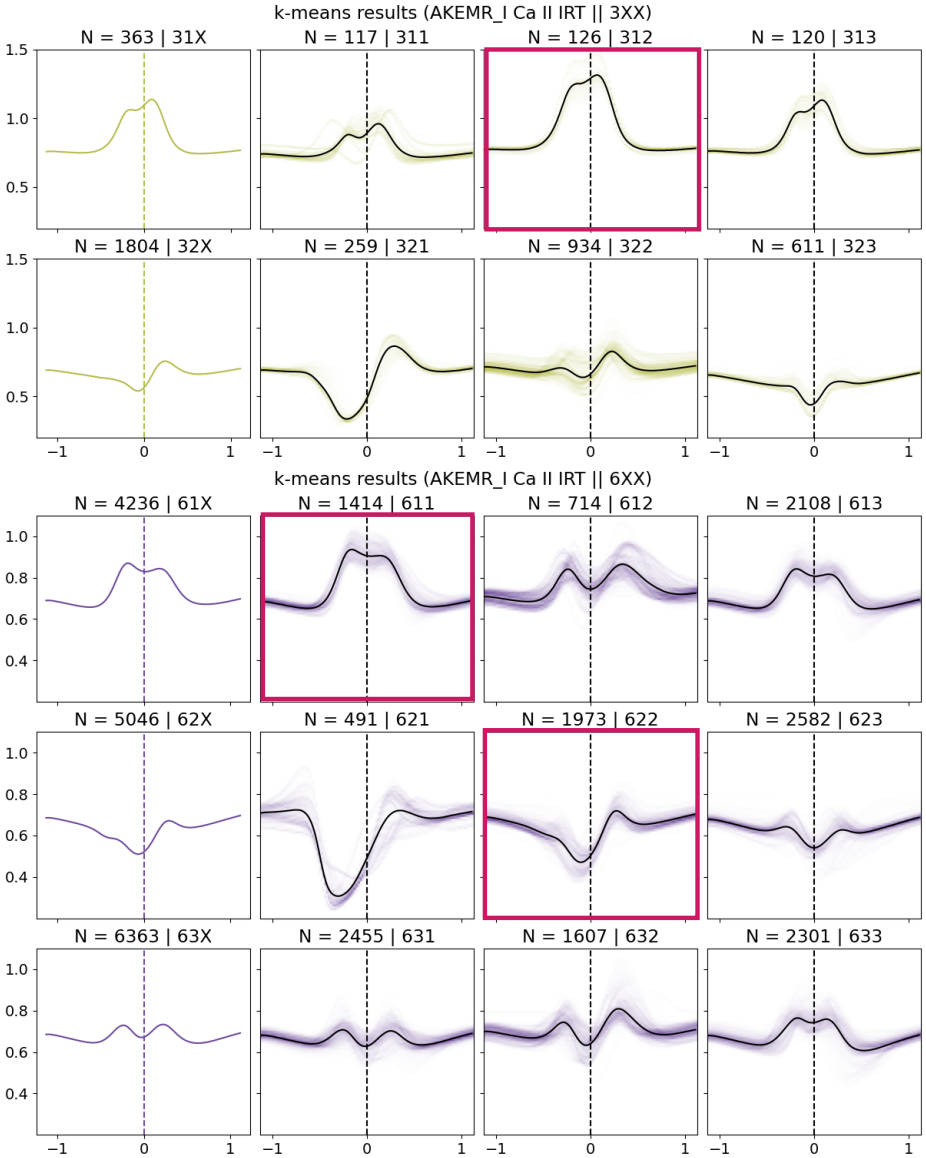
Epoch-driven approach

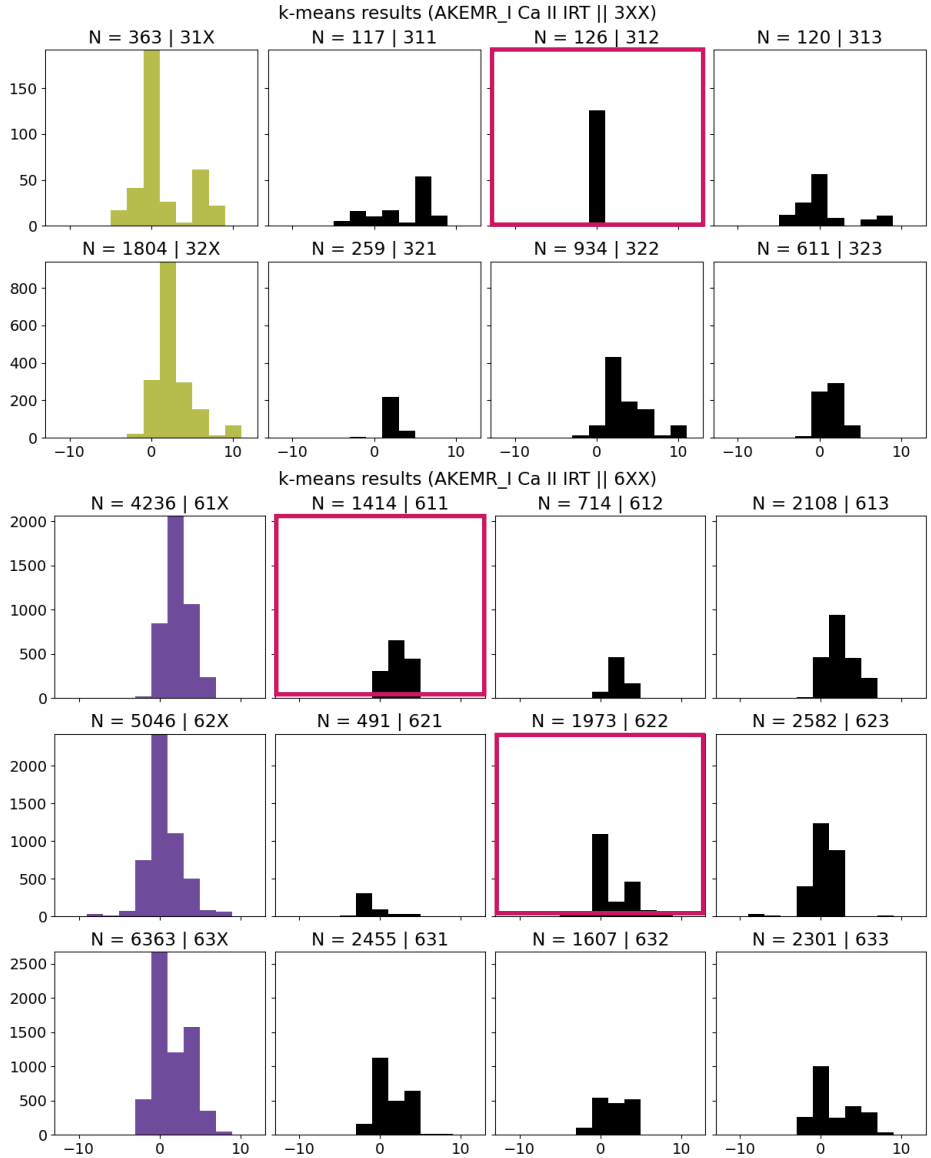




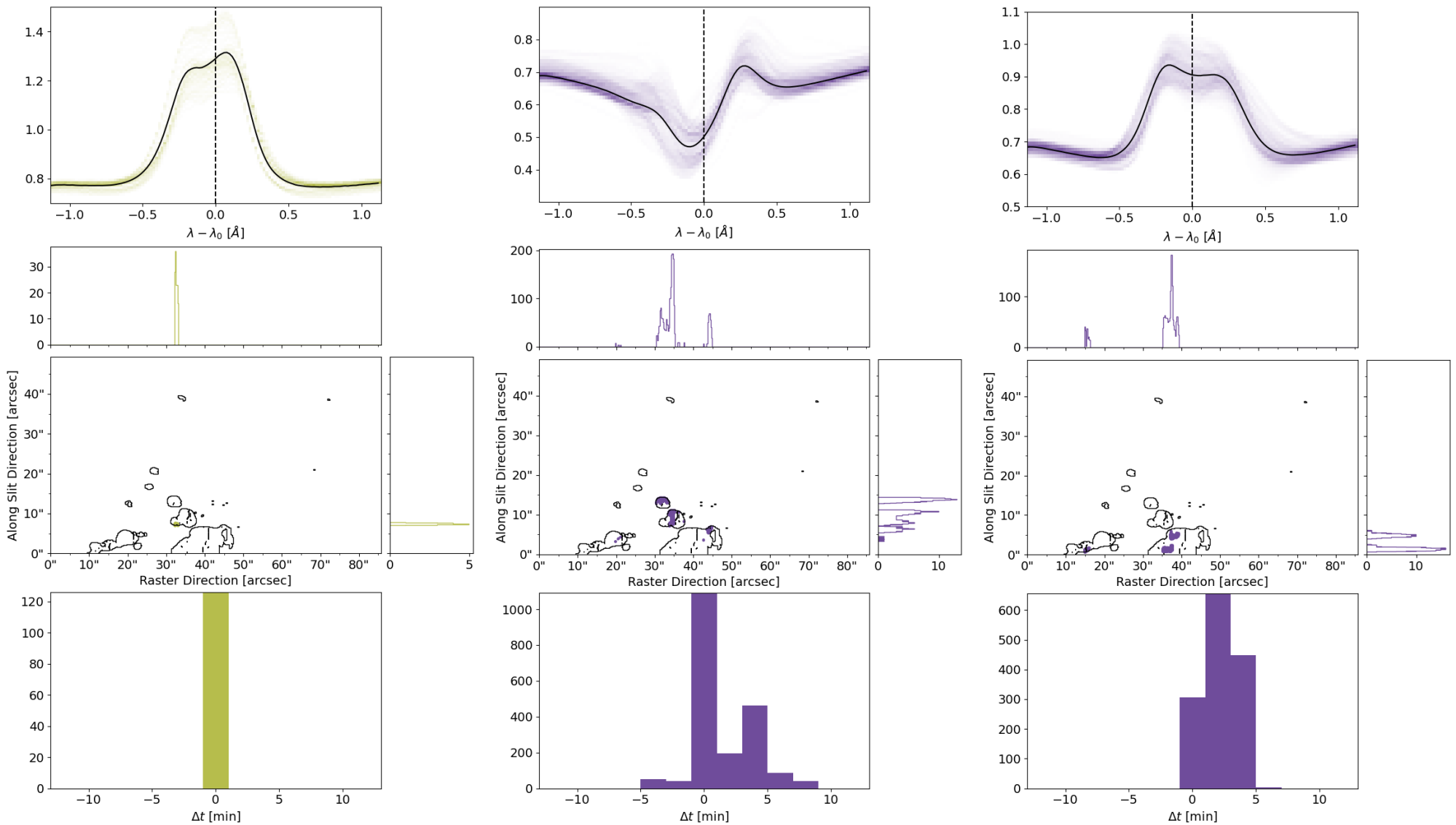
2022 Dec 27

Epoch-driven approach





2022 Dec 27 Wrap up

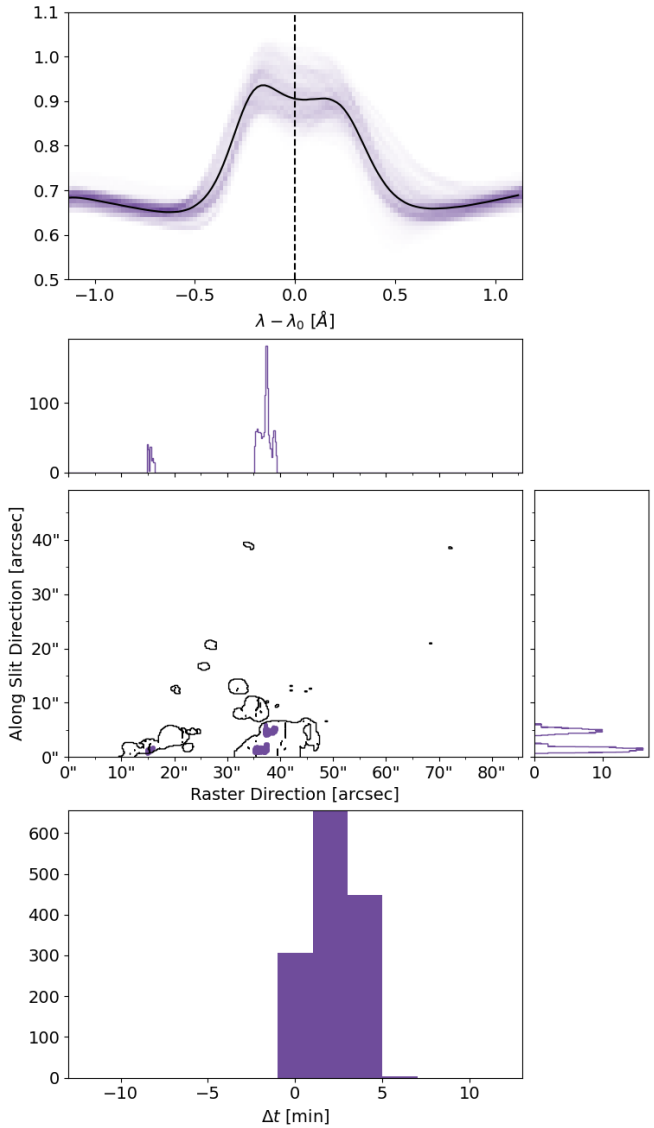


Wrap up

In the **epoch-driven** approach we have:

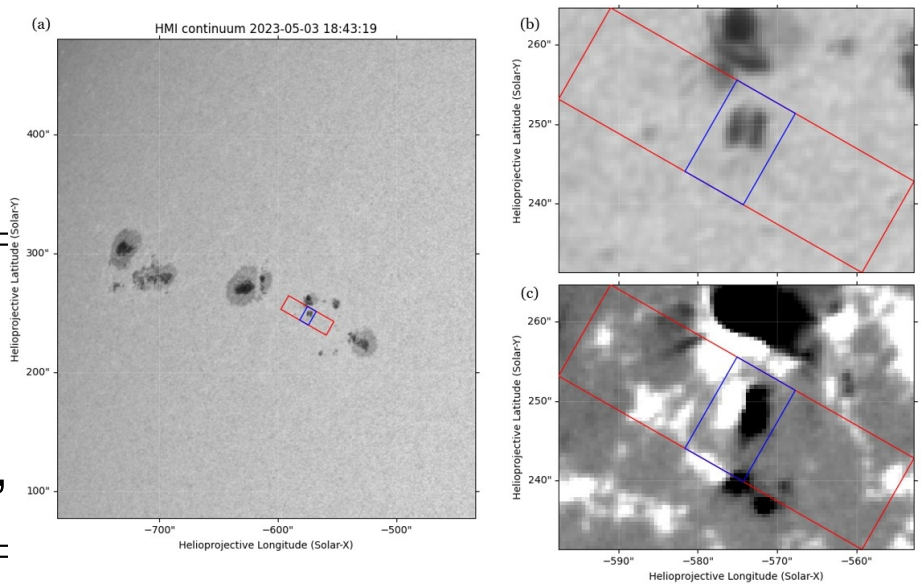
- Identified dynamical signatures
- Identified the temporal-spatial scales of the signatures

From this analysis, we have answered **Q1** and **Q2** of our science questions.



ViSP Observation Info

Observed	:	**Ca II λ8542** **Na I D** Fe I
Slit Width	:	0.1071”/pxl
Pxl Scale (Ca II)	:	0.0194”/pxl
Pxl Scale (Na I)	:	0.0239”/pxl
FOV	:	13.4” $\times$ 60.7”
Step Cadence	:	1.5 s
Raster Cadence	:	3.11 min
Total time	:	2hr 44 min



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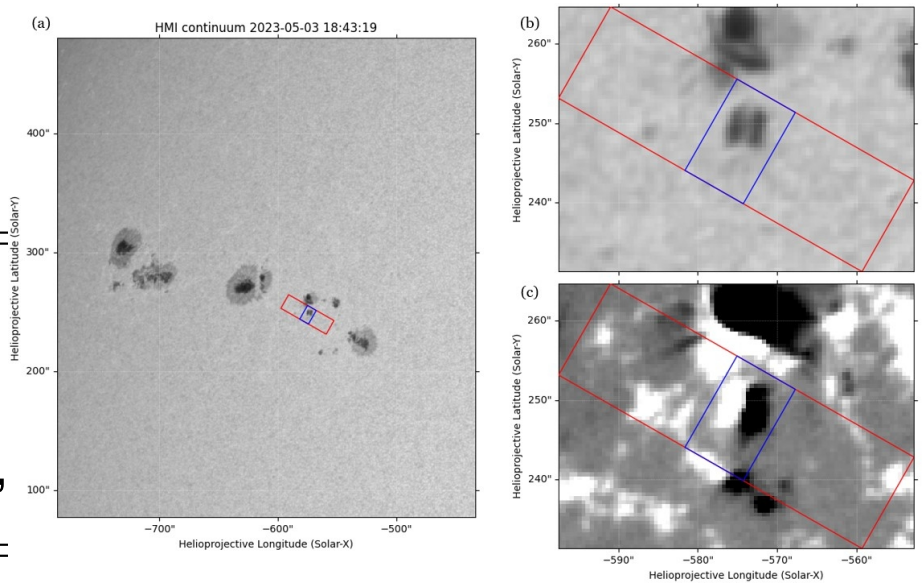
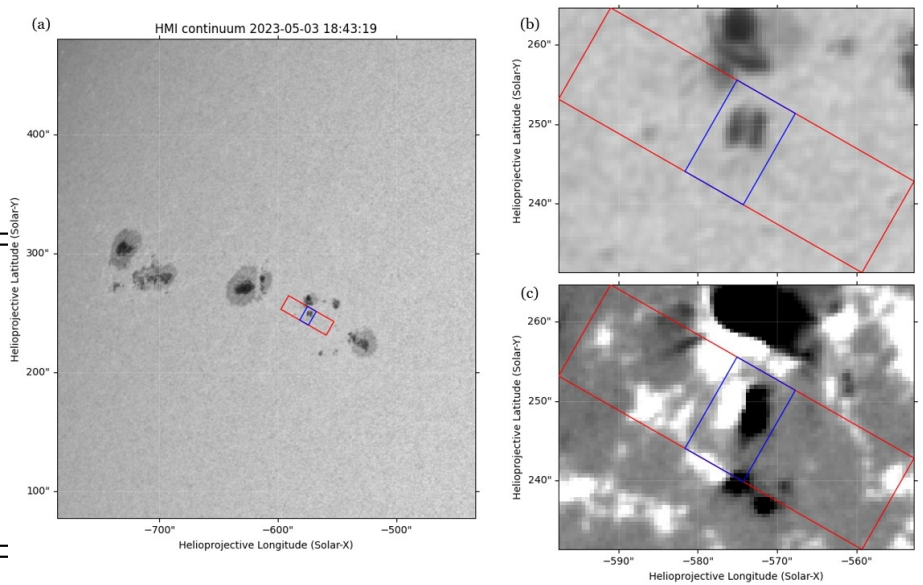


ViSP Observation Info

Observed	:	**Ca II λ8542** **Na I D** Fe I
Slit Width	:	0.1071”/pxl
Pxl Scale (Ca II)	:	0.1196”/pxl
Pxl Scale (Na I)	:	0.1196”/pxl
FOV	:	13.4” $\times$ 9”
Step Cadence	:	1.5 s
Raster Cadence	:	3.11 min
Total time	:	2hr 44 min

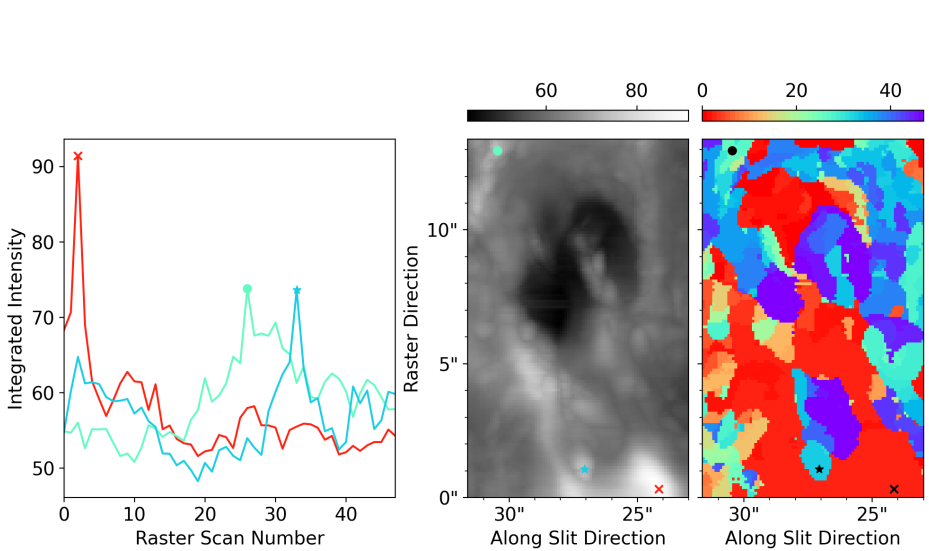


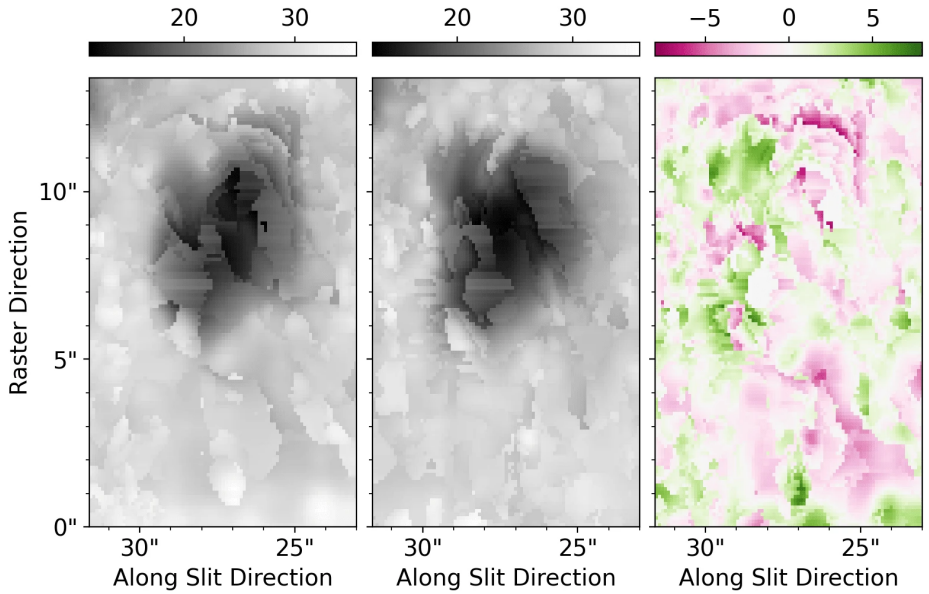
Peak Frame

- Each pixel contains the maximum integrated intensity

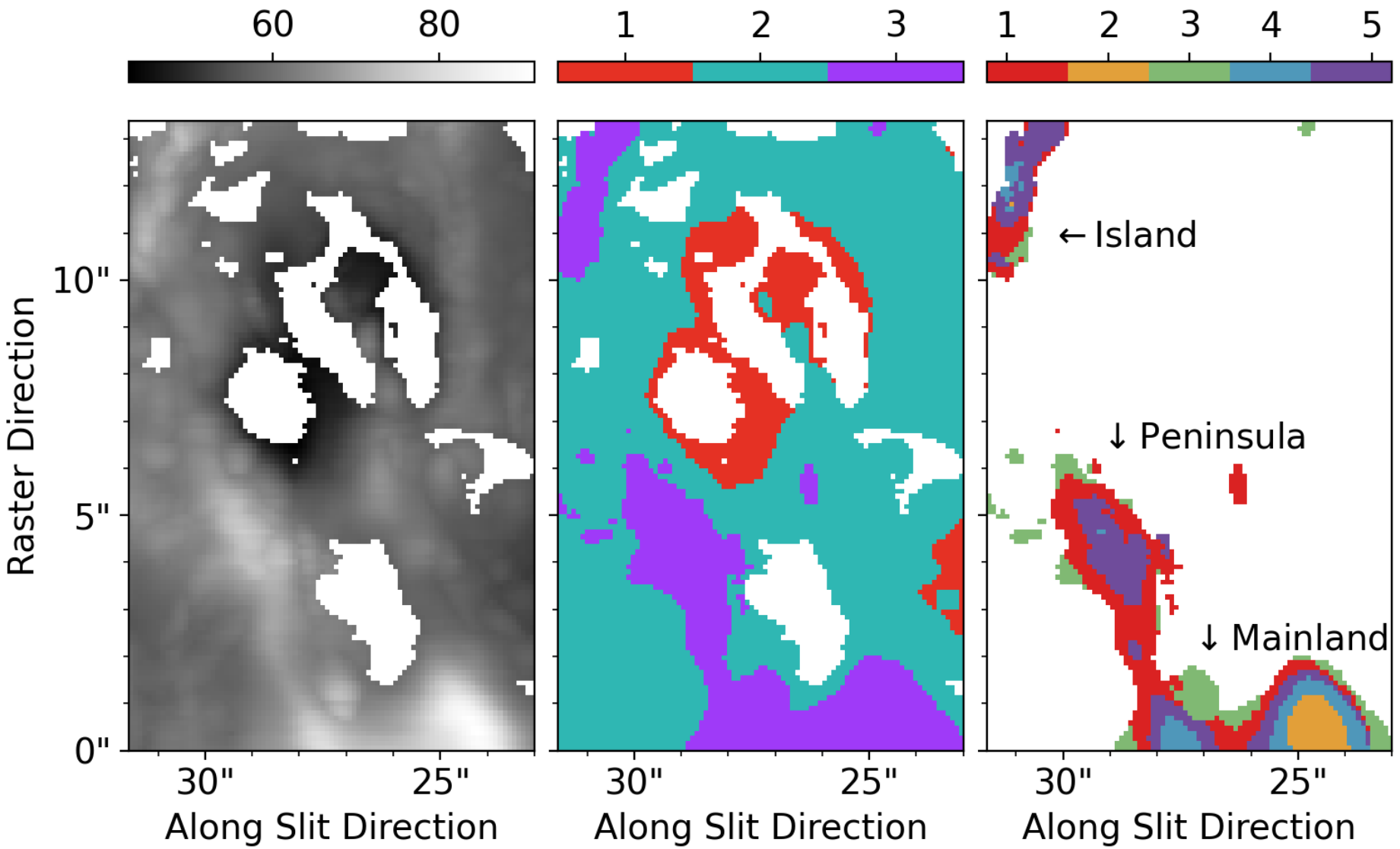
Quiet Frame

- Each pixel contains the minimum normalized line core intensity



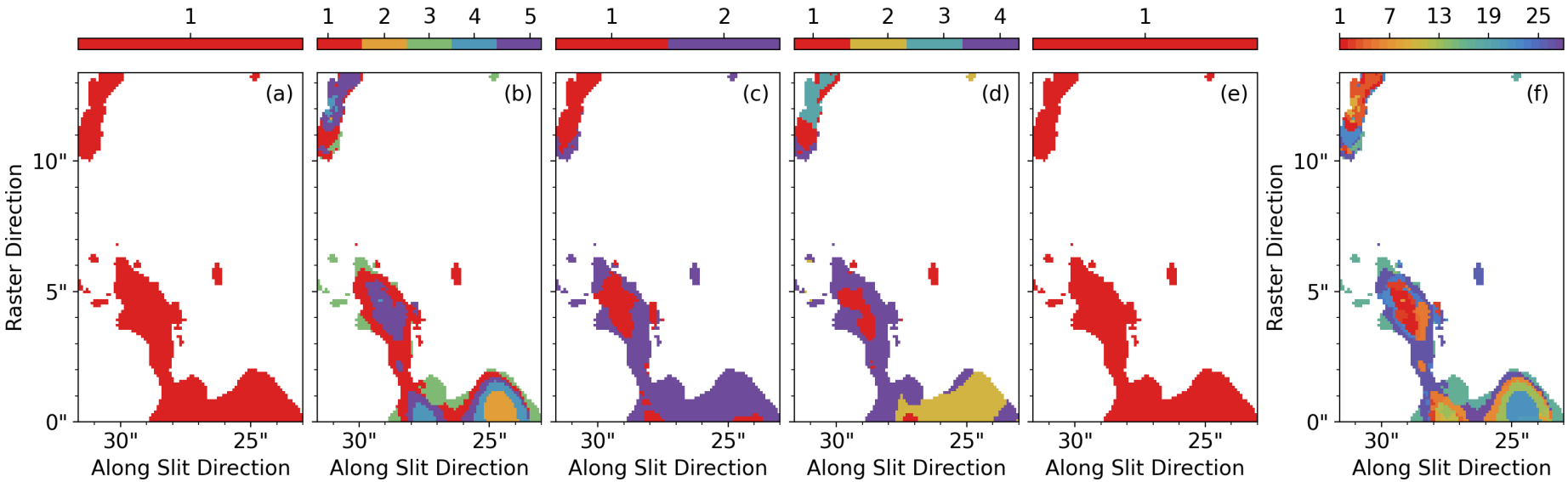


2023 May 03 Clustering (Peak frame)



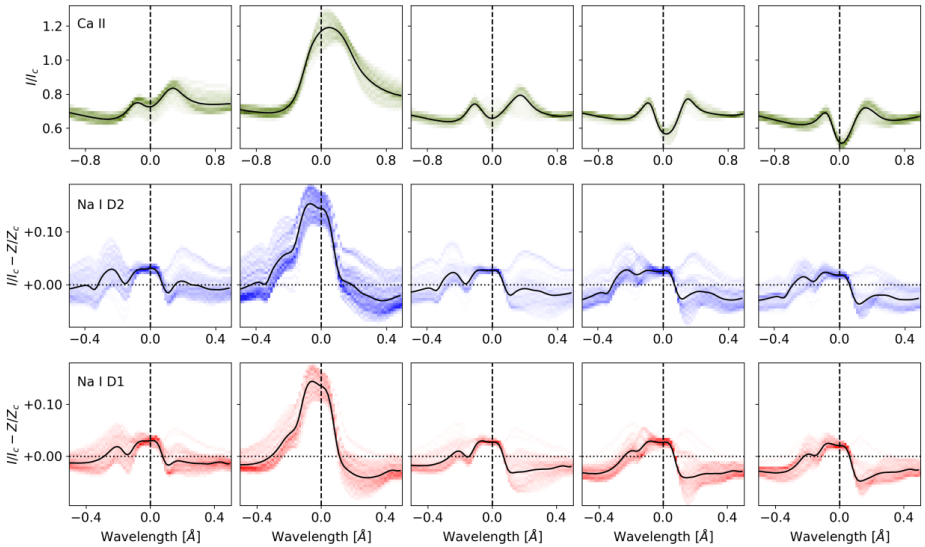
2023 May 03

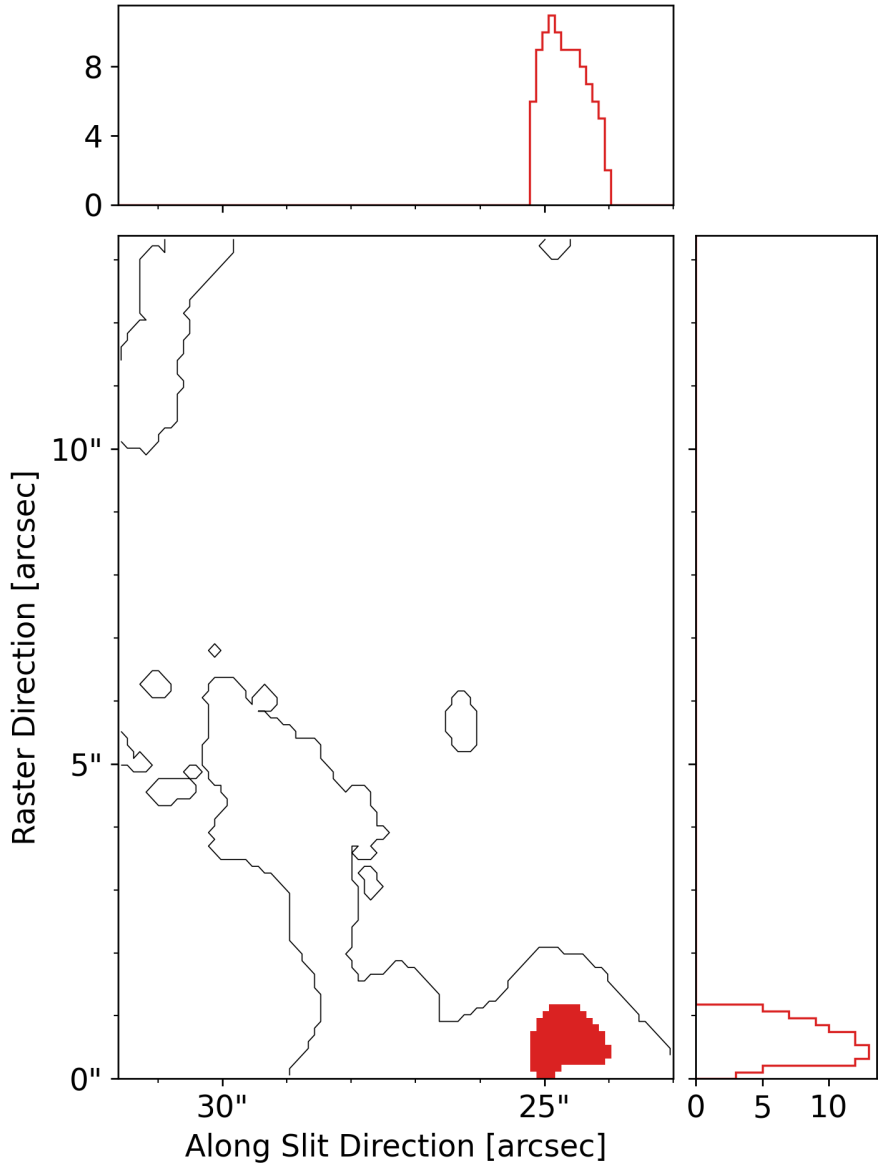
Clustering (Full sequence)



2023 May 03

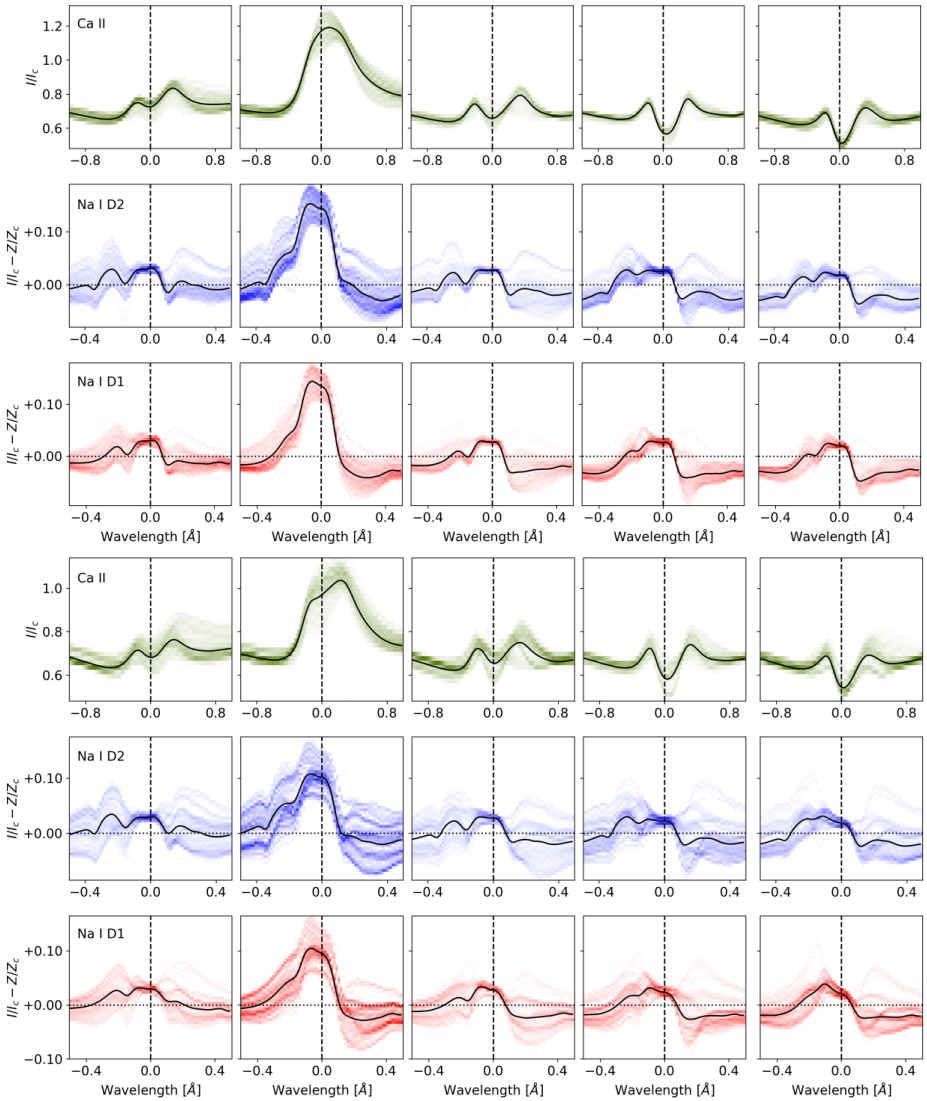
Evolution-driven (Mainland)

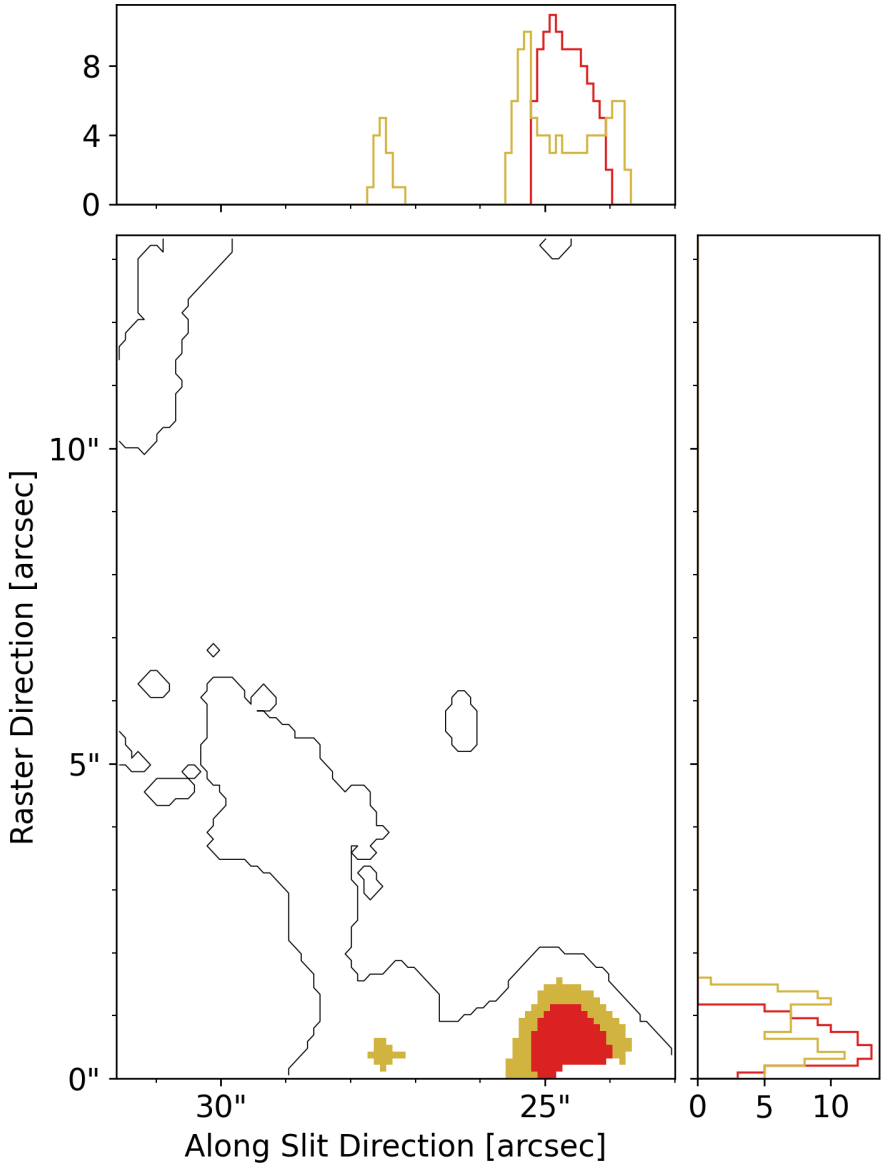




2023 May 03

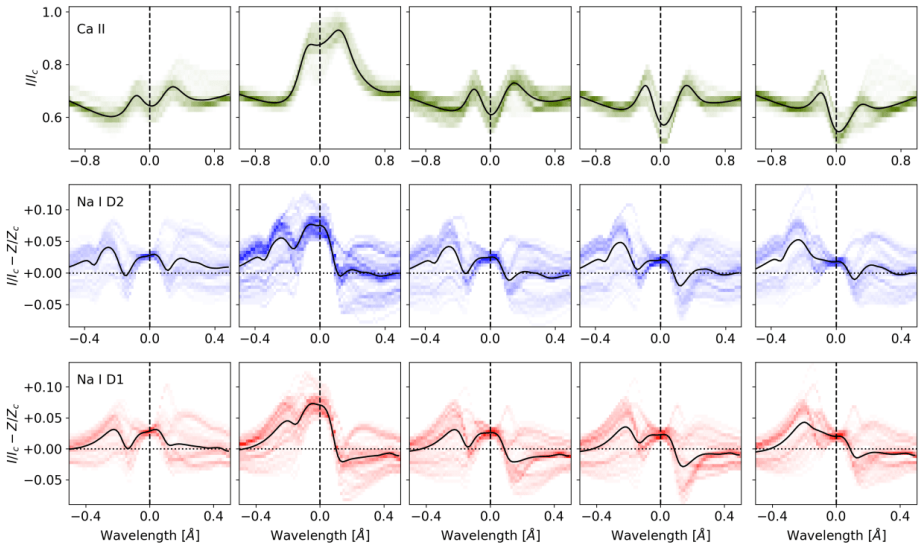
Evolution-driven (Mainland)

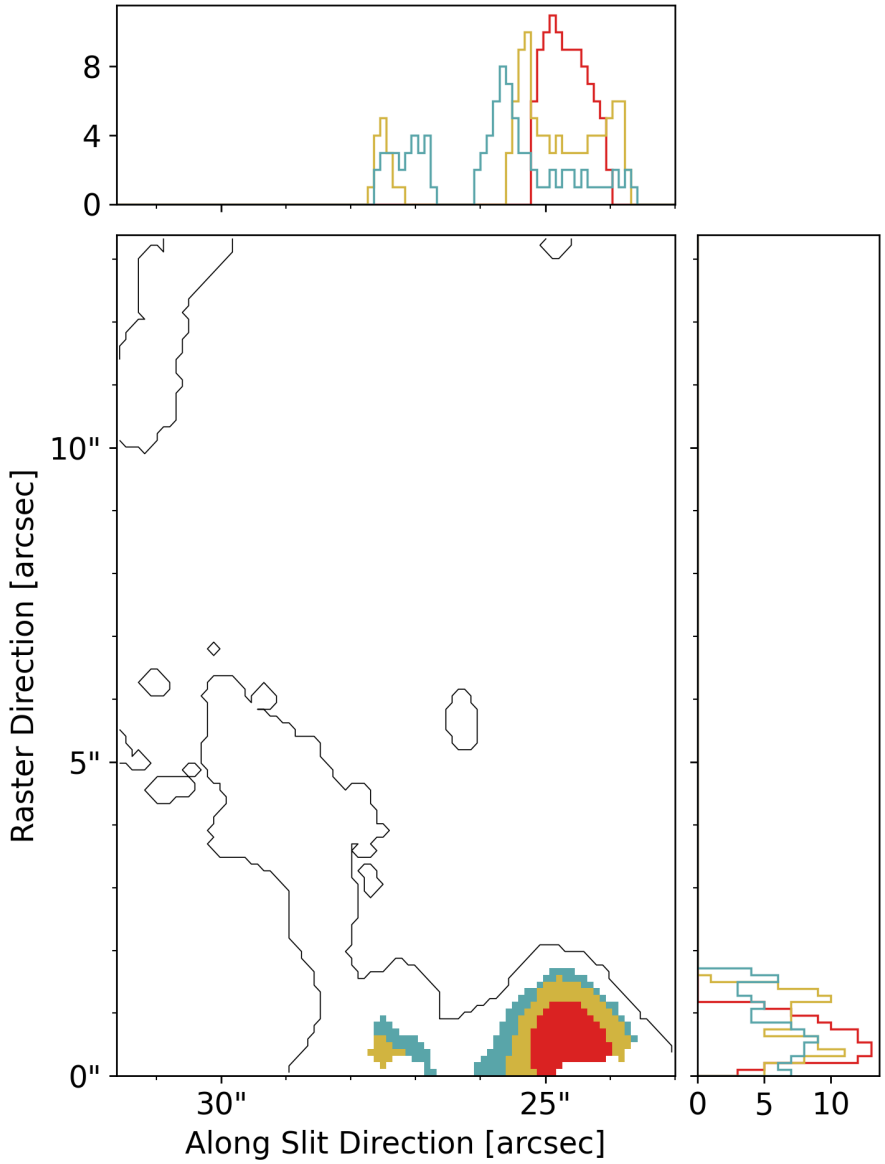




2023 May 03

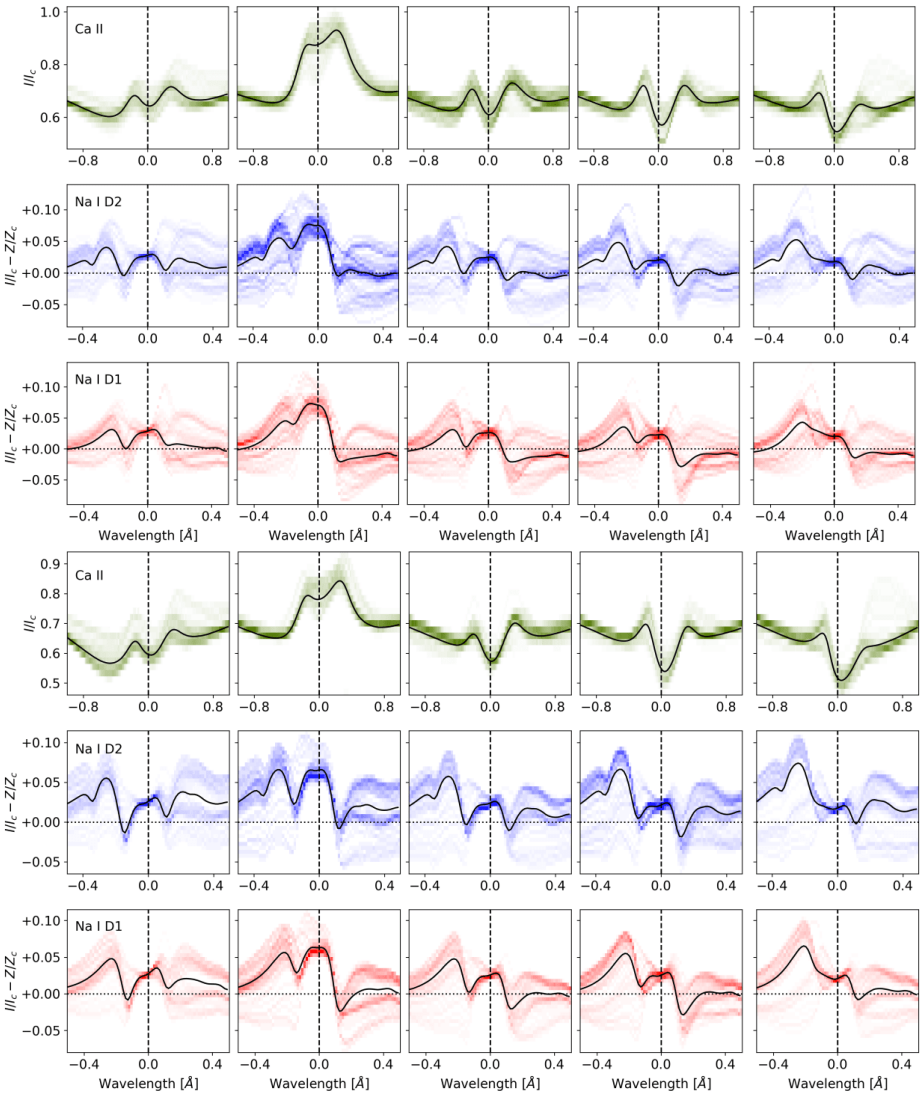
Evolution-driven (Mainland)

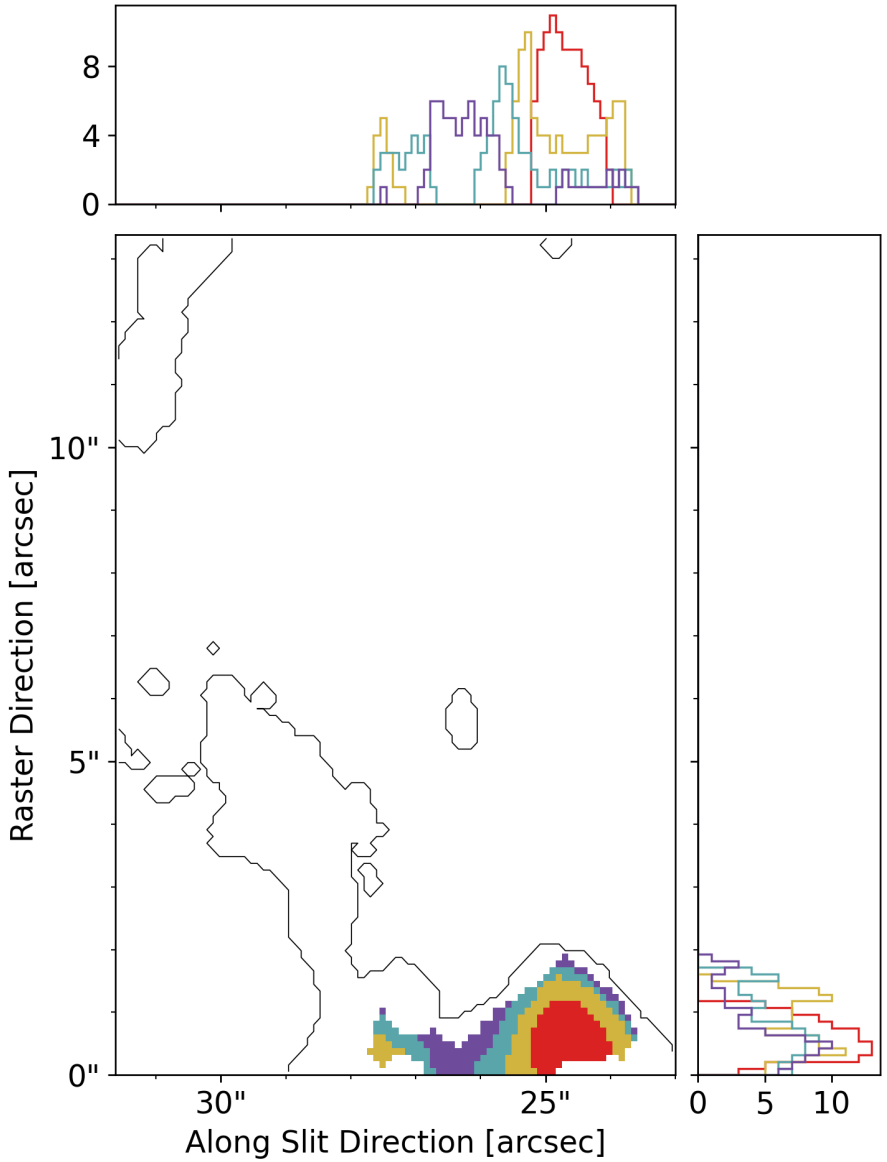




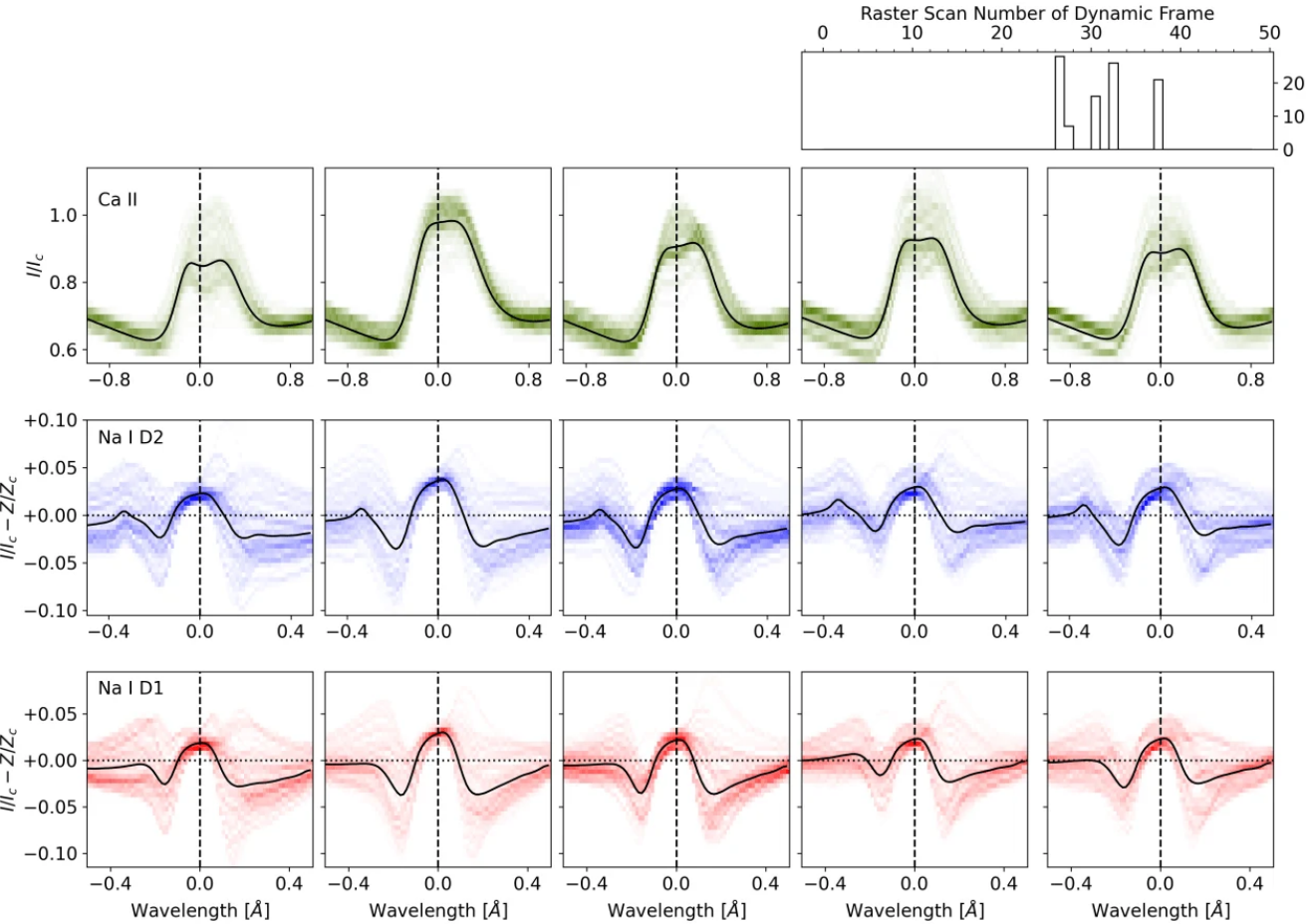
2023 May 03

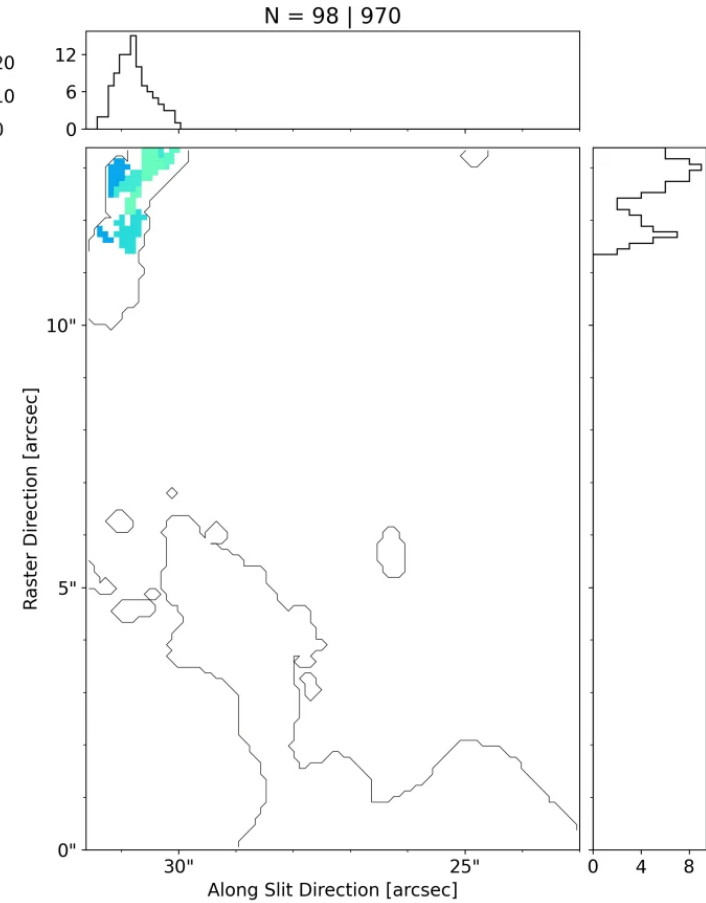
Evolution-driven (Mainland)





2023 May 03 Evolution-driven (Island)





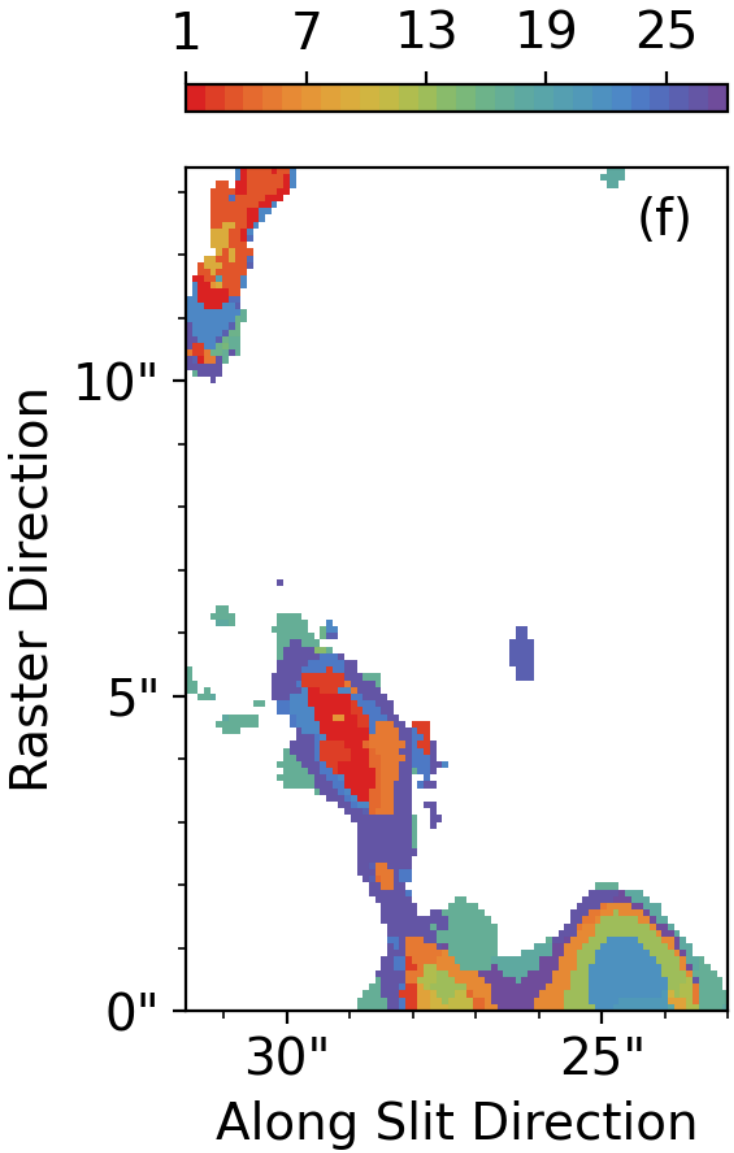
Wrap up

In the **evolution-driven** approach, we've identified two **spatially coherent** subgroups:

1. Impulsive ($<$ 3.11 minutes)
   - On the Mainland (377 0.1" sq pxls)
   - Ca II, Na I enhancement

2. Persistent ($>$ 10 minutes)
   - On the Island (207 0.1" sq pxls)
   - Only Ca II enhancement

From this analysis, we have answered **Q1** and **Q2** of our science questions.



Concluding remarks

Review

Clustering algorithm

- We efficiently identified dynamic signatures on DKIST spatial scales

Epoch-driven results

- We showed how the dynamic signatures are distributed in the AIA 1600 evolution of a flaring pixel

Evolution-driven results

- We have explicitly tracked the distinct dynamic signatures

Concluding remarks

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- We efficiently identified dynamic signatures on DKIST spatial scales

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- We showed how the dynamic signatures are distributed in the AIA 1600 evolution of a flaring pixel

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- We have explicitly tracked the distinct dynamic signatures

Next steps

- Apply the **evolution-driven** analysis to flare observations with higher cadence.
- Compare sequence of representative profiles to modeled spectra

Concluding remarks

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Clustering algorithm

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Epoch-driven results

- We showed how the dynamic signatures are distributed in the AIA 1600 evolution of a flaring pixel

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Acknowledgment

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Thank You

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