Observations and Numerical Modeling of the Impact of Spicules on the Heating of the Transition Region and Corona

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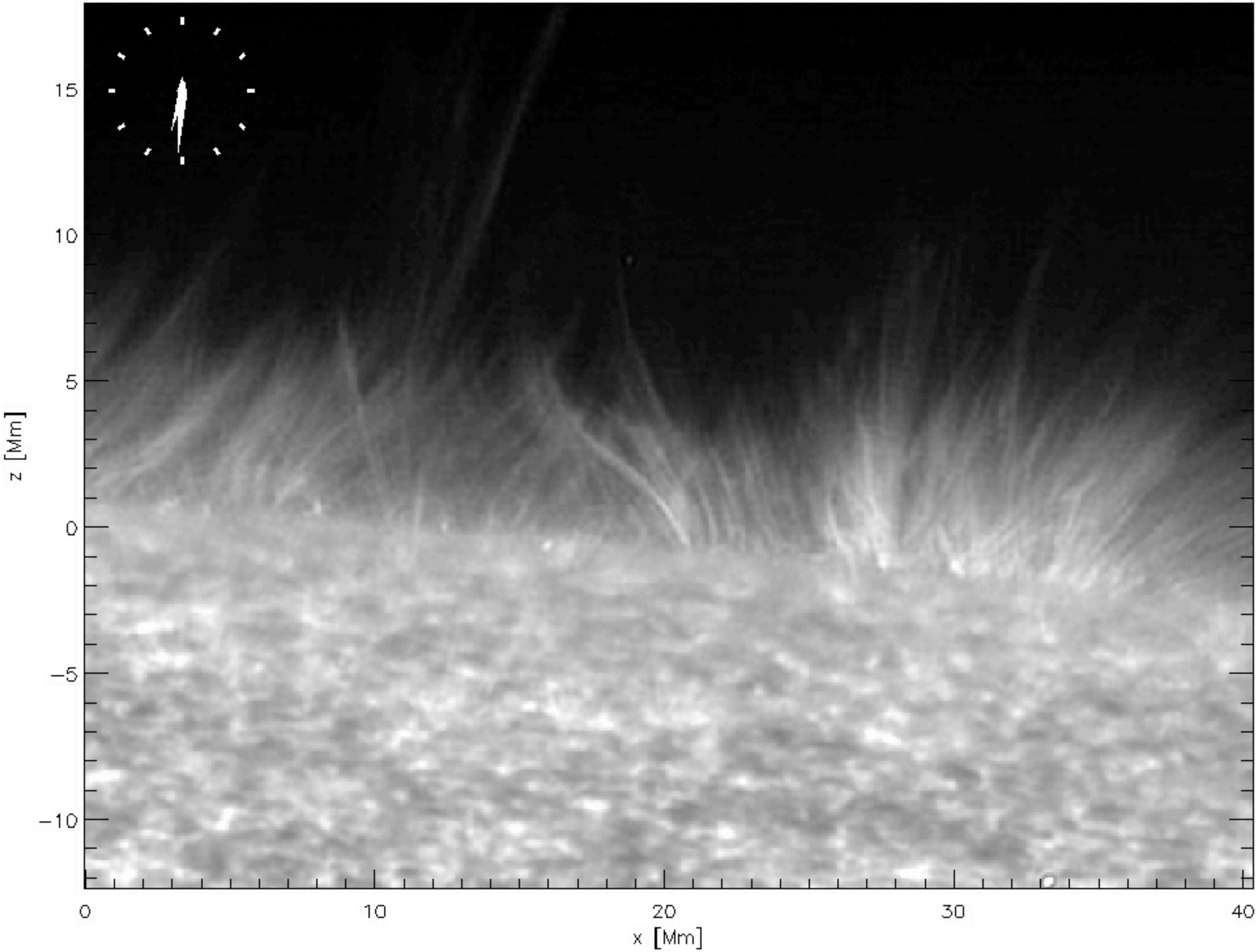
What are spicules? And why do we care?



- Dynamic jets at the interface between the chromosphere and corona

- Fast spicules (“type II”): upward flows of order 50 km/s, with counterpart at TR temperatures

- Have been associated with providing hot plasma to the million-degree corona (De Pontieu et al., 2009, 2010)

- Connection to coronal heating has been contested (Klimchuk et al., 2013, 2014, 2015) based on theoretical arguments

- *Previous models not able to simultaneously reproduce very high speeds, realistic chromospheric and TR observables, and impact on the corona*

New model for spicules: strong flows driven by magnetic tension that diffuses into upper chromosphere because of ambipolar diffusion

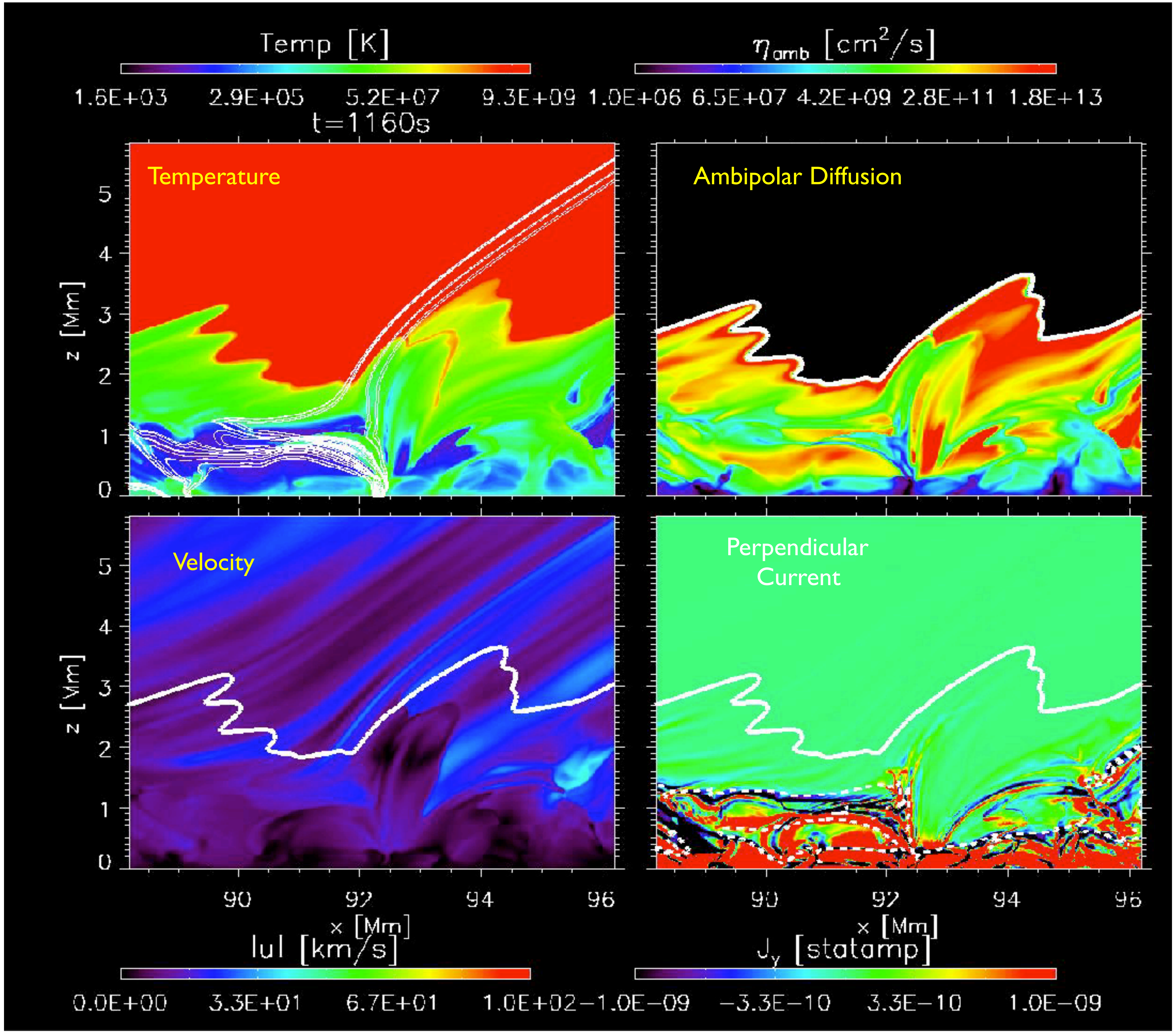
Neutrals not directly tied to magnetic field, but collisionally coupled to ions

When ion-neutral collision frequency low, slippage between ions and neutrals

In cold and/or low density pockets, this means magnetic field can diffuse through neutral population

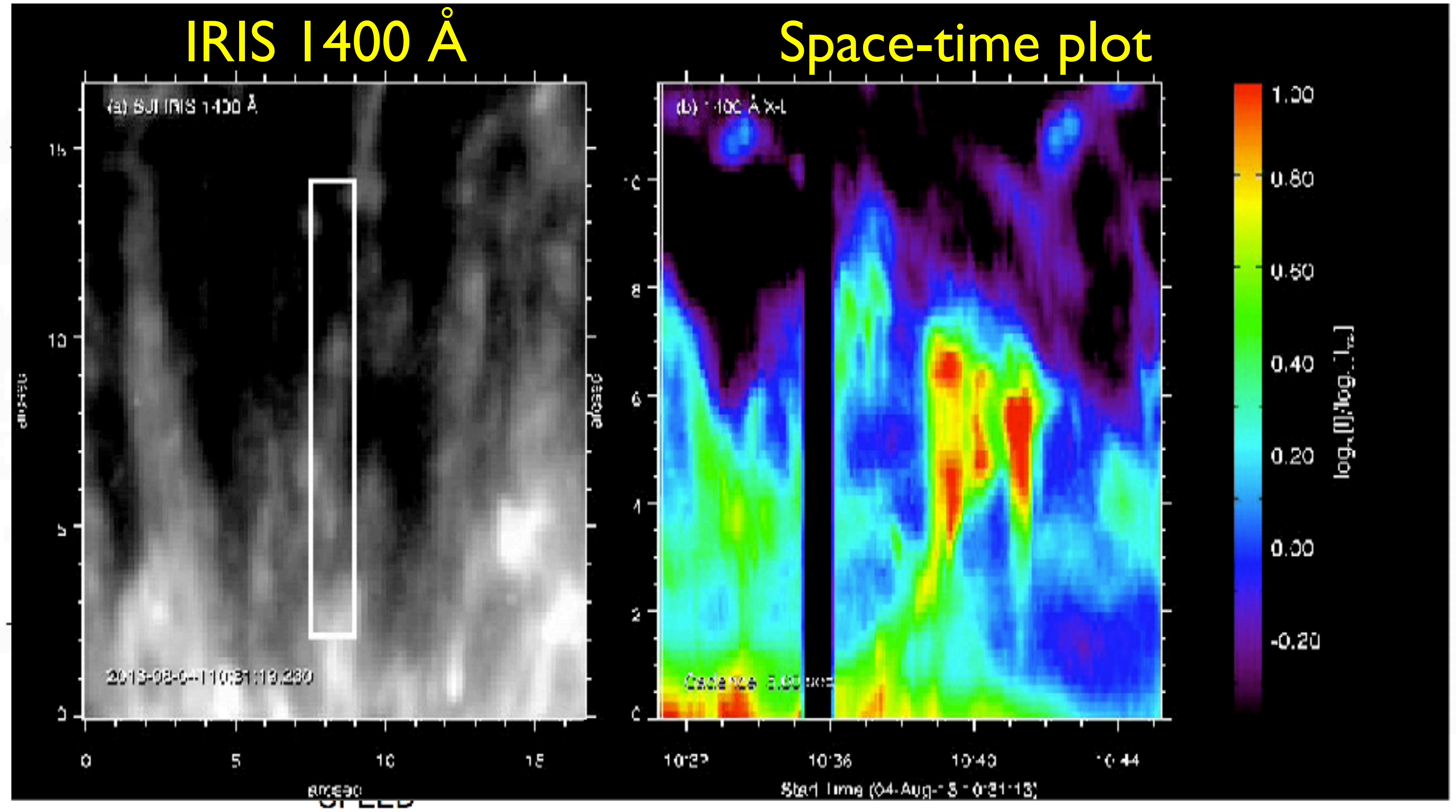
Spicule formation associated with:

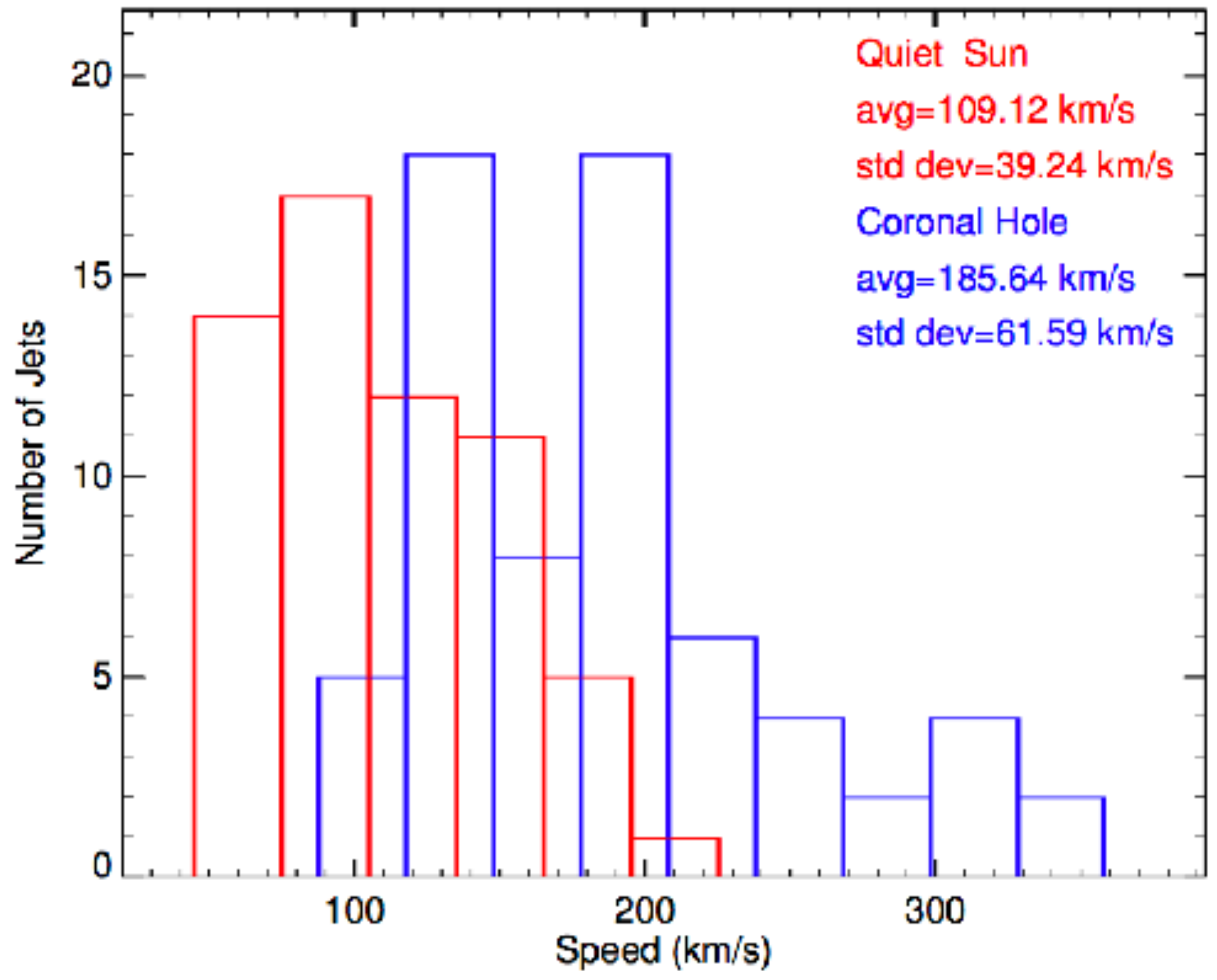
- localized strong transverse waves
- high density gradients
- electrical currents
- heating to at least TR temperatures



Martinez-Sykora et al., Science, 2017

Can the model reproduce very high apparent speeds (100-300 km/s) in TR counterparts?



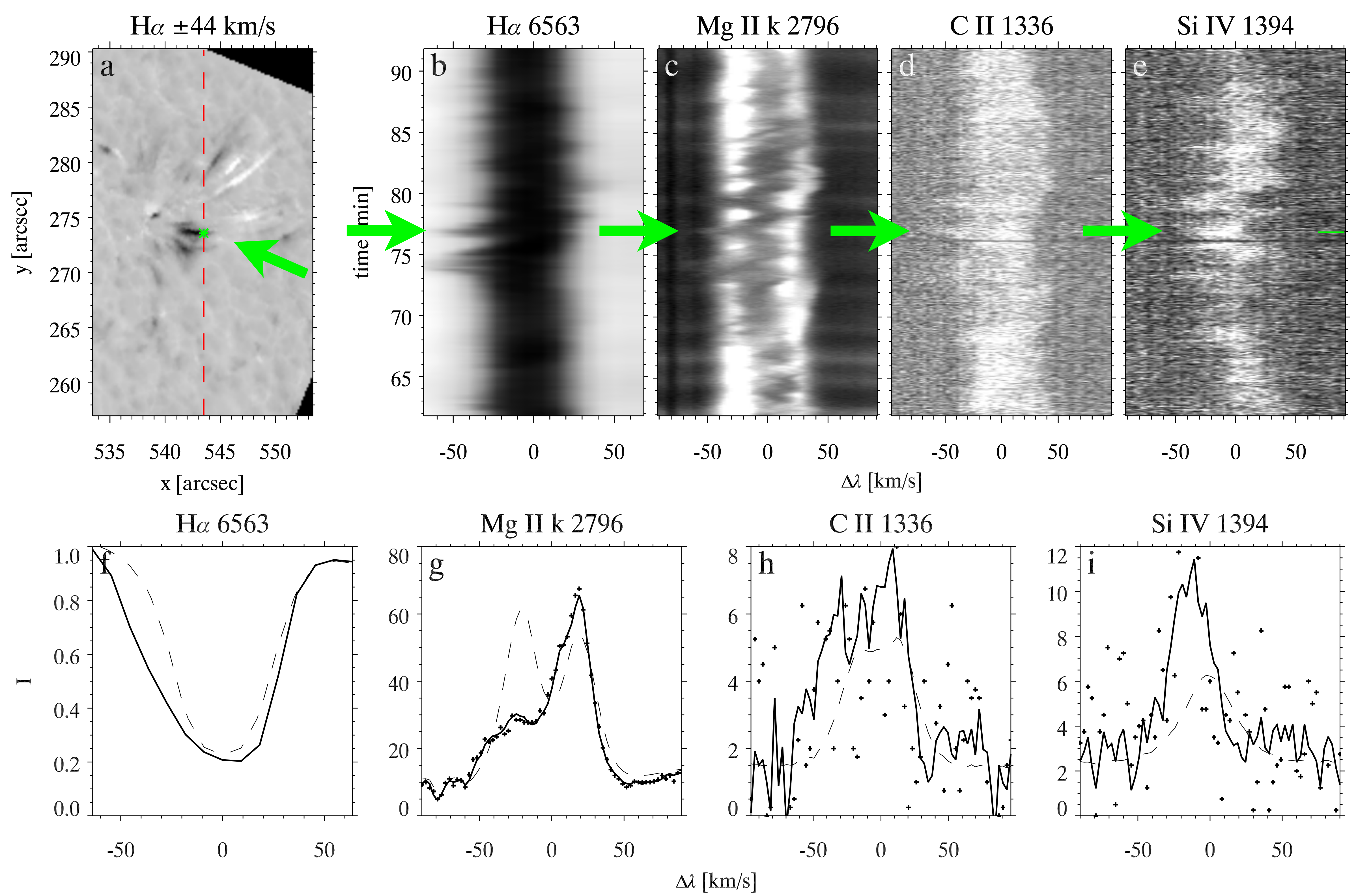


Tian et al., 2014, Narang et al., 2016

IRIS observations of transition region counterparts of spicules show extremely high apparent speeds

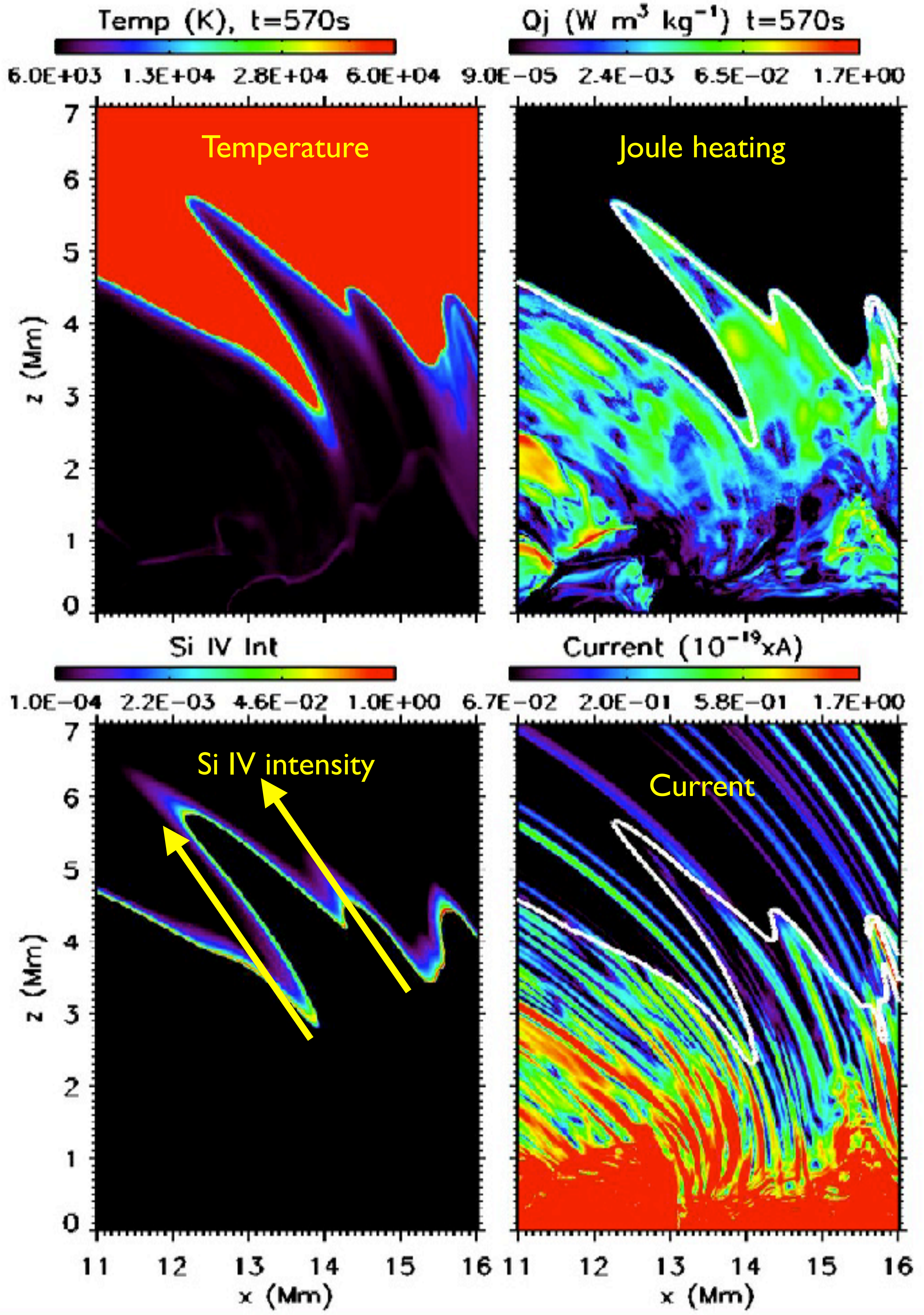
They often occur on previously formed spicules

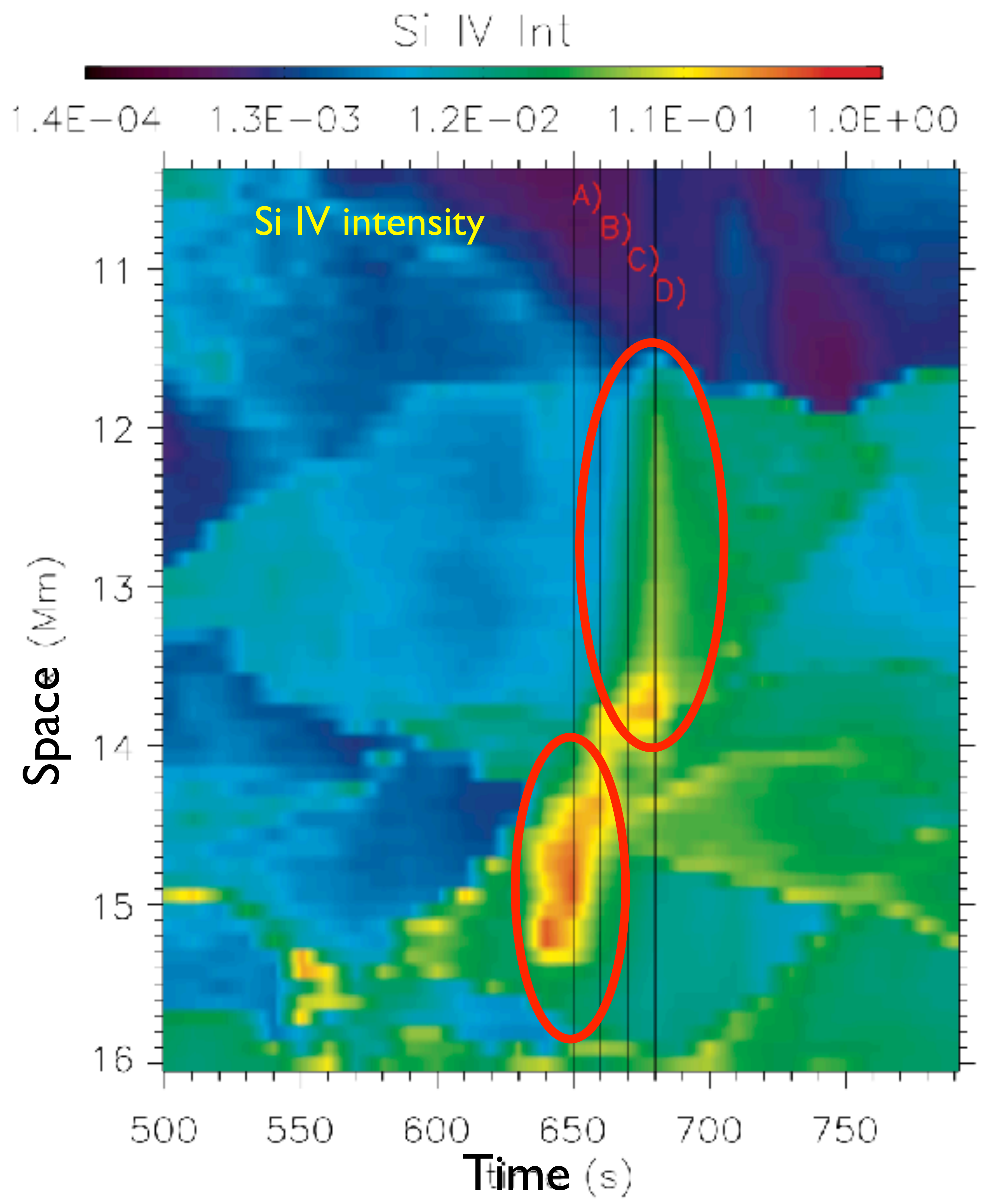
And the discrepancy with measured Doppler shifts (<100 km/s)?



Yet Doppler shifts of the same features reveal speeds < 100 km/s

High apparent speeds in transition region and chromospheric spicules caused by heating fronts



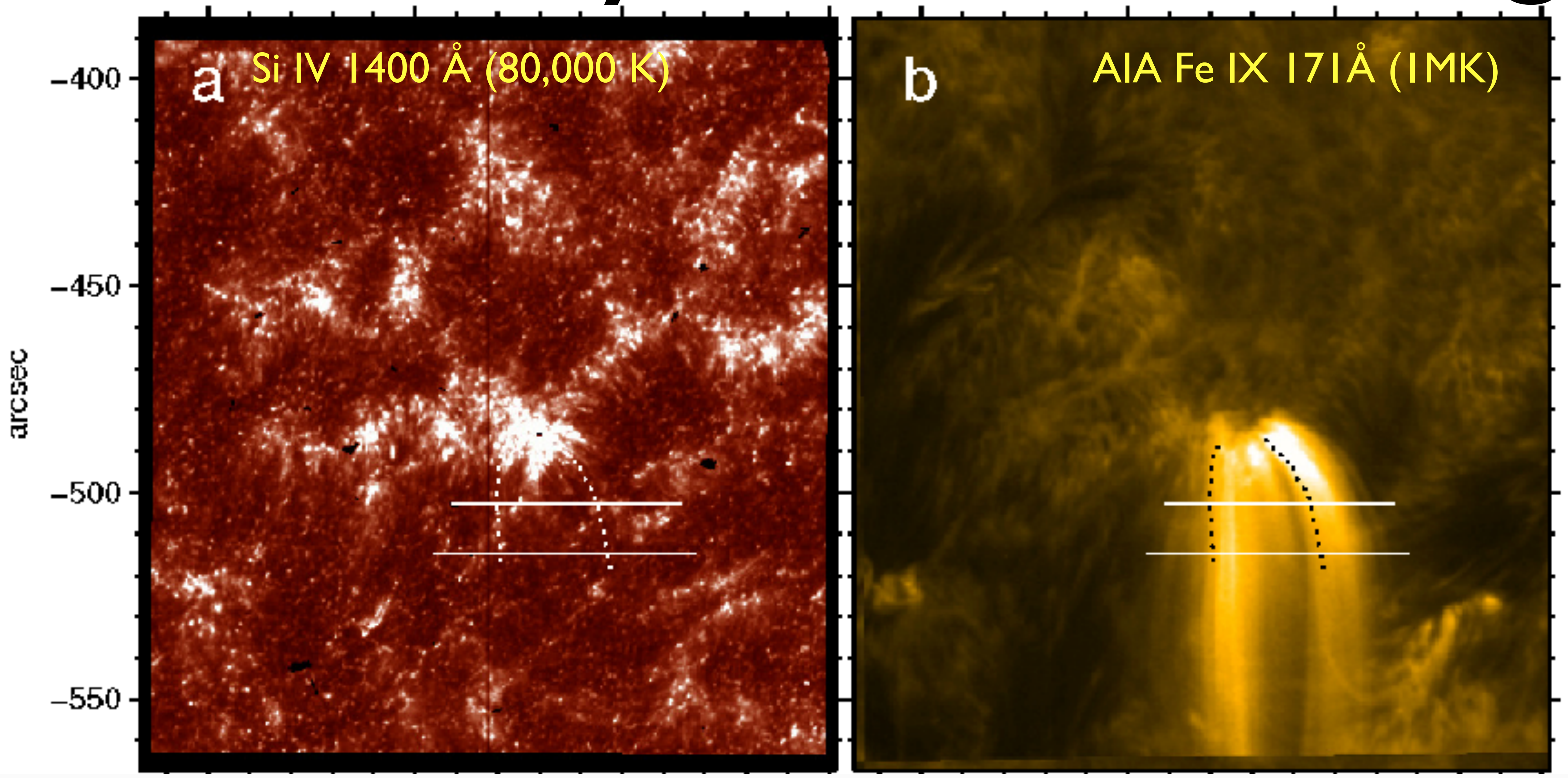


Heating fronts caused by propagation of electrical currents at Alfvenic speeds and subsequent rapid dissipation by ambipolar diffusion

This can explain some of the very high apparent speeds in Ca II spicules

Affects any estimates of kinetic energy or mass flux in spicules

Is there any coronal heating associated with these spicules?

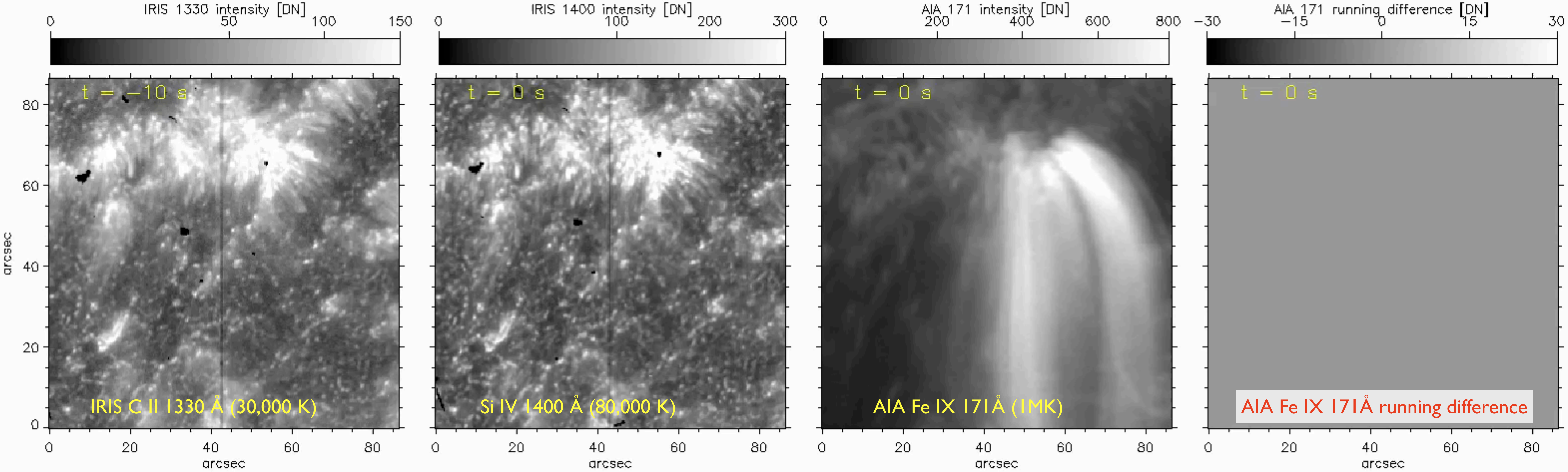


Spicules abound at footpoints of coronal loops: *exploit longevity in TR observables from IRIS (5-10 min vs. 30 s)*

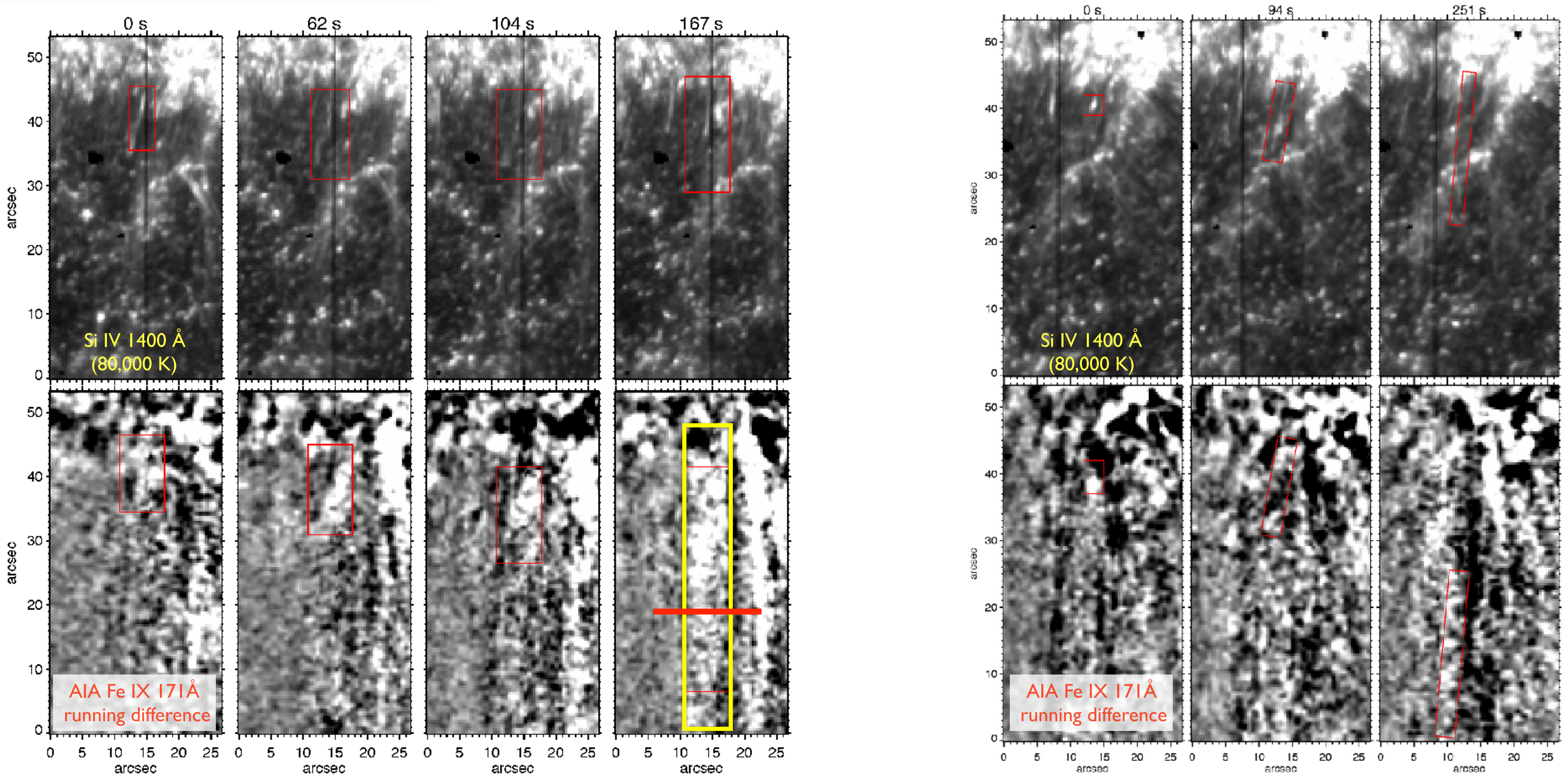
Coronal loops carry multitude of propagating disturbances

Are these two types of features connected?

Previously suggested by De Pontieu et al., 2005, De Pontieu & McIntosh 2010, Petralia et al., 2014

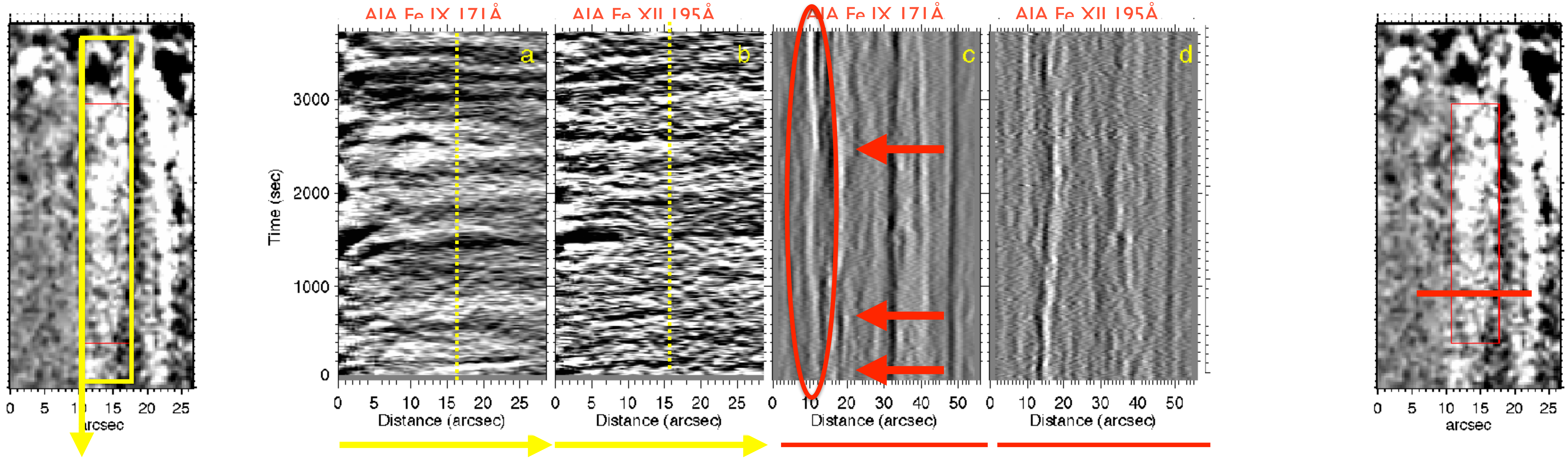


Spicules often lead to propagating coronal disturbances (PCDs)



See also McIntosh et al., 2009 (indirect evidence of spicules), De Pontieu et al., 2011 (at the limb), Tanmoy et al., 2016 (at the limb)

Are these propagating disturbances just transient events (flows, waves,…)?



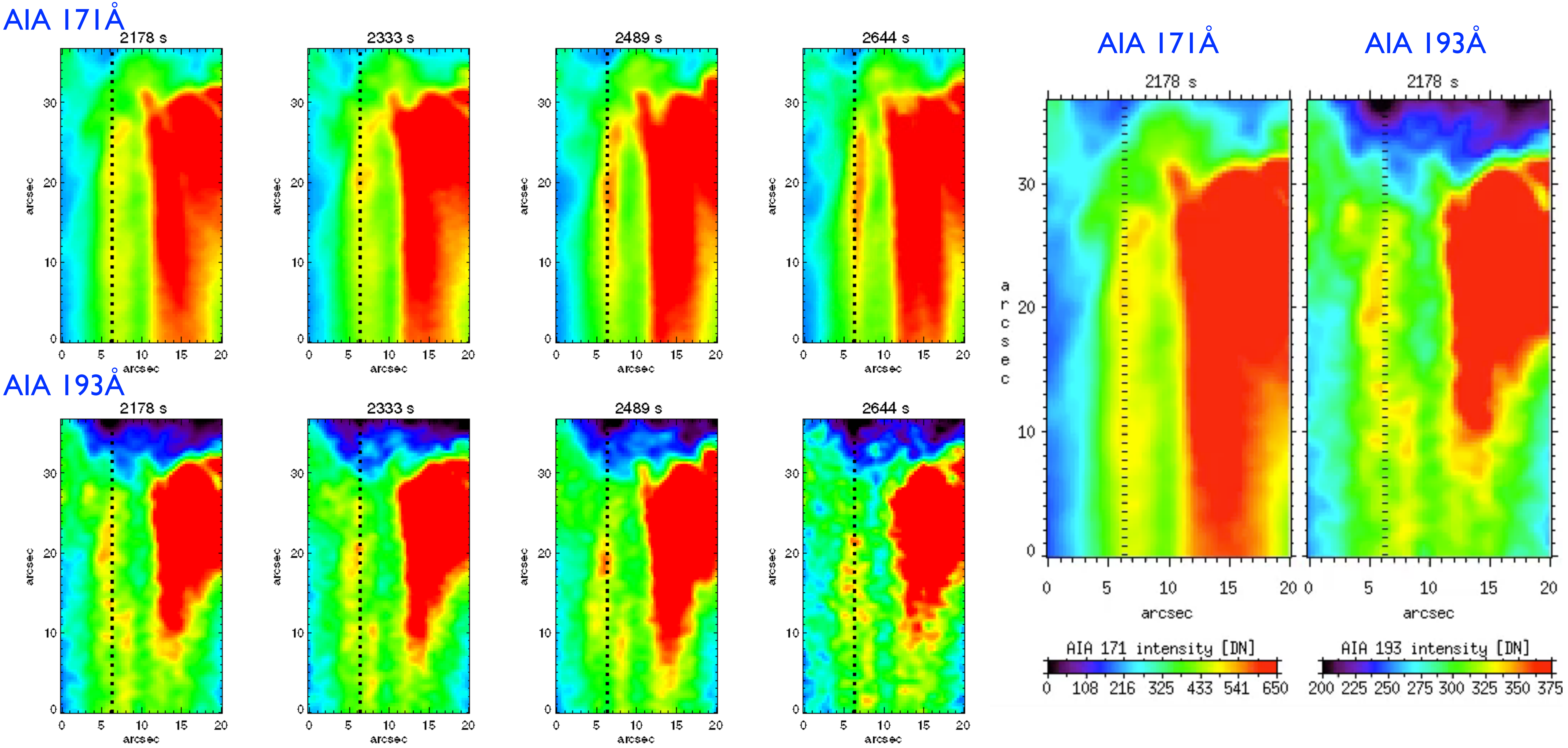
- Propagating disturbances leads to long-lived brightenings in both 195 and 171Å channels

- Previous interpretations for PCDs (transient flows, waves) would not lead to long-lived brightenings

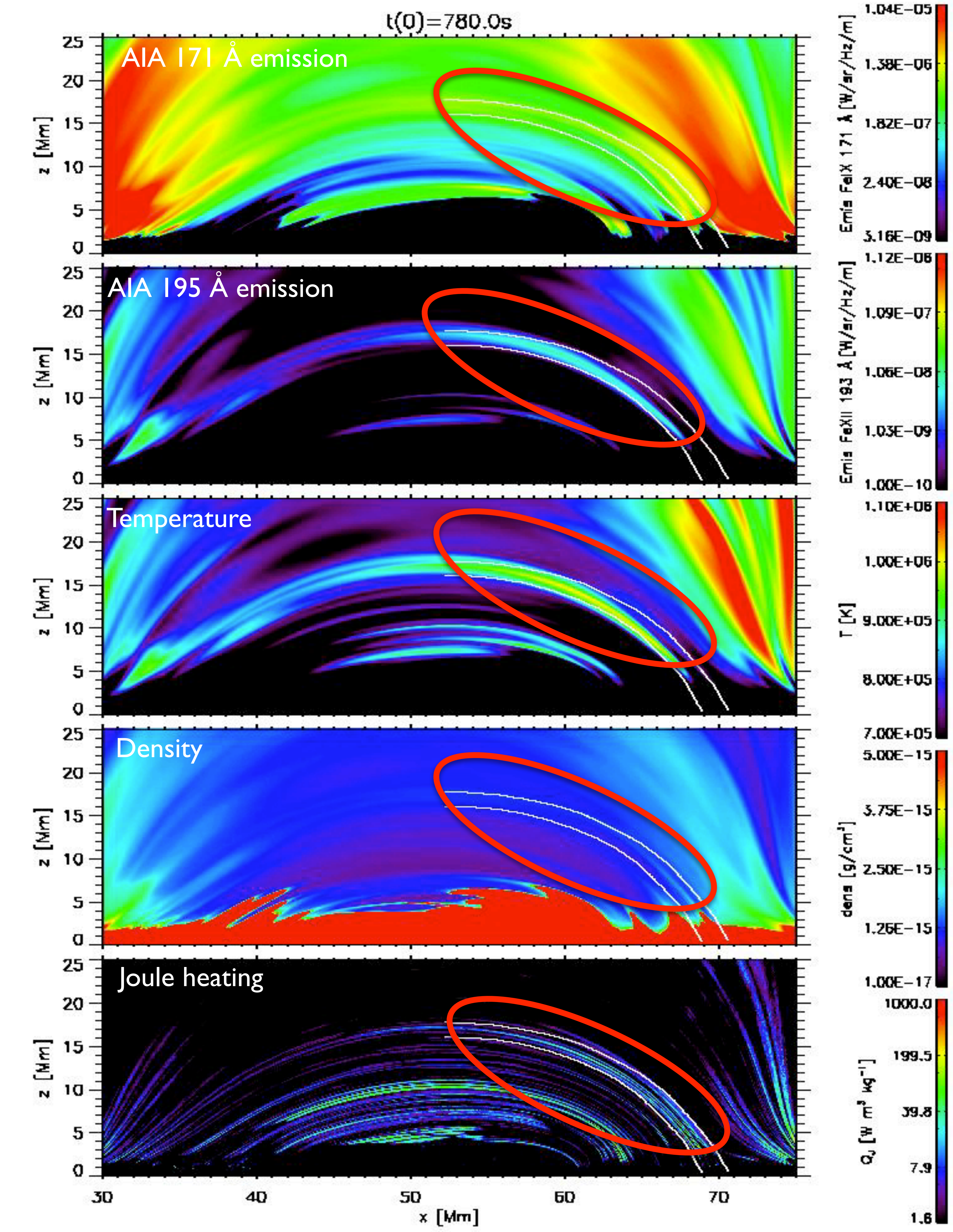
- Timing of brightenings (195Å followed by 171Å) suggests scenario in which:
  - heating associated with PCD/spicules forms a new coronal loop strand
  - followed by slow cooling over 10-15 minutes

- Other examples show that PCDs "revive" longer-lived coronal structures

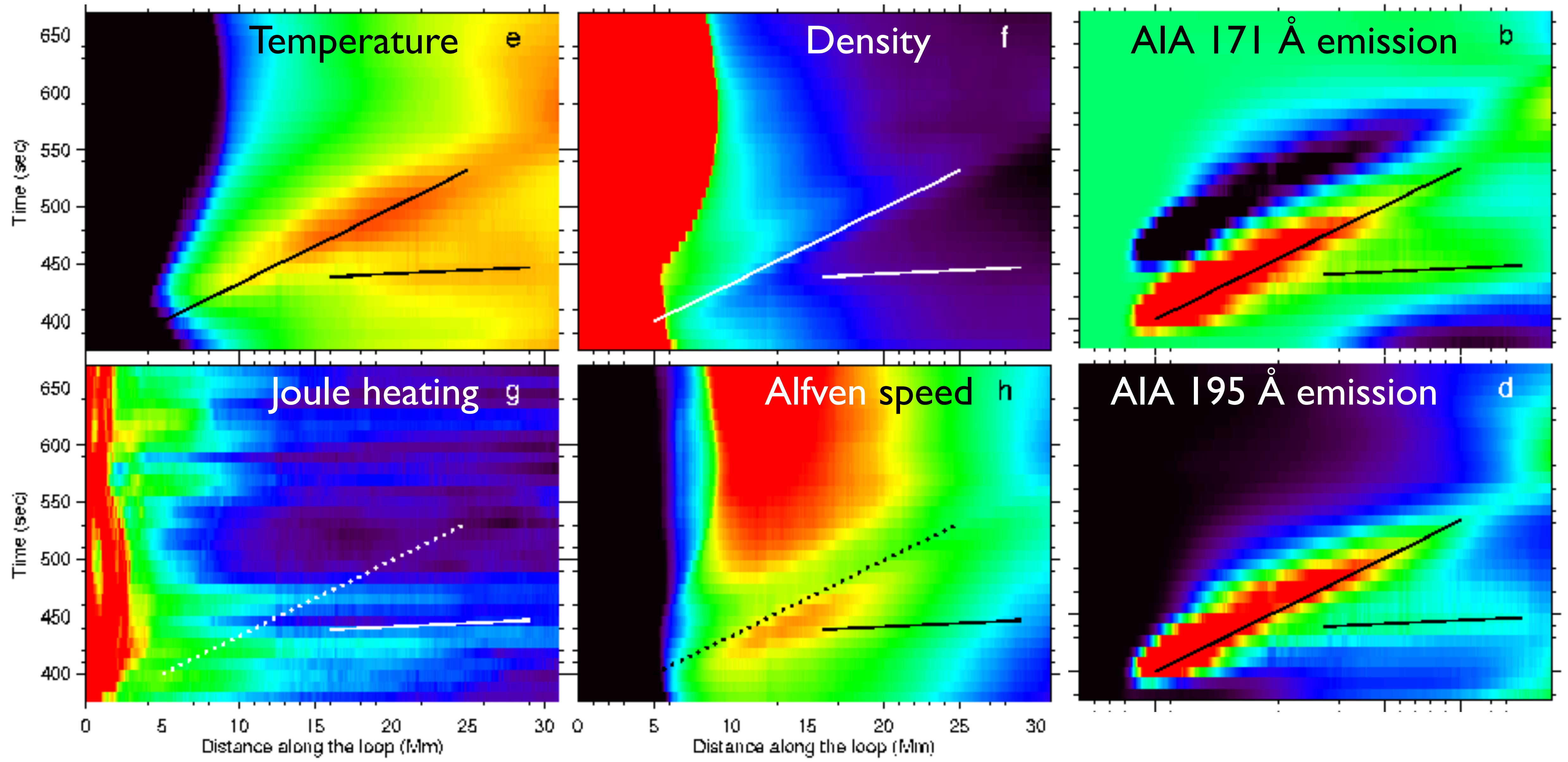
Formation of coronal loop strands associated with PCDs/spicules



Loop strand formation appears to occur after initial PCD passes through



Type II spicules create PCDs and lead to coronal heating



Spicule leads to:

- propagating shock wave
- strong flows at coronal temperatures
- *heating throughout the volume because of Joule dissipation of ambipolar currents associated with spicule formation mechanism*

PCD is combination of all of the above

In this scenario, spicules are a signature of coronal heating:

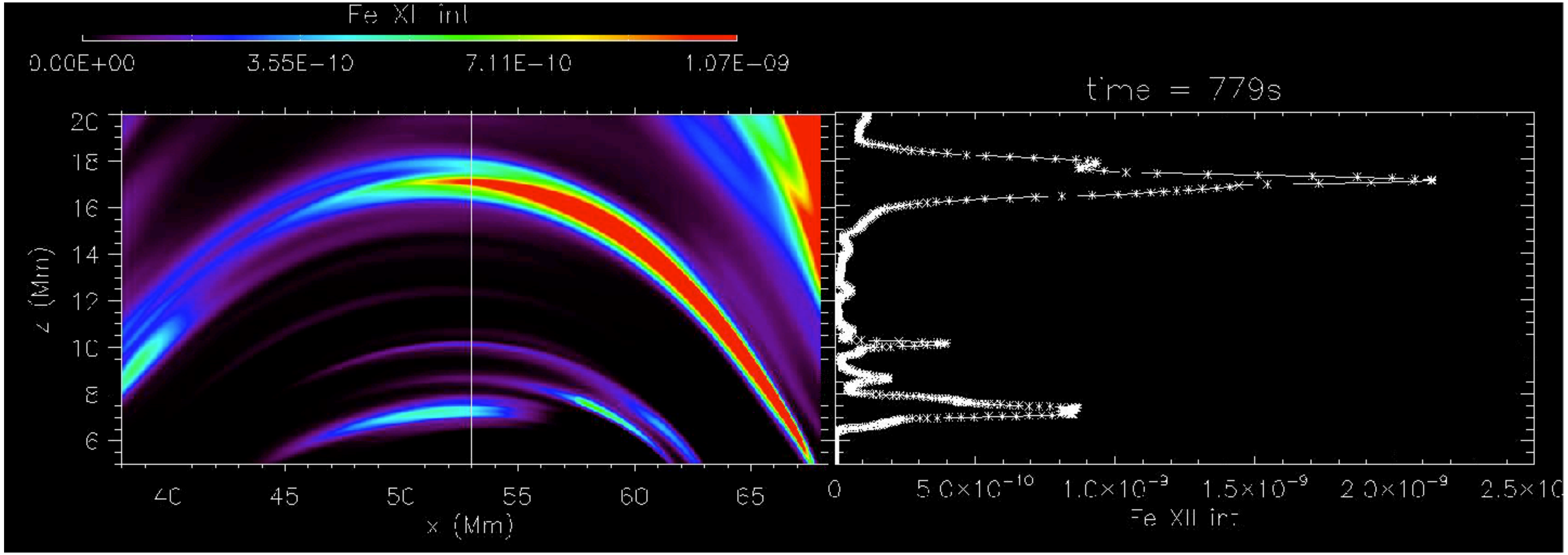
spicular plasma to TR temperatures,

TR plasma to coronal temperatures,

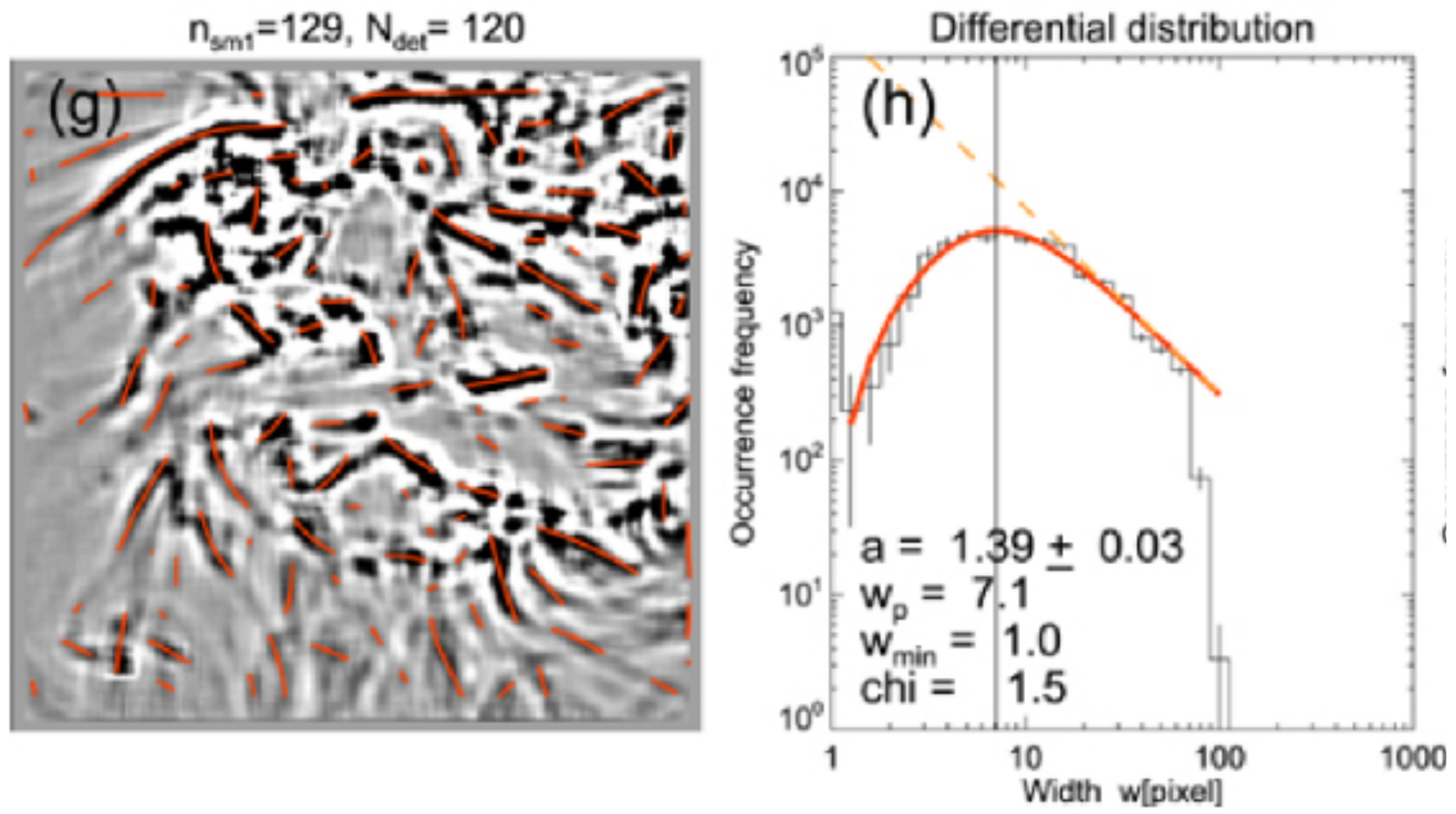
coronal plasma to even higher temperatures

The Sun does not care about 1D approximations

Heating associated with spicules creates coronal loops with widths of a few hundred km



Hi-C loop widths peak at ~500 km?



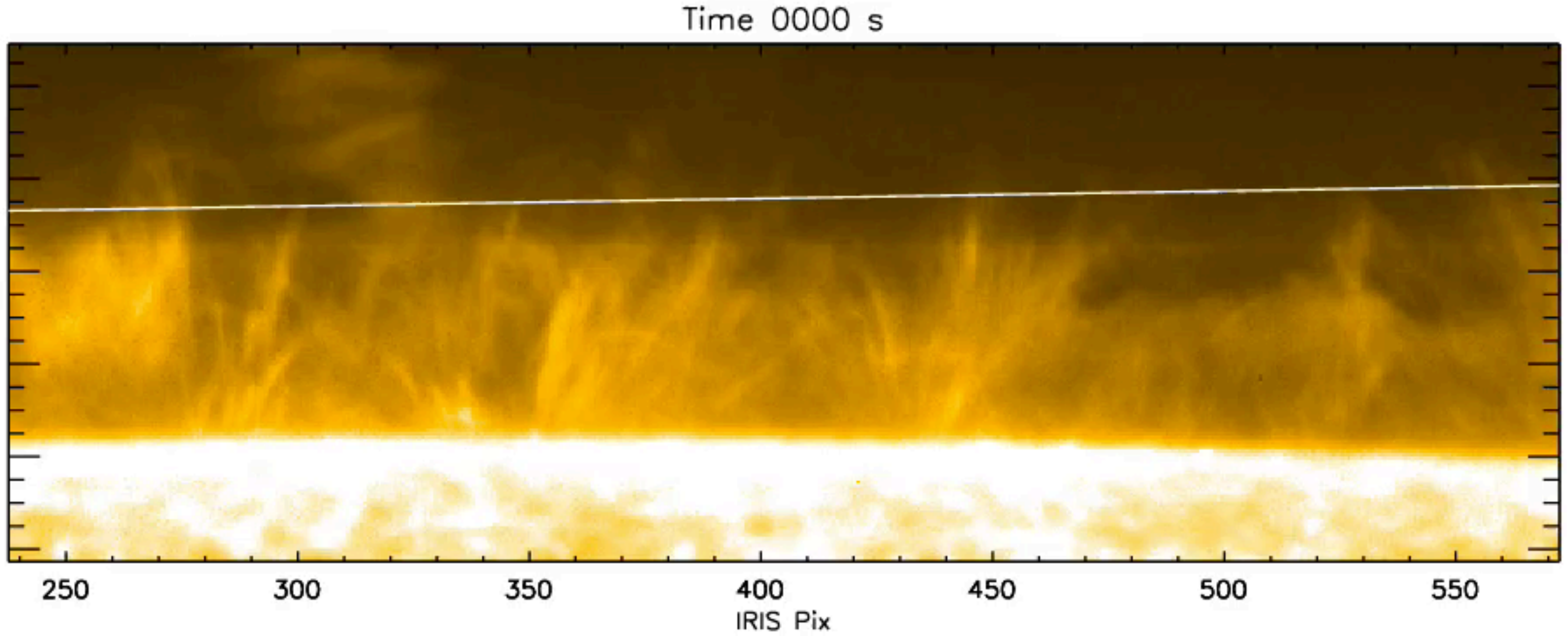
Aschwanden, M., & Peter, H. (2017)

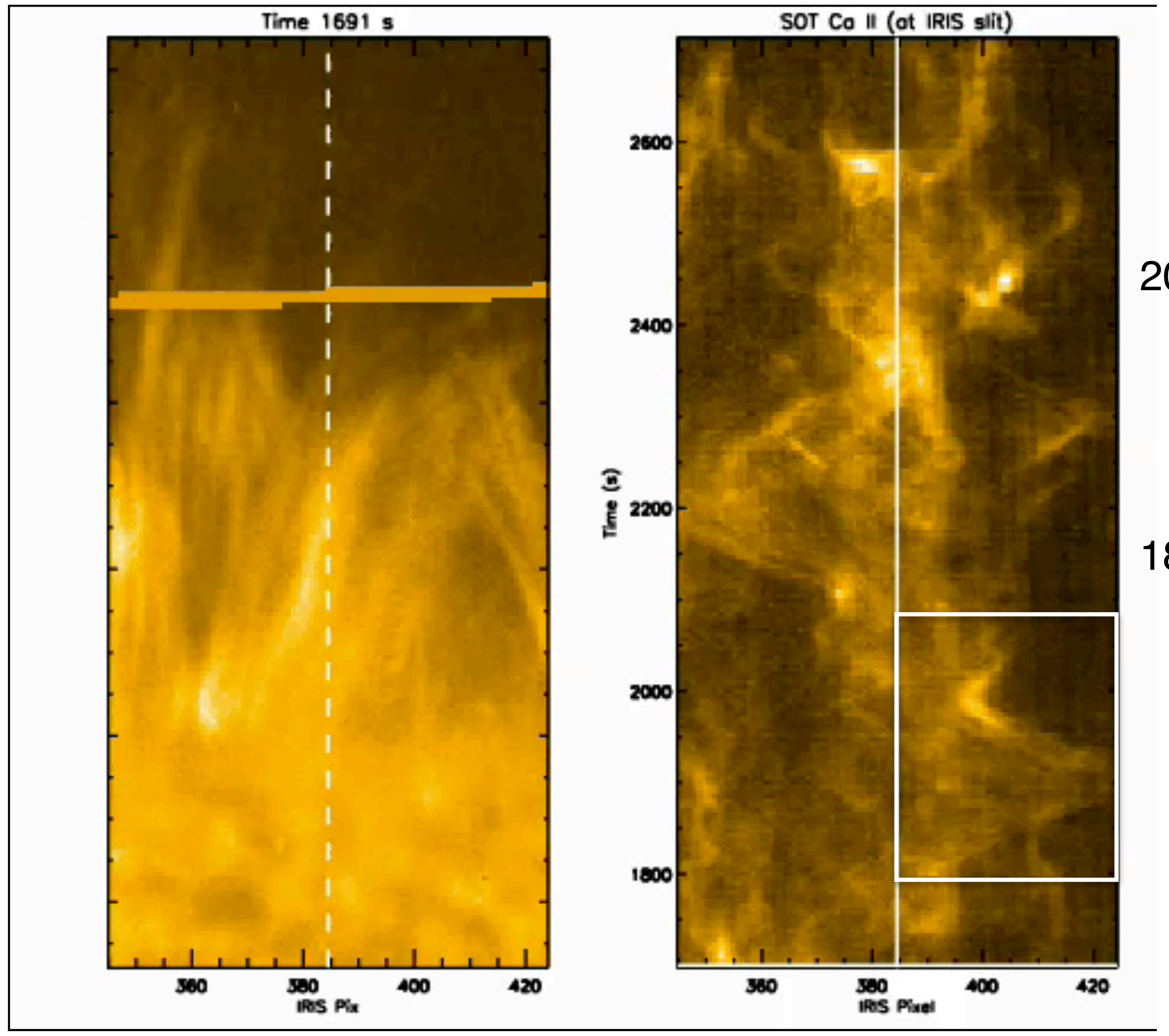
In our simulations, loop widths arise naturally from the sub-granular scales involved in spicule formation

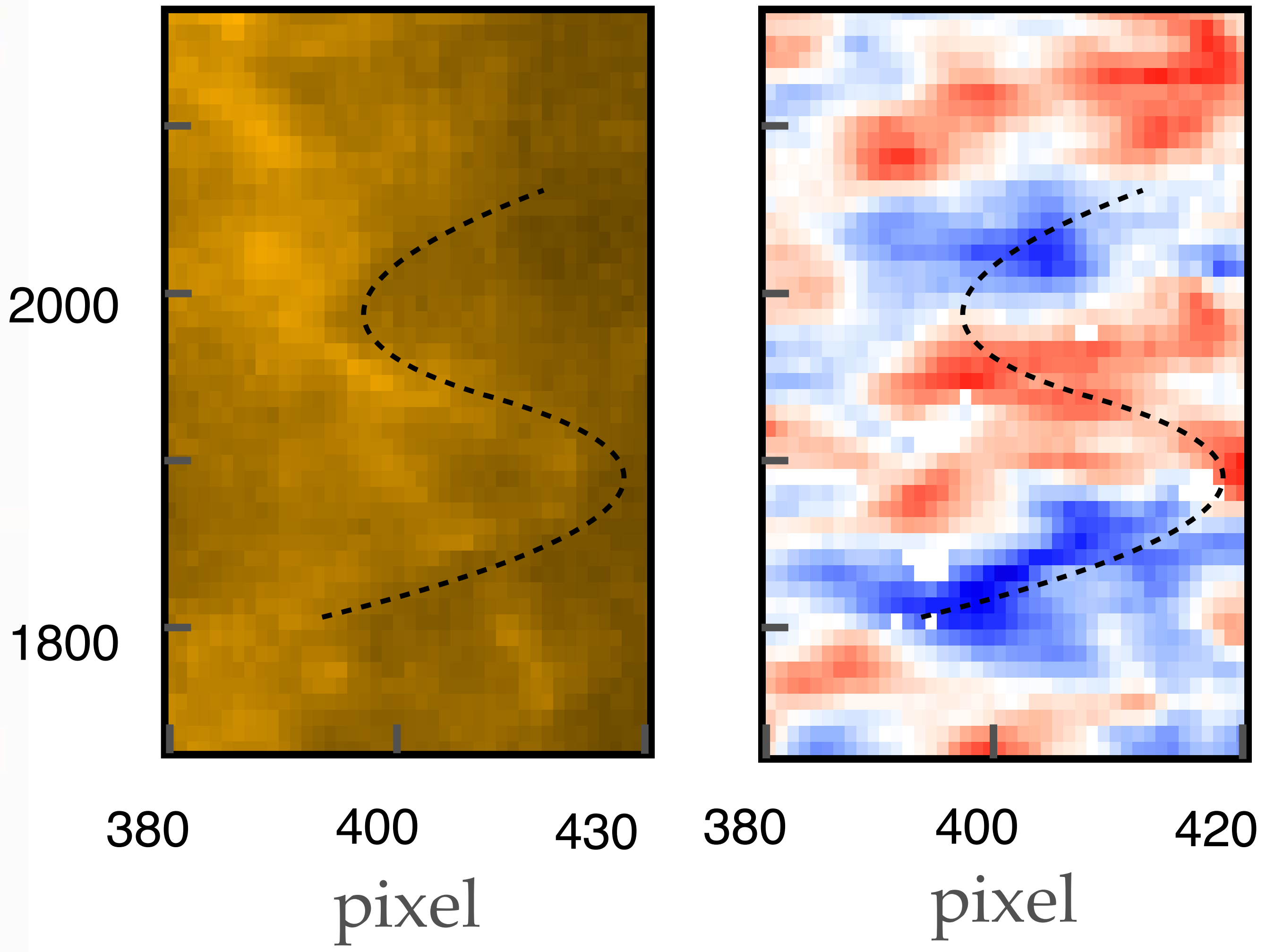
Is it a coincidence that type II spicule diameters are similar to coronal loop widths?

How would heating associated with spicules really occur on the Sun?

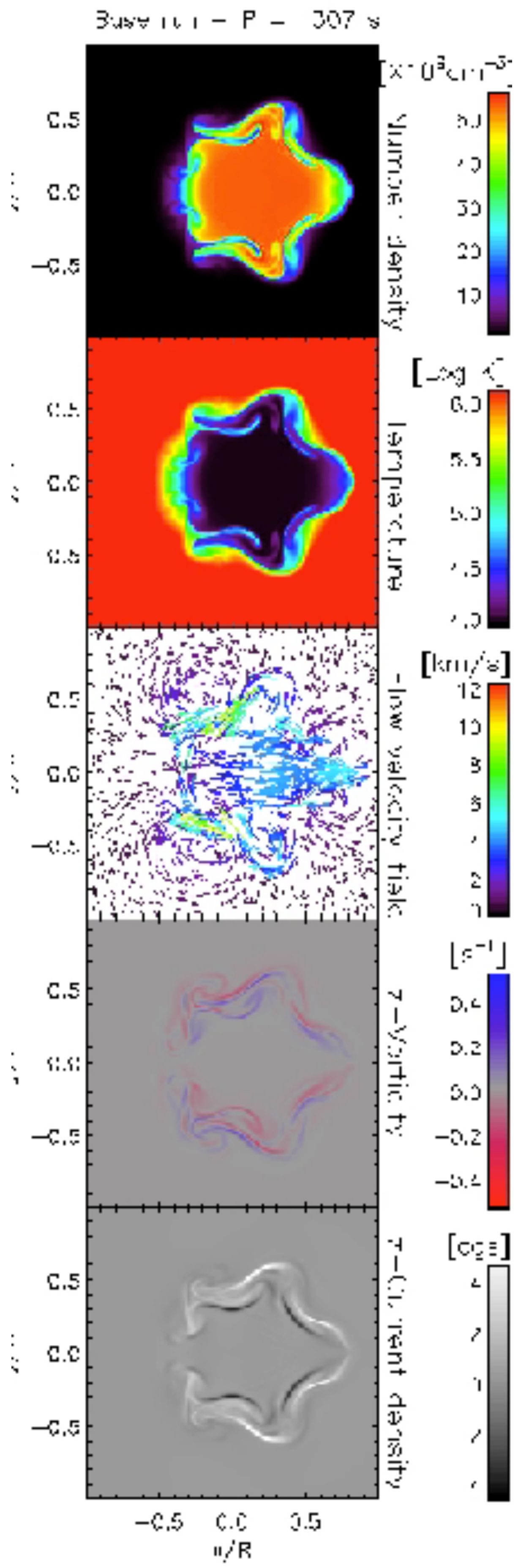
Observations show evidence of a variety of wave modes

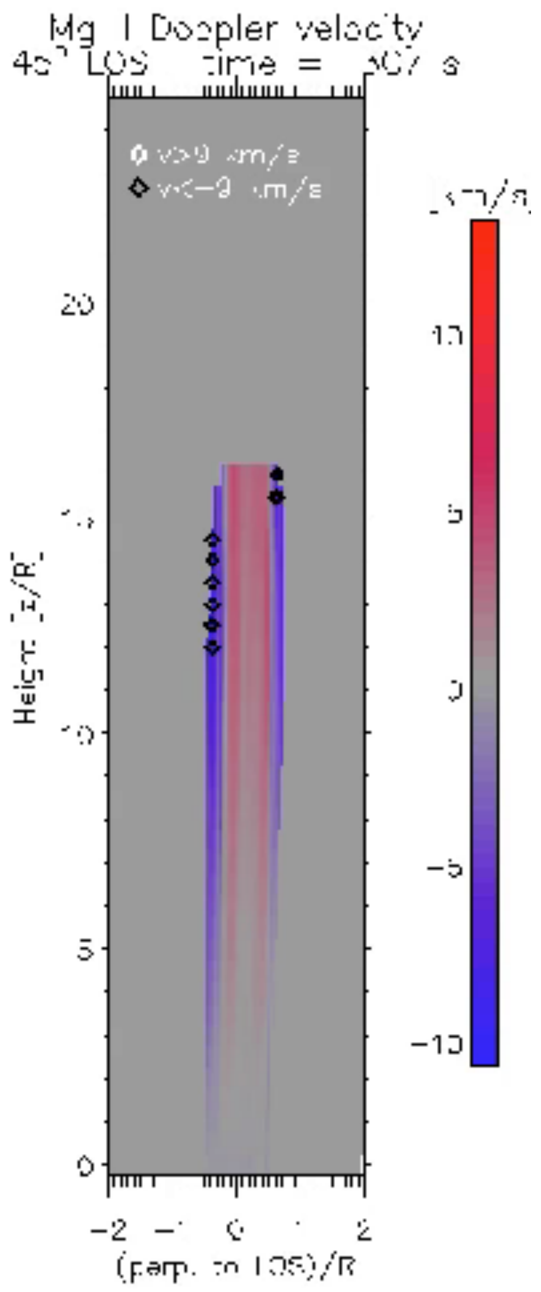


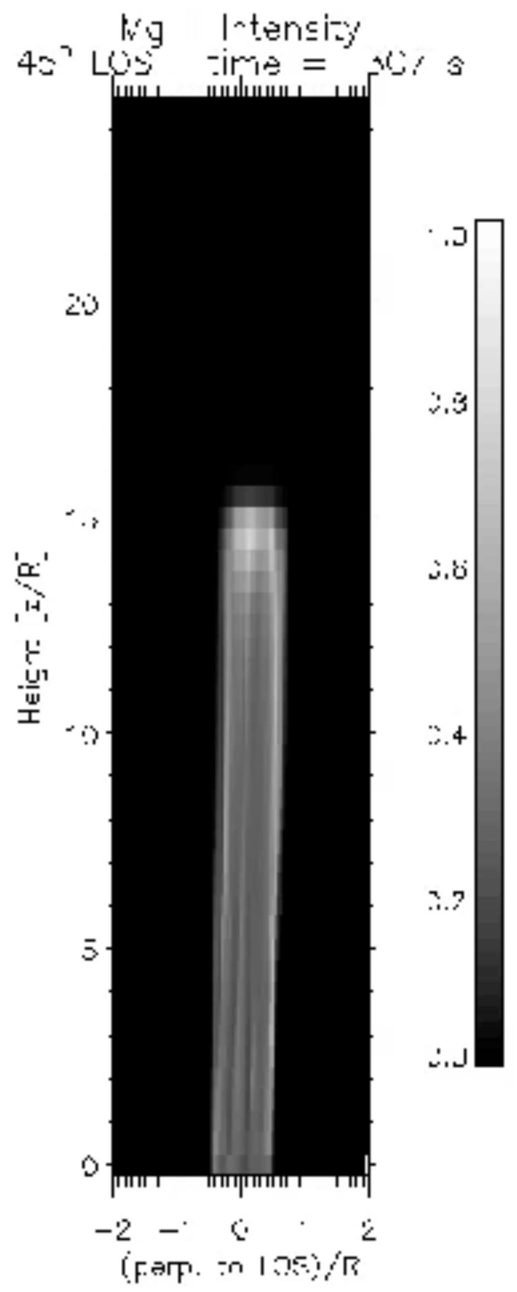




Including evidence of resonant absorption and Kelvin Helmholtz instabilities + dissipation







See Patrick Antolin's talk

Conclusions and Discussion points

1. New numerical model (only 1 “free” parameter) naturally generates spicules if partial ionization of chromosphere and interaction of strong/weak fields included

2. Explains heating of spicules to TR temperatures and high apparent speeds in spicules: heating fronts from current dissipation

3. IRIS/AIA observations show spicules associated with propagating coronal disturbances (PCDs) and formation of coronal loop strands

4. PCDs in plage/network often create or “revive” coronal loop strands: not just passage of a transient (waves/flows)

5. Spicules are signature of significant coronal heating and PCDs are a combination of flows, waves and heating

6. *Spicule generation associated with transverse waves (which can trigger TWIKHS rolls) and electrical currents: - both AC and DC mechanisms triggered by spicules,*
   - as well as the density gradients needed for wave dissipation
   - unclear whether this would lead to footpoint or uniform heating (depends on dissipation mech.)