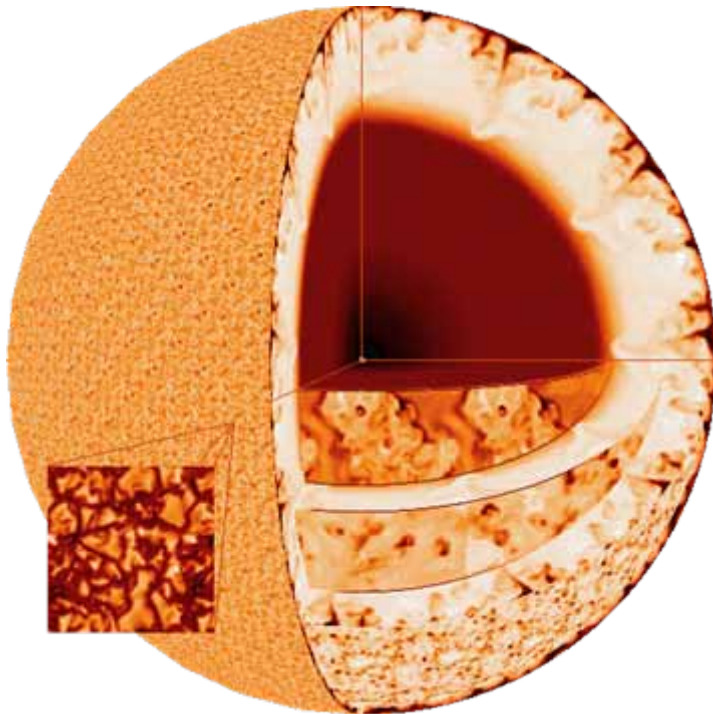
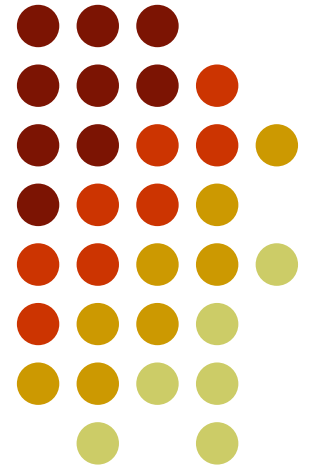


Euler Equations 250 Years On

Solar Hydrodynamics



Åke Nordlund
Niels Bohr Institute
Copenhagen
with
Bob Stein
Martin Asplund
Boris Gudiksen and others



Aussois, June 18-23, 2007

The Euler Equations in Astrophysics



- Really concerned with EE1 = “NS, $v \rightarrow 0$ ”
... which are *physically meaningful*
- What with EE0 = “NS, $v = 0$ ” ?
 - The extent to which these eqs. are singular is an interesting question, and is probably directly related to the dissipative behavior of NS (cf. Eyink’s talk today)

Executive summary; what can we learn from solar modeling?

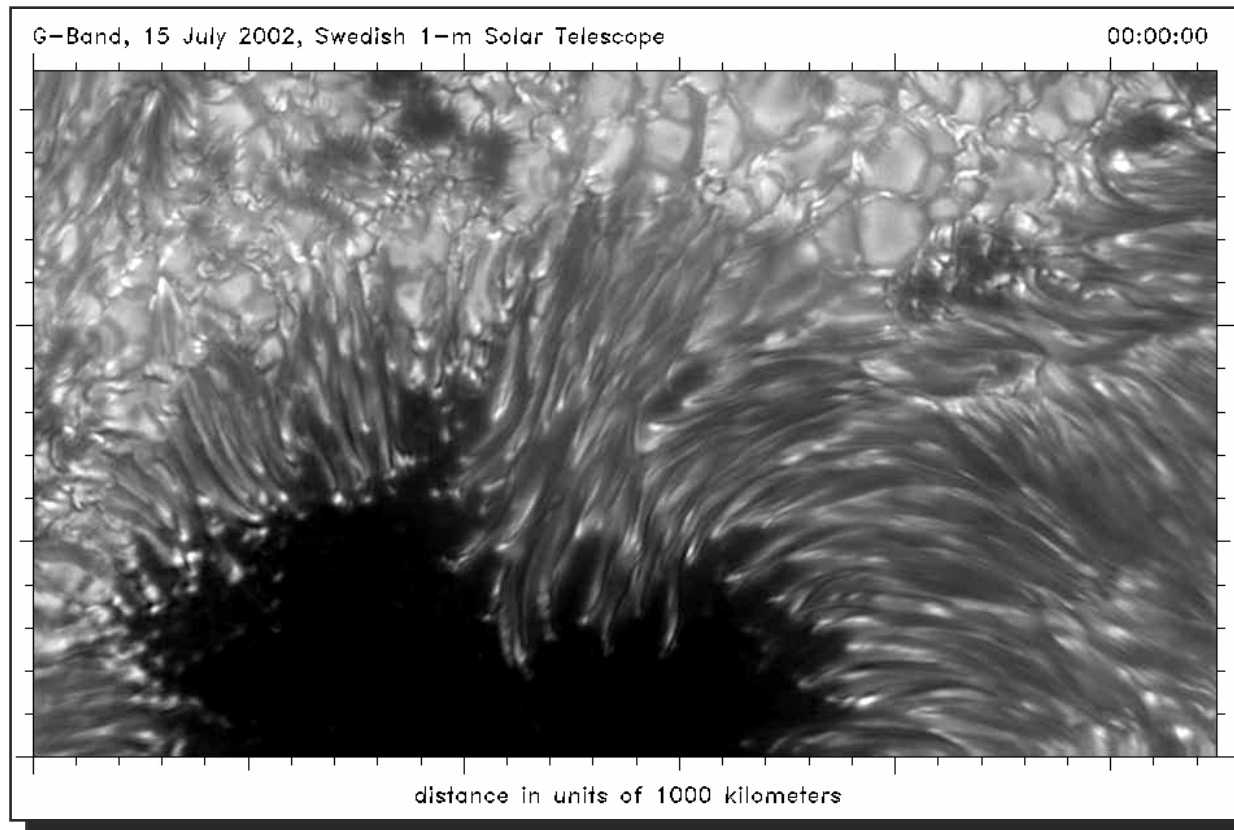


- Explicit verification; $\varepsilon \rightarrow \text{constant}$, $\text{Re} \rightarrow \infty$
 - The turbulent kinetic ***energy dissipation remains independent of Reynolds number*** far beyond the range of numerical simulations!!
 - How can one conclude this from numerical simulations??
 - By comparison of ***~parameter-free simulations*** with observations!

The role of the Sun and Solar Physics in Astrophysics



- The Rosetta Stone of astrophysical dynamics
 - Full availability of the time domain



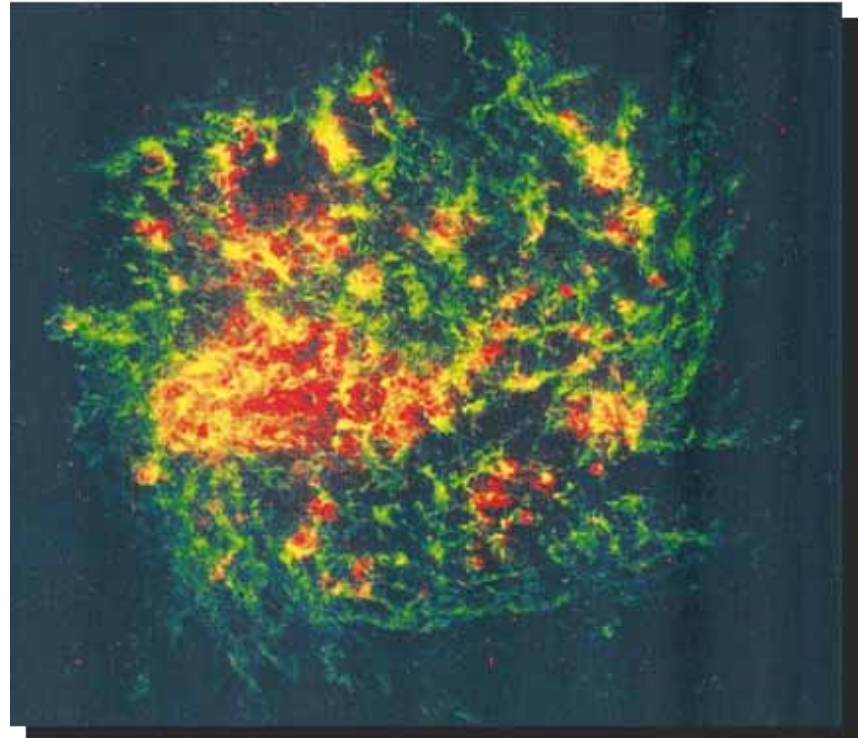
The role of the Sun and Solar Physics in Astrophysics



- The Rosetta Stone of astrophysical dynamics
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 - rest of astrophysics \approx “snap shots” (w few exceptions)

Large Magellanic Cloud

Global time scale: 100's of Myr



The role of the Sun and Solar Physics in Astrophysics



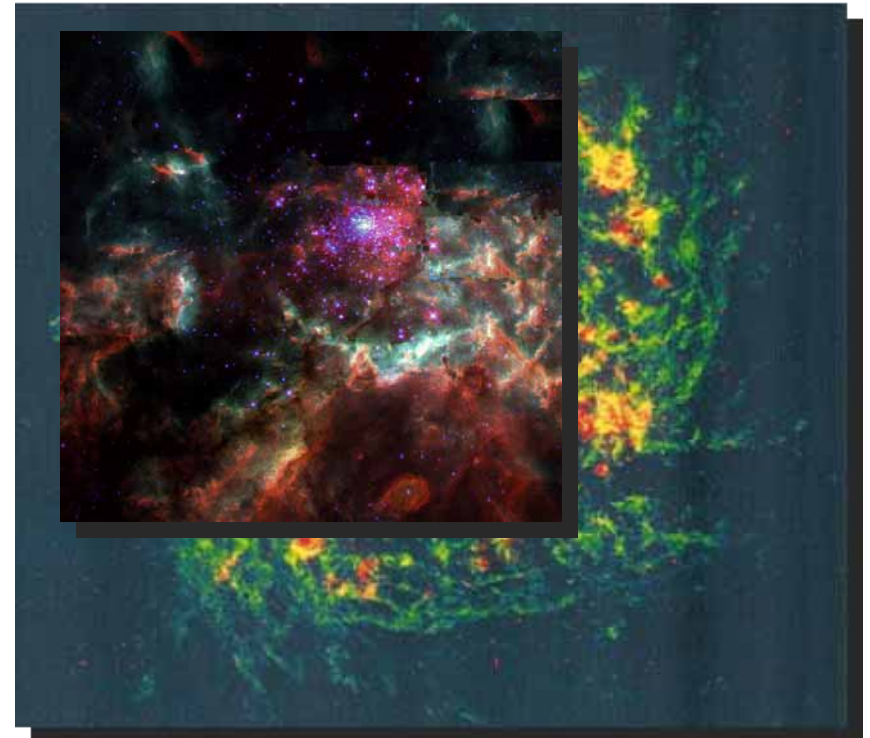
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 - Full availability of the time domain
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Large Magellanic Cloud

Global time scale: 100's of Myr

Star Forming Region (30 Dor)

Time scale: \sim Myr

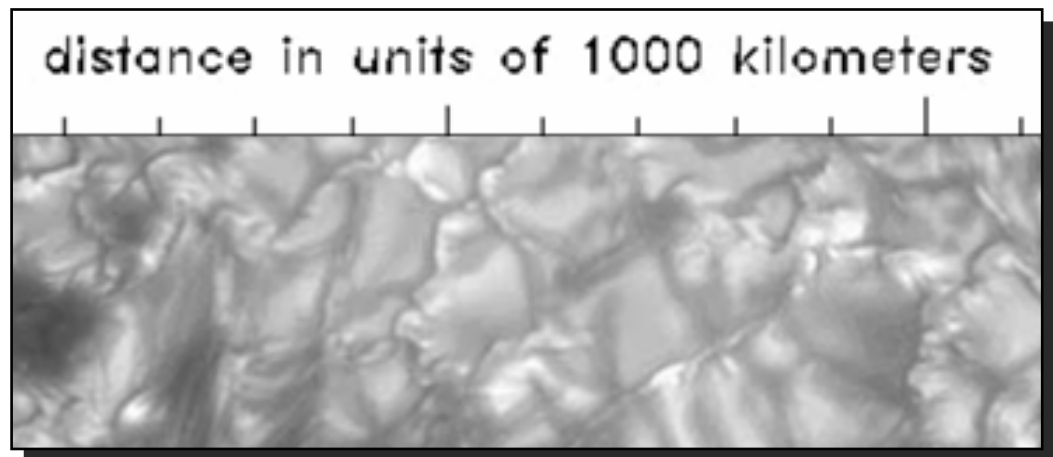


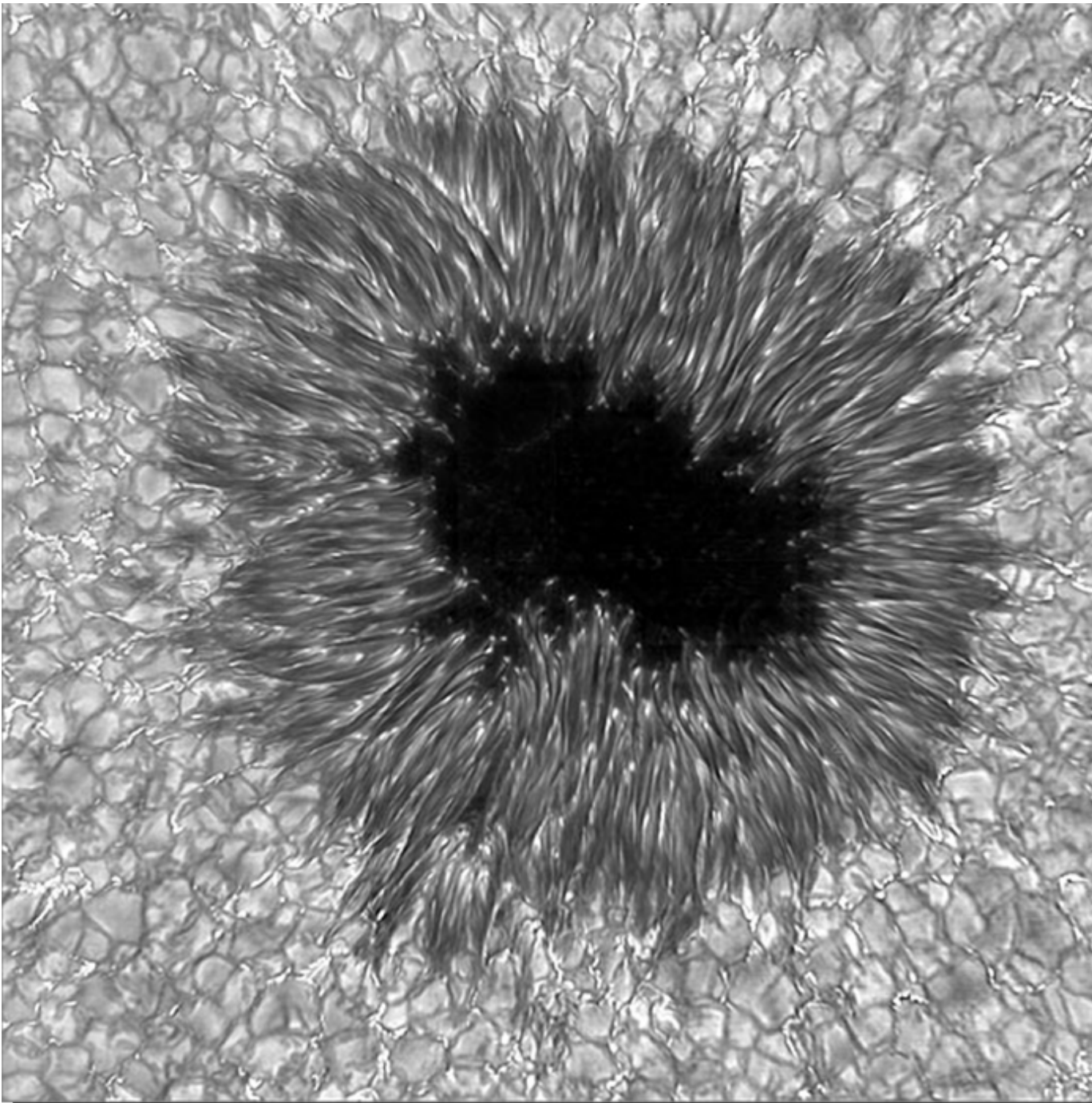
The role of the Sun and Solar Physics in Astrophysics



- The Rosetta Stone of astrophysical dynamics
 - Full availability of the time domain
 - rest of astrophysics \approx “snap shots”
 - Sub-arcsecond observations \Rightarrow rich spatial details
 - reaching below energy injection scales

**small scale detail
of sun spot image:**





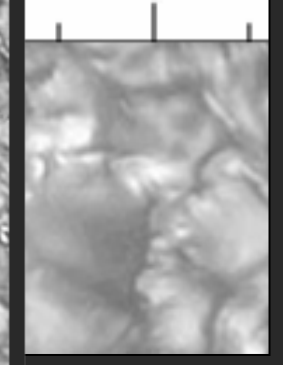
CS



ynamics

tial details

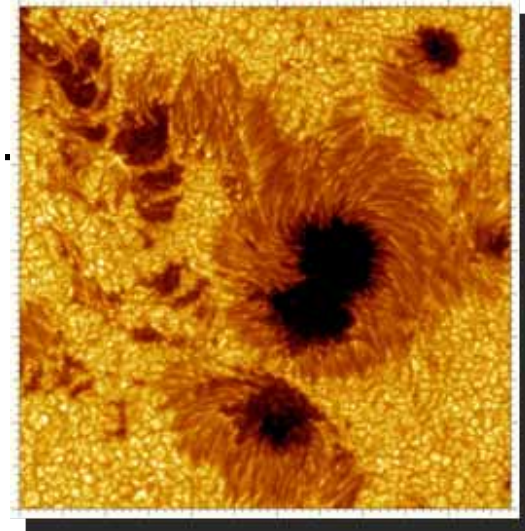
ometers



The role of the Sun and Solar Physics in Astrophysics



- The Rosetta Stone of astrophysical dynamics
 - Full availability of the time domain
 - rest of astrophysics \approx “snap shots”
 - Sub-arcsecond observations \Rightarrow rich spatial details
 - reaching below energy injection scales
 - Dynamically active magnetic fields
 - “Active Regions” = sunspots, plages, ..



The role of the Sun and Solar Physics in Astrophysics



- The Rosetta Stone of astrophysical dynamics
 - Full availability of the time
 - rest of astrophysics \approx “snapshots”
 - Sub-arcsecond observations
 - reaching below energy injection
 - Dynamically active magnetic fields
 - “Active Regions” = sunspots
 - Non-thermal phenomena
 - chromospheric and coronal heating, solar flares, ...



The relevance of Solar Hydrodynamics



- A ***benchmark case***, where numerical models can be tested and calibrated
 - ***Can affordable numerical models produce quantitatively accurate results?***

The relevance of Solar Hydrodynamics



- A **benchmark case**, where numerical models can be tested and calibrated
 - *Can affordable numerical models produce quantitatively accurate results?* **Yes!**
- Hydrodynamics (convection) is the **driving “engine”**, also for the (electro-)magnetic phenomena

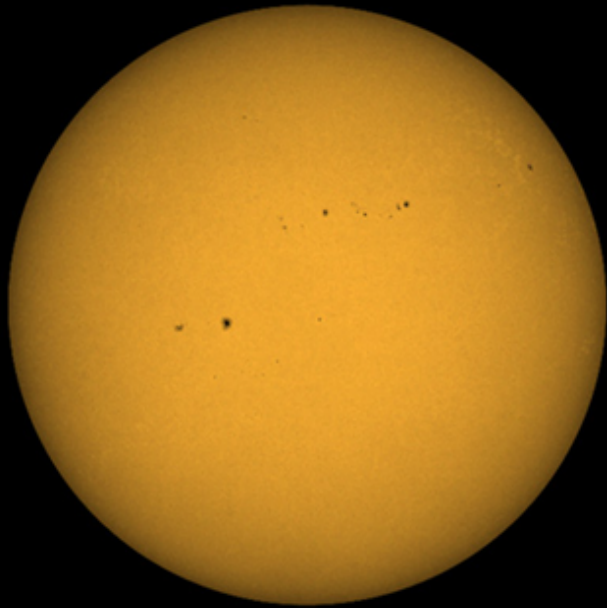
The relevance of Solar Hydrodynamics



- A **benchmark case**, where numerical models can be tested and calibrated
 - *Can affordable numerical models produce quantitatively accurate results?* **Yes!**
- Hydrodynamics (convection) is the **driving “engine”**, also for the (electro-)magnetic phenomena. **Crucial to get this right!**

Solar surface structures

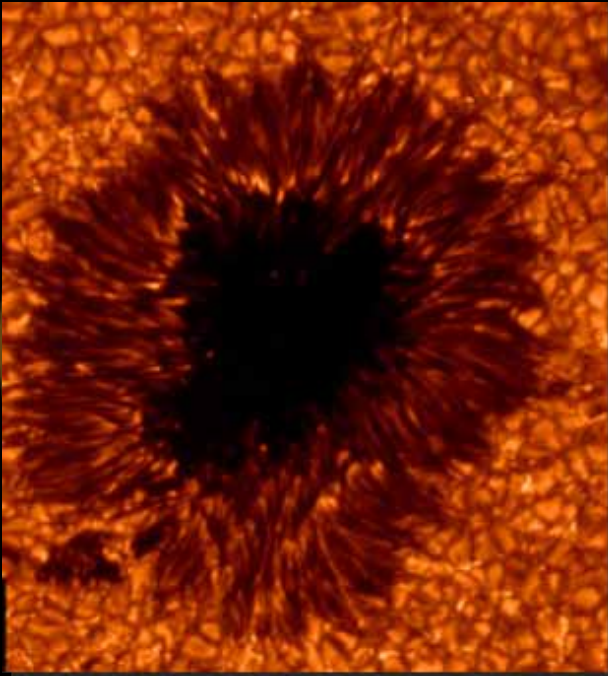
Visible Continuum



Solar surface structures



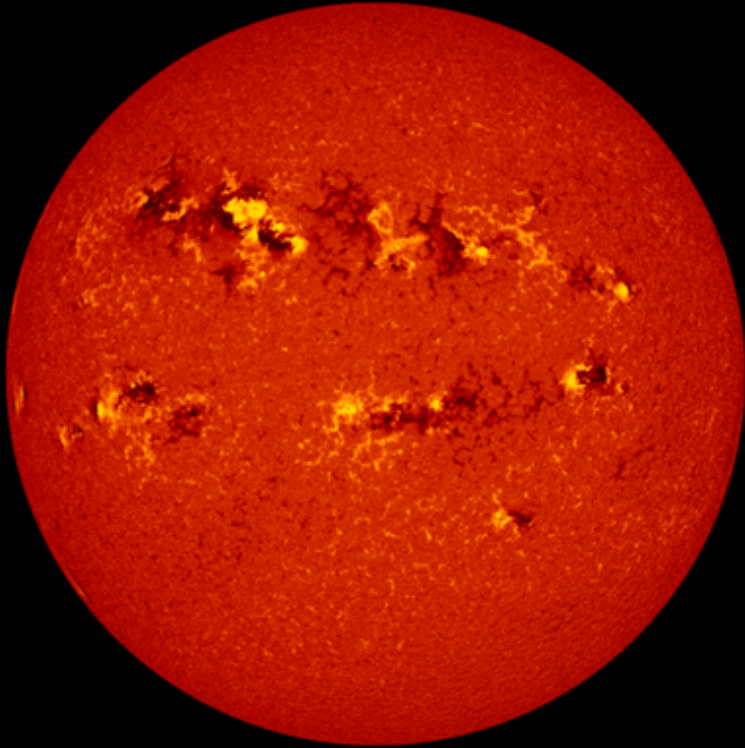
Visible Continuum



Solar surface structures



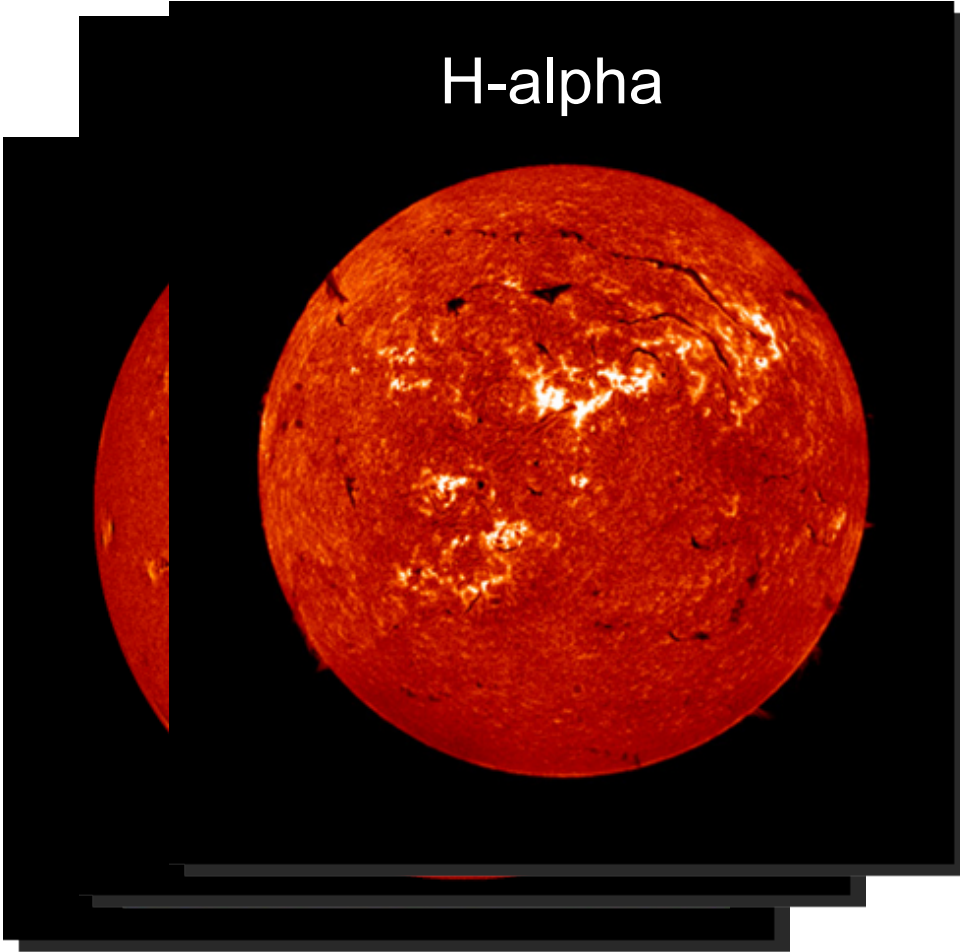
Magnetometer



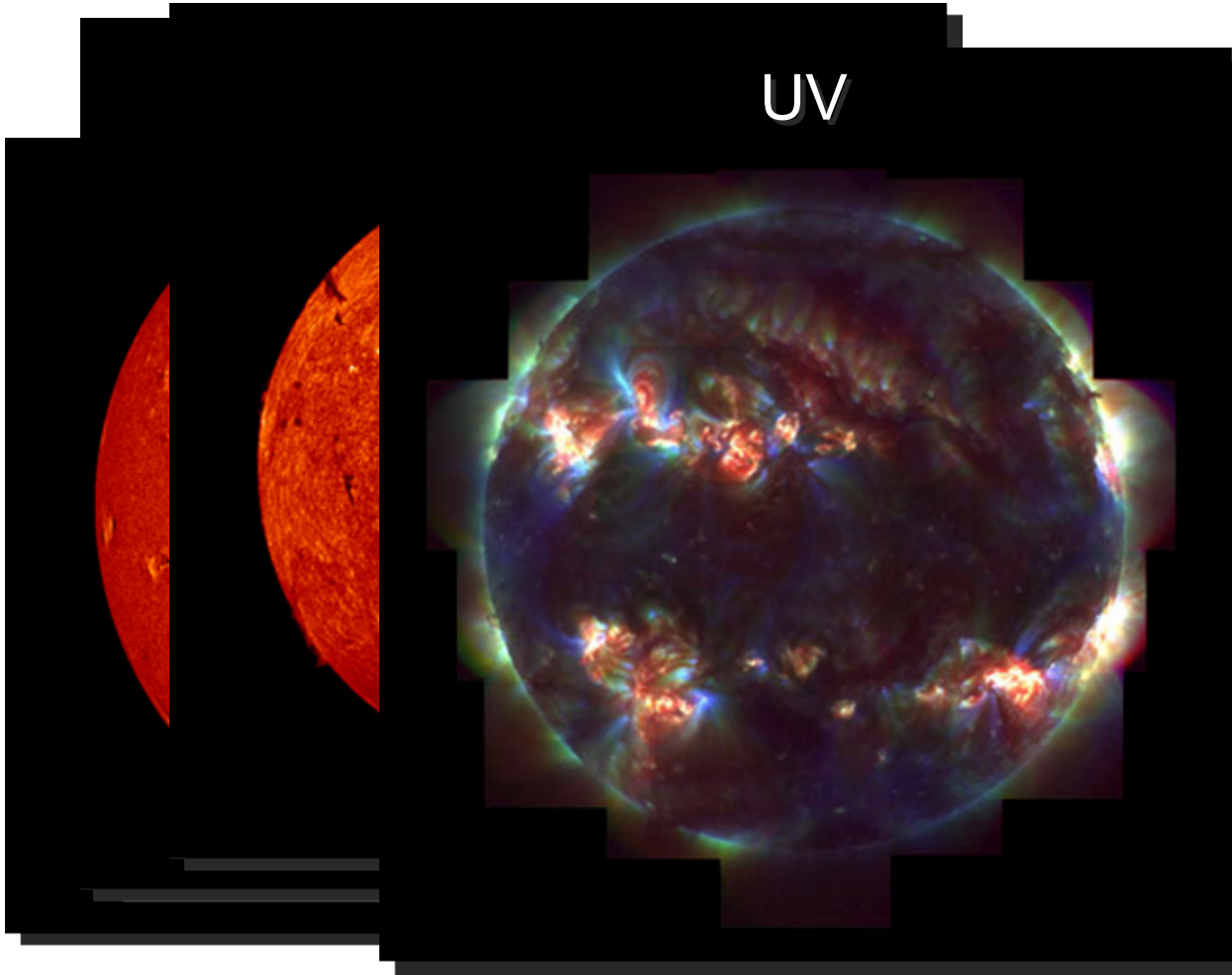
Solar surface structures



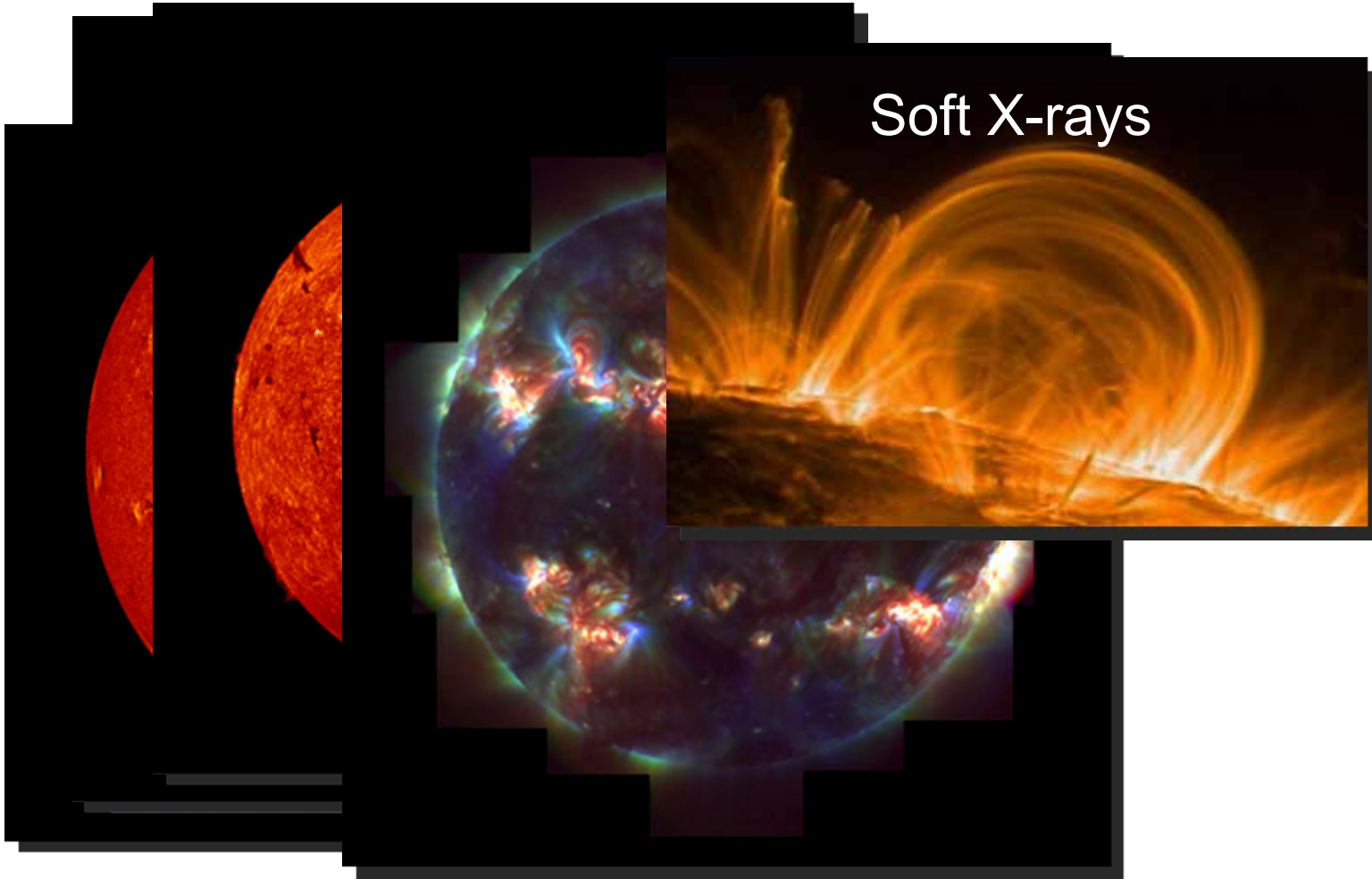
H-alpha



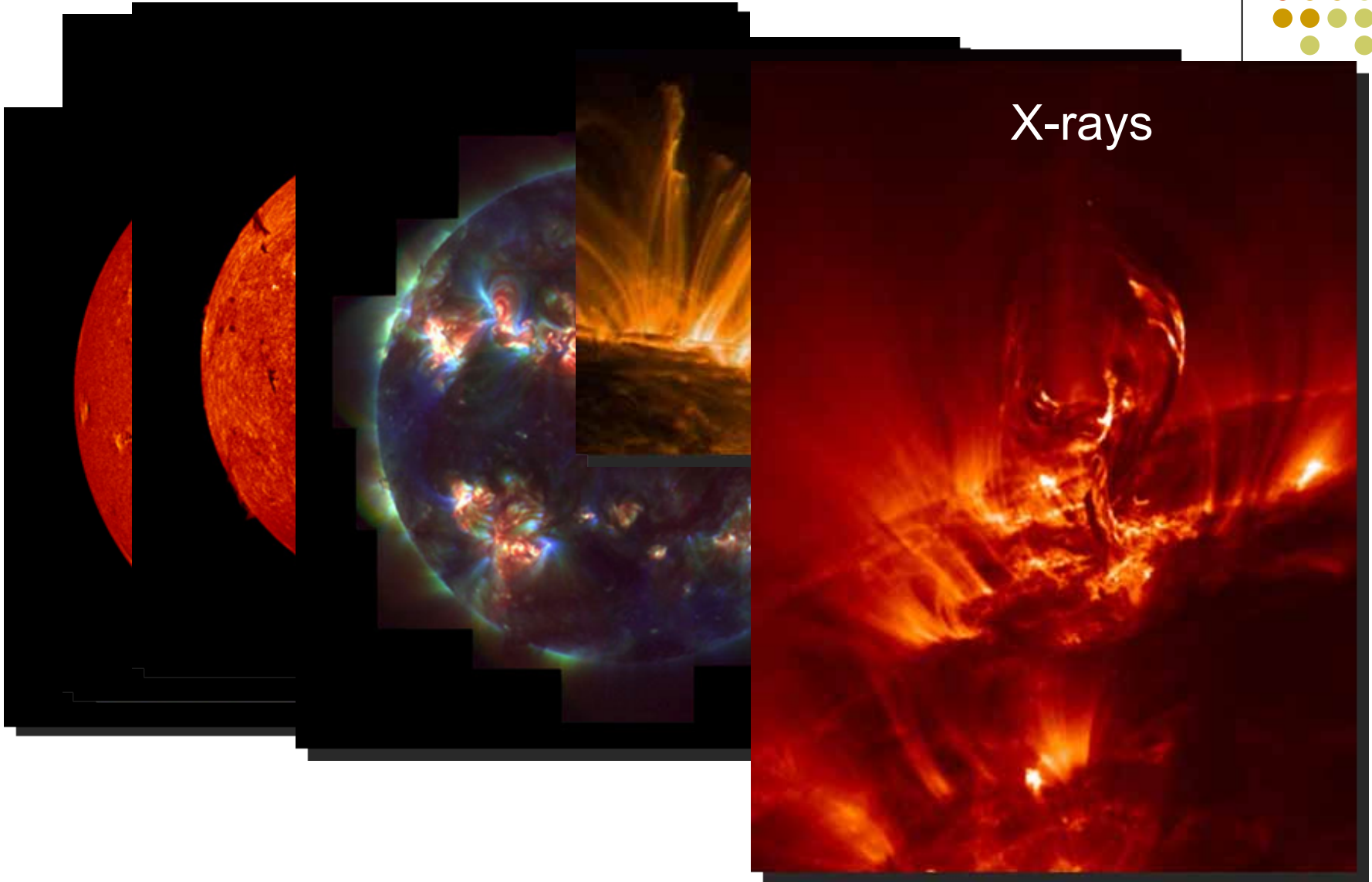
Solar surface structures



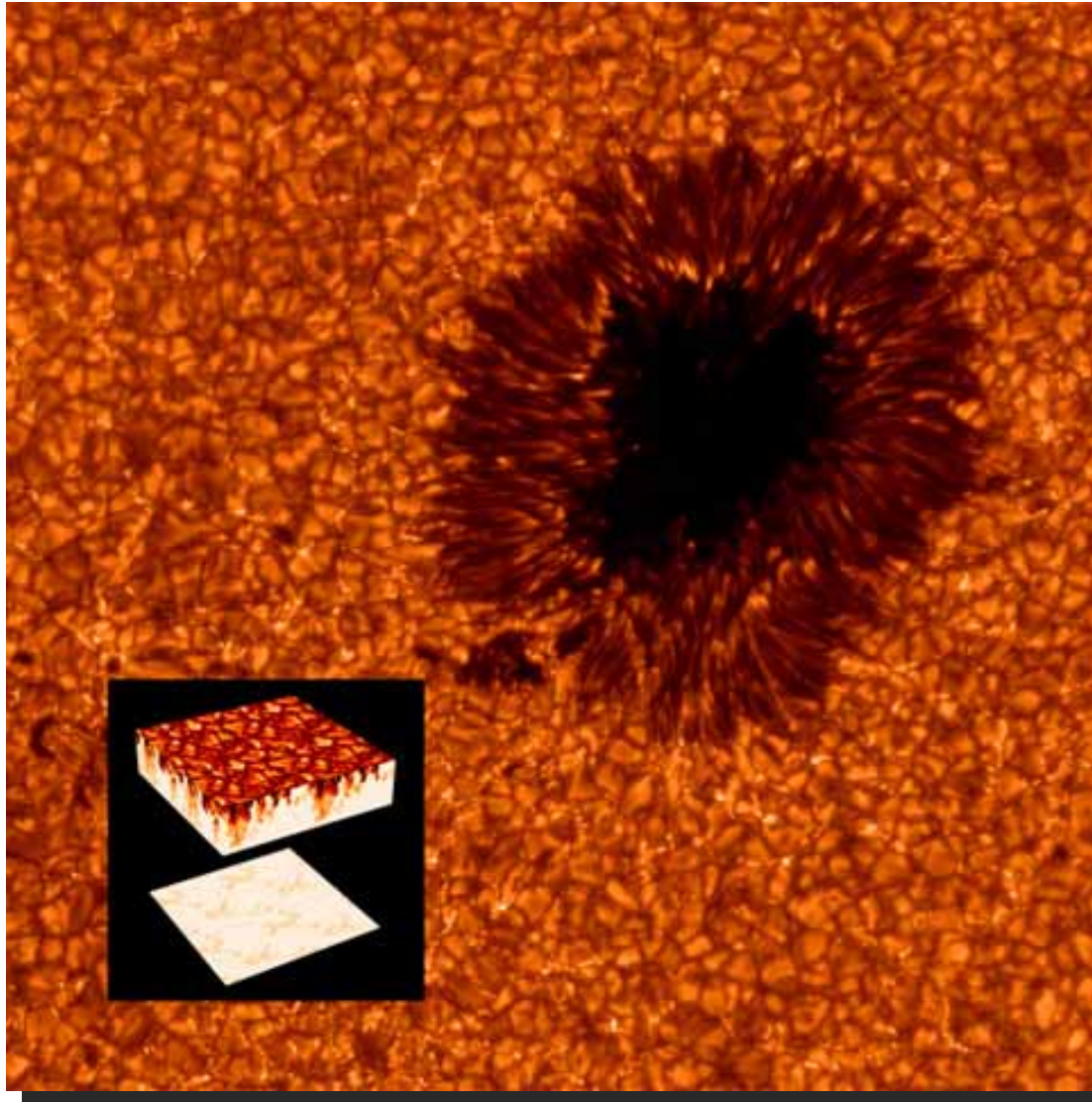
Solar surface structures



Solar surface structures



3D-modeling the solar surface and convection zone



Realistic and accurate 3D-modeling of solar convection



- Realistic *equation-of-state*
 - Ionization equilibria that include the main electron contributors at low T (Fe, Al, Mg, ...)
 - molecule dissociation equilibria (H^- , H_2 , CO, ...)
- Realistic radiative energy transfer
 - Multi-group treatment of $\sim 10^5$ spectral lines
 - Sufficient angular coverage
- Sufficient numerical resolution
 - *Which is?*

Realistic and accurate 3D-modeling of solar convection



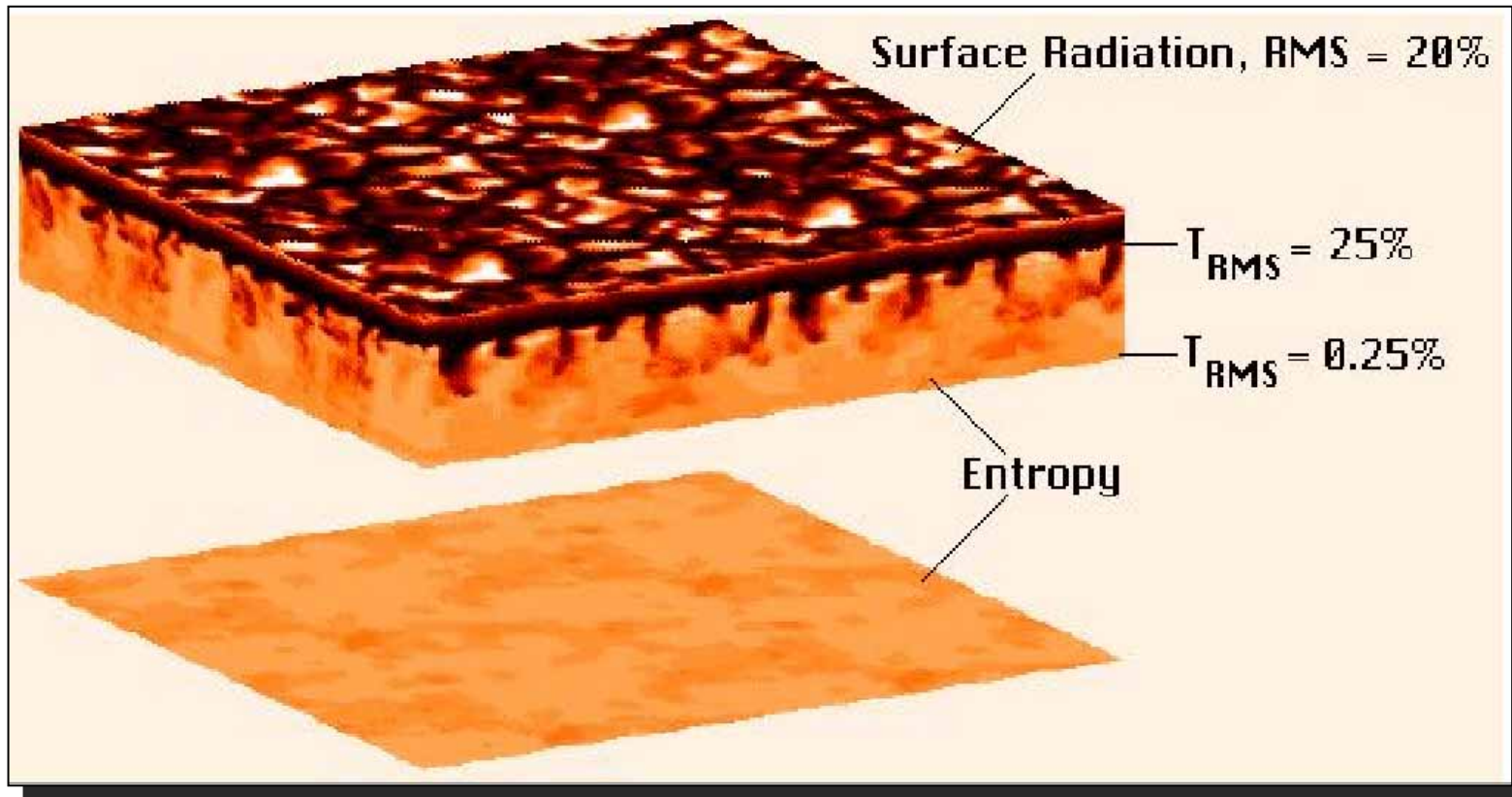
- Realistic *equation-of-state*
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- Realistic radiative energy transfer
 - Multi-group treatment of $\sim 10^5$ spectral lines
 - Sufficient angular coverage
- Sufficient numerical resolution
 - *Which is? – and how do you know?*

But first – a qualitative overview

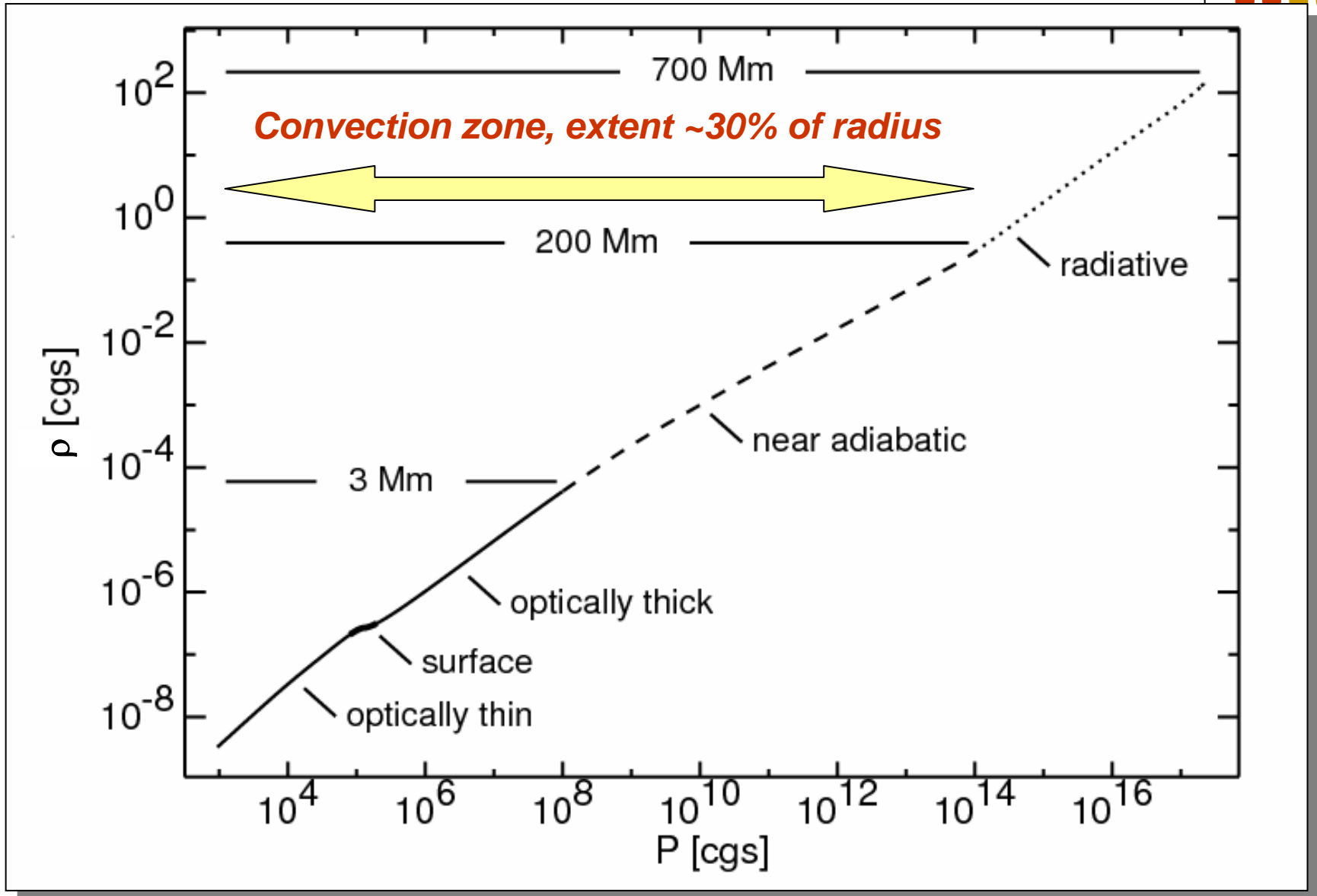
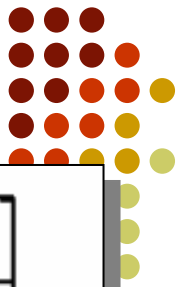


- The crucial importance of stratification
 - "compressibility" (?)
- The crucial importance of the surface
 - Source of all entropy fluctuations
- Scaling behavior with depth

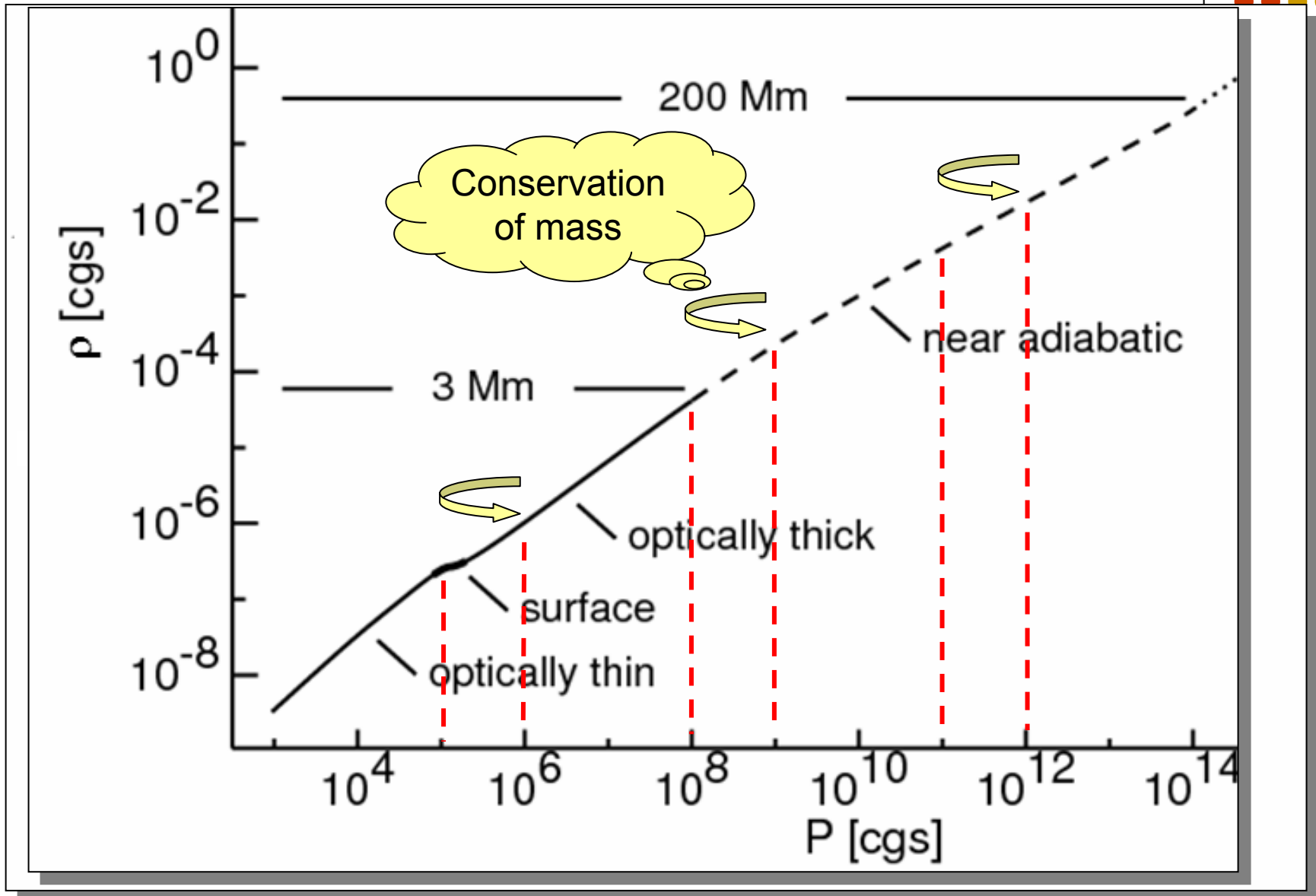
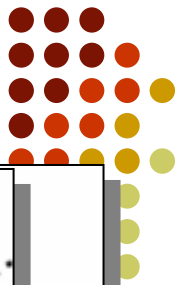
Fluctuations decrease very rapidly with depth



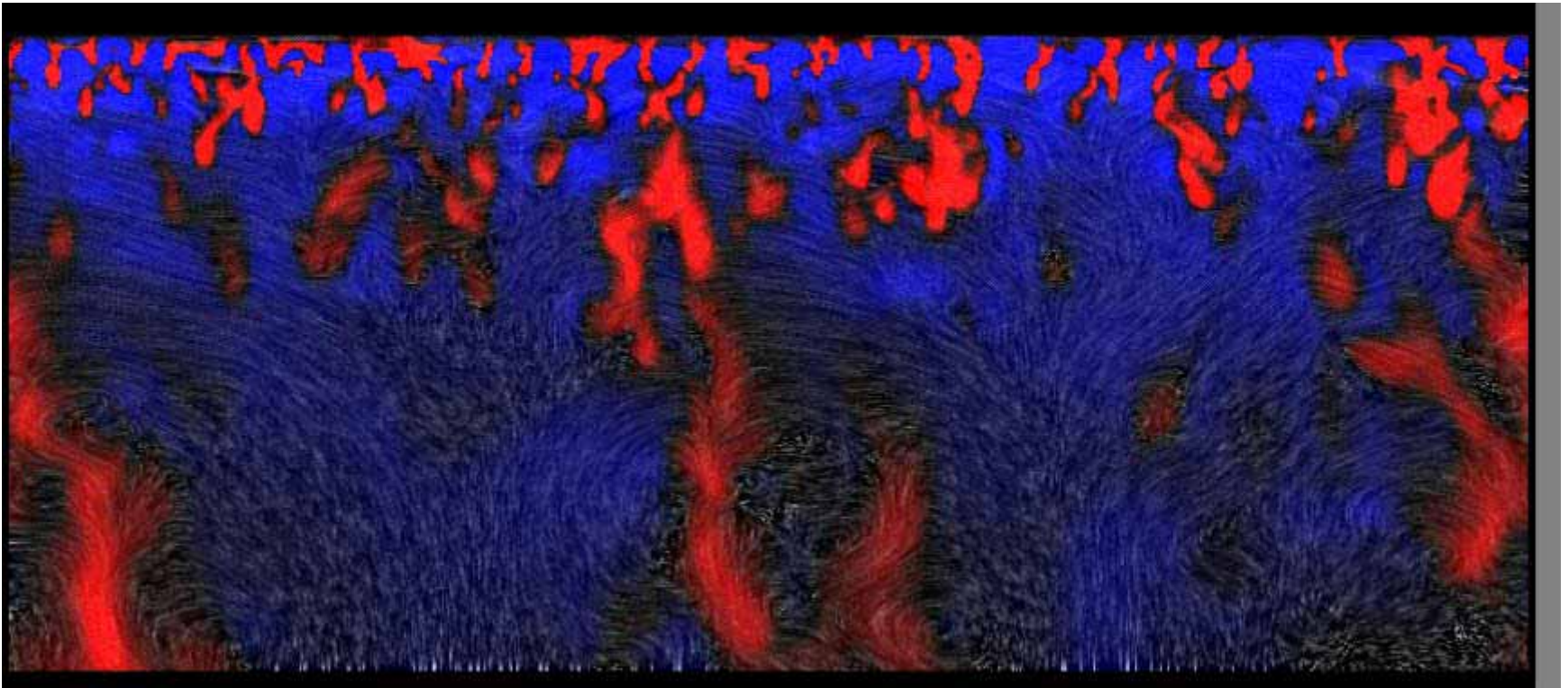
Overall Solar Structure



Convection Zone

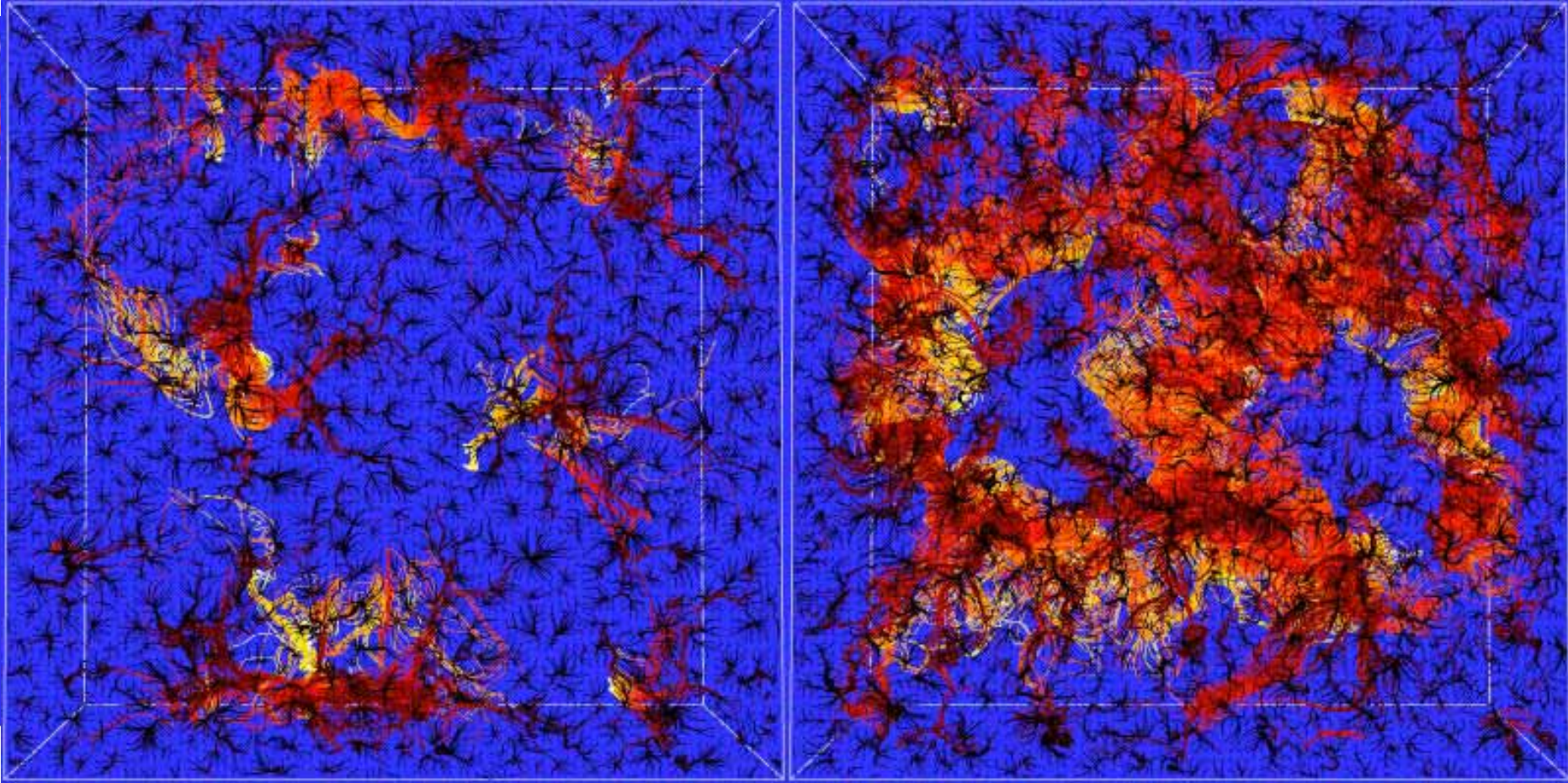


Surface flow 3-D model (vertical extent 3% of radius)

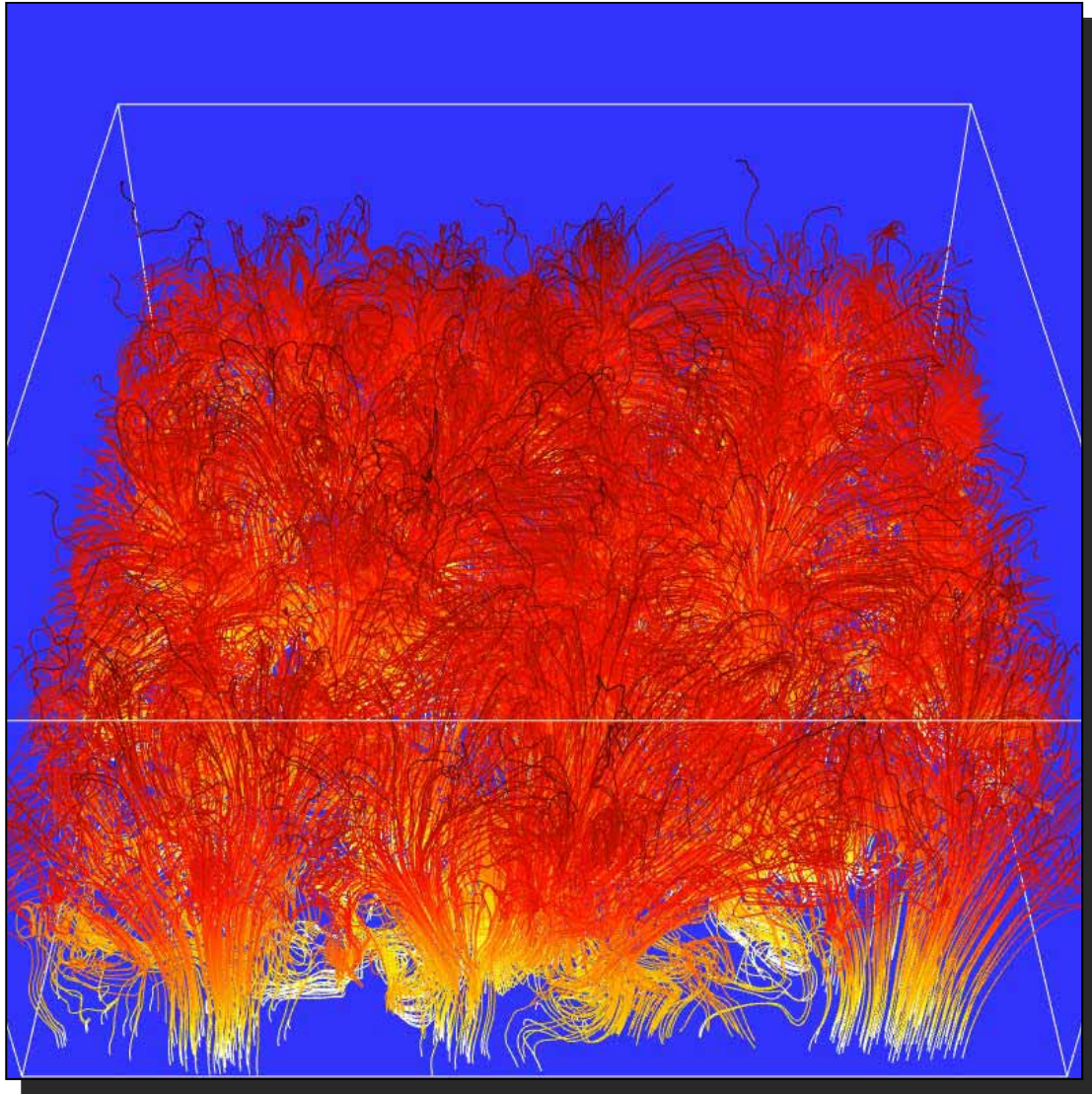


Upflows at surface come from small area at bottom

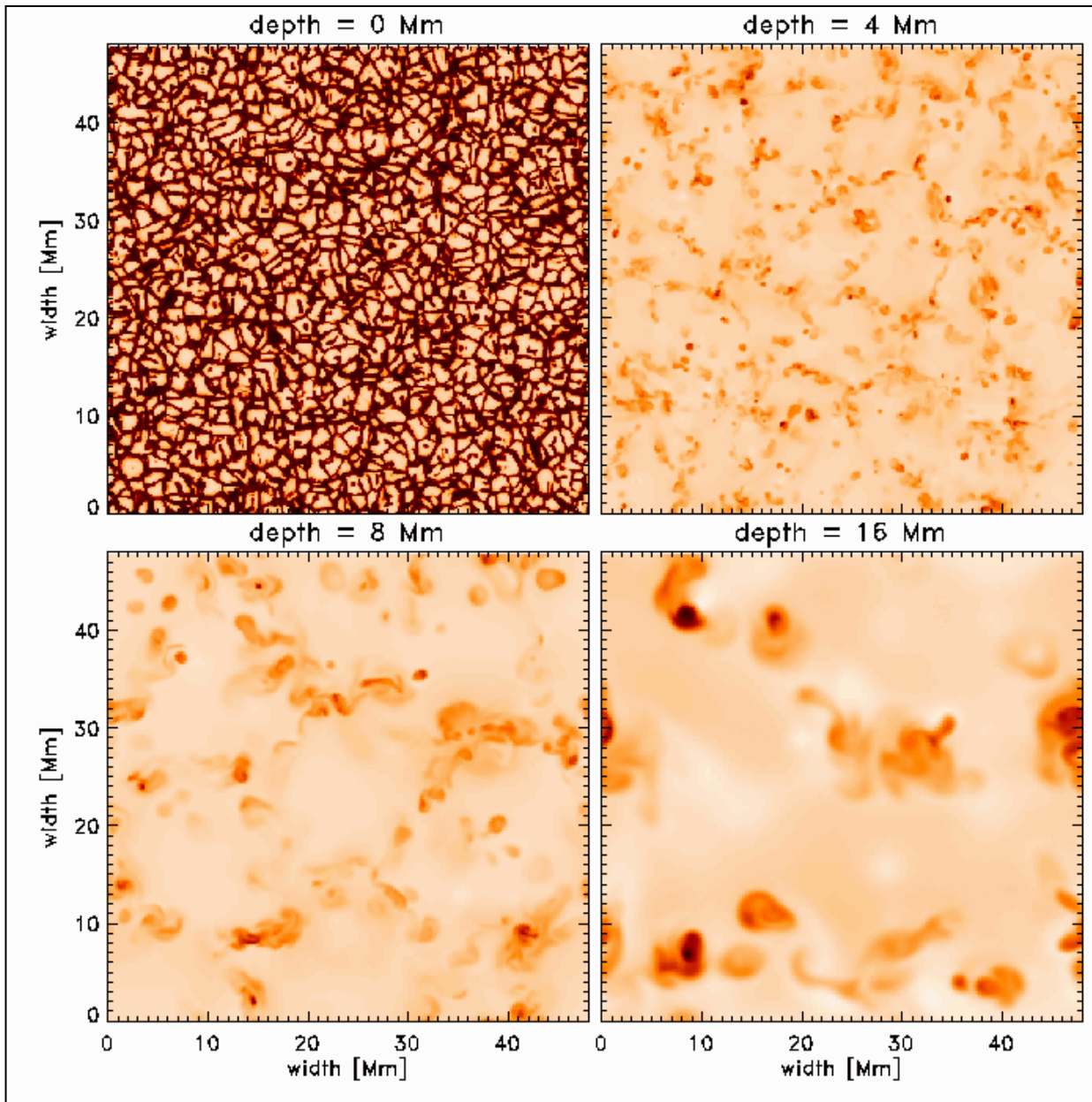
Downflows at surface converge to large scale boundaries



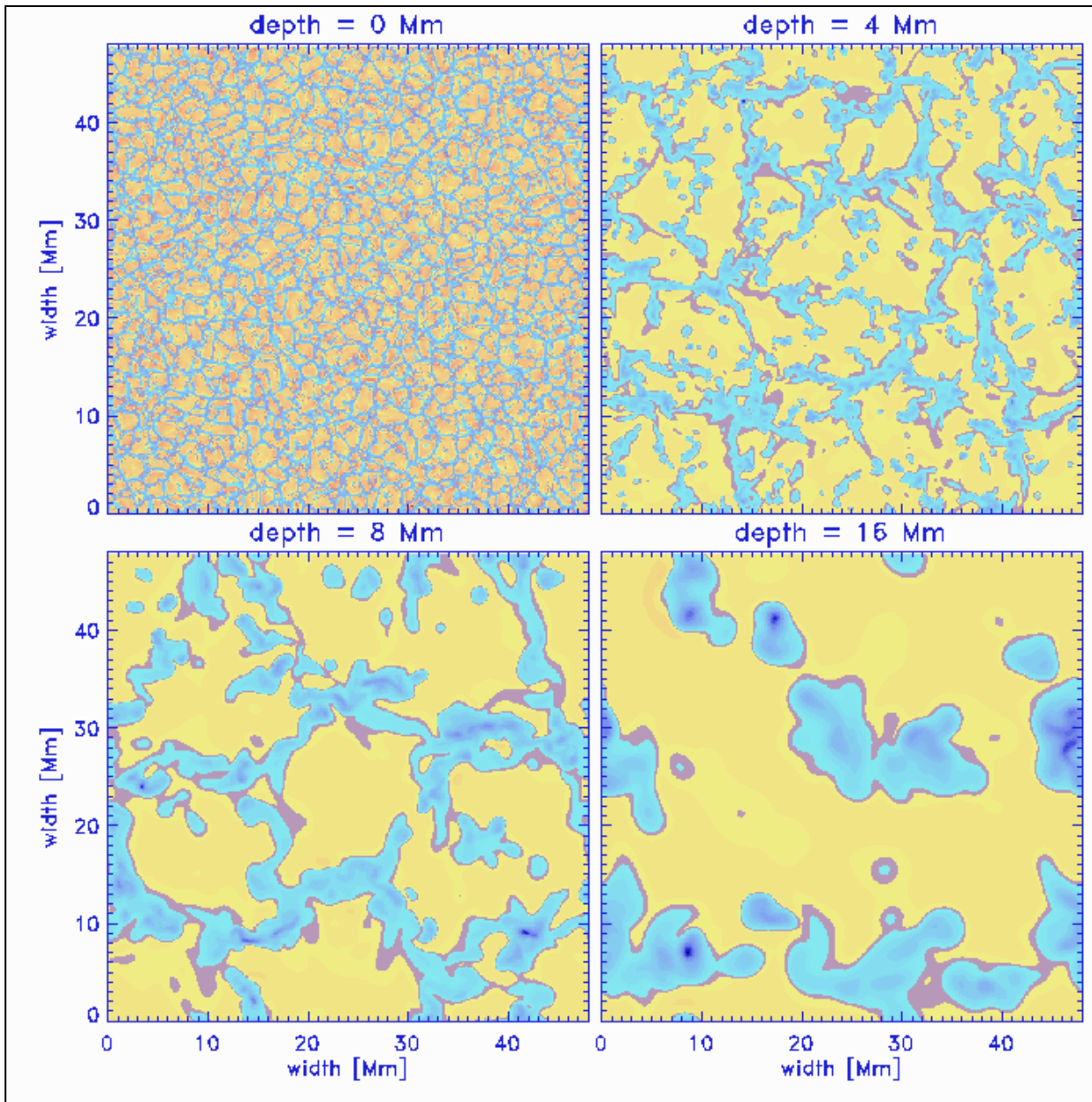
**Fluid from the midplane
very rarely reaches the surface!**



Temperature patterns at four different depths

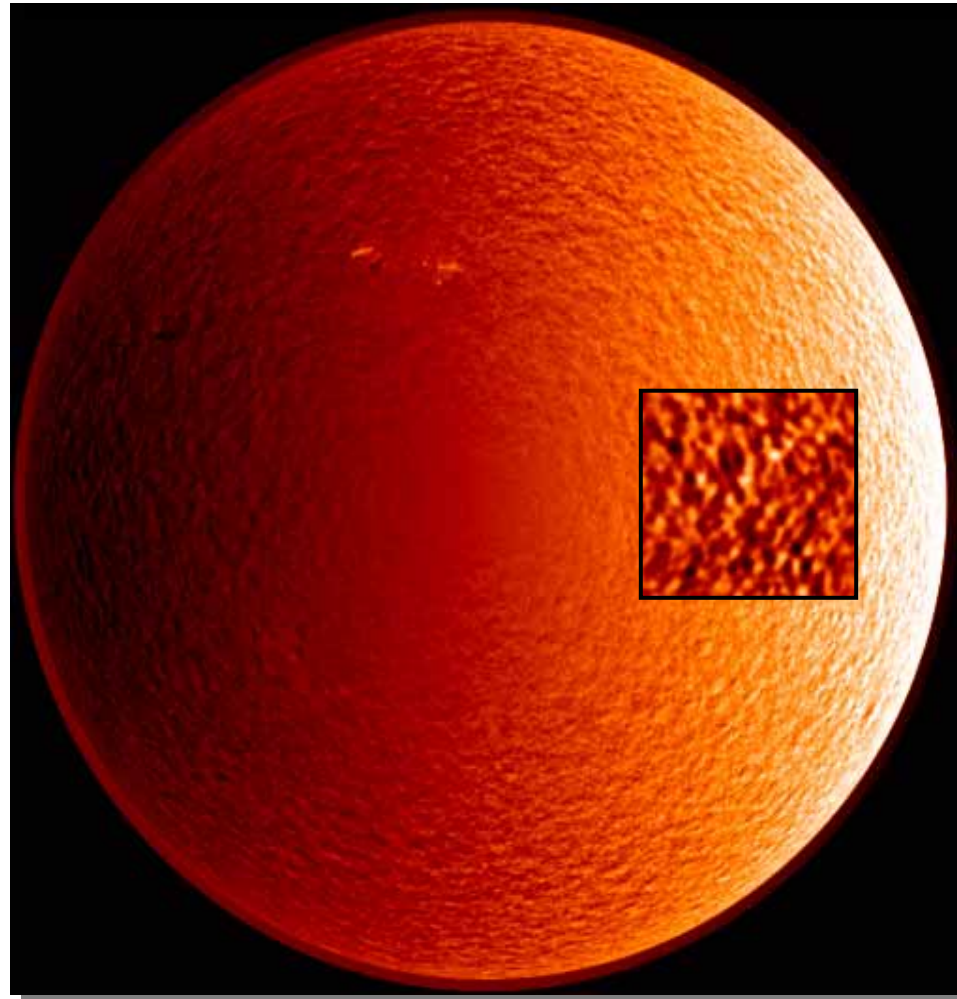


Velocities at the same depths



A Nearly Scale Free Spectrum?

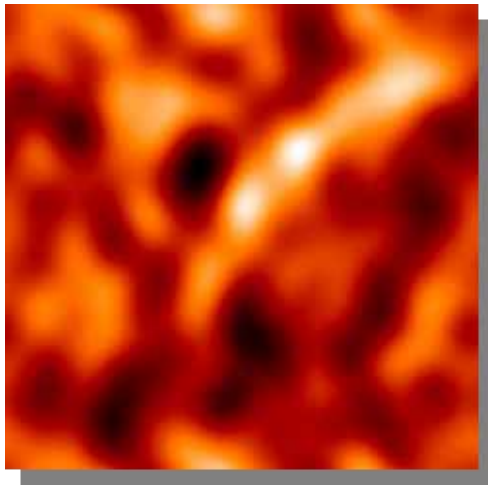
Doppler Image of the Sun (SOHO/MDI)



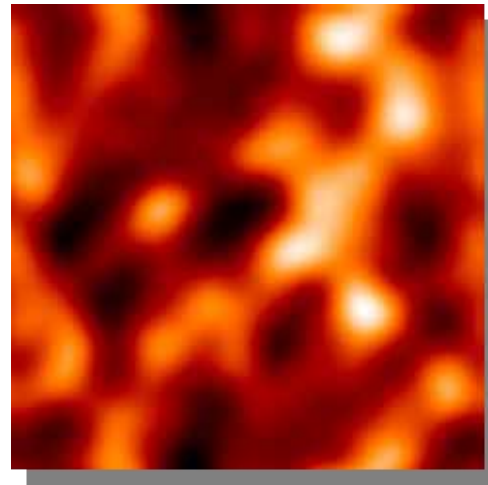
Solar horizontal velocity (observed)

Scales differ by factor 2 – which is which?

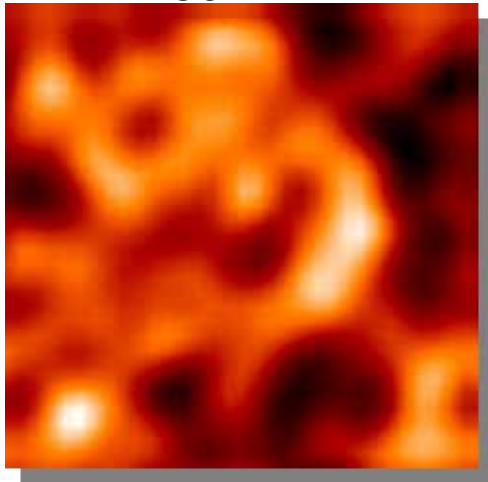
400 Mm



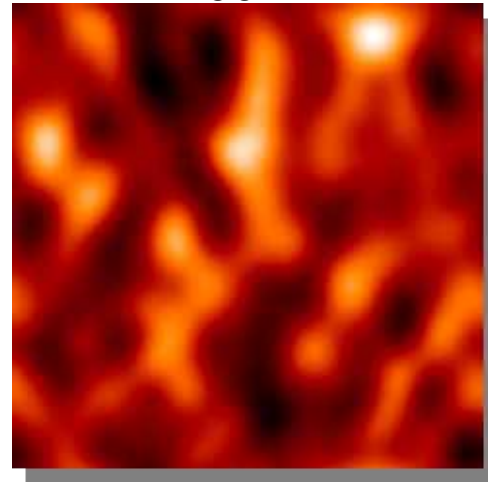
100 Mm



50 Mm



200 Mm

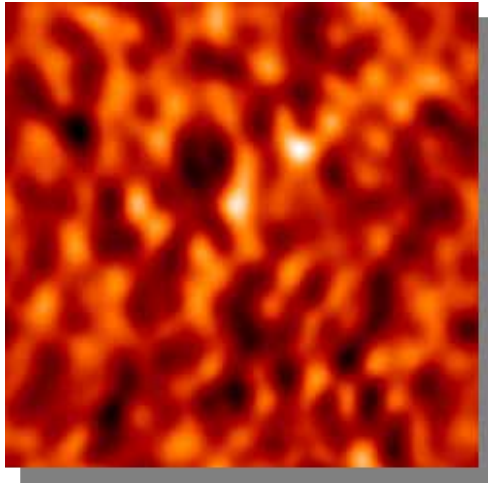


Solar horizontal velocity (observed)

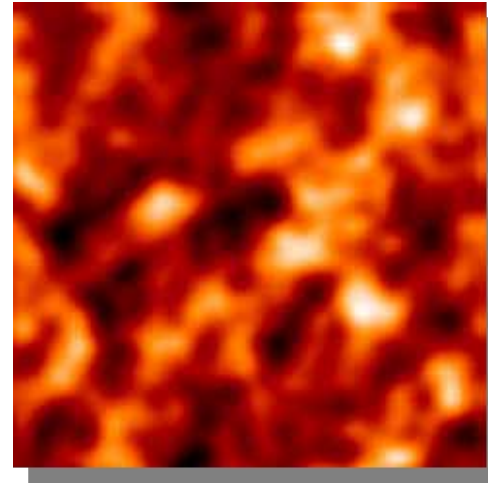
Scales differ by factor 2 – which is which?



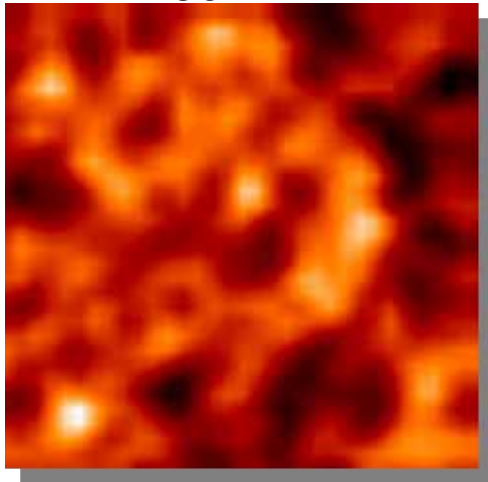
400 Mm



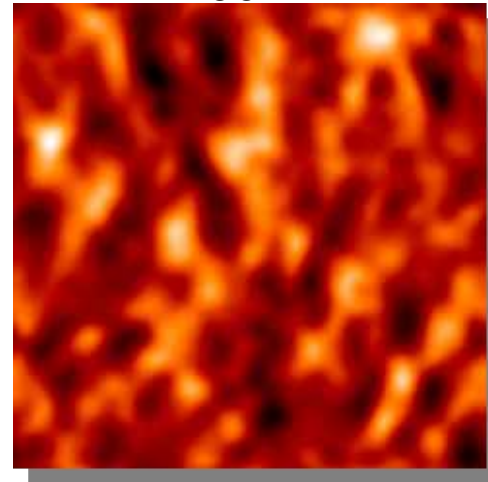
100 Mm



50 Mm



200 Mm

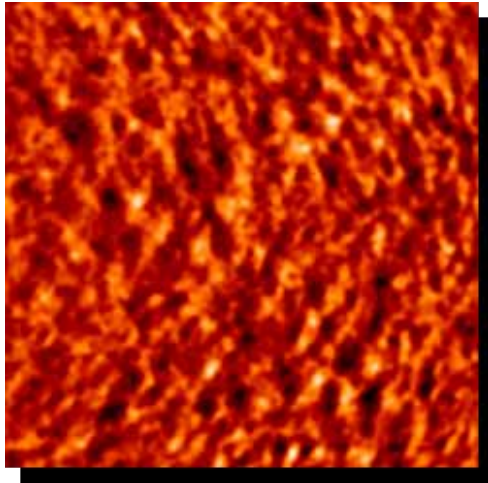


Solar horizontal velocity (observed)

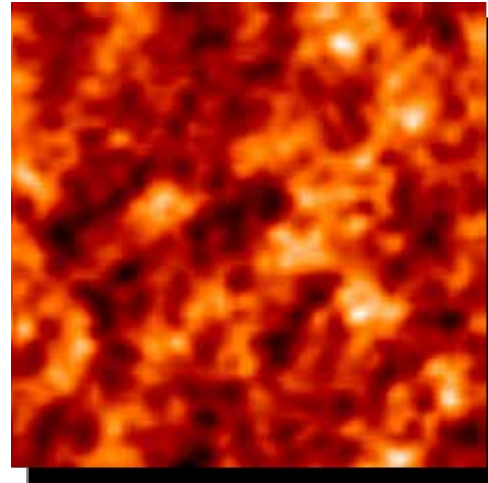
Scales differ by factor 2 – which is which?



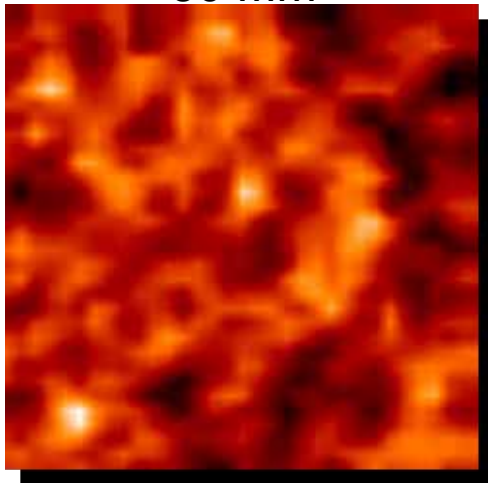
400 Mm



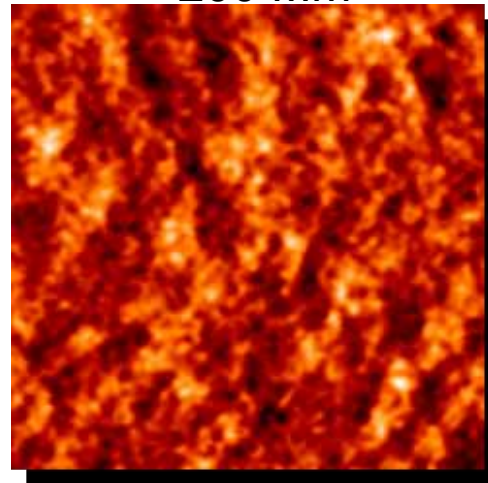
100 Mm



50 Mm



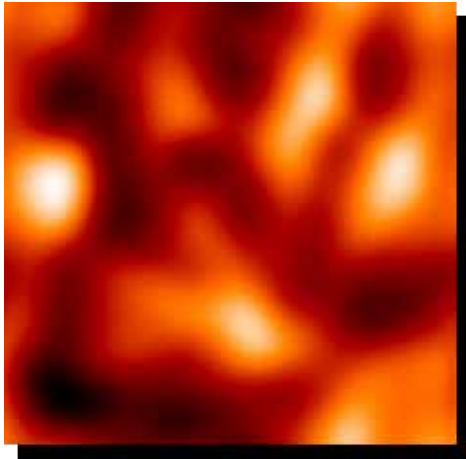
200 Mm



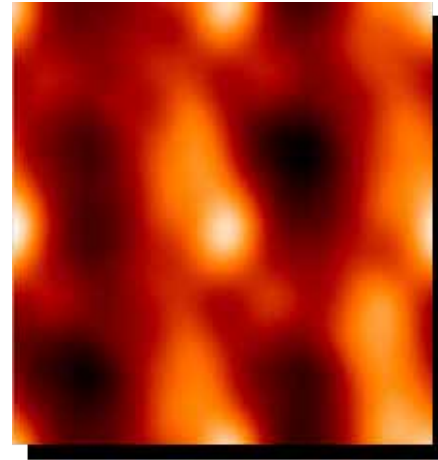
Solar horizontal velocity (model)

Scales differ by factor 2 – which is which?

12 Mm



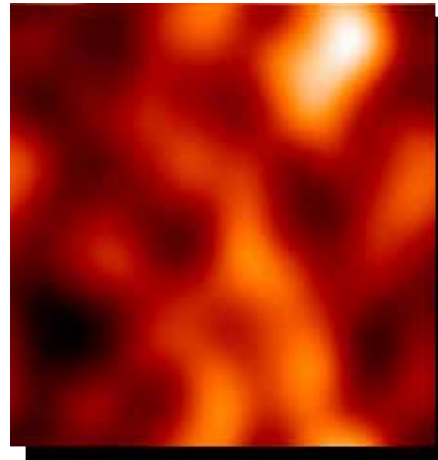
24 Mm



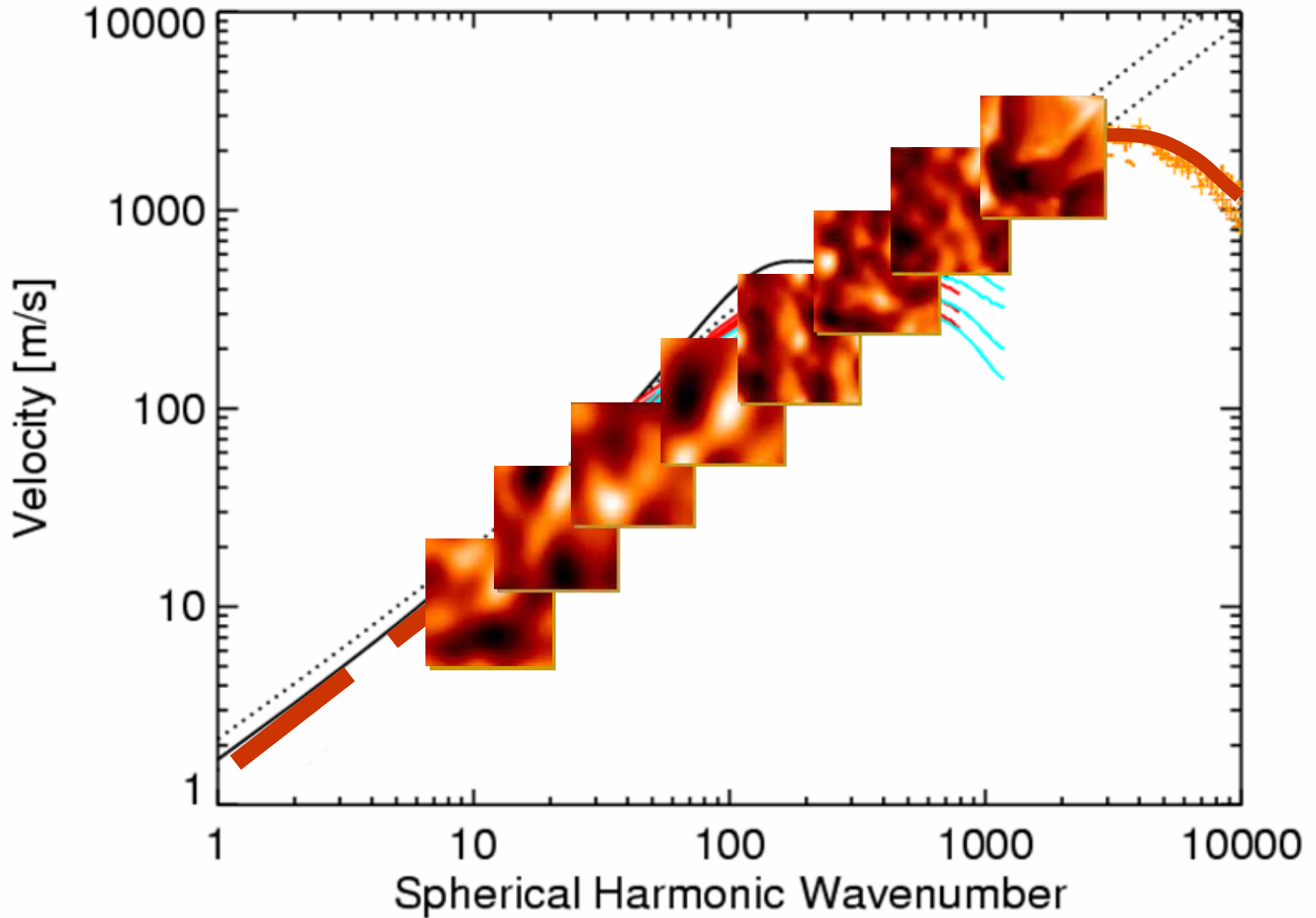
3 Mm



6 Mm



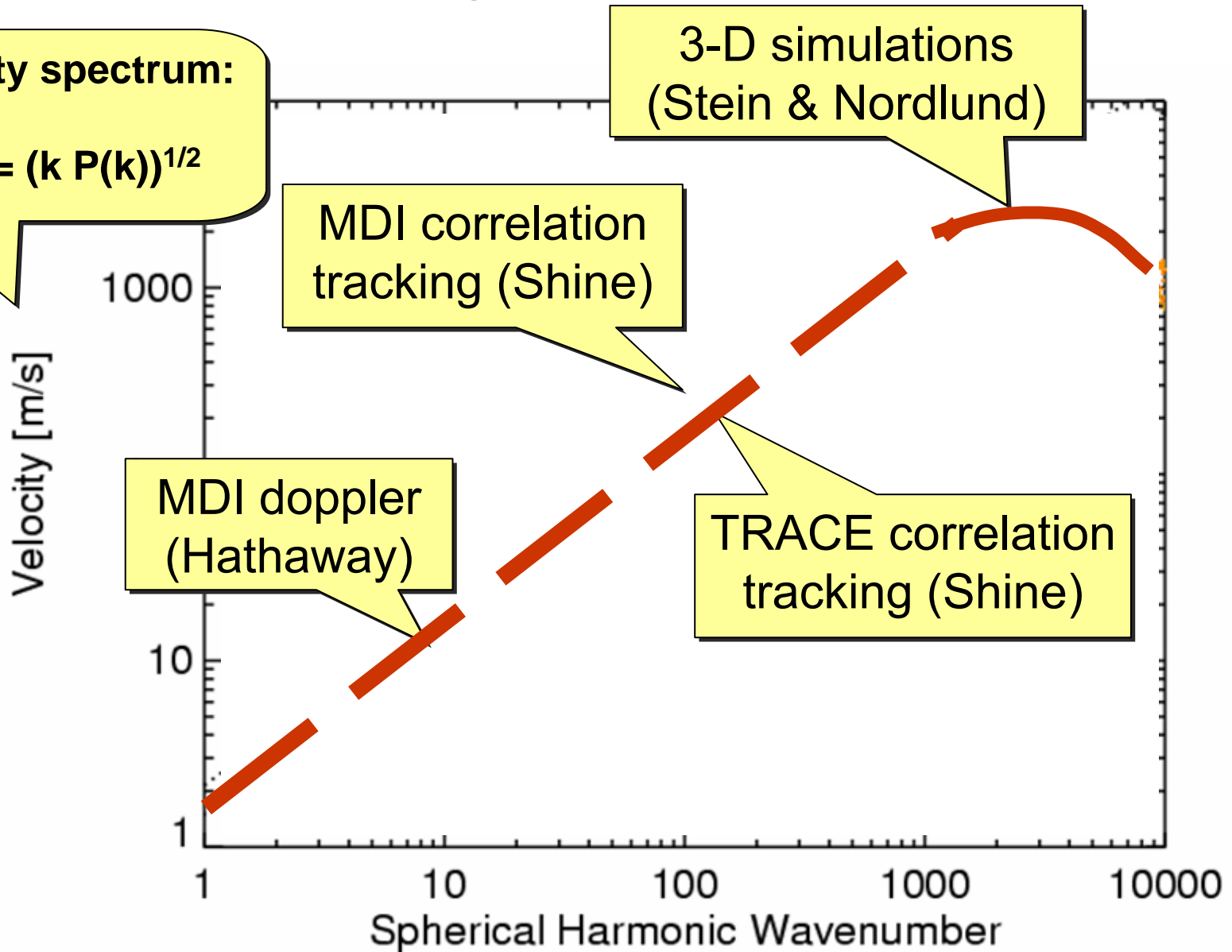
Solar velocity spectrum



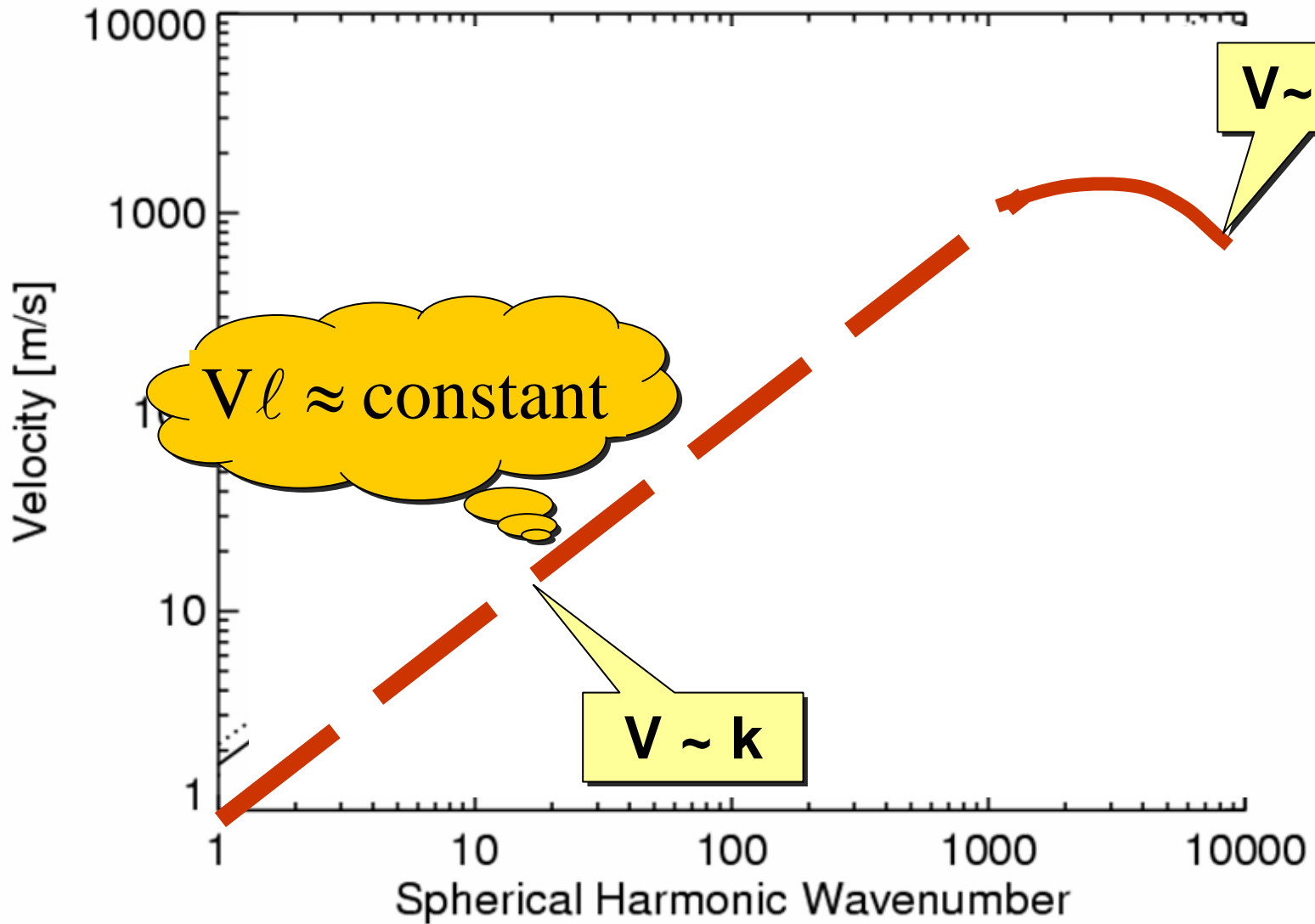
Solar velocity spectrum

Velocity spectrum:

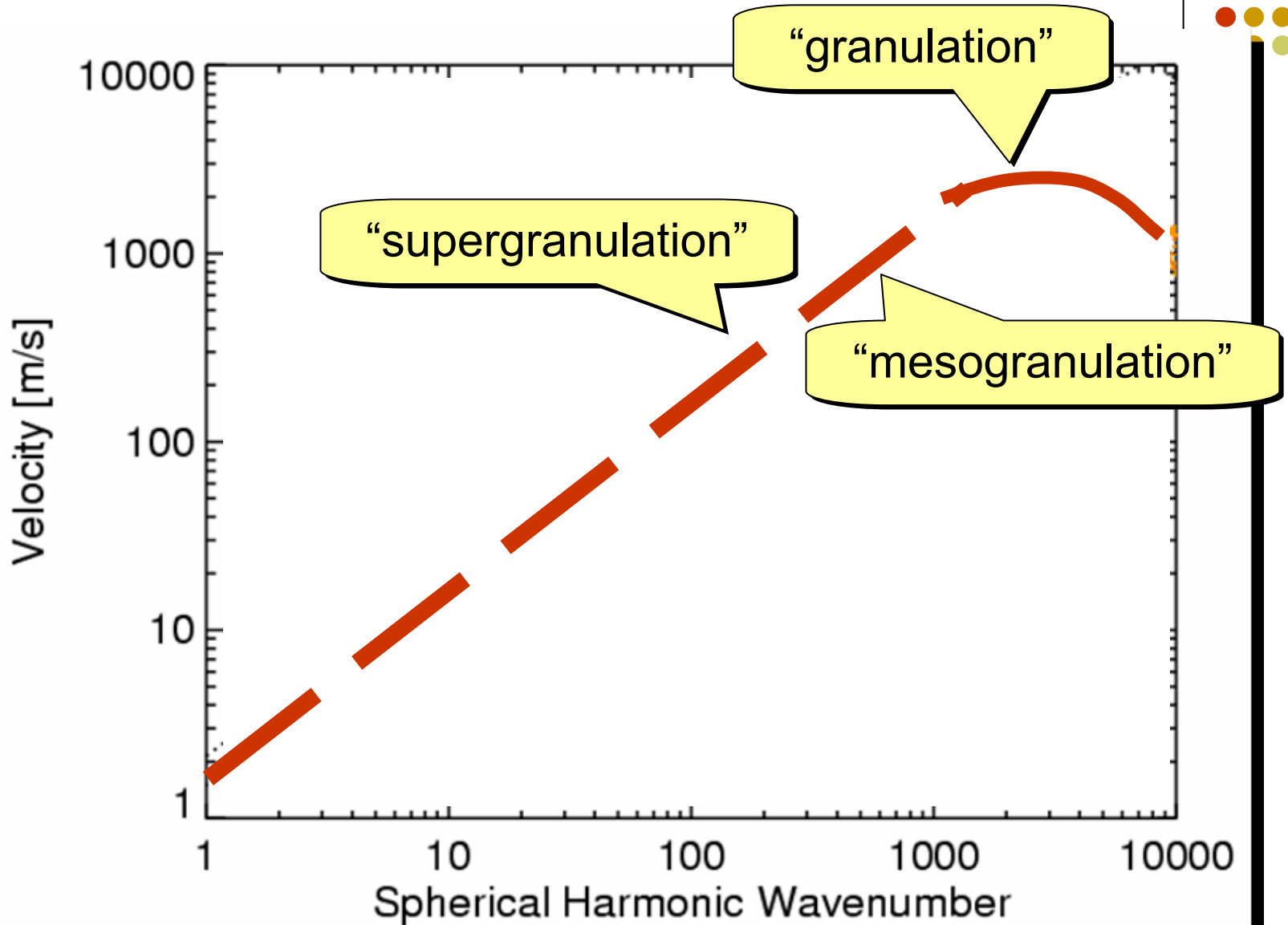
$$v(k) = (k P(k))^{1/2}$$



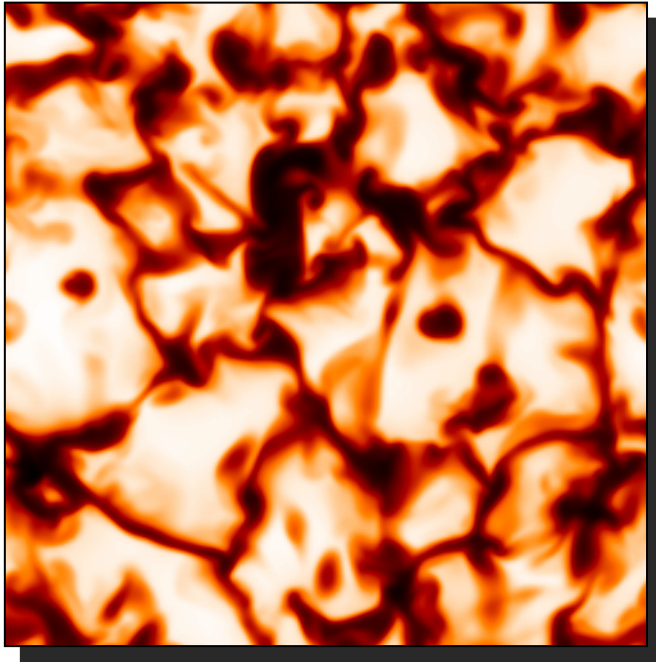
Solar velocity spectrum



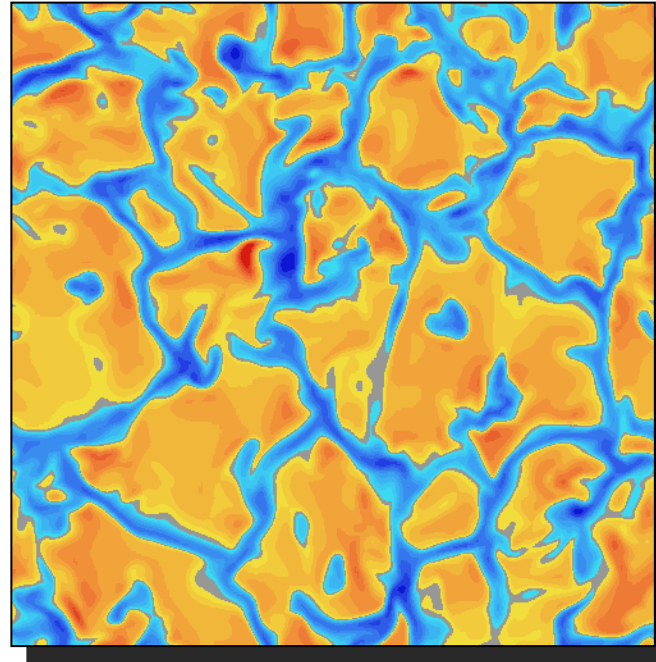
Solar velocity spectrum



Synthetic solar spectral lines – a crucial fingerprint!

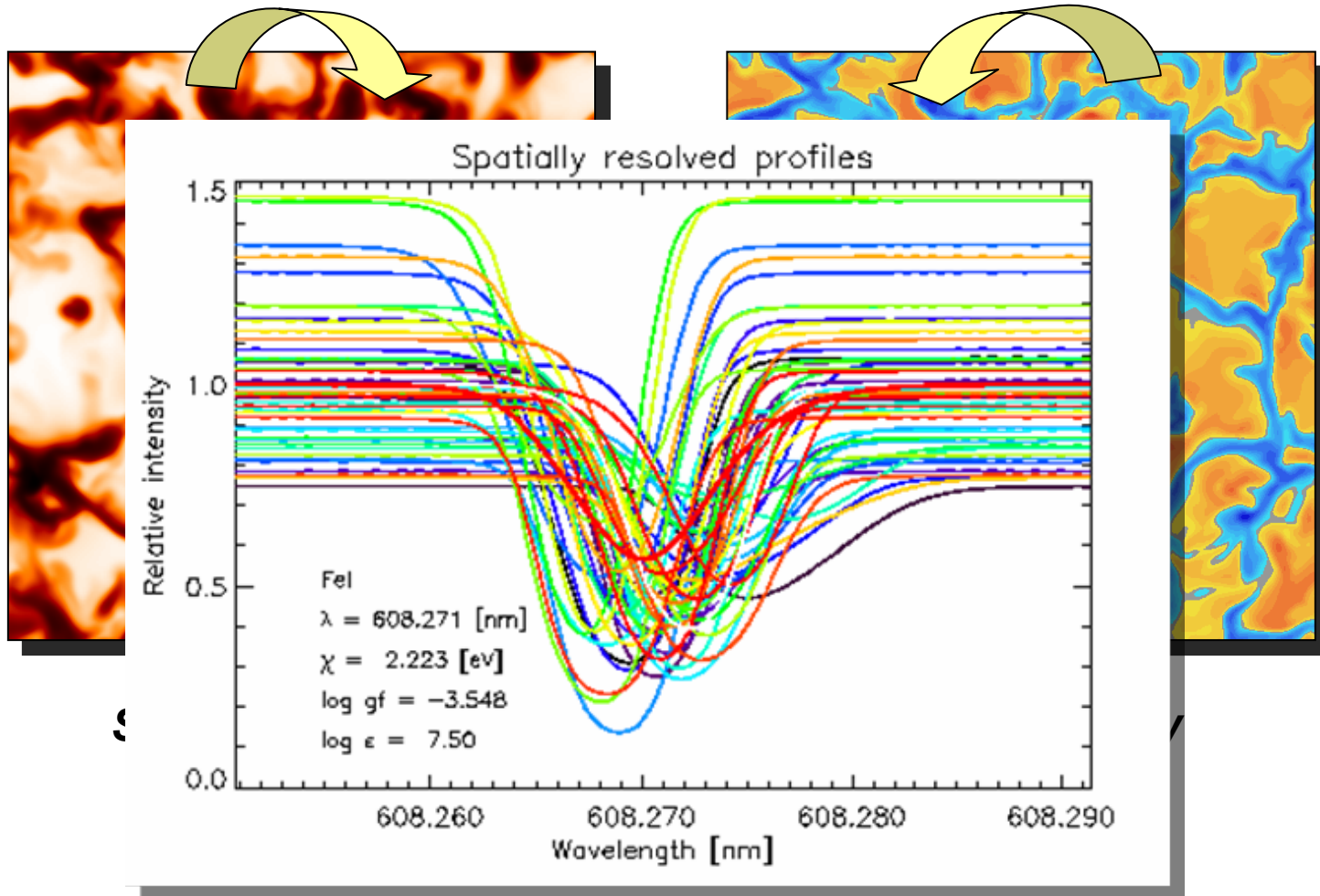


Surface brightness



Vertical velocity

Synthetic solar spectral lines – a crucial fingerprint!



Spatially resolved spectral line profiles

Spectral line, with and w/o convective velocity field

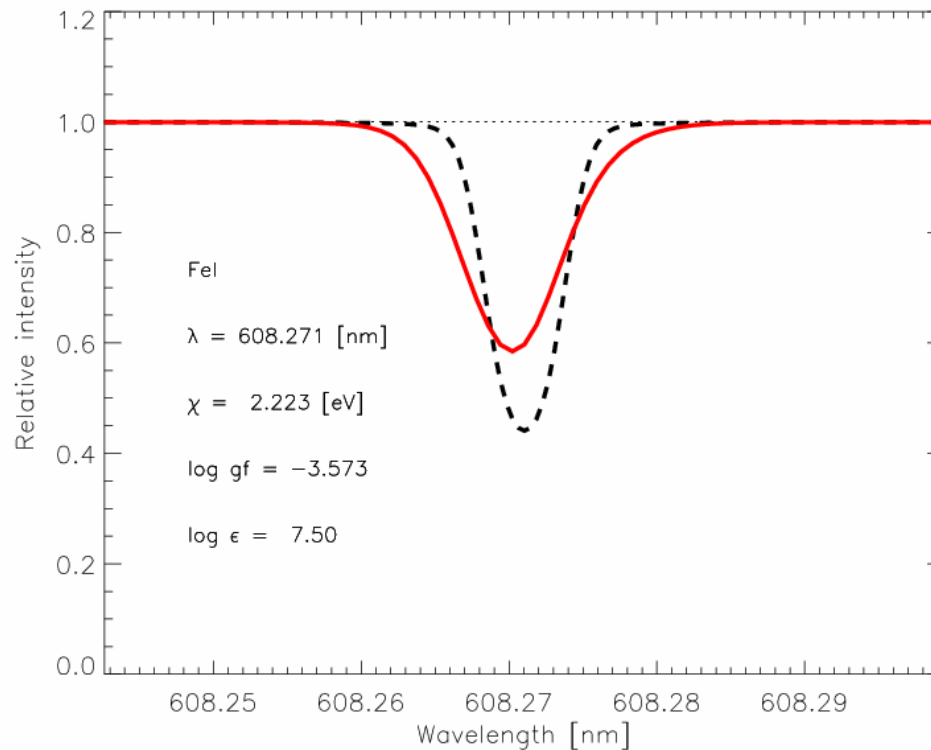


Figure 28: The predicted spatially and temporally averaged 3D LTE solar line profile of a typical Fe I line (solid line) compared with the corresponding calculation when ignoring all Doppler shifts arising from the photospheric velocity field (dashed line), demonstrating the importance of convective line broadening. The latter profile closely resembles 1D line profiles without application of the fudge parameters micro- and macroturbulence.

Synthetic and observed spectral line profiles

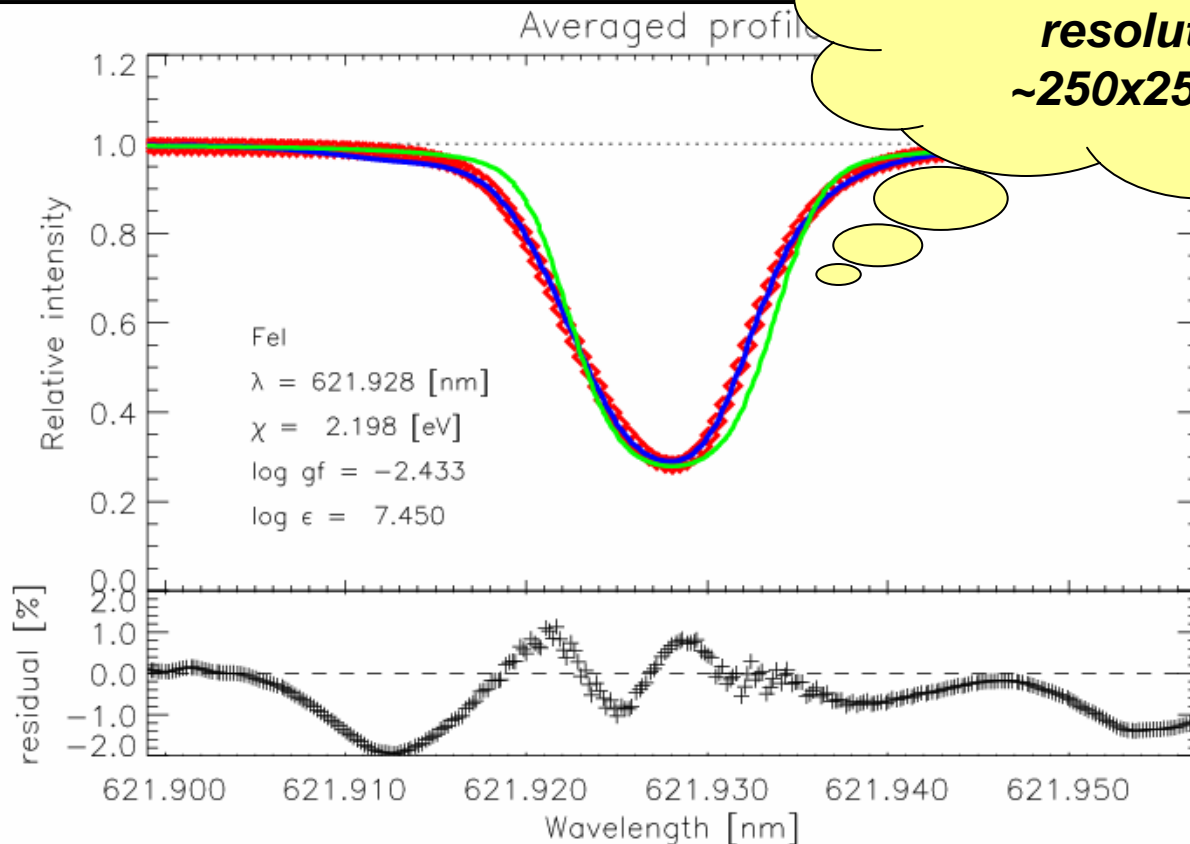
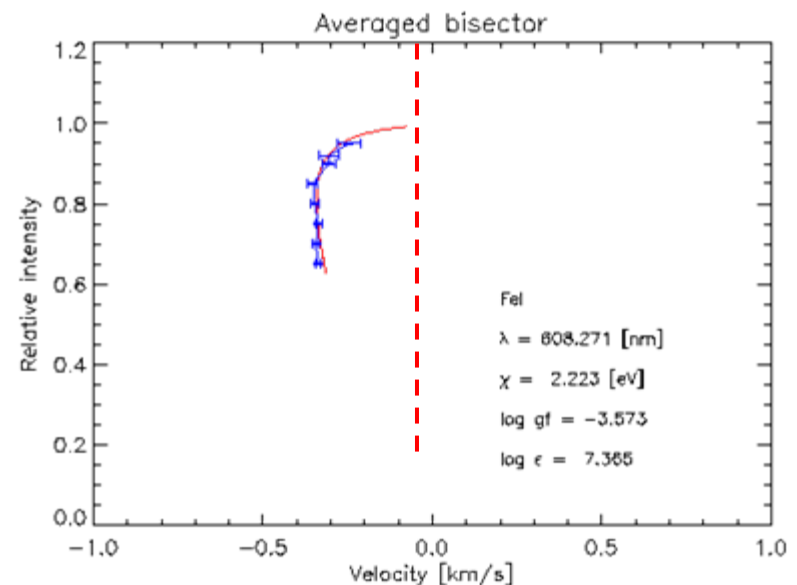
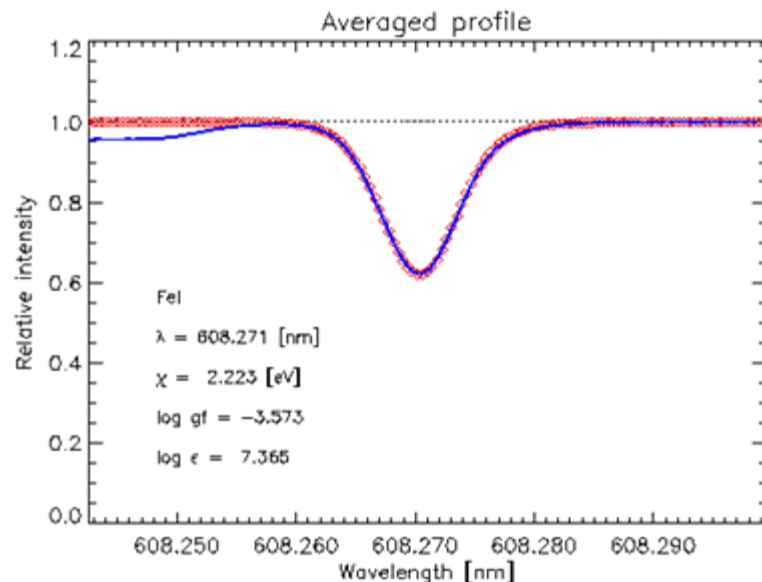


Figure 29: The predicted temporally and spatially averaged 3D profile (blue solid line) compared with the observed solar disk-center line (red diamonds). Note the excellent agreement as seen in the residuals (the discrepancies in the far red and blue wings are due to unaccounted for blends). Also shown is the best-fitting 1D line profile after having optimized the micro- and macroturbulence (green solid line), which clearly has the wrong shape, asymmetry and shift.

Accurate match; widths, shapes *and* shifts!



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

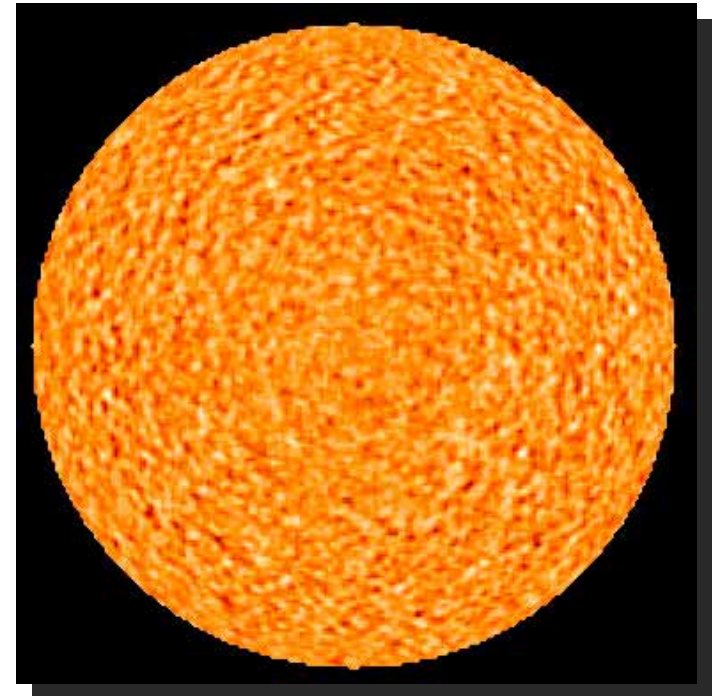


Local and global helio-seismology



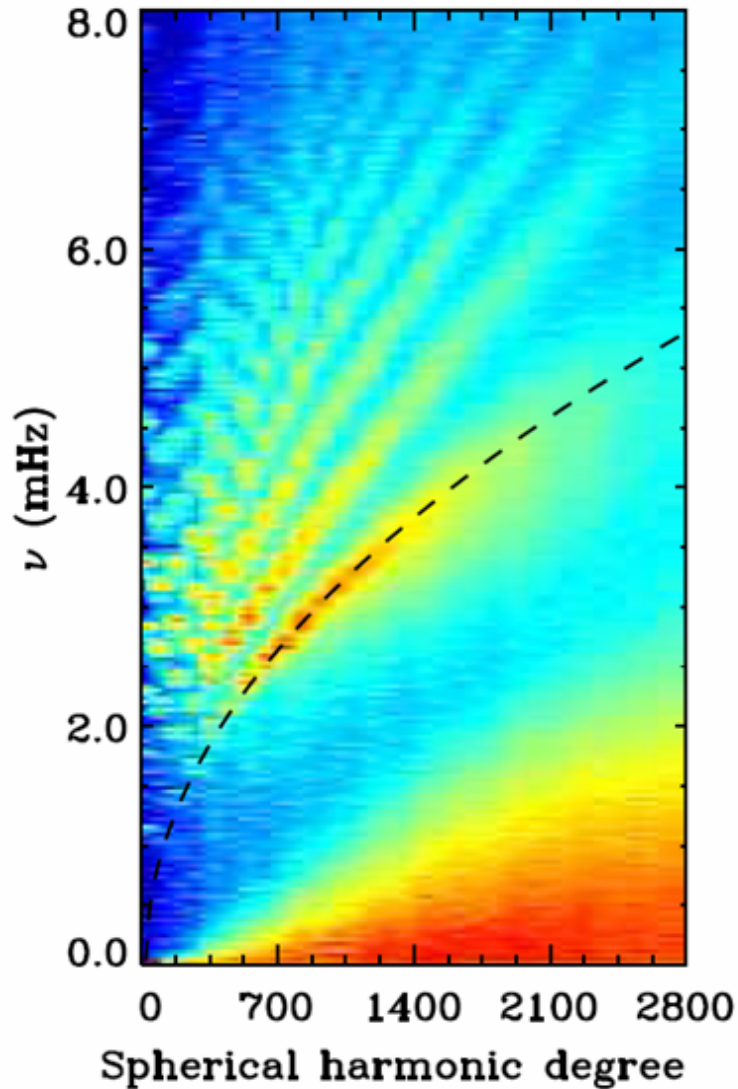
- The propagation of (modified) sound waves is another application, where simulations can help unravel what is going on below the solar surface, using various techniques – such as *tomography*

**Rotation subtracted
solar Doppler image**

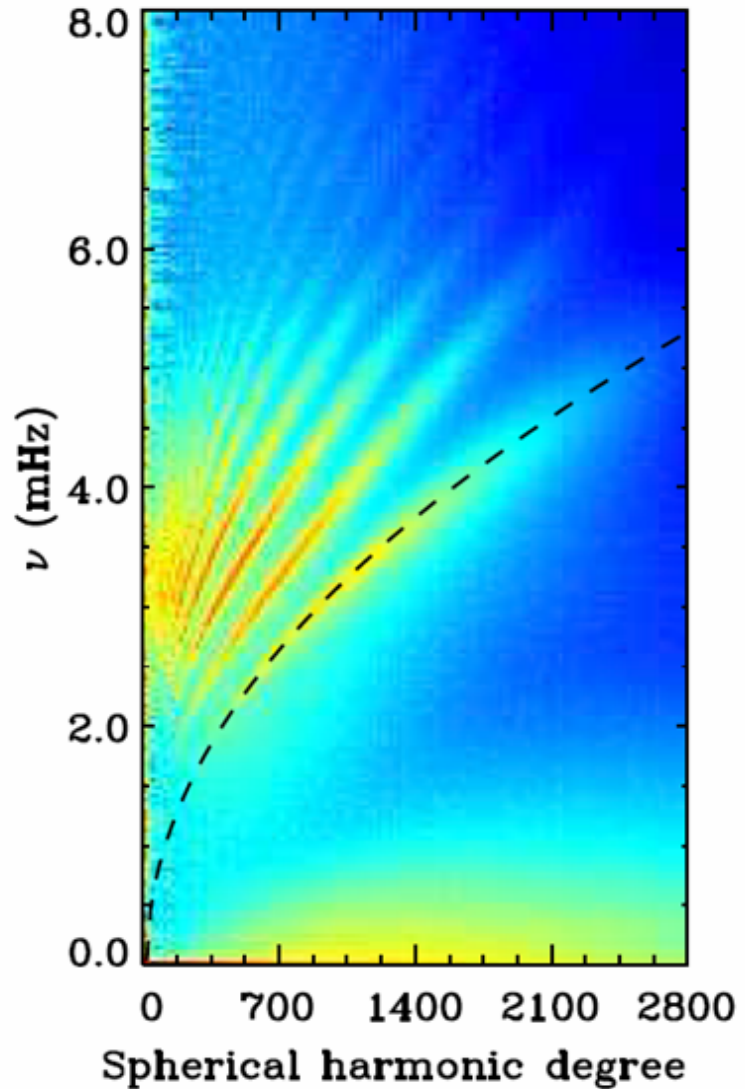


Solar oscillations, modelled and observed

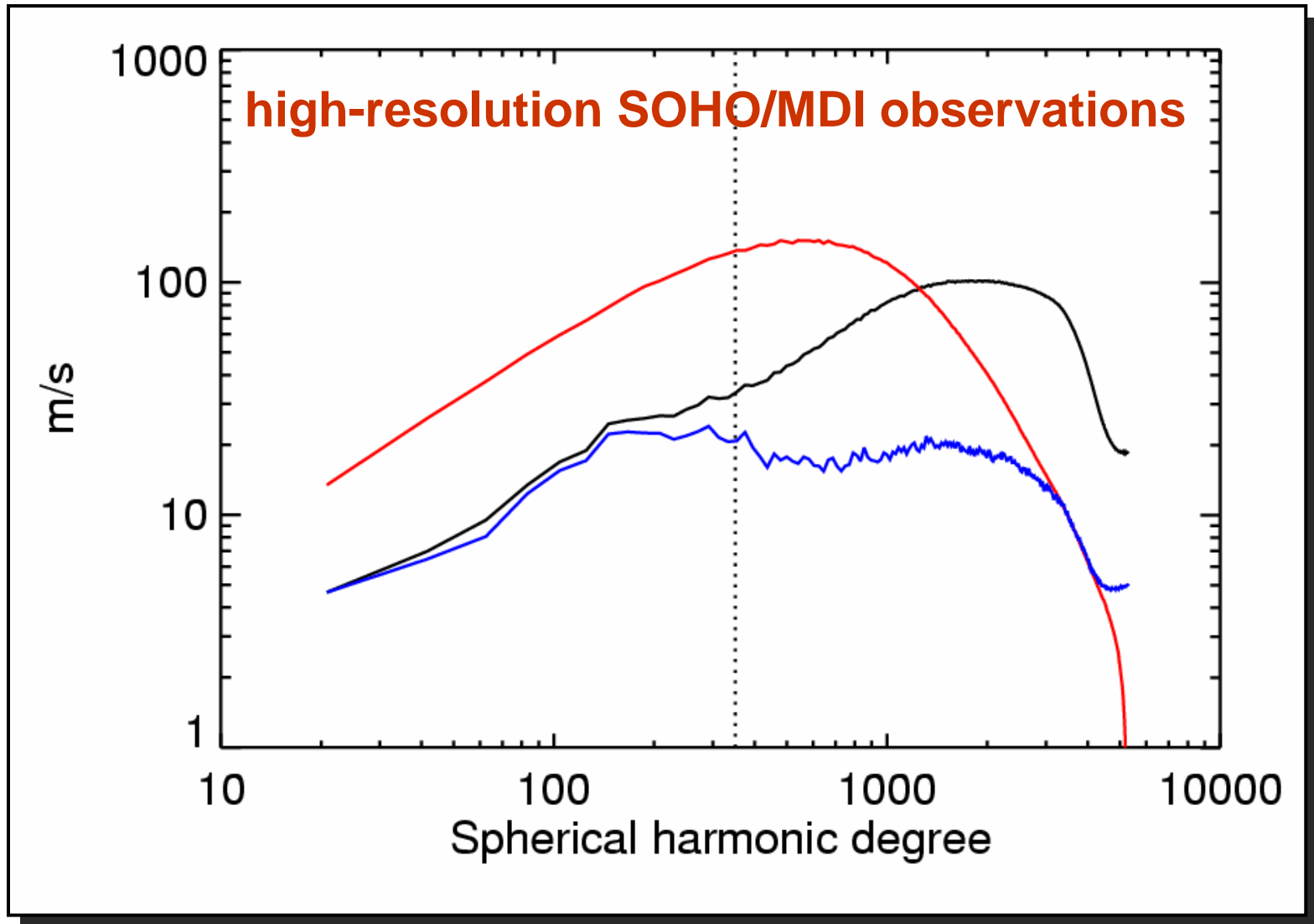
model



observation

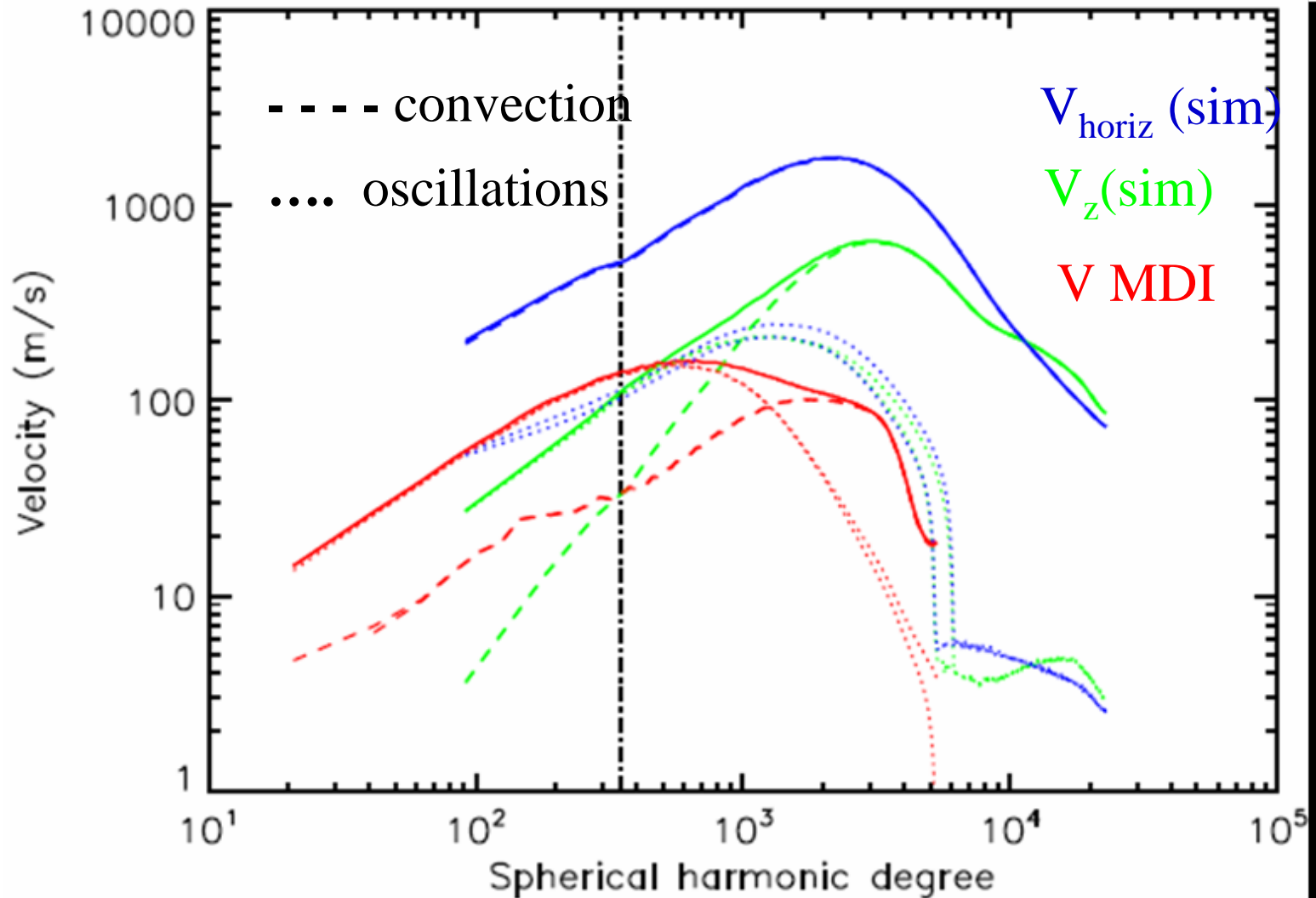


oscillation power (red), convective power (black) – time average (blue)



Velocity spectrum

the only distinct scale is granulation!



Application to modeling the solar chromosphere and corona

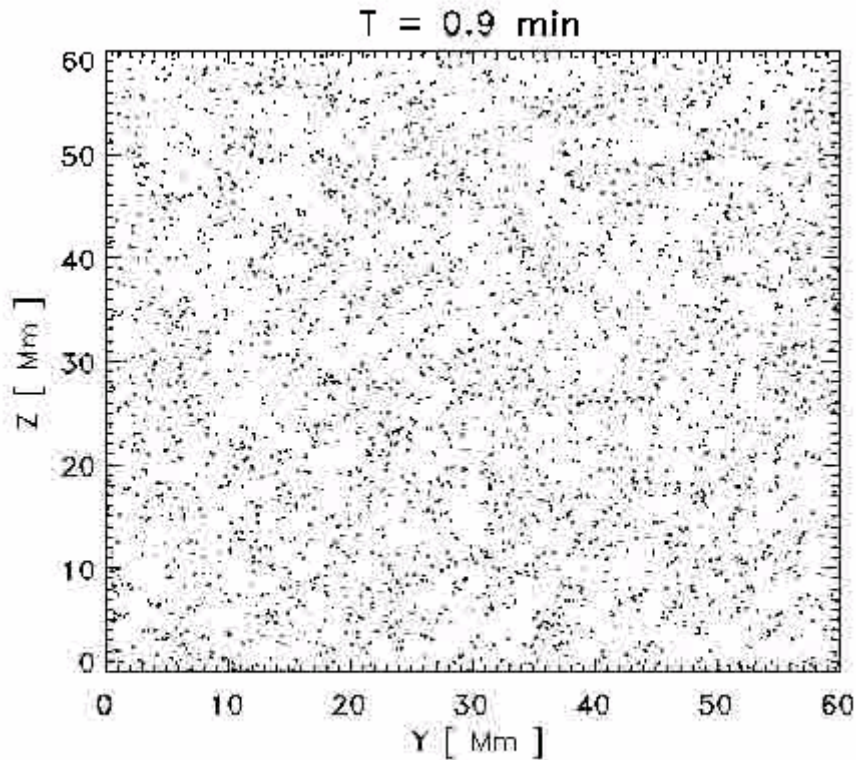


- Given accurate knowledge of the solar velocity field, combined with ***observed solar active region magnetic fields***
- Attempt to model the ***dynamics and heating of the outer solar atmosphere***

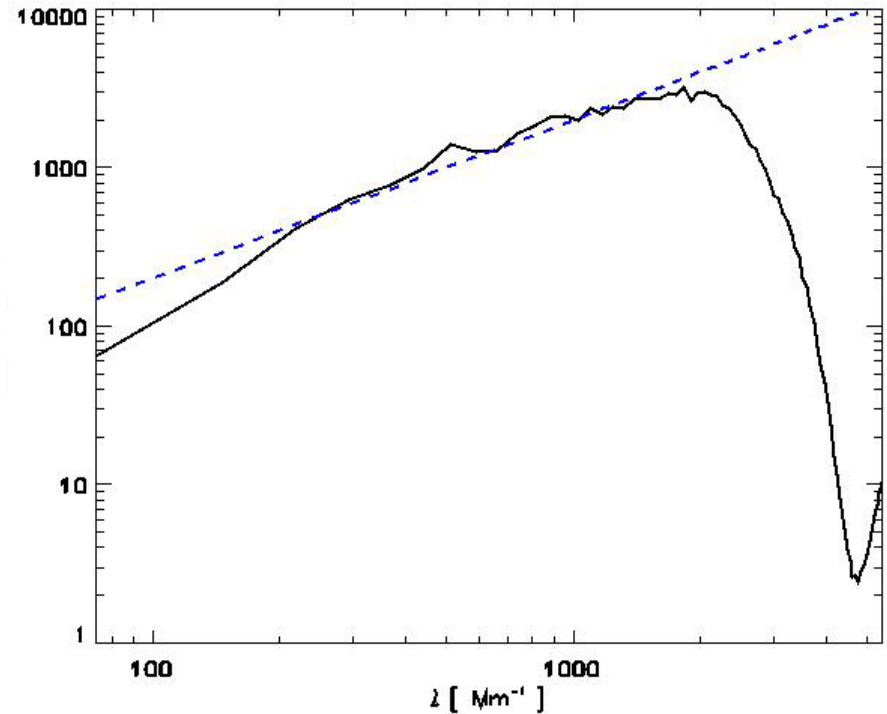


Velocity driving for the corona

Voronoi tessellation
ensemble

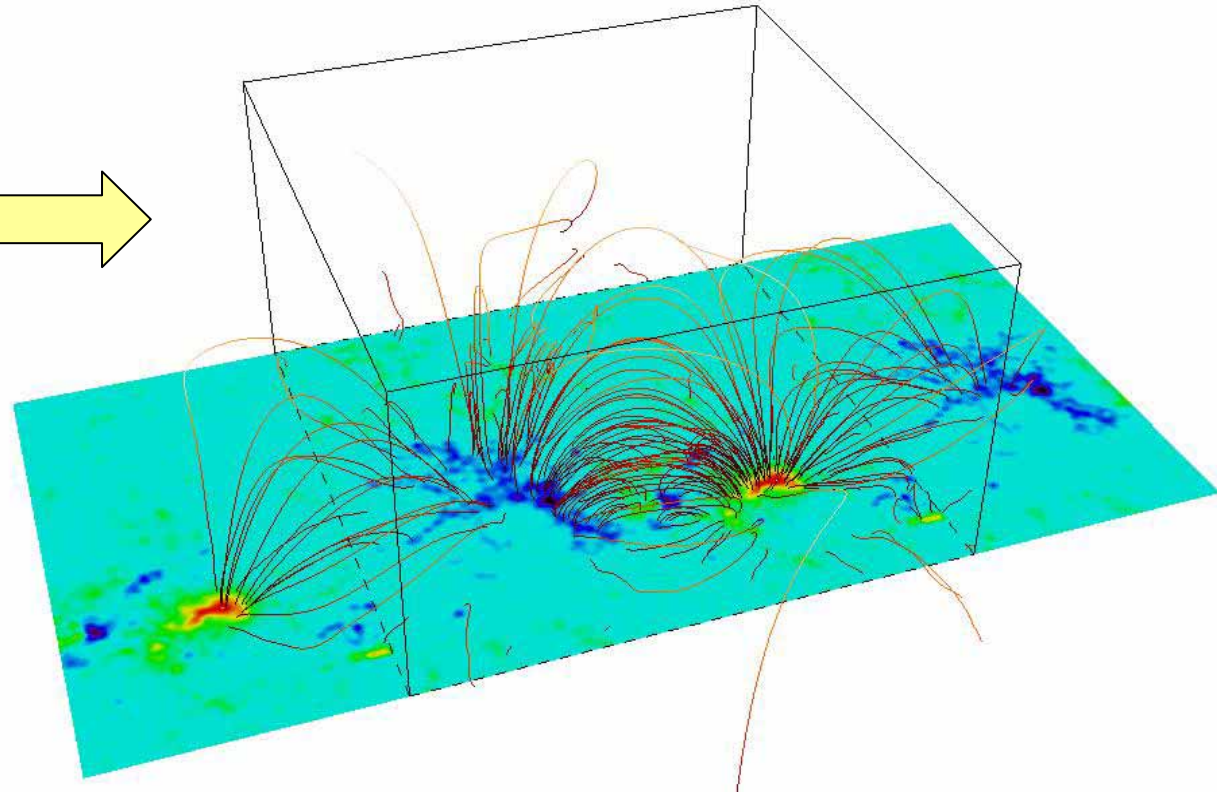
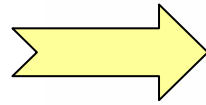
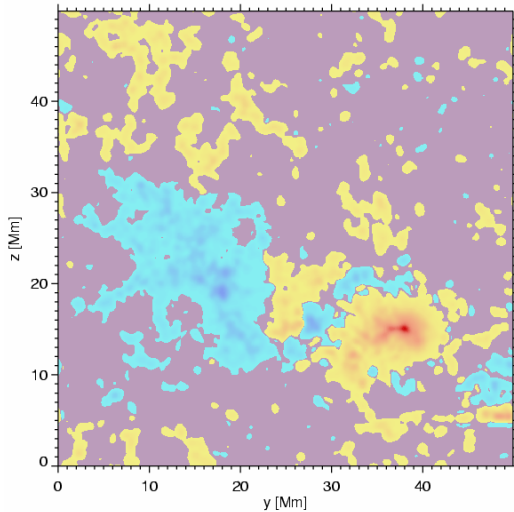


Velocity spectrum from
three superposed ensembles



Initial Magnetic Field

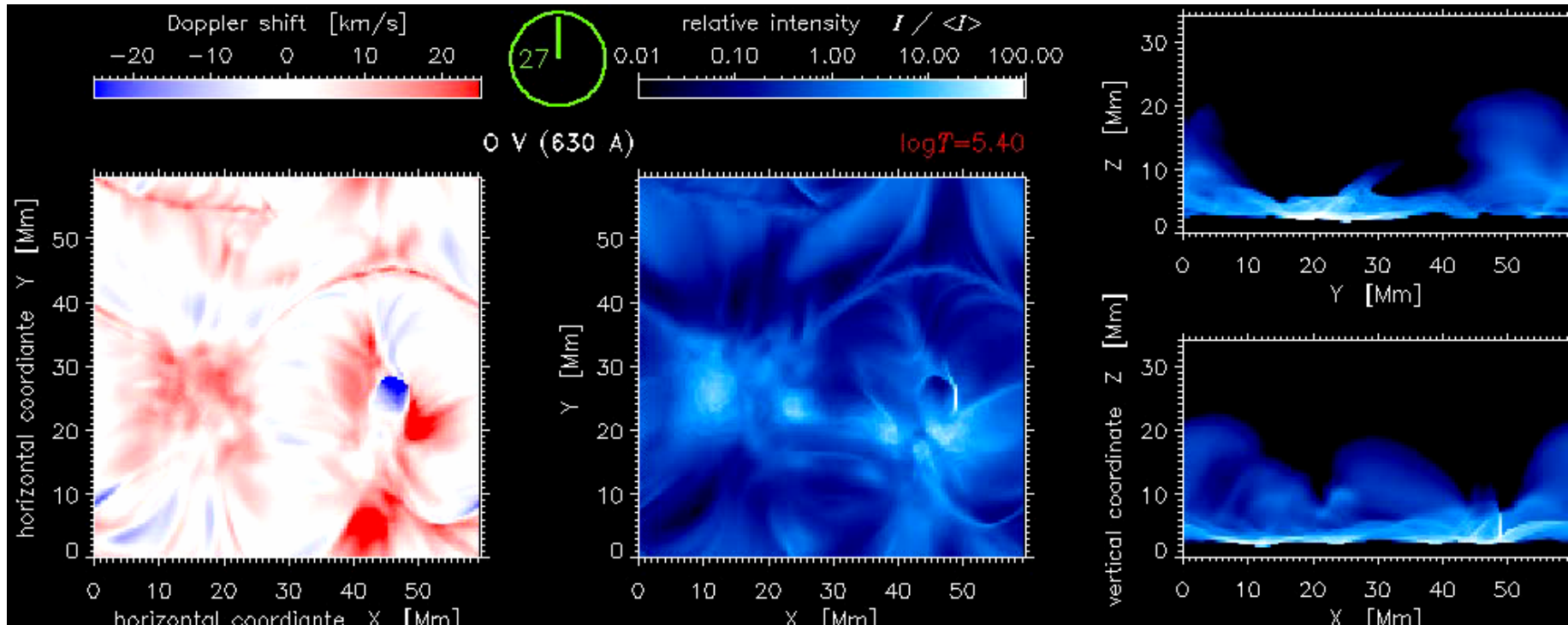
- Potential extrapolation of AR 9114



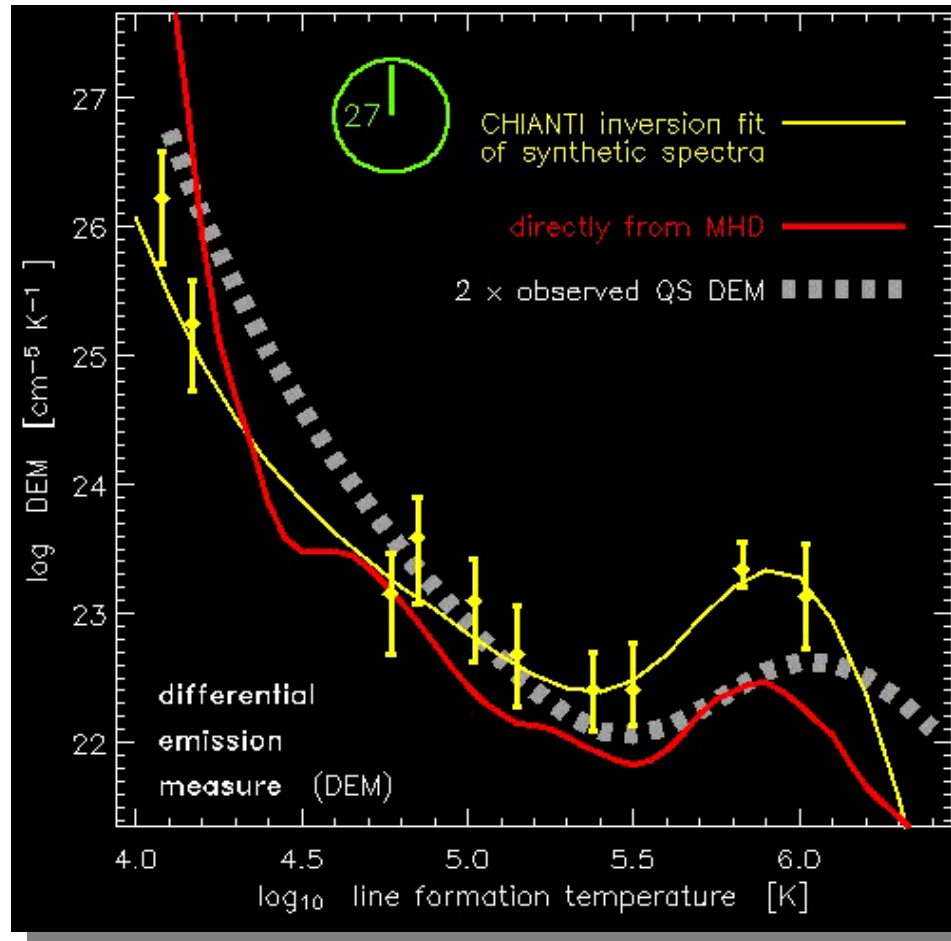
Spectral line diagnostics

(Peter, Gudiksen, ÅN 2004,2005)

- Oxygen V synthetic images

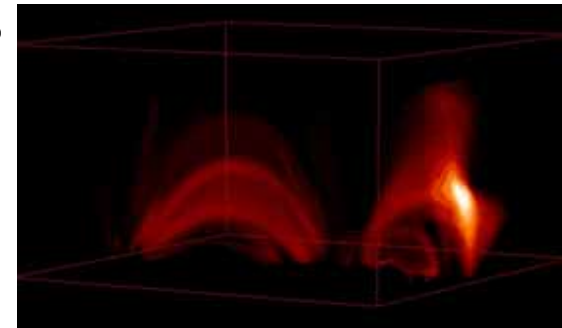
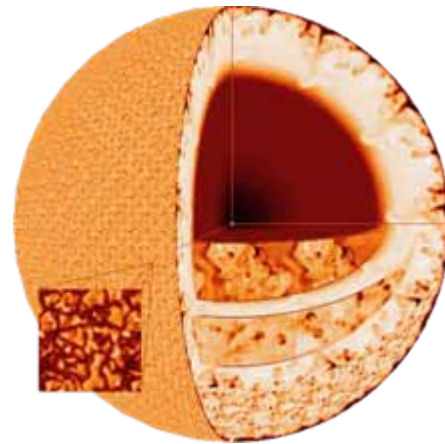


Fingerprints – differential emission measure

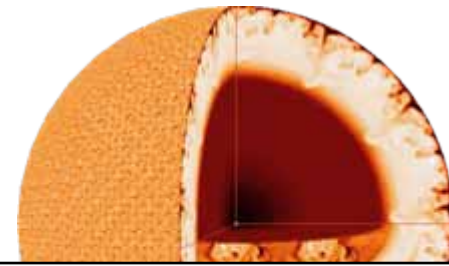


Summary

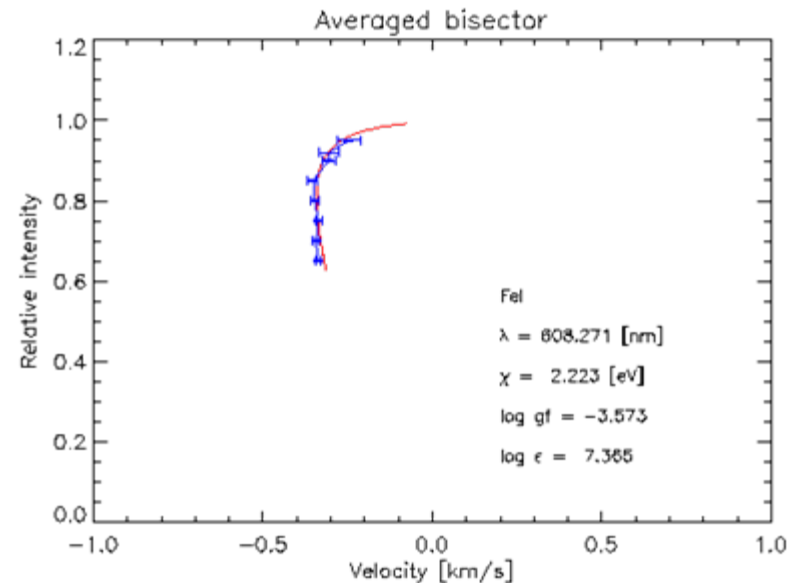
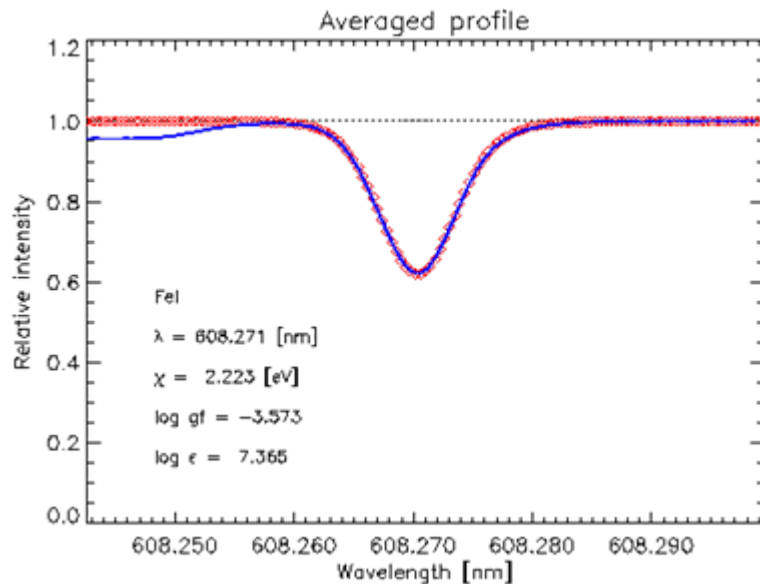
- Solar advantage
 - observable time-dependence!
- Accurate comparisons model / observations
 - ***verifies independence of Reynolds number!***
 - reveal sub-surface motion hierarchy, \sim linear with k
 - help interpret local helio-seismology
- Driving magnetic field structures
 - surface motions coupled to corona
 - heating & particle acceleration



Summary



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



Thanks for your attention!