AST5770

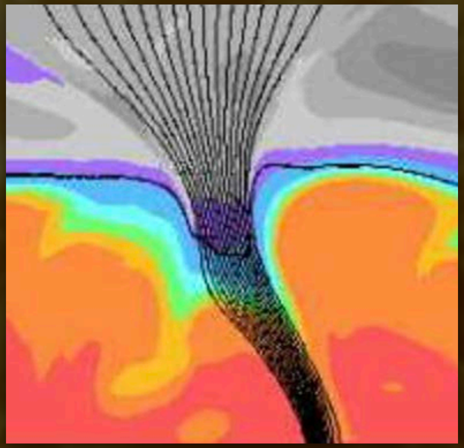
Solar and stellar physics

Sven Wedemeyer, University of Oslo, 2023

Magnetic field in the solar atmosphere

Magnetism

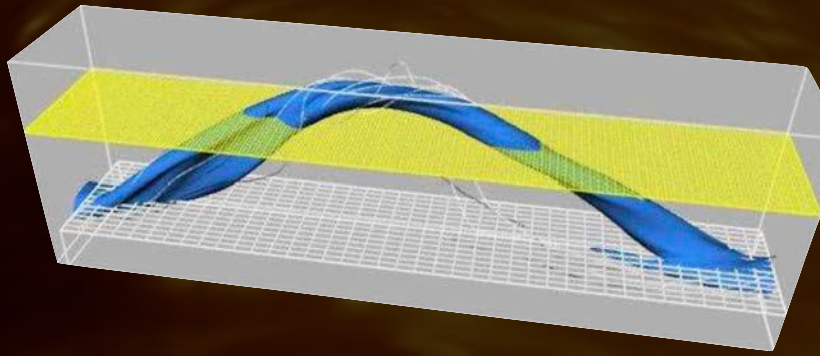
Recap



- **Magnetic pressure** $P_m = B^2 / 8\pi$
  - Affects structure and dynamics of the plasma by "competing" with thermal pressure.
    - Magnetic flux structures funnel out in the atmosphere.
    - Magnetic flux bundles in the convection zone become buoyant.

- **Plasma-β parameter** = ratio of thermal to magnetic pressure
  - $\beta < 1$: Magnetic field dominates and dictates the dynamics of the gas
  - $\beta > 1$: Thermal gas dynamics dominate and forces the field to follow

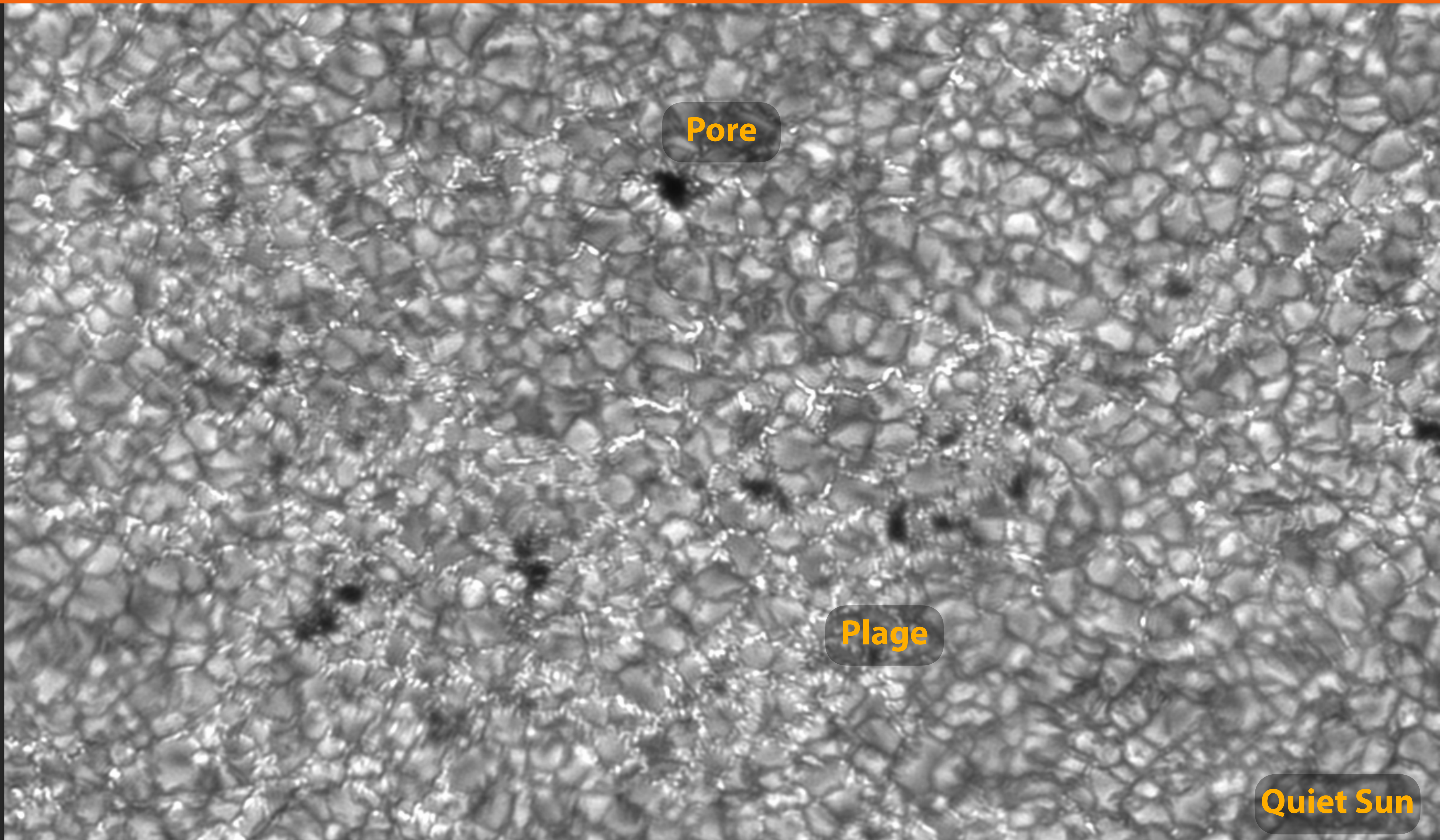
    — The magnetic field is **frozen-in.**



- **Flux emergence**
  - Magnetic flux "ropes" become buoyant and rise
  - Emergence of bipolar regions with a large range of contained magnetic flux
  - Occurrence scales with contained magnetic flux

SST — Scharmer

Magnetic field in the solar atmosphere

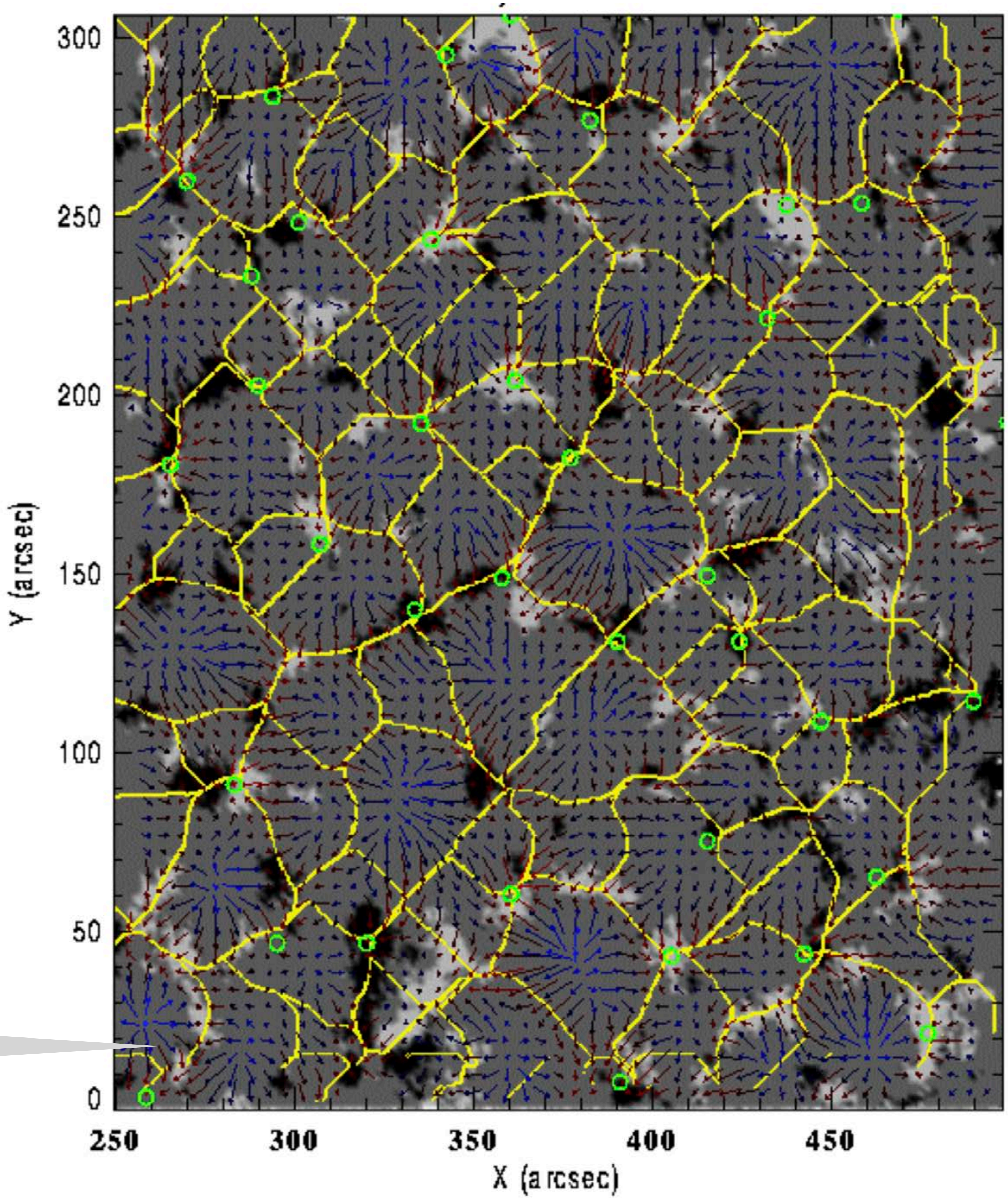


G-band observation — magnetic field concentrations visible with high contrast in this band

Magnetic field in the solar atmosphere

Advection — supergranulation scales

- Magnetic field emerges to the surface
- Away from strong fields (sunspots): **High plasma-β** in the photosphere
- **Frozen-in** magnetic field
- Field is advected with the photospheric velocity field towards the **edges of supergranules**
- Concentrated there, resulting in stronger magnetic flux concentrations
- Observable as **magnetic network**
- Encloses **inter-network regions**

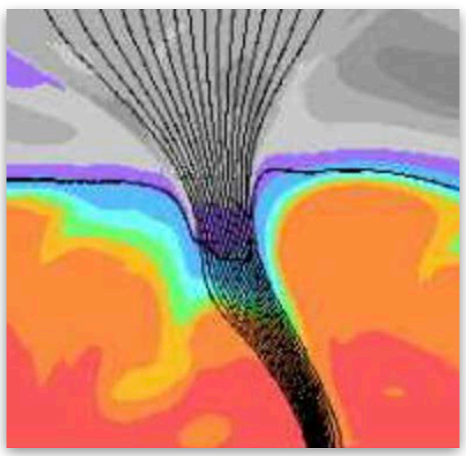


- Magnetogram (grayscale)
- Horizontal flow field (arrows)
- Supergranule boundaries: yellow

Magnetic field in the solar atmosphere

Advection — granulation scales

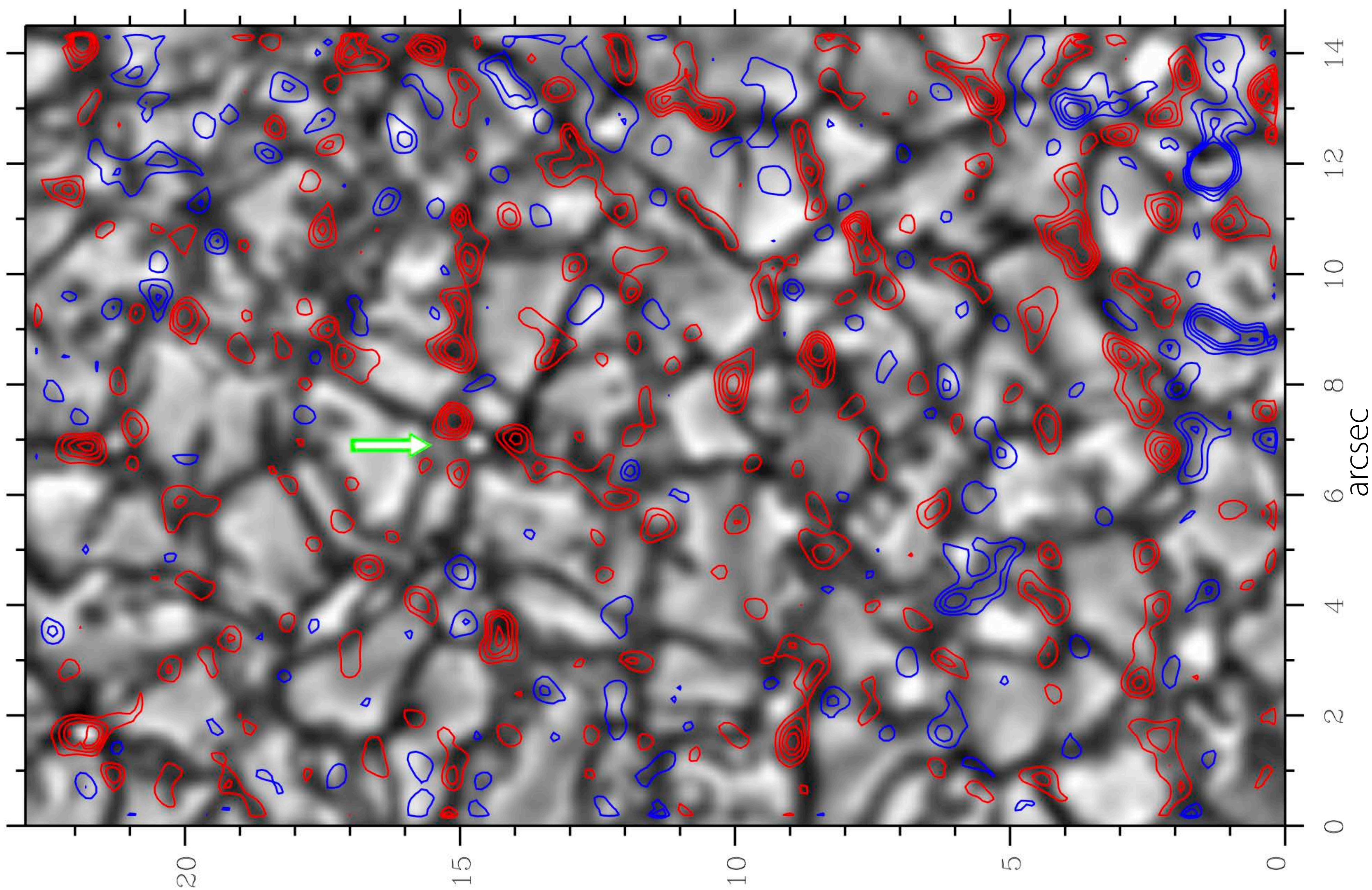
- Advection into intergranular lanes (downflow lanes between granules)
- Concentration into stronger flux concentrations but fewer than in the network



Granulation image, Fe I 630.25 nm line

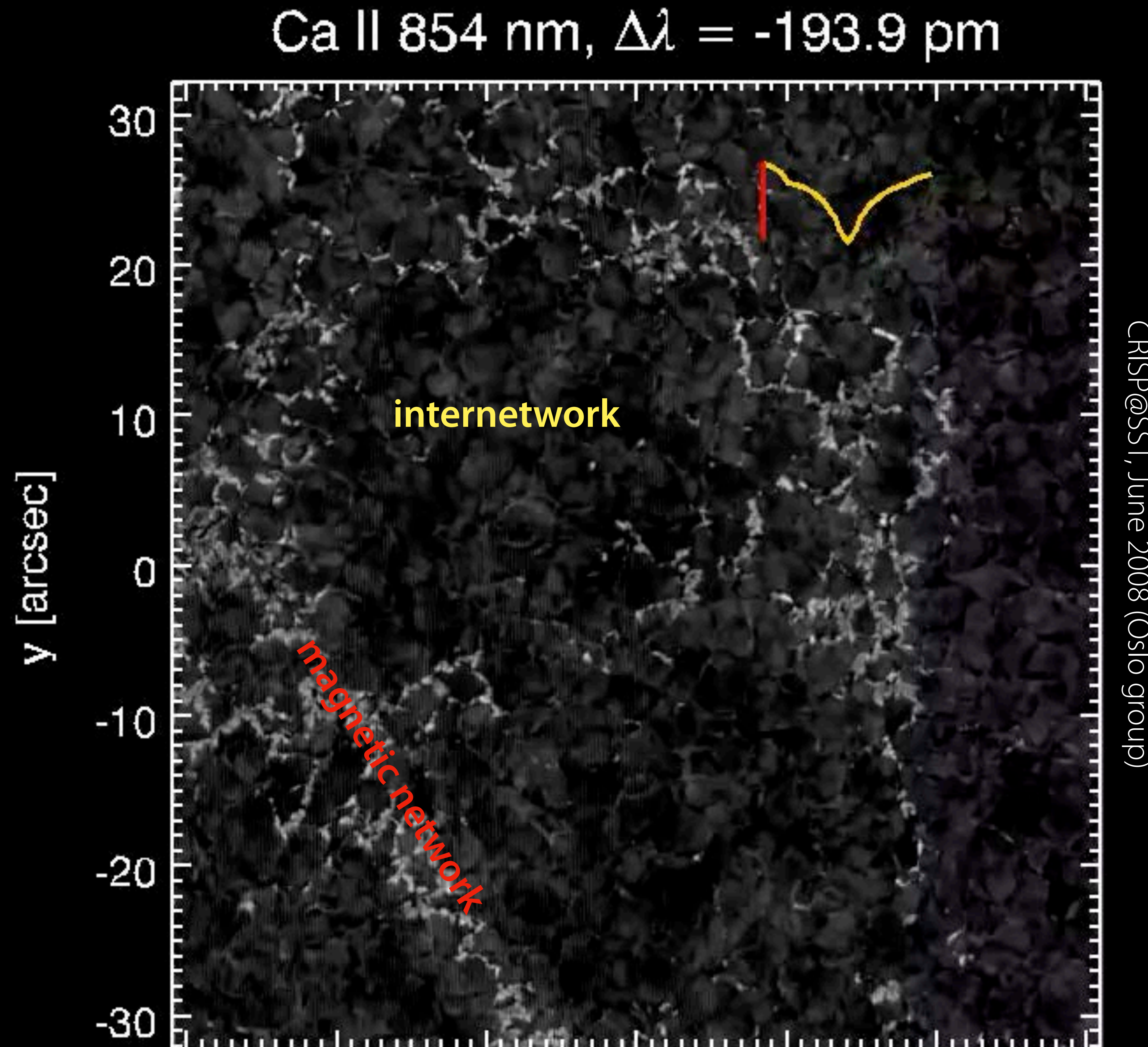
Overlaid magnetogram contours 30, 50, 70 and 90 G

(Dominguez Cerdena et al., 2003)



Magnetic field in the solar atmosphere

- Different parts of the line formed at different heights
- Looking a bit higher in the atmosphere
- Spatial scales corresponding to granulation visible
- Prominent scale with super granulation, here with cell sizes of ~30Mm
- Extension of magnetic field from photospheric footprints into the chromosphere



Magnetic field in the solar atmosphere

photo-
sphere

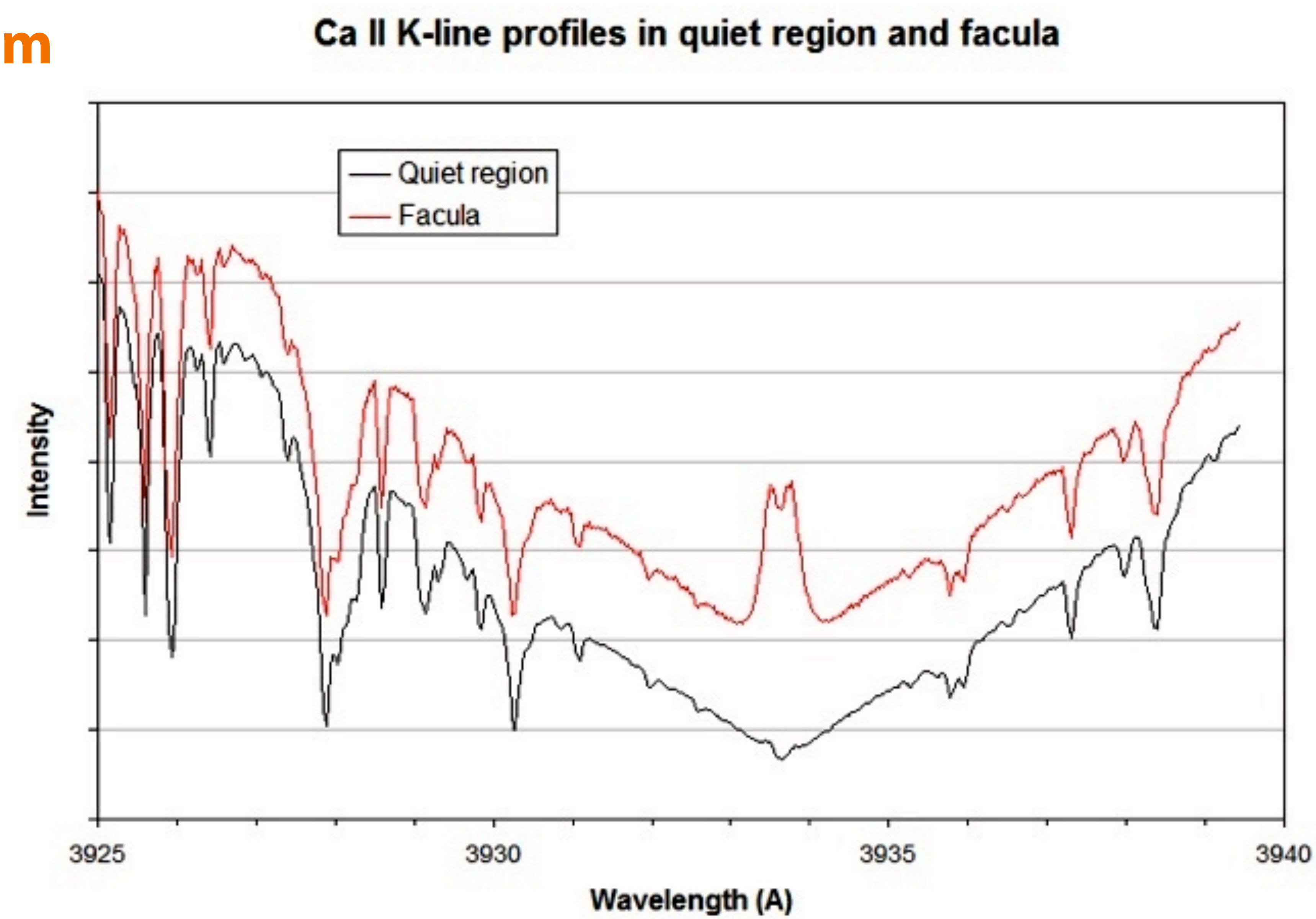
chromo-
sphere

formation height

continuum

line wing

line core



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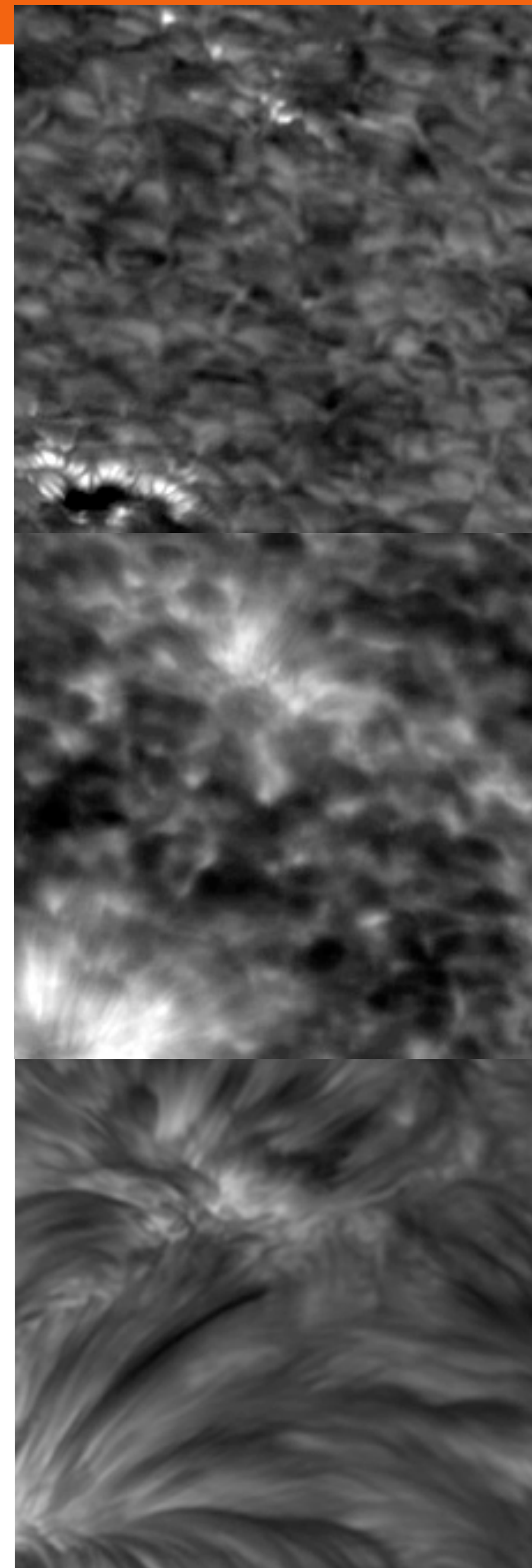
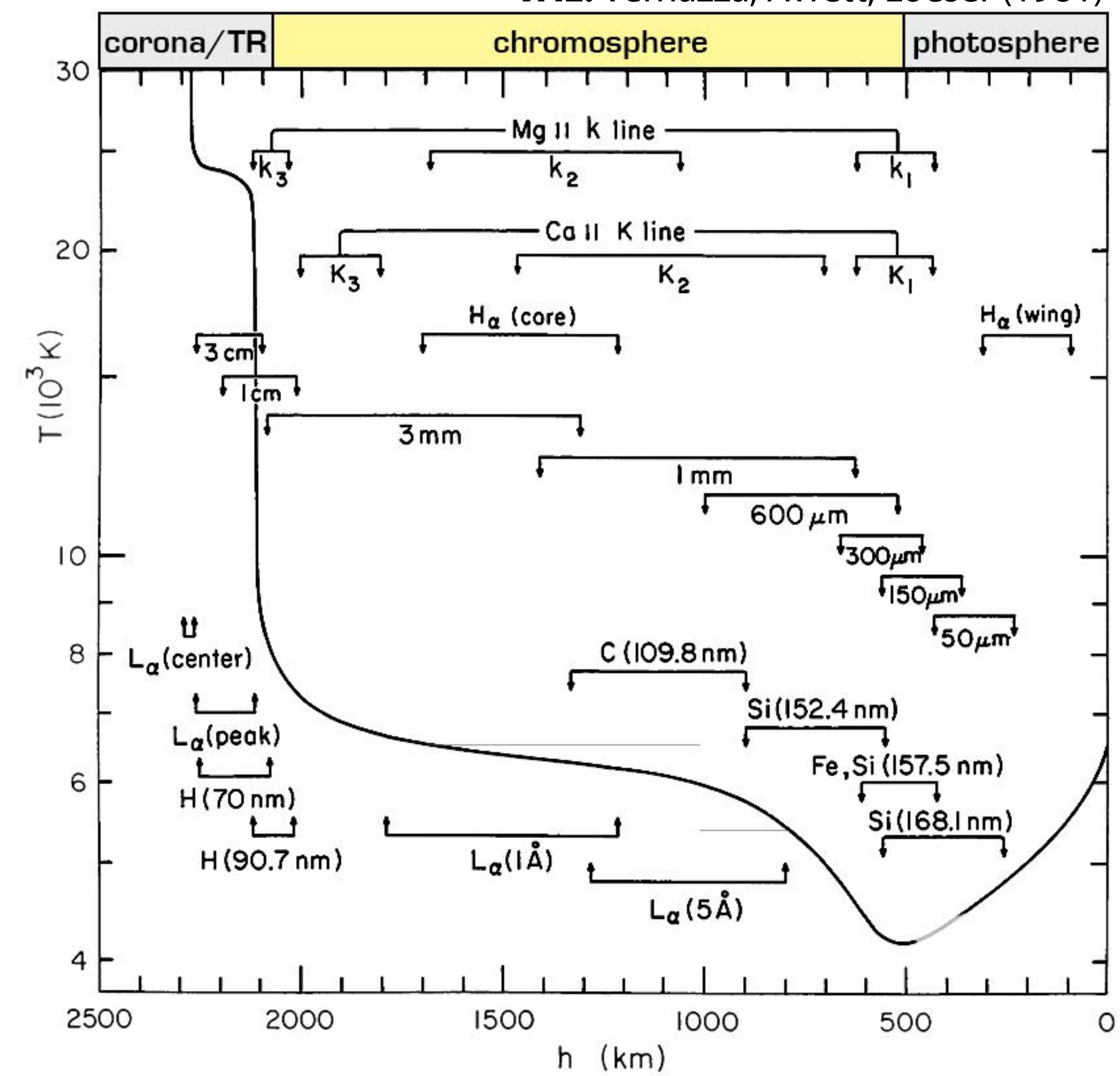
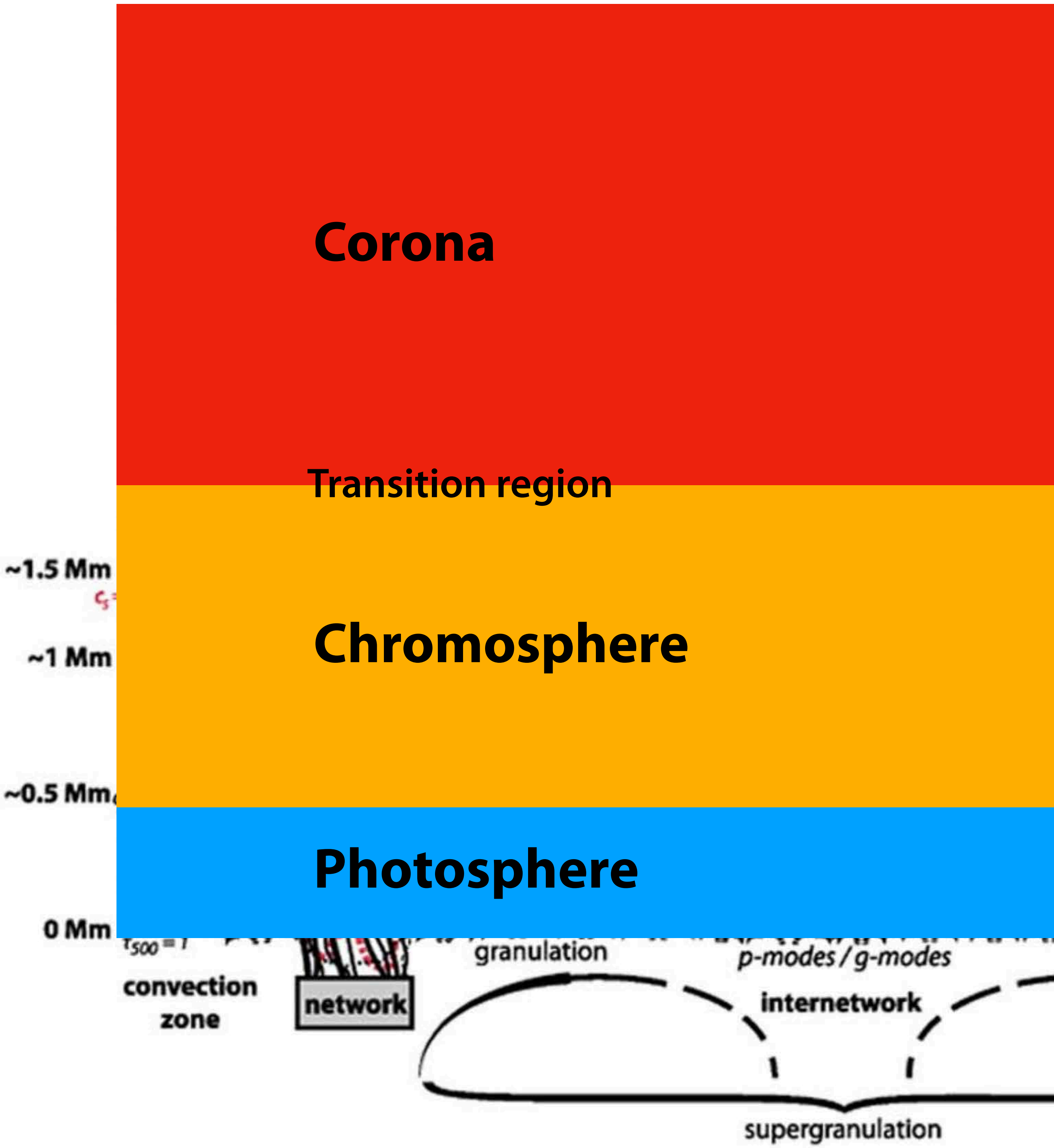


Magnetic field in the solar atmosphere

Structure of Quiet Sun regions

VAL: Vernazza, Avrett, Loeser (1981)



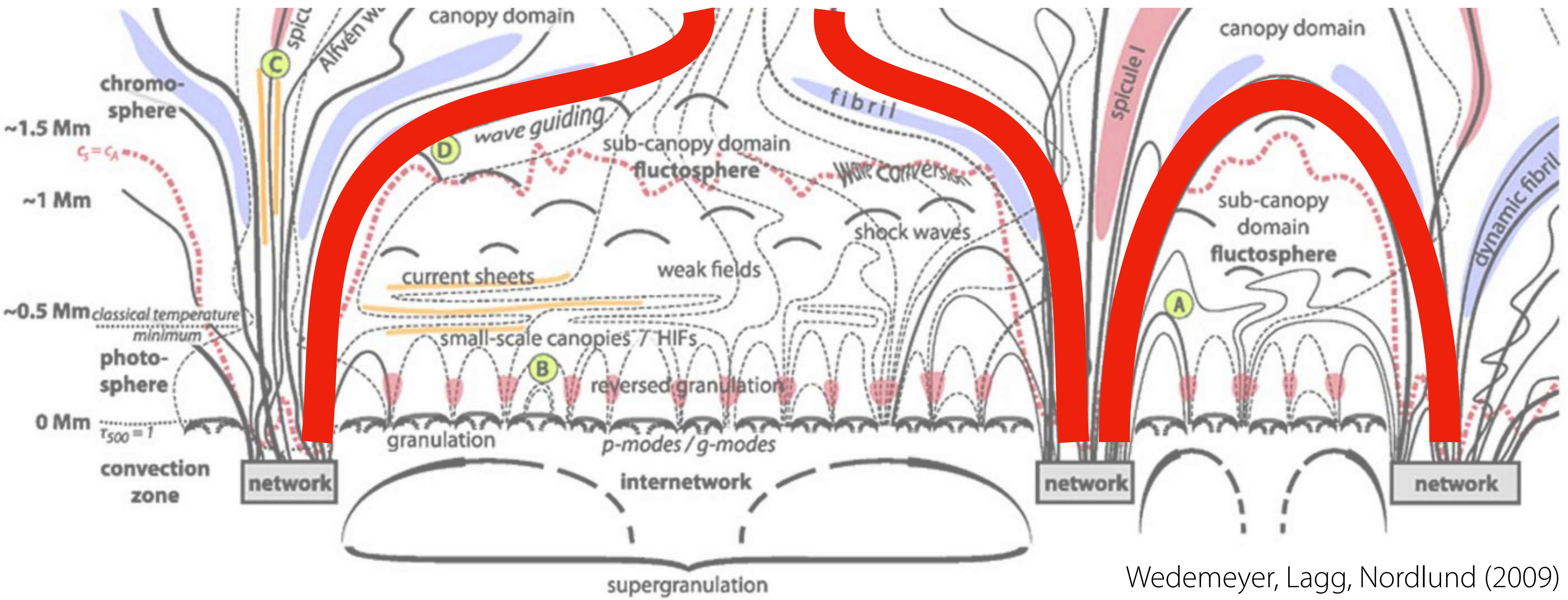


Wedemeyer, Lagg, Nordlund (2009)

Magnetic field in the solar atmosphere

Structure of Quiet Sun regions

- Magnetic field in the photosphere: Footpoints with vertical field
- Chromosphere: Magnetic field connects polarities, forms loop with horizontal field, forms “canopies”
- Different diagnostics (spectral lines/continua) show different layers and aspects
  - Horizontal chromospheric field clearer at some wavelengths (e.g. : Hα core) than at others

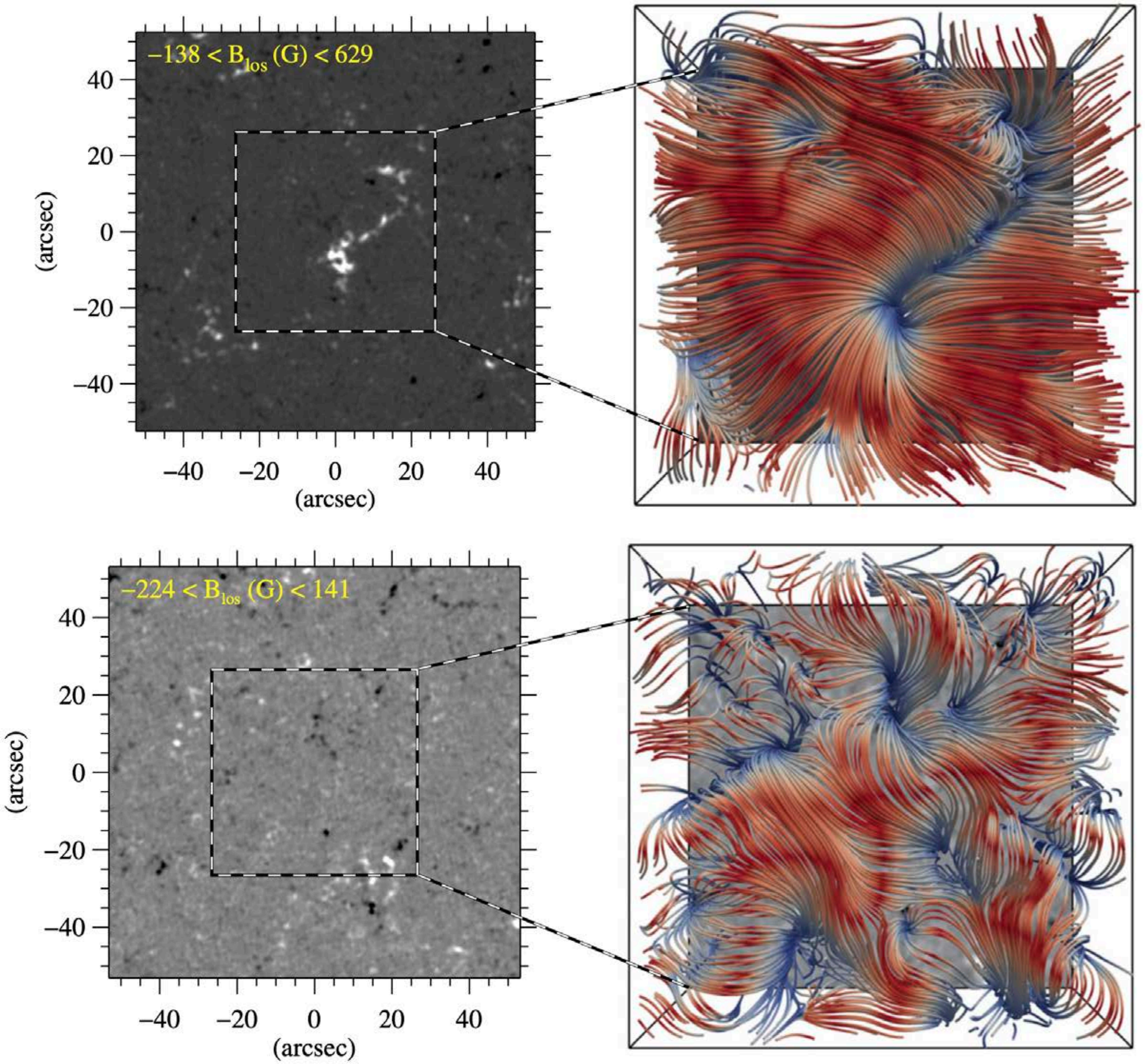


Wedemeyer, Lagg, Nordlund (2009)

Magnetic field in the solar atmosphere

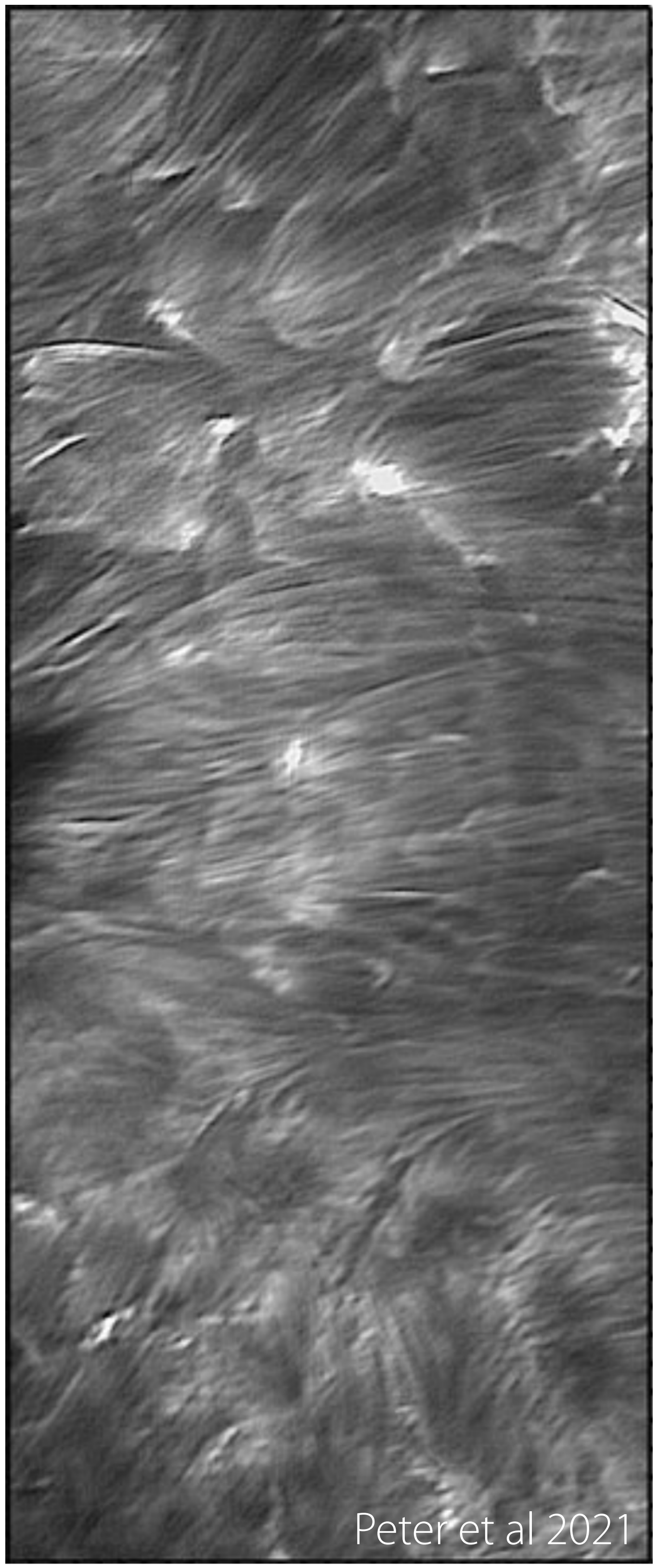
Structure of Quiet Sun regions

Magnetic field extrapolation from photospheric magnetograms



Jafarzadeh et al 2021

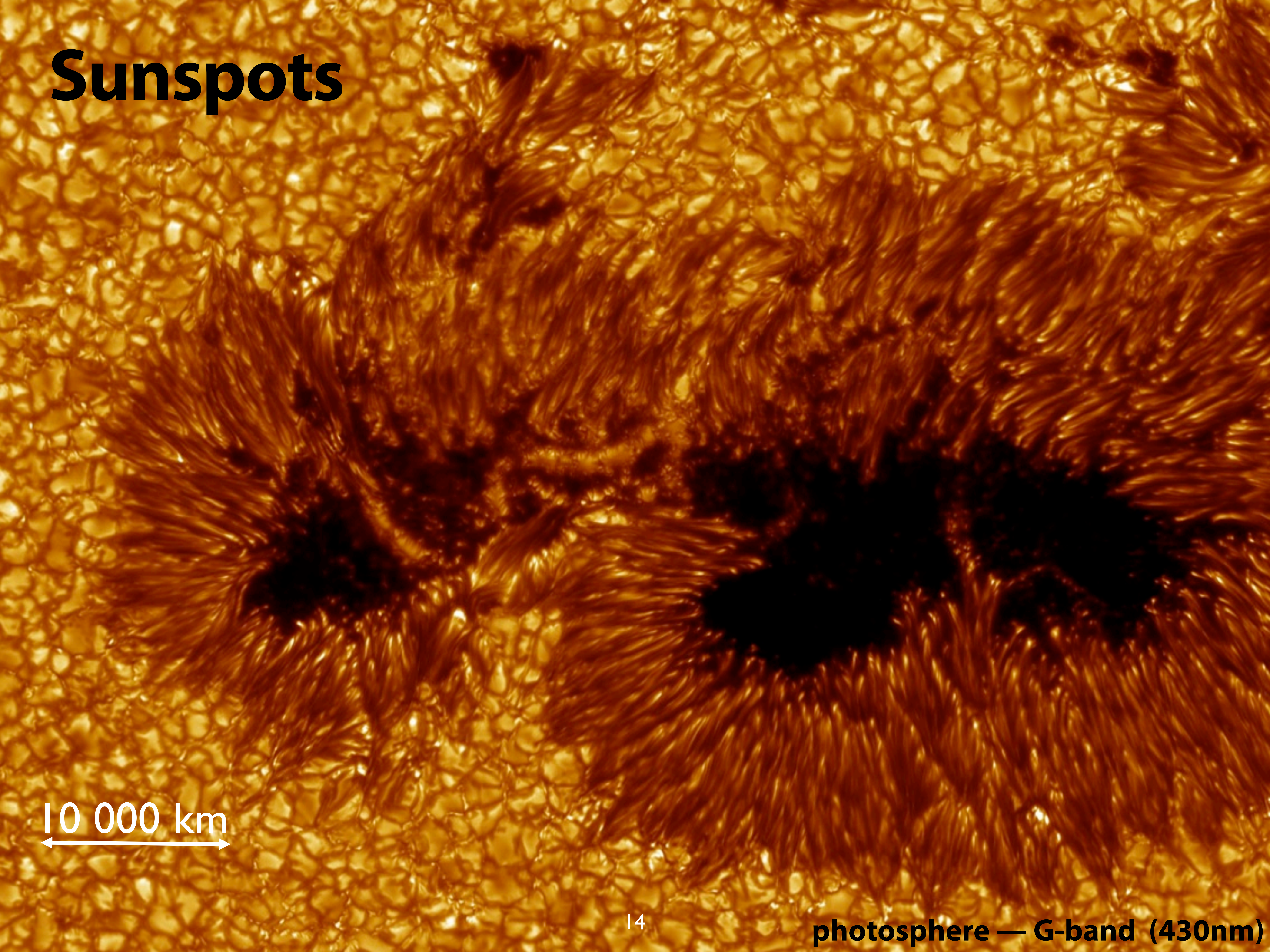
Observed: Fibrils in Ca II K



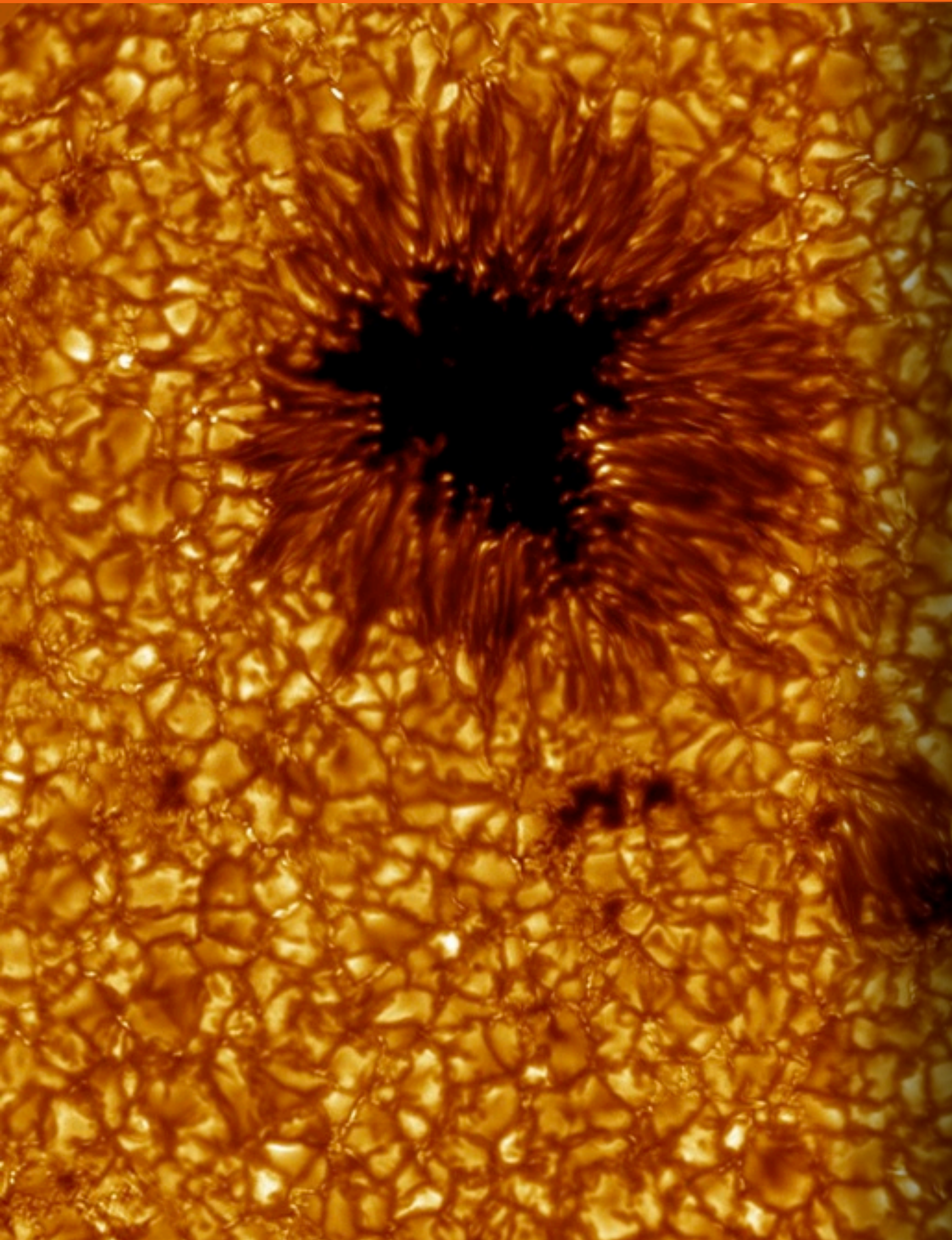
Peter et al 2021

Sunspots

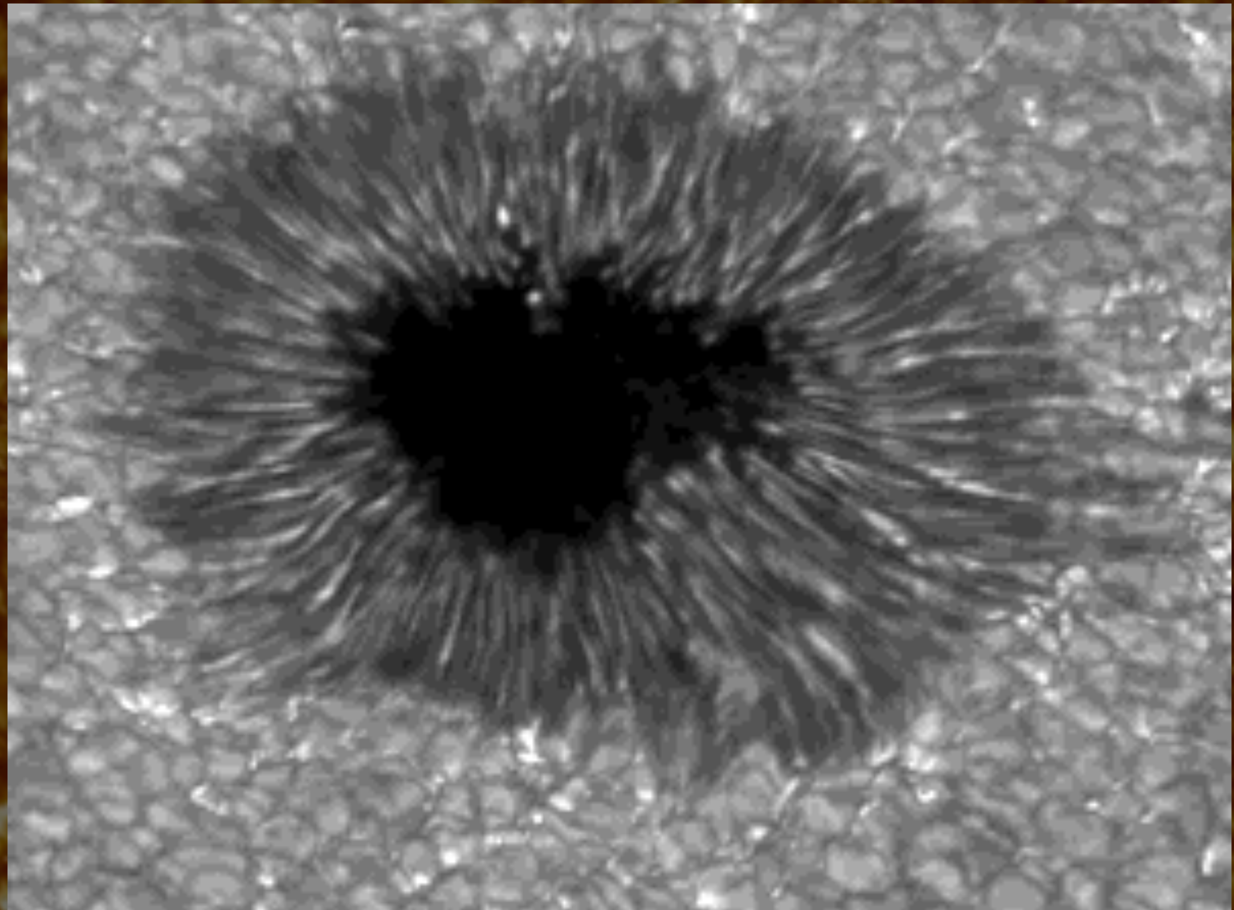
Sunspots



Sunspots



- **Magnetic field strength:** Max. values in the (central) umbra 2000-3500 G
- Field strength decreases radially outwards, ~1000 G at the boundary
- **Brightness** with respect to Quiet Sun: umbra: 20%, penumbra: 75%



Sunspots

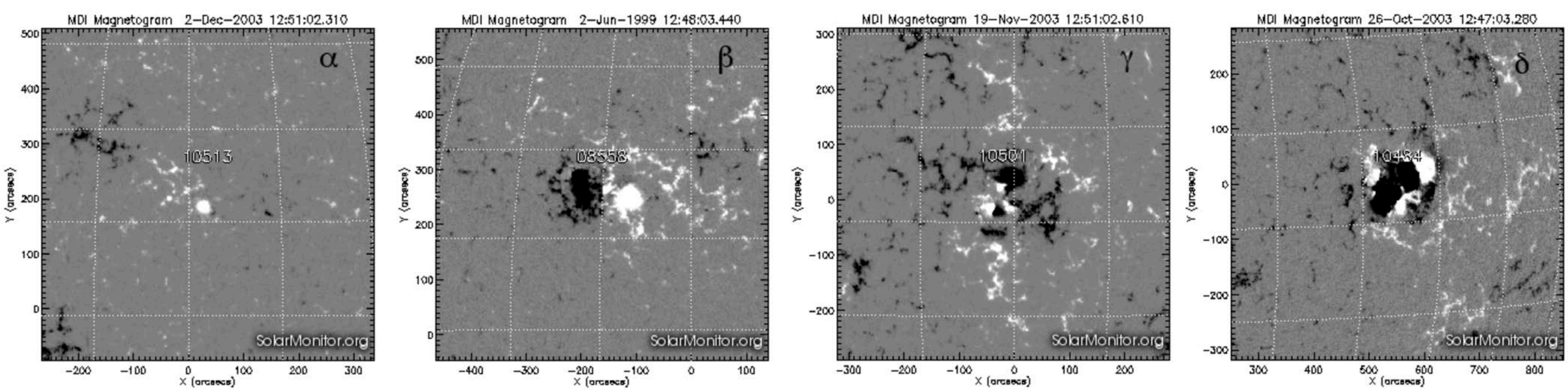
Evolution

Sunspots

Classification

- Several classification schemes (going back to e.g. Hale et al. 1919)
- **Modified Mount Wilson sunspot classification scheme** (Bray & Loughhead, 1964; Künzel (1960)

α — Unipolar sunspot group.	**β — Bipolar** sunspot group with both positive and negative magnetic polarities (bipolar), simple and distinct division between polarities.	**γ — Multipolar.** Complex sunspot group, pos. and neg. polarities irregularly distributed.	**δ** — Sunspot group with umbrae of pos. and neg. polarities within 2 degrees, sharing same penumbra



Murray (2013)

Sunspots

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βγ — Bipolar sunspot group but complex so that no single, continuous line can be drawn between spots of opposite polarities.	**βδ —** Sunspot group of β class but containing one (or more) δ spots.	**βγδ —** Sunspot group of βγ class but containing one (or more) δ spots.	**γδ —** Sunspot group of γ class but containing one (or more) δ spots.

The Sun's magnetic field has a complicated topology.

Nikbakhsh et al. 2019

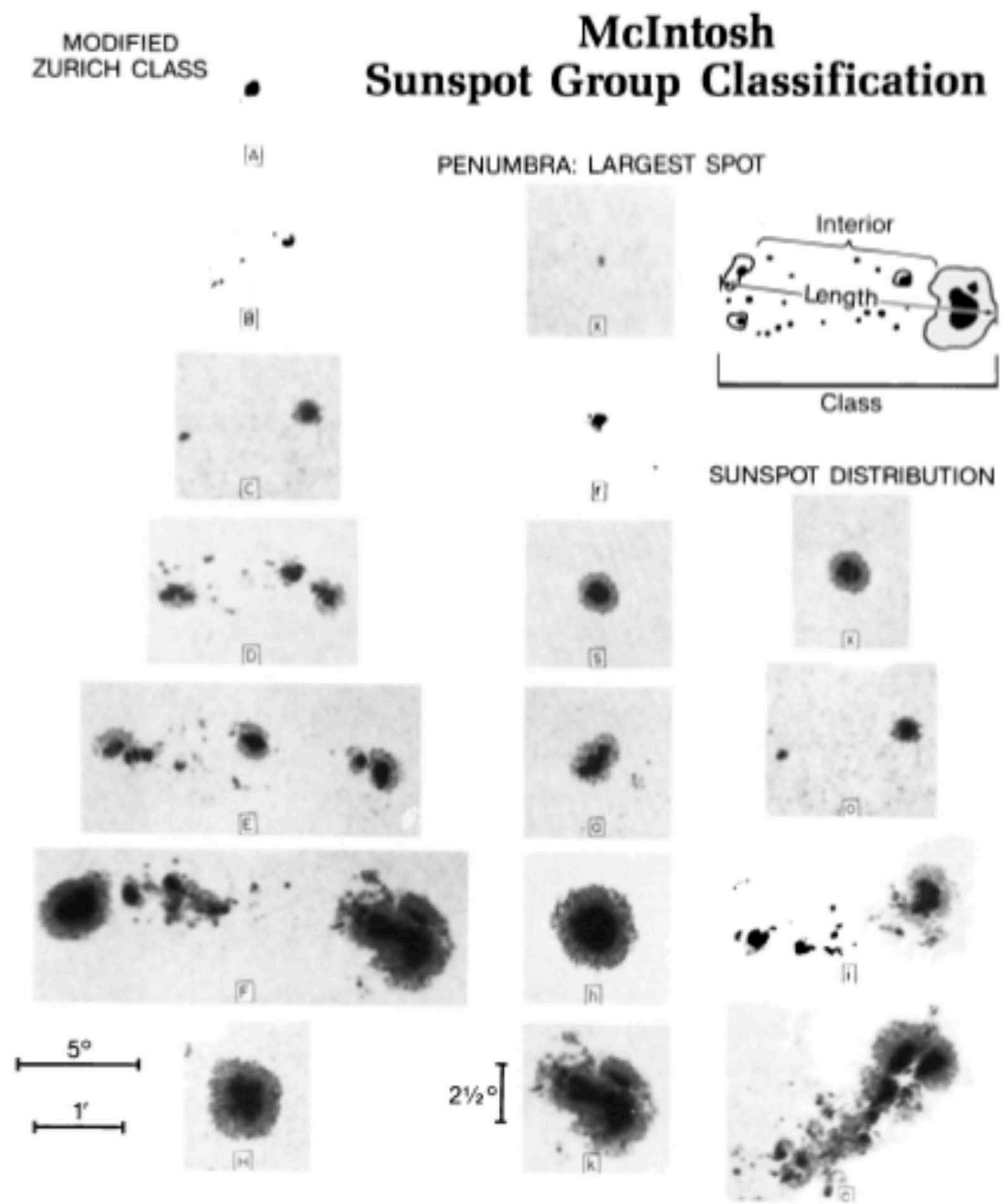
Table 2: Total and relative abundances of each complexity class according to the daily number of ARs from January 1996 to December 2018.

Complexity	Count [number]	Relative abundance [%]	
α	10296	30.73	**88.30**
β	19284	57.57	
$\beta\gamma$	2919	8.71	**11.68**
$\beta\gamma\delta$	997	2.97	
$\beta\delta$	166	0.49	
γ	4	0.01	
$\gamma\delta$	5	0.01	
Total count	33671		

Sunspots

Classification

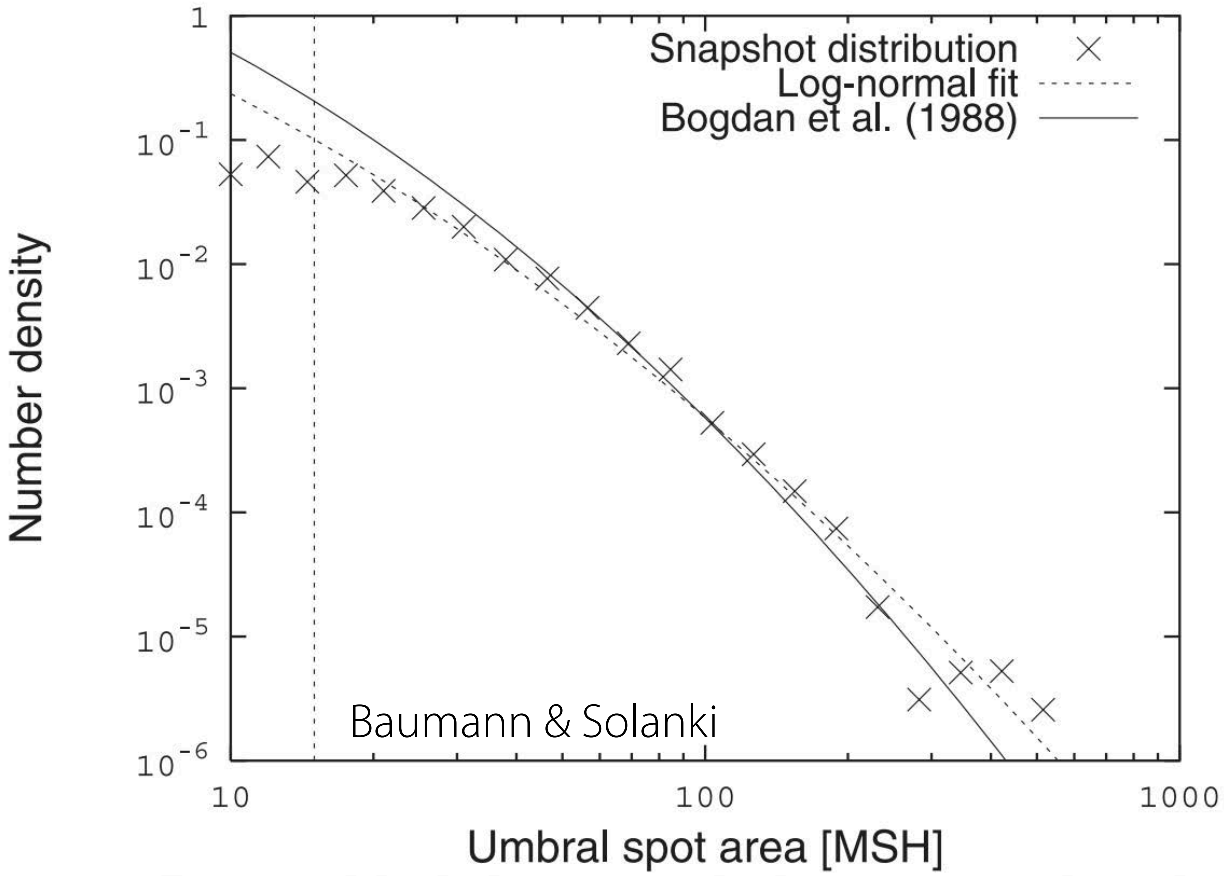
- New classification of sunspots based on their likelihood of flaring (McIntosh 1990 / Zürich class)
- Fkc class spots are much more **likely to flare**!
    - F = bipolar group with penumbra around spots at both ends of the group
    - k = Large, asymmetric penumbra
    - c= Compact sunspot distribution.
- Note: **Sunspots change classification during their evolution**, often beginning with simple structure and becoming more complex.



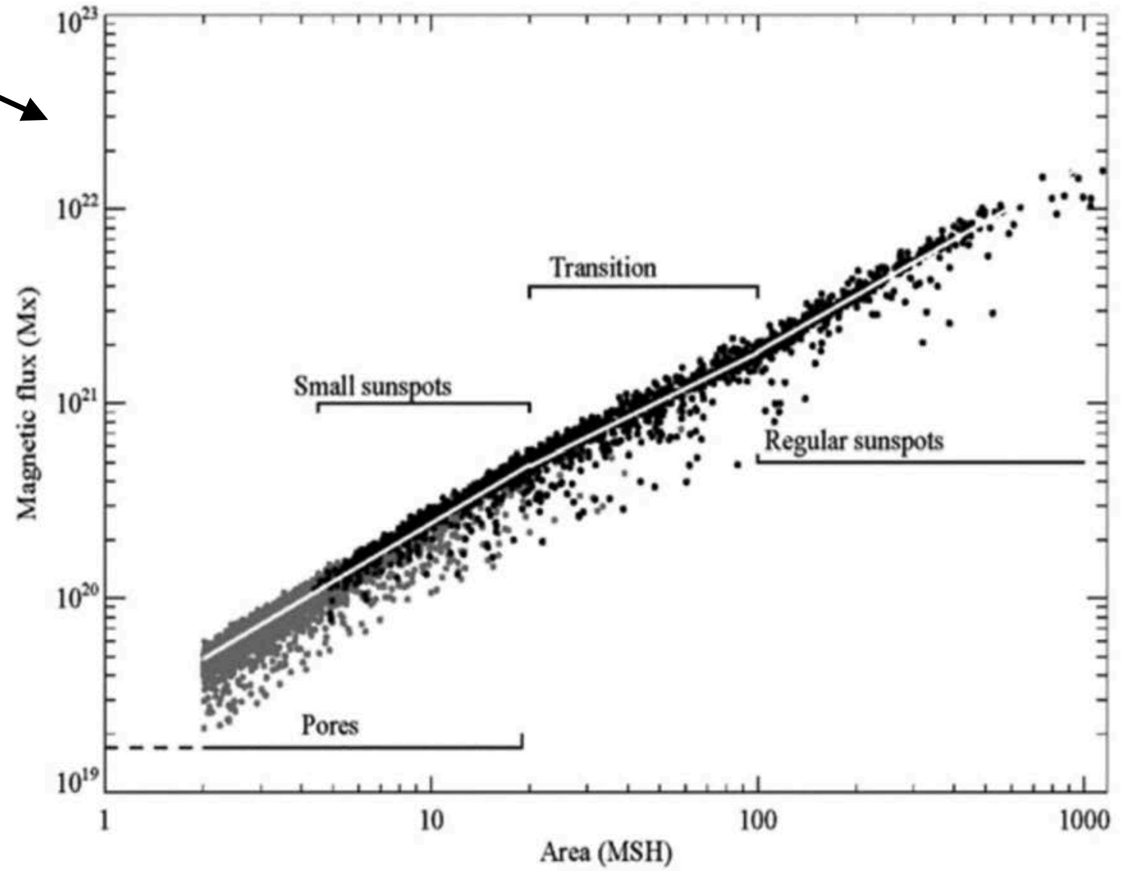
Sunspots

Sizes and lifetimes

- **Large range of diameters:**
  - very large sunspots up to 60 000 km (rare) and down to 3000 km (also rare)
  - Smaller photospheric magnetic structures: pores and magnetic elements



- Contained **magnetic flux** scales with area
- Smooth transition to smaller features (pores)



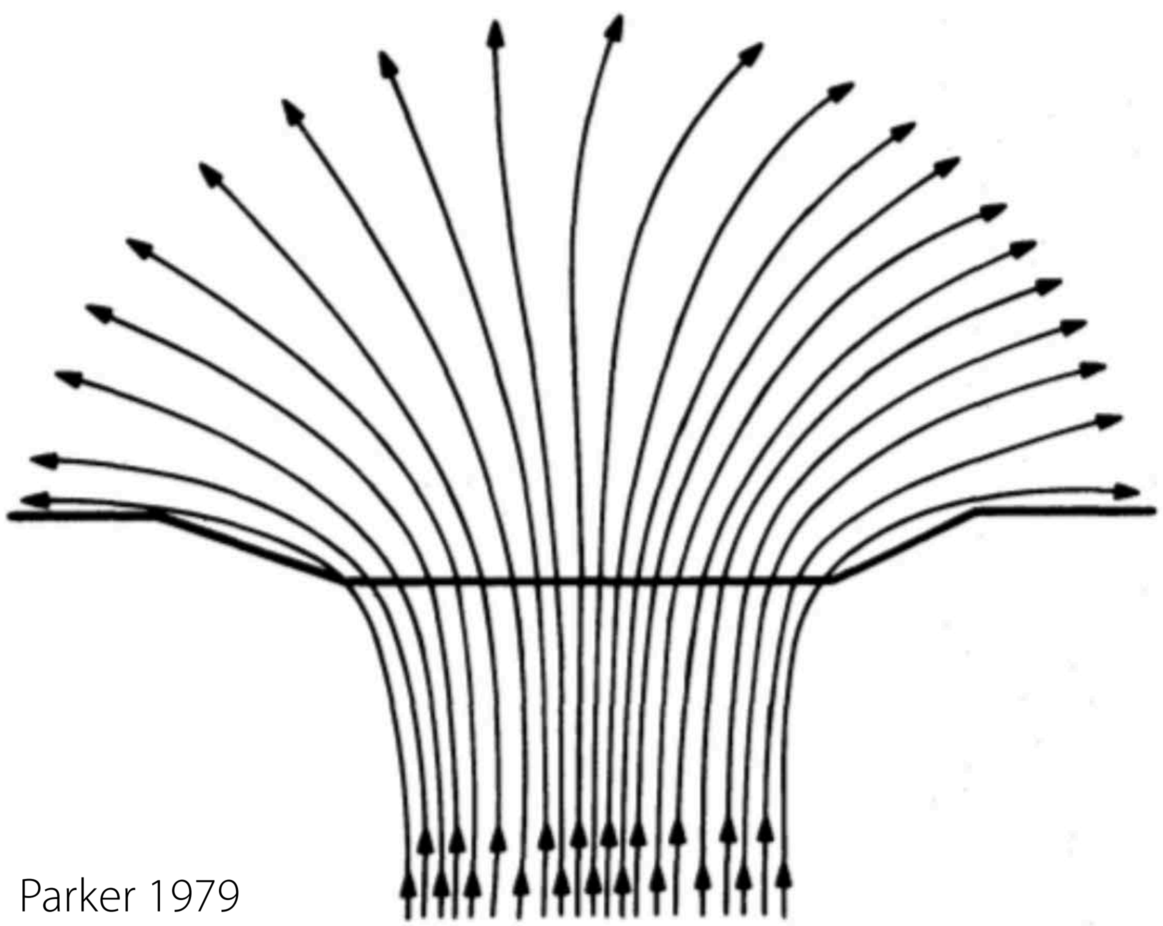
- **Lifetimes:** from hours for small sunspots to (rarely) months for the largest ones
  - Lifetime increases linearly with max. sunspot area
  - Sunspots decay steadily soon after reaching max. size due turbulent diffusion of the magnetic field at the surface

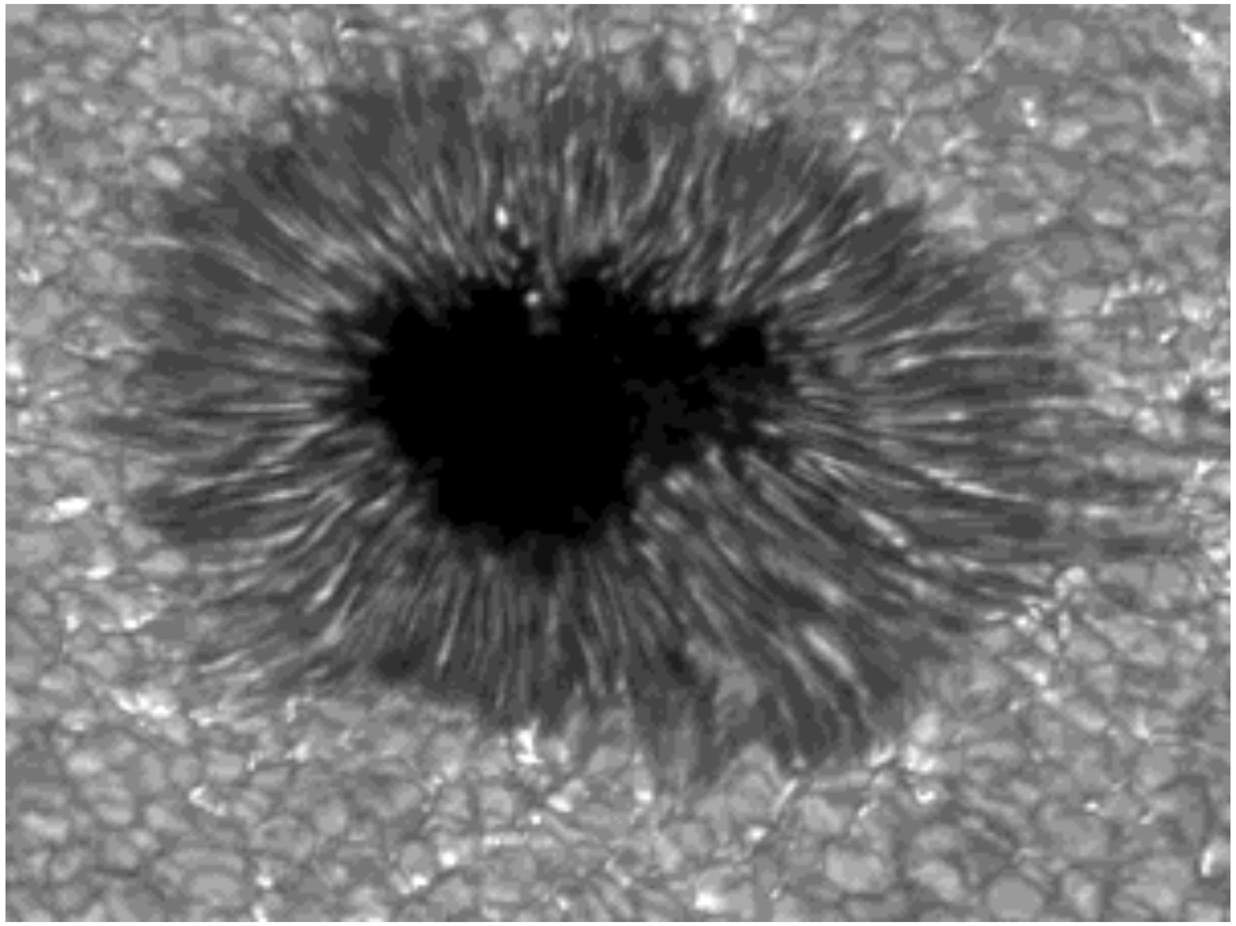
Sunspots

Magnetic field structure

- In the centre of the umbra (photosphere): Vertically aligned
- Increasing inclinations outwards, becoming almost horizontal in the penumbra
- Penumbra: bright radial filaments with field inclination ~40 deg* in outer penumbra, alternates with dark filaments with nearly horizontal field
- Regular spot (pairs): dipolar structure on large scales
- Complex field structure on small scales

*with respect to the horizontal


Parker 1979



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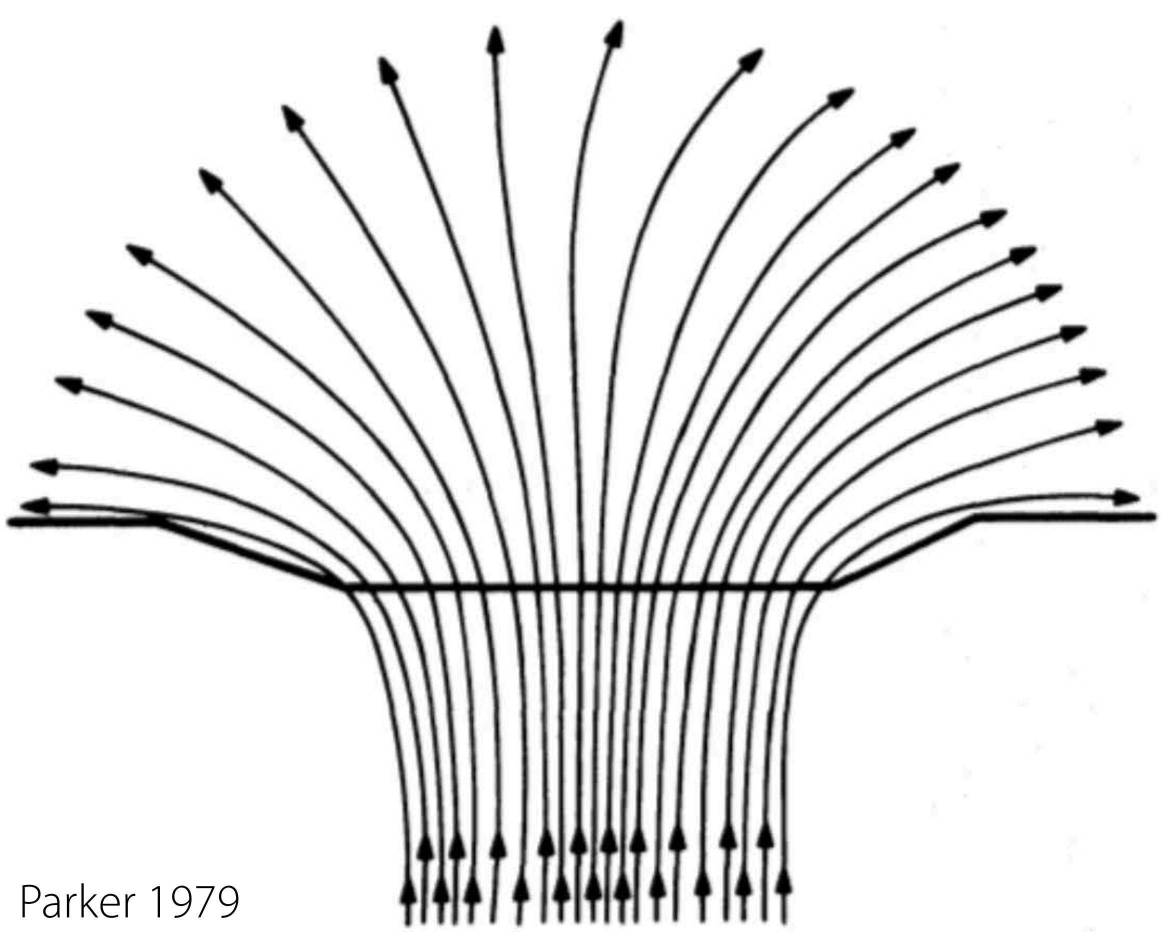

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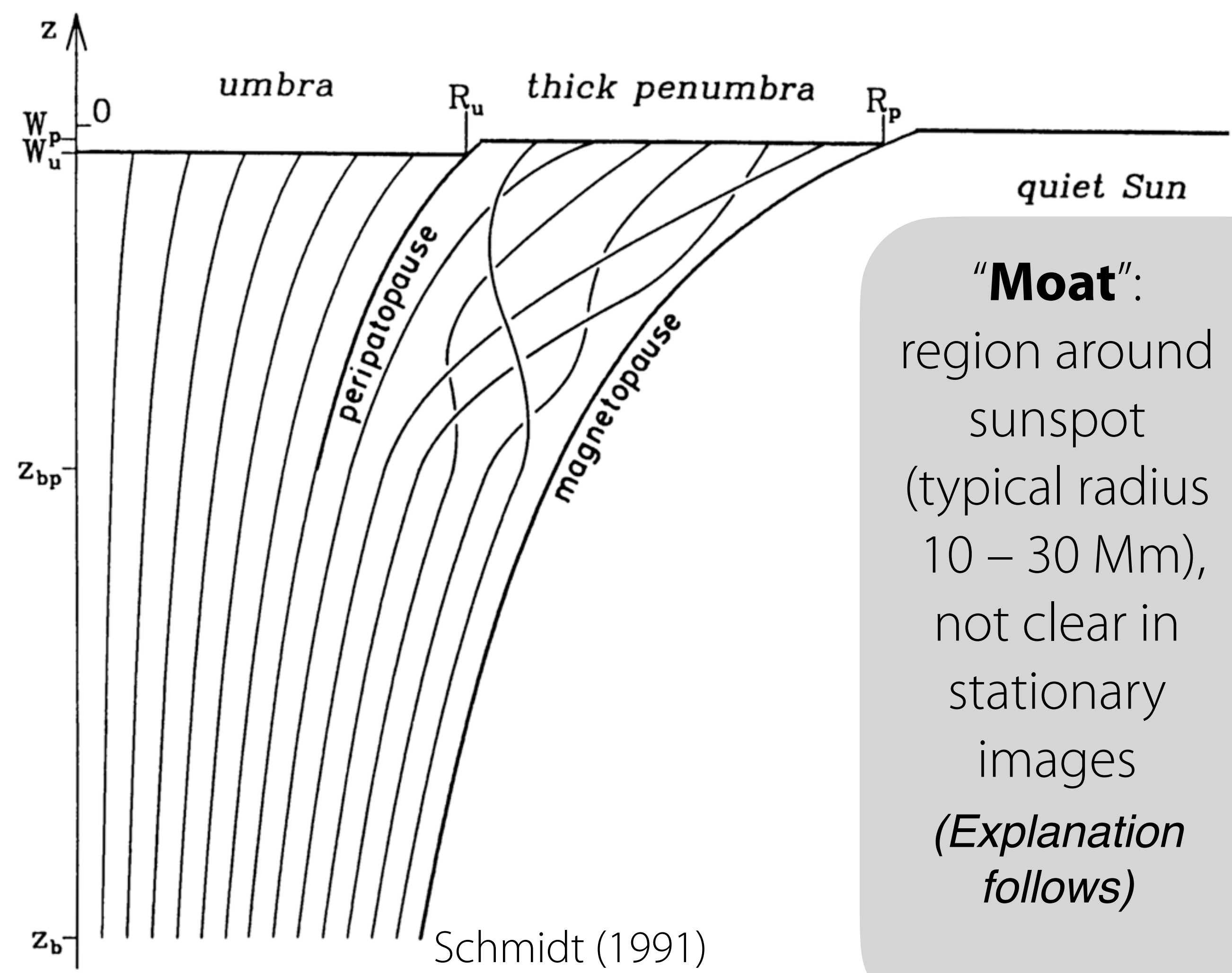

Schmidt (1991)

"**Moat**": region around sunspot (typical radius 10 – 30 Mm), not clear in stationary images

(Explanation follows)

Sunspots

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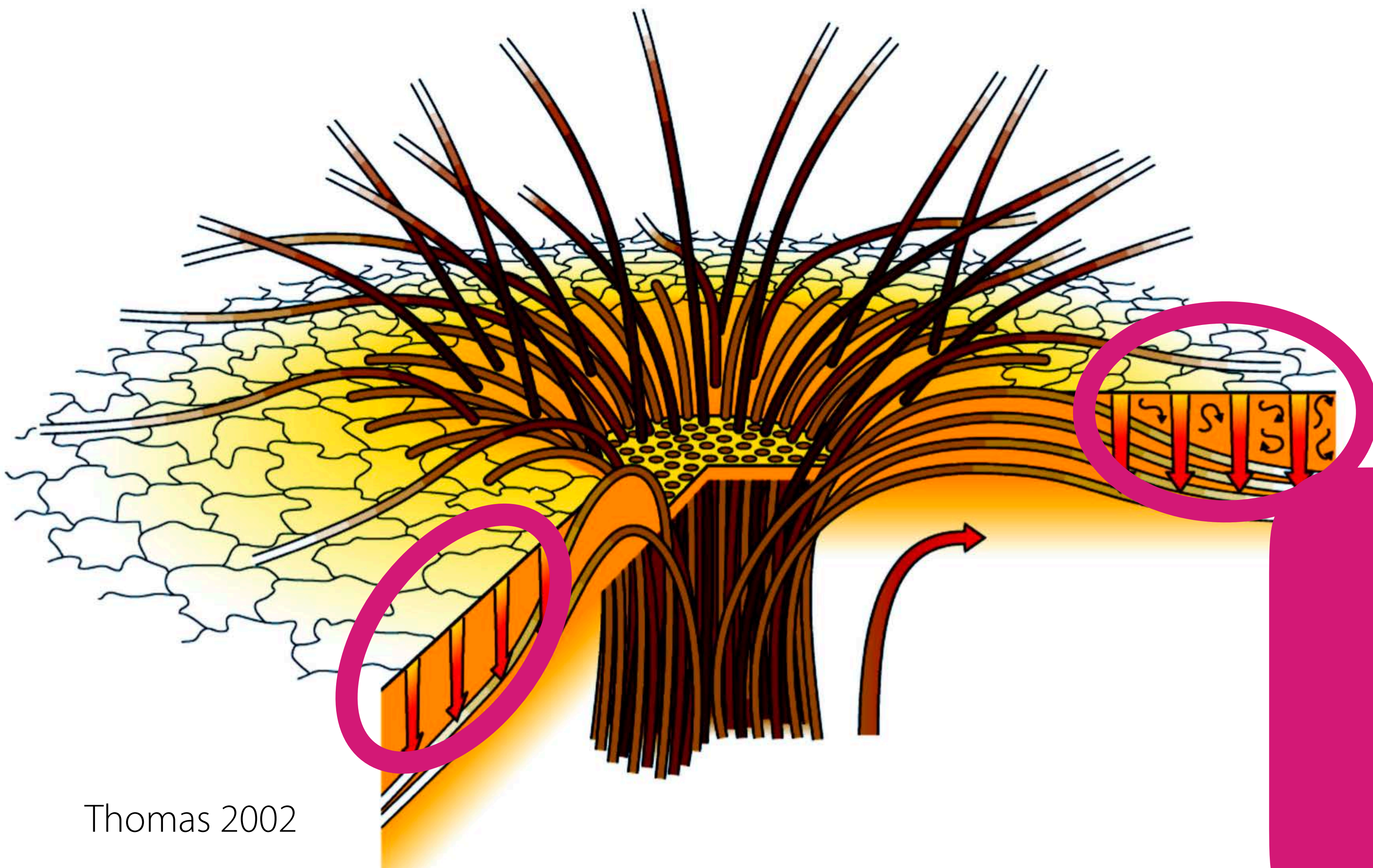
"Uncombed penumbra"
Mix of horizontally aligned and inclined magnetic field

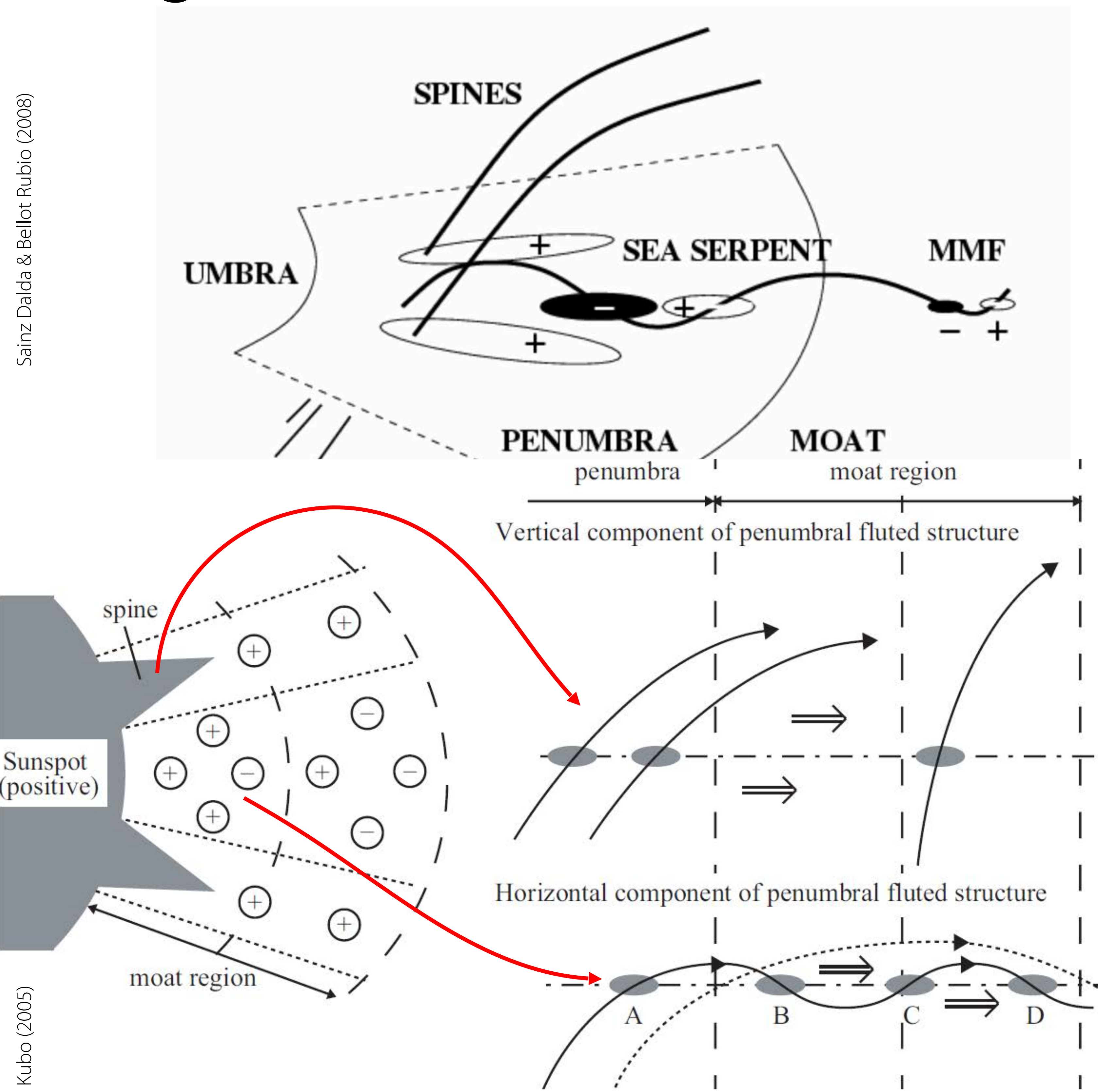


Thomas 2002

- Submerged parts penumbral flux tubes **dragged/held down by convection** on granule scales (in the moat), referred to as "turbulent pumping"

Sunspots

Magnetic field structure



Sainz Dalda & Bellot Rubio (2008)

Kubo (2005)

- Submerged parts penumbral flux tubes **dragged/held down by convection** on granule scales (in the moat), referred to as “turbulent pumping”

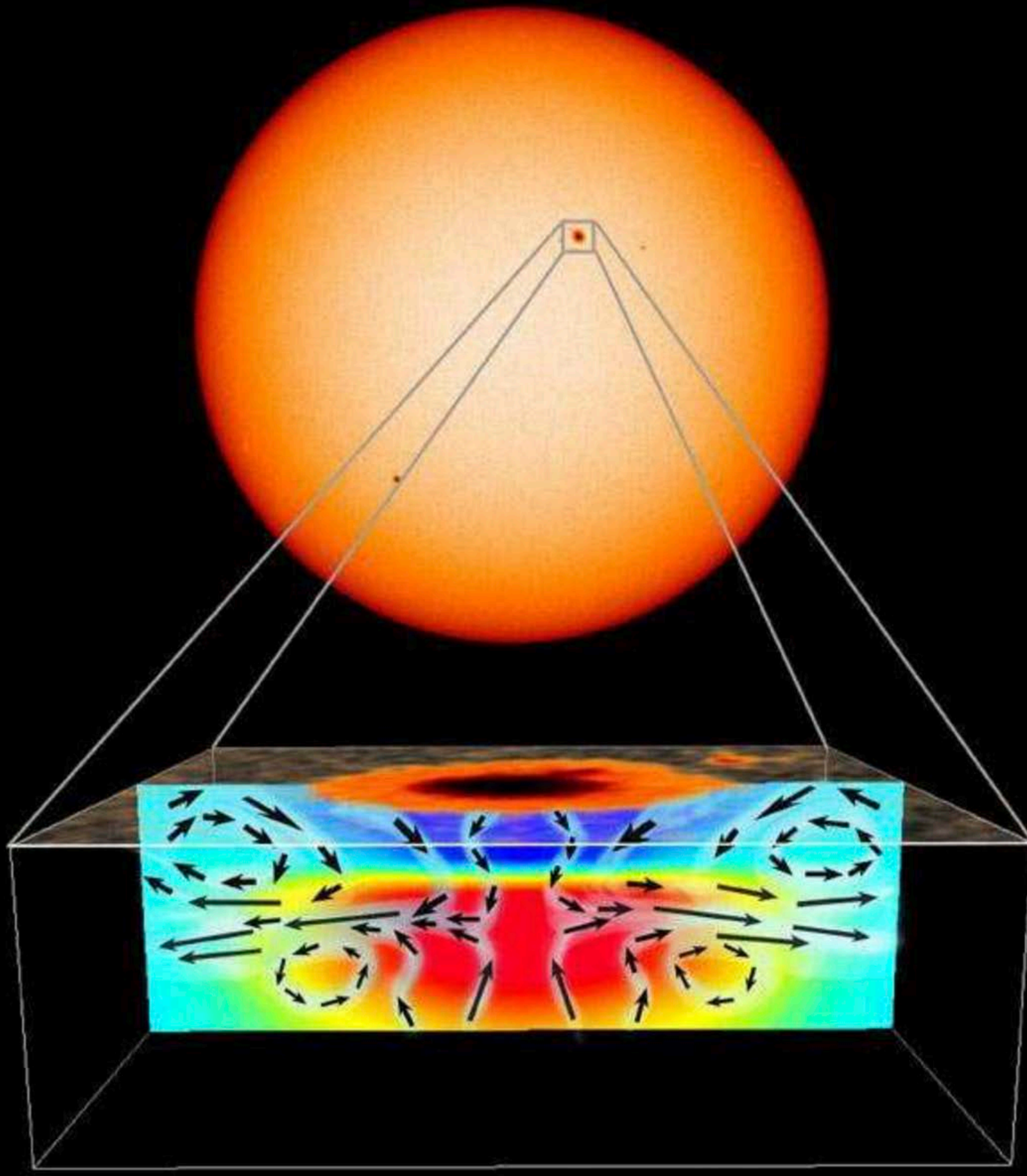
➡ **“Sea serpents”**

- **Spines** are more inclined (more vertical) magnetic filaments
- **Moving magnetic features** (MMF):
  - Extensions of penumbral field in the moat region
  - Bipolar small-scale features (<1”)
  - Move away from sunspot
  - ➡ Dynamic behaviour distinguishes moat from Quiet Sun

Sunspots

Why are sunspots dark?

- **Umbra**: Strong (~vertical) magnetic field below sunspot hampers convective motion
  - ➡ Convective energy transport suppressed
  - ➡ Less energy reaches the surface
  - ➡ Surface appears dark in umbra
- Where does the energy go that is blocked by sunspots? Why is the area surrounding the sunspot not heated by the surplus energy?
  - Additional energy distributed in convection zone around and under sunspot
  - High heat capacity and conductivity in convection zone — additional heat produces insignificant temperature increase (Spruit 1982)
- **Penumbra**: brightness due to convective energy flux from below

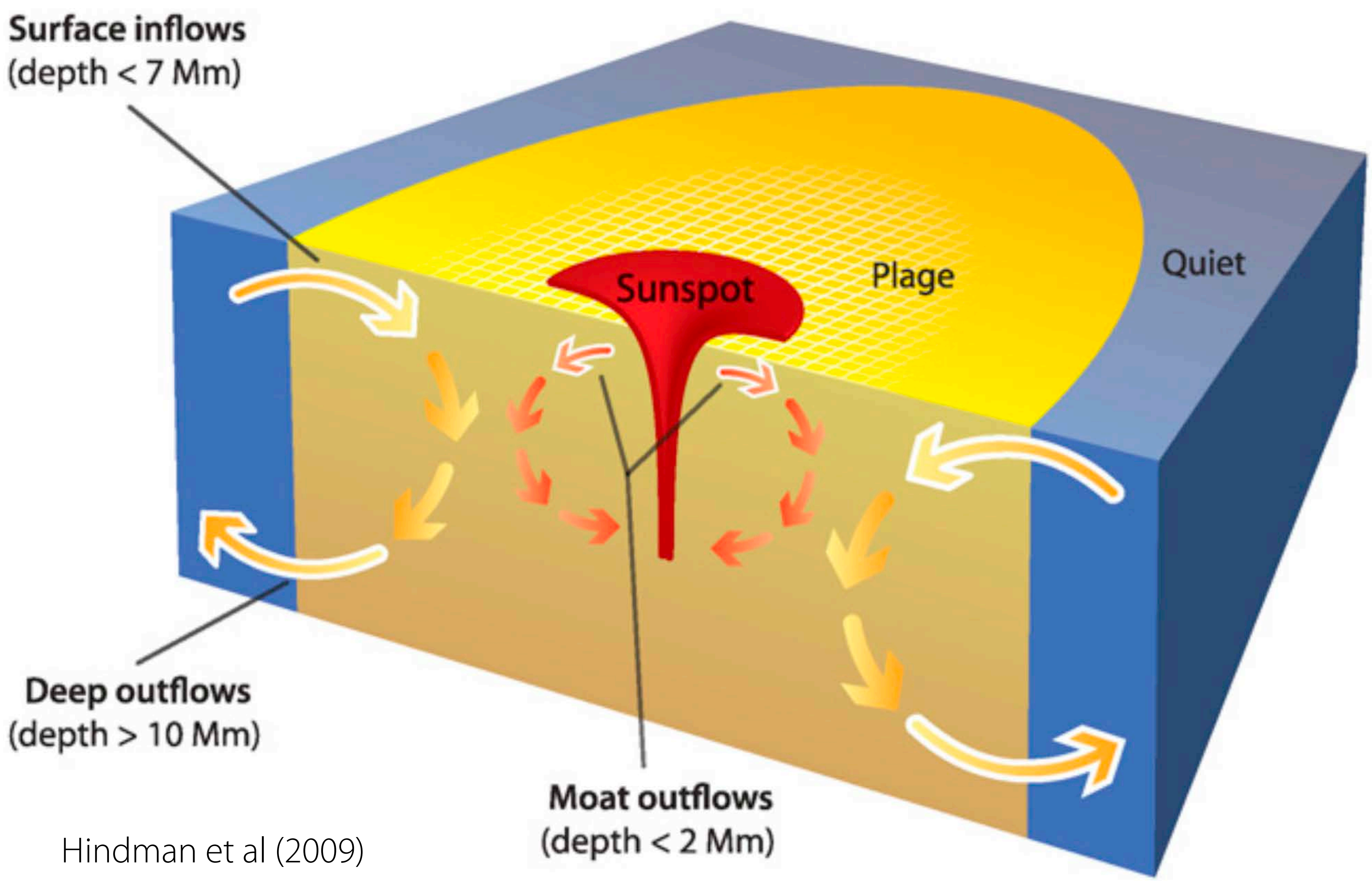


Structure below sunspot derived from helioseismological studies Kosovichev et al. 2000)

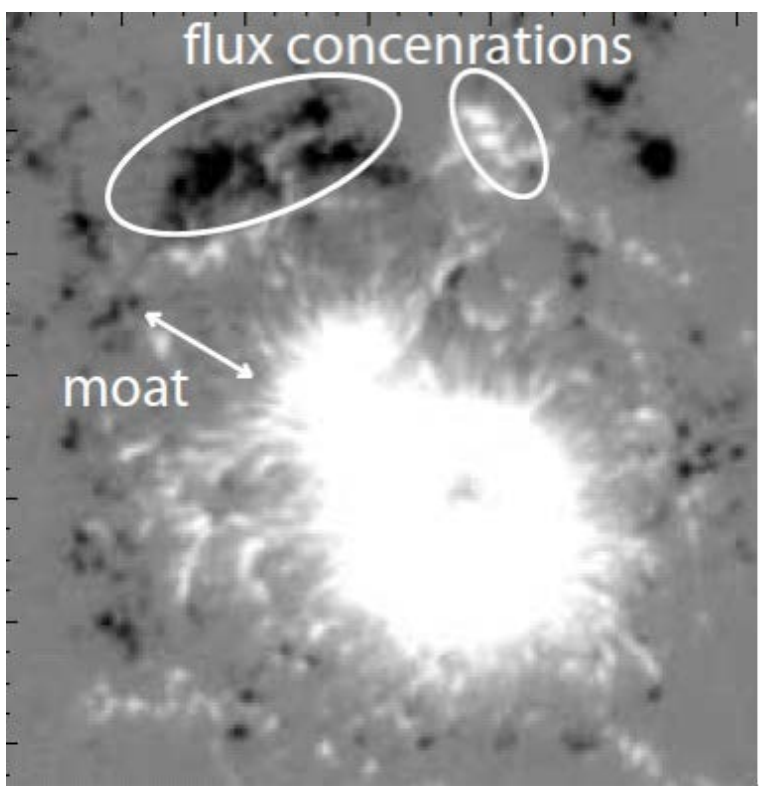
Sunspots

Flows around sunspots

- Blocked energy transports leads to reversal of the originally convergent supergranular flow
  ➡ Around sunspot: large-scale circulation with surface inflow, outflows at depths > 10 Mm
- **Moat flow:** Annular outflow observed at the surface around sunspot (Sheeley Jr, 1969)
  ➡ Return flow at depths <2 Mm — moat circulation very shallow

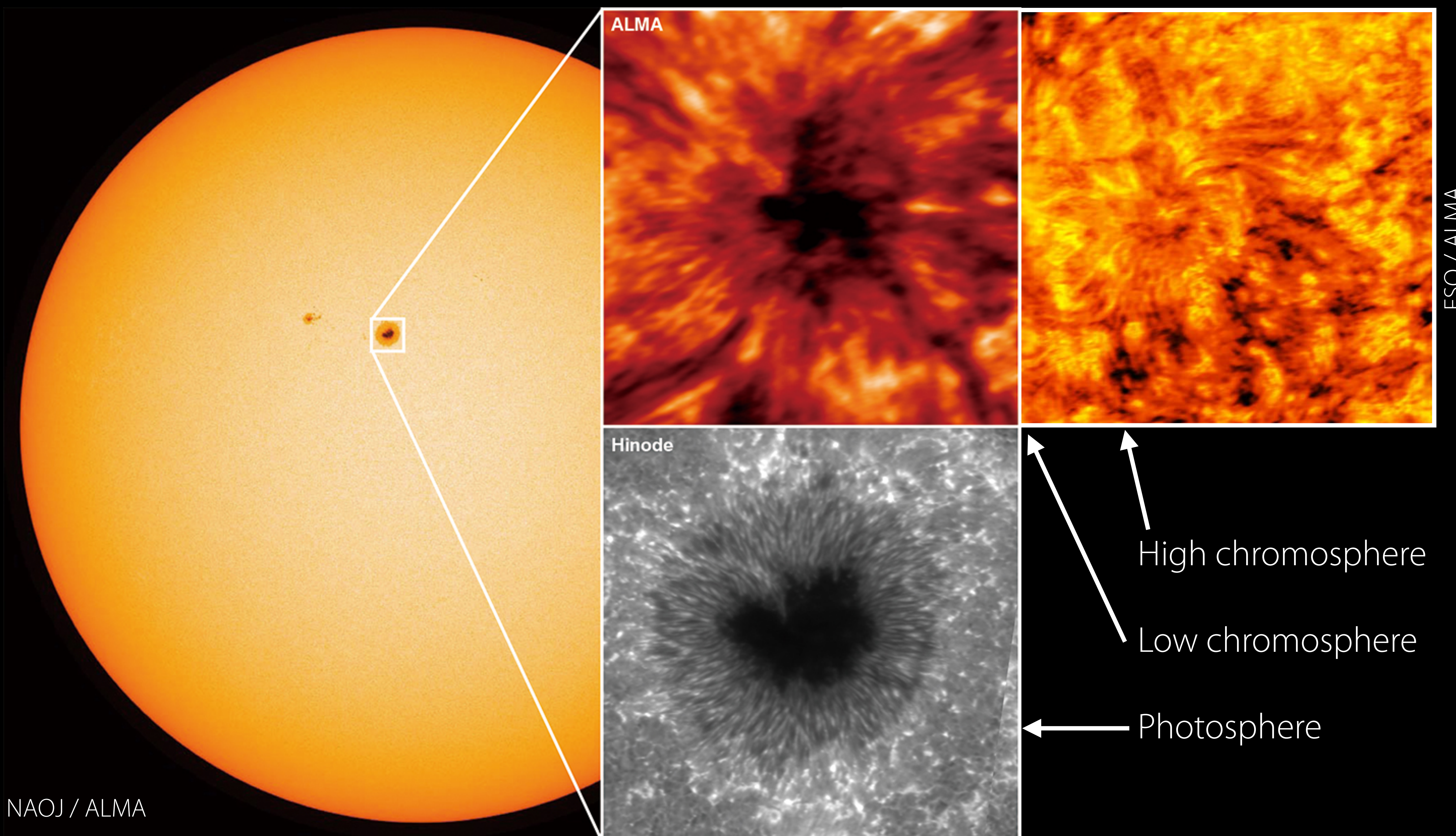


Hindman et al (2009)



Sunspots

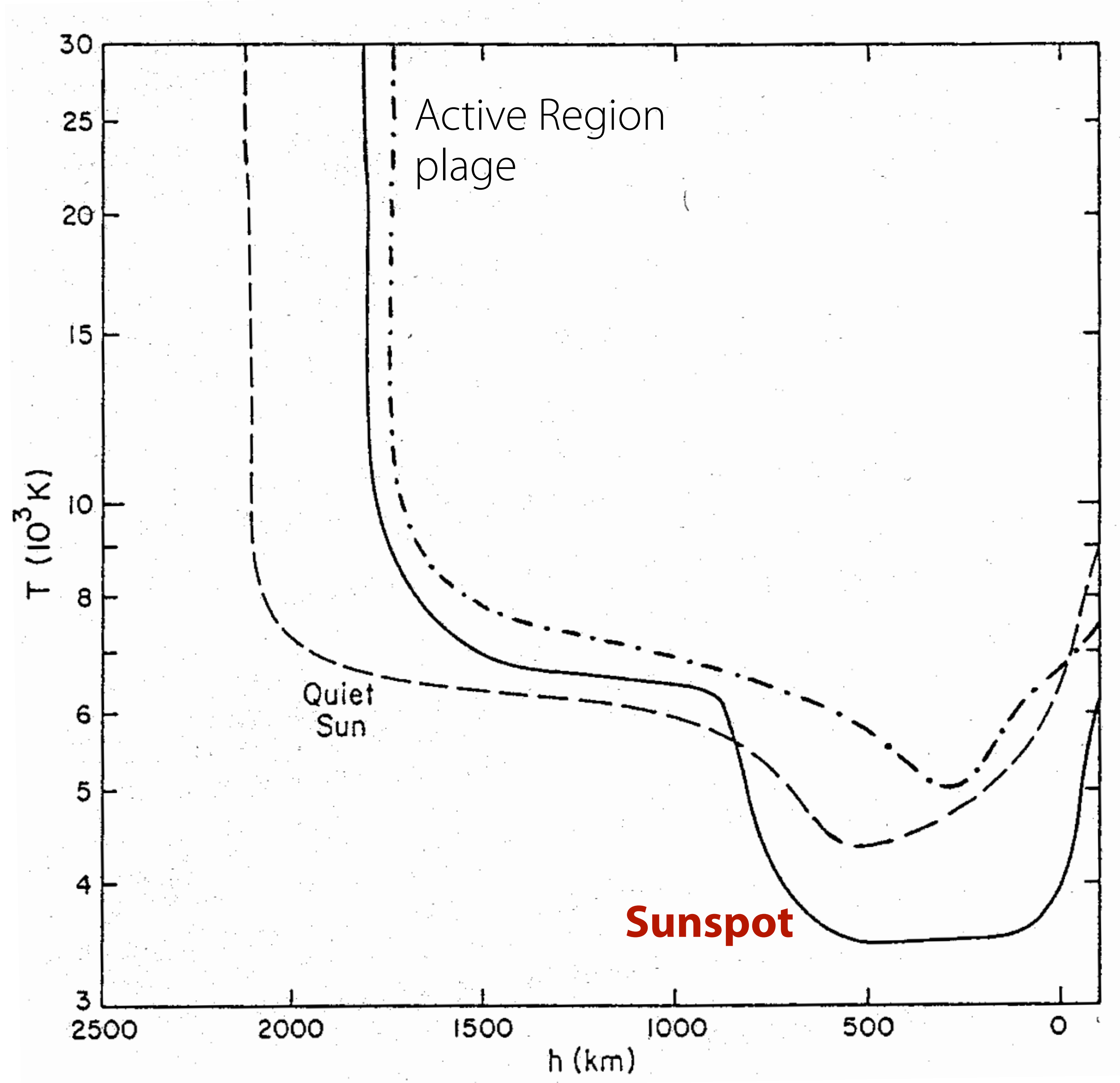
Temperature stratifications



Sunspots

Temperature stratifications

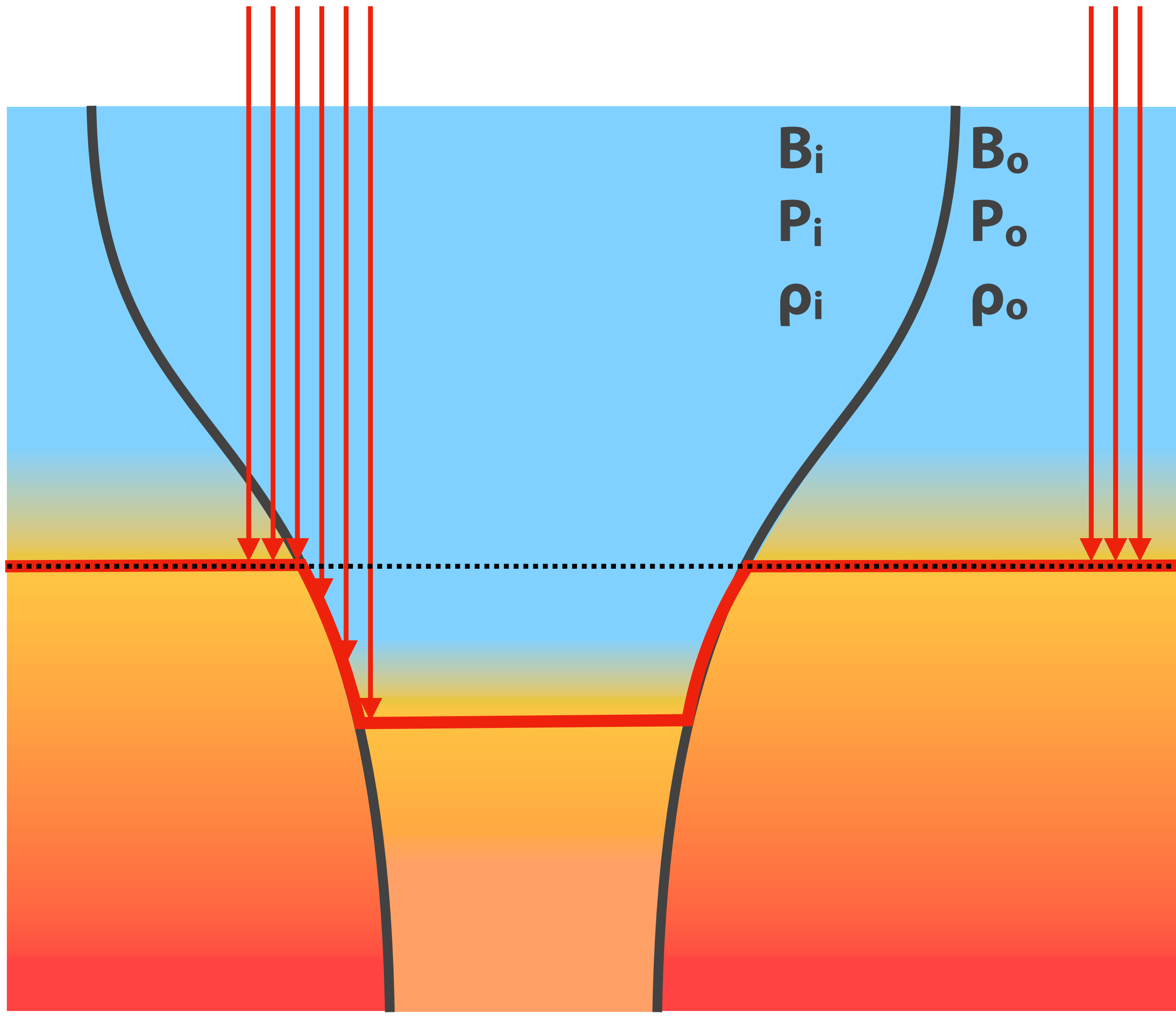
- Temperatures in sunspot umbra much below Quiet Sun values
  - Sunspots appear dark in the photosphere relative to surrounding
- Sunspot temperatures rise quickly in low chromosphere, surpass Quiet Sun temperatures
  - Sunspots appear brighter than surrounding (e.g. in the continuum at $\lambda = 3$mm)



Sunspots

Wilson depression

- Remember: Magnetic pressure counterbalances thermal (gas) pressure
- $B_i >> B_o$
- Lower thermal pressure inside region with strong magnetic field $P_{g,i} << P_{g,o}$
- Lower gas density (=fewer atoms) $\rho_i << \rho_o$
- **Lower opacity** inside the magnetic flux structure
- Remember: Optical depth according to opacity along line of sight



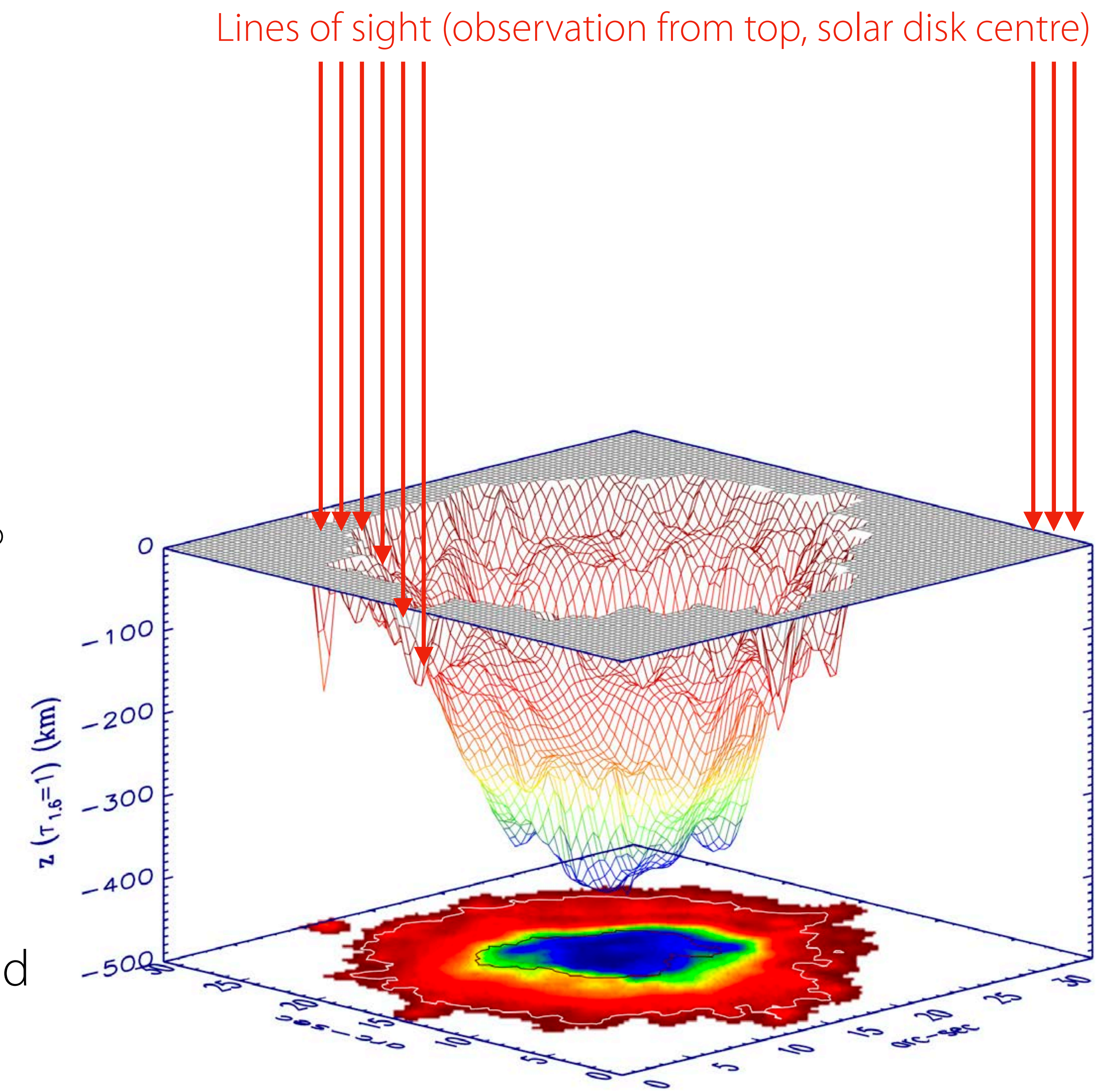
➡ **Optical depth lower** inside magnetic field structure than outside

➡ Looking deeper into the Sun inside the magnetic field structure

- Lower height of optical depth unity = **Wilson depression**

Sunspots

Wilson depression



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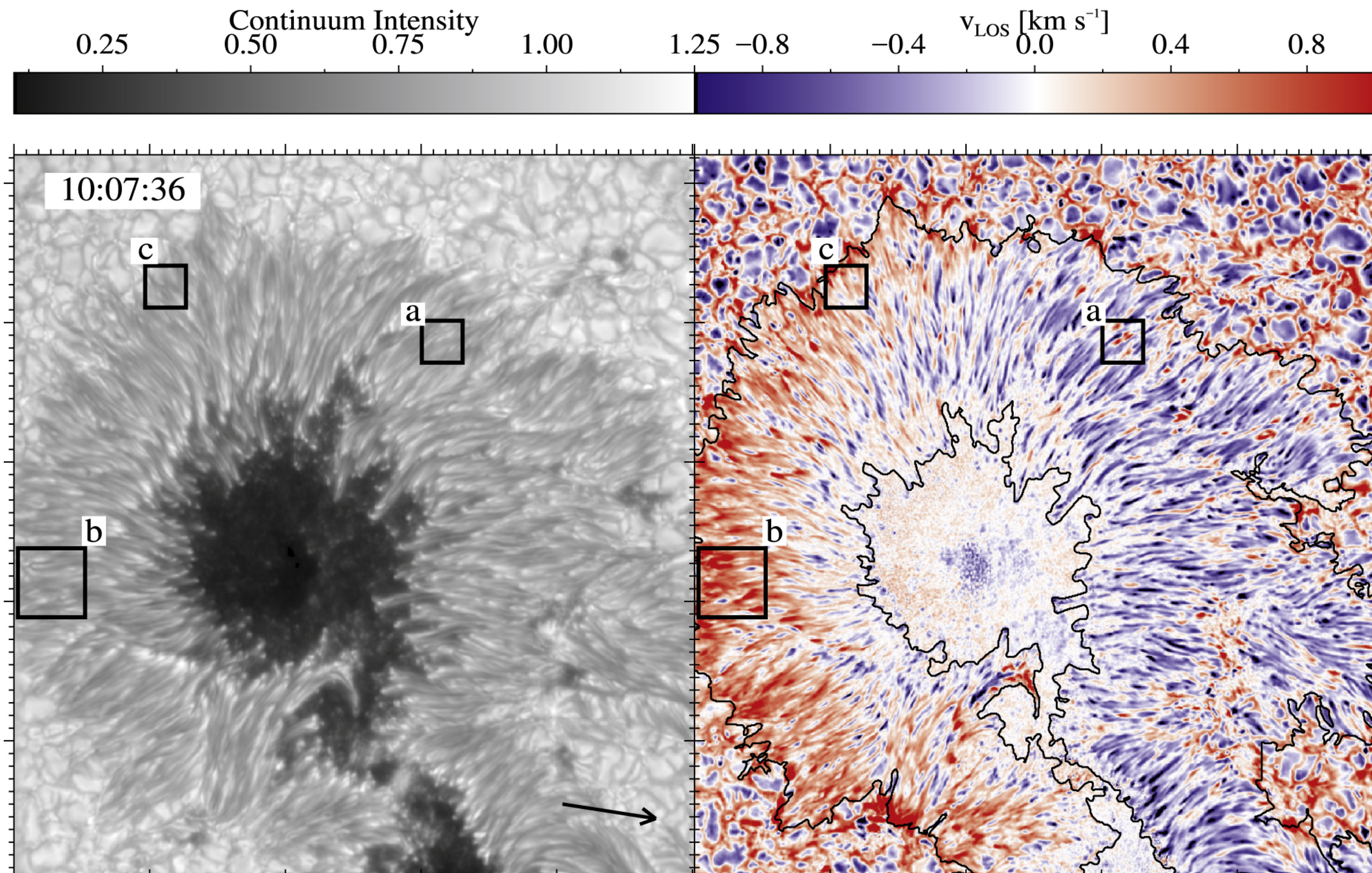
➡ Looking deeper into the Sun inside the magnetic field structure

- Lower height of optical depth unity = **Wilson depression**
    - **A few 100 km!**

Sunspots

Evershed effect / flow



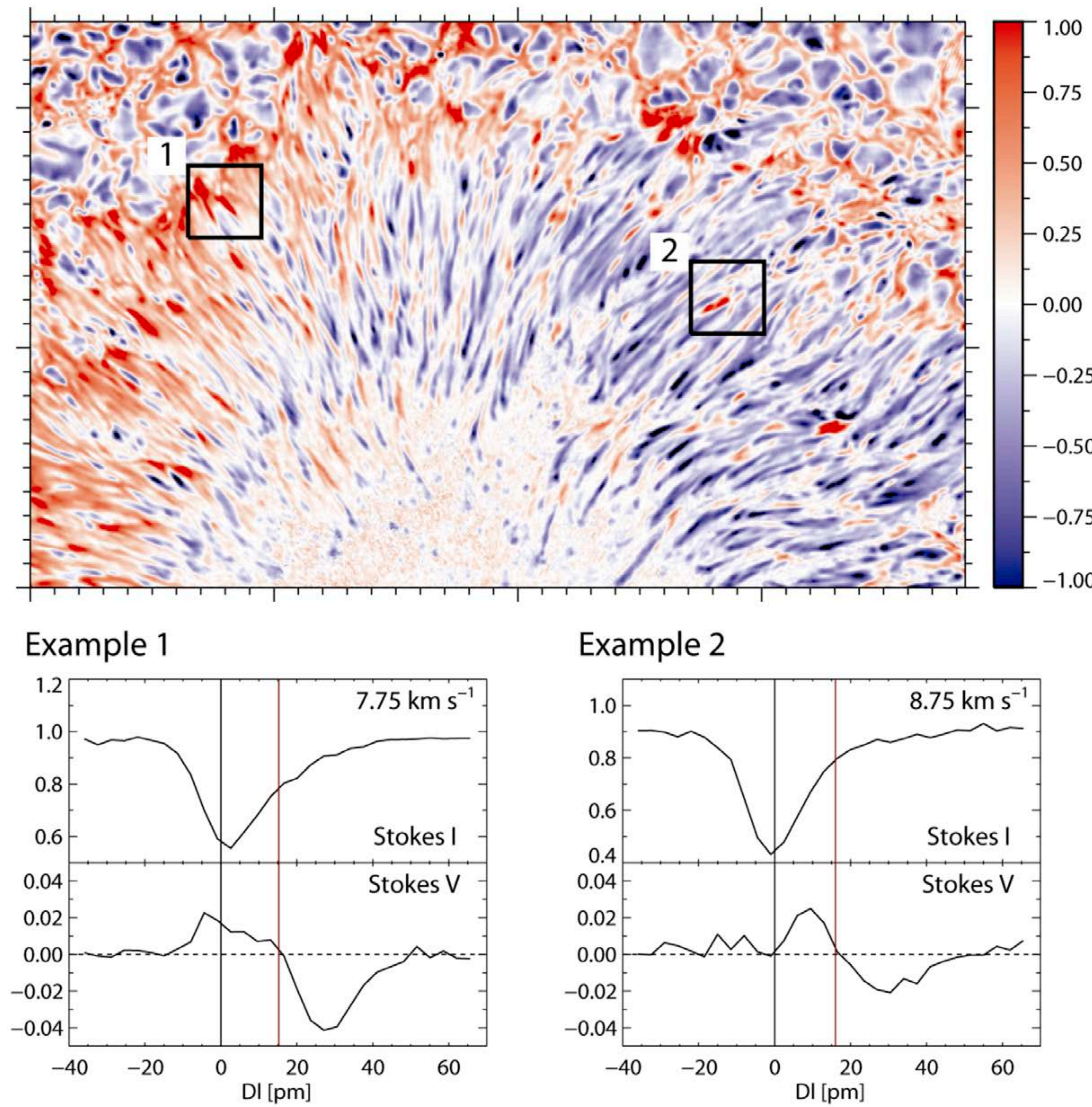
Esteban Pozuelo et al. (2016)

Be aware of project effects depending on the location of the sunspot on the solar disk.

Sunspots

Evershed effect / flow

- Evershed flow = outflows in the penumbra along filaments with nearly horizontal magnetic field
  - Field strengths 1 — 2kG (only slightly larger than average penumbral values)
- First discovered by Evershed (1909) from Dopper-shifted spectral lines in sunspots
- Division in mid-penumbra: most penumbral grains inside move inwards to umbra, those outside move **towards moat**
- **Supersonic** components with velocities ~8 km/s in photosphere, occasionally up to 15-16 km/s
  - Supersonic flows last 1-5min



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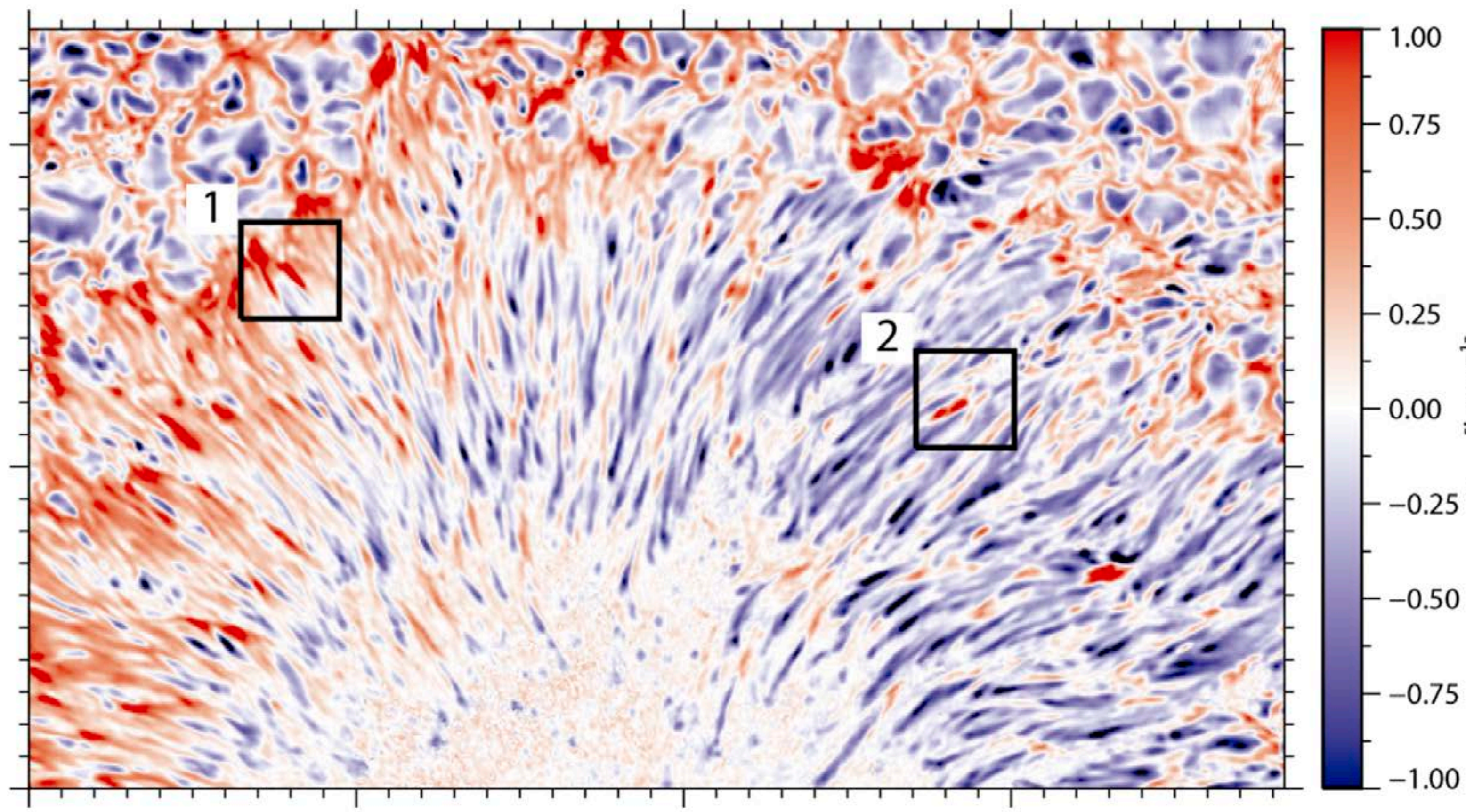

- Rapid decline of flow speed with height (in the photosphere)
- In chromosphere/transition: **Inflow** with higher velocities than the outflows below
  - Known as **inverse Evershed flow.**

Esteban Pozuelo et al. (2016)

Be aware of project effects depending on the location of the sunspot on the solar disk.