AST5770

Solar and stellar physics

Sven Wedemeyer, University of Oslo, 2023

Assignment #5

Discussion — Conclusion

Sometimes discussion & conclusions are combined in one section.
Not for you here! ;-)

Results	Discussion	Conclusion
• Detailed but yet focused **description** of the **new results** found in this study • Thorough analysis of the introduced data, using the introduced methods • Results presented with good figures (and tables if applicable)	• **Interpretation** of the new results (described in the previous section), setting them into **context** / comparing them to results in the literature (and possibly complementary data)	• The **essence** and take-away message • **Brief** summary of the most important results and conclusions!

Avoid details and repetitions!

- Be **thorough but still focused on the main results of your analysis**
- **Discussion based on the material you presented in the previous sections!**
- Possible questions to address:
  - Are this results expected in comparison of published results? Or do they contradict? If so, why? And what are the implications? How do your results change the field?
  - How could your results inform future observations/models?
  - What are the limitations of your study (due to data accuracy, methods, assumptions)? And how could they impact your results?

Assignment #5

Discussion — Conclusion

- **Discussing and drawing conclusions**
  - Use logic! Think of a court case:
    ➡ How do you present and defend your results?
    ➡ You need robust evidence for any statement you make (e.g., in form of a supporting reference) or a solid result of your analysis
    ➡ No handwaving or vague statements!

- **Conclusion section:**
  - NOT a detailed summary but only a very **brief** presentation of the **essence**
  - Only repeat the main aspects of your main results but not in all detail.
  - Avoid too many details and focus on the main message(s)!

- **Note:** You may find this difficult to write as it requires some knowledge of the literature and experience. That's why it is important to practise! ;-)

Assignment #5

Abstract

- **Purpose**
  - The abstract is a brief summary of the paper (usually one paragraph).
  - Contains the essence !
- **Length**
  - Usually: ~ 5% of total length of the whole paper but max. 200 words
  - Some journals may have specific limits.
- **Format**
  - The abstract stands for itself.

    ➡ No figures, no tables, no footnotes, no references to other places in the paper!

    ➡ Avoid if possible references to other papers (some journals do not allow them at all). Exception: if paper mainly checks results of another paper
  - Keep abbreviations, equations and symbols to a minimum
  - As always: Write concise and clear sentences. (Split too long sentences!)
  - Some journals (e.g., Astronomy & Astrophysics) offer structured abstracts (with headings like context, aim, method, …)

Assignment #5

Abstract

- **Structure**
  - Follows the structure of the paper and summarises the most important parts at each step.
  - Typical structure:
    - **Context** (wider scientific topic/question), typically 1-2 sentences, sometimes dropped.
    - **Aim:** What is the intention of your paper? What scientific question do you address? What does this paper try to prove/disprove?
    - **Method:** x A brief summary of the most important data and methods used in this study. What observatories/instruments? Which spectral line? But not too many details, essence only!
    - **Results:** What are the most important results of your analysis? Brief summary!
    - **Conclusion:** What do you conclude? The major message of the paper! Can also point out limitations, need for further studies. May contain an outlook if meaningful.

- **For assignment #5:** First draft of abstract in form of bullet points is sufficient (but write full sentences if you like and want to receive early feedback.)

Assignment #5

Consistency check

- **Once written** — check that discussion, conclusion and abstract are consistent
  - Is there any important information in the conclusion that is missing in the abstract?
  - Any information given in the conclusion and abstract must stem/connect to other parts in the paper. (You must not add new/additional information only in the abstract!)
  - Have you mentioned the main results and conclusions in the abstract?

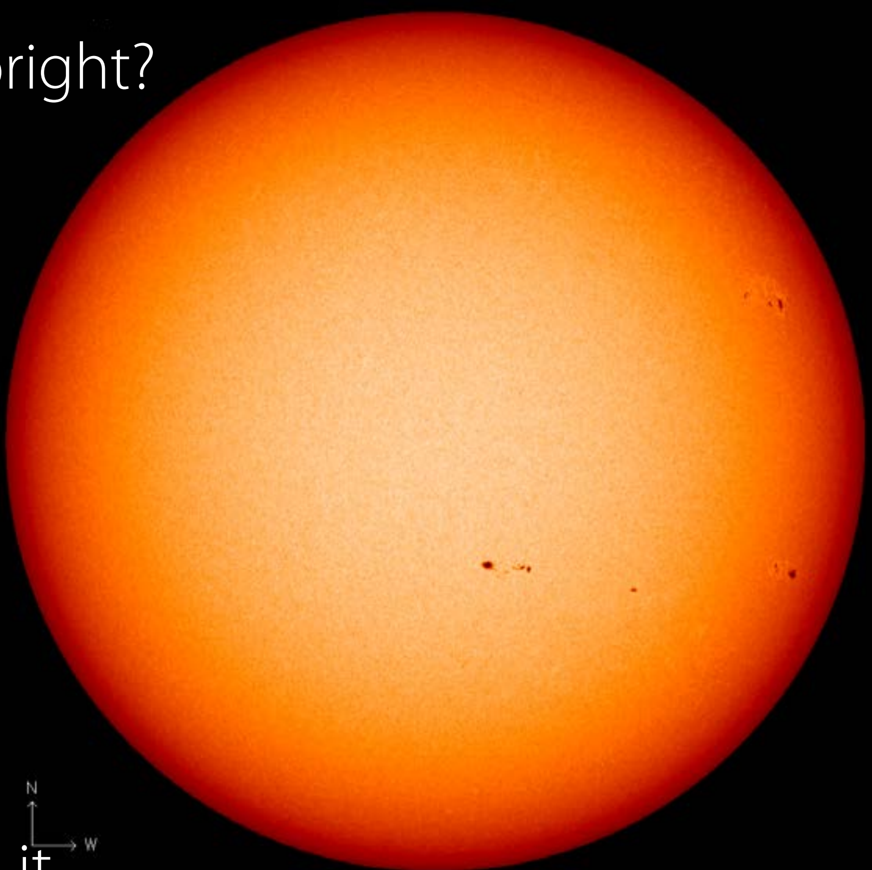
- **For the final assignment:** Apply such a consistency check to the whole paper.

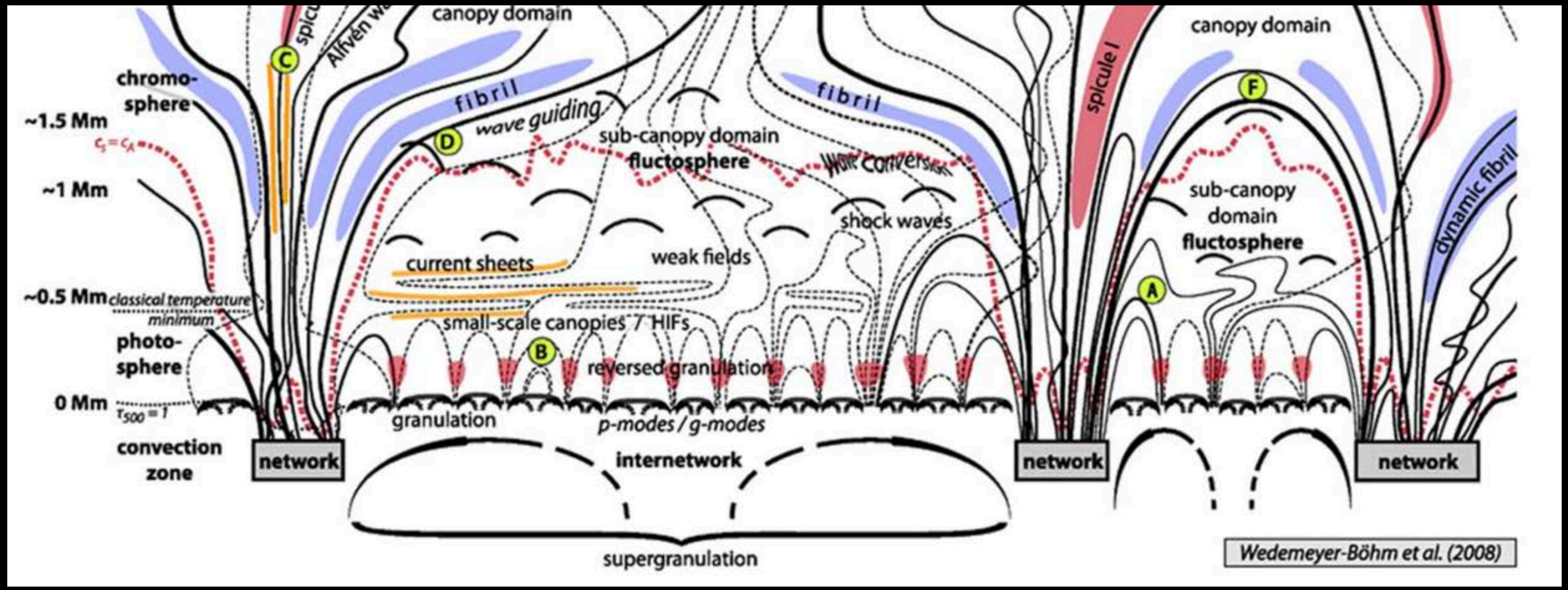
The Quiet Sun atmosphere

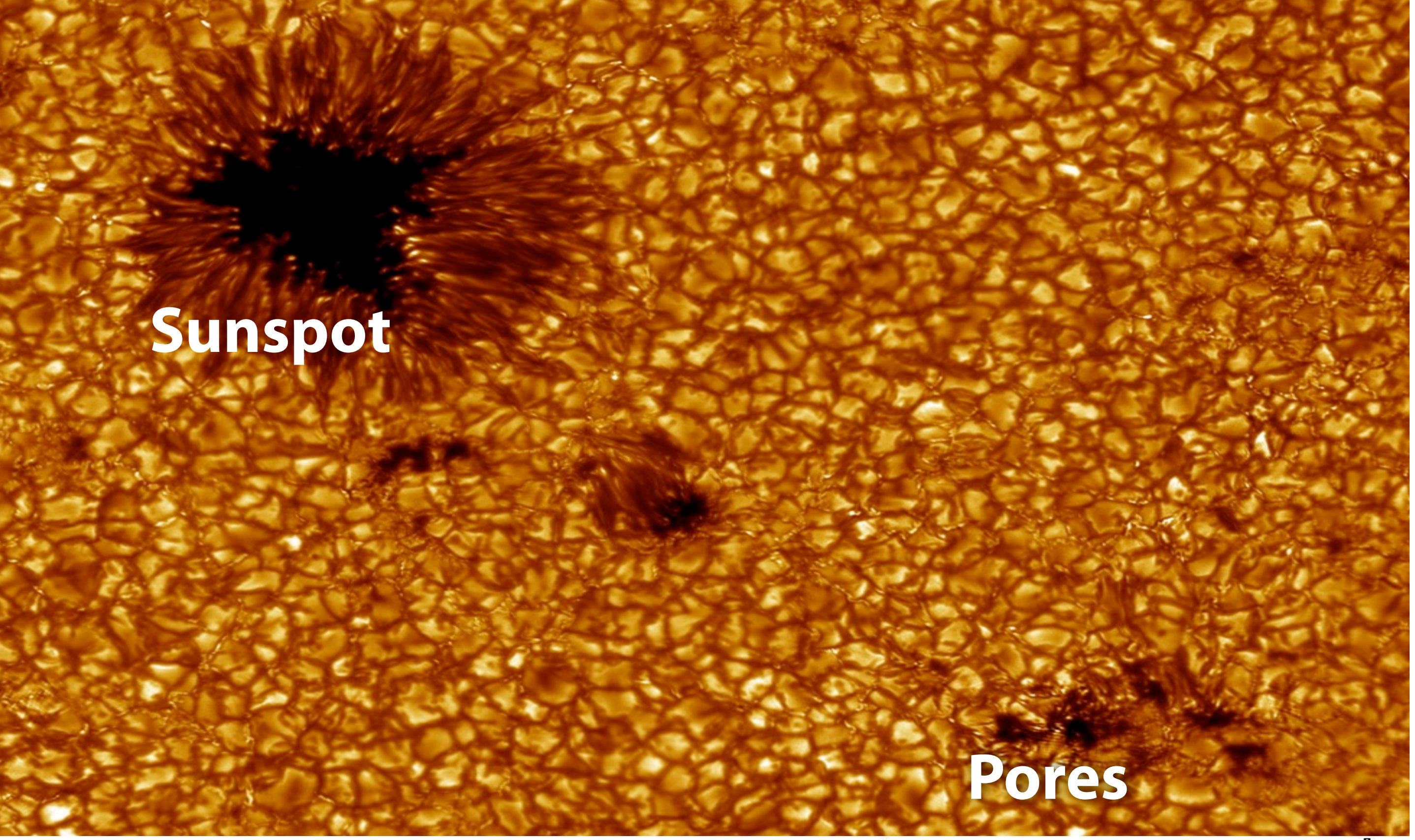
The Quiet Sun atmosphere

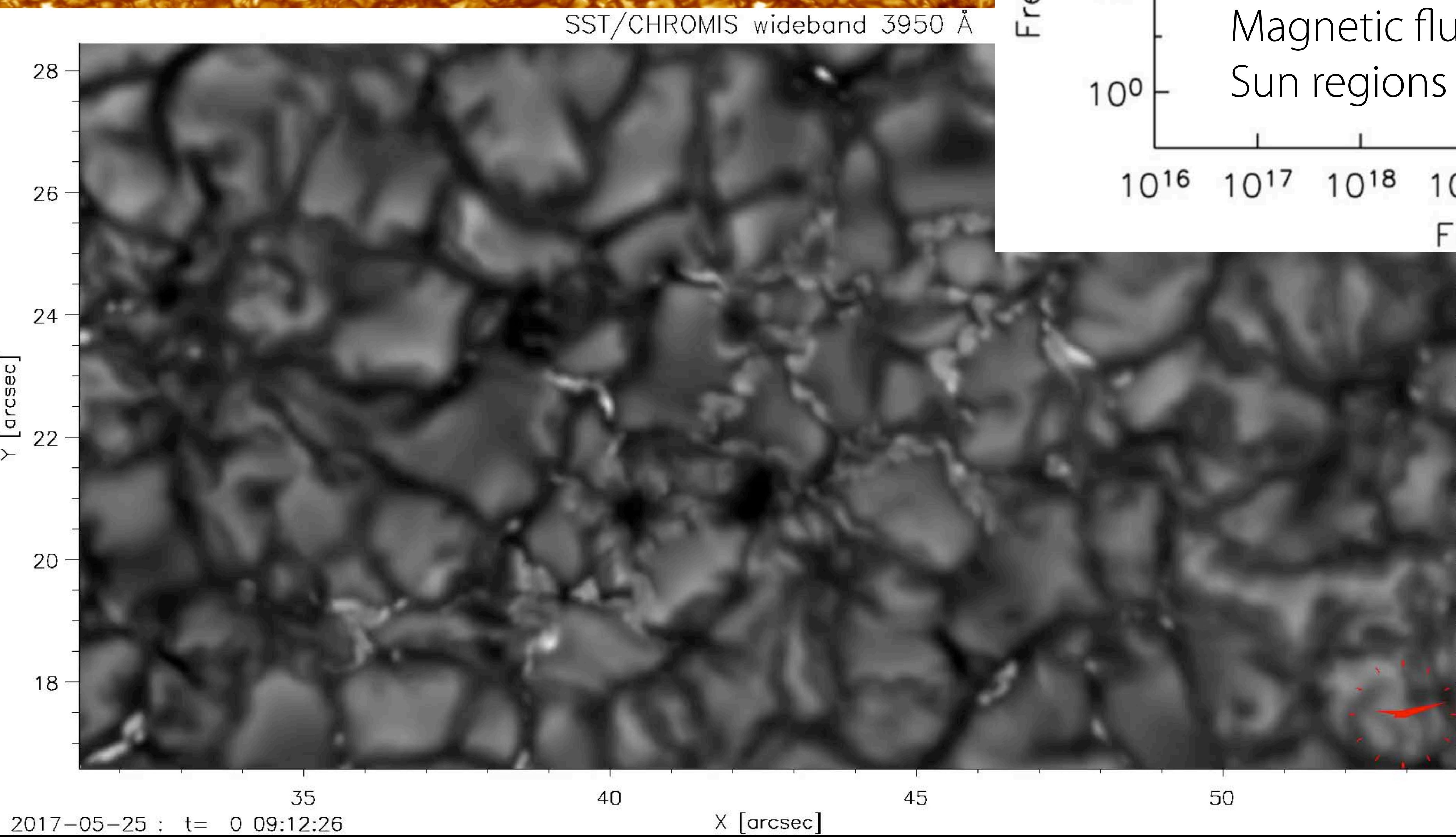
Recap

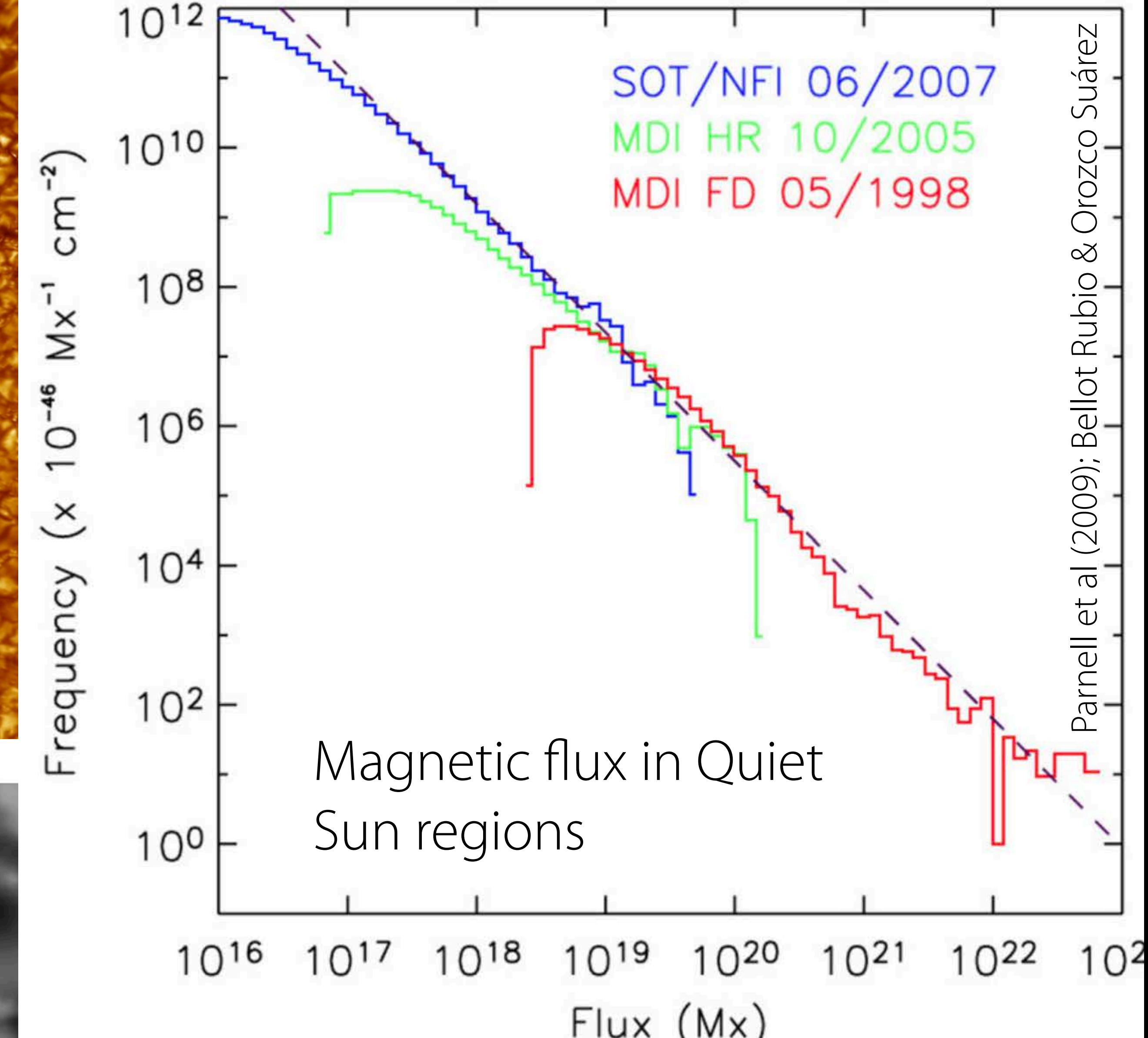
1. Why do sunspots appear dark and small magnetic elements bright? Hot wall effect?
2. Why do we see a centre-to-limb variation?
3. Why do see limb darkening for some continua but limb brightening for others?
4. What can we learn from observing at different wavelengths across a spectral line, from continuum to line core?
5. How is the magnetic network produced?
6. Is there any magnetic field in internetwork regions and how is it distributed?
7. Can you name some dynamic phenomena that occur in the Quiet Sun?











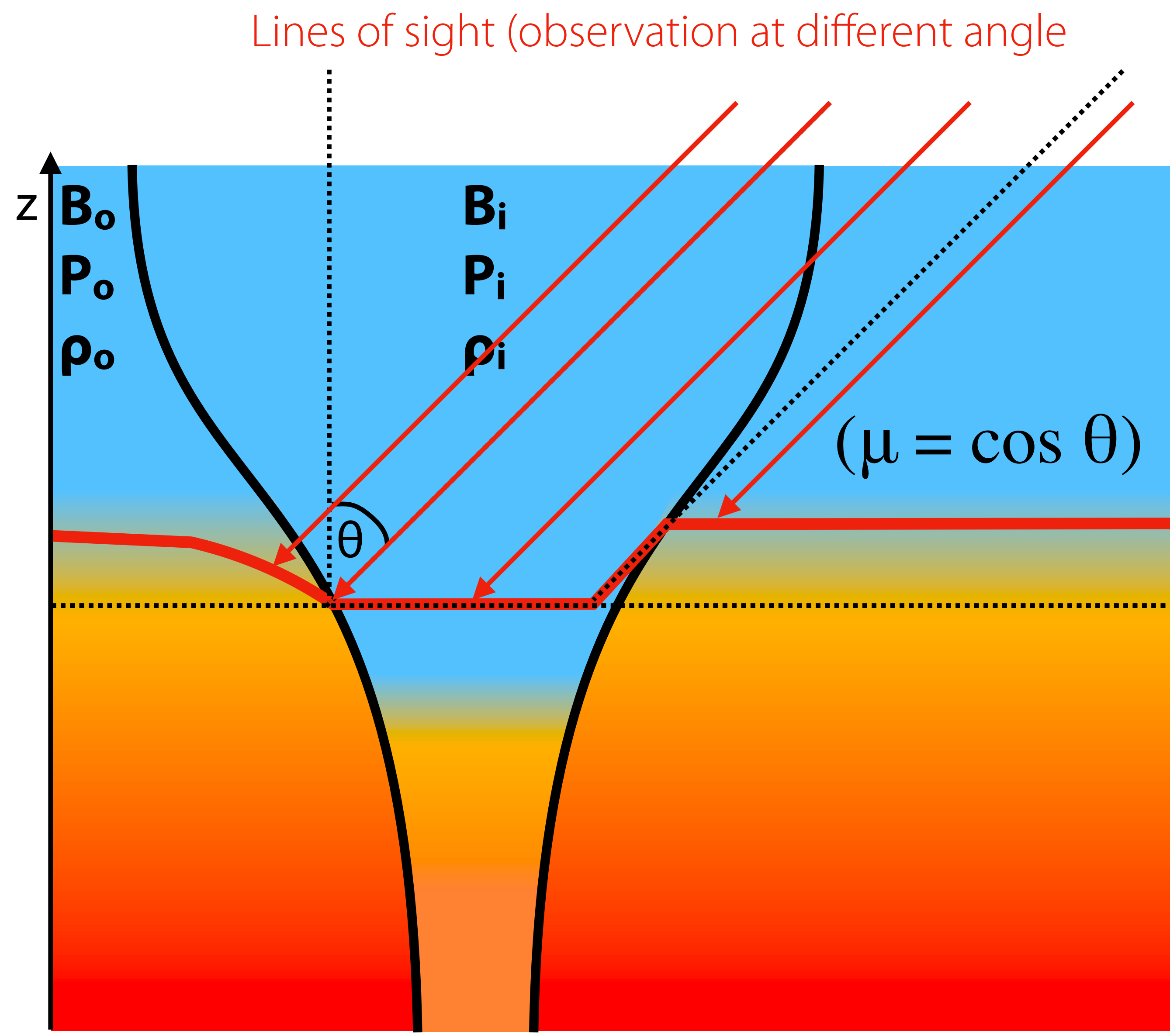
"Quiet Sun"

- 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:

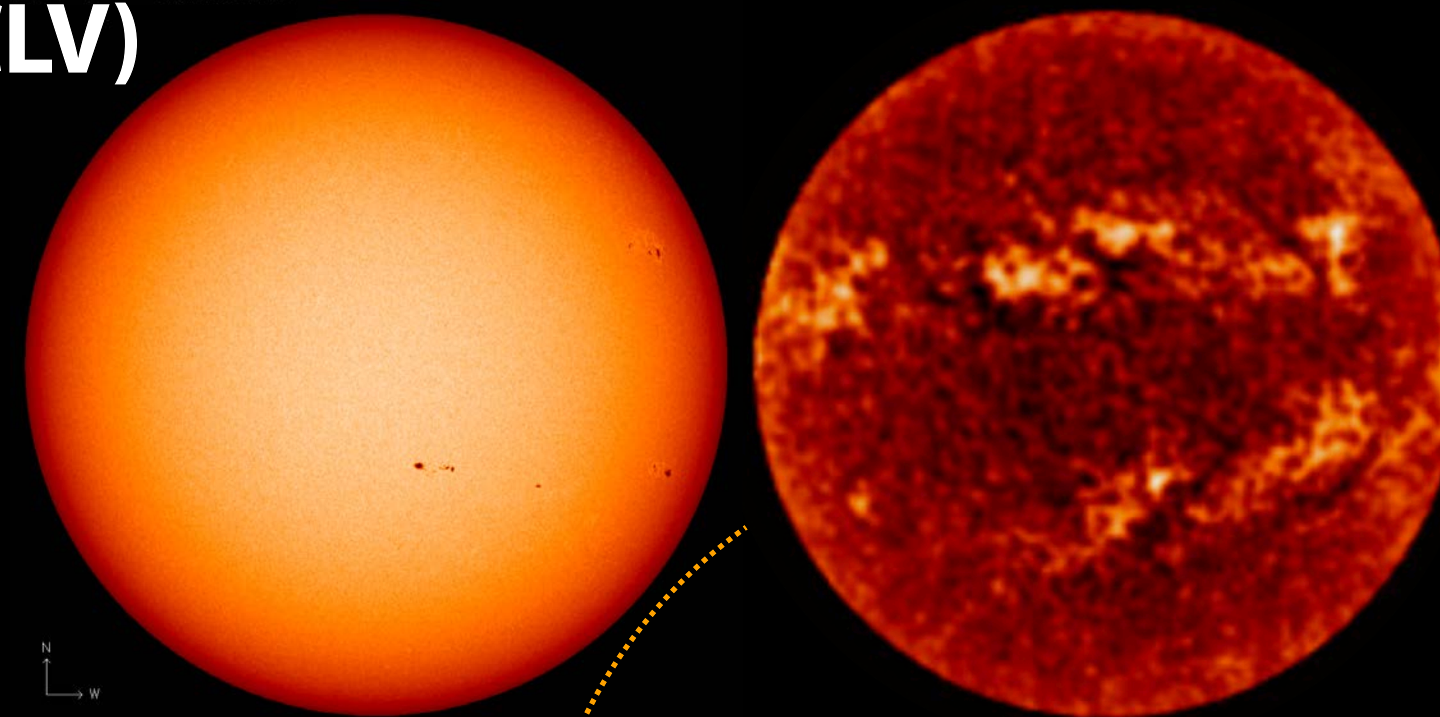


- **Hot wall effect**
  (when looking at significant angle)
  - Magnetic feature appears to be brighter on one side!
  - Seen in faculae towards the limb!

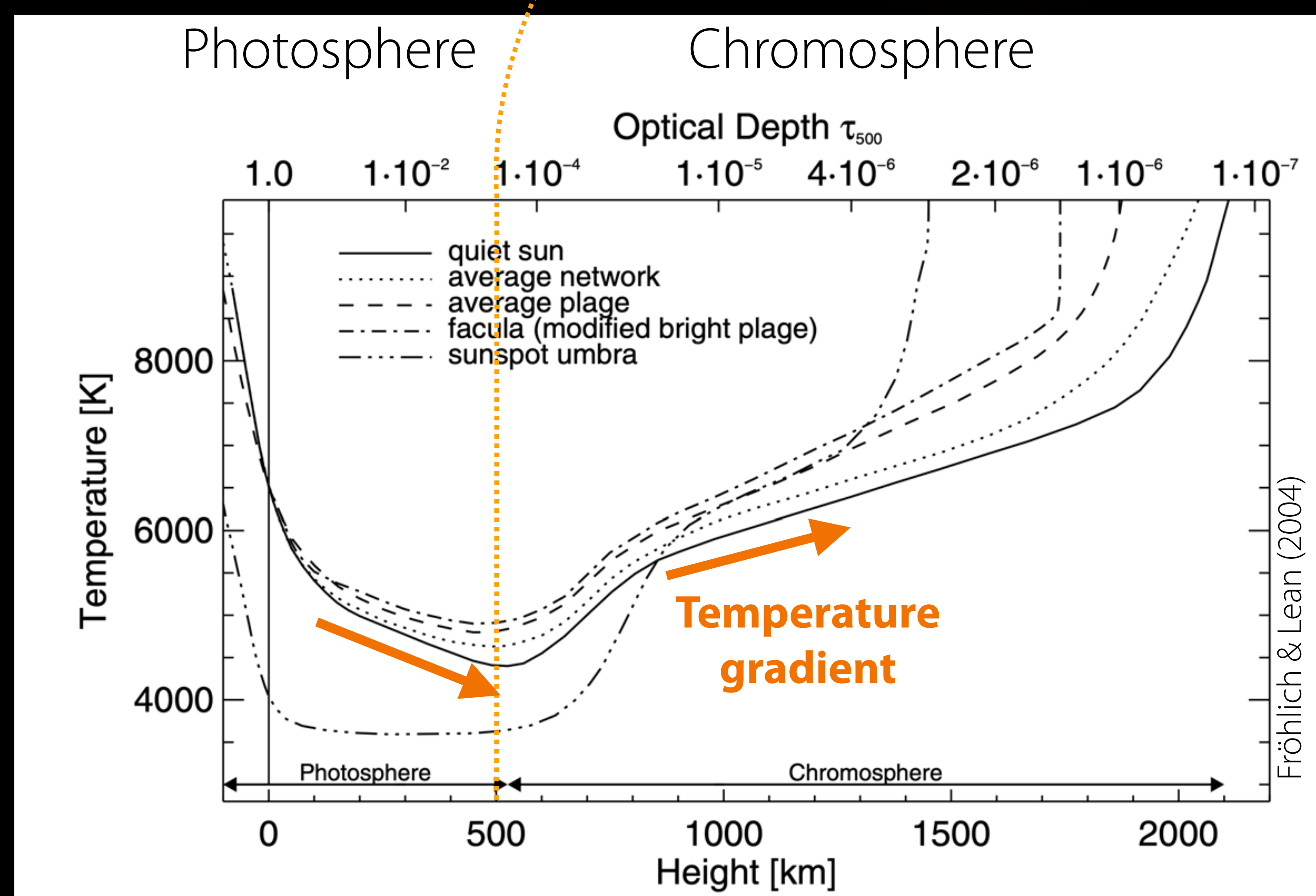
- **Magnetic bright points**
  - (Close to) vertical view: look deeper into the atmosphere inside magnetic flux structure
  - Note: Seen for small/weak magnetic field structures where convective heat transport from below is not hampered
    - For sunspots: Wilson depression and lower temperature (sunspots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

Density

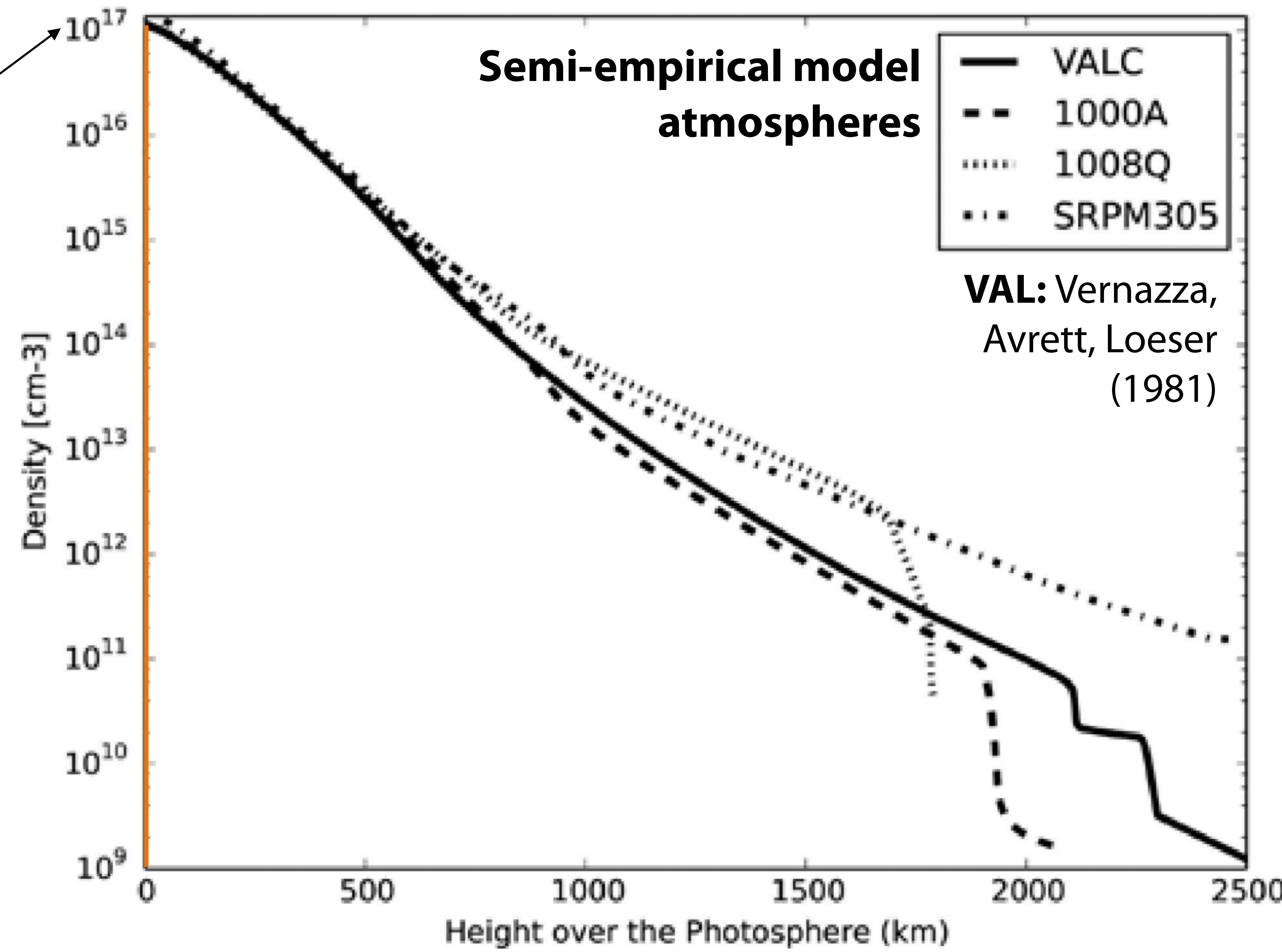
- At **bottom of photosphere** (z=0km): particle density $n \approx 1.5\ 10^{17}\ cm^{-3}$
- Assume gas consists only of hydrogen

➡ Mass density $\rho = n\ m_H \approx 2.3\ 10^{-7}\ g\ cm^{-3}$

➡ Opacity at 500 nm $\kappa \approx 0.3\ cm^2\ g^{-1}$

➡ **Mean free path** of photons $l = (\kappa\ \rho)^{-1} \approx (7\ 10^{-8}\ cm^{-1})^{-1}$

➡ $\mathbf{l \approx 140\ km}$



- Assumption of **local thermodynamic equilibrium (LTE)** valid as long as conditions (e.g. change in temperature) do not change significantly over this distance!

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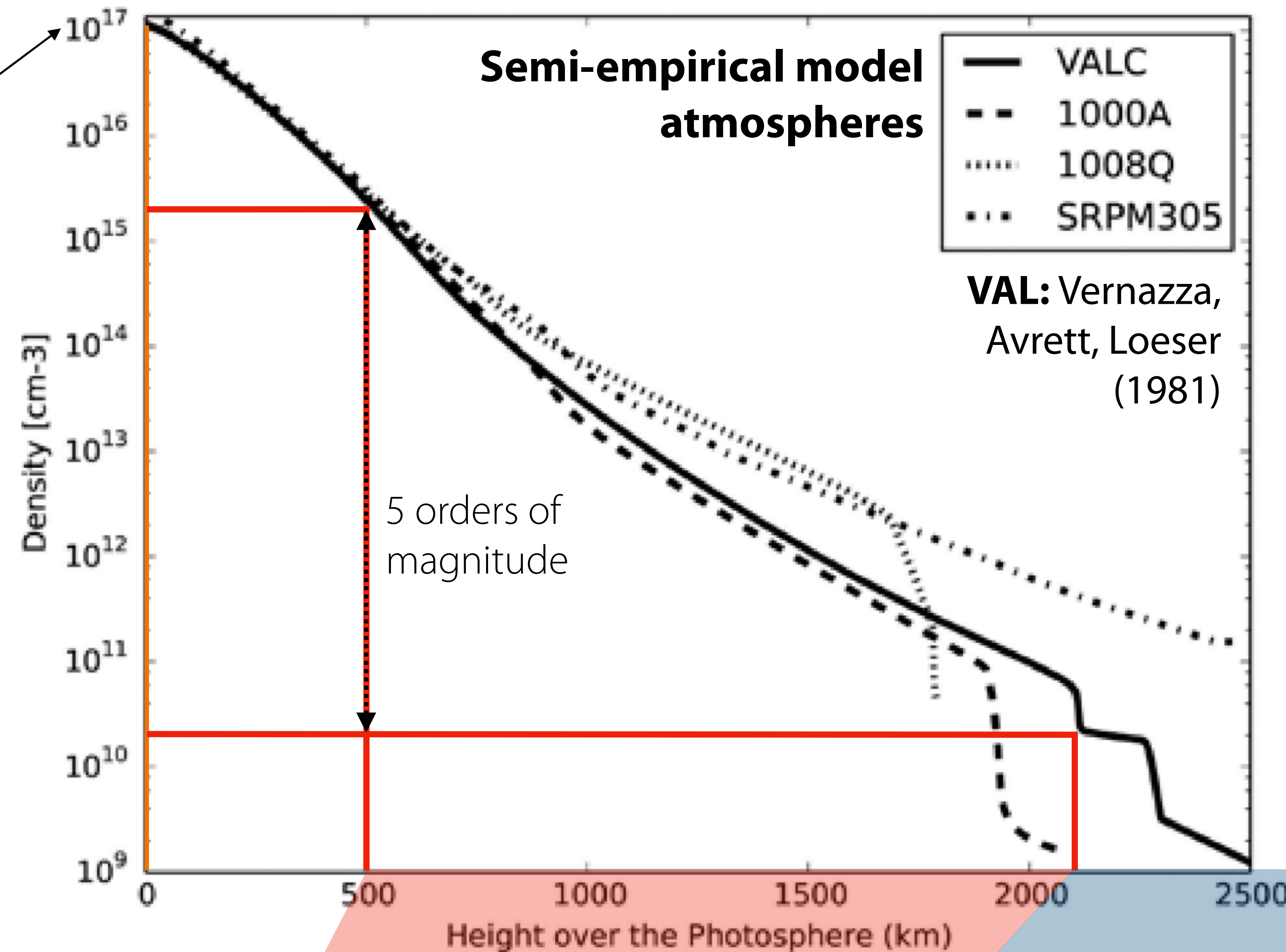

	Chromosphere		Corona
	Bottom	Top	Bottom
n_H $[cm^{-3}]$	$2\ 10^{15}$	$2\ 10^{10}$	$\gtrsim 10^{10}$
ρ $[g\ cm^{-3}]$	$3\ 10^{-9}$	$3\ 10^{-14}$	$\gtrsim 10^{-14}$

- Assumption of **local thermodynamic equilibrium (LTE)** valid at lower density in the layers above?
- What is the opacity there?

The solar atmosphere

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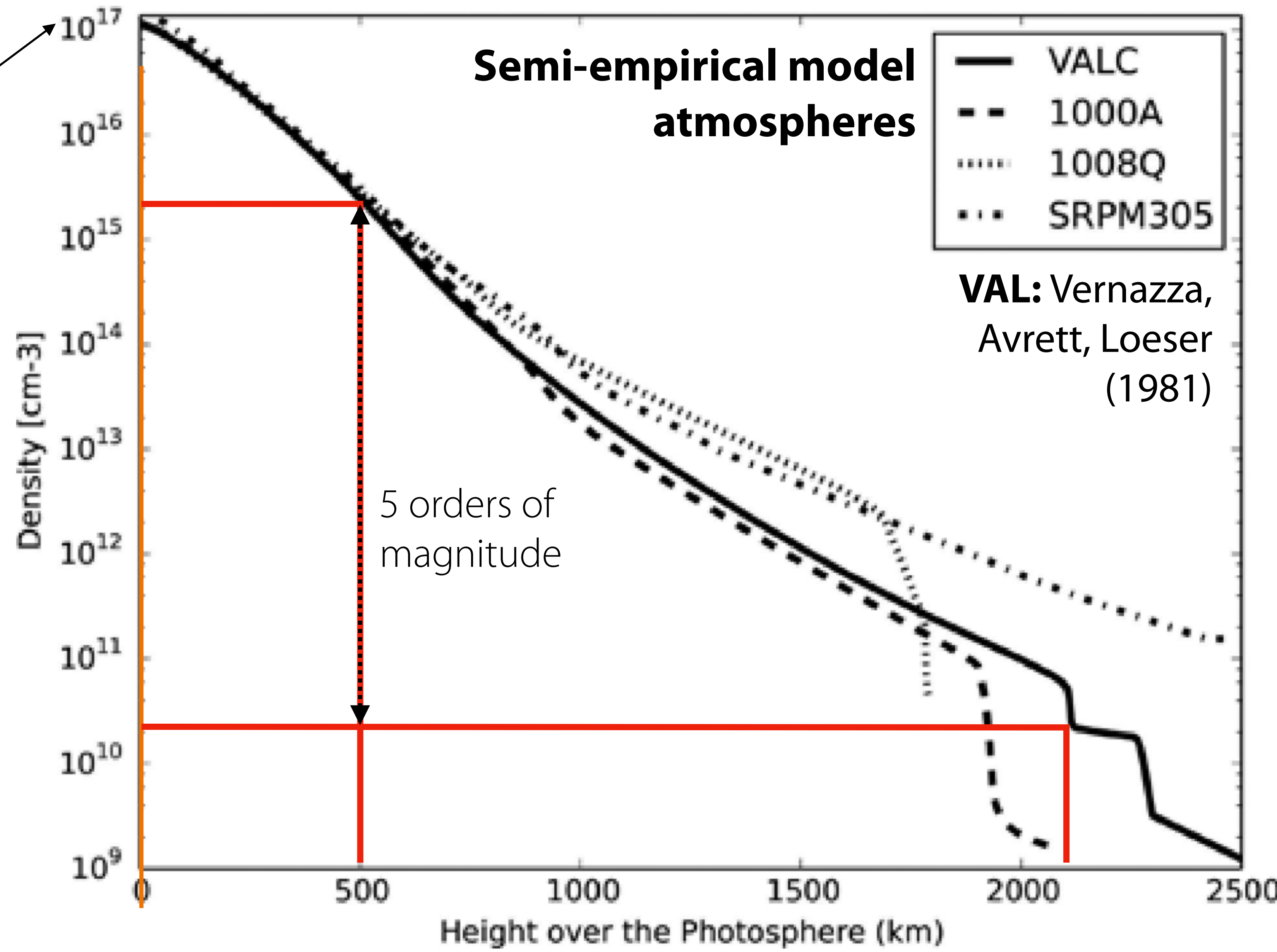


- Assumption of **local thermo-dynamic equilibrium (LTE)** valid at lower density in the layers above?
- What is the opacity there?

- For comparison: mass density on Earth at sea level $\rho \approx 1.2\ 10^{-3}\ g\ cm^{-3}$ (5000 times denser!)
- If opacity were the same:

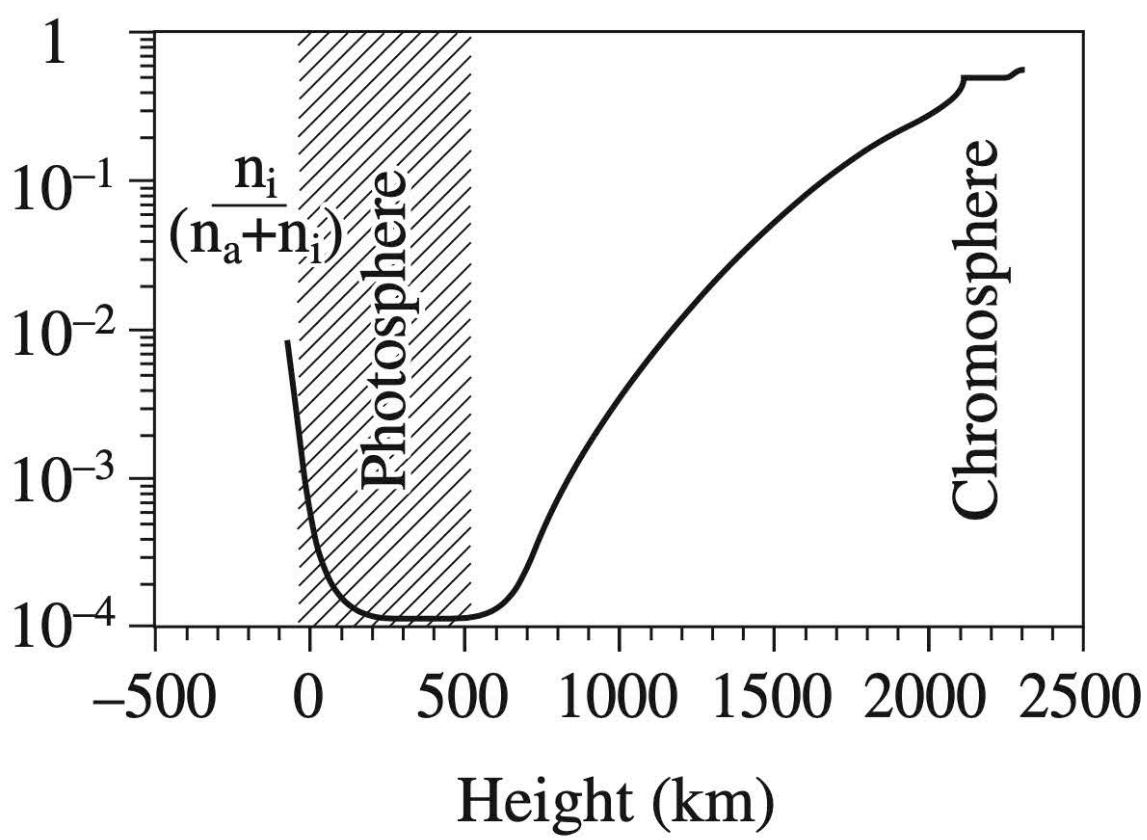
➡ Mean free path = 31 m !?!

How can that be?

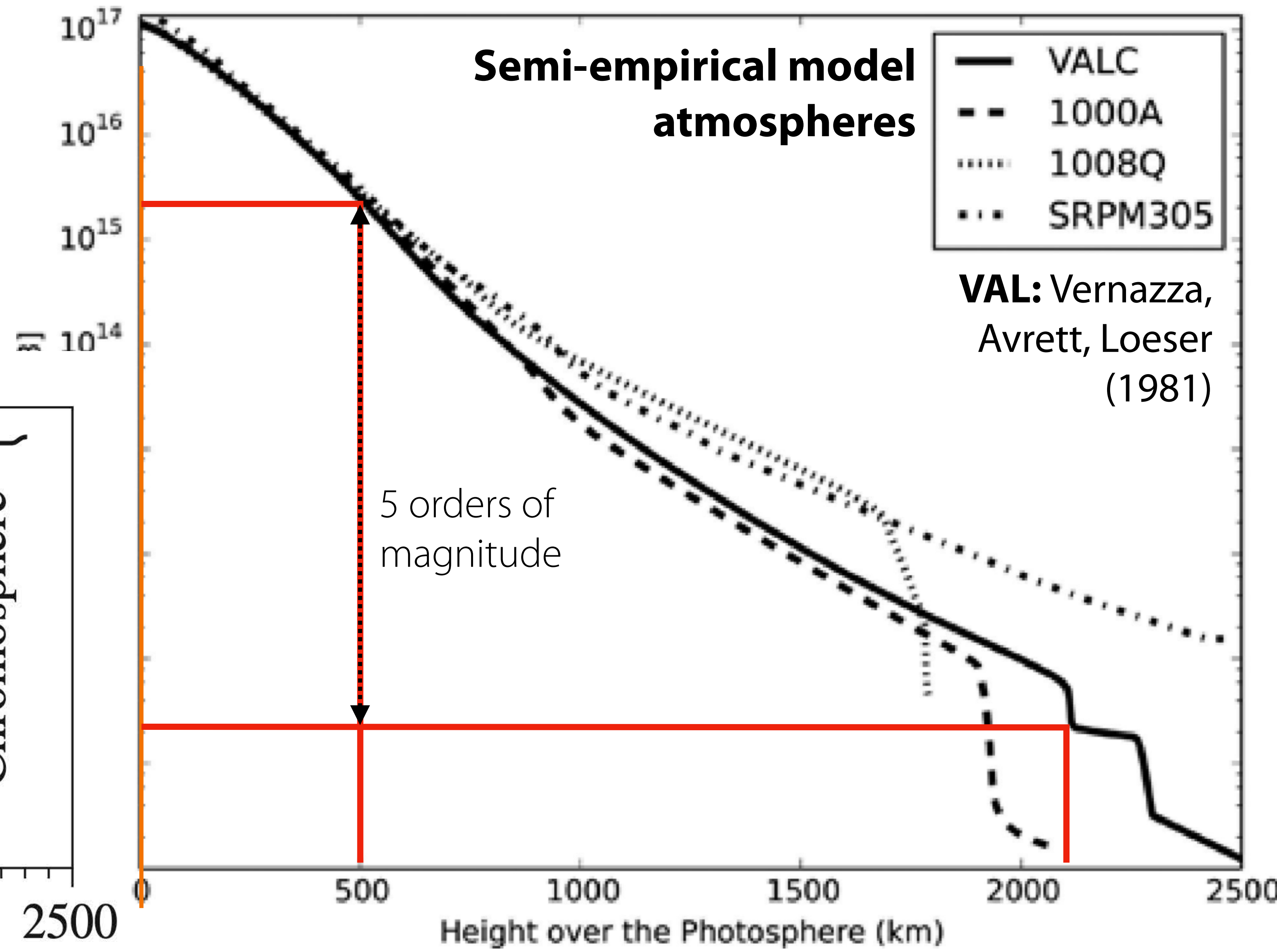
The solar atmosphere

Ionisation degree

- Change in temperature leads changes in (hydrogen) ionisation degree and thus the number of free electrons!



Khomenko; Priest 2014



- Fully ionised in solar interior
- Ionisation degree drops to 10^{-4} in photosphere
- Increases to high values in the chromosphere

Note: So far only a static atmosphere considered
➡Ionisation degree will be impacted by dynamics in chromosphere!

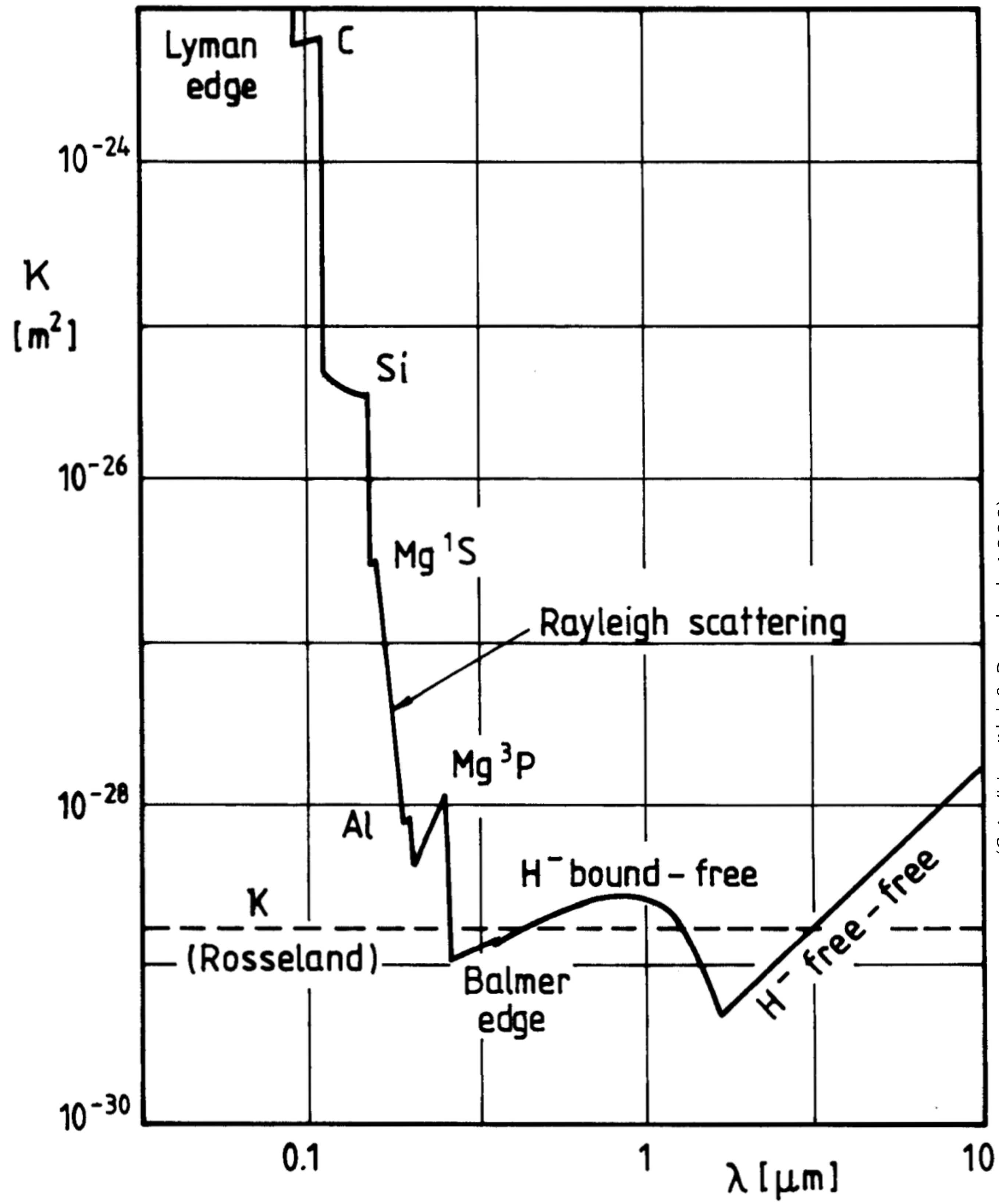
The solar atmosphere

Opacity

- High temperature
  ➡ High degree of ionisation
  ➡ Many free electrons
  ➡ High opacity

- **Opacity sources:**
  - Many different types
  - Which process contributes how much opacity depends on photon energy (wavelength) and local thermodynamic properties (if in **LTE**).
  - Deviations from LTE:
    - Radiation field (coupling different regions that can be far apart, deviations from LTE = non-LTE (**NLTE**))
    - Significant temporal variations from equilibrium conditions

Continuum absorption coefficient per particle in solar atmosphere at τ_{500}=0.1

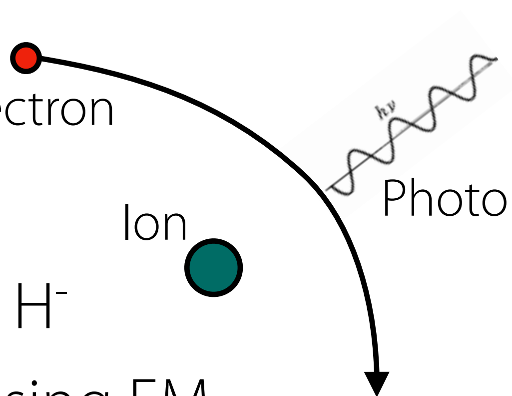


(Stix/Unsöld & Baschek 1999)

The solar atmosphere

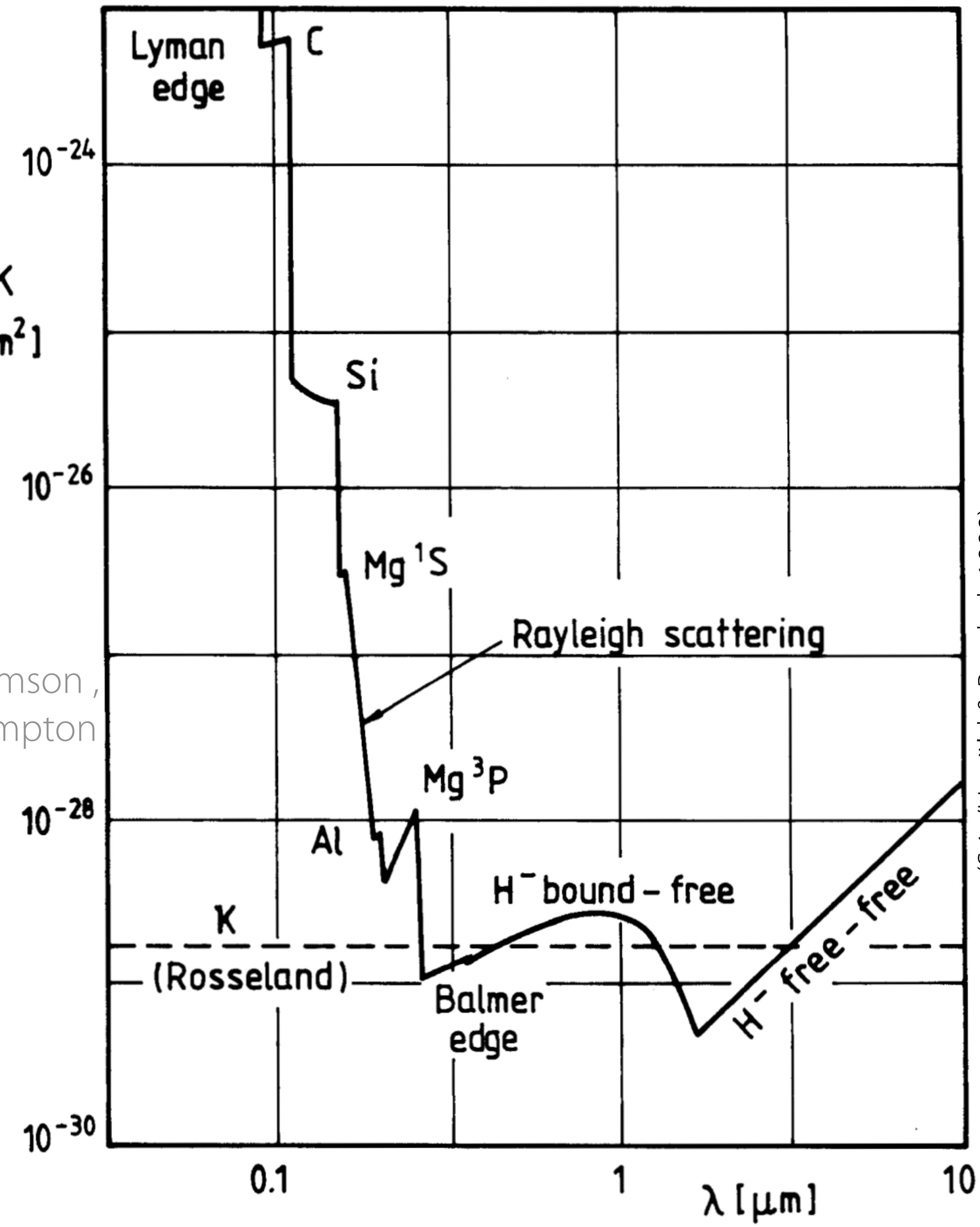
Opacity

- Bound-free (ionisation — edges)
- Bound-bound absorption (line transitions)
- Free-free absorption: free electron gains energy during collision with an ion by absorbing a photon
  (inverse process: emission — bremsstrahlung)



- Negative hydrogen ion H^-
- Electron scattering: passing EM waves make electrons oscillate and radiate in other directions
  Low energy: Thomson , High energy: Compton
- Rayleigh scattering (polarisation, dipole moment)
- Molecules and dust (at low temperatures),
  - In the Sun: H_2, CO, SiO,…
- At very high magnetic field strengths: gyroresonance and gyrosynchrotron (not in Quiet Sun but flares)

Continuum absorption coefficient per particle in solar atmosphere at τ_{500}=0.1



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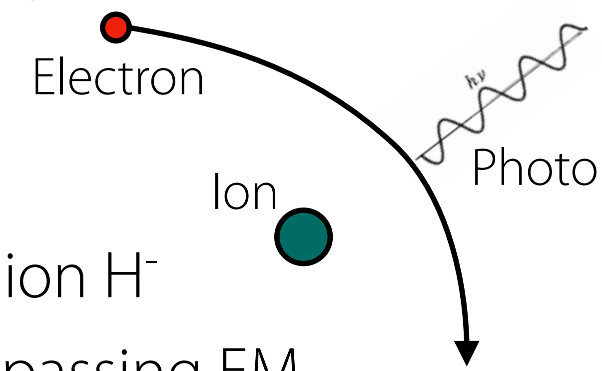

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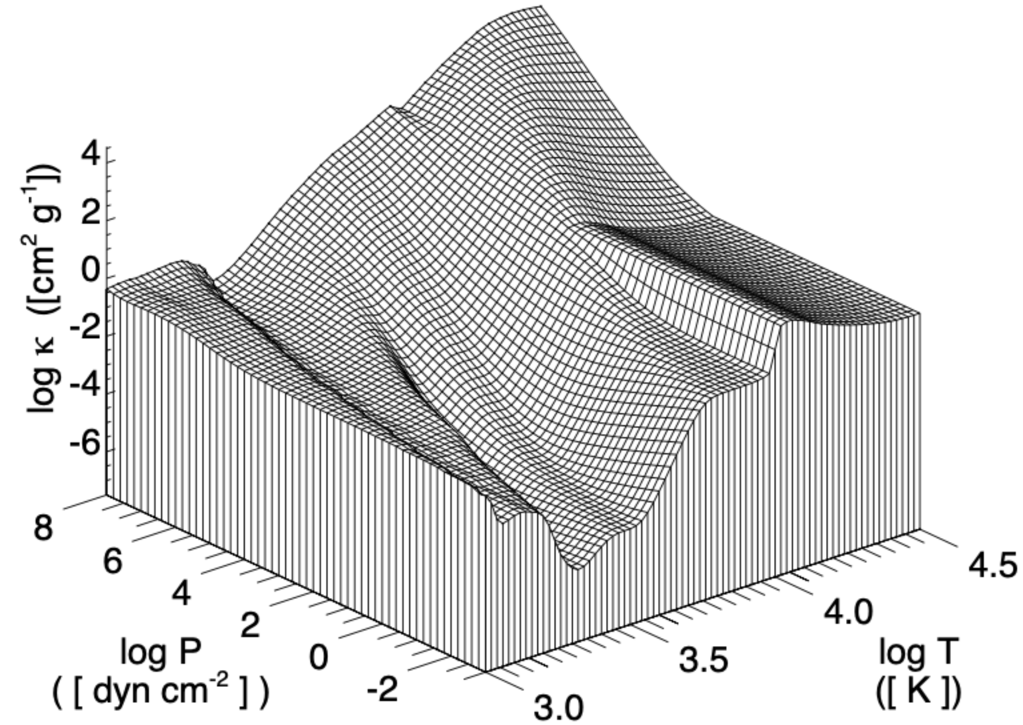
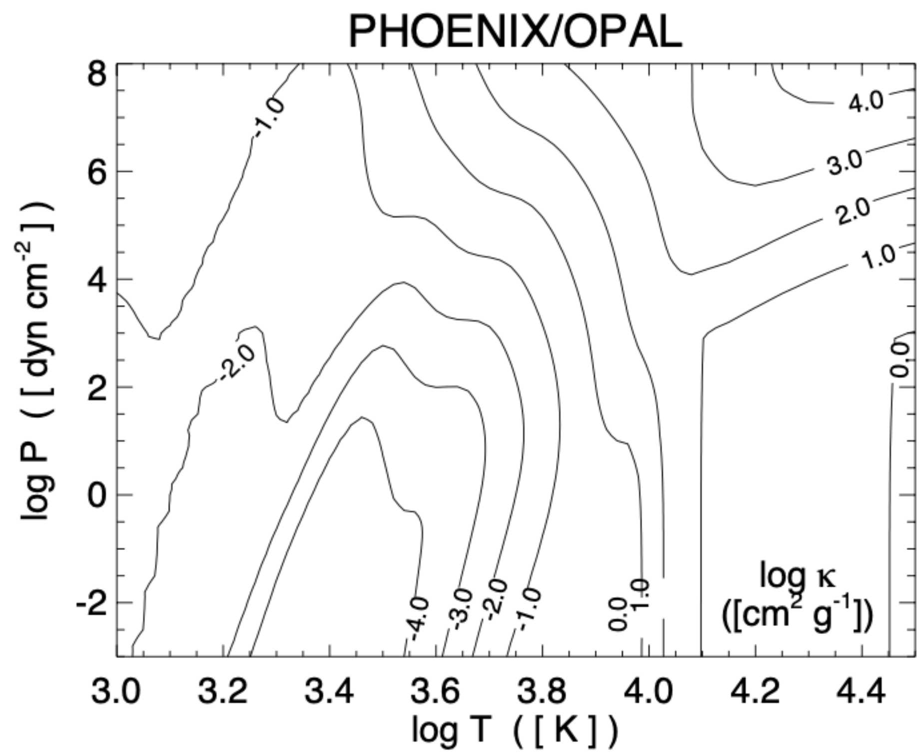




Opacity look-up table used in numerical simulations

(assumes equilibrium conditions)

Modelling the chromosphere — A numerical challenge

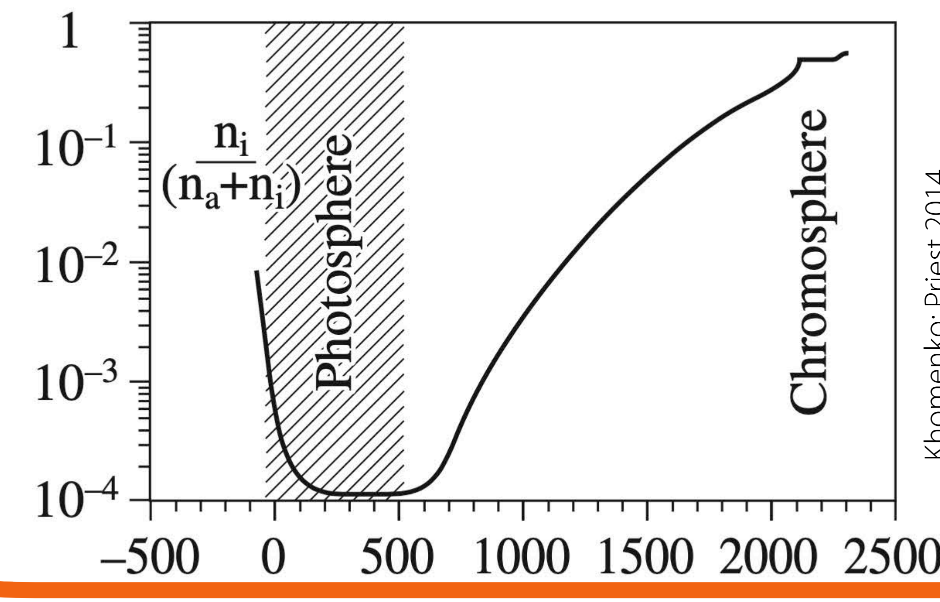
Hydrogen ionisation

- Remember: Change in temperature leads changes in (hydrogen) ionisation degree and thus the number of free electrons!
    - Fully ionised in solar interior
    - Ionisation degree drops to 10^{-4} in photosphere
    - Increases to high values in the chromosphere
- Strong temperature fluctuations in chromosphere!
- Instantaneous equilibrium: Ionisation degree is a function of local temperature, follows changes.
- BUT: Ionisation and especially recombination (of H^+ and e^-) occur on finite time scales!
- Hot shock fronts ionise quickly but recombination in shock wake takes time

➡ Ionisation degree lacks behind

➡ Time-dependence of ionisation needs be taken into account for realistic electron densities in chromosphere!

- First shown in by 1D by Carlsson & Stein (2002)



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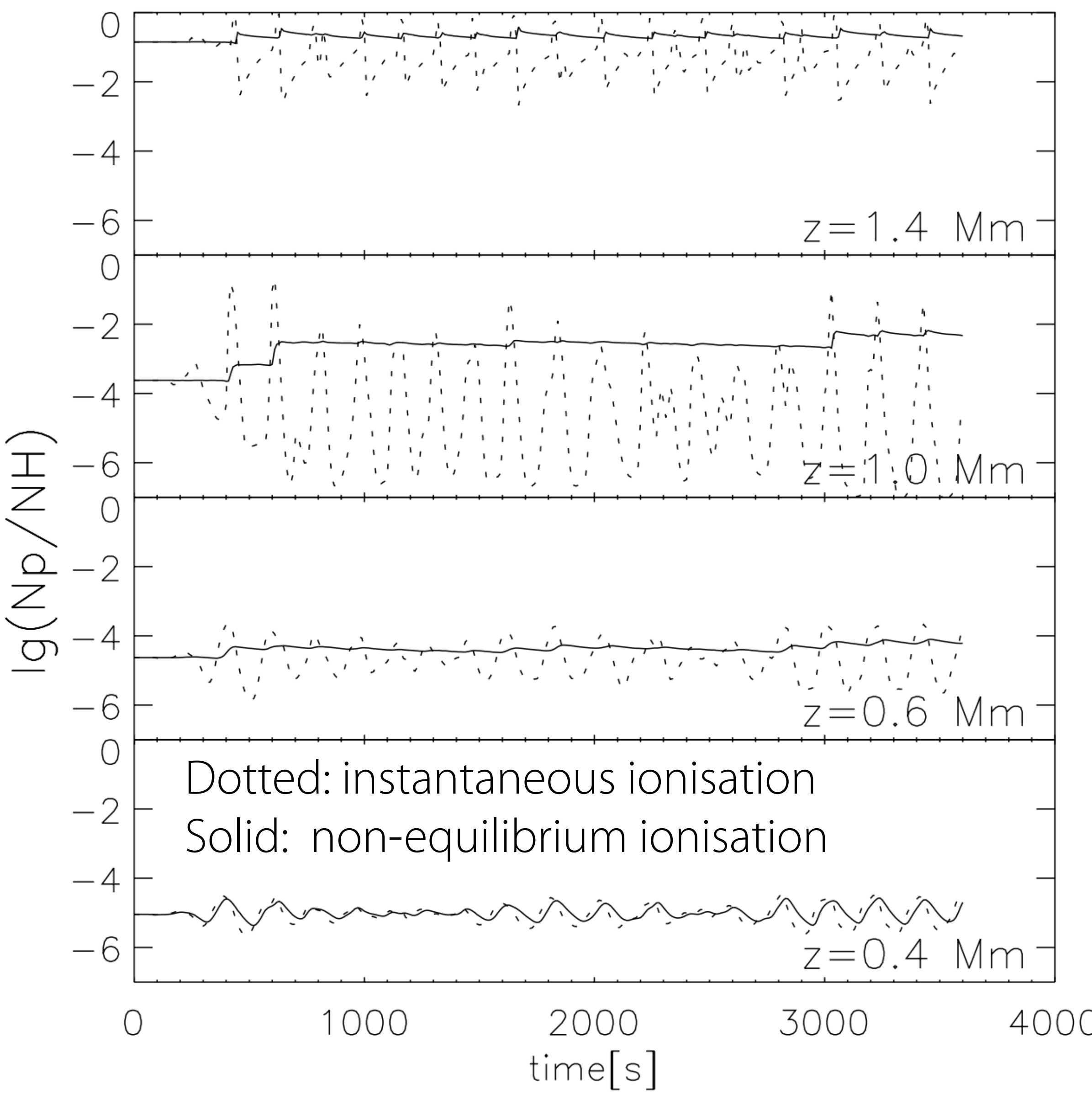
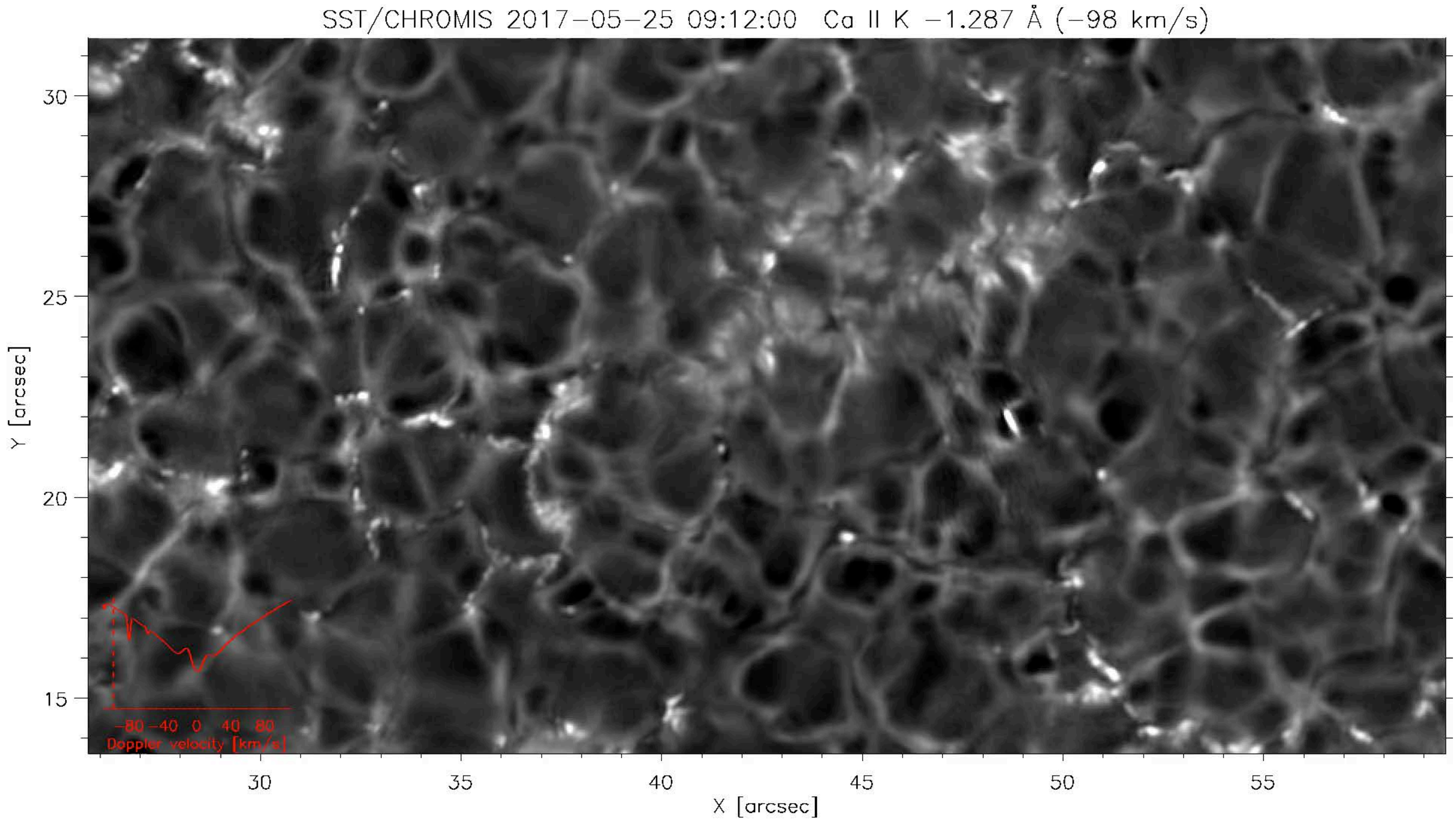


The solar atmosphere

Intermittent and dynamic

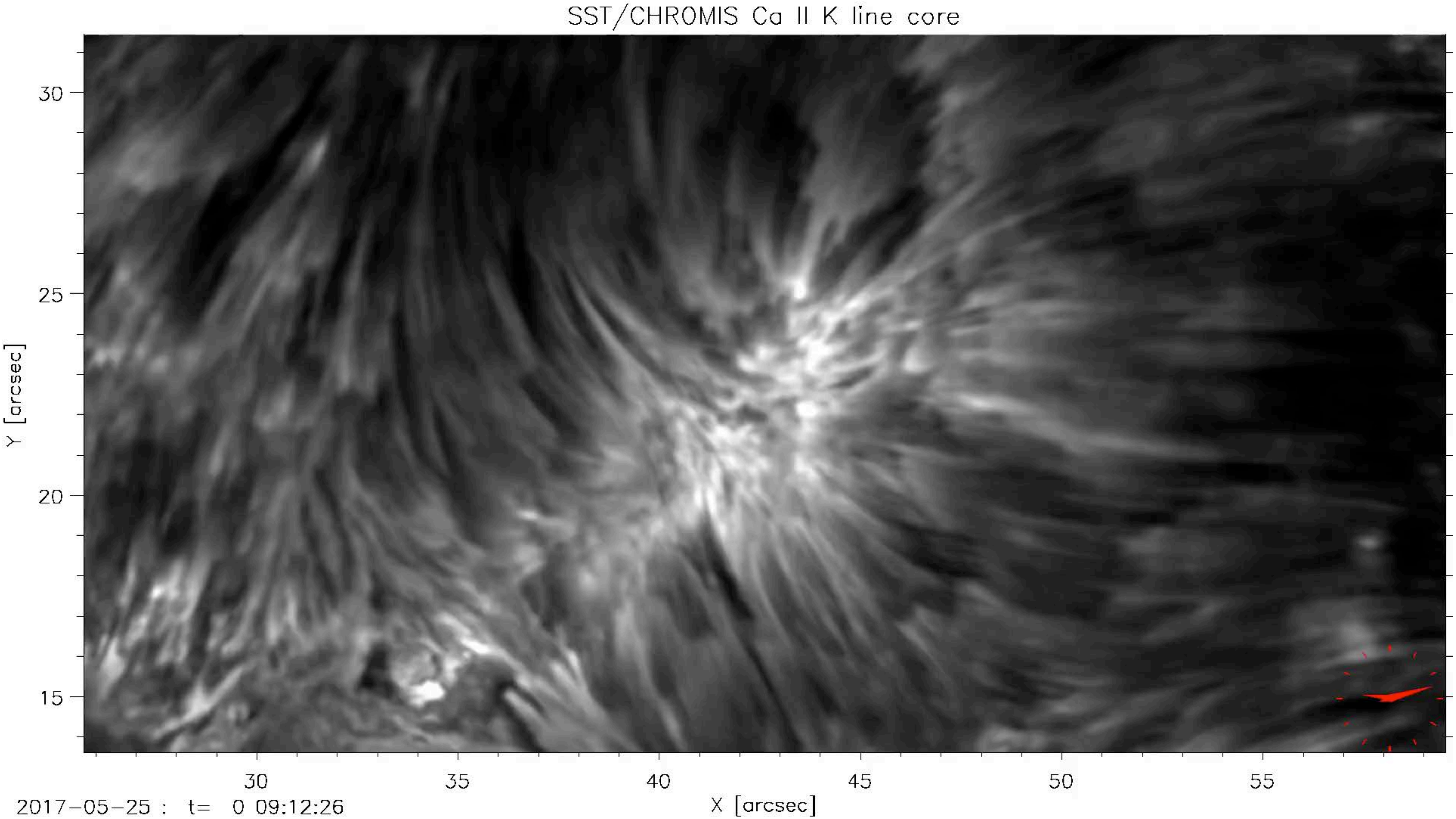
- Scan (in wavelength) through spectral line (here Ca II K) gives first impression of the change with height (sampling different layers, but careful: height varies across FOV)



The solar atmosphere

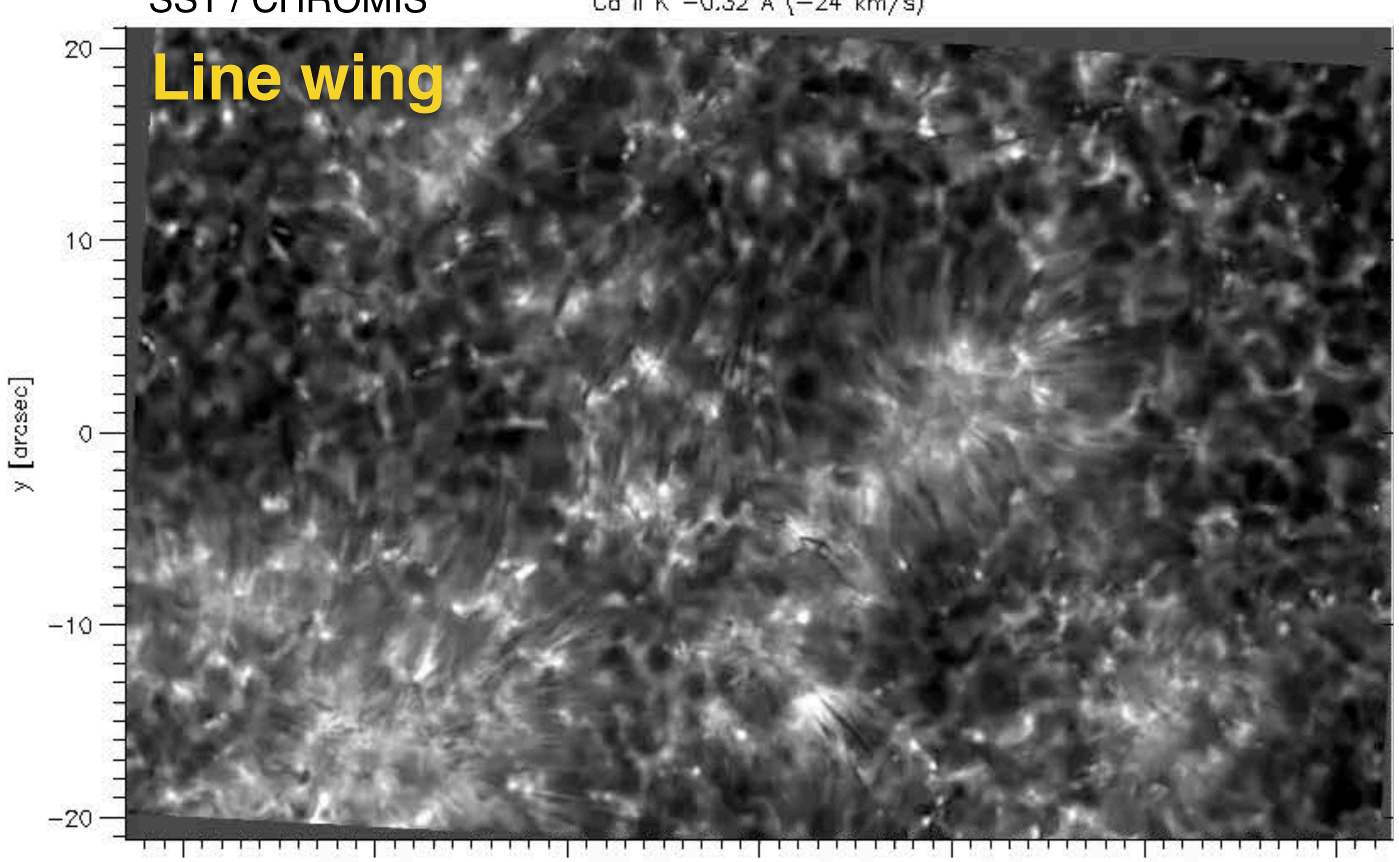
The chromosphere — A highly dynamic place

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

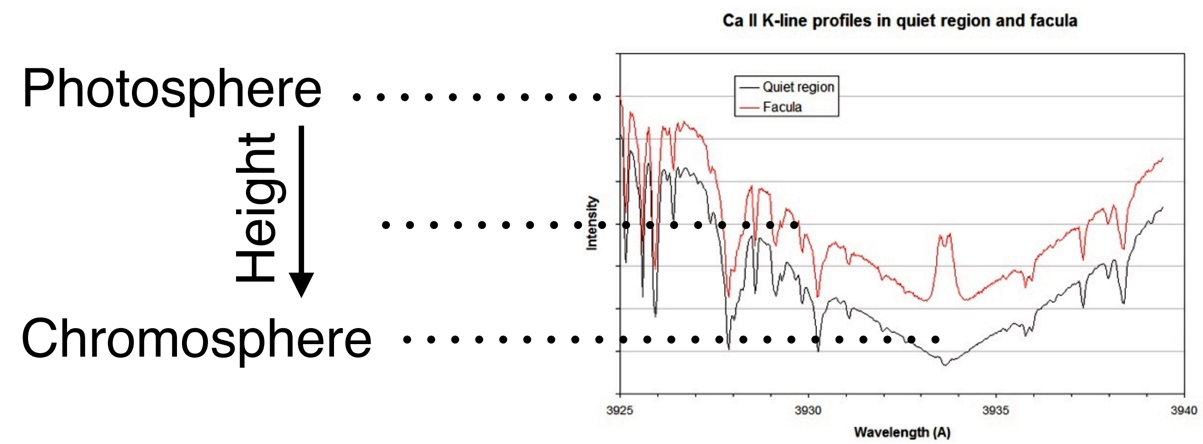


The solar atmosphere

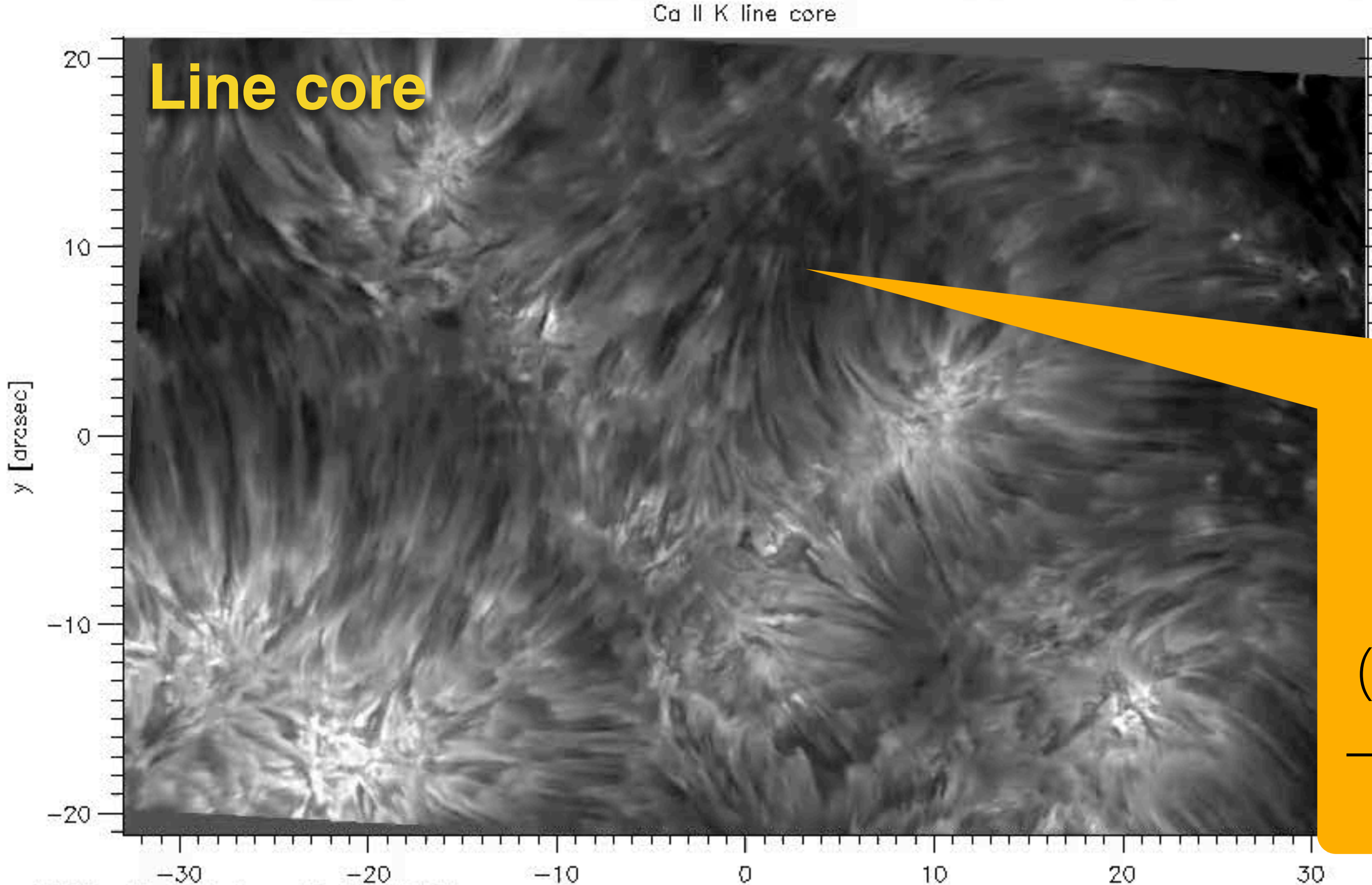
SST / CHROMIS

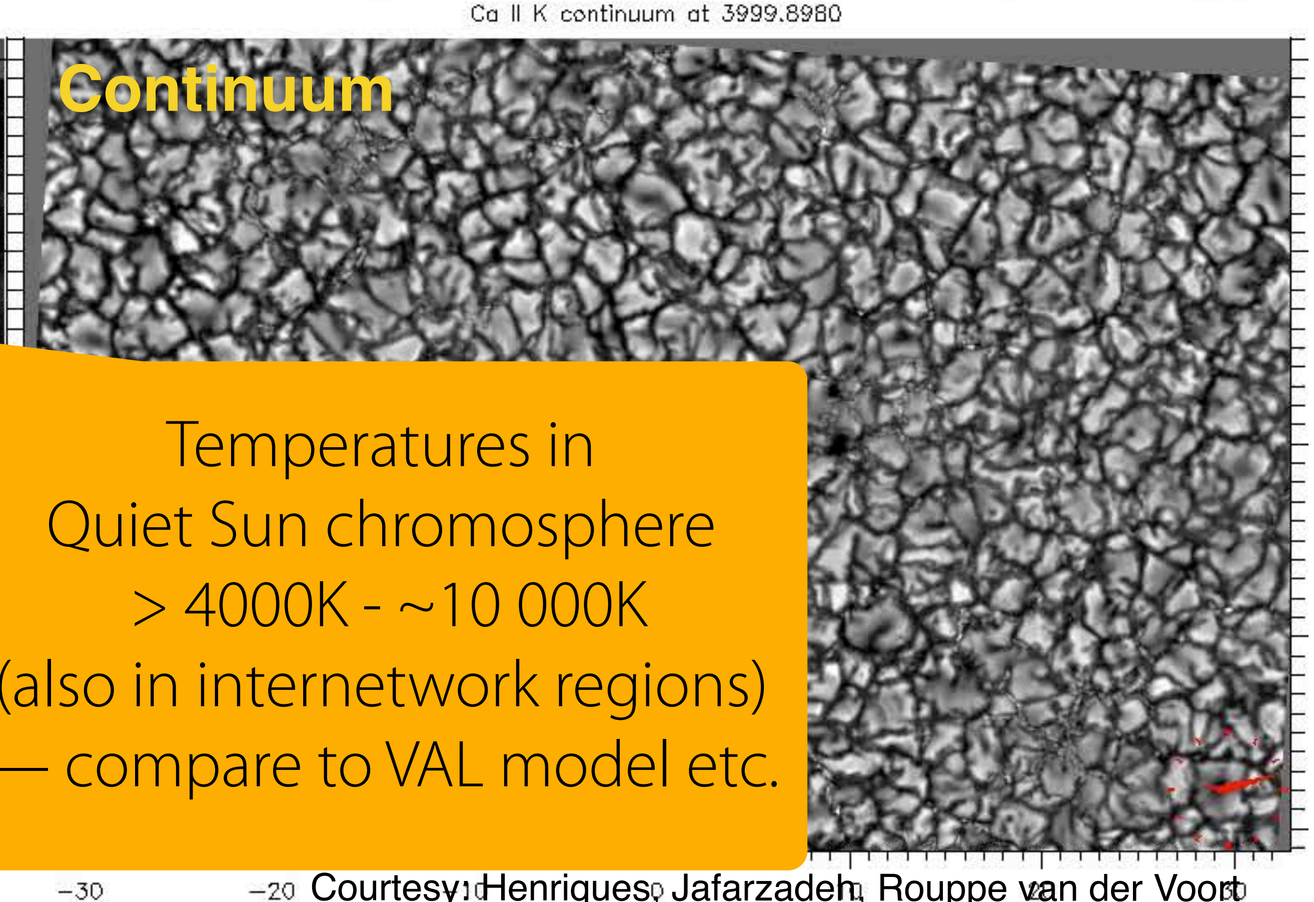


- Different parts of spectral formed at different atmospheric heights



Ca II K 393 nm





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

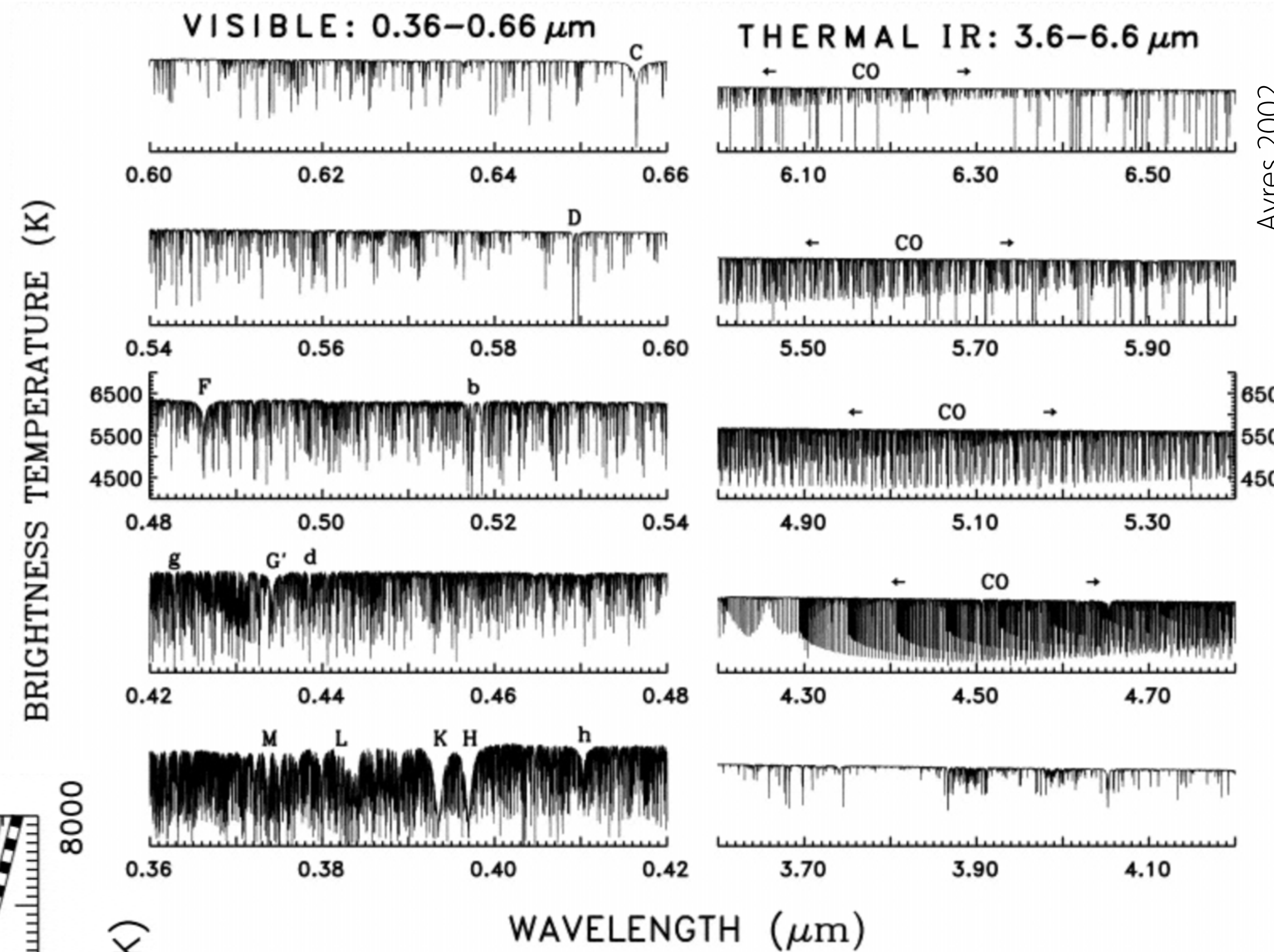
Courtesy: Henriques, Jafarzadeh, Rouppe van der Voort

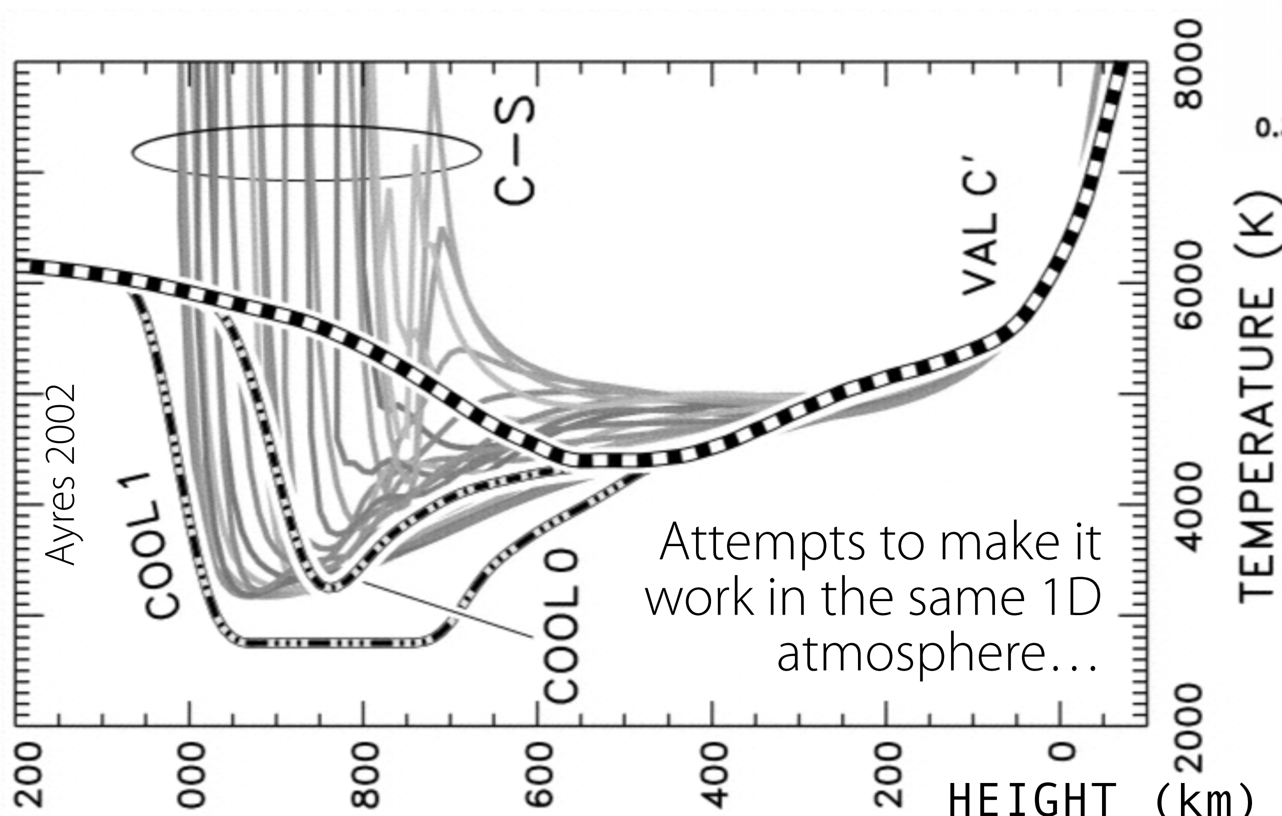
The solar atmosphere

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)

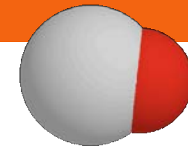




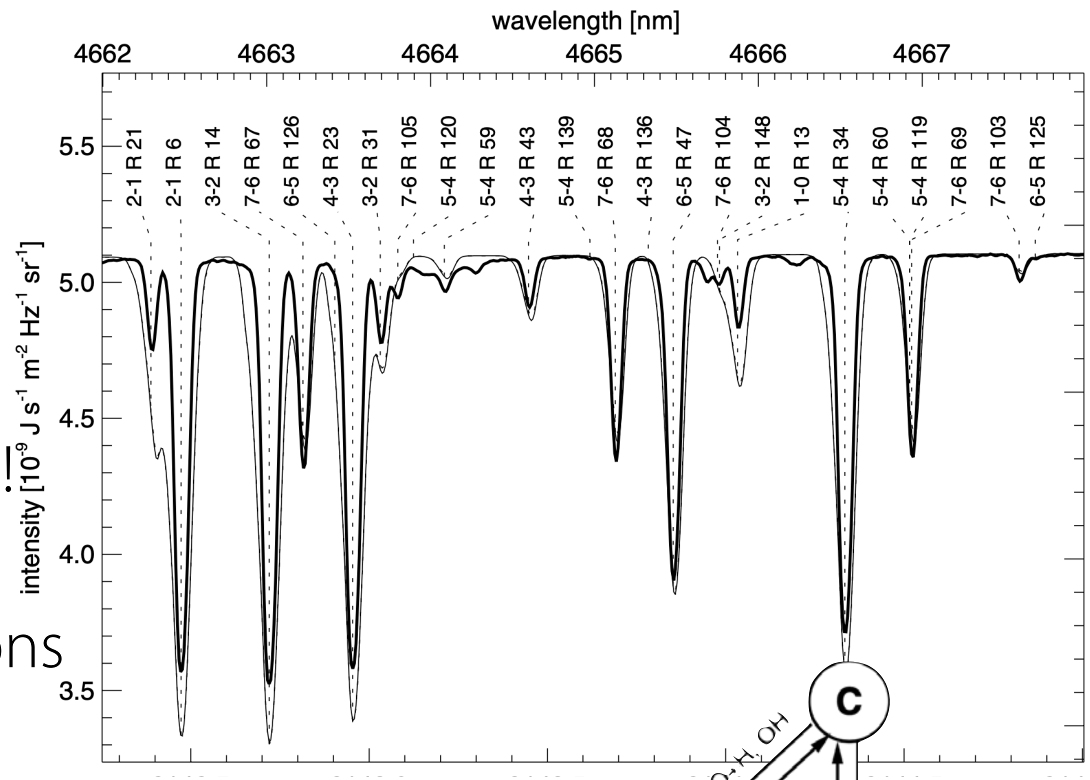
- **Solution: The solar atmosphere is not static but highly dynamic and intermittent on short time scales and small spatial scales**

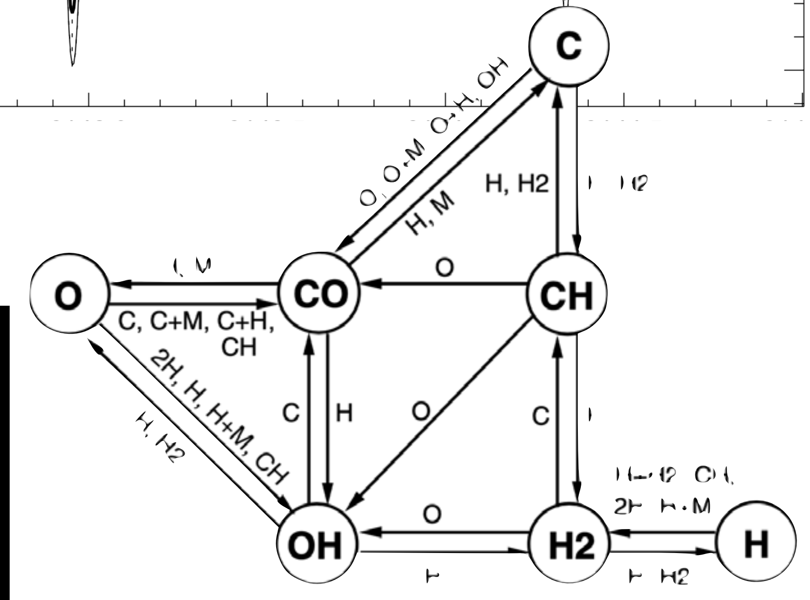
The solar atmosphere

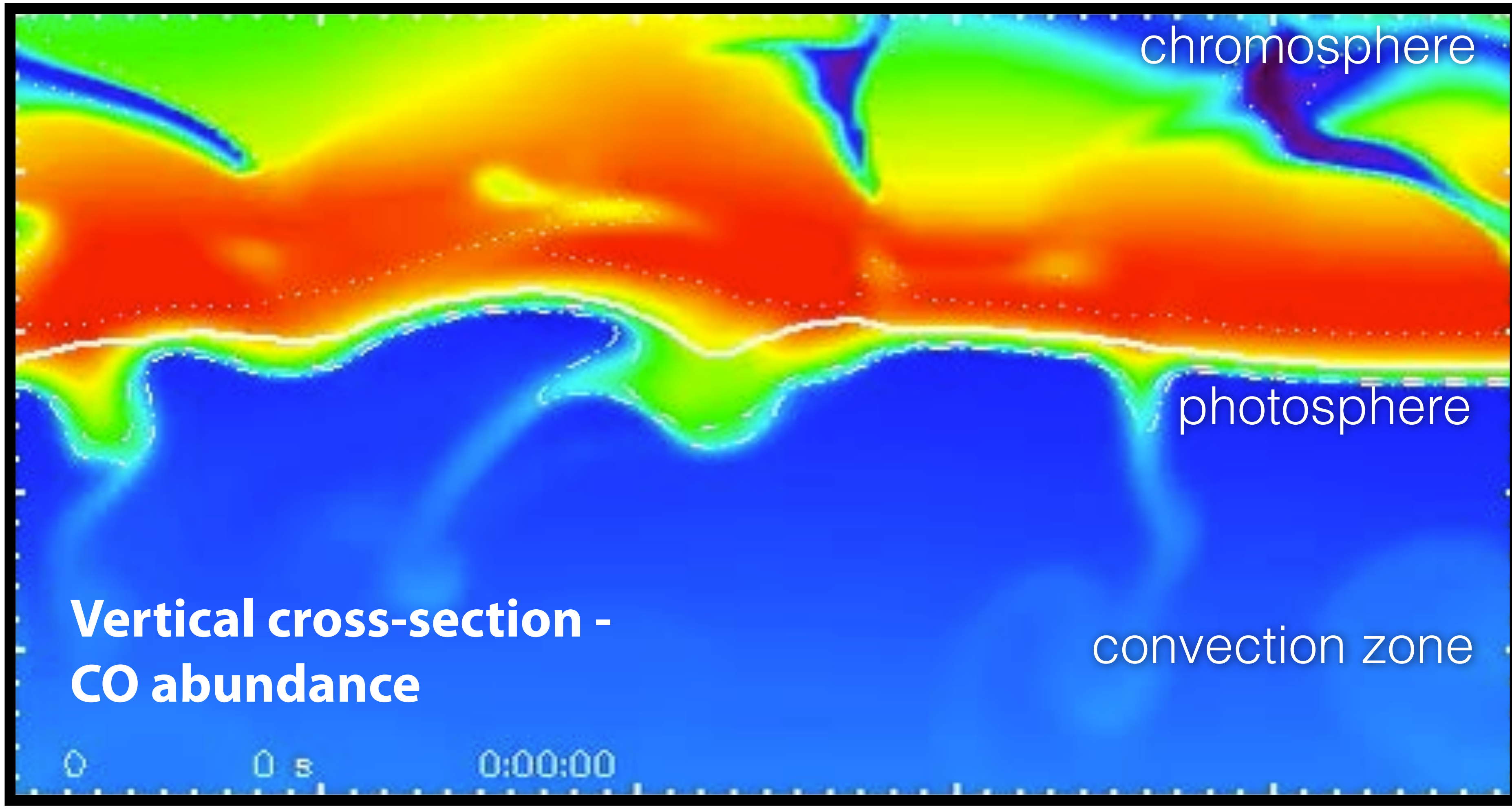
The CO problem — solved



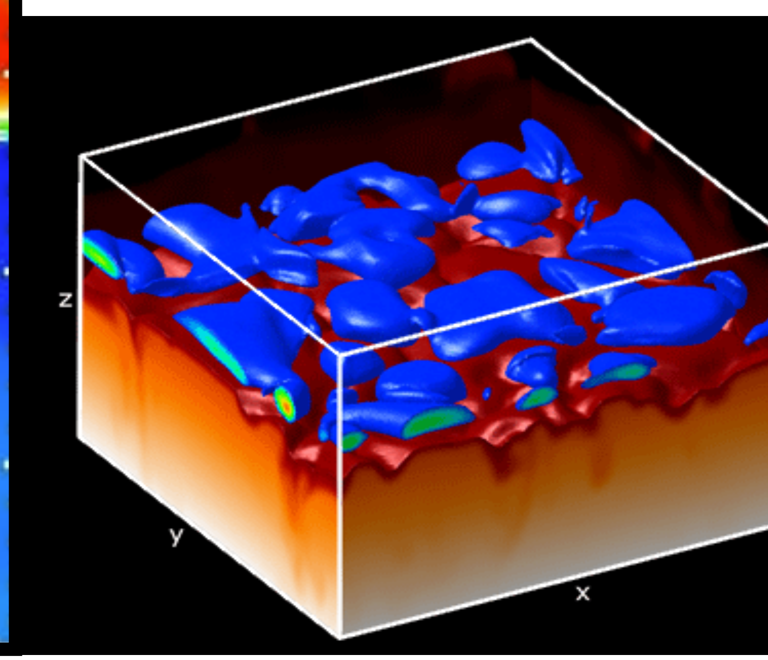
- Explained by numerical simulations!
- CO can form and persist (for some time) in cool pockets!
- CO dissociated by moving hot shock waves in chromosphere, builds up again in cold post-shock regions
- CO as integral part of a highly dynamic environment
- CO observations (cold gas) and UV observations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







Wedemeyer et al. 2006

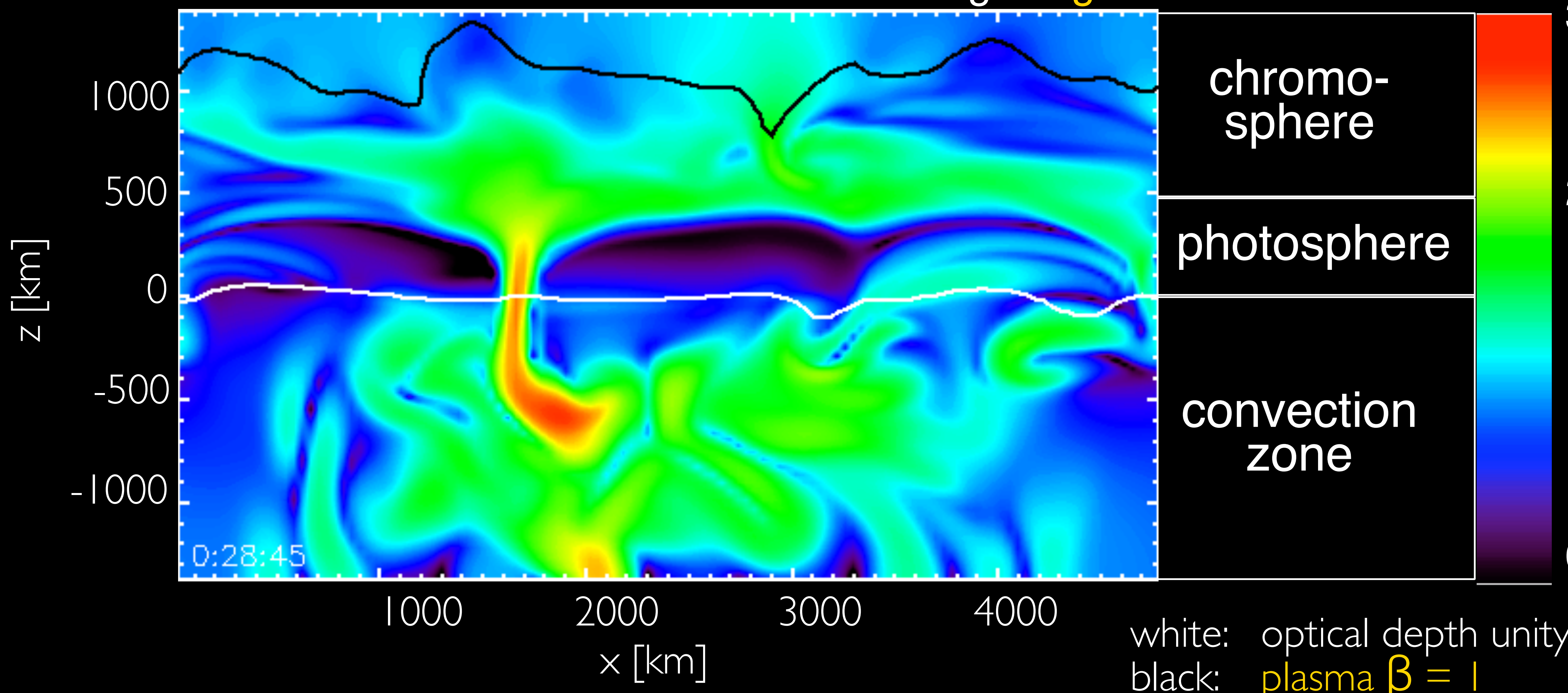


Wedemeyer et al. (2005, 2006)

The solar atmosphere

- 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|



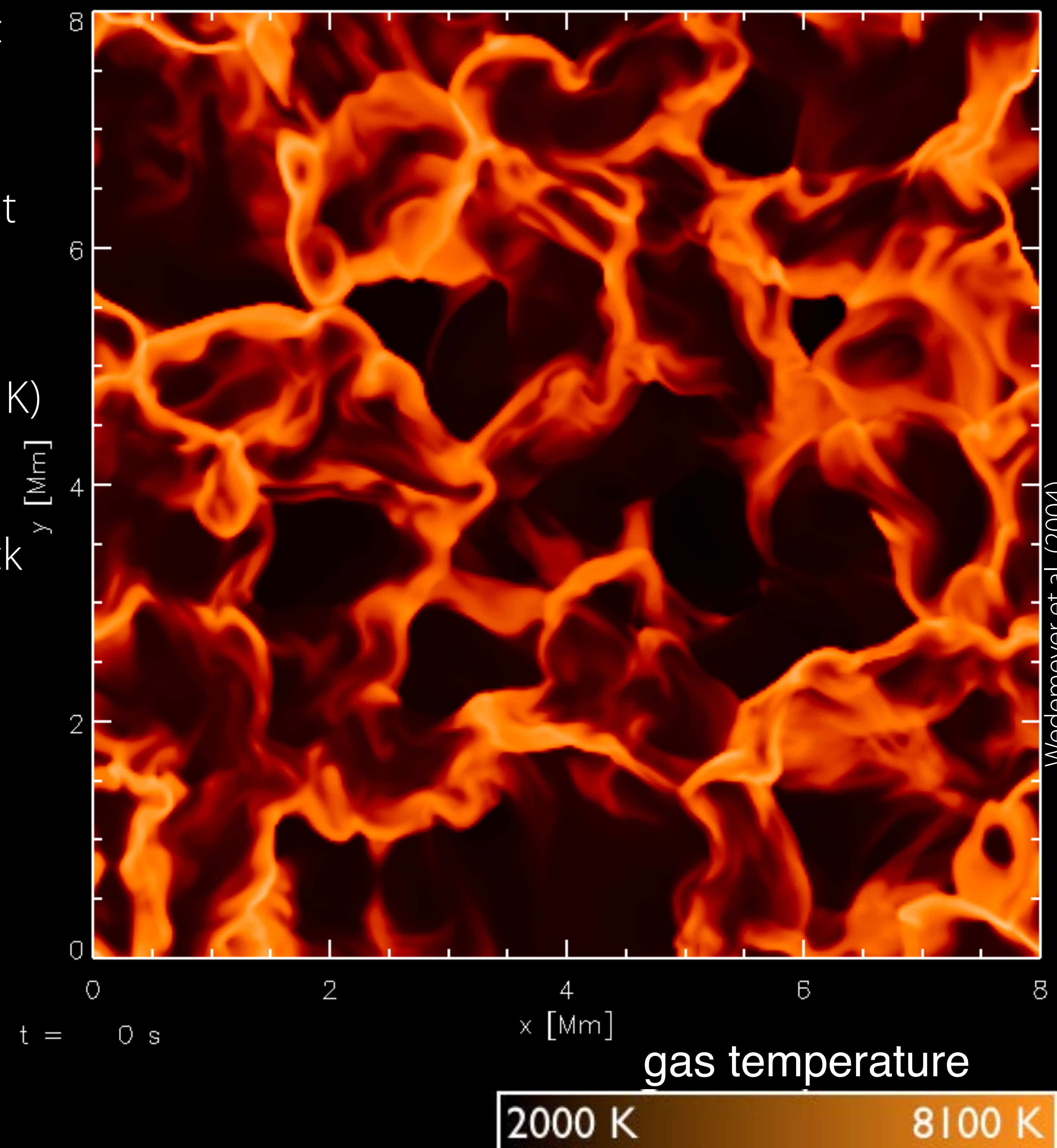
$|B_0|=10$ G

Schaffenberger, Wedemeyer, Steiner, Freytag (2005)

The solar atmosphere

Thermal structure of a (very) Quiet Sun chromosphere

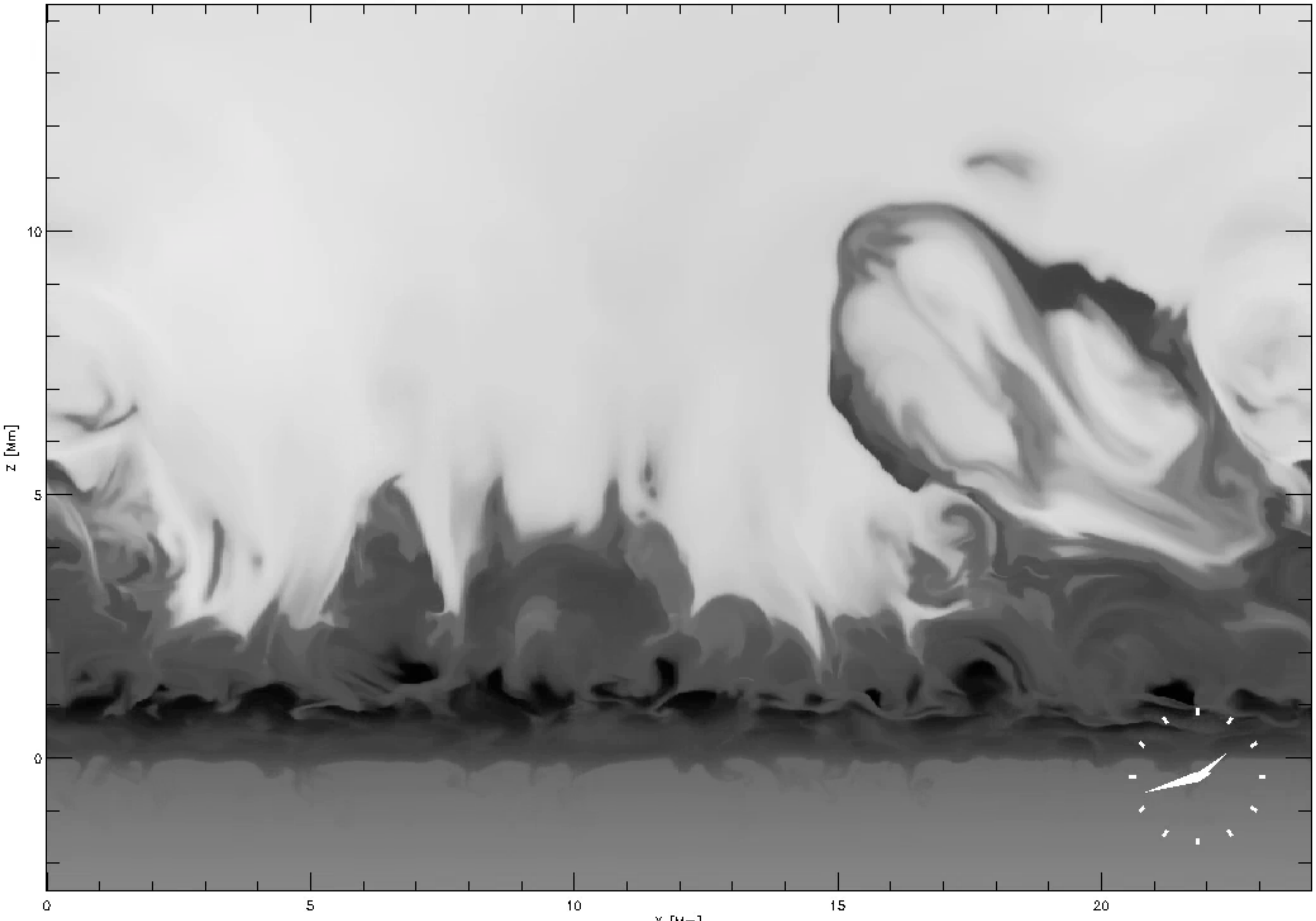
- Numerical simulation without magnetic fields (representing a hypothetical extremely quiet region)
- Horizontal cut through chromosphere at z=1000 km, gas temperature
- Hot shock fronts (~7000 - 8000 K) and cool post-shock regions (down to ~2000 K)
- Mean T_{gas} ~ 4000 K
- Pattern produced by interaction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

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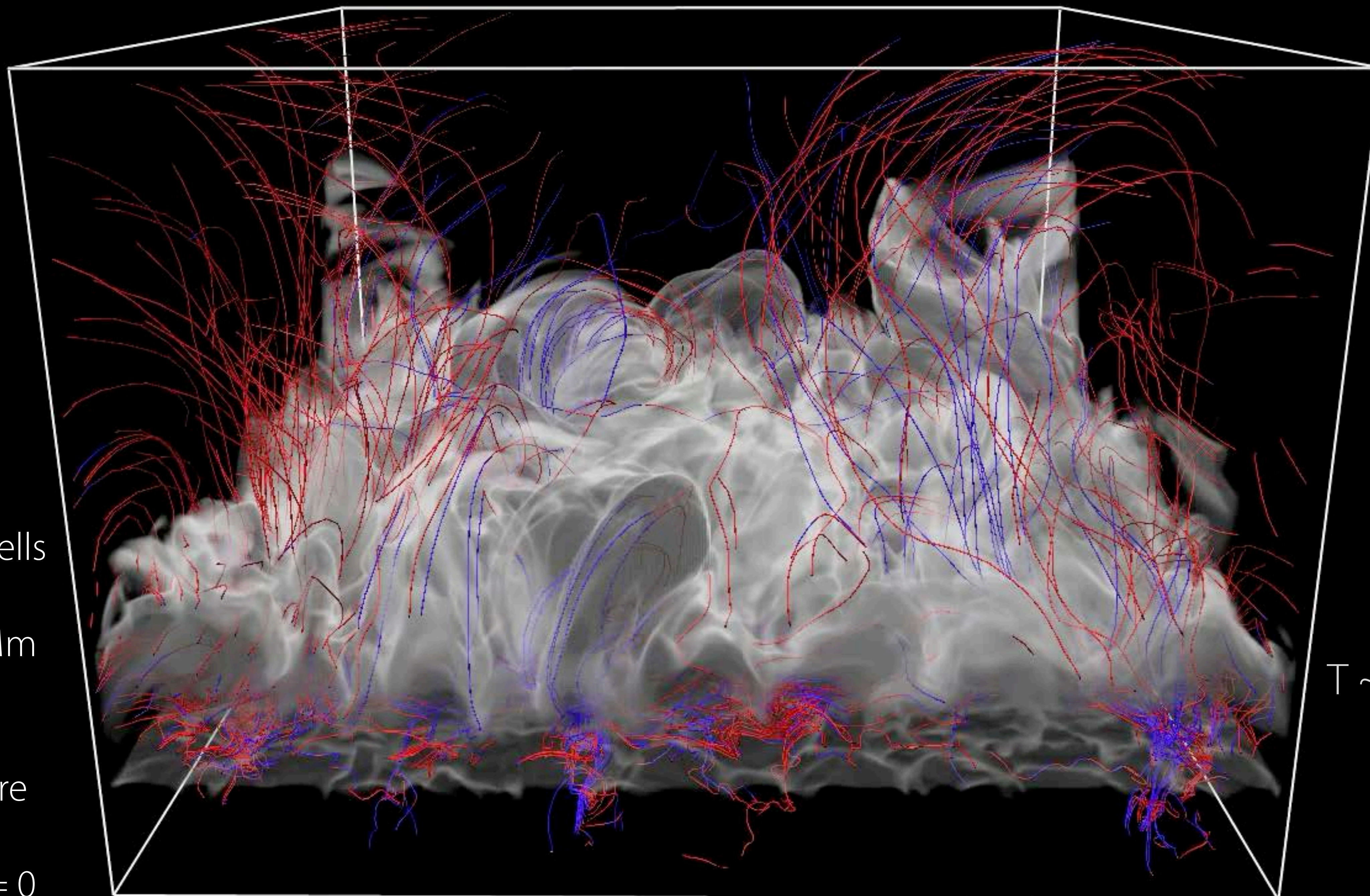


504 x 504 x 496 cells
24Mm x 24Mm
z: -2.4Mm .. +14Mm

No large-scale magnetic structure

Avg. signed flux = 0

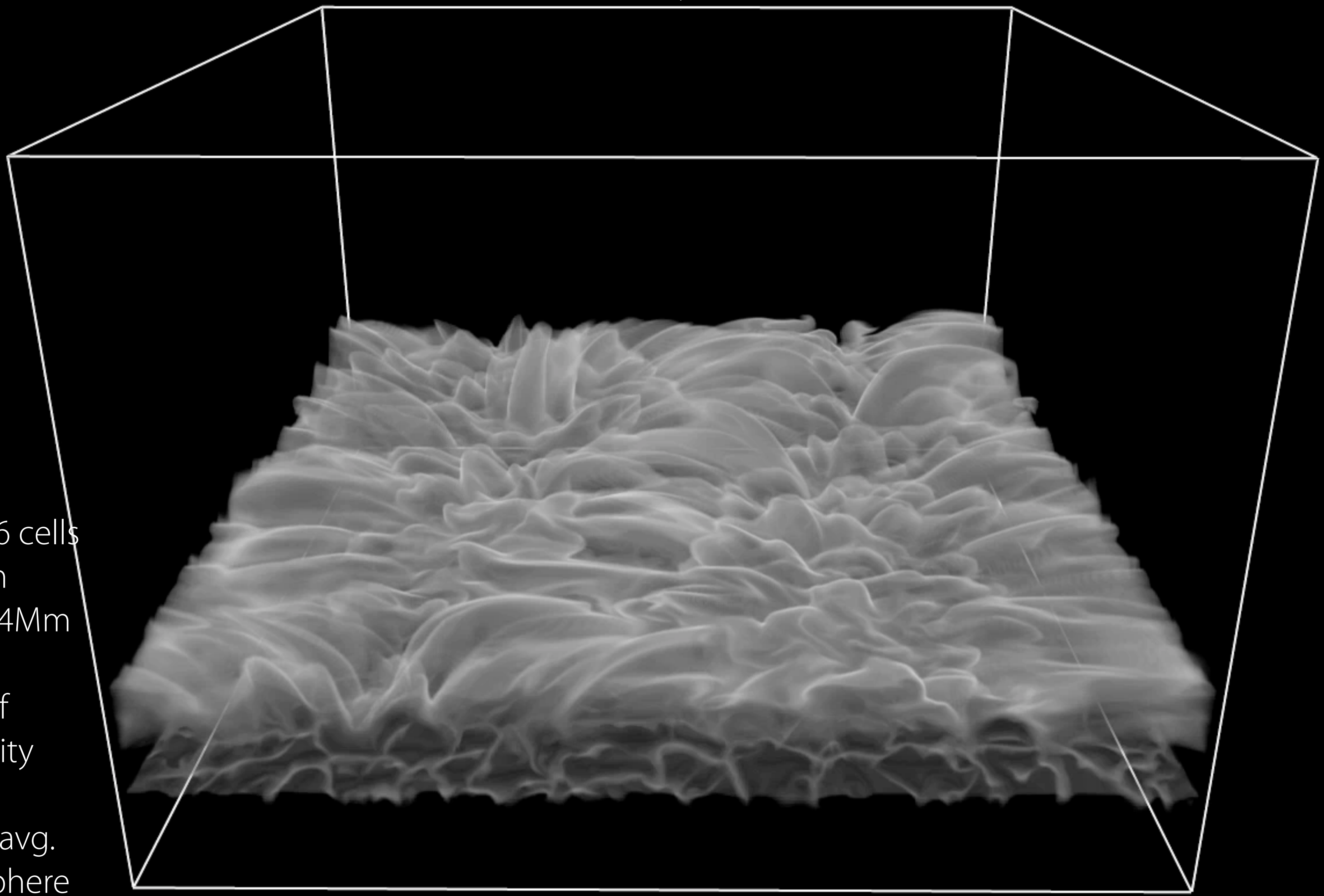
T ~ 7000 K

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

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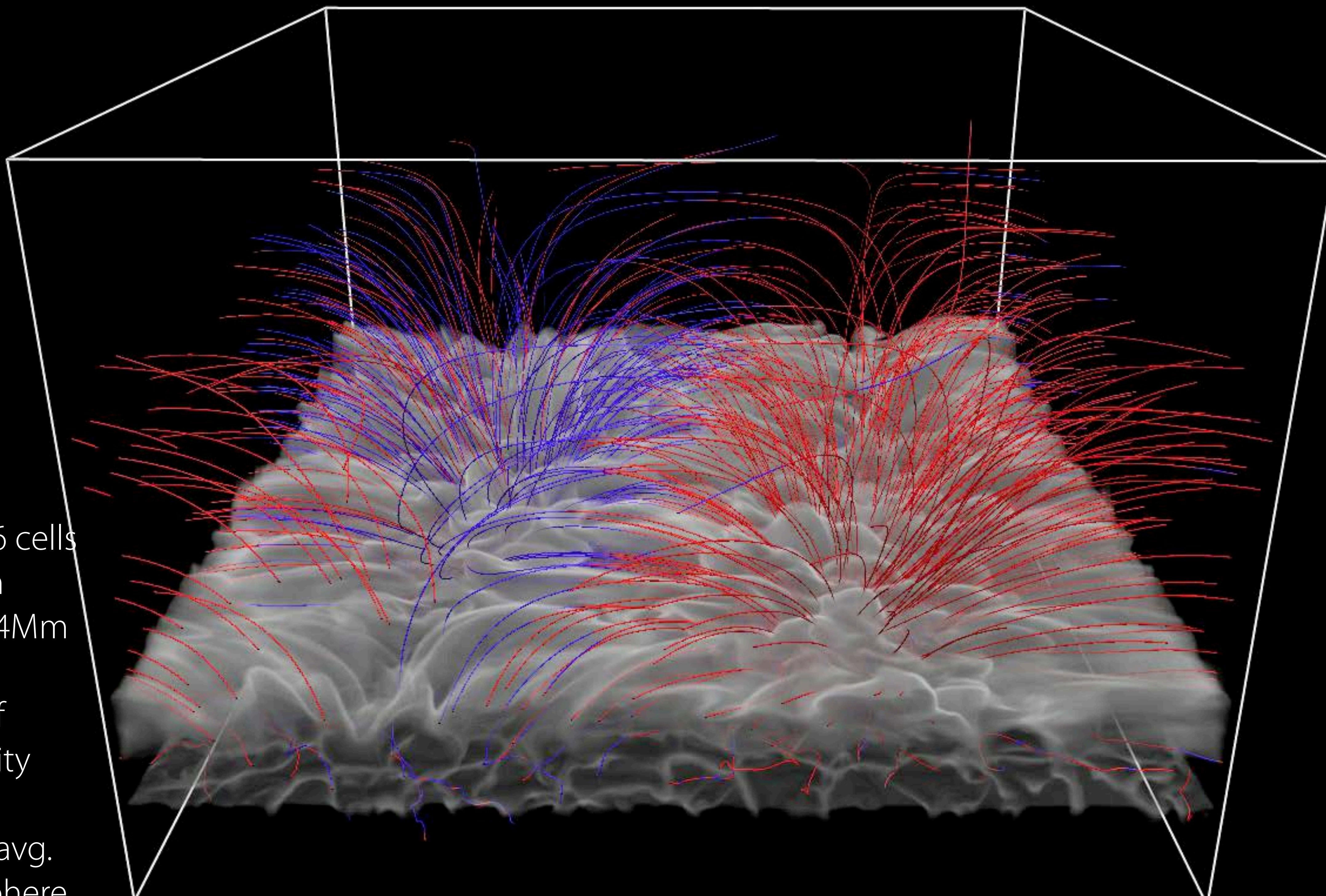
http://sdc.uio.no/search/simulations
IRIS Technical Note 33; Carlsson et al 2016



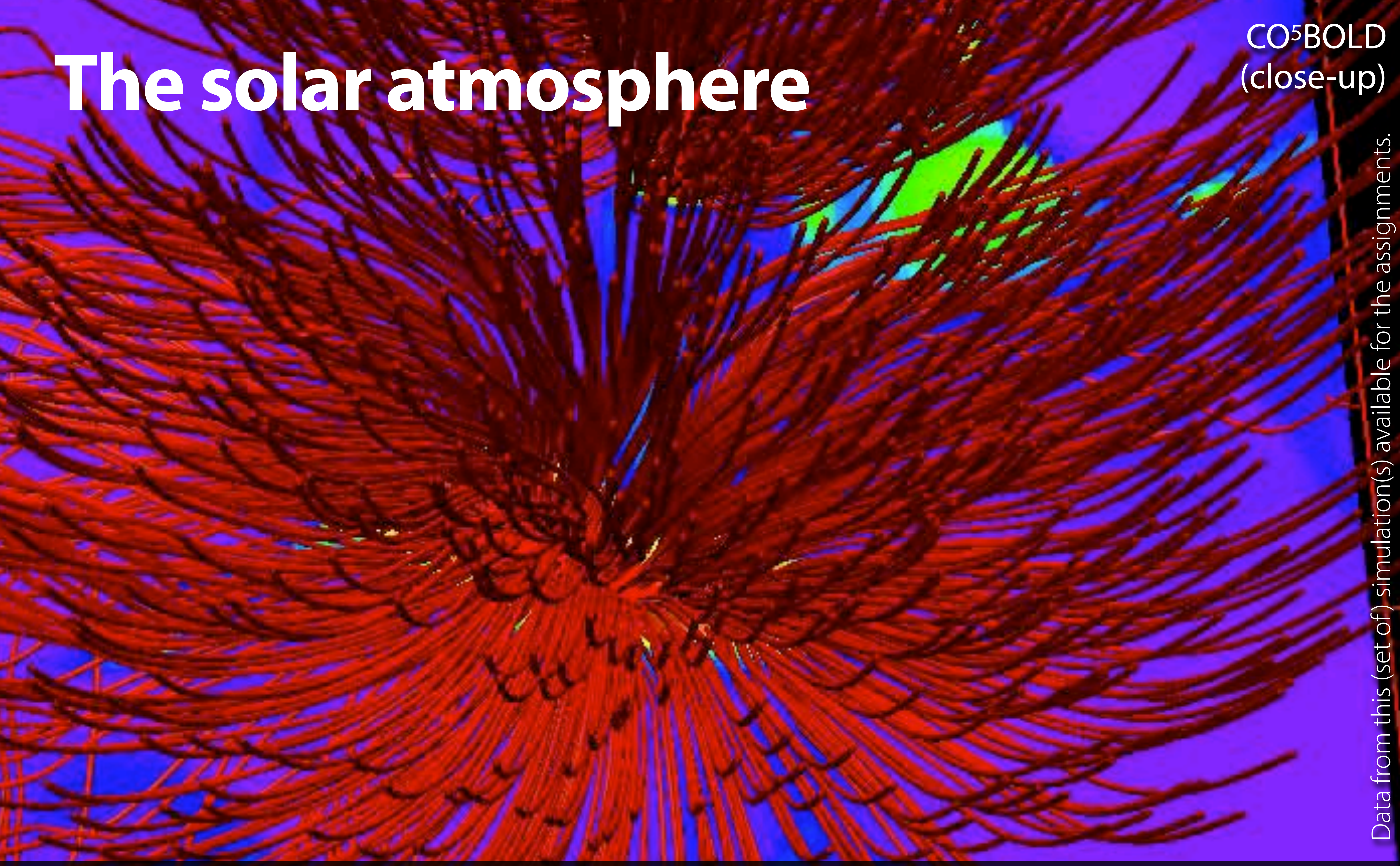
504 x 504 x 496 cells
24Mm x 24Mm
z: -2.4Mm .. +14Mm

Two patches of opposite polarity

50G unsigned avg. flux in photosphere

The solar atmosphere

CO^{5}BOLD (close-up)



Data from this (set of) simulation(s) available for the assignments.

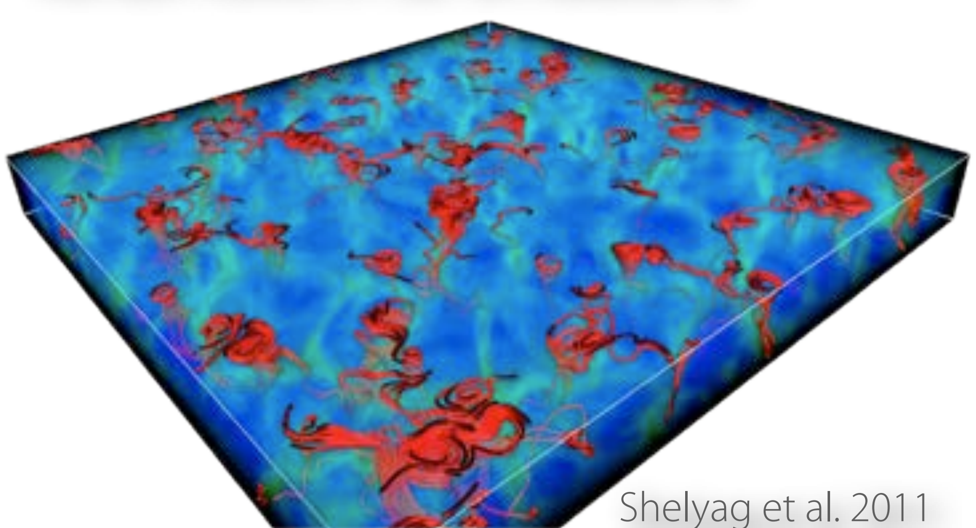
- Complicated field structure with rotating and/or swaying subgroups
- Continuous reorganisation of structure
- More complicated than individual “flux tubes”

The solar atmosphere

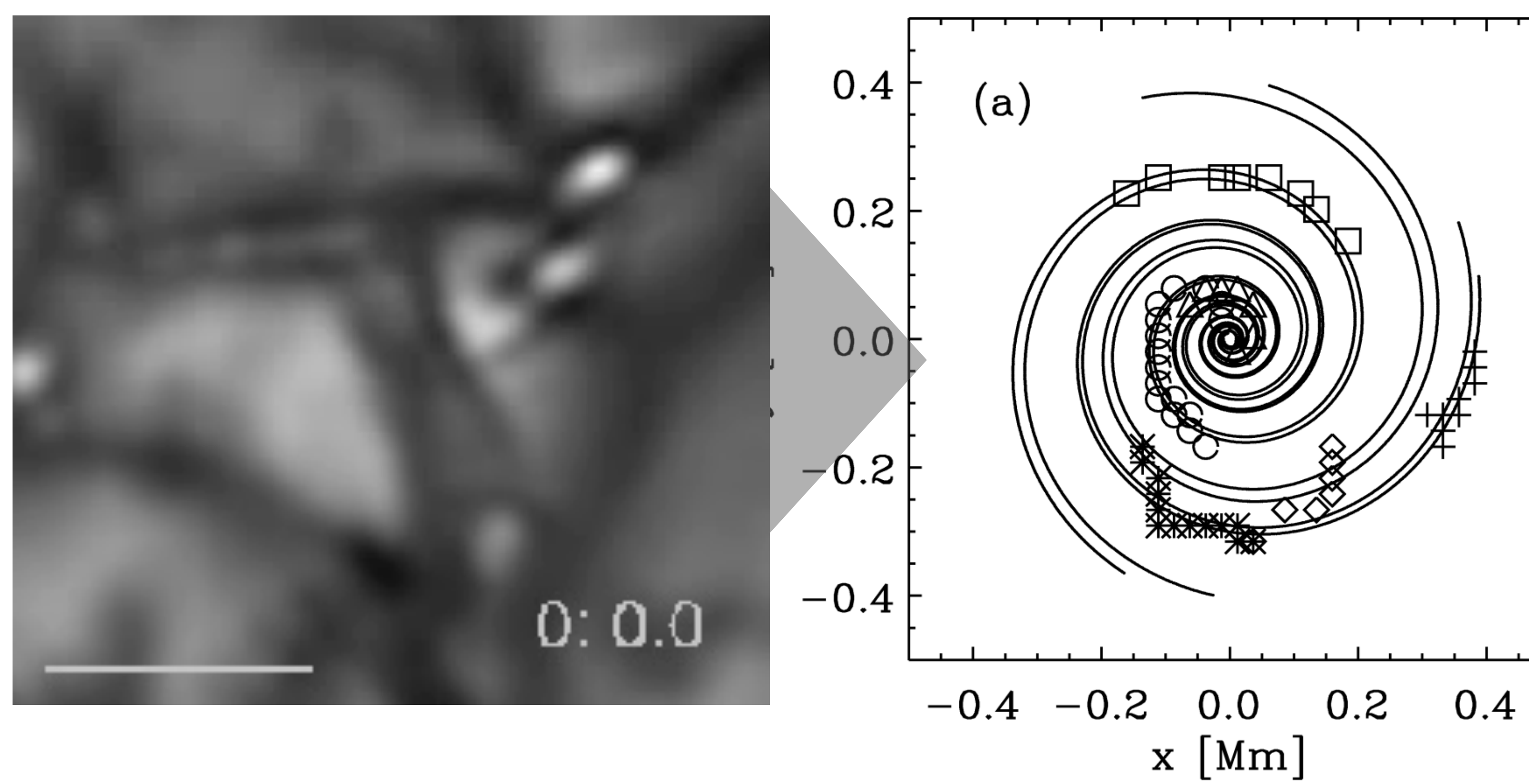
Vortex flows

- 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



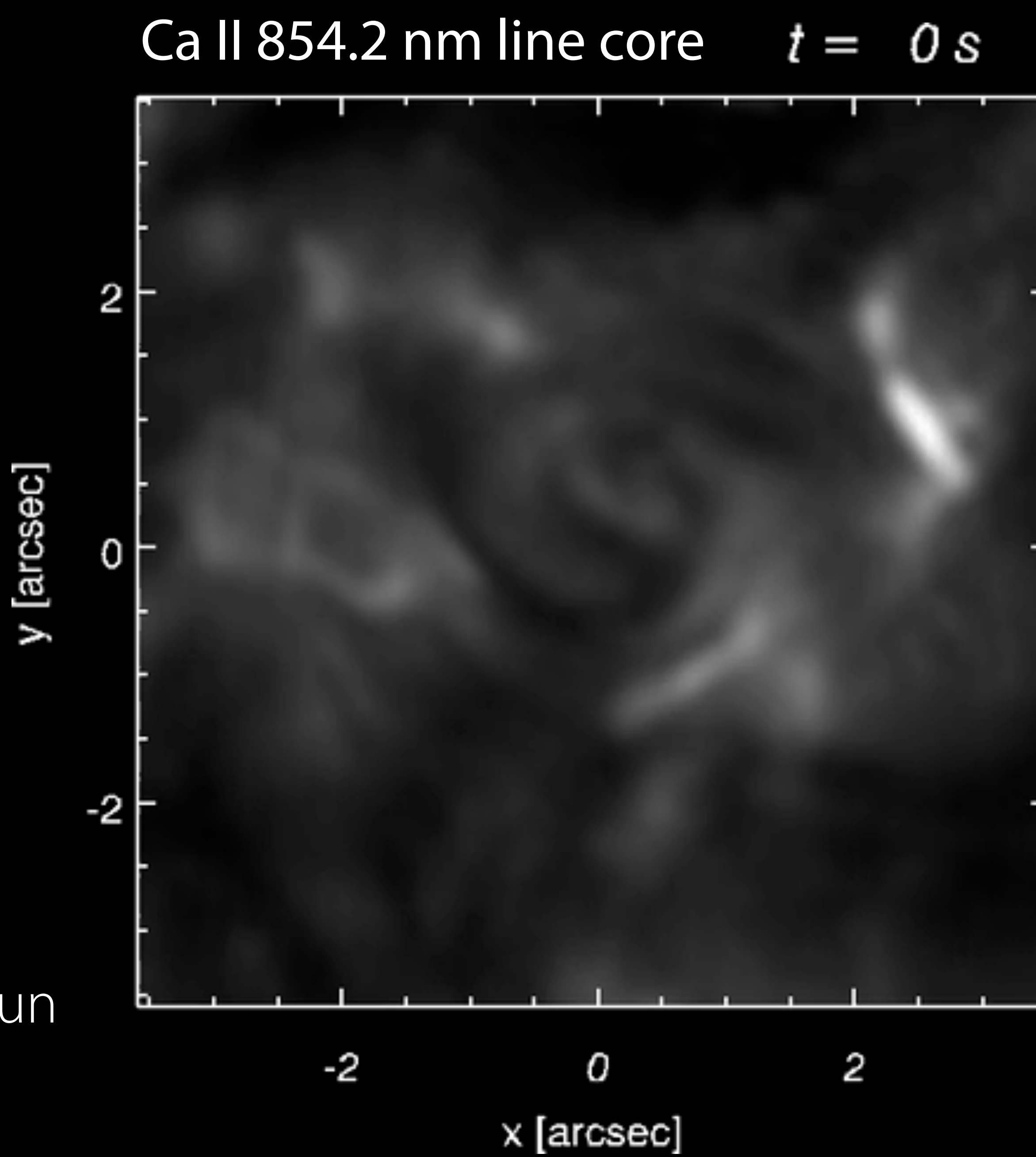
Bonet et al 2008

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

Wedemeyer et al 2012



Wedemeyer & Rouppe van der Voort 2009

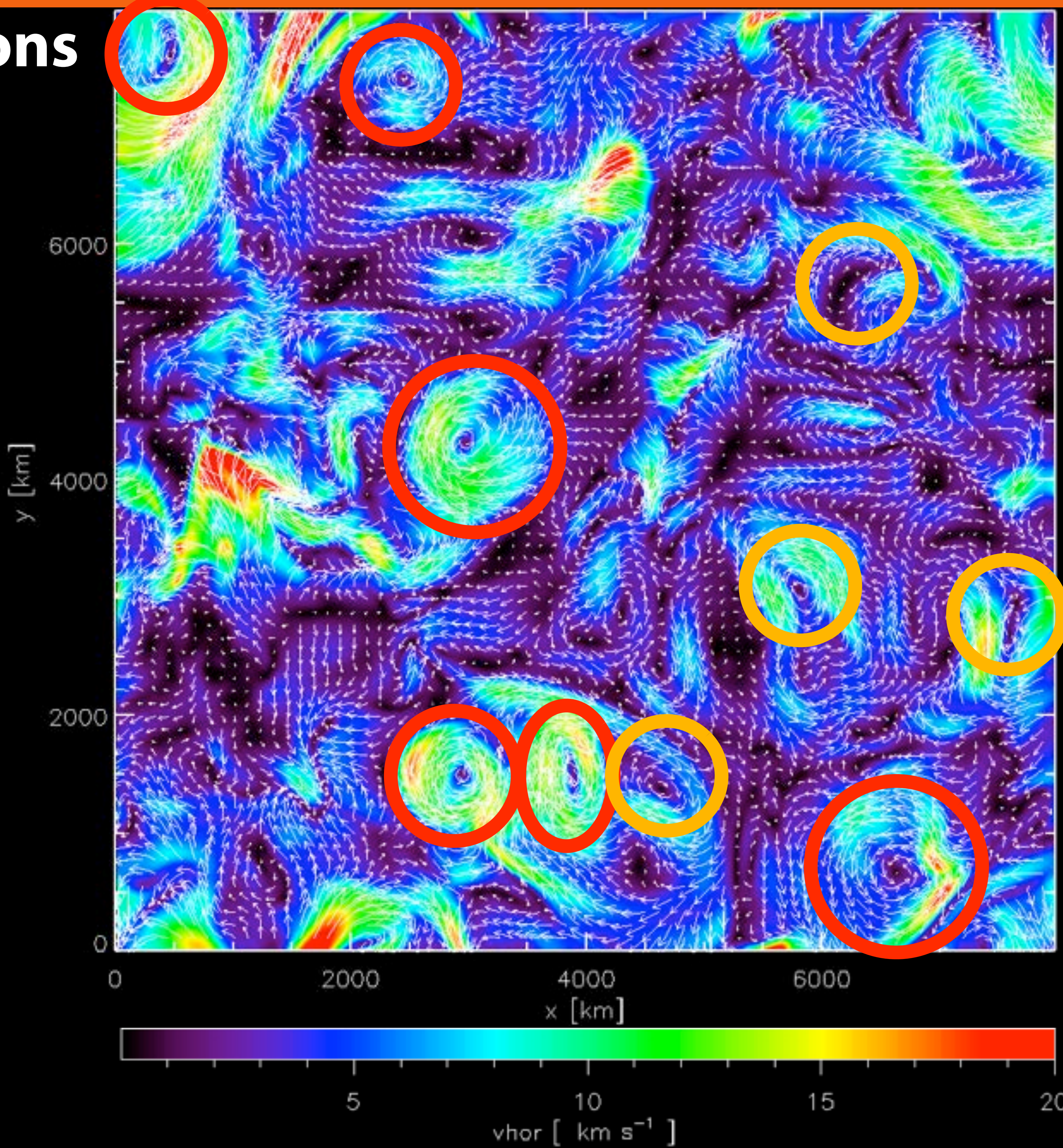
Explanation: **Rotating magnetic field structure** that produces observable signatures in all atmospheric layers from photospheric bright points to chromospheric swirls and bright features in the corona

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**

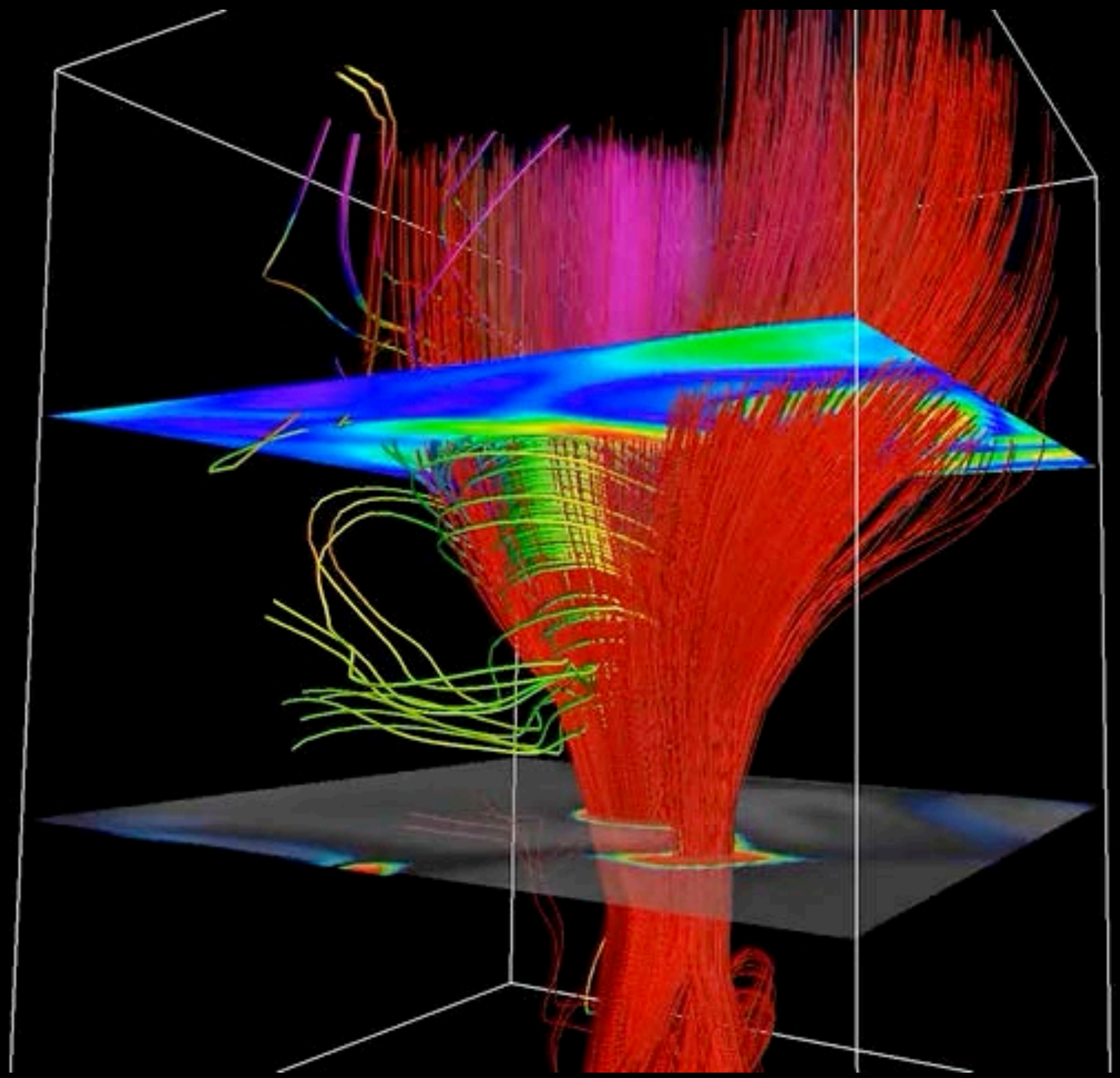


Wedemeyer et al 2012

The solar atmosphere

Magnetic tornadoes

cross-section of horizontal velocity at z=1000 km



grey surface:
granulation
superimposed
color: magnetic field

Wedemeyer et al 2012

CO5BOLD/VAPOR

The solar atmosphere

Magnetic tornadoes

- vortex flow in the photosphere:
- magnetic field "frozen in"

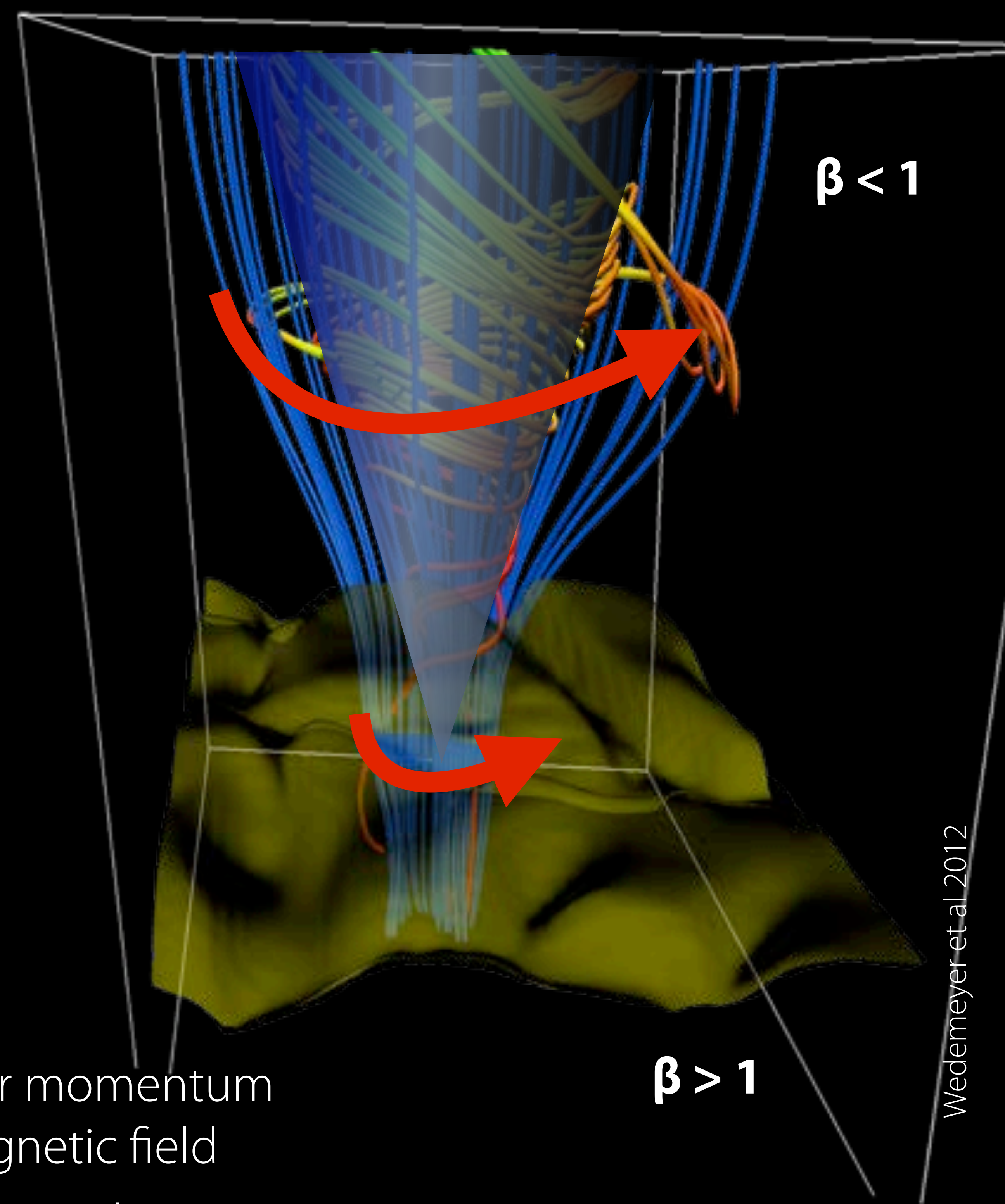
➡ photospheric vortex flow rotates magnetic flux structure

- 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

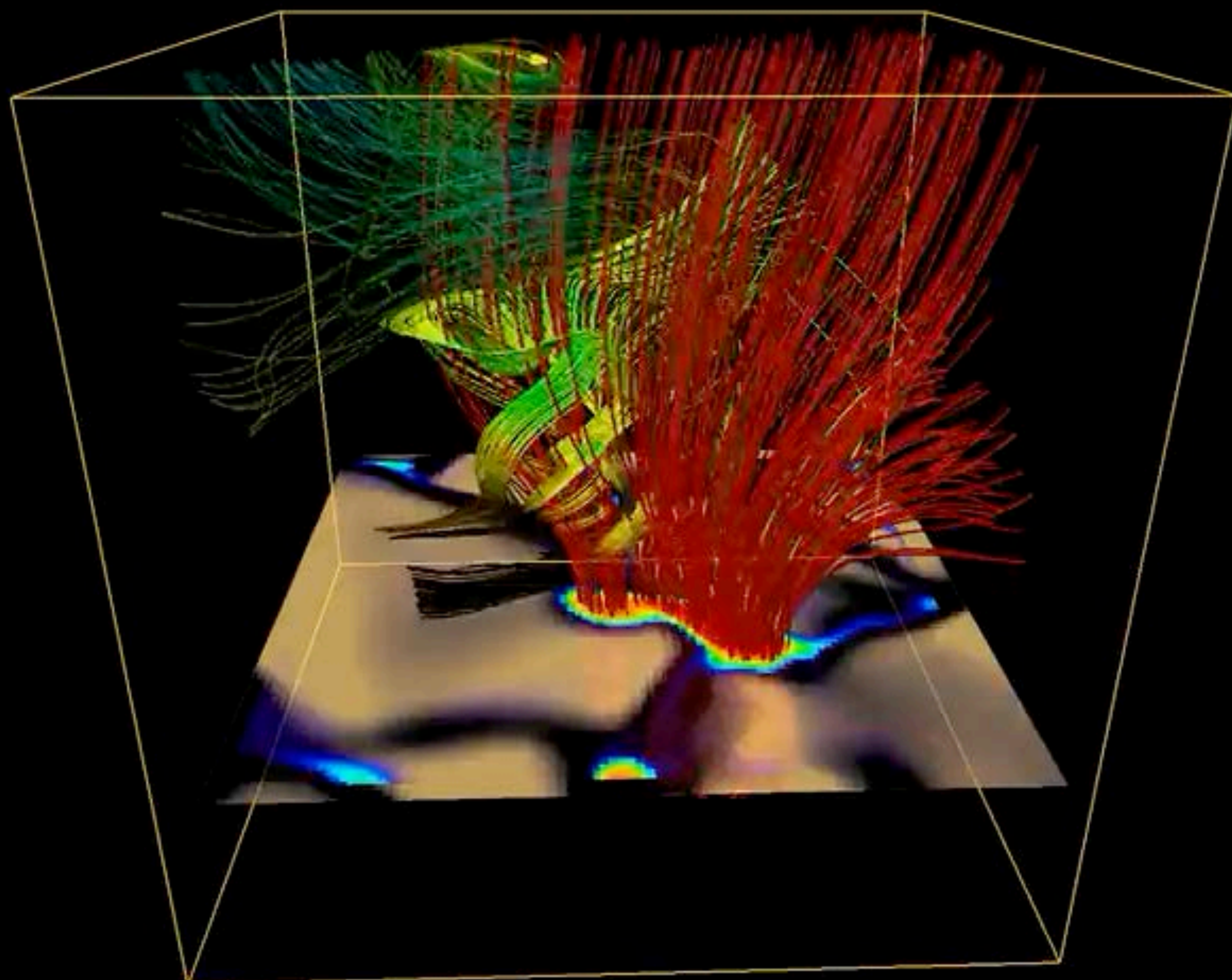
  ➡ spiral motions (both up and down)



- 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