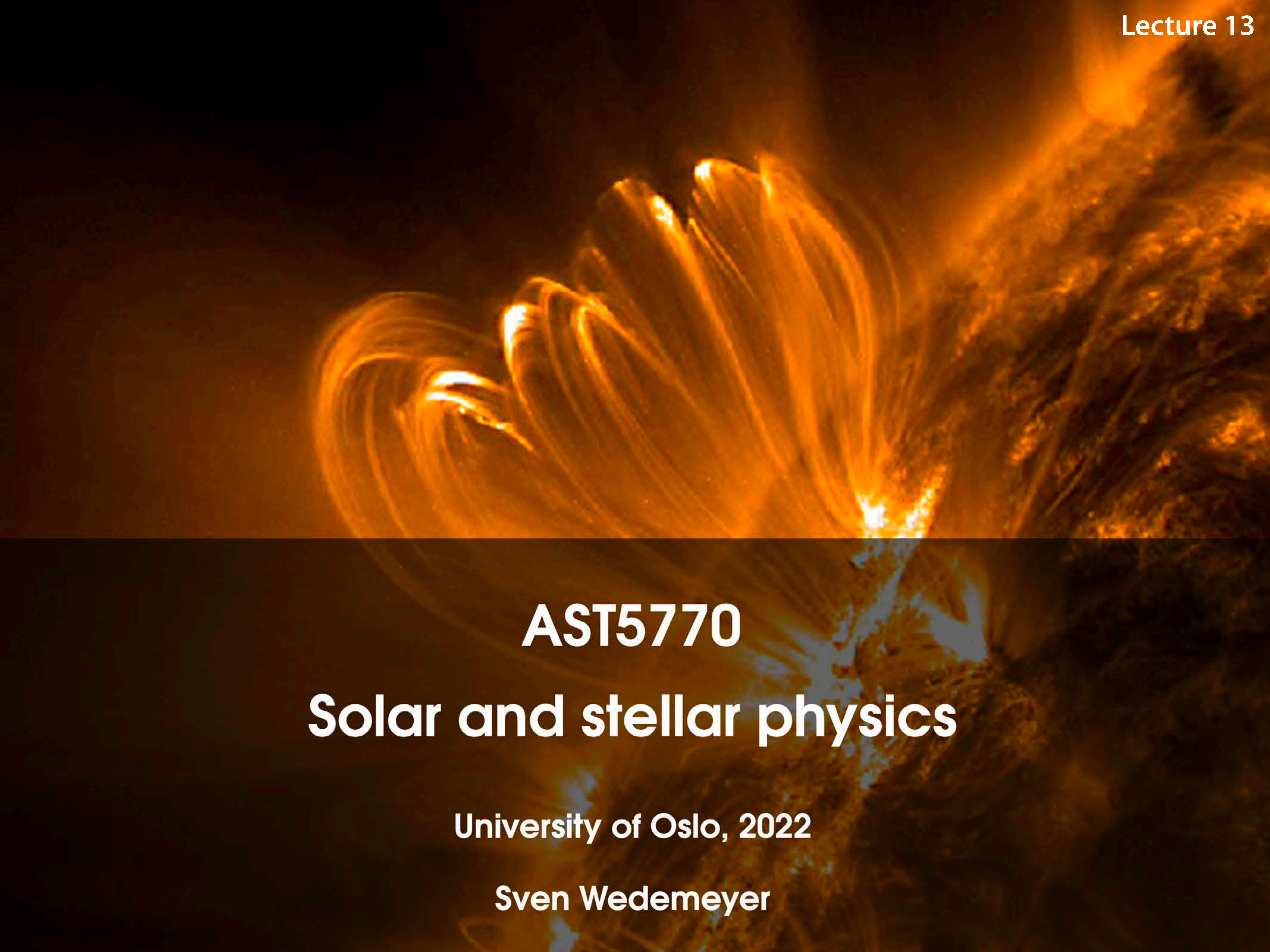


AST5770

Solar and stellar physics

University of Oslo, 2022

Sven Wedemeyer

Practical information

Updates

- **Assignment #2:** New minimum word count = 1500
  - Remember: Not the introduction of a real scientific article but starting at a bit lower level and can contain "textbook level" content.
- **New deadline for assignment #4:** April 20 (previously April 18)
- **Group class next week** (March 16):
  - Group teacher Aditi
  - Discussion on Fourier transformations and spatial/temporal power spectra
- **Week 12** (21.3. - 25.3.): No lectures and no group class (due to clash with block course)
- **Last lecture** (most likely): May 12
  - More time to work on the final project assignment (due May 31)

Magnetism

Magnetism

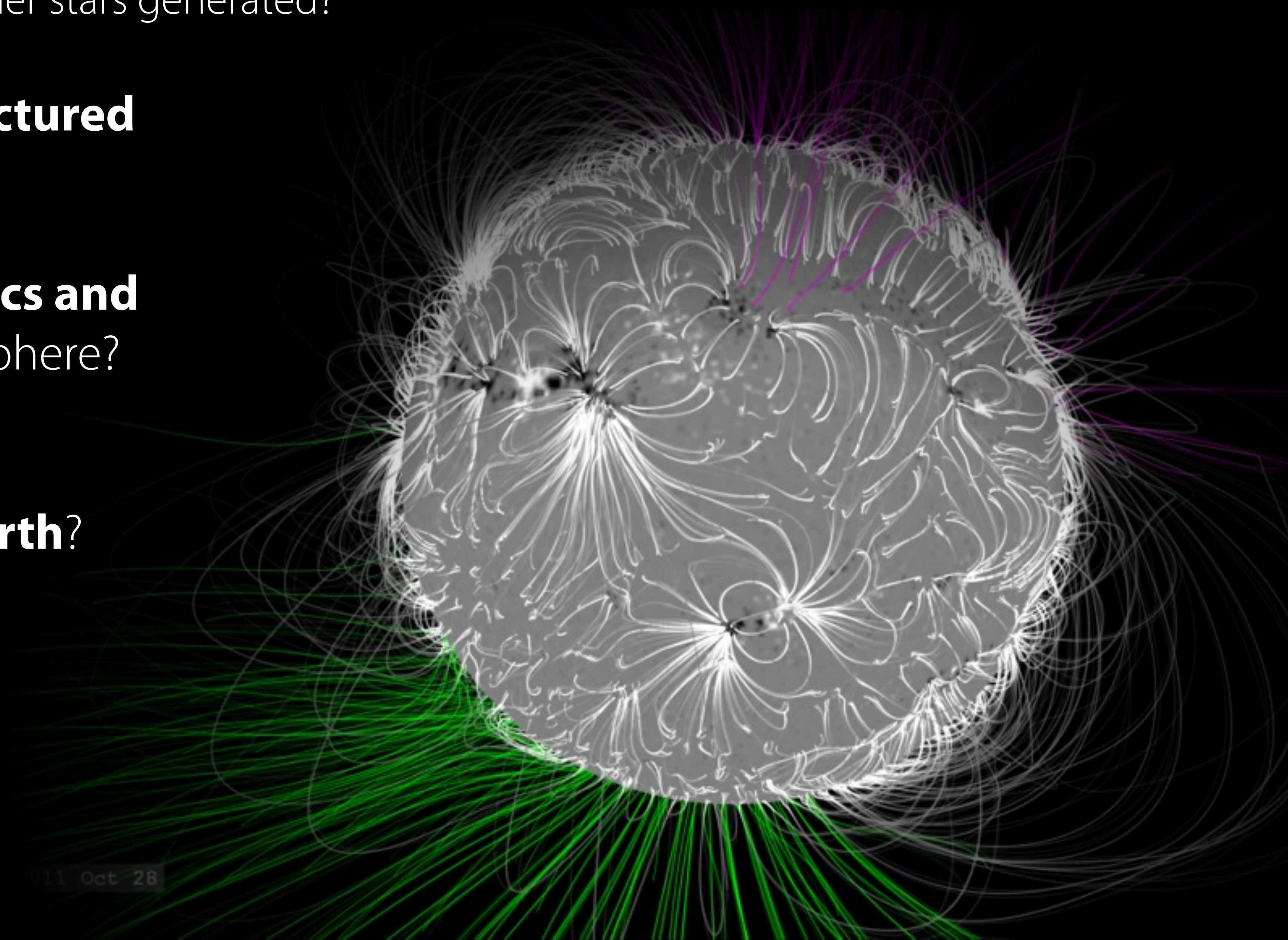
Many important questions …

- **How is the magnetic field of the Sun generated?**
  - Is the Sun generating "new" magnetic field? Is there a dynamo process at work?
  - Or are those the remainders of a "primordial" magnetic field of the material from which the solar system and the Sun formed?
  - How is the magnetic field of other stars generated?

- How is the magnetic field **structured** in the atmosphere of the Sun?

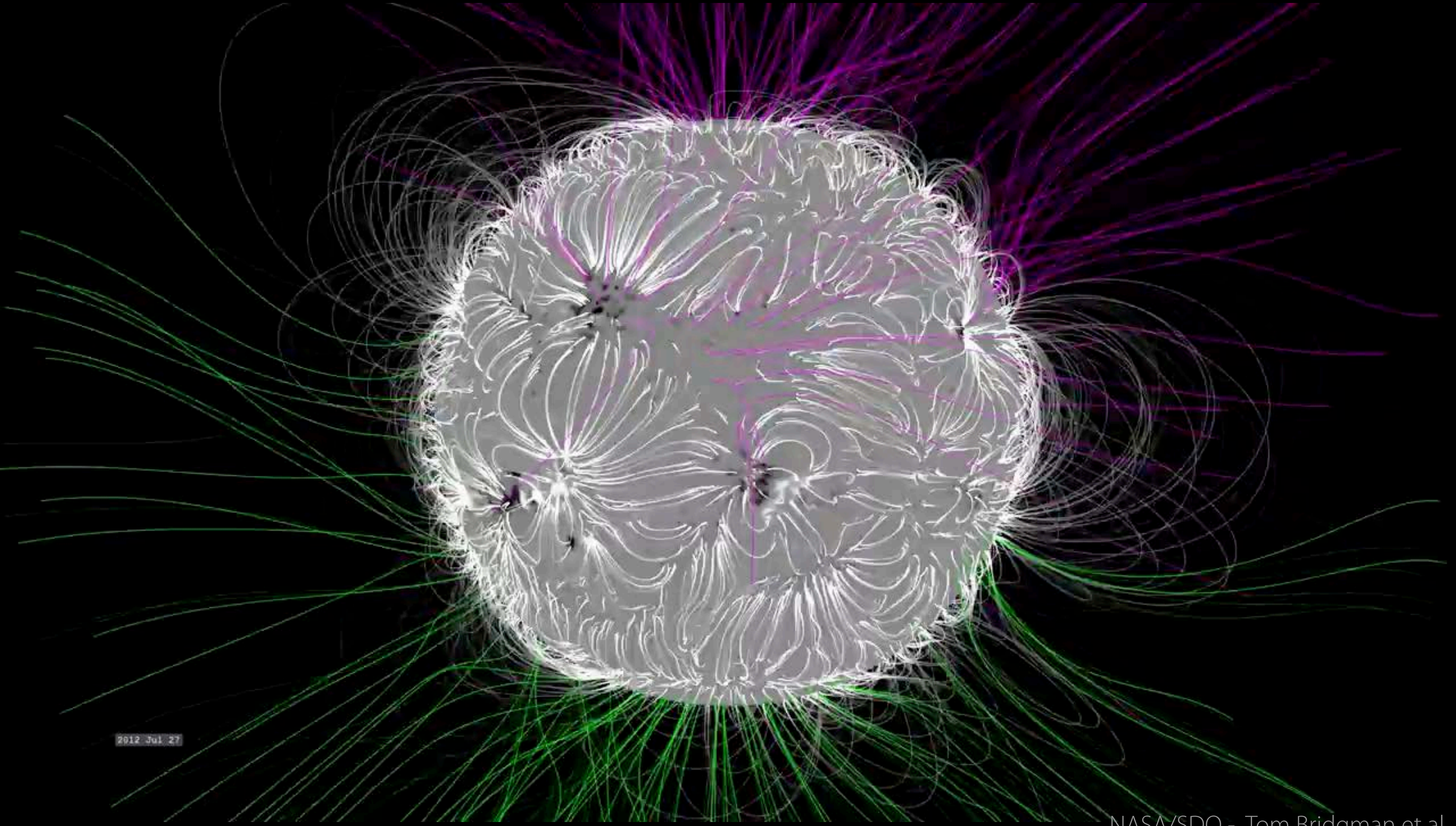
- How does it affect the **dynamics and energy balance** of the atmosphere?

- And how does it affect the **interplanetary space and Earth**?



Magnetism

Magnetic fields on the Sun — Introduction

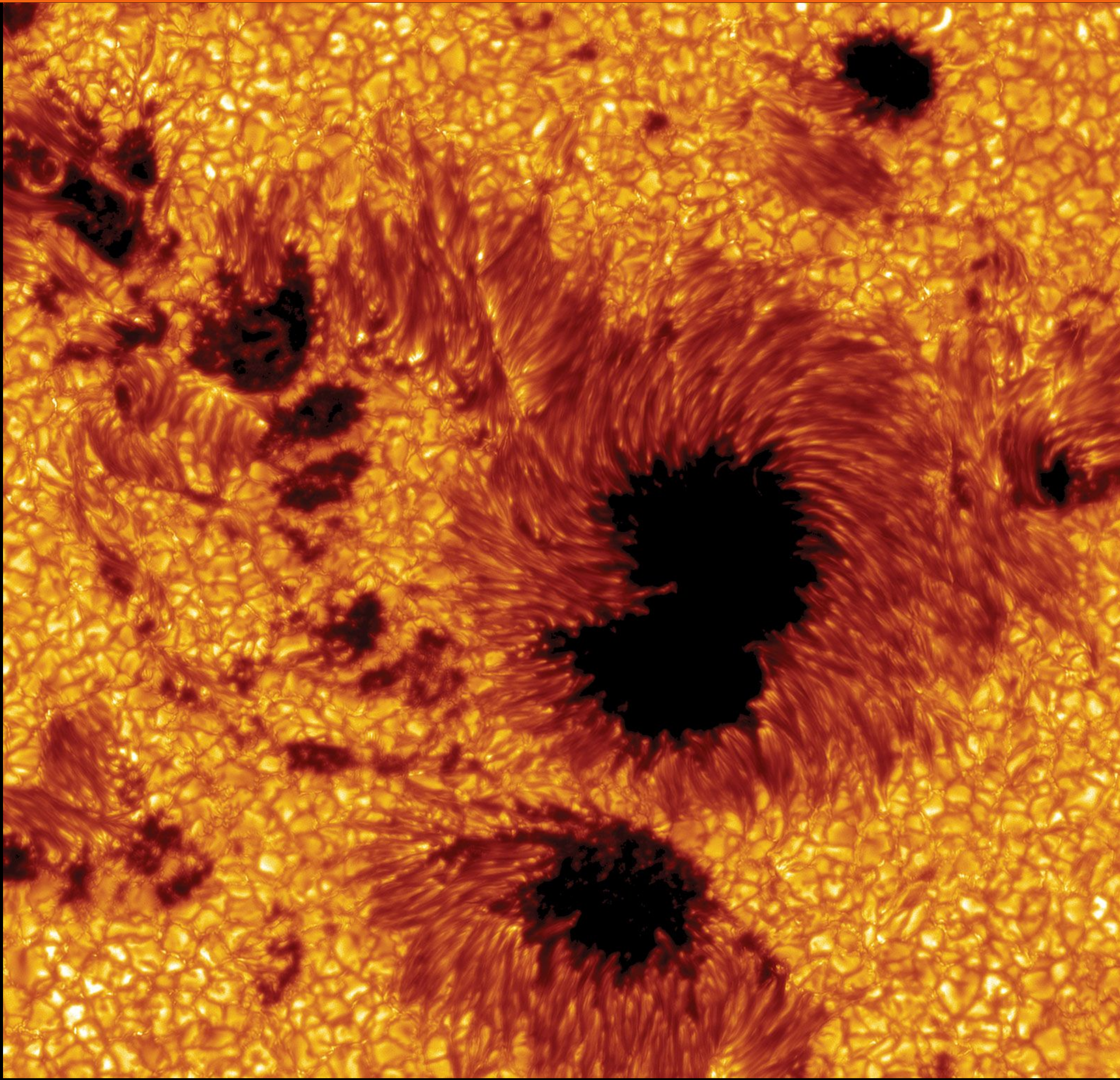


NASA/SDO - Tom Bridgman et al

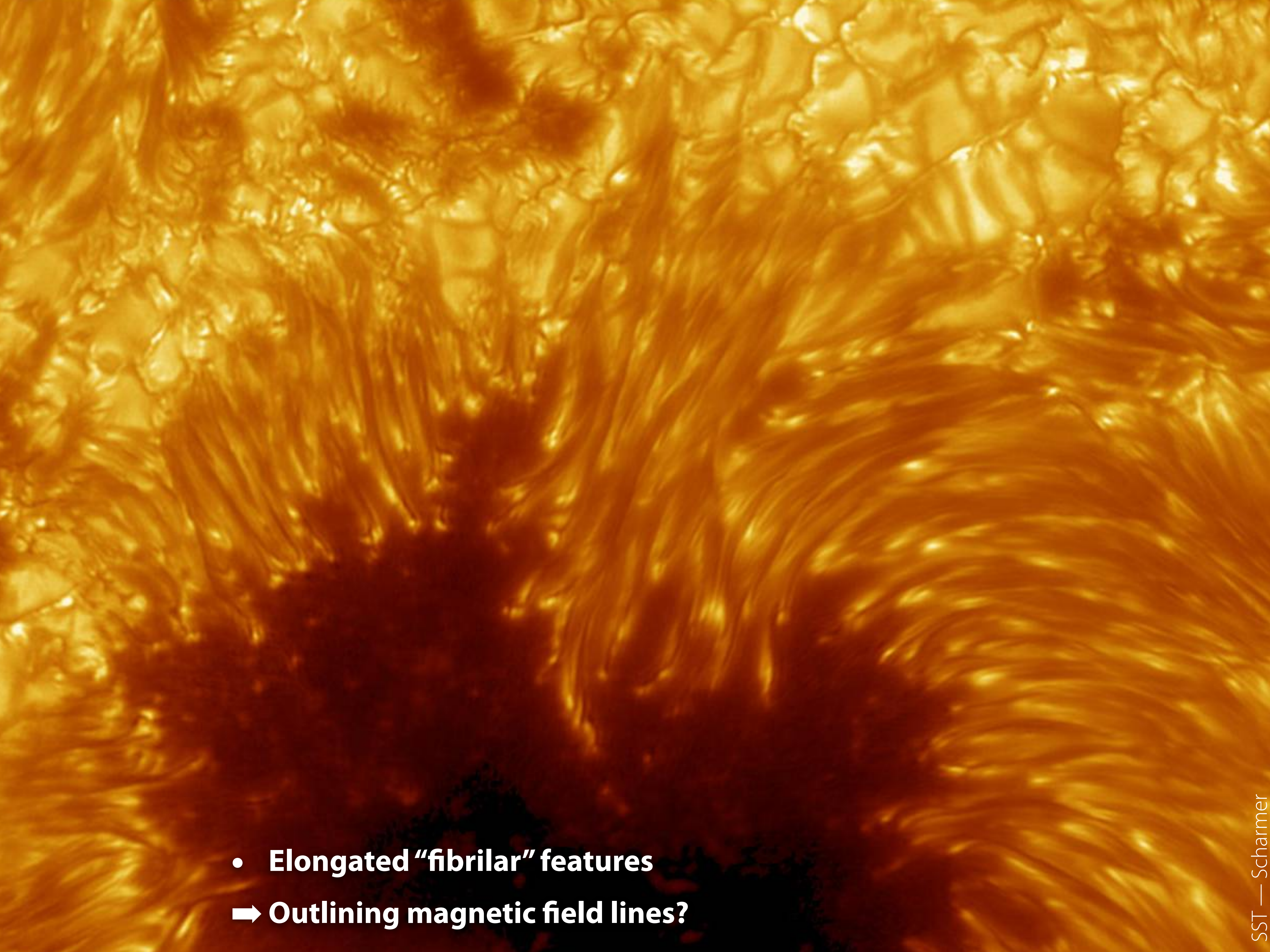
Magnetism

On the Sun

- Sunspots are clear imprints at the surface and in the atmosphere above
- Magnetism on the Sun occurs on all scales.
- Smallest features at or below spatial resolution limit of current telescopes
- Largest features on global scales
- Temporal scales between many years (activity cycle) to extremely short scales (<1s).

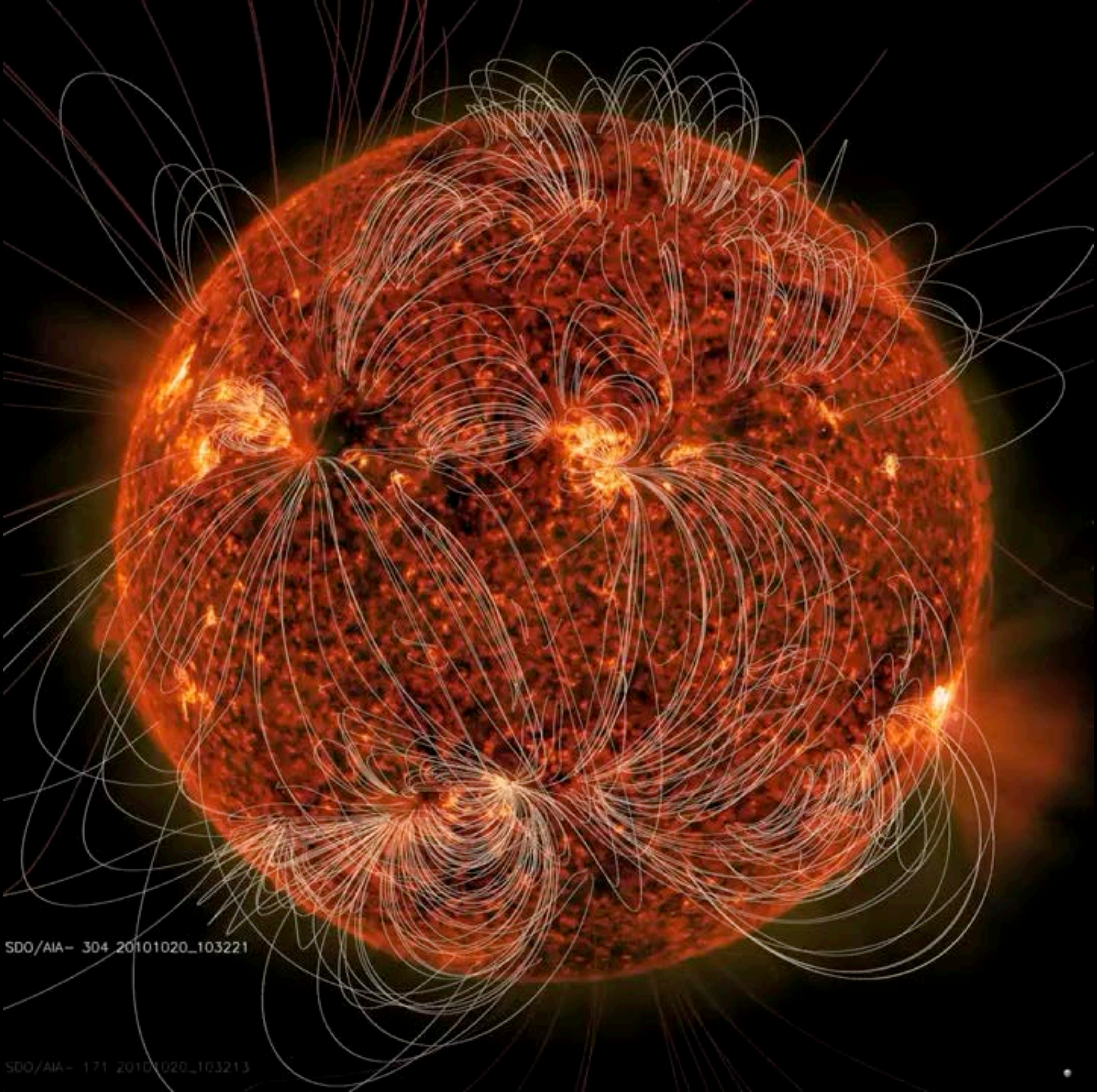


The Royal Swedish Academy of Sciences/
The Institute for Solar Physics



- **Elongated “fibrilar” features**

➡ **Outlining magnetic field lines?**

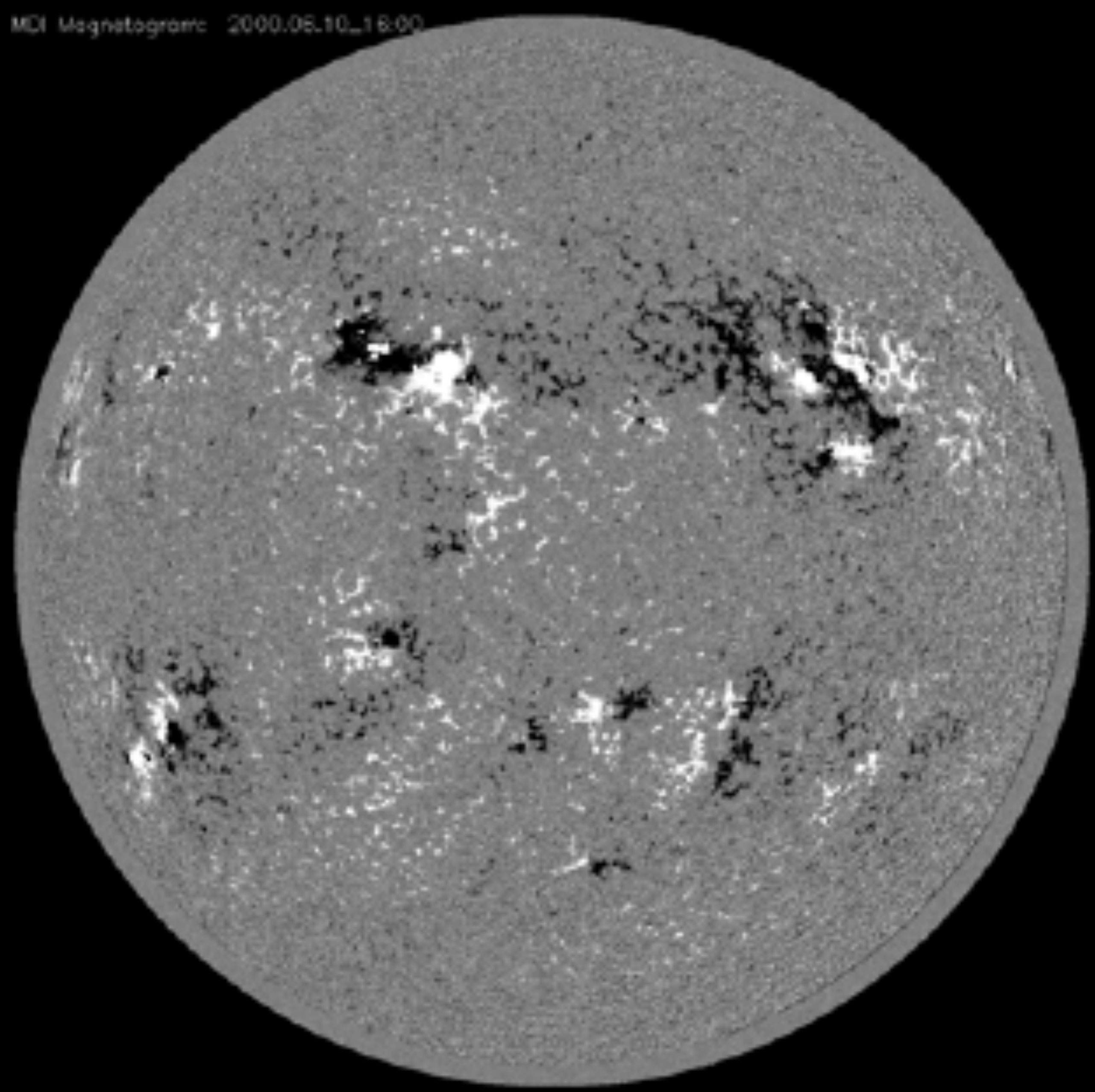


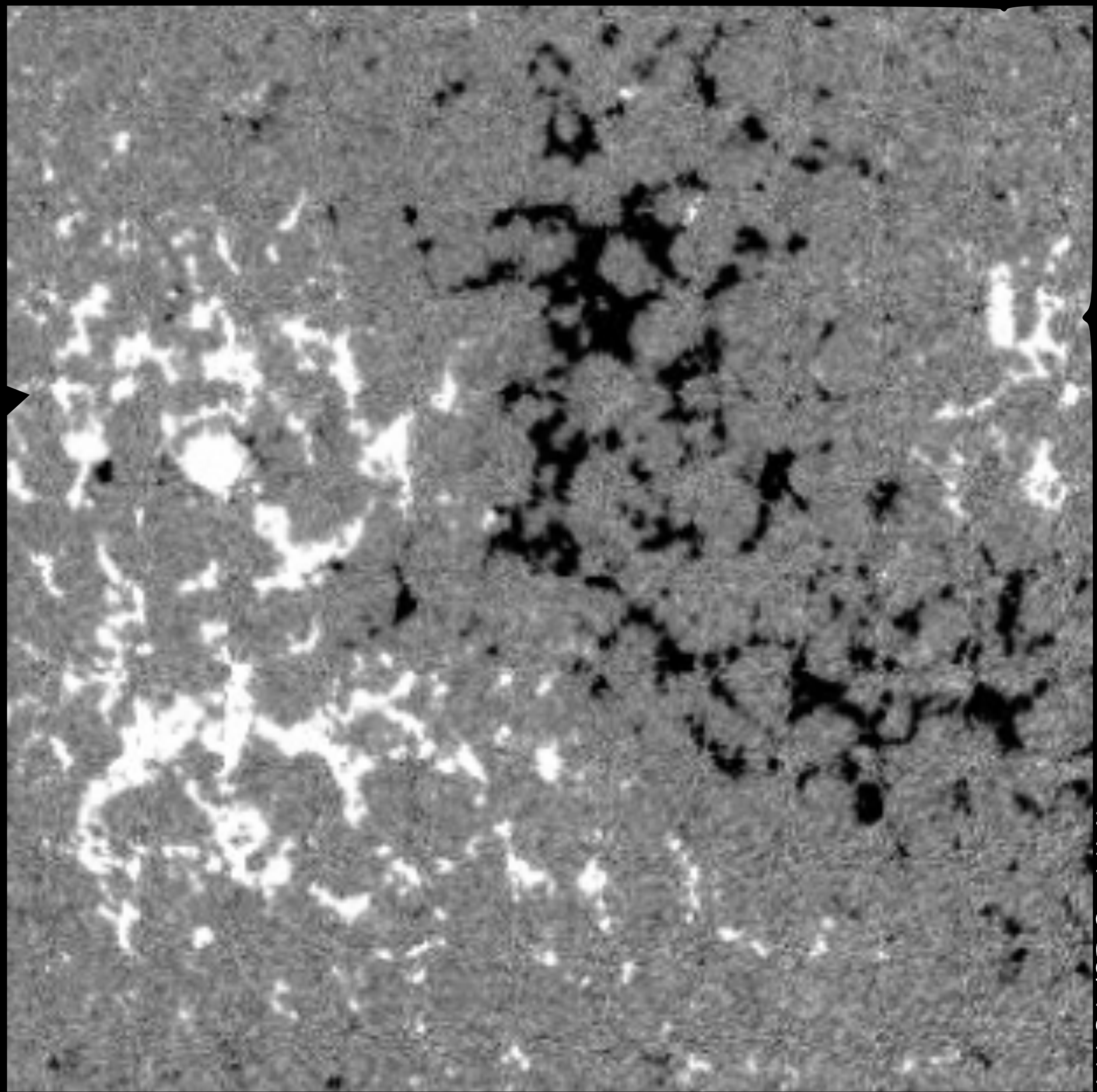
NASA/SDO - HMI

Magnetism

Photospheric magnetograms

- Active regions, bi-polarity systematic east-west orientation opposite in the south





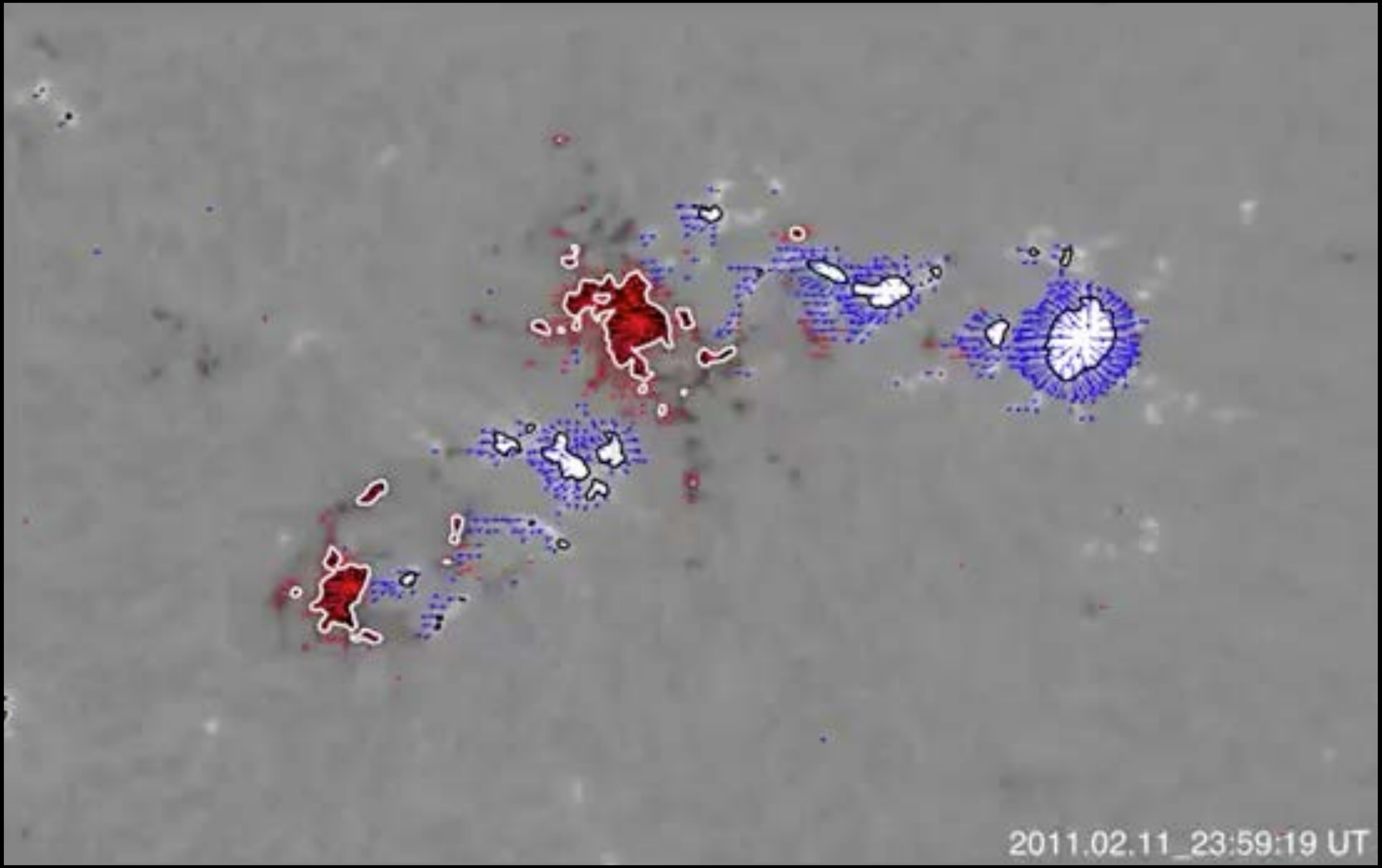
NASA/SDO - HMI

Magnetism

Photospheric magnetograms

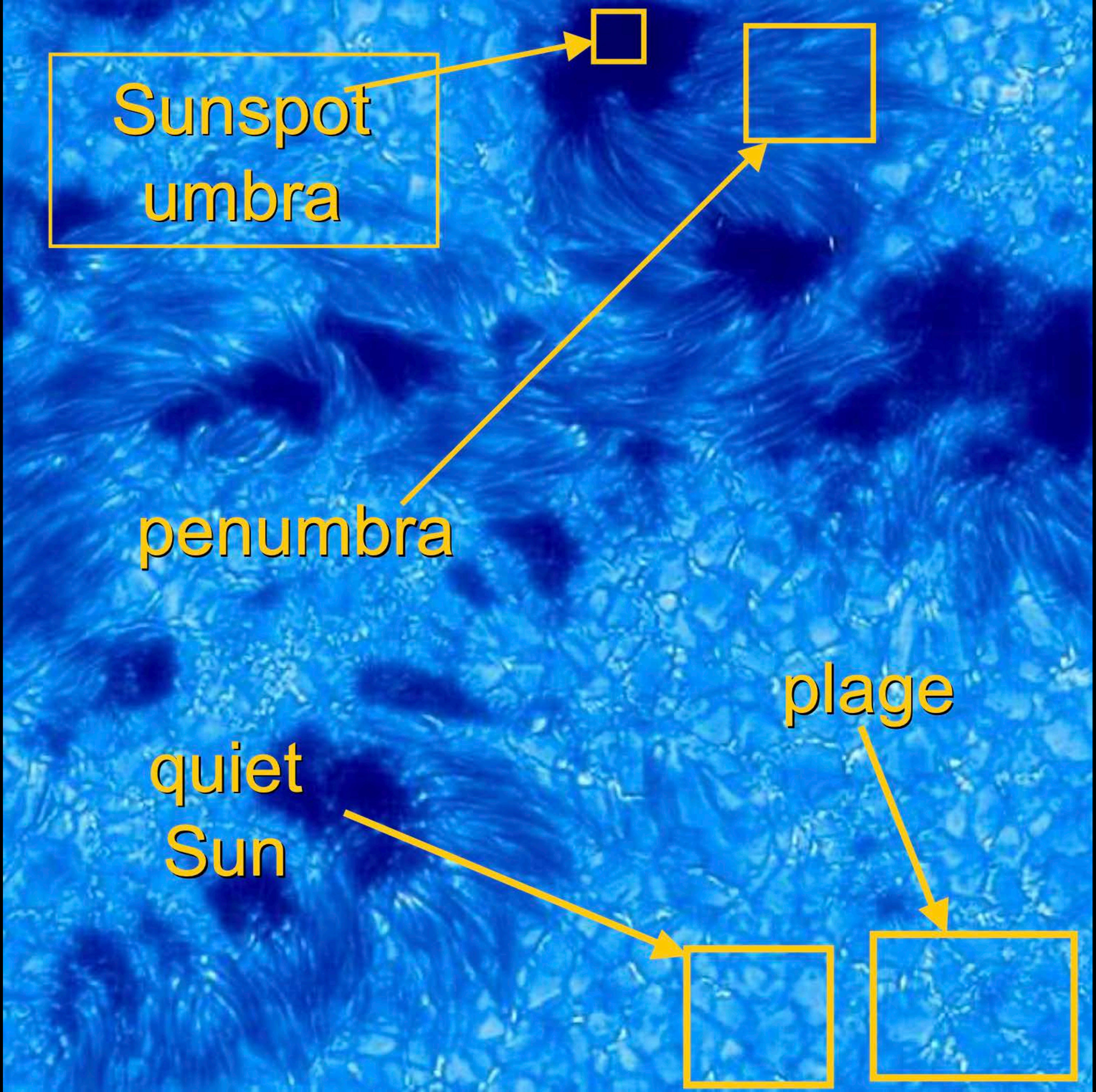
- Observation of the Sun with SDO/HMI, 2/2011
- Evolution of magnetic field in an Active Region

Blue arrows: magnetic field lines "point up"
Red arrows: magnetic field lines "point down"



Observation follows target region, removing effect of solar rotation

NASA/SDO - HMI


Sunspot umbra
penumbra
quiet Sun
plage

Magnetism

So far — Radiative-Hydrodynamic Equations

- Hydrodynamic equations:
  - Conservation of mass (density): (*mass* continuity equation)
  - Conservation of momentum:
  - Conservation of energy:

$$\partial_t \rho = -\boldsymbol{\nabla} \cdot (\rho \boldsymbol{v}),$$

$$\partial_t \rho \boldsymbol{v} = -\boldsymbol{\nabla} \cdot (\rho \boldsymbol{v} \boldsymbol{v} + \underline{\tau}) - \boldsymbol{\nabla} p + \rho \boldsymbol{g},$$

$$\partial_t e = -\boldsymbol{\nabla} \cdot (e \boldsymbol{v}) - p \boldsymbol{\nabla} \cdot \boldsymbol{v} + q_{\mathrm{rad}} + q_{\mathrm{visc}},$$

- Coupling with the radiation field is give by the radiative cooling and heating term (as derived from the radiative transfer equation)

$$q_{\mathrm{rad}} = 4\pi\rho \int_\lambda \kappa_\lambda (J_\lambda - S_\lambda)\, \mathrm{d}\lambda,$$

- Equation of state

Additional equations needed when dealing with charged particles (plasma) and magnetic and electric fields

Magnetism

Magnetohydrodynamics (MHD)

- MHD equations describe how a magnetic field interacts with a continuous plasma (ionized gas).
    - "Like hydrodynamics", but with extra equations (Lorentz-force etc.)

- **Ideal MHD**
    - Simplifying assumption: infinite conductivity (no resistance), perfectly conducting (and thus fully ionised) plasma, no dissipation of electro-magnetic energy
    - Currents are present, but no charge densities
    - Applicable in the solar interior and in good approximation in the solar atmosphere (note that there will be deviations)

- **Non-ideal MHD conditions**:
    - Ions and neutrals slip past each other (ambipolar diffusion)
    - Magnetic reconnection (localized events, flares)
    - Turbulence induced reconnection

Magnetism

Magnetohydrodynamics (MHD)

- MHD equations describe how a magnetic field interacts with a continuous plasma (ionized gas).
- primary variables v, B, p, ρ and T

Conservation of mass (density) (*mass* continuity equation)	$\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0$
Conservation of momentum — extra term	$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B} + \mathbf{F}_g + \mathbf{F}_v$
Conservation of energy	$\frac{\rho^\gamma}{\gamma - 1} \frac{d}{dt} \left(\frac{p}{\rho^\gamma} \right) = -\nabla \cdot \mathbf{q} - L_r + j^2/\sigma + F_H$
Equation of state	$p = \frac{k_B}{m} \rho T \quad \left(= \frac{\tilde{R}}{\tilde{\mu}} \rho T \right)$

$j \times B$: Lorentz force per unit volume — describes the interaction between the magnetic field and the plasma

j^2/σ: Ohmic dissipation

q: heat flux due to particle conduction

Lr: net radiation

Magnetism

Magnetohydrodynamics (MHD)

- MHD equations describe how a magnetic field interacts with a continuous plasma (ionized gas).
- primary variables v, B, p, ρ and T

Conservation of mass (density) (*mass* continuity equation)	$\frac{d\rho}{dt} + \rho \boldsymbol{\nabla} \cdot \mathbf{v} = 0$
Conservation of momentum — extra term	$\rho \frac{d\mathbf{v}}{dt} = -\boldsymbol{\nabla} p + \mathbf{j} \times \mathbf{B} + \mathbf{F}_g + \mathbf{F}_v$
Conservation of energy	$\frac{\rho^\gamma}{\gamma - 1} \frac{d}{dt} \left(\frac{p}{\rho^\gamma} \right) = -\boldsymbol{\nabla} \cdot \mathbf{q} - L_r + j^2/\sigma + F_H$
Equation of state	$p = \frac{k_B}{m} \rho T \quad \left(= \frac{\tilde{R}}{\tilde{\mu}} \rho T \right)$
Induction equation	$\frac{\partial \mathbf{B}}{\partial t} = \boldsymbol{\nabla} \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$
Ohm's Law	$\mathbf{j} = \sigma (\mathbf{E} + \mathbf{v} \times \mathbf{B})$

- *Further reading: Solar Magnetohydrodynamics, E. Priest (2014), downloadable via UiO bib.*

Magnetism

Magnetohydrodynamics (MHD)

- MHD equations describe how a magnetic field interacts with a continuous plasma (ionized gas).
- primary variables: v, B, p, ϱ, T

- Numerical simulations need to account for a lot physics — computationally very challenging
- Certain terms can be neglected depending on the simulated scenario in order to make problem computationally feasible
  - Validity of resulting model then limited by these simplifying assumptions
- Numerical simulations have historically developed from simplified cases to increasingly more complex and realistic cases

$\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0$
$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B} + \mathbf{F}_g + \mathbf{F}_v$
$\frac{\rho^\gamma}{\gamma - 1} \frac{d}{dt}\left(\frac{p}{\rho^\gamma}\right) = -\nabla \cdot \mathbf{q} - L_r + j^2/\sigma + F_H$
$p = \frac{k_B}{m}\rho T \quad \left(= \frac{\tilde{R}}{\tilde{\mu}}\rho T\right)$
$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$
$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B})$

- *Further reading: Solar Magnetohydrodynamics, E. Priest (2014), downloadable via UiO bib.*

Magnetism

Magnetohydrodynamics (MHD)

- Additional equation can be derived from the Maxwell Equations and the Lorentz force

Maxwell's Equations	Gauss's law	$\nabla . \mathbf{E} = \frac{\rho_q}{\varepsilon_o}$
	Gauss's law of magnetism	$\nabla . \mathbf{B} = 0$
	Maxwell–Faraday equation (Faraday's law of induction)	$\nabla \times \mathbf{E} = - \frac{\partial \mathbf{B}}{\partial t}$
	Ampère's circuital law (with Maxwell's addition)	$\nabla \times \mathbf{B} = \mu_o \mathbf{j} + \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t}$
Lorentz force (electromagnetic force) *Charged particle moving in electric and magnetic fields.*		$\boldsymbol{F} = q\boldsymbol{E} + q(\boldsymbol{v} \times \boldsymbol{B})$

- *Further reading: Solar Magnetohydrodynamics, E. Priest (2014), downloadable via UiO bib.*

Magnetism

Fundamental plasma properties

- **Electrical conductivity** σ
  - For a fully ionised, collision-dominated plasma: $\sigma = n_e e^2 \tau_{ei} / m_e$

n_e: number density of electrons
e: electric charge
m_e: electron mass
τ_{ei}: electron-ion collision time

- **Magnetic diffusivity** $\eta = 1/(\mu\sigma)$

μ: magnetic permeability;
magnetic field production due to moving electric charge (current)

- **Magnetic Reynolds number**

$$R_\mathrm{m} = \frac{\text{induction or advection of a magnetic field due to the motion of a conducting medium}}{\text{magnetic diffusion}}$$

- Small R_m: Advection is unimportant, magnetic field is diffusive.
- Large R_m: Diffusion unimportant. Magnetic field advected with the fluid flow.
  - In the Sun: $R_\mathrm{m} \sim 10^6$ (very large) — Diffusion and related dissipation of magnetic field unimportant.

Magnetism

Charge Conservation

- Charge is also a conserved quantity, the MHD charge continuity equation:

$$\frac{\partial \rho_q}{\partial t} + \nabla \cdot \left(\rho_q \mathbf{v} \right) = 0$$

$$\Rightarrow \frac{\partial \rho_q}{\partial t} + \nabla \cdot \mathbf{j} = 0$$

$$\varrho_q = q\, n$$

$$\varrho_q \boldsymbol{v} = \boldsymbol{j}$$

v : Velocity
ϱ_q : Charge density
q : Charge per particle
n : Number density
j : Current

Magnetism

Ohm's law

- Lorentz force combined for large number of charged particles (making up a plasma)

$$\vec{F} = \underbrace{q\vec{E}}_{\text{Electric force}} + \underbrace{q\vec{v} \times \vec{B}}_{\text{Magnetic force}}$$

$$\varrho_q \boldsymbol{v} = \boldsymbol{j}$$

- For a plasma moving at a non-relativistic velocity v in the presence of a magnetic field

➡ Electric field (v × B) in addition to the electric field (E) which would act on material at rest.

➡ Current density

$$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

- **More general:** For a plasma that consists of a mix of electrons, protons and neutral atoms:

➡ Generalised Ohm's law

Magnetism

Generalized Ohms Law

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta\ \mathbf{j}$$

Electric field in a moving plasma

Resistive term (cf V=IR; η = resistivity

- **Ideal MHD**: $\eta = 0 \Longrightarrow E + v \times B = 0$
  - A very good approximation for many applications (incl. solar interior)
  - 'frozen-in flux' approximation
  - Simplifies computations!

Magnetism

Generalized Ohms Law

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta\ \mathbf{j} + \left(\frac{1}{ne}\right)(\mathbf{j} \times \mathbf{B}) - \left(\frac{1}{ne}\right)\nabla . \mathbf{P_e} + \left(\frac{m_e}{ne^2}\right)\frac{\partial \mathbf{j}}{\partial t}$$

Electric field in a moving plasma	Resistive term (cf V=IR; η = resistivity	Hall term	Electron anisotropy	Electron inertia

These terms are small on long length and time scales and/or in regions of weak currents → often ignored

- **Ideal MHD**: $\eta = 0 \Longrightarrow E + v \times B = 0$
  - A very good approximation for many applications (incl. solar interior)
  - 'frozen-in flux' approximation
  - Simplifies computations!

Magnetism

Momentum Equation

- Conservation of momentum — the MHD equation of motion

$$\underbrace{\rho\left(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla\right)\mathbf{v}}_{\text{convective derivative of the momentum}} = \underbrace{-\nabla.\underline{\underline{\mathbf{P}}}+\rho_q\,\mathbf{E}+\mathbf{j}\times\mathbf{B} \quad + \text{any other forces acting on the plasma (e.g. gravity)}}_{\text{sources and sinks of momentum (forces)}}$$

convective derivative of the momentum

sources and sinks of momentum (forces)

- $\nabla.\underline{\underline{\mathbf{P}}}$: plasma pressure gradient
- $\varrho_q\, E$: electric field force (can be neglected if no net charge density in plasma)
- $j \times B$: Lorentz force

Magnetism

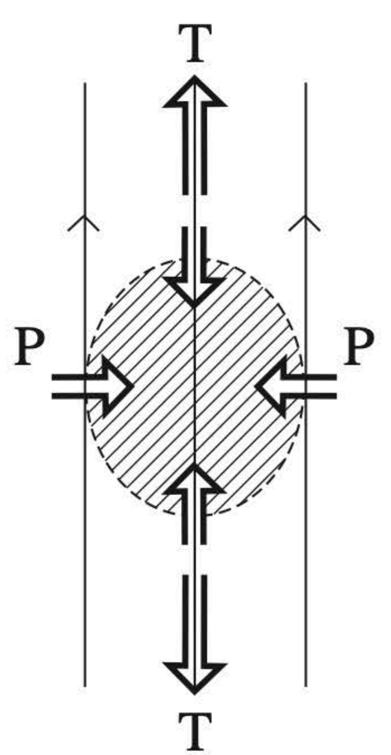
Magnetic pressure

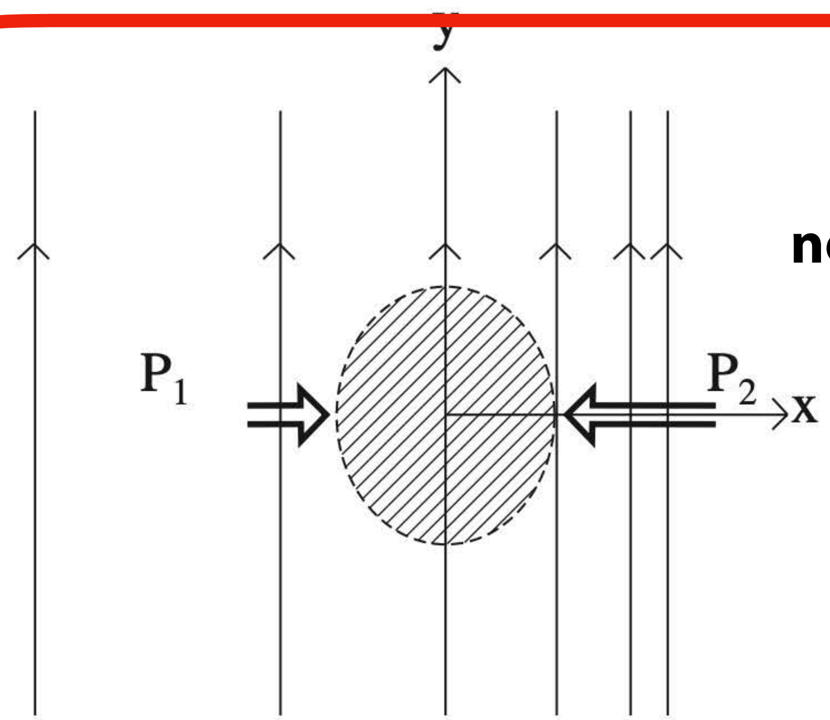
$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B} + \mathbf{F}_g + \mathbf{F}_v$$

- Assume a static case, no net charge, ignore gravity and viscosity $\Longrightarrow j \times B = \nabla p$
- Magnetic field exerts a pressure force, for short: **magnetic pressure**.
  - In SI units: $P_{\text{mag}} = \frac{B^2}{2\mu_0}$ SI units: P in Pa, B in T, μ_0 in H/m
  - In cgs units: $P_{\text{mag}} = \frac{B^2}{8\pi}$ cgs units: P in dyn/cm^2, B in G

μ_0: magnetic permeability in vacuum

uniform field:
magnetic pressures (P) and tensions (T) are in balance





non-uniform field:

$dB/dx > 0$

Imbalance:

$P_2 > P_1$

Priest (2014)

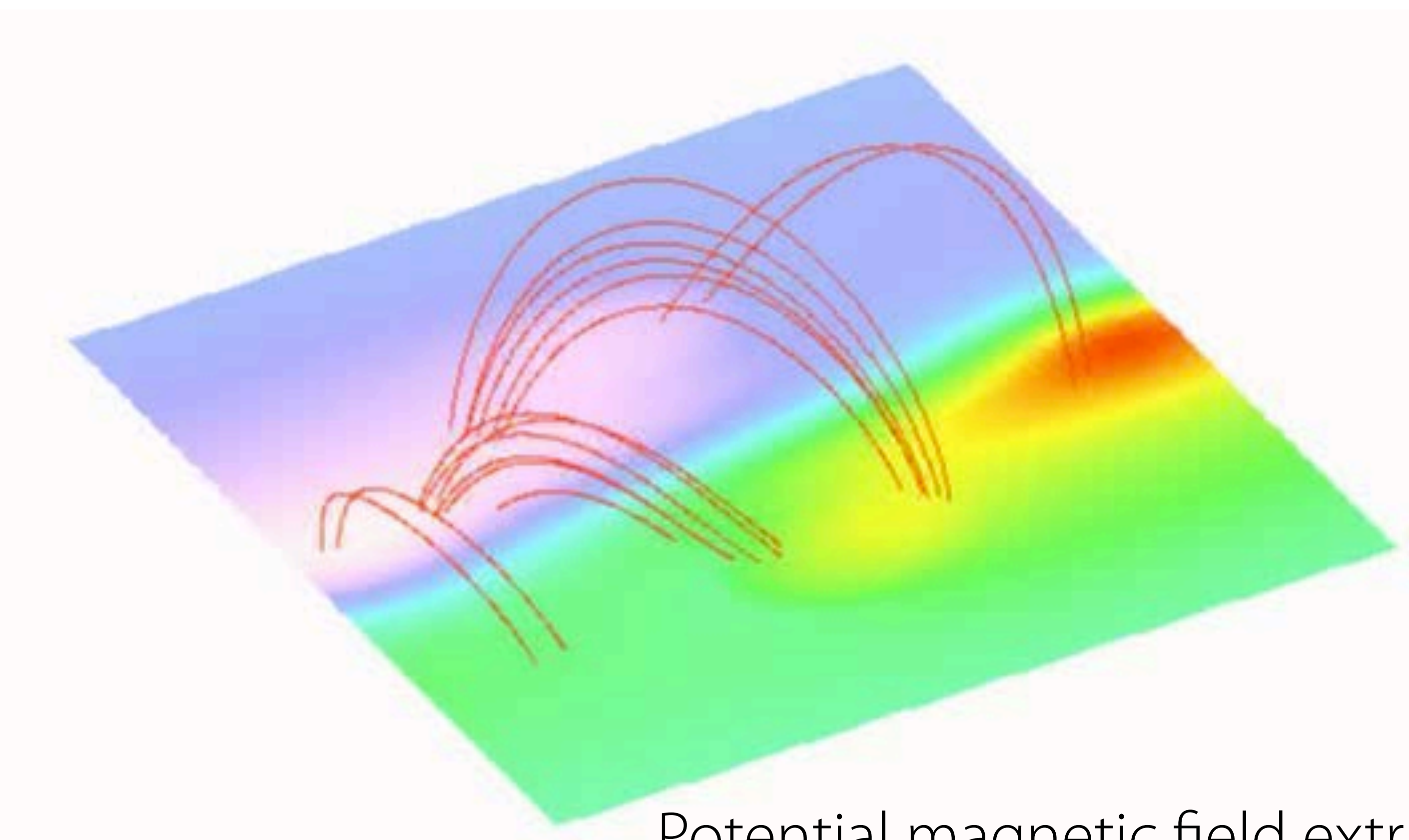
Magnetism

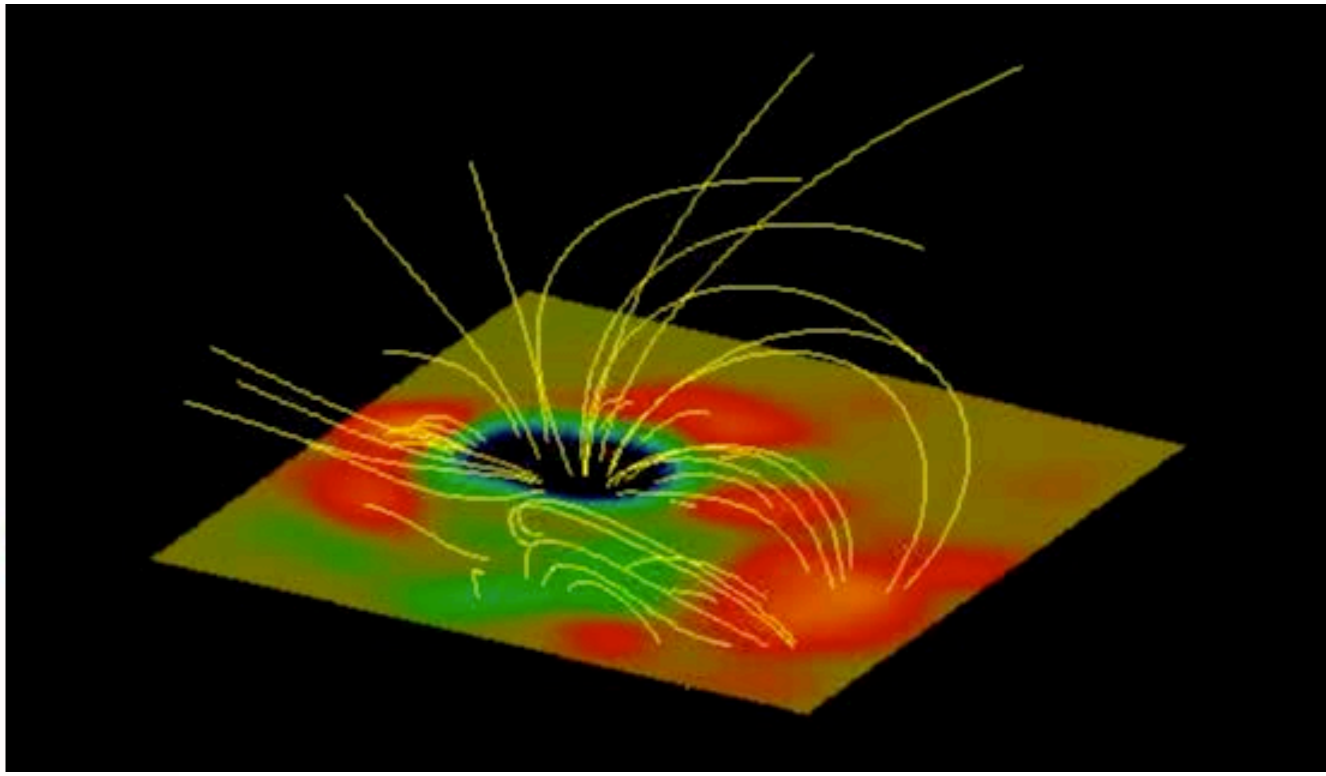
Force-free fields

- Magnetic field configuration for which Lorentz force is zero ($j \times B = 0$) — called **force-free**
- **Example:** potential magnetic field configuration with no electric current at all.

$$\mathbf{B} = \nabla \Psi$$

Ψ: magnetic (scalar) potential



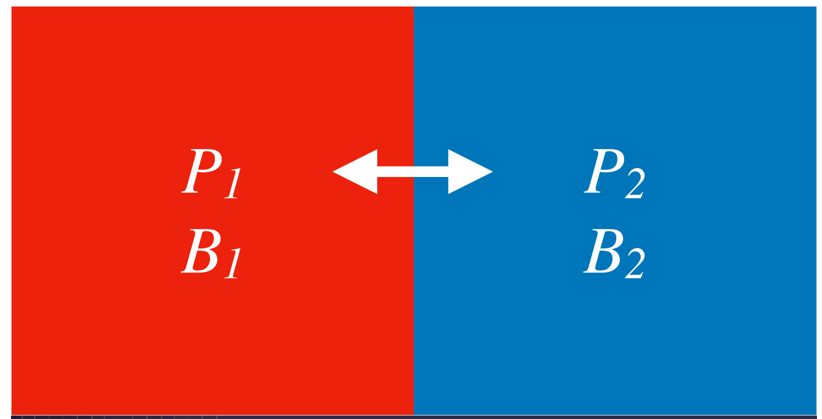


Potential magnetic field extrapolation

Wiegelmann

Magnetism

Magnetic pressure

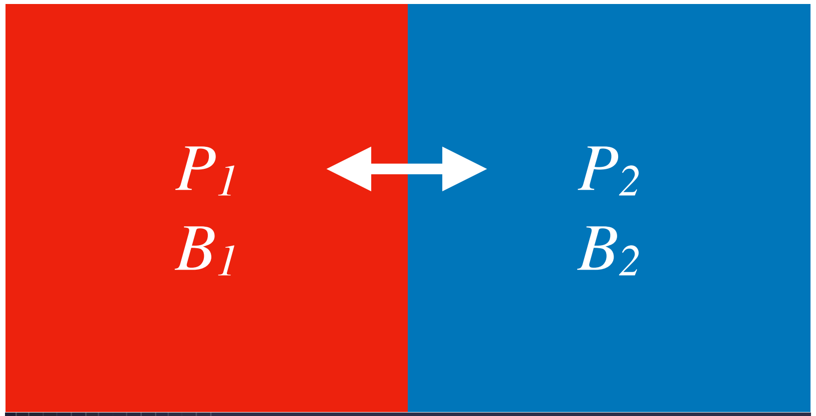


$$\frac{B_1^2}{8\pi} + P_1 = P_2 + \frac{B_2^2}{8\pi}$$

- **Pressure balance** between two different plasma domains (1 and 2):
- If $B_2 = 0$:
  - Extreme case: Component 1 is evacuated: $P_1 = 0$
  - Sets a maximum field strength B_{eq}
  - If $B > B_{eq}$: Not in pressure balance, overpressure in component 1, tends to expand

Magnetism

Magnetic pressure



$$\frac{B_1^2}{8\pi} + P_1 = P_2 + \frac{B_2^2}{8\pi}$$

- **Pressure balance** between two different plasma domains (1 and 2)
- If $B_2 = 0$ and $T_1 = T_2$, then also $\rho_1 < \rho_2$ (Equation of state!)

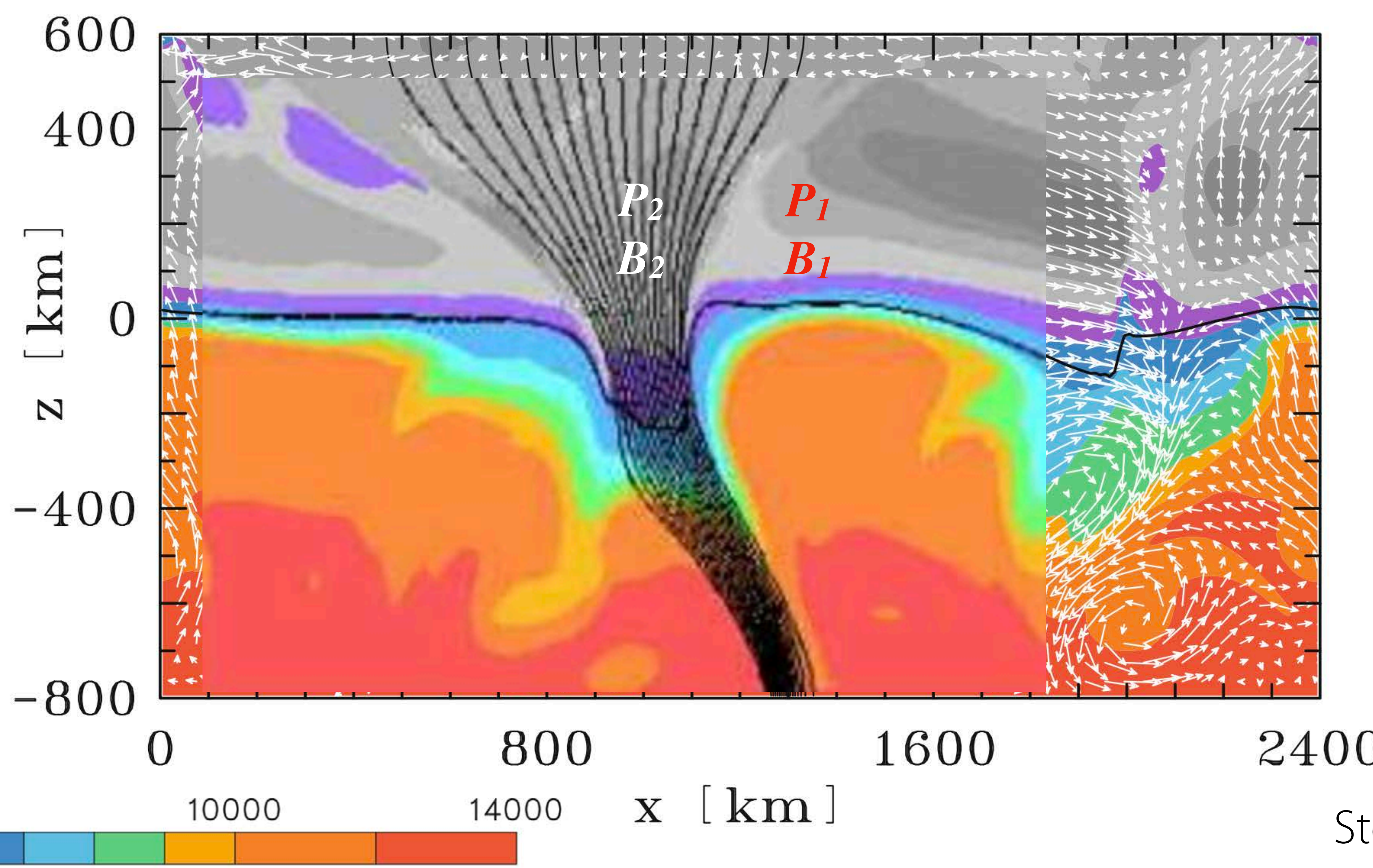
  ➡ Magnetic features are buoyant compared to the surrounding gas.
- In the convection zone:
  - Lower density inside magnetic flux bundles compared to surrounding plasma
  - Magnetic flux bundle becomes buoyant and rises towards the surface (down the gradient) unless stopped by other forces

Magnetism

Magnetic pressure

- Additional contributions from magnetic pressure inside magnetic flux concentration
- Pressure balance $\Longrightarrow$ lower gas pressure inside the flux concentration than outside
- Gas pressure of surrounding drops with height $\Longrightarrow$ Magnetic structure funnels out (wine-glass shape)

- $B_2 > B_1$
- ➡ $P_2 < P_1$
- ➡ $\varrho_2 < \varrho_1$



Steiner

Magnetism

Plasma-Beta

- Plasma-β describes the ratio of thermal to magnetic pressure

$$\beta = \frac{P_g}{P_m} = \frac{8\pi P_g}{B^2}$$

- **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.**

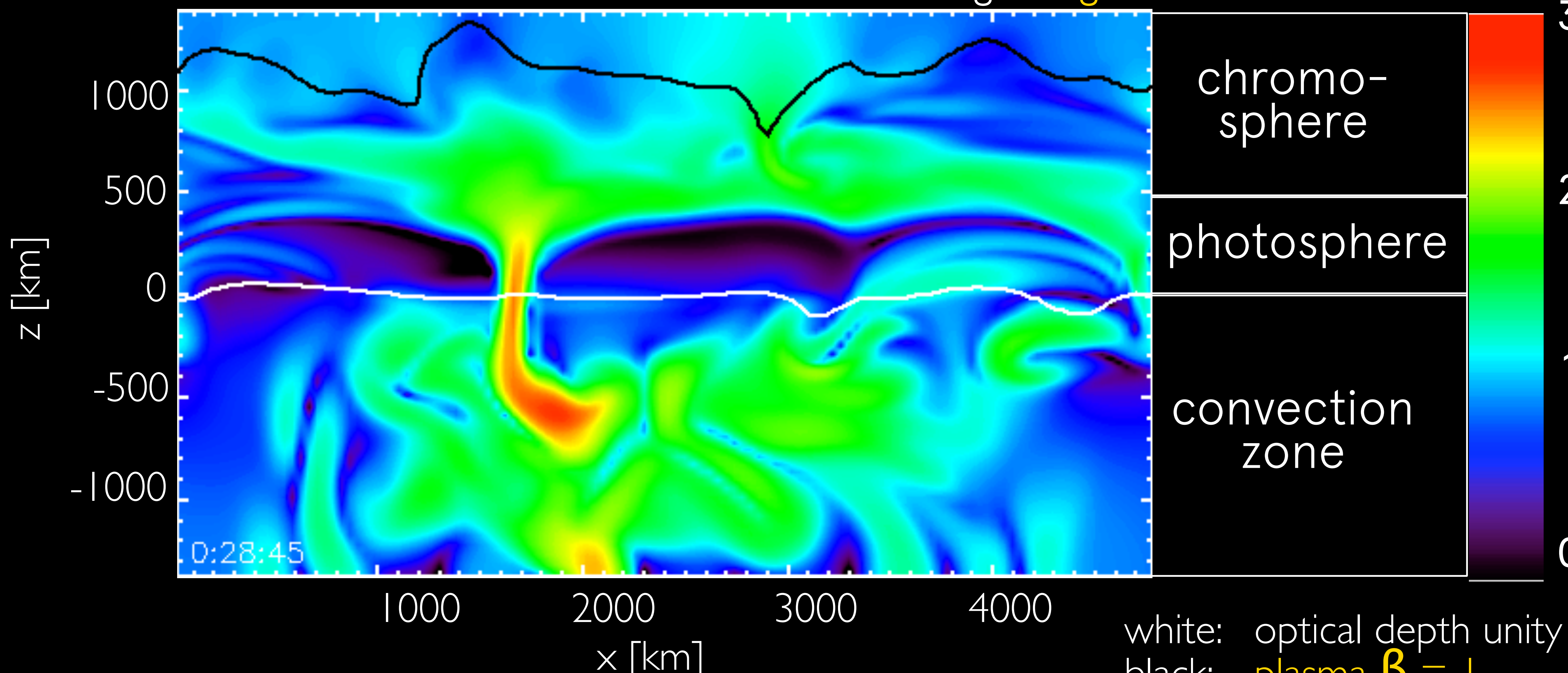
- β is a local quantity but the typical range of values changes with radius:
  - Convection zone: β >1
  - Lower atmosphere (outside strong magnetic field concentrations): β >1
  - Chromosphere: transition to β < 1
  - Corona: β <<1

Magnetism

Plasma-Beta

- Magnetic field in chromosphere is highly dynamic
  - Propagating shock waves compress magnetic field
  - Fast moving filaments of enhanced field

vertical cross-section: absolute field strength log |B|



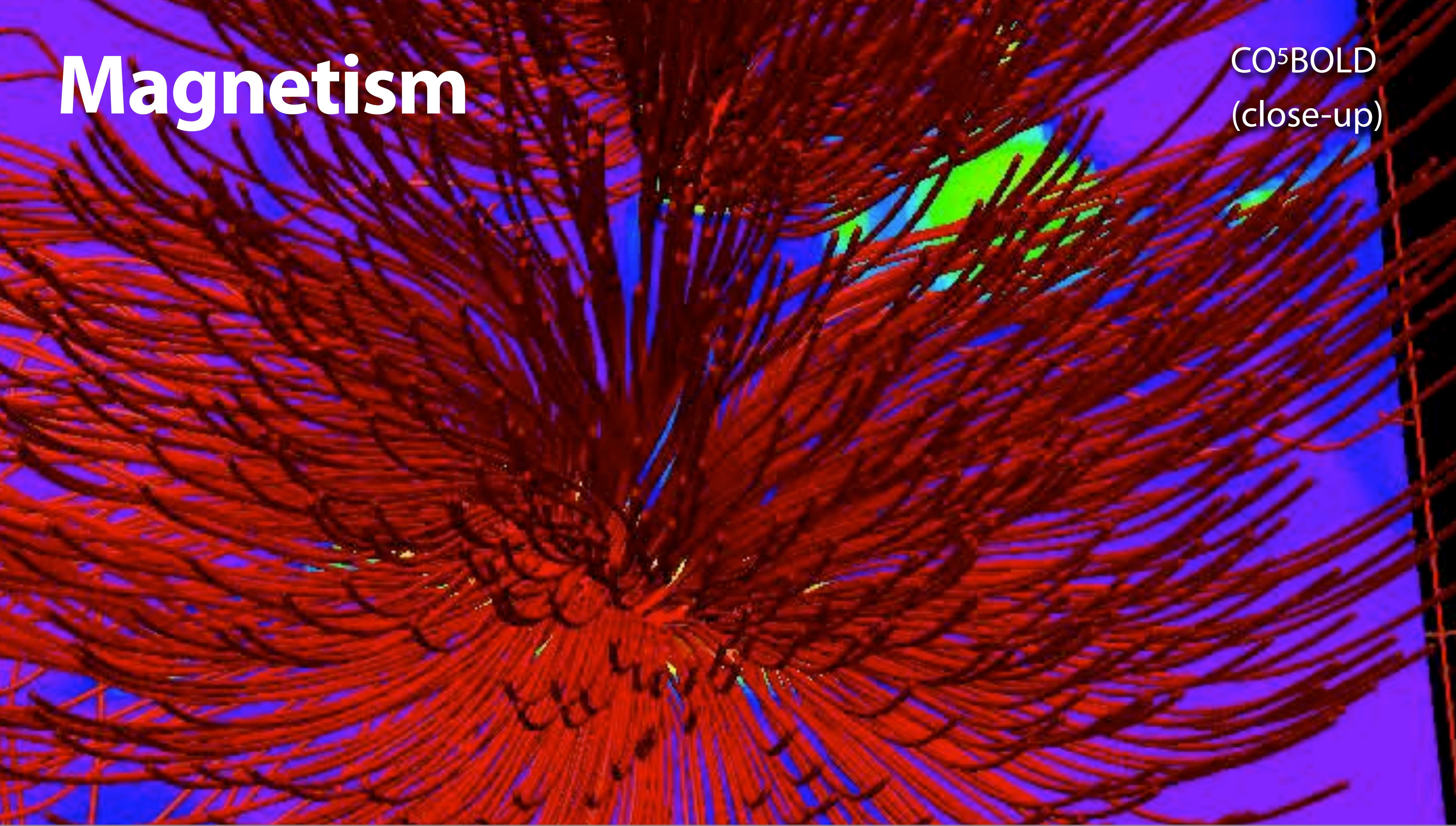
white: optical depth unity
black: plasma $\beta = 1$

$|B_0| = 10$ G

Schaffenberger, Wedemeyer, Steiner, Freytag (2005)

Magnetism

CO^{5}BOLD
(close-up)

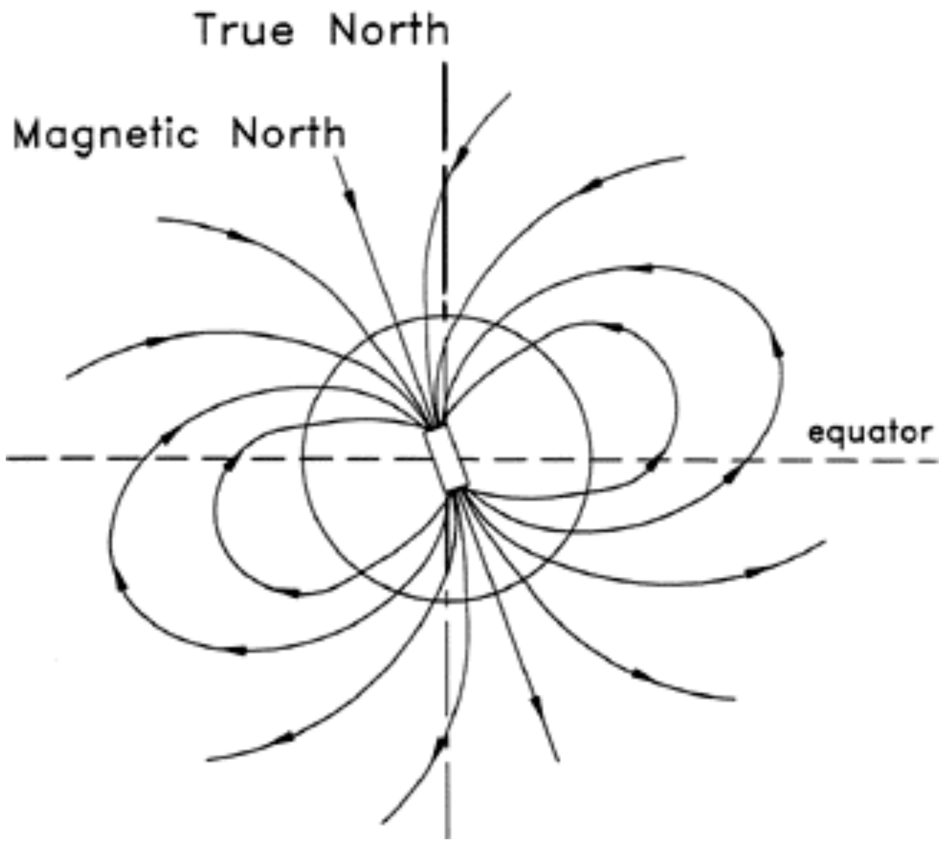


- Complicated field structure with rotating and/or swaying subgroups
- Continuous reorganisation of structure
- More complicated than individual “flux tubes”

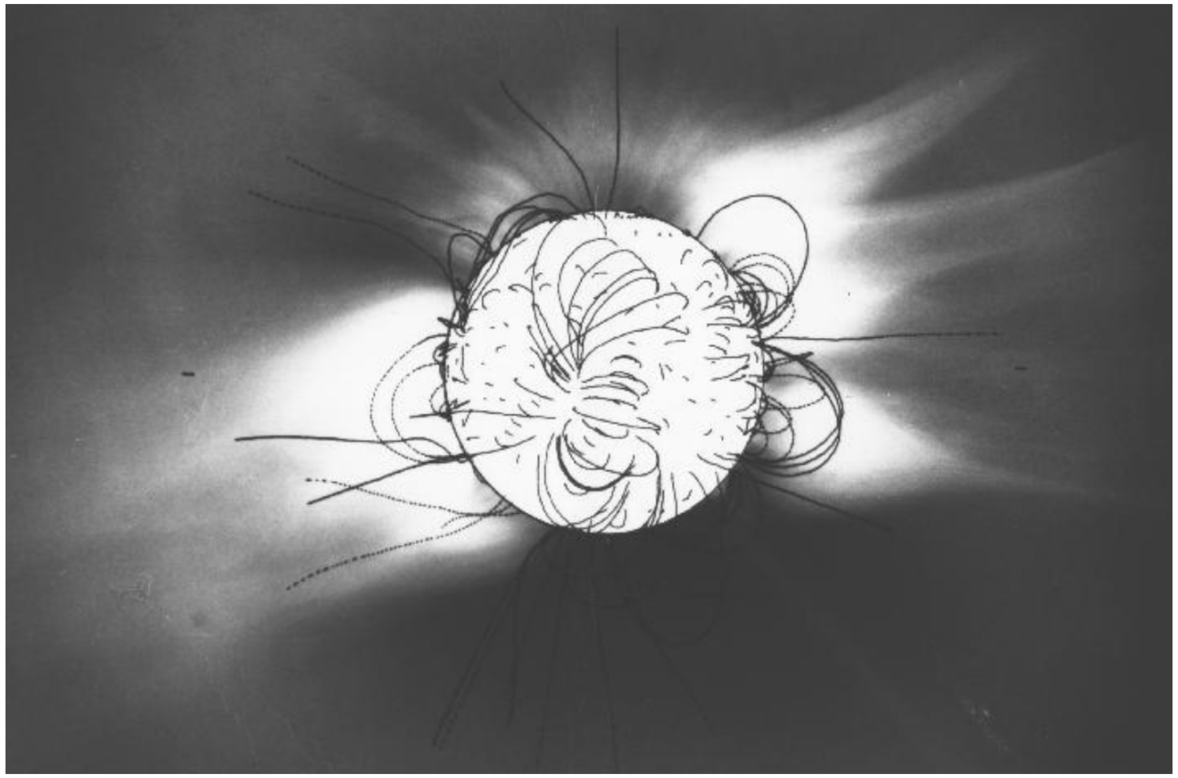
Magnetism

Global magnetic field configurations

Earth — dipole field



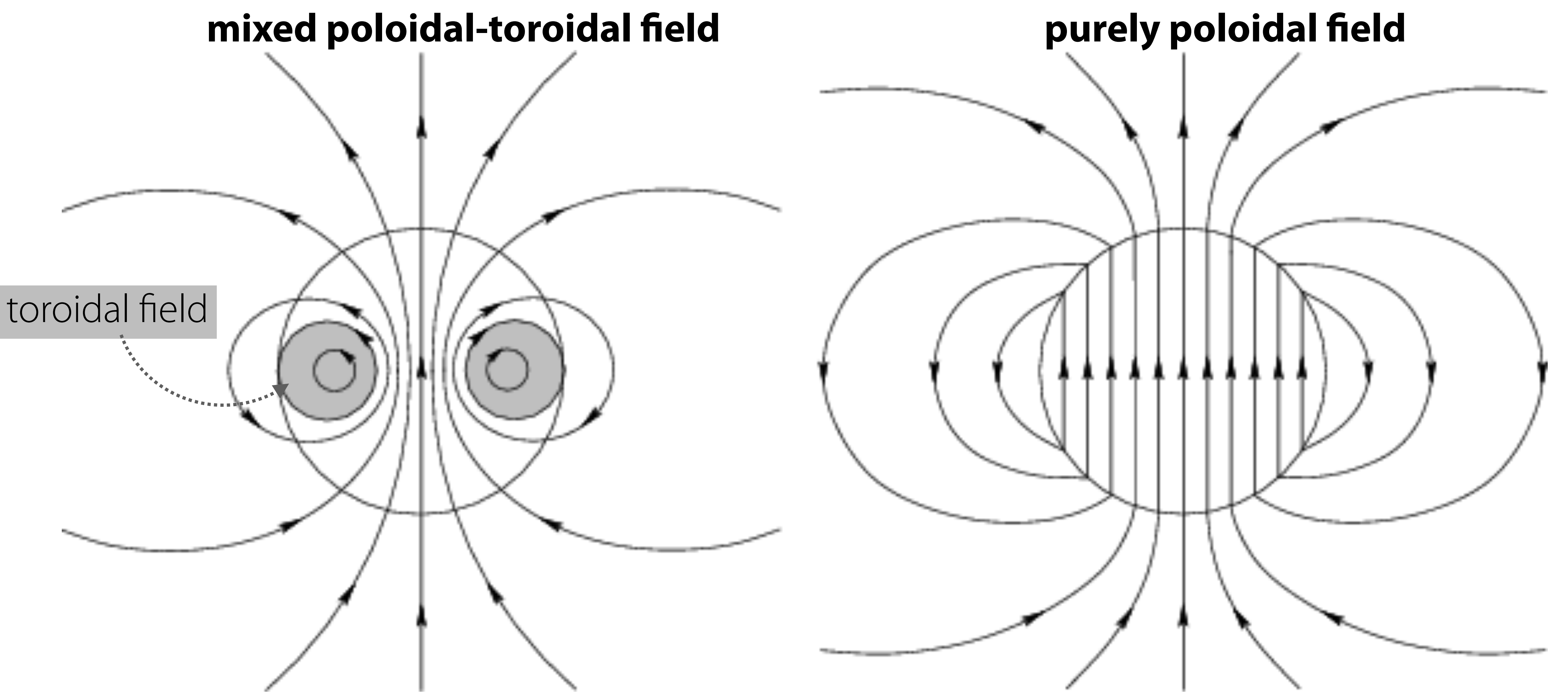
Sun — more complicated



- Like Earth, also the Sun is permeated by a dipole field but with much more complicated additional field geometry that changes over time (solar cycle)

Magnetism

Global magnetic field configurations



Braithwaite & Spruit 2004

- Note — in the hypothetical case of a non-rotating star: the left config. is stable, the right one not

Magnetism

Take aways

- Ionised gas (plasma) in motion — electric and magnetic fields need to be considered

- Magnetic pressure arises — impacts structure and dynamics of the plasma
  - Higher magnetic field means lower thermal pressure and lower density with respect to the surrounding

- 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.**

The solar dynamo

Dynamo

Overview

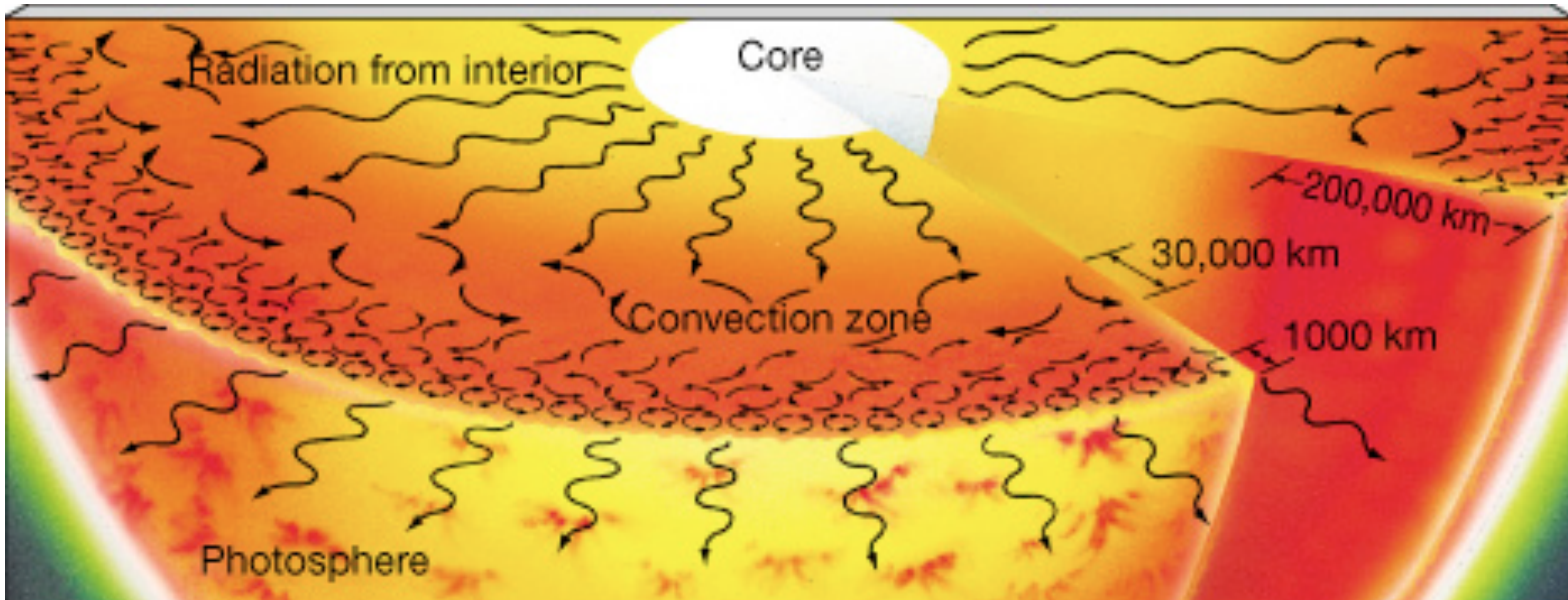
- Interior of the Sun: plasma (ionized gas) — charged particles
- Convection moves around the plasma (turbulence)

  ➡ Moving charged particles generate electric currents

  ➡ Electric currents generate magnetic fields (via Ampere's law).

  ➡ Changing magnetic fields change, induce electric currents (Faraday's law).

  ➡ **Self-reinforcing dynamo process**
- Continuous generation of magnetic dipole fields
- Convection currents **stretch and twist** the magnetic field lines, increases magnetic tension *(analogy for magnetic field lines: rubber bands)*
- Magnetic field gets stronger in some locations and/or orientation of field varied



Dynamo

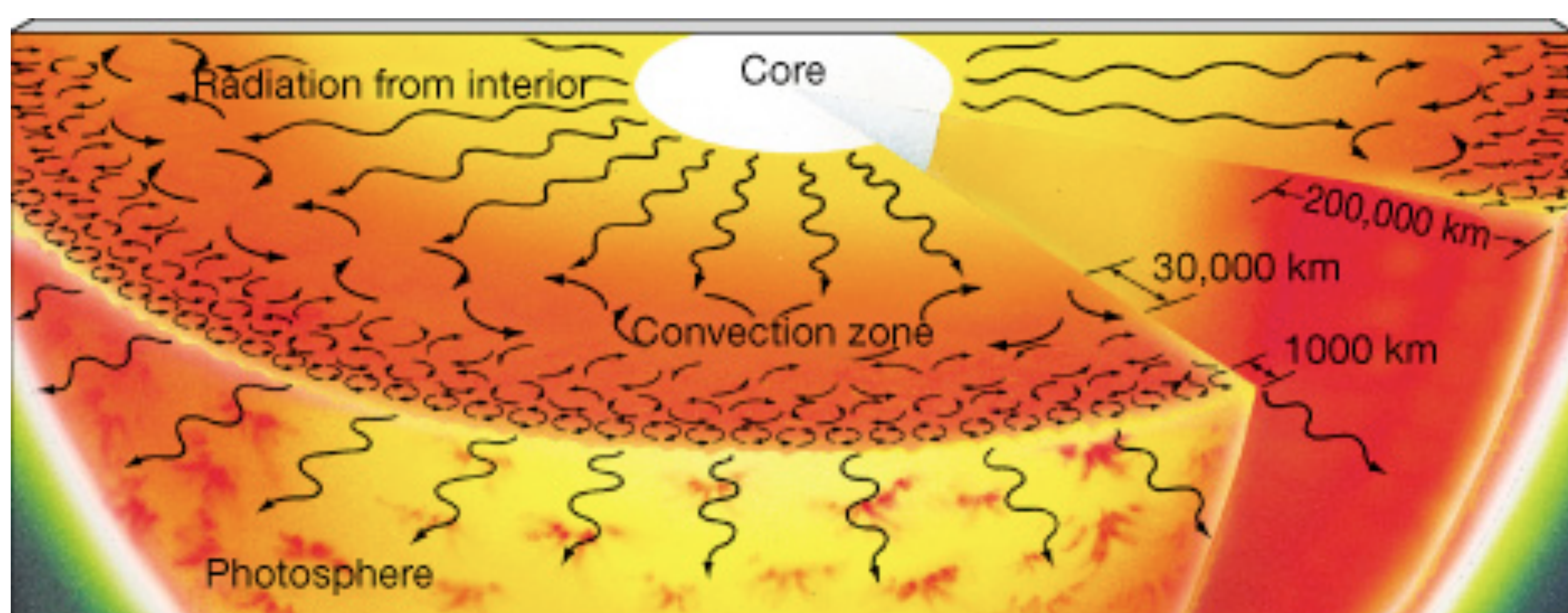
Overview

$$\frac{\partial \vec{B}}{\partial t} = \eta \vec{\nabla}^2 \vec{B} + \vec{\nabla} \times (\vec{u} \times \vec{B})$$

Magnetic diffusivity (η) — Velocity ($\vec{u}$)

- Requirements for an efficient dynamo
  - **Properties of the flows** in the solar interior
    - convection
    - differential rotation
    - meridional flow
  - ★ **Tachocline:** Strong radial change in rotation speed, exhibits a strong radial shear
- Plasma motions must convert meridional (poloidal) magnetic field into an azimuthal (toroidal) magnetic field, and vice versa.
- **Induction** has to overcome magnetic diffusion (large magnetic Reynolds number)
- Magnetic field decays on time scales much shorter than the Sun's life time

➡ **New field is generated** continuously



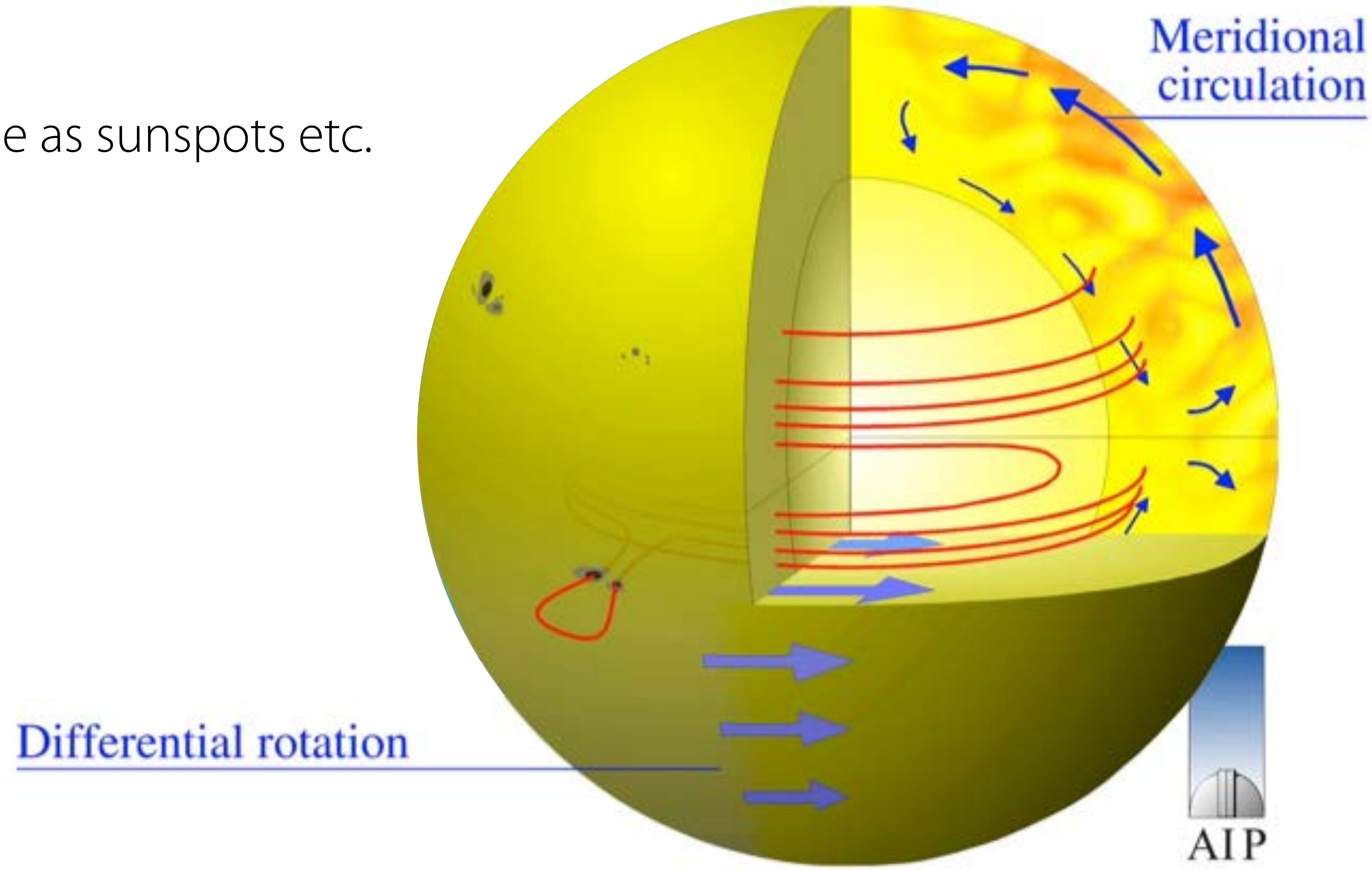
Dynamo

Overview

- Current understanding: Magnetic field generated by a dynamo located near the bottom of the convection zone (overshoot layer, tachocline)
- Produces toroidal flux bundles
- Once magnetic field sufficiently strong, flux bundles become buoyant (Parker instability)

➡ Rise towards surface

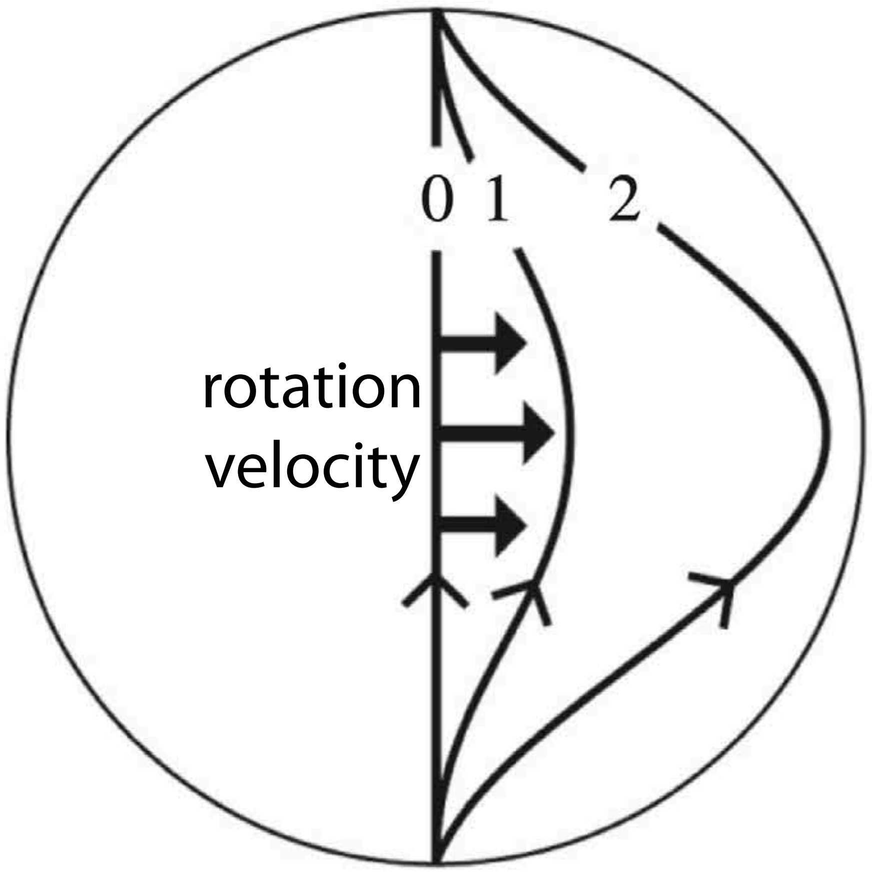
➡ Break through surface, visible as sunspots etc.



Dynamo

Ω-effect (Omega effect)

- Omega effect converts initially meridional (poloidal) magnetic field into azimuthal (toroidal) magnetic field due to **differential rotation**



magnetic
field
(“flux ropes”)

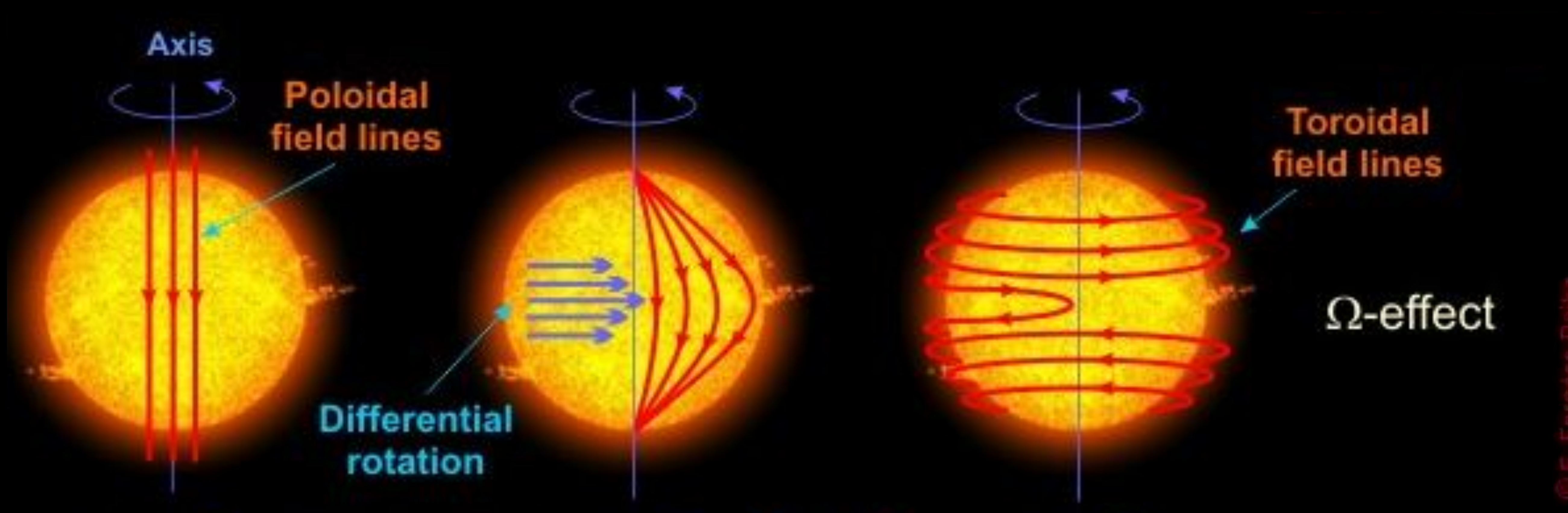
Dynamo

Ω-effect (Omega effect)

- Omega effect converts initially meridional (poloidal) magnetic field into azimuthal (toroidal) magnetic field

➡ Initial meridional magnetic field is twisted and coiled around the Sun due to **differential rotation**

➡ Creates magnetic flux strands in the azimuthal (toroidal) direction in shallow depths and low latitudes

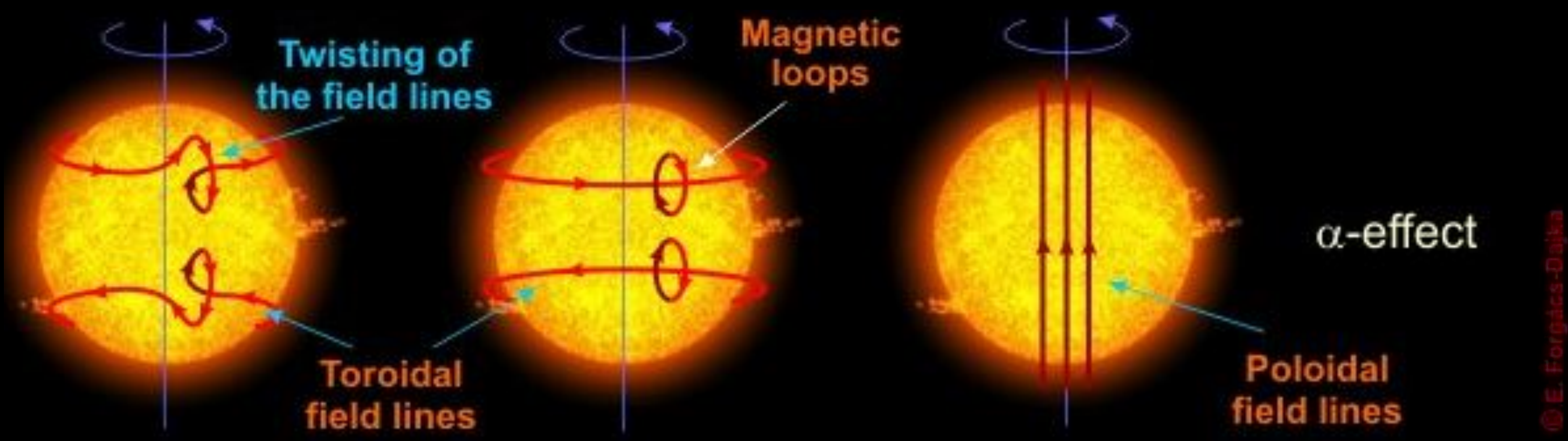


Dynamo

α-effect (Alpha effect)

(Parker 1955, Babcock 1961)

- Alpha effect converts an azimuthal (toroidal) magnetic field into a meridional (poloidal) magnetic field.
- Precise mechanism still not fully understood
- Most likely due to interaction between
  - velocity field of the plasma
  - rotation of the sun
  - toroidal magnetic field
  - Coriolis force acting on rising flux tubes



Dynamo

α-effect (Alpha effect)

- Sphere of hot plasma rotating at an angular velocity $\boldsymbol{\omega}$.
- Convection: Plasma "bubbles" rise upwards with velocity $\boldsymbol{v}$.
- High gas pressure (deep) in the convection zone: $P_g >> P_m \Rightarrow \beta >> 1$

  ➡ **High plasma-beta** conditions, magnetic field frozen in

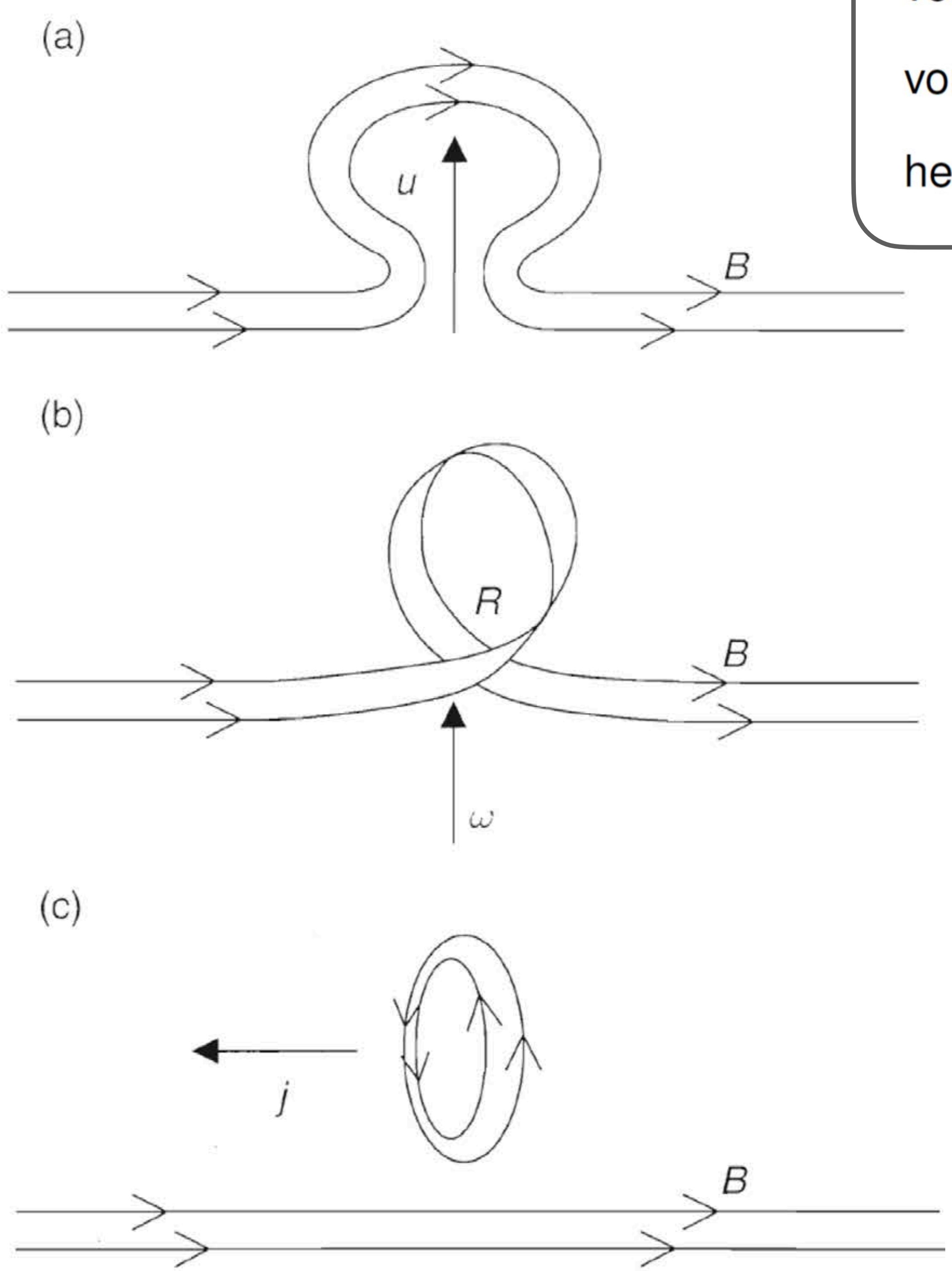
  ➡ Toroidal magnetic field gets partially dragged along by the moving plasma bubbles
- Solar rotation induces **Coriolis force** ($\boldsymbol{\omega} \times \boldsymbol{v}$) on plasma bubbles
- Bubbles and with it the frozen-in magnetic field twists as it moves upwards and expands.
- Note: Signs of both the Coriolis force and toroidal magnetic field are reversed in the northern versus the southern hemisphere!

  ➡ Small-scale magnetic field loops of the same polarity in both hemispheres
- Small-scale loops gradually merge due to magnetic diffusivity

  ➡ Generates a large scale poloidal magnetic field (Parker 1955).

Dynamo

α-effect (Alpha effect)

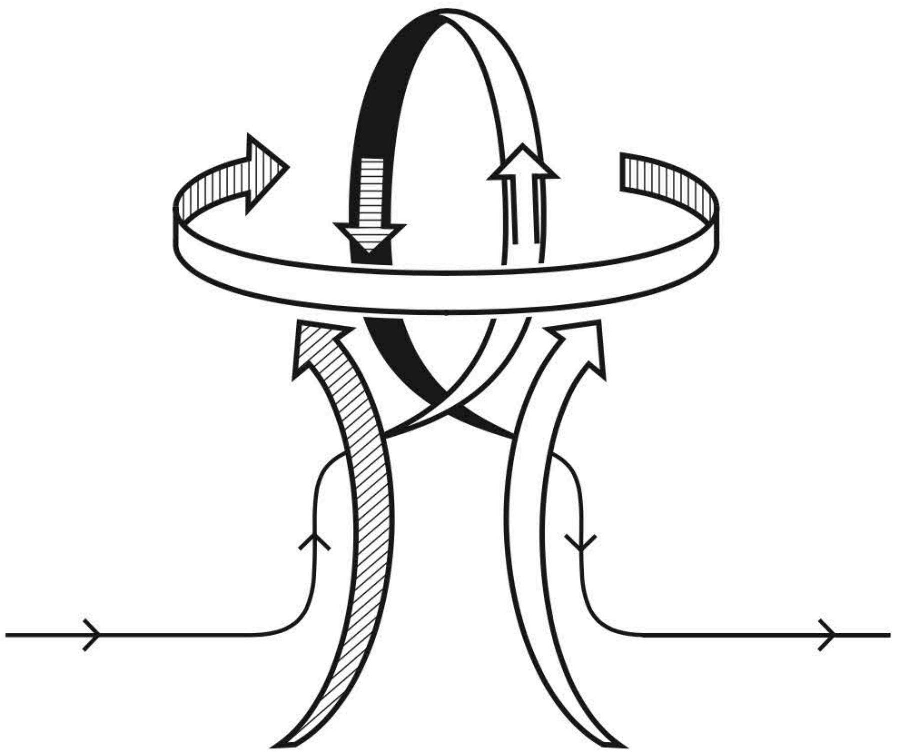


Parker 1955

velocity $\boldsymbol{u}$

vorticity $\omega = \nabla \times \boldsymbol{u}$

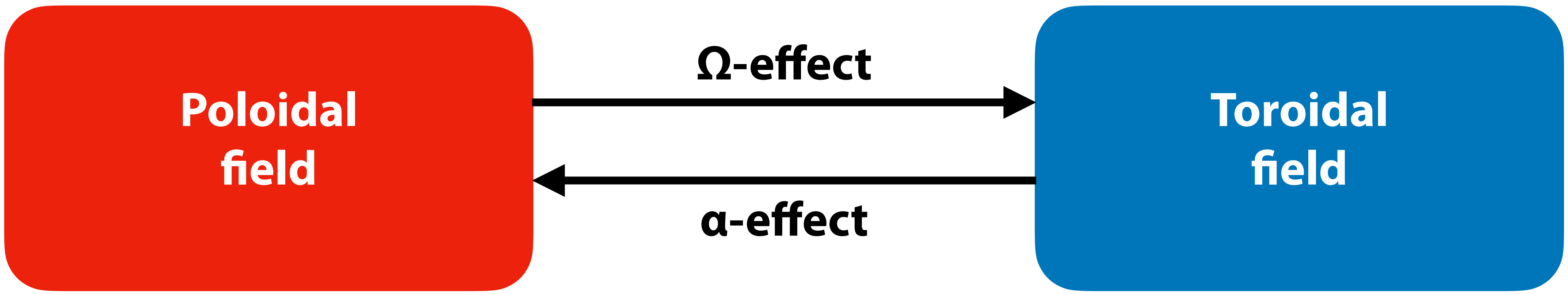
helicity $H = \boldsymbol{u} \cdot \omega$



Rising and twisting converts toroidal into poloidal flux

Dynamo

α and Ω



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

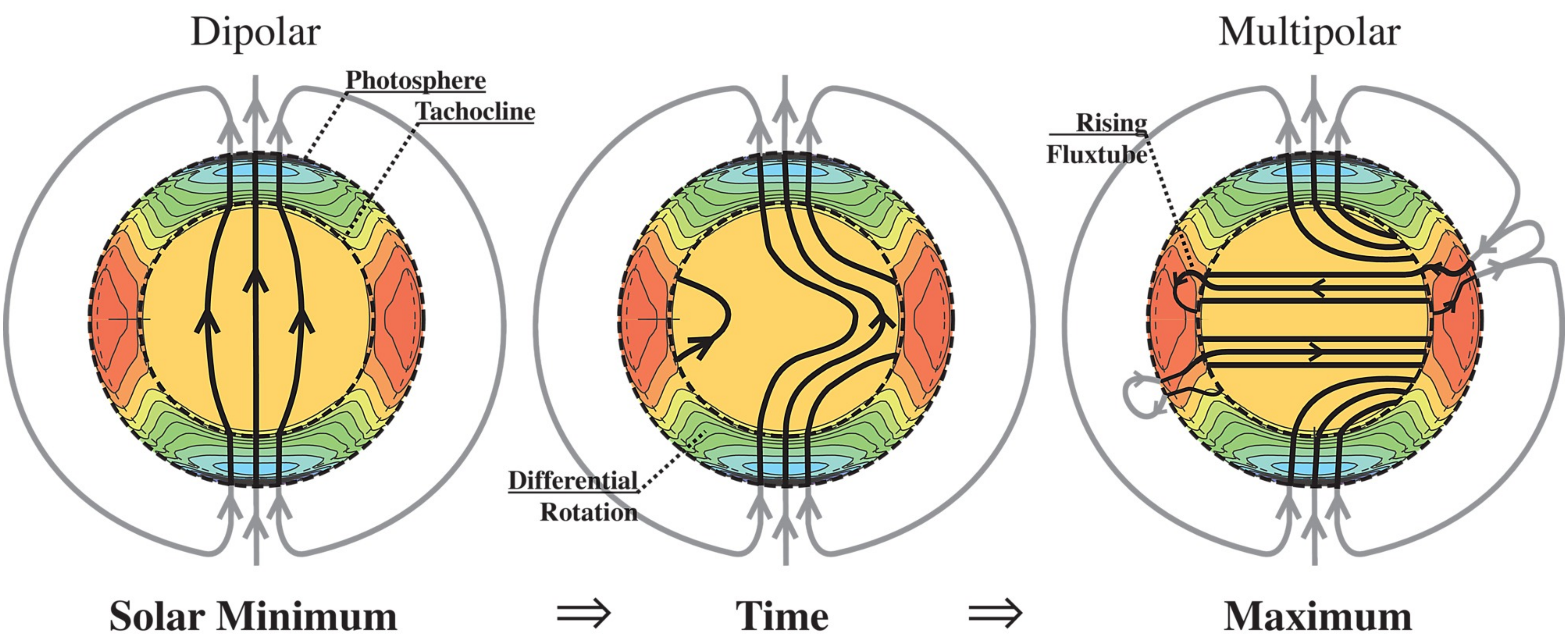
- generates magnetic activity (e.g., sunspots) during **solar (activity) maxima**

- **Solar cycle**: Change between these extreme configurations, forming a solar activity minimum
  - One cycle period ~11 year
  - 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

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 into toriodal configuration.



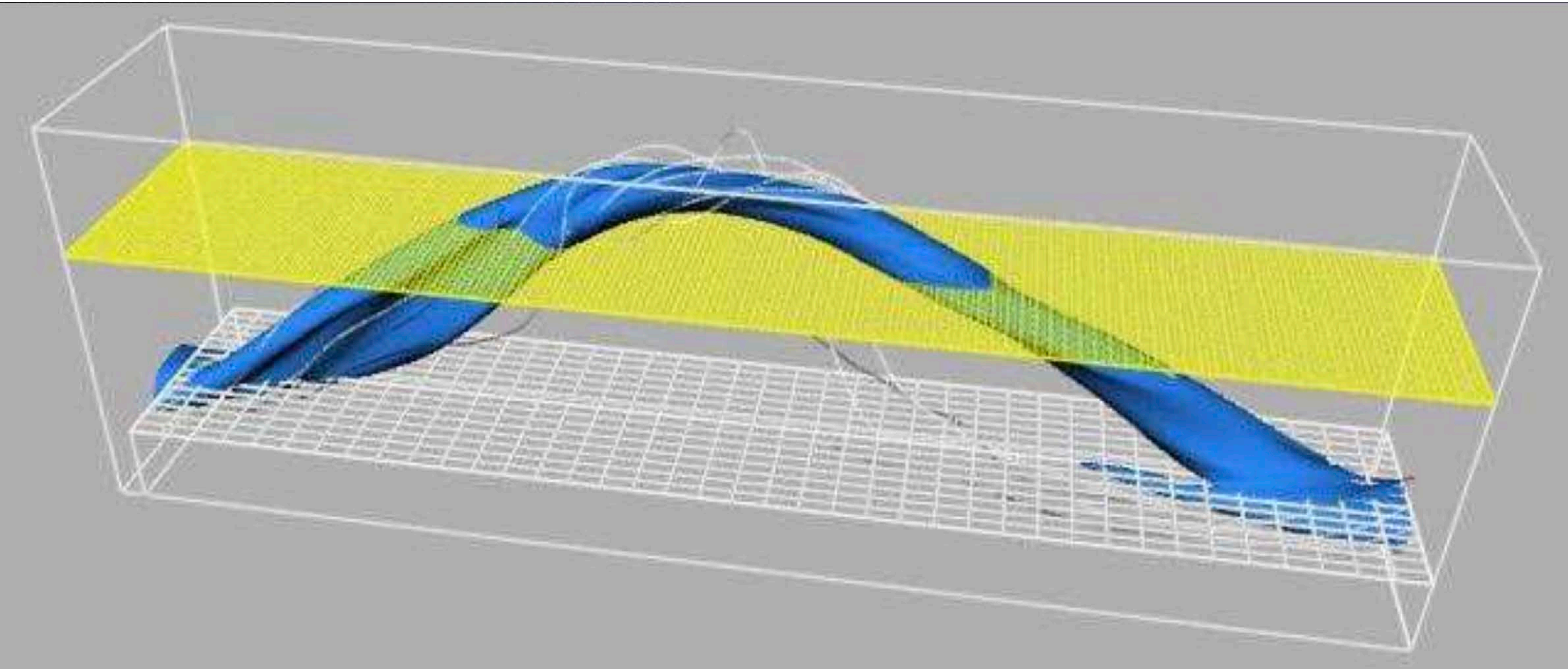
Higgins, Paul (2012): Schematic of the Solar Dynamo. figshare. Figure. https://doi.org/10.6084/m9.figshare.102094.v1

Dynamo

Emergence of a magnetic flux tube

- Magnetic field generated mainly in the tachocline near bottom of convection zone
- **Magnetic pressure** inside flux rope — lower density inside than in the surrounding plasma

➡ Magnetic flux rope becomes **buoyant, rises upwards** (Parker instability)

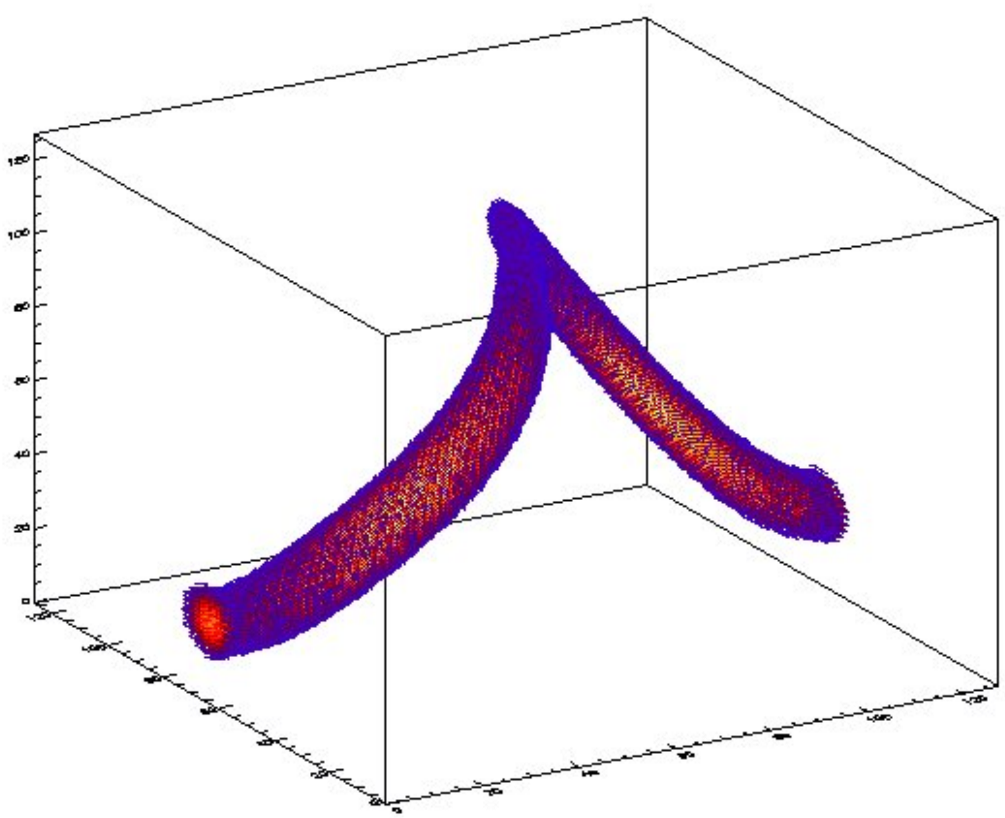


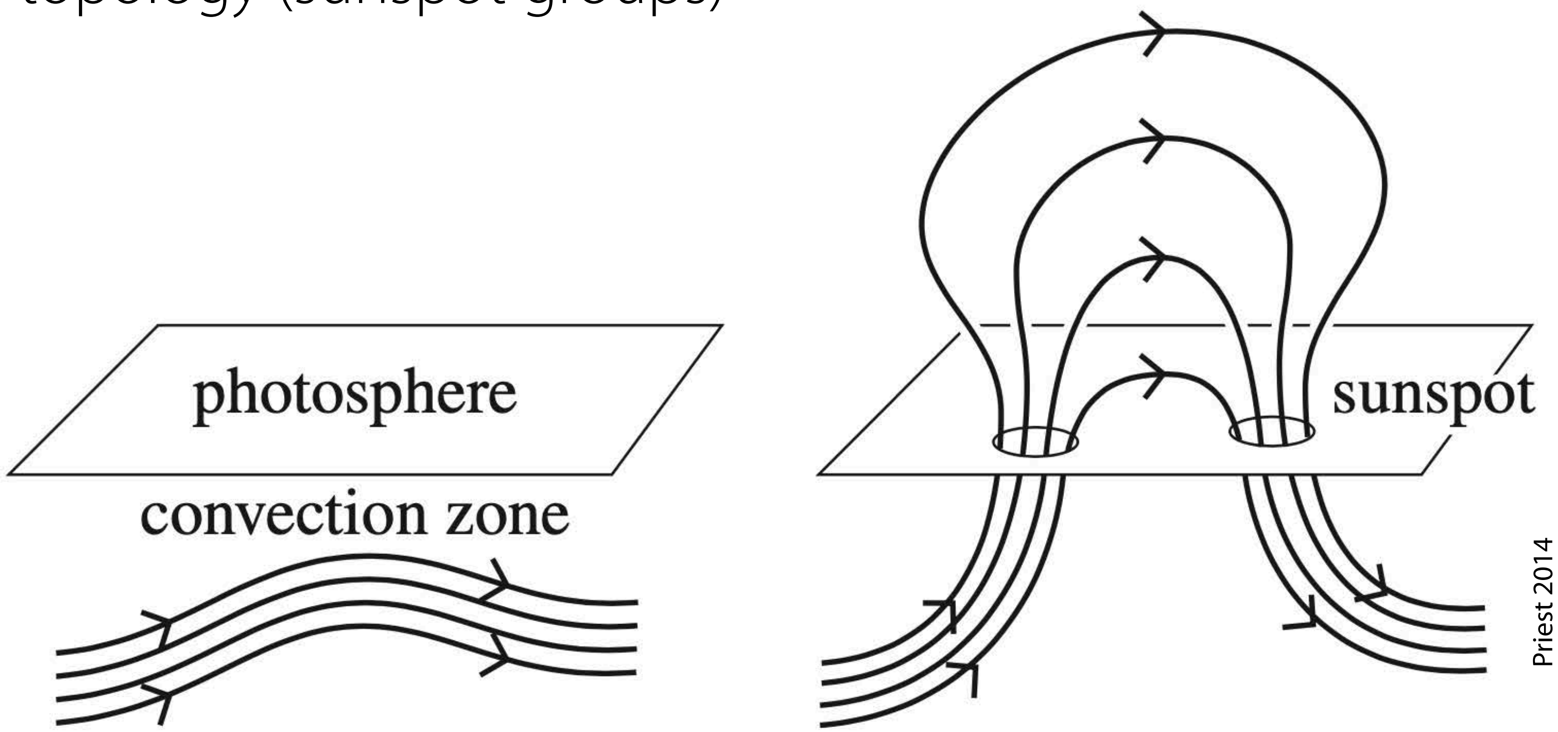
Dynamo

Emergence of a magnetic flux tube

- Magnetic flux rope rises to surface due to its buoyancy (Parker instability)
- Flux rope reaches surface eventually
- The two points where the loop breaks through the surface are sunspots of opposite polarity
- Flux rope produces a bipolar active region at the surface
  - In reality often more complicated topology (sunspot groups)

- While rising, the magnetic flux structure can become twisted





Priest 2014

Dynamo

Magnetic fields at the surface — Active Regions

Dynamo

Magnetic fields at the surface — Active Regions

Dynamo

Magnetic fields at the surface — Active Regions

- Magnetogram (HMI)