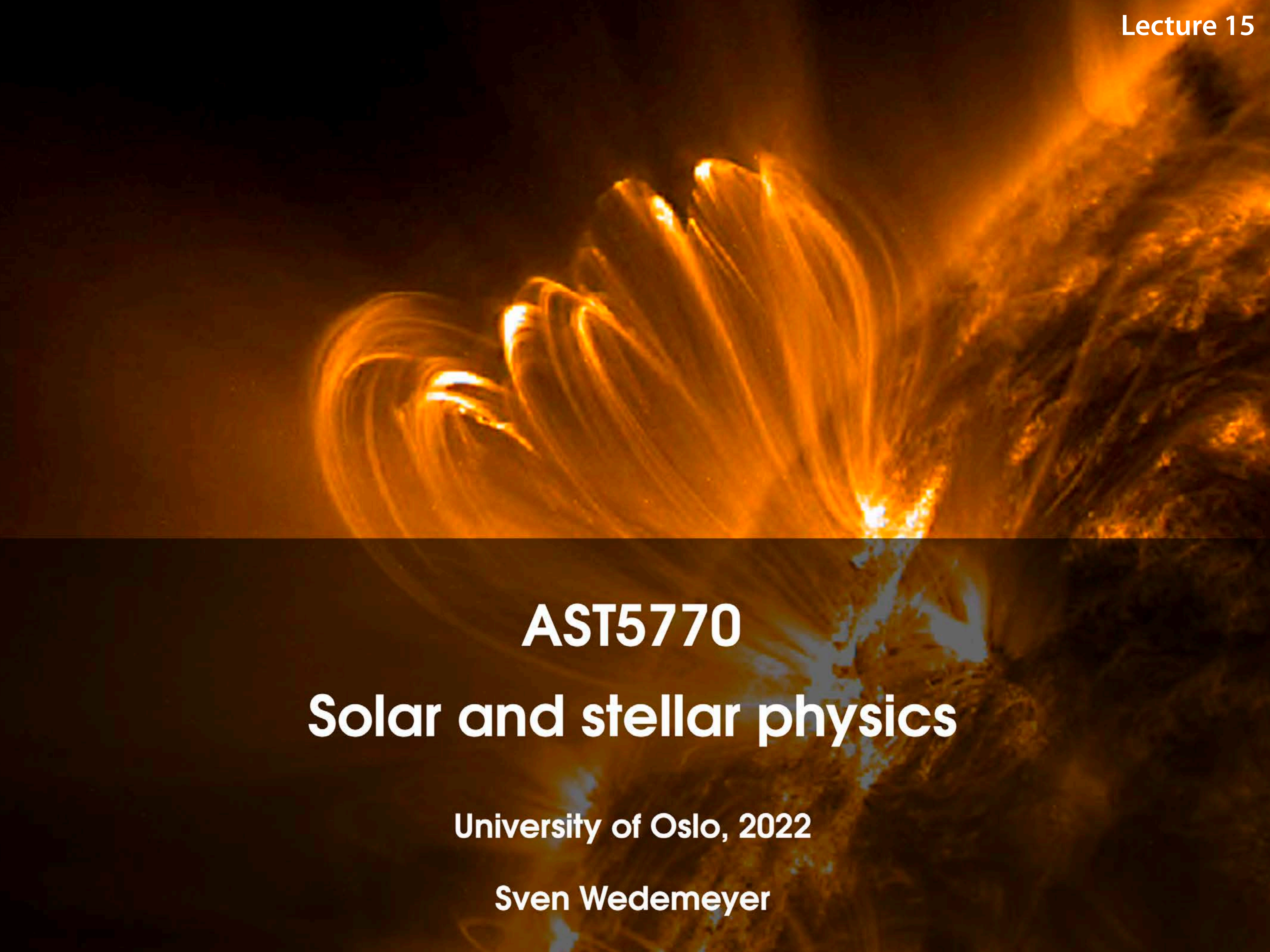


AST5770

Solar and stellar physics

University of Oslo, 2022

Sven Wedemeyer

Practical information

- Remember: Next week no lectures, no group exercises

- EST video: https://youtu.be/Ieq1Pa2b_dw
on YouTube: ("Reaching for the Sun", 57min)

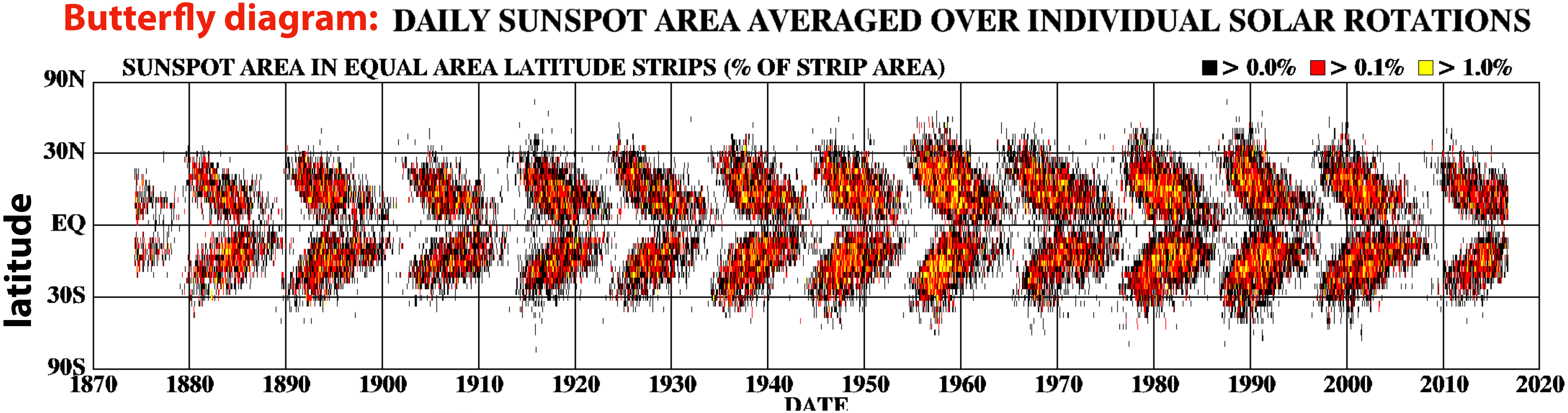
- Any question regarding the feedback on assignment #2?

Solar cycle

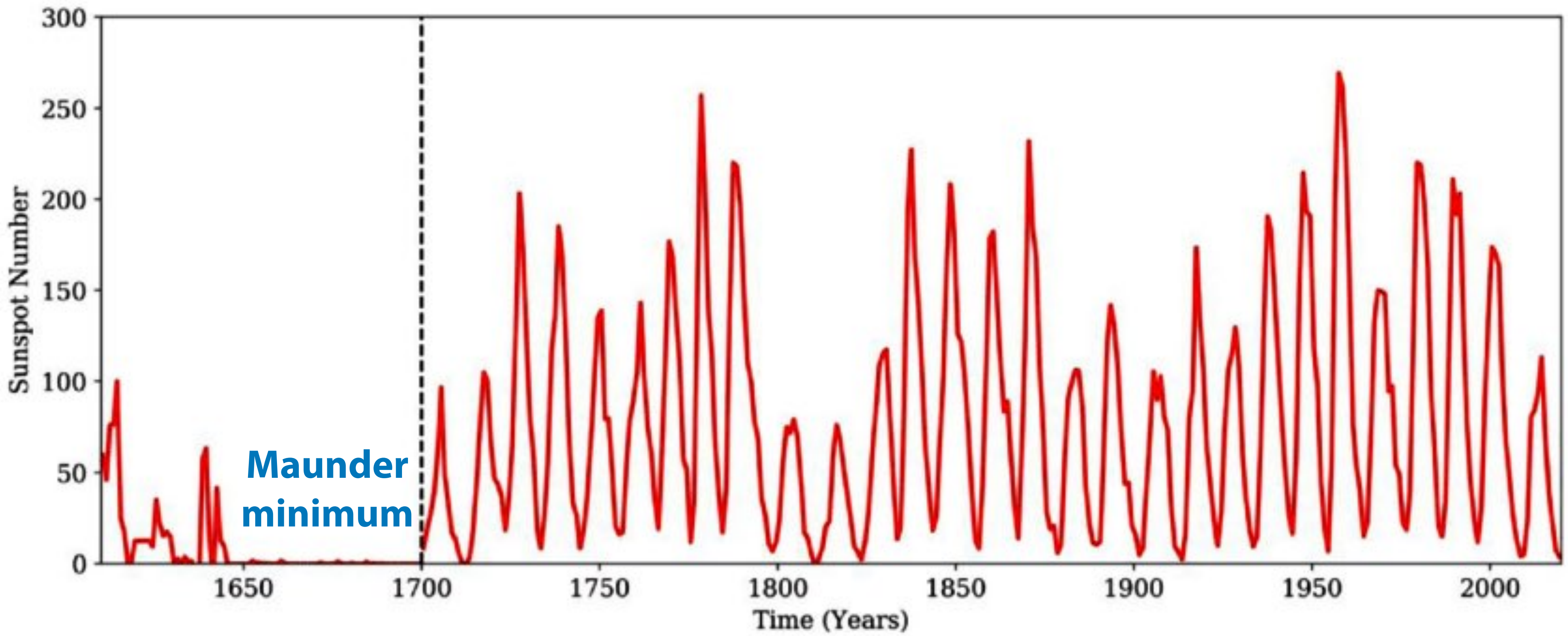
Recap

- Solar cycle — sunspots first at 30deg N/S, then gradually towards equator

Butterfly diagram:



- Solar cycle: 11 yr
- N/S swap
- **Hale cycle** = 22 yr
- Sunspot number as measure for solar activity level

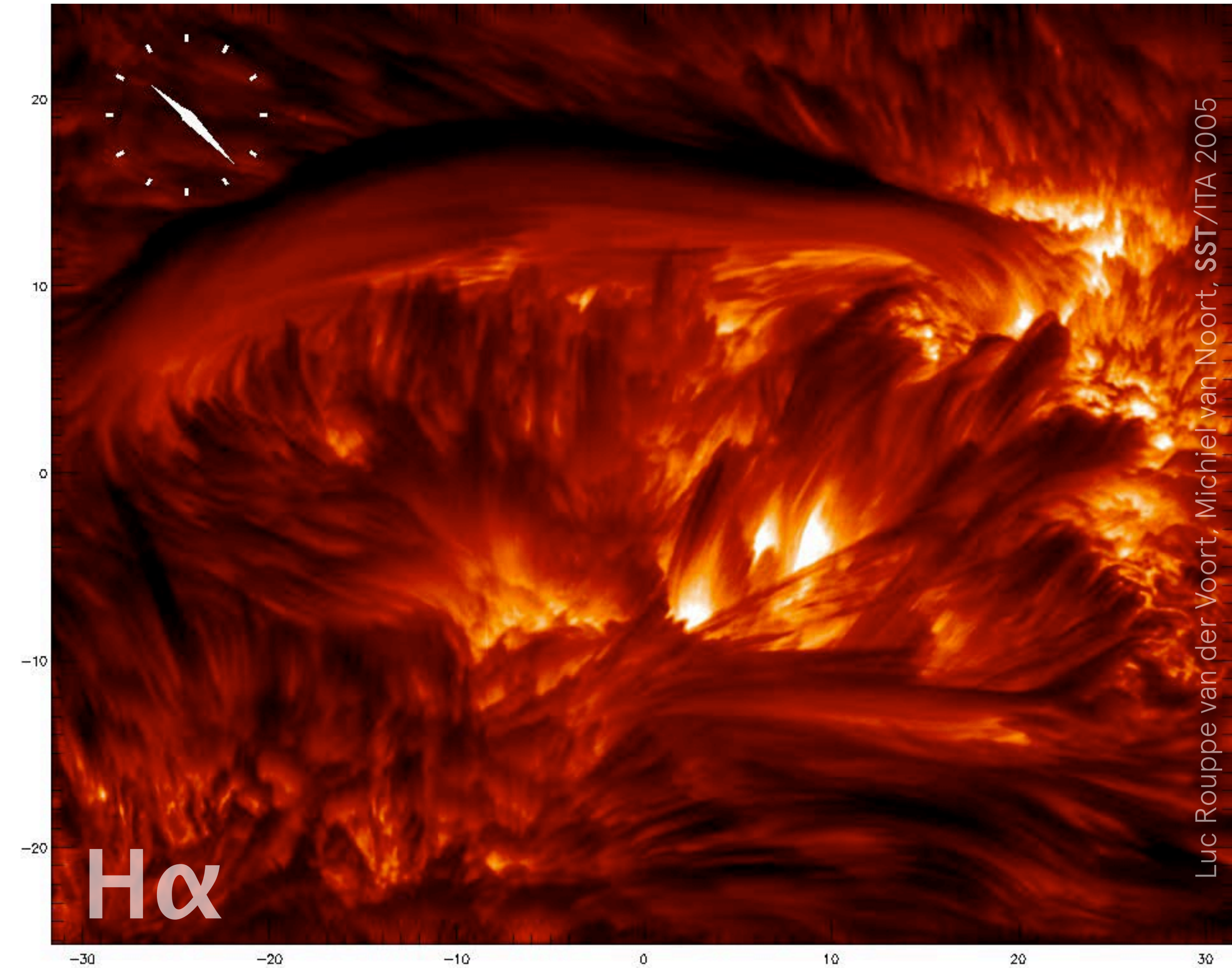


SILSO, Royal Obs. of Belgium, Brussels / Nandy et al. 2021

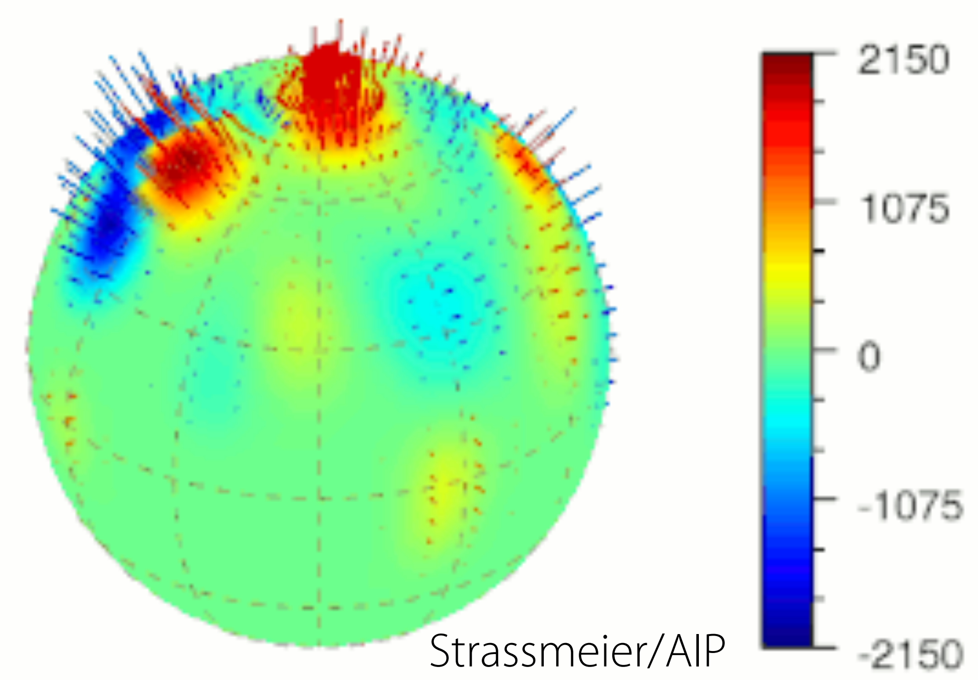
Measuring magnetic fields

Recap

- **Direct methods:** Zeeman effect (polarisation)
- **Indirect methods**, e.g. Hα, Ca II H/K spectral lines



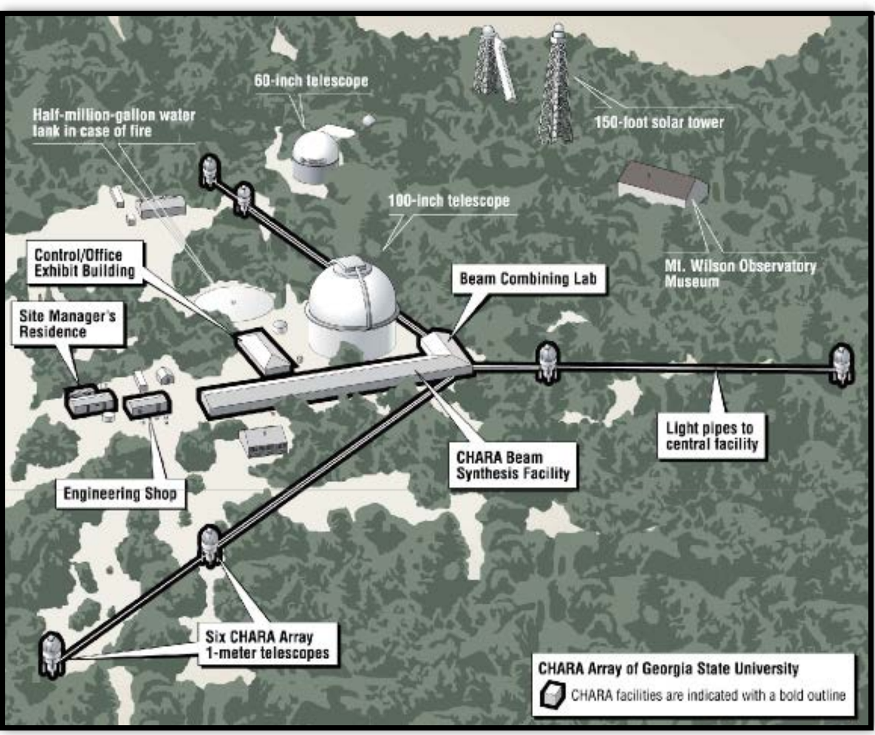
- **Zeeman Doppler Imaging (ZDI)**: Zeeman splitting of spectral lines plus Doppler shifts due to stellar rotation
- Deriving magnetic field configuration of stars from spatially unresolved observations
- Problem: Uncertain north–south distribution of starspots (ambiguity)



Measuring magnetic fields

Direct interferometric imaging

- Works only for stars with significant angular extent in the sky (physical size vs. Distance)
  ➡ Few examples so far (limited by achievable angular resolution)
  - Observation with CHARA of **ζ Andromedae** (Roettenbacher et al 2016)
    - K-type cool giant star (15 times larger than Sun)
    - Observations in 2011 and 2013 over several consecutive days to cover the star's rotation period



CHARA, USA: array of 6 telescopes

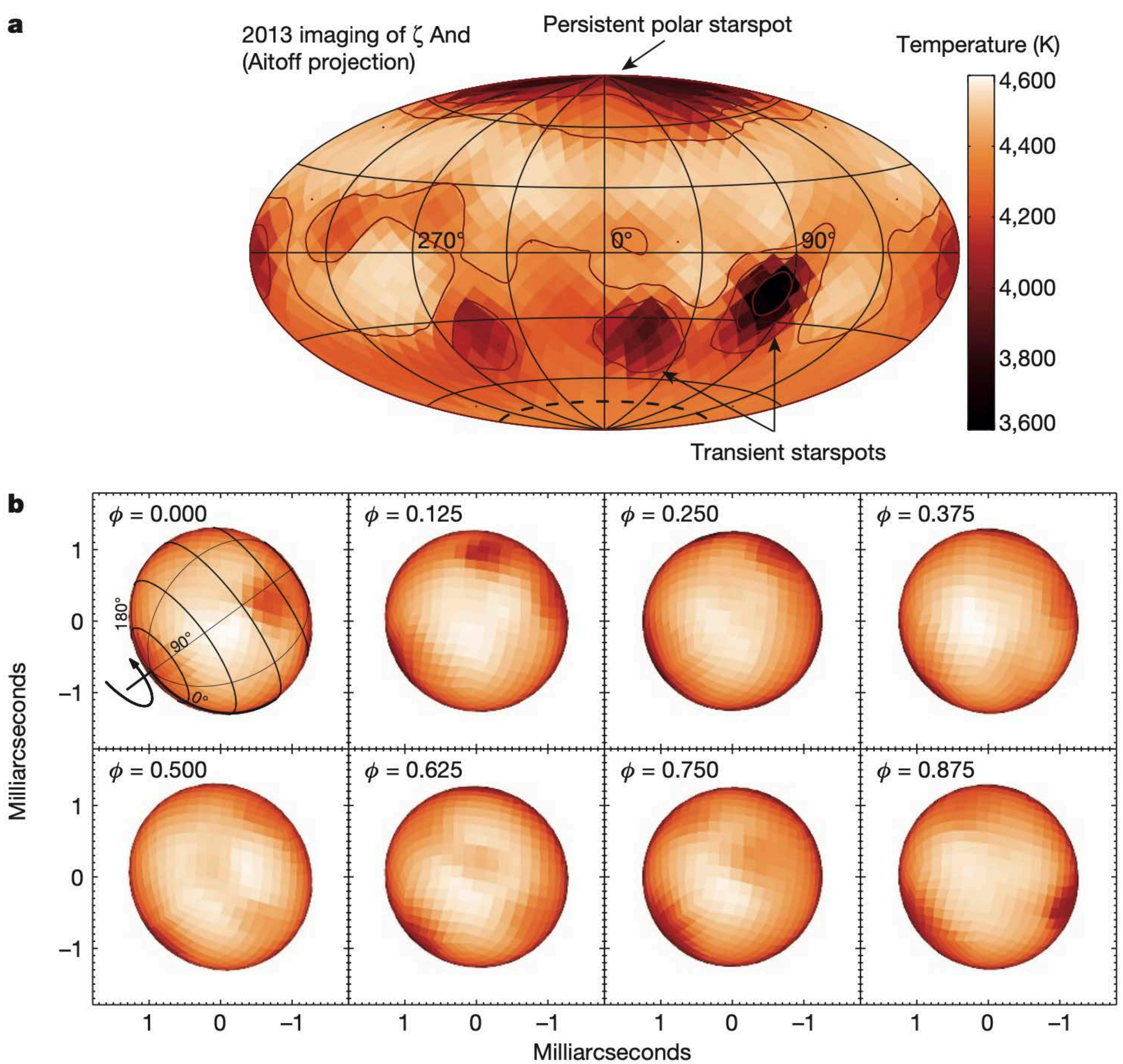
Table 1 | Parameters of ζ And

Measured parameter	Value
Angular polar diameter, θ_{LD} (mas)	2.502 ± 0.008
Polar radius ($R_\odot$)	15.0 ± 0.8
Oblateness (major to polar axis)	1.060 ± 0.011
Inclination, i (°)	70.0 ± 2.8
Pole position angle (°, E of N)	126.0 ± 1.9
Values from the literature	
Distance, d (pc)	17.98 ± 0.83 (ref. 29)
Effective temperature, T_{eff} (K)	4600 ± 100 (ref. 9)
Luminosity, log $L/L_\odot$	1.98 ± 0.04 (ref. 9)
Primary mass ($M_\odot$)	2.6 ± 0.4 (ref. 9)
Secondary mass ($M_\odot$)	~0.75 (ref. 9)
Iron metallicity [Fe/H]/[Fe/H]$_\odot$	-0.30 ± 0.05 (ref. 9)

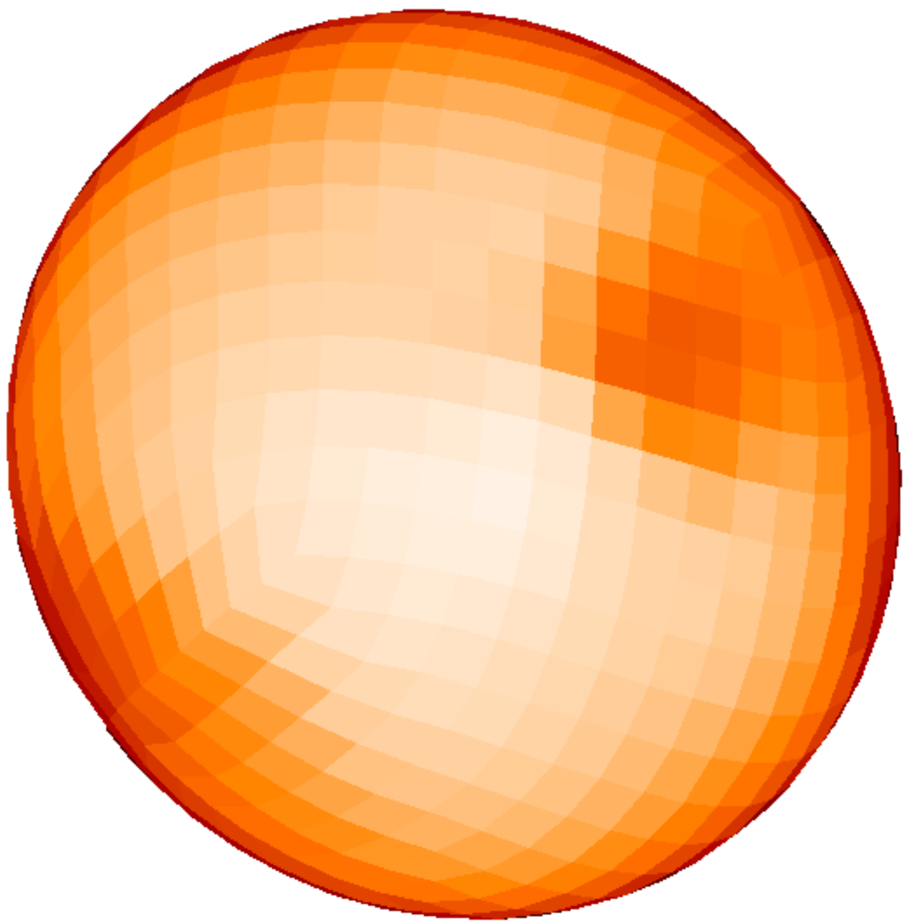
Measuring magnetic fields

Direct interferometric imaging — ζ Andromedae

Time sequence of interferometric images



➡Time-dependent model of the star's surface



- Dark polar spot seen in both observation epochs but lower-latitude spot structures in both hemispheres do not persist between observations

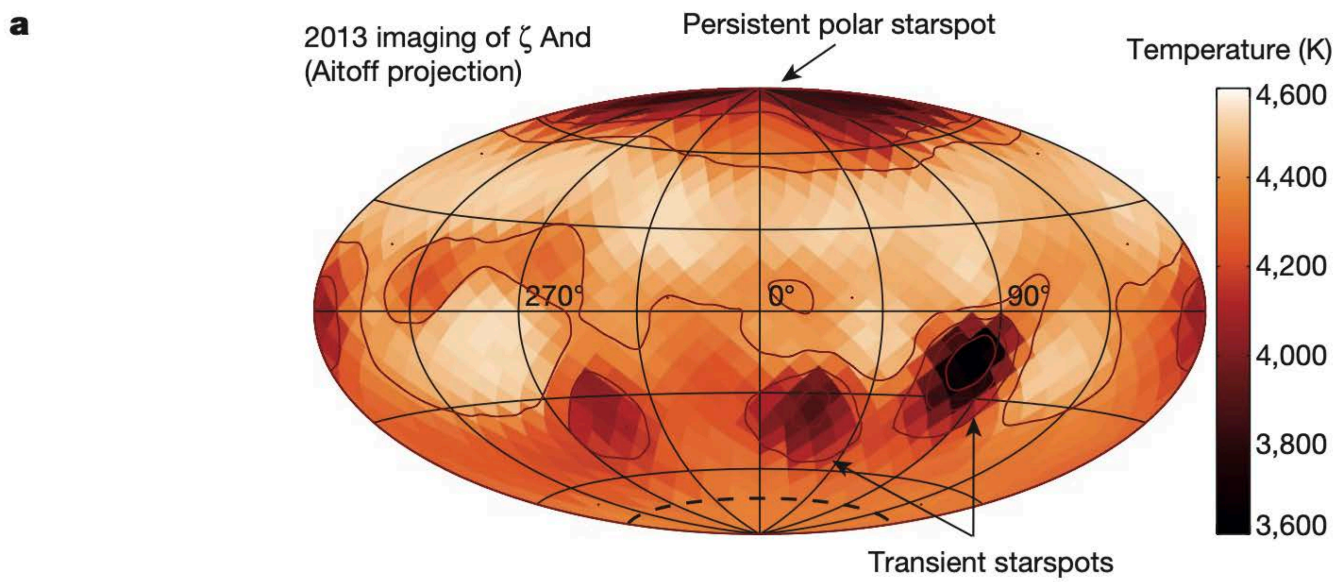
Roettenbacher et al 2016

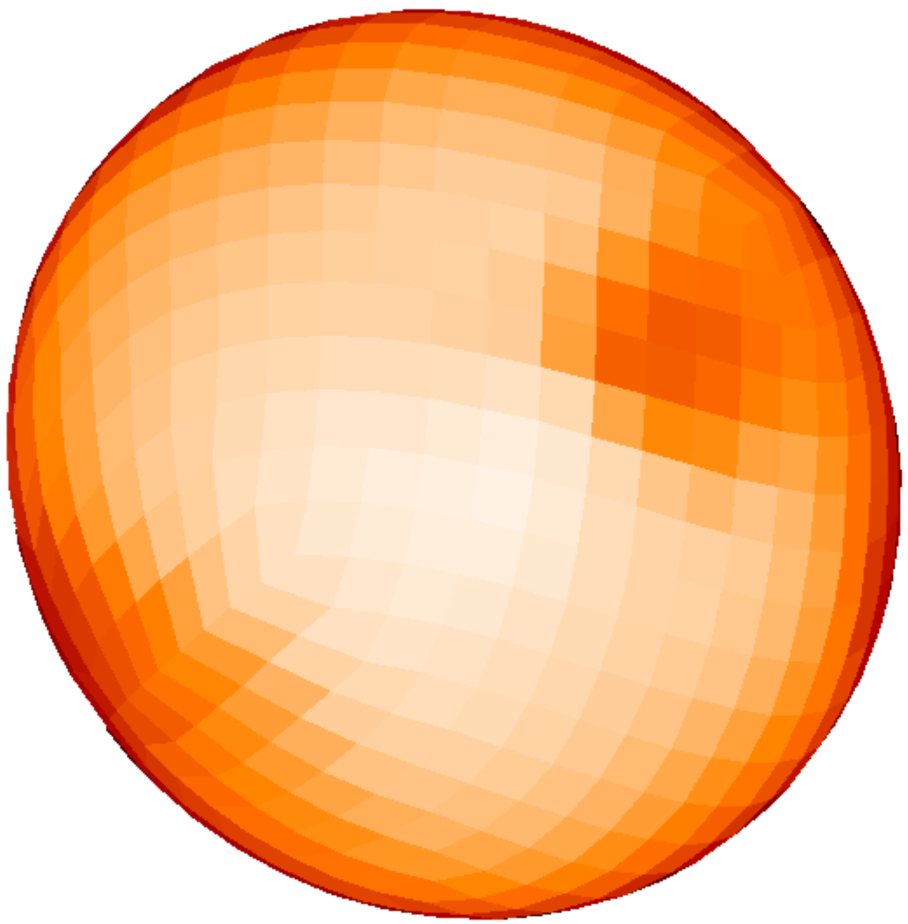
Measuring magnetic fields

Direct interferometric imaging — ζ Andromedae

Time sequence of interferometric images

➡Time-dependent model of the star's surface





(Potential) problem:

- Conclusion: Inferred magnetic field configuration difficult to produce with a global dynamo
- Is there enough data for this conclusion?
- Interferometry is challenging but promising
- **Can provide important constraints on stellar dynamos and the resulting magnetic fields!**

Dark polar spot seen in both observation epochs but lower-latitude spot structures in both hemispheres do not persist between observations

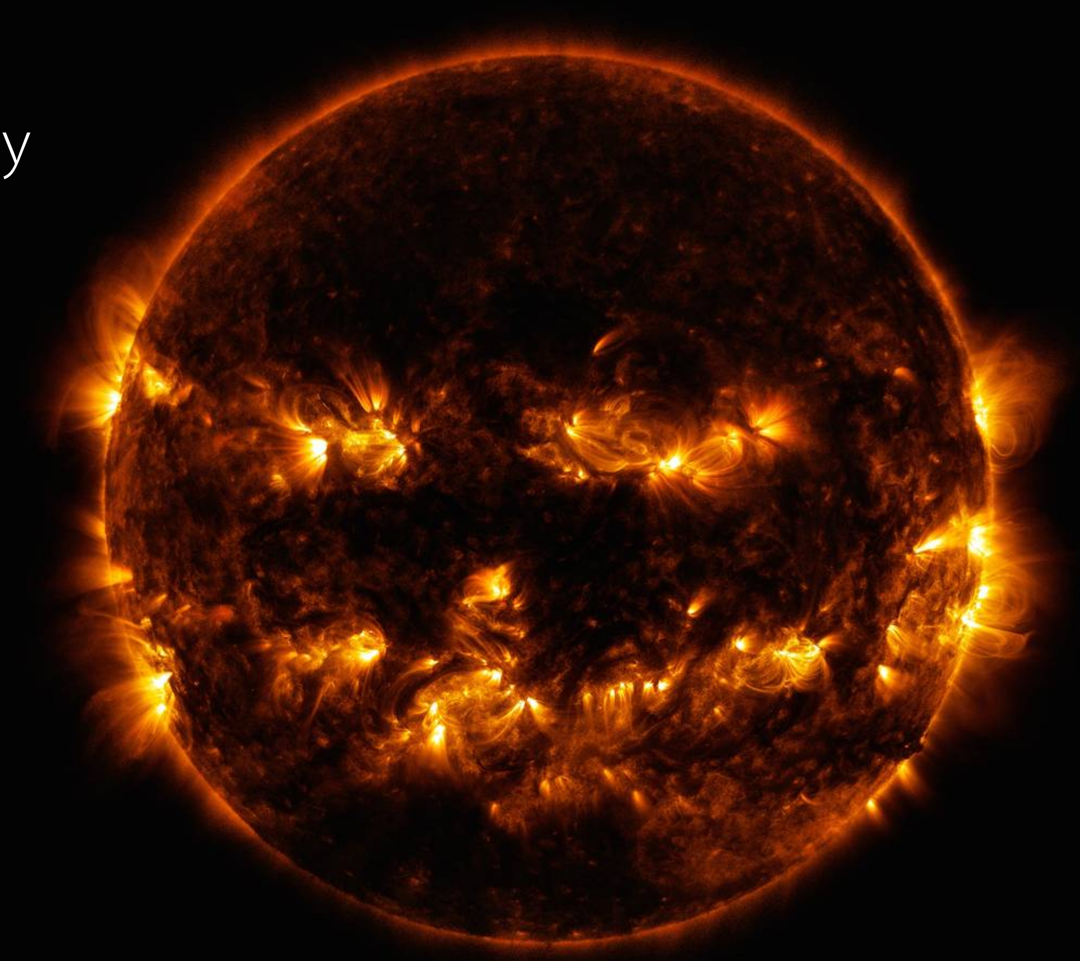
Stellar activity

Stellar activity

What is stellar activity?

- **Stellar activity** refers to all phenomena in a stellar atmosphere that result in
  - **Variability** of the emitted radiation
    (on different timescales, except for pulsations, or influences of accompanying objects/disks)
  - **Heating** of the outer atmosphere
    (existence of a chromosphere, temperatures above radiative equilibrium)
- Mostly found for **cool late-type stars** due to the presence of surface convection and the resulting highly structured magnetic fields in their atmospheres
  - Initially activity thought to be produced by the dissipation of acoustic waves in the atmosphere (acoustic heating; Biermann 1948; Schwarzschild 1948).
  - Today understood that dissipation of magnetic energy is essential.

➡ **Magnetic activity** is synonym of stellar activity.



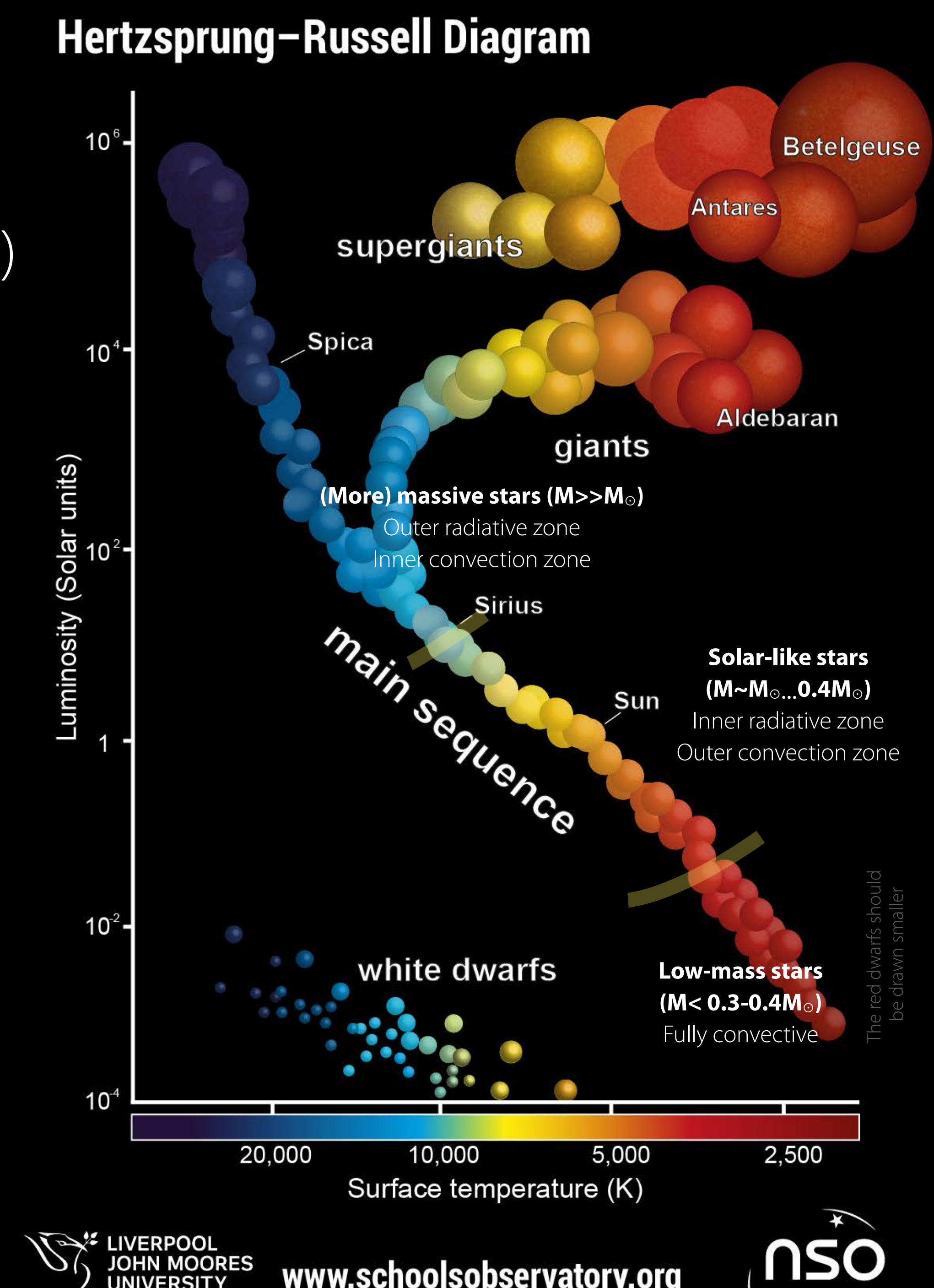
Further reading: Hall, Living Rev. Solar Phys., 5, (2008), 2

Stellar activity

What is stellar activity?

- **We have learned so far about…**
  - **… main-sequence stars:**
    - Differences of global properties (mass, radius, T_{eff},…)
    - Differences in their inner structure incl. extent and location of convection zones
  - **… the Sun:**
    - generation of magnetic via a dynamo
    - resulting solar activity cycle

- **What do we now expect to see in terms of activity cycles for other main sequence stars?**



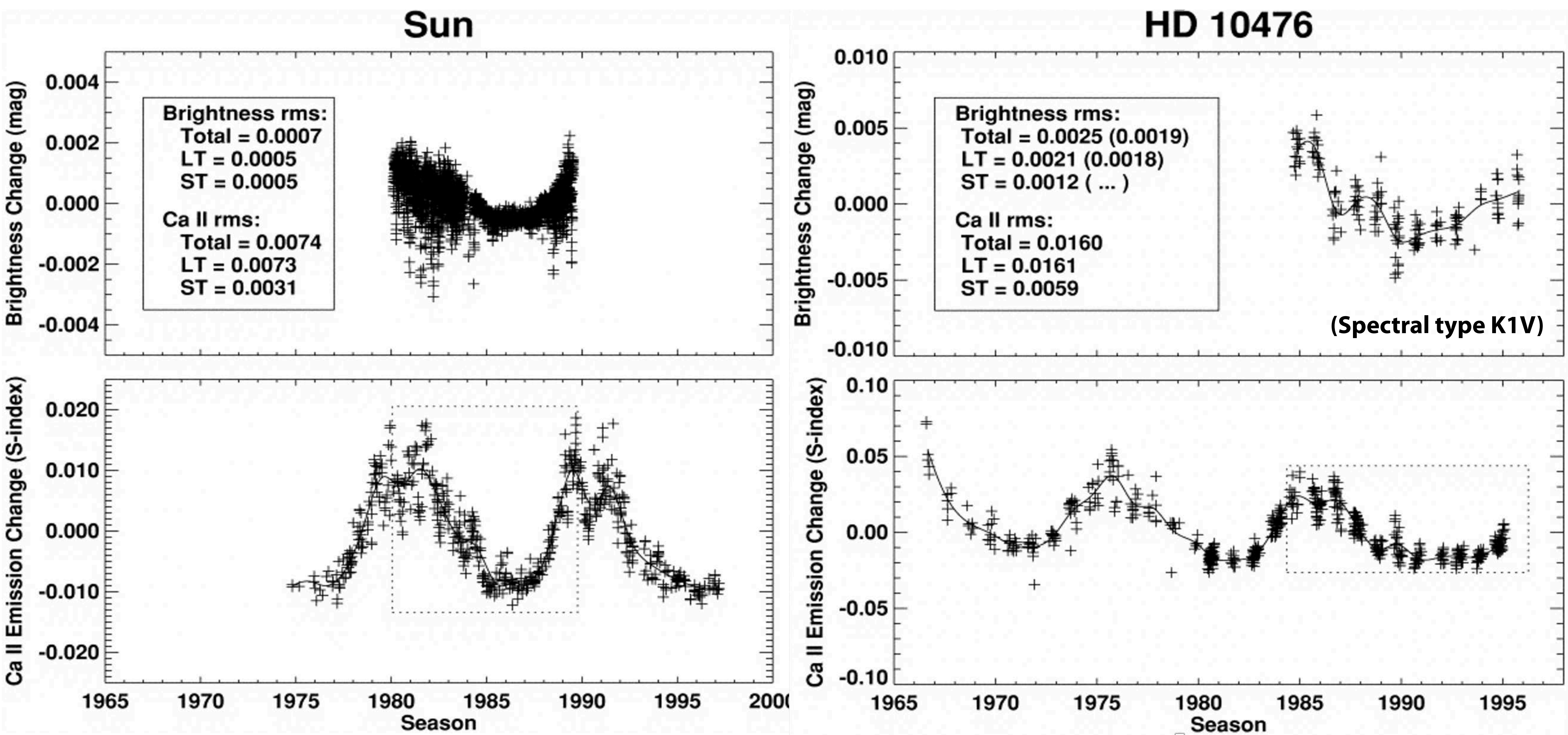
Stellar activity

How to detect activity cycles?

- The usual problem: Stellar observations are **spatially not resolved**, starspots not observed directly* — no "starspot number" can be derived directly
- Visible brightness changes of Sun only few milli-mags anyway

**except for a few interferometric observations*

➡ More **sensitive indicators**? ➡ indicators based on spectral lines! (Example below: Ca II)



Stellar activity

Activity indicators

- Other activity indicators use impact of magnetic field on the cores of the Ca II H and K spectral lines (integrated across the (unresolved) stellar disk))

  ➡ Measures of the overall magnetic activity level of the star, for instance:

R_{HK}-index

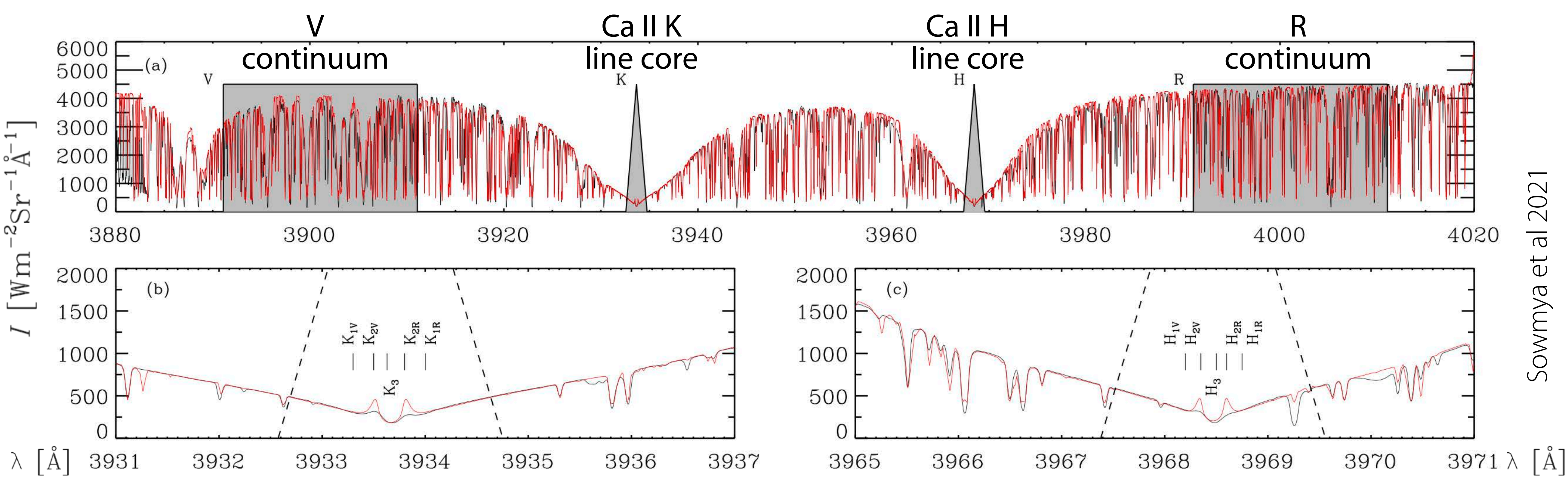
$$R'_{\mathrm{HK}} = \frac{F_{\mathrm{HK}} - F_{\mathrm{HK,phot}}}{\sigma T_{\mathrm{eff}}^4}$$

F_{HK}: flux, $F_{\mathrm{HK,\,phot}}$: flux, photospheric contributions

S-index

$$S(t) \propto \frac{N_{\mathrm{H}}(t) + N_{\mathrm{K}}(t)}{N_{\mathrm{R}}(t) + N_{\mathrm{V}}(t)}$$

N: Counts (flux) in the passbands



Sowmya et al 2021

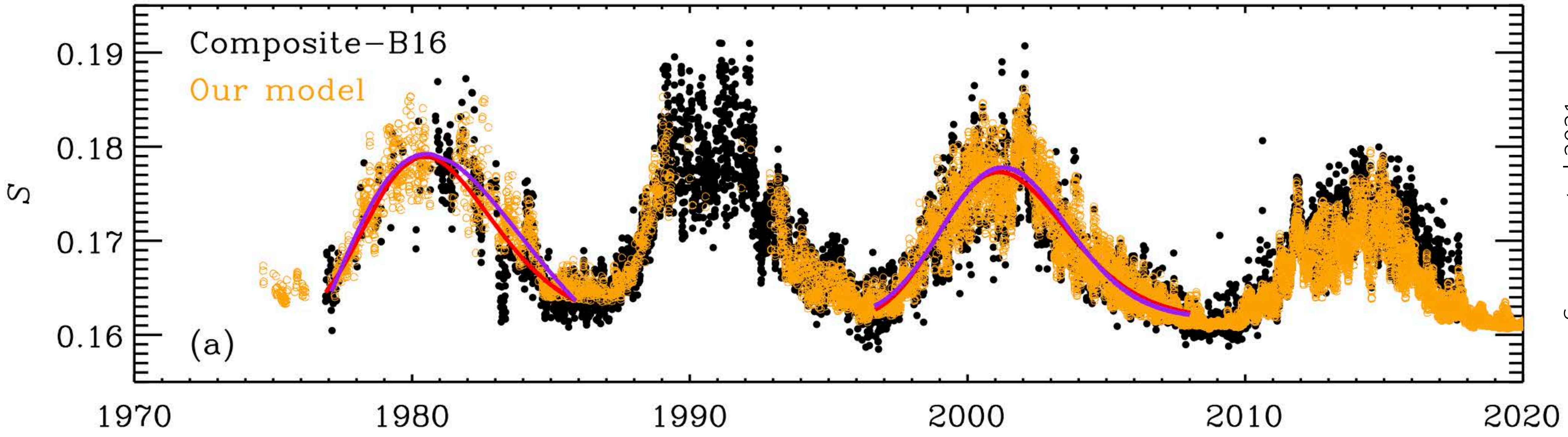
Stellar activity cycles

Activity indicators

S-index $$S(t) \propto \frac{N_{\mathrm{H}}(t) + N_{\mathrm{K}}(t)}{N_{\mathrm{R}}(t) + N_{\mathrm{V}}(t)}$$

N: Counts (flux) in the passbands

- S-index over several solar cycles:

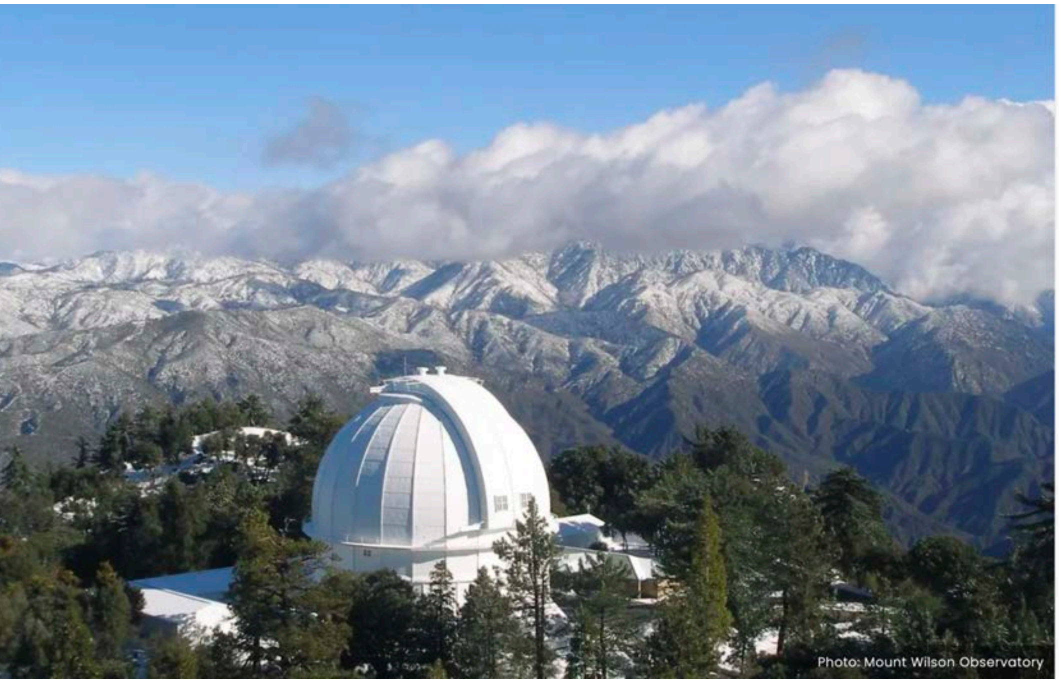


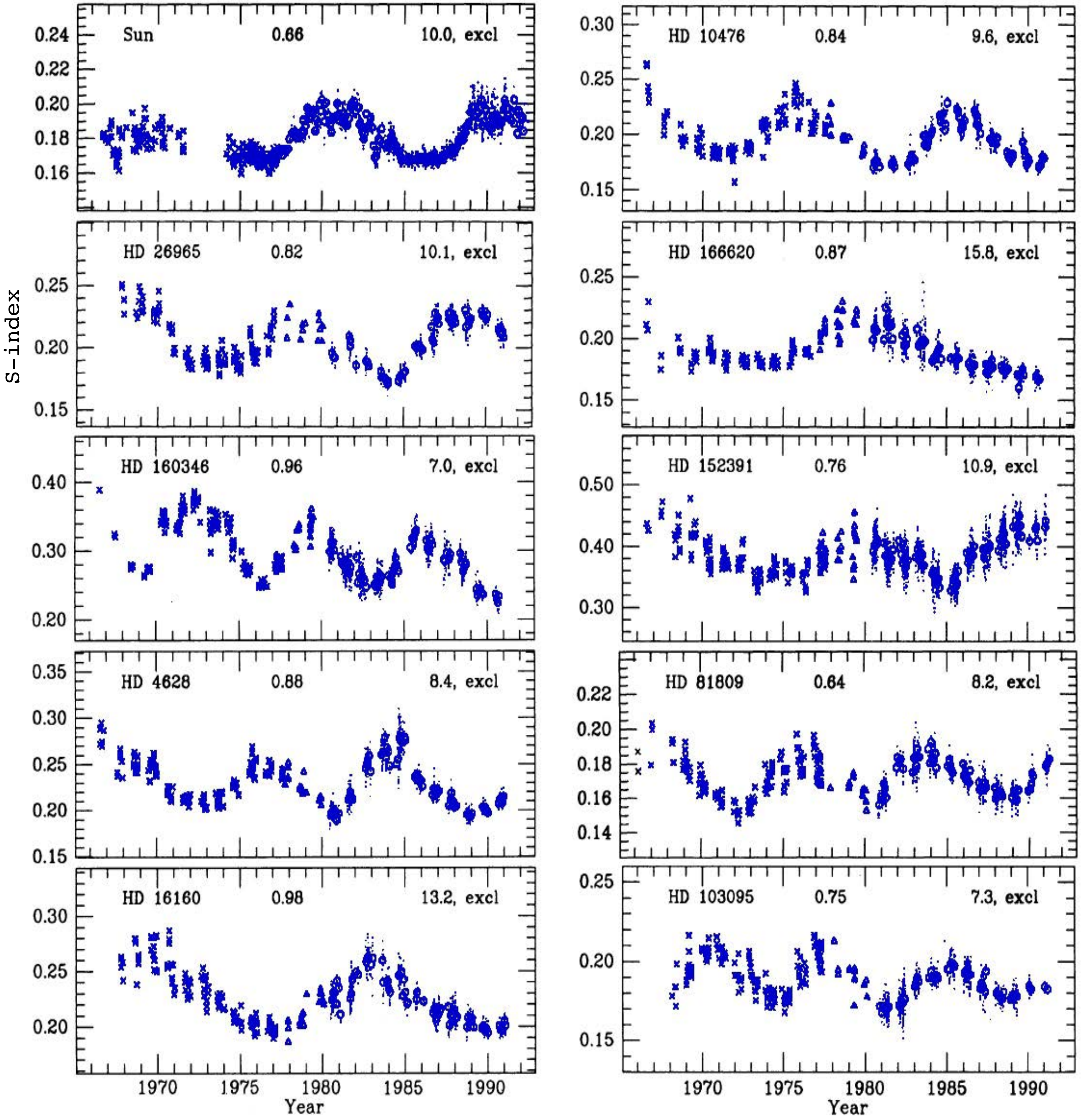
Sowmya et al 2021

Stellar activity cycles

Ca II observations

- Magnetic activity cycles found for many stars (survey at **Mount Wilson Observatory**)
- Survey ended in 2000's after more than 30 years of Ca II HK observations

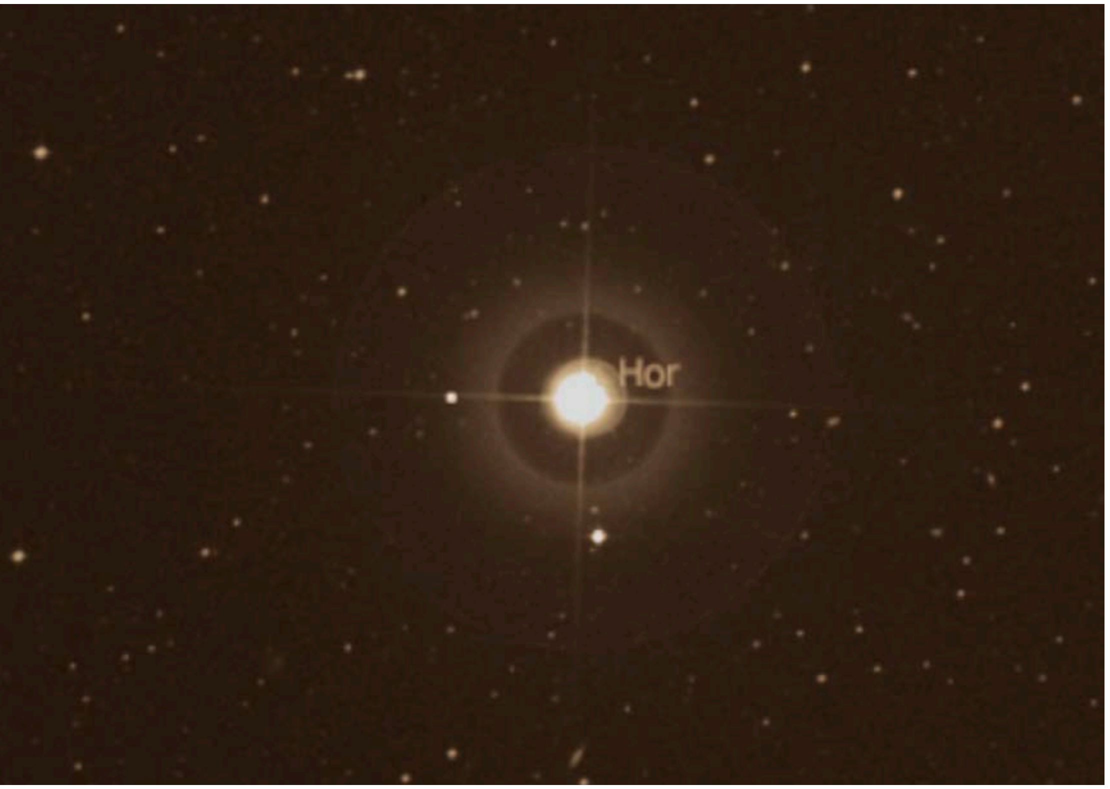


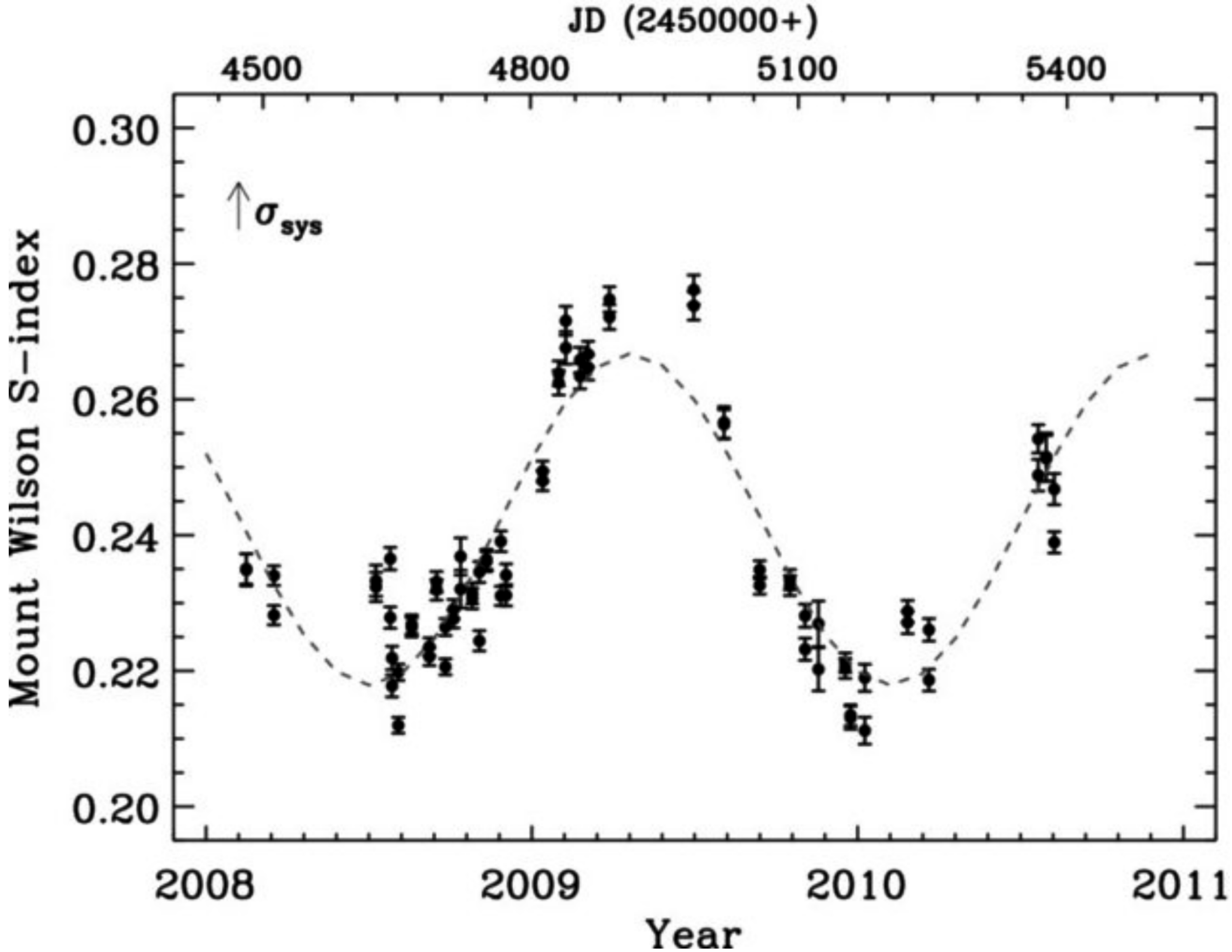


Baliunas et al. (1995)

Stellar activity cycles

Shortest measured stellar activity cycle in a solar-like star





Metcalfe et al 2010

- G0V star ι Horologii *(iota)*
- **Magnetic activity cycle of 1.6 yr**
- M=1.25 $M_\odot$
- R = 1.18 $R_\odot$
- Rotation period 8.5 d
- Rotation speed $v \sin i$ ~ *7 km* s^{-1}

➡ 3 times faster than the Sun, among the faster rotating stars of that spectral type

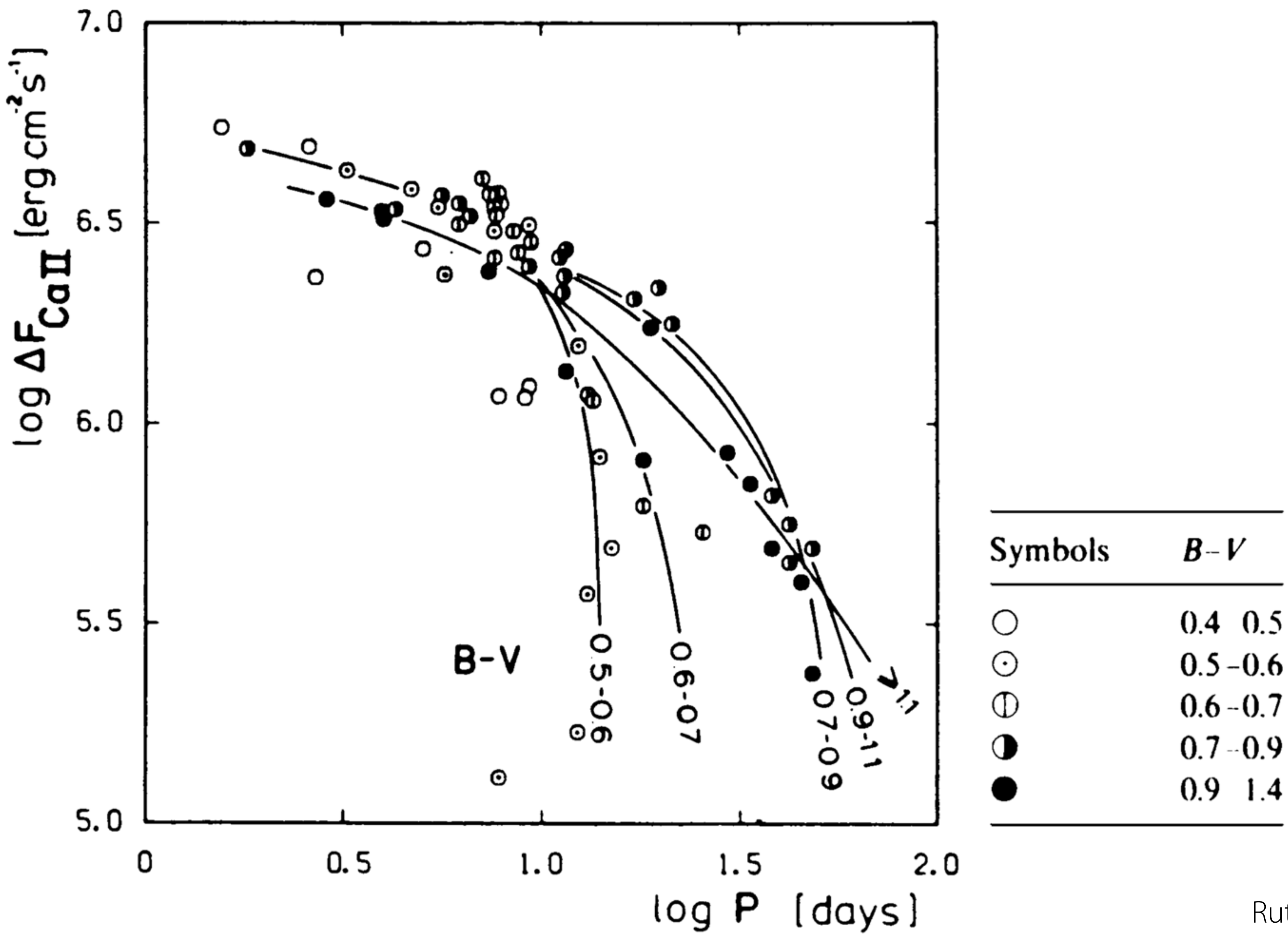
- Consistent with coronal activity cycle found from XMM x-ray measurements

Stellar activity cycles

Ca II observations

- Statistical analysis of many (cool) stars: Ca II flux vs. rotation period
- Increase of Ca II flux with decreasing rotation period

➡ Faster rotators have higher activity — generation of stronger magnetic field via a dynamo

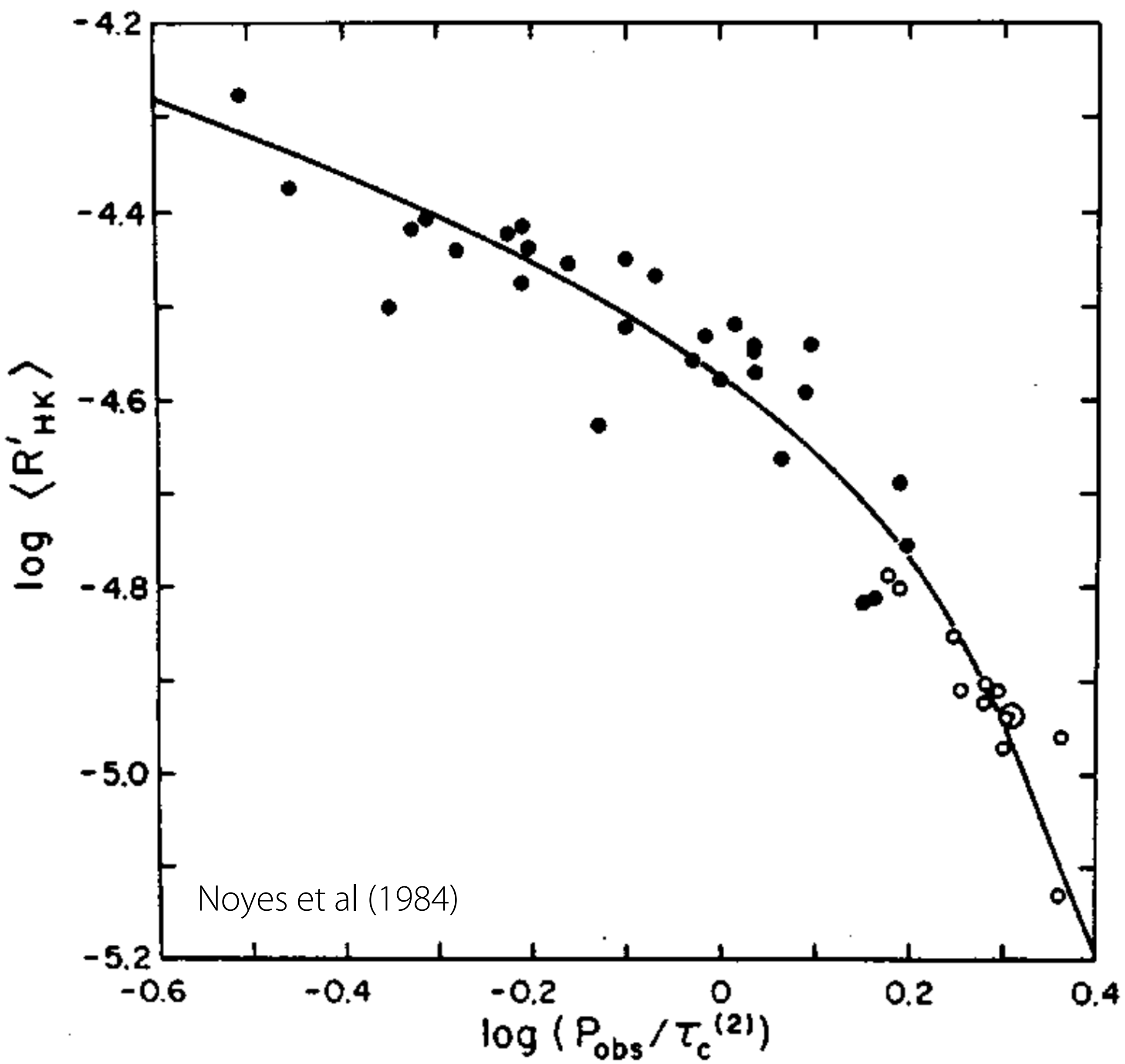


Rutten & Schrijver (1987)

Stellar activity cycles

Ca II observations

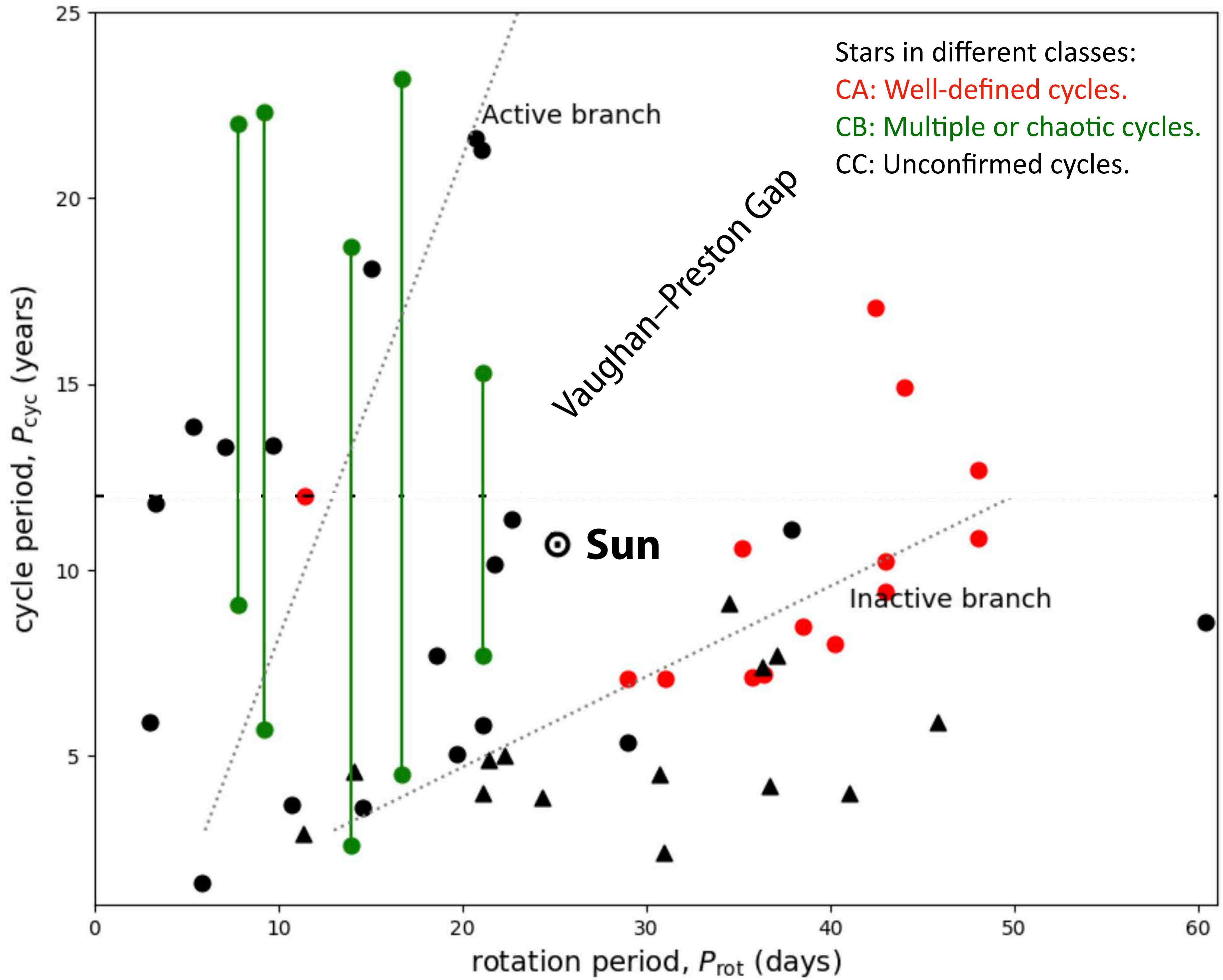
- Similar: Ca II activity indicator (R'_{HK}) vs. Rossby number
  (Rossby number: ratio of observed rotation period to convective turnover time)
- Clear indication of the **importance of stellar rotation and convection** for the efficiency of stellar dynamos and the resulting (magnetic) activity level



Stellar activity cycles

Activity cycle vs. rotation

- Statistics for many stars shows trend:
- Longer activity cycles for longer rotation periods
- Range between **active branch** (stars with strong activity) and **inactive branch** (stars with weak chromospheric activity)
- Branches divided by Vaughan–Preston Gap
  - *Due to properties of stellar dynamos?*
  - *Or a statistical artefact?*



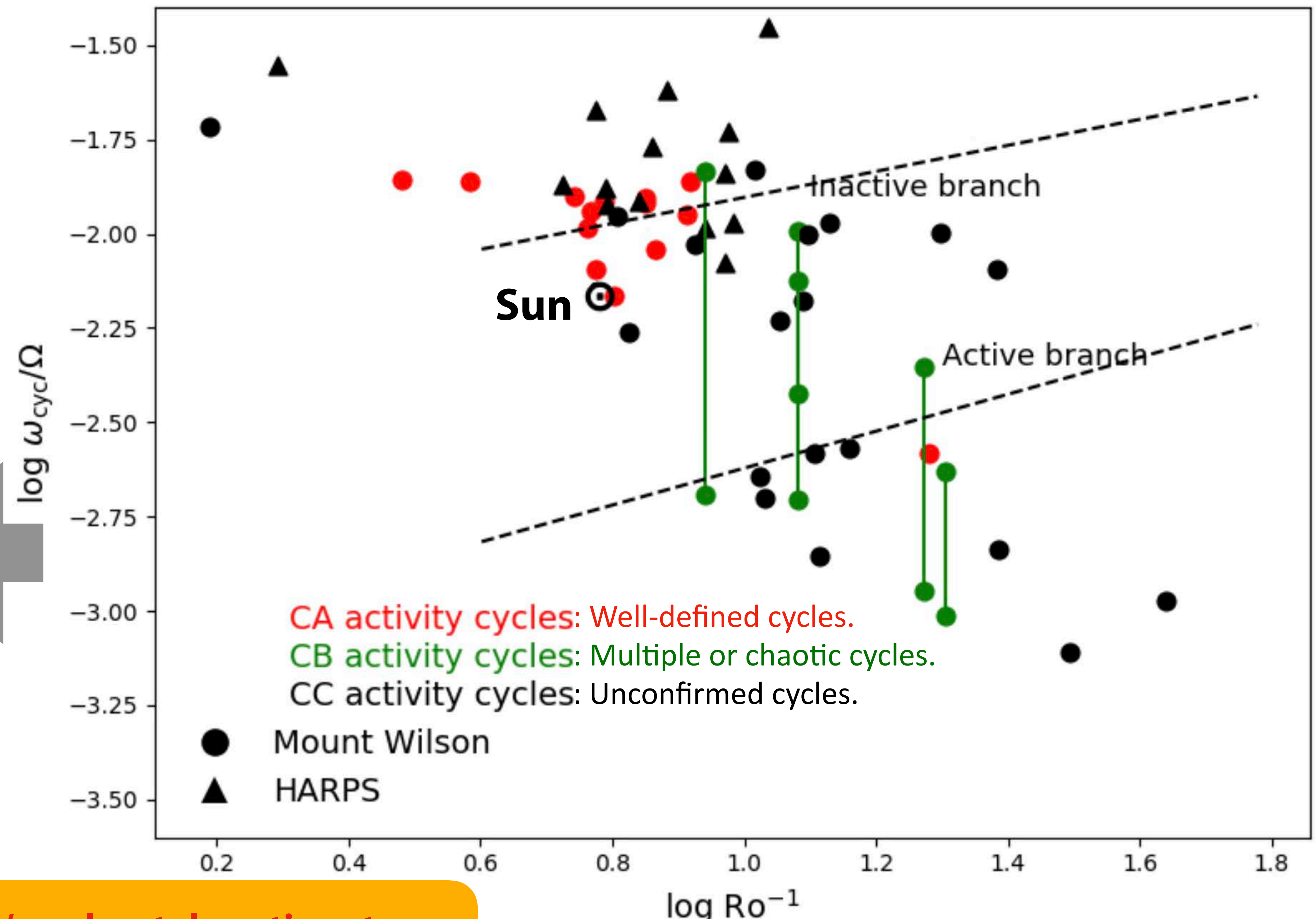
Boro Saikia et al. (2018) A&A 616, A108 (2018)

Stellar activity cycles

Activity cycle vs. rotation

- For same stars: ratio of cycle frequency $\omega_{\rm cyc}$ and rotation rate Ω vs. Rossby number Ro
- Remember:
  Rossby number =
  ratio of inertial to Coriolis forces
  (Ratio of rotation period to convective turnover time)
- Dependence of activity cycle and Rossby number

➡ Properties of the global dynamo of stars and thus their activity cycles depend on Rossby number and rotation rate



Boro Saikia et al. (2018) A&A 616, A108 (2018)

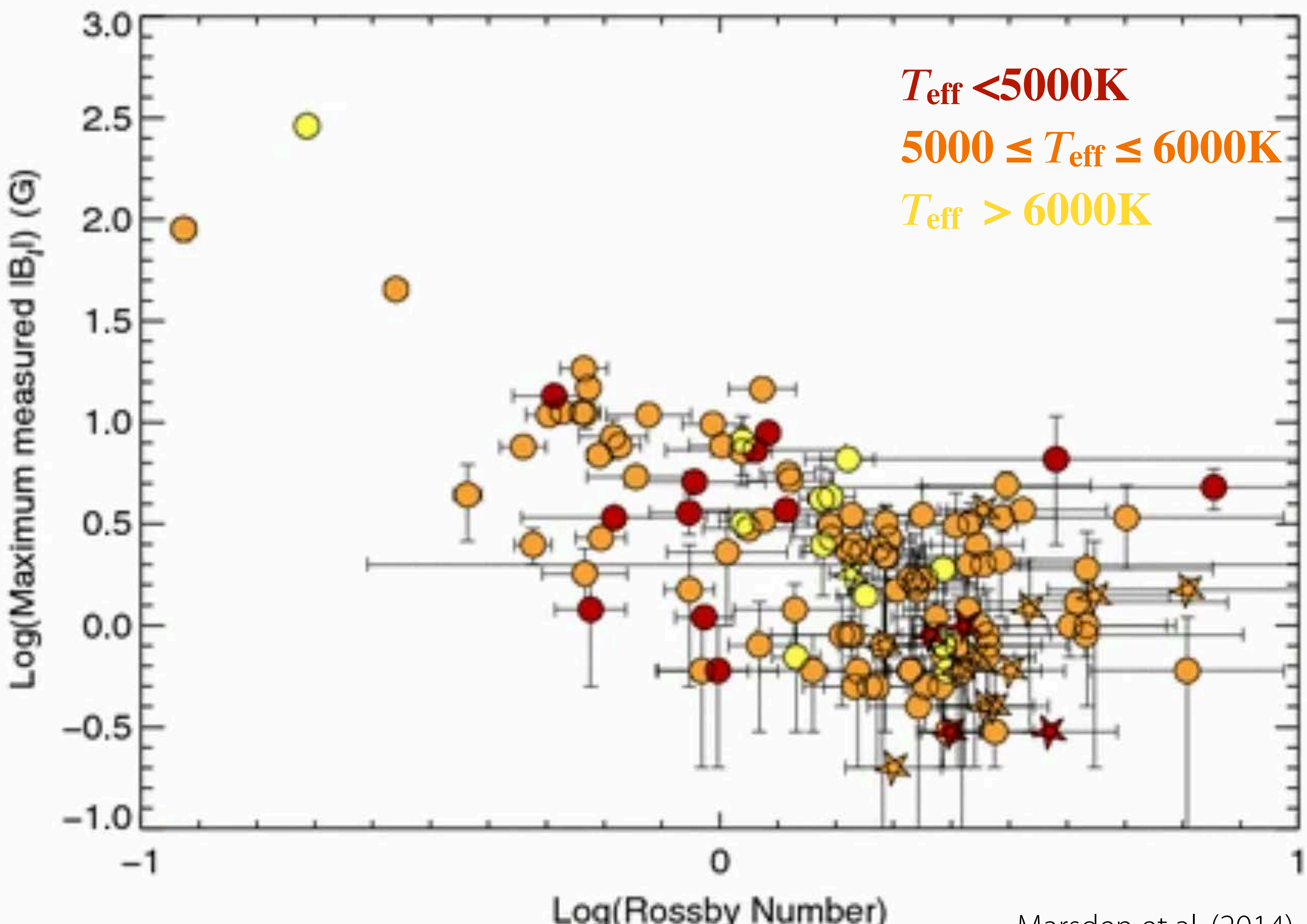
➡ **The Sun is only a weakly/moderately active star.**

Stellar activity cycles

Stellar dynamos

- BCOOL survey: Magnetic field strength correlates with Rossby number in solar-like stars and subgiants.

- Trend: Stronger magnetic fields for smaller Rossby numbers
- Supports rotation being important for global stellar dynamos and thus the generation of magnetic field

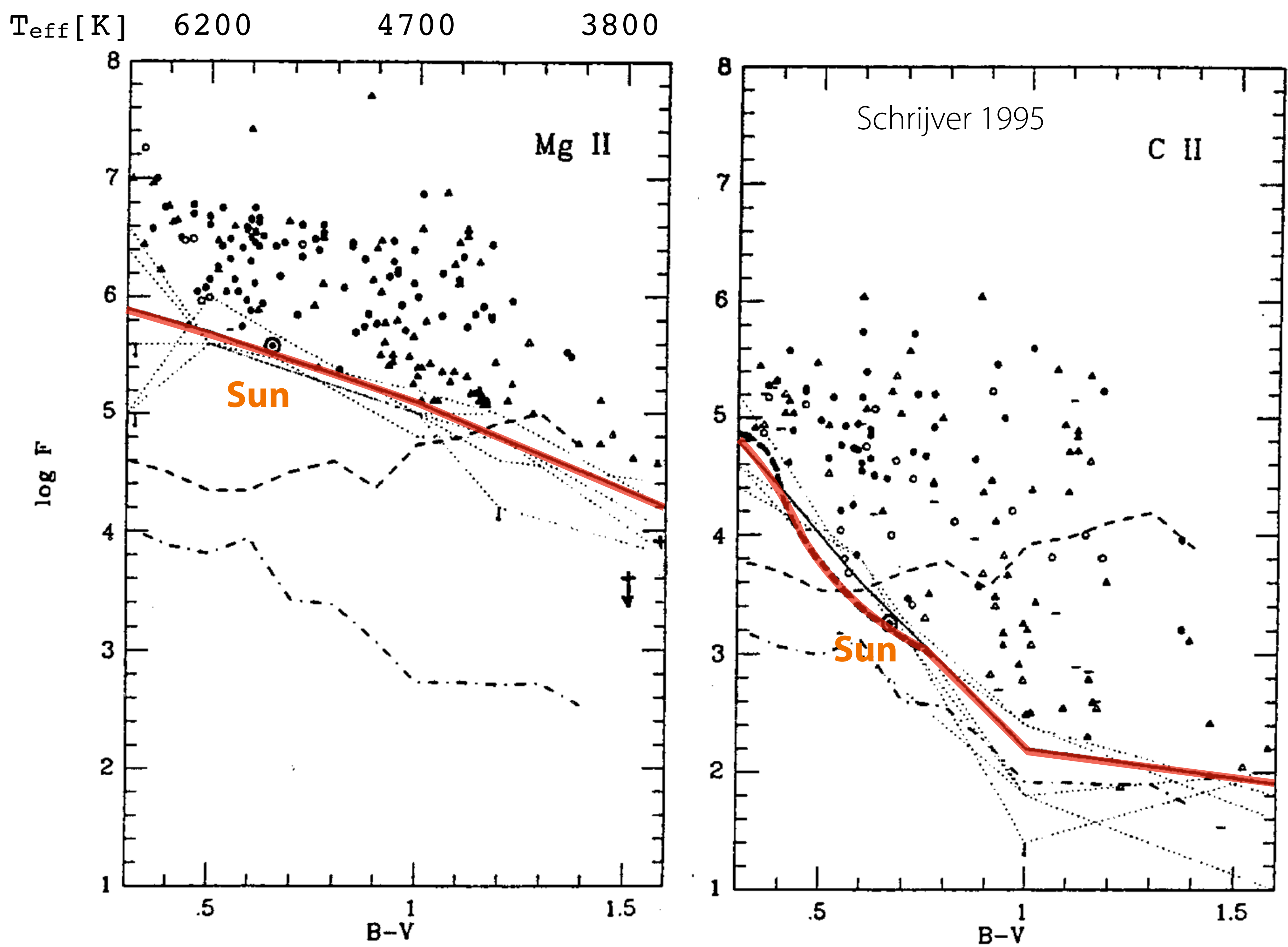


Marsden et al. (2014)

Stellar activity

Basal flux limit

- Next to Ca II, spectral lines of other species used as activity indicators (here Mg II and C II)
- Large spread in values for the flux in these lines
- Lower limit: **Basal flux limit**
- (Was) thought of being produced by acoustic waves that would be present even for a star without magnetic field (Biermann 1948; Schwarzschild 1948)



- **Wilson-Bappu Effect (1957):** Linear relation between the absolute magnitude and log of Ca II K line widths for G-type and later stars (dwarfs and giants)

$M_v = 27.59 - 14.94 \log W_o$

Stellar activity

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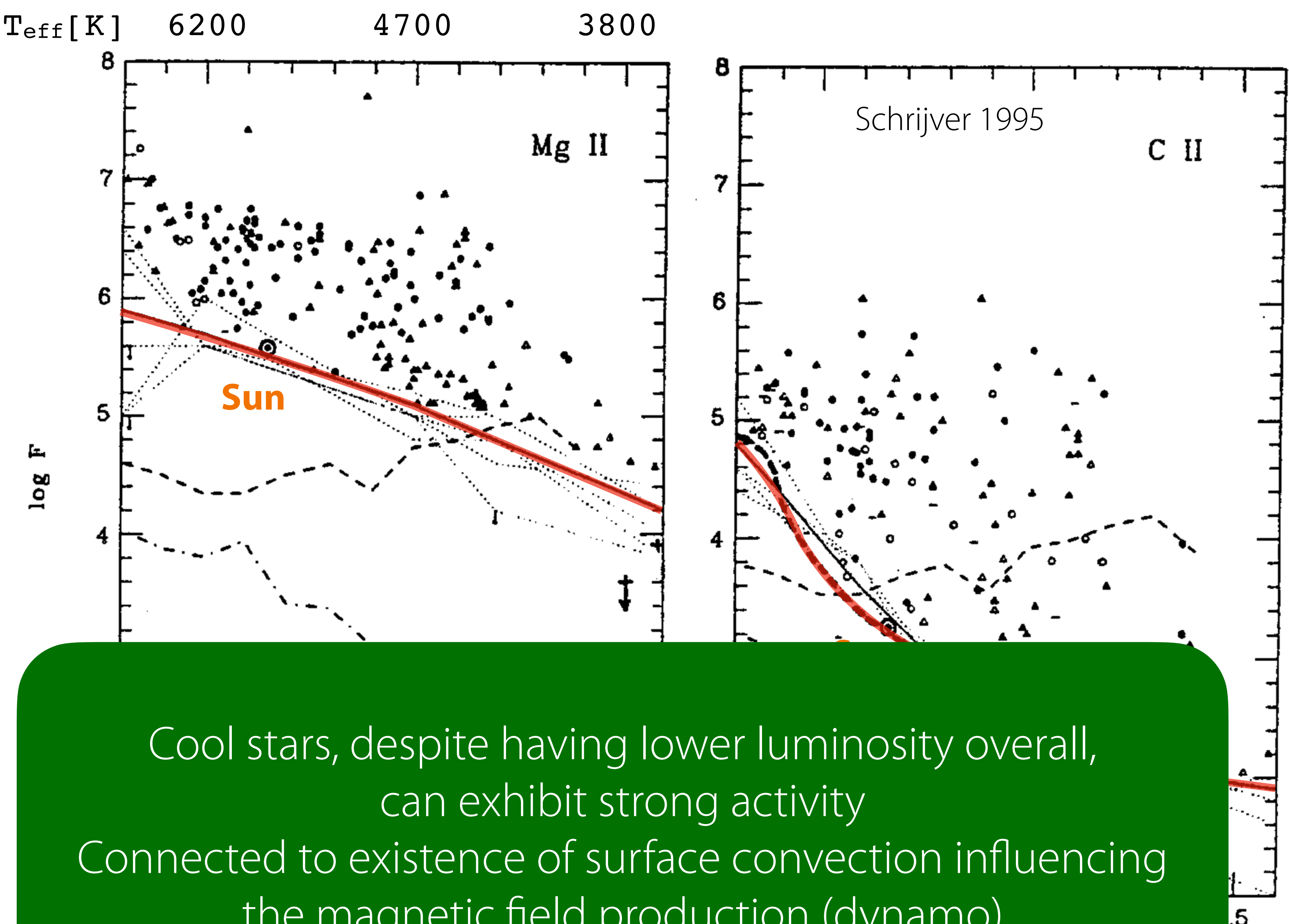


Cool stars, despite having lower luminosity overall, can exhibit strong activity
Connected to existence of surface convection influencing the magnetic field production (dynamo)

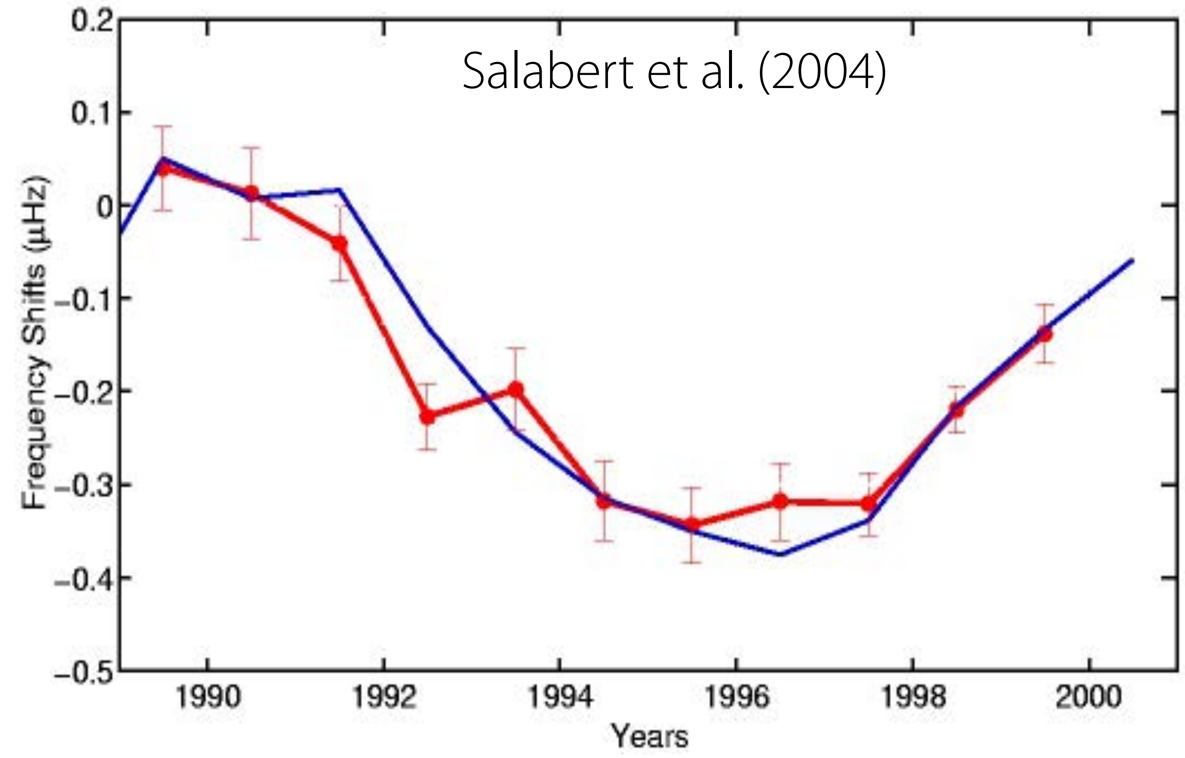
Stellar activity cycles

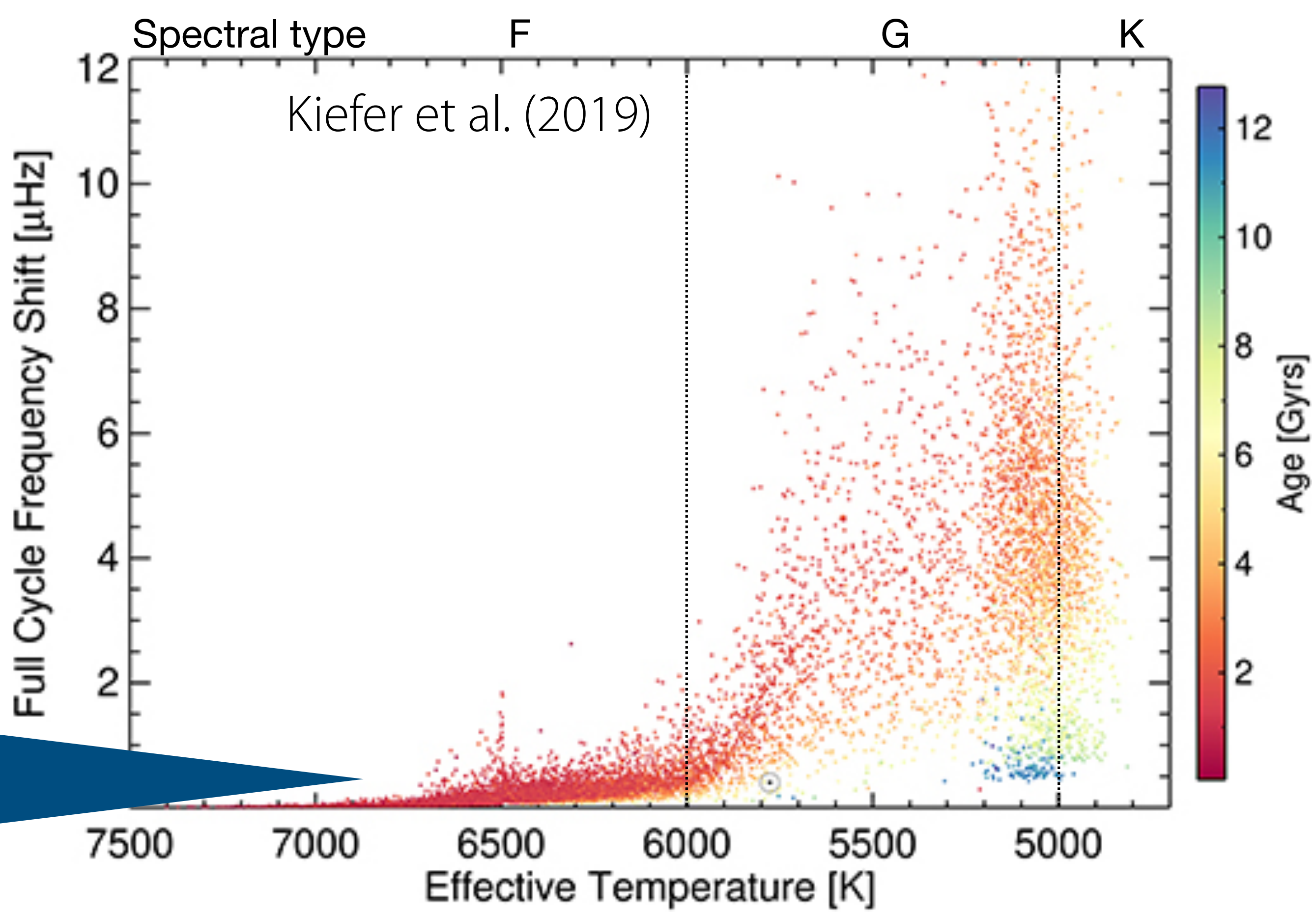
Impact on stellar oscillations

- Magnetic field modifies the near-surface propagation speed, convective velocity and interior stratification

  ➡ Results in frequency shifts of p-modes!
- Solar p-mode shifts first detected in 1990, depend on frequency and degree
- Even the lowest degree solar p-modes are shifted by the magnetic cycle
- The amplitude of shifts depend on stellar properties (spectral type, T_{eff}, age…)

➡ Asteroseismology can provide additional constraints for stellar activity cycles





- Note the effect being much smaller for F-type stars

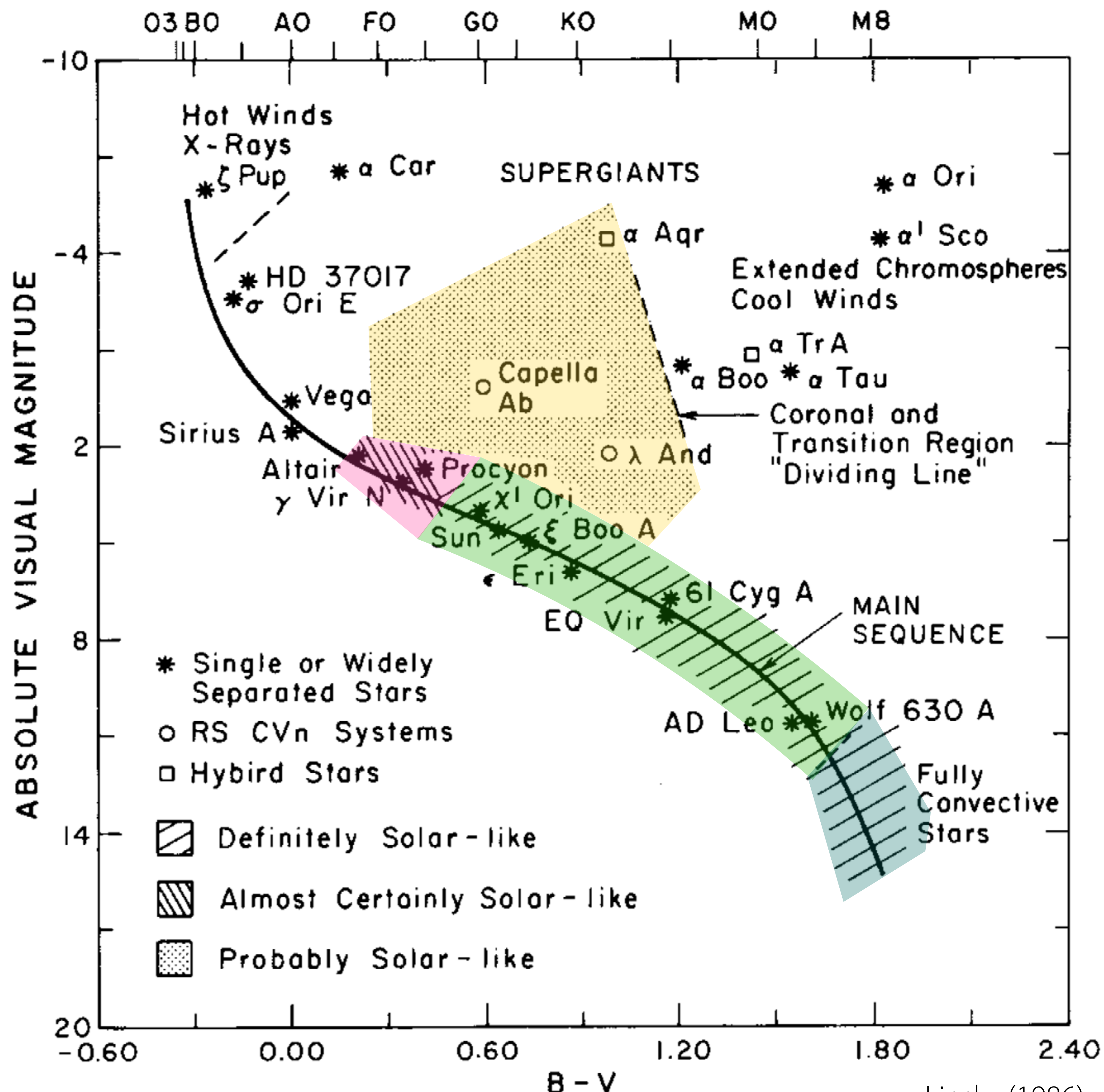
➡ Global dynamo needs surface convection

➡ Found for cool stars, not for hot stars

Stellar activity

Across the HRD

- Activity across the HRD as indicated by the existence of chromospheres (and coronae), resulting emission (e.g. Ca II), and (measurable) magnetic fields
- Clearly connected to presence of surface convection



Linsky (1986)

Stellar dynamos

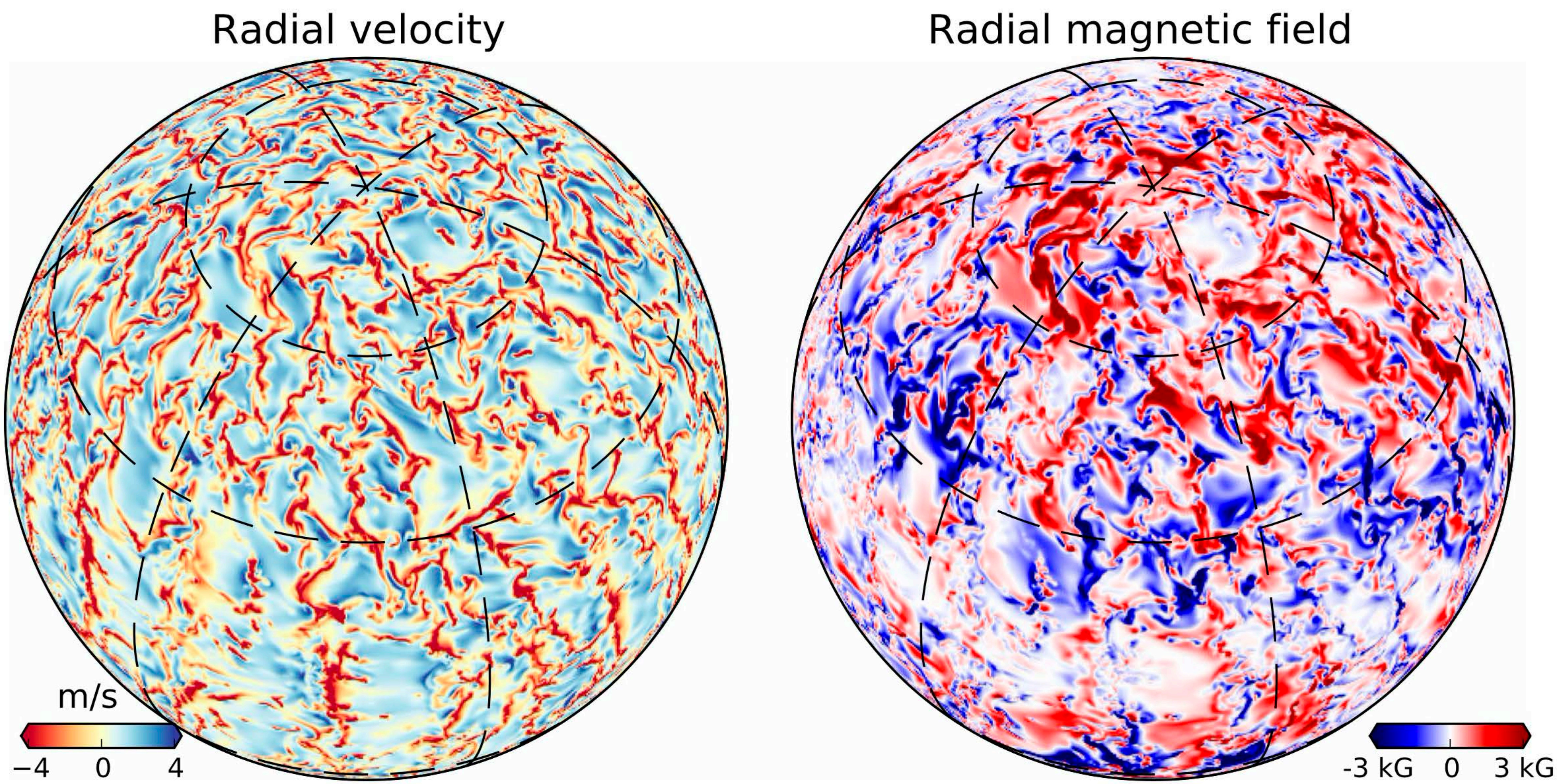
Fully convective stars

- Stars with low mass $M < 0.3\text{-}0.4 M_\odot$ are fully convective
  - No inner radiative zone and no tachocline
  - ➡ How do they generate the strong magnetic fields / activity that are/is observed?
- Observational challenging: stars at and beyond transition (sp. type > M5) are very faint objects, reliable magnetic field measurements etc. difficult
  - BUT: coolest stars seem to be active (detected H α in emission with no obvious discontinuity, flares observed for very cool M-dwarfs)
  - Relationship rotation rate — activity level poorly known for M-type dwarf stars
  - Many M-dwarfs relatively rapid rotators
- Theoretical models succeed in explaining dynamos for fast rotating low-mass stars but still difficult for slower rotators

Stellar dynamos

Fully convective stars

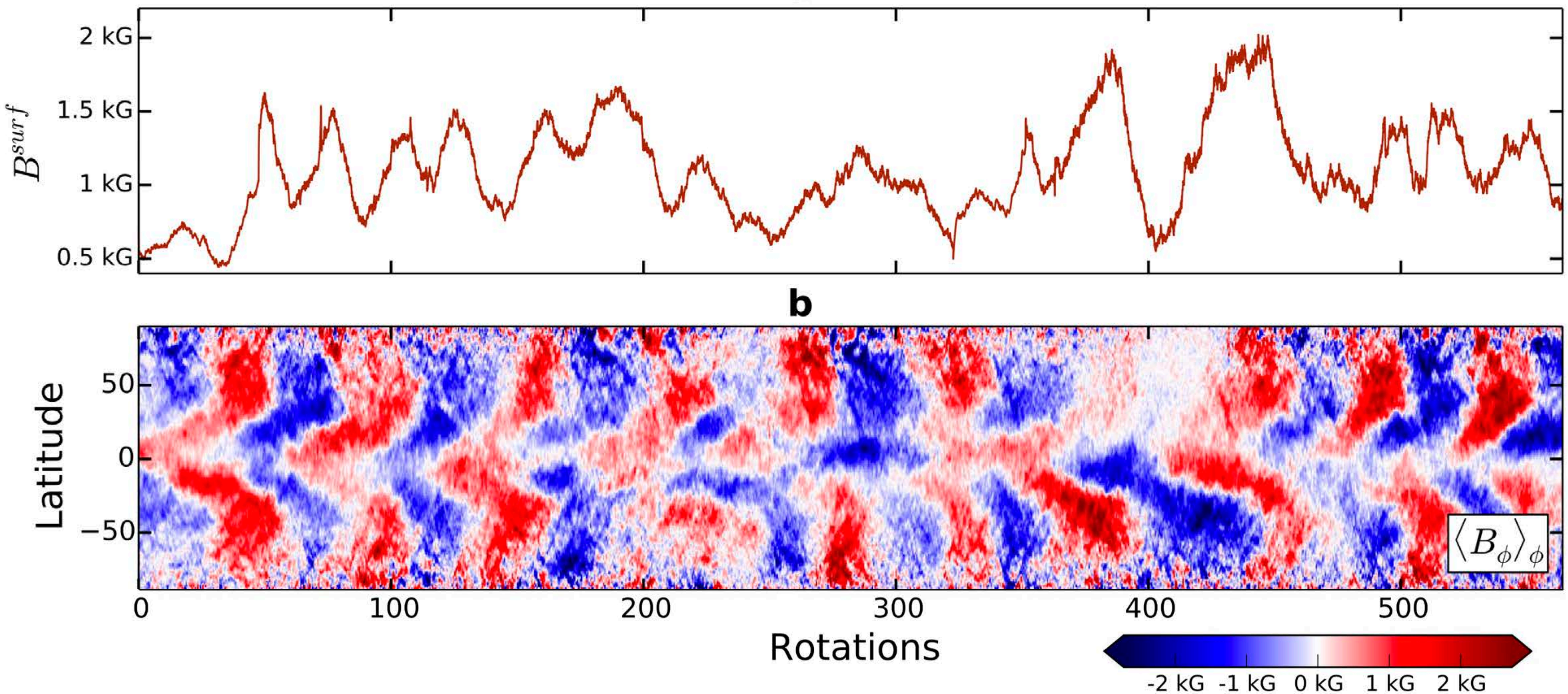
- **Example: Proxima Centauri** — representative of slowly rotating fully convective M-dwarfs
- Numerical simulations (Yadav et al. 2016) show **rotating convection spontaneously generates differential rotation** in the convection zone (without the need of a tachocline)



Stellar dynamos

Fully convective stars

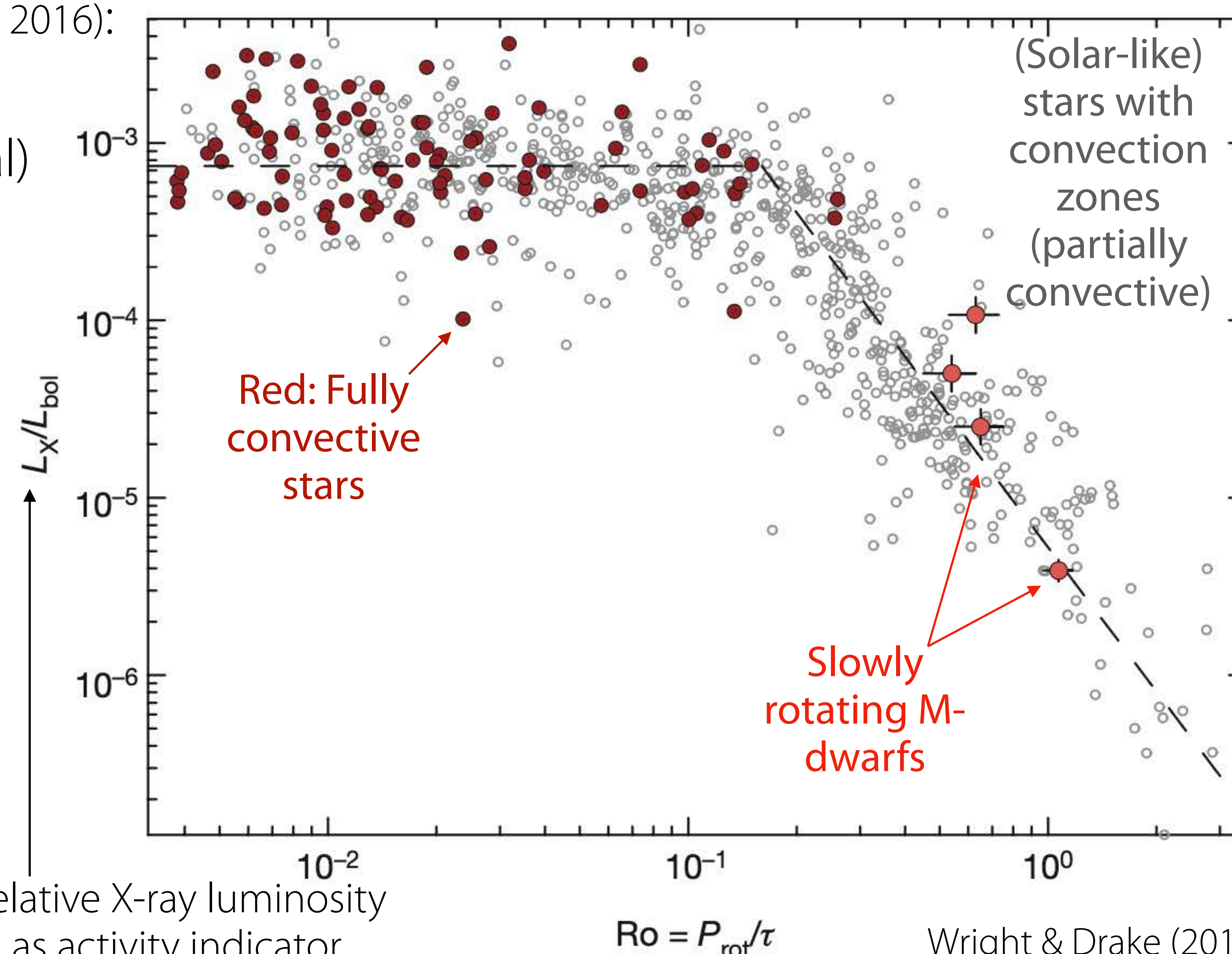
- **Example: Proxima Centauri** — representative of slowly rotating fully convective M-dwarfs
  - Drives magnetic cycles with axisymmetric magnetic field repeatedly changing polarity at all latitudes as time progress.
  - Resulting cycle length of ~9yr in line with observations of Proxima Centauri



Stellar dynamos and activity

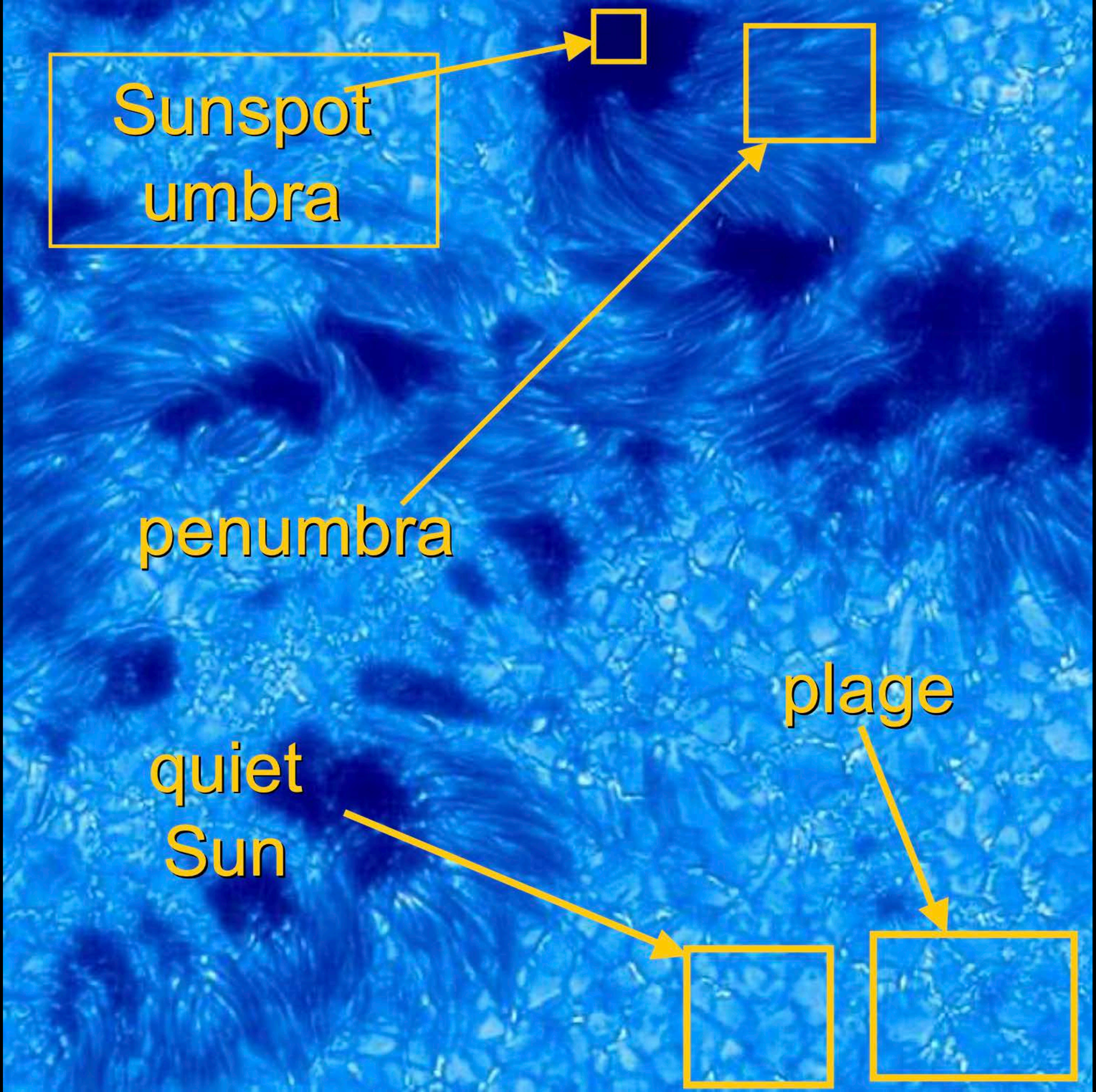
Rotation-activity relation

- Despite lack of a tachocline: Fully convective M-dwarfs fit the same rotation–activity sequence as solar-type stars with outer convection zones!
  - Activity and magnetism of late-type stars increase with decreasing Rossby number, then saturate
- Most likely explanation (Wright & Drake 2016):
  - Both rotation and turbulence (convection) important for (global) dynamos in all late-type stars (Lehtinen et al 2020)
  - Fully and partially convective stars have rotation-dependent dynamos that share important properties
  - Tachocline not a vital ingredient. — **Differential rotation** **+ Coriolis force is sufficient!**
  - **Still many open questions, active field of research!**

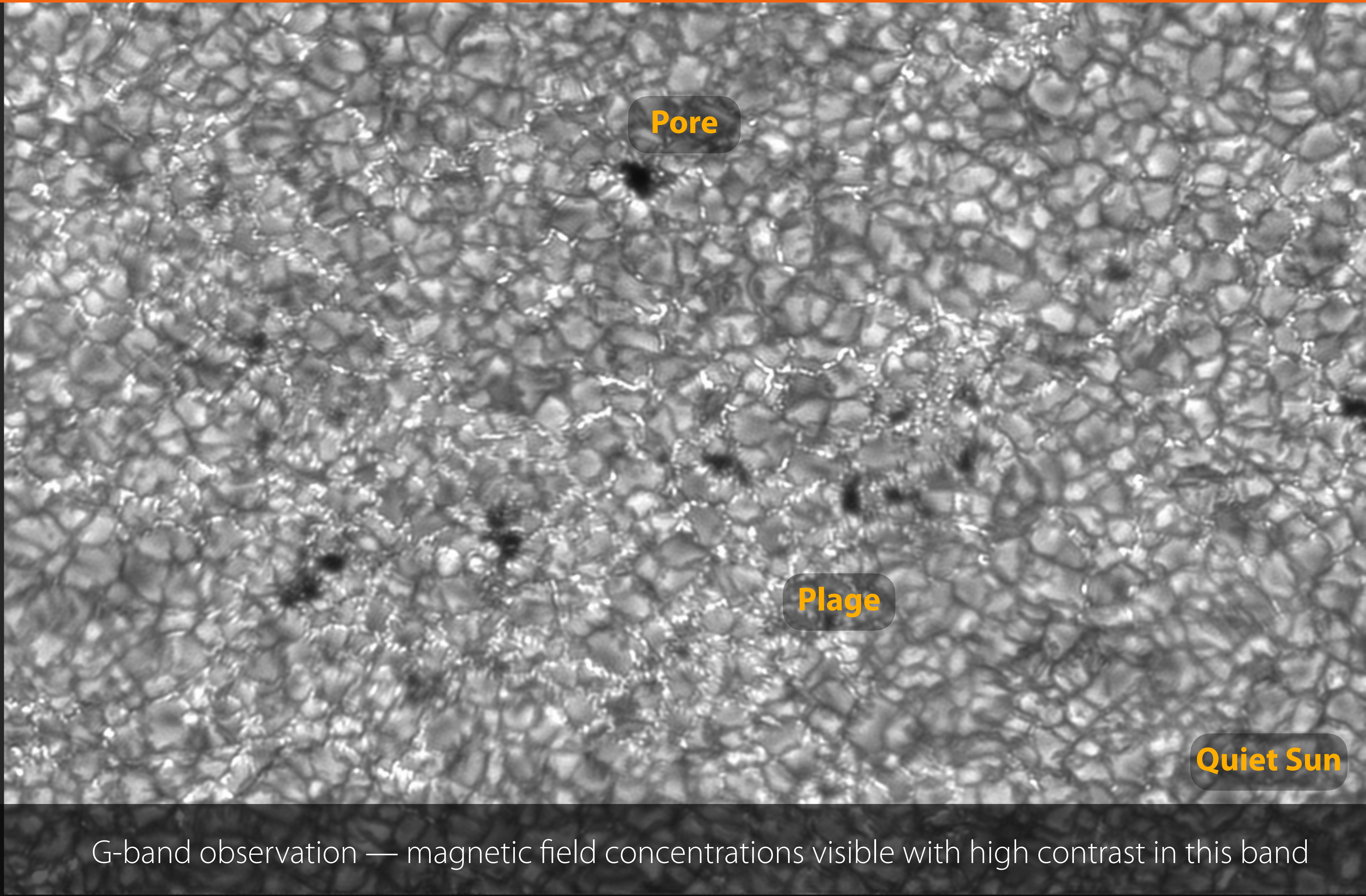


Wright & Drake (2016)

Magnetic field in the solar atmosphere


Sunspot umbra
penumbra
quiet Sun
plage

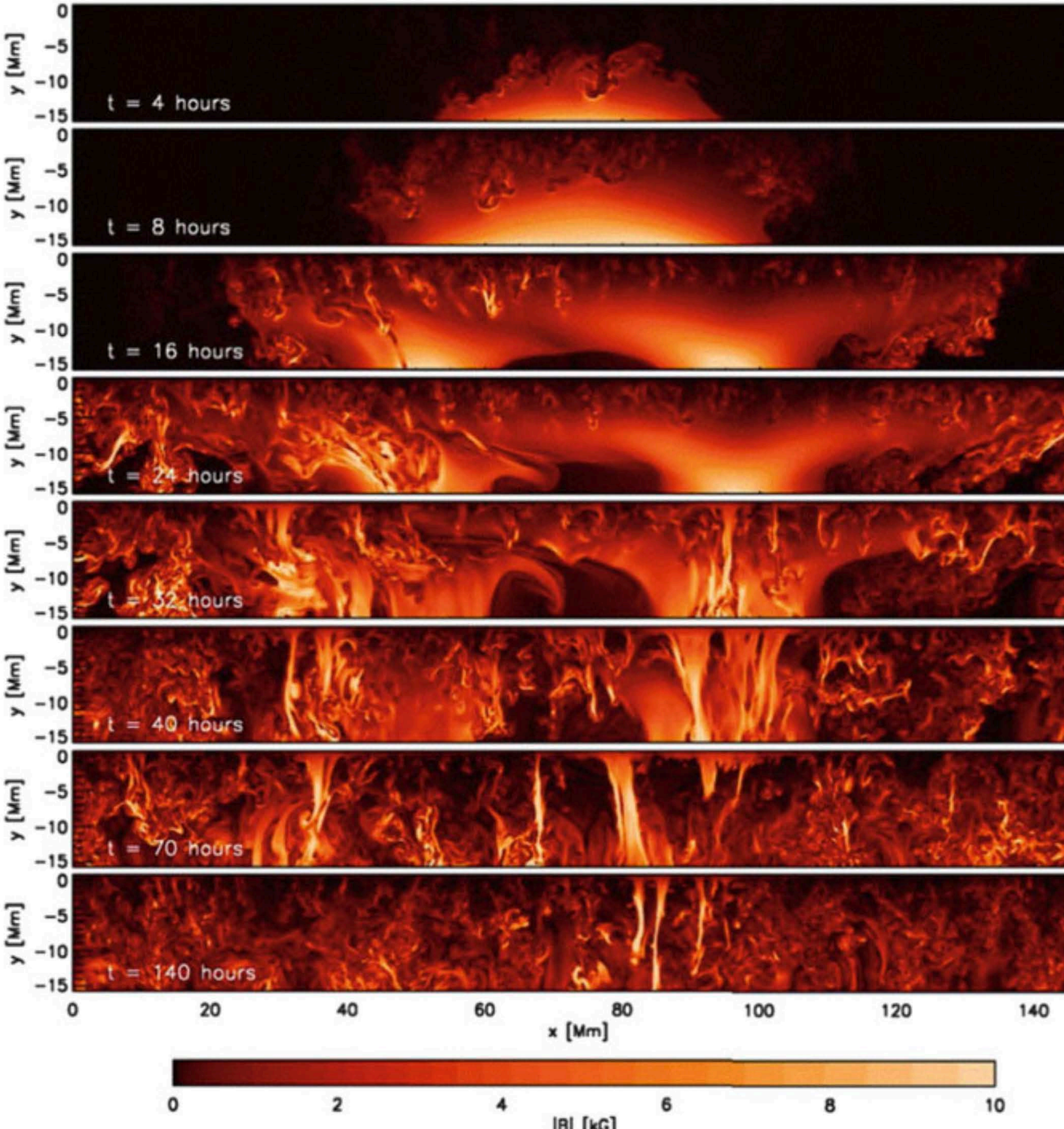
Magnetic field in the solar atmosphere



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

Mag. field

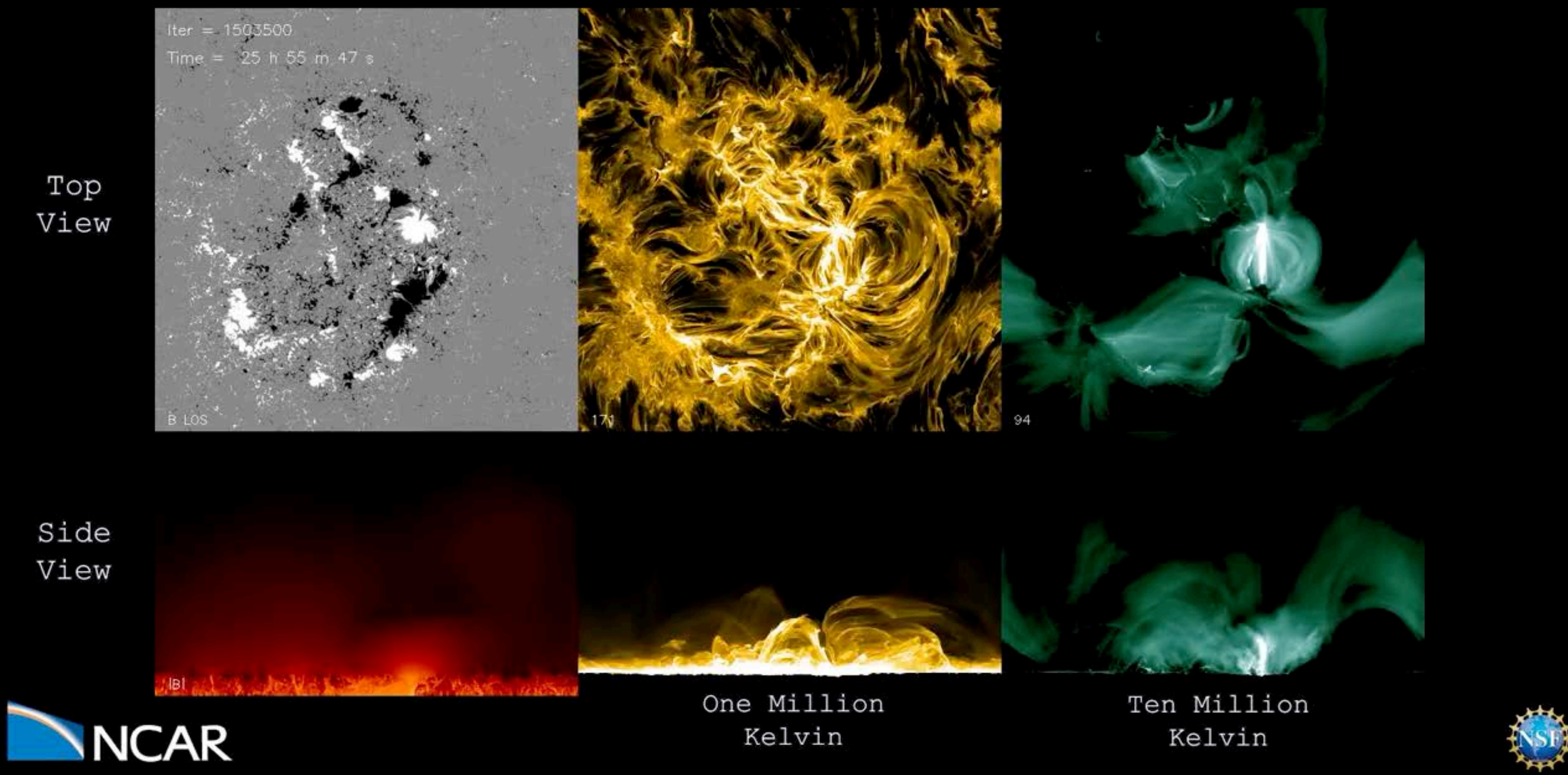
Flux emergence



Rempel & Cheung (2014)

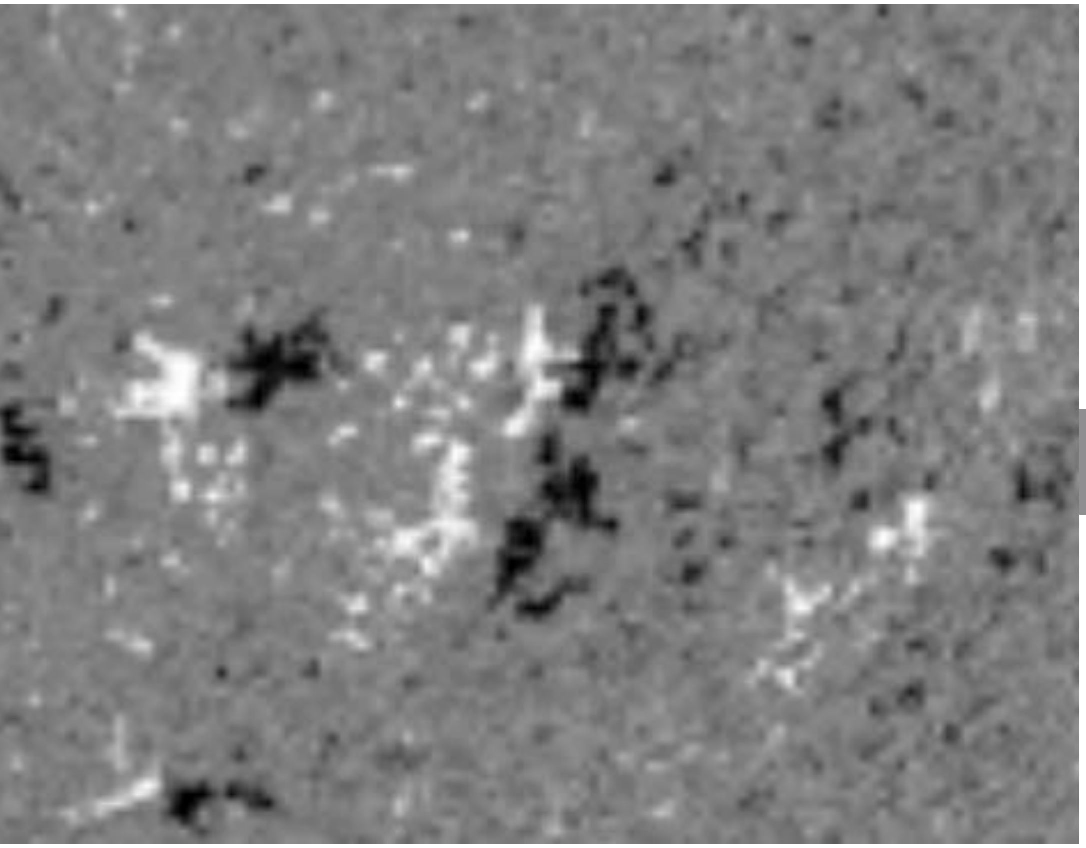
Magnetic field in the solar atmosphere

Flux emergence



Magnetic field in the solar atmosphere

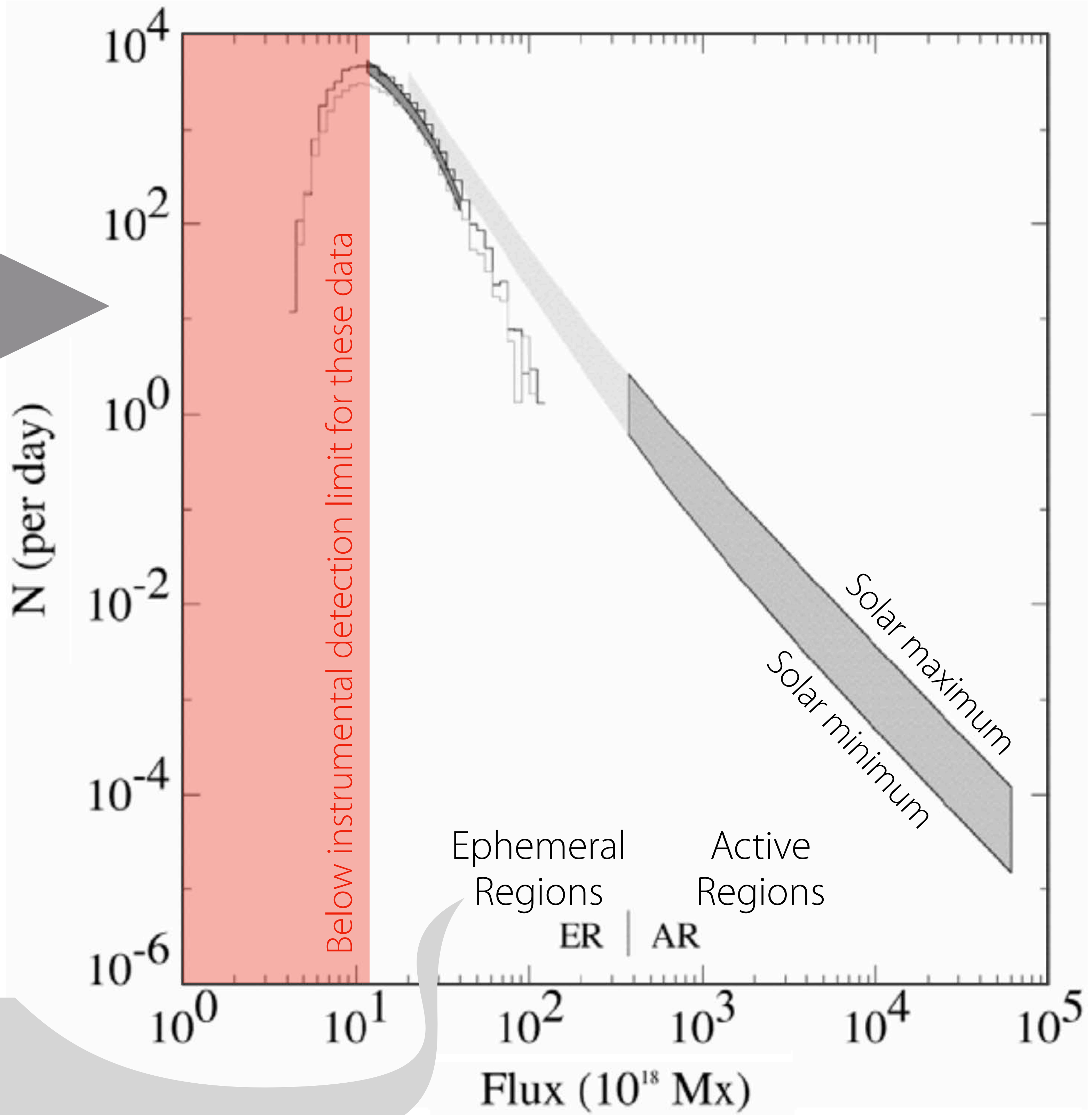
Flux emergence



- Emergence of bipolar regions with a large range of contained magnetic flux
  - Many regions with little flux, fewer with a lot of flux
- Varies over solar cycle

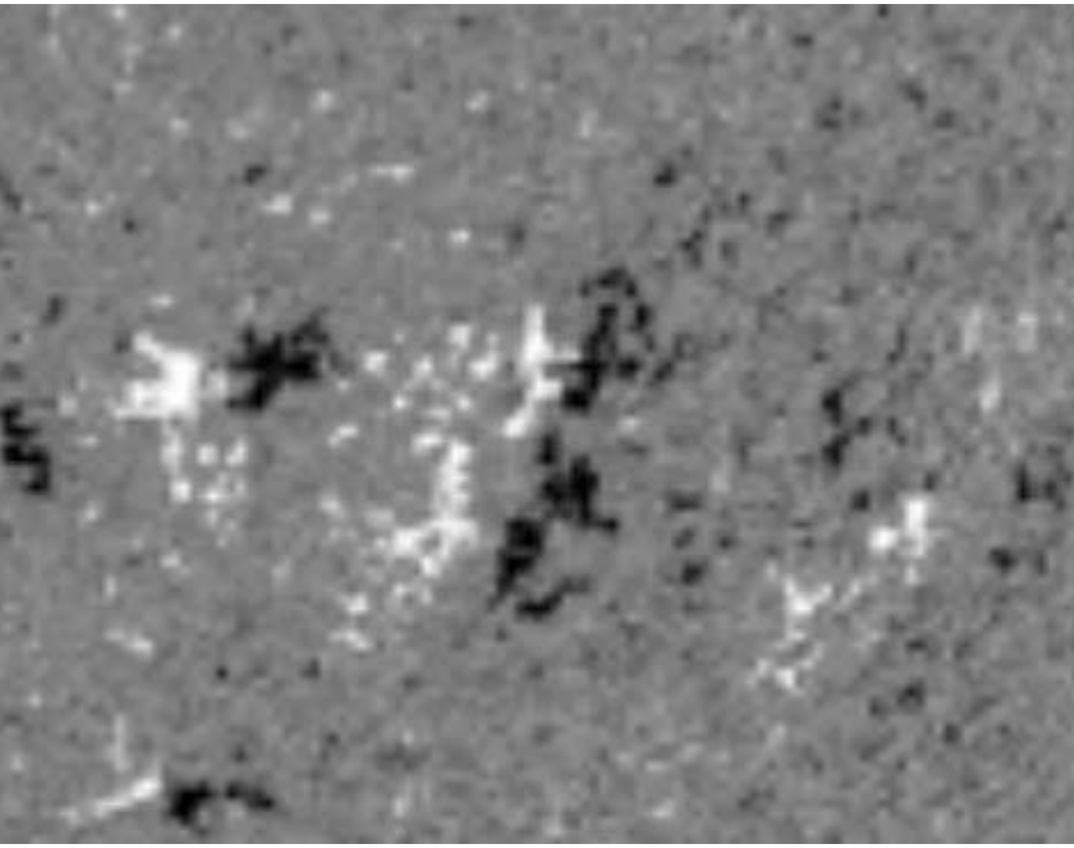
Ephemeral regions = short-lived, small bipolar regions (do not develop sunspots)

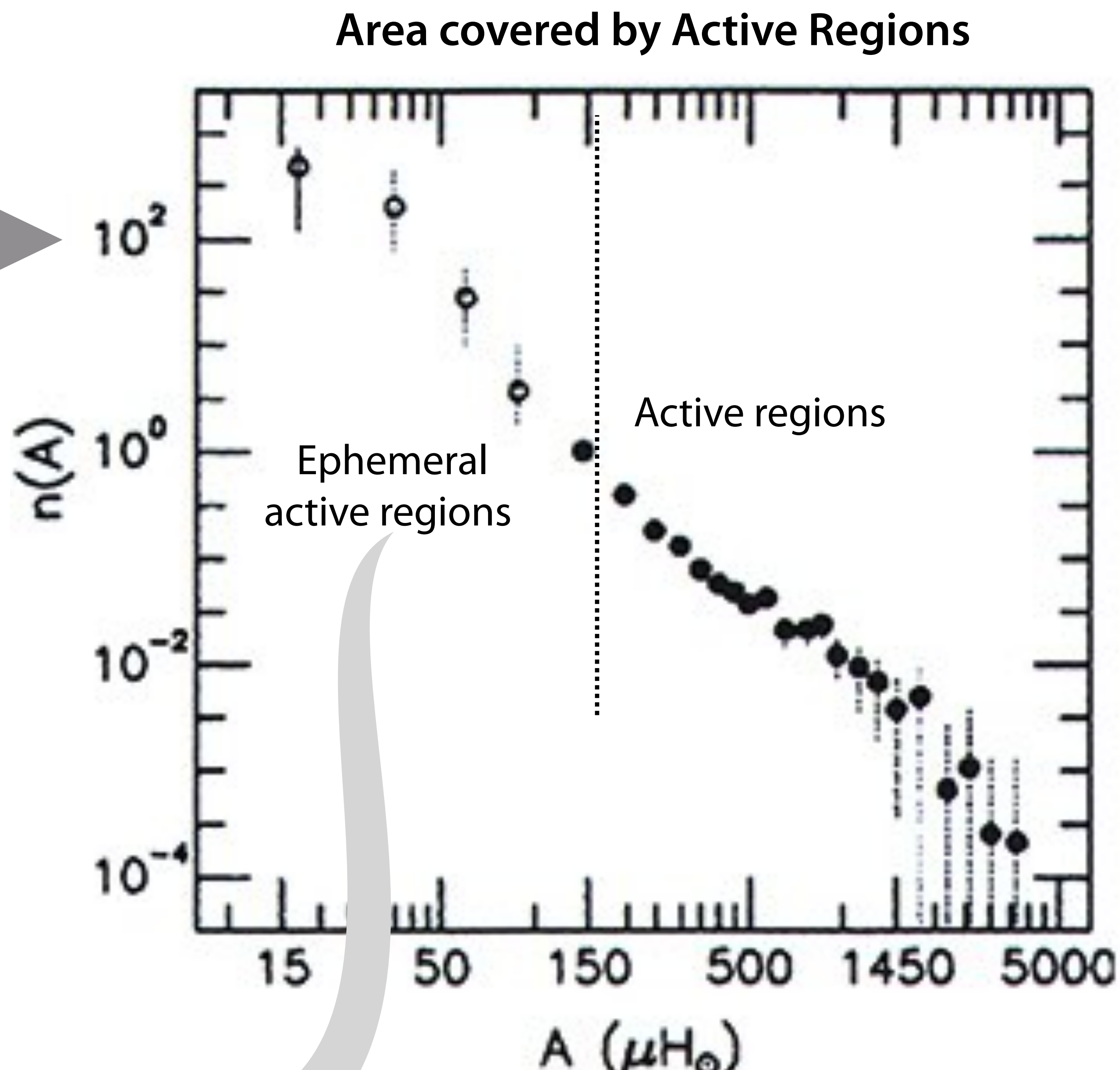
Emergence rate of bipolar regions per (unsigned) flux



Magnetic field in the solar atmosphere

Flux emergence





Martin (2018)

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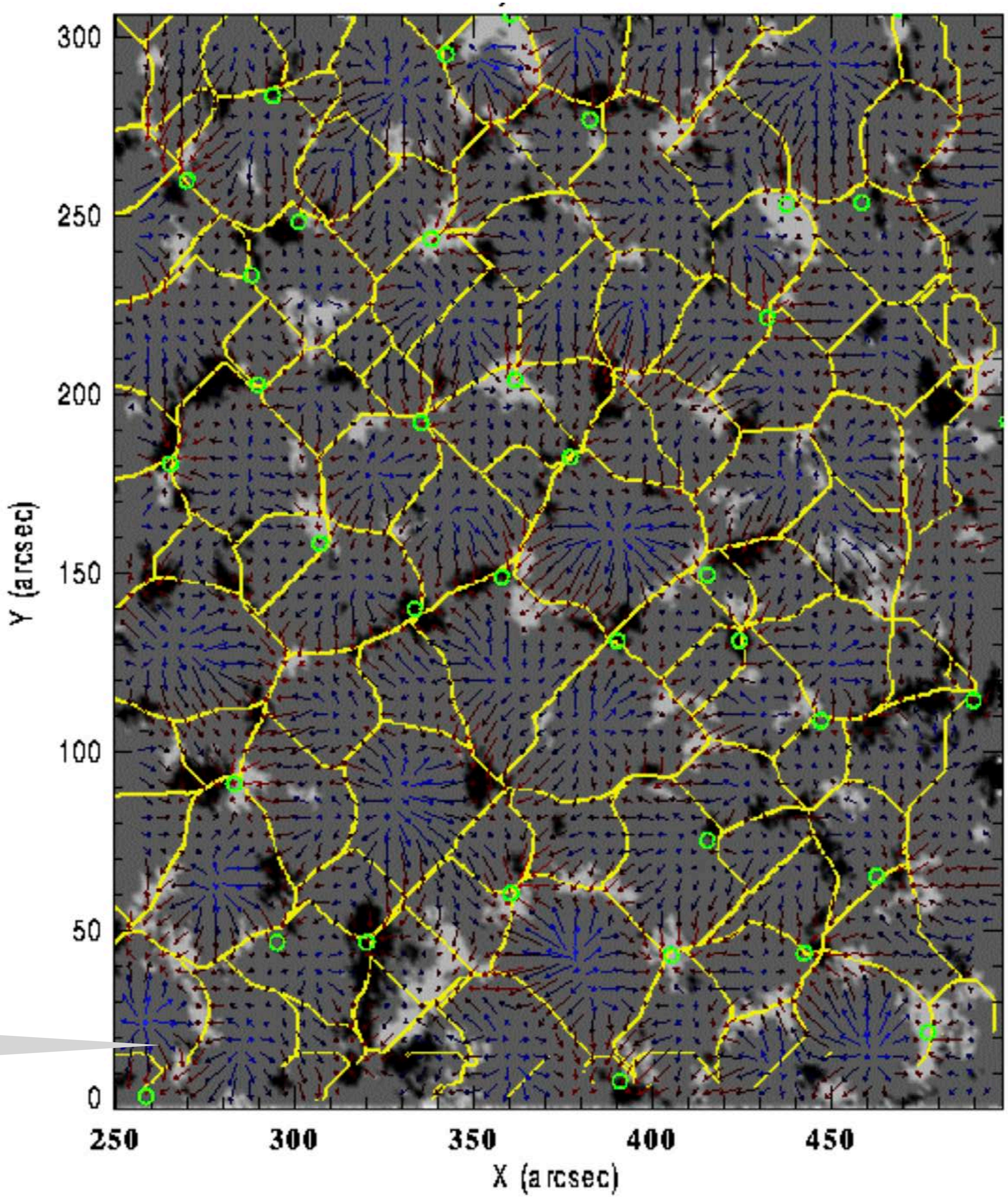
Magnetic field in the solar atmosphere

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**

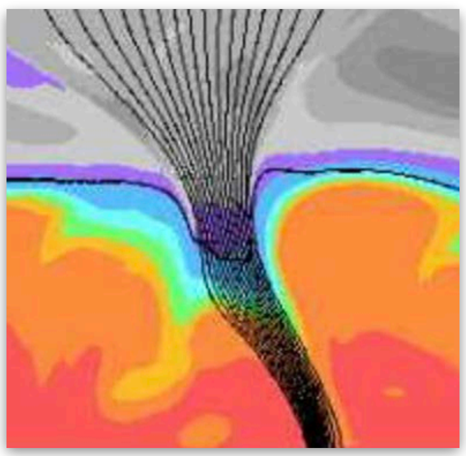


- Magnetogram (grayscale)
- Horizontal flow field (arrows)
- Supergranule boundaries: yellow

Magnetic field in the solar atmosphere

Advection — granulation scales

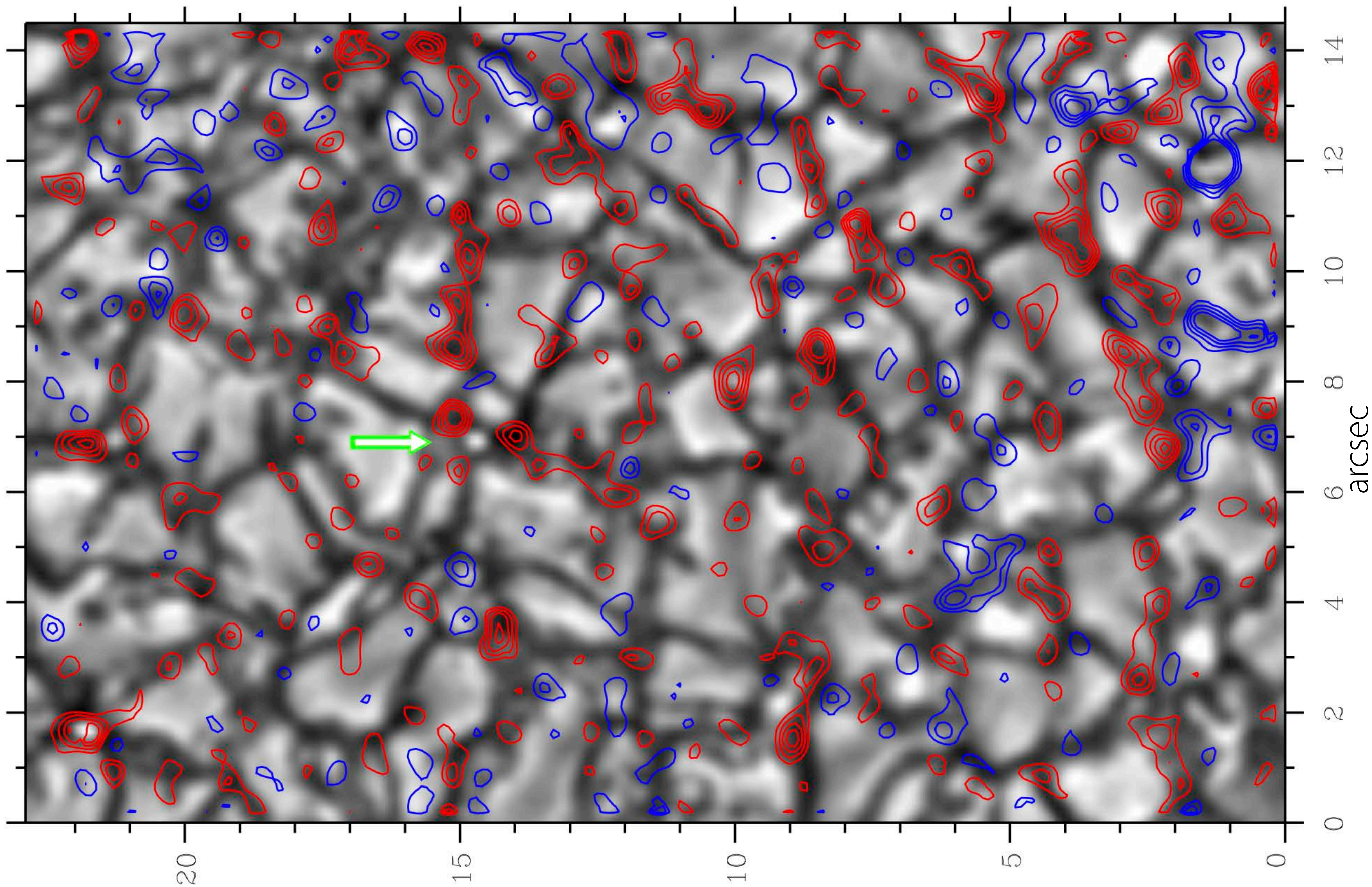
- Advection into intergranular lanes (downflow lanes between granules)
- Concentration into stronger flux concentrations but fewer than in the network



Granulation image, Fe I 630.25 nm line

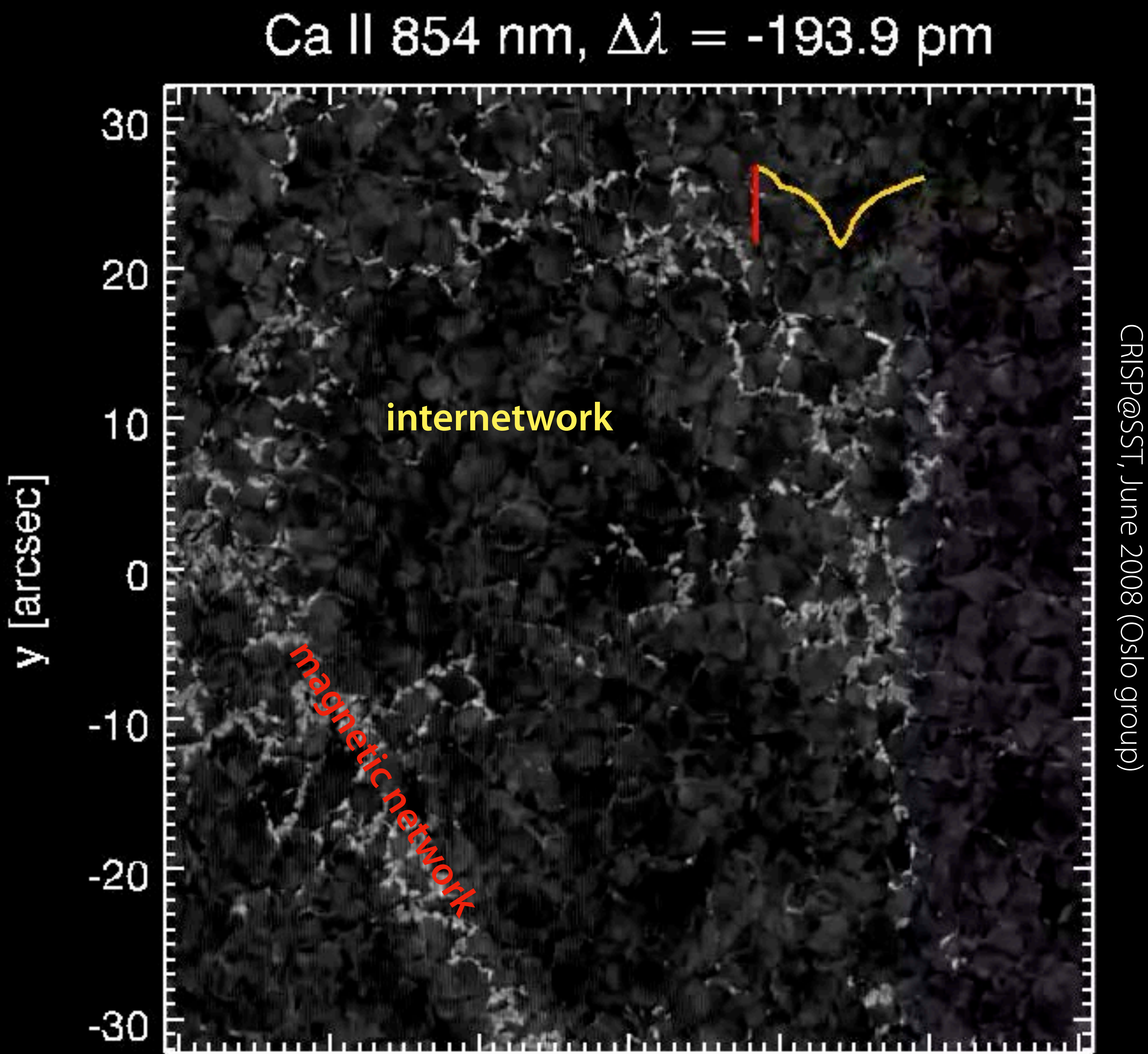
Overlaid magnetogram contours 30, 50, 70 and 90 G

(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

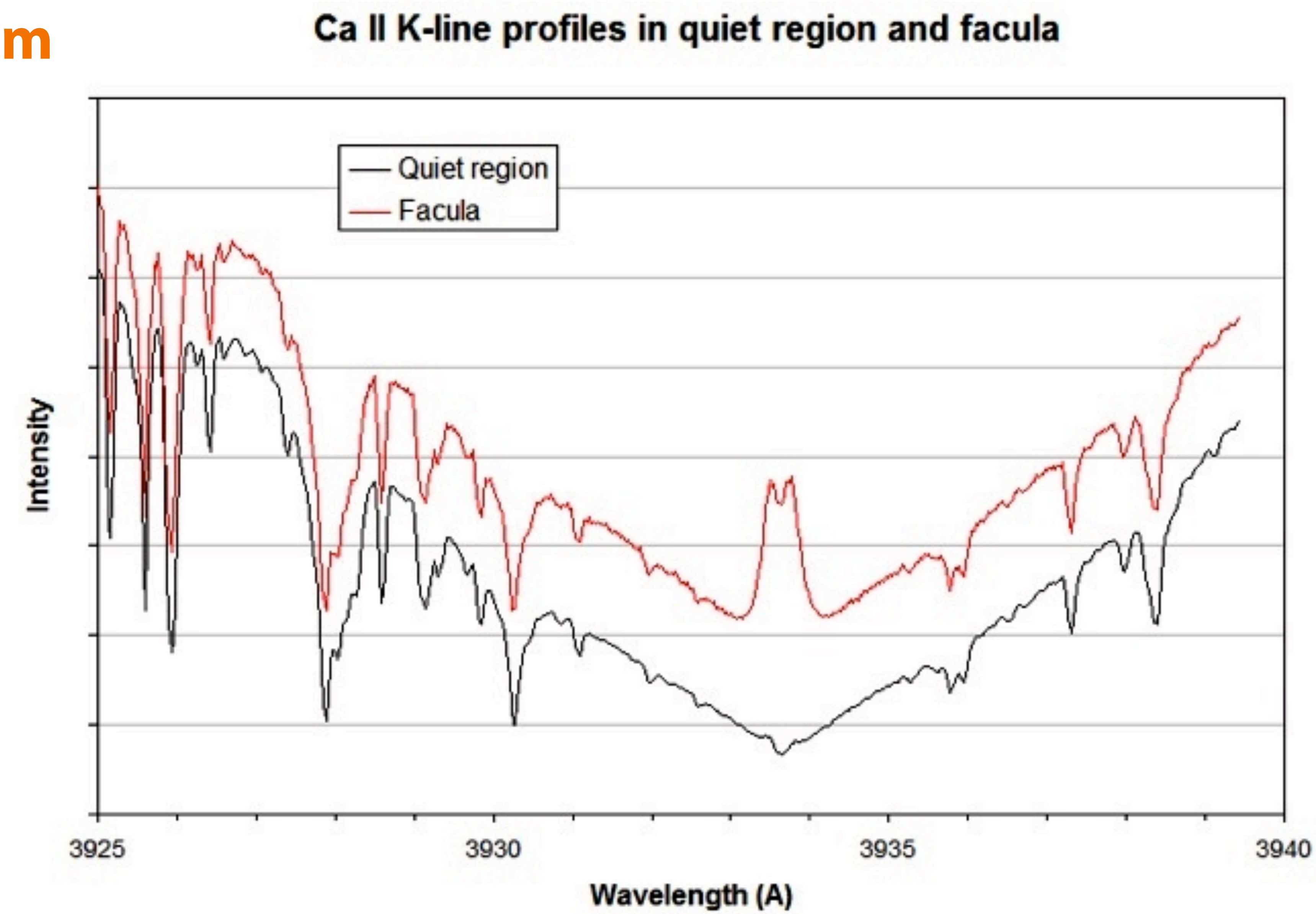
chromo-
sphere

formation height

continuum

line wing

line core



Magnetic field in the solar atmosphere

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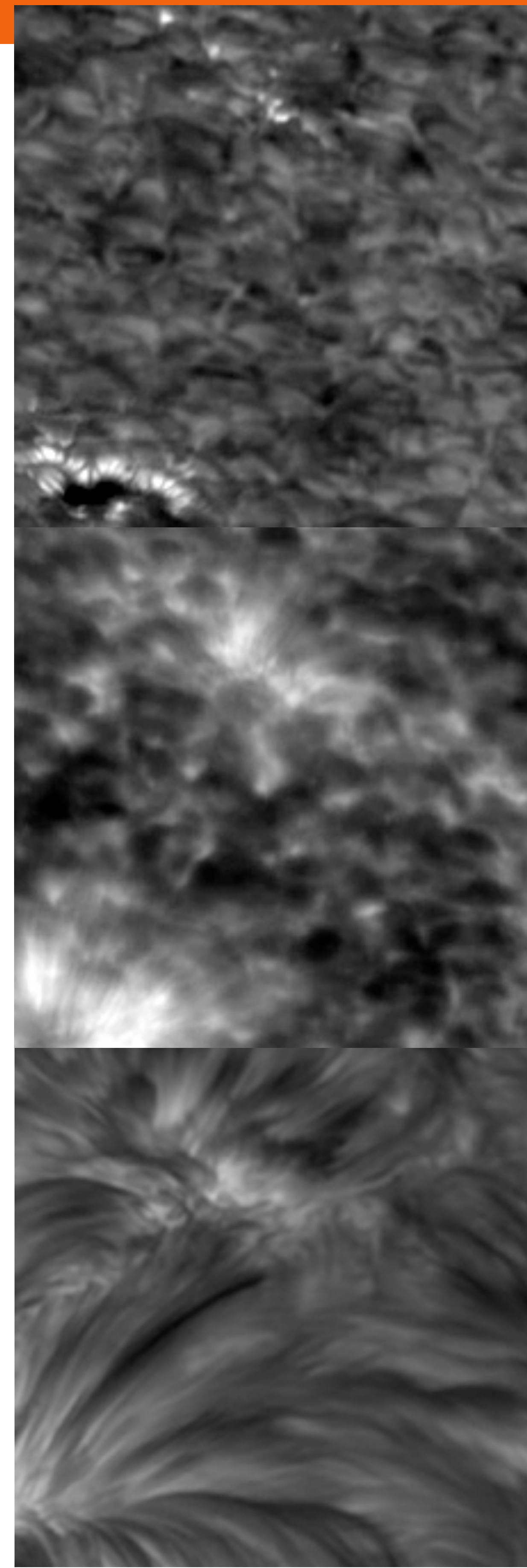
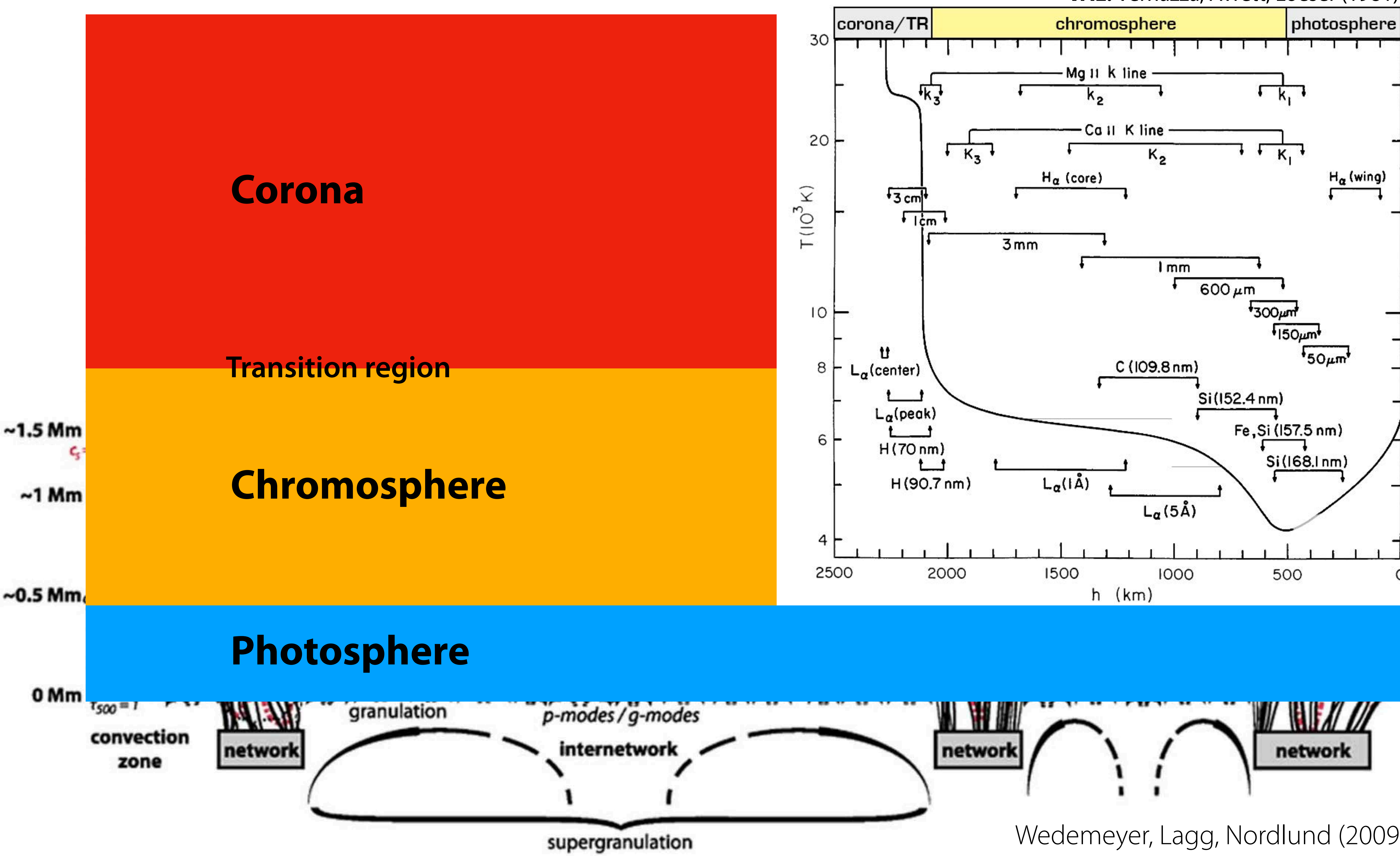


Magnetic field in the solar atmosphere

Structure of Quiet Sun regions

VAL: Vernazza, Avrett, Loeser (1981)

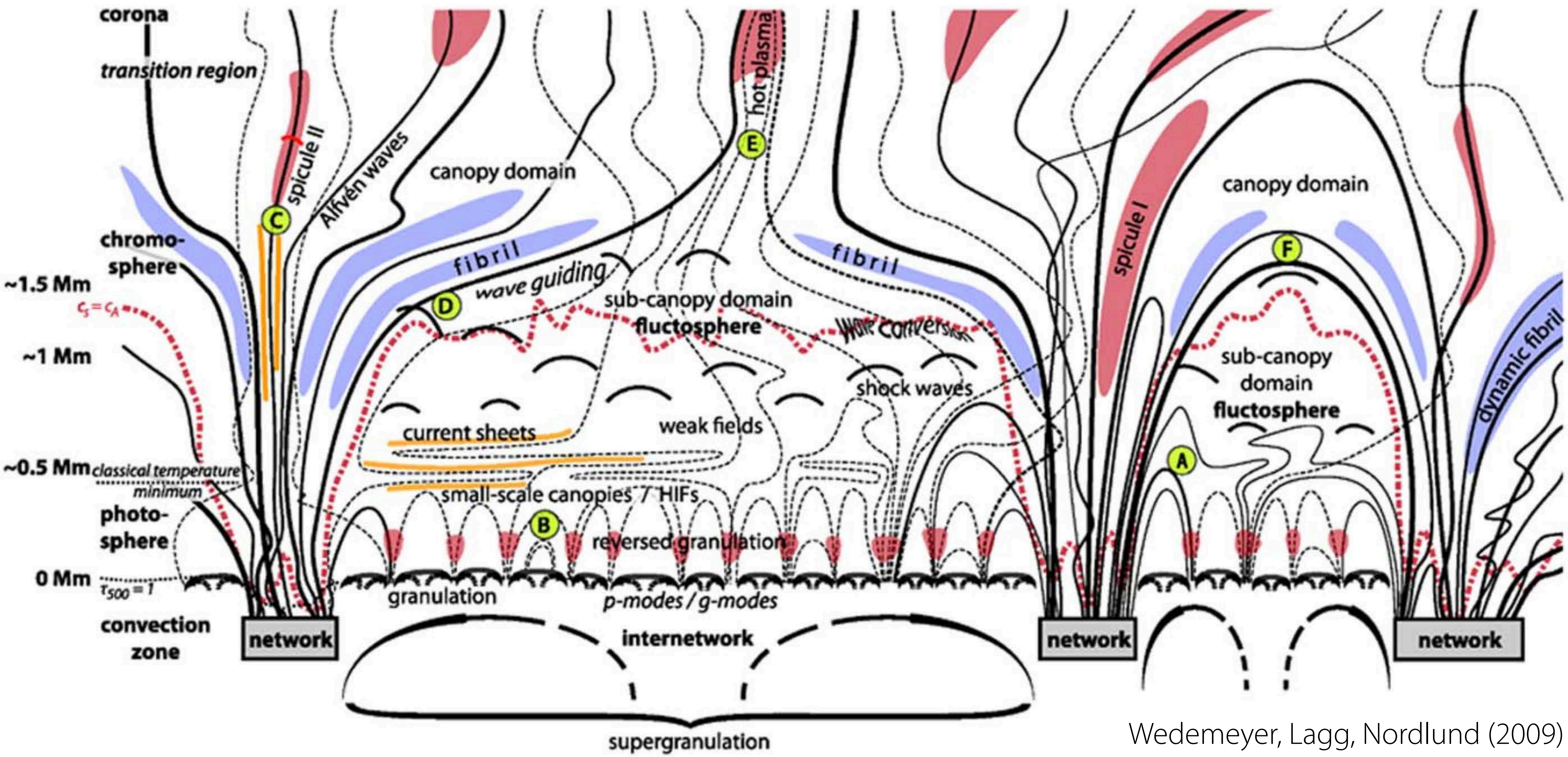


Wedemeyer, Lagg, Nordlund (2009)

Magnetic field in the solar atmosphere

Structure of Quiet Sun regions

- 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

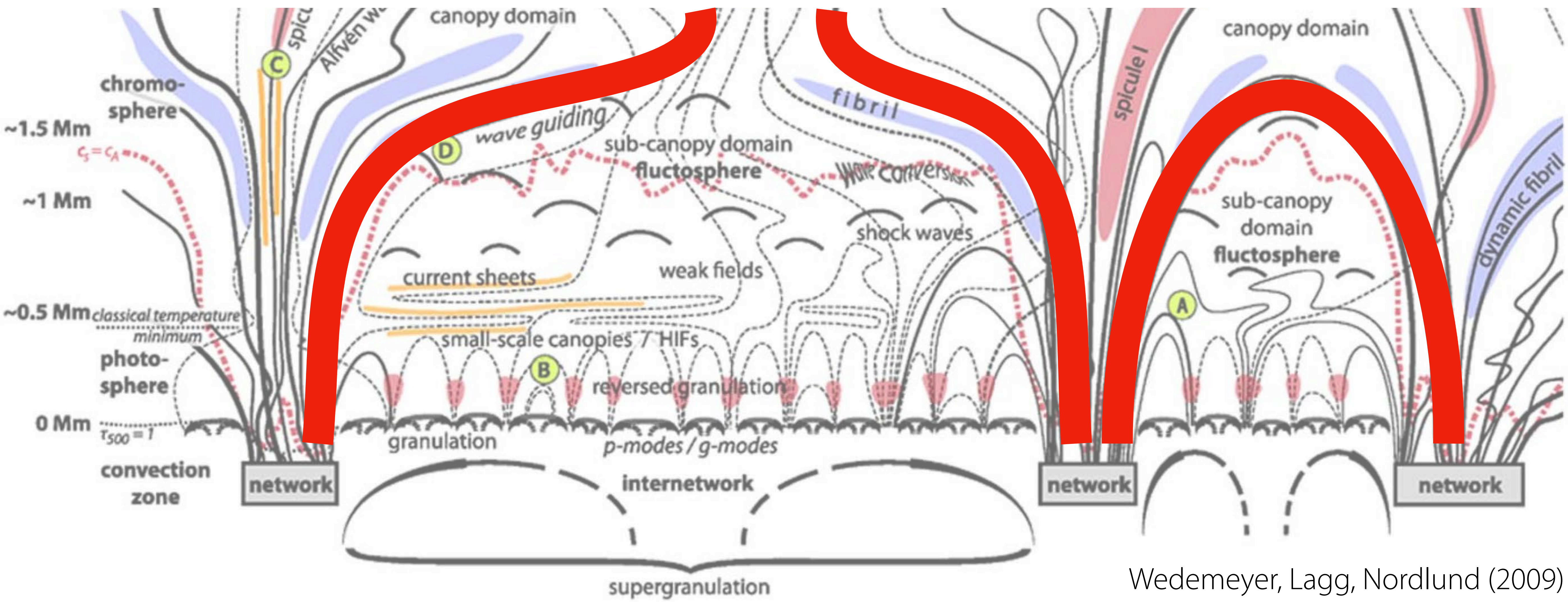


Wedemeyer, Lagg, Nordlund (2009)

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

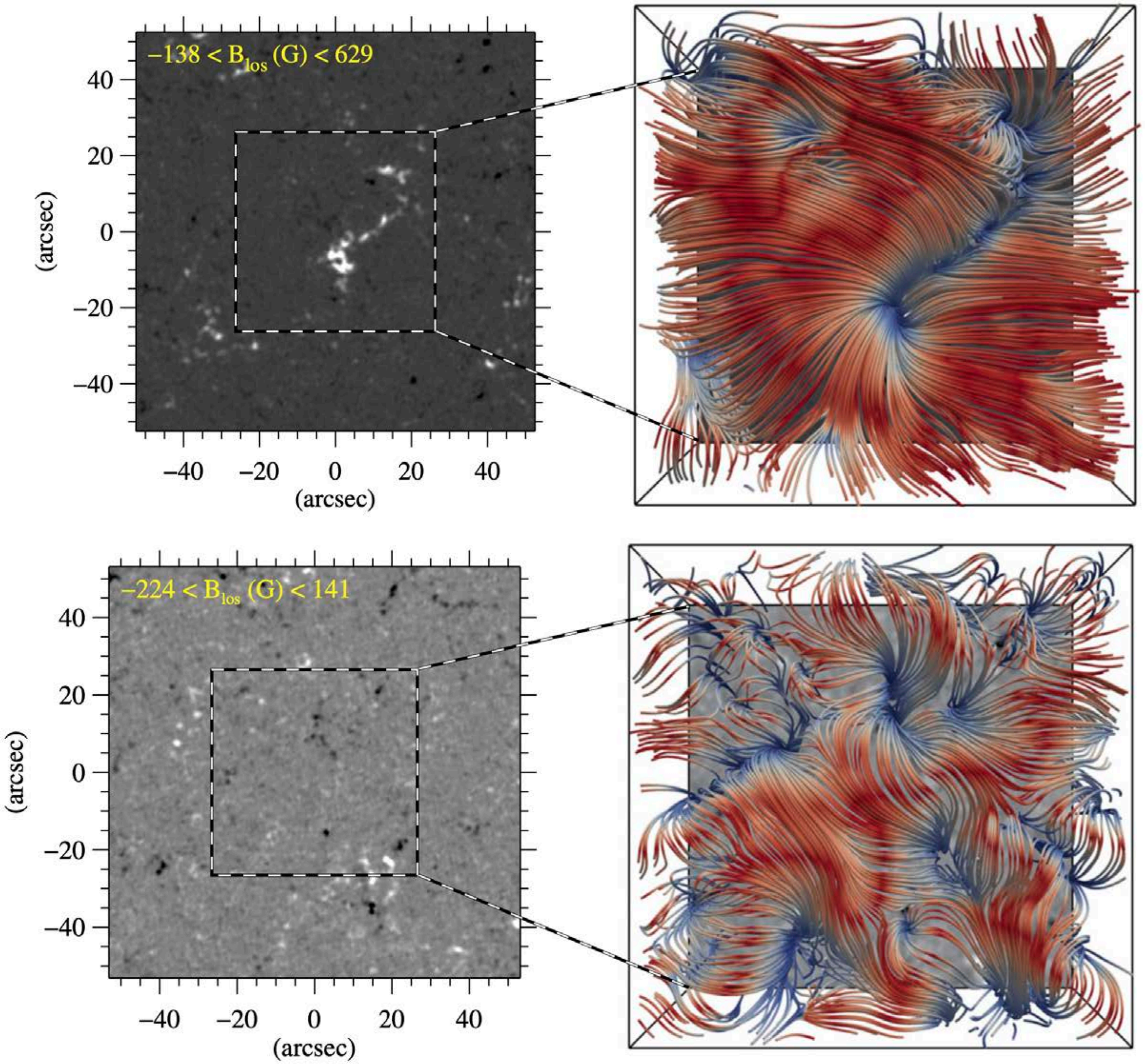


Wedemeyer, Lagg, Nordlund (2009)

Magnetic field in the solar atmosphere

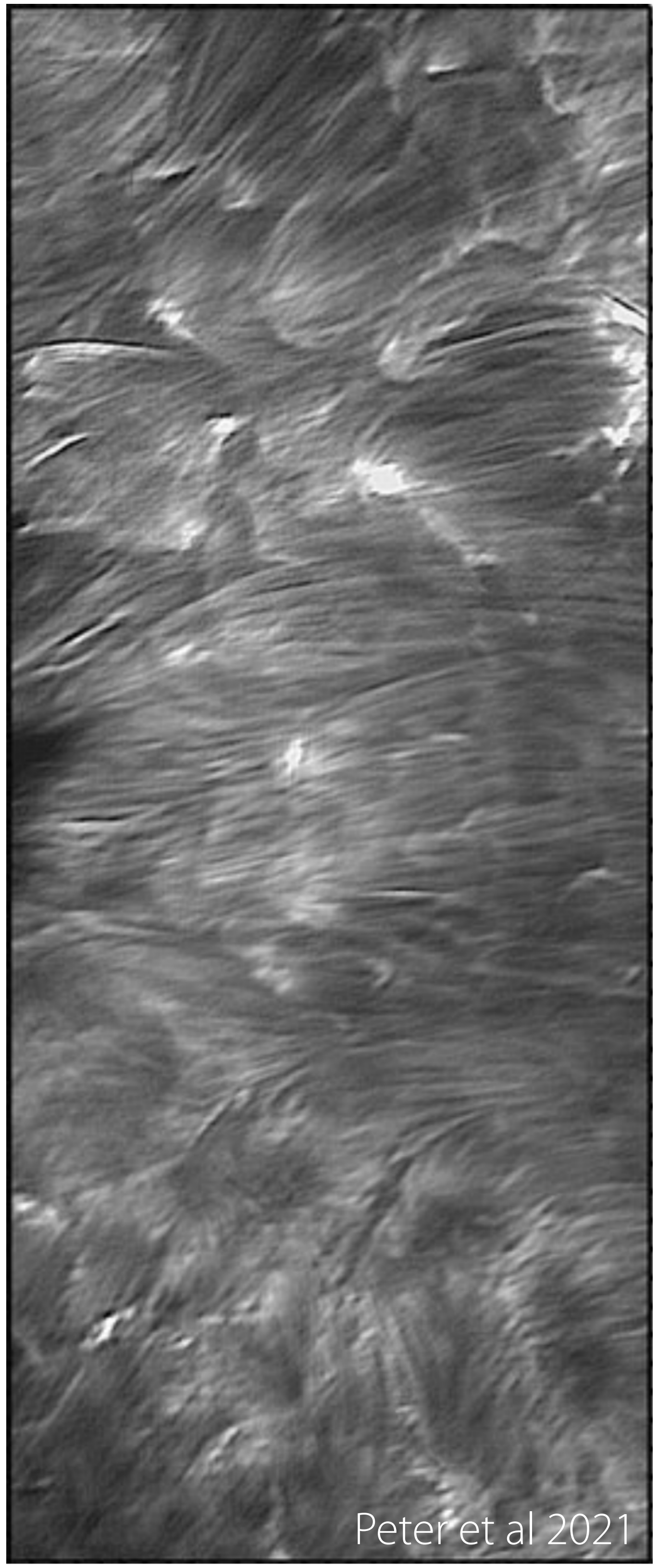
Structure of Quiet Sun regions

Magnetic field extrapolation from photospheric magnetograms



Jafarzadeh et al 2021

Observed: Fibrils in Ca II K



Peter et al 2021