Observations and Modeling of Transition Region and Coronal Heating Associated with Spicules

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Thanks to Juan Martinez-Sykora, Ineke De Moortel, Georgios Chintzoglou, Scott McIntosh, Mats Carlsson, Viggo Hansteen, Tiago Pereira, Luc Rouppe van der Voort

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Contributed Talk

3. Magnetic coupling and mass flux through the atmosphere

Observations and Modeling of Transition Region and Coronal Heating Associated with Spicules

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Spicules have been proposed as significant contributors to the coronal energy and mass balance. While previous observations have provided a glimpse of short-lived transient brightenings in the corona that are associated with spicules, these observations have been contested and are the subject of a vigorous debate both on the modeling and the observational side so that it has remained unclear whether plasma is heated to coronal temperatures in association with spicules. We use high-resolution observations of the chromosphere and transition region with the Interface Region Imaging Spectrograph (IRIS) and of the corona with the Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamics Observatory (SDO) to show evidence of the formation of coronal structures as a result of spicular mass ejections and heating of plasma to transition region and coronal temperatures. Our observations suggest that a significant fraction of the highly dynamic loop fan environment associated with plage regions may be the result of the formation of such new coronal strands, a process that previously had been interpreted as the propagation of transient propagating coronal disturbances (PCD)s. Our observations are supported by 2.5D radiative MHD simulations that show heating to coronal temperatures in association with spicules. Our models also matches observations of TR counterparts of spicules and provides an elegant explanation for the high apparent speeds of these "network jets".

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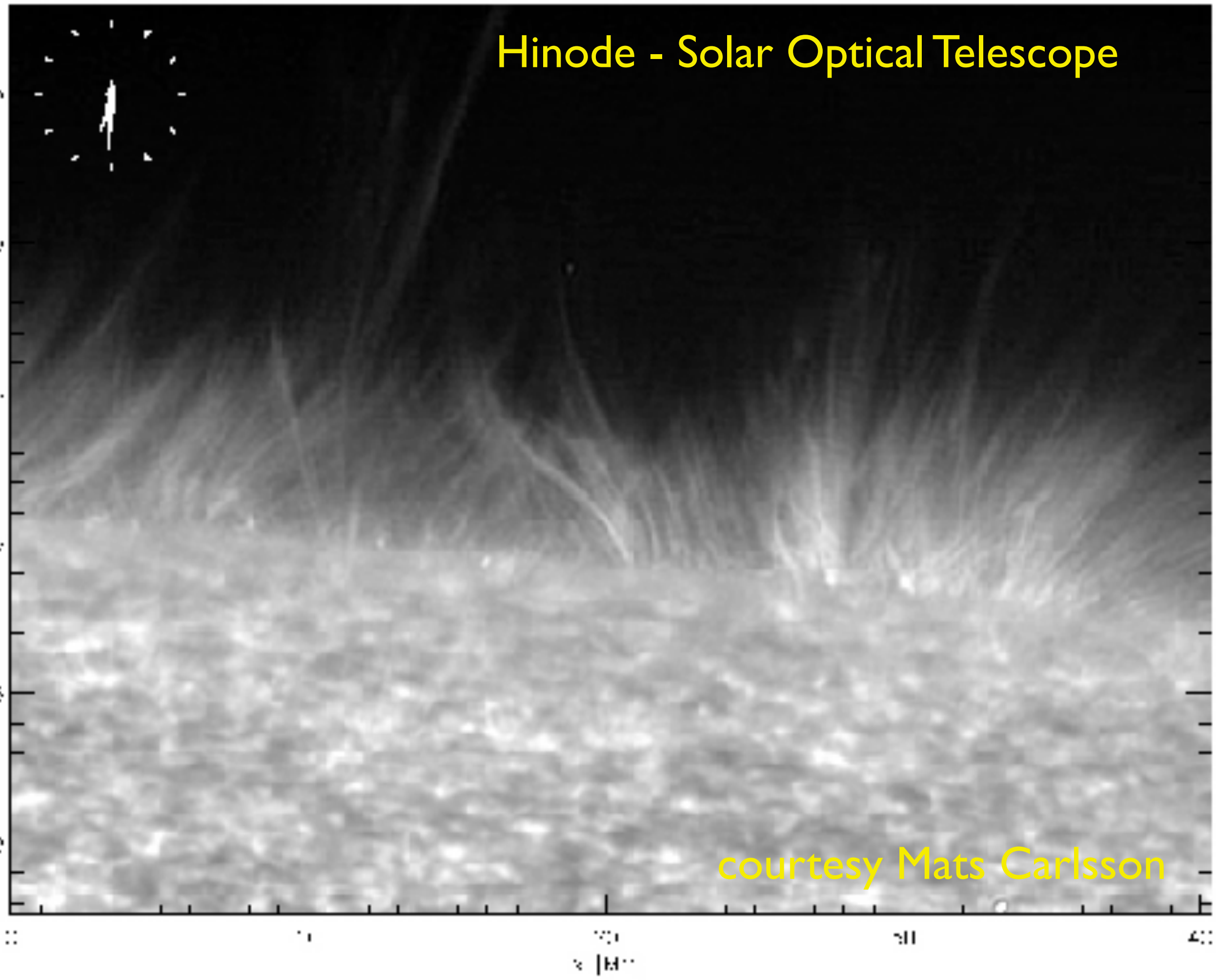
Chromospheric Spicules

Before IRIS

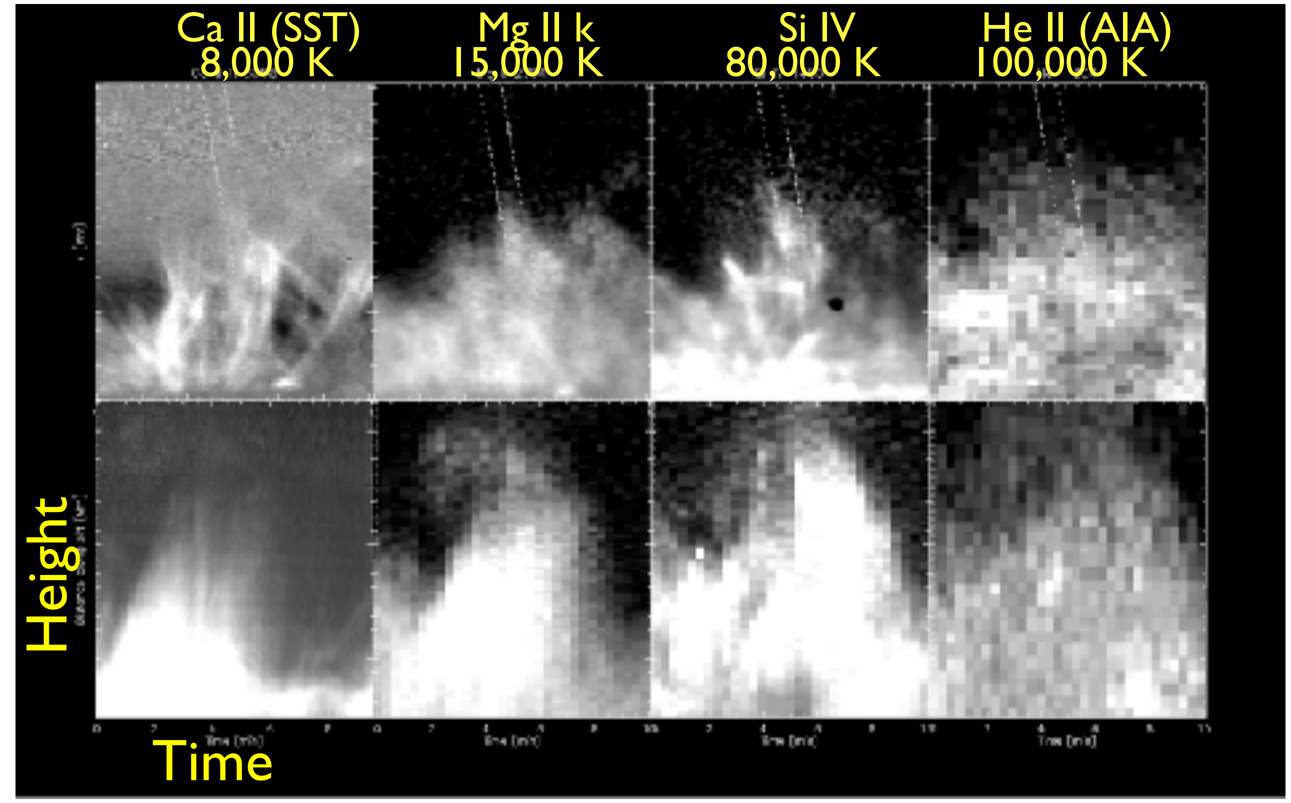


- Dynamic jets at interface between chromosphere and corona

- Fast spicules ("type II"): upward flows of order 50 km/s, with counterpart at TR temperatures, much faster than previously reported (De Pontieu et al., 2007, Pereira et al., 2012)
- Carry strong Alfvenic waves (20 km/s, De Pontieu et al., 2007b, McIntosh et al., 2011)
- 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

After IRIS



Ca II H spicules are the initial, rapid phase of violent upward motions…

Some threads appear to show rapid heating over the whole length to TR temperatures (Si IV, C II)

Heating timescales of order ~ 1 minute or less

(Pereira et al., 2014, Skogsrud et al., 2016)

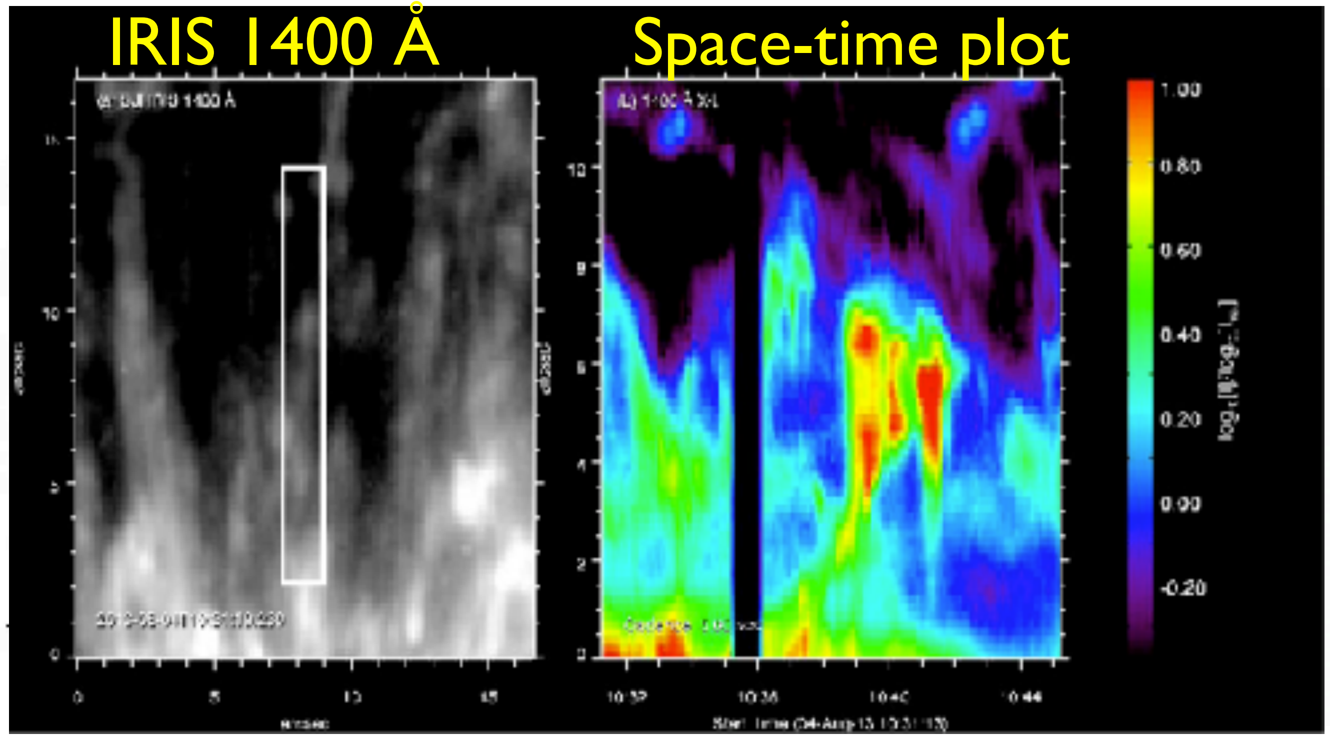
Spicules appear to be multi-threaded with different threads at different temperatures

(see also De Pontieu et al., 2014, Rouppe van der Voort et al., 2015)

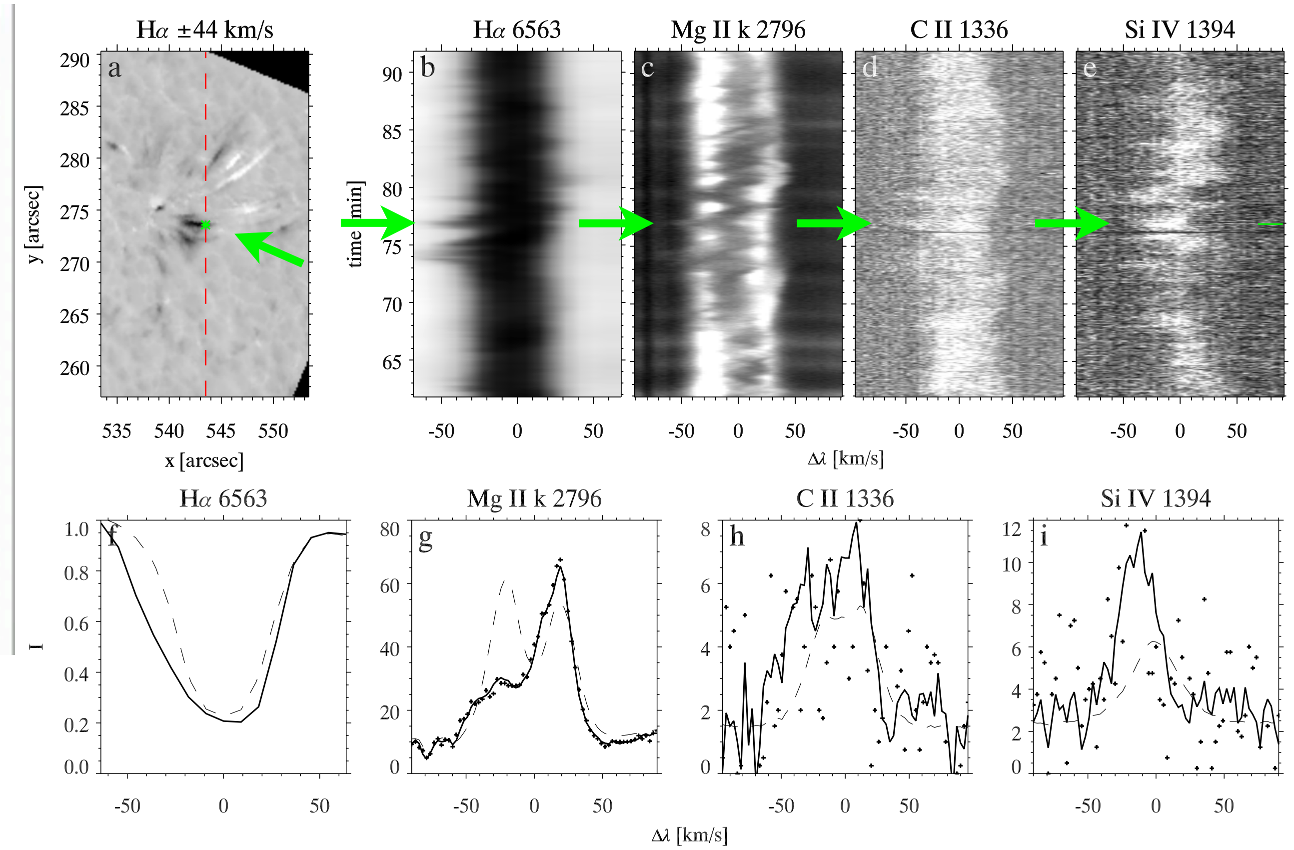
Transition Region Counterparts to Spicules

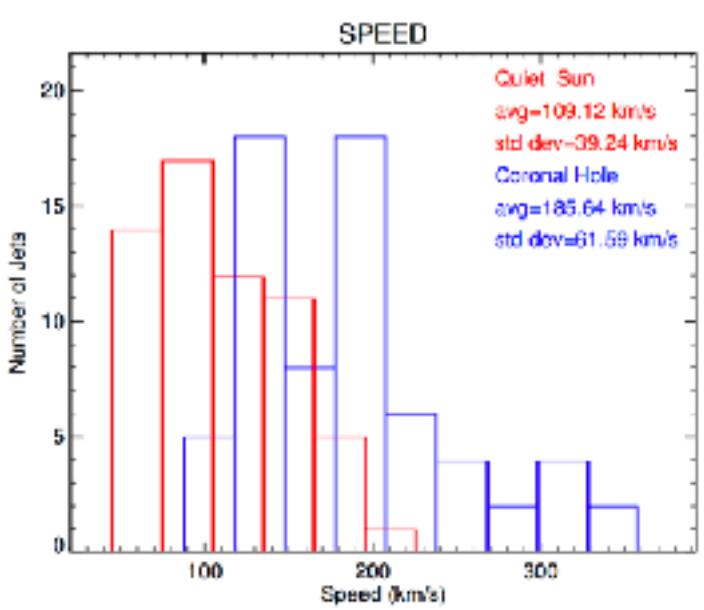
Observations show very high apparent speeds (100-300 km/s) in TR counterparts

With substantial discrepancy with measured Doppler shifts (<100 km/s)?



Rouppe van der Voort et al., 2015





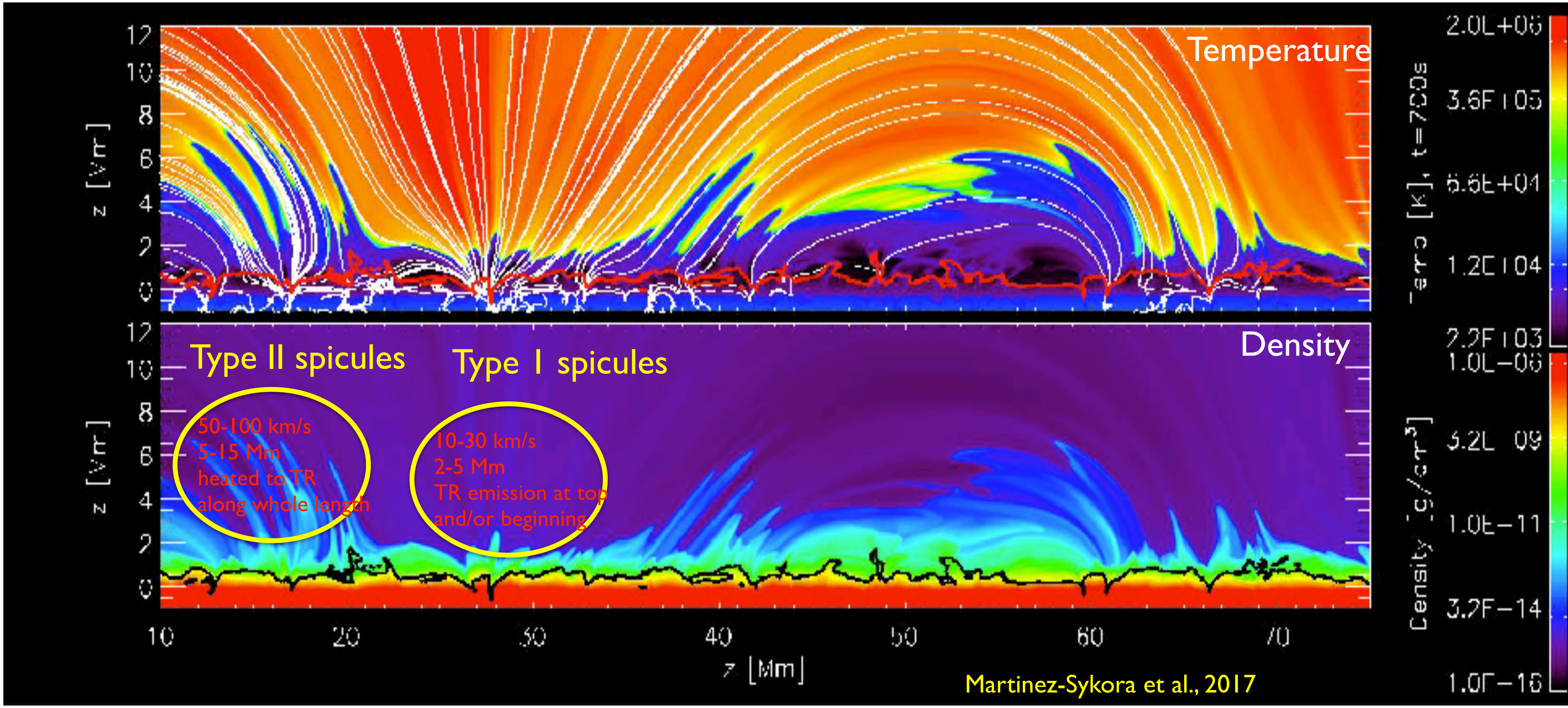
Tian et al., 2014, Narang et al., 2016

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

They often occur on previously formed spicules

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

Numerical simulations of chromospheric spicules



Numerical simulations using Bifrost code solve for 2.5 or 3D radiative MHD equations and include scattering, non-LTE approximations for radiative losses in chromosphere, optically thin radiative losses, thermal conduction

Numerical domain covers convection zone to chromosphere/corona, which are self-consistently created
Main free parameter is magnetic field configuration
Single-fluid MHD simulations only produce type I spicules, driven by magneto-acoustic shocks from p-mode leakage, convective flows (Hansteen et al., 2006)

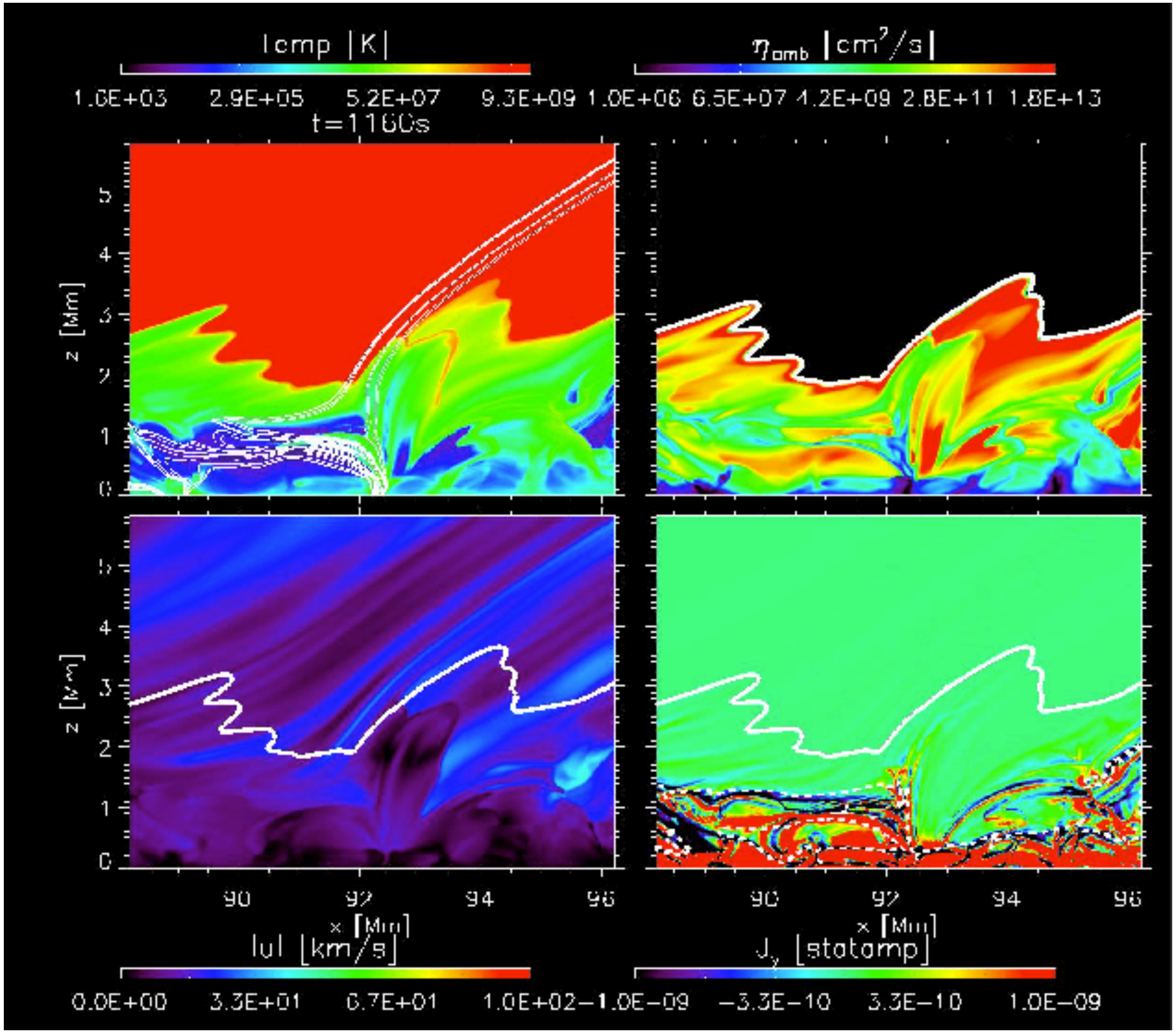
Strong flows driven by magnetic tension that diffuses into upper chromosphere because of ambipolar diffusion

Martinez-Sykora et al., 2017

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

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

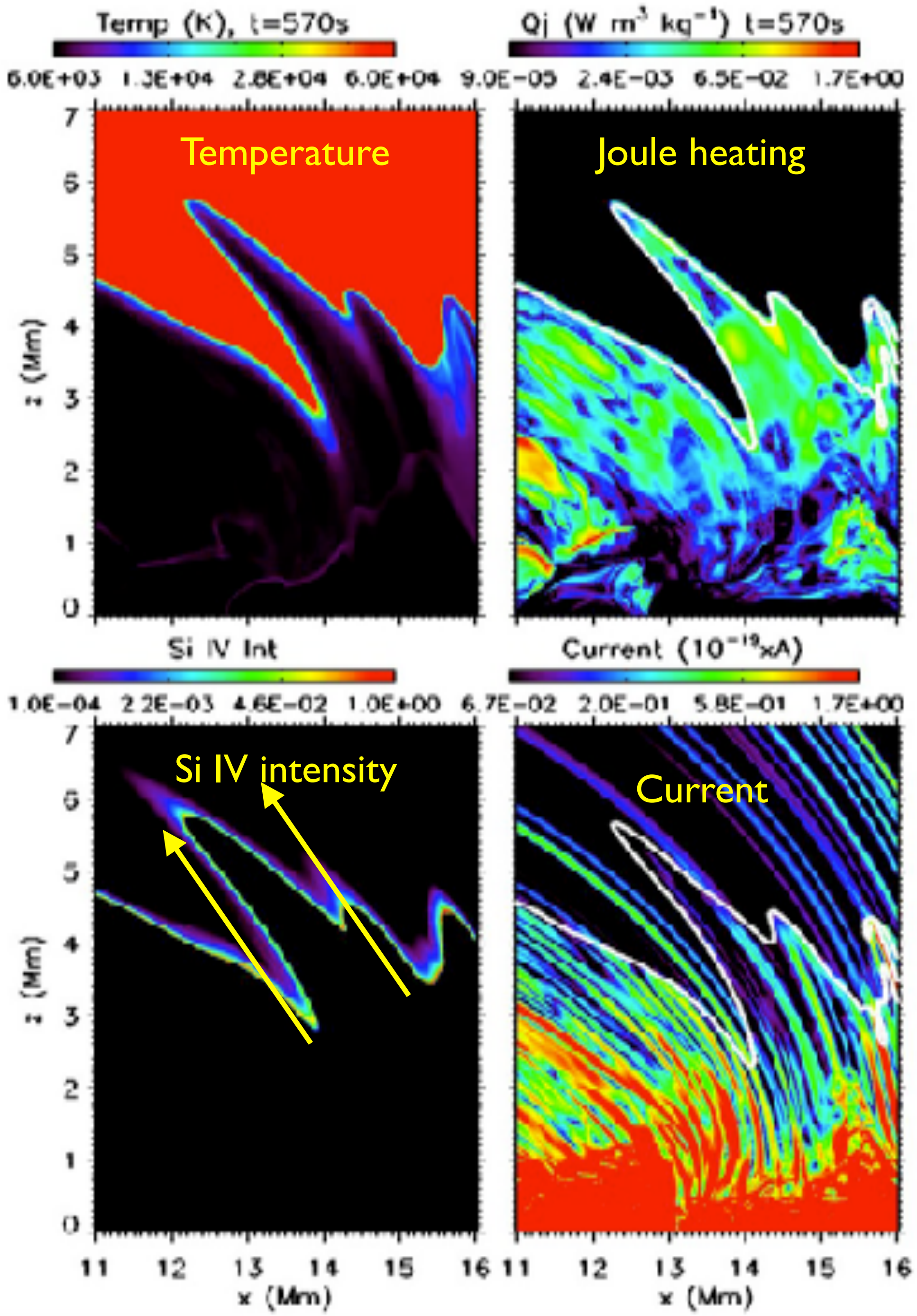
In cold and/or low density pockets, this means magnetic field can diffuse through neutral population

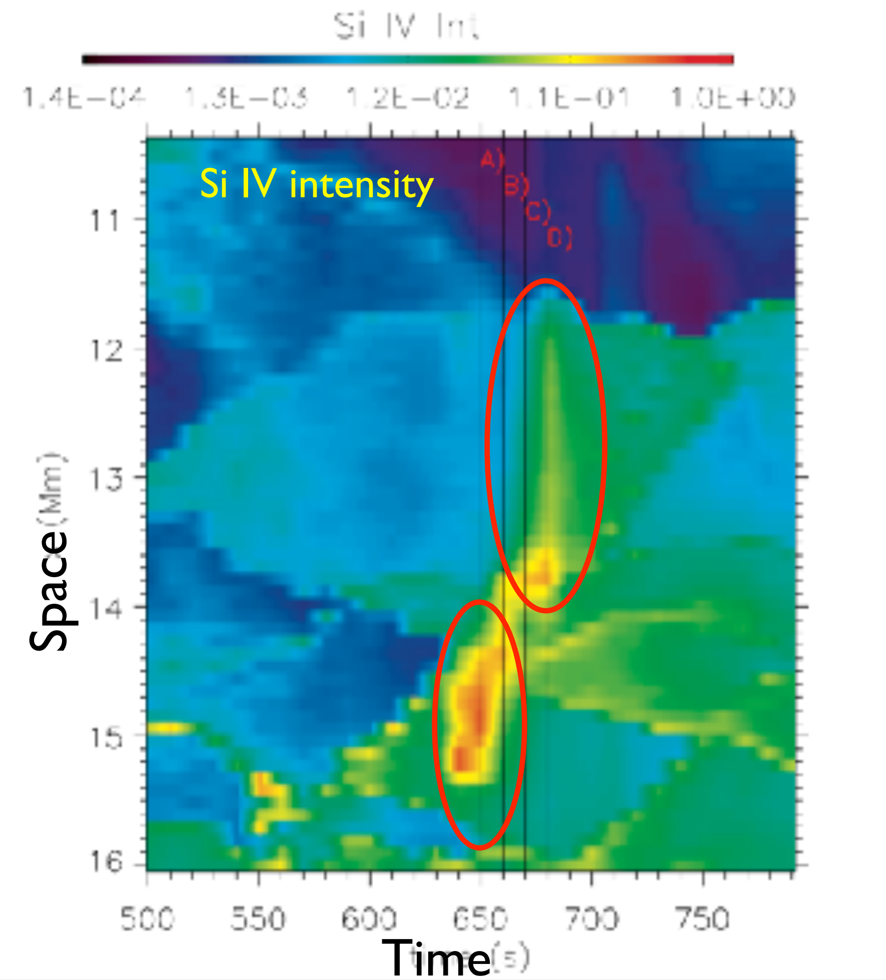


Spicule formation associated with:

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

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

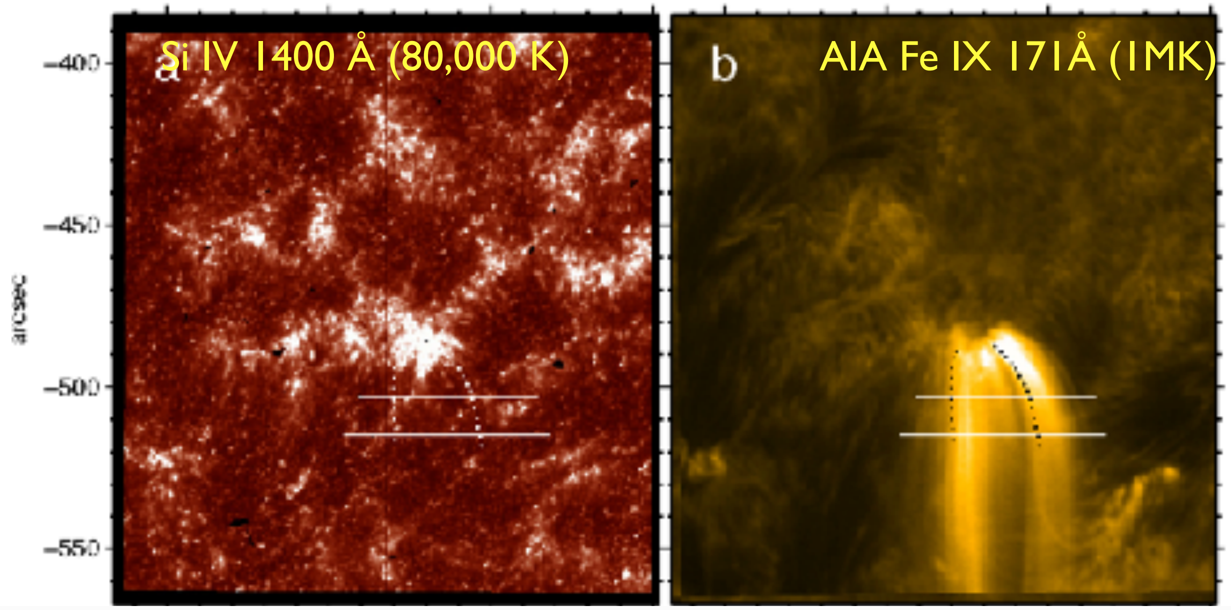
Affects any estimates of kinetic energy or mass flux in spicules

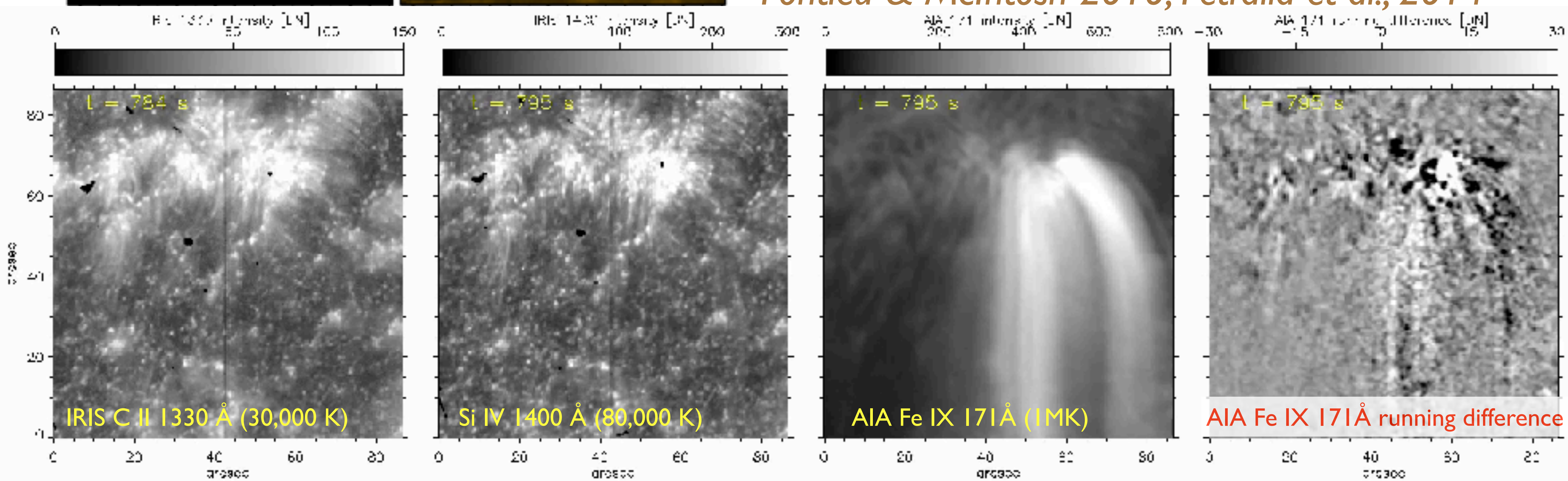
Is there any coronal heating associated with these spicules?

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

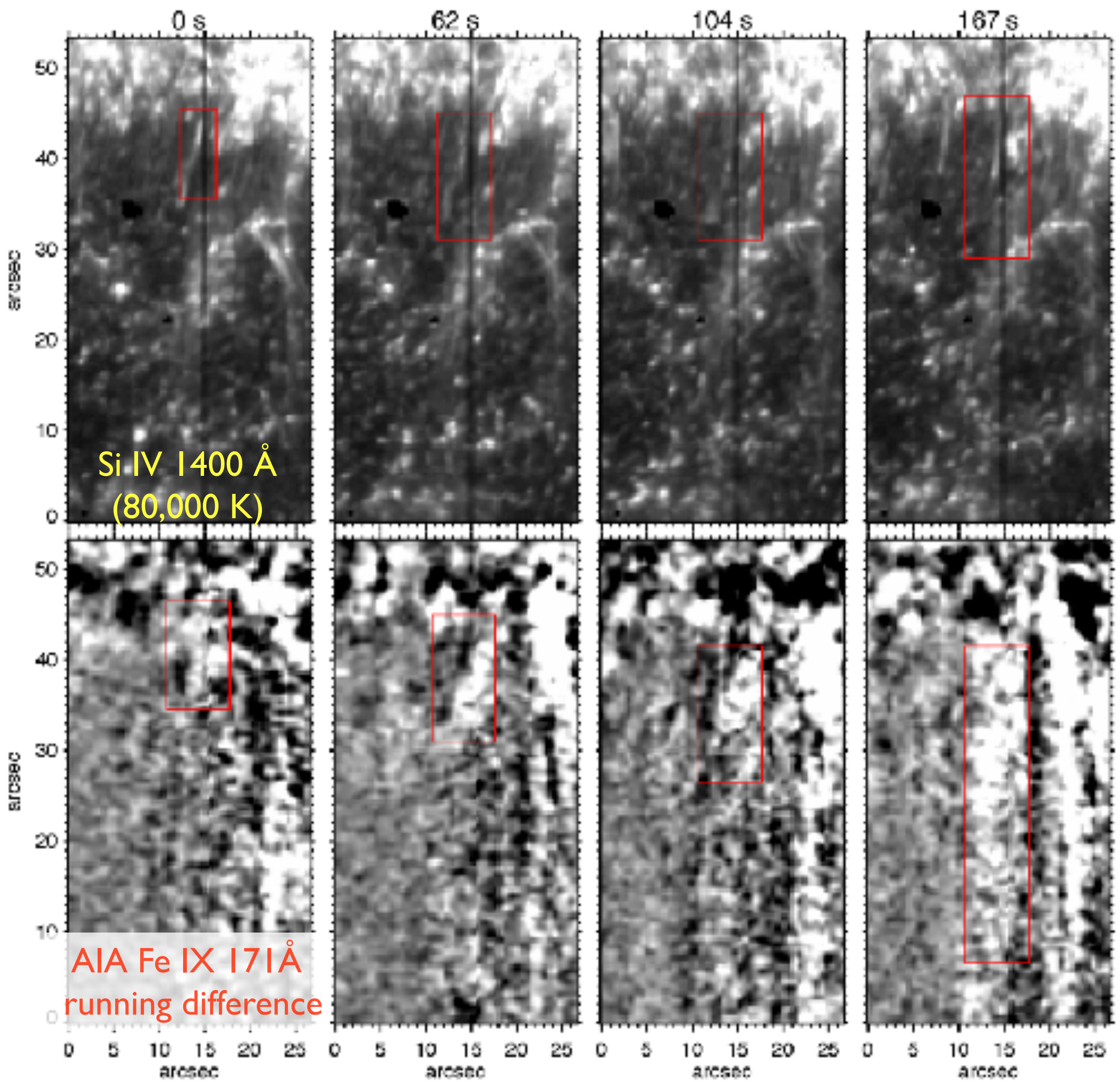
Coronal loops carry multitude of propagating disturbances

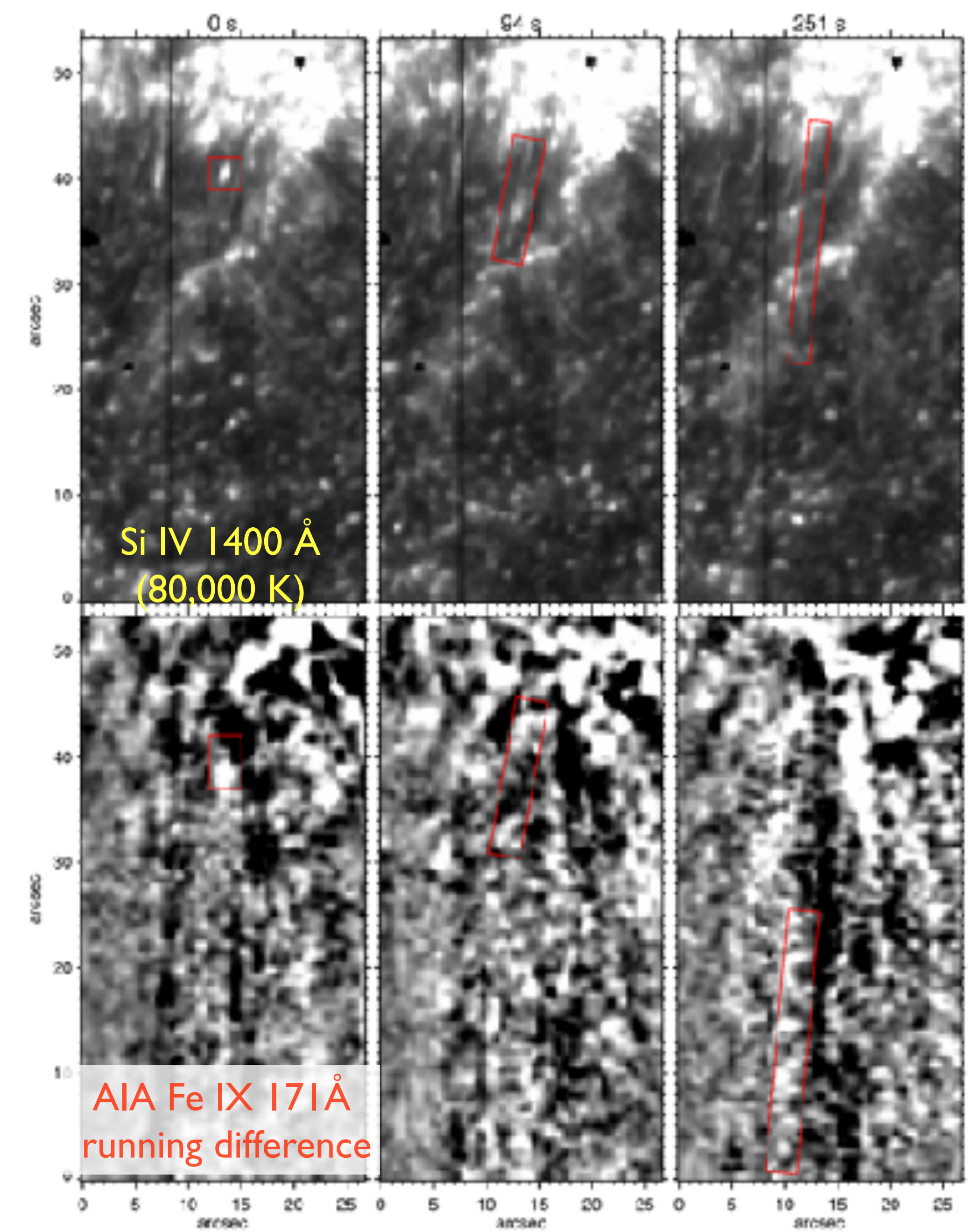
Are these two types of features connected?
Previously suggested by De Pontieu et al., 2005, De Pontieu & McIntosh 2010, Petralia et al., 2014





Spicules often lead to propagating coronal disturbances (PCDs)

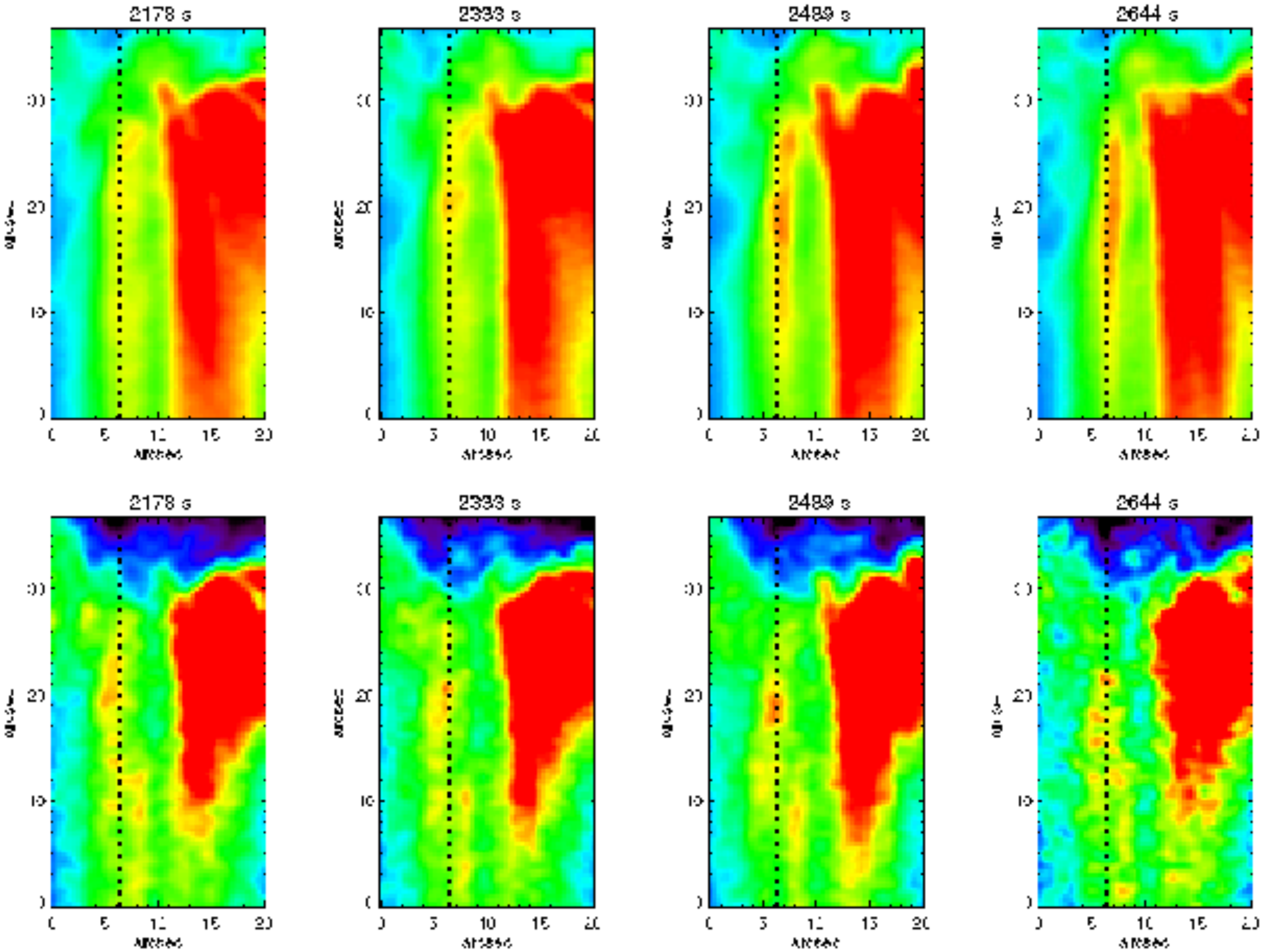




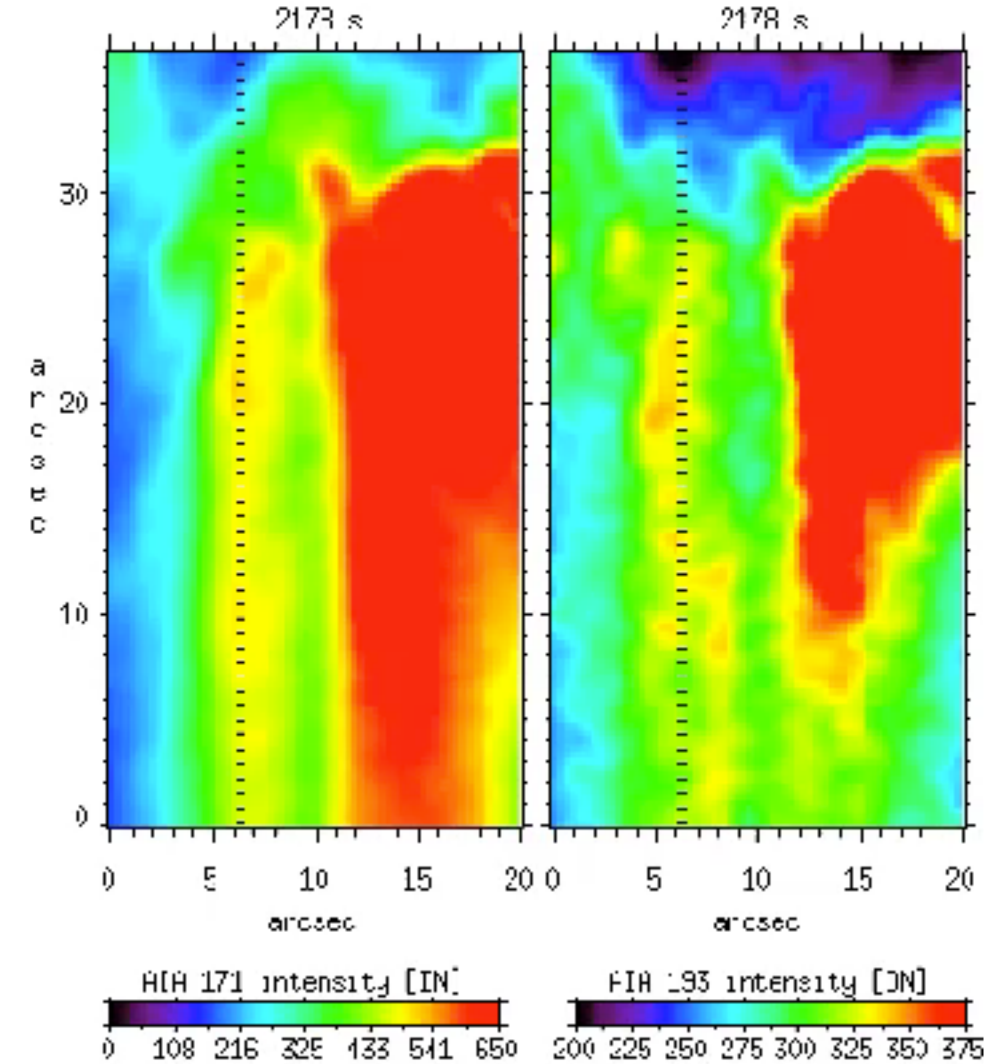
See also McIntosh et al., 2009 (indirect evidence of spicules), De Pontieu et al., 2011 (at the limb), Tanmoy et al., 2016 (at the limb)

Formation of coronal loop strands associated with PCDs/spicules

AIA 171Å



AIA 171Å AIA 193Å



AIA 193Å

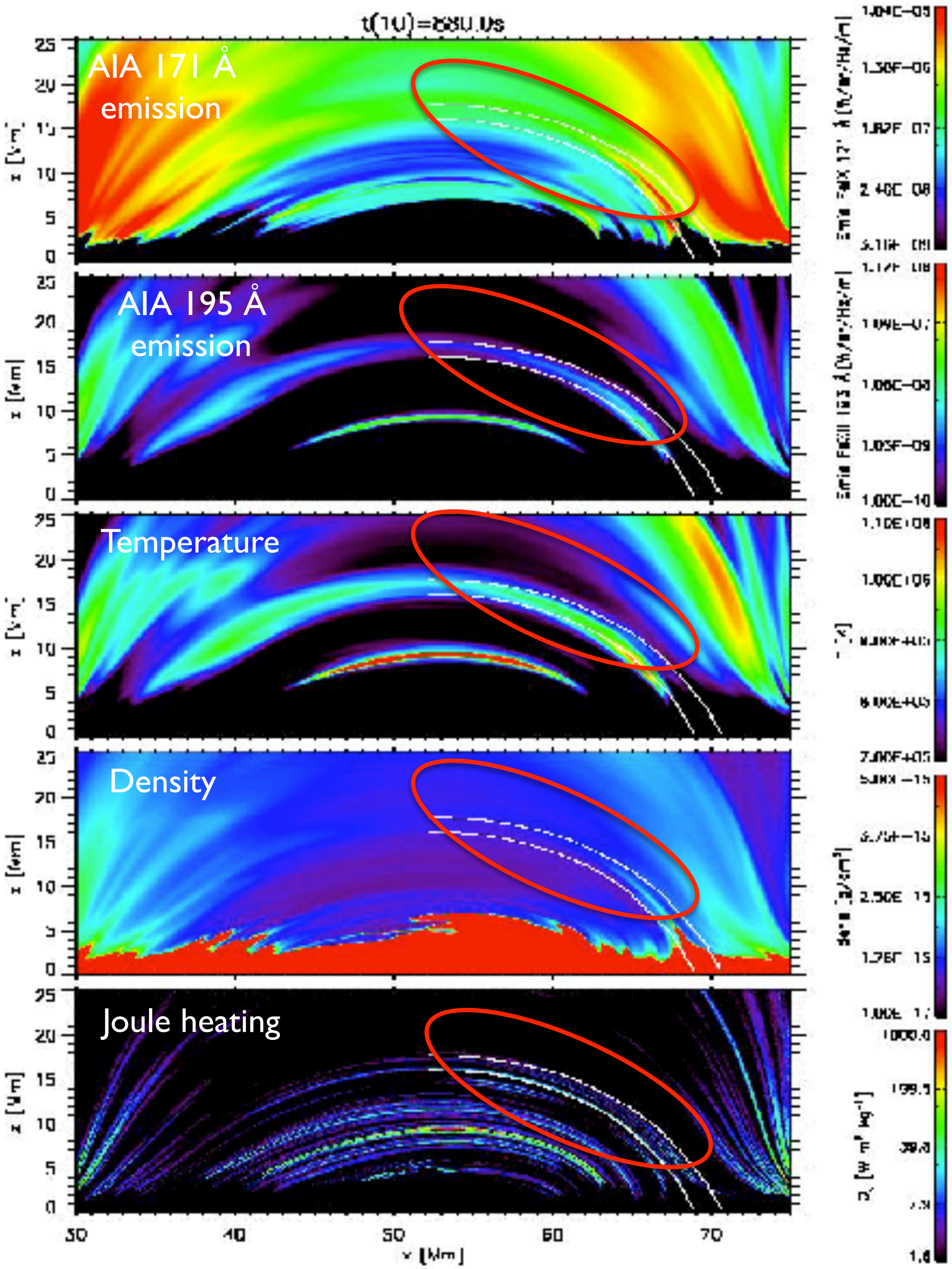
Loop strand formation appears to occur after initial PCD passes through

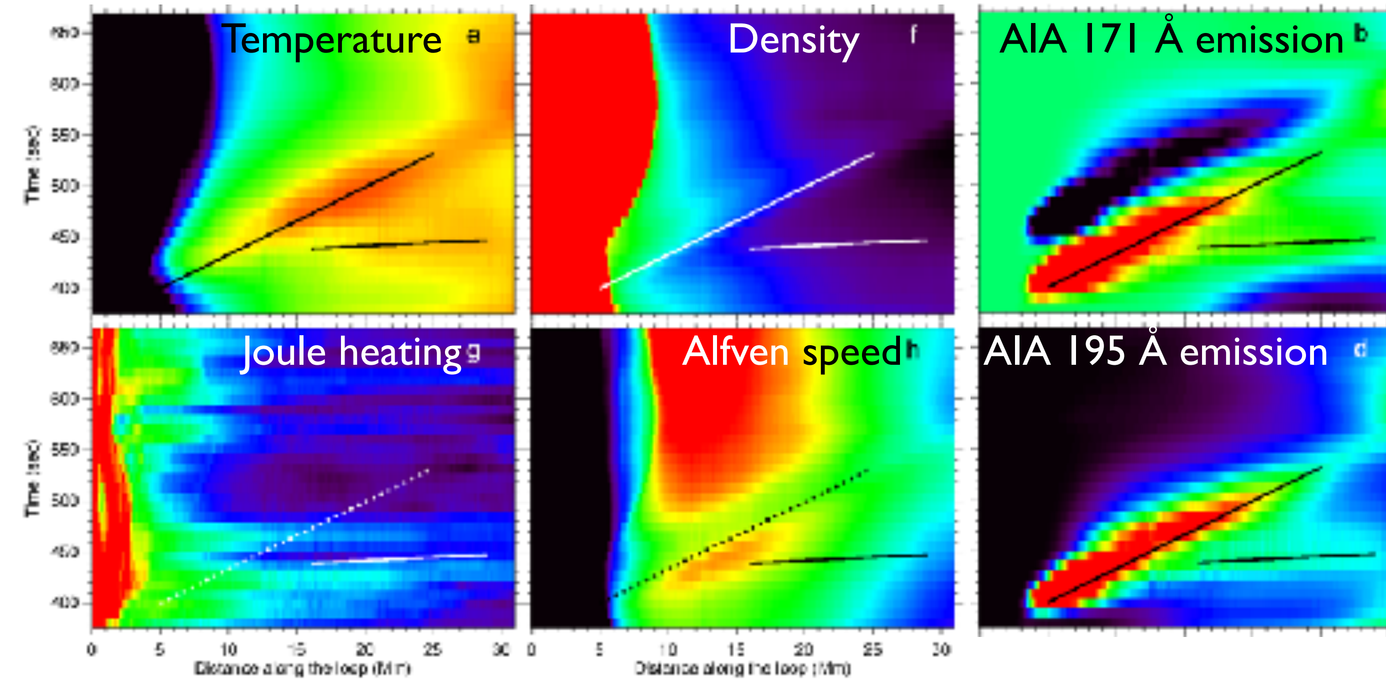
- Propagating disturbances leads to long-lived brightenings in both 195 and 171Å channels

- 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

Model predicts heating of coronal plasma and generation of propagating coronal disturbances





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

De Pontieu et al., 2017

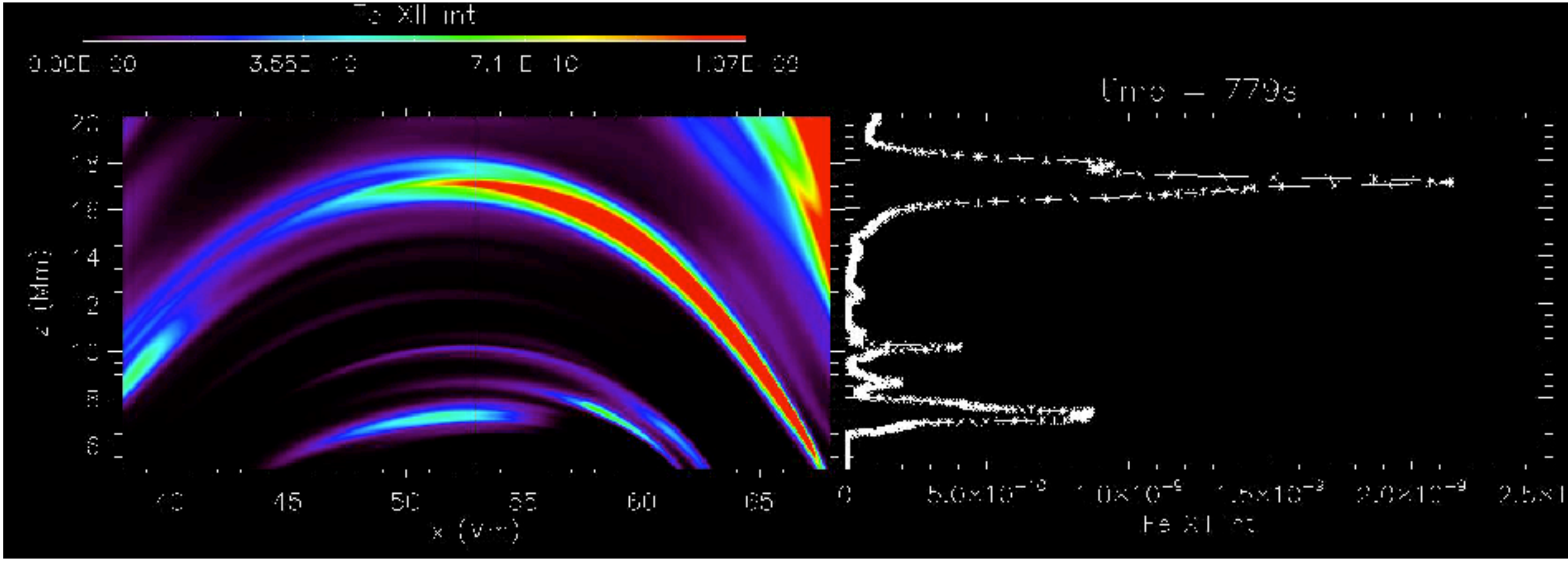
Conclusions

1. IRIS observations show chromospheric spicules heated to transition region temperatures, with coronal counterparts
2. 2.5D radiative MHD models including ambipolar diffusion lead to fast jets (100 km/s) that share many properties with spicules
3. Interaction between strong and weak, granular-scale fields combined with ambipolar diffusion drives spicules and triggers Alfven waves
4. Spicule formation process includes strong currents that help heat spicular plasma to transition region temperatures and leads to coronal counterparts and heating of coronal plasma

Outstanding issues

1. How well does this work in 3D? With non-equilibrium H/He ionization?
2. What is the role of the variety of wave modes in dissipation/heating?
3. What is the role of spicules in coronal heating?

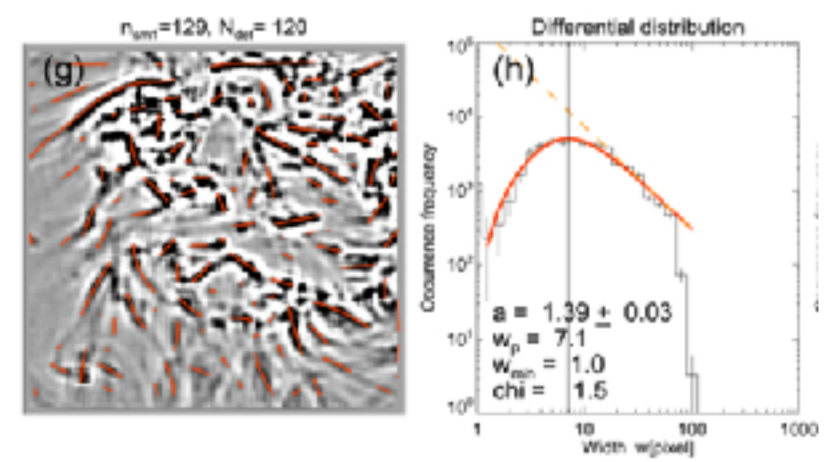
Heating associated with spicules creates coronal loops with widths of a few hundred km



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?

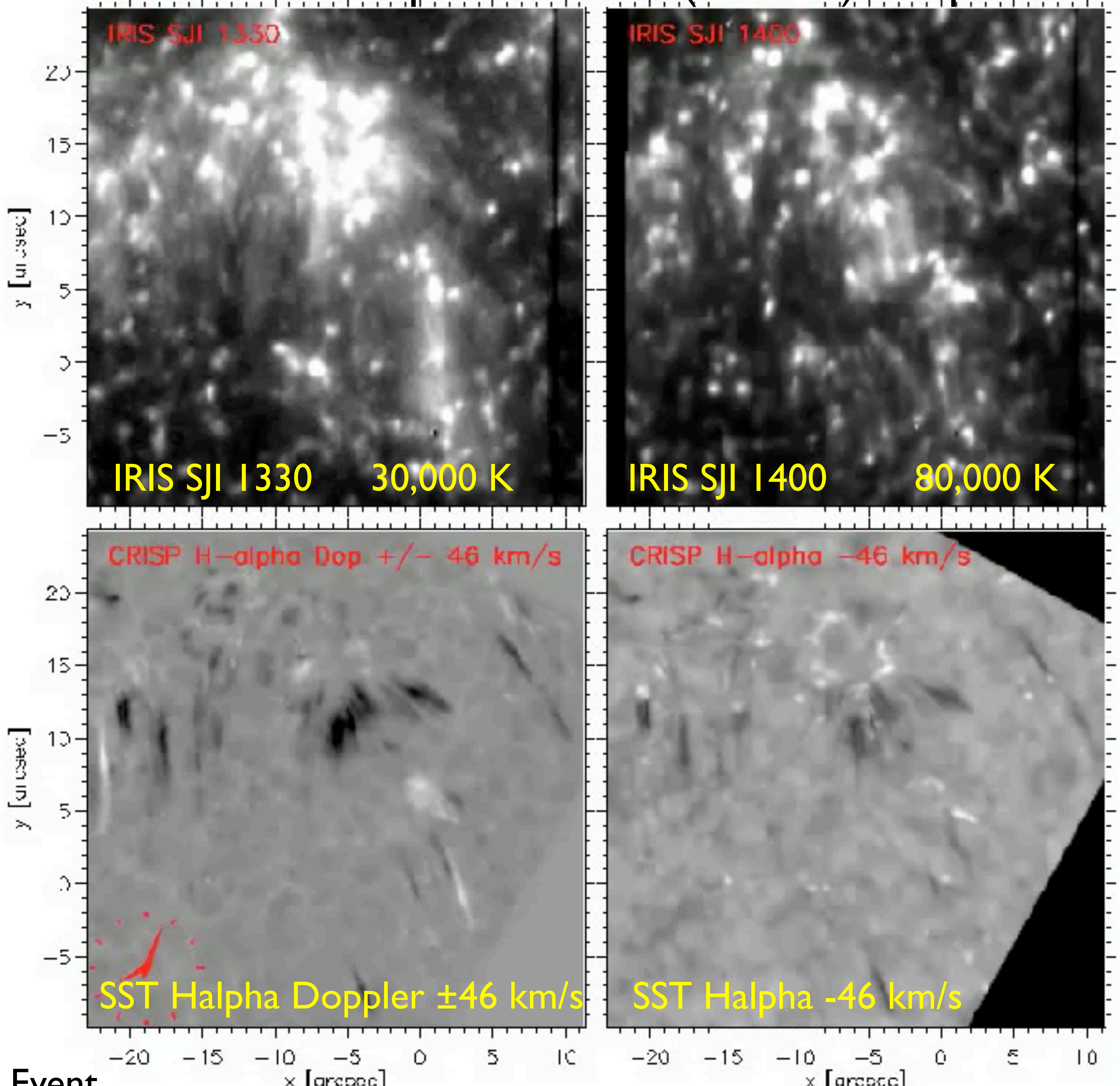
Hi-C loop widths peak at ~500 km?



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

What does IRIS tell us about heating of spicules?

Heating of plasma associated with spicules to TR (0.1 MK) temperatures

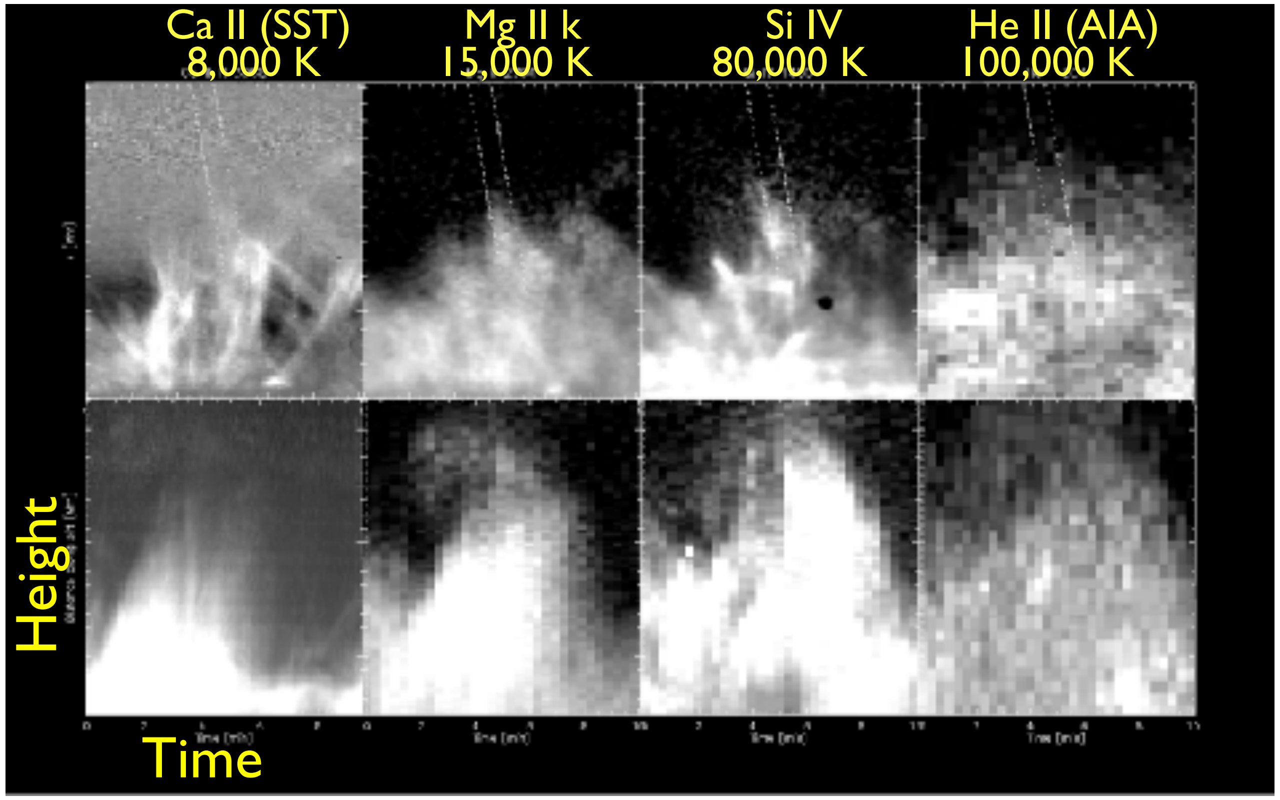


RRE: Rapid Redshifted Event

RBE: Rapid Blueshifted Event

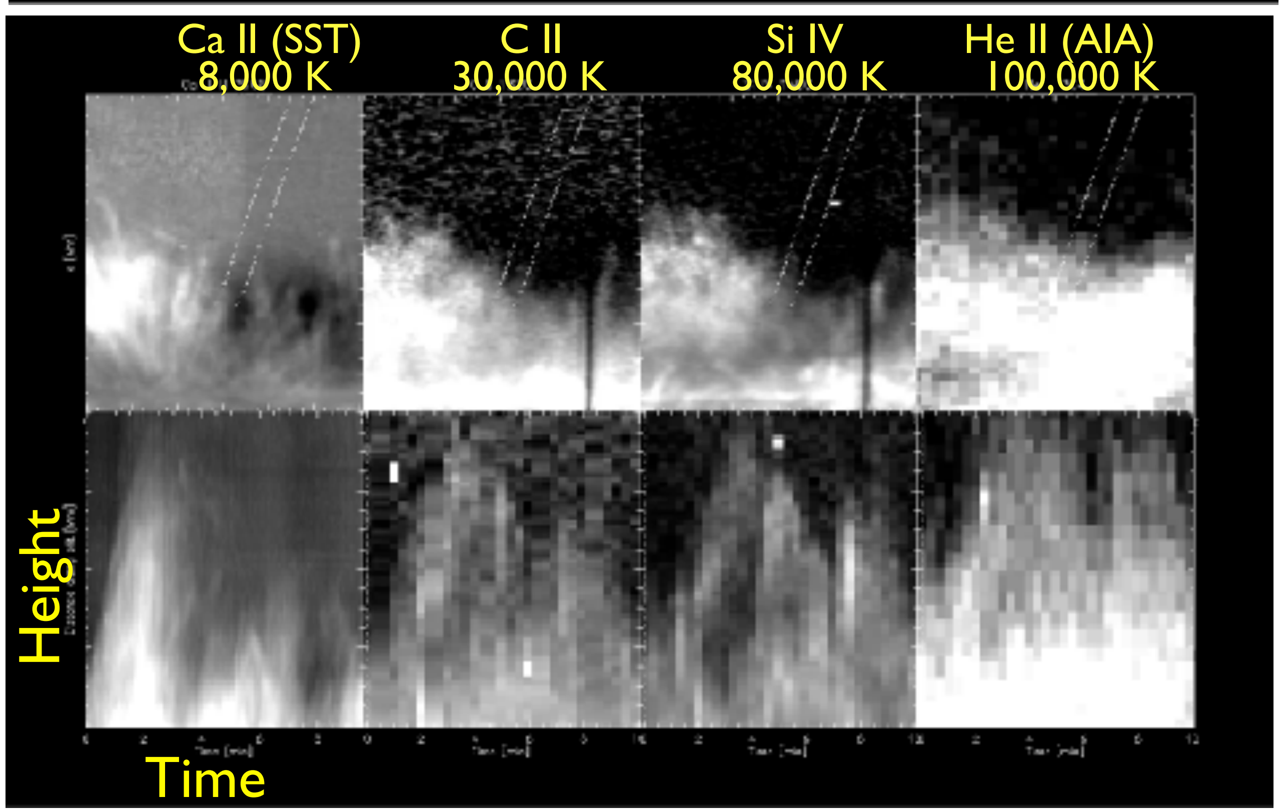
De Pontieu et al. 2014, Rouppe van der Voort et al. 2015

What does IRIS tell us about heating of spicules?



Spicules are multi-threaded with different threads at different temperatures

Heating timescales of order ~1 minute

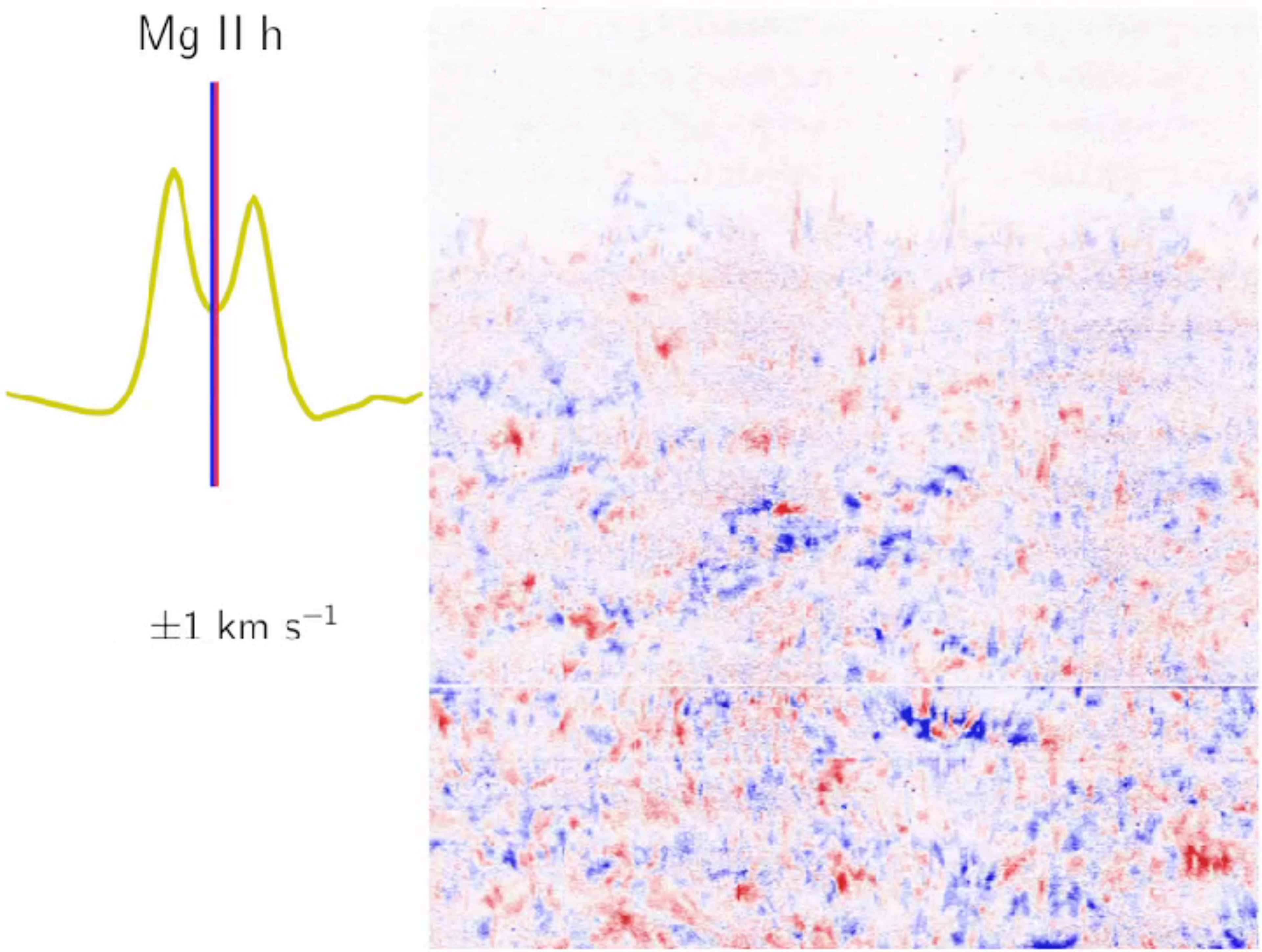


Ca II H spicules are the initial, rapid phase of violent upward motions…

Some threads appear to show rapid heating over the whole length to TR temperatures (Si IV, C II)

Skogsrud et al., 2015 (see also Pereira et al., 2014)

Spicules associated with strong Alfvenic waves

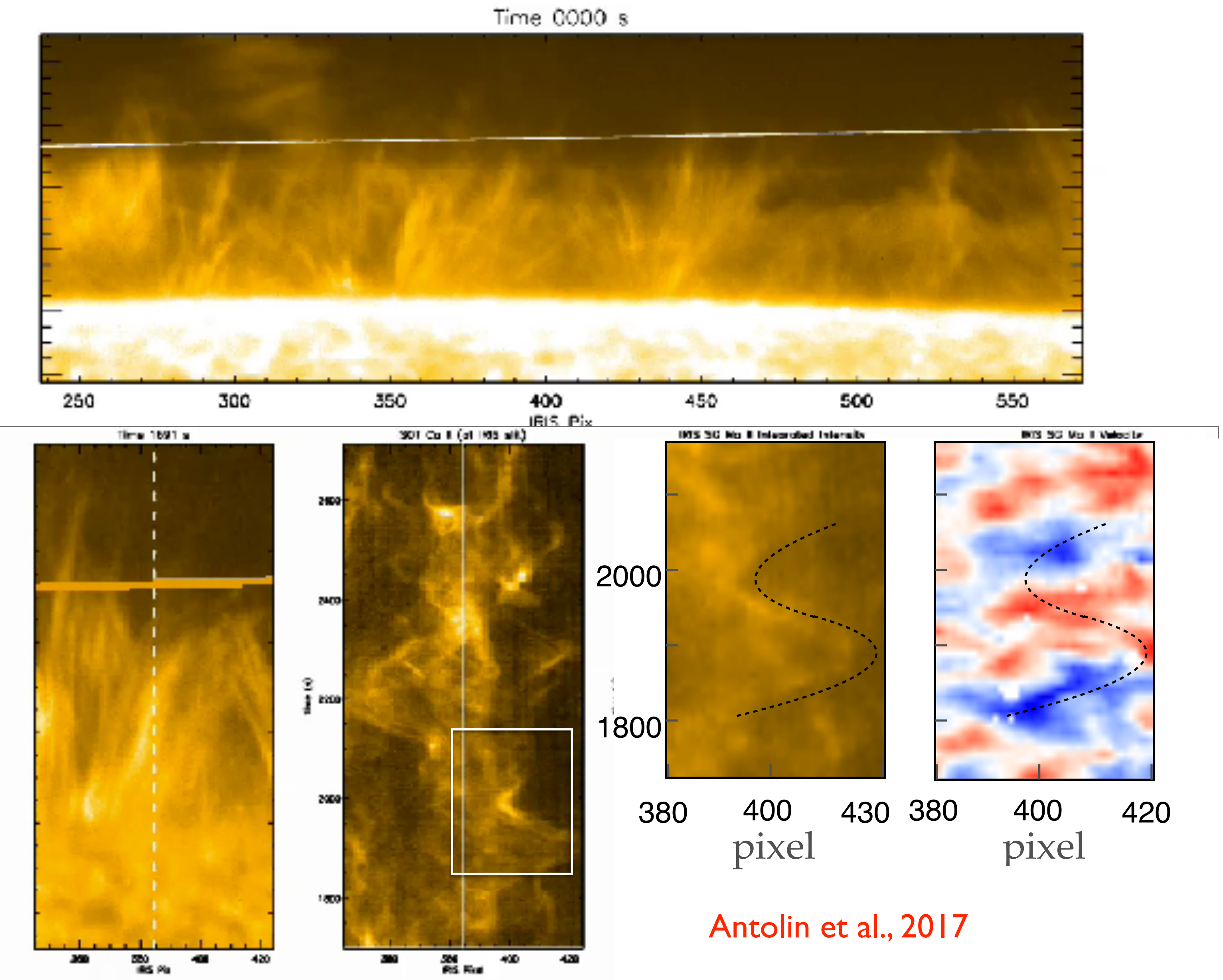


IRIS Mg II spectra show ubiquitous twisting motions in chromosphere with associated heating to transition region temperatures

De Pontieu et al., Science, 2014

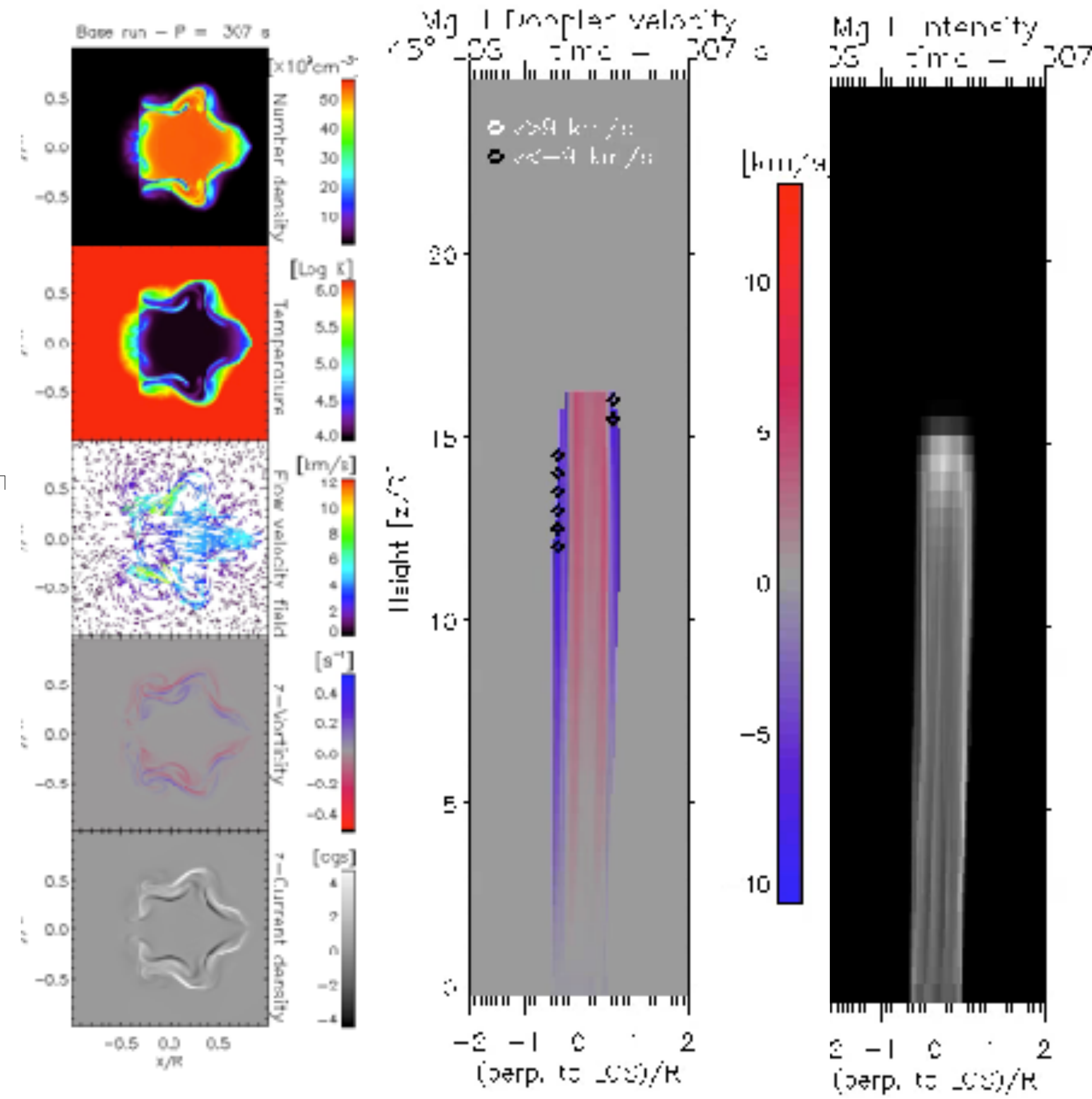
How would heating associated with spicules really occur on the Sun?

Observations show evidence for a variety of wave modes



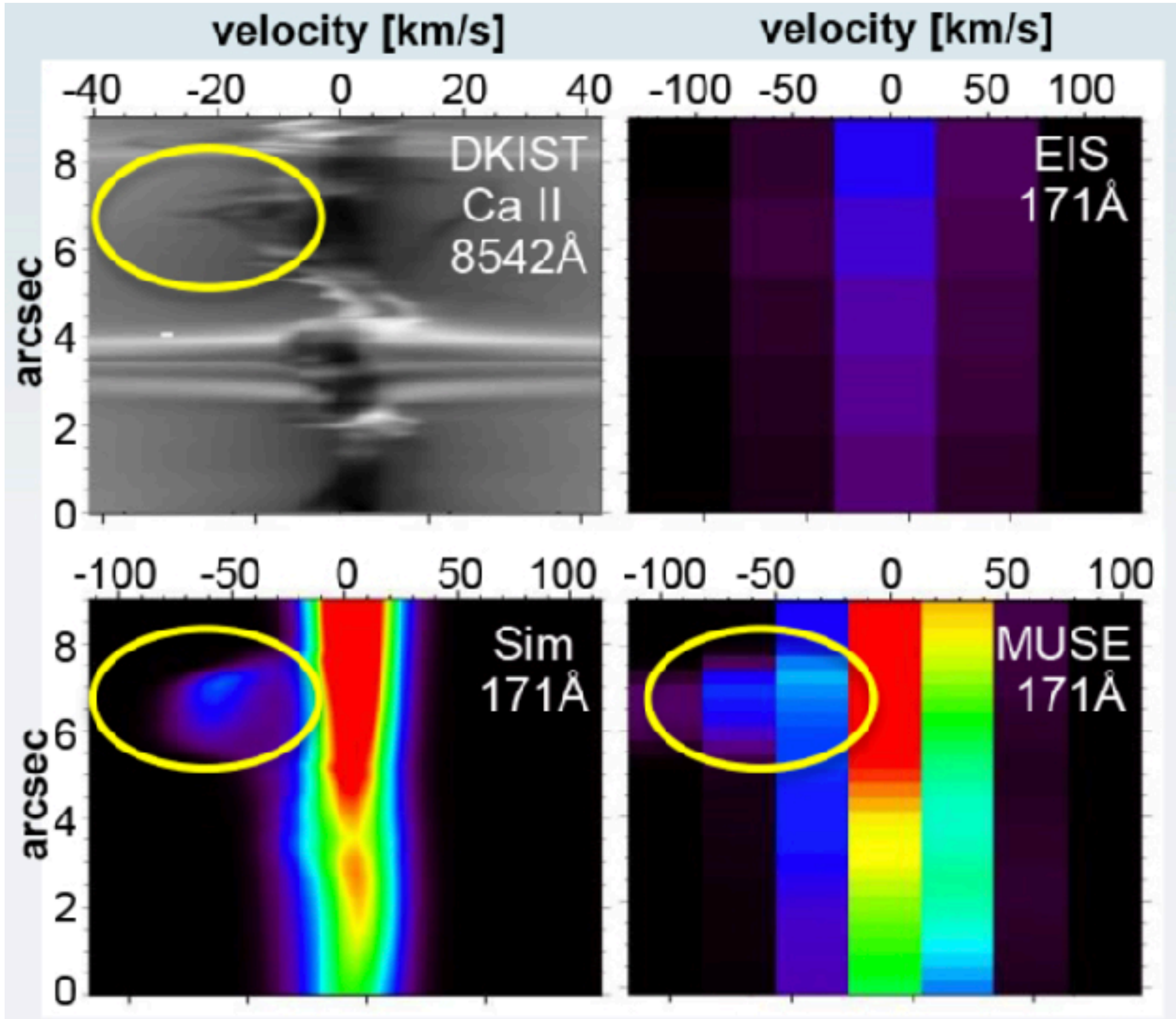
Antolin et al., 2017

Including resonant absorption and Kelvin Helmholtz instability



Evidence for resonant absorption first reported in prominences (Okamoto et al., 2015, Antolin et al., 2015)

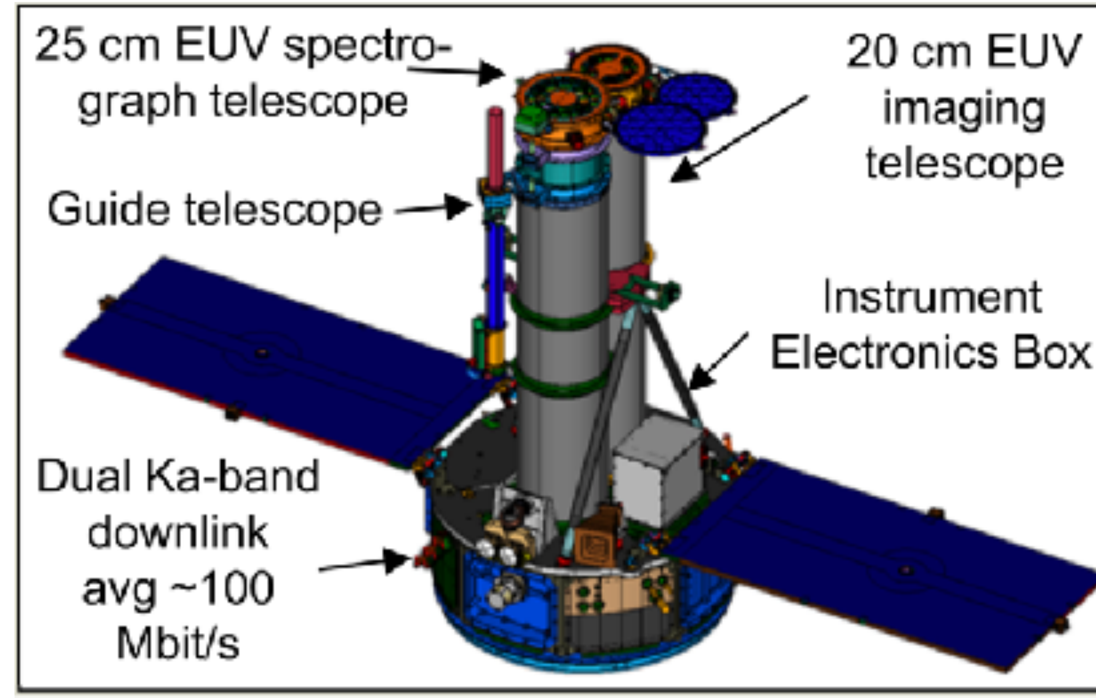
How can we measure impact of spicules on coronal heating?



MUSE will be the first spectrograph with the spatial resolution (0.4 arcsec) and temporal cadence (1-12s) to track the coronal response to chromospheric jets

MUlti-slit Solar Explorer (MUSE)

Principal Investigator: Ted Tarbell

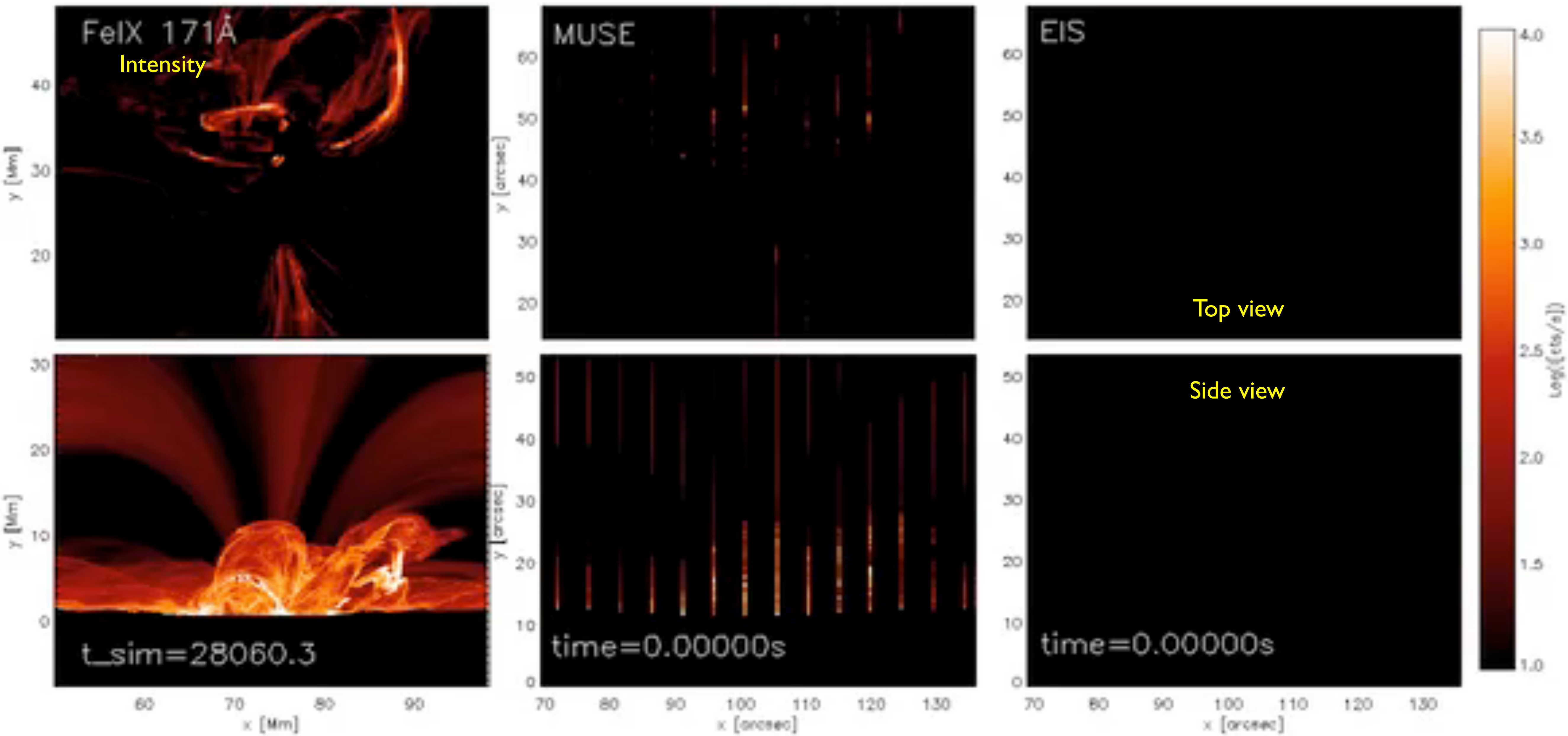


MUSE is like "IRIS for the corona" with better spatial resolution than AIA (16 MUSE pixels for each AIA pixel) and 100x faster than previous spectrographs

- Small Explorer based on heritage from IRIS, SDO, Hinode
- LMSAL Proposal submitted in October 2016
- Selected by NASA for phase A study with concept study report due July 2018
- Competing with 4 other missions for 1 or 2 launch spots (decision in spring 2019)
- Launch scheduled for late 2022

MUSE provides a breakthrough in spectroscopy of the solar corona

MHD Simulation of M-class Flare (courtesy Rempel & Cheung) | Multi-Slit Solar Explorer MUSE | Hinode/EIS (previous generation, single slit)



MUSE will be the first spectroscopic instrument capable of capturing the rapid evolution of dynamic events such as flares, something existing or planned spectrometers cannot do