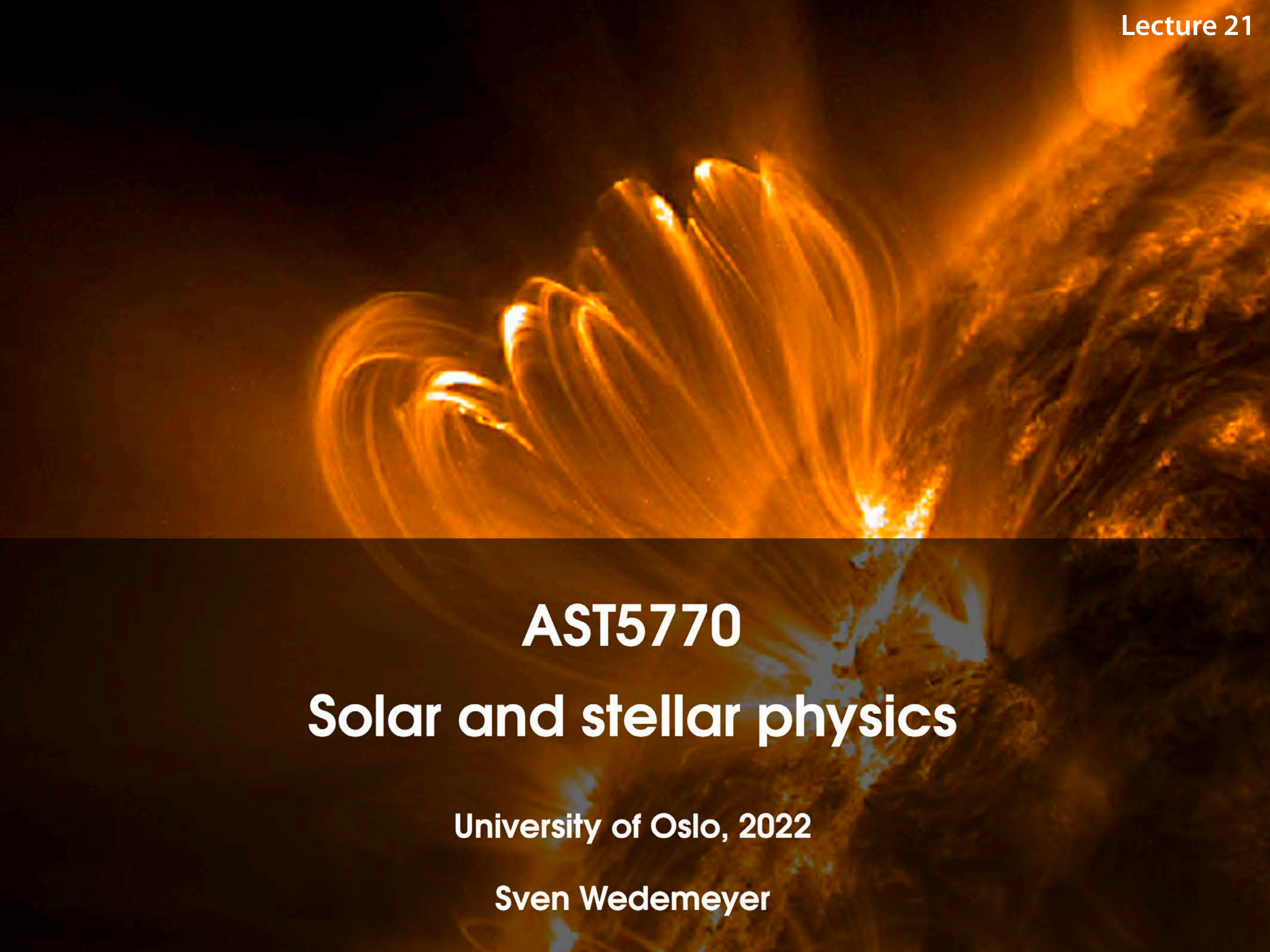


AST5770

Solar and stellar physics

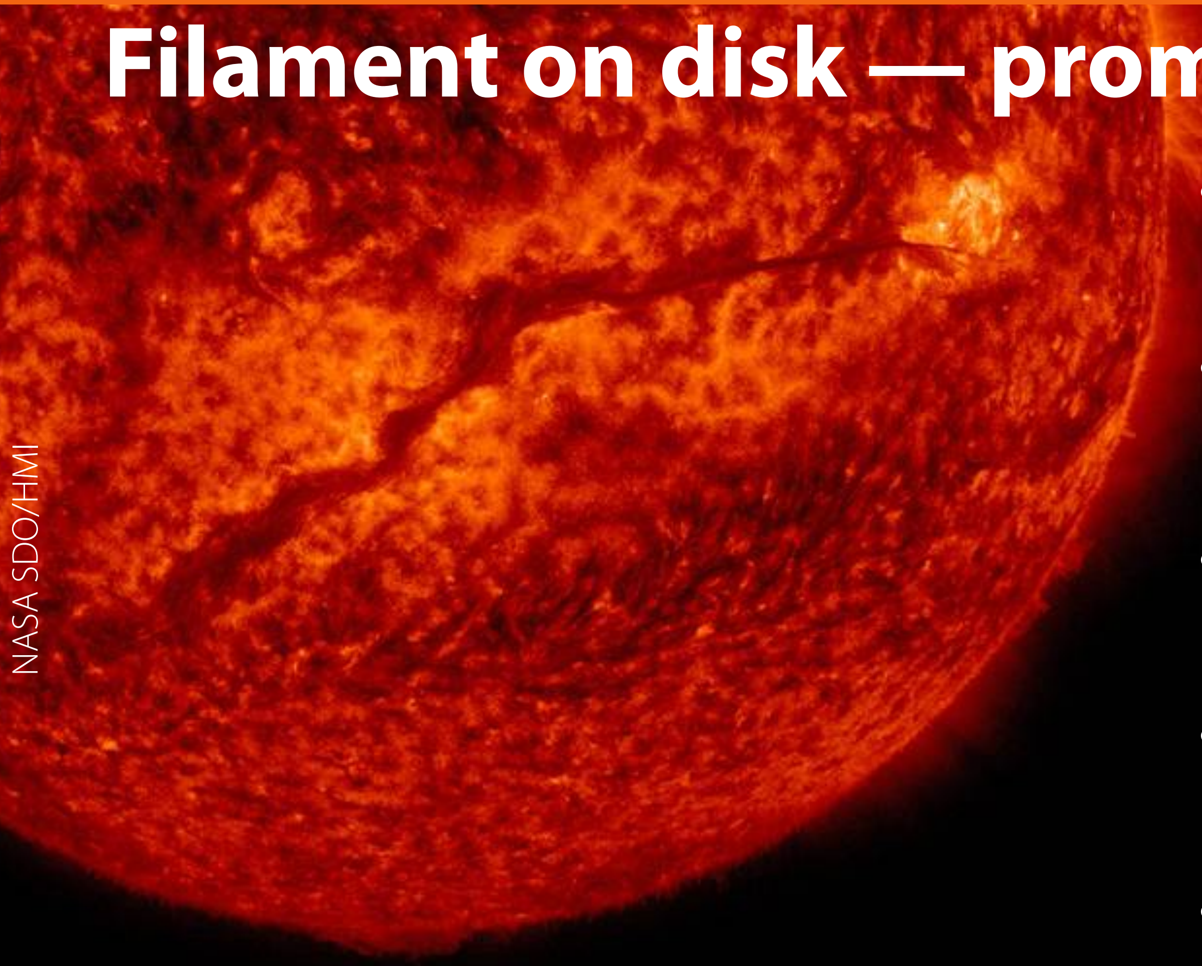
University of Oslo, 2022

Sven Wedemeyer

Solar filaments, prominences, CMEs Recap

Filaments and prominences — recap

Filament on disk — prominence at the limb

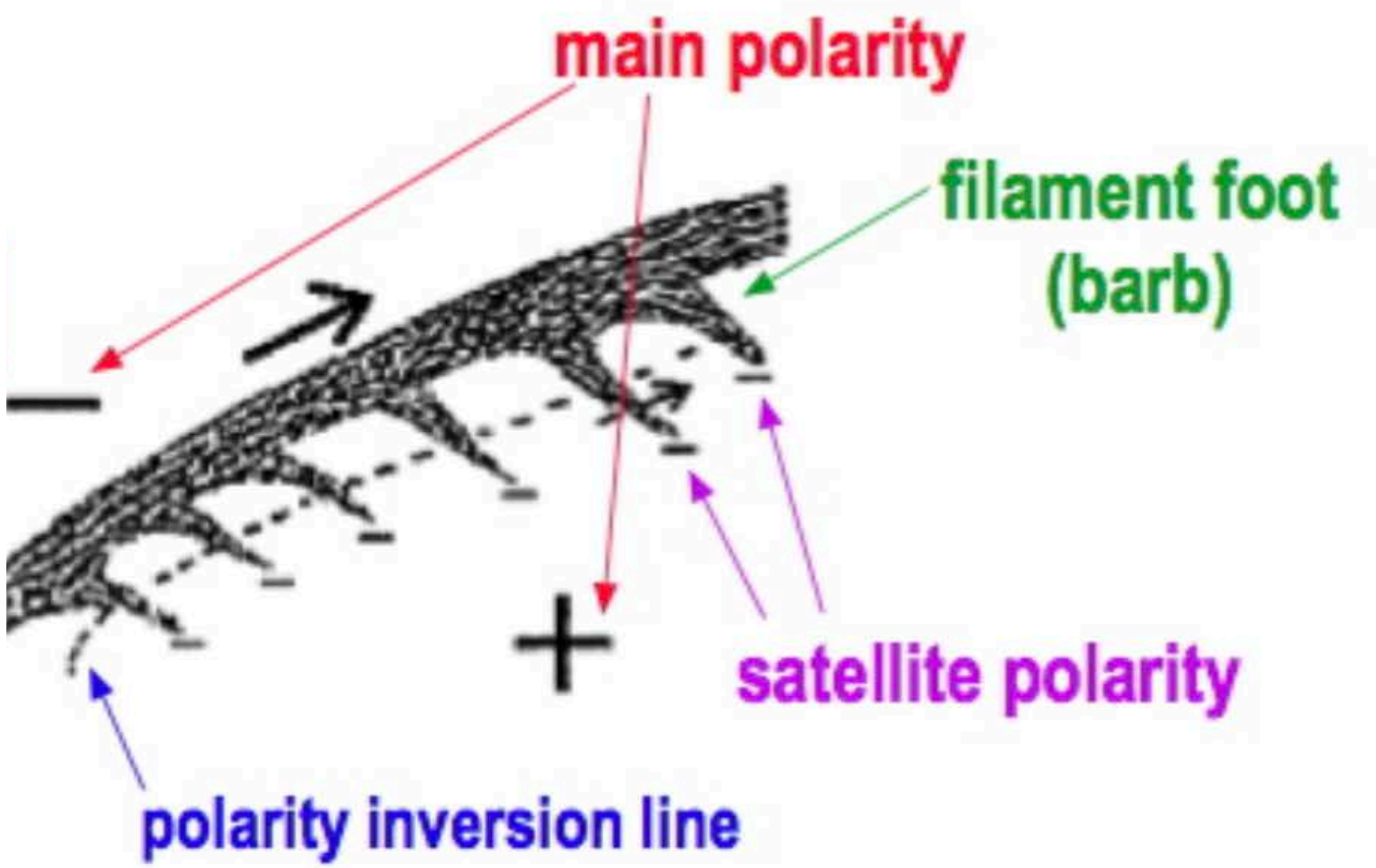


- Called prominence when above limb, filament when seen on disk
- Seen in absorption (filament) or emission prominence compared to surrounding/background
- Plasma cooler (T ~ 10 000 K) and denser than surrounding corona (at ~1 MK)
- Interface between the two environments is called **Prominence-Corona-Transition Region (PCTR).**
- Long and thin structures
- Quiescent filaments can reach lengths > 100 Mm and persist for days or weeks
- Active Region filaments smaller (still large) and shorter-lived
- Filaments can erupt when becoming unstable

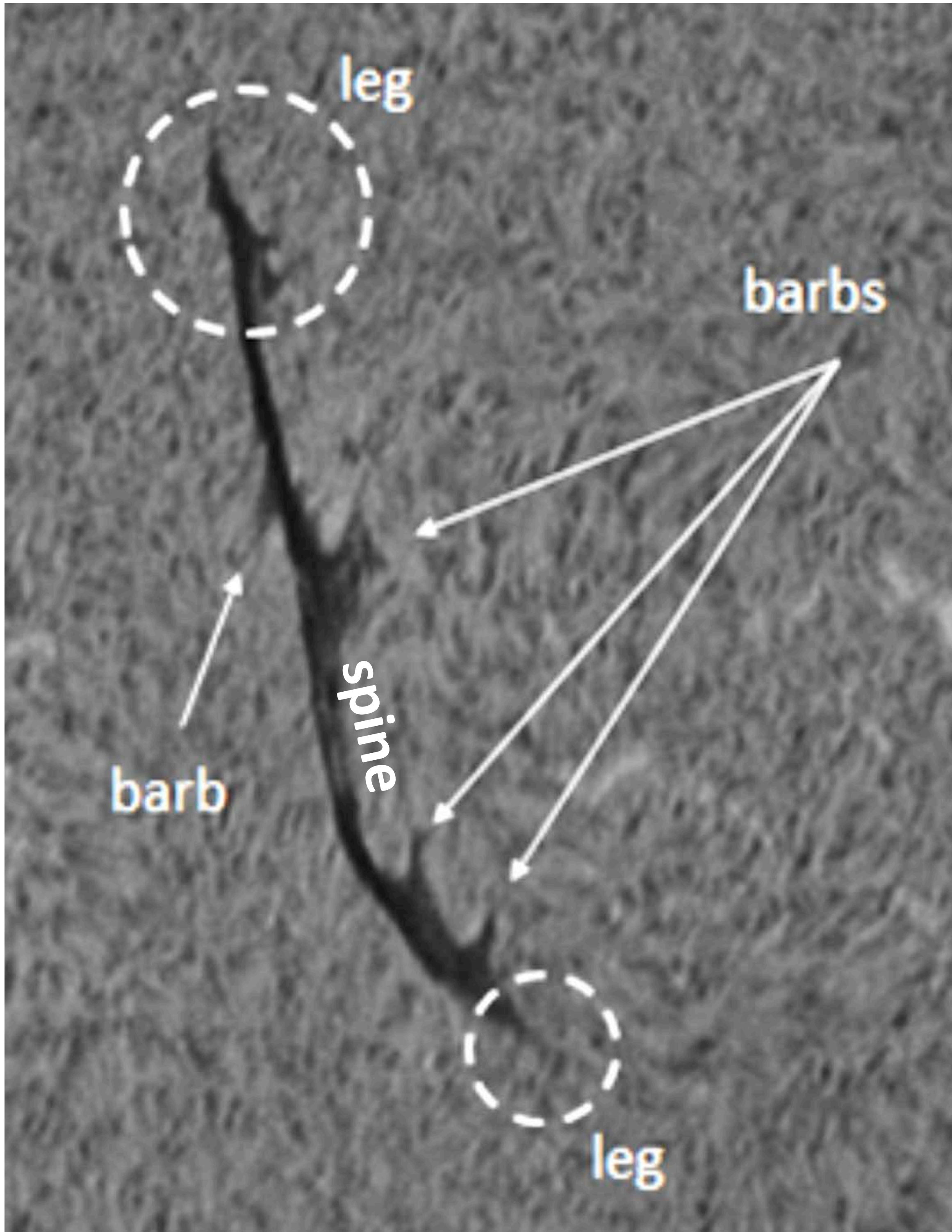
Filaments and prominences

"Anatomy" of filaments and prominences

- Filament consists of a spine, legs, and barbs
- Magnetic field structure + dense plasma supported against gravity
- Magnetic twist important
- Overlying coronal loops may hold filament in place

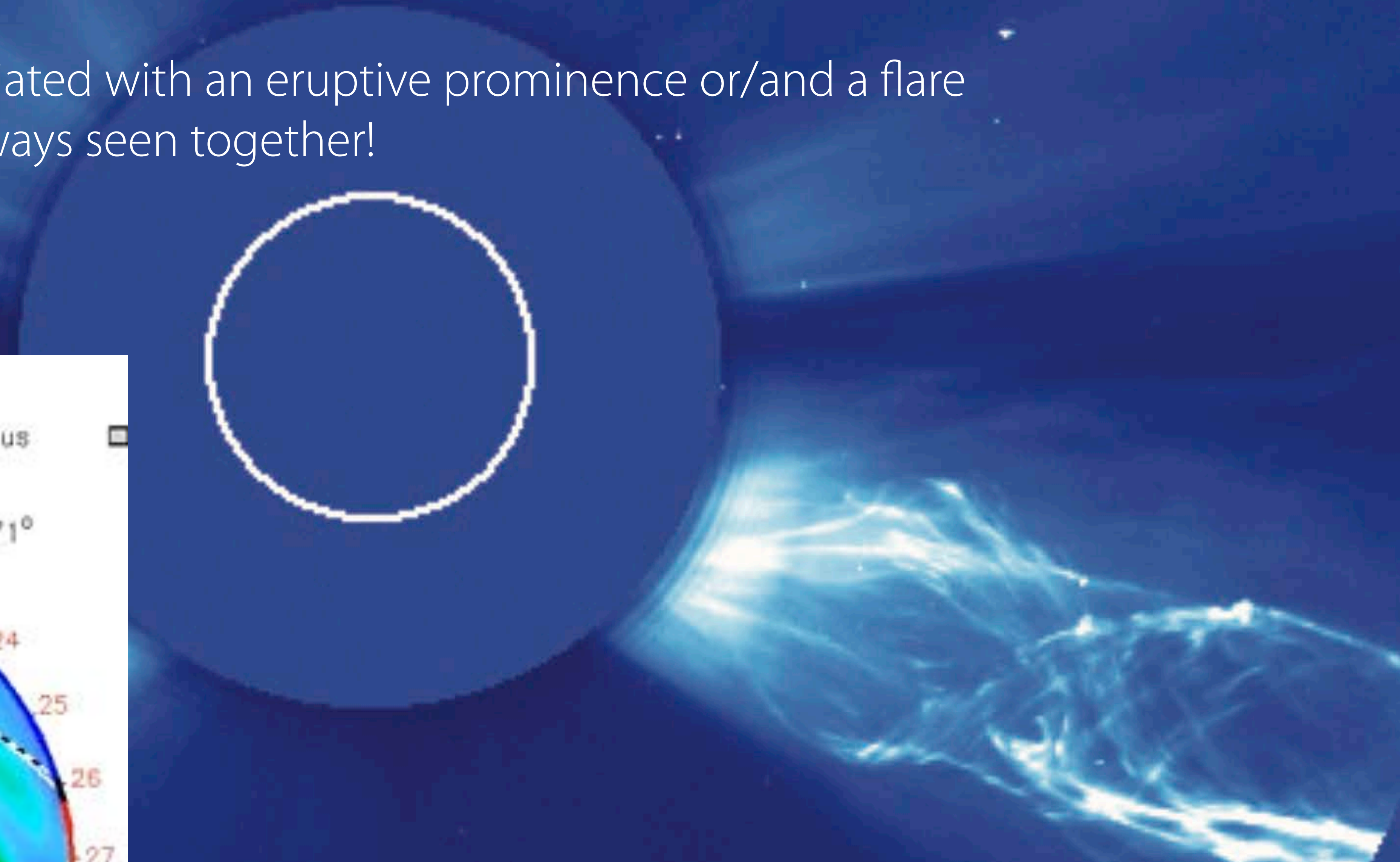


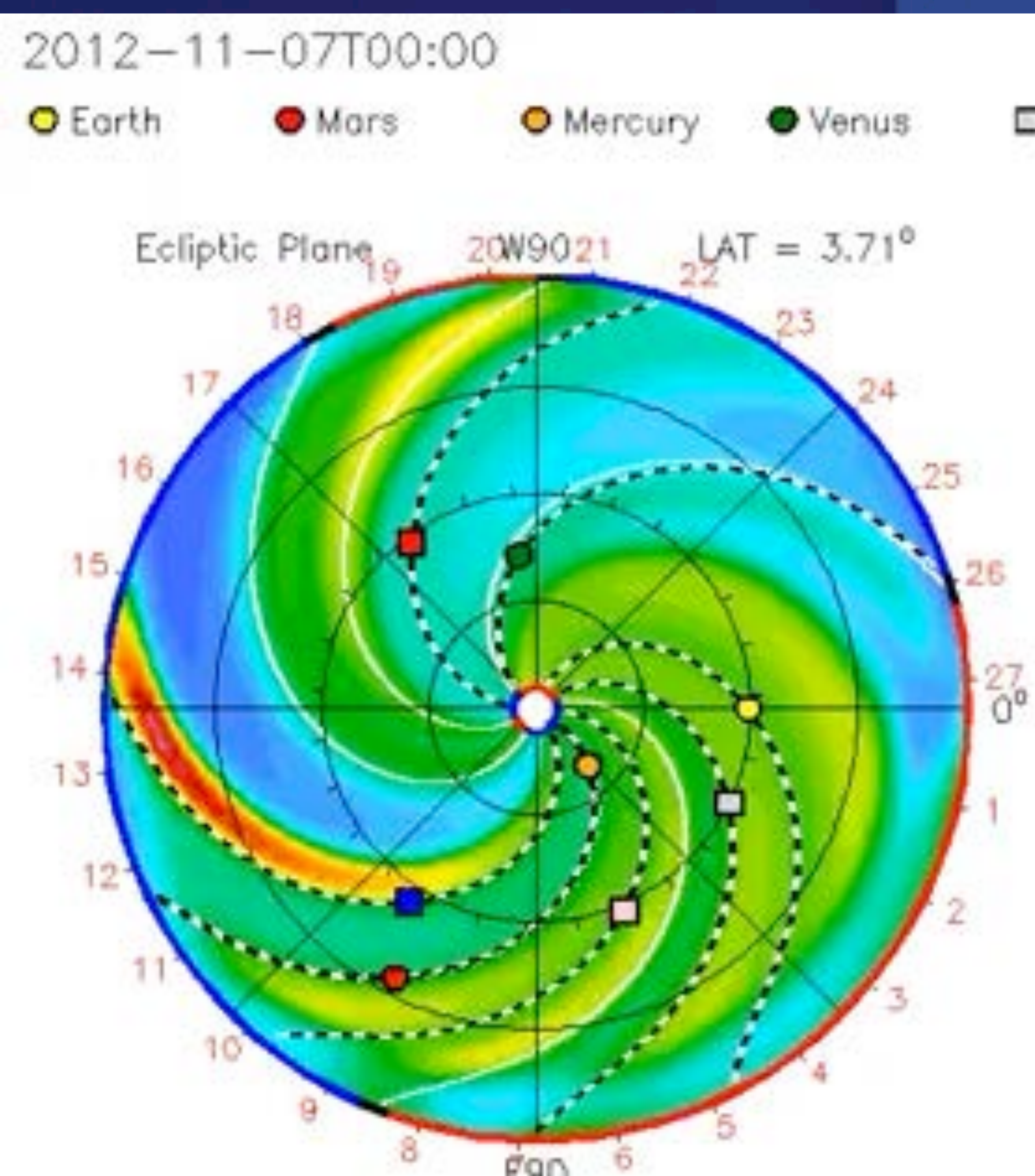
Martin (1998), Chae et al. (2001)



Coronal Mass Ejection

- Central bright helical structure = erupting filament
  ➡ Unwinding of filament
- In most cases CMEs associated with an eruptive prominence or/and a flare BUT CME and flare not always seen together!

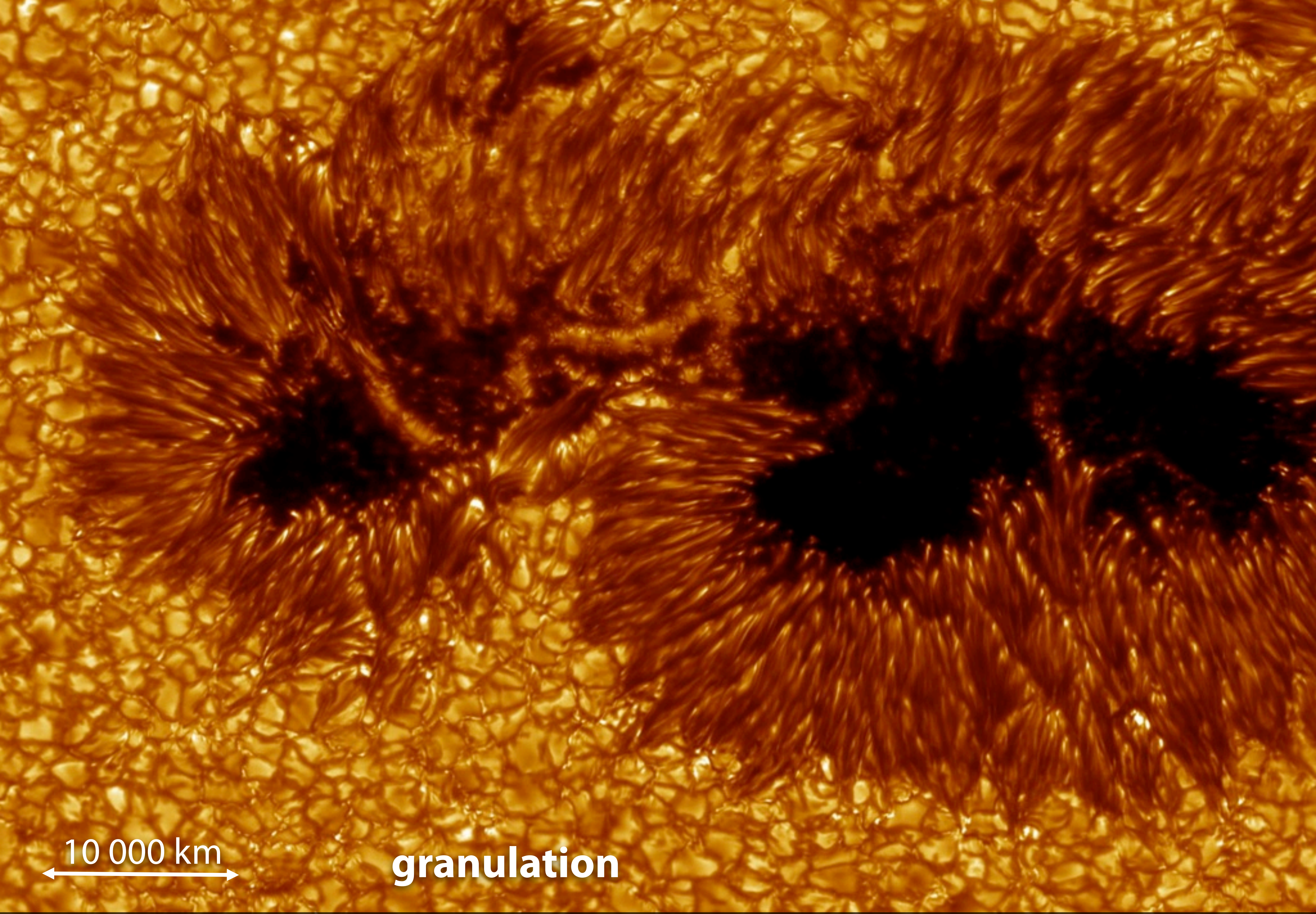




- CME propagates away from Sun, reaches Earth orbit within a few days
- Can cause geomagnetic storms (space weather)
- Space weather forecast needed!
  — Currently under development.

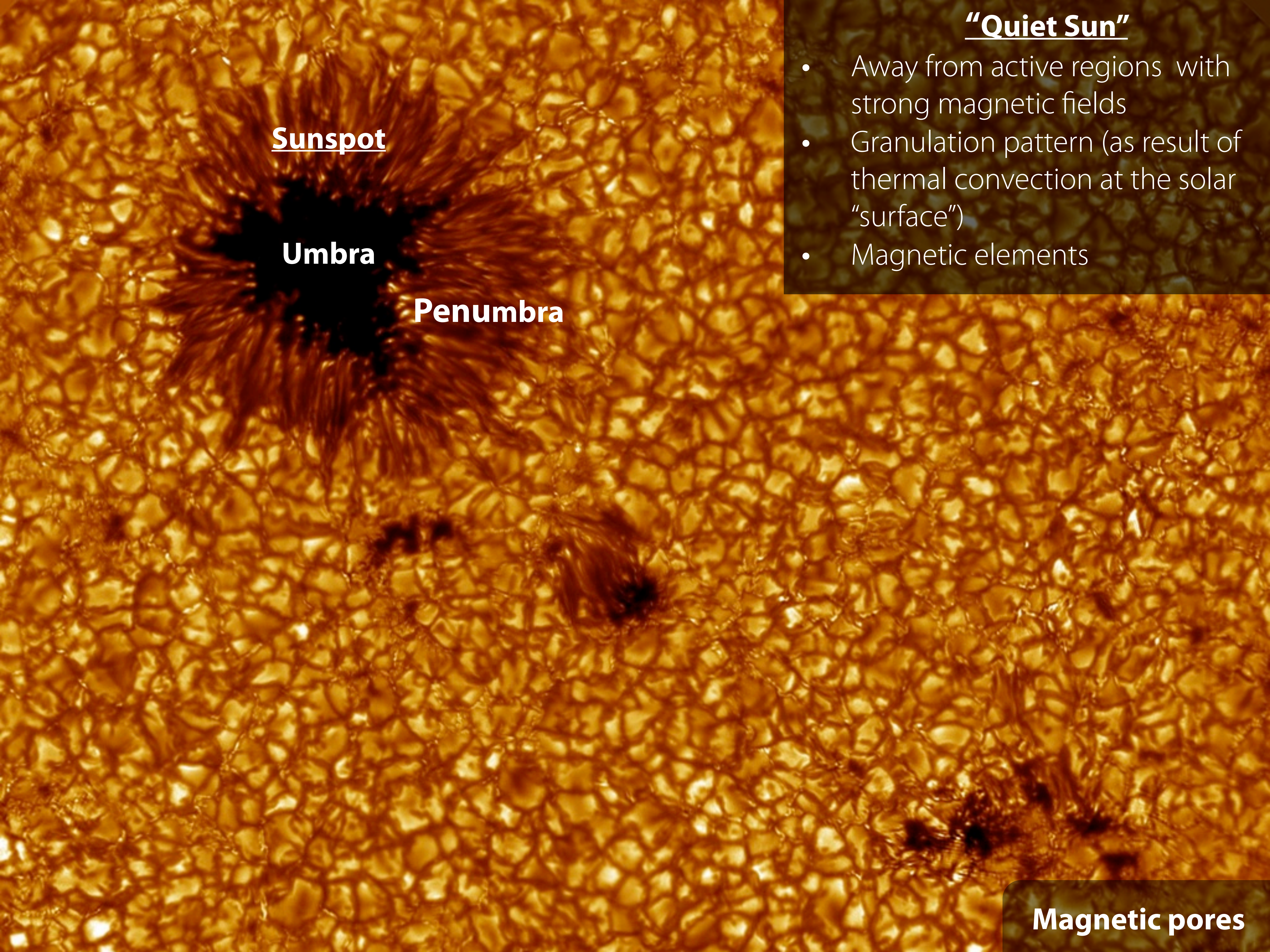
Magnetic features in the solar atmosphere

(smaller than sunspots)



Photosphere of the Sun = $\tau(\lambda=500nm) = 1$
narrow layer where visible continua become optically thick

G-band (430nm)



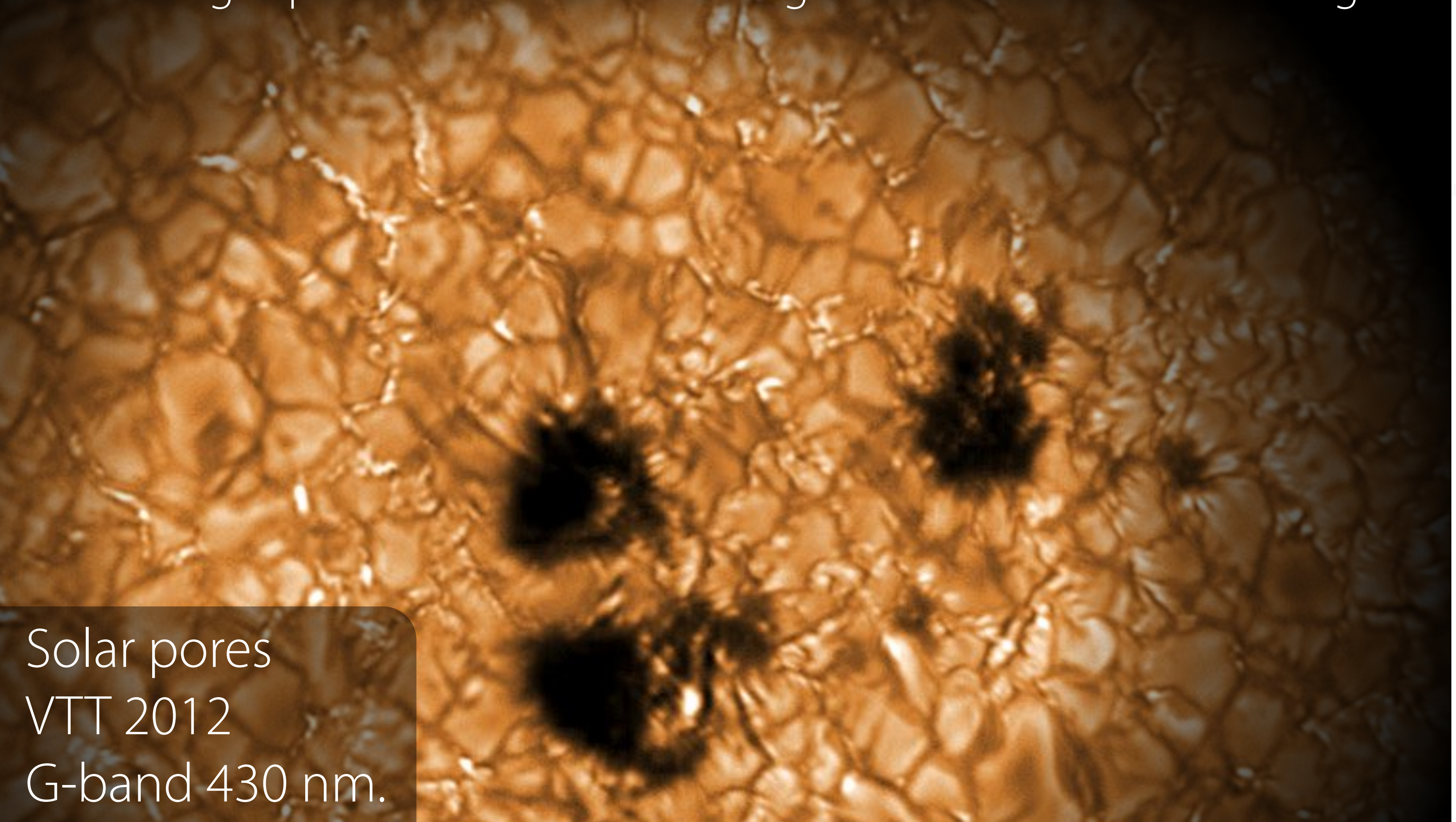
"Quiet Sun"

- Away from active regions with strong magnetic fields
- Granulation pattern (as result of thermal convection at the solar "surface")
- Magnetic elements

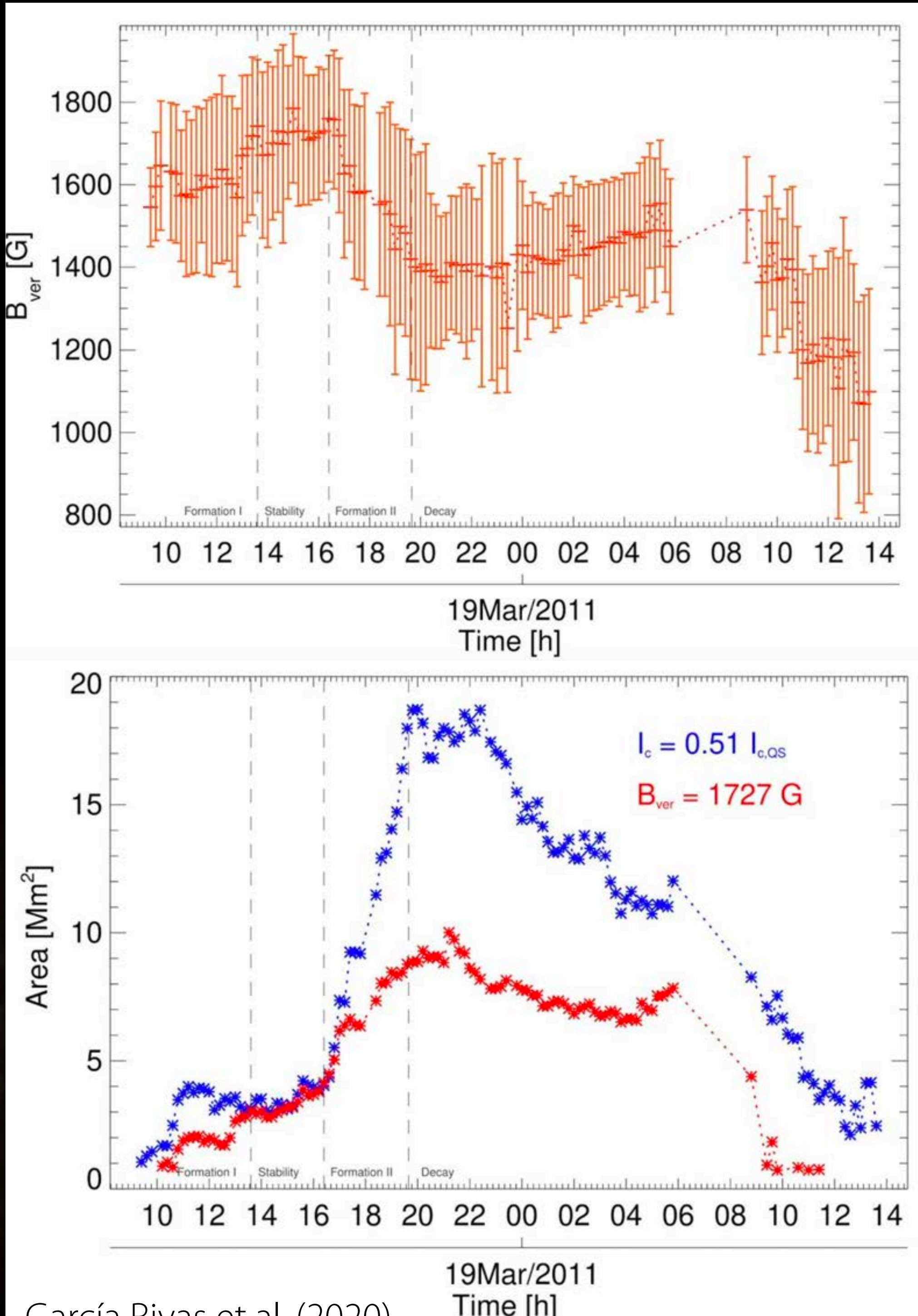
Magnetic field in the solar atmosphere

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.

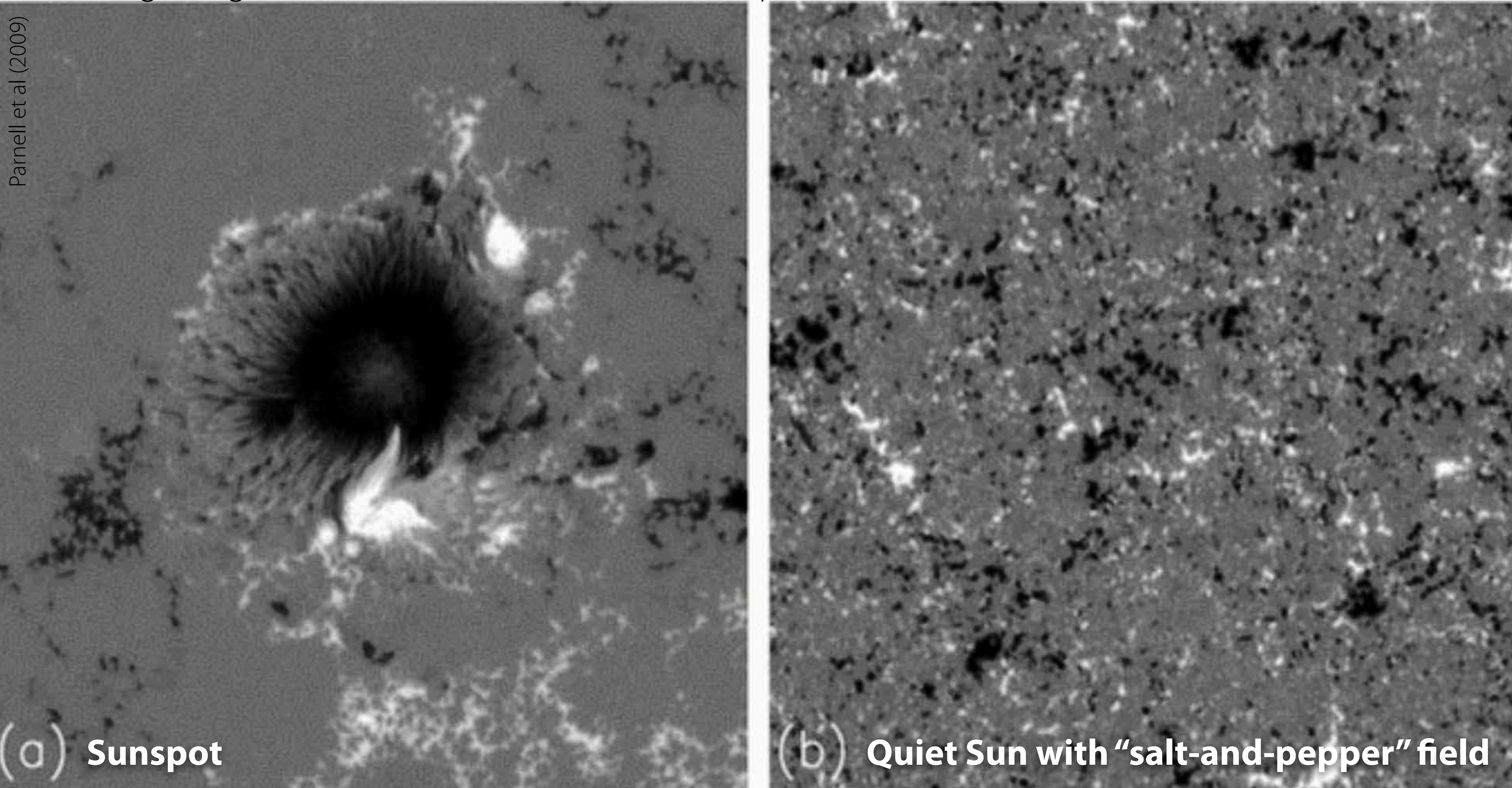


García Rivas et al. (2020)

Magnetic field in the solar atmosphere

Photospheric magnetic field

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

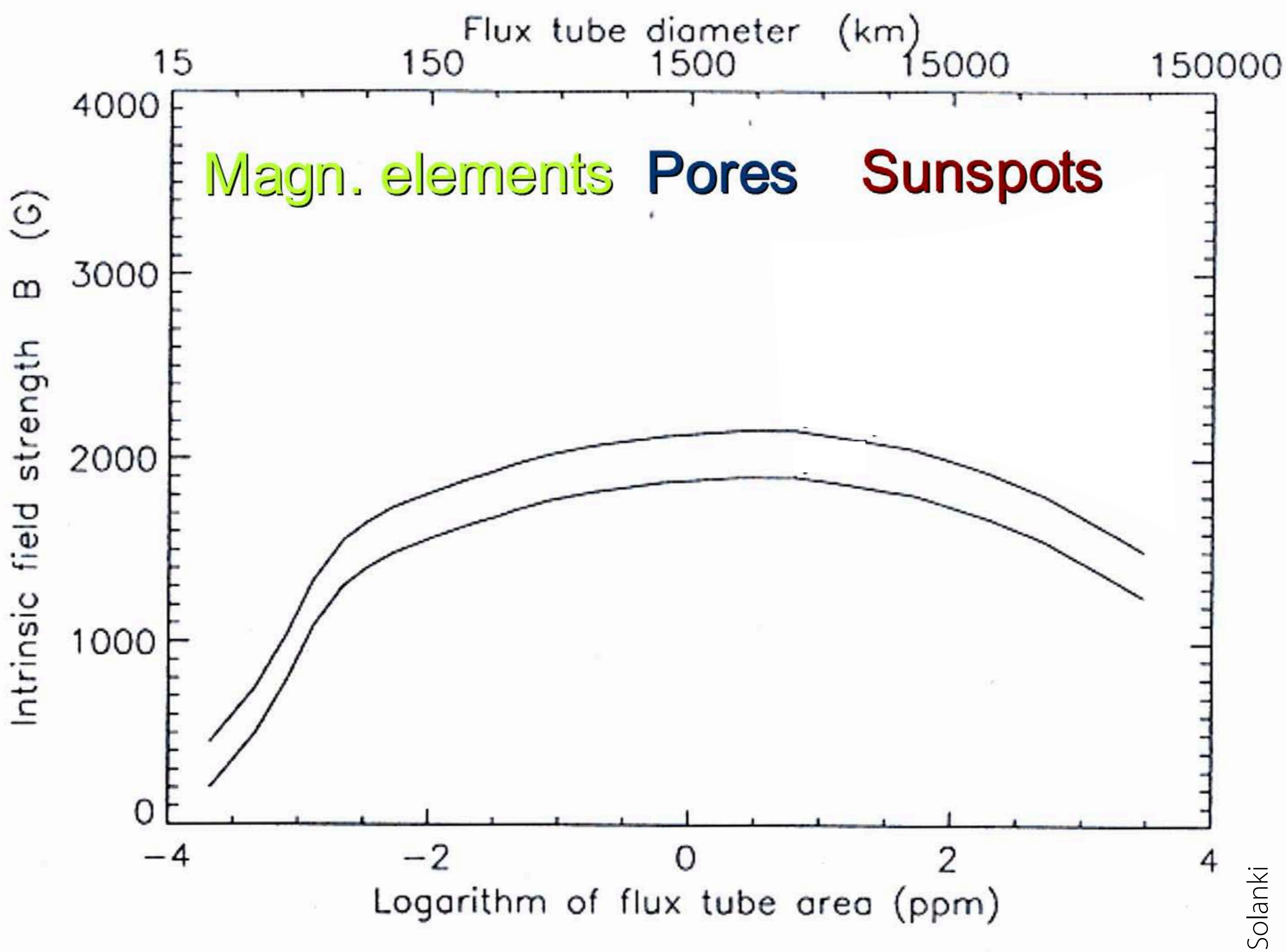


Magnetic field in the solar atmosphere

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

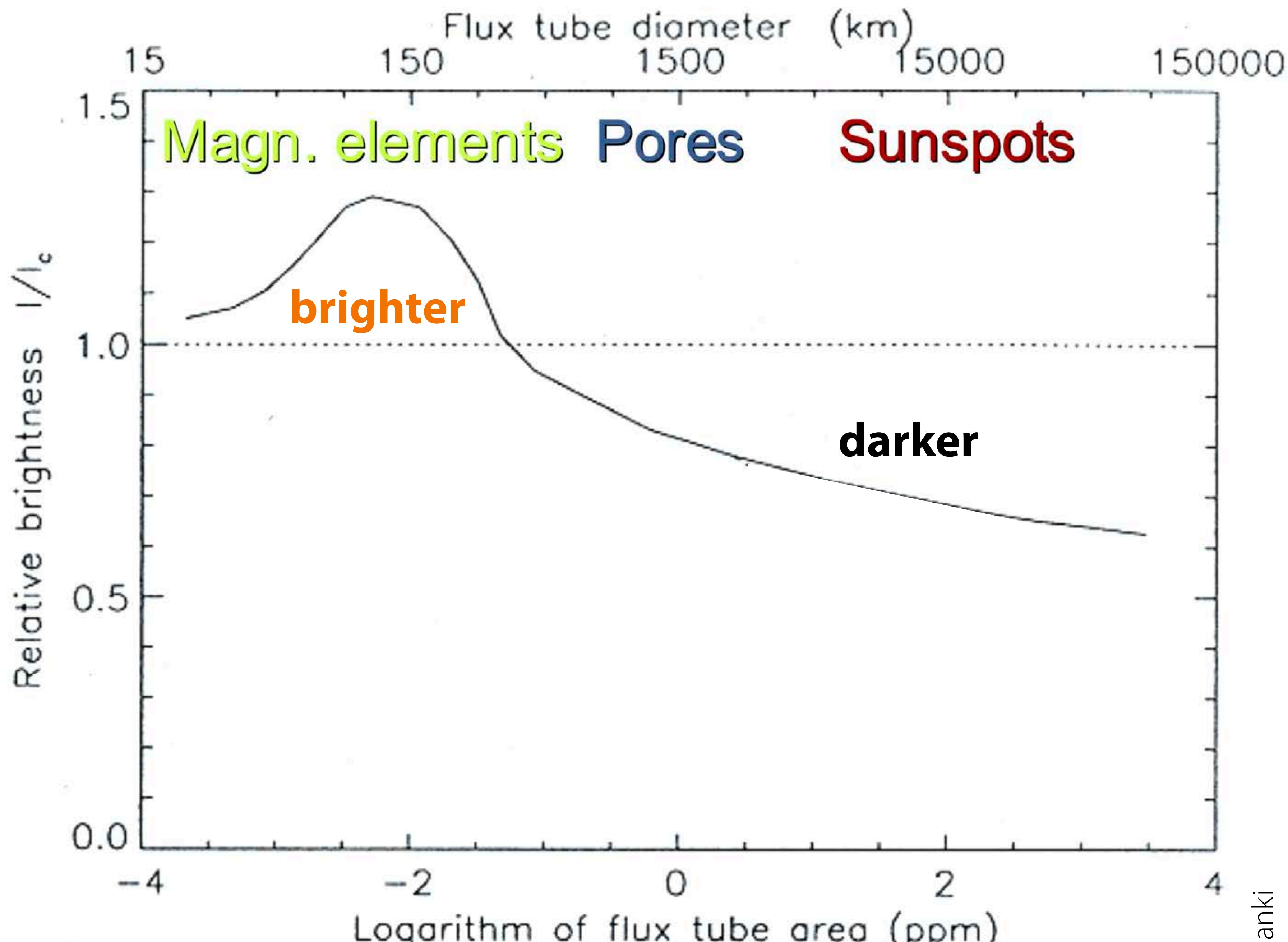


Solanki

Magnetic field in the solar atmosphere

Magnetic field as function of spatial scale

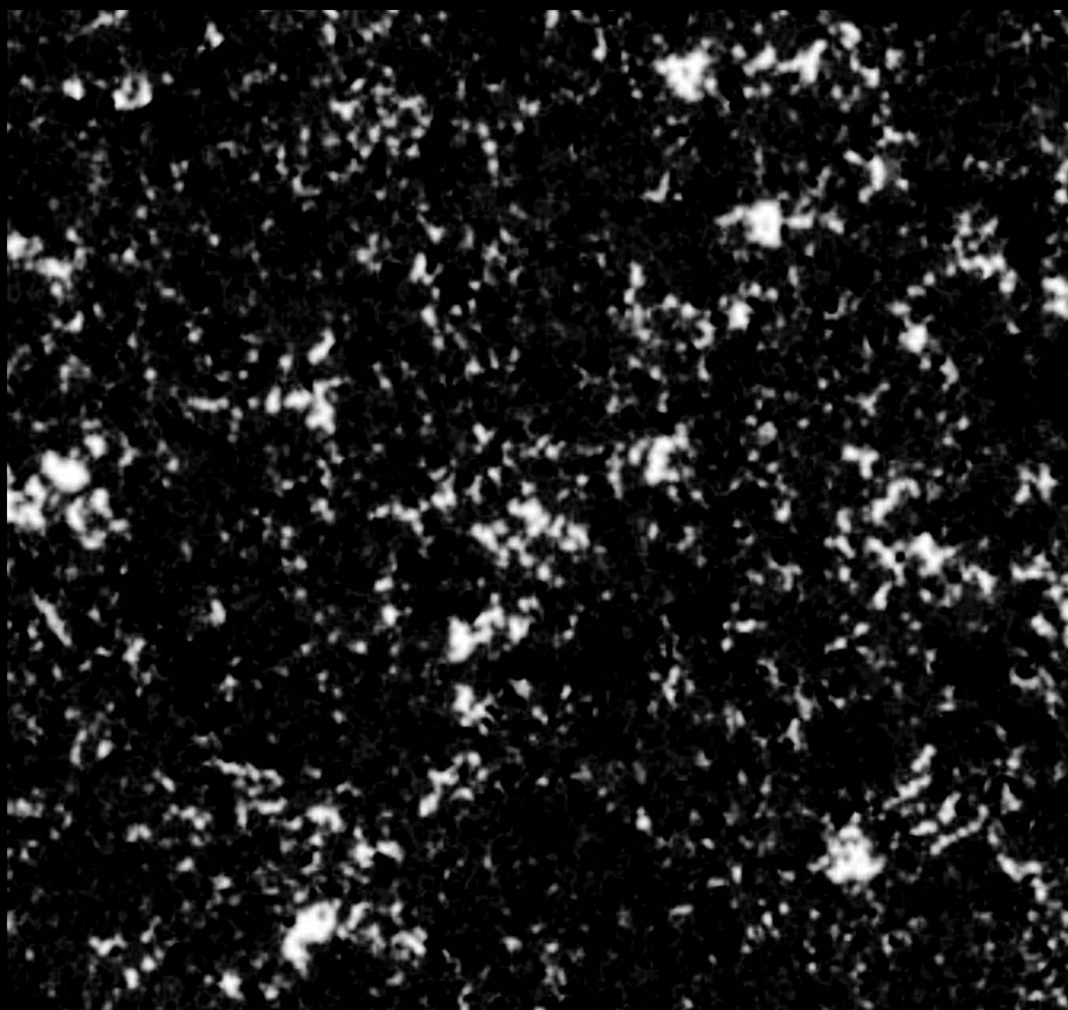
- Observable consequences strongly depend on area covered by magnetic field structure
  - Large: darker than surrounding
  - Small: brighter (!) than surrounding
- Remember: Sunspots — strong magnetic fields impede convective heat transport from below, resulting in lower temperature
- **What about small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



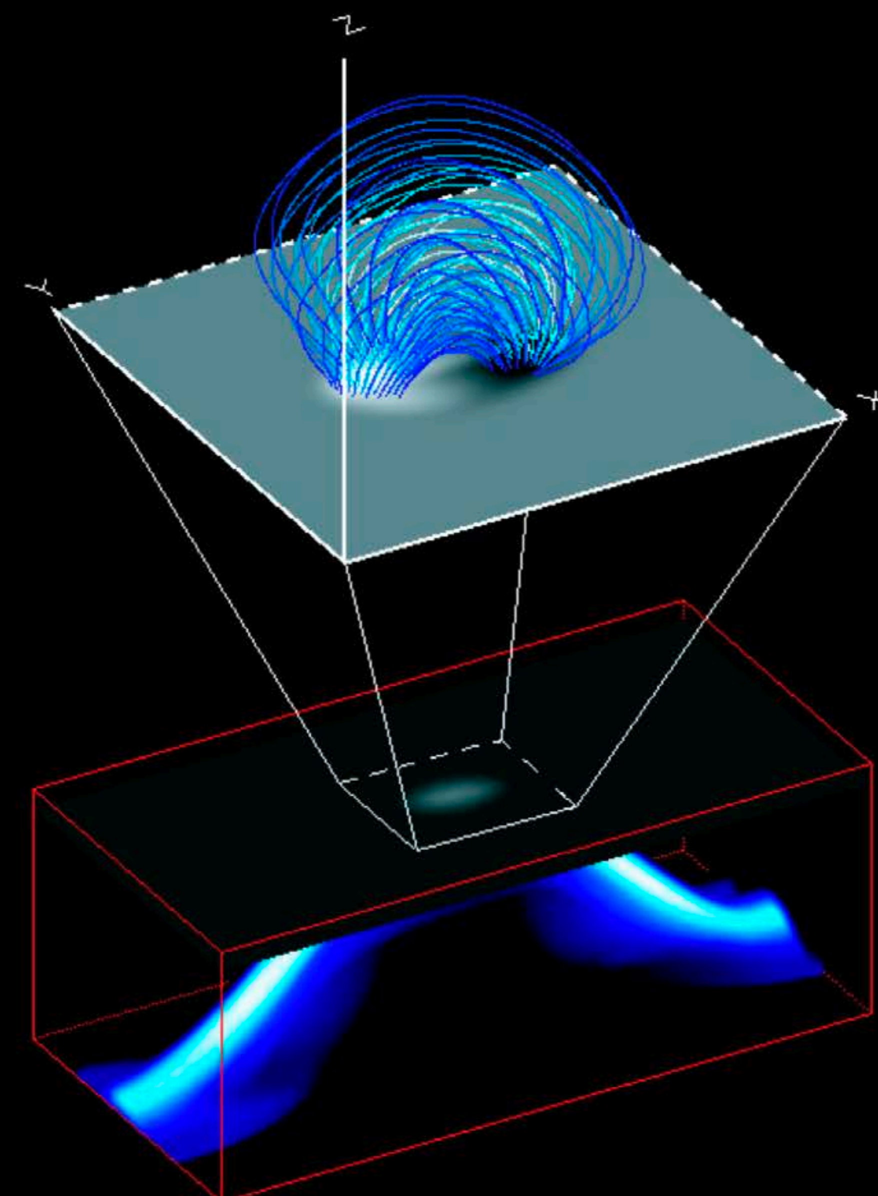
Solanki

Magnetic field in the solar atmosphere

Photospheric magnetic field in Quiet Sun regions



Parnell et al (2009)



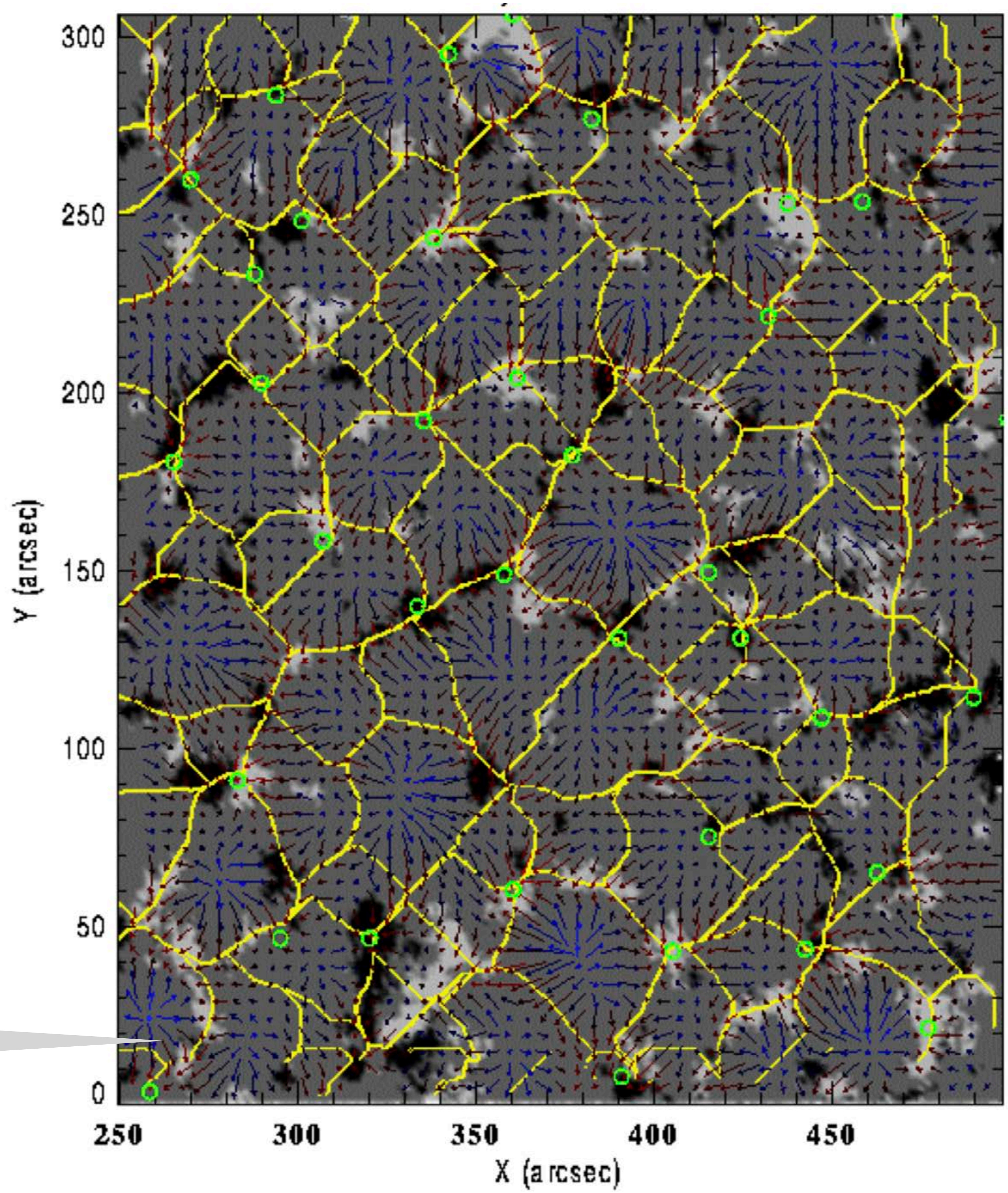
Abbett & Fisher (2003)

- **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

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**

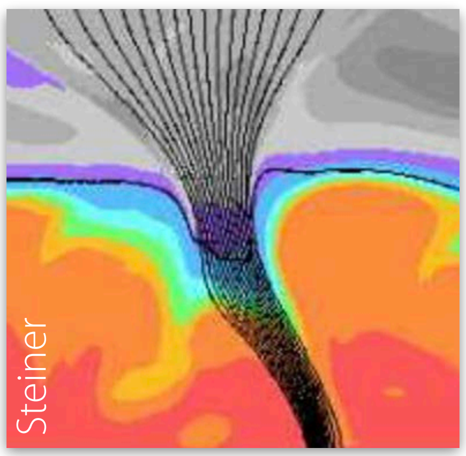


- Magnetogram (grayscale)
- Horizontal flow field (arrows)
- Supergranule boundaries: yellow

Magnetic field in the solar atmosphere

Advection — magnetic field on granulation scales

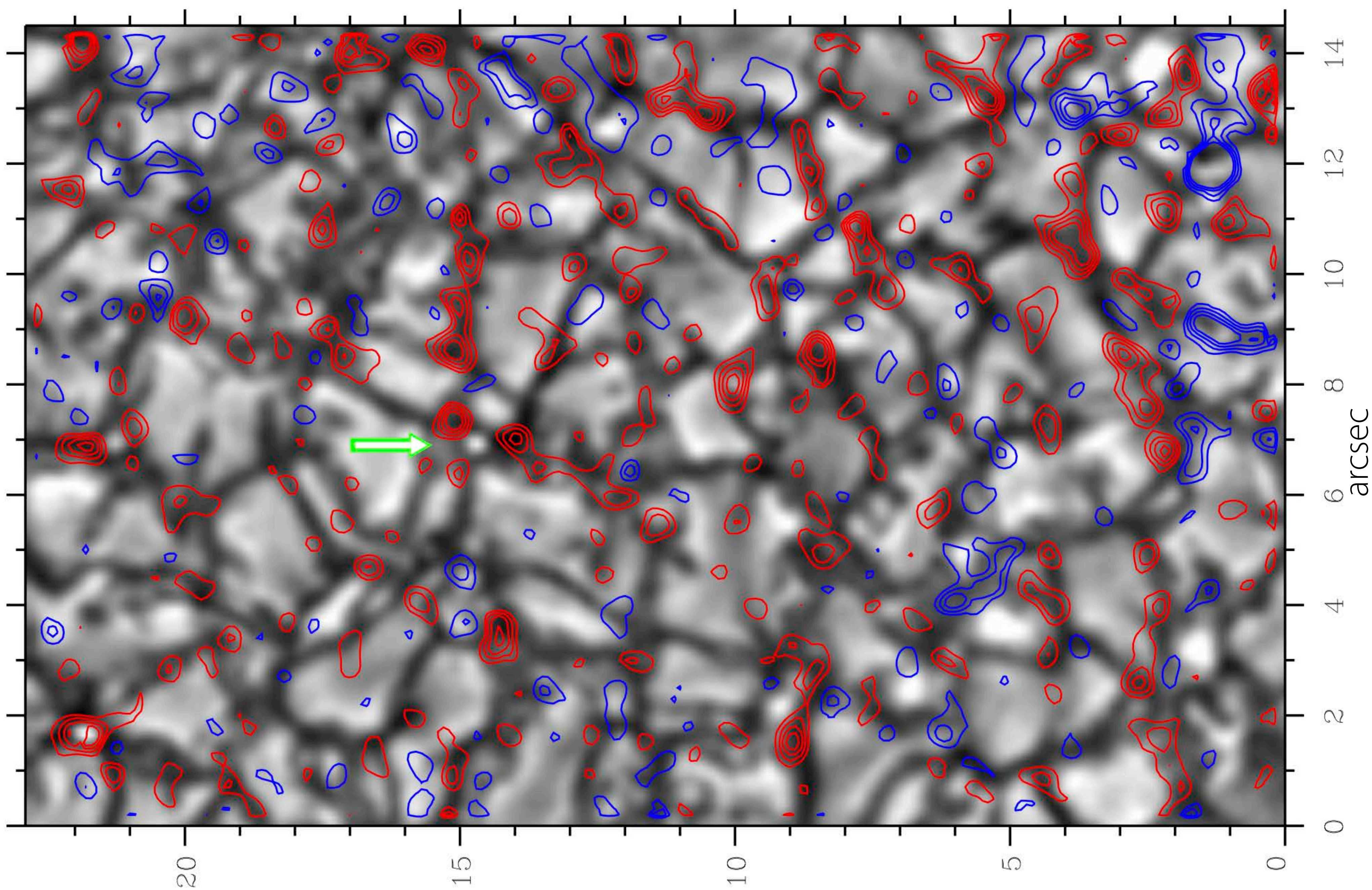
- Advection into intergranular lanes (downflow lanes between granules)
- Concentration into stronger flux concentrations but fewer than in the network



Granulation image, Fe I 630.25 nm line

Overlaid magnetogram contours 30, 50, 70 and 90 G

(Domınguez Cerdena et al., 2003)



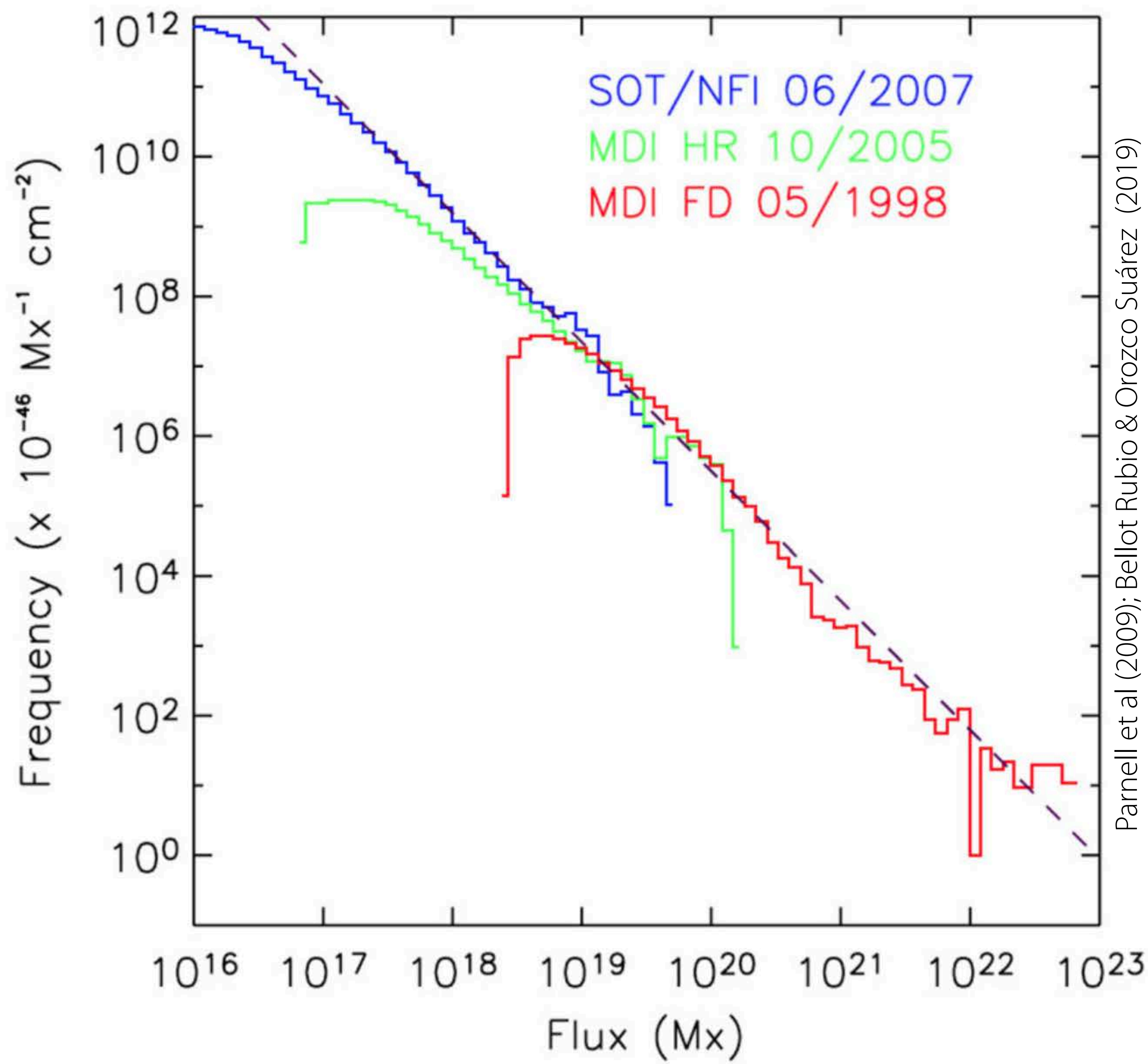
Magnetic field in the solar atmosphere

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?



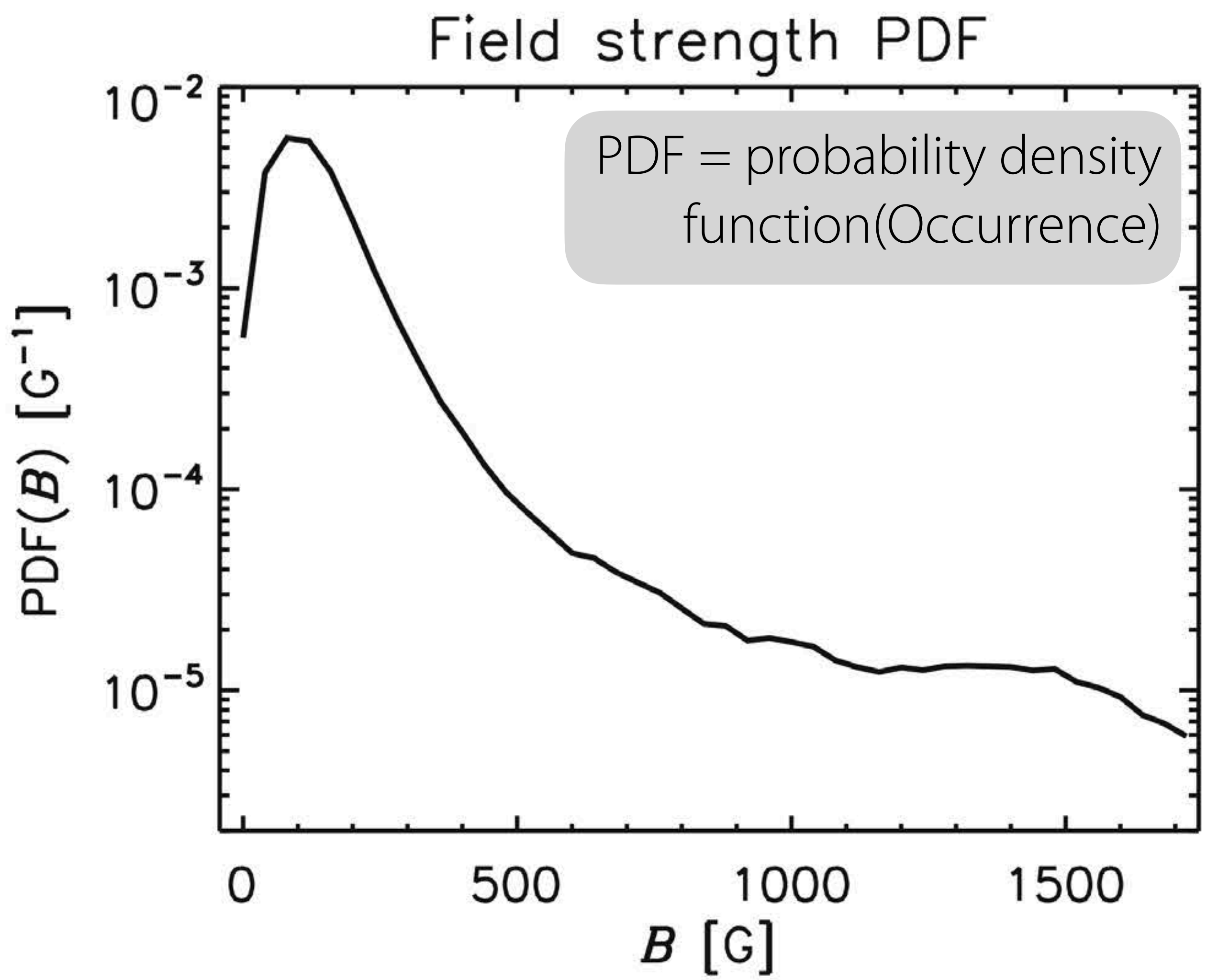
Parnell et al (2009); Bellot Rubio & Orozco Suárez (2019)

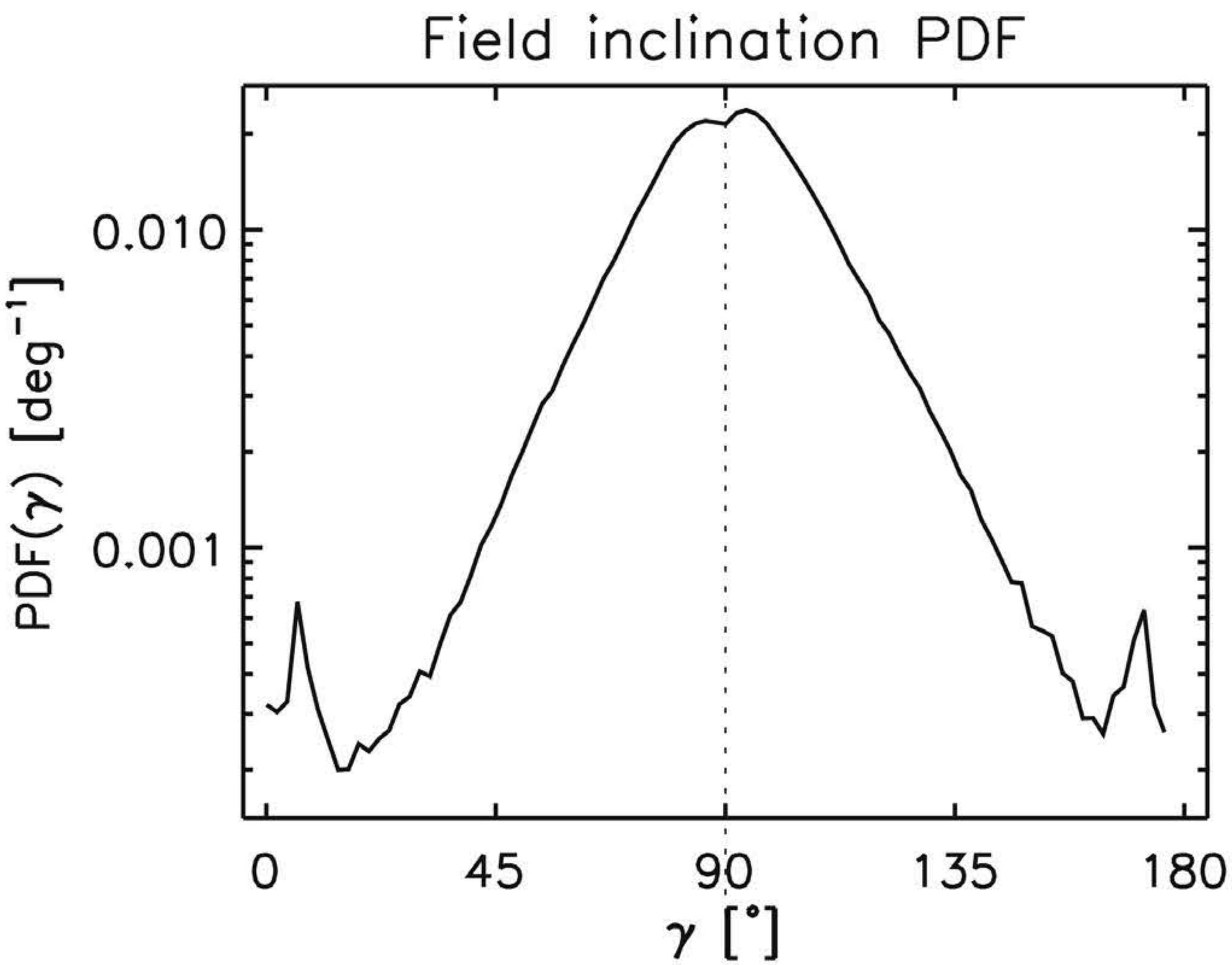
Magnetic flux Φ
(Flux = per area!)
cgs unit: Maxwell (Mx)
1 Mx = 1 G cm^{-2}

Longitudinal = component parallel (along) magnetic field vector

Magnetic field in the solar atmosphere

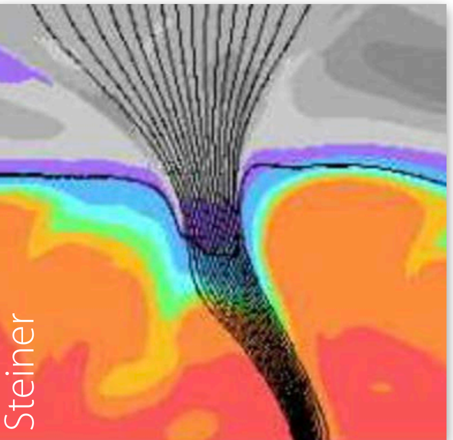
Photospheric magnetic field in internetwork regions





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

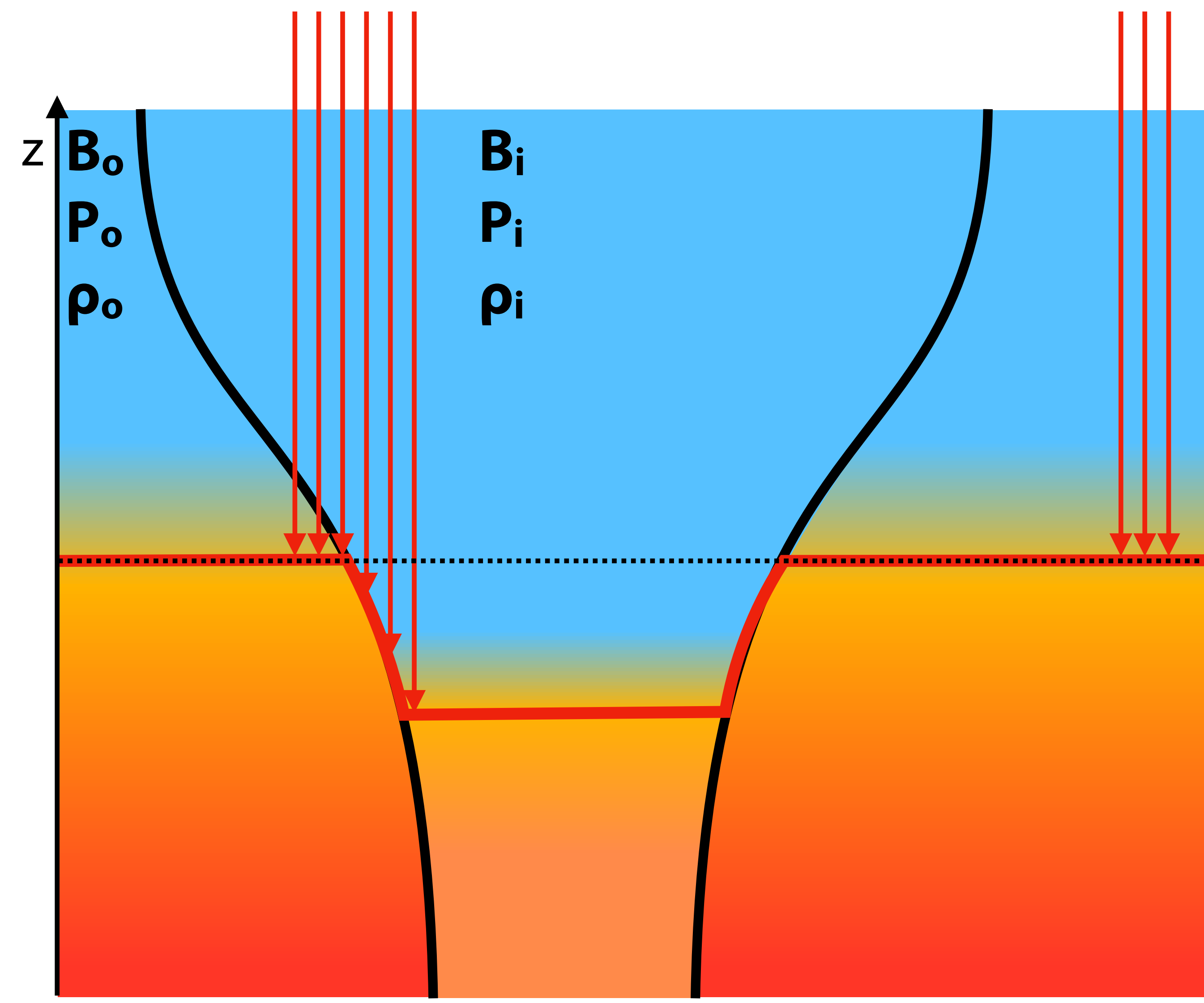
- Remember: Magnetic pressure counterbalances thermal (gas) pressure
- $B_i >> B_o$

➡ 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



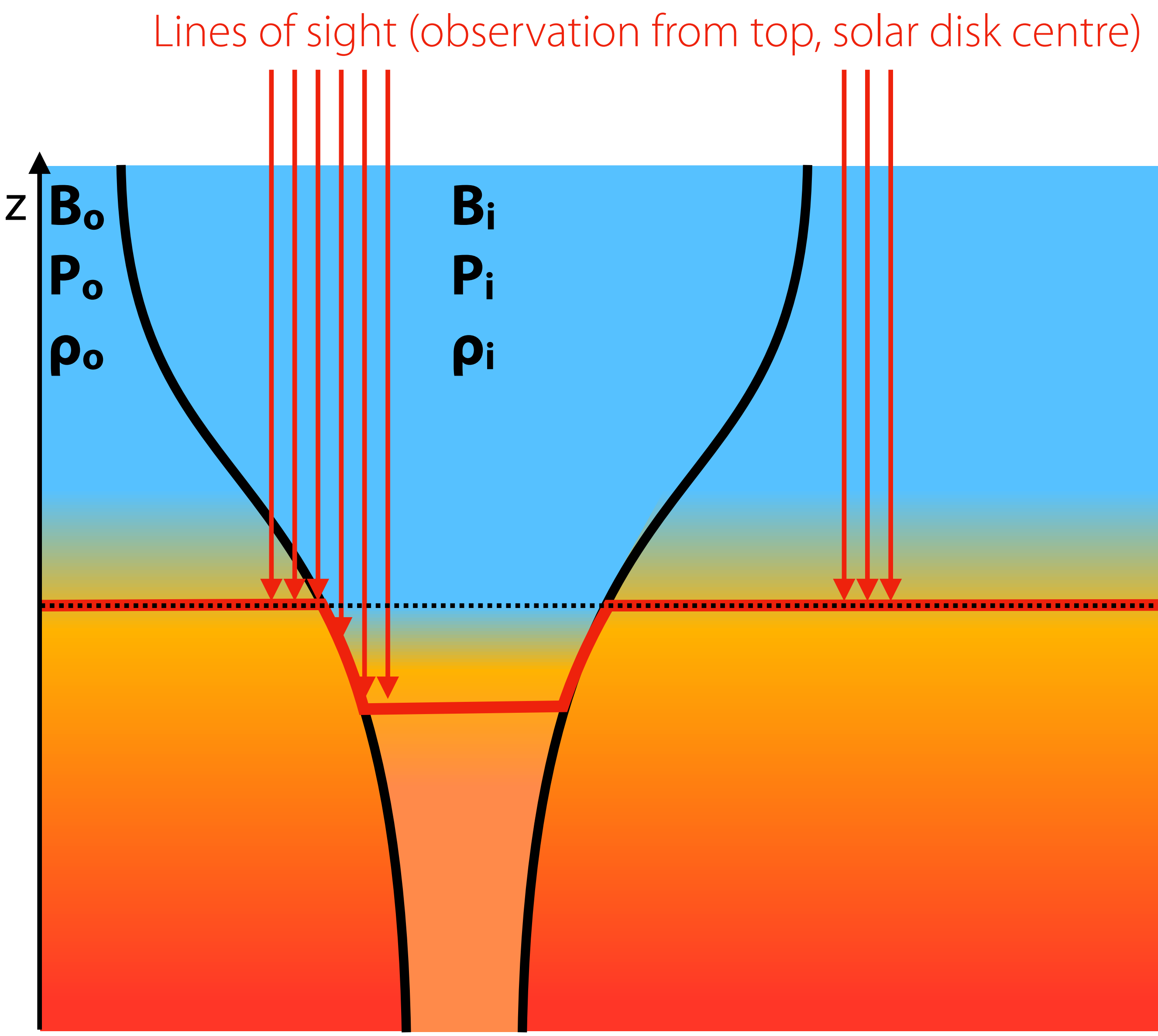
➡ **Optical depth lower** inside magnetic field structure than outside

➡ 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!

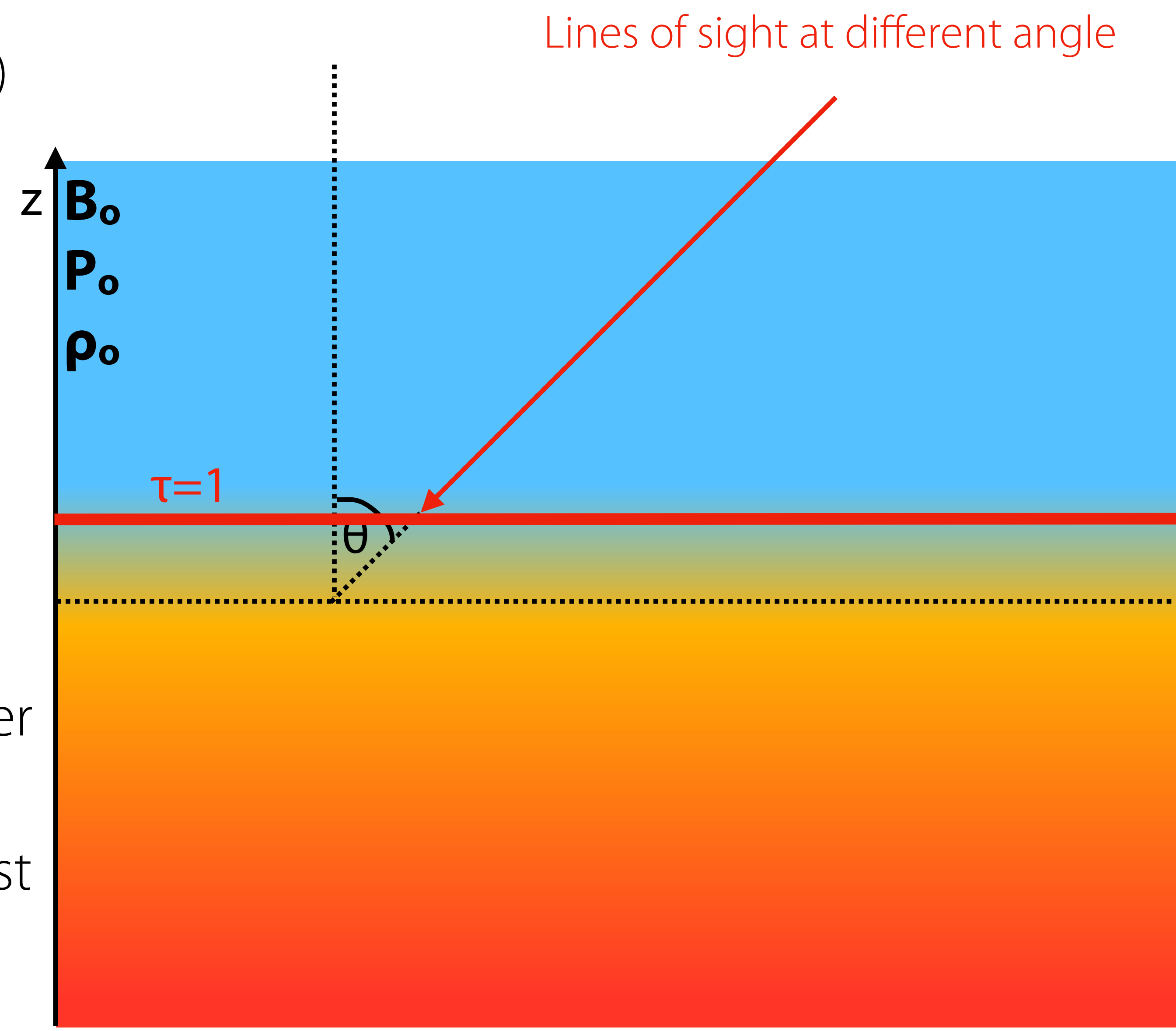


Radiative transfer effects

- 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**

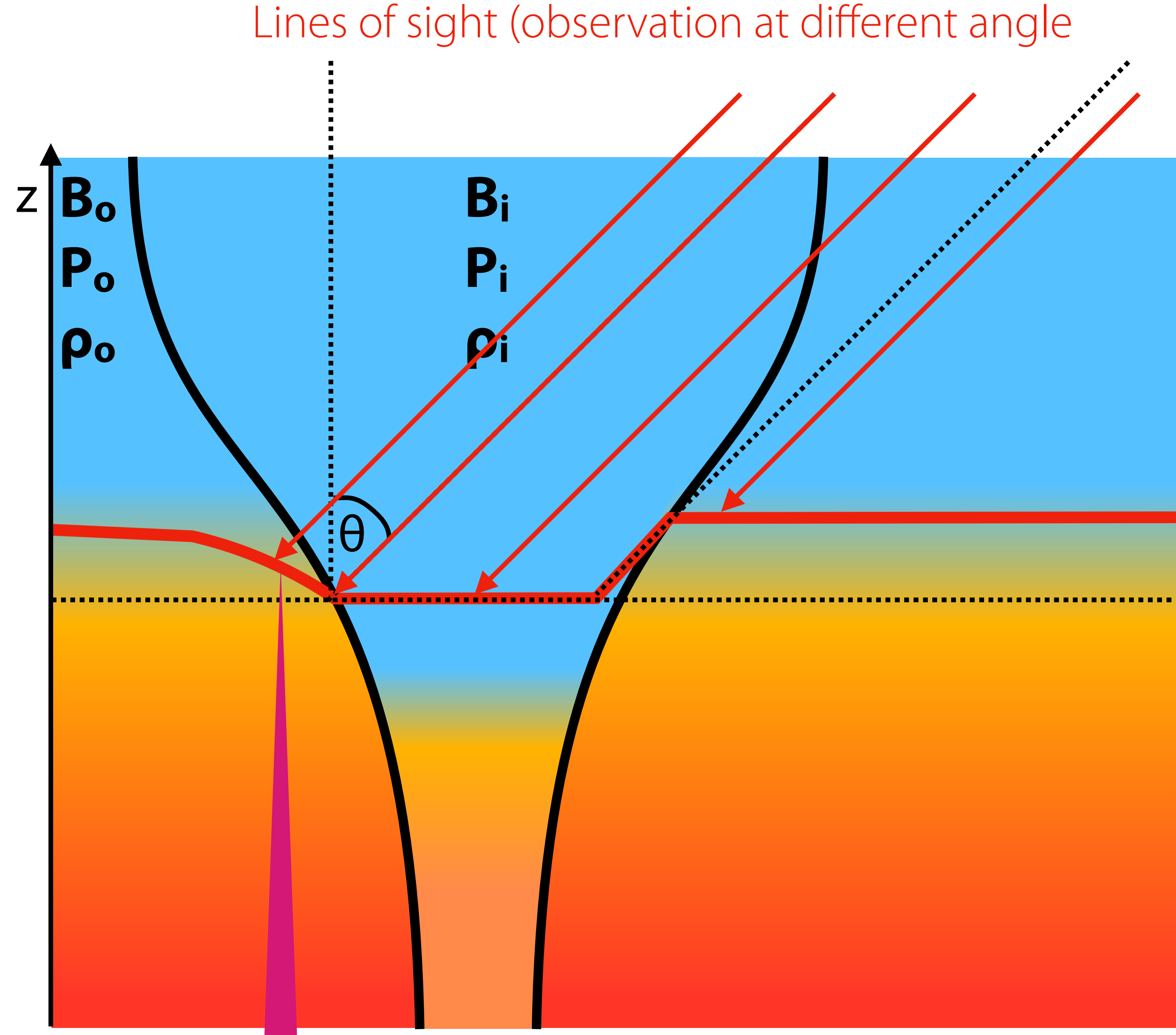
Radiative transfer effects

- 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 appears to be brighter on one side!

Radiative transfer effects

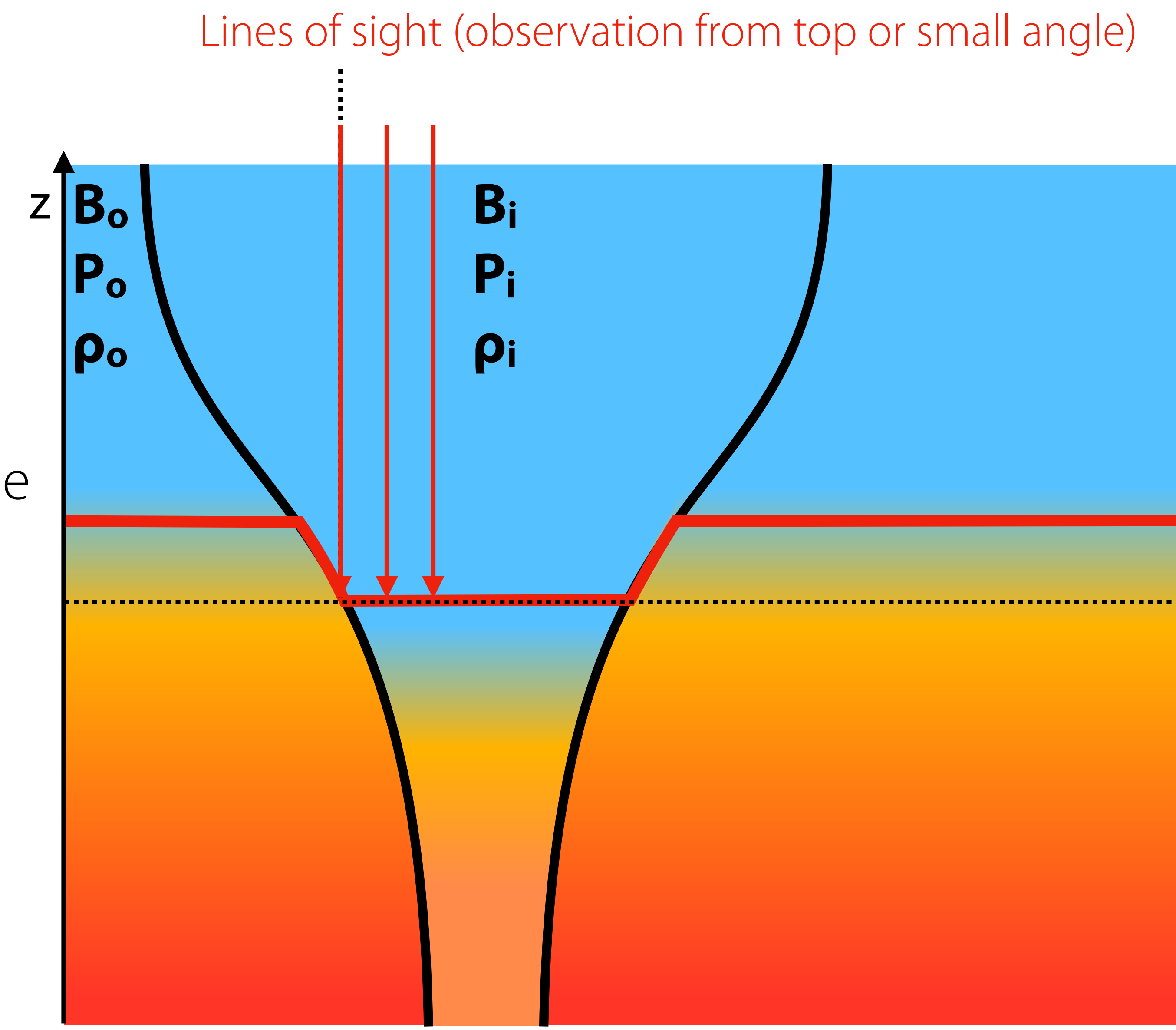
- View from top $\theta = 0$

➡ “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

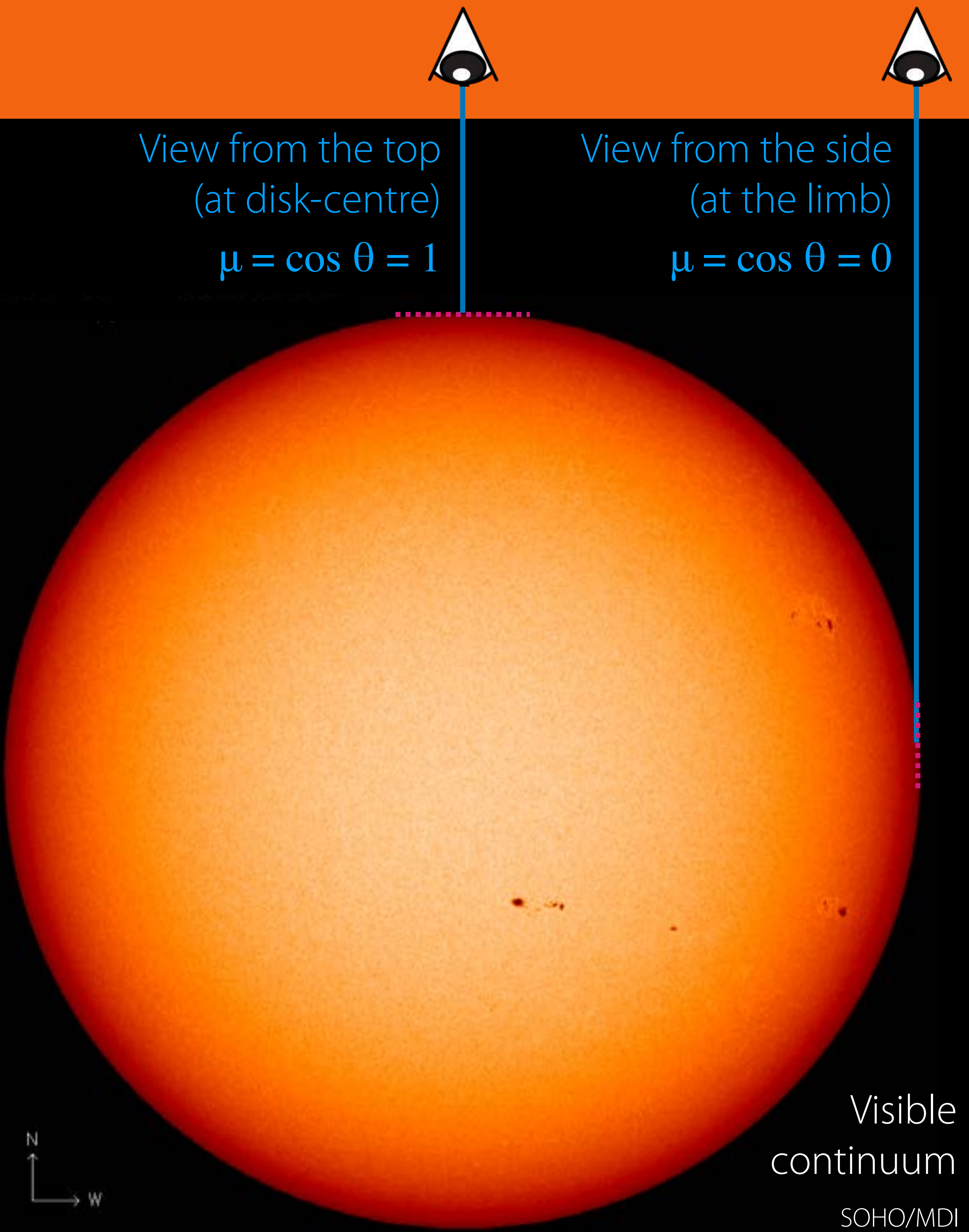
Limb darkening

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

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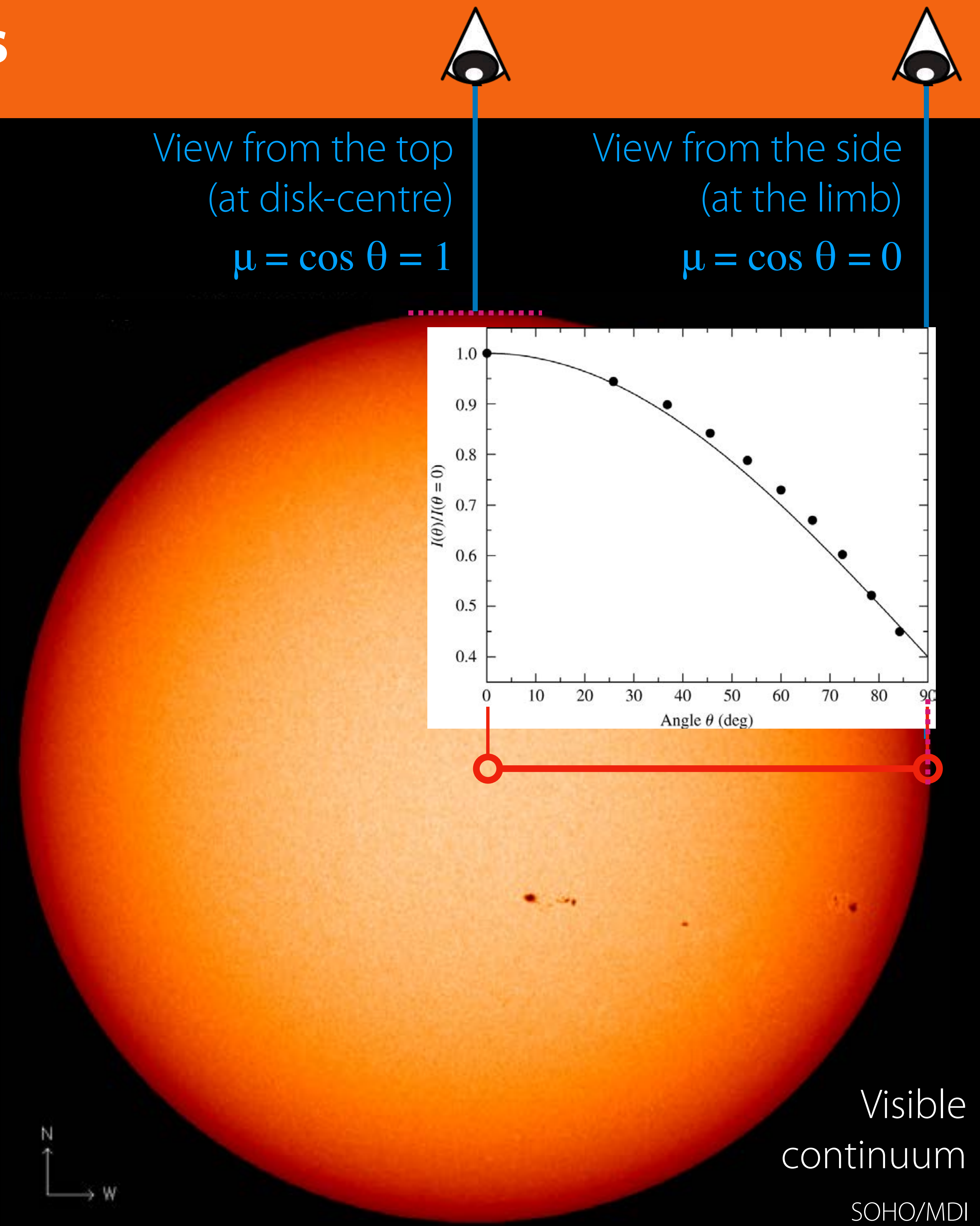


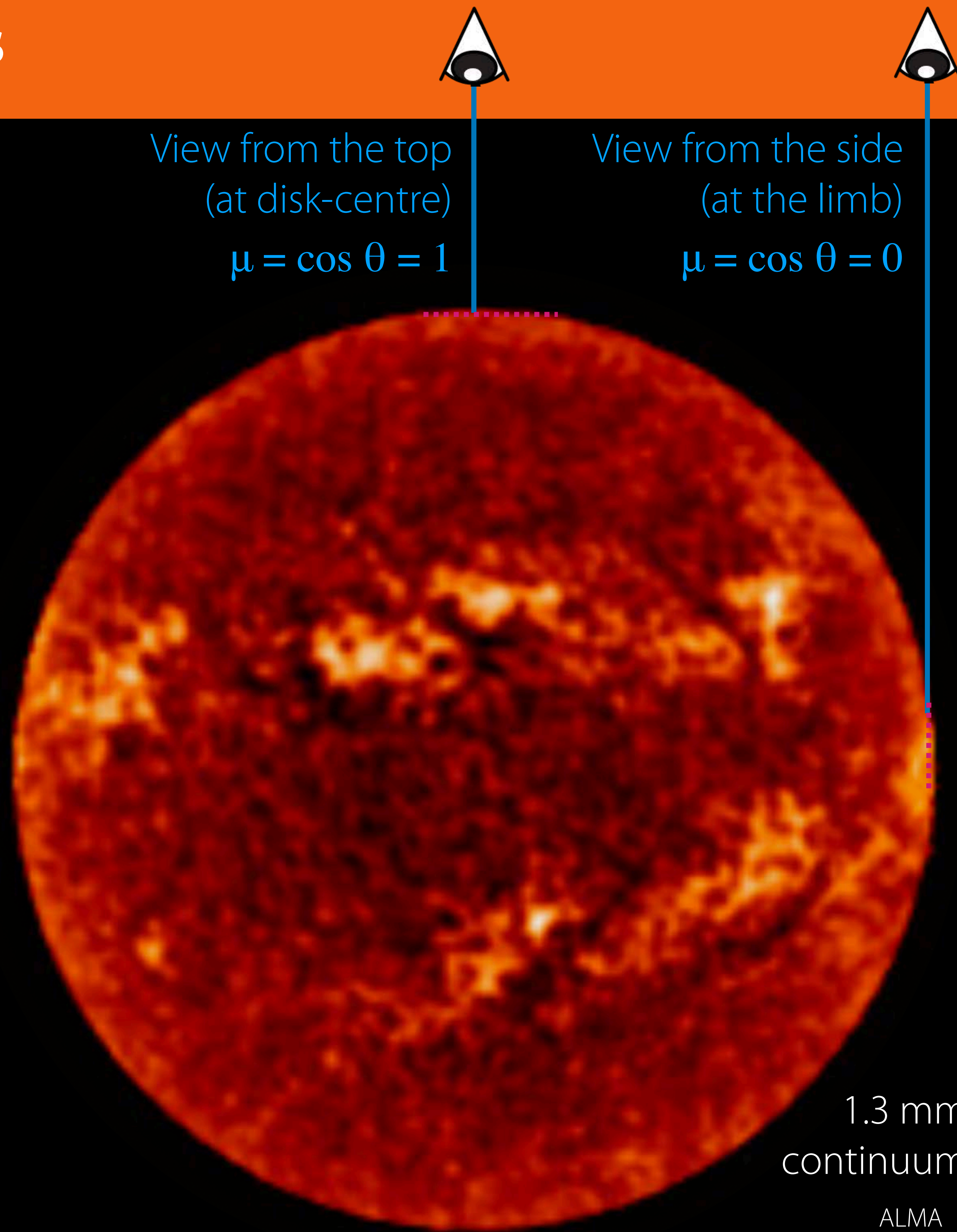
Radiative transfer effects

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

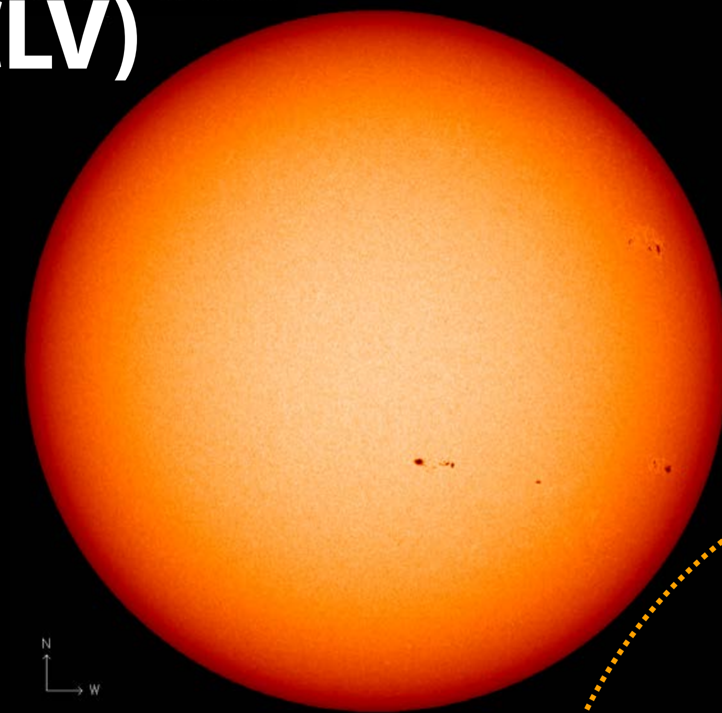
➡ Temperature **increases** with height for the height range mapped by this continuum range!

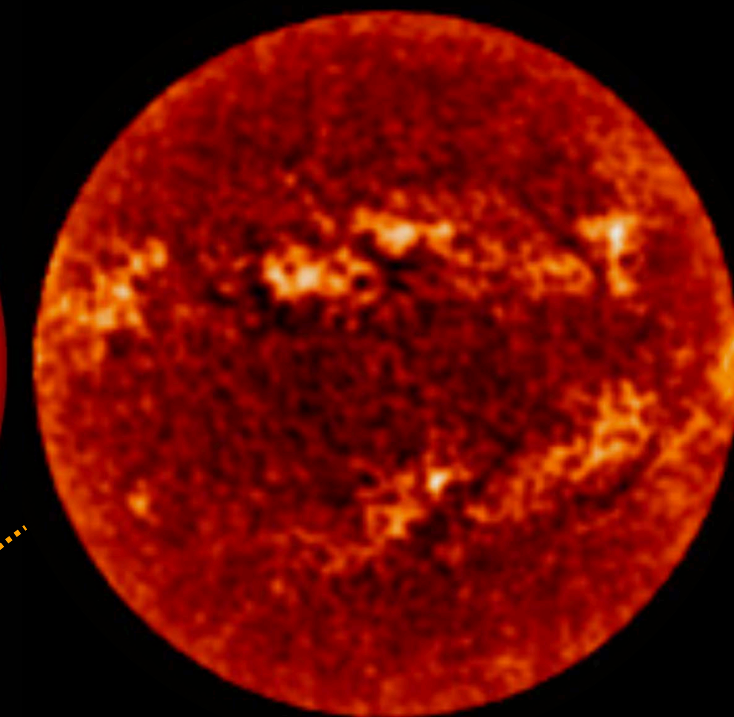
- Note: Optical depth unity reached in the chromosphere, i.e. much higher than the visible continuum



Radiative transfer effects

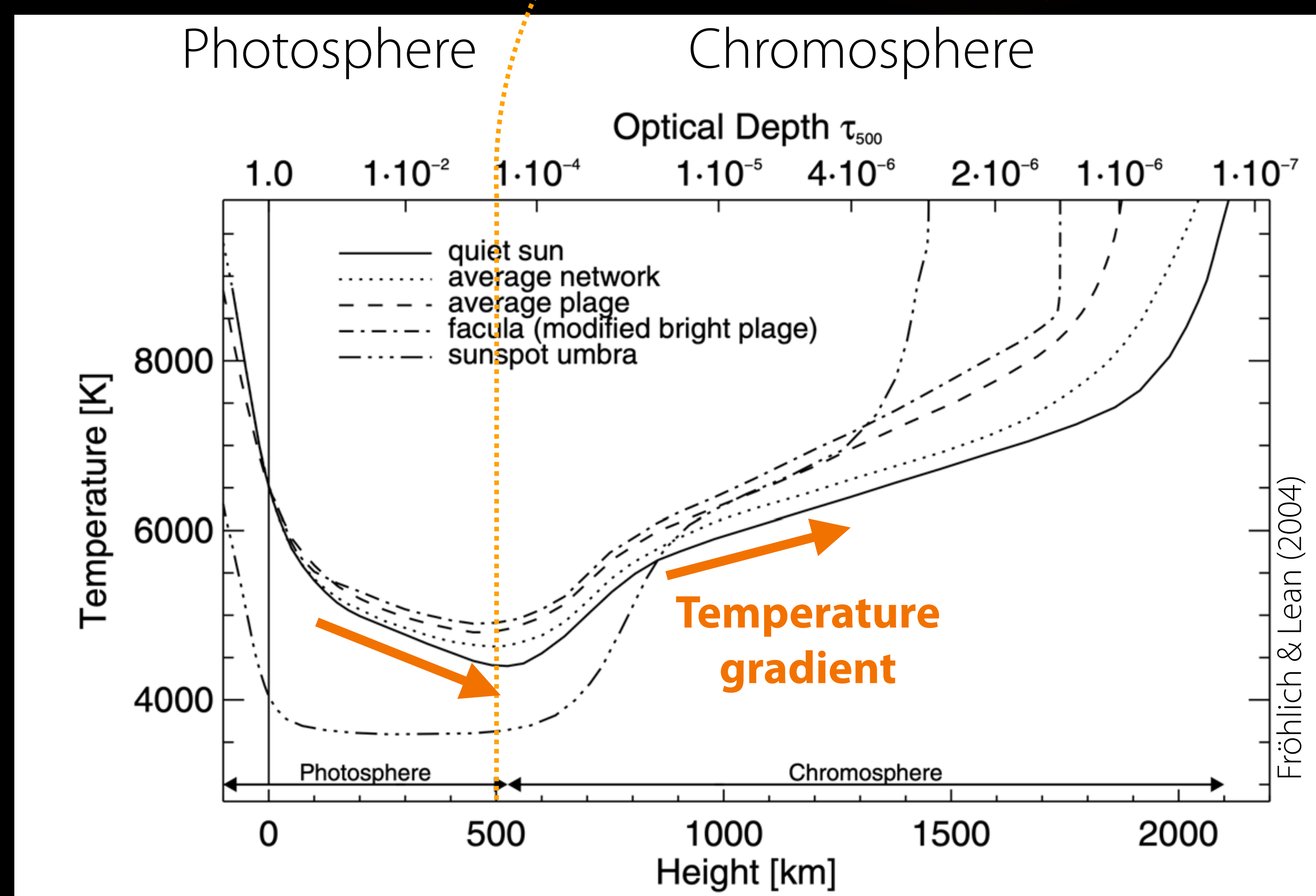
Centre-to-limb variation (CLV)





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

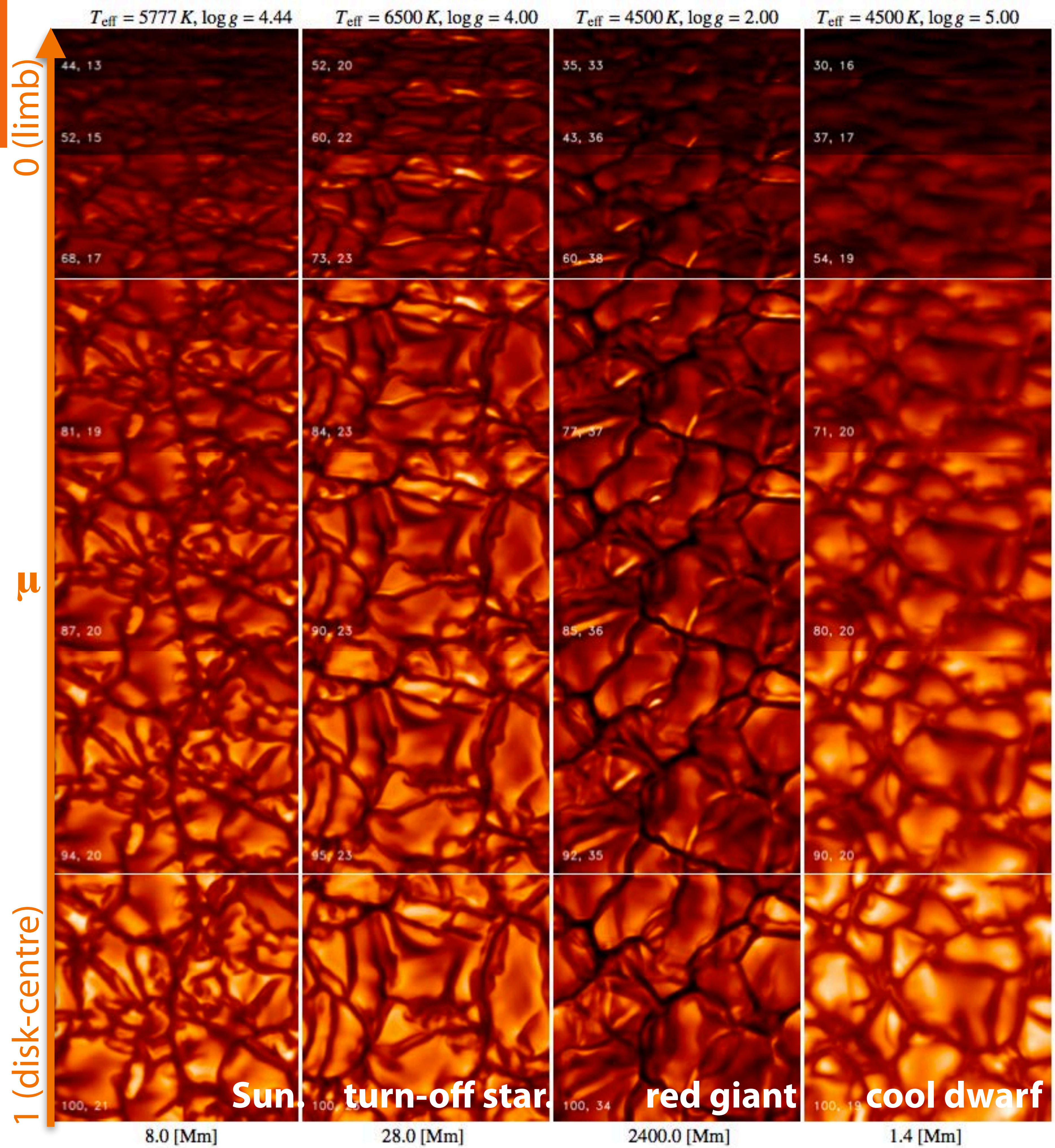
- CLV measured from observations help to construct (1D) average atmosphere models
  (even for different types of region from Quiet Sun to sunspot umbra)



Radiative transfer effects

Centre-to-limb variation (CLV)

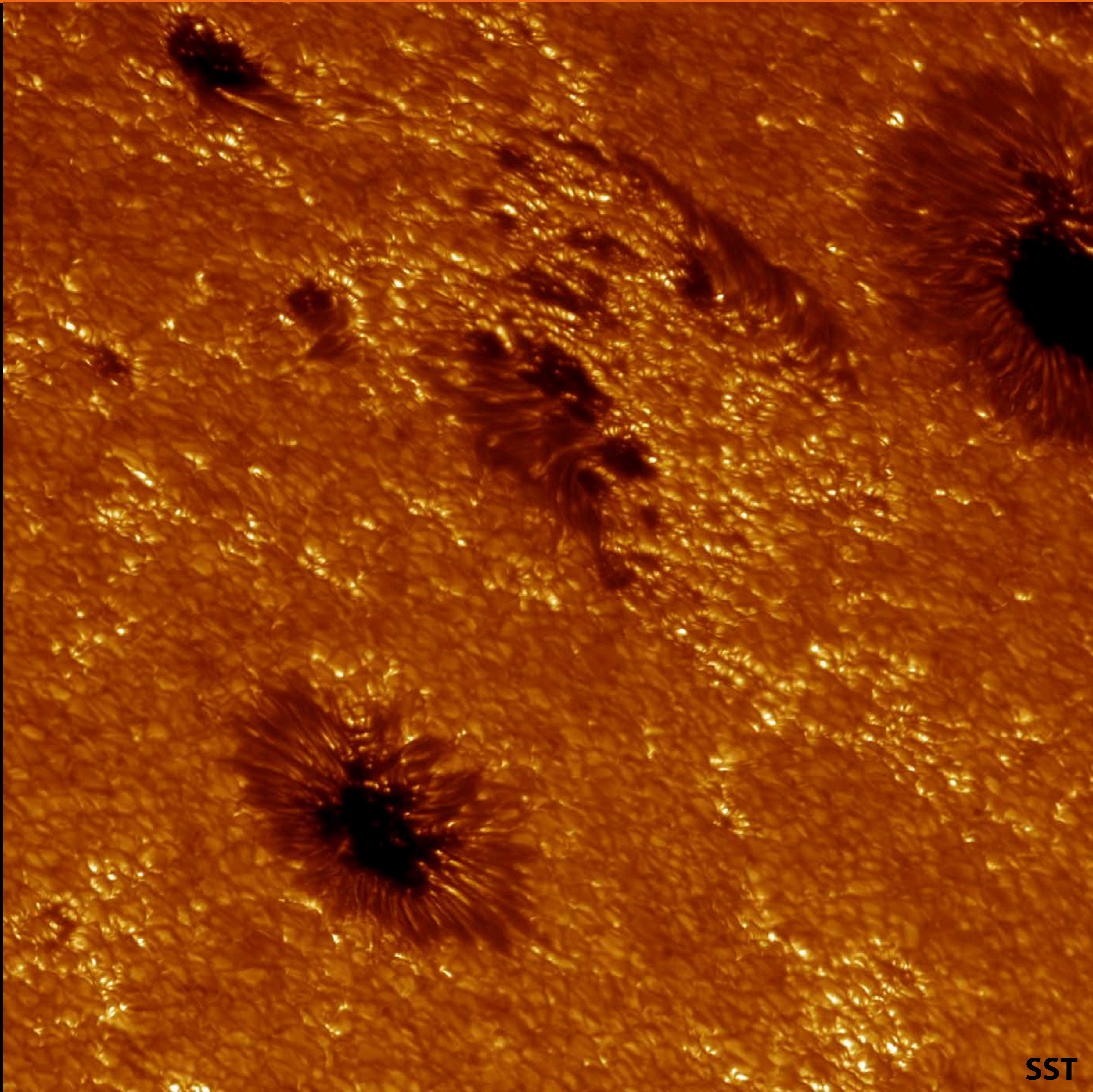
- 3D numerical simulations for different stellar types
- Intensity maps for as function of inclination angle μ from disk-center to limb (visible continuum).
- All show limb darkening.
- Observational imprint of photospheric temperature stratification!



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

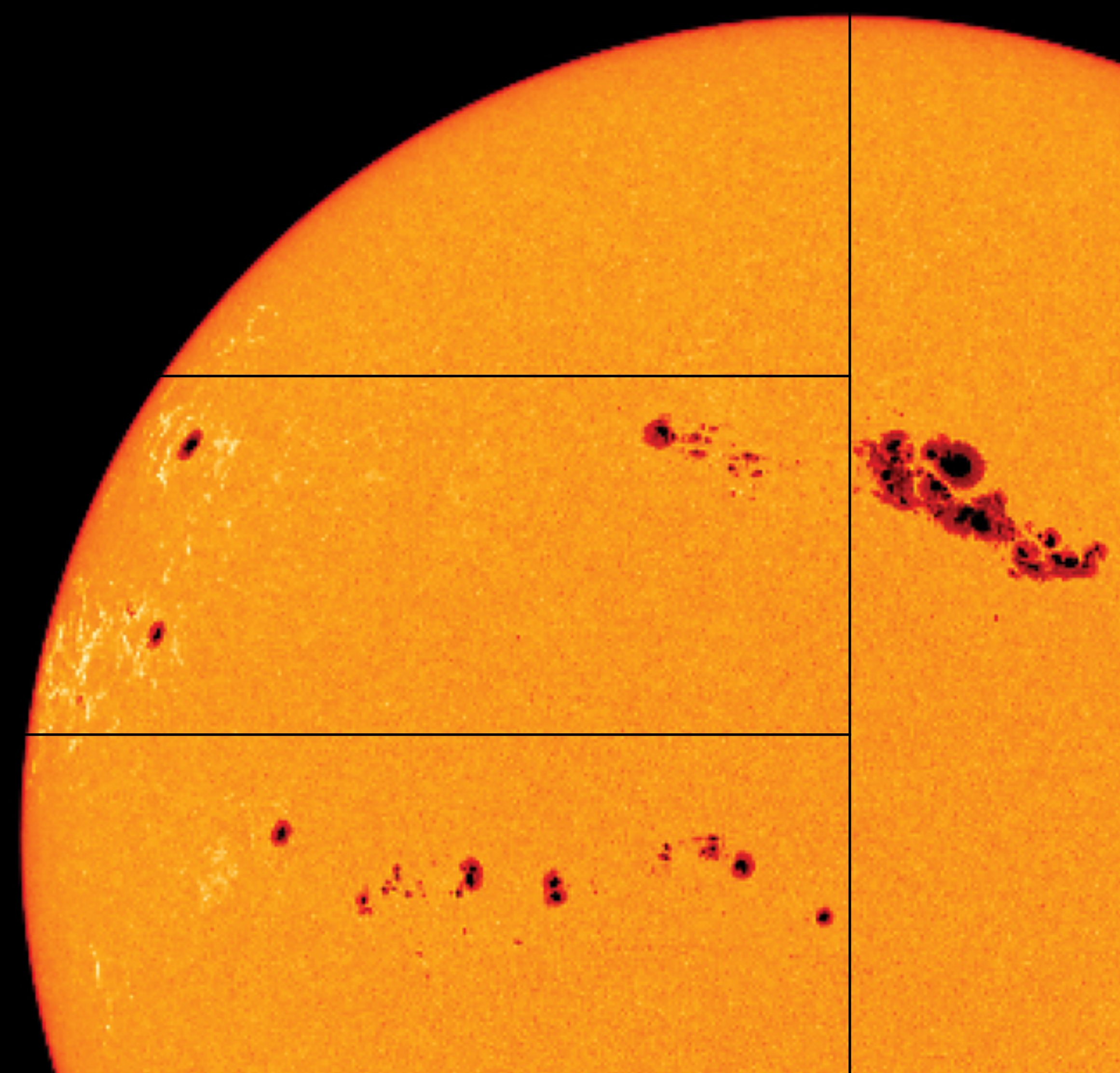


The solar atmosphere

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	

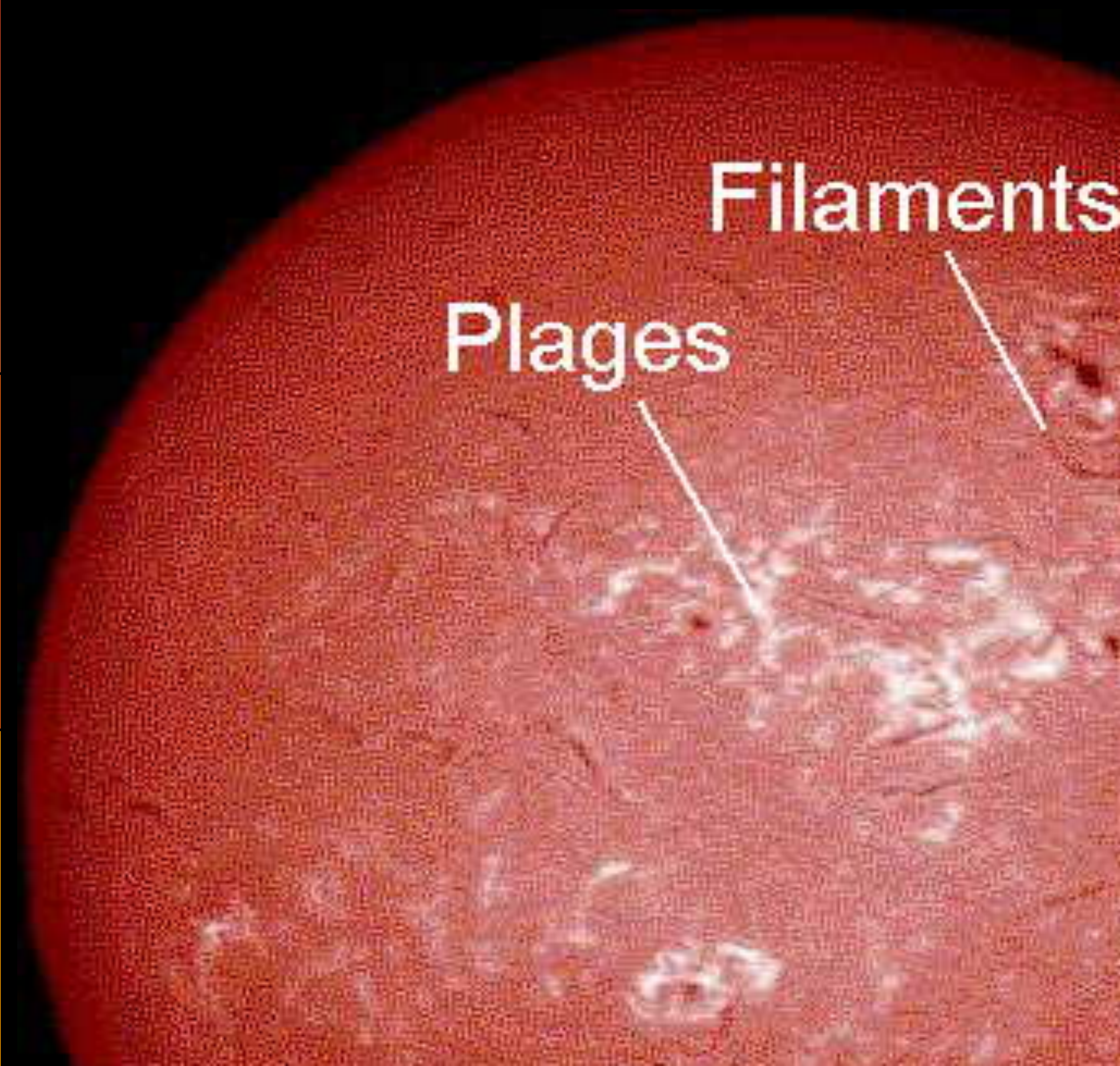


The solar atmosphere

Different regions — chromosphere

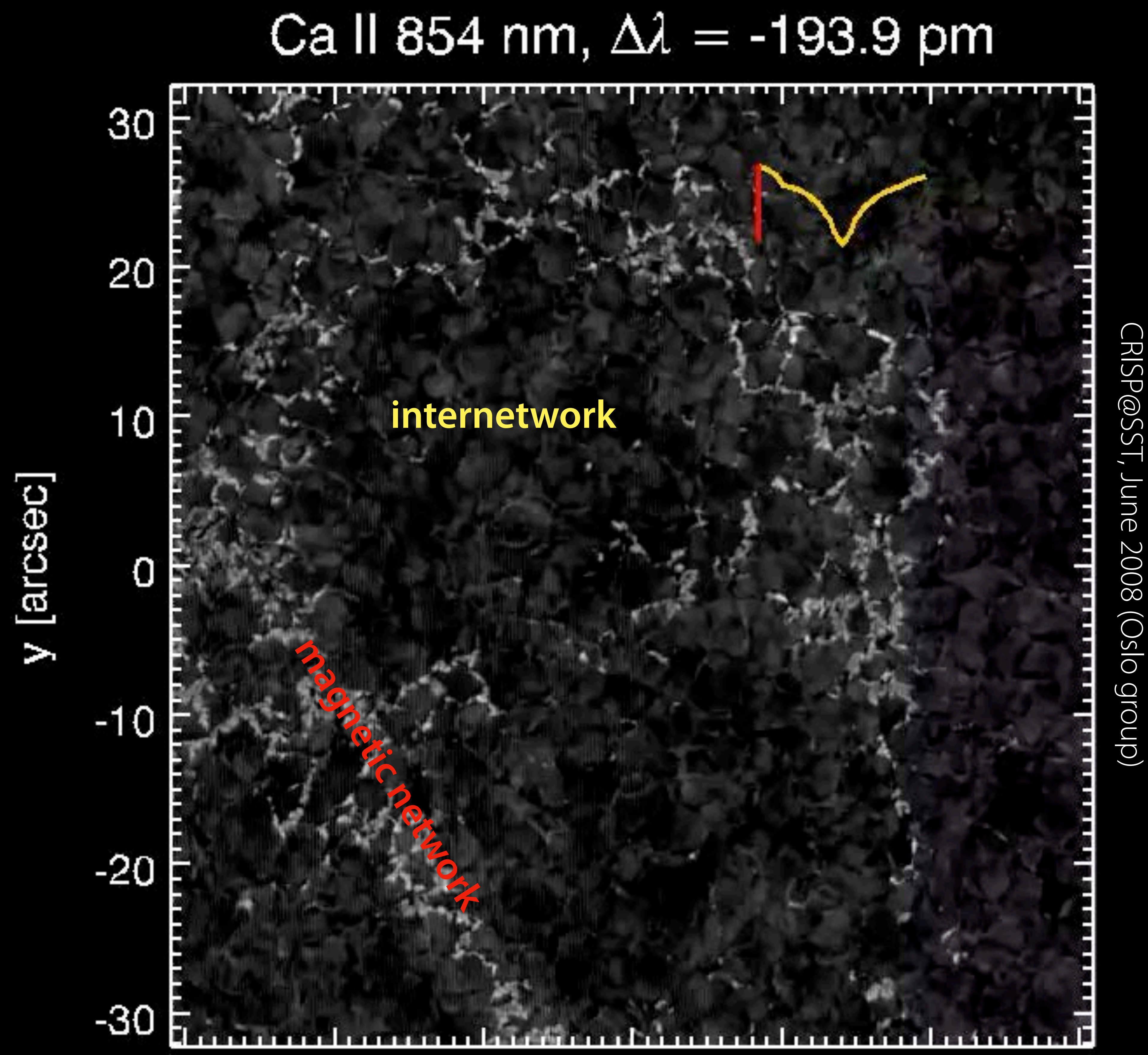
(Average) magnetic field strength

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	

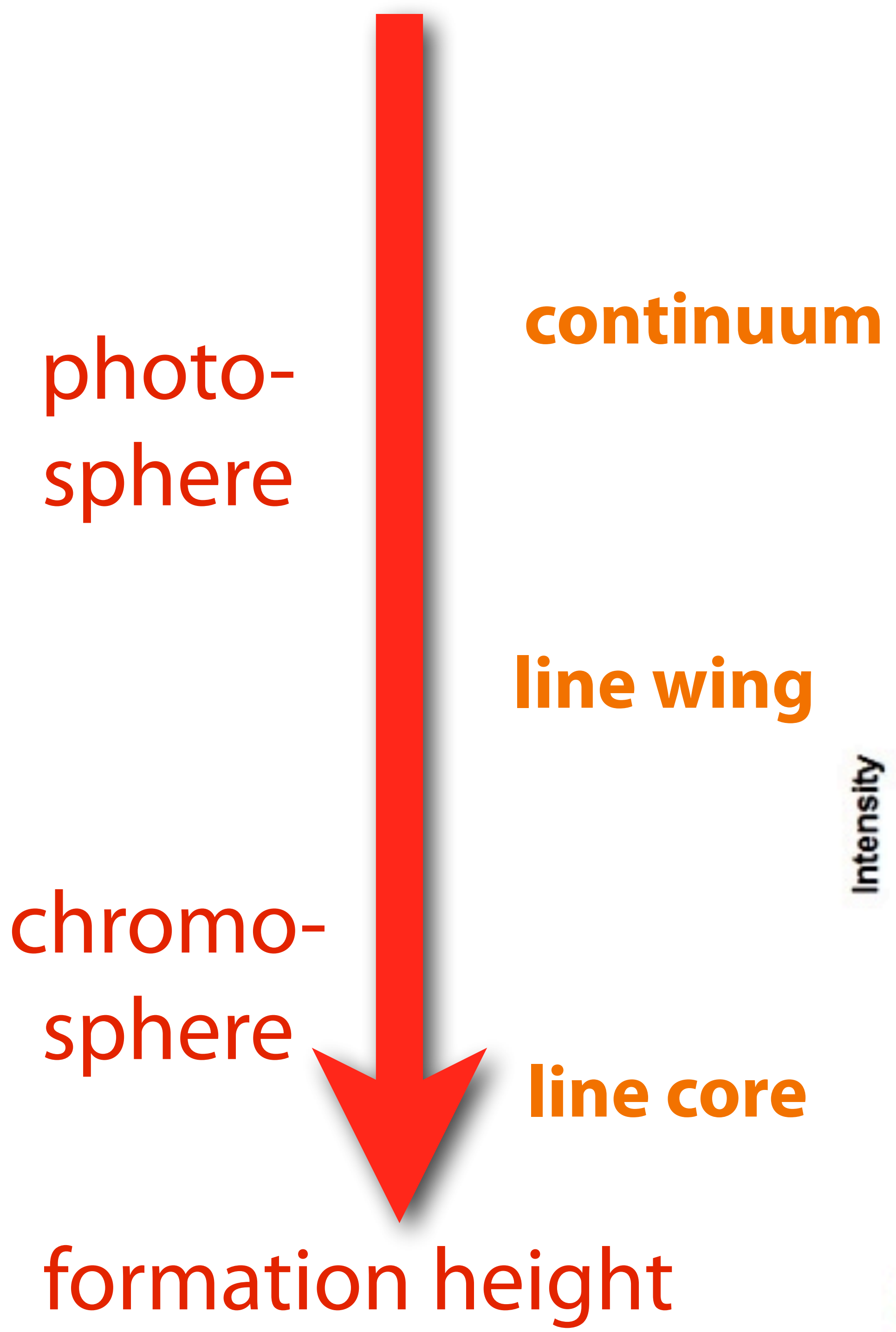


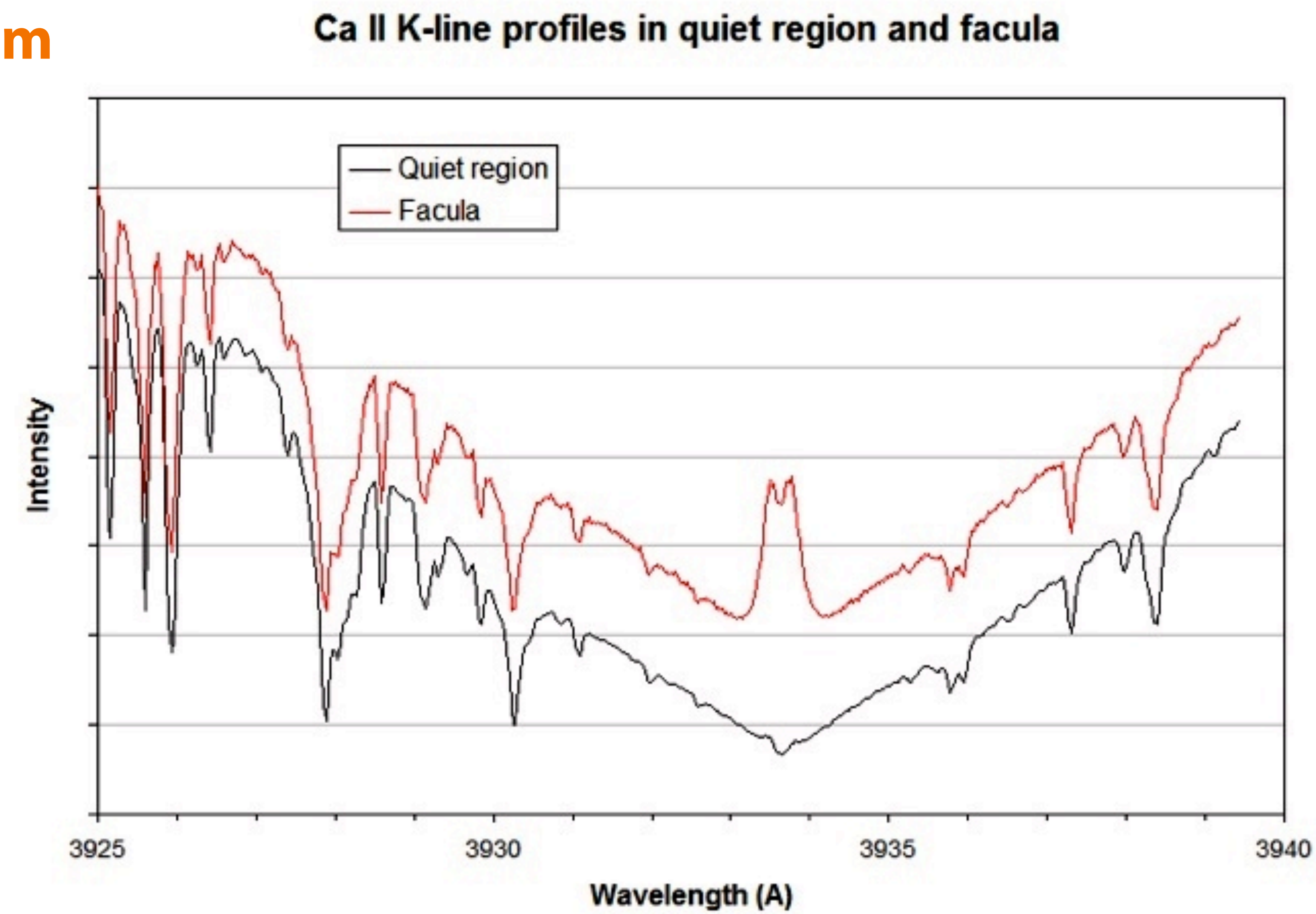
The solar atmosphere

- 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

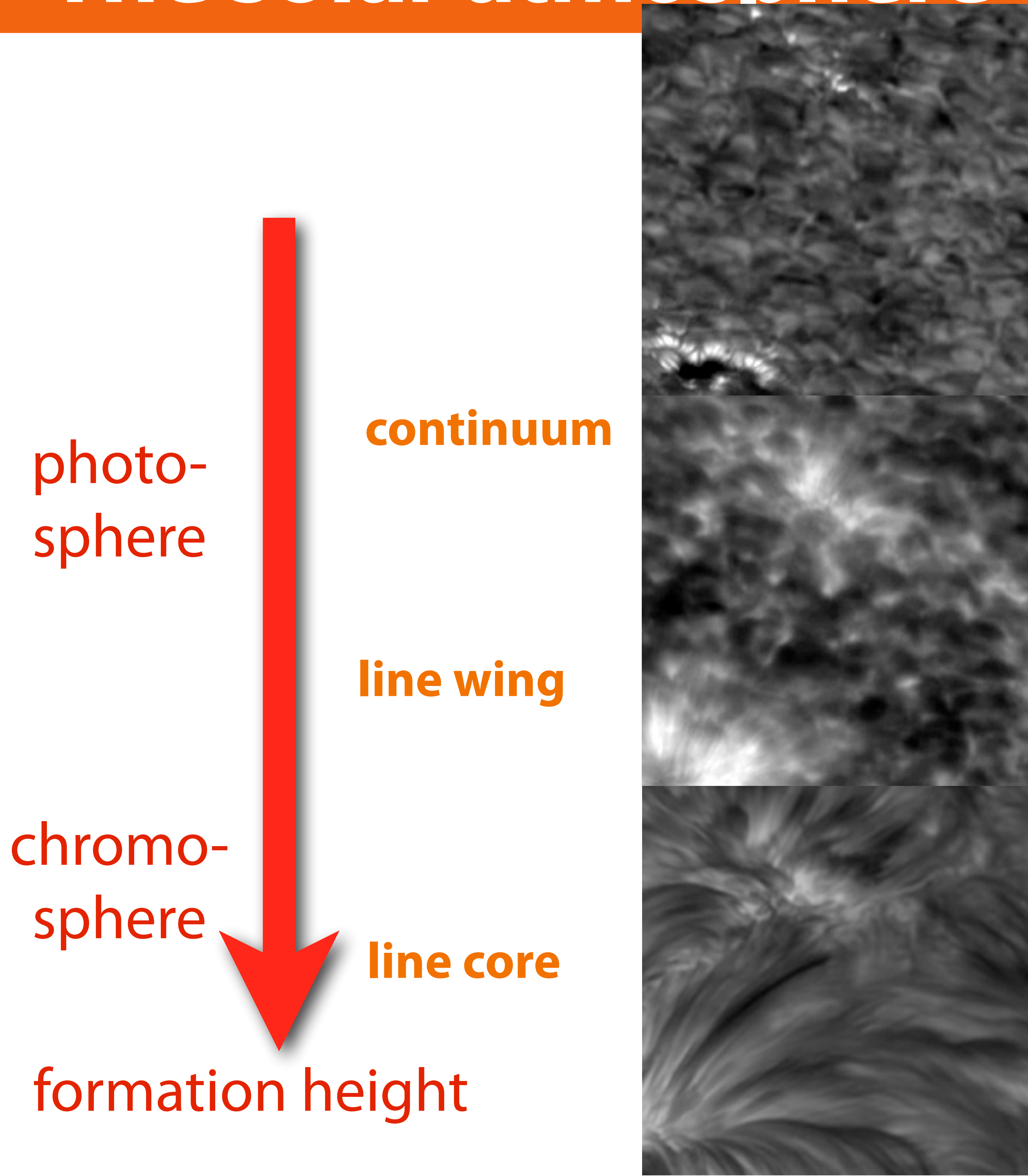


The solar atmosphere





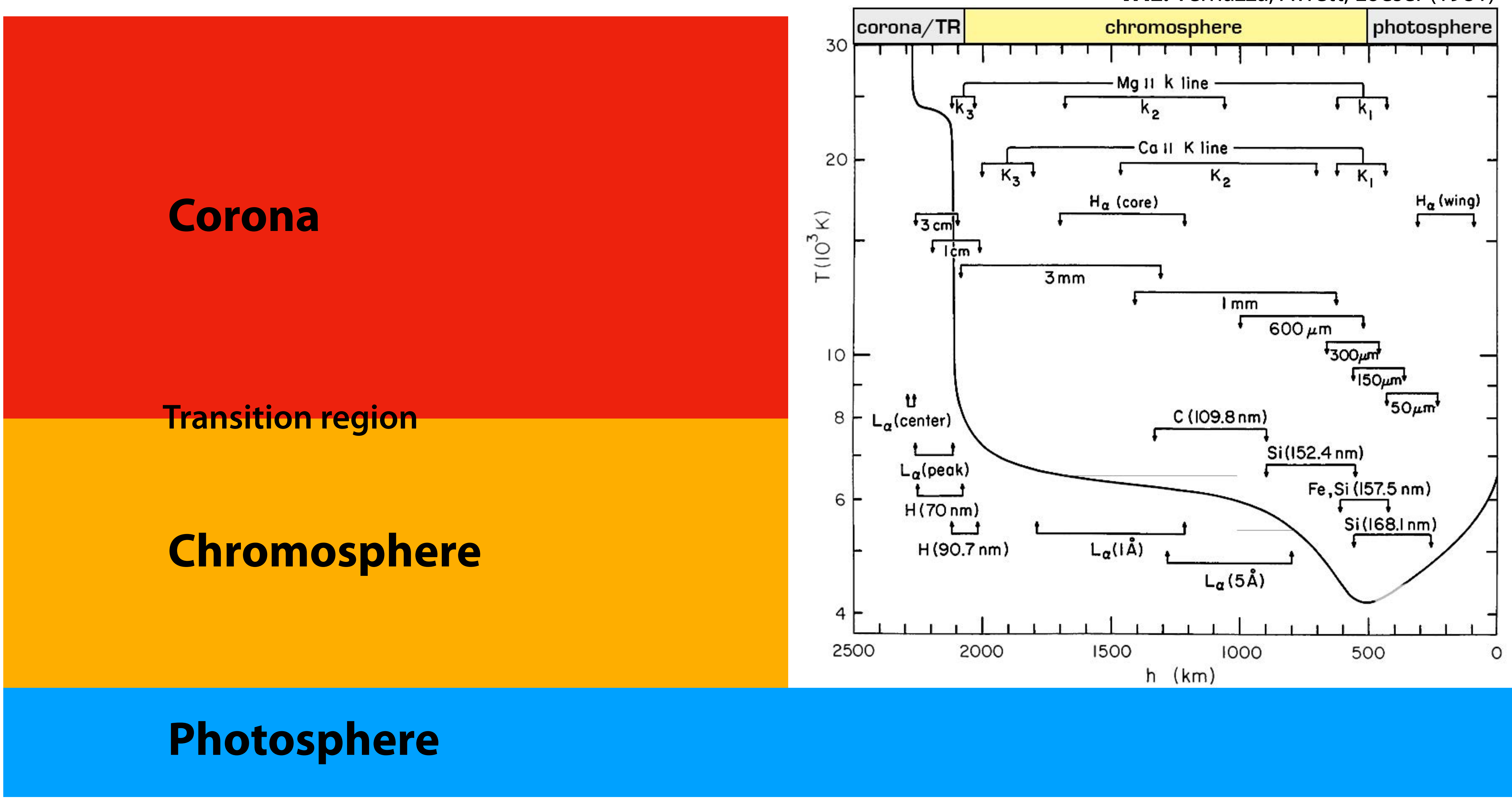
The solar atmosphere



Magnetic field in the solar atmosphere

Structure of Quiet Sun regions

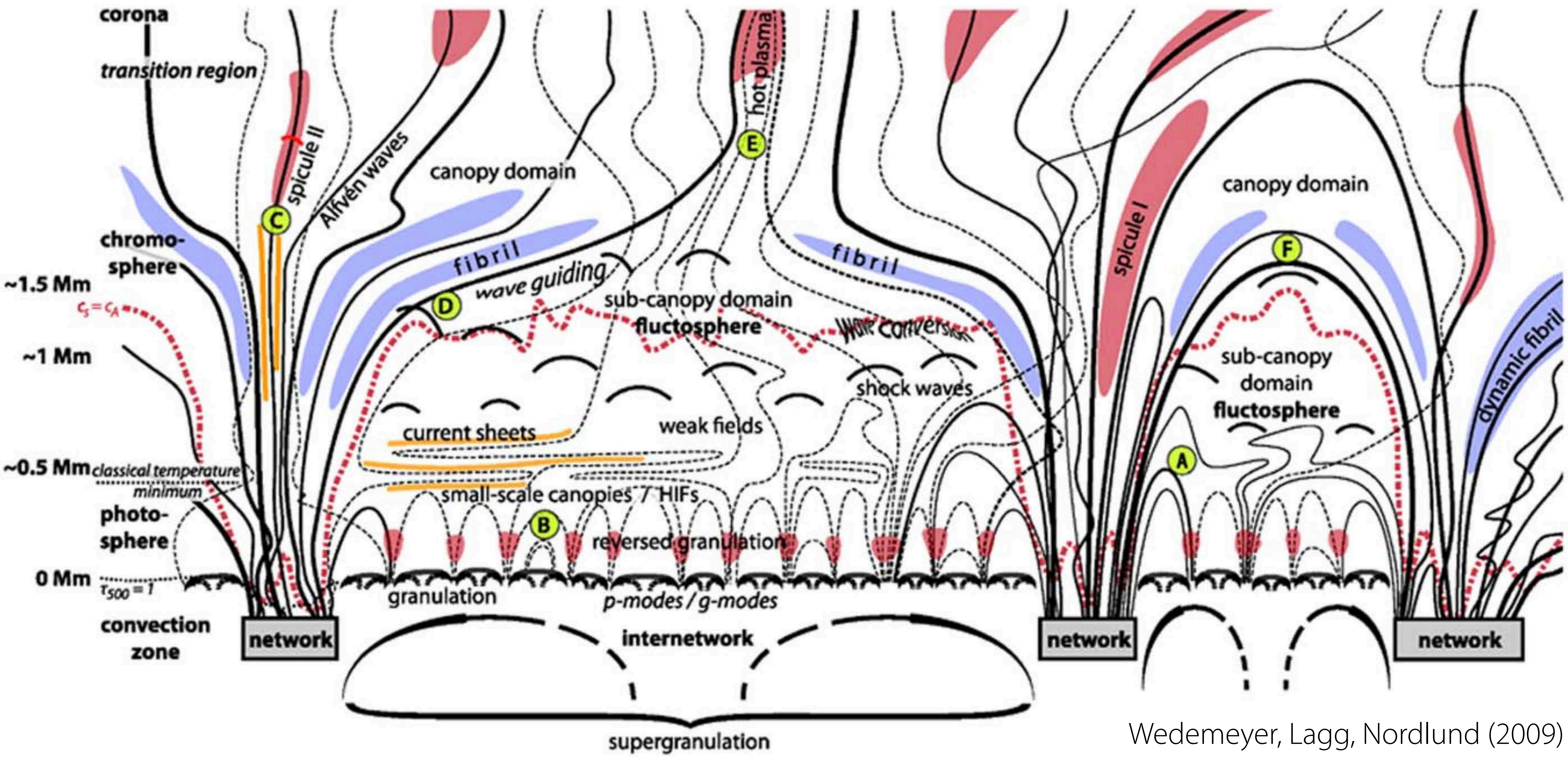
VAL: Vernazza, Avrett, Loeser (1981)



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

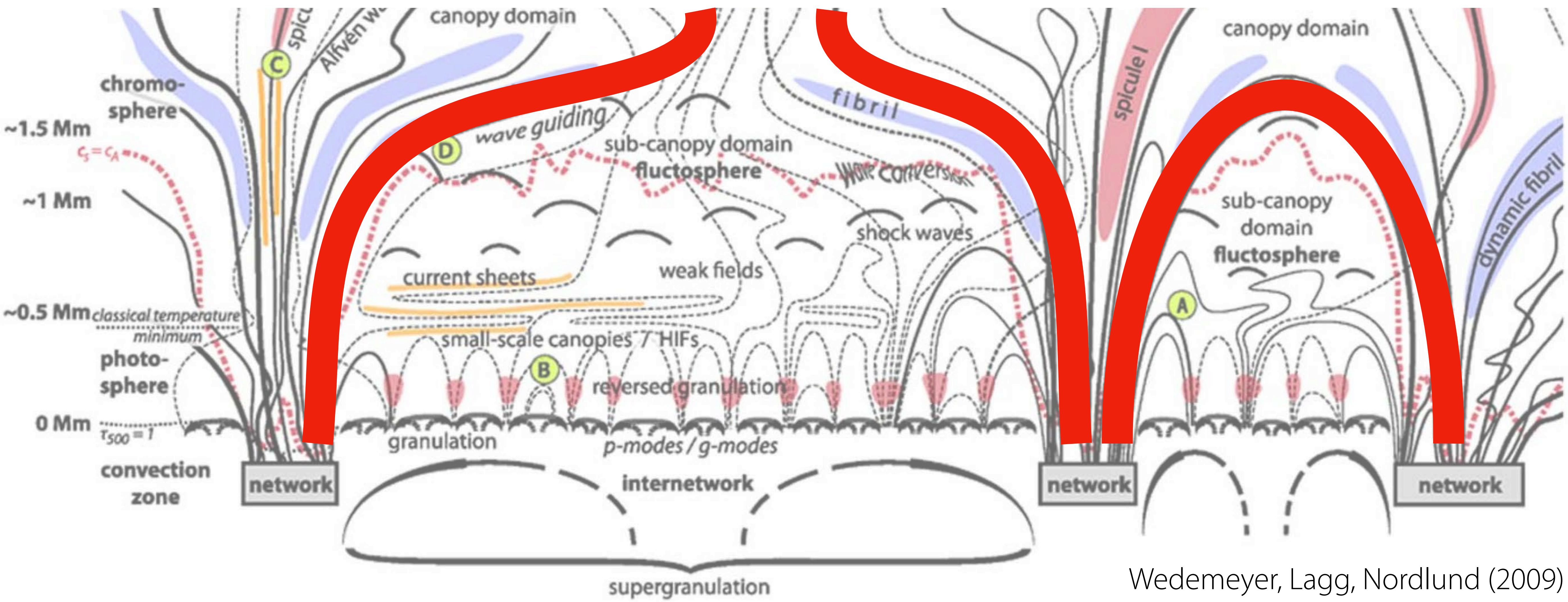


Wedemeyer, Lagg, Nordlund (2009)

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)

The solar atmosphere

Density

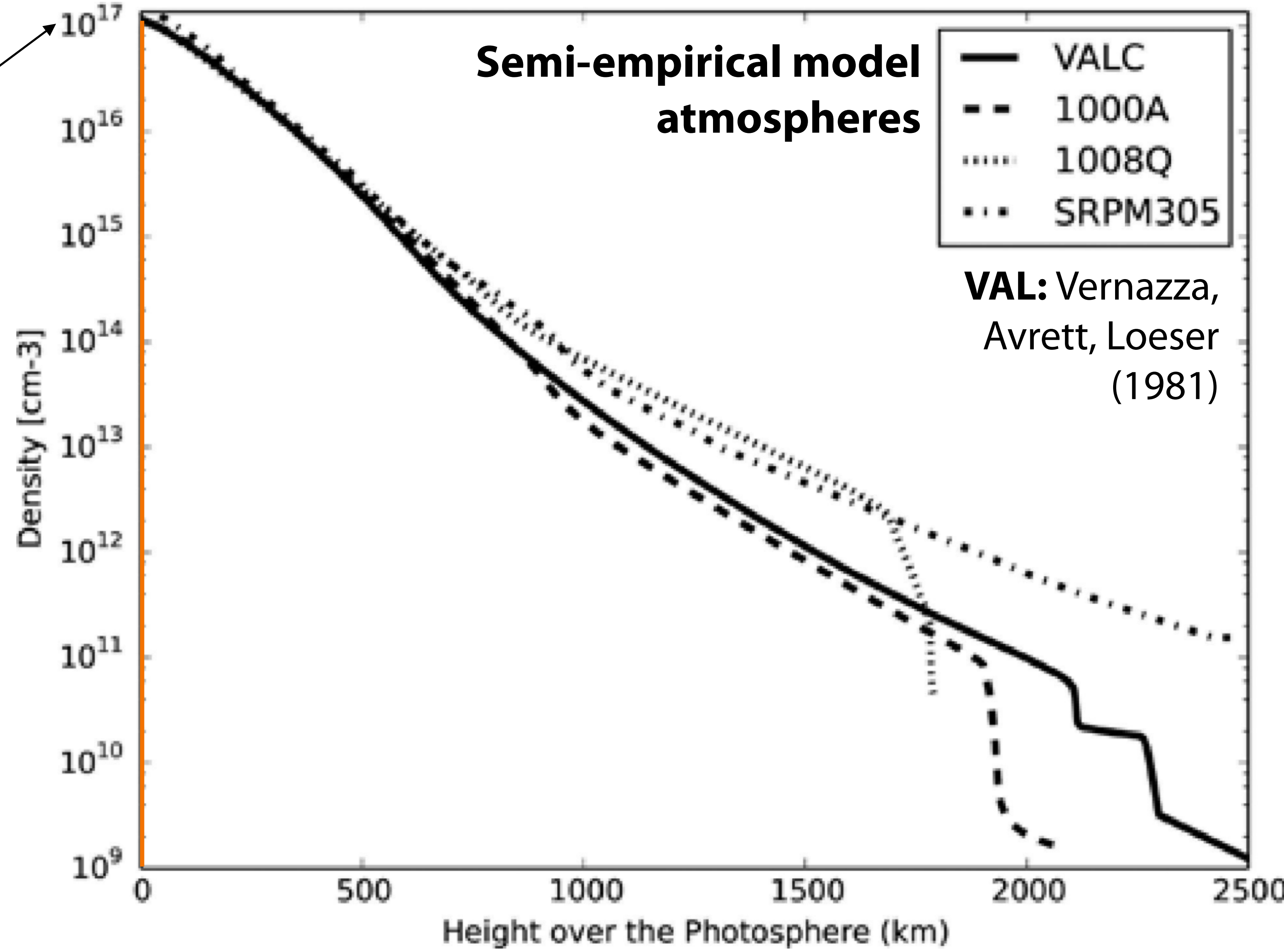
- At **bottom of photosphere** (z=0km): particle density $n \approx 1.5\ 10^{17}\ cm^{-3}$
- Assume gas consists only of hydrogen

➡ 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 $l = (\kappa\ \rho)^{-1} \approx (7\ 10^{-8}\ cm^{-1})^{-1}$

➡ **$l \approx 140$ km**



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

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 $\kappa \approx 0.3\ cm^2\ g^{-1}$

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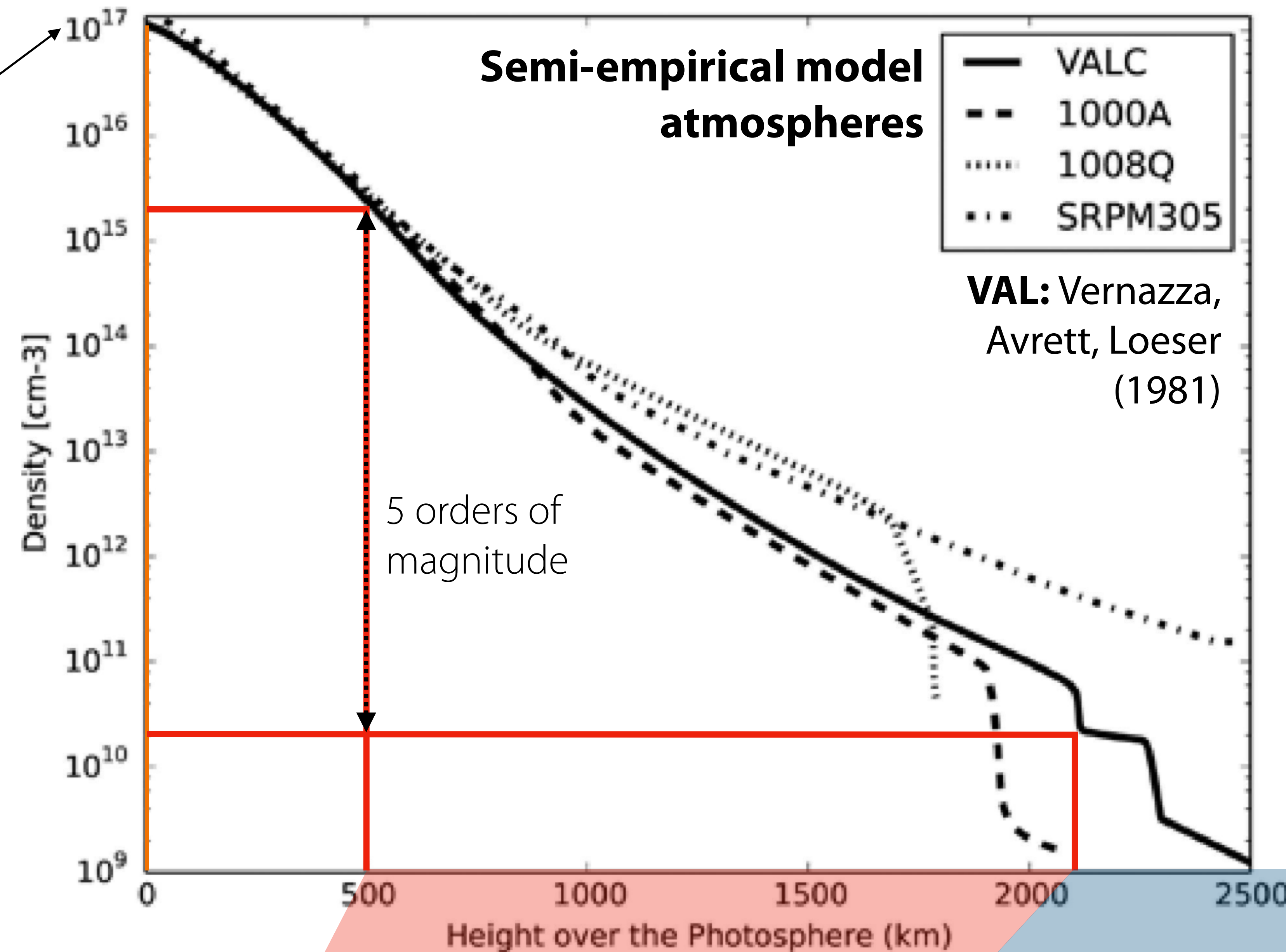

- Assumption of **local thermo-dynamic equilibrium (LTE)** valid at lower density in the layers above?
- What is the opacity there?

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

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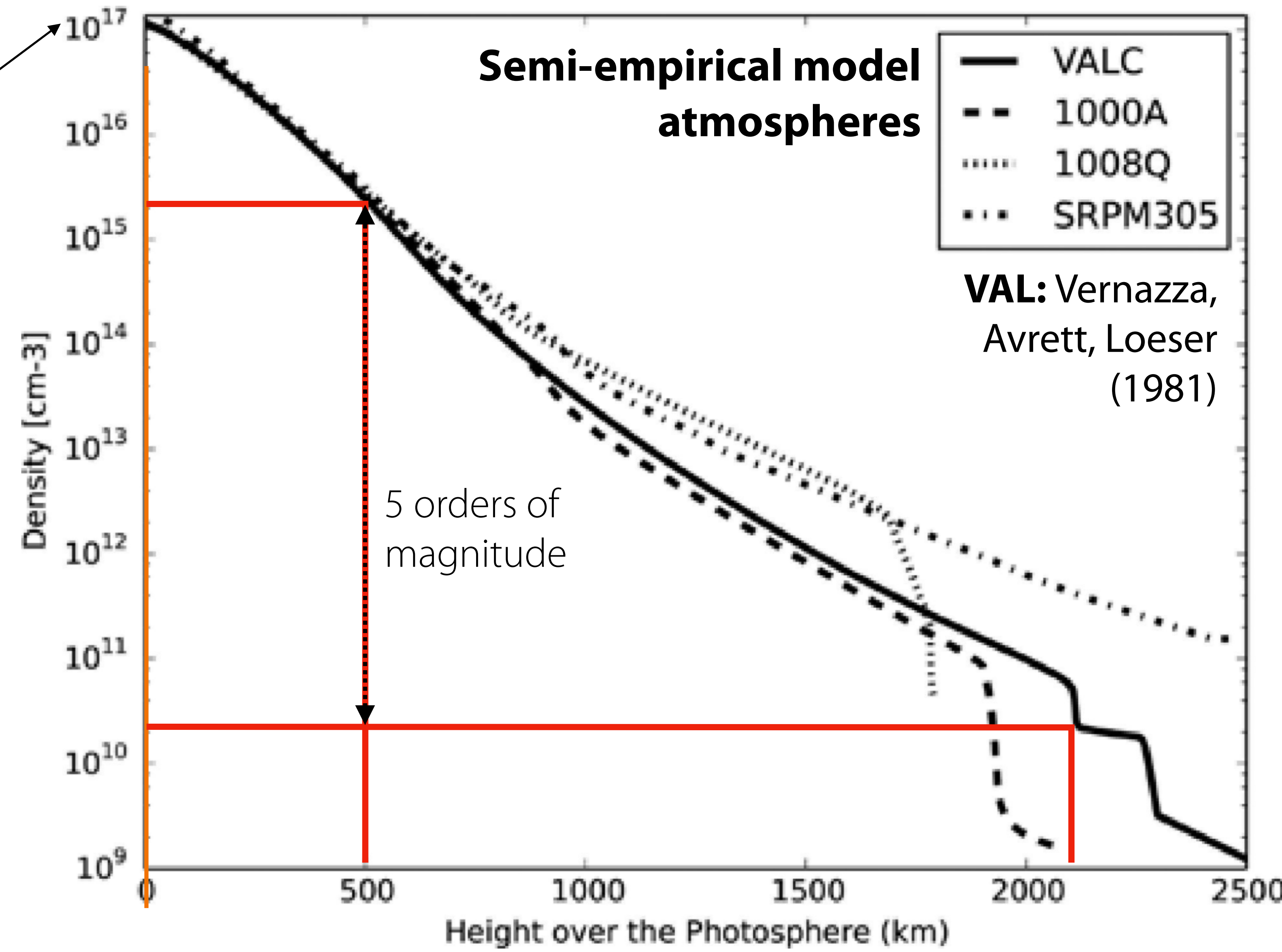


- Assumption of **local thermo-dynamic equilibrium (LTE)** valid at lower density in the layers above?
- What is the opacity there?

- 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:

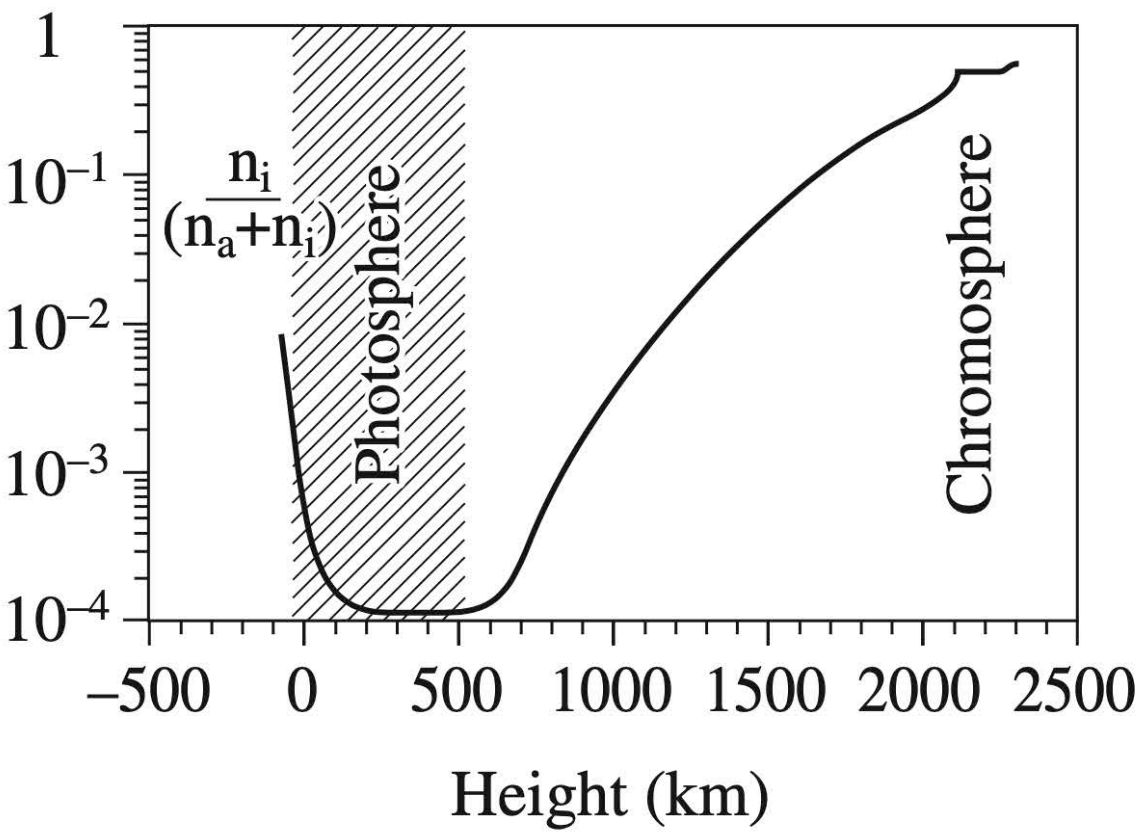
➡ Mean free path = 31 m !?!

How can that be?

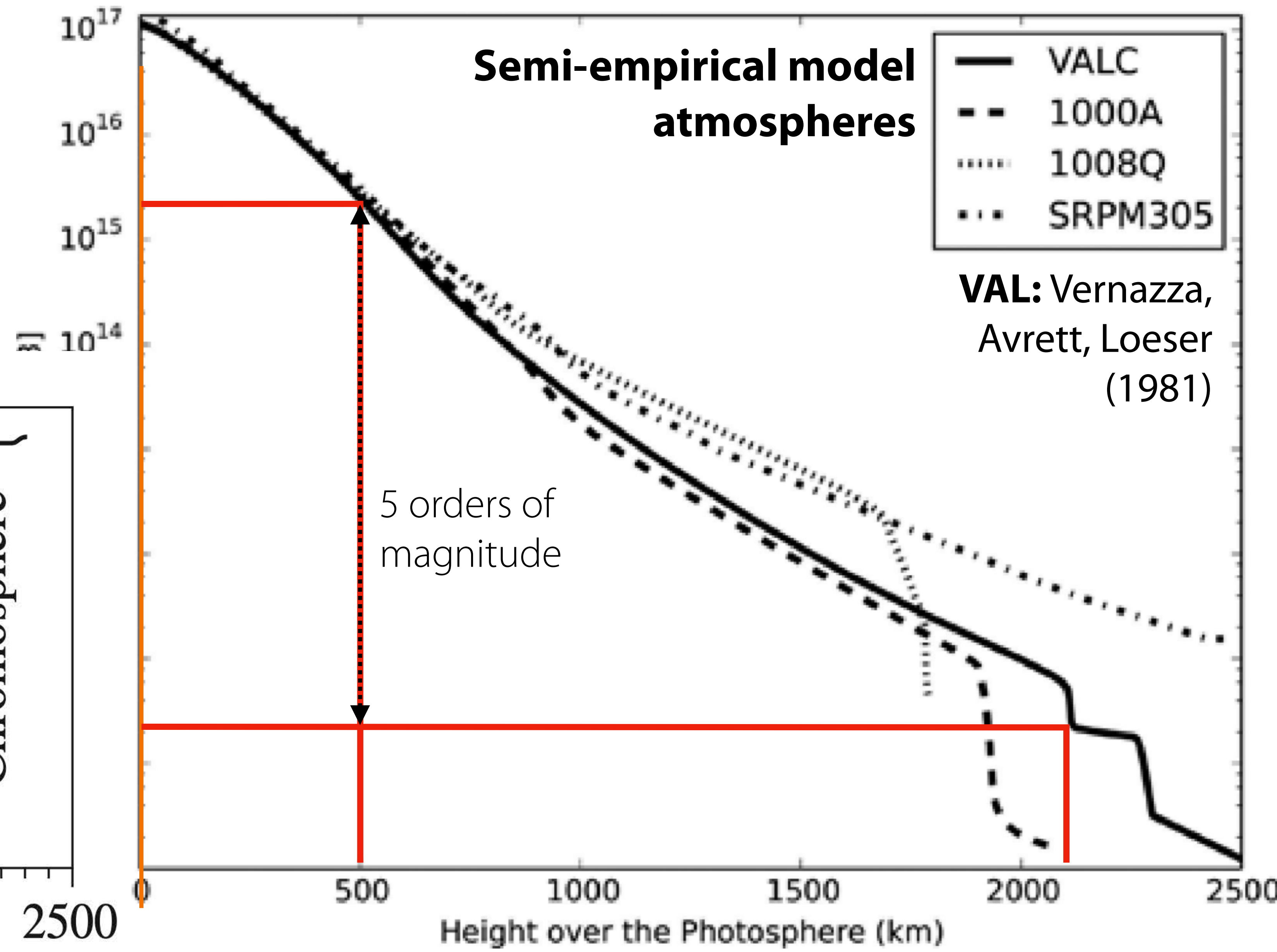
The solar atmosphere

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!

(Next time…)

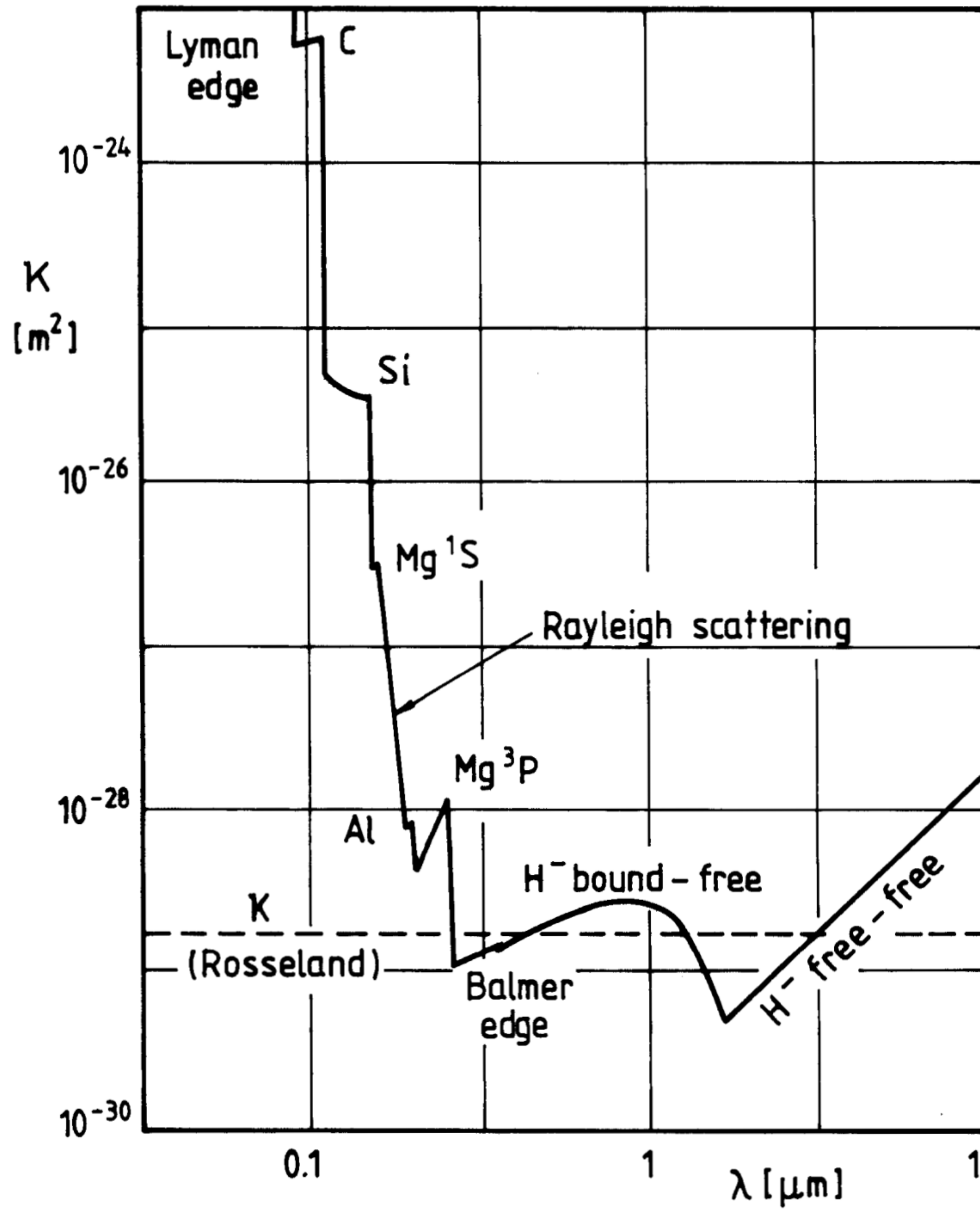
The solar atmosphere

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

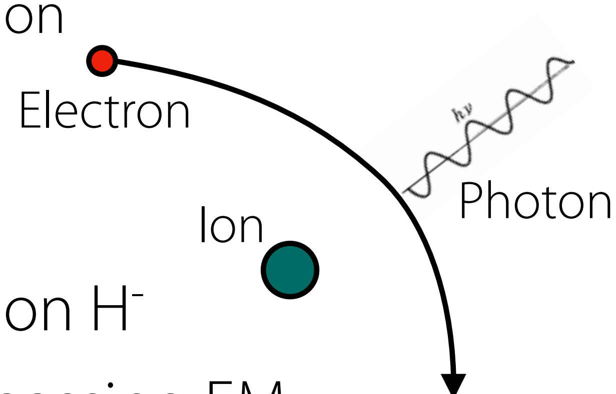


(Stix/Unsöld & Baschek 1999)

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)

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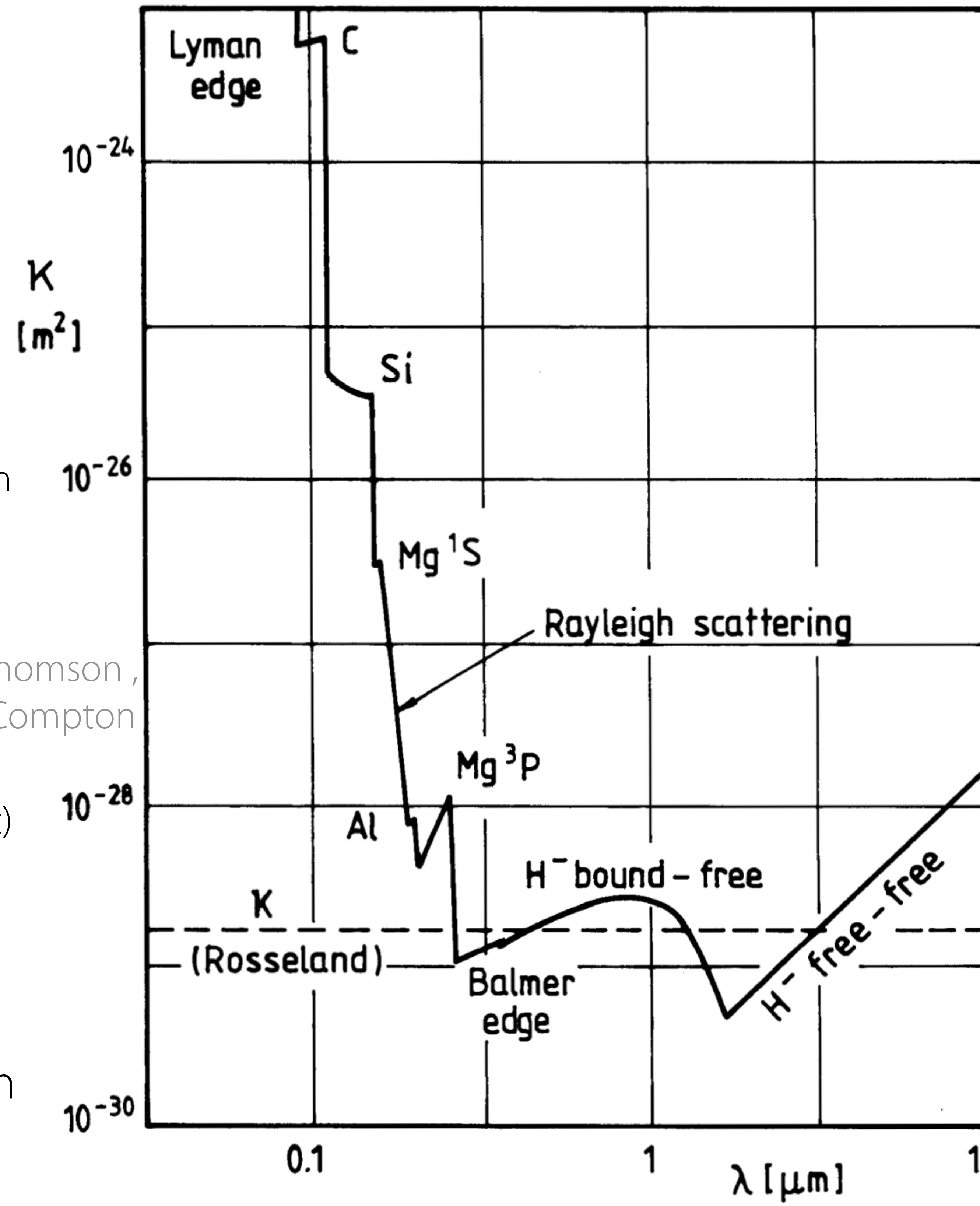

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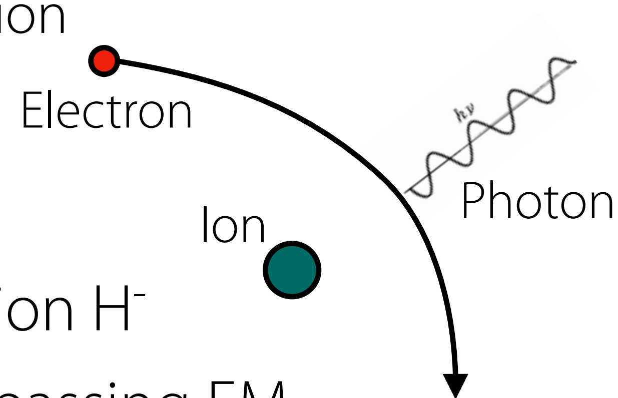

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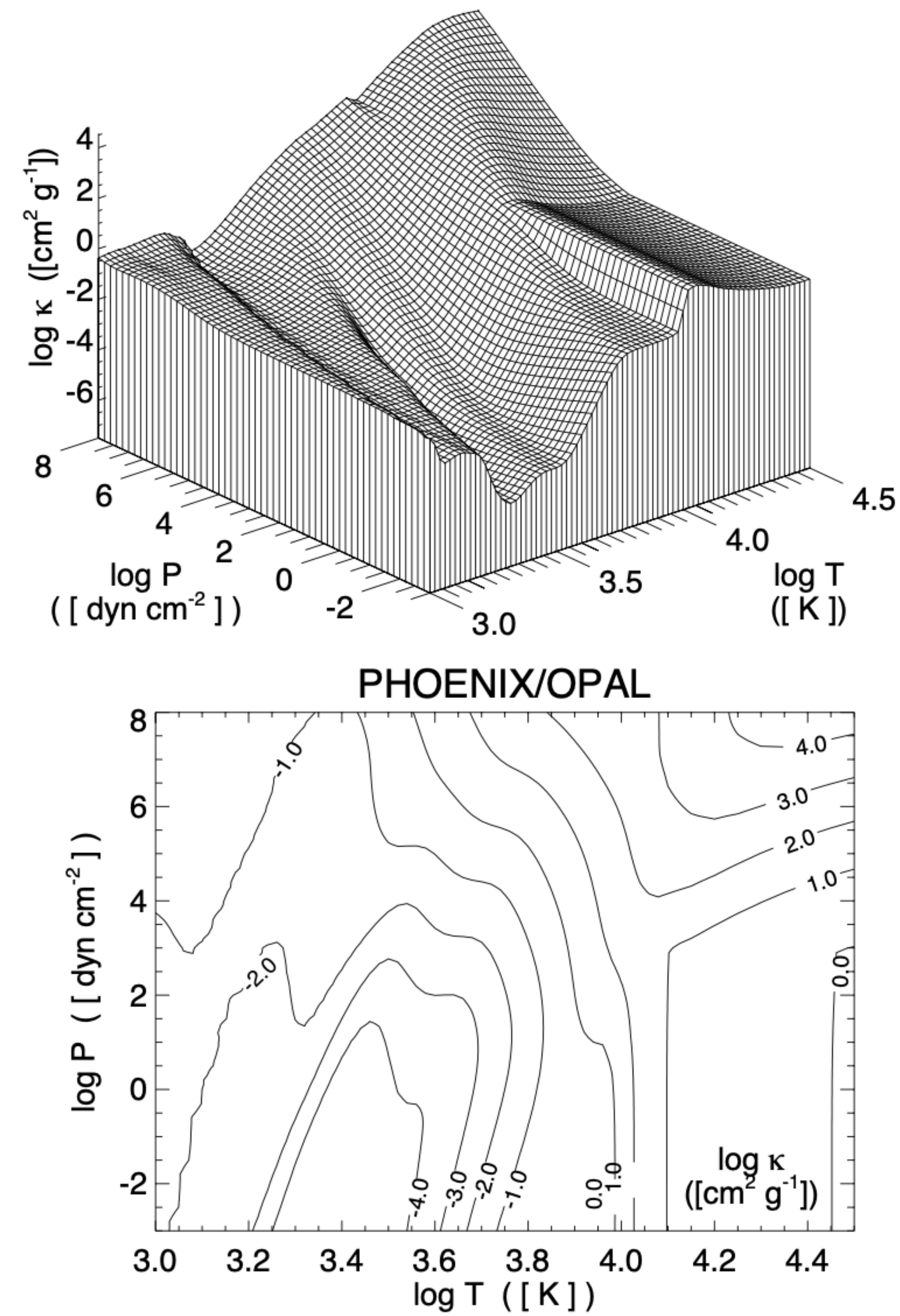

Opacity look-up table used in numerical simulations
(assumes equilibrium conditions)