Lecture 21

AST5770

Solar and stellar physics

Sven Wedemeyer, University of Oslo, 2023

Solar filaments, prominences, CMEs Recap

Filaments and prominences — recap

Filament on disk — prominence at the limb

1. What is the difference between a filament and a prominence?
2. What are the main three types?
3. How long can filaments be?
4. Why are filaments dark and prominences bright?
5. How can cool dense plasma “just hang up there”?
6. What is the plasma temperature in filaments and how does that compare to their environment?
7. Can you explain the following parts of filaments?
    1. Leg
    2. Spine
    3. Barb
    4. Nose
8. Why do erupting filaments often show an unwinding motion?
9. How long does it take for ejected plasma to reach Earth?

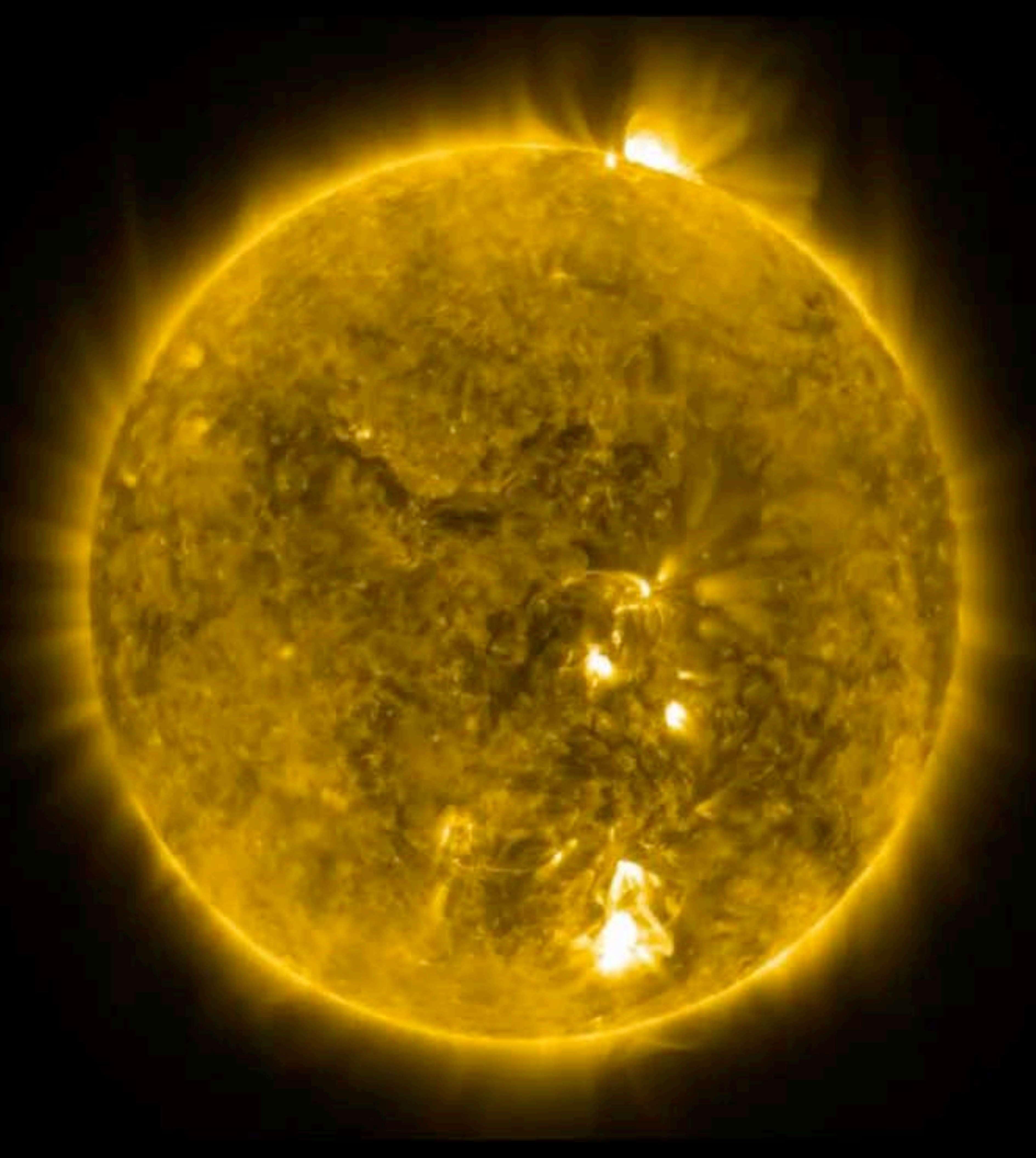
NASA SDO/HMI

Pete Lawrence

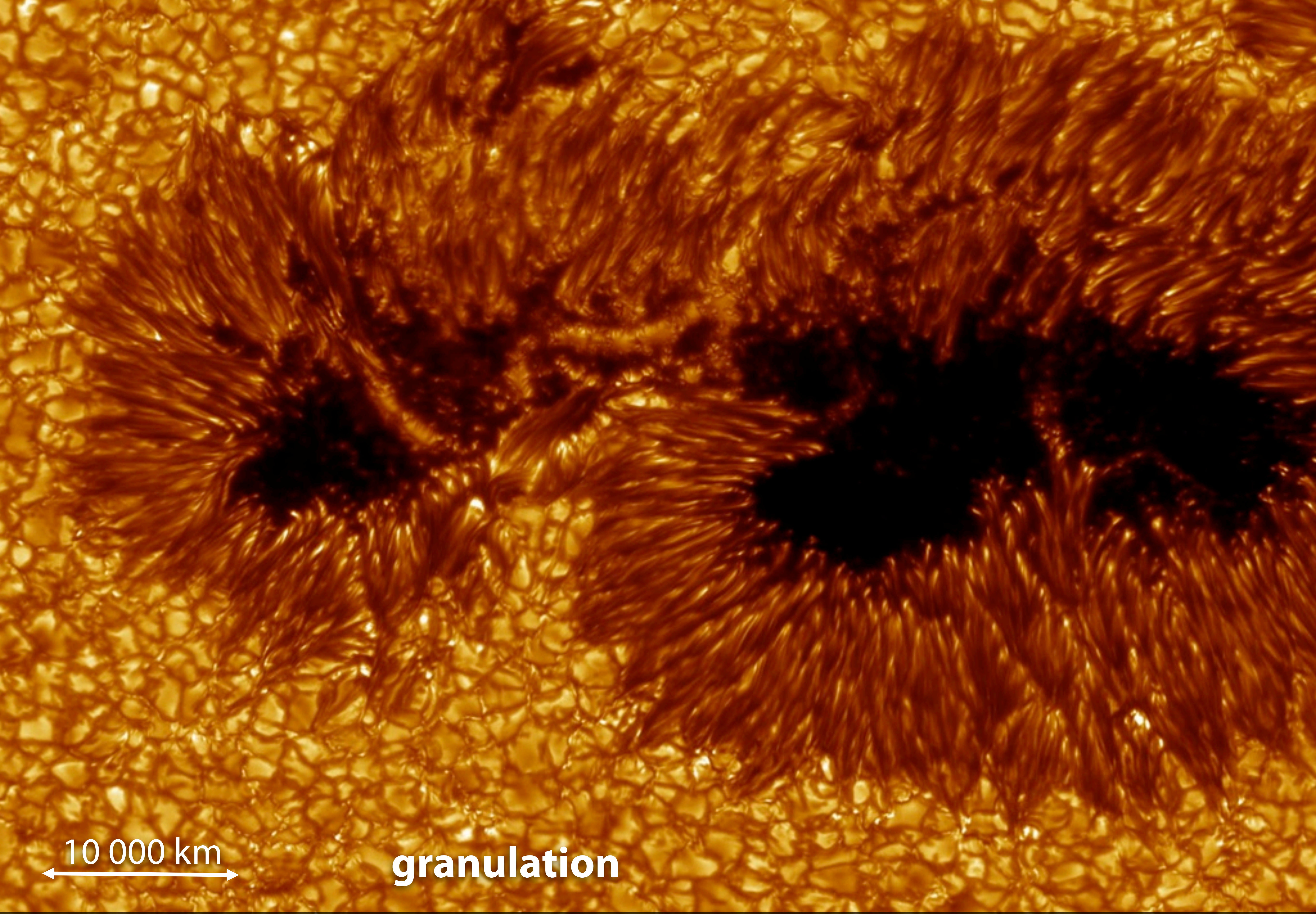
Magnetic features in the solar atmosphere

(smaller than sunspots)

The solar atmosphere outside from Active Regions

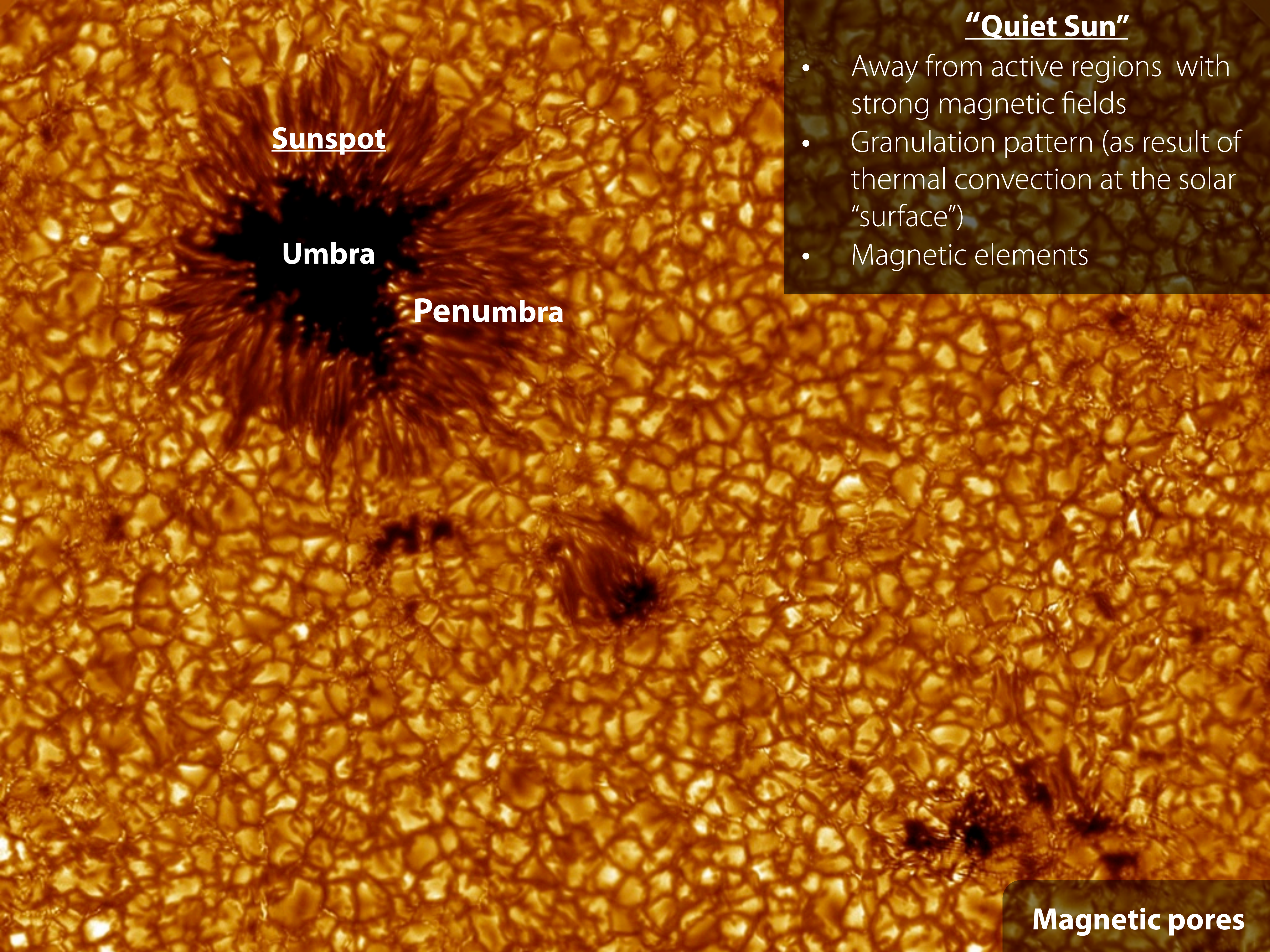


Credit to Big Bear Solar Observatory and NASA for data and video content.
Credit to Tanmoy Samanta and Hui Tian from Peking University for video production.



Photosphere of the Sun = τ(λ=500nm) =1
narrow layer where visible continua become optically thick

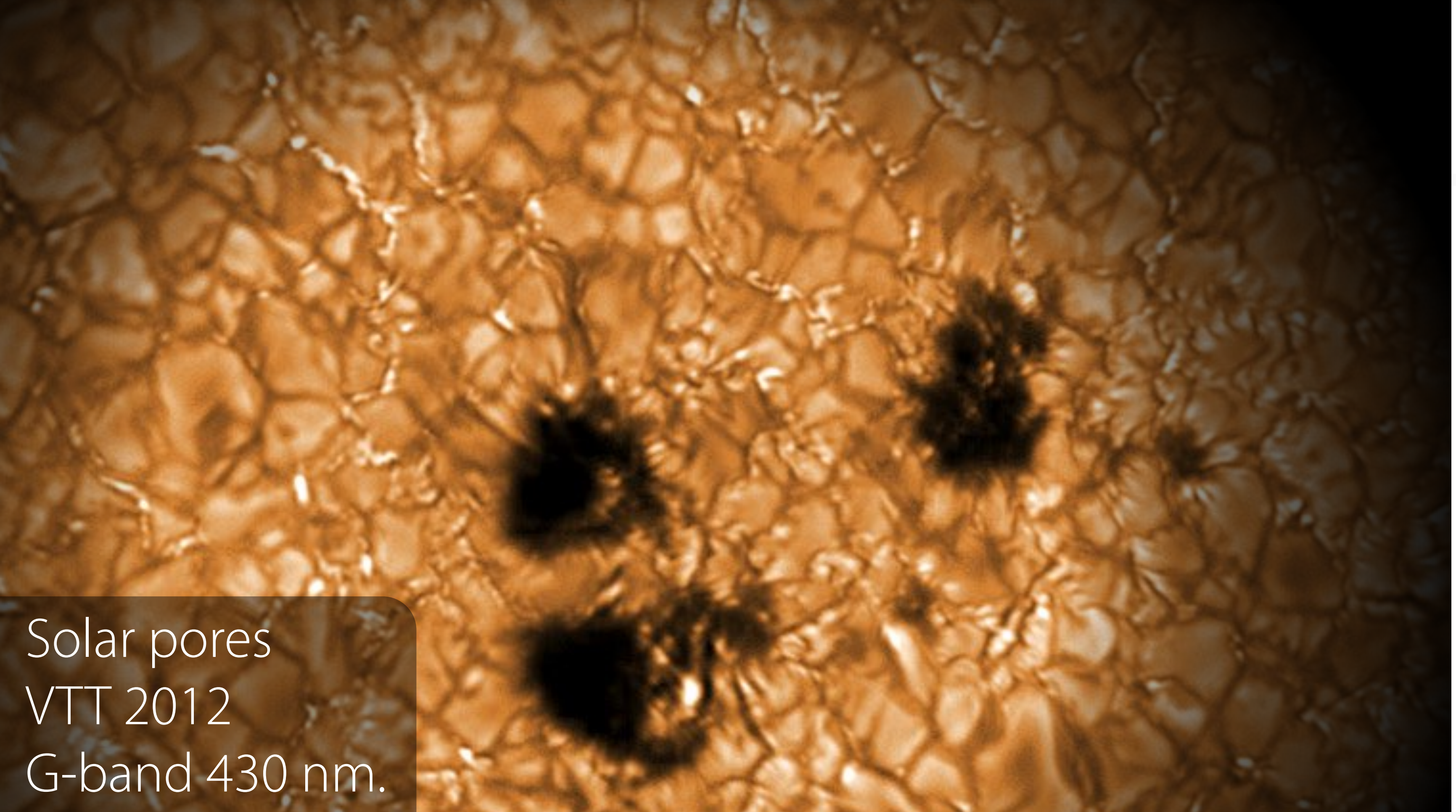
G-band (430nm)


Sunspot
Umbra
Penumbra
"Quiet Sun"
• Away from active regions with strong magnetic fields
• Granulation pattern (as result of thermal convection at the solar "surface")
• Magnetic elements
Magnetic pores

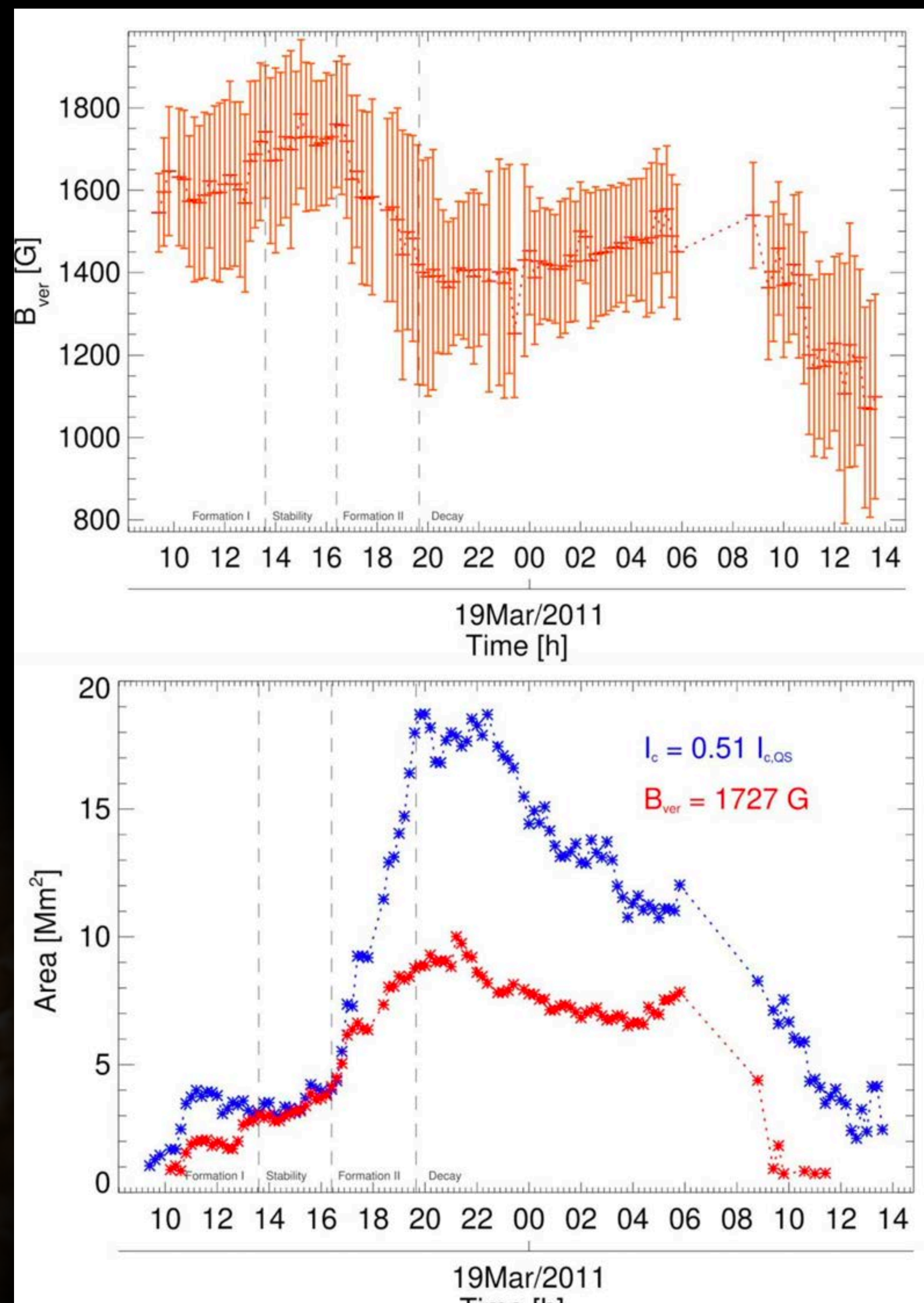
Magnetic field in the solar atmosphere

Pores

- Umbra only — like sunspots but without a penumbra.
- Appear when a strong magnetic field emerges through solar surface (inhibits convective transfer of heat from below as in sunspots, appears dark)
- “Small” (1000 - 6000 km in diameter) but can include smaller bright structures (convective heat transfer from below not completely suppressed there)
- Dispersed magnetic fields around pores can produce bright points and chains in intergranular lanes in surrounding



Solar pores
VTT 2012
G-band 430 nm.

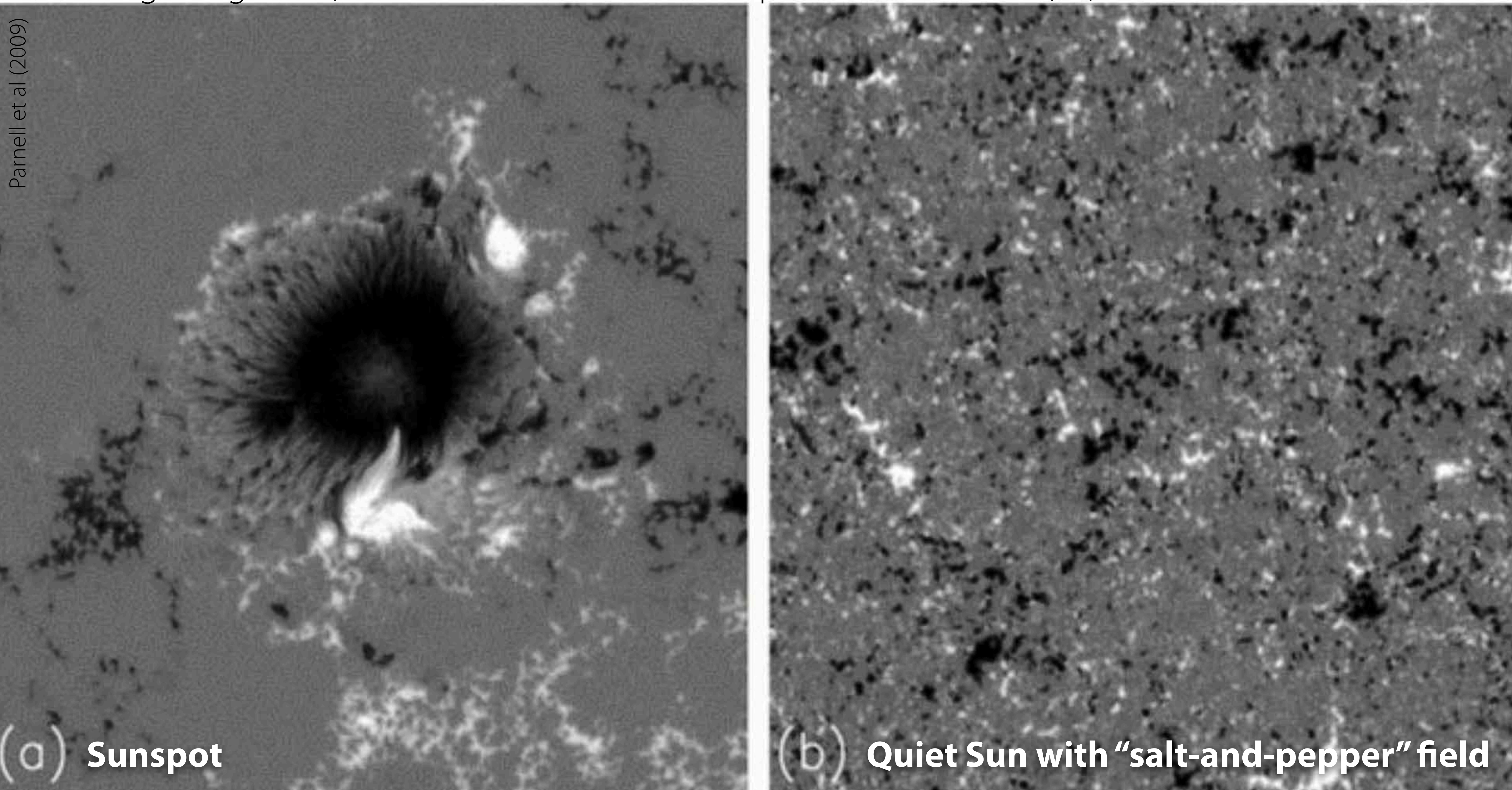


García Rivas et al. (2020)

Magnetic field in the solar atmosphere

Photospheric magnetic field

Magnetograms (via Stokes V at 632nm from Spectro-Polarimeter (SP) onboard Hinode/SOT

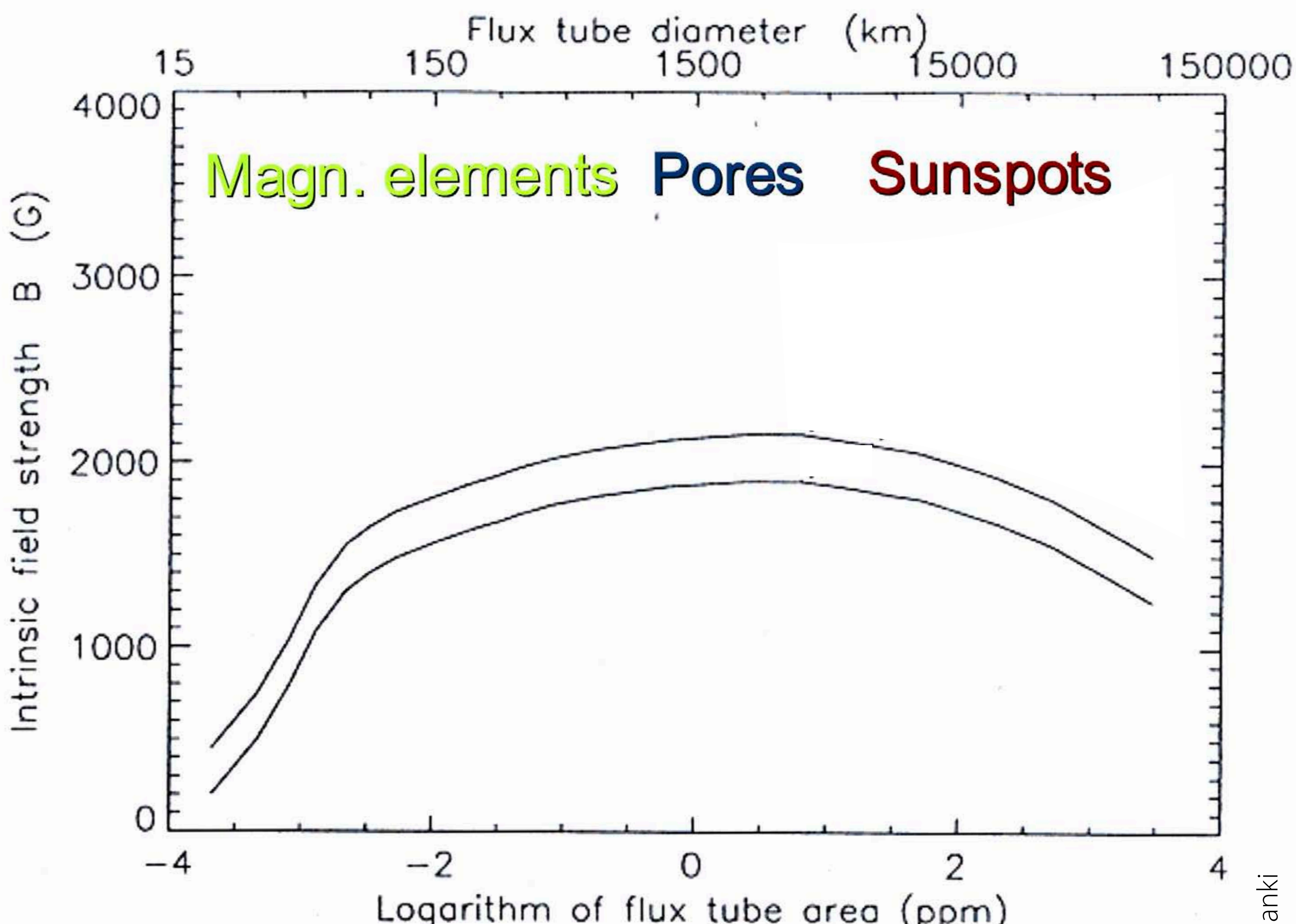


Magnetic field in the solar atmosphere

Magnetic field as function of spatial scale

- (Average) magnetic field strength measured for structures ("flux tubes") with different sizes
  - From large sunspots to the smallest detectable magnetic elements
- Surprisingly constant field strength per area
- Remember: Magnetic fields "compete" with thermal pressure (and convective motions)

➡ Equipartition field strength sets limits

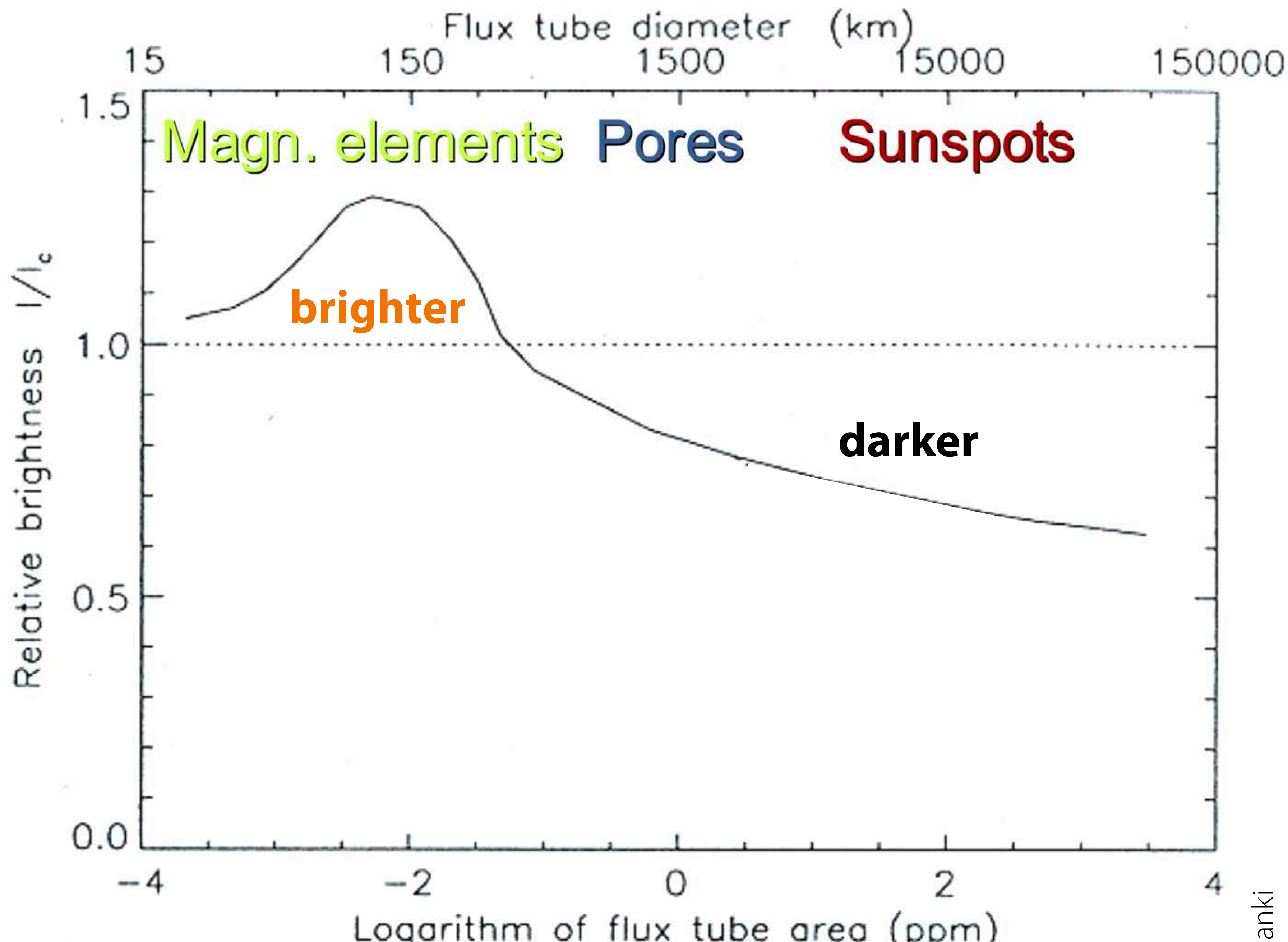


Solanki

Magnetic field in the solar atmosphere

Magnetic field as function of spatial scale

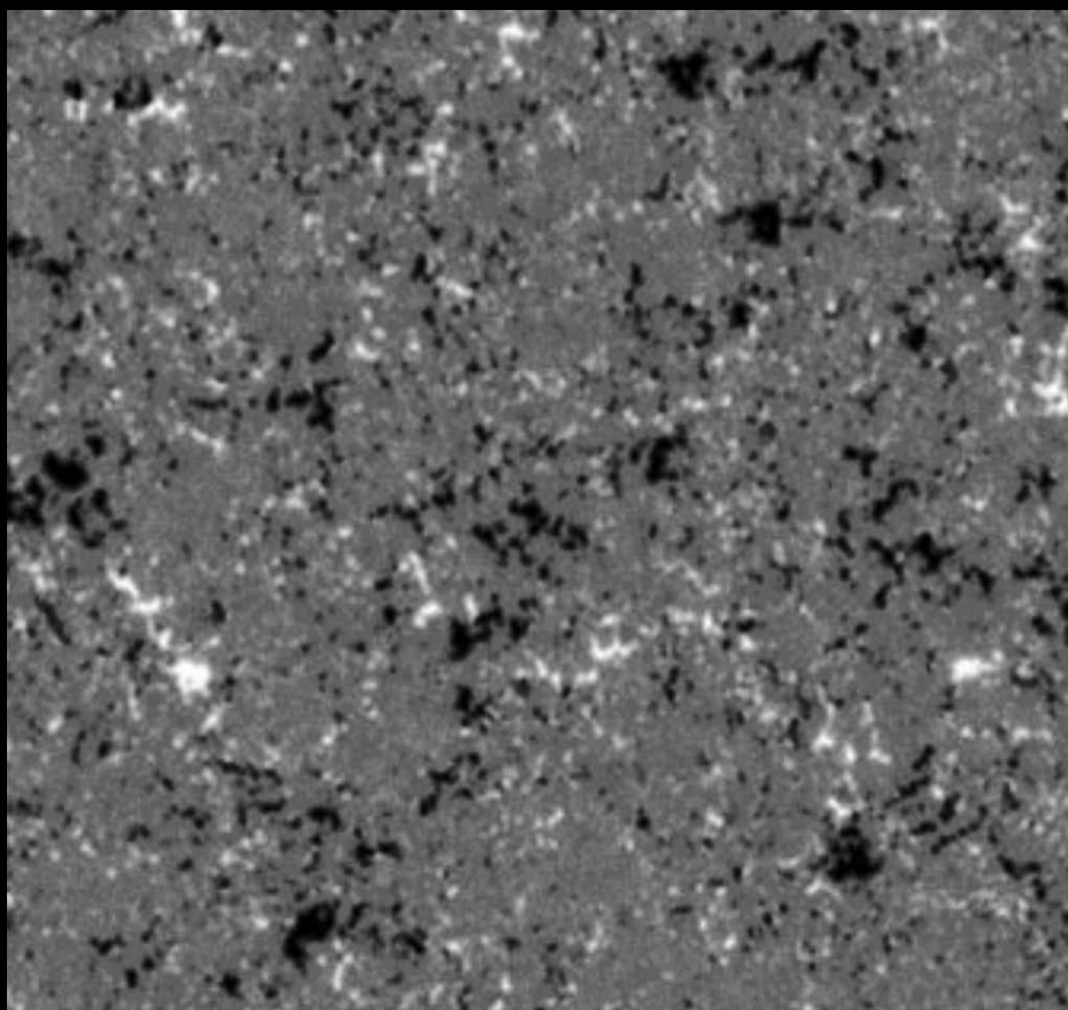
- Observable consequences strongly depend on area covered by magnetic field structure
  - Large: darker than surrounding
  - Small: brighter (!) than surrounding
- Remember: Sunspots — strong magnetic fields impede convective heat transport from below, resulting in lower temperature
- **What about small magnetic elements?**



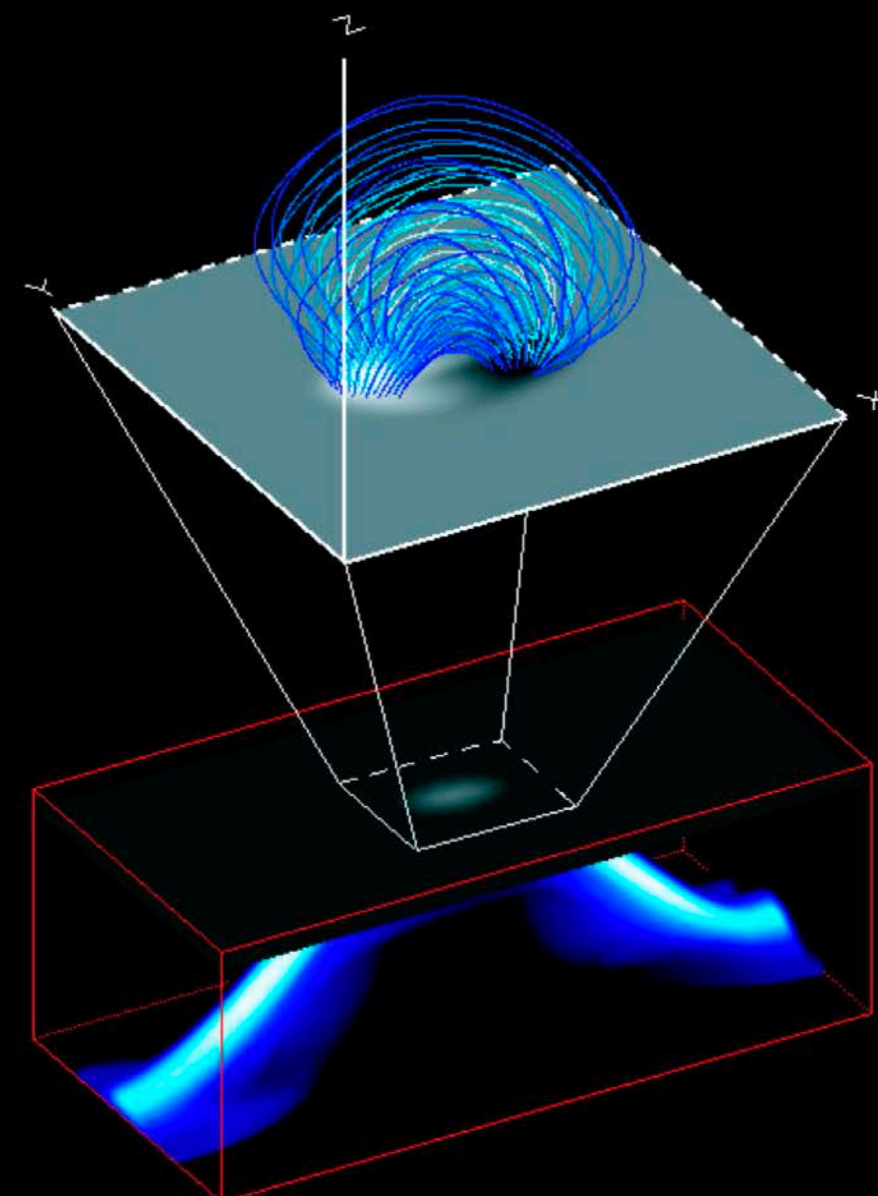
Solanki

Magnetic field in the solar atmosphere

Photospheric magnetic field in Quiet Sun regions



Parnell et al (2009)

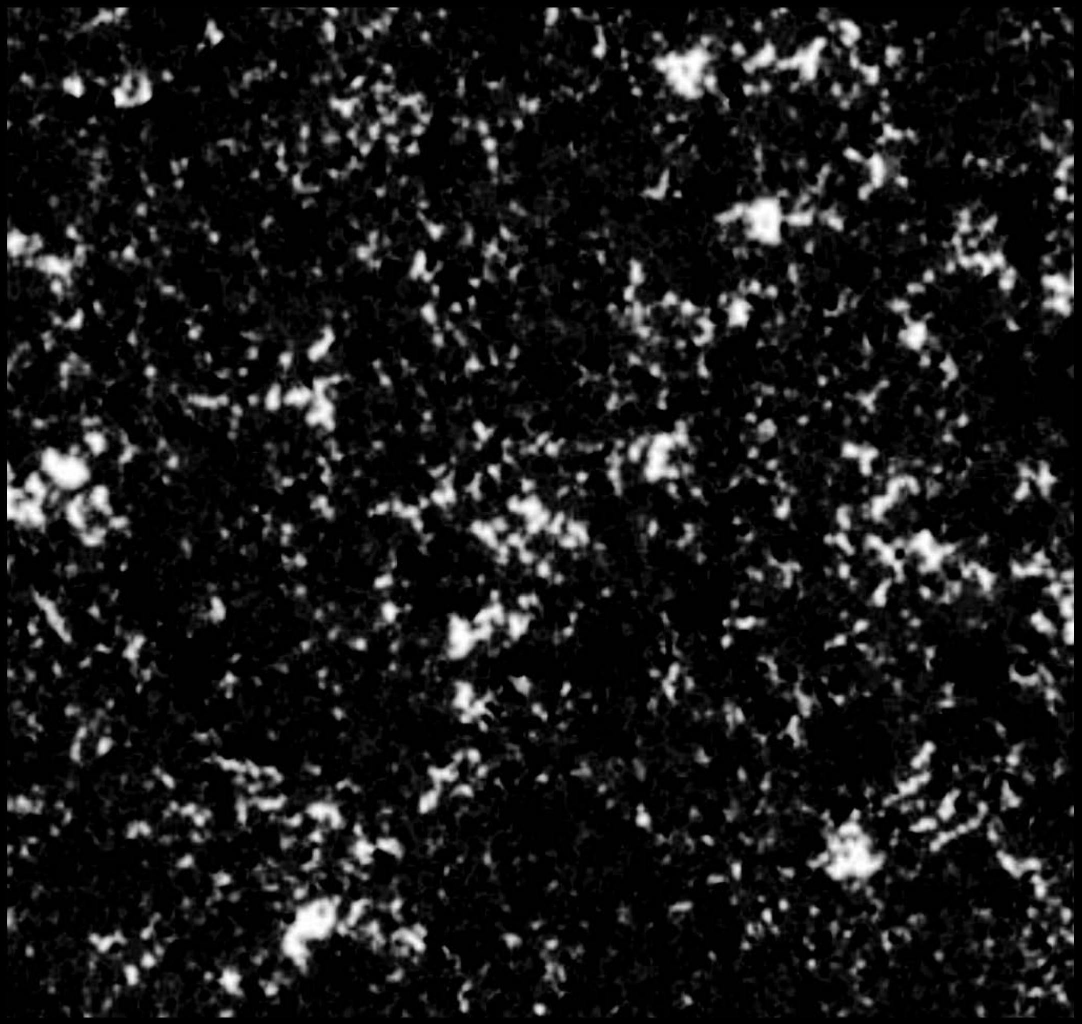


Abbett & Fisher (2003)

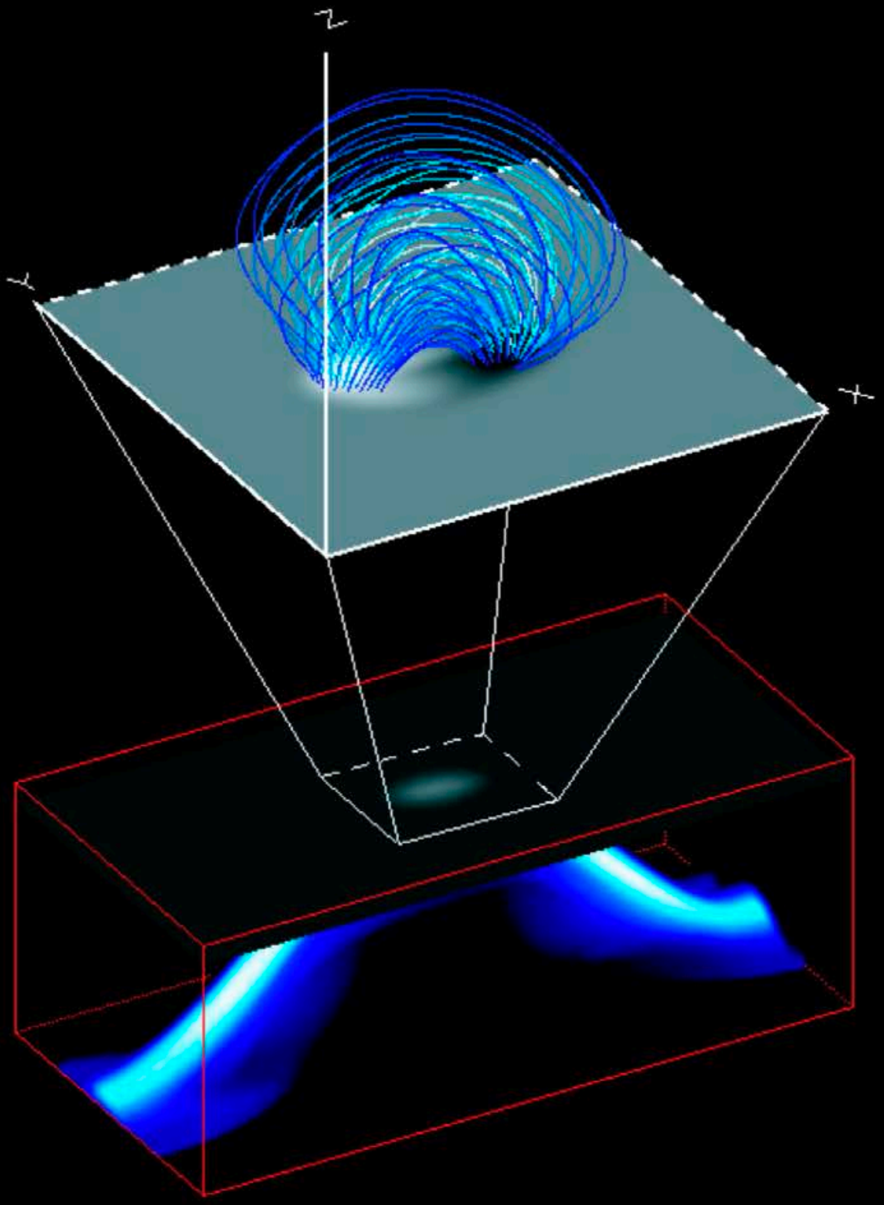
- **Remember:**
  1. Magnetic field **emerges** through the "surface" (photosphere)
     - Magnetic field structure on a large range of spatial scales
  2. Field is **advected**

Magnetic field in the solar atmosphere

Photospheric magnetic field in Quiet Sun regions



Parnell et al (2009)



Abbett & Fisher (2003)

- **Remember:**
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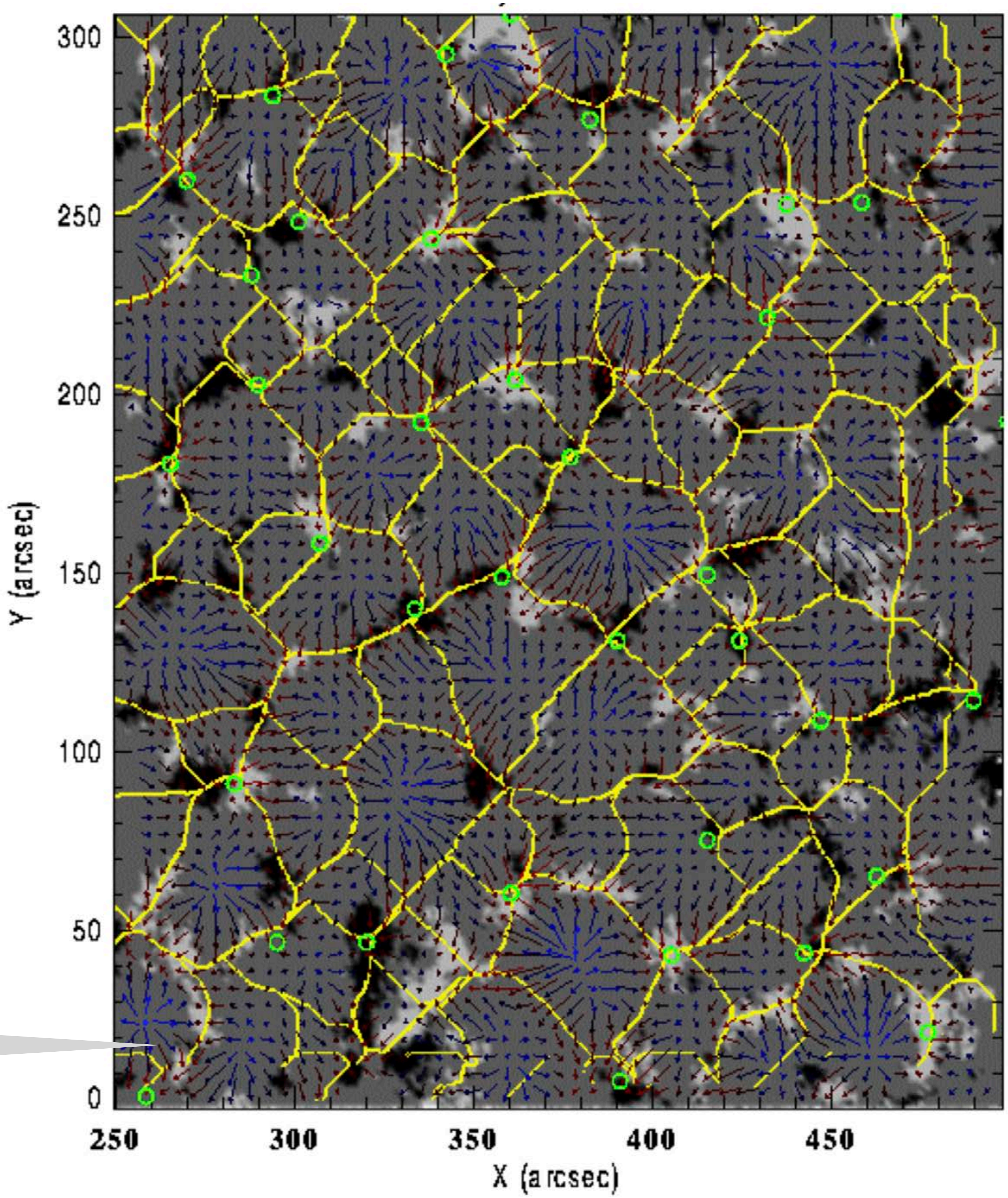
  2. Field is **advected**

Magnetic field in the solar atmosphere

Advection — supergranulation scales

- 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**

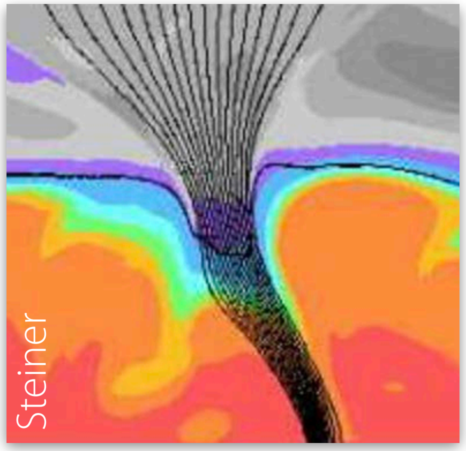


- Magnetogram (grayscale)
- Horizontal flow field (arrows)
- Supergranule boundaries: yellow

Magnetic field in the solar atmosphere

Advection — magnetic field on granulation scales

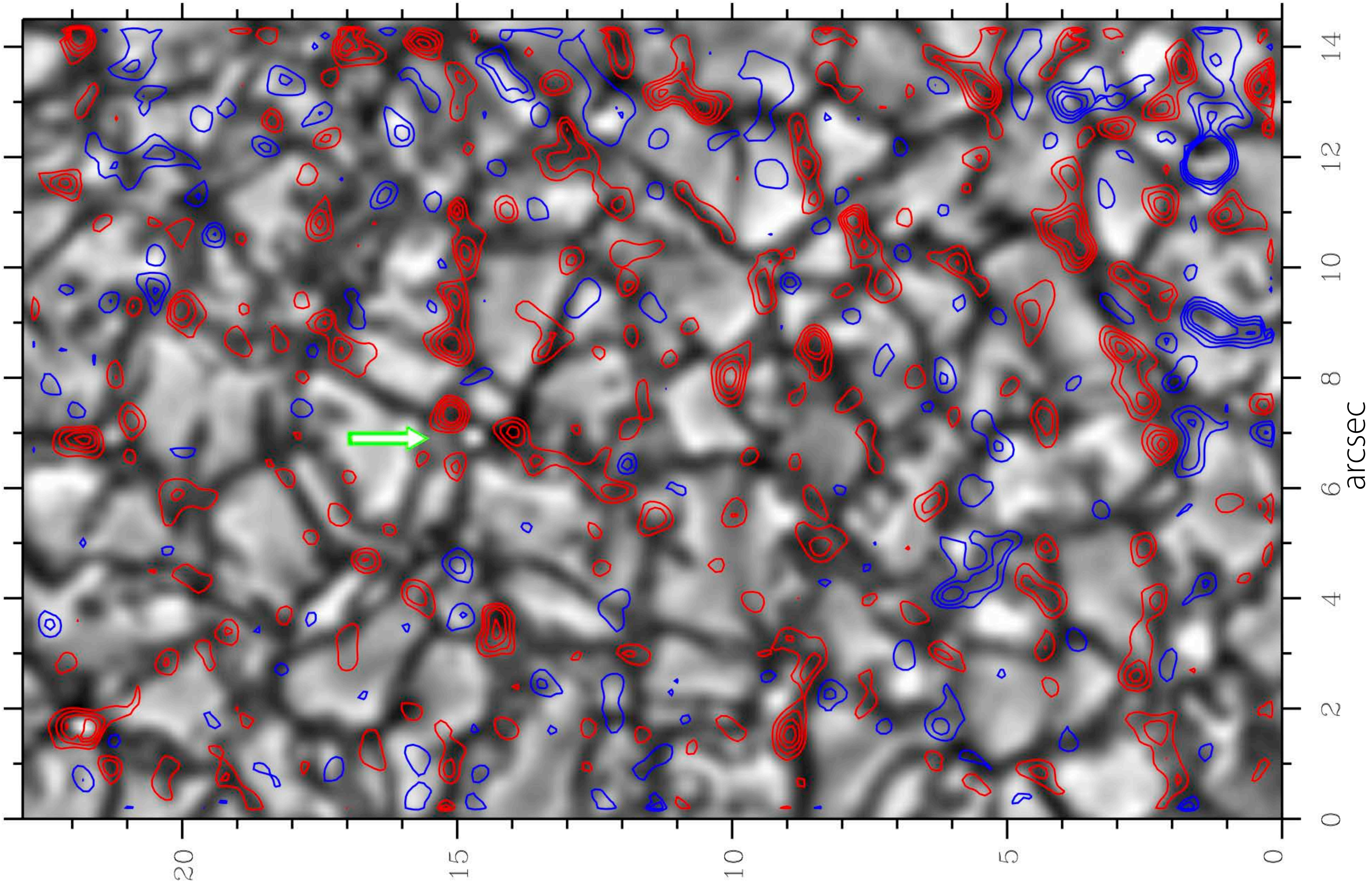
- Advection into intergranular lanes (downflow lanes between granules)
- Concentration into stronger flux concentrations but fewer than in the network



Granulation image, Fe I 630.25 nm line

Overlaid magnetogram contours 30, 50, 70 and 90 G

(Domınguez Cerdena et al., 2003)



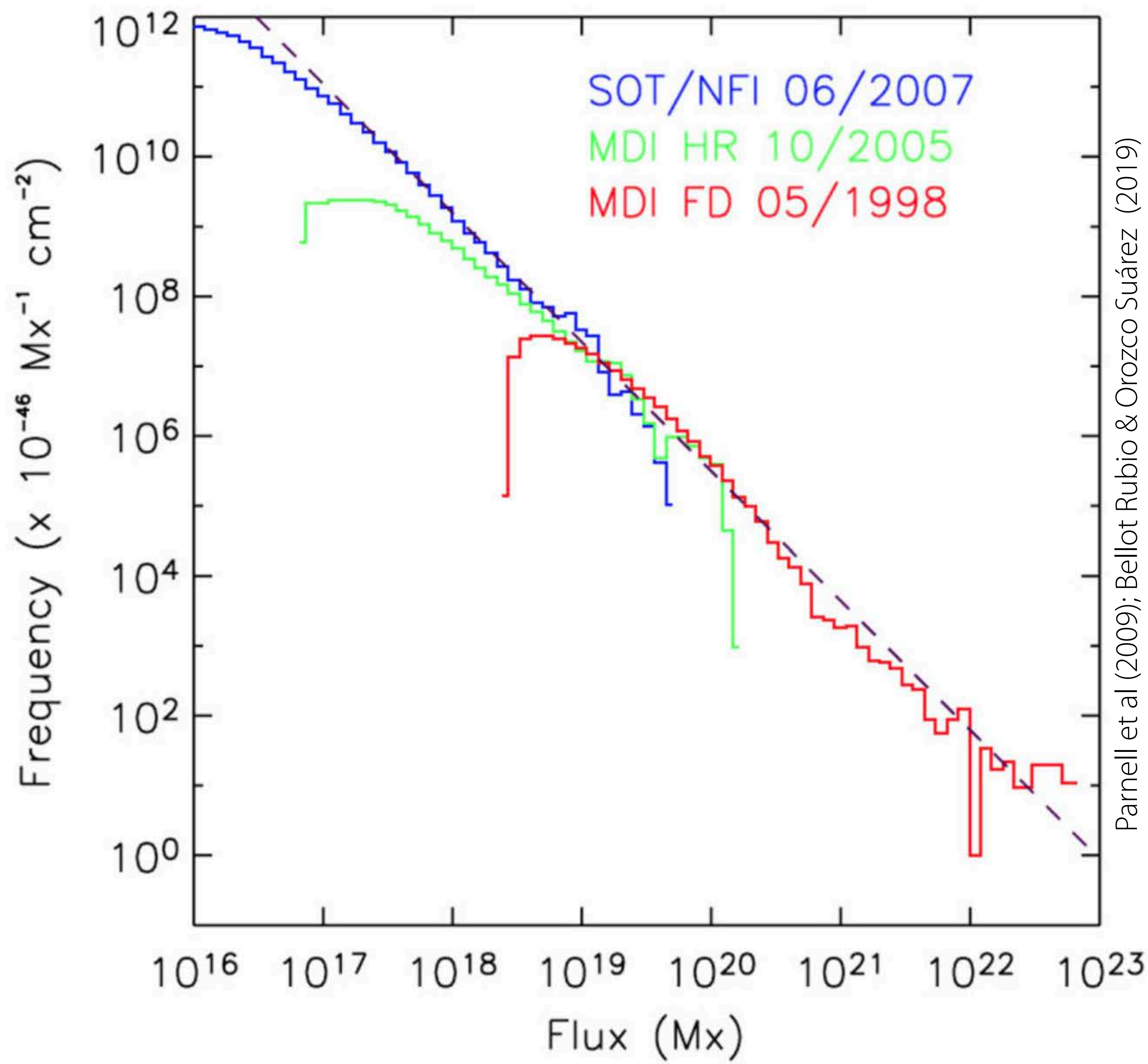
Magnetic field in the solar atmosphere

Photospheric magnetic field in Quiet Sun regions

- Distribution of longitudinal magnetic fluxes observed with different instruments
  (Hinode/NFI magnetograms, SOHO/MDI high resolution + full disk magnetograms)
- Magnetic flux value vs. its occurrence scales follows a power law (=linear in log-log)

➡ Scalable phenomena

➡ Beyond current detection limit?



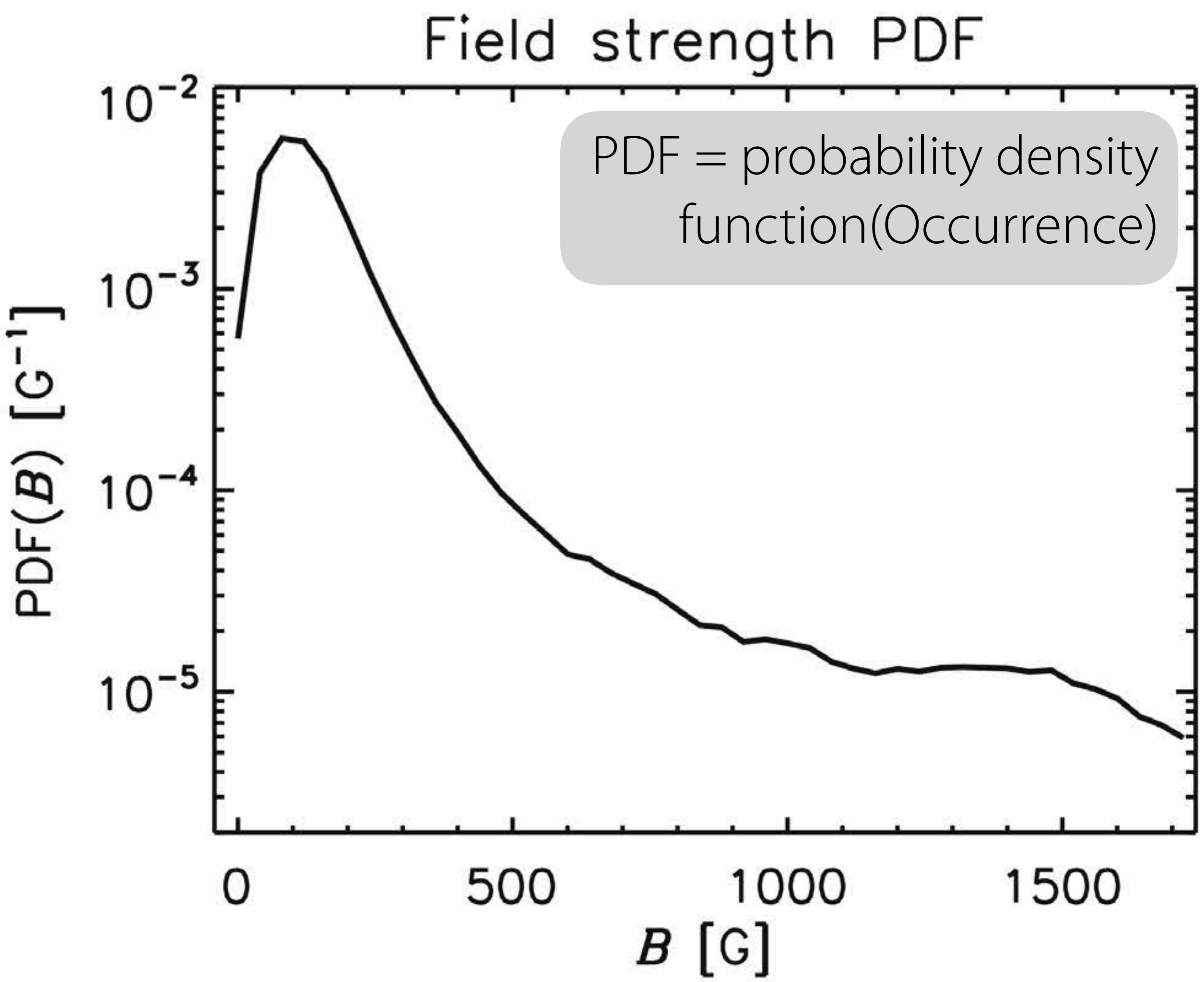
Parnell et al (2009); Bellot Rubio & Orozco Suárez (2019)

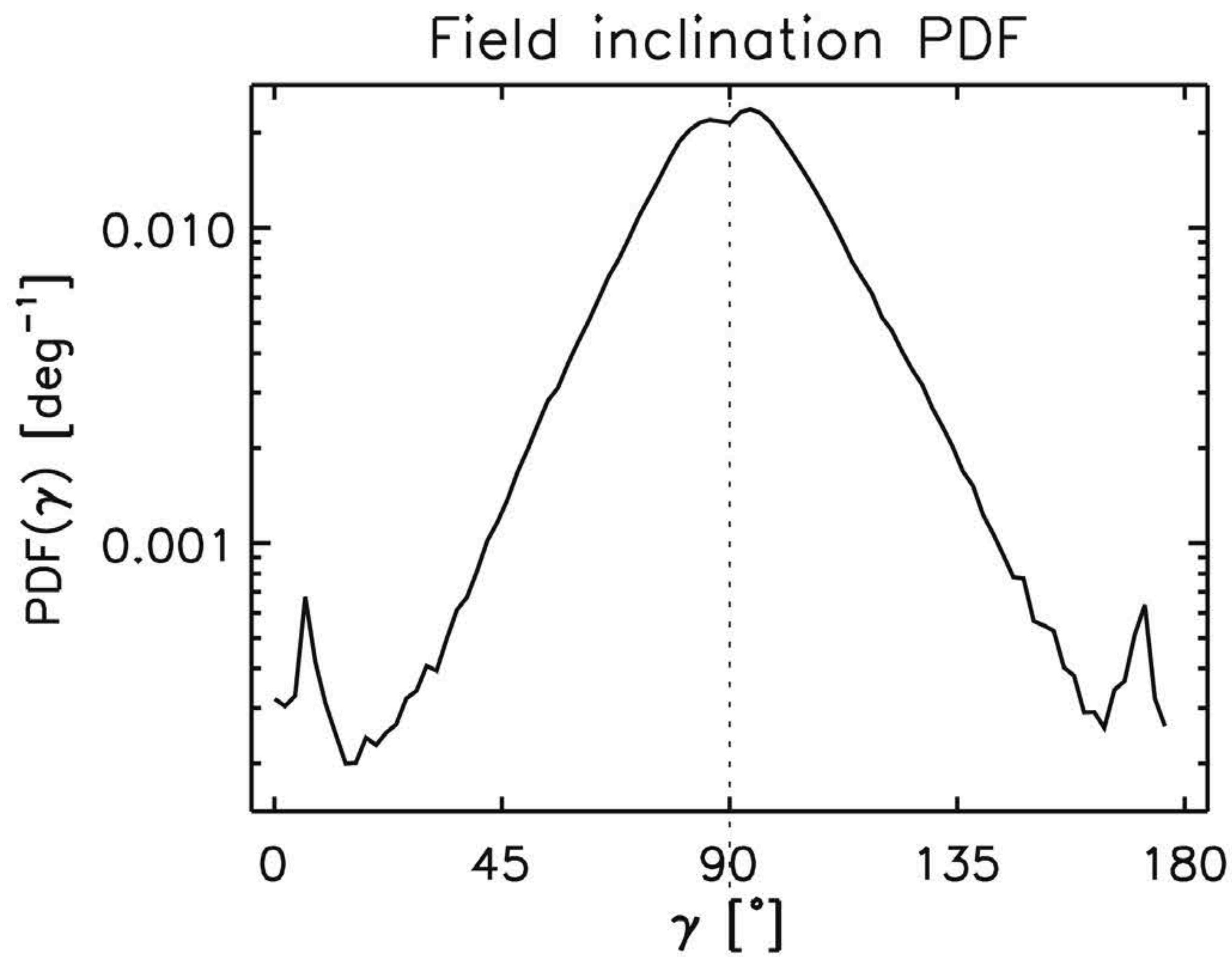
Magnetic flux Φ
(Flux = per area!)
cgs unit: Maxwell (Mx)
1 Mx = 1 G cm^{-2}

Longitudinal = component parallel (along) magnetic field vector

Magnetic field in the solar atmosphere

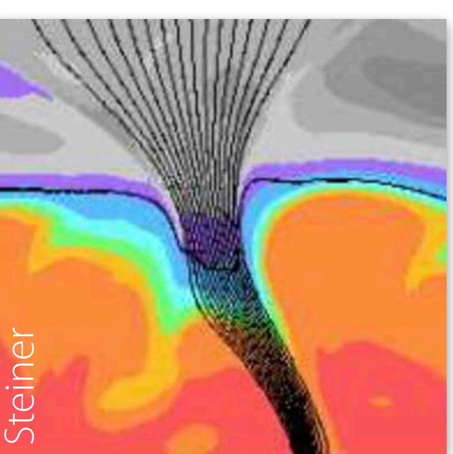
Photospheric magnetic field in internetwork regions





Orozco Suárez and Bellot Rubio (2012)

- Average field strength = 170 G,
  FWHM of distribution = 190 G.



Steiner

- Flux tubes with B > 1 kG occur but not dominant
  - More of those in the magnetic network

- Magnetic field inclination:
  highly inclined fields very abundant!
  - Maximum at 90°(horizontal fields)
  - Bumps near 0° and180°: vertical fields in intergranular lanes

The solar atmosphere
—
Radiative transfer effects

Radiative transfer effects

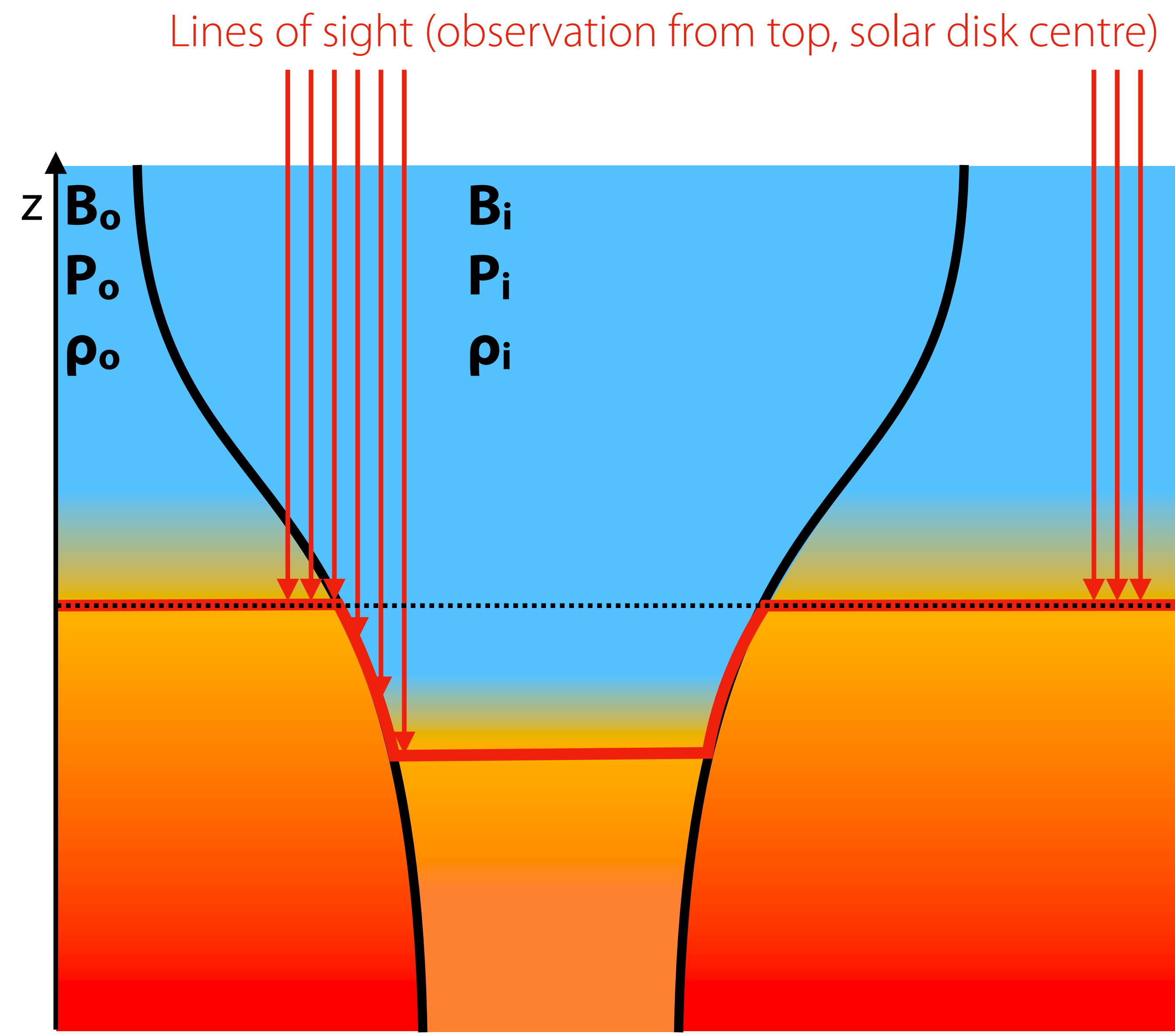
- Remember: Magnetic pressure counterbalances thermal (gas) pressure
- $B_i >> B_o$

➡ 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



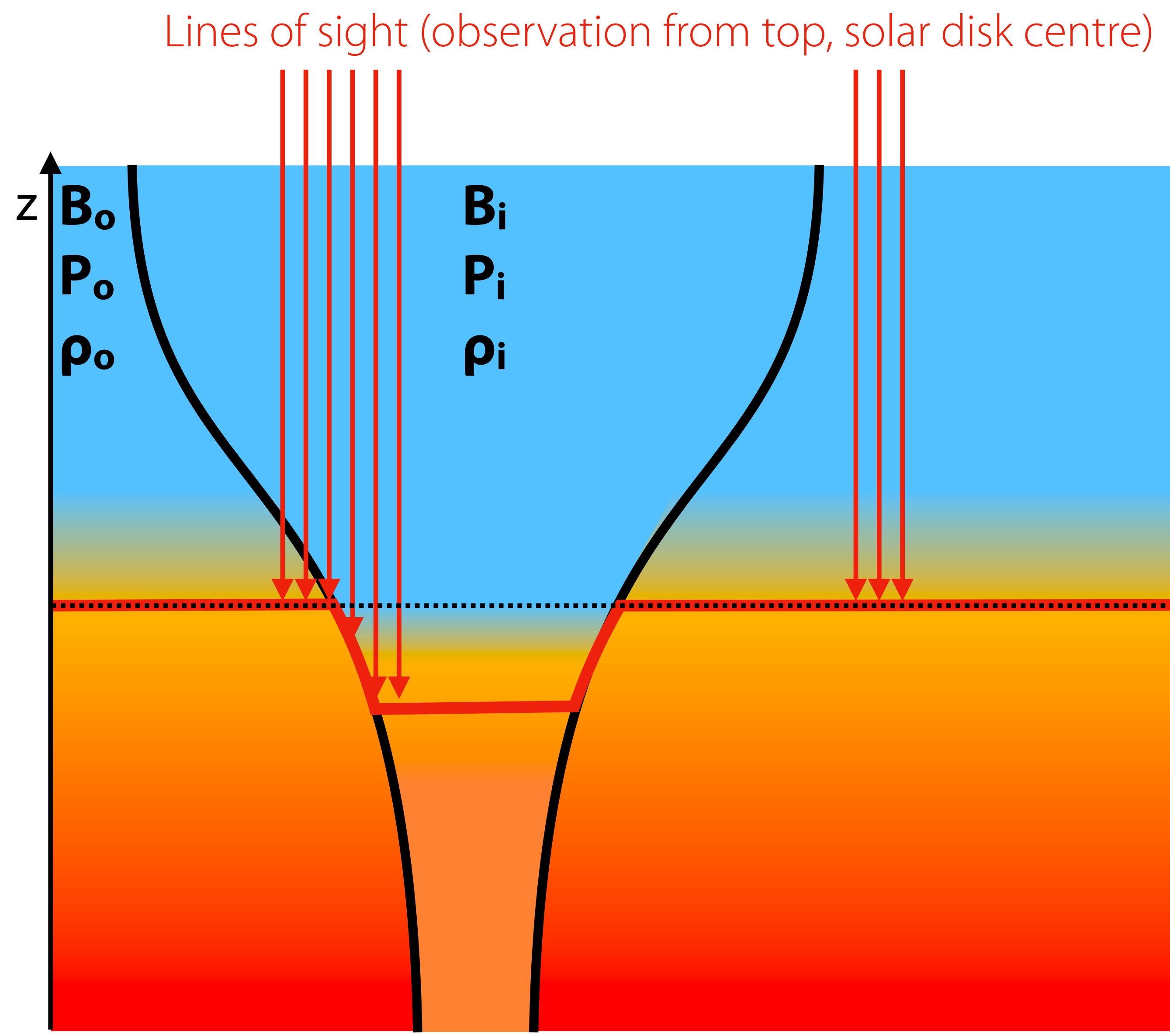
➡ **Optical depth lower** inside magnetic field structure than outside

➡ Looking deeper into the Sun inside the magnetic field structure

- Lower height of optical depth unity = **Wilson depression** (in sunspots),

Radiative transfer effects

- Effect also visible for weaker magnetic field structures on smaller spatial scales
- Difference: Convective energy transport not suppressed (as much) as under sunspots!

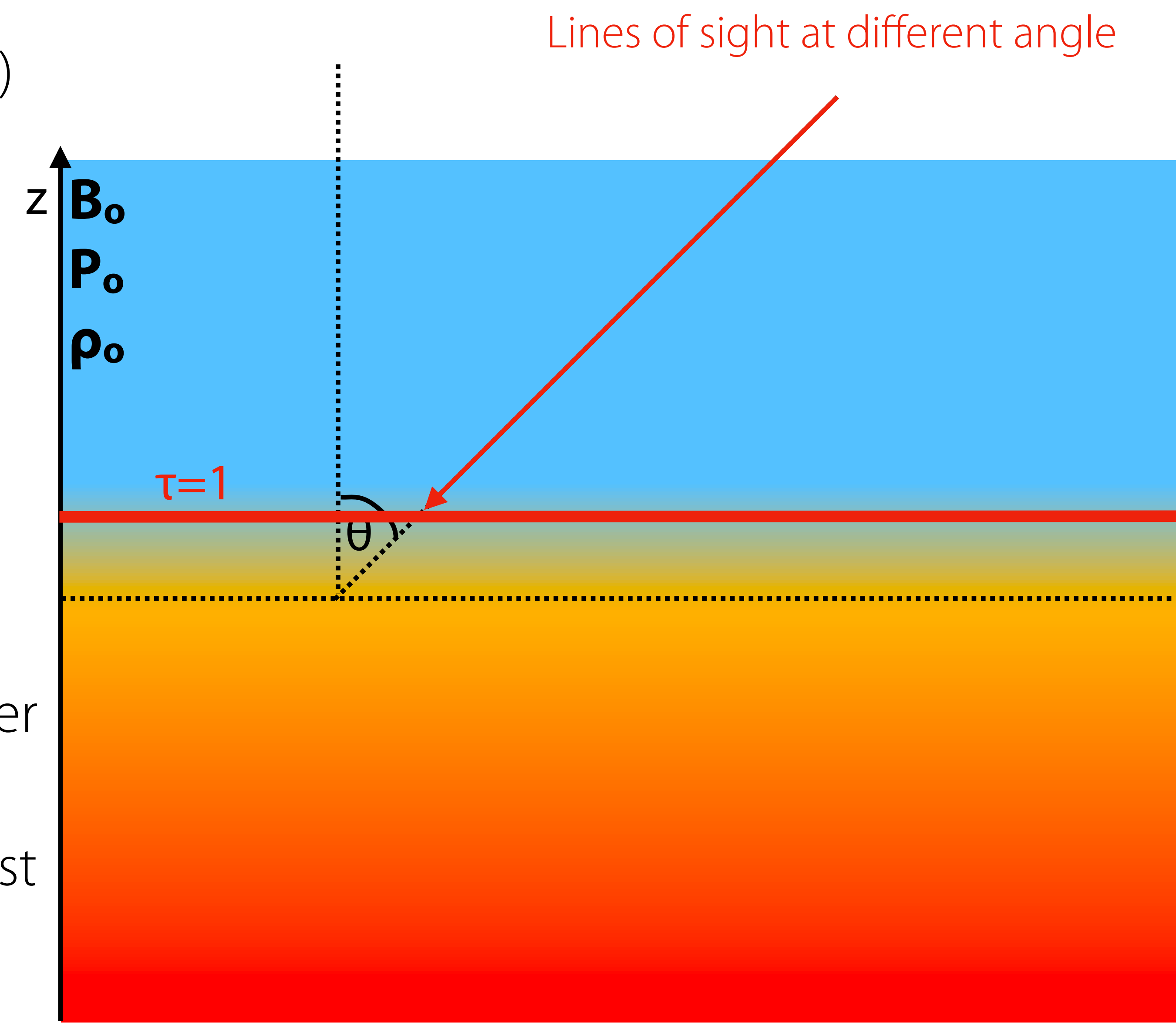


Radiative transfer effects

- Observing at inclination angle $\theta > 0$ (oblique) $(\mu = \cos\,\theta)$

➡ Geometrically: Longer line of sight path element per change in height

➡ "Picking up" more opacity already higher up in atmosphere due to projected



Consequence 1 (outside magnetic field structures)

- Optical depth unity reached already higher up!
- View directly from top allows look deepest into atmosphere
- **Mapped height** in the atmosphere (i.e. z where τ=1) **increases with viewing angle θ**

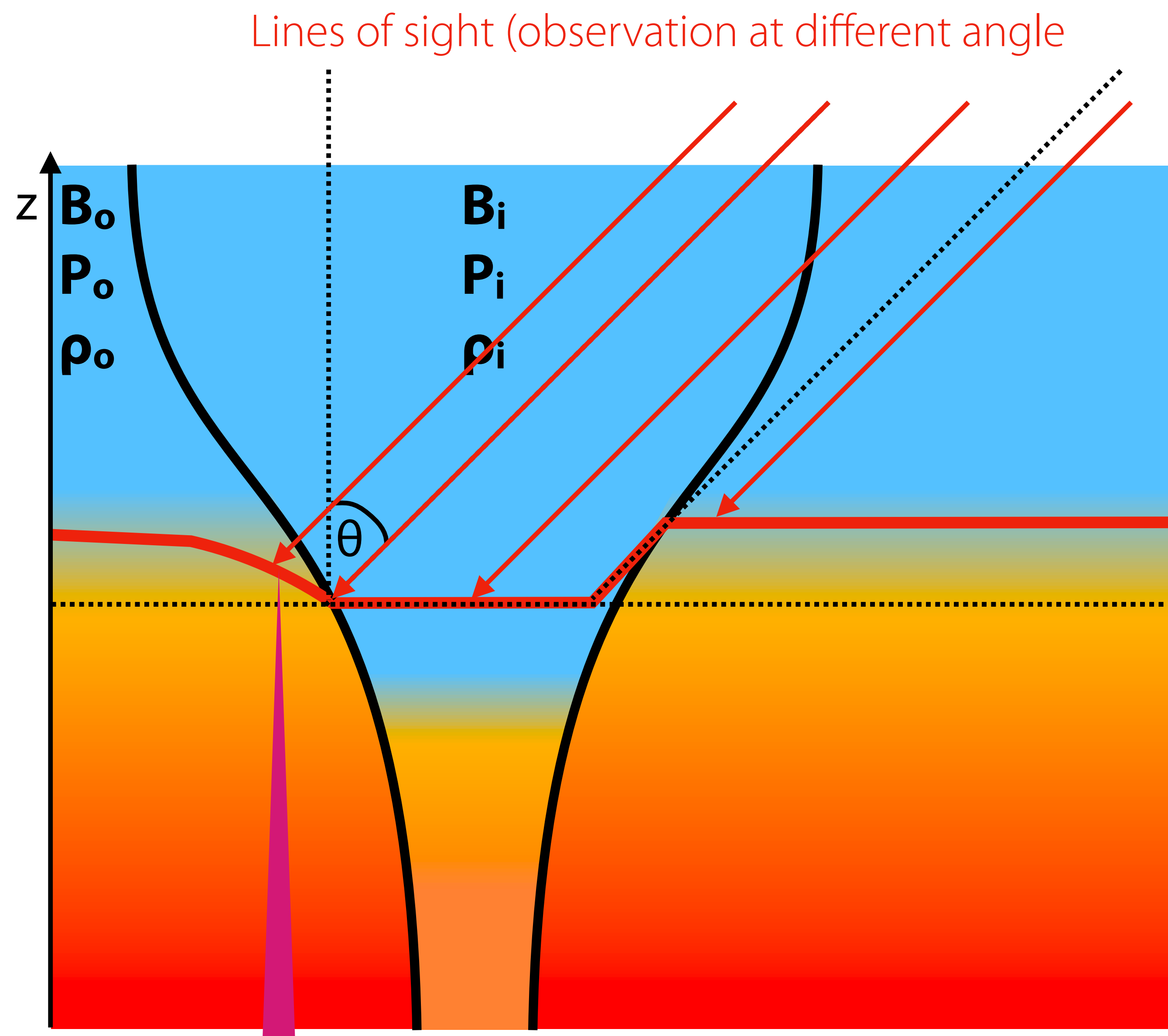
Radiative transfer effects

- Observing at inclination angle $\theta > 0$ (oblique) ($\mu = \cos\theta$)

➡ Geometrically: Longer line of sight path element per change in height

➡ "Picking up" more opacity already higher up in atmosphere due to projected

➡ Now looking through a "thin flux tube"



Consequence 2:

- Views deeper into the atmosphere through the flux tube
- Temperature is higher deeper down
- Higher temperature sampled at inclined viewing angle but only on the side where one sees trough the flux tube

➡**Hot wall effect:** Magnetic feature <u>appears</u> to be brighter on one side!

Radiative transfer effects

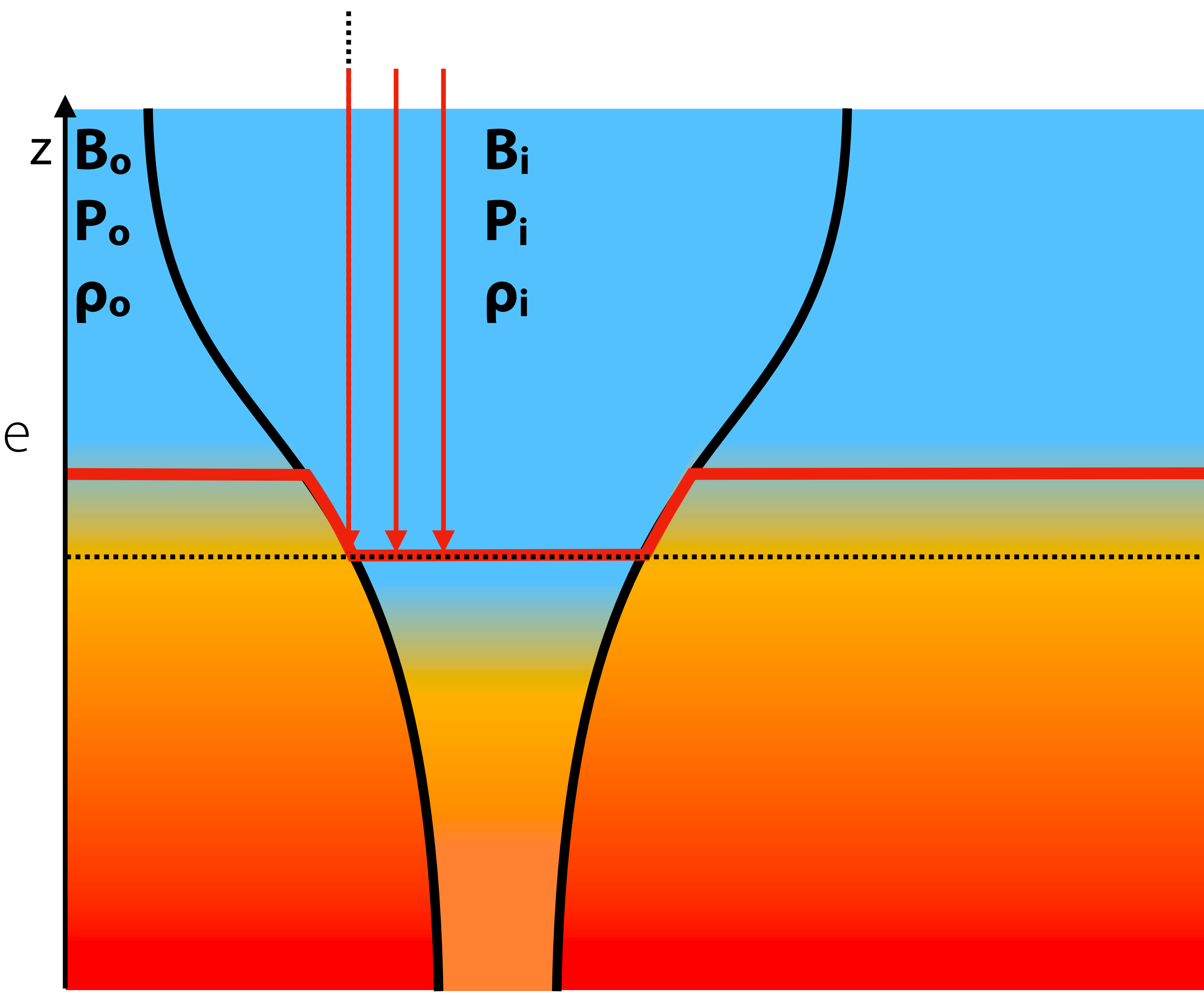
- View from top $\theta = 0$

➡ "Picking up" less opacity when looking through a "thin flux tube" from top

Consequence 3:

- Views deeper into the atmosphere through the flux tube
- Temperature is higher deeper down
- Higher temperature sampled
- Magnetic feature appears bright!

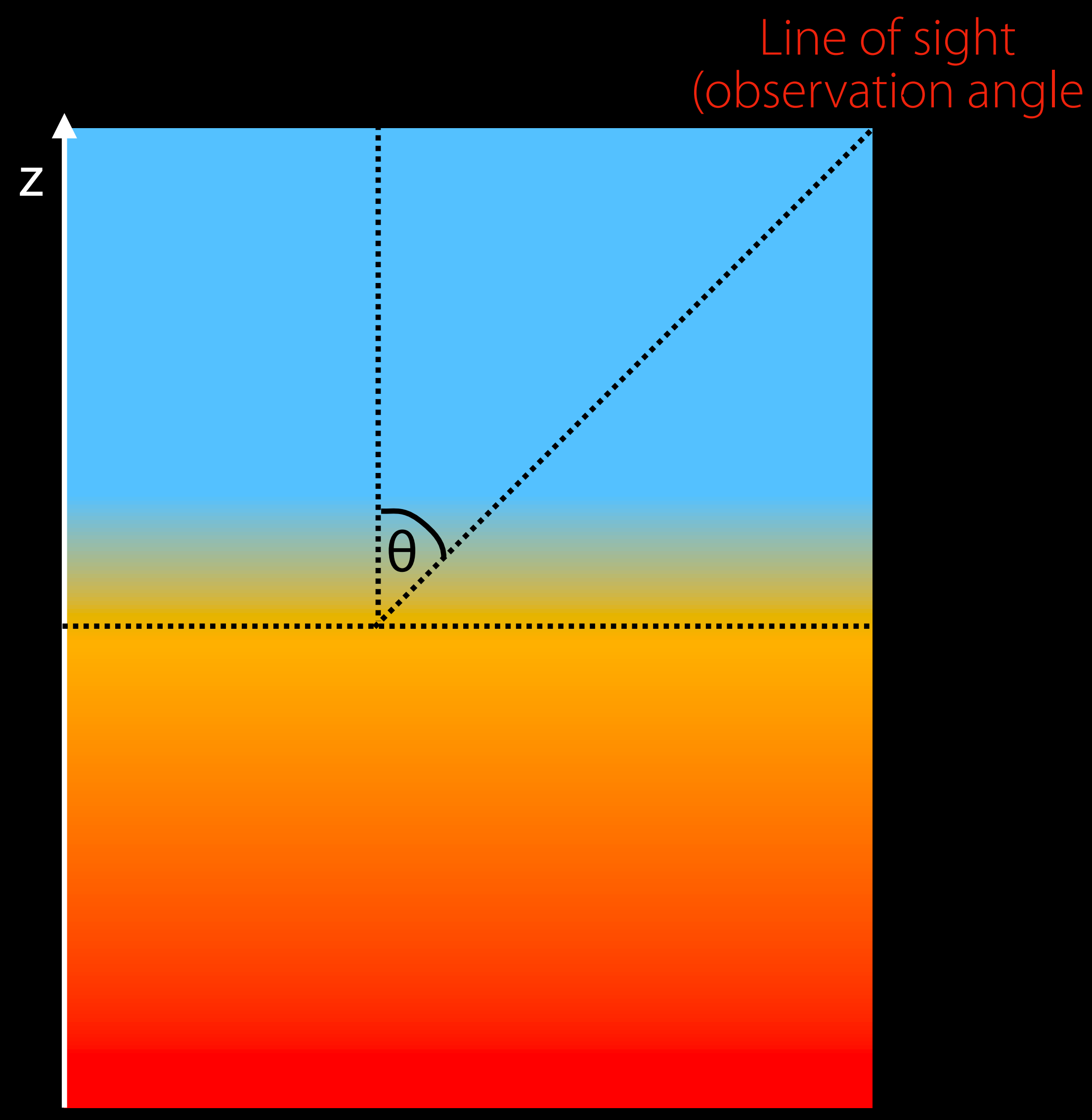
➡ **Magnetic bright point**

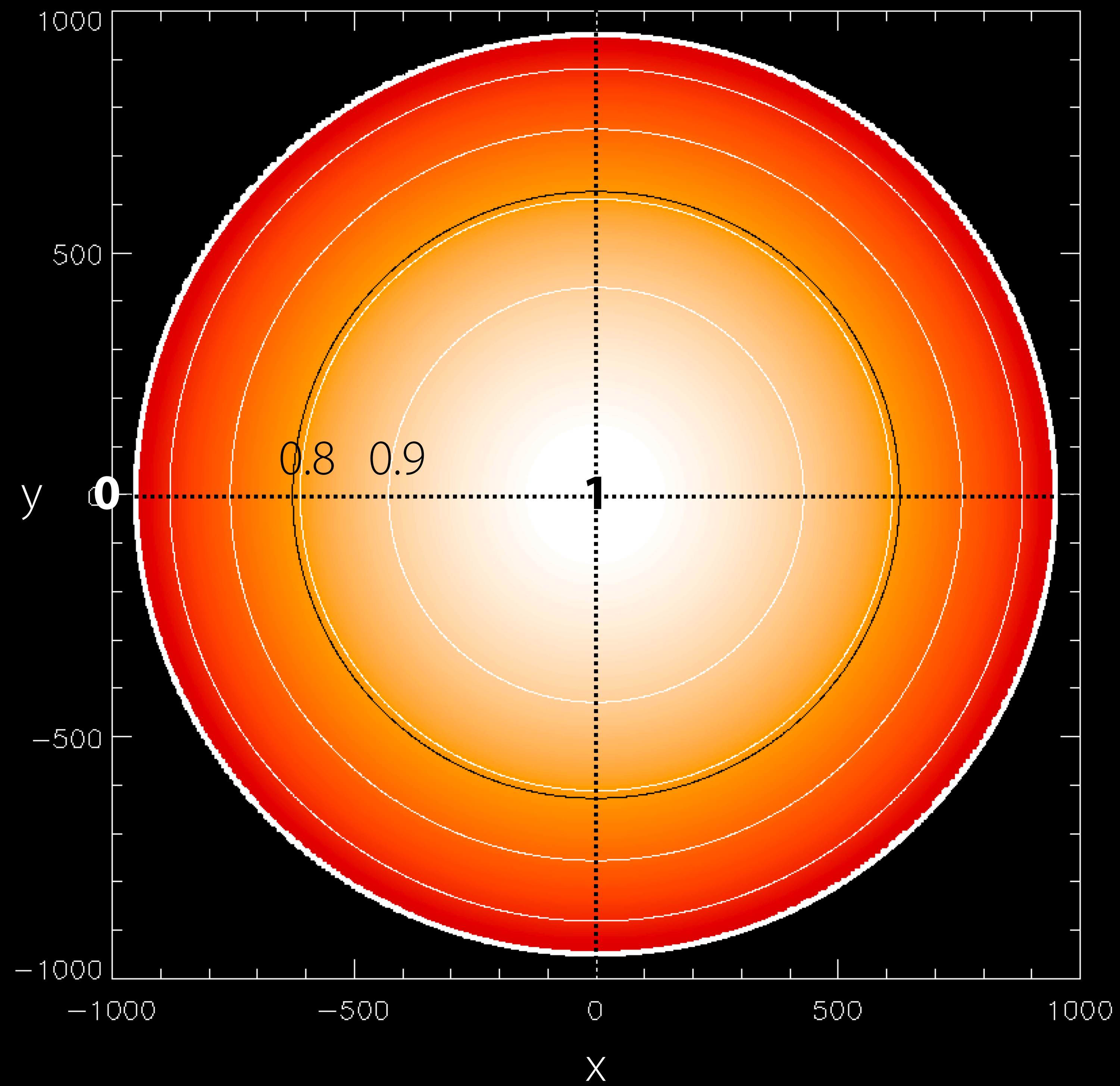


Radiative transfer effects

Inclination angle

$\mu = \cos\theta$





Radiative transfer effects

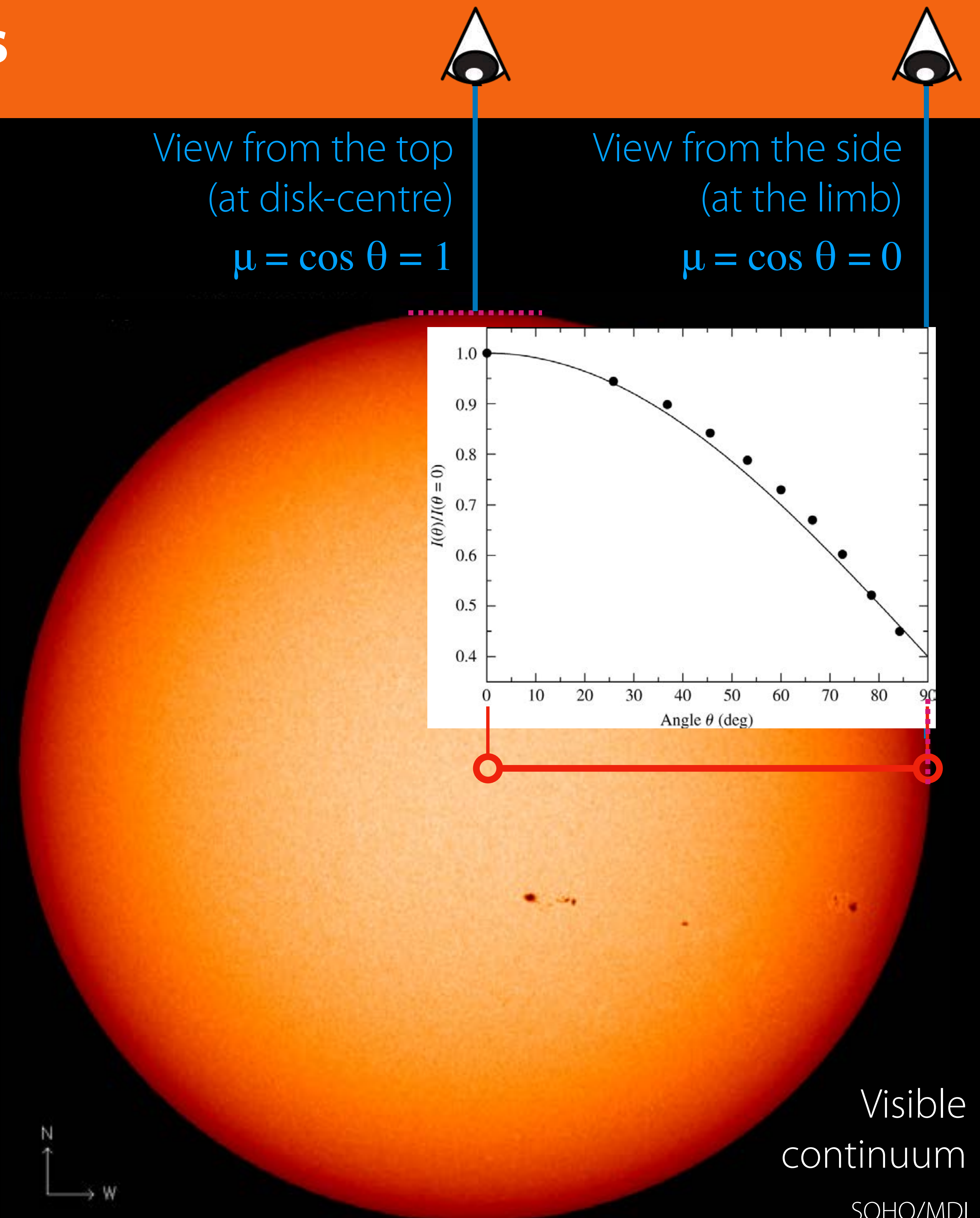
Limb darkening

In the **visible continuum**:

- Solar disk darker at the edge (limb) than at the centre of the solar disk!
- Decreasing brightness implies decreasing temperature (assuming simple blackbody radiation)
- Remember: Observation at increasing angle θ (=decreasing μ) maps layer at increasing height in the atmosphere

➡ Temperature decreases with height for the height range mapped by this continuum range!

- Note: Optical depth unity reached at bottom of photosphere (basically defines it) in visible continuum, "looks" deepest into the atmosphere



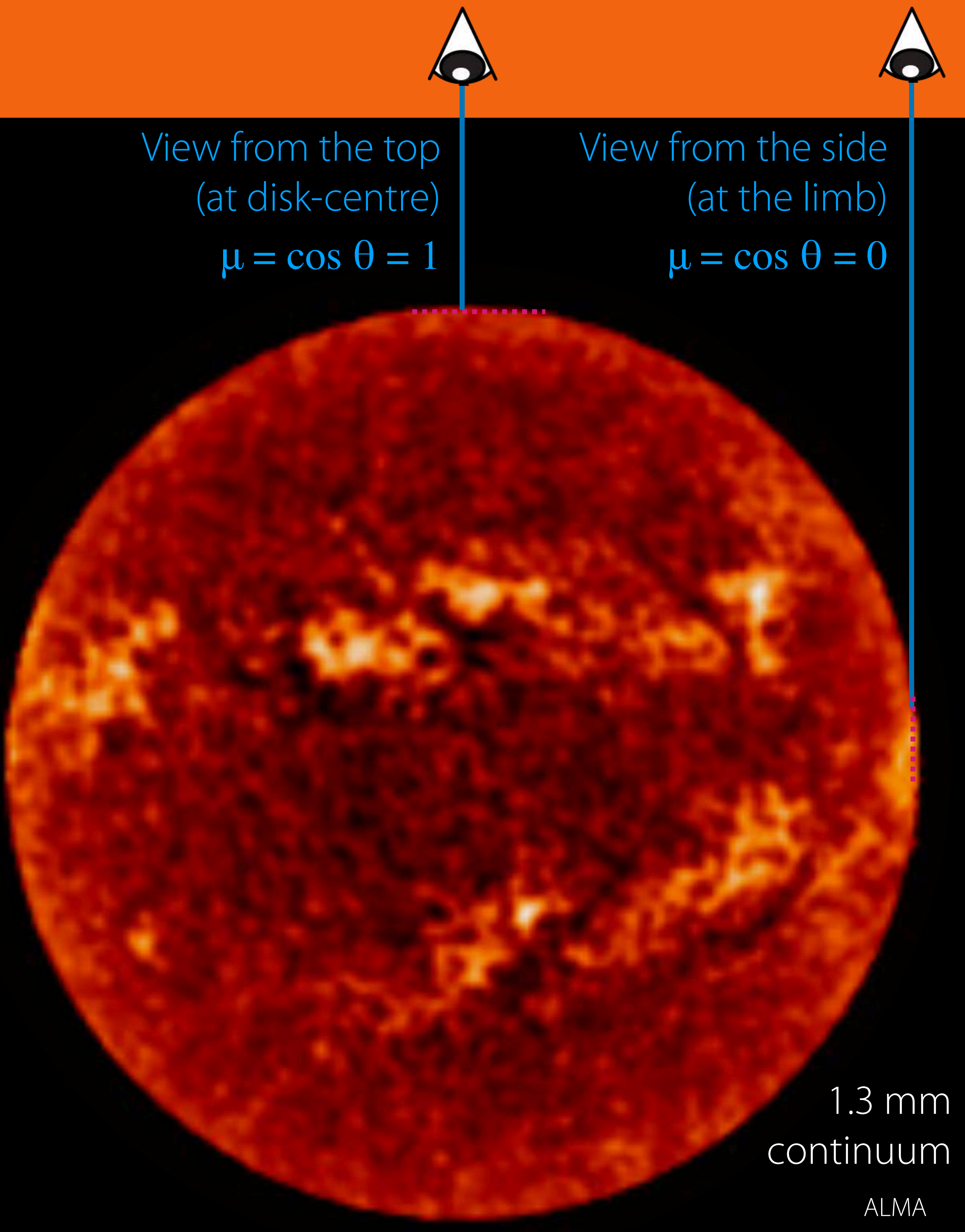
Radiative transfer effects

Limb brightening

- In the **mm continuum**:
  Solar disk **brighter** at the edge (limb) than at the centre of the solar disk
  (on average, do not look at ARs)!
- **Increasing** brightness implies increasing temperature (assuming simple blackbody radiation)
- Remember: Observation at increasing angle θ (=decreasing μ) maps layer at increasing height in the atmosphere

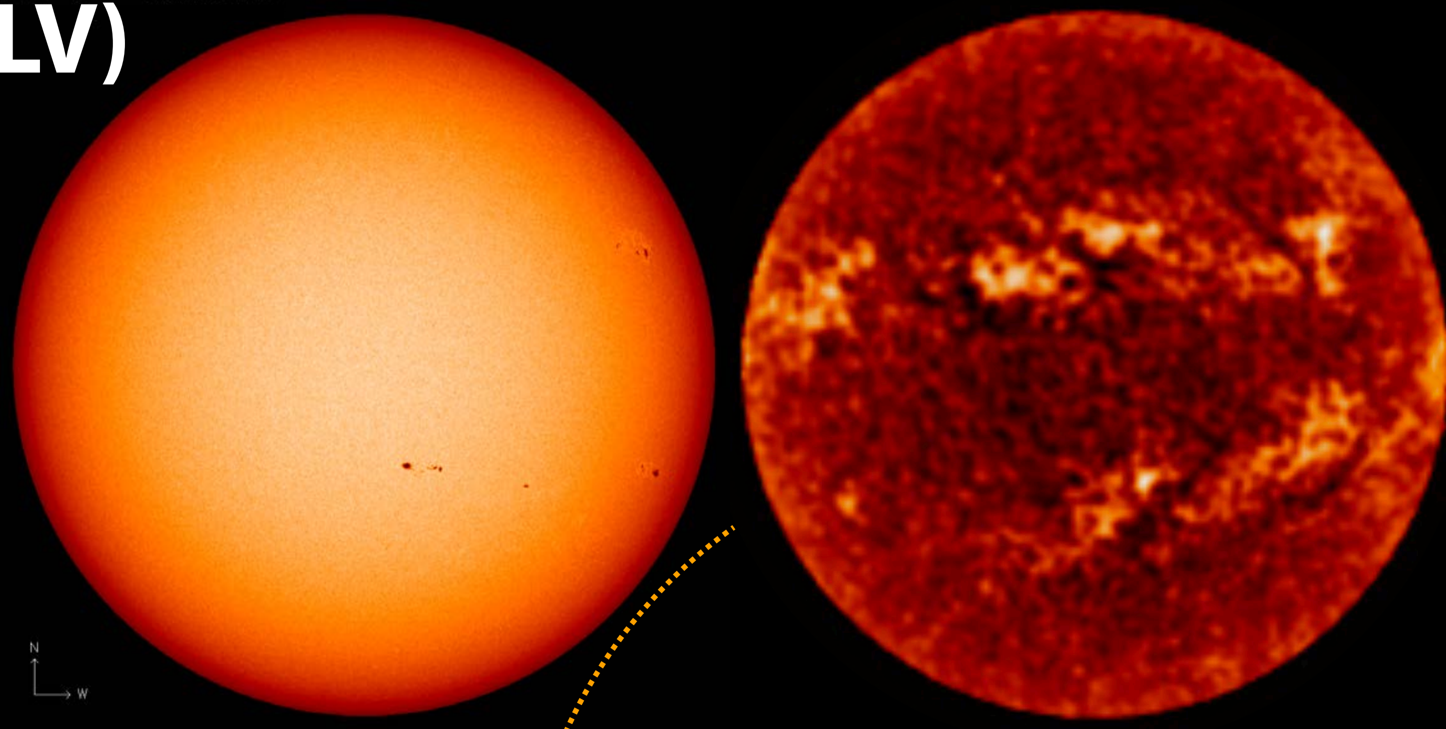
➡ Temperature **increases** with height for the height range mapped by this continuum range!

- Note: Optical depth unity reached in the chromosphere, i.e. much higher than the visible continuum



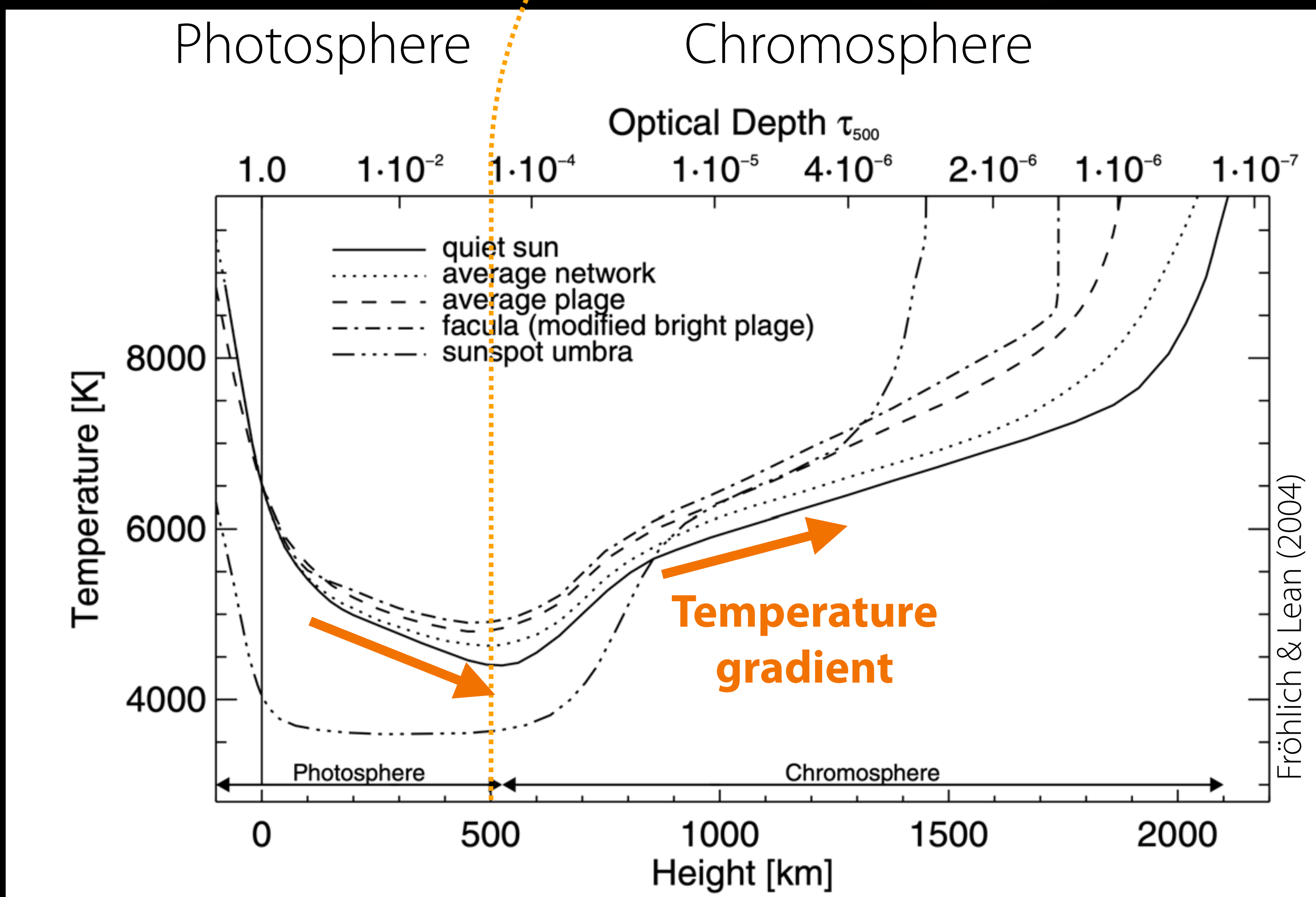
Radiative transfer effects

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!

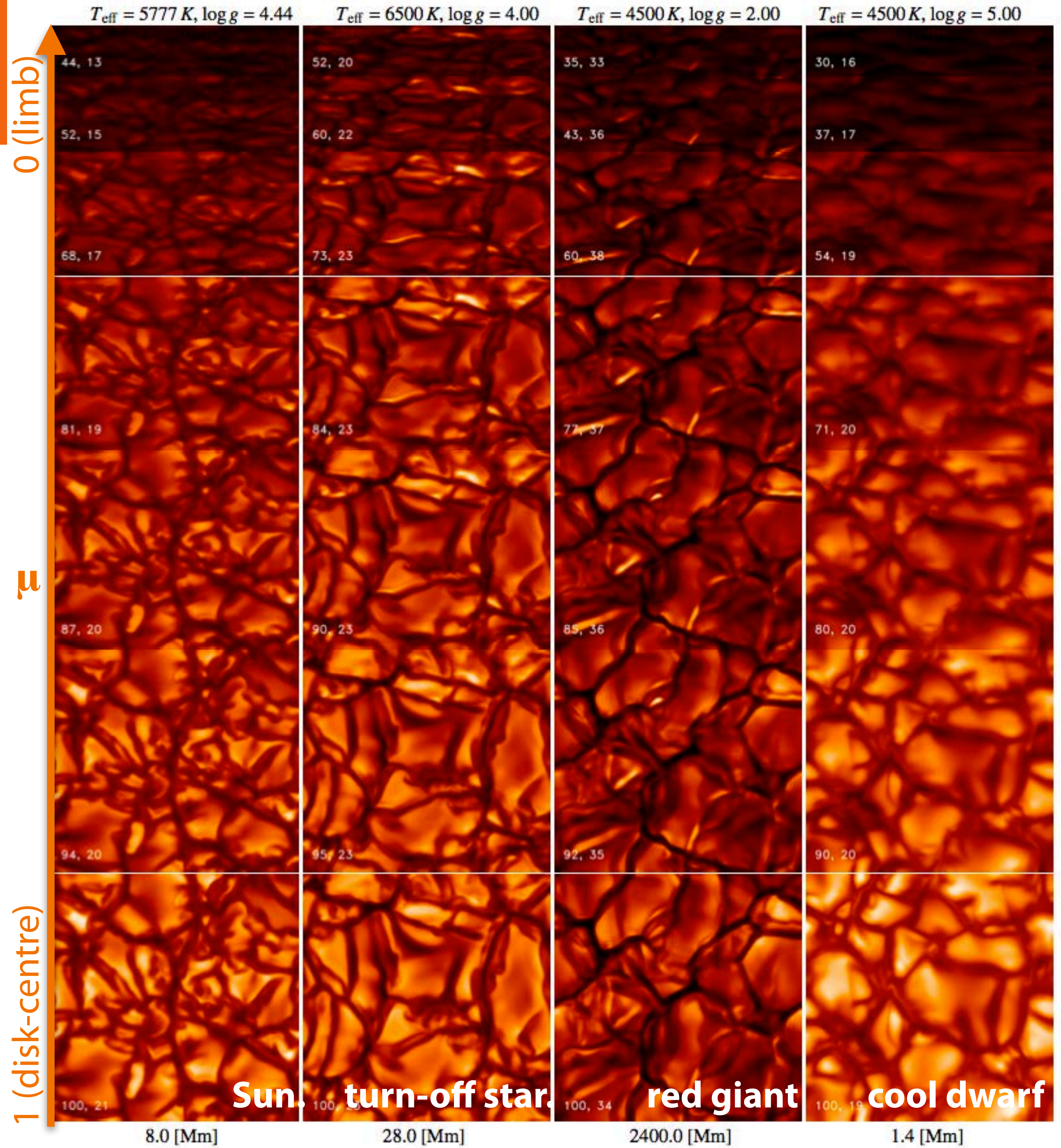
- CLV measured from observations help to construct (1D) average atmosphere models (even for different types of region from Quiet Sun to sunspot umbra)



Radiative transfer effects

Centre-to-limb variation (CLV)

- 3D numerical simulations for different stellar types
- Intensity maps for as function of inclination angle μ from disk-center to limb (visible continuum).
- All show limb darkening.
- Observational imprint of photospheric temperature stratification!

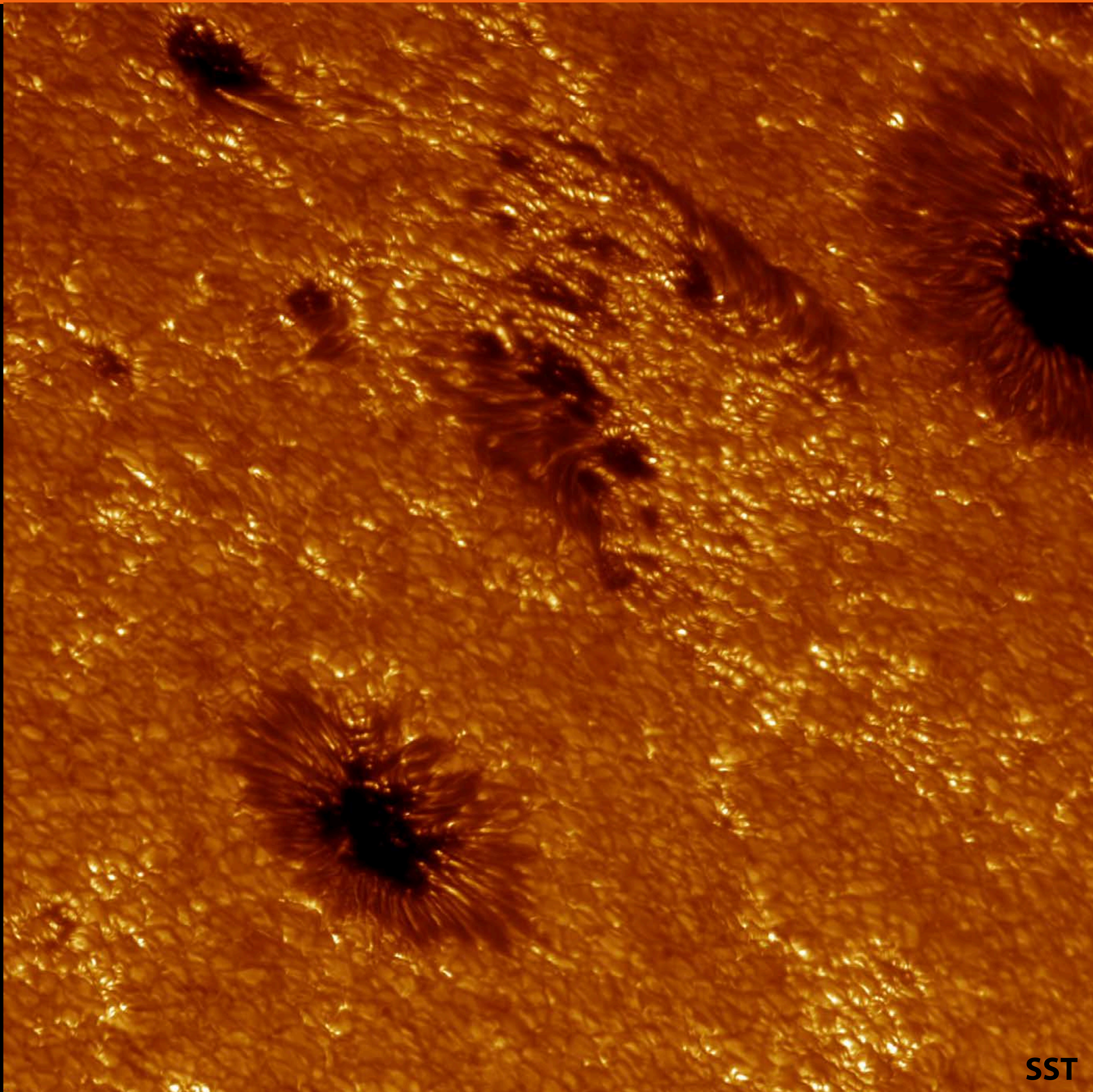


Radiative transfer effects

Faculae

- Faculae = **bright** areas most easily seen near solar limb (hot wall effect!)
- Areas with (small-scale) magnetic elements (in photosphere)
- Area on Sun covered with faculae varies over solar cycle
- Corresponding increase in brightness (across whole disk) more than compensates for darkening by sunspots!
- ~0.1% brighter at solar maximum than at solar minimum

- **Plage** = chromospheric counterpart of a facular region

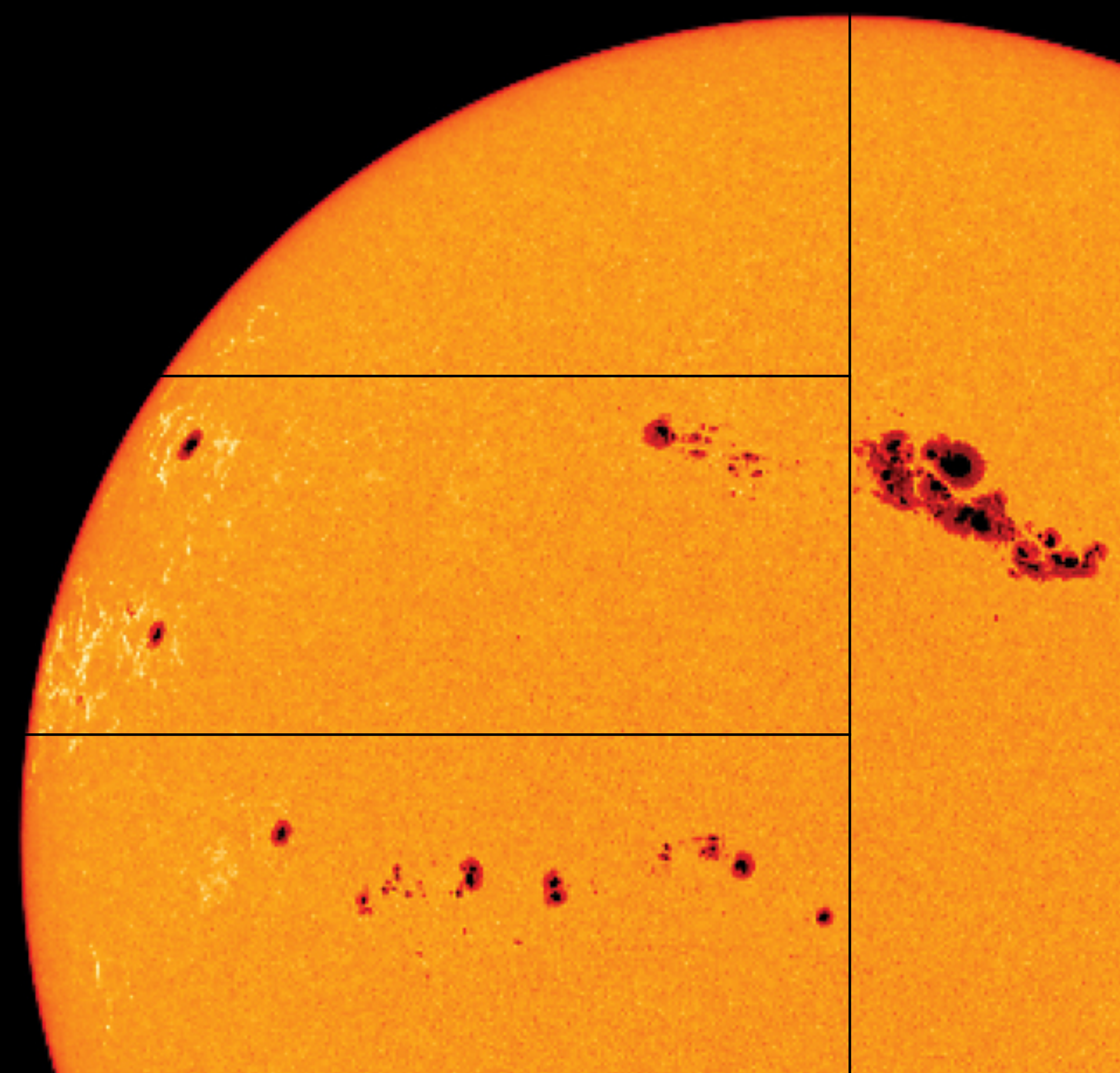


The solar atmosphere

Different regions — photosphere

(Average) magnetic field strength

Active Region (Large) area with strong magnetic field	**Sunspot** Areas of concentrated very strong field, appear dark	**Umbra** Central compact part, dark **Penumbra** Surrounding, filamentary
	Faculae bright (filamentary) areas	
Quiet Sun Outside Active Regions, weaker magnetic field	**Network** Concentrations of strong magnetic field, filamentary/ mesh-like	
	Inter-network Areas with weak magnetic field inside network cells	

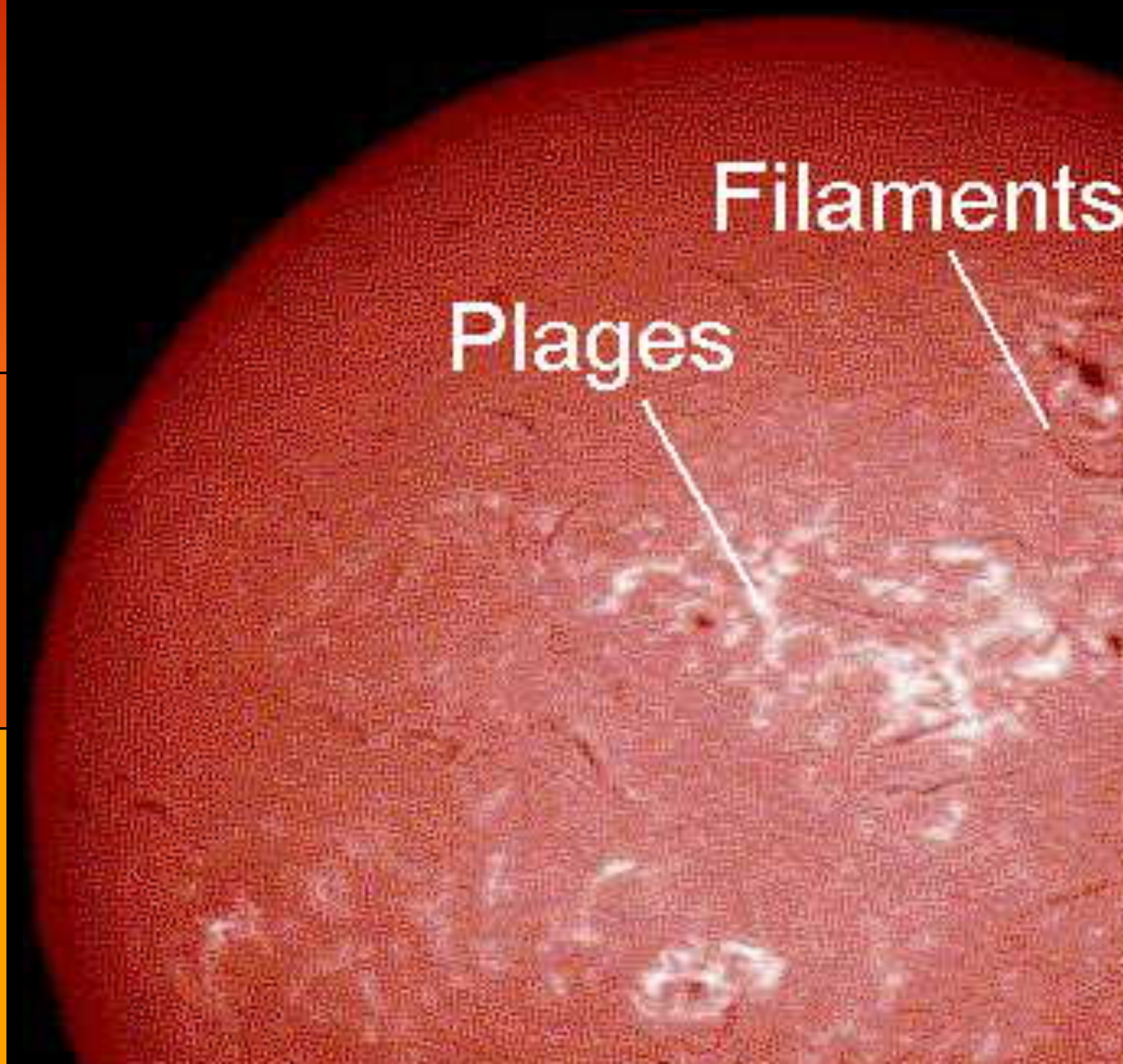


The solar atmosphere

Different regions — chromosphere

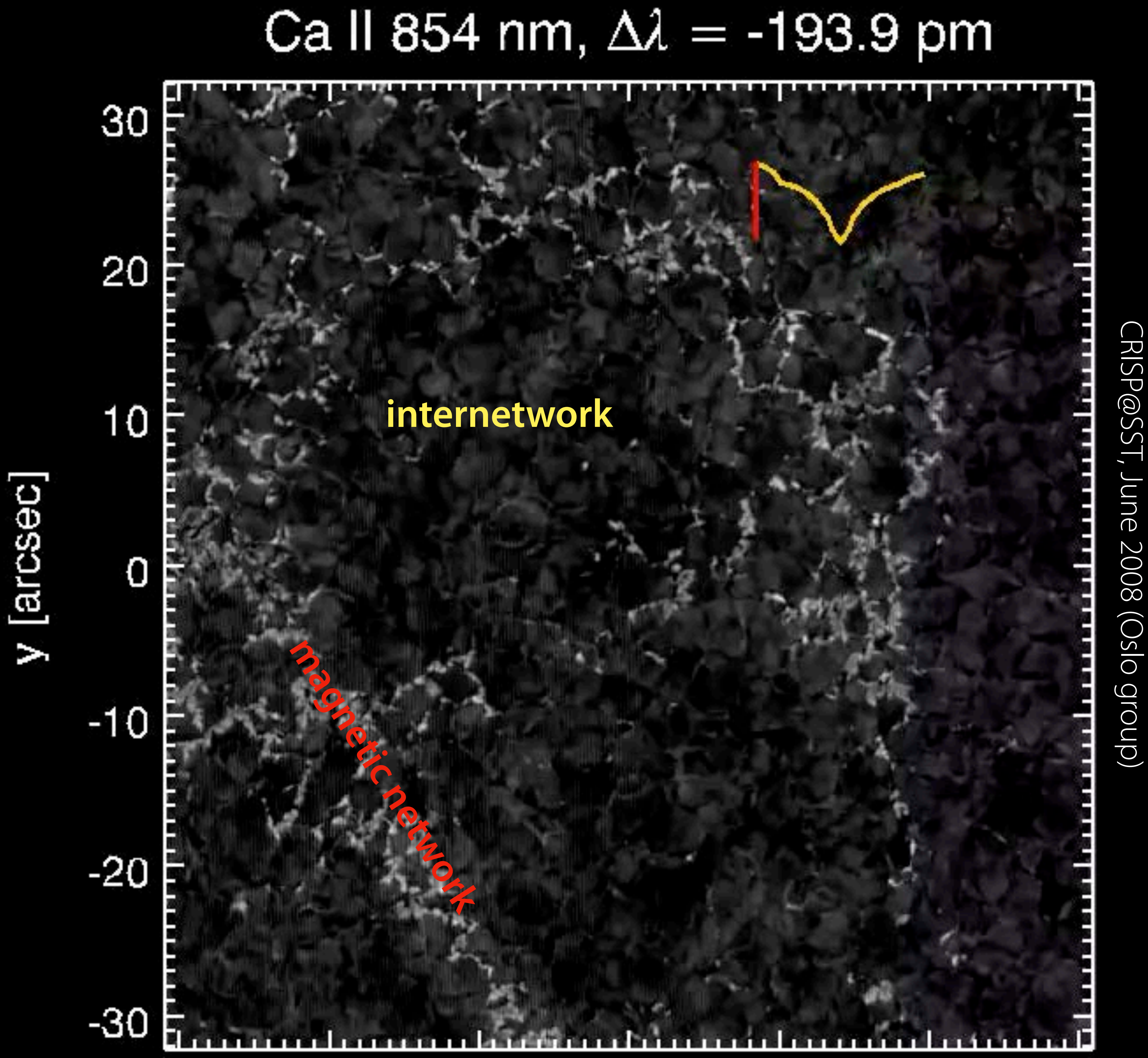
(Average) magnetic field strength

Active Region (Large) area with strong magnetic field	**Sunspot** Areas of concentrated very strong field, appear dark	**Umbra** Central compact part, dark **Penumbra** Surrounding, filamentary
	Plage bright area, higher temperature, often proceeds formation of sunspots	
Quiet Sun Outside Active Regions, weaker magnetic field	**Network** Concentrations of strong magnetic field, filamentary/ mesh-like	
	Inter-network Areas with weak magnetic field inside network cells	



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



The solar atmosphere

photo-
sphere

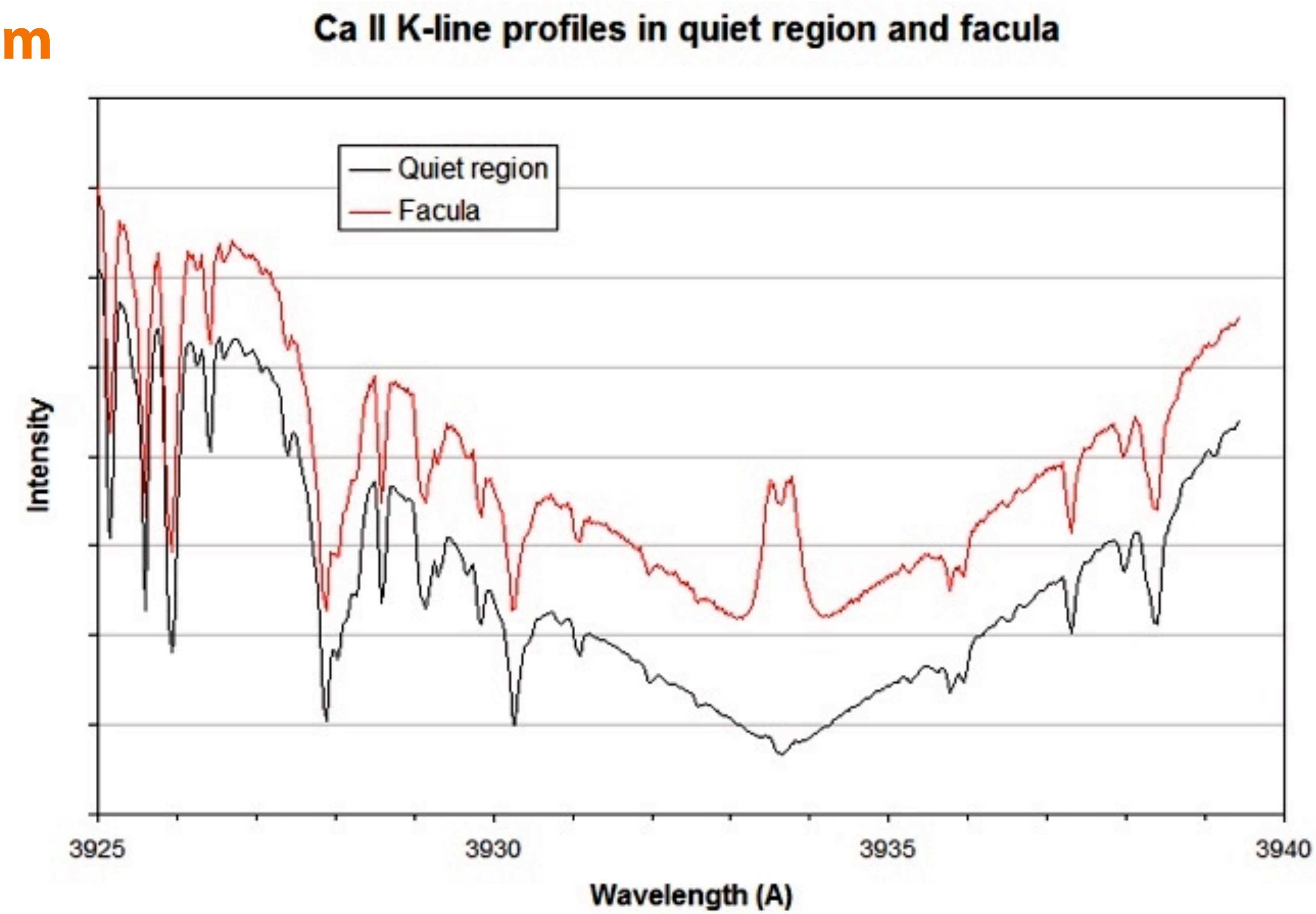
continuum

line wing

chromo-
sphere

line core

formation height



The solar atmosphere

photo-
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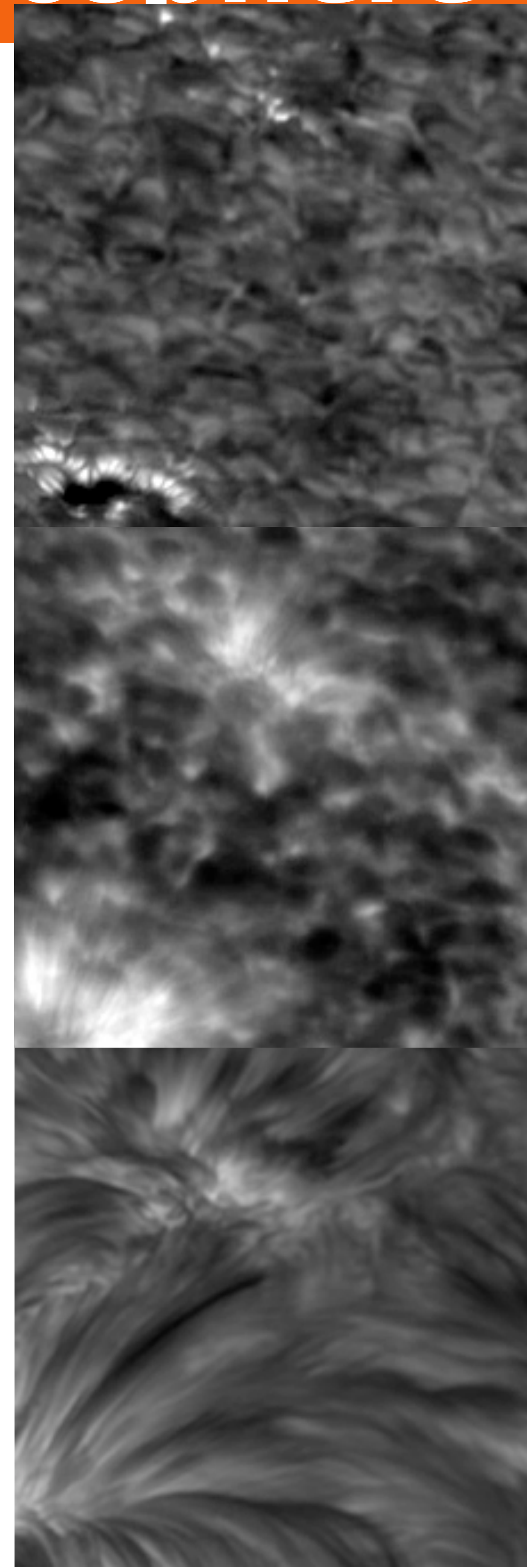
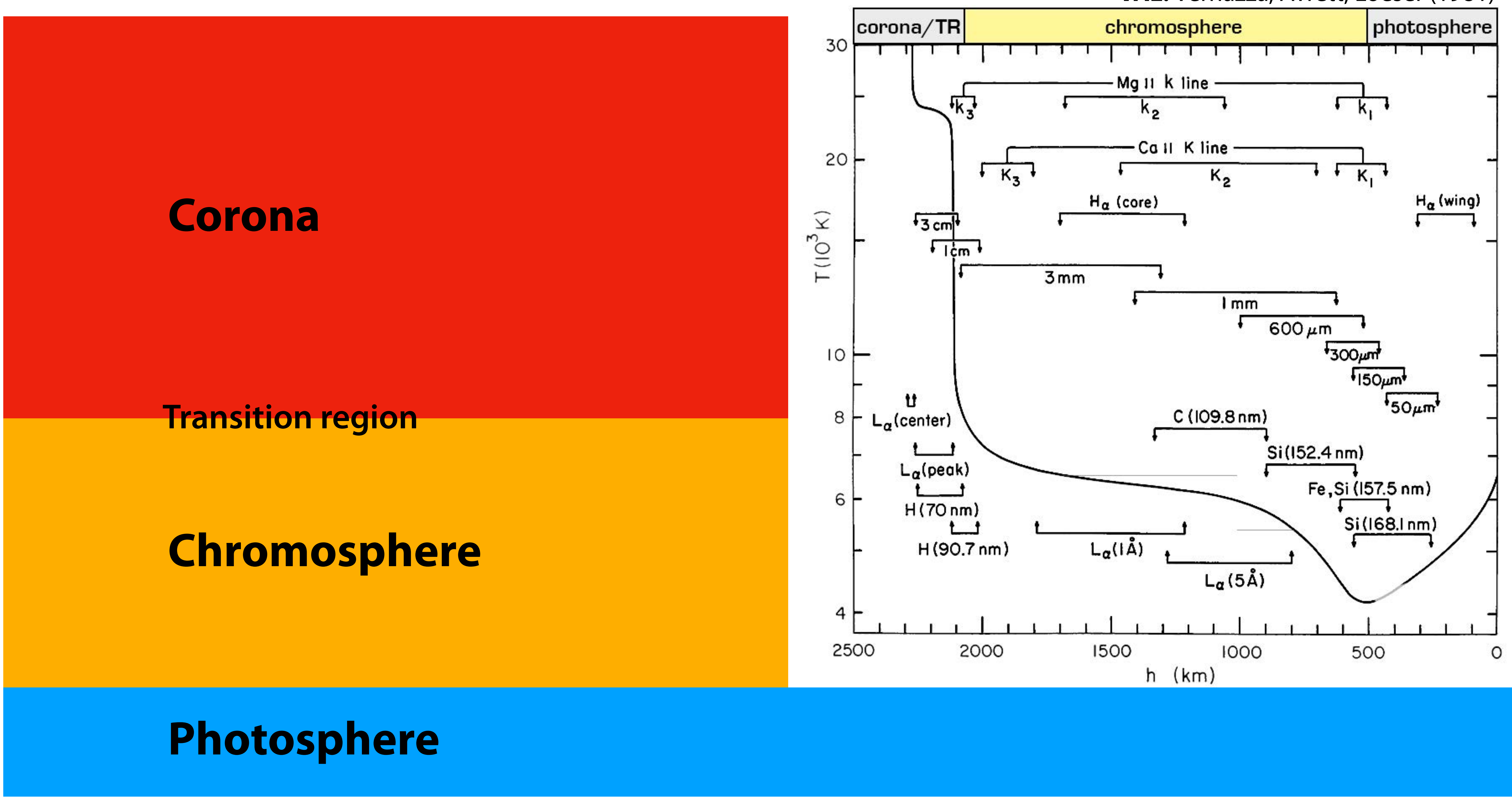


Magnetic field in the solar atmosphere

Structure of Quiet Sun regions

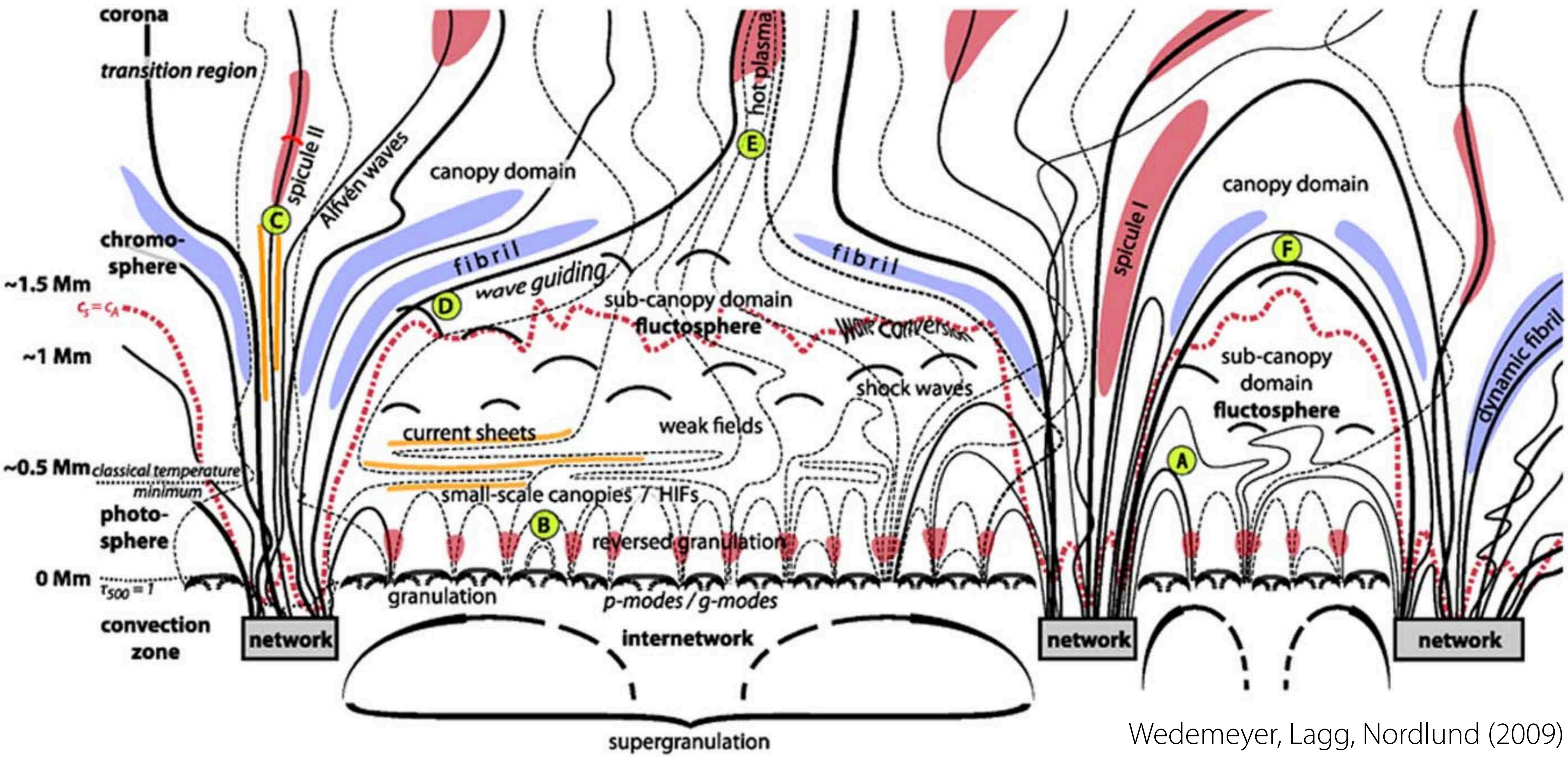
VAL: Vernazza, Avrett, Loeser (1981)



Magnetic field in 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

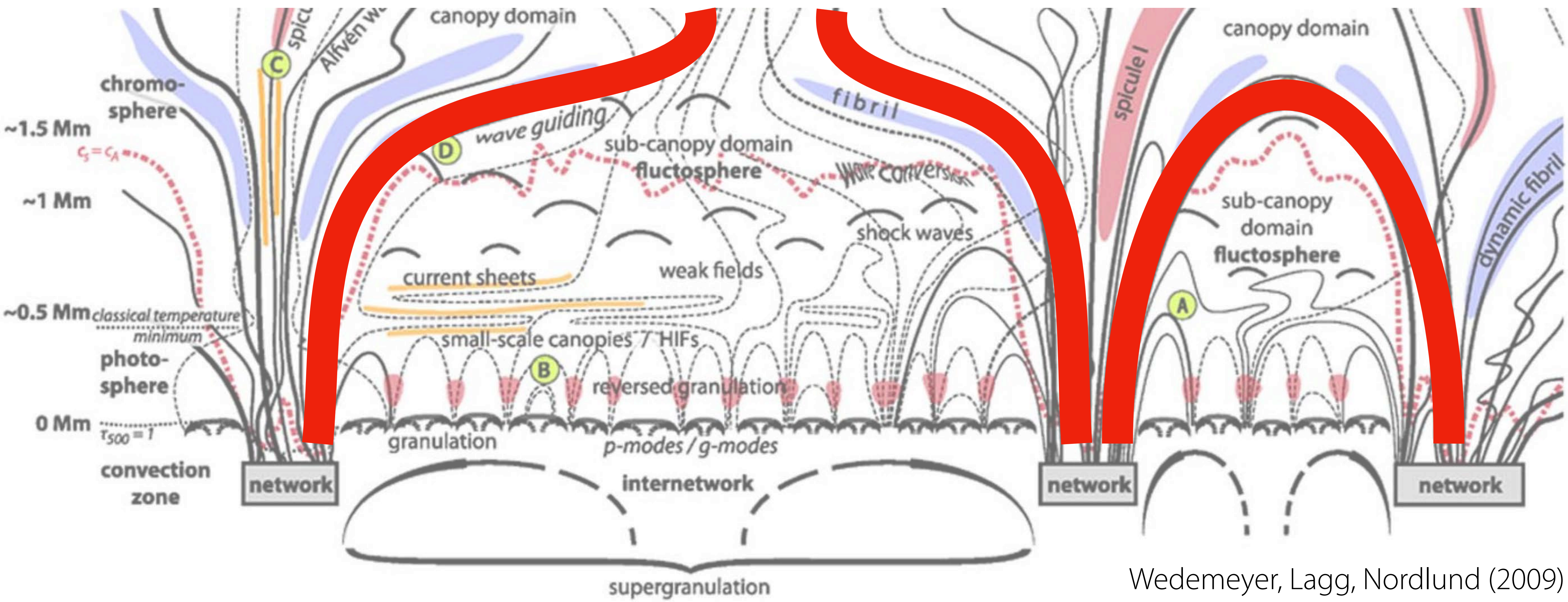


Wedemeyer, Lagg, Nordlund (2009)

The solar atmosphere

Structure of Quiet Sun regions

- Magnetic field in the photosphere: Footpoints with vertical field
- Chromosphere: Magnetic field connects polarities, forms loops (horizontal field, "canopy")
- Smaller loops can connect lower (small-scale canopies, horizontal field in photosphere)
- 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)