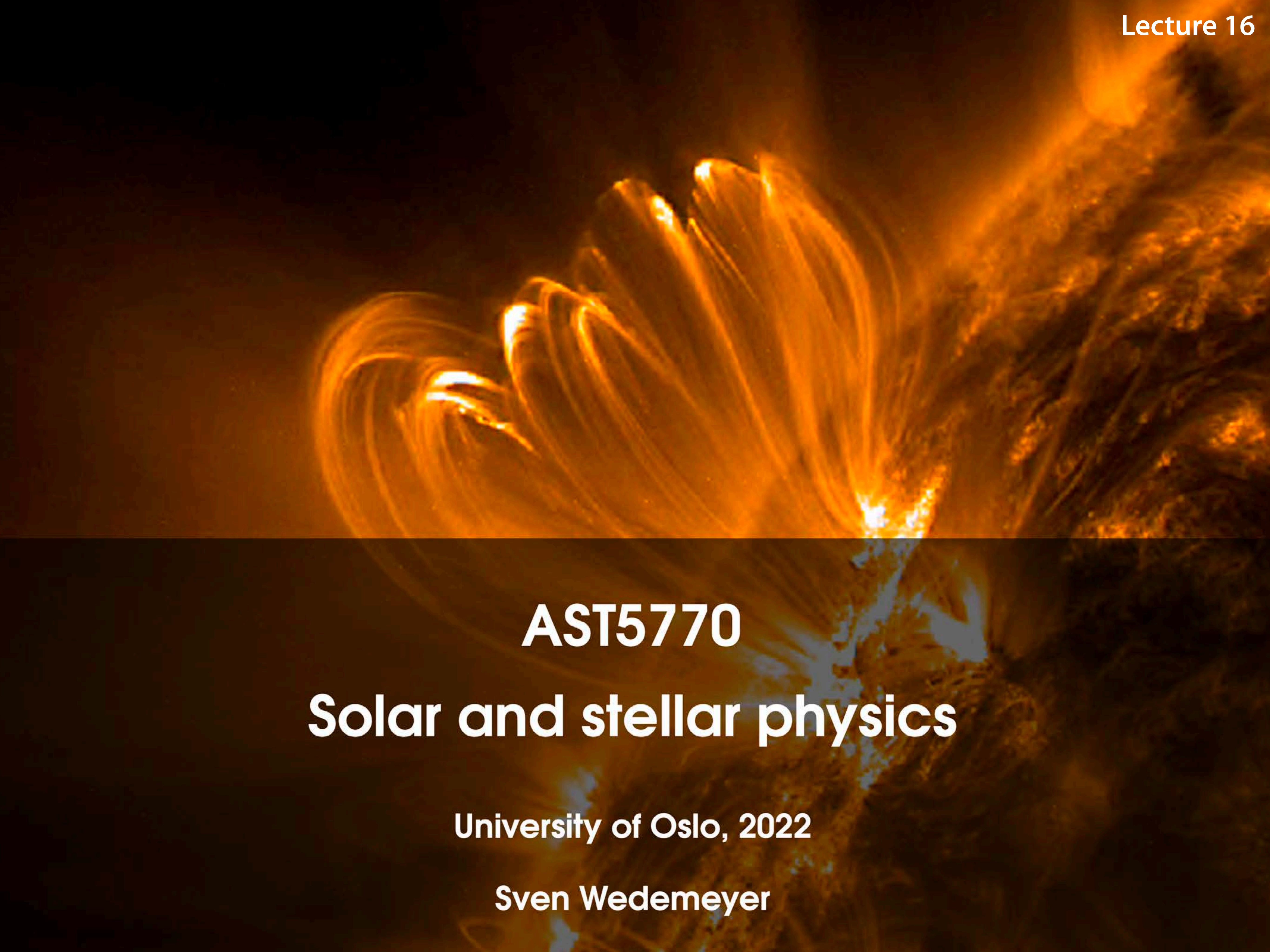


AST5770

Solar and stellar physics

University of Oslo, 2022

Sven Wedemeyer

Assignment #4

Results

- The part of paper, in which the **new results are presented in detail**.
- **Describe** the results and leave the detailed interpretation (and comparison to literature) will be done in the discussion section!
- It should not be a (random) collection of all facts and things out find out.

  ➡ **Select** the results that serve a purpose in exploring and addressing the scientific question/topic of your paper!
- Be **concise and focused but yet consistent and complete**.

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!

Assignment #4

How to start?!

1. **Get familiar with the data.**
   - Start with the data analysis by plotting different aspect of your data — use standard tools like profiles, maps, histograms etc.
   - Do you see any trends/properties of the data that might be relevant with regard to your science question?
2. **Initial detailed data analysis.**
   - Try to split the scientific question into small steps/aspects and investigate in detail.
   - How can you check these sub-questions by plotting the data in different ways?
   - Find good ways to visualise your findings. Make preliminary plots/tables (simple, do not yet use much time on making them "pretty").
3. **Collect, sort, and filter your findings and plots so far.**
   - Pre-select material (your "puzzle pieces") and start with the most important ones (as far as you can tell at this point)
   - Now put your findings and material into order (in your tentative manuscript)
   - Describe the figures/tables in detail in your text.
4. **Connect the dots.**
   - Put the results into a logical order and create a "story" with a "red thread".
5. **Polish — Make the text, figures, table nice and consistent**
   - Go through the text again and again and make sure it connects well and that all figures and tables are referred to and made good use of. You may want to update your figures to emphasise your findings.

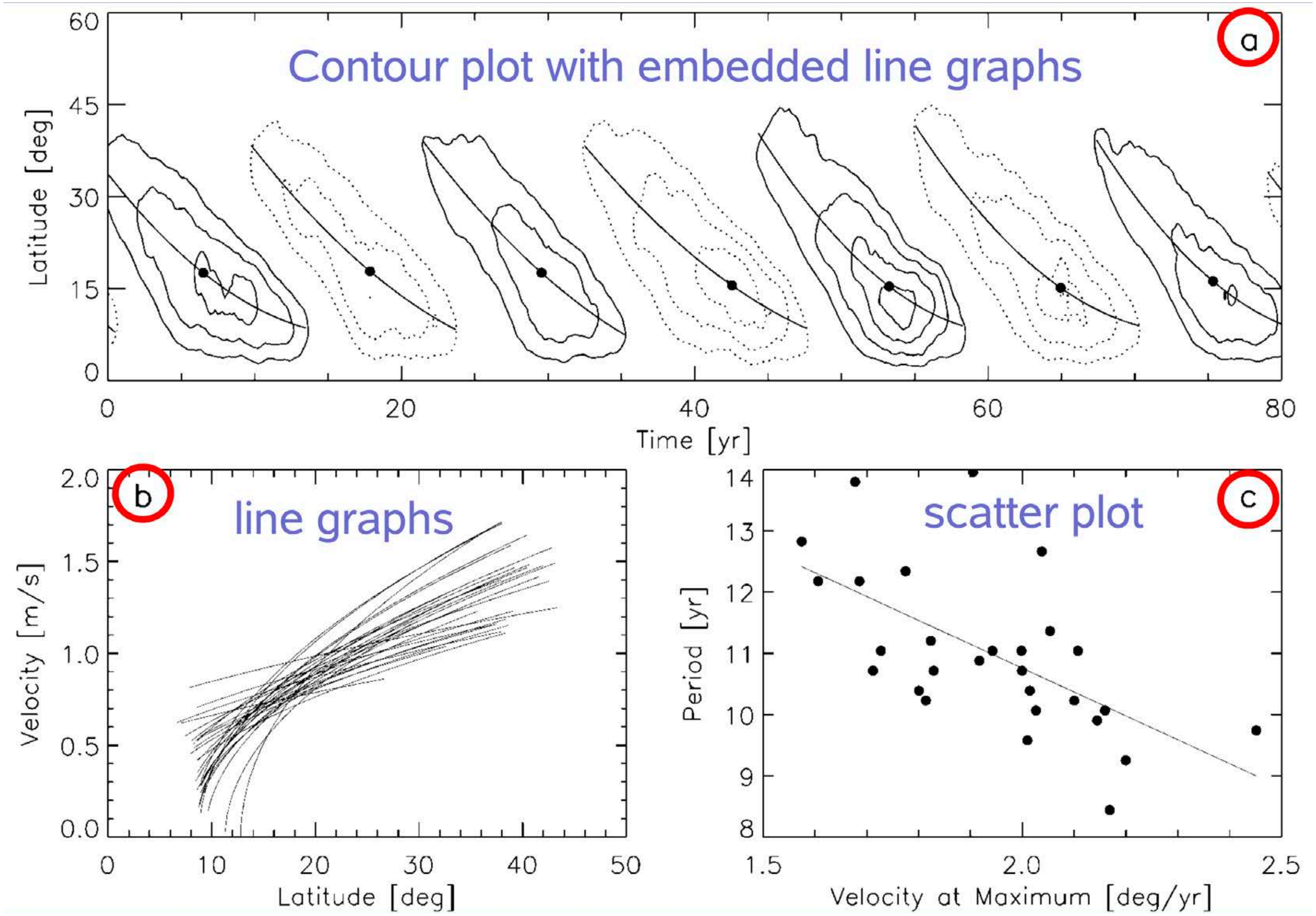
Assignment #4

Figures

- **Important:**
    - Each figure must be **referred** to in the text.
        - Figures are typically set in the order they are referred to in the text (it starts with Fig. 1)
    - Each figure must have a **caption.**
        - Captions are short but self-explaining. It should be possible to interpret a figure just by looking at it and reading the caption (without the main text). What does the figure show?
        - All graphical elements should be explained in the caption (symbols, different lines, colors).
        - Captions **describe what is plotted**. Any interpretation is done in the main text.
    - Make it easy for the reader to navigate the figure. Use letters to identify panels so that they can be referred to as, e.g. "Fig. 1a and Fig. 3c"
    - *It can be possible to use/reproduce figures from other publications if really necessary/useful. That usually requires explicit consent of the authors and journal and of course a proper reference/acknowledgment.*

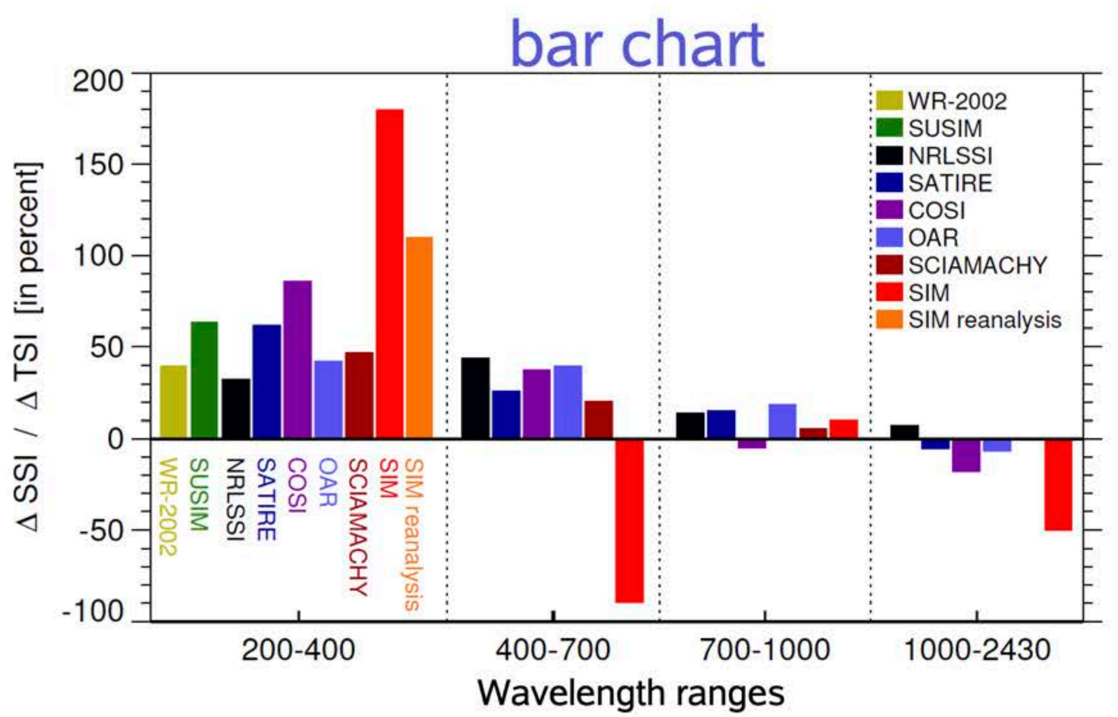
Assignment #4

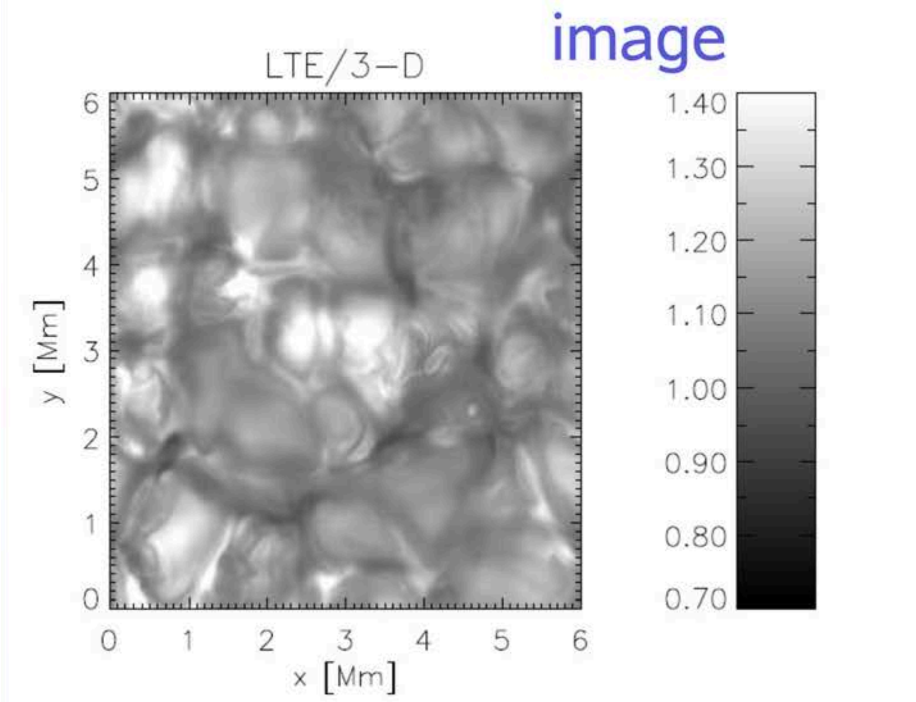
Figures - Examples

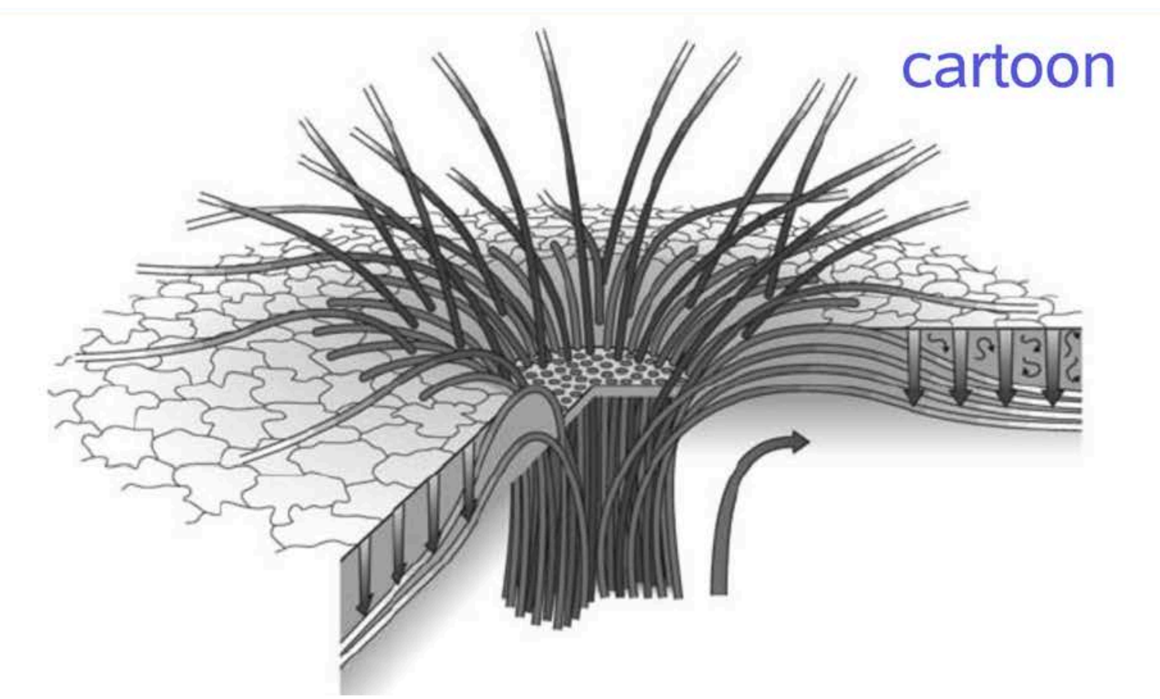


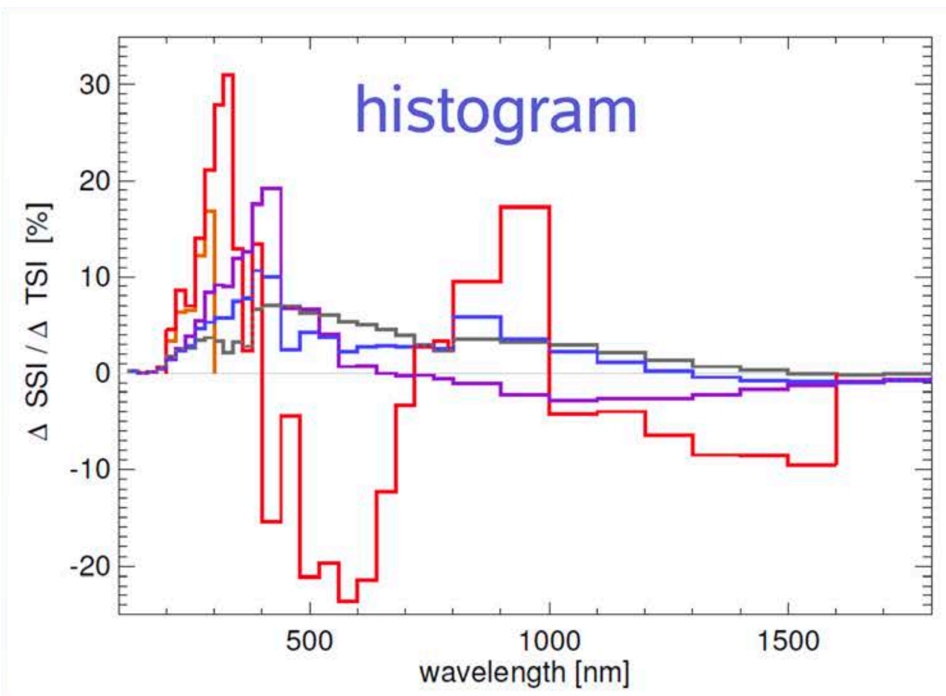
Assignment #4

Figures - Examples









Assignment #4

Components of a professional figure

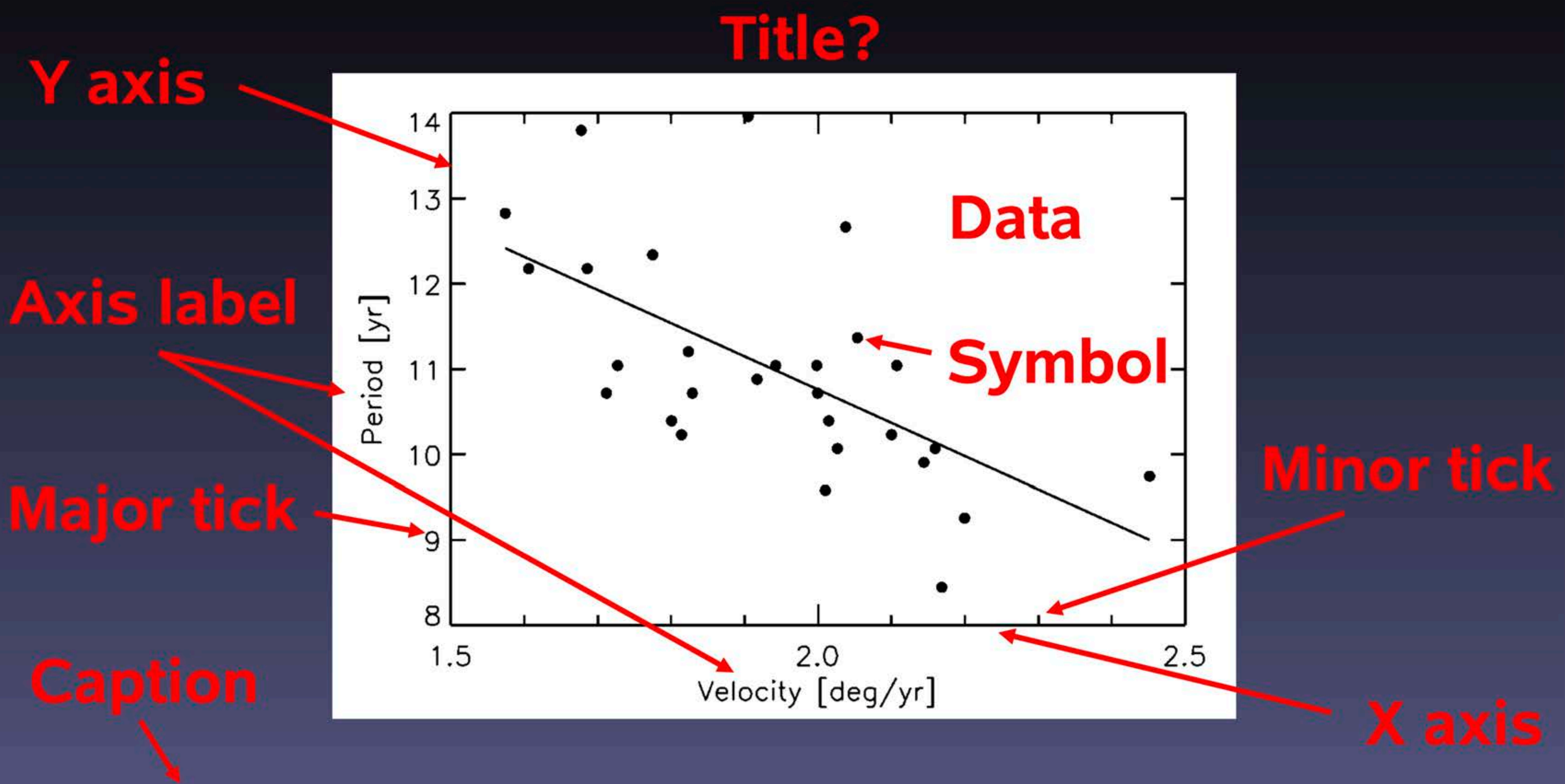


Figure 1. Solar cycle period vs. latitudinal drift velocity at cycle maximum, taken from an $\alpha\Omega$-dynamo model. The dots represent the data of 28 simulated cycles and the line denotes a linear least-square fit

- The caption starts by stating what is plotted.
- All graphical elements are described: dots and the line.

Assignment #4

Figures

- **Readability:** Make sure that all graphical elements and text are clearly visible/readable.
  - Line thickness, image resolution, labels
  - Font size not too small, best about the same as in the figure caption (must be clearly readable) — Careful: Check this once it is in your document as the figure might be scaled.
  - Number and size of major and minor ticks
- Meaningful axis ranges (round numbers, fill the frame), linear/log scale
- **Do not overload figures** (do not plot too many different quantities)
  - Consider splitting figures into panels or repeating them on a linear or log/log scale or different axis ranges or different subsets — Whatever makes most sense when describing the results in the text.
- Make sure **all quantities can be distinguished**.
  - If two lines are essentially identical so that only one is visible, try different line styles (one solid, one dashed?), colors, etc. to make both visible
  - Provide a legend if you use many symbols (either in plot and/or in caption)

Assignment #4

Tables

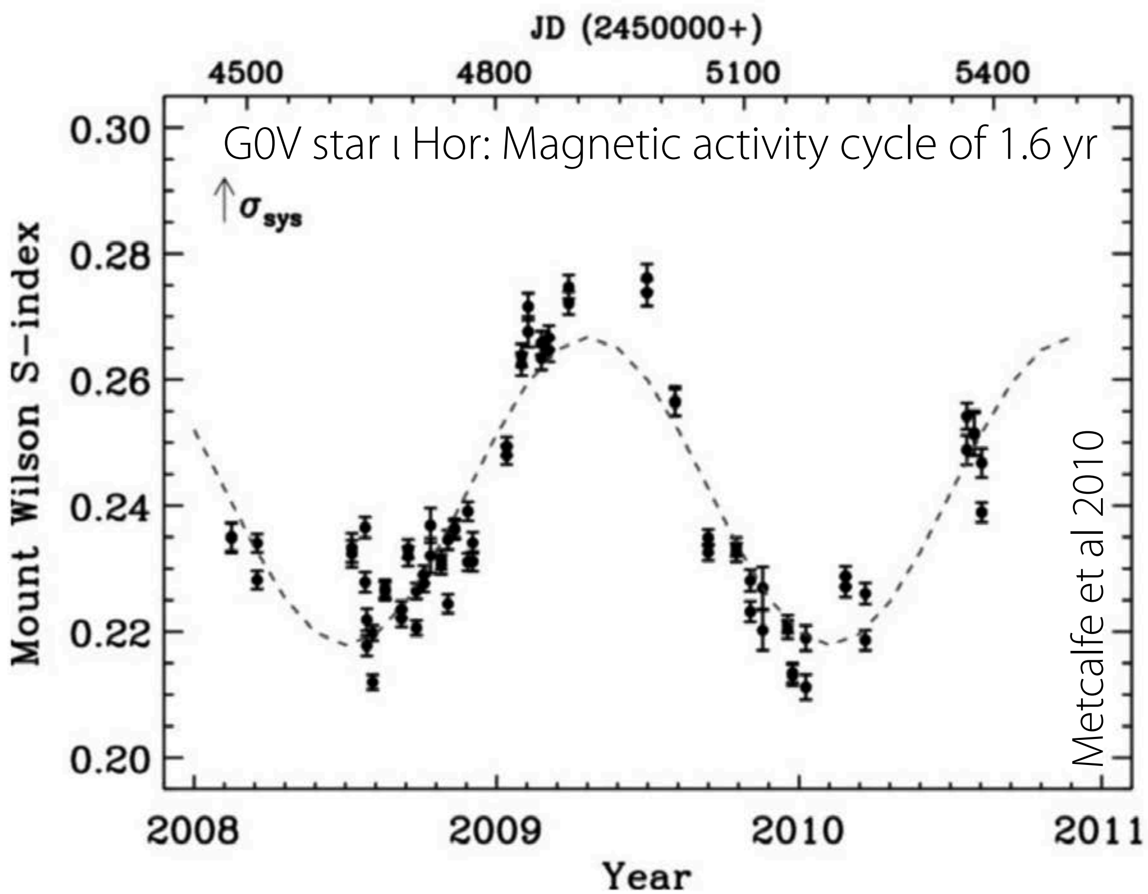
- When to use a table?
  - Many numbers that cannot be presented in a meaningful figure.
  - Exact numbers are needed (which is difficult to infer from a figure). Can be in addition to figure.
  - Overview over data properties, especially when several sets are used.

- Note:
  - Figures are easier to interpret than tables.
  - Tables need a caption that explains all content.
  - The table must be referred to in the text (in the order of them being first referred to in the text).

Stellar activity

Recap

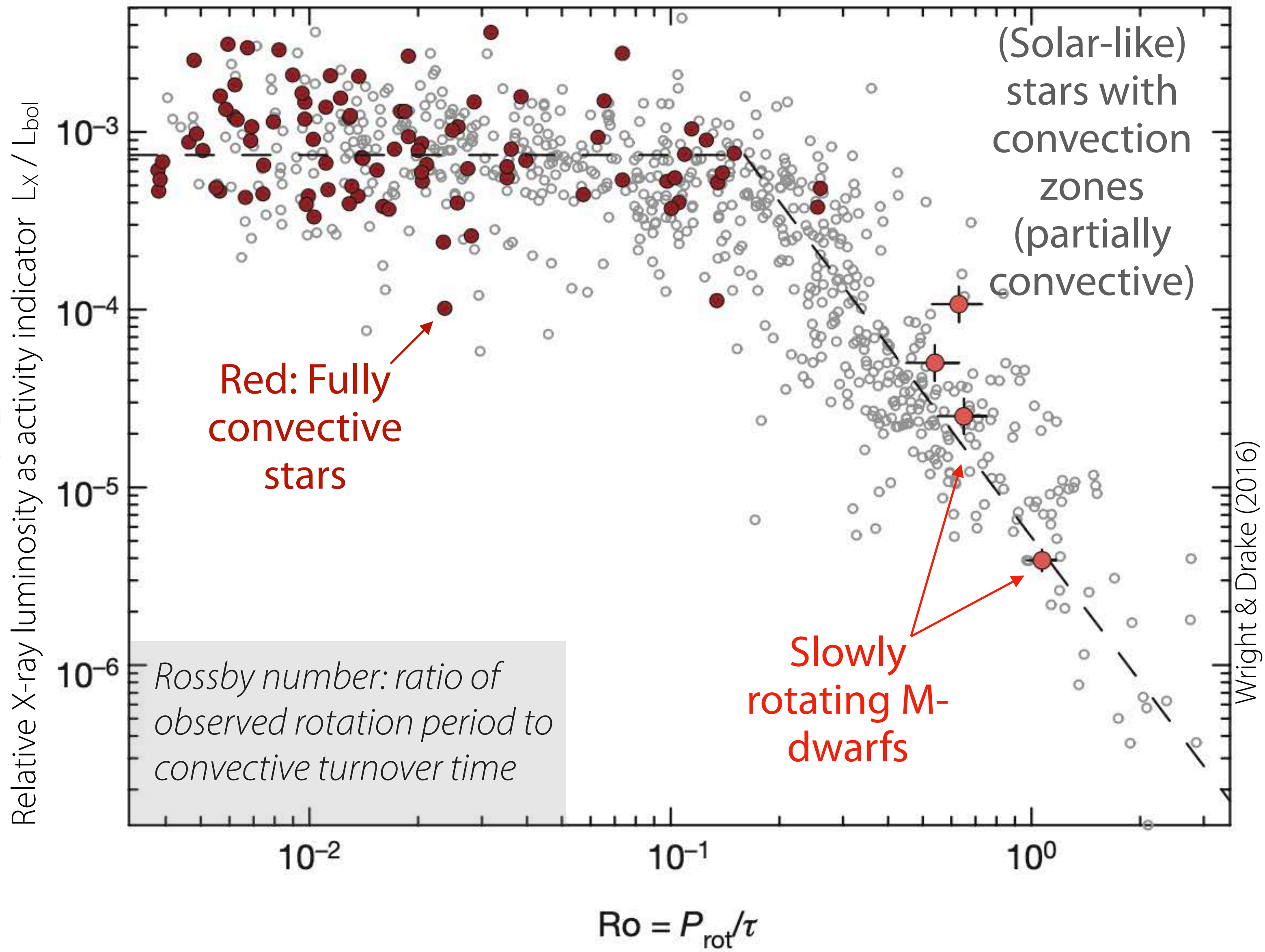
- **Stellar activity** refers to all phenomena in a stellar atmosphere that result in **variability** of the emitted radiation and **heating** of the outer atmosphere (existence of a chromosphere, temperatures above radiative equilibrium)
- Found for **cool late-type stars** due to the presence of surface convection, dynamo and the resulting highly structured **magnetic fields** in their atmospheres
- Activity indicators based on spectral features from in the upper atmosphere (chromosphere/corona), e.g.: S-index based on Ca II H & K
    - Large spread in activity with a basal flux limit — between active and inactive branch
- The Sun is only a weakly/moderately active star.
- Activity related to magnetic field strength of a star!
- **Rotation and convection important for dynamos.**
- Activity cycles periods vary (as short as 1.6 yr) →



Stellar dynamos and activity

Recap

- Clear **rotation-activity relation**: Activity and magnetism of late-type stars at a saturated level for small Rossby number, decline for larger Ro values
- **Fully convective** M-dwarfs fit the same relation as solar-type stars with outer convection zones despite lack of a tachocline!



- Most likely: Fully and partially convective stars have rotation-dependent dynamos that share important properties
- Tachocline not a vital ingredient.

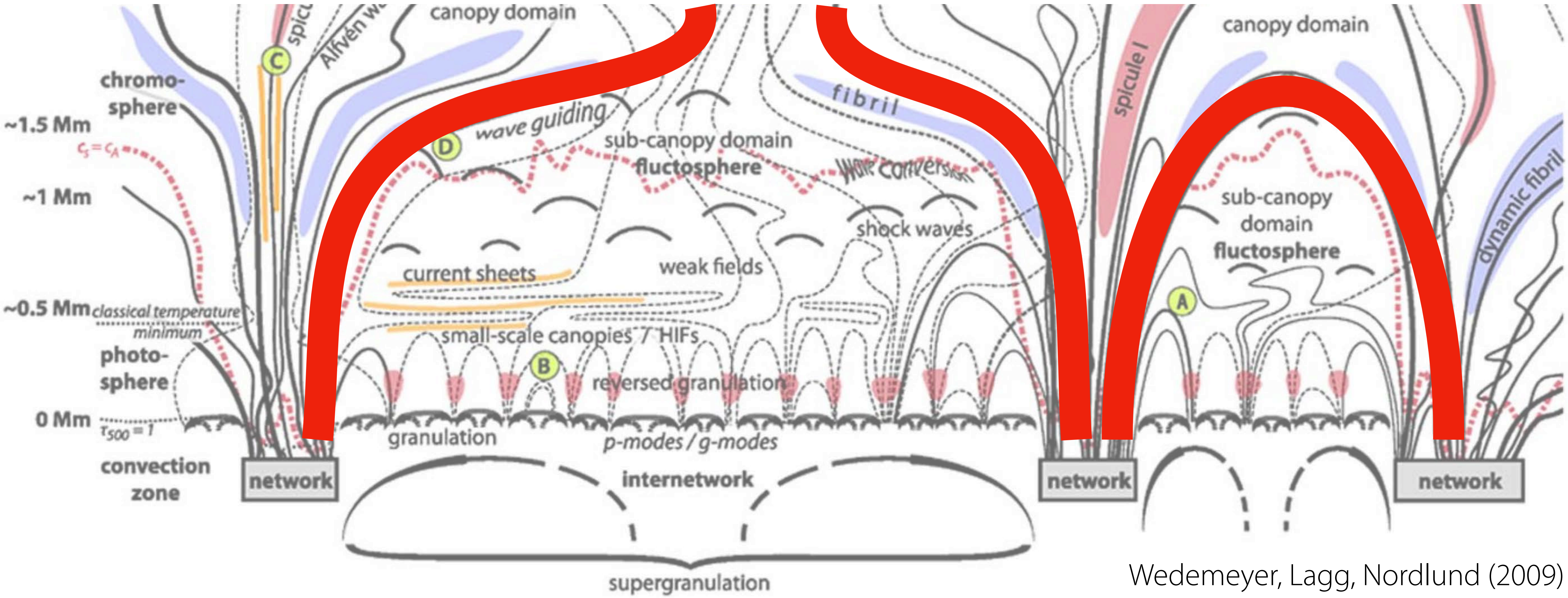
➡ **Differential rotation + Coriolis force sufficient!**

- **Still many open questions, active field of research!**

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

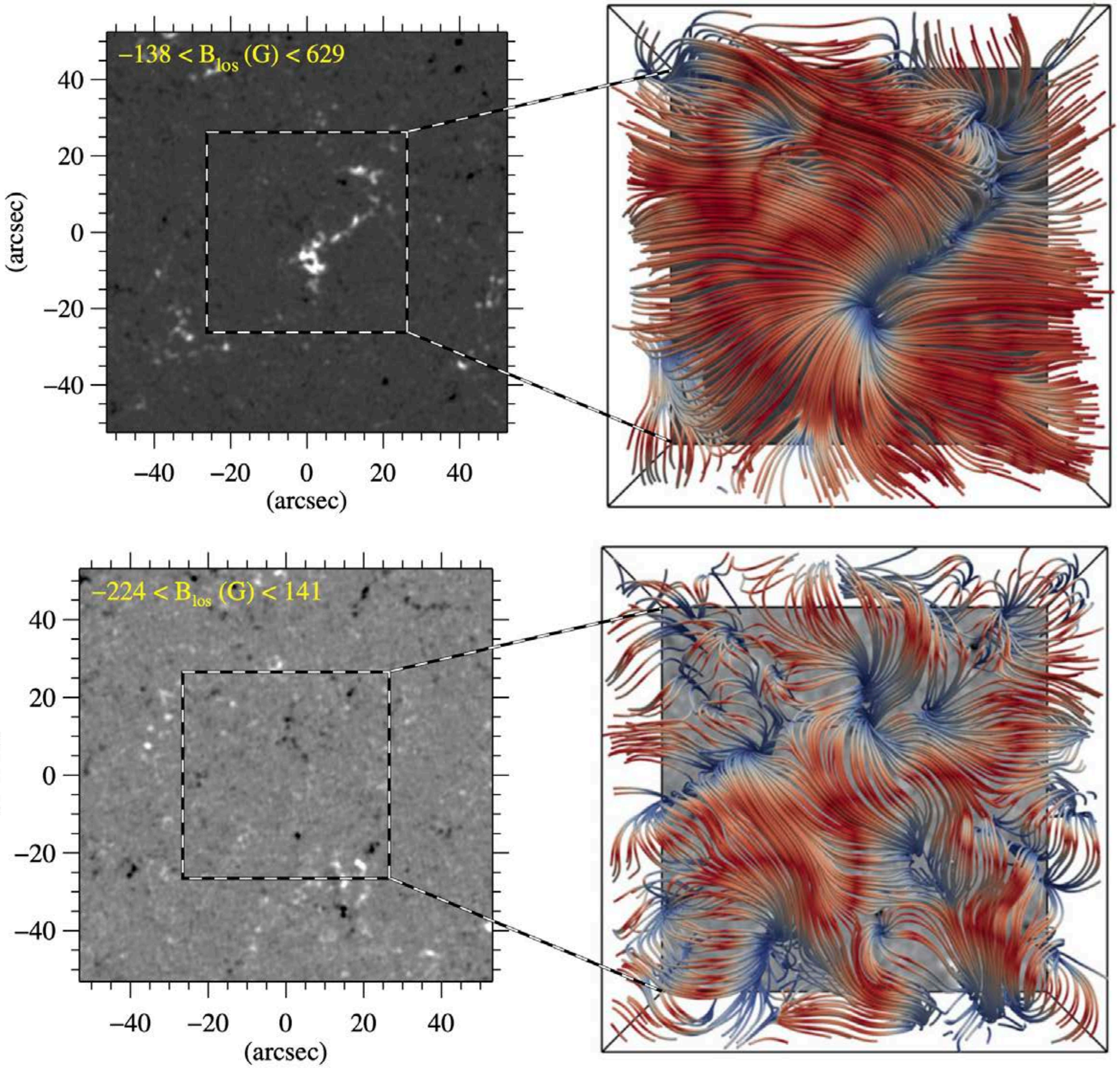


Wedemeyer, Lagg, Nordlund (2009)

Magnetic field in the solar atmosphere

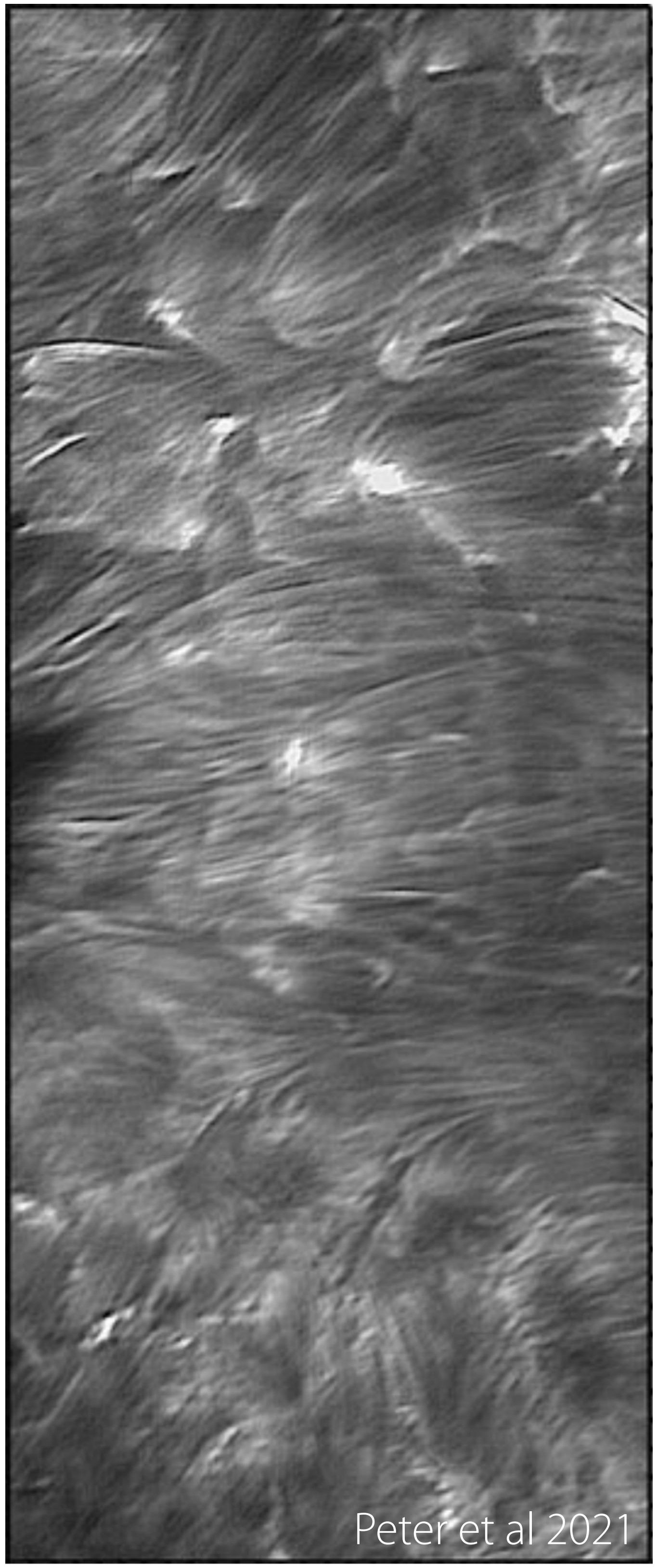
Structure of Quiet Sun regions

Magnetic field extrapolation from photospheric magnetograms



Jafarzadeh et al 2021

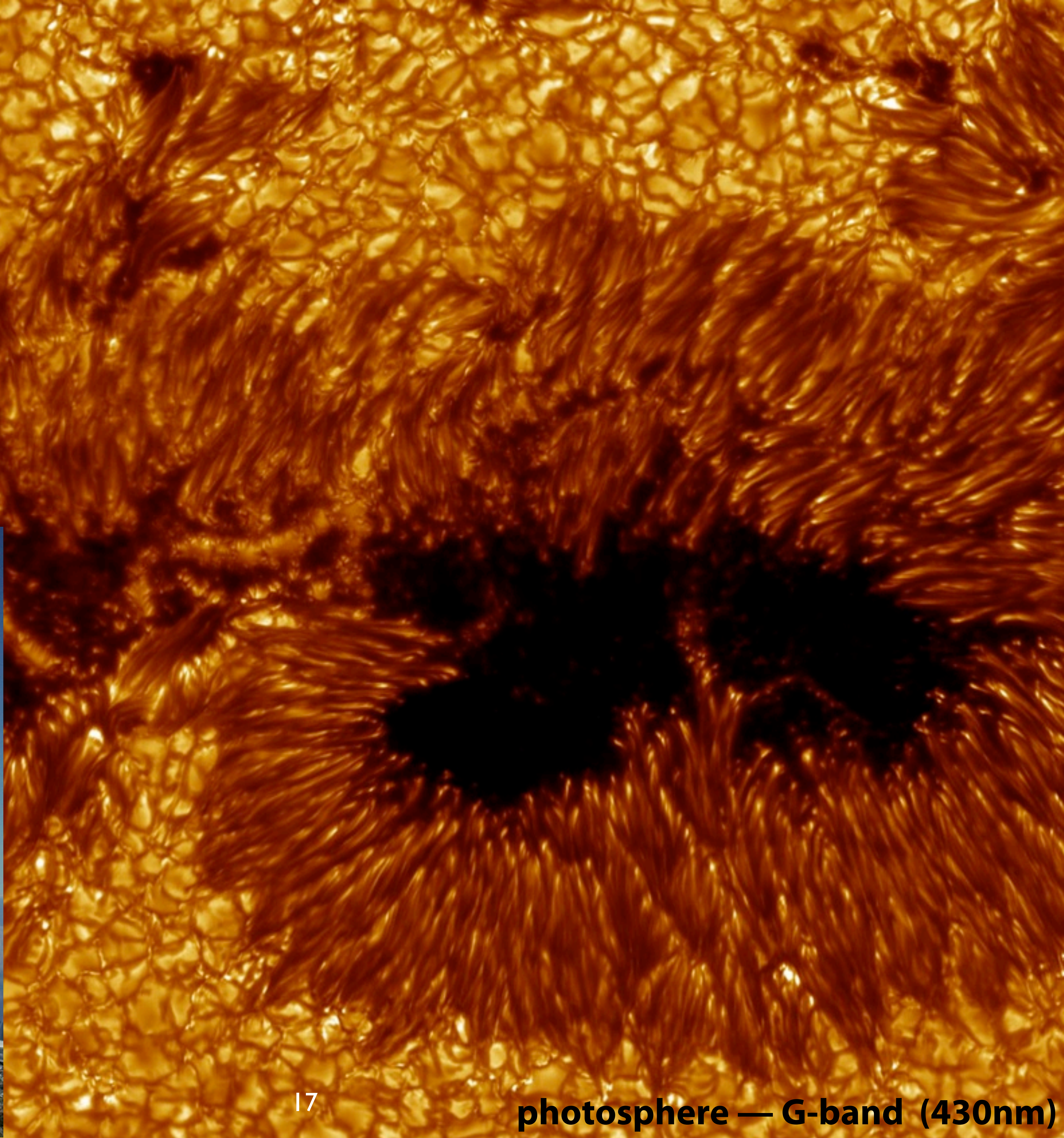
Observed: Fibrils in Ca II K



Peter et al 2021

Sunspots

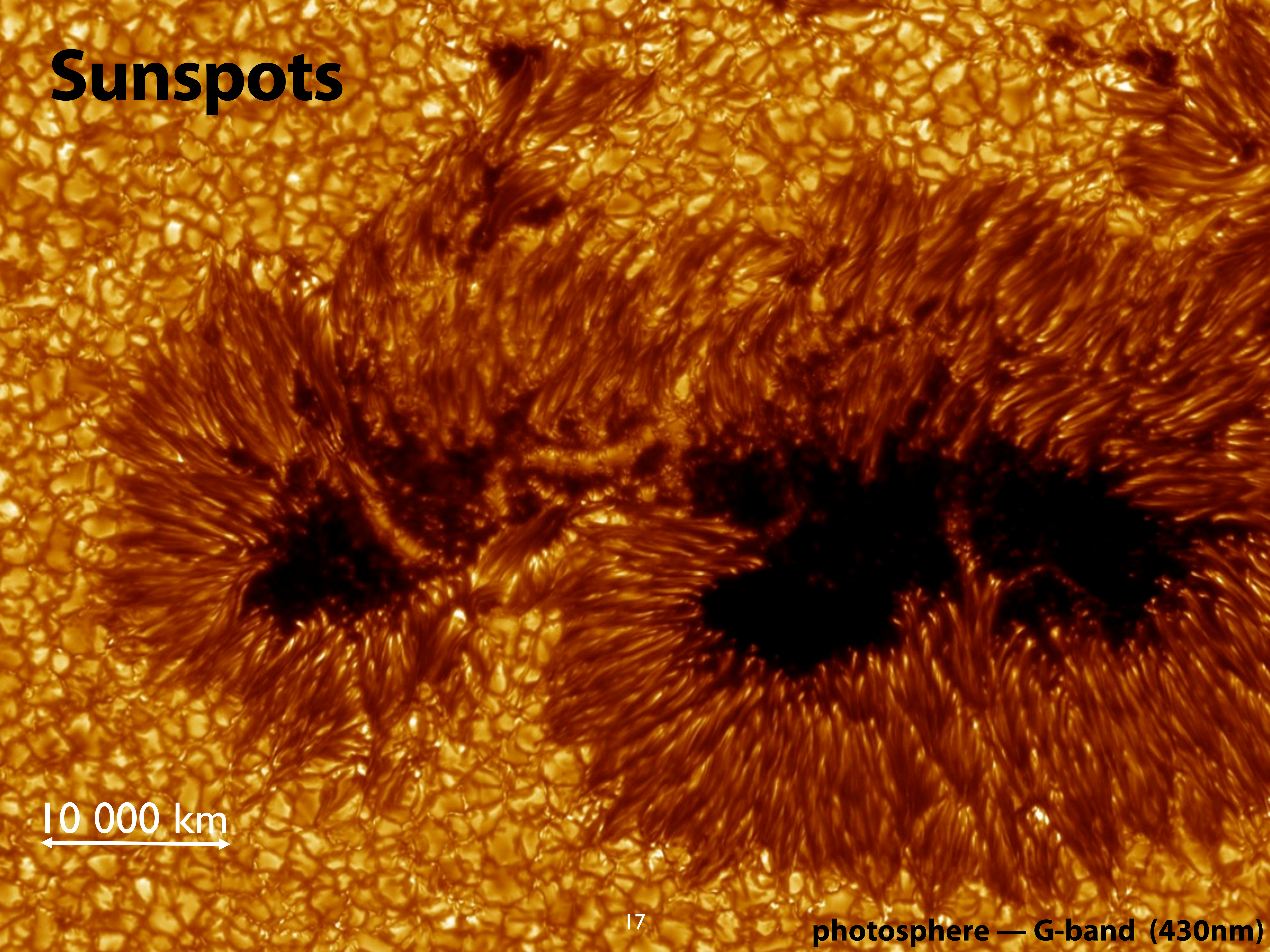
Sunspots



photosphere — G-band (430nm)

Swedish 1-m Solar Telescope,
La Palma, Canary Isl.

Sunspots



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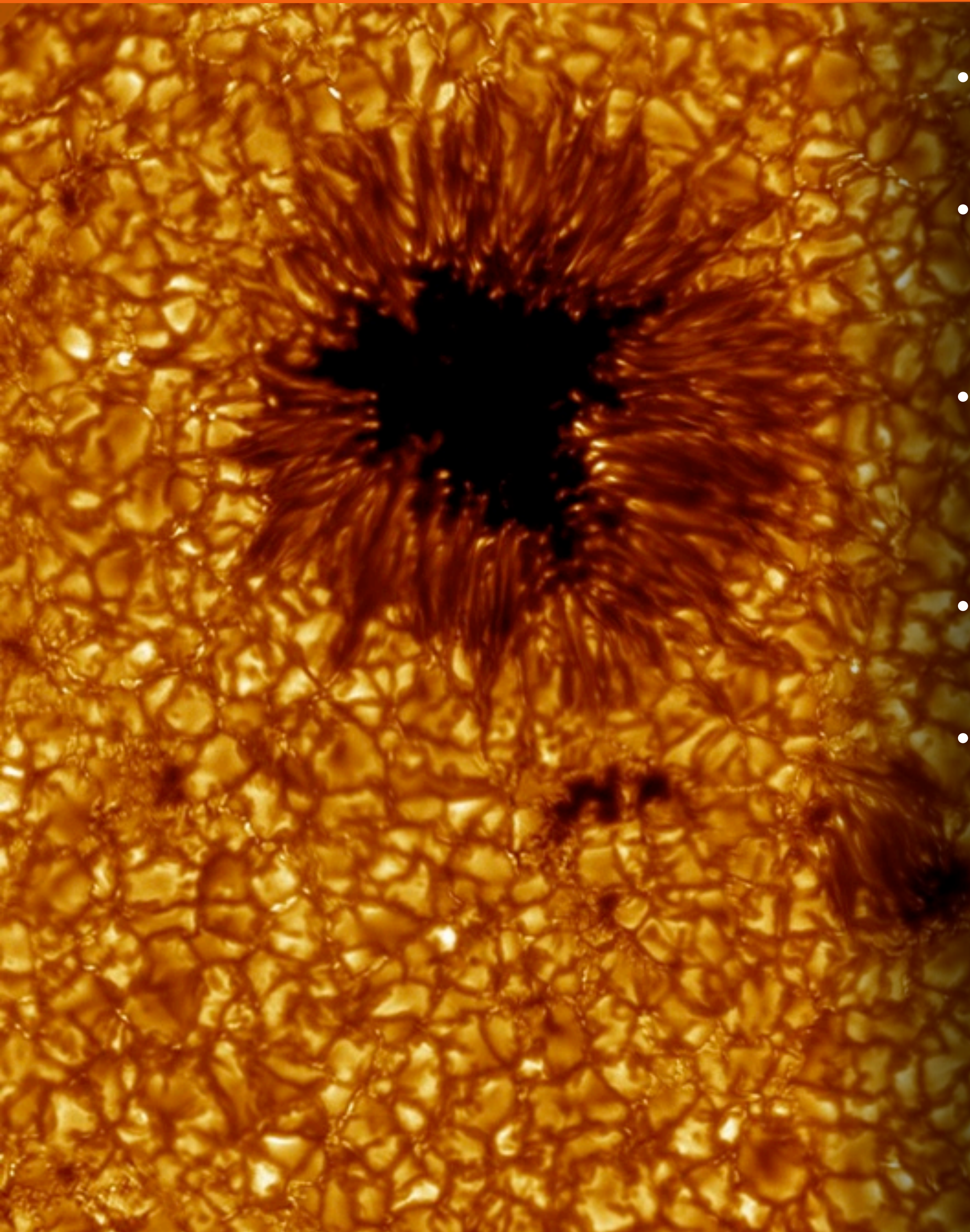
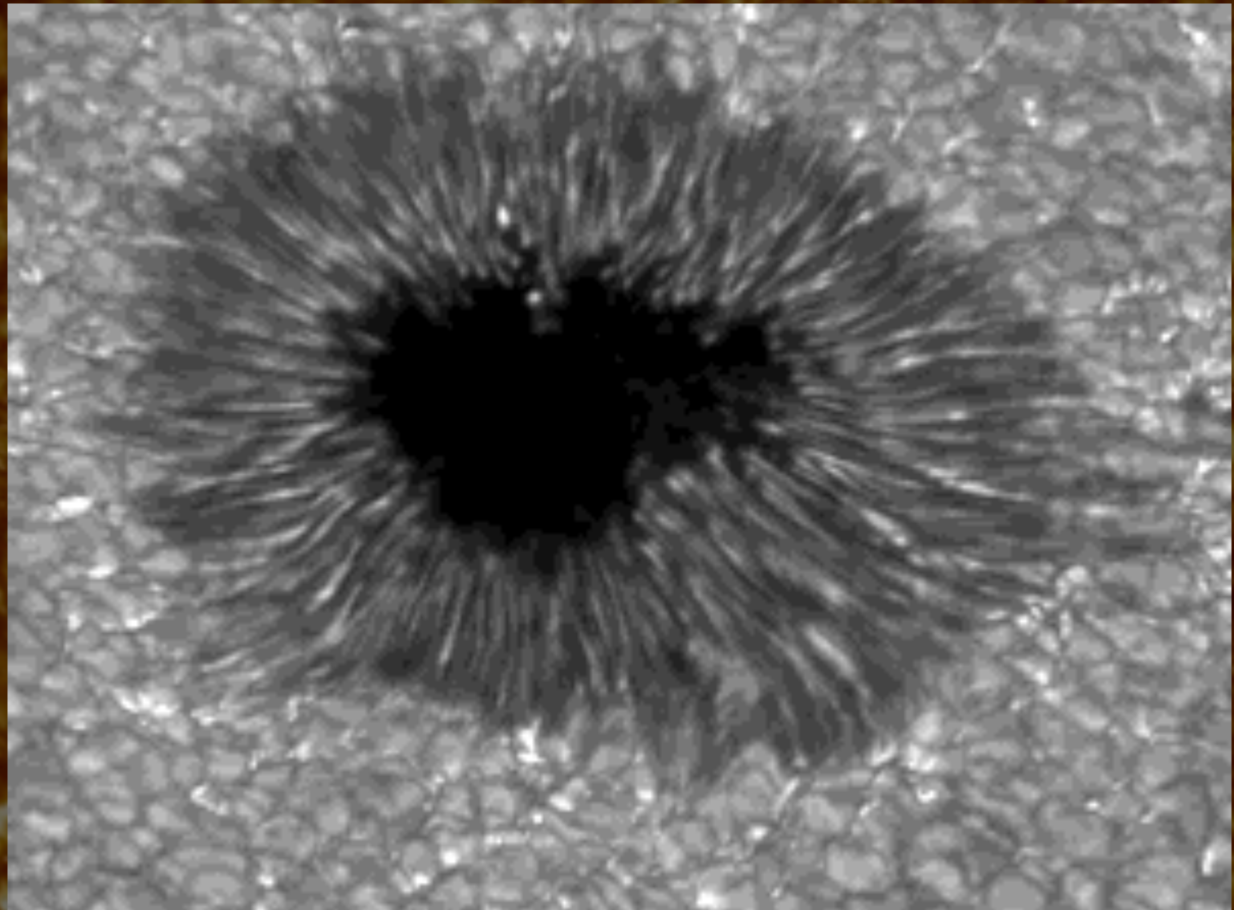
Sunspots



- **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

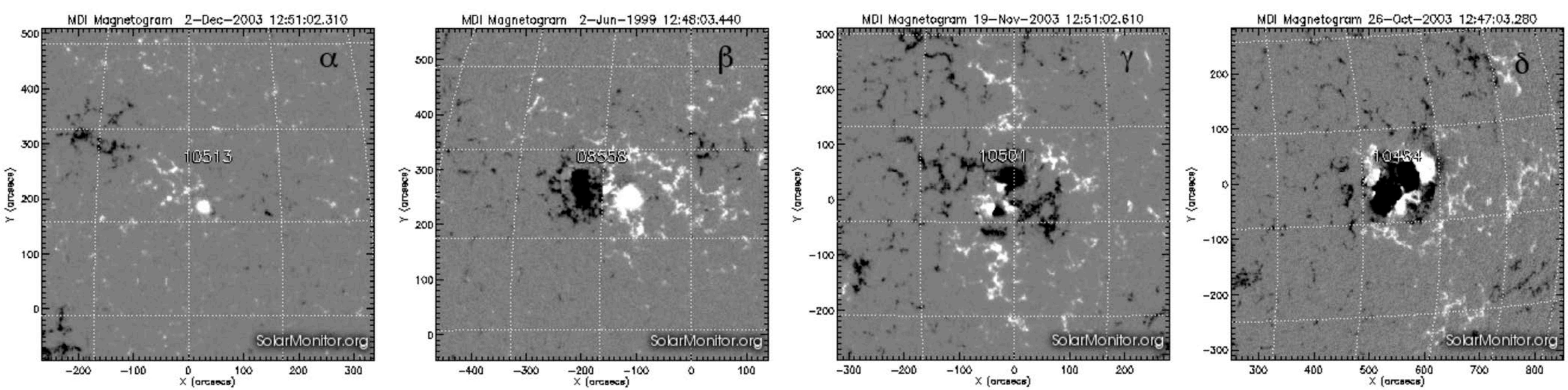
Evolution

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

Classification

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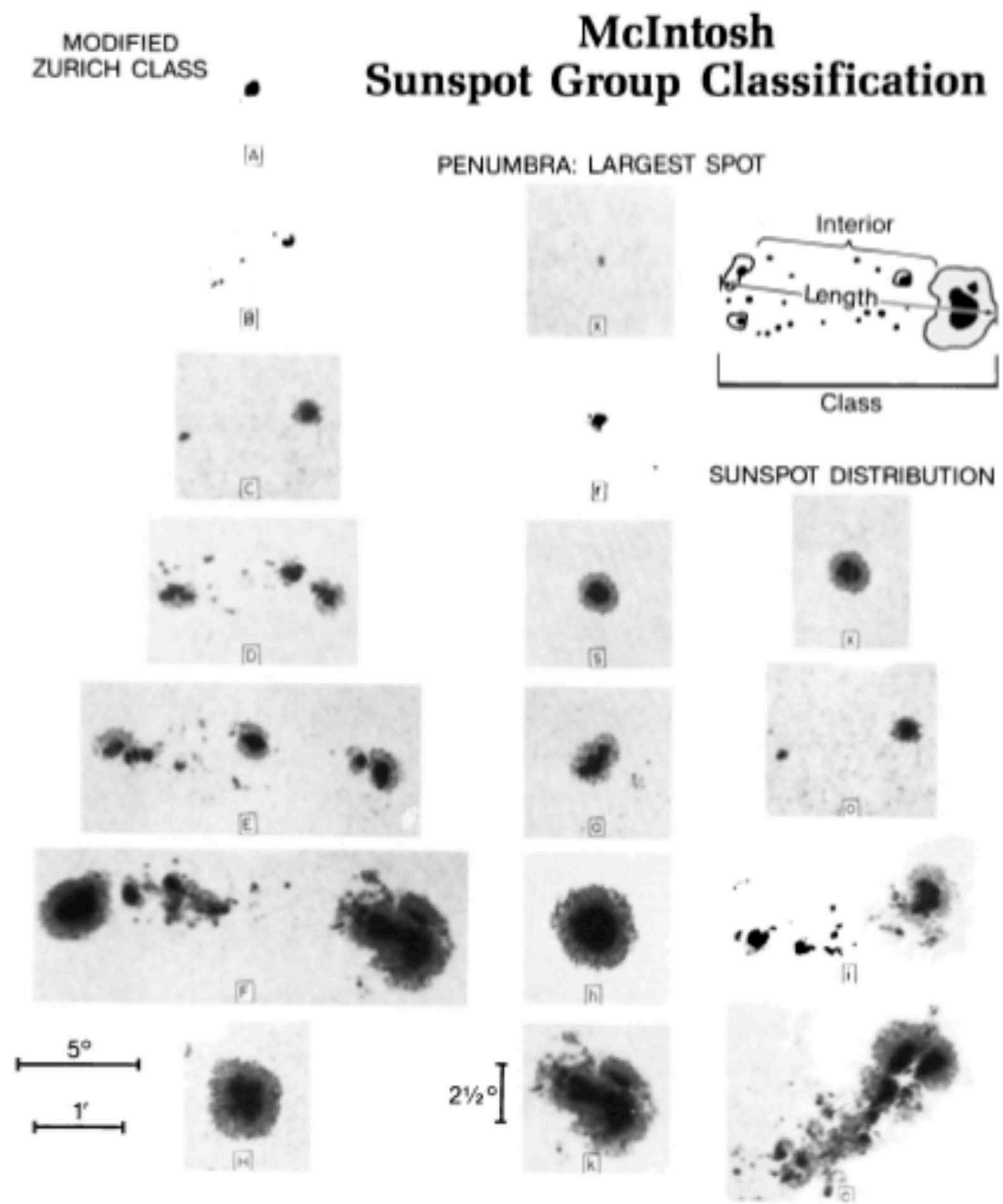
βγ — Bipolar sunspot group but complex so that no single, continuous line can be drawn between spots of opposite polarities.	**βδ —** Sunspot group of β class but containing one (or more) δ spots.	**βγδ —** Sunspot group of βγ class but containing one (or more) δ spots.	**γδ —** Sunspot group of γ class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

The Sun's magnetic field has a complicated topology.

Sunspots

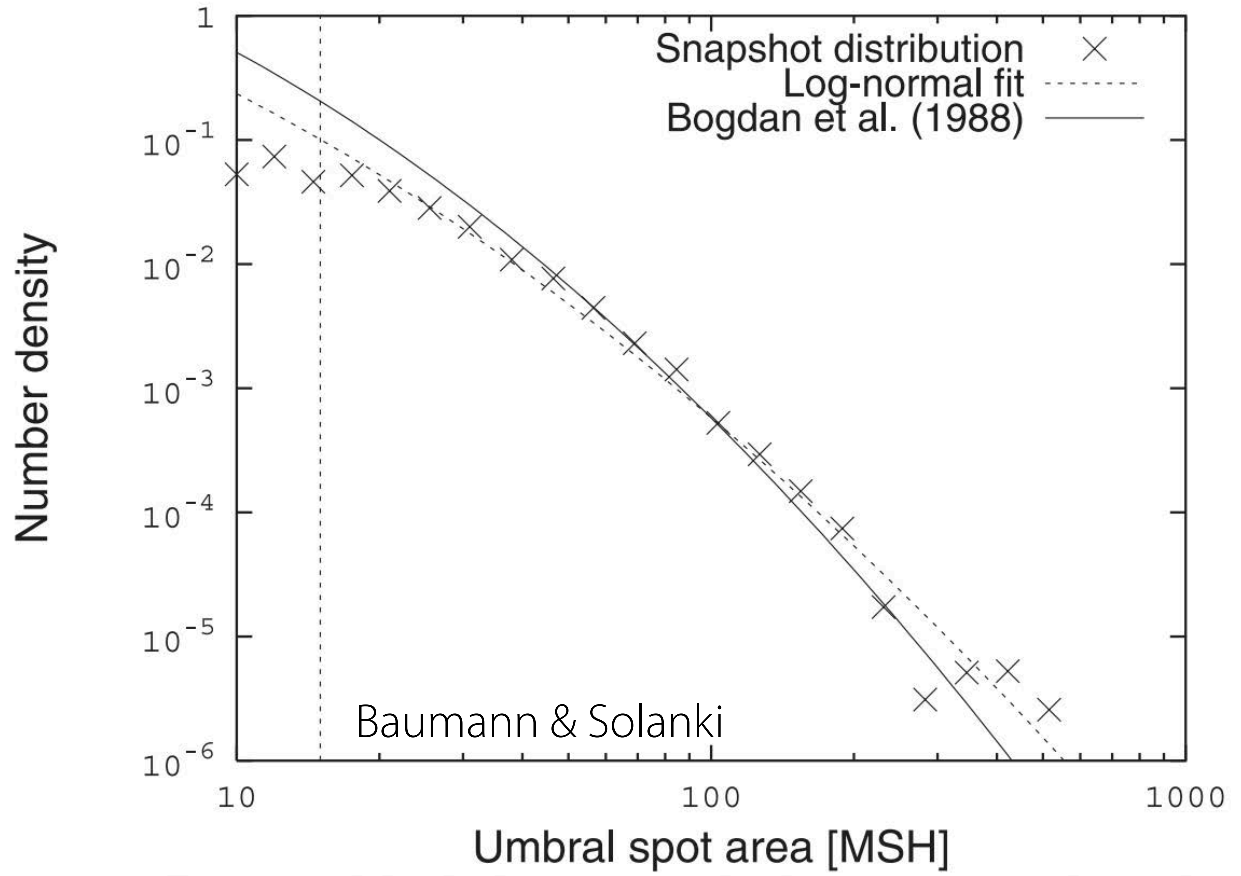
Classification

- 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.



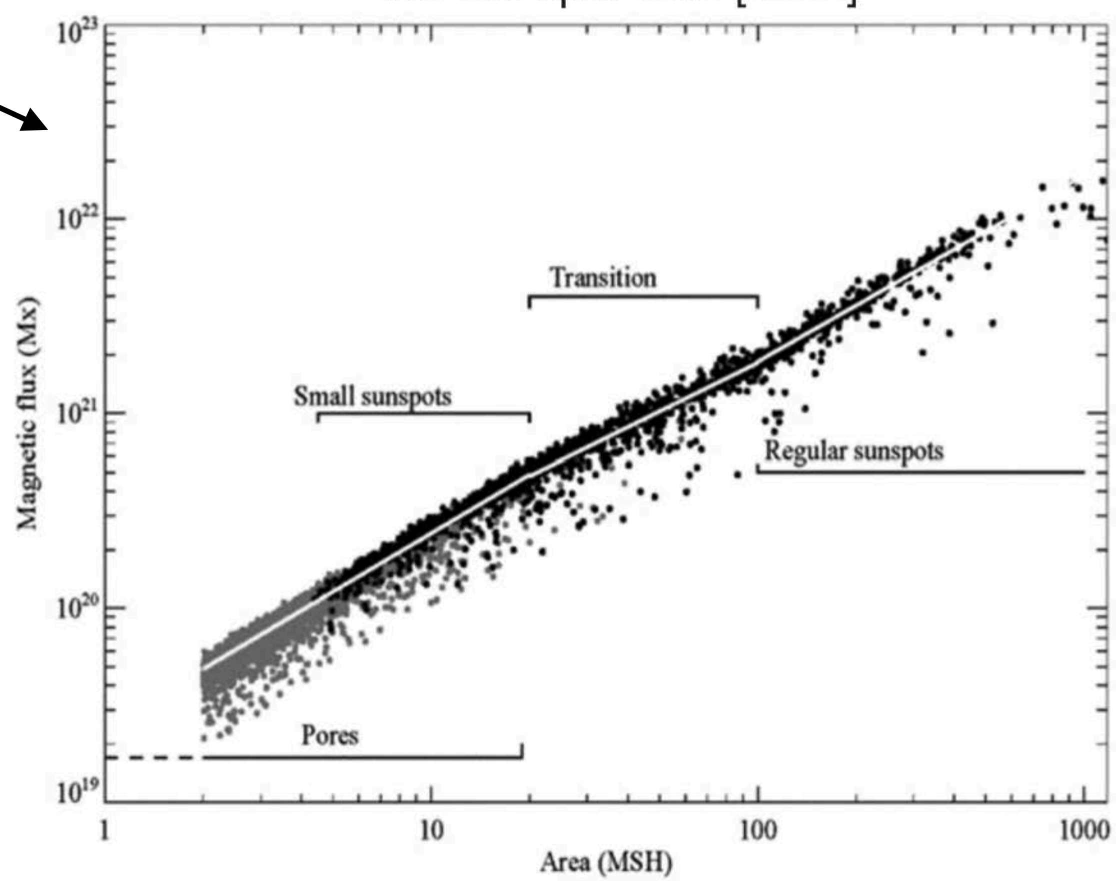
Sunspots

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)



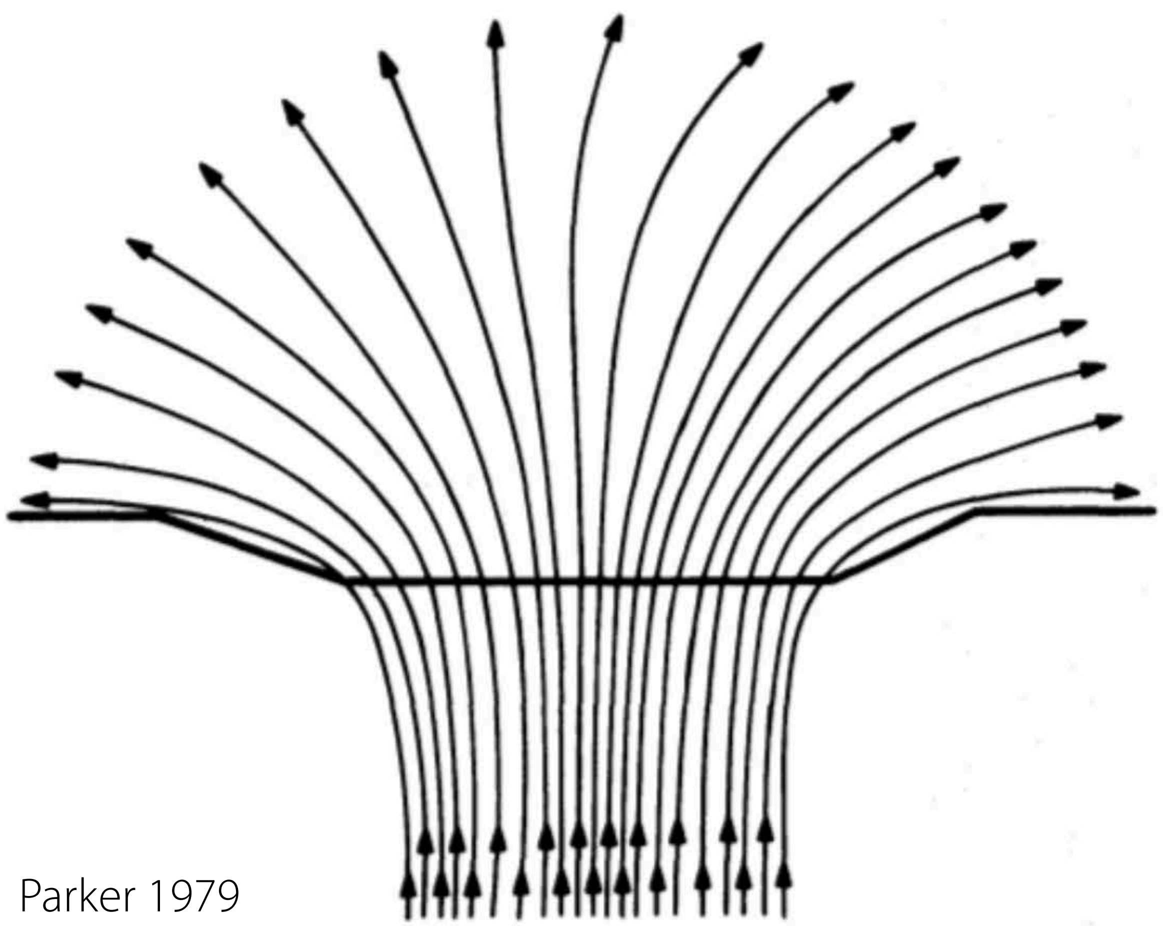
- **Lifetimes:** from hours for small sunspots to (rarely) months for the largest ones
  - Lifetime increases linearly with max. sunspot area
  - Sunspots decay steadily soon after reaching max. size due turbulent diffusion of the magnetic field at the surface

Sunspots

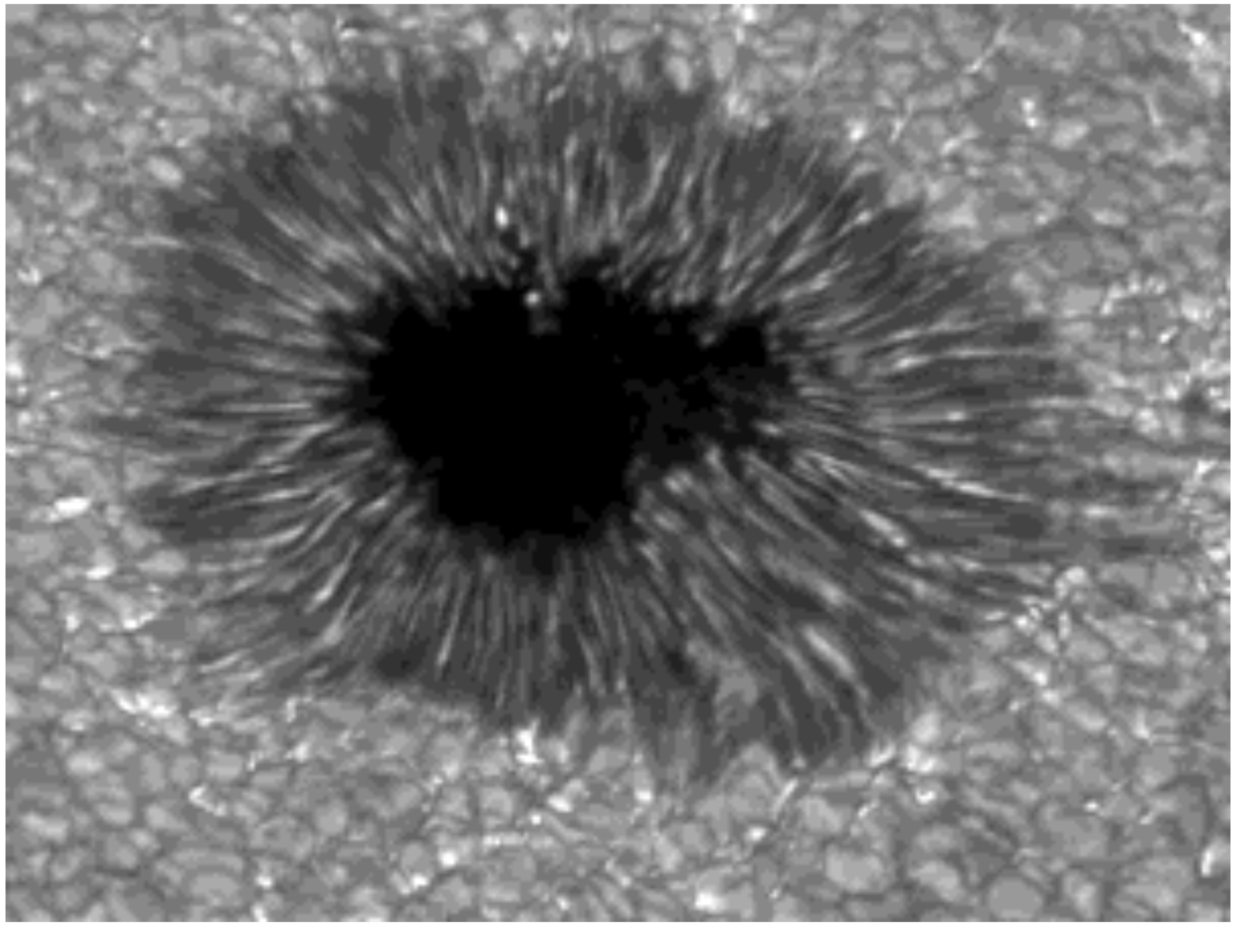
Magnetic field structure

- 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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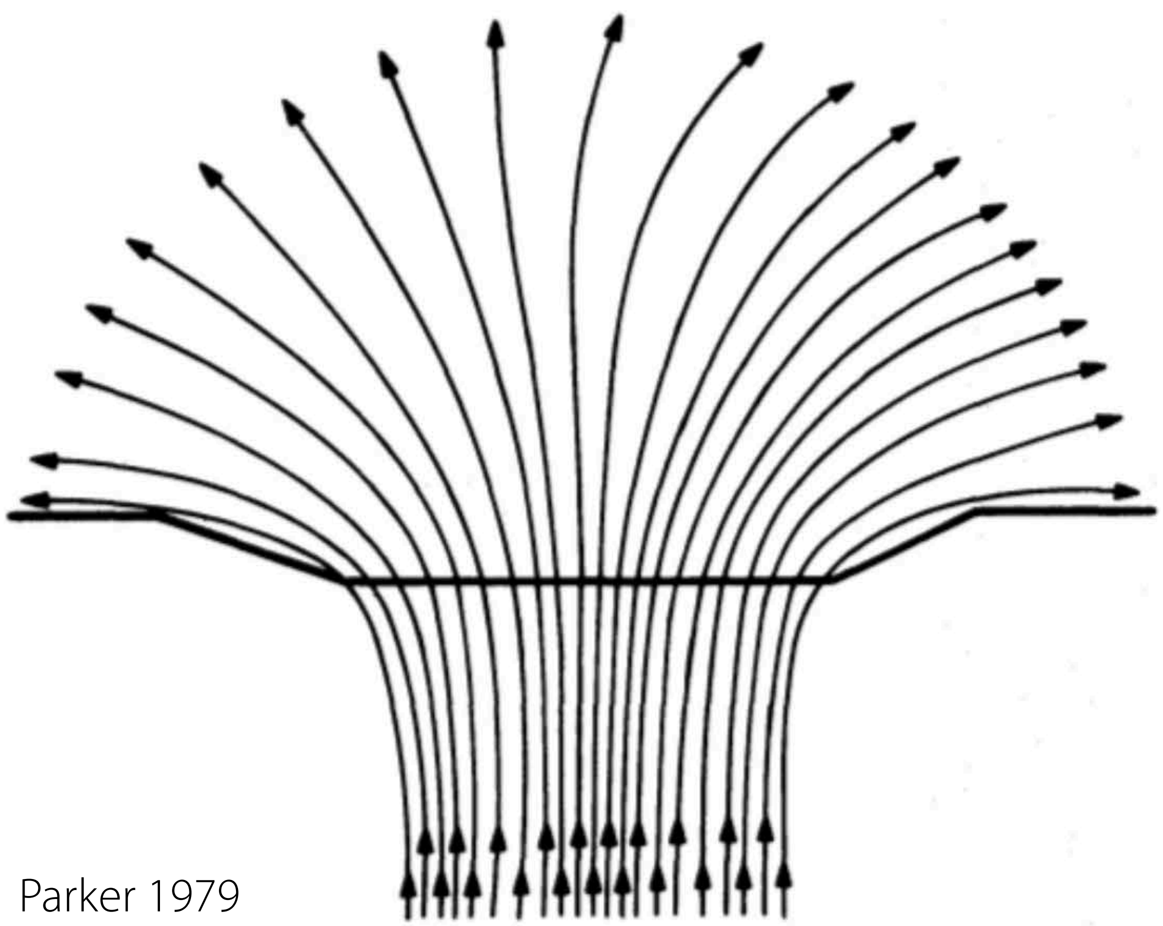
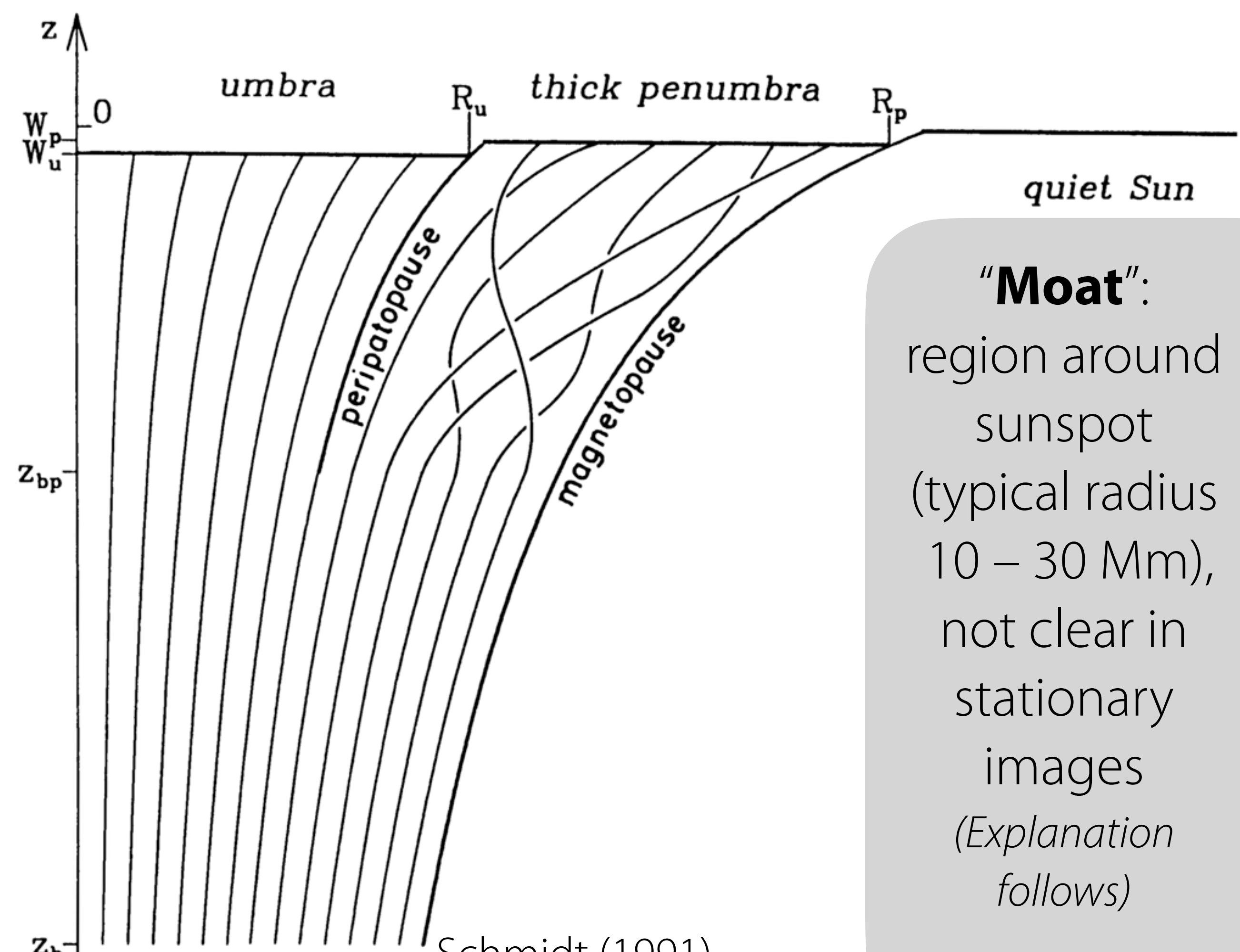


Parker 1979



Schmidt (1991)

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

Sunspots

Magnetic field structure

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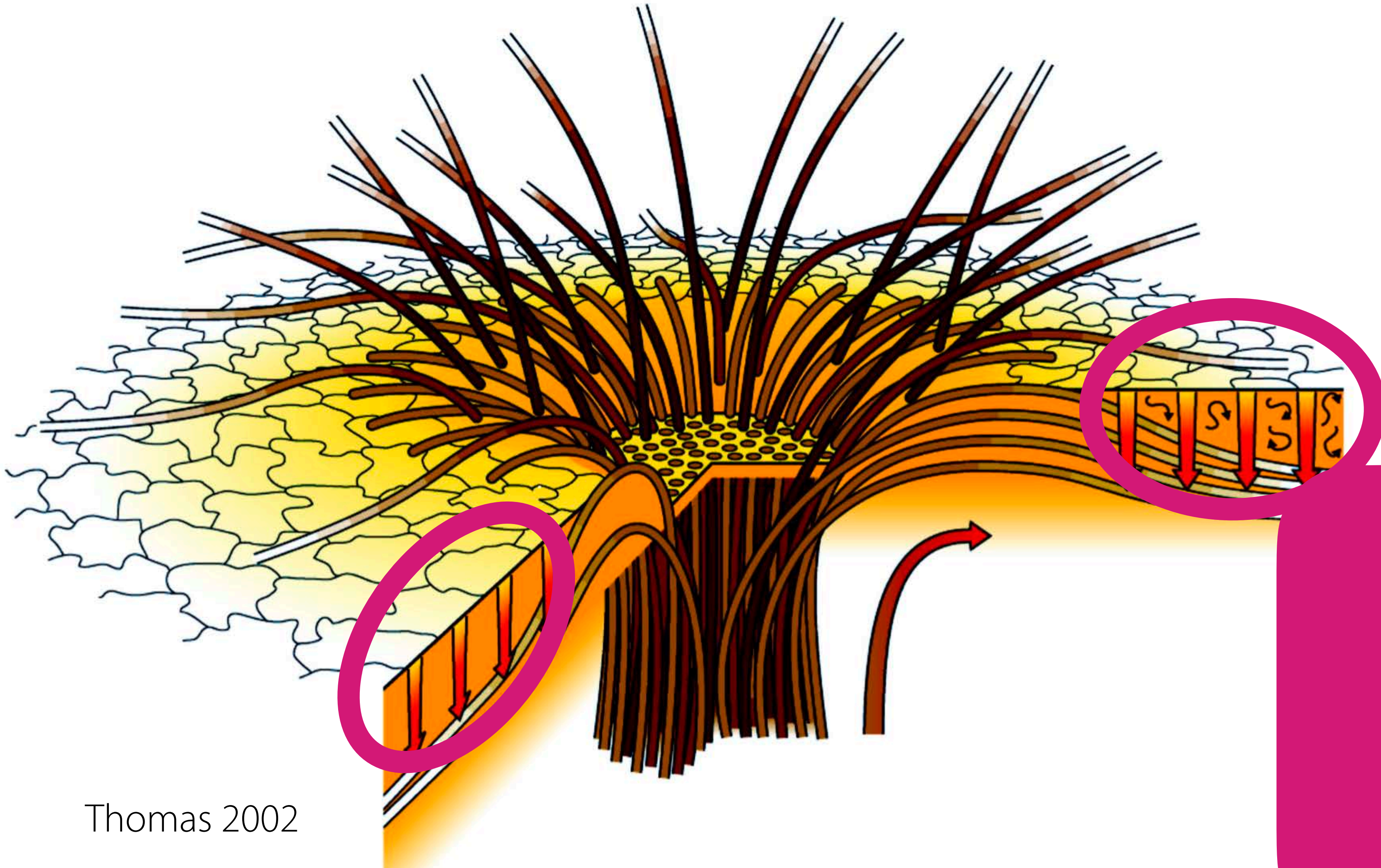
"Uncombed penumbra"
Mix of horizontally aligned and inclined magnetic field

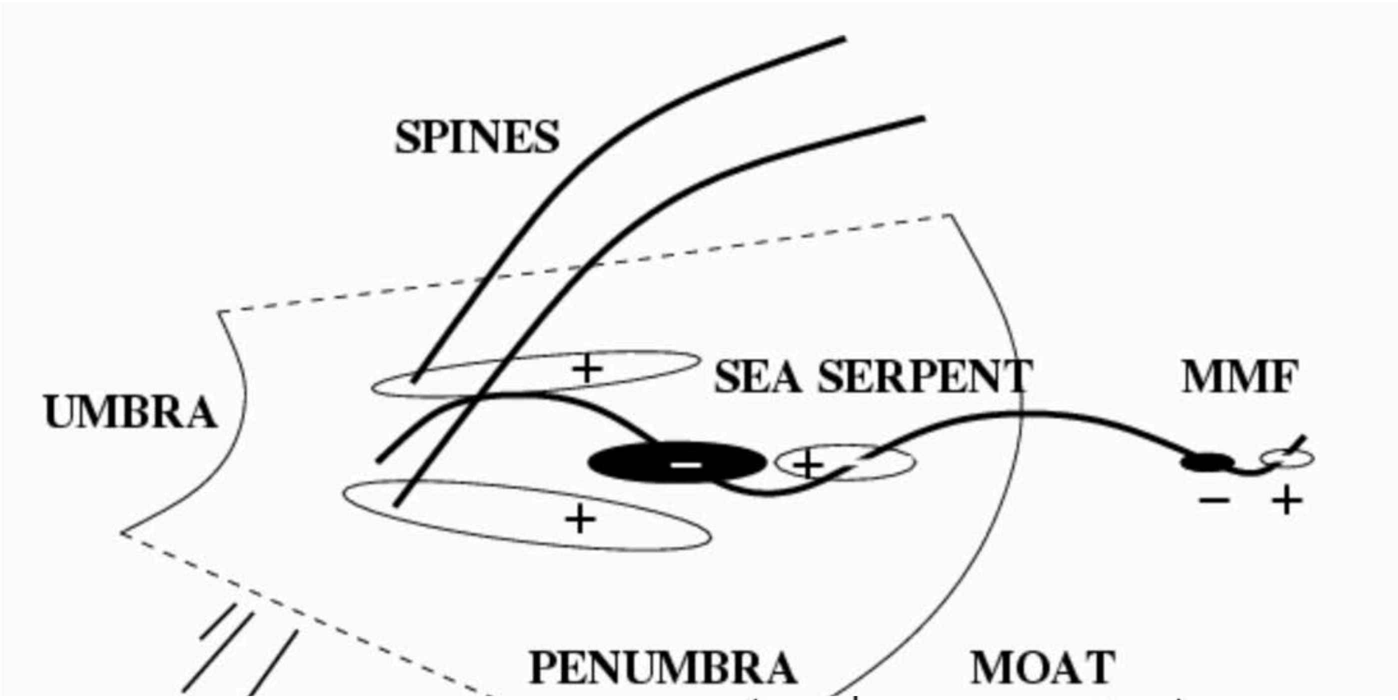


Thomas 2002

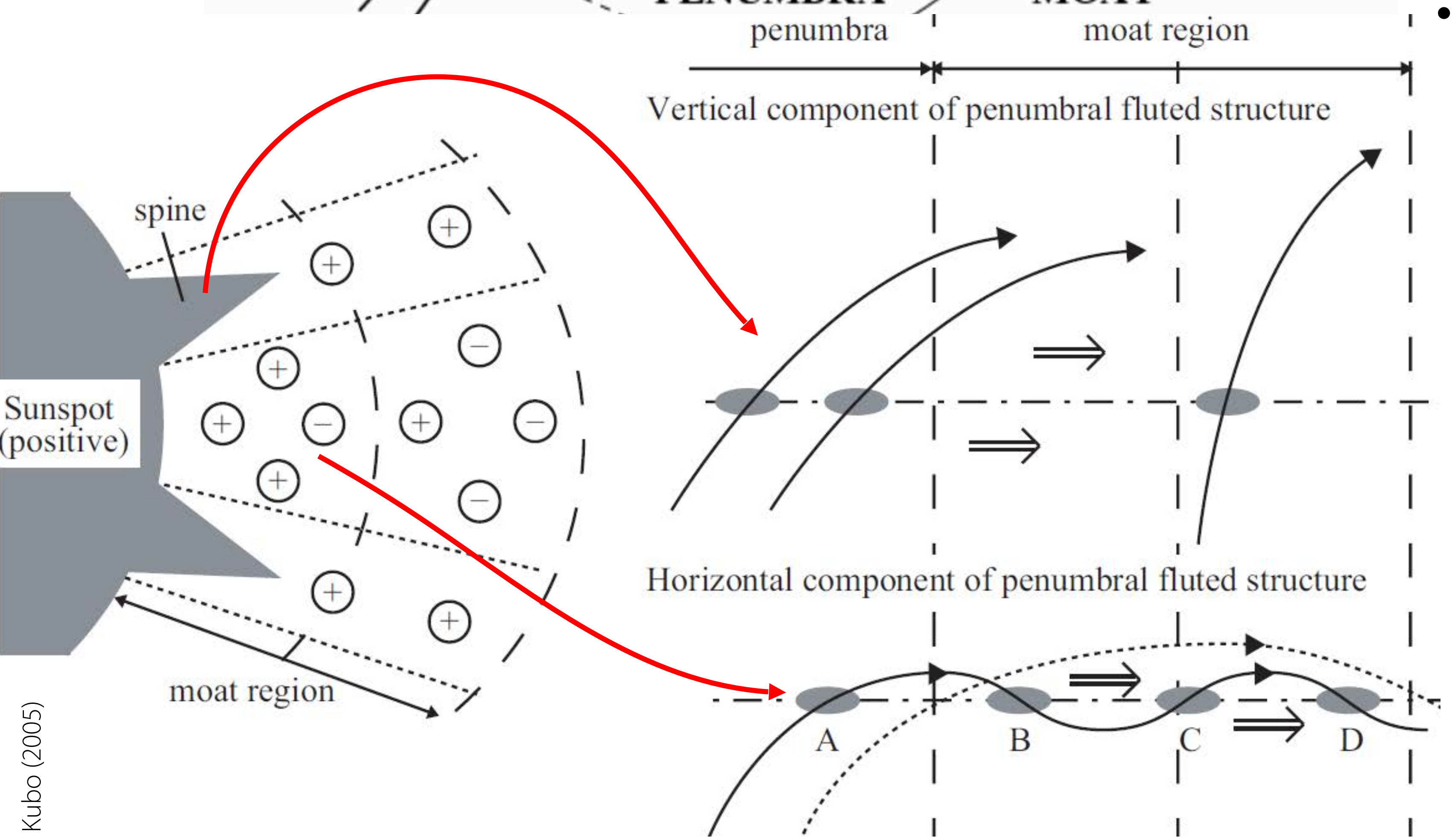
- Submerged parts penumbral flux tubes **dragged/held down by convection** on granule scales (in the moat), referred to as "turbulent pumping"

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"

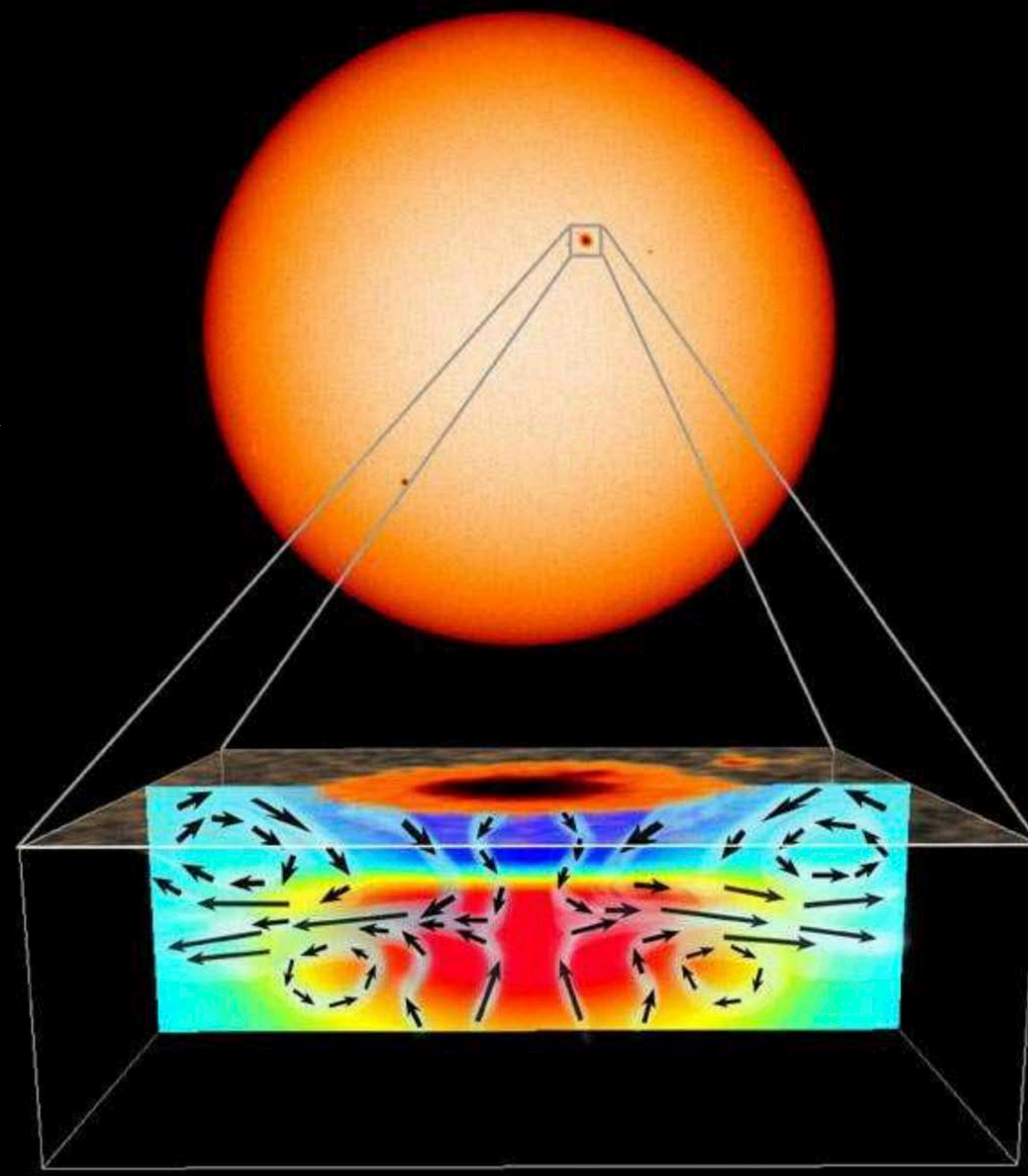
➡ **"Sea serpents"**

- **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

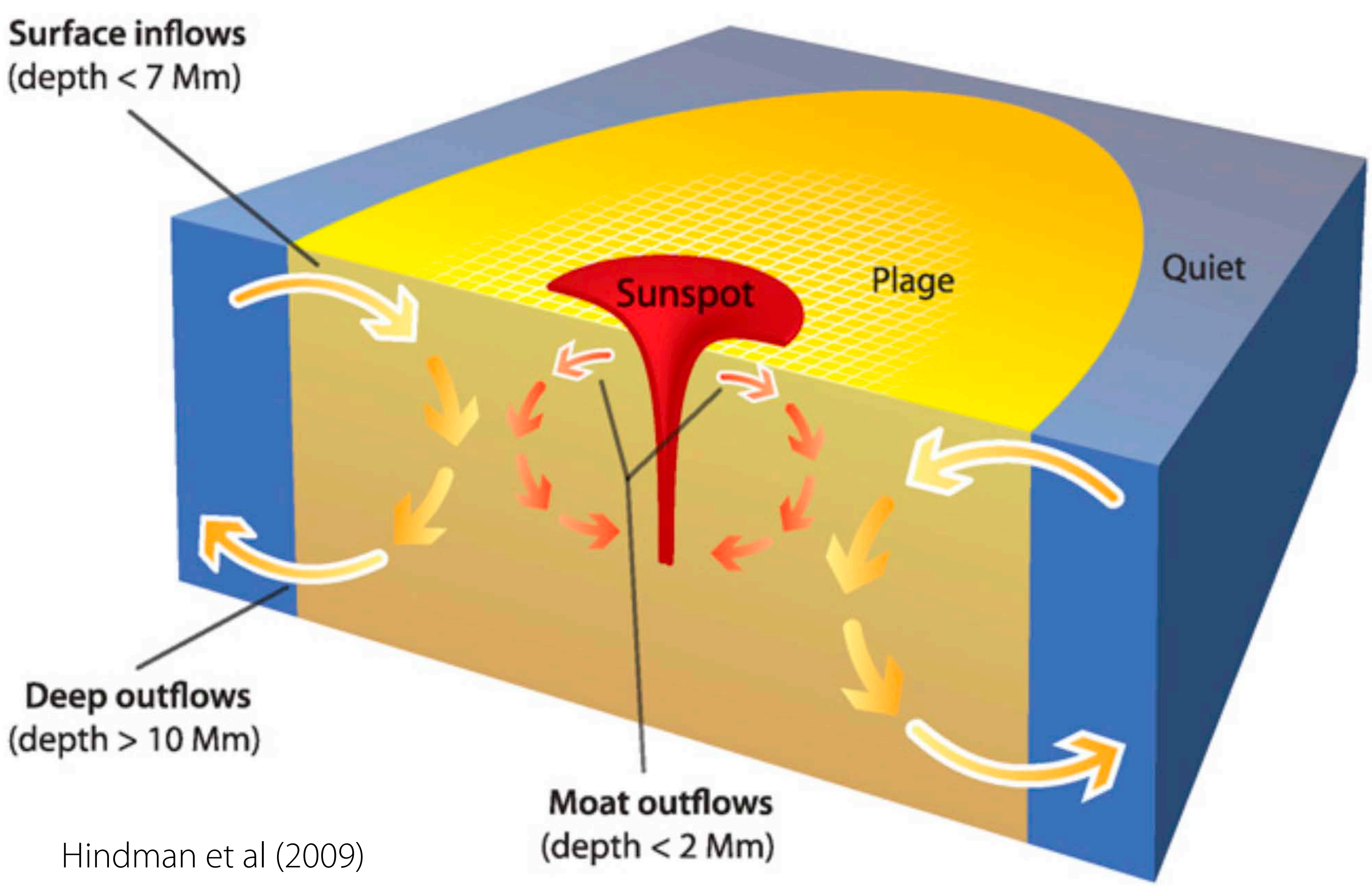


Structure below sunspot derived from helioseismological studies Kosovichev et al. 2000)

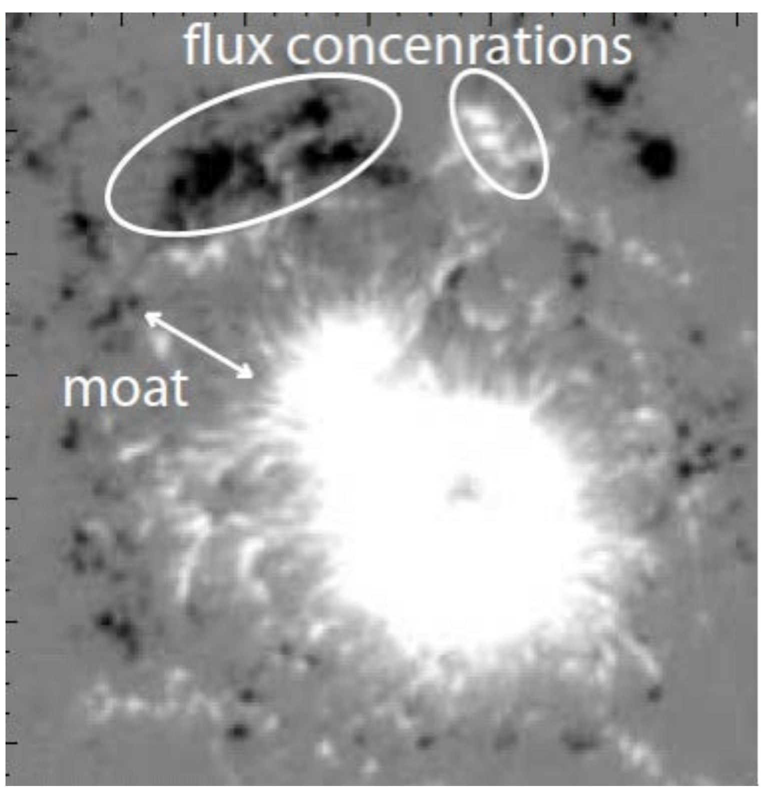
Sunspots

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

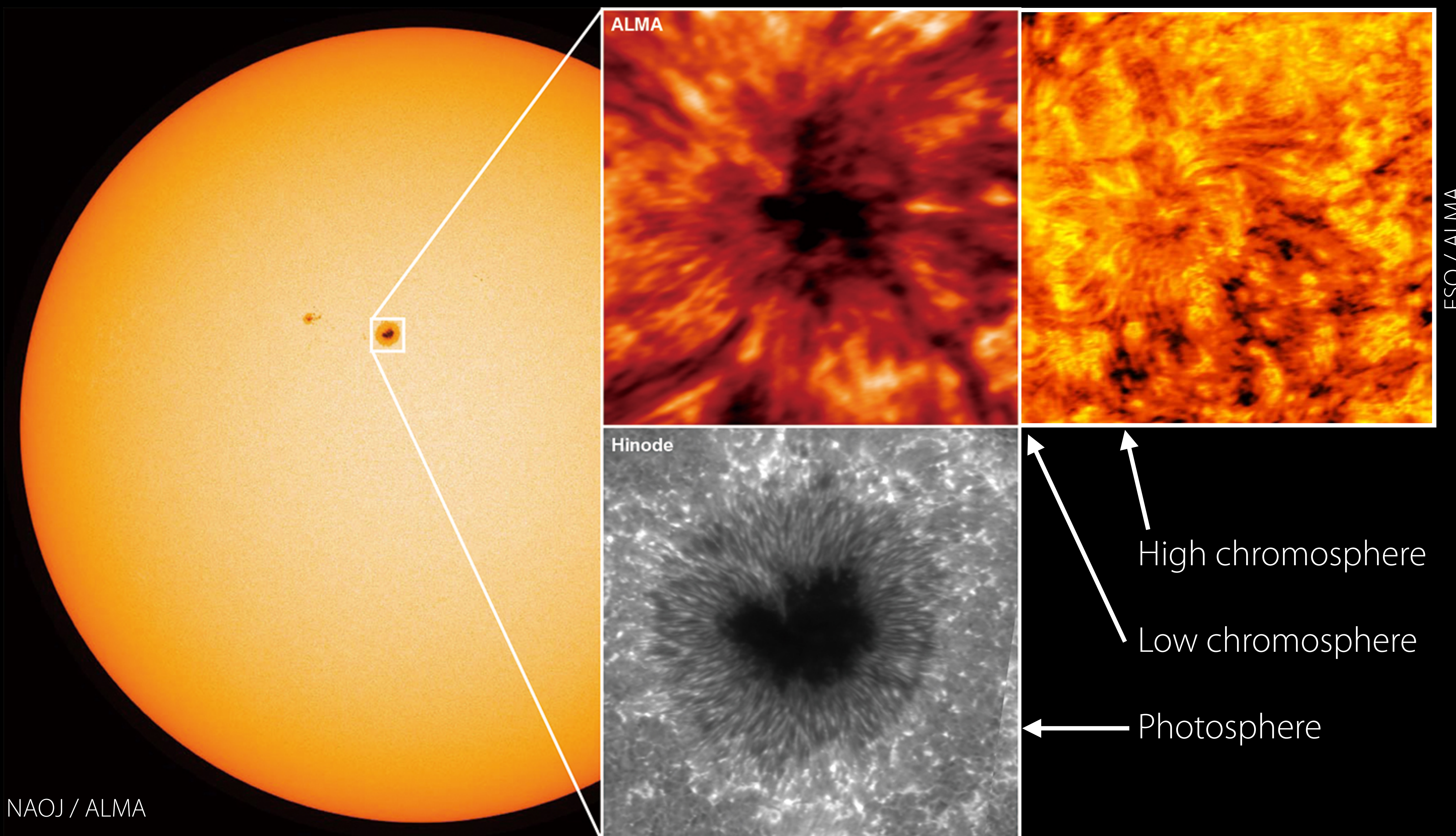


Hindman et al (2009)



Sunspots

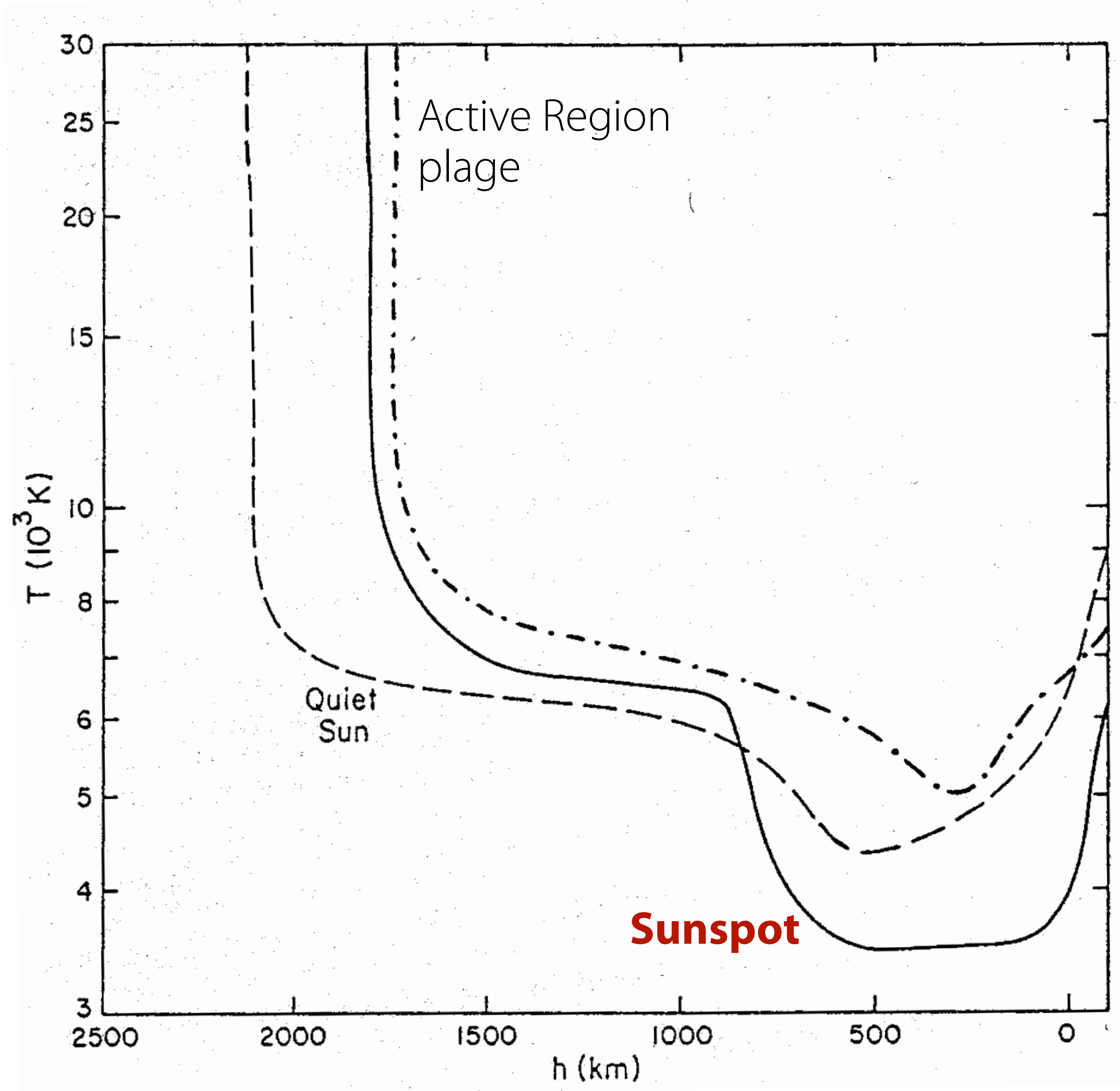
Temperature stratifications



Sunspots

Temperature stratifications

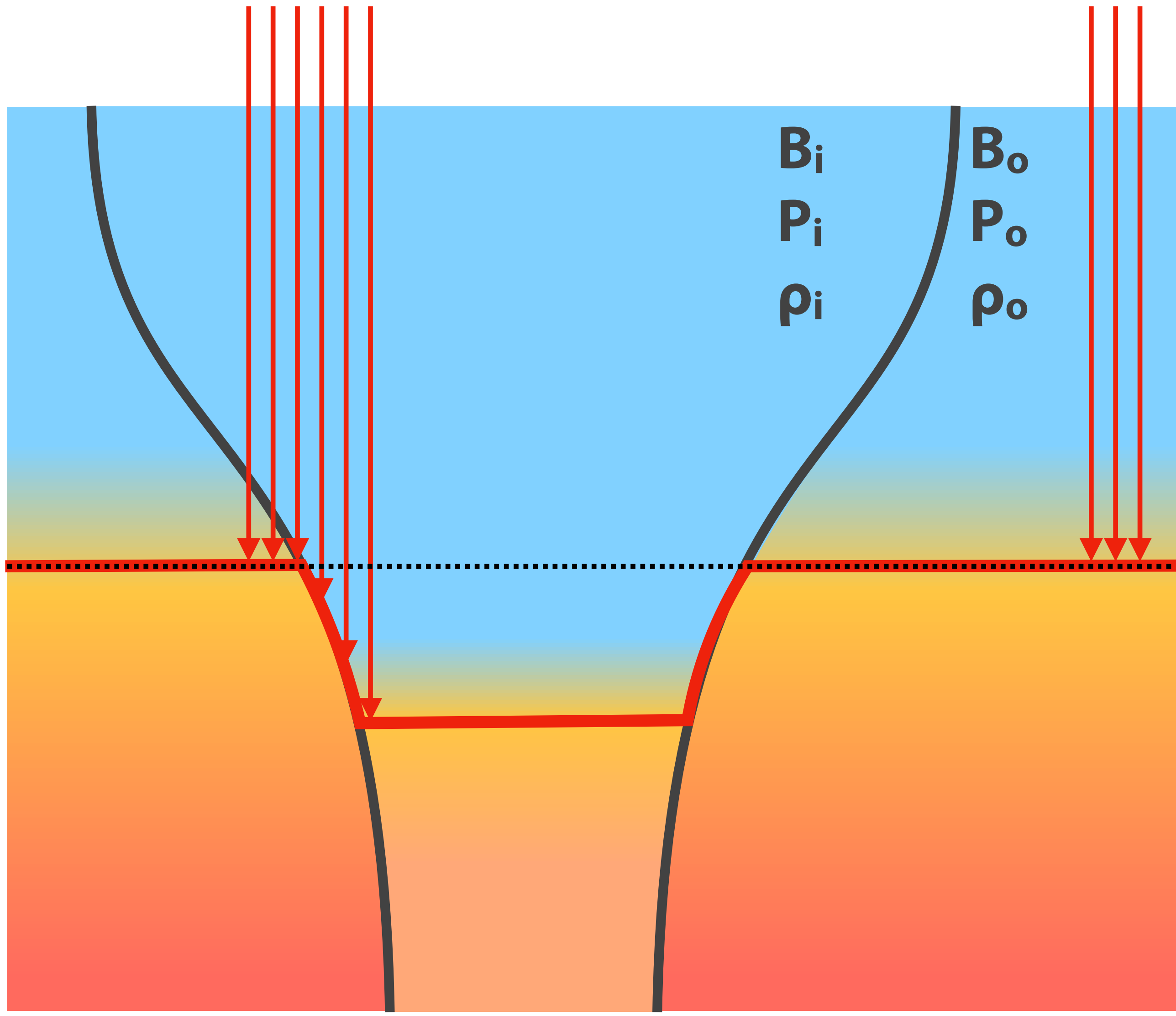
- Temperatures in sunspot umbra much below Quiet Sun values
    - Sunspots appear dark in the photosphere relative to surrounding
- Sunspot temperatures rise quickly in low chromosphere, surpass Quiet Sun temperatures
    - Sunspots appear brighter than surrounding (e.g. in the continuum at $\lambda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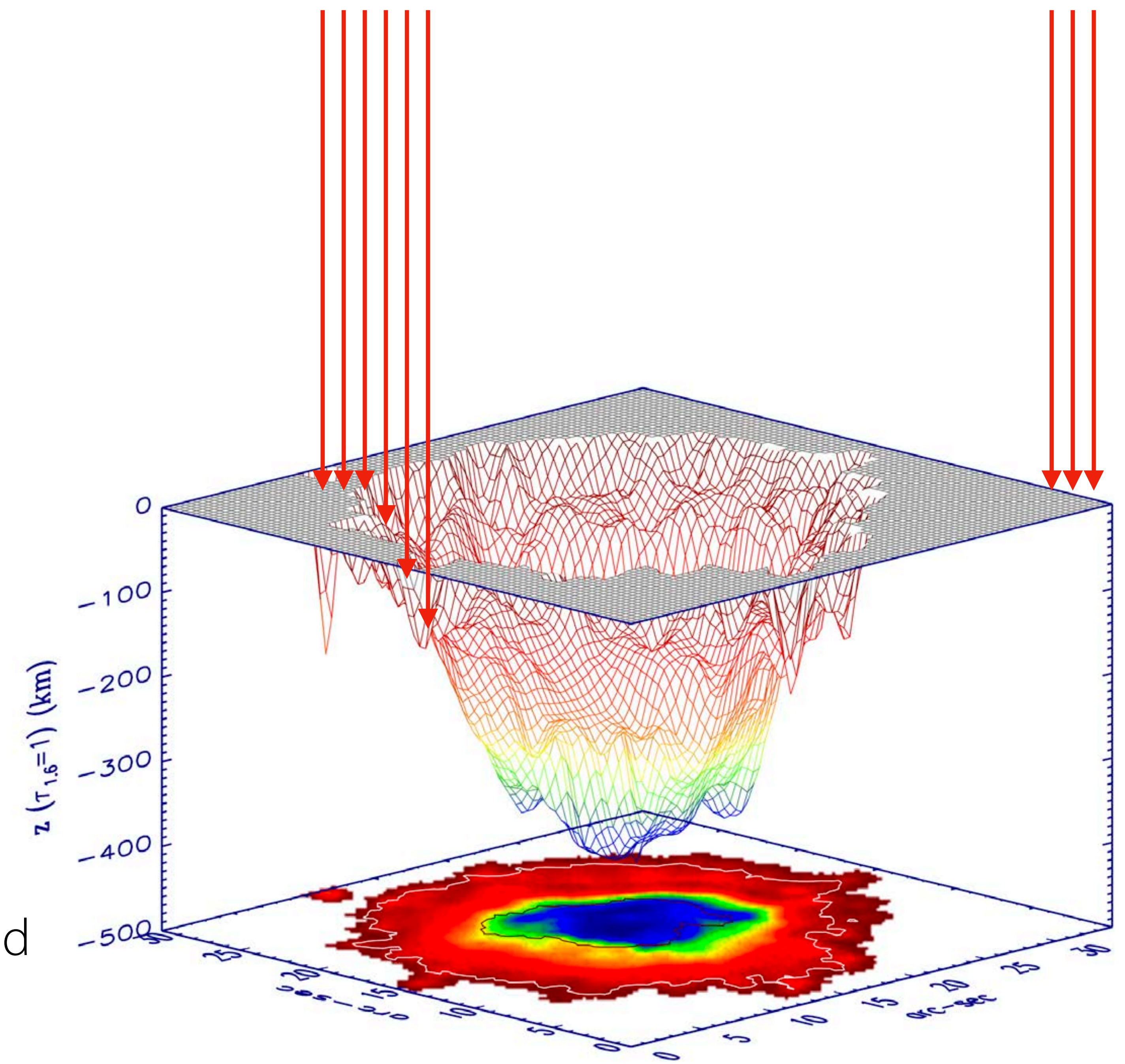


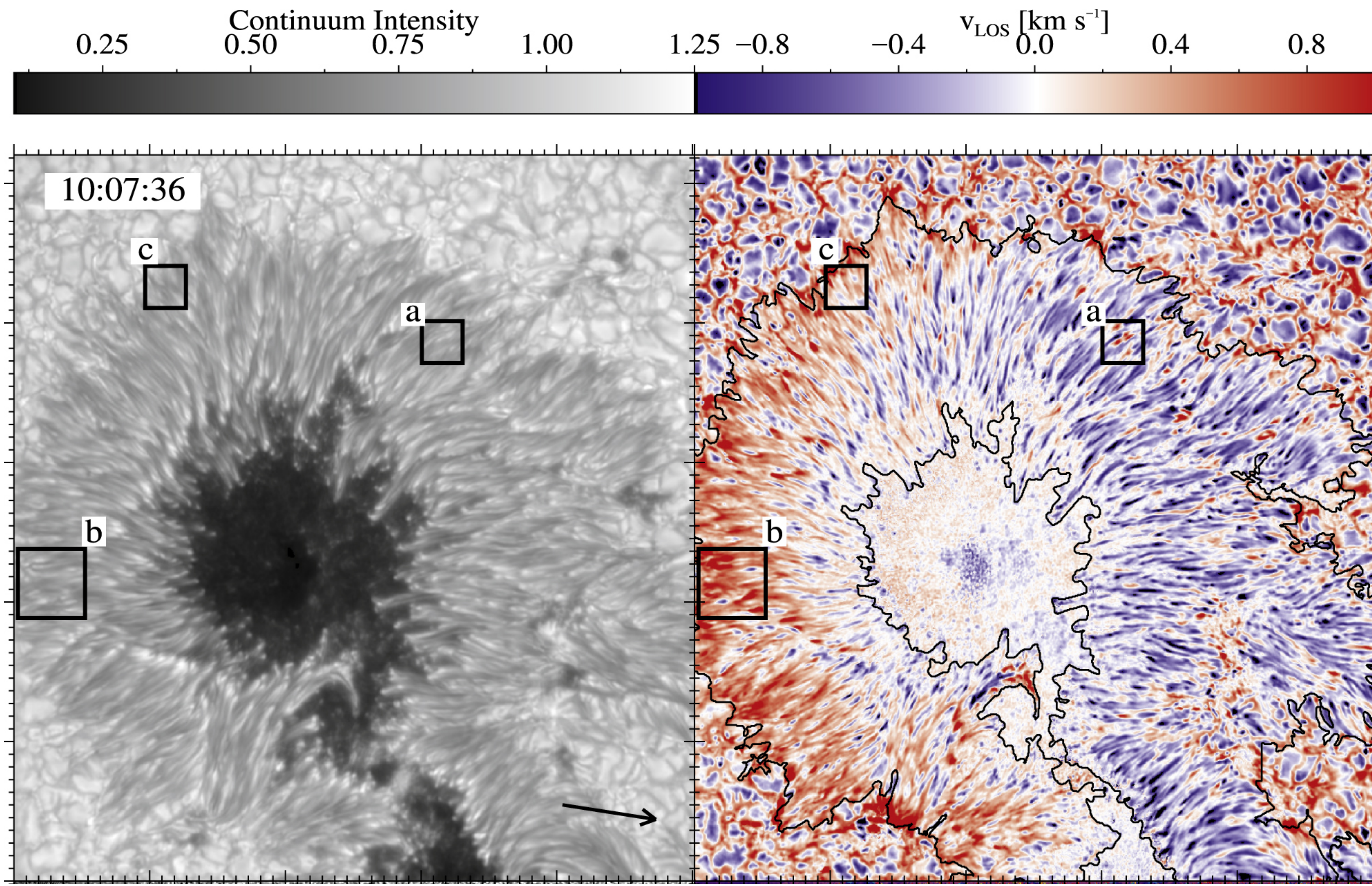
➡ **Optical depth lower** inside magnetic field structure than outside

➡ Looking deeper into the Sun inside the magnetic field structure

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

Sunspots

Evershed effect / flow



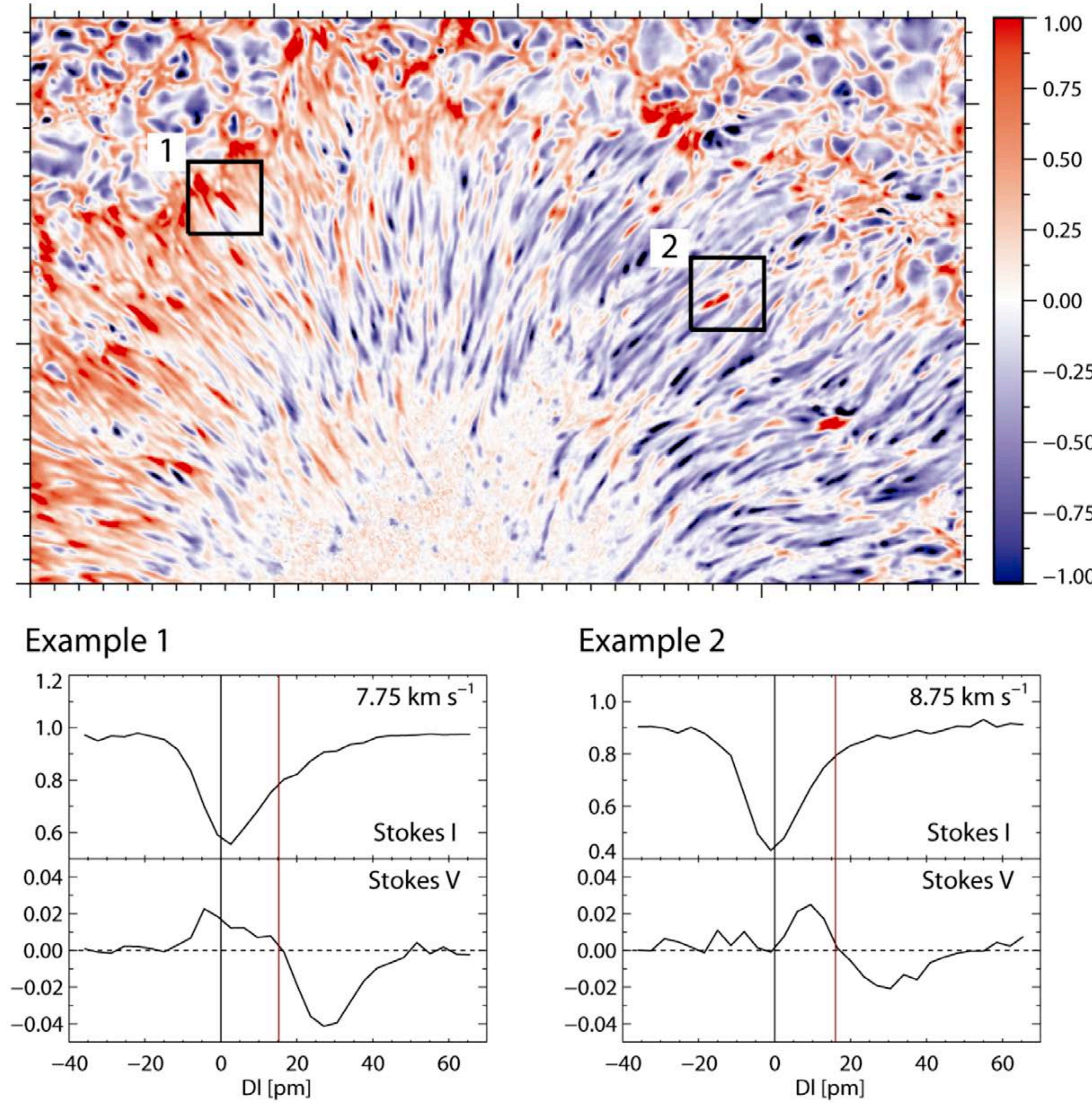
Esteban Pozuelo et al. (2016)

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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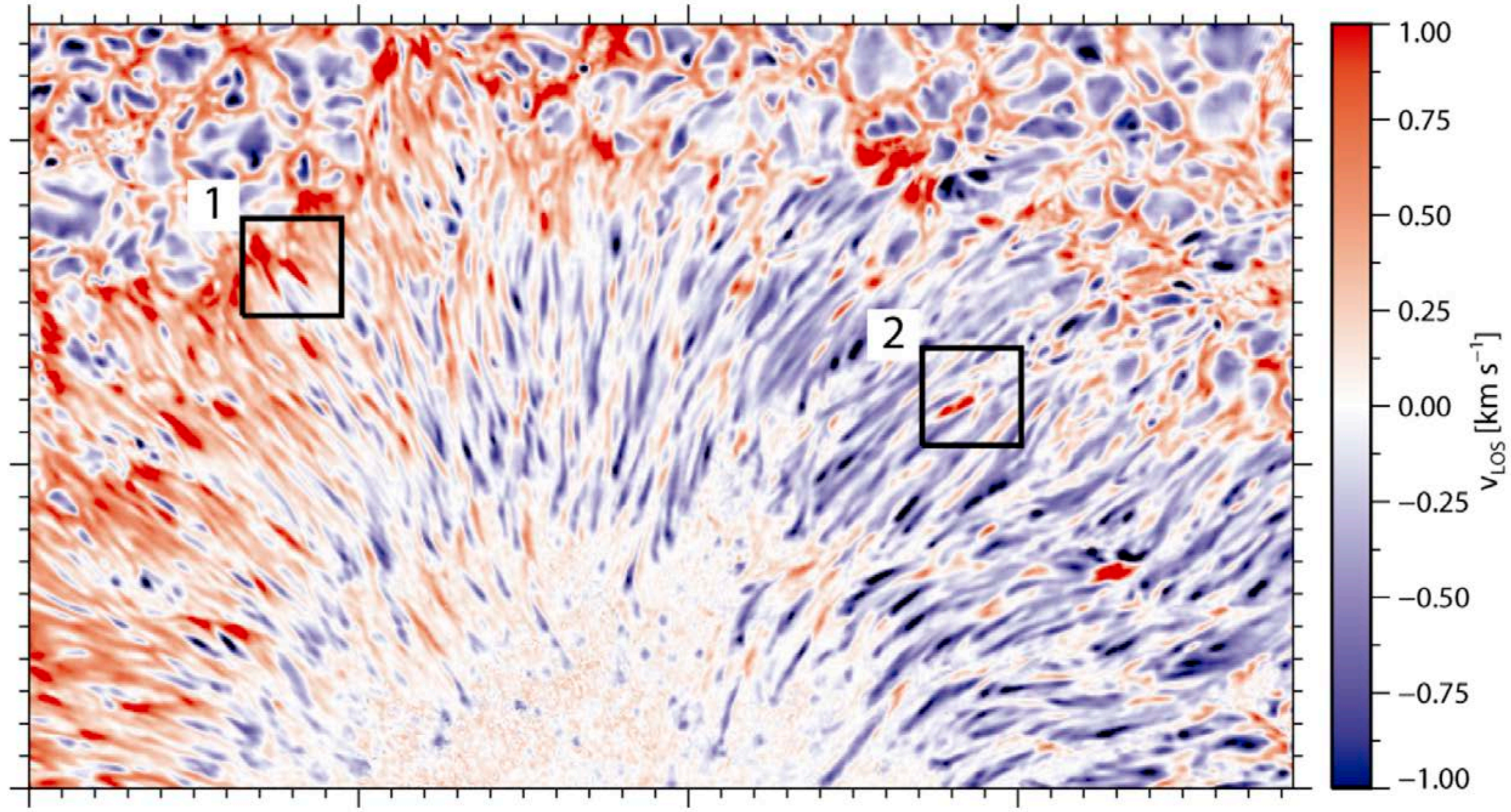
- **Supersonic** components with velocities ~8 km/s in photosphere, occasionally up to 15-16 km/s
    - Supersonic flows last 1-5min



- 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.**

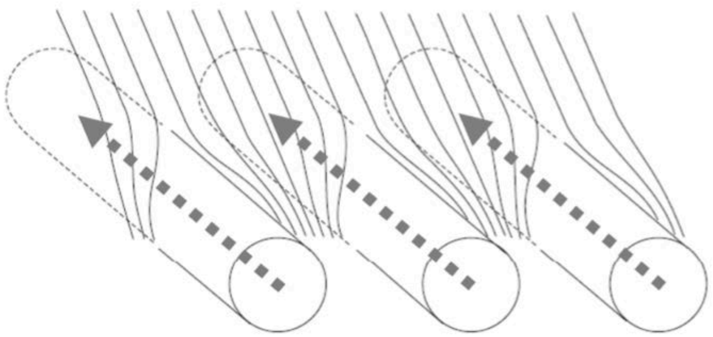
Be aware of project effects depending on the location of the sunspot on the solar disk.

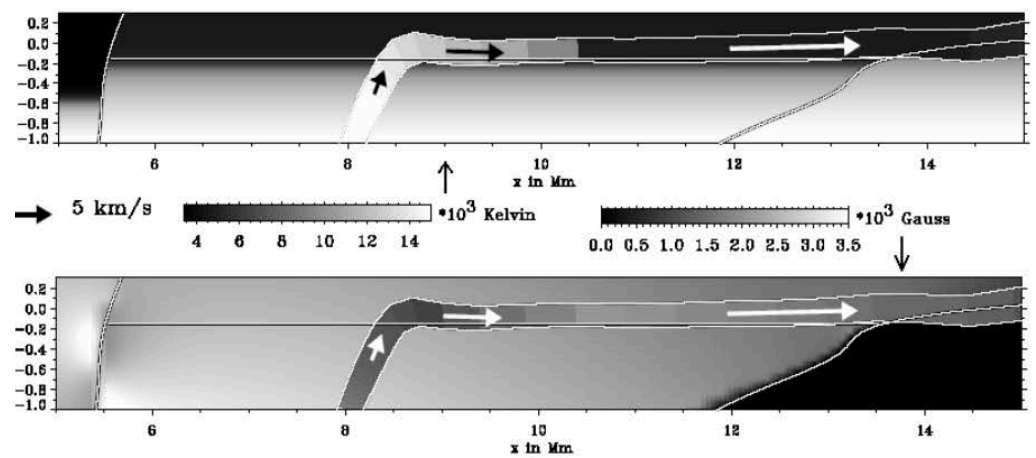
Esteban Pozuelo et al. (2016)

Sunspots

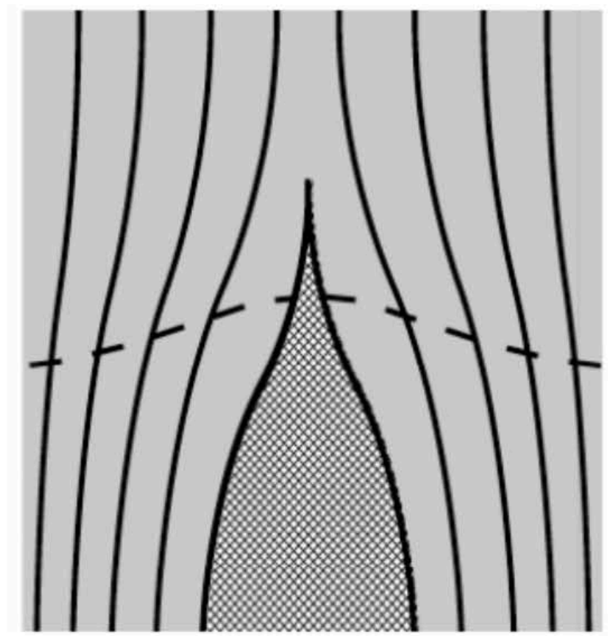
Evershed effect / flow

Embedded flux tube model
(e.g., Solanki & Motavon 1993
Schlichenmaier etal 1998)





Gappy model
(e.g., Spruit & Scharmer 2006)



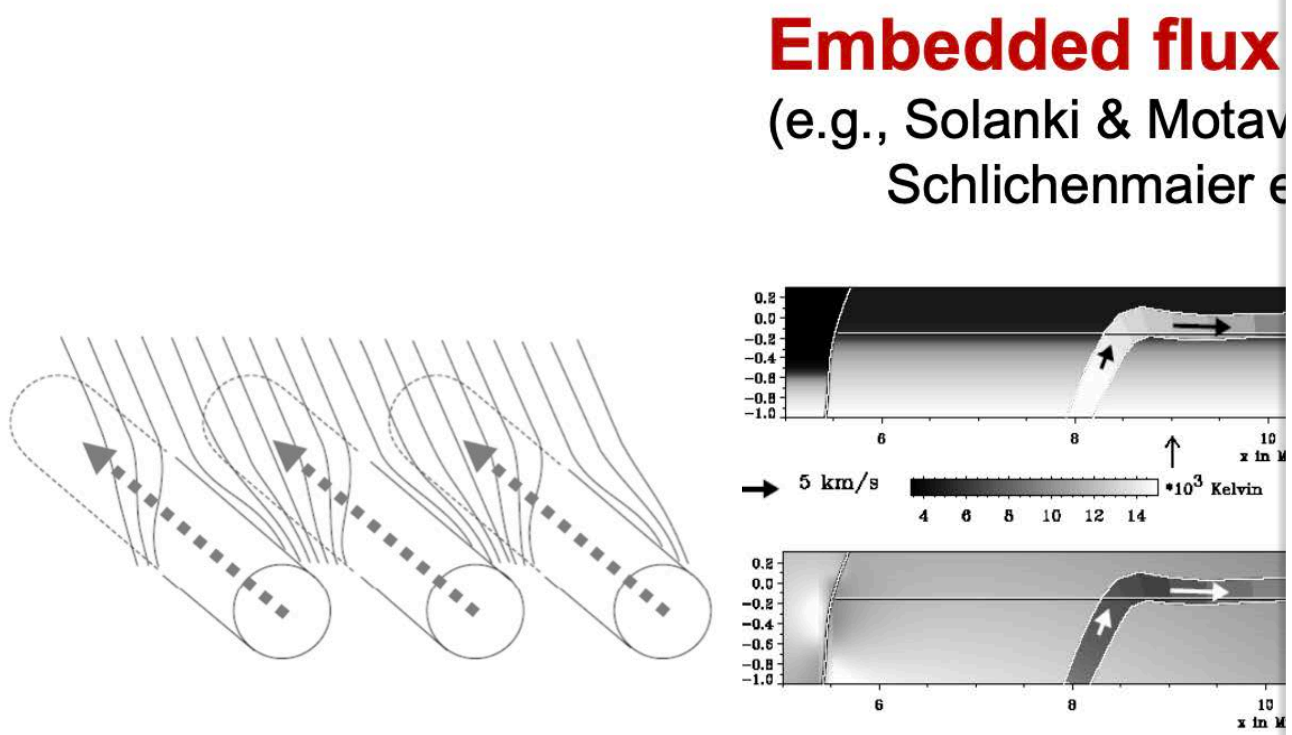
Bright filaments = field free gap = protrusion of convection

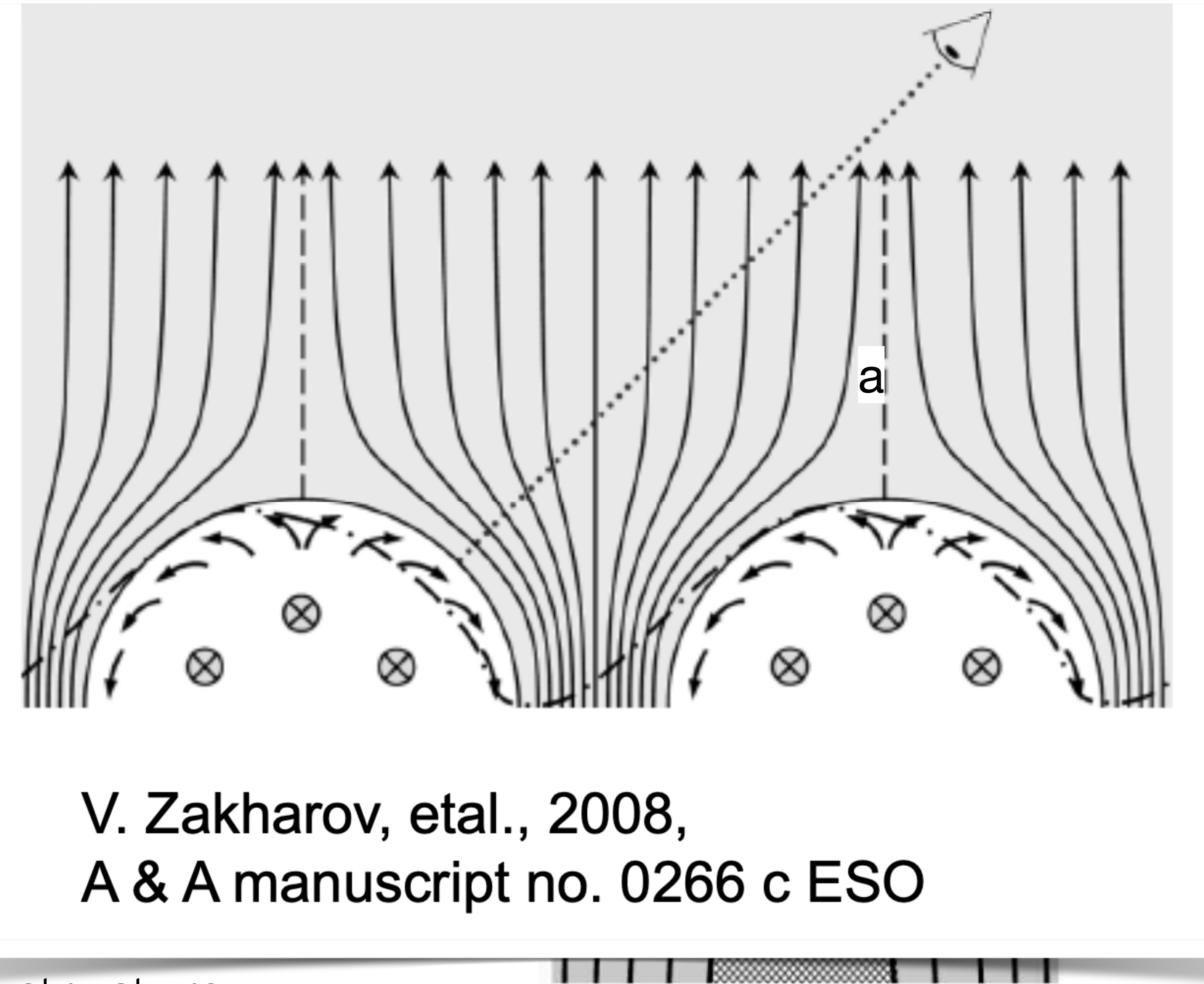
- Different models explaining the penumbral structure and flows but typically only accounting for some and not all observed aspects
- Explanation lies in combination of overturning **convection** in competition with strong magnetic field *(inhibiting convection when strong, permitting otherwise)* and the **complicated magnetic field structure of the penumbra** (horizontal and inclined field)

➡ Evershed flow identical to horizontal component of penumbral convection, driven by pressure gradients, flows deflected horizontally through Lorentz-force generated by horizontally stretched magnetic fields

Sunspots

Evershed effect / flow





V. Zakharov, etal., 2008,
A & A manuscript no. 0266 c ESO

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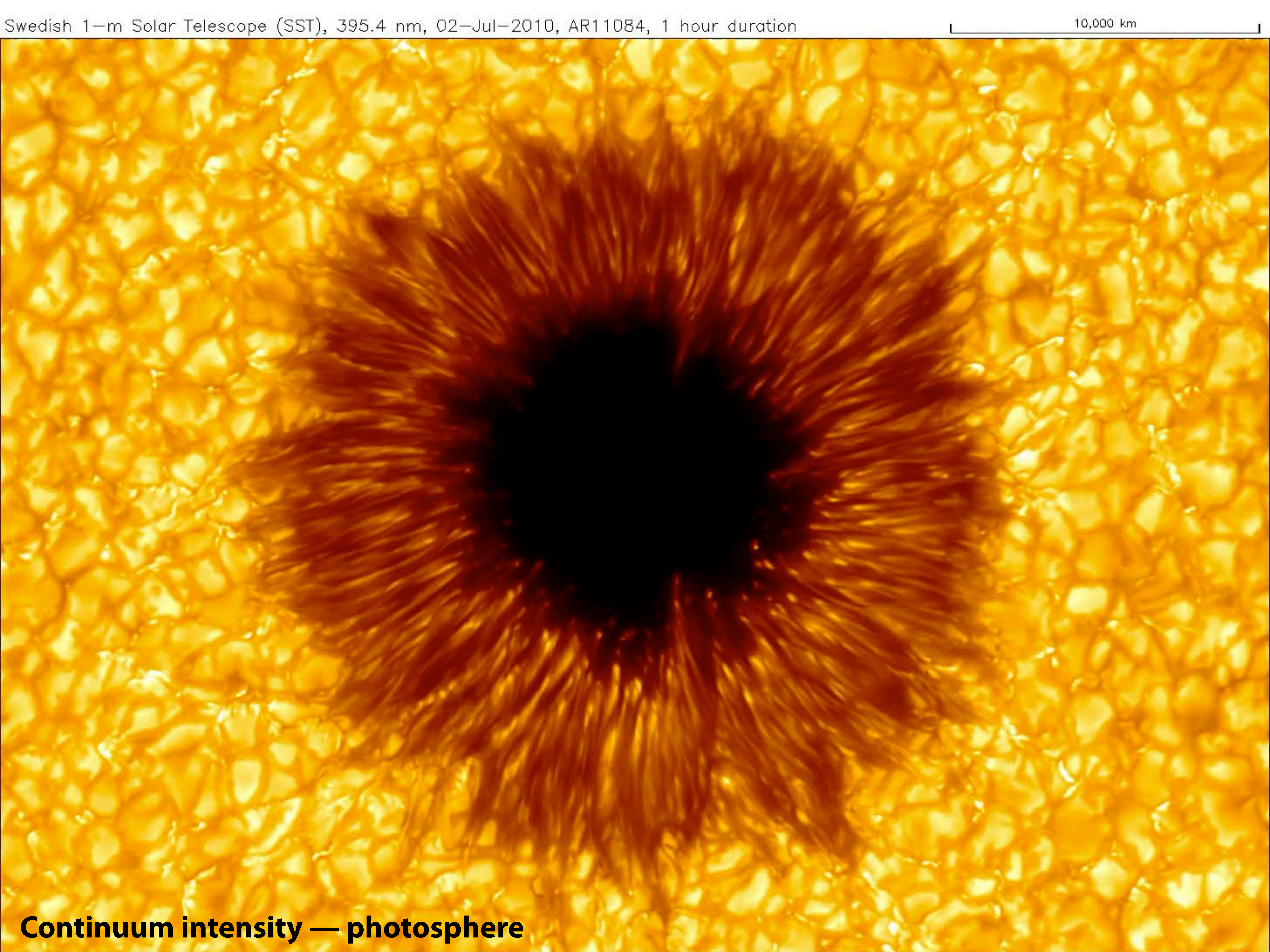

Continuum intensity — photosphere

Swedish 1-m Solar Telescope (SST), Ca II H 396.8 nm, 02-Jul-2010, AR11084, 1 hour duration

10,000 km