# Realistic 3D simulations of a small flare resulting from flux emergence

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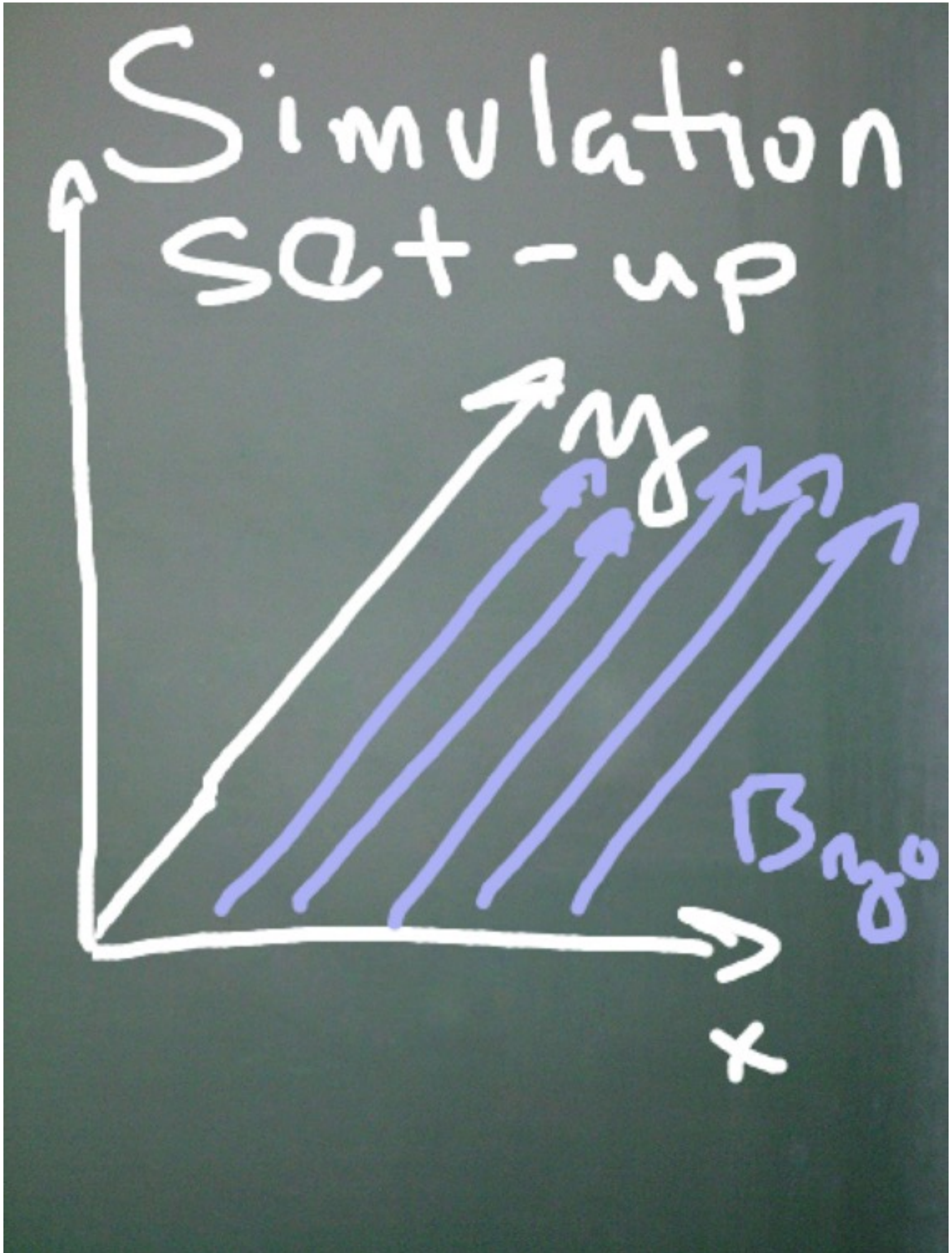



Domain 24x24x17 $Mm^3$
(504,504,496 grid points),
2.5 Mm below photosphere
14.5 Mm above

Weak initial field B < 0. 1G,
inclination $45^\circ$

Flux sheet with By = 3360G
in domain [0–24, 3–16] Mm
for a period of 105 minutes.

# BIFROST: Basic assumptions

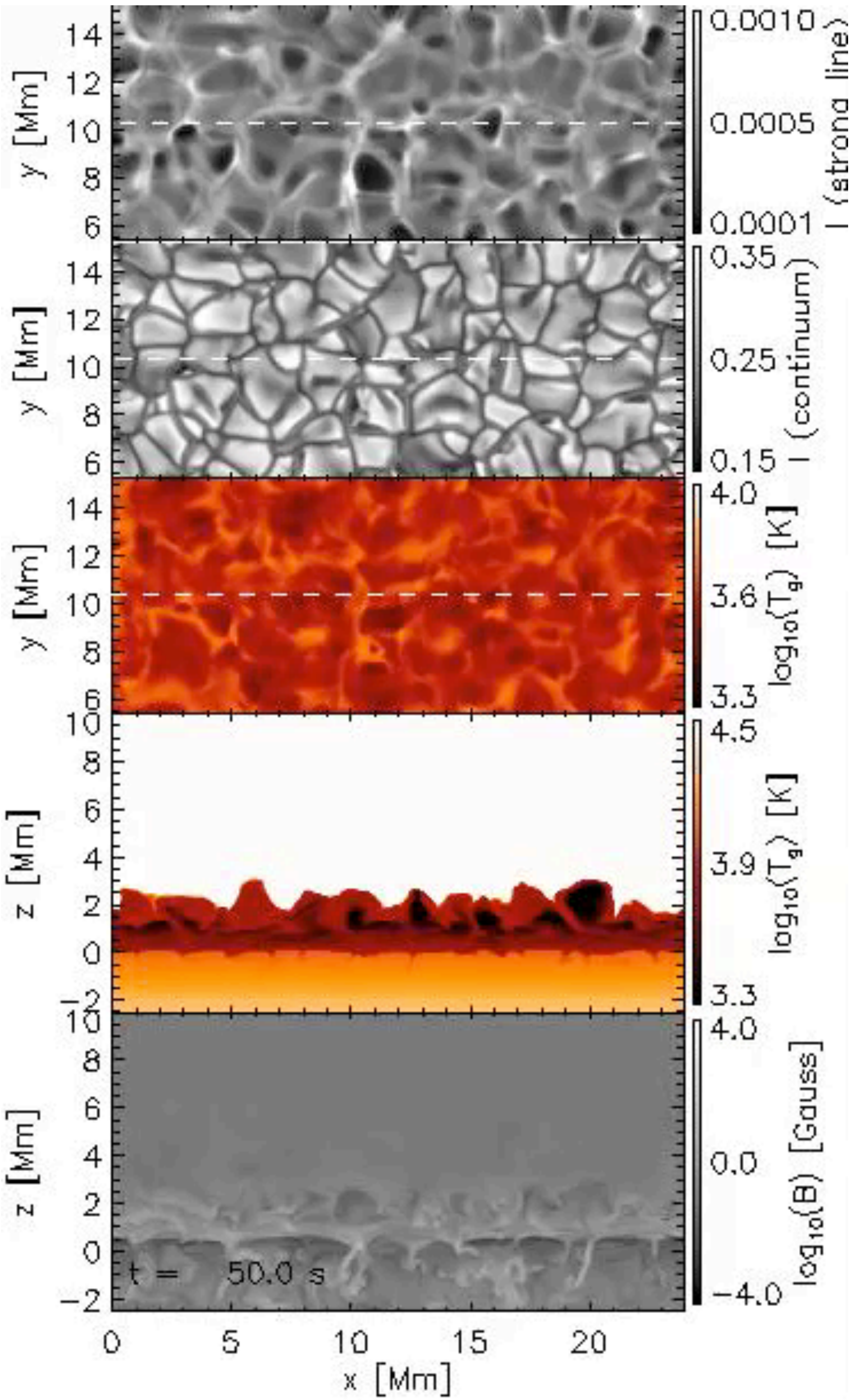
Hansteen 2004, Hansteen, Carlsson, Gudiksen 2007,
Martínez Sykora, Hansteen, Carlsson 2008, Gudiksen et al 2011

- 6th order scheme, with "artificial viscosity/diffusion"
- Open vertical boundaries, horizontally periodic
- Possible to introduce field through bottom boundary

- "Realistic" EOS
- Detailed radiative transfer along 48 rays
  - Multi group opacities (4 bins) with scattering
- NLTE radiative losses in the chromosphere, optically thin in corona

- Conduction along field lines
  - Operator split and solved by using multi grid method

- Time dependent Hydrogen ionization
- Generalized Ohm's Law




Photospheric and chromospheric intensity little changed by emergence of flux sheet through convection zone.

Some large granules appear towards end of this animation.

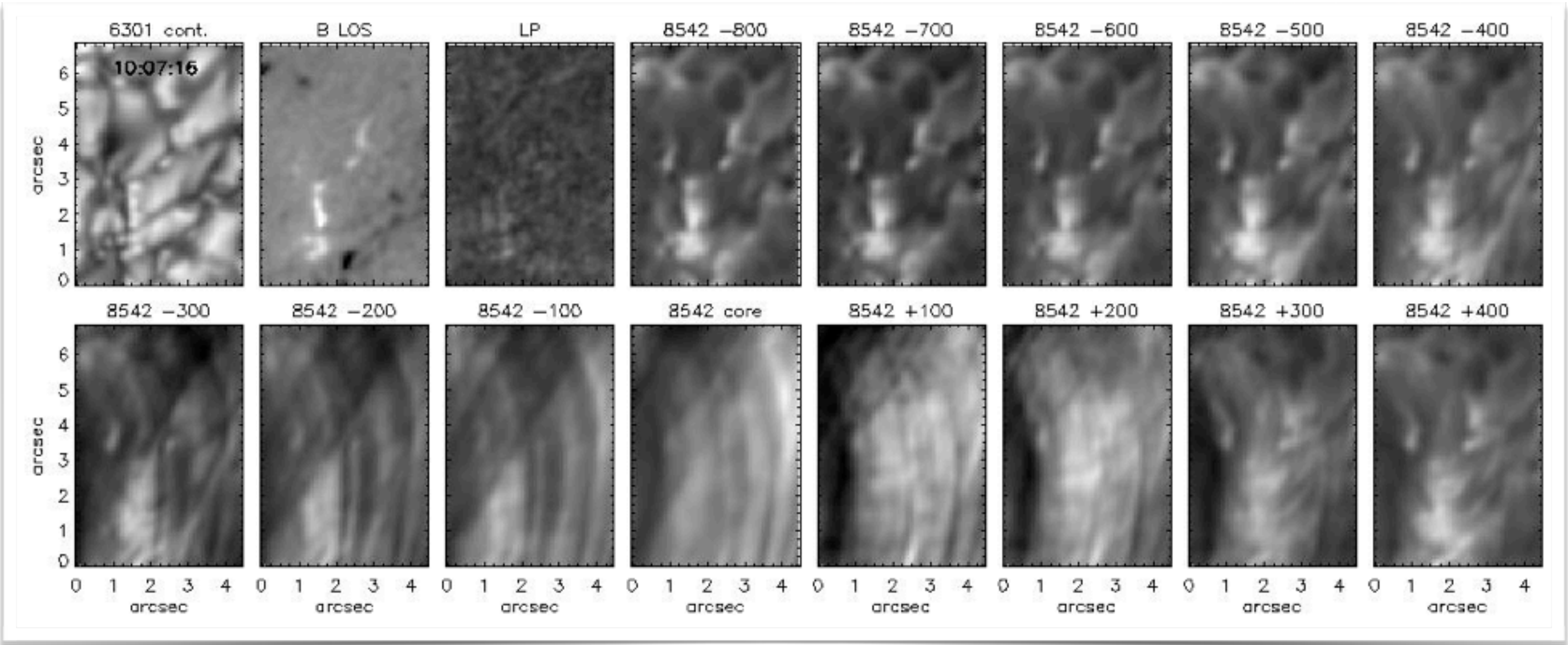
Horizontal panel at z=700 km above photosphere. Chromospheric vertical extent initially some 2 Mm.

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.

# What do we observe when field penetrates photosphere and rises into outer atmosphere?




Ortiz et al. 2014, ApJ 781, 126

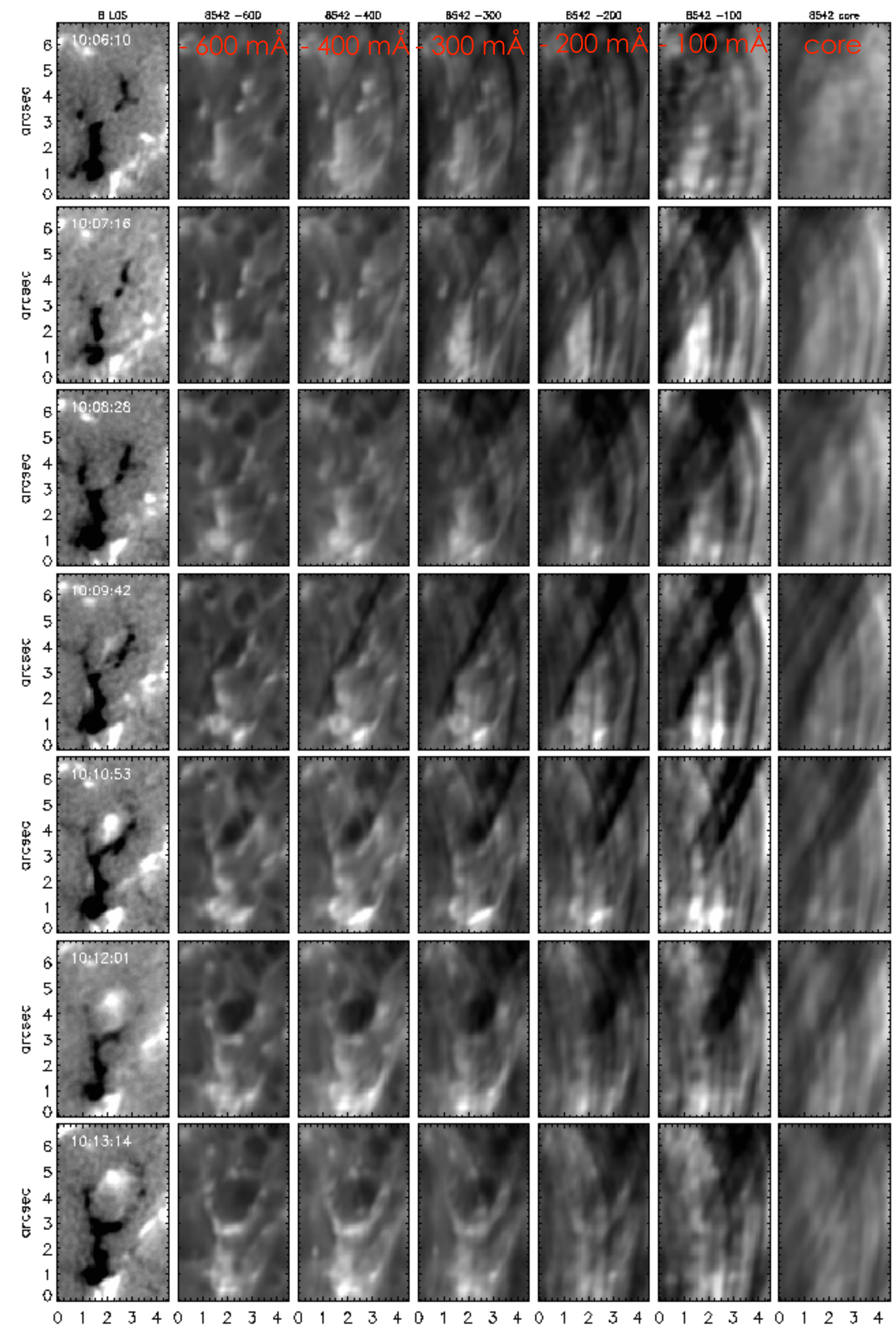
see also Title 1994, AAS 26, 1464, Strous et al. 1996, A&A 306, 947, and Strous & Zwaan ApJ 527, 435

# Dark bubbles

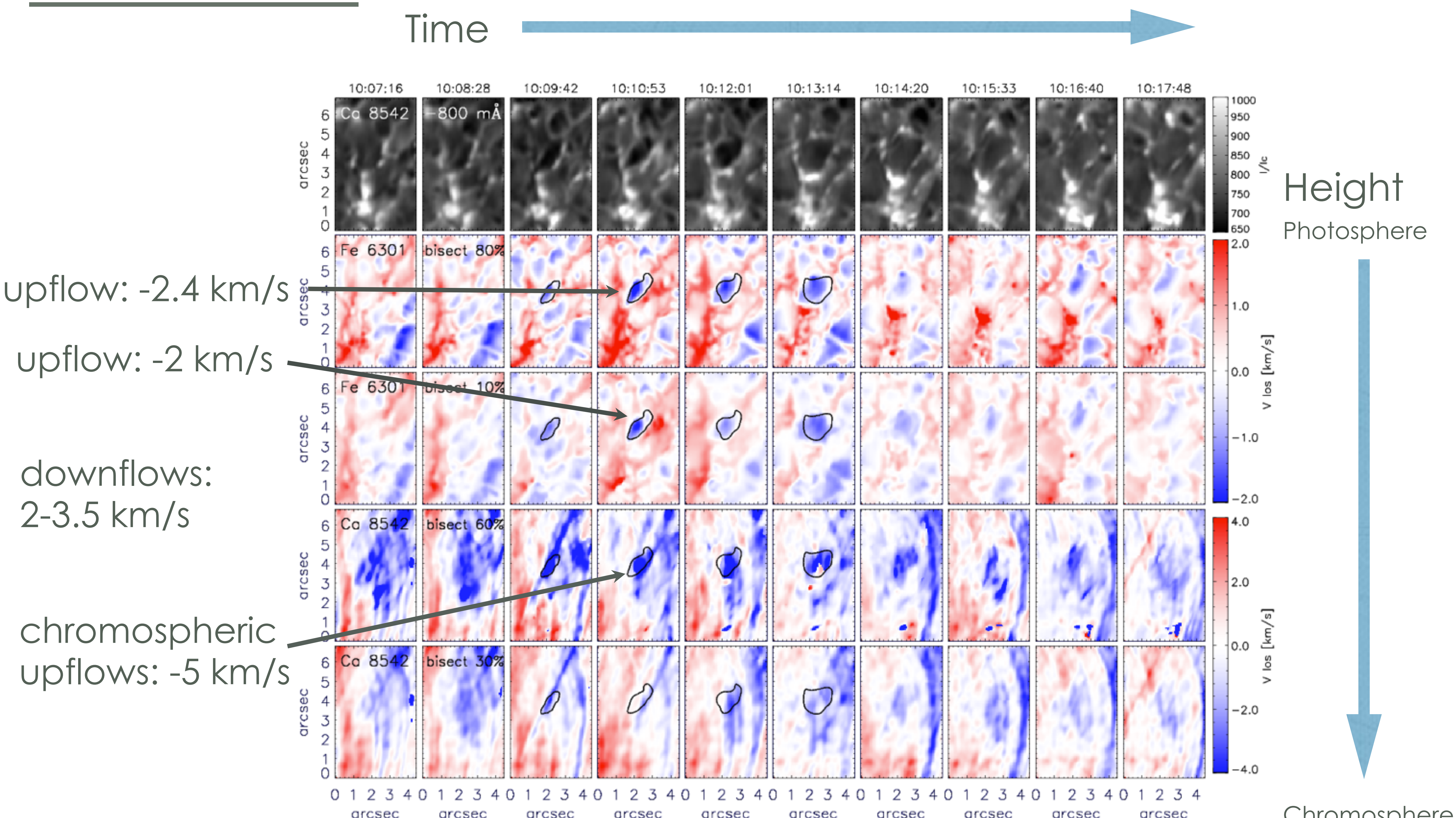
Wavelength

Photosphere → Chromosphere

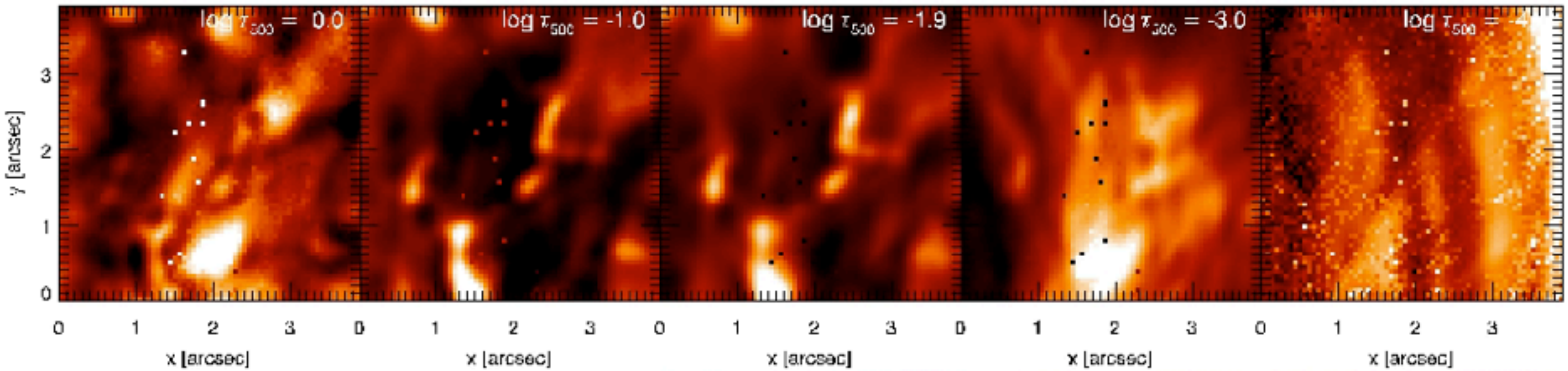
Time: 7 minutes
1 min. / time step

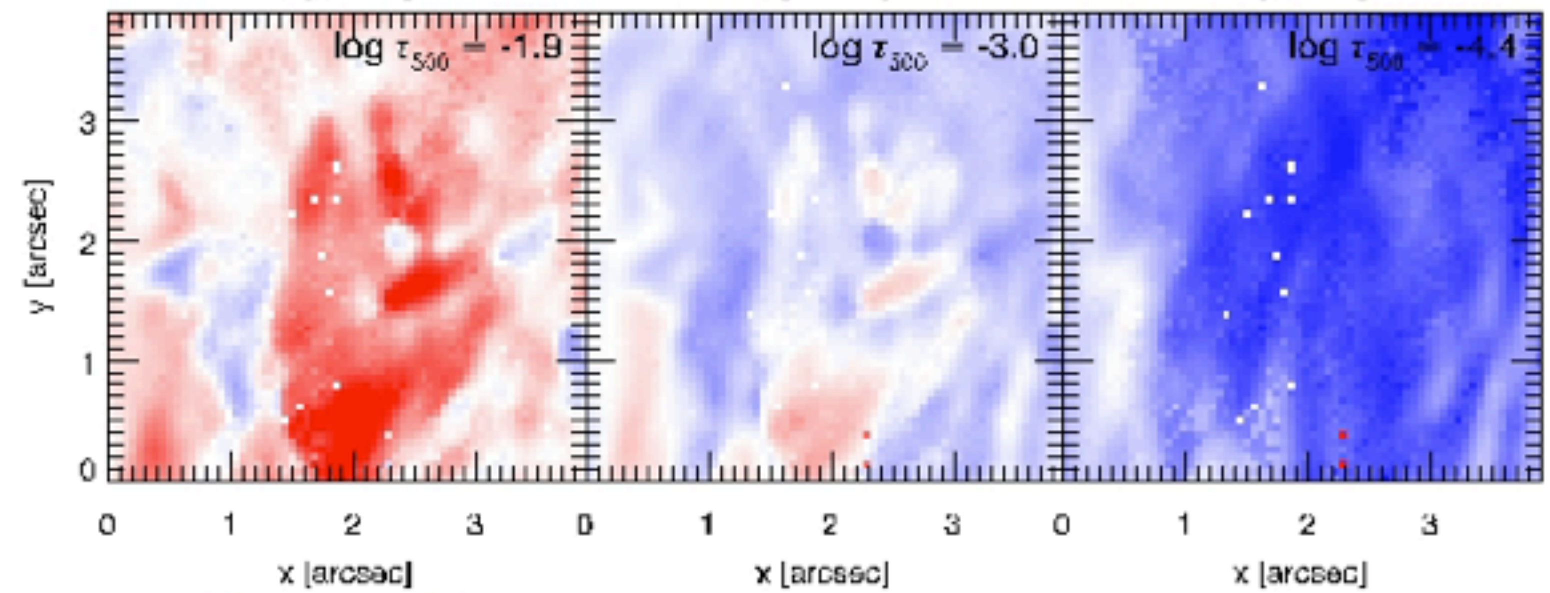


# Velocities

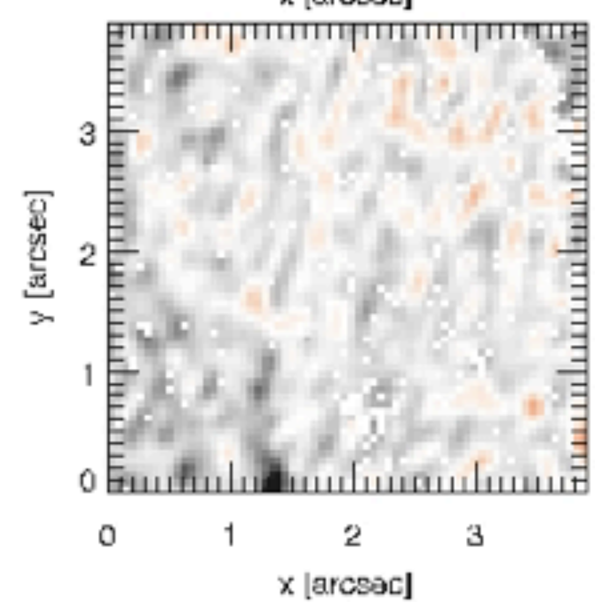

Time
Height
Photosphere
Chromosphere
upflow: -2.4 km/s
upflow: -2 km/s
downflows:
2-3.5 km/s
chromospheric
upflows: -5 km/s
10:07:16
10:08:28
10:09:42
10:10:53
10:12:01
10:13:14
10:14:20
10:15:33
10:16:40
10:17:48
Ca 8542
-800 mÅ
Fe 6301
bisect 80%
Fe 6301
bisect 10%
Ca 8542
bisect 60%
Ca 8542
bisect 30%
arcsec
I/Ic
V los [km/s]

# non-LTE inversions: structuring of atmospheric parameters



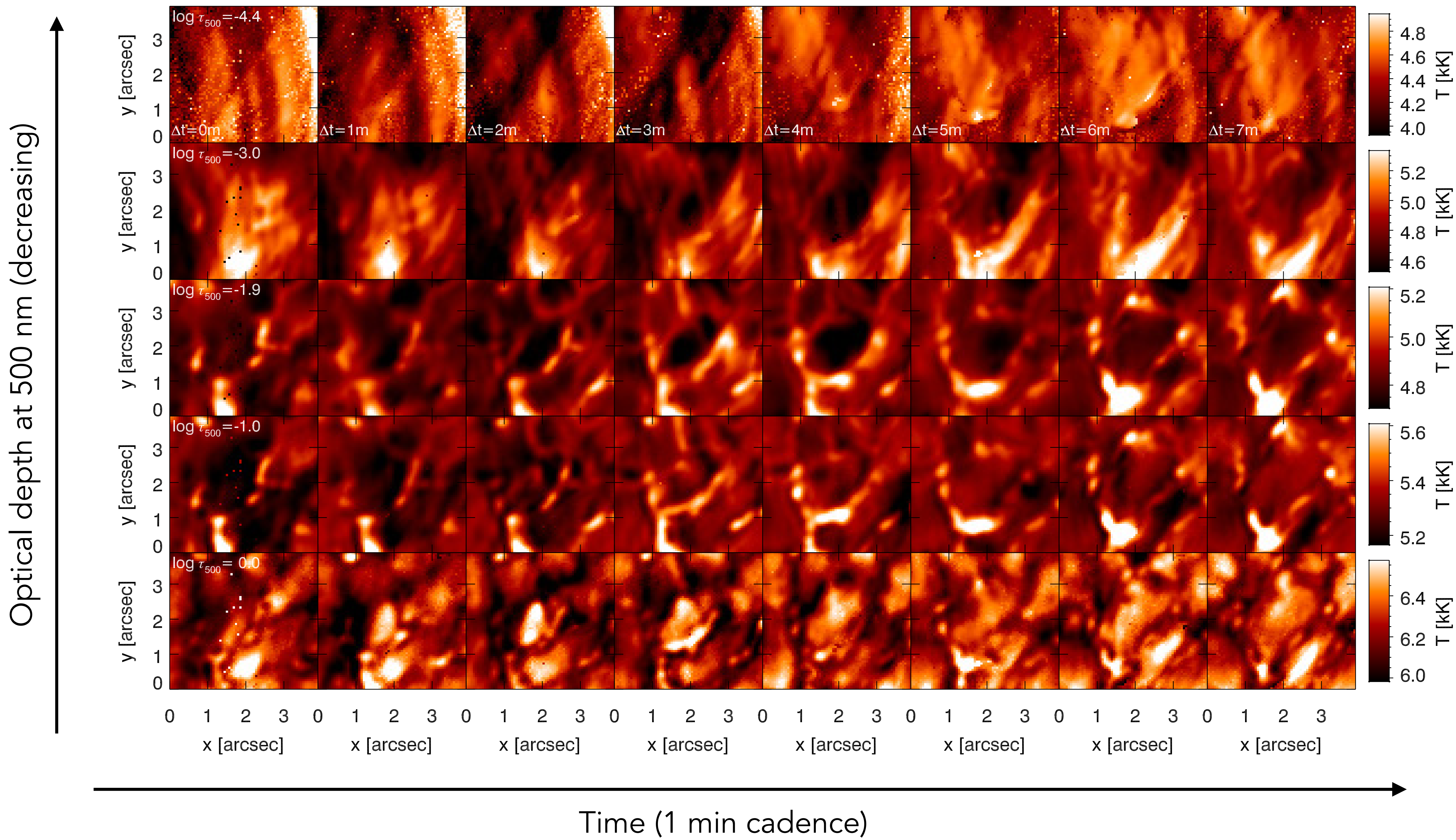

- Canopy of (upflowing) fibrils from log $\tau_{500}$ = -4.4.
- Cold bubble clearly visible between log $\tau_{500}$ = -1.9 and -3.0 (upper photosphere). Delay.
- Up flowing material within the bubble.
- Hints of heating initiated at the footpoints at log $\tau_{500}$ = -3.0.
- Traces of the magnetic field at the location of the footpoints.




de la Cruz Rodriguez et al. (2015)

# non-LTE inversions: structuring of atmospheric parameters

Canopy of fibrils in the chromosphere: bubble gets stalled?




de la Cruz Rodriguez et al. (2015)

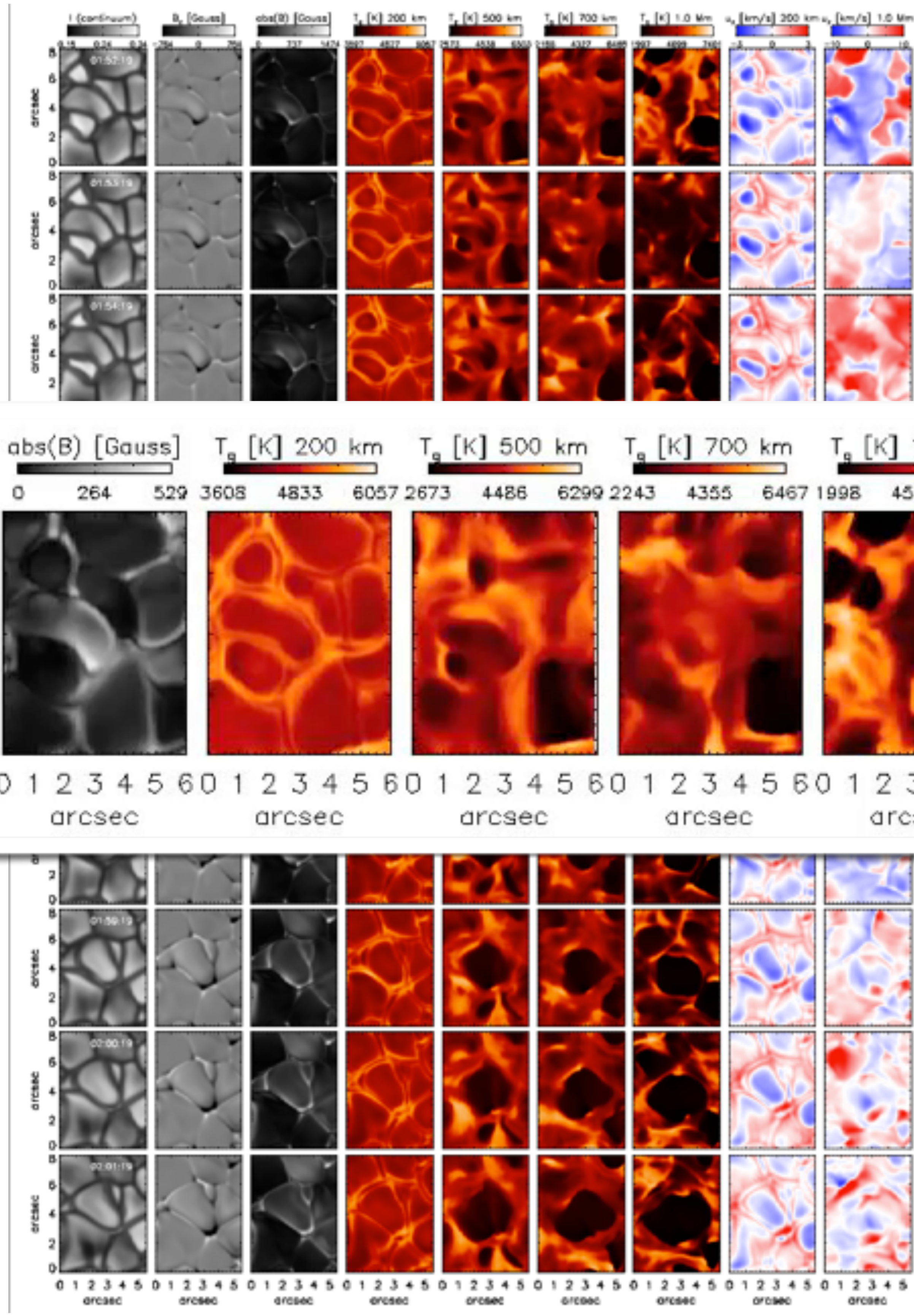
# Simulations

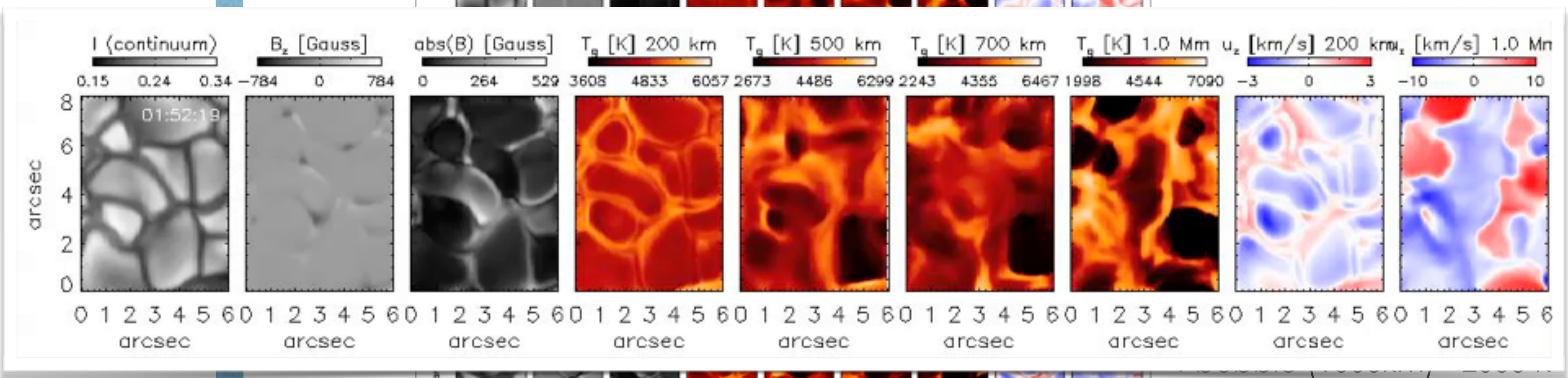
Height

Time: 9 minutes

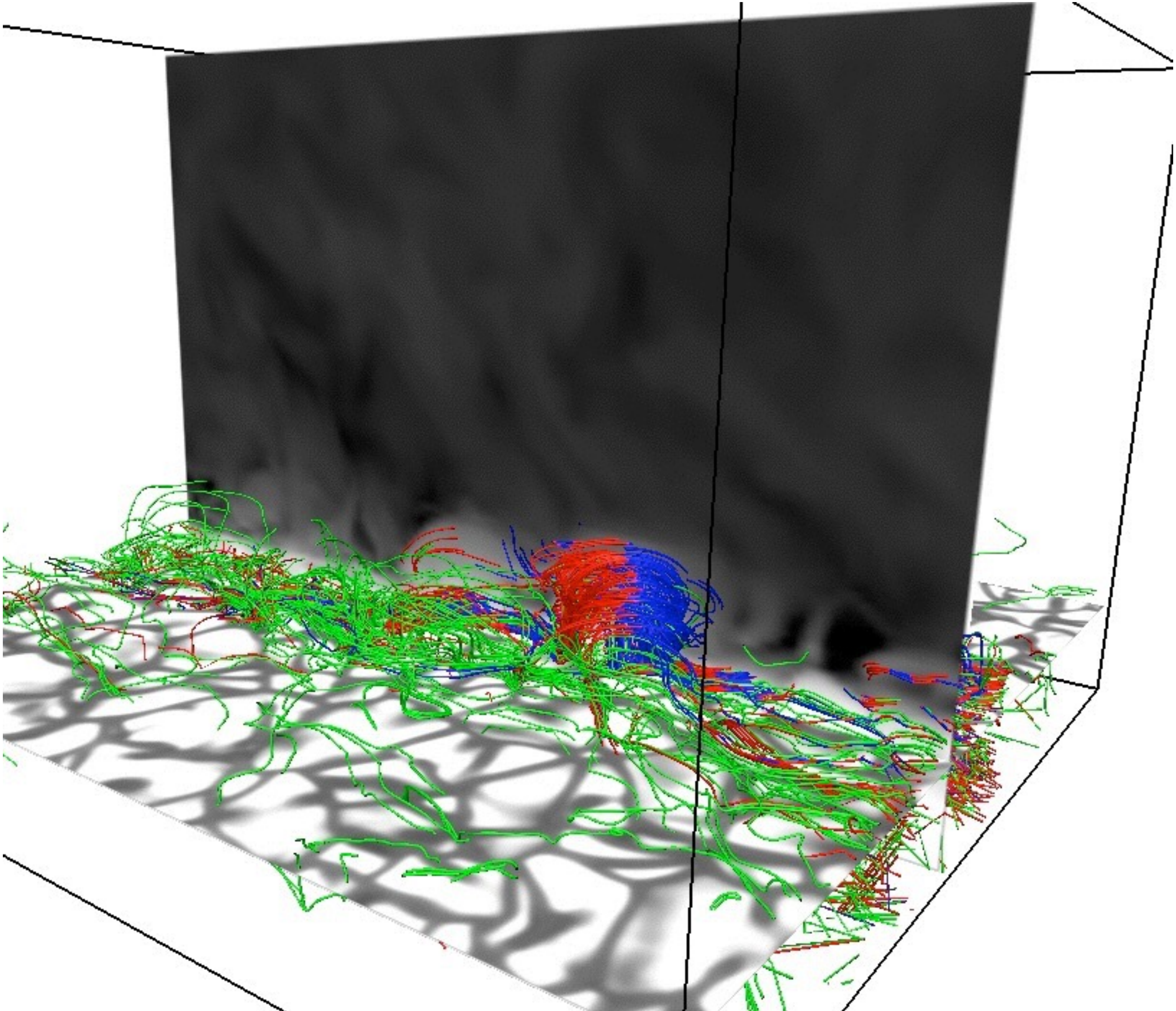
1 min. / time step

- BIFROST: MHD+RT
- 24x24 Mm box
- Vertical range: -2.5 Mm to +14 Mm above
- 3360 G flux sheet injected at lower boundary for 105 min

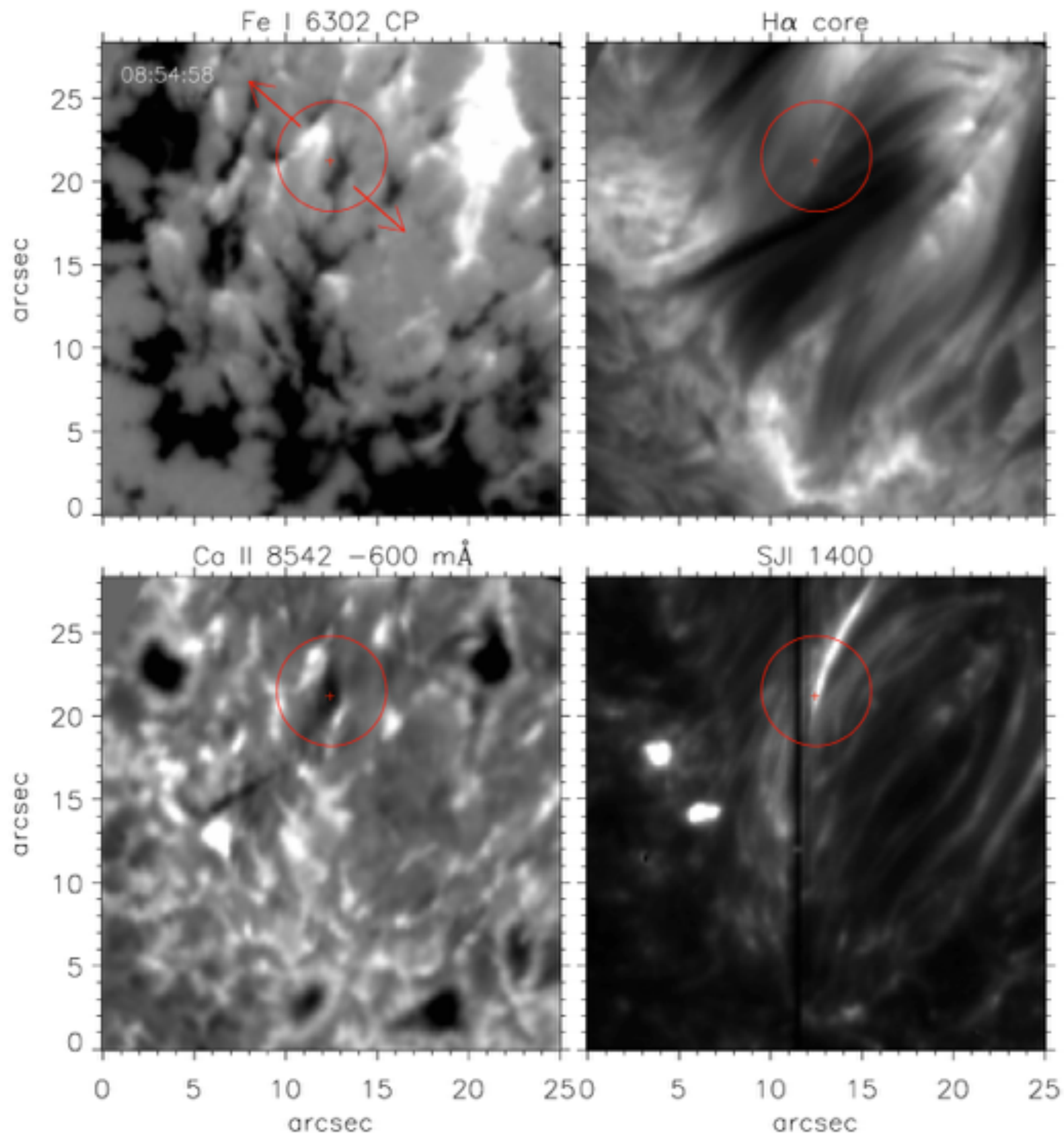





Ortiz et al. 2014, ApJ 781, 126



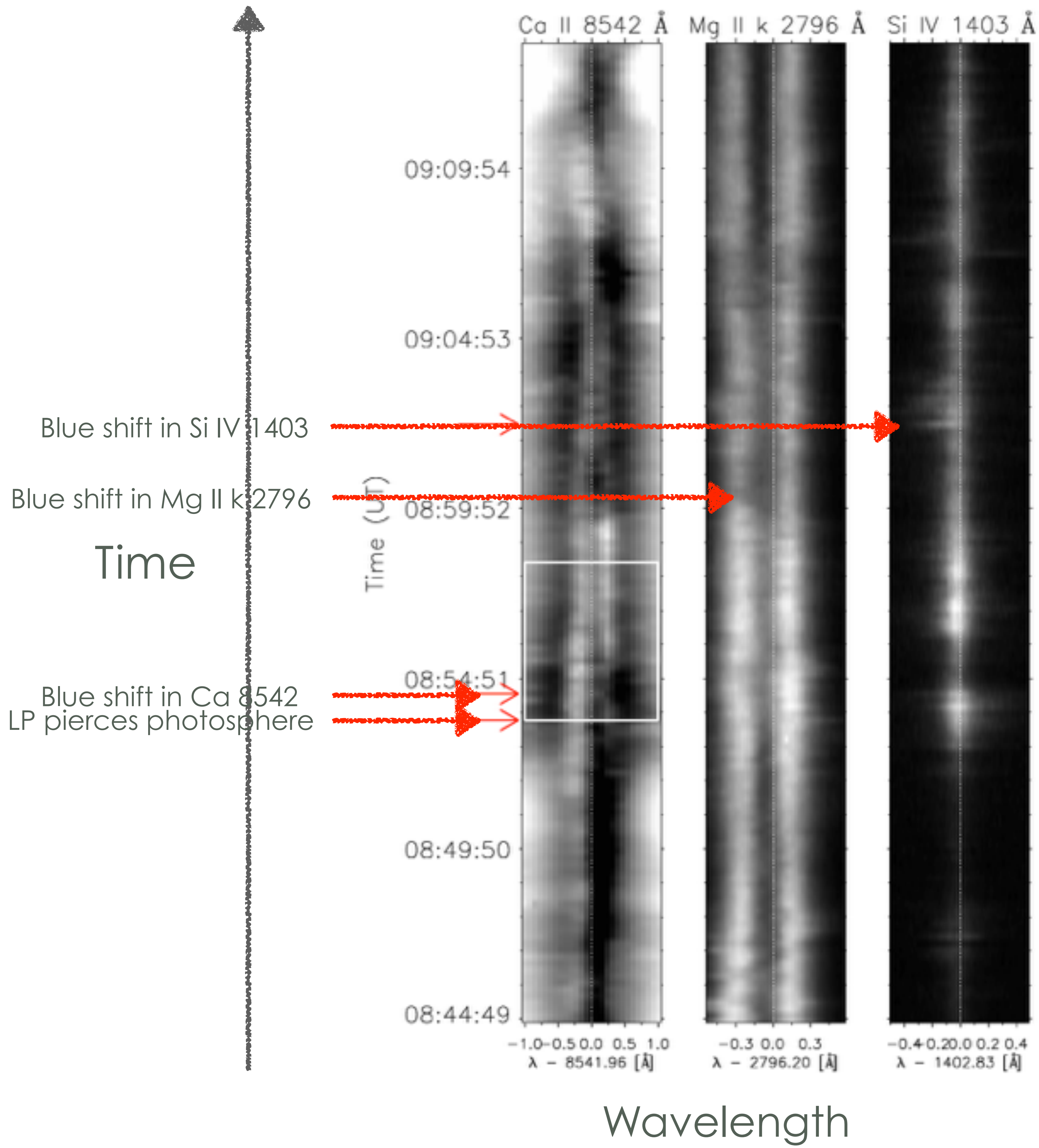
# What happens when bubble interacts with "ambient" atmosphere? Use of SST and IRIS



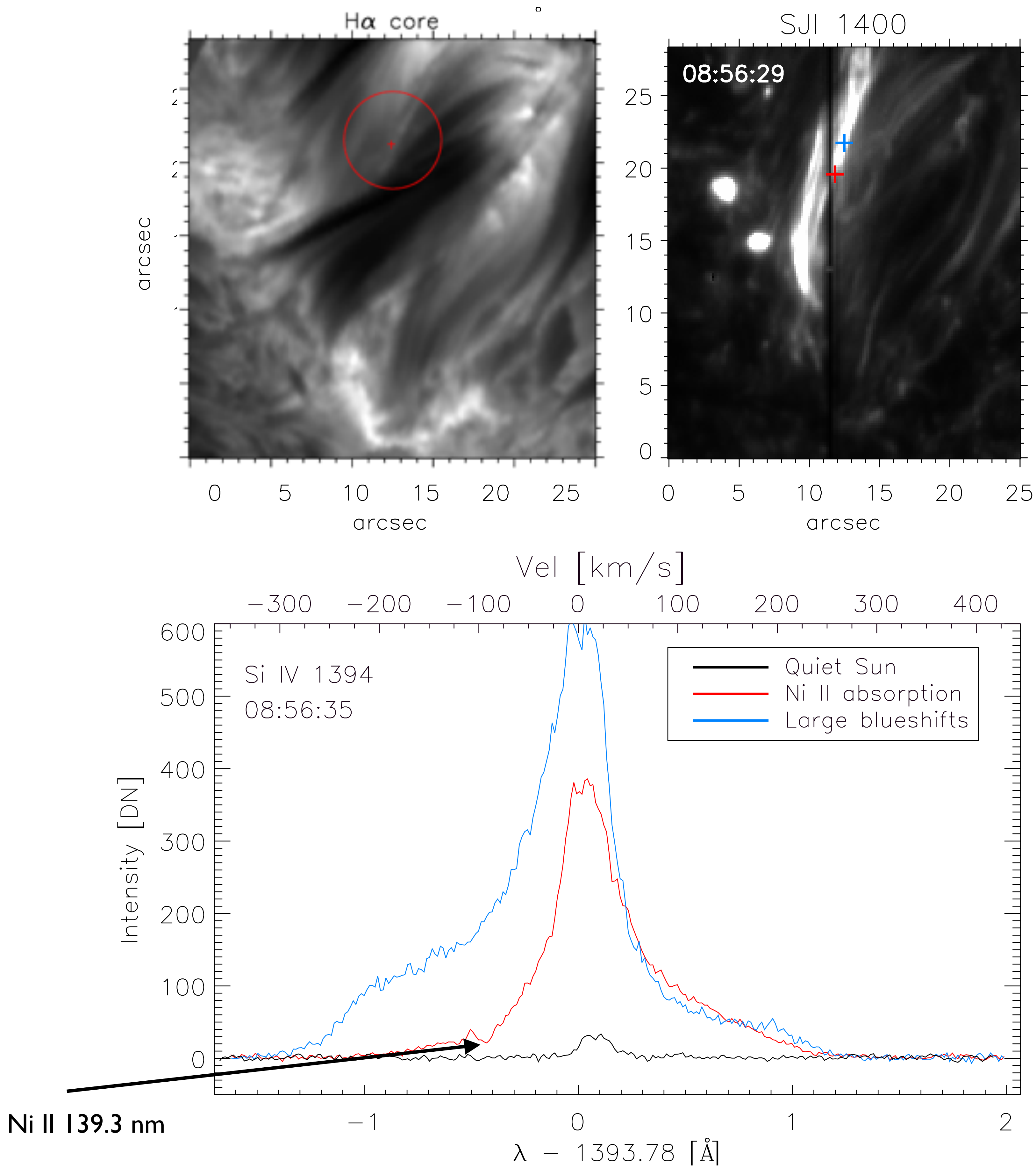

Configuration of the magnetic field lines at 08:54:58 UT

Ortiz et al. 2015, in prep

Time-sliced spectra at highlighted pixel: history of event #2

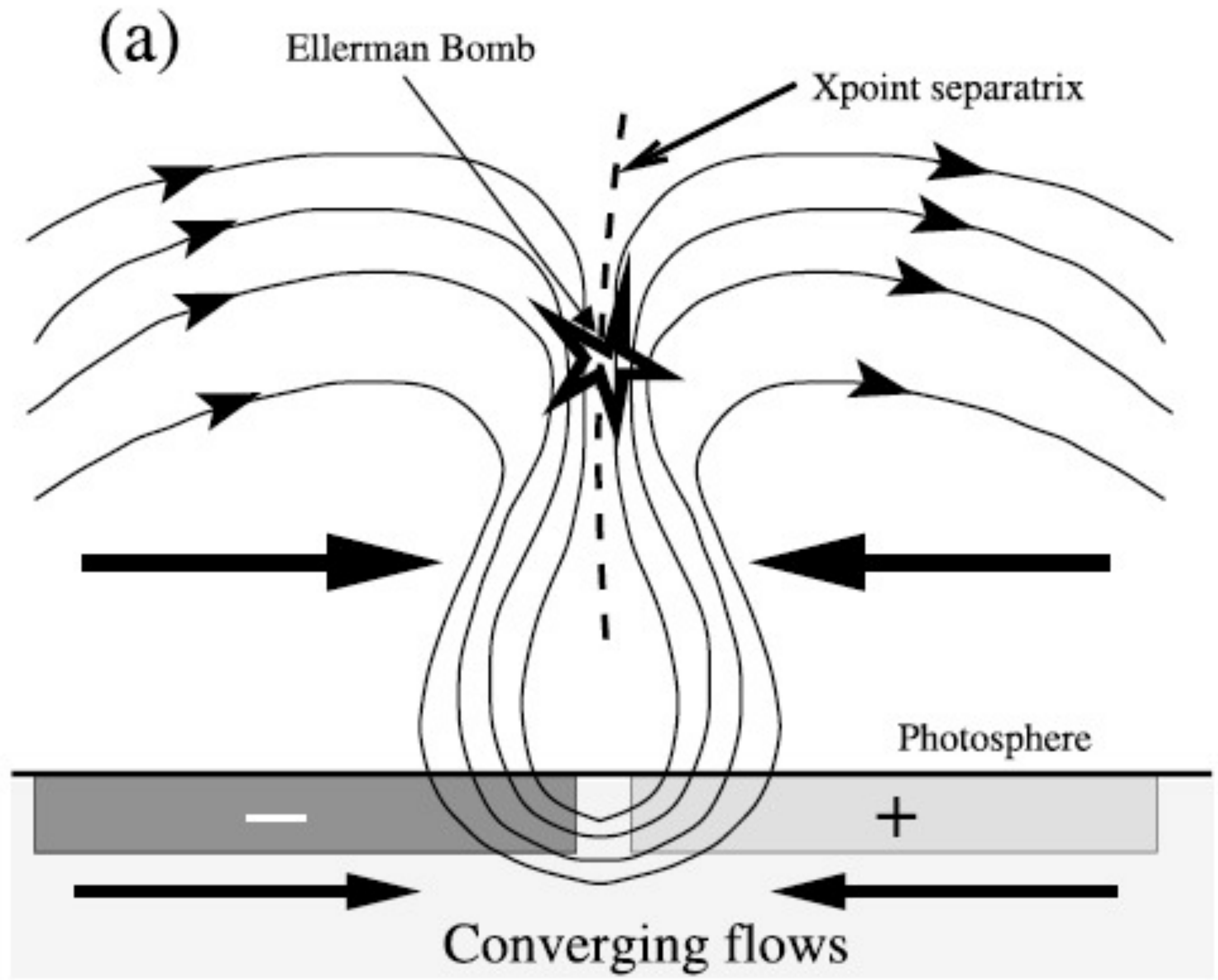



Ortiz et al. 2015, in prep

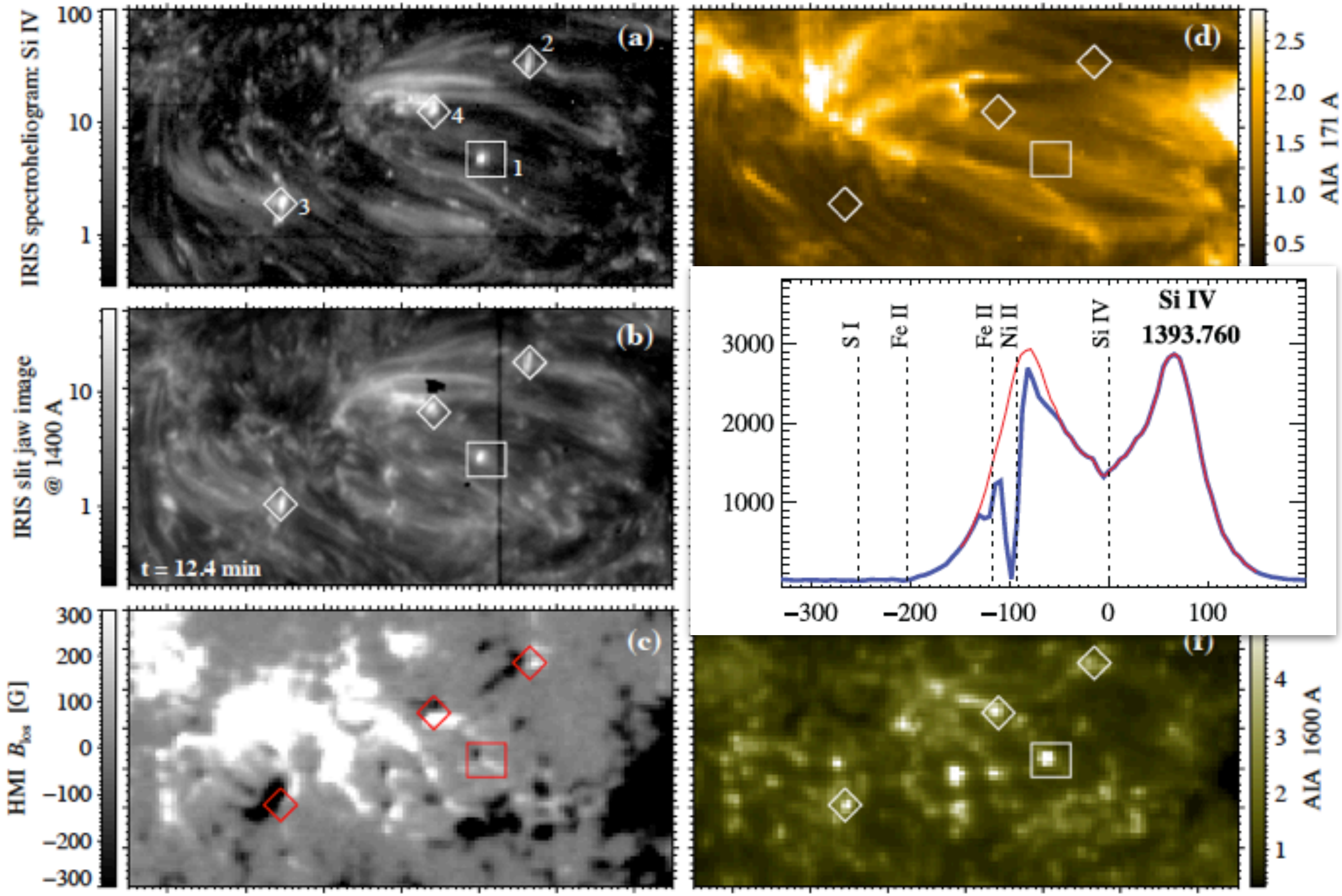


Hα core
arcsec
arcsec
SJI 1400
08:56:29
arcsec
Vel [km/s]
Si IV 1394
08:56:35
Quiet Sun
Ni II absorption
Large blueshifts
Intensity [DN]
λ − 1393.78 [Å]
Ni II 139.3 nm

# http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons/

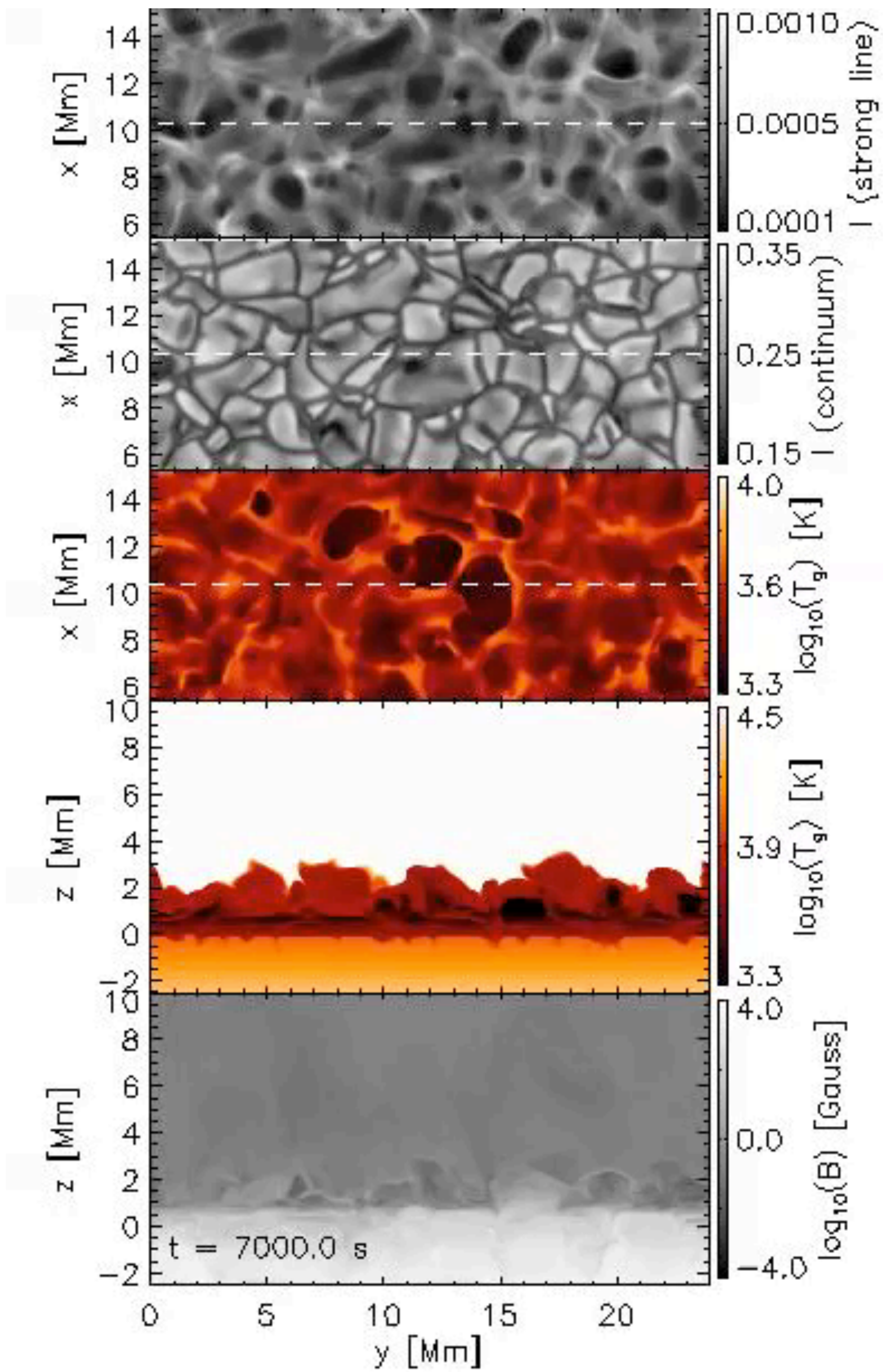



Georgoulis, M. K., Rust, D. M., Bernasconi, P. N., and Schmieder, B., "Statistics, morphology, and energetics of Ellerman bombs," ApJ 575, 506 (2002).




# Ellerman bombs and IRIS bombs

Hardi Peter 2014, "Hot explosions in the cool atmosphere of the Sun", Science 346, C315



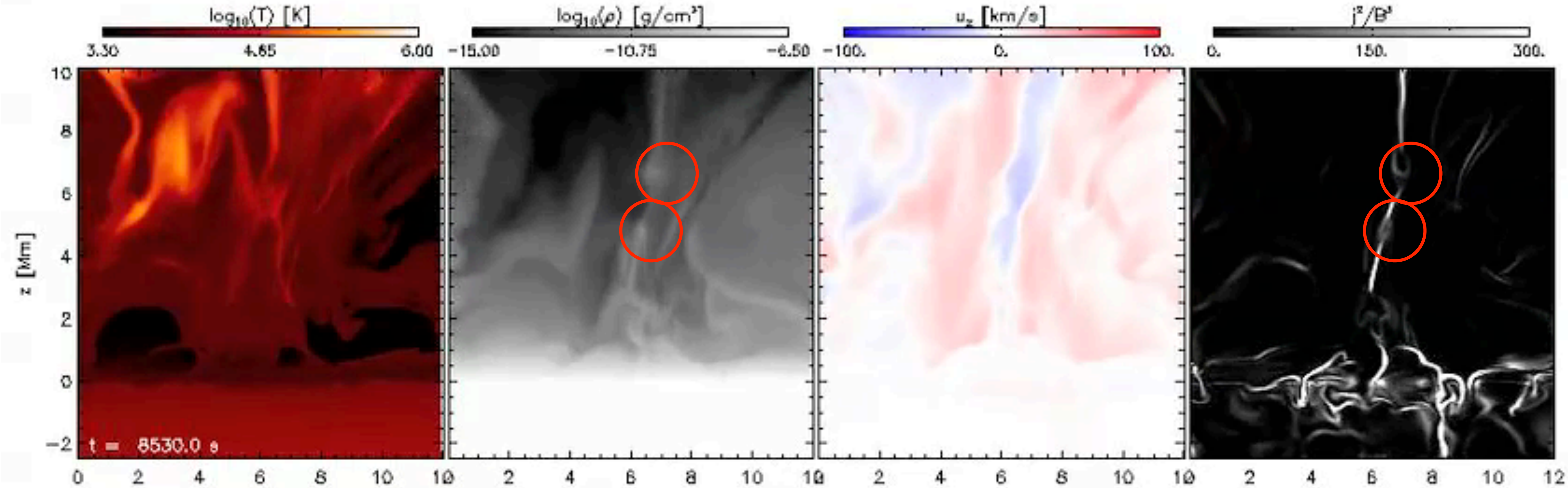

Large oblong granules and bright points appear as emerging photospheric field grows strong.

(Low) chromosphere intensity and contrast increase.

Horizontal panel at z=700 km above photosphere: Acoustic shock structure severely modified by magnetic field as waves are expelled from bubbles.

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.



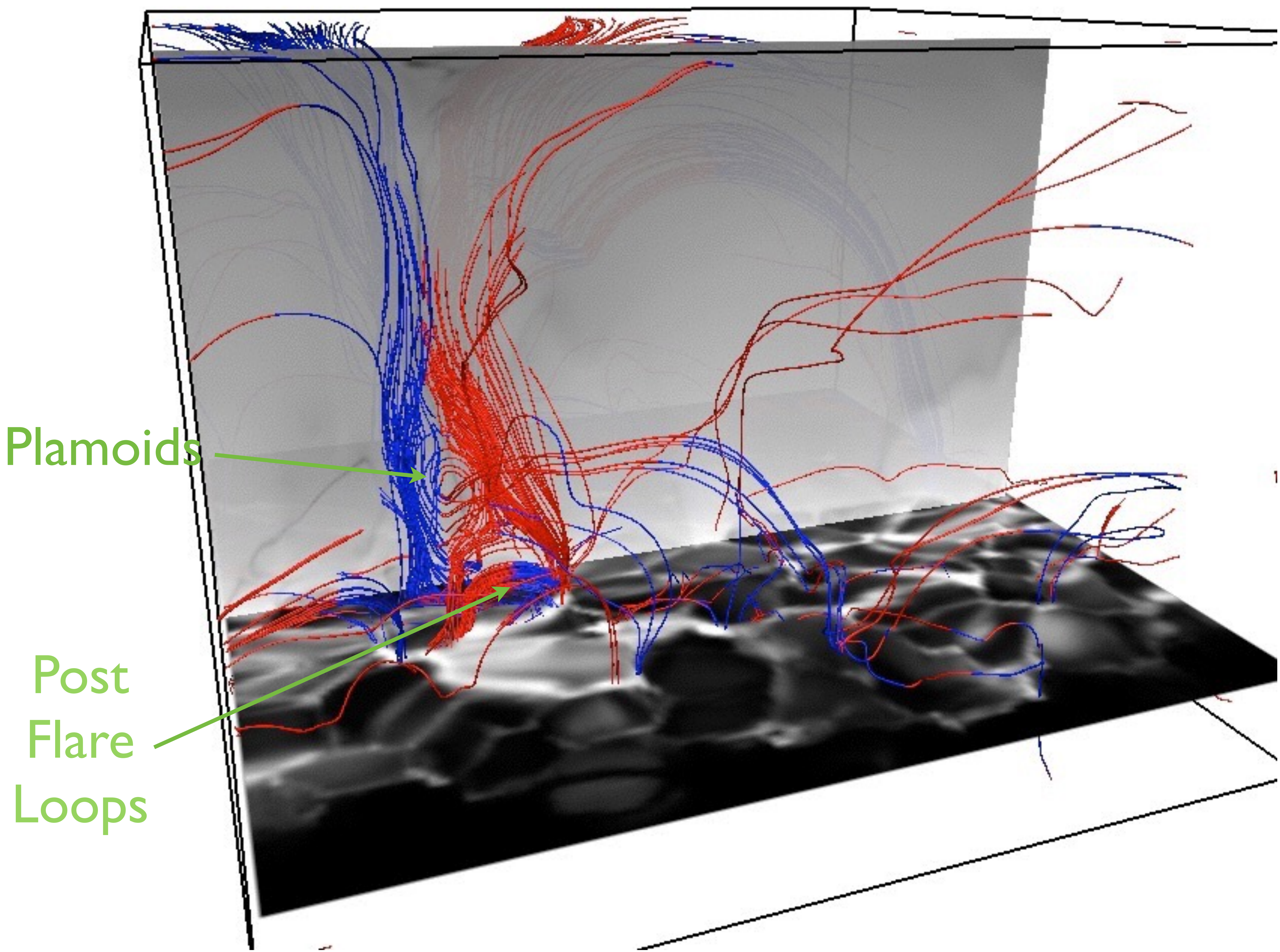

Long and thin current sheet develops, subject to tearing mode instability: Plasmoids form along current sheet, with x-type reconnection between.

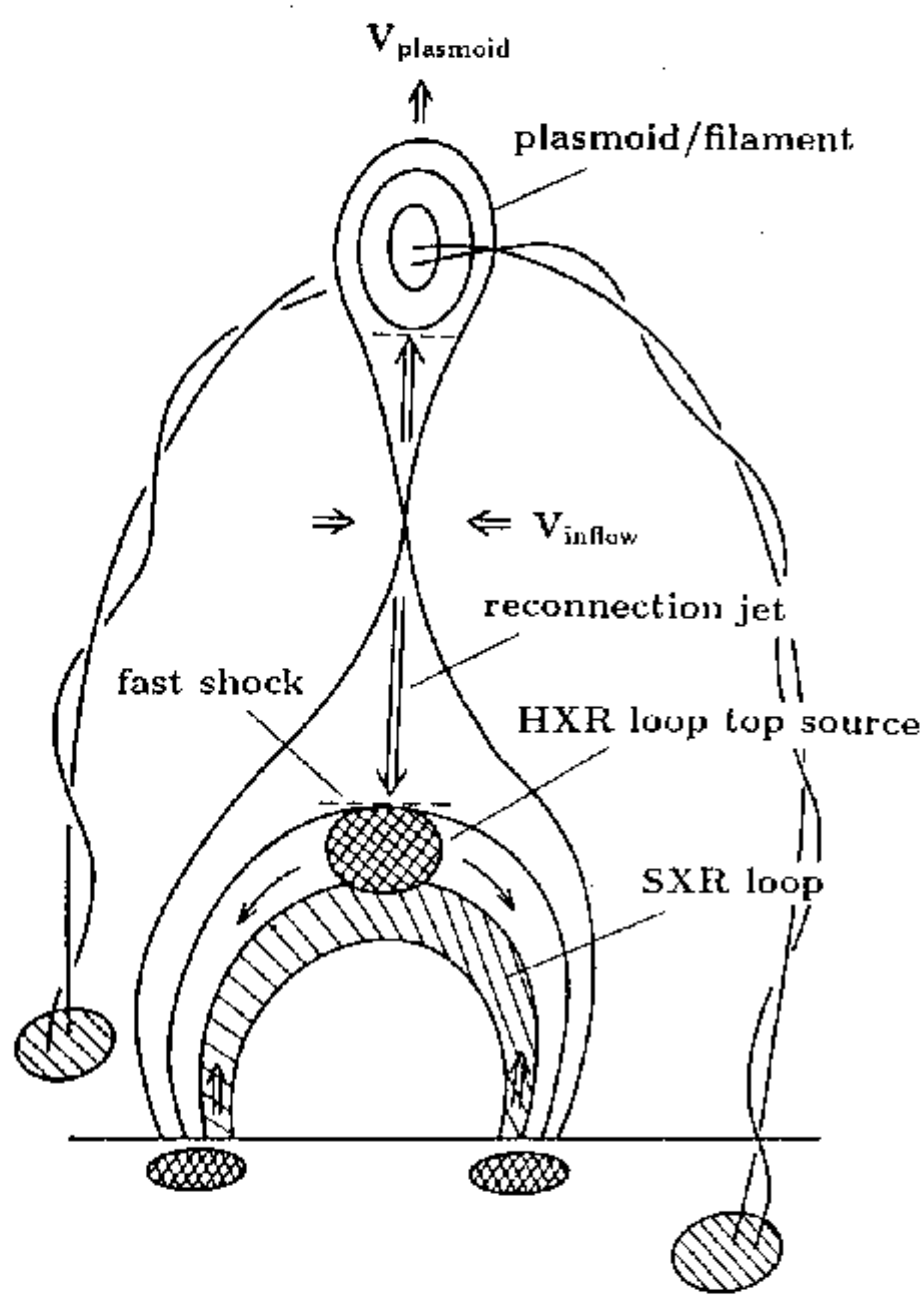
Jets with velocities of 200 km/s appear. Plasma is heated to 2.5 MK (or more) along current sheet.

Reconnected field lines form small post flare loop, heated at top by collision of downward reconnection jet with local plasma.

Newly reconnected field lines successively pile up on post flare loop, which adopts cups like shape.

Lifetime of event is of order 100 s and energy release $10^{25}$ - $10^{26}$ erg.


Plamoids
Post
Flare
Loops




K. Shibata, K., S. Masuda, M. Shimojo, H. Hara, T. Yokoyama, S. Tsuneta, T. Kosugi, and Y. Ogawara, "Hot-Plasma Ejections Associated with Compact-Loop Solar Flares," ApJ 451, L83, 1995.

# Joined plasmoids along filamentary current sheet - and small two ribbon flare

THE ASTROPHYSICAL JOURNAL LETTERS, 788:L2 (6pp), 2014 June 10 ARCHONTIS & HANSTEEN

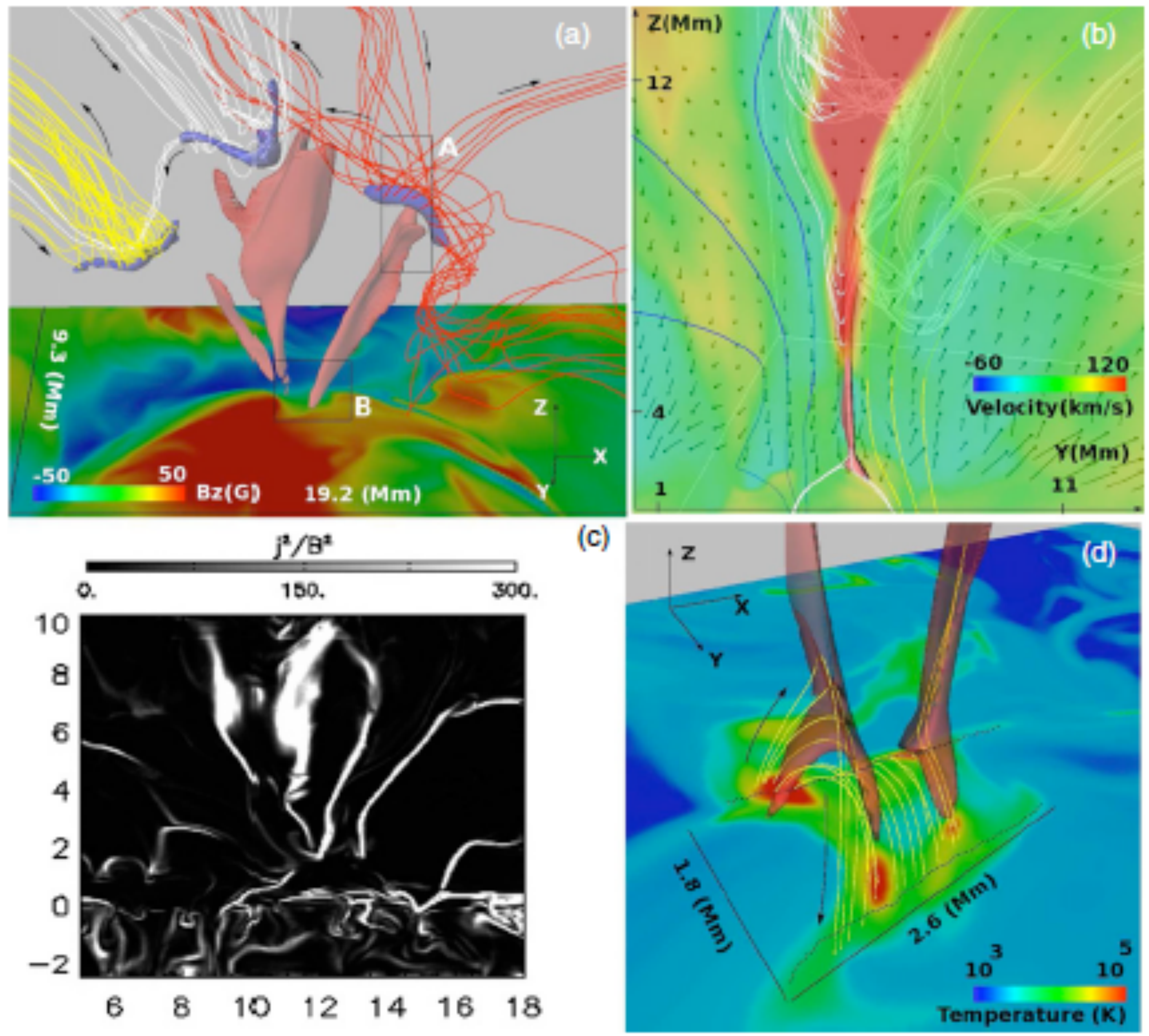
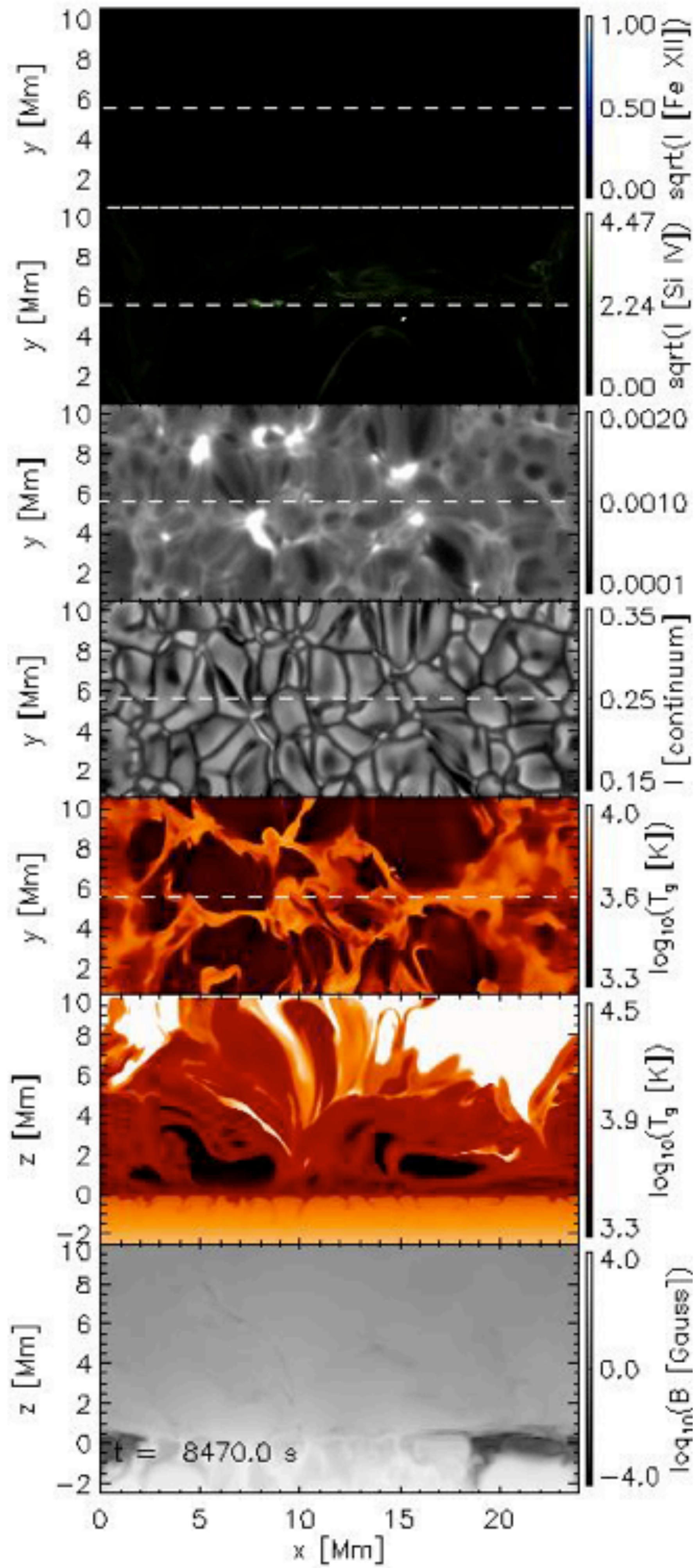



**Figure 4.** (a) Intermittent heating (isosurfaces with $T \geqslant 5.5 \times 10^5$ K; red) at the interface and the erupting plasmoids (isosurfaces of $\rho \approx 10^{-12}$ g cm$^{-3}$; blue) at $t = 8800$ s. The (black) arrows show the direction of the field along the field lines. The horizontal slice is the $B_z$ distribution at $z = 3.14$ Mm, demonstrating that the heating occurs between opposite polarity fields. (b) Close-up of the region around the plasmoid, which is outlined by frame A in panel (a). The $B$-field vector (arrows) shows the highly sheared field across the interface. Field lines (yellow; blue belong to the interacting loops) reconnect and a fast jet is emitted underneath the erupting plasmoid (twisted field lines, white) and above the flare loops (lower white field lines). (c) Two-dimensional vertical cut at the interface ($y = 5.6$ Mm) showing $J^2/B^2$. Time is $t = 8850$ s. (d) Close-up of the temperature isosurfaces (framed at inset (B), panel (a)). The cusp-shaped reconnected field lines (in yellow) show the topology of the post-flare loops. The dashed lines indicate the length of the small two-ribbon flare.



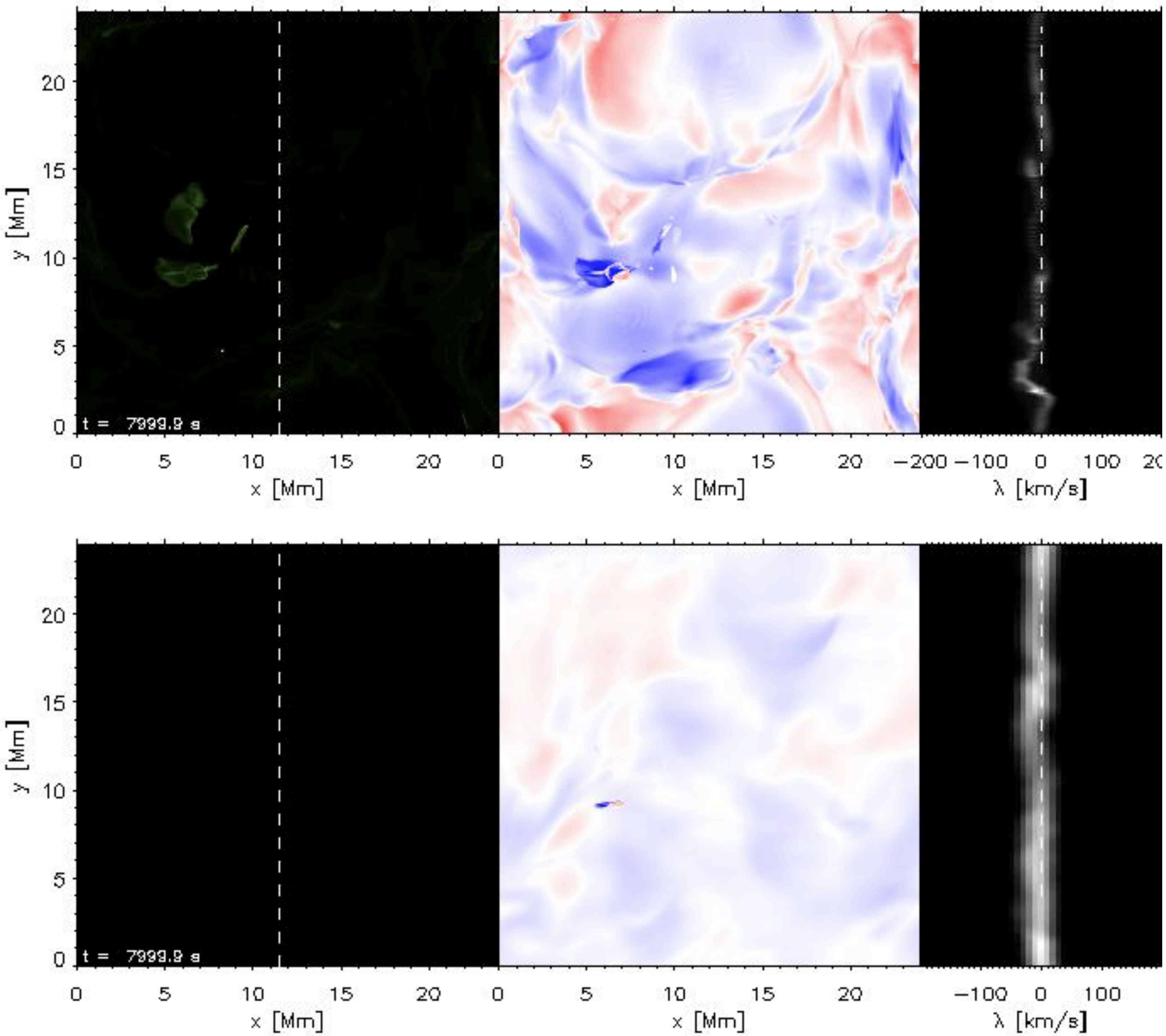

# Transition region and coronal observables

- Highly episodic emission along spine of current sheet
- Forms appearance somewhat reminiscent of "two ribbon flare"

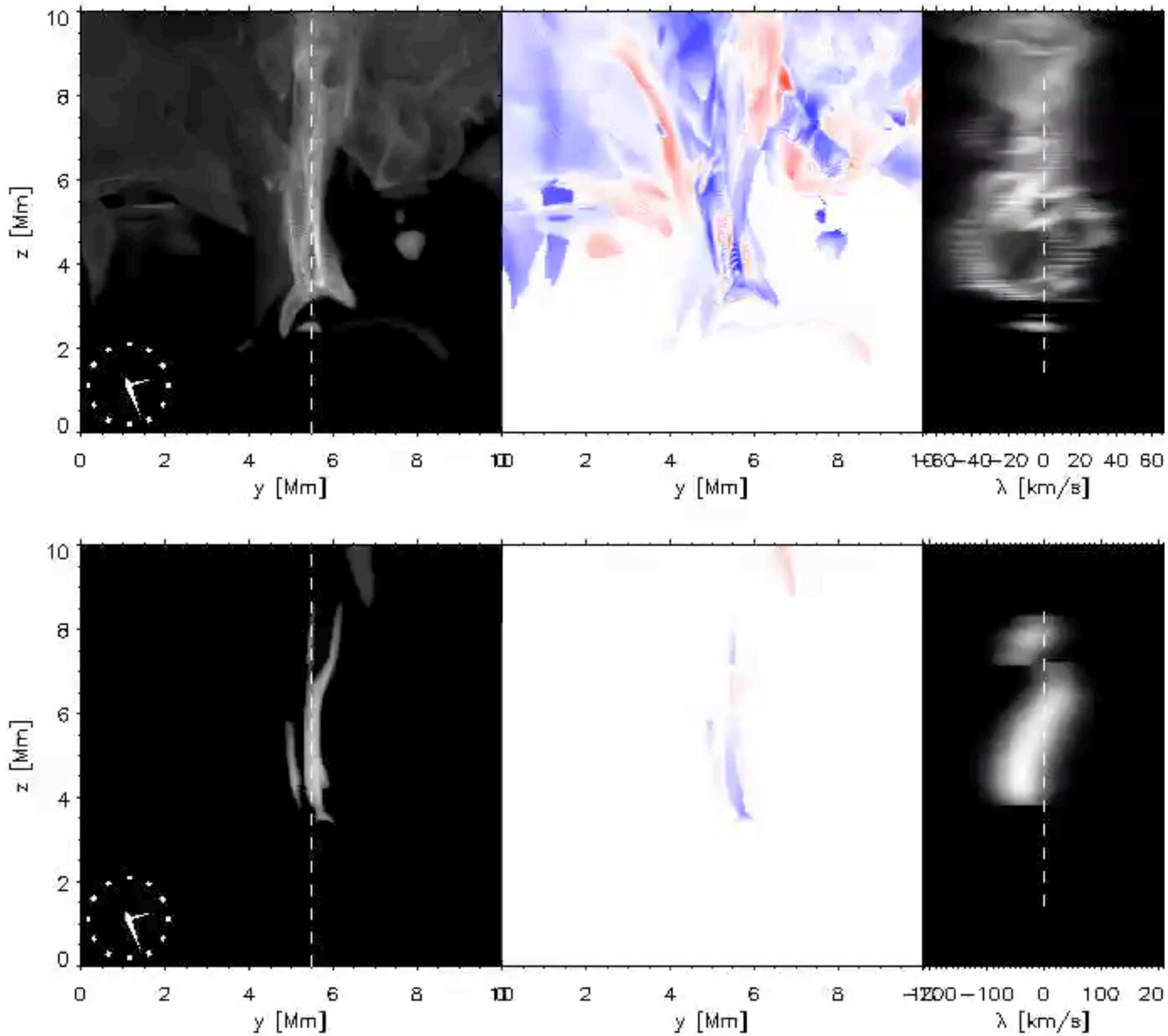
# Top view

Si IV
139.3 nm

Fe XII
19.5 nm

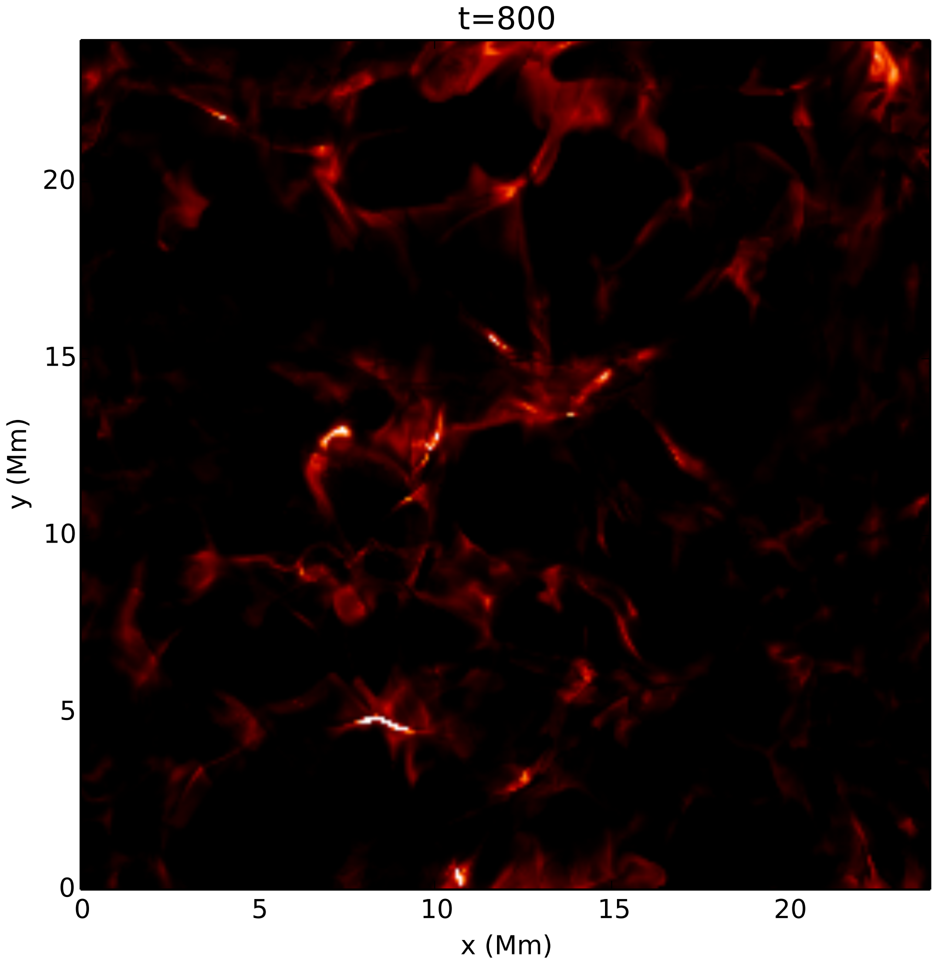


# Side view

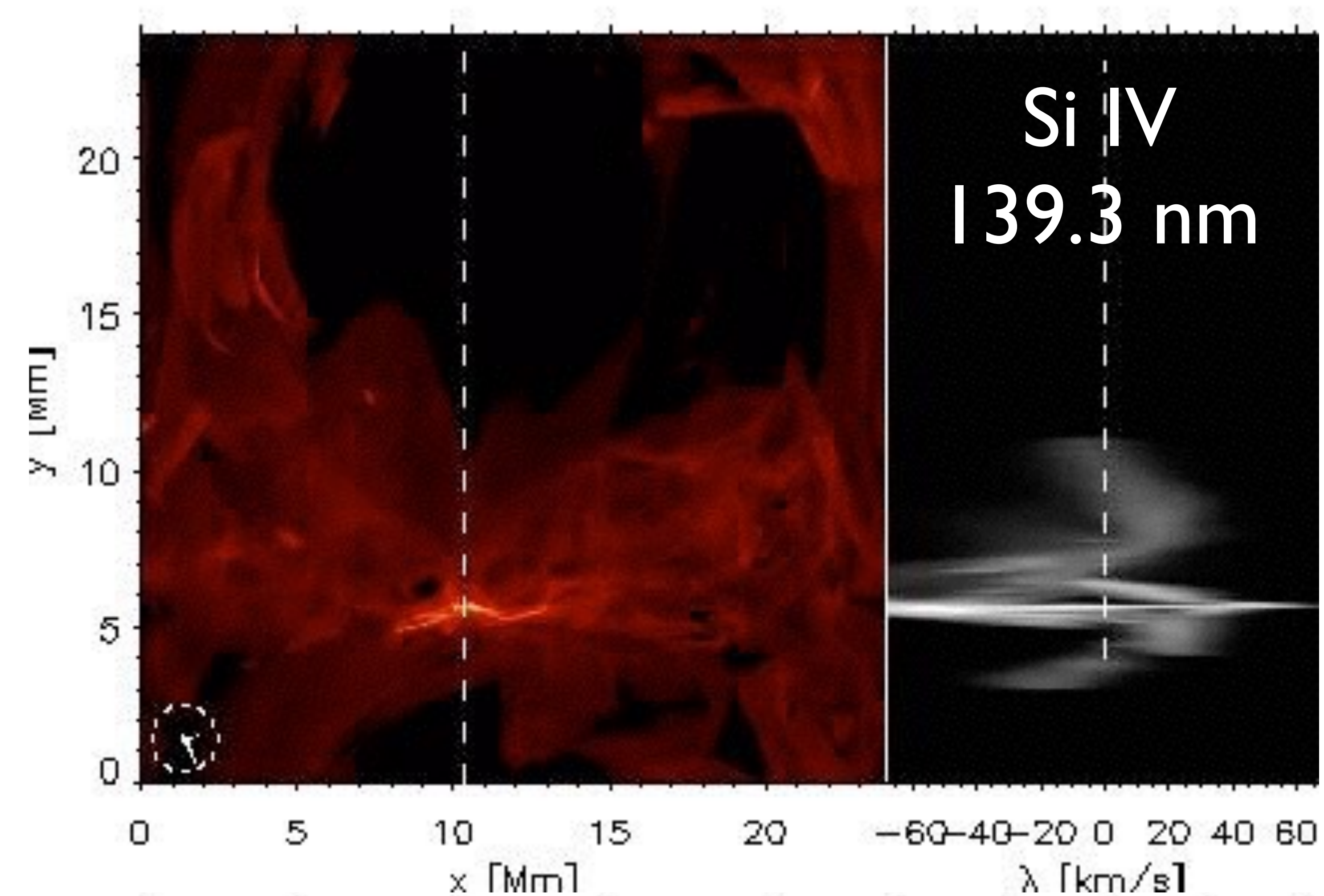


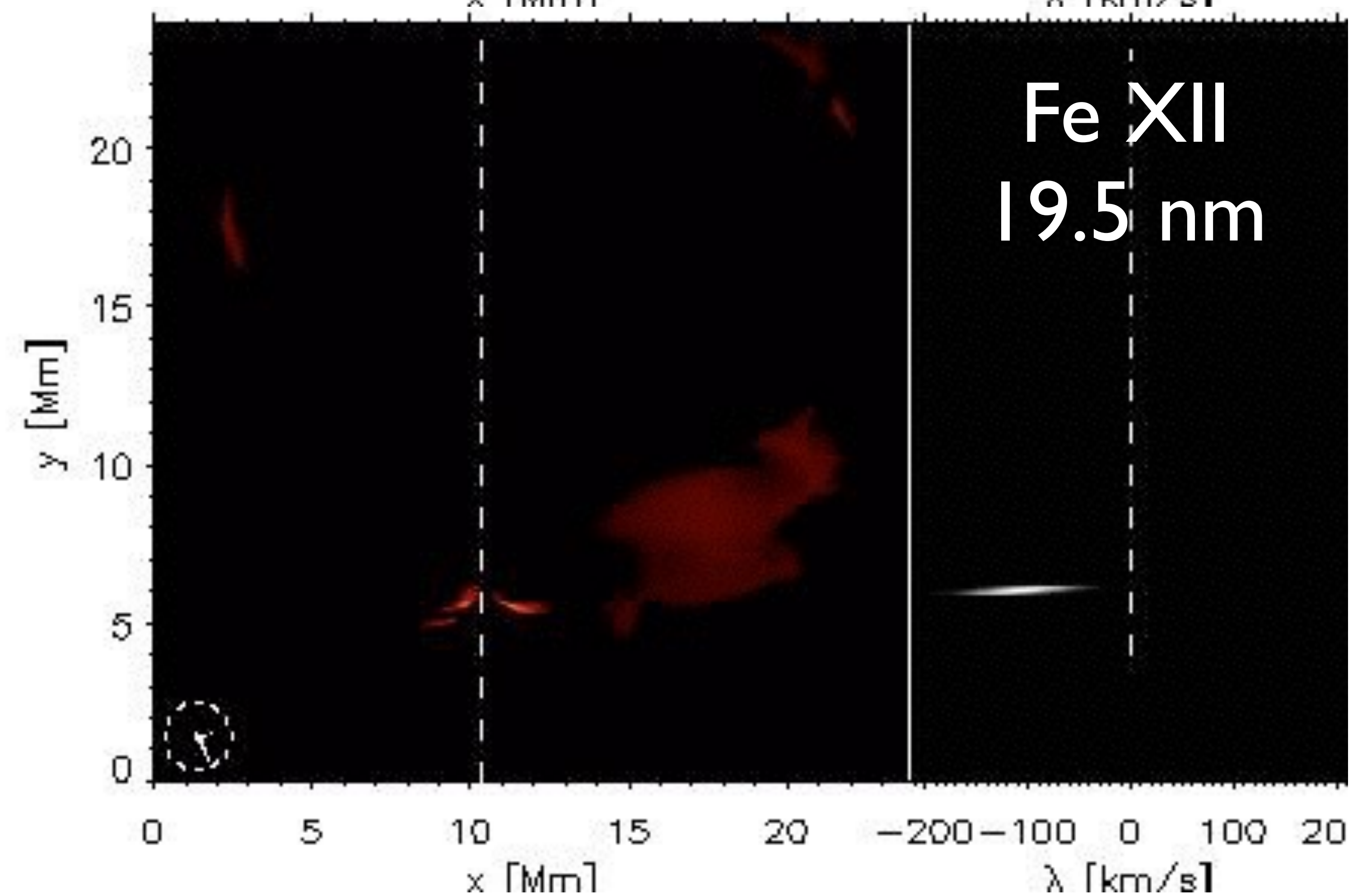

Si IV
139.3 nm

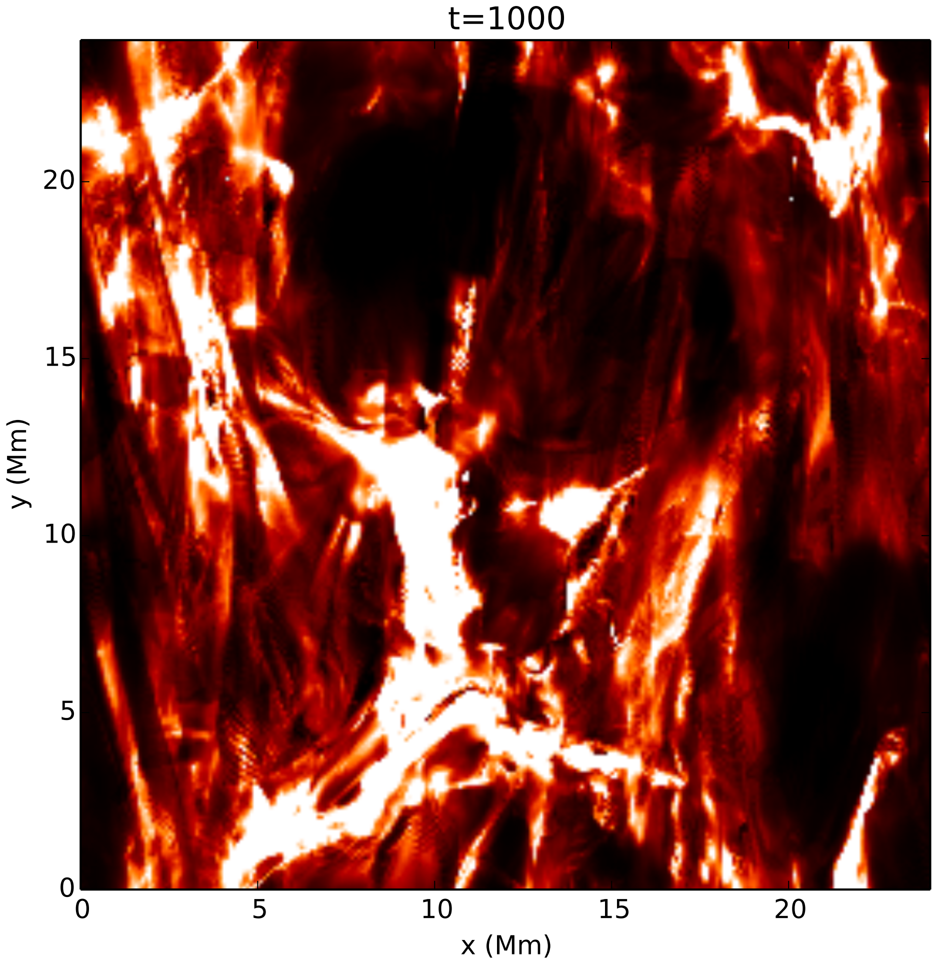
Fe XII
19.5 nm



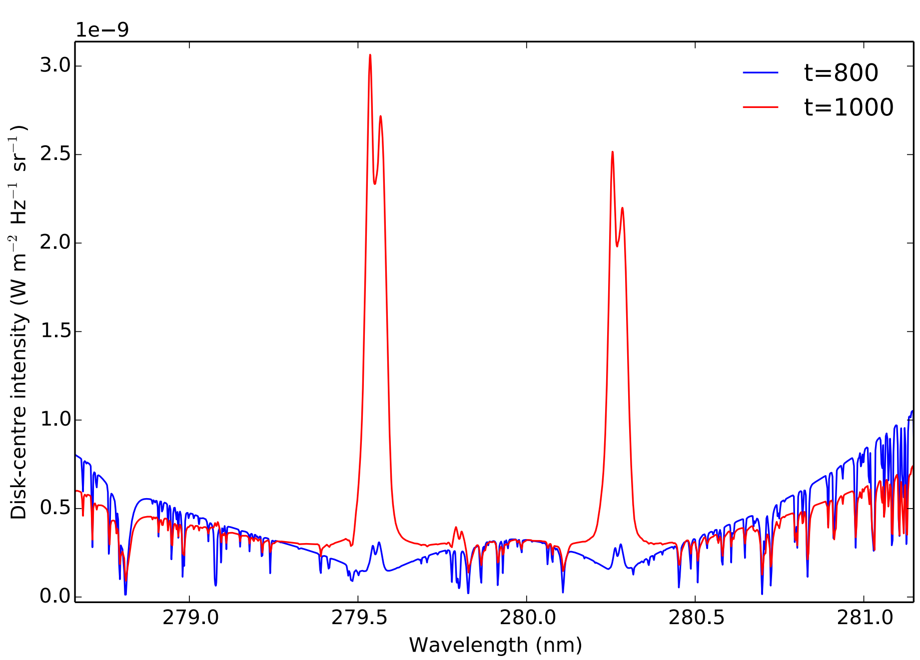

Mg II h
279.5 nm

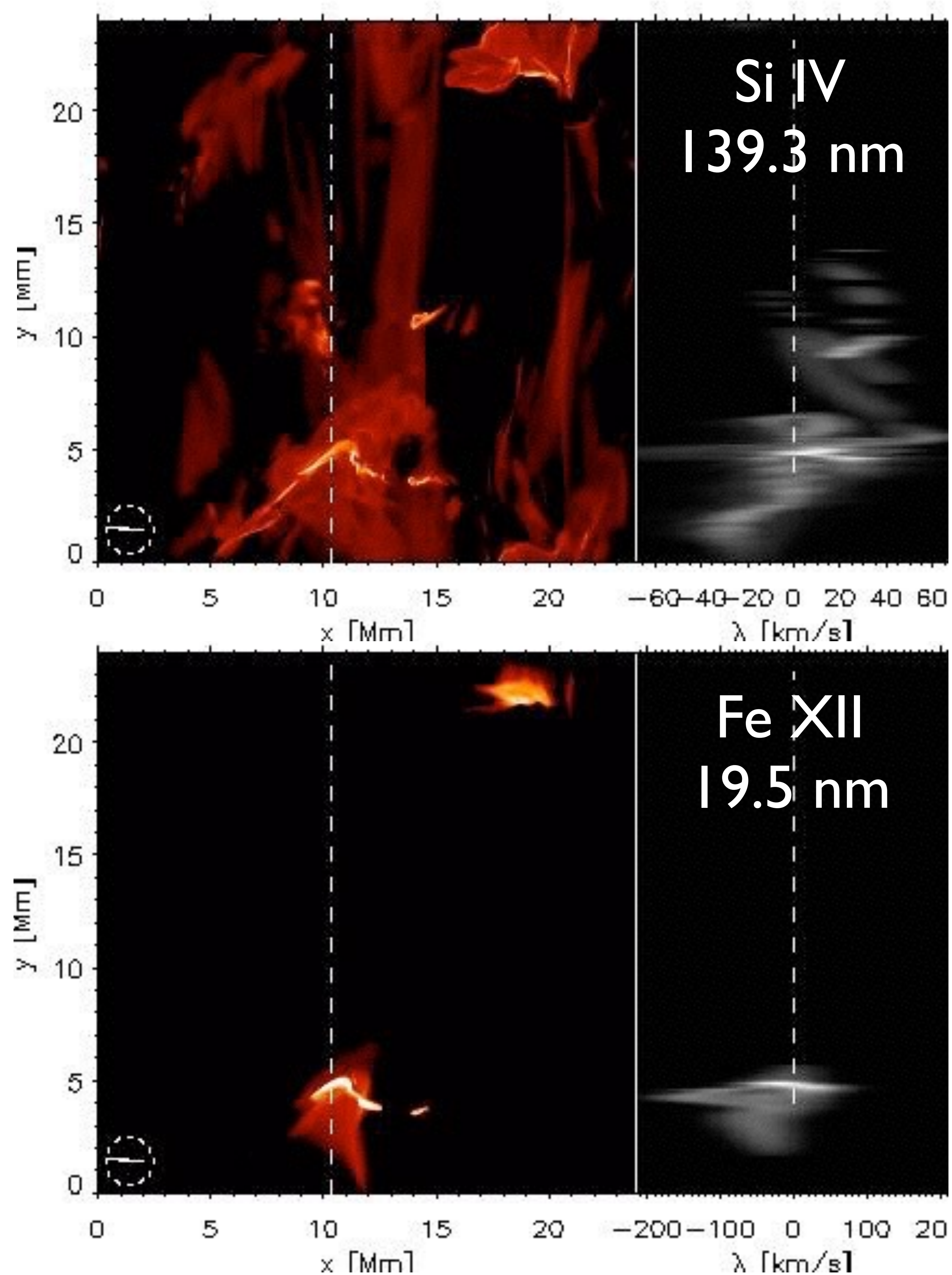




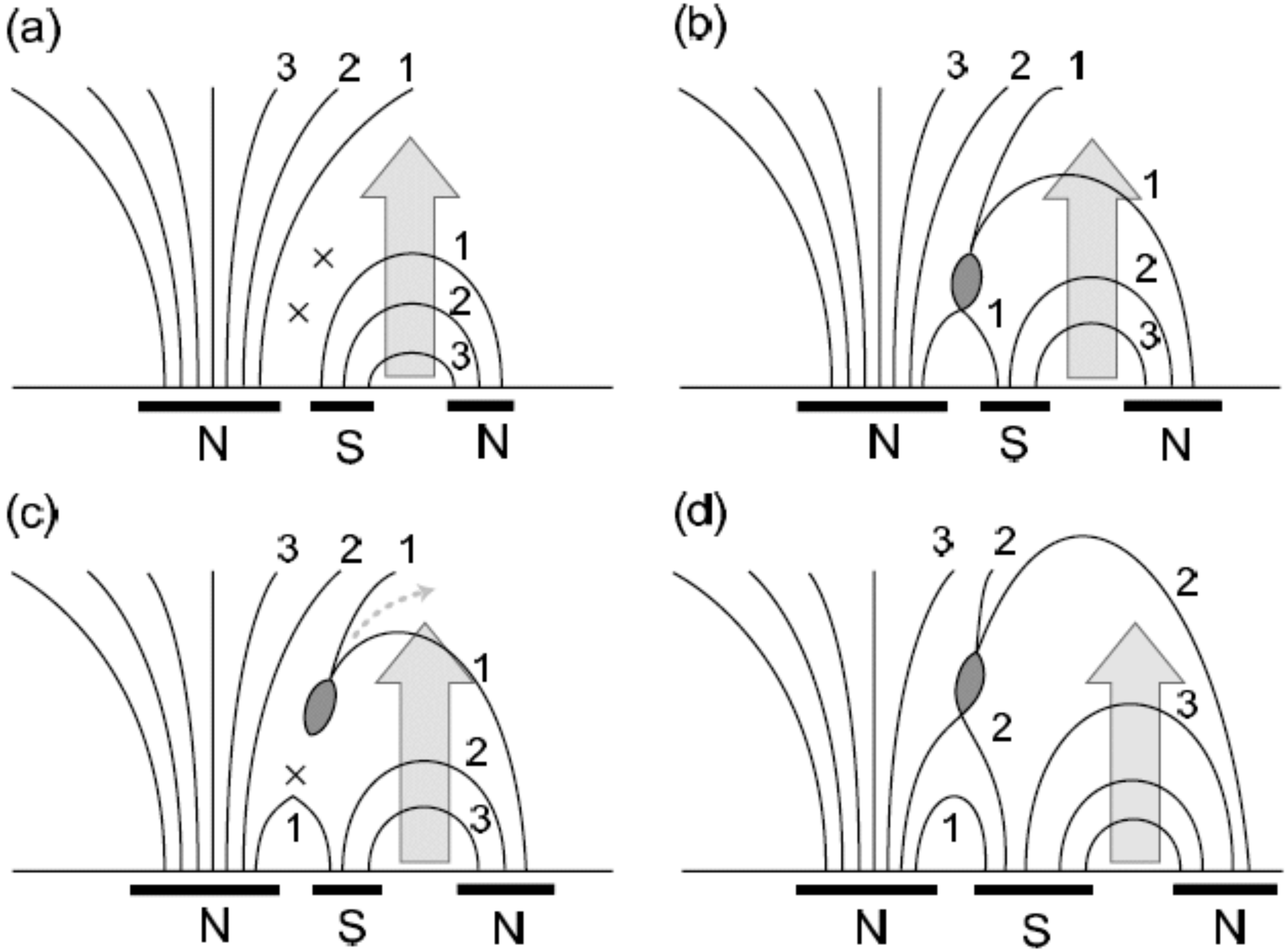

## Mg II h
## 279.5 nm



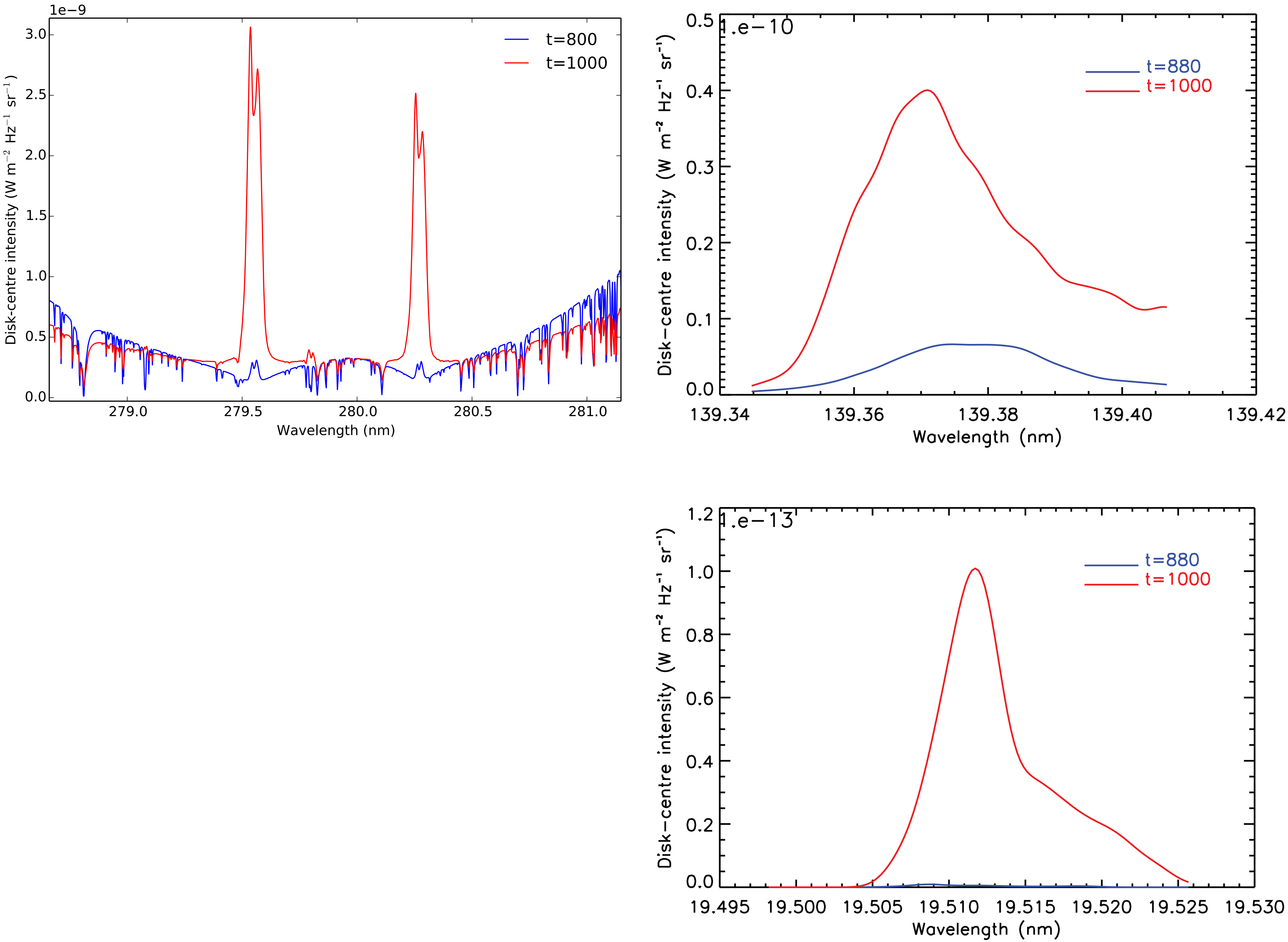



# Discussion/Summary

- Ejection of plasmoids leads to ‘patchy’ reconnection and thus spatially intermittent heating.
- Plasmoids share field lines, thus the eruption of one plasmoid initiates the sympathetic eruption of others.
- Eruption of plasmoids evolves into helical jets. Velocities comparable to local Alfvén speed.
- Average lifetime of individual small flares is of order 30 s - 3 minutes. Plasma heated to 1-6 MK.
- Some larger flares have energies of $O(10^{27})$ erg, but many events are superpositions of several small flares; $10^{25}$-$10^{26}$ erg.




Takasaki, H., Asai, A., Kiyohara, J., Shimojo, M., Terasawa, T., Takei, Y., and Shibata, K., ApJ 613, 592 (2004).



1e-9
t=800
t=1000
Disk-centre intensity (W m$^{-2}$ Hz$^{-1}$ sr$^{-1}$)
Wavelength (nm)
1.e-10
t=880
t=1000
Disk-centre intensity (W m$^{-2}$ Hz$^{-1}$ sr$^{-1}$)
Wavelength (nm)
1.e-13
t=880
t=1000
Disk-centre intensity (W m$^{-2}$ Hz$^{-1}$ sr$^{-1}$)
Wavelength (nm)

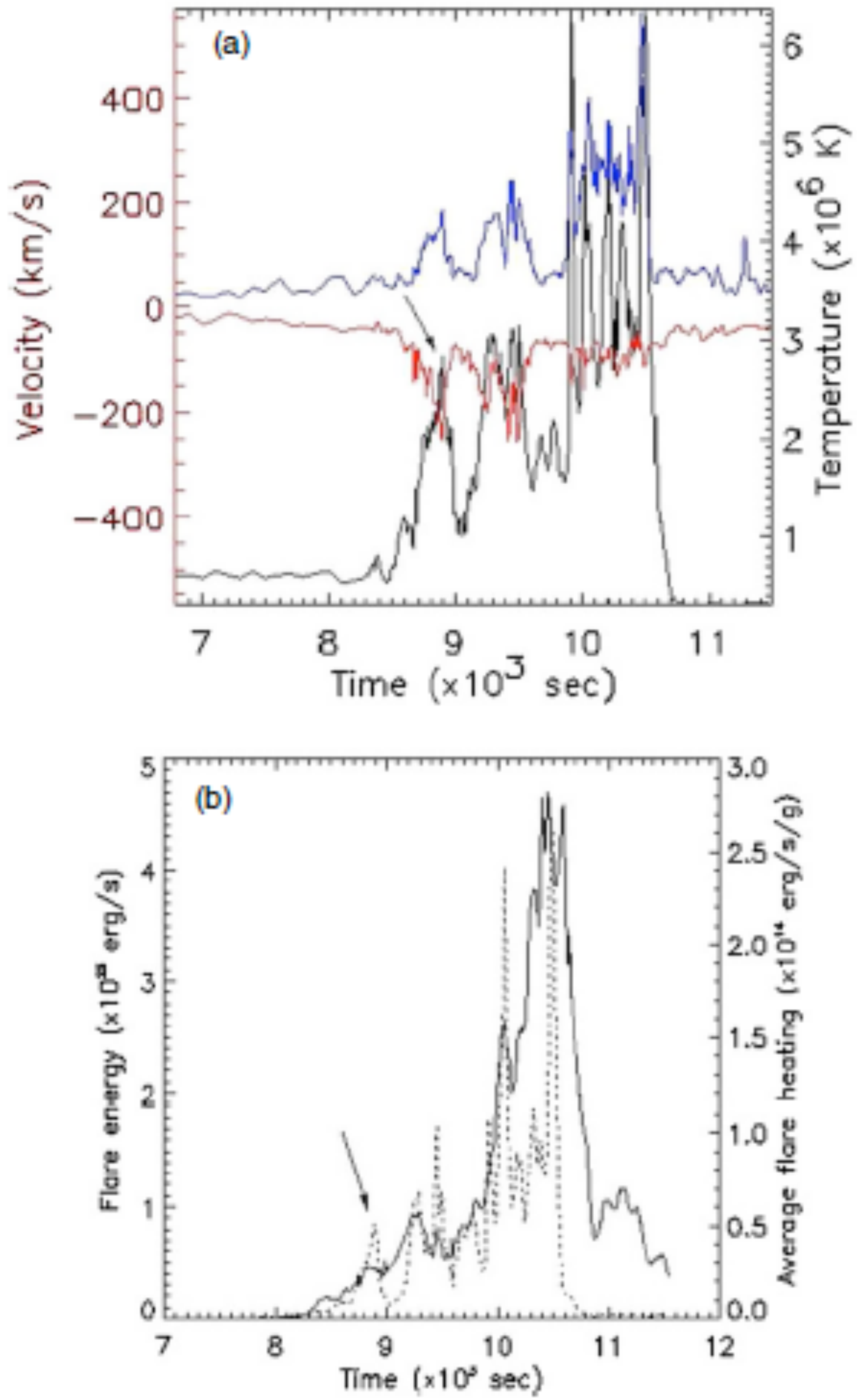



**Figure 5.** (a) Temporal evolution of maximum temperature and maximum (blue)/minimum (red) vertical velocity at the volume interface that surrounds the small flares: $x = [8.6, 12.9]$ Mm, $y = [2.4, 7.1]$ Mm, $z = [2, 10]$ Mm. (b) The same for the total flare energy per second (solid line) and the average flare energy per unit mass (dashed line). The arrow indicates the explosive reconnection event at $t = 8900$ s.