Magneto-convection

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with

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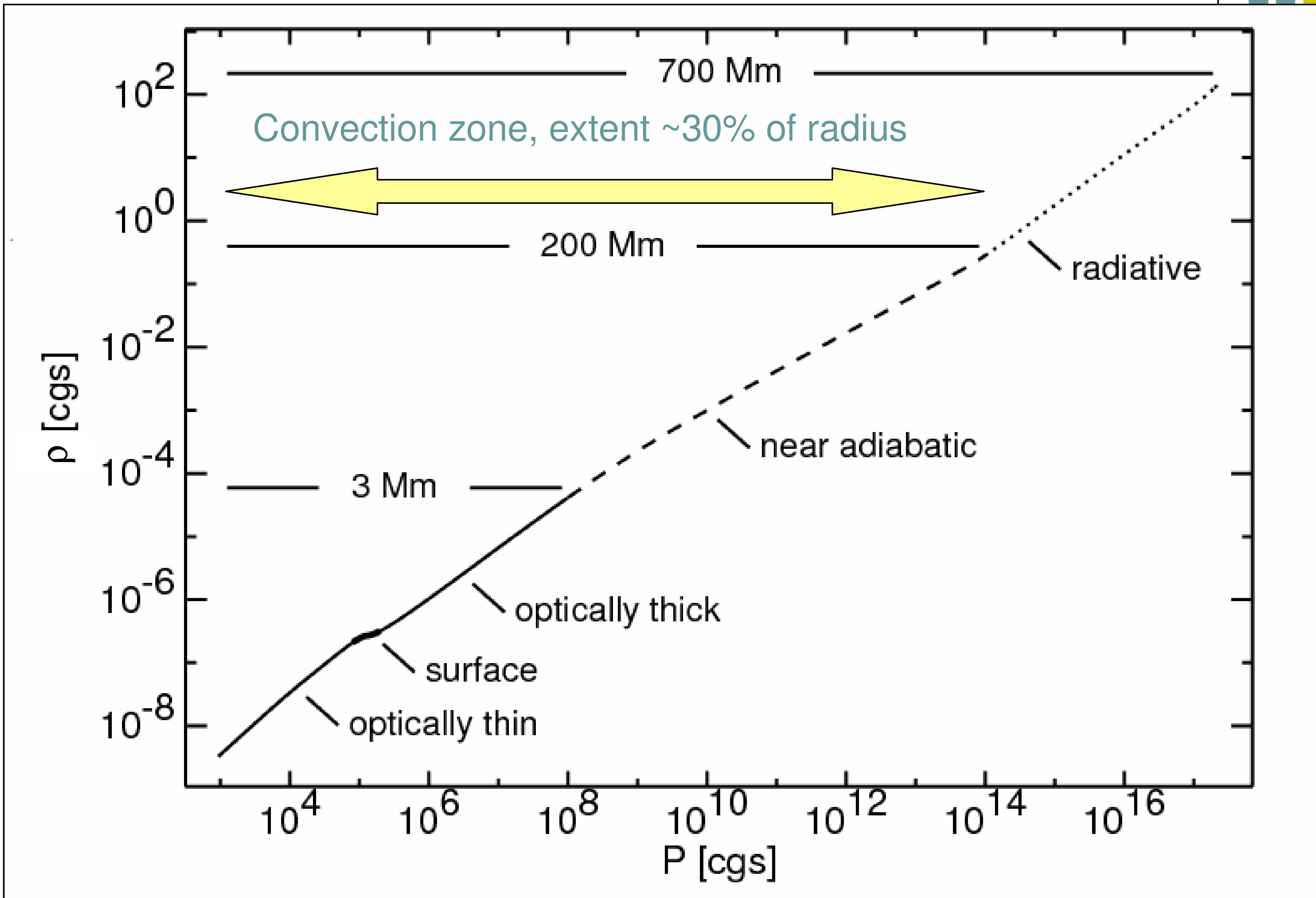
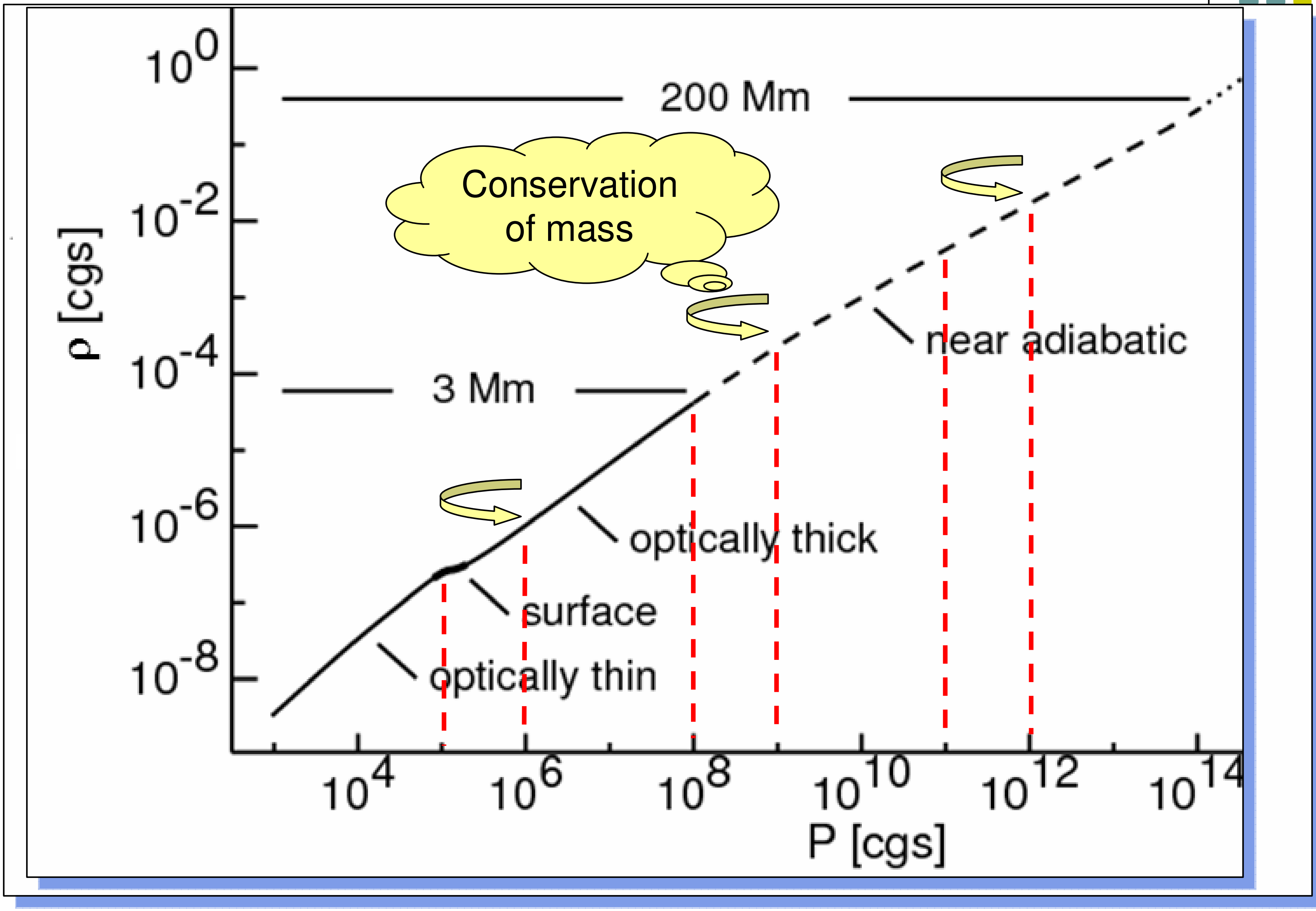
Summary of main points

- Stellar magneto-convection is fundamentally ***multi-scale***
- But also has ***scale invariance*** to some extent
- Two asymptotic regimes; **small *and* large**
  - The Sun + simulations prove that ***turbulent dissipation converges*** at relatively low Re
- Implications for sunspots and penumbrae
  - More on Thursday …

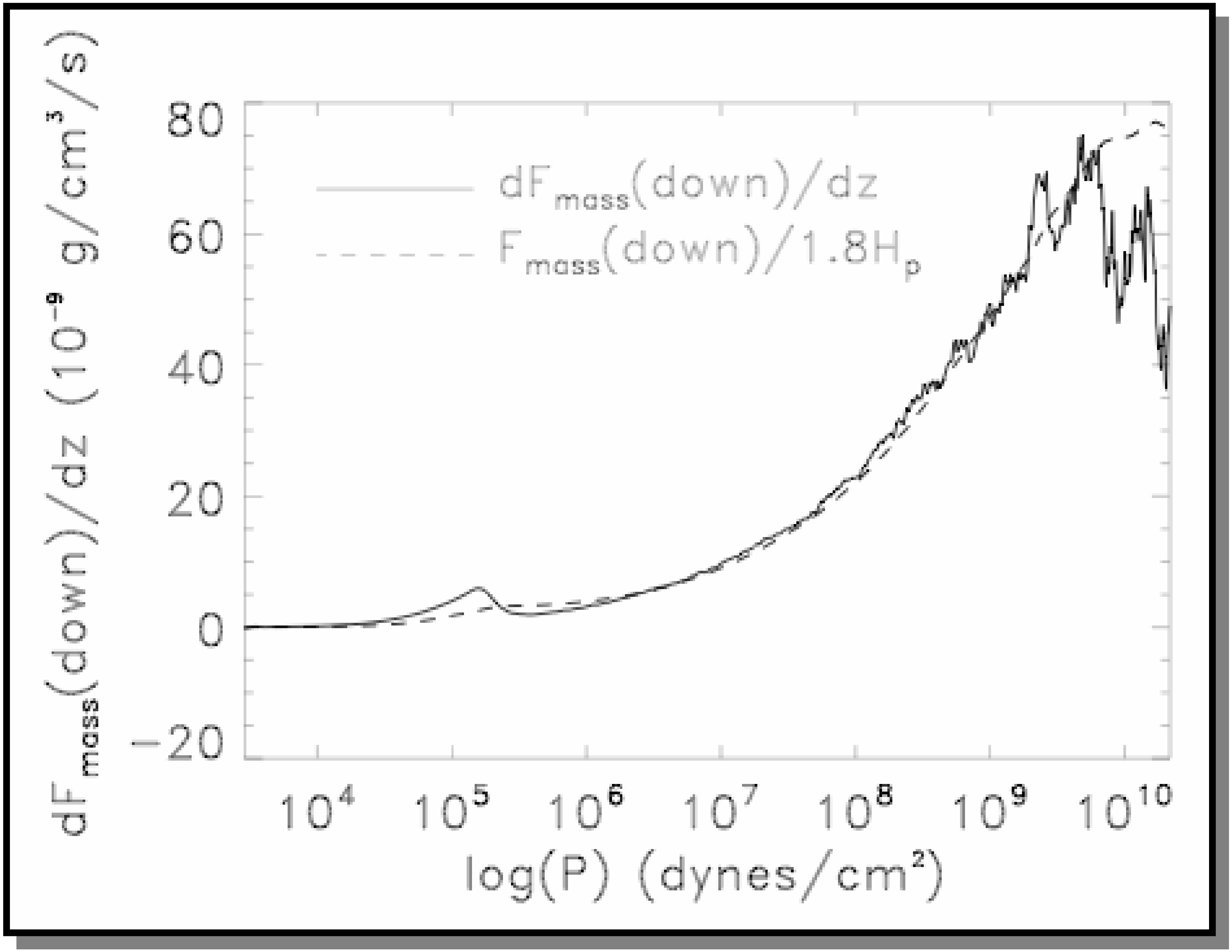
Overall Solar Structure



Convection Zone

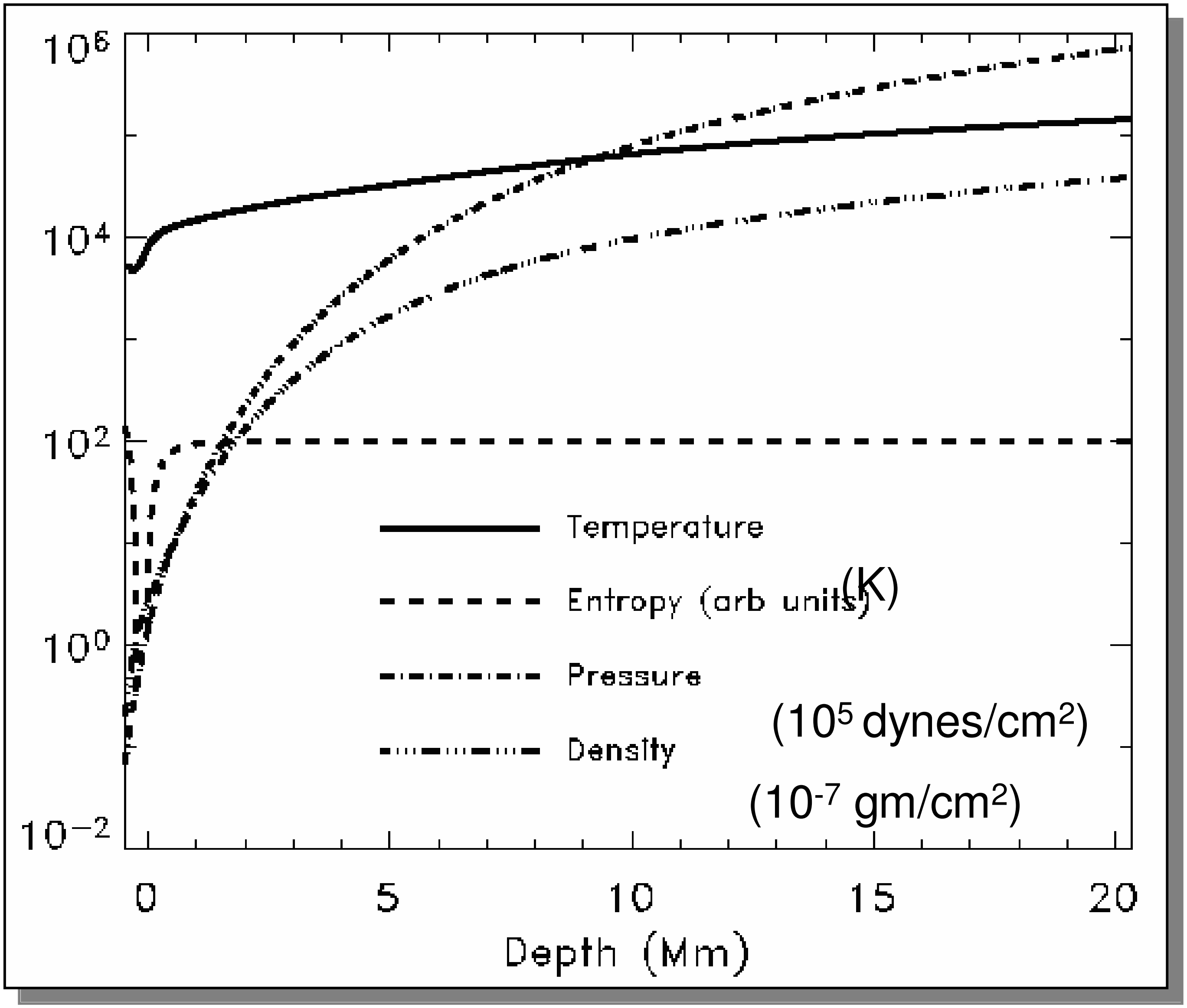


Mass conservation

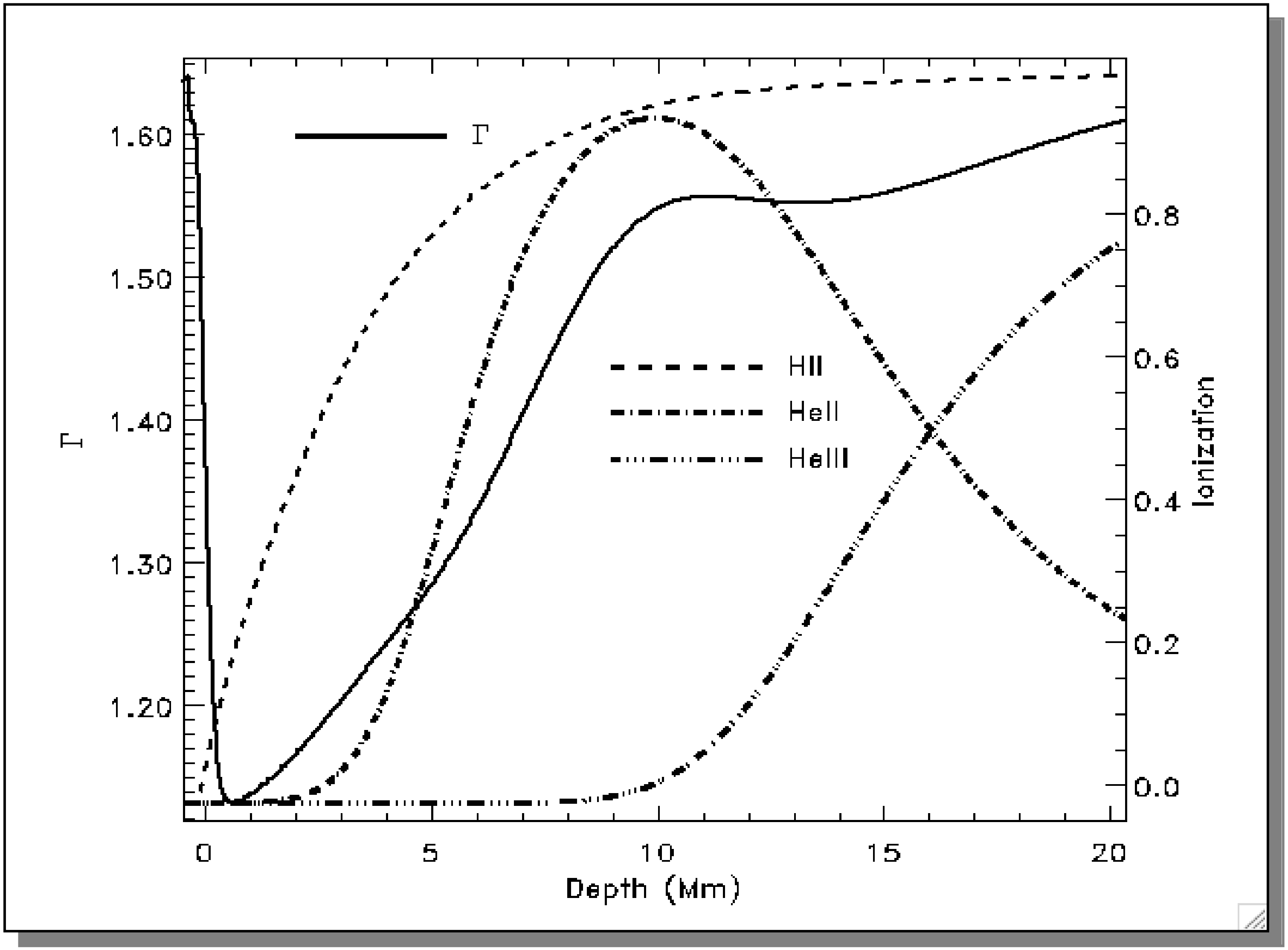


Rising fluid must turn over and descend within about a scale height to conserve mass. The actual mixing (entrainment) length in simulations is 1.8 H_P.

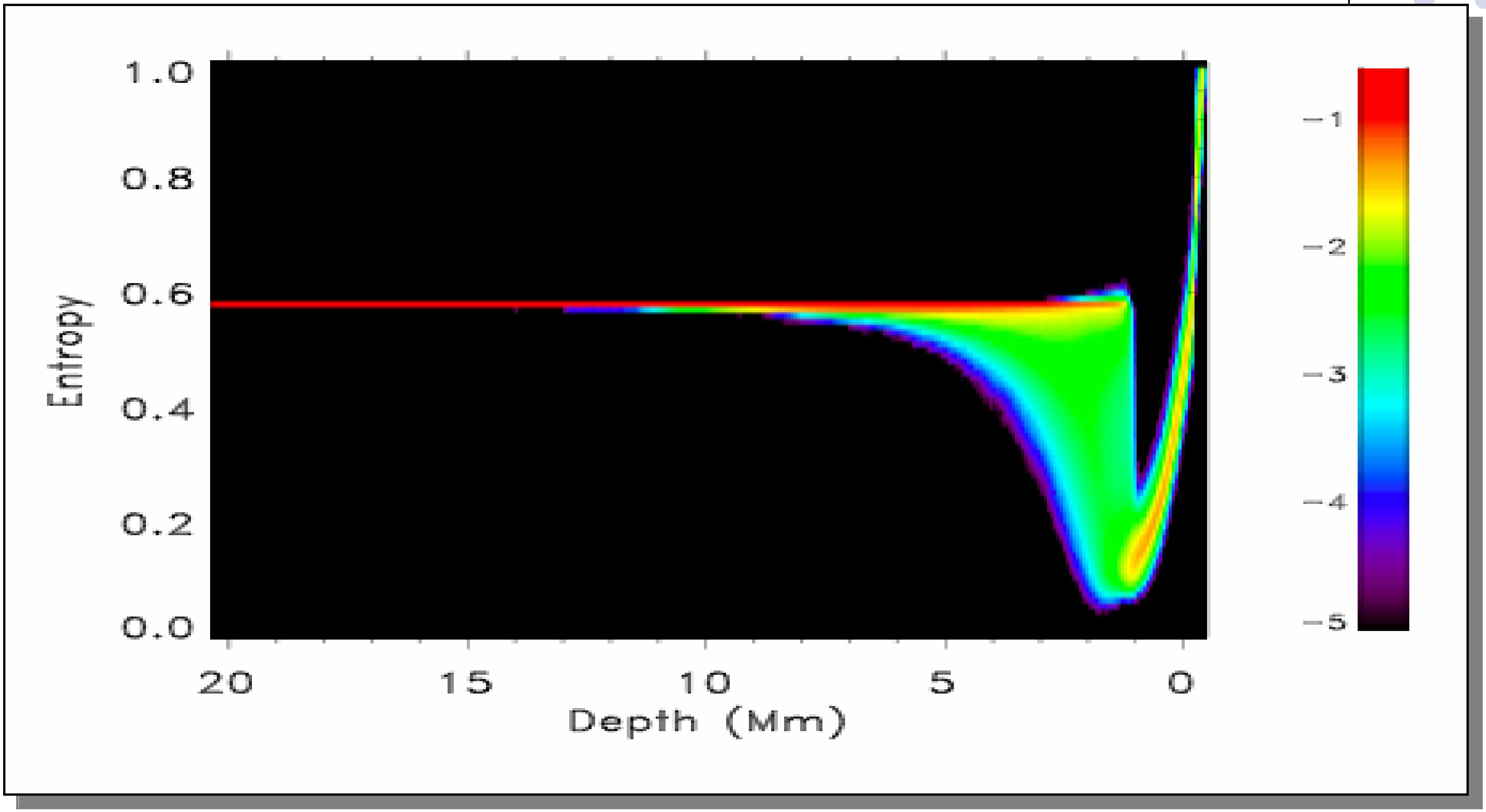
Mean stratification



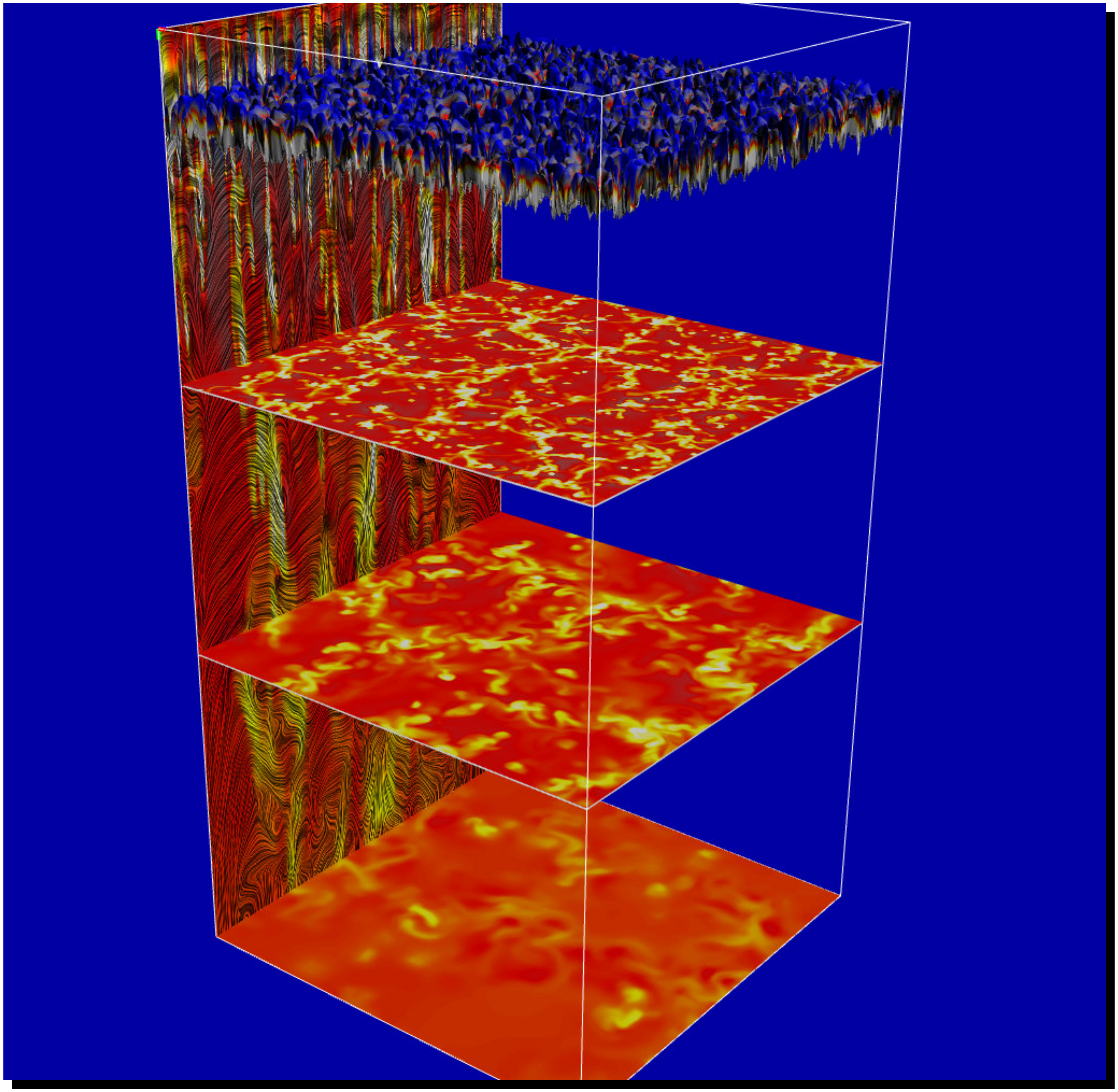
Ionization of H and He



Entropy Histogram

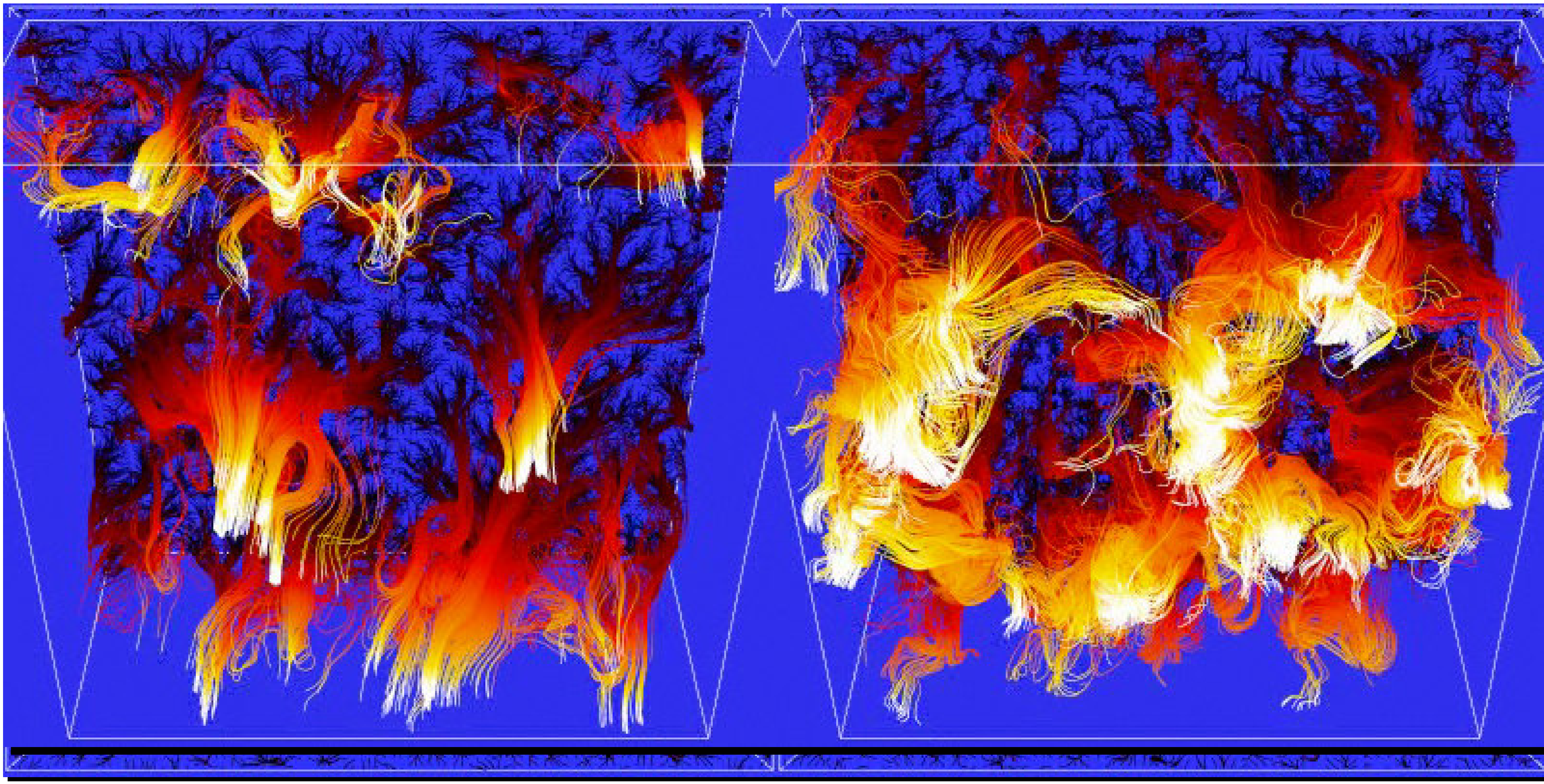


Velocity patterns

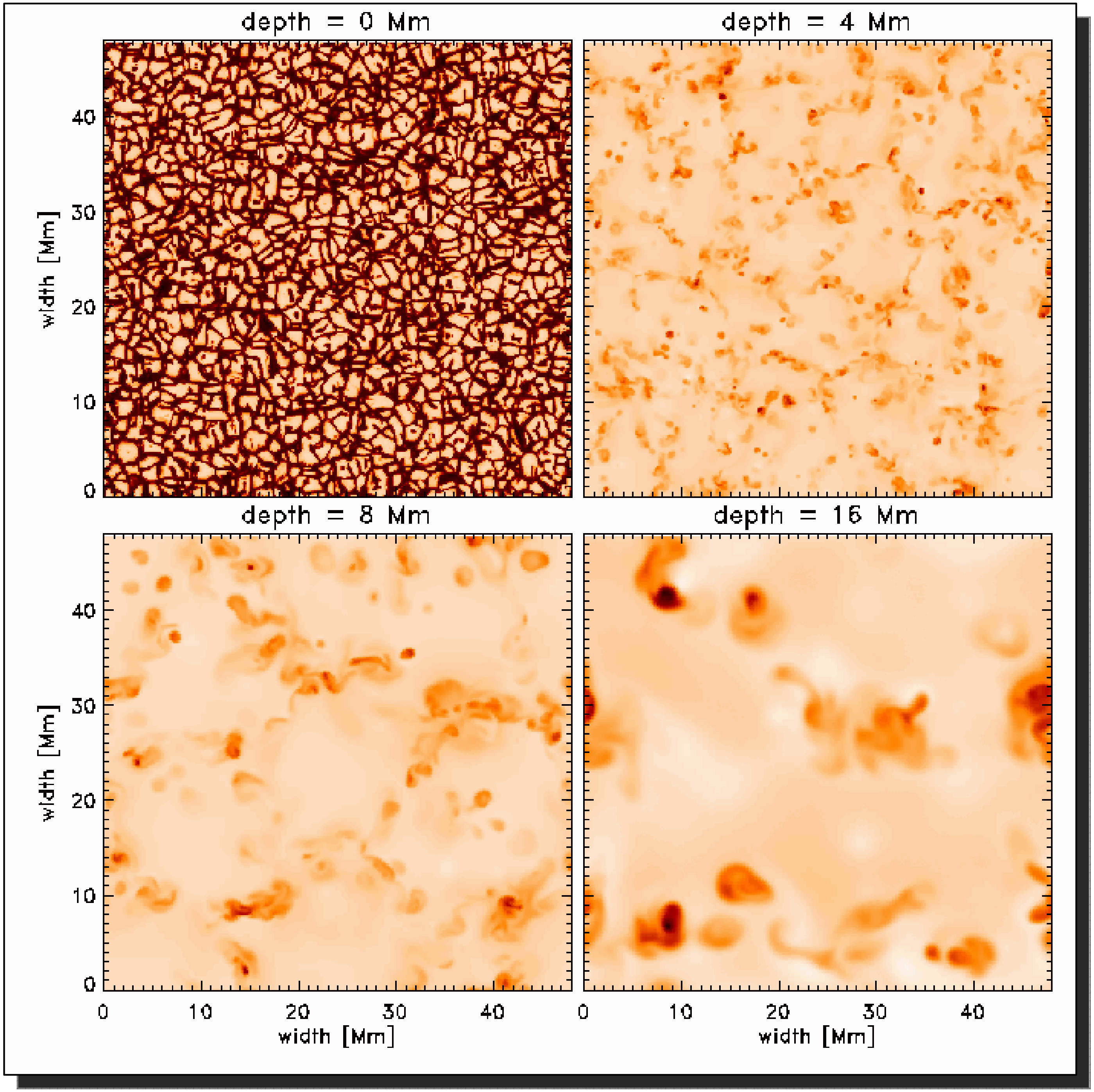


Upflows at surface come from small area at bottom (left)

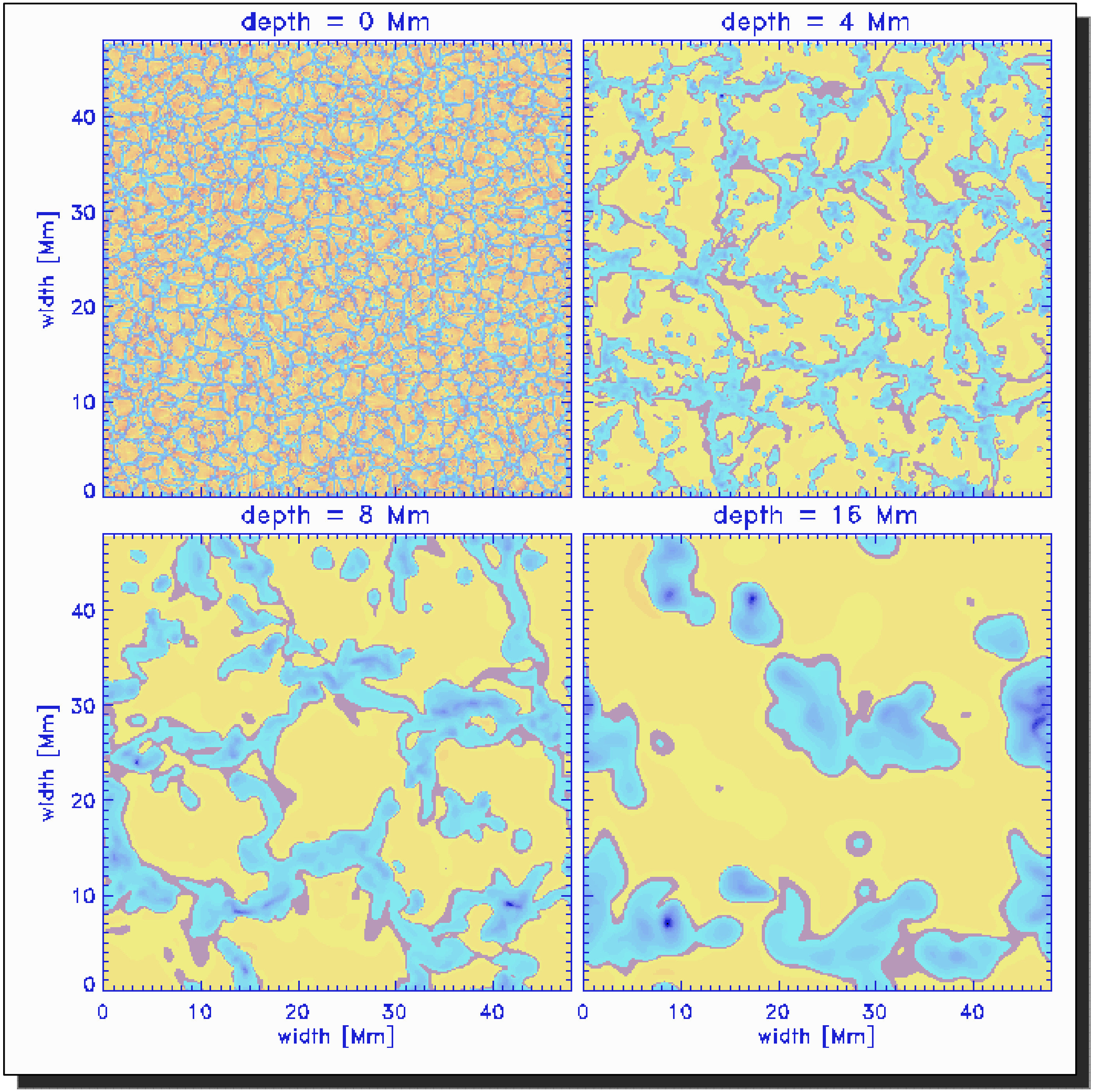
Downflows at surface converge to supergranule boundaries (right)



Temperature patterns at four different depths

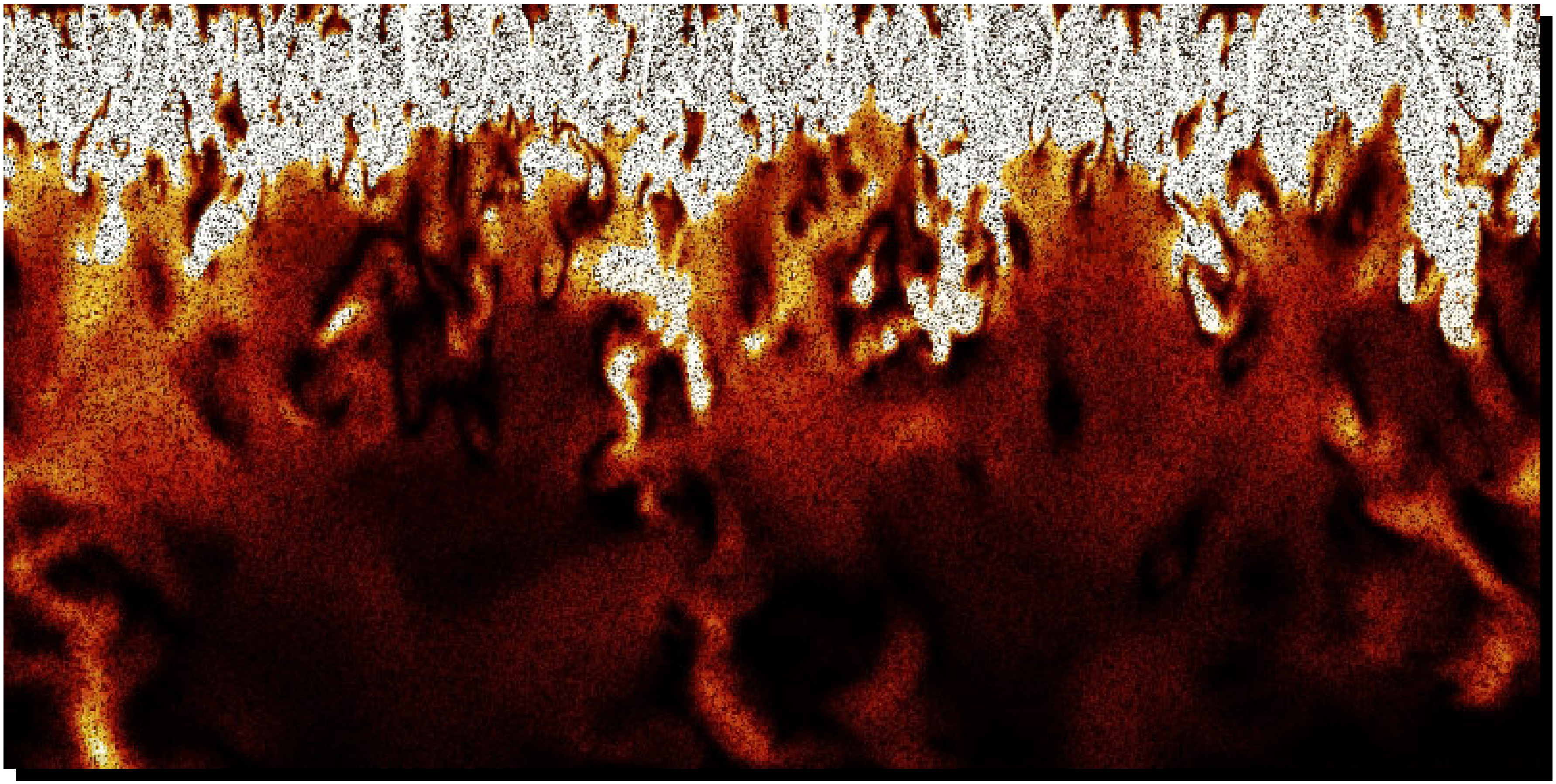


Velocities at the same depths



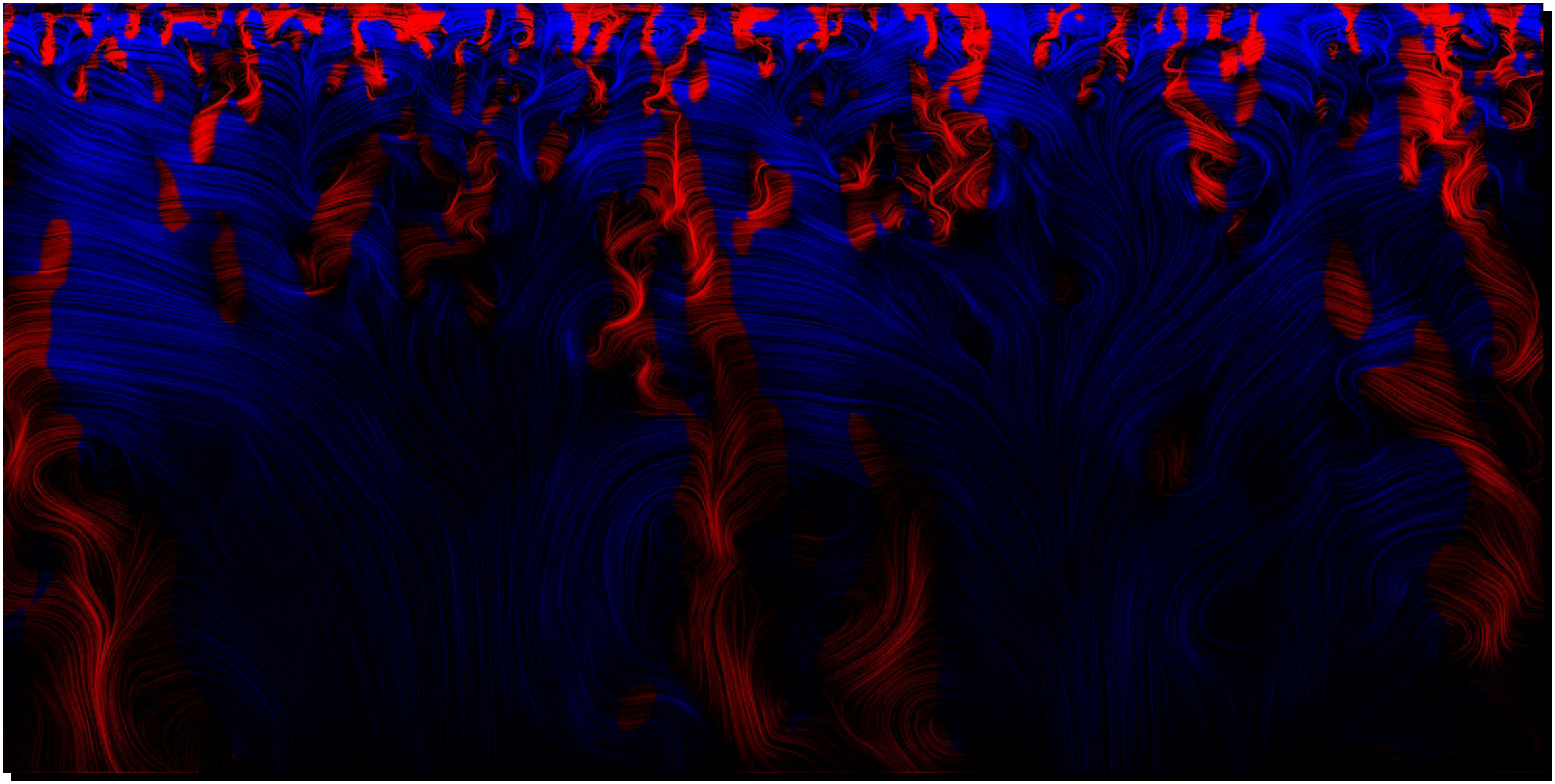
Large scale solar convection (48x48x20 Mm) -- Stein & Nordlund 2008

Finite lifetime corks, on top of color ~ velocity magnitude

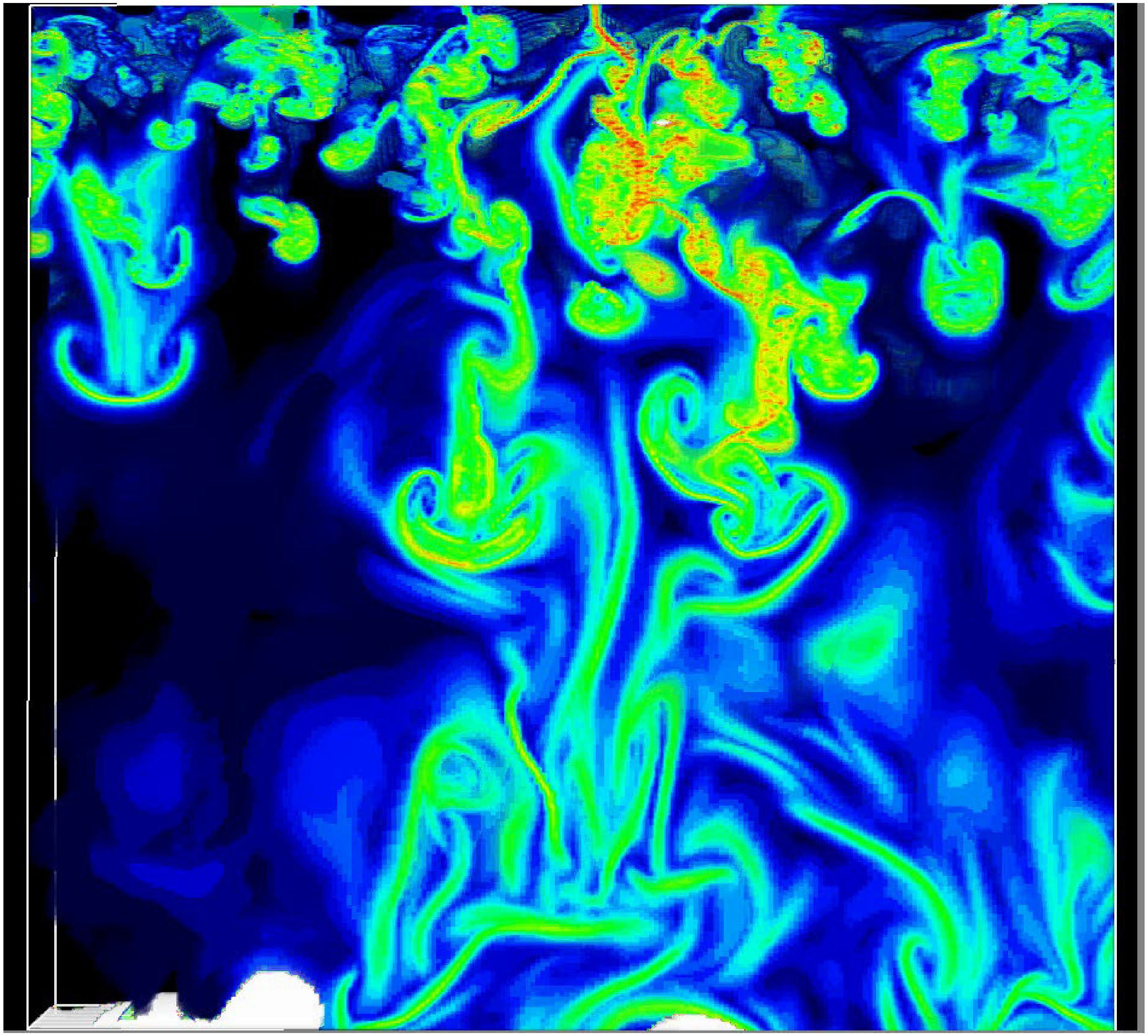


Large scale solar convection (48x48x20 Mm) -- Stein & Nordlund 2008

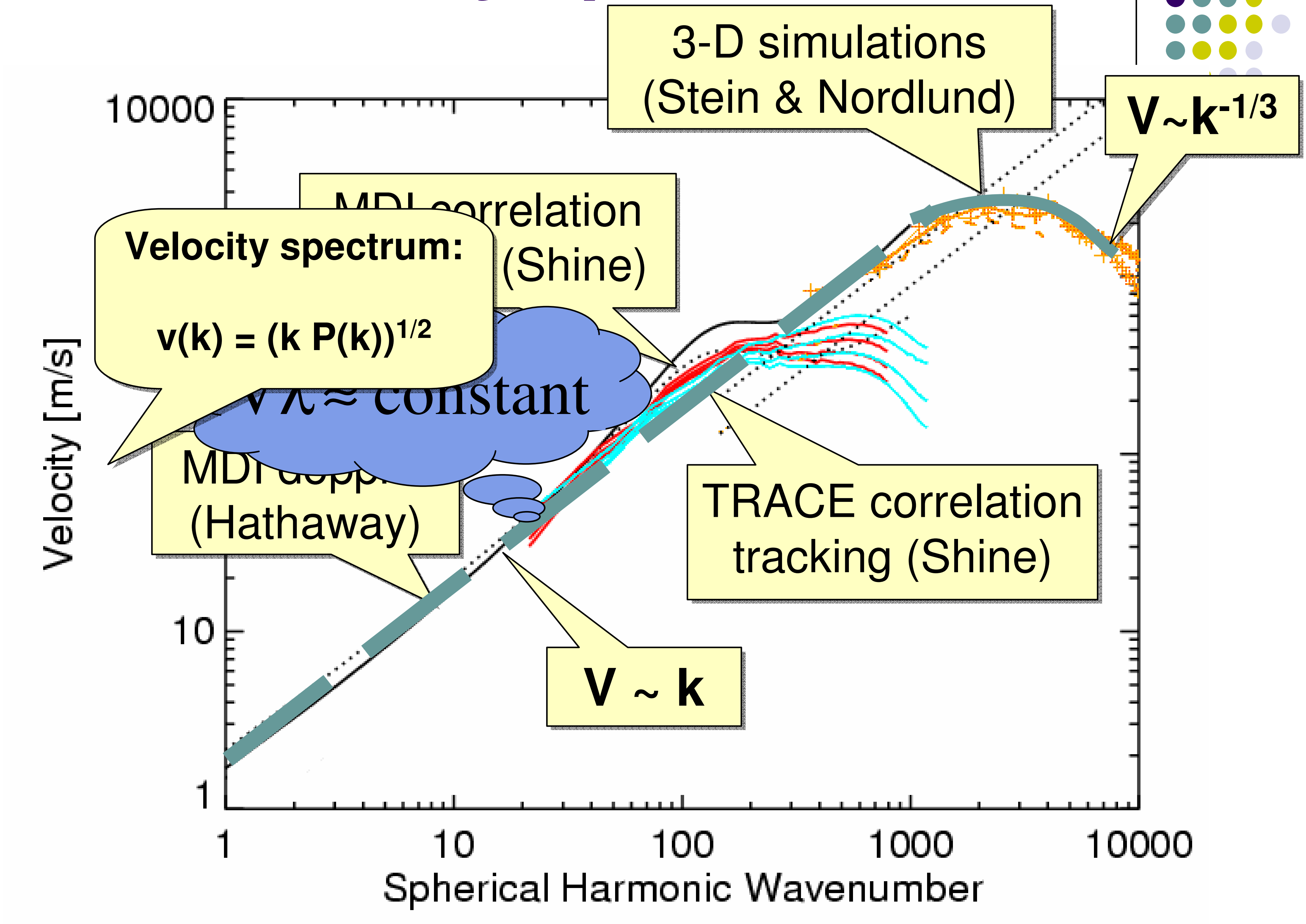
Blue and red show up and down velocity



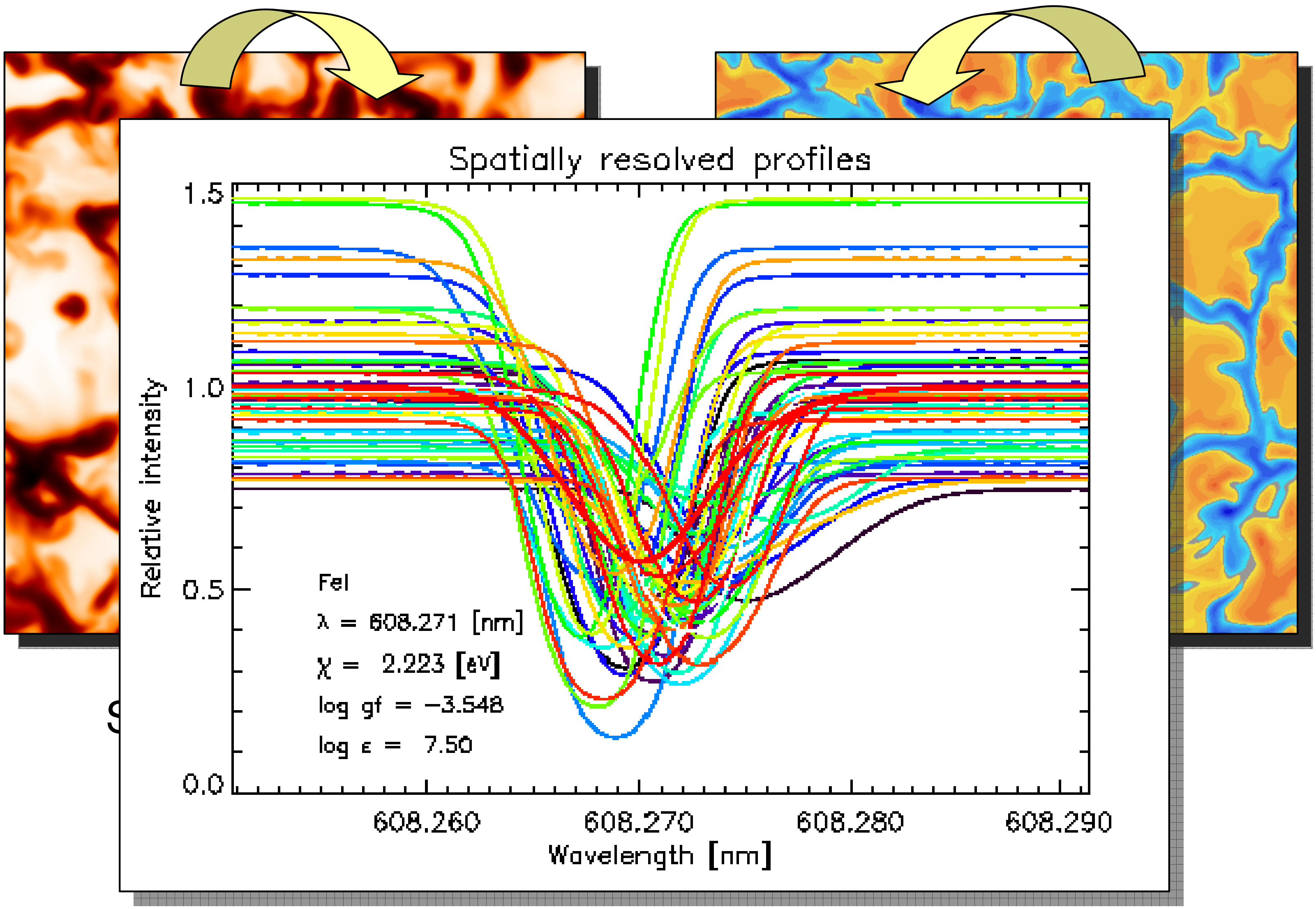
Vorticity



Solar velocity spectrum



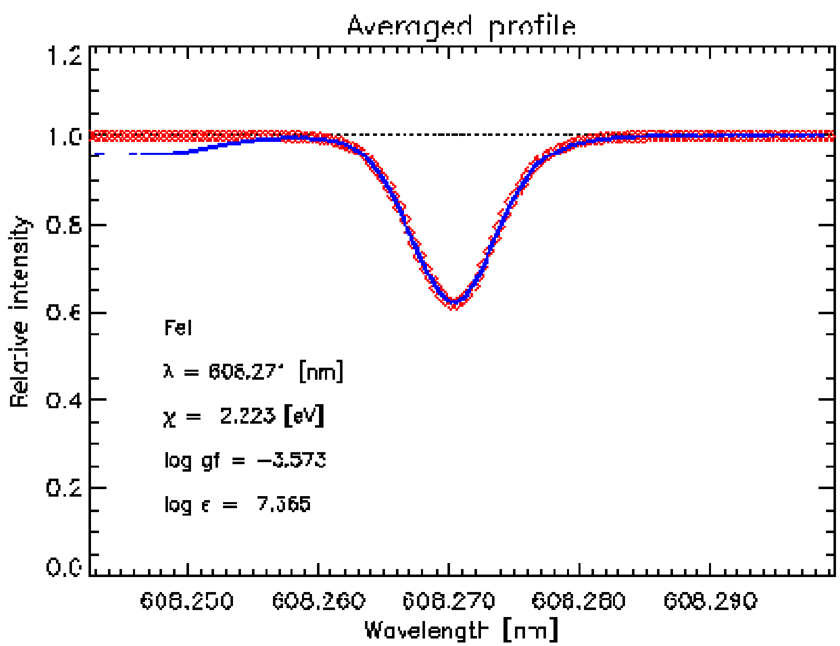
Synthetic solar spectral lines – a crucial fingerprint!

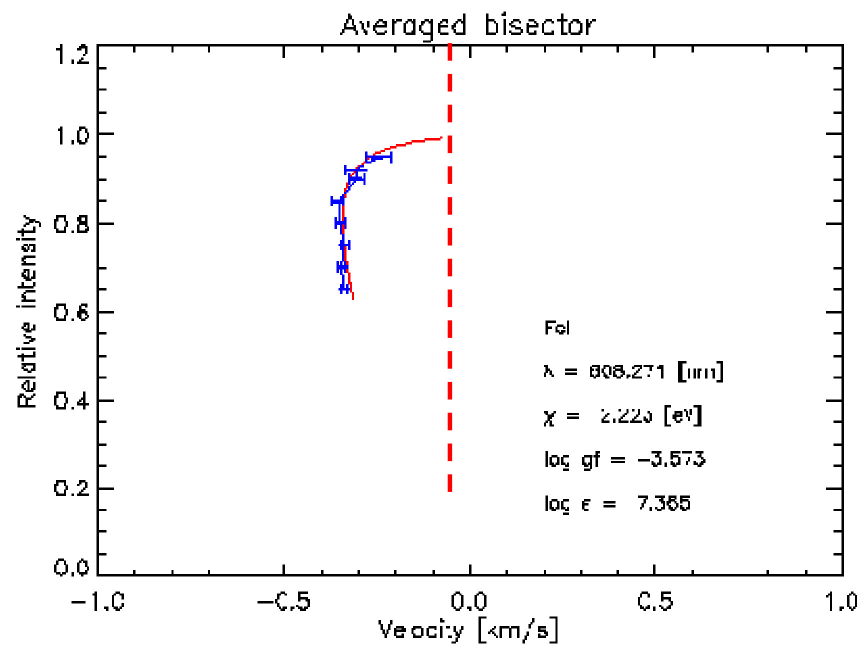


Spatially resolved spectral line profiles

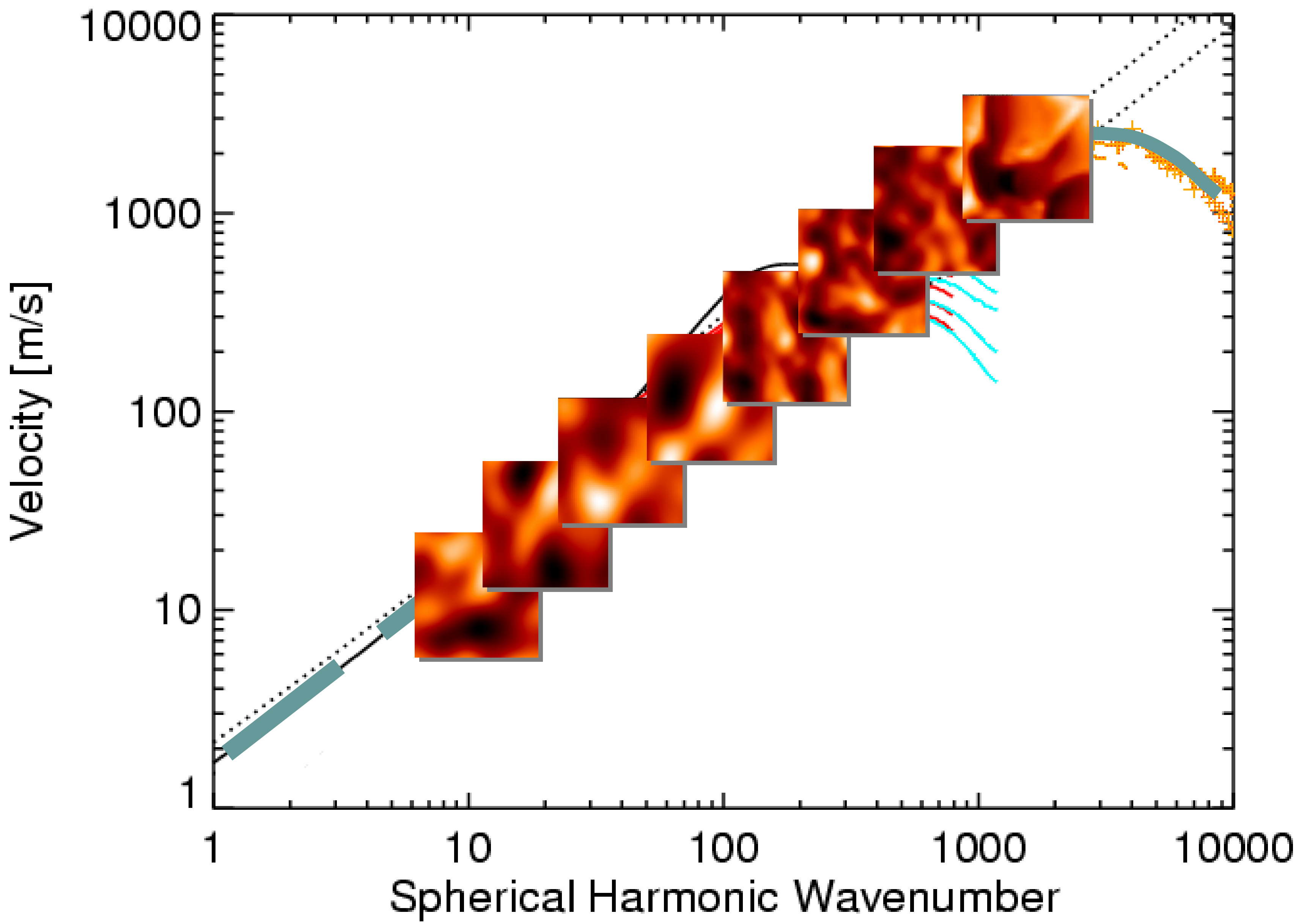
Accurate match; widths, shapes *and* shifts!

- **<u>Requires</u>** that both ***temperature and velocity amplitudes are accurate***!
- **<u>Proves</u>** that dissipation is practically ***identical at model and solar Reynolds numbers!***

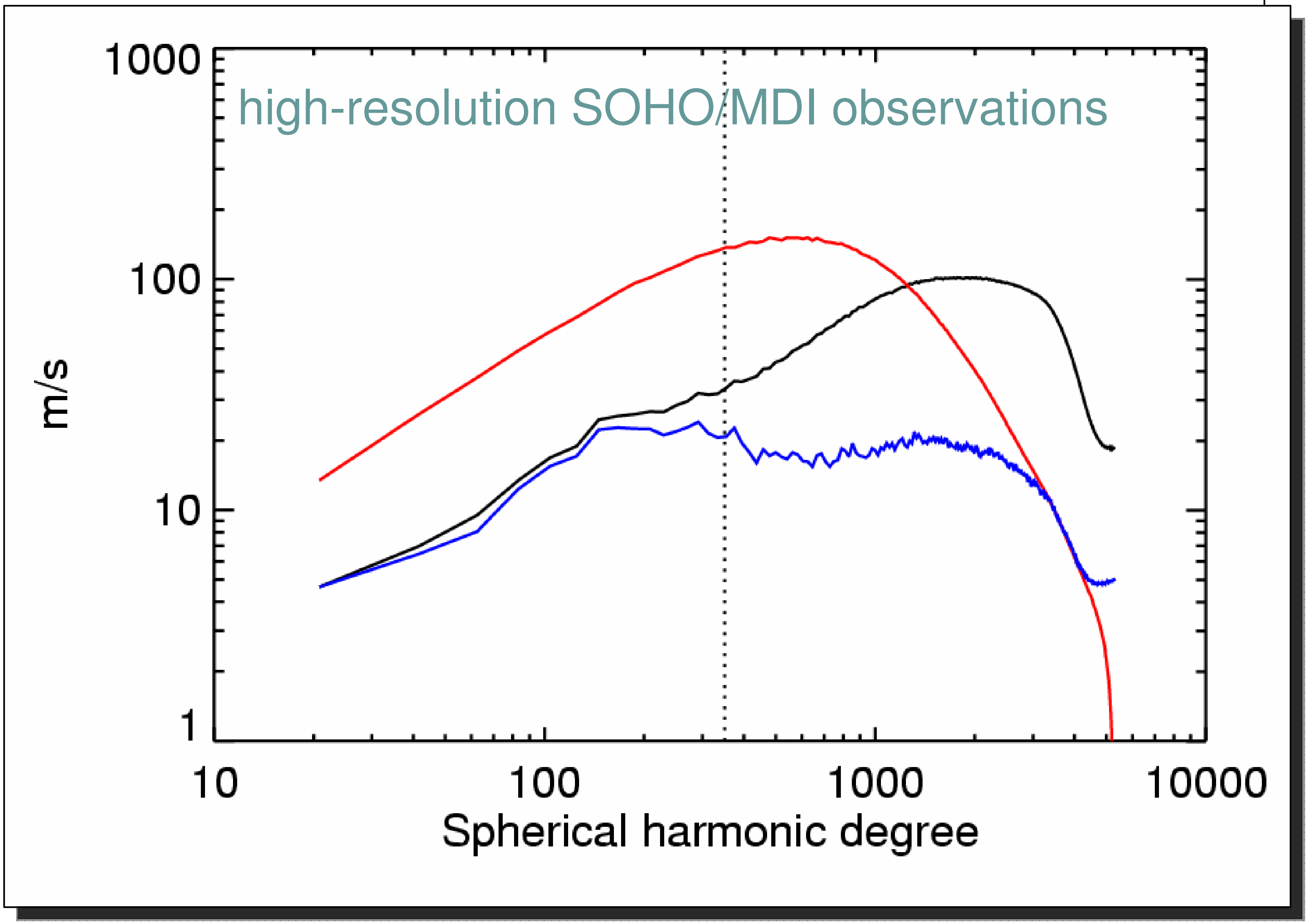




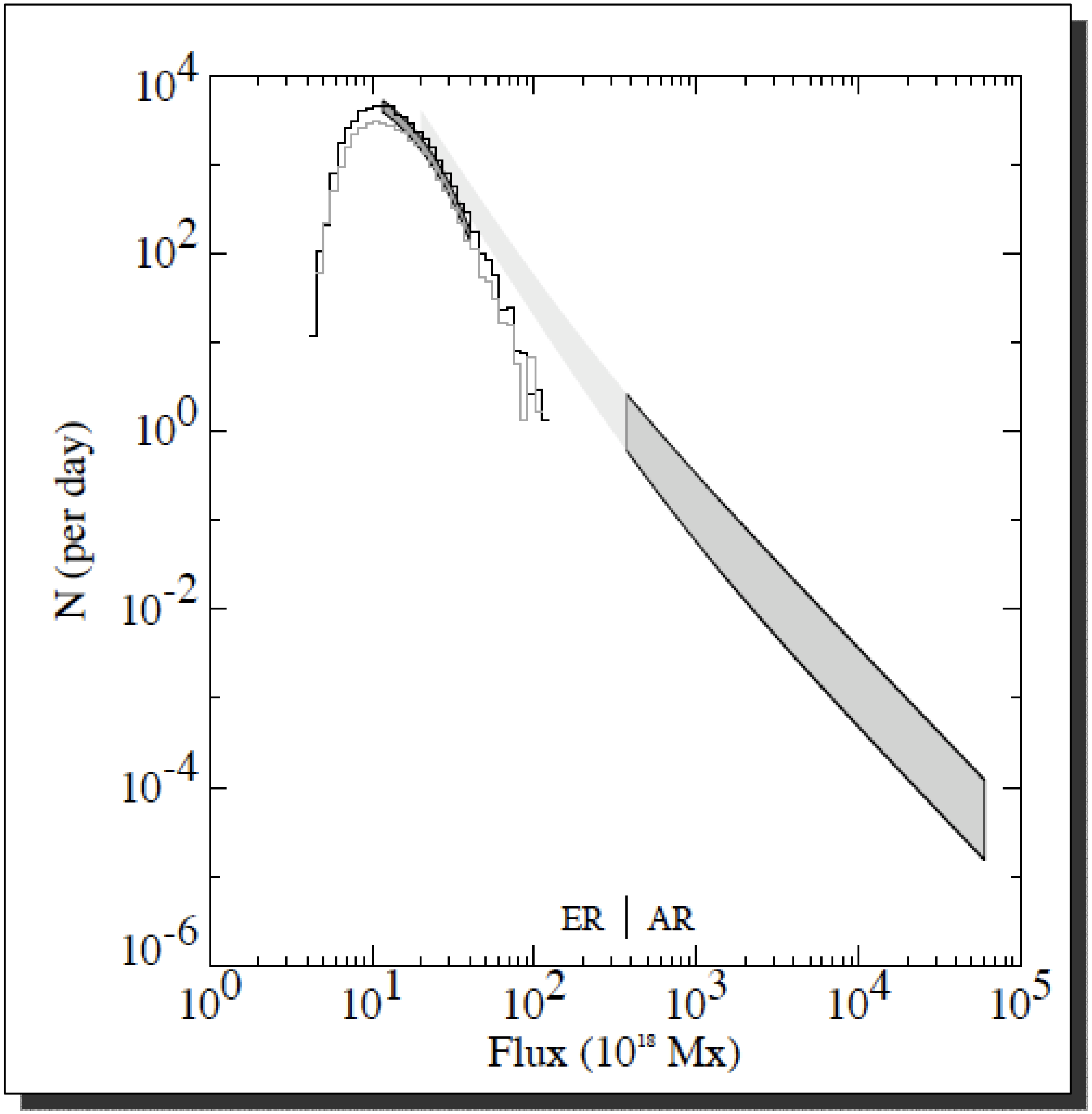
Solar velocity spectrum – observations and simulations



oscillation power (red), convective power (black) – time average (blue)



Near-scale free surface magnetic flux distribution



Magnetic field patterns and distributions also show self-similarity

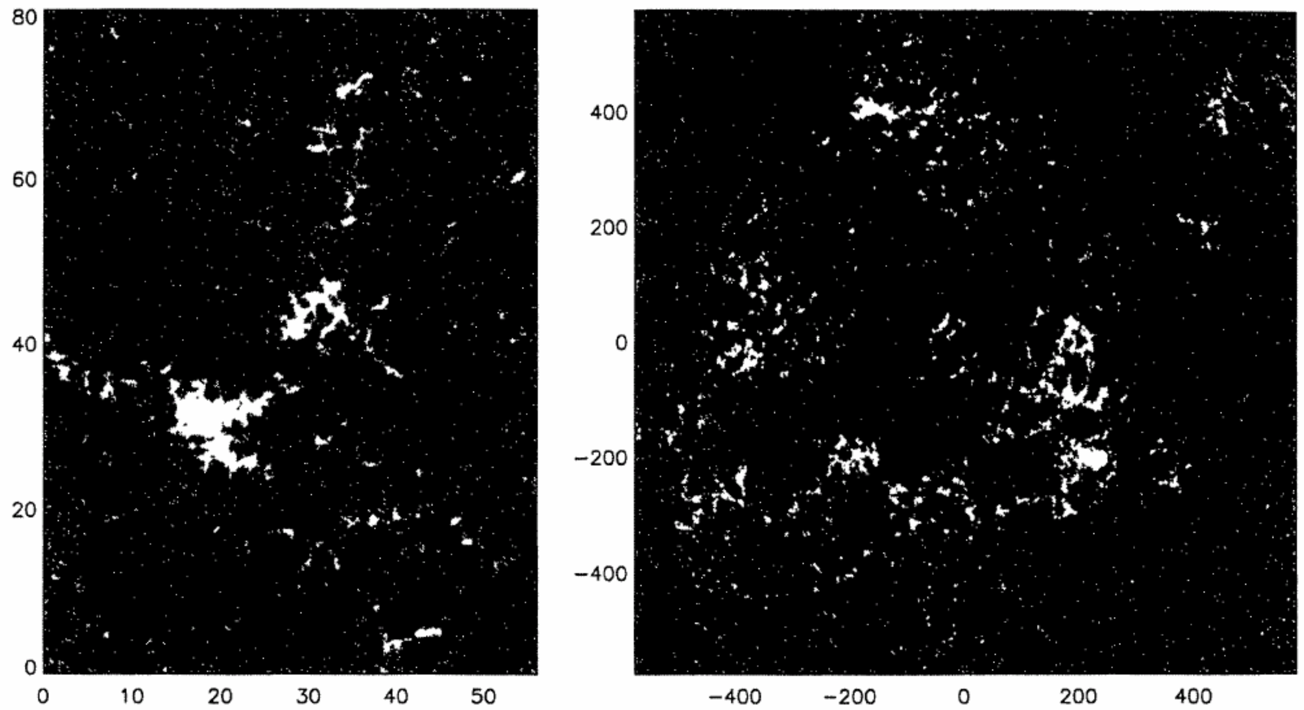


Figure 1. Illustration of pattern self-similarity over a large dynamic range. The La Palma high-resolution magnetogram (left panel), obtained on 9 February 1996, covers an area at the center of the quiet Sun that is only 0.35 % of the area covered by the MDI magnetogram in the right panel, obtained on 20 March 2002. The spatial scale is given in arcsec. The grey scale cuts are identical for the two magnetograms: white represents +100 G, dark −100 G. Although the MDI magnetogram contains many active regions with sunspots, both the morphology and field-strength distribution are similar in the two magnetograms.

Stenflo & Holzreuter 2002

Magnetic field patterns and distributions also show self-similarity

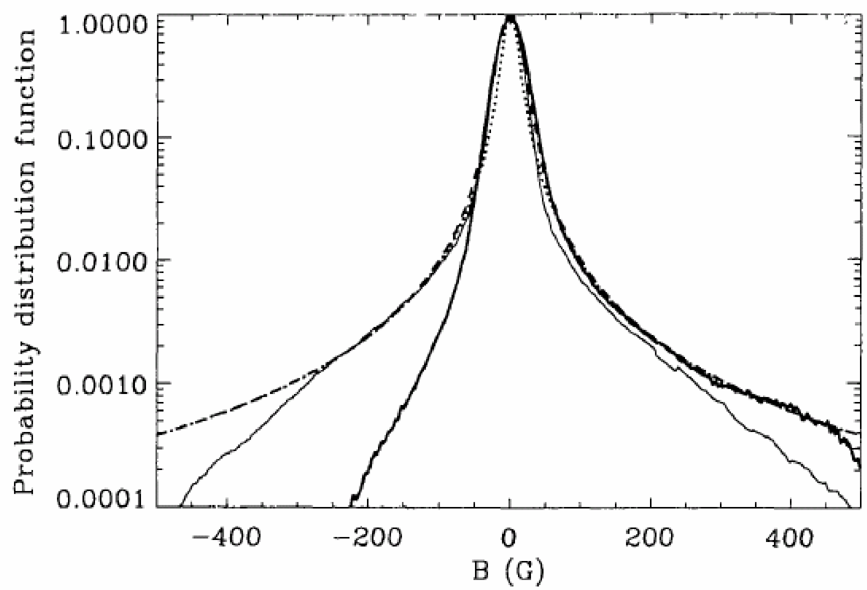


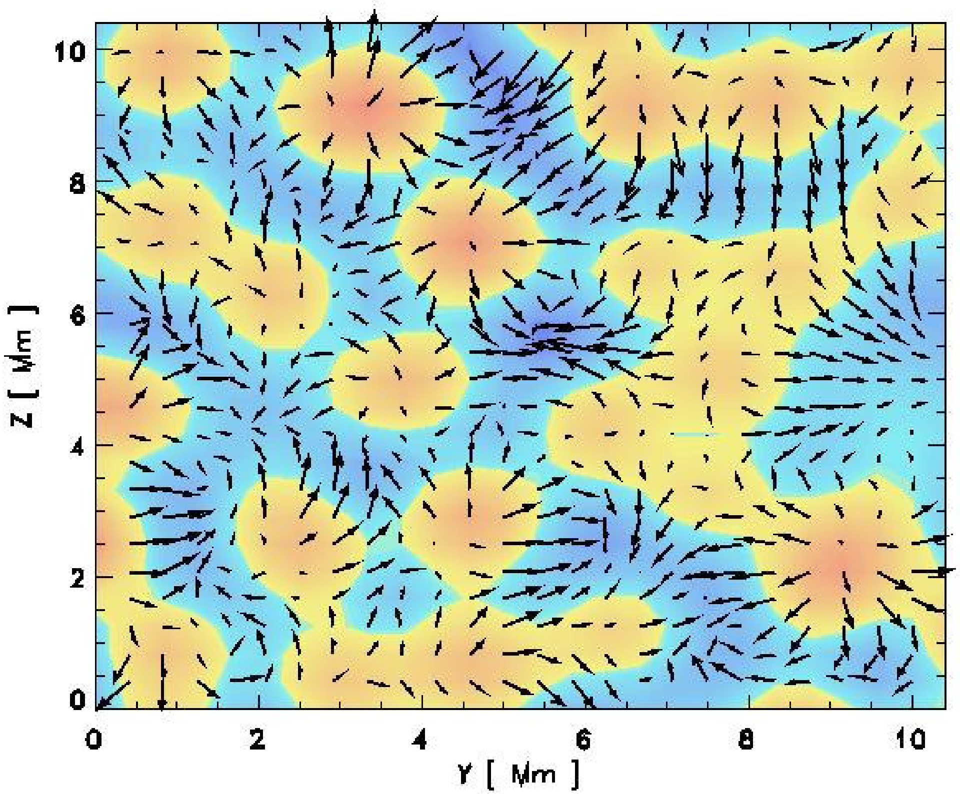
Figure 2. *Probability distribution functions (PDF) for the La Palma magnetogram (thick solid line) and the MDI magnetogram (thin solid line). The dashed and dotted curves represent two Voigt functions: the dashed curve has a "Doppler width" of 17.0 G, while the dotted curve that represents a "noise-free" PDF has a "Doppler width" of 6.0 G.*

Figure 1. … *magnetogra…* … *only 0.35 %* … *spatial scale* … *+100 G, da…* … *morphology* … *-resolution* … *Sun that is* … *2002. The* … *represents* … *s, both the*

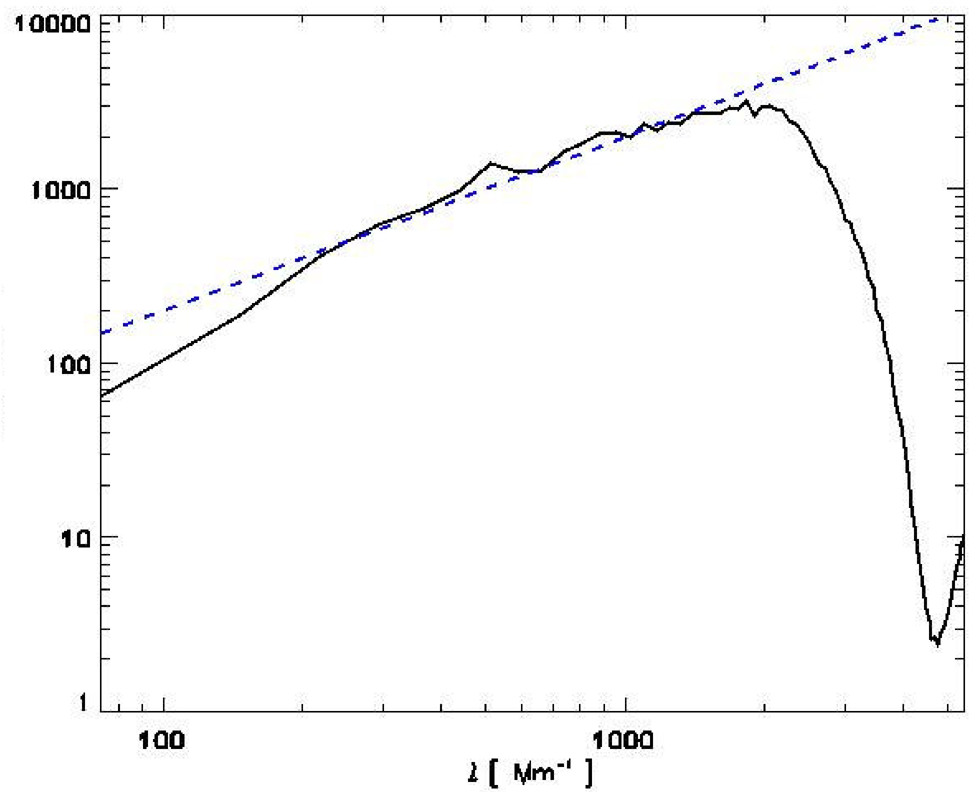
Stenflo & Holzreuter 2002

Velocity driving for the corona

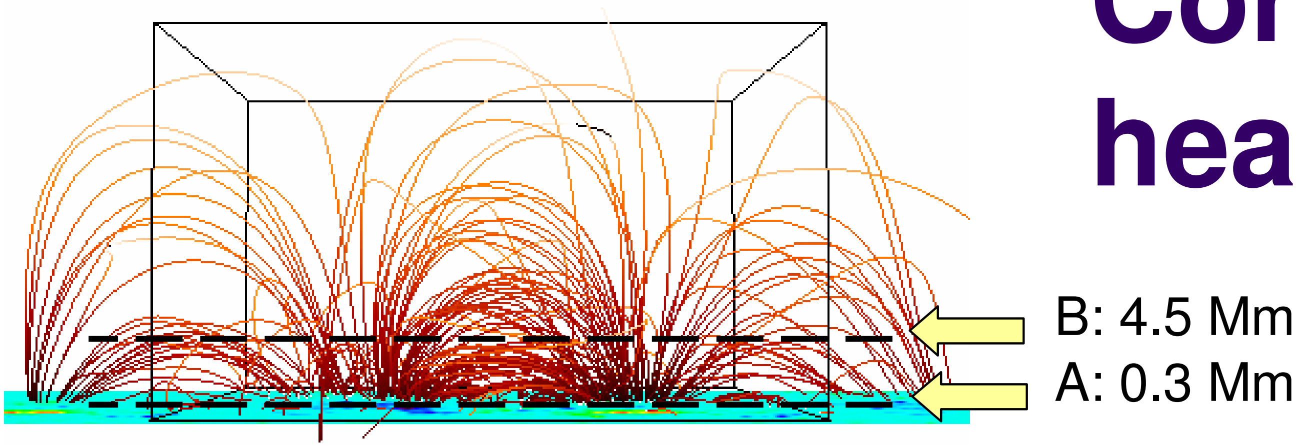
Voronoi tessellation ensemble

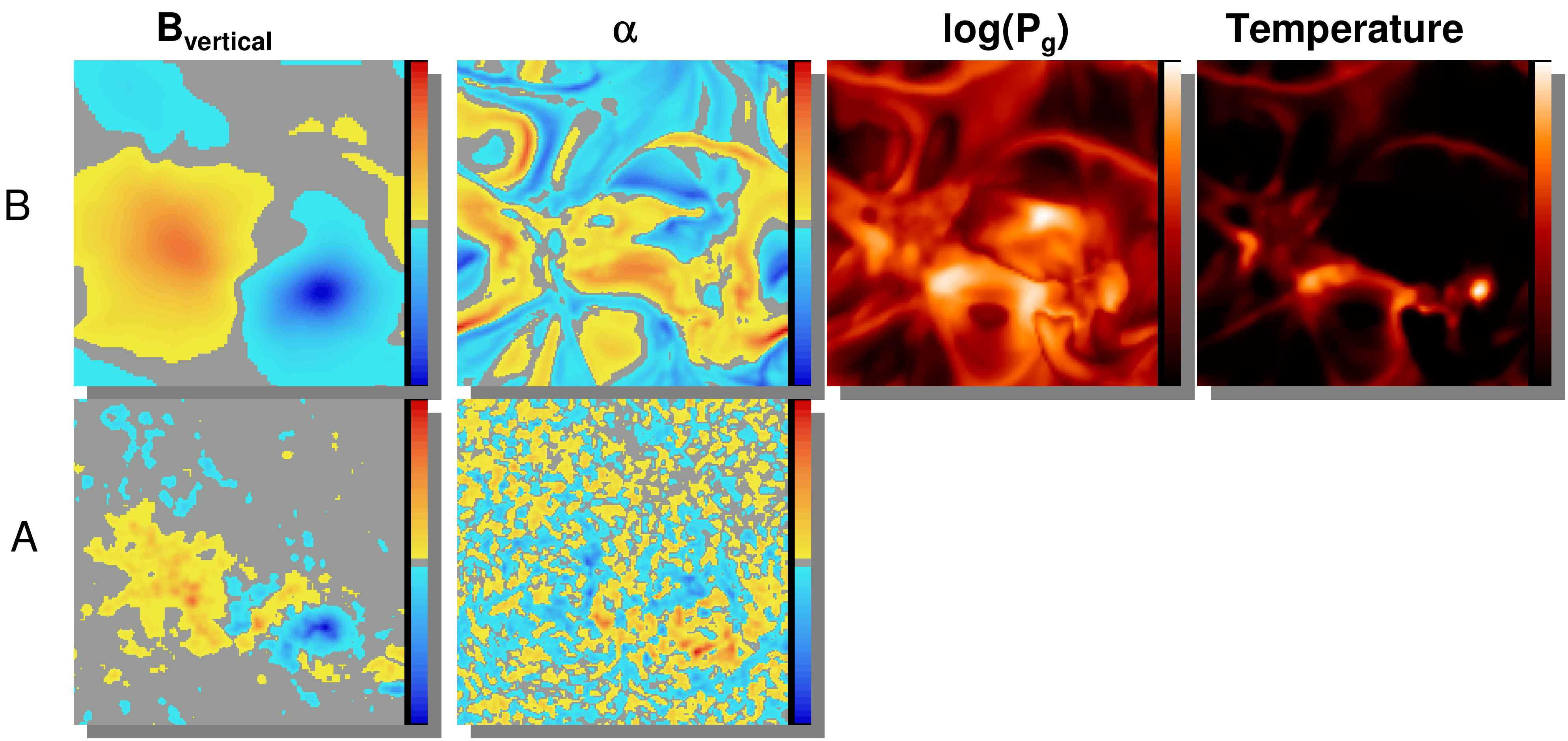


Velocity spectrum from three superposed ensembles



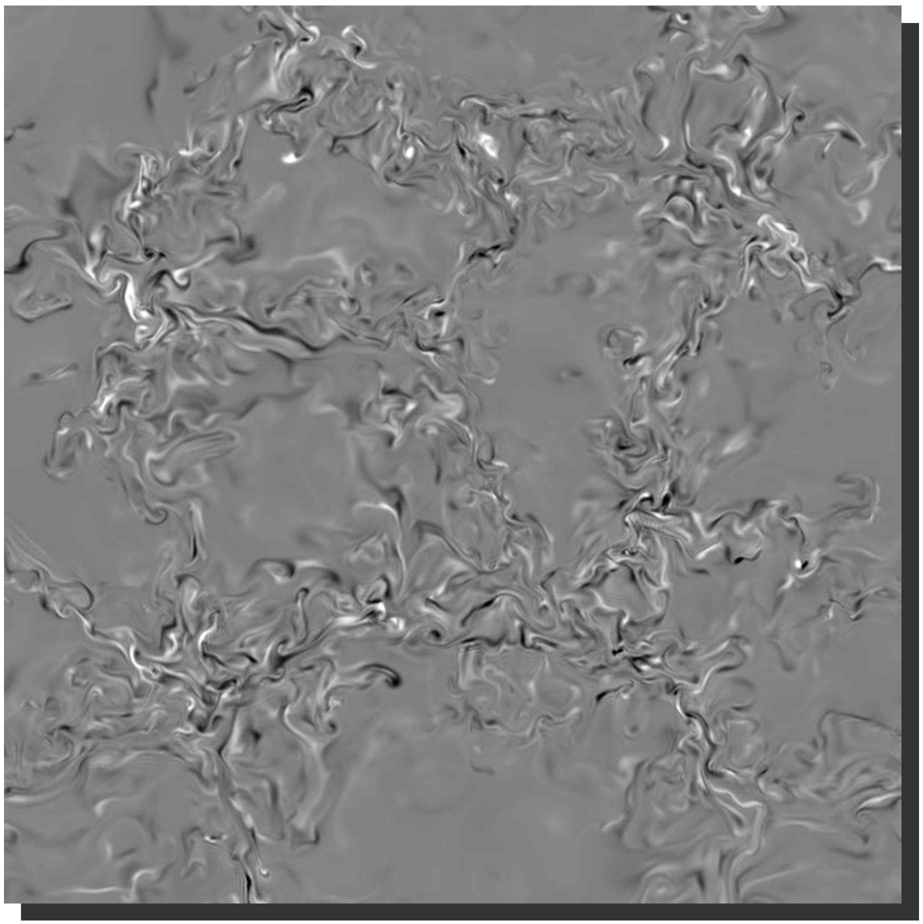
Coronal heating

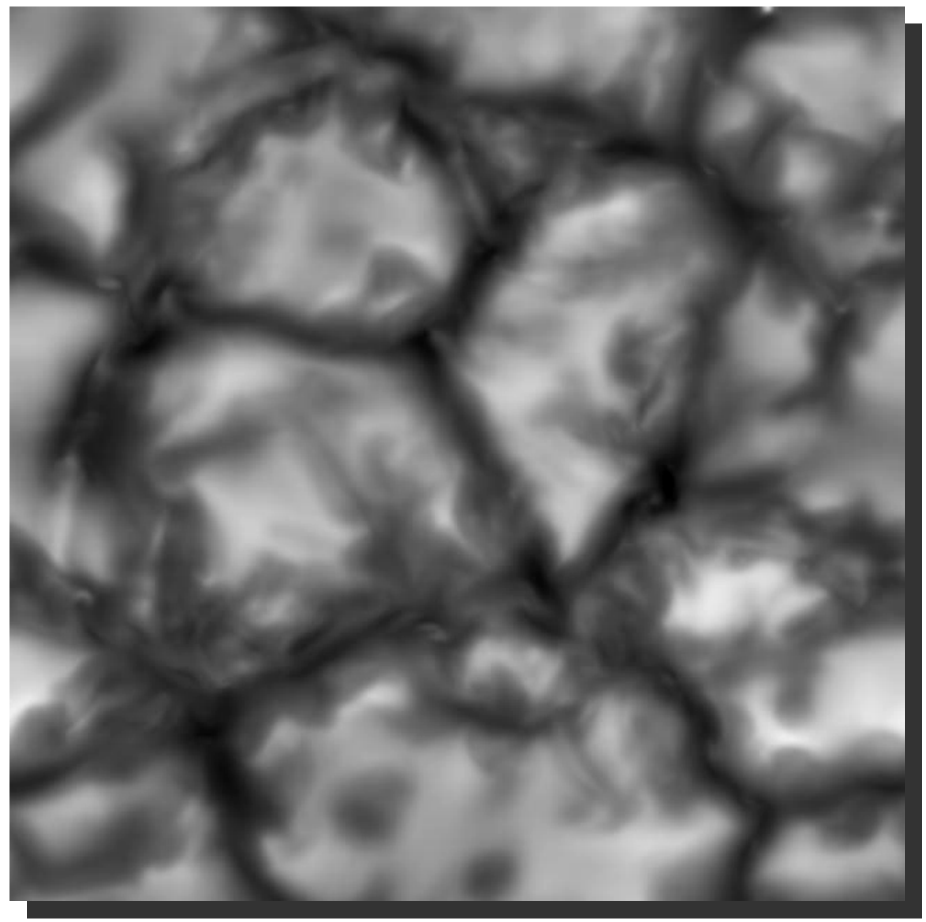




Local dynamo action in surface convection

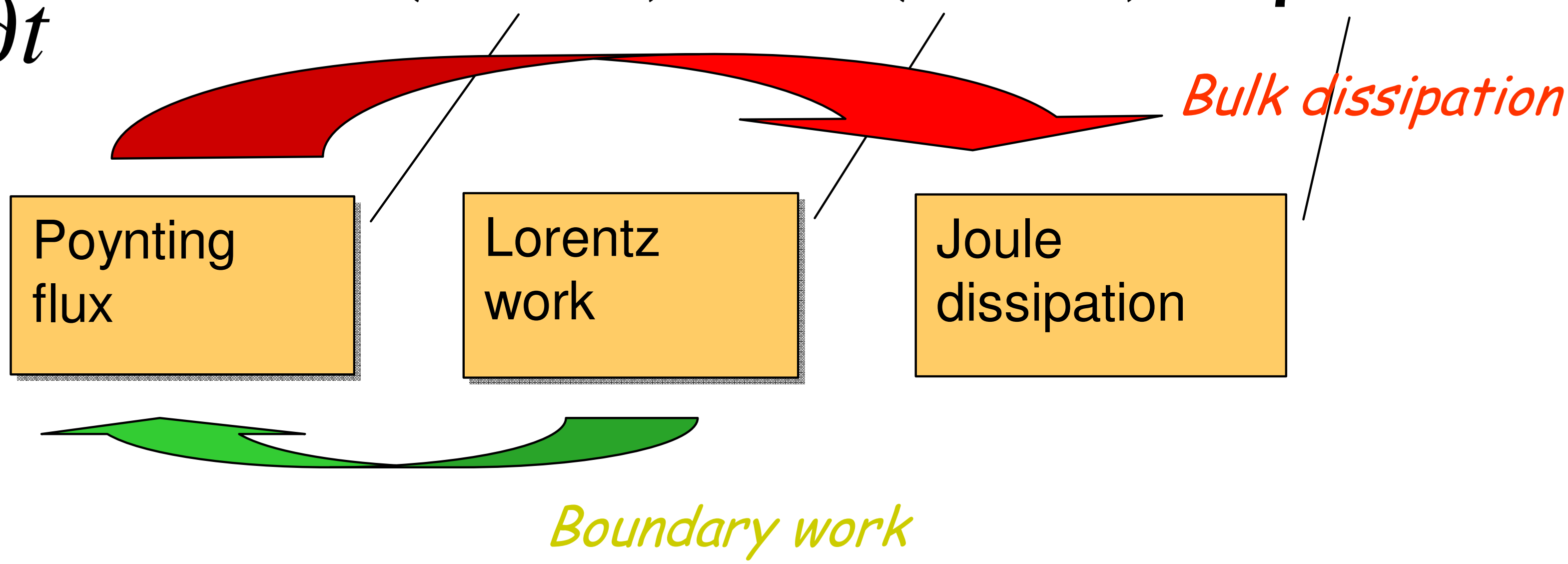
(Vögler & Schüssler, 2007)





Magnetic energy equation

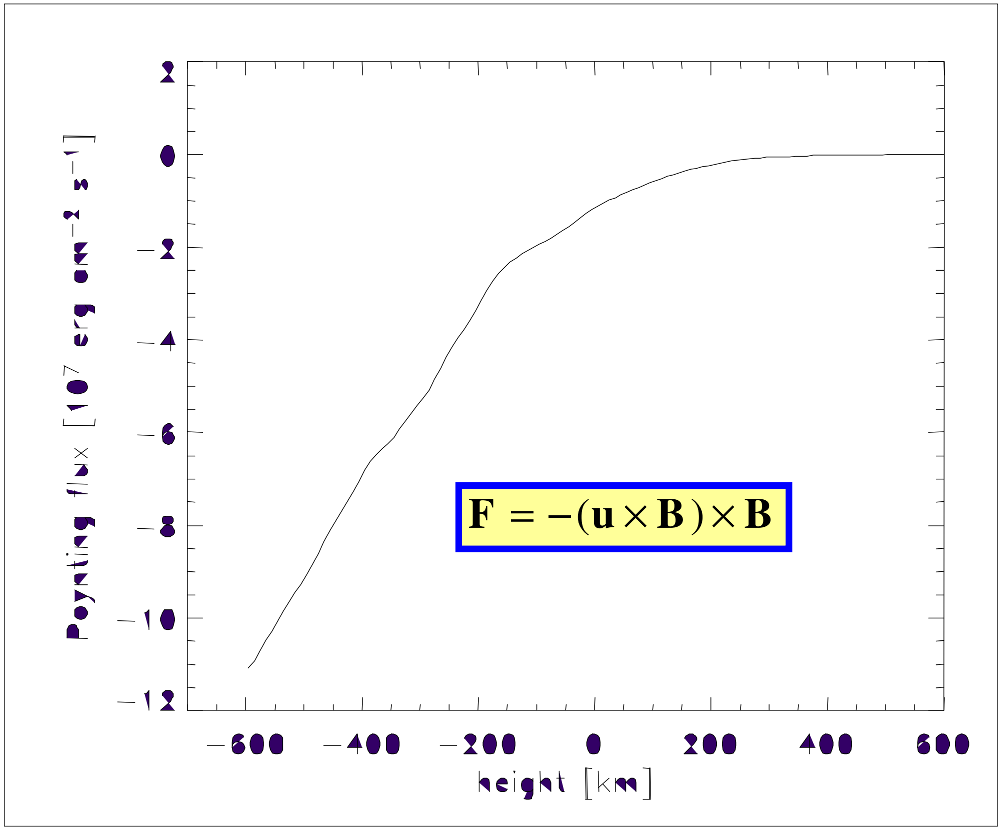
$$\frac{\partial E_B}{\partial t} = -\nabla \cdot (\vec{E} \times \vec{B}) - \underline{u} \cdot (\vec{J} \times \vec{B}) - \eta J^2$$



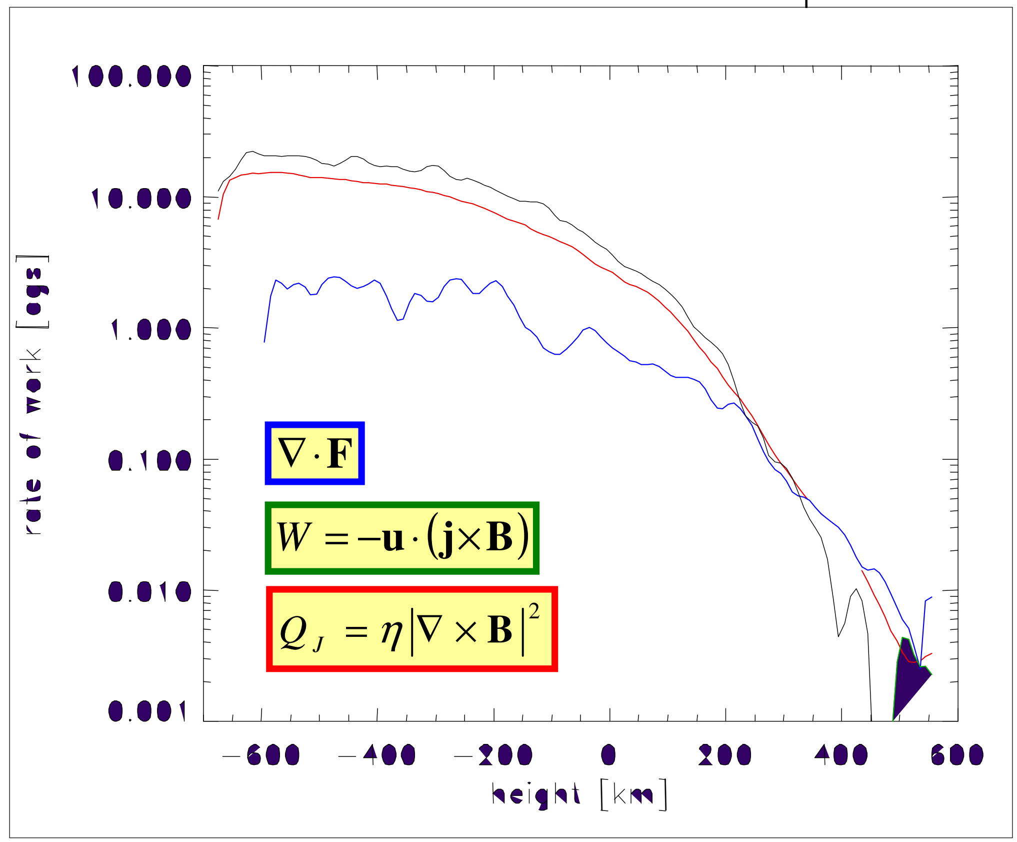
- Poynting flux: energy input; e.g. boundary work
- Lorentz work: drives, supports energy dissipation
- Joule dissipation: supports radiative losses

Distributed dynamo action

Poynting Flux



Energy Balance

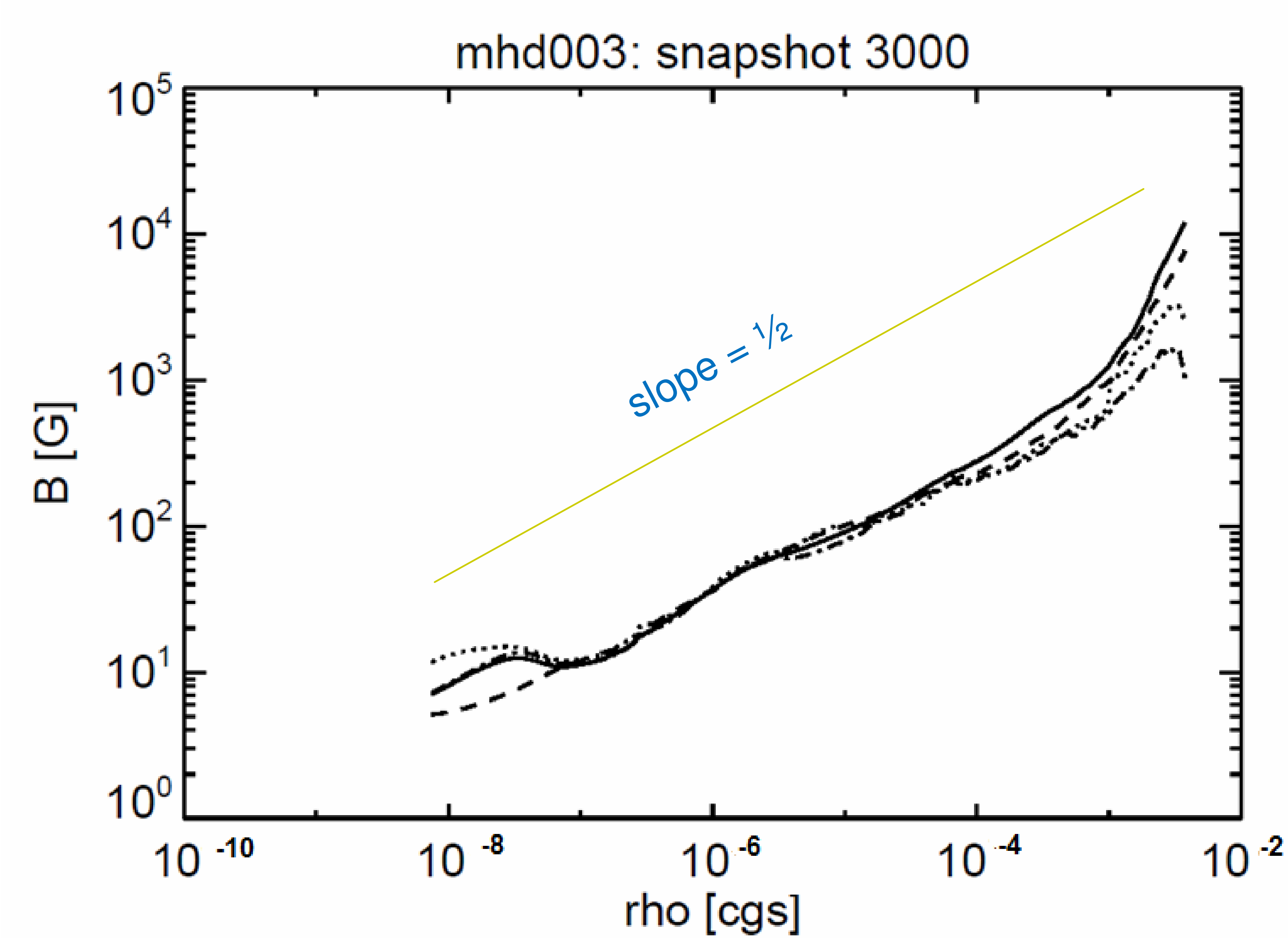


Negative Poynting flux → Convective pumping into deeper layers

$\nabla\cdot\mathrm{F}/(W-Q_J)\approx 0.8$ → large part of net energy input lost due to downward pumping

Generalize this!

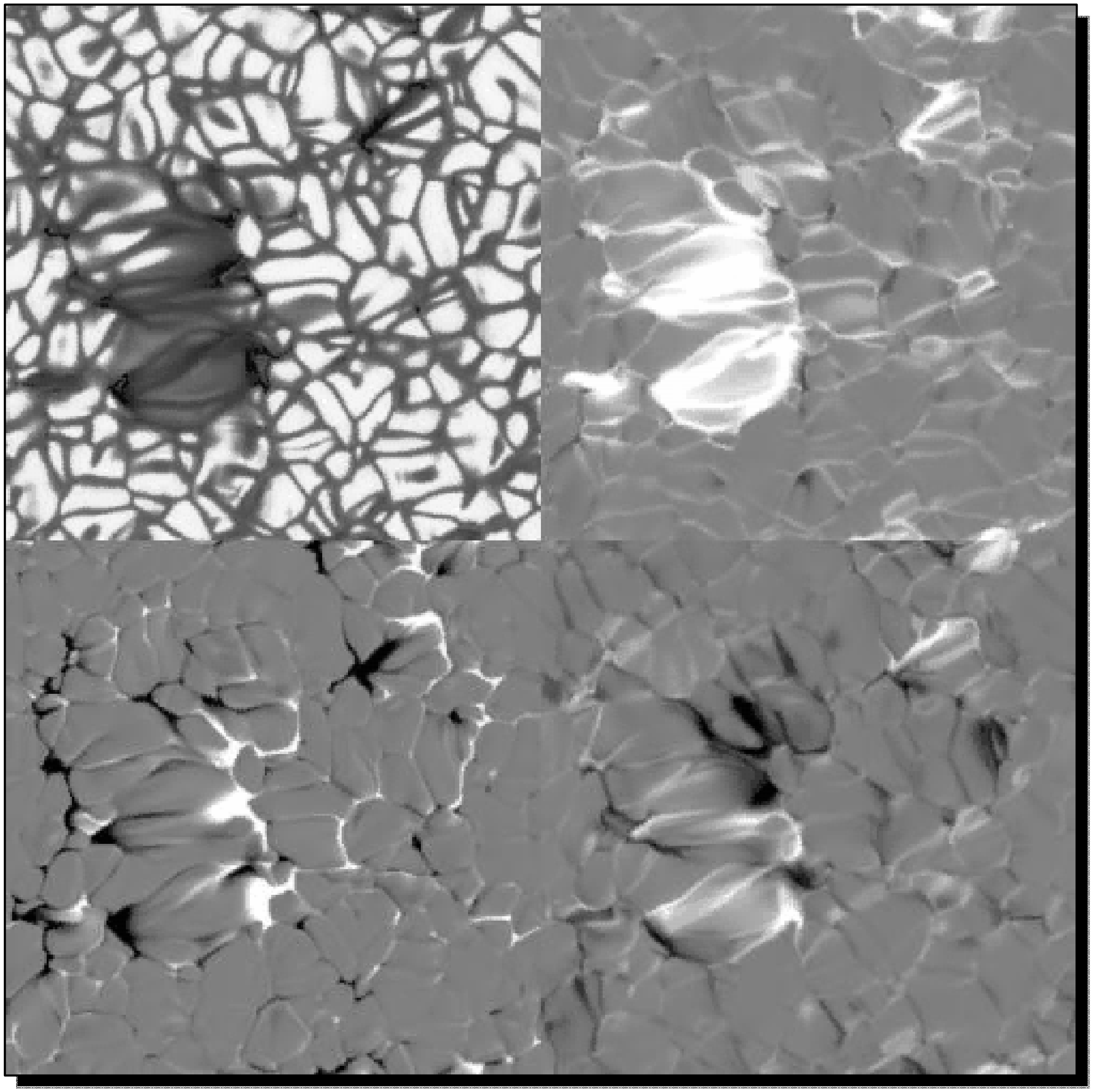
- Likely that there is net small scale dynamo action at each depth in the CZ!
  - Net magnetic energy delivered to the next layer
- On the largest scale = largest depths (and only there) differential rotation enables a large scale – global – dynamo action
  - With buoyancy eventually pushing the field back up



The scaling of average (full drawn) and fluctuating magnetic field components (x:dotted, y:dashed, z:dot-dashed) after 25 solar hours.

A2

24x24x20 Mm magnetoconvection Horizontal boundary field

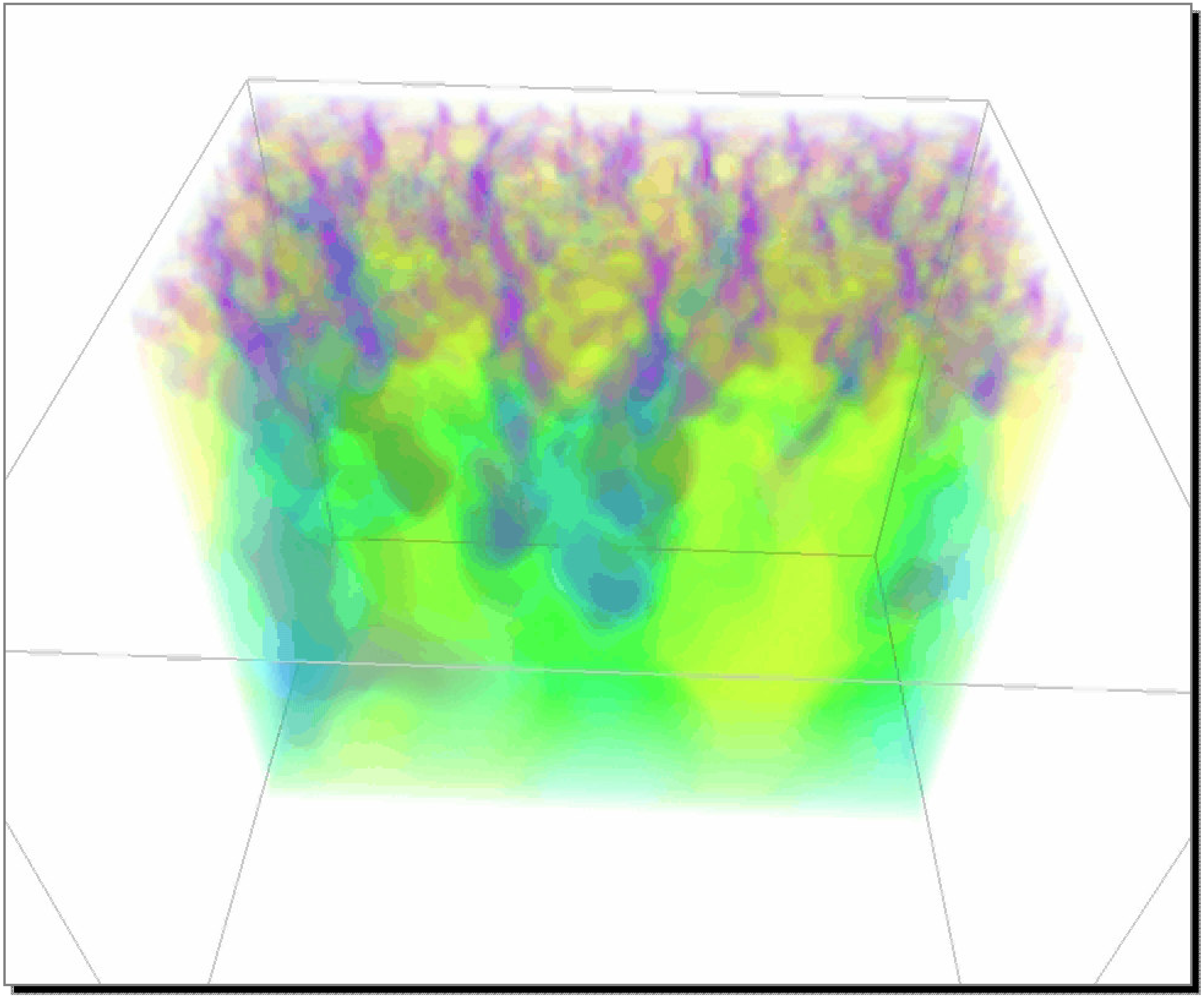


Slide 31

A2 Aake, 6/22/2008

A1

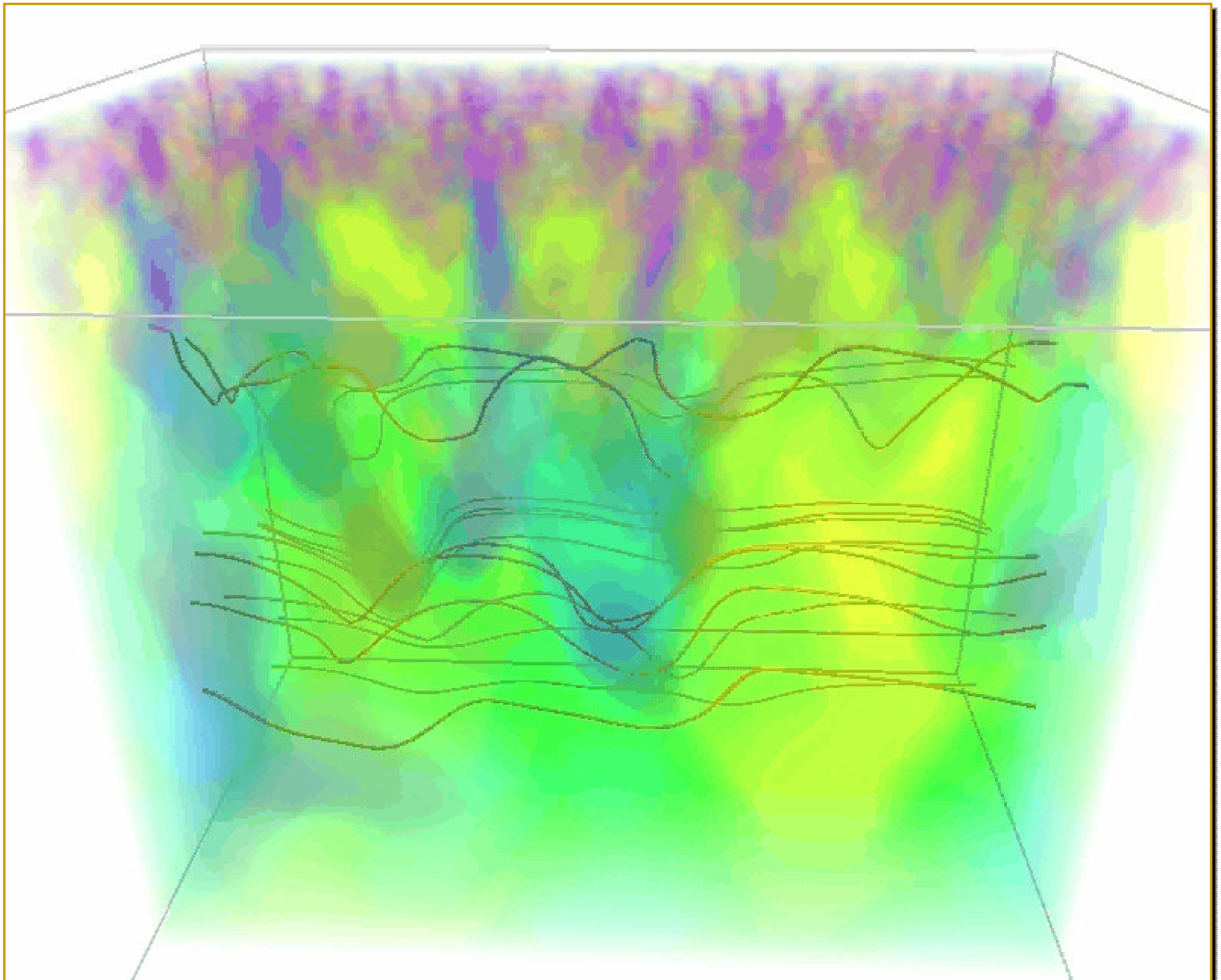
Multi-scale convection; 24x24x20 Mm (cut-out)

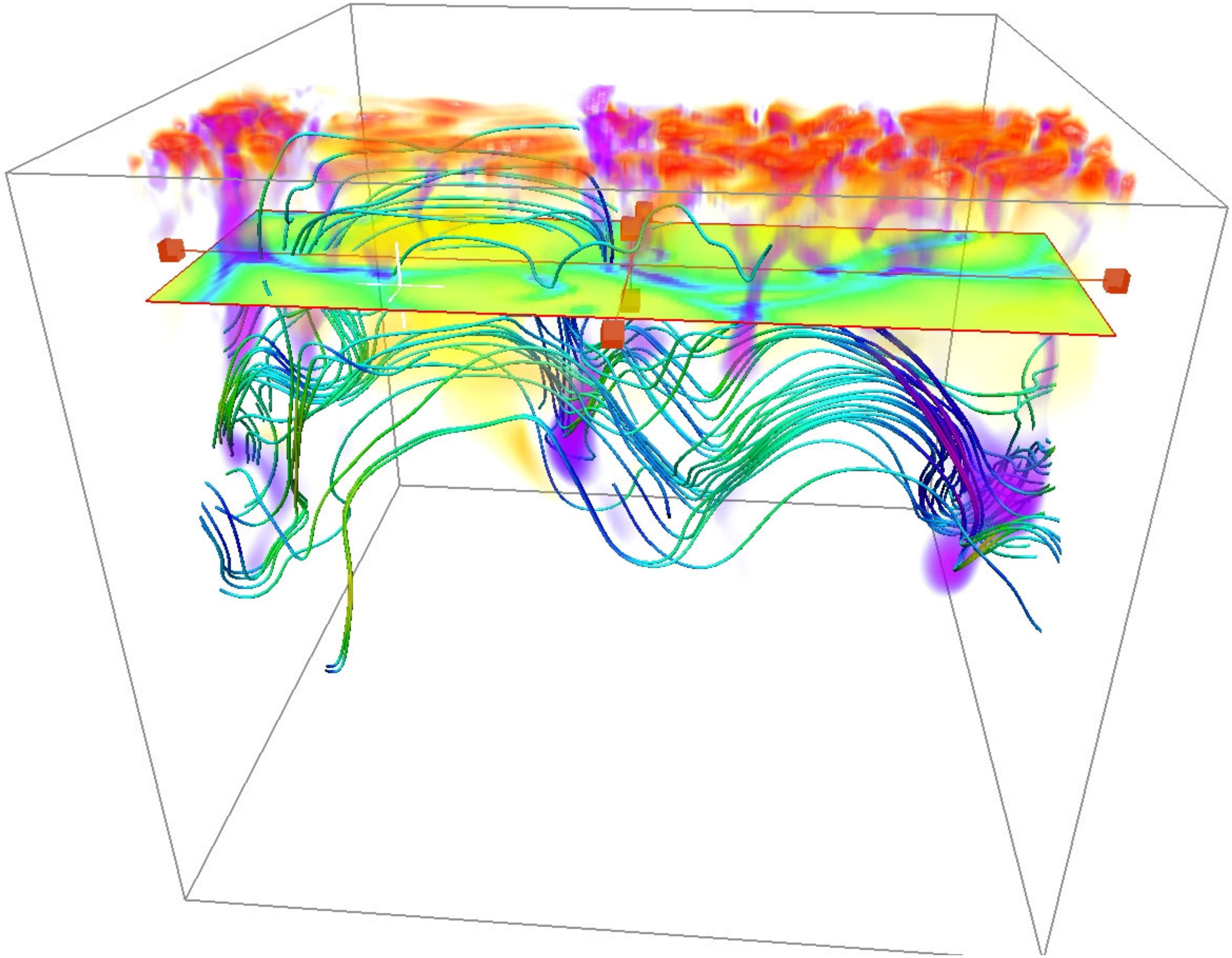


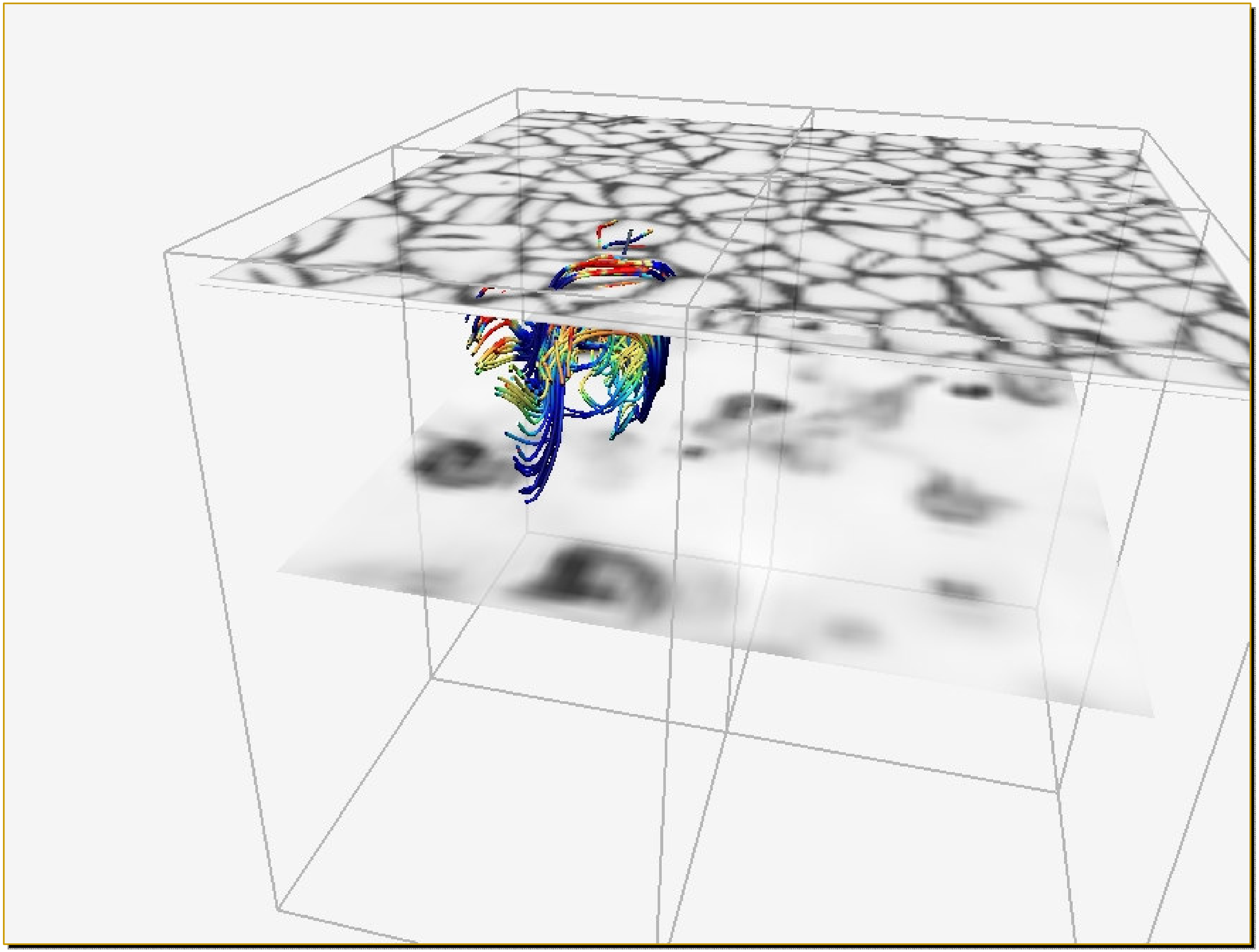
Slide 32

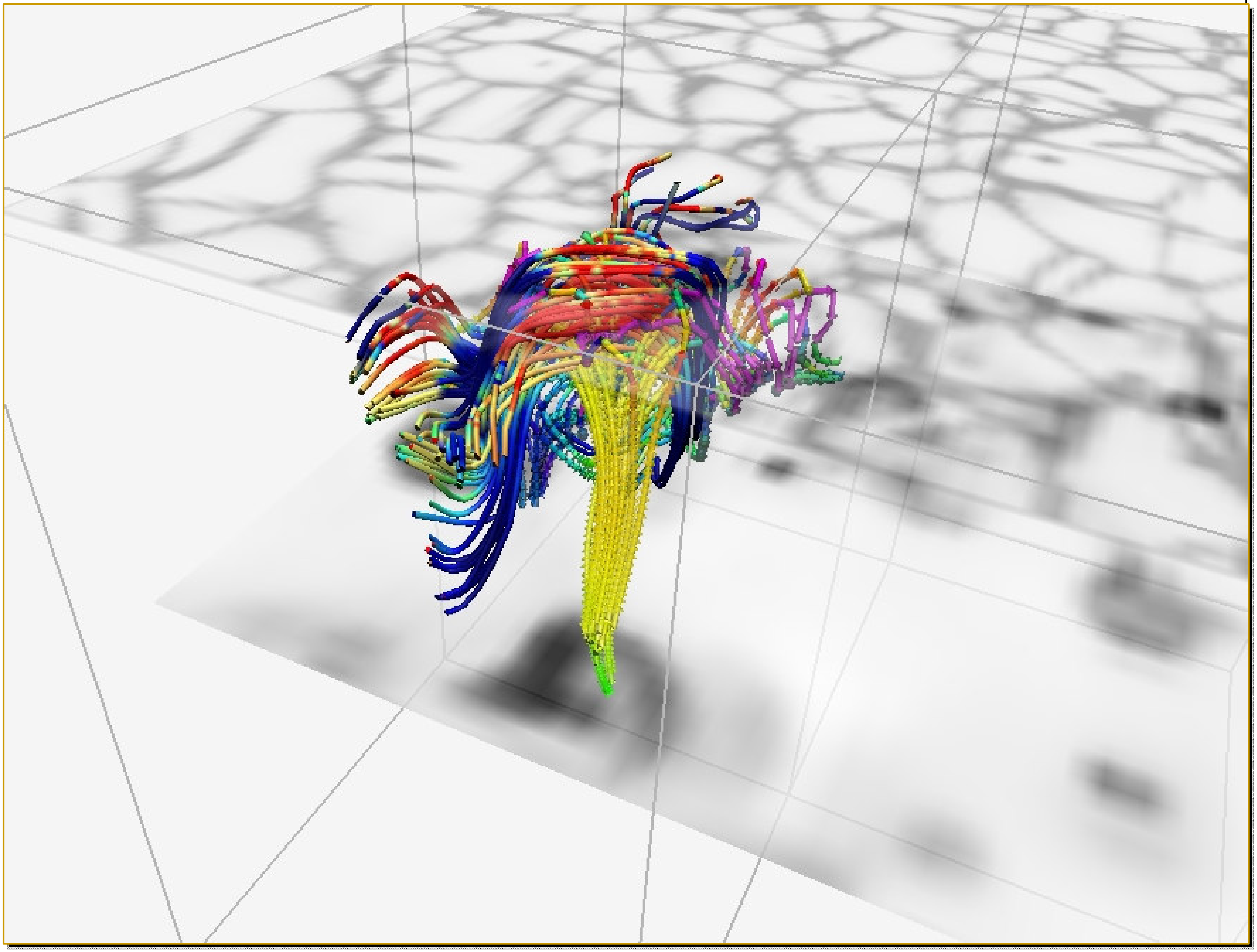
A1 Aake, 6/22/2008

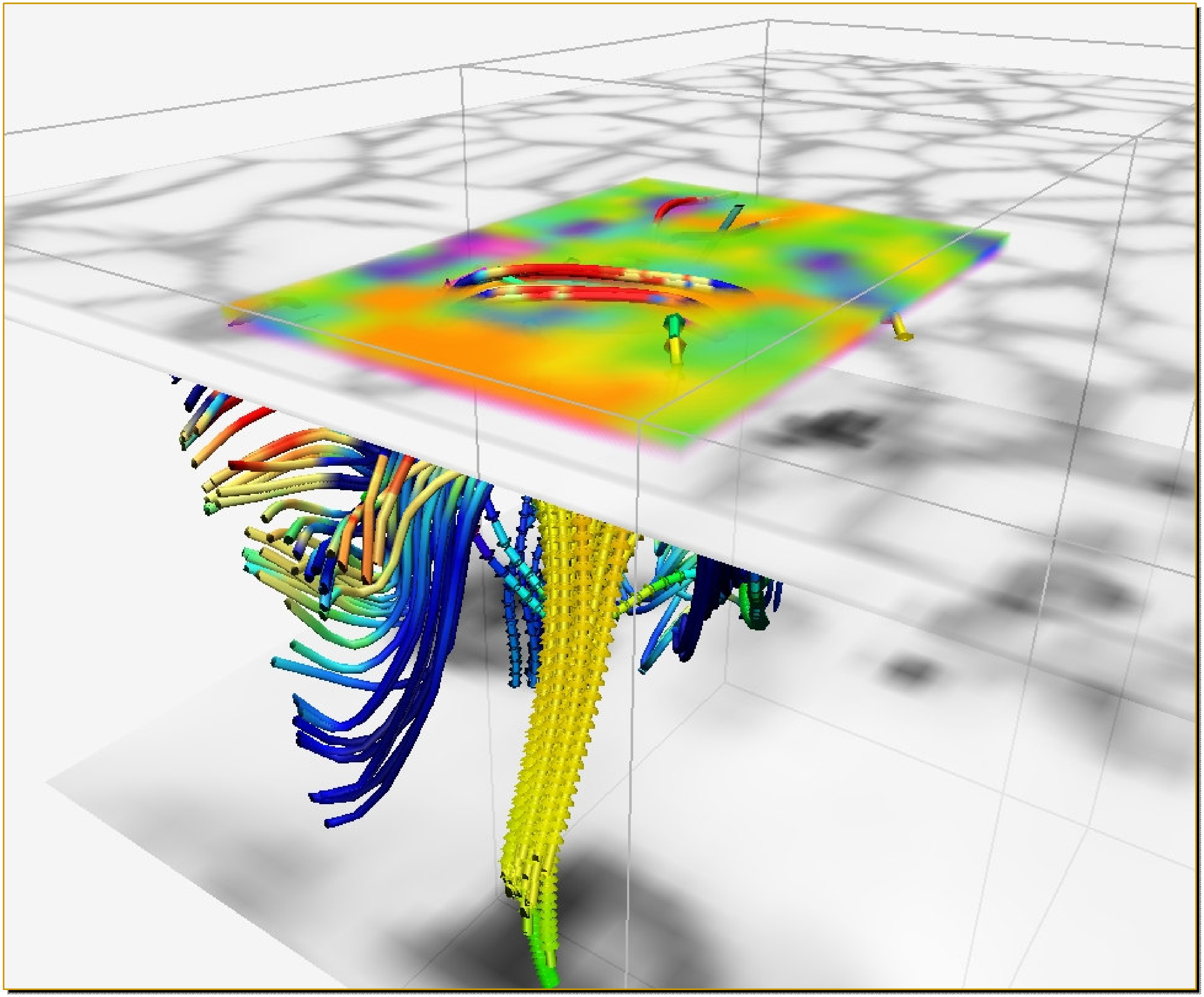
Multi-scale magneto-convection; initially horizontal field

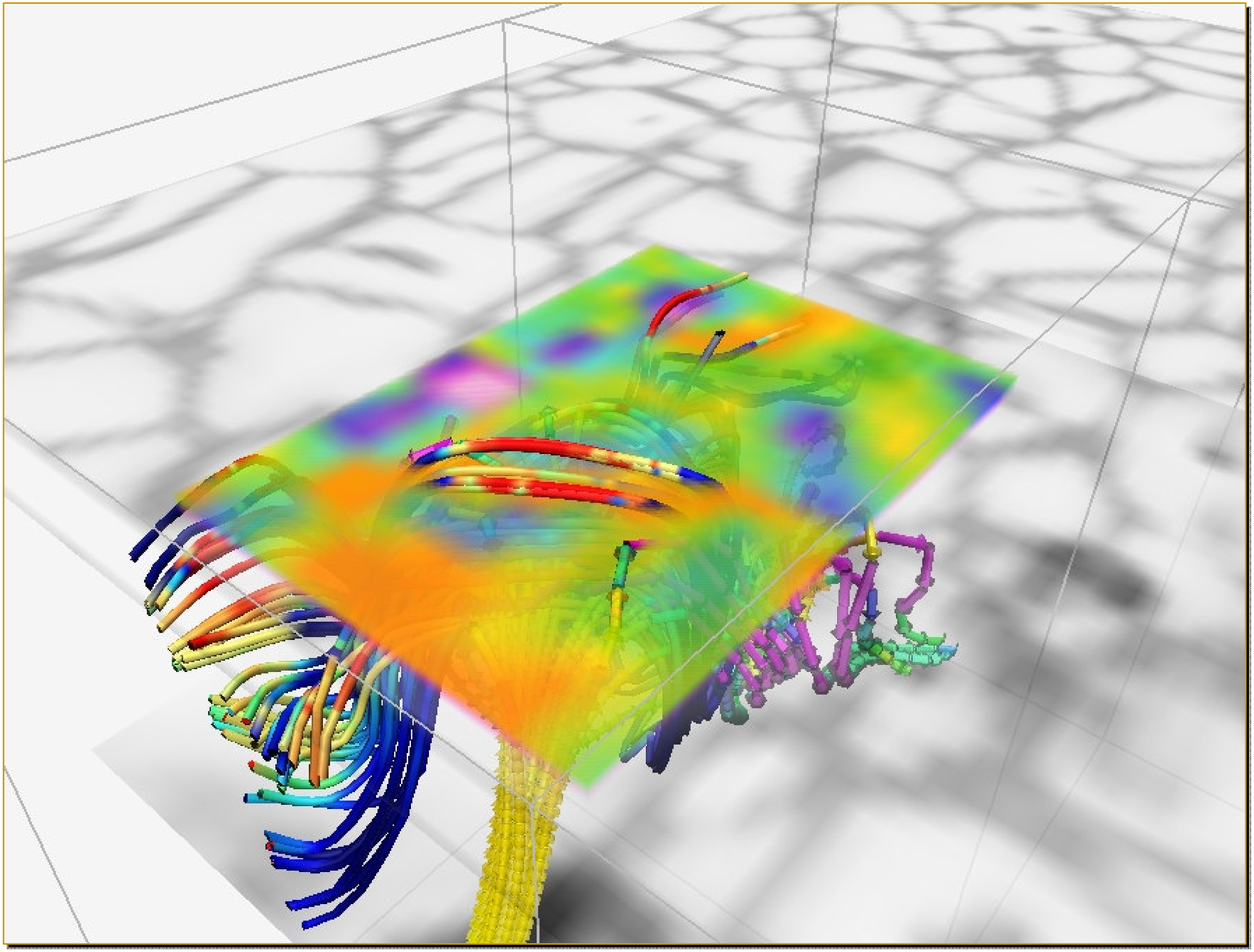


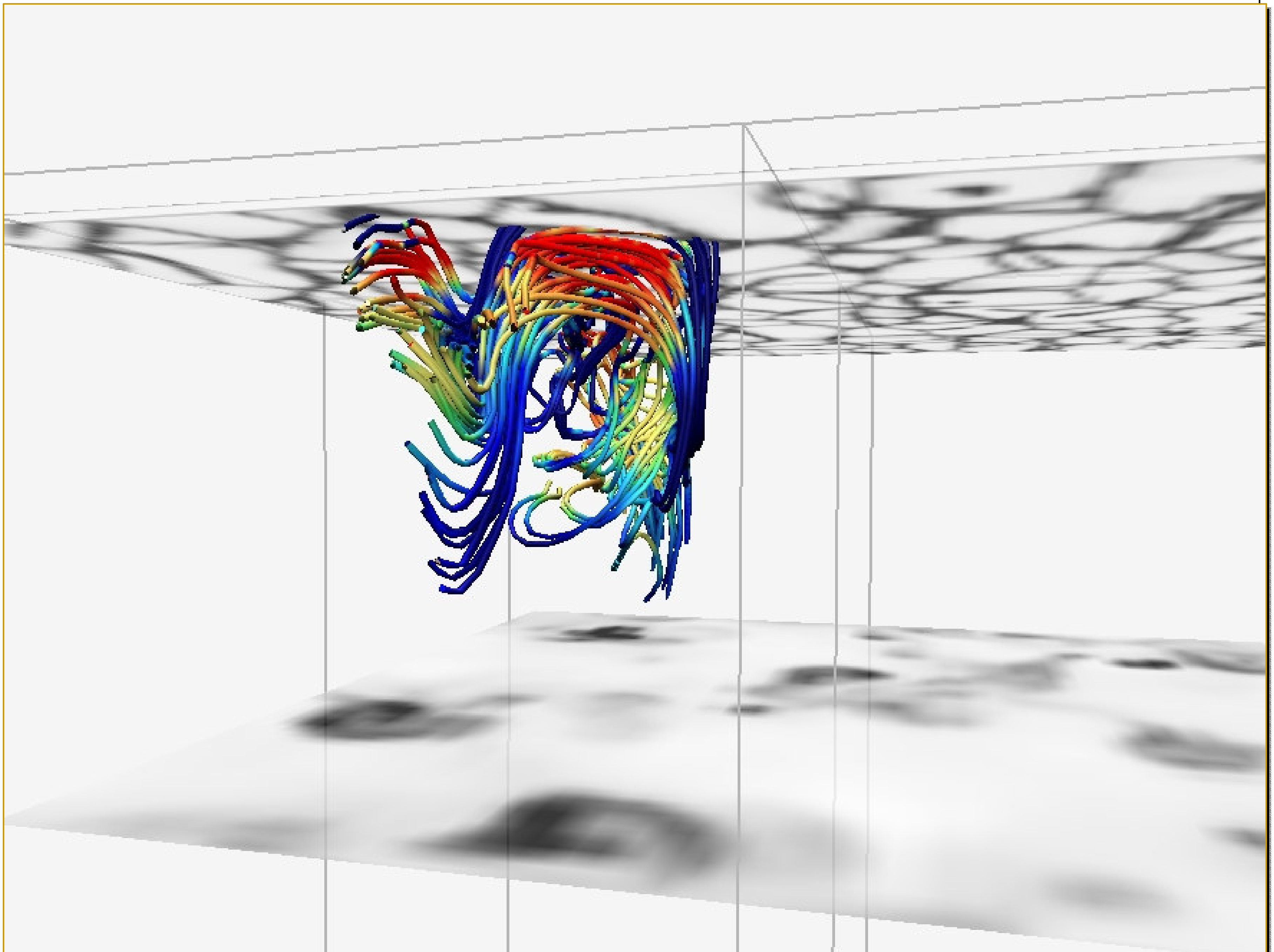




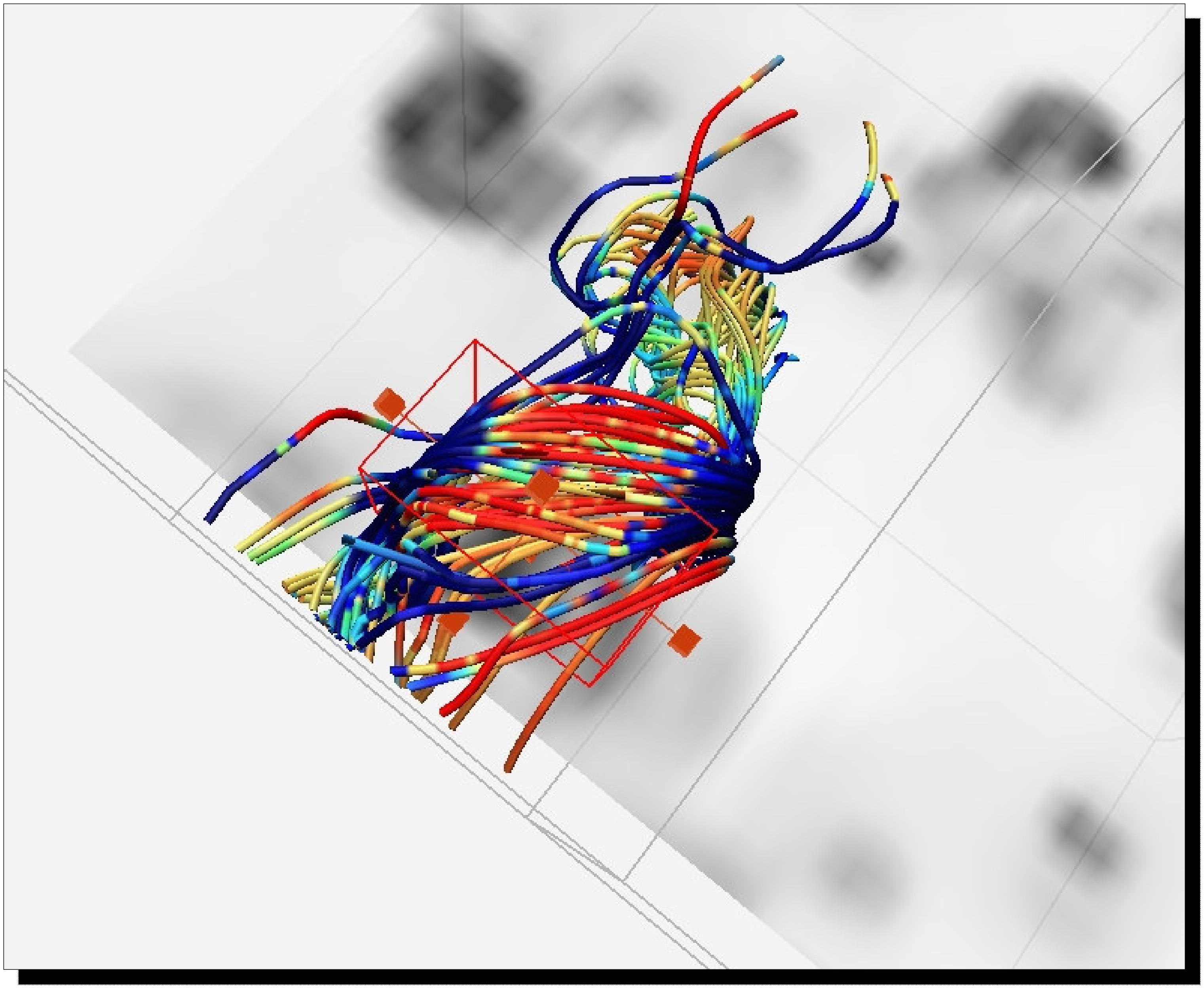




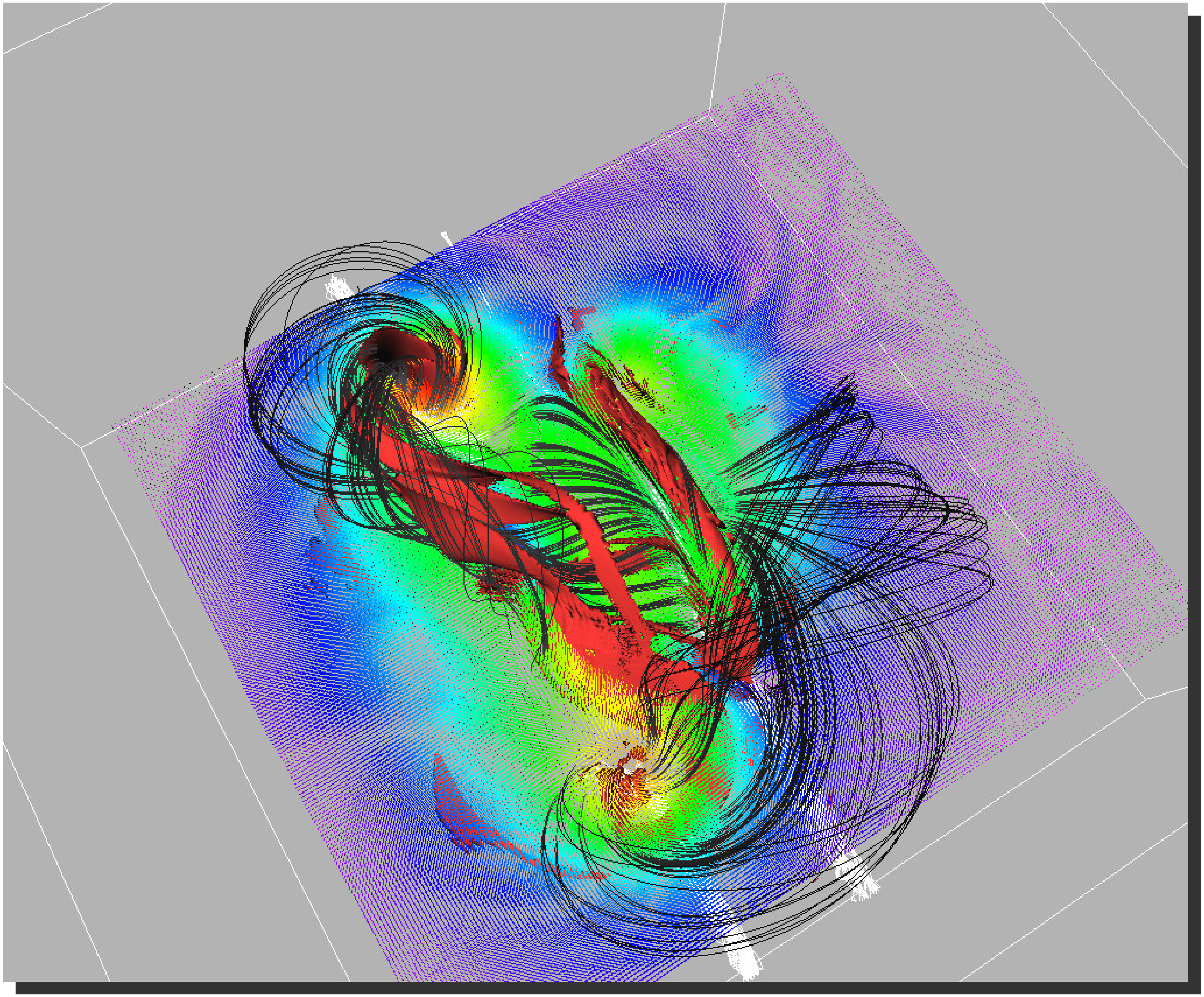




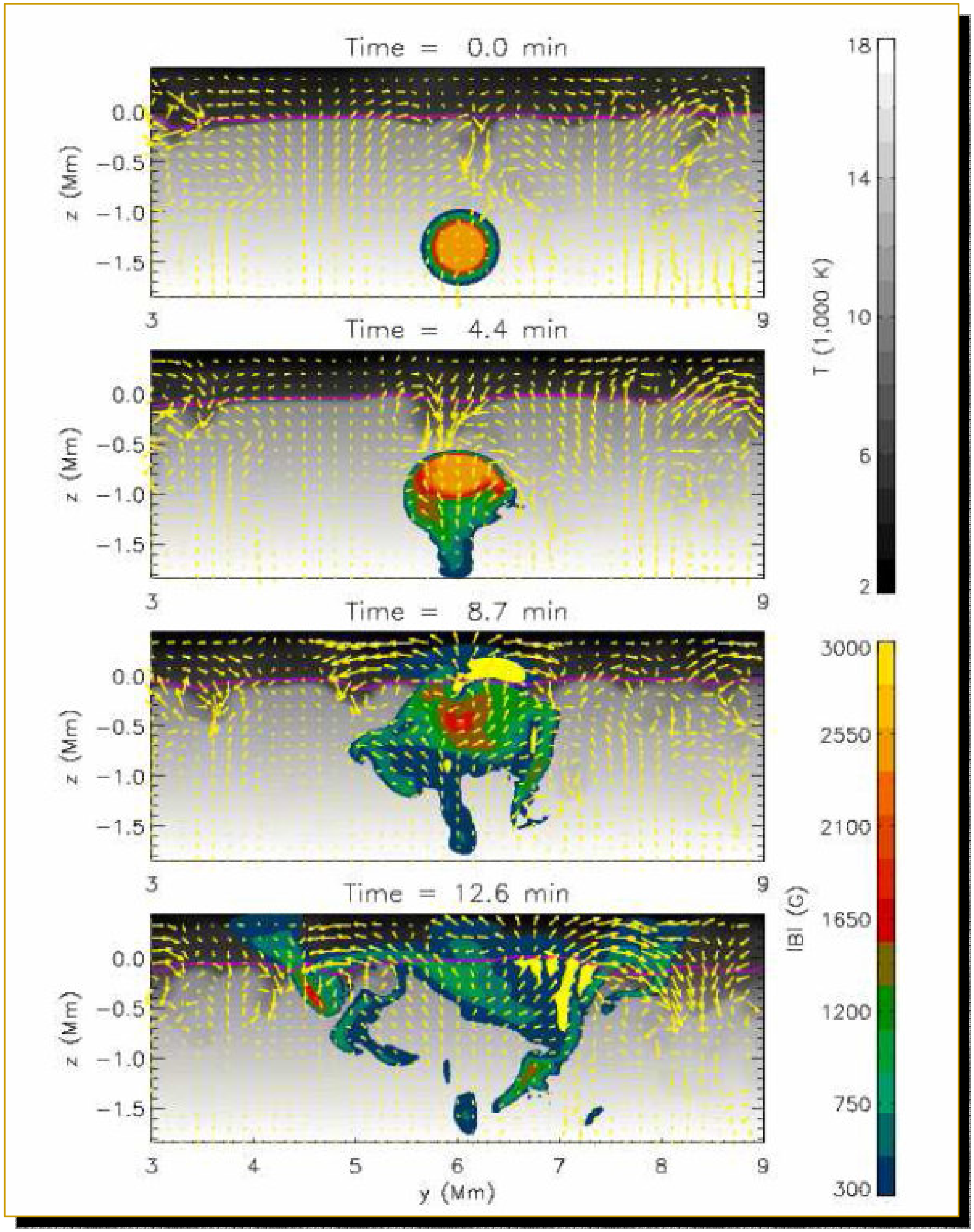
View from above; sheared field lines



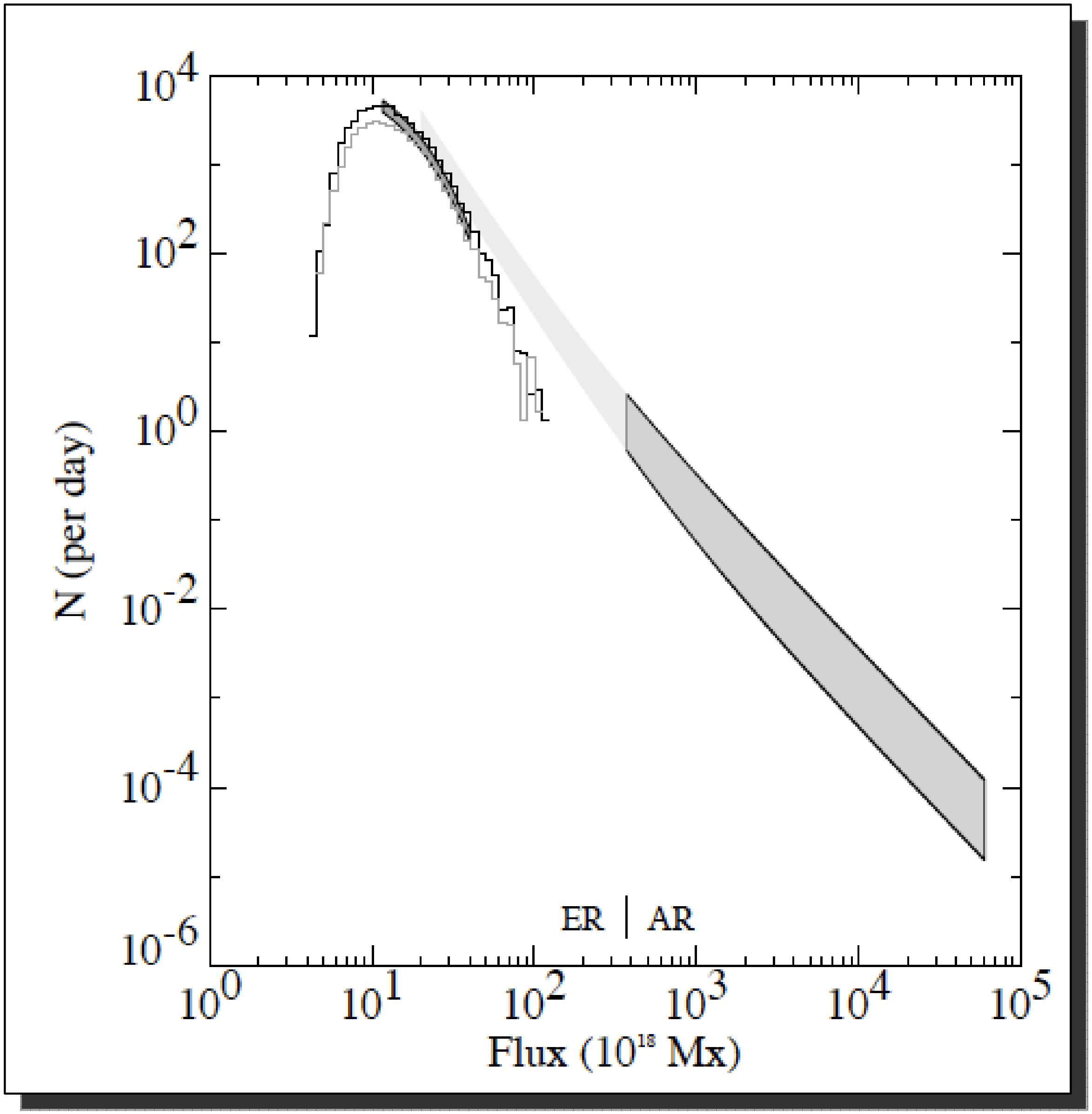
St. Andrews' team; Archontis ..



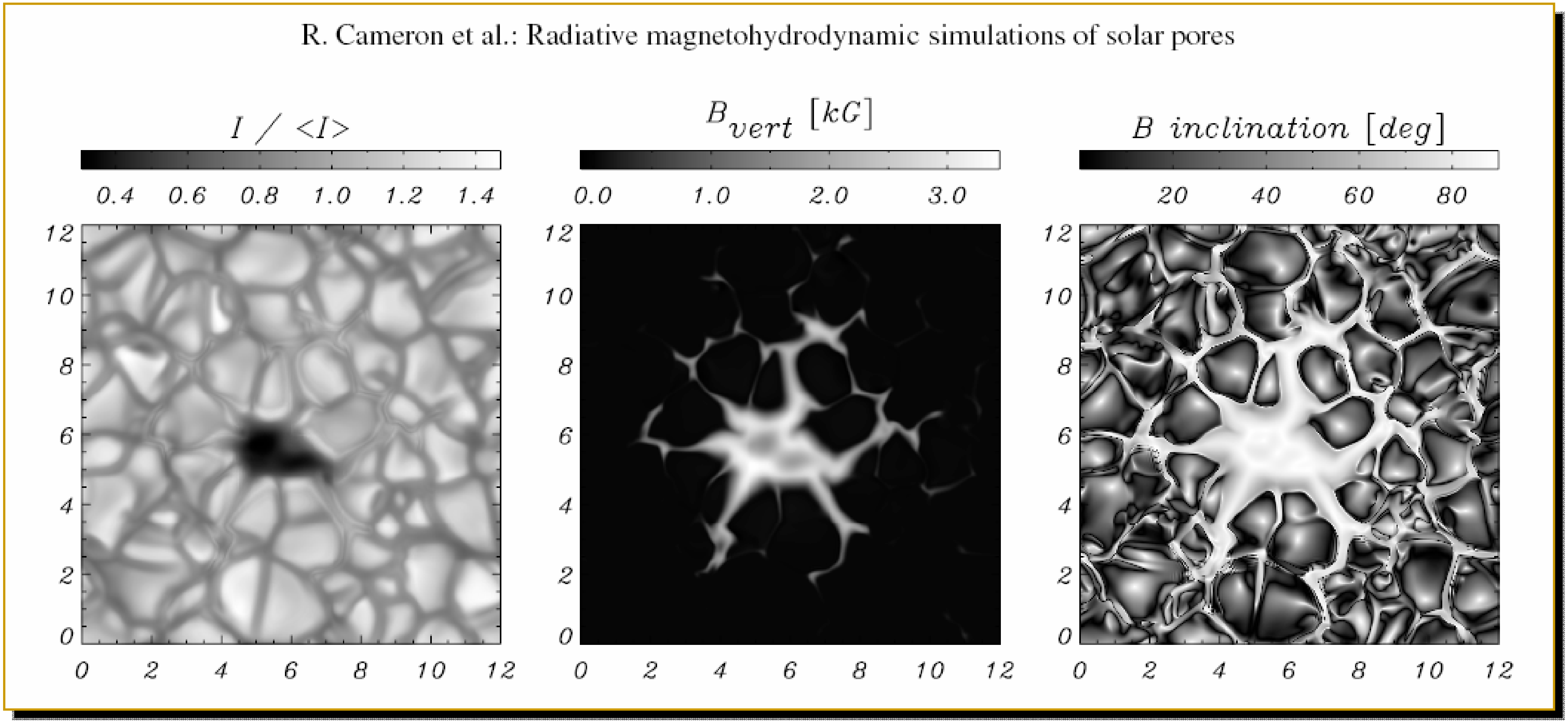
”Classical” emerging flux studies



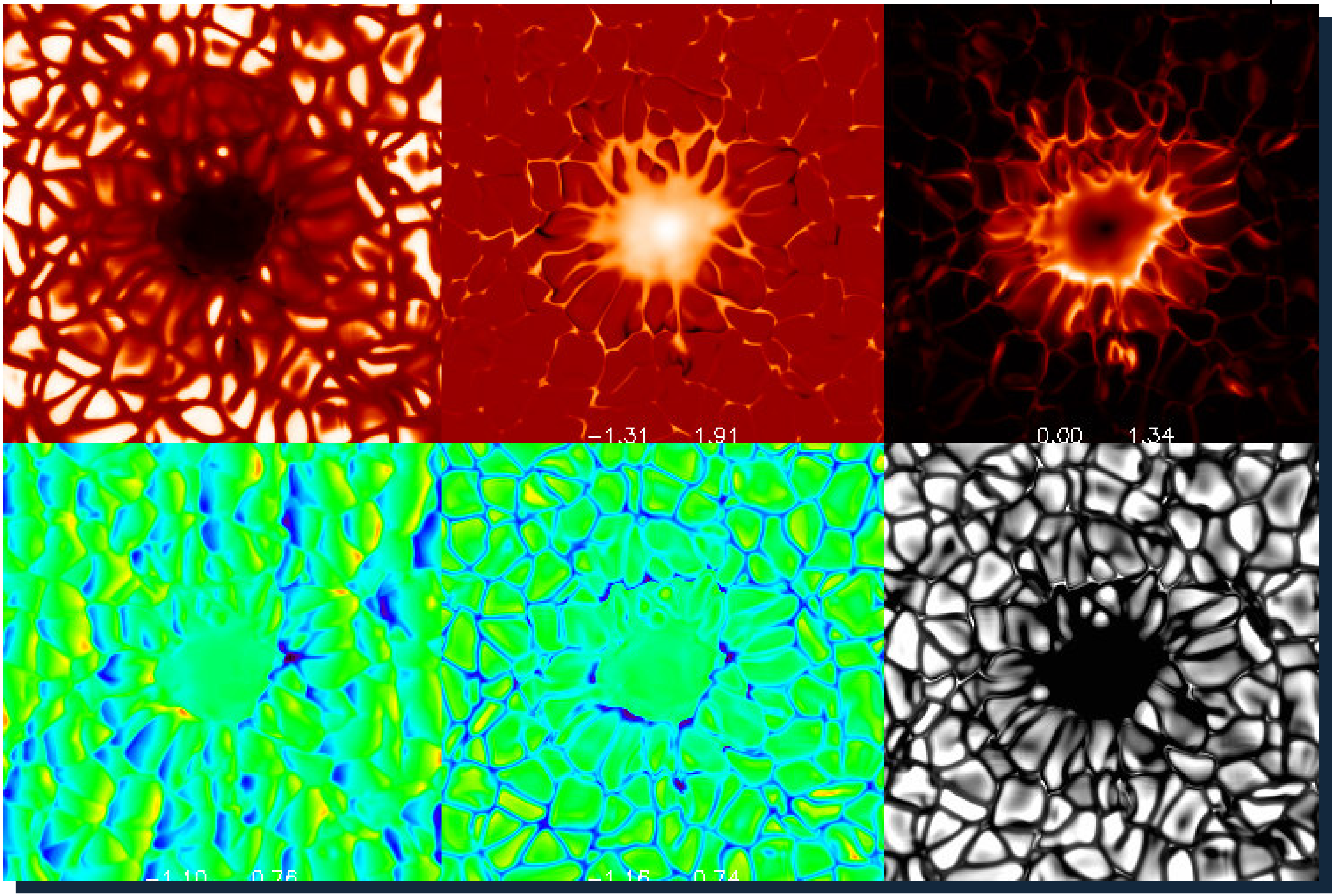
Near-scale free surface magnetic flux distribution



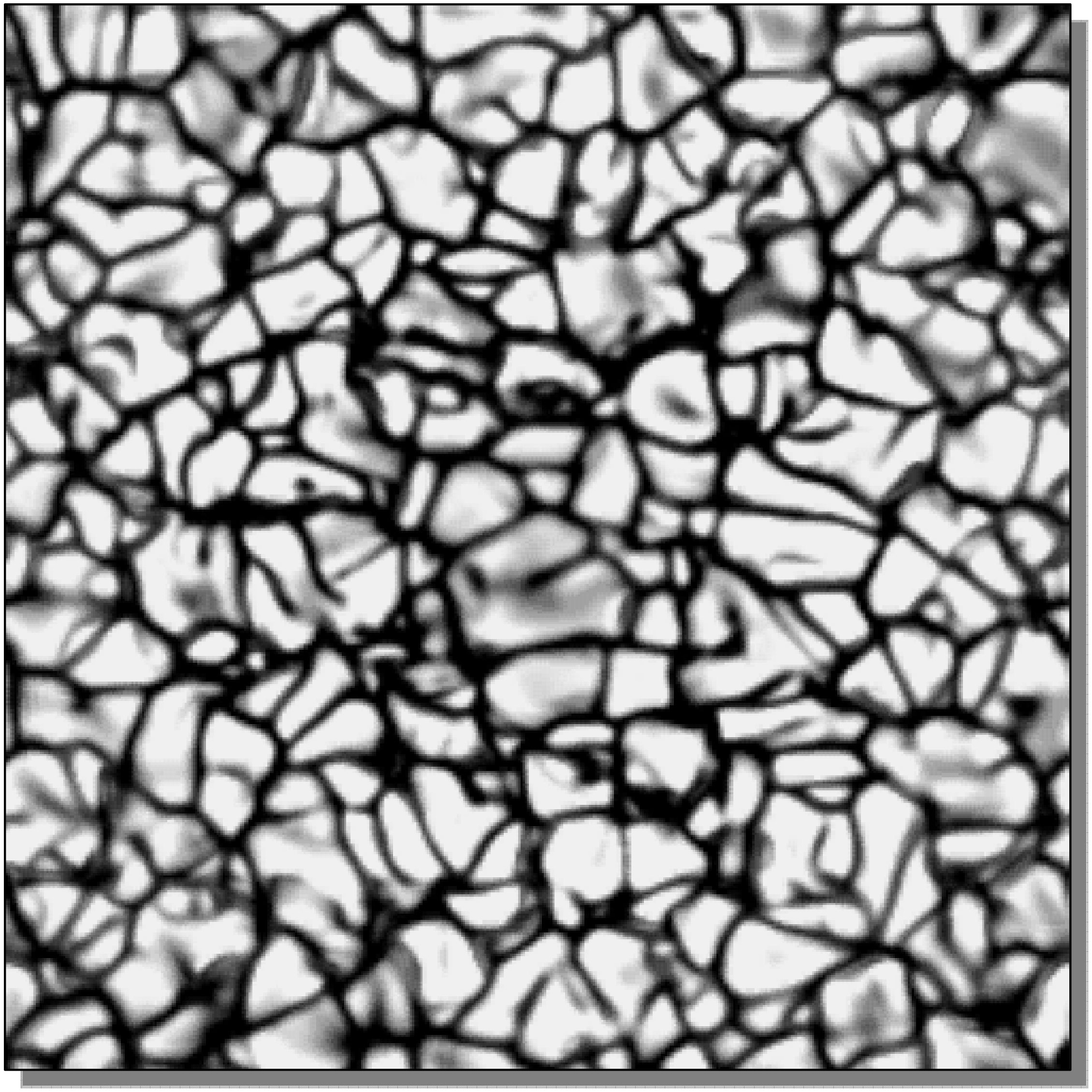
Magneto-convection: Pores and sunspots



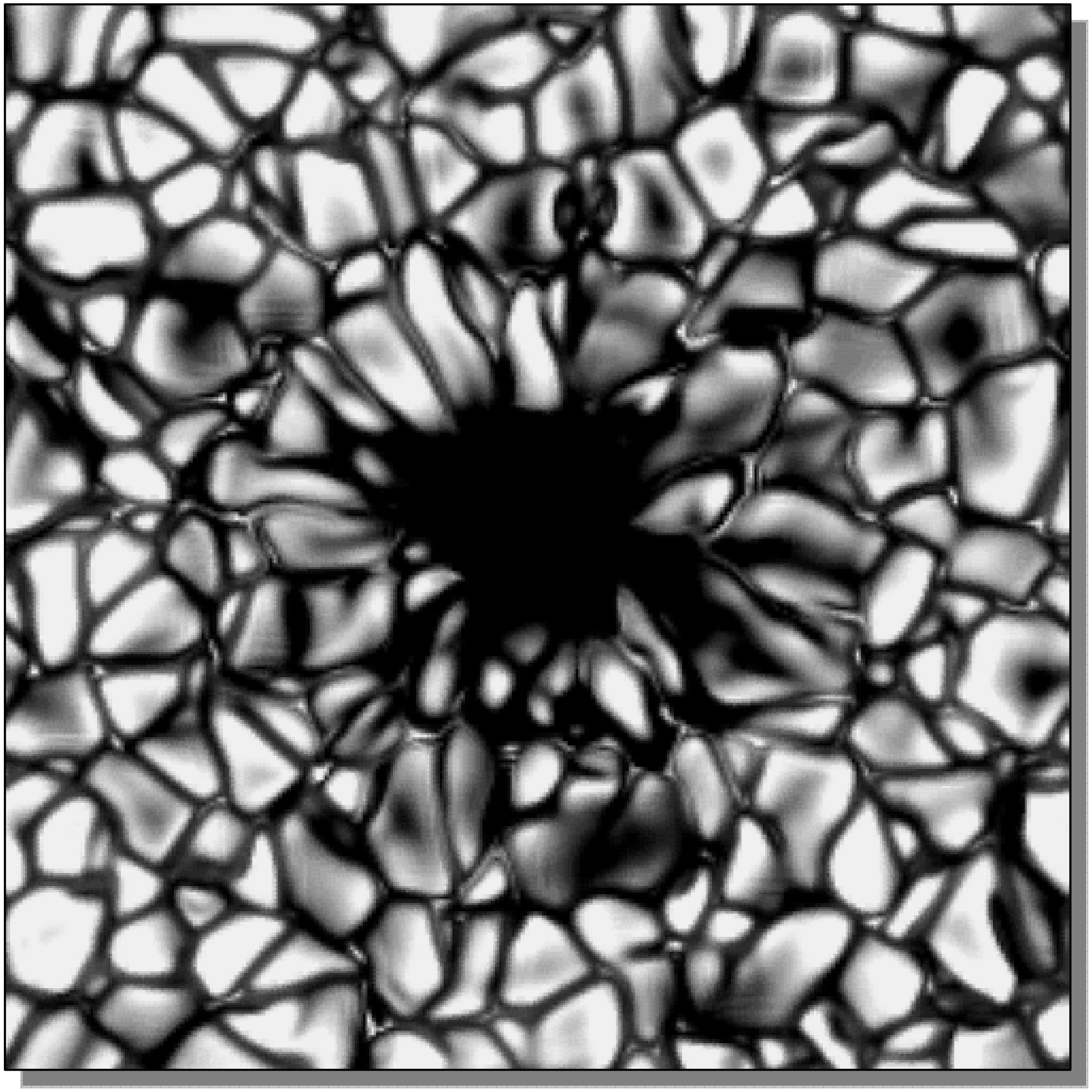
Temperature, hor. & vert. magn. field, hor. & vert. velocity, surface intensity



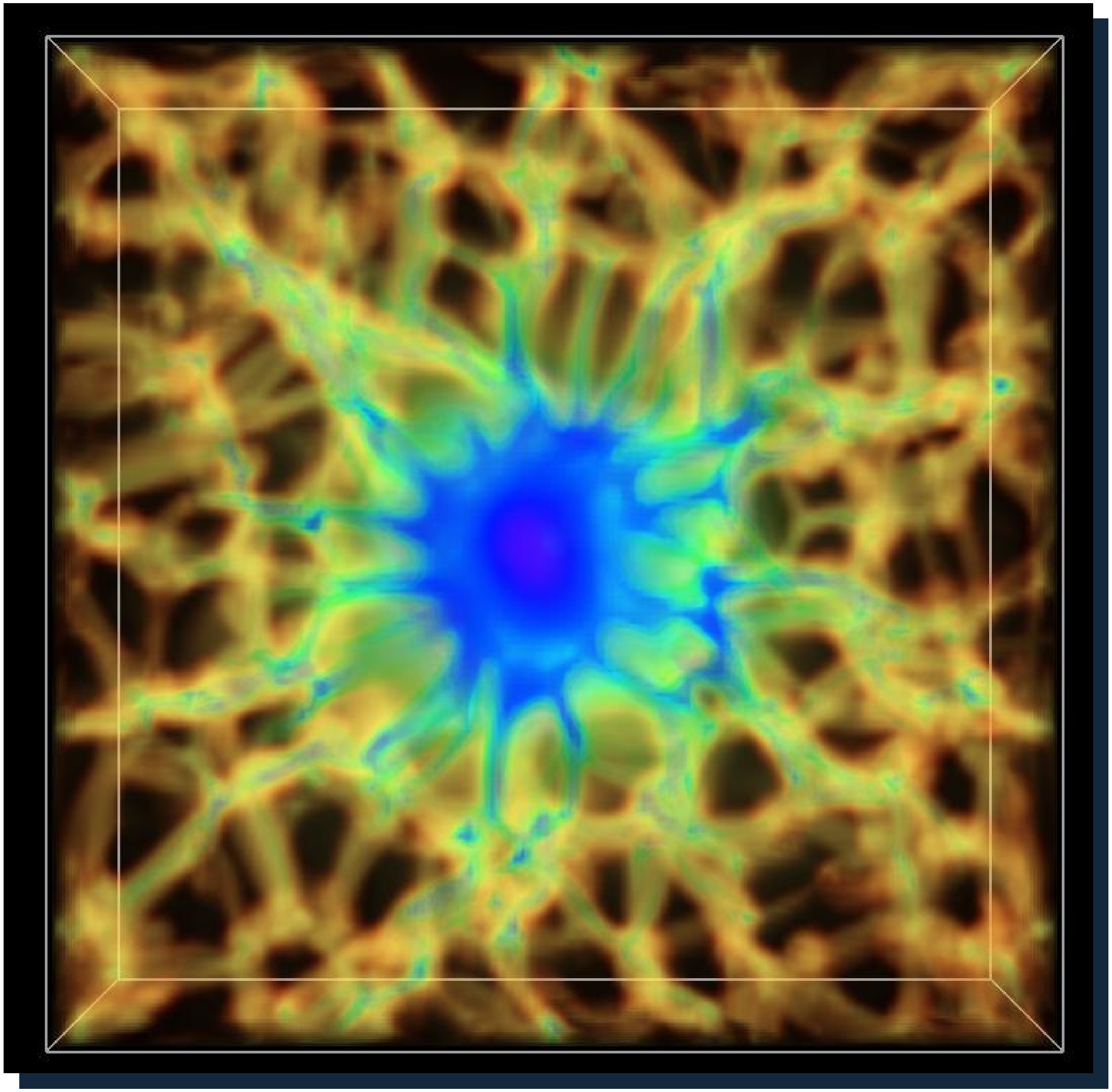
Sunspot, initial time evolution



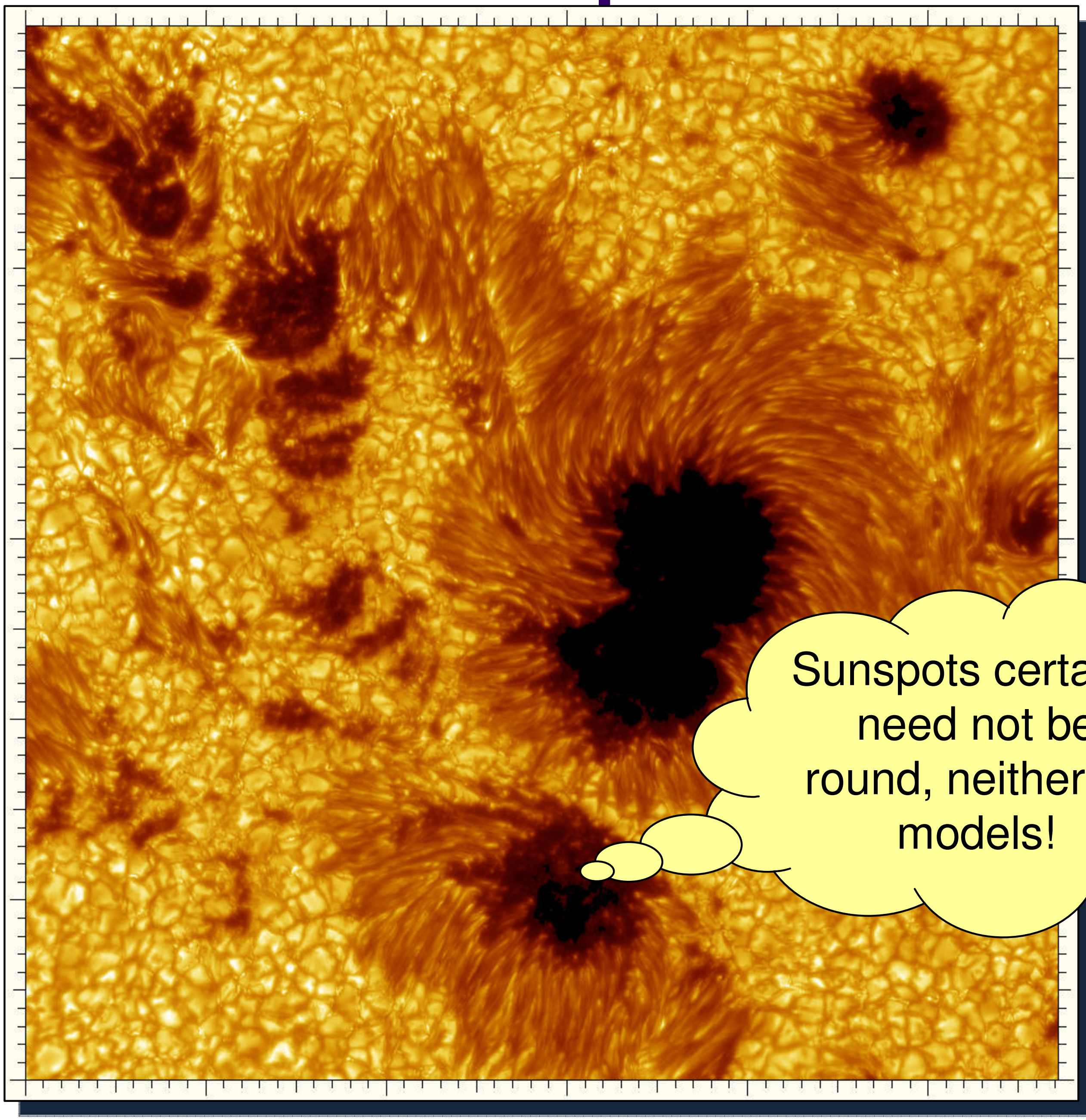
Sunspot, time evolution (rep.)



Sunspot,
log magnetic pressure

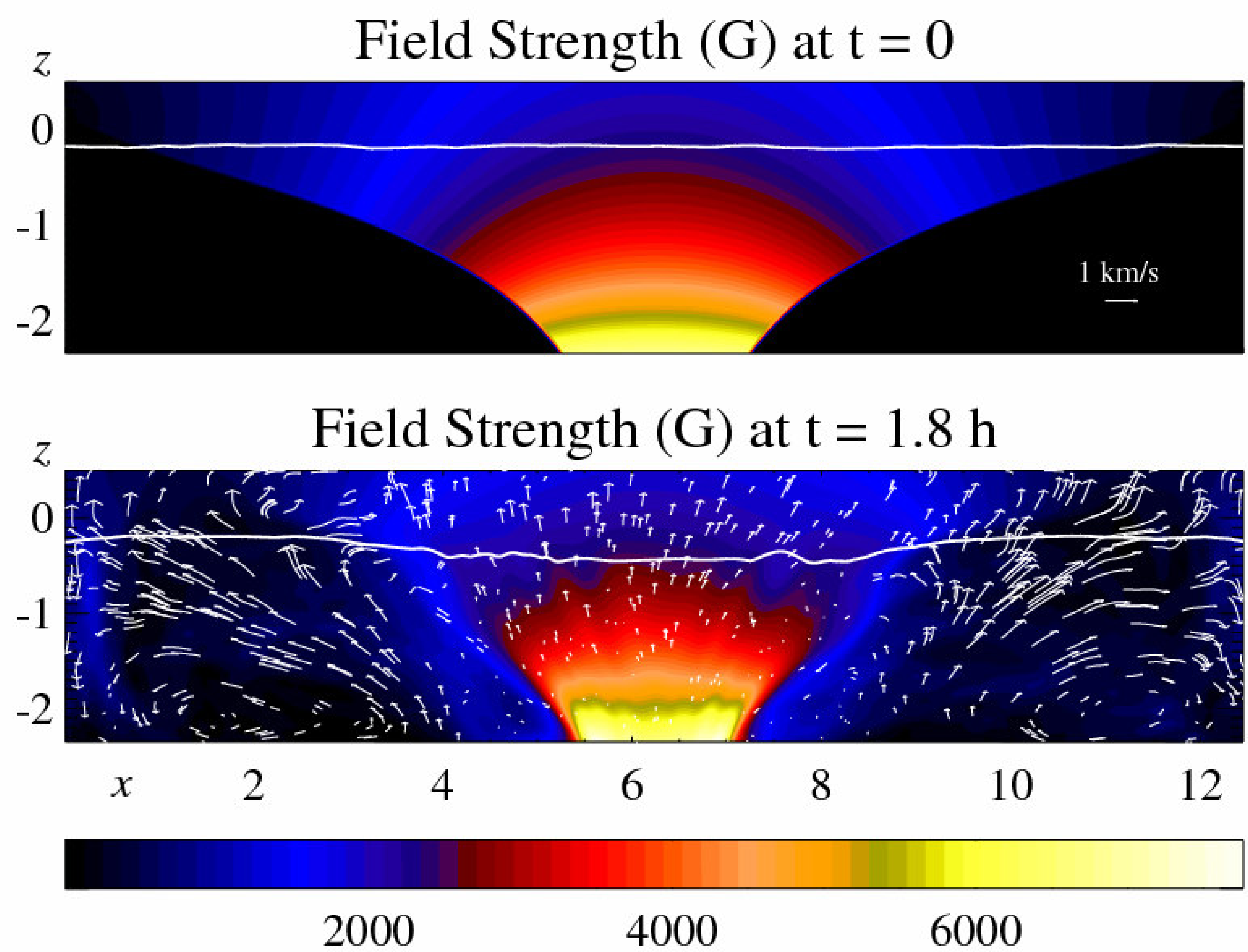


Sunspots w/o Penumbrae
Penumbrae w/o Sunspots

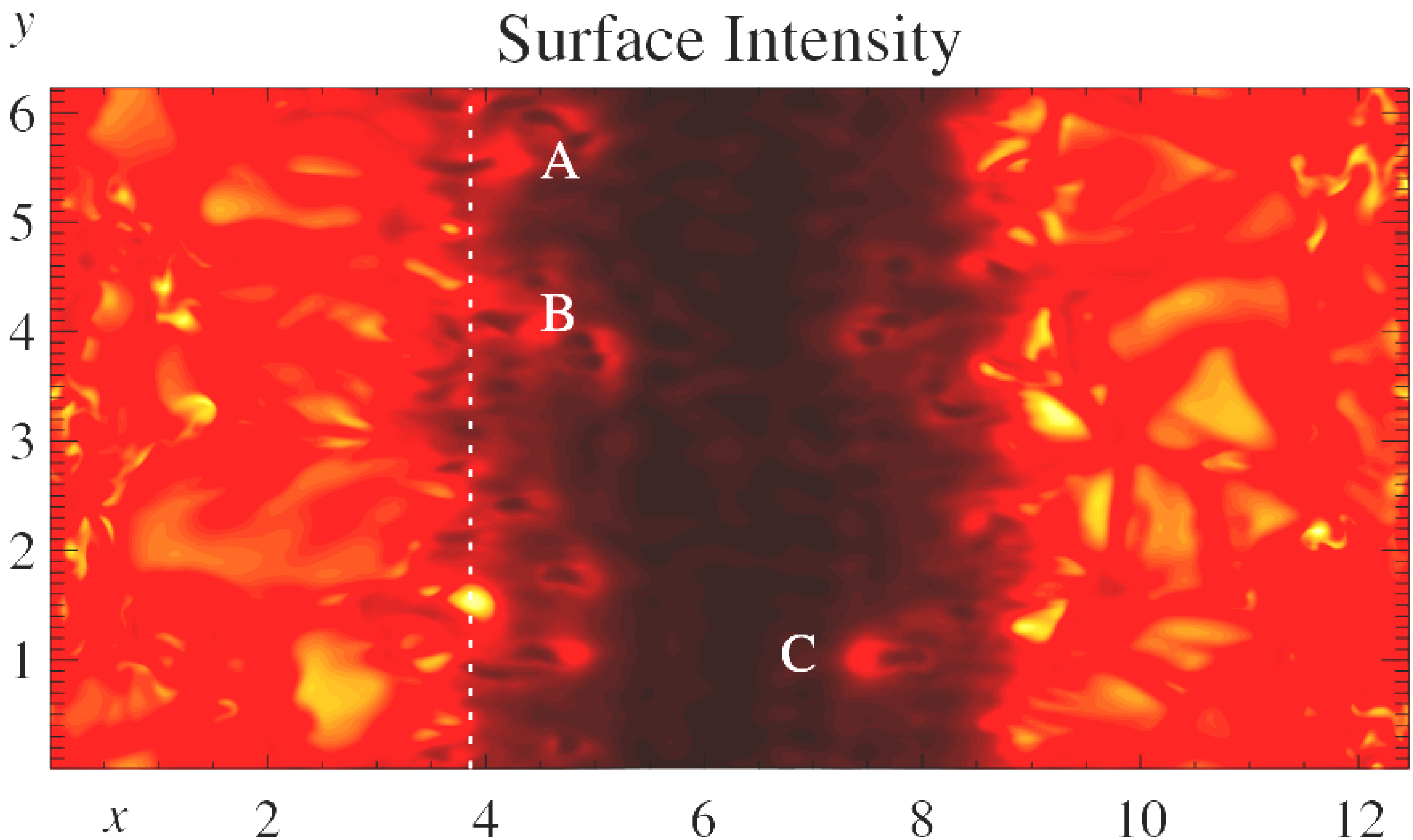


Sunspots certainly need not be round, neither do models!

Cross section of model

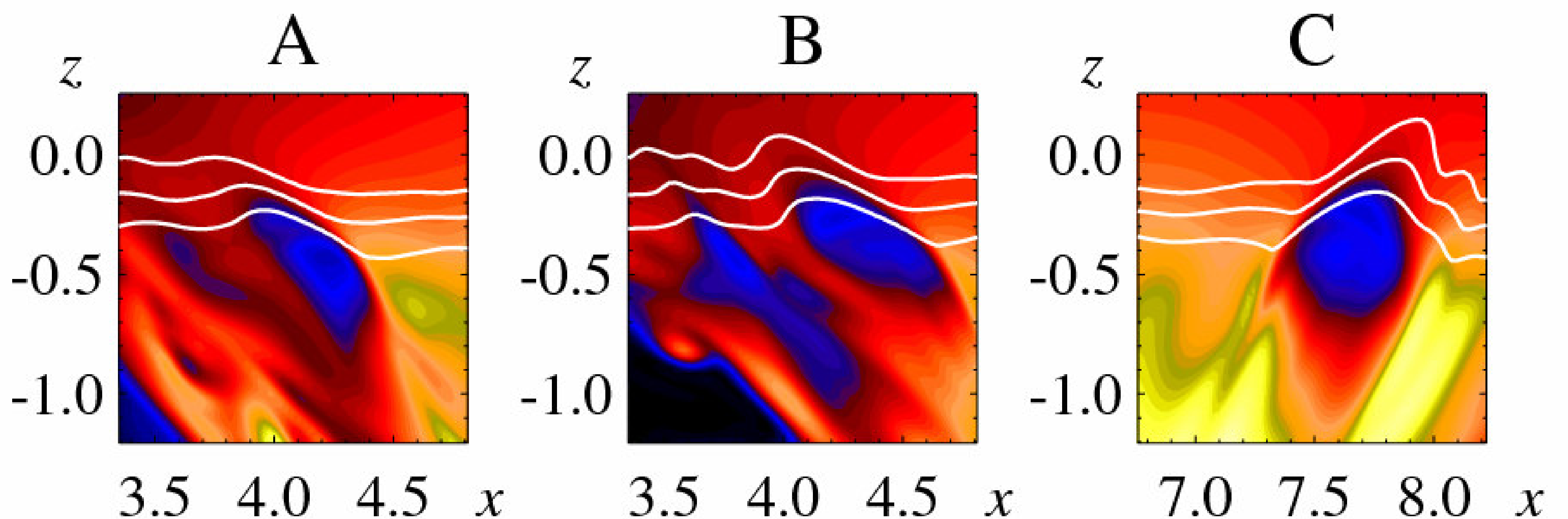


Snapshot, with dark filaments

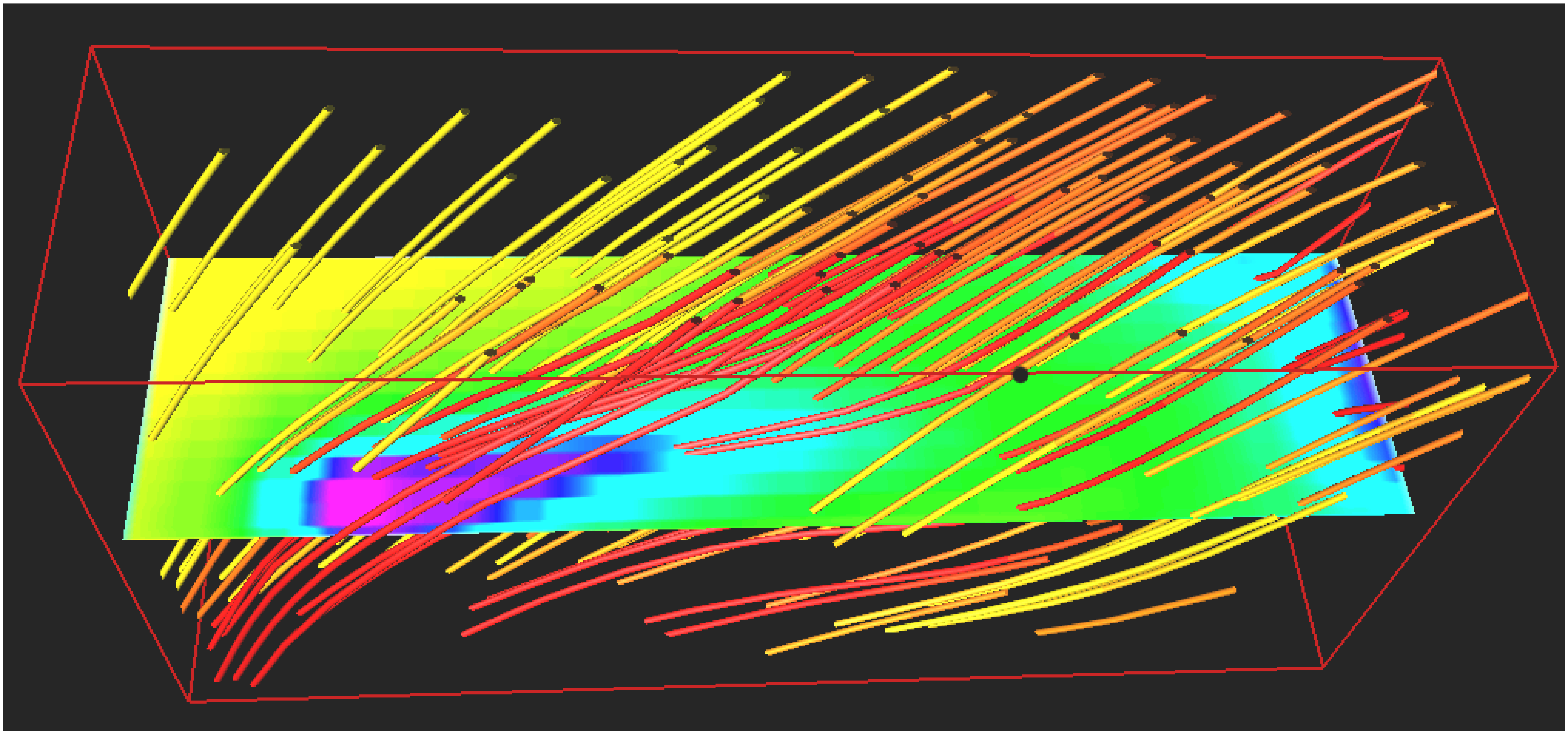


Heinemann, Nordlund, Scharmer & Spruit 2007
Scharmer, Nordlund & Heinemann 2008

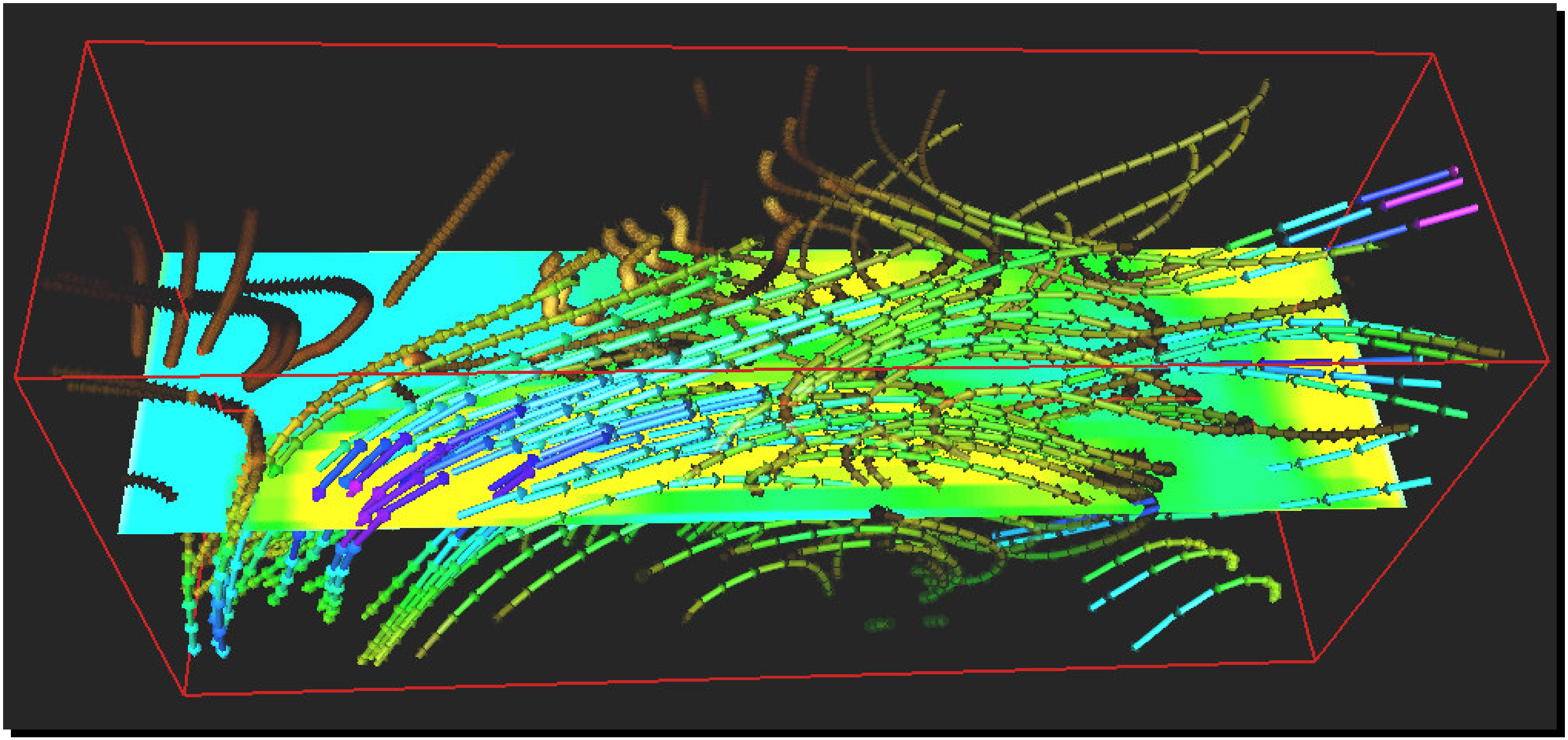
Zoom in on dark filaments, from the side



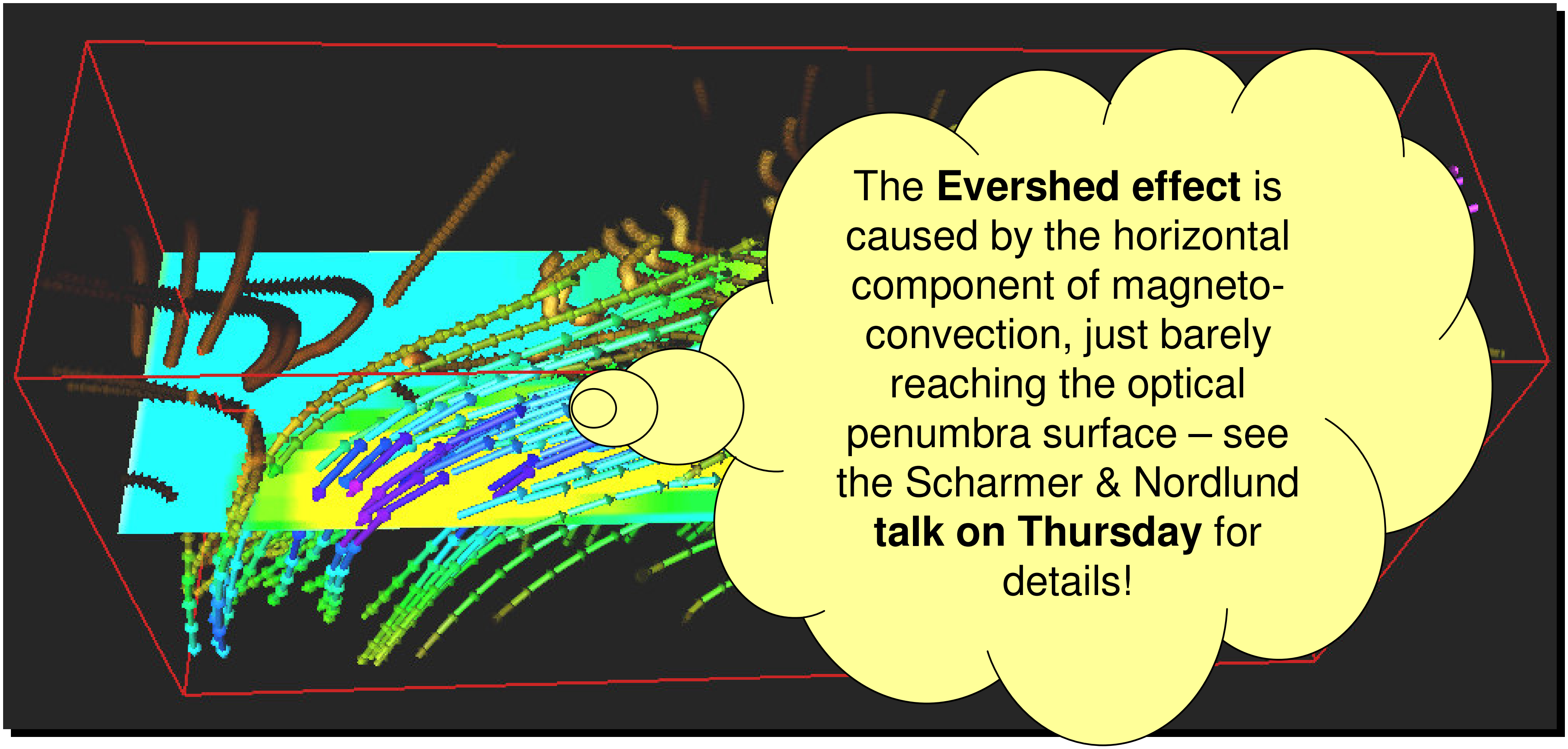
Magnetic field lines and vertical velocity (image plane)



Velocity field and magnetic field strength (image plane)



Velocity field and magnetic field strength (image plane)



Summary

- Stellar magneto-convection is fundamentally ***multi-scale***
  - Major difficulty for modeling and understanding!
- But also has ~ ***scale invariance***
  - That helps a lot!
- Two asymptotic regimes; **small *and* large**
  - Approx. self-similarity also in B, flare event size,...
- The Sun + simulations provide ***proof*** that ***dissipation converges*** at relatively low Re
  - Similar behavior expected for magnetic dissipation

Thanks for your attention!

Acknowledgments

The results presented here were made possible by hardware grants to ÅN from the Danish Center for Scientific Computing, and by Columbia computing resource grants to Bob Stein from NASA / NAS.

Visualizations partly done with VAPOR from NCAR.