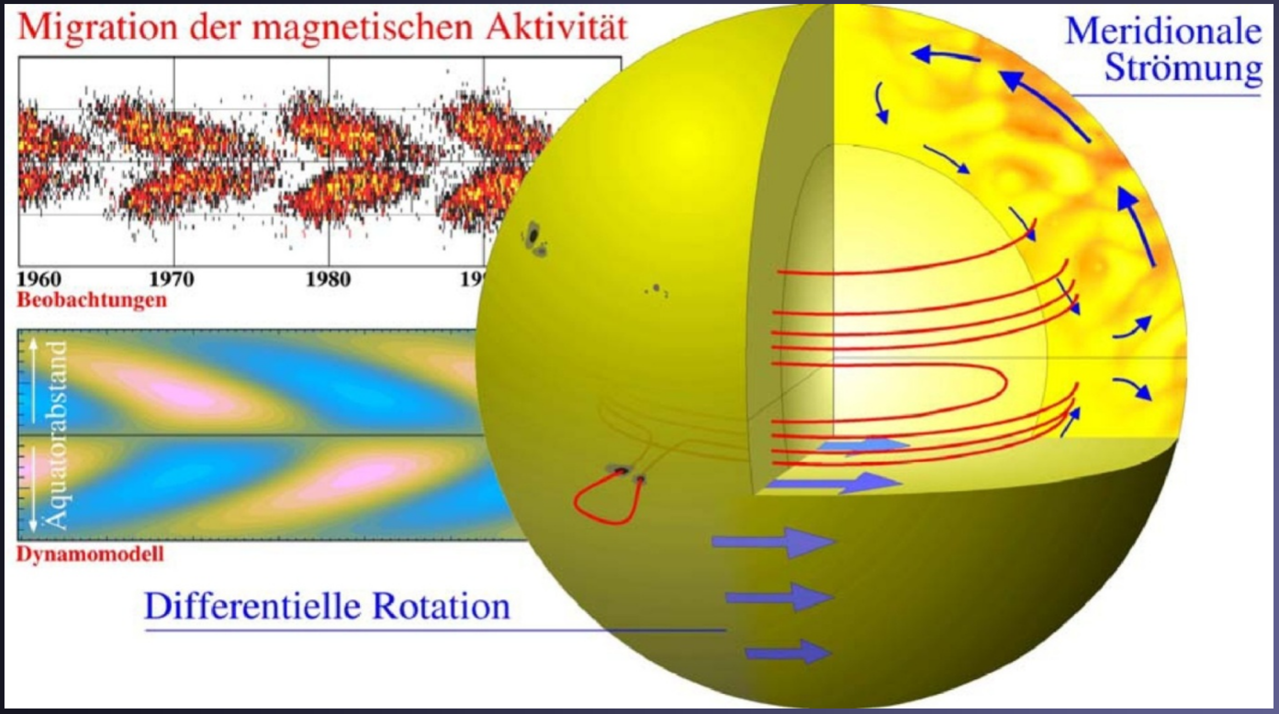
The variable Sun: why do sunspots come and go?

Lecture 5: Solar cycle and dynamo



Spots: emergence and development

Sunspots often start as pores and grow, often by merging of multiple pores or of small magnetic features into the growing spot

One idea is that the merging spots are part of the same flux tube below the surface and are simply re-coallescing

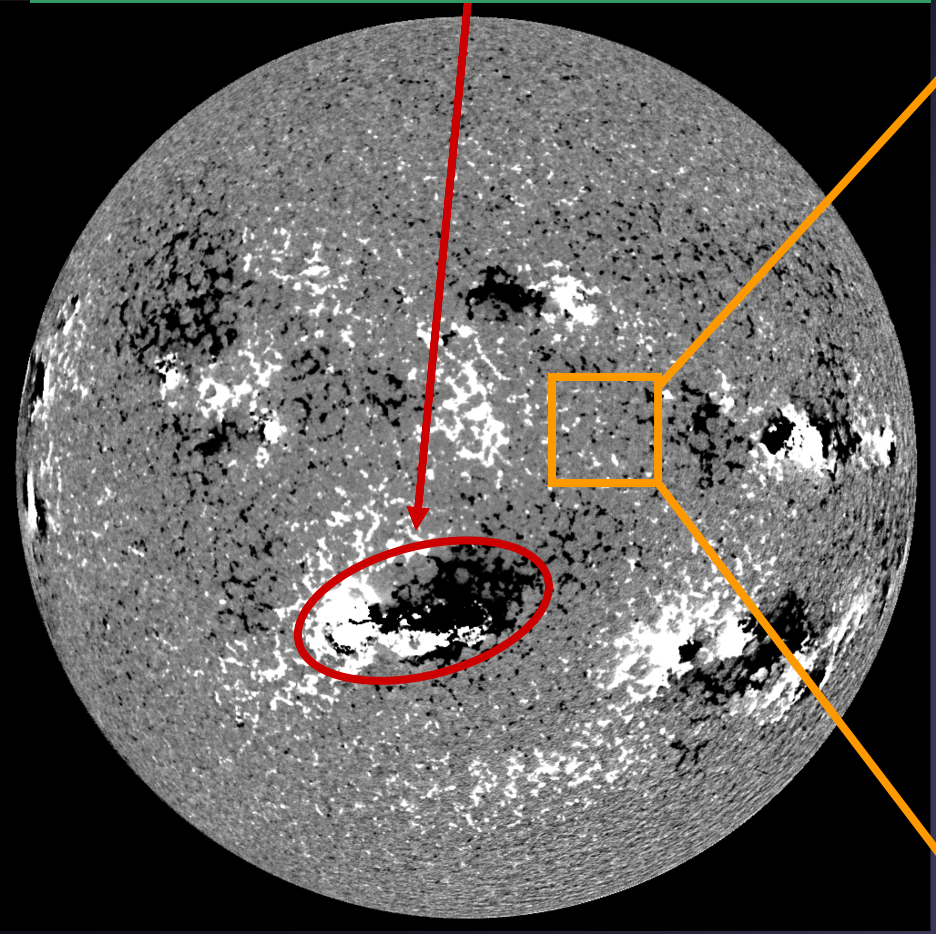
Magnetic flux per region

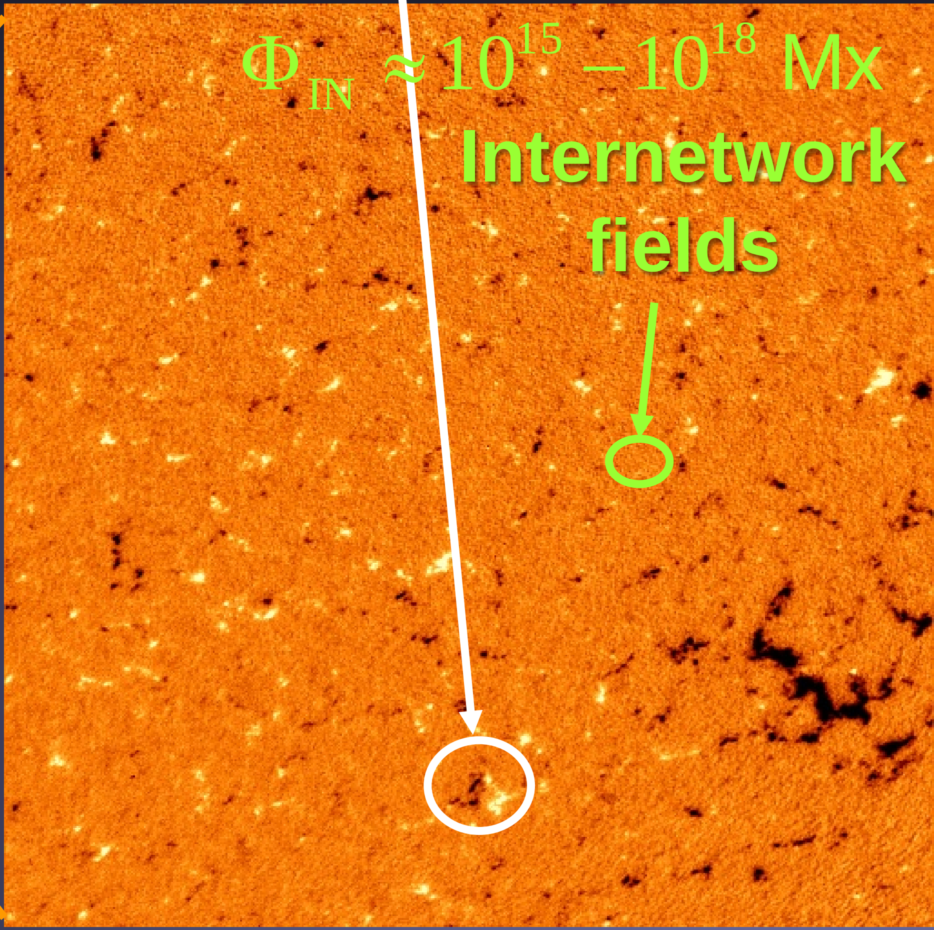
Active regions

$$\Phi_{\mathrm{act\ reg}} \approx 5\cdot10^{20}\ldots5\cdot10^{22}\ \mathrm{Mx}$$

Ephemeral regions

$$\Phi_{\mathrm{eph\ reg}} \approx 10^{18}-5\cdot10^{20}\ \mathrm{Mx}$$





SOHO/MDI magnetograms

Size distribution of active regions

- Distribution of active region areas, A: $N(A) \sim A^{-\gamma}, \quad \gamma \approx 2$

  (Harvey 1993, Meunier 2003)

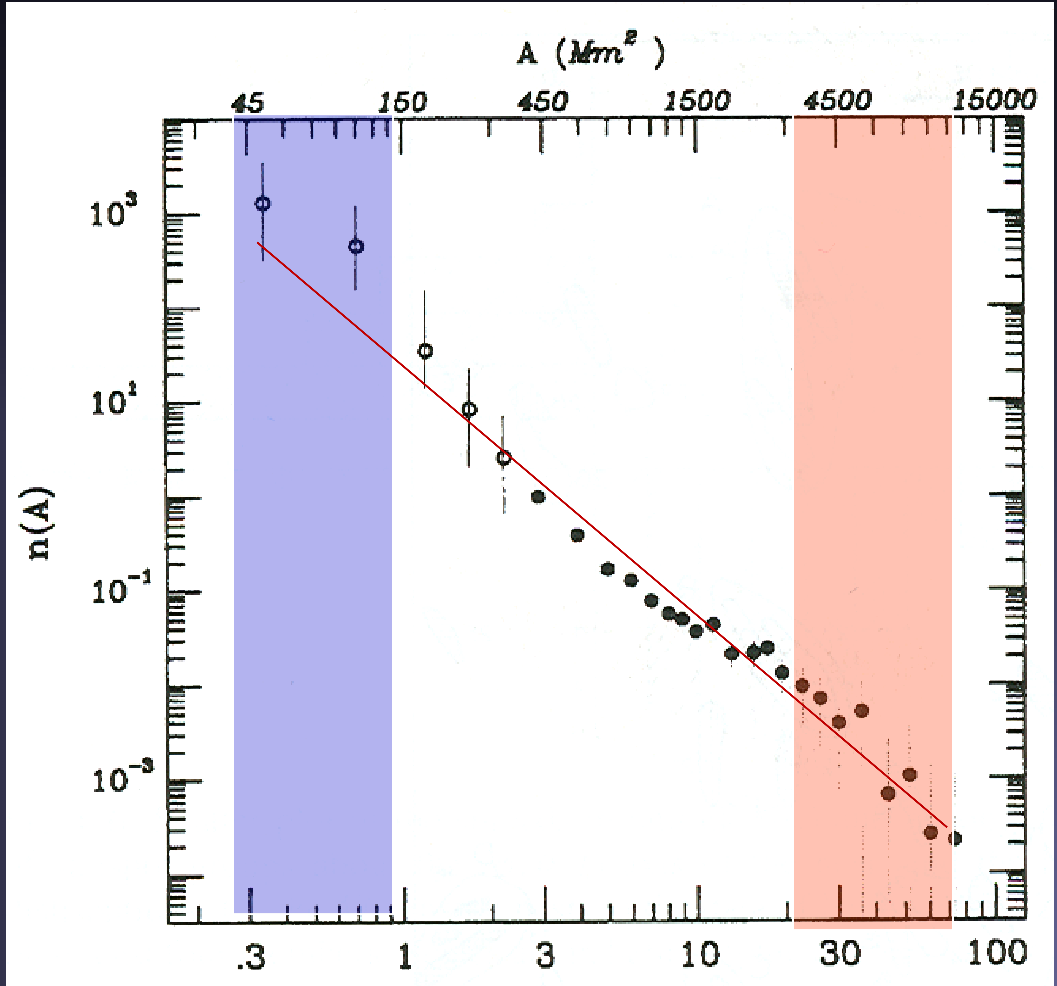
- Magnetic flux Φ of active region, $\Phi \sim A$

- At a given time t:

$$\Sigma_{\text{small}}\Phi_{\text{small}} \approx \Sigma_{\text{large}}\Phi_{\text{large}}$$

- Lifetimes τ of active regions $\sim 1/A$

- Most flux emerges in smaller regions



K. Harvey (1993)

Values integrated over activity cycle

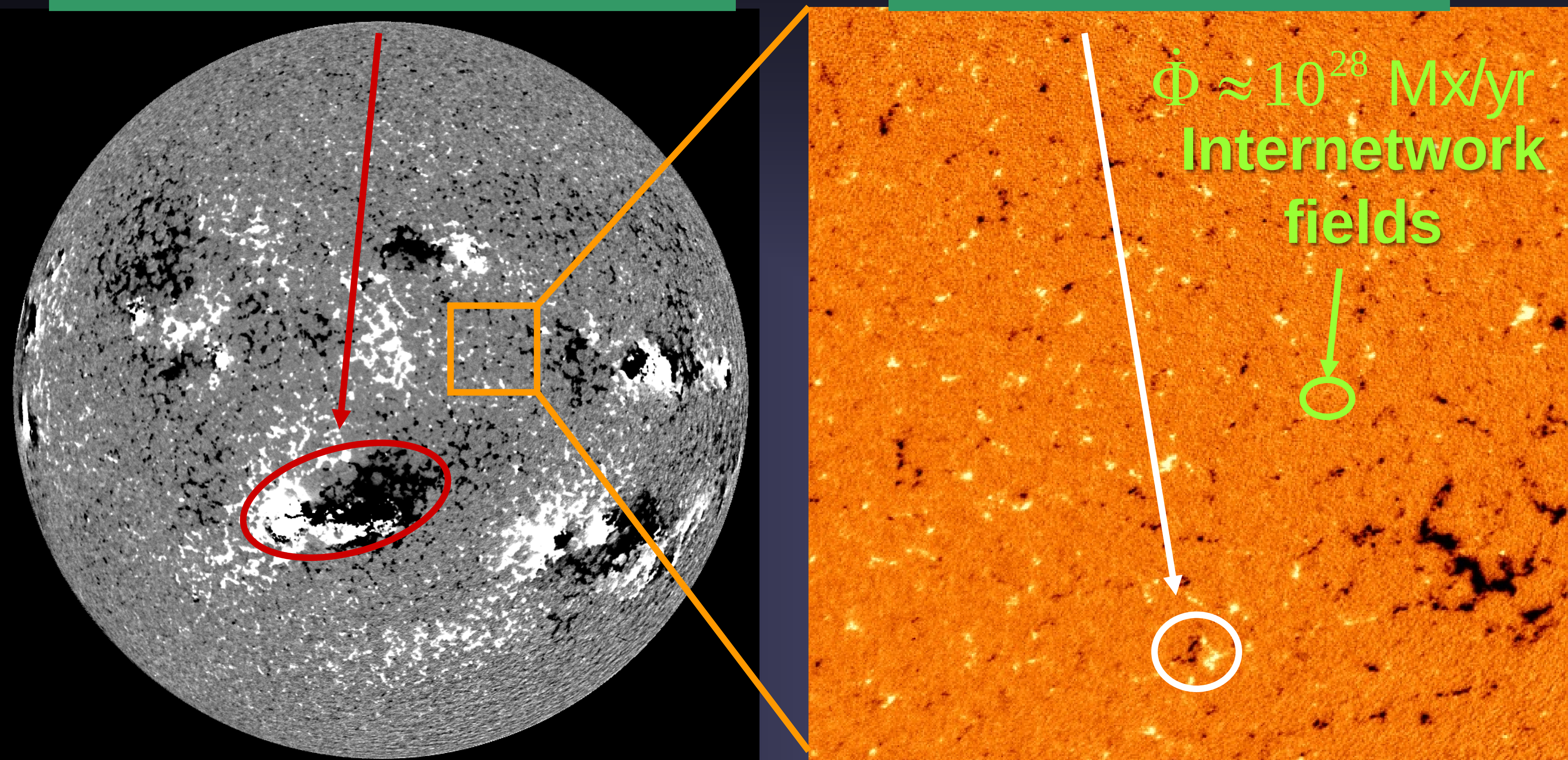
Magnetic flux emerging over solar cycle

Active regions

$\dot{\Phi} \approx 3 \cdot 10^{23} \ldots 3 \cdot 10^{24}$ Mx/yr

Ephemeral regions

$\dot{\Phi} \approx 2 \ldots 4 \cdot 10^{26}$ Mx/yr



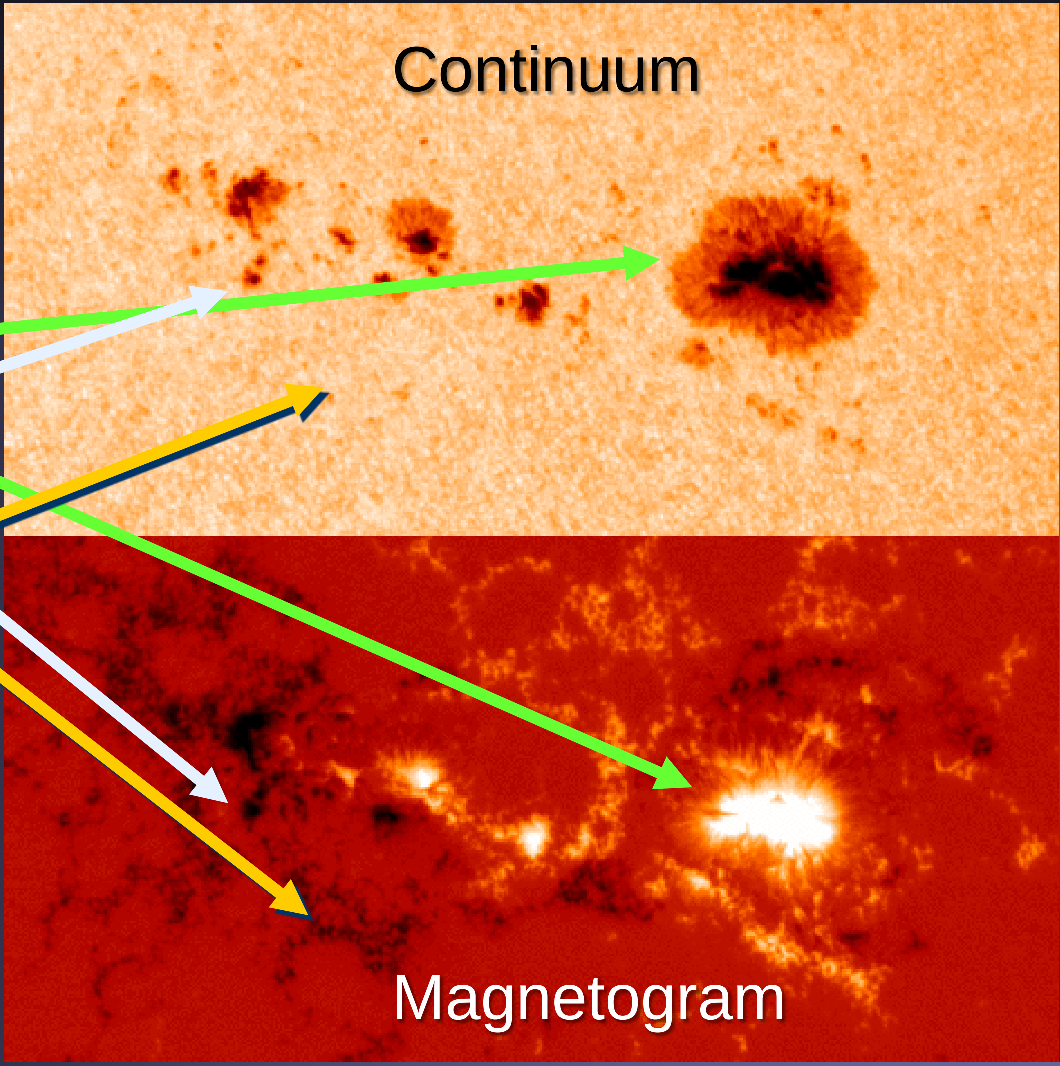
SOHO/MDI magnetograms

What are active regions composed of?

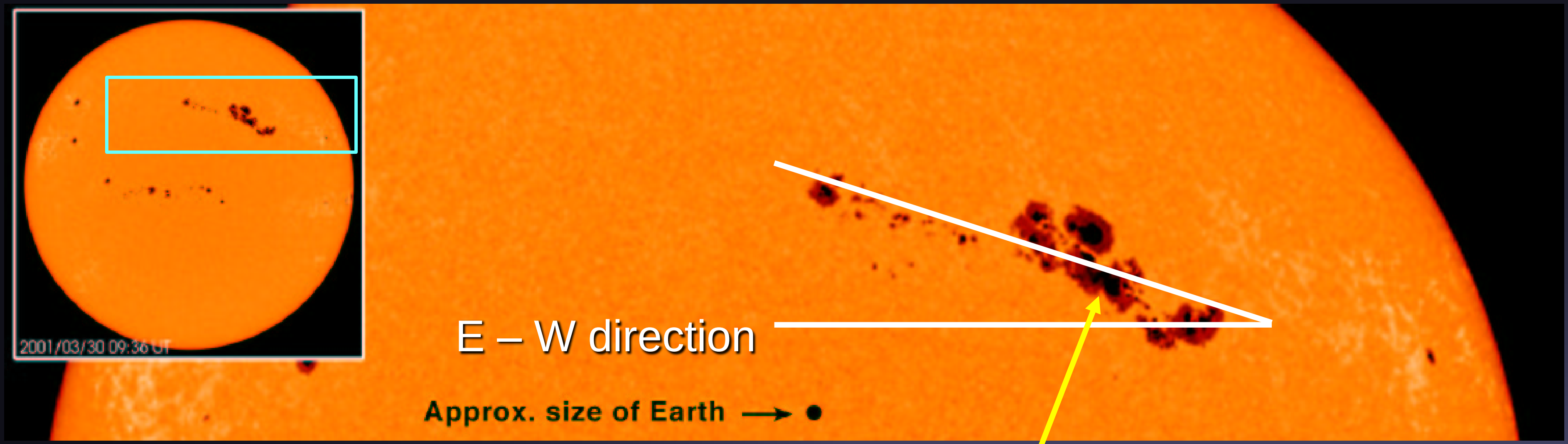
Magnetic structure of active regions is determined by

- sunspots
- pores
- plage or facular magnetic elements

- Flux per features:
  - Spot: $\Phi=10^{20}\text{-}10^{22}$ Mx
  - Pore: $\Phi=3\cdot10^{18}\text{-}3\cdot10^{20}$
  - ME: $\Phi=10^{17}\text{-}3\cdot10^{18}$ Mx



Tilt angle of sunspot groups



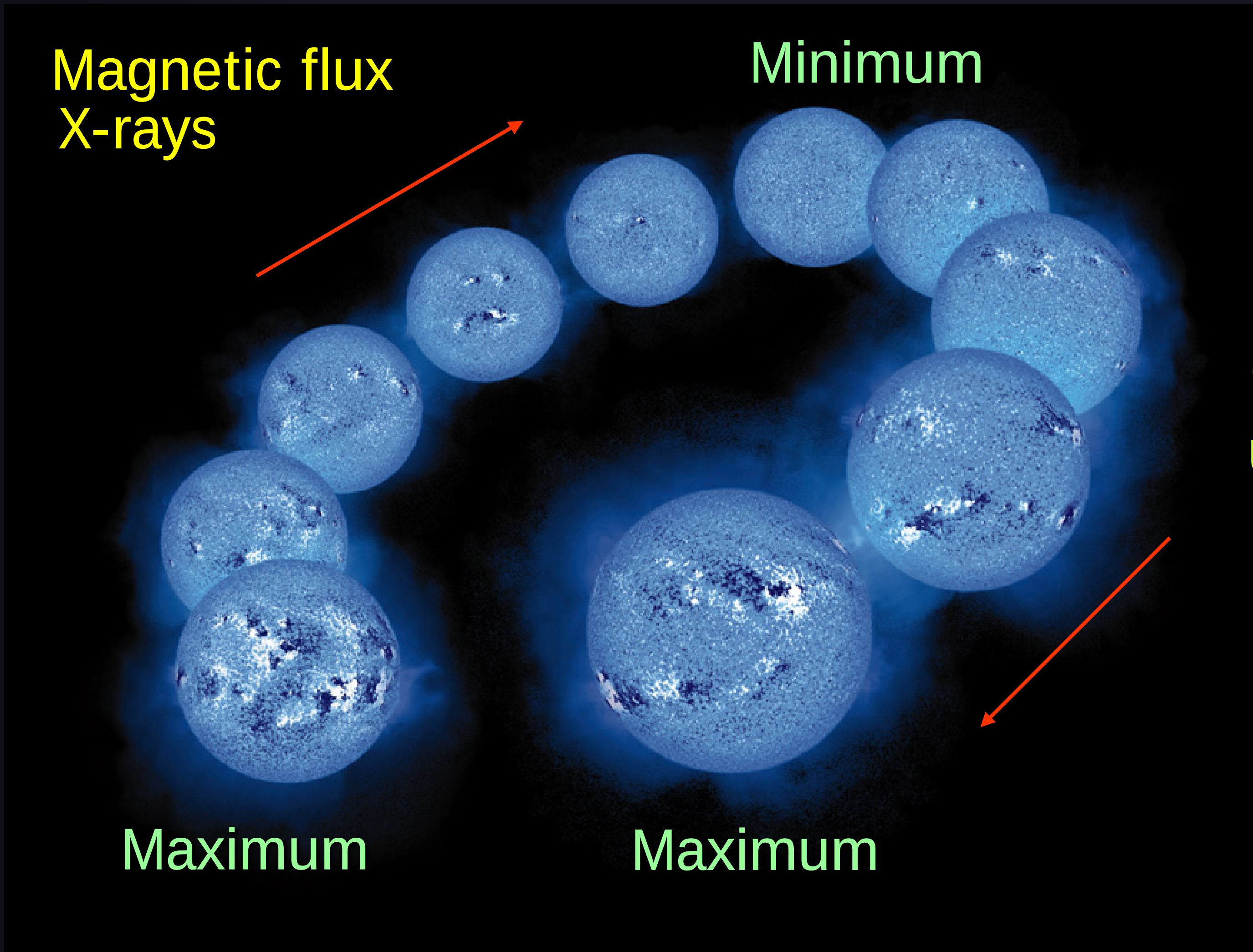
Following spots closer to pole

Tilt angle $\gamma \propto \sin(\lambda)$

("Joy´s law")

Here λ = latitude

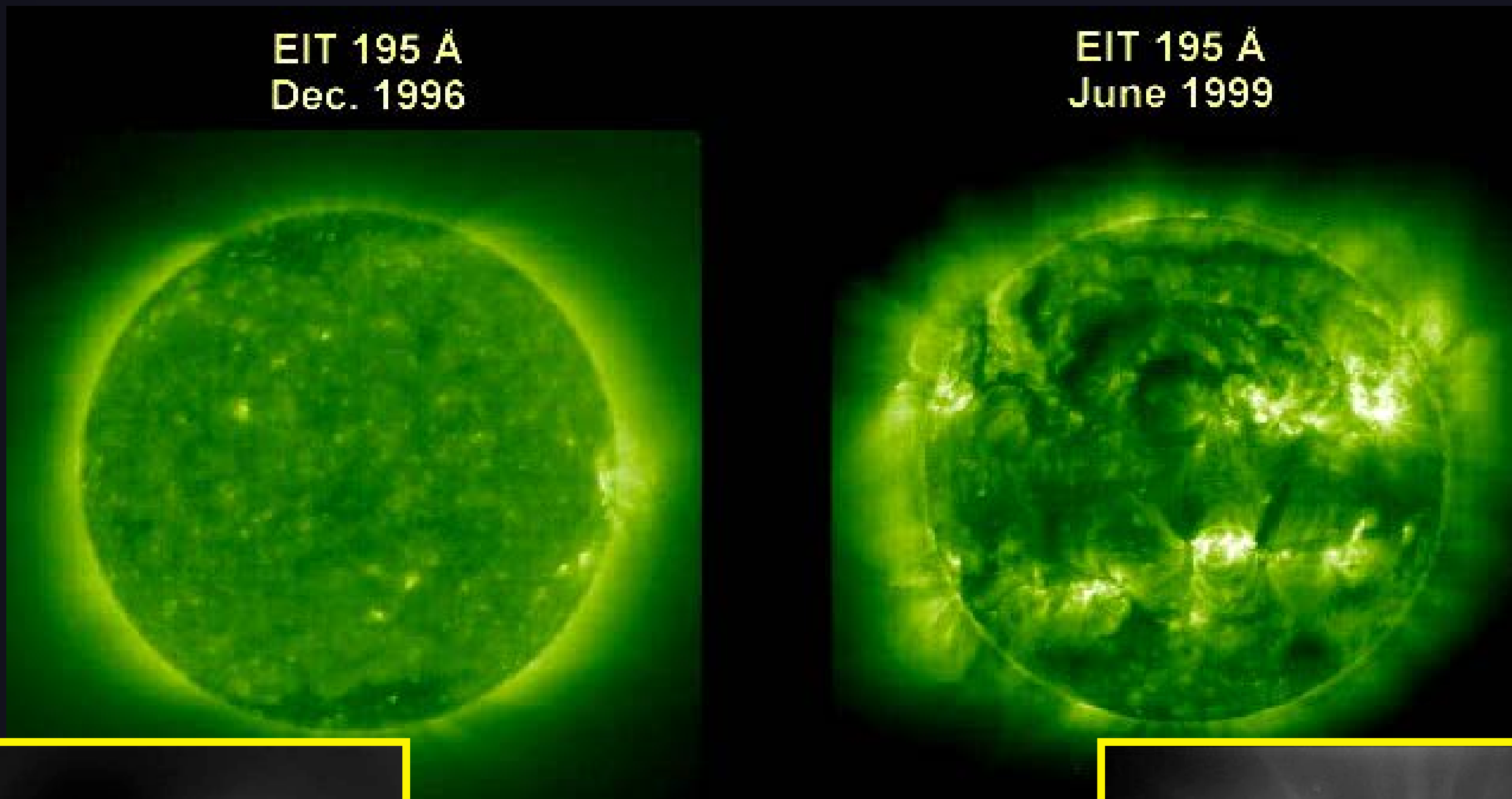
The solar activity cycle (Schwabe cycle)

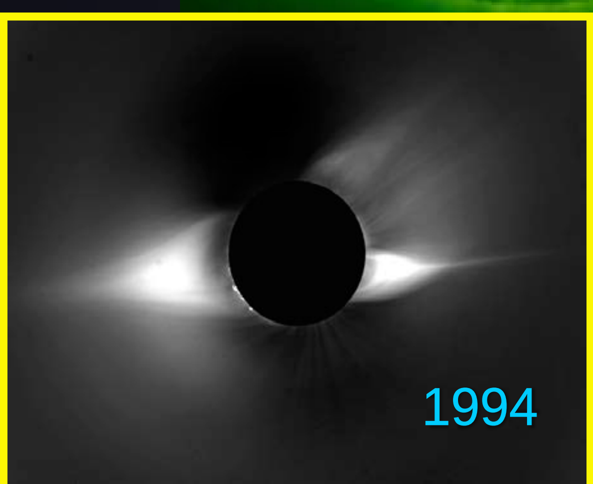


The short-wave radiation varies strongly through the activity cycle: from a factor 2 in the UV (<100nm) up to a factor 100 in X-rays

The magnetic flux at the solar surface also varies quasi-periodically over the 11-year solar cycle

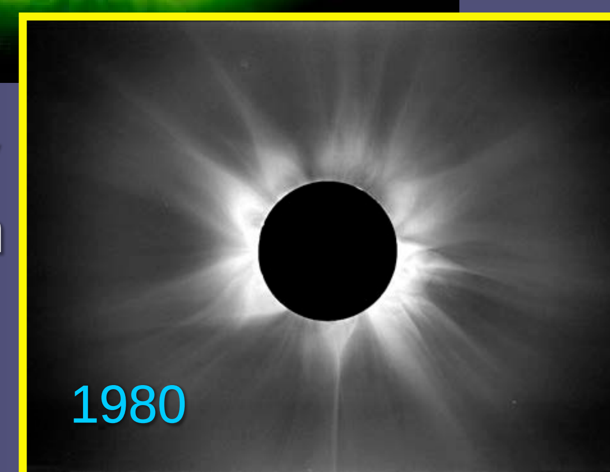
Solar minimum & maximum in EUV





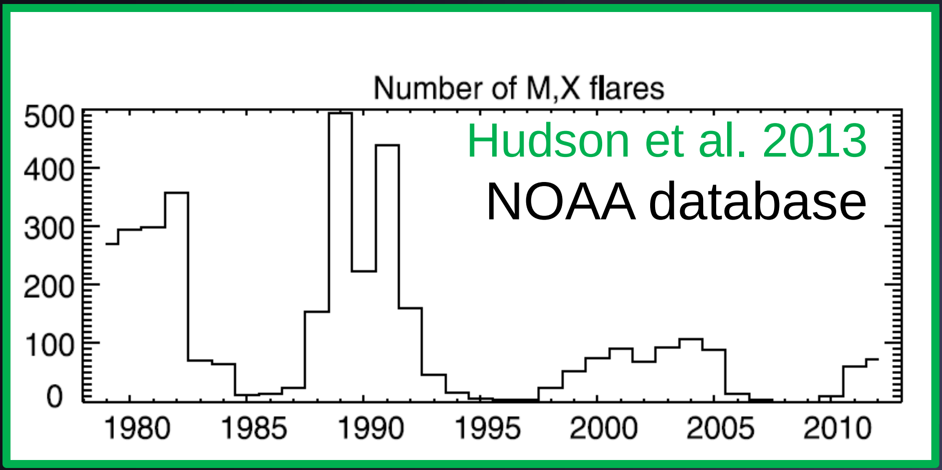
Activity minimum

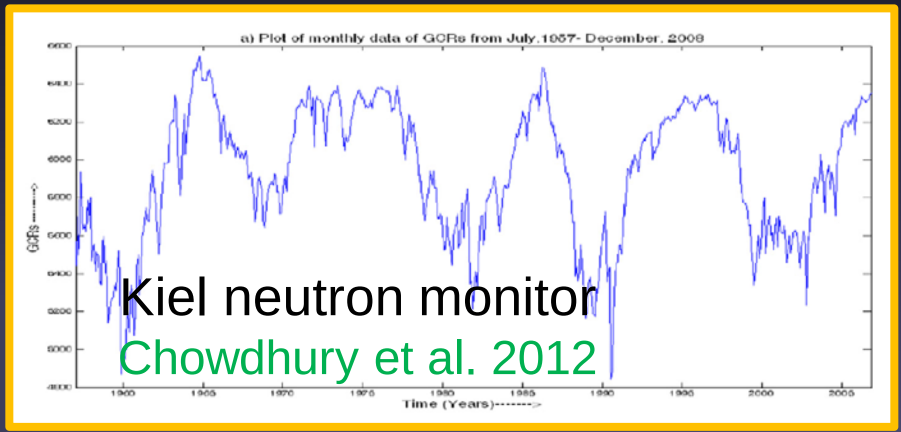
Activity maximum

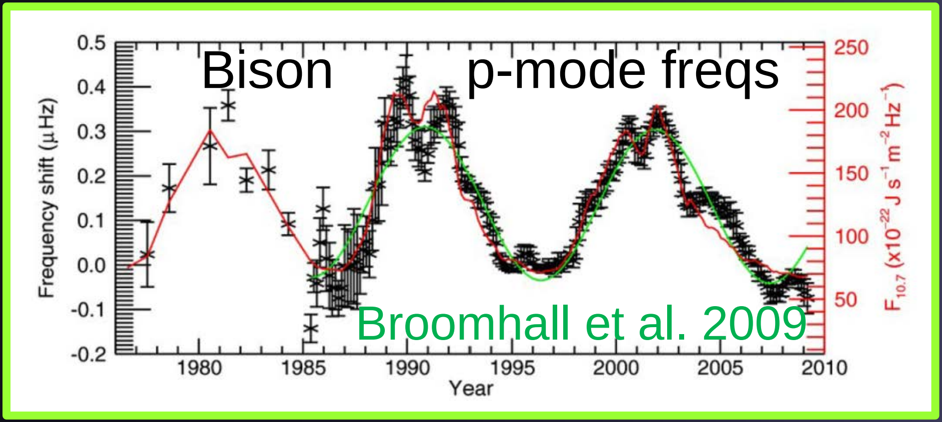


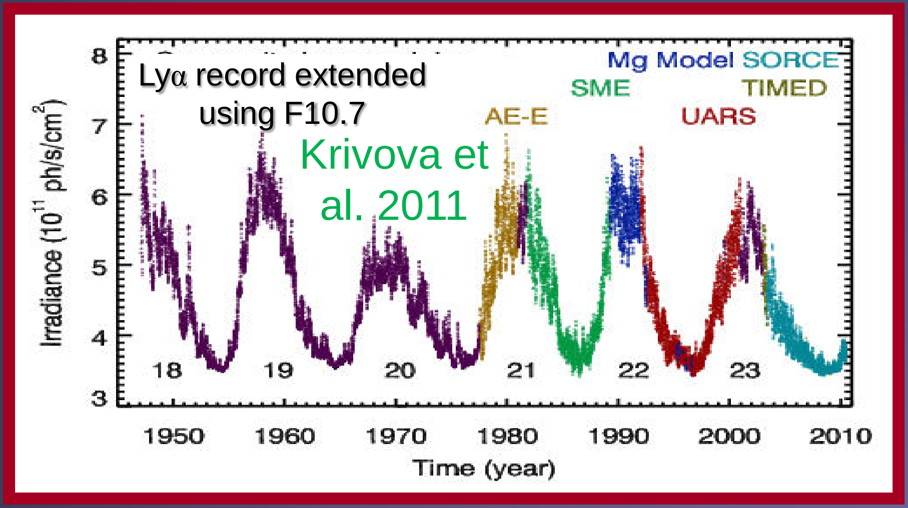
More proxies of the solar cycle

Further activity indicators following the solar cycle: Number of flares, galactic cosmic rays, Ly α flux, Number of CMEs, p-mode frequencies, and many more

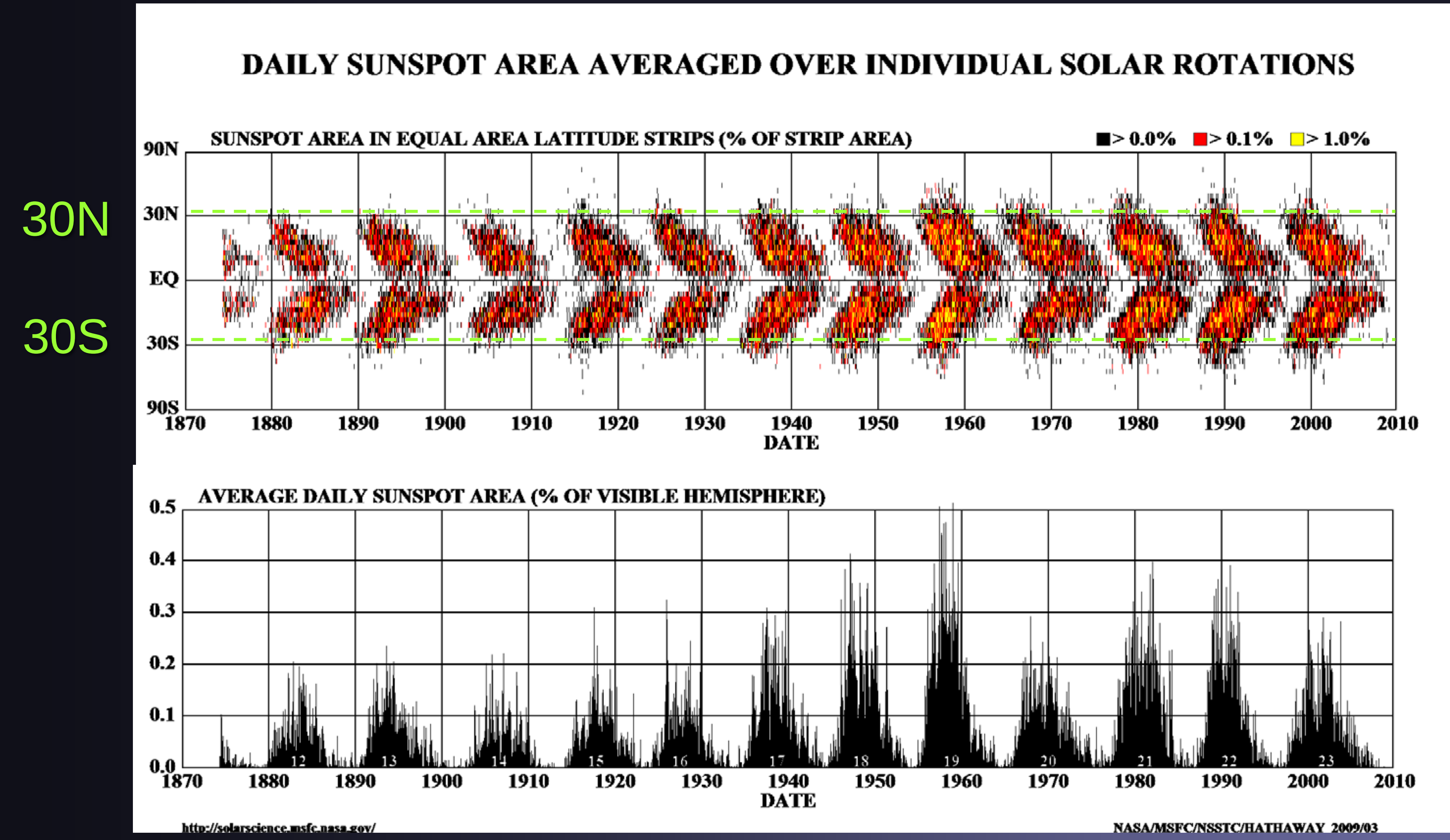






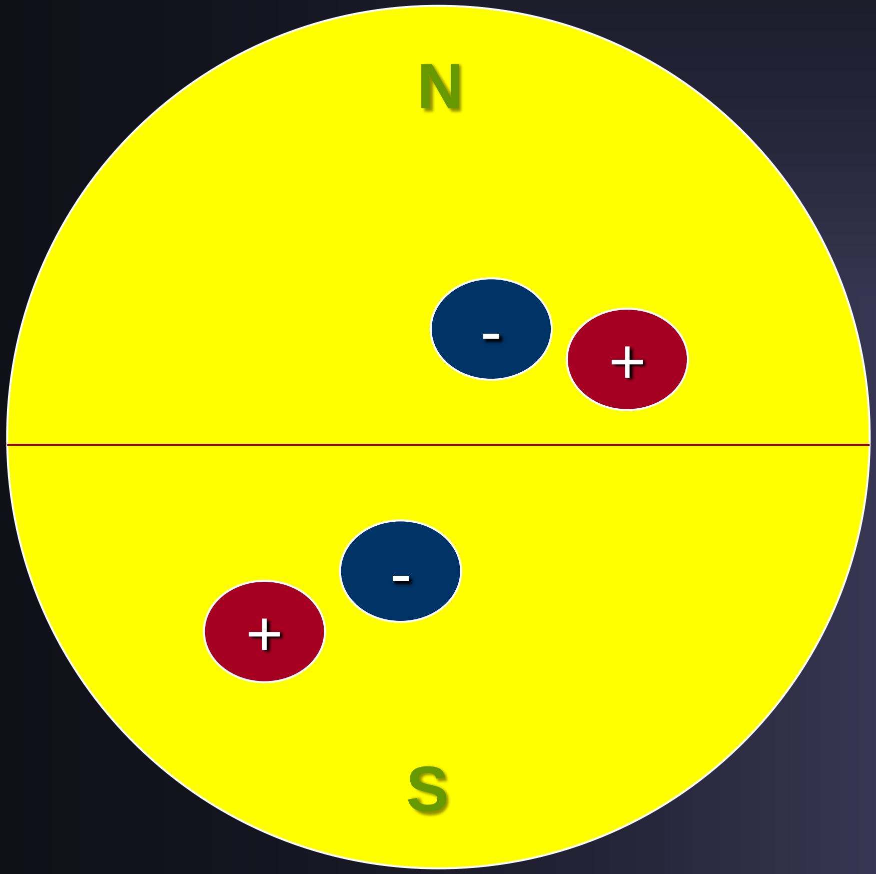


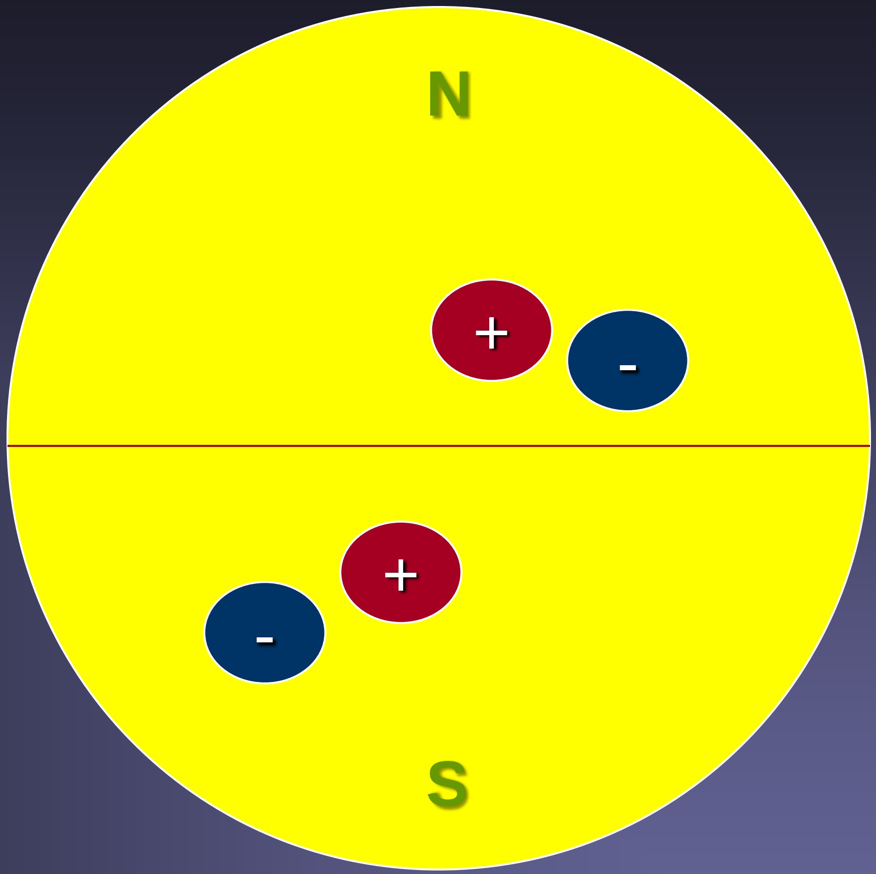
The sunspot cycle and the butterfly diagram: Spörer's law



Magnetic cycle: Hale's polarity law II

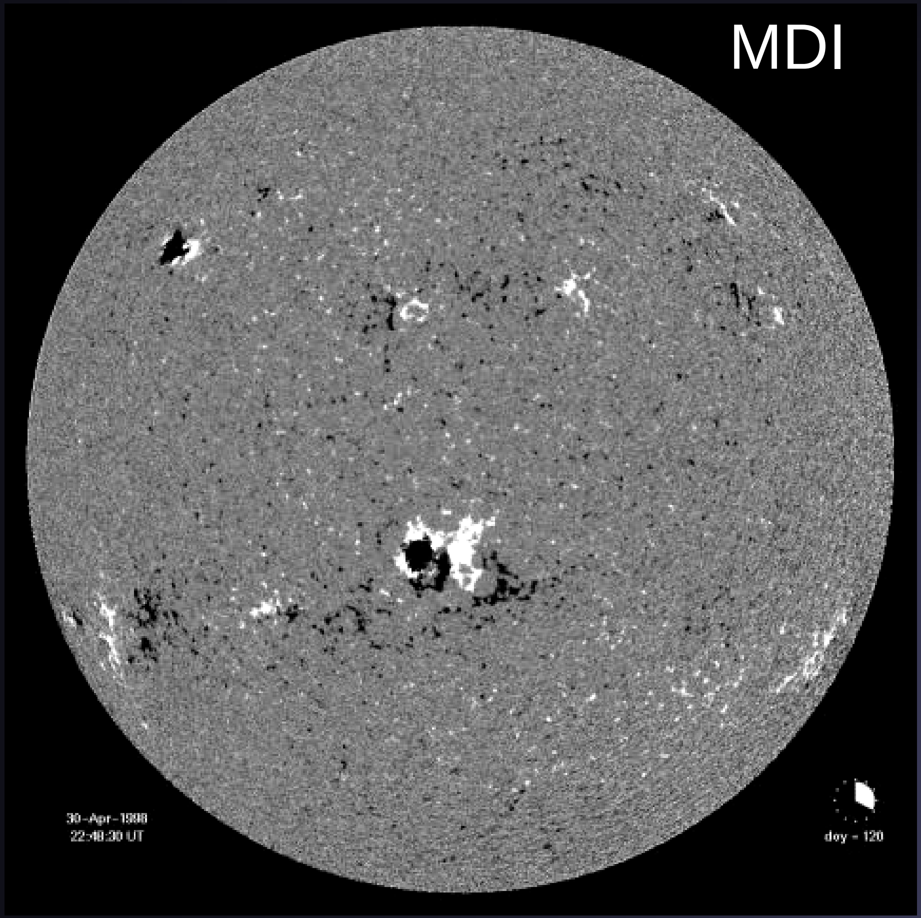
Polarity is re-established after 22 years, length of magnetic cycle

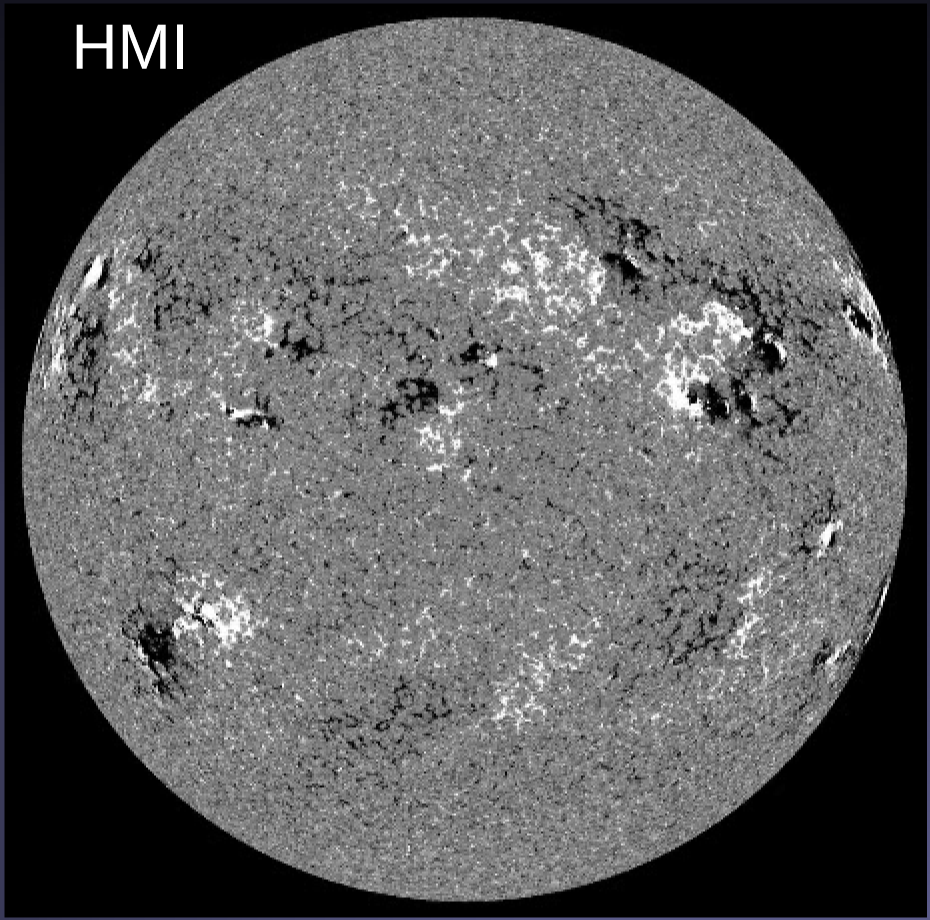




cycle n G.E. Hale cycle n+1

The Hale cycle





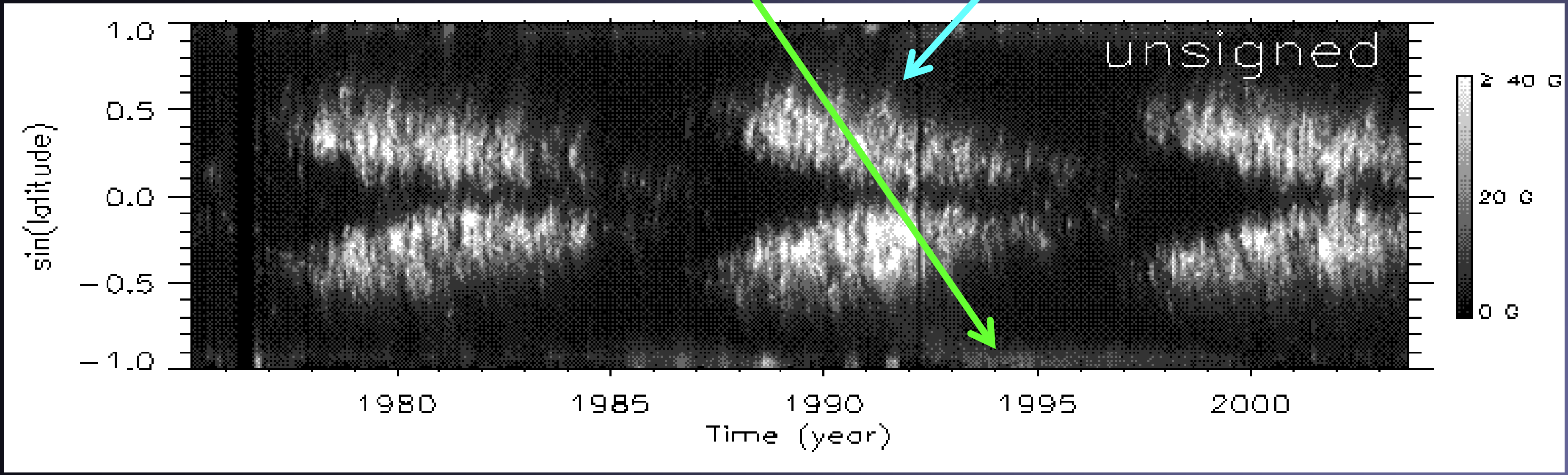
Schwabe cycle 23

Schwabe cycle 24

Hale cycle (Hale & Nicholson 1925)

Magnetic butterfly diagram:
Azimuthal averages of unsigned flux

- Unsigned magnetic flux (averaged over all longitudes) displays very similar butterfly diagram to the sunspots
- There are signs of additional features:
  - flux moving periodically to the poles from active bands
  - some concentration of field at poles



Butterfly diagram of net magnetic flux

Azimuthal average of **net** magnetic flux

➔ Active regions now appear weaker, since bipolar

➔ Polar fields appear stronger, since unipolar

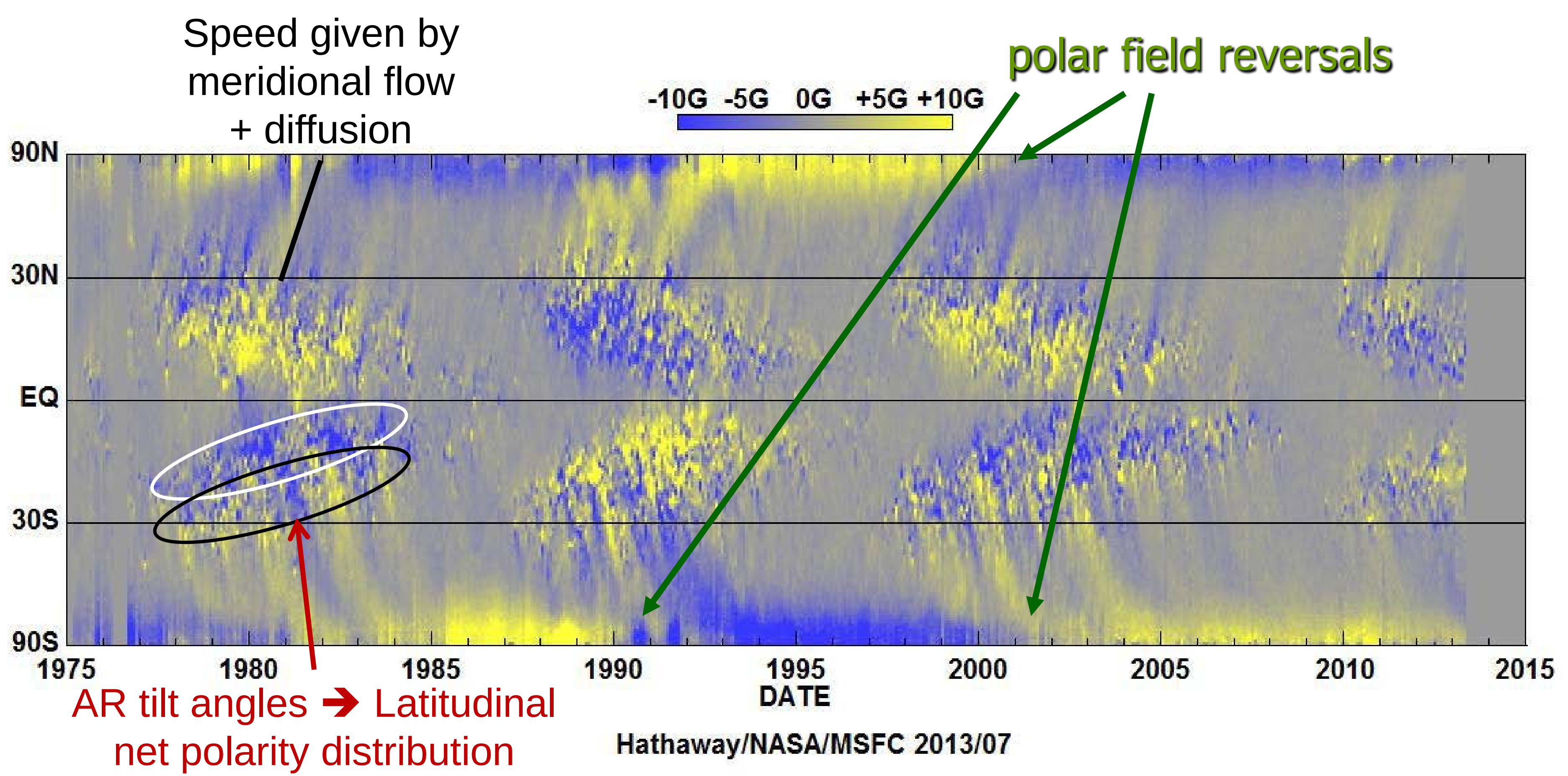
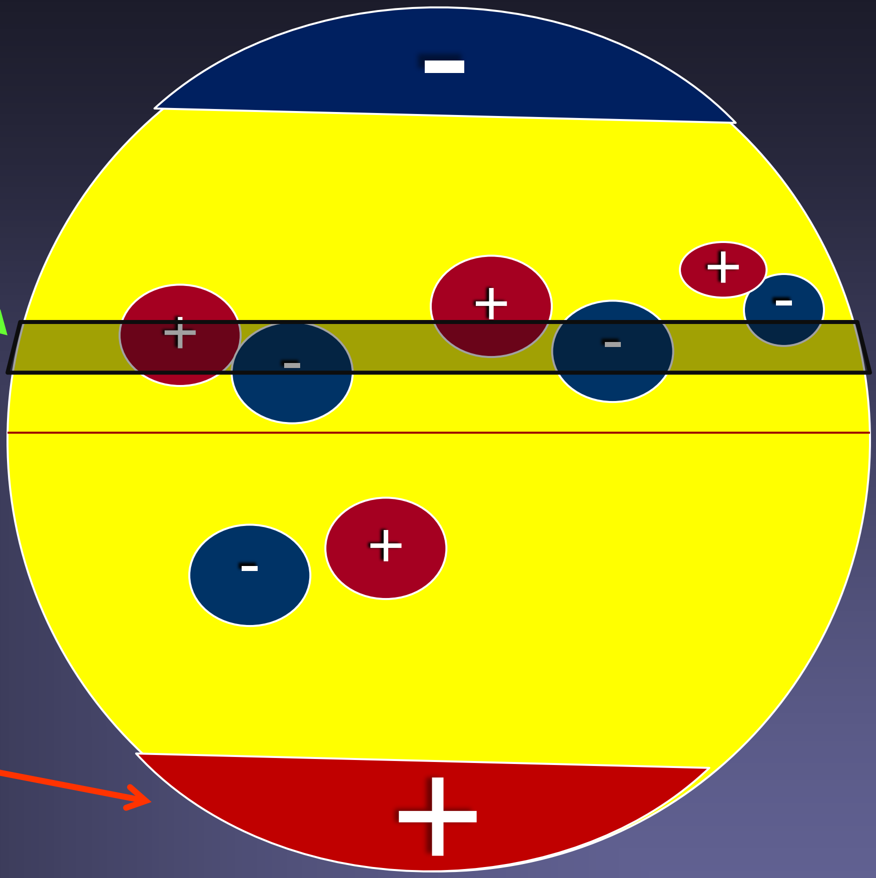


Illustration why signed flux shows larger signal near the poles

- Azimuthal averaging leads to cancellation of signal at low latitudes
- Azimuthal averaging does not affect signal at high latitudes



How is the solar cycle produced?

- Currently accepted model: dynamo located at lower boundary of convection zone (global dynamo: responsible for active regions)
- Other possible contributors: dynamo acting within the convection zone, possibly also at solar surface (local dynamo: responsible for weaker fields)
- Dynamo: enhances an already present (seed) field by converting a part of the energy of motion (e.g. rotation) of a conducting fluid into magnetic energy
- Drivers of the dynamo are flow fields: rotation and differential rotation, turbulence, meridional flow

Induction equation

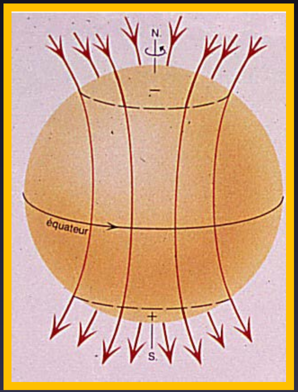
$$\boxed{\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}}$$

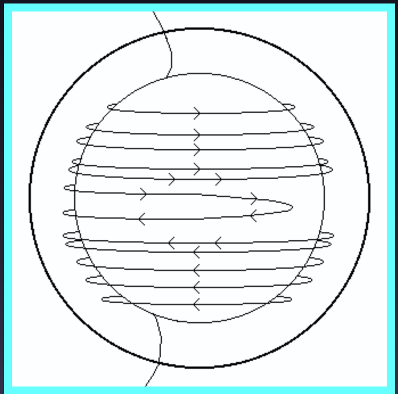
Here $\eta = \sigma^{-1} c^2 / 4\pi$ is the magnetic diffusivity (in cgs units)
σ = electric conductivity; σ^{-1} = electric resistivity, c = light speed

- First term on RHS is advection term (influence of velocity, e.g. strengthening of $\mathbf{B}_{\text{toroidal}}$ by differential rotation)
- Second term describes diffusion (decay of field)
- Ratio of 1st to 2nd term: Magnetic Reynolds number: $R_m = UL/\eta$, where U= typical velocity, L= typical length scale. $R_m = 10^{12}$ in lower solar convection zone
- Dynamo acts only if $R_\mathrm{m} > R_{\mathrm{m,\,crit}}$, i.e. flows $\gg$ diffusion

How is the solar cycle produced? II

- Field oscillates between
  - poloidal field (activity minimum)
  - toroidal field (activity maximum)

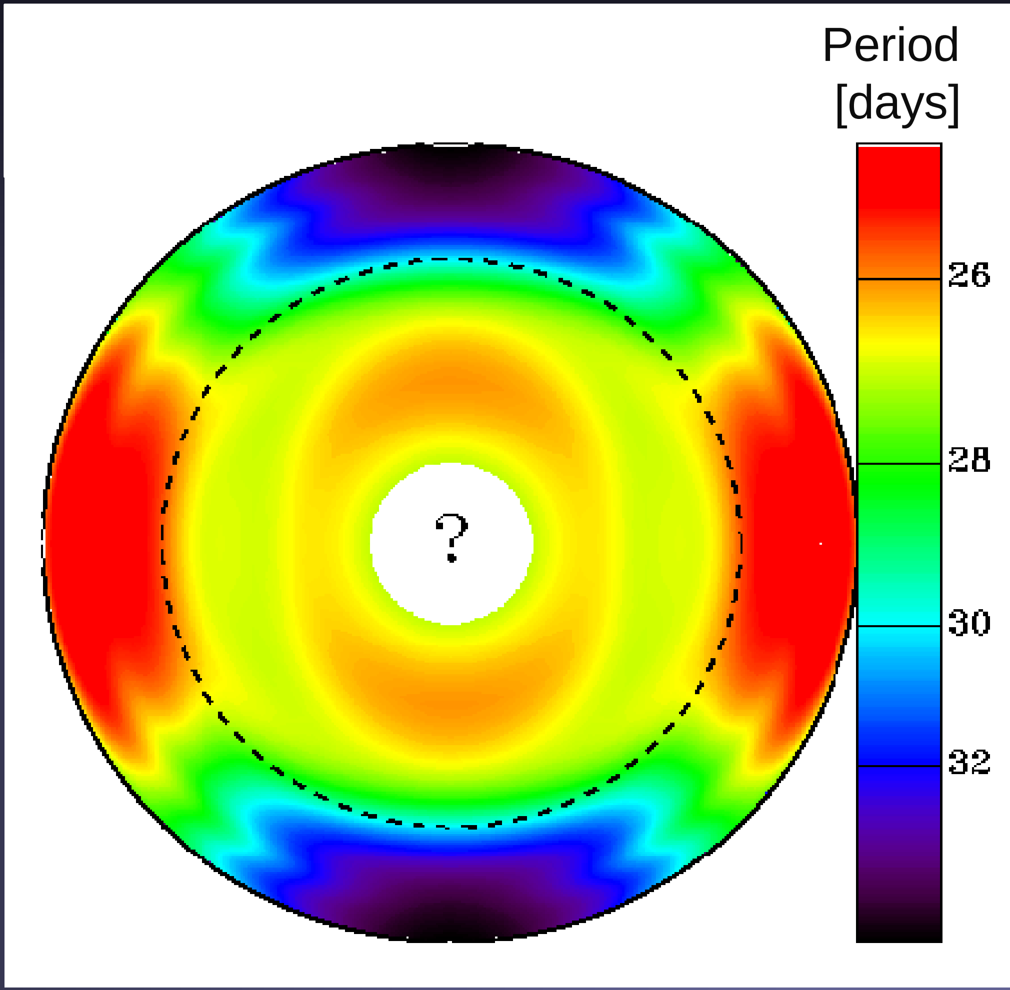




- Ingredients of Babcock-Leighton distributed dynamo
  - Winding up (strengthening) of field by differential rotation → toroidal field (Ω-effect)
  - Production of poloidal field by the Coriolis force (α-effect)
  - Transport of fields from location of dynamo to solar surface (α-effect acts during this step)
  - Transport of surface fields to the pole by meridional flow
  - Dissipation of field by turbulence and cancellation

Flows relevant to dynamo
No. 1: Rotation and differential rotation

- Only convection zone rotates differentially
- Equator rotates faster than poles
- Shear layer (tachocline) at bottom of convection zone
- Differential rotation invoked to convert poloidal field into toroidal



(MDI + GONG). (Schou et al.)

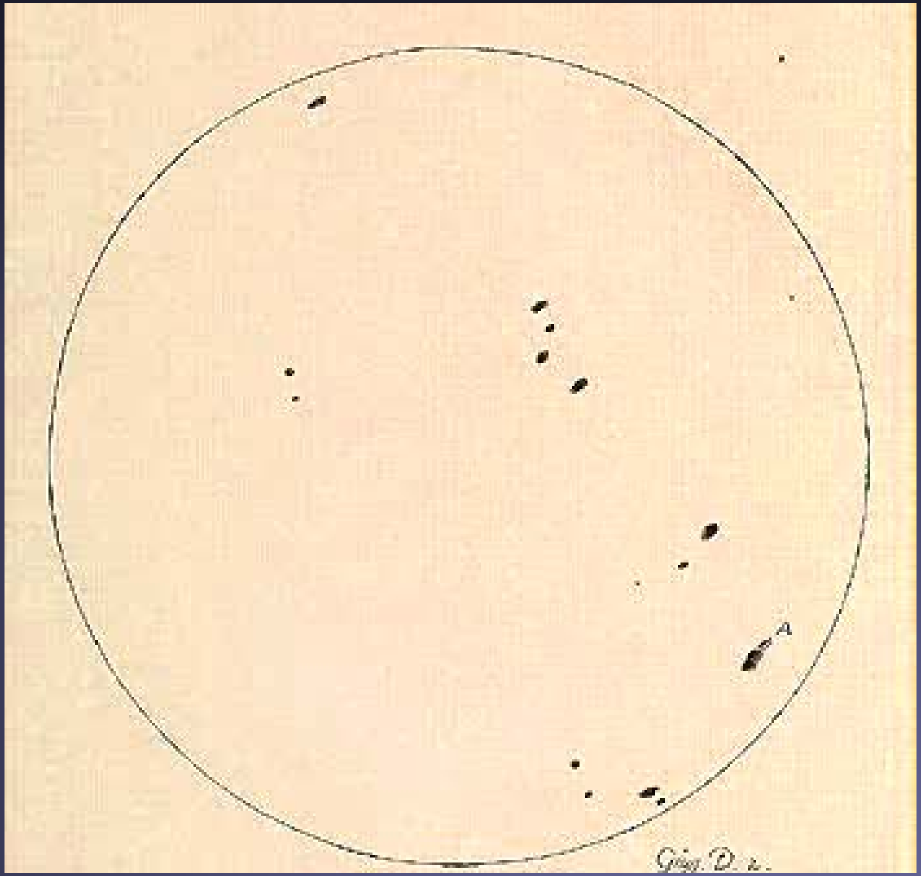
Detour: Solar rotation

Discovery of solar rotation

- Galileo Galilei and Christoph Scheiner noticed already in 1610s that sunspots move across the solar disk in accordance with the rotation of a round body

➔ Sun is a rotating sphere

- Movie based on Galileo Galilei's historical data

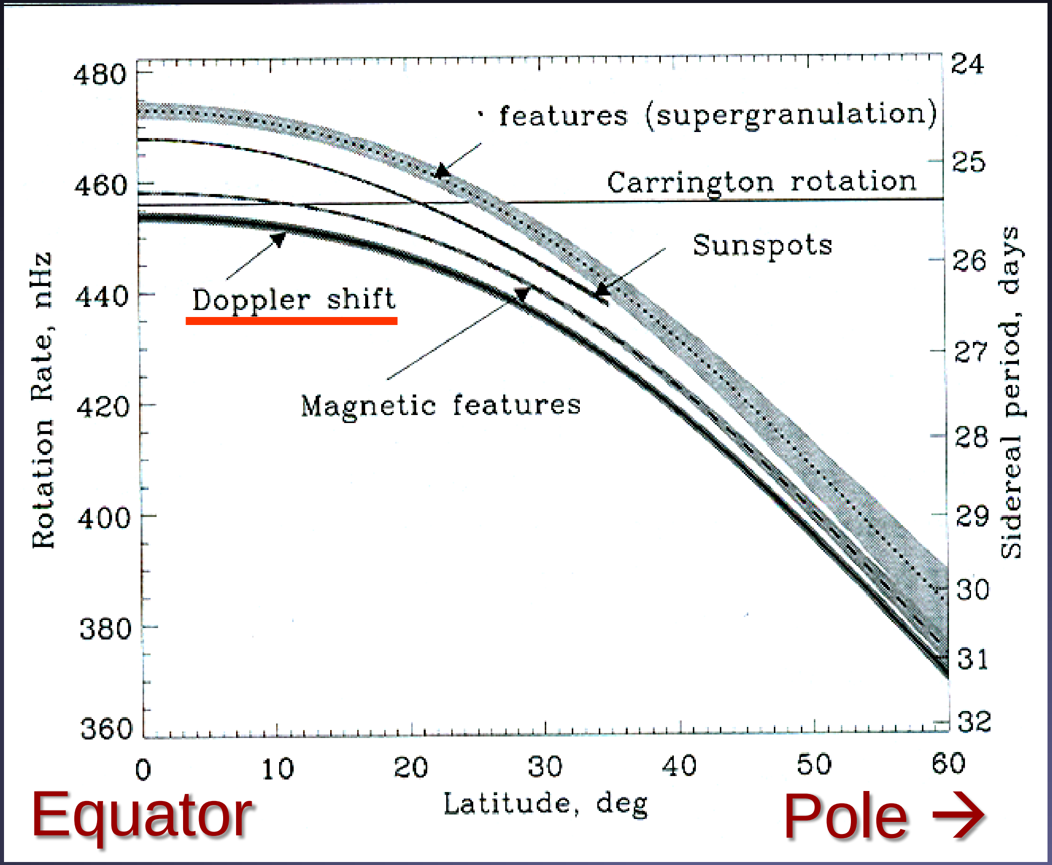


Sidereal and synodic rotation

- Synodic rotation period = rotation period as seen from Earth. I.e. the period of time it takes for a feature on the Sun to return to the same position as seen from Earth
  - the Standard synodic rotation period is the Carrington period of 27.2753 days (refers to different latitudes for features with different rotation rates)
- Sidereal rotation period = rotation period relative to the stars
  - The sidereal rotation period corresponding to the Carrington period is: 25.38 days
- Difference between the two is due to the rotation of the Earth around the Sun (Earth moves in same direction as Sun rotates ➔ Synodic period is longer than sidereal)

Surface differential rotation

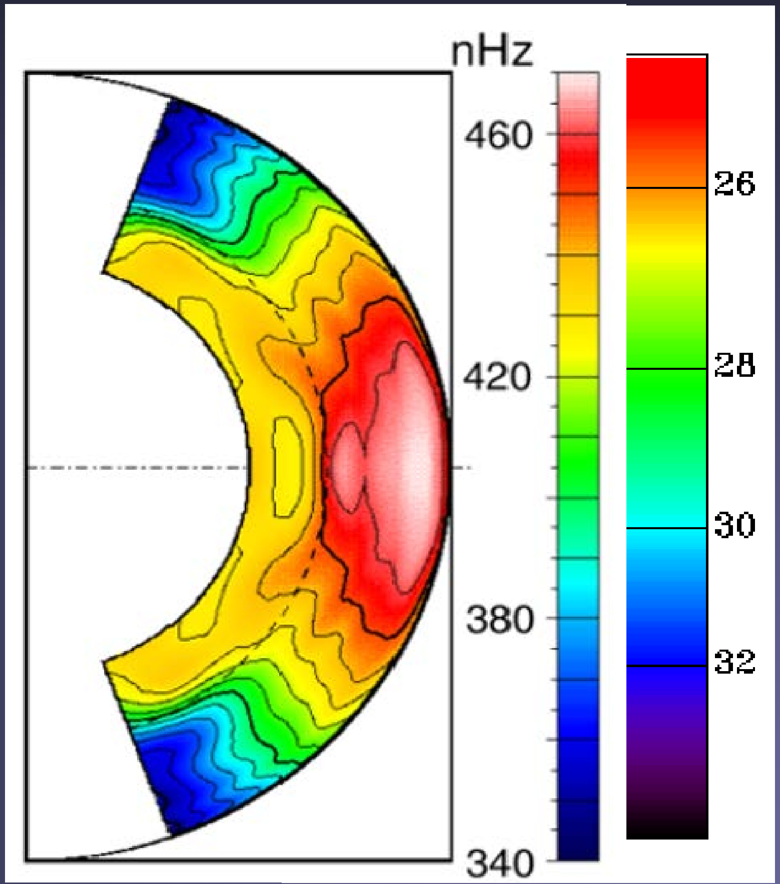
- Surface differential rotation from measurements of:
  - Tracers: Sunspots or magnetic field elements (these indicate the rotation rate of magnetic field)
  - Doppler shifts of the gas
- Poles rotate more slowly than equator
  - Coronal holes (not plotted) rotate rigidly



Variety of rotation laws: Are the tracers anchored at different depths in the convection zone?

Internal differential rotation

- Structure of internal rotation deduced through helioseismic inversion of MDI data
- Note: differential rotation in CZ, solid rotation below
- Rotation near the poles cannot at present be determined through helioseismology
- A spacecraft at high latitudes is needed ➔ Solar Orbiter



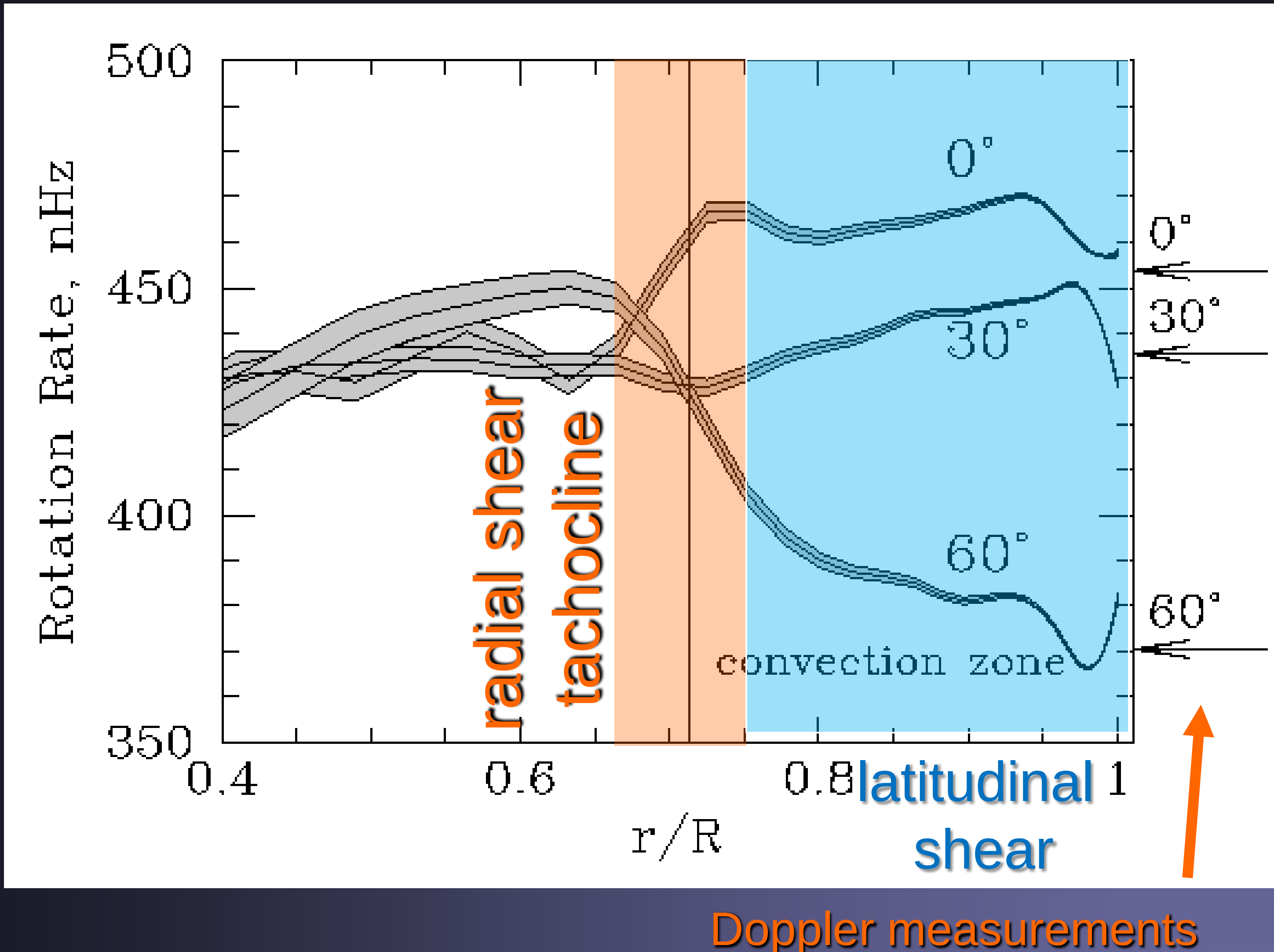
Schou et al. 1998

Latitudinal and radial differential rotation: Tachocline

Large radial gradients in rotation rate at bottom of CZ (tachocline) & also just below solar surface

Note the slight missmatch of helioseismic and Doppler measurements

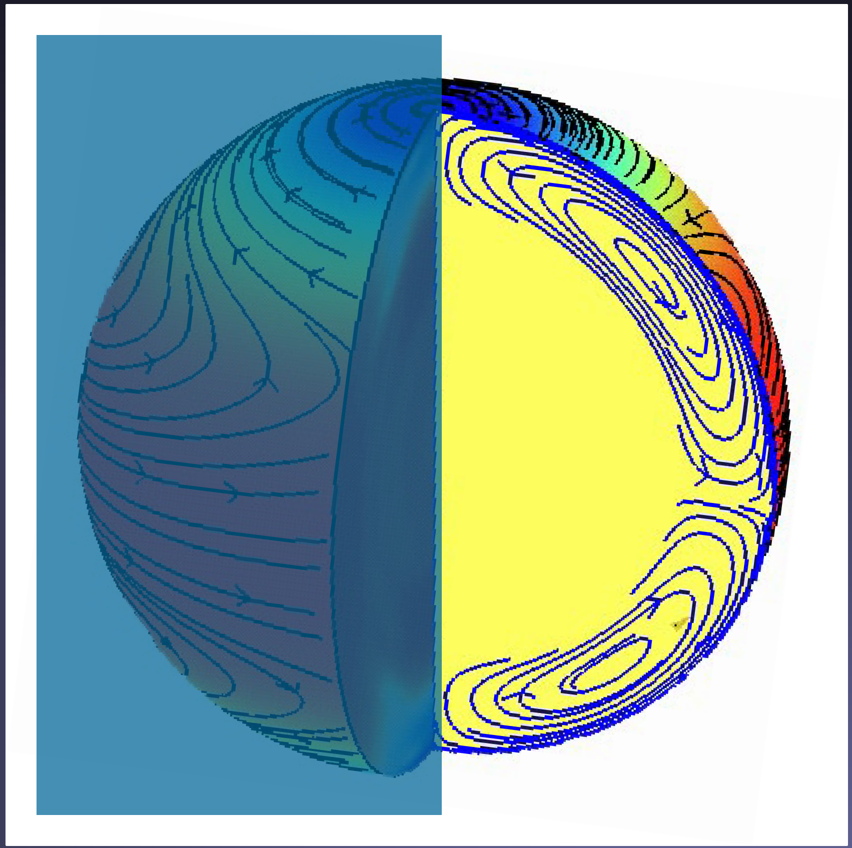
Weak radial gradient in CZ



Back to the main story

Flows relevant to dynamo
No. 2: Meridional circulation

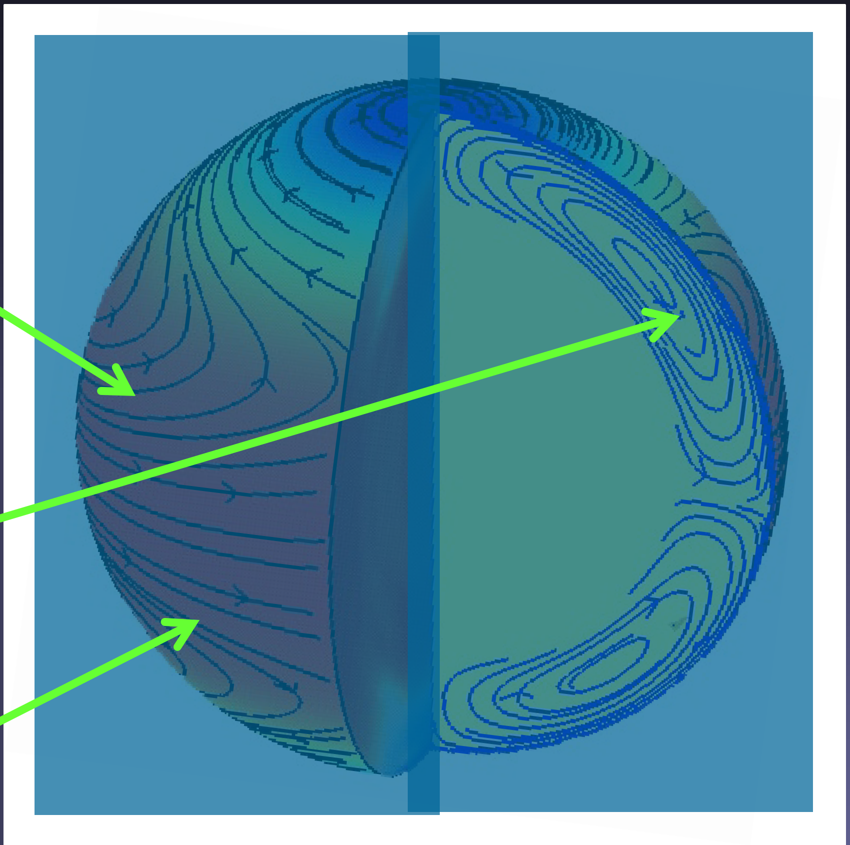
- Convection zone displays meridional circulation
- $\beta > 1$: Meridional flow moves fields at solar surface towards poles
- Following polarity of emerged field cancels with opposite polarity polar field from previous cycle



At bottom of CZ the reversed meridional flow moves field towards equator

Combined effect of differential rotation and meridional circulation

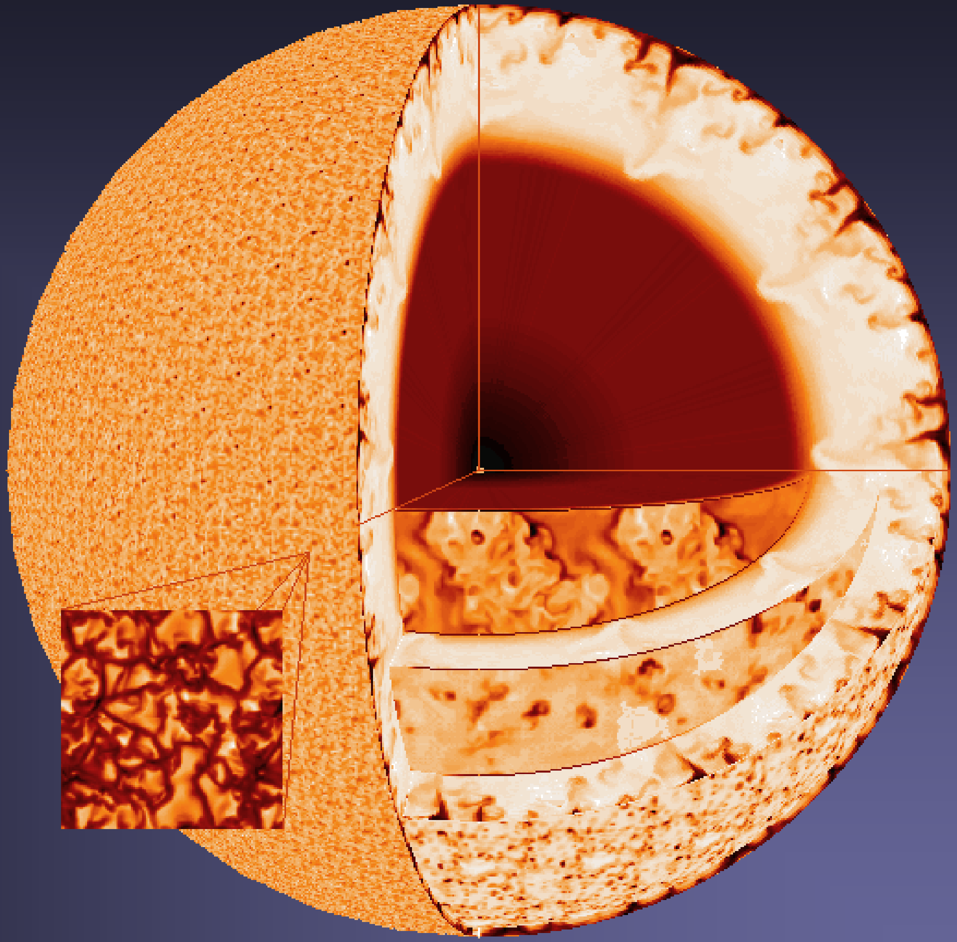
- Differential rotation: Equator (27 days) moves faster than the poles (33-36 d): colour (flow speed relative to average rotation speed)
- Meridional circulation: large convection cell taking material from equator to poles (~50 m/s): blue lines in cut-away part
- Combined flow lines: black curves (relative to average rotation of solar surface)



Field is frozen in plasma & $\beta = 8\pi p/B^2 > 1$ ➔ Flows drag fields along with them

Flows relevant to dynamo
No. 3: Turbulent convection

- Only convection zone displays turbulent convection
- In a $\beta > 1$ situation, convection causes field to carry out a random walk
- Turbulent convection leads to diffusion and finally dissipation of a complex field

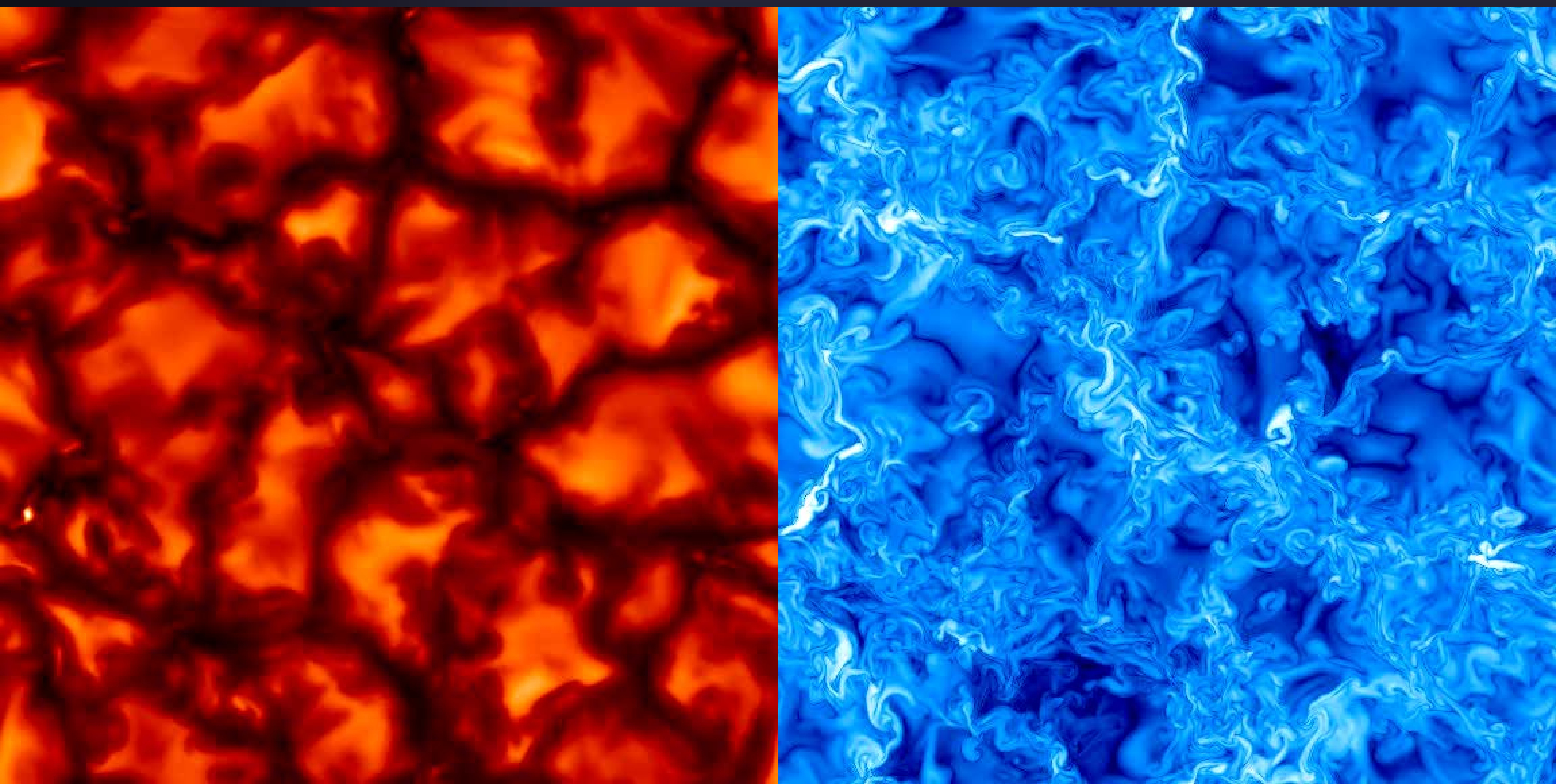


3-D MHD simulations

Vögler, Cameron, Schüssler

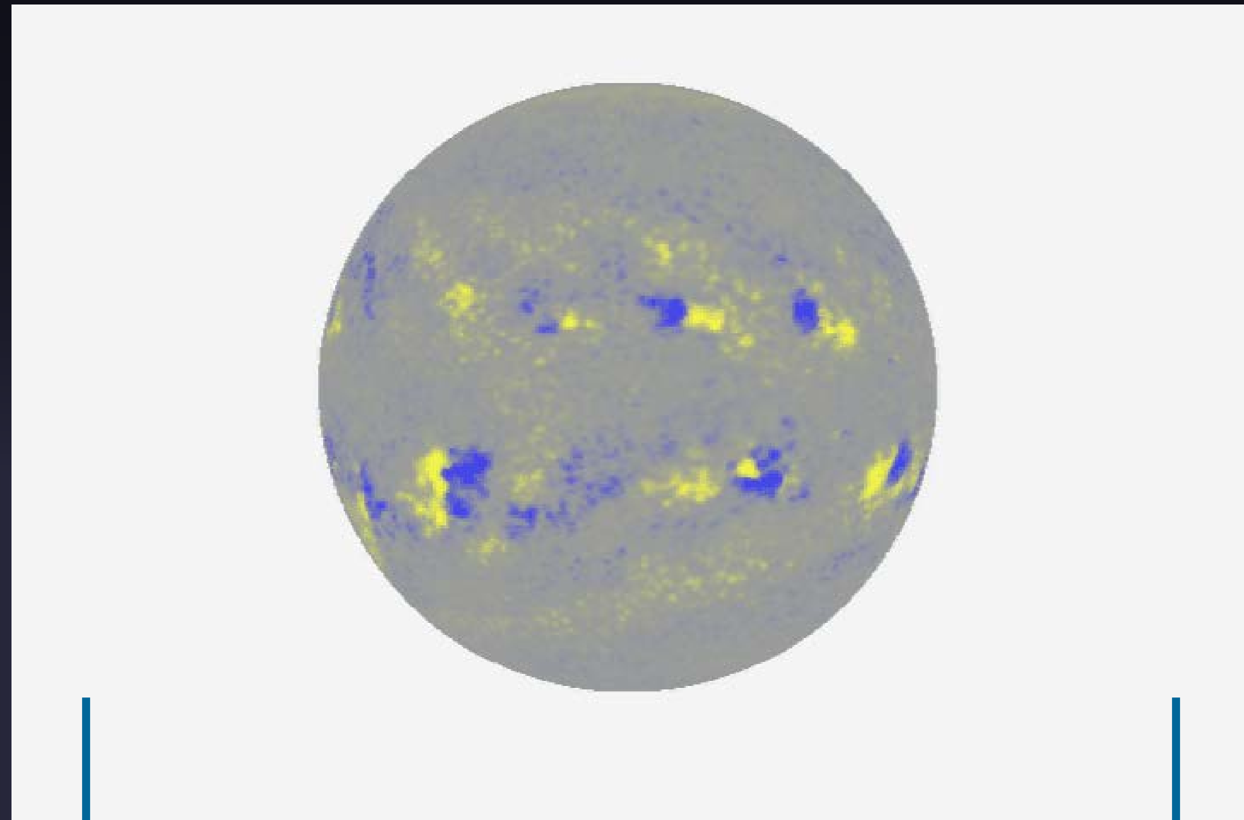
Simulations with 5 km grid: <B>=10G

Intensity log(B)



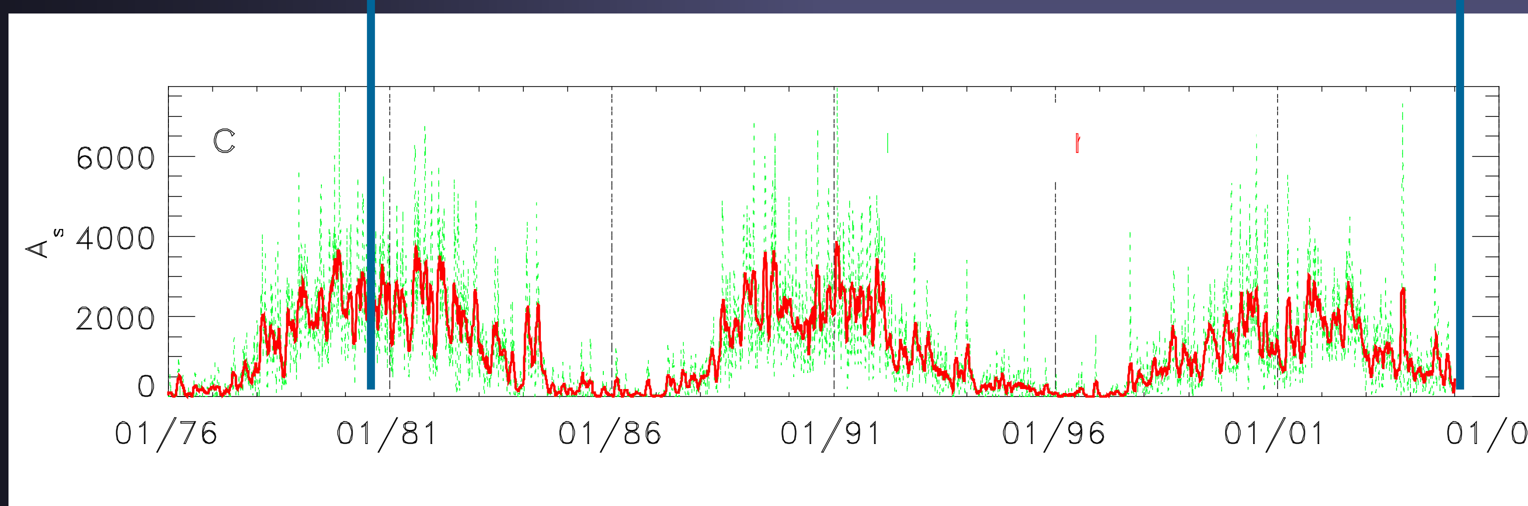
Synoptic charts and solar cycle

Synoptic chart is made with Sun's average rotation rate: features at small latitudes move faster, at high latitudes slower

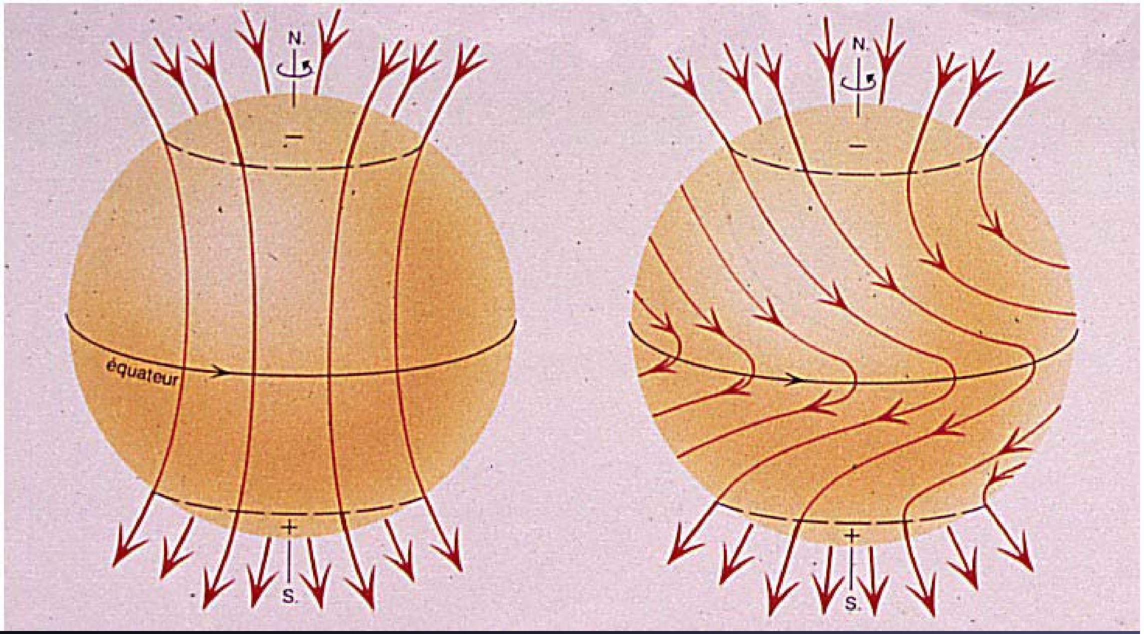


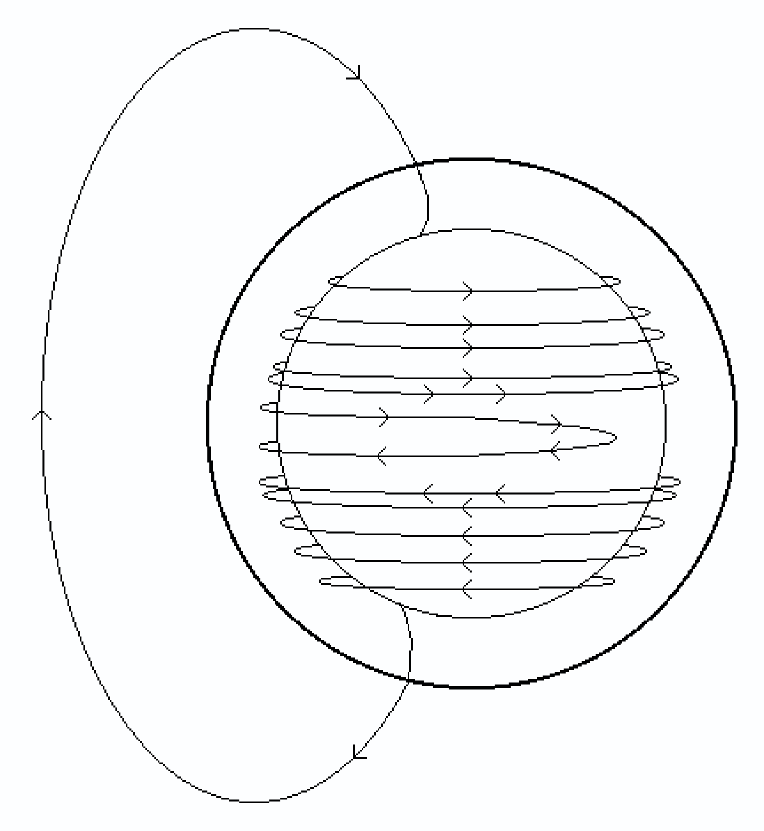
Spot areas over same time

Sunspot areas



Poloidal to toroidal field: Ω - effect



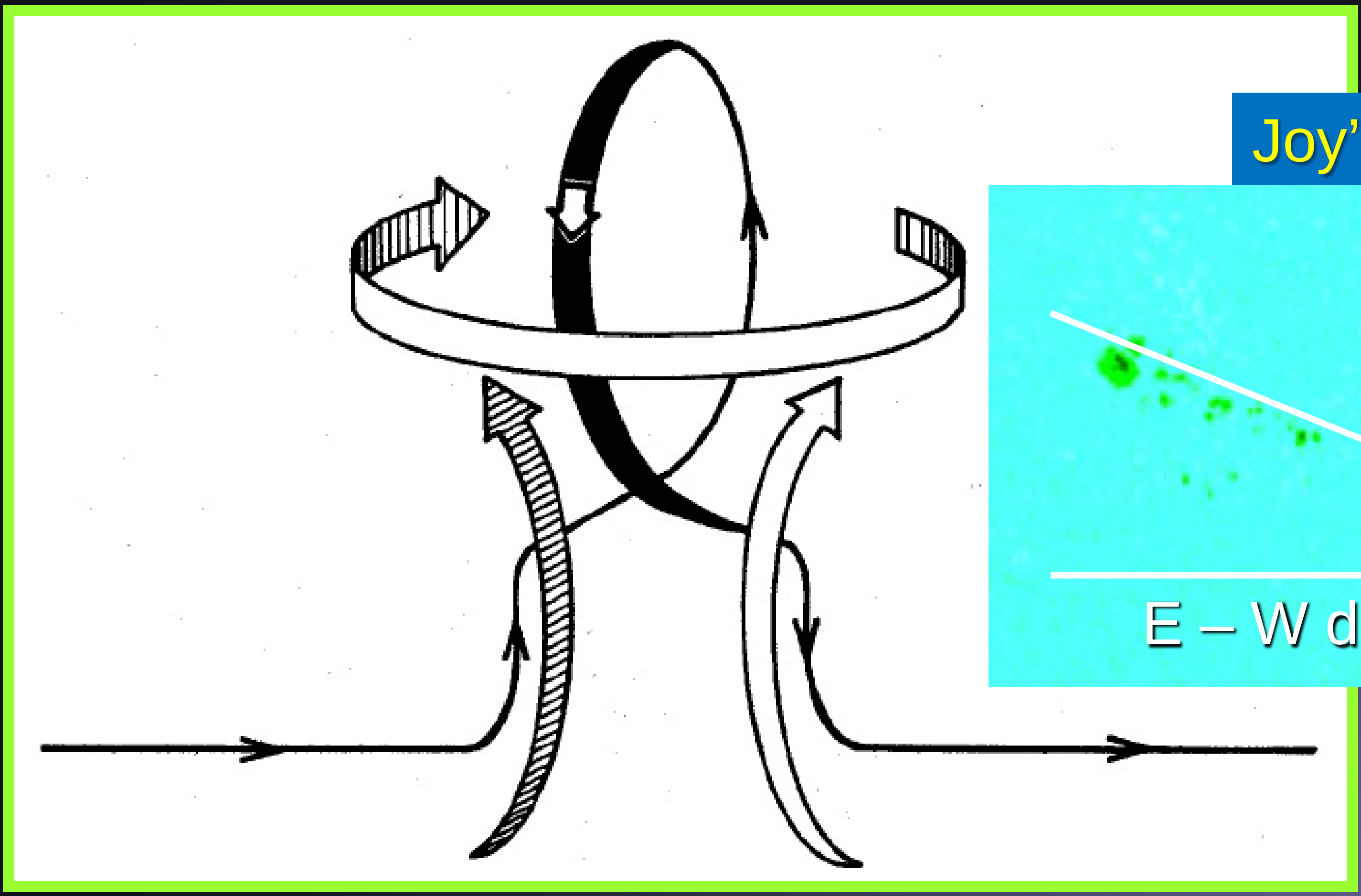


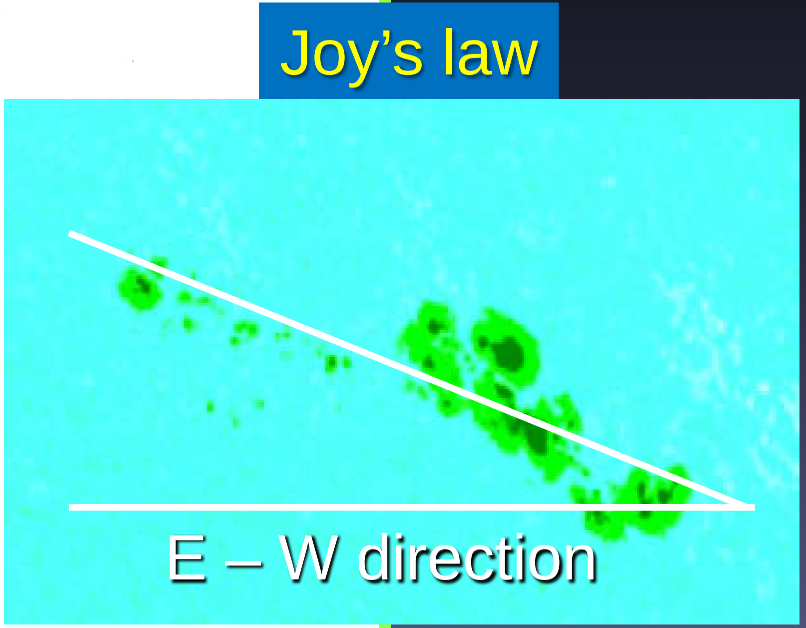
Field is wound up by differential rotation: both latitudinal and radial differential rotation can act

If $\Delta\Omega/\Omega \approx 20\%$ ➔ in 5 rotations (4.5 months) field is wound once

➔ field is wound (and strengthened) 10 times in < 4 years

Toroidal to poloidal field: α - effect





Twisting of a field line in a rising & expanding (convective) flow by action of Coriolis force (Parker, 1955). Driver is rotation

Magnetic field in the convection zone

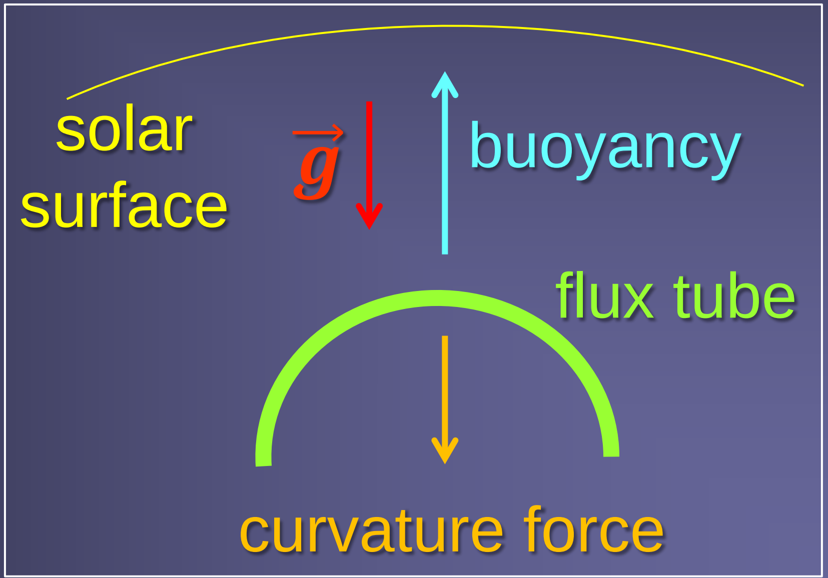
- Ω-effect winds up the magnetic field in tachocline below the CZ and produces toroidal flux tubes in pressure balance with surroundings:

$$\frac{B_i^2}{8\pi} + P_i = P_e + \frac{B_e^2}{8\pi}, \qquad i = \text{internal}, \qquad e = \text{external}$$

- If $B_i > Be$ and $T_i = Te$, then $\rho_i < \rho_e$ (ideal gas law) ➔ intense B-fields are evacuated and buoyant relative to surroundings (Parker instability)

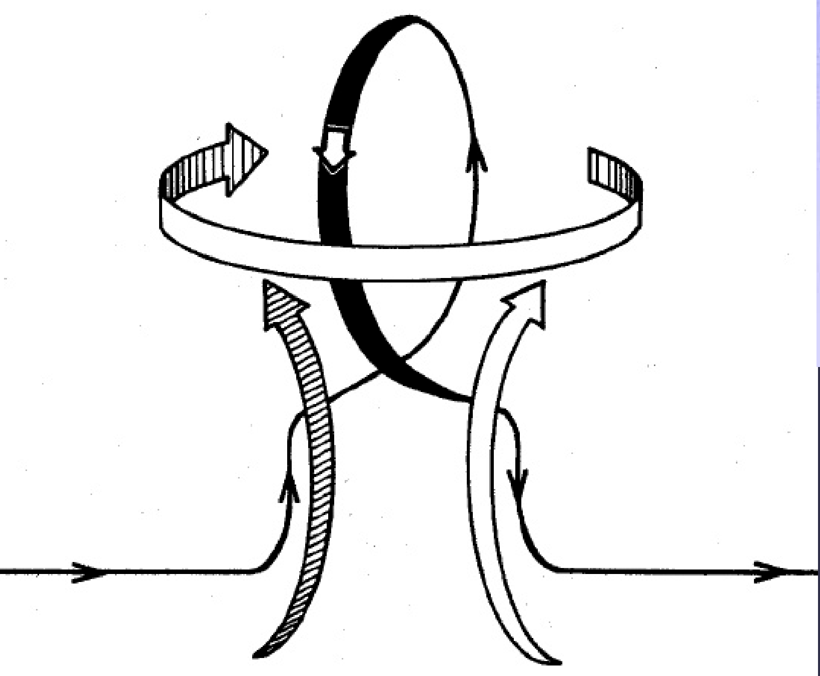
- Buoyancy dominates over curvature force for $B \geq 10^5$ G

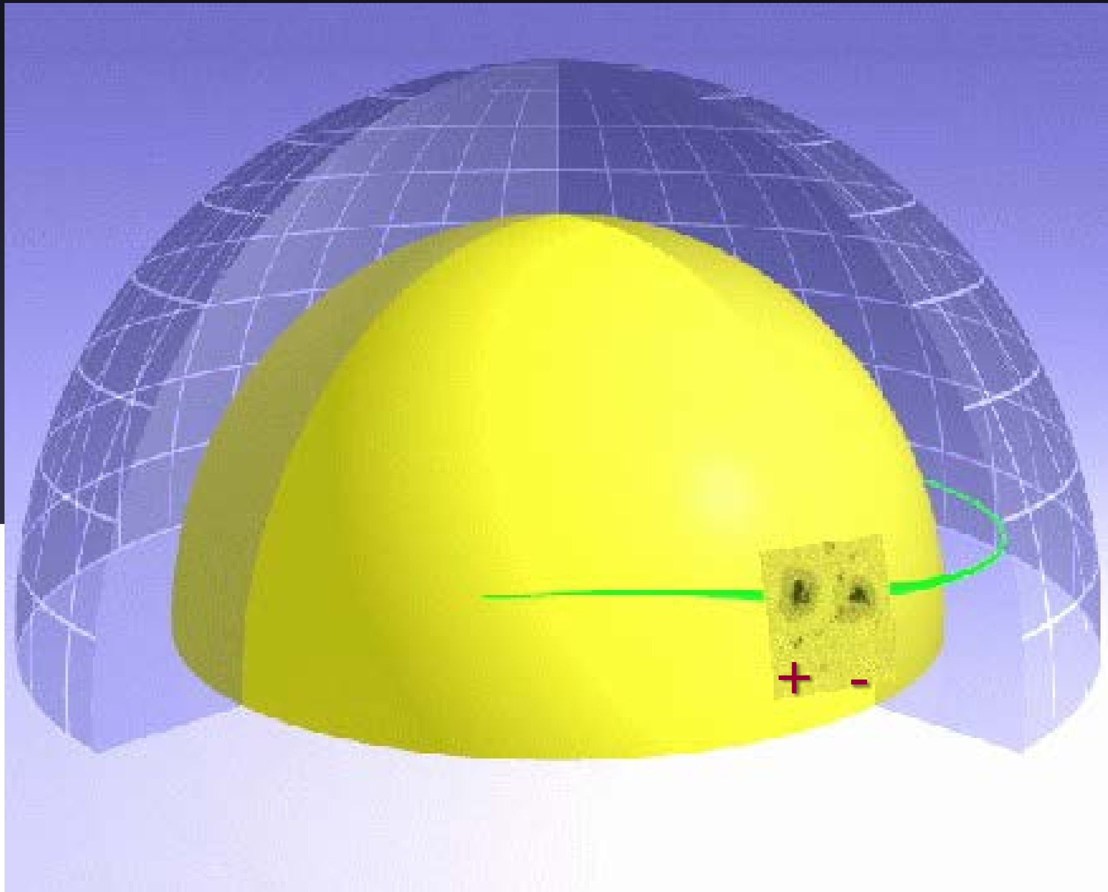
- Flux tubes form loops that rise & eventually reach solar surface



Emergence at surface

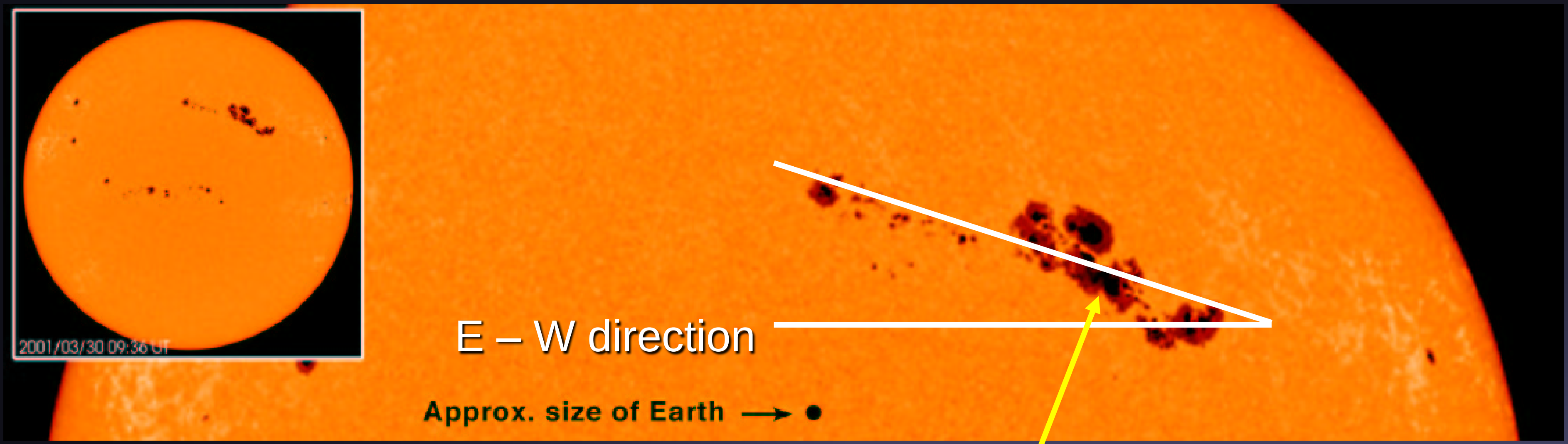
- Active region lies at intersection of flux tube with solar surface
- Each polarity corresponds to a footpoint of the loop
- Loop rises on into corona

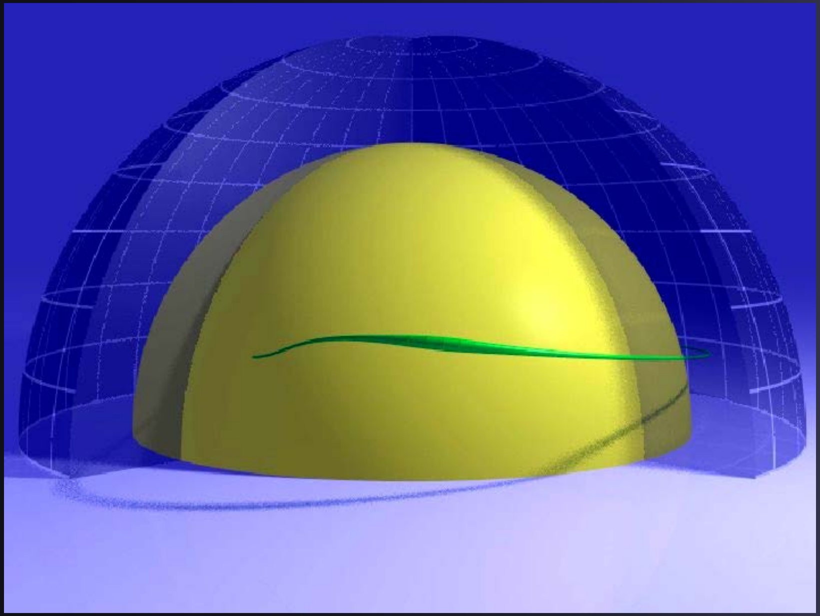




Coriolis force causes rising tube to writhe & get a poloidal component

Tilt angle of sunspot groups





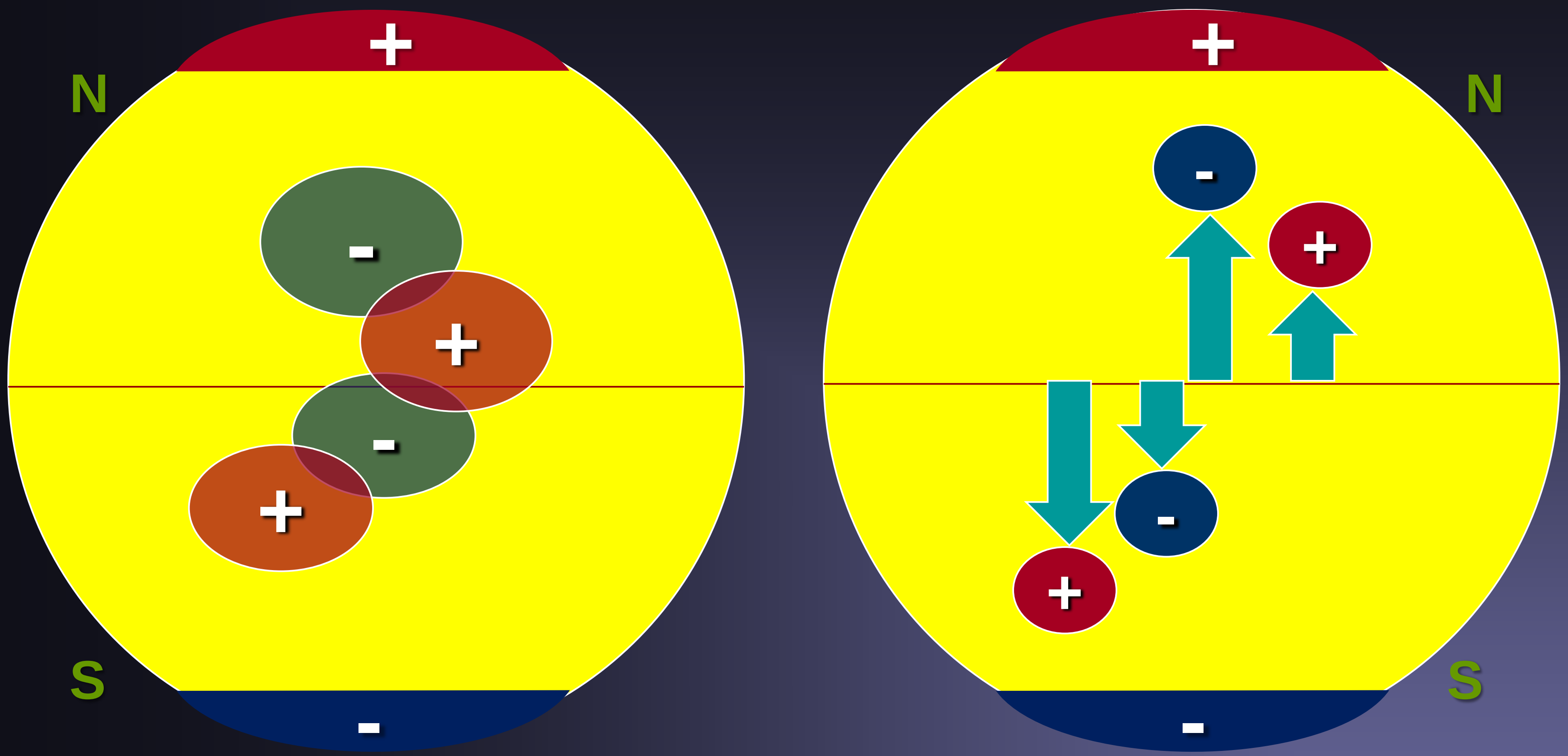
Following spots closer to pole

Tilt angle $\gamma \propto \sin(\lambda)$

("Joy´s law")

Here λ = latitude

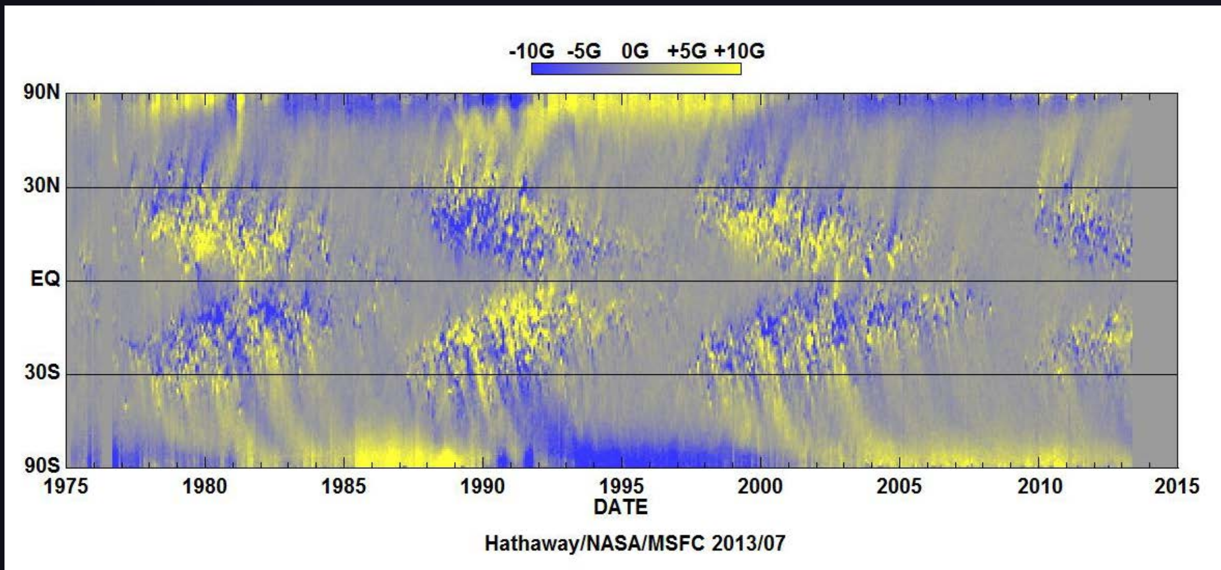
Reversal of poloidal (meridional) field



Diffusion: cancellation in AR & across equator

Meridional circulation moves AR field to the poles

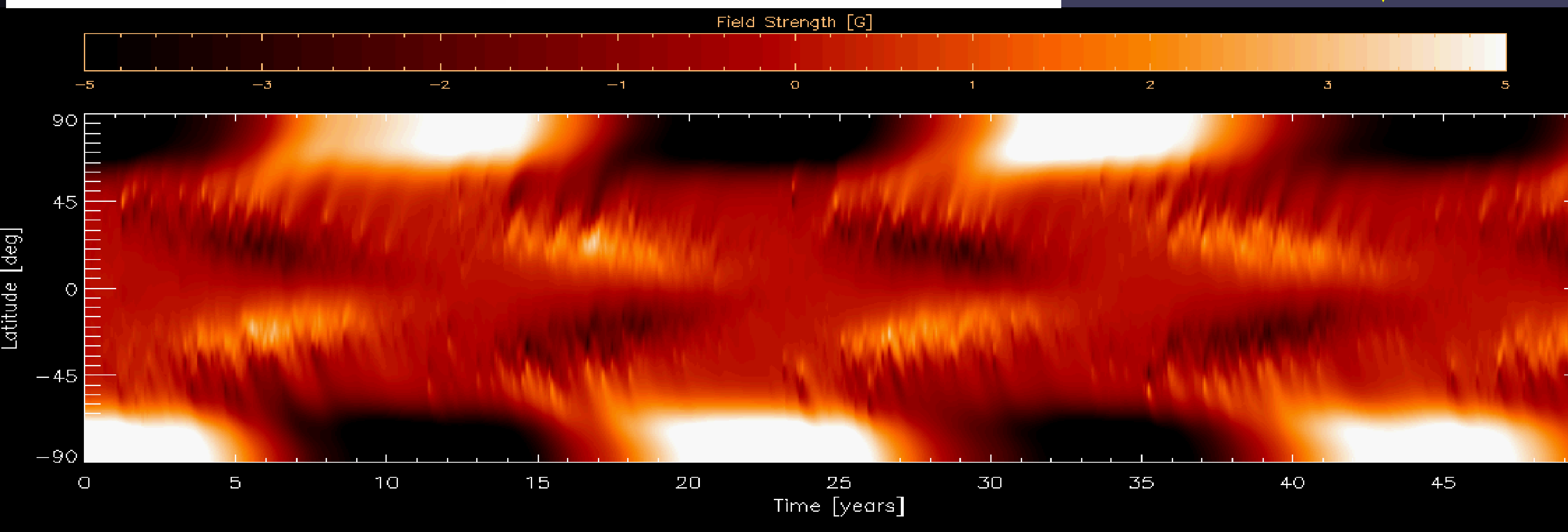
Time-latitude diagram: obs. & model



← Observation

Flux transport model

(Baumann et al. 2004)



Where is solar dynamo located?

- Due to buoyancy instability in convectively unstable layers, concentrated magnetic fields rise towards solar surface

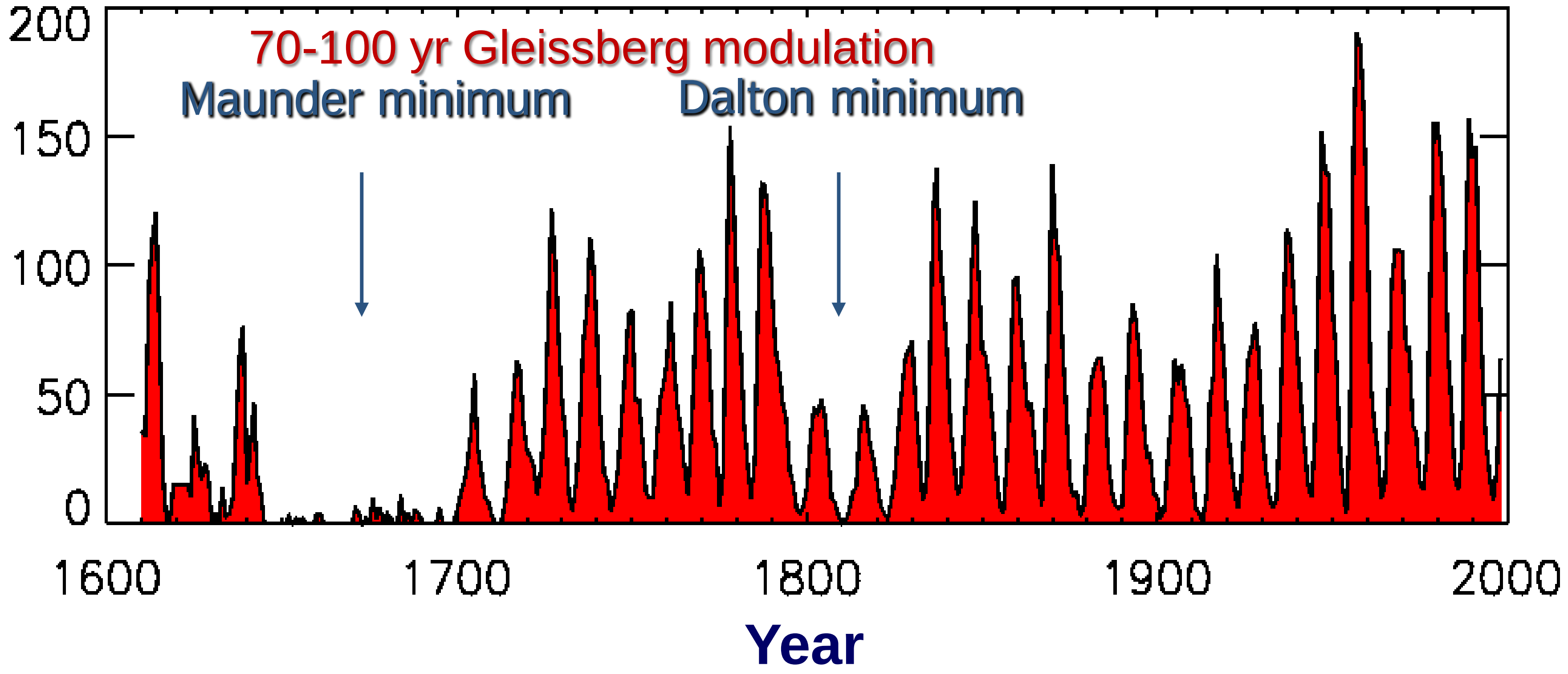
➔ Field must be stored below convection zone, but flux cannot escape from radiative interior (convectively stable)

➔ Dynamo is located in overshoot layer below CZ

- Overshoot layer is thick, $H_p \approx 10^4$ km ➔ sufficient magnetic flux can be stored to feed solar cycle
- This layer also experiences the largest shear in rotational velocity, so that the Ω-effect should be large there
- Note that there are also alternatives: thus, turbulent pumping can also keep the field trapped inside the convection zone (Nordlund)

Longer term variations in activity: The Modulated Sunspot Cycle

Sunspots provide longest running record of solar activity

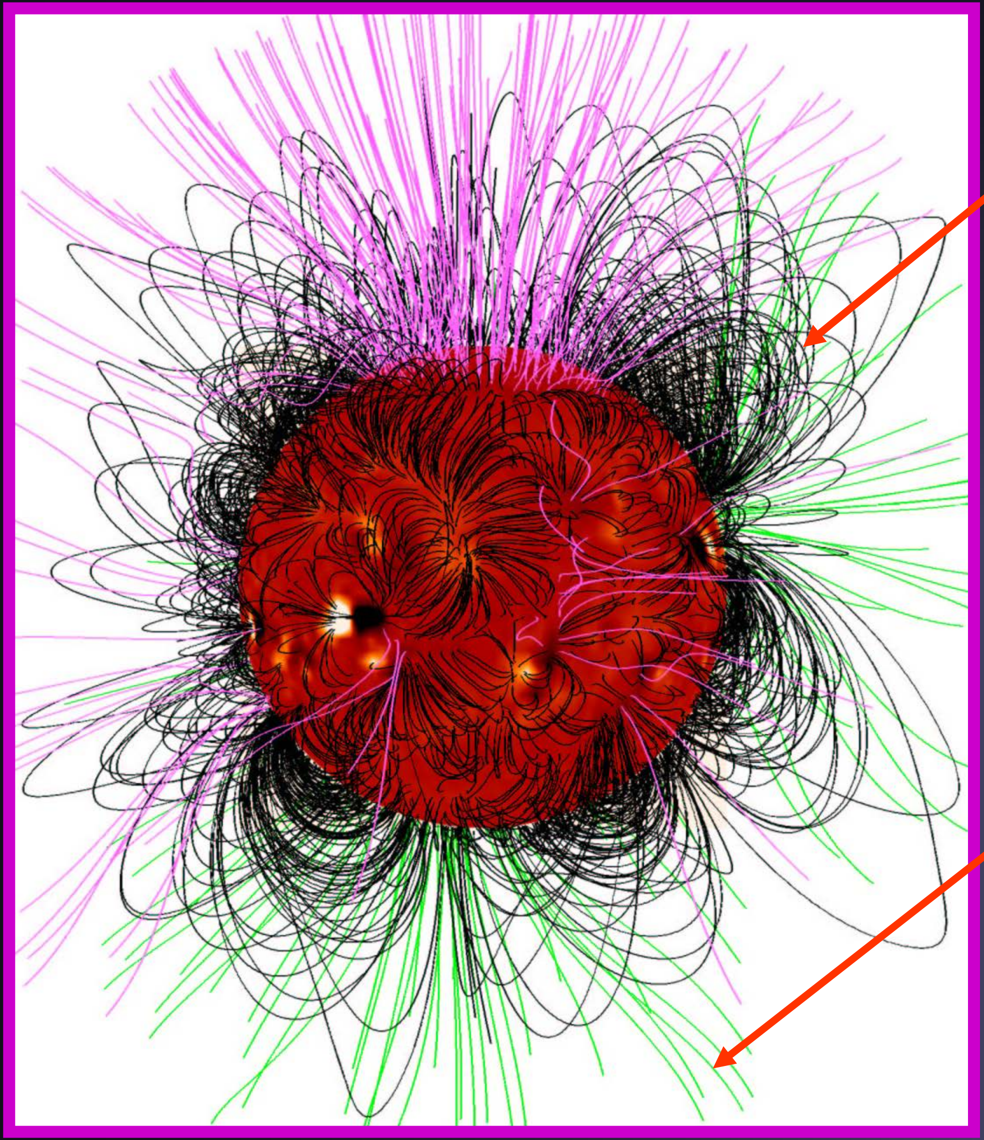


The 11-year solar activity cycle shows a long-term amplitude & length variation with a significant non-cyclic component ➔ non-linearity in dynamo

Long-term evolution of magnetic field

- Sunspots are a proxy of magnetic field, but do not capture many of its effects (e.g. no spots in quiet Sun; spots disappear at activity minimum, while field does not).
- Problem: regular B-field measurements available since 1950s, while sunspot number, counted with a simple white-light telescope, available since 1610.
- Required:
  - alternative record of solar magnetic field, e.g. through its influence of the Earth’s field
  - Model describing B-field evolution, for known sunspot No.

Open magnetic flux



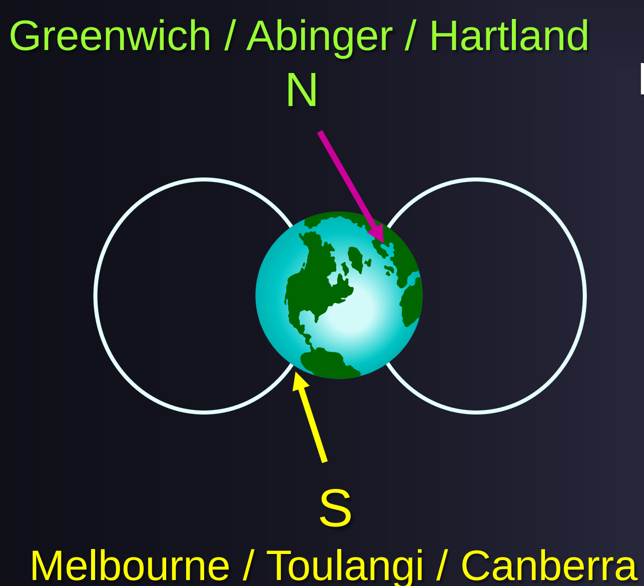
Closed flux: Most of the solar magnetic flux returns to the solar surface within a few $R_\odot$

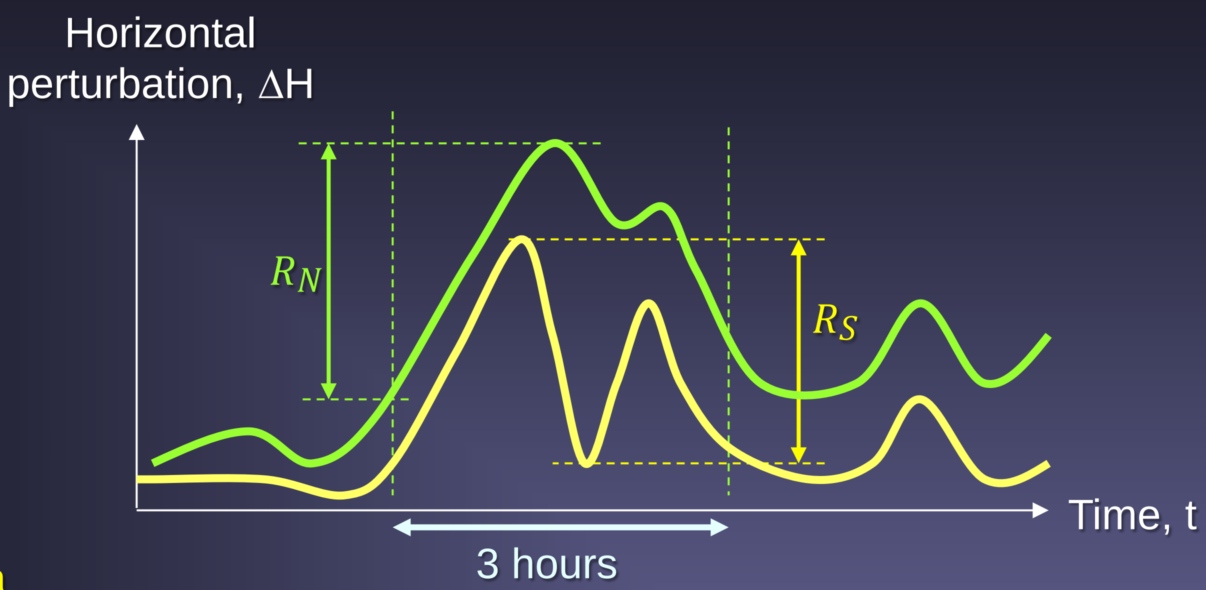
Open flux: A small part of the Sun's total magnetic flux connects as "open flux" to interplanetary space.

Variations in the solar open flux produce fluctuations in the geomagnetic field

The aa geomagnetic index

aa index: measure of Sun's influence on geomagnetic field: contains information on the Sun's open magnetic flux



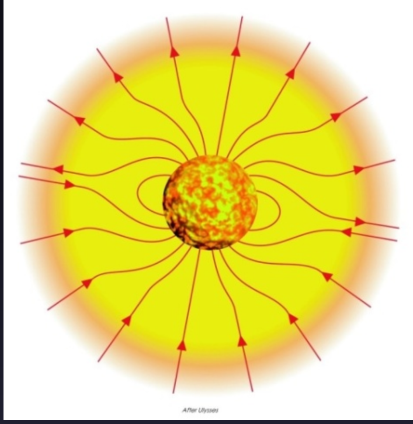


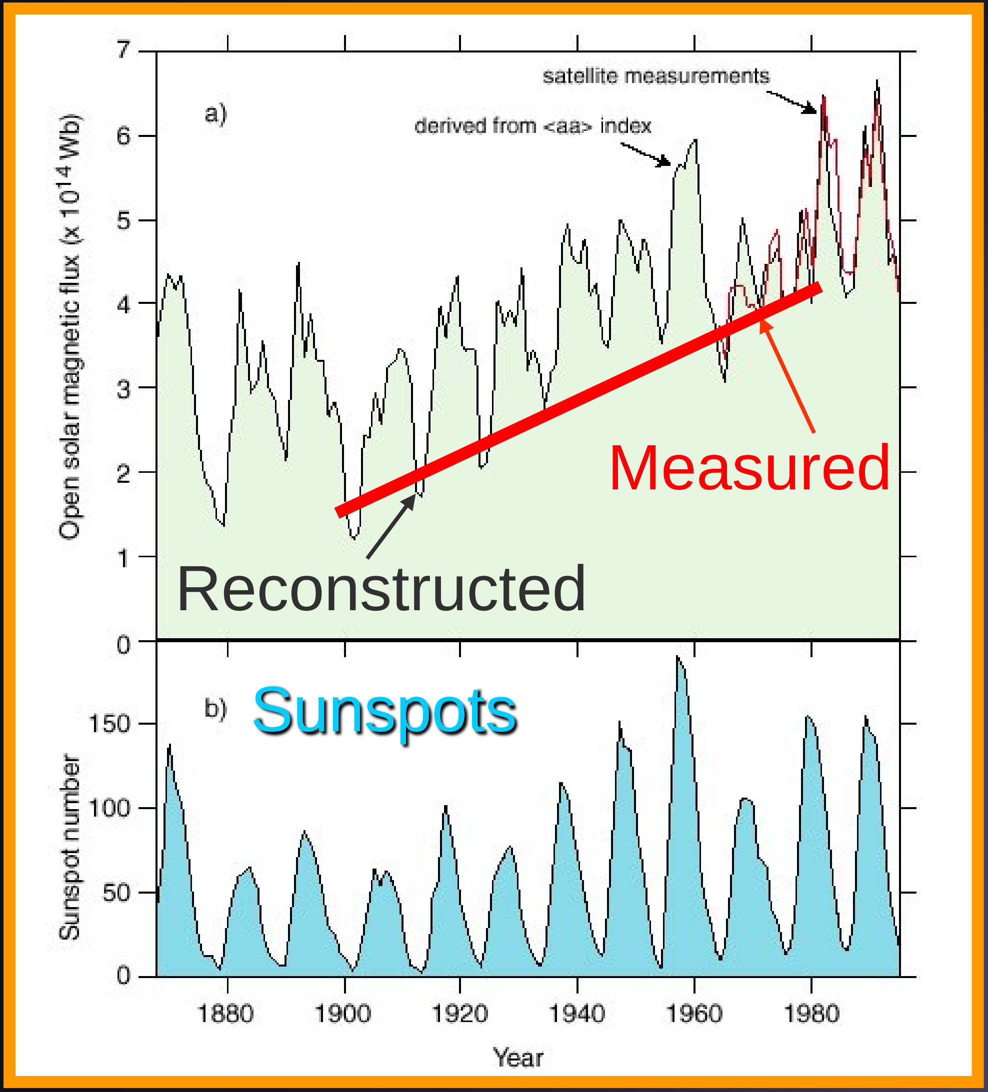
For each 3 hour interval the ranges of ΔH, R_N and R_S are converted to aa_N and aa_S taking into account location of magnetometer

$$\boxed{aa = (aa_N + aa_S)/2}$$

Mayaud, 1976

Evidence for secular change: Interplanetary magnetic field





- Reconstructed from geomagnetic aa index
- Interplanetary B-field (≈ Sun's open flux; Ulysses) approx. doubled during the last century

➔ What is solar origin of this trend?

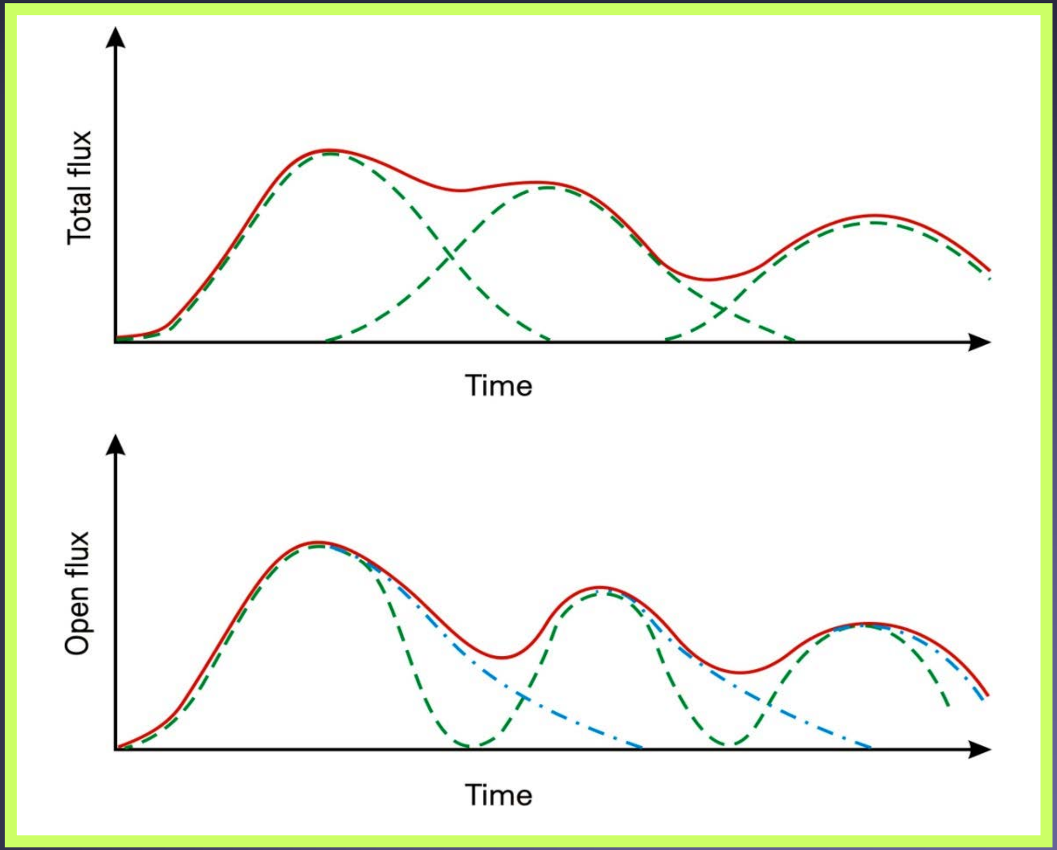
➔ Does total magnetic flux show similar trend?

Lockwood et al. 1999

Rouillard et al. 2007

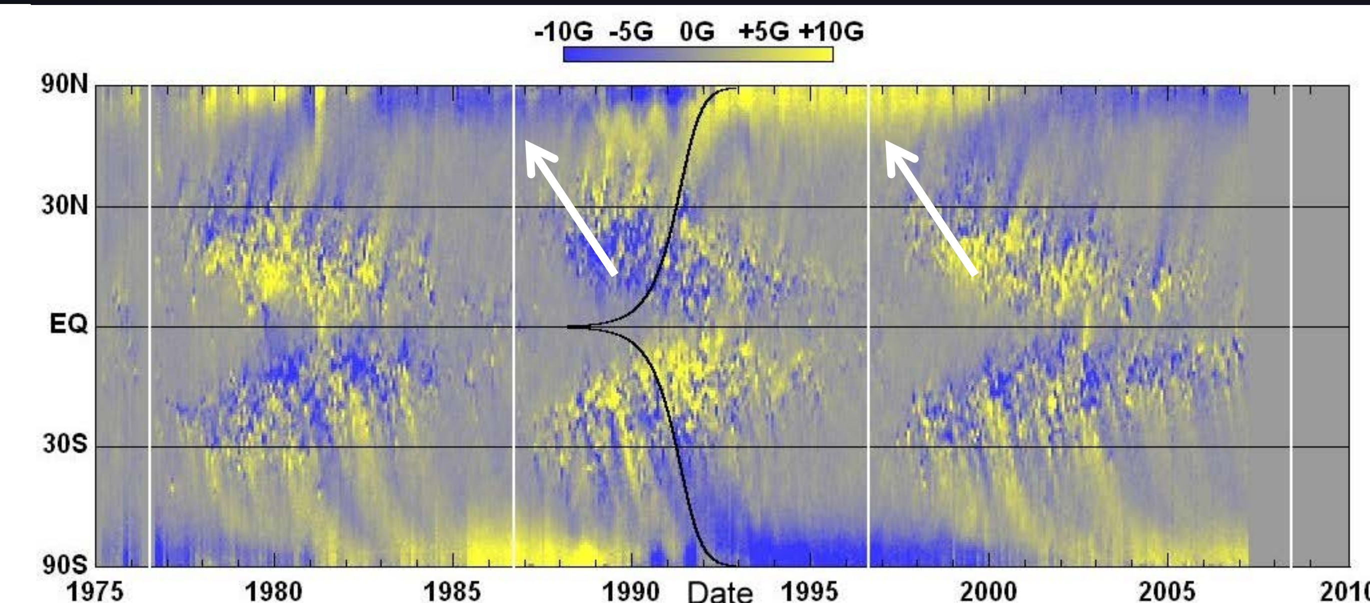
Secular change of Sun's magnetic flux: a mechanism

- Underlying concept: overlapping solar cycles (Wilson et al. 1991: extended solar cycle). Overlap can be produced by
  - Emergence of magn. flux of new cycle (e.g. in ephemeral regions) before end of previous cycle (K. Harvey 1992)
  - Long lifetime (decay time) of open (and closed) magnetic flux



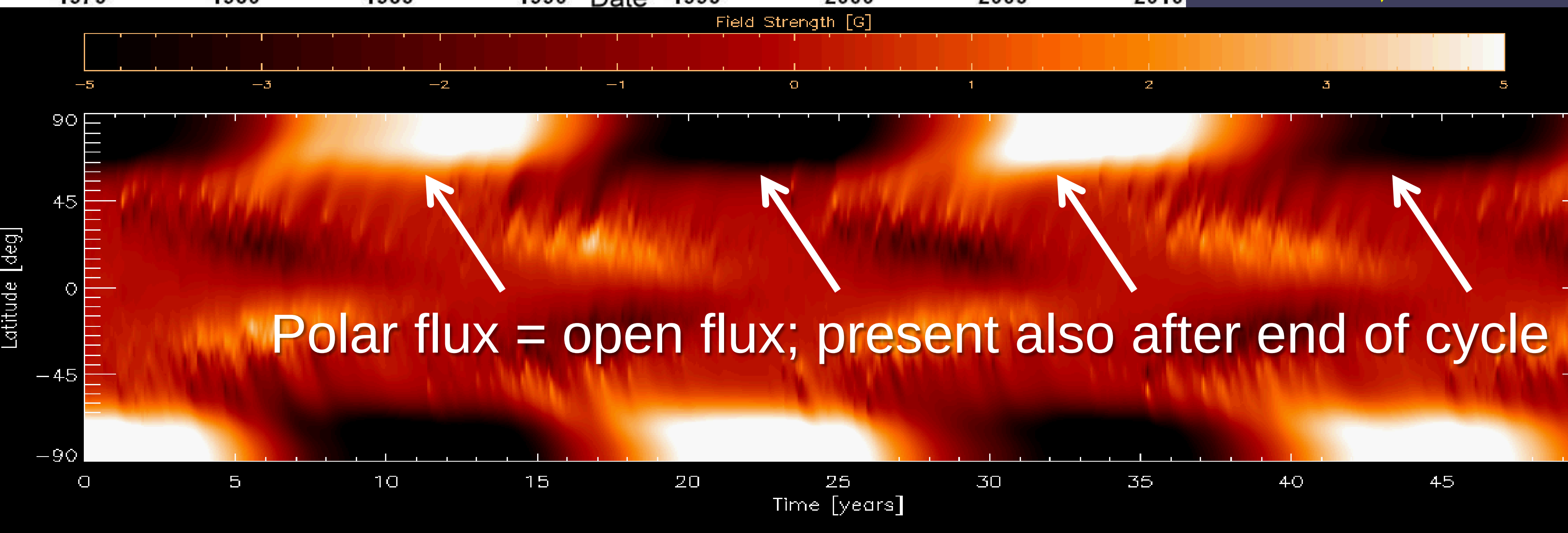
Solanki et al. 2000, 2002

Time-latitude diagram: obs. and model



Observation

Flux transport model
(Baumann et al. 2004)



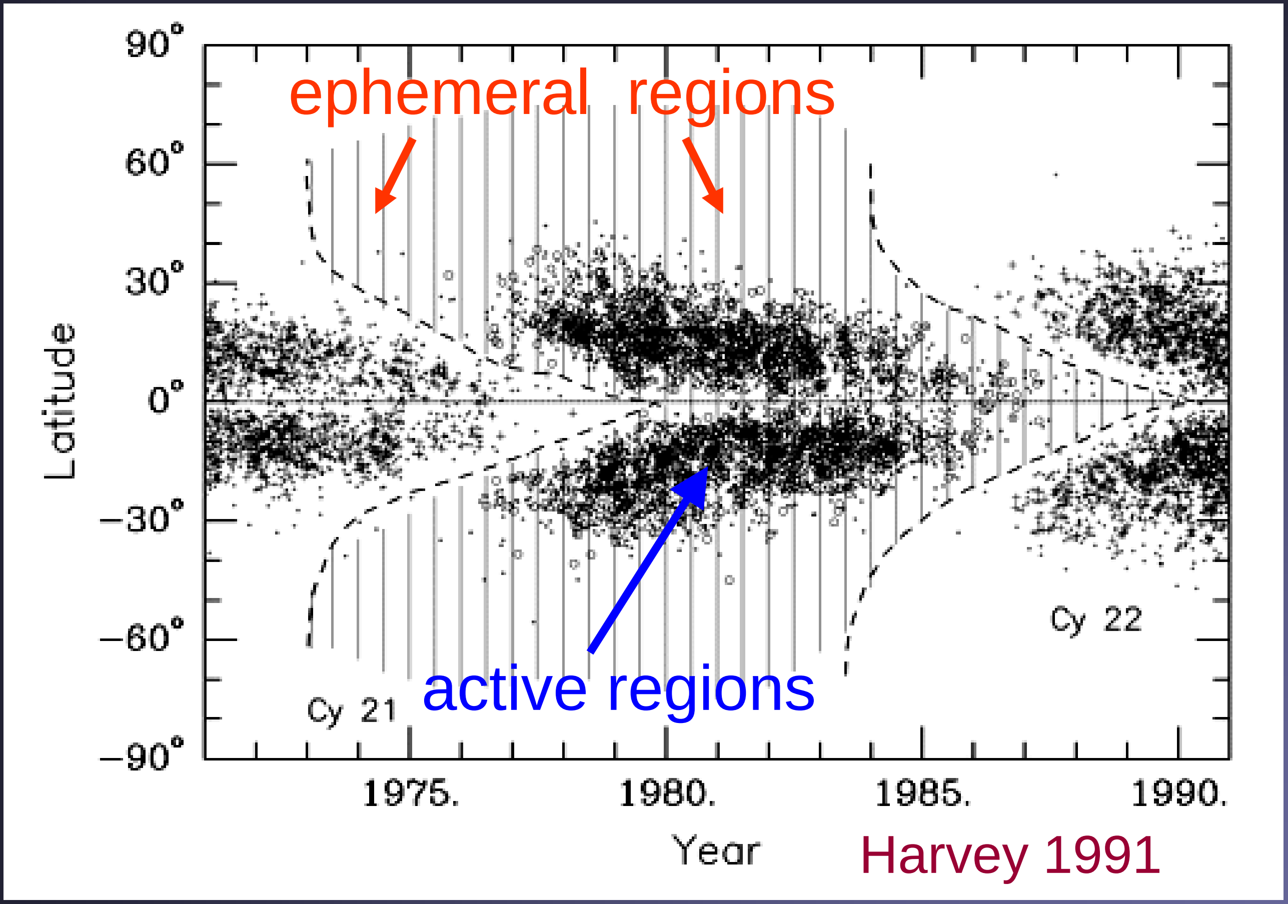
Polar flux = open flux; present also after end of cycle

Ephemeral Regions: Extended Cycle

Reminder: Ephemeral active regions are small magnetic bipoles. They emerge in large quantities, bringing 100 times more magnetic flux to solar surface than the much larger active regions

In a given solar cycle ephemeral regions emerge over a longer period of time than active regions → overlap between solar activity cycles

(Harvey, 1993, 2000), Hagenaar et al. 2001, 2003)



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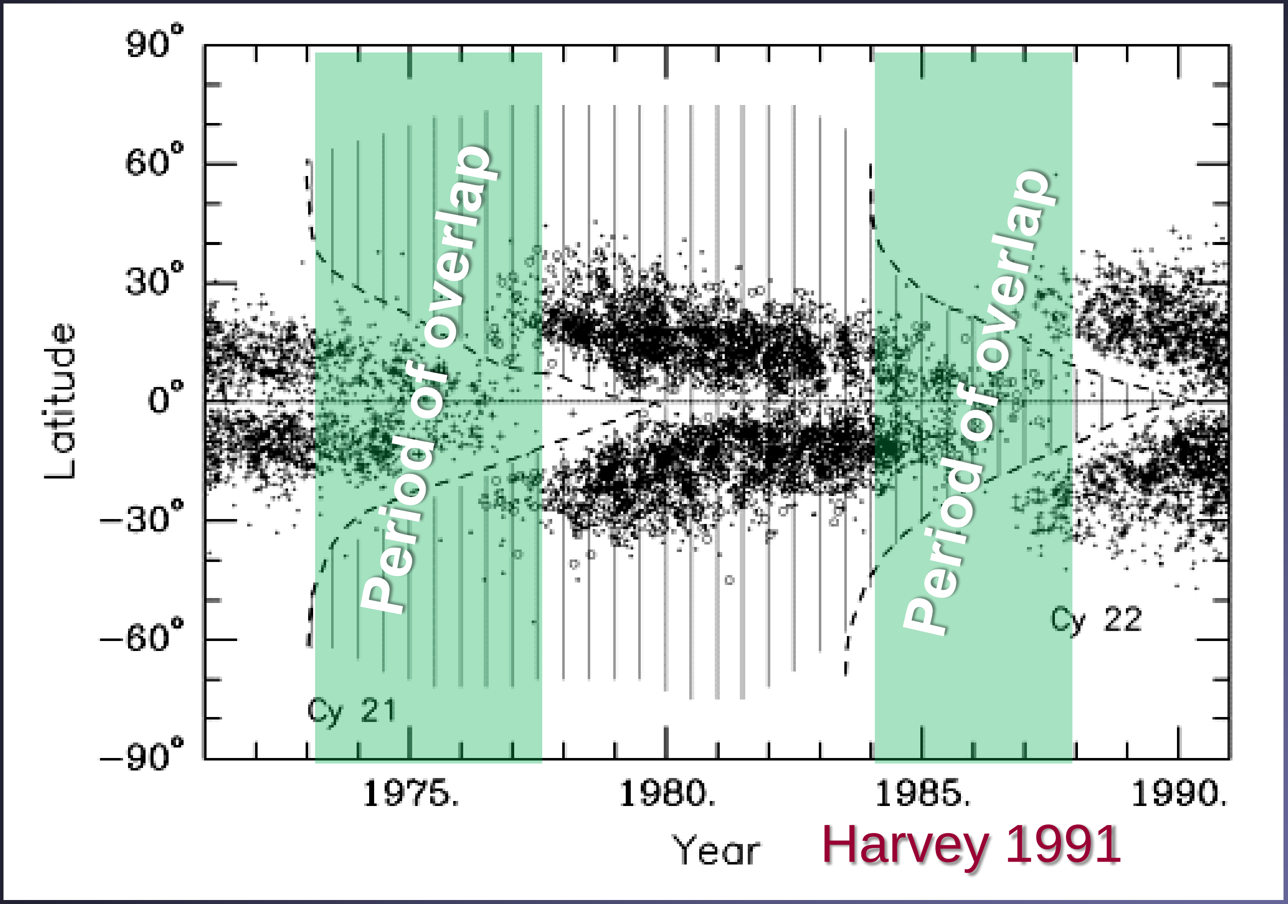
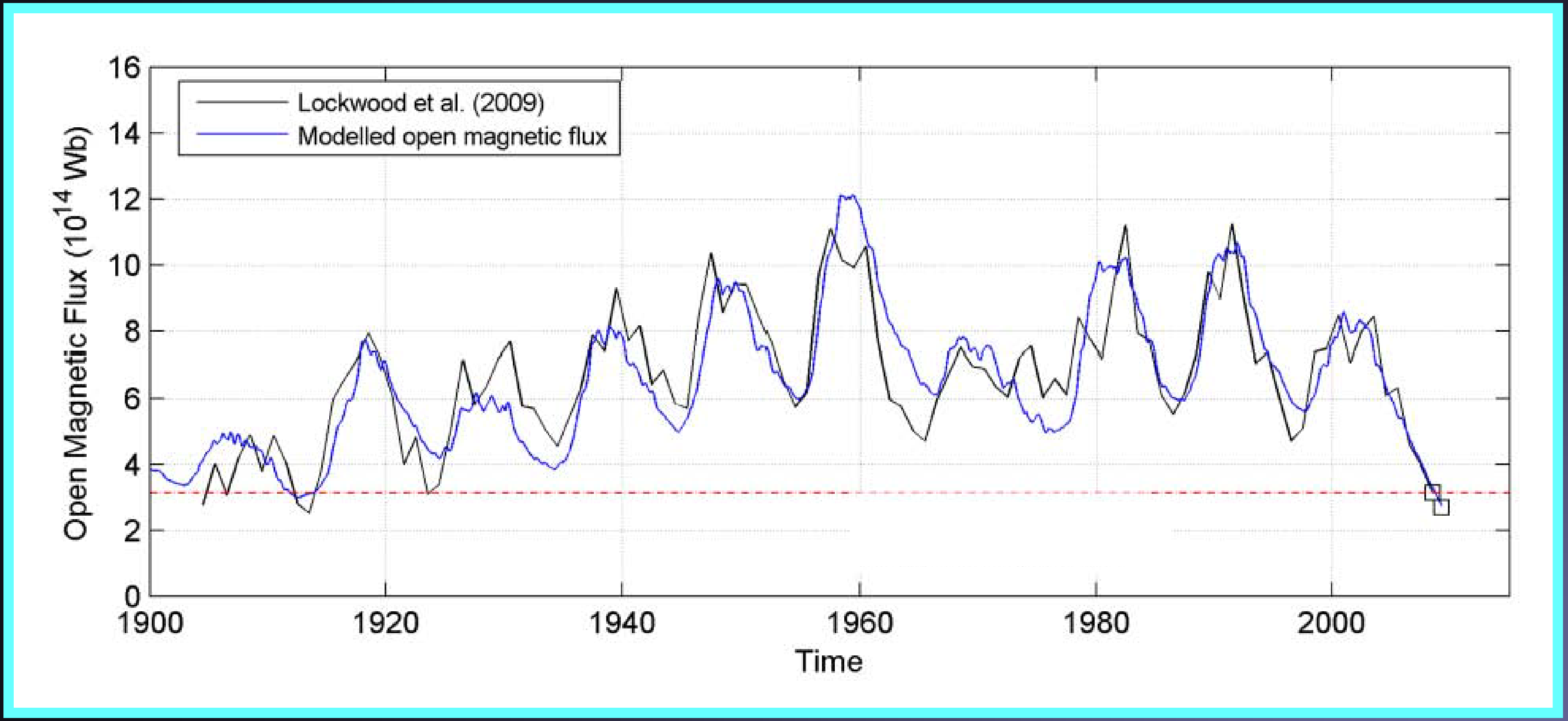


Comparison of modelled and reconstructed open flux



Vieira & Solanki 2010

Which dynamo feeds quiet Sun flux?

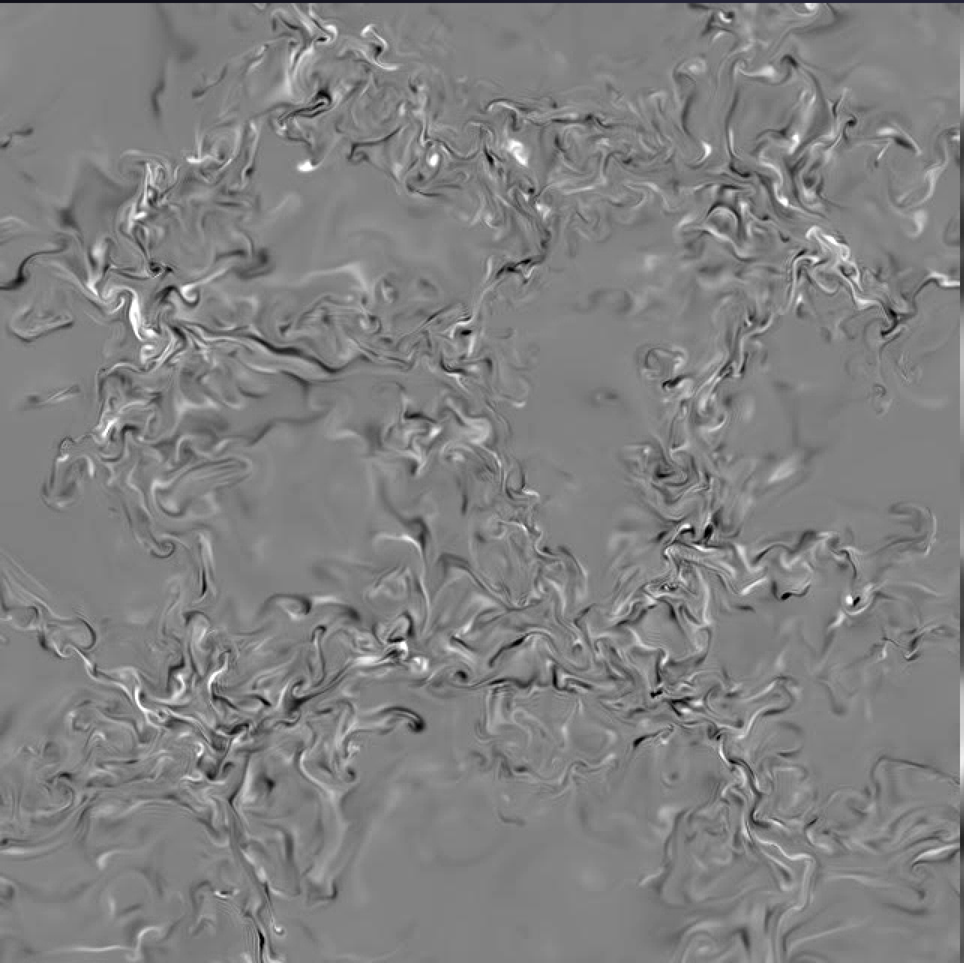
- Active and ephemeral regions: main dynamo (orientation of bipolar regions & solar cycle variation of their number and location)

- Internetwork & turbulent fields: not yet decided
  - local turbulent dynamo (Cattaneo 1999; Vögler & Schüssler 2007; 2008)
  - main dynamo, with fluctuations due to flux recycling (e.g. Ploner et al. 2002; de Wijn et al. 2005; Stenflo 2012)

Surface dynamo

Vögler and Schüssler 2007

$B_{vertical}$



Continuum intensity