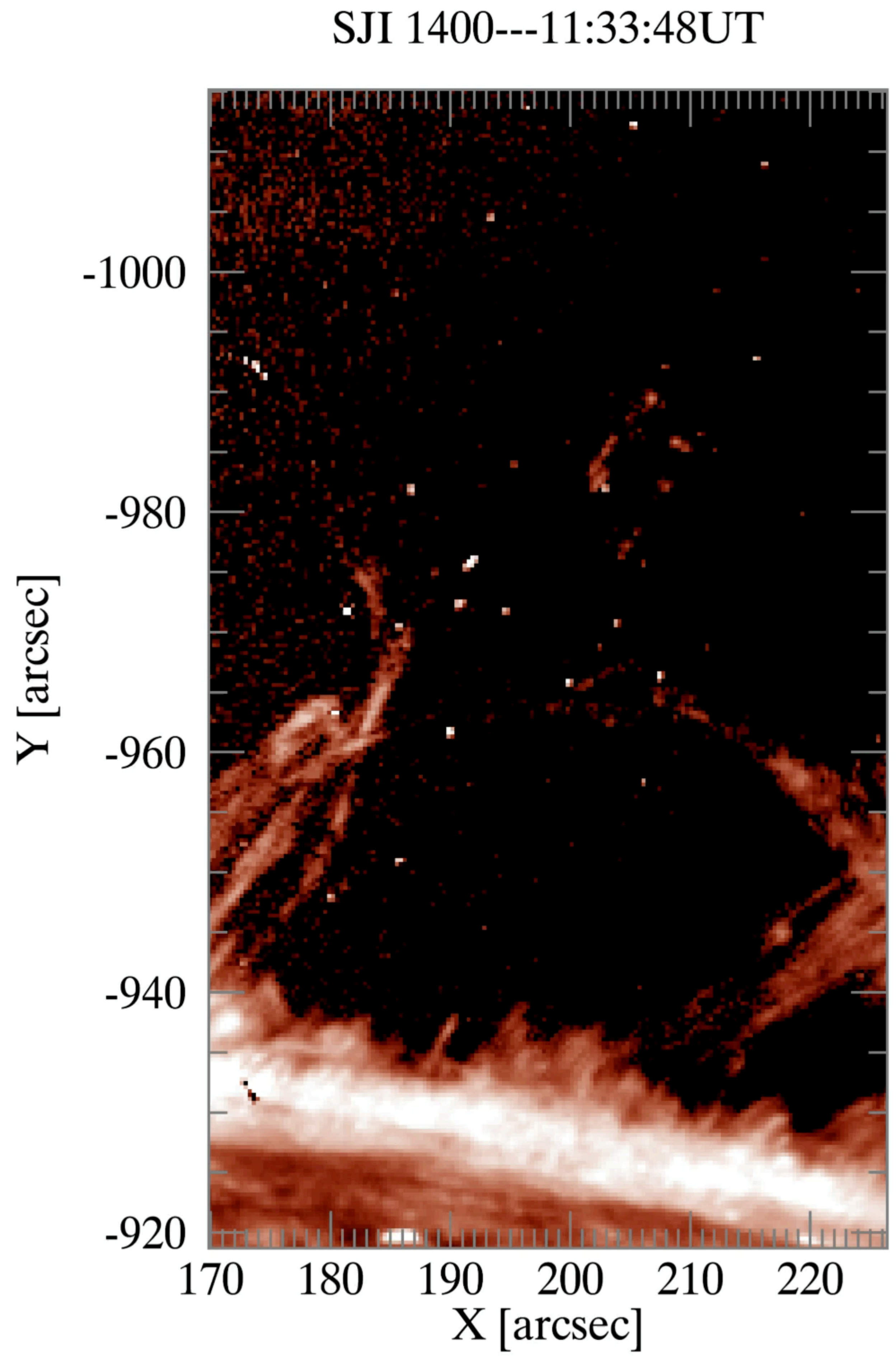

Prevalence of thermal non-equilibrium (TNE) over an active region

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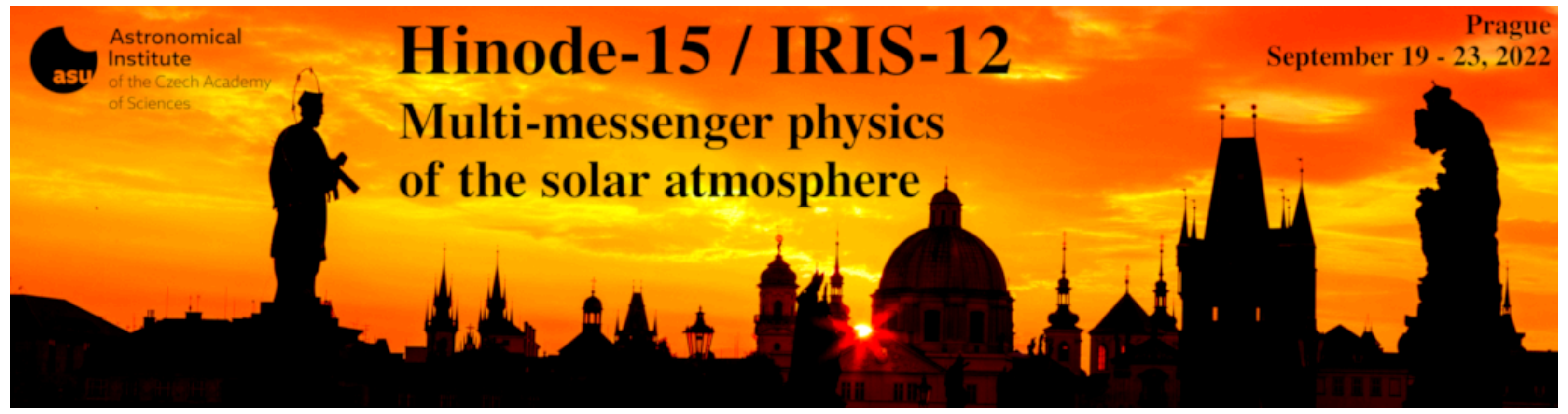


**** Supported by AAS/SPD METCALF Award***

Northumbria University NEWCASTLE

Outline

Introduction:

- Coronal Heating & Coronal Loops
- Long Period EUV Intensity Pulsations
- Coronal Rain
- Rain Showers
- Thermal Instability (TI) & Thermal non-equilibrium (TNE)

Data & Method:

- IRIS & SDO
- Rolling Hough Transform (RHT)
- Region Grow Technique
- Differential Emission Measurement (DEM)

Results:

- Coronal Rain Shower + TNE

Conclusion

Introduction:

Coronal Heating & Coronal Loops

The high temperature of the solar corona is a puzzling problem in solar physics == <u>CORONAL HEATING!</u>

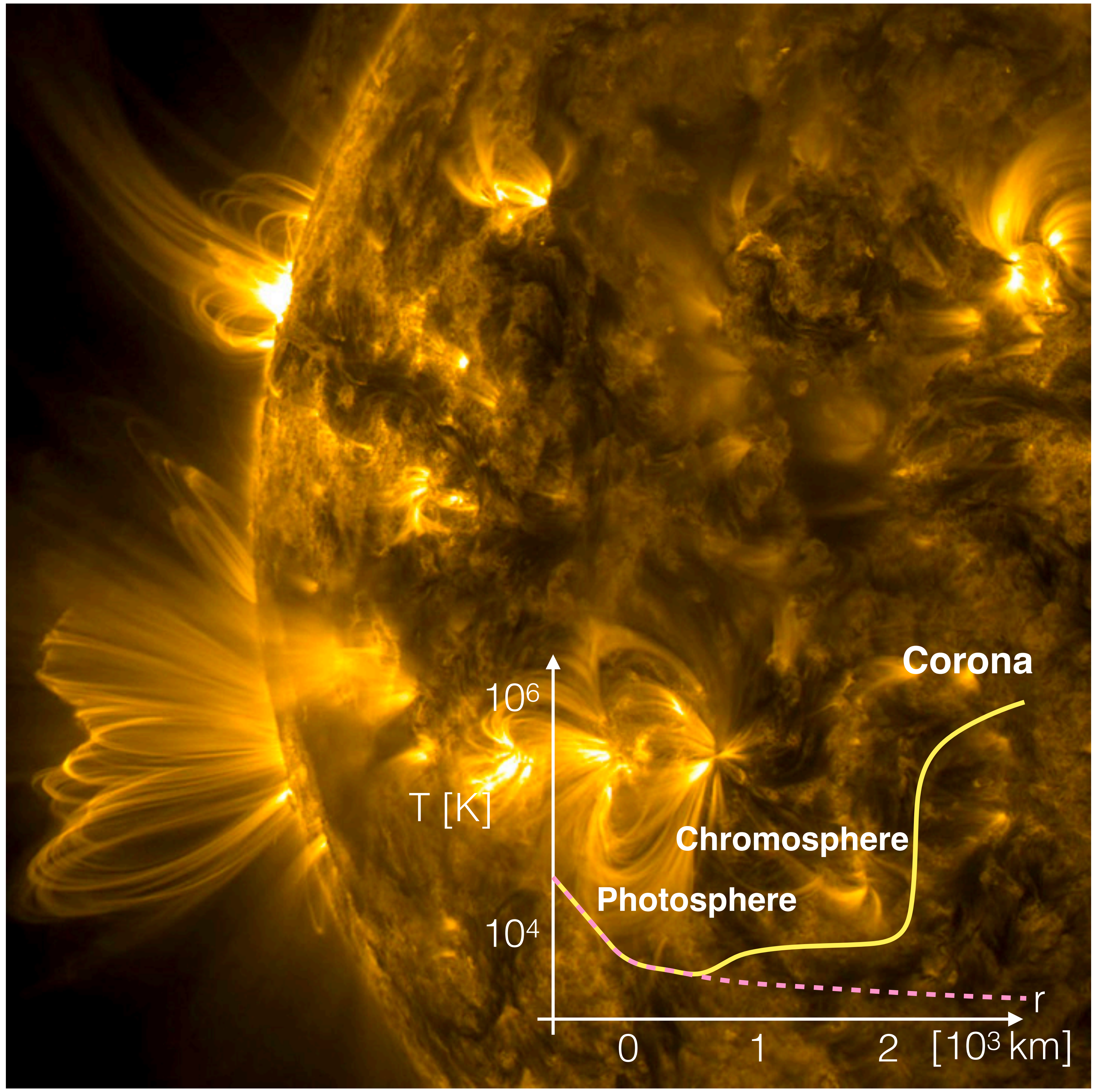
- building blocks of the solar corona.
- hot and dense plasma confined by a guiding magnetic flux tube (Marsch et al. 2004)

Temperature: 10^5 K up to 10^7 K (Reale 2014)

Width: 1.5 - 2 Mm (isolated loop) (Aschwanden & Boerner 2011; Peter et al. 2013)

Width:
Hypothesis from modelling results: cross-field temperature variation effect + instrumental temperature response function effect (Peter & Bingert 2012, Chen et al. 2014)

- The loops appear to have constant cross-section with height. This is puzzling because loops are expected to expand with height.

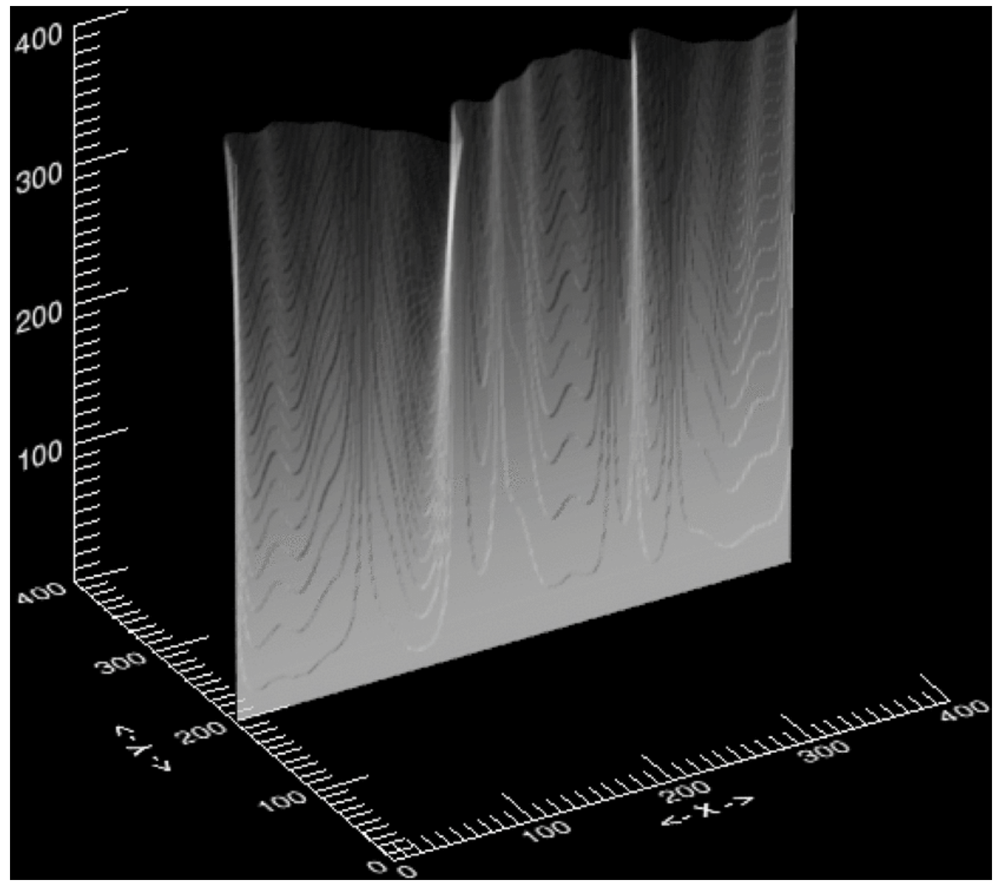


SDO/AIA 171

Introduction:

Solar Corona has optically thin radiation! = emission superposes along the line-of-sight

Spicules



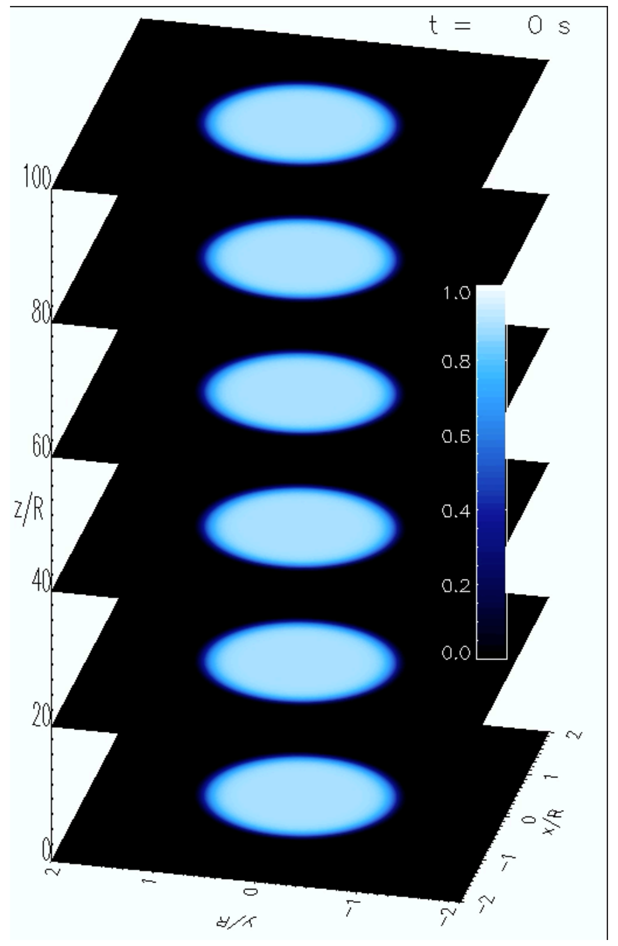
The emission from various structures along a given line-of-sight overlaps, which can lead to apparent structures that are not really there:

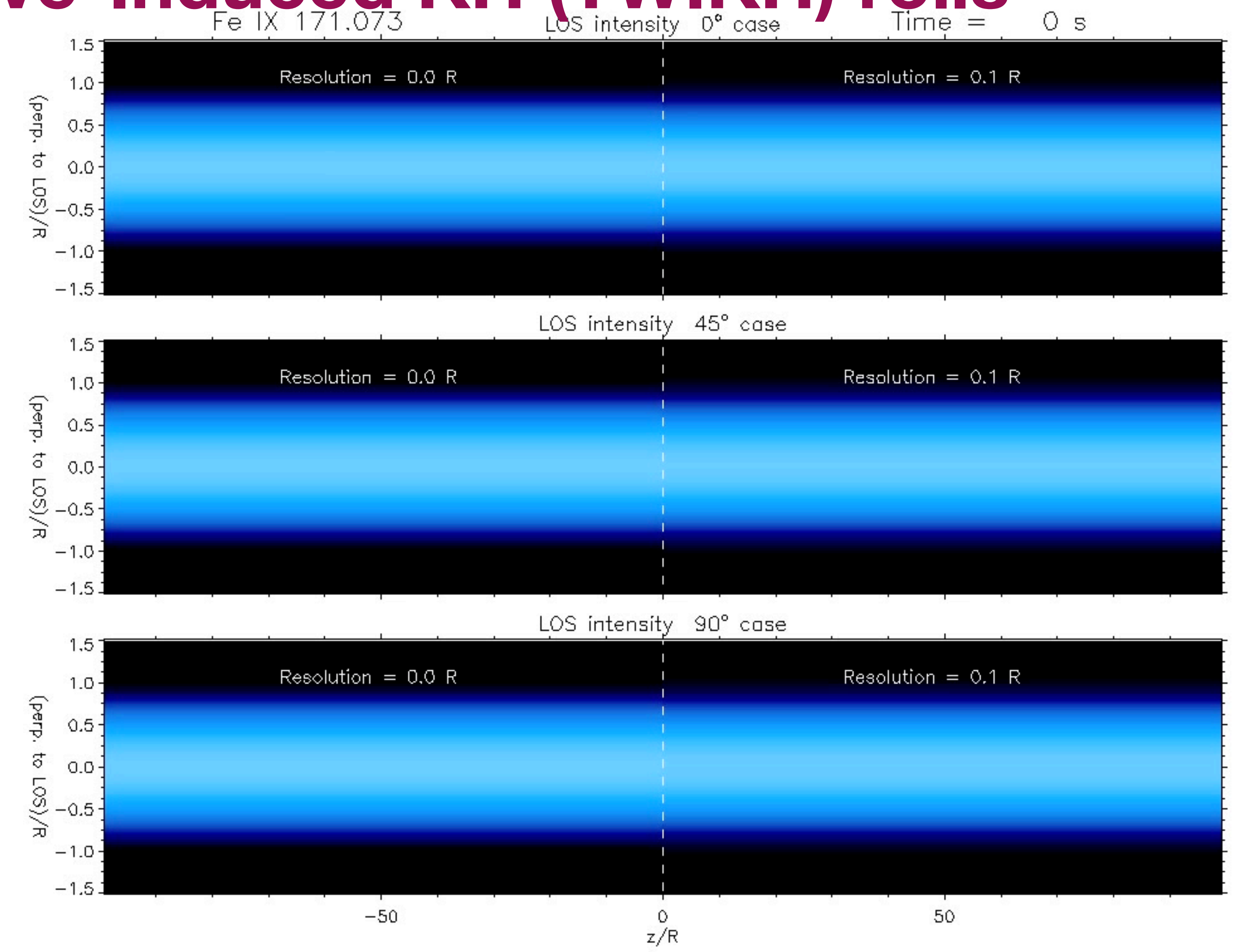
✦ may partly explain morphologies and dynamics observed in spicules (Judge et al. 2011)

✦ may partly explain coronal strands when TWIKH rolls are generated (Antolin et al. 2014)

Judge et al. 2011

Transverse Wave-Induced KH (TWIKH) rolls

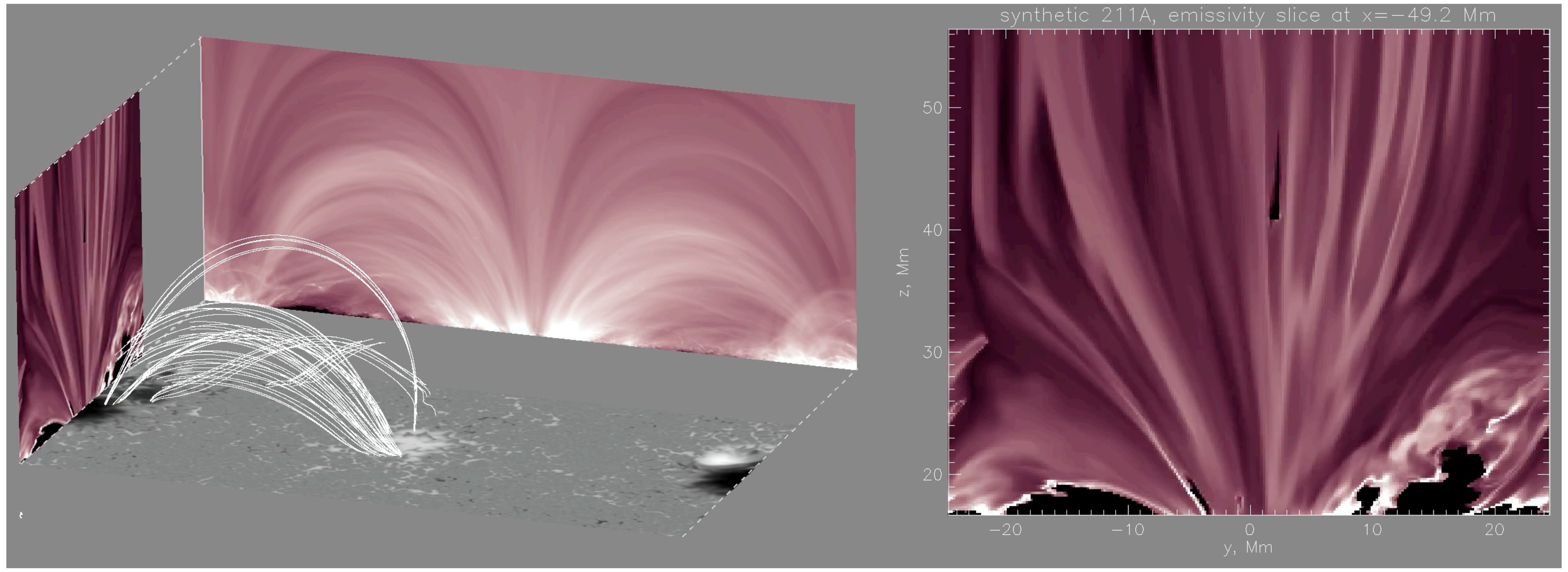




Antolin et al. 2014

Coronal loops

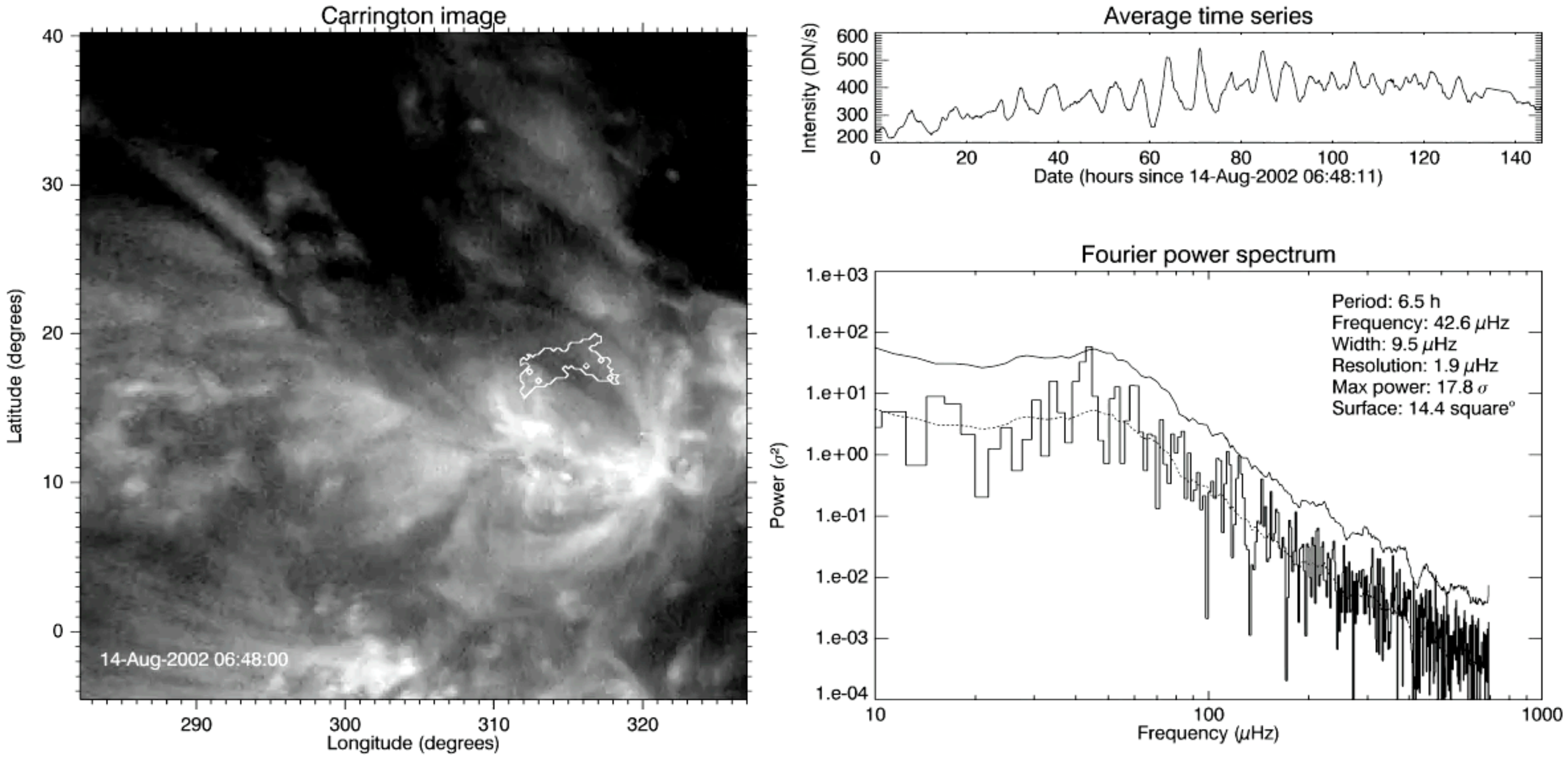
Malanushenko et al. 2022 - 3D Simulations



Coronal veil may explains several things that are difficult to explain with loops (Malanushenko et al. 2022)

Introduction:
Long-period EUV intensity pulsations

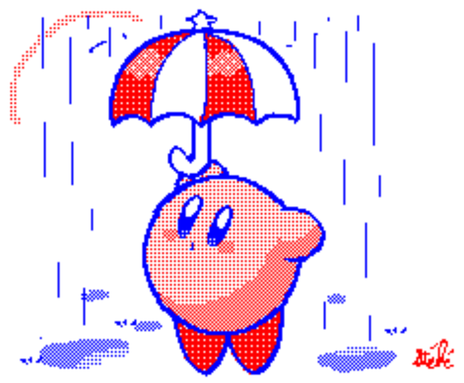
- Coherent thermodynamic evolution on global scale clearly exists —> long-period intensity pulsations in EUV channels (Auchère et al. 2014; Froment et al. 2015).
- More than 1000 events in the 6 EUV channels —> 54% AR (visually associated with loops), 45% QS
- Linked to coronal rain



Auchère et al. 2014

Introduction:

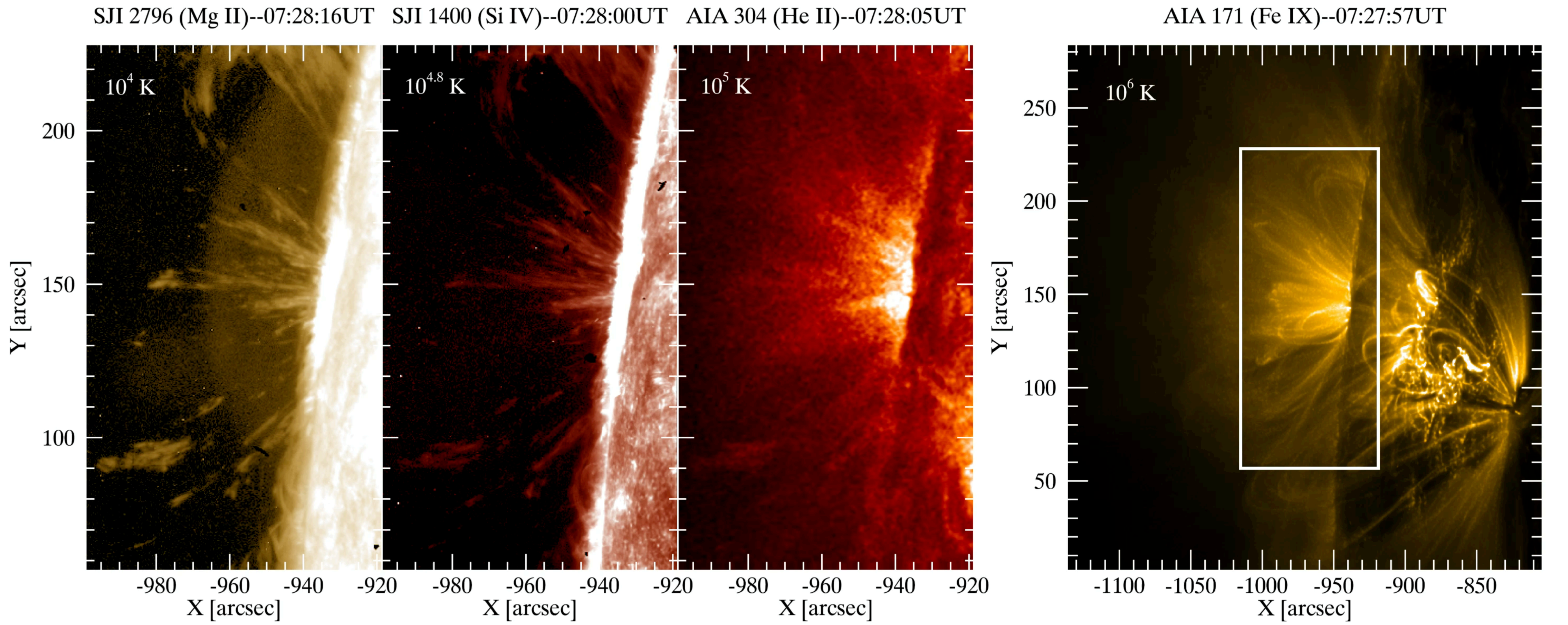
Coronal Rain



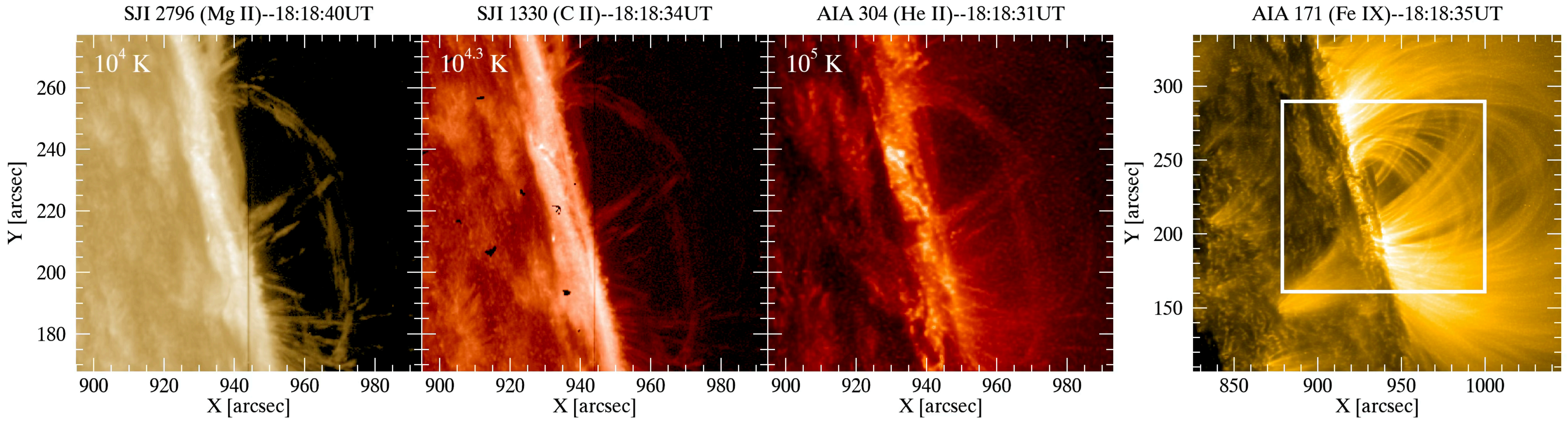
- Cool and dense partially ionised plasma
- Higher optical thickness (in the TR and Chromosphere)
- Morphology
  - clumpy (~ 300 km width)
  - elongated (~ 700 km length)
  - ubiquitous (AR & QS)
- Dynamic (~ 70 km/s) and
- multi-thermal ([10^3 > 10^5] K)

Antolin et al. 2012, Antolin & Froment 2022

Quiescent Coronal Rain *Sahin, Antolin et al. (in prep)*



Flare-driven coronal rain



Hybrid prominence / coronal rain

Video courtesy of Wei Liu

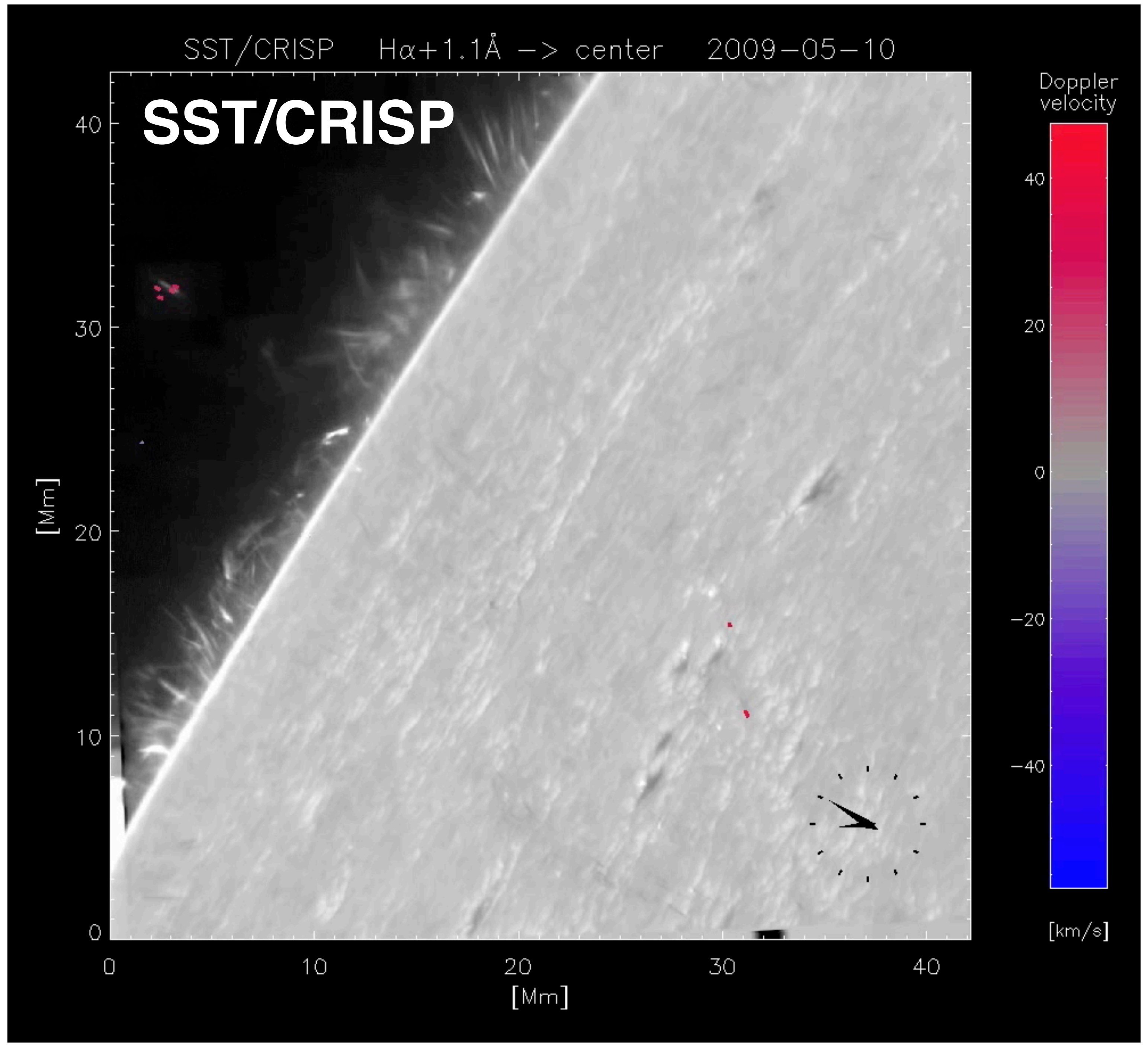
Introduction:

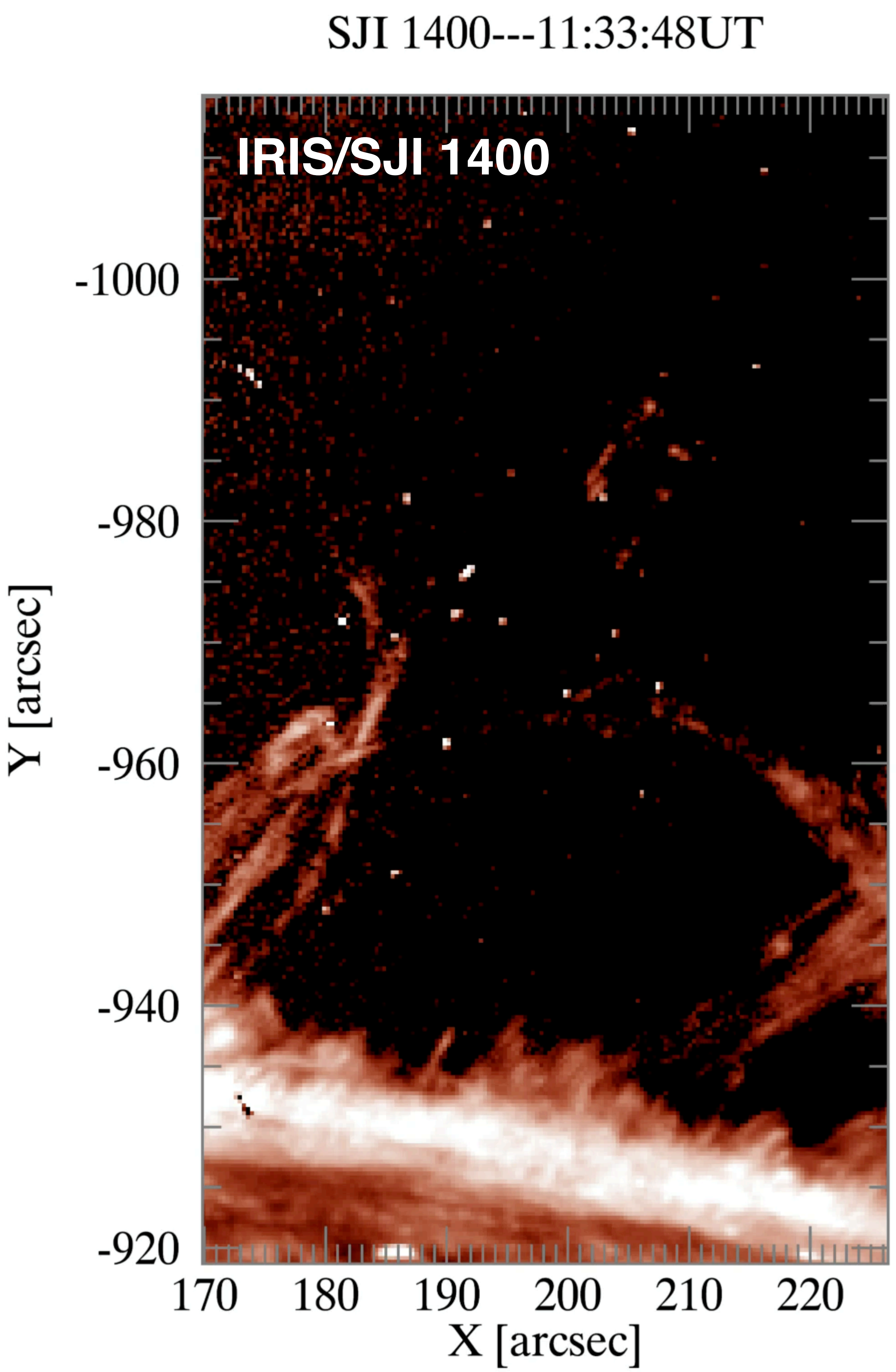
Rain Showers: Observational Side

- Coronal rain often occurs at similar times over a significantly wide structure, with a cross-field length scale of a few Mm —> **SHOWER**

- Coherently evolving structures

Antolin & Rouppe van der Voort, 2012



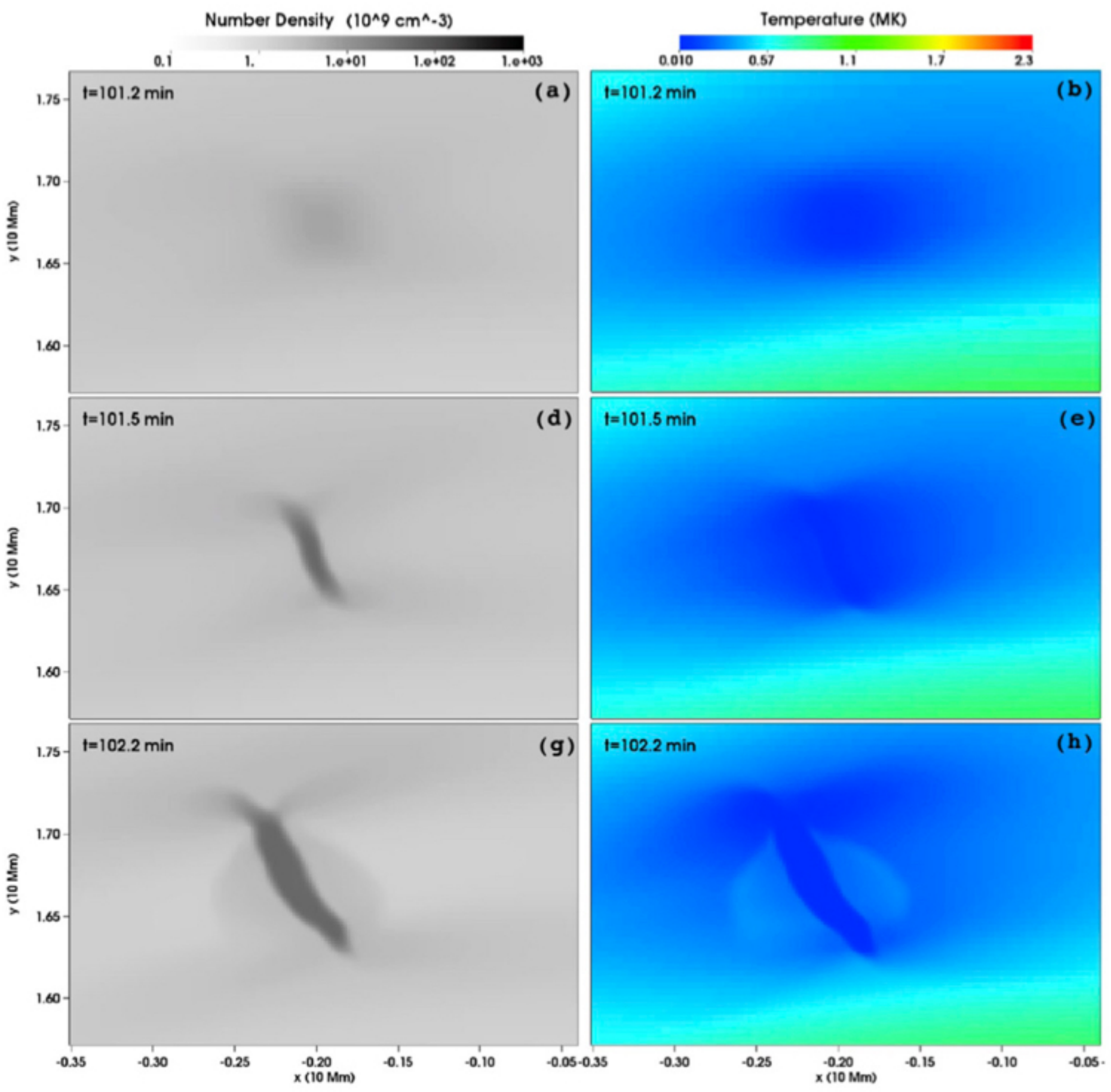


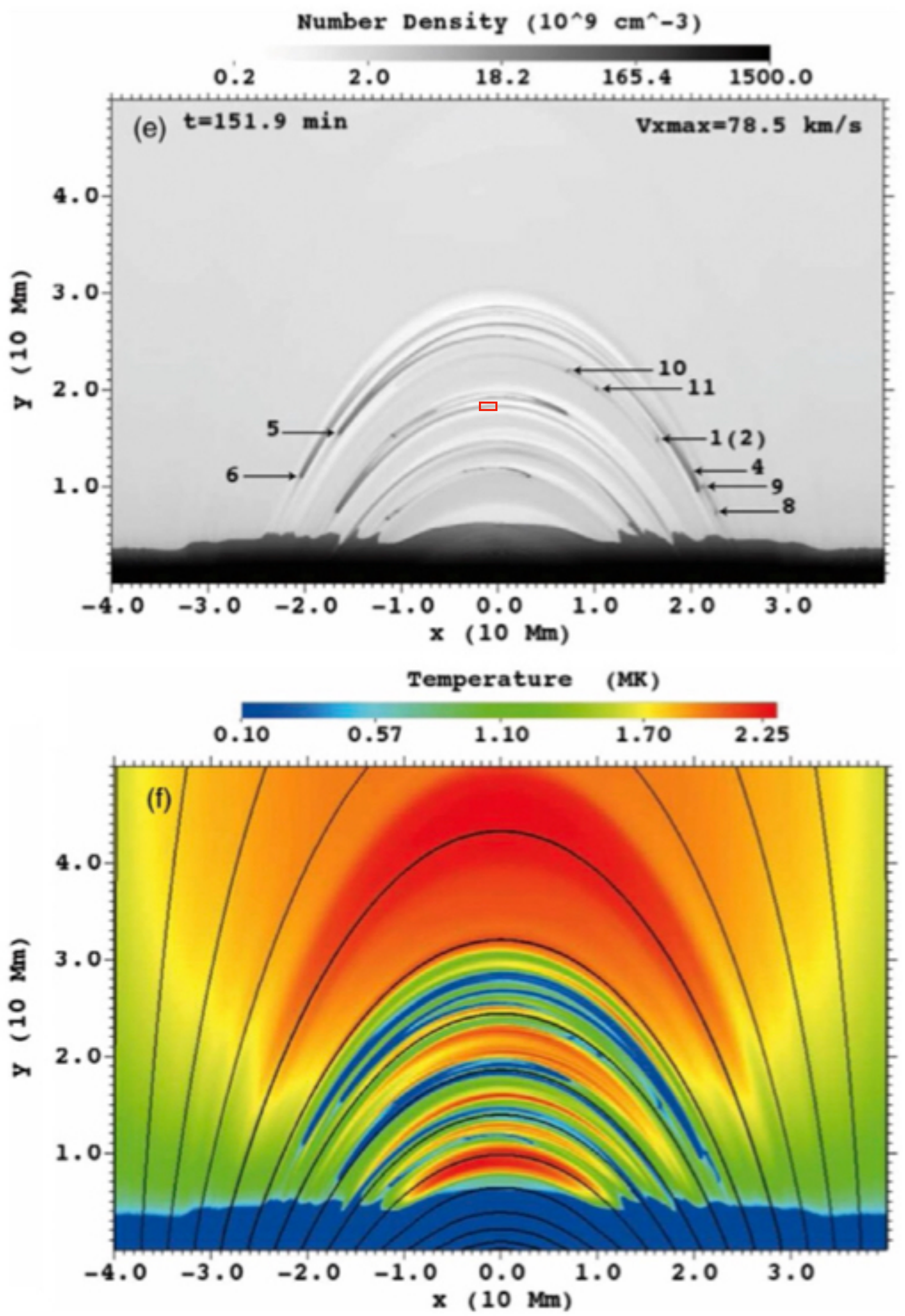
- **There is no observational study to date that properly quantifies the properties of showers, nor the spatial and temporal scales over which the sympathetic cooling occurs.**

Introduction:

Rain Showers: Numerical Side

- 2.5D MHD Simulations





- Rain occurs locally due to thermal instability (TI)
- ‘Sympathetic cooling’: Neighbouring magnetic field strands that are critically stable become unstable due to perturbations
- Rain clump first forms in the transverse direction
- Growth in perpendicular direction over a distance of ~1 Mm within 1 min.
- **How is thermal instability achieved in a coronal loop?**

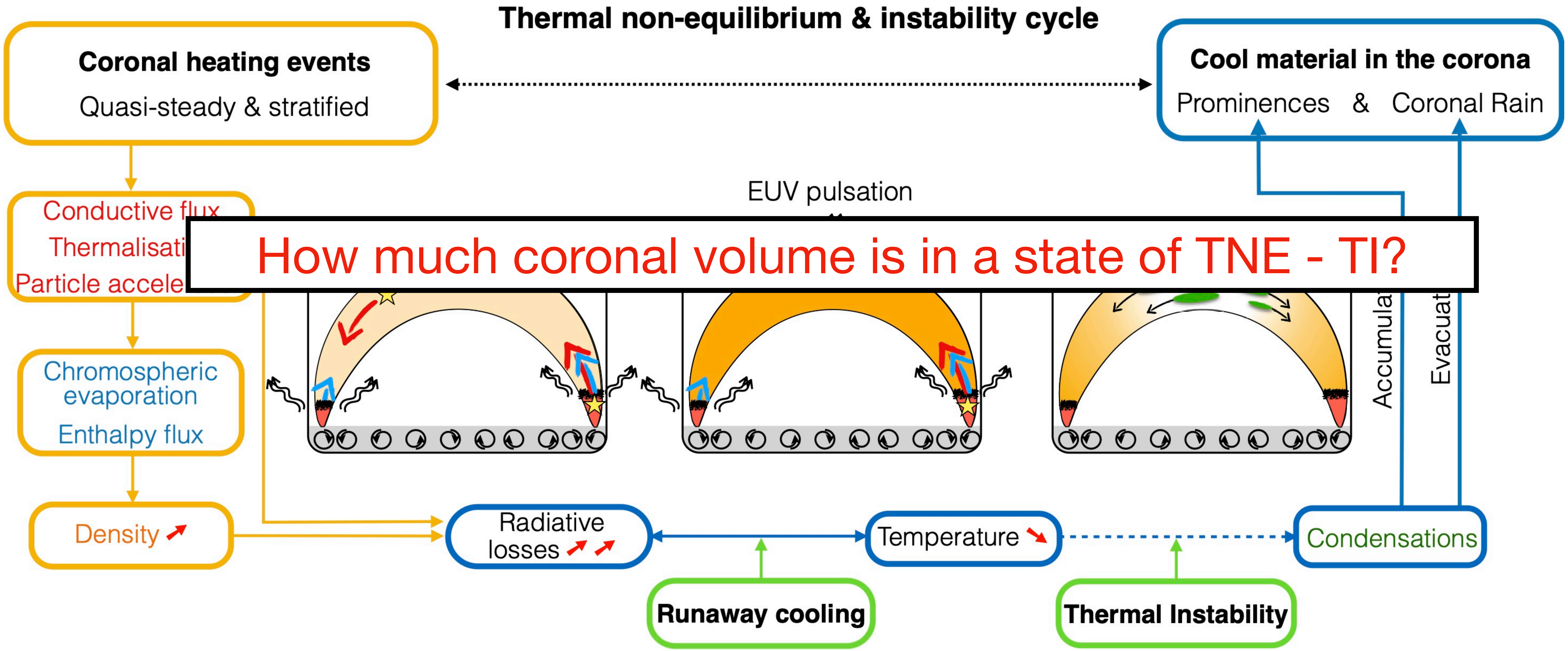
Fang et al. 2013,2015; Antolin & Froment 2022.

Introduction:

Thermal non-equilibrium (TNE)

Coronal rain believed to originate due to thermal instability (TI) within a coronal loop in a state of thermal non-equilibrium (TNE).

(Antolin 2020, Antolin & Froment, 2022).



How much coronal volume is in a state of TNE - TI?

Aims:

What are the general properties of showers?

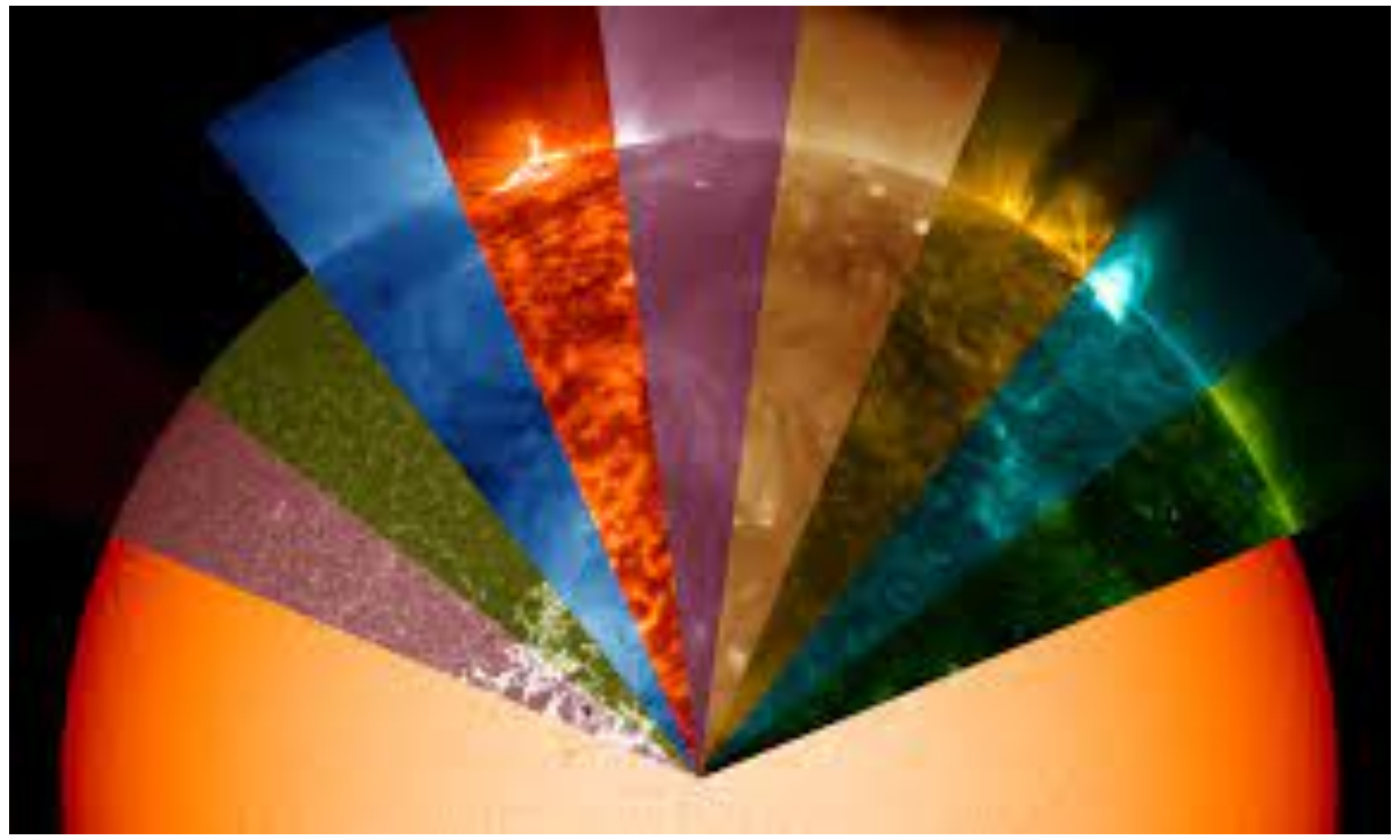
Can showers help us identify coronal loops?

Can showers help us estimate the coronal volume subject to TNE - TI?

Data

Interface Region Imaging Spectrograph **(IRIS)** slit-jaw imager **(SJI)**

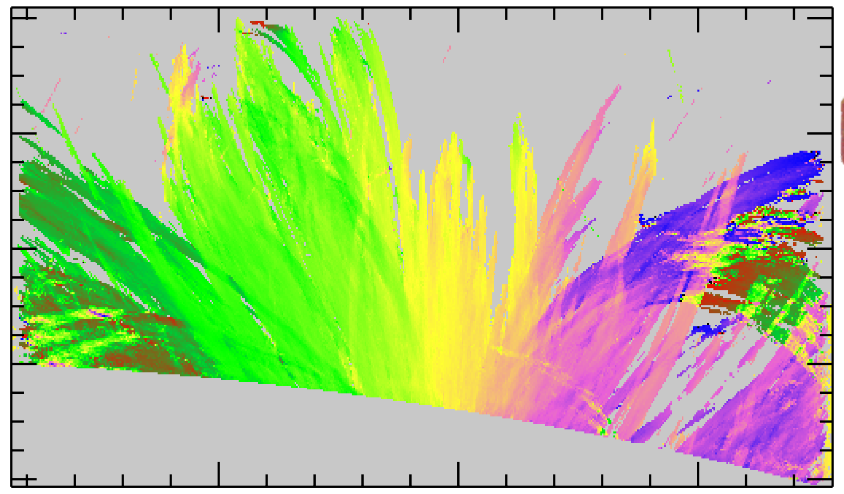
Atmospheric Imaging Assembly **(AIA)** on board Solar Dynamics Observatory **(SDO)**



Date	6/2/2017	6/2/2017	6/2/2017
Time Sequence	07:28 - 12:55 UT	07:28 - 12:55 UT	07:28 - 12:55 UT
Instruments	Mg II 2796 Å 10^4 K SJI 2796 Chromospheric Region	Si IV 1402 Å $10^{4.8}$ K SJI 1400 Transition Region	He II 303.8 Å 10^5 K AIA 304 Si XI 303.32 Å
Cadence	SJI 2796 - 32.2 s	SJI 1400 - 43.1 s	AIA 304 - 12 s
Spatial Sampling	0.3327 ″/pixel	0.3327 ″/pixel	0.6 ″/pixel
FOV	232″ x 182″	232″ x 182″	

- Automatic detection with **Rolling Hough Transform Technique** (Schad 2017)

IRIS SJI 2796



Sahin, Antolin et al. (in prep)

- **Region Grow** Algorithm —> to identify a shower (selection a group of pixels within a specific range of values in the spatial and temporal domain bounded by a standard deviation)

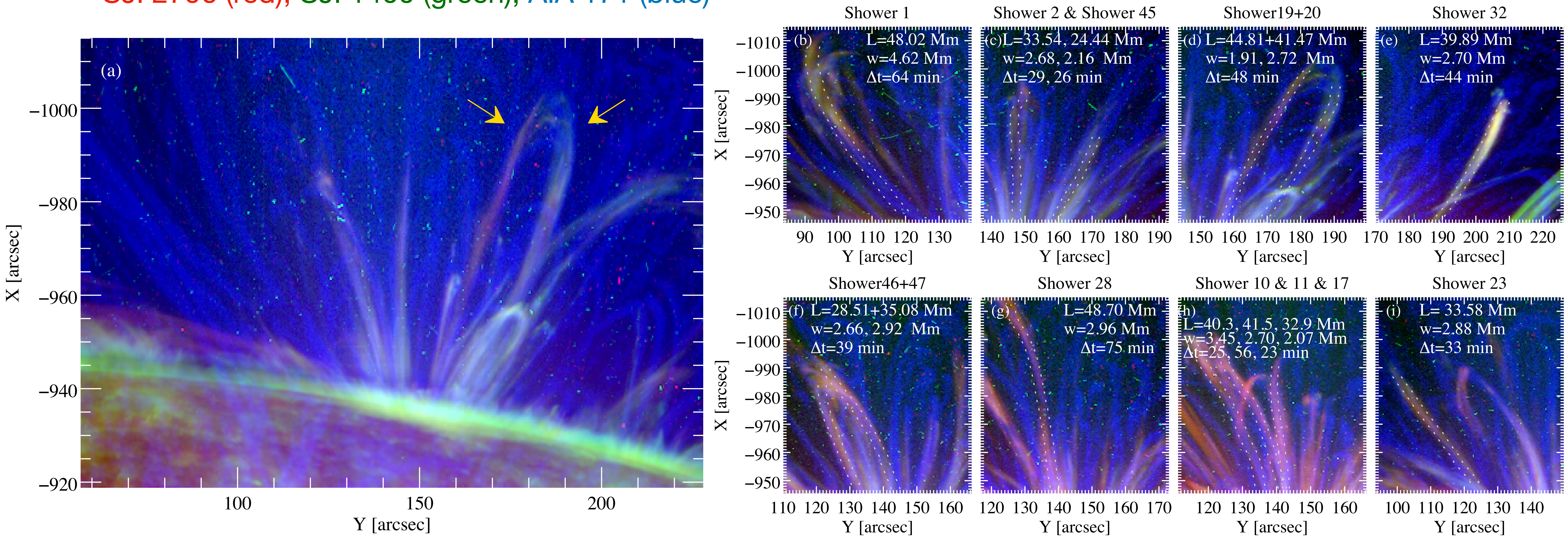
Prevalence of Thermal Nonequilibrium over an Active Region

Sahin & Antolin 2022, ApJL 931 (2), L27

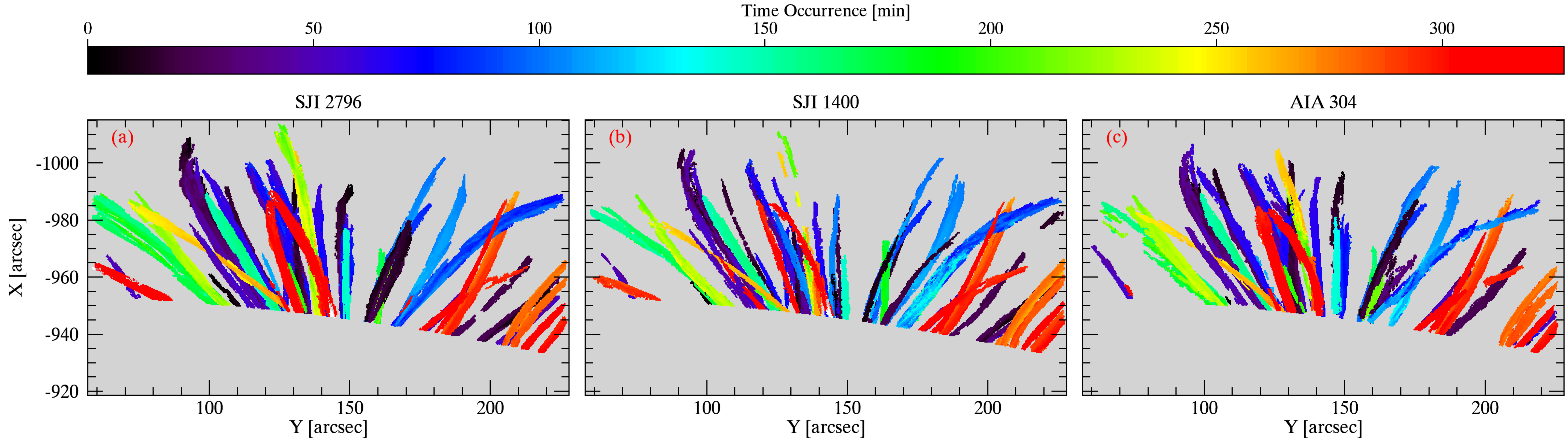
Results: Showers - 1. Morphology

- We manually traced 50 shower events
- **Coronal loops and showers are very similar in width**

SJI 2796 (red), SJI 1400 (green), AIA 171 (blue)

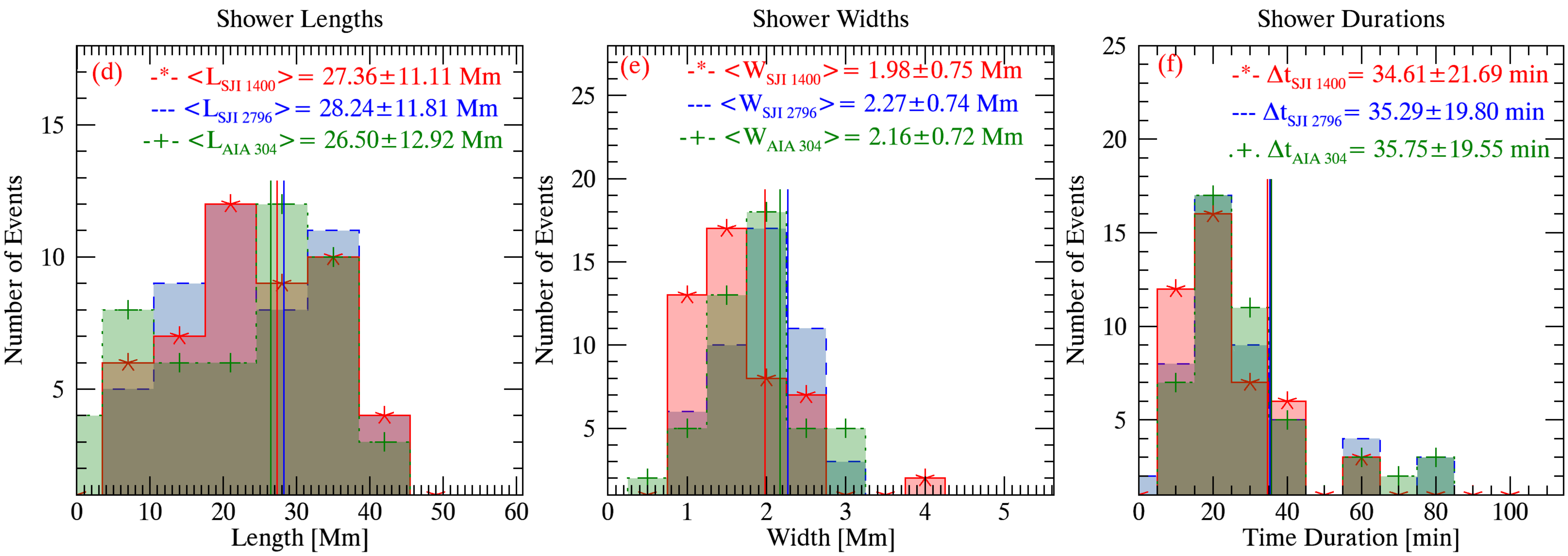


Results: Showers - 1. Morphology



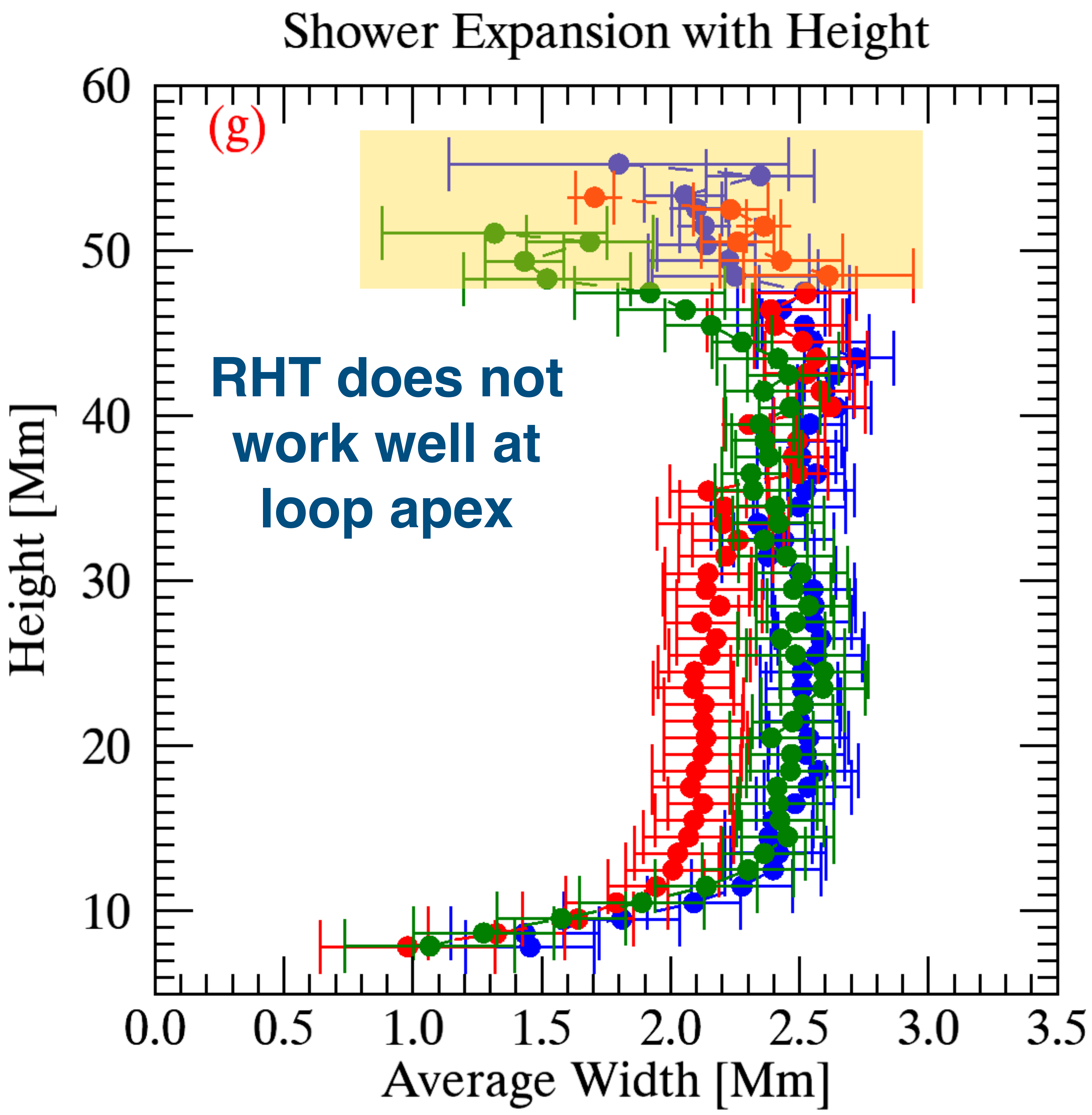
- Showers can be clearly distinguished
- Ubiquitous over the active region and at all time during the 5.45 hours.

Results: Showers - 1. Morphology



- The average length (~27 Mm) and width (~2 Mm) of showers are very similar across the channels.
- Showers are relatively long-lived. They have similar time duration with peaks around 20 minutes. The average time duration is around 35 minutes.

Results: Showers - 1. Morphology

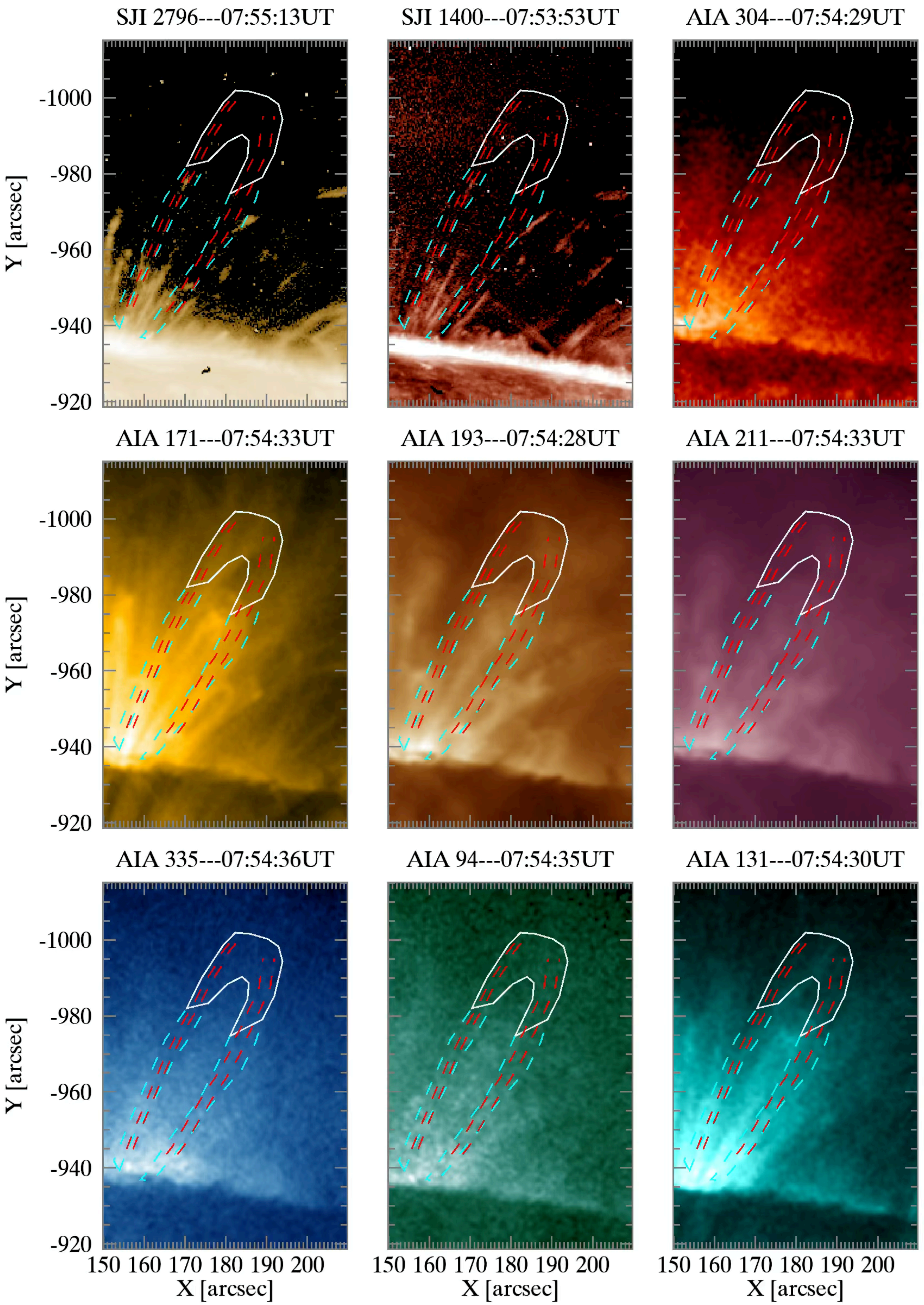


- Almost no expansion in the upper corona up to 40 Mm in agreement with EUV observations (Klimchuk 2000; DeForest 2007; Lopez Fuentes et al. 2008)

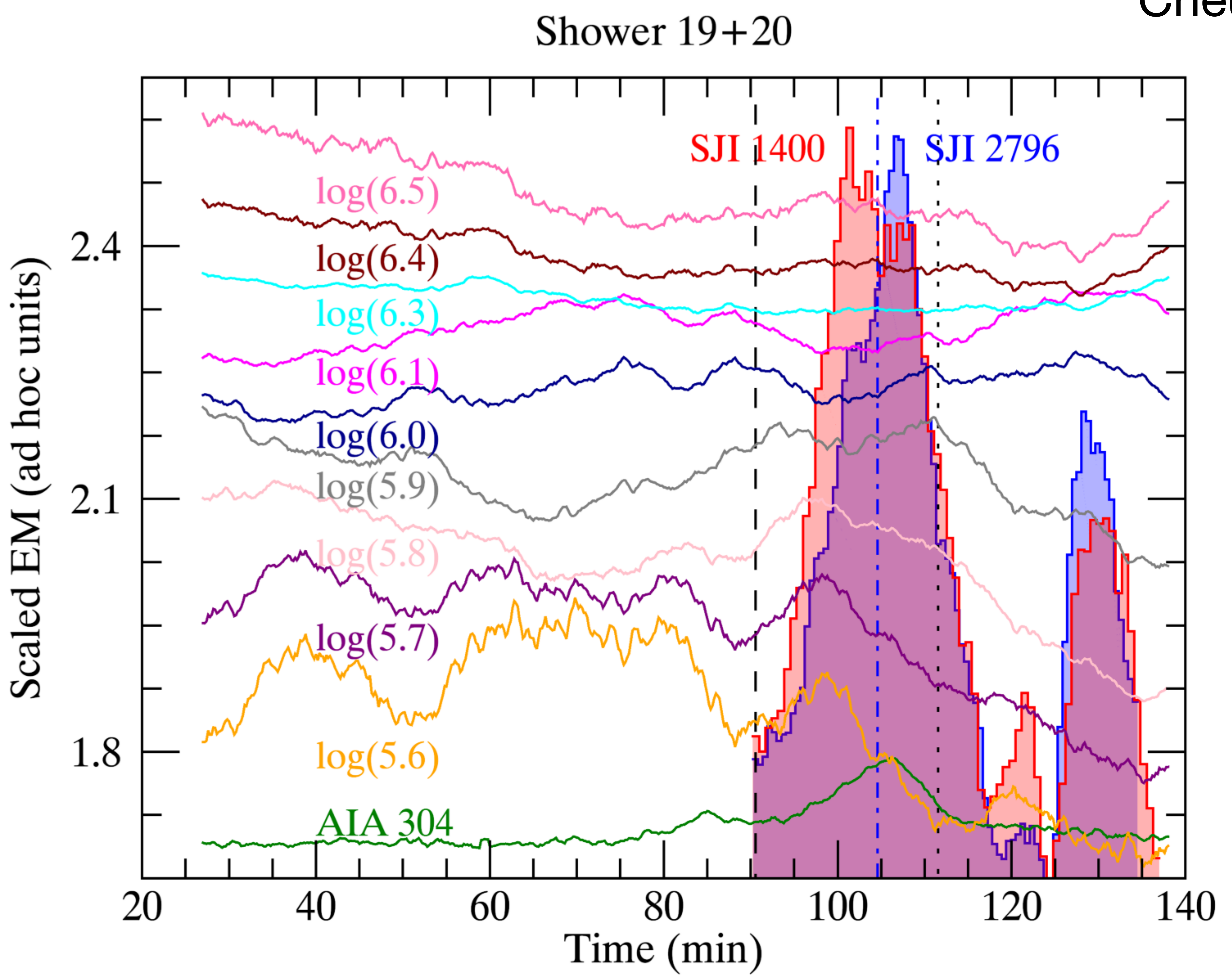
- A very strong expansion below 12 Mm -> the width increases from 1 to 2.4 Mm between 8-12 Mm above the surface (area expansion factor = 5.7)

- Shower —> uniform cross-field temperature and density with constant cross-section.

Results: Temperature Evolution in Shower



Start Time: 08:54:29 —> 48 min



Differential Emission Measurement (DEM) —> to estimate temperature variation of the loops hosting the showers (based on the Basis Pursuit - Cheung et al., 2015)

- Radiative cooling time:

$$\tau_{\text{rad}} = \frac{(3/2)p}{n^2\Lambda} \approx 30\left(\frac{3\times 10^{10}}{n}\right)\left(\frac{T}{10^6}\right)\text{ s}$$

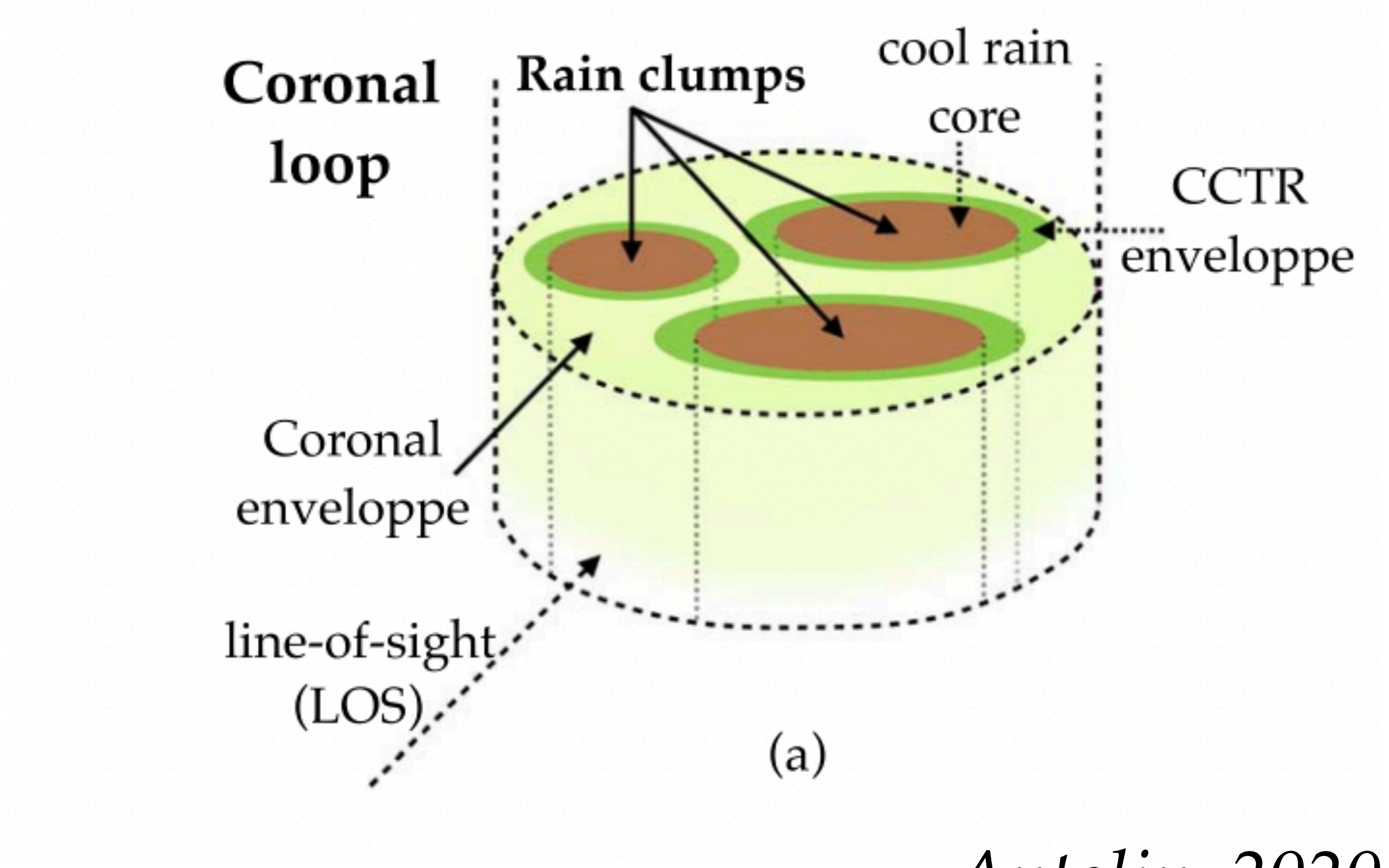
- Observed cooling timescale is consistent with this radiative cooling time for a typical coronal loop.

Antolin & Froment 2022

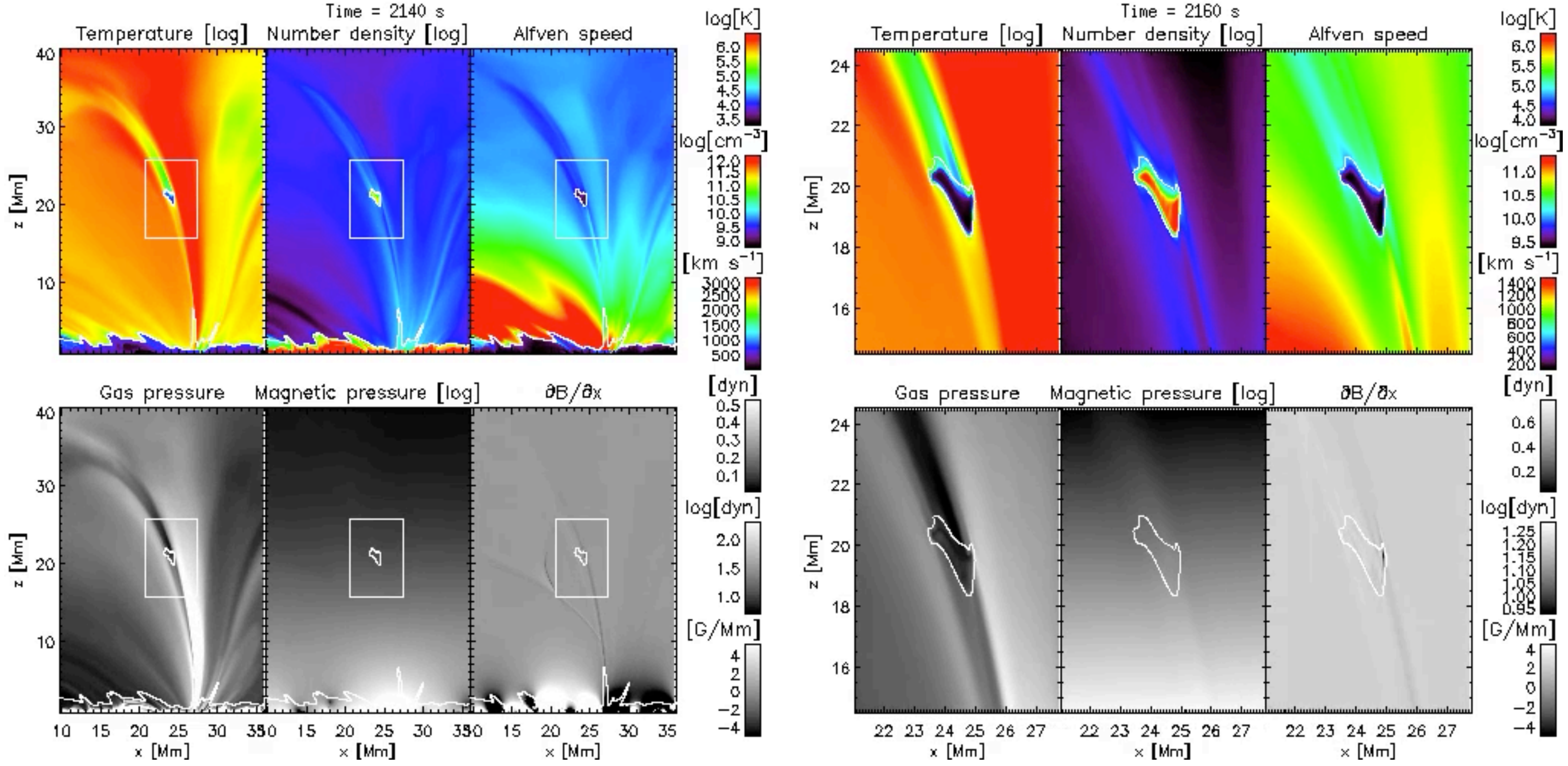
- Decreasing trend in hot temperature bins
- Increasing trend in cool temperature bins
- Strong variability at TR temperatures (5.6 - 5.7) prior & during catastrophic cooling

Results: Showers - 2. Temperature Evolution

- The EUV emission variation is interpreted as the cooling of plasma, with strong variations prior to the shower appearance probably due to the continued cooling passing through temperature ranges and moving out of the apex.



Antolin, 2020



Antolin, Martínez-Sykora & Sahin 2022

- See poster by Patrick Antolin

- The EUV emission variations seen during the shower appearance are probably due to the Condensation Corona Transition Region (=CCTR), as expected from numerical modelling (Antolin et al., 2022).

TNE Volume

Step 1: $\langle length\_overlap \rangle = \langle l_{clump} \rangle - cadence \times \langle v_{clump} \rangle$

Step 2: $\langle area\_overlap \rangle = \langle length\_overlap \rangle \, x \, \langle w_{clump} \rangle$

Two successive snapshots may have an overlap of rain pixels in the FOV area, depending on the clump length, velocity, width and instrument cadence.

Step 3: $\langle area\_clump \rangle = \langle l_{clump} \rangle \, x \, \langle w_{clump} \rangle$

The area in the FOV occupied by a single clump

Step 4: $\langle fraction \rangle = \frac{\langle area\_overlap \rangle}{\langle area\_clump \rangle}$

The fraction of rain overlapping between 2 consecutive images

Step 5: $\langle N_{no\_overlap} \rangle = N_{\theta xy} \times (1 - \langle fraction \rangle)$

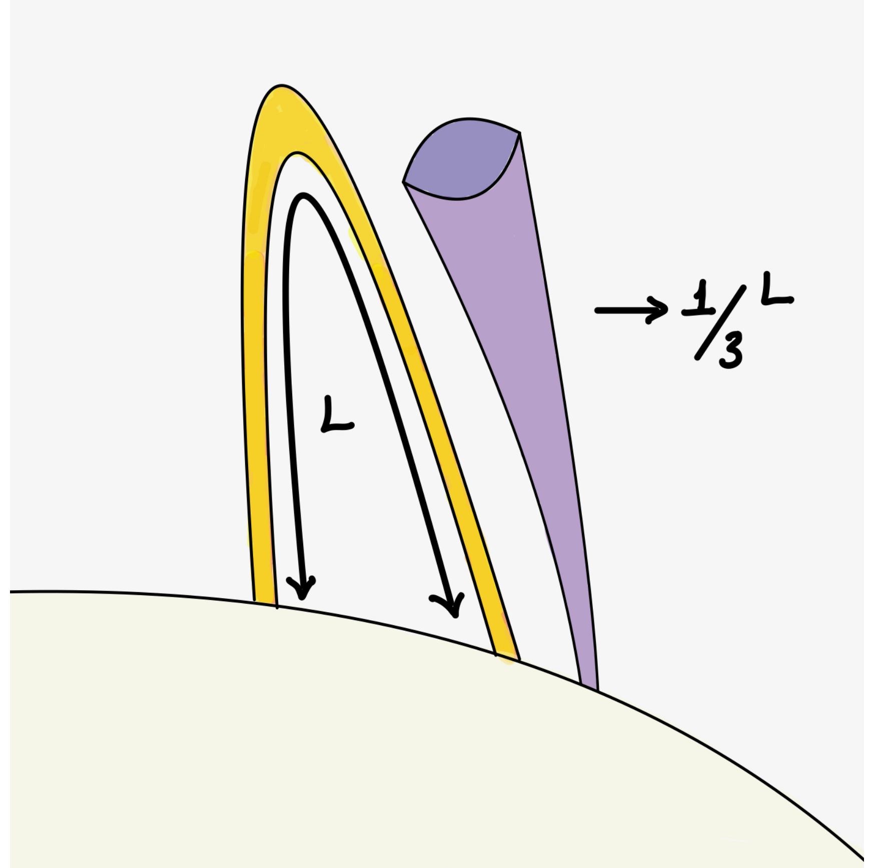
The number of pixels in the non-overlapping area

Step 6: $N_{expected\_shower} = \frac{\langle no\_overlap \rangle \times N_{shower}}{N_{shower\_pixels}}$

The number of expected shower events

Step 7: $V_{TNE} = \pi \frac{1}{f} N_{expected\_shower} \, x \, \langle l_{shower} \rangle \left(\frac{\langle w_{shower} \rangle}{2} \right)^2$

The TNE volume estimation



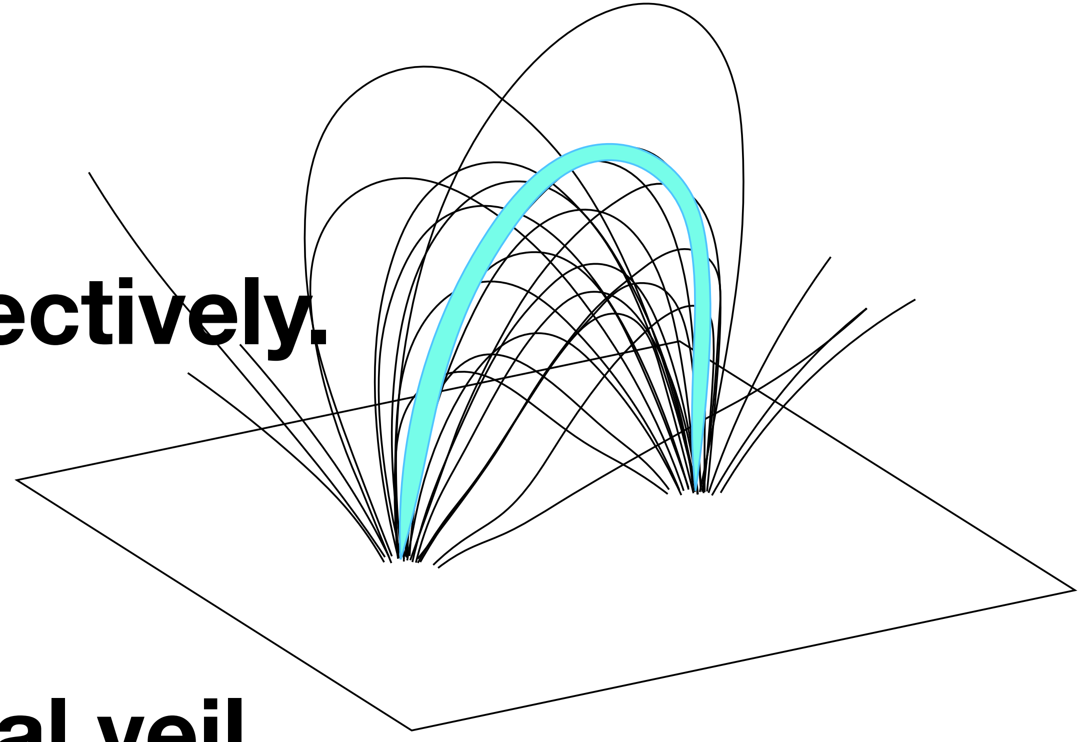
- f, the average fraction of the loop occupied by a shower (f=1/3).
- Approximation ~ a shower as a cylinder
- Lower estimation of TNE volume -> strict conditions in RHT routine.

TNE Volume

Channel	Estimated Number of Showers	TNE Volume (cm^3)
AIA 304	71±4	$2.07 \pm 1.71 \times 10^{28}$
SJI 1400	208±77	$5.26 \pm 4.52 \times 10^{28}$
SJI 2796	185±39	$6.34 \pm 4.91 \times 10^{28}$

- The total number of showers: 155±40
- TNE volume: $4.56 \pm 3.71 \times 10^{28}$ cm^3
- TNE Volume > 50% AR Volume

Conclusion



✦ **Length, width and duration of the shower: 27.37±11.95 Mm, 2.14±0.74 Mm, 35 min, respectively.**

✦ A good correspondence between showers and the cooling coronal structures:

consistent with the TNE-TI scenario, thereby **properly identifying coronal loops in the coronal veil**,

zero expansion in corona recovered: cross-section with similar thermodynamic evolution is constant with height.

✦ DEM analysis: global averaged cooling, in agreement with previous results (Viall & Klimchuk 2012).

✦ Steady cooling from hot temperatures (log T ~ 6.5) one hour prior to condensation formation: consistent with radiative cooling time.

✦ Strong TR temperature changes due to catastrophic cooling and CCTR formation.

✦ **TNE volume of 4.56±3.71x10^{28} cm^{3}** (>50% AR volume) —> **Prevalence of TNE and therefore strongly stratified and high-frequency heating.**

Acknowledgment I am very grateful to the AAS/SPD committee and the Hinode-15/IRIS-12 meeting LOC for this award.

Sahin & Antolin 2022, ApJL 931 (2), L27