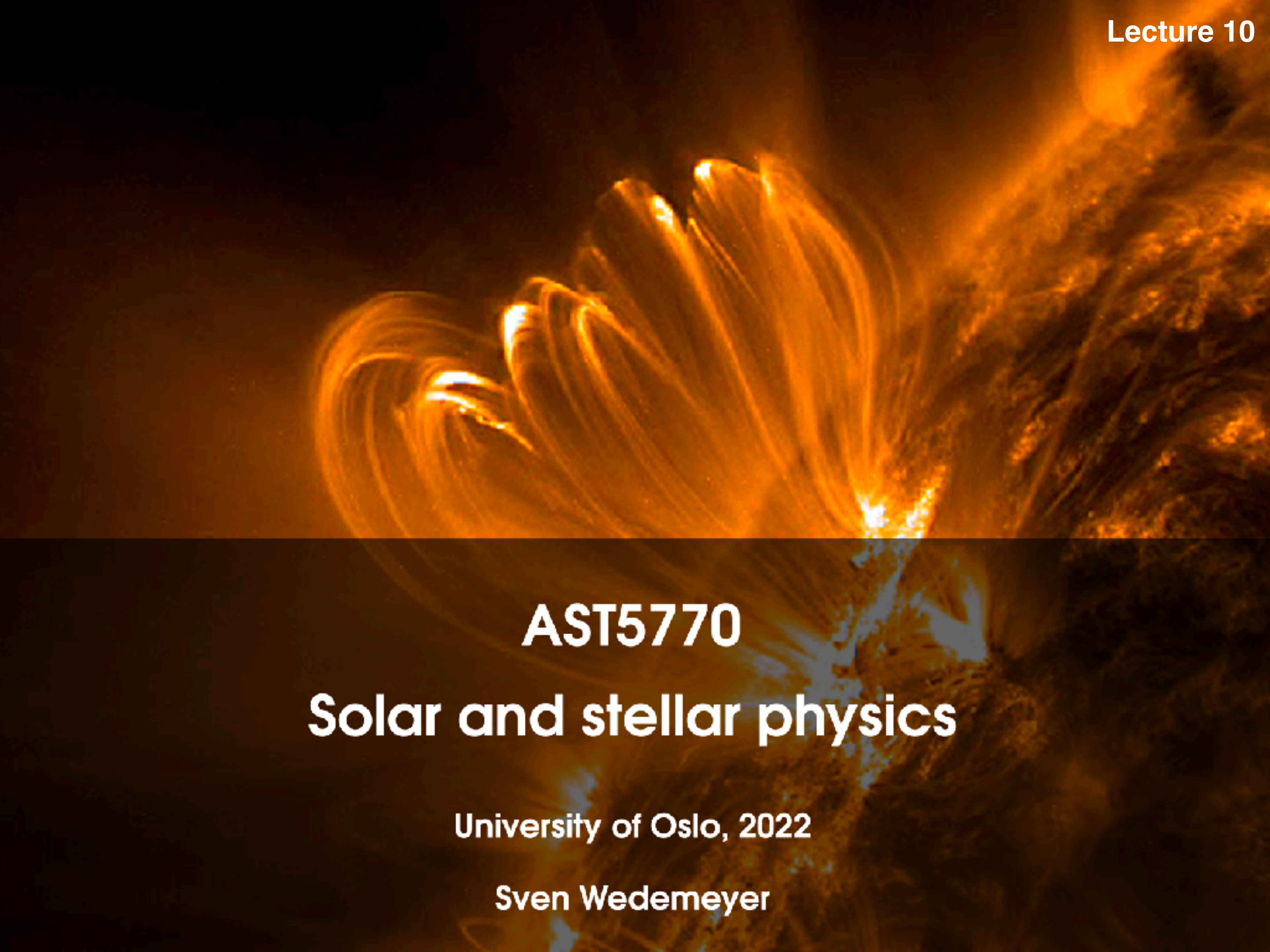


Lecture 10

AST5770

Solar and stellar physics

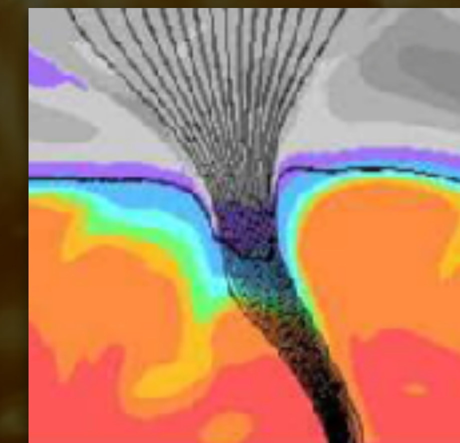
University of Oslo, 2022

Sven Wedemeyer

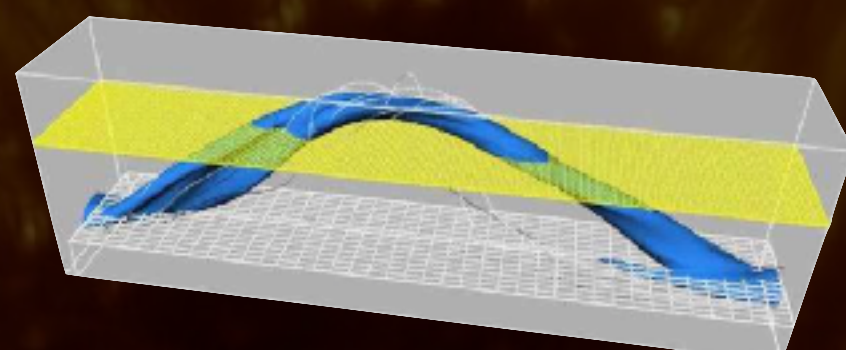
Magnetism and Dynamo Recap

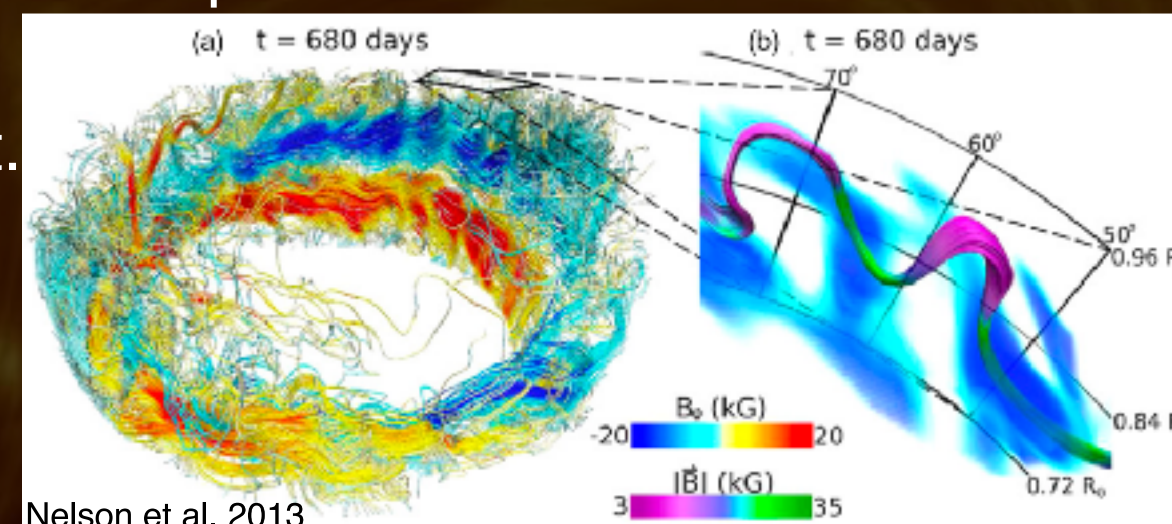
Magnetism

Recap



- Ionised gas (plasma) in motion — electric and magnetic fields need to be considered
- **Magnetic pressure** $P_m = B^2 / 8\pi$
  - Affects structure and dynamics of the plasma by "competing" with thermal pressure.
    - Magnetic flux structures funnel out in the atmosphere.
    - Magnetic flux bundles in the convection zone become buoyant.





Nelson et al. 2013

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

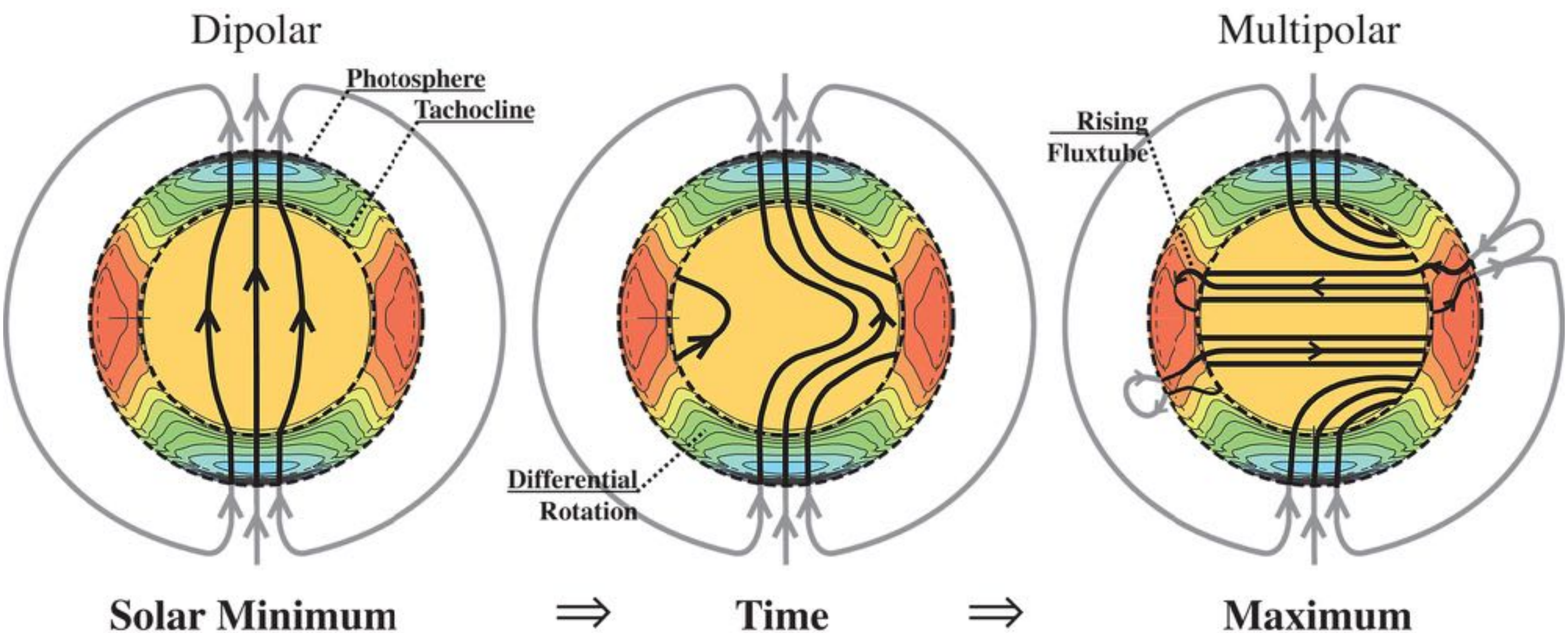
    — The magnetic field is **frozen-in.**

SST — Scharmer

Dynamo

Solar cycle — change of magnetic field configuration

- Below **tachocline**: Rotation as solid body
- Above tachocline: **differential rotation** — faster rotation near equator, slower at poles
- Magnetic dipole field (poloidal) at solar minimum

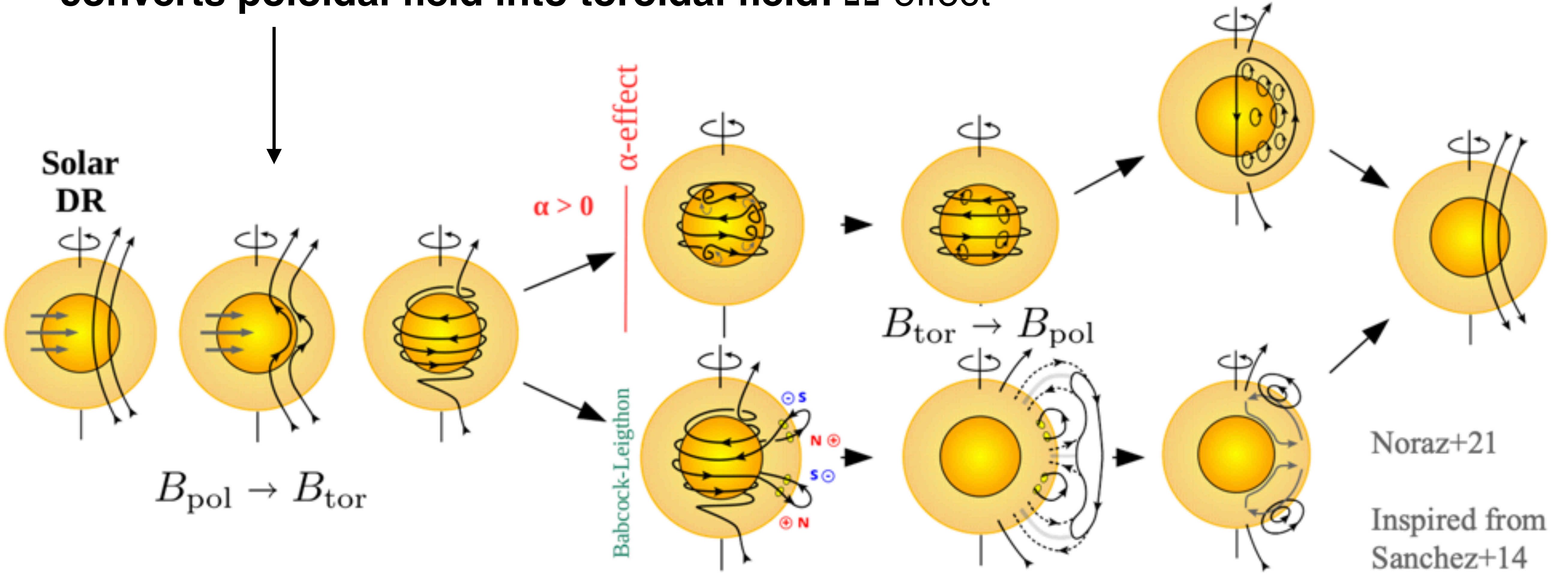


Higgins, Paul (2012): Schematic of the Solar Dynamo. figshare. Figure. https://doi.org/10.6084/m9.figshare.102094.v1

Dynamo

Solar cycle — change of magnetic field configuration

- Over time: differential rotation shears magnetic field (mostly at the tachocline), **converts poloidal field into toroidal field:** Ω-effect

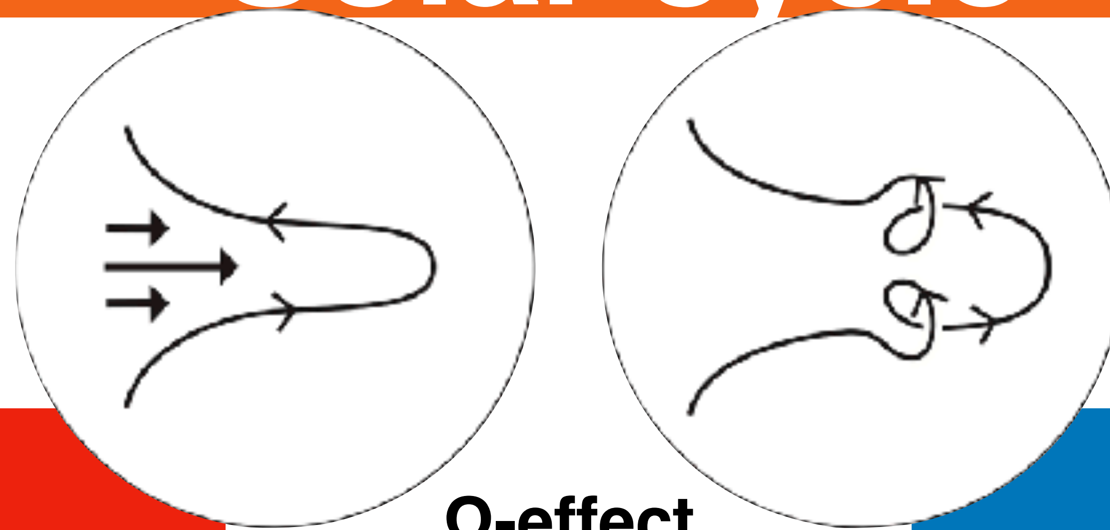


NB :

- Poloïdal generation is likely to be a **combination of both processes** α and BL
- The α-effect can also take part in toroïdal generation aside with the Ω-effect

Dynamo — Solar cycle

α and Ω

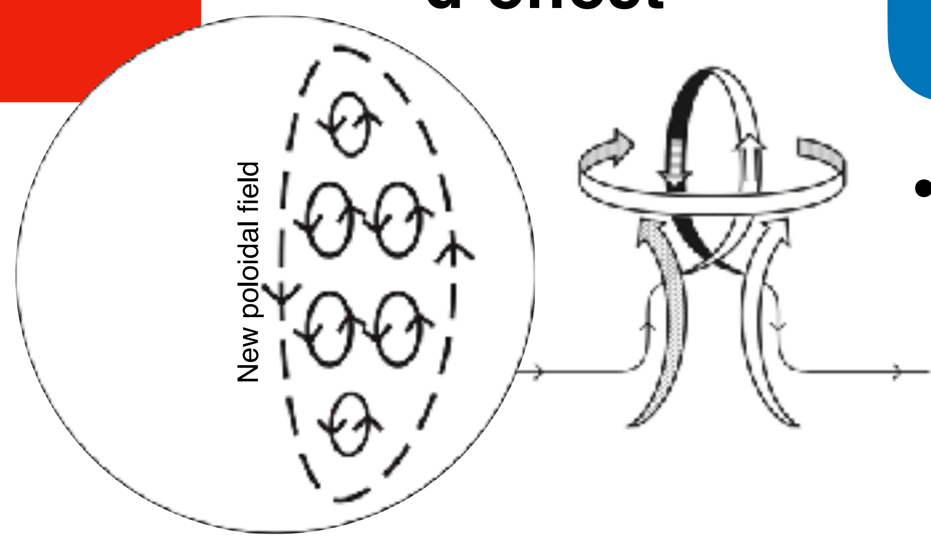


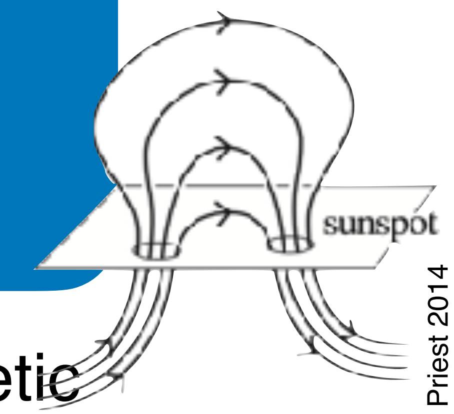
Poloidal field

Ω-effect →

← **α-effect**

Toroidal field





Priest 2014

- Predominates during **solar (activity) minima**

- generates magnetic activity (e.g., sunspots) during **solar (activity) maxima**

- **Solar cycle**: Changes back and forth between these extreme configurations, forming a solar activity cycle with ~11 year period
    - Global polarity of the Sun's magnetic field (N-S) swaps during that period
    - Complete cycle back to the same polarity = 2 x 11 yr = **22 yr = Hale cycle. -> How this process has been observed?**

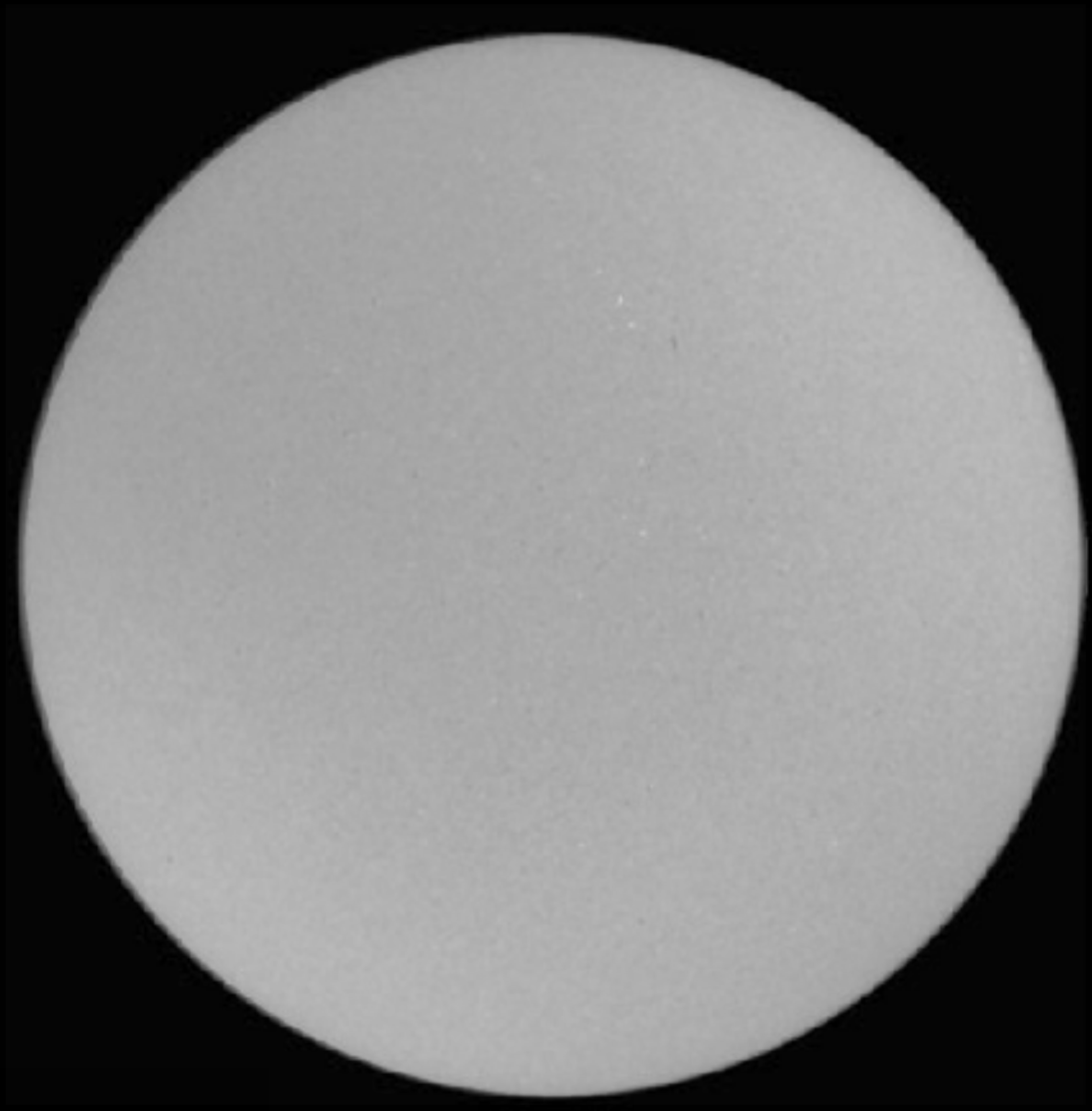
Dynamo
And
Solar cycle

Dynamo — Solar cycle

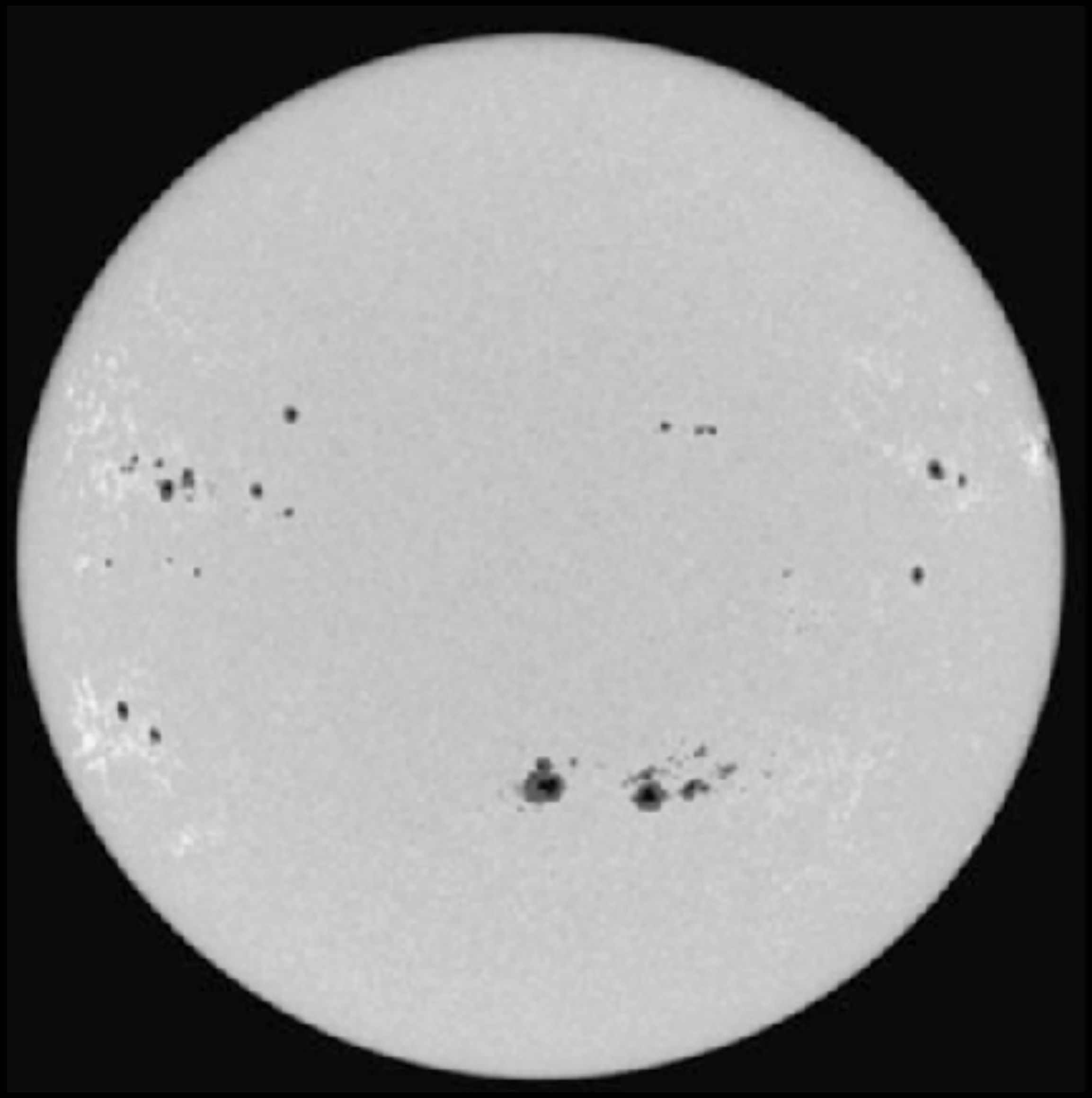
Continuum intensity

- How to quantify solar cycles ?
- Relatively small area covered by sunspots — Overall variation in brightness?

Minimum



Maximum



SOHO/MDI

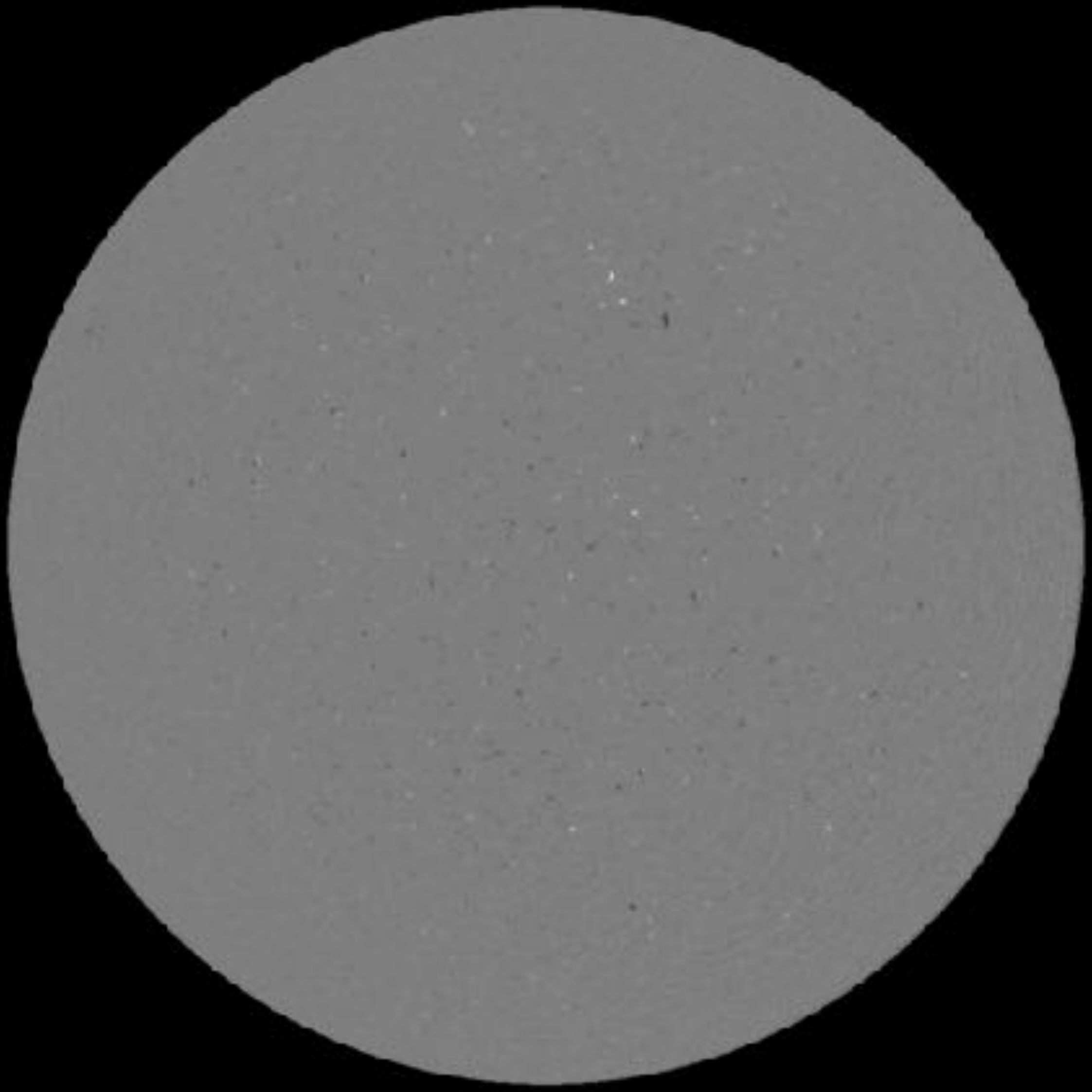
Dynamo — Solar cycle

Magnetograms

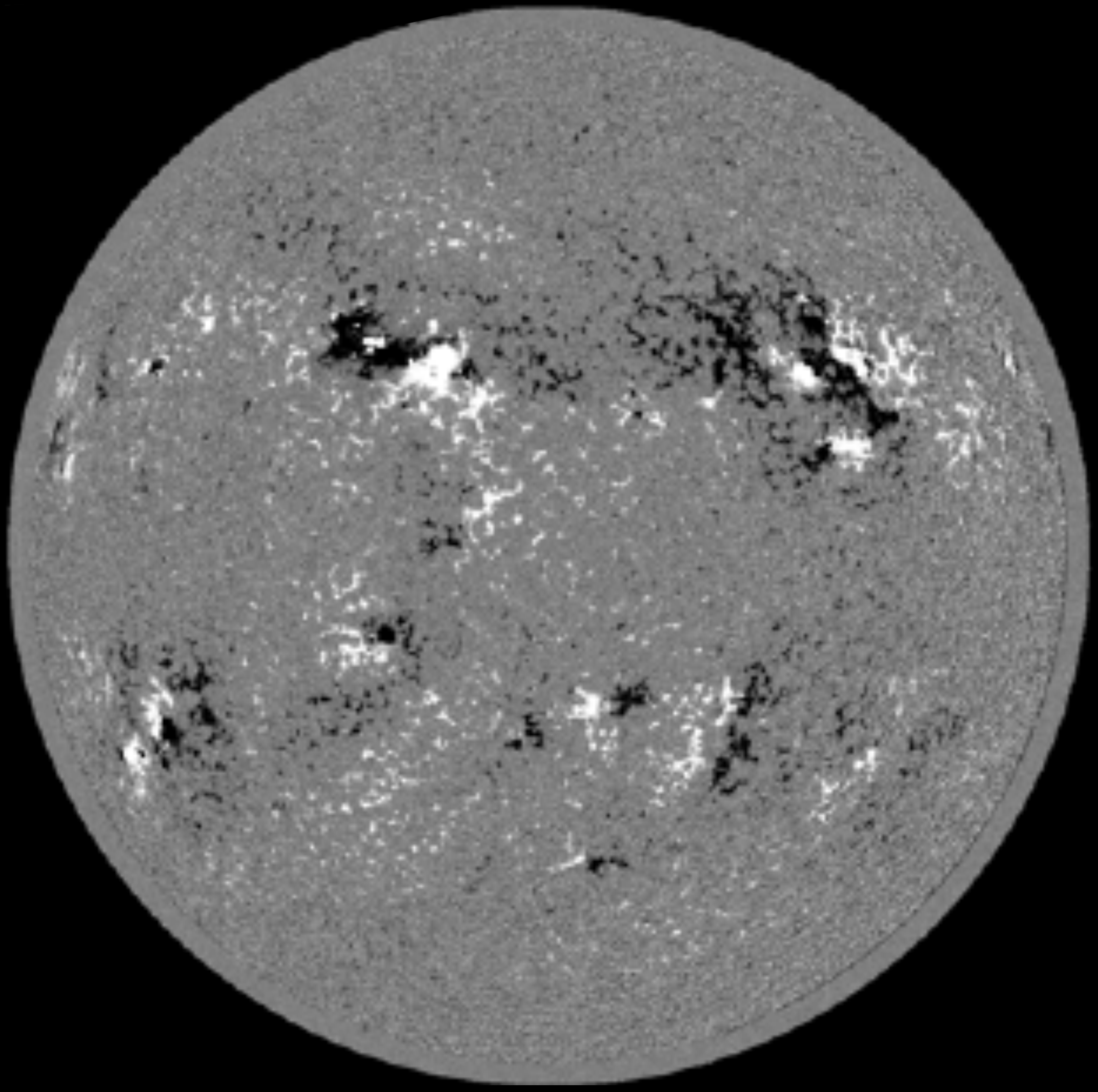
- Changes are more drastic when looking at magnetograms

Solar magnetograms:
Line of sight B-field from circularly polarized light

Minimum



Maximum

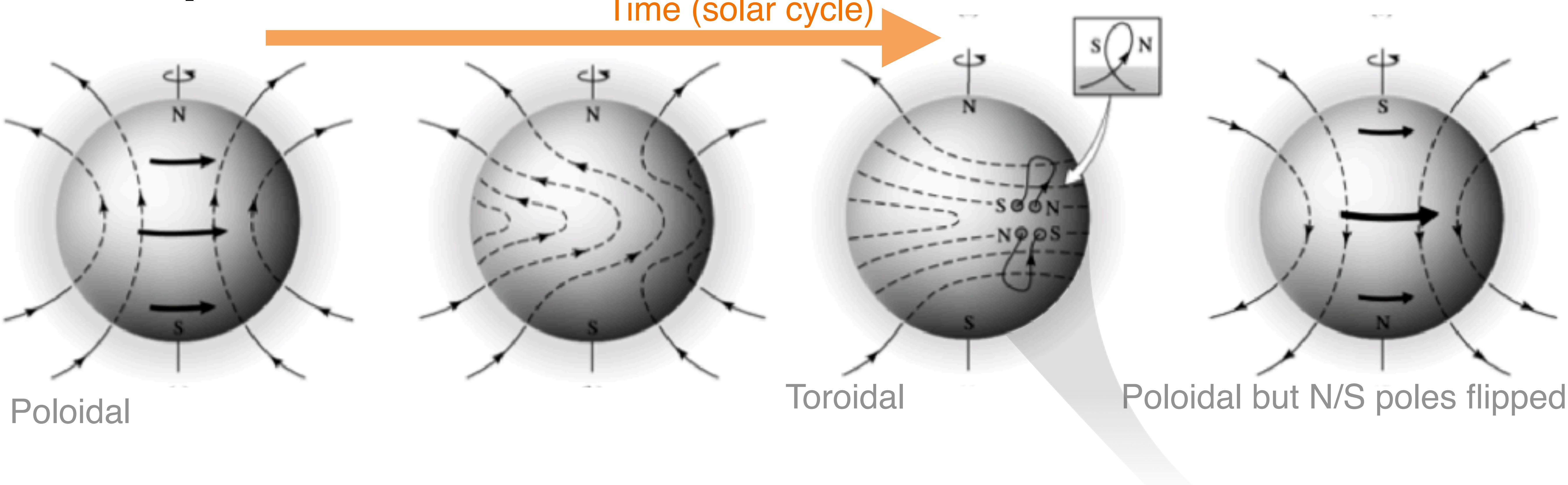


- Hemispheric inversion of polarities

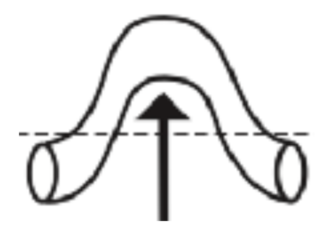
SOHO/MDI

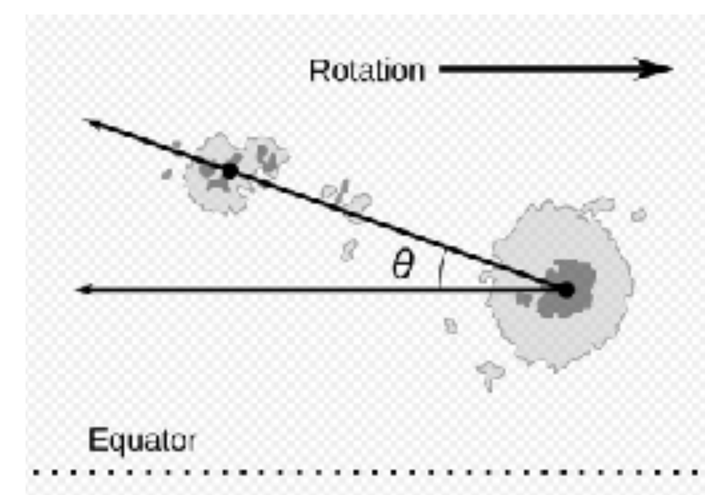
Dynamo — Solar cycle

Sunspots — latitude



- Coriolis force depends on latitude λ
  -> tilt angle θ stronger at high latitudes (Joy's law)





- Polarities of the northern and southern hemispheres cancel out at the equator!

➡ **Cancellation** of magnetic field at the equator

➡ More sunspots develop at **intermediate latitudes**

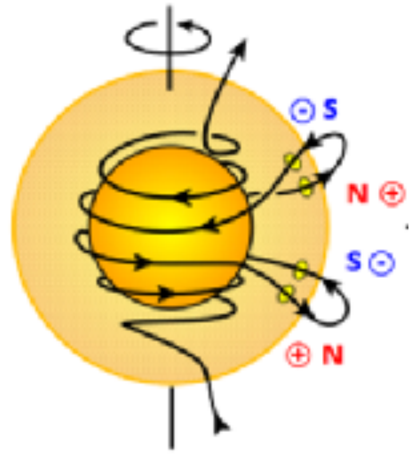
- With time, the poloidal field will be re-established (but with opposite polarity)

Carroll & Ostlie

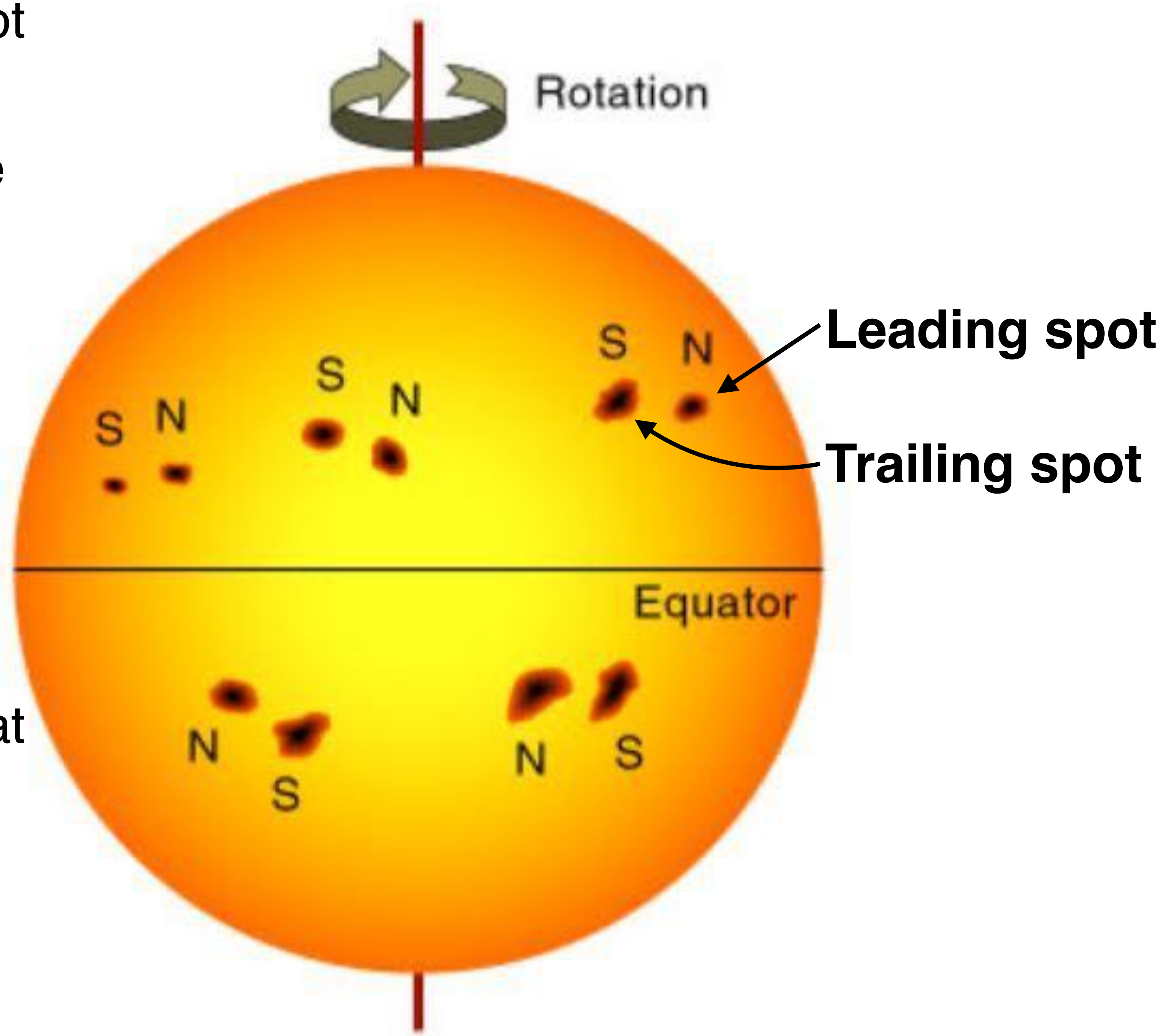
Dynamo — Solar cycle

Sunspots — latitude and orientation

- Active Regions with a leading spot and a trailing spot
- Order of polarities reversed in the two hemispheres



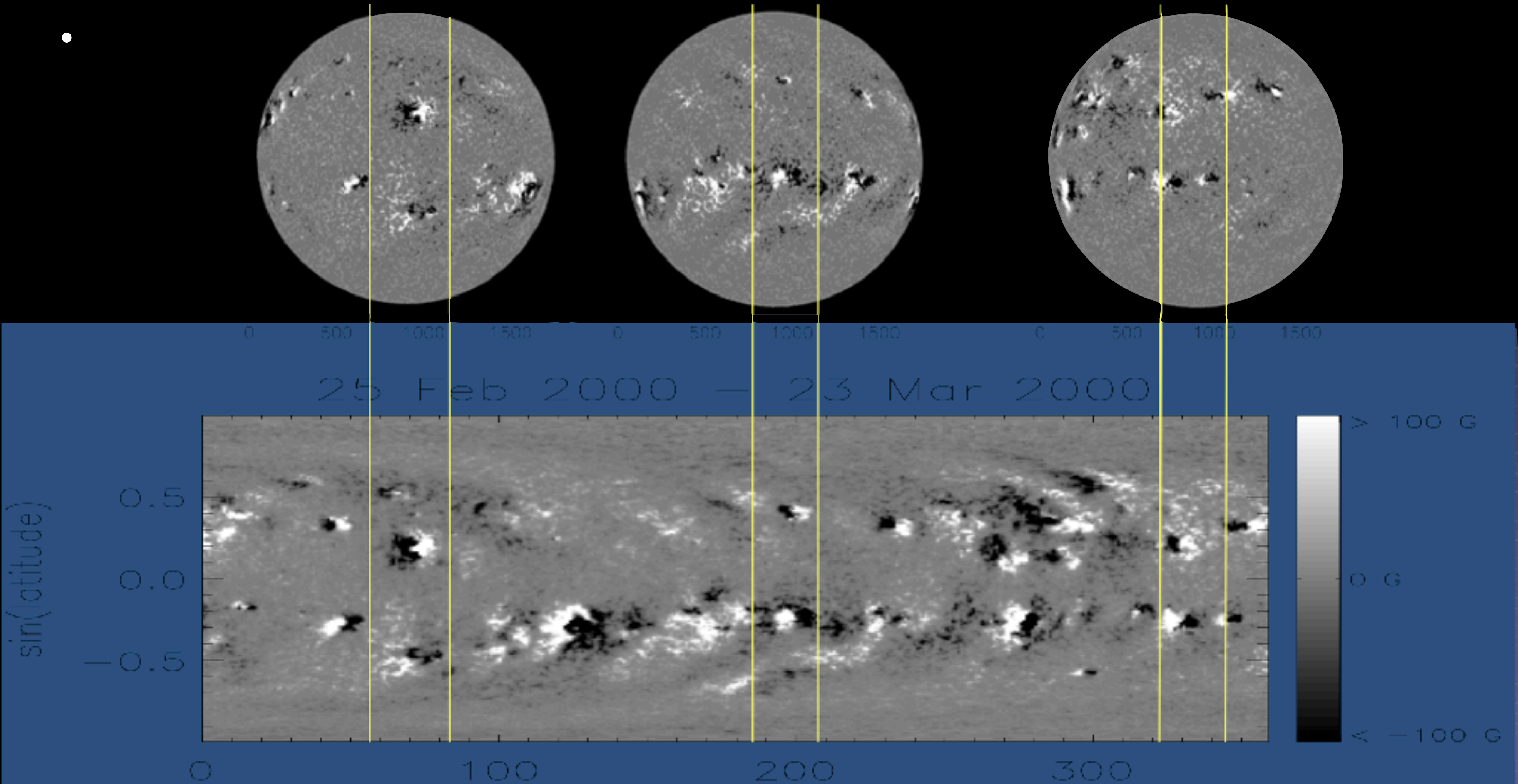
- Flips with global magnetic field orientation every 11yr
- New cycle begins with sunspots at latitudes of 30-45 degrees on bother hemispheres
- During a solar cycle: Sunspots appear gradually more towards equator (Spörer’s law)
- Cycle ends with sunspots at low latitudes (~7 degrees)



Dynamo — Solar cycle

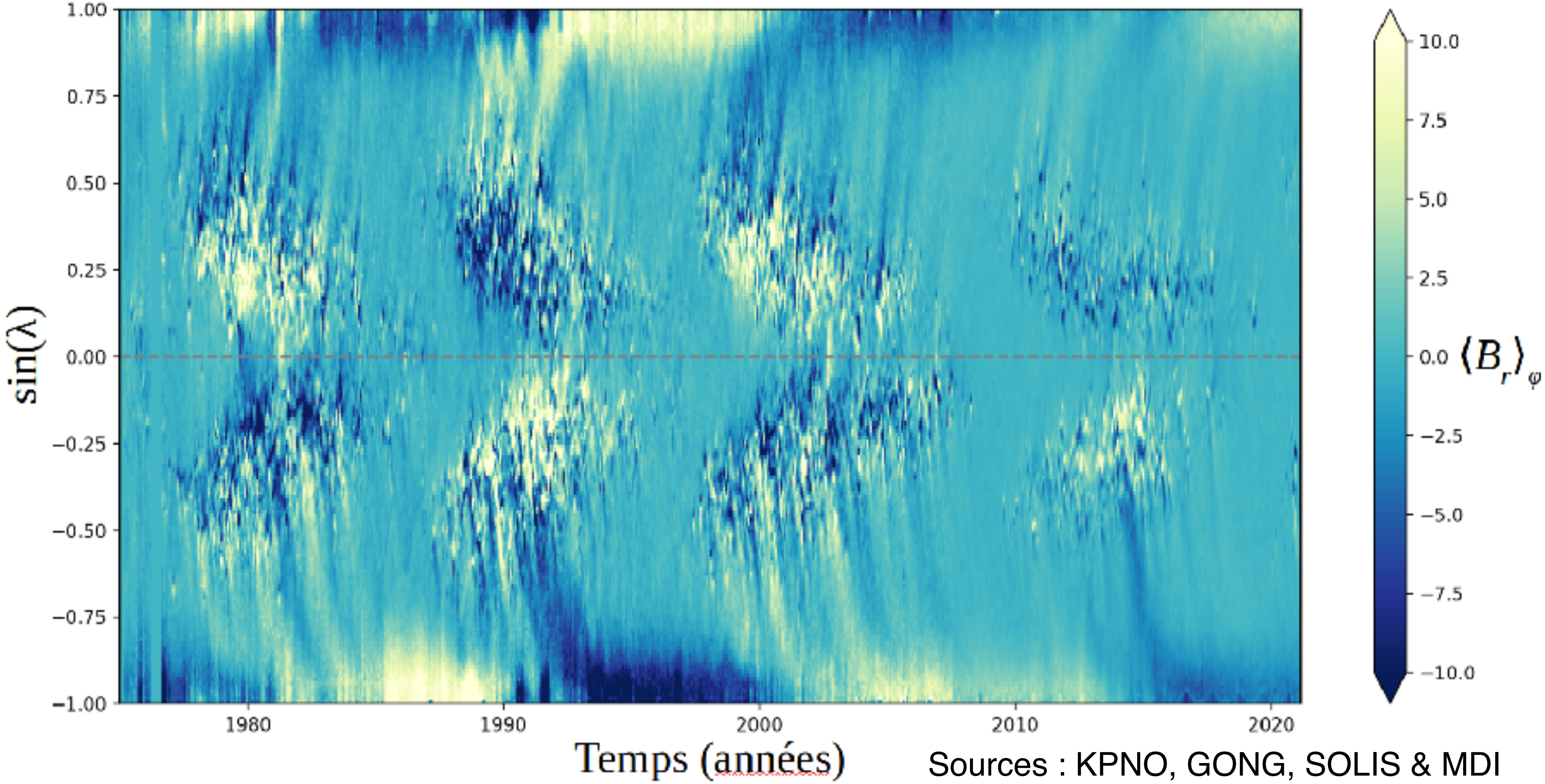
Magnetic field configuration at surface

- Synoptic maps approximate the radial magnetic flux observed near the central meridian over a period of 27.27 days (= 1 Carrington rotation)
-



Dynamo - Solar cycle

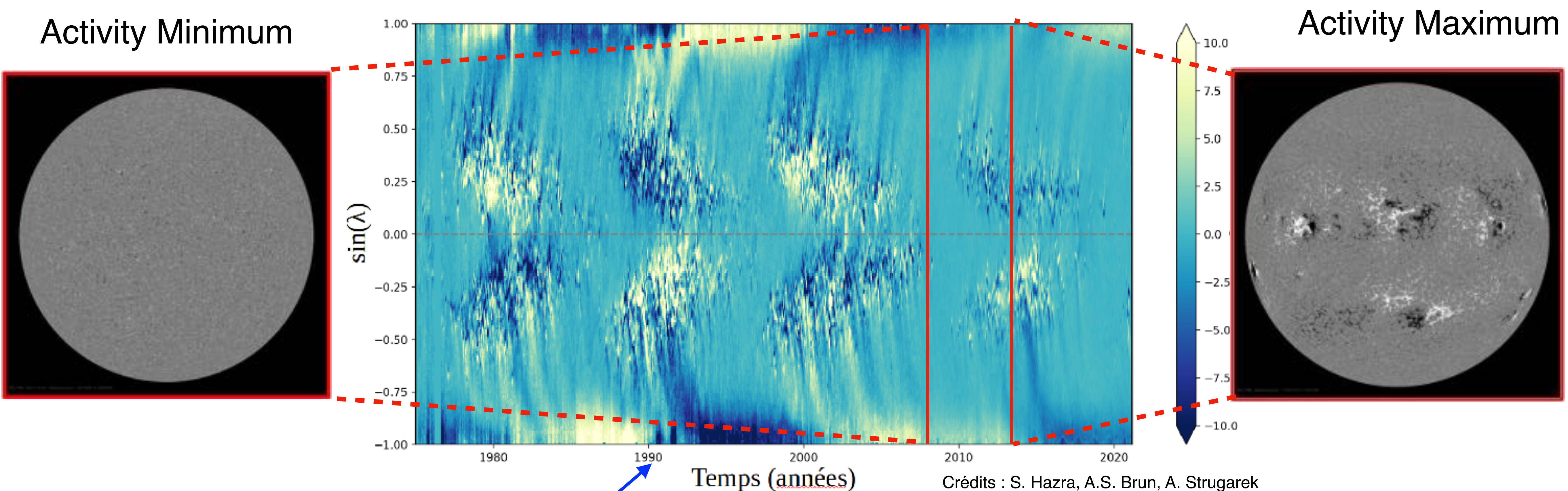
Butterfly diagram



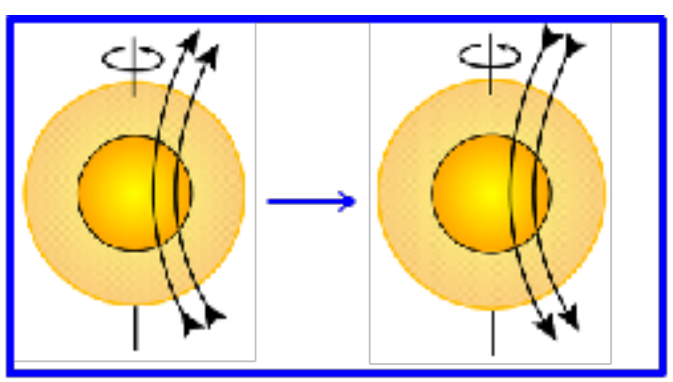
Sources : KPNO, GONG, SOLIS & MDI
Crédits : S. Hazra, A.S. Brun, A. Strugarek

Dynamo - Solar cycle

Butterfly diagram



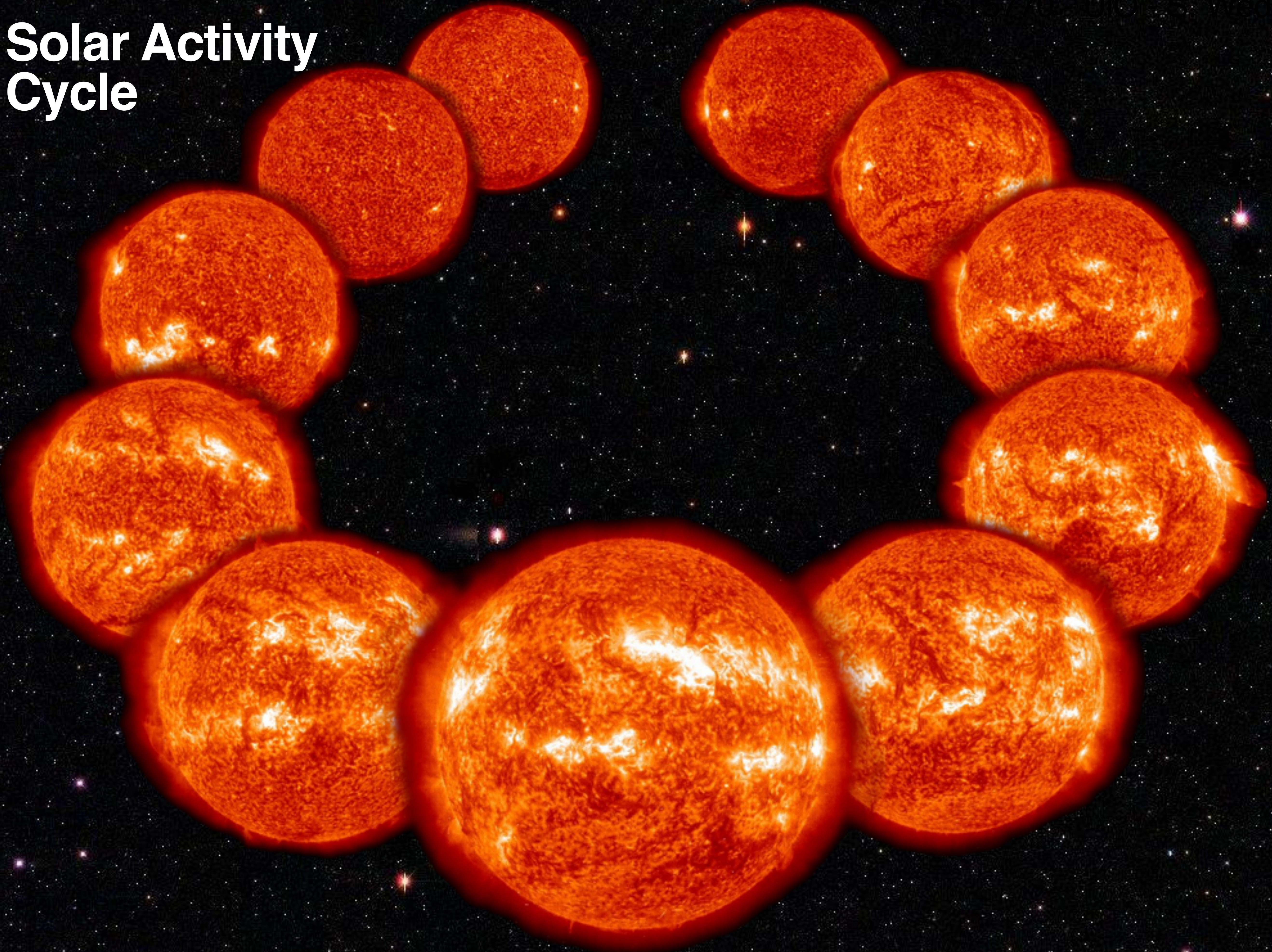
Crédits : S. Hazra, A.S. Brun, A. Strugarek



Global polarity reversal

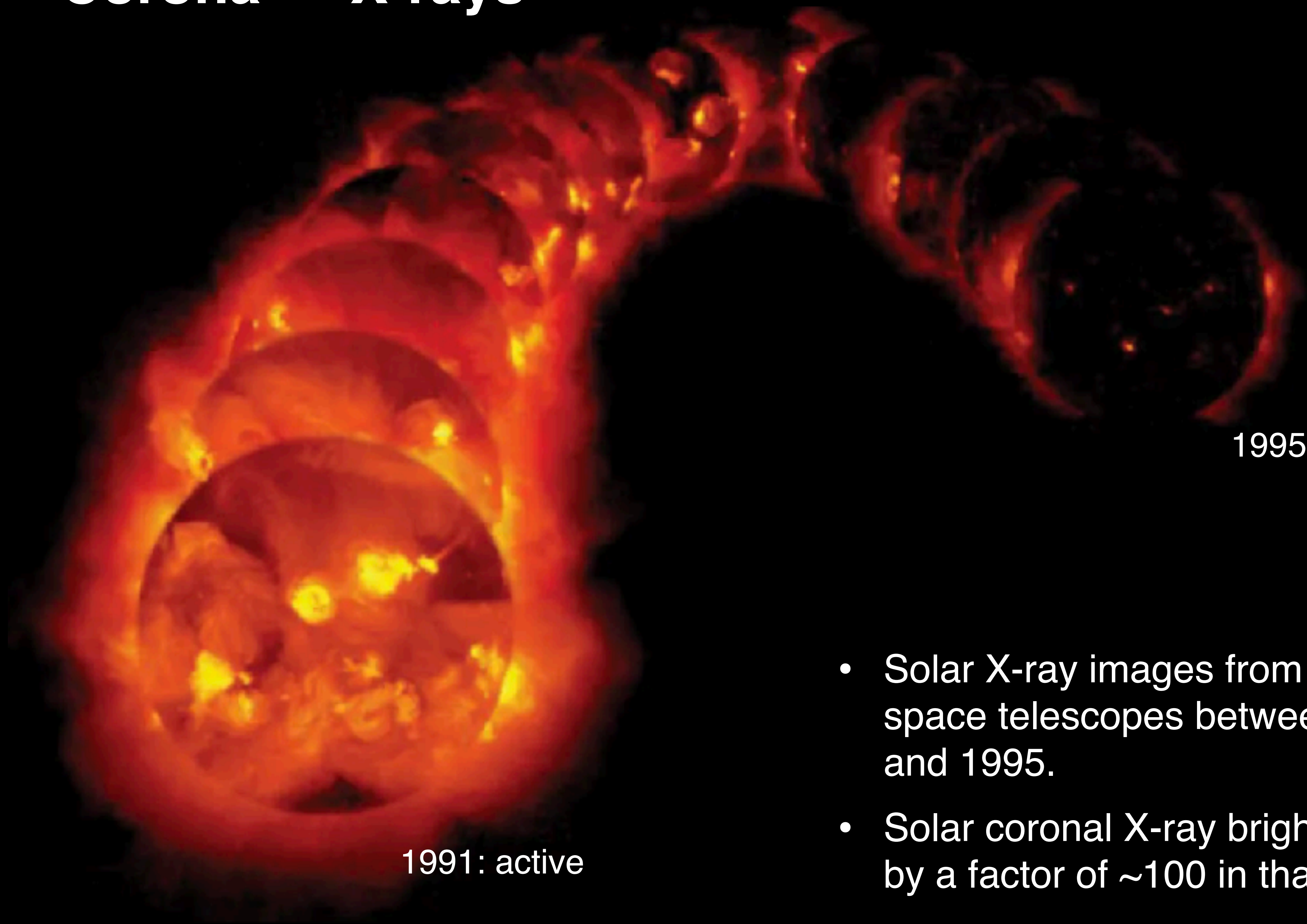
- 11-years activity cycle
- Migration of structures toward equator
- Opposite hemisphere polarities
- 22-years magnetic cycle

Solar Activity Cycle



Dynamo — Solar cycle

Corona — X-rays



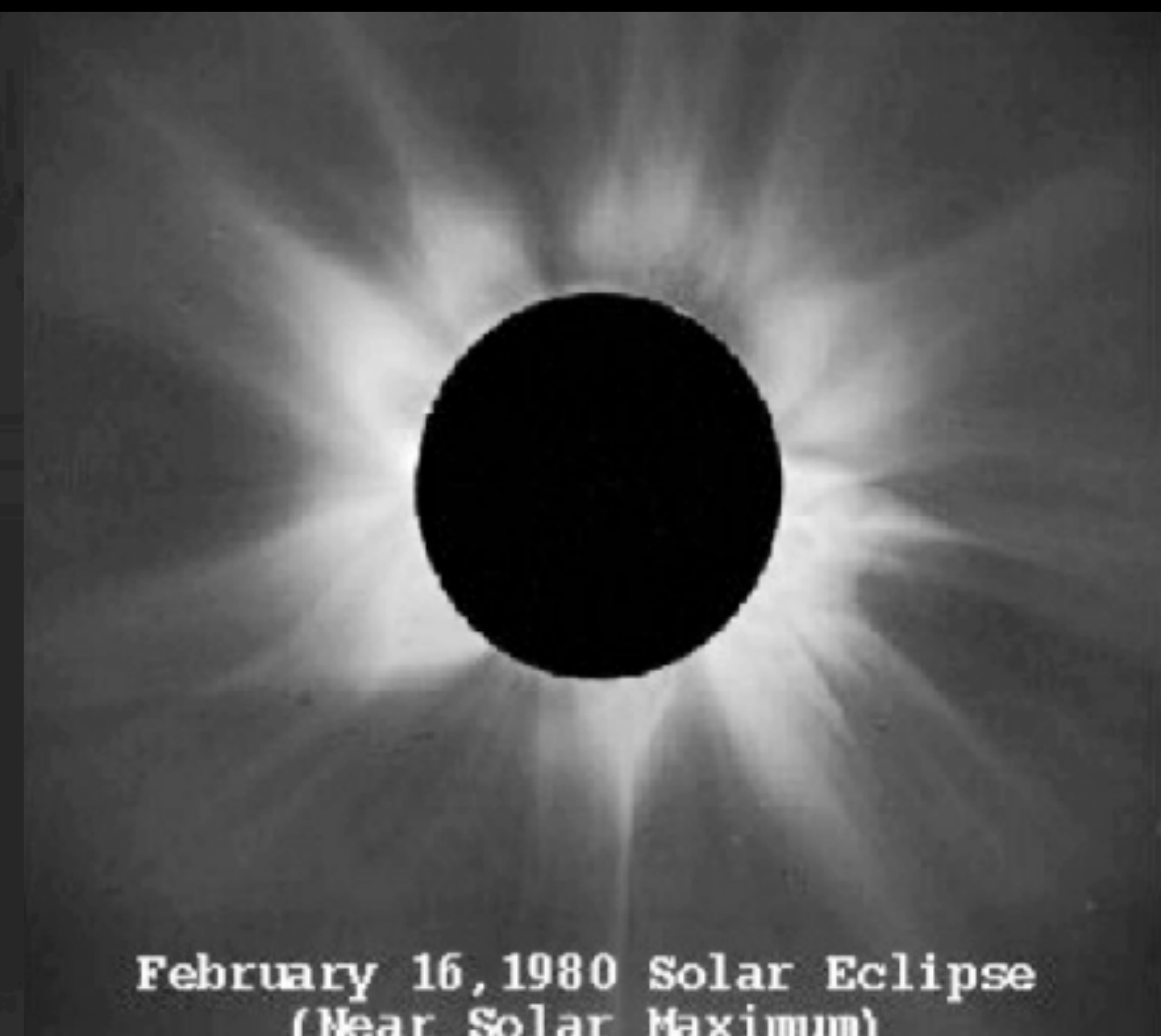
- Solar X-ray images from Yohkoh space telescopes between 1991 and 1995.
- Solar coronal X-ray brightness drops by a factor of ~100 in that period

G.L. Slater and G.A. Linford; S.L. Freeland; the Yohkoh Project

Dynamo — Solar cycle

Corona

- Solar cycle clearly visible in the change of the coronal magnetic field
- The solar disk can be hidden using a “coronograph”
- Topology changes are then visible with eclipse

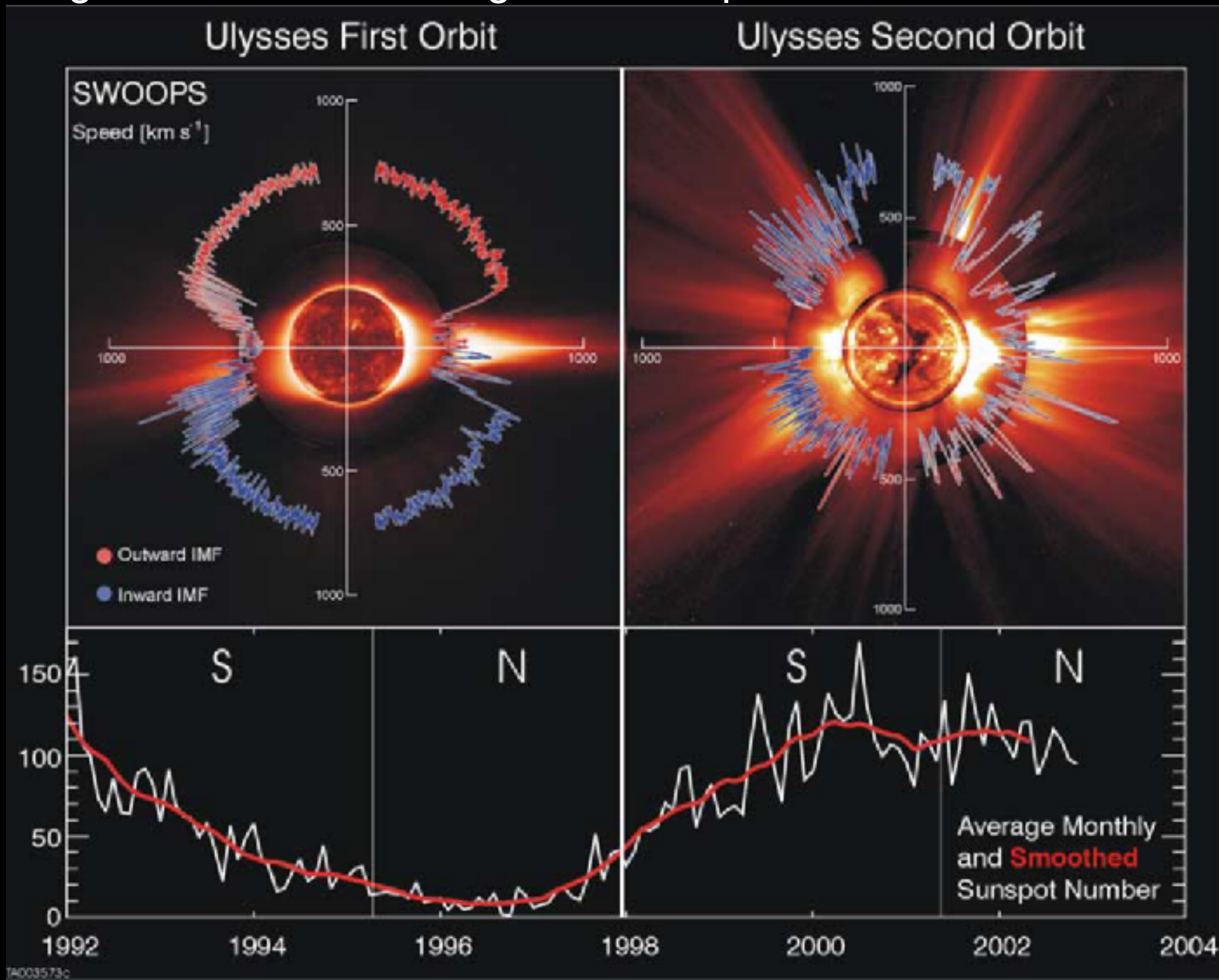


Corona visible — brighter solar disk is blocked out

Dynamo — Solar cycle

From corona to wind formation

- Cyclic changes of the coronal magnetism shape the solar wind



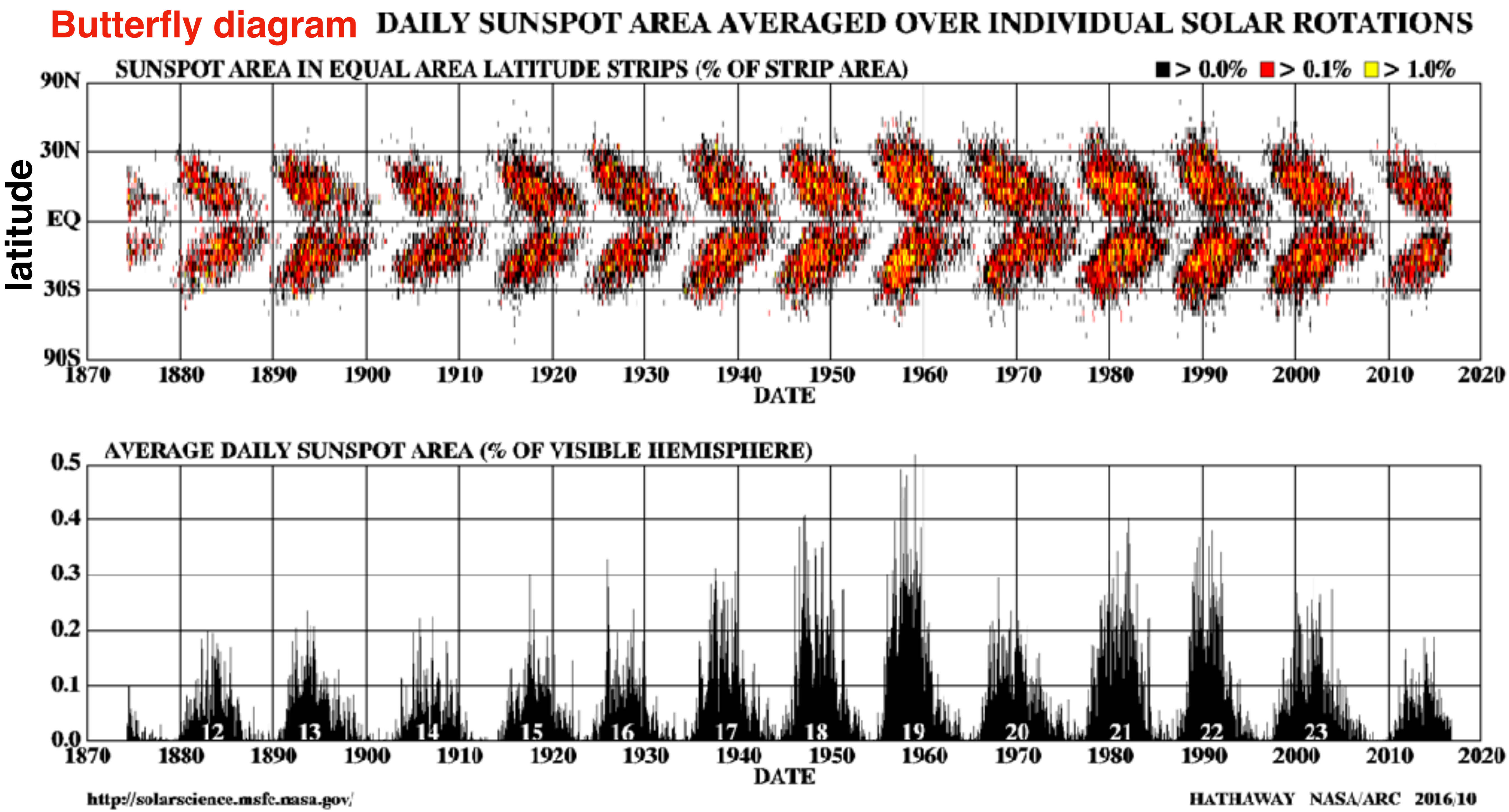
McComas 2003

Dynamo — Solar cycle

Sunspots — latitude and time

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

Butterfly diagram



Solar cycle

Sunspot number (Wolf number/Zürich sunspot number)

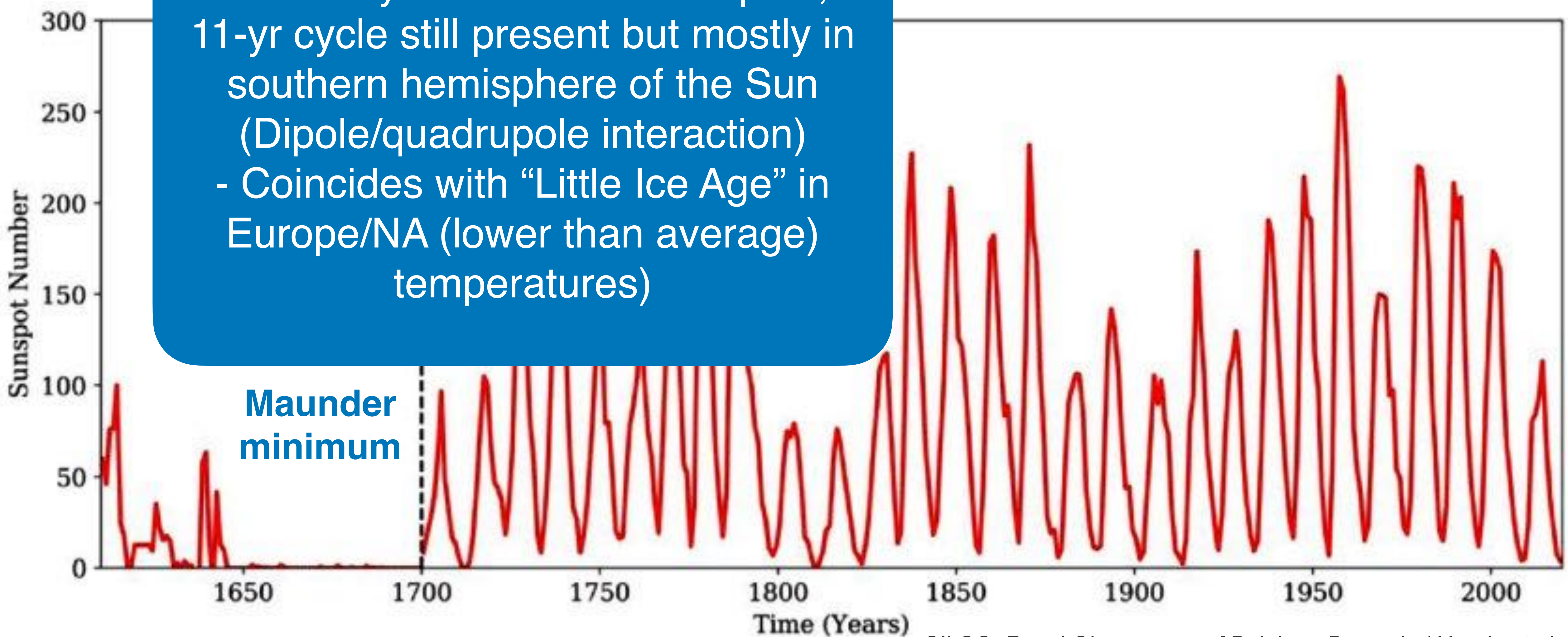
- Numerical measure for the "spottedness" of the Sun and thus its magnetic activity level

$$R = k\ (10\, g + s)$$

s: number of individual sunspots
g: number of sunspot groups
k: calibration factor (instrument, personal bias)

- Captu … e (Gleissberg)
- Correl … f screening from cosmic rays

- Maunder Minimum 1645 - 1715
Unusually small number of spots, 11-yr cycle still present but mostly in southern hemisphere of the Sun (Dipole/quadrupole interaction)
- Coincides with "Little Ice Age" in Europe/NA (lower than average) temperatures)

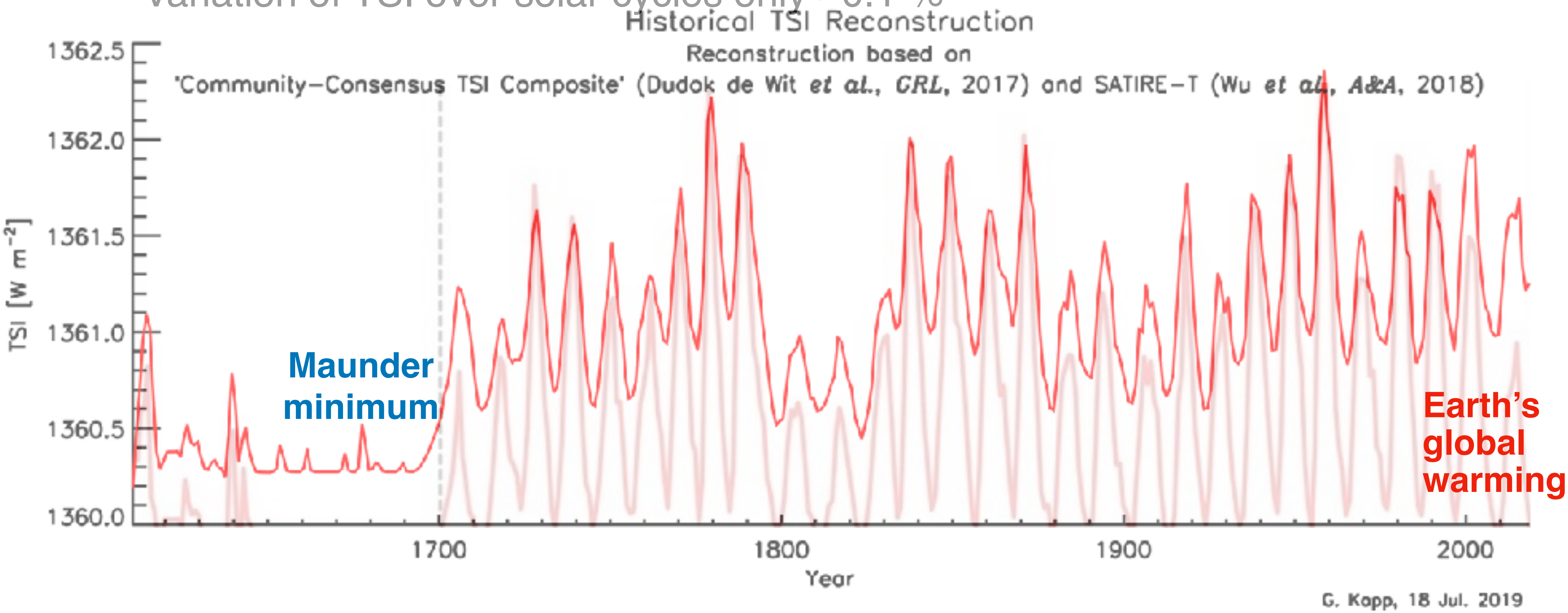


SILSO, Royal Observatory of Belgium, Brussels / Nandy et al. 2021

Solar cycle

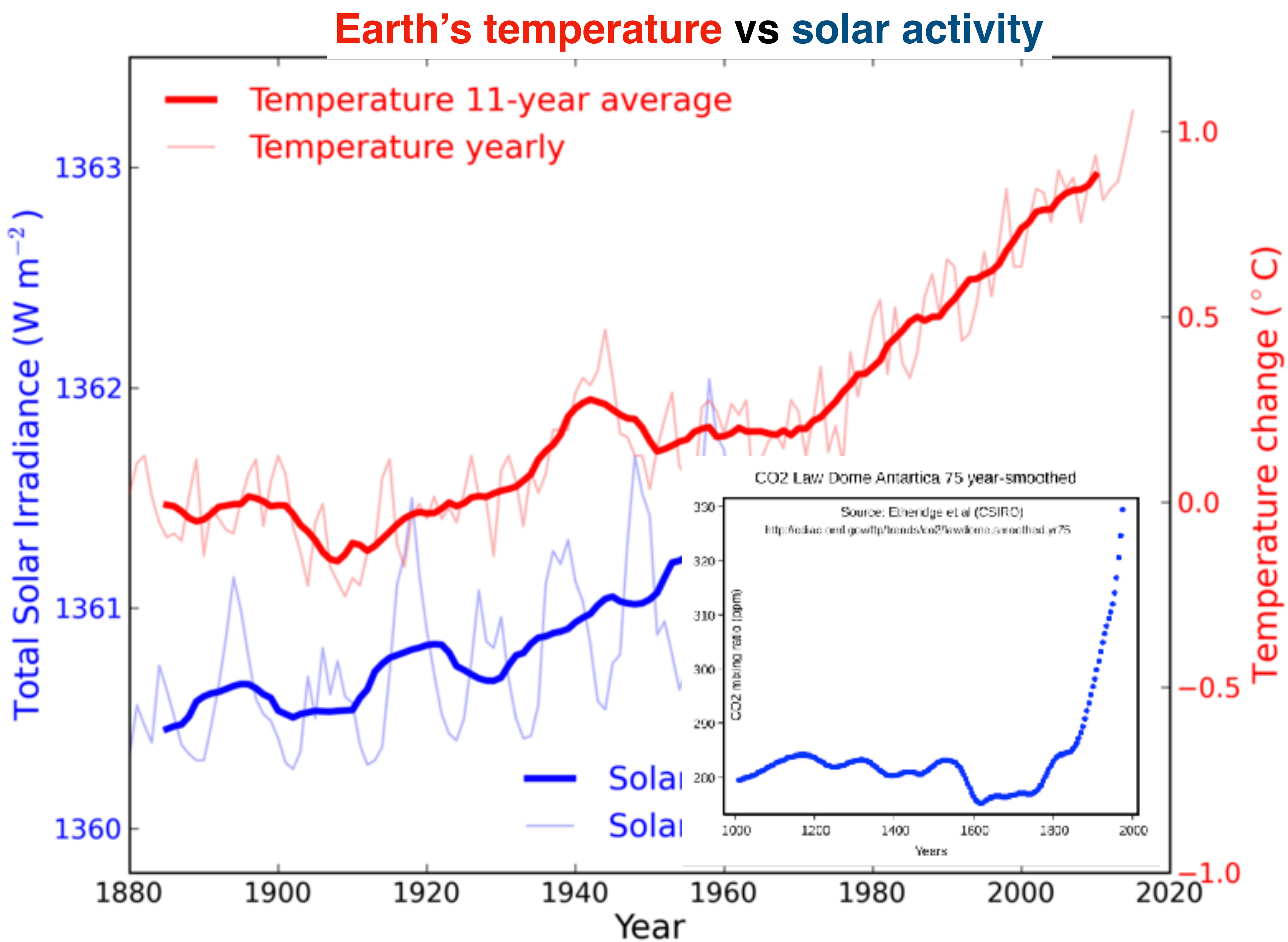
Variation of the Sun’s total irradiance

- Magnetic fields produce sunspots and faculae (to be discussed later) at the surface
  - Visible brightness changes of Sun correlated with number of sunspots but only a few milli-mags!
- **Total Solar Irradiance** (TSI, measure of the radiation flux from the Sun that is received at Earth)
  - Variation of TSI over solar cycles only ~0.1 %



Solar cycle

Variation of the Sun's total irradiance

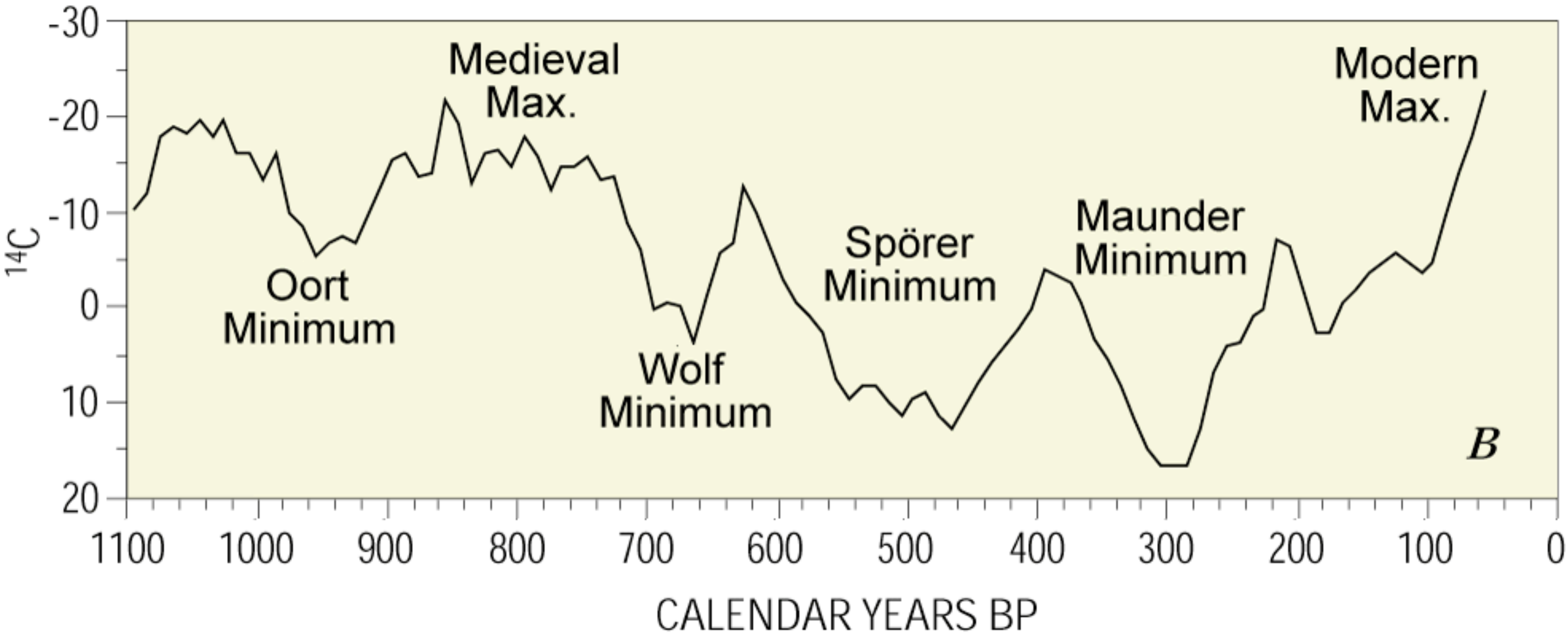


NASA/ Krivova et al 2007/World Radiation Center/PMOD

Solar cycle

Long-term variation of solar activity

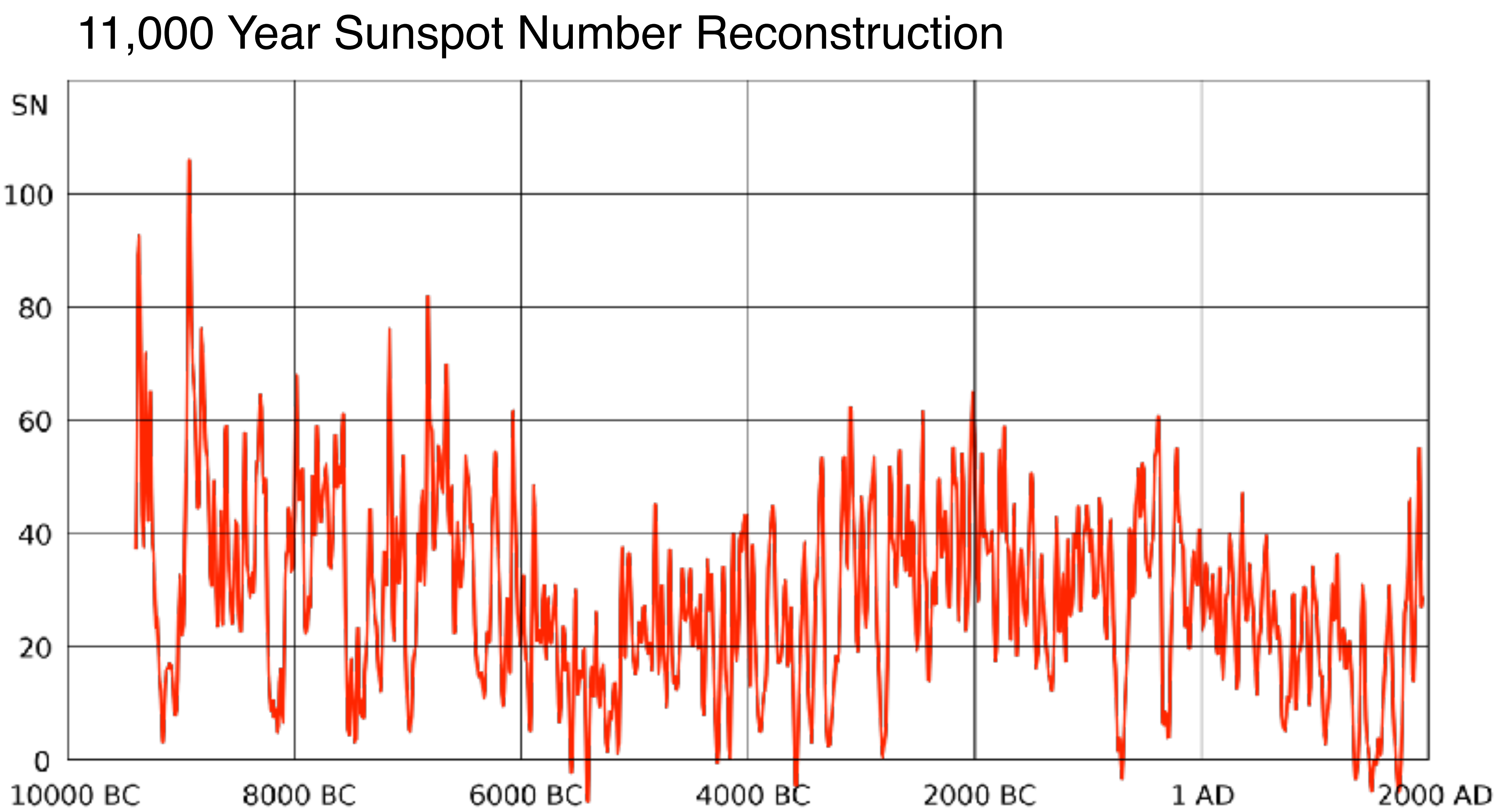
Changes in **carbon-14** concentration in the Earth's atmosphere, which serves as a long term **proxy of solar activity**.



United States Geological Survey

Solar cycle

Long-term variation of solar activity (2)

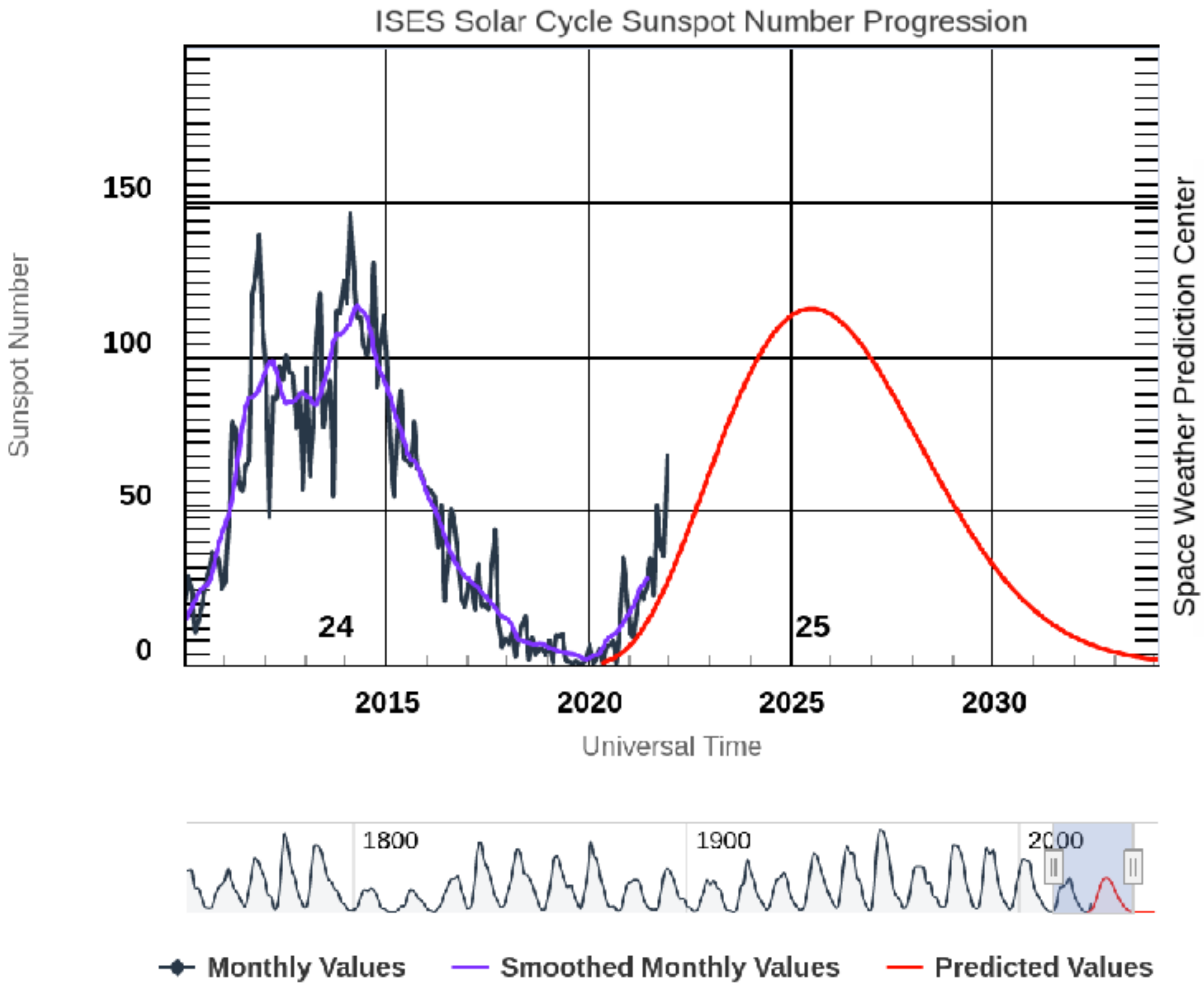


Solanki, S.K., et al. 2005.

Solar cycle

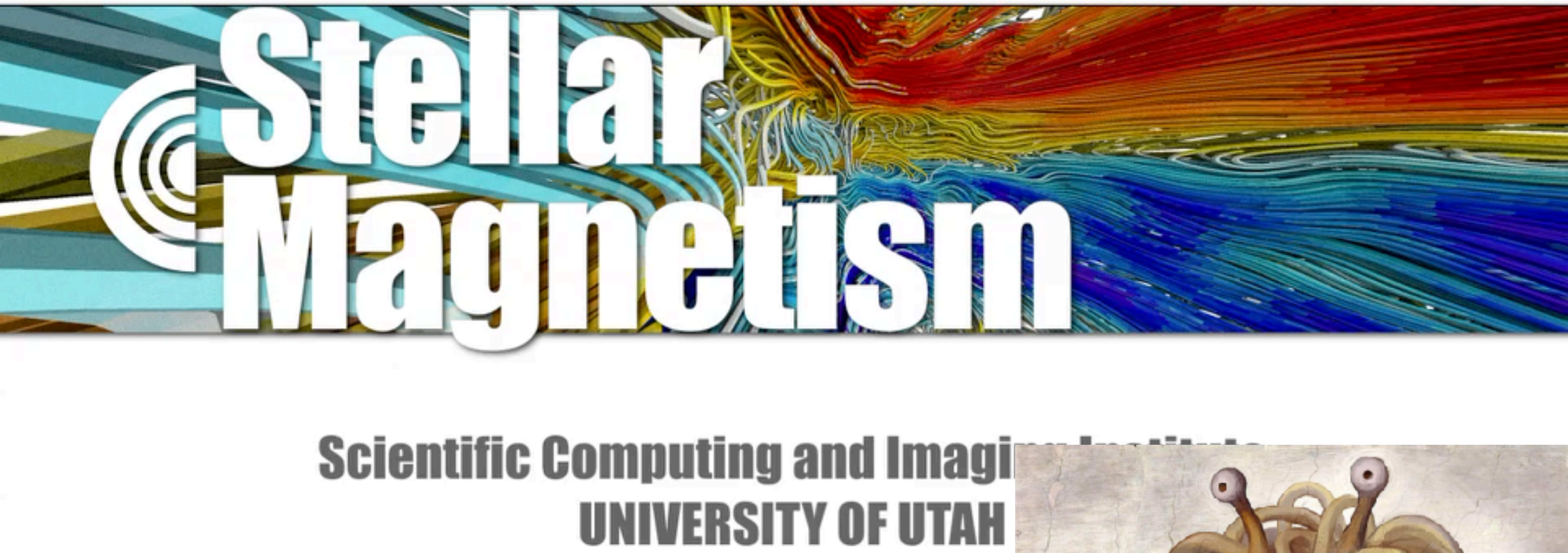
Current and future cycle (prediction)

- Models of the solar dynamo allow for prediction of the next cycle
- Comparison of actual sunspot number (as they occur) as a crucial test of the model



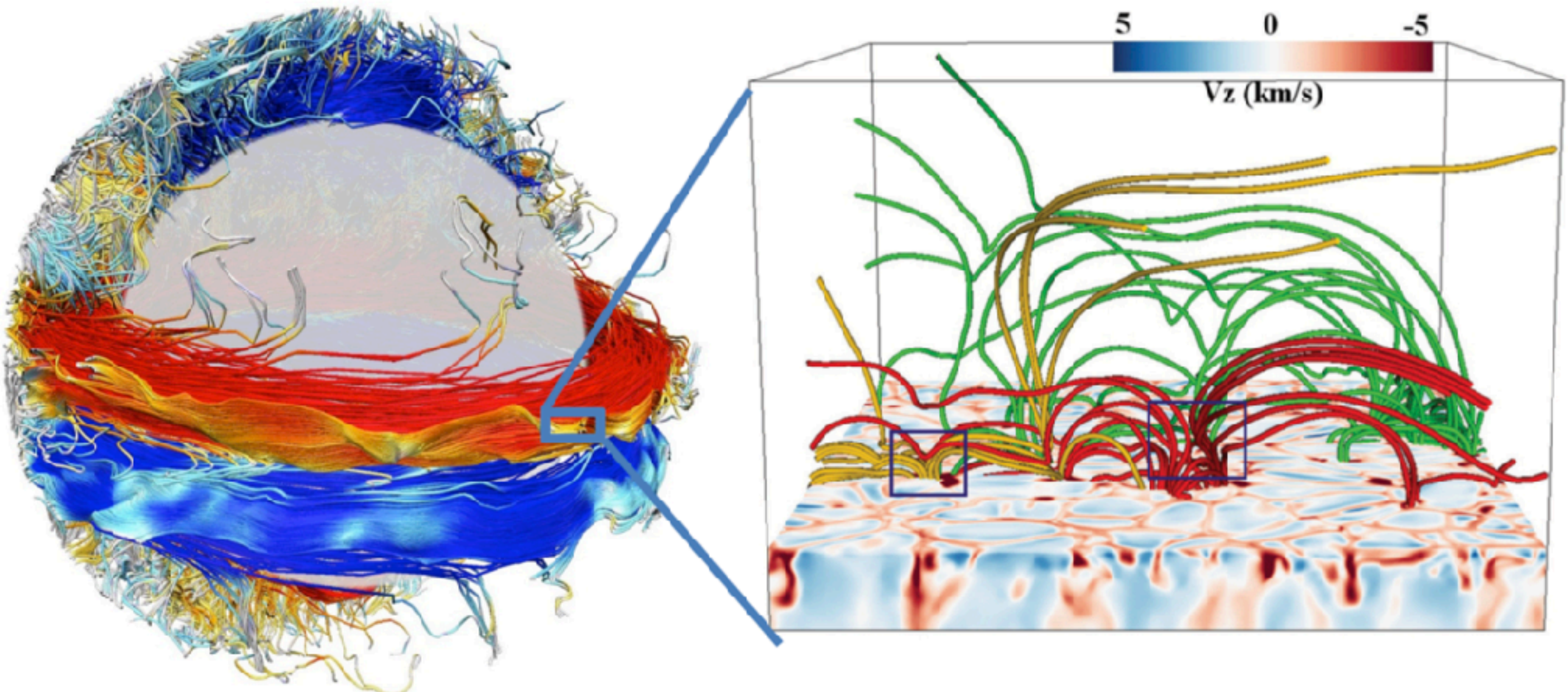
Dynamo — Solar cycle

Global dynamo simulations



Dynamo

WholeSun project



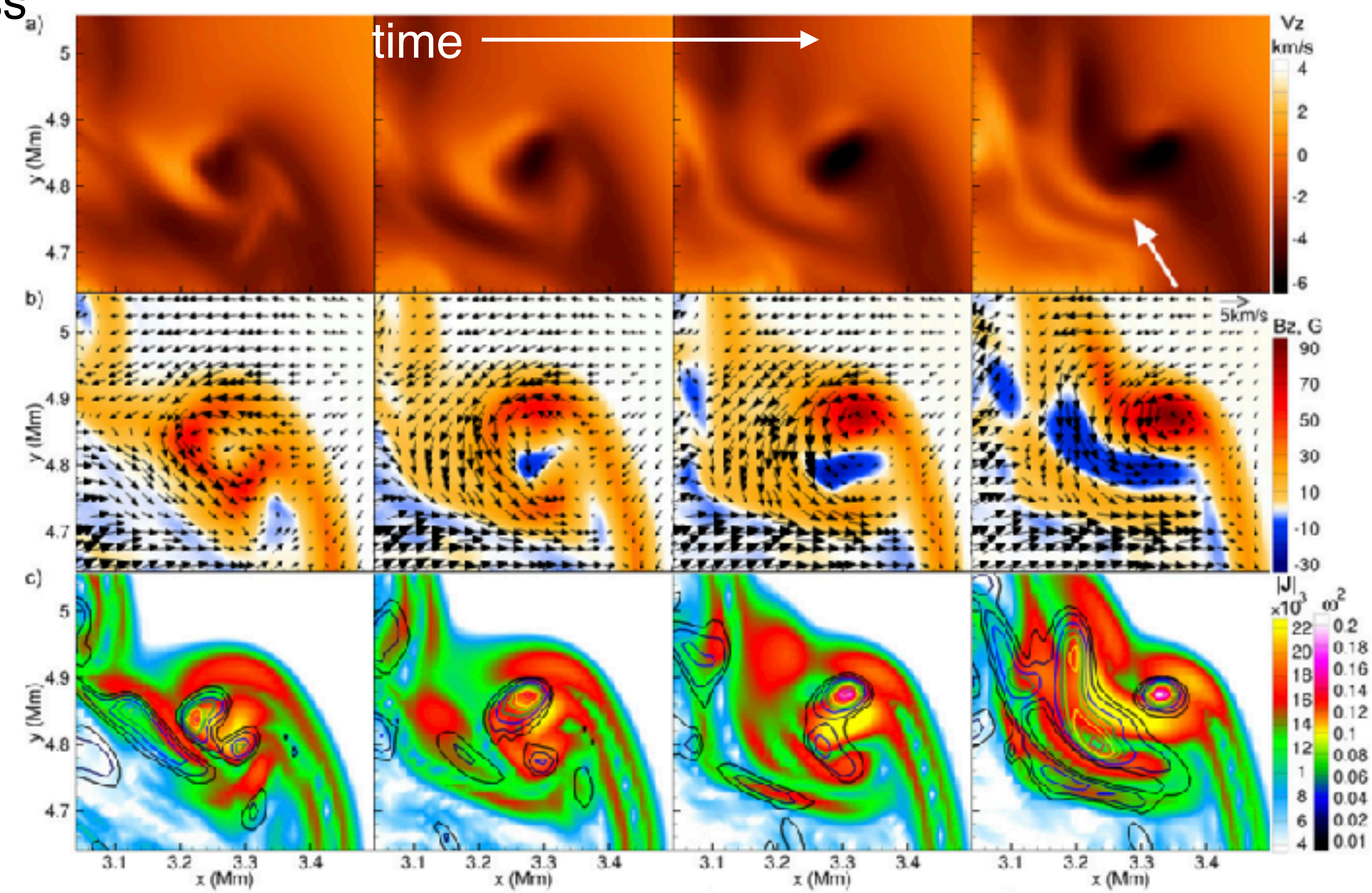
Dynamo

Local dynamo

- In addition to the global solar dynamo: local dynamo action near the solar surface
- Dynamo action will occur in a turbulent medium even in the absence of rotation (Emonet and Cattaneo 2001)

➡ Strong enough surface convection can lead to magnetic field generation due to a local dynamo process

Magnetic field is generated by swirling turbulent flows (Kitiashvili et al. 2015)



Stellar activity

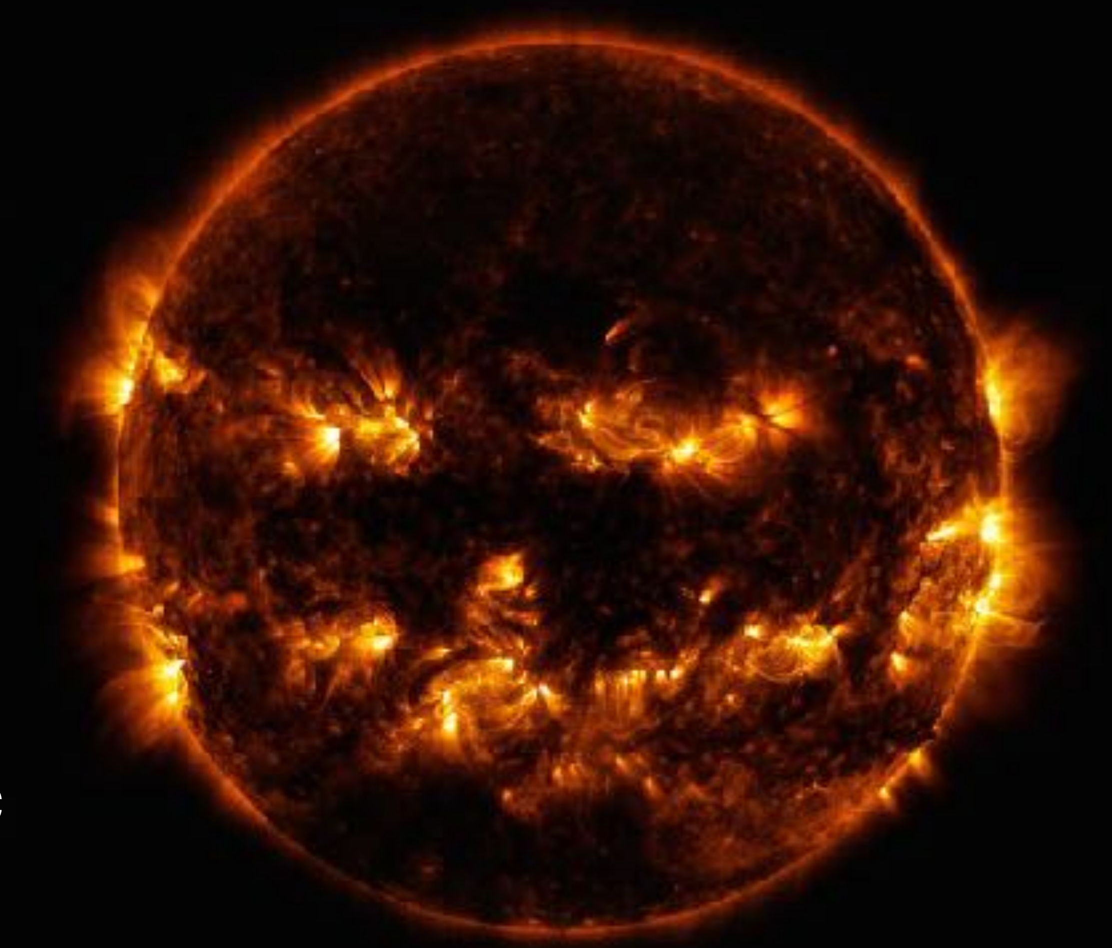
Stellar activity

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.



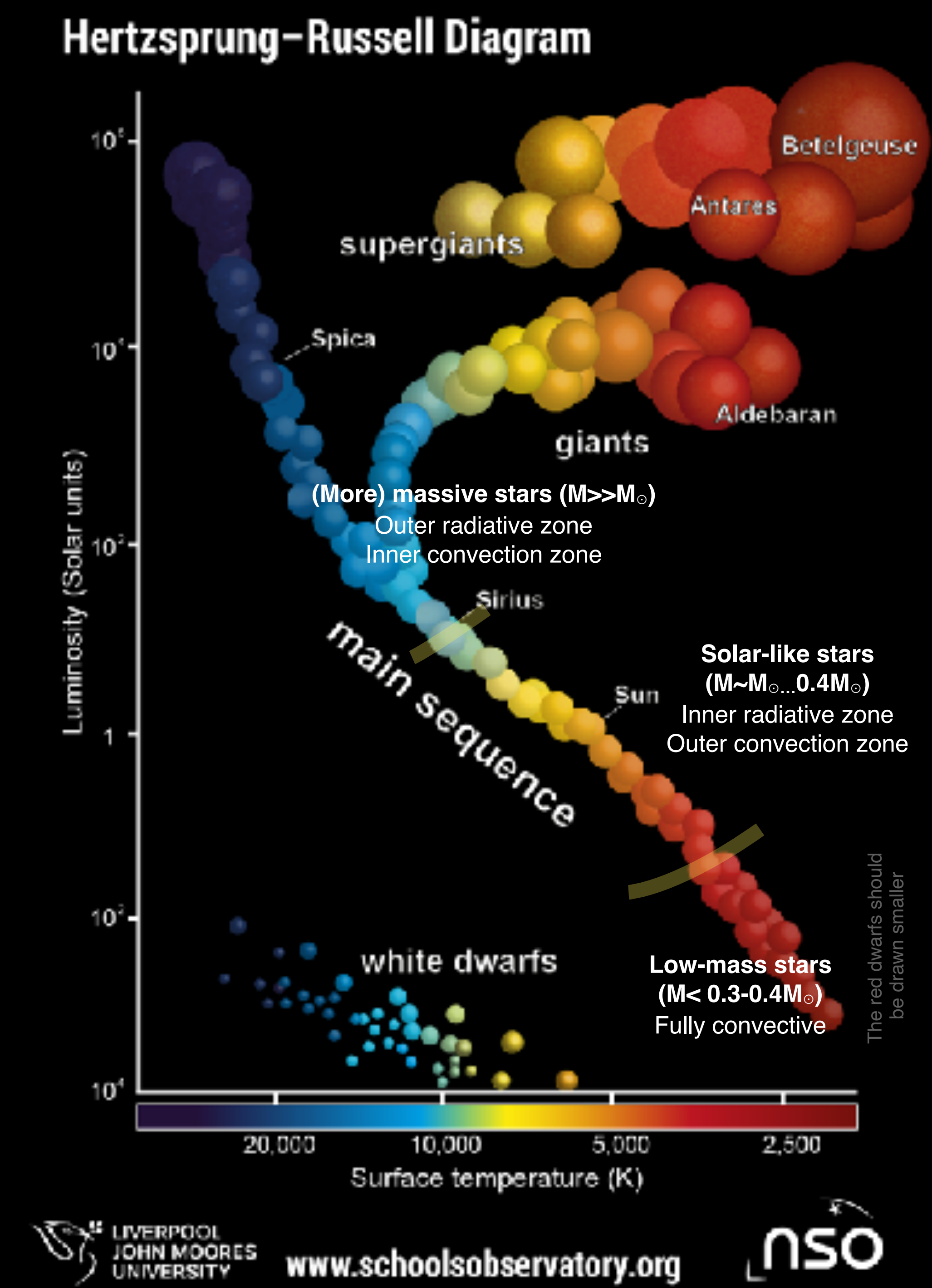
Further reading: Hall, Living Rev. Solar Phys., 5, (2008

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
  - … radiative zone? (Tayler-Spruit / Zahn+07)

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



Stellar activity

How to detect activity cycles?

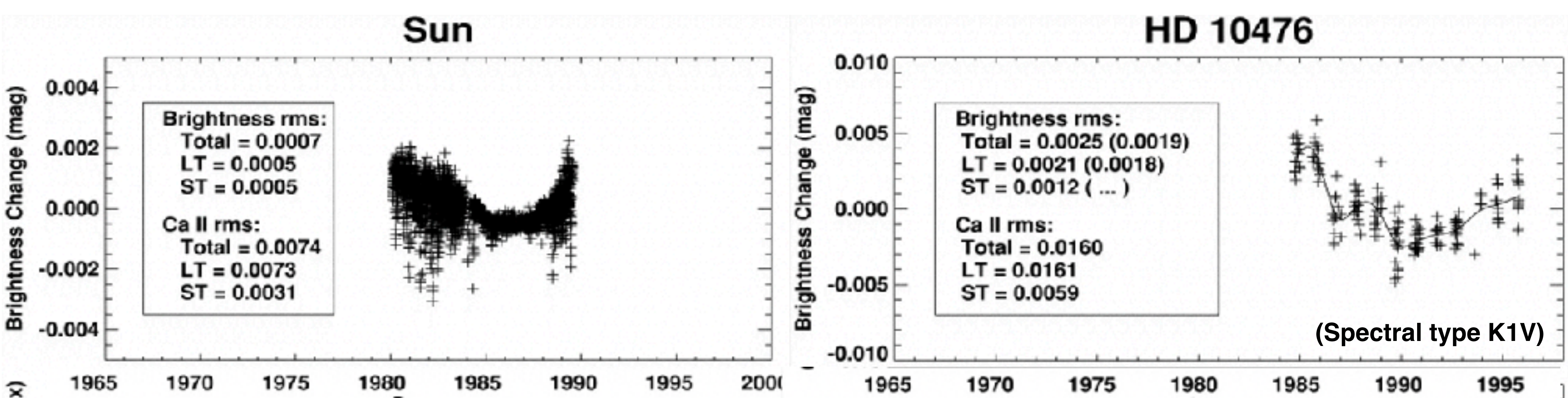
- The usual problem: Stellar observations are **spatially not resolved**, starspots not observed directly* — no "starspot number" can be derived directly

**except for a few interferometric observations*

- Visible brightness changes of Sun only few milli-mags anyway

➡ 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)) : **chromosphere**

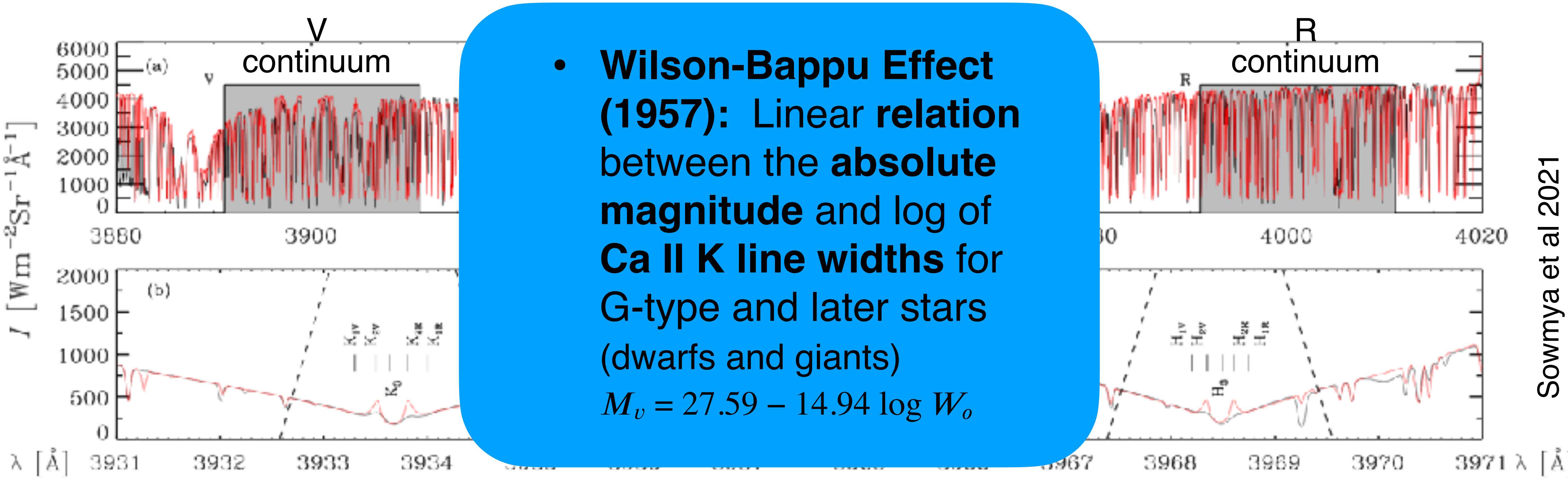
➡ Measures of the overall magnetic activity level of the star, for instance:
https://pyastronomy.readthedocs.io/en/latest/pyaslDoc/aslDoc/sindex.html

R_{HK}-index. $$R_{HK} = \frac{F_H + F_K}{\sigma T_{eff}^4}$$

F_{HK}: flux in H and K band ; σT_{eff}^4 : bolometric flux

S-index $$S(t) \propto \frac{N_H(t) + N_K(t)}{N_R(t) + N_V(t)}$$

N: Counts (flux) in the passbands



- **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

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

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S-index $$S(t) \propto \frac{N_H(t) + N_K(t)}{N_R(t) + N_V(t)}$$

N: Counts (flux) in the passbands

- When R_{HK} and the S-index are absolute measure of emitted light, they exist similar indicator looking at the variability of these emissions :

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

F_{HK}: flux, F_{phot}: flux, photospheric contributions

➡ S_{ph} is a measure of the variability of the **photometric** light-curve (Santos et al. 2014)

Sowmya et al 2021

λ [Å] λ [Å]

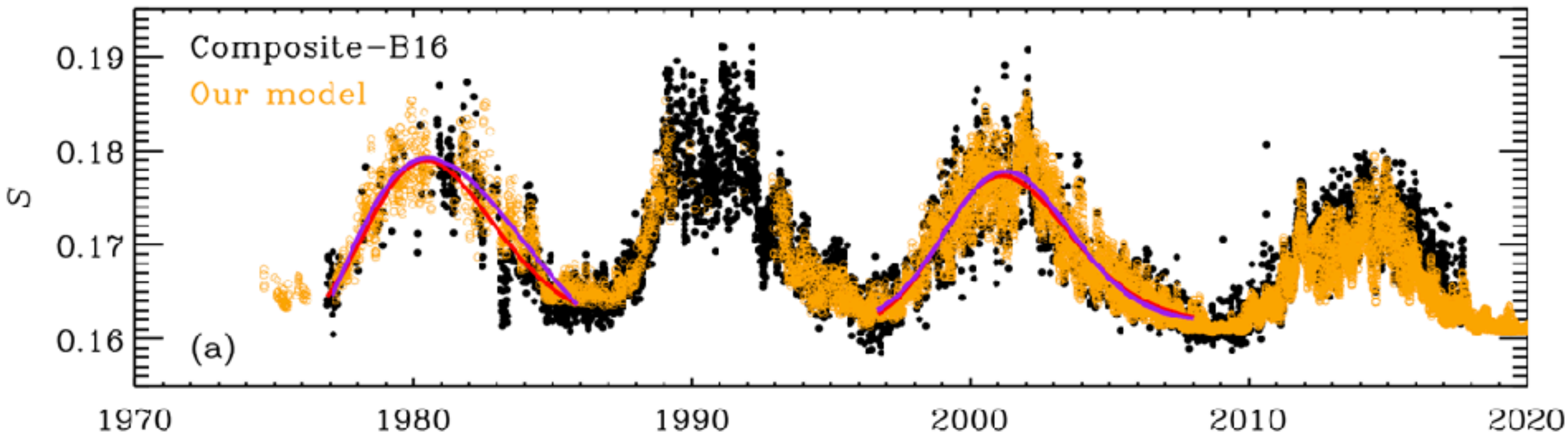
Stellar activity cycles

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 (photo):

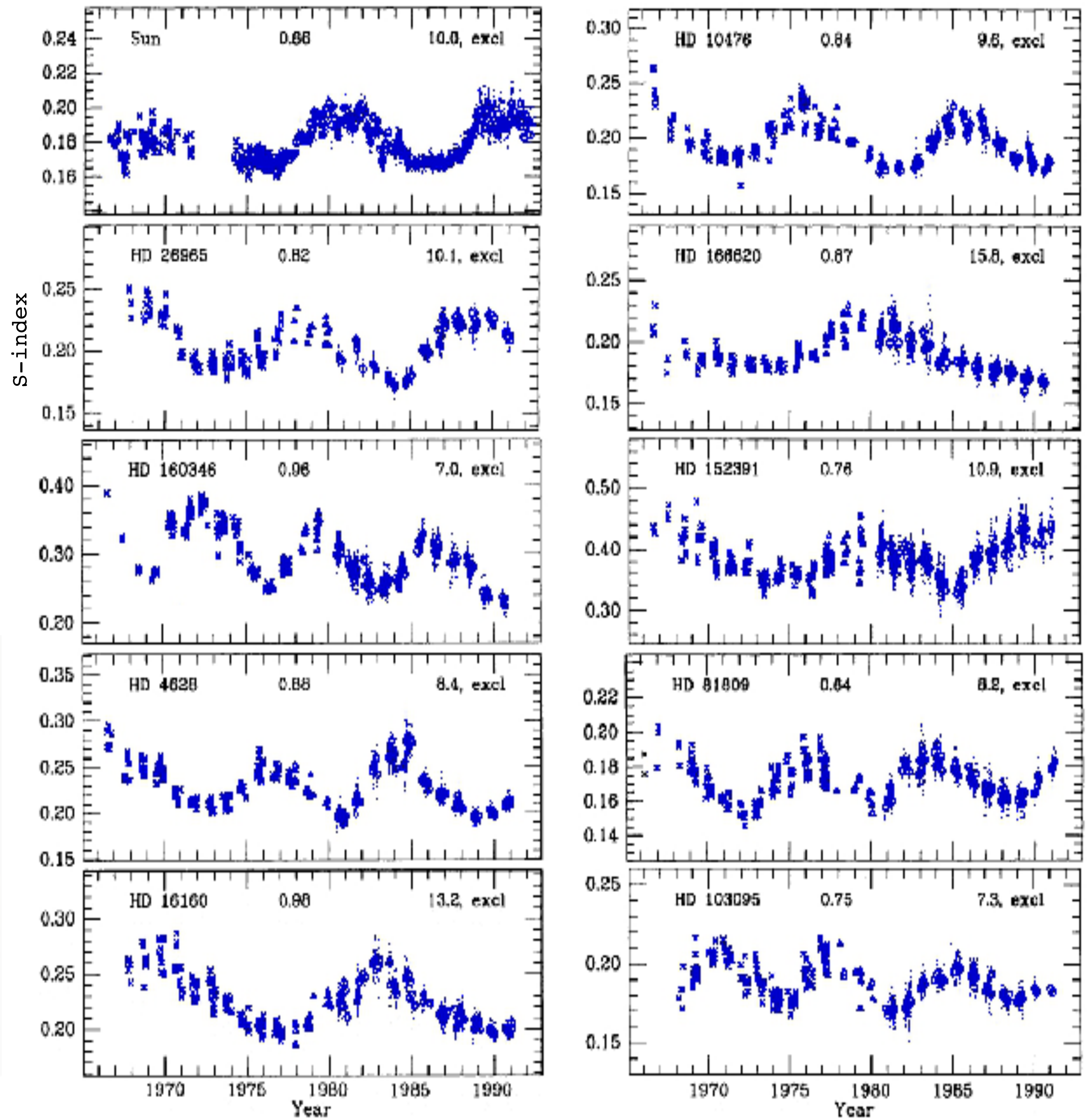


Sowmya et al 2021

Stellar activity cycles

Ca II observations

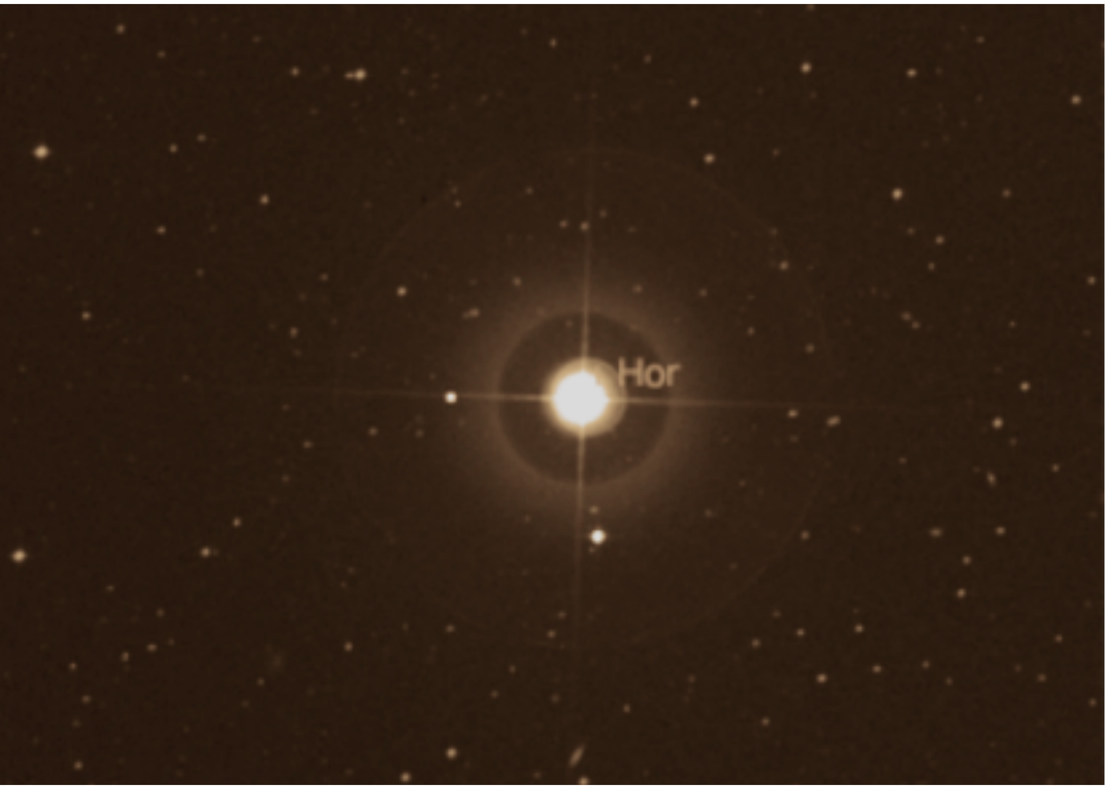
- Magnetic activity cycles found for many stars (survey at **Mount Wilson Observatory**)
- Survey ended in 2000's after more than 30 years of Ca II HK observations

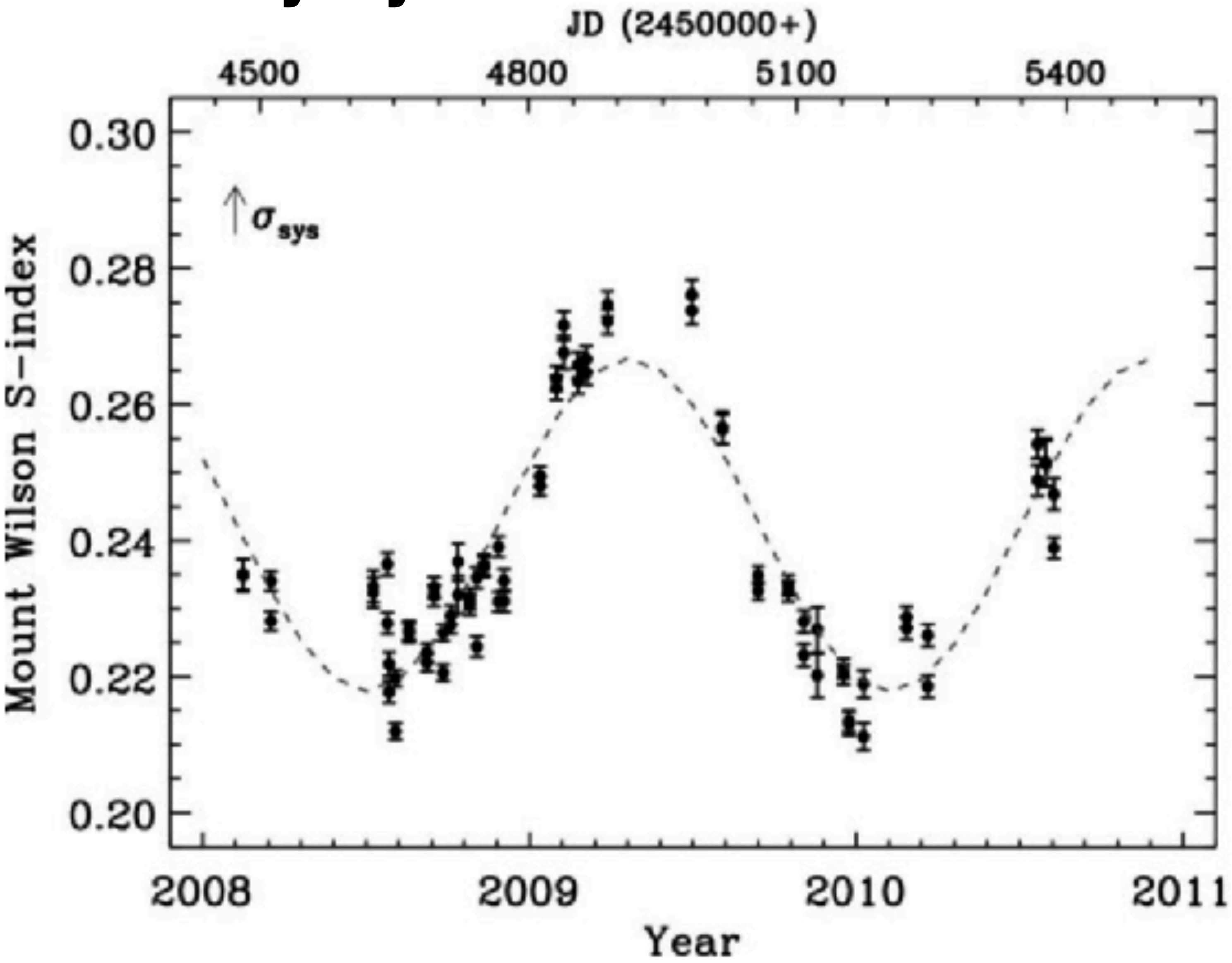


Baliunas et al. (1995)

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 $v \sin i \sim 7\ km\ s^{-1}$

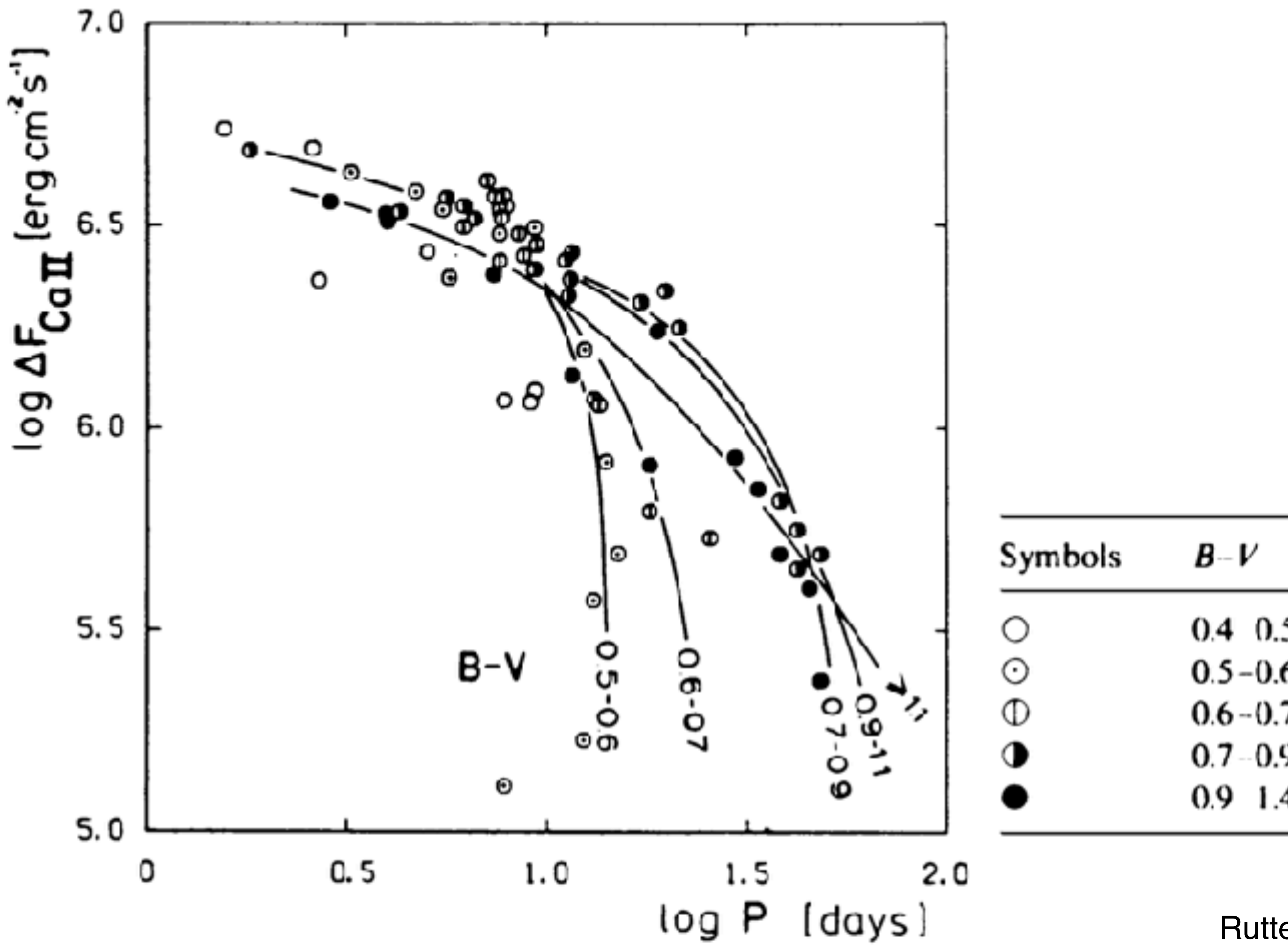
  ➡ 3 times faster than the Sun, among the faster rotating stars of that spectral type
- Consistent with coronal activity cycle found from XMM x-ray measurements

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

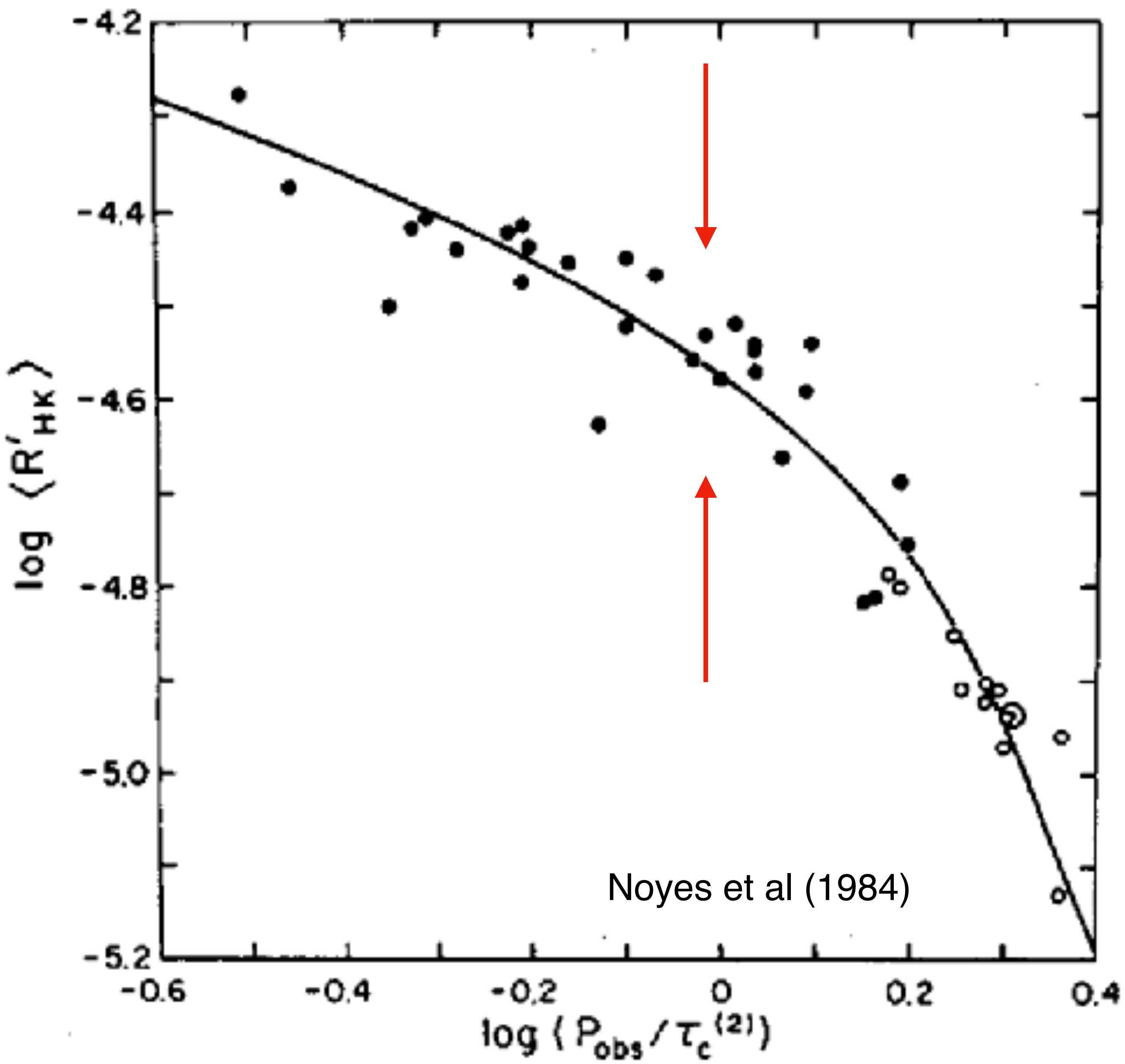


Rutten & Schrijver (1987)

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



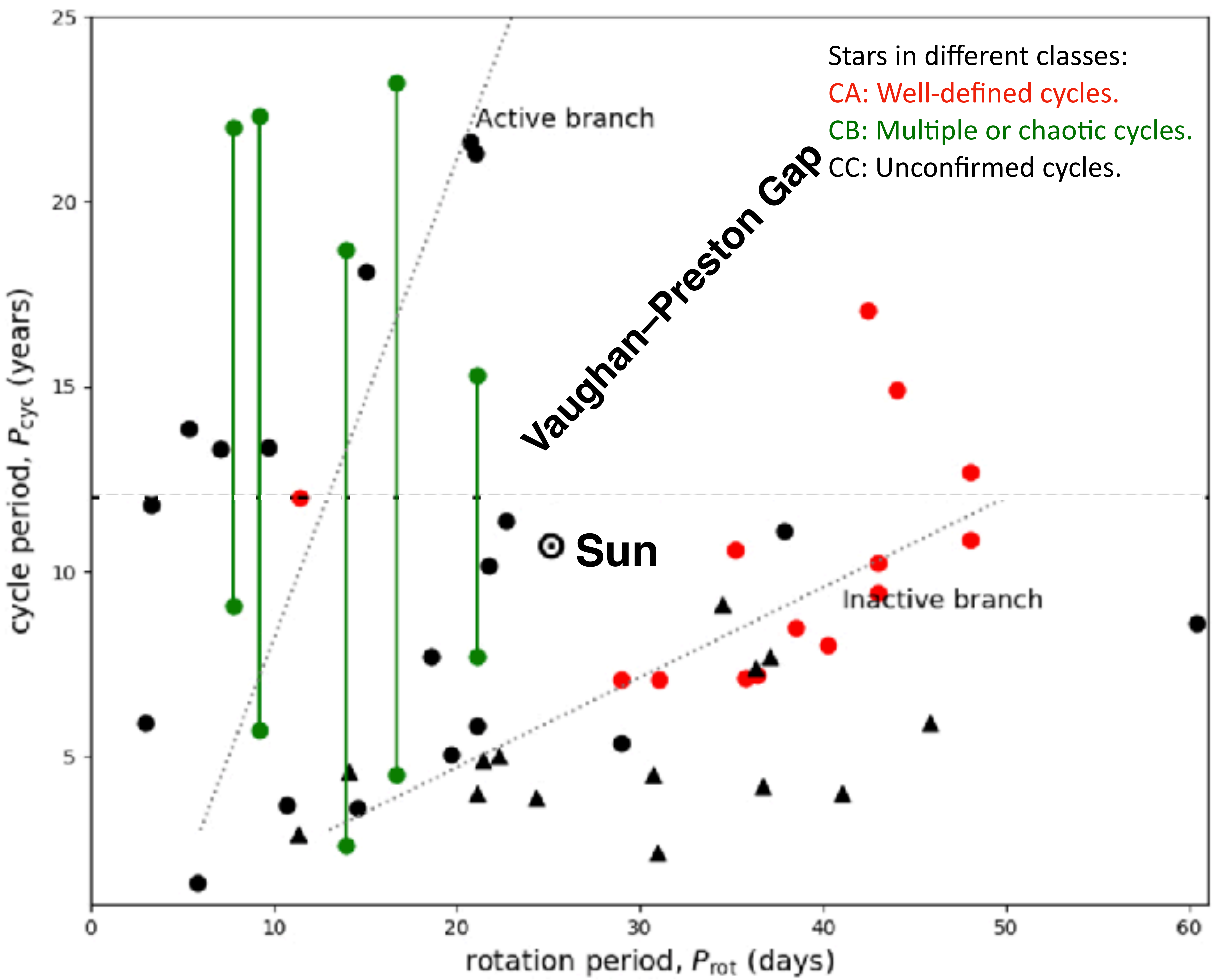
$$Ro = \frac{\text{Advection}}{\text{Coriolis}} = \frac{\text{Convection}}{\text{Rotation}} \propto \frac{M_*^{1.7}}{\Omega_*}$$

Brun et al. 2017

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?*



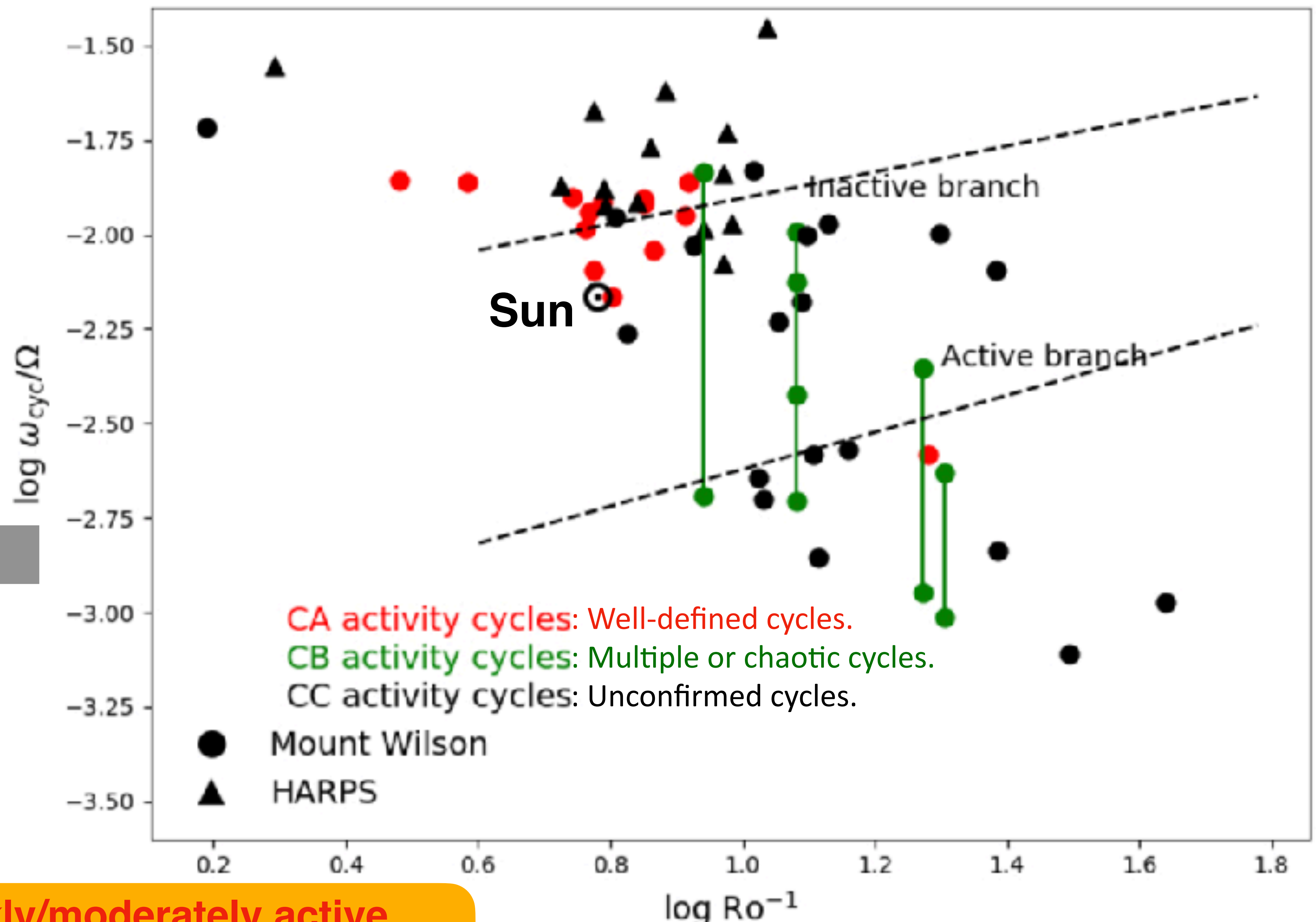
Boro Saikia et al. (2018) A&A 616, A108 (2018)

Stellar activity cycles

Activity cycle vs. rotation

- For same stars: ratio of cycle frequency ω_{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



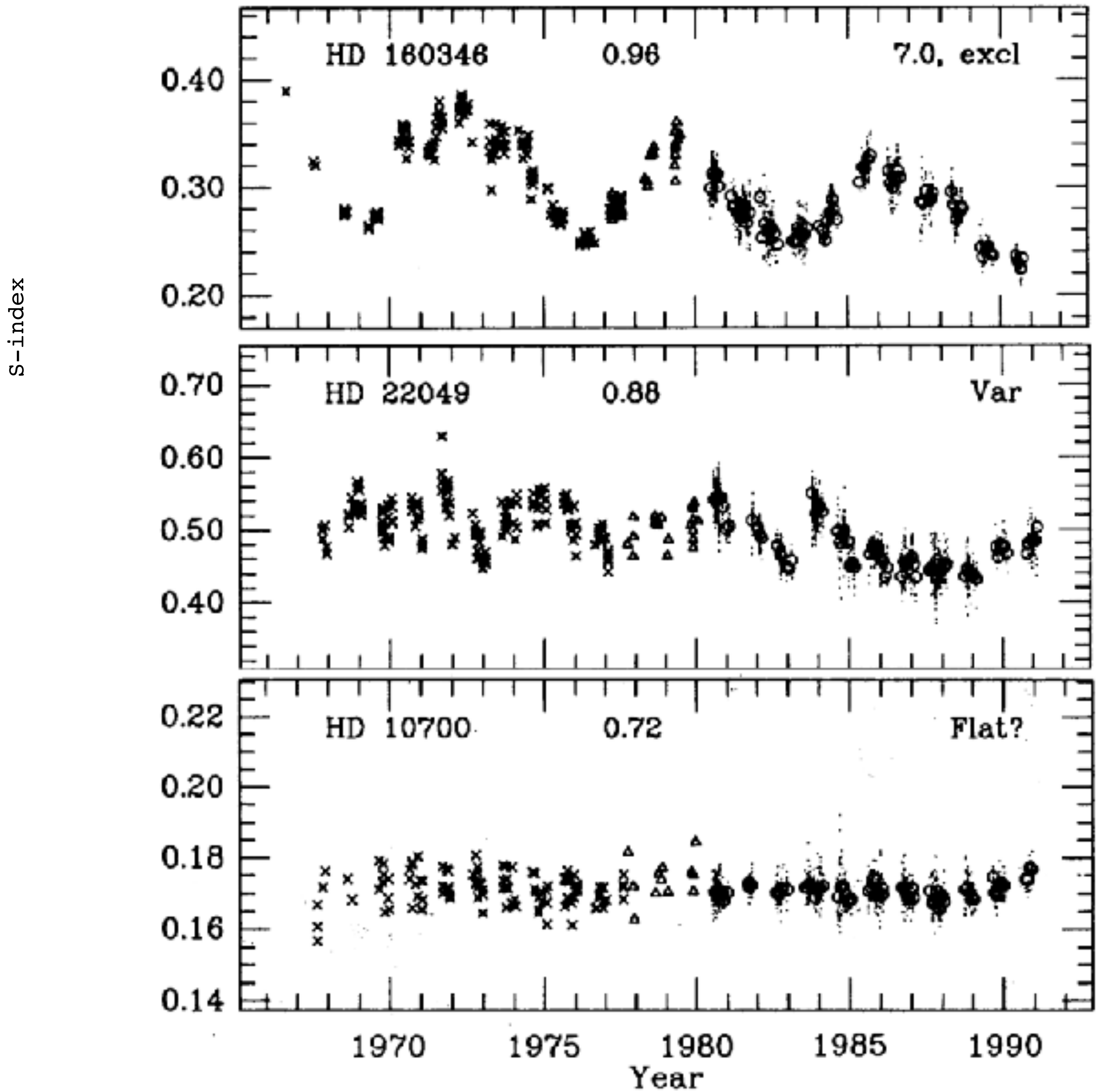
Boro Saikia et al. (2018) A&A 616, A108 (201

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

Stellar activity cycles

Ca II observations

- Magnetic activity cycles found for many stars (survey at **Mount Wilson Observatory**)
- Not all stars have clear magnetic cycle, some may have none
  - ➡ **Stationary dynamo?**
  - ➡ **Observational biais?**



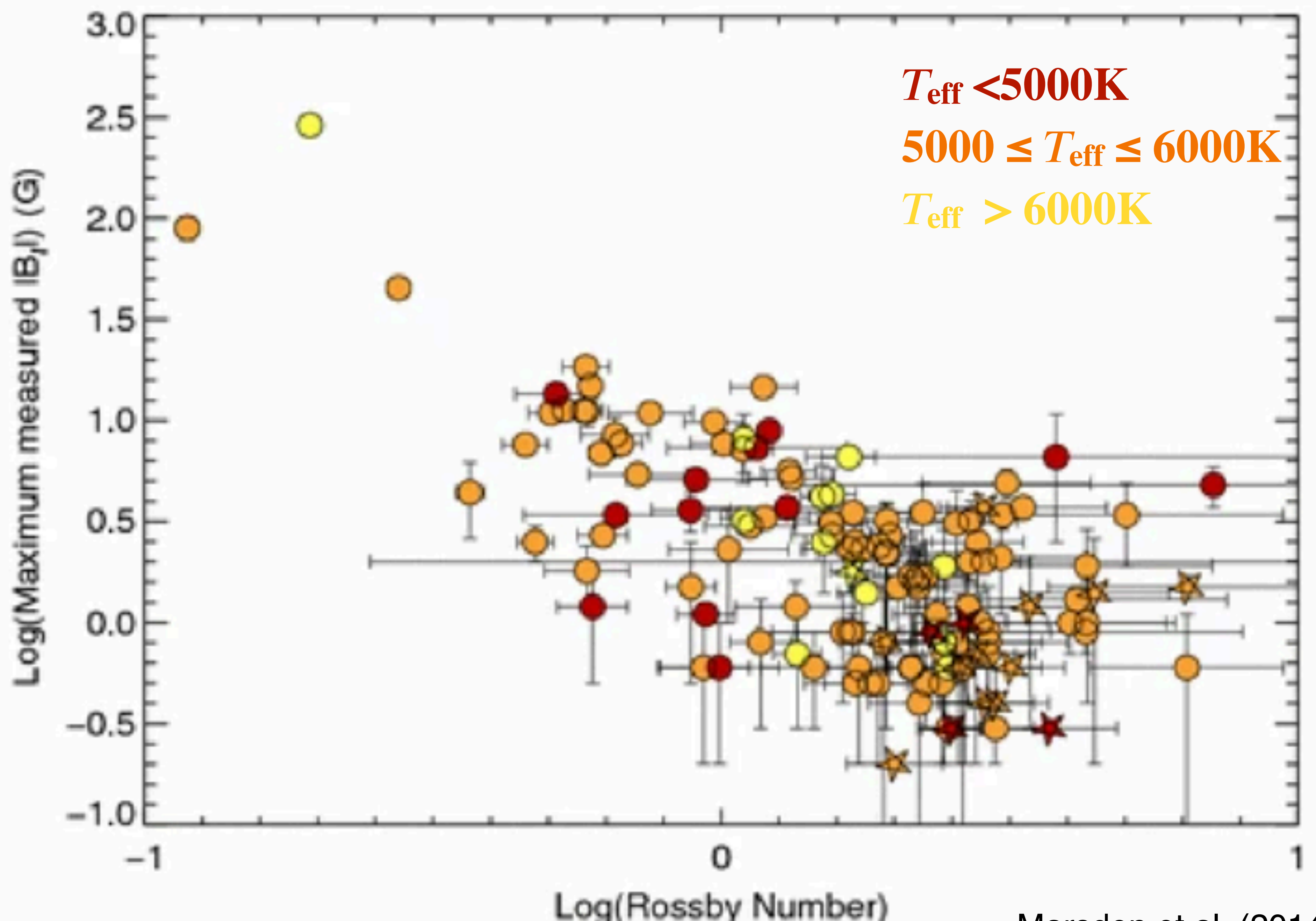
Baliunas et al. (1995)

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



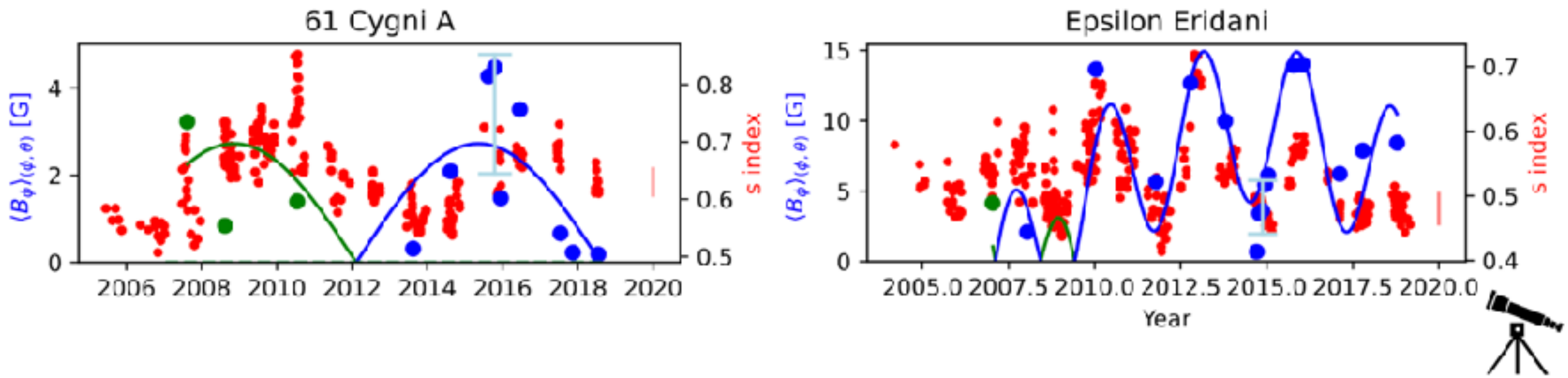
Marsden et al. (2014

Stellar activity cycles

Stellar dynamos

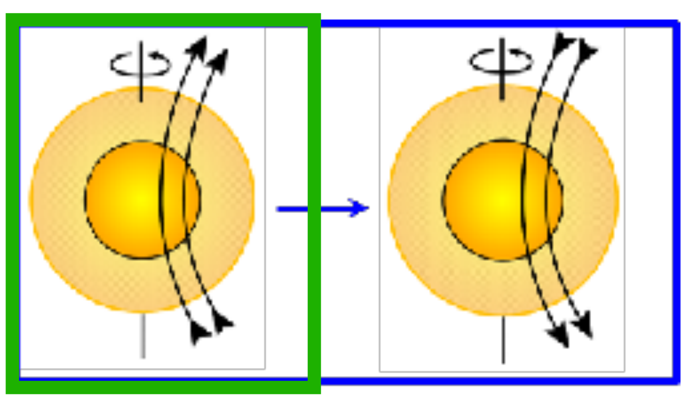
- BCOOL survey: **different nature of magnetic cycle can be found**

Jeffers et al. (2022)



- Cyclic global polarity reversal

No cyclic global reversal



- Hard to caracterized, global reversals only found for **5 stars** :
  61 Cigny A ; ϵ - Eridani ; κ Ceti ; AF Lep & V1358 Ori

(Bourrier et al. 2018, Jeffers et al. 2022, Boro Saikia et al. 2022, Marsden et al. 2021)

Stellar activity cycles

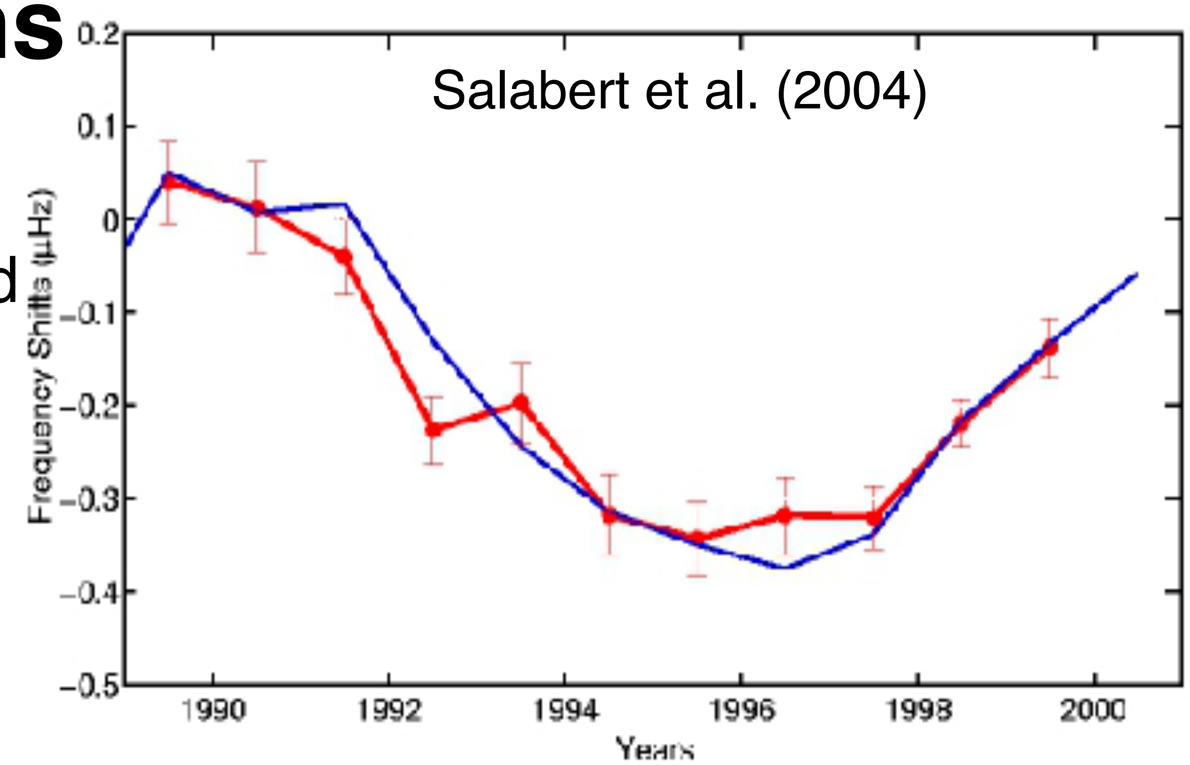
Impact on stellar oscillations

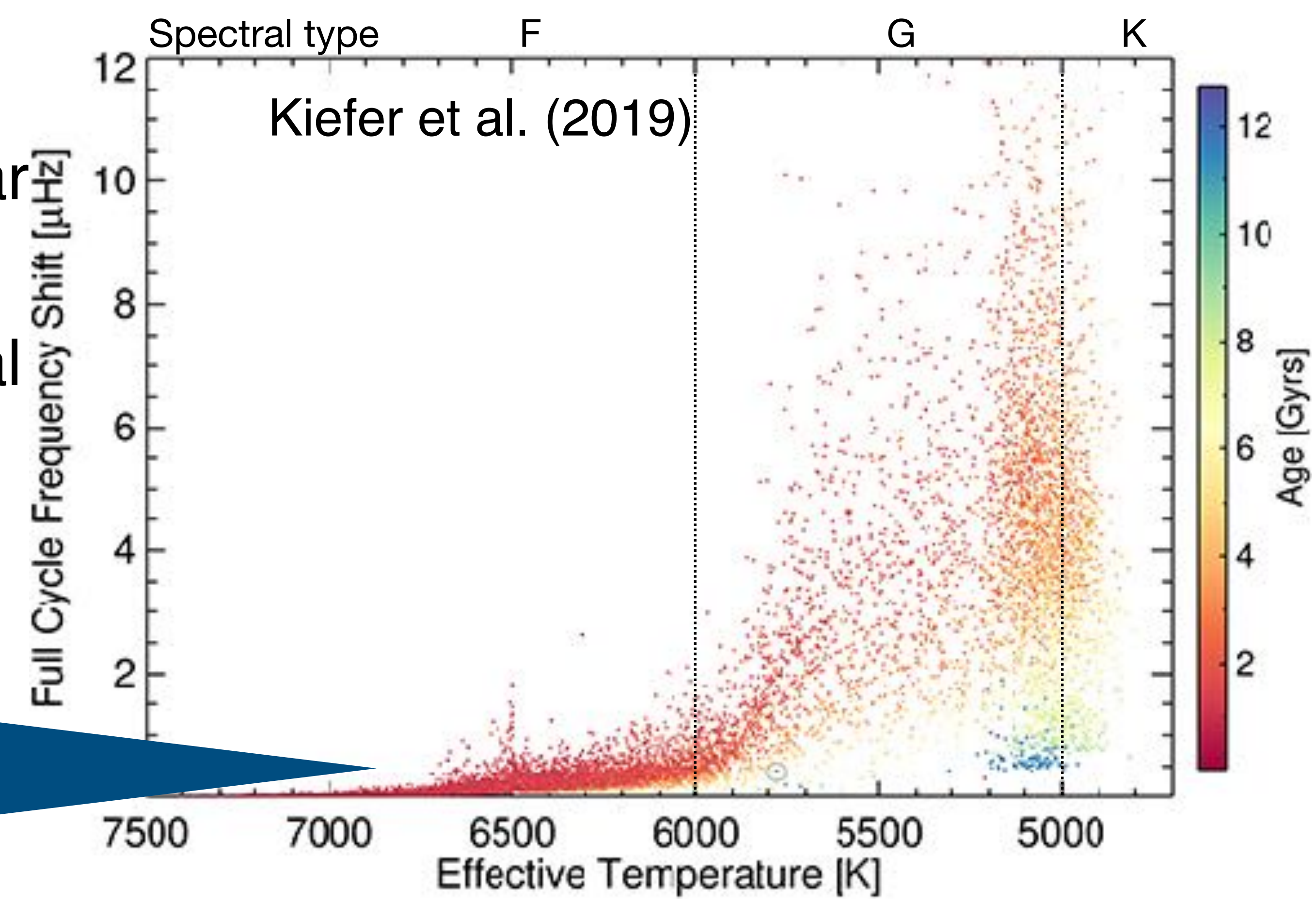
- Magnetic field modifies the near-surface propagation speed, convective velocity and interior stratification

  ➡ 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



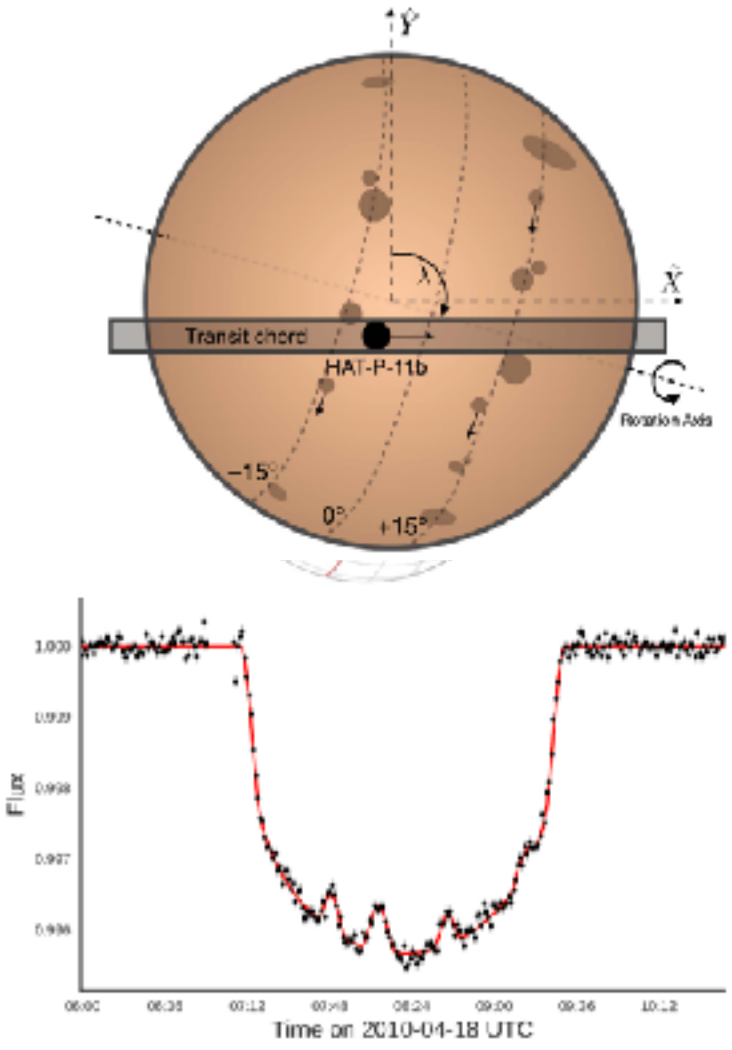


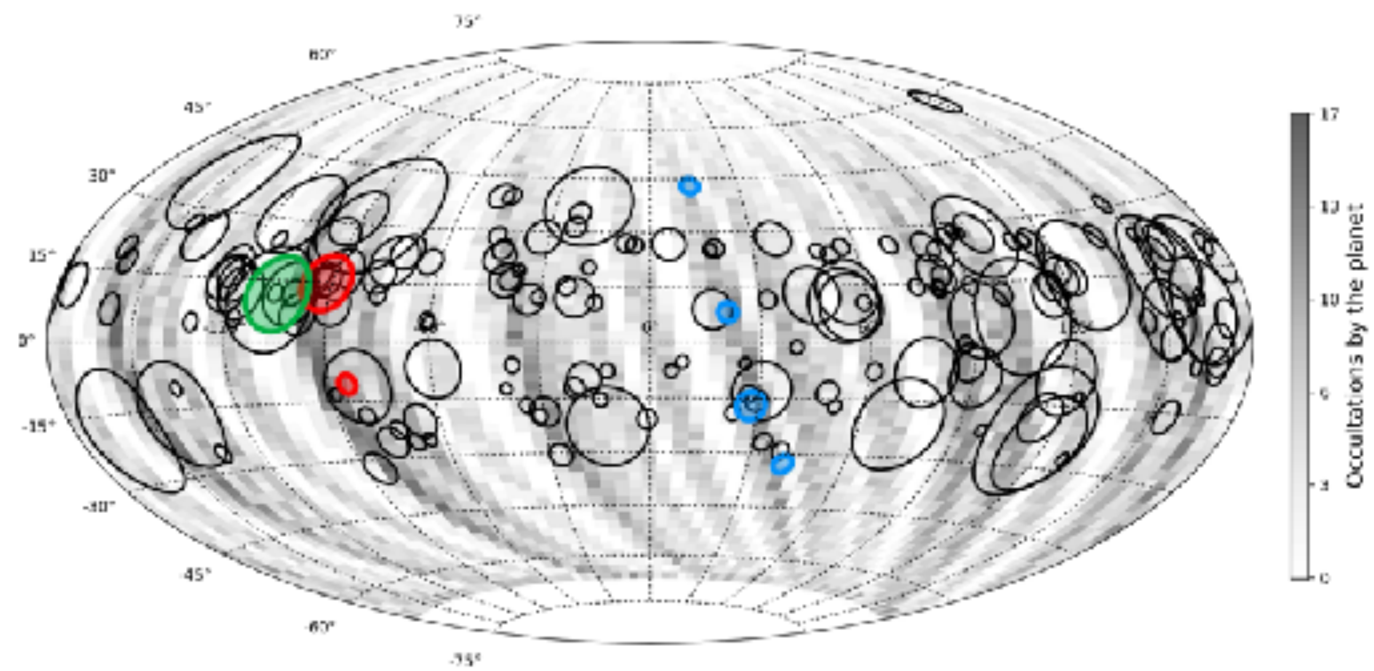
- Note the effect being much smaller for F-type stars

➡ Global dynamo needs surface convection

Stellar activity cycles

"Photometric help" from transit



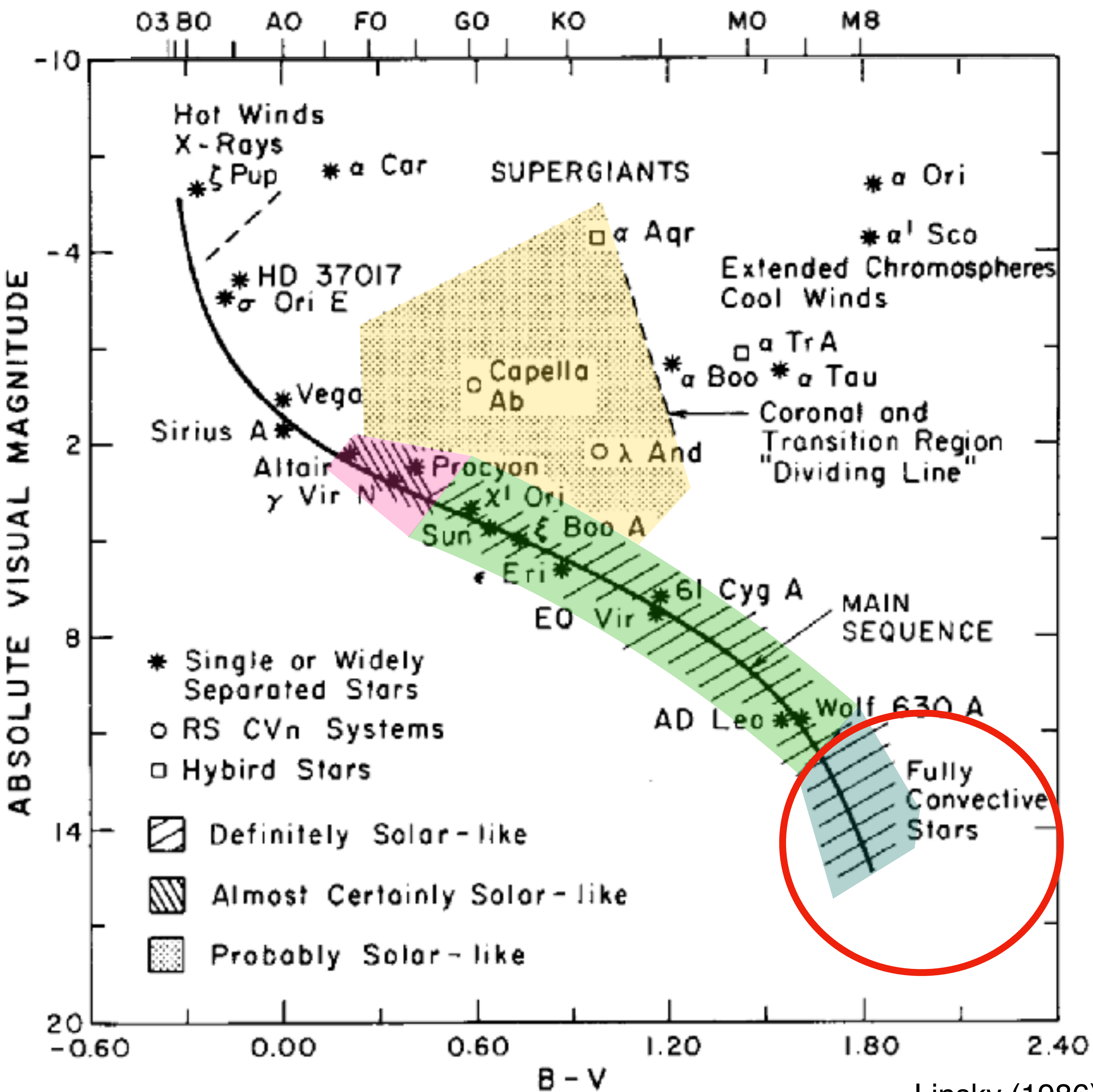


Morris et al. 2017

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

- **Example: Proxima Centauri** — representative of slowly rotating **fully convective** M-dwarfs (Stars with low mass M< 0.3-0.4$M_\odot$) - **no tachocline**
- Numerical simulations (Yadav et al. 2016) show **rotating convection spontaneously generates differential rotation** in the convection zone (without the need of a tachocline)

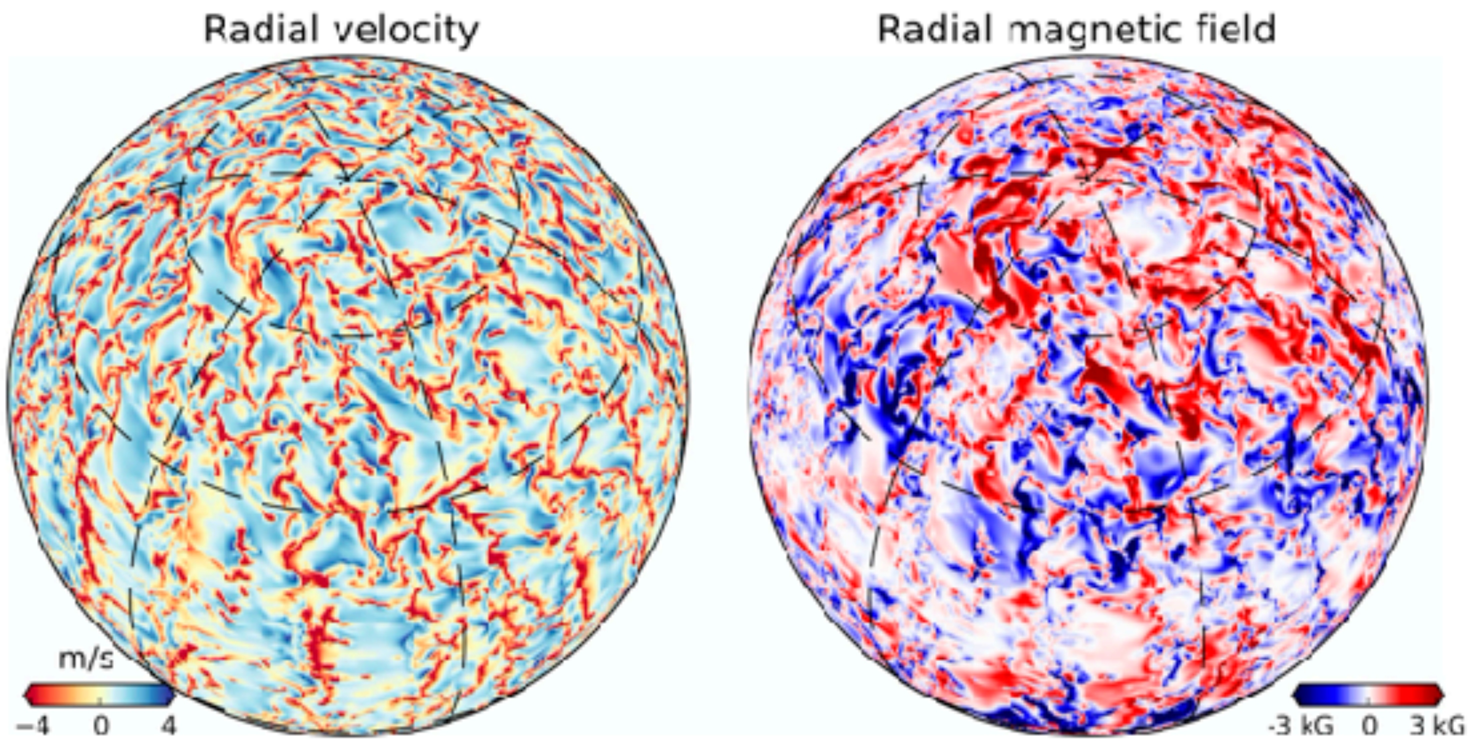
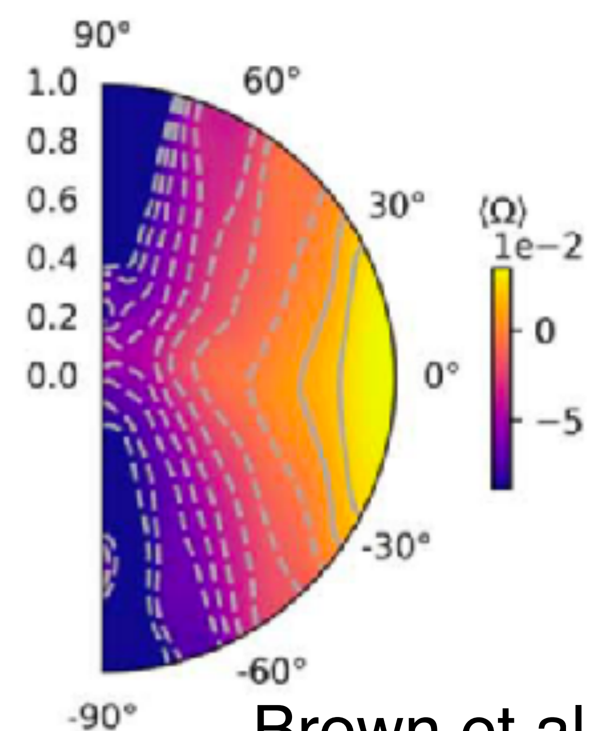


Figure 4. Radial velocity and radial magnetic field on a layer close to the outer boundary ($r = 0.97r_o$) of the simulation. Note that this snapshot is from a simulation segment that was run on a higher-resolution grid (2048 in longitude, 1024 in latitude, 161 in radius).



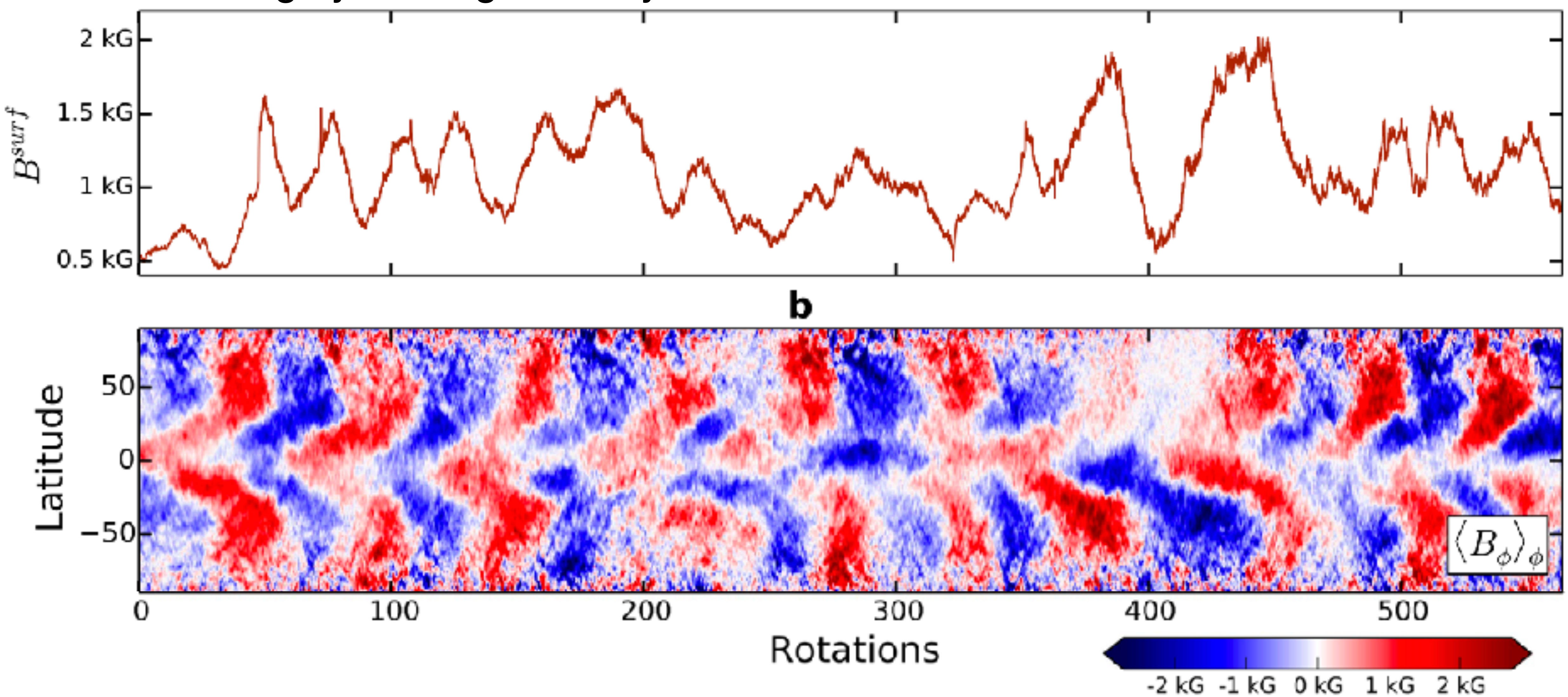
Brown et al. 2020

- Observational challenging: very faint objects, but active in Hα
- Relationship rotation rate — activity level poorly known for M-type dwarf stars
- Many M-dwarfs relatively rapid rotators

Stellar dynamos

Fully convective stars

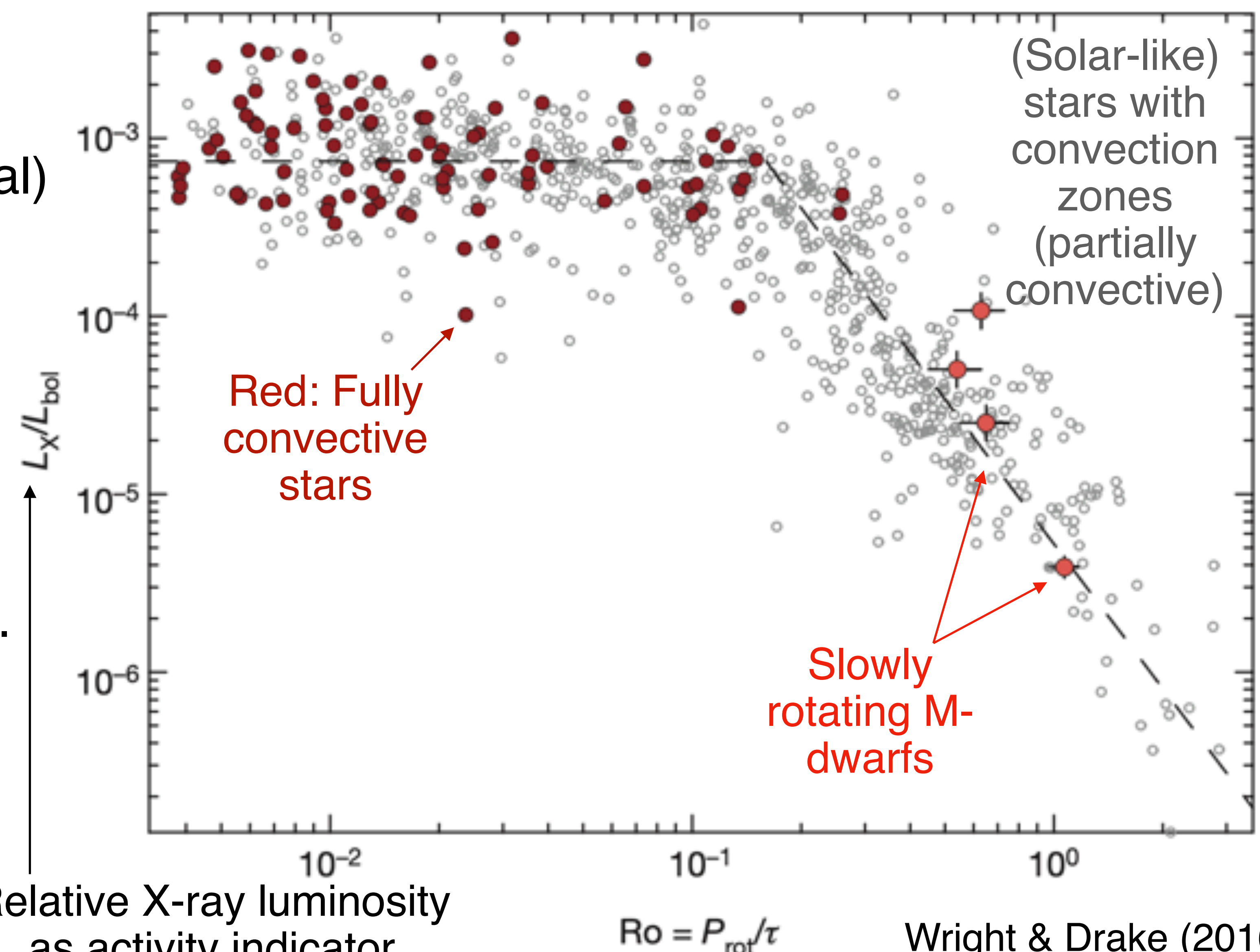
- **Example: Proxima Centauri** — representative of slowly rotating fully convective M-dwarfs
  - Drives magnetic cycles with axisymmetric magnetic field repeatedly changing polarity at all latitudes as time progress.
  - Resulting cycle length of ~9yr in line with observations of Proxima Centauri



Stellar dynamos and activity

Rotation-activity relation

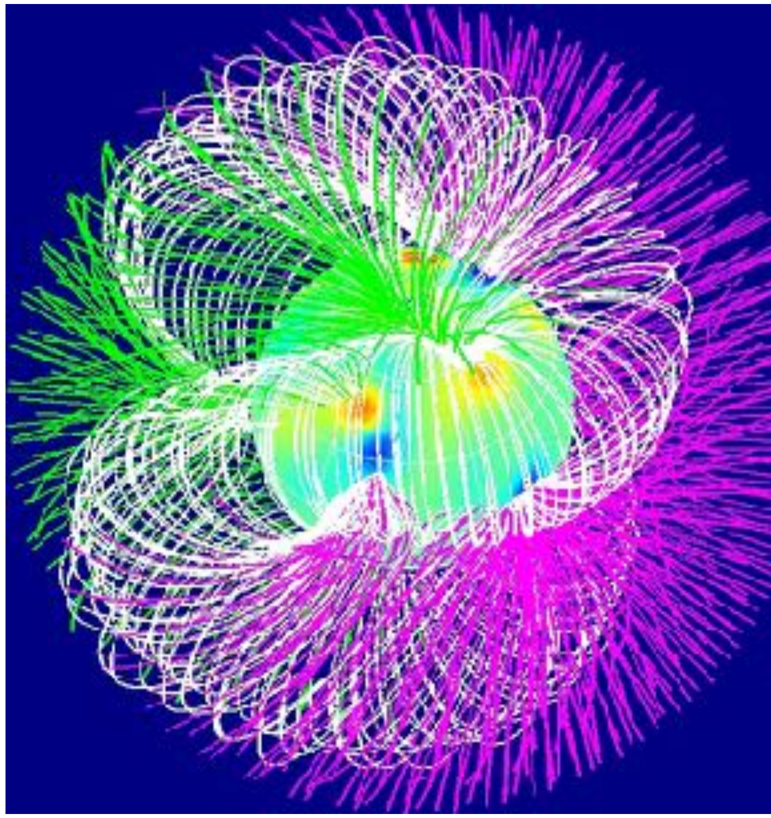
- Despite lack of a tachocline: Fully convective M-dwarfs fit the same rotation–activity sequence as solar-type stars with outer convection zones!
  - Activity and magnetism of late-type stars increase with decreasing Rossby number, then saturate
- Most likely explanation (Wright & Drake 2016):
  - Both rotation and turbulence (convection) important for (global) dynamos in <u>all</u> 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)

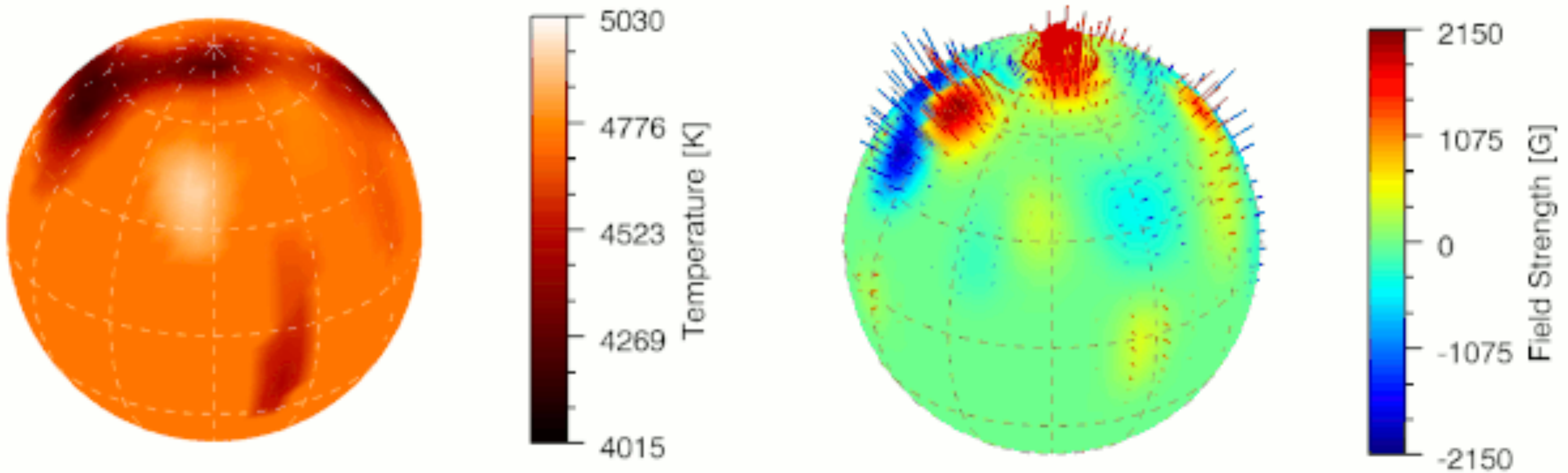
Measuring magnetic fields

Zeeman Doppler Imaging (ZDI)



- ZDI: observational constraints for dynamos in Sun-like stars
- Commonly used: Problem: Latitude degeneracy -
  - ZDI cannot always distinguish the hemisphere in which the starspots are located
  - Uncertain north–south distribution of starspot active latitudes
  - Limits constraints of dynamo theory !
- Alternative measurements via direct interferometric imaging

Example: II Pegasi A (HD 224085)



Strassmeier/AIP