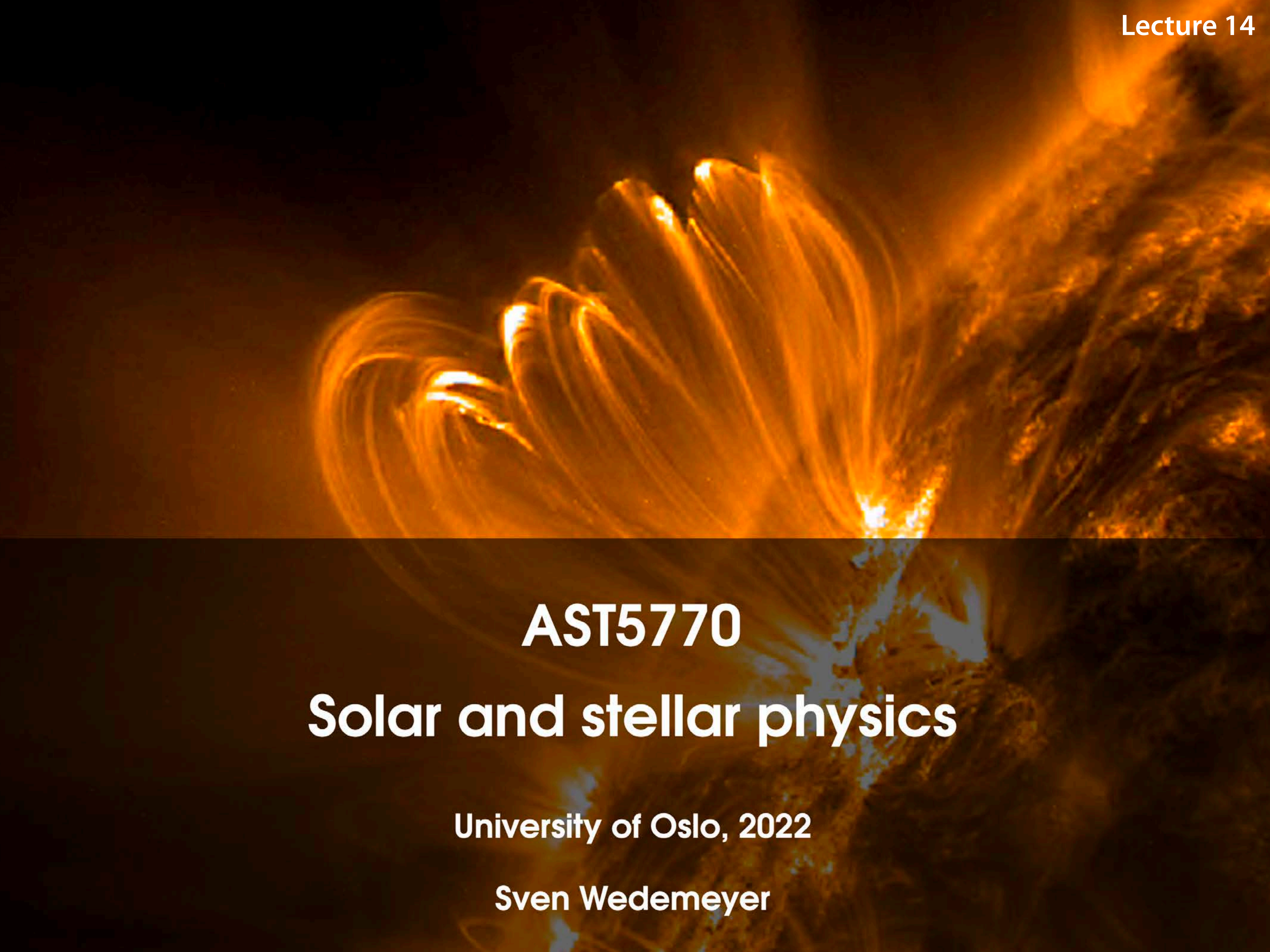


AST5770
Solar and stellar physics

University of Oslo, 2022

Sven Wedemeyer

Assignment III

Data and method

- **Requirements:** 1500 - 3000 words and at least one figure illustrating the used data set(s).
- **Content:** Please describe the data set(s) and methods used in your scientific study.

- **Method(s)** with which the data was
  - obtained/produced *(e.g., instrumentation/code, observational/numerical technique)*
  - processed *(if applicable: e.g., post-processing/adjustment incl. noise reduction, rescaling, filtering etc.)*
  - analysed *(analysis steps that are central for the presented data analysis — as being presented in the next assignment)*.

- **Aim - REPRODUCIBILITY:** This section should allow any reader with access to the described data, methods and resources to **reproduce** the results (to be) reported in your paper! *(However, trivial/unimportant details are usually left out.)*

- Remember: You are supposed to deliver a **tentative draft** of this section that reflects your current ideas and plans.
  - You will get ideas how to adapt/update/improve this part as you work on the data analysis during the next weeks. Updated version as part of the final project assignment.

Assignment III

Data and method

- **Level of detail: Describe on a lower level than in a real scientific article.**
  - Examples:
    - If you use data from a telescope (SST, SDO, etc)., then please **outline** how the telescope (and instrument) works: Principle of the employed telescope and instrument (not every optical component).
    - If you use numerical data, then please describe the basic workings the numerical code(s): General numerical approach/method used (but not all details of its implementation).

- Please let us know if you are missing information regarding how the data was produced!
- **Typical details** provided:
  - Type of region observed/simulated, set into context with additional data (if applicable)
  - Size of the field-of-view or computational domain, duration of used time series, time & date … (if applicable)
  - Resolution (in relevant domains) and other fundamental parameters (especially for simulations)
- Please have a look at data/method section of scientific articles to check the extent and level of detail of the typical content and how it is typically structured and presented.

Assignment III

Data and method

- **Section structure:**
  - Typically divided into subsections dealing with different stages (e.g. observation, post-processing, analysis methods…)

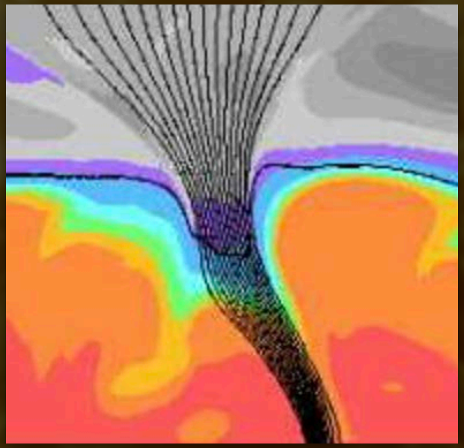
- **Figure:**
  - At least 1 figure (and preferably not more than 3) that illustrate(s) the properties of the data (and method(s) if applicable).

- **References**
  - Known/standard methods can be addressed with the proper reference and a short summary (to extent useful for the reader to understand what you are doing)
  - Example: You would explain briefly how the equation of state is handled in the simulation code but not how the Fast Fourier Transform algorithm is implemented

Magnetism and Dynamo Recap

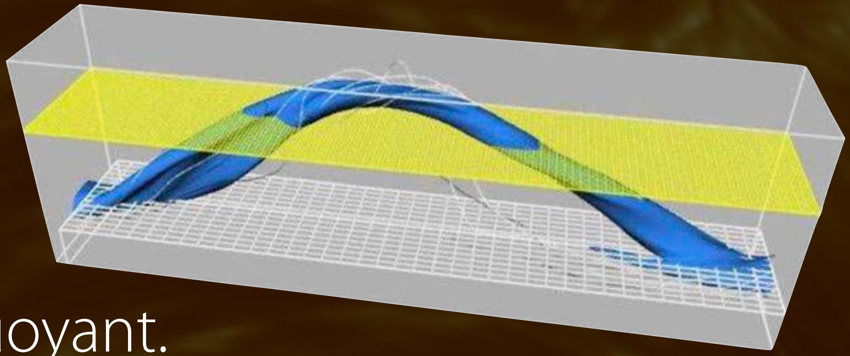
Magnetism

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.



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

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

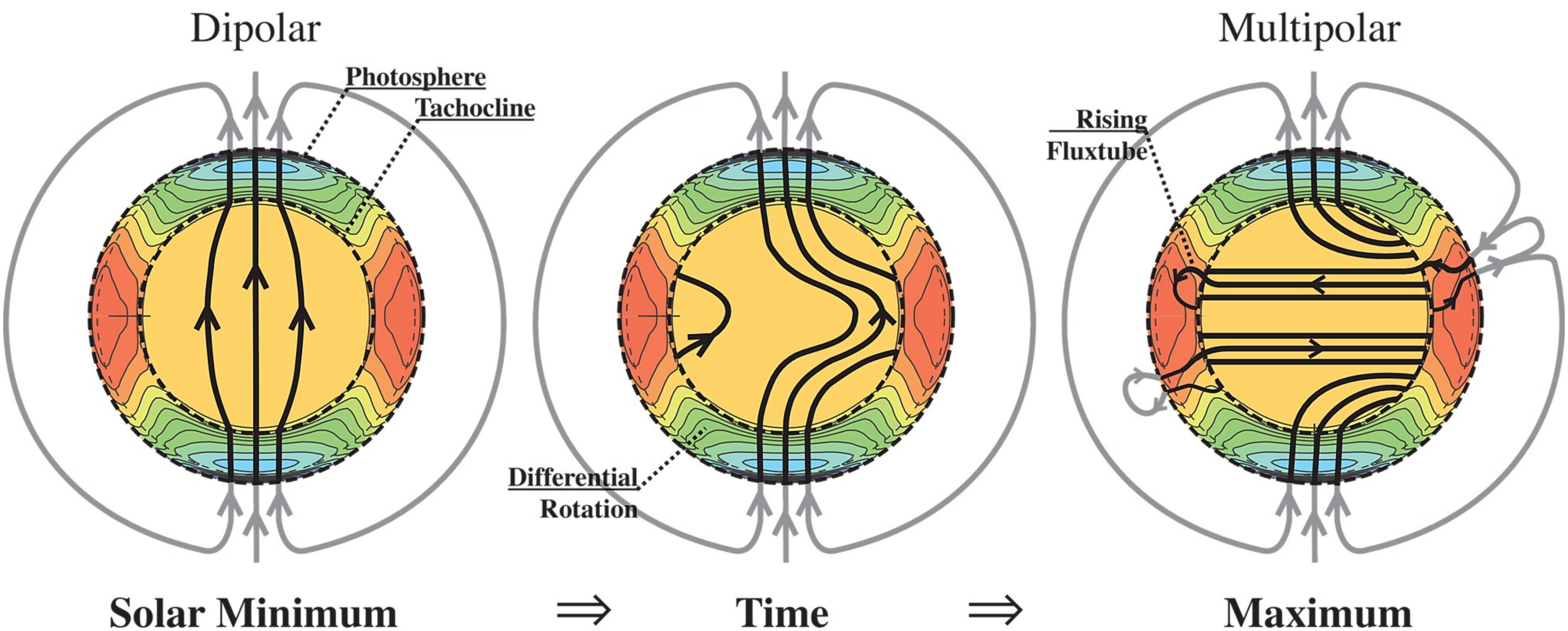
SST — Scharmer

Dynamo
And
Solar cycle

Dynamo

Solar cycle — change of magnetic field configuration

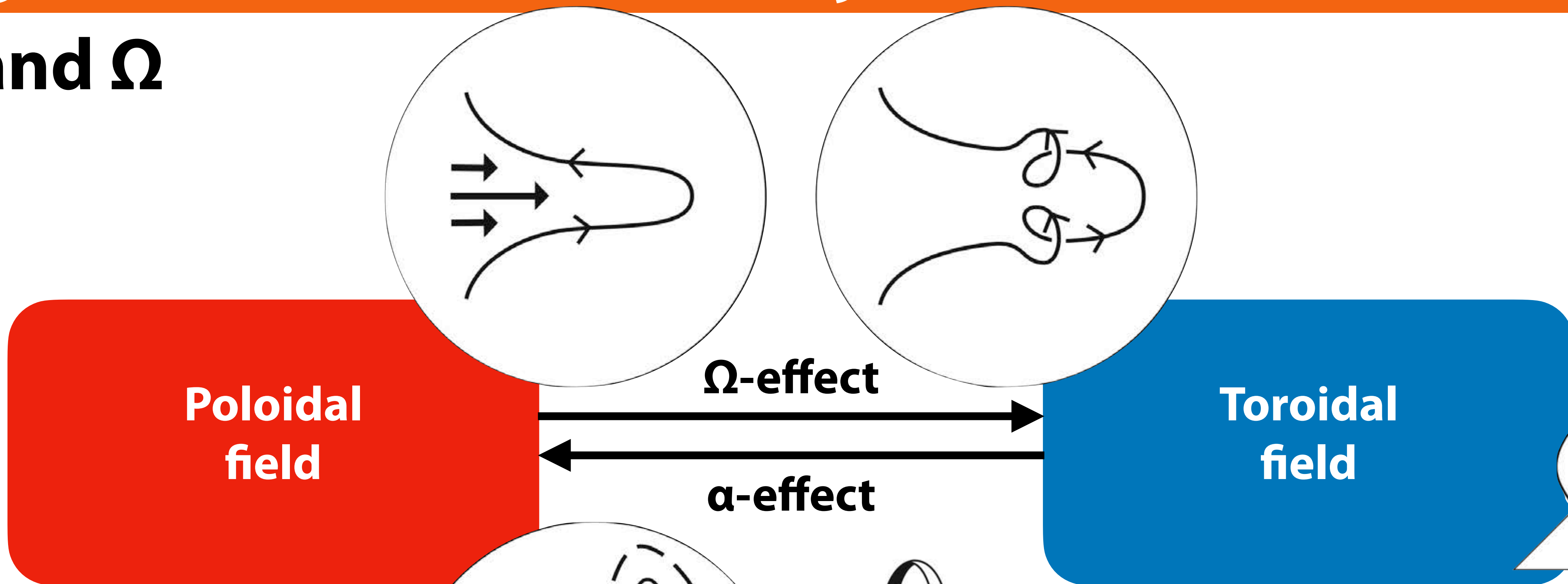
- Below **tachocline**: Rotation as solid body
- Above tachocline: **differential rotation** — faster rotation near equator, slower at poles
- Magnetic dipole field (poloidal) at solar minimum
- Over time: differential rotation shears magnetic field at the tachocline, drags it along the equator, **converts poloidal field into toroidal field**.

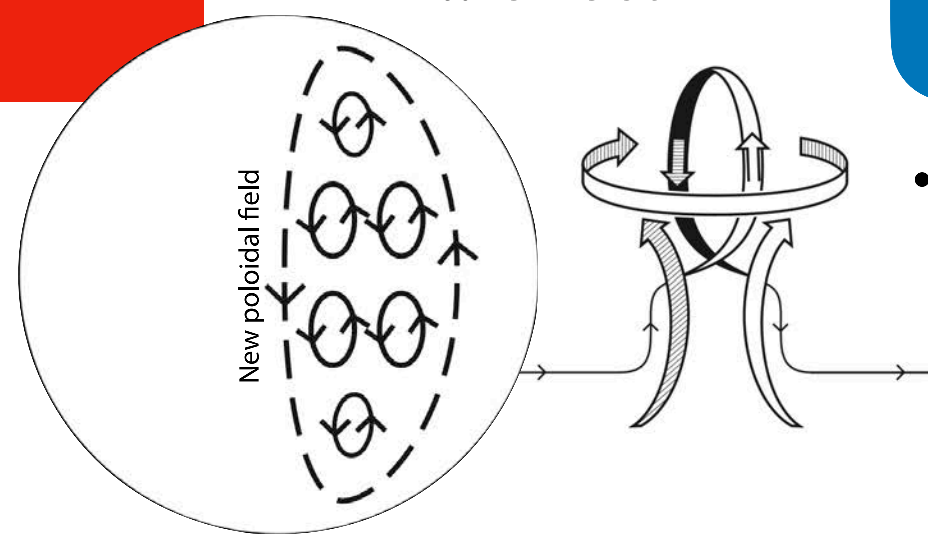


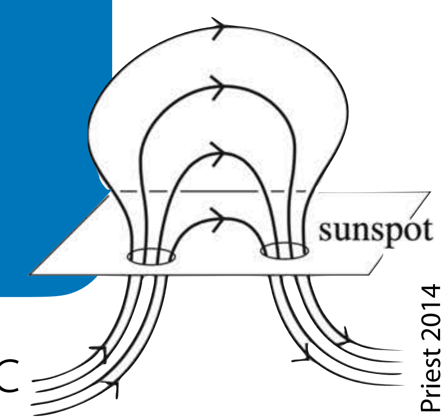
Higgins, Paul (2012): Schematic of the Solar Dynamo. figshare. Figure. https://doi.org/10.6084/m9.figshare.102094.v1

Dynamo — Solar cycle

α and Ω







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

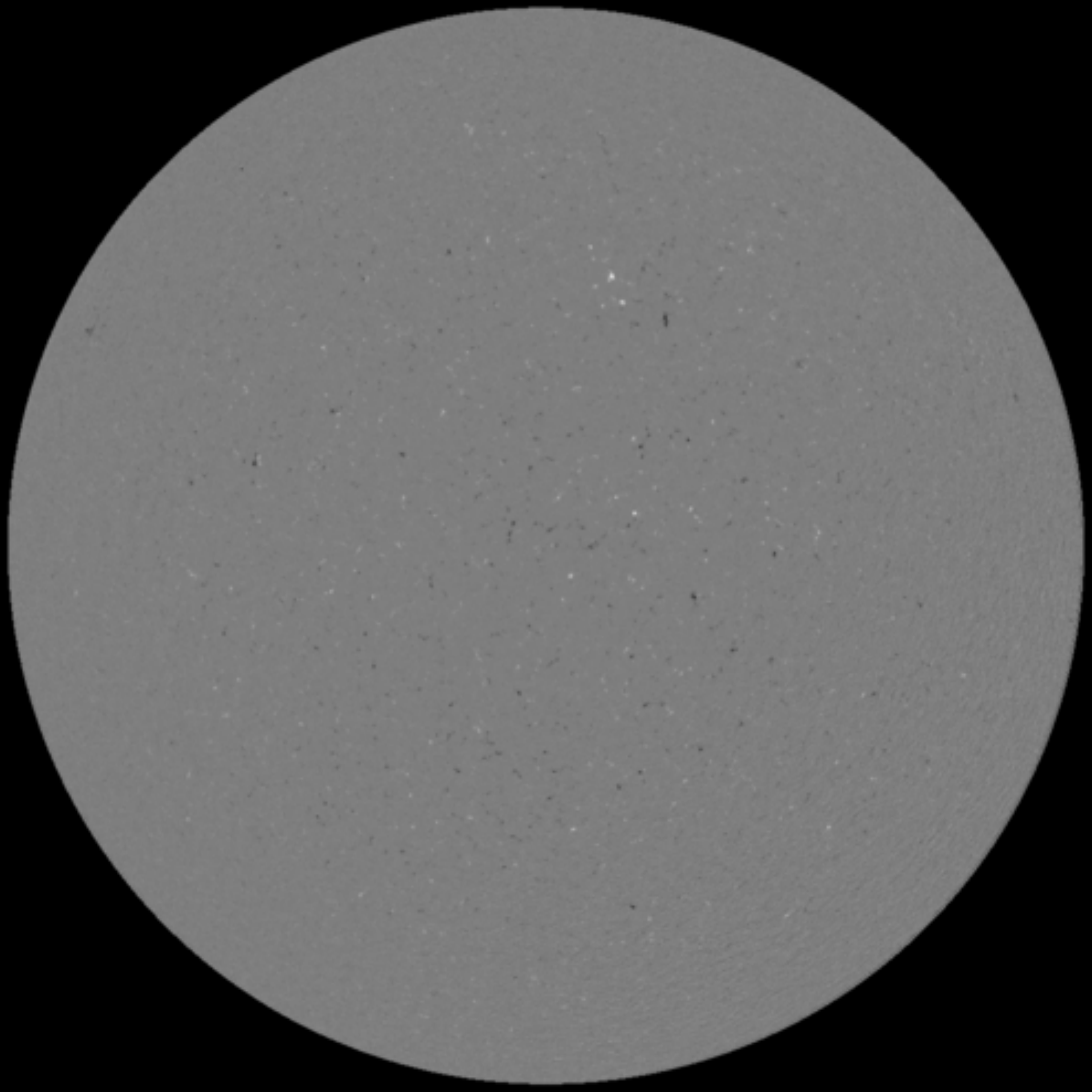
- generates magnetic activity (e.g., sunspots) during **solar (activity) maxima**

- **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**

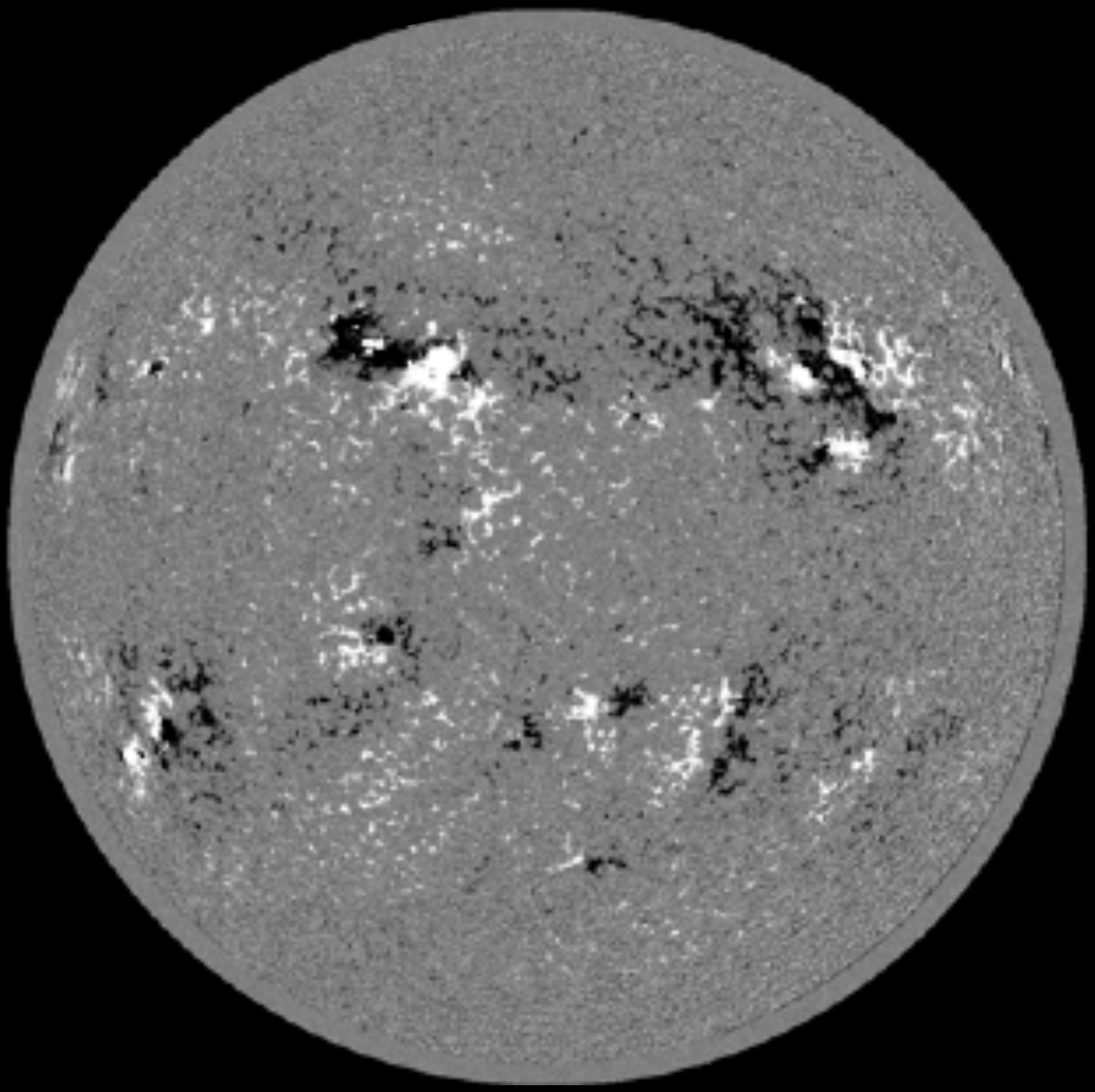
Dynamo — Solar cycle

Magnetograms

Minimum



Maximum



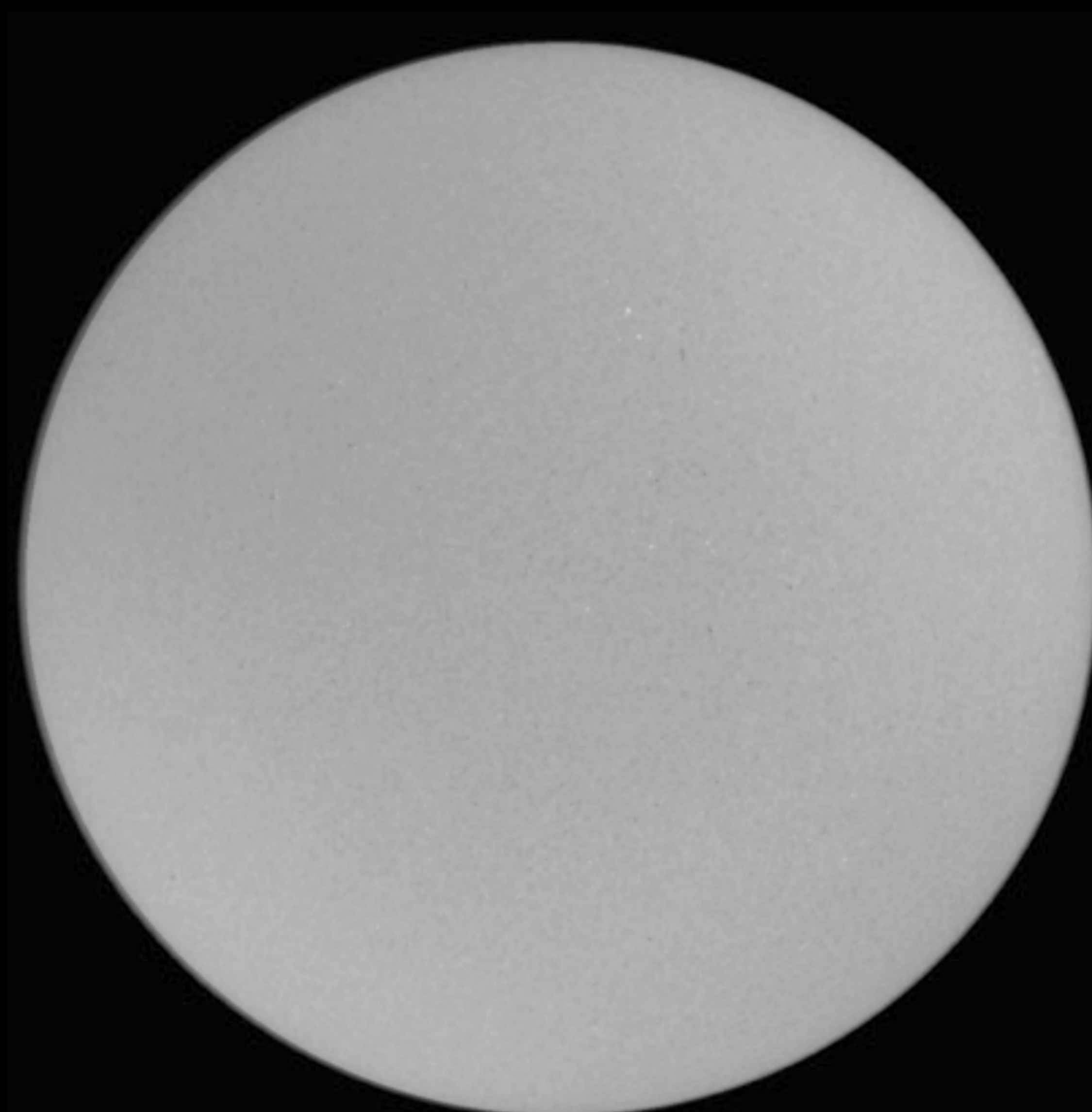
SOHO/MDI

Dynamo — Solar cycle

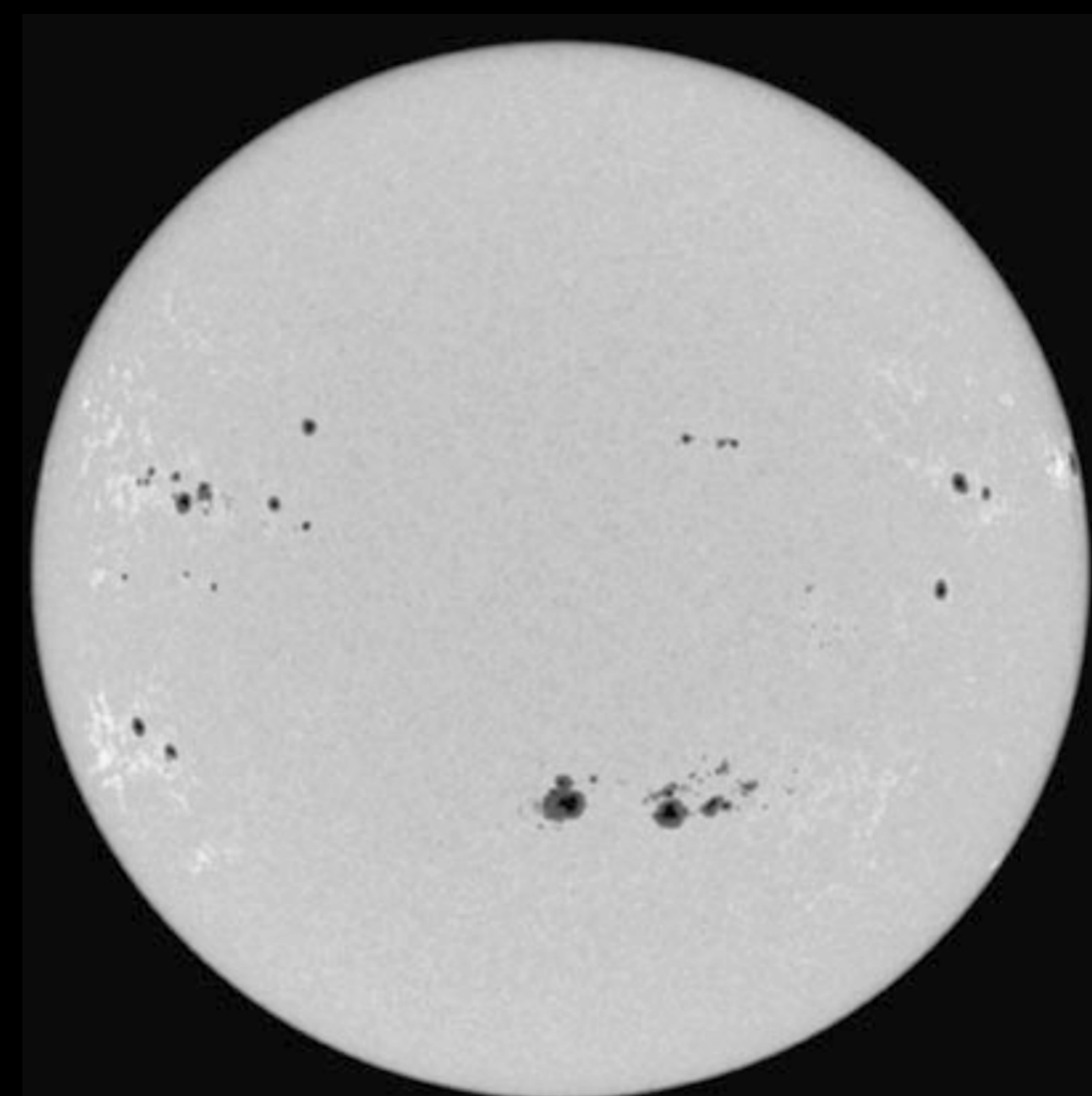
Continuum intensity

- Relatively small area covered by sunspots — Overall variation in brightness?

Minimum

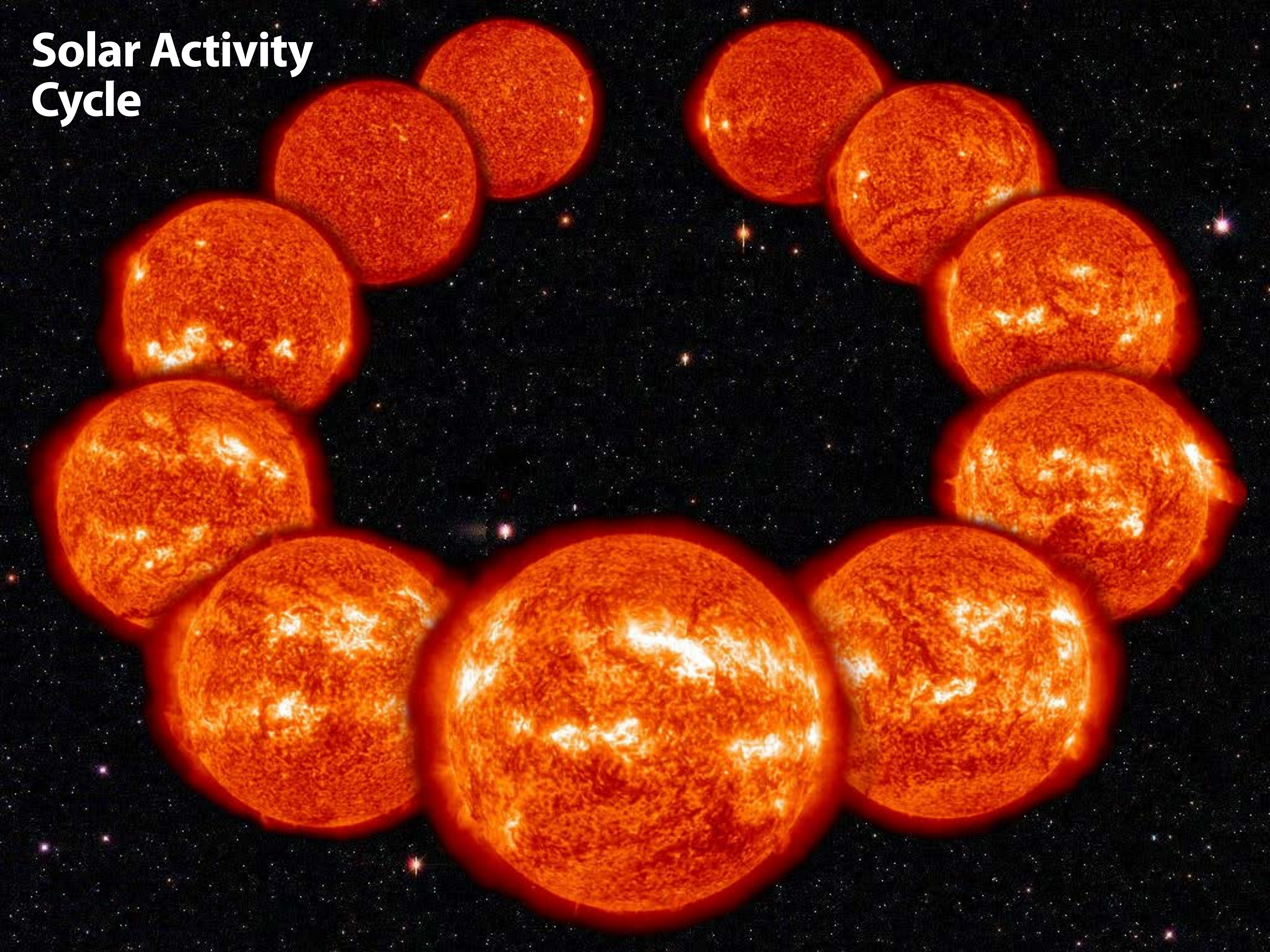


Maximum



SOHO/MDI

Solar Activity Cycle



Dynamo — Solar cycle

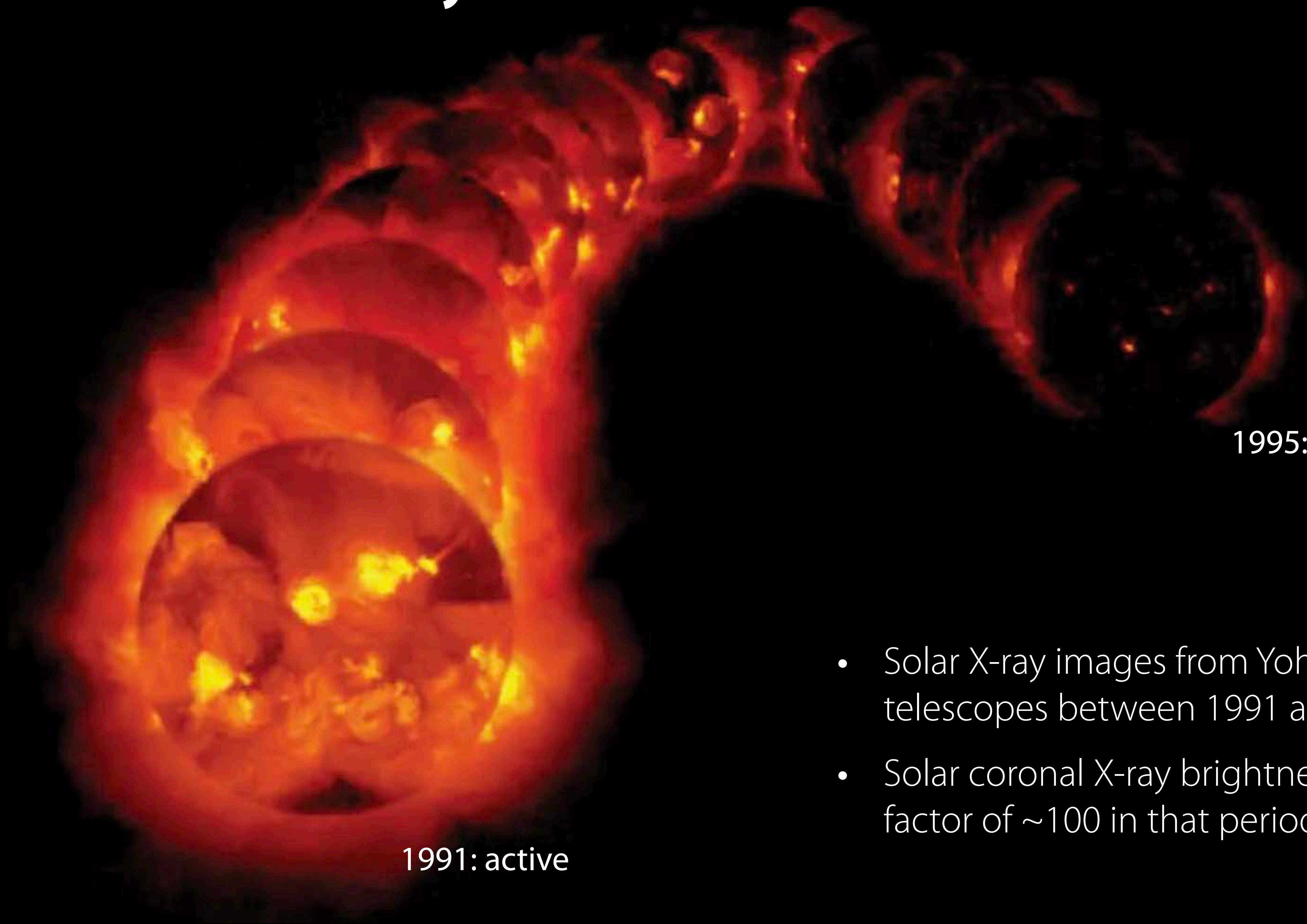
Corona

- Solar cycle clearly visible in the change of the coronal magnetic field

Corona visible — brighter solar disk is blocked out

Dynamo — Solar cycle

Corona — X-rays



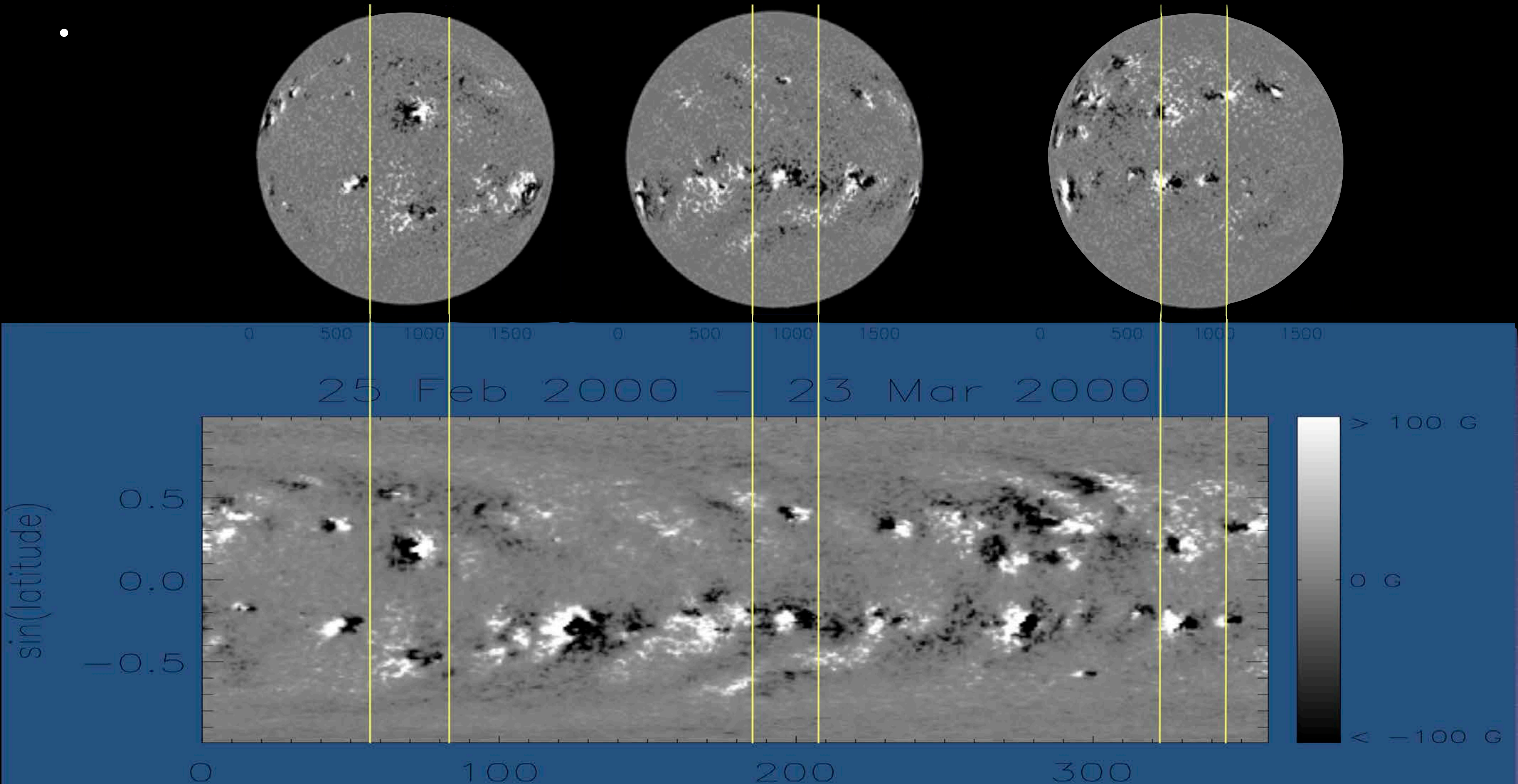
- Solar X-ray images from Yohkoh space telescopes between 1991 and 1995.
- Solar coronal X-ray brightness drops by a factor of ~100 in that period

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

Dynamo — Solar cycle

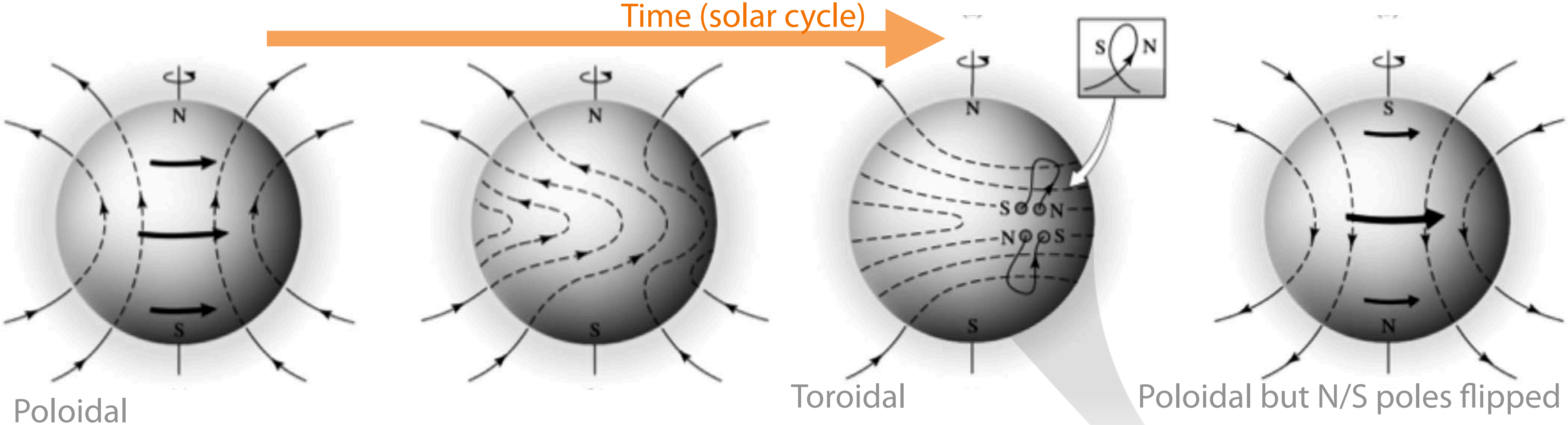
Magnetic field configuration at surface

- 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

Sunspots — latitude

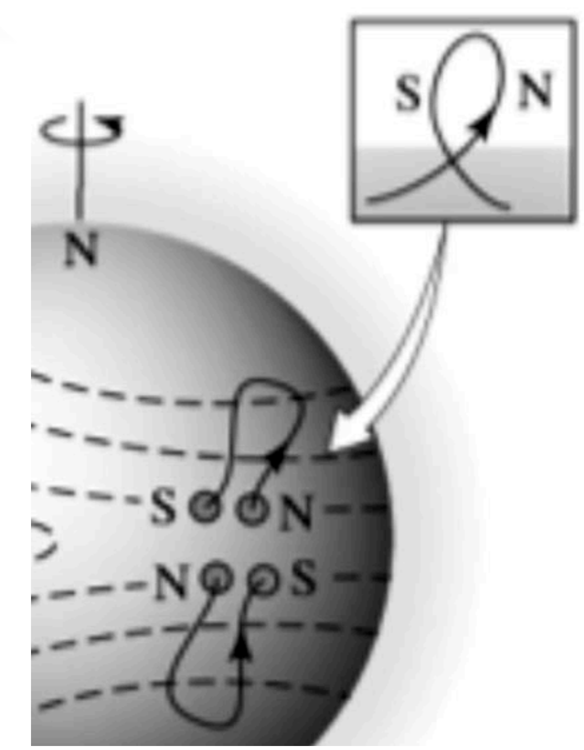


- Coriolis force depends on latitude
- Largest number of sunspots should occur at equator BUT polarities of the northern and southern hemispheres cancel out at the equator!

➡ **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)

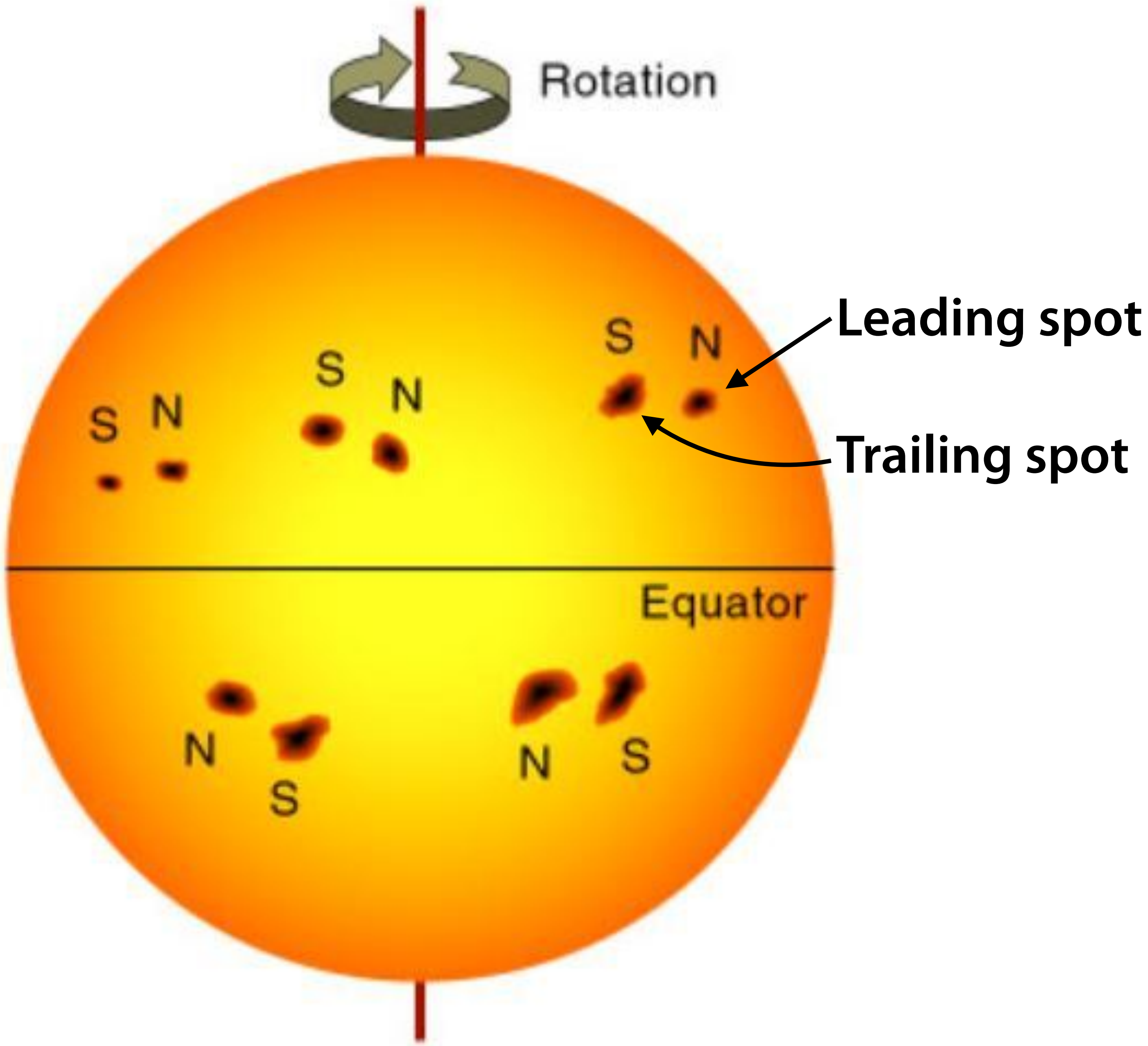


Carroll & Ostlie

Dynamo — Solar cycle

Sunspots — latitude and orientation

- Active Regions with a leading spot and a trailing spot
  - systematic east-west orientation
- Order of polarities reversed in the two hemispheres
- Flips with global magnetic field orientation every 11yr



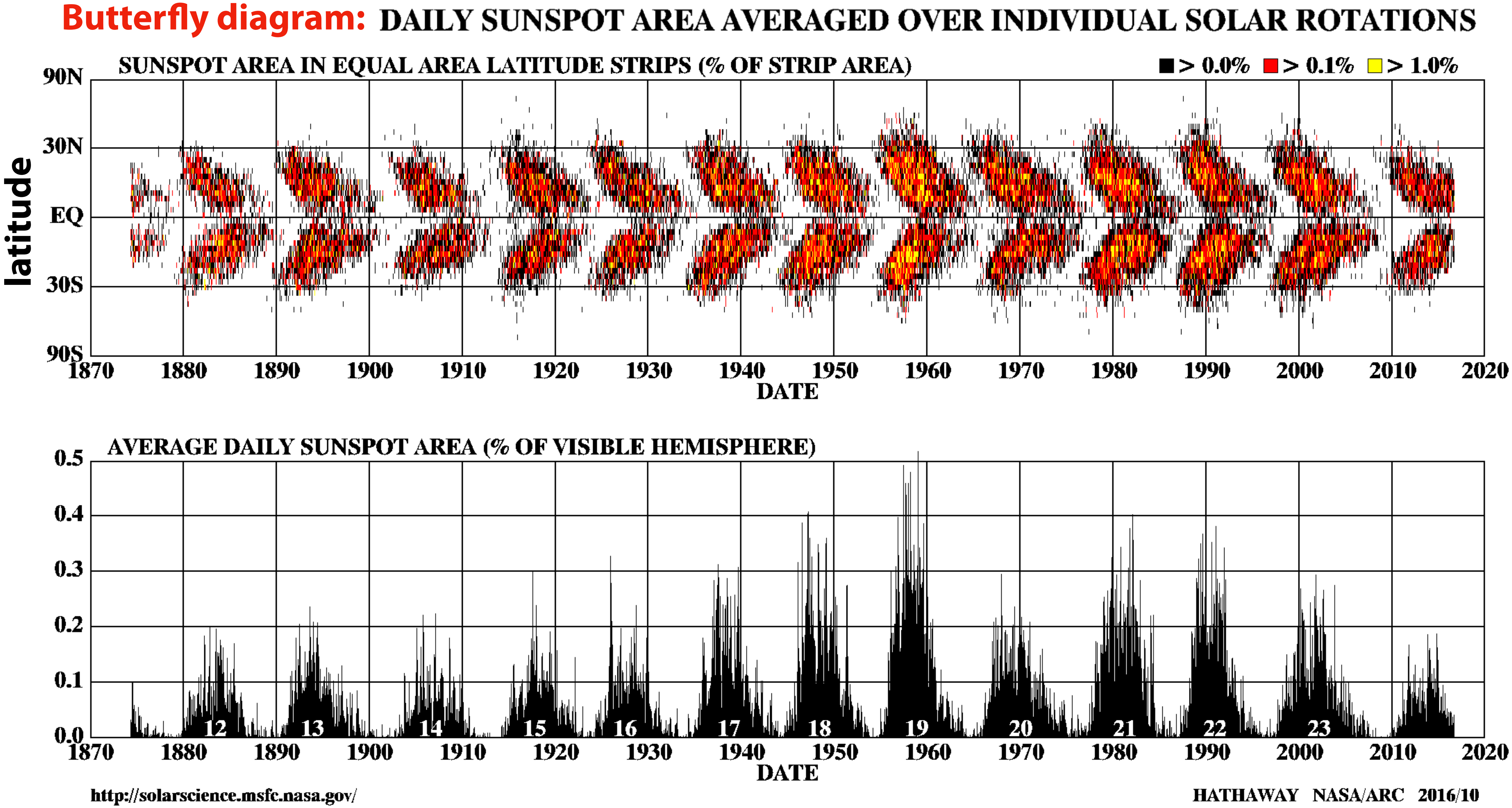
- New cycle begins with sunspots at latitudes of 30 degrees on bother hemispheres
- During a solar cycle: Sunspots appear gradually more towards equator
- Cycle ends with sunspots at low latitudes

Dynamo — Solar cycle

Sunspots — latitude and time

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

Butterfly diagram:



Solar cycle

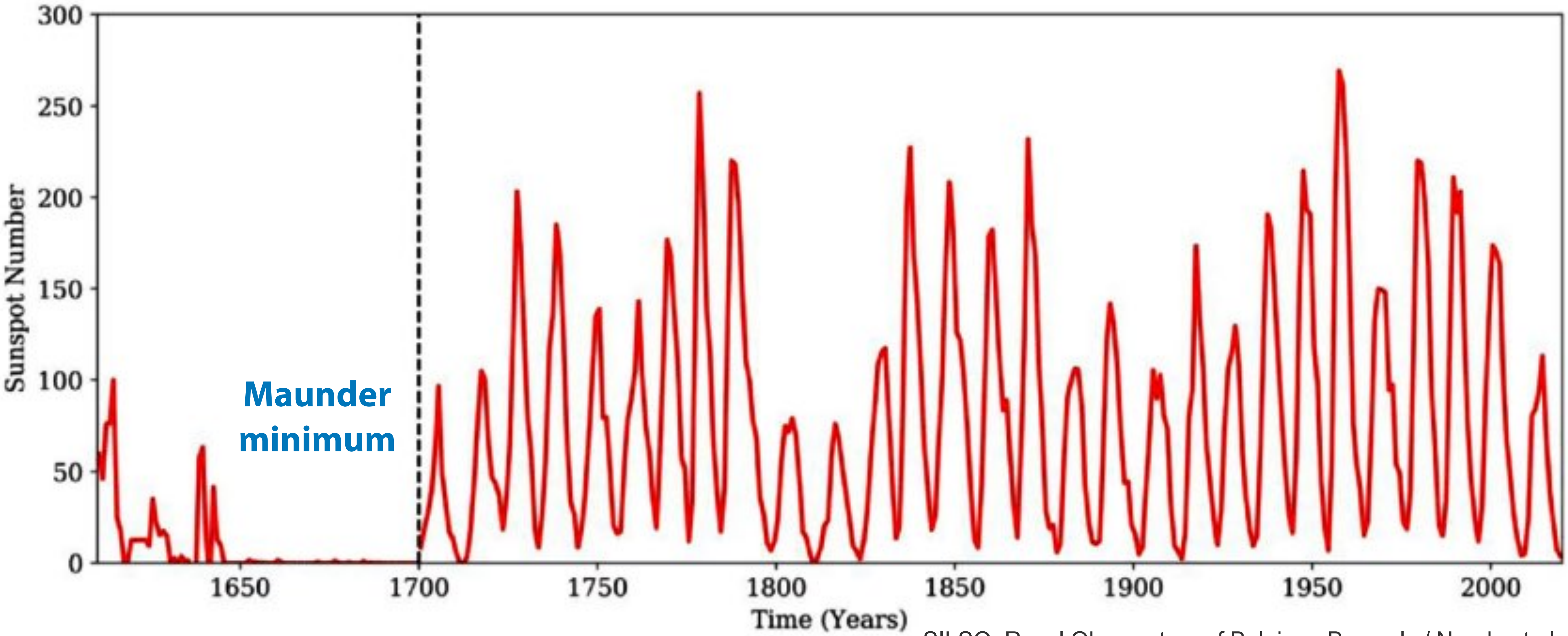
Sunspot number (Wolf number/Zürich sunspot number)

- 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)

- Captures 11-yr cycle
- Correlates with indicators due to modulation of screening from cosmic rays (isotopes); tree rings, ice cores



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

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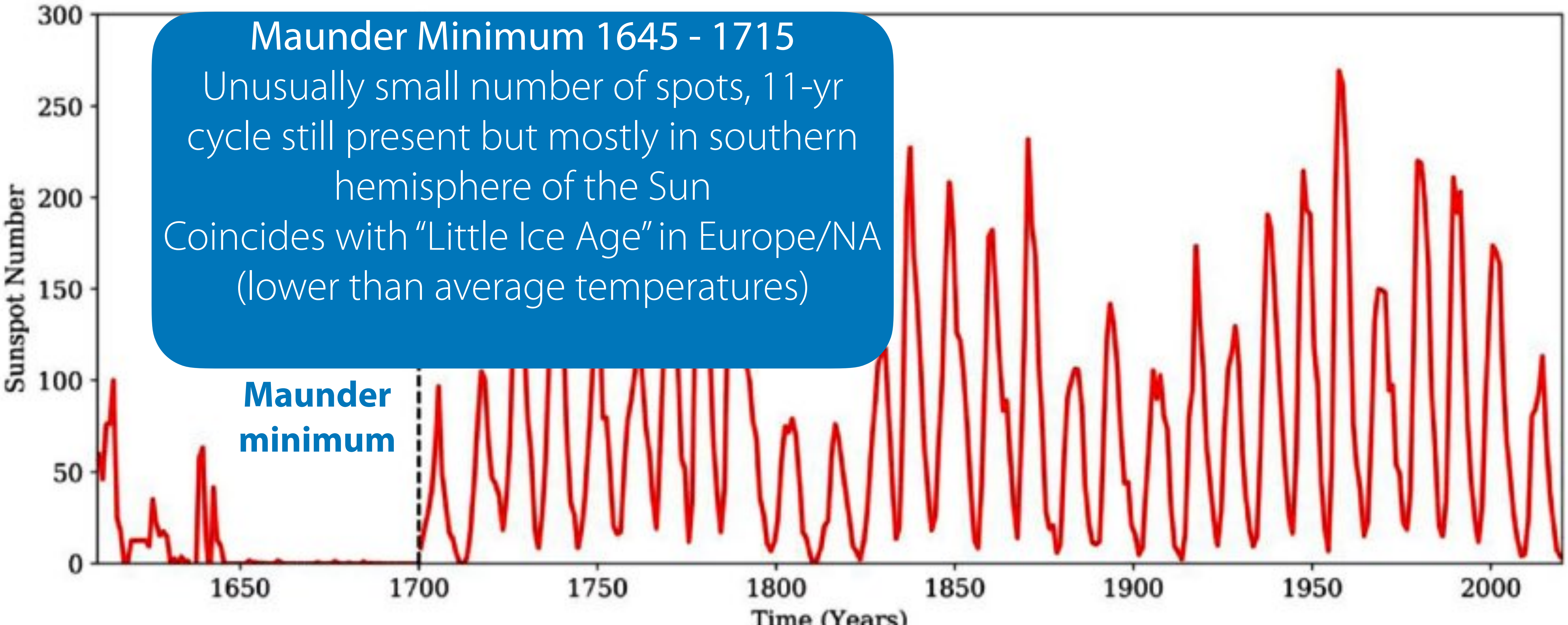
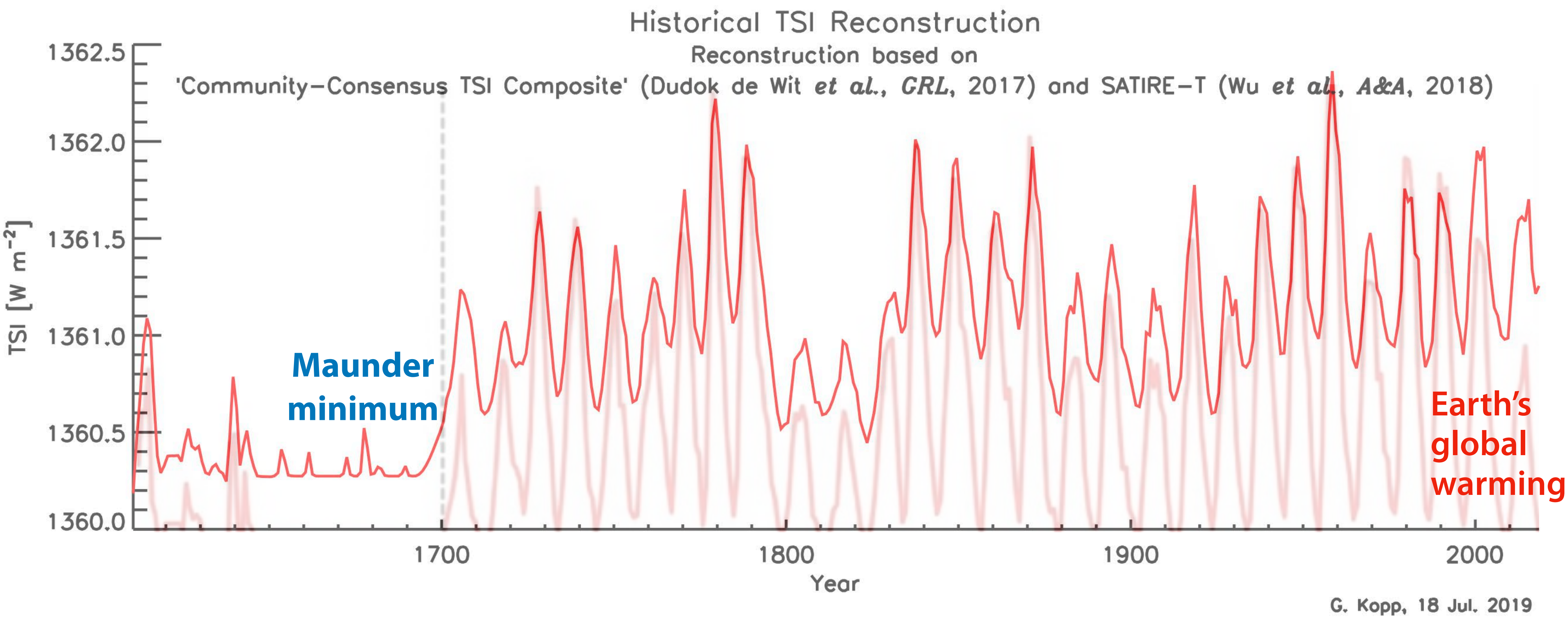


SILSO, Royal Observatory of Belgium, Brussels / Nandy et al. 2021

Solar cycle

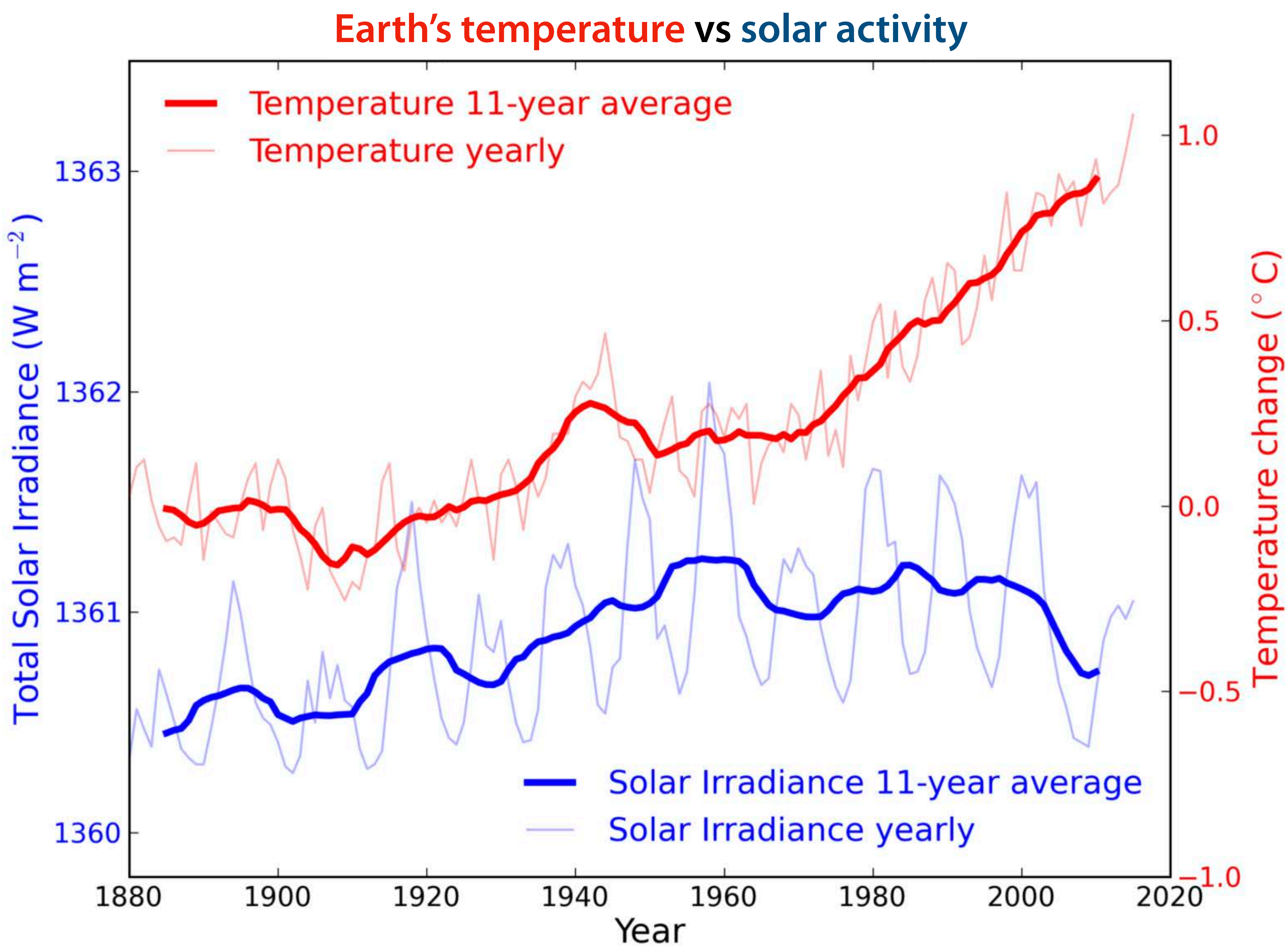
Variation of the Sun's total irradiance

- 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

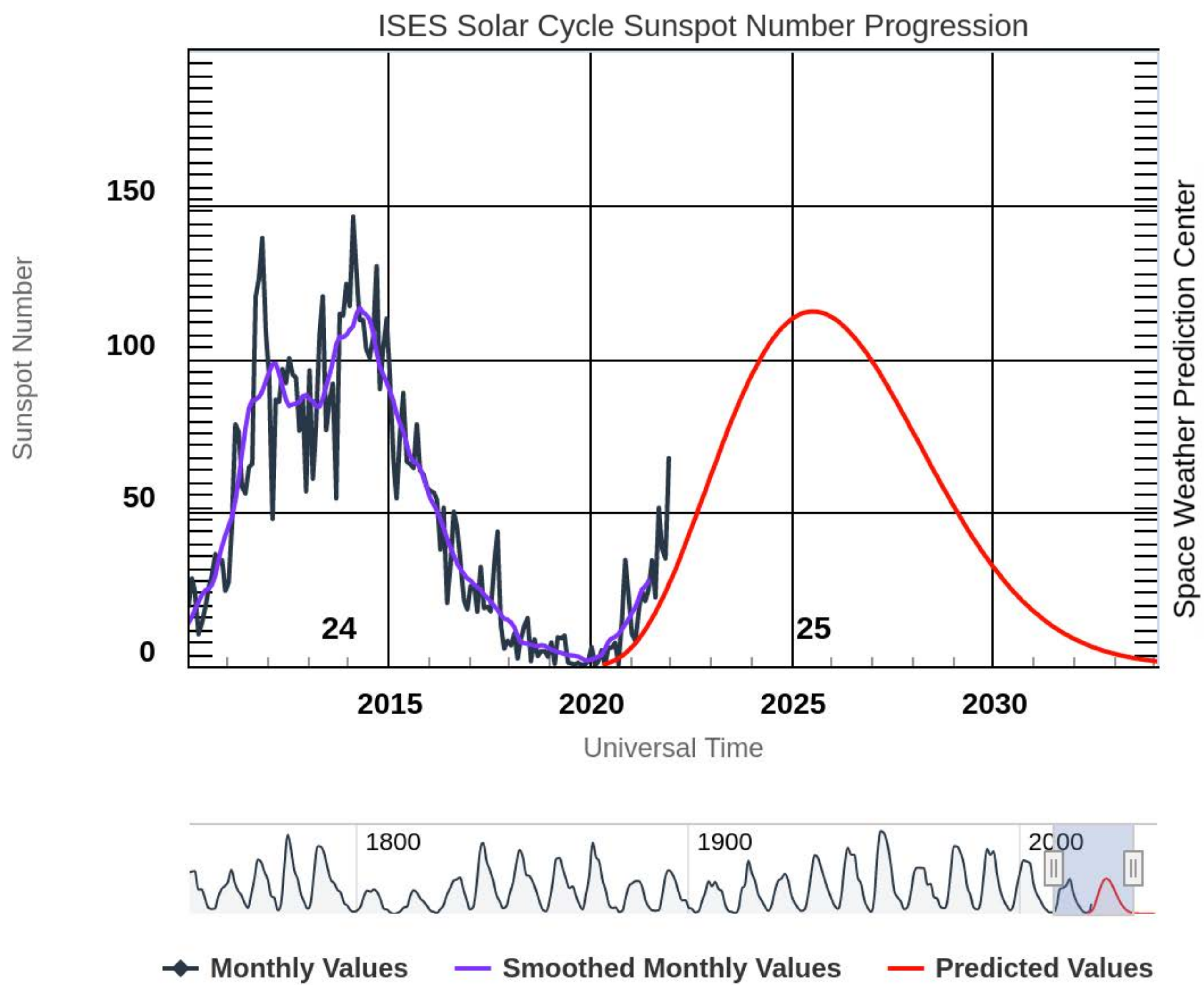


NASA/ Krivova et al 2007/World Radiation Center/PMOD

Solar cycle

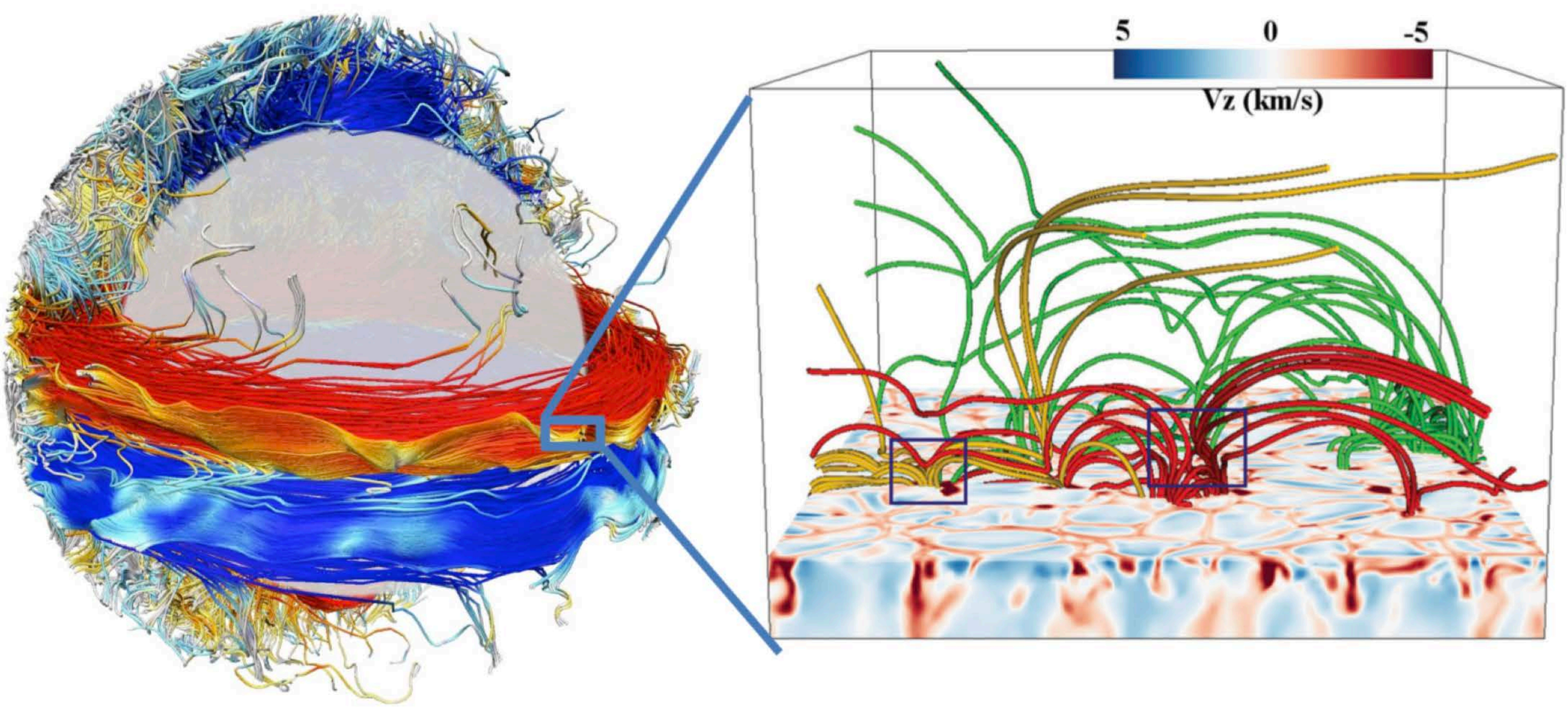
Current and future cycle (prediction)

- 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

WholeSun project



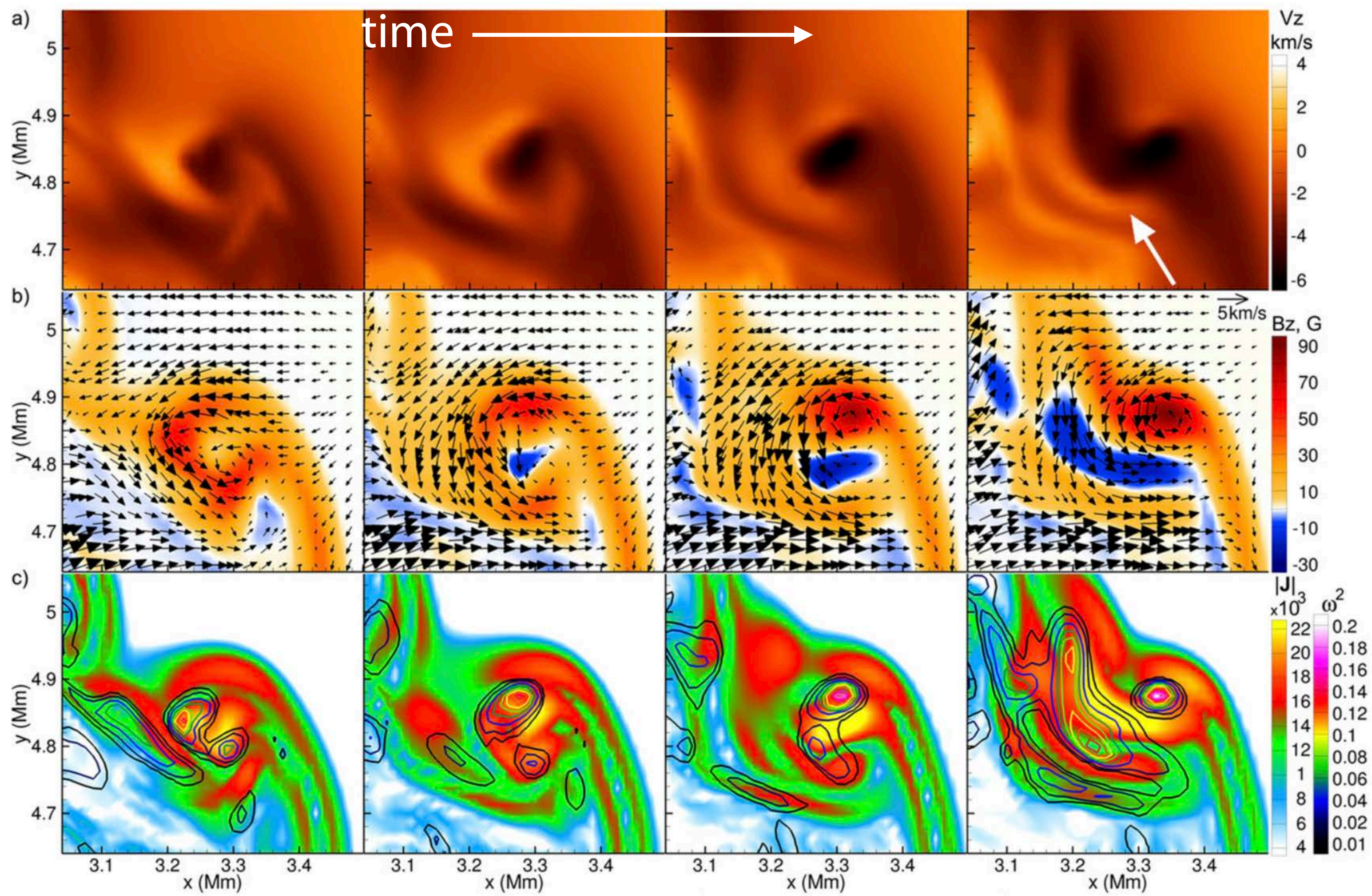
Dynamo

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)



How to measure magnetic fields

Measuring magnetic fields

Methods of magnetic field measurement

- **Direct methods:**
  - Zeeman effect — polarized radiation
  - Hanle effect — polarized radiation (scattering)
  - Gyroresonance — radio spectra

- **Indirect methods** (proxies)
  - Bright or dark features in photosphere (sunspots, G-band bright points)
  - Ca II H and K plage
  - Fibrils seen in chromospheric lines, e.g. H
  - Coronal loops seen in EUV or X-radiation

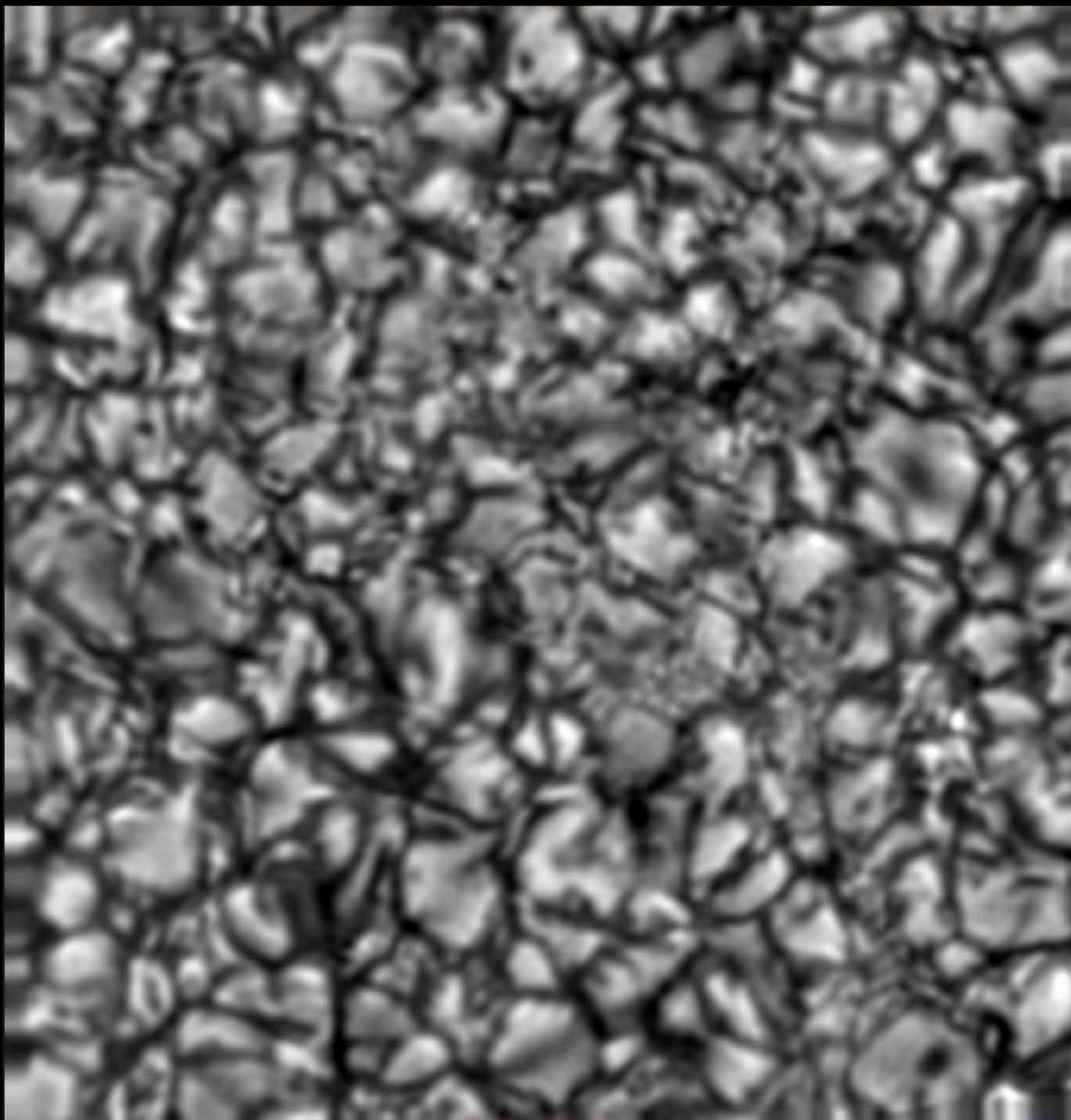
Measuring magnetic fields

Indirect methods

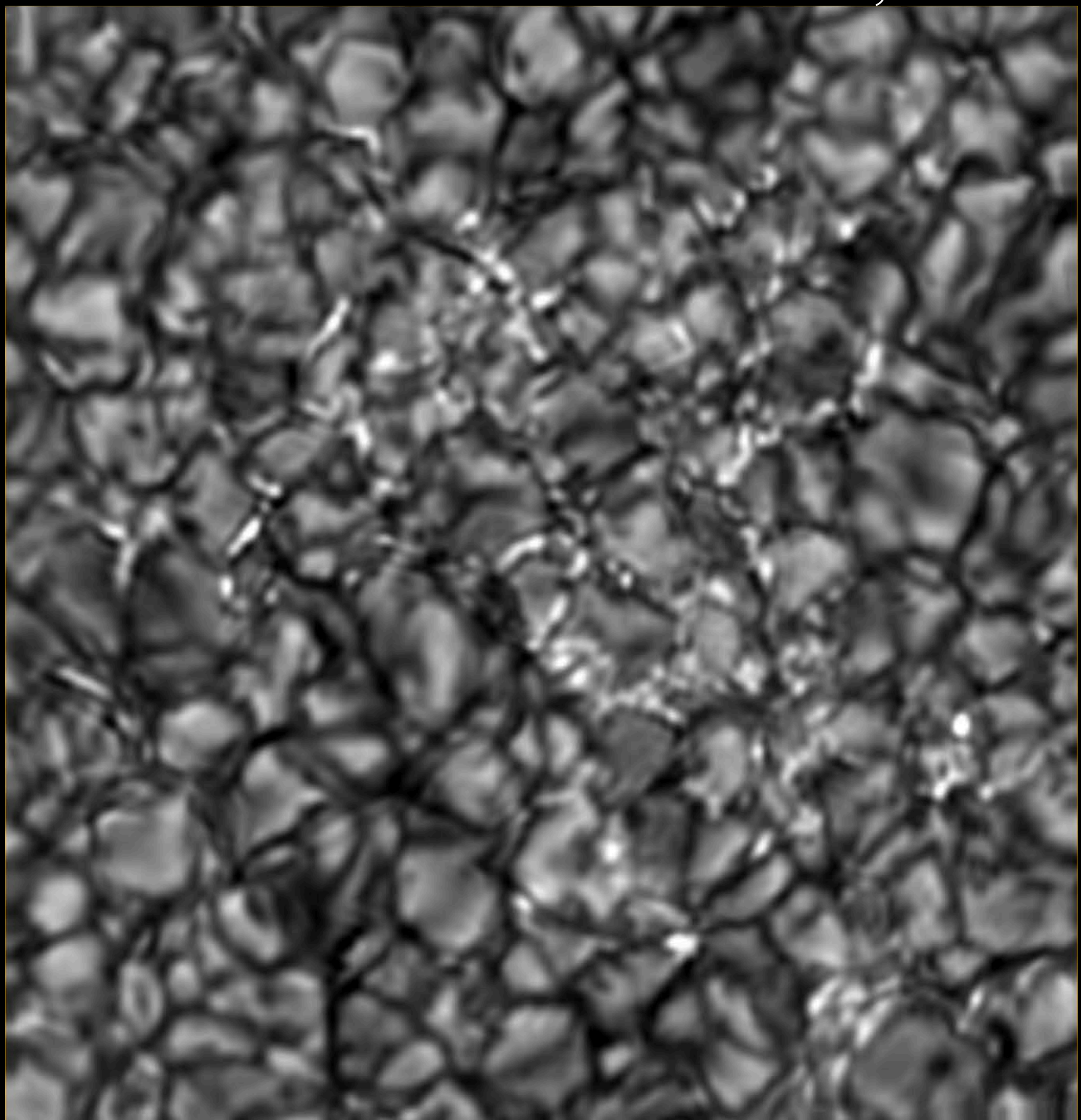
- **G-band:** Spectral range at ~431nm with a lot of absorption due to CH molecules + Fe I lines
  - Results in higher contrast for magnetic field than (regular) visible continuum

Spectral feature G classified by Fraunhofer

Visible continuum



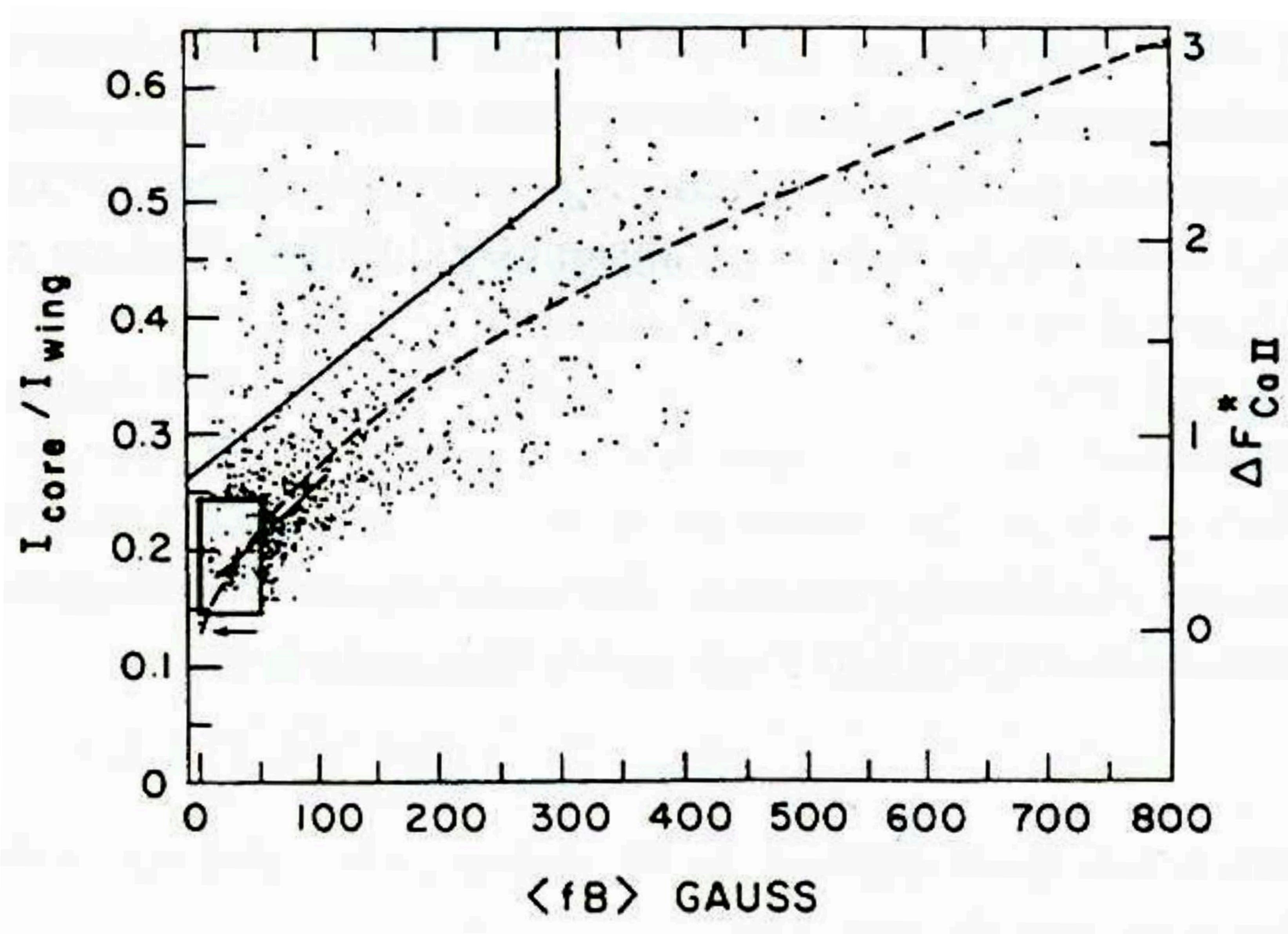
G-band



Measuring magnetic fields

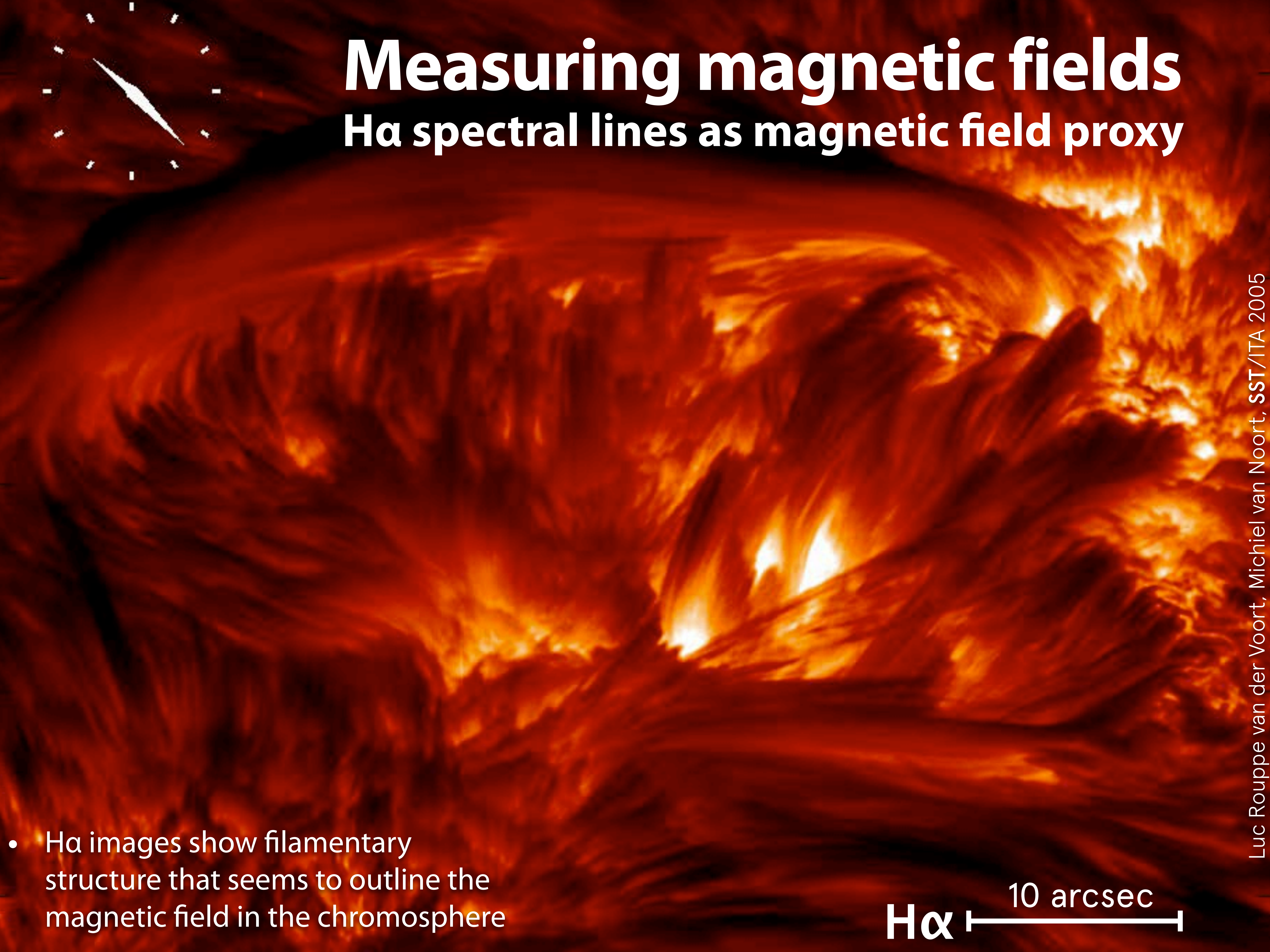
Ca II spectral lines as magnetic field proxy

- Ca II H & K lines = strongest lines in the visible solar spectrum
- Show a strongly increasing brightness with non-spot magnetic flux.
- increase is slower than linear
- Magnetic regions (except sunspots) appear bright in Ca II: Ca plage and network regions



Measuring magnetic fields

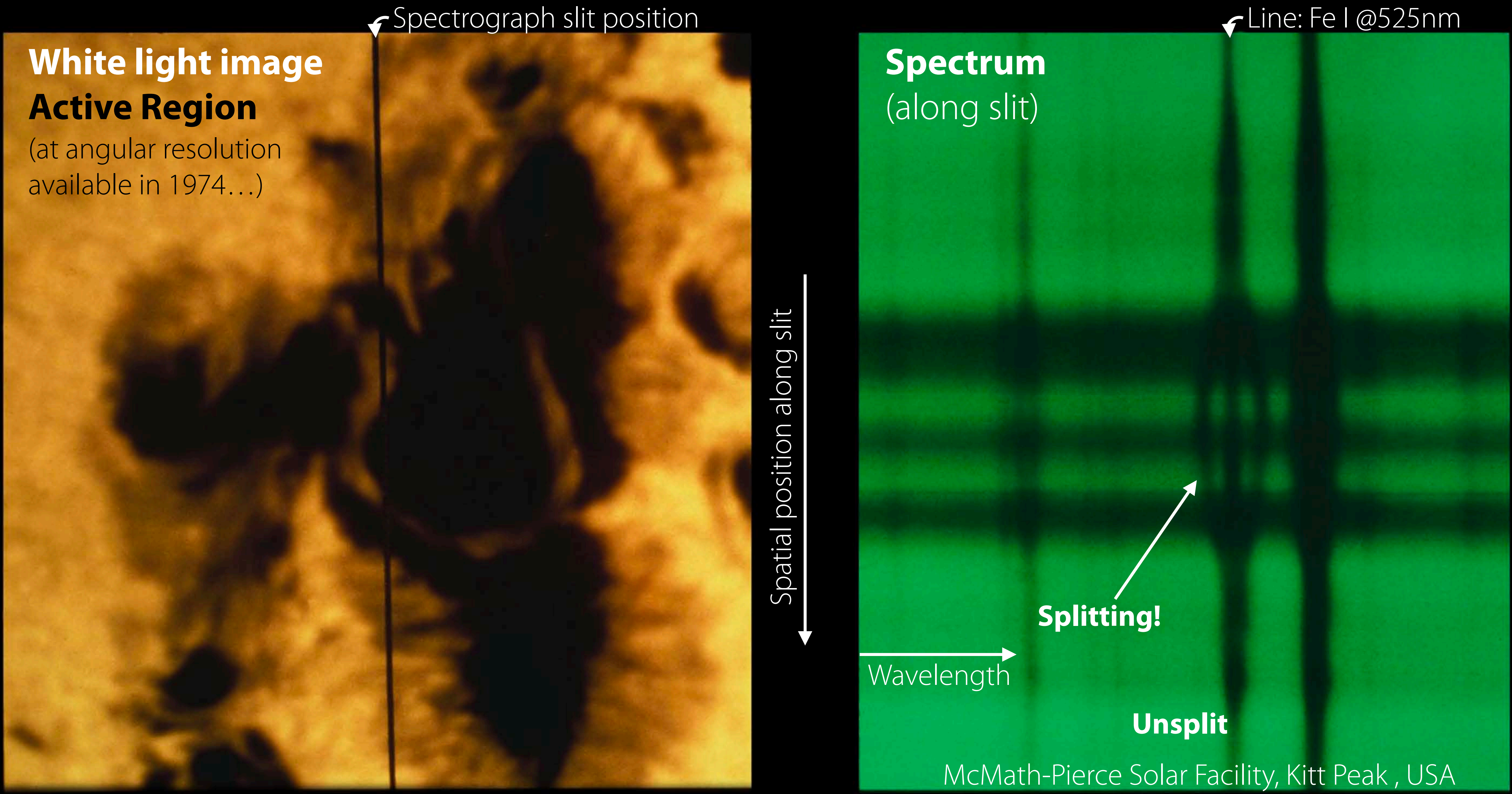
Hα spectral lines as magnetic field proxy



- Hα images show filamentary structure that seems to outline the magnetic field in the chromosphere

Measuring magnetic fields

Zeeman diagnostics

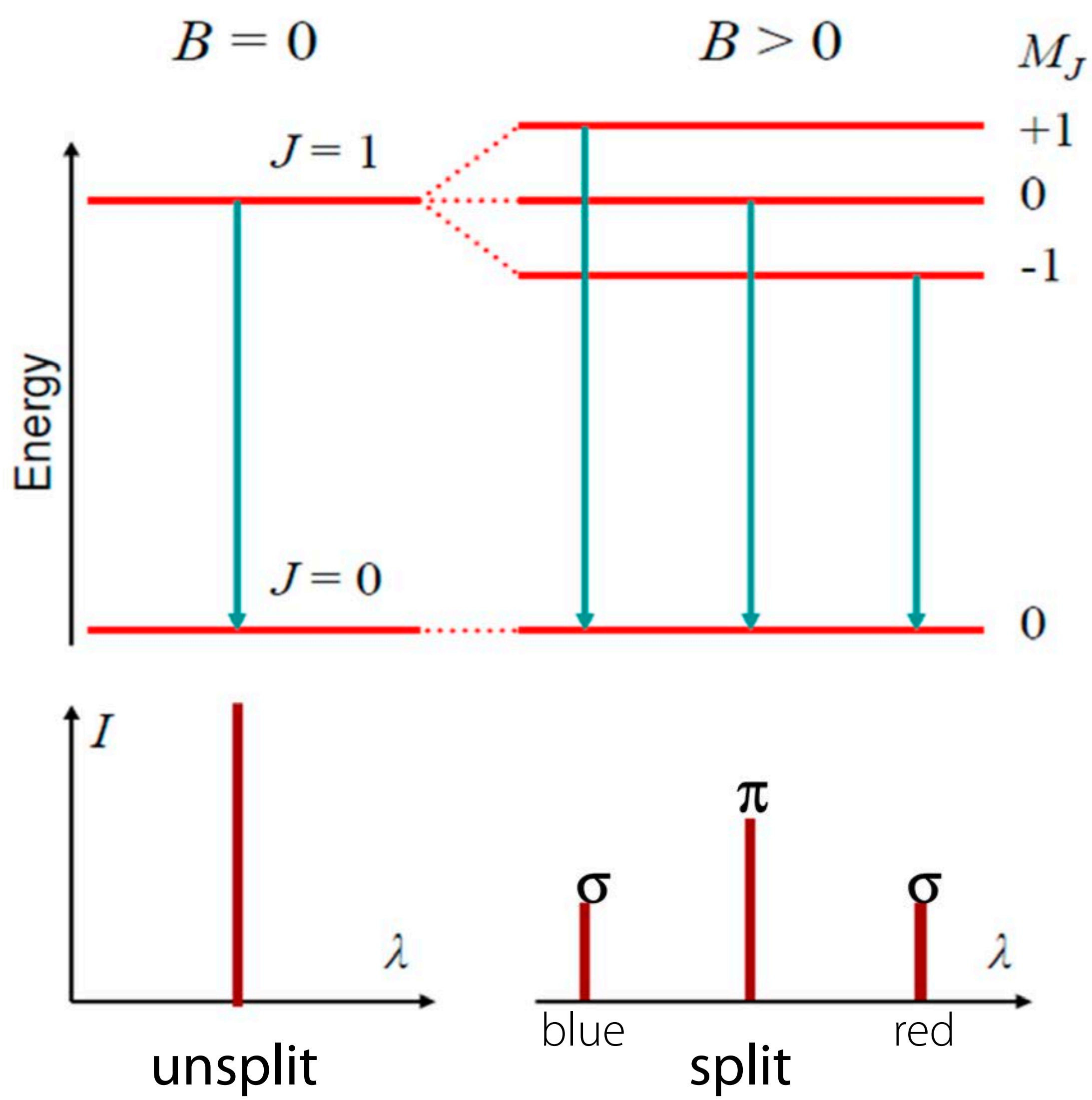


- Zeeman splitting in this example indicates a magnetic field strength of ~4 kG in the sunspot

Measuring magnetic fields

Zeeman diagnostics

- Splitting of atomic energy in presence of magnetic field
  - Total angular moment j splits into $2J+1$ sublevels with different M_J.
  - Transitions allowed between levels with $\Delta J = 0, \pm 1$ & $\Delta M_J = 0\ (\pi), \pm 1\ (\sigma_b, \sigma_r)$
- Splitting depends on strength and orientation of magnetic field (wrt line of sight)
- Observation perpendicular to mag. field $\vec{B}$: three components:
  - π component linearly polarized parallel to $\vec{B}$
  - σ components are linearly polarized perpendicular to $\vec{B}$
  - No information about the direction of magnetic field vector $\vec{B}$



π component at original wavelength

L is the total orbital moment of the electrons
S is the spin quantum number
J is the total angular momentum
M_J is the magnetic quantum number: -J,…,J

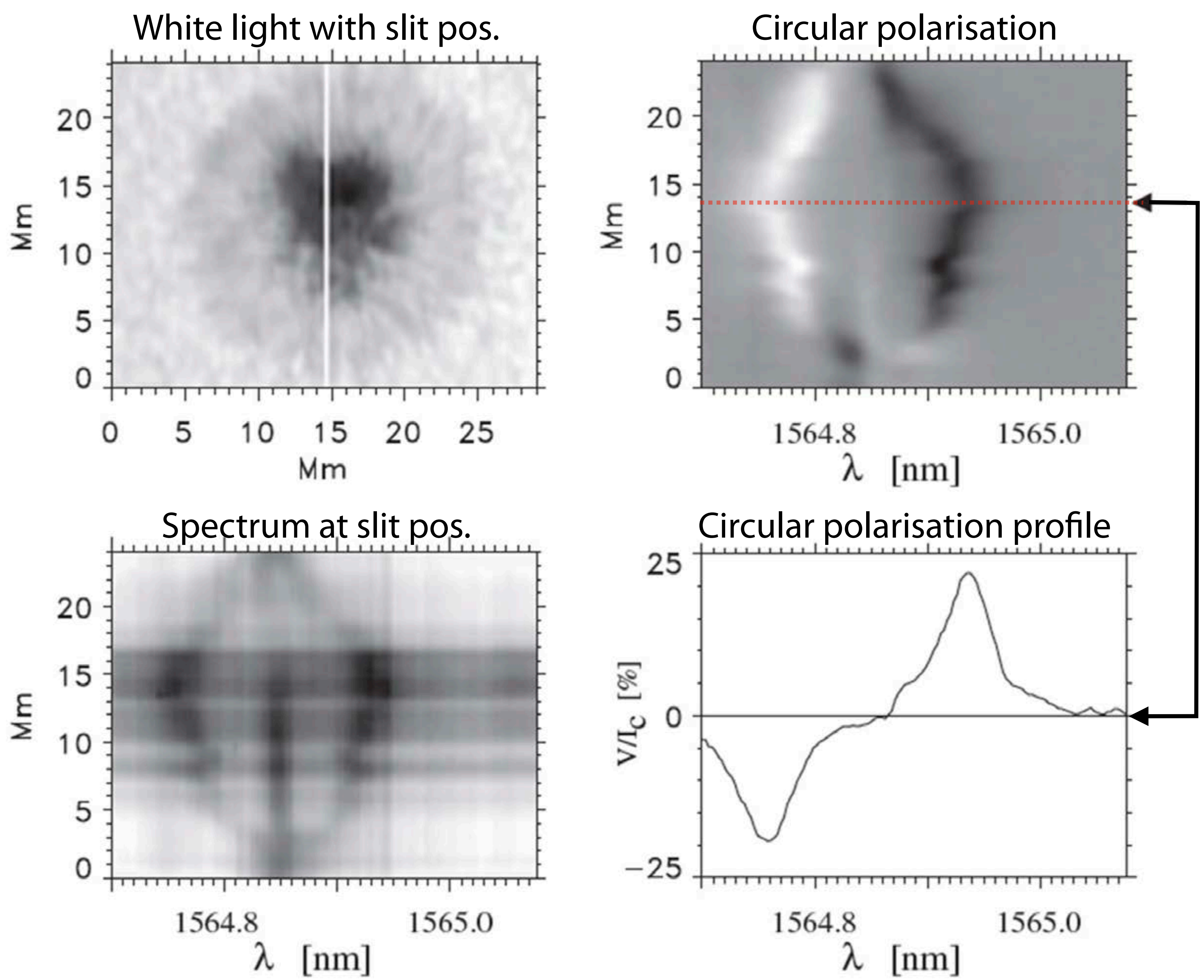
Measuring magnetic fields

Zeeman diagnostics

➡ Zeeman effect allows direct detection and measurement of magnetic field

- Note: Zeeman effect can be subtle and difficult to measure
- BUT: Unique **polarisation** signature in addition to change of spectral line shape/split
- Measurement of polarization is central to measuring solar magnetic fields

Zeeman splitting and circular polarization of the infrared Fe I line at 1564.8 nm



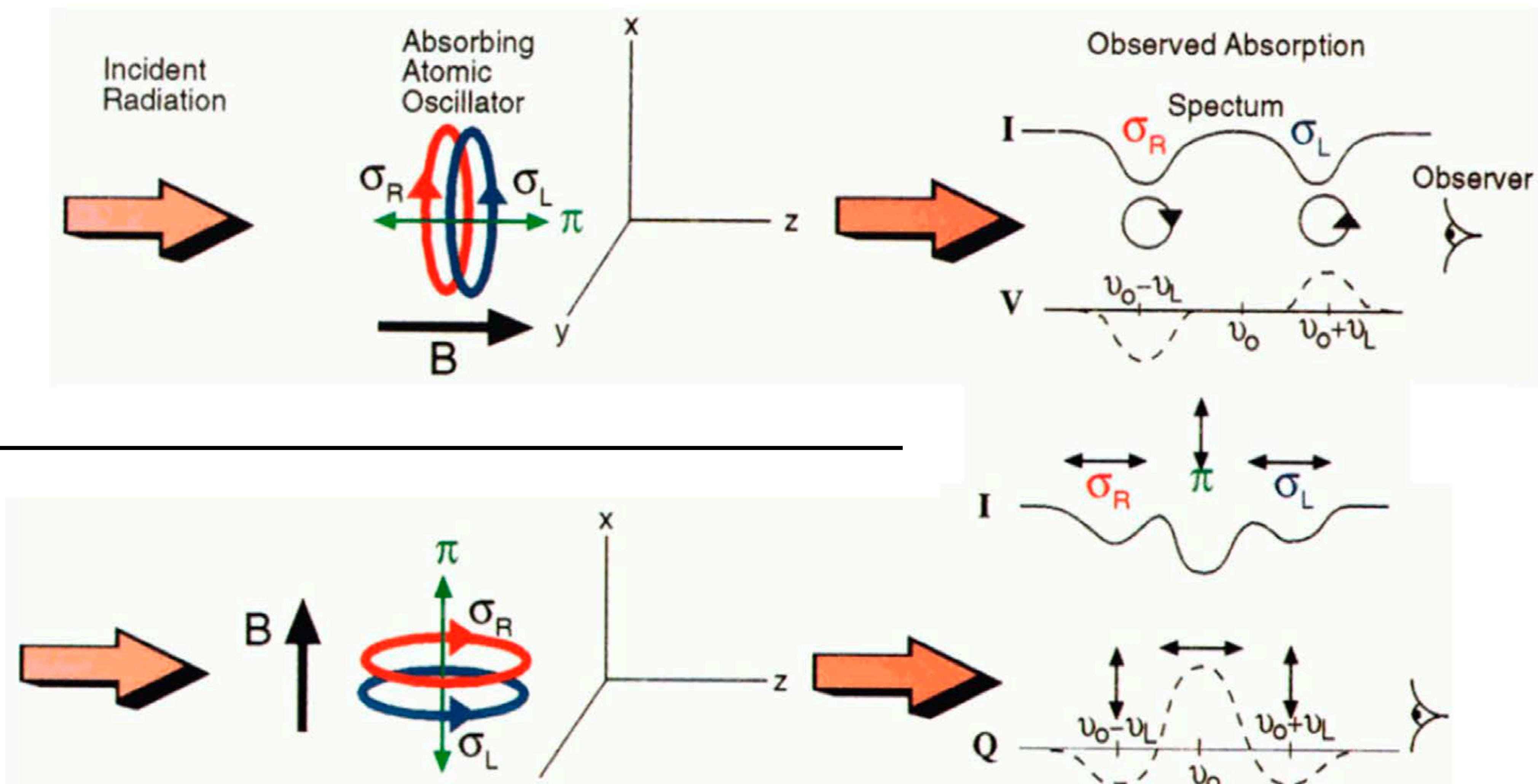
German Vacuum Tower Telescope, Tenerife (1999)

Measuring magnetic fields

Zeeman diagnostics

Longitudinal Zeeman Effect

- Absorption of right- and left circularly polarized light at shifted frequencies corresponding to Zeeman σ components; no absorption of π component



Stokes parameters

$$I = I_{\leftrightarrow} + I_{\updownarrow}$$

$$Q = I_{\leftrightarrow} - I_{\updownarrow}$$

$$U = I_{\nearrow} - I_{\nwarrow}$$

$$V = I_{\circlearrowright} - I_{\circlearrowleft}$$

(from B.Lites, 2000)

Transverse Zeeman Effect

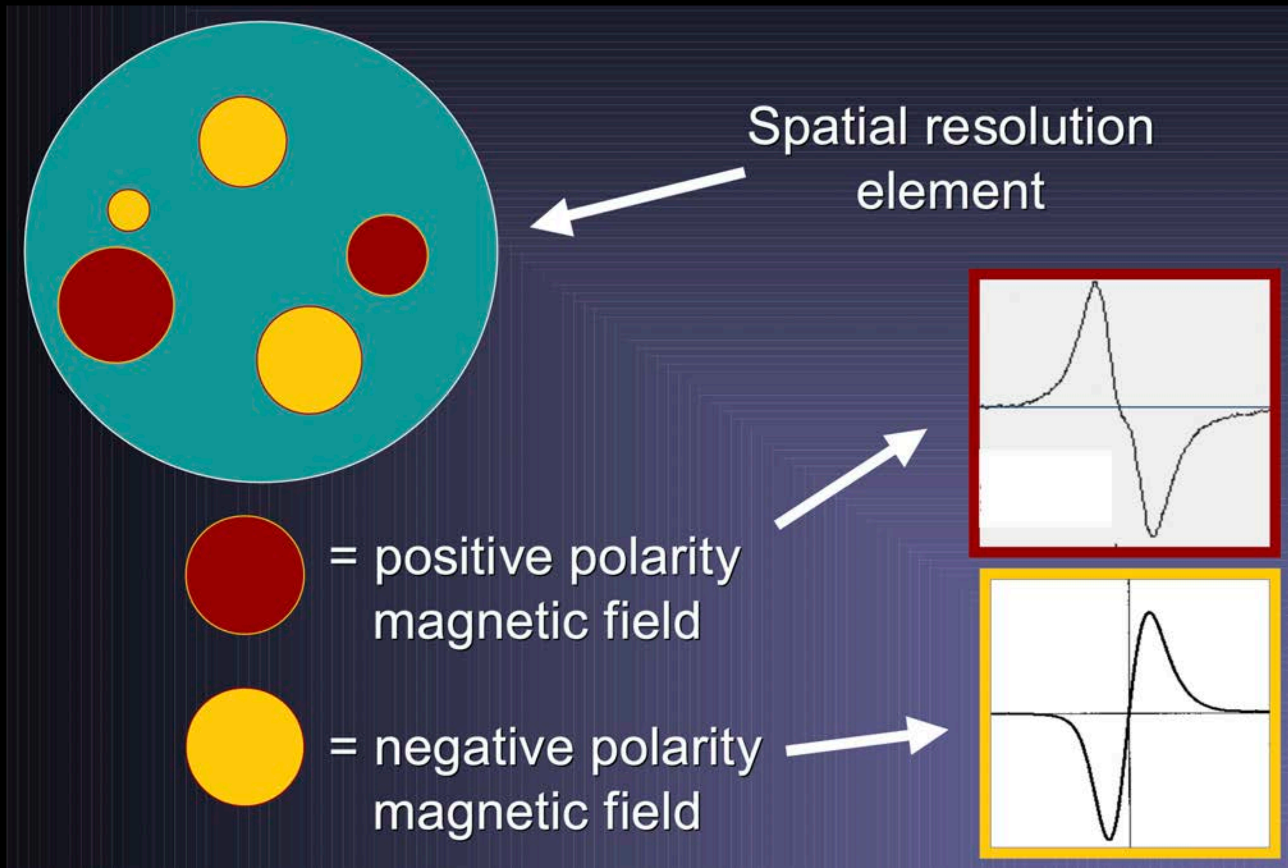
- Absorption for all components $(\sigma^{+}, \pi, \sigma^{-})$ with intensity ratios 1/4 : 1/2 : 1/4
- Stokes U = 0

Measuring magnetic fields

Zeeman polarimetry

- Most used remote sensing of astrophysical (and certainly solar) magnetic fields
- Effective measurement of field strength if Zeeman splitting is comparable to Doppler width or more: B > 200 G ... 1000 G (depending on spectral line)
- Works best in photosphere
- Splitting scales with wavelength — works best in IR

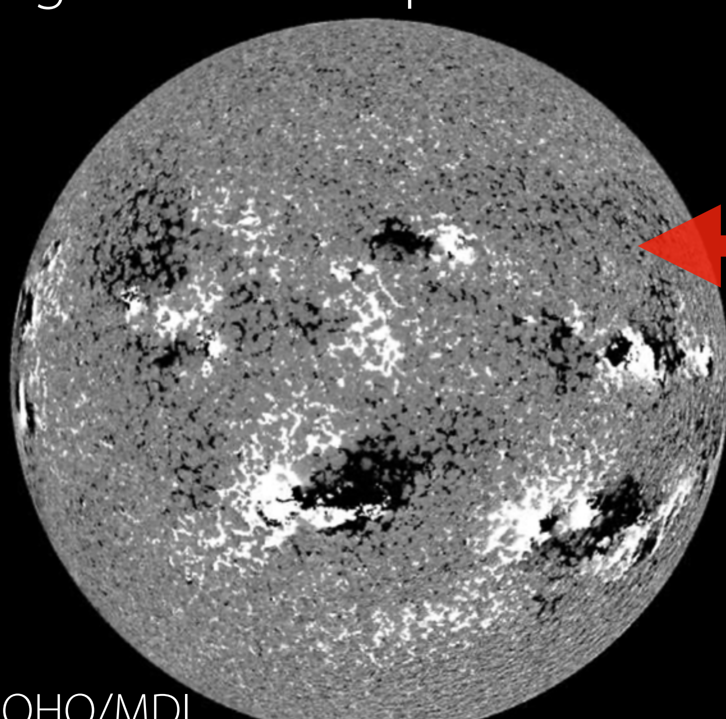
- Sensitive to cancellation of opposite magnetic polarities — needs high spatial resolution



Measuring magnetic fields

Magnetograms

- Magnetograph = Instrument that makes maps of (net circular) polarisation in wing of Zeeman sensitive line.
- Conversion of polarisation into magnetic field requires a careful calibration.
- Usually only Stokes **V** is used (simplest to measure),
- Provides longitudinal component of **B**.

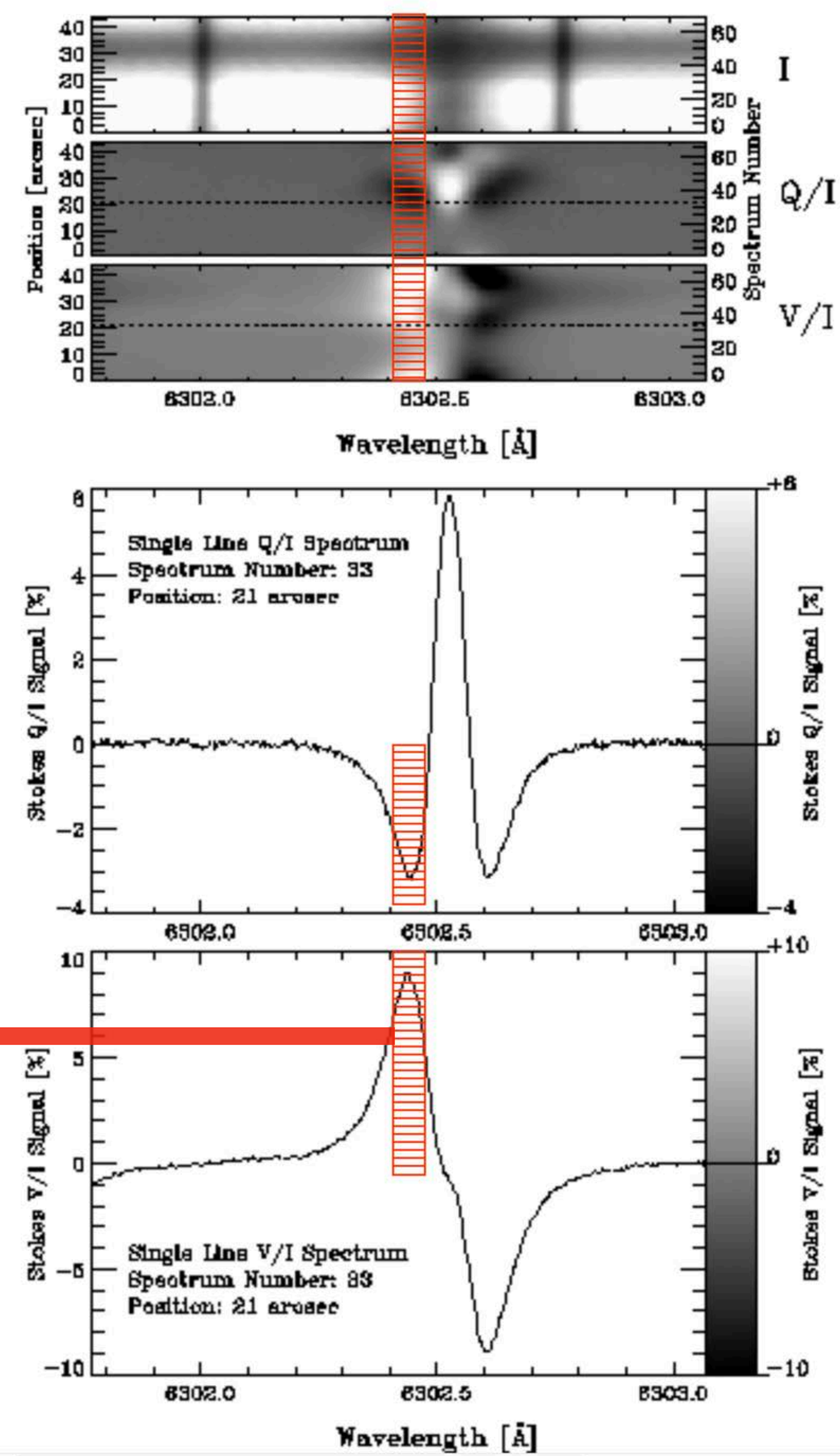


SOHO/MDI

Stokes I, Q and V along spectrograph slit

Stokes Q profile

Stokes V profile

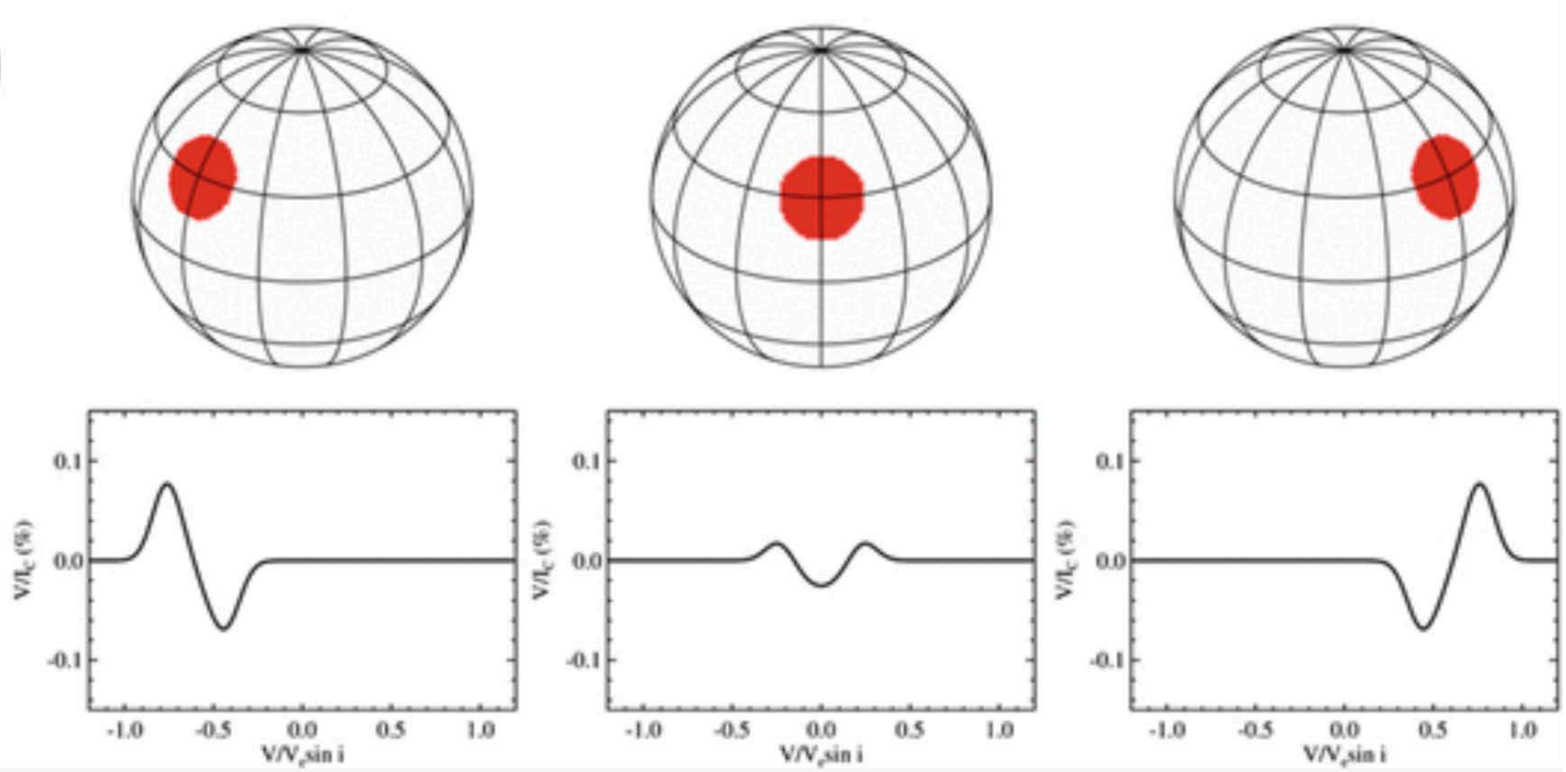


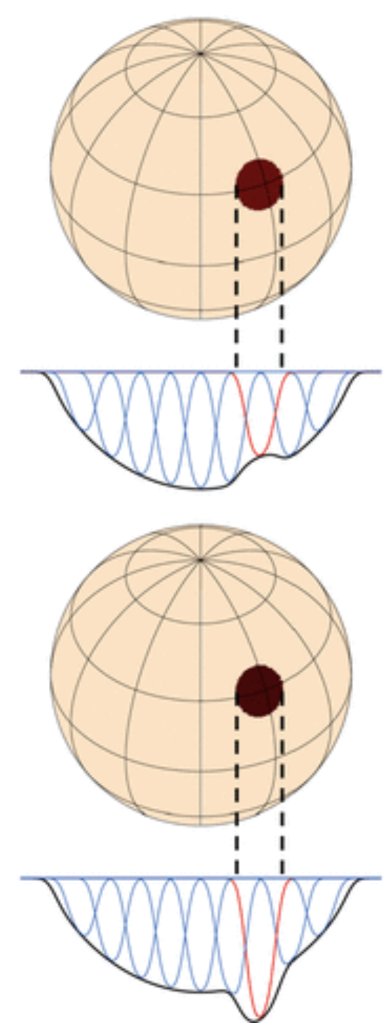
$$I = I_{\leftrightarrow} + I_{\updownarrow}$$
$$Q = I_{\leftrightarrow} - I_{\updownarrow}$$
$$U = I_{\nearrow} - I_{\nwarrow}$$
$$V = I_{\circlearrowright} - I_{\circlearrowleft}$$

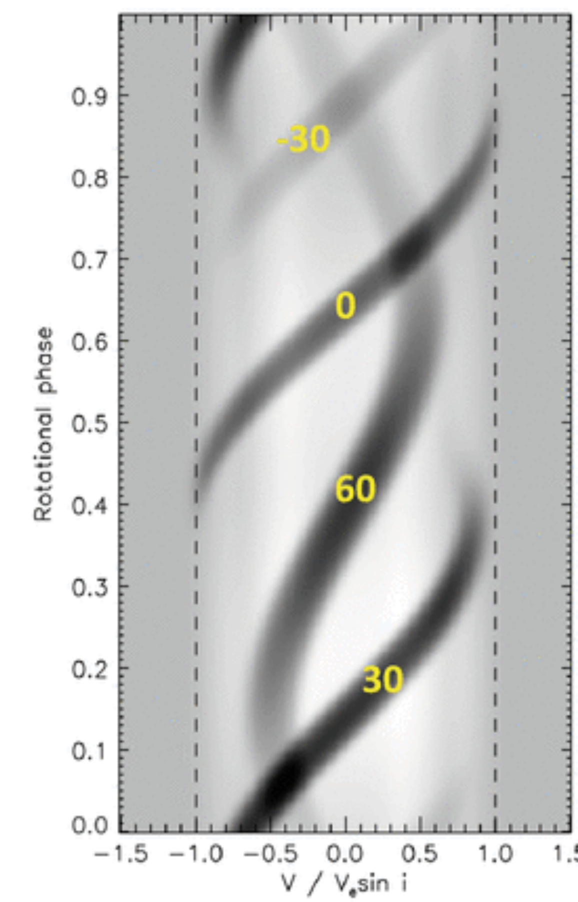
Measuring magnetic fields

Zeeman Doppler Imaging (ZDI)

- Derives magnetic field information from Zeeman splitting of spectral lines from spatial unresolved observations
- As function of time over stellar rotation period(s)
- Requires observations over a sufficient number of nights
- Data then used to reconstruct the stellar surface as it rotated
- Mapping the star's surface

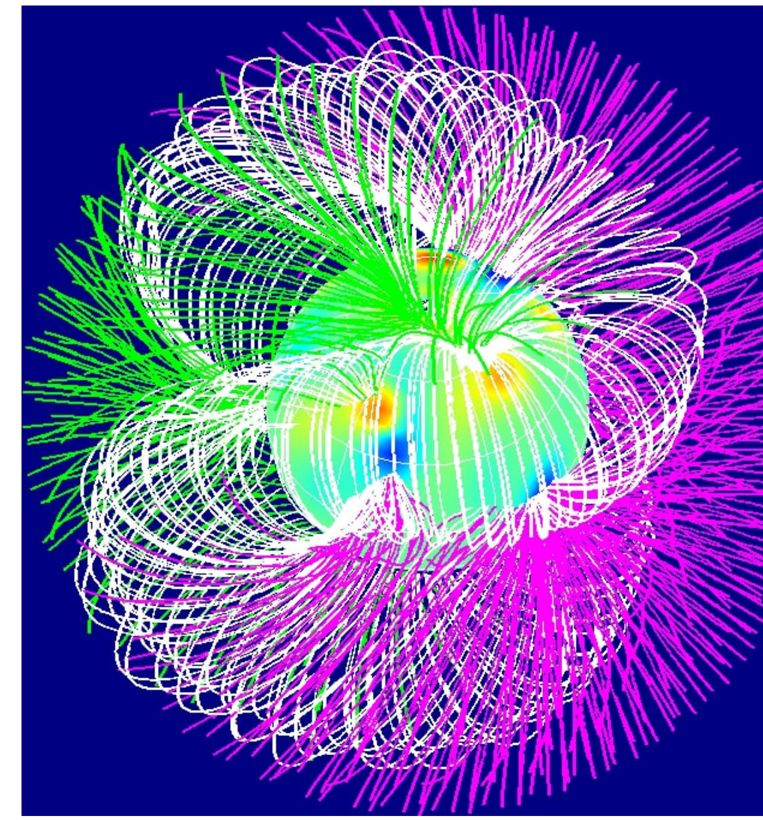






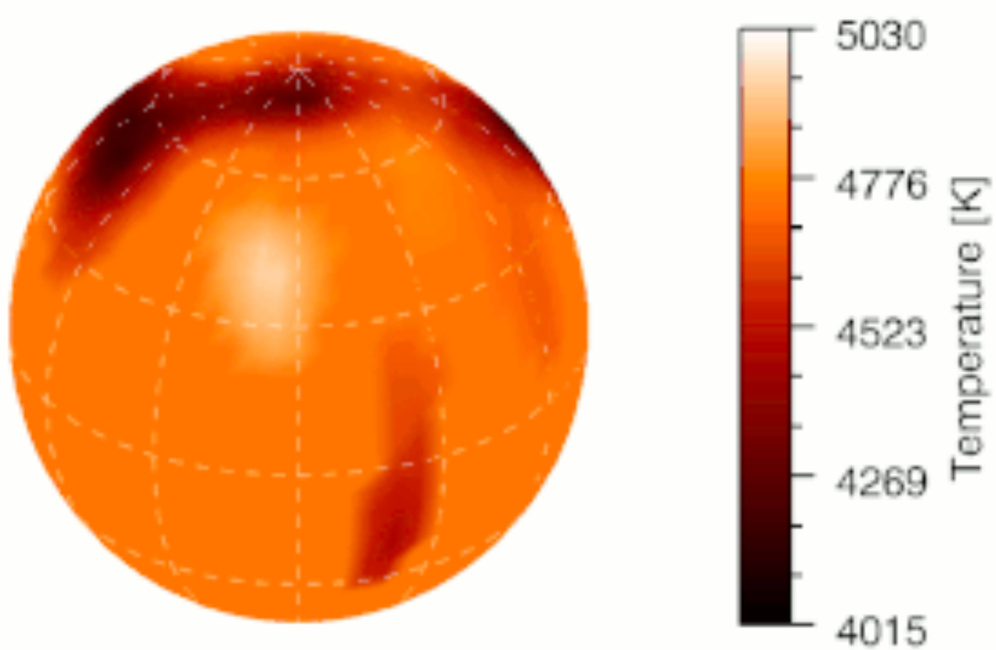
Measuring magnetic fields

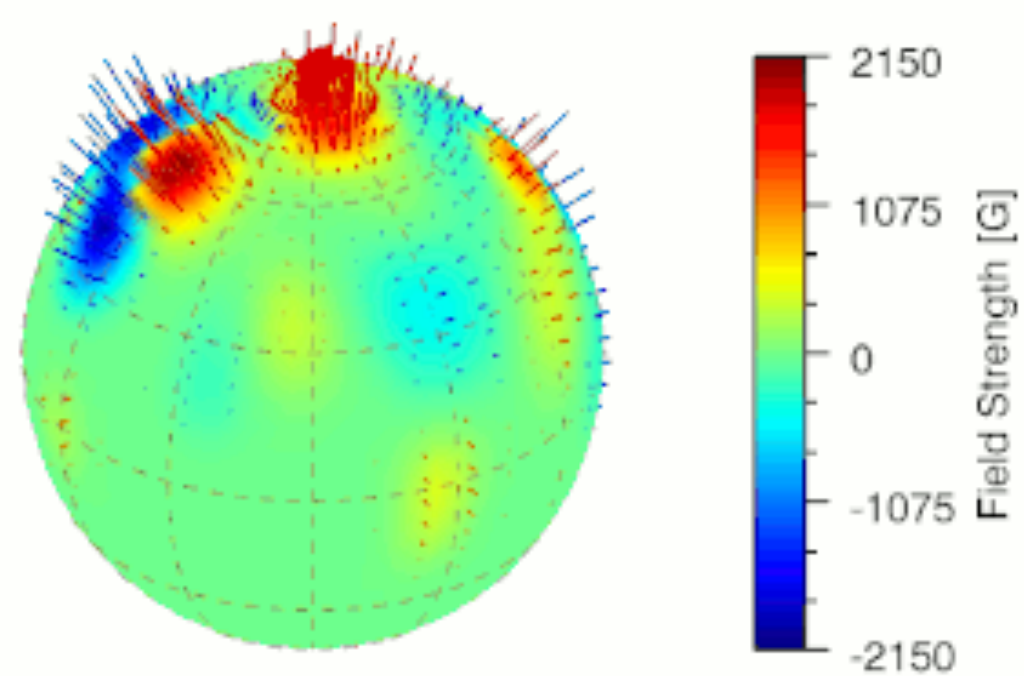
Zeeman Doppler Imaging (ZDI)



- 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