

Heating of the upper chromosphere, transition region, and lower corona

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Pune India, 10-14/11 2014

July 29, 1998 Fe IX/X 171Å @TRACE

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

Hannes Alfvén

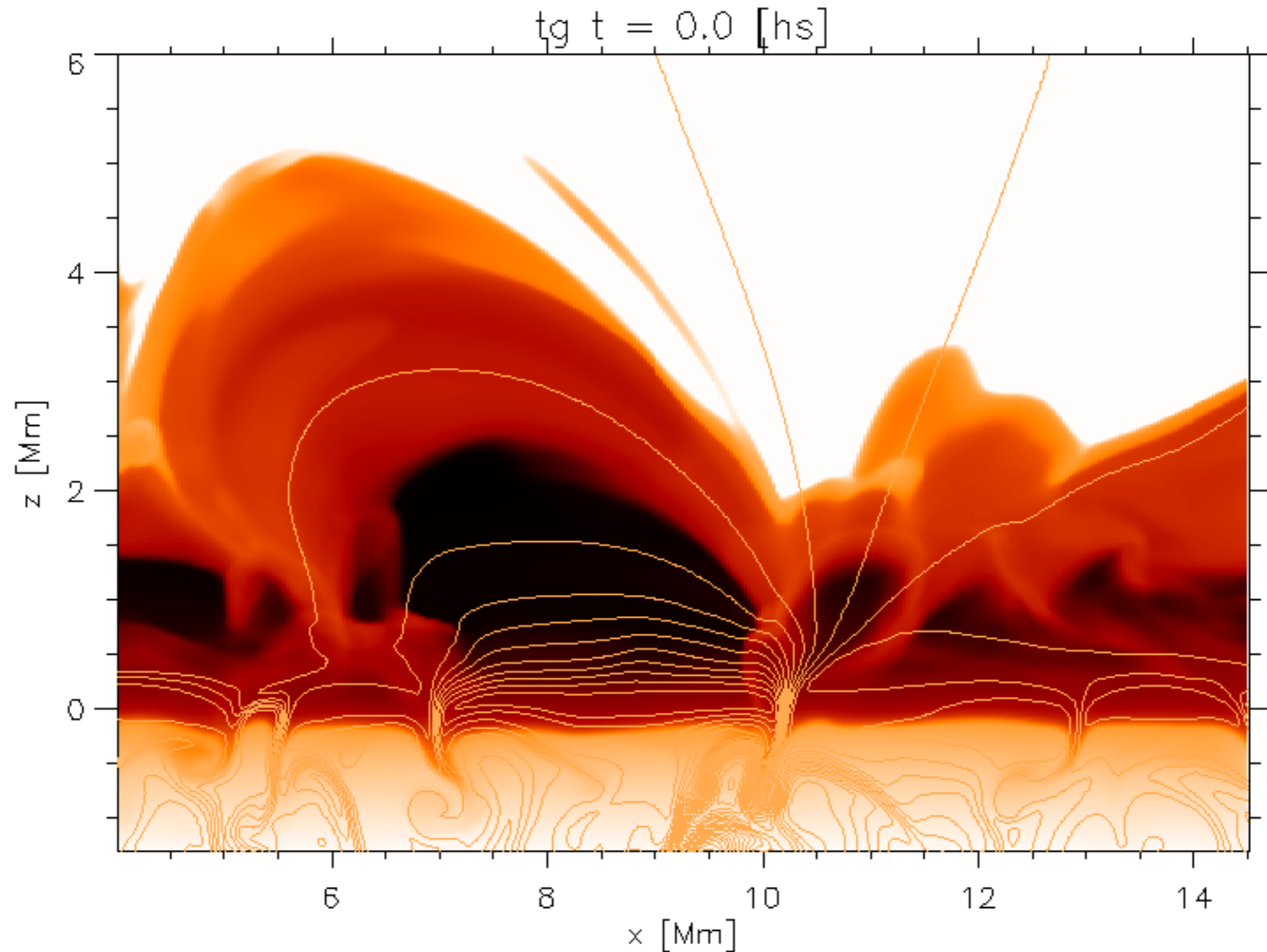
(Communicated by B. Lindblad)

(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.

Lower chromosphere acoustic waves, upper chromosphere magnetic heating



Braiding & nanoflare heating

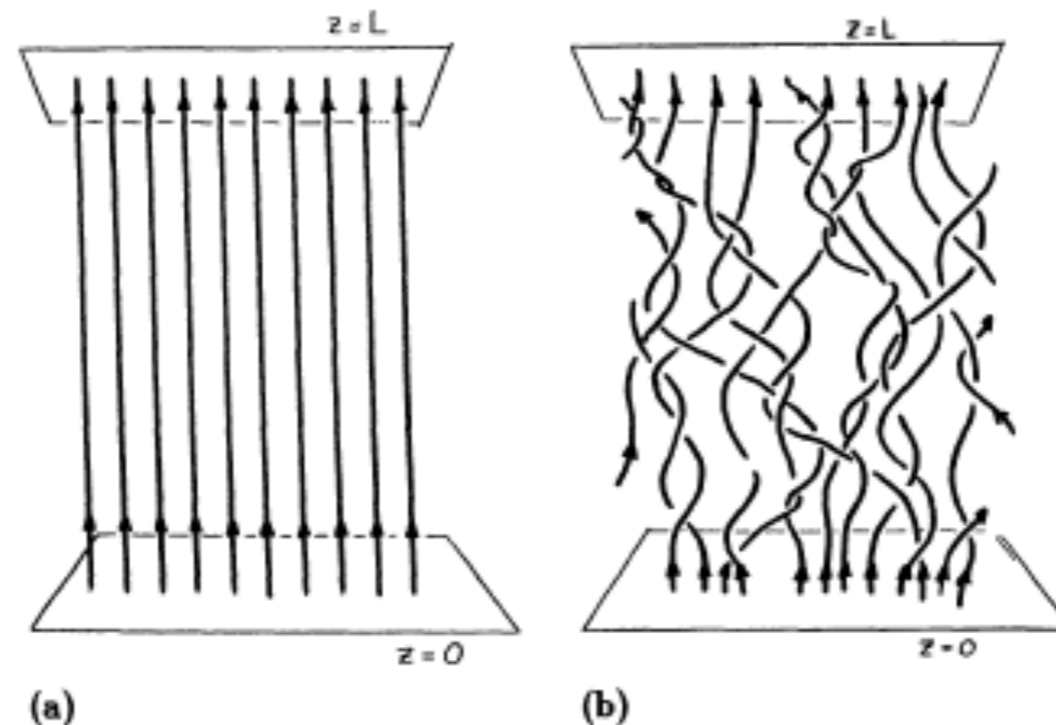


Fig. 2. (a) A sketch of the initial uniform magnetic field B_0 through $0 < z < L$. (b) A sketch of the continuous field of equation (2).

Parker, E.N., 1991, Reviews in Modern Astronomy, p 1-17

Hendrix D. L. et al., 1996, ApJ 470 p 1172

Galsgaard, K. & Nordlund, Å., 1996, JGR101 p 13445

Gudiksen, B. & Nordlund, Å., 2005, ApJ 618 p 1031

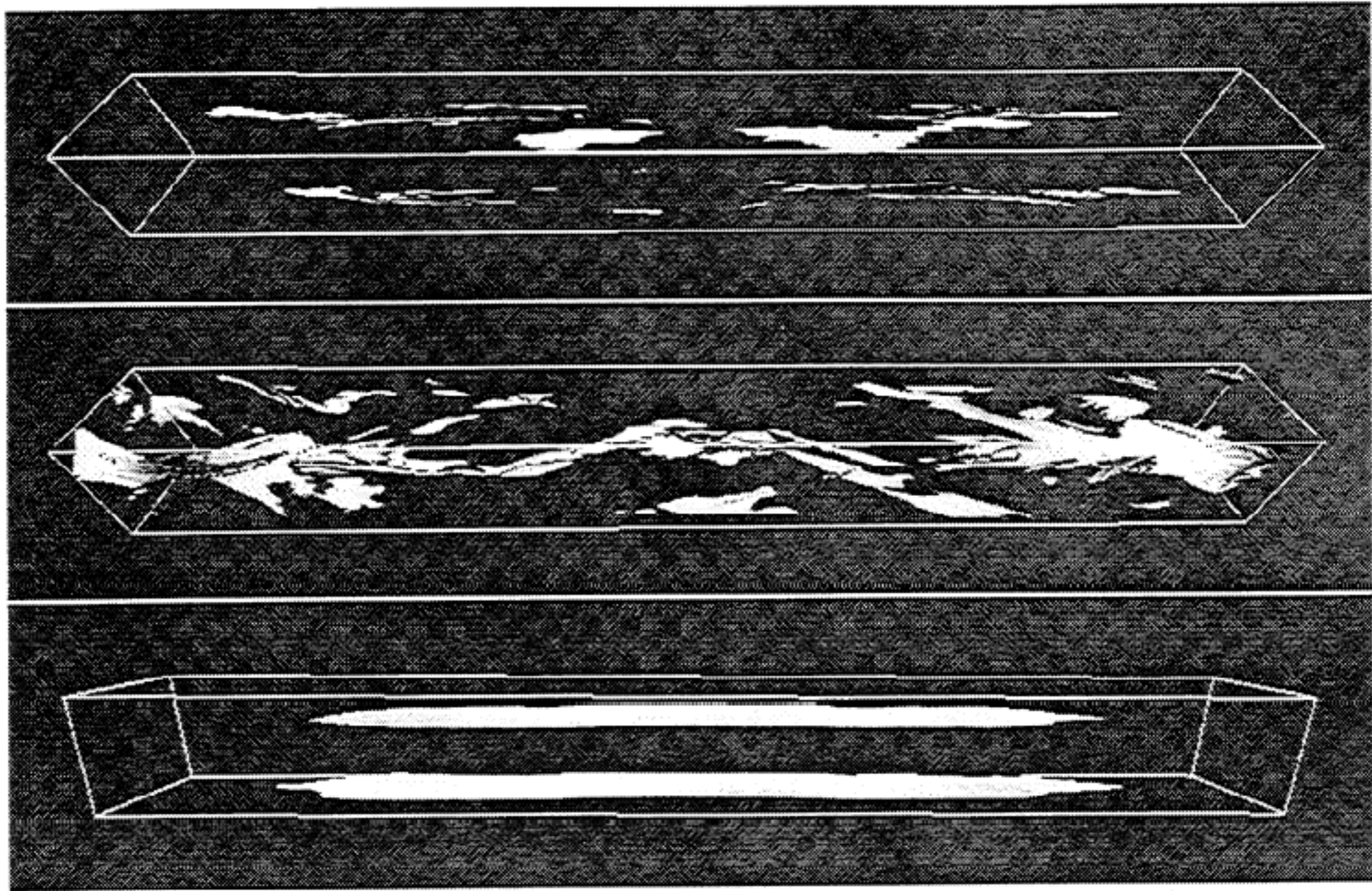


Figure 9. Isosurfaces of Joule dissipation for runs (top) 3, (middle) 4, and (bottom) 6 at the times 103.2, 71.7, and 81.1 (in units where $L_x/V_A = 10L_y/V_A = 10$).

Quasi-steady current sheets form rapidly

Models with given photospheric driving

1028

TRACE 171

GUDIKNEN & NORDLUND

TRACE 195

Vol. 618

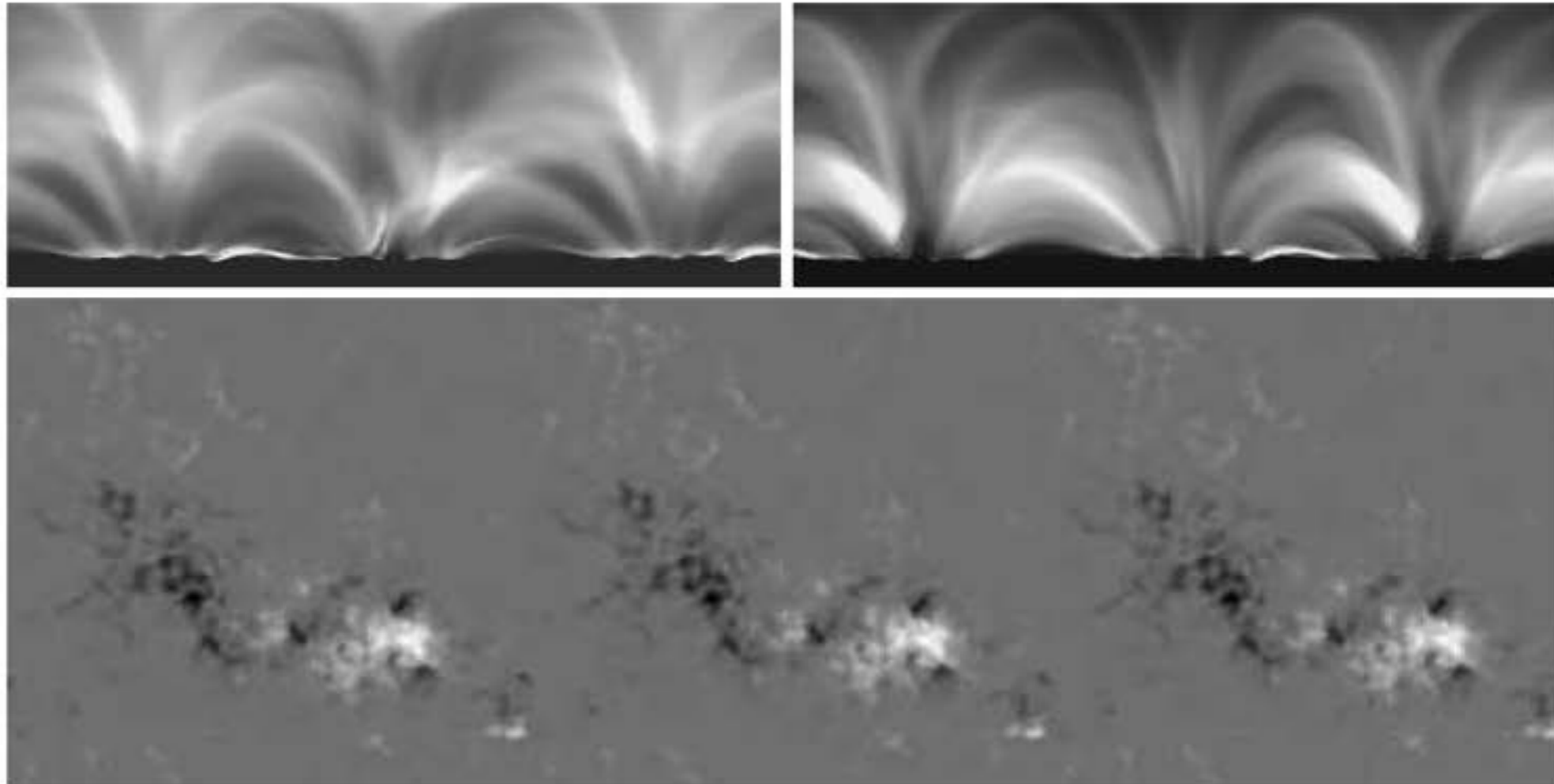
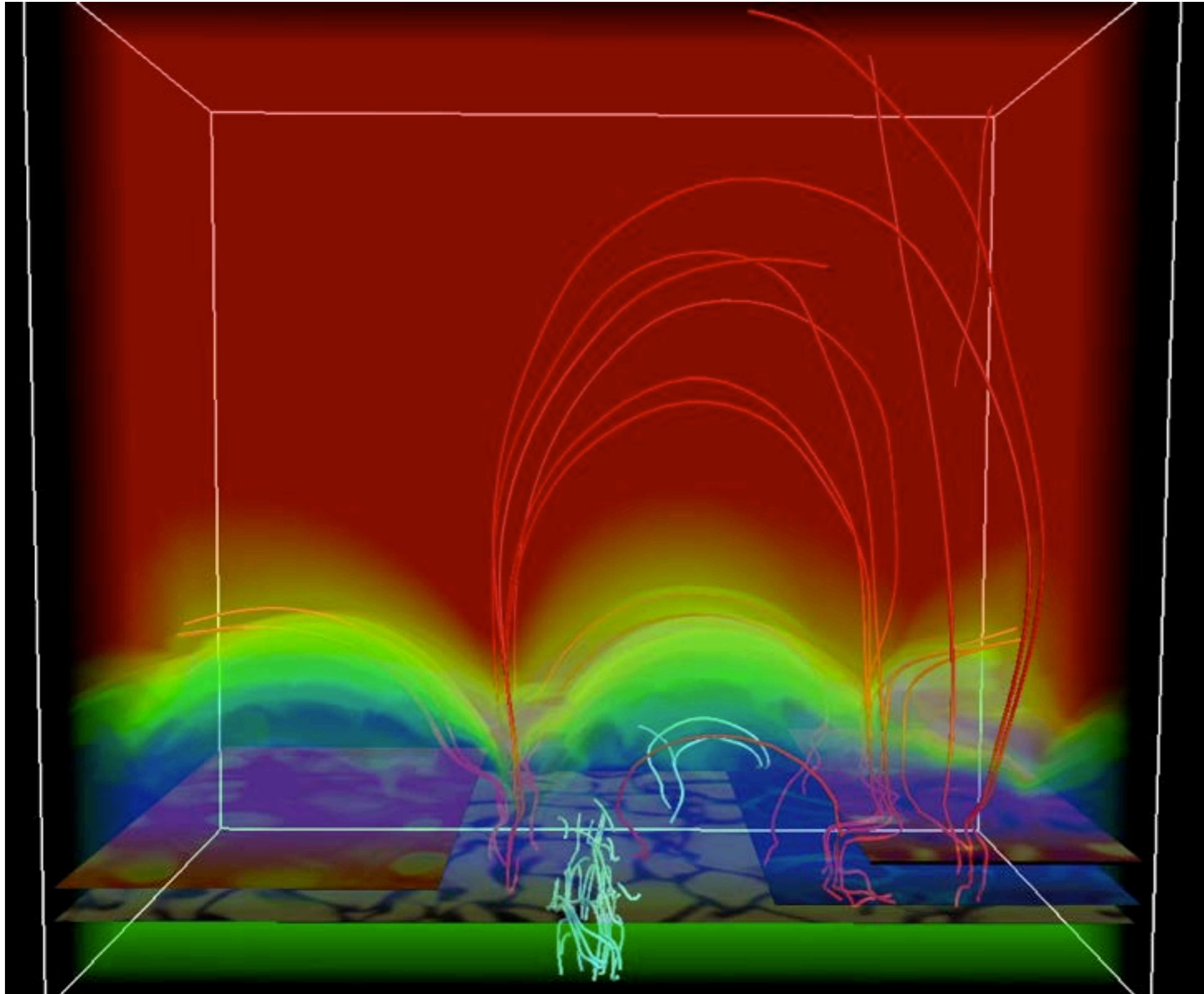


FIG. 14.—Emulated *TRACE* 171 (*top left*) and 195 (*top right*) images both spanning 1.5 box lengths, and the underlying photospheric magnetic field.

Underlying photospheric field from
MDI, parameterized velocity field

“Realistic” (Bifrost) models: Free parameter is B

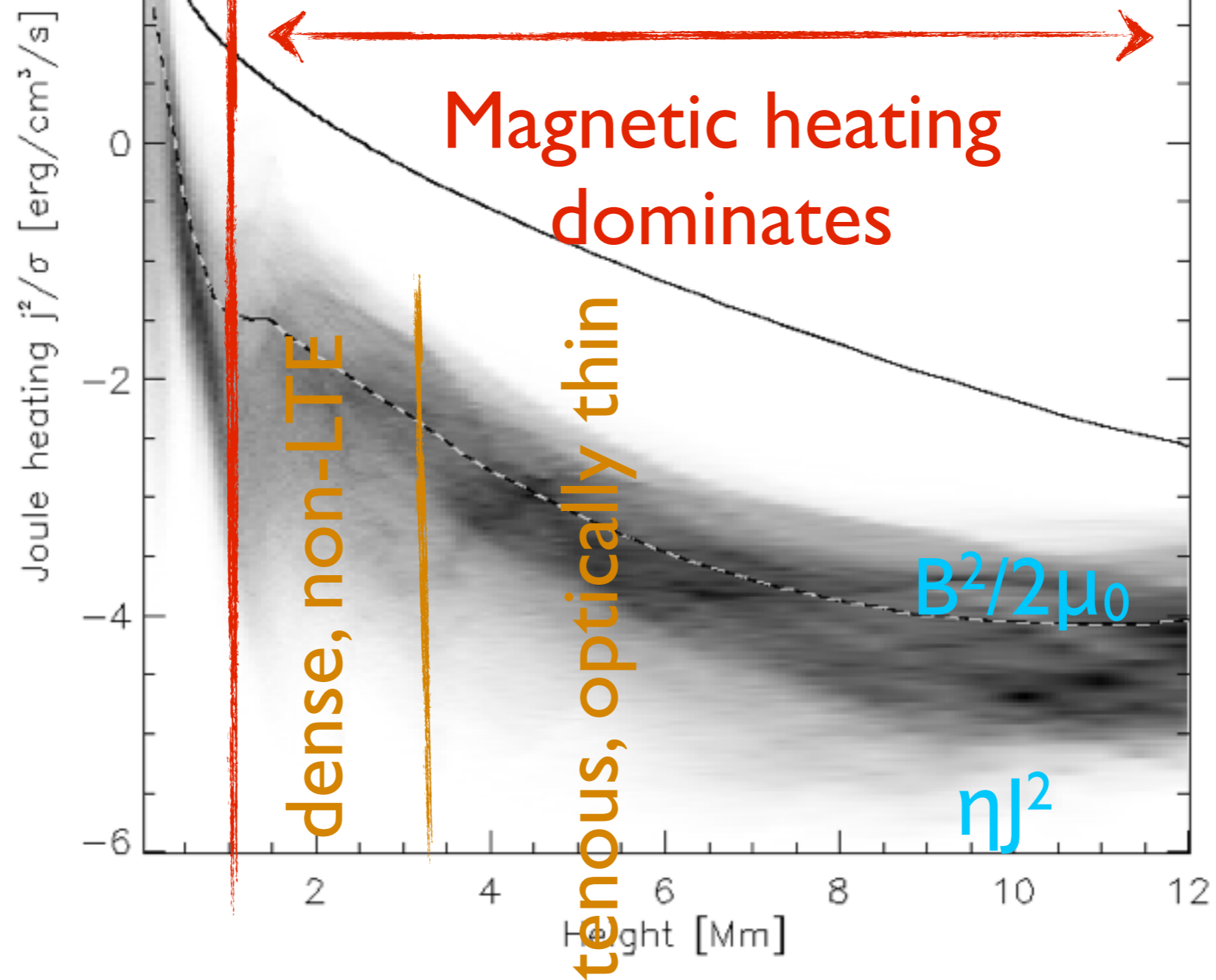


Corona

Transition region
Chromosphere
Photosphere

Coronal Heating from field line braiding - “nano flares”

$$H_{\text{chrom}} \approx 200 \text{ km} < H_{j^2/\sigma} < H_{\text{cor}} \approx 50 \text{ Mm}$$

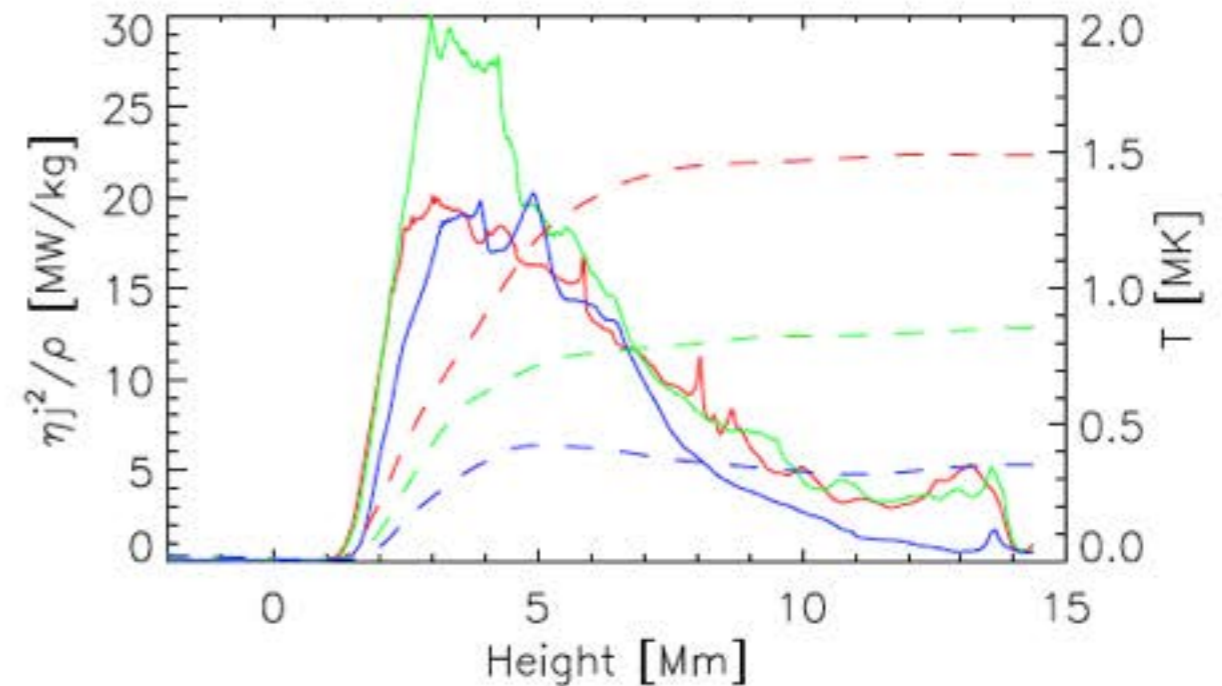
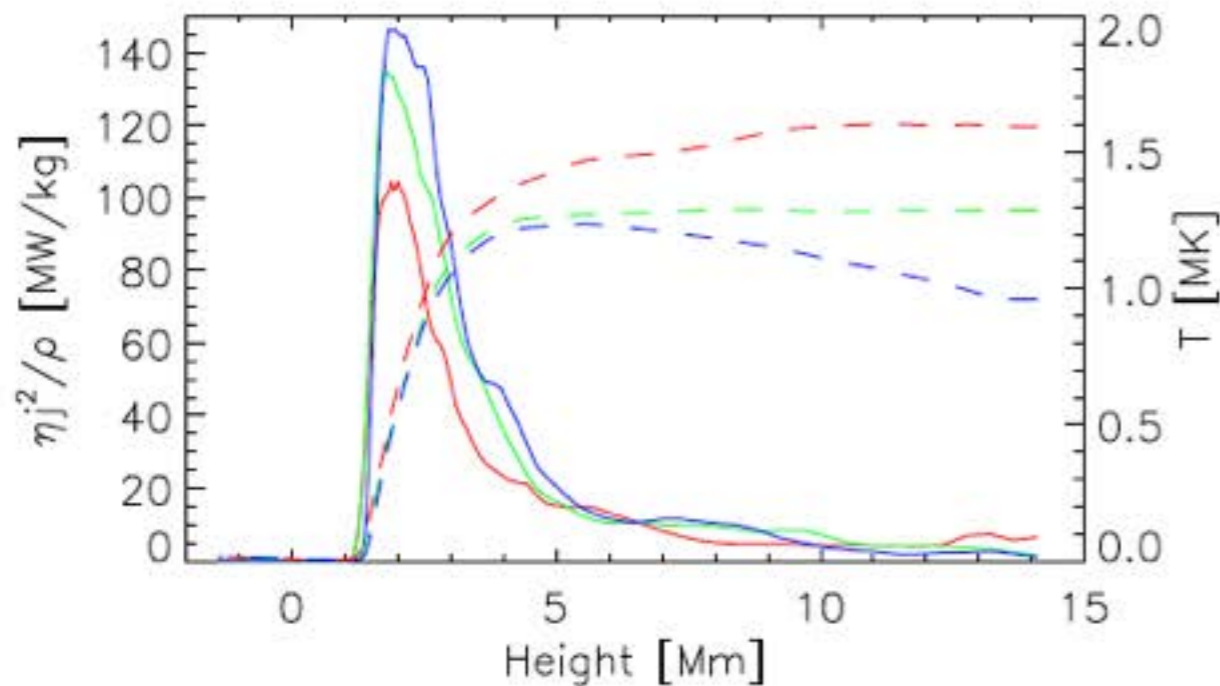


Hansteen et al. 2010, ApJ 718, 1070

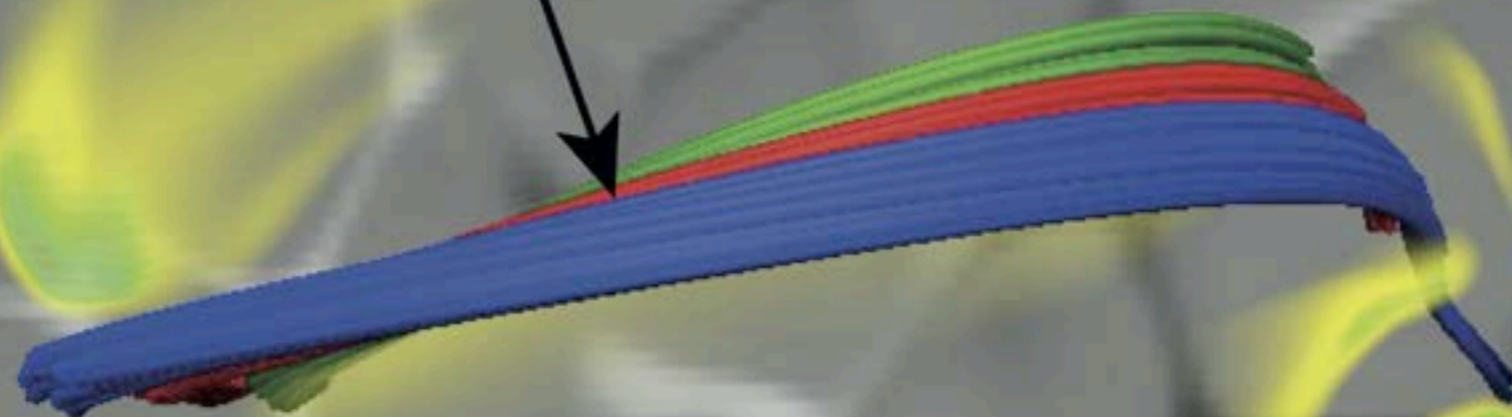
Gudiksen et al. 2011, A&A 531, A154

Heating per particle $\eta j^2/\rho$

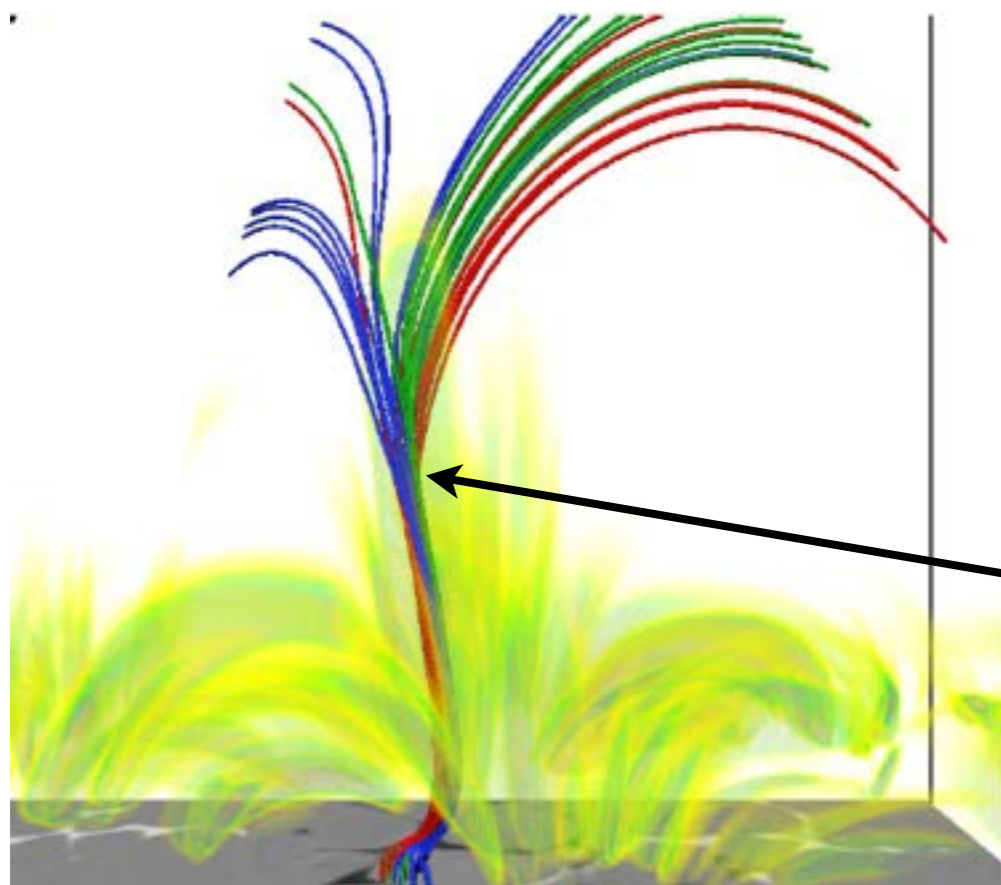
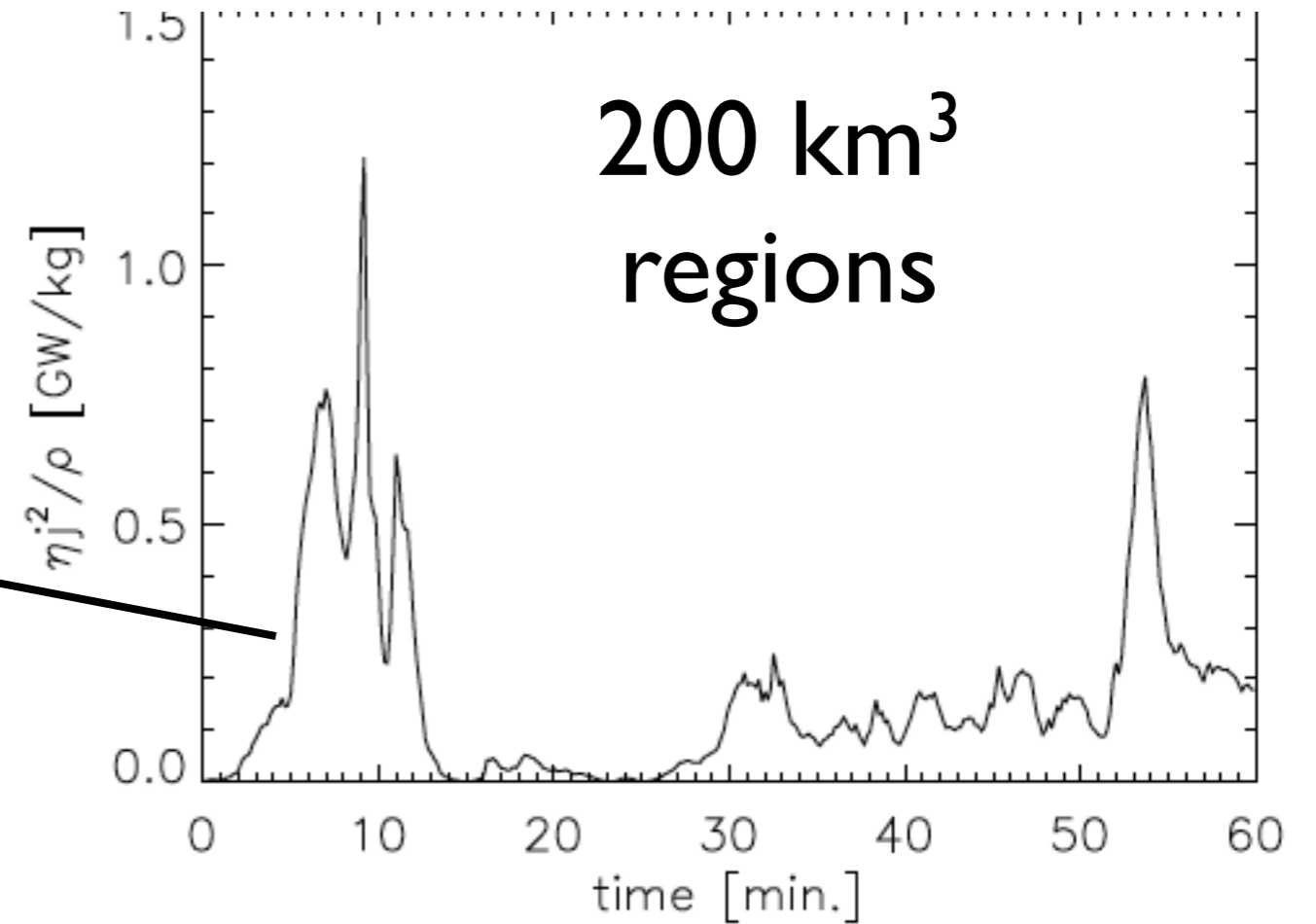
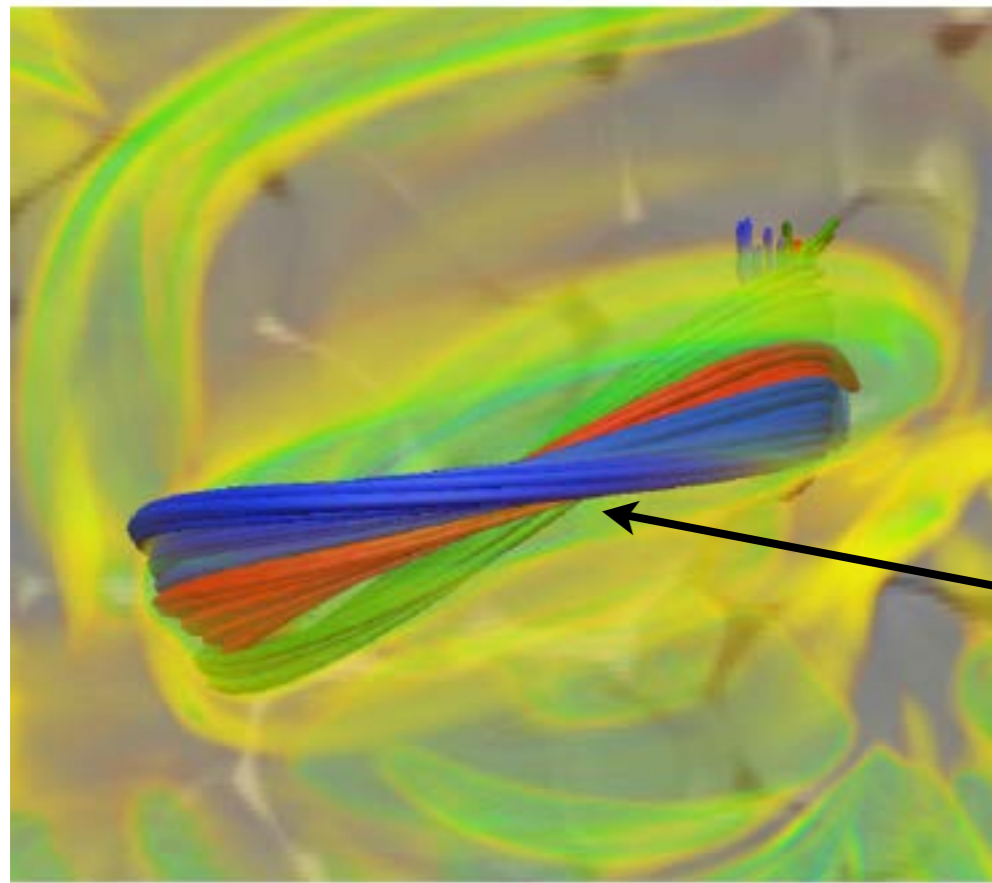
...maximum is generally concentrated to the vicinity of the transition region, but detailed structure varies with large scale magnetic field topology...



$t = 100 \text{ s}$



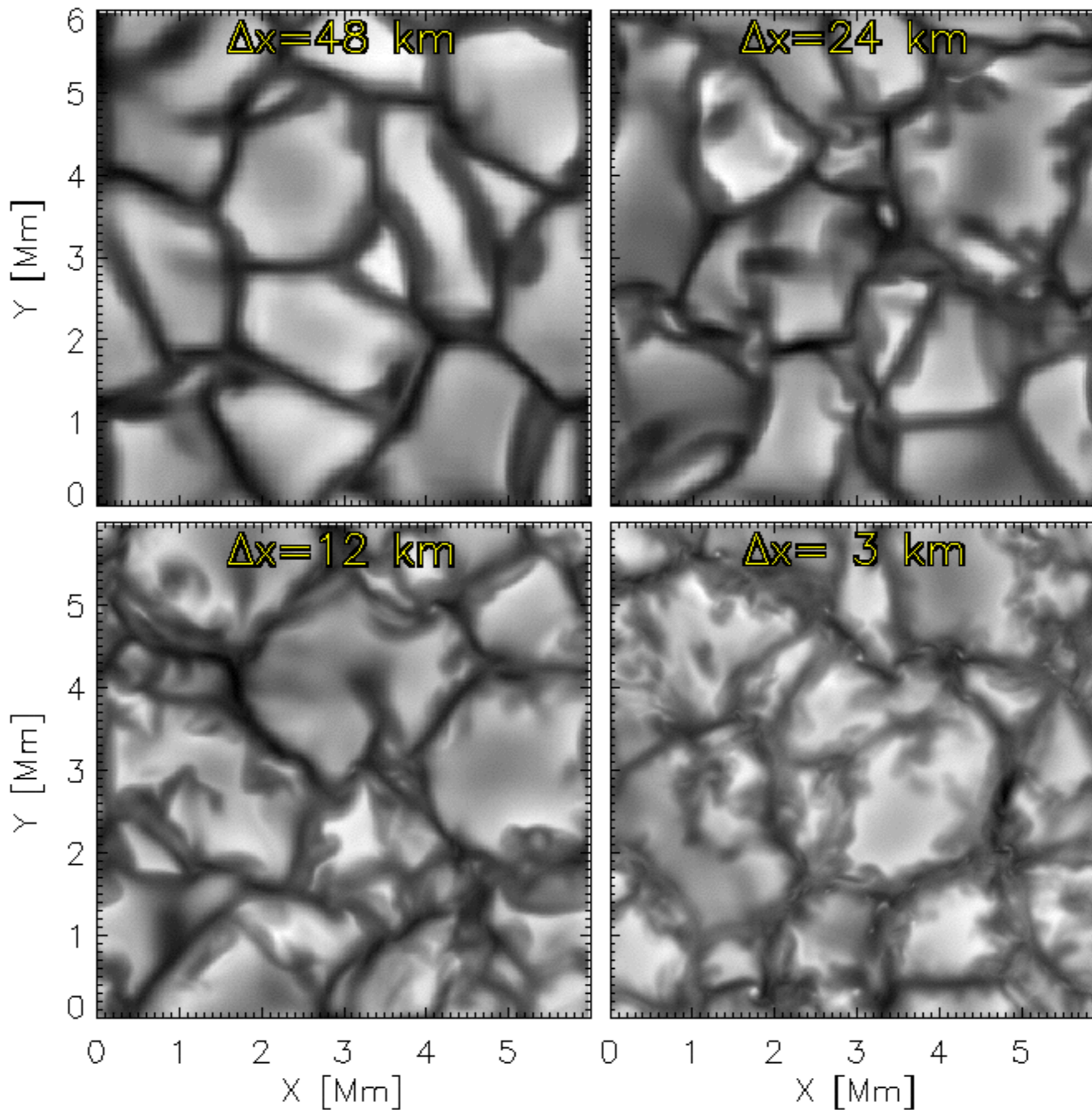
η_j^2 highly variable in space and time



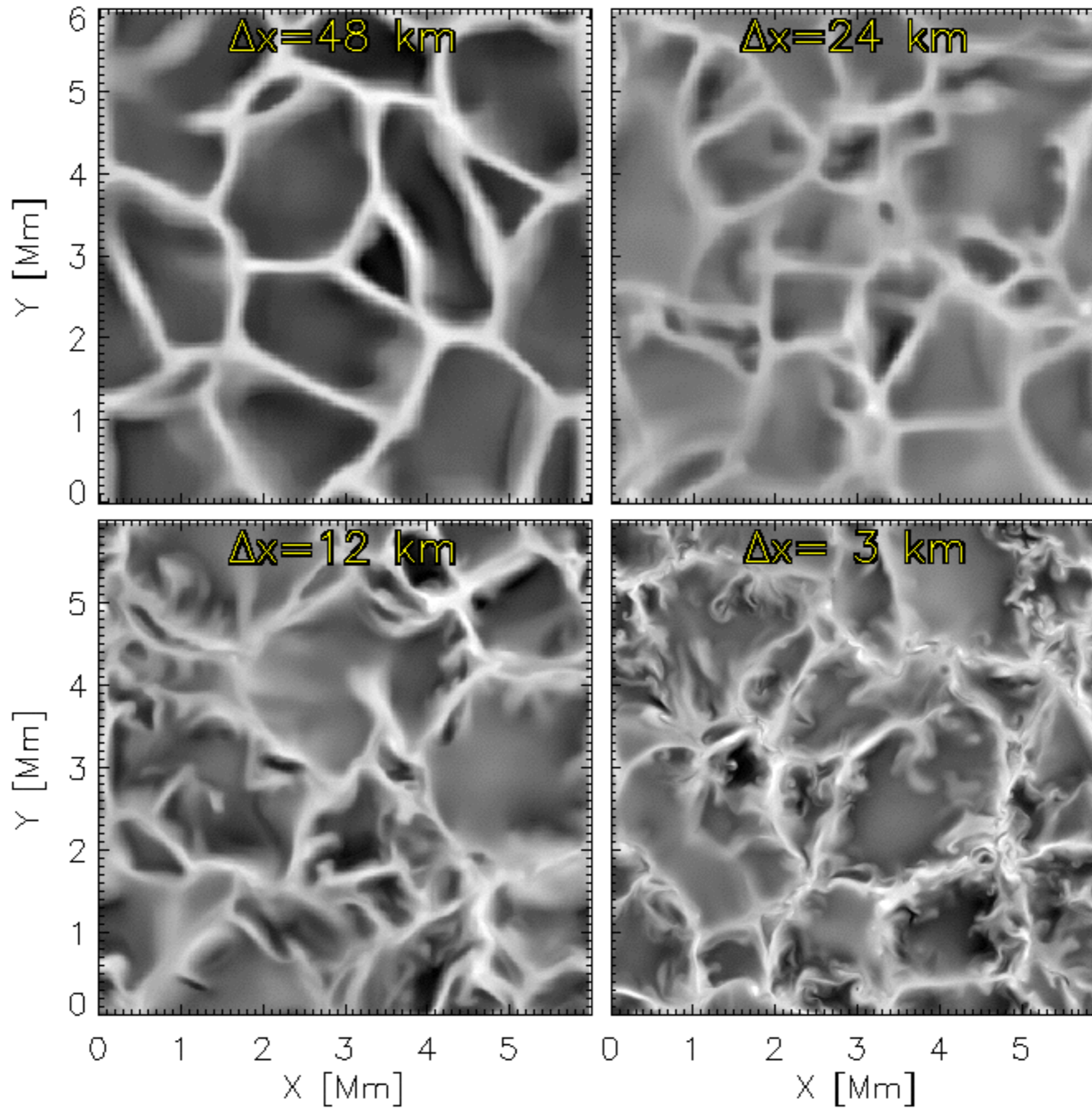
Clearly braiding leads to heating sufficient to produce a corona.

Can we stop here?

Effects of numerical resolution



Uz at z=0



As resolution increases and increasing number of vortical flows are produced

A&A 533, A126 (2011)

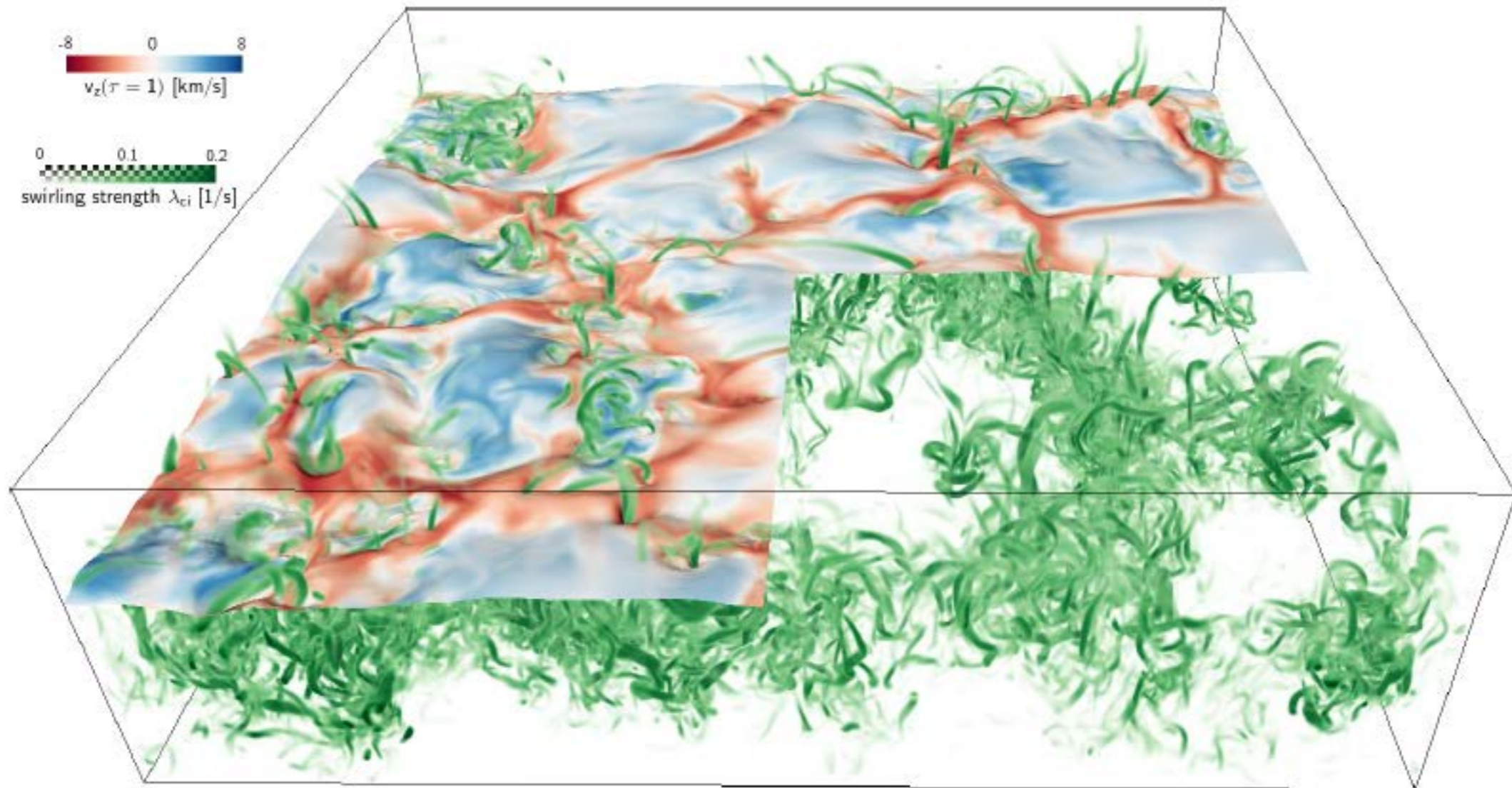


Fig. 1. Snapshot of the swirling strength (green volume rendering) and the optical surface color-coded with vertical velocity (downflows in red and upflows in blue) in Run C. The size of the box shown is $4.8 \times 4.8 \times 1.4 \text{ Mm}^3$. The optical surface is hidden in the lower right quadrant, uncovering the swirling structure in the subsurface layers. An animated plot that shows the temporal evolution of the swirling strength without the optical surface is available in the electronic edition of the journal.

Photospheric motions generate Alfvén waves modeled dissipated through non-linear interactions

THE ASTROPHYSICAL JOURNAL, 787:87 (14pp), 2014 May 20

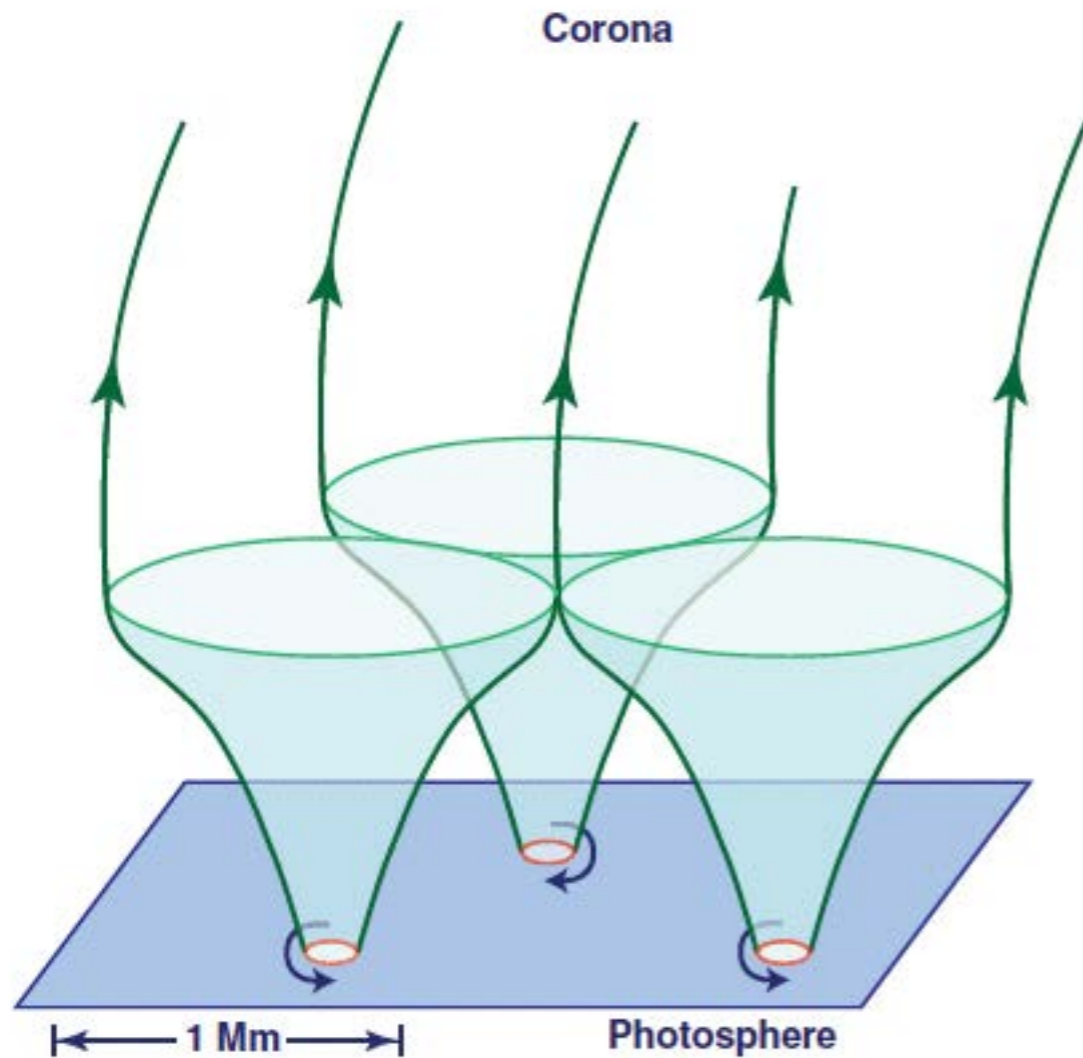
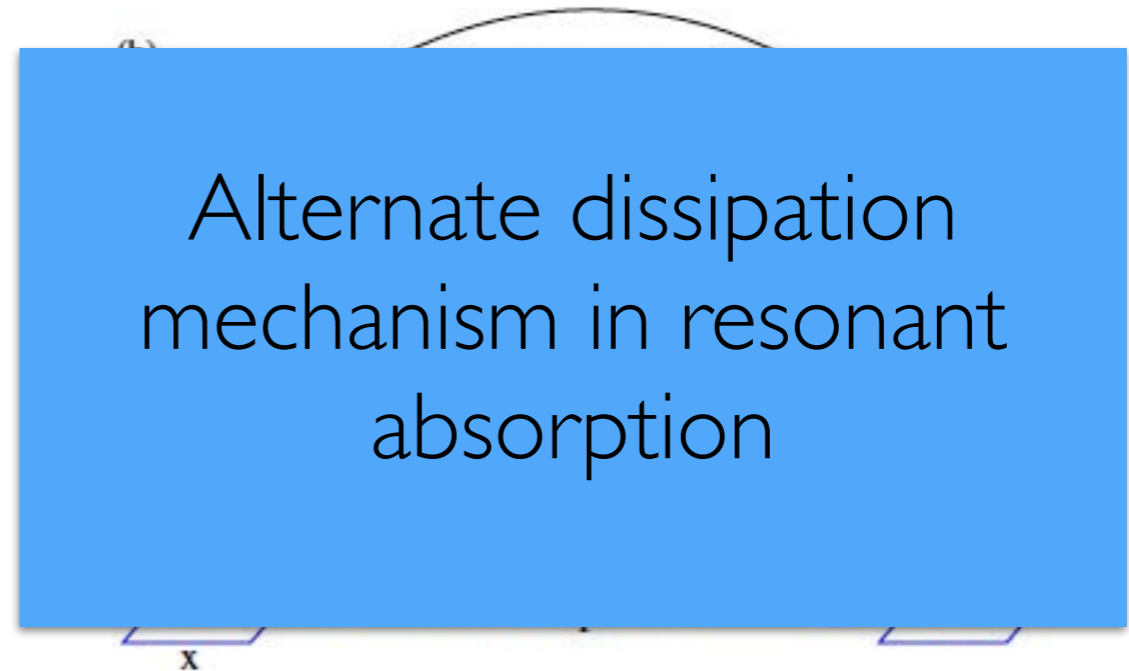


Figure 1. Schematic view of unipolar magnetic flux elements at one end of a coronal loop in a solar active region. The flux tubes expand with height in the photosphere, merge at height $z \sim 1$ Mm in the chromosphere (circles), and fill the available volume in the corona.



(c)

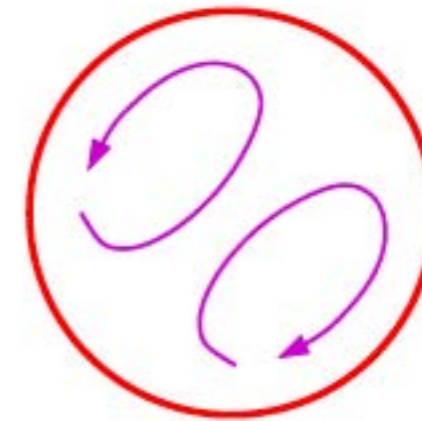
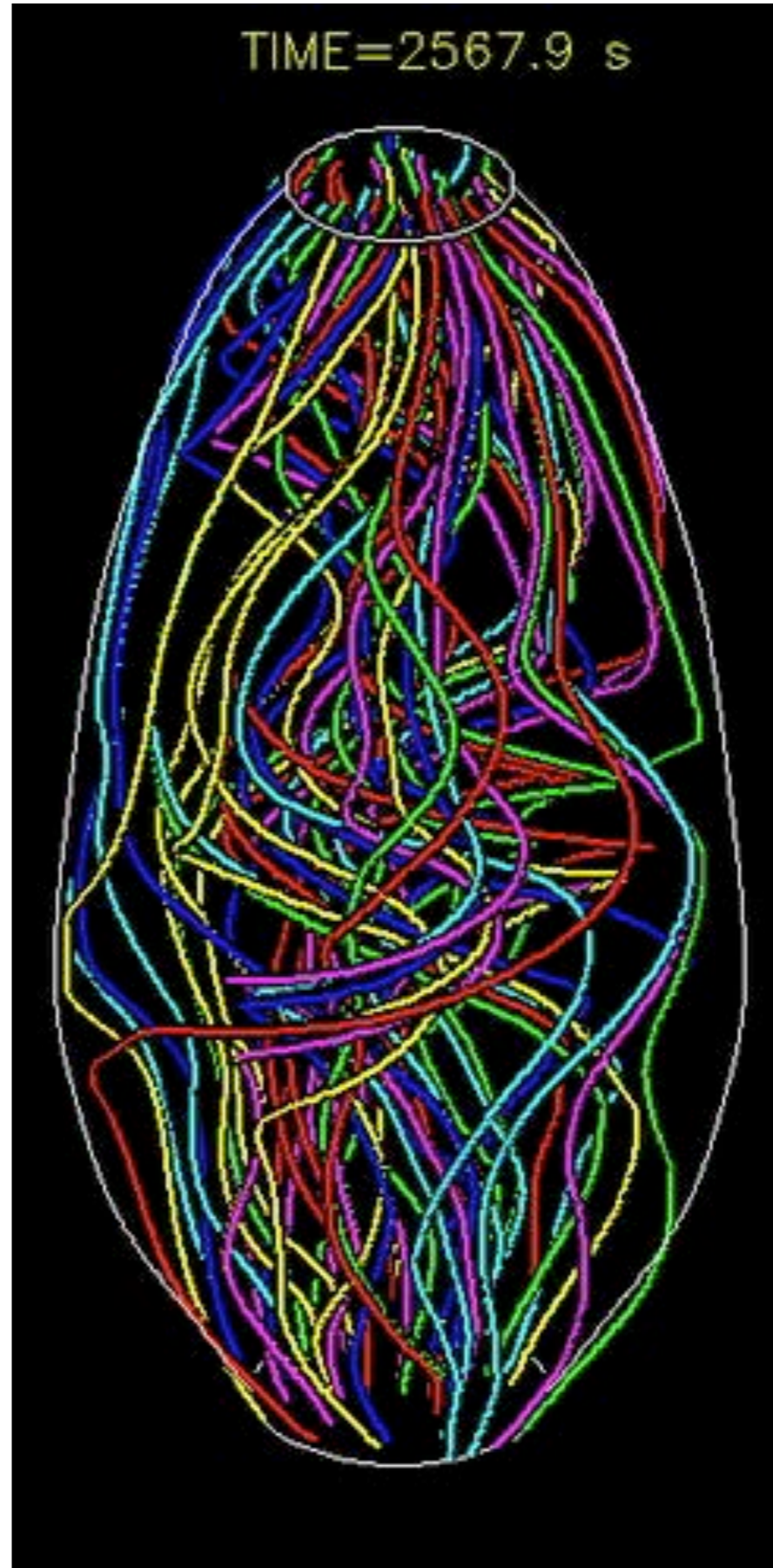


Figure 2. Two versions of the reduced MHD model, and imposed footpoint motions. (a) Version 1 in which only the coronal part of the loop is modeled, and boundary conditions are imposed at the TRs, leading to DC heating. (b) Version 2 in which the entire loop is modeled, and boundary conditions are imposed at the photosphere, leading to AC heating. (c) In both cases the footpoint motions have a velocity pattern consisting of two counter-rotating cells. The velocity stream function $f(x, y, t)$ is a superposition of two modes that depend on $\cos \varphi$ and $\sin \varphi$, respectively, where φ is the azimuth angle (see [paper 1](#) for details).

Interactions of Alfvén waves in (static) background atmosphere, modeled by reduced MHD, give sufficient heating for chromospheric and coronal heating



Heating of order 10^4 W/m^2 to corona

THE ASTROPHYSICAL JOURNAL, 787:87 (14pp), 2014 May 20

VAN BALLEGOIJEN, ASGARI-TARGHI, & BERGER

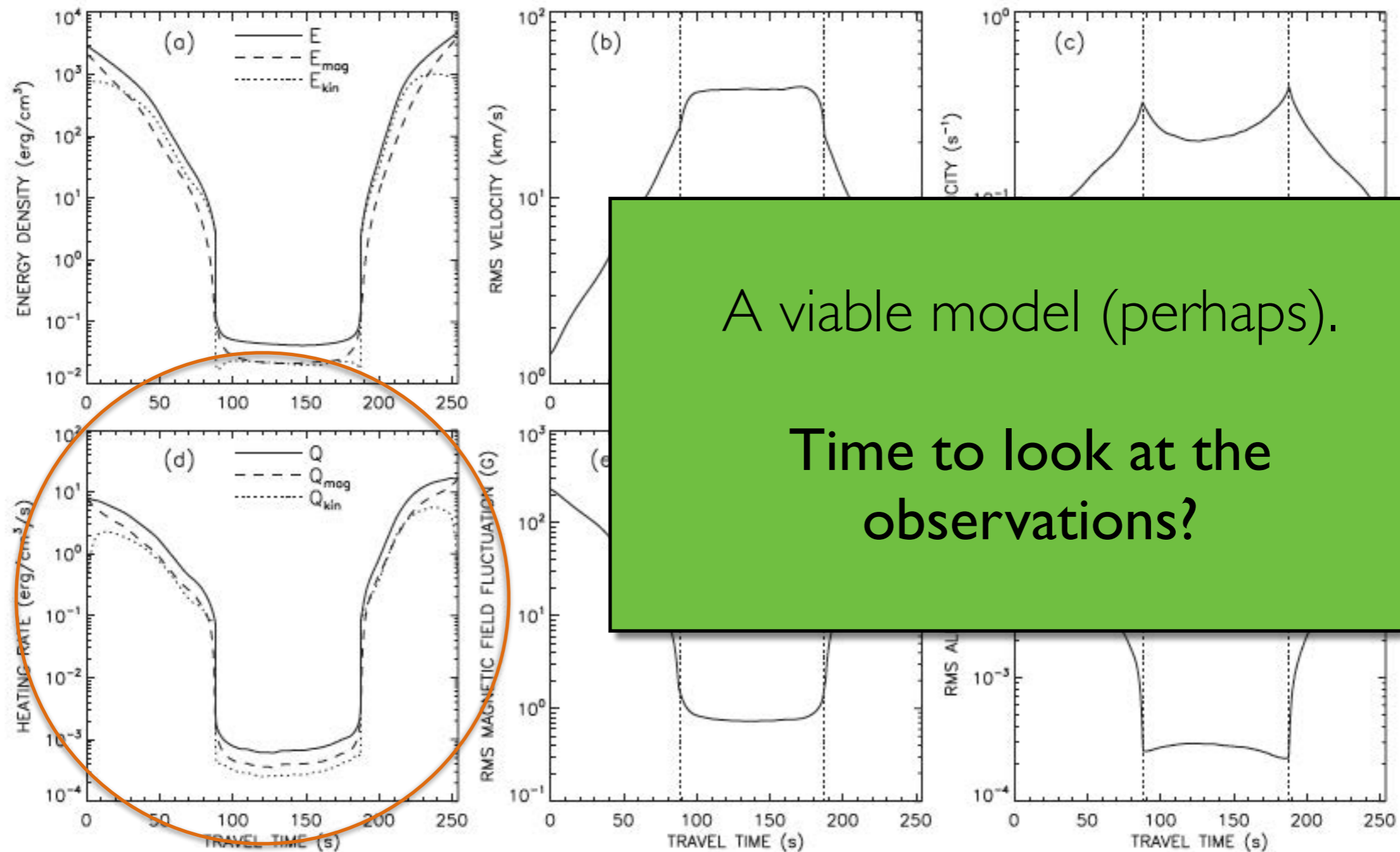


Figure 8. Results for model M2 in which the full loop is simulated, including the lower atmospheres. In this case the footpoint motions are applied in the photosphere, producing Alfvén wave turbulence within the loop. Various wave-related quantities are plotted as function of position along the loop: (a) total energy density $E(s)$ (full curve) and contributions from kinetic and magnetic energy, (b) velocity amplitude, (c) parallel component of vorticity, (d) energy dissipation rate $Q(s)$ (full curve) and contributions from kinetic and magnetic energy dissipation, (e) transverse magnetic field fluctuation, (f) parameter $\alpha_{\text{rms}}(s)$ describing the twist of magnetic field lines. All quantities have been averaged over the cross-sectional area of the loop and over time (last 2800 s of simulation). The vertical dotted lines in these panels indicate the positions of the TRs.

return to Parker's cartoon

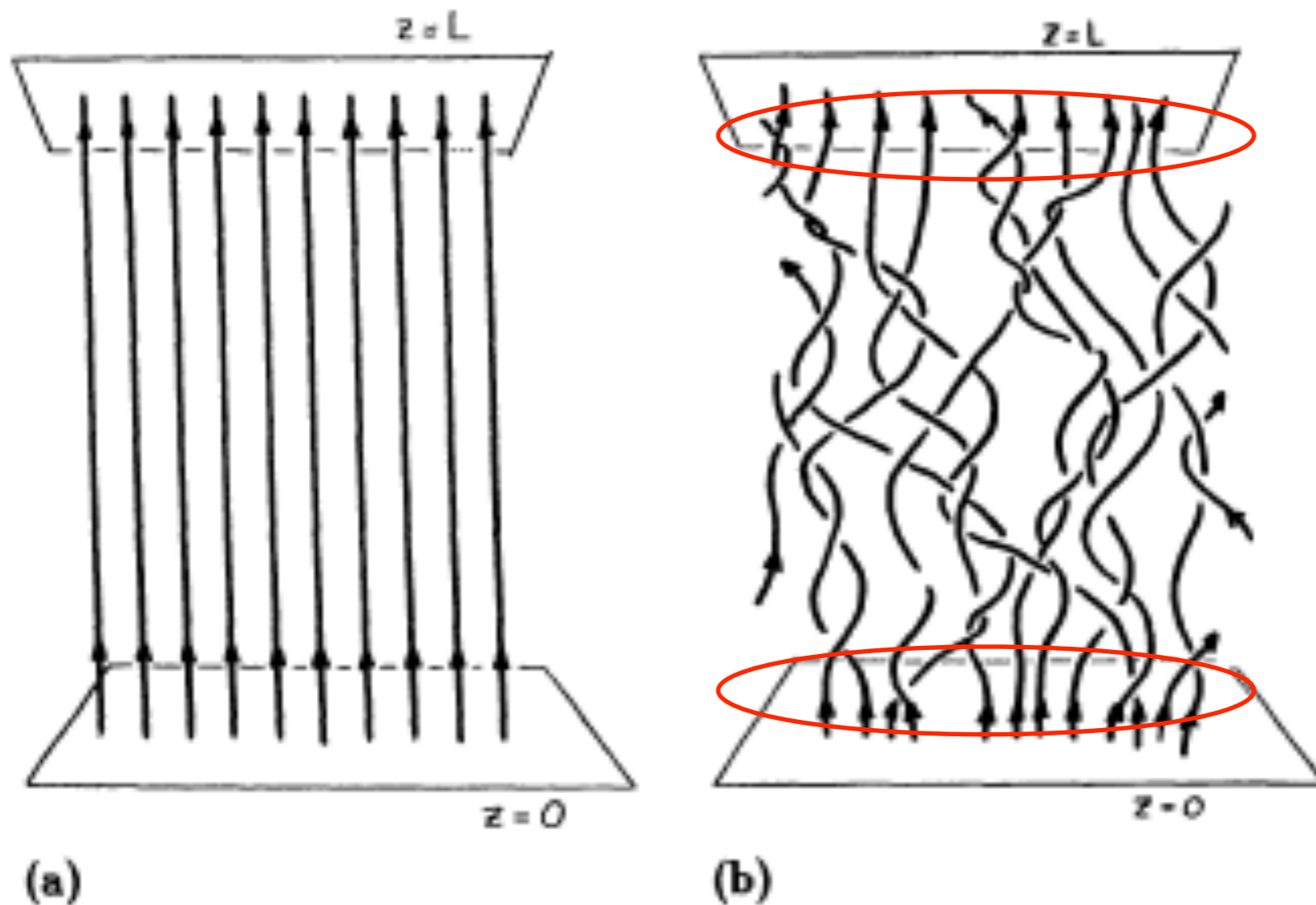
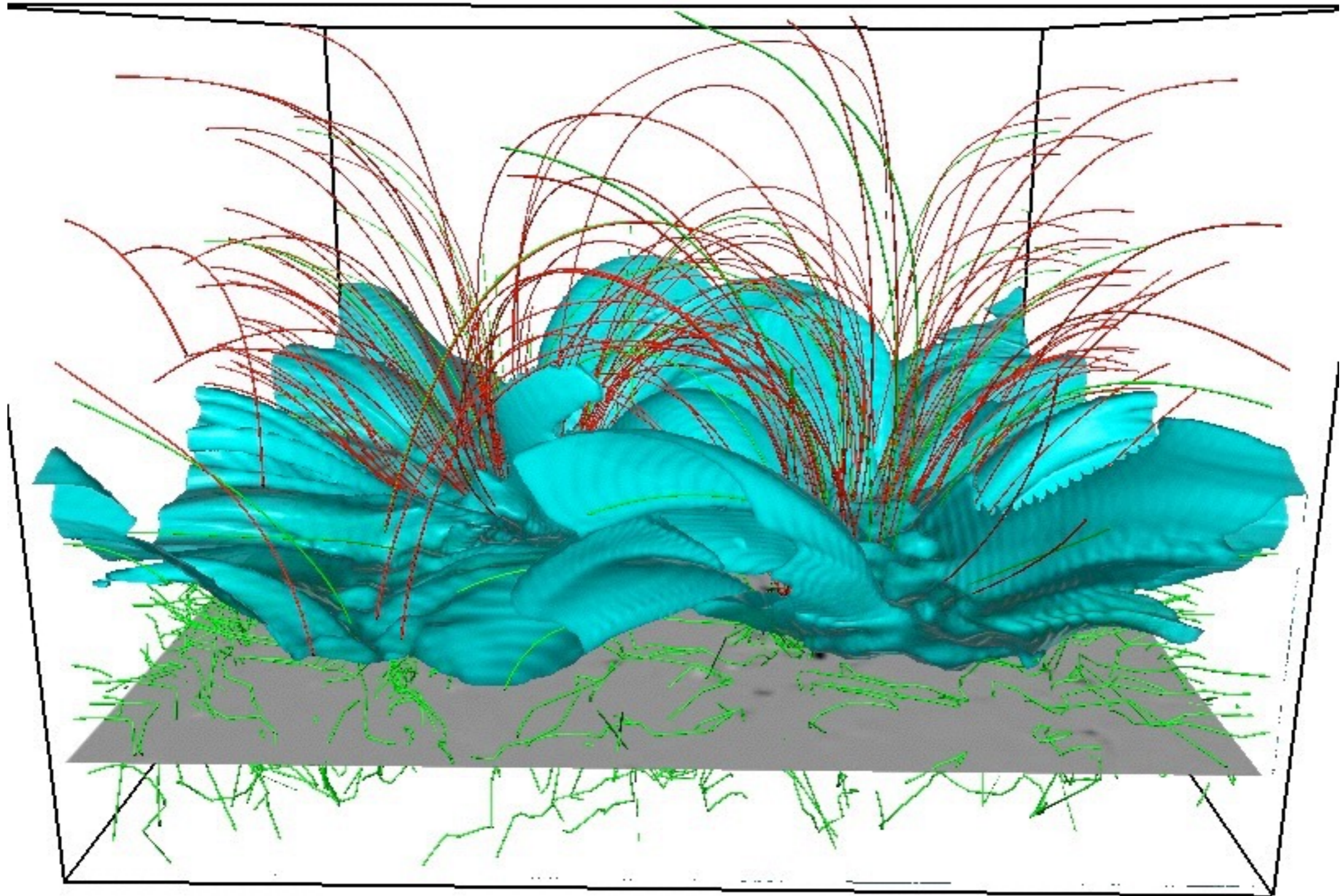


Fig. 2. (a) A sketch of the initial uniform magnetic field B_0 through $0 < z < L$. (b) A sketch of the continuous field of equation (2).

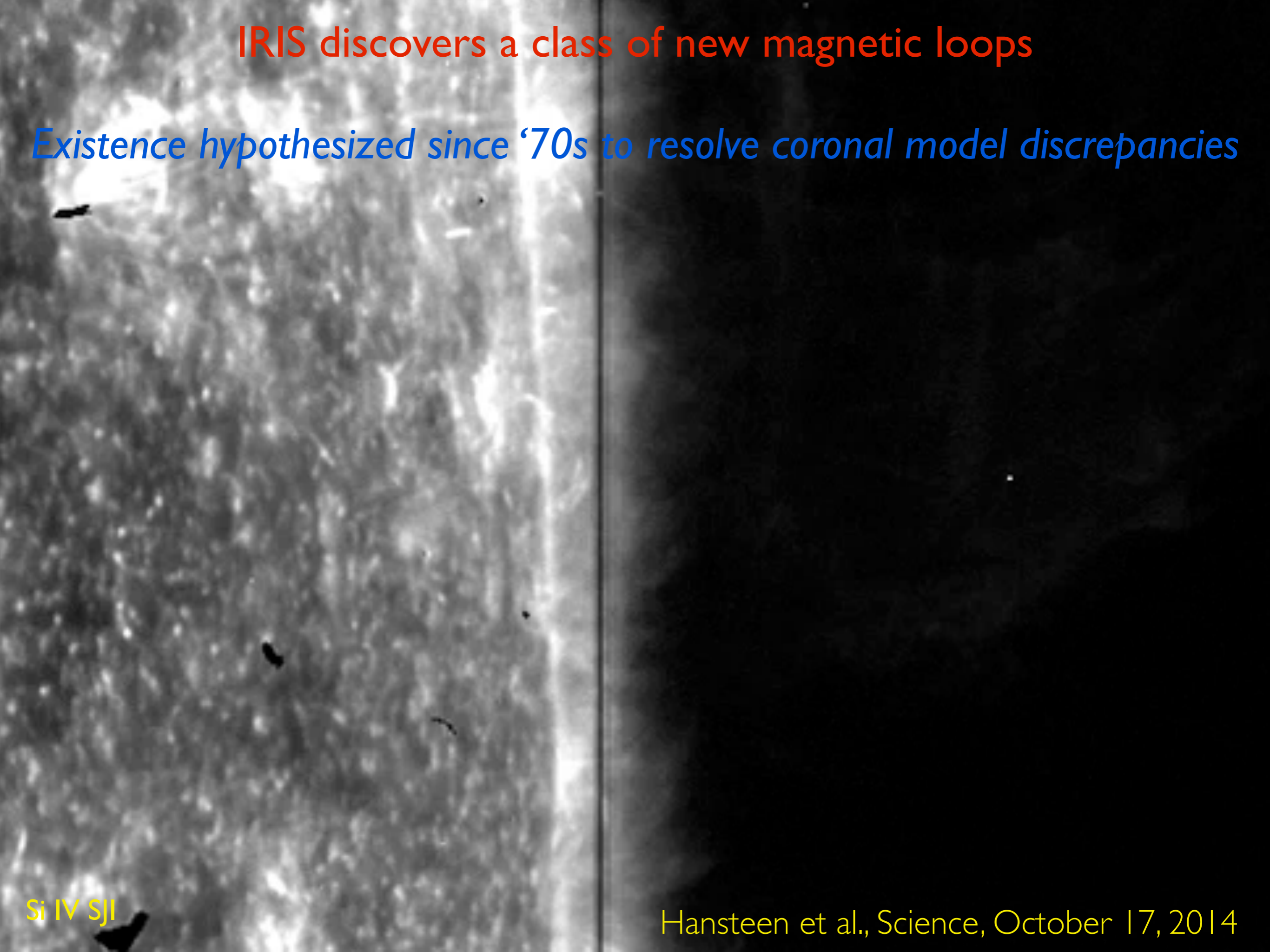
...perhaps a better cartoon?



Bifrost en024048_hion (IRIS data product)

IRIS discovers a class of new magnetic loops

Existence hypothesized since '70s to resolve coronal model discrepancies

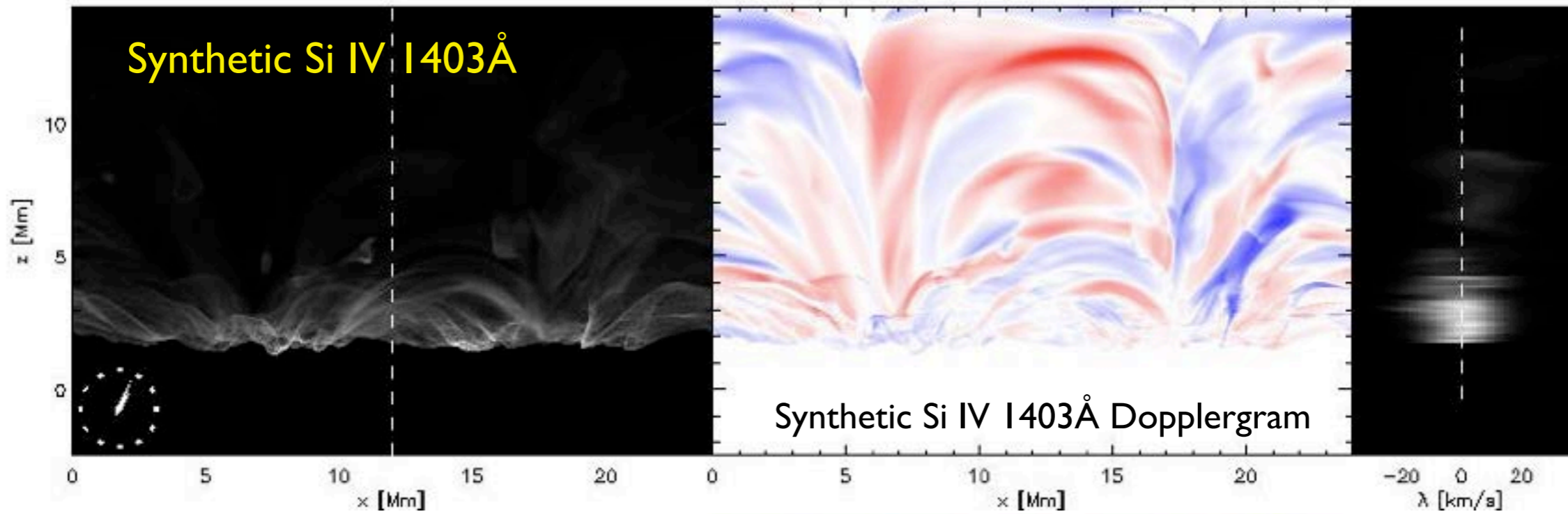


Si IV SJI

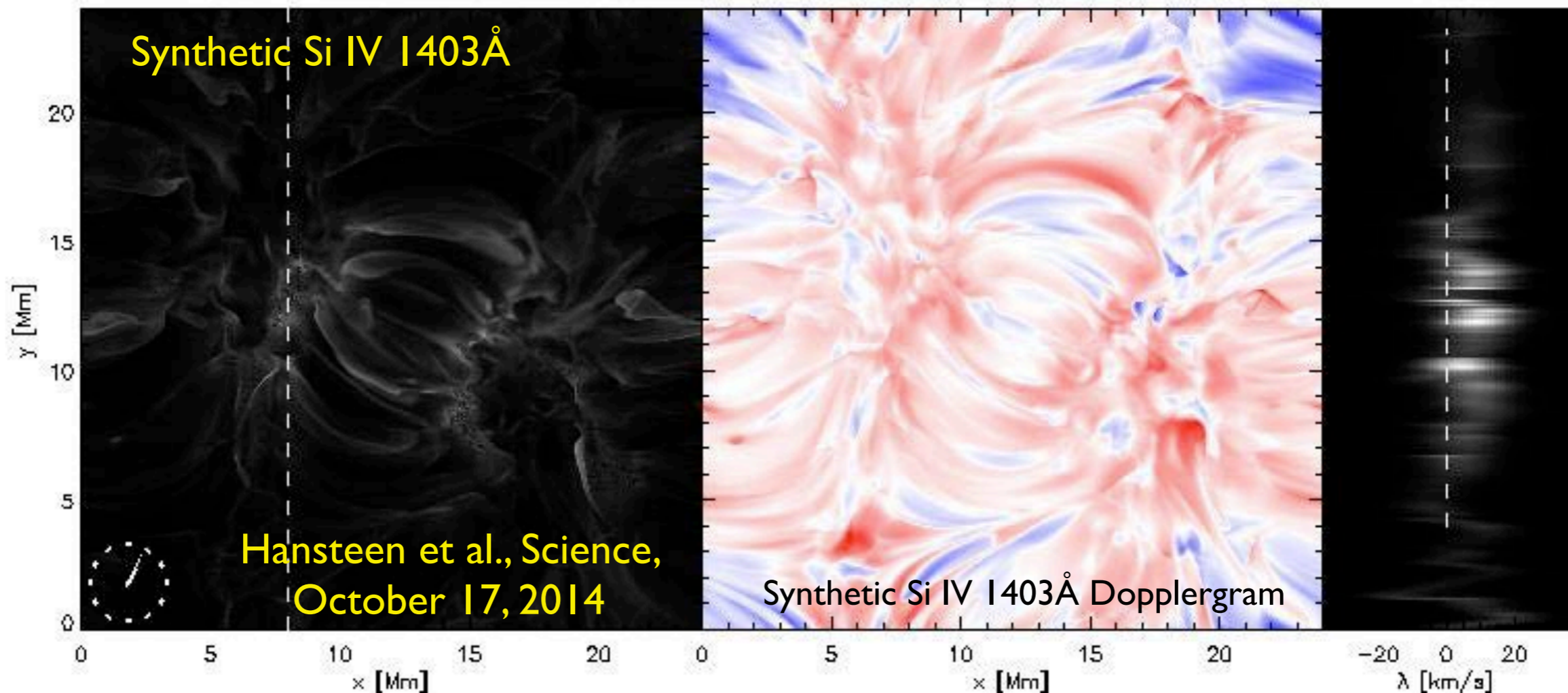
Hansteen et al., Science, October 17, 2014

These types of loops naturally occur in advanced numerical simulations

Side View

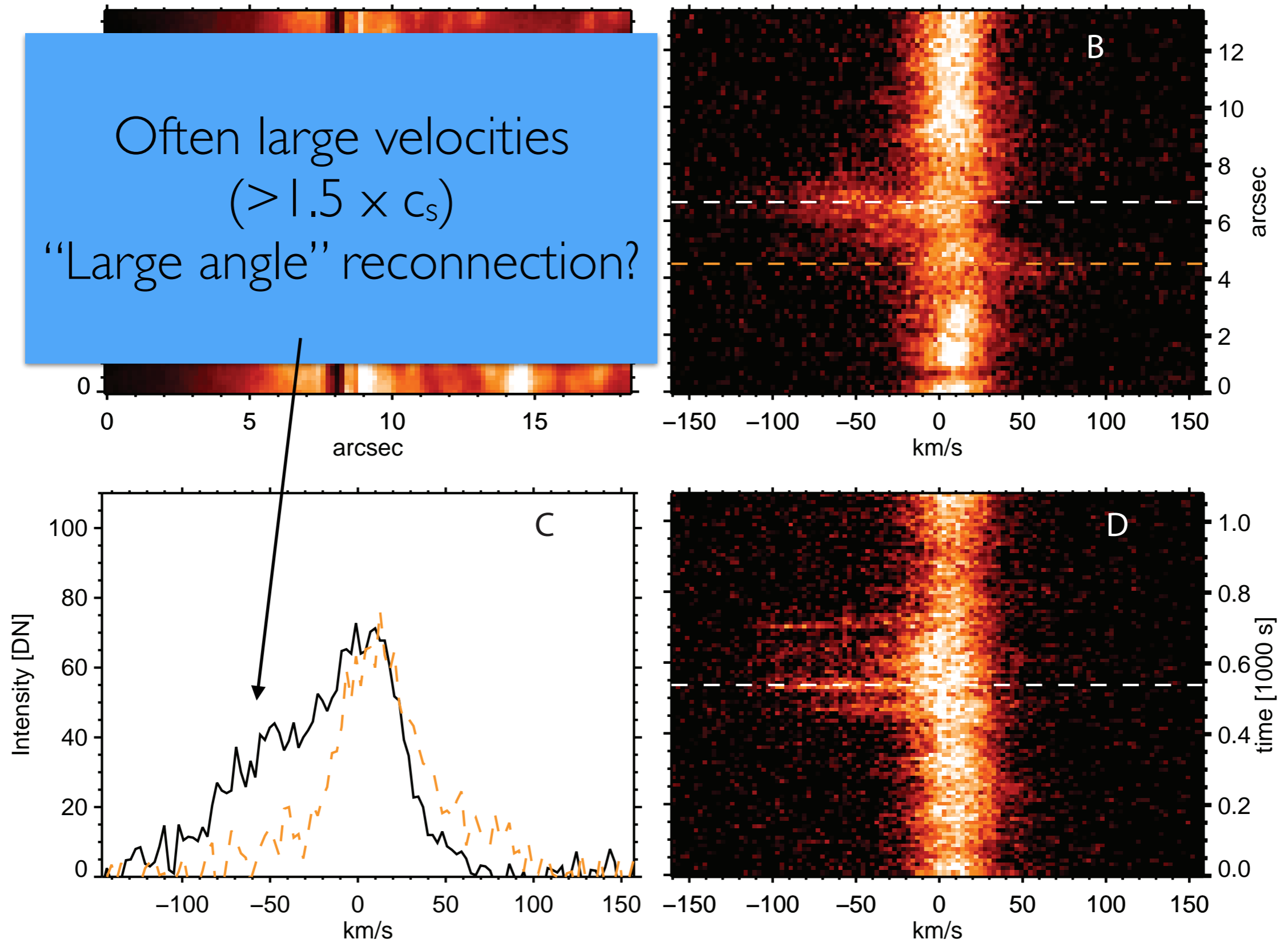


Top View



IRIS Si IV spectra of UFS at the limb

Often large velocities
($> 1.5 \times c_s$)
“Large angle” reconnection?



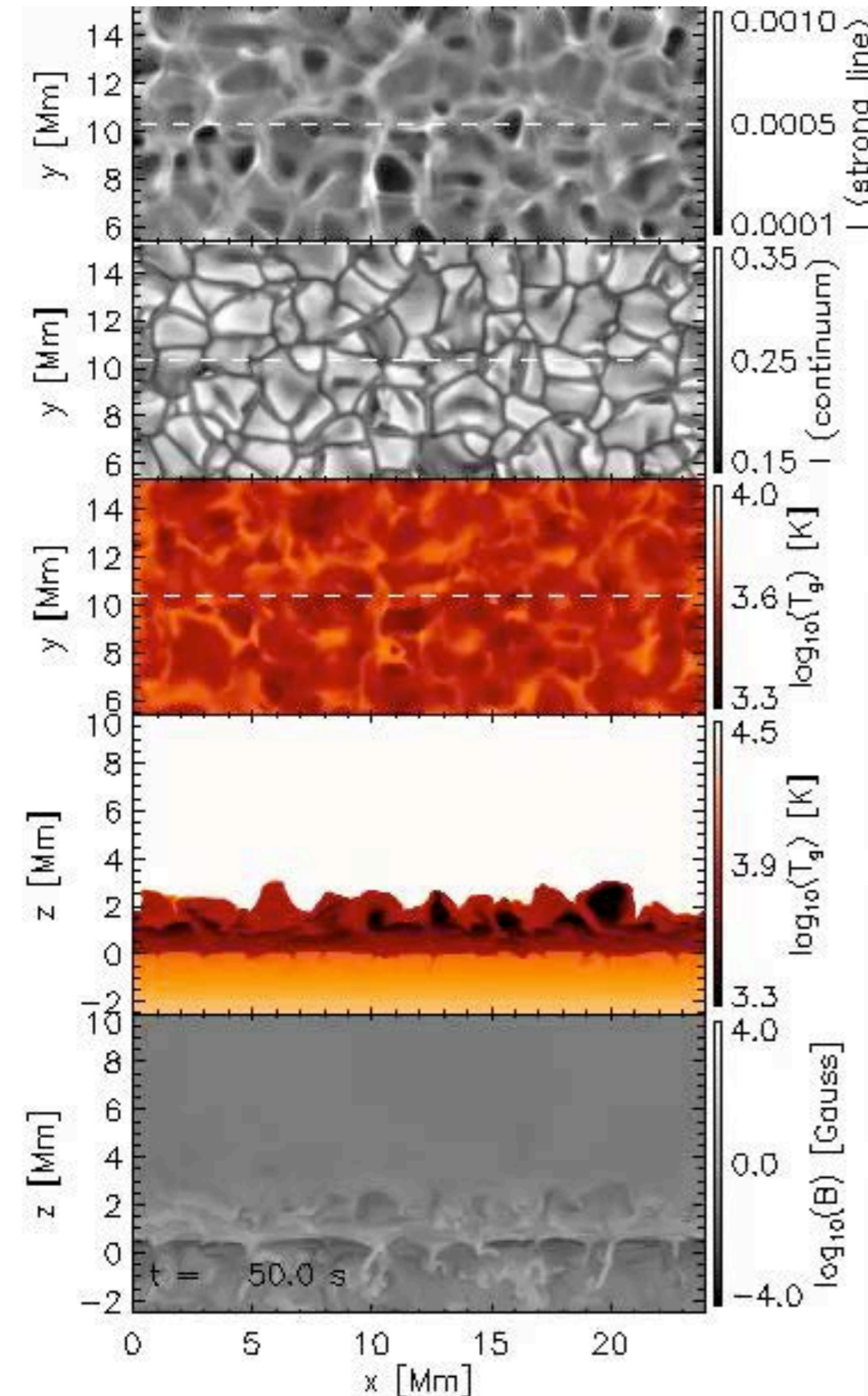
Need “Large angle”
reconnection, implies flux
emergence?

Horizontal panel at $z=700$ km above
photosphere. Chromospheric vertical extent
initially some 2 Mm.

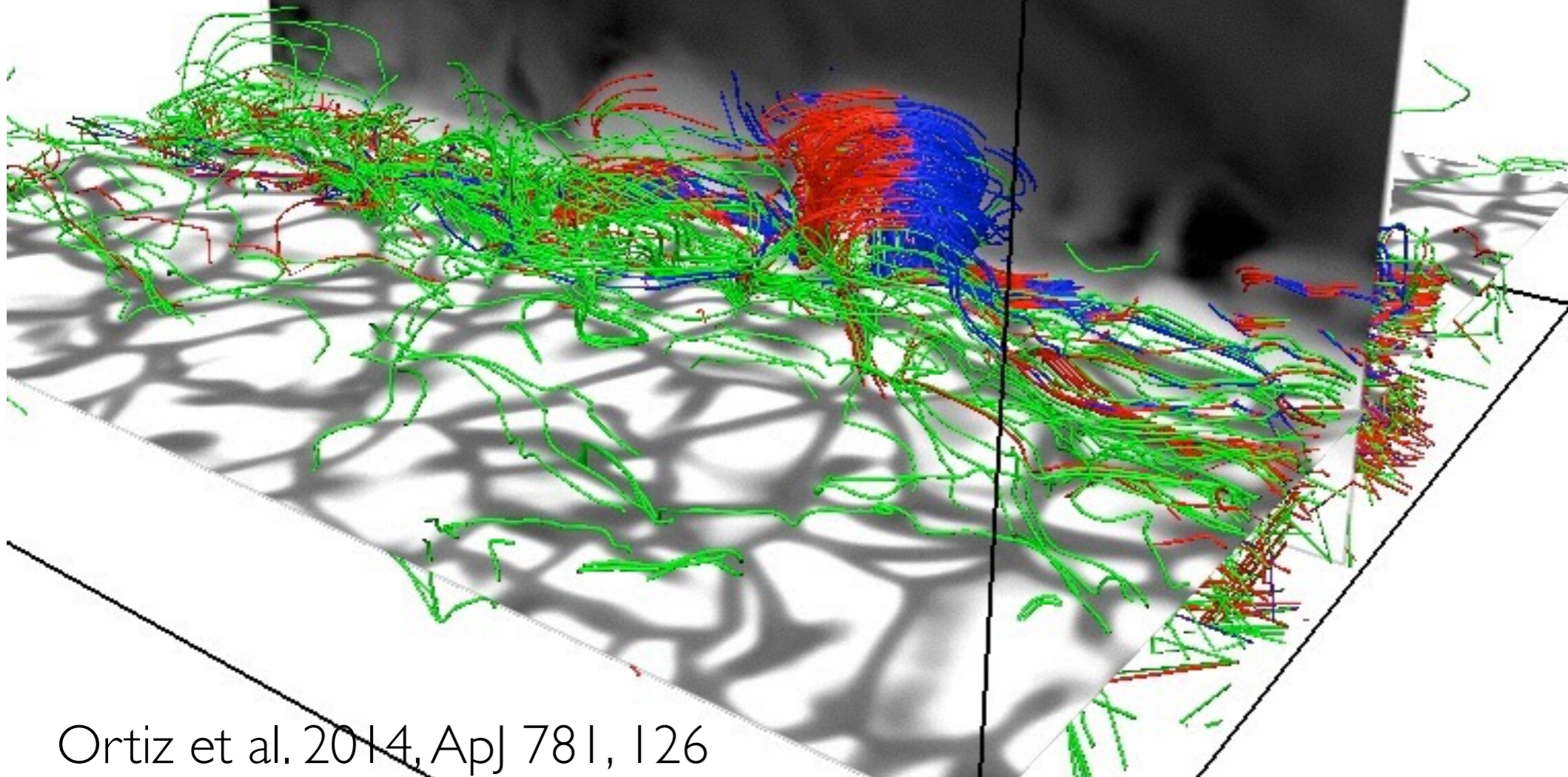
Chromospheric temperature structure set by
acoustic shocks until magnetic field emerges
into outer atmosphere.

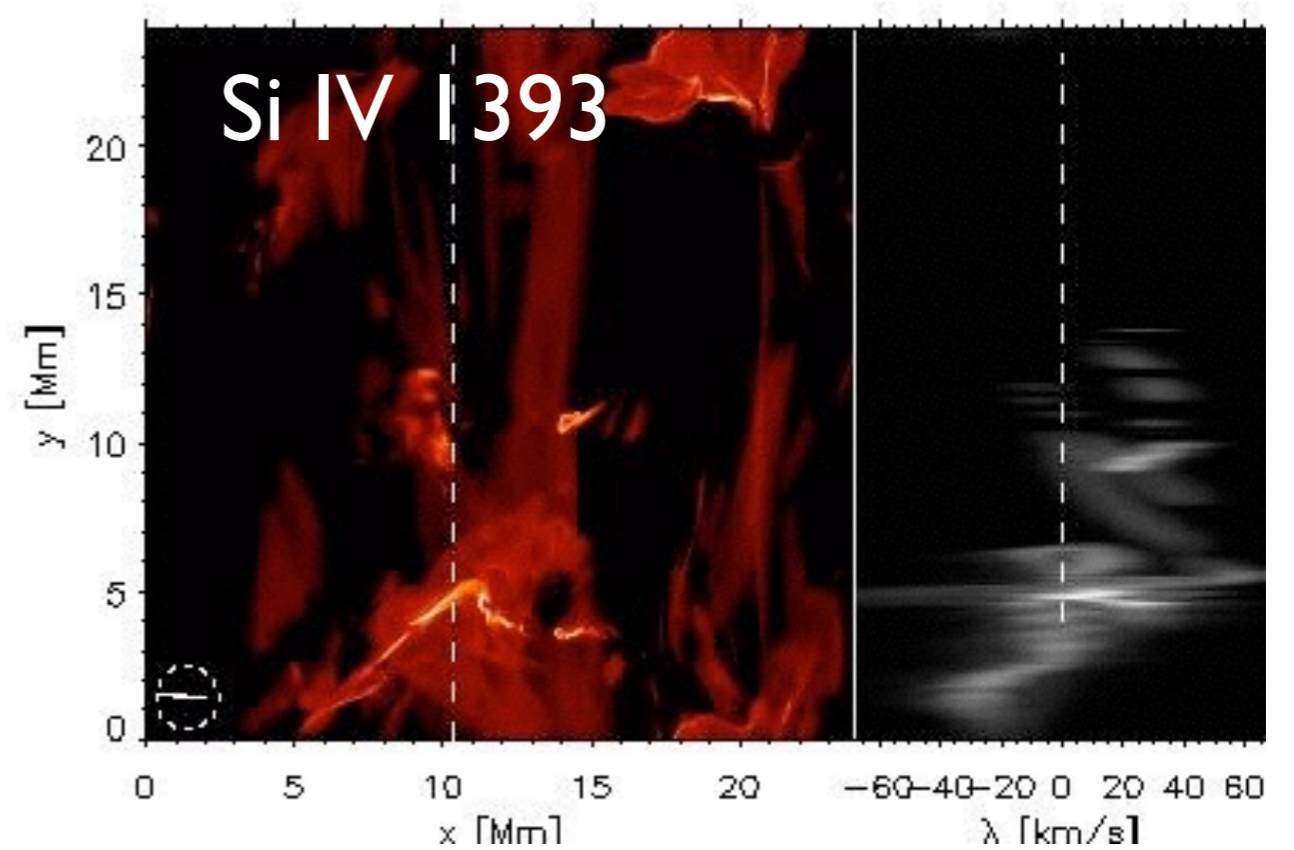
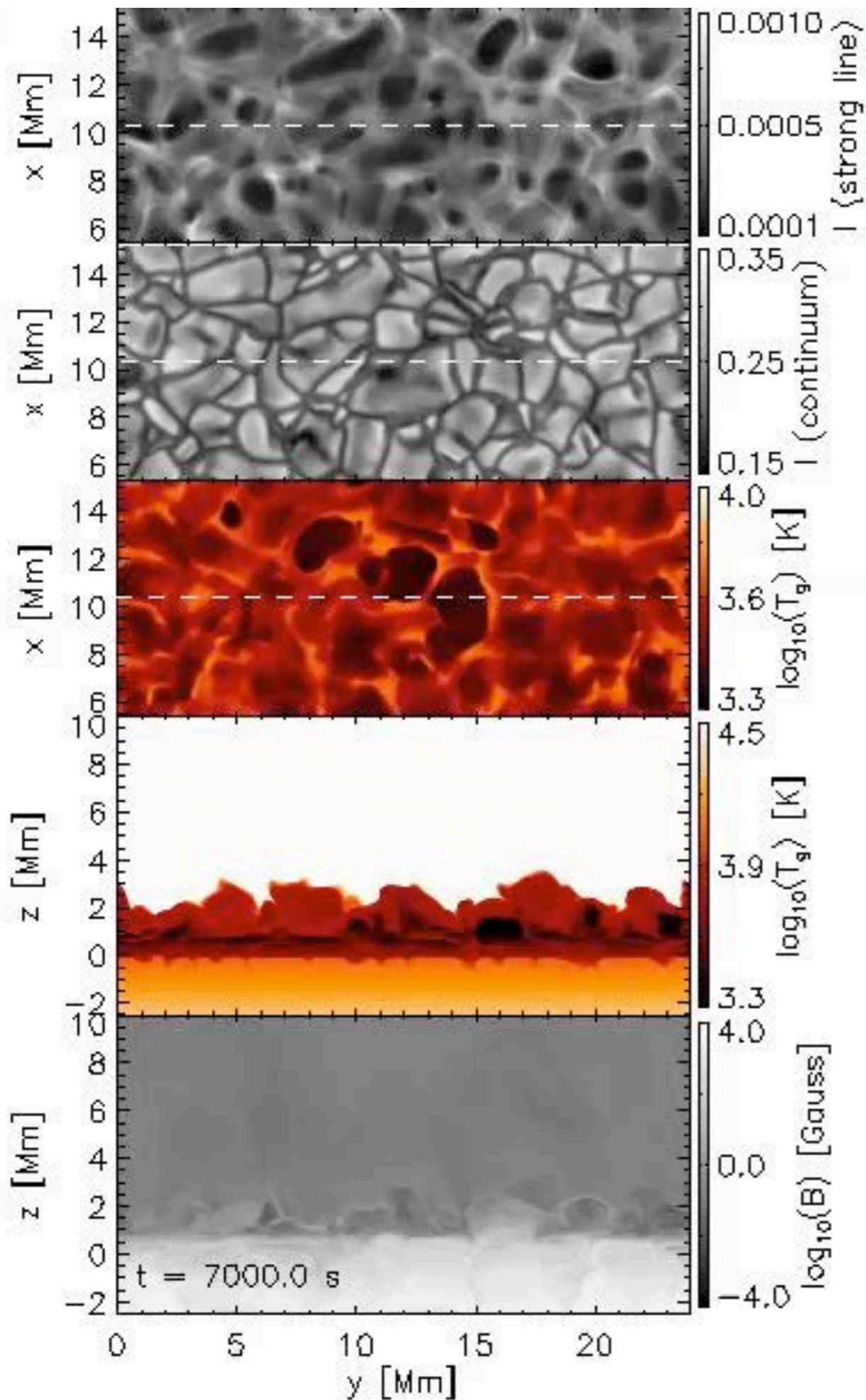
Flux sheet ($B=3300$ G at bottom boundary)
rapidly rises to photosphere...Where it stalls.

Initial ambient field of $B=0.1$ G with inclination
of 45° with respect to z axis.



Need “Large angle”
reconnection, implies
flux emergence?





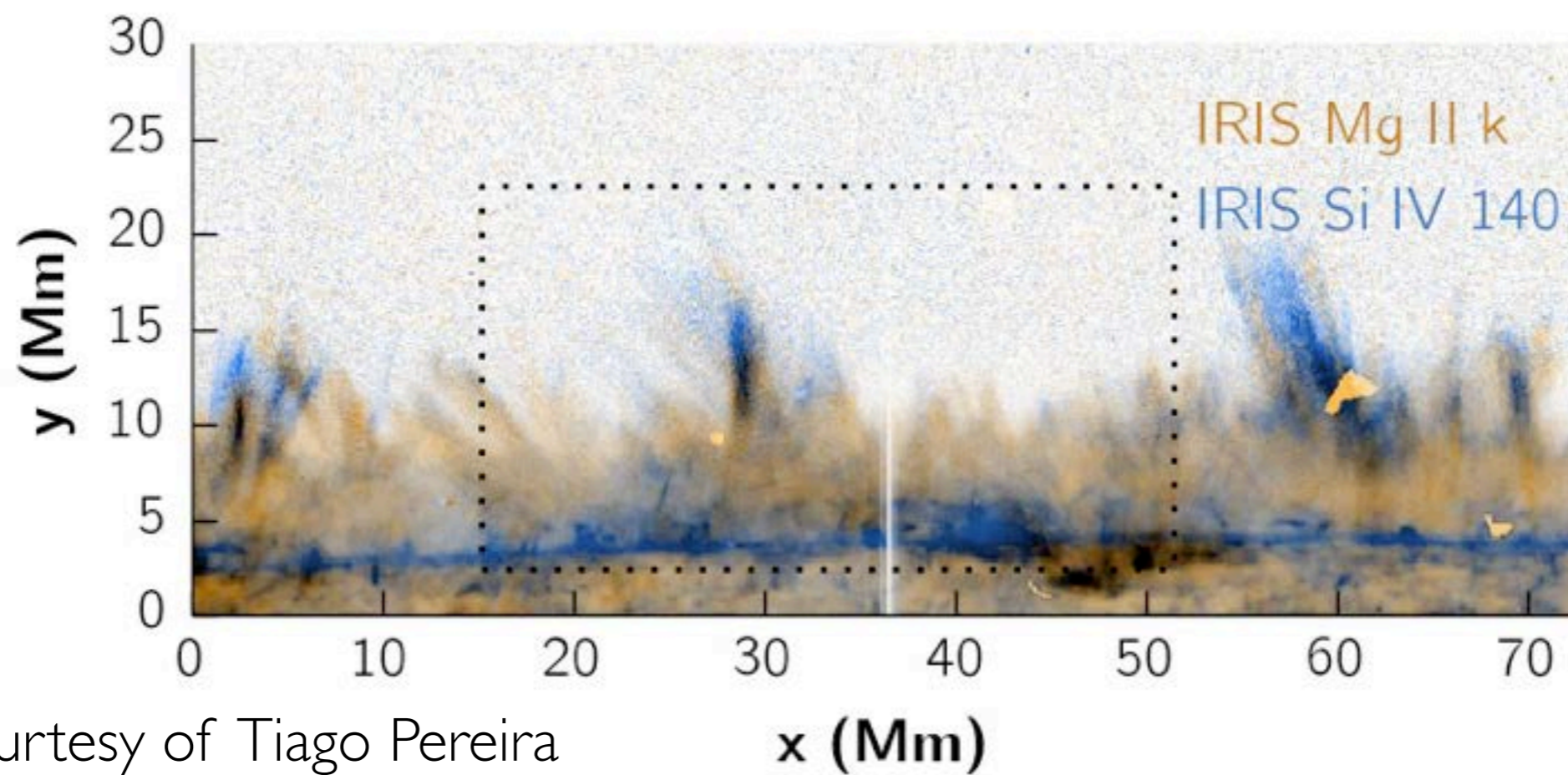
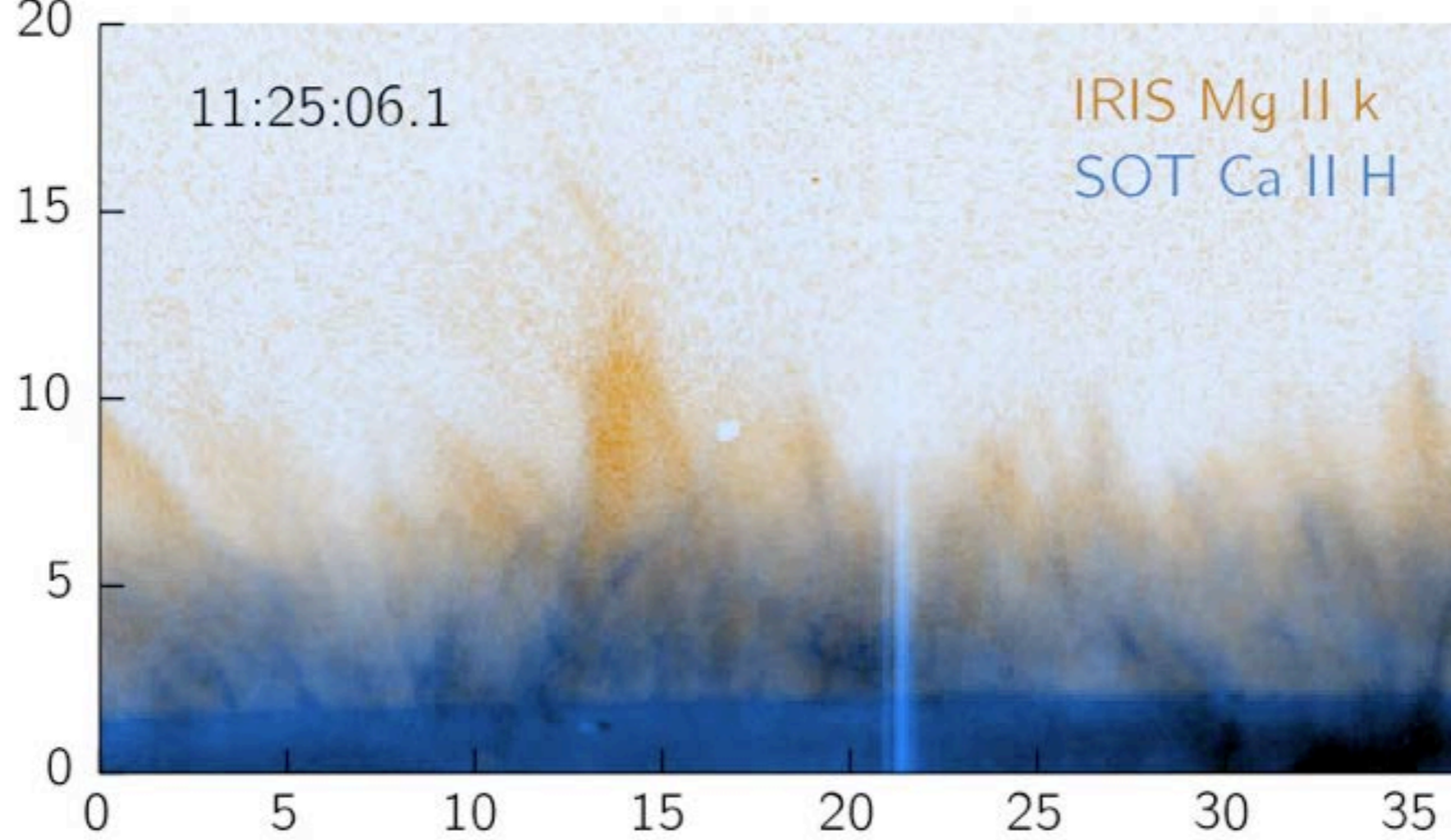
Magnetic field “pushes” pre-existing corona away filling coronal volume with cold high density plasma. Reheating occurs at reconnection sites.

Once past the photospheric barrier (several) magnetic field bubbles rapidly fill the chromosphere and corona, where they eventually abut each other.

Archontis & Hansteen 2014, ApJL 788, L2

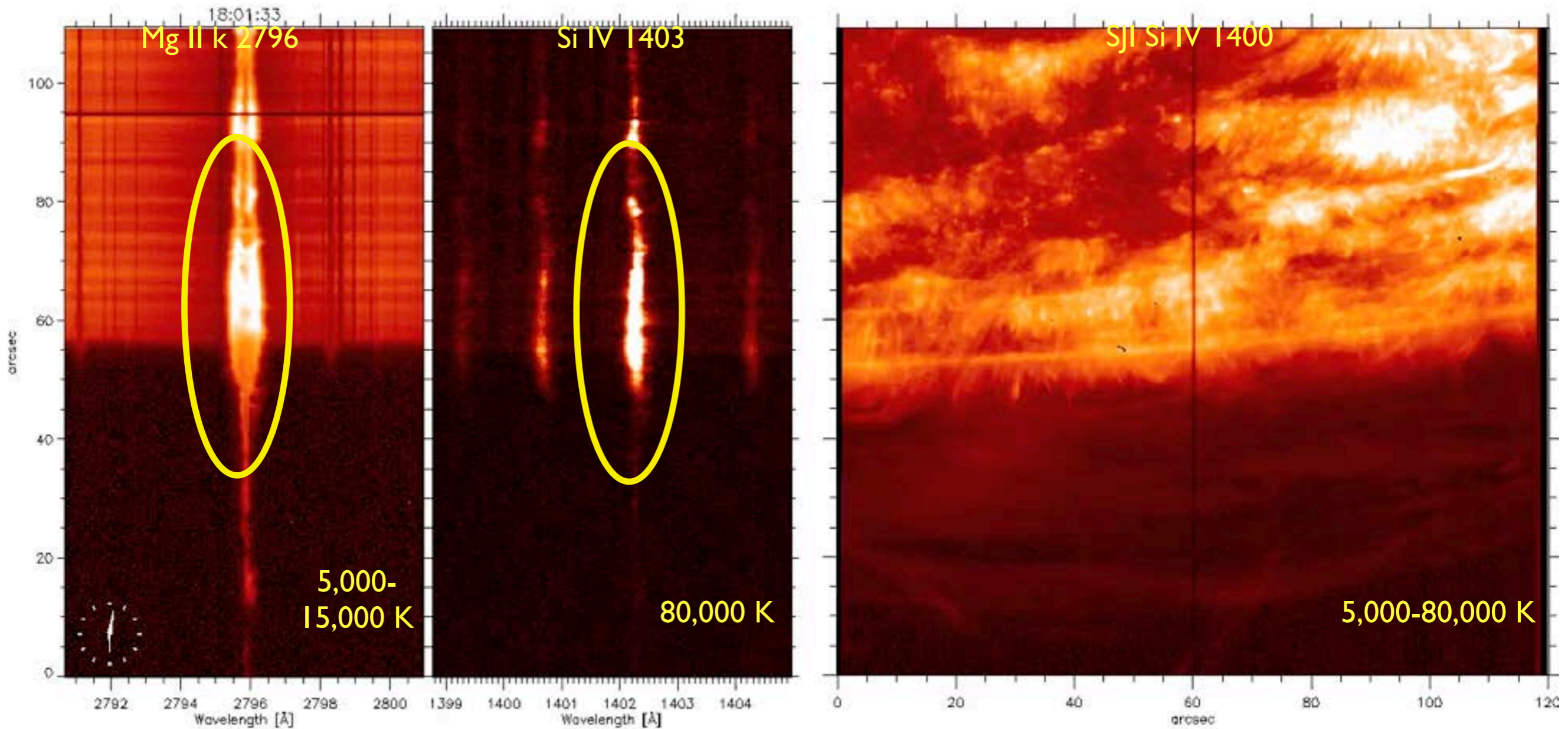
UFS not the only thing seen on the limb
Hinode/SOT Ca II H (gradient filter) 07-Nov-2007

- lifetimes 10-100 s
- velocities 30-150 km/s
- carry strong Alfvén waves
- rapid fading (heating?)



movie courtesy of Tiago Pereira

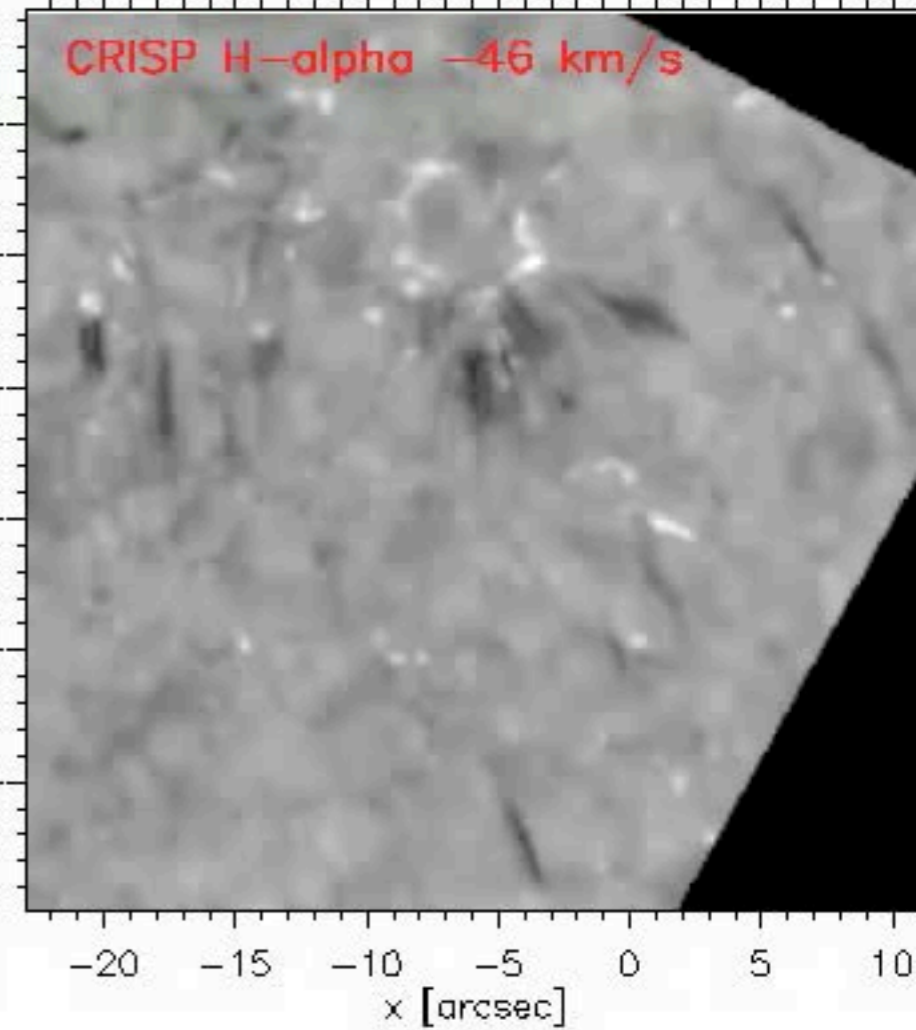
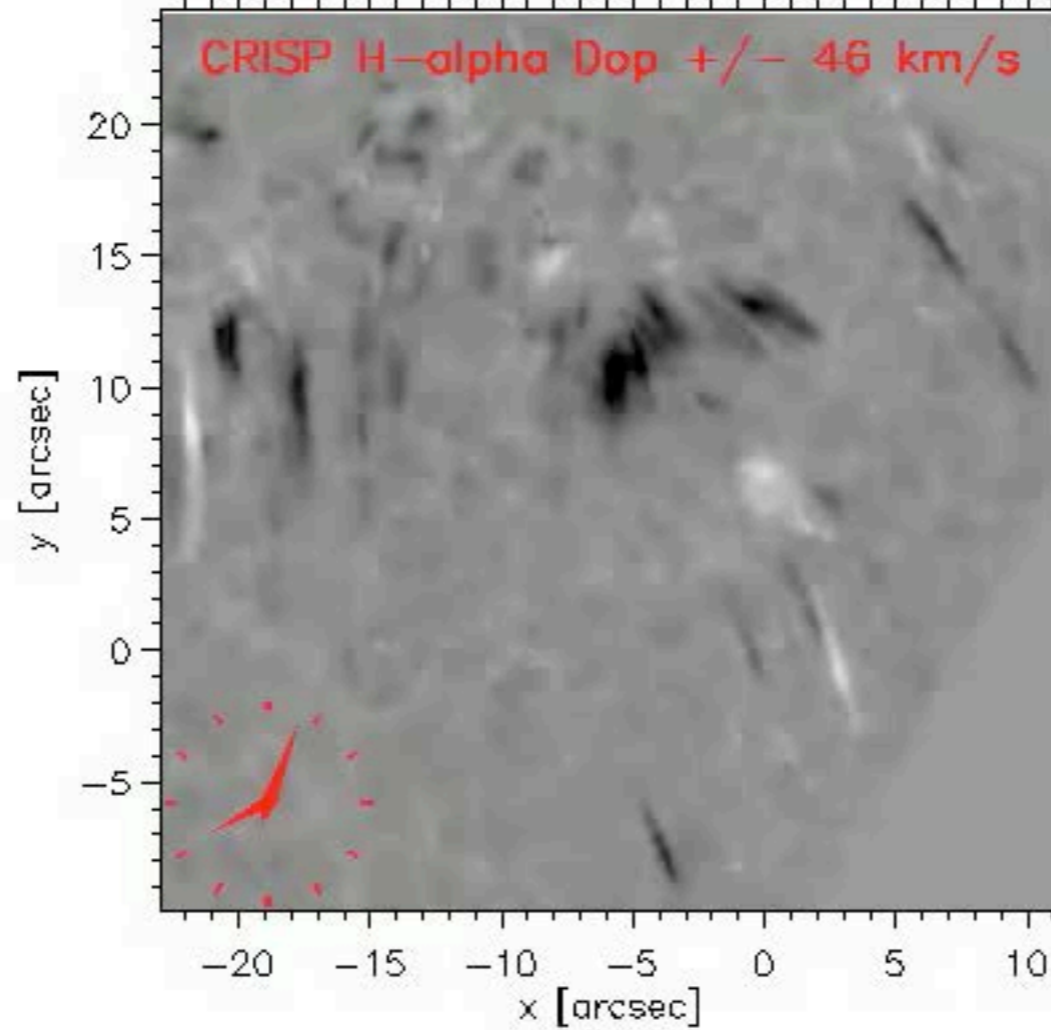
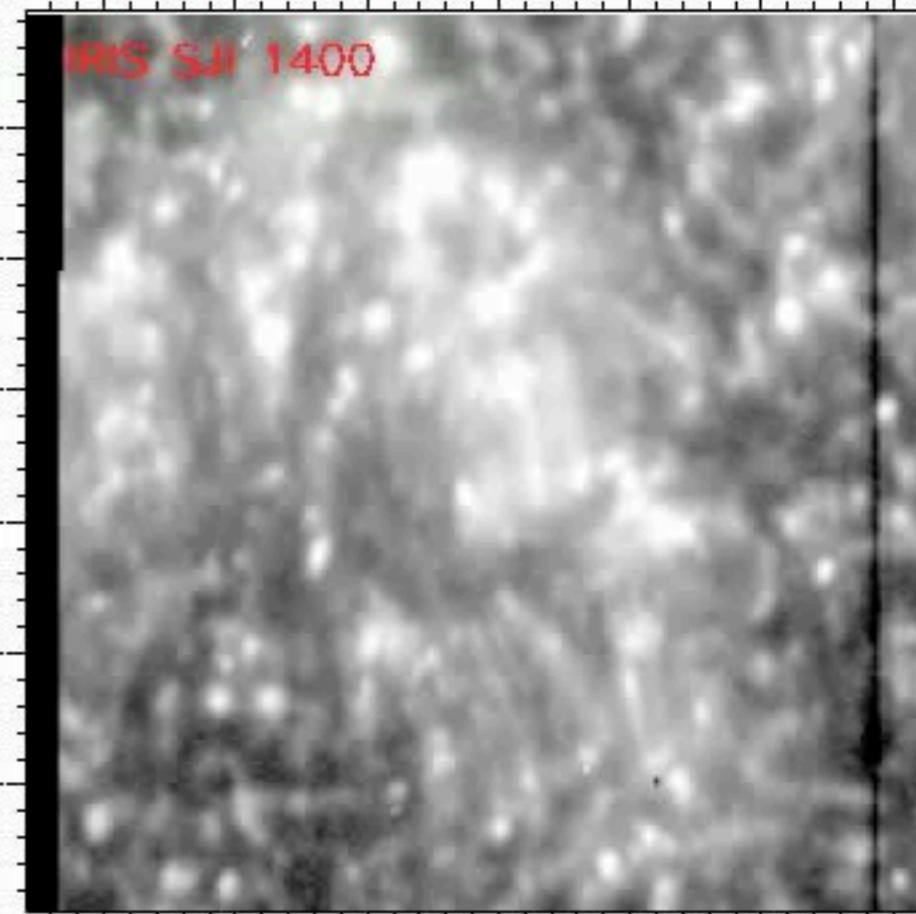
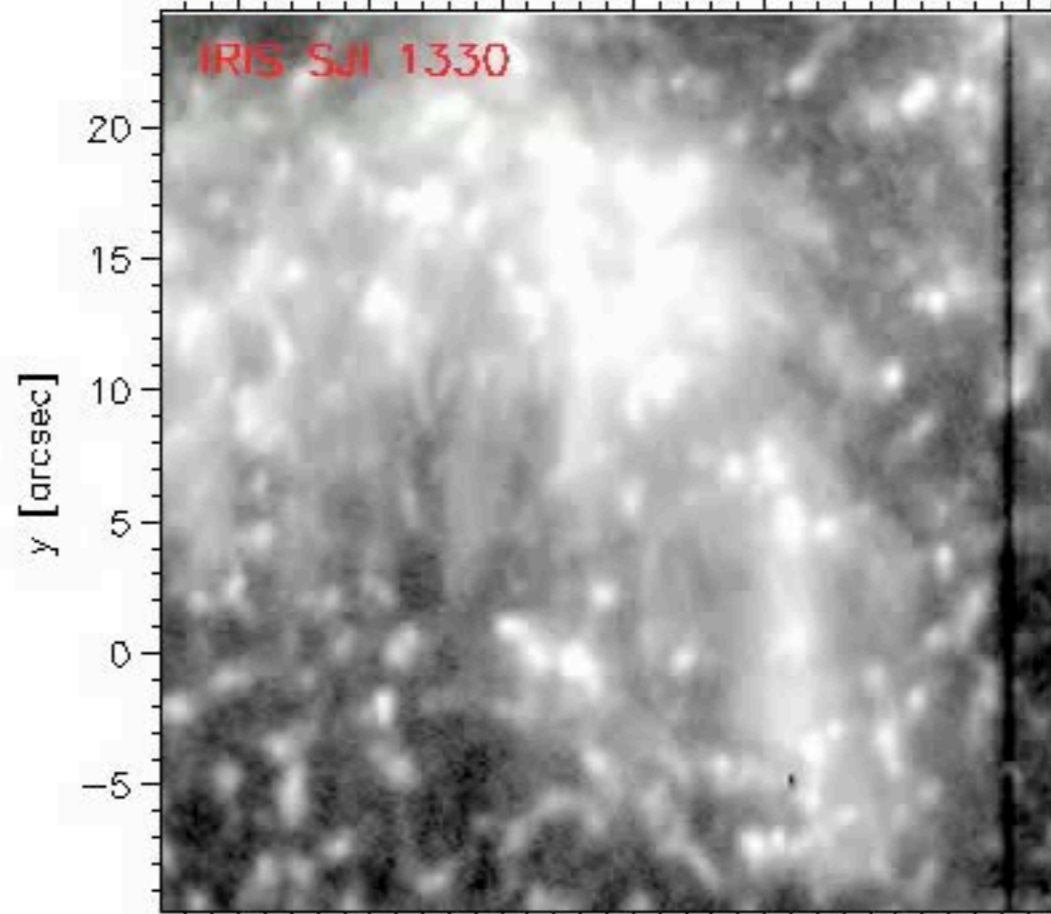
SST H α observations, and later IRIS spectra show bidirectional flows at limb suggestive of torsional motions



Limb geometry suggests bidirectional flows of 10-30 km/s are perpendicular to the magnetic field direction and short-lived (<1 min)

SST/IRIS co-
observing show
RBEs/RREs are
disk counterparts
of spicules

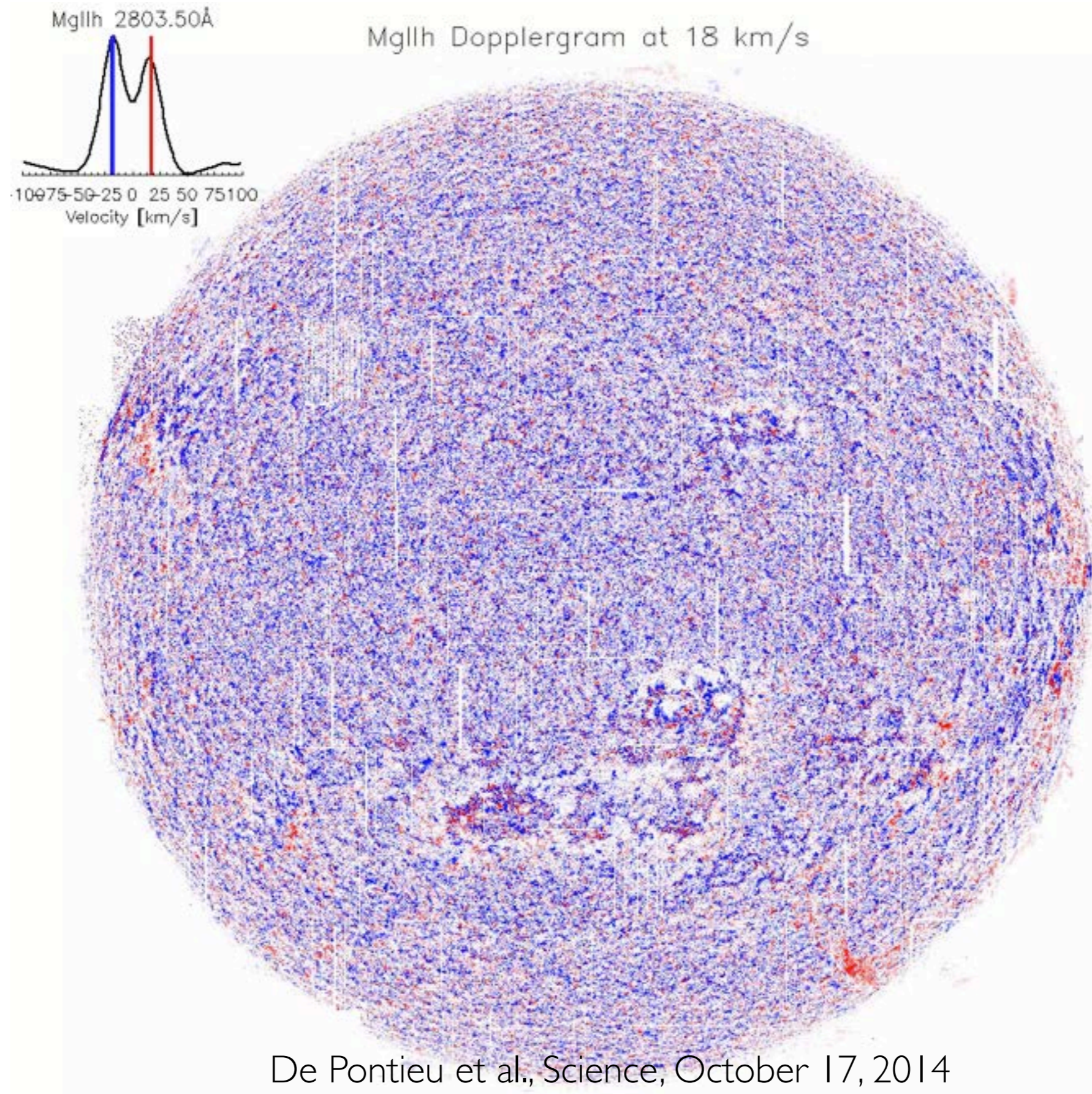
IRIS Si IV SJI



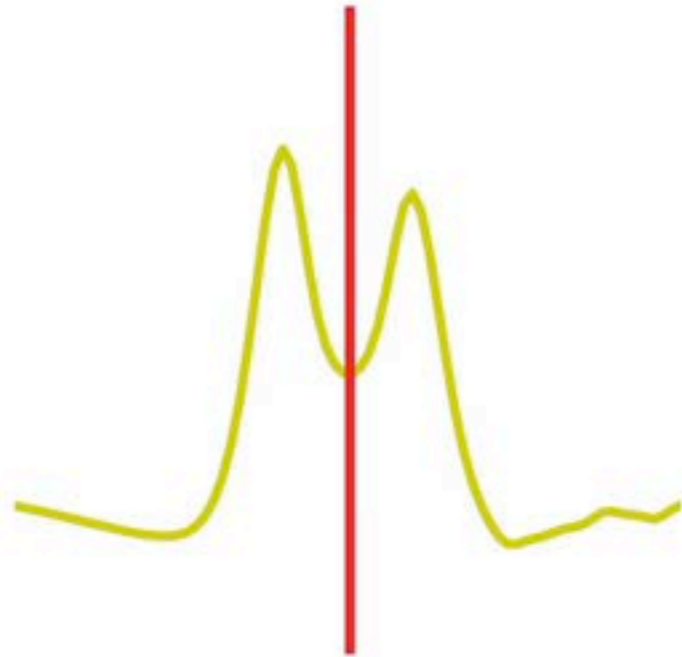
SST H α

movie courtesy of Luc
Roupe van der Voort

IRIS observations reveal ubiquity of twist in chromosphere

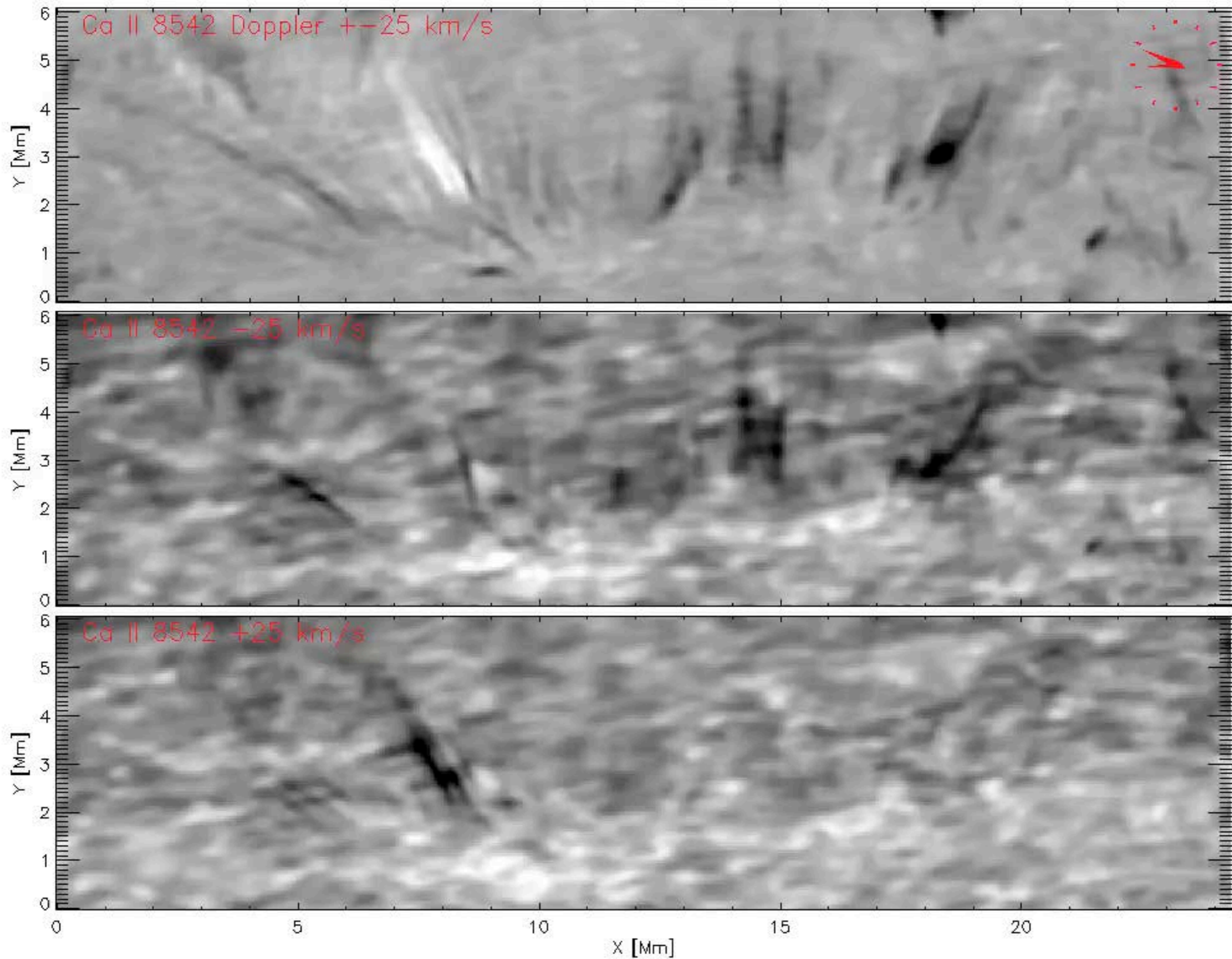


Mg II h



$\pm 0.0 \text{ km s}^{-1}$

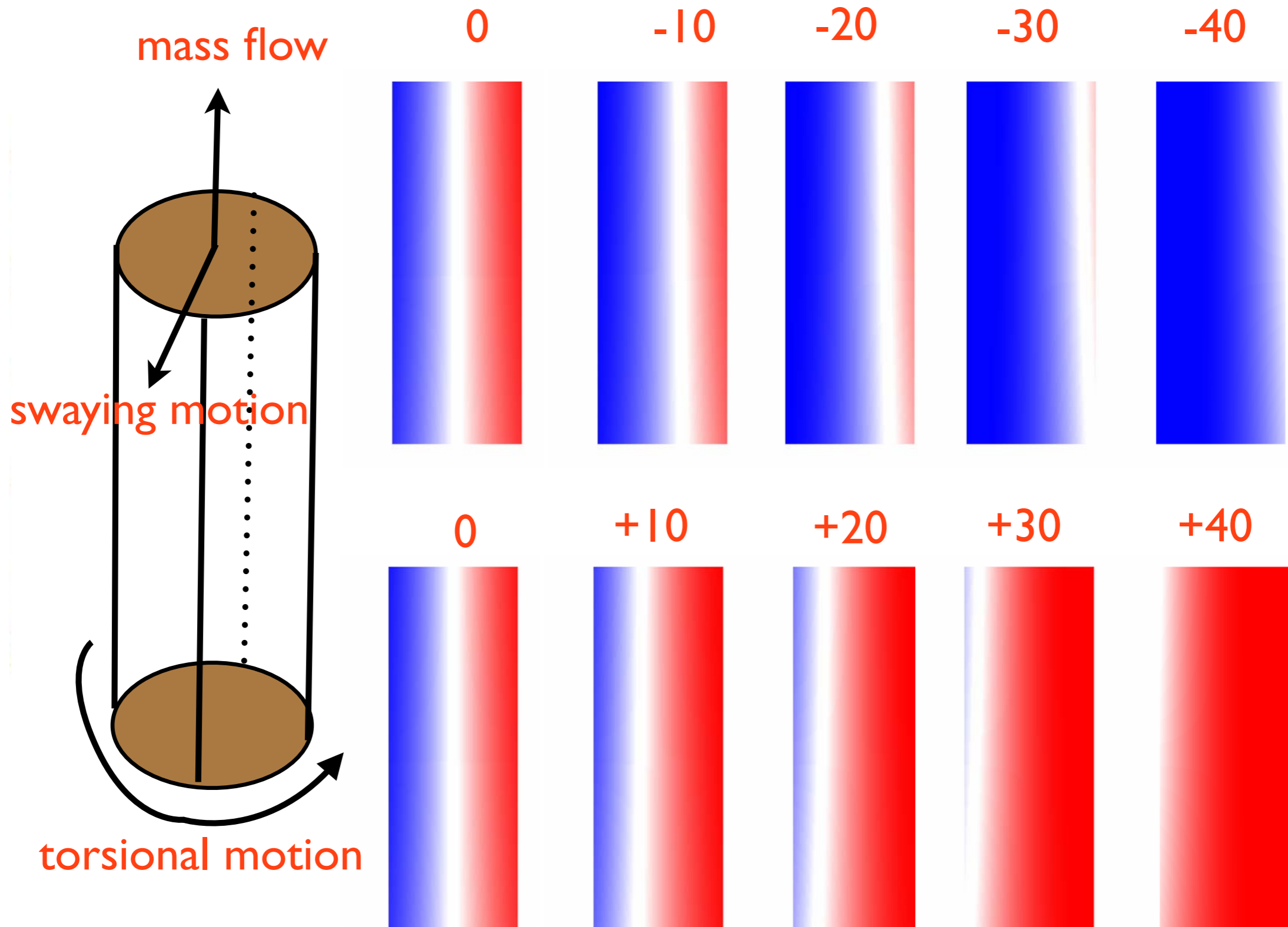




Discussion & Conclusions

- Observed upper chromosphere, transition region and lower corona dynamics give unique insight into “chromospheric/coronal” heating
 - ...both through UFS and through spicules.
- Simulations show braiding to be a viable coronal heating candidate
 - reproduces several (difficult) observables
 - ...but so far few spicules.
- Alfvén waves dissipated through turbulence (or resonant absorption) can also heat corona
 - could explain observed prevalence of twist
 - ...but how to generate?
- Role of flux emergence in coronal heating is unknown, but potentially interesting

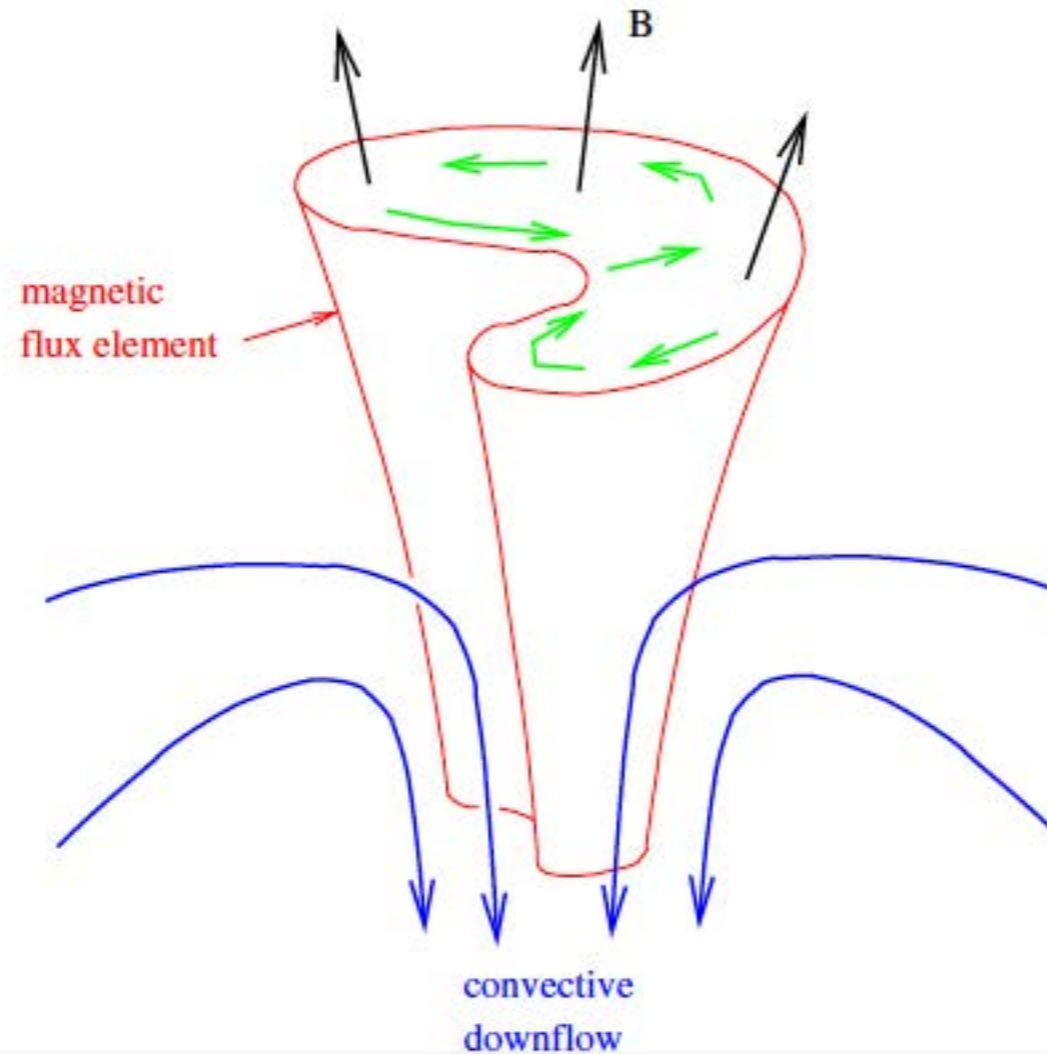
How do we determine prevalence of torsional motions?



Evidence for three types of motion: mass flow, swaying, and torsional

Alfvén wave turbulence

THE ASTROPHYSICAL JOURNAL, 736:3 (27pp), 2011 July 20



Hollweg 1986, JGR 91,4111

Heaverts & Priest 1984, A&A 137, 63

Verdini & Velli 2007, ApJ 662, 669
and many others!

van Ballegoijen et al. 2011, ApJ 736, 3
van Ballegoijen et al. 2014, ApJ 787, 87