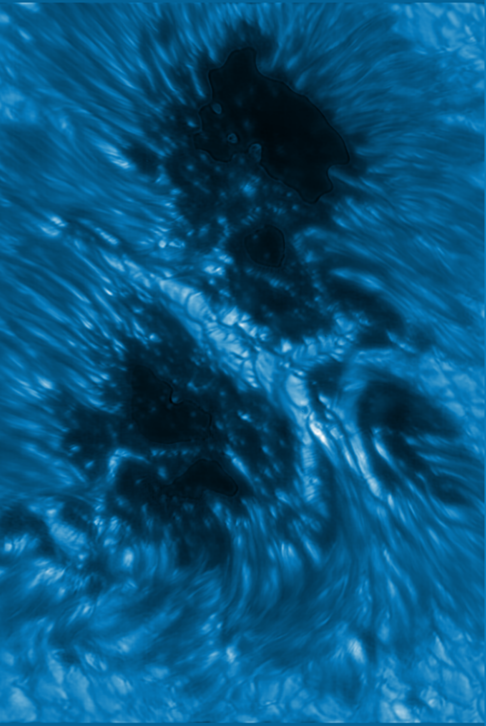


Probing elementary scales of solar flare energetics with the Daniel K. Inouye Solar Telescope

Sarah Riley[1]

[1]Montana State University,
Department of Physics

Ph.D. Candidacy Presentation
2024 December 02

Outline

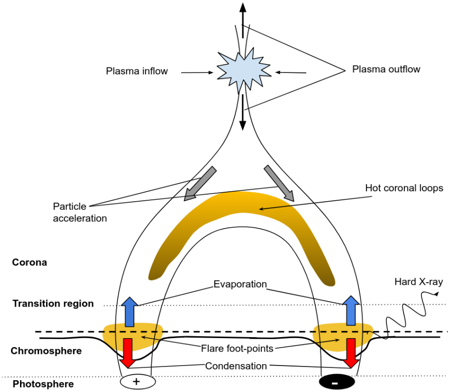
Anatomy of solar flares

Standard flare model

(Carmichael, 1964; Sturrock, 1966;

Hirayama, 1974; Kopp and Pneuman, 1976)

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



(Yadav et al., 2021)

Open questions

- What is the mechanism converting the energy?
- How is the energy transported?

Anatomy of solar flares

Energy transport from the corona to chromosphere

- Non-thermal electrons

  (Emslie et al., 2012)

- Thermal conduction

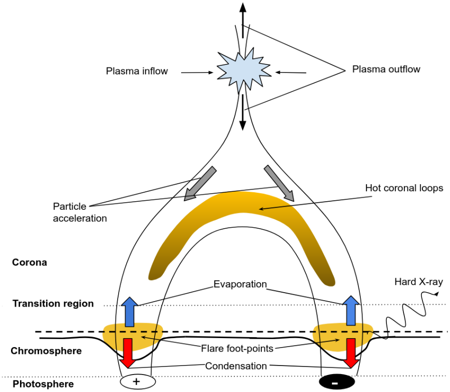
  (Gan et al., 1991; Longcope and Klimchuk, 2015)

- Waves

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

- Ion beams

  (Vilmer et al., 2011)

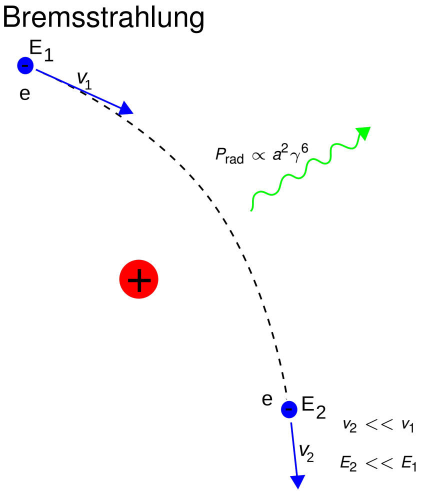


(Yadav et al., 2021)

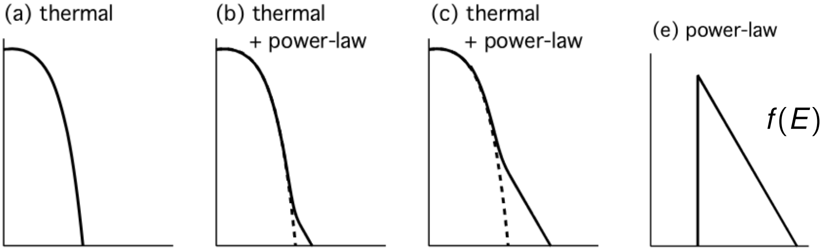
Non-thermal electrons

Properties

- Small collisional cross-section
- Energy released **heats the chromosphere** and **produces hard x-rays**

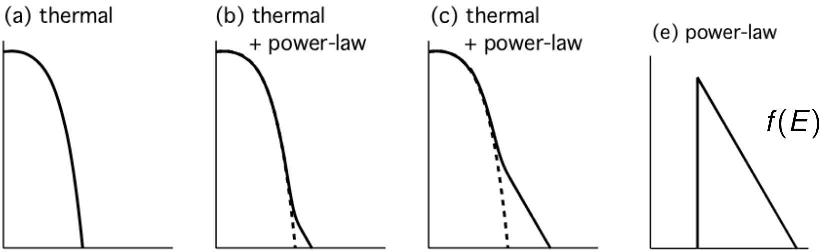


Non-thermal electrons



(Oka et al., 2018)

Non-thermal electrons



(Oka et al., 2018)

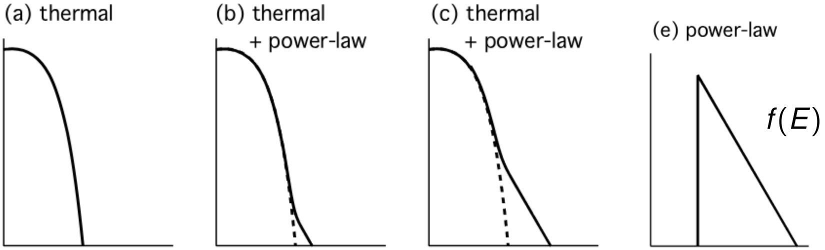
Energy spectrum

$$f(E) = \frac{dN}{dE} \propto \left(\frac{E}{E_0}\right)^{-\delta} \left[\frac{\mathrm{e^-\ s^{-1}\ erg^{-1}}}{\mathrm{Area}}\right]$$

Energy Flux

$$F = \int_{E_0}^{\infty} E\, f(E) dE \left[\frac{\mathrm{erg\ s^{-1}}}{\mathrm{Area}}\right]$$

Non-thermal electrons



(Oka et al., 2018)

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Energy Flux

$$\mathbf{F} = \int_{E_0}^{\infty} E\, f(E) dE \left[\frac{\mathrm{erg \ s^{-1}}}{\mathrm{Area}}\right]$$

Science background Non-thermal electrons

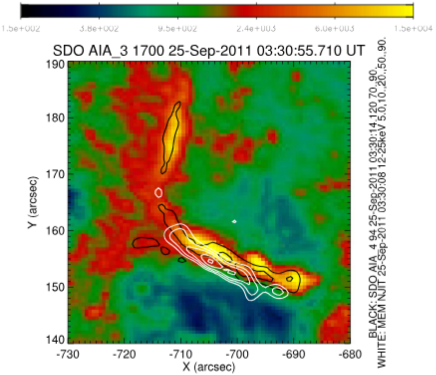
Properties

- Small collisional cross-section

- Energy released **heats the chromosphere** and **produces hard x-rays**

- **Low spatial resolution**

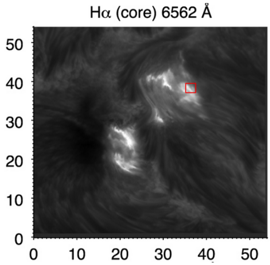
- Flare loops are made of many strains



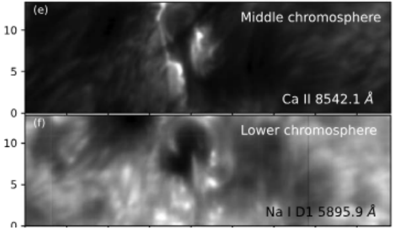
(Dennis and Tolbert, 2019)

The chromosphere

- **High spatial resolution**



(Kuridze et al., 2017)



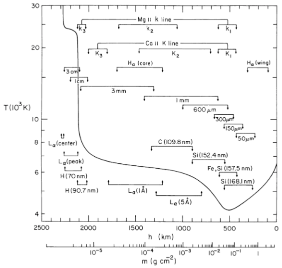
(Yadav et al., 2024)

The chromosphere

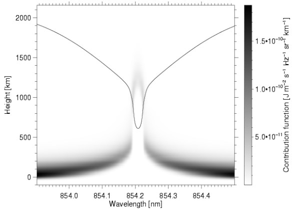
- **High spatial resolution**

Spectral observations

- Provide information on the structure of the atmosphere

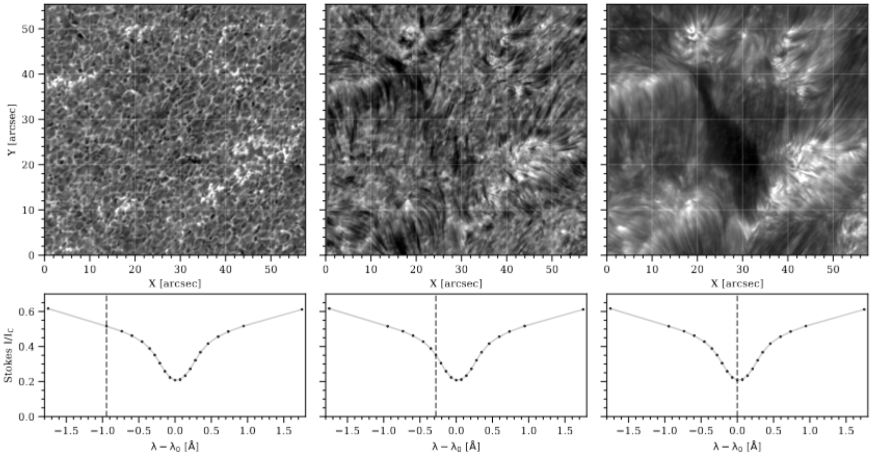


(Vernazza et al., 1981)



(Cauzzi et al., 2008)

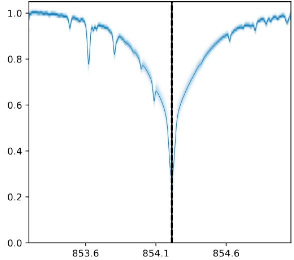
The chromosphere

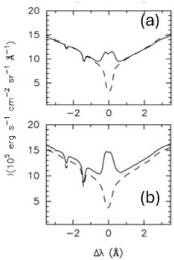


(Diaz Baso et al., 2019)

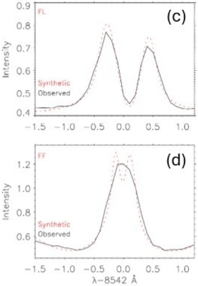
Dynamical signatures

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

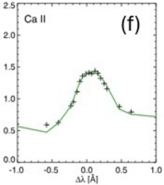




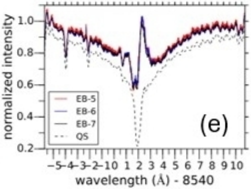
(Fang et al., 2006)



(Kuridze et al., 2017)



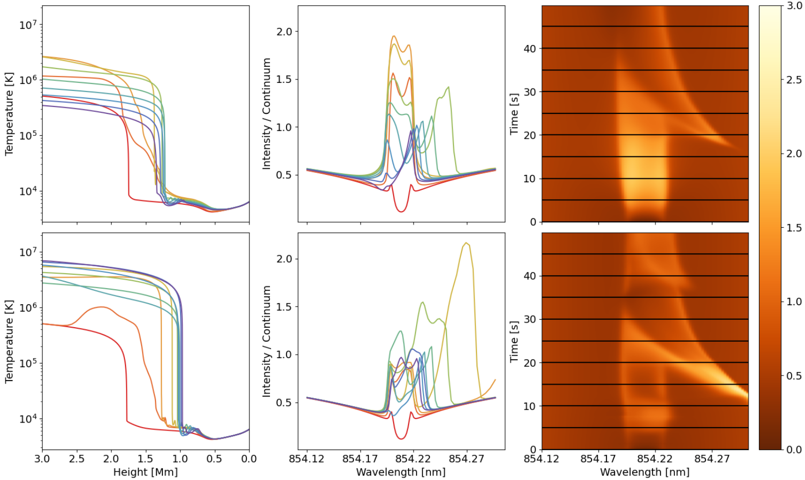
(Rezaei and Beck, 2015)



(Ferrente et al., 2024)

Dynamical signatures

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



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

Driving questions

- What dynamical signatures are associated with different evolutionary stages of individual heating events?
- What are the physical mechanisms behind these dynamical signatures?
- What are the **temporal-spatial scales** relevant to these physical mechanisms?

Science objectives

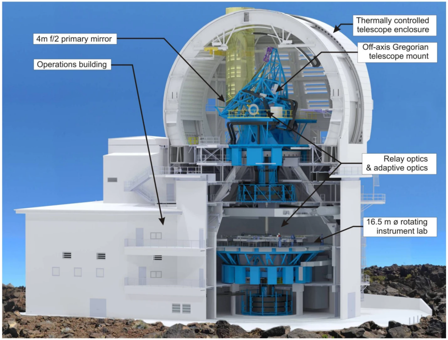
DKIST

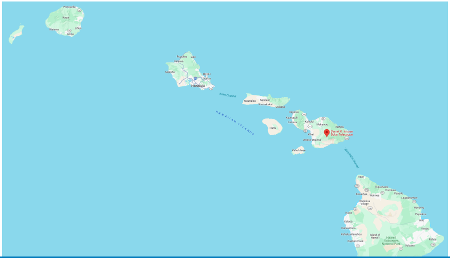
Notable features

- 4-meter primary mirror
- Adaptive optics

Instruments

- Visual Broadband Imager
- Visible Spectropolarimeter
- Visible Tunable Filter
- Diffraction-Limited Near-InfraRed Spectropolarimeter
- Cryogenic Near-InfraRed Spectropolarimeter





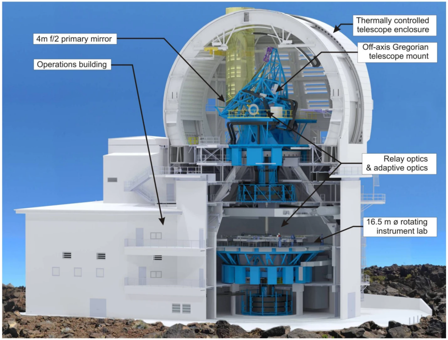
DKIST

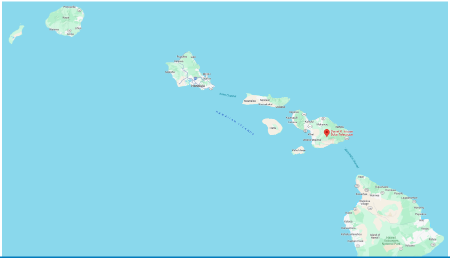
Notable features

- 4-meter primary mirror
- Adaptive optics

Instruments

- Visual Broadband Imager
- **Visible Spectropolarimeter**
- Visible Tunable Filter
- Diffraction-Limited Near-InfraRed Spectropolarimeter
- Cryogenic Near-InfraRed Spectropolarimeter

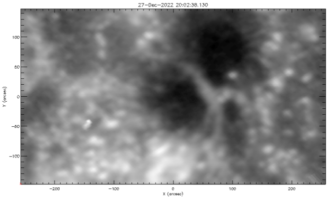




High-resolution

1” = 730 kilometers

AIA 1600 (0.6” x 0.6”)

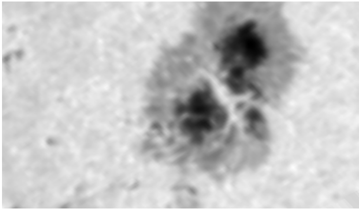


High-resolution

1” = 730 kilometers

AIA 1600 (0.6” x 0.6”)

HMI Cont (0.5” x 0.5”)



High-resolution

1” = 730 kilometers

AIA 1600 (0.6” x 0.6”)

HMI Cont (0.5” x 0.5”)

ViSP (0.019” x 0.214”)

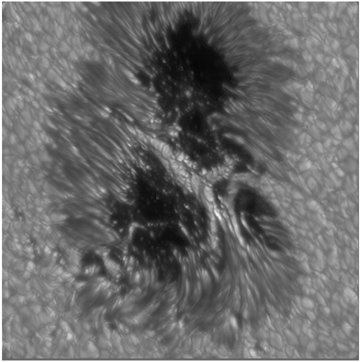
Science objectives

High-resolution

1” = 730 kilometers

AIA 1600 (0.6” x 0.6”)

HMI Cont (0.5” x 0.5”)



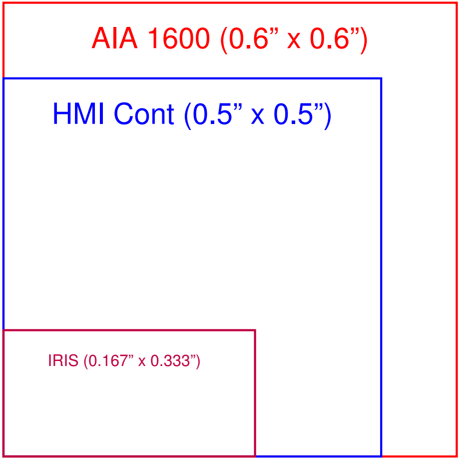
ViSP (0.019” x 0.214”)

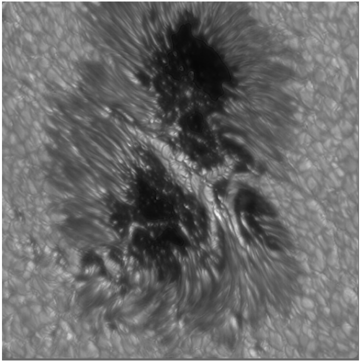
VBI (0.010” x 0.010”)

Science objectives

High-resolution

1” = 730 kilometers





ViSP (0.019” x 0.214”)

VBI (0.010” x 0.010”)

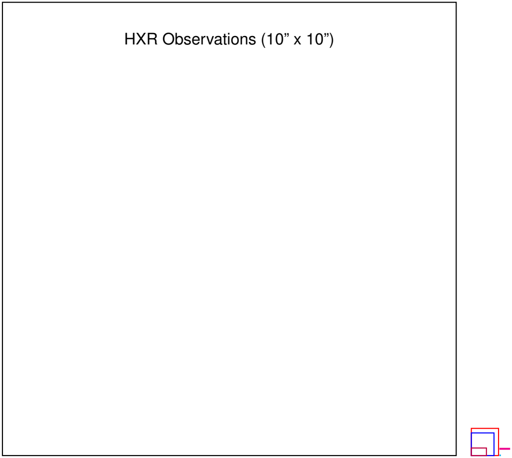
High-resolution

1” = 730 kilometers

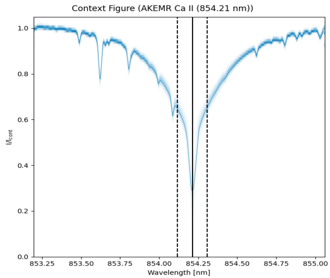
HXR Observations (10” x 10”)

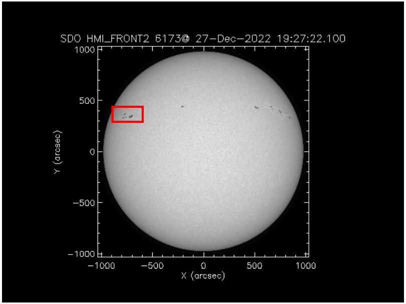
High-resolution

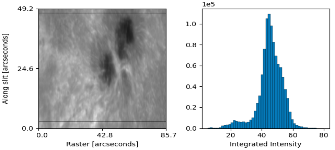
1” = 730 kilometers



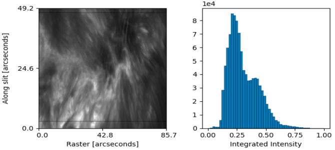
2022 Dec 27 (AR 13176) Overview







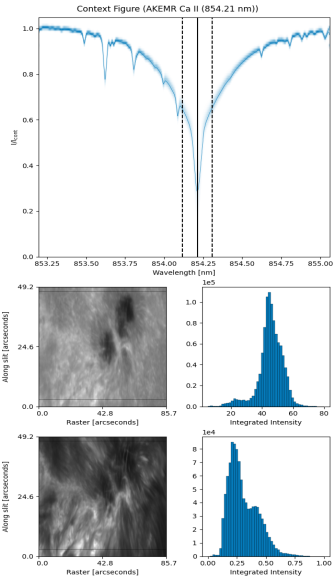
Intensity calculations with the spectral interval

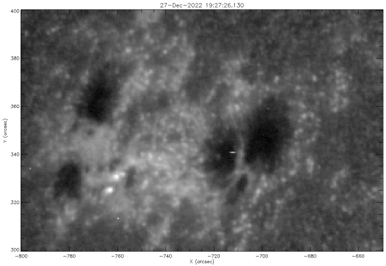


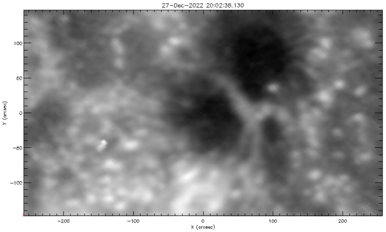
Intensity calculations of the line core

Overview

AIA 1600Å







Catalog Clustering Scheme

Analysis objective

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

Analysis objective

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

Two approaches

Epoch

- Additional observations to define the heating history

Evolution-driven

- Heating history is provided by ViSP observations

Analysis objective

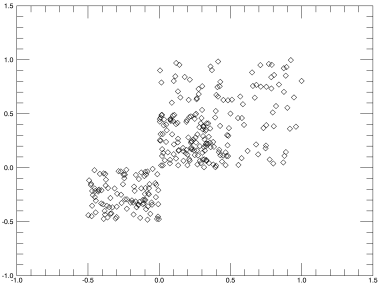
- To develop a method of characterizing large amounts of spectral data by the **dynamical signatures** and **evolution**

Hierarchical structure

- (L_0) Intensity binning
- (L_1 & L_2) *k*-means
- (L_3) Discrimination

CCS (*k*-means)

Goal: Minimize the “Within Cluster Distance”



Start

- Initialize the representatives

Iterate

- Update the label association

- Update the representative

Stop

- Representative converges on a location

Analysis CCS (k-means)

Goal: Minimize the "Within Cluster Distance"

Start

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Iterate

- Update the label association
- Update the representative

Stop

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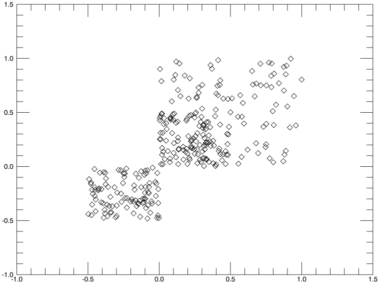

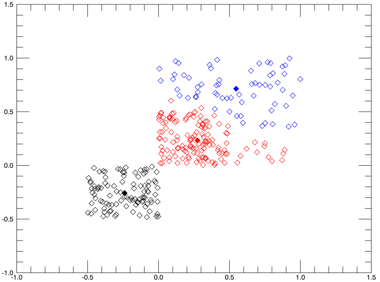

CCS (*k*-means)

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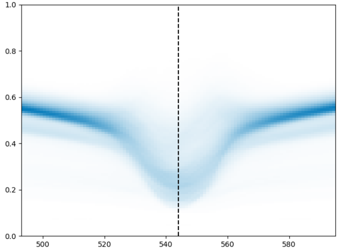
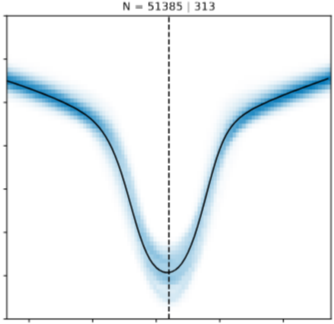
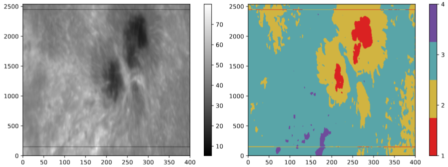




2022 Dec 27


2500
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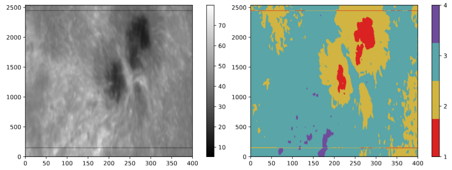
2022 Dec 27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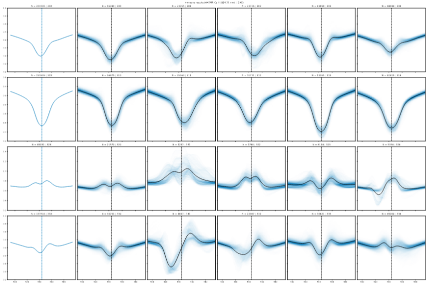
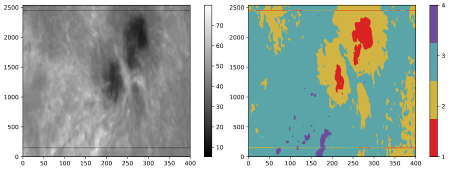
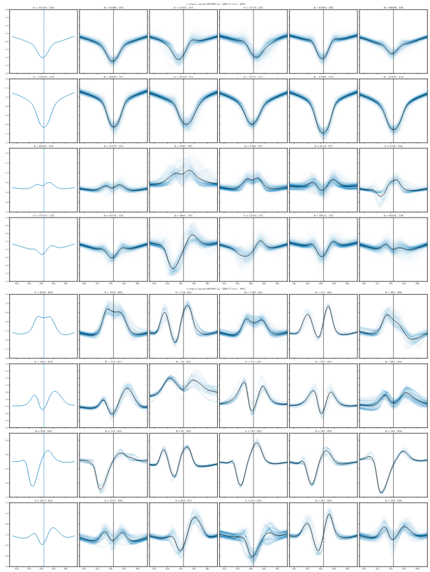


Analysis

2022 Dec 27





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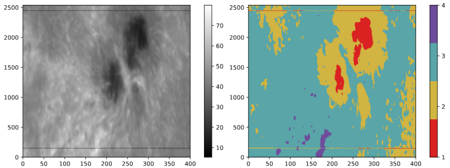
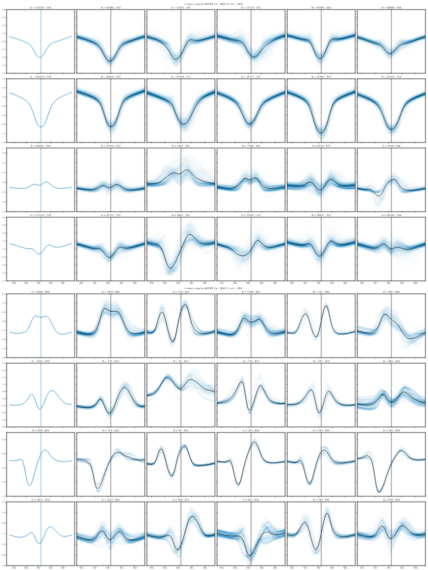




- Only snapshots. We can't directly obtain the evolution

Epoch analysis

Analysis objective

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

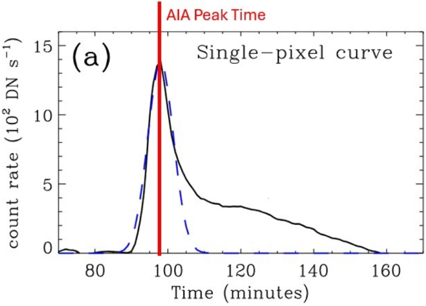
Epoch analysis

Analysis objective

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

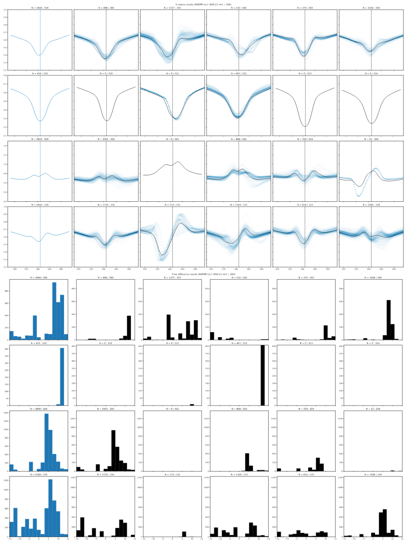
$\Delta t = \text{ViSP Time} - \text{AIA Peak Time}$

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

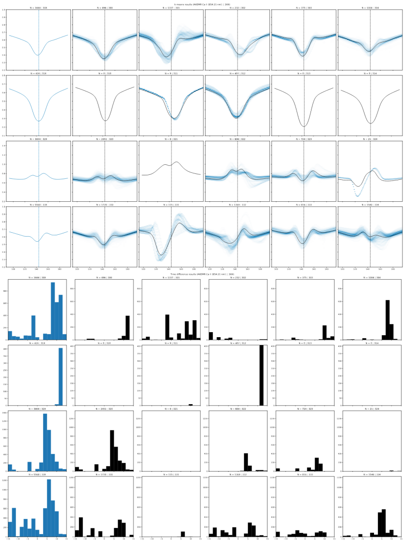


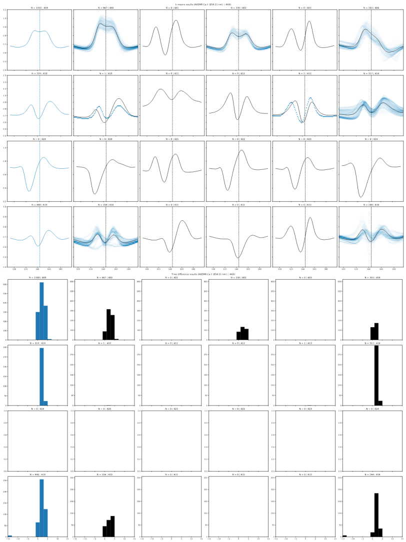
(Adapted from Zhu et al., 2018)

2022 Dec 27 (±15 min)



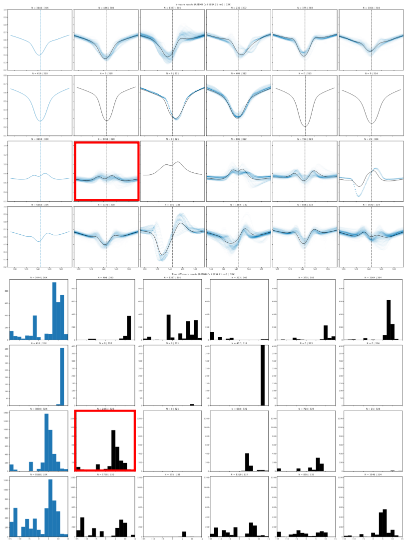
2022 Dec 27 ($\pm$15 min)

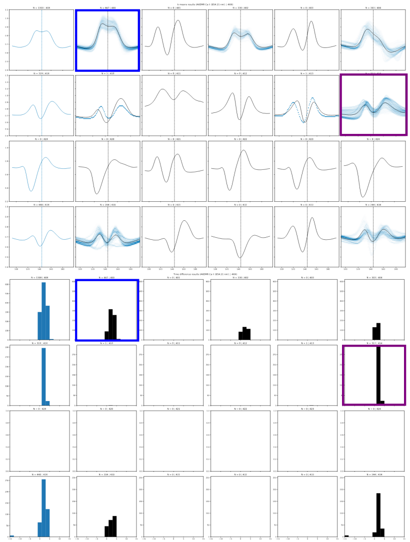




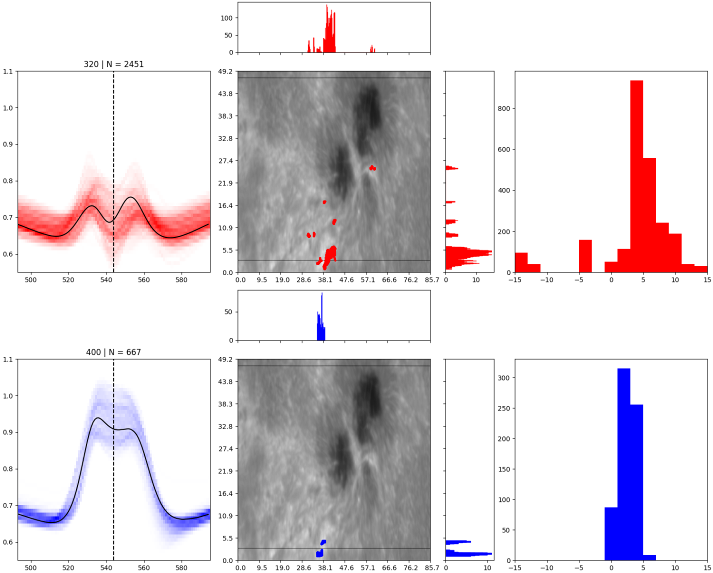
Analysis

2022 Dec 27 (±15 min)

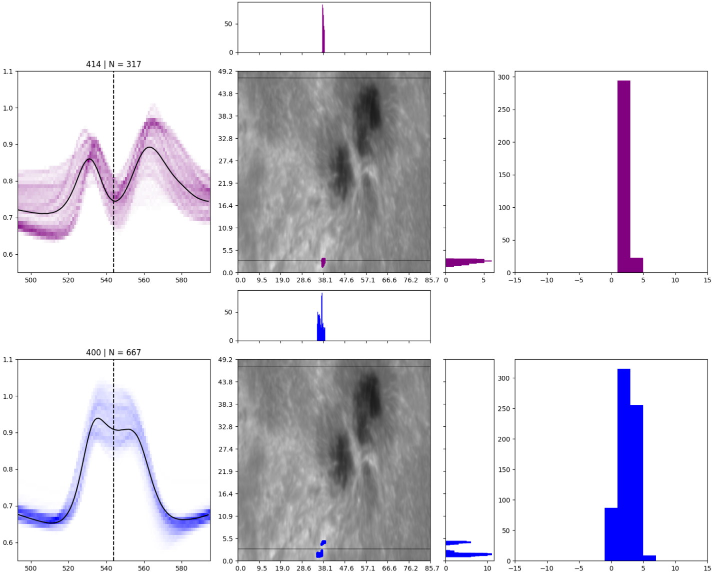




Analysis 2022 Dec 27 ($\pm$15 min)



Analysis 2022 Dec 27 (±15 min)



Wrapping up

Review

From the **CCS**

- We efficiently identified dynamic signatures on DKIST spatial scales

From the **epoch analysis**

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

2023 May 03

- Finite cadence!
- Observed a flare!
- 15$\times$ as much data!

Observation Details

- ViSP
  - Ca II λ8542
  - Na I D
- VBI
  - Hβ
  - Ca II K

Wrapping up

2023 May 03

- Finite cadence!
- Observed a flare!
- 15$\times$ as much data!

Observation Details

- ViSP
  - Ca II λ8542
  - Na I D
- VBI
  - Hβ
  - Ca II K

Proposed 2025

- Sit-N-Stare!
- Will Observe a flare!
- Higher Spatial resolution!

Observation Details

- ViSP
  - Ca II λ8542
  - Hα
  - Na I D
- VBI
  - Hβ

Wrapping up

Review

From the **CCS**

- We efficiently identified dynamic signatures on DKIST spatial scales

From the **epoch analysis**

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

Next steps

- Develop the **evolution-driven** approach for the 2023 and 2025 data.
- Compare sequence of representative profiles to modeled spectra

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Thank You

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