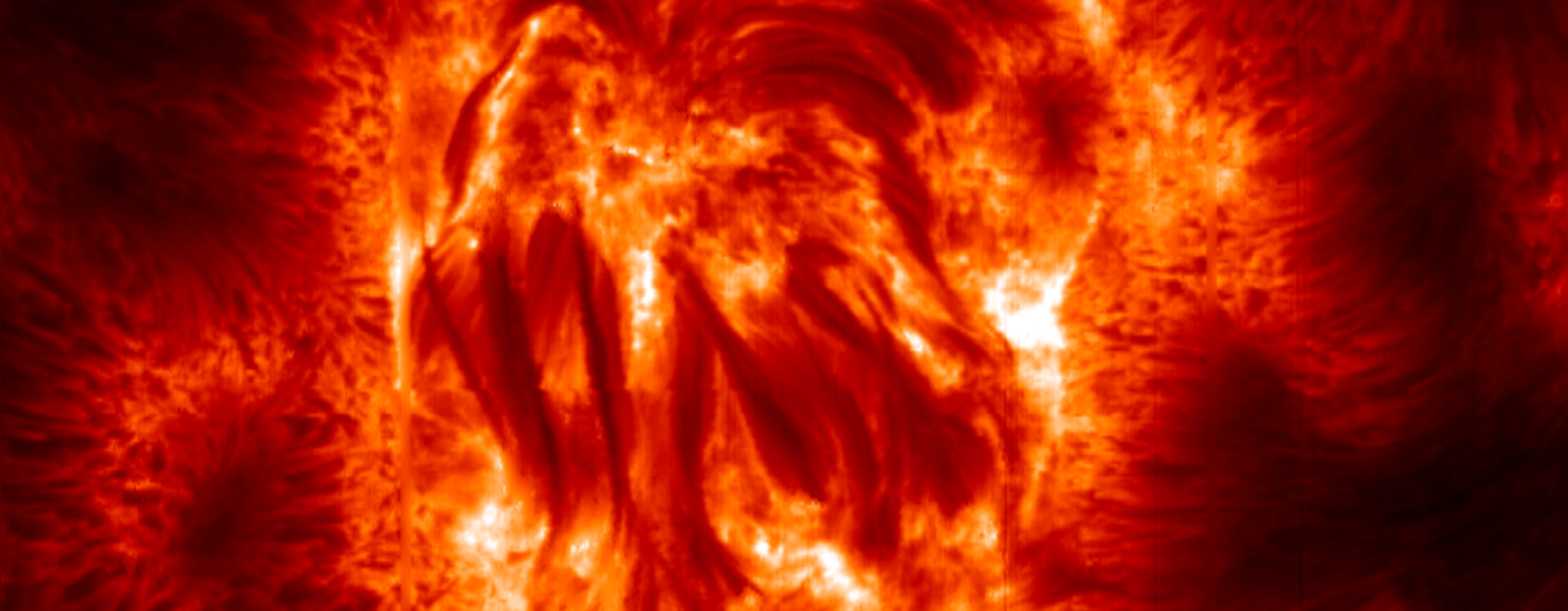
Observations and Modeling of the Chromosphere and its Connections to the outer Solar Atmosphere

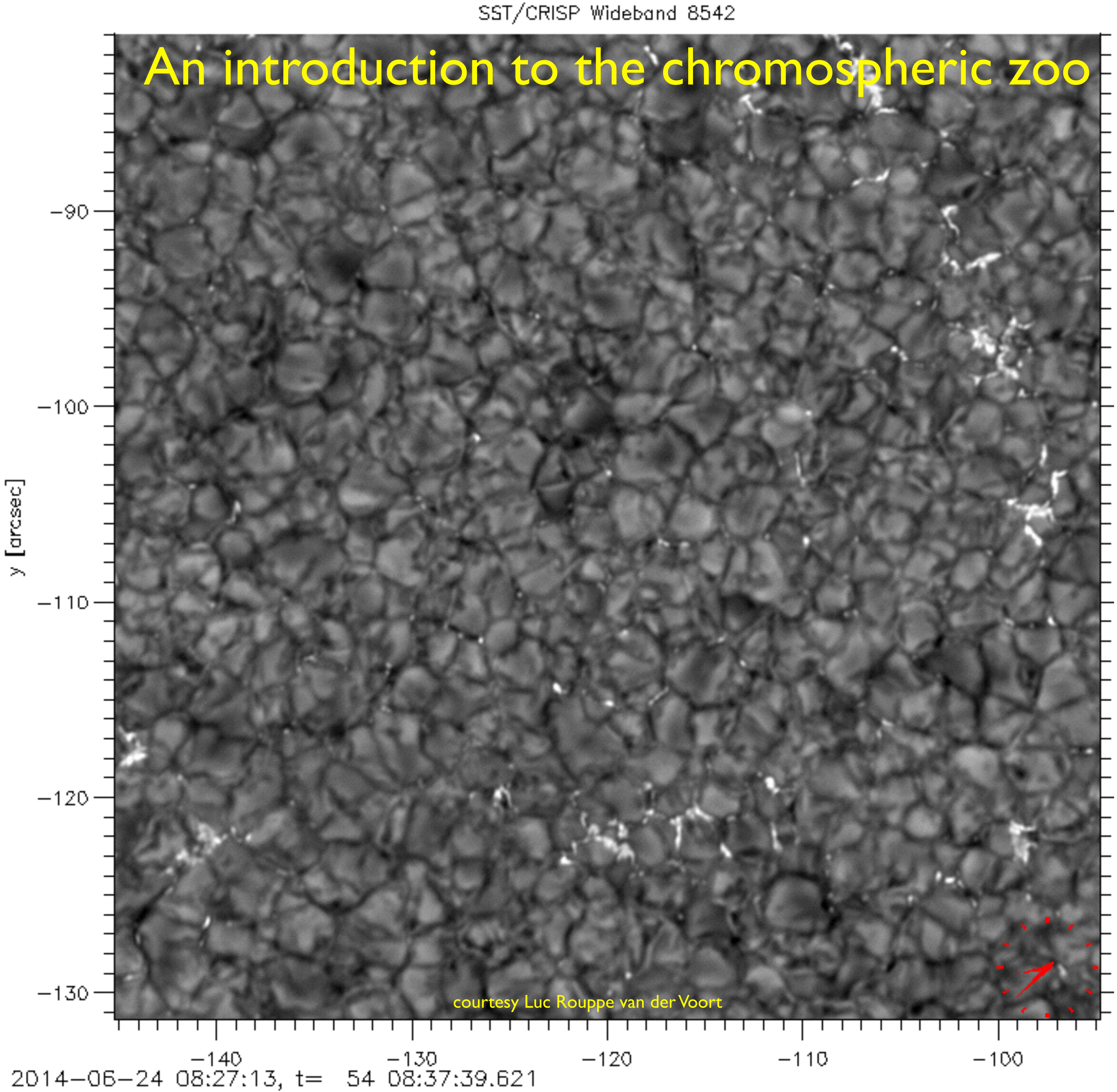


Bart De Pontieu
Lockheed Martin Solar & Astrophysics Laboratory

Thanks to Viggo Hansteen, Juan Martinez-Sykora, Mats Carlsson, Jorrit Leenaarts Paola Testa, Joten Okamoto, Patrick Antolin, Luc Rouppe van der Voort, Haakon Skogsrud, Tiago Pereira

Outline of the Talk

1. Brief introduction to chromospheric dynamics and morphology
2. Chromospheric Heating
    - Plage heating
    - Heating from braiding
    - Heating from ion-neutral interactions
    - Heating from wave dissipation
3. Connections to outer atmosphere
    - Impact of chromosphere on transition region
        - shocks
        - jets and spicules
    - Correlation between chromospheric and coronal heating


SST/CRISP Wideband 8542
An introduction to the chromospheric zoo
y [arcsec]
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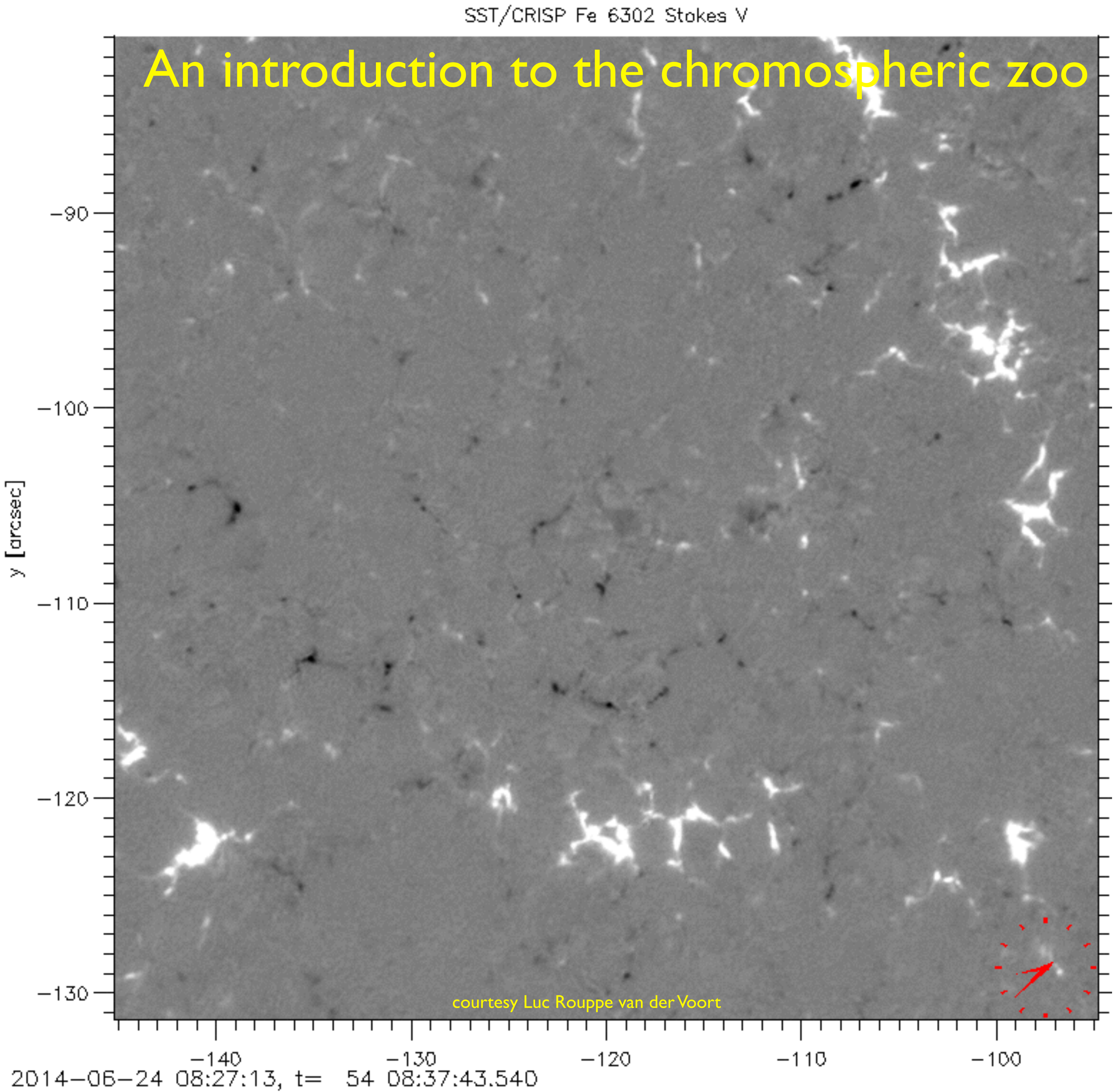
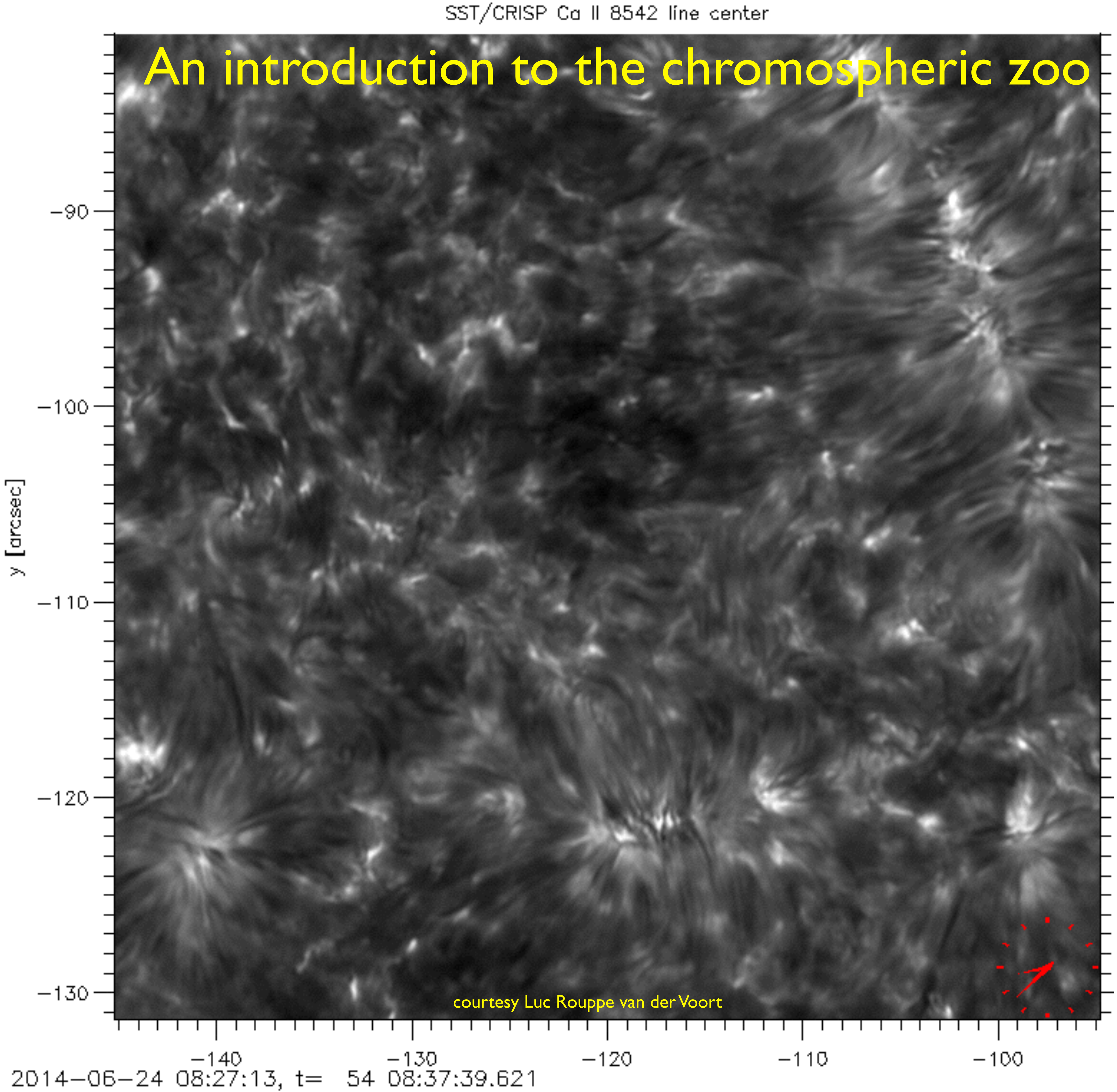
courtesy Luc Rouppe van der Voort
2014−06−24 08:27:13, t= 54 08:37:39.621

An introduction to the chromospheric zoo




SST/CRISP Ca II 8542 line center
An introduction to the chromospheric zoo
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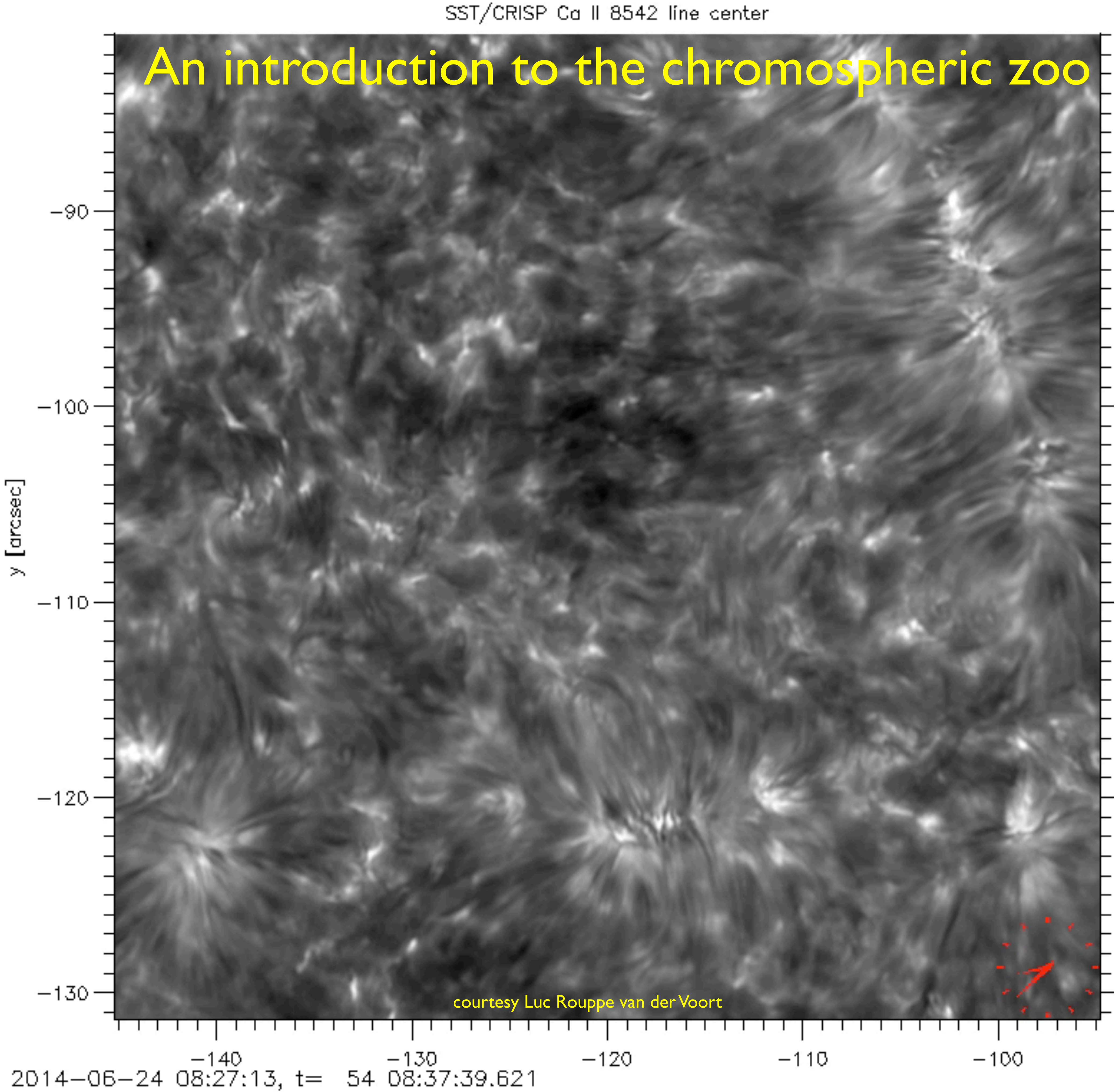
SST/CRISP Ca II 8542 line center
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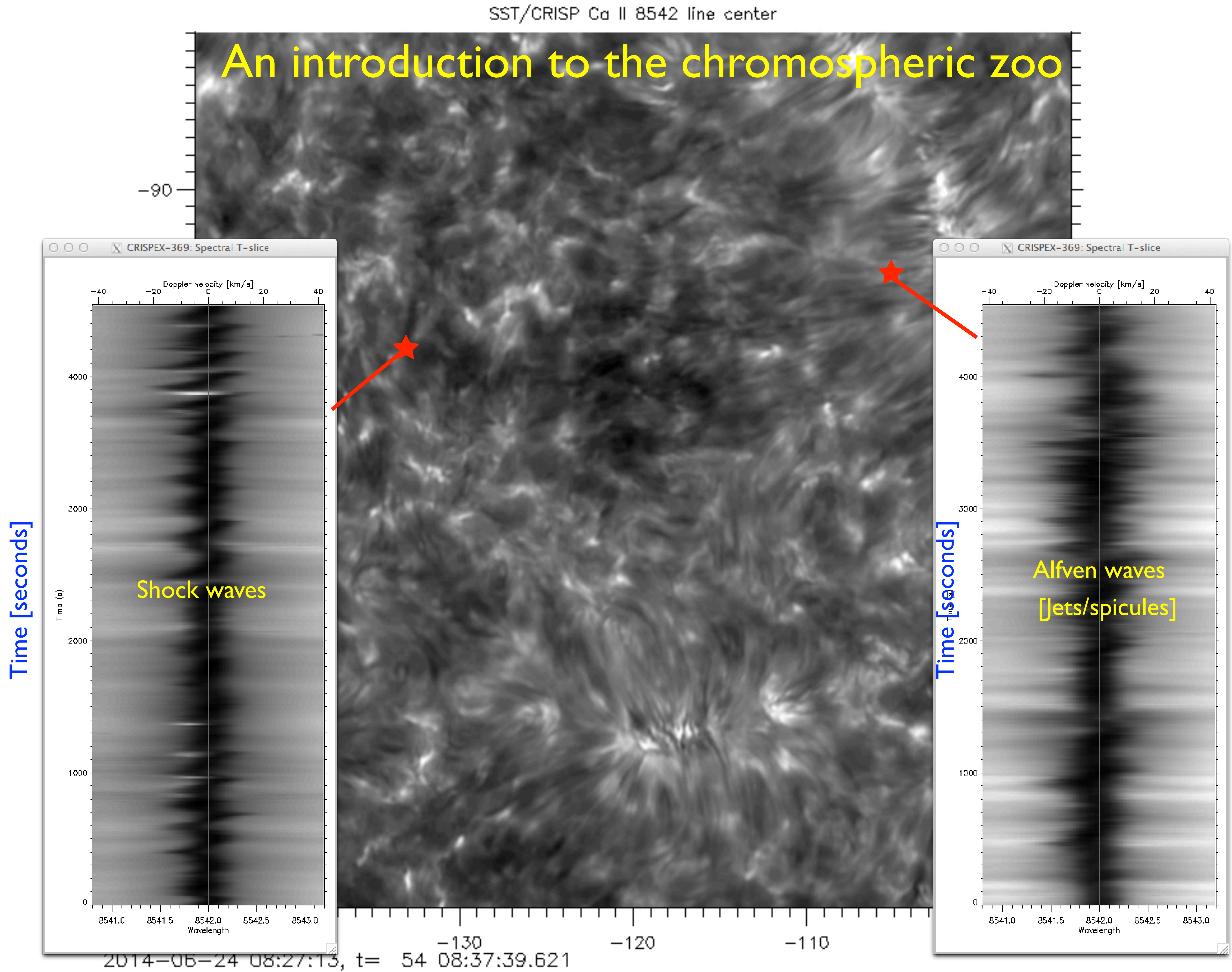
SST/CRISP Ca II 8542 line center
An introduction to the chromospheric zoo
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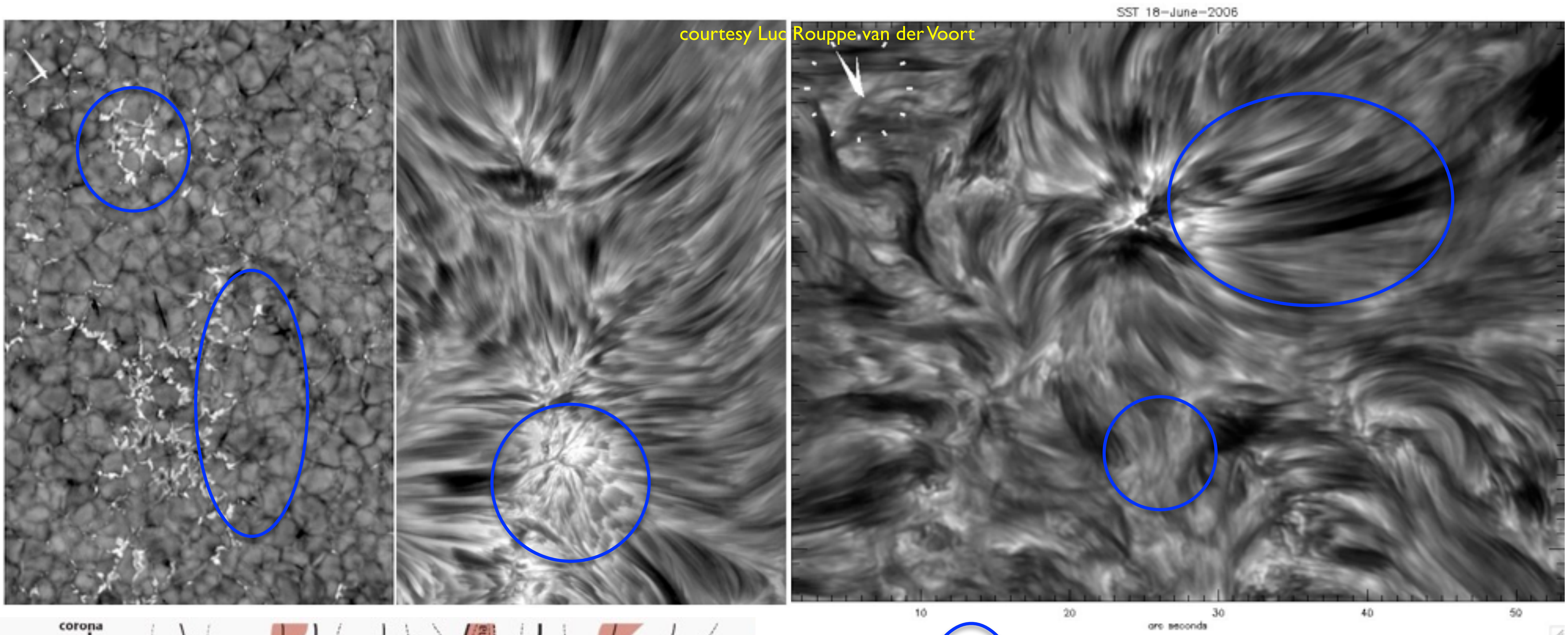
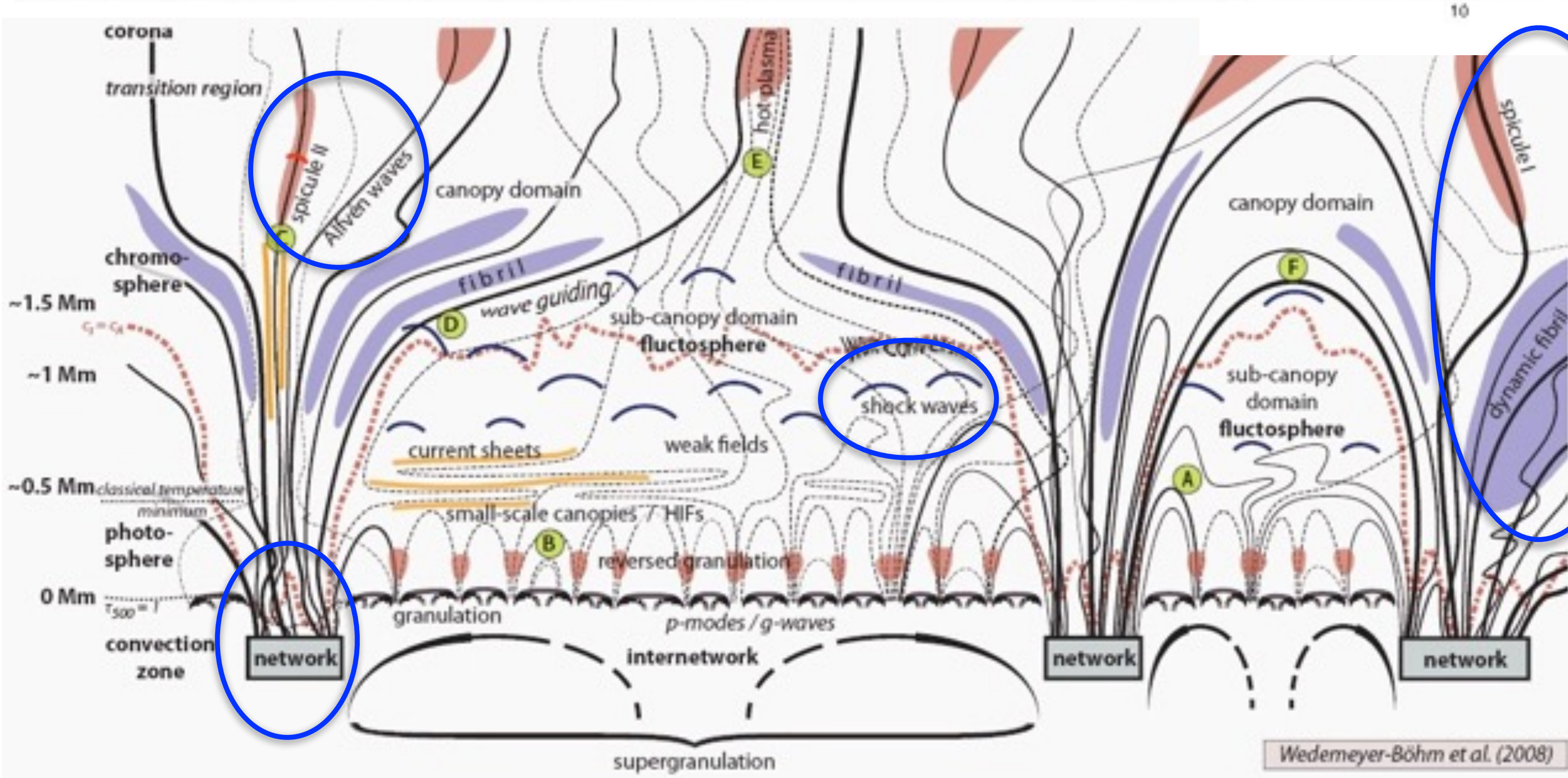
2014-06-24 08:27:13, t= 54 08:37:39.621
CRISPEX-369: Spectral T-slice
Doppler velocity [km/s]
Time (s)
Wavelength
Time [seconds]
Shock waves
Alfven waves
[Jets/spicules]

An introduction to the chromospheric zoo





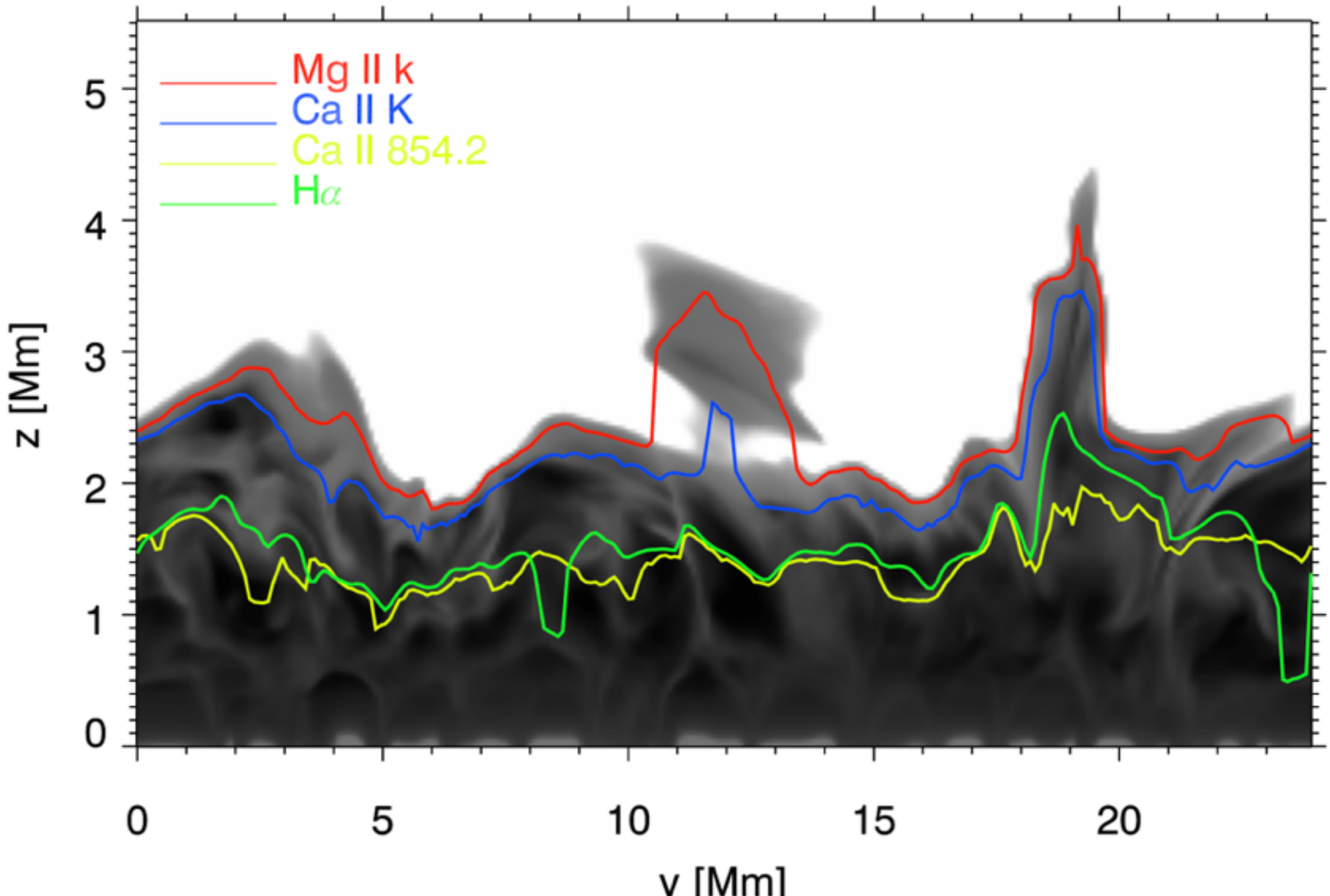
Magneto-acoustic shock waves
(dynamic fibrils, internetwork shocks)

Alfven waves
(RRE, RBE, type 2 spicules)

Magnetic Field Concentrations
(bright points, network)

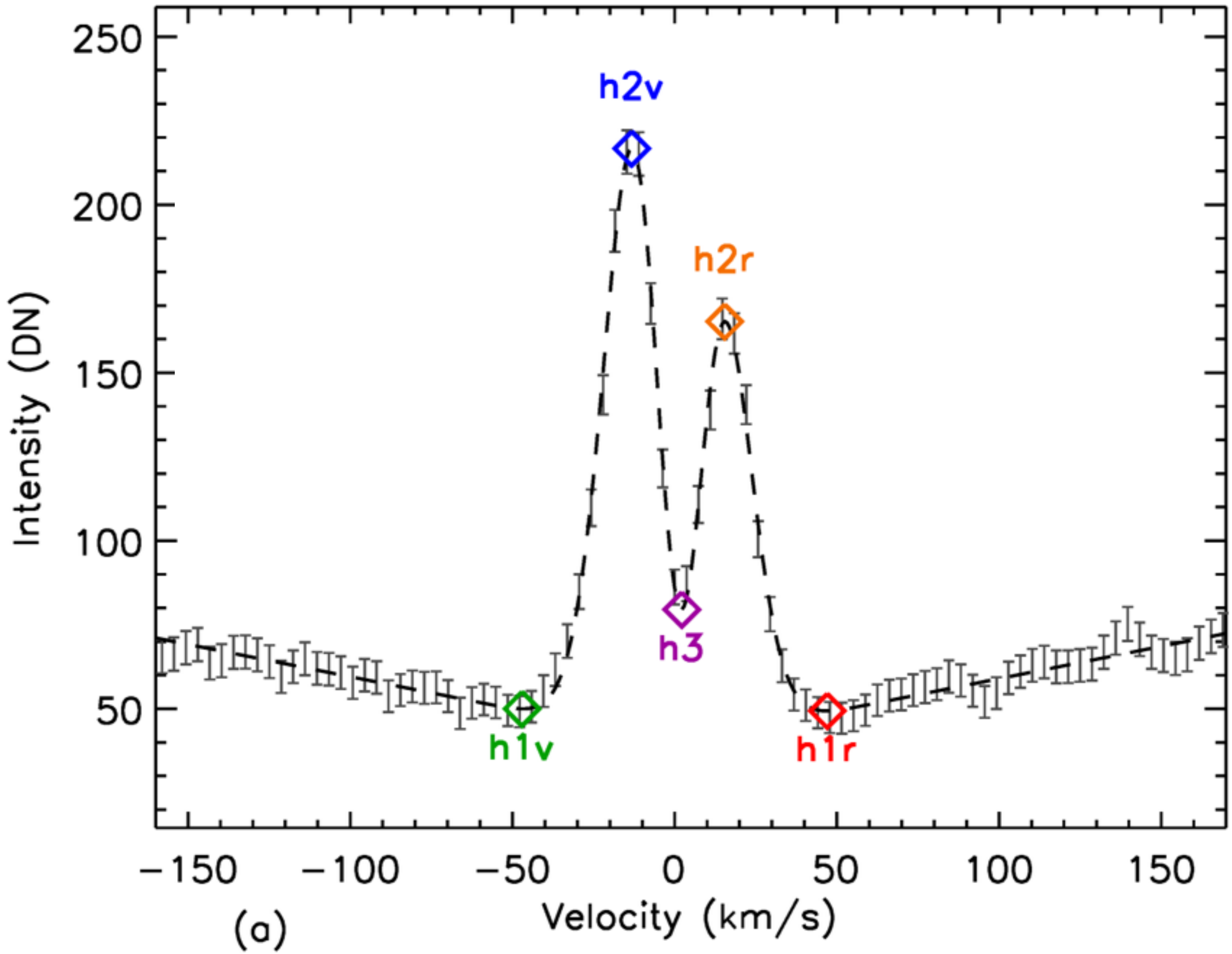
How does IRIS help diagnose chromospheric conditions?

Mg II h/k line diagnostics:
Mg II h/k unique windows into upper chromosphere,
not accessible with other lines



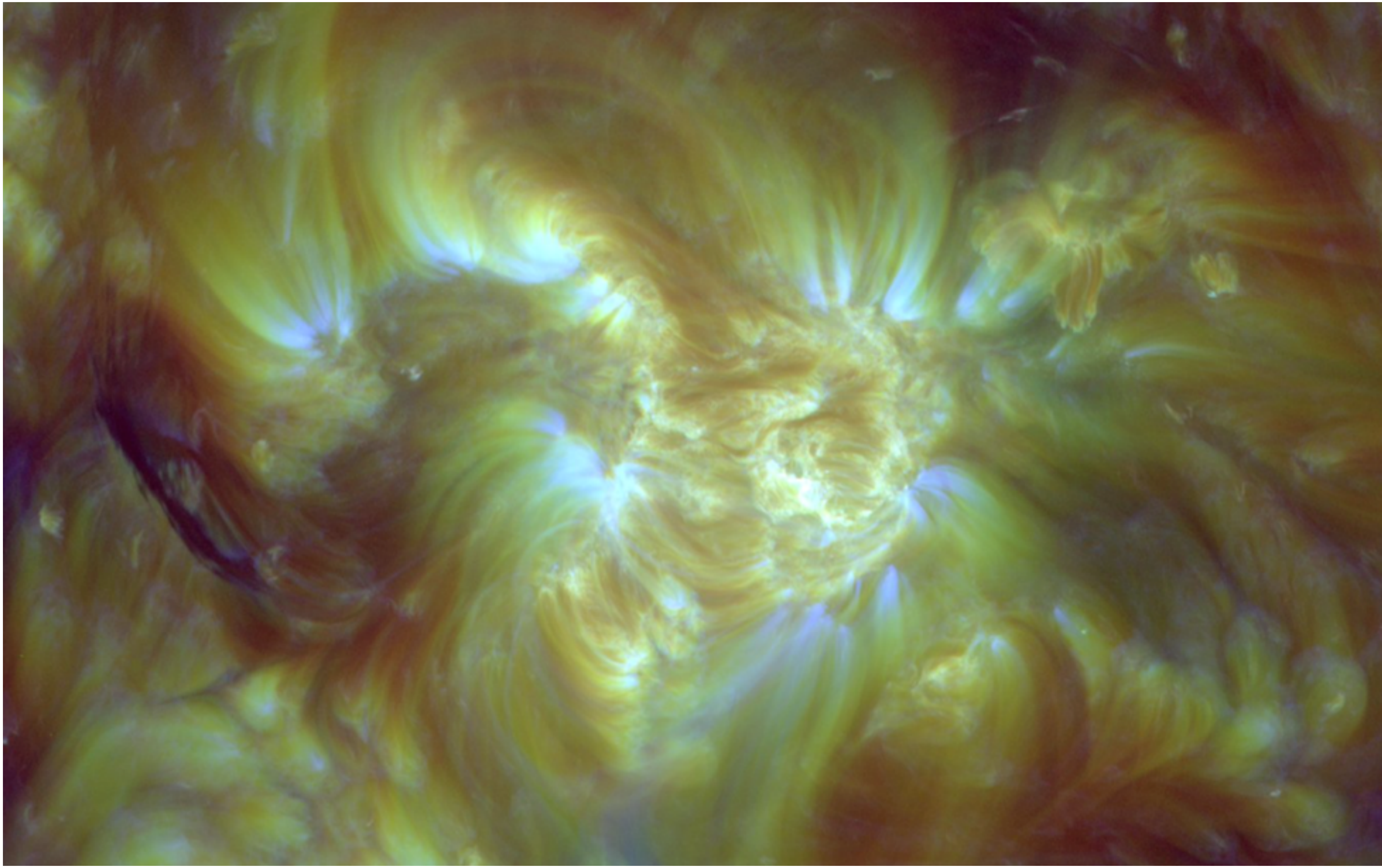
Leenaarts et al., 2013

How does IRIS help diagnose chromospheric conditions?



courtesy Don Schmit

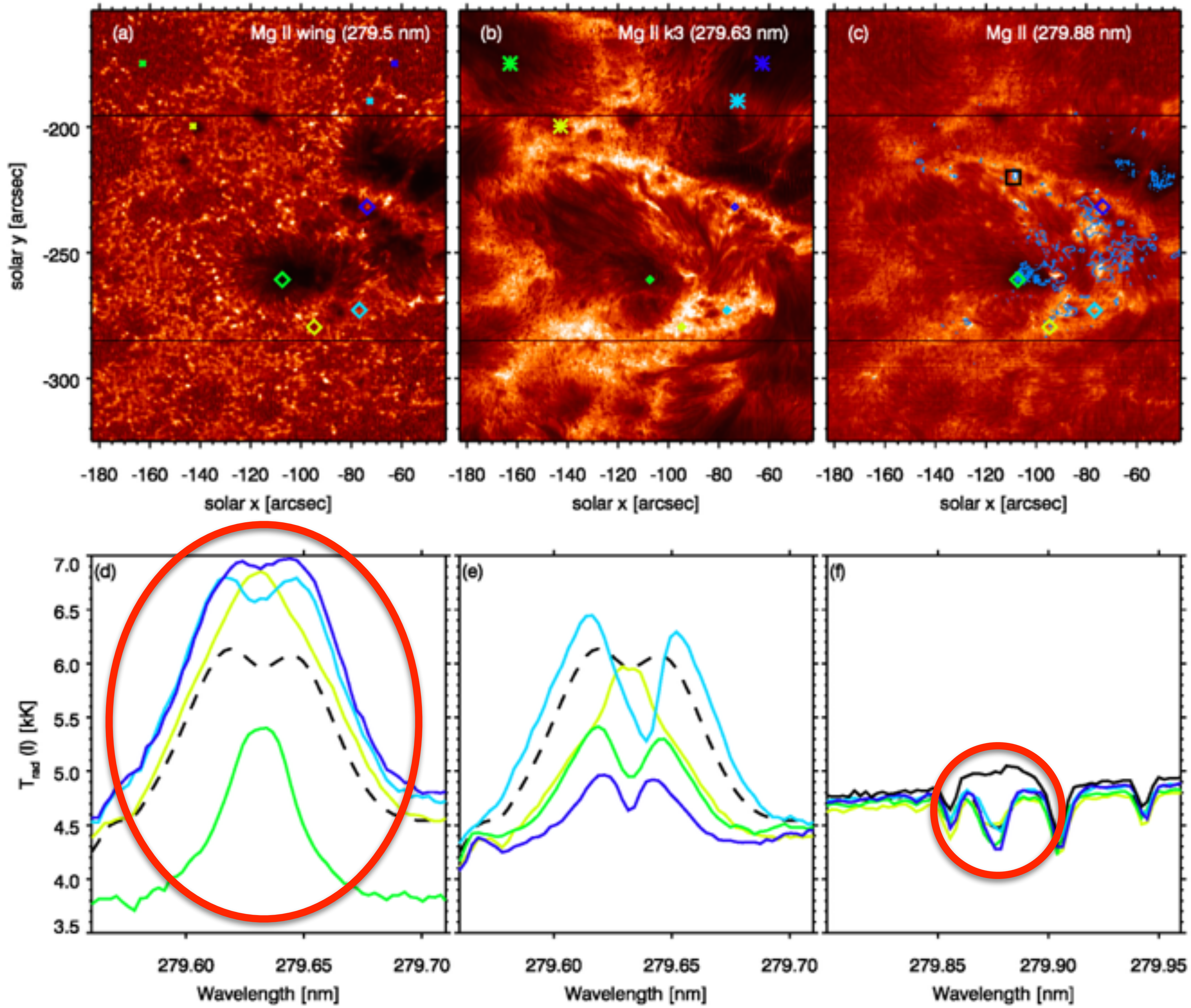
IRIS “scans” from photosphere to the top of the chromosphere



What are the chromospheric conditions at the footpoints of coronal loops?
Why is plage bright in chromospheric lines?

Moving on from “energy flux requirements”…

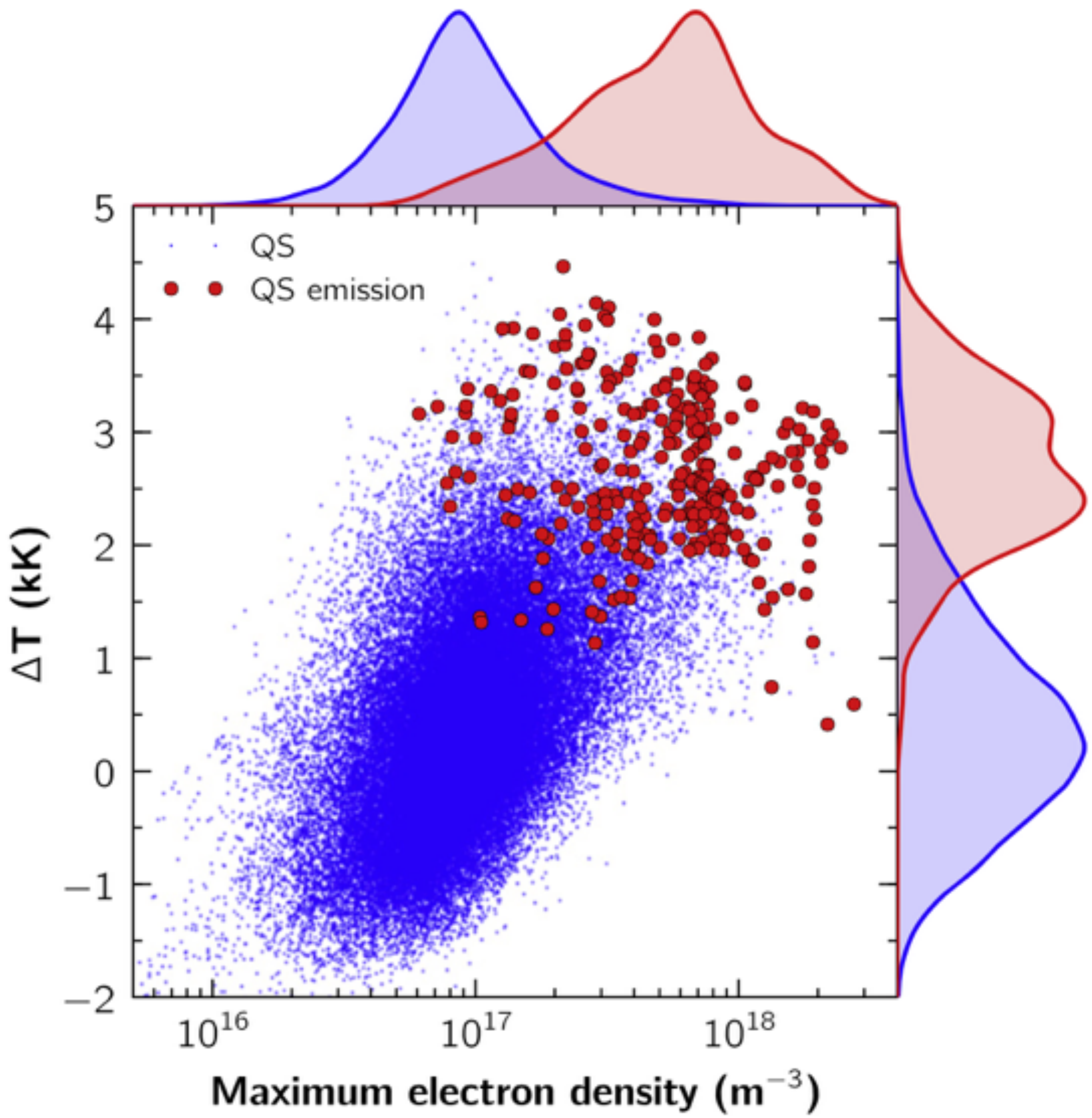
Chromospheric heating requirements based on static models (!) and other model assumptions (2,000-14,000 W/m^2 from Athay, 1976 to Anderson & Athay 1989)



Forward modeling and synthetic spectra of chromospheric lines provides more robust “requirement”

Peculiar (“filled in”) Mg II k profiles in plage regions, without emission in subordinate lines

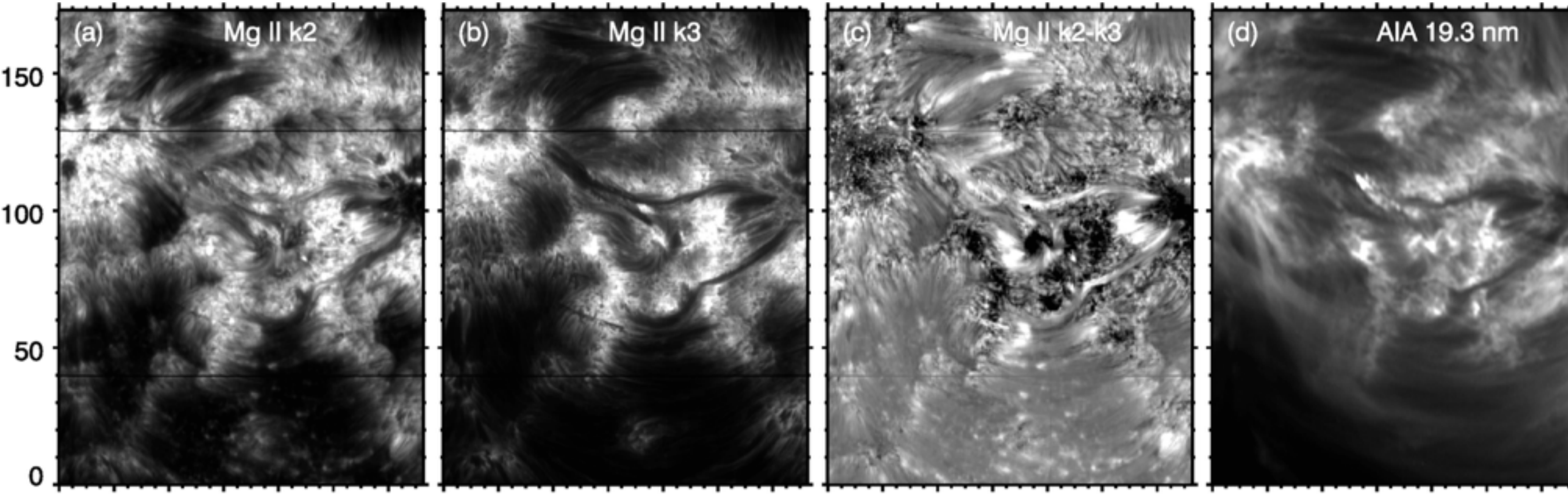
Exploiting all chromospheric diagnostics in IRIS passbands



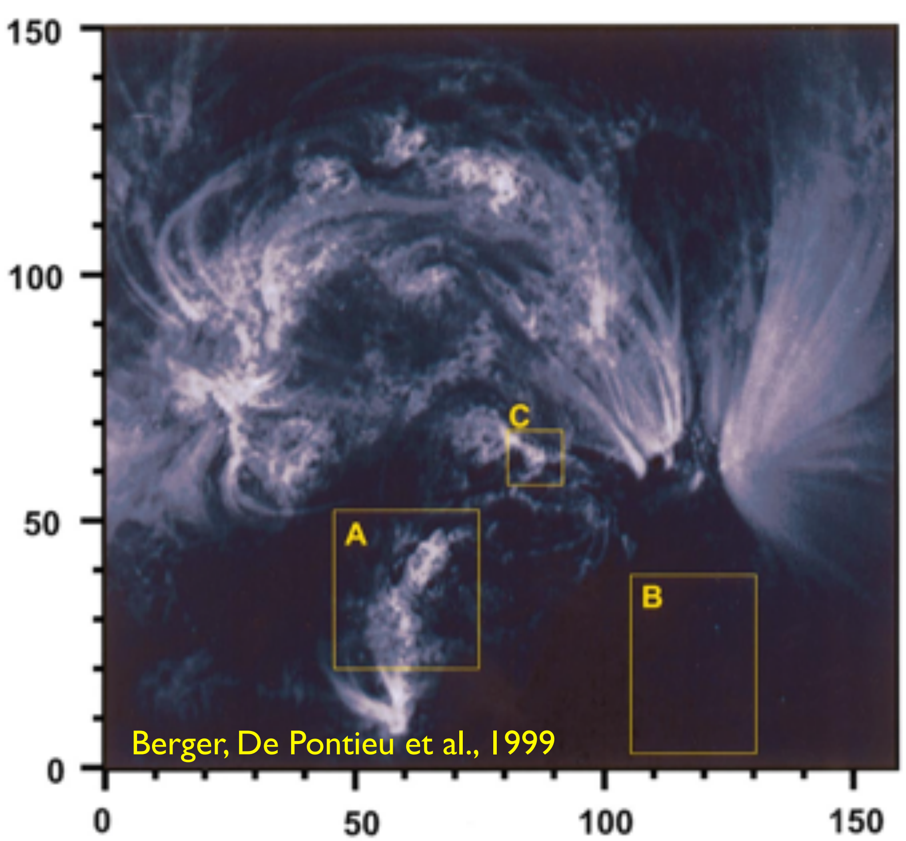
Pereira et al., 2015

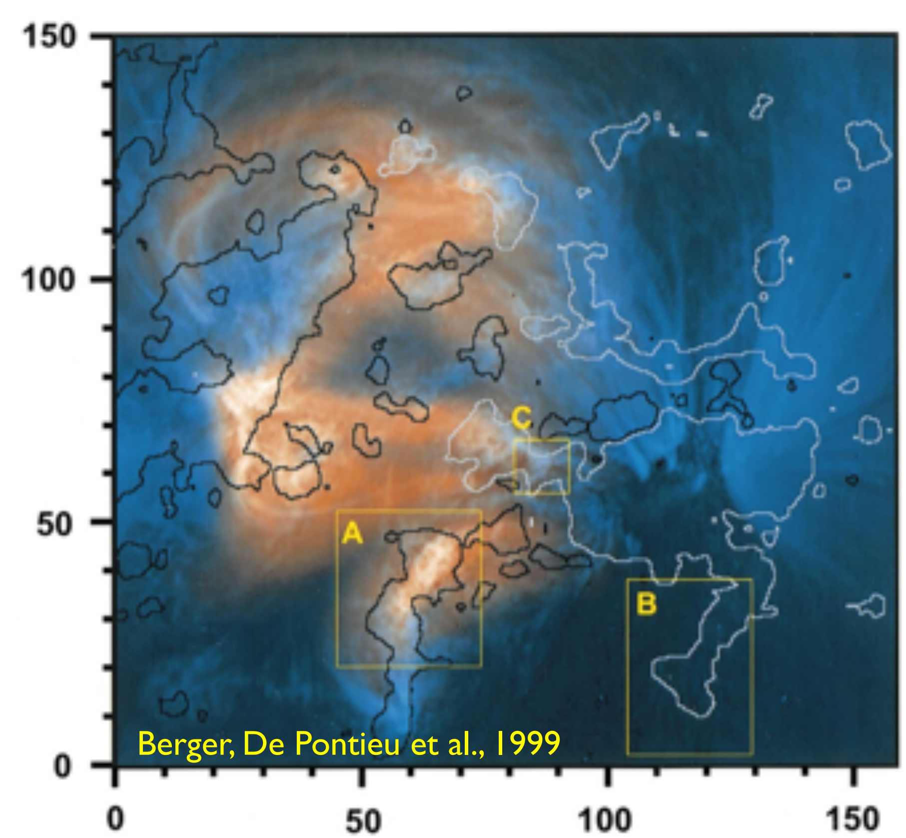
Mg II subordinate lines go into emission for strong chromospheric heating at high densities (i.e., low chromospheric heights)

Single-peak Mg II k plage profiles correlated with upper TR “moss”



Single peak profiles (where k2 and k3 are equal, i.e., k2-k3 black) often occur in bright AIA 193 moss:
relation between single-peak profiles and TR at high column mass

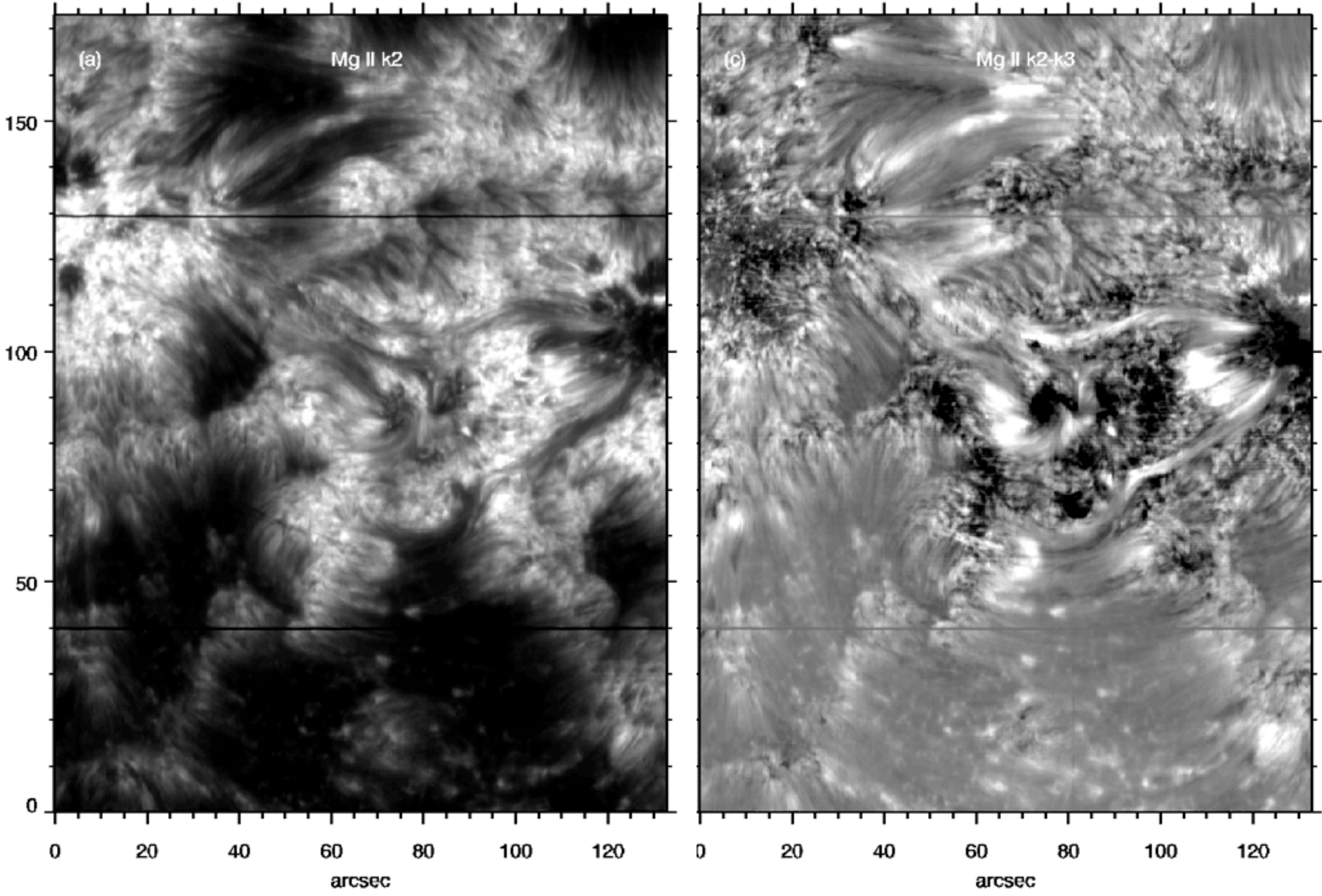




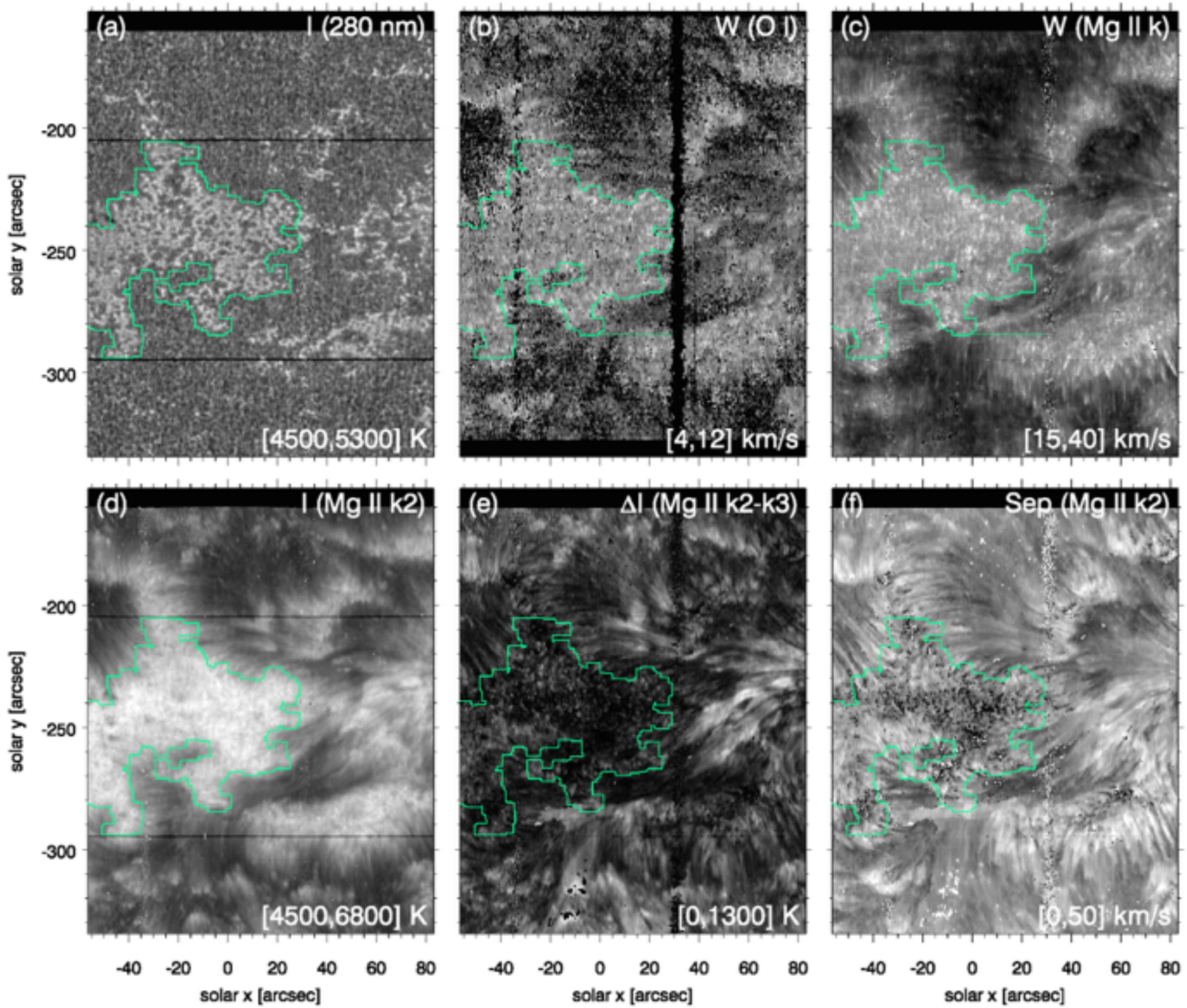
Moss occurs at the footpoints of hot, high-density coronal loops

Moss brightness good proxy for coronal pressure

Single-peak Mg II k plage profiles correlated with upper TR “moss”



Plage Properties from Mg II k 2796Å and O I 1355Å

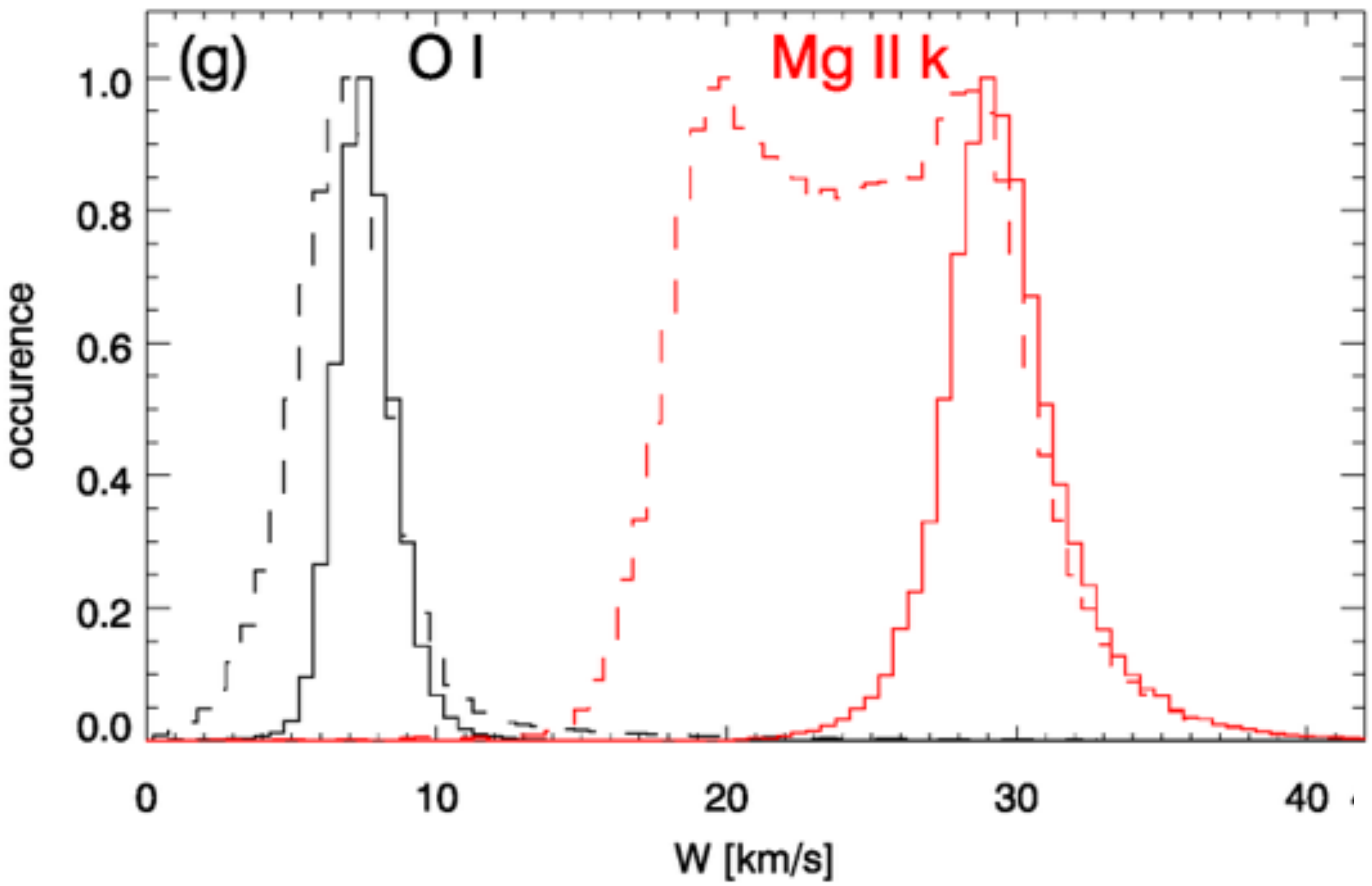


Mg II k width remarkable constant, larger than width of optically thin O I because of opacity broadening

Intensity of K2 (~T_{chromo}) constant

Many locations have single-peak profiles

Constraints on temperature and non-thermal motions in plage

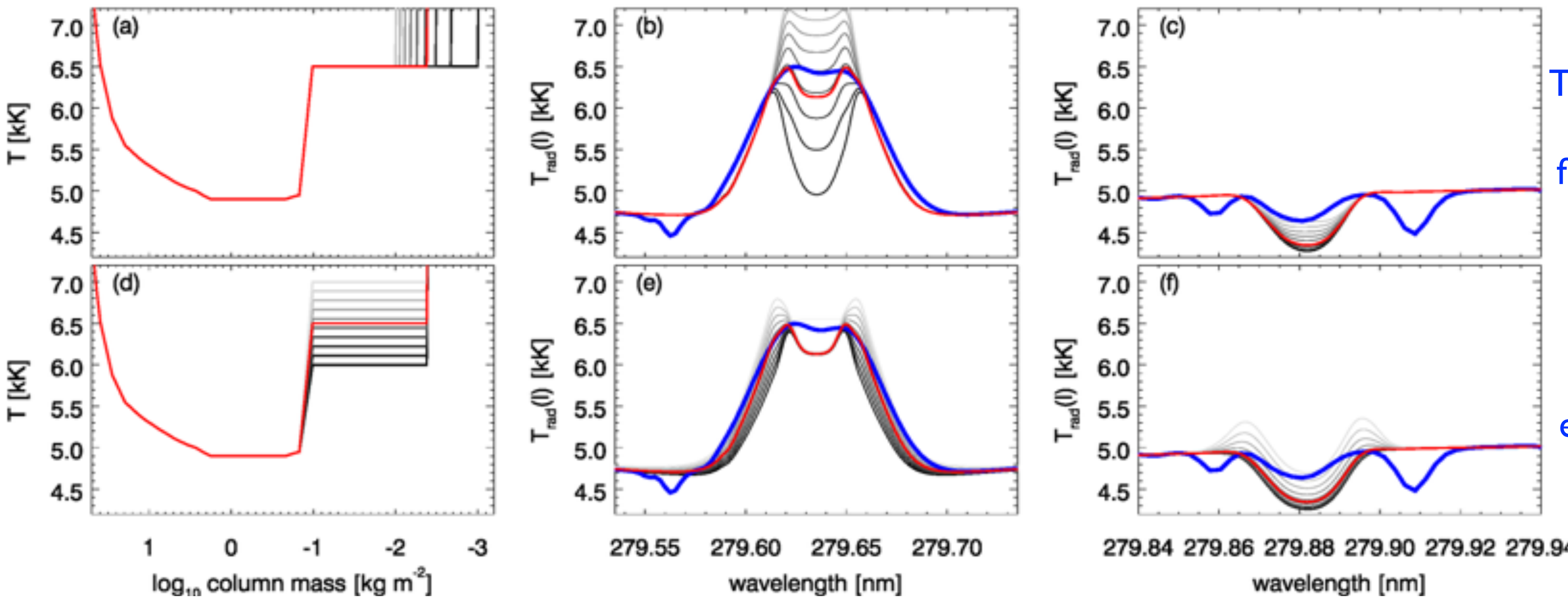


Mg II k broadening in part because of opacity

Plage Non-Thermal Broadening from optically thin O I line is of order ~ 7 km/s

Constraint on Alfvenic motions (see Asgari-Thargi talk), turbulence, or shocks (see De Pontieu talk, in a few minutes)

Pushing a toy model to its limits: constraints on plage properties



TR at high column mass (low heights) causes filled-in Mg II k profiles

Temperatures above 6500K would lead to emission of subordinate line

Plage properties:

1. High density and high temperature in mid to upper-chromosphere (~6500K)

2. Highest densities (and T increase) at moss footpoints

3. Sharp step in T at low heights

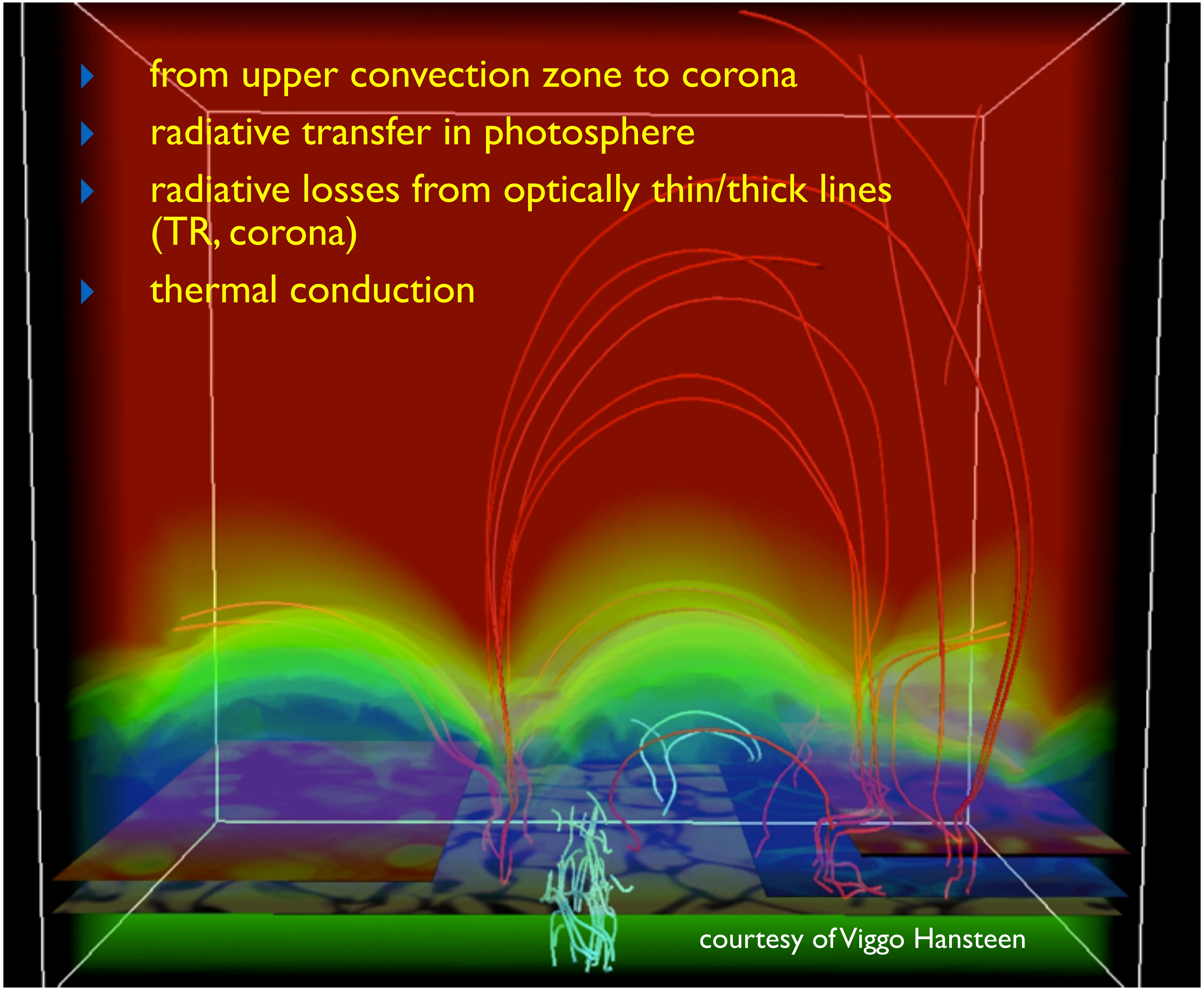
4. Remarkably constant non-thermal motions

Investigating sensitivity of plage Mg II k profiles to hydrostatic model properties

How well does a more sophisticated model reproduce Mg II k?

Bifrost code (Gudiksen et al. 2011) solves full 3D radiative MHD equations

"Only" free parameter is magnetic field distribution on the surface



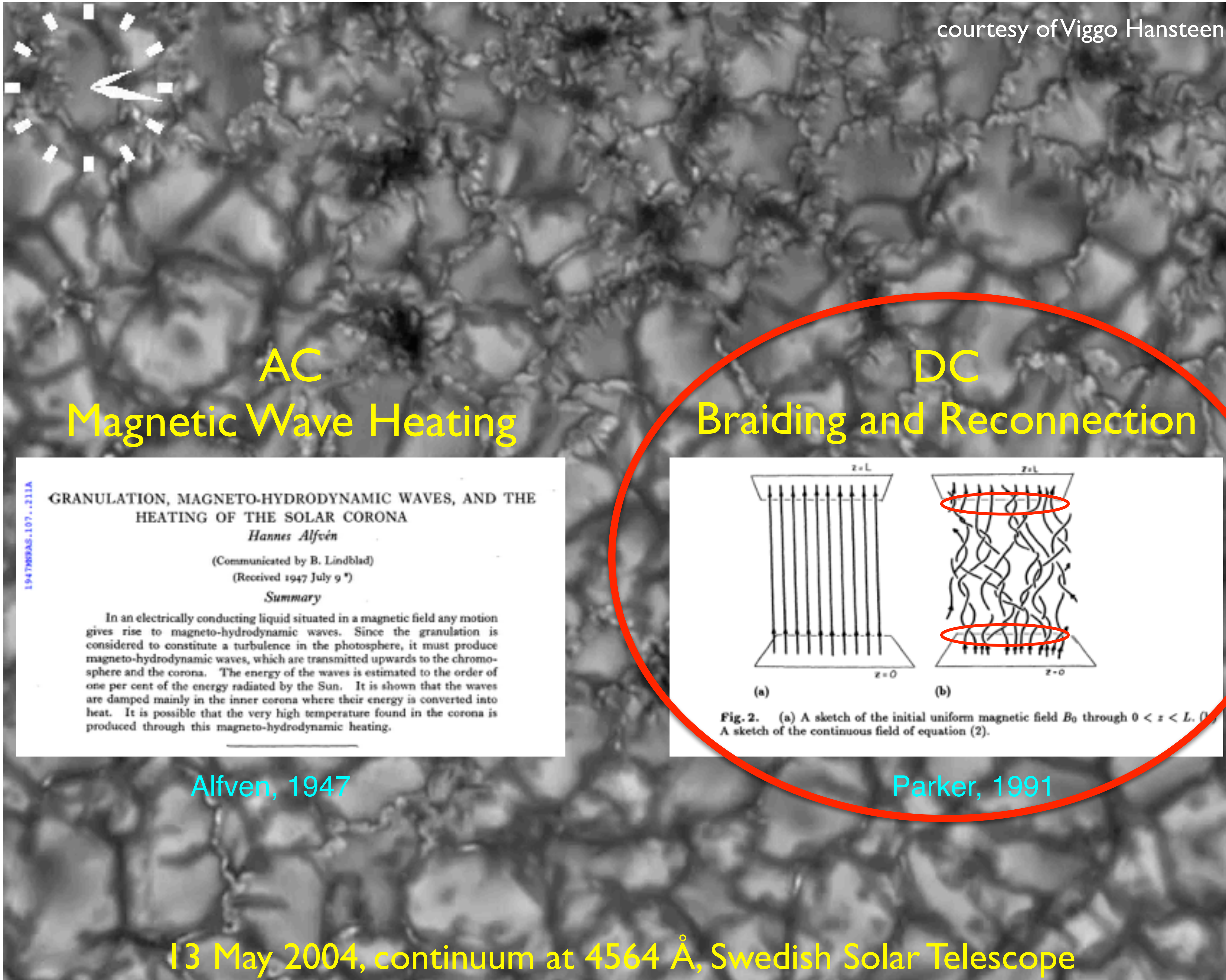
Corona

Transition region

Chromosphere

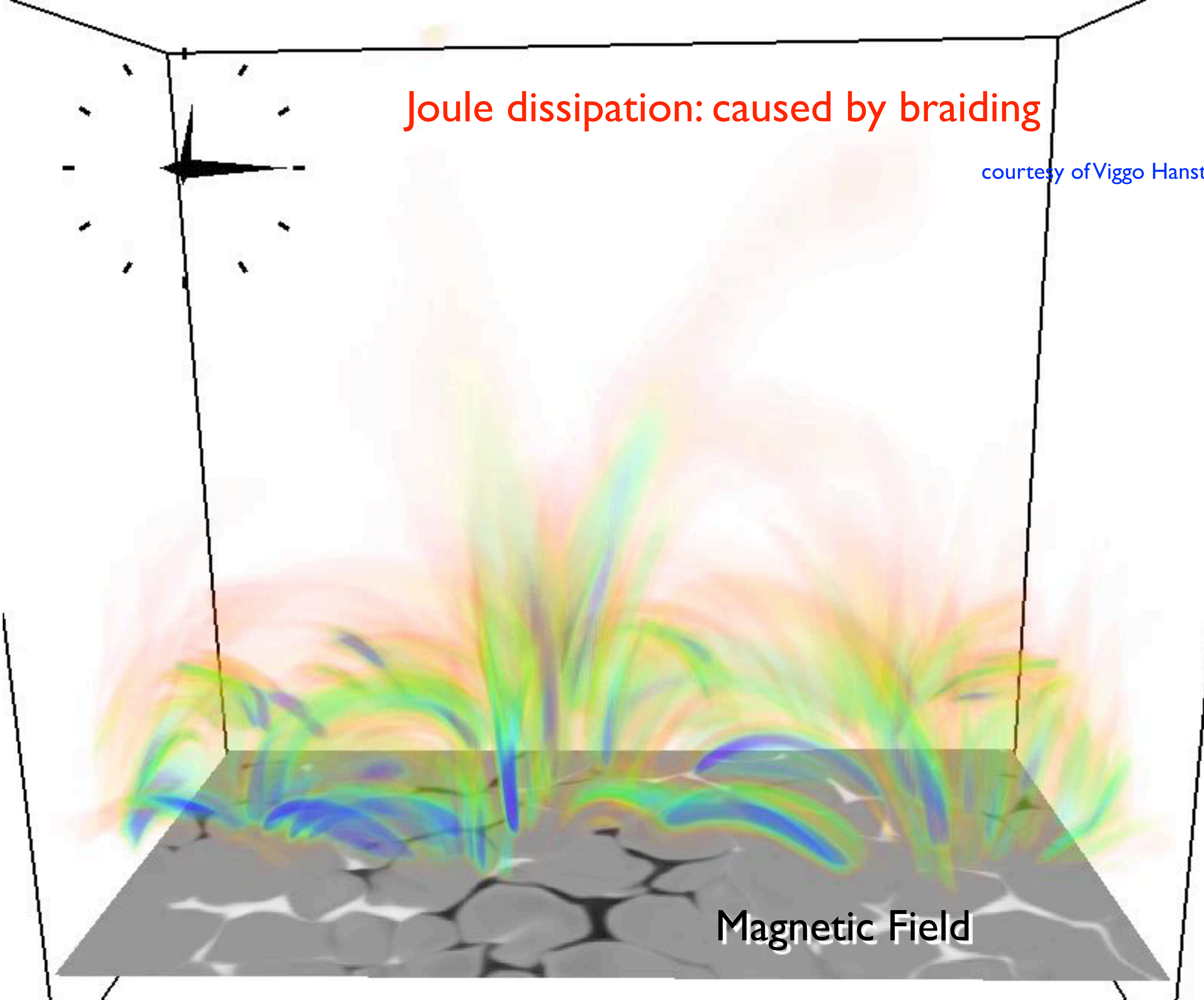
Photosphere

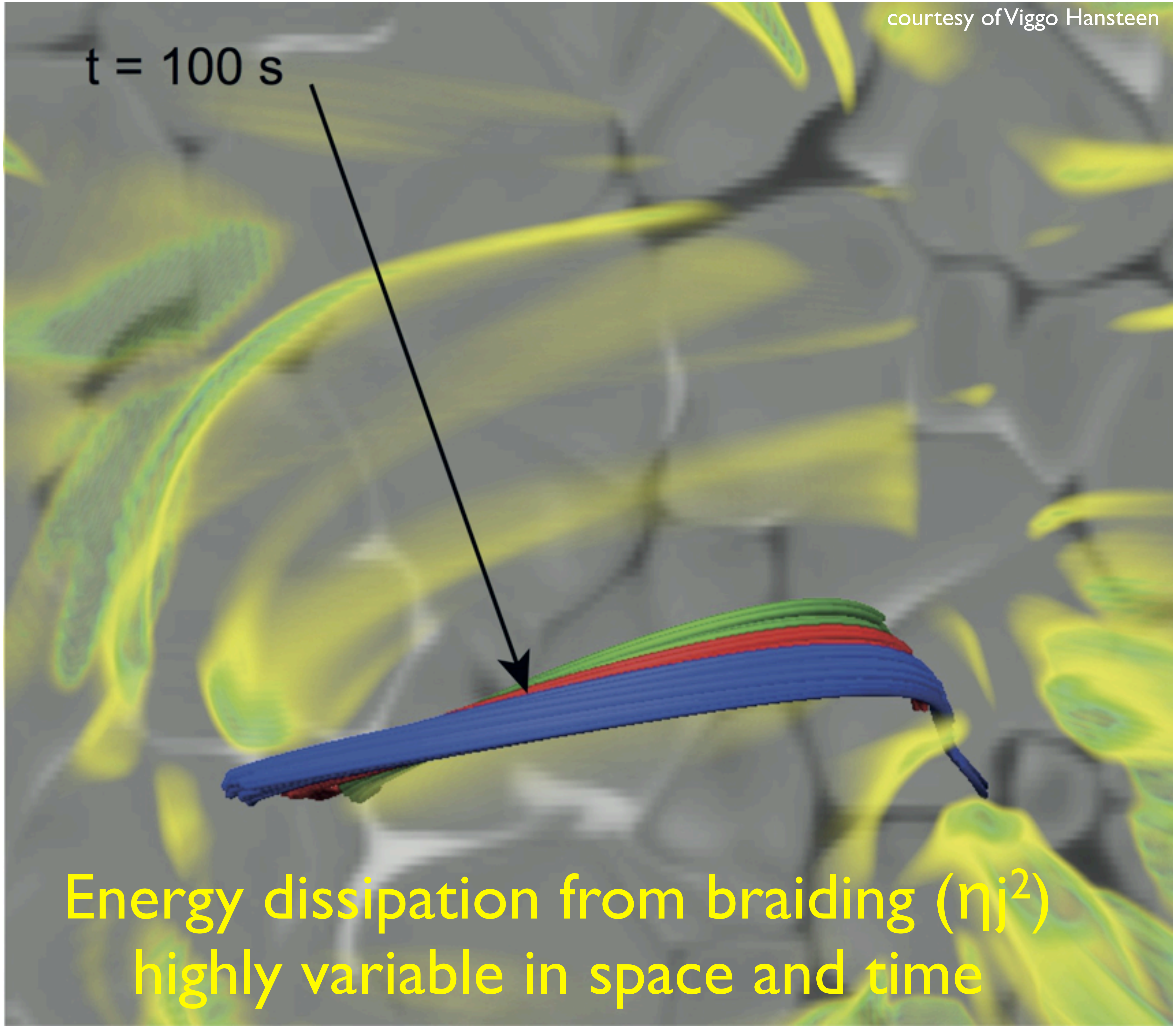
Which heating mechanism dominates in Bifrost simulations?



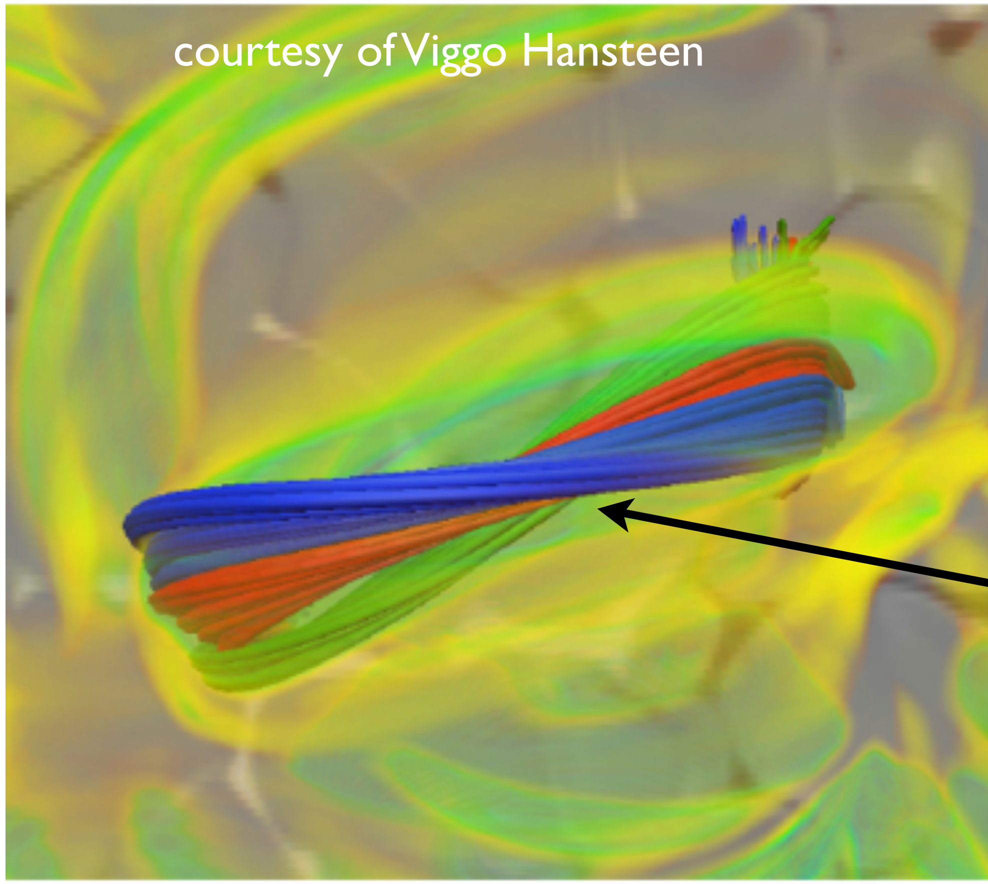
Joule dissipation: caused by braiding

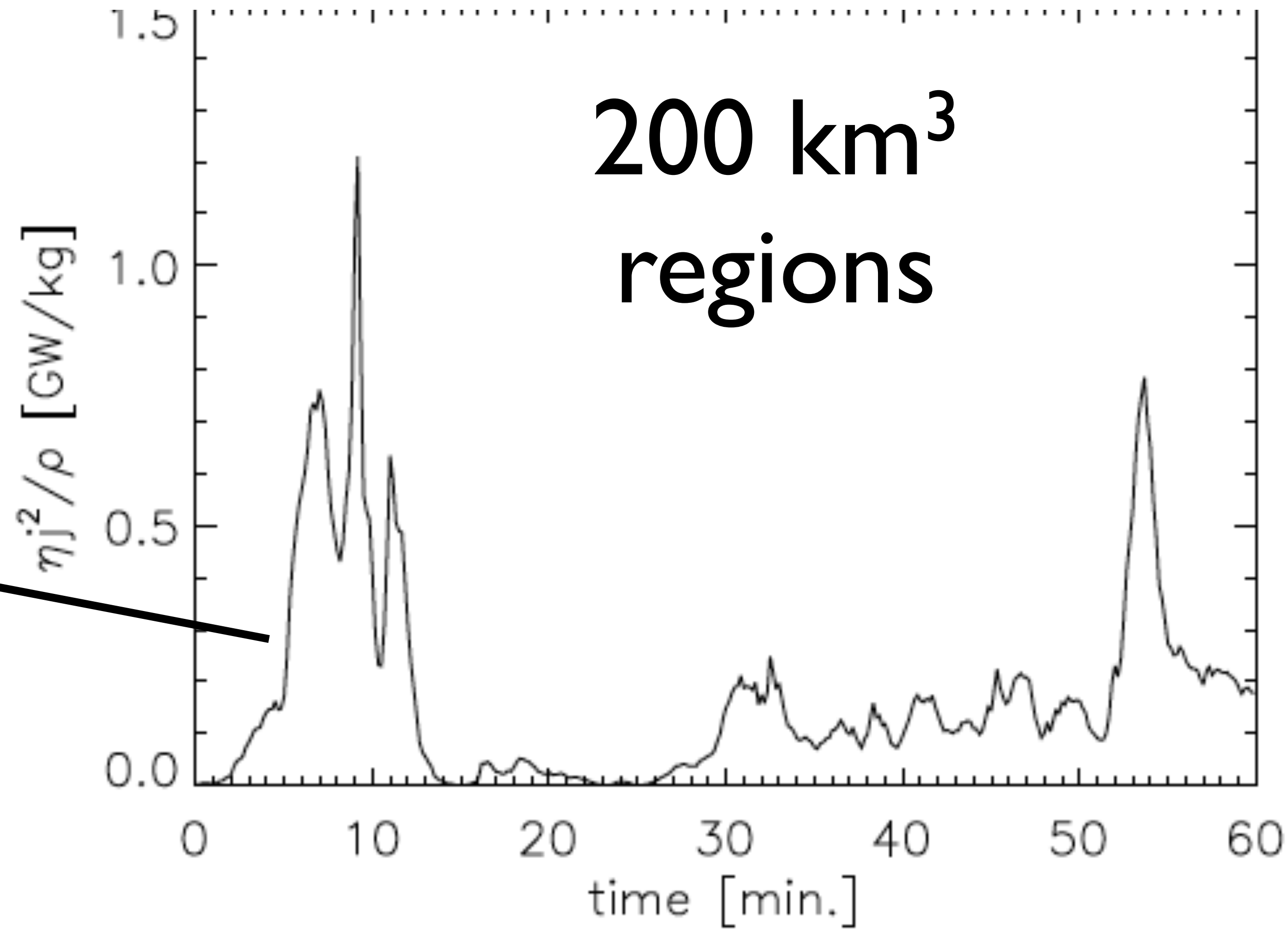
courtesy of Viggo Hansteen

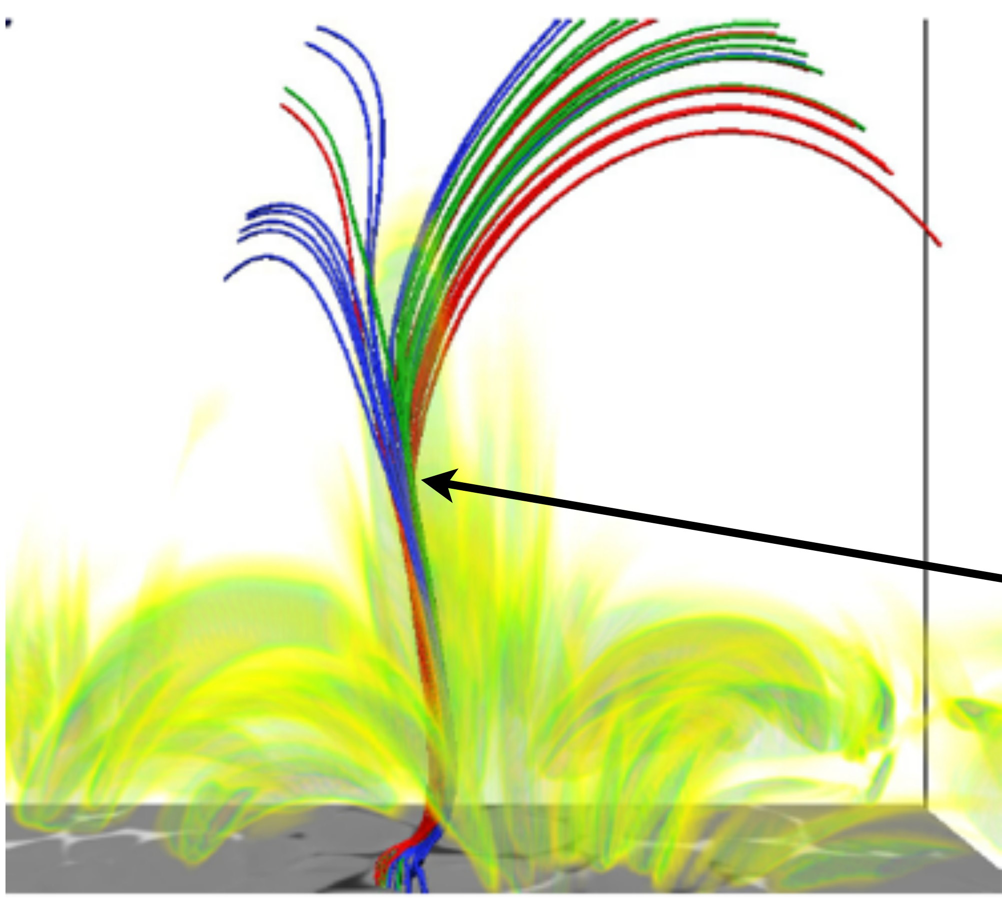




Energy dissipation from braiding (ηj^2)
highly variable in space and time

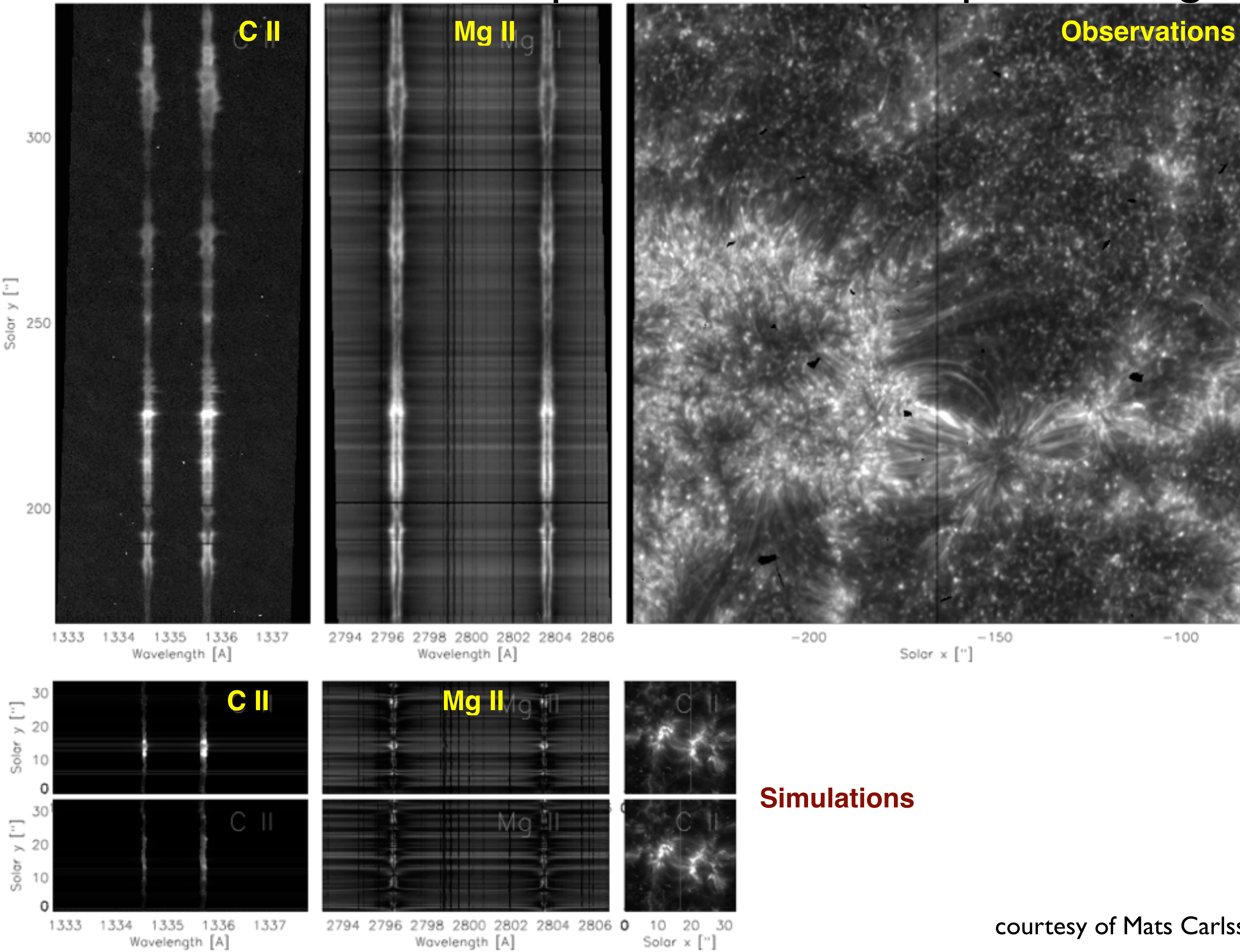






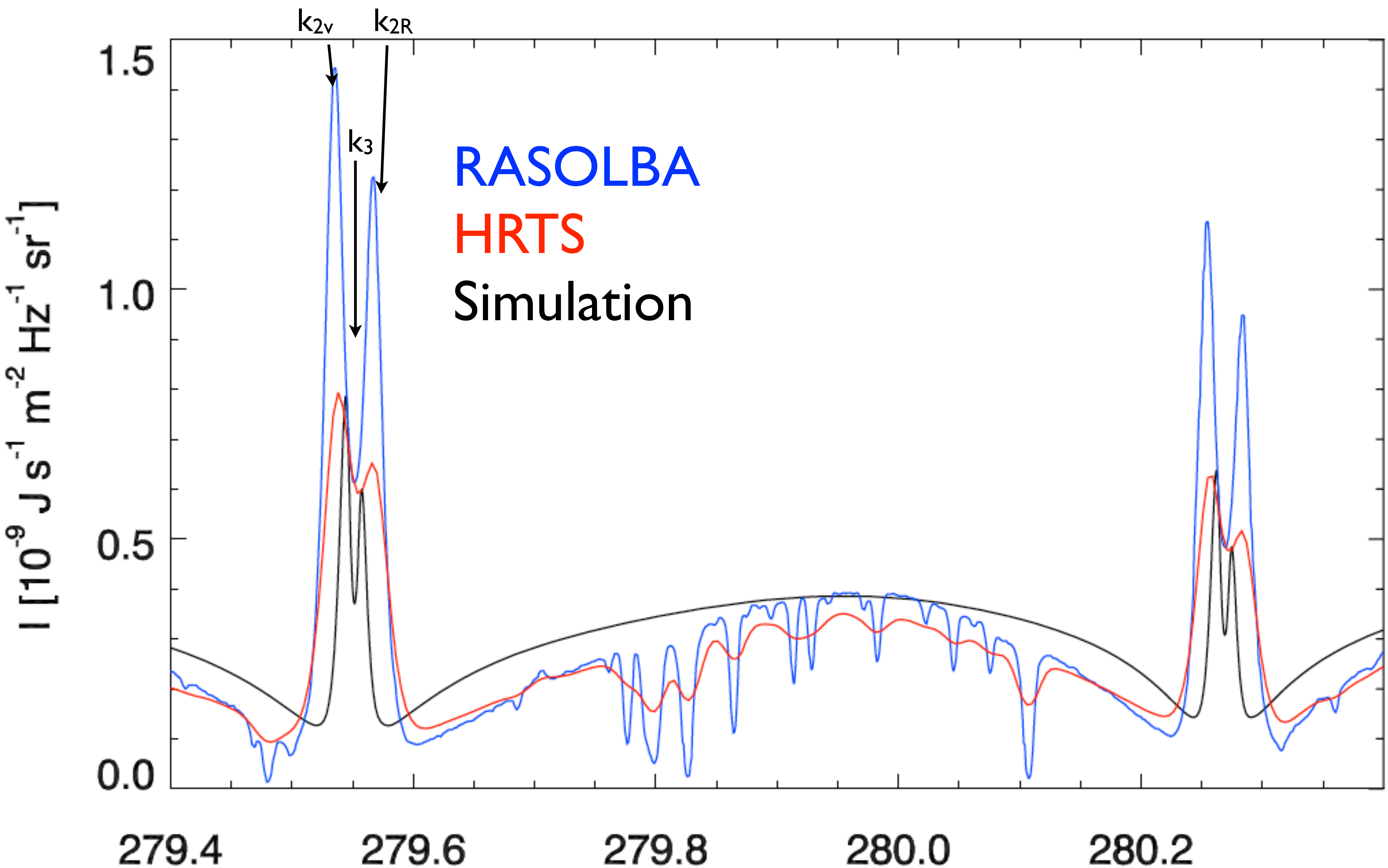
Braiding clearly appears to lead to heating sufficient to produce a chromosphere & corona.

How well does a more sophisticated model reproduce Mg II k?



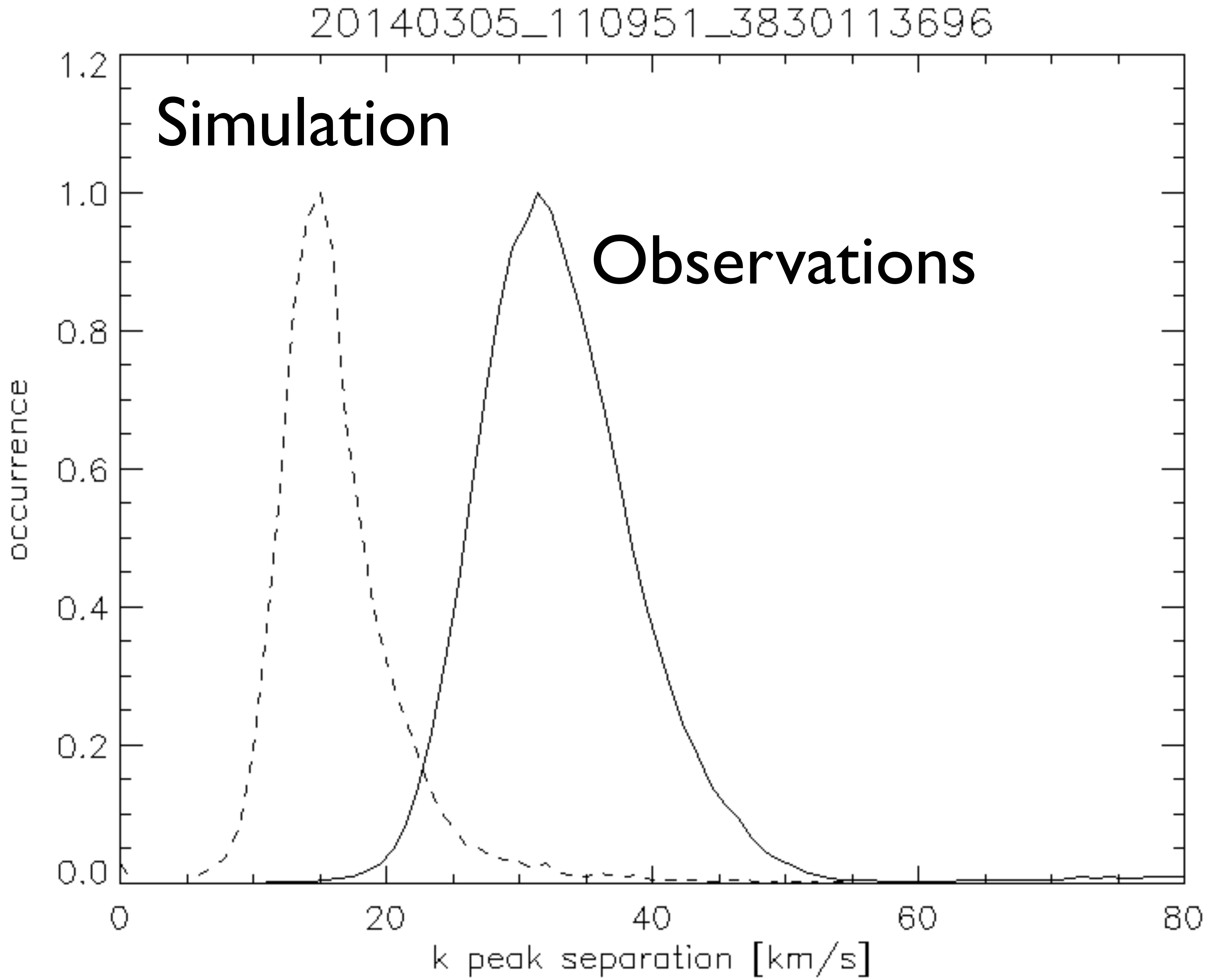
courtesy of Mats Carlsson

Current simulations show synthetic profiles that are too narrow



courtesy of Tiago Pereira

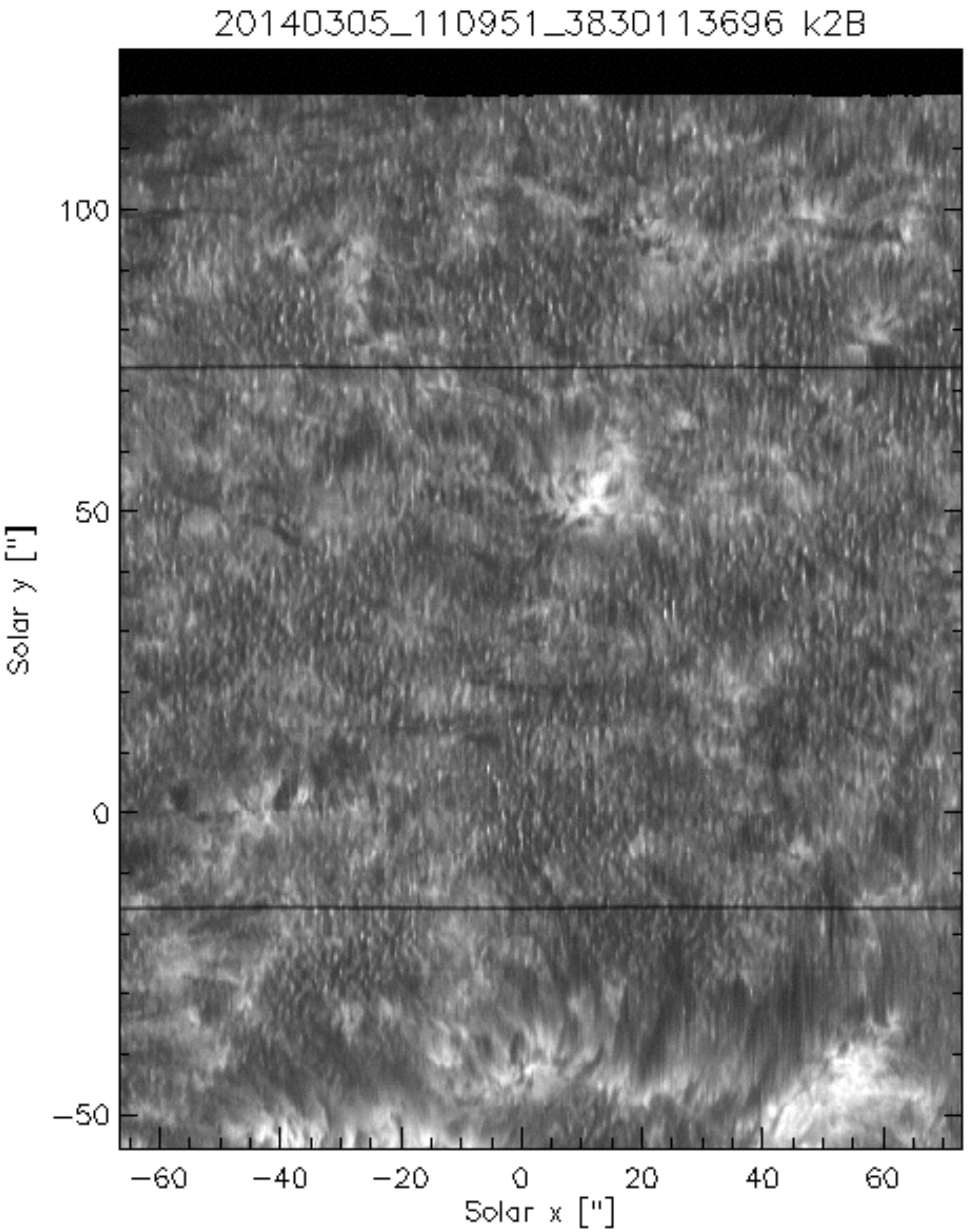
Current simulations seem to lack violence, mass & heat



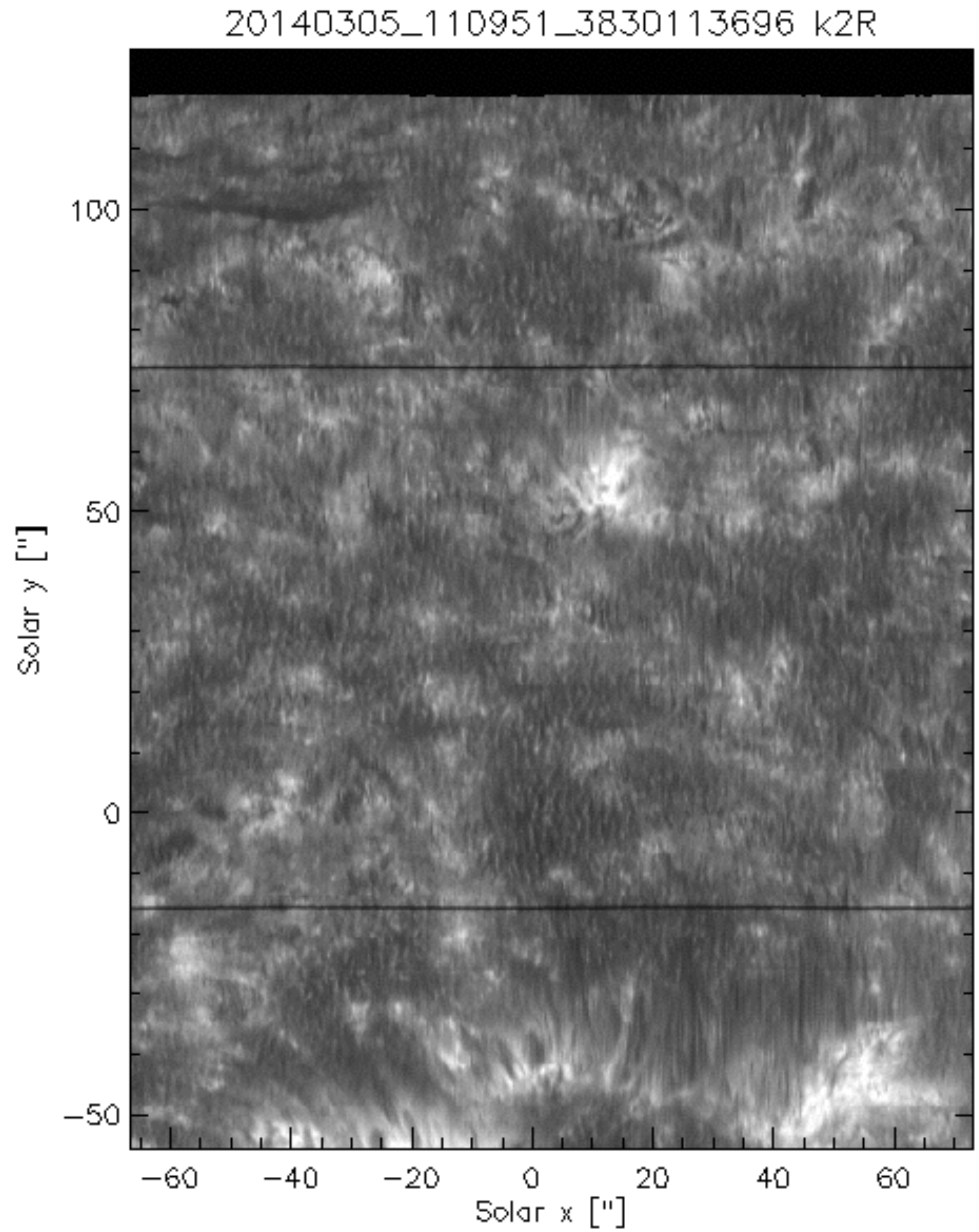
Mg II k2 peak separation related to velocity gradients and column mass in chromosphere

courtesy of Mats Carlsson

Current simulations seem to lack "heat"



k2v intensity

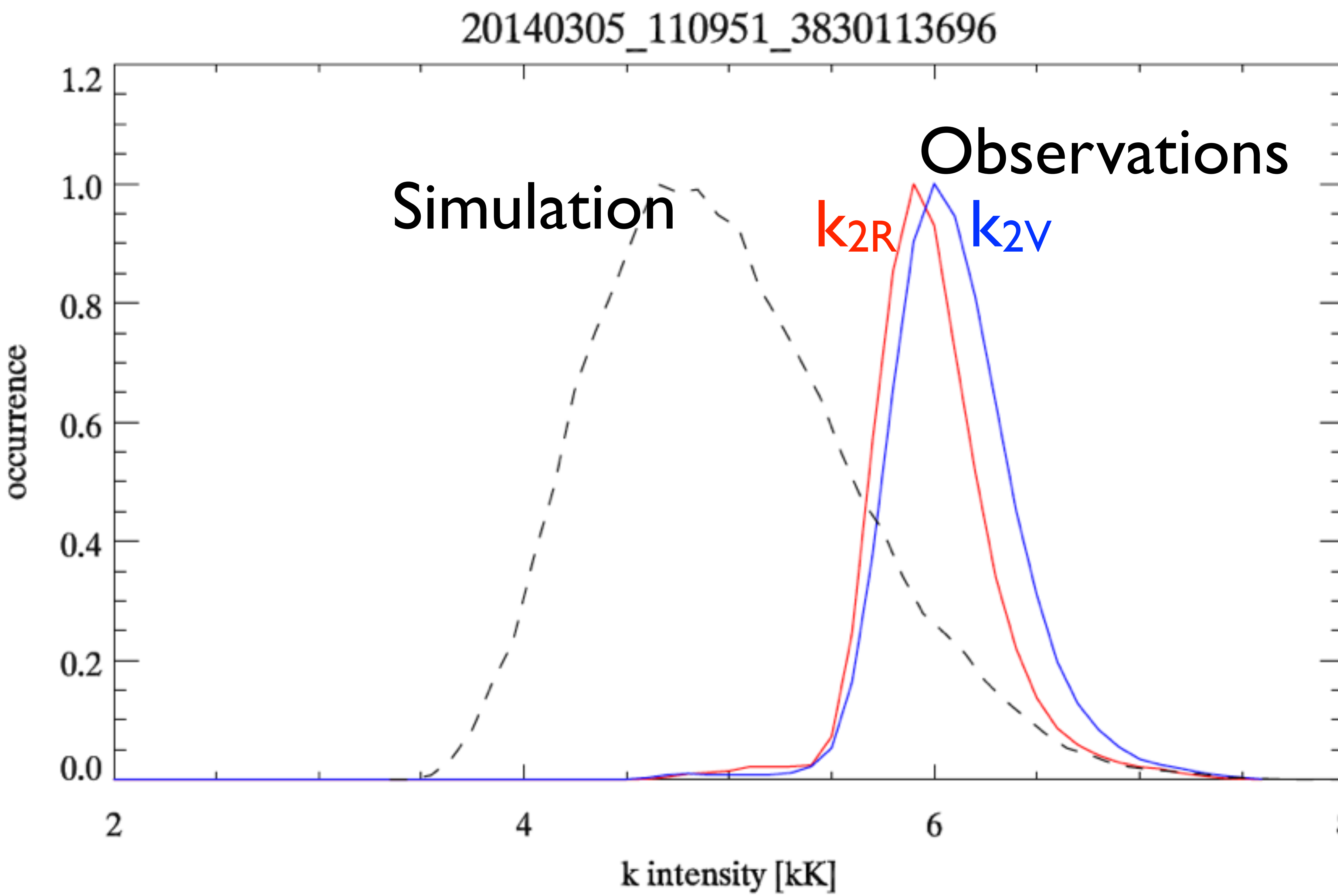


k2r intensity

courtesy of Mats Carlsson

Current simulations seem to lack "heat"

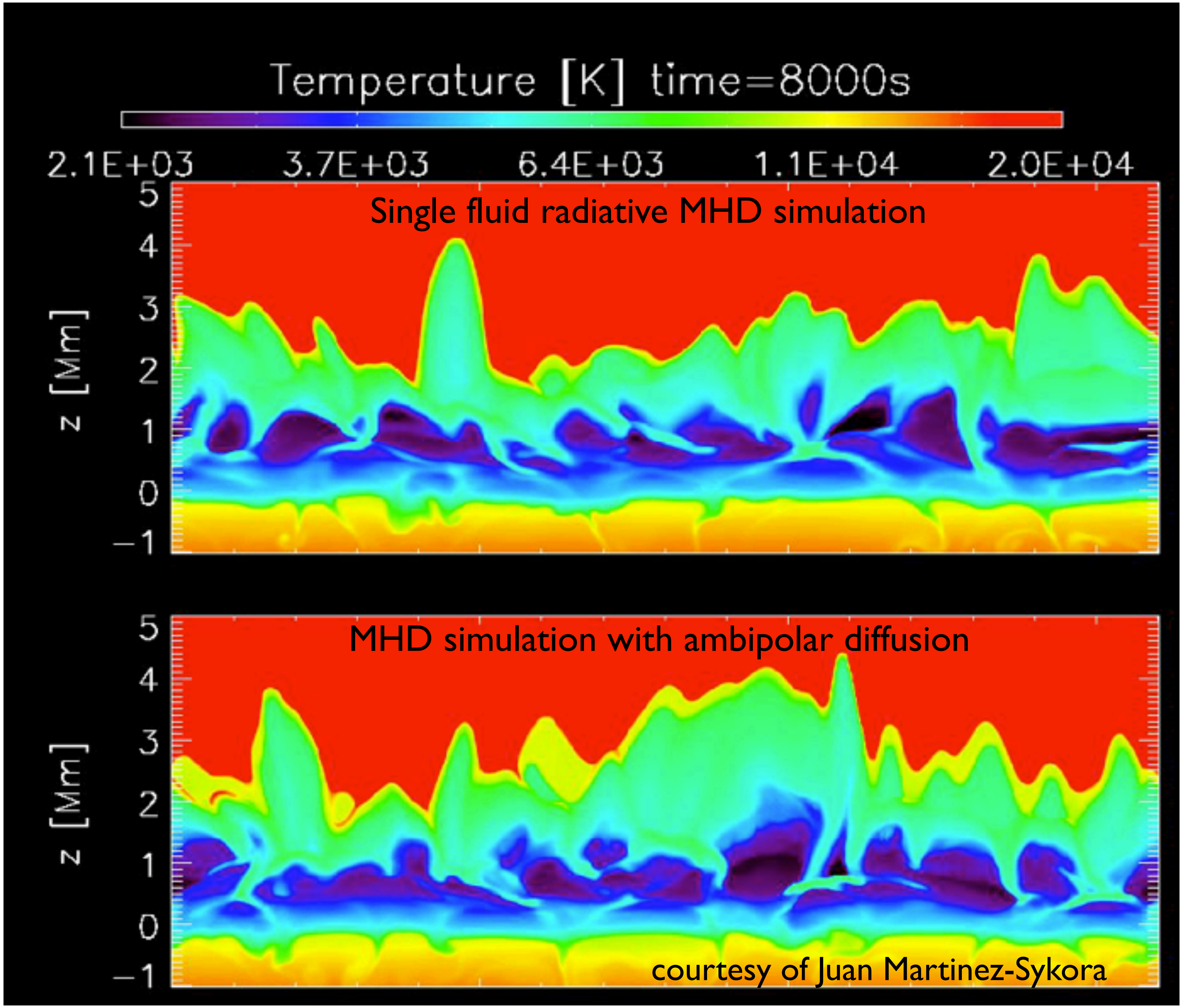
Caused by lack of spatial resolution, lack of small-scale fields, non-MHD effects?



Mg II k2 peak intensity

courtesy of Mats Carlsson

Numerical simulations now include ion-neutral interactions

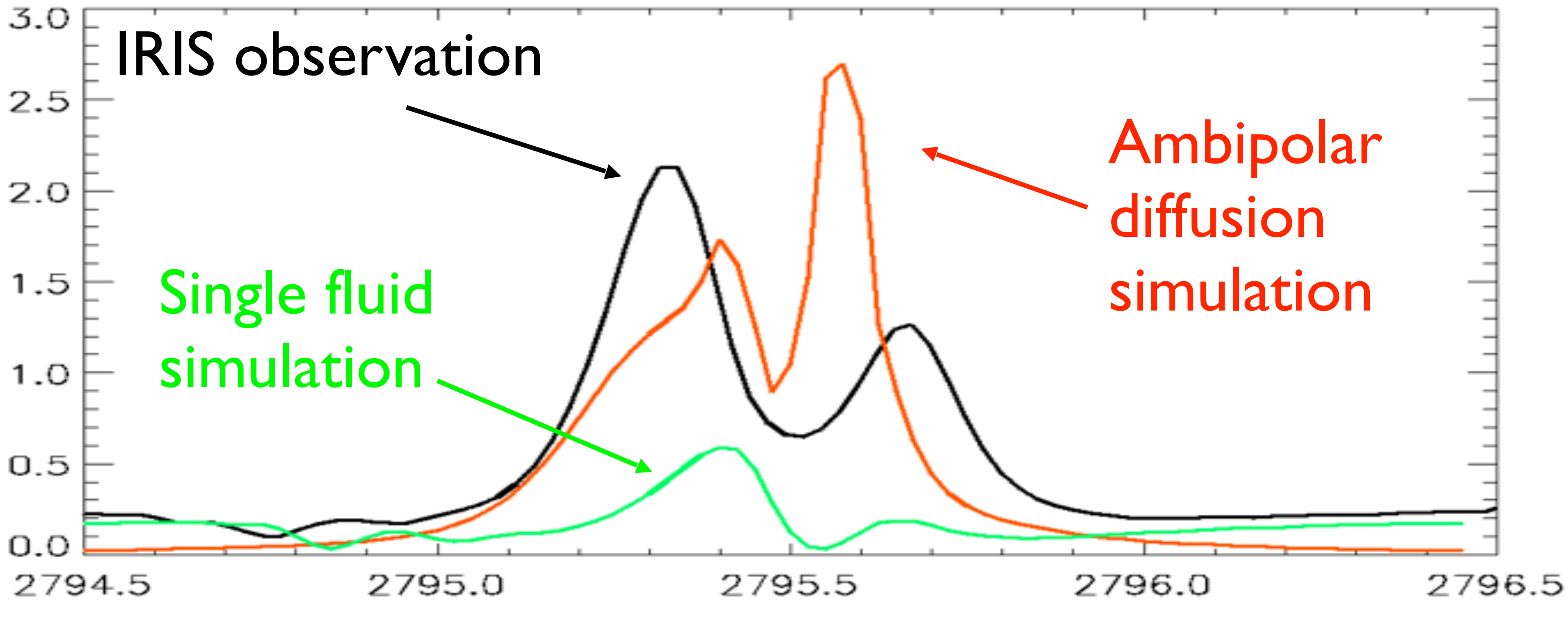


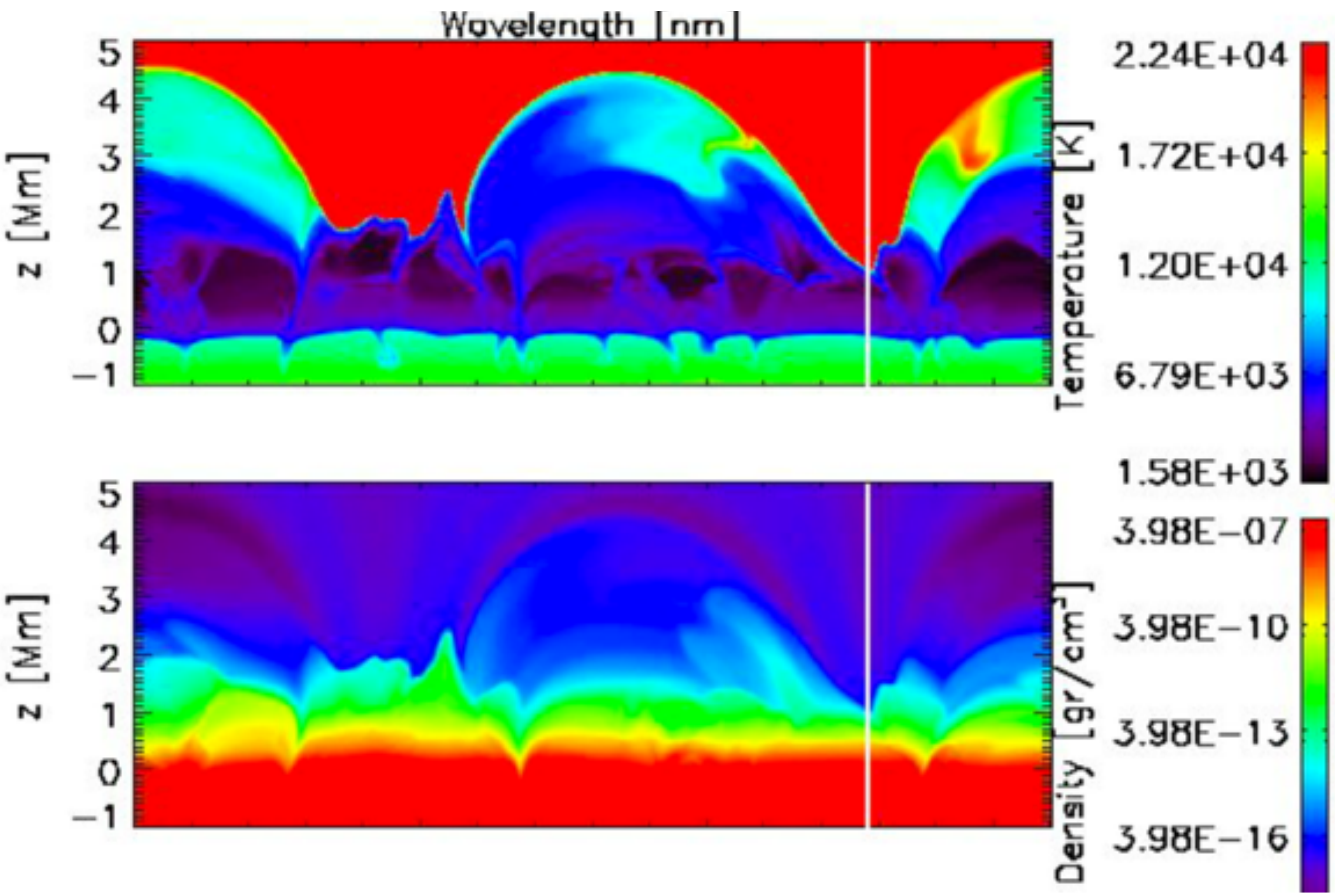
Single-fluid MHD simulations use generalized Ohm's law (GOL) to include ambipolar diffusion

Leads to chromospheric heating and more diffuse transition region

Dissipation of magnetic energy from ion-neutral interactions appears to play significant role in chromospheric heating

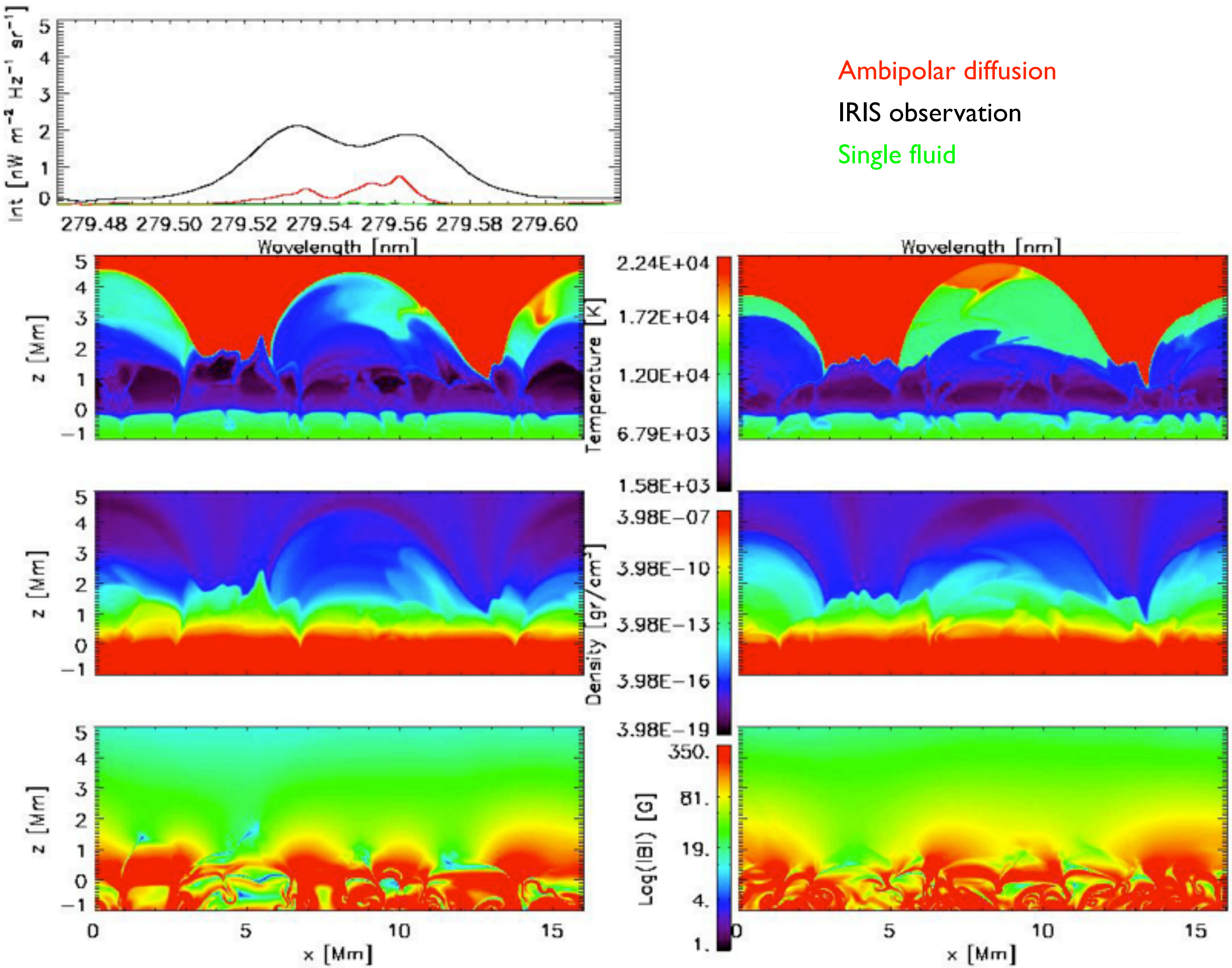
Ambipolar diffusion reduces Mg II k discrepancies: broader and brighter





Single fluid MHD simulation

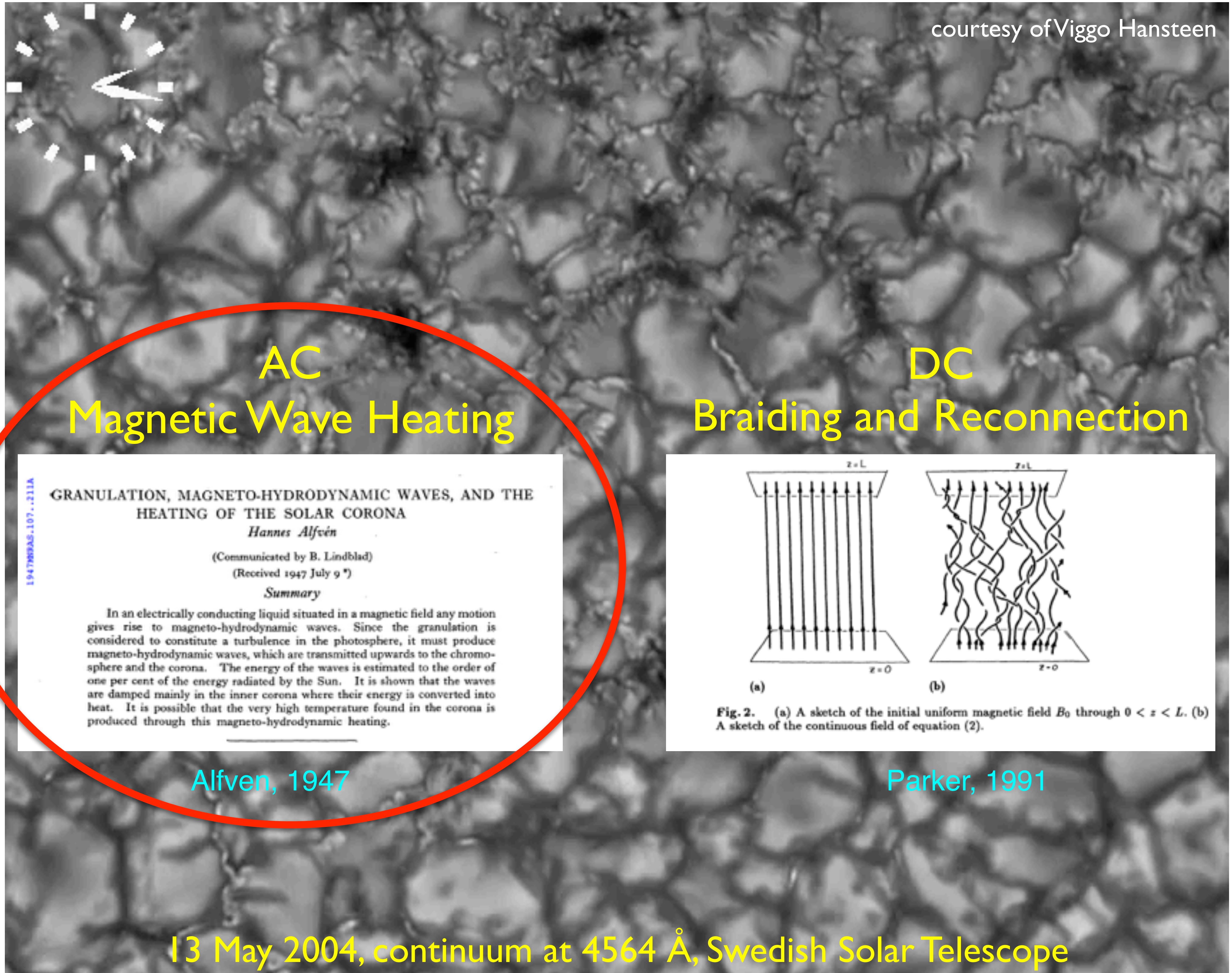
Ambipolar diffusion reduces Mg II k discrepancies: broader and brighter



Single fluid MHD simulation

MHD simulation with ambipolar diffusion

Is there also a role for Alfven waves?



AC
Magnetic Wave Heating

GRANULATION, MAGNETO-HYDRODYNAMIC WAVES, AND THE HEATING OF THE SOLAR CORONA

Hannes Alfvén

(Communicated by B. Lindblad)

(Received 1947 July 9 *)

Summary

In an electrically conducting liquid situated in a magnetic field any motion gives rise to magneto-hydrodynamic waves. Since the granulation is considered to constitute a turbulence in the photosphere, it must produce magneto-hydrodynamic waves, which are transmitted upwards to the chromosphere and the corona. The energy of the waves is estimated to the order of one per cent of the energy radiated by the Sun. It is shown that the waves are damped mainly in the inner corona where their energy is converted into heat. It is possible that the very high temperature found in the corona is produced through this magneto-hydrodynamic heating.

Alfven, 1947

DC
Braiding and Reconnection

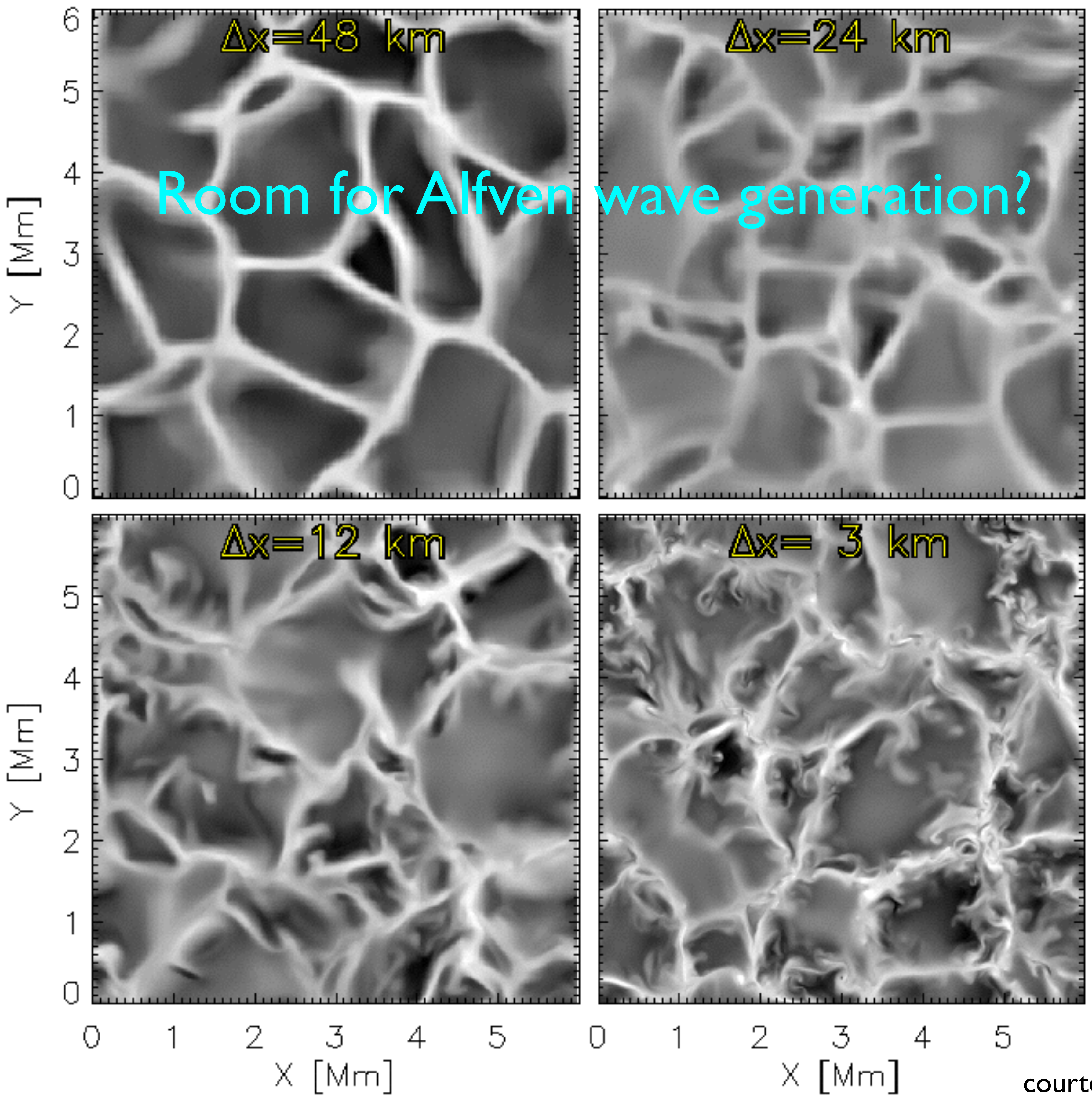
Fig. 2. (a) A sketch of the initial uniform magnetic field B_0 through $0 < z < L$. (b) A sketch of the continuous field of equation (2).

Parker, 1991

13 May 2004, continuum at 4564 Å, Swedish Solar Telescope

Vorticity increases as numerical resolution of simulations increases

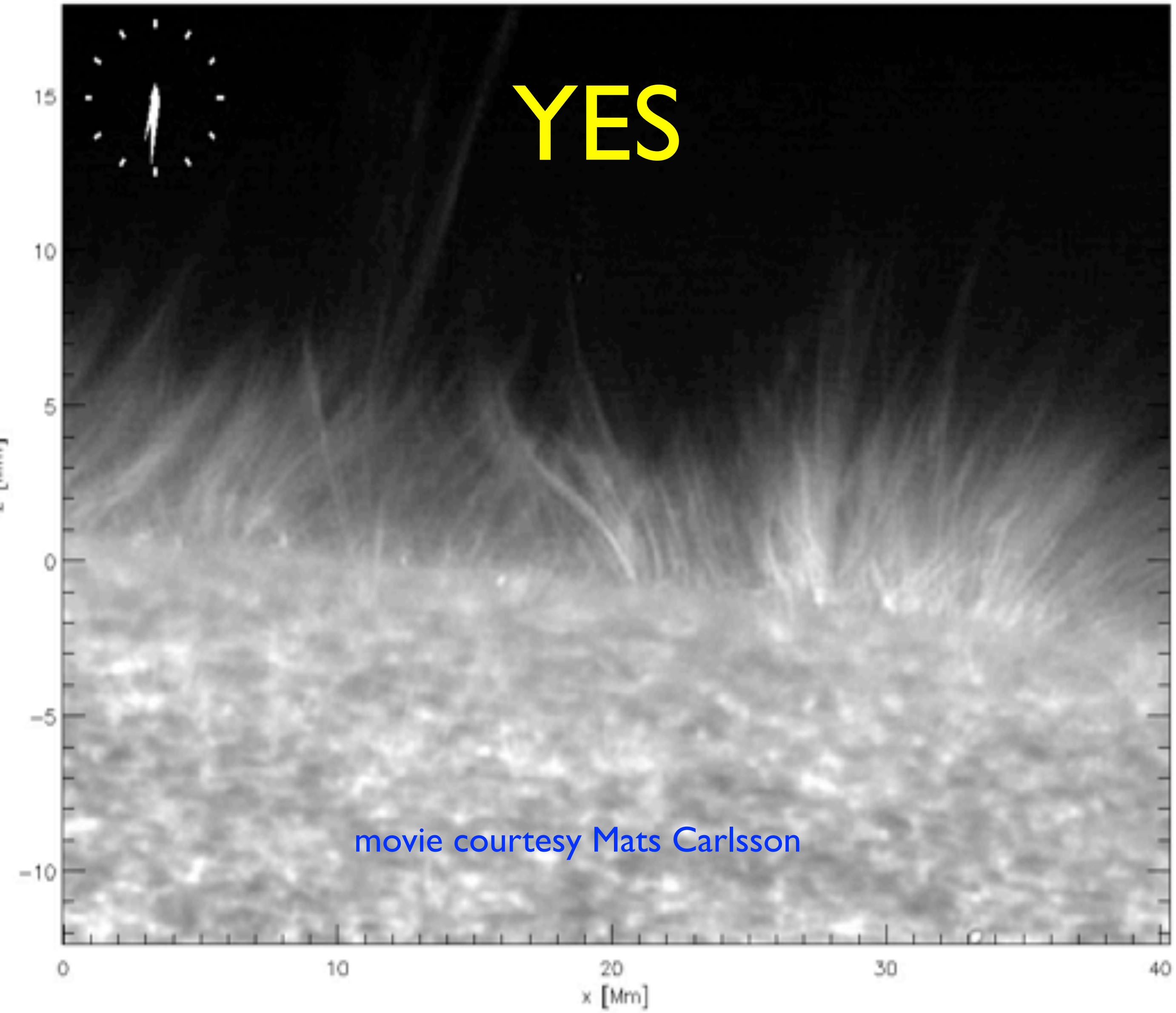
Vertical velocity at surface



Room for Alfven wave generation?

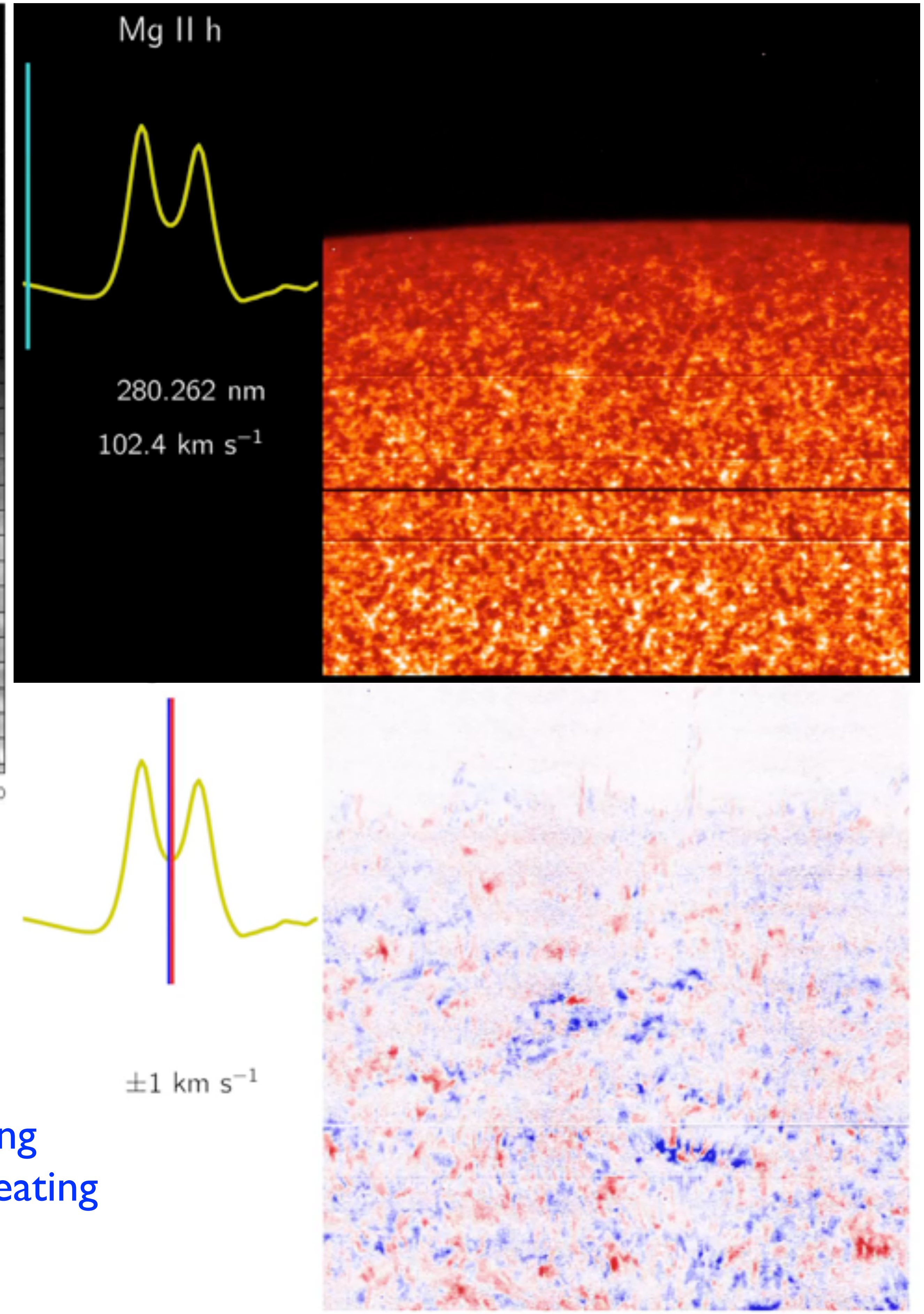
courtesy of Viggo Hansteen

Is there any observational evidence for Alfven waves?



Hinode/SOT Ca II H (~10,000 K) shows multitude of transverse Alfvenic waves with amplitudes of ~20 km/s

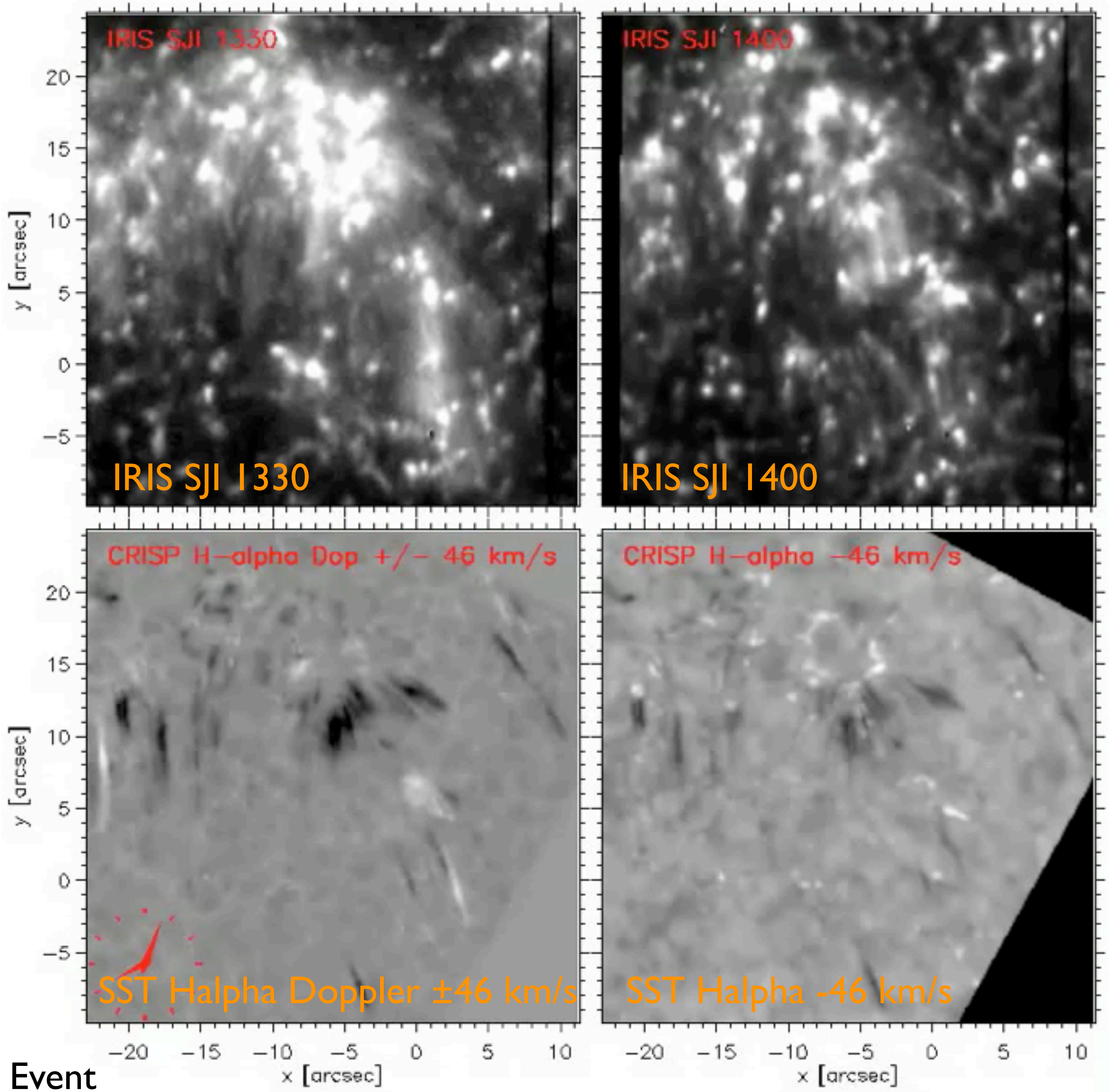
De Pontieu et al. 2007a, 2007b, McIntosh et al., 2011



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

De Pontieu et al., Science, October 17, 2014

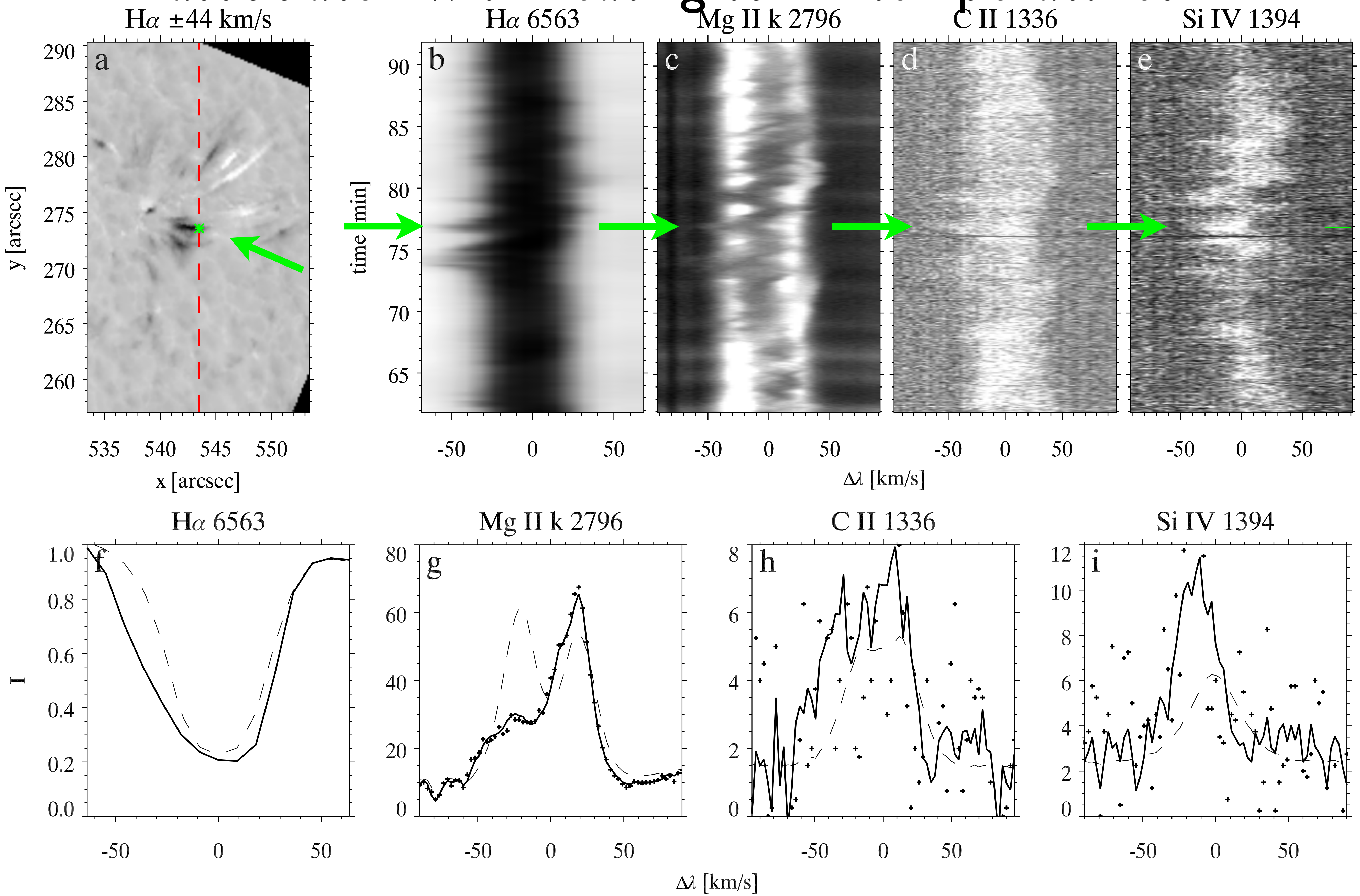
IRIS/SST observations reveal ubiquity of twist in chromosphere



RRE: Rapid Redshifted Event
RBE: Rapid Blueshifted Event

De Pontieu et al. 2014 Science, Rouppe van der Voort et al. 2015 ApJL 799

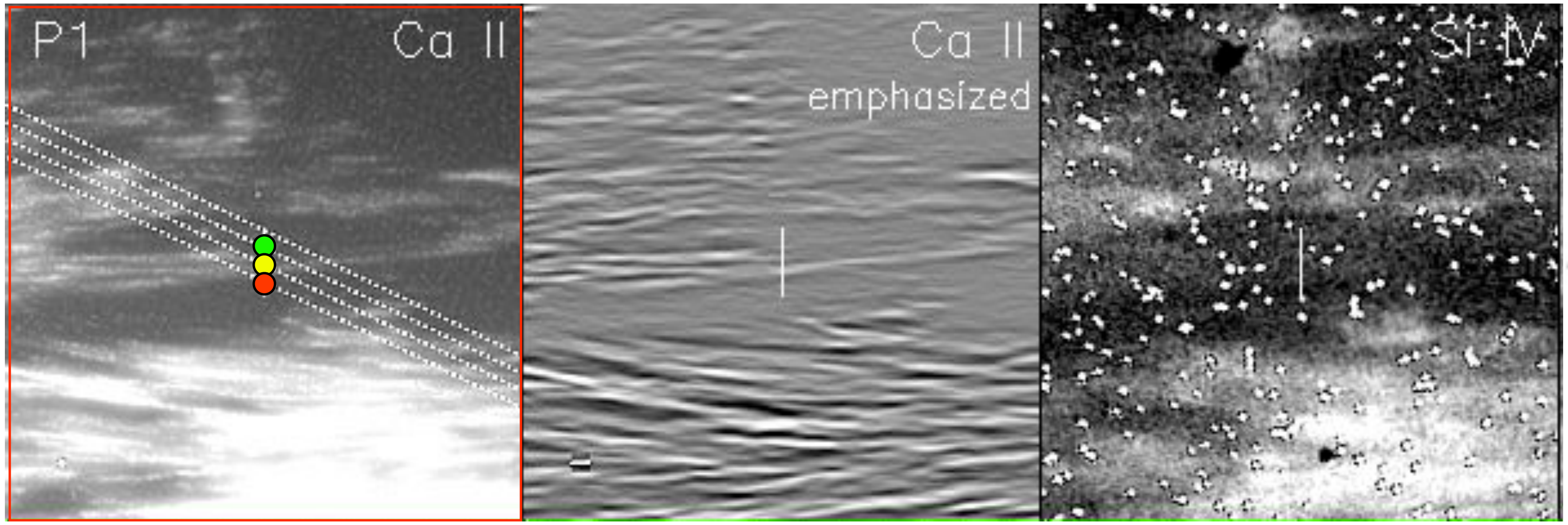
SST/IRIS observations show how torsional motions often associated with heating to TR temperatures



Rouppe van der Voort et al. 2015 ApJL 799

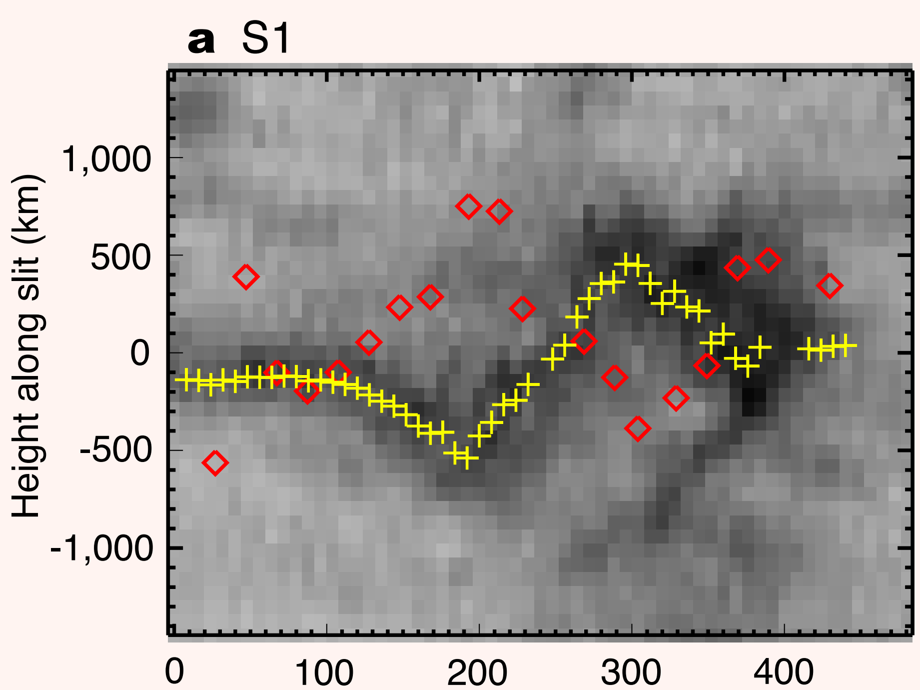
Is there evidence for Alfven wave dissipation?

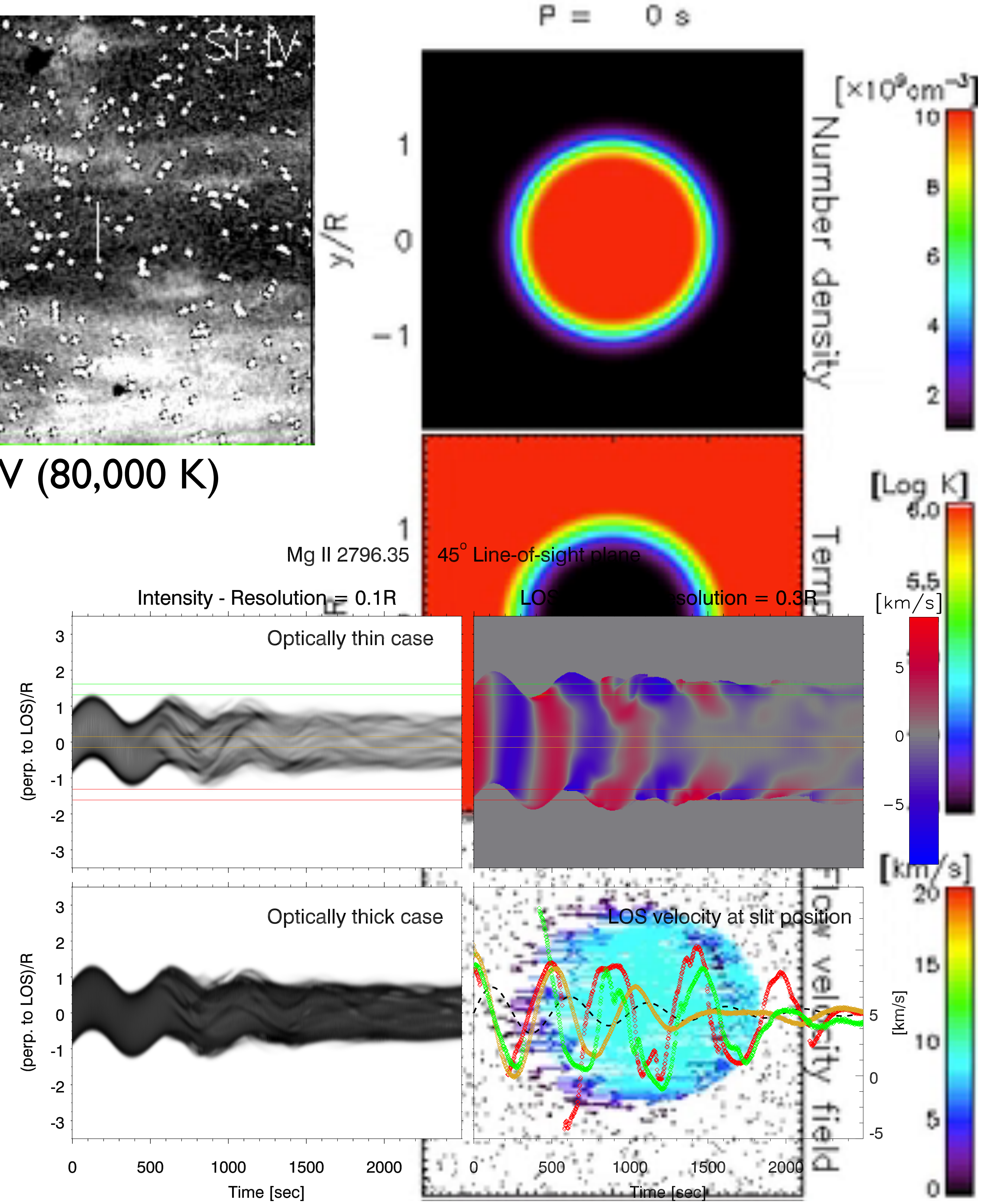
IRIS/Hinode/SDO-AIA observations discover tell-tale signs of previously undetected heating mechanism



Ca II (10,000 K) (original) | Ca II (10,000 K) (emphasized) | Si IV (80,000 K)

90-180 degree phase relationship between line-of-sight flows and plane-of-sky oscillations





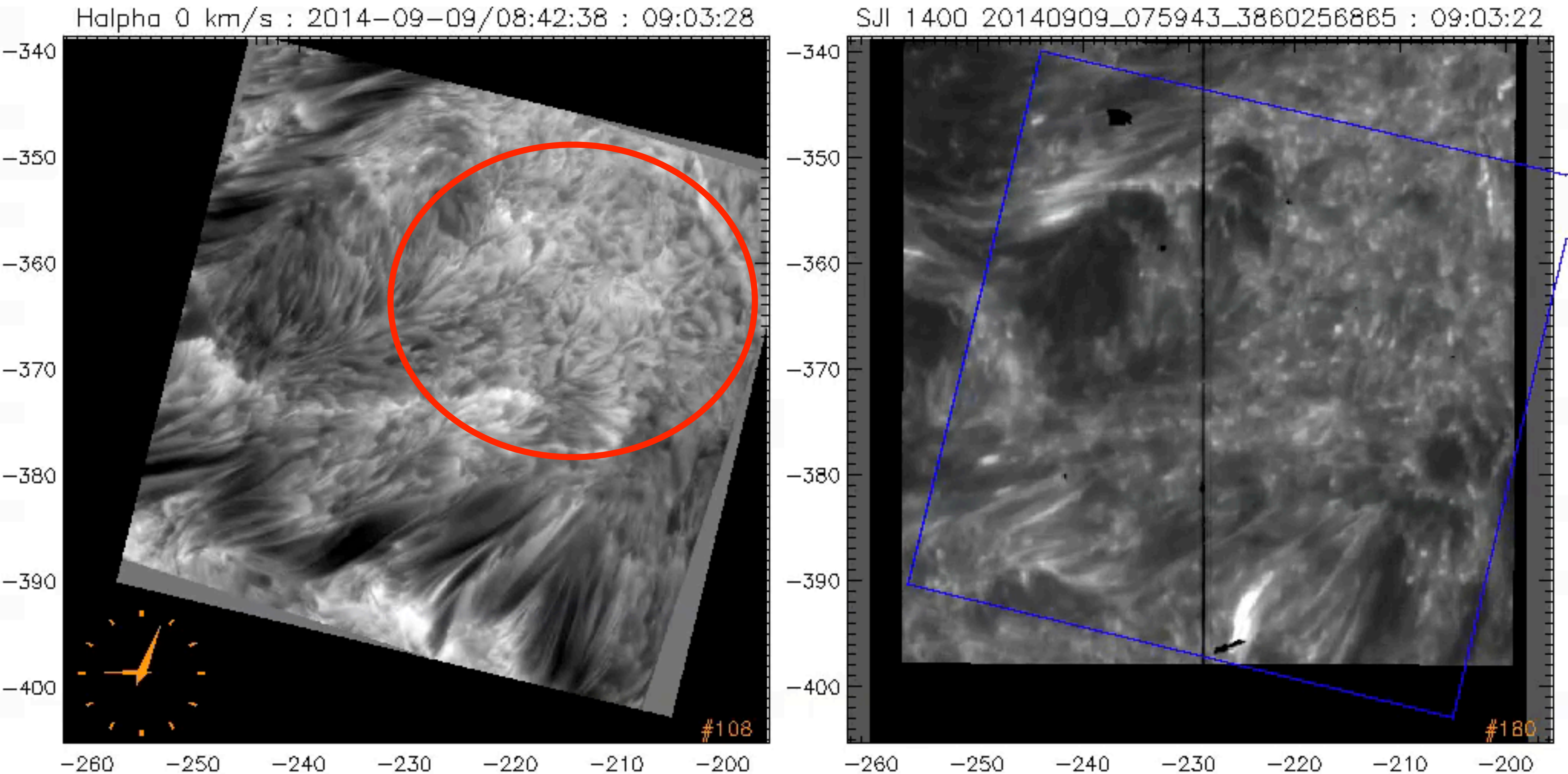
See also talk by Patrick Antolin

Simulations of resonant absorption

courtesy of Joten Okamoto & Patrick Antolin

Impact of the chromosphere on the outer atmosphere

What drives the dynamics of the transition region spectral lines?

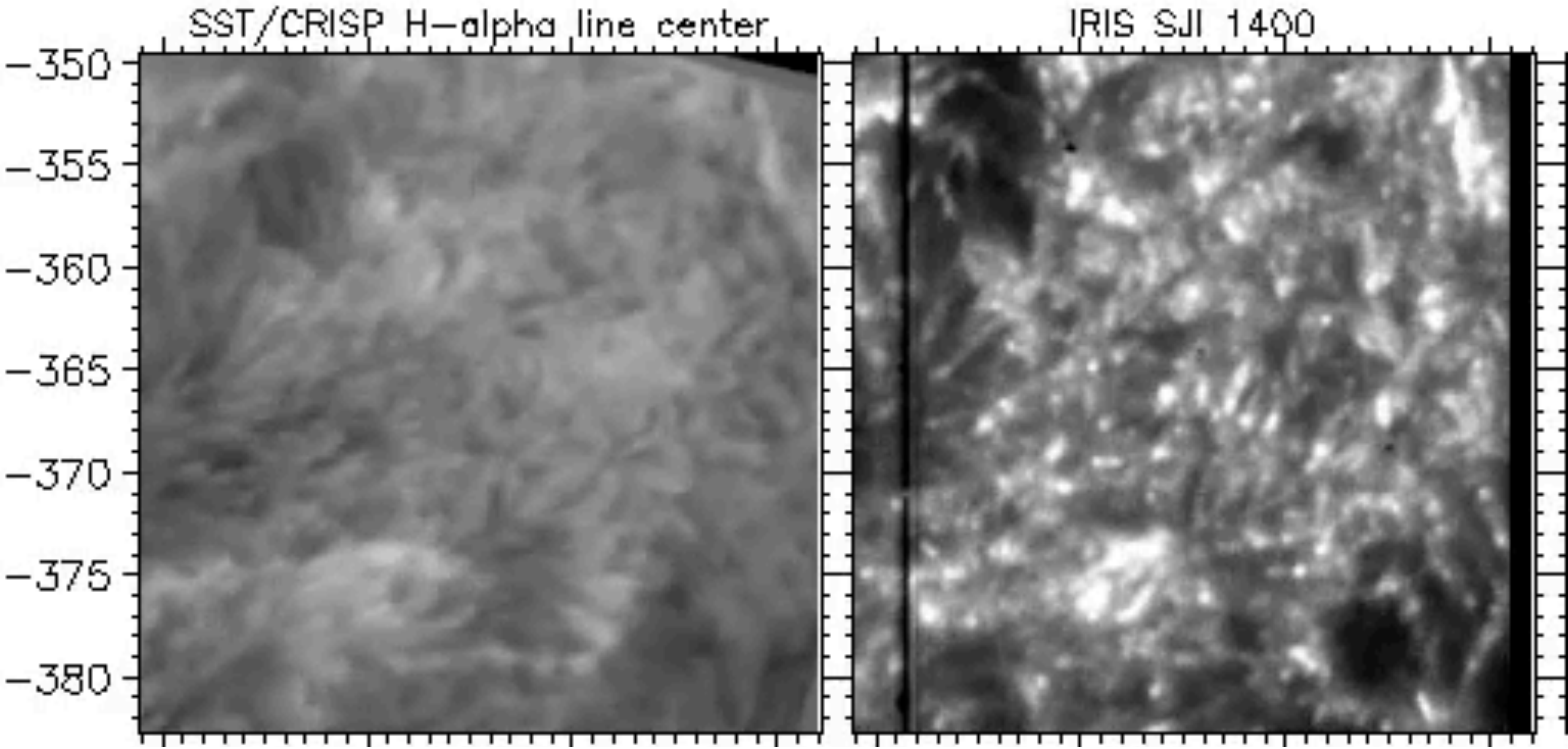


Active region plage: dynamic fibrils (type I spicules)
often associated with Si IV brightenings

Skogsrud et al., 2015

Impact of the chromosphere on the outer atmosphere

What drives the dynamics of the transition region spectral lines?



Active region plage: dynamic fibrils (type I spicules)
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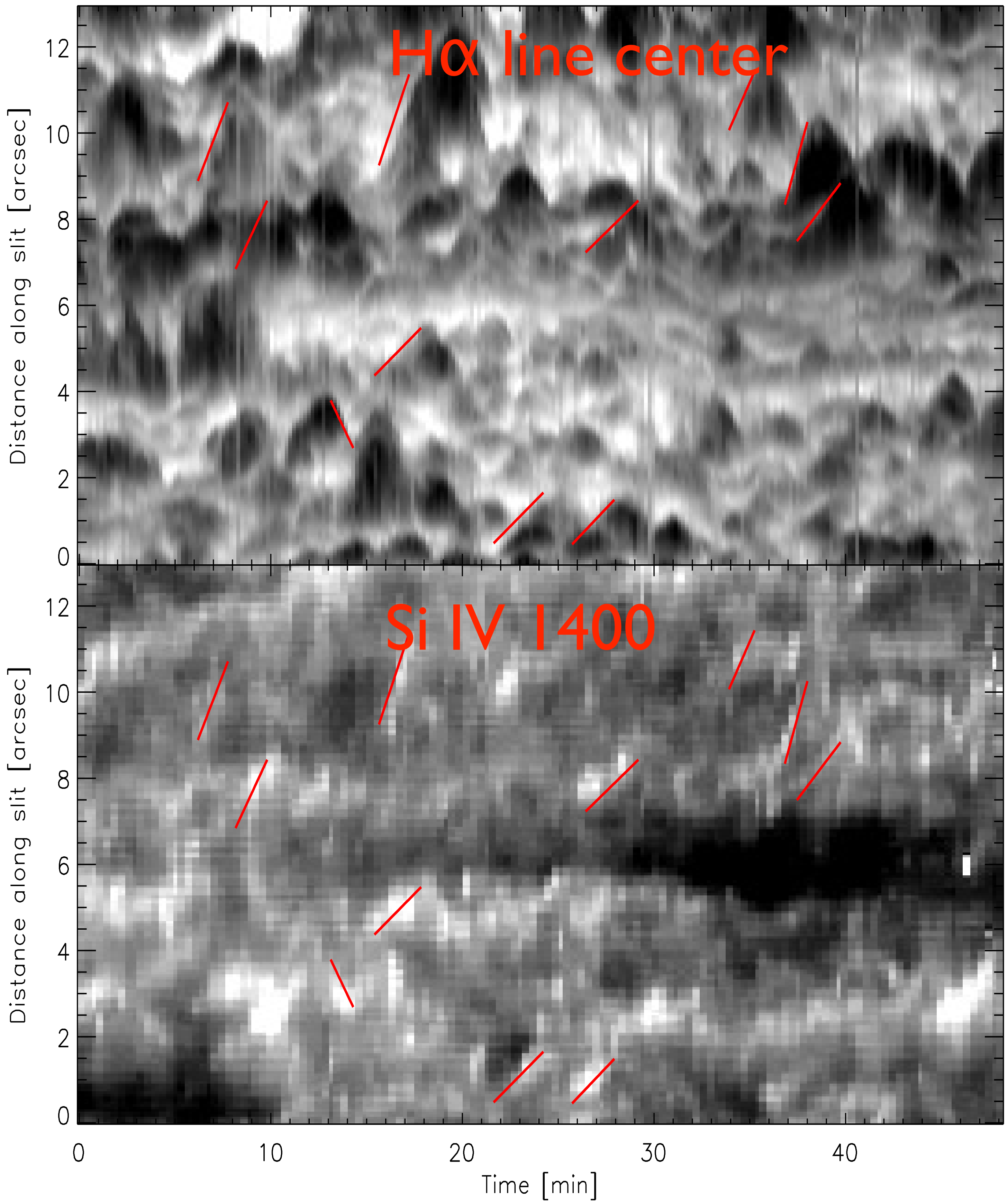
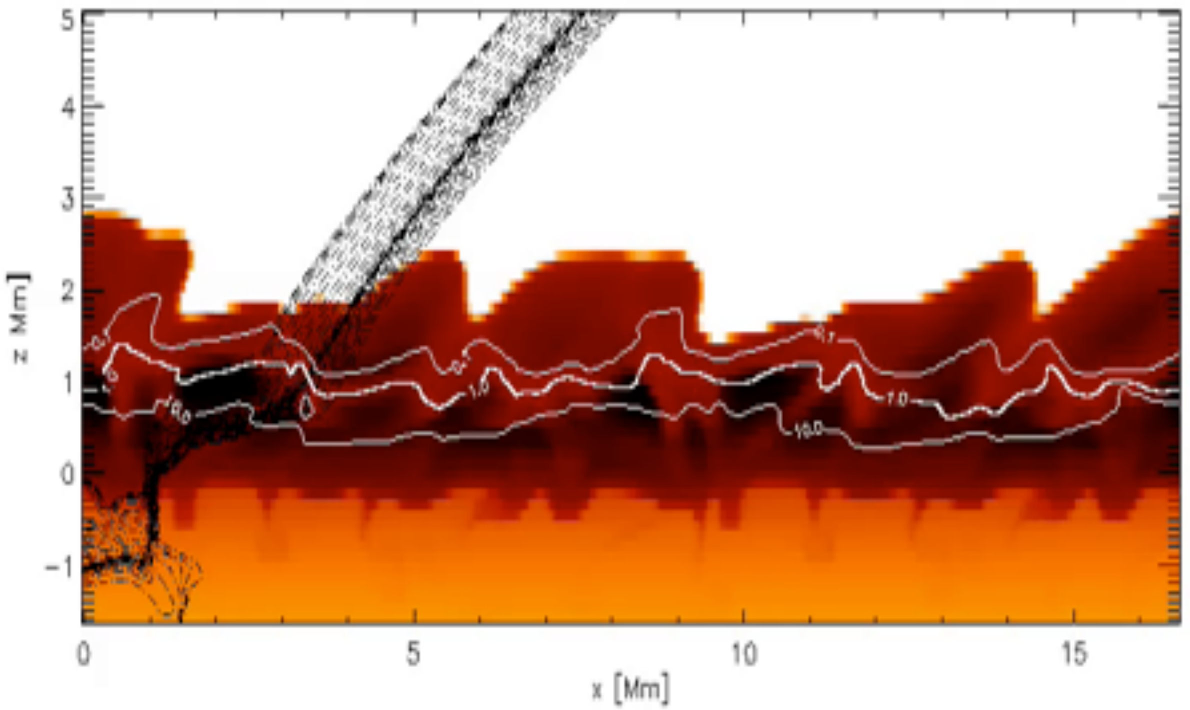
Skogsrud et al., 2015



Dynamic fibrils (type I spicules)
often associated with Si IV brightenings

Skogsrud et al., 2015

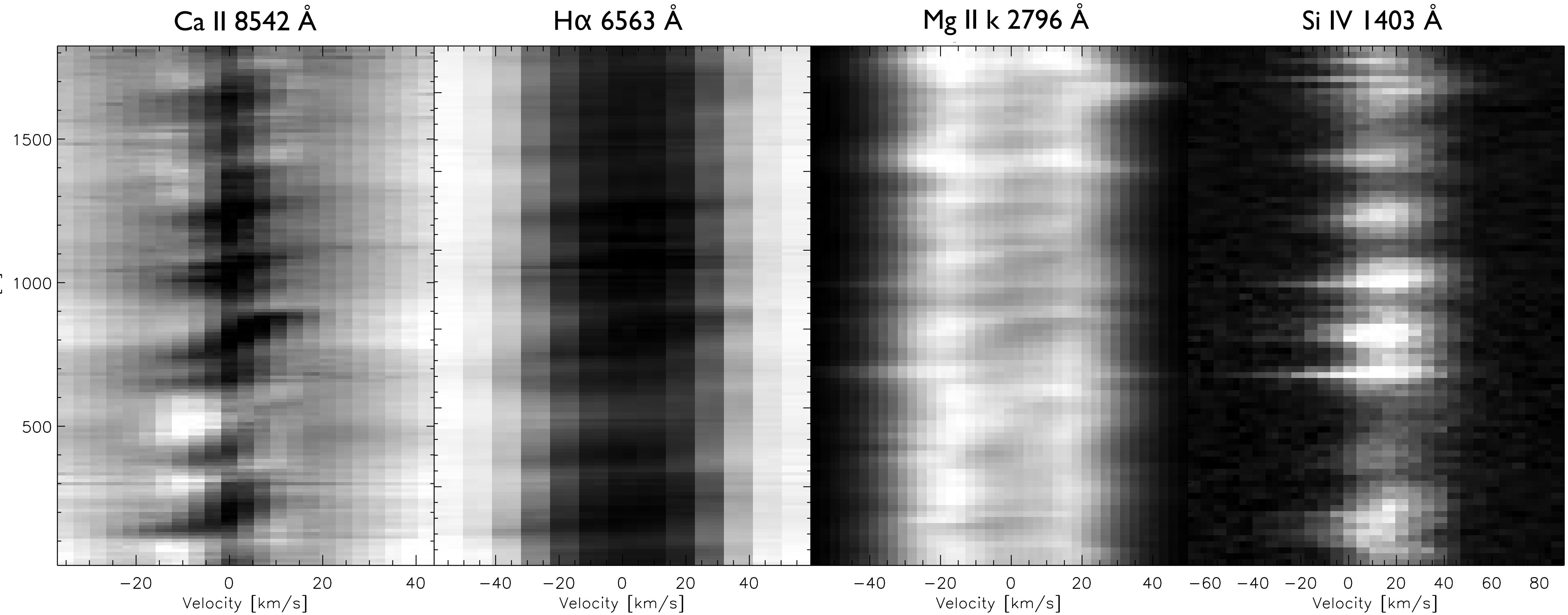
Numerical Simulations



2D/3D radiative MHD simulations show that magneto-acoustic slow-mode shocks in low-beta environment lead to dynamic fibrils and quiet Sun mottles

(Hansteen et al., 2006, De Pontieu et al., 2007, Rouppe van der Voort et al., 2007, Martinez-Sykora et al., 2009)

Transition Region response to dynamic fibrils: Si IV brightening, blueshift and line broadening

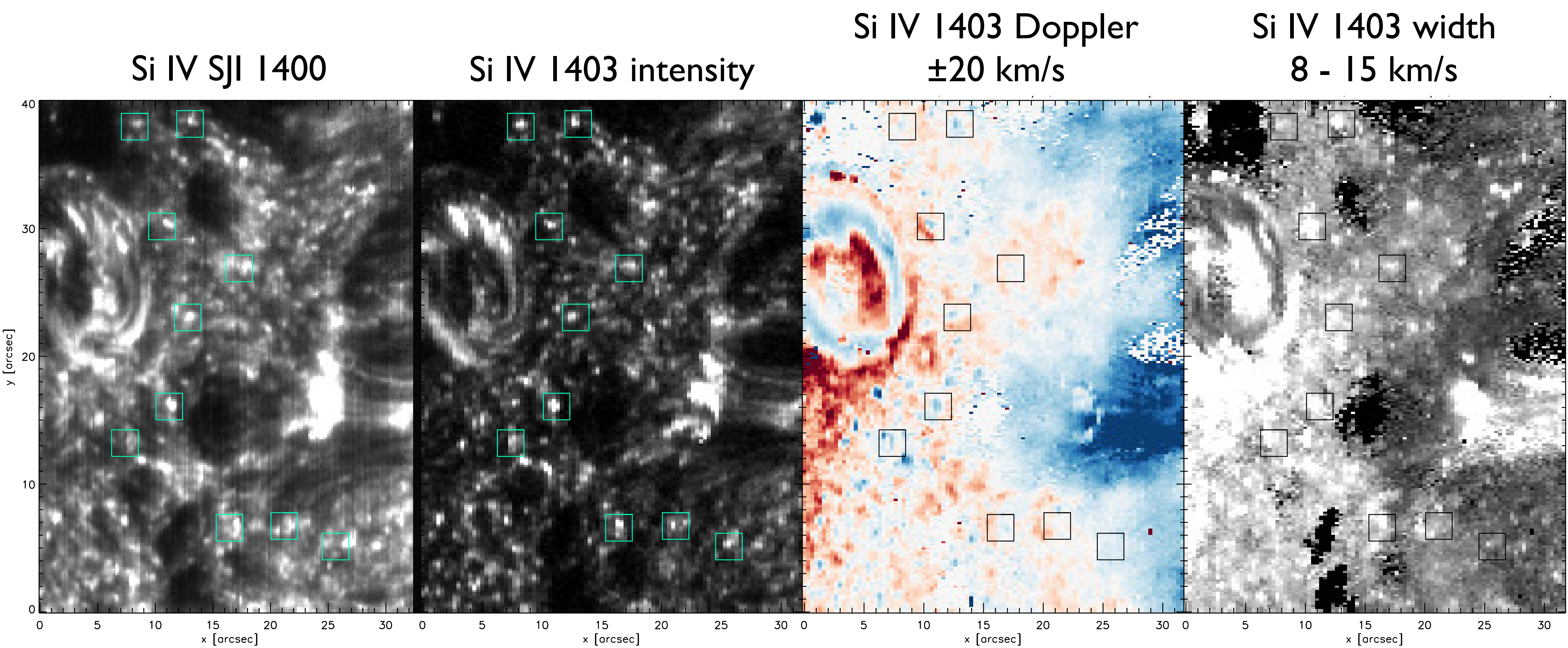


Si IV spectra clearly related to magneto-acoustic shock waves in chromosphere

Combined λ-t plots of Mg IIh and Si IV reveal a frequent connection of Si IV emission/ broadening with shock passage in magnetized regions.

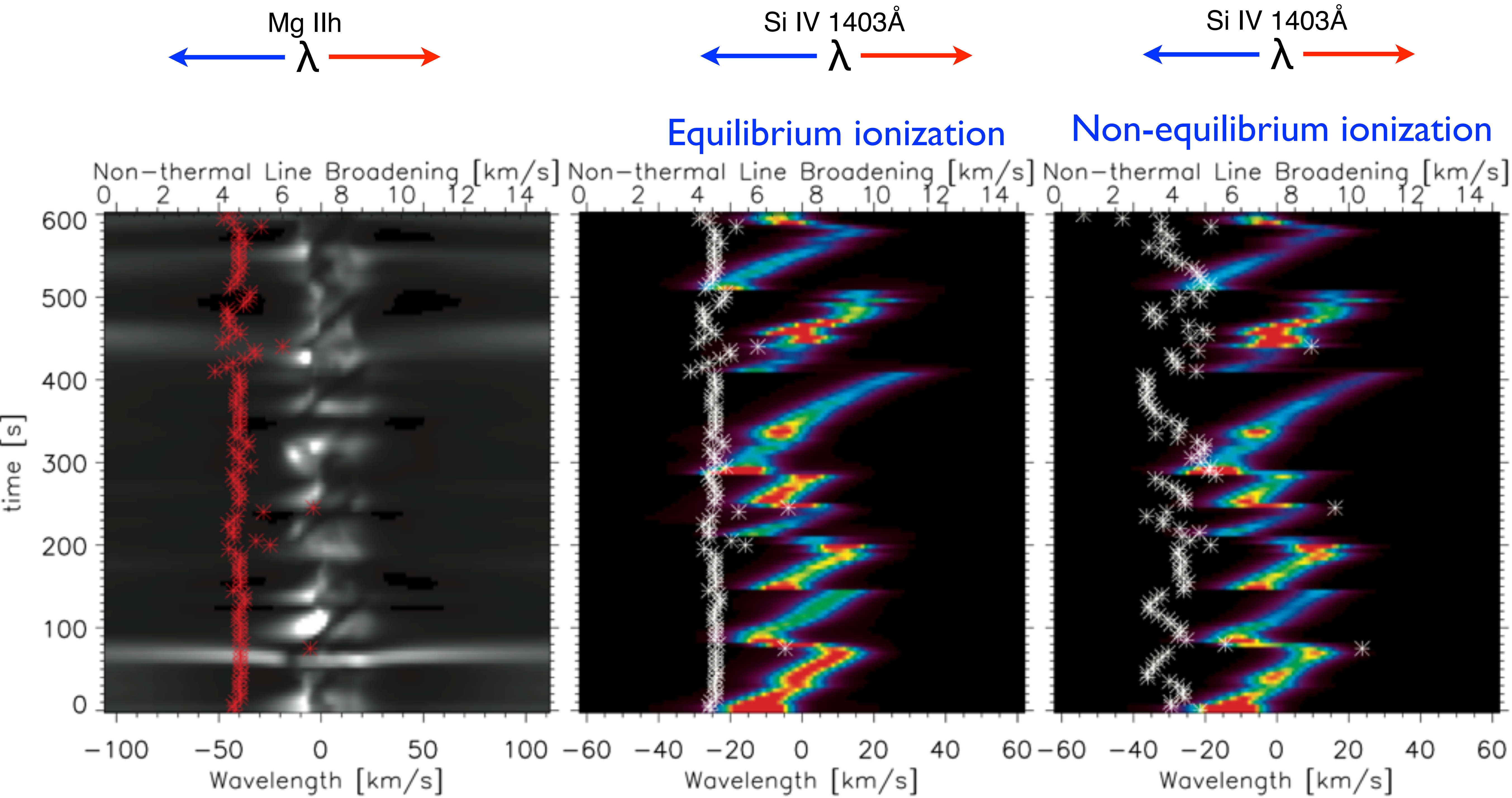
Skogsrud et al., 2015

Transition Region response to dynamic fibrils: Si IV brightening, blueshift and line broadening



Skogsrud et al., 2015

Correlation between chromospheric shocks and TR line broadening also in MHD simulations

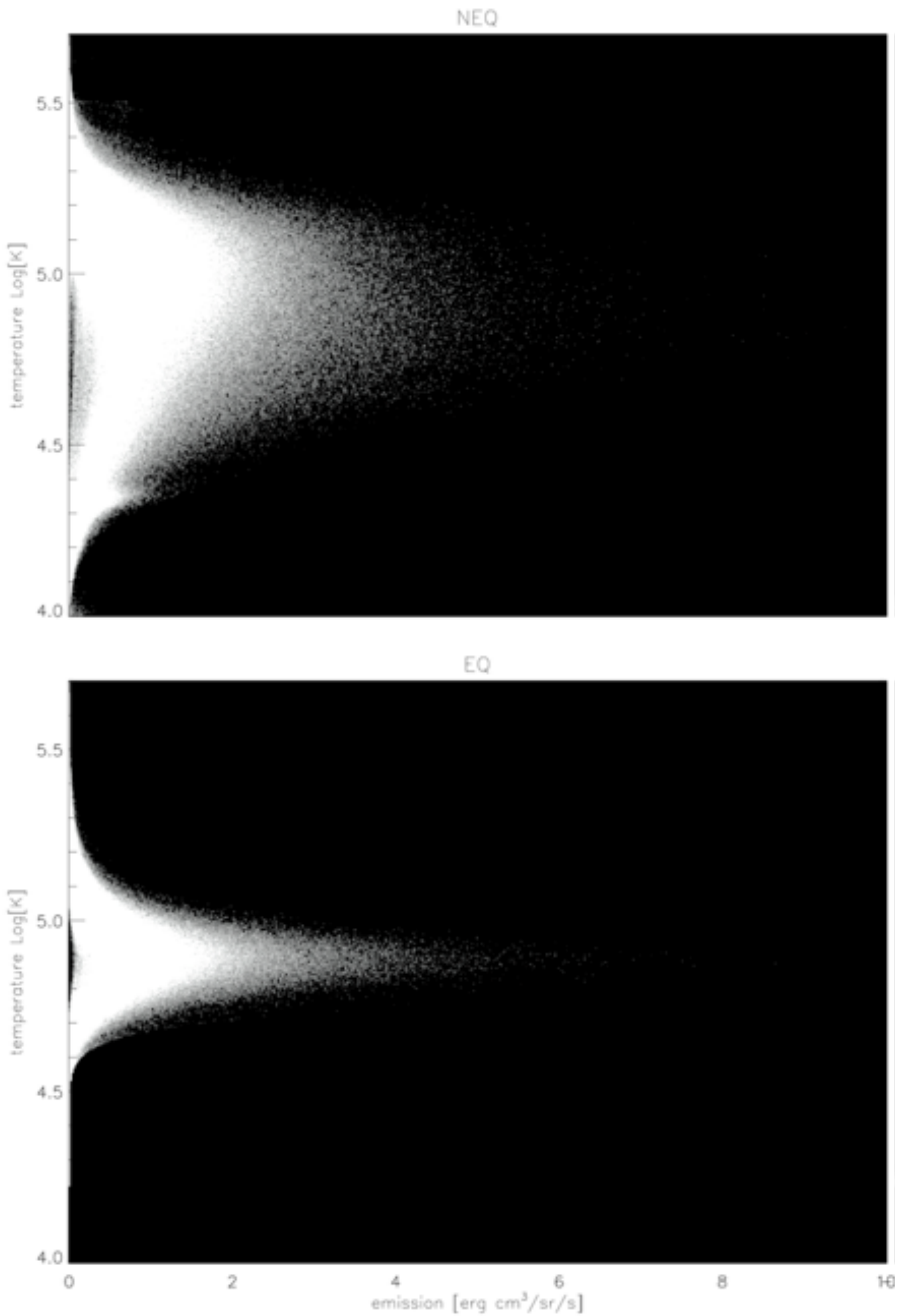


Correlation much stronger in MHD simulations with non-equilibrium ionization of Si 3+

Combined λ-t plots of Mg IIh and Si IV reveal a connection of Si IV emission/broadening with shock passage in magnetized regions

De Pontieu et al., 2015

Non-equilibrium ionization leads to Si IV formation over wider temperature range



Temperature

Non-equilibrium ionization

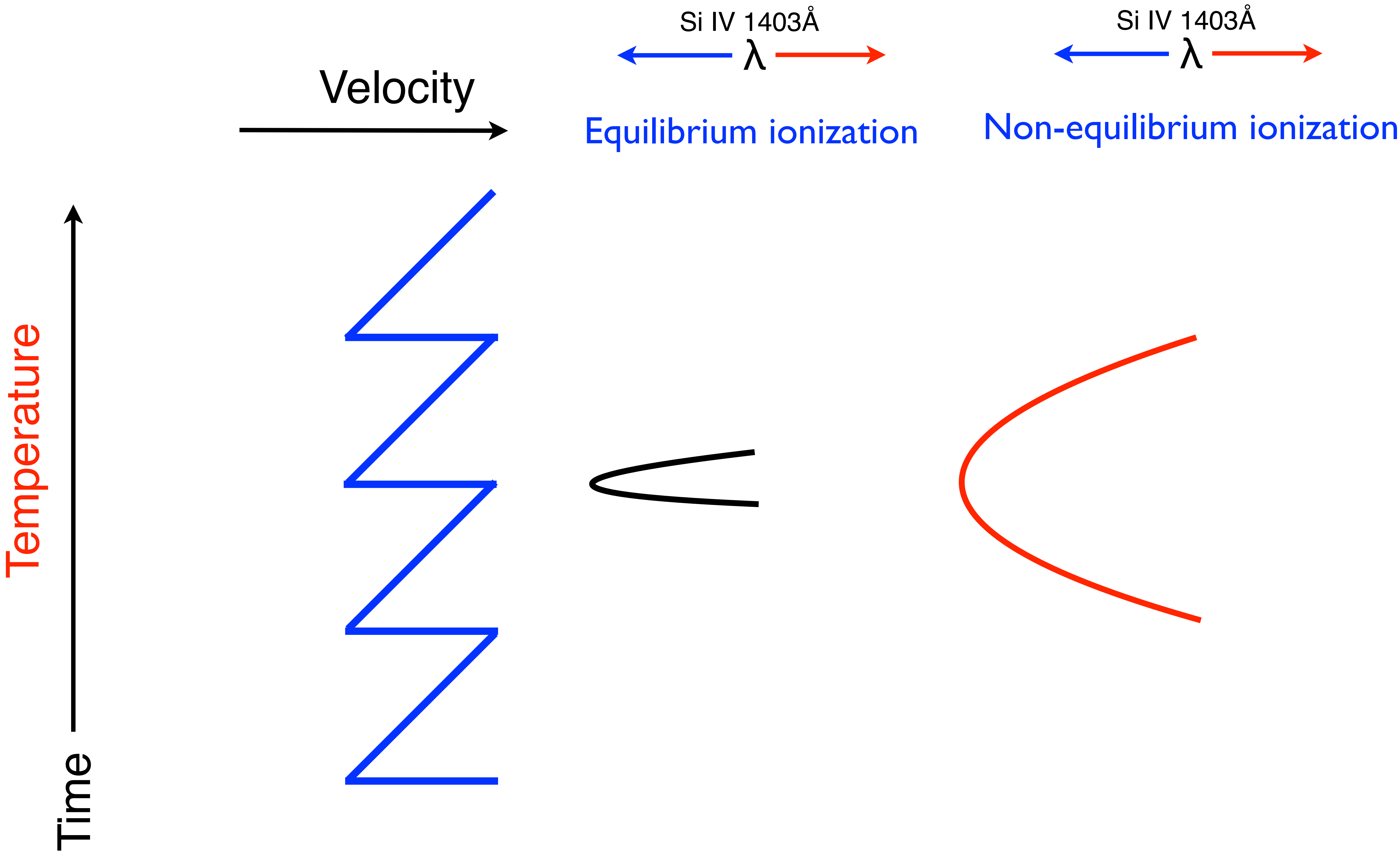
Temperature

Ionization equilibrium

Emission

De Pontieu et al., 2015

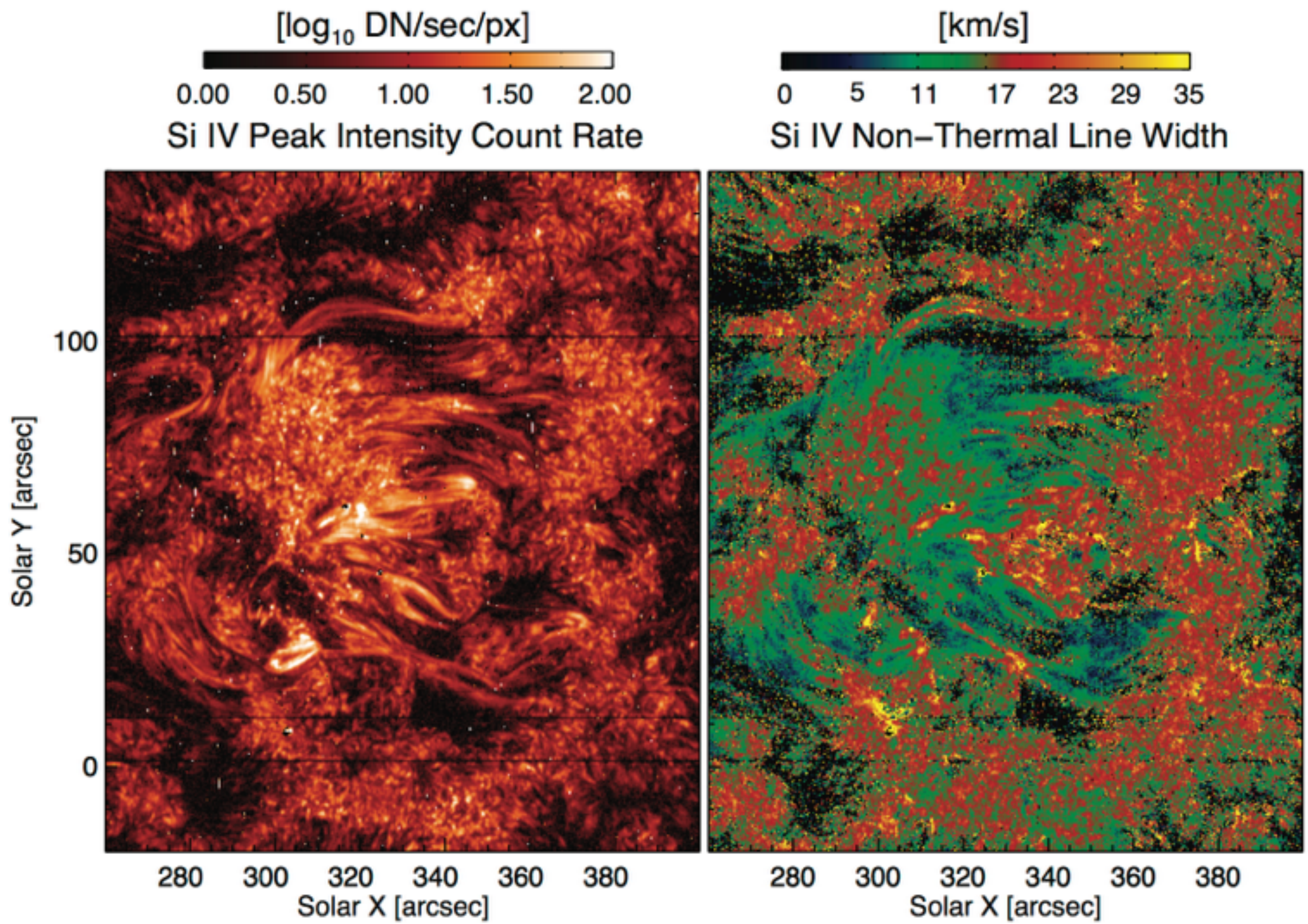
Non-equilibrium ionization leads to Si IV formation over wider temperature range



Wider temperature range leads to larger range of velocities along line-of-sight, and thus non-thermal line broadening, especially during shock passage

De Pontieu et al., 2015

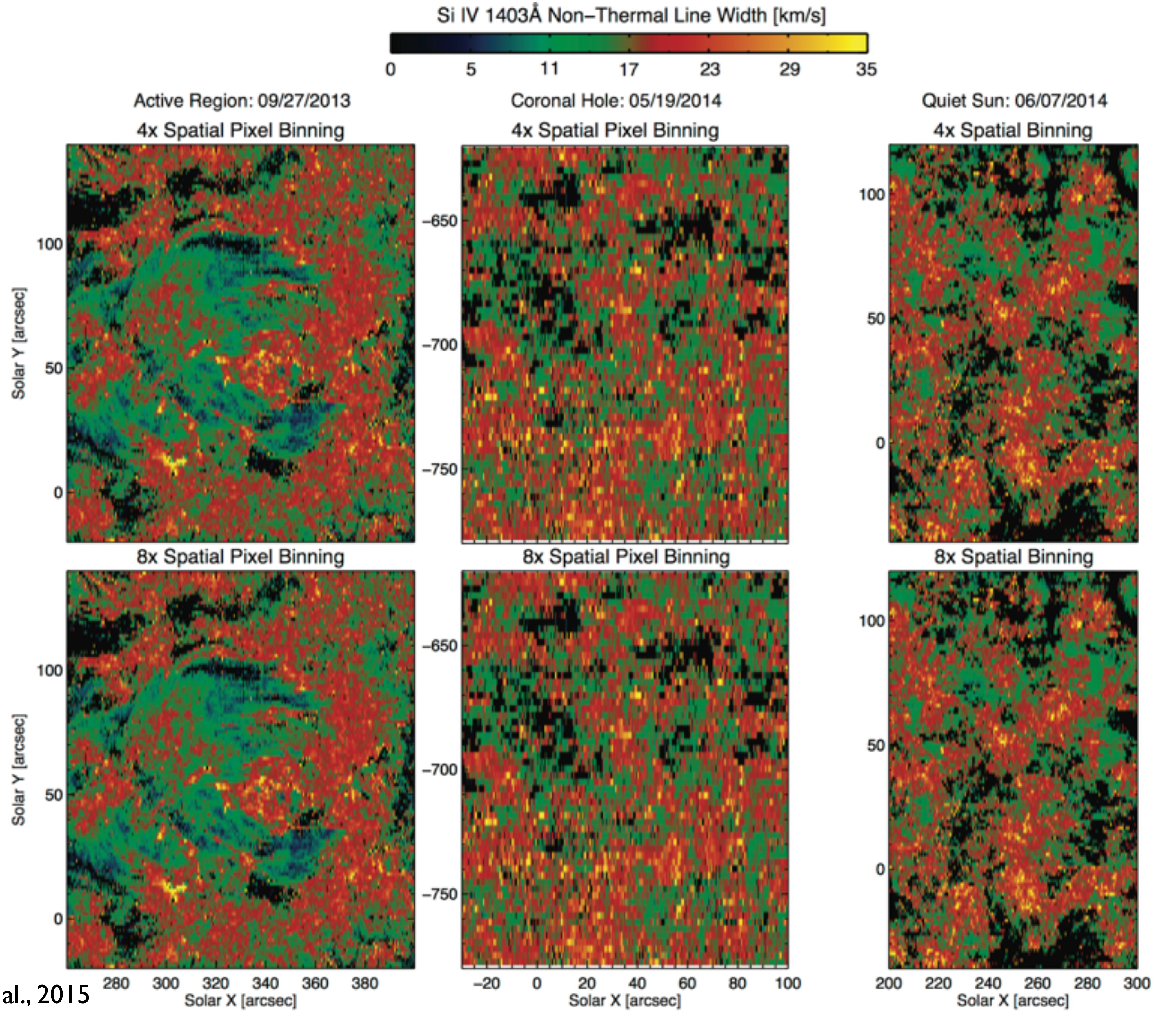
Impact of chromospheric shocks on TR may help explain apparent invariance of non-thermal line broadening to spatial resolution



Why does IRIS (0.33 arcsec, 2.7 km/s) not resolve the non-thermal line broadening of Si IV (~20 km/s) already observed by SUMER (2 arcsec, 8 km/s)?

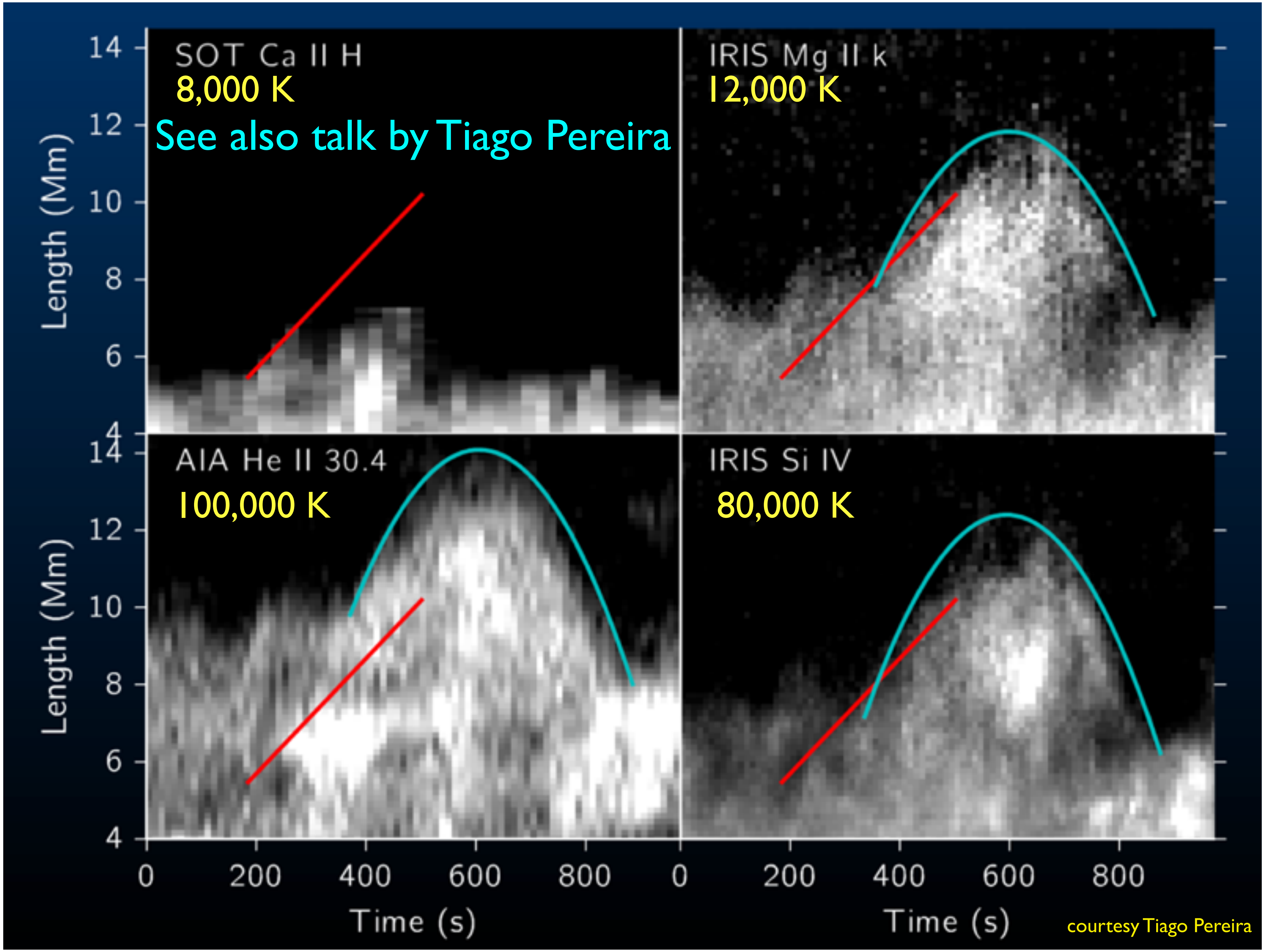
De Pontieu et al., 2015

Rebinning IRIS data to lower resolution confirms the invariance to spatial resolution



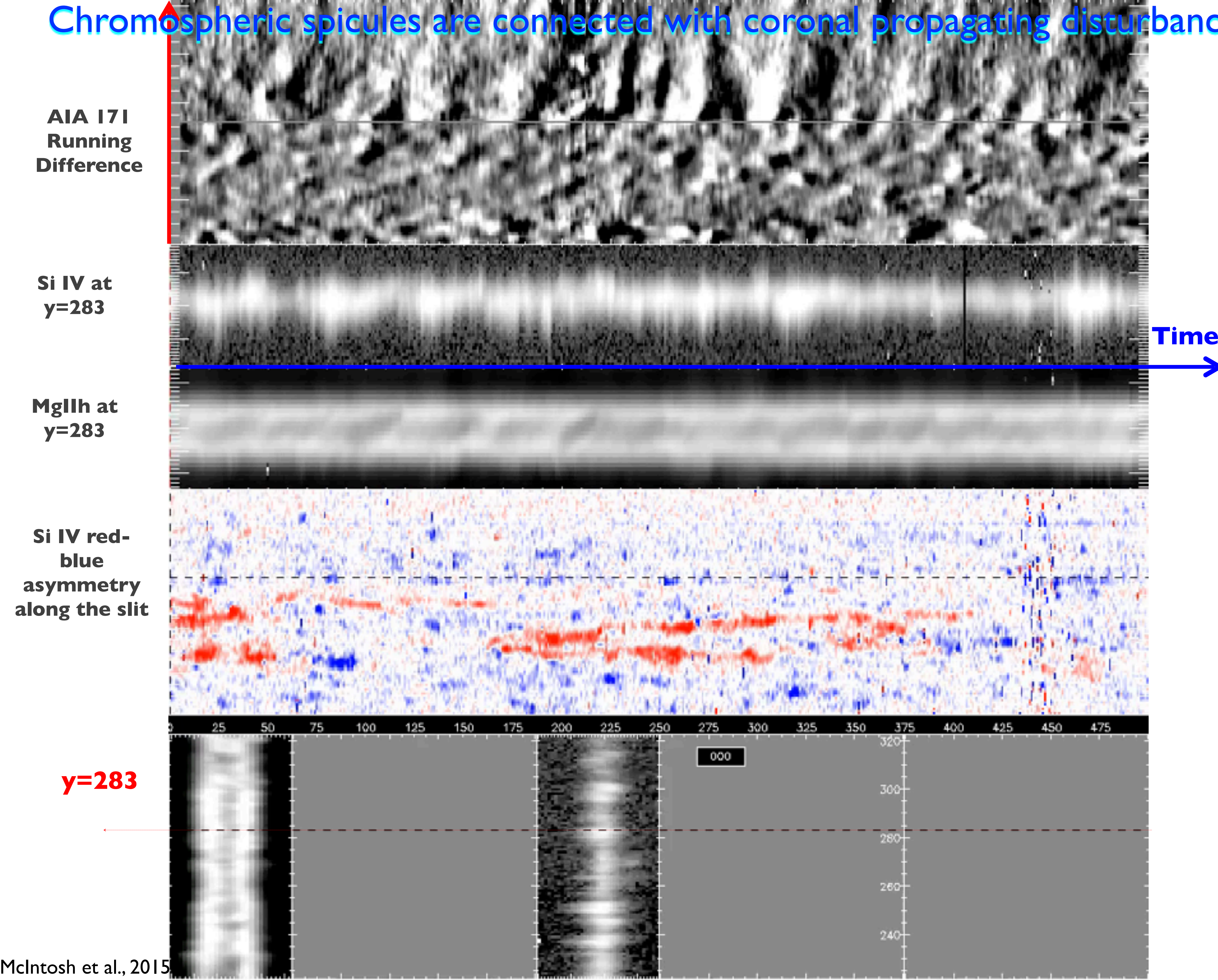
De Pontieu et al., 2015

Chromospheric spicules are heated to transition region temperatures



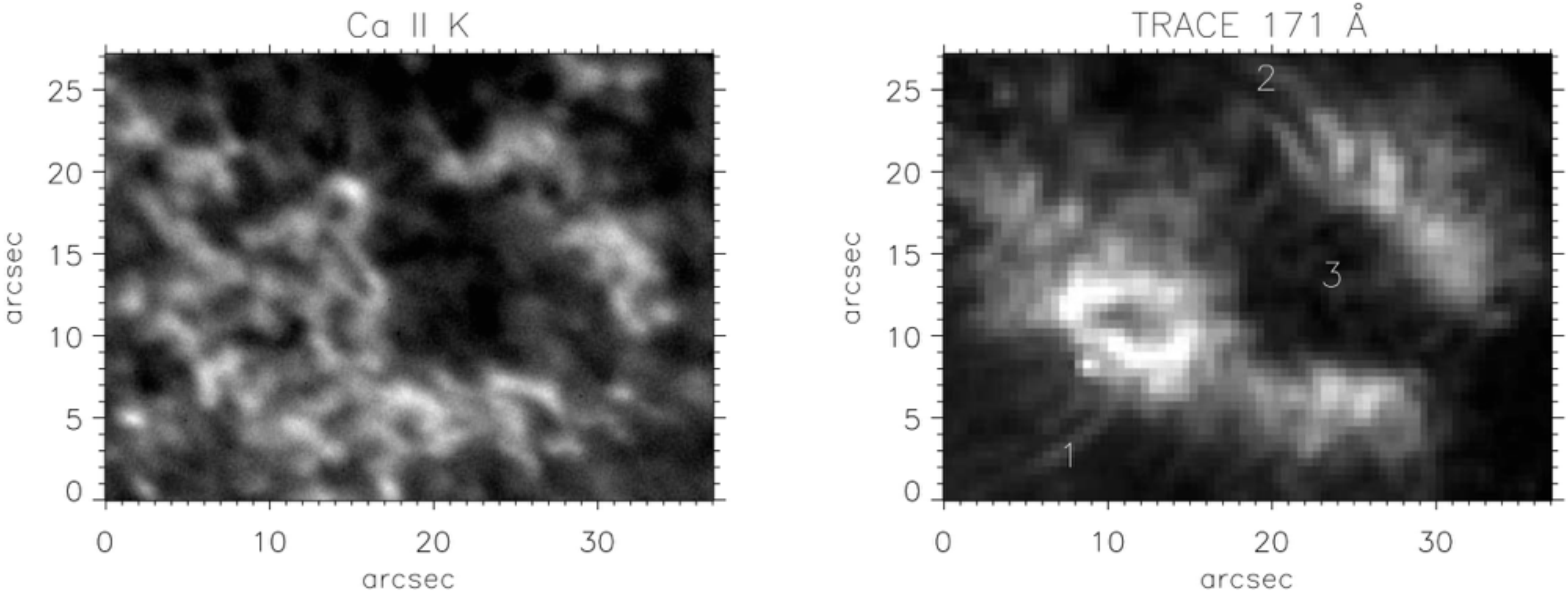
Ca II H spicules are the initial, rapid phase of violent upward motions
Followed by Mg II k and Si IV spicules which are the extensions of Ca II H

Chromospheric spicules are connected with coronal propagating disturbances



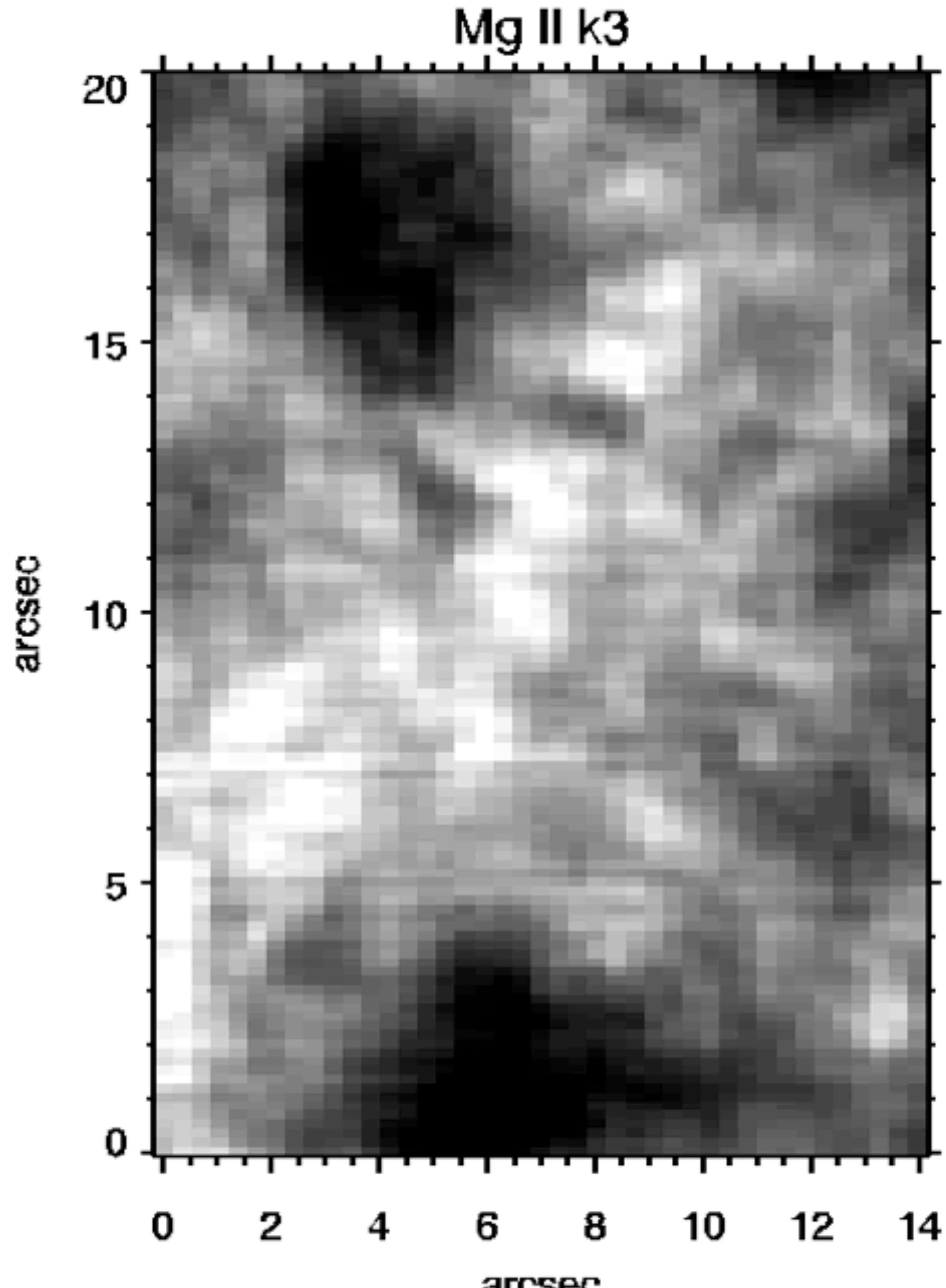
McIntosh et al., 2015

Chromospheric and coronal heating are linked on global scales



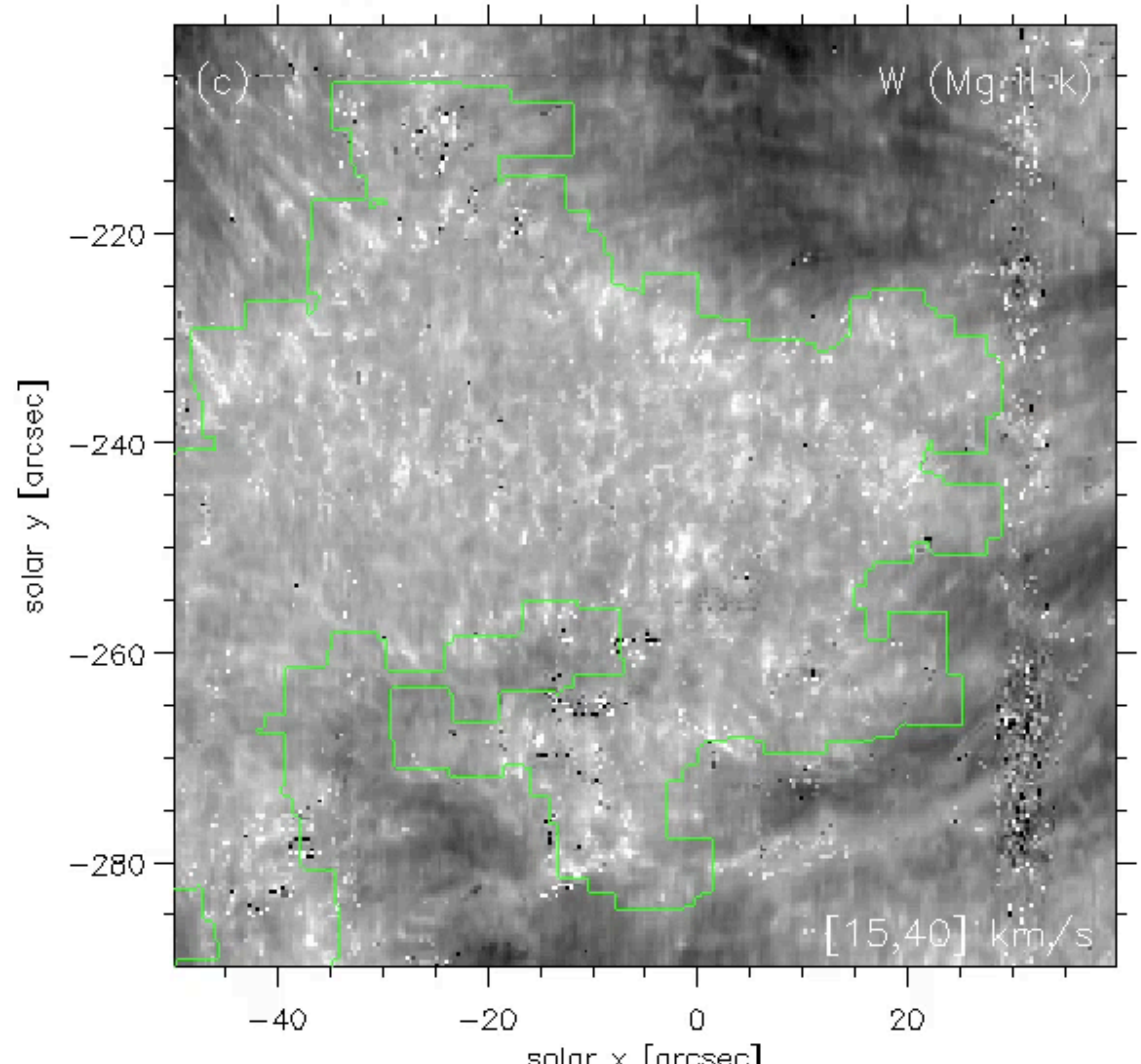
But on small, subarcsec scales, previous observations did not find a good correlation (e.g., moss brightness and Ca II k emission in plage, De Pontieu et al., 2003)

Connection between chromospheric and coronal heating in plage



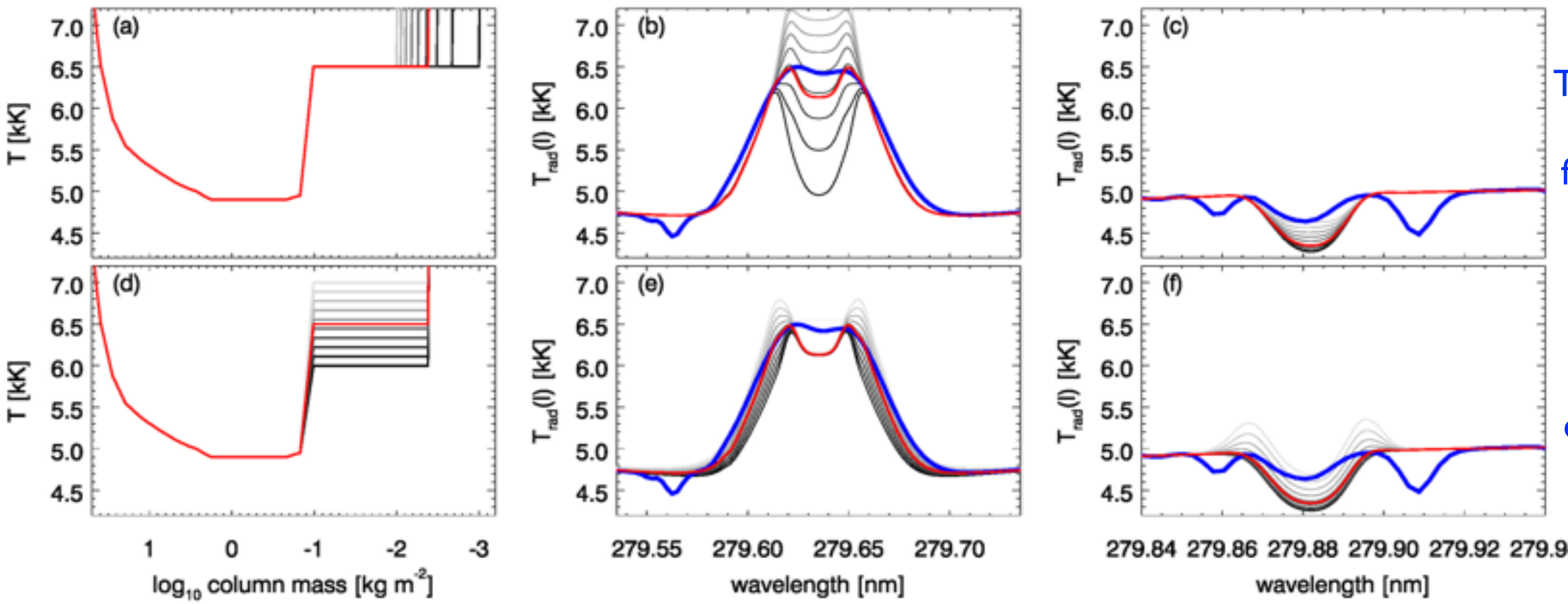
Footpoints of loops show tight connection between moss brightness and chromospheric dynamics (dynamic fibrils)

Connection between chromospheric and coronal heating in plage



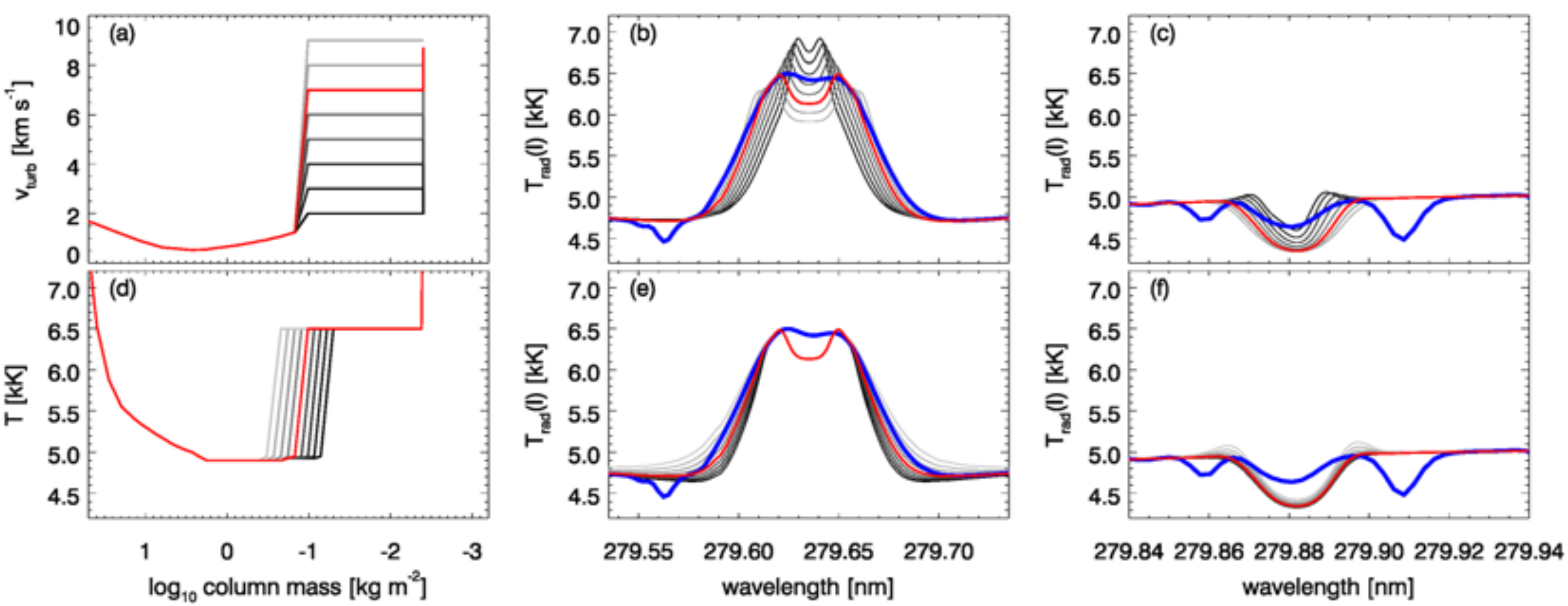
Footpoints of loops show connection between "filled in profiles" and chromospheric heating
i.e., connection between chromospheric heating and coronal pressure?

Pushing a toy model to its limits: constraints on plage properties



TR at high column mass (low heights) causes filled-in Mg II k profiles

Temperatures above 6500K would lead to emission of subordinate line



Non-Thermal motions broaden wings of Mg II k

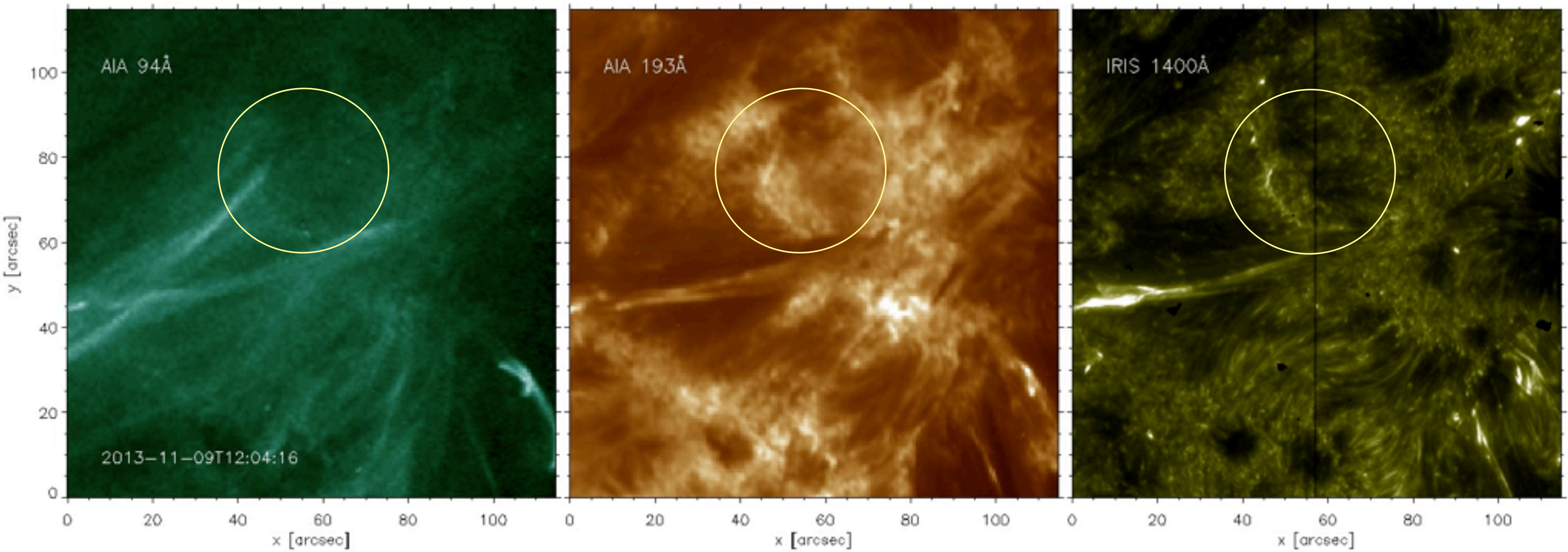
Height of step in T also affects wings of Mg II k

Investigating sensitivity of plage Mg II k profiles to hydrostatic model properties

Impact of coronal nanoflares and non-thermal electrons on the chromosphere

IRIS often observes short-lived brightenings (<30s) at footpoints of hot loops: signature of small-scale heating events in corona

SDO, 6 MK SDO, 1.5 MK IRIS, 0.08 MK



Chromosphere and transition region
sensitive diagnostics of coronal heating processes

See also talk by Paola Testa

Testa et al., Science, 2014

Outline of the Talk

1. Brief introduction to chromospheric dynamics and morphology
2. Chromospheric Heating
   - Plage heating: ~6,500 K
   - Heating from braiding
   - Heating from ion-neutral interactions
   - Heating from wave dissipation: Alfven waves, resonant absorption

3. Connections to outer atmosphere
   - Impact of chromosphere on transition region
     - shocks, non-thermal line broadening
     - jets and spicules: heating to TR (maybe coronal) temperatures
   - Correlation between chromospheric and coronal heating