Flux emergence and the state of the outer solar atmosphere

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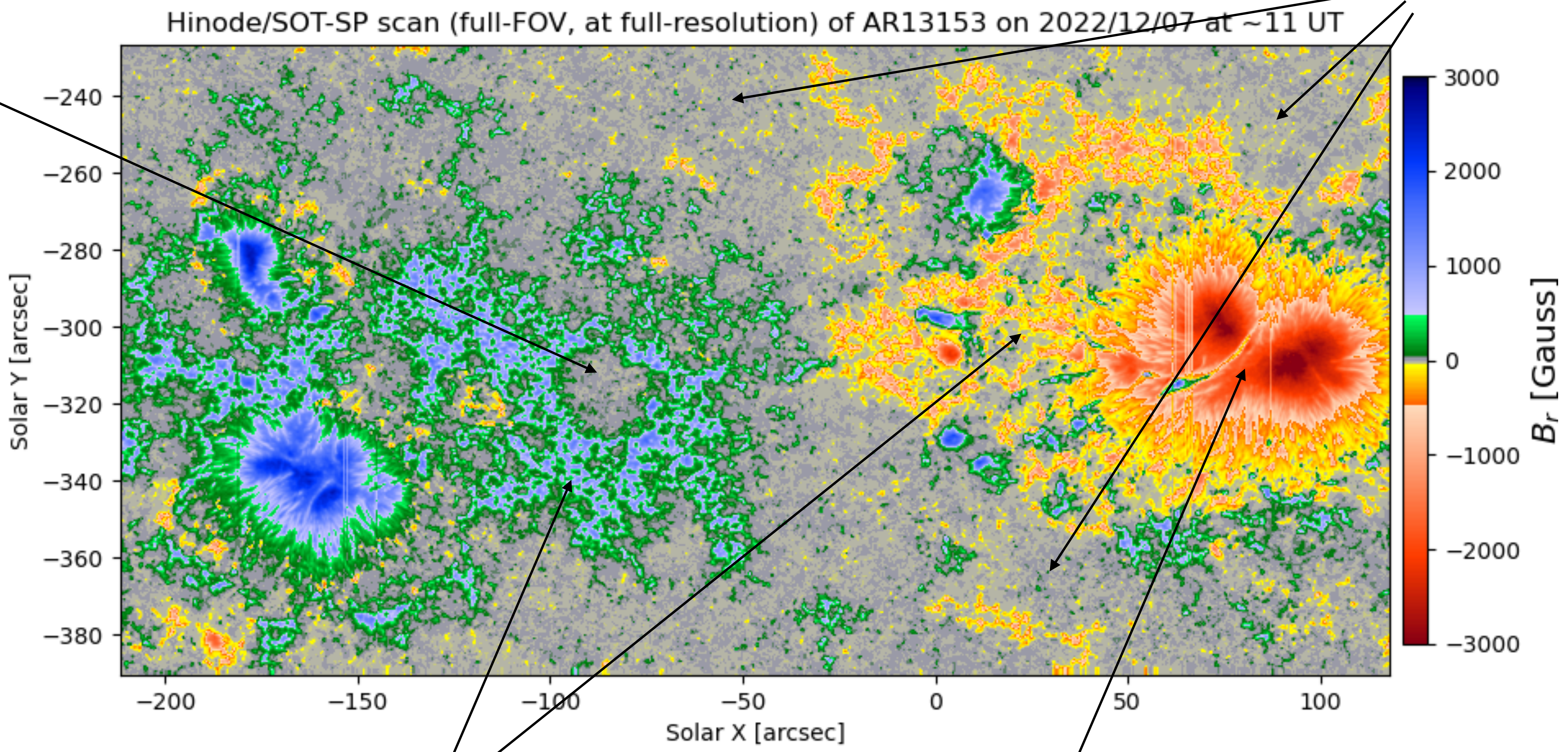
February 28, 2023 Longyearbyen, Svalbard

R C S

Field components; full-FOV, full resolution Hinode/SOT-SP scan

Supergranulation; what sets the scale?

Granulation scale; set by surface dynamics



Plage; no longer connected to global field?

Spots; rooted > 20 Mm below near surface shear layer?

Dynamics; surface and convective flows

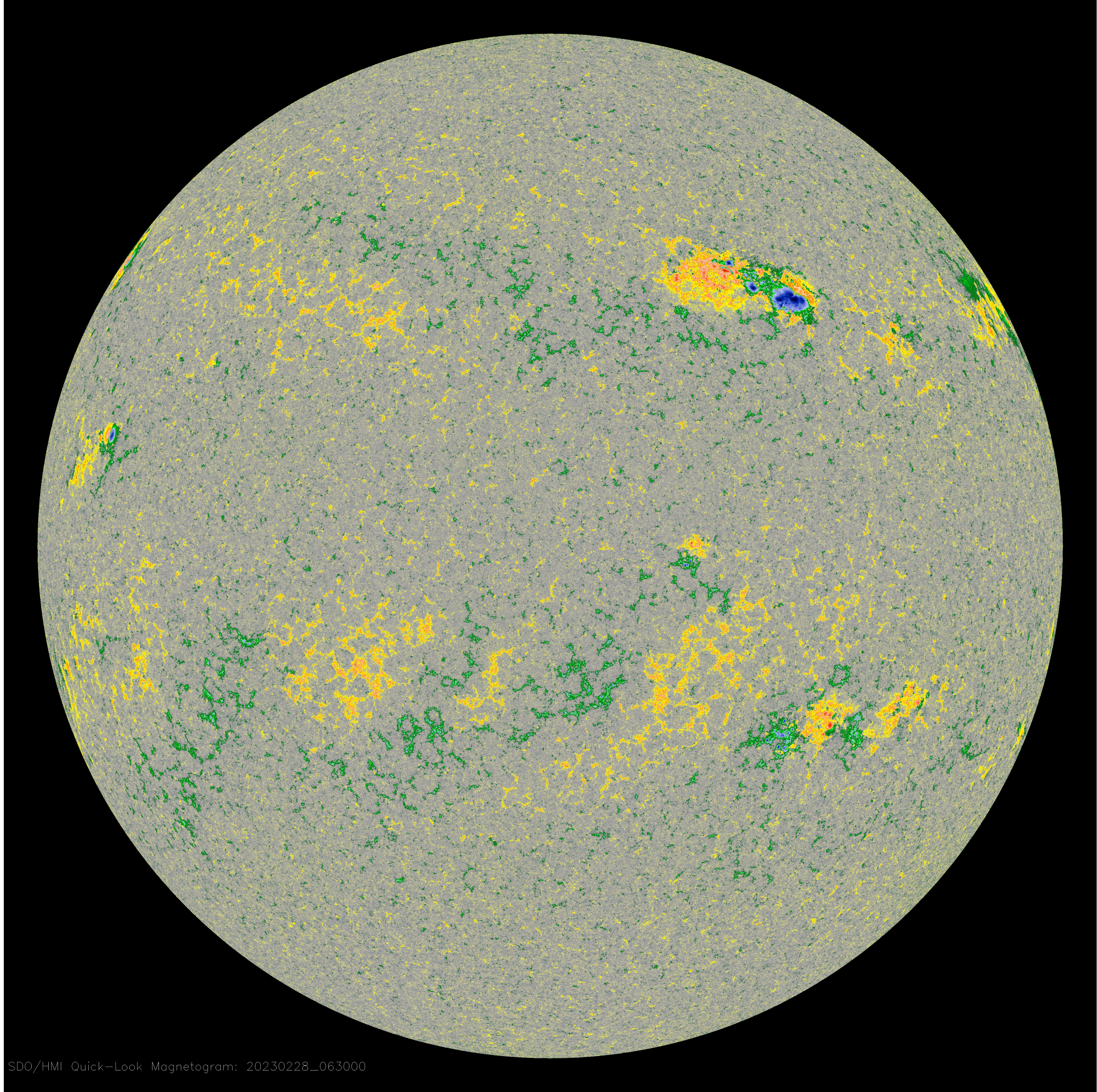
- **Surface flux transport models**

- Differential rotation
- Meridional circulation
- Diffusion
- Near surface shear layer (20 Mm?)

- Flux emergence
  - Active regions
  - Local "small scale"

What needs to be set for flux "box in the Sun" emergence Simulations?

- Field strength
- Depth, and height, of simulation
- Shape/topology
- Twist
- Associated velocities
- Pre-existing ambient field
  - QS
  - Plage
  - AR…
  - …or none?



ARs and spots

- Cheung et al. 2010 ApJ 720, Rempel & Cheung 2014, ApJ 785.
- Inserted a torus, at speed, with and without twist, without and with a torus aligned flow.
- Spectacularly successful! But… Problems with formation of penumbrae. (Now resolved?)
- Flow leads to significant asymmetry between “leading” and “following” spot
- Decay through turbulent diffusion

The Astrophysical Journal, 785:90 (17pp), 2014 April 20 doi:10.1088/0004-637X/785/2/90

NUMERICAL SIMULATIONS OF ACTIVE REGION SCALE FLUX EMERGENCE: FROM SPOT FORMATION TO DECAY

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ABSTRACT

We present numerical simulations of active region scale flux emergence covering a time span of up to 6 days. Flux emergence is driven by a bottom boundary condition that advects a semi-torus of magnetic field with 1.7×10^{22} Mx flux into the computational domain. The simulations show that, even in the absence of twist, the magnetic flux is able the rise through the upper 15.5 Mm of the convection zone and emerge into the photosphere to form spots. We find that spot formation is sensitive to the persistence of upflows at the bottom boundary footpoints, i.e., a continuing upflow would prevent spot formation. In addition, the presence of a torus-aligned flow (such flow into the retrograde direction is expected from angular momentum conservation during the rise of flux ropes through the convection zone) leads to a significant asymmetry between the pair of spots, with the spot corresponding to the leading spot on the Sun being more axisymmetric and coherent, but also forming with a delay relative to the following spot. The spot formation phase transitions directly into a decay phase. Subsurface flows fragment the magnetic field and lead to intrusions of almost field free plasma underneath the photosphere. When such intrusions reach photospheric layers, the spot fragments. The timescale for spot decay is comparable to the longest convective timescales present in the simulation domain. We find that the dispersal of flux from a simulated spot in the first two days of the decay phase is consistent with self-similar decay by turbulent diffusion.

Key words: convection – magnetohydrodynamics (MHD) – radiative transfer – sunspots
Online-only material: animations, color figures

The Astrophysical Journal Letters, 753:L13 (2pp), 2012 July 1 doi:10.1088/2041-8205/753/1/L13

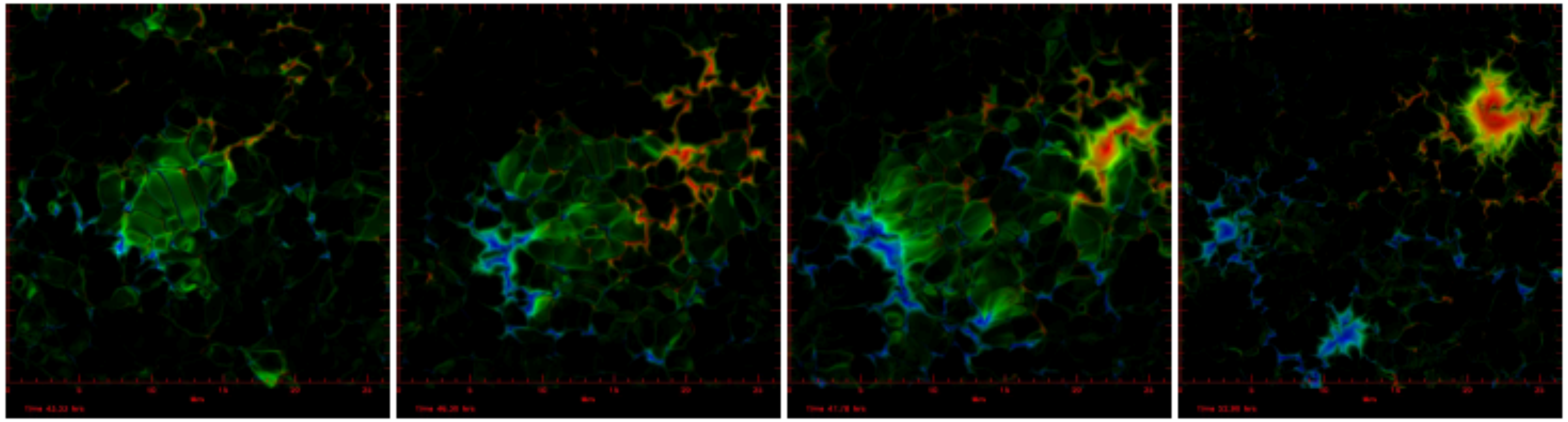

Fig. 3.— Image of horizontal (green) and vertical (blue and red) magnetic field. Magnetic field first emerges horizontally over granules followed by the appearance of vertical field at the granule edges. The orizontal field is quickly swept into the intergranular lanes.

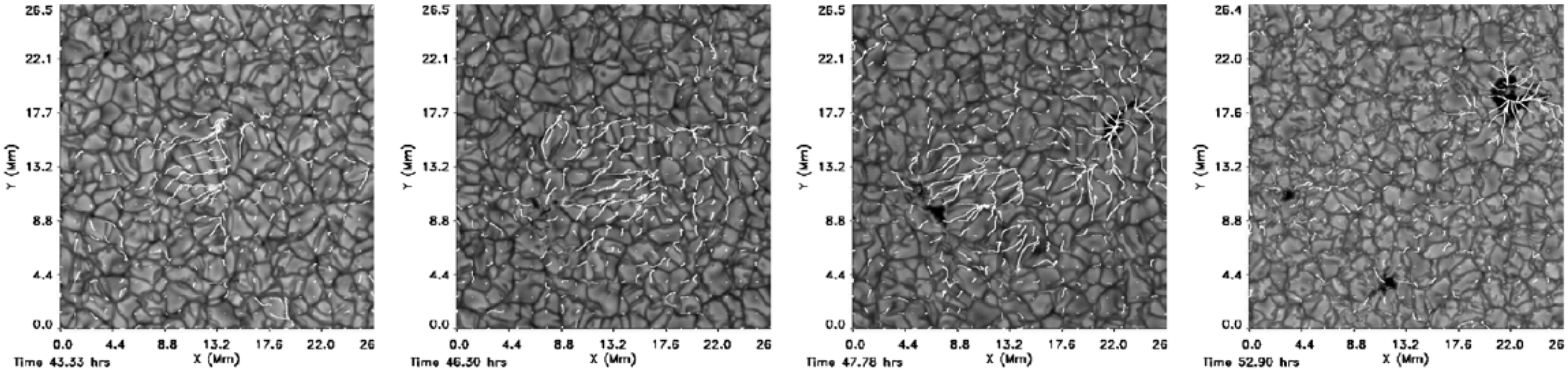

Figure 2. Continuum intensity image with horizontal magnetic field vectors superimposed. The images are clipped at $2.3 > I/\langle I \rangle > 0.5$. The actual range is [0.2, 2.5]. In the initial emergence the granules are elongated transverse to the horizontal field. Thereafter the granules appear elongated along the magnetic field direction.

Draft version October 12, 2018
Preprint typeset using LaTeX style AASTeX6 v. 1.0

Fan & Fang 2014, ApJ 789, 35

Chen et al. ApJ 2017, 846, 149.

EMERGENCE OF MAGNETIC FLUX GENERATED IN A SOLAR CONVECTIVE DYNAMO.

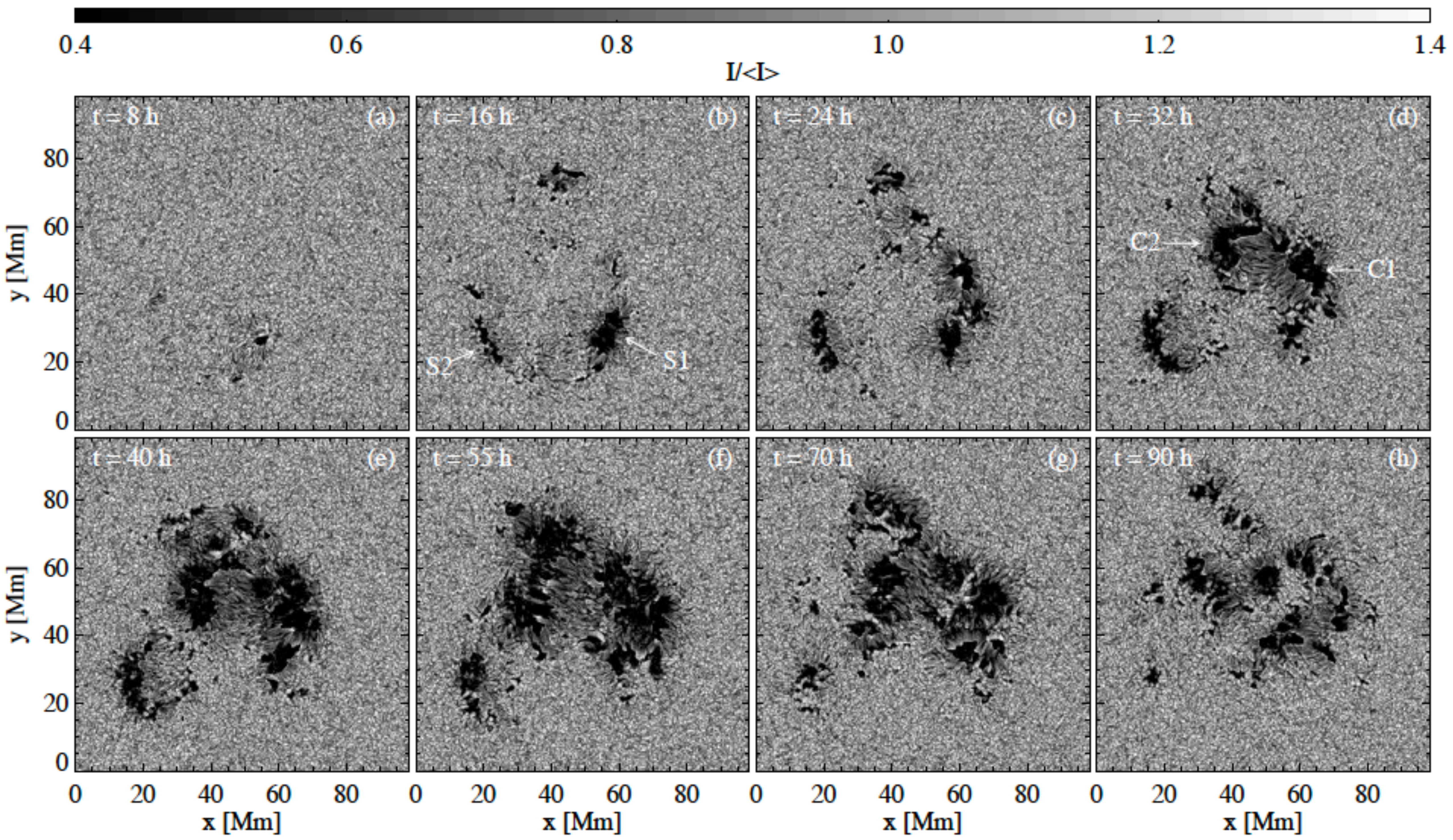

Figure 5. Continuum intensity images for the same time period as in Figure 4. The intensity is normalized by the mean intensity

“Correct” asymmetries set by properties of injected flux/flow

Draft version September 7, 2022
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A Comprehensive Radiative Magnetohydrodynamics Simulation of Active Region Scale Flux Emergence from the Convection Zone to the Corona

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ABSTRACT

We present a comprehensive radiative magnetohydrodynamic simulation of the quiet Sun and large solar active regions. The 197 Mm wide simulation domain spans from 18 (10) Mm beneath the photosphere to 113 Mm in the solar corona. Radiative transfer assuming local thermal equilibrium, optically-thin radiative losses, and anisotropic conduction transport provide the necessary realism for synthesizing observables to compare with remote sensing observations of the photosphere and corona. This model self-consistently reproduces observed features of the quiet Sun, emerging and developed active regions, and solar flares up to M class. Here, we report an overview of the first results. The surface magnetoconvection yields an upward Poynting flux that is dissipated in the corona and heats the plasma to over one million K. The quiescent corona also presents ubiquitous propagating waves, jets, and bright points with sizes down to 2 Mm. Magnetic flux bundles emerge into the photosphere and give rise to strong and complex active regions with over 10^{23} Mx magnetic flux. The coronal free magnetic energy, which is approximately 18% of the total magnetic energy, accumulates to approximately 10^{33} erg. The coronal magnetic field is clearly non-force-free, as the Lorentz force needs to balance the pressure force and viscous stress as well as drive magnetic field evolution. The emission measure from $\log_{10} T$=4.5 to $\log_{10} T$>7 provides a comprehensive view of the active region corona, such as coronal loops of various lengths and temperatures, mass circulation by evaporation and condensation, and eruptions from jets to large-scale mass ejections.

…and now all the way into the corona…

Any outstanding problems?

Flux emergence in the Quiet Sun

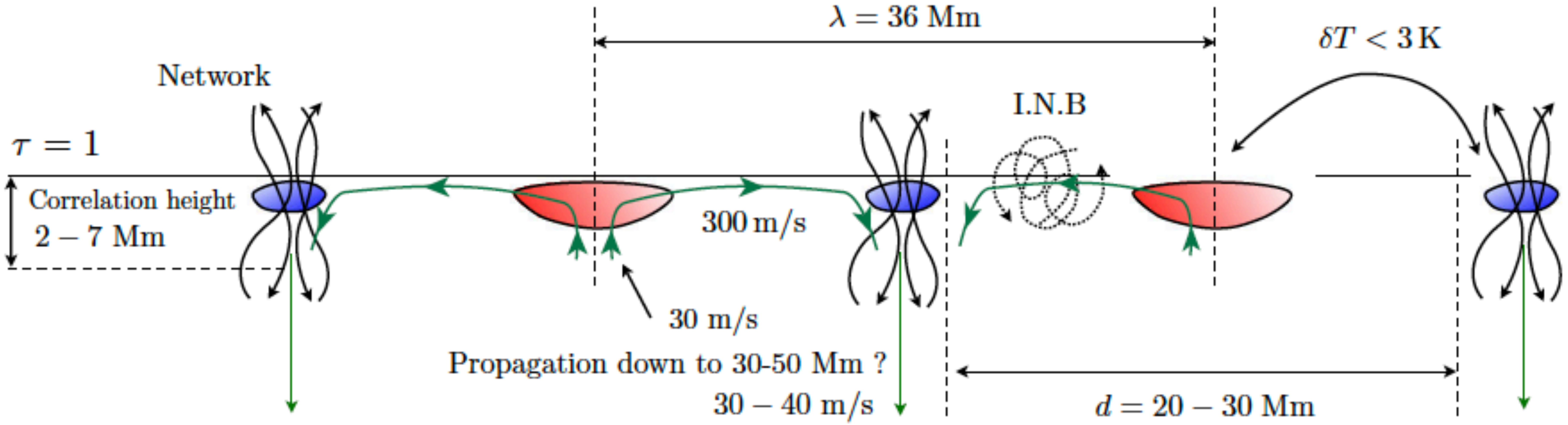

Fig. 17 A schematic view of the supergranulation phenomenon as currently constrained by observations. λ is the scale where the horizontal kinetic energy spectral density is maximum. d is the diameter of "coherent structures" (supergranules). The red and blue patches depict the warm and cold regions of the flow. I.N.B denotes the internetwork magnetic field (the dichotomy between network and internetwork fields is probably not quite as clear as indicated in this drawing). The vertical structure and extent of the dynamics remains one of the main unknowns in this cartoon

Rincon & Rieutord 2018, LRSP 15, 6

The solar internetwork. III. Unipolar versus bipolar flux appearance

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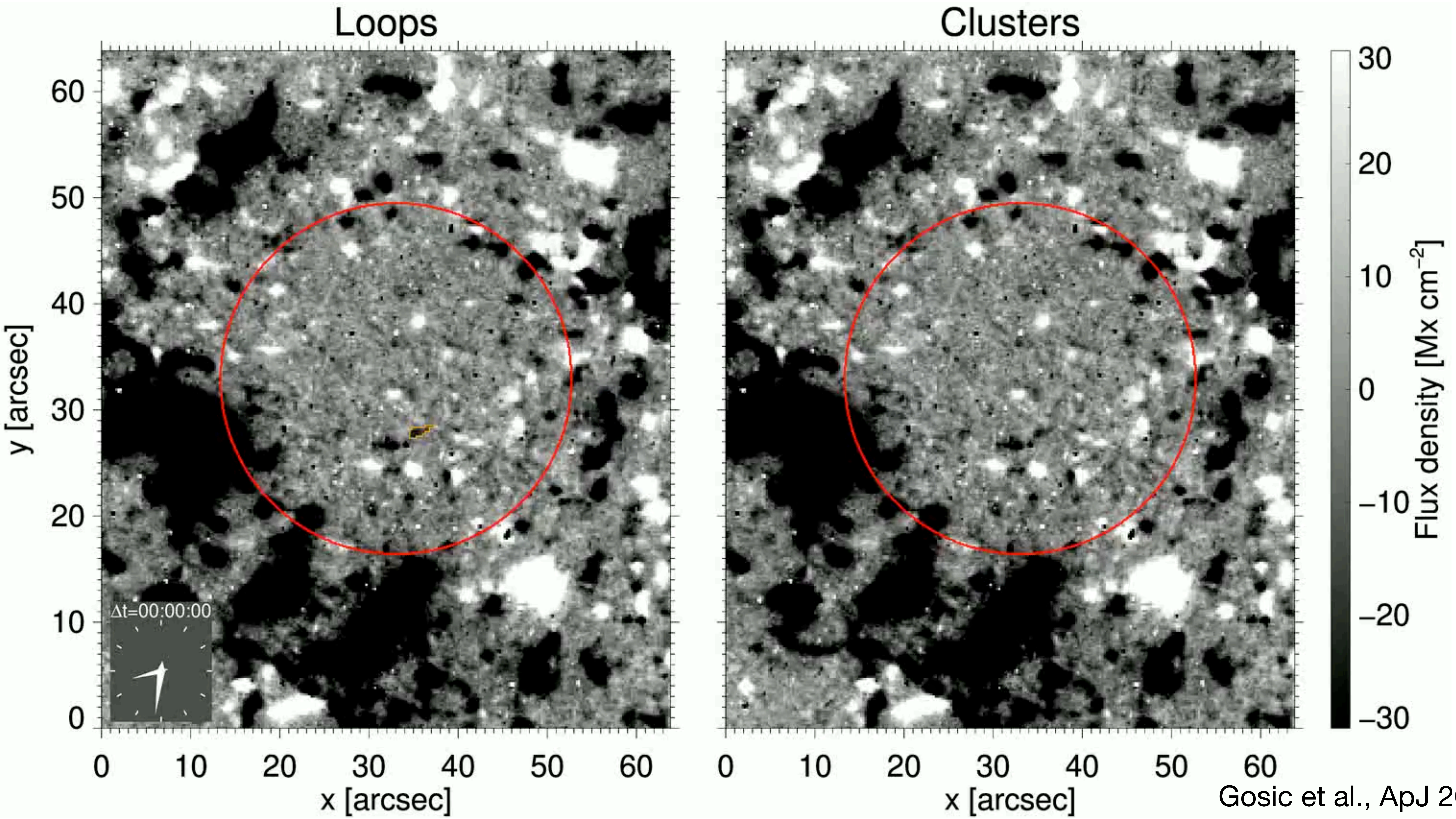
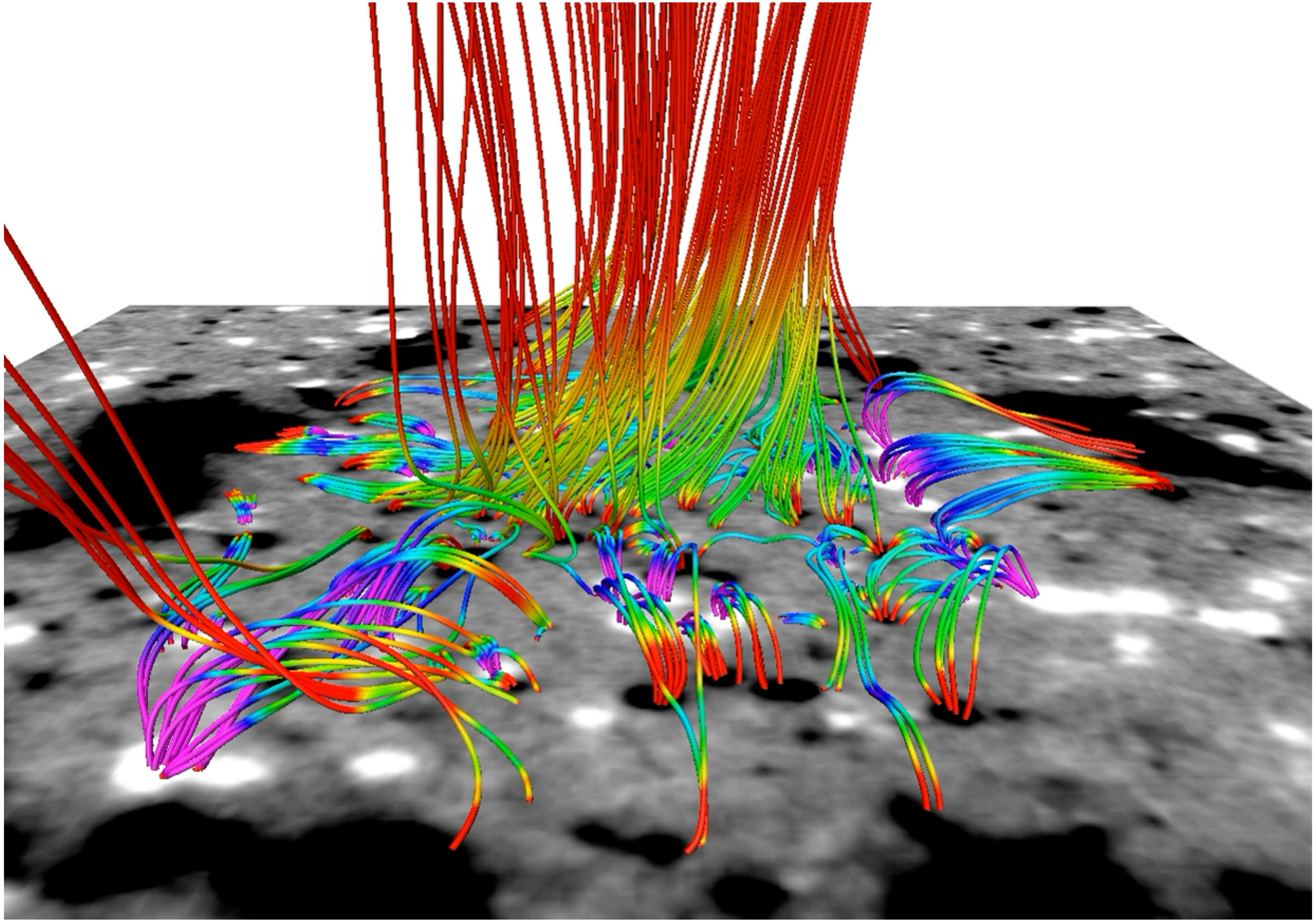


Gosic et al., ApJ 2022 925, 188

Magnetofrictional simulation



How much does this emerging flux contribute to chromospheric (and coronal) heating?

Gosic et al., ApJ 2022 925, 188

Astronomy & Astrophysics manuscript no. main
June 29, 2020

LETTER TO THE EDITOR

Signatures of ubiquitous magnetic reconnection in the lower solar atmosphere

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June 29, 2020

ABSTRACT

Ellerman Bomb-like brightenings of the hydrogen Balmer line wings in the quiet Sun (QSEBs) are a signature of the fundamental process of magnetic reconnection at the smallest observable scale in the solar lower atmosphere. We analyze high spatial resolution observations (0.″1) obtained with the Swedish 1-m Solar Telescope to explore signatures of QSEBs in the Hβ line. We find that QSEBs are ubiquitous and uniformly distributed throughout the quiet Sun, predominantly occurring in intergranular lanes. We find up to 120 QSEBs in the FOV for a single moment in time; this is more than an order of magnitude higher than the number of QSEBs found in earlier Hα observations. This suggests that about half a million QSEBs could be present in the lower solar atmosphere at any given time. The QSEB brightening found in the Hβ line wings also persist in the line core with a temporal delay and spatial offset towards the nearest solar limb. Our results suggest that QSEBs emanate through magnetic reconnection along vertically extended current sheets in the solar lower atmosphere. The apparent omnipresence of small-scale magnetic reconnection may play an important role in the energy balance of the solar chromosphere.

Key words. Sun: activity – Sun: atmosphere – Sun: magnetic fields

Quiet Sun EBs!

- Smaller in size and weaker enhancement of the Hα wings than AR counterparts.
- Estimate that about half a million QSEBs could be present in the lower solar atmosphere at any given time.
- Thus indication of omnipresent magnetic reconnection in the (lower) Quiet Sun chromosphere.
- QSEBs appear everywhere in QS, but more frequently near network where they are bigger, longer lived, and brighter.

Joshi et al. 2020, A&A 641, L5, Joshi & Rouppe van der Voort 2022, A&A 2022, 664, 72.

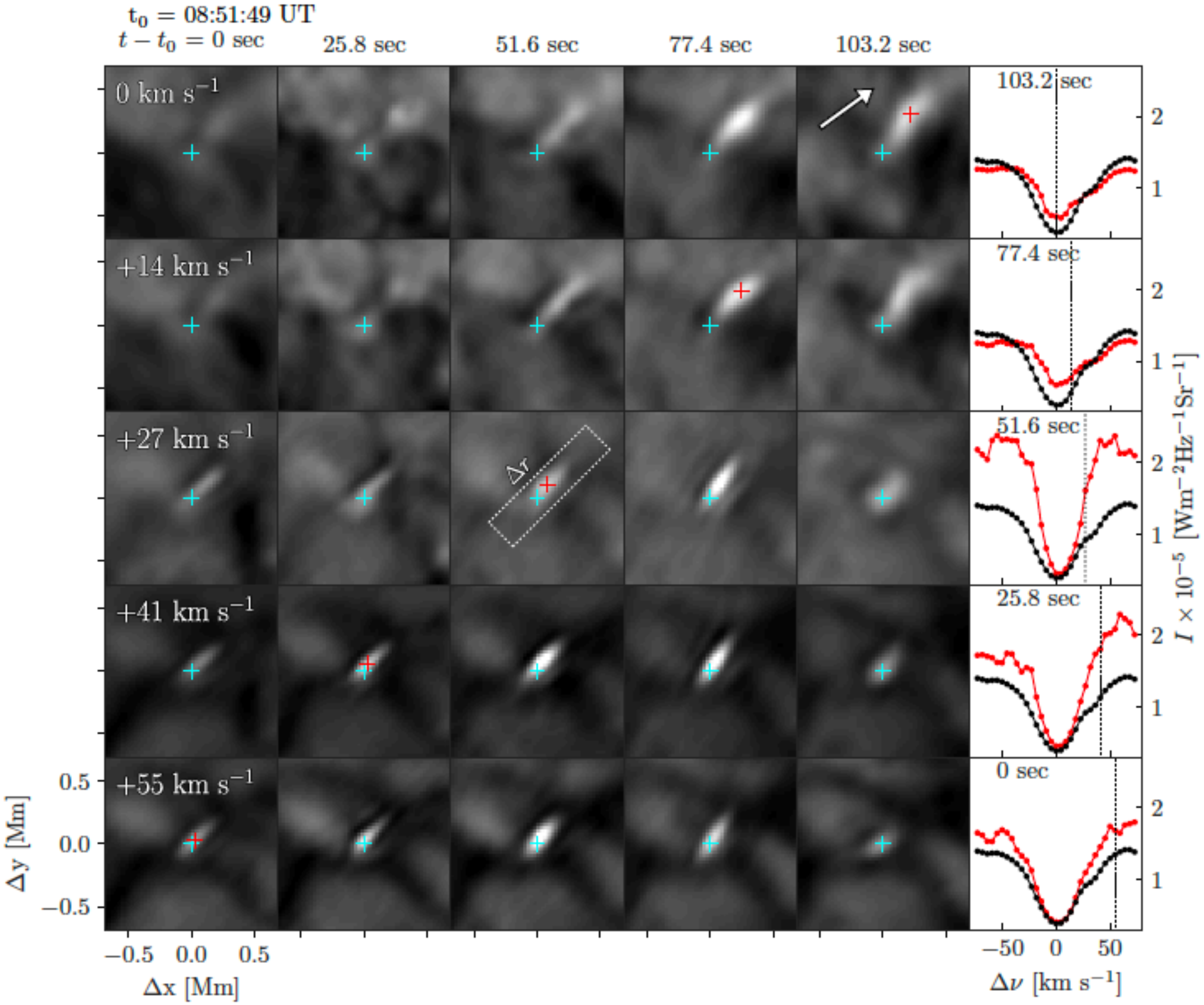


Fig. 4. Temporal evolution of a QSEB. Time is progressing along the rows of Hβ images from left to right, Doppler offset is varying along the columns from line core at the top to far wing in the bottom. The rightmost column shows the evolution of the QSEB Hβ line profiles in red (the location of the line profile is marked with the red plus sign in the images), the black line is a reference profile averaged over the presented FOV. The vertical dotted line marks the Doppler offset in the corresponding row. The Hβ profile is selected from the location of maximum intensity at that Doppler offset within the area of the QSEB. The cyan plus signs mark the centre of the FOV. Images in a particular row are displayed on the same intensity scale. The dotted rectangle on the central image shows the area used to create the space-time map displayed in Fig. 5(b).

…but no (not much) heating in the chromosphere and above?

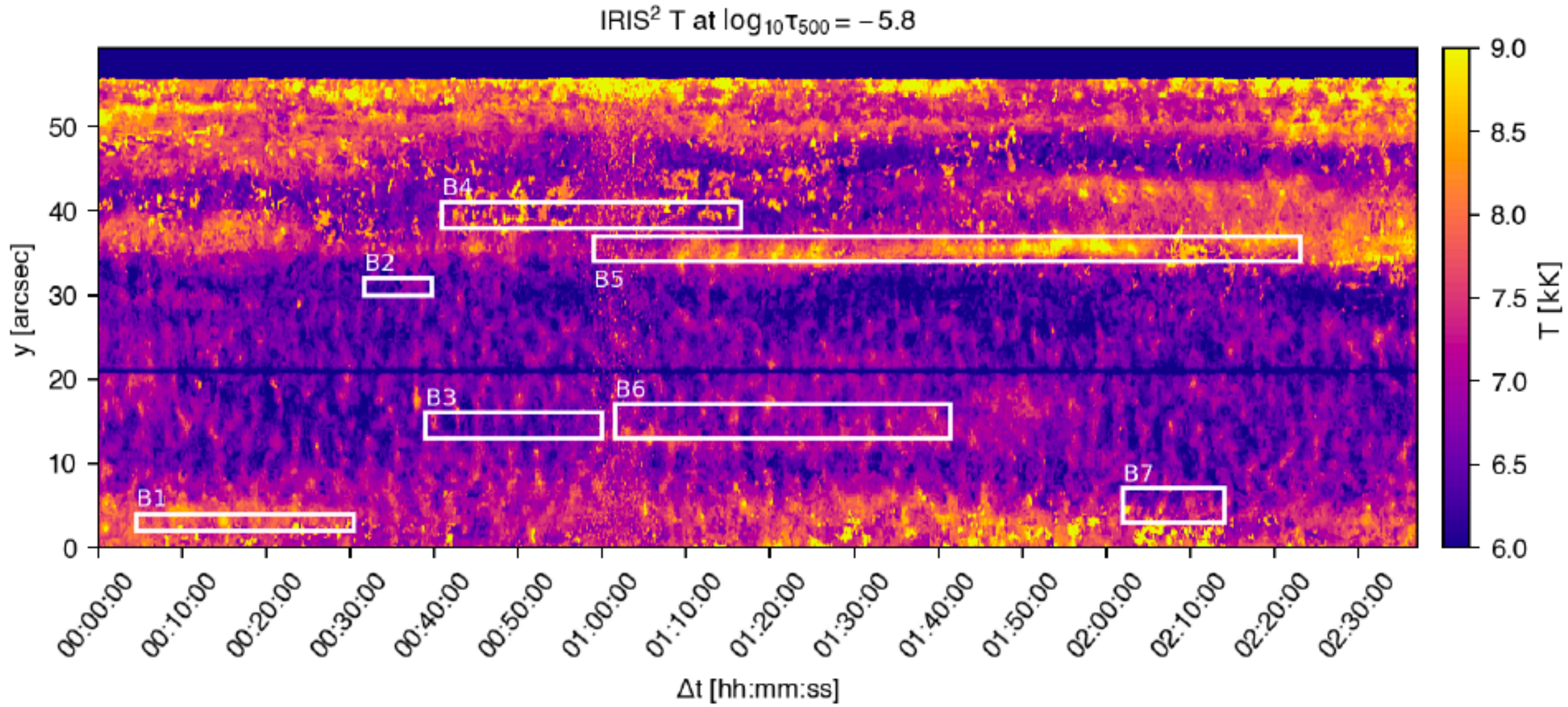
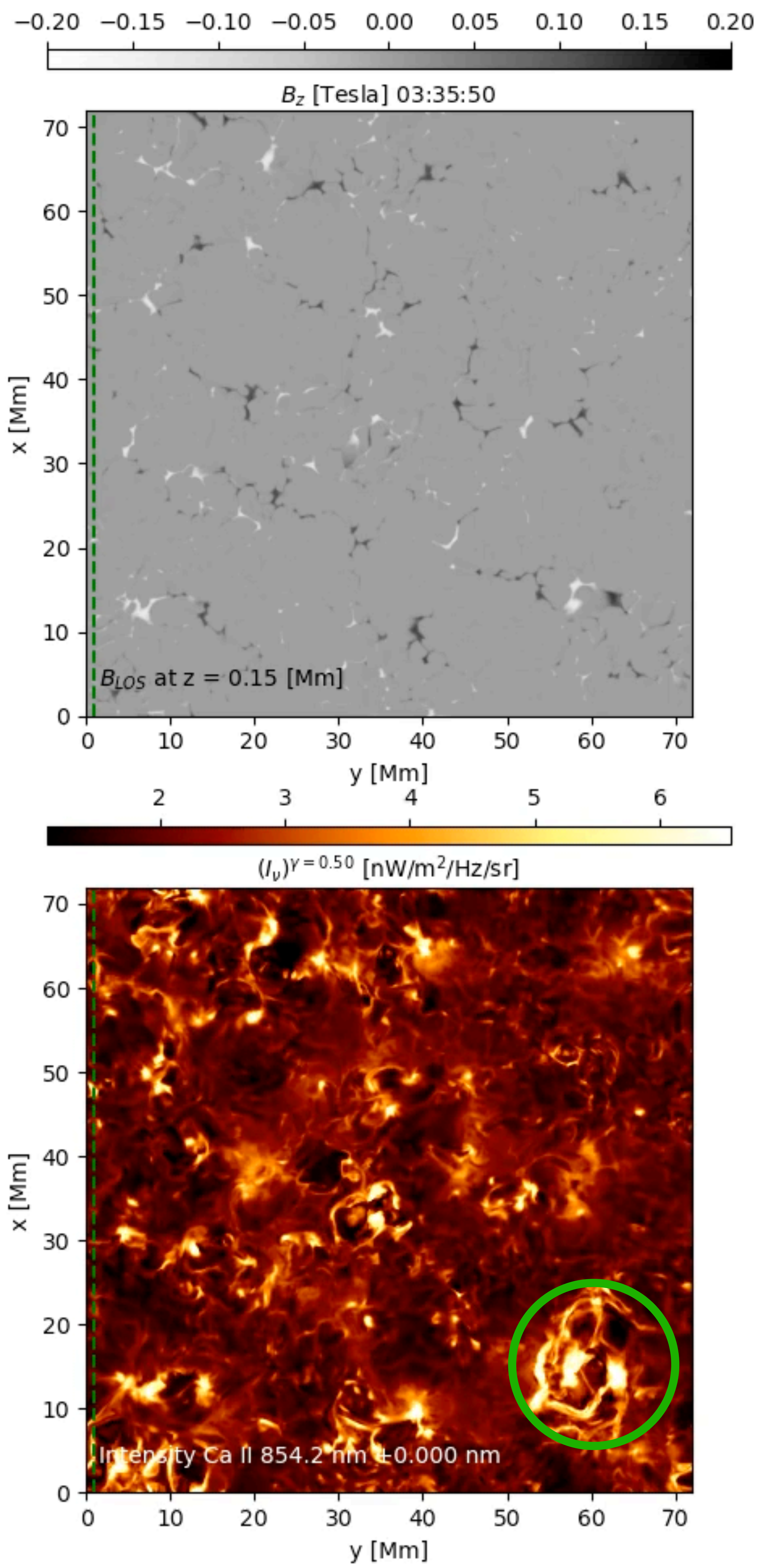


Figure 2. Temperature spatio-temporal map from the IRIS^2 inversions at $\log_{10}\tau_{500} = -5.8$. The white boxes indicate locations and times when the emerging IN bipoles were under the IRIS slit.

Few specific events identified, but leaves open the possibility of contribution to the general "background heating" of the chromosphere.

Gosic, De Pontieu, Sainz Dalda, ApJ 2022 925, 188



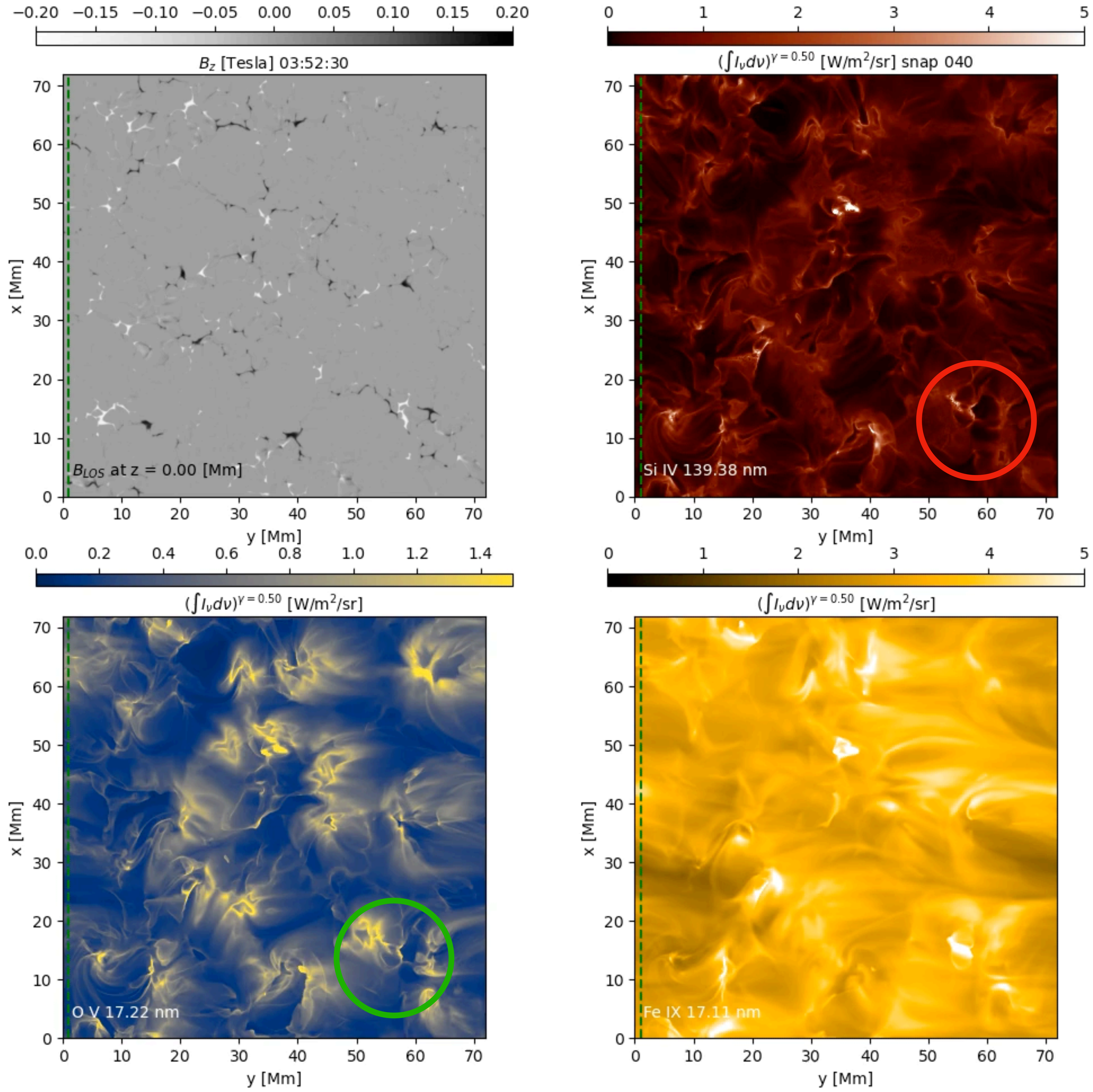
Simulated QS/network

- a bigger box: $72 \times 72 \times 60\ \mathrm{Mm}^3$
- depth 8.5 Mm below, height 52 Mm above photosphere
- horizontal resolution $\Delta x = 100\ \mathrm{km}$
- unsigned $|B_z| \approx 30\ \mathrm{G}$

- movie roughly 40 minutes, 500 s cadence

- some flux emergence events are visible
- synthetic IRIS Mg II k3 and 283.2 nm photosphere emission…
- …as well as Ca II 854.2 nm

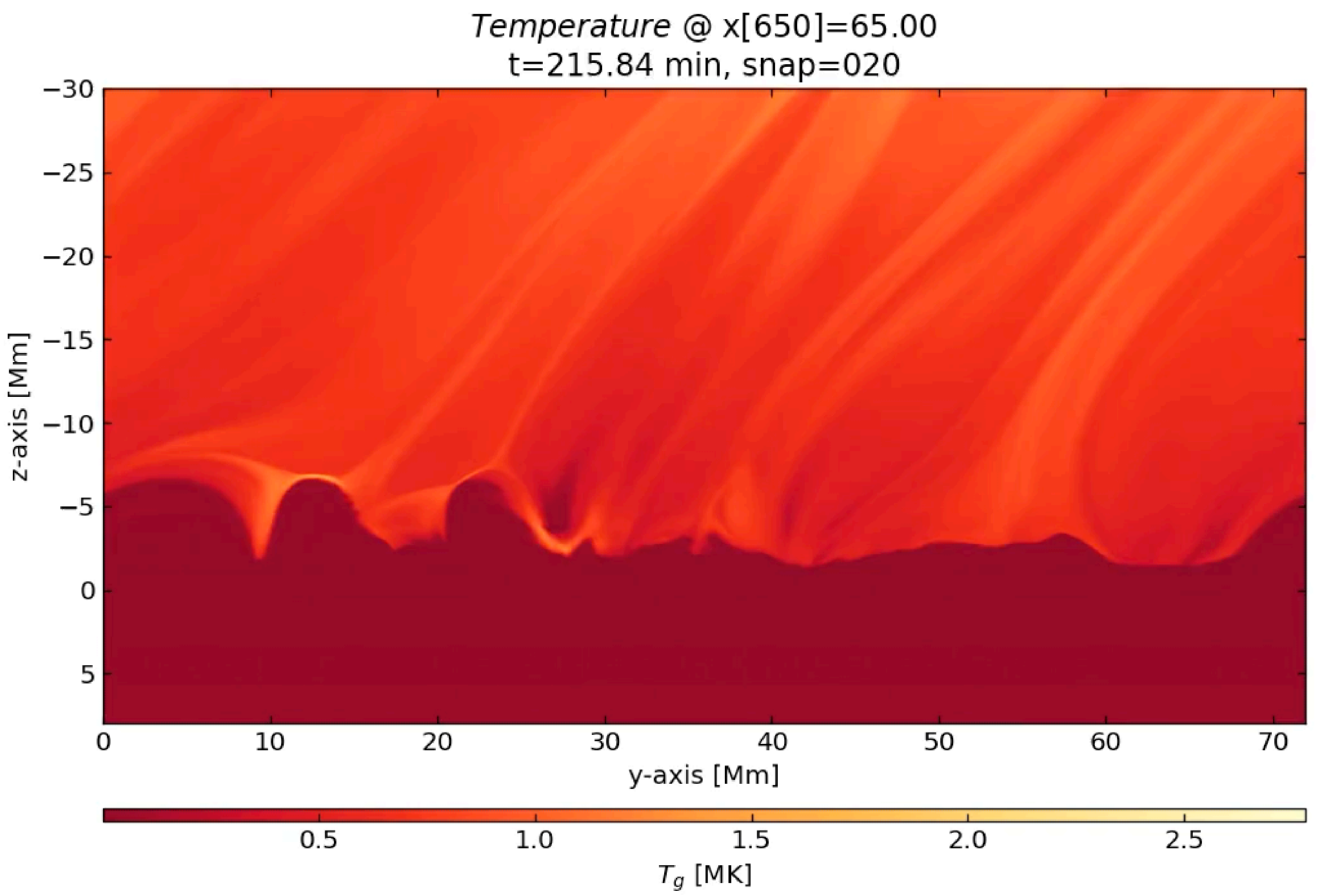
TR or coronal response?



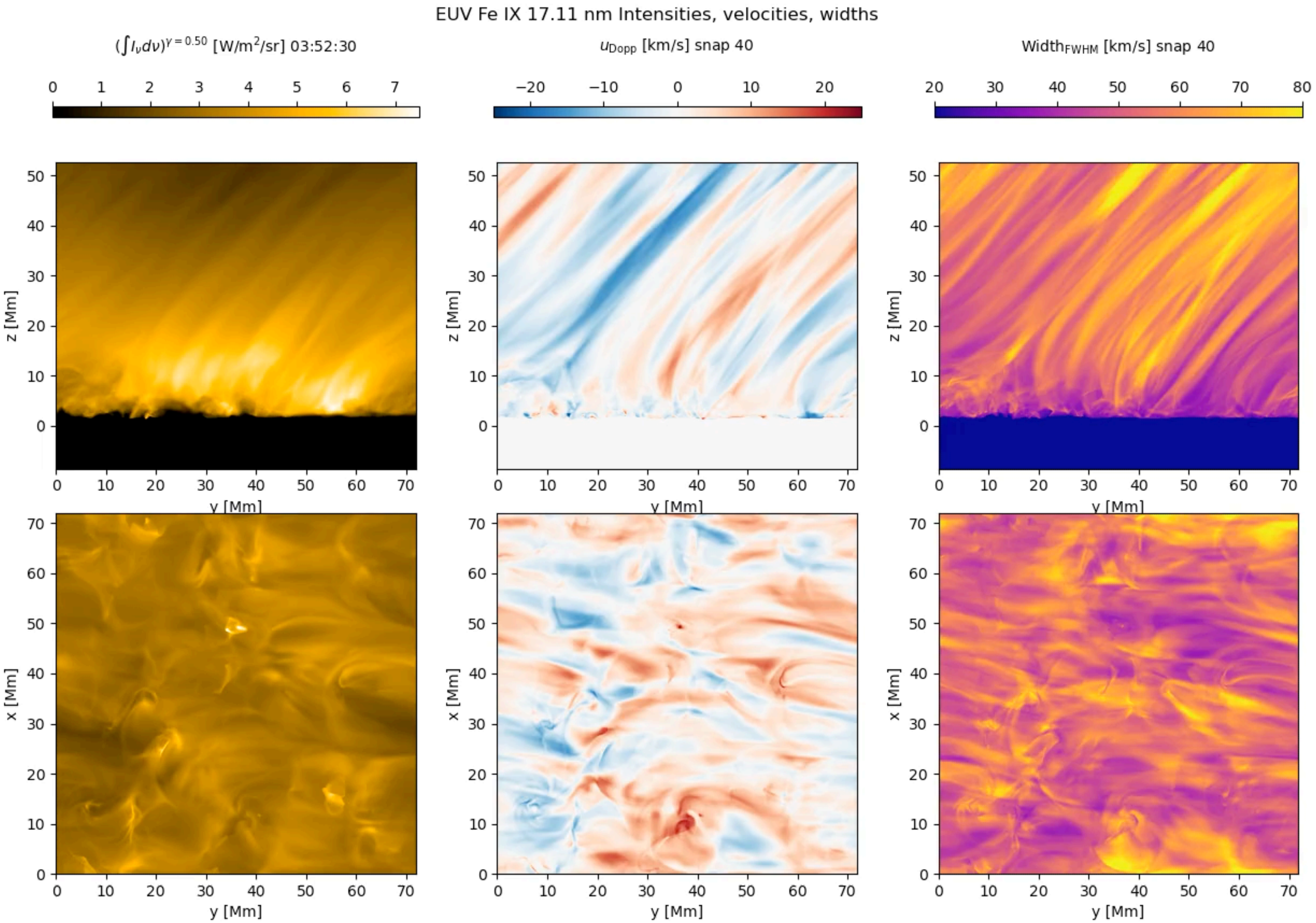
- movie roughly 35 minutes, 50 s cadence

- both heating through braiding and as a result of flux emergence…
- …difficult to separate, but Tg at limb clearly shows emerging/expanding flux

- synthetic IRIS Si IV 139.3 as well as O V 17.2 nm
- …and SDO/AIA 17.1 nm



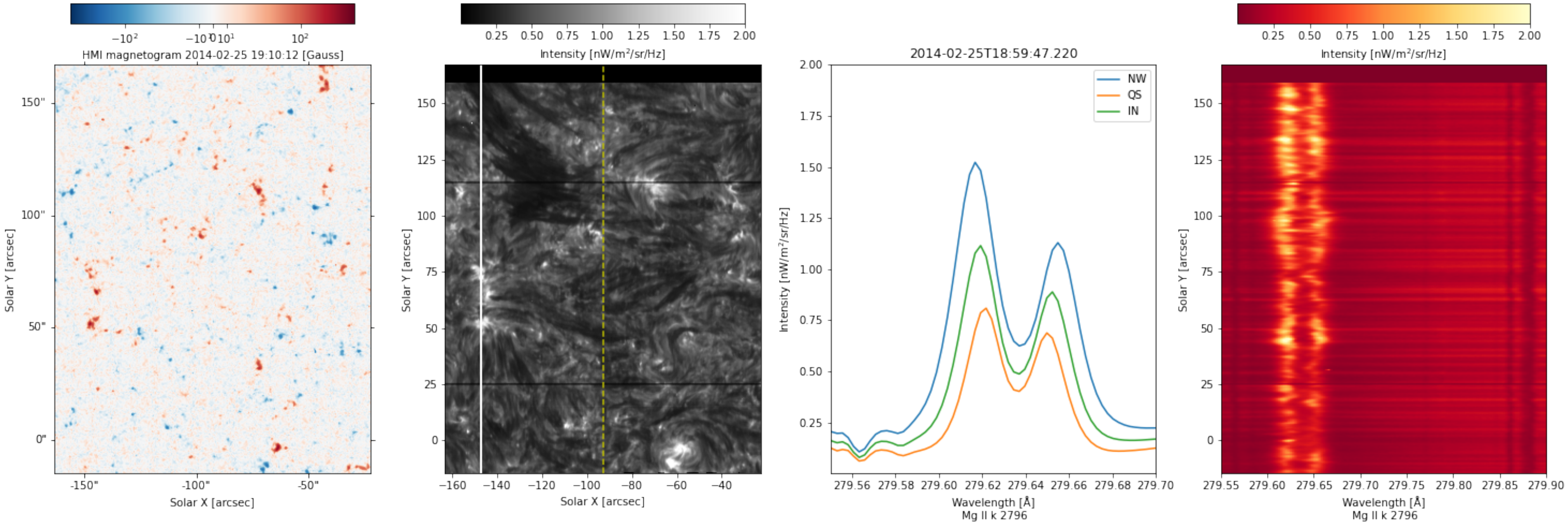
Limb emission in TR and corona



- Note absorption in Fe IX 17.1 nm line
- How much cold material at great heights?

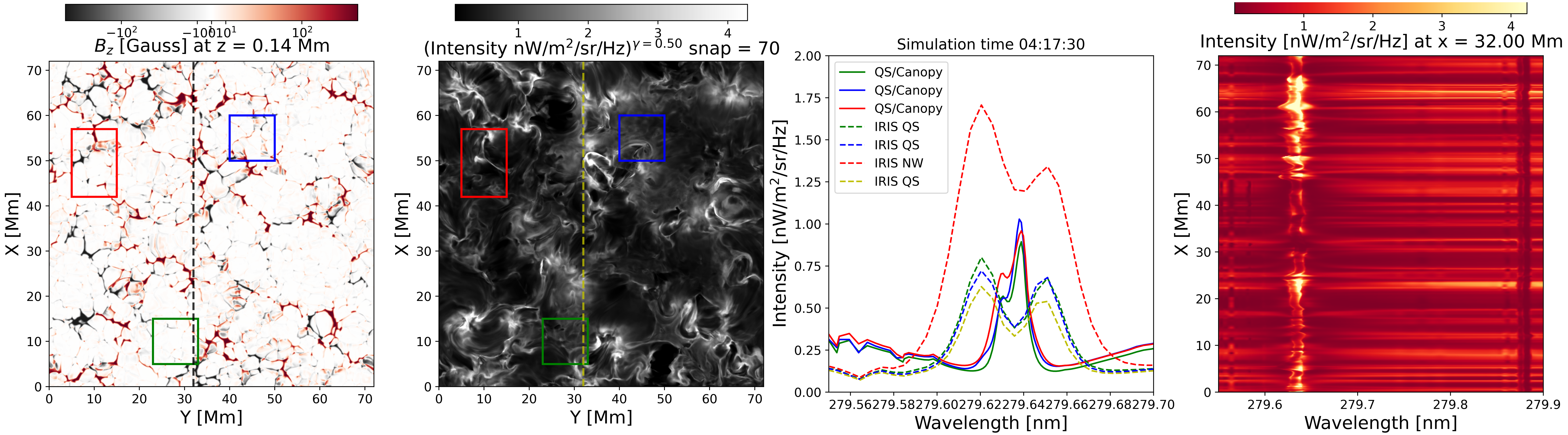
“Typical” Mg II k Spectra in a region of “typical” Quiet Sun

IRIS raster 2014-02-25 18:59 UT, with co-temporal HMI magnetogram



- Line core FWHM is > 0.05 nm (53 km/s) with k2 peak intensities of order 1 nW/m^2/sr/Hz
- k3 is fairly deep of order 1/2 intensity of k2 peaks
- There is some asymmetry; the k2v peak is some 30% brighter than k2r
- Network is 2x brighter than “darkest” QS, clear correlation between photospheric fields and Mg II peak brightness
- What is magnetic topology in the chromosphere here?
- What is the magnetic field strength in the photosphere? “Typical” average field strength $\langle |B_z| \rangle \approx 60 \text{ Gauss}$ (not measured here using HMI data)

Comparison with “typical” quiet Sun model

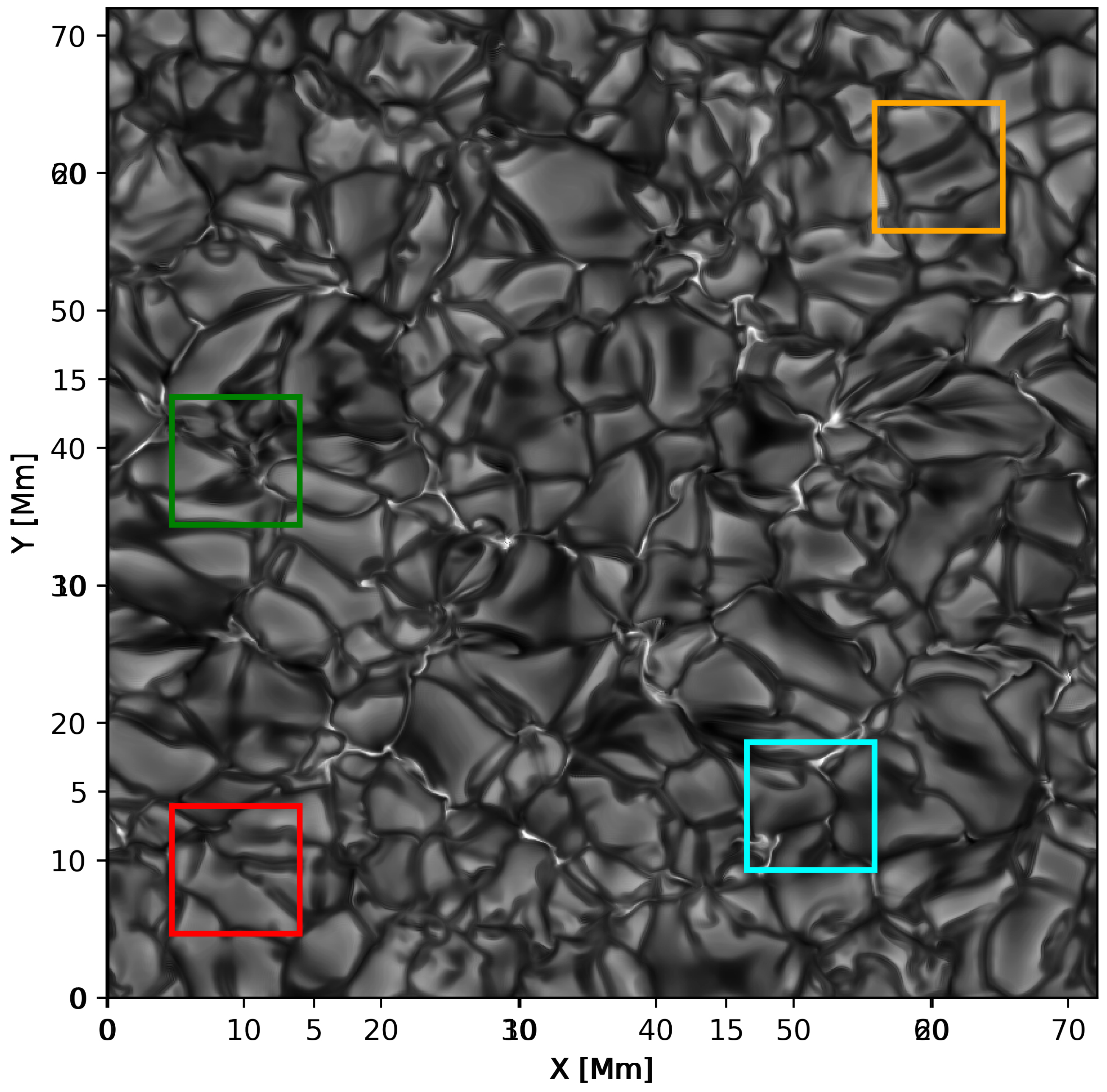


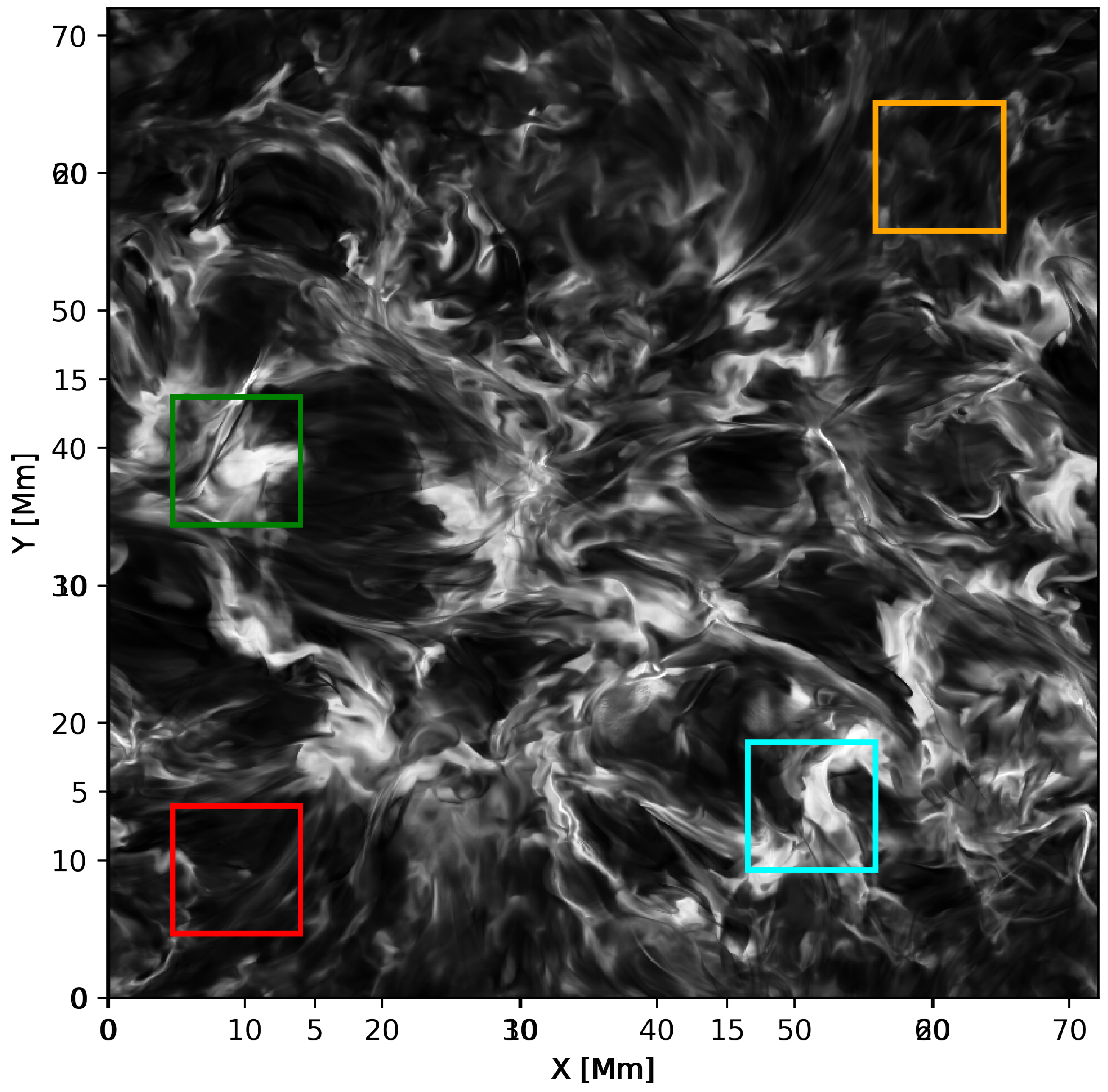
- …maybe not “kind of OK” after all..
- Profiles are too intense, asymmetry is with stronger k2r than k2v,
- And profiles **too narrow,** 0.027 nm (30 km/s) vs 0.05 nm

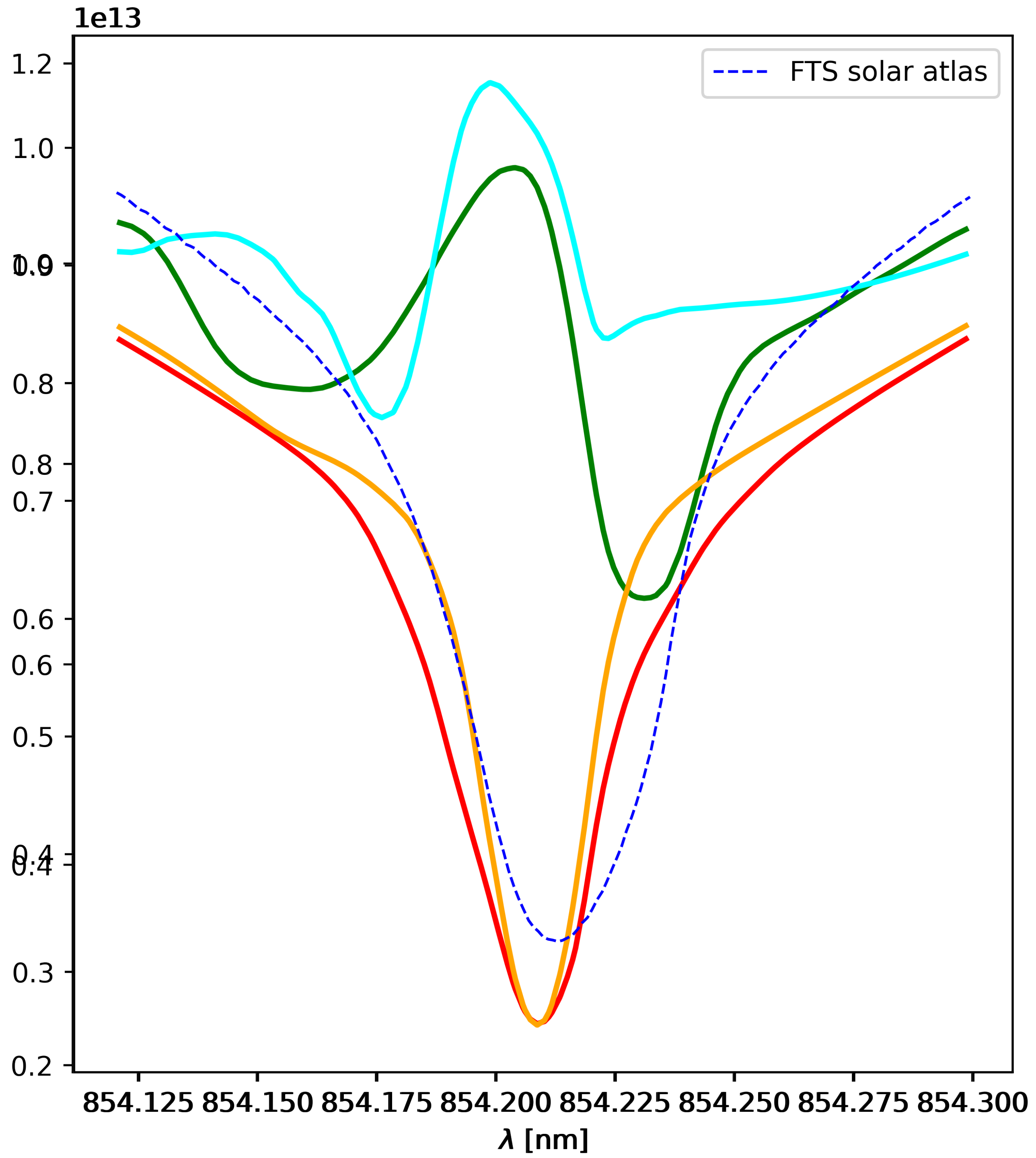
- **Not enough dynamics in upper chromosphere?**
- **Lack of opacity?**
- **Simulated field too weak?**

“Bifrost is too diffusive”

Spatial mean spectra Ca II 854.2 nm

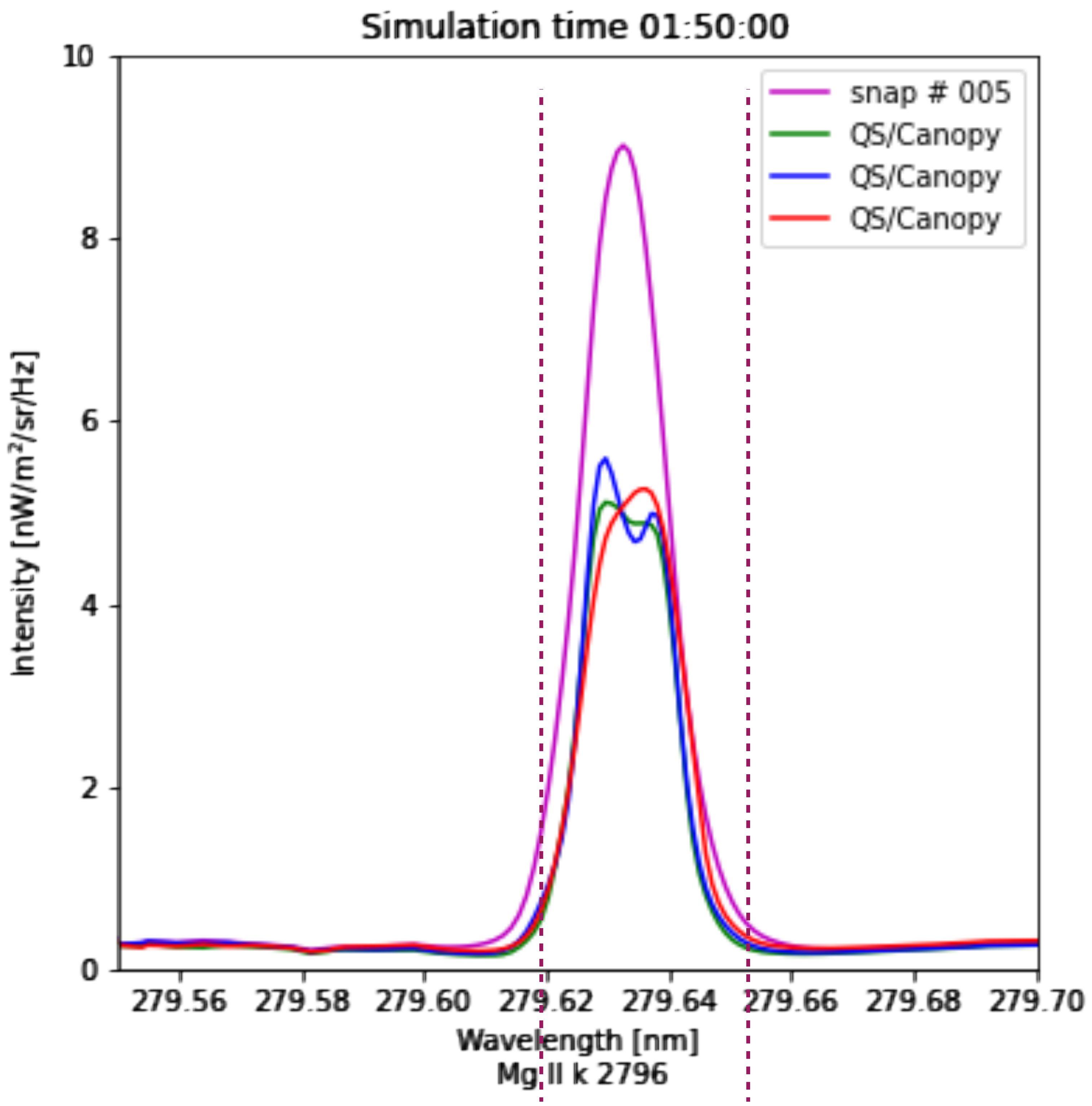






$\Delta x = 100$ km **vs** $\Delta x = 31$ km

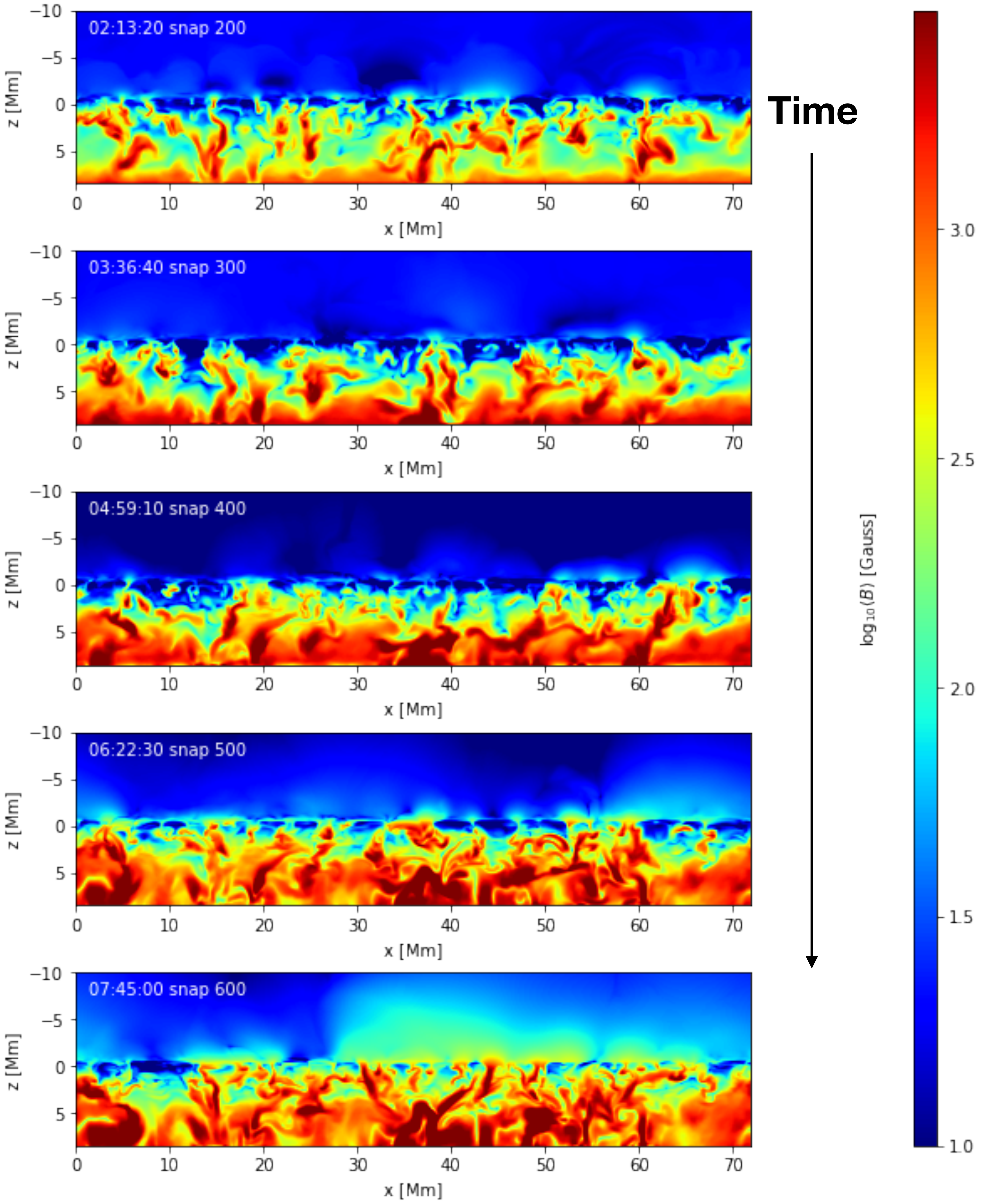
For Mg II too? $\Delta x = 100$ km vs $\Delta x = 50$ km

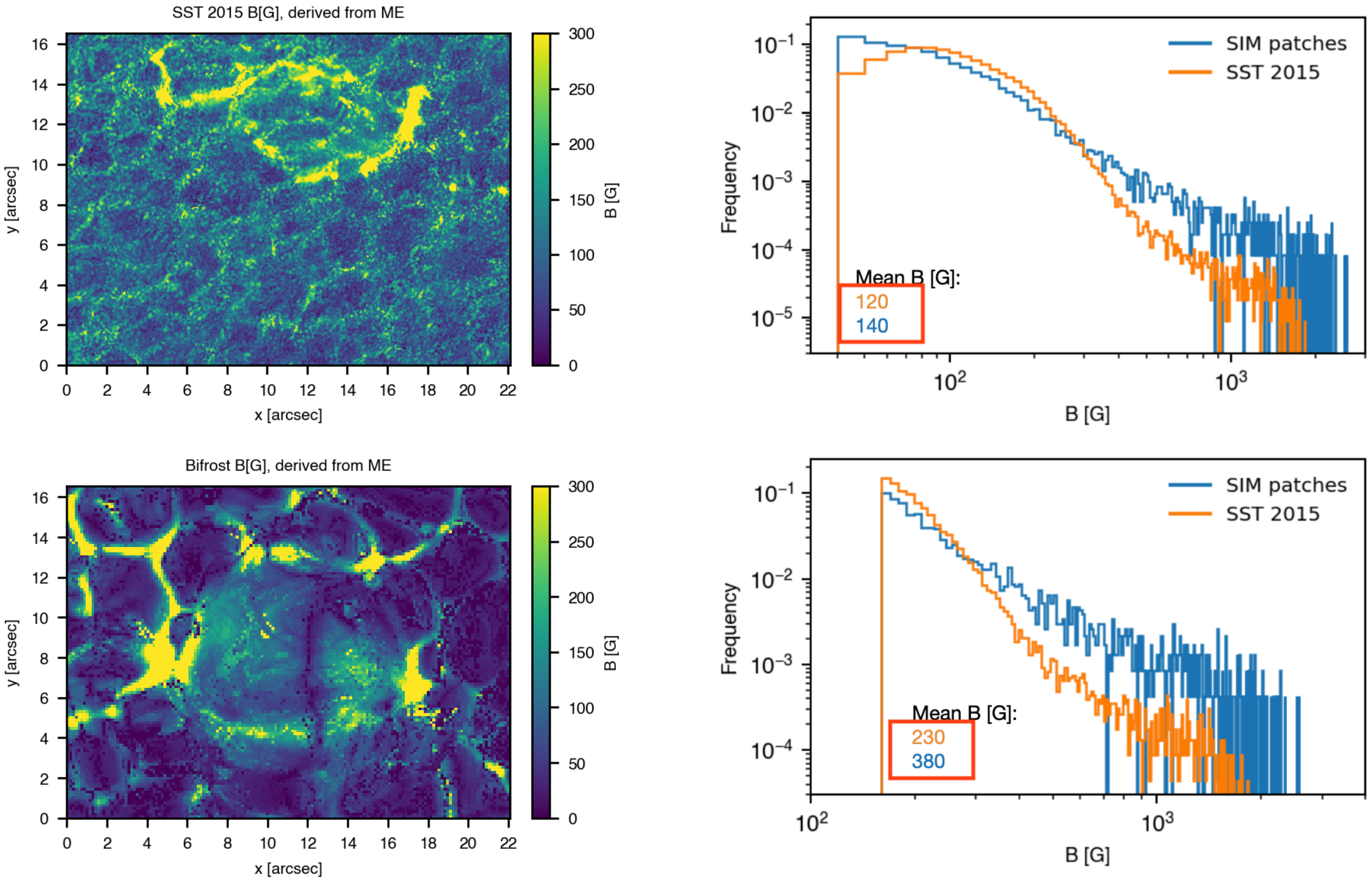


- Doubling resolution does very little
- …and even going to 25x resolution ($\Delta x = 4$ km) is not sufficient to match observed width
- **NB** These low resolution models run w/o non-equilibrium H ionisation and Generalised Ohm's Law

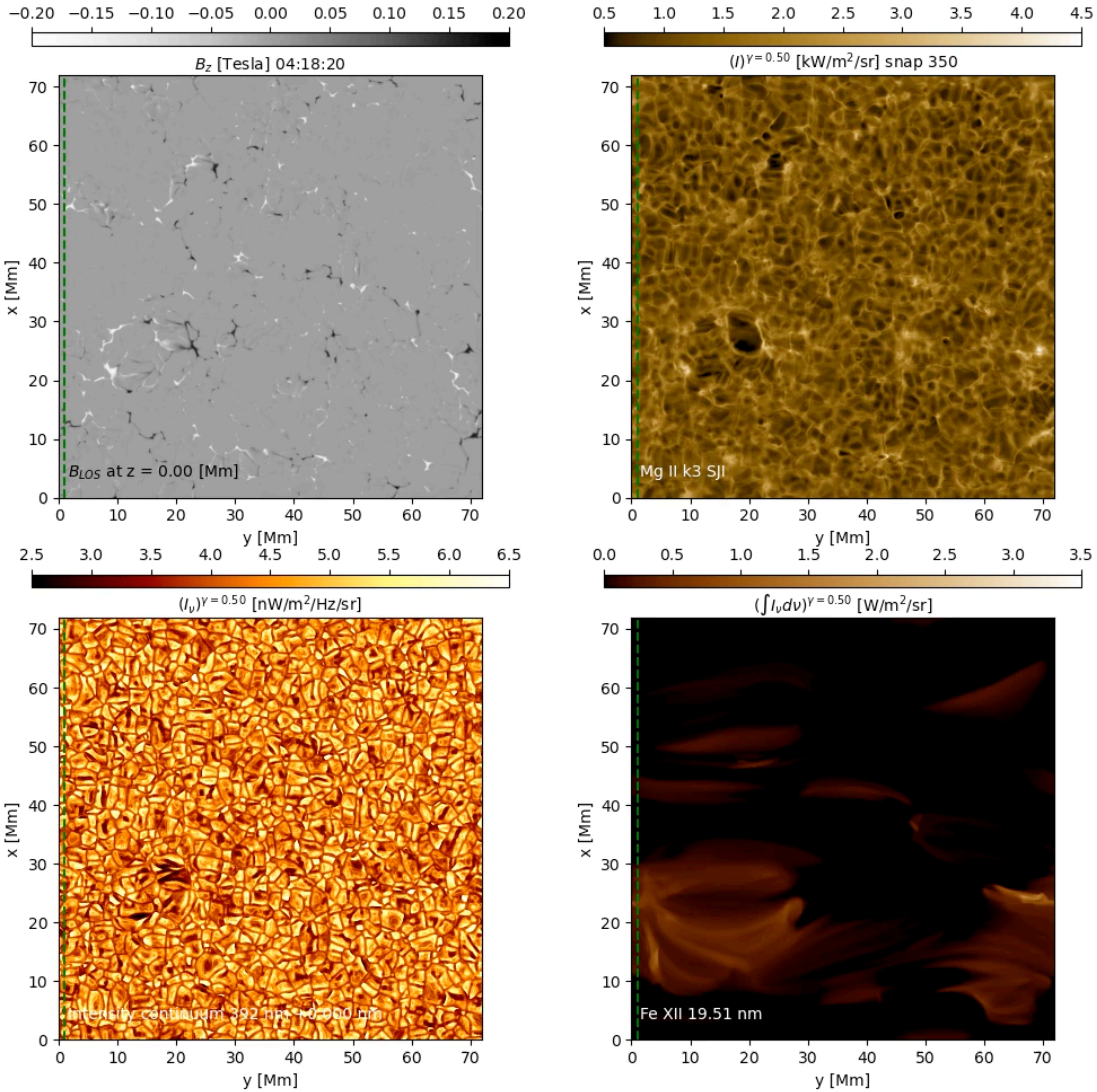
Model with emergence of flux sheet.

- 72 x 72 x 60 Mm box
- Δx,y = 100 km horizontal
- Δz variable with 20 km in photosphere and chromosphere, larger in convection zone and corona
- Horizontal field of 100 G initial up to photosphere; nearly 0 G in corona
- Initial flux injection in whole domain $B_y = 200\ \text{Gauss}$ for 95 minutes
- Then Flux sheet with $B_y = 1000\ \text{Gauss}$ or 70 minutes followed by $B_y = 2000\ \text{Gauss}$ for 150 minutes
- Afterward $B_y = 300\ \text{Gauss}$ injected continually at lower boundary



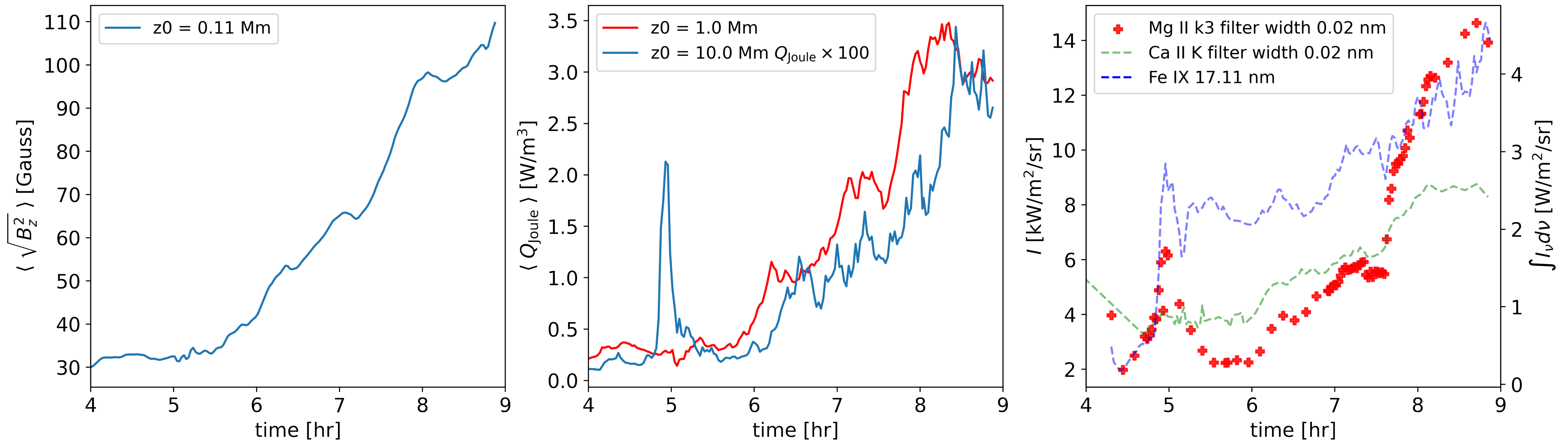

SST 2015 B[G], derived from ME
y [arcsec]
x [arcsec]
B [G]
Frequency
B [G]
SIM patches
SST 2015
Mean B [G]:
120
140
Bifrost B[G], derived from ME
y [arcsec]
x [arcsec]
B [G]
Frequency
B [G]
SIM patches
SST 2015
Mean B [G]:
230
380

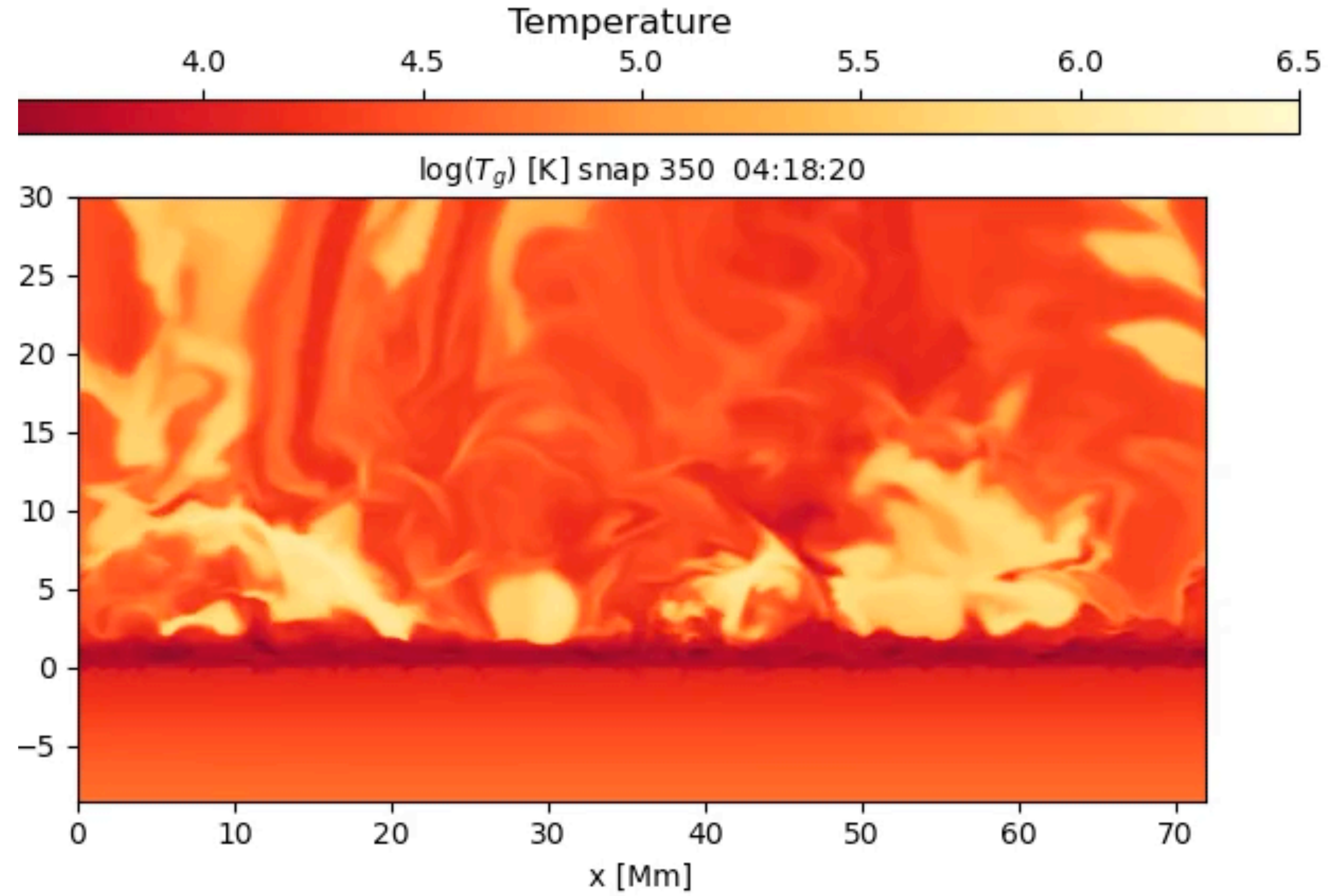
SST 2015
SST 2016
HTMS
Frequency
Number of fragmentations
SST 2015
SST 2016
HTMS
Frequency
Number of mergings
SST patches 2016
SST patches 2015
SIM patches
Frequency
Mean lifetime [min]:
3
2
5
Lifetime [min]



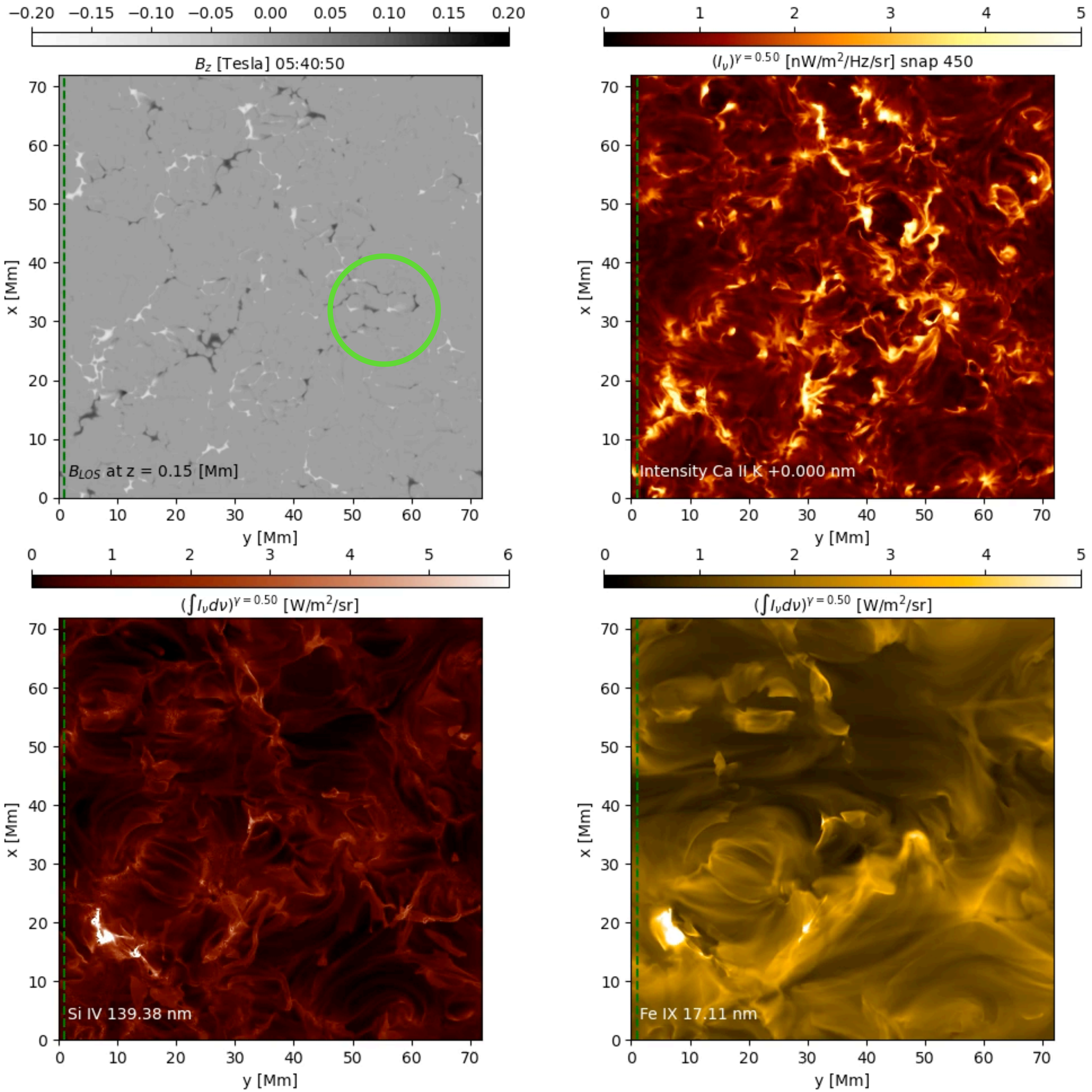
Evolution as field emerges

- Unsigned flux goes from $|B_z| \approx 30$ to > 100 G
- Mg II k both chromospheric and coronal line (as opposed to Ca II K)

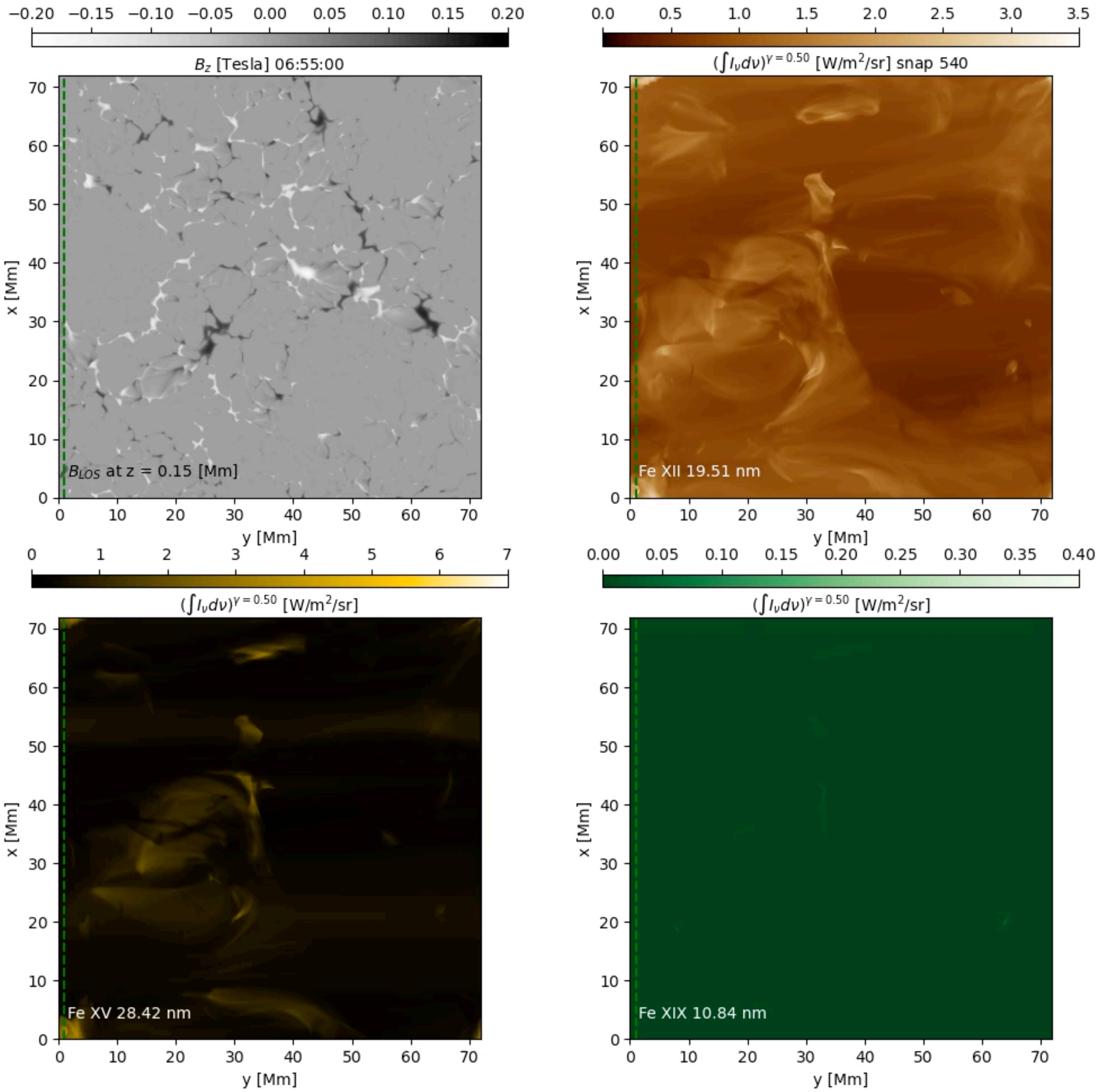




Chromosphere to lower corona

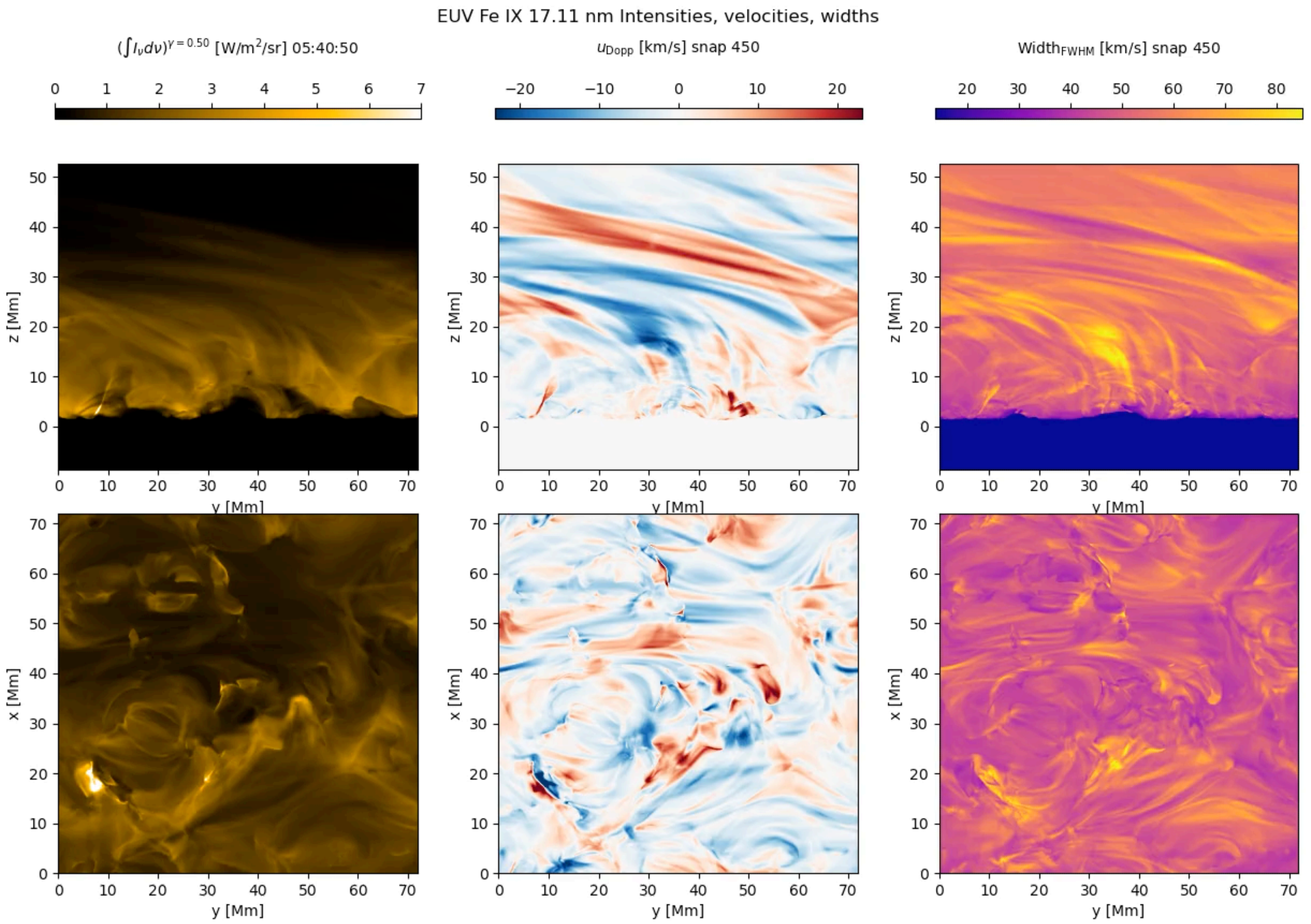


- Very clear response in chromosphere (Ca II K, but also Mg II k)
- Also TR (Si IV 139.3 nm) and lower corona (Fe IX 17.1 nm) show clear response to flux emergence
- Also emergence in many other locations…



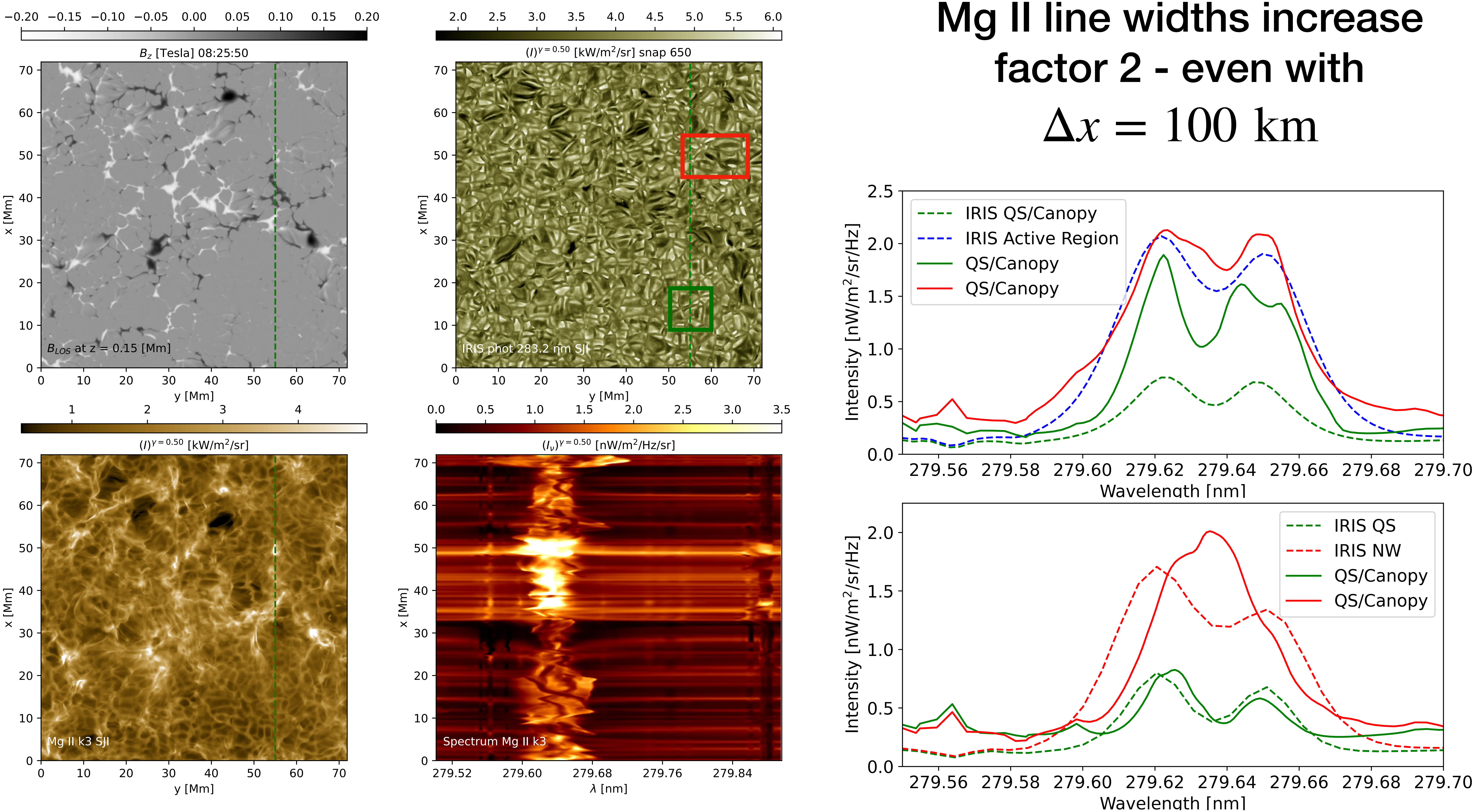
..and hotter corona, (even up to Fe XIX)

Fe XII 19.5 nm, Fe XV 28.4 nm, and (eventually) Fe XIX 10.8 nm



Limb view: even more cool material

Mg II line widths increase factor 2 - even with $\Delta x = 100$ km



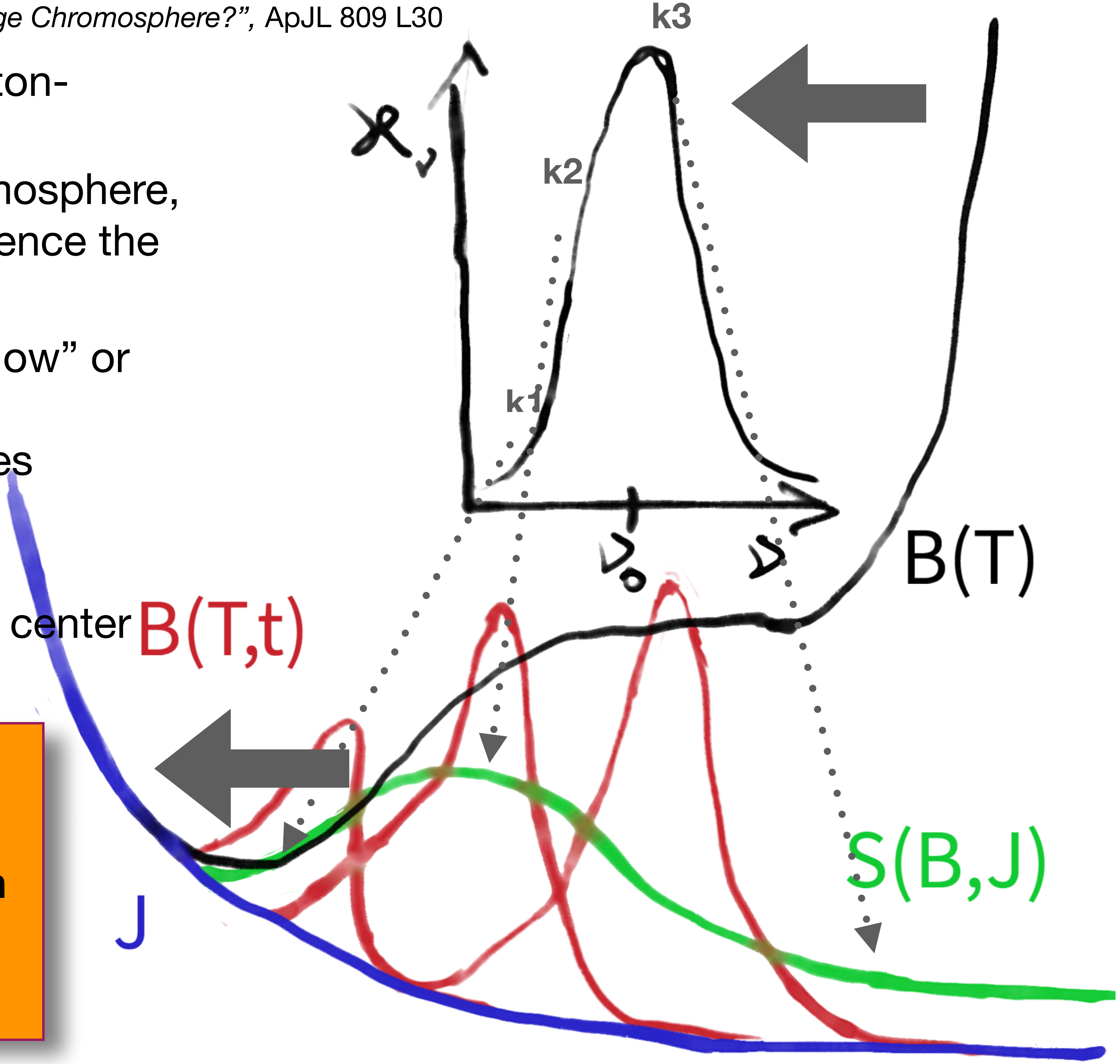
Discussion and Conclusions

- AR flux emergence informs us of the global dynamo and the state of the convection zone,
- while network and internetwork flux emergence inform us of the layers above the near surface shear layer.
- Can we separate global fields from local fields when setting up simulations? The ambient coronal field plays an important role, how do we take this into account in limited size “box in the Sun” models?
- …is continual QS flux emergence energising the chromosphere and/or lifting cool material to significant heights?
- Alternately, are there other physical effects that need to be taken into account, such as ion-neutral effects, or can we trust that higher resolution models will save the day?

Formation of the Mg II k line

see Carlsson, Leenaarts, De Pontieu, *"What Do IRIS Observations of Mg II k Tell Us about the Solar Plage Chromosphere?"*, ApJL 809 L30

- Intensity of the line $I_\nu \approx S(\tau_\nu = 1)$; use of Eddington-Barbier
- Line intensity determined by temperature of chromosphere, but also by how close source function S is to B; hence the opacity $\kappa_\nu(n, \ldots)$
  - High density/intensity if corona is hot and TR "low" or "deep"
  - …which also will lead to "single peaked" profiles
- Line width dependent on
  - Velocity structure or "turbulence"
  - Opacity broadening - how far out in ν from line center before temperature begins to fall to k1?



To achieve high intensity we need high S => hot chromosphere at high opacity/density.
Single peaked profiles need high S at k3 => high opacity/density at "top" of chromosphere
Wide lines need extended dense chromosphere