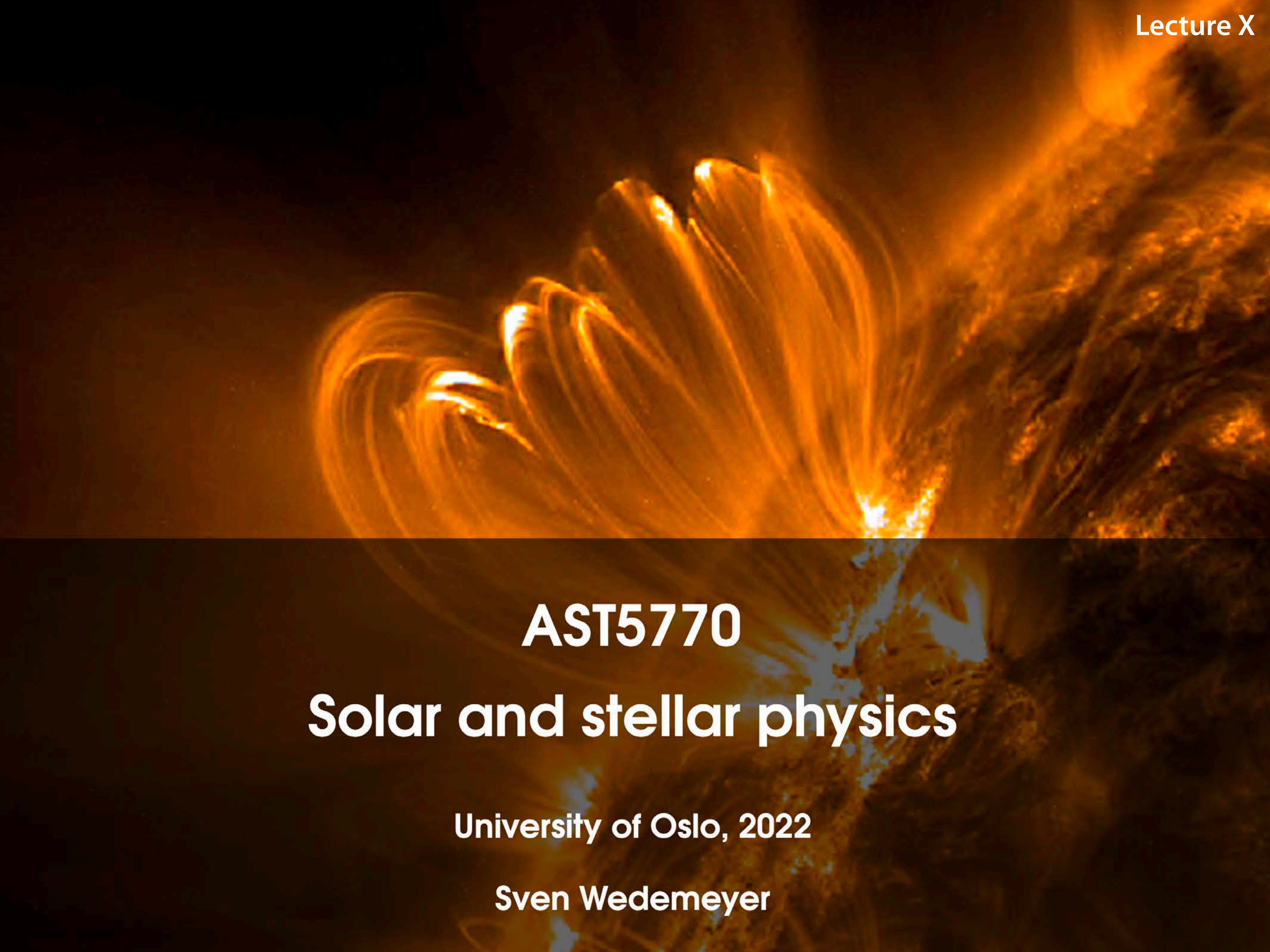
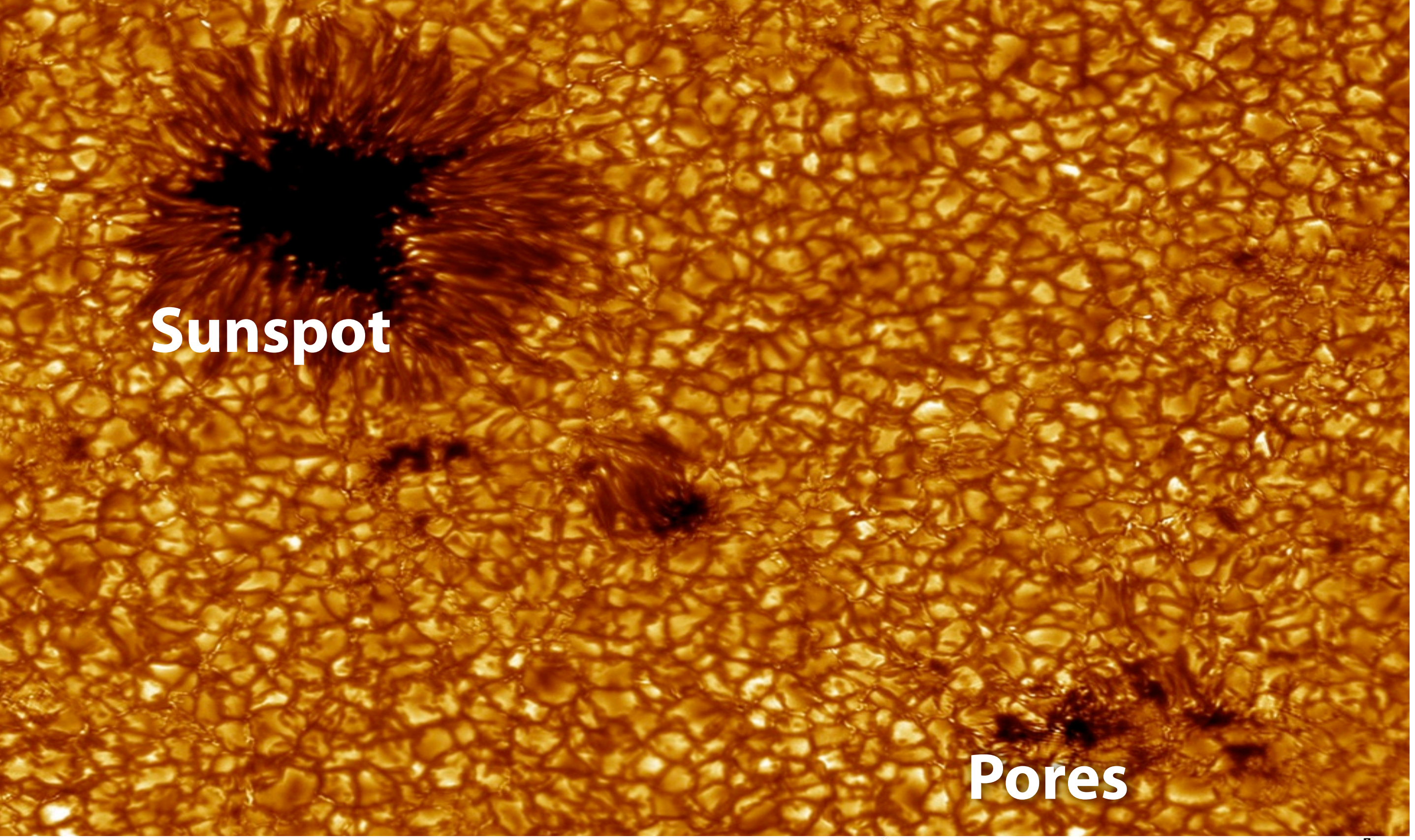


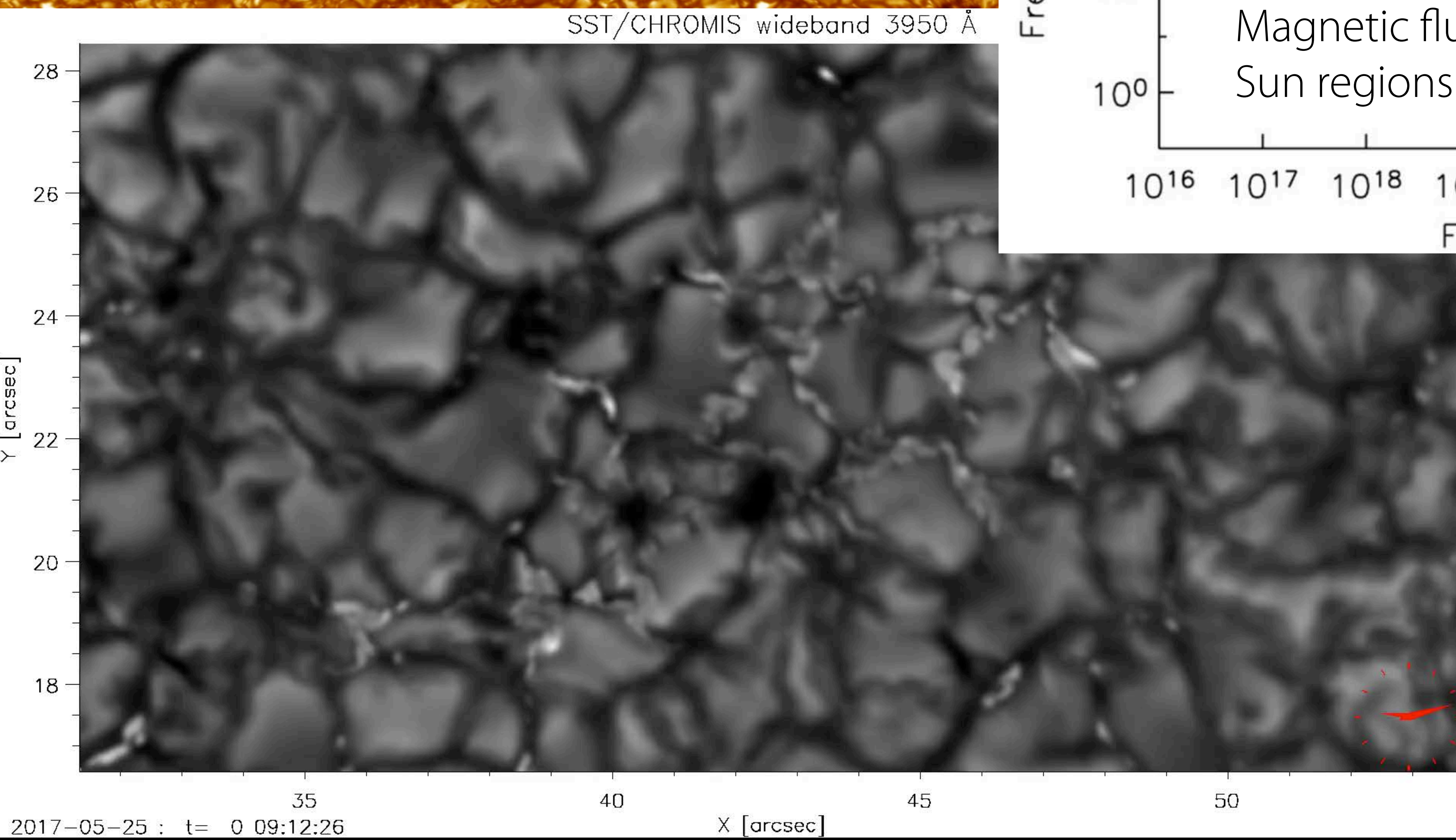
AST5770
Solar and stellar physics

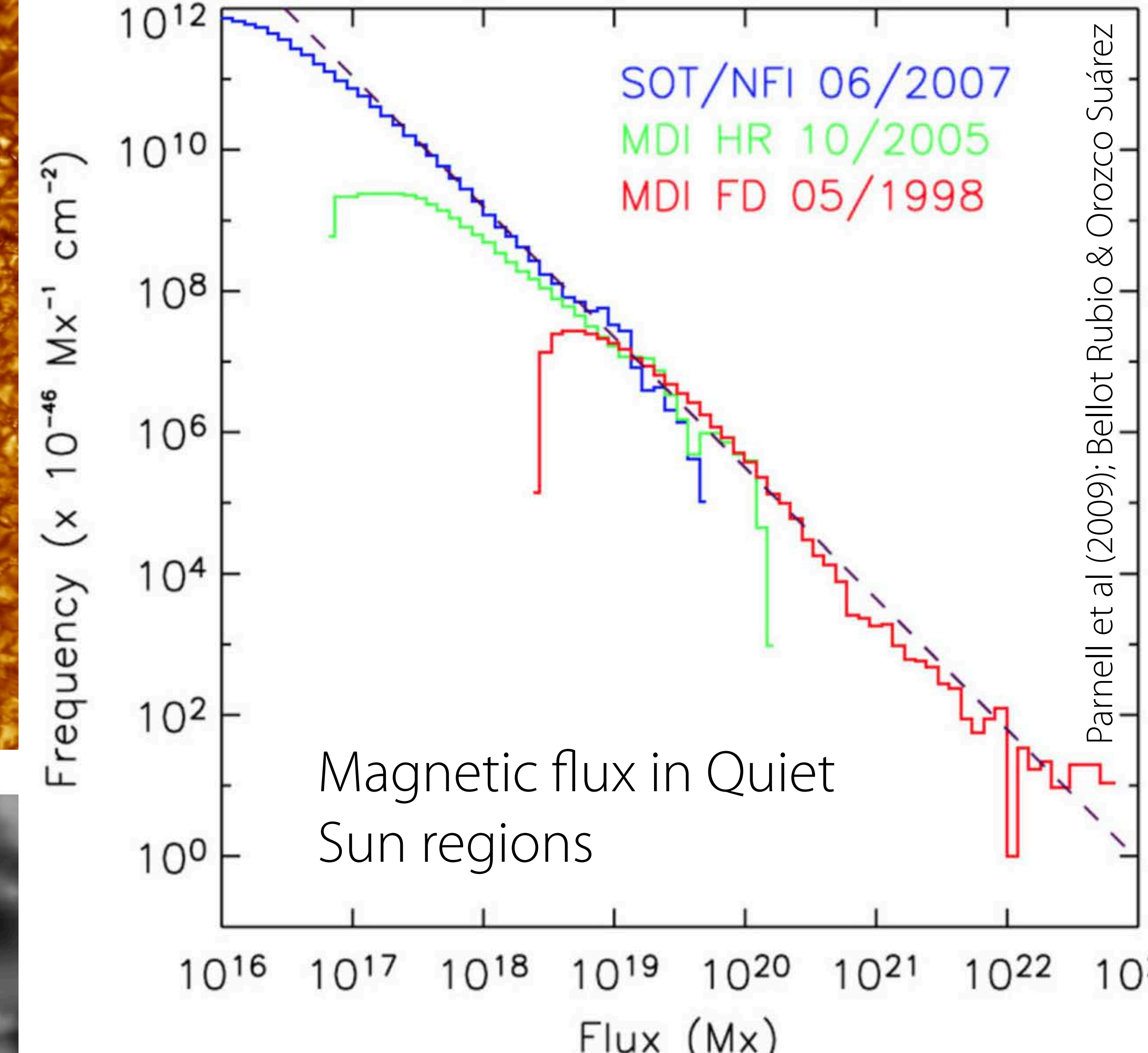
University of Oslo, 2022

Sven Wedemeyer

Small-scale dynamics







"Quiet Sun"

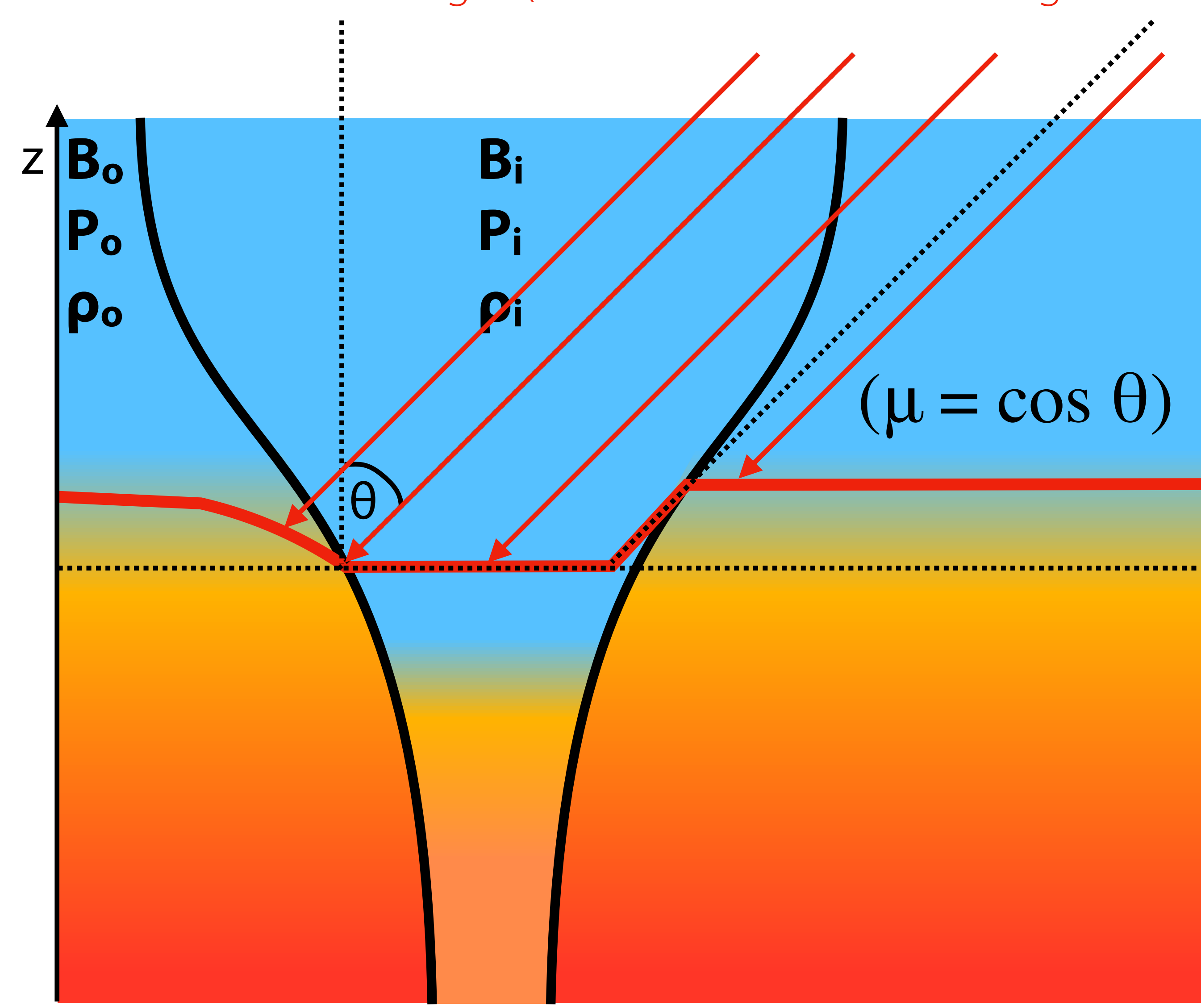
- Granulation pattern
- Magnetic elements mostly in intergranular lanes (kG fields)

Radiative transfer effects — recap

- Observing at different inclination angles θ
- Longer line of sight path element per change in height
- Lower density and thus opacity when looking through magnetic flux structures

➡ Radiative transfer effects:

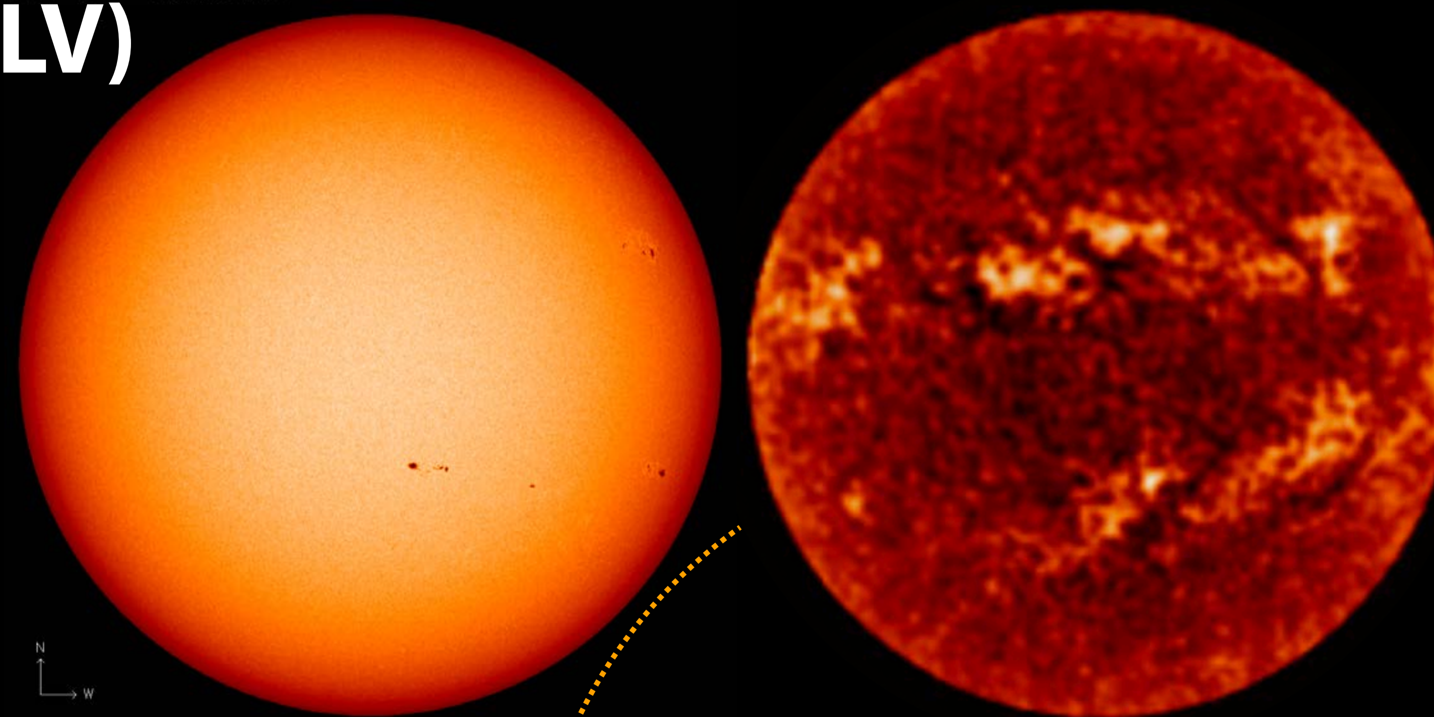
- **Hot wall effect**
  (when looking at significant angle)
  - Magnetic feature appears to be brighter on one side!
  - Seen in faculae towards the limb!



- **Magnetic bright points**
  - (Close to) vertical view: look deeper into the atmosphere inside magnetic flux structure
  - Note: Seen for small/weak magnetic field structures where convective heat transport from below is not hampered
    - For sunspots: Wilson depression and lower temperature (sunspots appear dark)

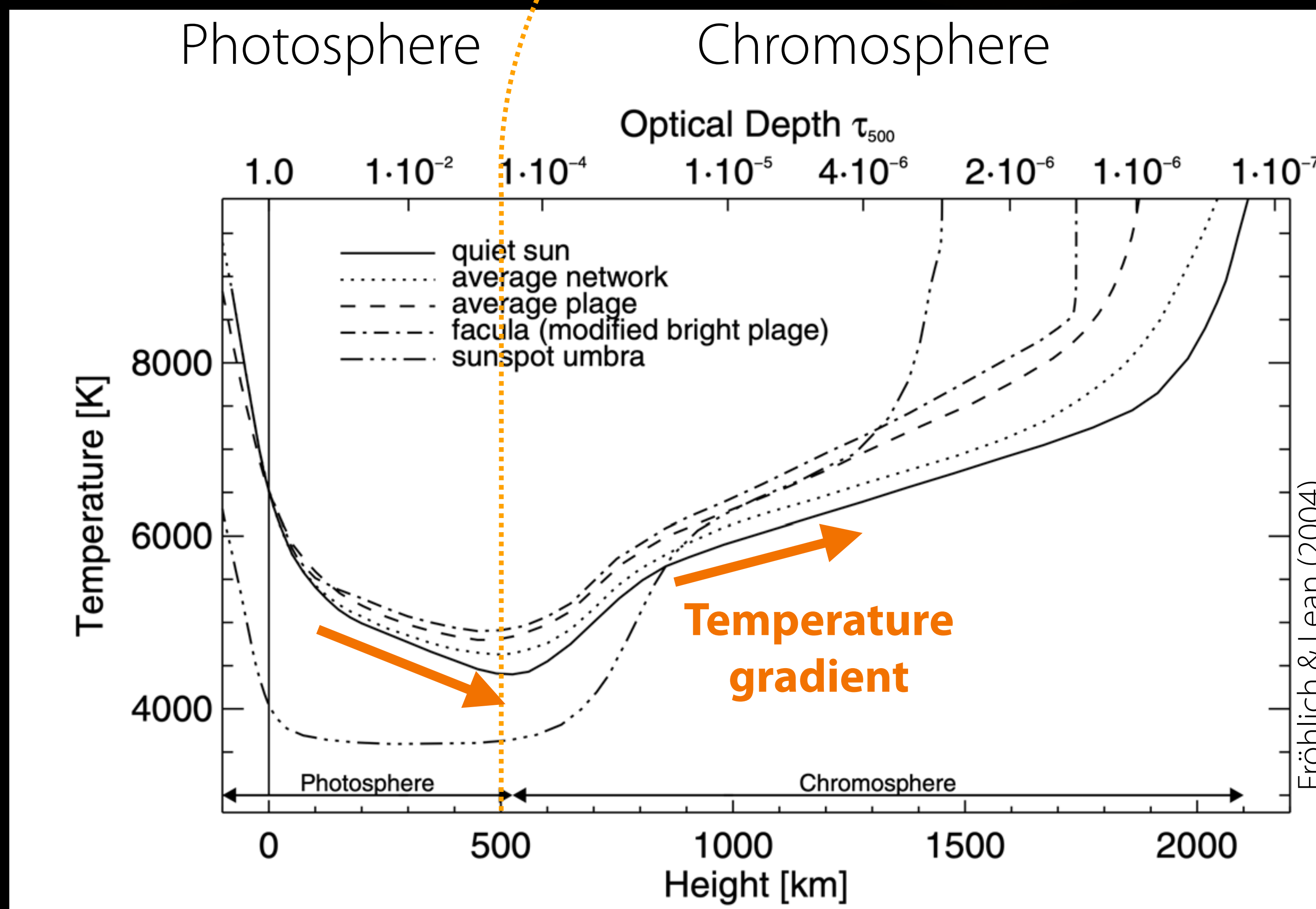
Radiative transfer effects — recap

Centre-to-limb variation (CLV)



- Centre-to-limb variation depends on mapped height range in the atmosphere
  - Photosphere: darkening
  - Chromosphere: brightening
  - Opposite gradient of the temperature stratification!

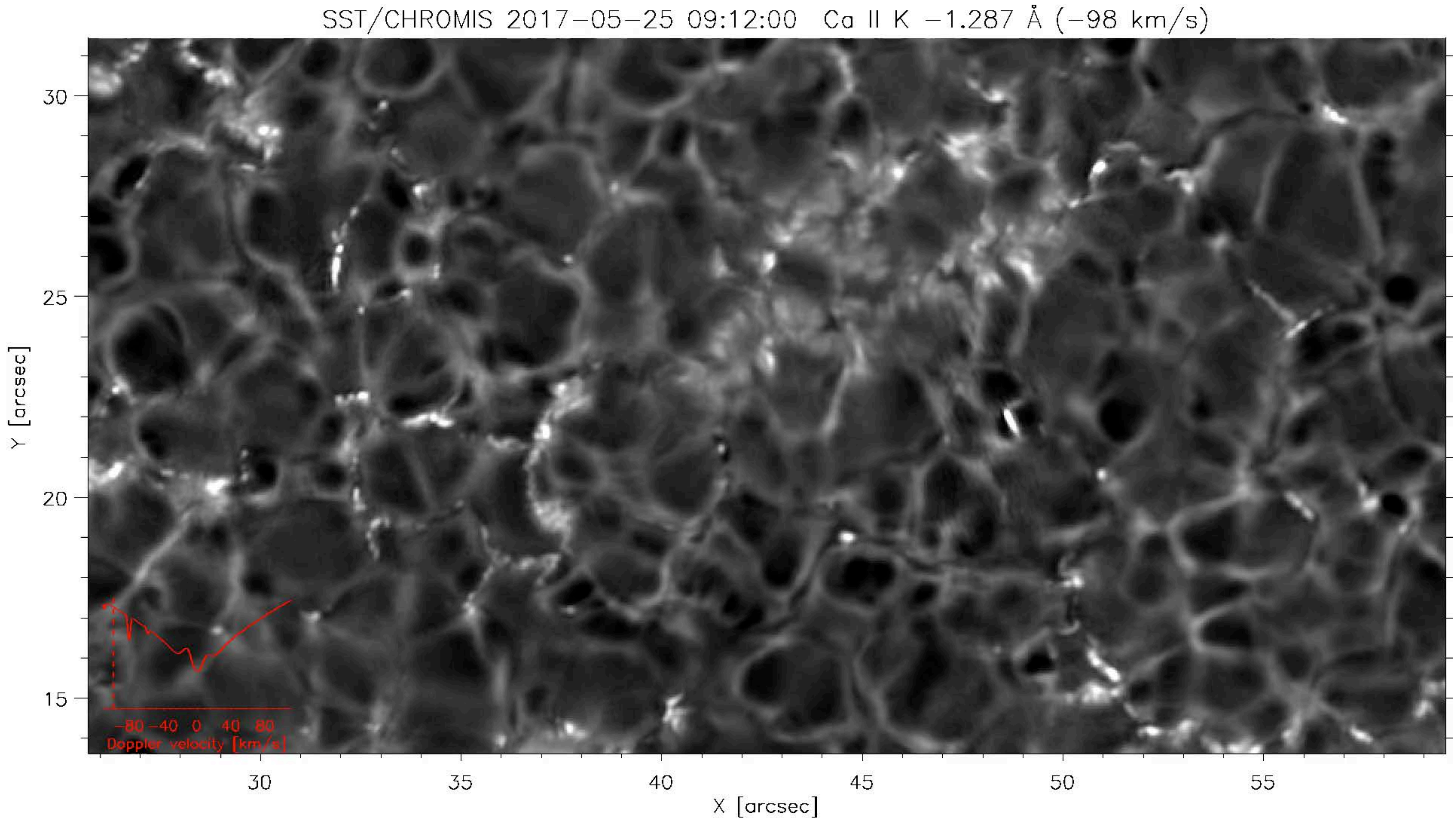
- CLV measured from observations help to construct (1D) average atmosphere models
(even for different types of region from Quiet Sun to sunspot umbra)



The solar atmosphere

Intermittent and dynamic

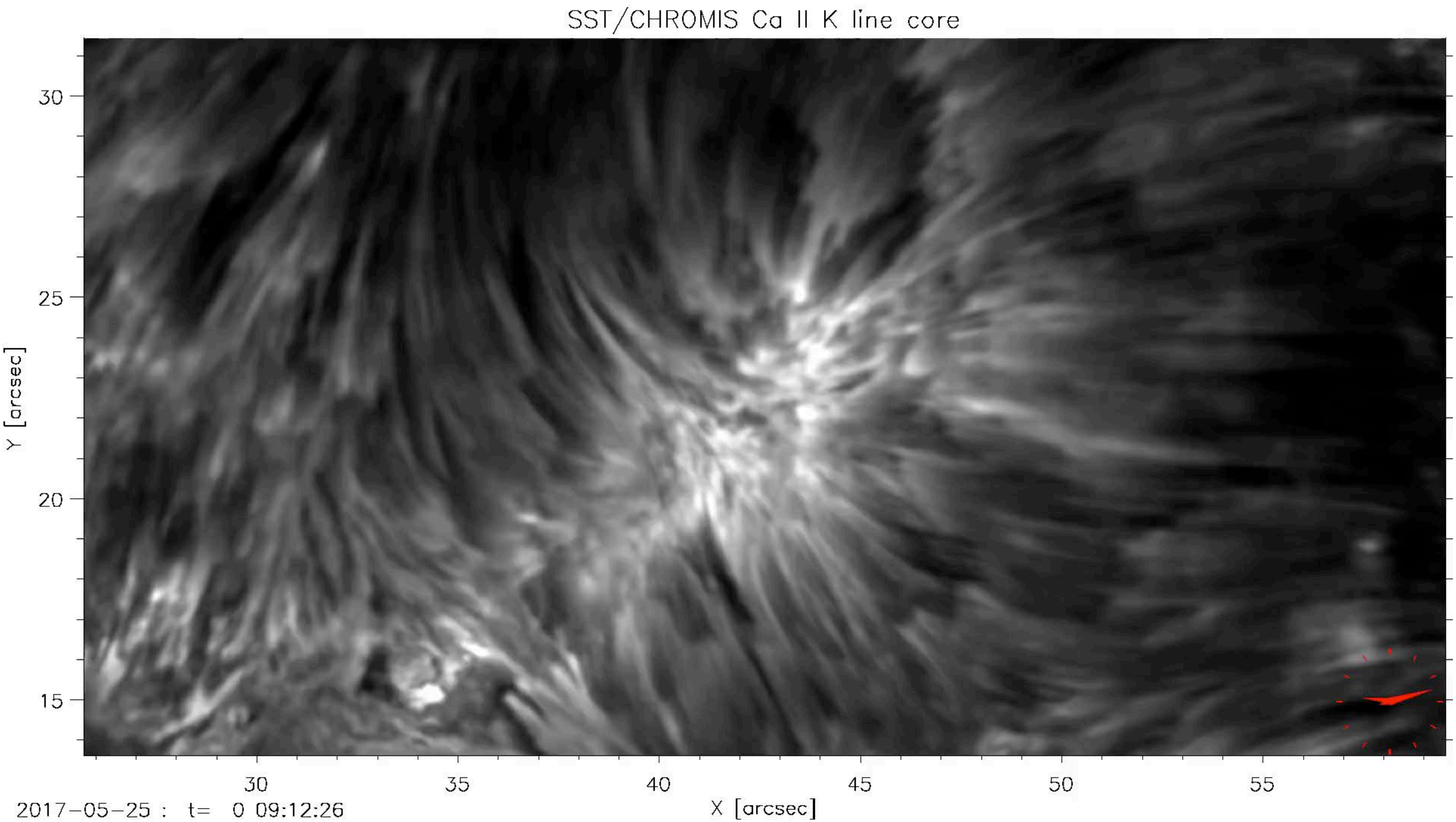
- Scan (in wavelength) through spectral line (here Ca II K) gives first impression of the change with height (sampling different layers, but careful: height varies across FOV)



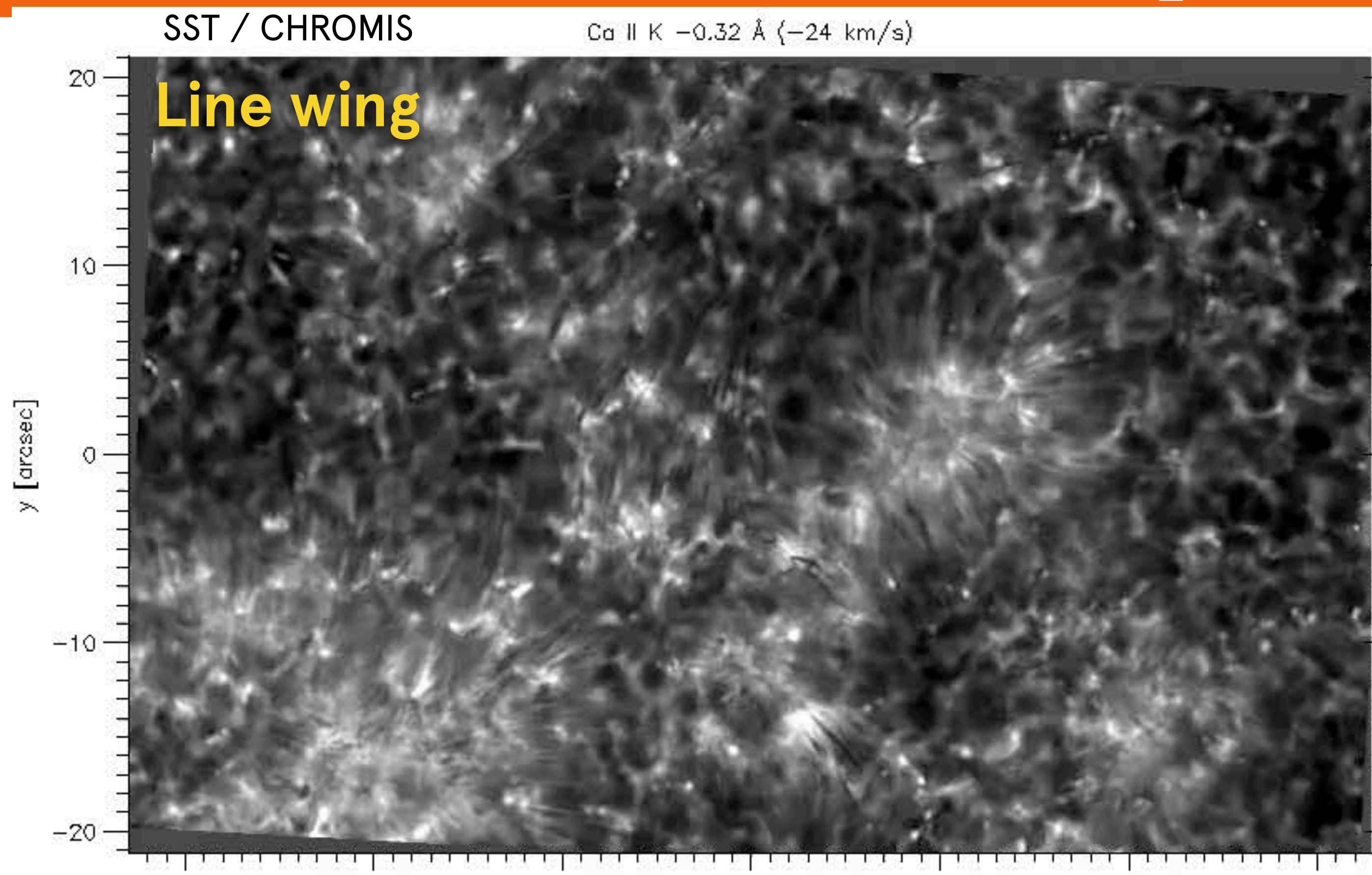
The solar atmosphere

The chromosphere — A highly dynamic place

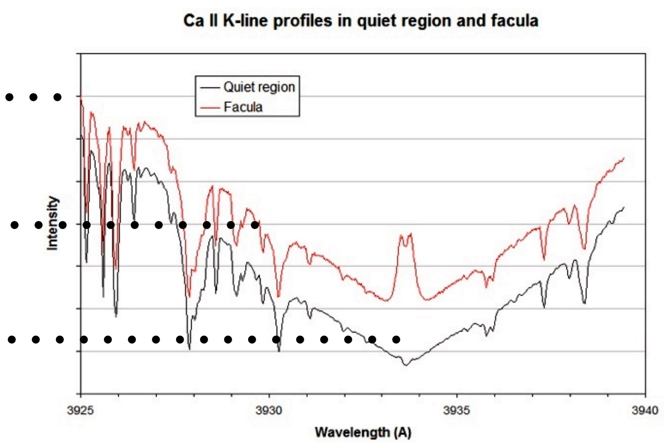
- Chromosphere often dominated by chromospheric fibrils, very dynamic on short time scales — challenges for observation and simulation



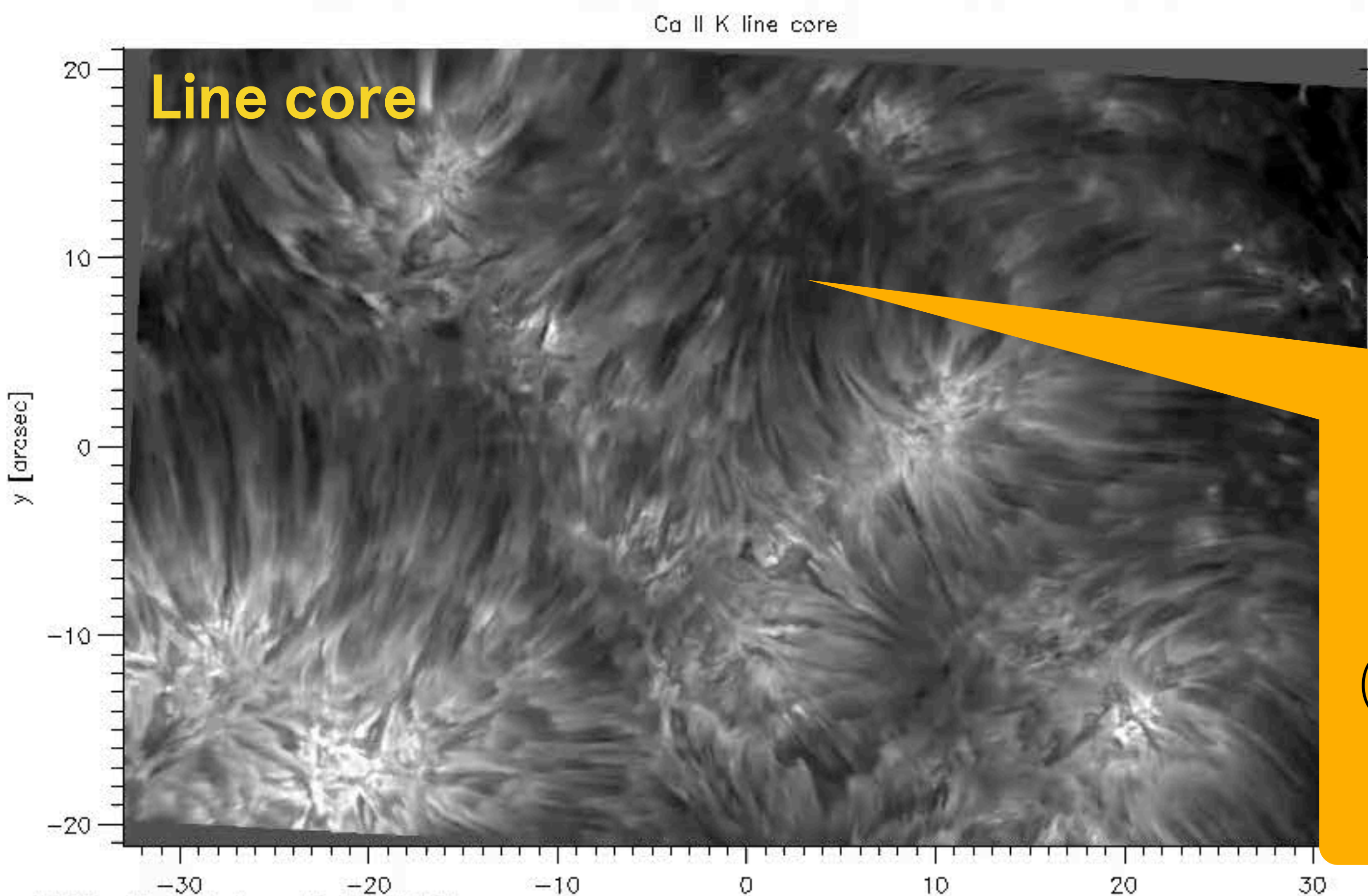
The solar atmosphere

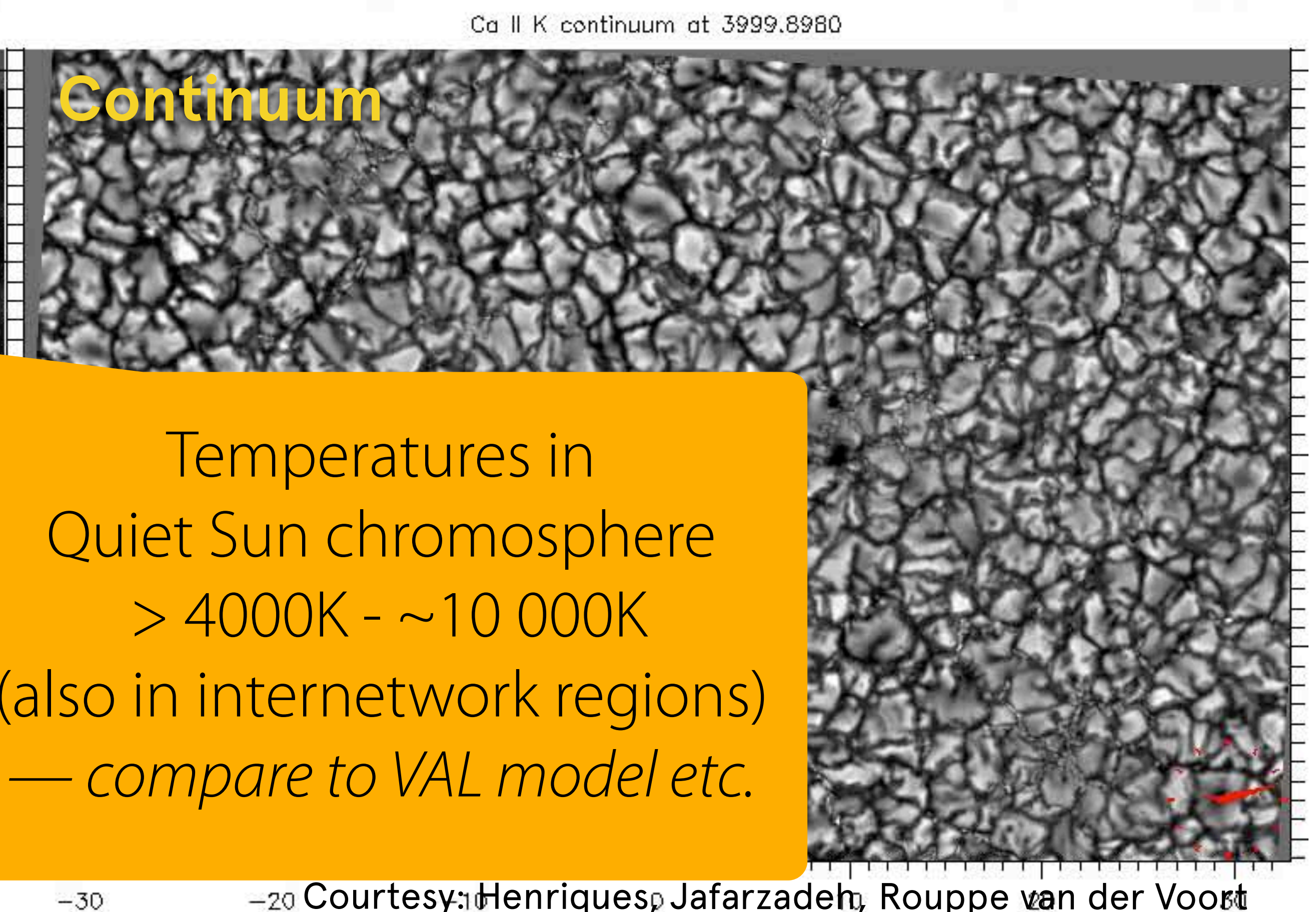


- Different parts of spectral formed at different atmospheric heights



Ca II K 393 nm





Temperatures in
Quiet Sun chromosphere
> 4000K - ~10 000K
(also in internetwork regions)
— *compare to VAL model etc.*

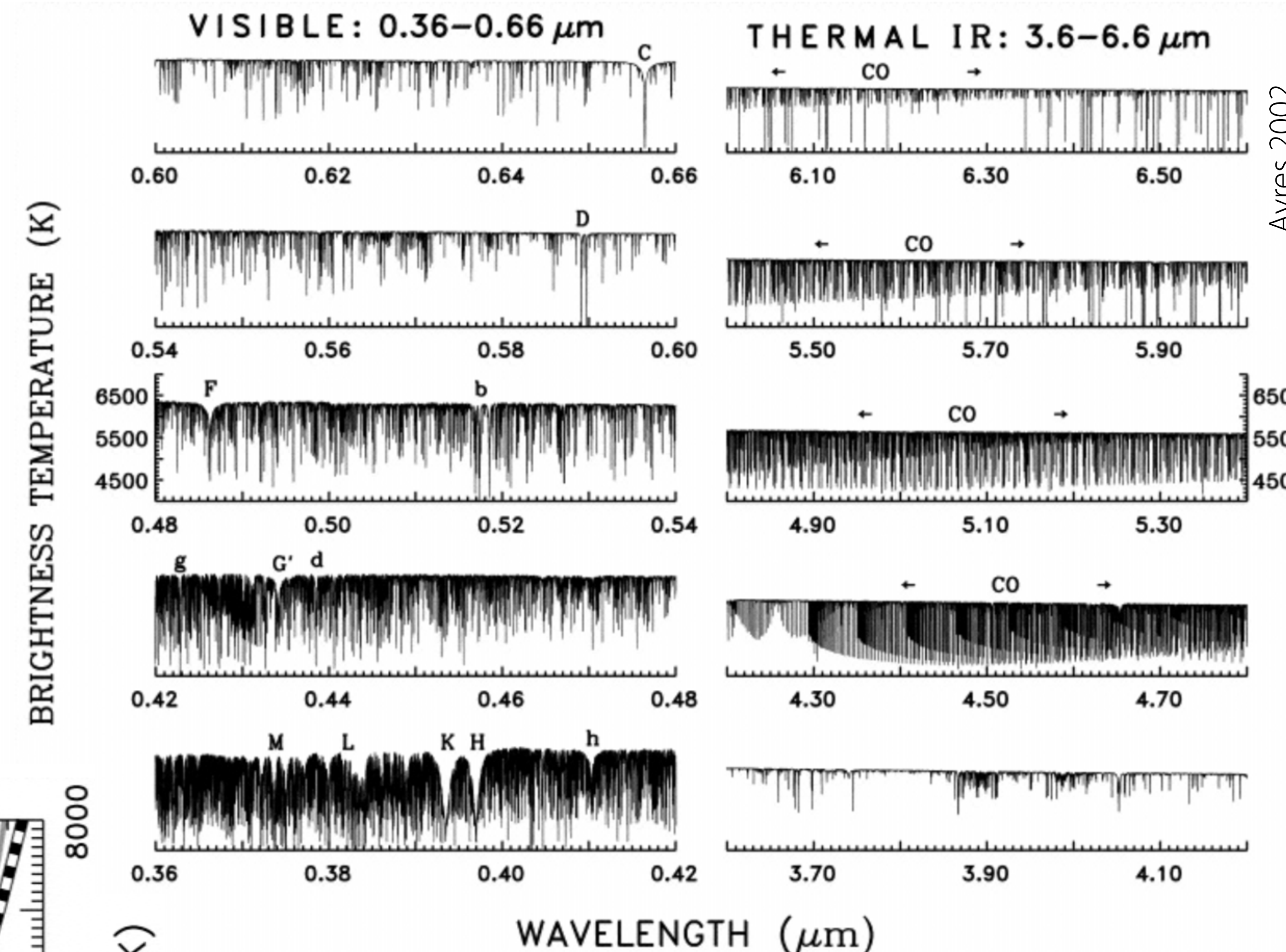
Courtesy: Henriques, Jafarzadeh, Rouppe van der Voort

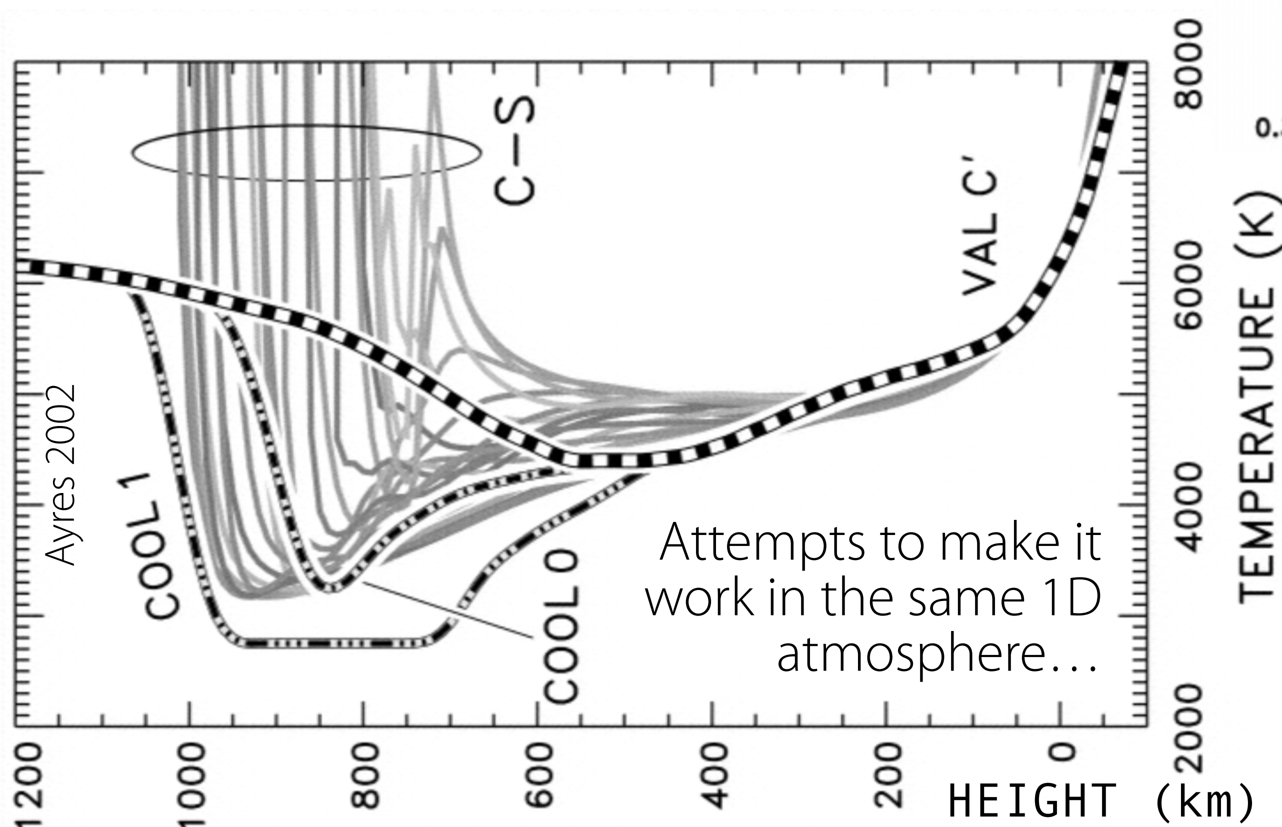
The solar atmosphere

The CO problem

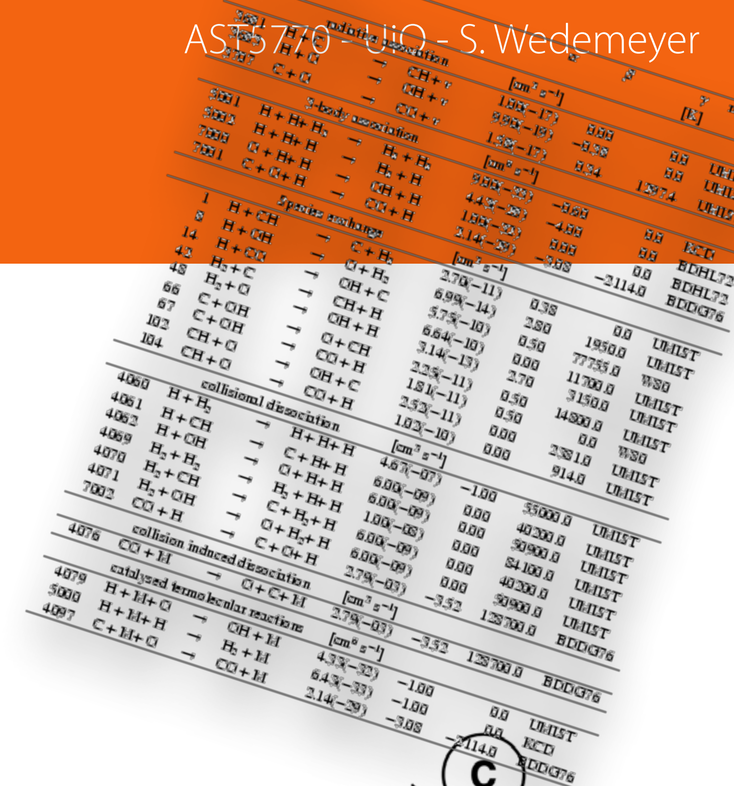
- **Observations of spectral lines of CO in the Sun!**
- CO needs sufficiently low temperatures, will otherwise be dissociated into C and O

➡ **In contrast to high temperatures as implied by UV observations**
(and as seen in model atmospheres as VAL)



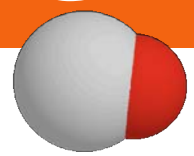


- **Solution: The solar atmosphere is not static but highly dynamic and intermittent on short time scales and small spatial scales**

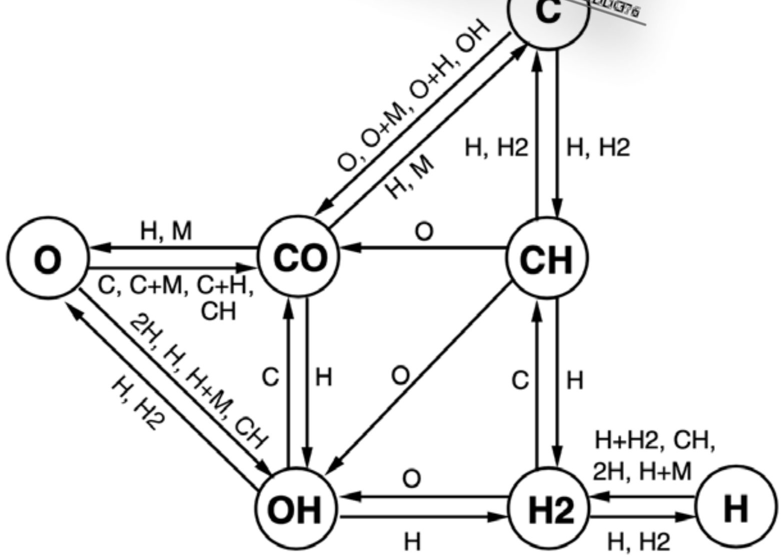


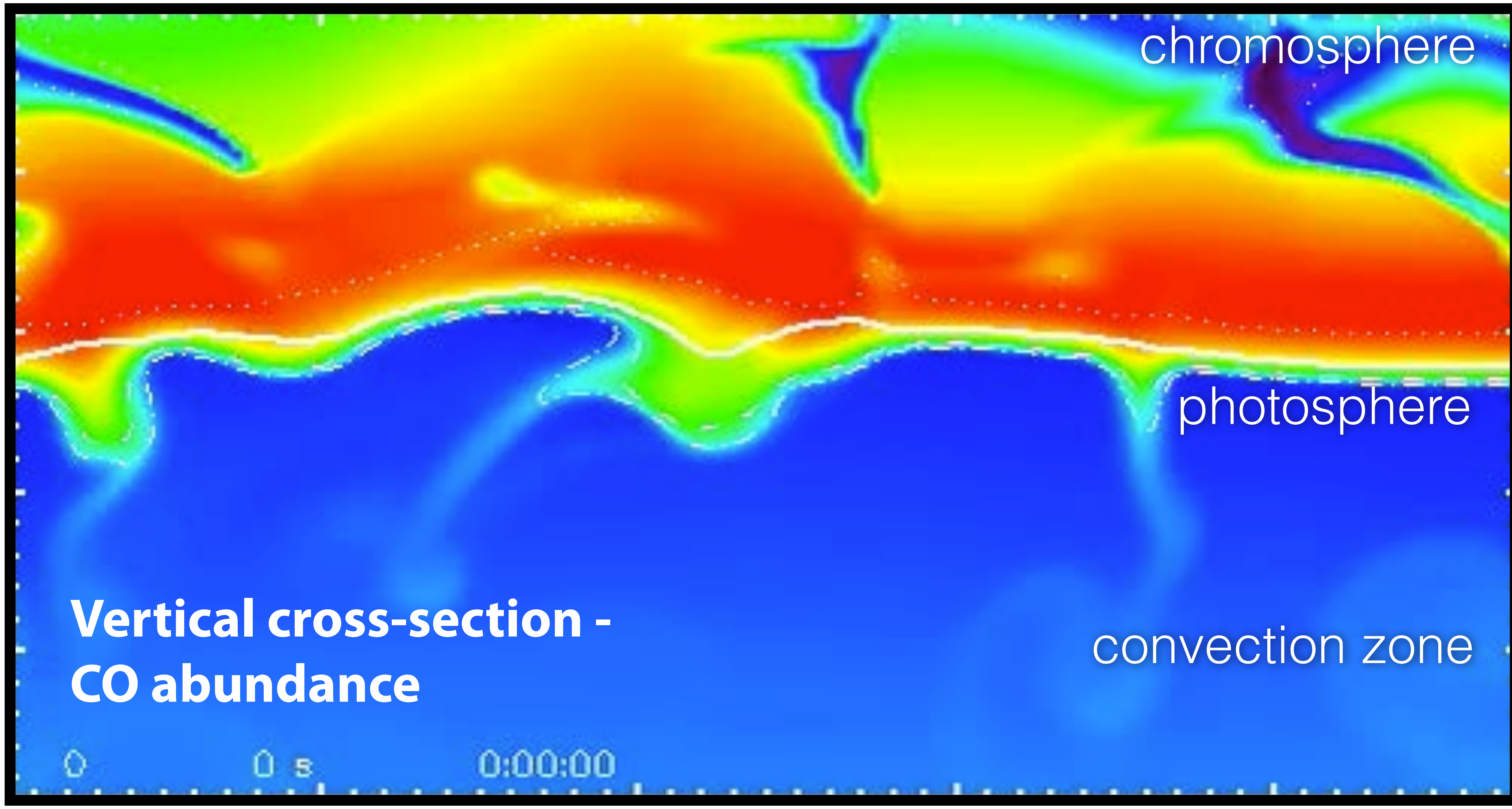
The solar atmosphere

The CO problem — solved

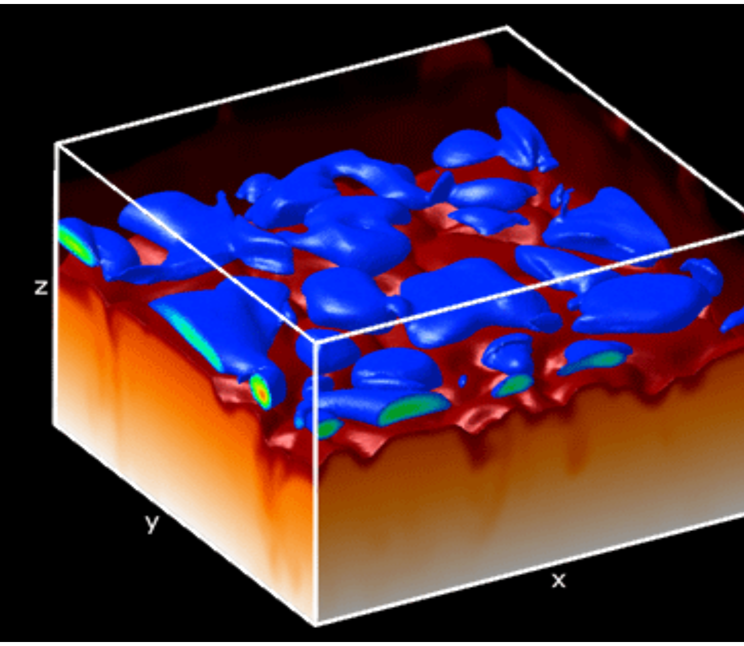


- Explained by numerical simulations!
- CO can form and persist (for some time) in cool pockets!
- CO dissociated by moving hot shock waves in chromosphere, builds up again in cold post-shock regions
- CO as integral part of a highly dynamic environment
- CO observations (cold gas) and UV observations (hot gas) explained with same model





Wedemeyer et al. 2006

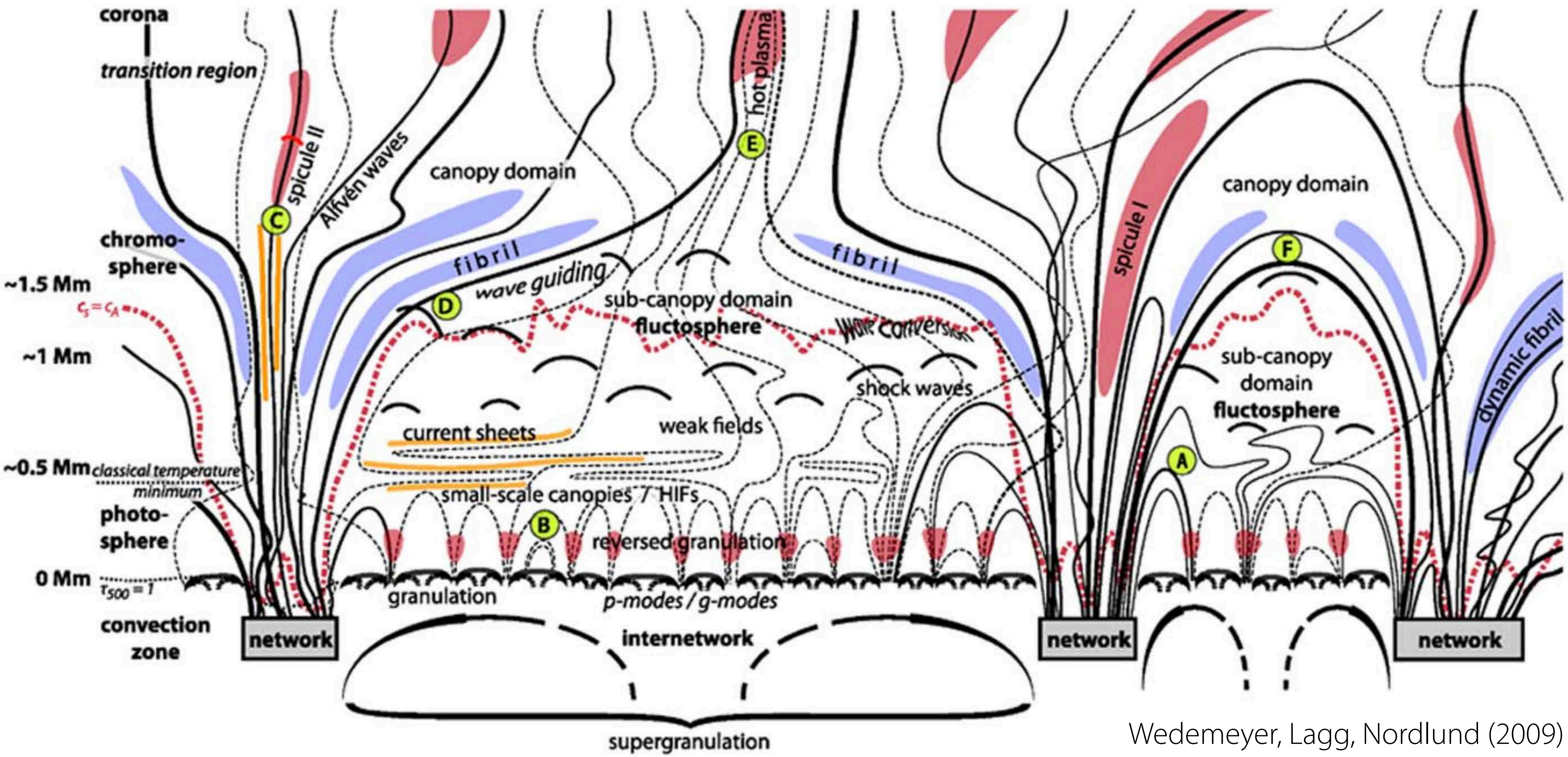


Wedemeyer et al. (2005, 2006)

The solar atmosphere

Structure of Quiet Sun regions

- Modern telescopes with high spatial + temporal + spectral show a new picture of the "Quiet" Sun
- Dynamic intermittent structure across many scales, plethora of physical processes

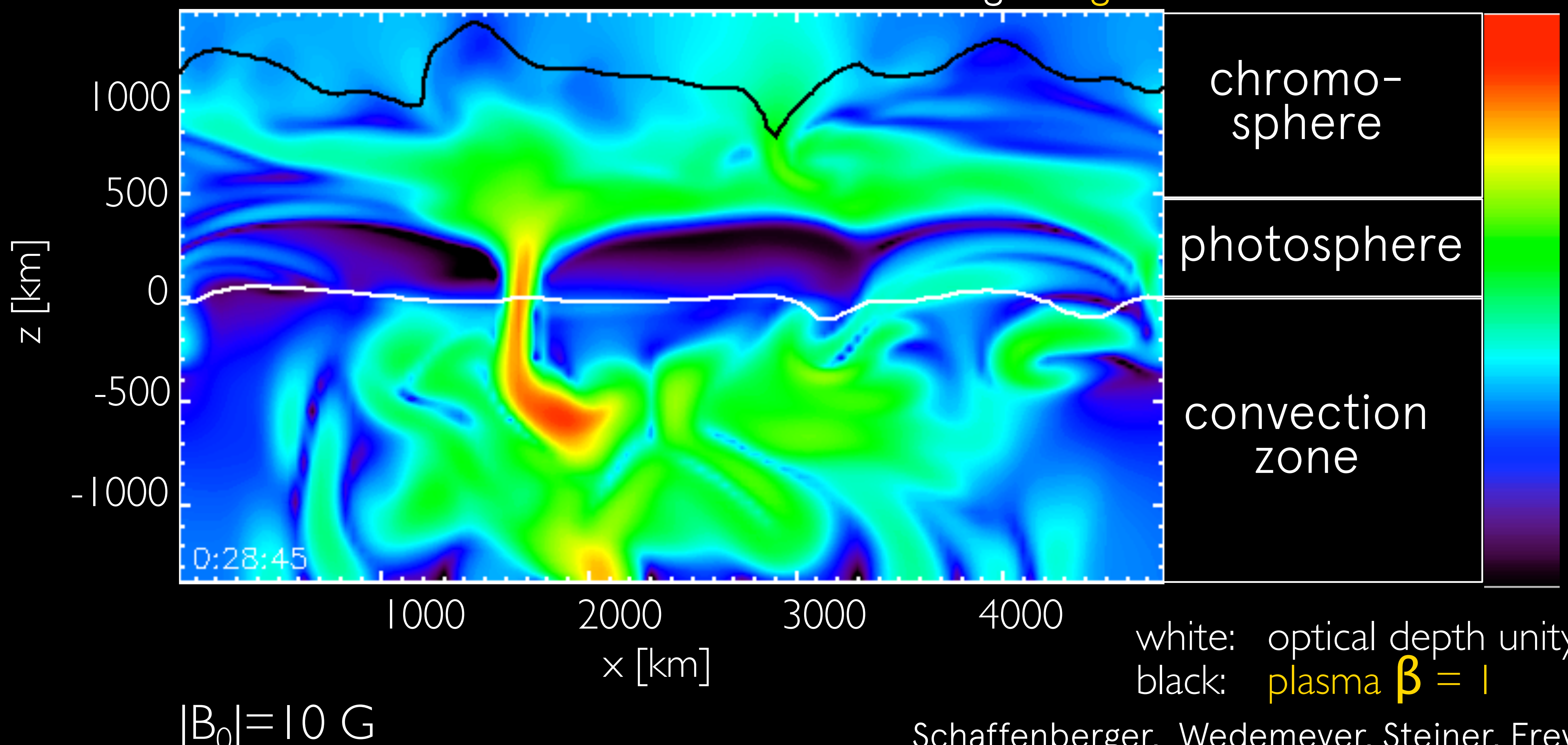


Wedemeyer, Lagg, Nordlund (2009)

The solar atmosphere

- Magnetic field in chromosphere is highly dynamic
  - Propagating shock waves compress magnetic field
  - Fast moving filaments of enhanced field

vertical cross-section: absolute field strength log |B|

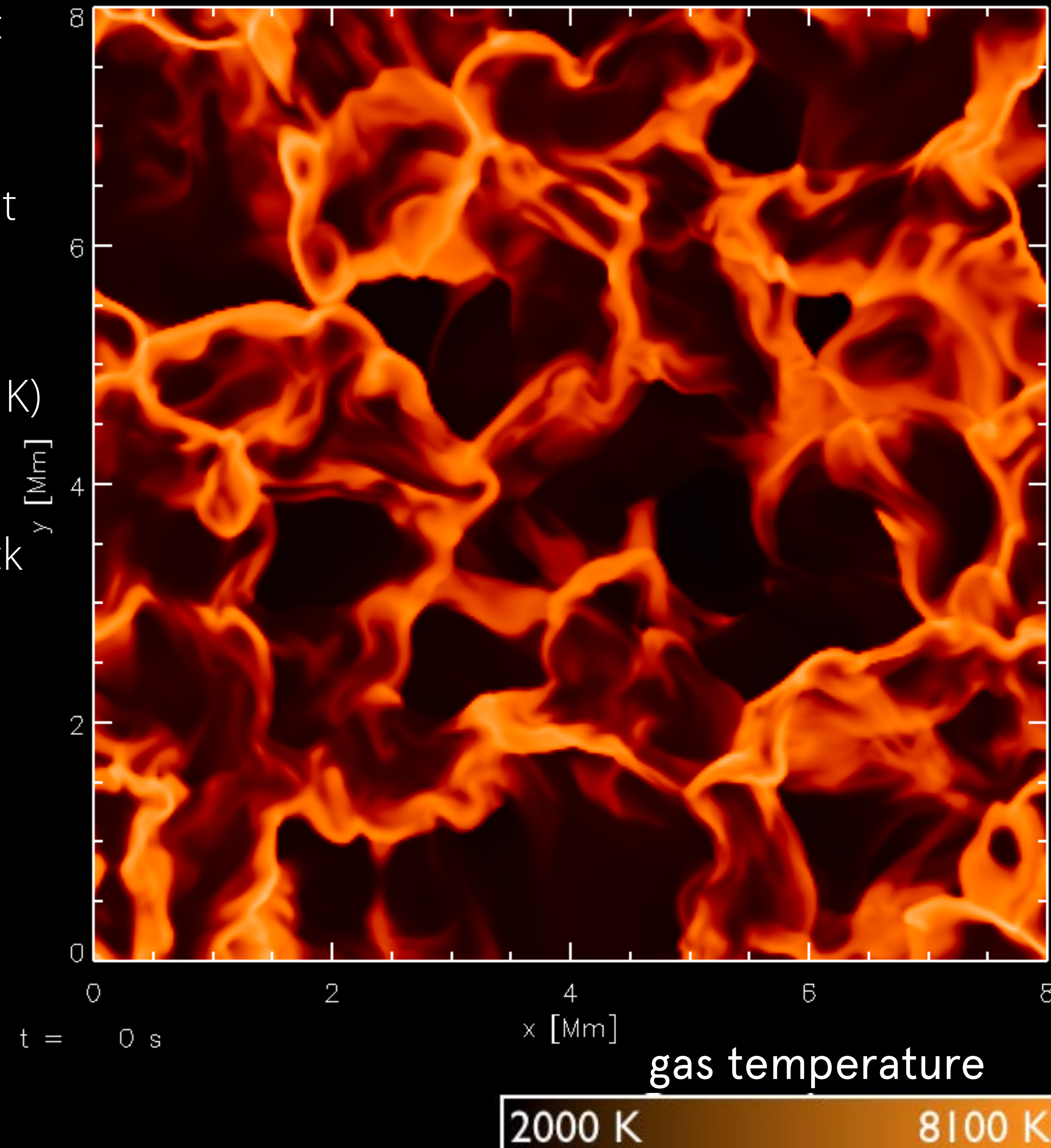


Schaffenberger, Wedemeyer, Steiner, Freytag (2005)

The solar atmosphere

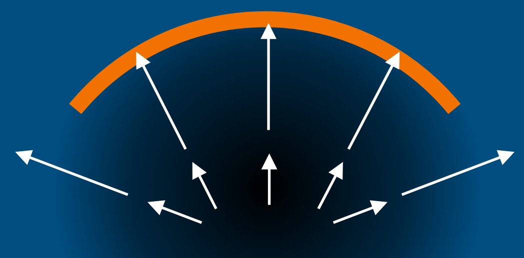
Thermal structure of a (very) Quiet Sun chromosphere

- Numerical simulation without magnetic fields (representing a hypothetical extremely quiet region)
- Horizontal cut through chromosphere at z=1000 km, gas temperature
- Hot shock fronts (~7000 - 8000 K) and cool post-shock regions (down to ~2000 K)
- Mean T_{gas} ~ 4000 K
- Pattern produced by interaction of shock fronts
  - Typical length scale ~1000 km (1.3")
  - Timescales of 20 -30 s



Wedemeyer et al. (2004)

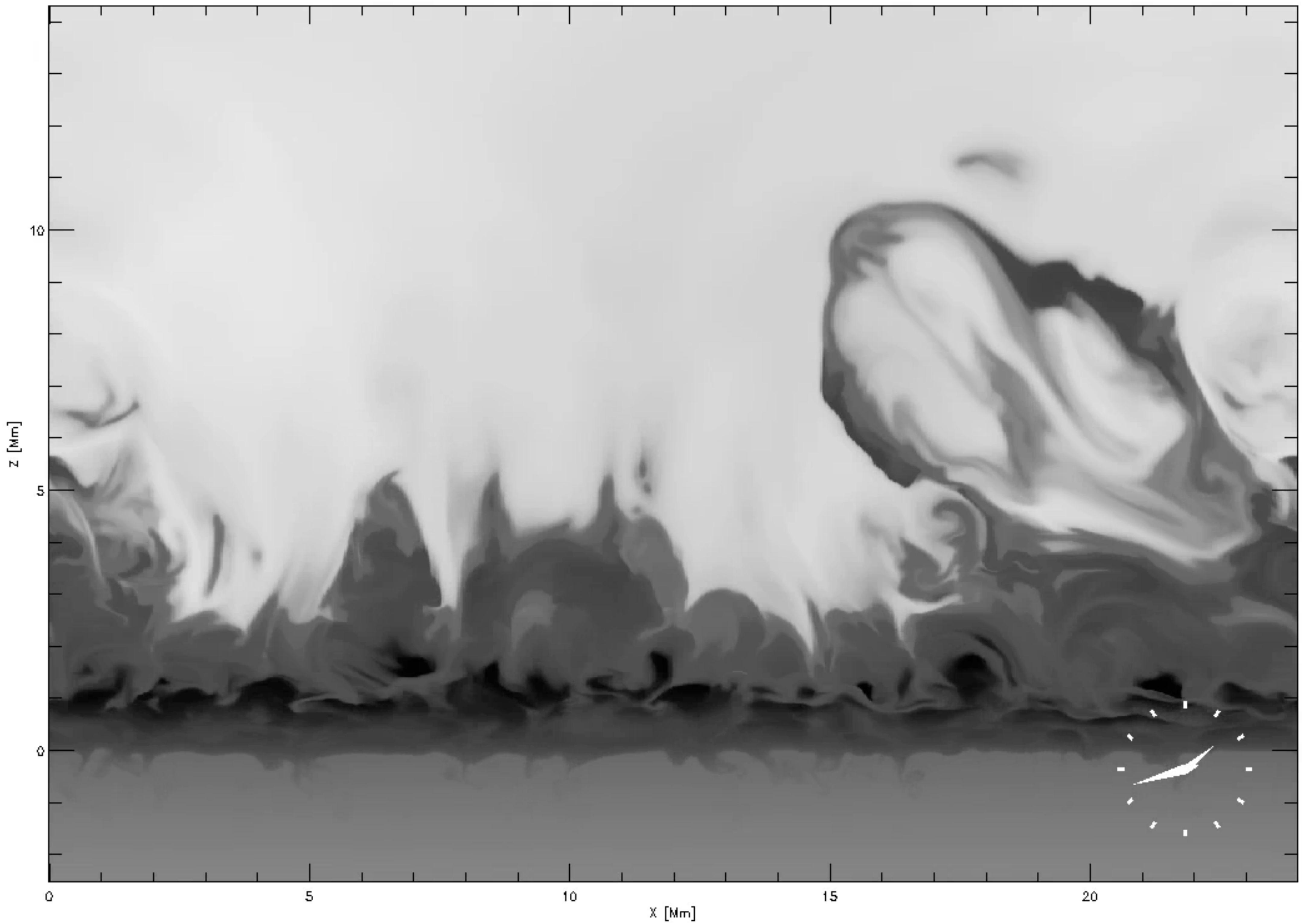
- Post-shock regions:
  Adiabatic expansion behind shock leads to low temperatures



The solar atmosphere

Numerical simulations — Quiet Sun

Bifrost (Gudiksen et al. 2011)



The solar atmosphere

Numerical simulations — Quiet Sun

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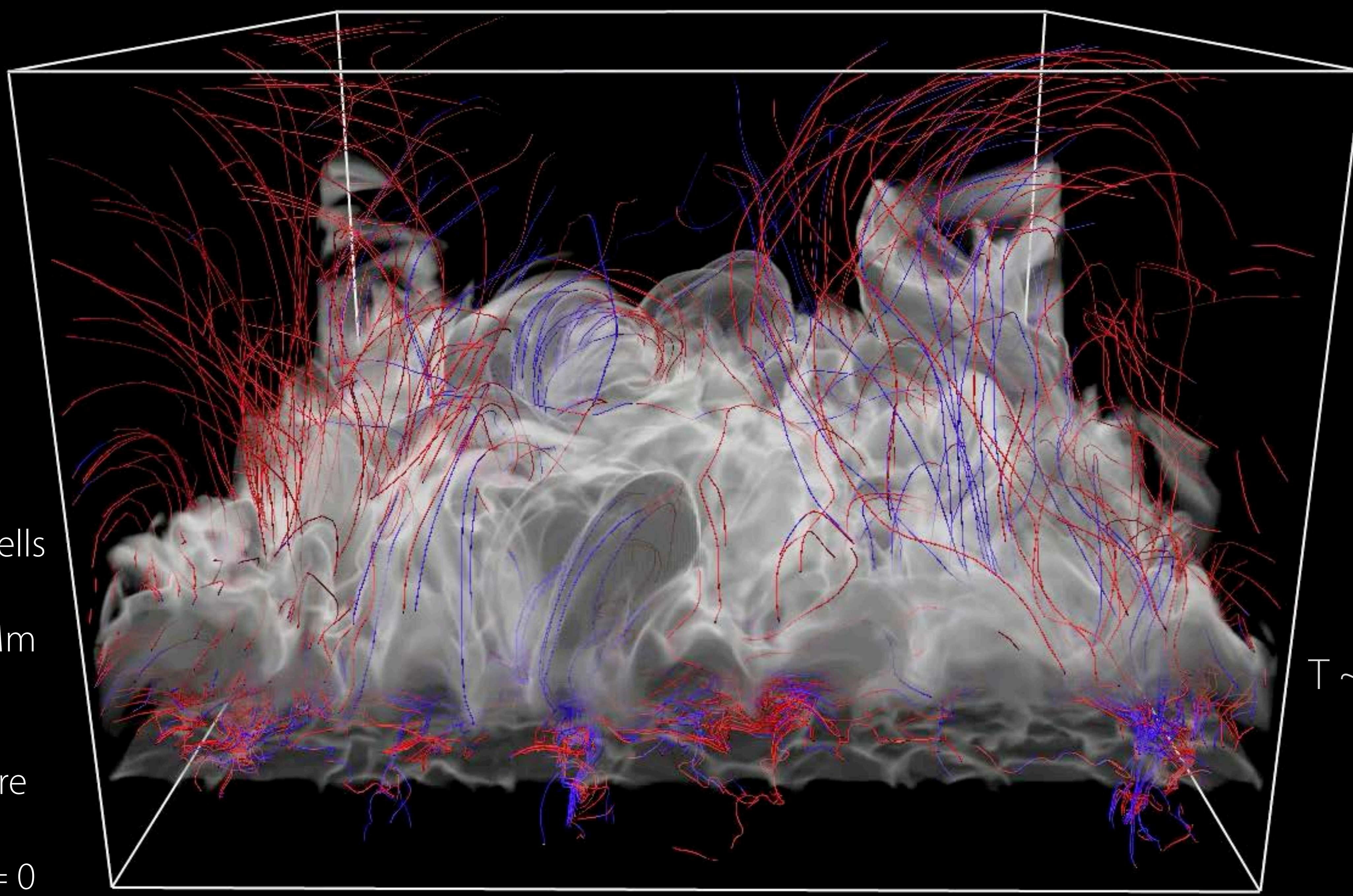


504 x 504 x 496 cells
24Mm x 24Mm
z: -2.4Mm .. +14Mm

No large-scale magnetic structure

Avg. signed flux = 0

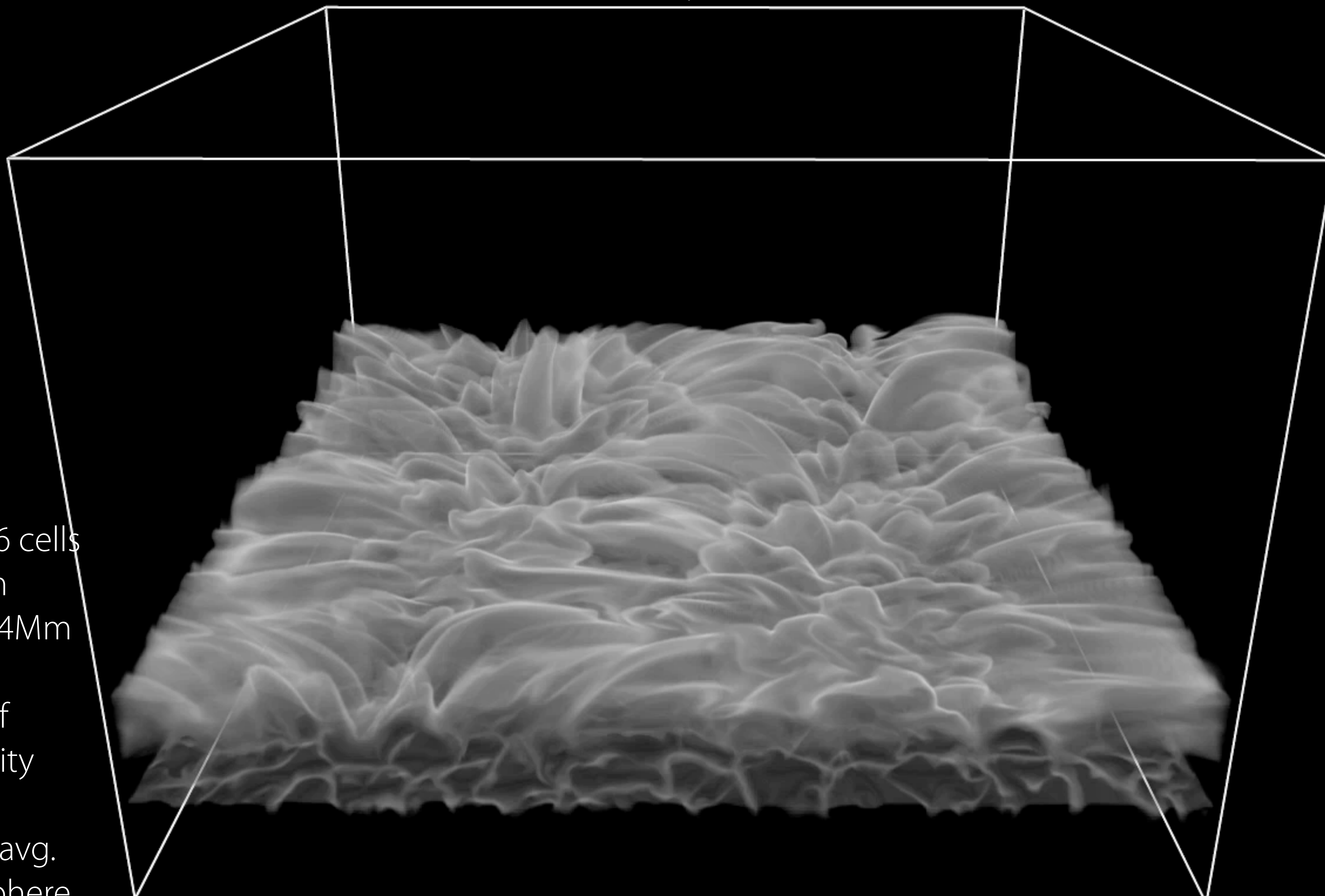
T ~ 7000 K

The solar atmosphere

Numerical simulations — Enhanced network region

Bifrost (Gudiksen et al. 2011)

http://sdc.uio.no/search/simulations
IRIS Technical Note 33; Carlsson et al 2016



504 x 504 x 496 cells
24Mm x 24Mm
z: -2.4Mm .. +14Mm

Two patches of
opposite polarity

50G unsigned avg.
flux in photosphere

The solar atmosphere

Numerical simulations — Enhanced network region

Bifrost (Gudiksen et al. 2011)

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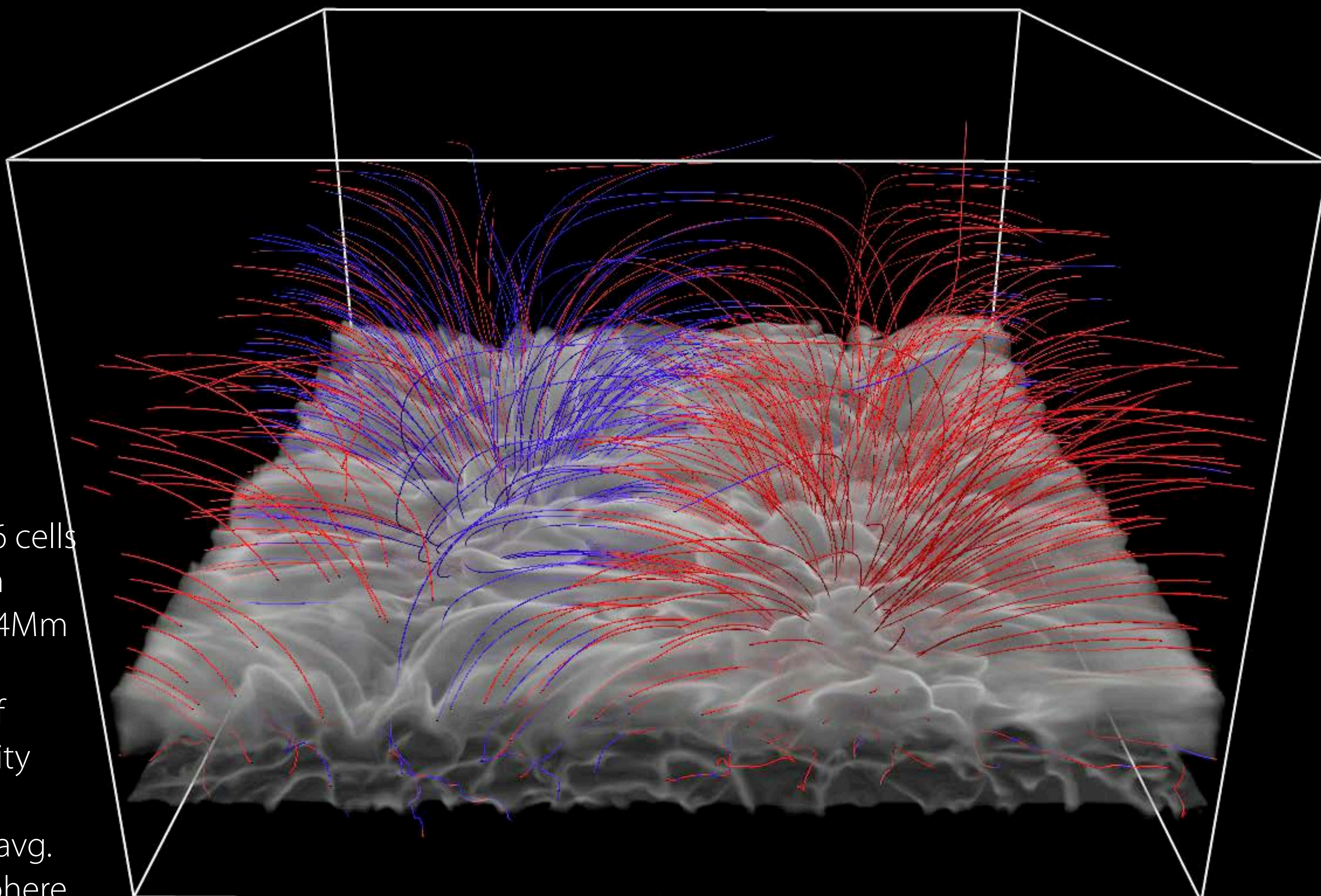

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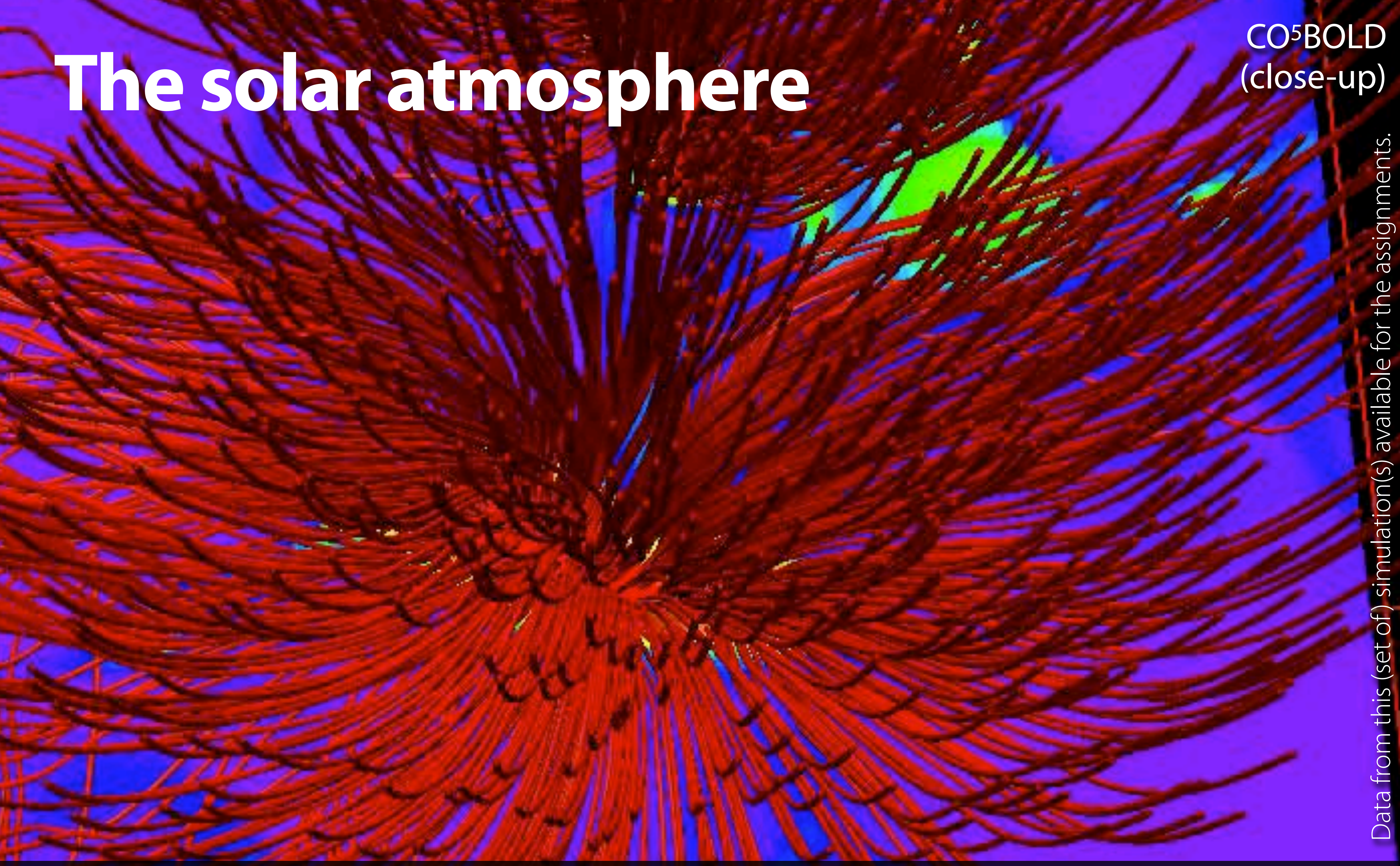
The solar atmosphere



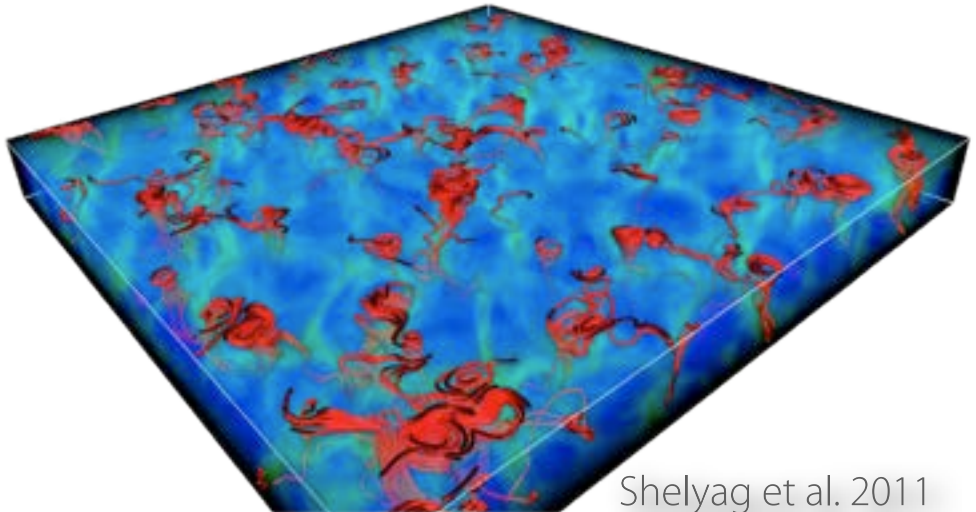
- Complicated field structure with rotating and/or swaying subgroups
- Continuous reorganisation of structure
- More complicated than individual “flux tubes”

The solar atmosphere

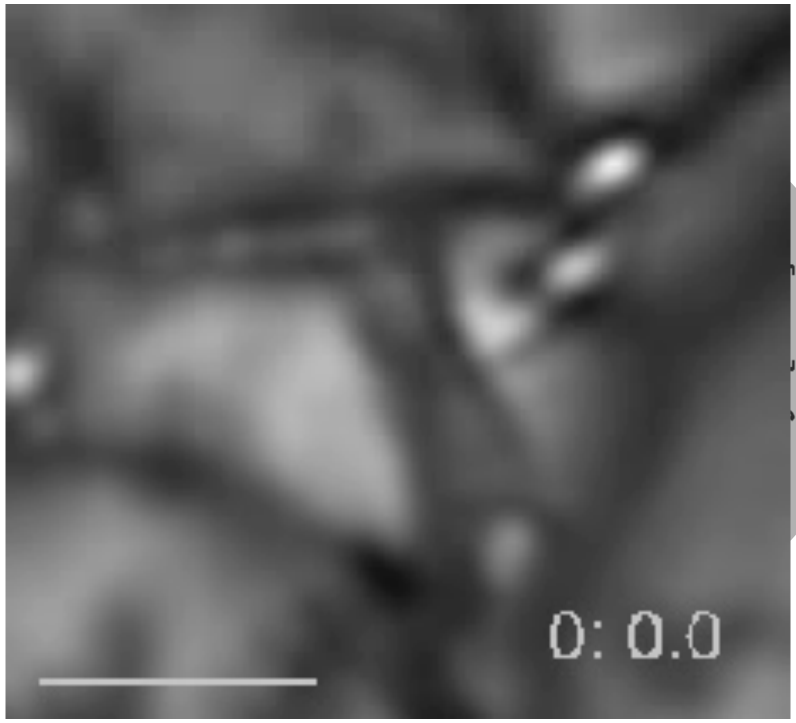
Vortex flows

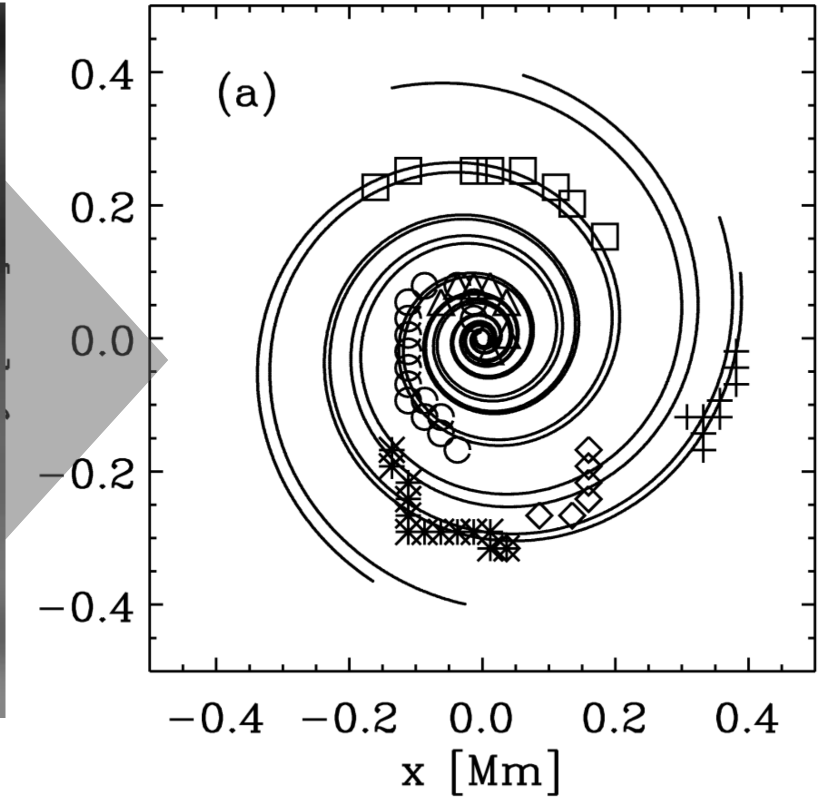
- Plasma that flows down in inter granular lanes carries angular momentum
  ➡ Conservation of angular momentum
  ➡ Photospheric vortex flows ("bathtub effect")
  - Photospheric vortex flows observed on a range spatial scales
    - (Larger) vortex flows can be detected by tracking motions of photospheric bright points

Vortex flows in 3D simulations



Shelyag et al. 2011





Bonet et al 2008

The solar atmosphere

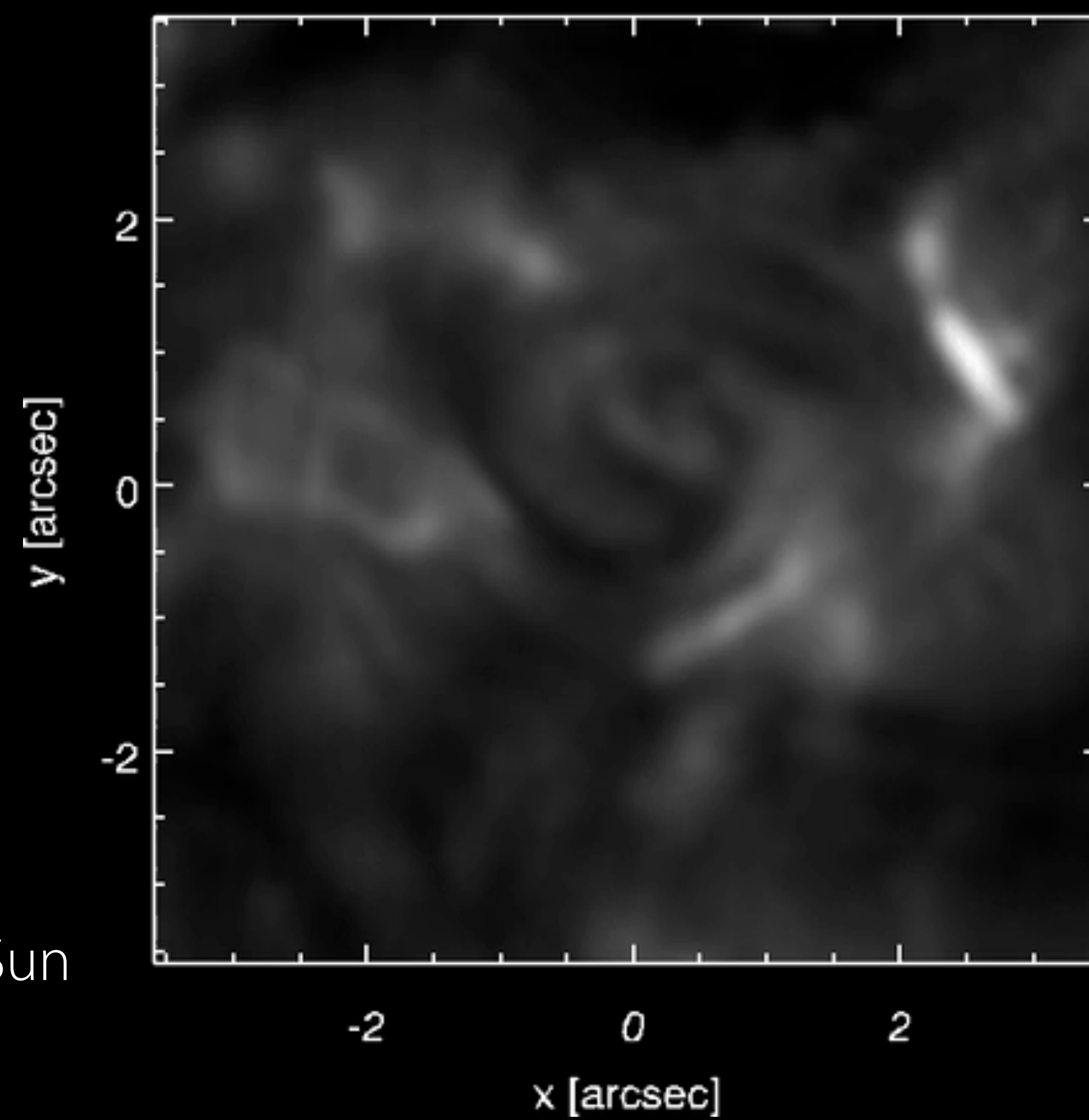
Chromospheric swirls

➡ SST observations, Ca II 854.2 nm line core

➡ Rotating dark ring (fragments)

➡ Chromospheric swirls

- Diameter ~ 2" and more (1.5 - 5.5 Mm)
- Width ~ 0."2 -0."5
- Doppler-shifts ~2 - 5 km/s and more
- Observed in continuum at the same time: **photospheric bright points** below the swirl



Wedemeyer & Rouppe van der Voort 2009

Wedemeyer et al 2012

- Lifetimes 7 - 19 min *(12.7 min ± 4.0 min)*
- Estimate: Over the whole Sun ~ 11 000 swirls at all times

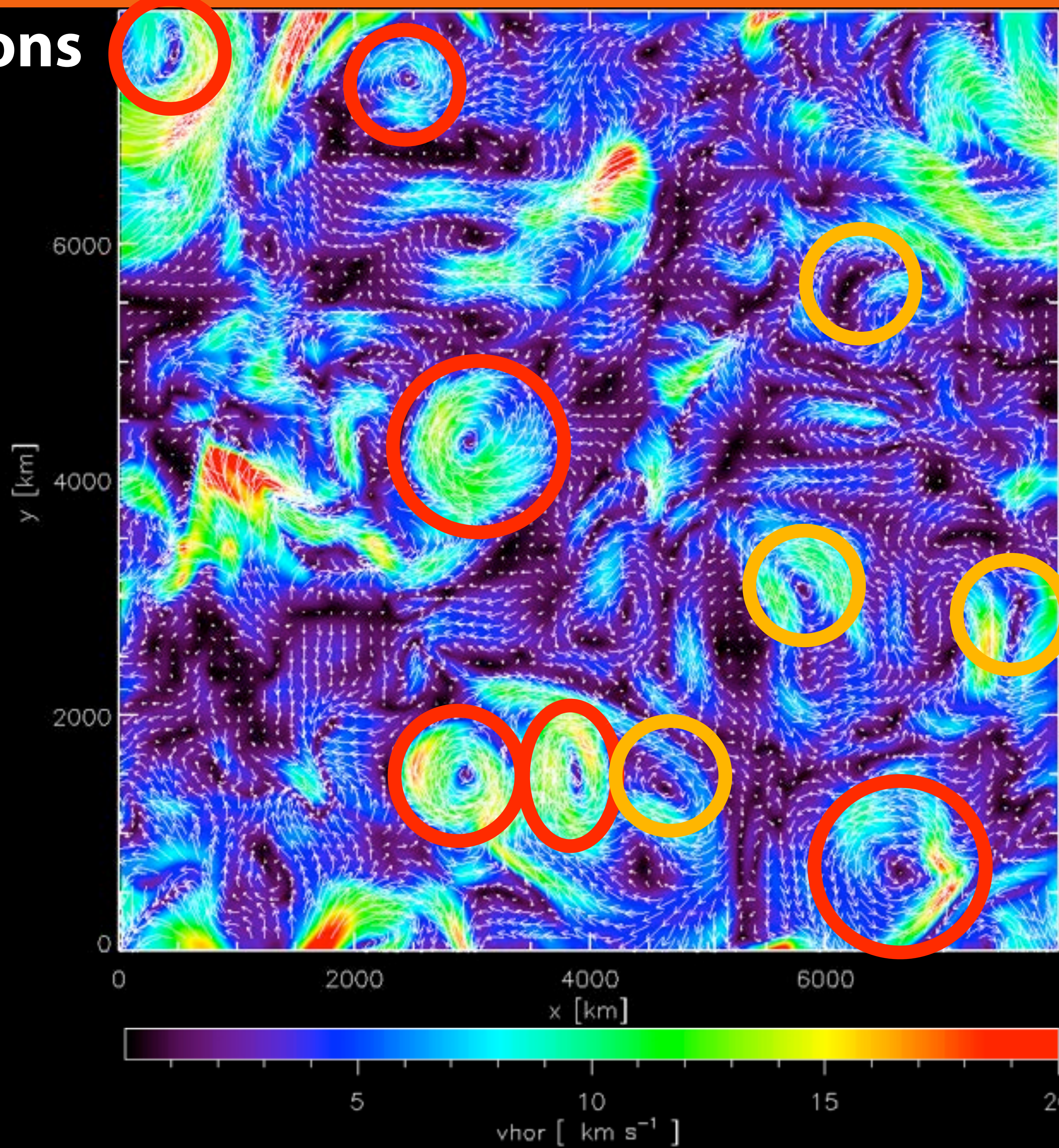
Explanation: **Rotating magnetic field structure** that produces observable signatures in all atmospheric layers from photospheric bright points to chromospheric swirls and bright features in the corona

The solar atmosphere

Numerical simulations

- Horizontal cross-section (x-y) in the chromosphere at z=1000km
- Horizontal velocity $v_{hor} = (v_x^2 + v_y^2)^{1/2} \sim 10$ km s^{-1}
- Features resemble swirls!

➡ **Magnetic tornadoes**



Wedemeyer et al 2012

The solar atmosphere

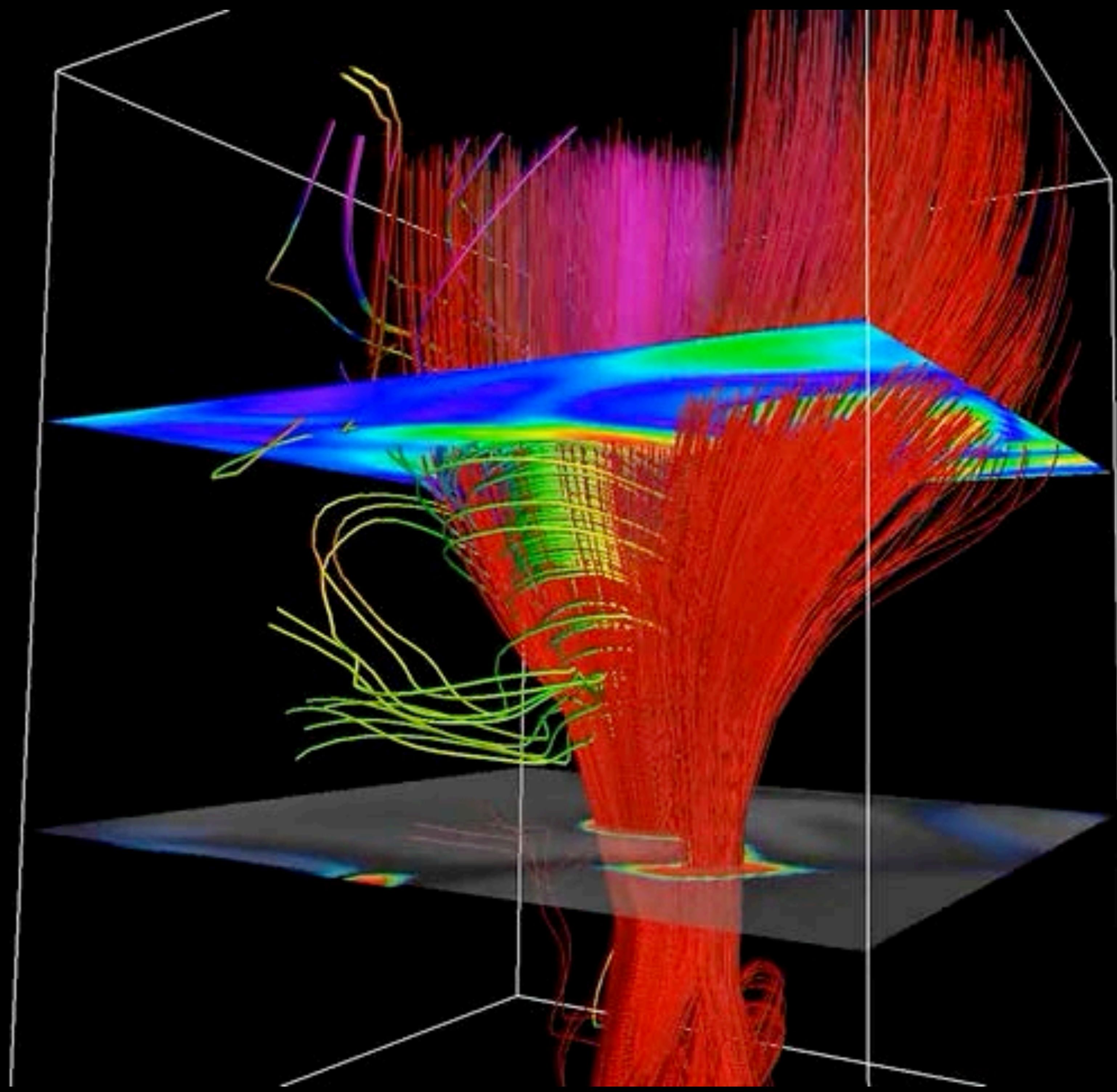
Magnetic tornadoes

cross-section of horizontal velocity at z=1000 km

regions with high horizontal velocity

magnetic field lines

velocity field (streamlines)



grey surface: granulation superimposed color: magnetic field

CO5BOLD/VAPOR

Wedemeyer et al 2012

The solar atmosphere

Magnetic tornadoes

- vortex flow in the photosphere:
- magnetic field “frozen in”

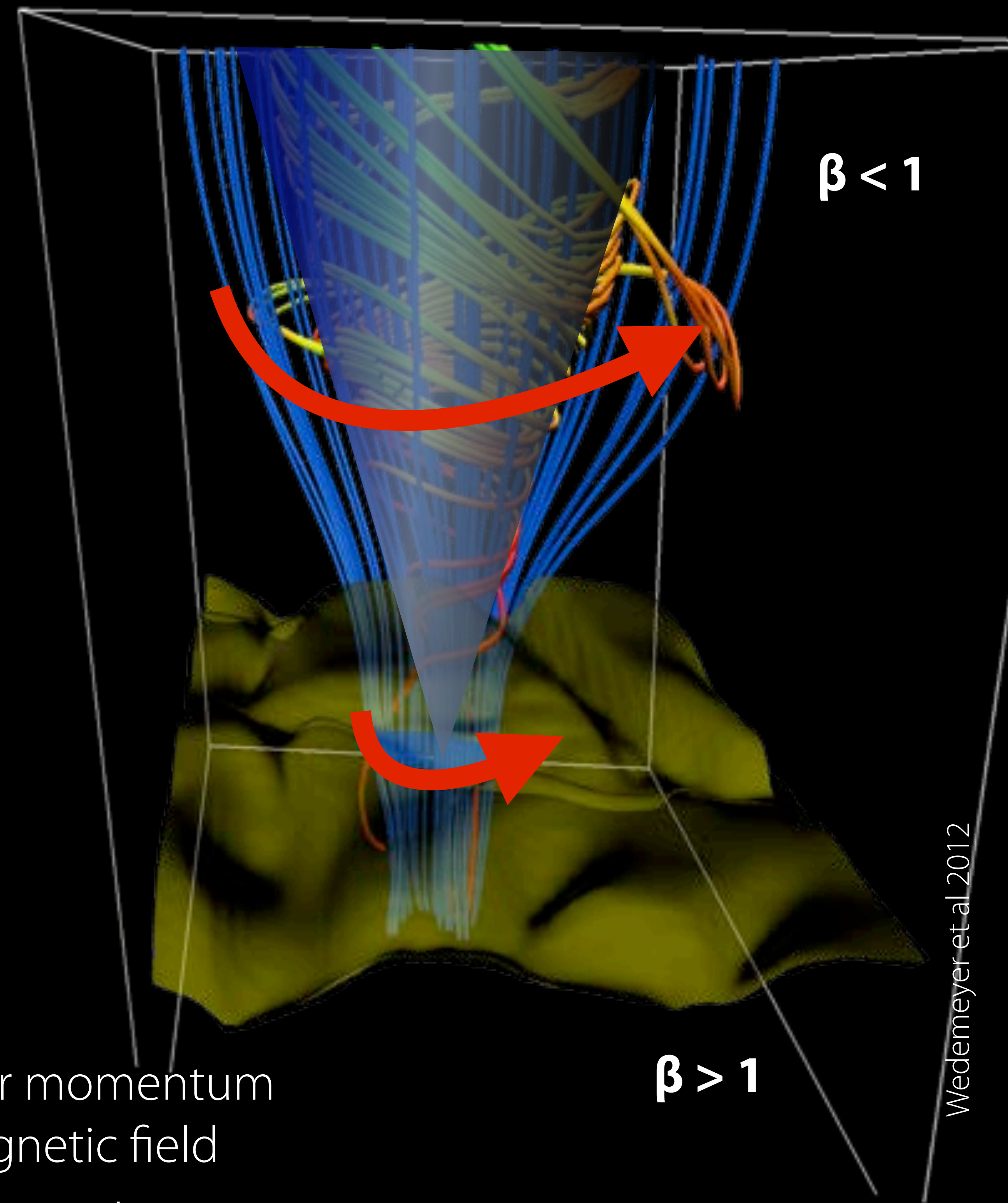
➡ photospheric vortex flow rotates magnetic flux structure

- Magnetic coupling of the atmospheric layers

➡ Rotation is mediated into the upper layers

- chromosphere and above:
    - plasma is forced to follow the rotating magnetic field lines

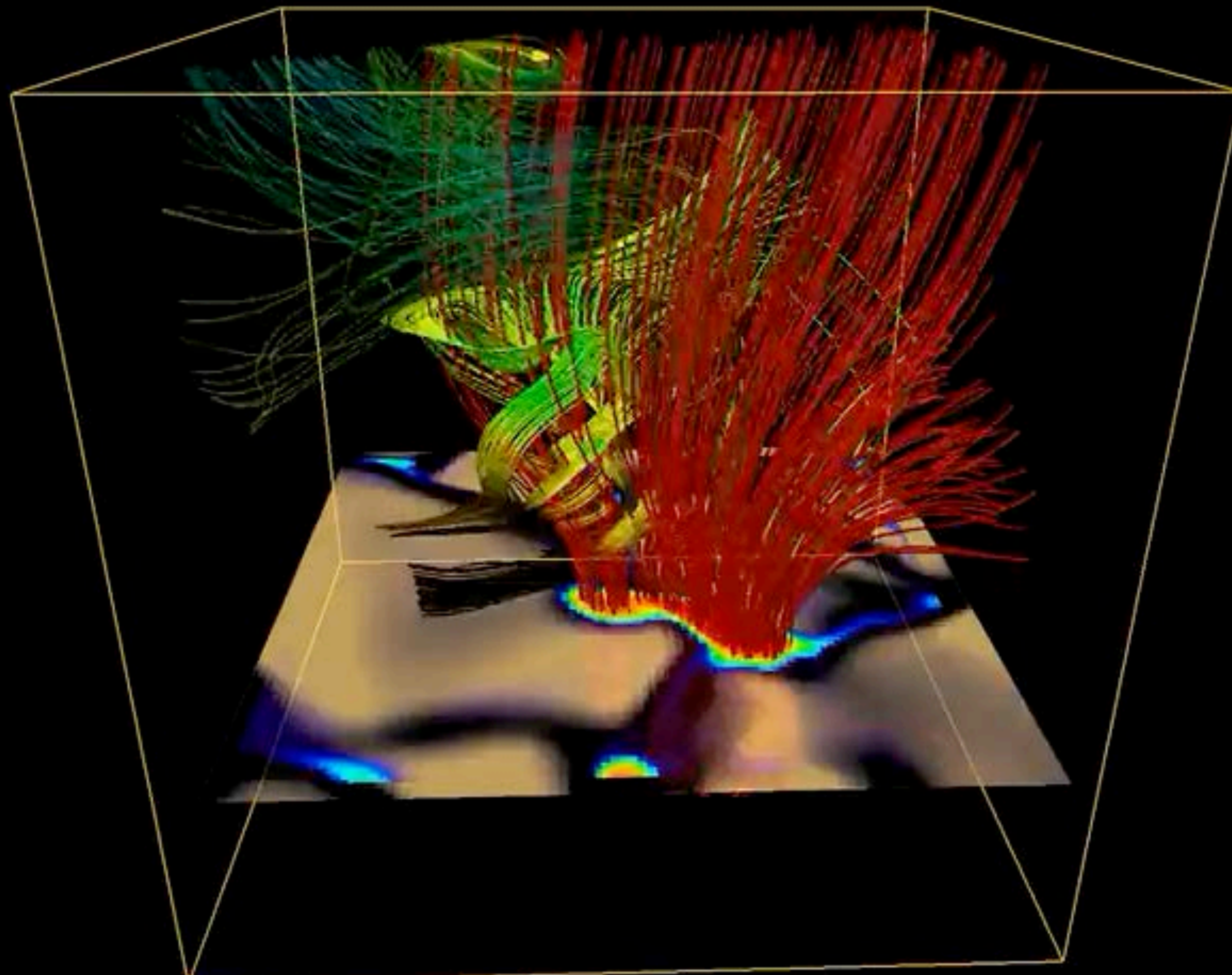
    ➡ spiral motions (both up and down)



- Direct consequence of conservation of angular momentum in surface convection and the presence of magnetic field
- Seen in numerical simulations for M-dwarf stars, too!

The solar atmosphere

Magnetic tornadoes



Wedemeyer et al 2012

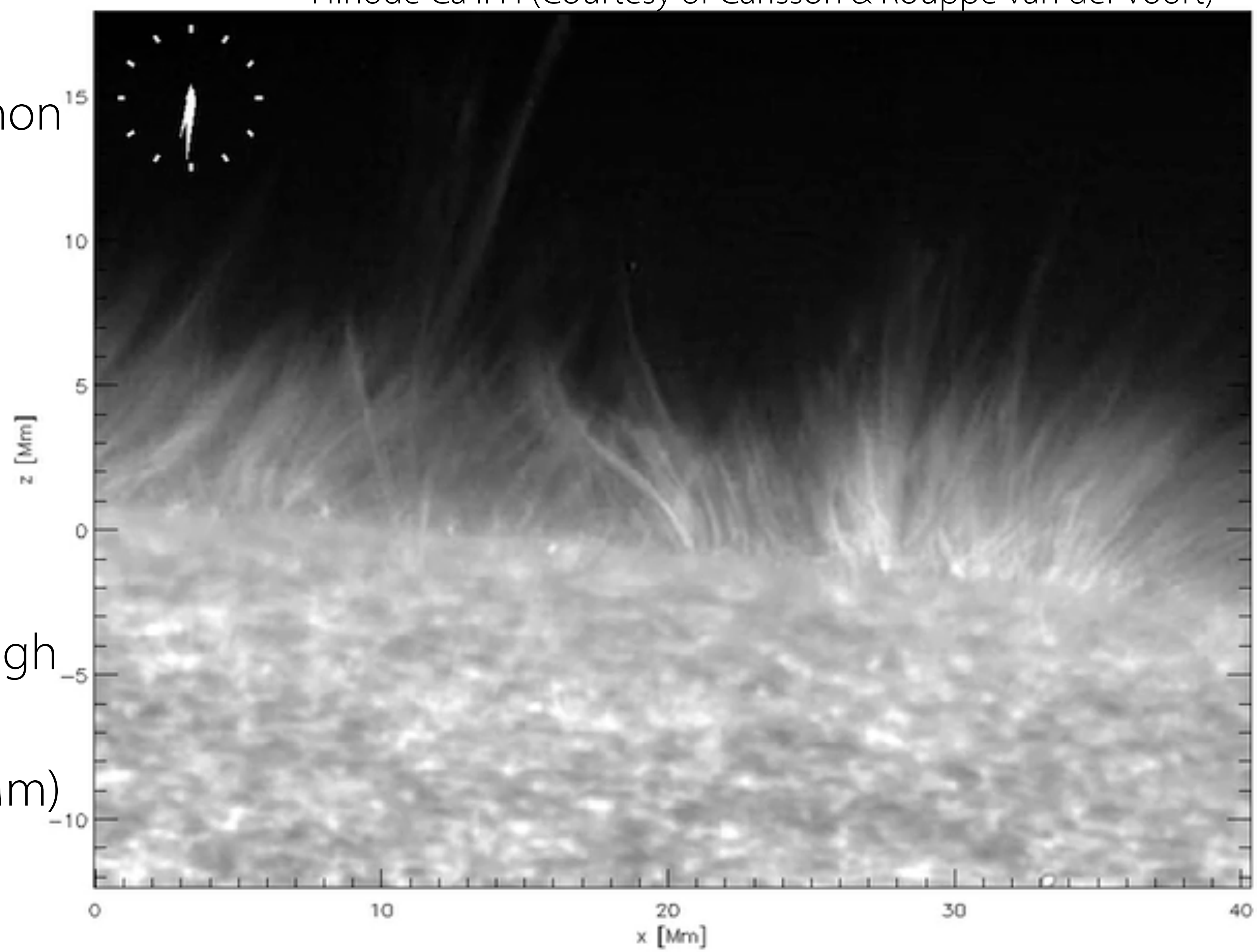
CO5BOLD/VAPOR

The solar atmosphere

Spicules

- Ubiquitous needle-like phenomenon on the Sun, visible at the limb (already seen by Secchi 1887)
- Now disk counterparts observed (also referred to as fibrils or mottles)
- At any time ~4 × 10^5 spicules
- Dynamic and short lived features (lifetimes typically 5–10 min)
- Jets with plasma shooting up at high speeds along magnetic field
- Reach heights of a few Mm (~10Mm)
- Triggered by p-modes at the footprints of the magnetic field structure
  - May serve as magnetic tunnels through which the coronal plasma is "refuelled" (Athay 2000).

Hinode Ca II H (Courtesy of Carlsson & Rouppe van der Voort)



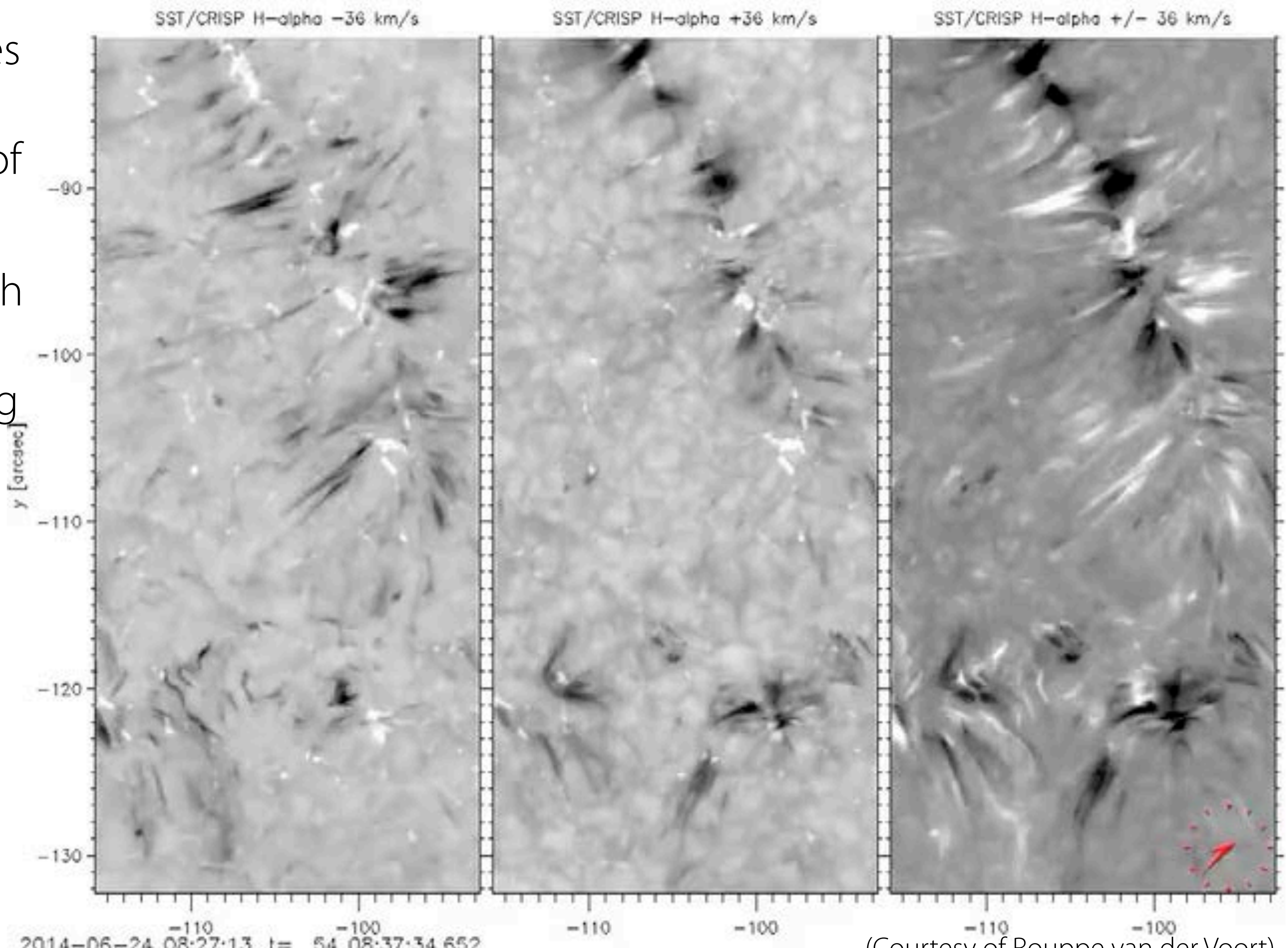
The solar atmosphere

Spicules

- Type II spicules (De Pontieu et al. 2007a) with shorter lifetimes (10–150 s), smaller diameters (< 200 km compared to < 500 km for type I spicules), and shorter rise times.

On disk

- Act as tracers/waveguides for Alfvén waves with amplitudes of the order of 10-25 km s^{-1}
- Carry, in principle, enough energy to play an important role for heating of the quiet Sun corona and for acceleration of the solar wind

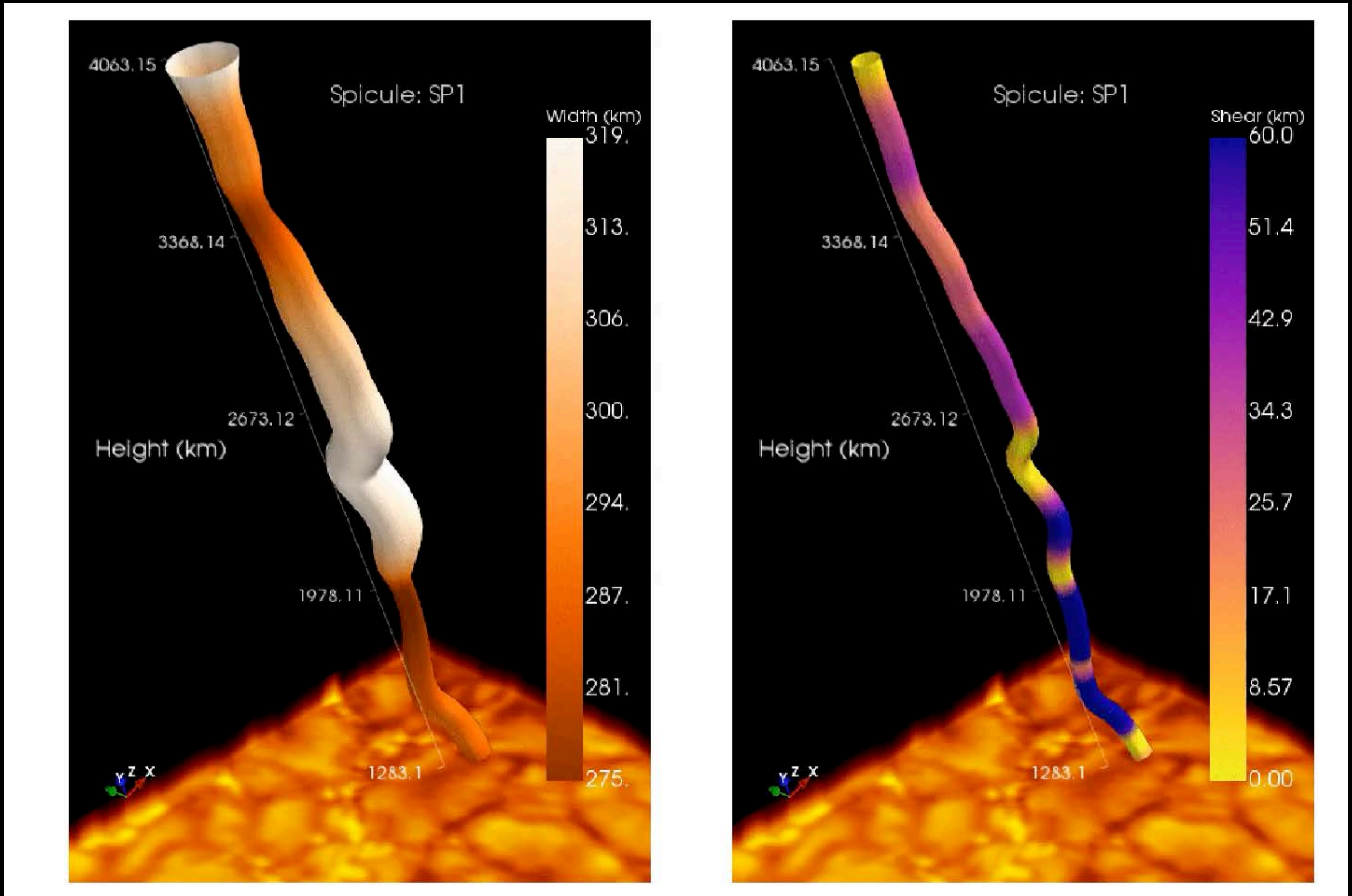


(Courtesy of Rouppe van der Voort)

The solar atmosphere

Spicules

- Combination of different MHD wave mode observed (incl. torsion)
- Oscillations coupled transverse and width with intensity
- transverse and azimuthal shear components



Sharma et al. 2018

The solar atmosphere

Modelling the chromosphere — A numerical challenge

- Many physical processes need to be taken into account
    - Radiative transfer
    - (Magneto-)hydrodynamics
    - Thermodynamics (equation of state)
    - Gravity
    - Ionisation
    - Conduction
    - Ion-neutral effects
    - (Chemistry)
    - …
- Deviations from equilibrium conditions:
    - Ionisation degree
    - Atomic level populations (non-LTE)
    - Molecules … (within limits for the Sun)

The solar atmosphere

Modelling the chromosphere — A numerical challenge

- Many physical processes need to be taken into account
    - Radiative transfer
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    - Conduction
    - Ion-neutral effects
    - (Chemistry)
    - …
- Deviations from equilibrium conditions:
    - Ionisation degree
    - Atomic level populations (non-LTE)
    - Molecules … (within limits for the Sun)

- Chromosphere (weakly) ionized

  ➡ Thermodynamics affected by interaction between ionized and neutral particles
- Next step: multi-fluid / multi-species 3D radiative MHD code (species, e.g.: ions, neutrals, free electrons, …)
- Hall and ambipolar diffusion in the electric field

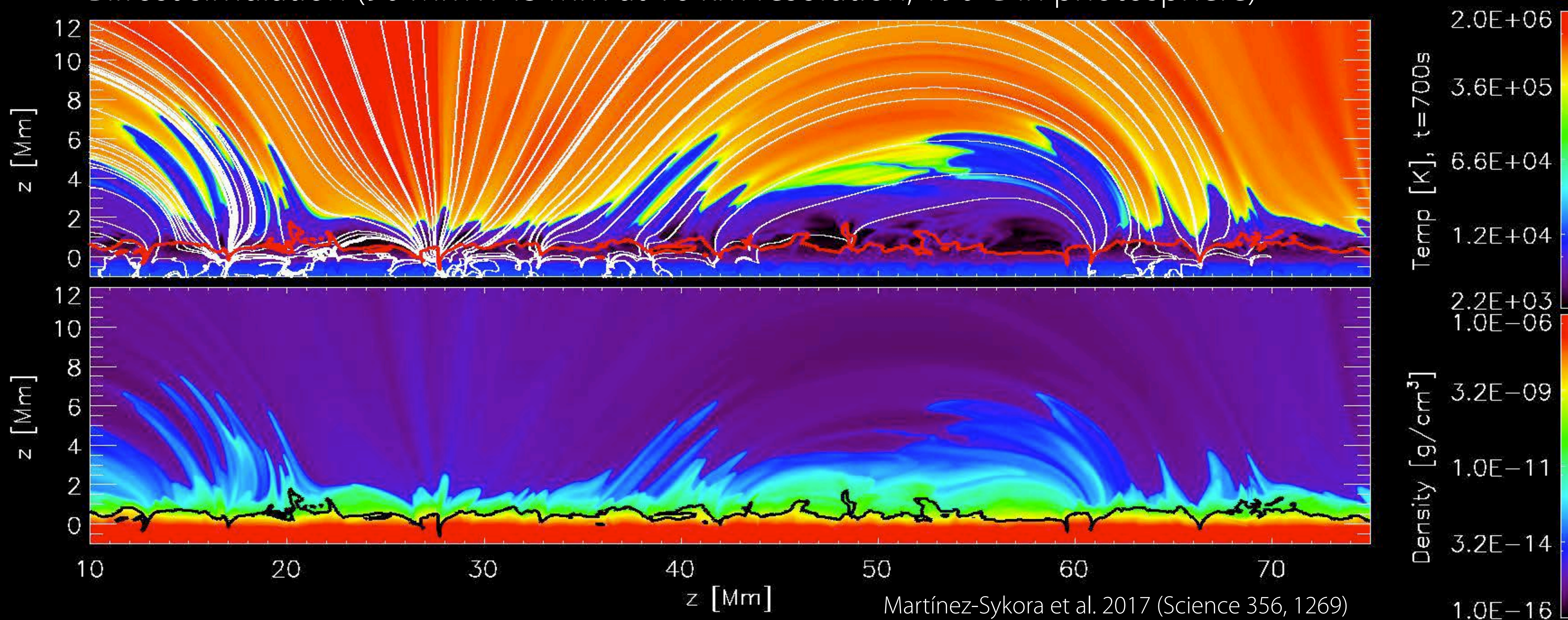
The solar atmosphere

Modelling the chromosphere — A numerical challenge

Ion-Neutral interactions

- So far ideal MHD but chromosphere partially ionized
- Next step: Single fluid MHD + Generalized Ohm's Law
  - Good approximation as long as collision times are short

Bifrost simulation (90 Mm x 43 Mm at 16 km resolution, 190 G in photosphere)



Martínez-Sykora et al. 2017 (Science 356, 1269)

Waves and oscillations in the solar atmosphere

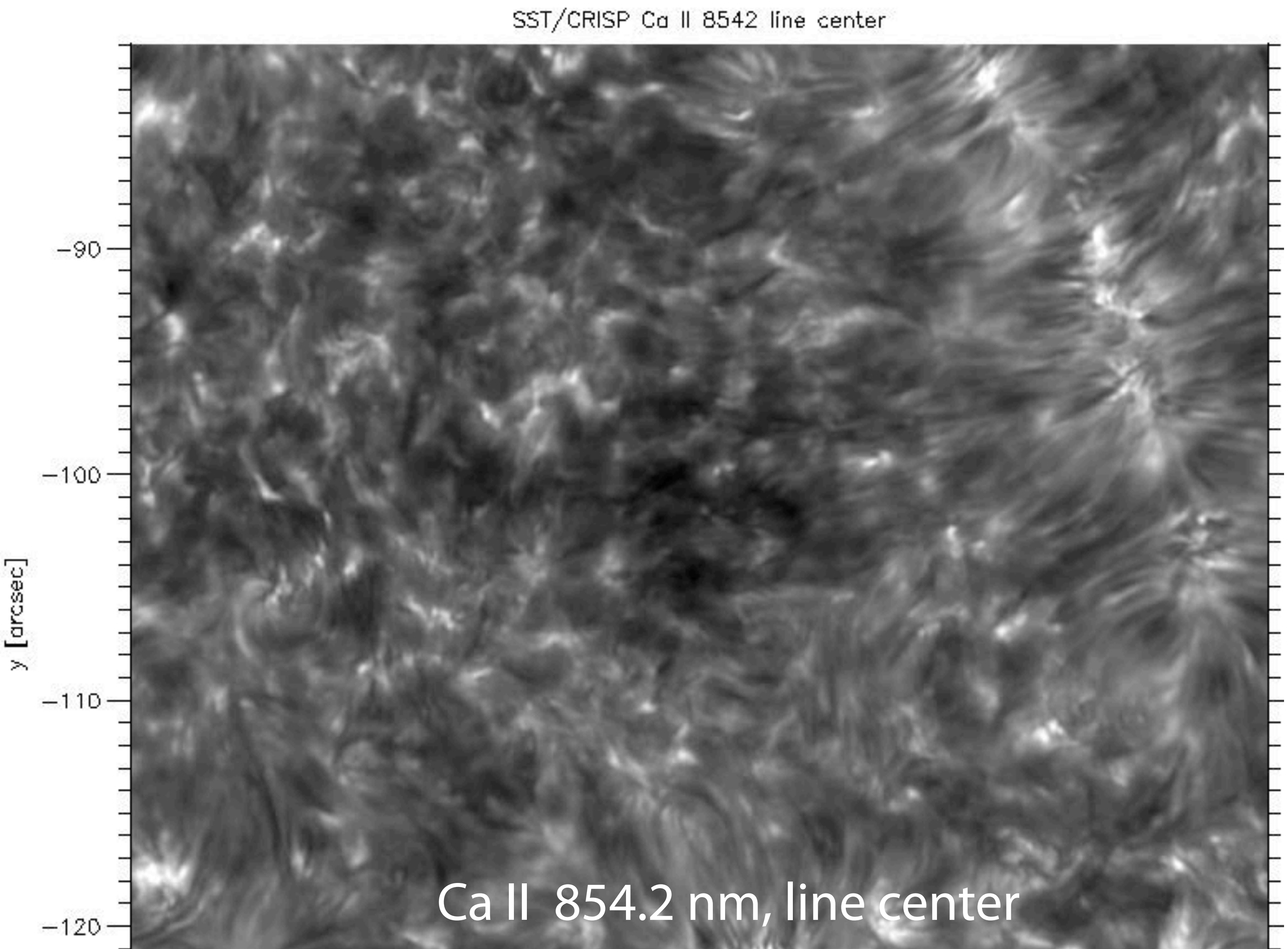
Waves in the solar atmosphere

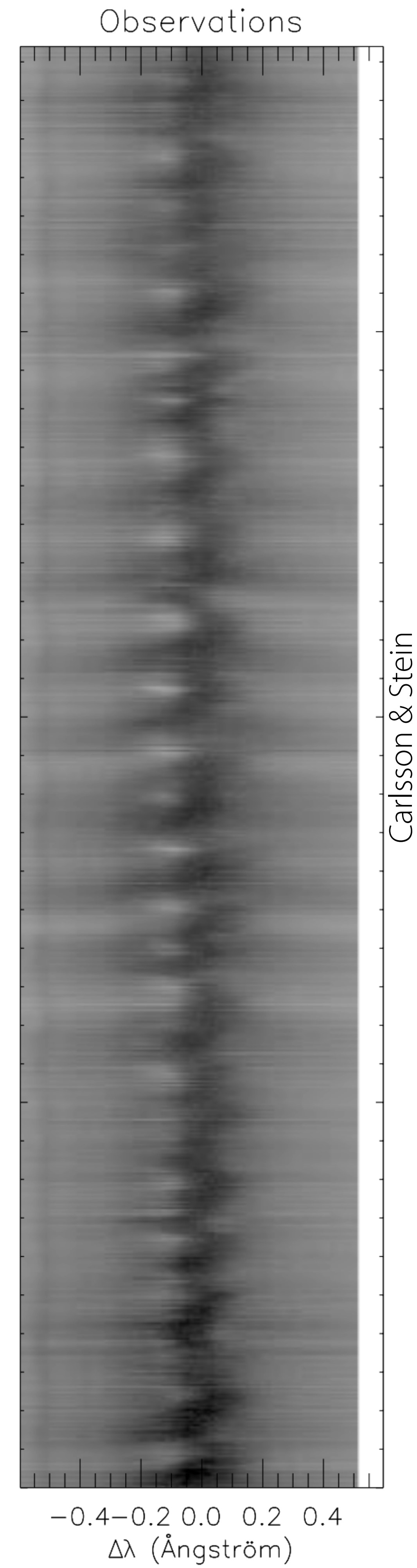
Acoustic waves and shocks

- Observations in spectral lines with cores formed in the chromosphere show periodic changes

➡ Bright grains with Dopplers shifts of several km/s

Ca II H

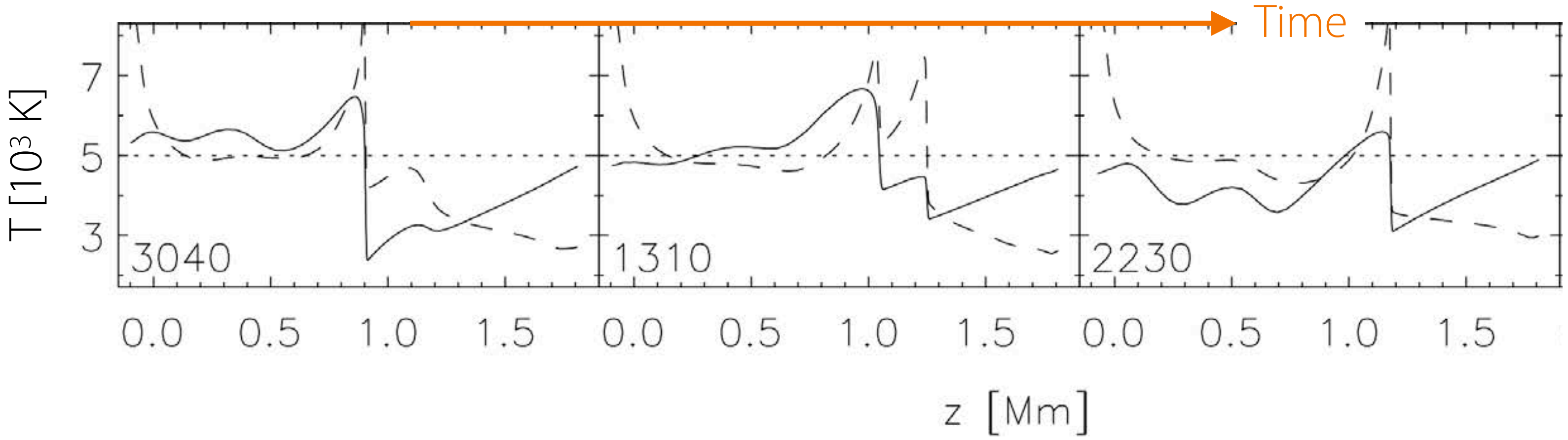


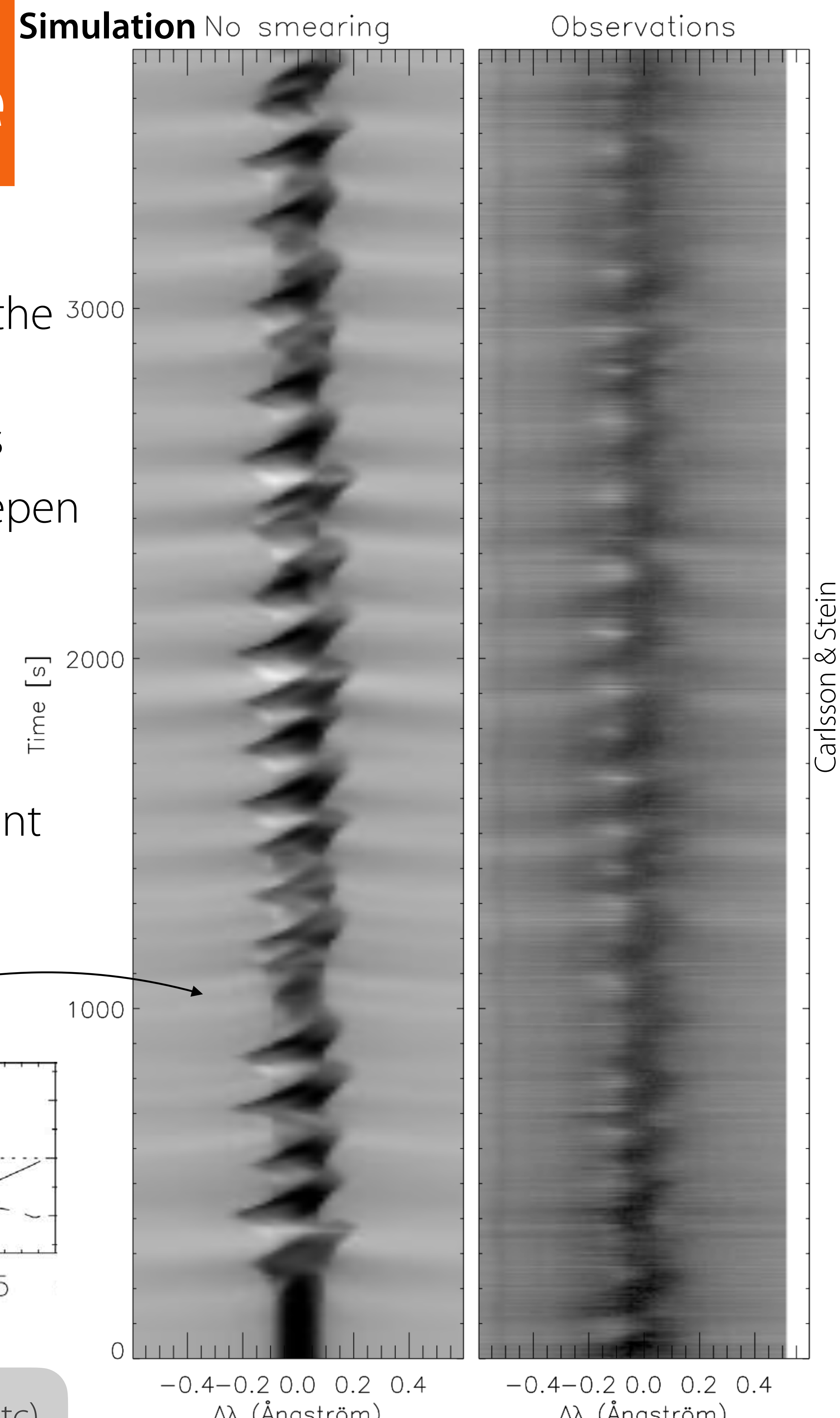


Waves in the solar atmosphere

Acoustic waves and shocks

- Observations in spectral lines with cores formed in the chromosphere show periodic changes
  ➡ Bright grains with Dopplers shifts of several km/s
  ➡ Caused by upwards propagating waves that steepen into shock waves in the chromosphere!
- Successfully explained by 1D simulations (Carlsson & Stein 1992-1997, RADYN code)
  - Time-dependent hydrodynamics, driven by empirical piston at the bottom, detailed treatment of physics (e.g., non-LTE, ionisation)
  - Radiative transfer calculations, produces observables that can be tested

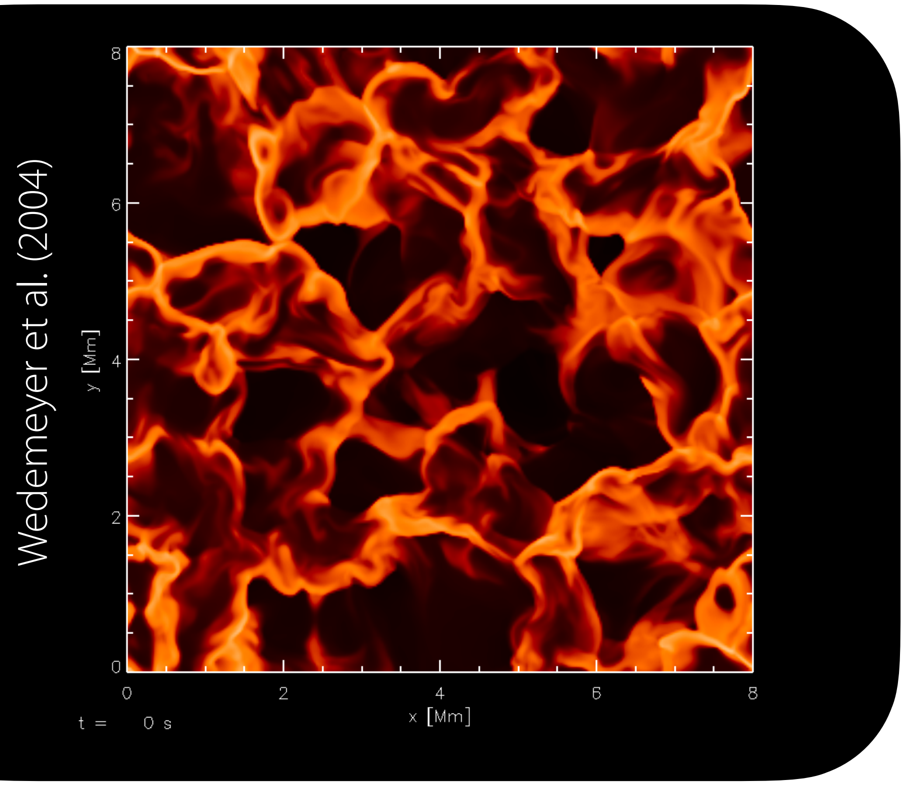


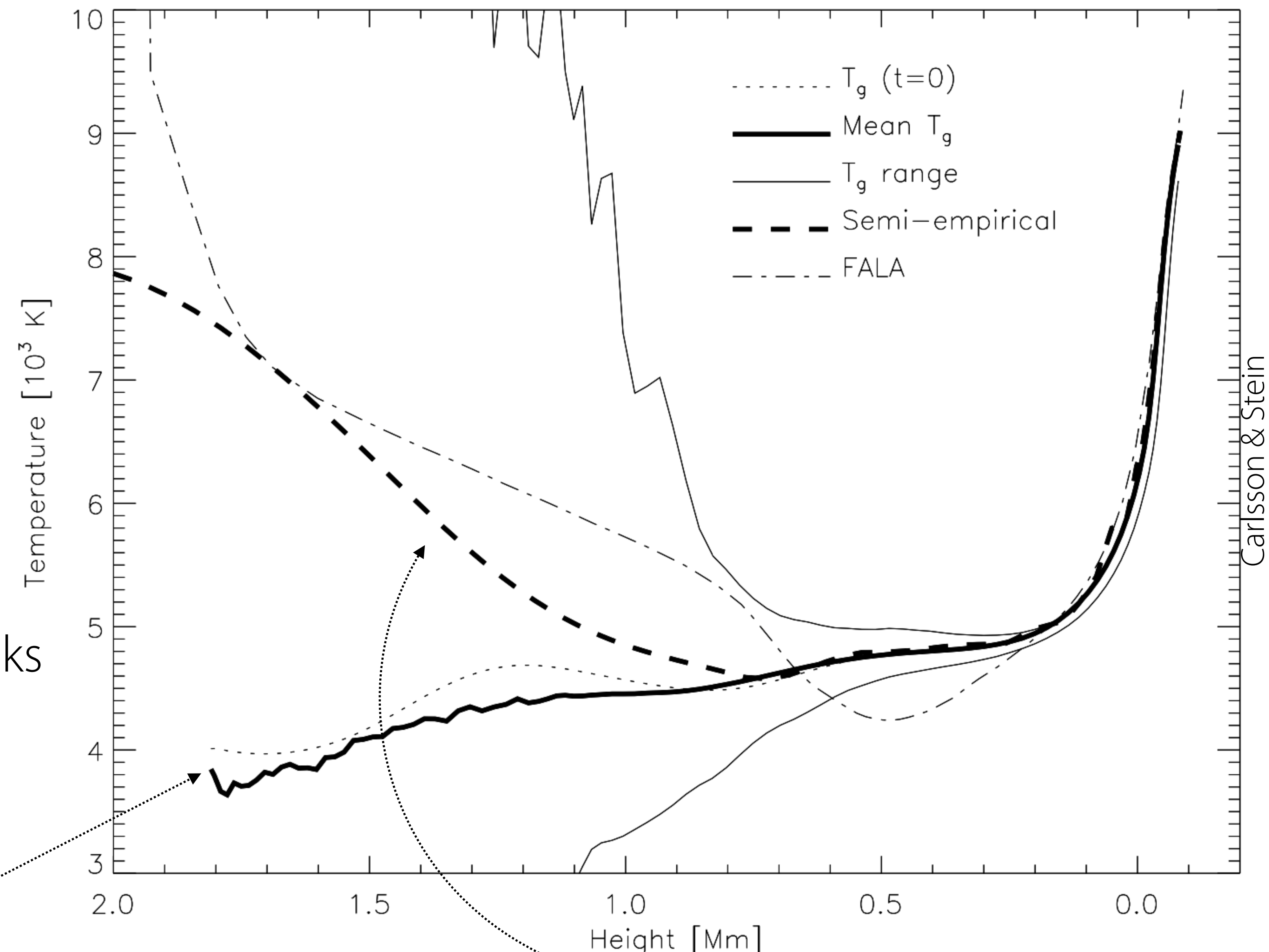


- Before that: static theoretical models (Ulmschneider 1971, etc)

Waves in the solar atmosphere

Acoustic waves and shocks





- Shock waves: high temperature peaks
- Post-shock regions (wake): low temperatures but fill more space than the shock fronts

➡ Arithmetic average shows no chromospheric temperature increase

➡ Reconstructing temperature stratification from UV emission averaged over these components (as for semi-empirical models) does show an increase!

- Reason: Non-linear dependence of UV intensity on temperature!!

Waves in the solar atmosphere

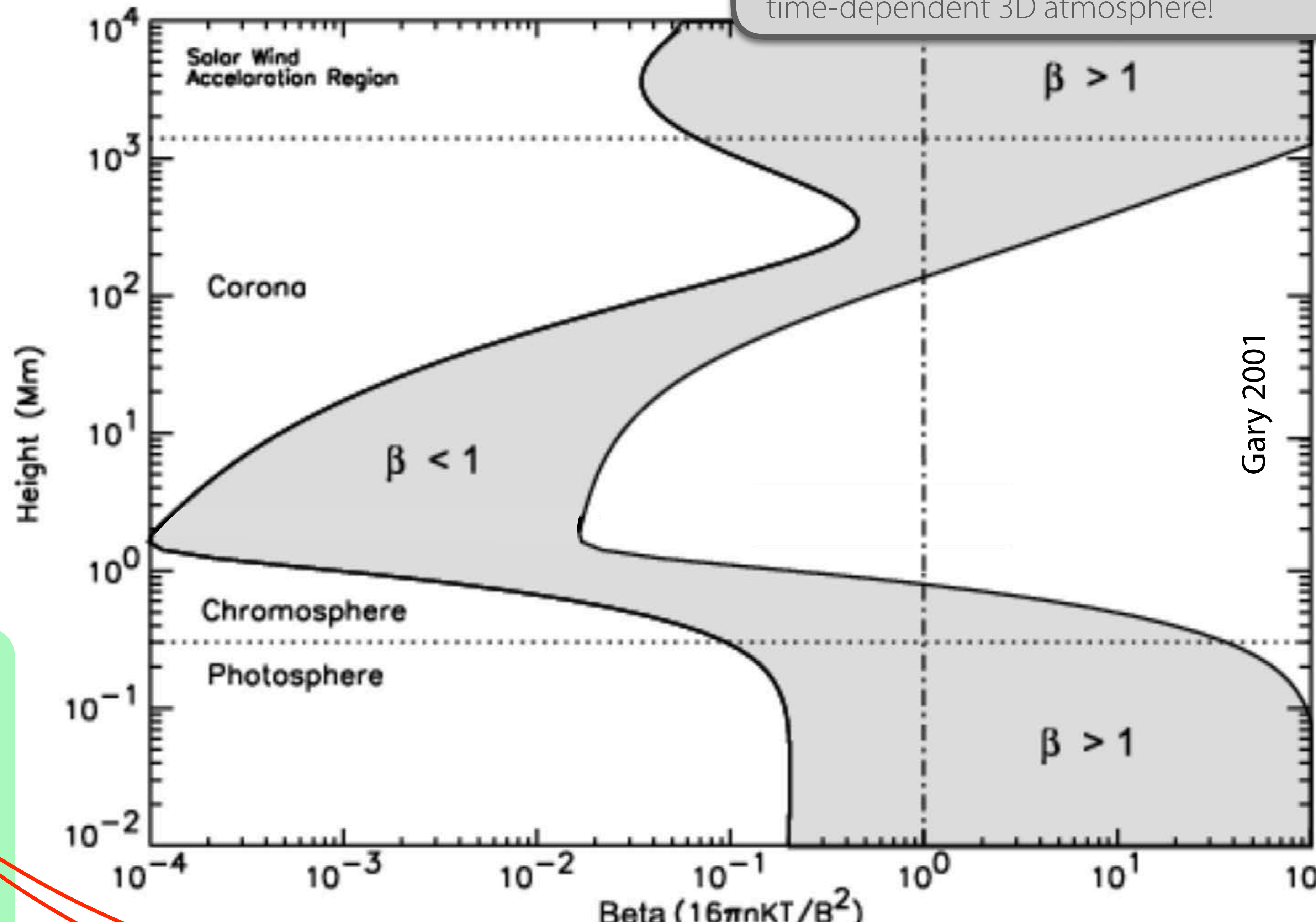
Waves in a magnetic environment

- **Plasma-β!**
- **Chromospheric plasma typically β<1**

➡ MHD wave modes to be considered

➡ Magnetic flux structures can serve as wave guides

Careful: Based on average stratification; more variations to be expected for a time-dependent 3D atmosphere!



Gary 2001

- Remember: Magnetic tension as restoring force

➡ Waves

Lorentz Force

$$\mathbf{J}\times\mathbf{B} = (\nabla\times\mathbf{B})\times\mathbf{B}/\mu = (\mathbf{B}.\nabla)\frac{\mathbf{B}}{\mu} - \nabla\left(\frac{B^2}{2\,\mu}\right)$$

Waves in the solar atmosphere

- Remember: Dispersion relations, evanescence, cutoff frequencies etc.
- Here now expanded to magnetohydrodynamic waves
- **Different wave modes**, incl.
  - **Acoustic** waves: Gas pressure fluctuations. Restoring force: pressure gradient.
  - **Fast** and **slow magnetoacoustic** waves: Acoustic character, modified by the magnetic field, coupling between magnetic field and pressure fluctuations.
  - **Alfvén** waves: Waves propagating along magnetic field, magnetic tension as restoring force; Only in the presence of a magnetic field, absent otherwise.

Wave type	Behavior	Weak field	Strong field
Fast	Isotropic $v_{\rm ph} \sim \max(v_s, V_{\rm A})$	Gas pressure $\mathbf{v} \parallel \mathbf{k}$	Magnetic pressure $\mathbf{v} \perp \mathbf{B}_0$
Slow	Propagates approximately along $\mathbf{B}_0$ $v_{\rm ph} \sim \min(v_s, V_{\rm A})$	Magnetic tension $\mathbf{v} \perp \mathbf{k}$	Gas pressure $\mathbf{v} \parallel \mathbf{B}_0$
Alfvén	Propagates along $\mathbf{B}_0$ $v_{\rm ph} = V_{\rm A}$	Magnetic tension $\mathbf{v} \perp \mathbf{k}$ and $\mathbf{B}_0$	

Narayanan, A. S., 2013

Waves in the solar atmosphere

- **Different wave modes** (incl. acoustic waves, magneto acoustic waves, Alfvén waves, …)
- Fast and slow magnetoacoustic mode due to two possible solutions in the dispersion relation
- Phase speed of Alfvén waves in between phase speed of slow and fast modes.
  ➡ Also referred to as "intermediate mode"

Sound speed $C_S = \sqrt{\frac{\gamma\, p_0}{\rho_0}}$

Kink speed $C_K = C_A \sqrt{\frac{\rho_0}{\rho_0 + \rho_e}} = \frac{B_0}{\sqrt{4\pi\,(\rho_0 + \rho_e)}}$

Alfvén speed $C_A = \frac{B_0}{\sqrt{\mu\, \rho_0}} \simeq \frac{B_0}{\sqrt{4\pi\, \rho_0}}$

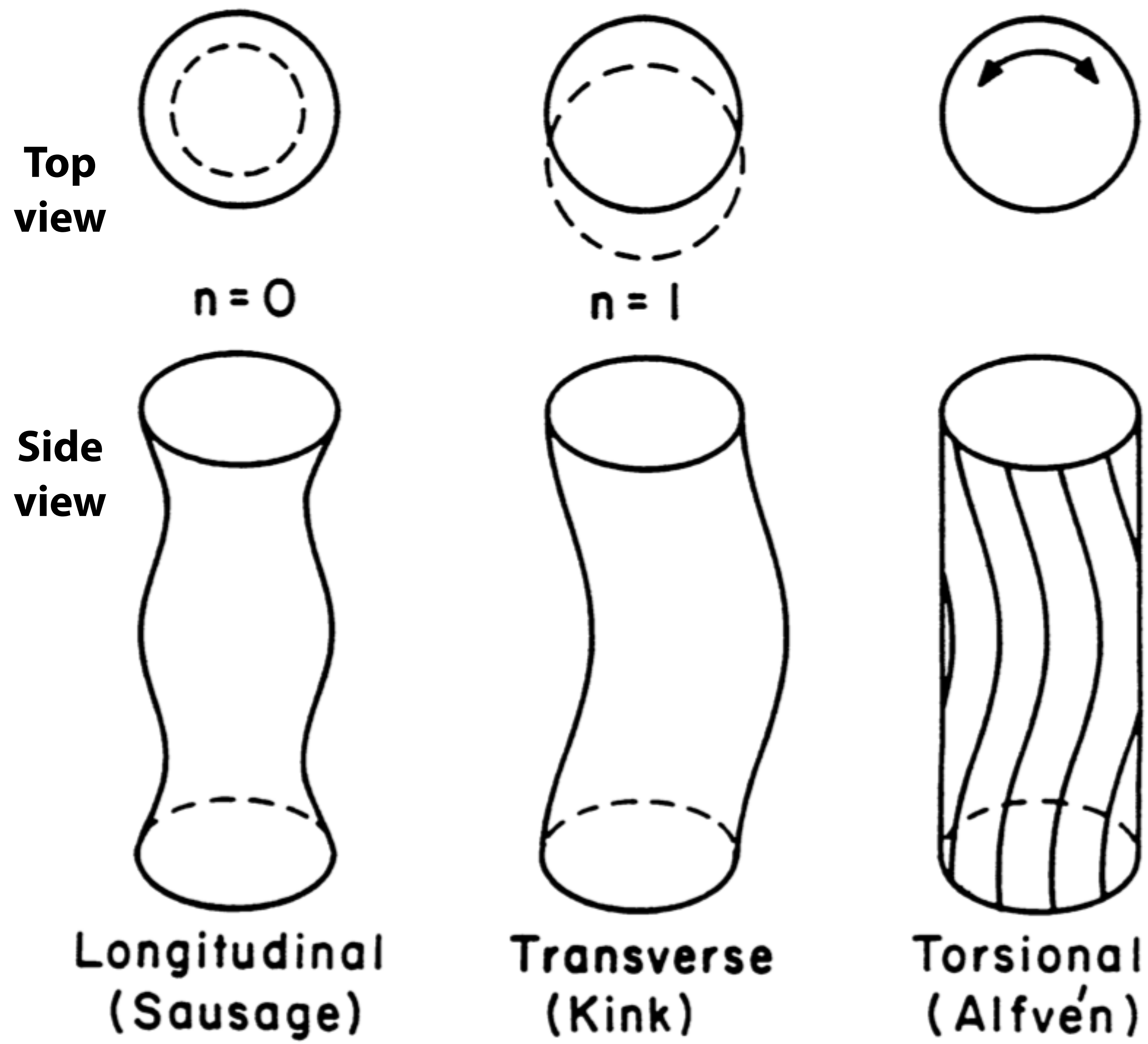
Tube speed $C_T = \frac{C_S\, C_A}{\sqrt{C_S^2 + C_A^2}}$

Fast wave's speed $V_{Fast} = \sqrt{C_S^2 + C_A^2}$

Waves in the solar atmosphere

MHD waves

- Magnetic flux "tubes" act as wave guide but also offer other possibilities for oscillation and waves, e.g. by periodic deformation, displacement, and/or twisting of the flux tube



Periodic squeezing and rarefying of the flux tube

Periodic displacement of central tube axis (Bulk motion)

Periodic twisting of tube (Torsional oscillations)

Solanki, S. K., 1993, Space Science Reviews 63: 1-188

Waves in the solar atmosphere

MHD waves

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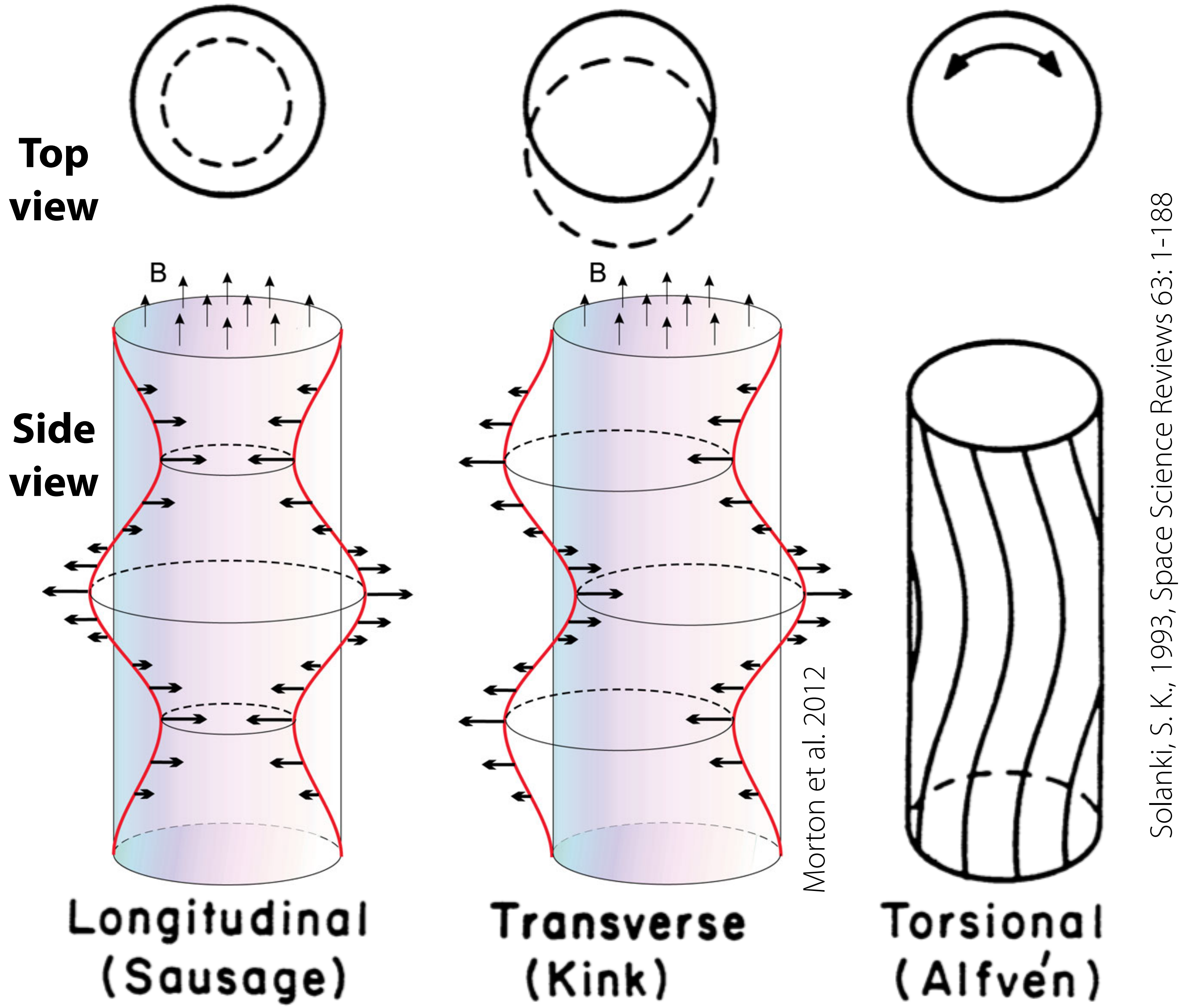


Periodic squeezing and rarefying of the flux tube

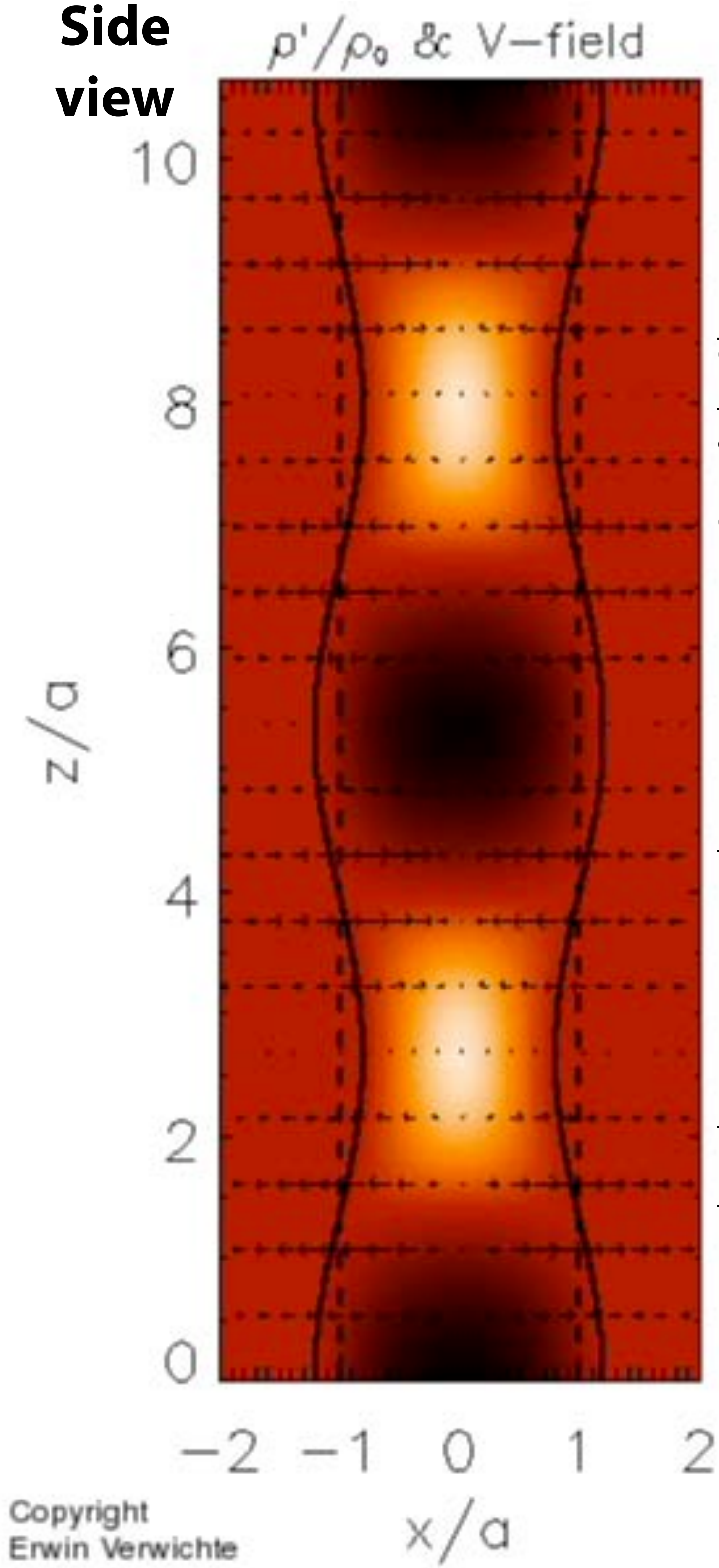
Periodic displacement of central tube axis (Bulk motion)

Periodic twisting of tube (Torsional oscillations)

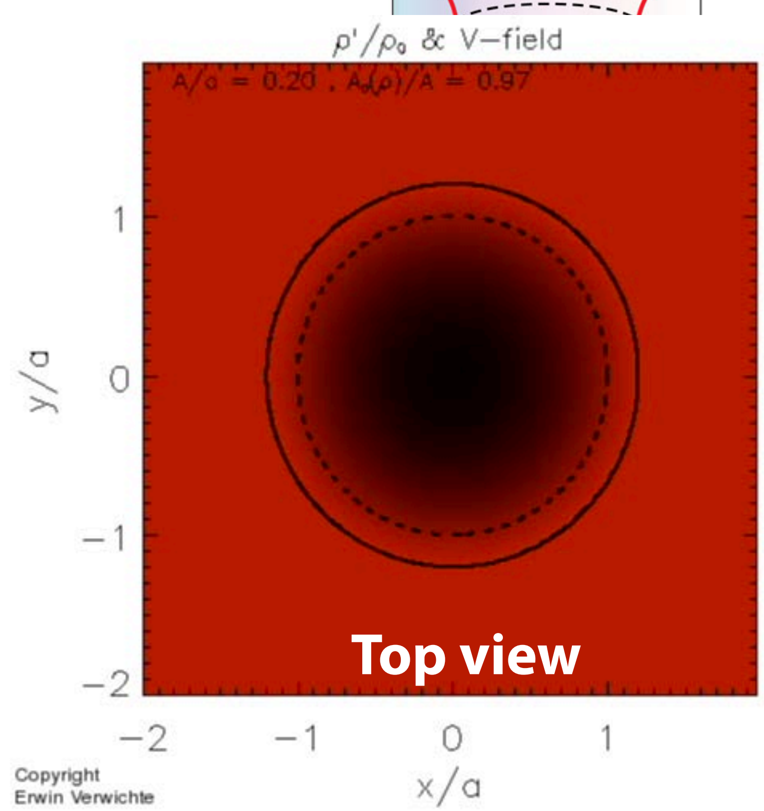
Waves in the solar atmosphere

MHD waves — Sausage mode

Side view

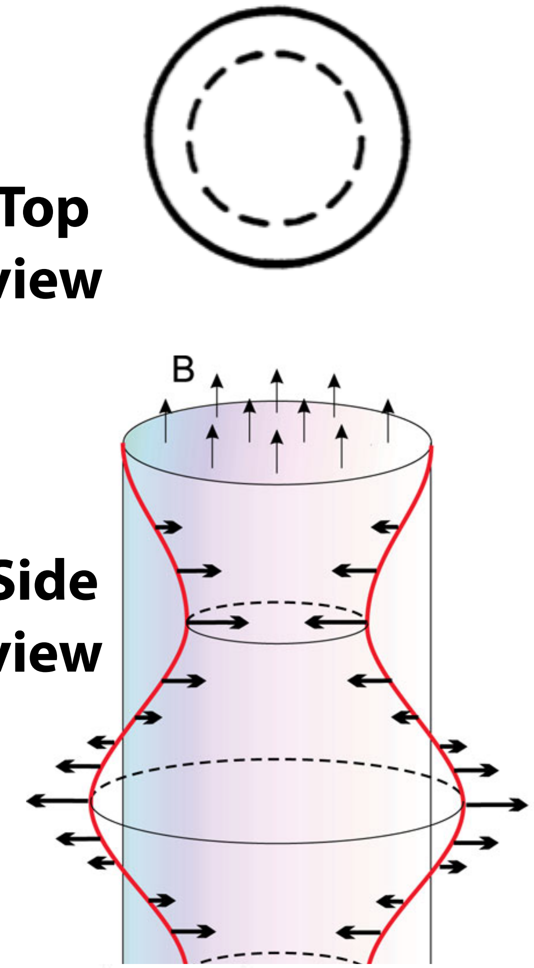


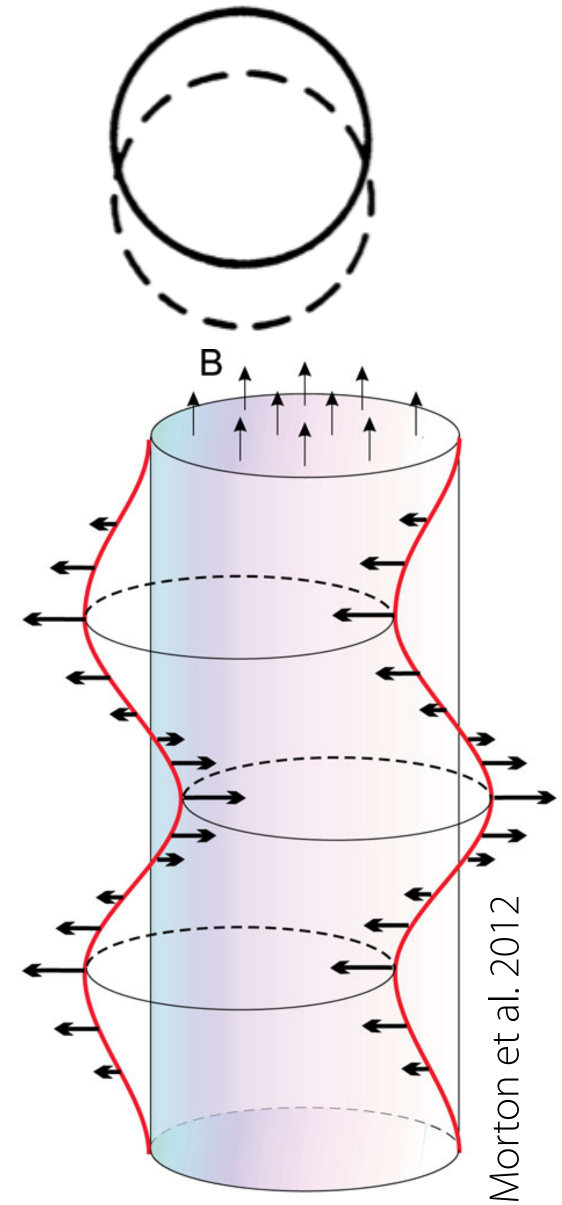
Nakariakov, V. M., Verwichte, E., 2005, Living Rev. Solar Phys., 2



Top view

Side view

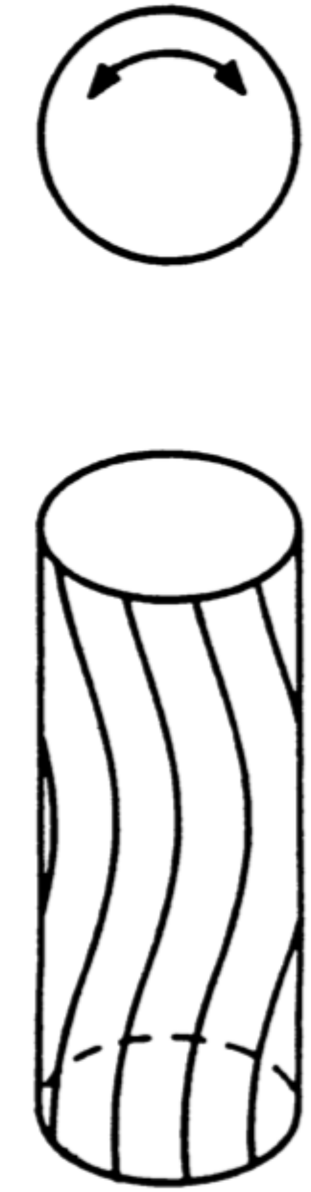




Morton et al. 2012

Transverse (Kink)

Periodic displacement of central tube axis (Bulk motion)



Torsional (Alfvén)

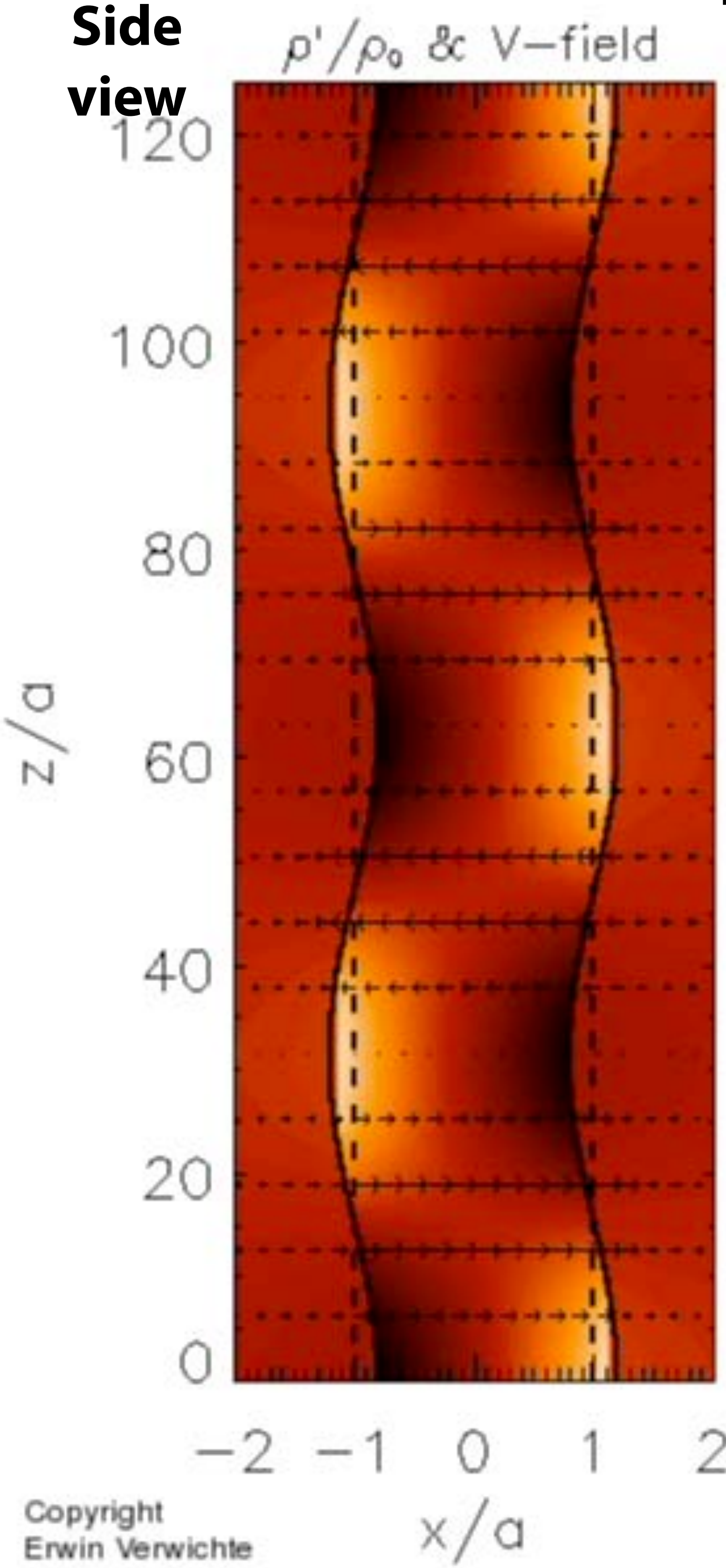
Periodic twisting of tube (Torsional oscillations)

Solanki, S. K., 1993, Space Science Reviews 63: 1-188

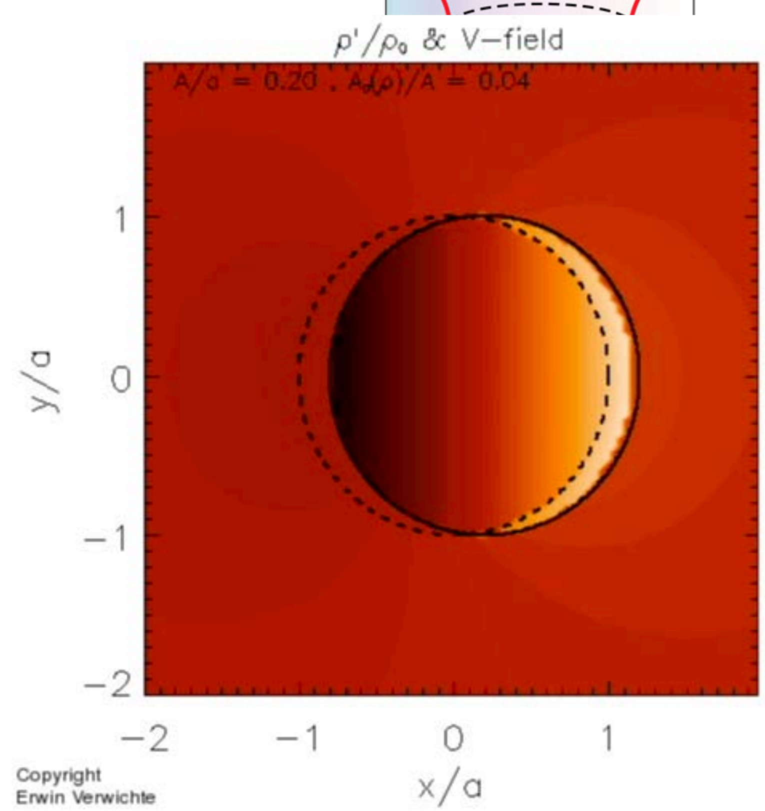
Waves in the solar atmosphere

MHD waves — Kink mode

Side view

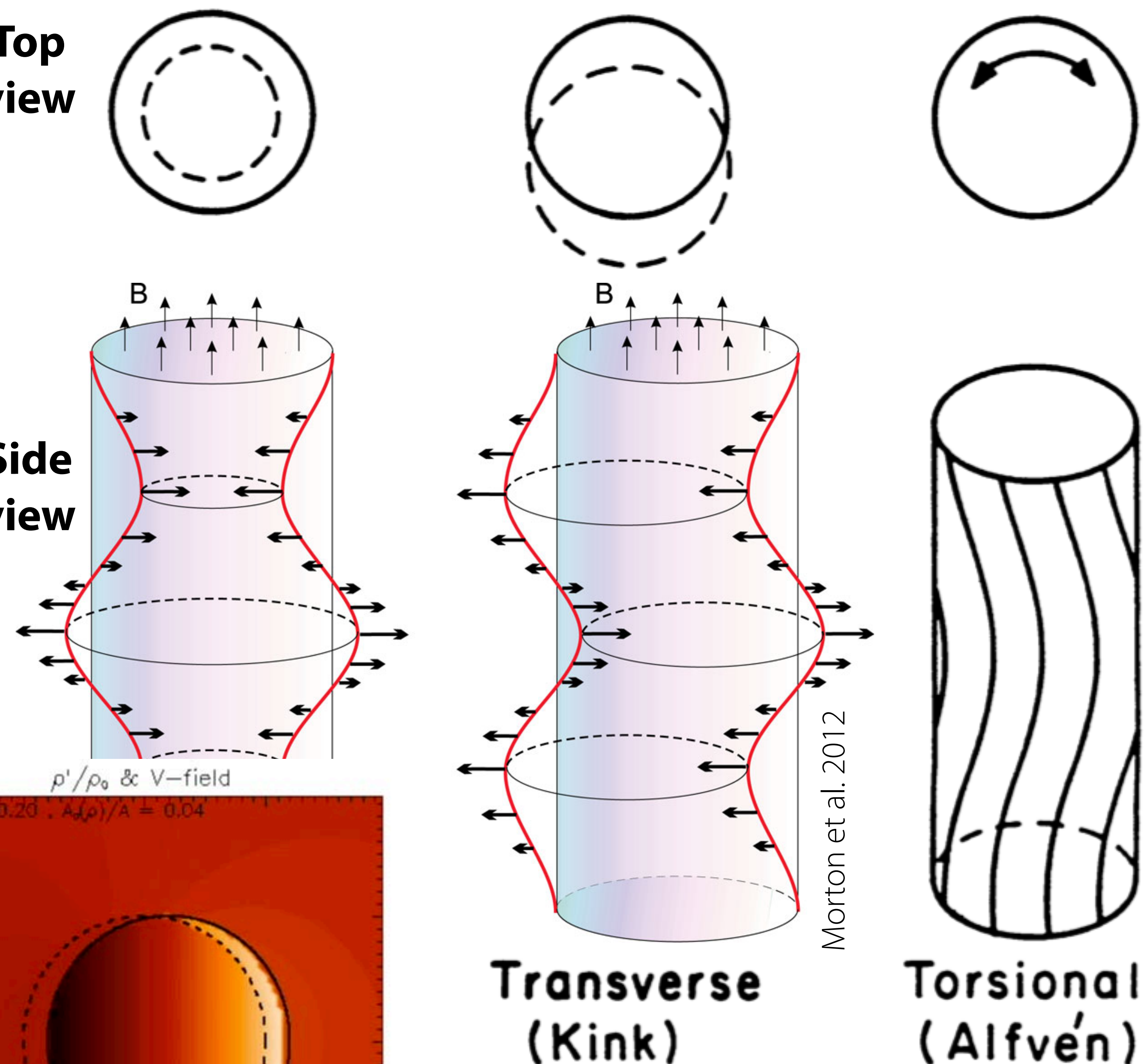


Nakariakov, V. M., Verwichte, E., 2005, Living Rev. Solar Phys., 2



Top view

Side view



Morton et al. 2012

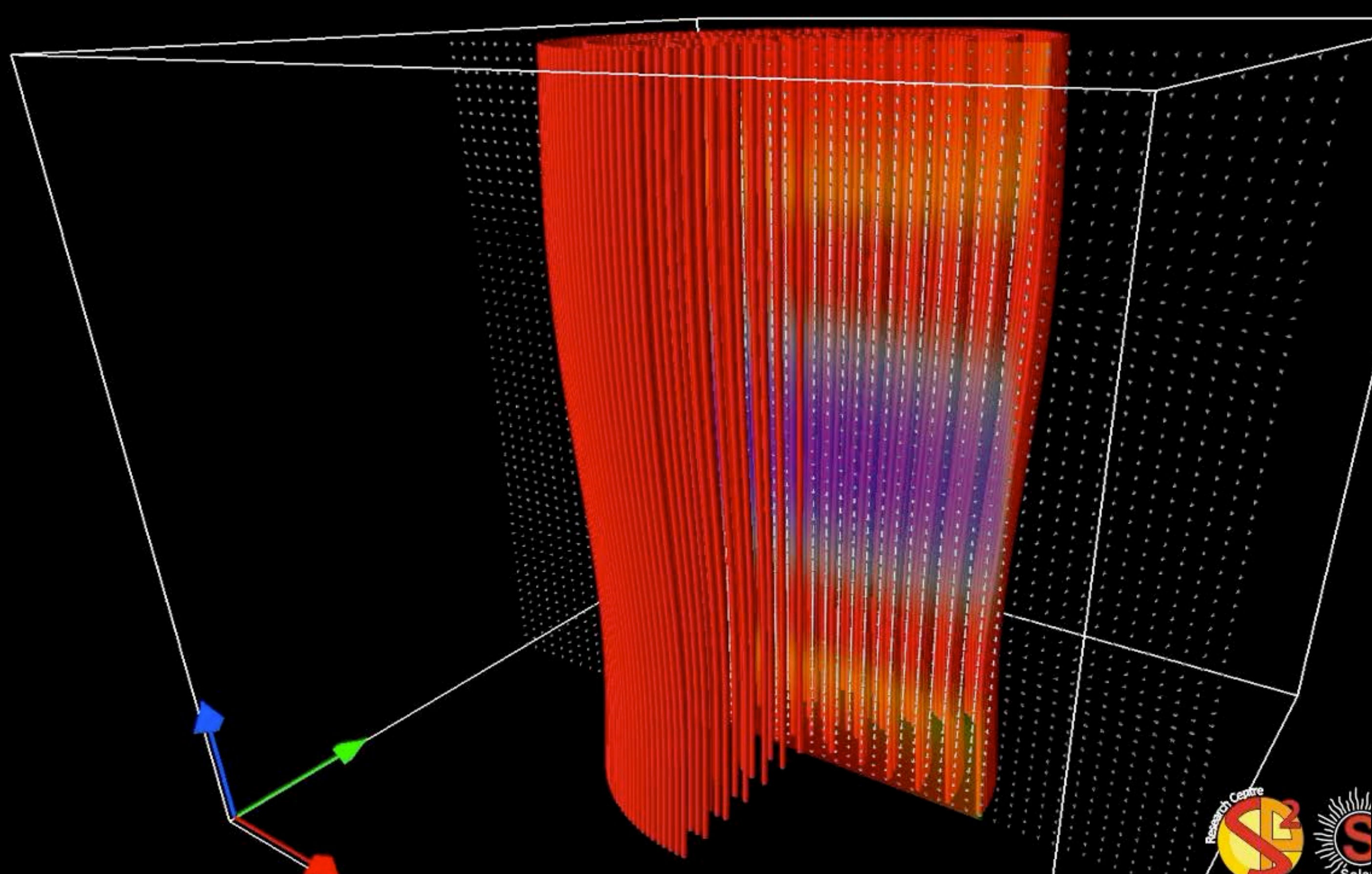
Periodic displacement of central tube axis (Bulk motion)

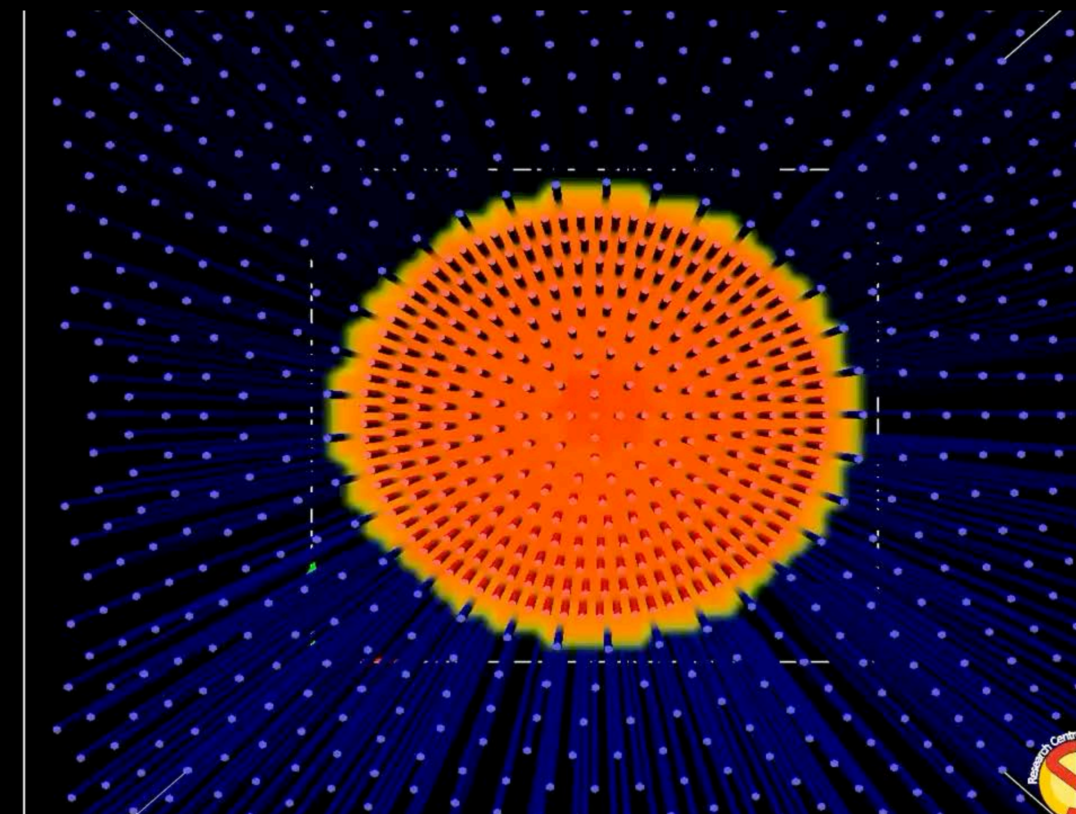
Periodic twisting of tube (Torsional oscillations)

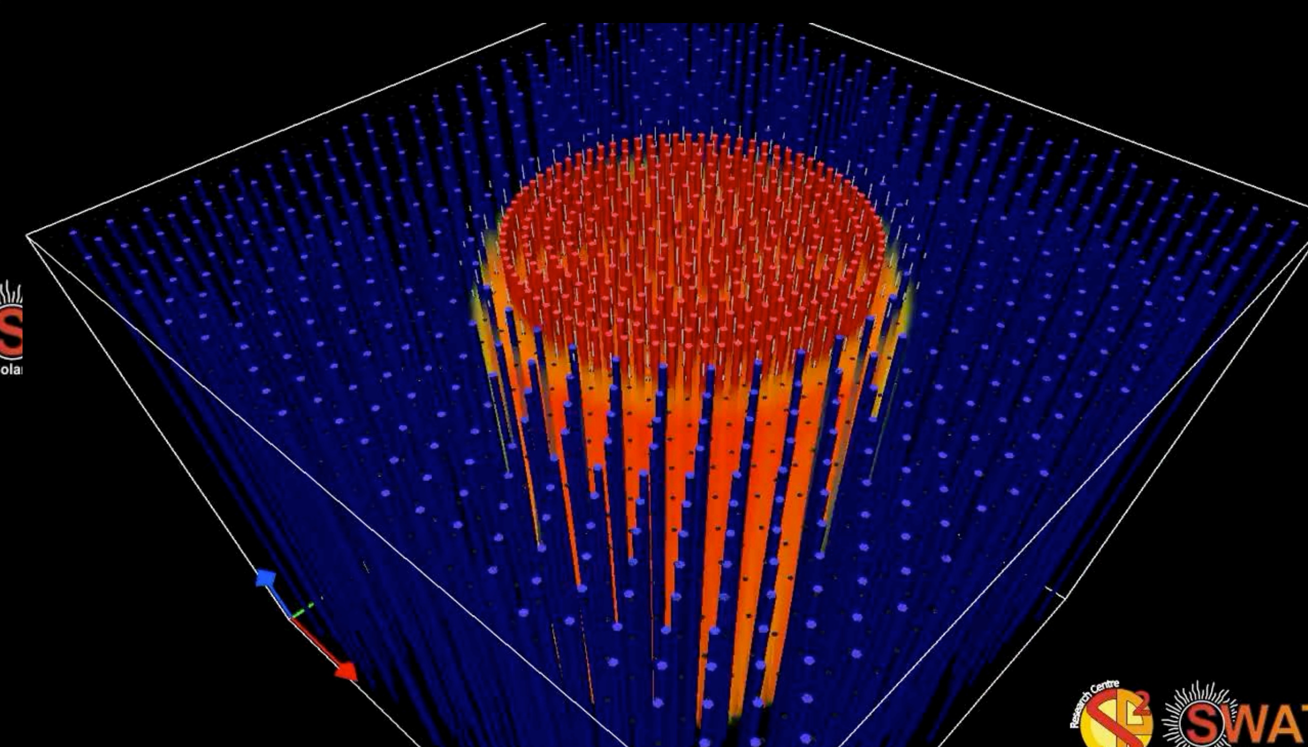
Solanki, S. K., 1993, Space Science Reviews 63: 1-188

Waves in the solar atmosphere

Sausage mode



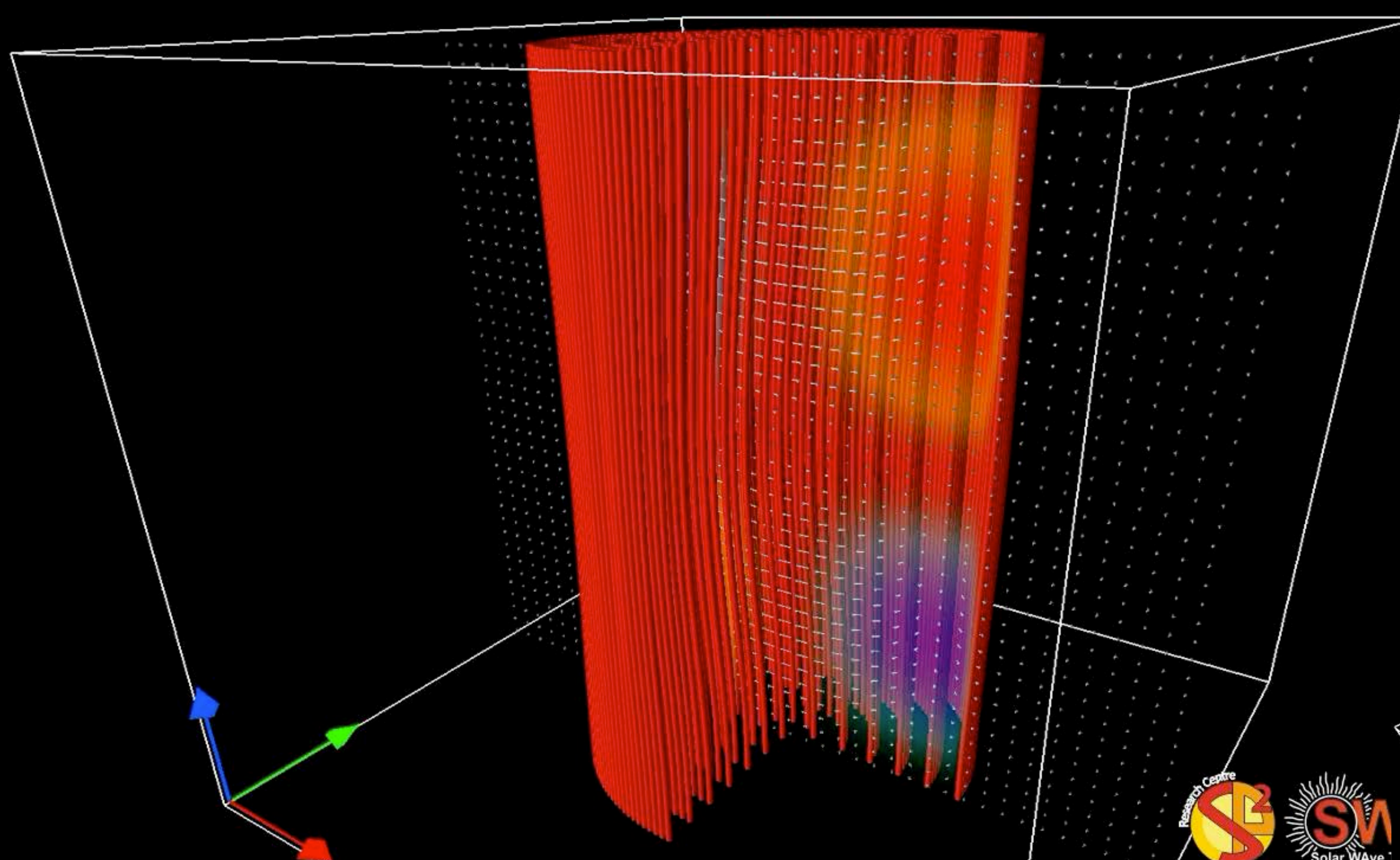


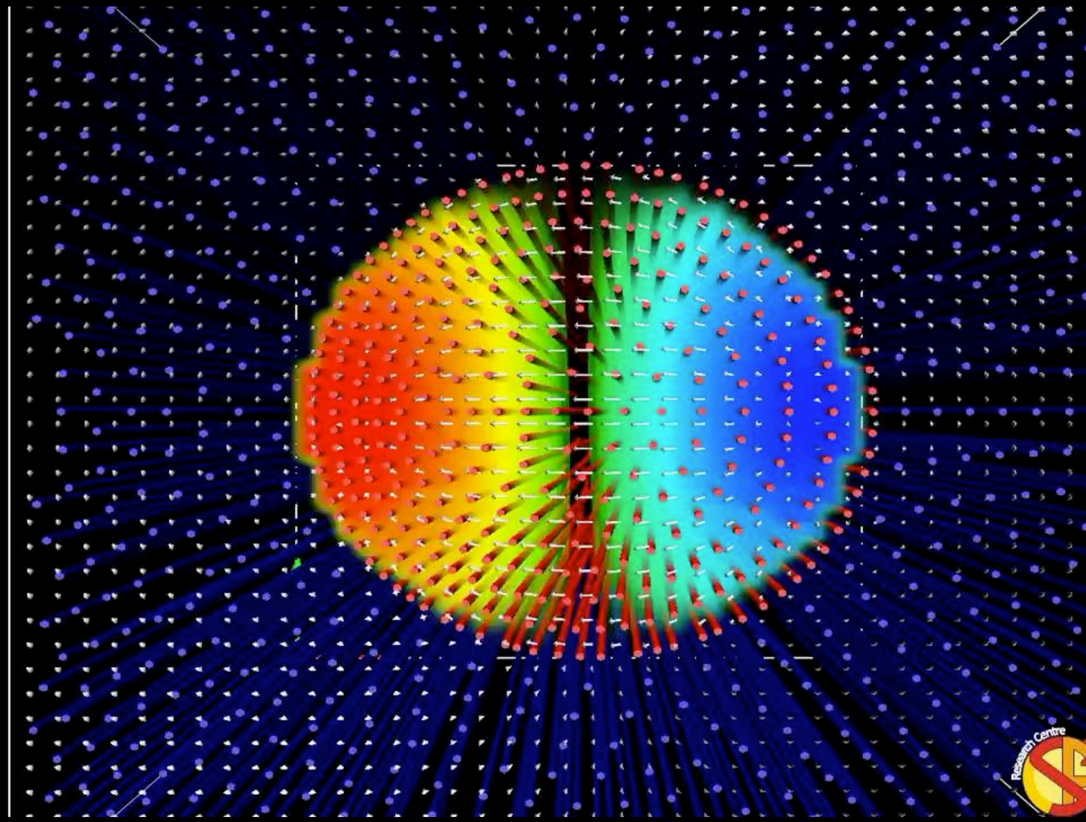


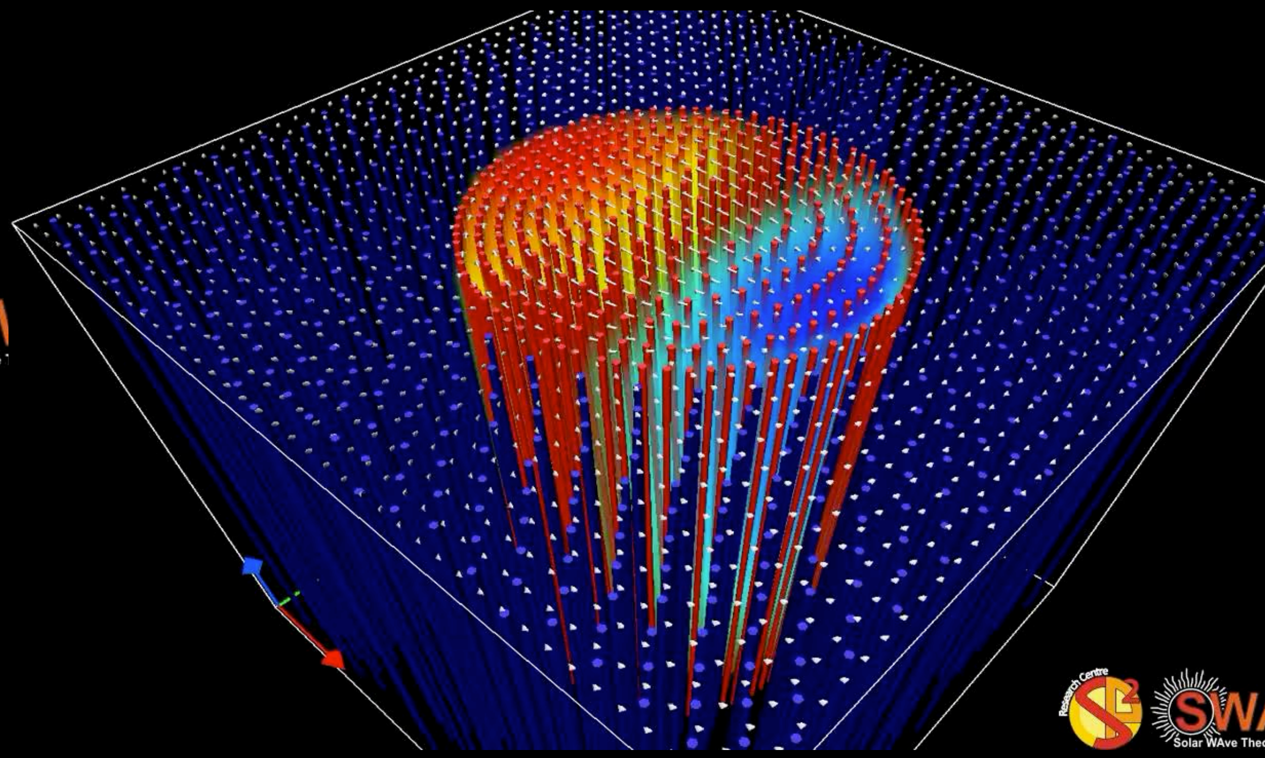
Courtesy of: The University of Sheffield — Edwin and Roberts (1983)

Waves in the solar atmosphere

Kink mode





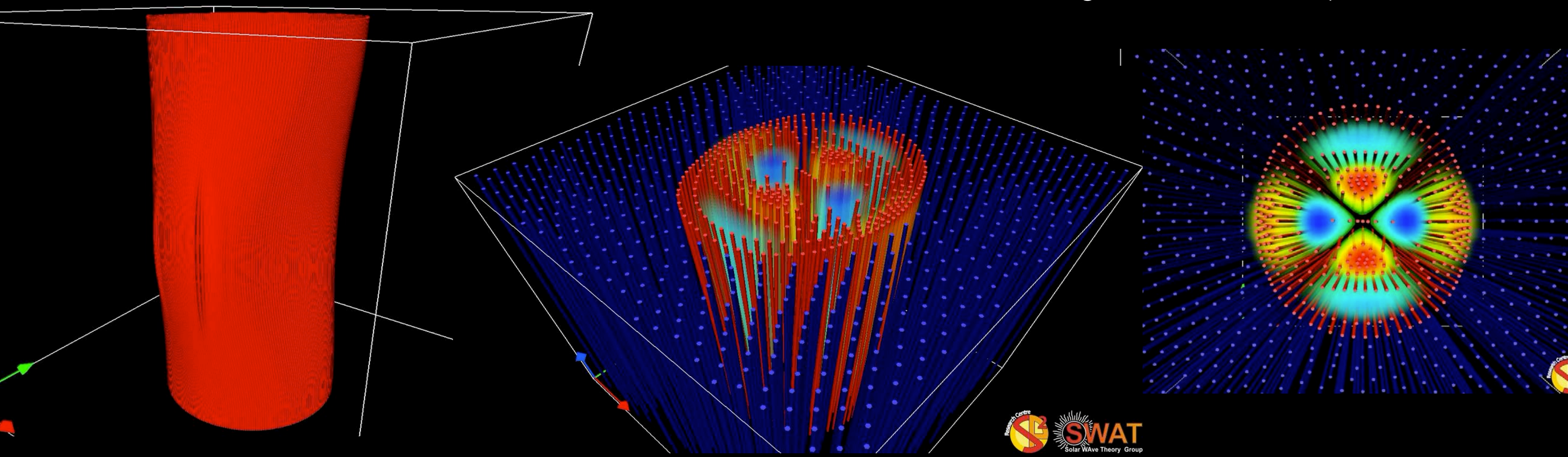


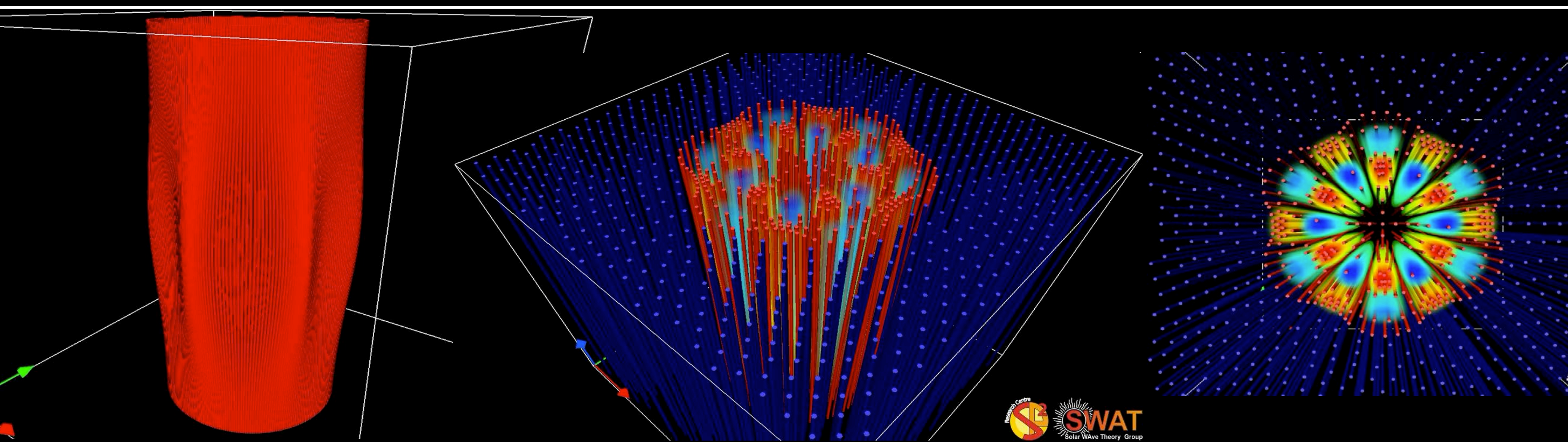
Courtesy of: The University of Sheffield — Edwin and Roberts (1983)

Waves in the solar atmosphere

Fluting modes

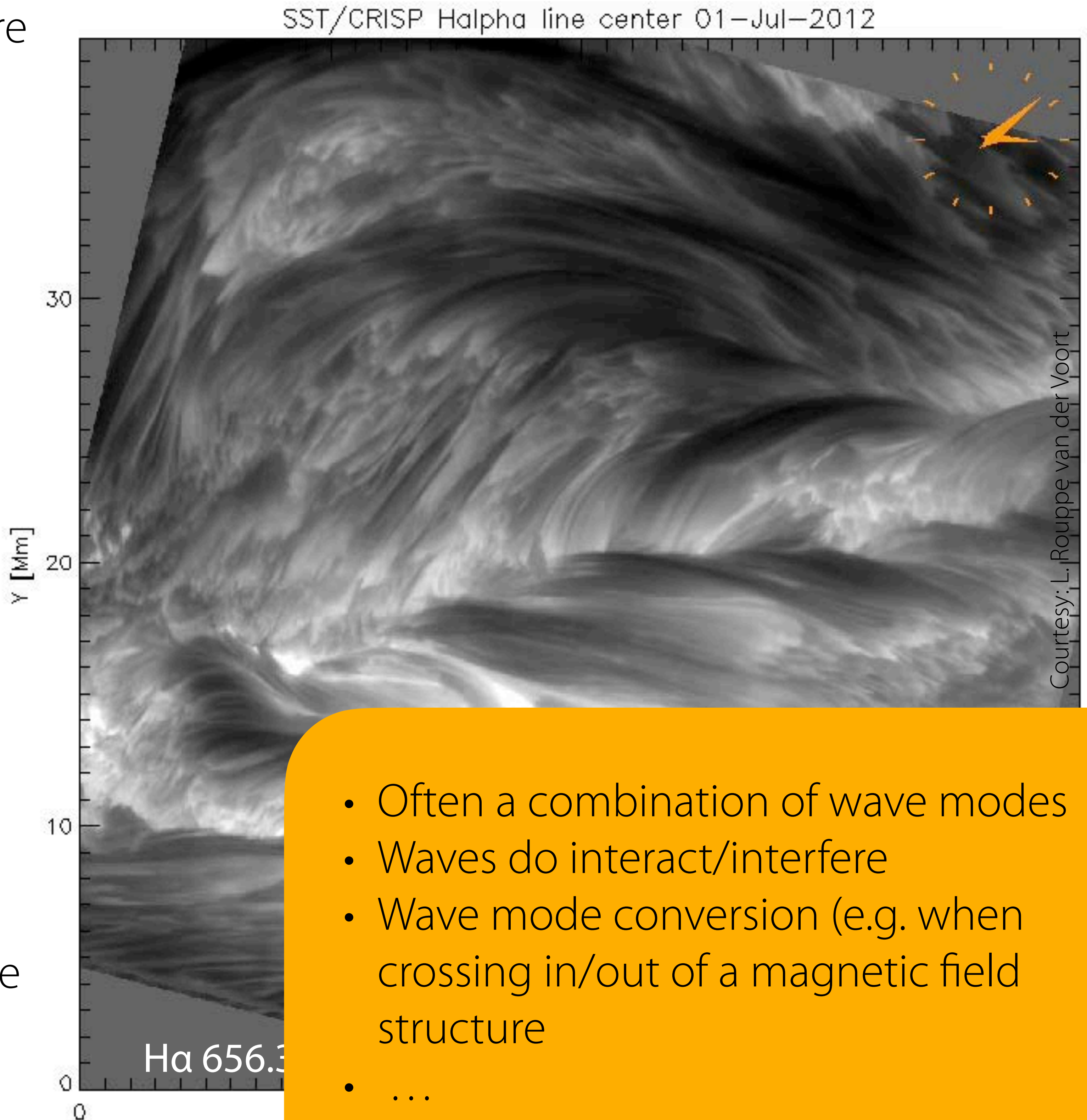
Periodic deformations of tube cross-section, deviating from circular shape





Waves in the solar atmosphere

- Oscillations and waves occur in many different places in the solar atmosphere
  - Sunspots
  - Pores
  - Large-scale magnetic structures (e.g. filaments, coronal loops)
  - Chromospheric fibrils
  - Small-scale magnetic elements
  - …
- Observable forms/affected properties
  - Intensity oscillations — Thermodynamic quantities
  - Velocity oscillations — Doppler Shifts
  - Magnetic oscillations — Magnetic field strength and inclinations
  - Note: Different wave modes leave different imprints, which in principle helps to identify different wave modes (not always easy!)



- Often a combination of wave modes
- Waves do interact/interfere
- Wave mode conversion (e.g. when crossing in/out of a magnetic field structure
- …