Event Detection in Spatio-Temporal Data Using Singular Value Decompositions (SVDs)

Identifying Patterns in Solar Flare Precursors

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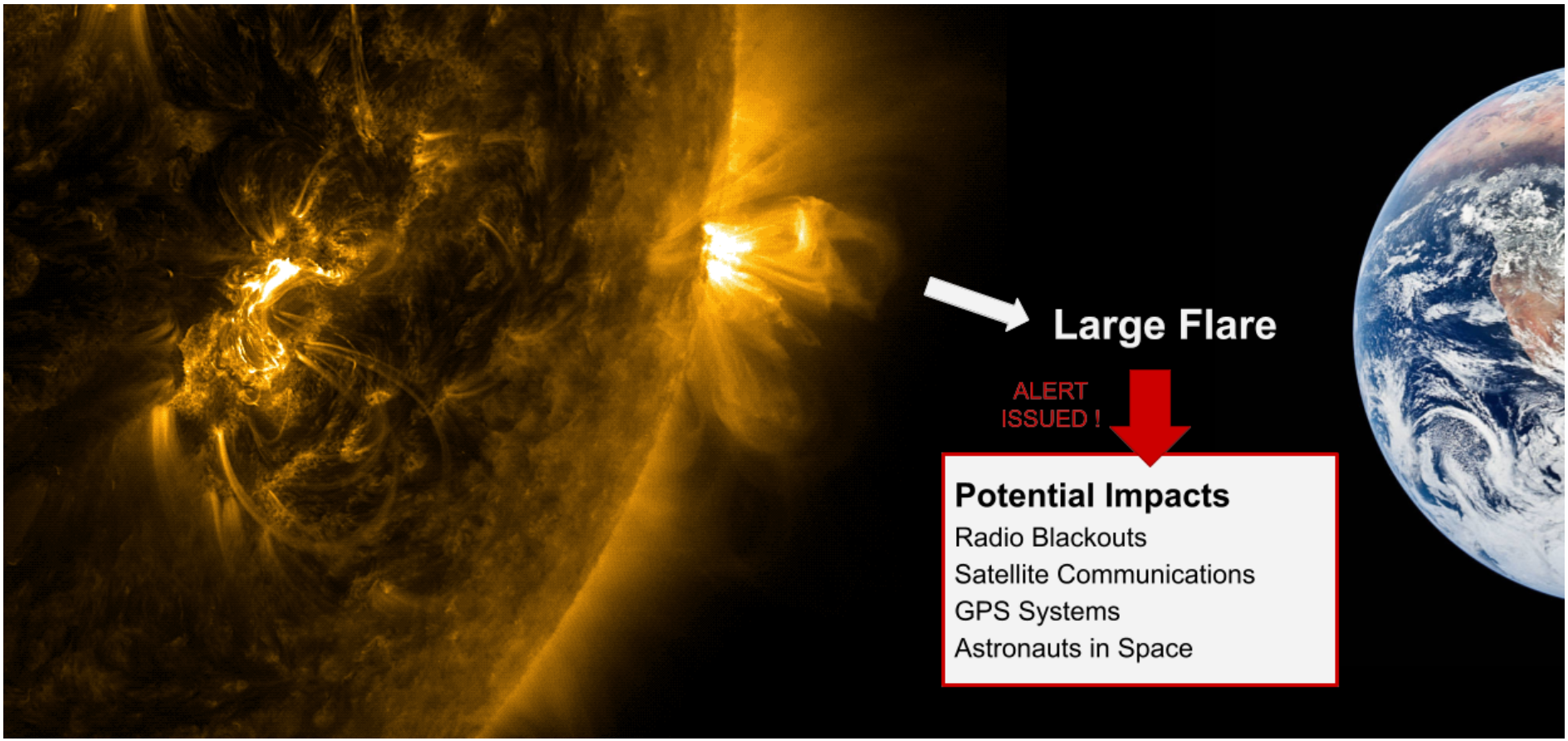
Outline

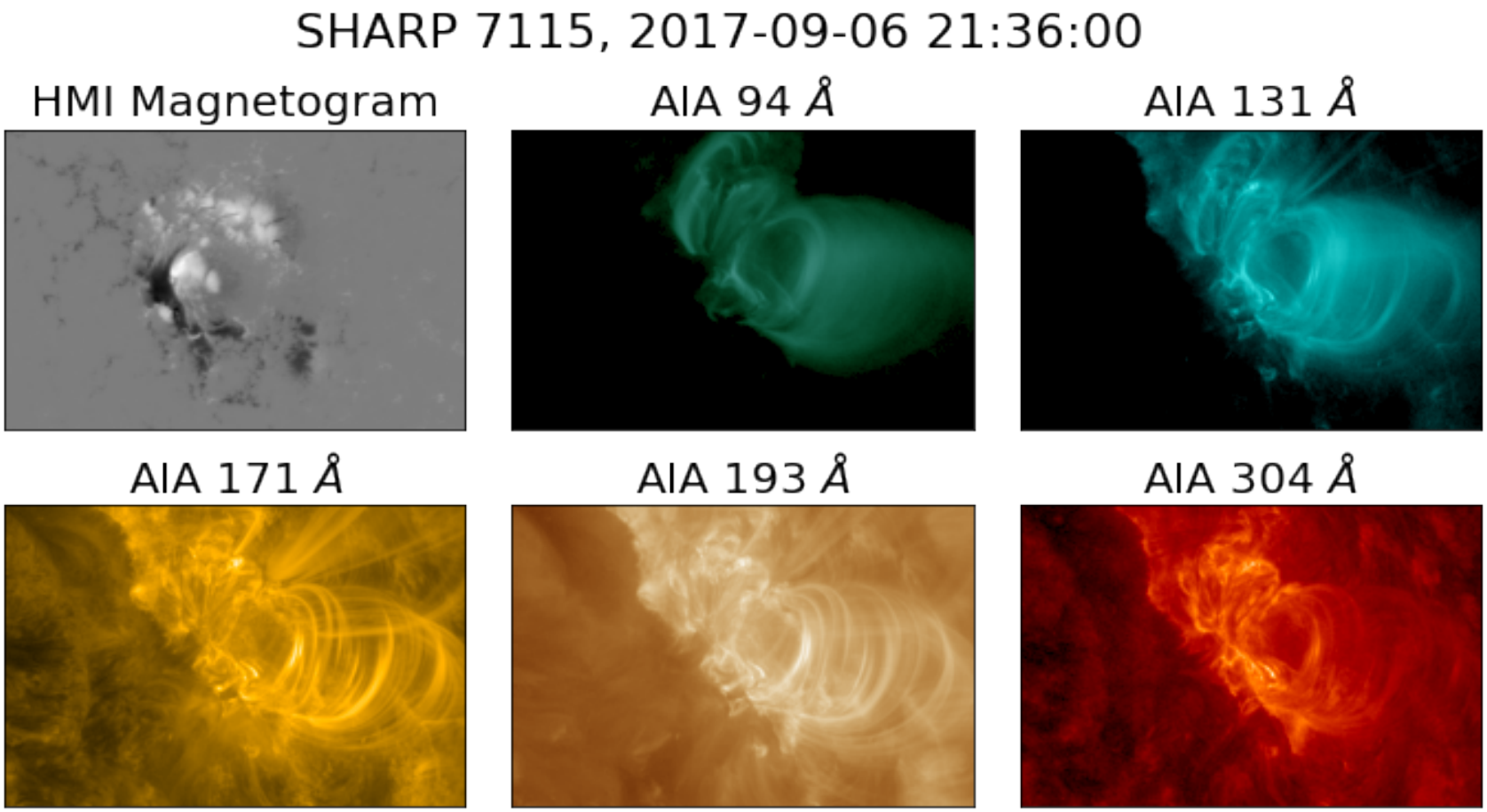
Solar flares are explosive bursts of electromagnetic radiation originating from the Sun. They occur in *active regions*.



Source: NASA Solar Dynamics Observatory

Full-disk solar magnetograms and images are taken every 12 s by instruments onboard NASA's Solar Dynamics Observatory (SDO).

SHARP - Spaceweather HMI Active Region Patch



Classification of Flares

Solar flares are classified by their peak x-ray flux as measured by the Geostationary Operational Environmental Satellites (GOES).

Class	Avg Peak Flux (W/m^2)
C	$10^{-6} \leq$ C $< 10^{-5}$
M	$10^{-5} \leq$ M $< 10^{-4}$
X	$\geq 10^{-4}$

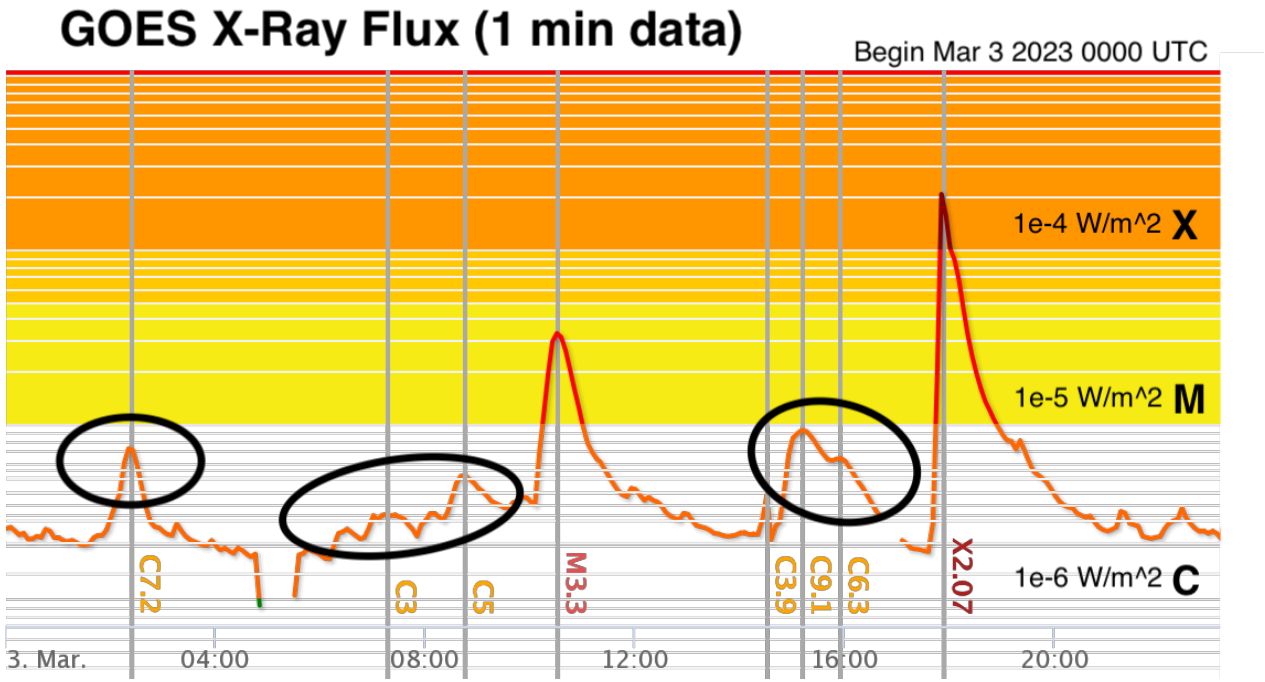
Source: NOAA SWPC

Ex: An M6.5 flare is a flare with a peak flux of $6.5 \times 10^{-5}\ W/m^2$.

The Space Weather Prediction Center (SWPC) issues an alert for flares with a peak flux $\geq$ M5 ($5 \times 10^{-5}\ W/m^2$).

Solar Flare Precursors

Large flare events are often preceded by precursor *microflares*[1]

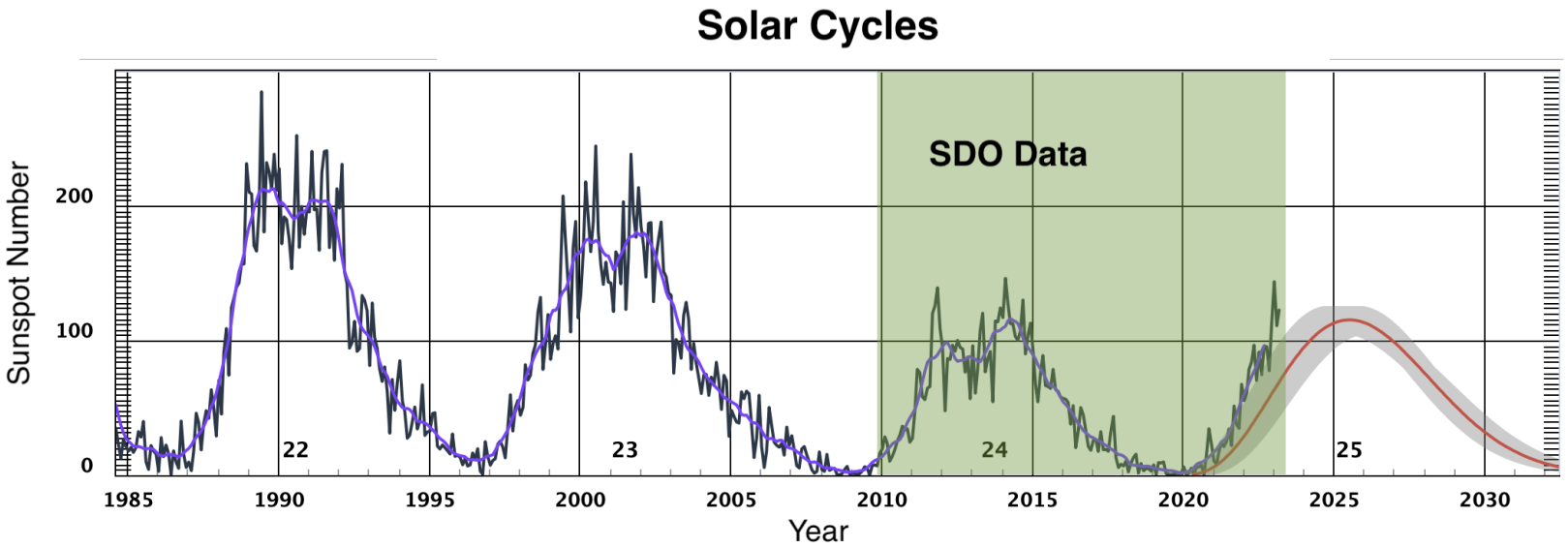


Source: NOAA SWPC

[1] Tappin, Astronomy and Astrophysics, 87 (1991)

Challenges for Prediction

1. Difficult to locate flare events within an AIA image
2. GOES flare catalog - missing spatial information
3. **Relative lack of large flares in Solar Cycle 24**



Source: NOAA SWPC

Before we can hope to *predict* large solar flares, it would be useful to identify patterns in the data leading up to an event.

The goal of my thesis is to identify patterns in microflares which precede M or X flares using spatiotemporal UV/EUV solar image data.

Data: Solar Cycle 24

We use AIA SHARPs in wavelengths 94 Å and 131 Å.

Flare Catalog	X	M5 - M9	M1 - M4	C
GOES	23	43	328	2242
AIA-based[2]	25	39	355	15687

Table: Total flare count by class.

Creating Samples

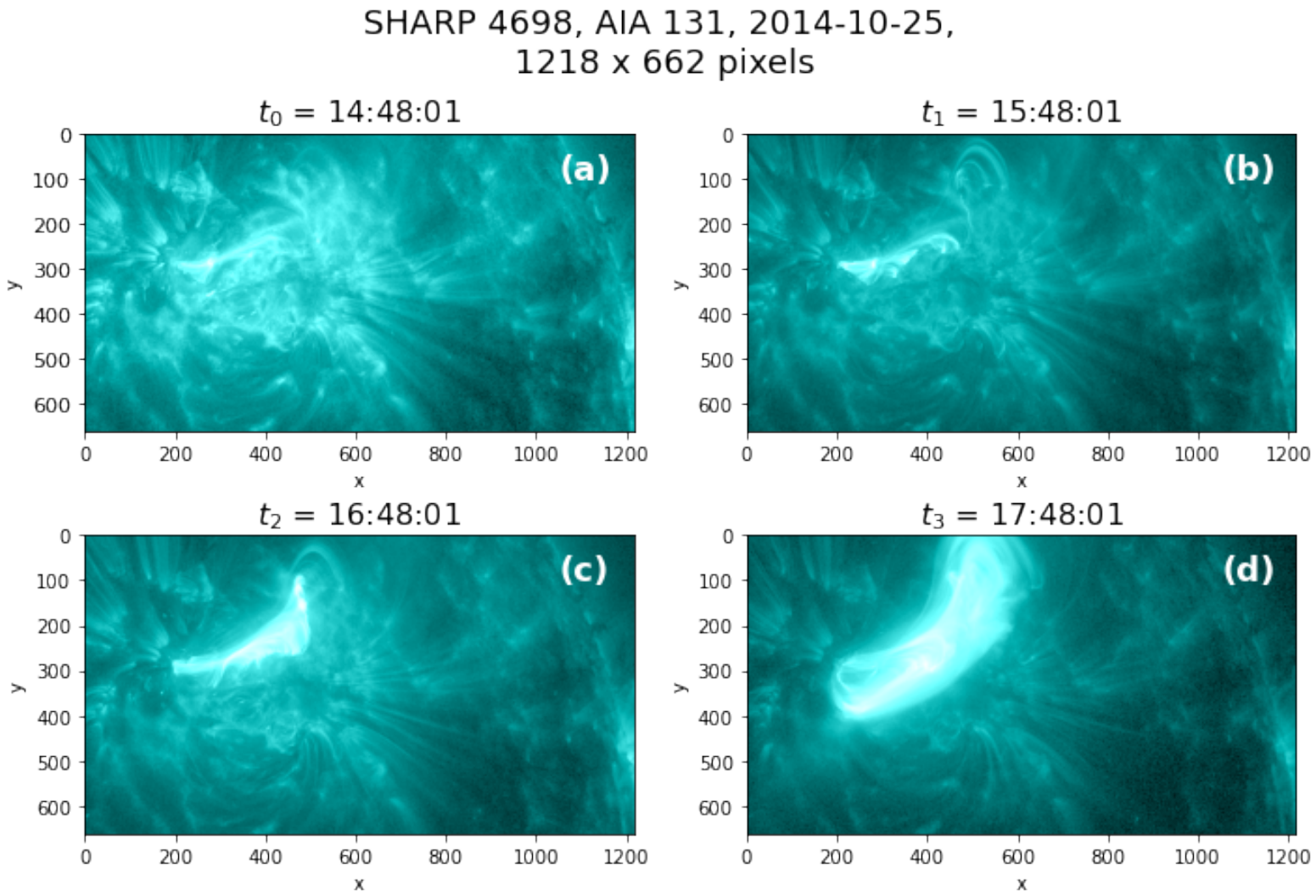
- A fixed time period of 12 hrs before an M/X flare
- Sample does not have $\geq$ M5 flare
- No limb flares

total samples	X flares	M5 - M9 flares	M1 - M4 flares
104	20	26	58

Table: Sample counts for X, M5-M9, and M1-M4 flares in this study. They occur in 27 SHARPs.

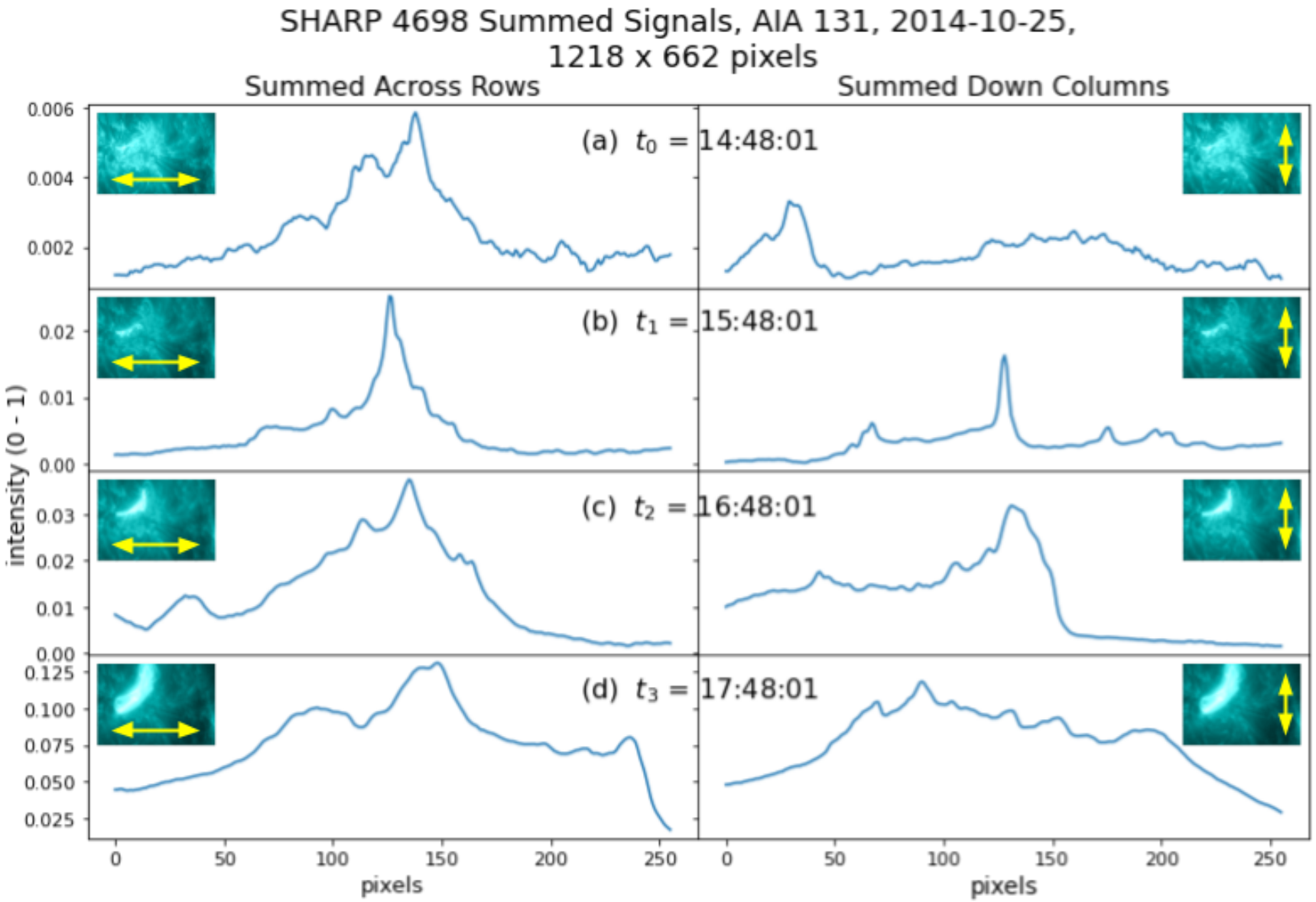
[2] van der Sande et al., Frontiers in Astronomy and Space Sciences, 9 (2022)

AIA Time Series of Images for Each SHARP

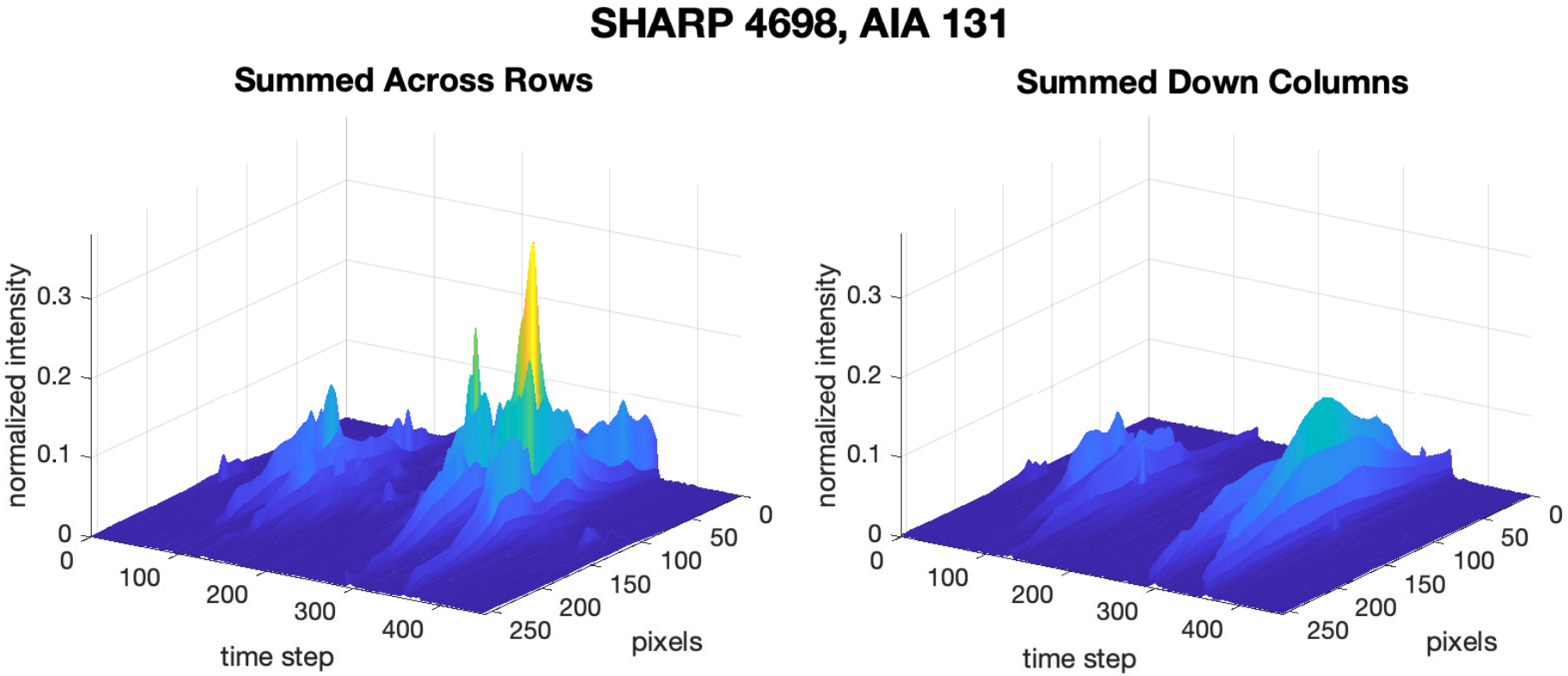


An X1 flare occurs 4 mins after (c).

Dimension Reduction of Images



Summed SHARP Matrices



Singular Value Decomposition (SVD)

For $M \in \mathbb{R}^{m \times n}$, taking the SVD of M gives

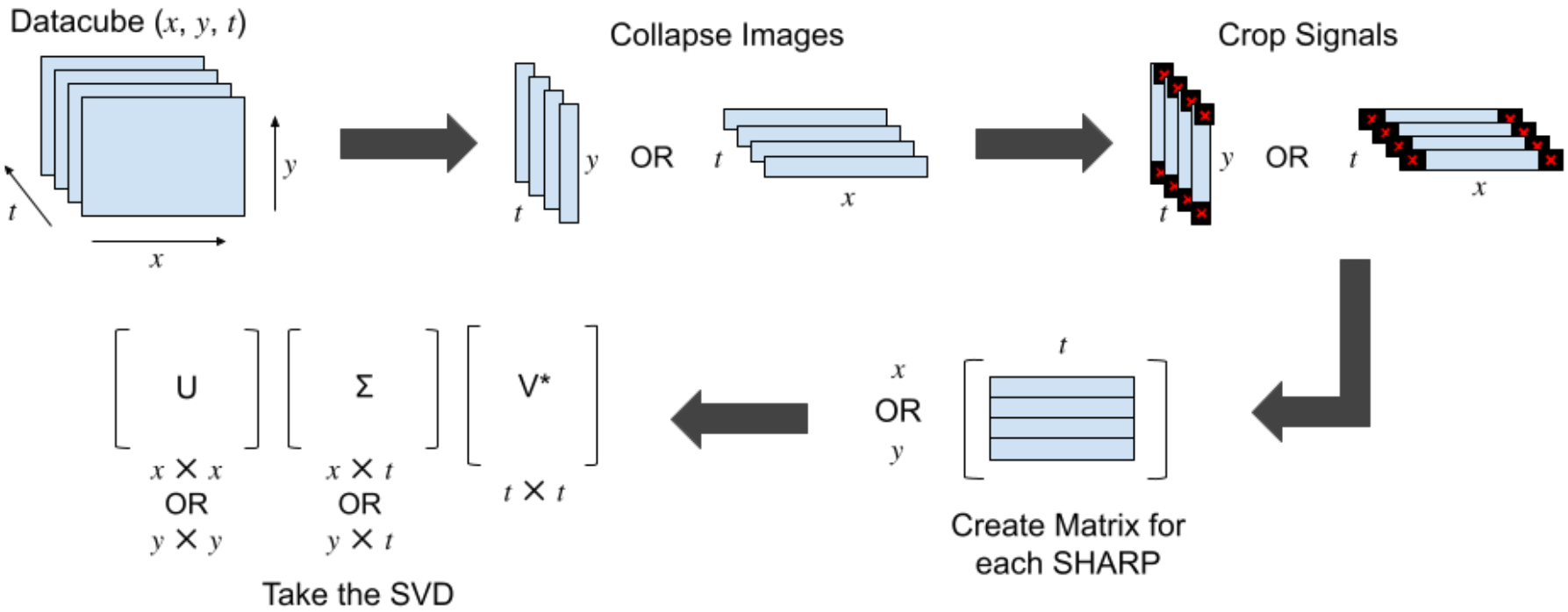
$$M = U\Sigma V^*$$

U (pixels): Unitary matrix that relates to the column space of M, columns are singular vectors u_i

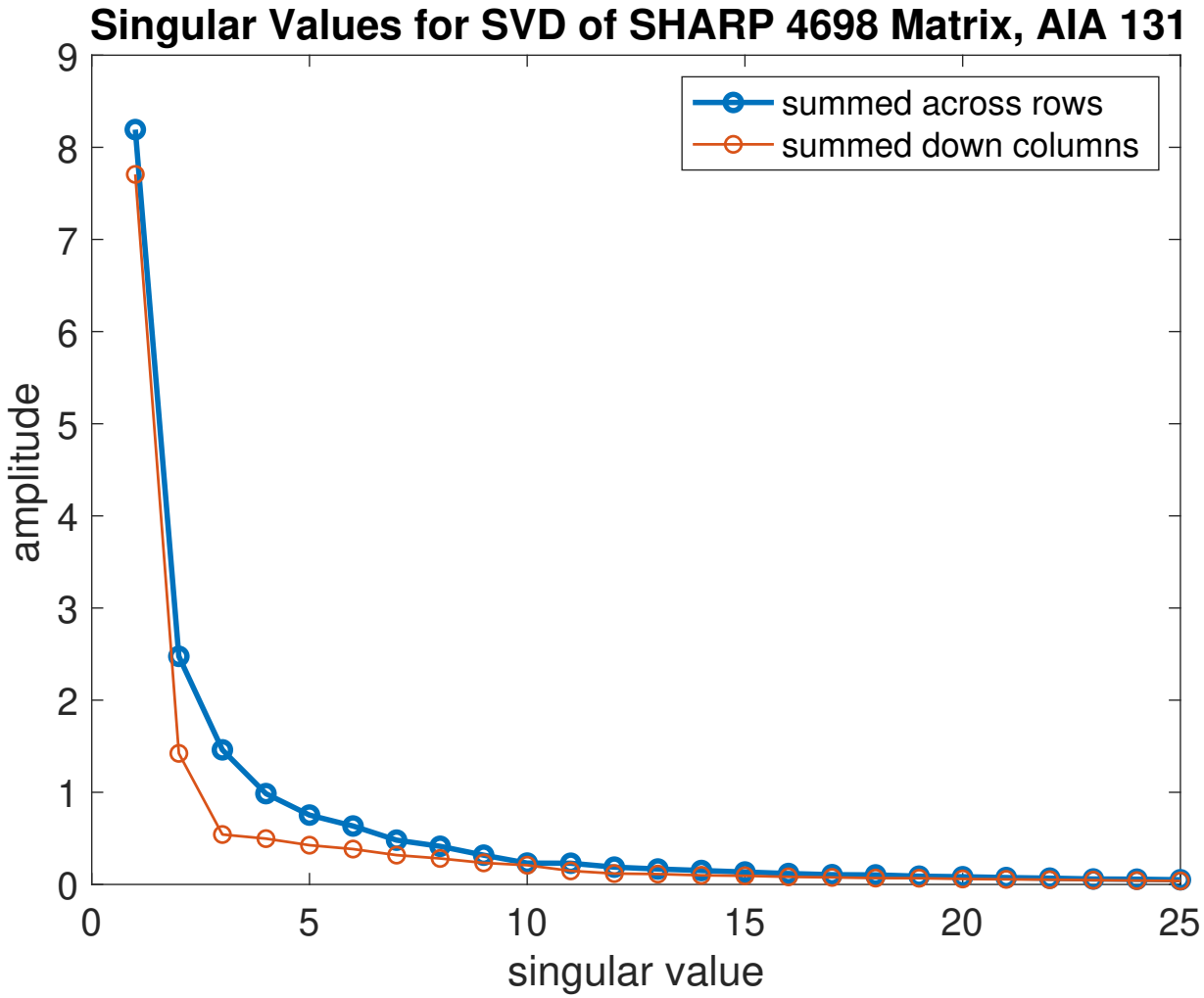
V (time): Unitary matrix that relates to row space of M, columns are singular vectors v_i

Σ: Diagonal matrix containing singular values σ_i

Data Transformations Taken to Perform SVD on Images

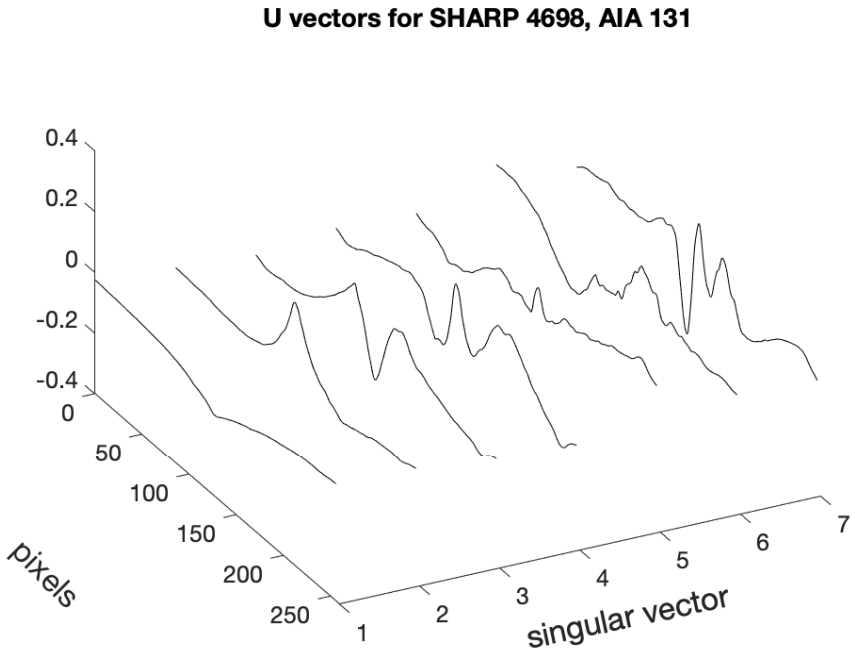


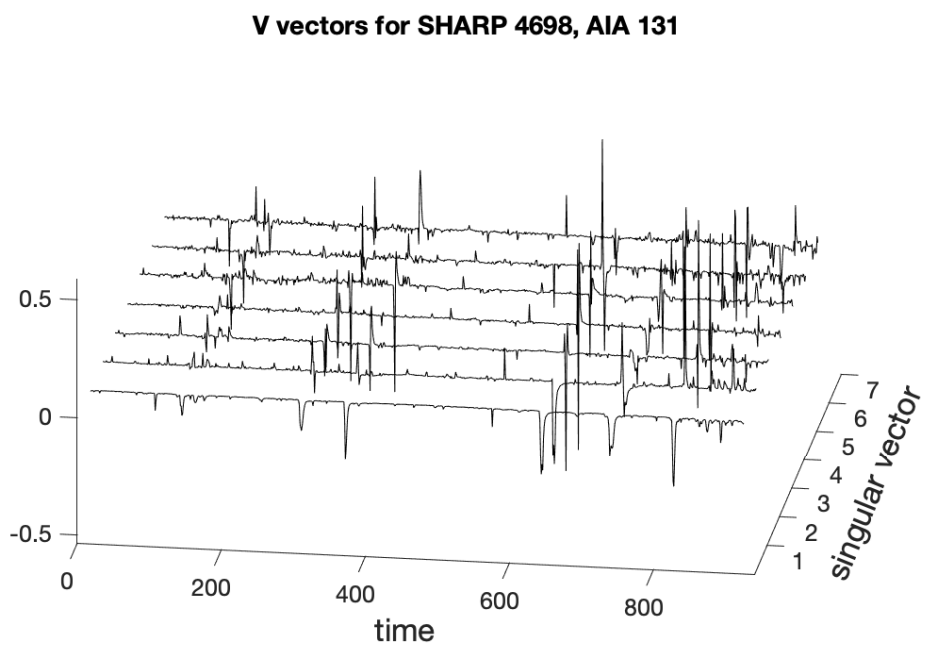
Singular Values σ_i Decay Exponentially



$\sigma_{10} << \sigma_1$

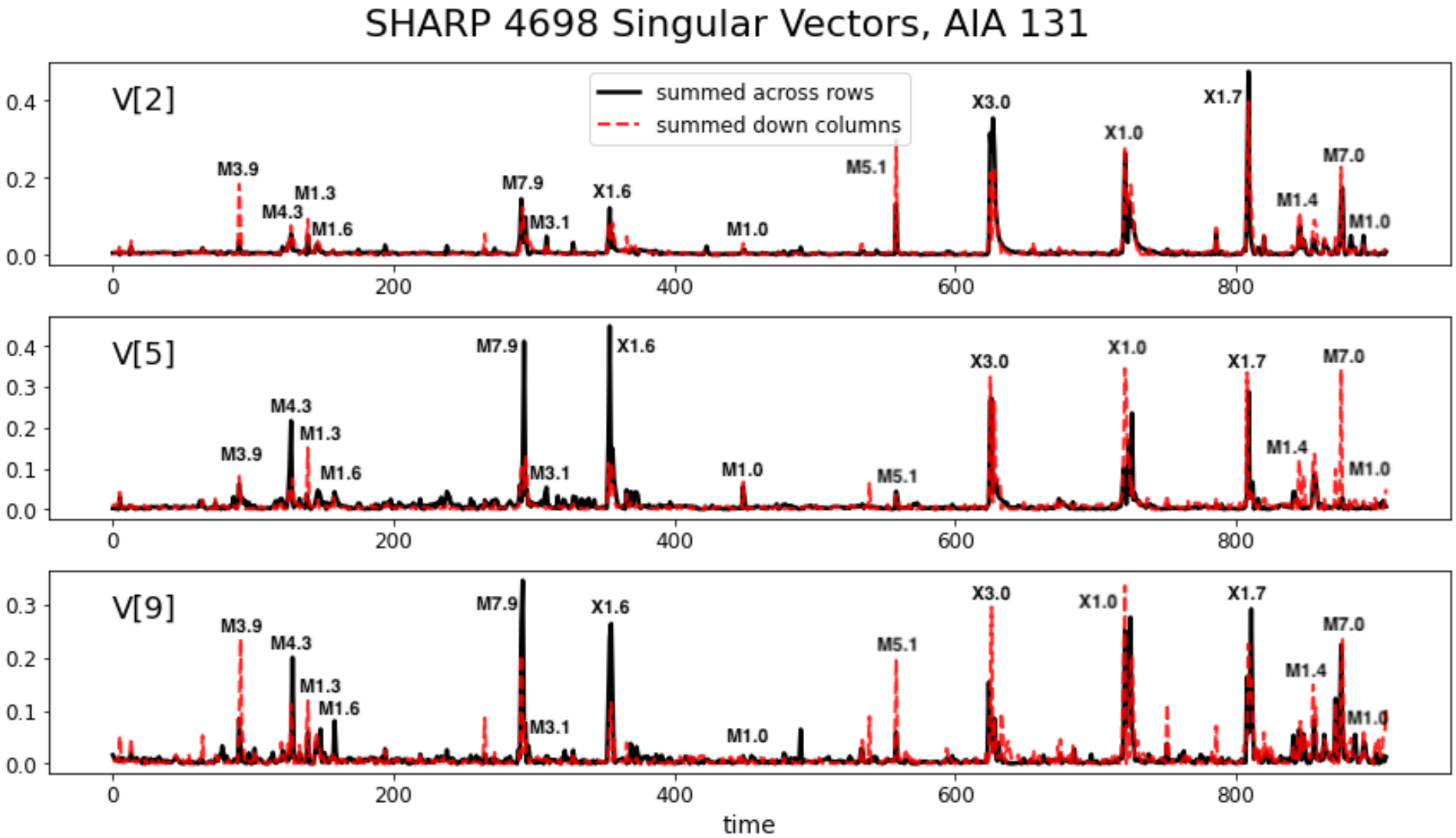
U and V Vectors (Summed Across Rows)





$\sigma_1 = 8.1926$	$\sigma_5 = 0.7528$
$\sigma_2 = 2.4756$	$\sigma_6 = 0.6341$
$\sigma_3 = 1.4607$	$\sigma_7 = 0.4807$
$\sigma_4 = 0.9858$	

Unexpected Isotropies in the Data



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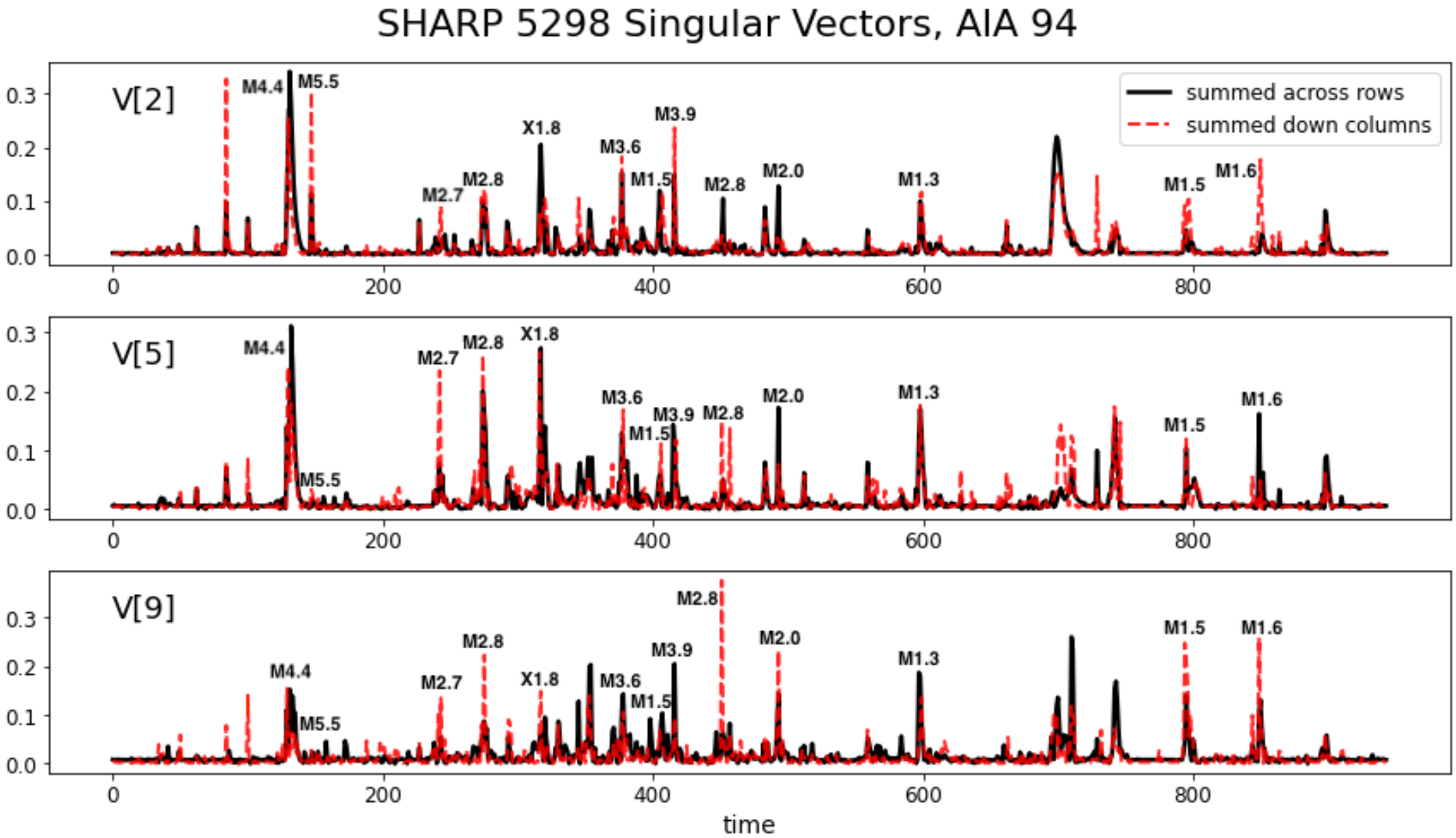
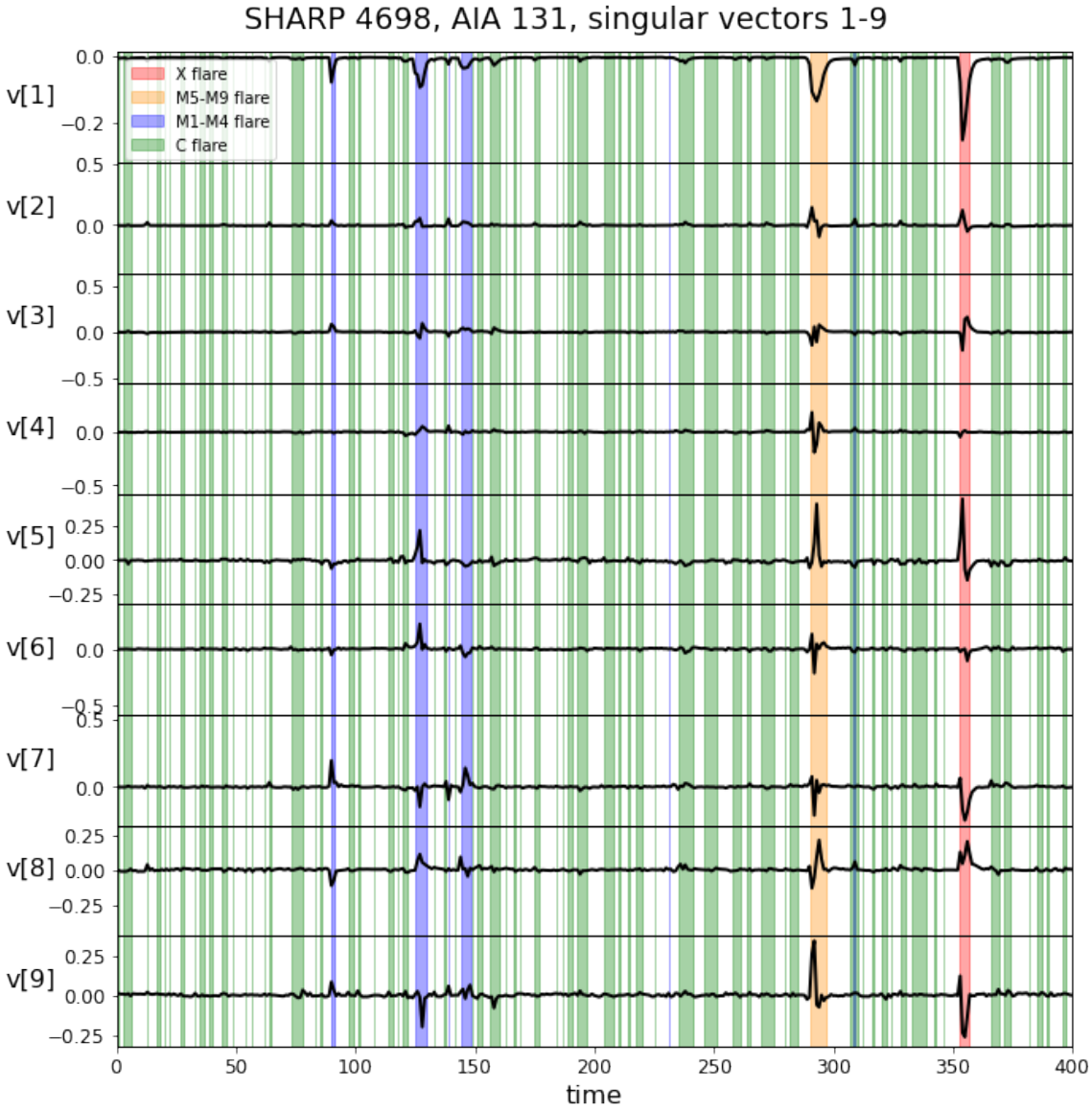


Singular Vector "Events" are Consistent with AIA Flare Catalog



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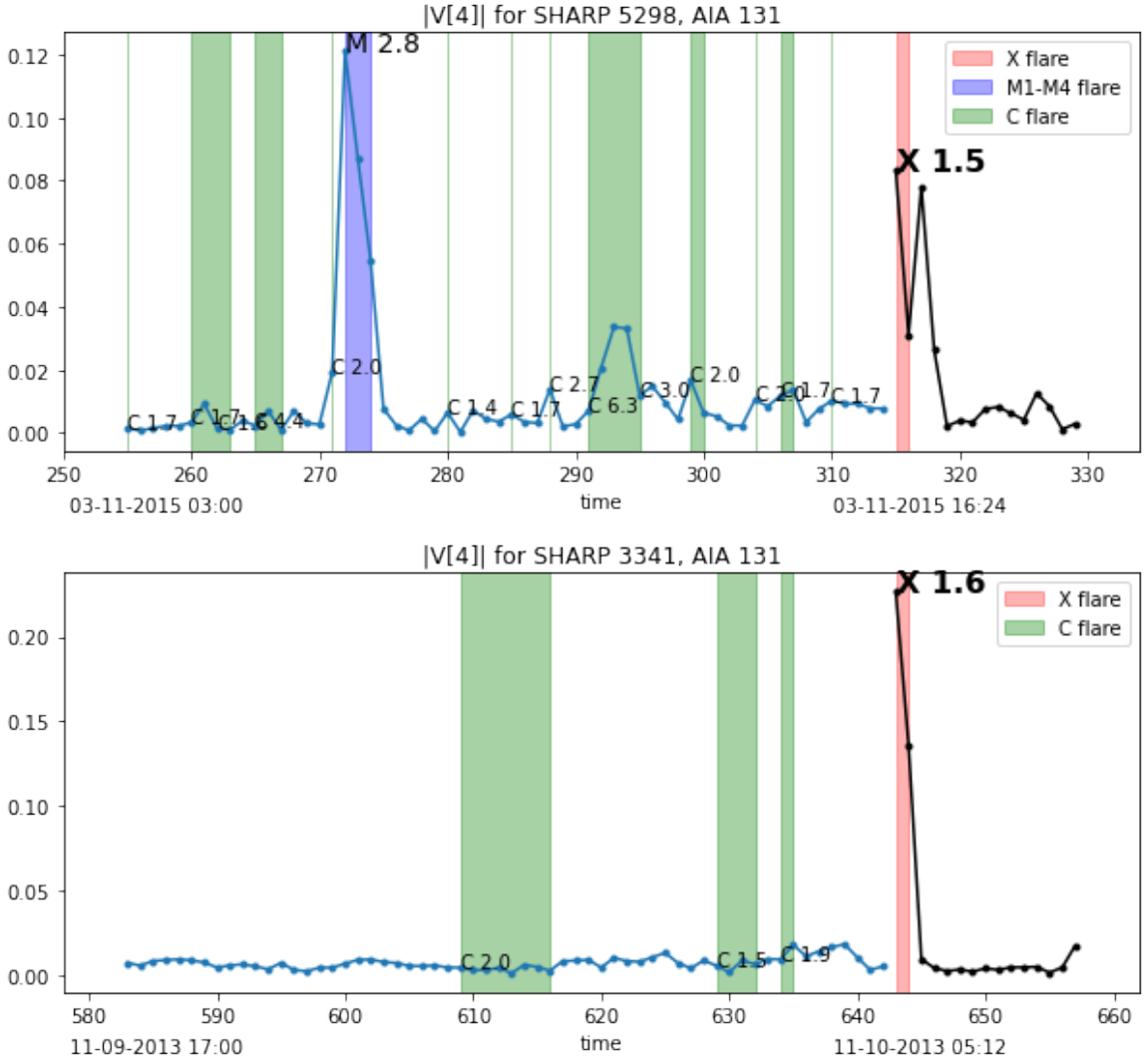

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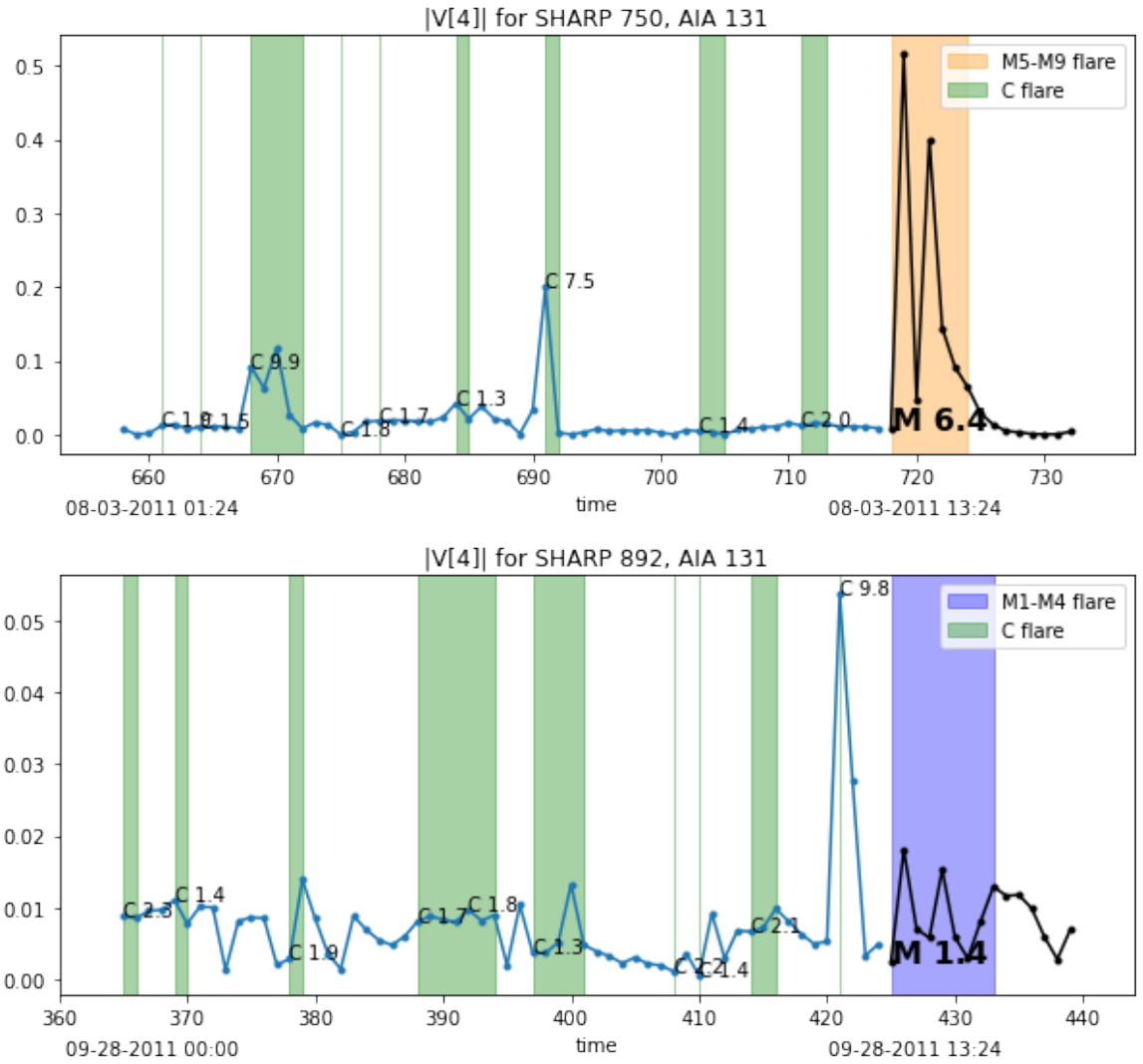

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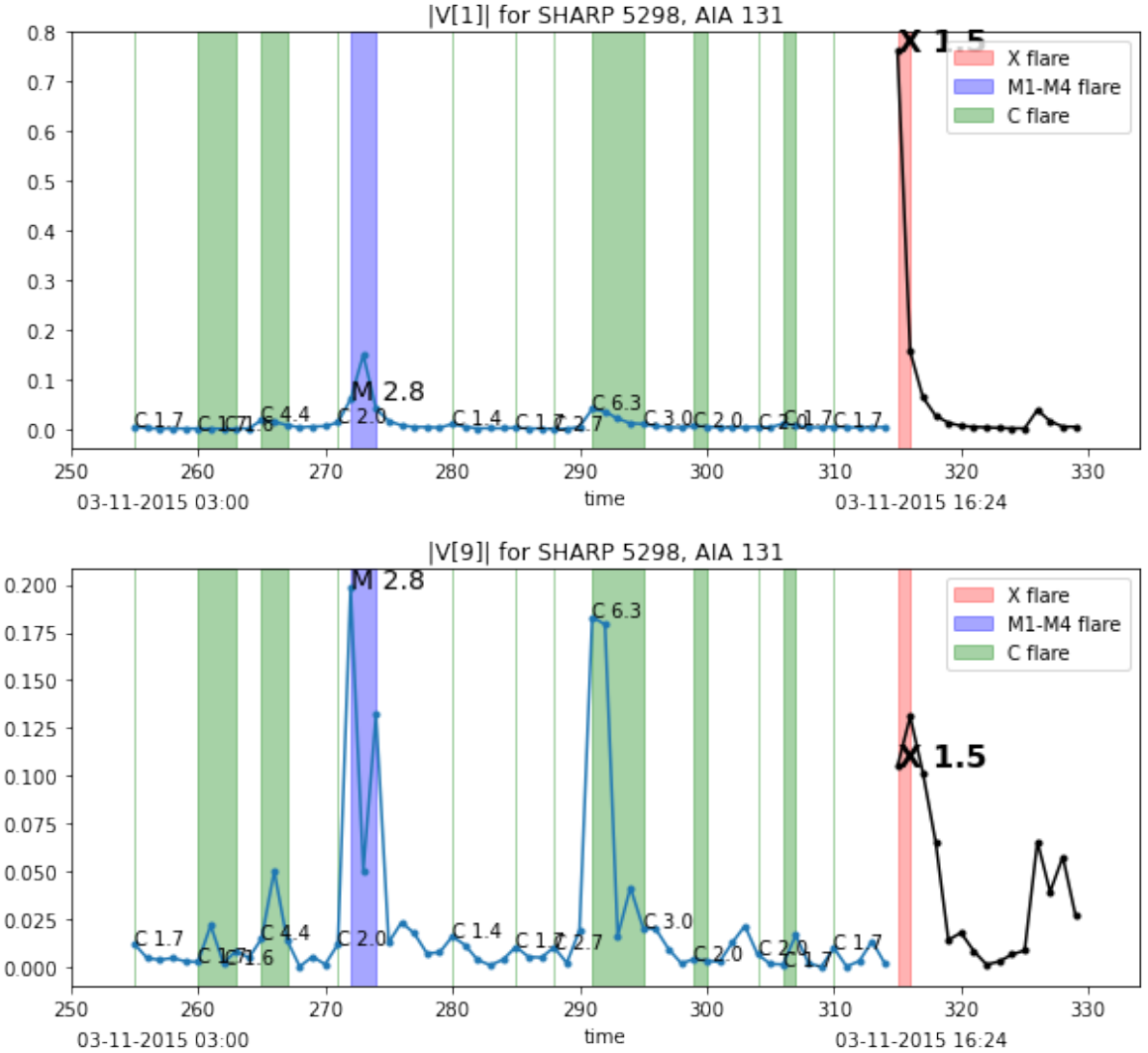
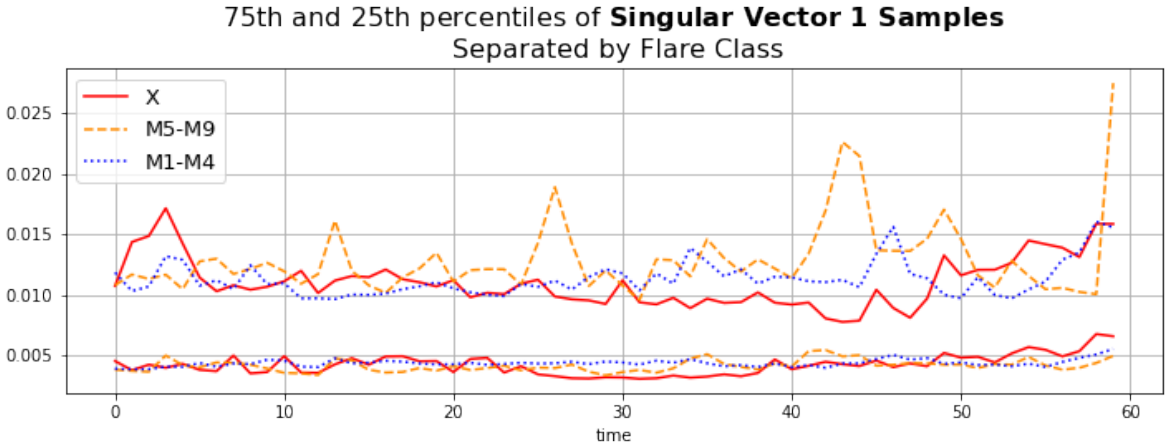
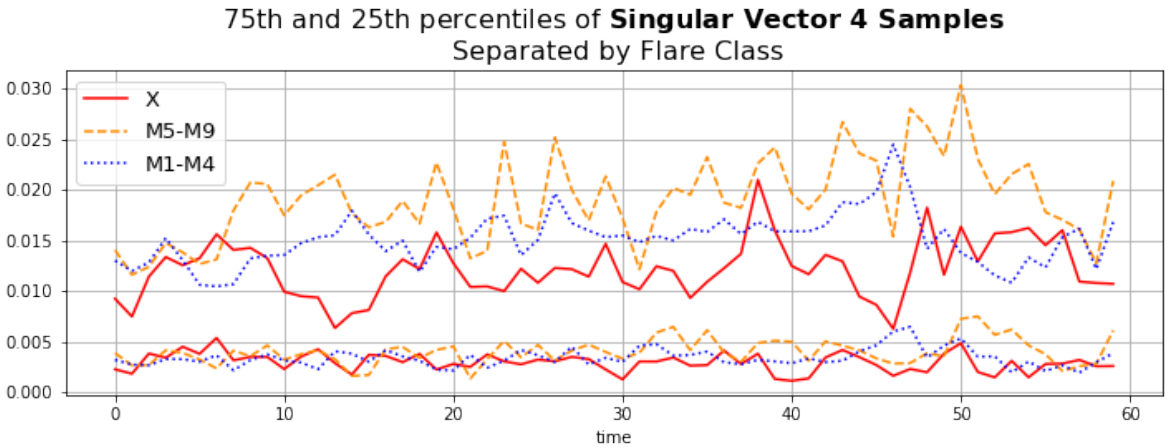
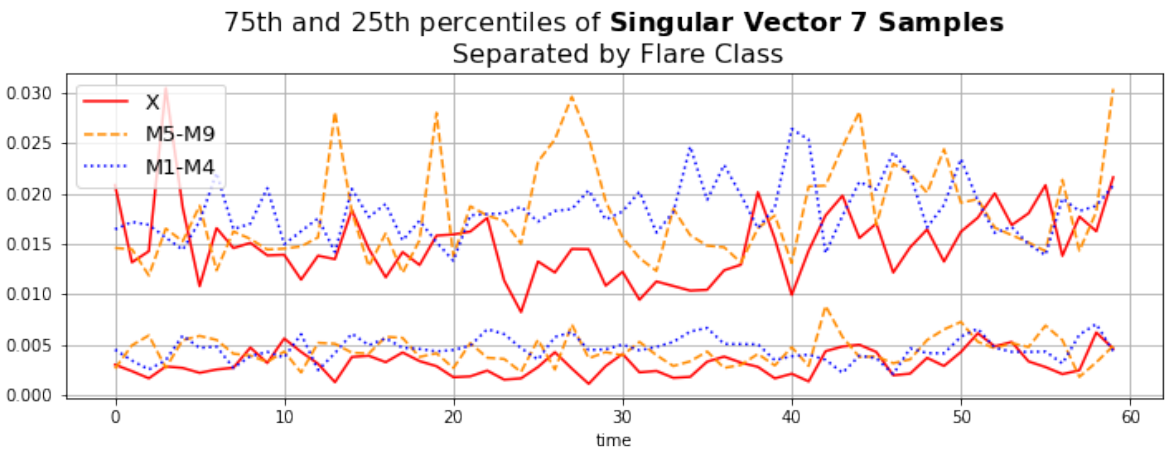


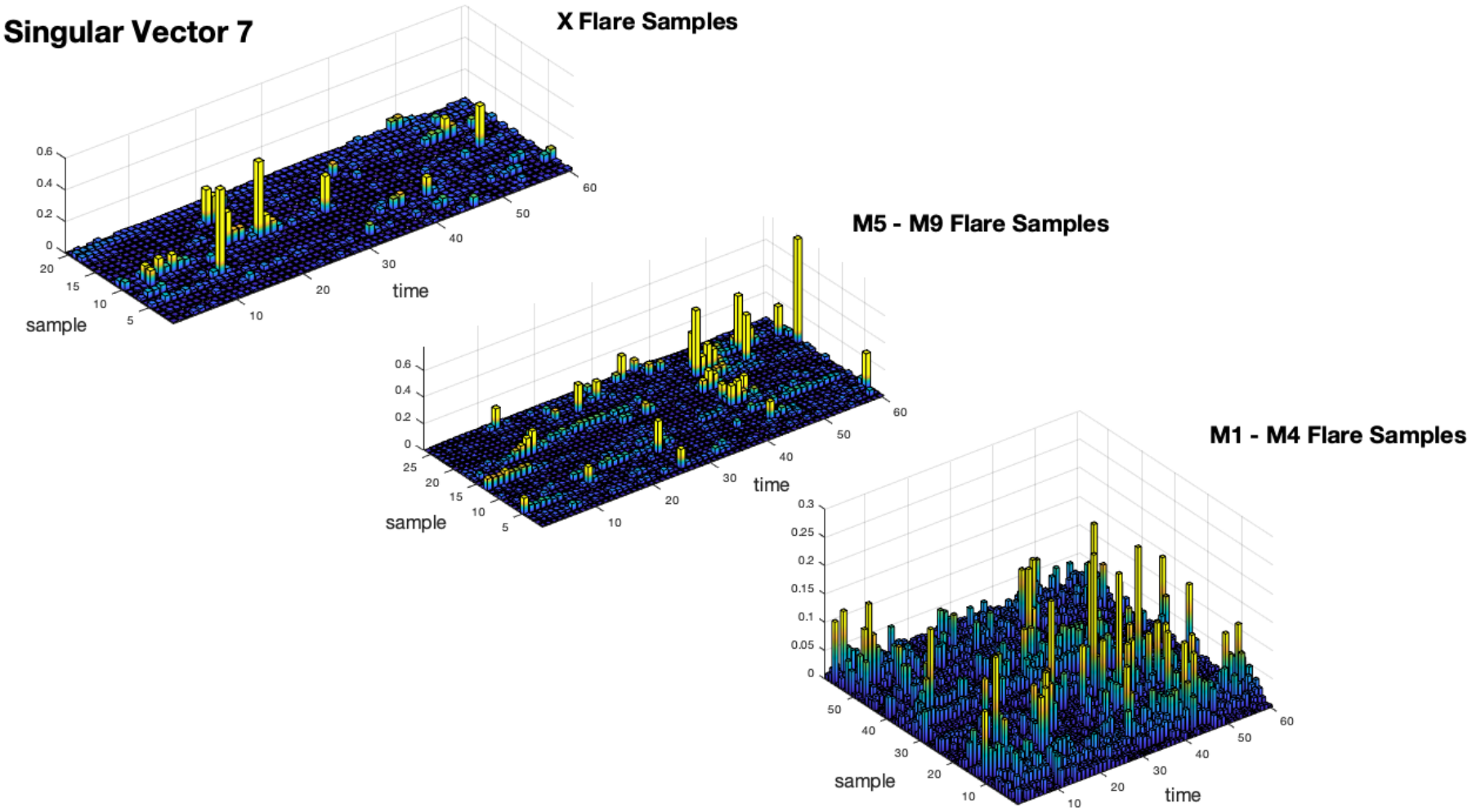
Correlating Precursor Activity to Solar Flare Event Magnitude Using Singular Vector Samples


75th and 25th percentiles of **Singular Vector 1 Samples**
Separated by Flare Class
X
M5-M9
M1-M4
0.025
0.020
0.015
0.010
0.005
0
10
20
30
40
50
60
time


75th and 25th percentiles of **Singular Vector 4 Samples**
Separated by Flare Class
X
M5-M9
M1-M4
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
10
20
30
40
50
60
time


75th and 25th percentiles of **Singular Vector 7 Samples**
Separated by Flare Class
X
M5-M9
M1-M4
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
10
20
30
40
50
60
time

Correlating Precursor Activity to Magnitude of Flare Event



Conclusion

1. AIA active region images tend to be invariant to summing across rows or down columns. Hence, the spatiotemporal data has natural isotropic properties
2. Singular vector peak amplitudes correspond with flare magnitudes in GOES and AIA catalogs
3. There is less precursor activity in larger flares, especially as shown in higher singular vectors

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Future Work

1. Incorporate flares from Solar Cycle 25 and Solar Cycle 23
2. Study different precursor activity windows (6 hr, 24 hr)
3. Explore other geophysical datasets using this technique (earthquakes, volcanoes, flooding, etc.)

Appendix

Wavelength (Å)	Region of solar atmosphere
94	flaring regions
131	flaring regions
171	quiet corona, upper transition region
193	corona and hot flare plasma
304	chromosphere and transition region
1600	transition region and upper photosphere

Table: Regions of the solar atmosphere observable by six AIA wavelength channels.[3]

[3] Source: AIA Instrument Website - https://www.lmsal.com/sdodocs