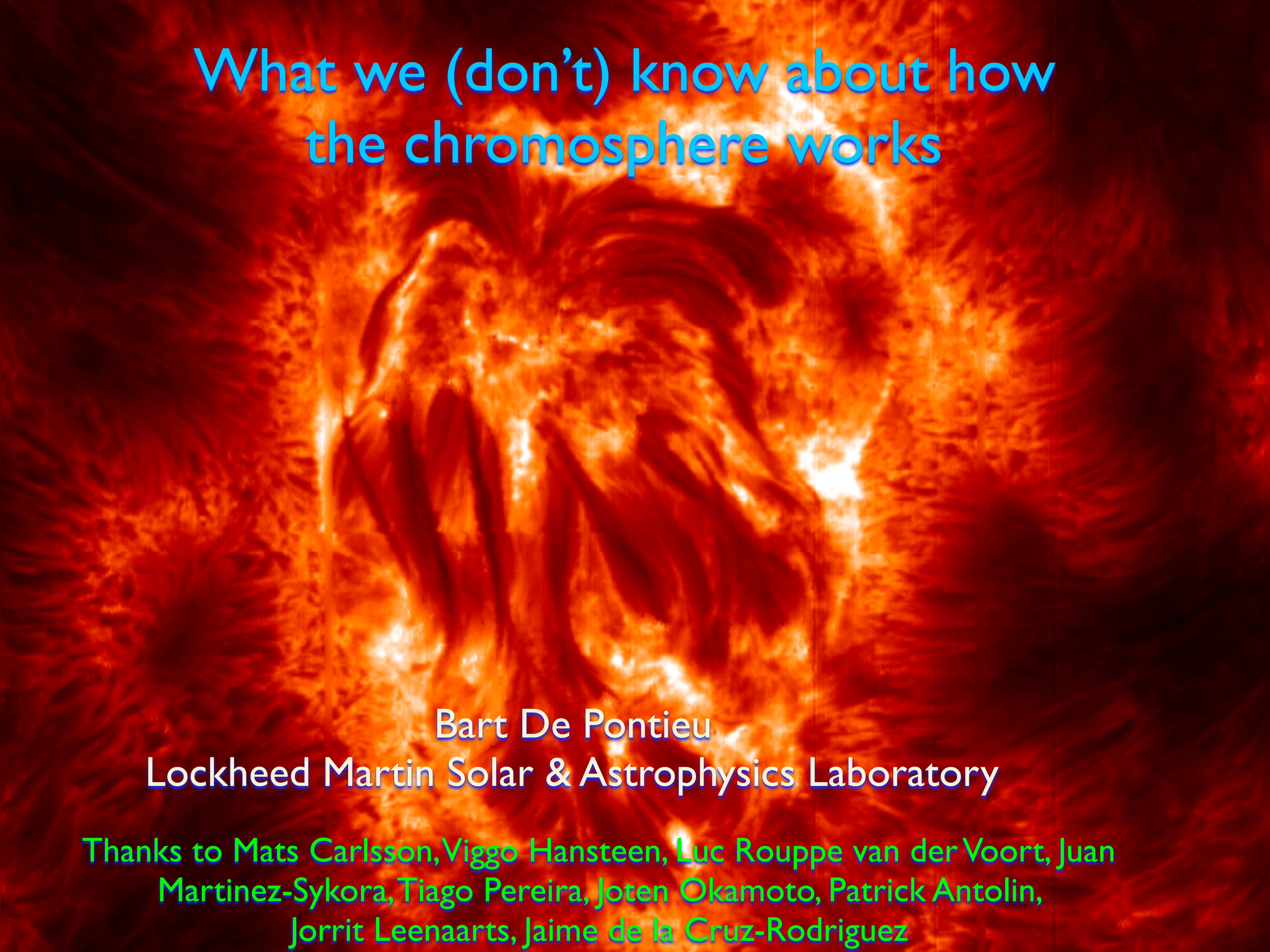
What we (don't) know about how the chromosphere works



Bart De Pontieu

Lockheed Martin Solar & Astrophysics Laboratory

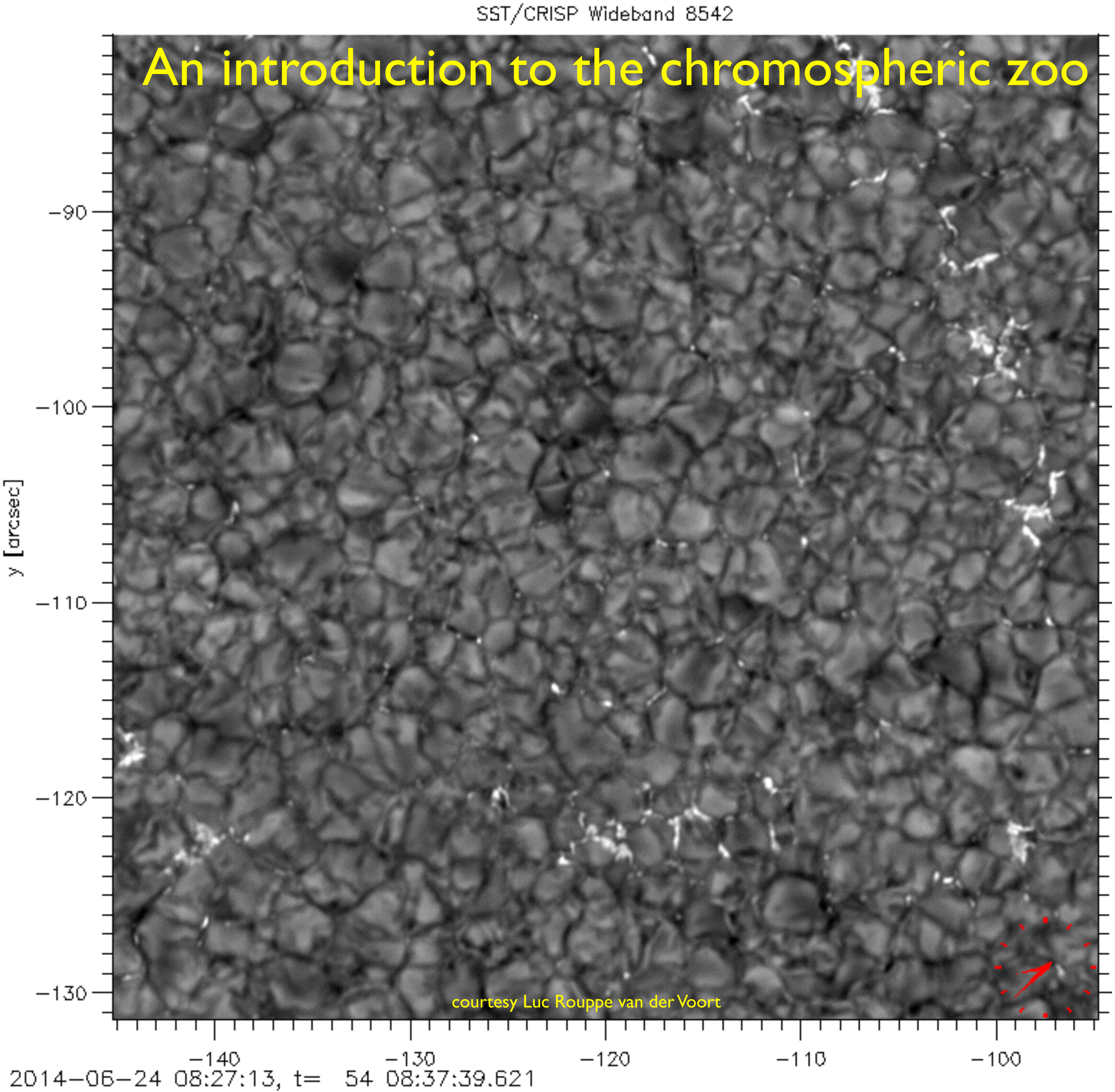
Thanks to Mats Carlsson, Viggo Hansteen, Luc Rouppe van der Voort, Juan Martinez-Sykora, Tiago Pereira, Joten Okamoto, Patrick Antolin, Jorrit Leenaarts, Jaime de la Cruz-Rodriguez

What do we (not) know about the chromosphere?

so much…

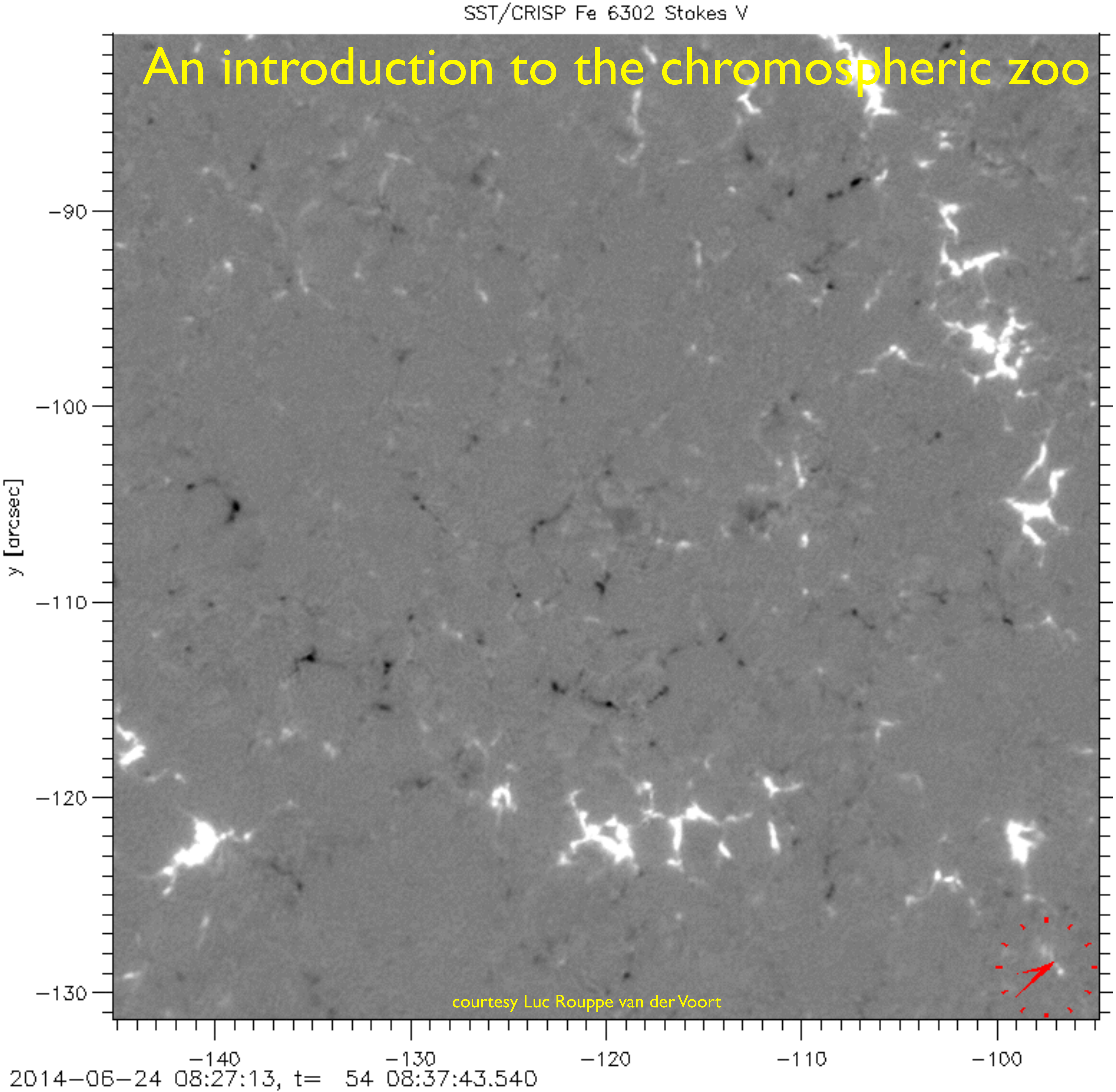
Luc Rouppe van der Voort, Michiel van Noort, SST/ITA October 4 2005

An introduction to the chromospheric zoo



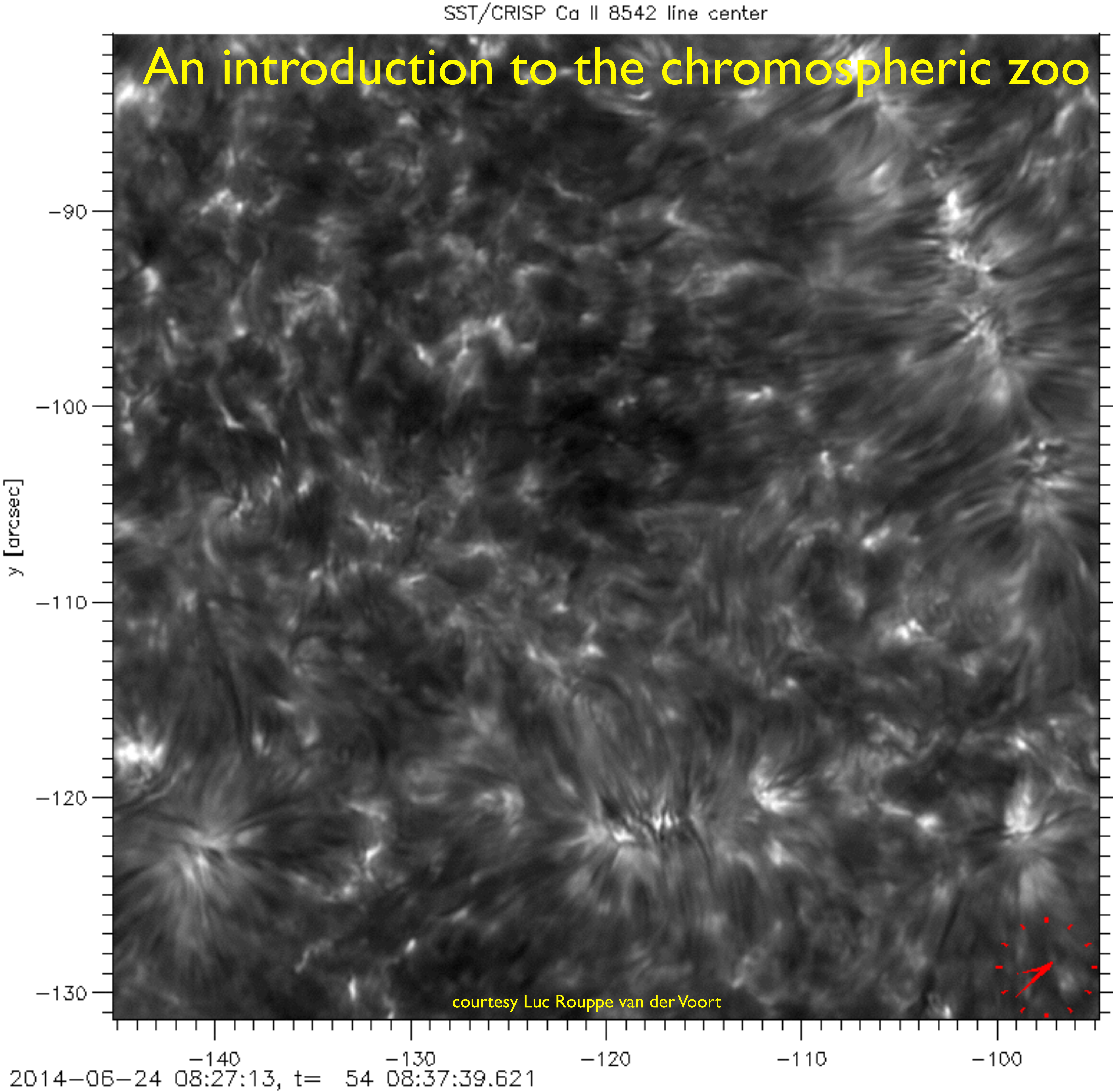
courtesy Luc Rouppe van der Voort

An introduction to the chromospheric zoo



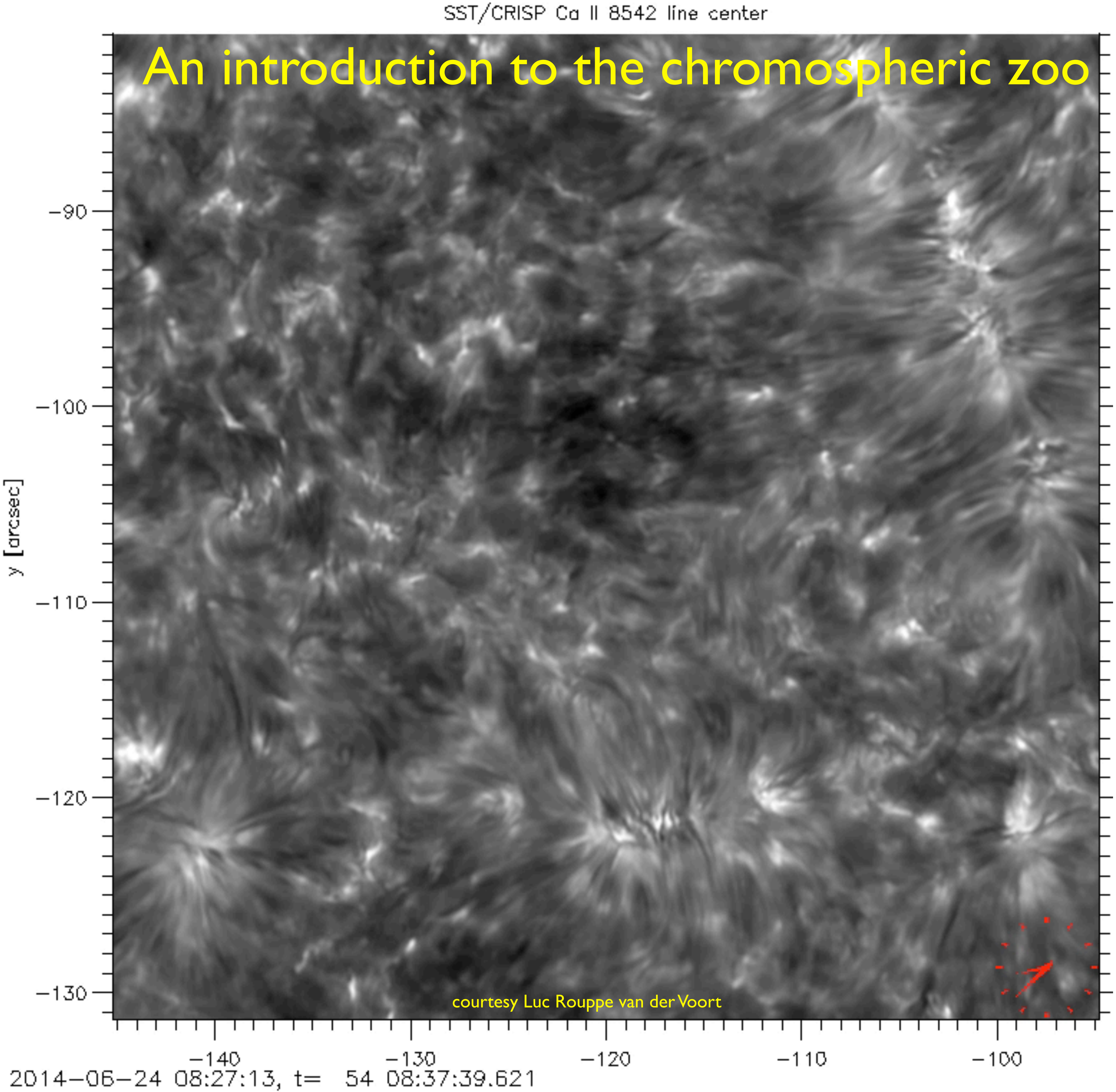
courtesy Luc Rouppe van der Voort

An introduction to the chromospheric zoo



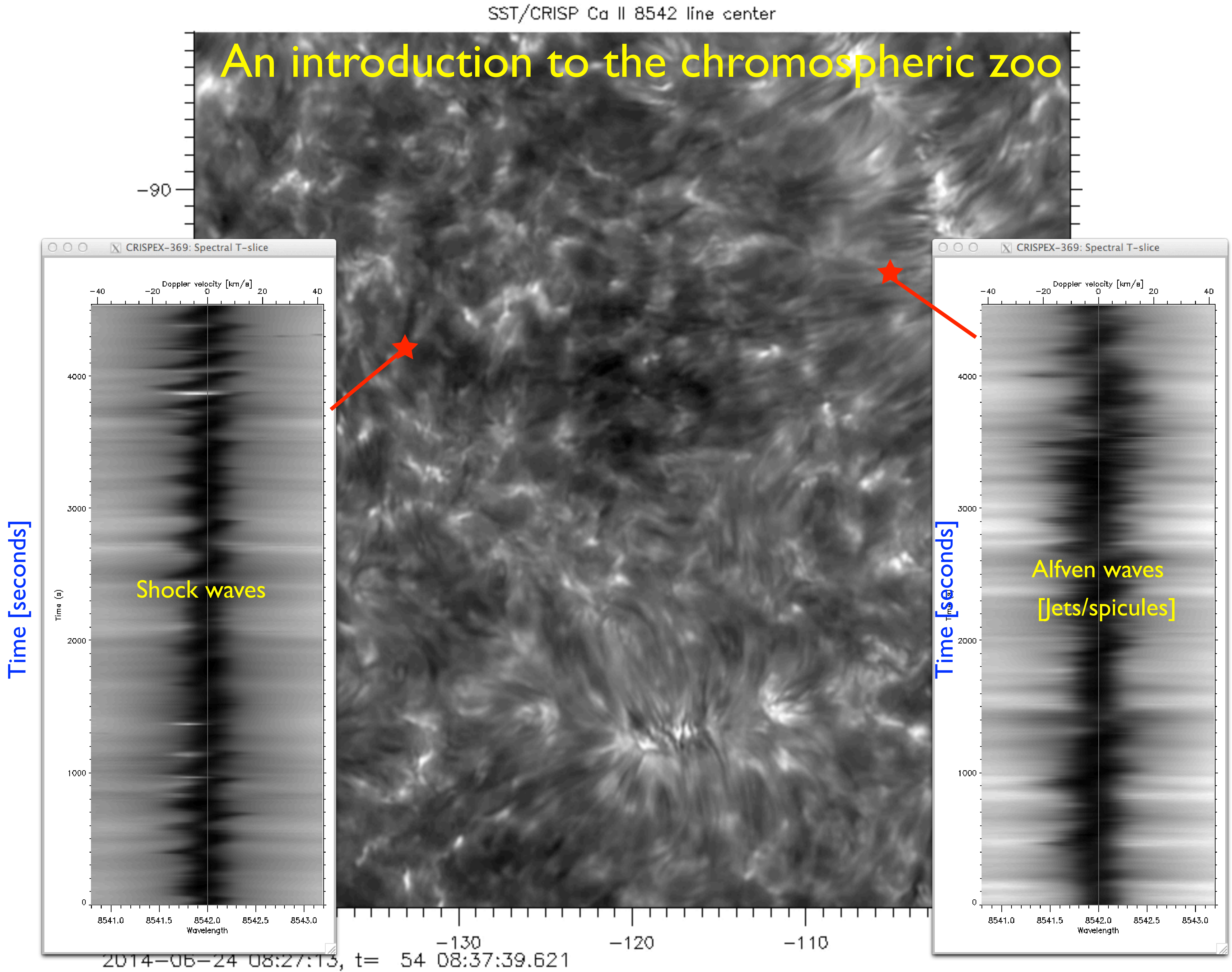
courtesy Luc Rouppe van der Voort

An introduction to the chromospheric zoo



courtesy Luc Rouppe van der Voort

An introduction to the chromospheric zoo



Time [seconds]

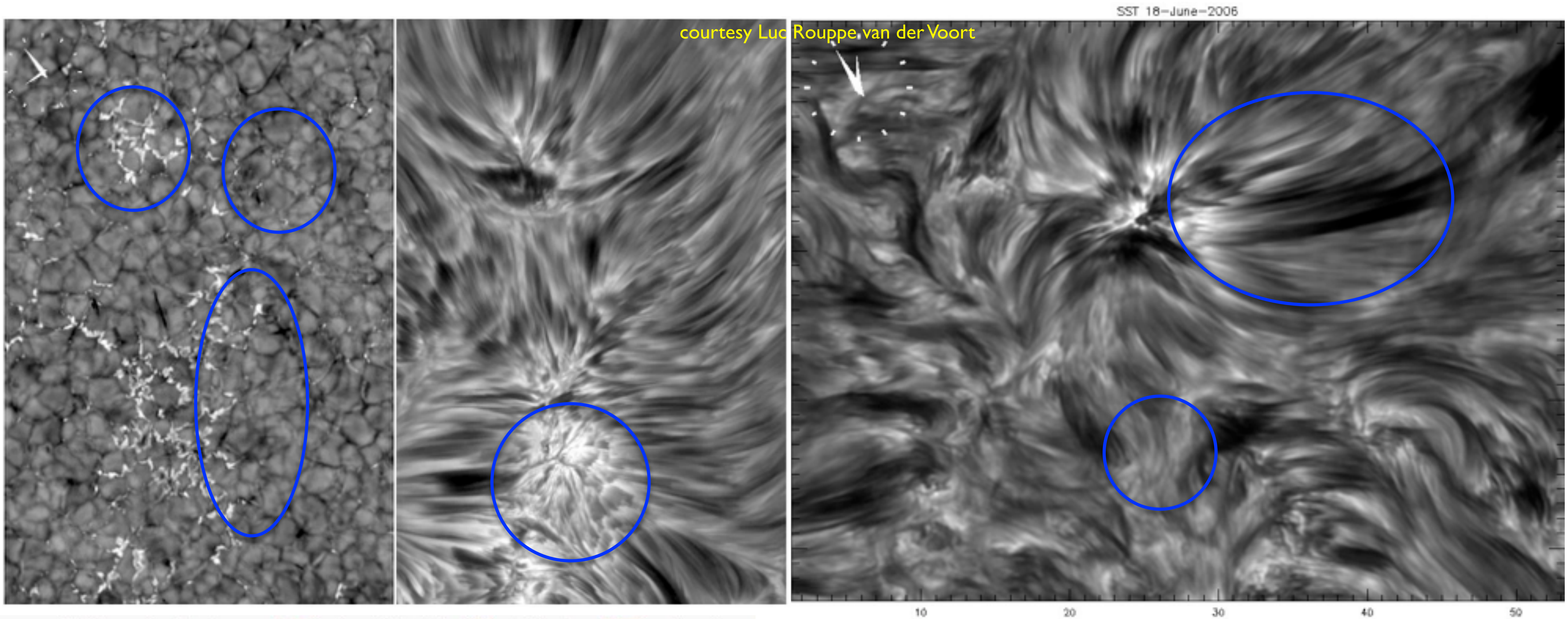
Shock waves

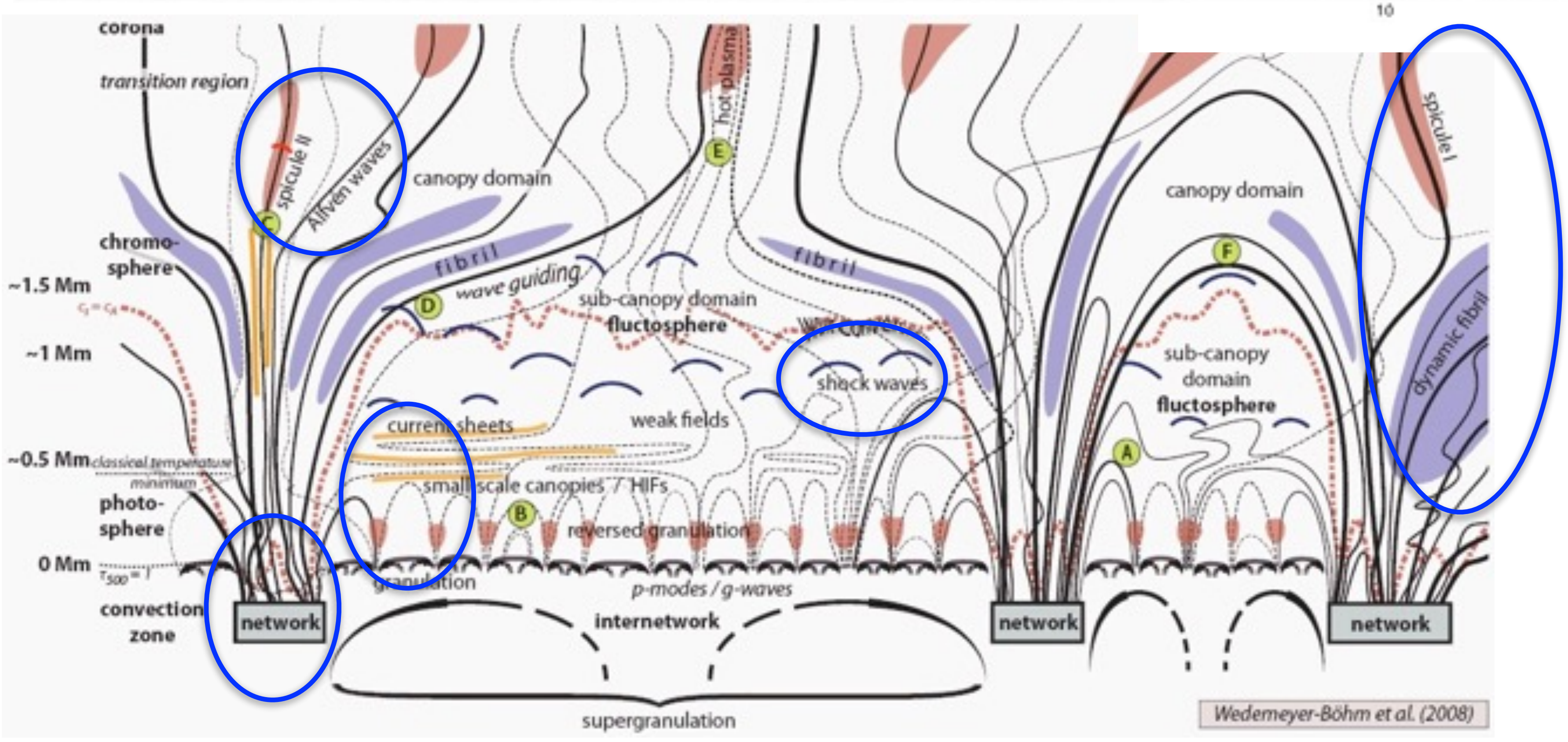
Time [seconds]

Alfven waves

[Jets/spicules]

An introduction to the chromospheric zoo


courtesy Luc Rouppe van der Voort


Wedemeyer-Böhm et al. (2008)

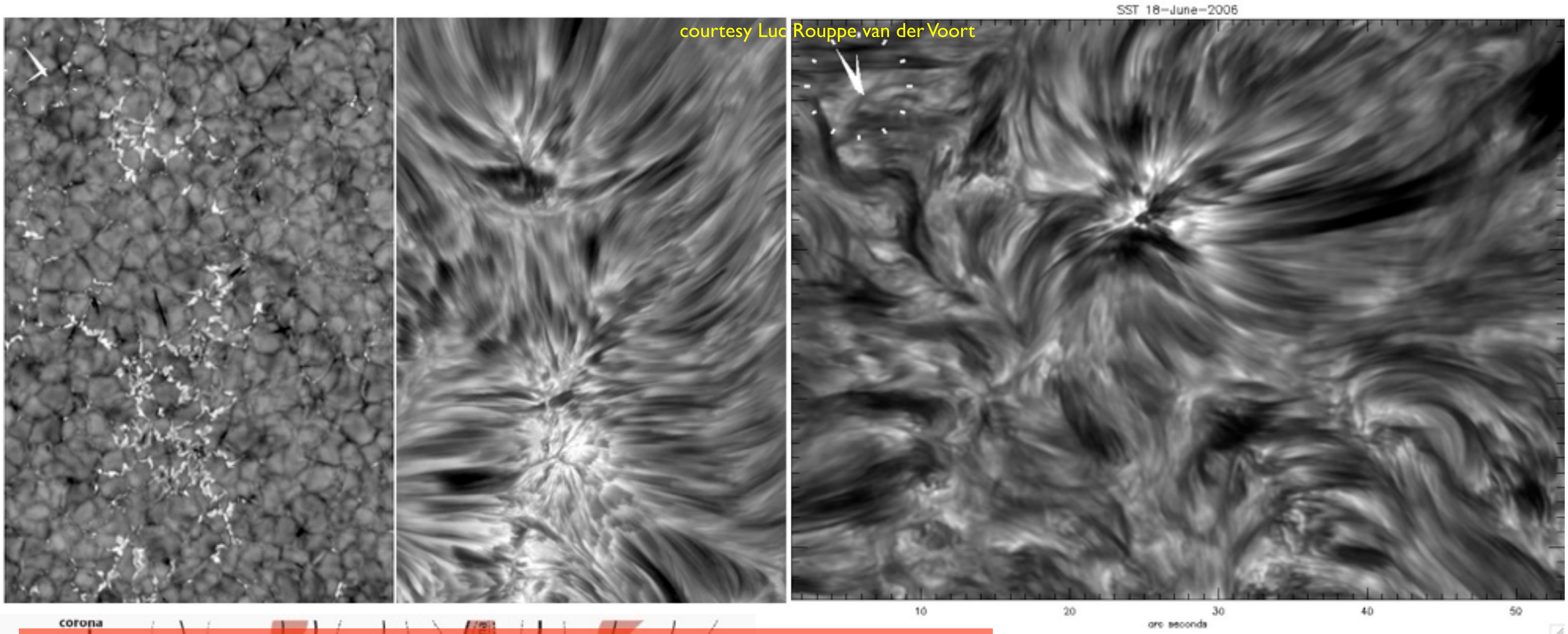
Magneto-acoustic shock waves
(energetic impact on chromo network and internetwork, and TR/corona?)

Alfven waves
(generation? dissipation? FIP? Jets?)

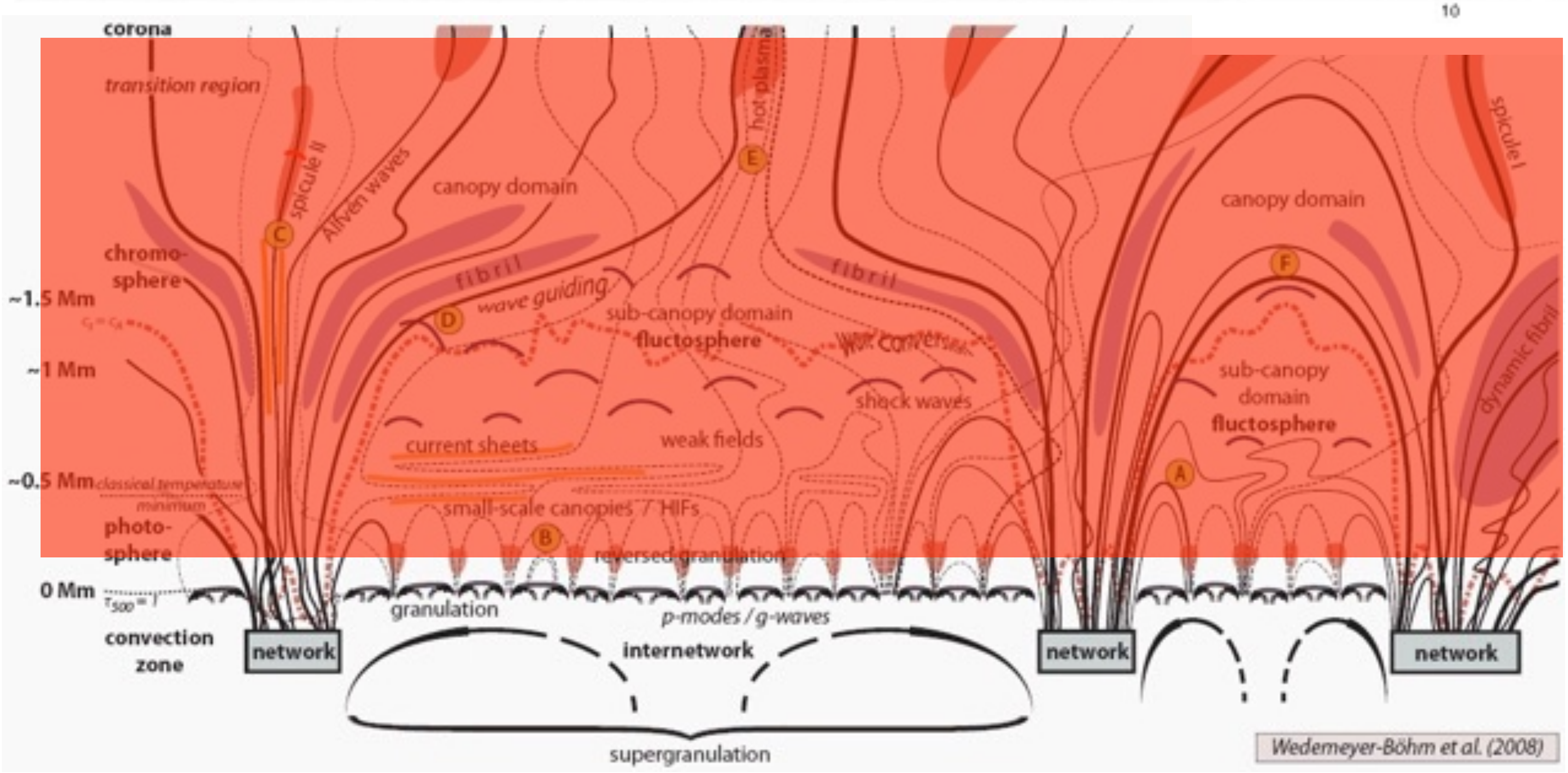
Magnetic Field Concentrations
(heating properties, mechanisms)

Weak fields
(granular flux emergence, impact?)

An introduction to the chromospheric zoo



courtesy Luc Rouppe van der Voort

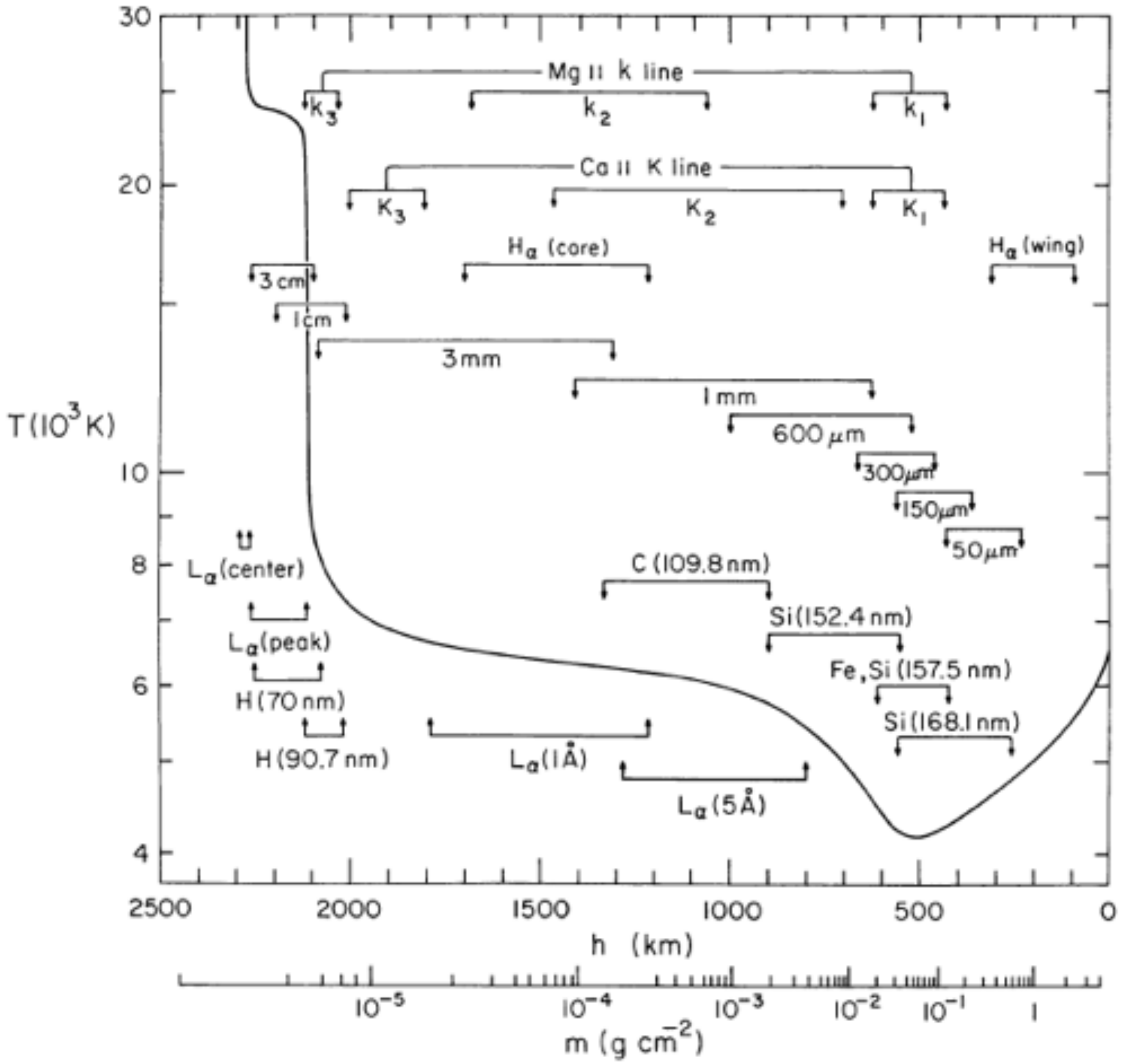


Wedemeyer-Böhm et al. (2008)

Ion-neutral effects, plasma physics
(heating, magnetic flux emergence, diffusion, coronal non-potentiality)

Heating properties of the chromosphere

Semi-empirical model VAL3C



Problems:

- the atmosphere is NOT static
- required energy flux depends critically on model assumptions: between 2000 and 14000 W/m^2 [Athay, 1976 to Anderson & Athay, 1989]
- observed "energy flux" are estimates highly dependent on observational limitations (resolution, frequency), and assumptions (static formation height, model/assumed density,…)
- "energy flux" carried by, e.g., waves does NOT mean those waves are dissipated and contribute to the local energy balance

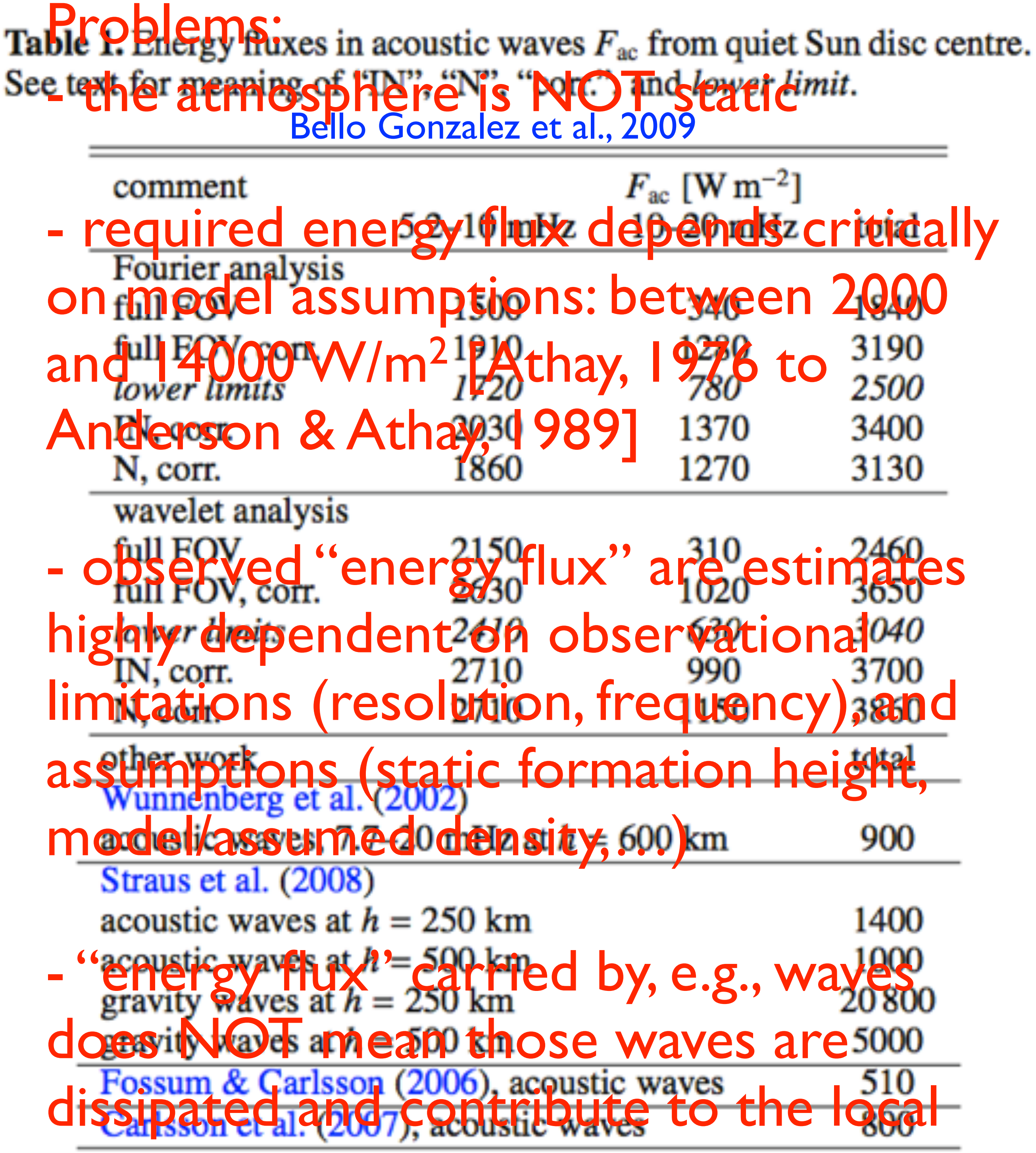


Table 1. Energy fluxes in acoustic waves F_{ac} from quiet Sun disc centre. See text for meaning of "IN", "N", "corr." and *lower limit*.

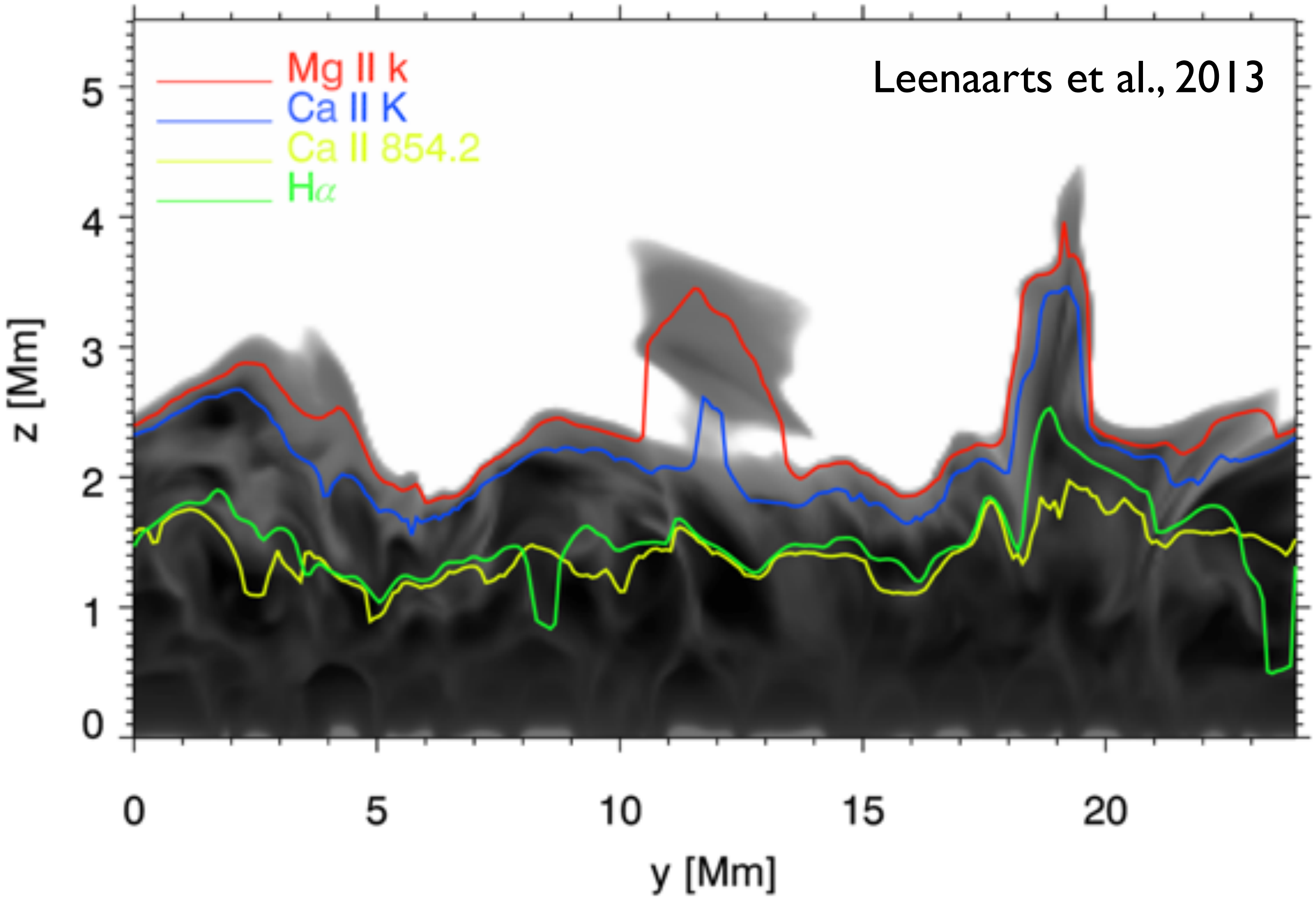
Bello Gonzalez et al., 2009

comment	F_{ac} [W m^{-2}] 5.2–10 mHz	10–20 mHz	total
Fourier analysis			
full FOV	1500	340	1840
full FOV, corr.	1910	1280	3190
lower limits	*1720*	*780*	*2500*
IN, corr.	2030	1370	3400
N, corr.	1860	1270	3130
wavelet analysis			
full FOV	2150	310	2460
full FOV, corr.	2630	1020	3650
lower limits	*2410*	*630*	*3040*
IN, corr.	2710	990	3700
N, corr.	2710	1150	3860
other work			total
Wunnenberg et al. (2002)			
acoustic waves, 7.5–20 mHz at h = 600 km			900
Straus et al. (2008)			
acoustic waves at h = 250 km			1400
acoustic waves at h = 500 km			1000
gravity waves at h = 250 km			20 800
gravity waves at h = 500 km			5000
Fossum & Carlsson (2006), acoustic waves			510
Carlsson et al. (2007), acoustic waves			800

Time/spatially averaged, ad-hoc (semi-empirical/static models) and "energy flux" comparisons are not sufficient

How do we diagnose chromospheric conditions?

Variety of ground-based and space-based observations provides observables formed over a wide range of heights with complex (non-LTE) line formation



Problems:

- the atmosphere is highly dynamic and structured
- line formation is complex, most lines formed under non-LTE conditions

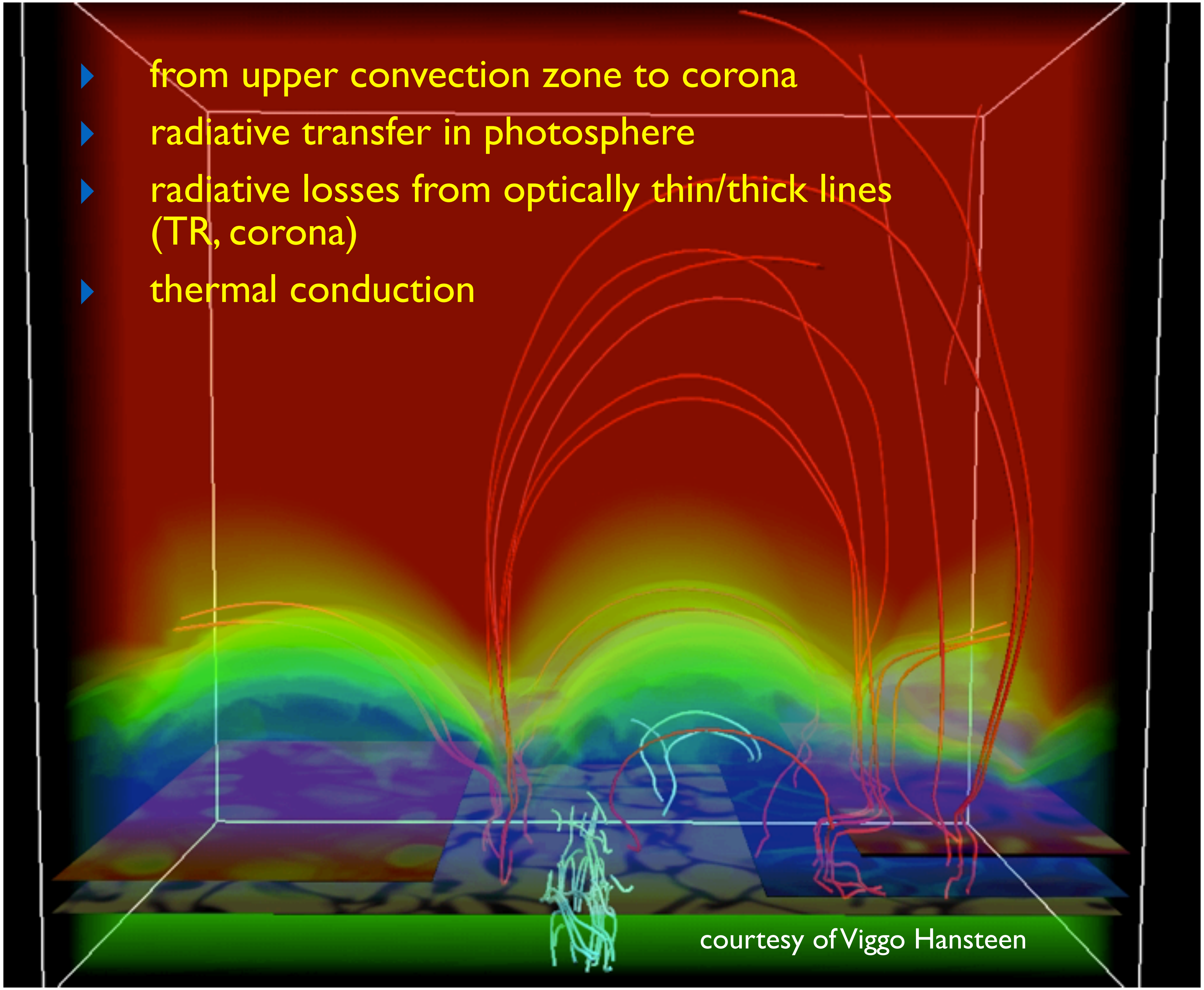
Solutions?

- forward modeling
- inversion codes
- New types of observations (ALMA, DKIST, IRIS,…)

Advanced 3D radiative MHD simulations

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

“Only” free parameter is magnetic field distribution on the surface



- from upper convection zone to corona
- radiative transfer in photosphere
- radiative losses from optically thin/thick lines (TR, corona)
- thermal conduction

courtesy of Viggo Hansteen

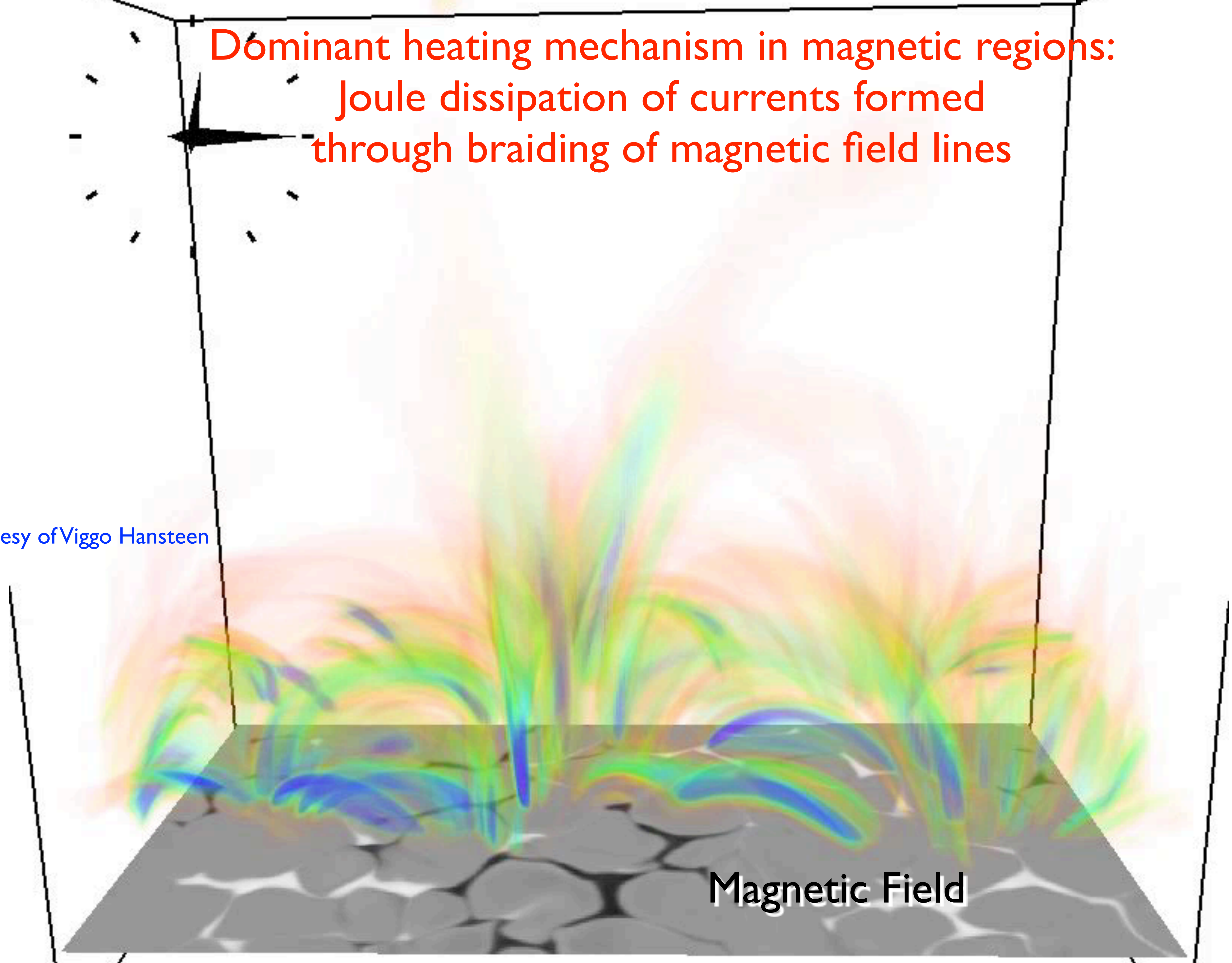
Corona

Transition region

Chromosphere

Photosphere

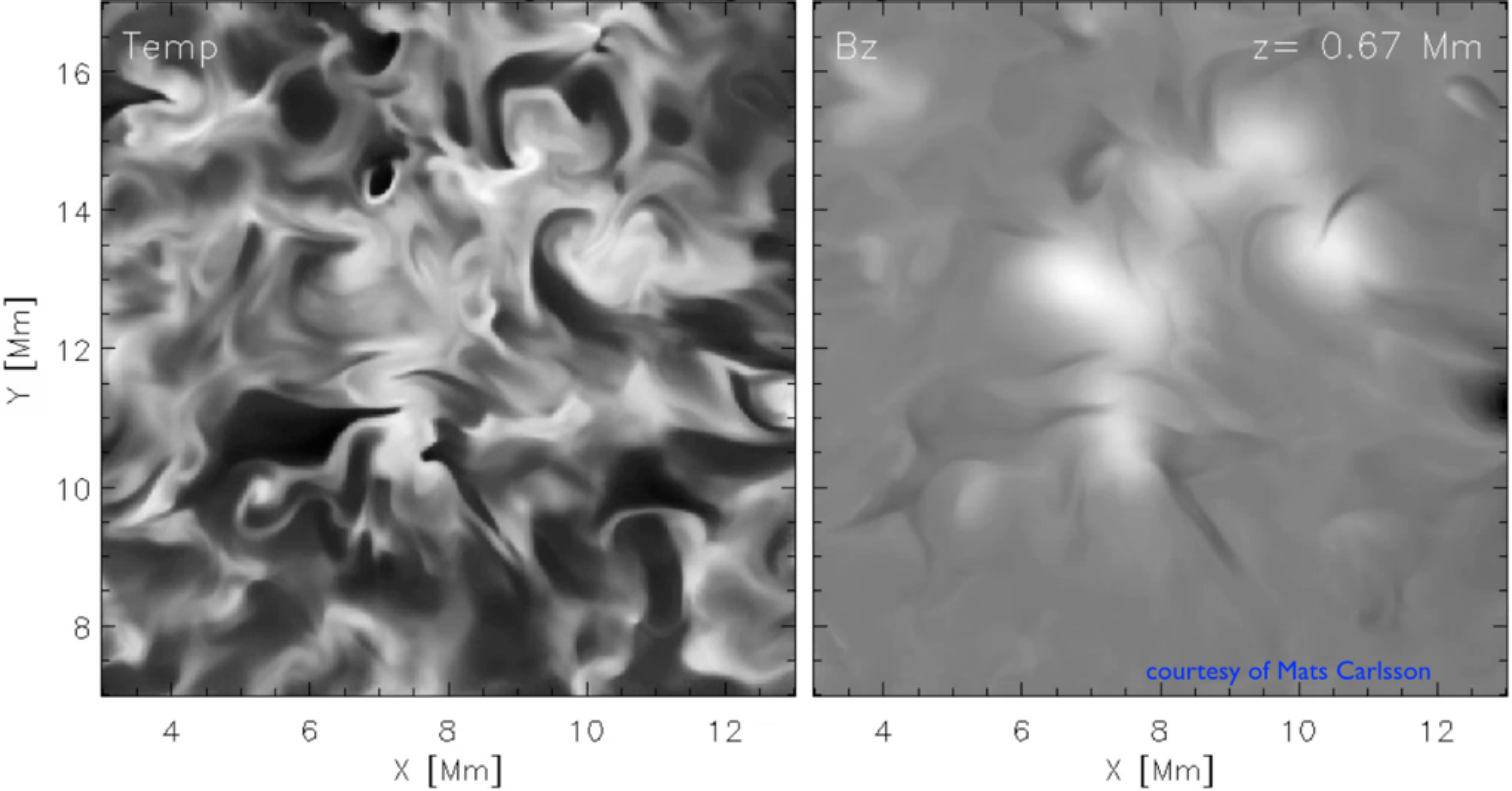
How do these models create their own hot atmosphere?



Dominant heating mechanism in magnetic regions:
Joule dissipation of currents formed
through braiding of magnetic field lines

courtesy of Viggo Hansteen

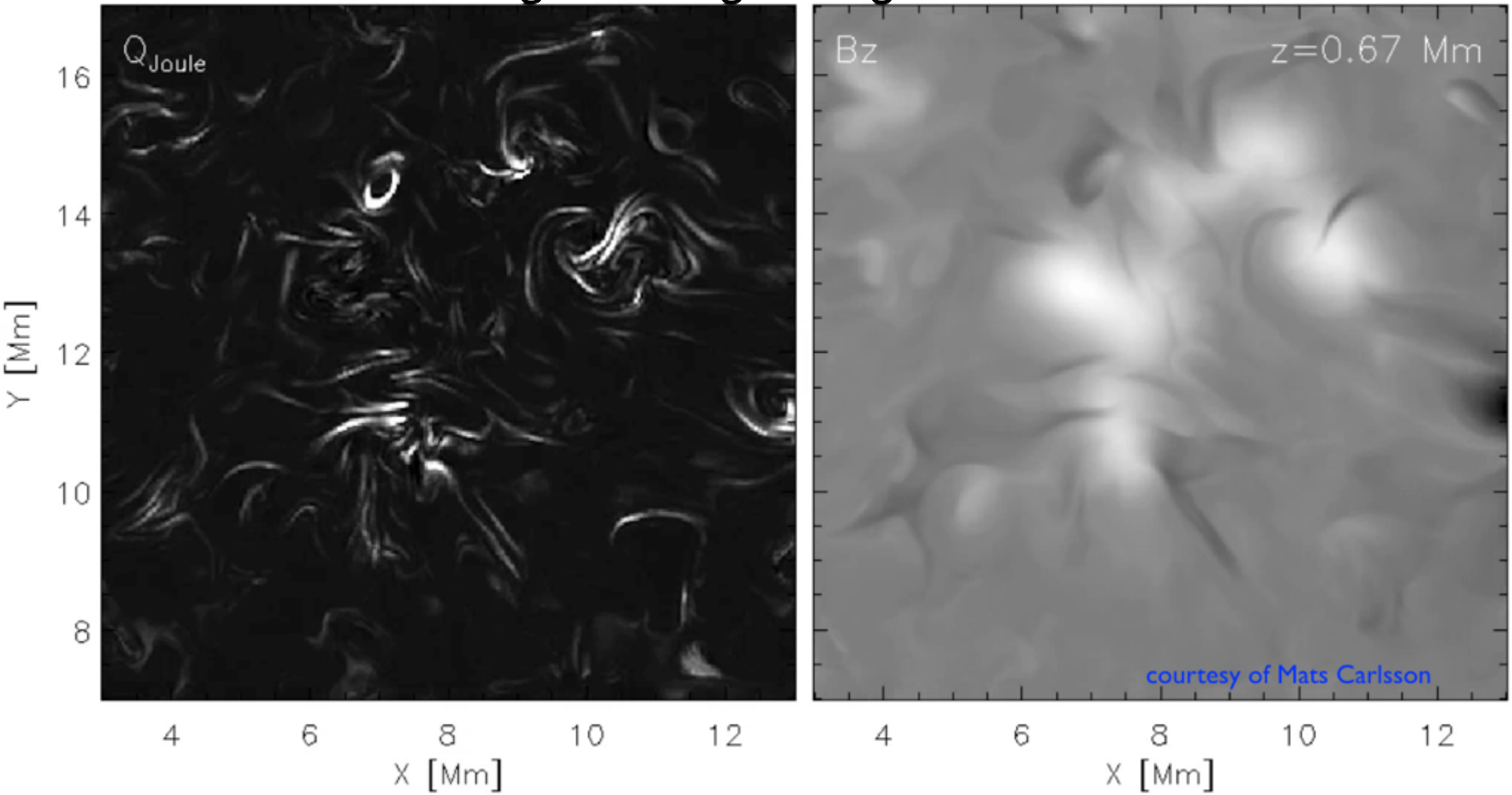
Dominant heating mechanism in magnetic regions: Joule dissipation of currents formed through braiding of magnetic field lines



courtesy of Mats Carlsson

Temperature(z) and B_z(z)

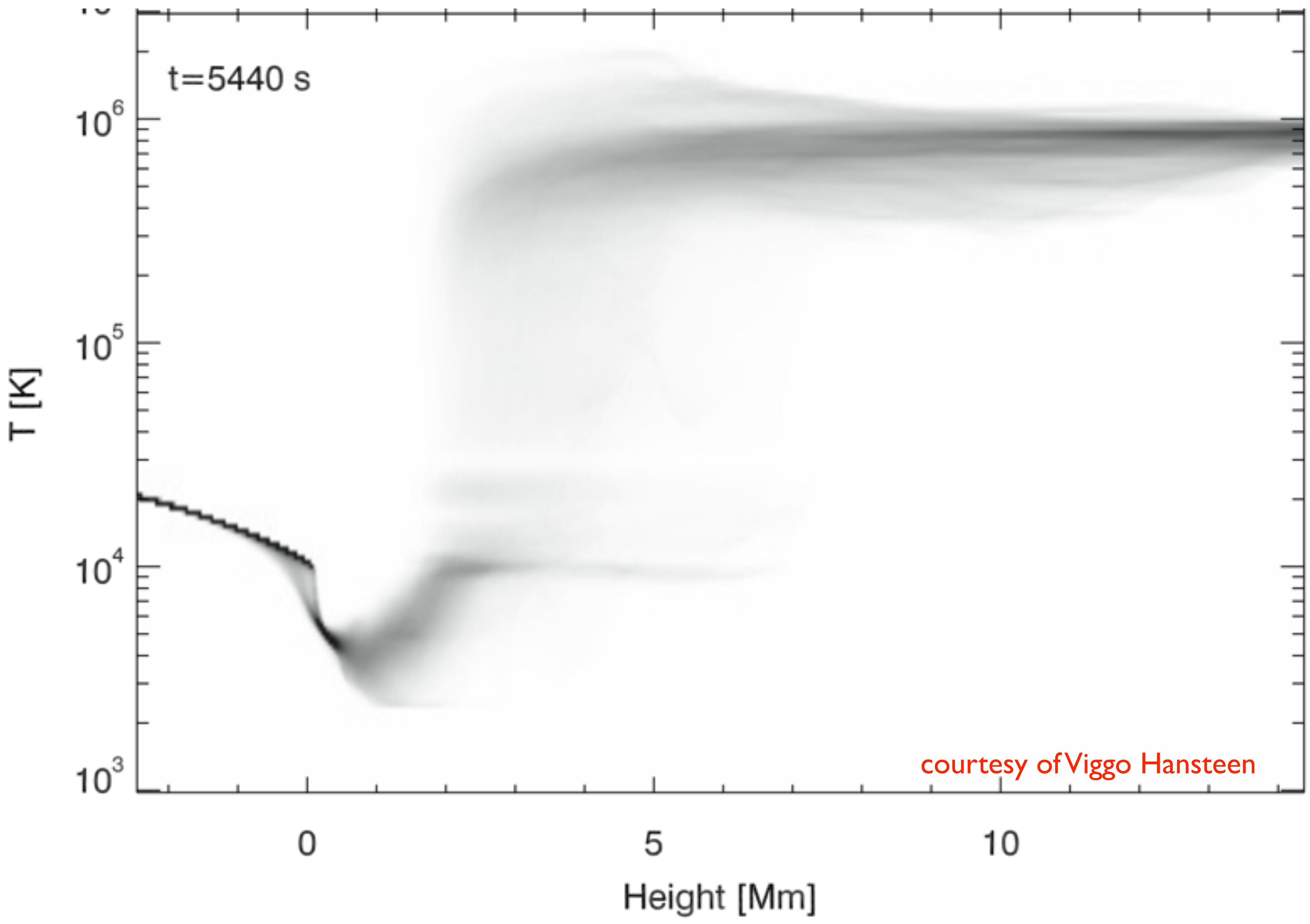
Dominant heating mechanism in magnetic regions: Joule dissipation of currents formed through braiding of magnetic field lines



courtesy of Mats Carlsson

$Q_{Joule}(z)$ and $B_z(z)$

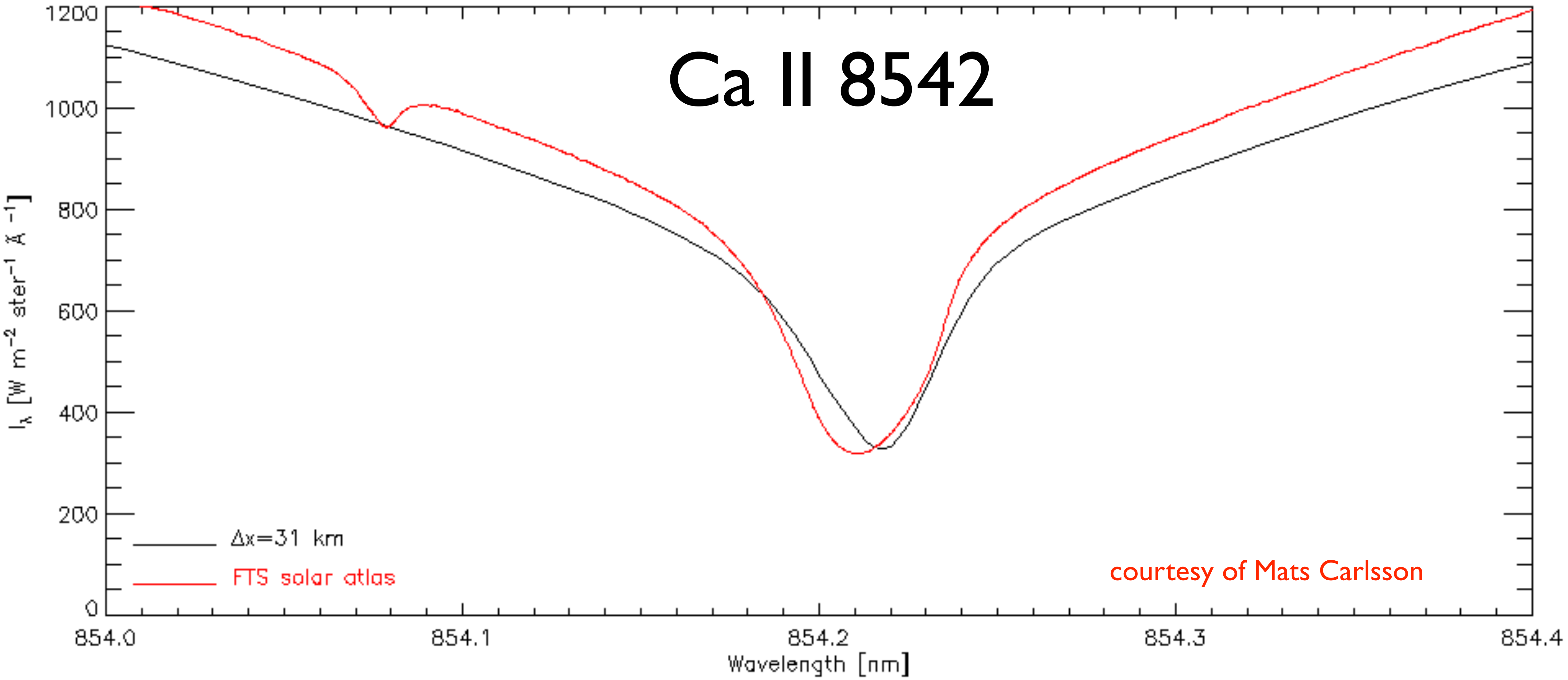
Bifrost "reproduces" VAL3C atmosphere



courtesy of Viggo Hansteen

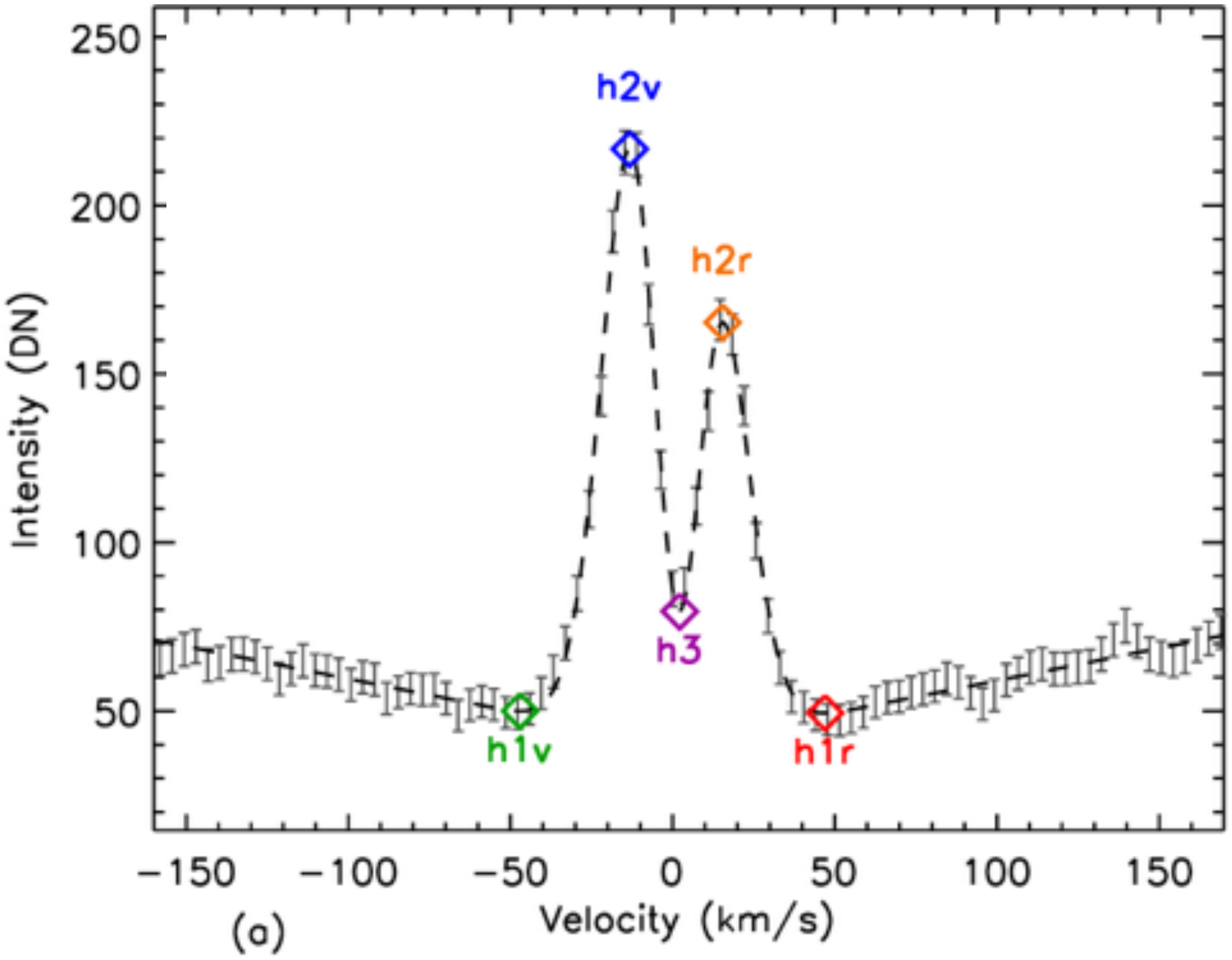
"Average" properties similar to VAL3C,
but lots of spatial and temporal deviations

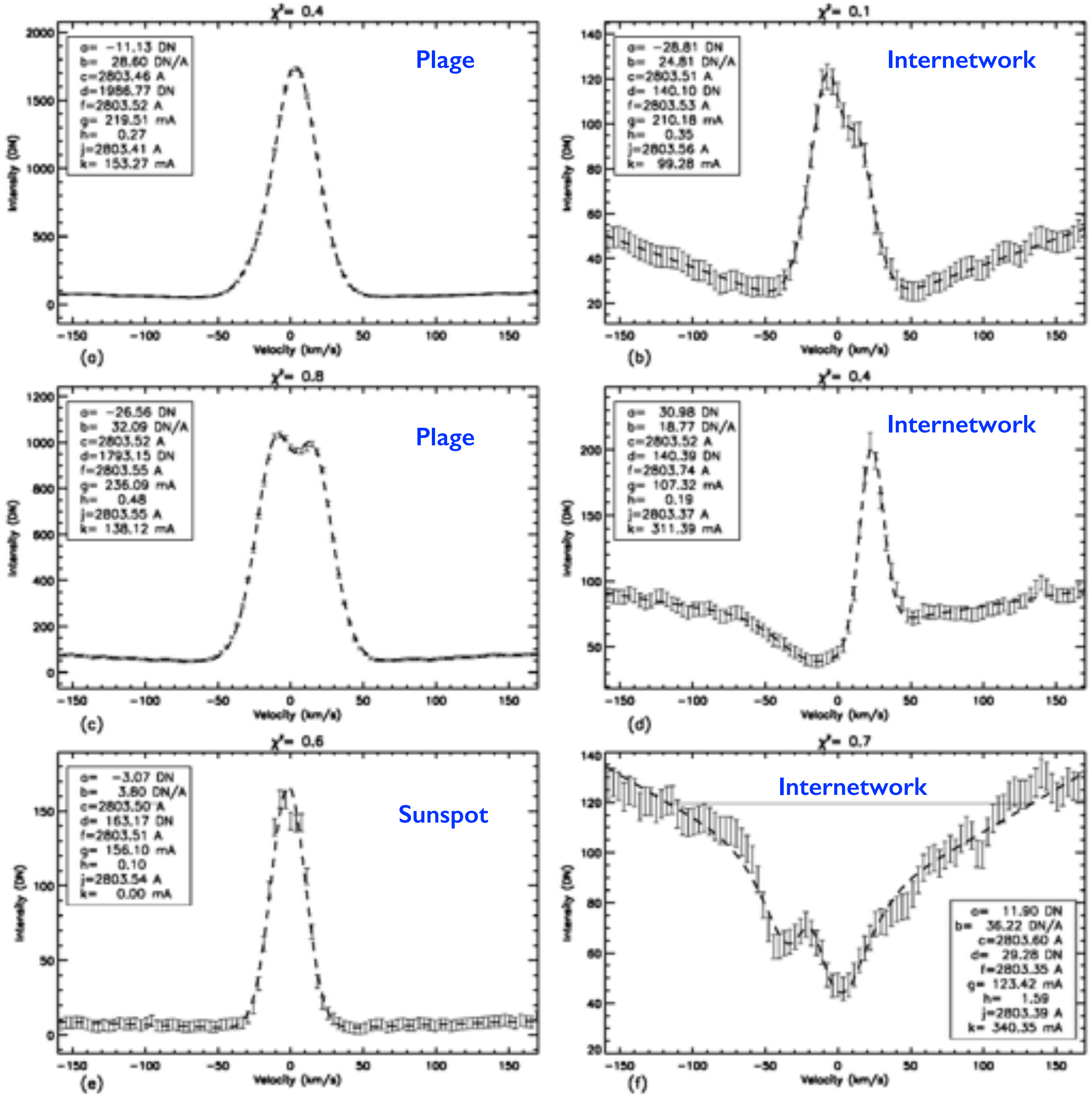
Validation of models must come through detailed comparison of observations and synthetic observables calculated from forward models



Bifrost does reasonably well reproducing average profiles of Ca II 8542Å which is formed in the lower to middle chromosphere

New diagnostics available from IRIS

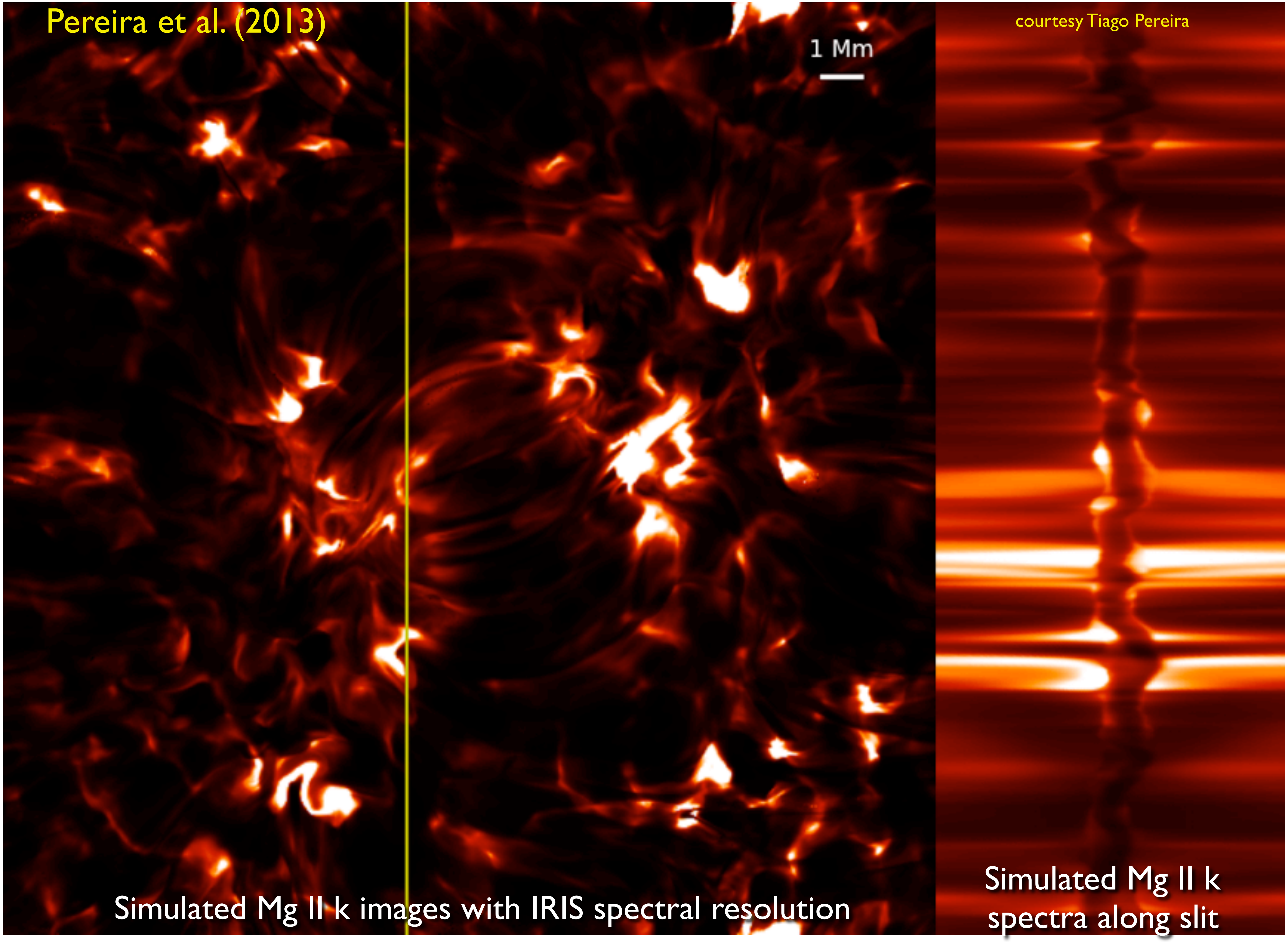




Schmit et al., 2015

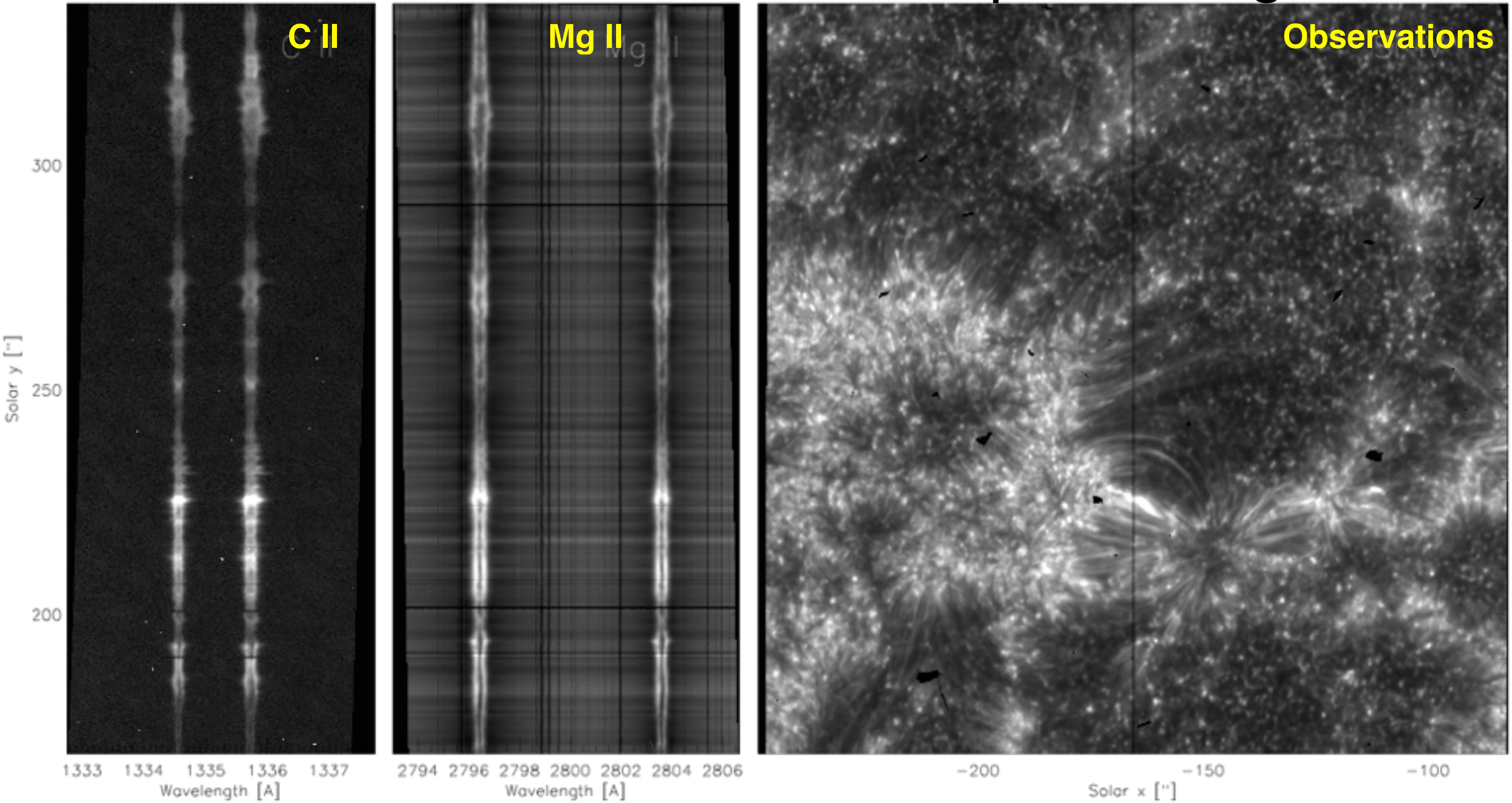
Mg II 2796/2803Å are formed in upper chromosphere
Wider variety of profiles observed than in models

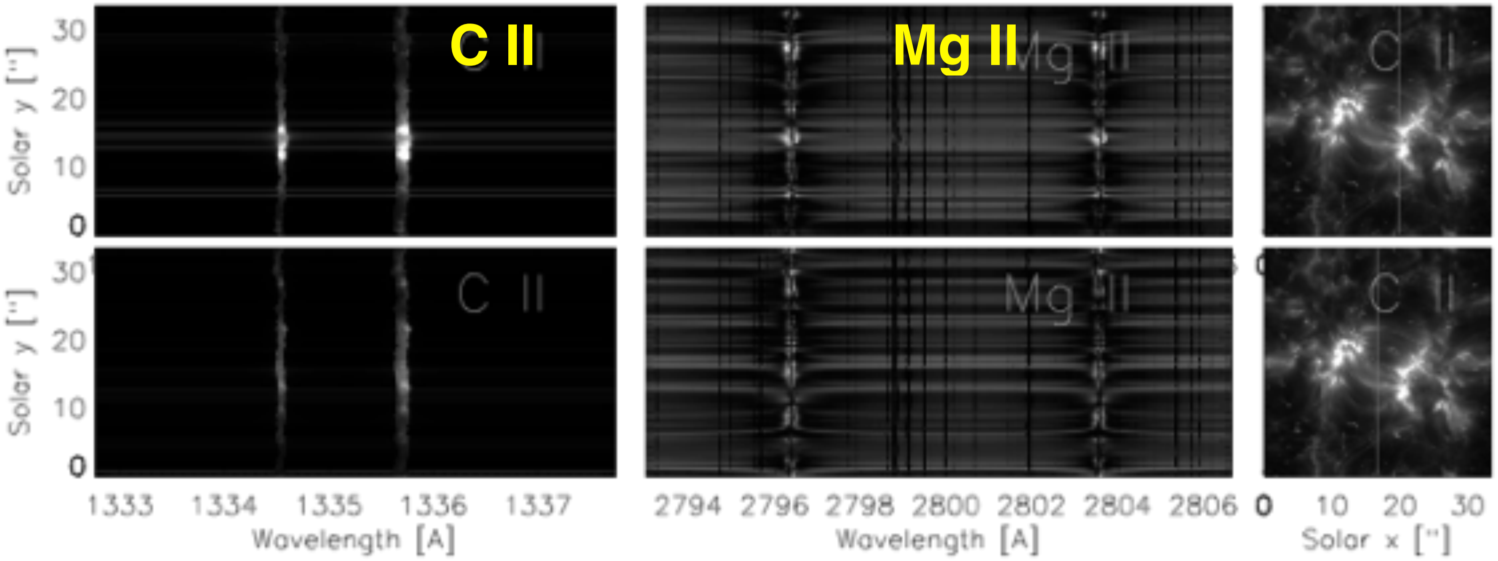
Synthetic Mg II k spectra allow detailed comparison of numerical models with IRIS observations



courtesy of Tiago Pereira

How well does Bifrost model reproduce Mg II k?





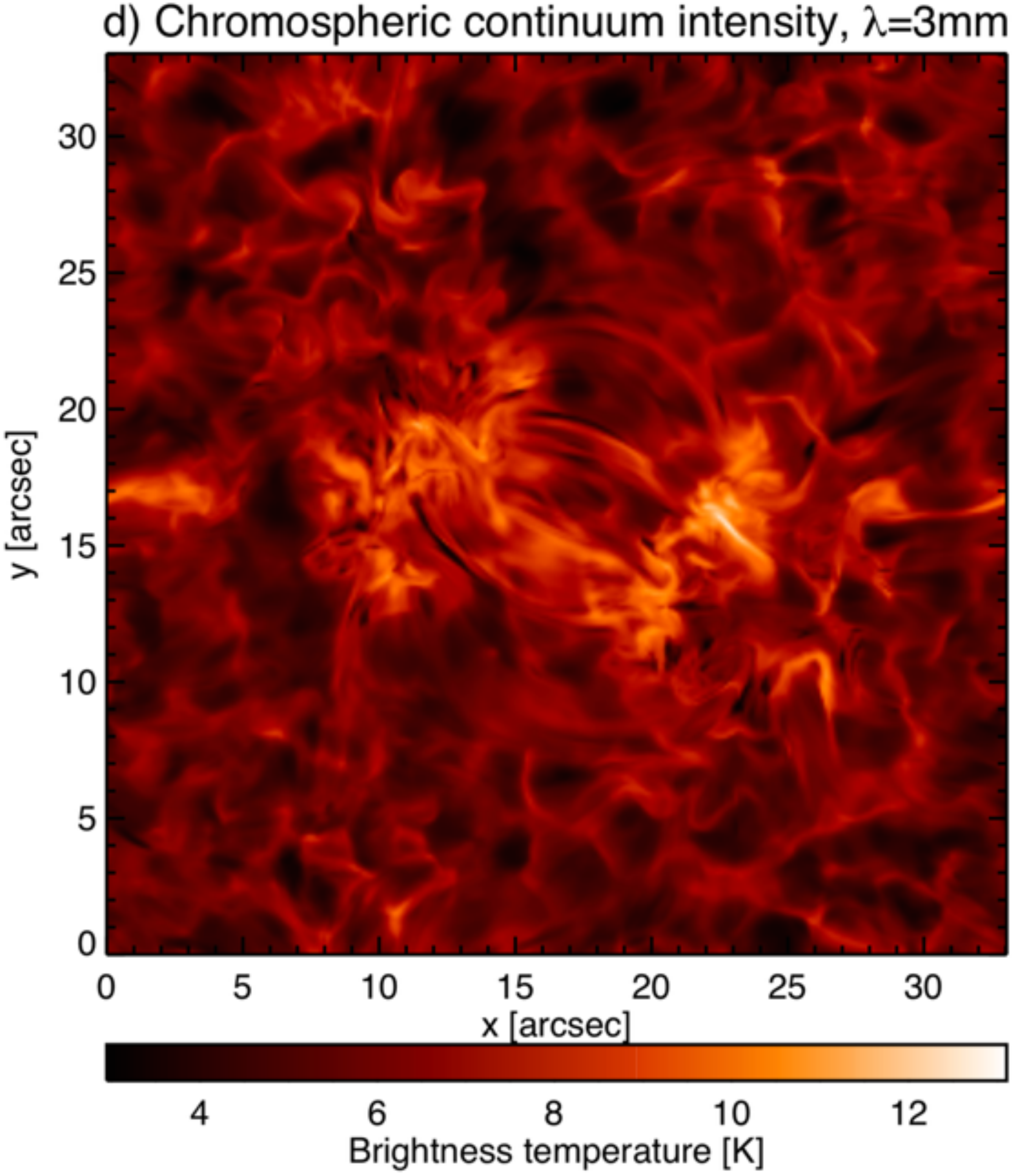
Bifrost Simulations

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

courtesy of Mats Carlsson

Current quiet Sun simulations show synthetic Mg II h/k profiles that are too narrow and too faint

Current simulations seem to lack violence, mass & heat



ALMA observations sensitive to temperature in linear fashion

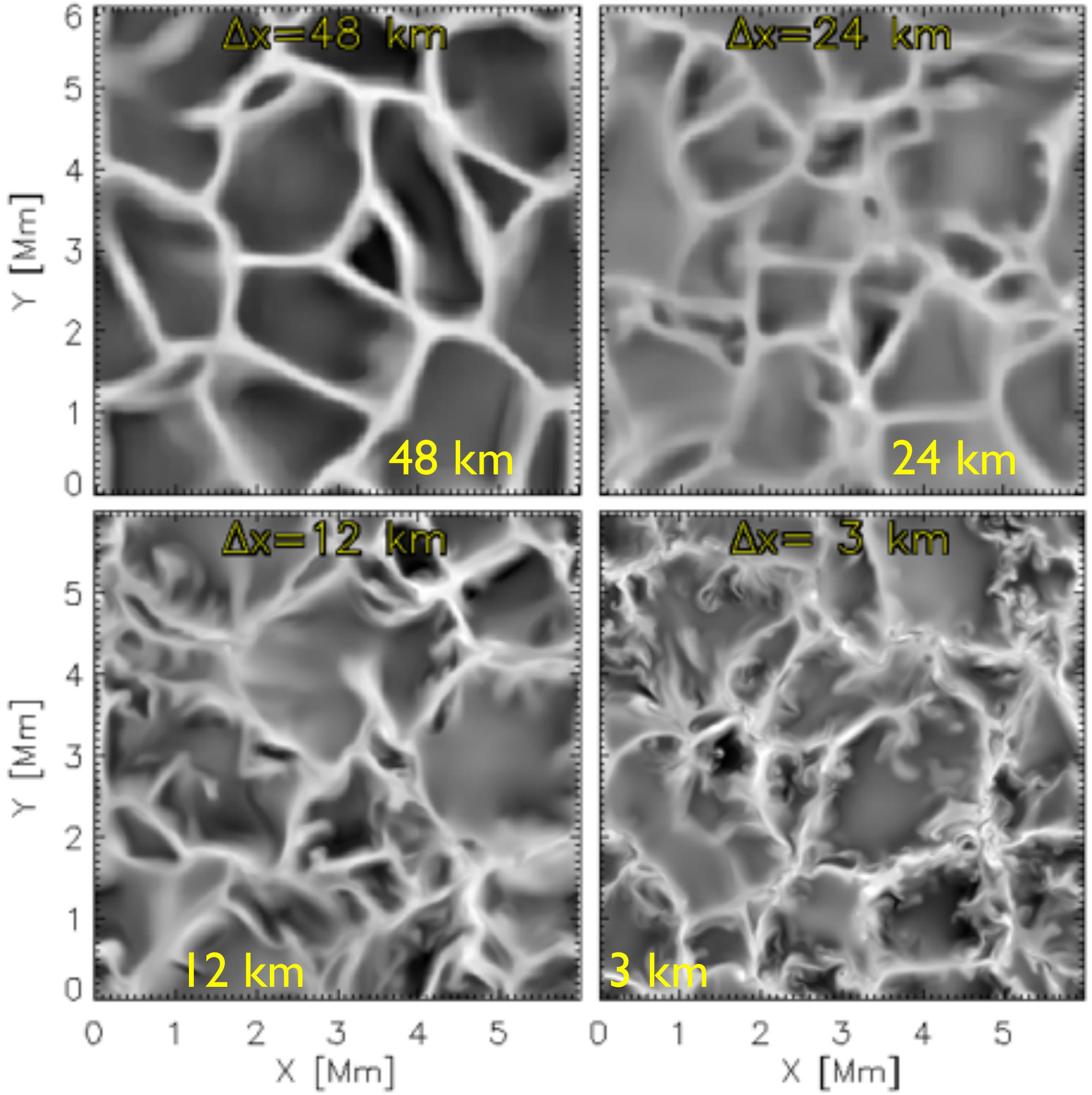
High-resolution, high cadence ALMA observations will provide much needed constraints on heating mechanisms of chromosphere

courtesy of Sven Wedemeyer

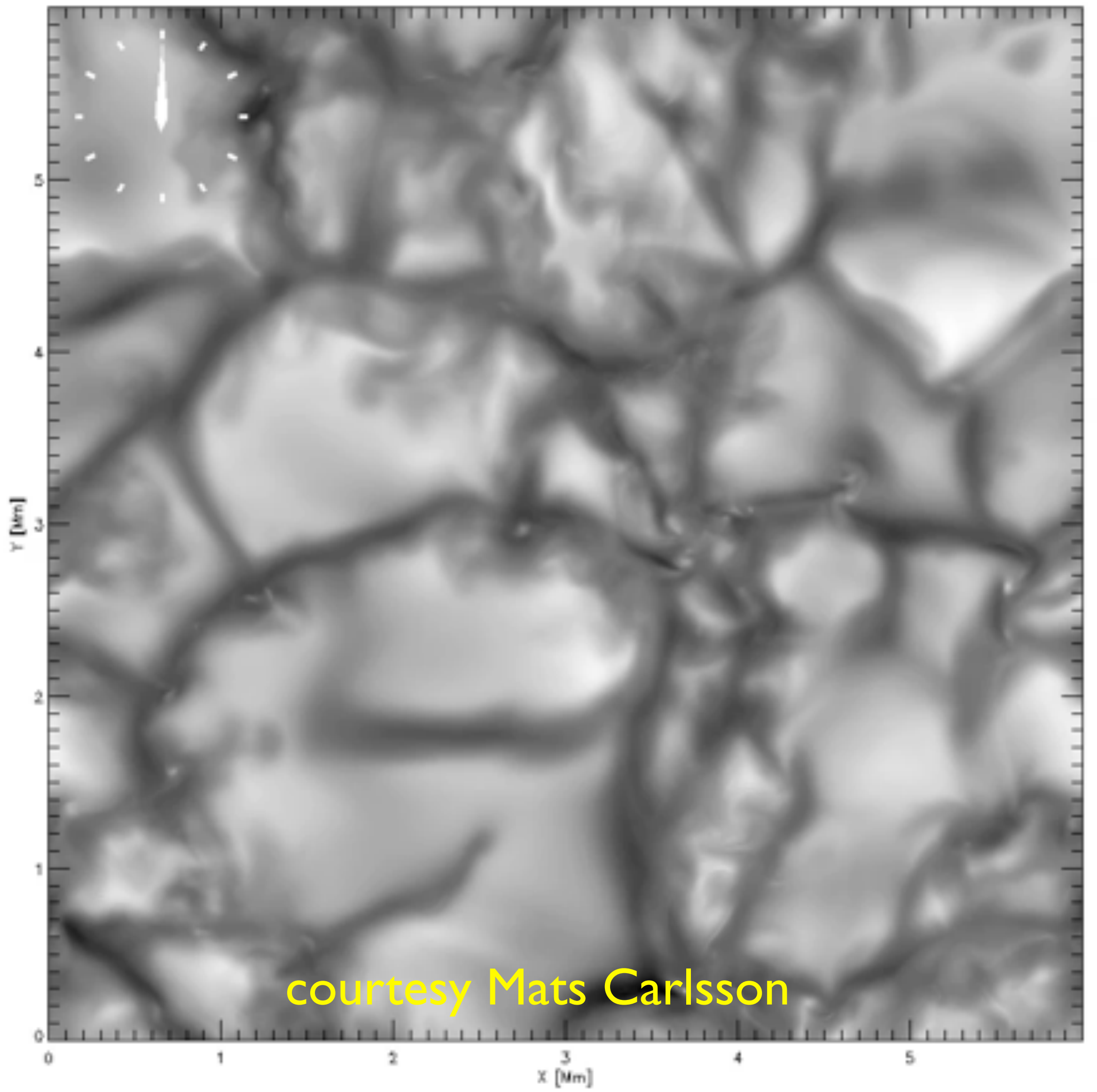
courtesy of Tiago Pereira

Path forward?

Vertical velocity at photosphere



High-resolution simulations shows strong motions

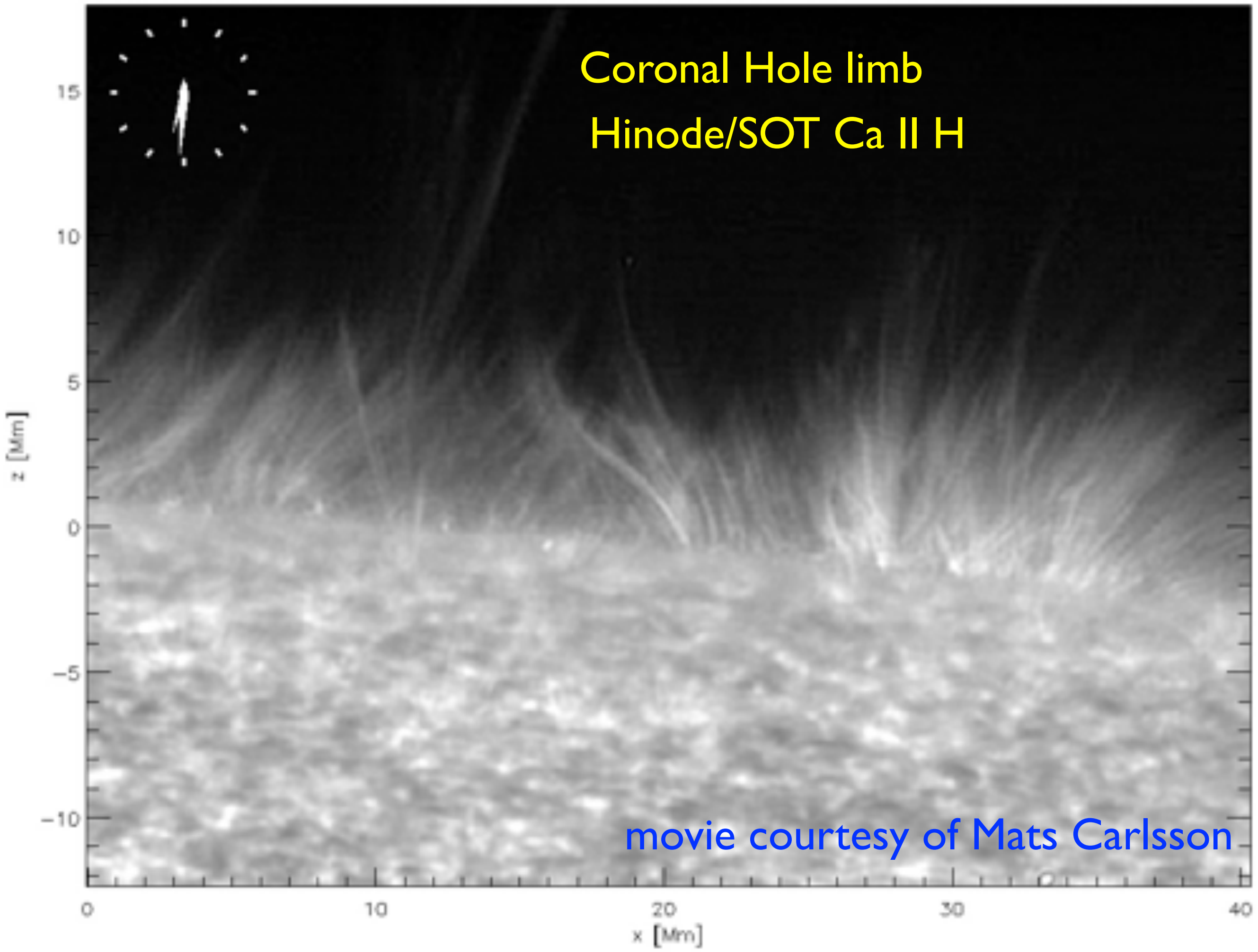


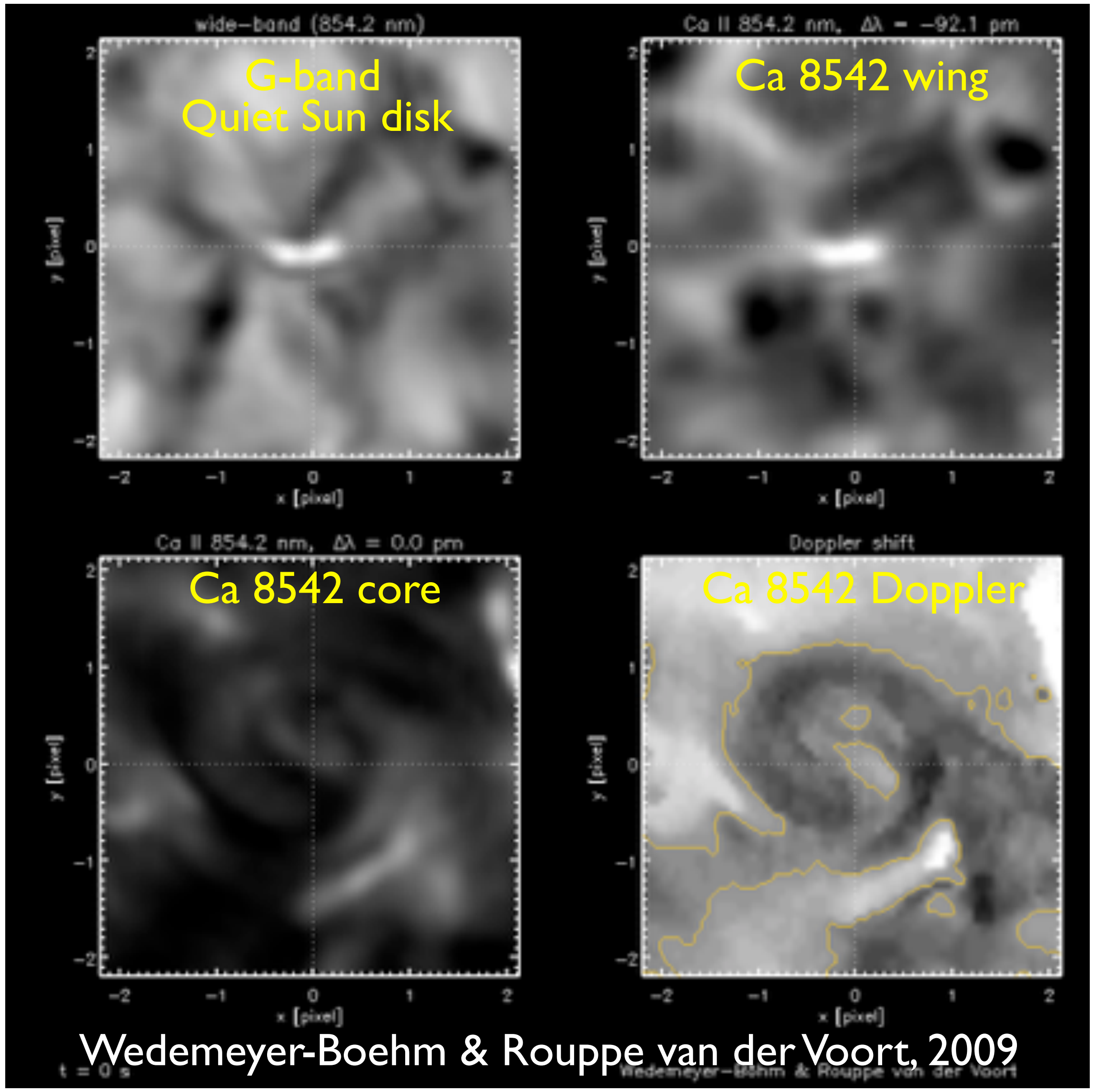
courtesy Mats Carlsson

Can the answer be found in simulations with:

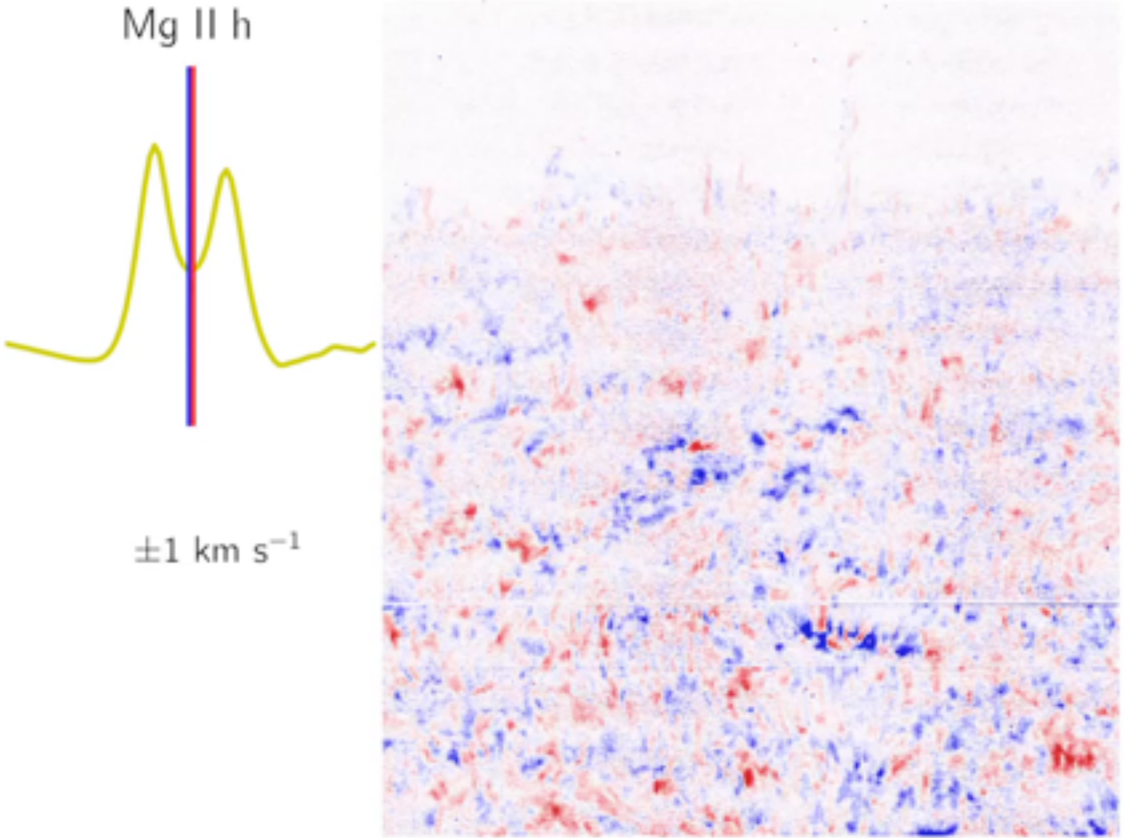
- higher resolution (more waves?!)
- impact of small-scale magnetic field
- ion-neutral effects, multi-fluid, plasma physics effects?
- alternative models (waves?)

Unknown contribution of Alfven, kink, transverse waves to chromospheric heating





Wedemeyer-Boehm & Rouppe van der Voort, 2009



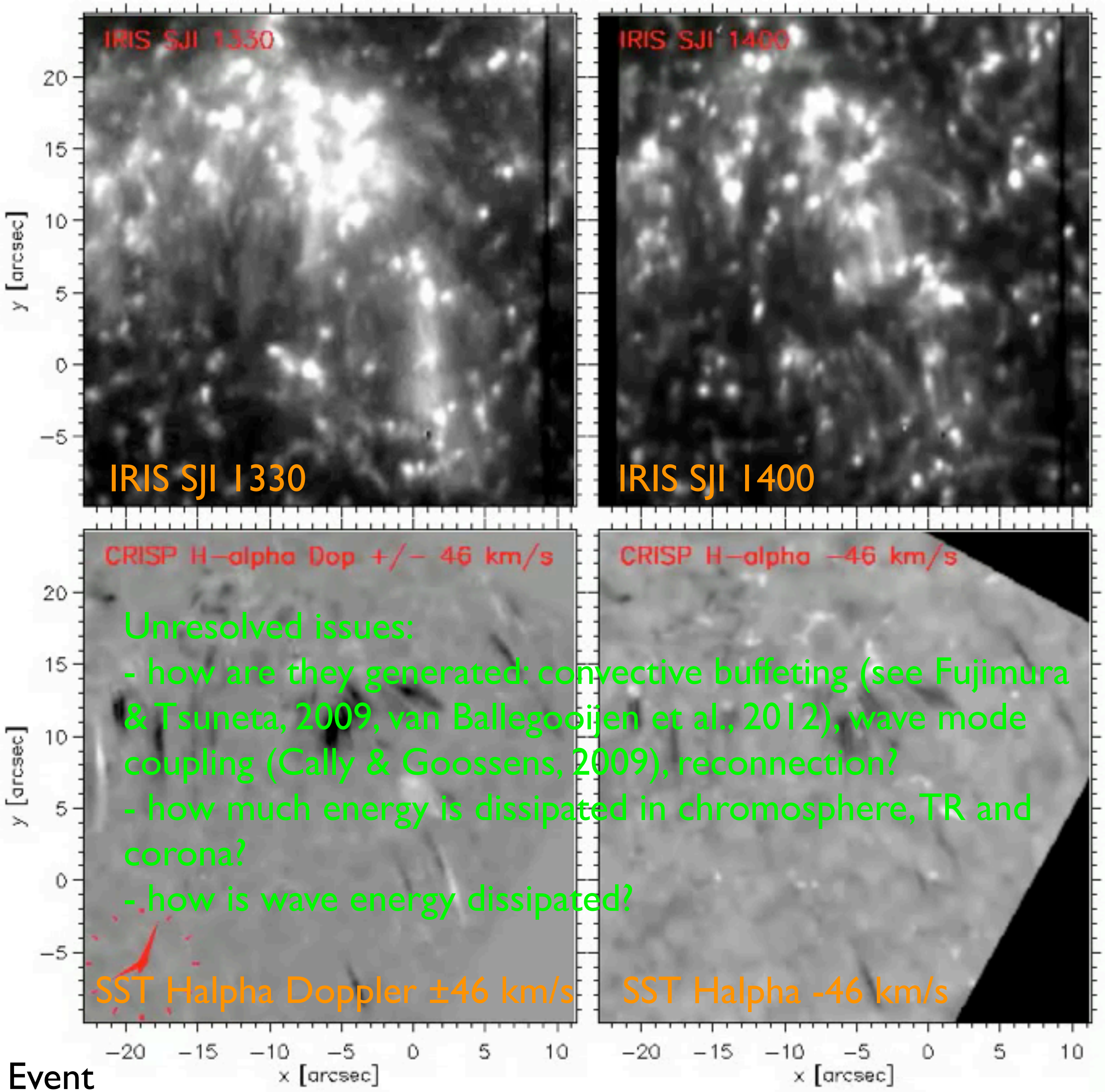
De Pontieu et al. 2014 Science, Rouppe van der Voort et al. 2015

Chromosphere (and spicules) undergo vigorous transverse, torsional and swirling motions

Periods of ~10-1000s (De Pontieu et al., 2007, 2014, He et al., 2009, and many other papers)

Chromosphere permeated with waves of all kinds

IRIS/SST observations reveal Alfven waves often associated with heating



Unresolved issues:

- how are they generated: convective buffeting (see Fujimura & Tsuneta, 2009, van Ballegooijen et al., 2012), wave mode coupling (Cally & Goossens, 2009), reconnection?
- how much energy is dissipated in chromosphere, TR and corona?
- how is wave energy dissipated?

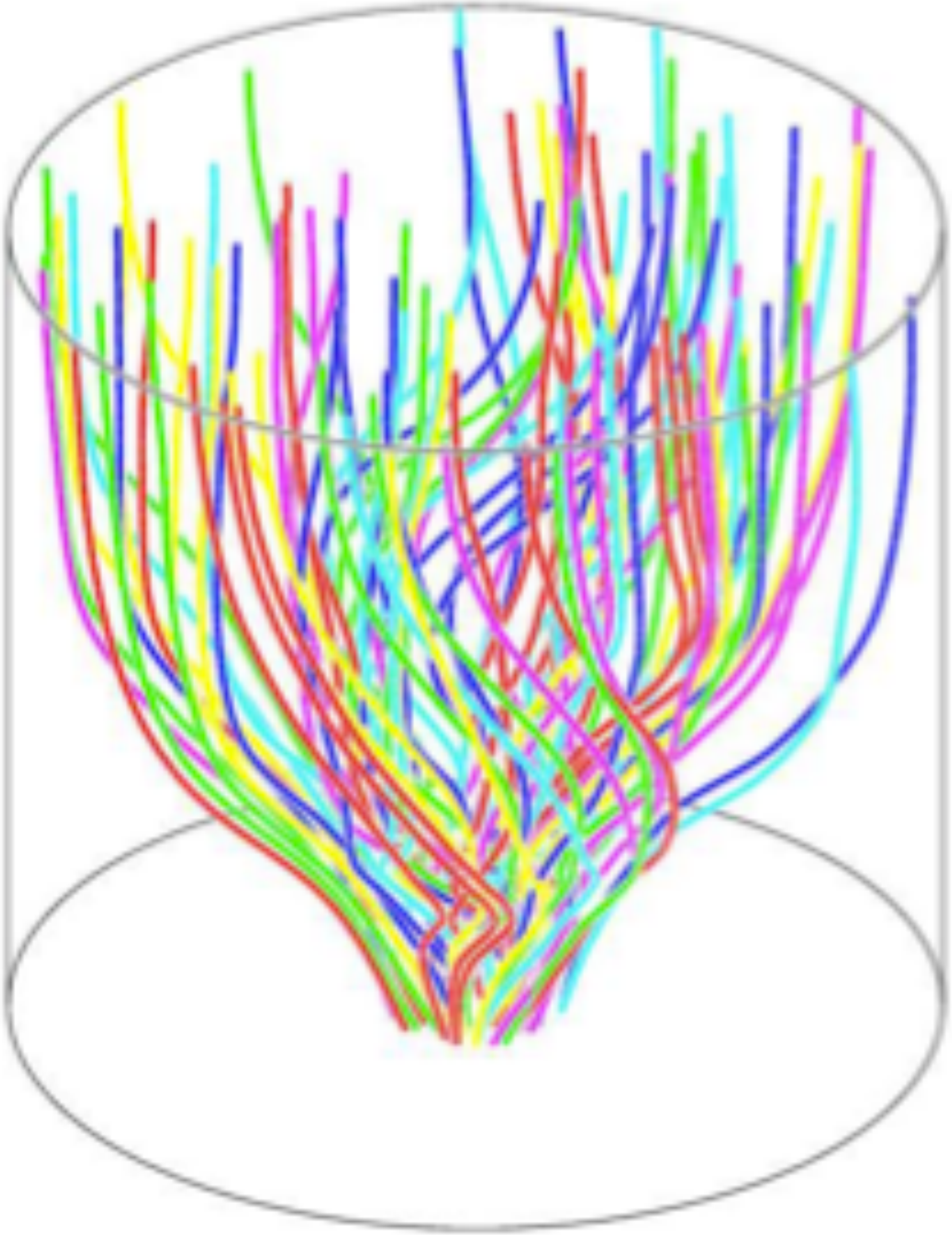
▬ RRE
▭ RBE

RRE: Rapid Redshifted Event
RBE: Rapid Blueshifted Event

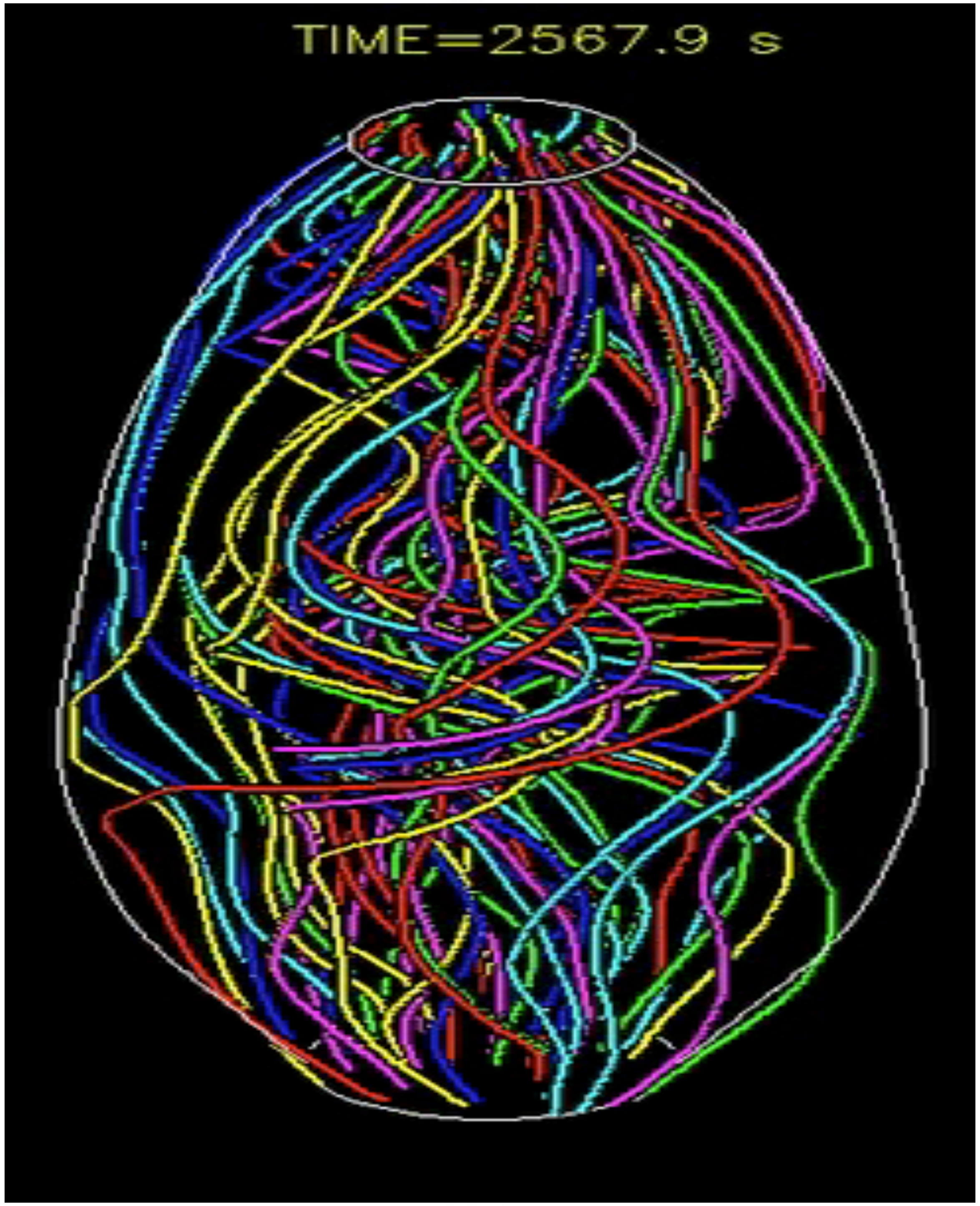
De Pontieu et al. 2014 Science, Rouppe van der Voort et al. 2015 ApJL 799

Is dissipation of Alfven waves responsible for chromospheric heating?

Model chromosphere

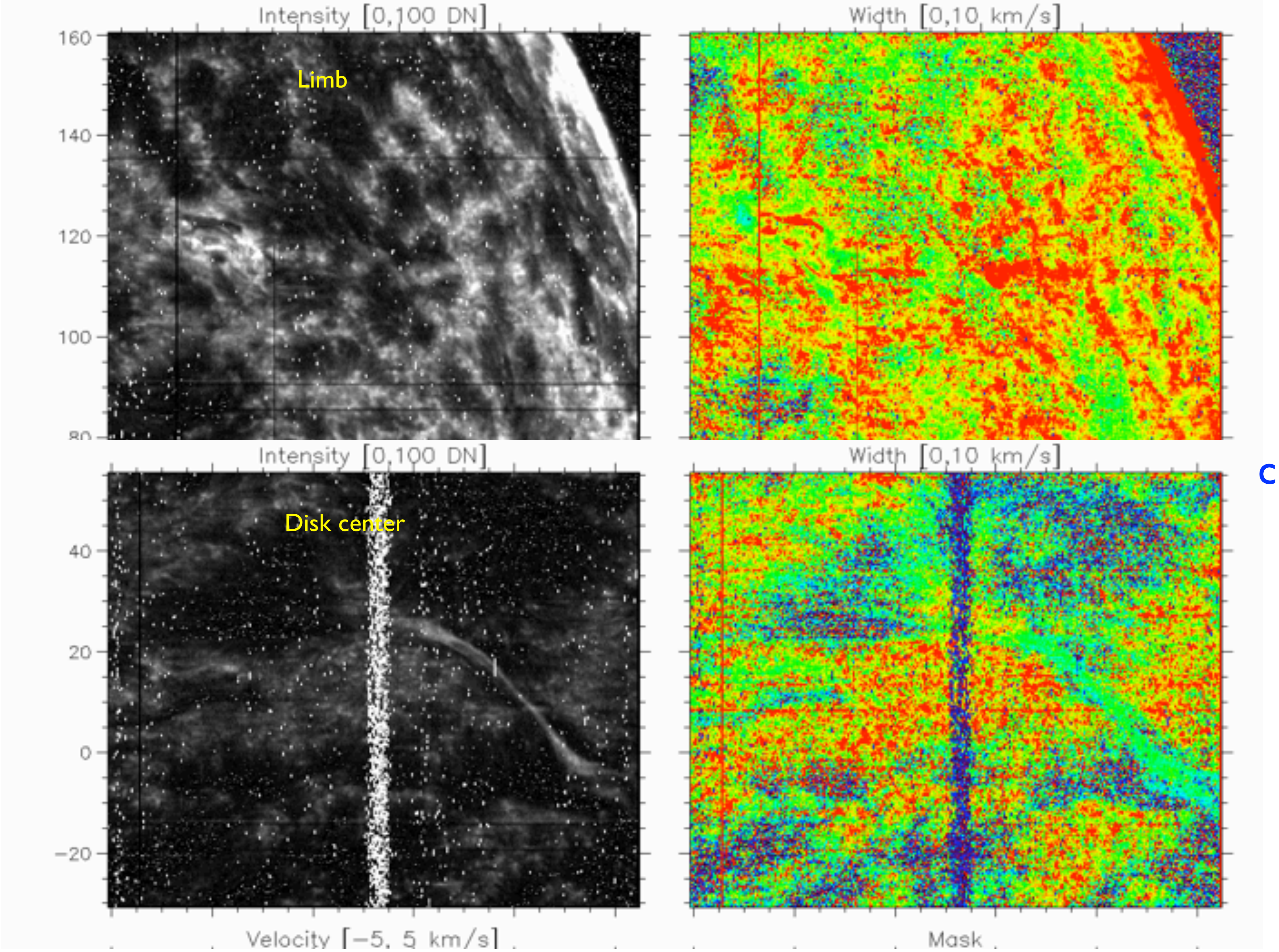


Model corona



Does chromospheric/coronal heating model through turbulent cascade of Alfven waves (van Ballegooijen et al., 2011, Asgari-Targhi et al., 2014) have observable consequences [non-thermal line broadening, DKIST field measurements?]

Non-thermal line broadening and (unresolved) Alfven waves



Optically thin chromospheric O I line

De Carlieu & Pontson, 2016

Average non-thermal line broadening of order 7 km/s

Constraint on Alfvenic motions, turbulence, shocks, FIP models, …

Shows significant increase towards limb and at edge of plage

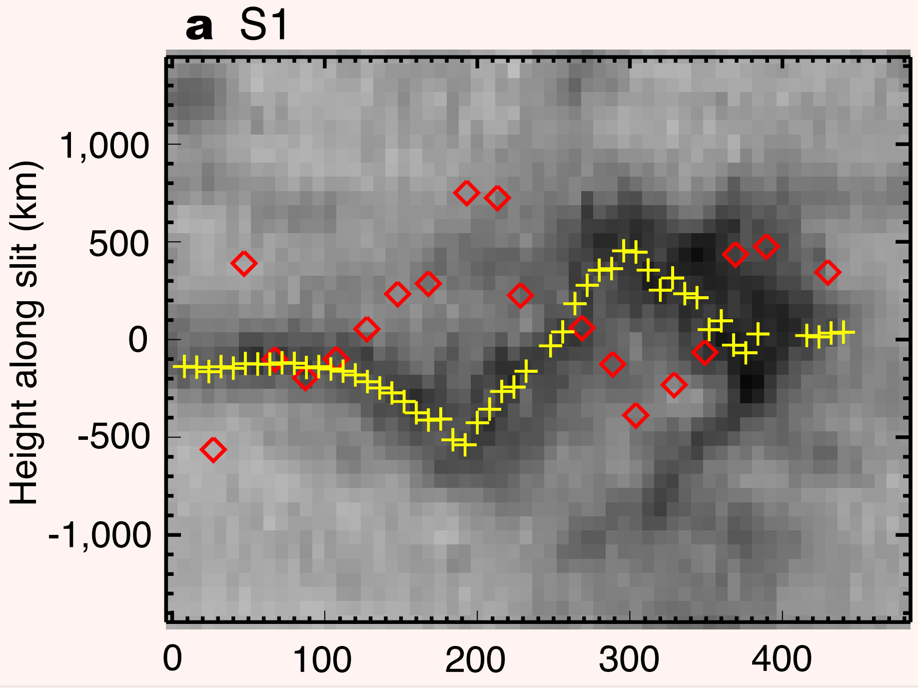
Unclear whether this is caused by larger LOS or Alfven waves

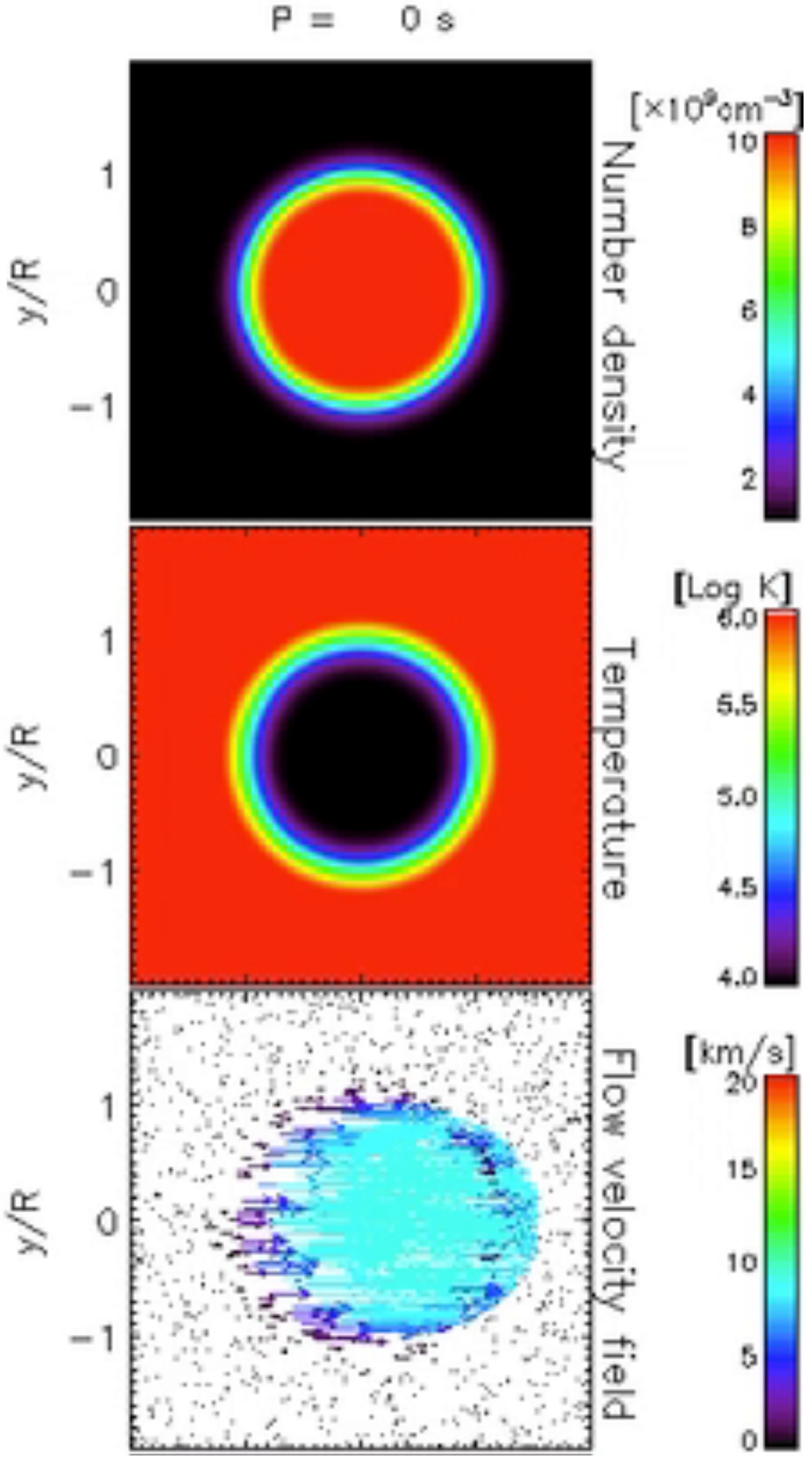
Is there evidence for Alfven wave dissipation?

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

How ubiquitous is this process?
Can it be observed in the chromosphere proper?
DKIST/ALMA/IRIS observations?
More sophisticated Alfven wave models required

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

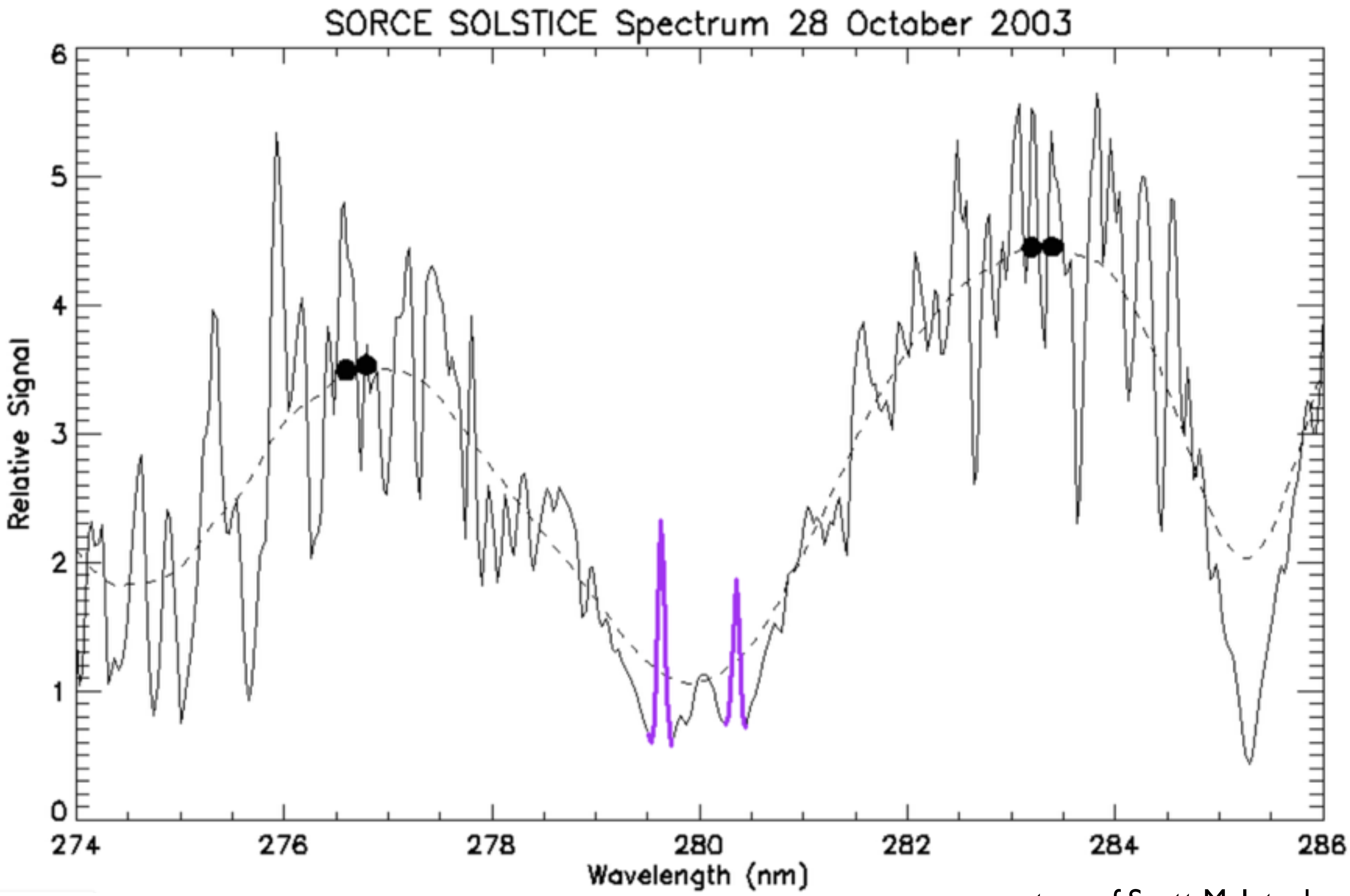




Simulations of resonant absorption

Okamoto et al., 2015; Antolin et al., 2015

Can we use Mg II h/k profiles to determine heating properties?

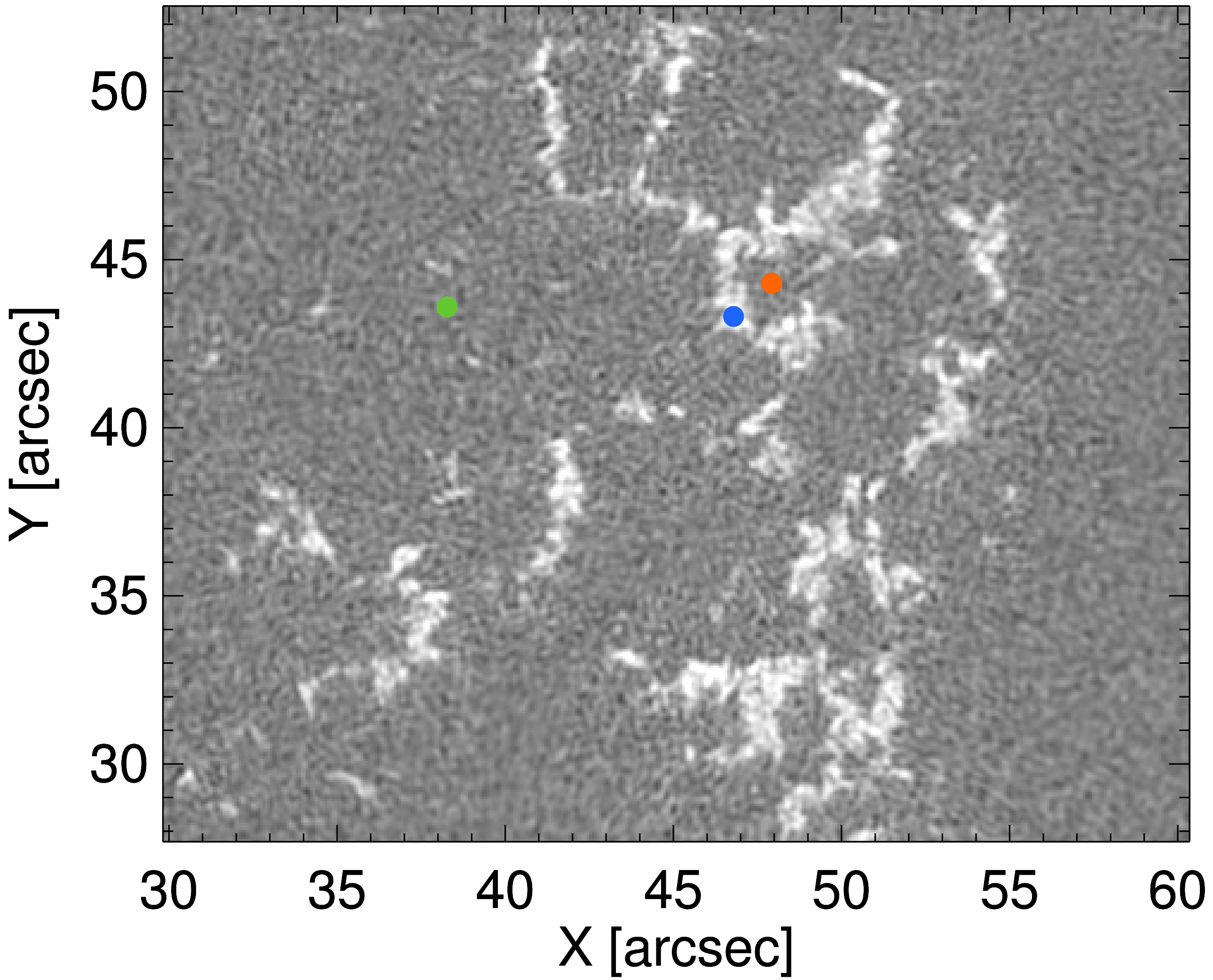


courtesy of Scott McIntosh

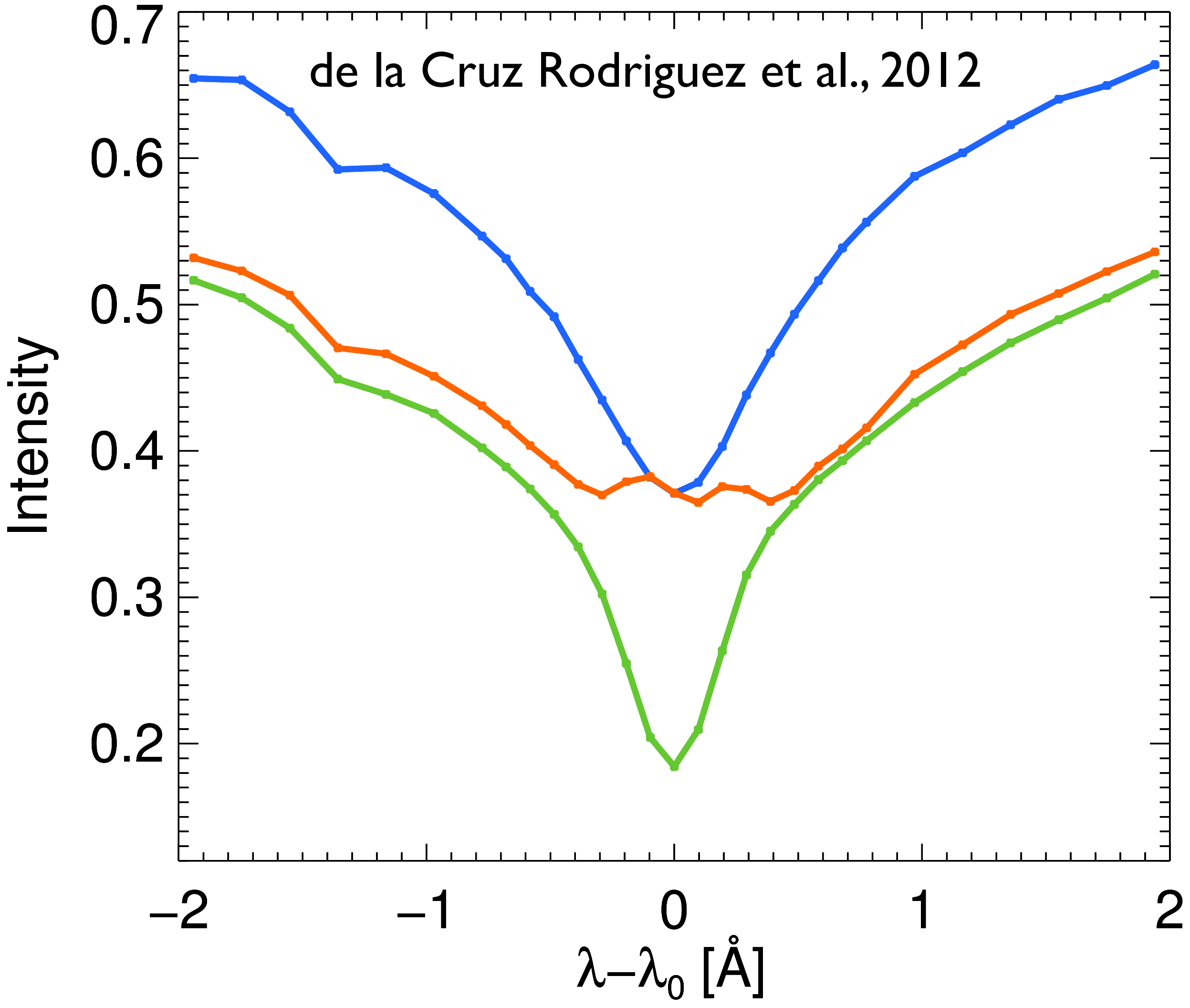
Mg II index good proxy
for solar impact on thermosphere

Spatio-temporal properties of chromospheric heating from Ca II 8542Å line profiles

Stokes V - Photosphere



Ca II 8542


de la Cruz Rodriguez et al., 2012

Quiet-Sun: Absorption profile

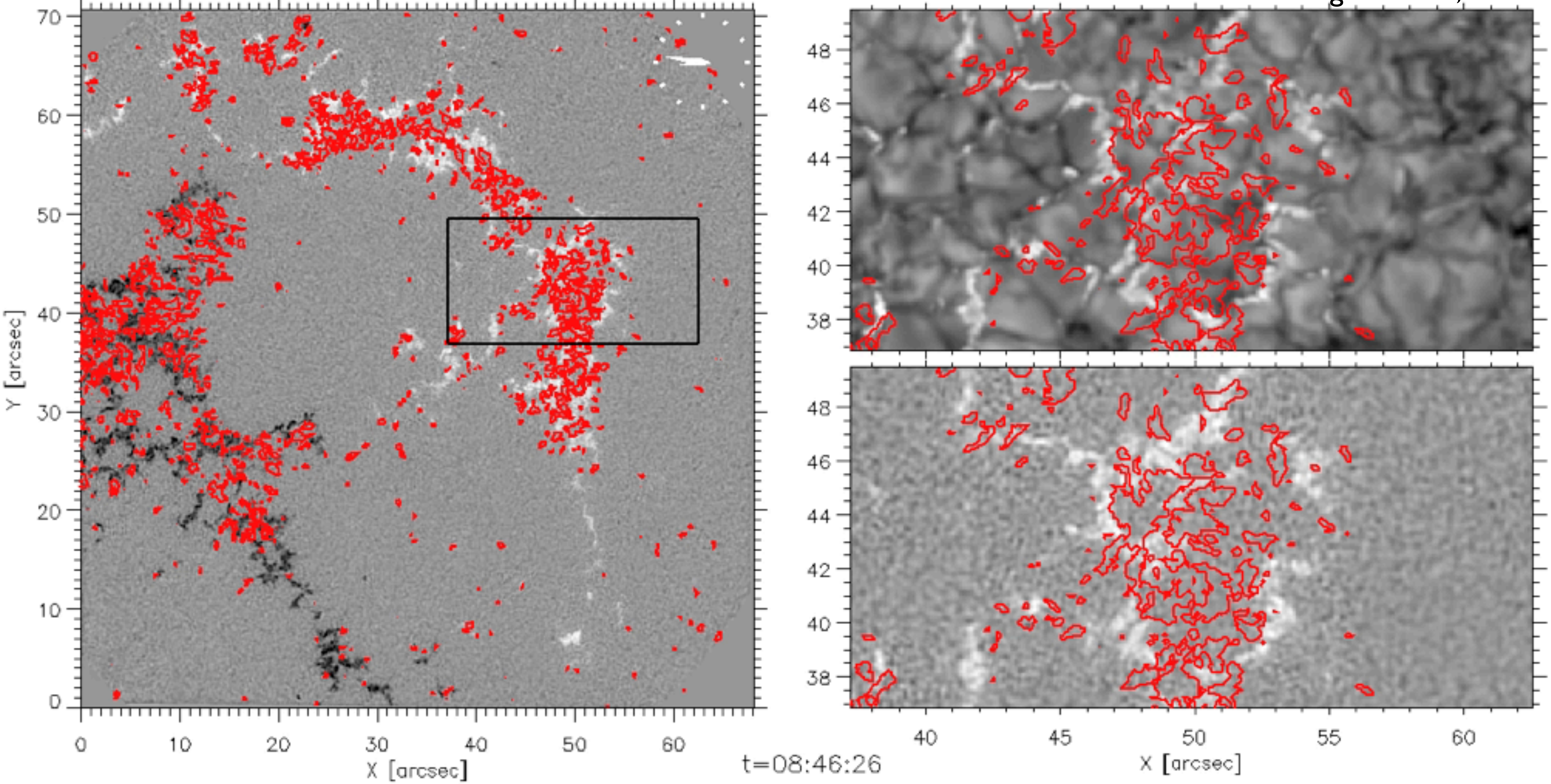
Bright-point: Absorption profile with higher intensity

Raised Core profile: quasi-flat-core Pietarila et al. (2007)

Plage heating highly variable in space and time

Auto-covariance timescale of order 1-2 minutes

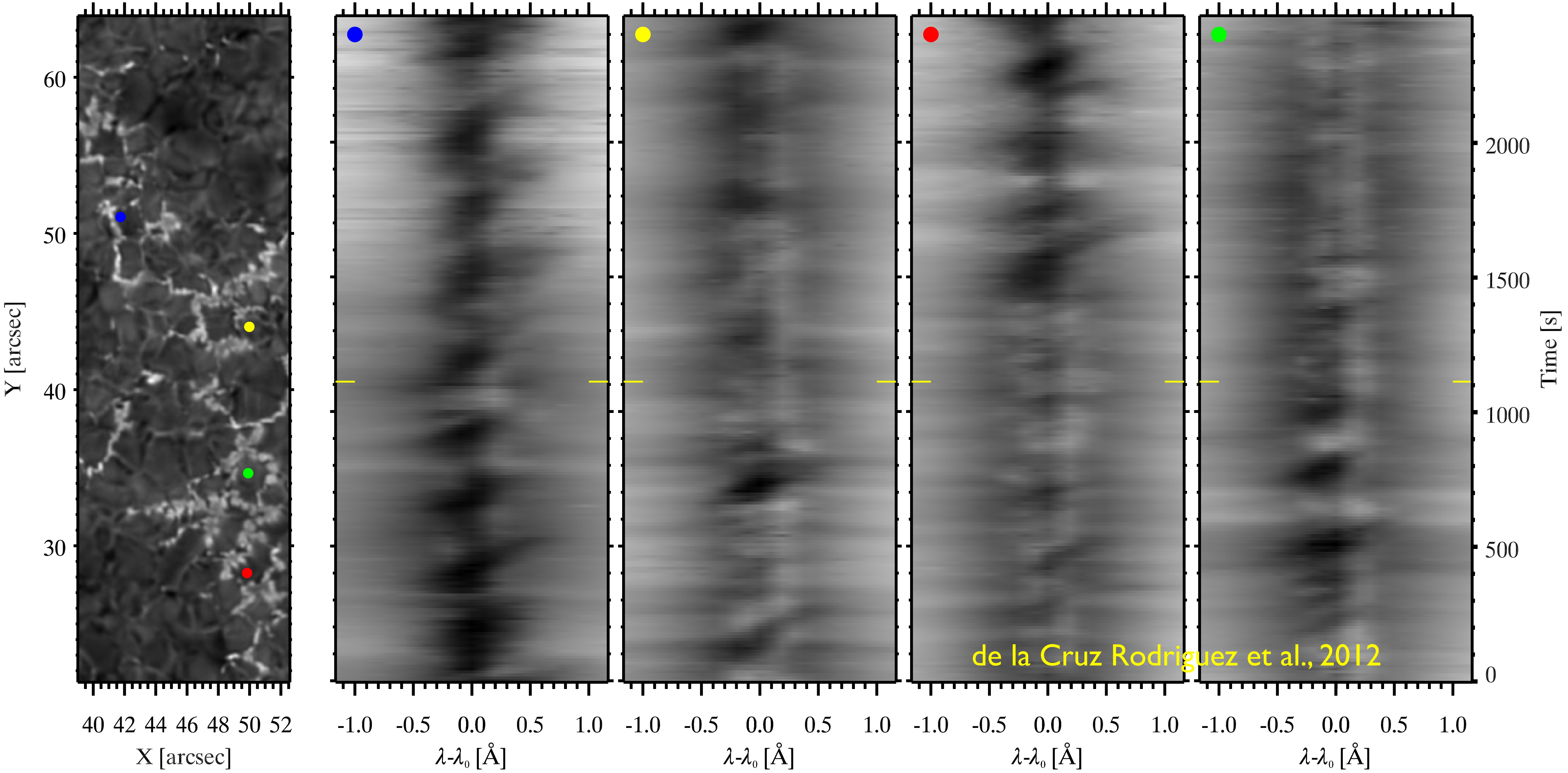
de la Cruz Rodriguez et al., 2012



Heating dependence on magnetic field/currents unclear

Combined measurements of DKIST (magnetic field),
ALMA (temperature/fields), IRIS (temperature, velocities) critical

Plage heating highly variable in space and time



de la Cruz Rodriguez et al., 2012

Ubiquitous presence of magneto-acoustic shock waves complicates line profiles and determination of heating properties

Unknown contribution to network/plage heating from shocks that drive fibrils

Hα linecenter

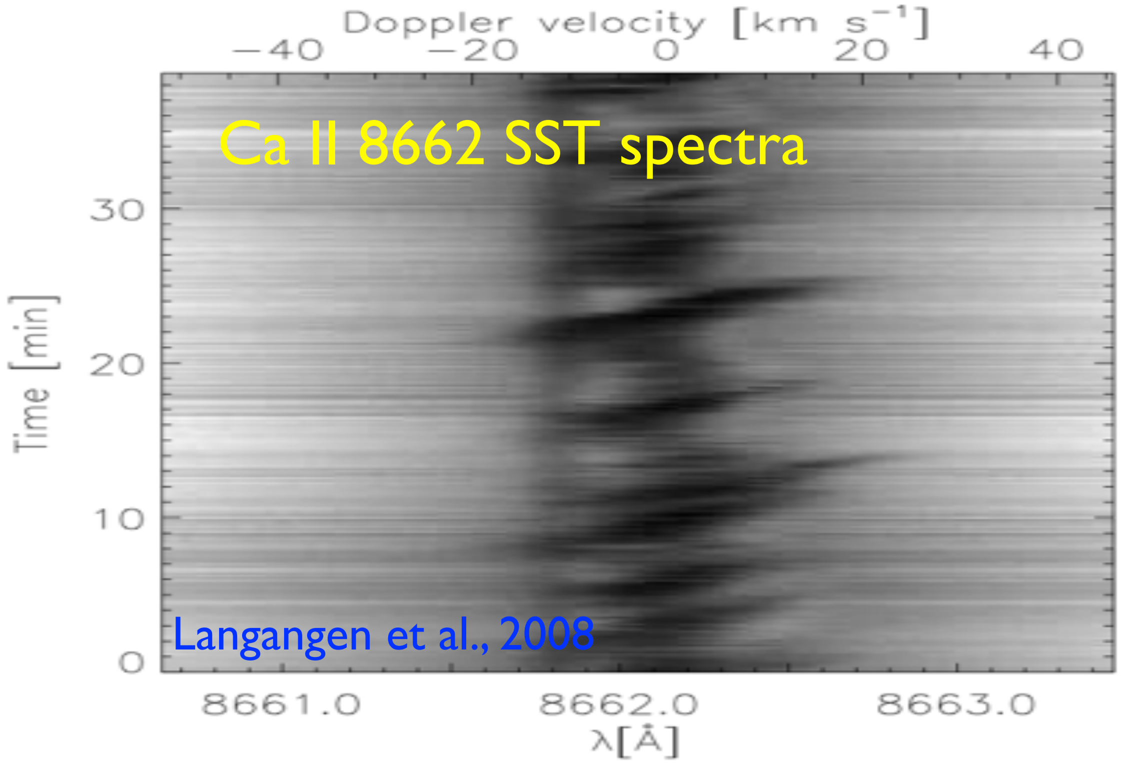
Hansteen et al., 2006, De Pontieu et al., 2007

Rouppe van der Voort et al., 2007, Heggland et al., 2007,

Martinez Sykora et al., 2009

SST Movie courtesy of Luc Rouppe van der Voort

Rezaei et al., 2007, Beck et al., 2008: network heating has both magnetic and non-magnetic components with similar contributions



Ca II 8662 SST spectra

Langangen et al., 2008

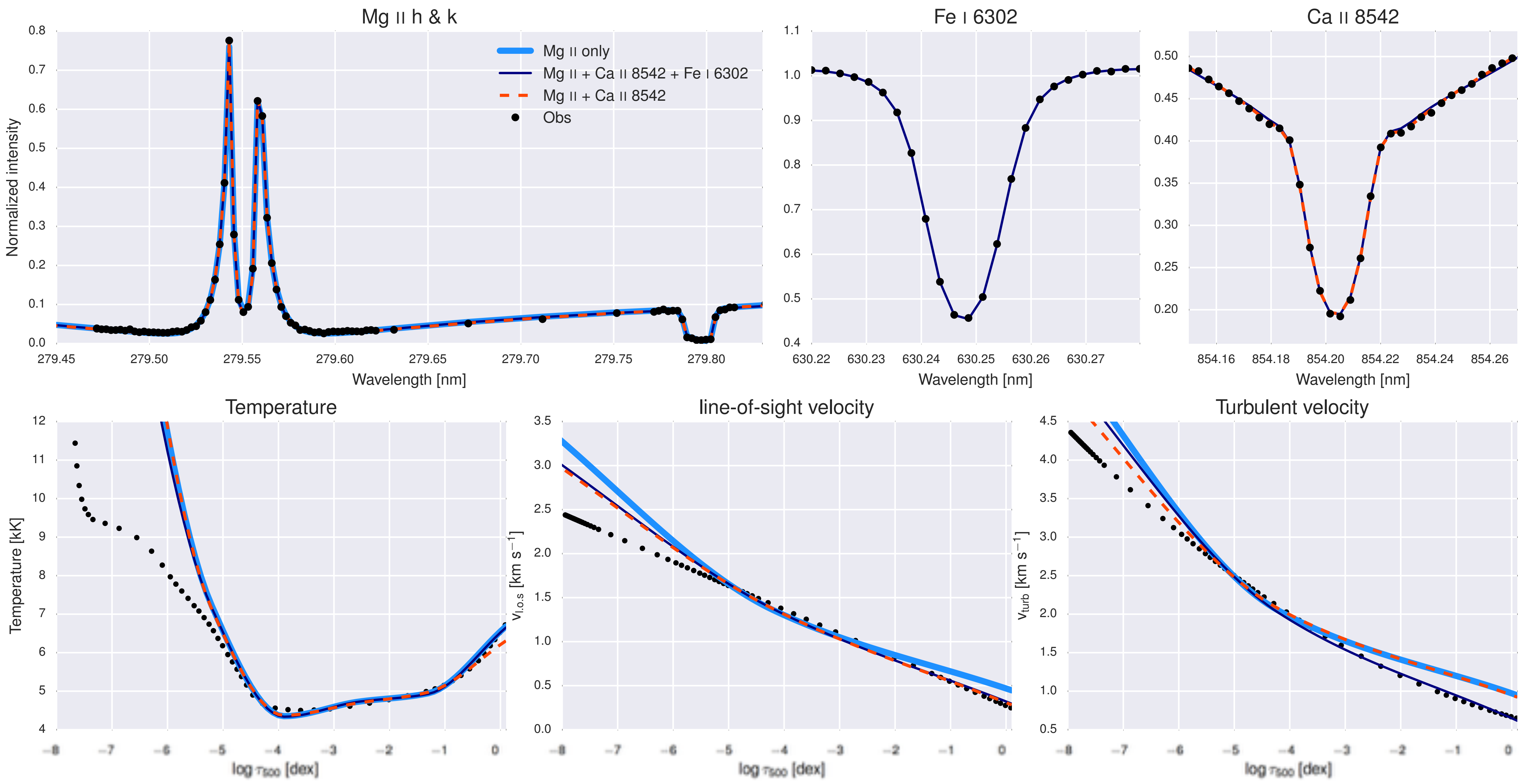
Magnetoacoustic shocks (from leakage of waves, convection, magnetic energy release along flux concentrations) drive flows (~20-30 km/s): dynamic fibrils in plage, mottles in QS network

To determine their role in chromospheric energetics, we need:

1. Comparison of high resolution spectroscopy with synthetic observables from 3D radiative MHD simulations
2. Better determination of heating properties

And what about wave-mode coupling?
Alfven wave generation, magneto-acoustic gravity waves, penumbral running waves, etc…

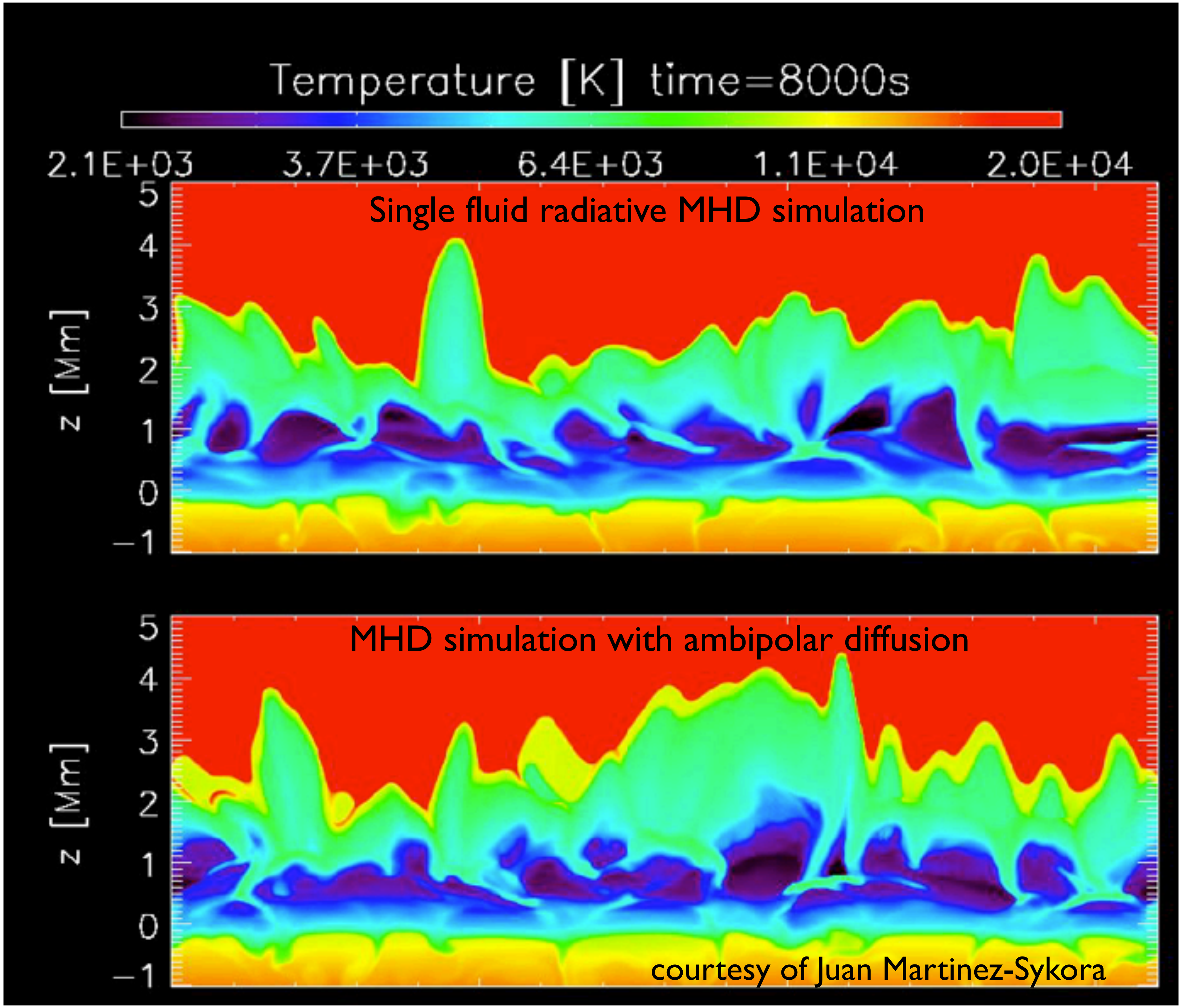
Are sophisticated inversion techniques the path forward?



Yes

See talk by Jaime de la Cruz Rodriguez on Thursday

How do ion-neutral effects impact chromospheric energetics?



courtesy of Juan Martinez-Sykora

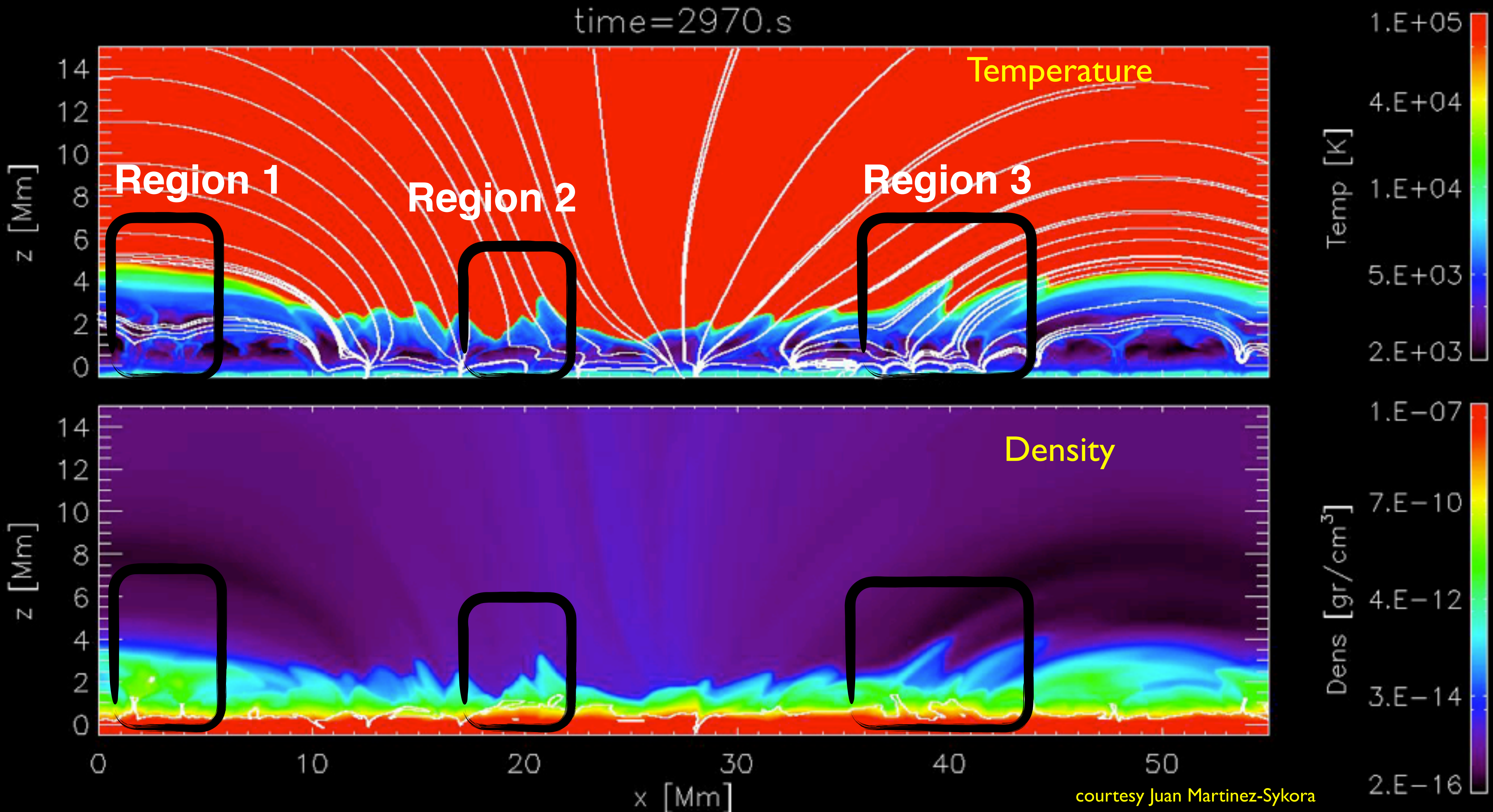
Single-fluid MHD simulations use generalized Ohm's law (GOL) to include ambipolar diffusion

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

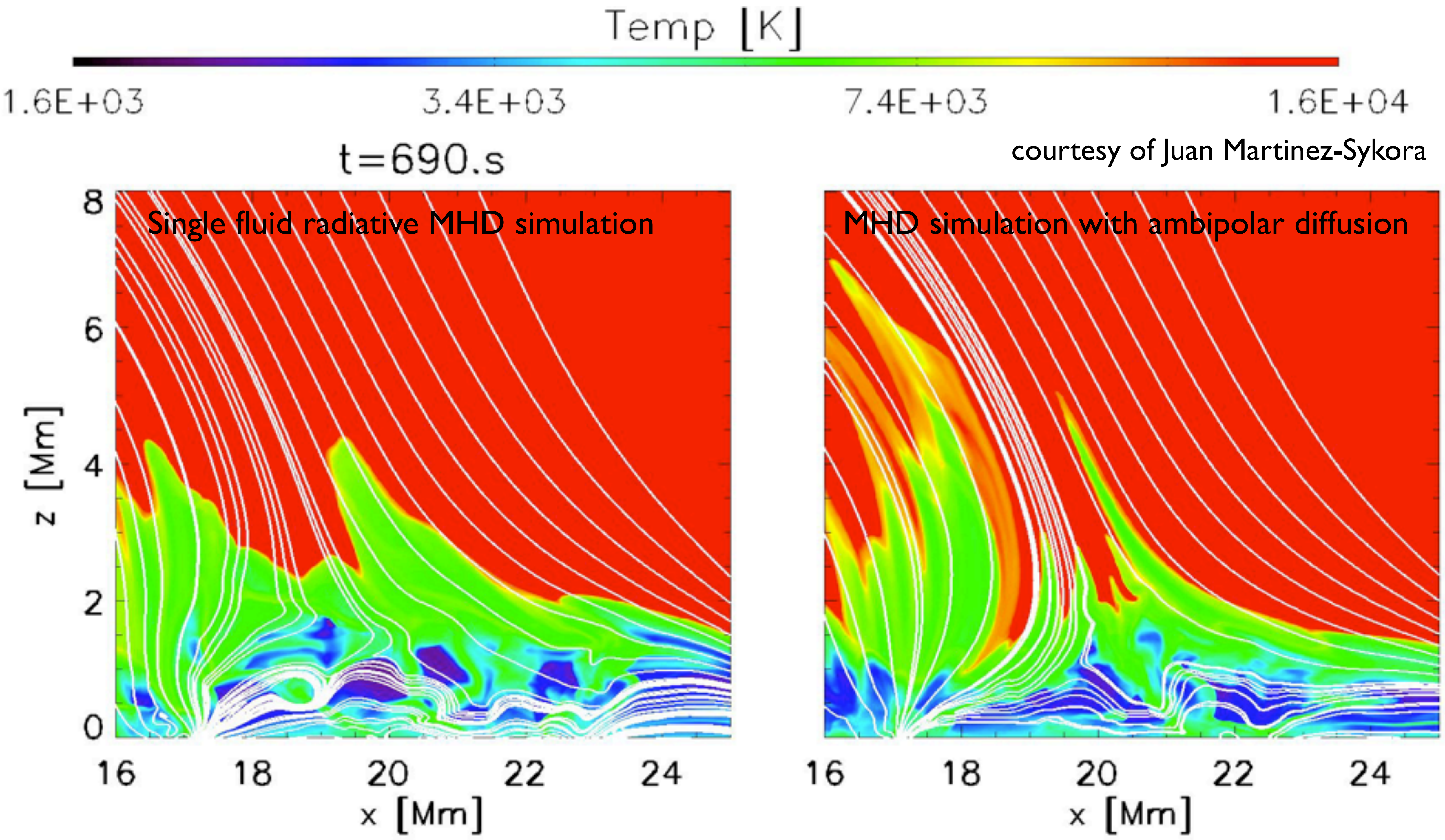
Simulations of chromospheric reconnection

Large variety of interesting reconnection processes in the chromosphere are present as a result of large and small scale magnetic properties.



courtesy Juan Martinez-Sykora

Reconnection jets in solar atmosphere strongly affected by ambipolar diffusion


courtesy of Juan Martinez-Sykora

Single fluid radiative MHD simulation

MHD simulation with ambipolar diffusion

Dynamics and Energetics of chromospheric reconnection jets significantly affected:

Ions and neutral decouple, leading to significant ambipolar diffusion and heating of plasma

Magnetic field is diffused and jets no longer outline magnetic field

But is generalized Ohm’s law good enough?

Impact of the chromosphere on the outer atmosphere

Chromospheric spicules are heated to transition region temperatures

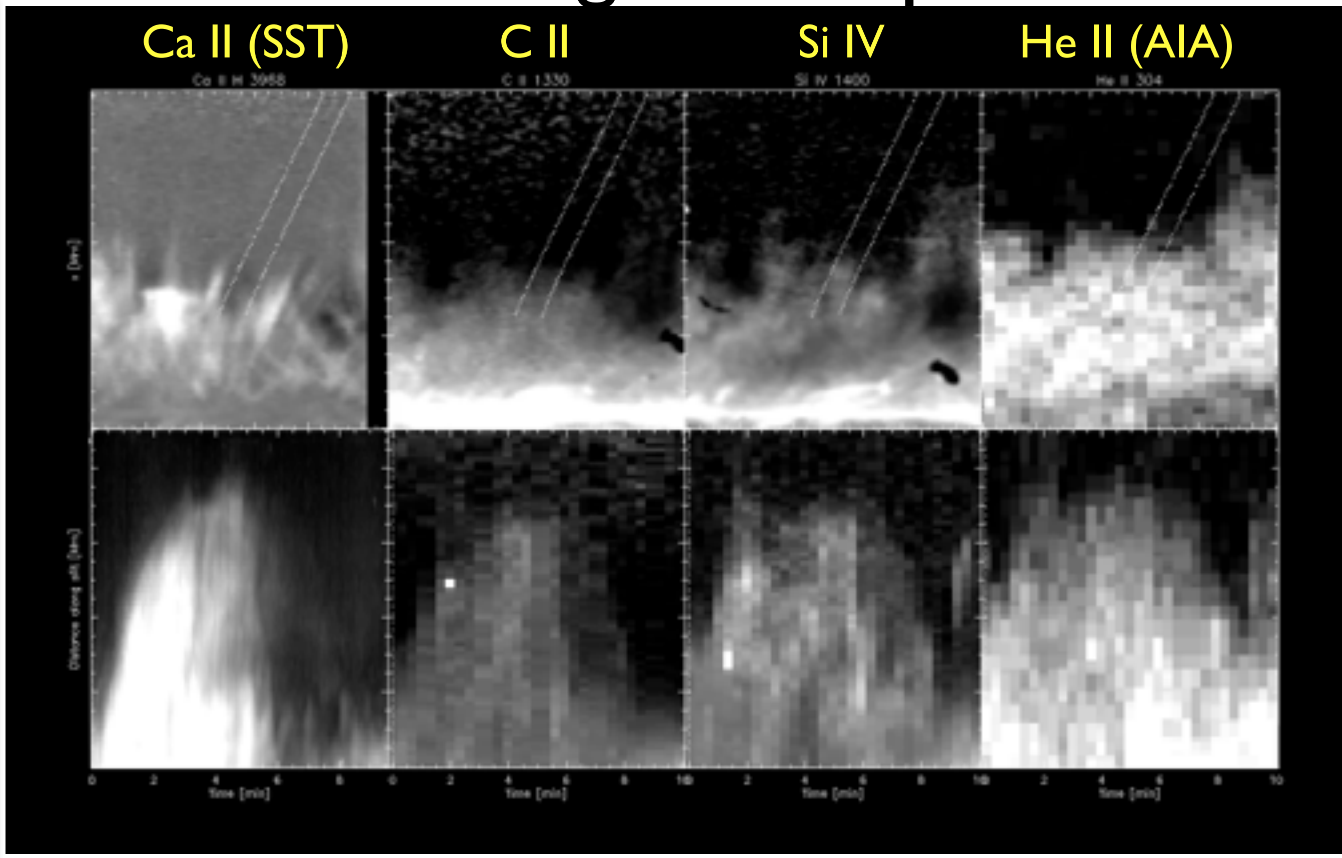
How are these formed?

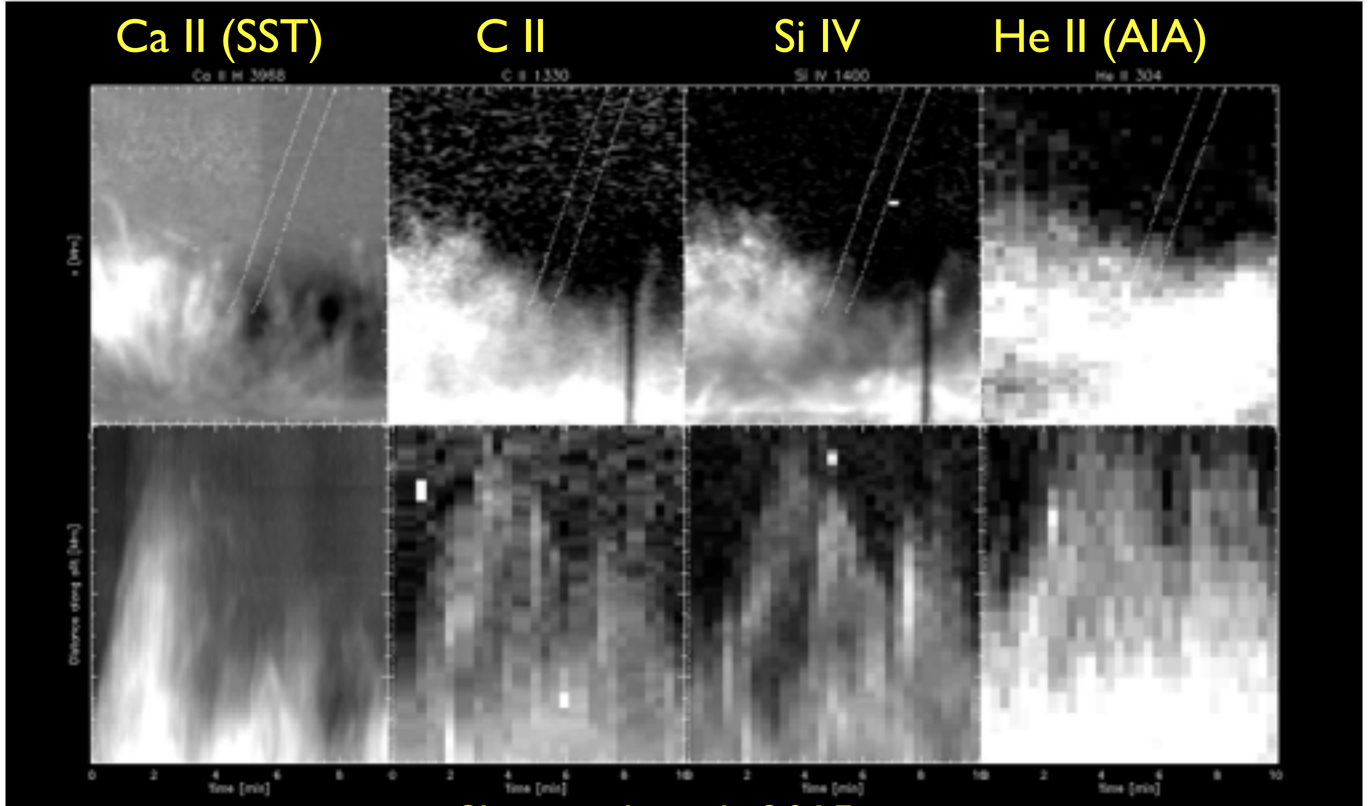
Reconnection from small-scale flux emergence?

How are they heated? To what temperatures?

Do these play a role in the pervasive redshift in the TR?

Do they play a role in the coronal energy balance?





Skogsrud et al., 2015

Type II spicules are heated and much more violent than type I spicules

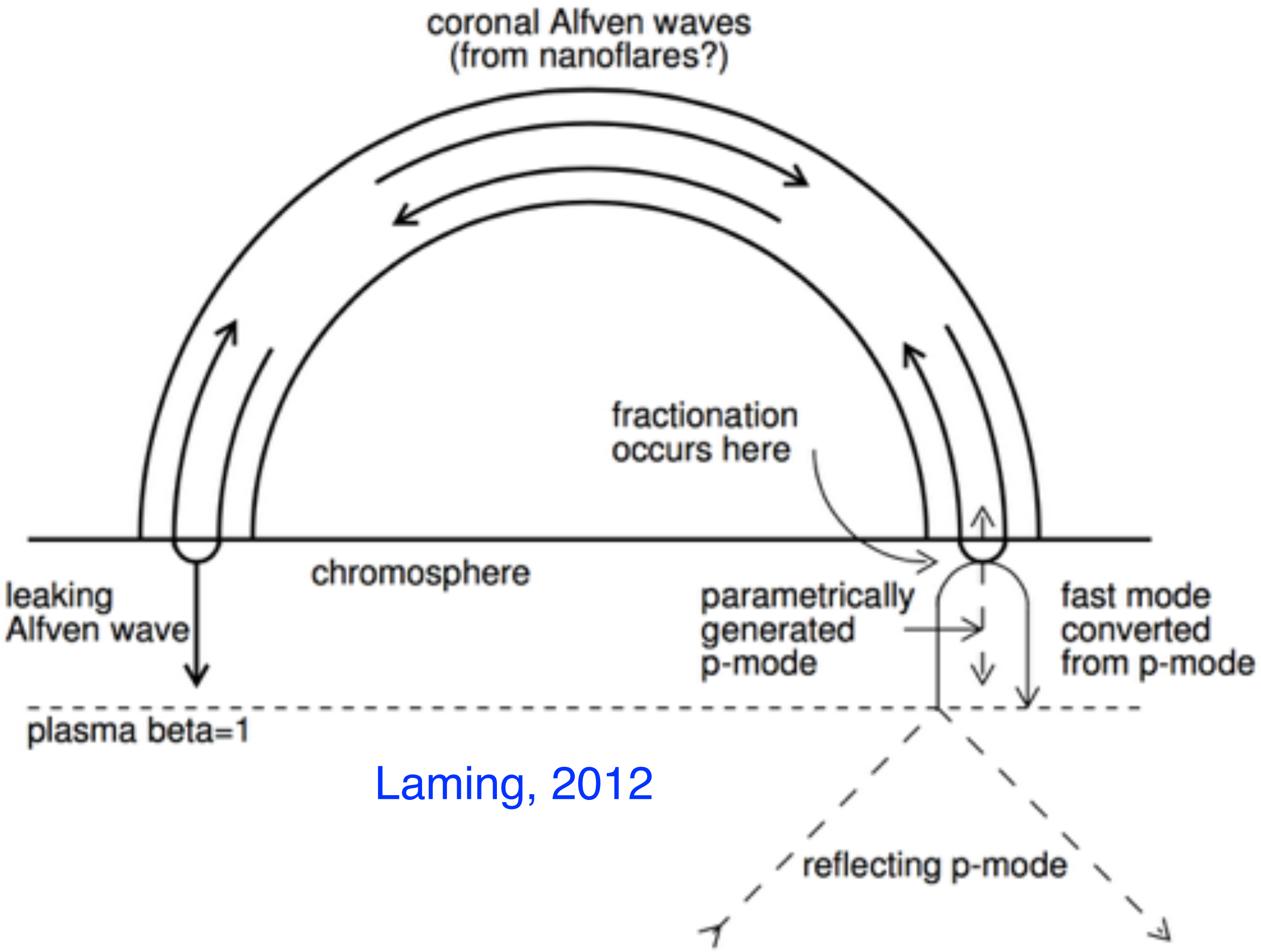
Heating timescales of order ~1 min

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 spatio-temporal extensions of Ca II H

Beyond MHD…

Can we constrain FIP models better with observations?

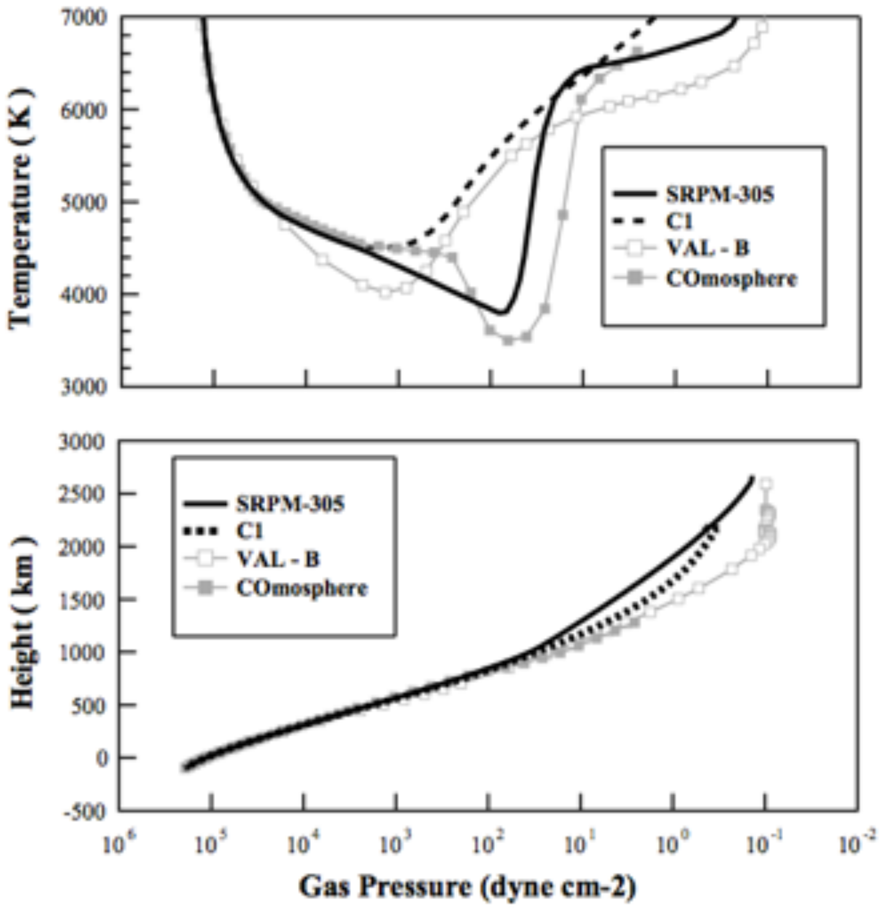


Laming, 2012

Alfven waves, generated in corona, leak into chromosphere
Fractionation from ponderomotive force on various ion species

Observations of these waves with DKIST?
Constraints on amplitudes?

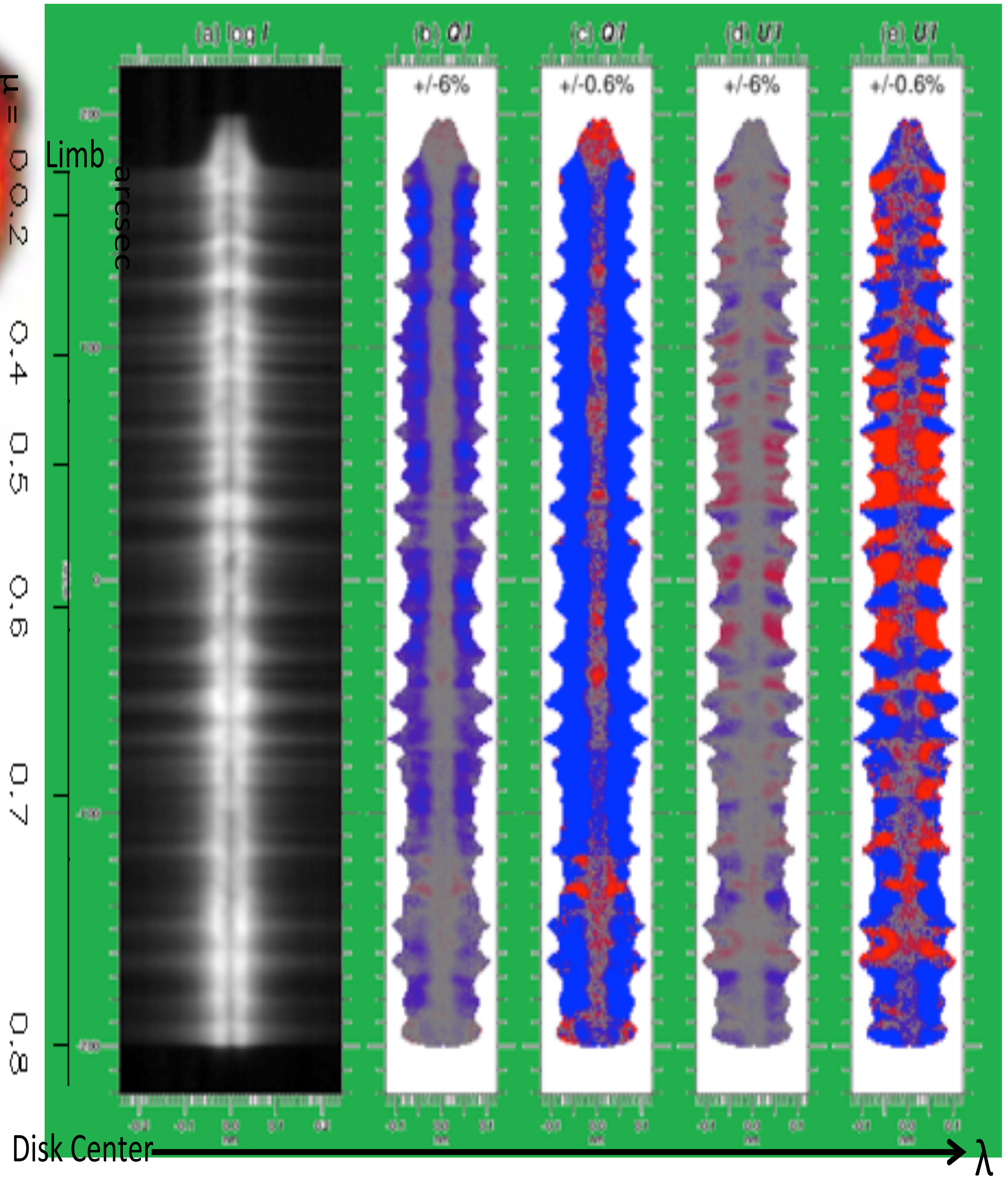
Plasma physics effects in chromosphere?



Switch-on nature of T increase result of Farley-Bunemann (FB) instability (Fontenla et al., 2008, Gogoberidze et al., 2009) caused by ion magnetization?

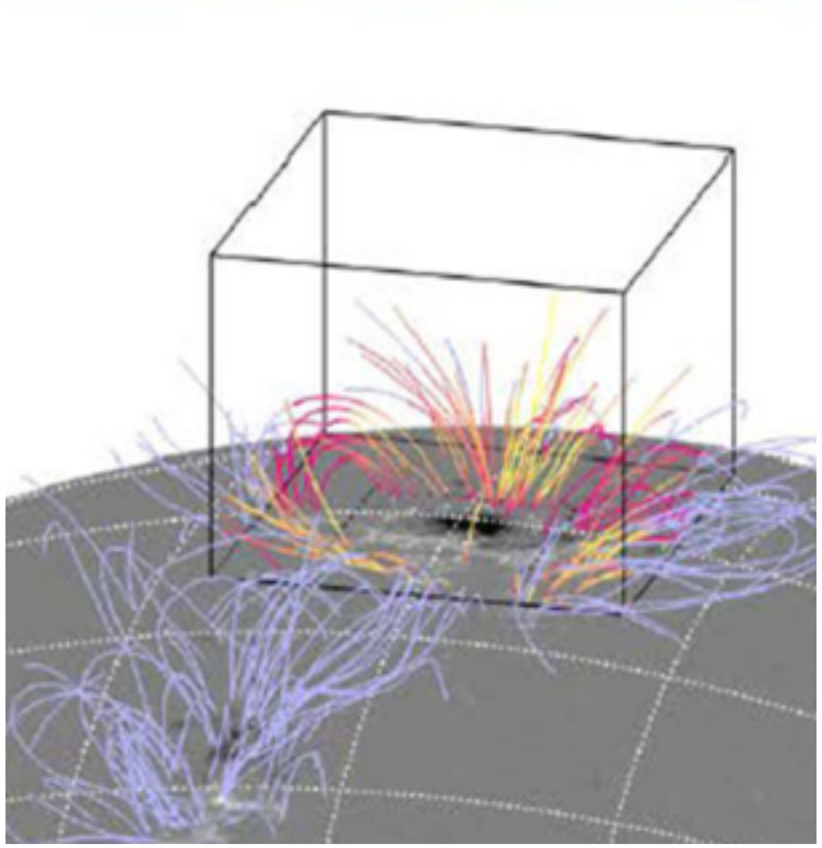
More sophisticated (e.g, multi-fluid) models required to make progress in understanding chromospheric heating, FIP effect, …

Inversion of spectropolarimetric data



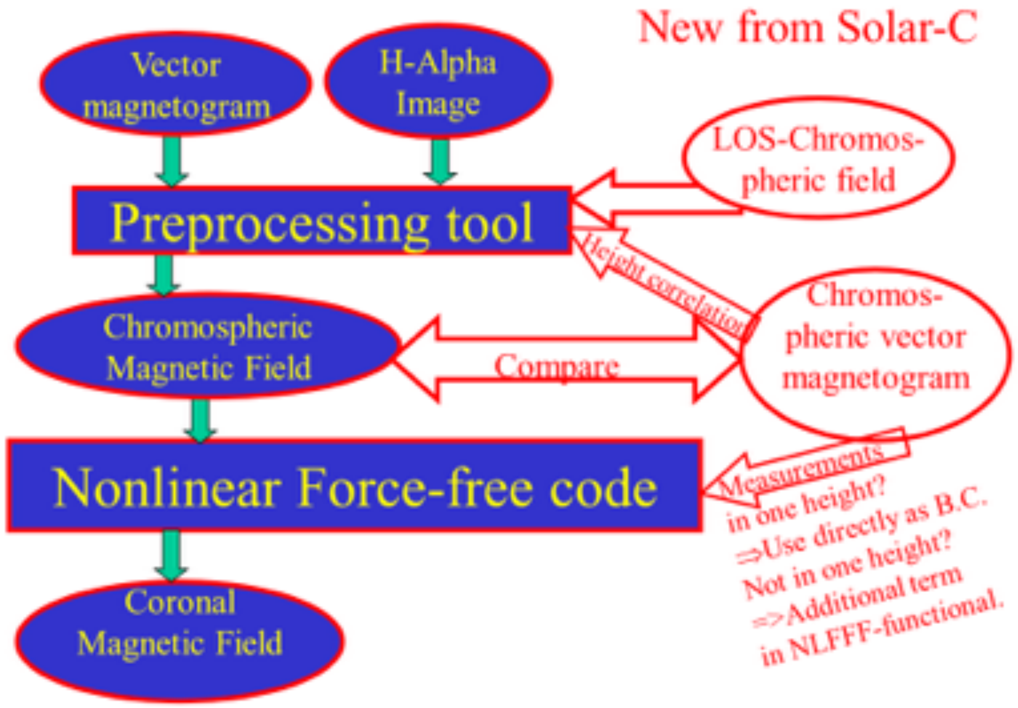
And what about Hanle effect?

The chromosphere and field extrapolations



DeRosa et al, 2009

Non-linear force-free extrapolations from photospheric magnetograms flawed (non-force-free nature of photosphere)



New from Solar-C

Vector magnetogram

H-Alpha Image

LOS-Chromospheric field

Preprocessing tool

Height correlation

Chromospheric Magnetic Field

Compare

Chromospheric vector magnetogram

Nonlinear Force-free code

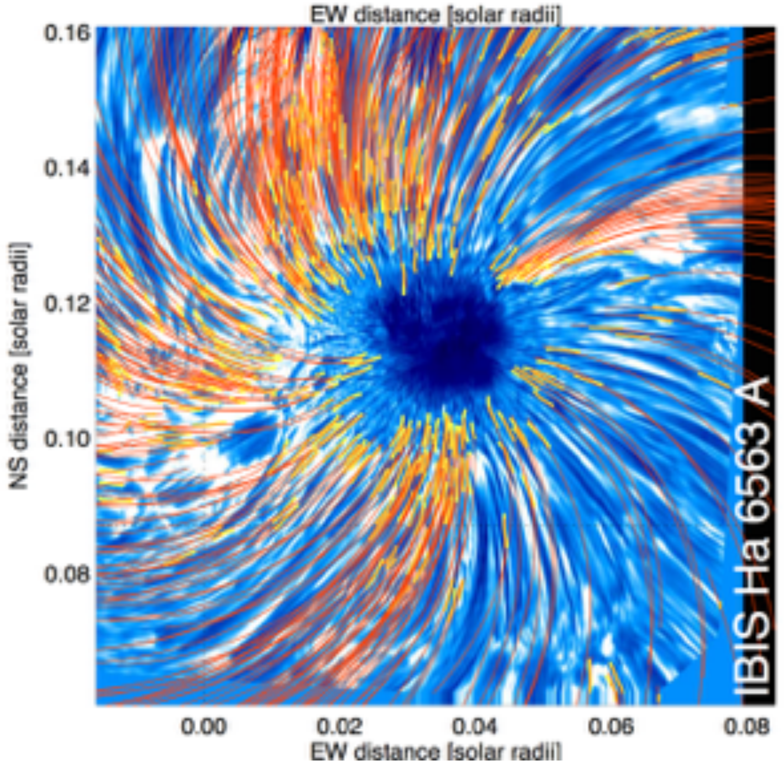
Measurements

in one height?
⇒Use directly as B.C.
Not in one height?
=>Additional term
in NLFFF-functional.

Coronal Magnetic Field

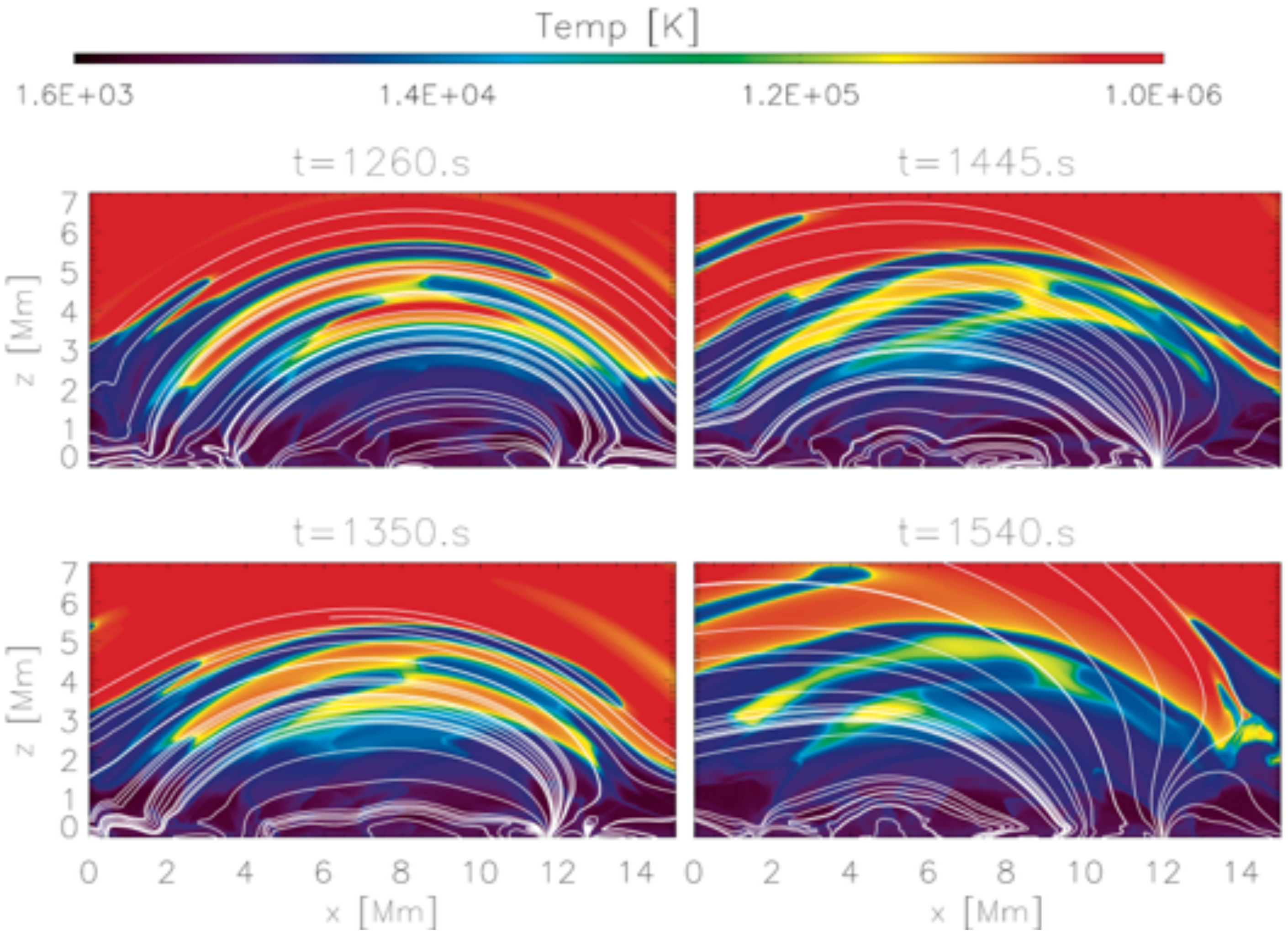
Wiegelmann et al., 2015

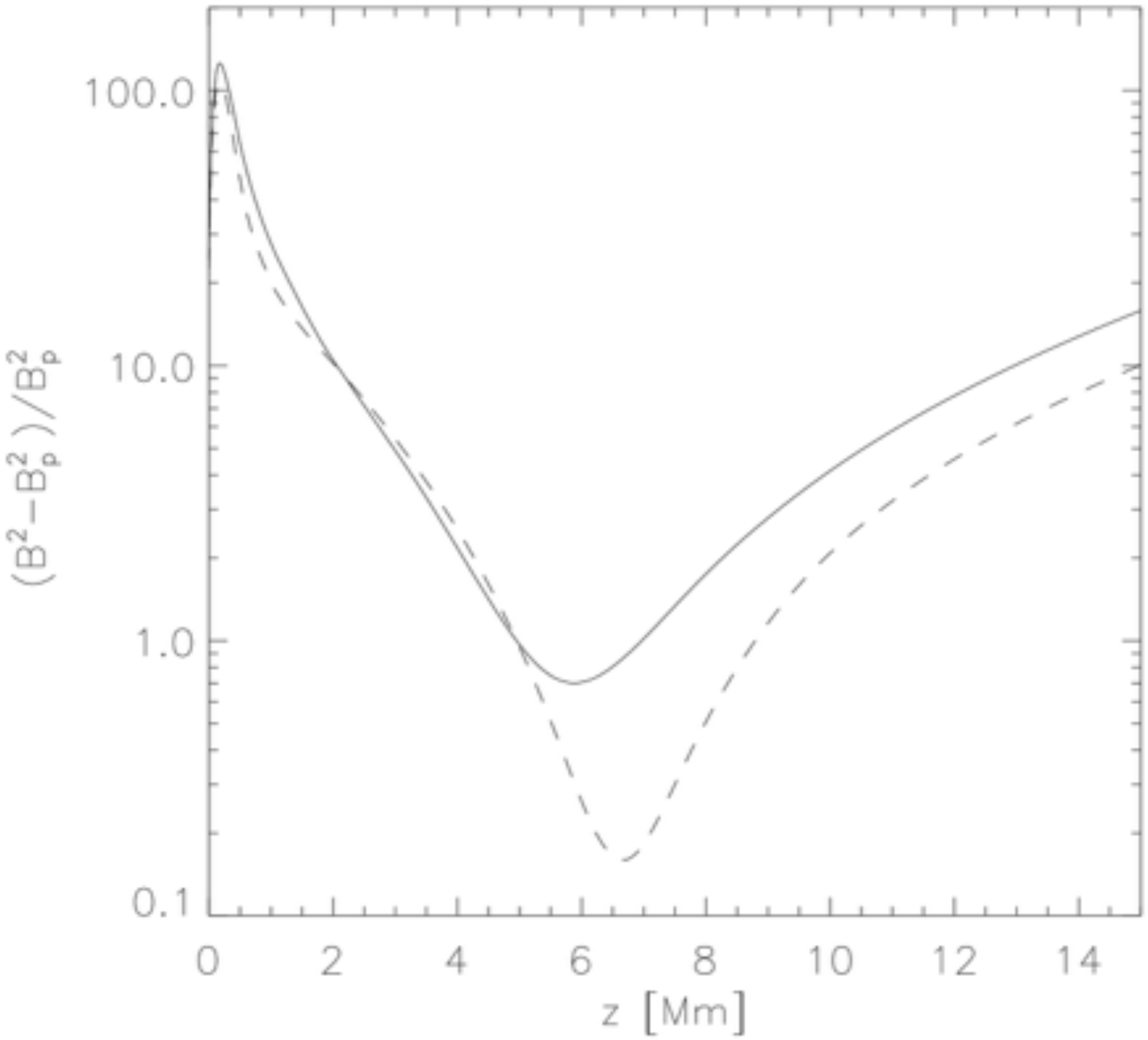
Inclusion of chromospheric data (images and magnetograms) critical for improvement of NLFFF



Aschwanden et al., 2016

Ion-neutral effects also affect coronal magnetic field



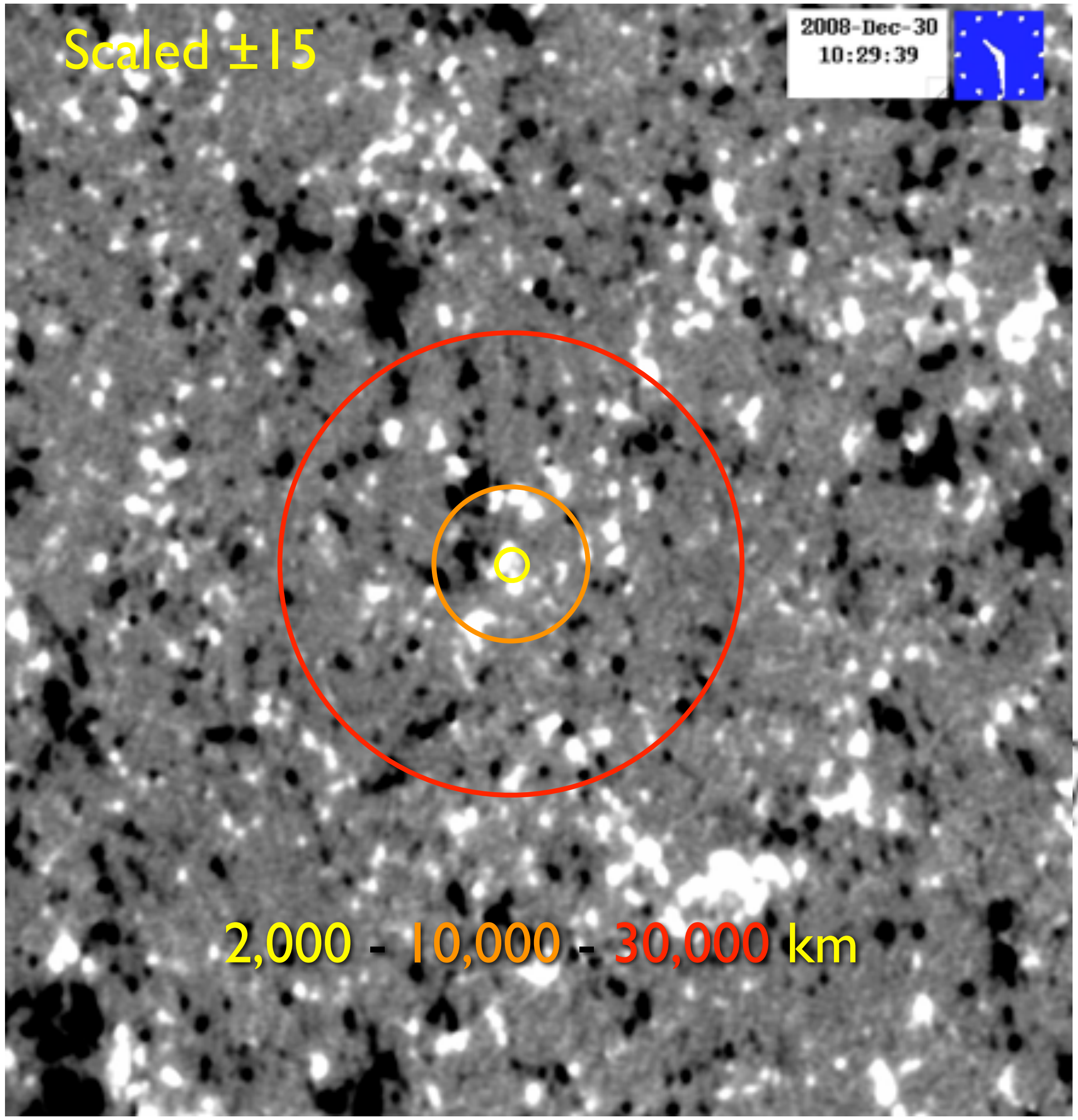


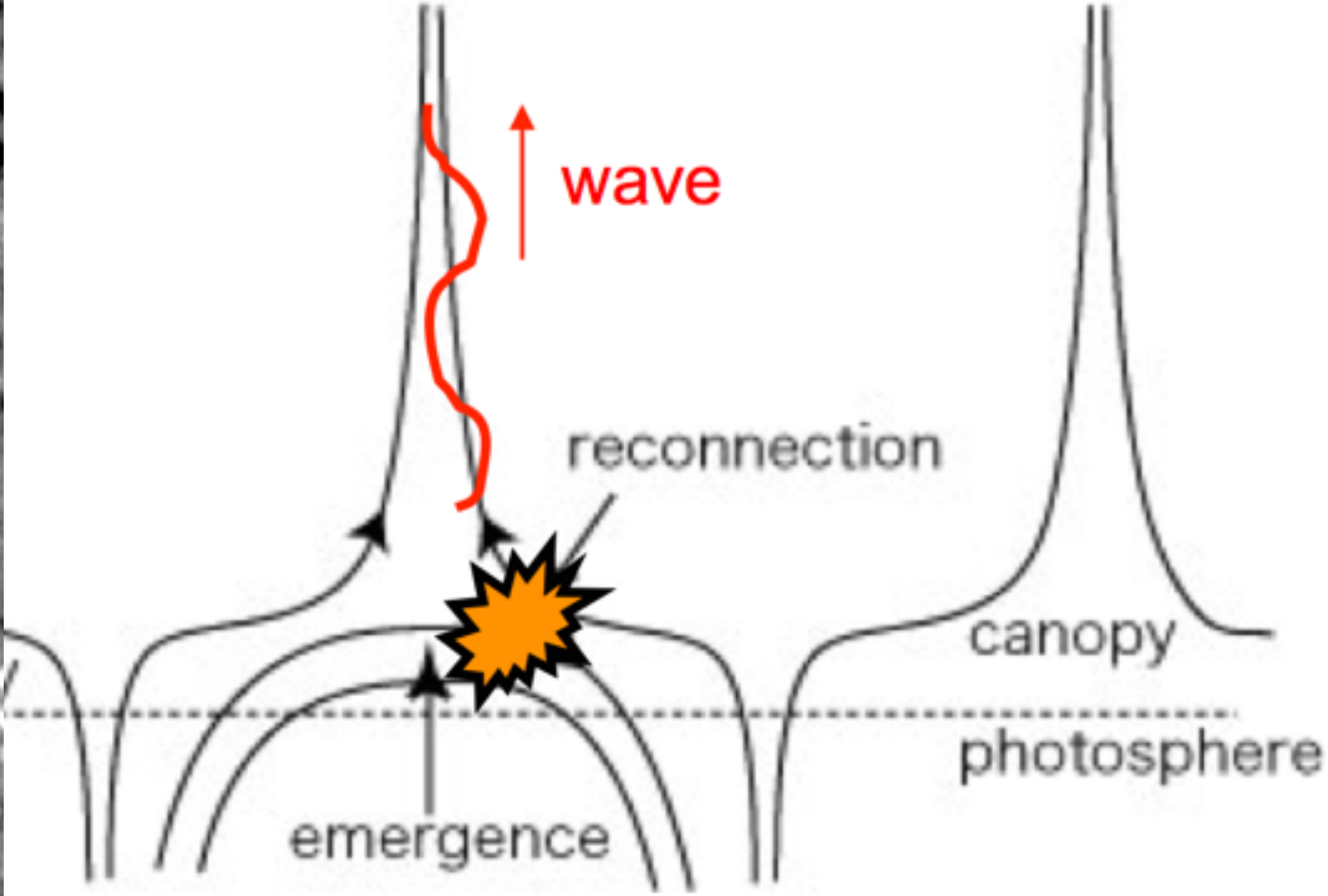
courtesy of Juan Martinez-Sykora

Chromospheric intensity structures (often used for field extrapolations) may not necessarily follow magnetic field direction (see also Socas-Navarro et al., 2012)

Ambipolar diffusion tends to render coronal field more "force-free"

Granular fields emerging into chromosphere may provide significant energy





Movies courtesy of Alan Title/Ted Tarbell

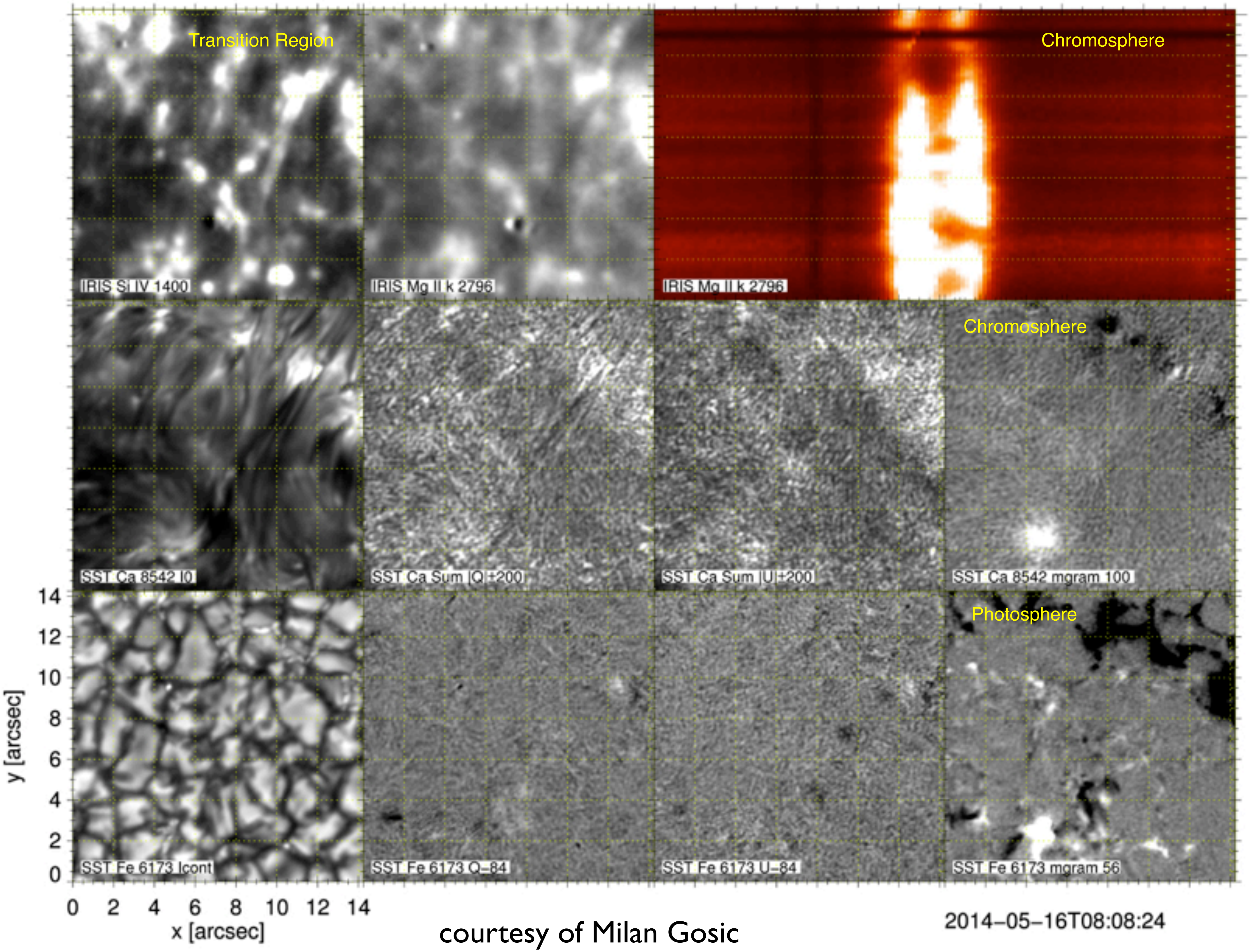
Granular fields are weak, but total flux emerging over whole Sun is enormous

Martinez Gonzalez & Bellot Rubio (2009), see also Ishikawa et al. (2009,2010)

Significant fraction of granular fields estimated to reach chromosphere within 5 min: chromospheric energy flux density of 10^6-10^7 erg/cm^2/s (Martinez-Gonzalez et al., 2010)

But remember: energy flux estimates are not enough! Need to track flux as it enters chromosphere

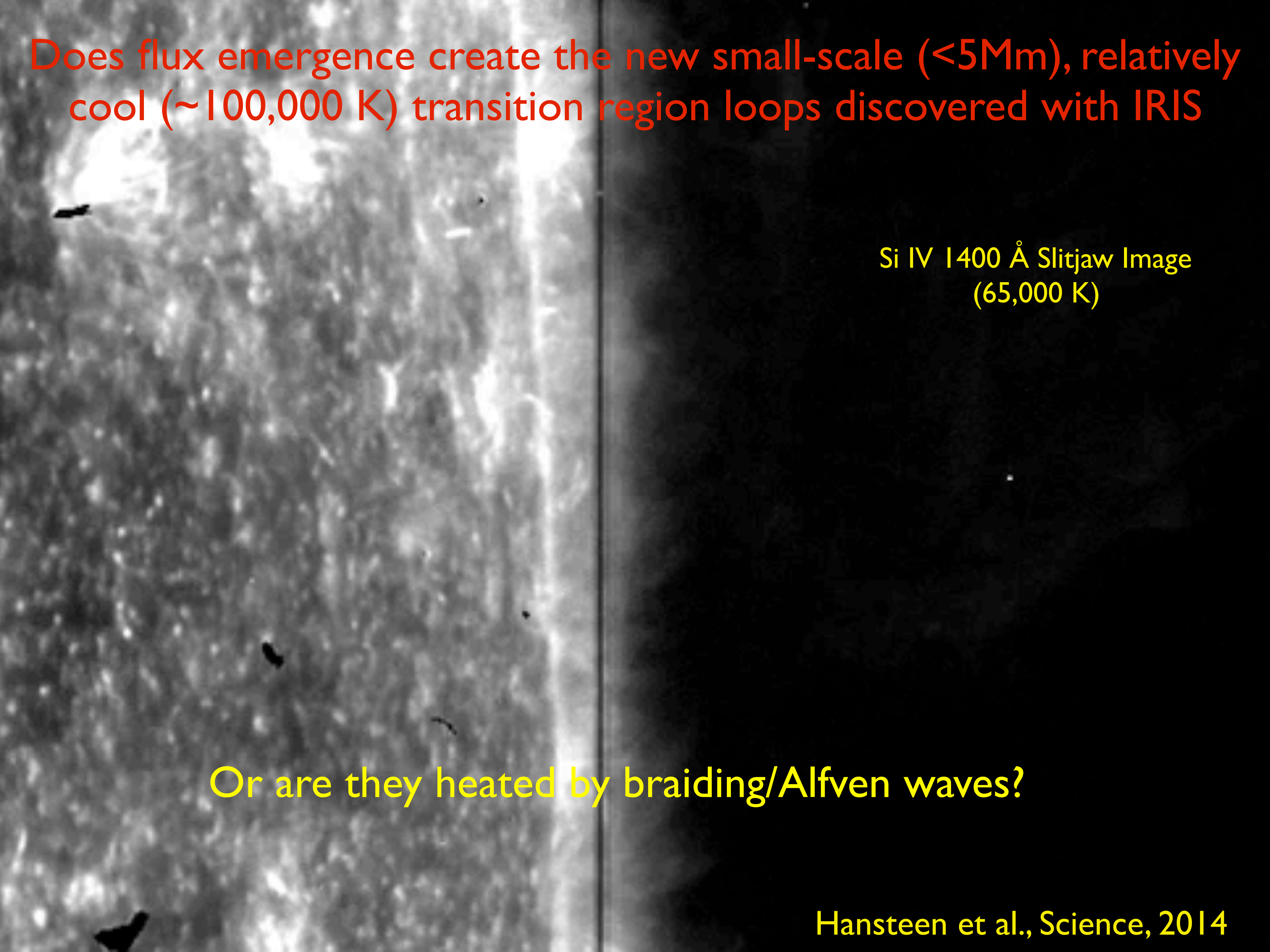
Impact of granular fields on chromospheric dynamics/energetics



courtesy of Milan Gosic

Requires high-resolution observations at multiple layers/diagnostics and advanced inversion codes

Does flux emergence create the new small-scale (<5Mm), relatively cool (~100,000 K) transition region loops discovered with IRIS



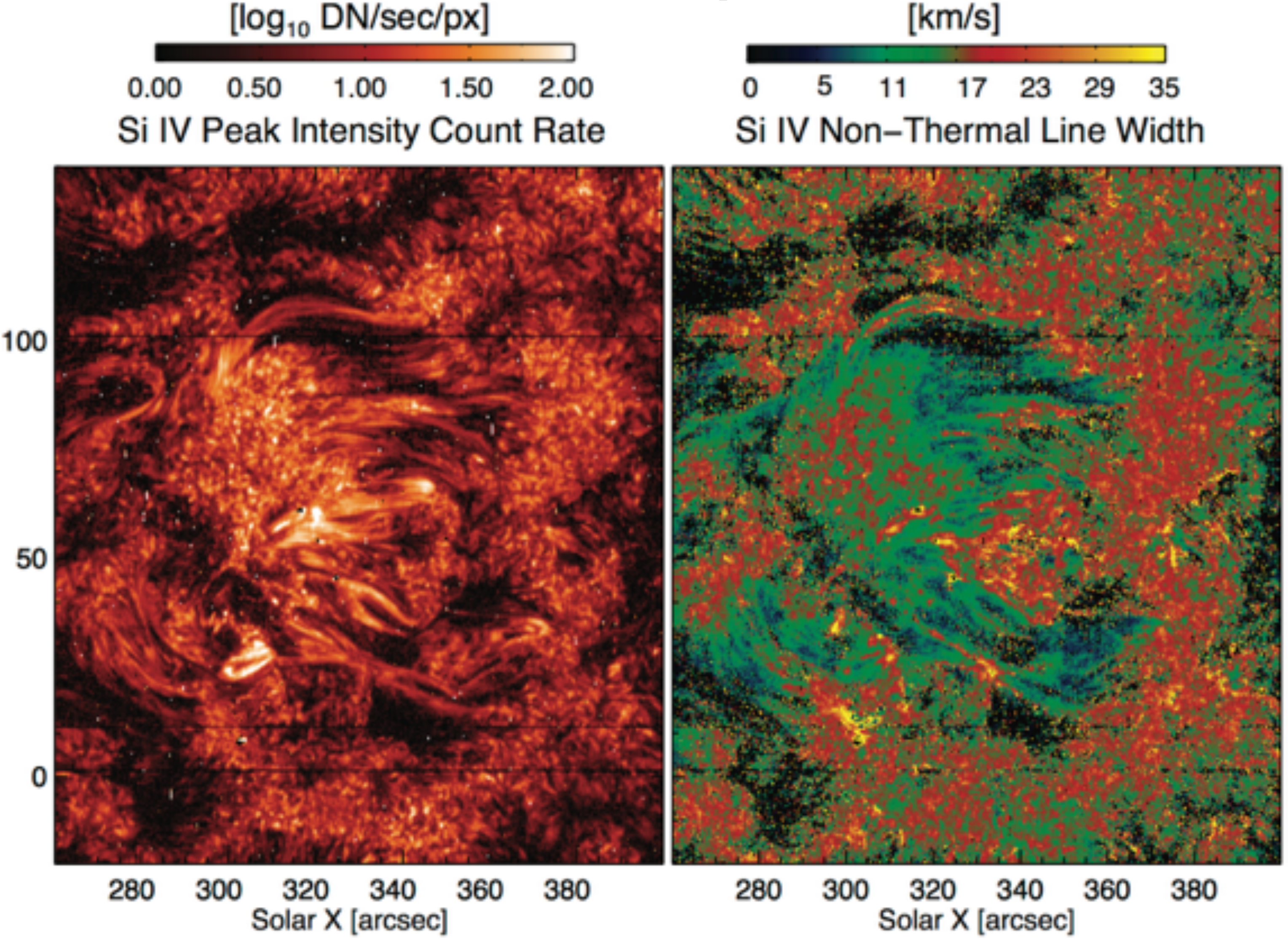
Si IV 1400 Å Slitjaw Image
(65,000 K)

Or are they heated by braiding/Alfven waves?

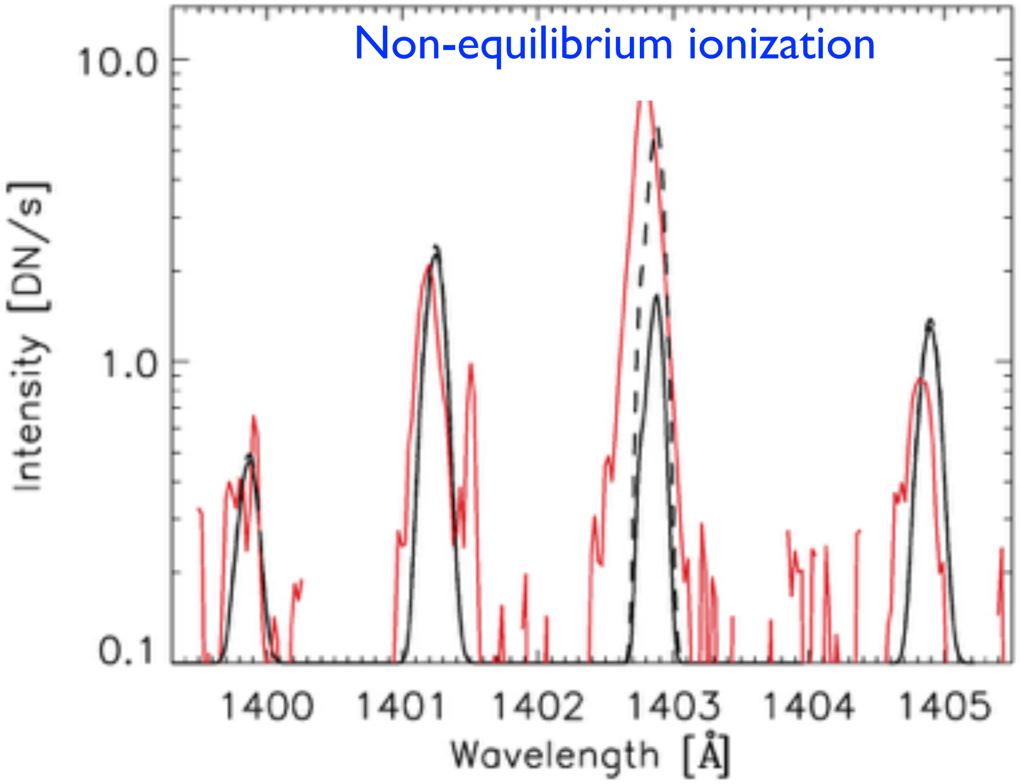
Hansteen et al., Science, 2014

Impact of the chromosphere on the outer atmosphere

What drives the dynamics of the transition region spectral lines?



De Pontieu et al., 2015



Non-equilibrium ionization

Martinez-Sykora et al., 2016

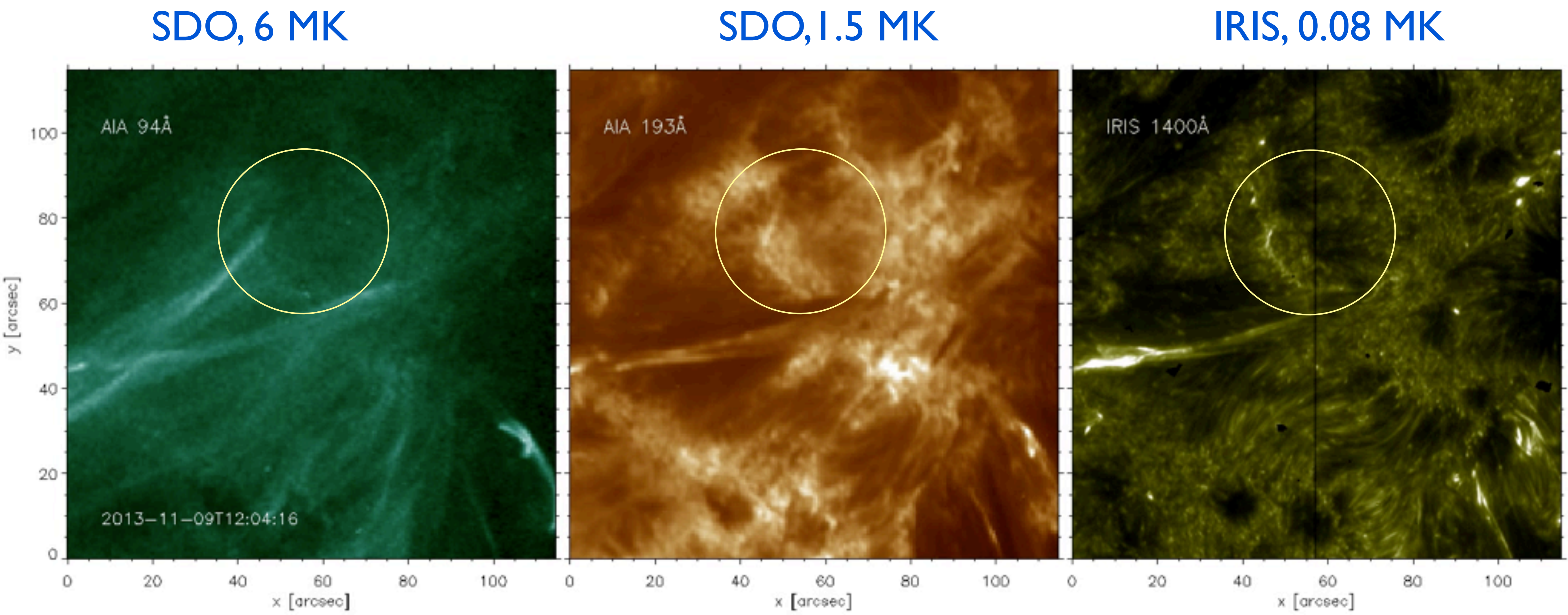
Active region plage: dynamic fibrils (type I spicules) often associated with Si IV brightenings, blueshifts, broadening

Impact of chromospheric shocks on TR may help explain apparent invariance of non-thermal line broadening to spatial resolution, non-equilibrium ionization in TR, etc…

Skogsrud et al., 2015

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

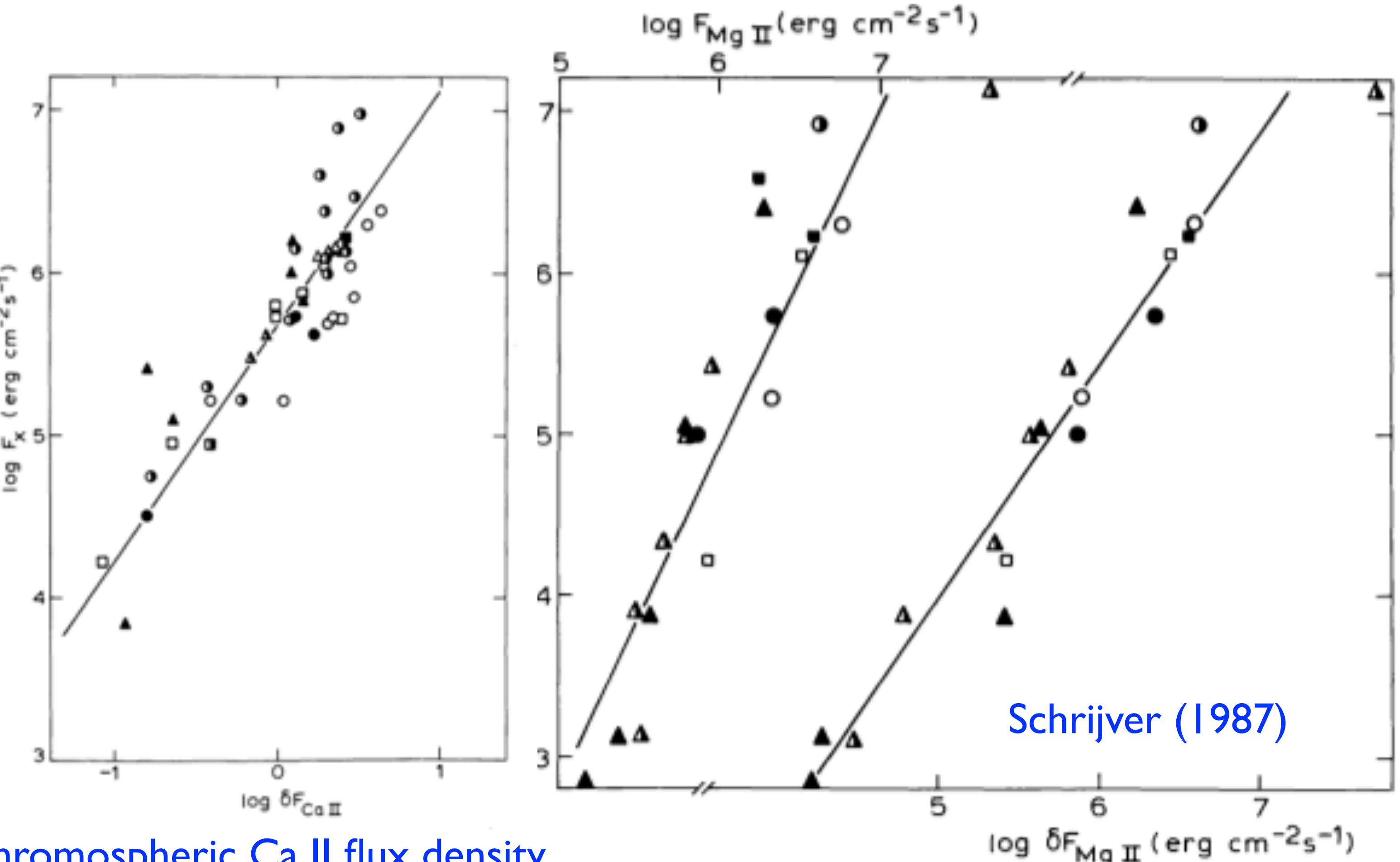
Coordinated high-resolution coronal, TR and chromospheric observations critical (Solar C, DKIST, etc…)

Testa et al., Science, 2014

Chromospheric and coronal heating are linked

Chromosphere-Corona

Coronal X-ray flux density



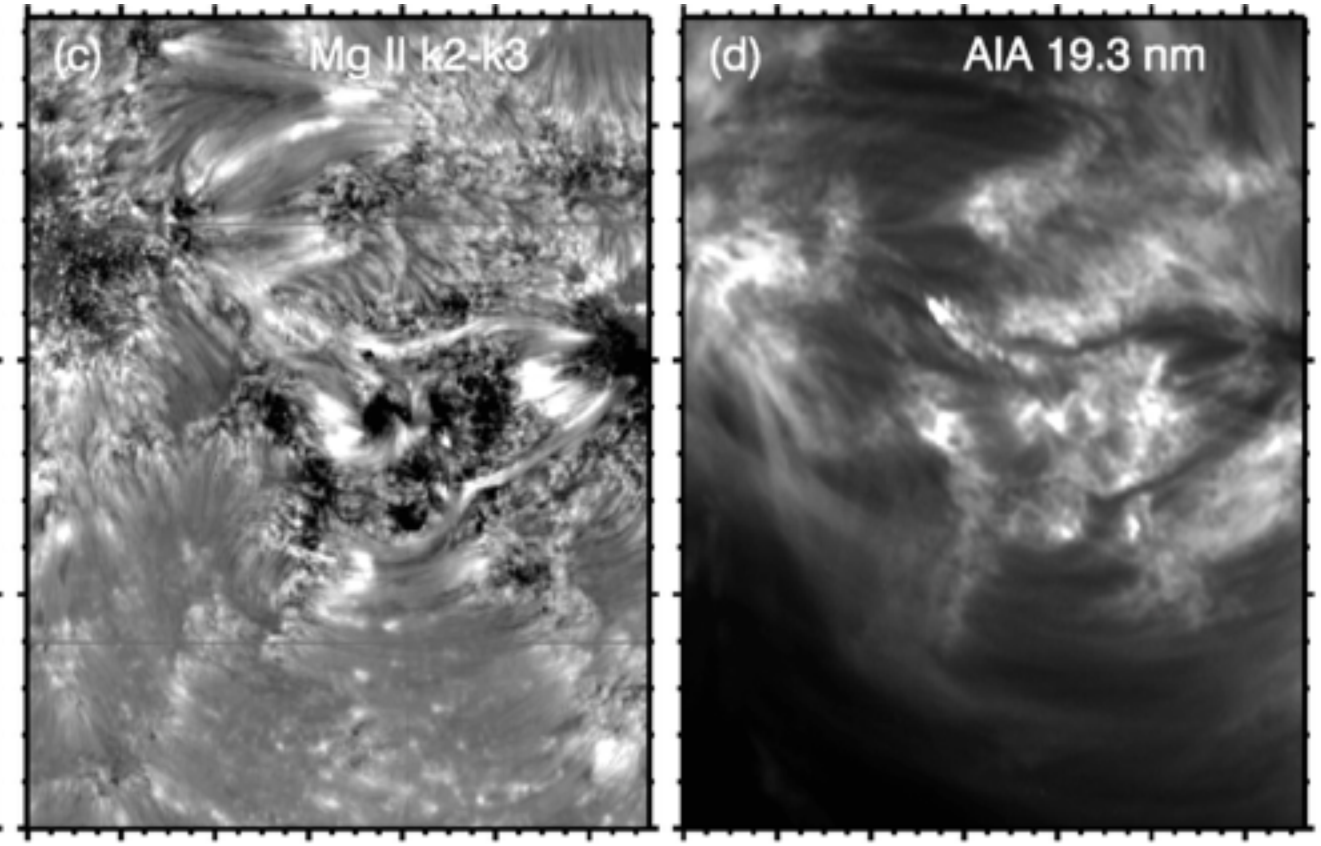
Schrijver (1987)

Chromospheric Ca II flux density
(basal flux subtracted)

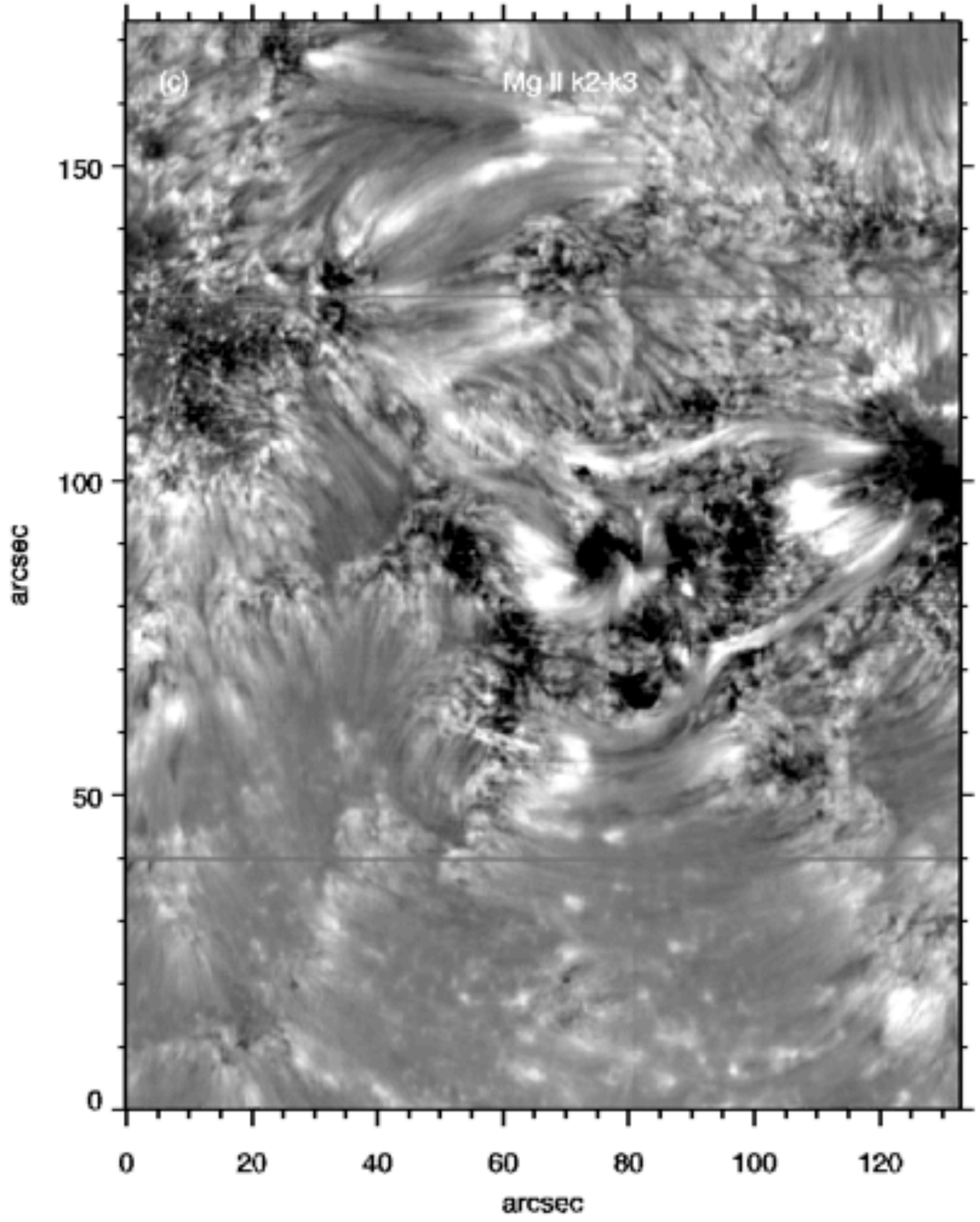
Chromospheric Mg II flux density

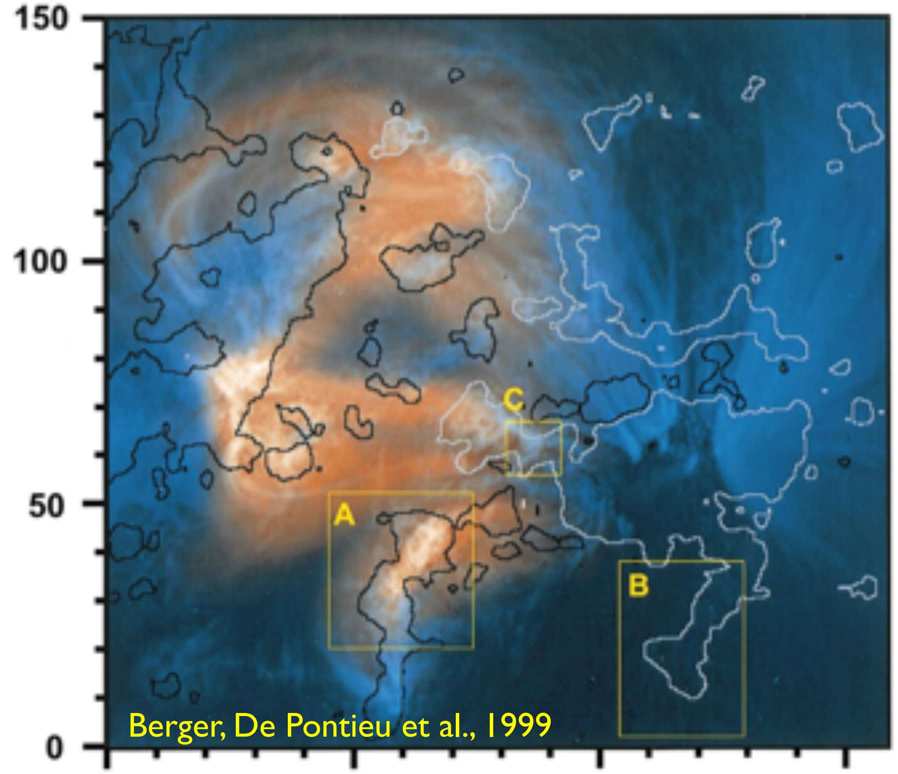
Chromospheric and coronal emission correlated on larger scales

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





Berger, De Pontieu et al., 1999

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

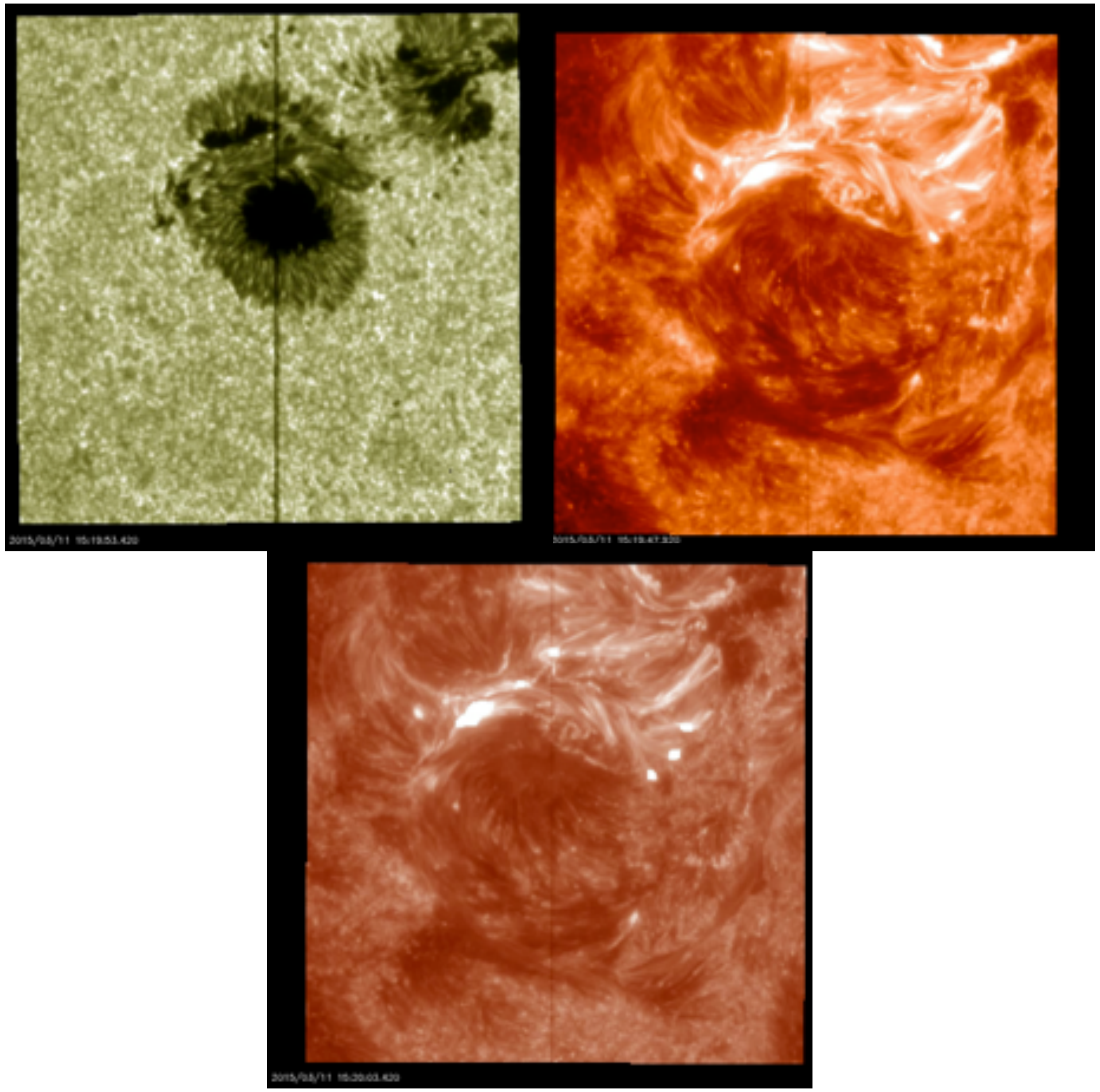
Moss brightness good proxy for coronal pressure

Tail wagging the dog?
Chromospheric observables and coronal properties linked

What do we really understand about prominences, flares?

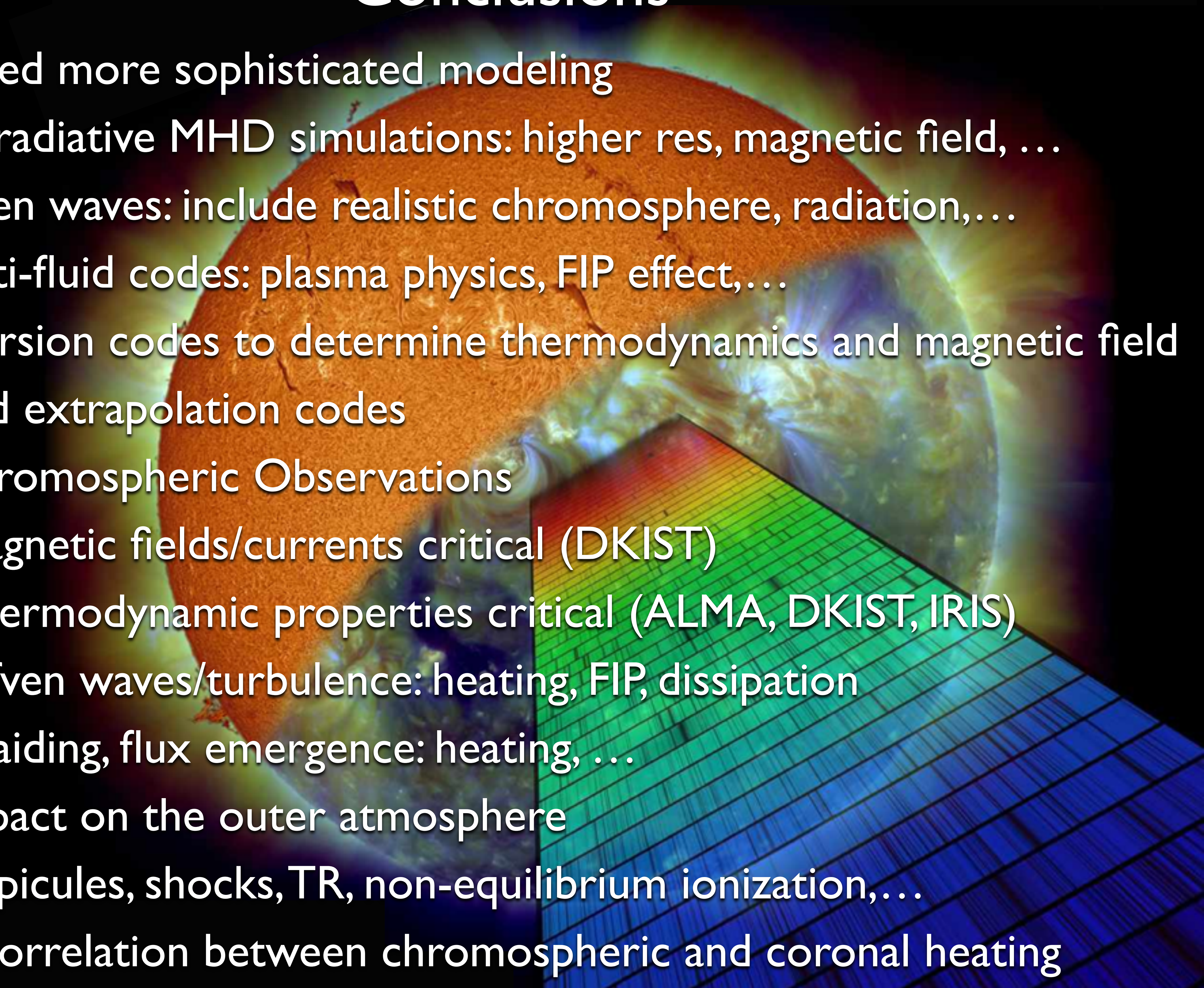
Berger et al., 2008

Properties, stability, dynamics…



Nature of white-light emission?
Role of Alfven waves?
Chromospheric evaporation/condensation?
Sunquakes?
Etc…

Conclusions



1. Need more sophisticated modeling
- 3D radiative MHD simulations: higher res, magnetic field, …
- Alfven waves: include realistic chromosphere, radiation,…
- Multi-fluid codes: plasma physics, FIP effect,…
- Inversion codes to determine thermodynamics and magnetic field
- Field extrapolation codes

2. Chromospheric Observations
   - Magnetic fields/currents critical (DKIST)
   - Thermodynamic properties critical (ALMA, DKIST, IRIS)
   - Alfven waves/turbulence: heating, FIP, dissipation
   - Braiding, flux emergence: heating, …

3. Impact on the outer atmosphere
   - spicules, shocks, TR, non-equilibrium ionization,…
   - correlation between chromospheric and coronal heating