Lecture 9

AST5770

Solar and stellar physics

University of Oslo, 2023

Sven Wedemeyer

Magnetism

Magnetism

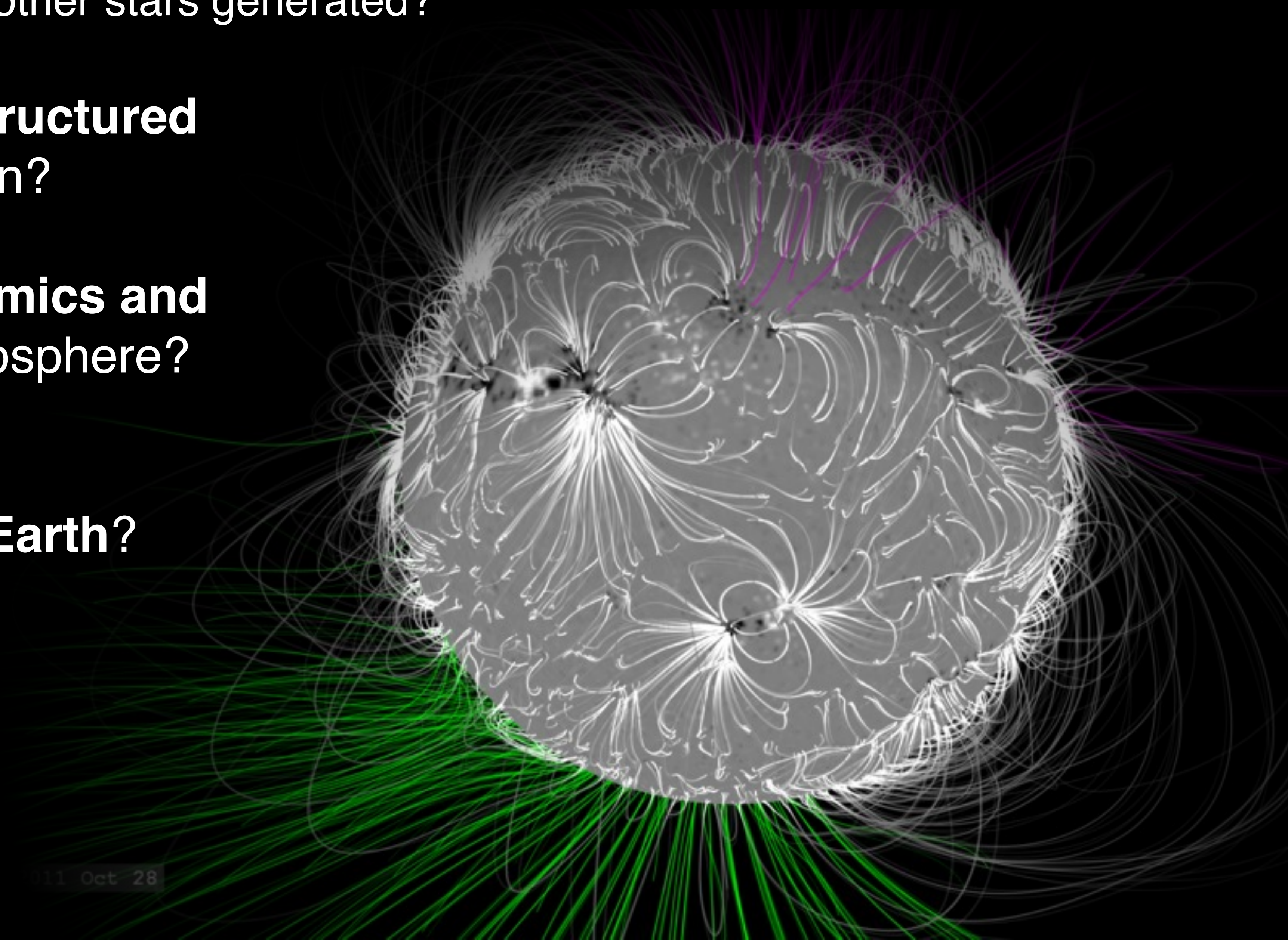
Many important questions …

- **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?

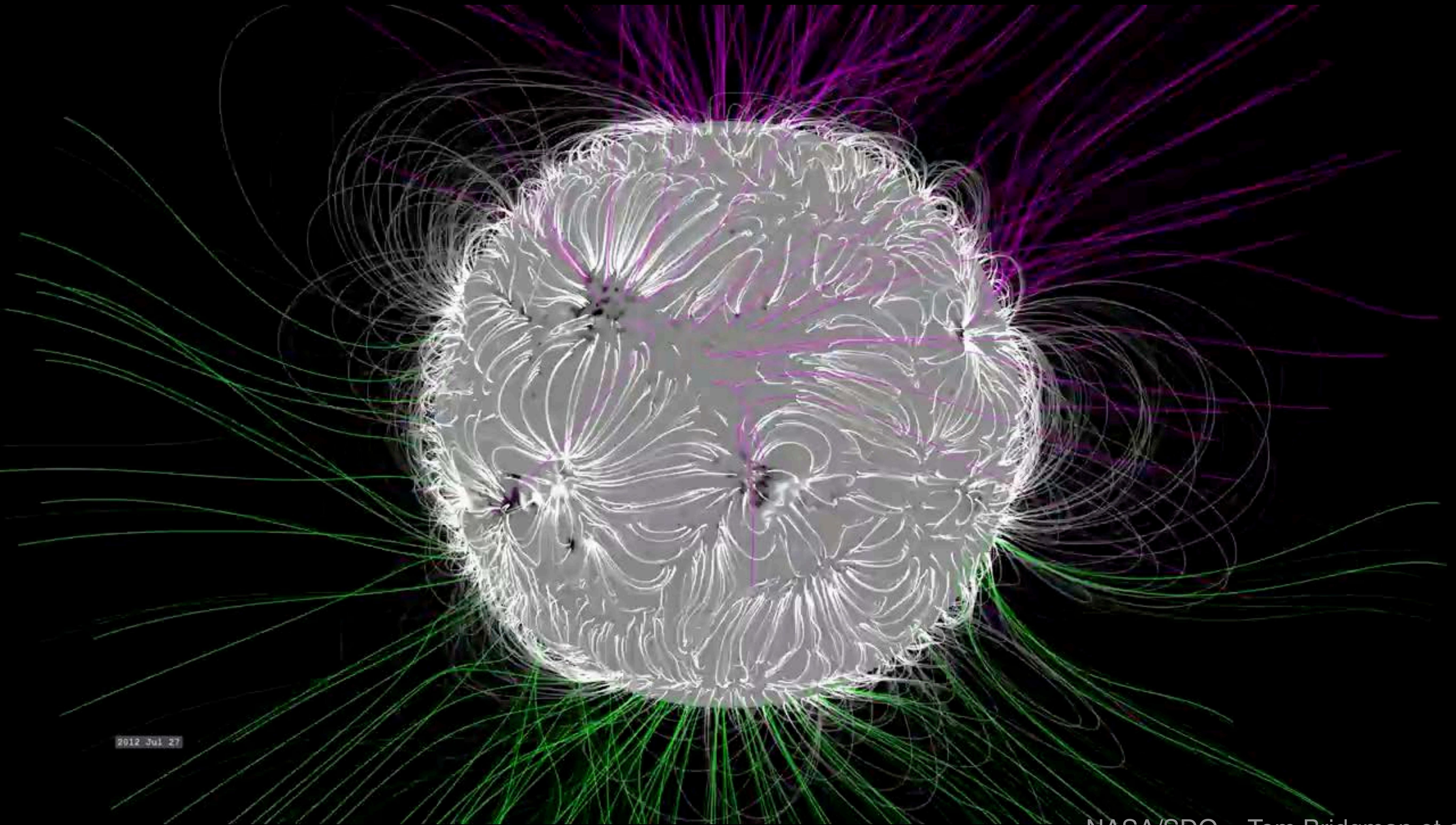
- How does it affect the **dynamics and energy balance** of the atmosphere?

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



Magnetism

Magnetic fields on the Sun — Introduction

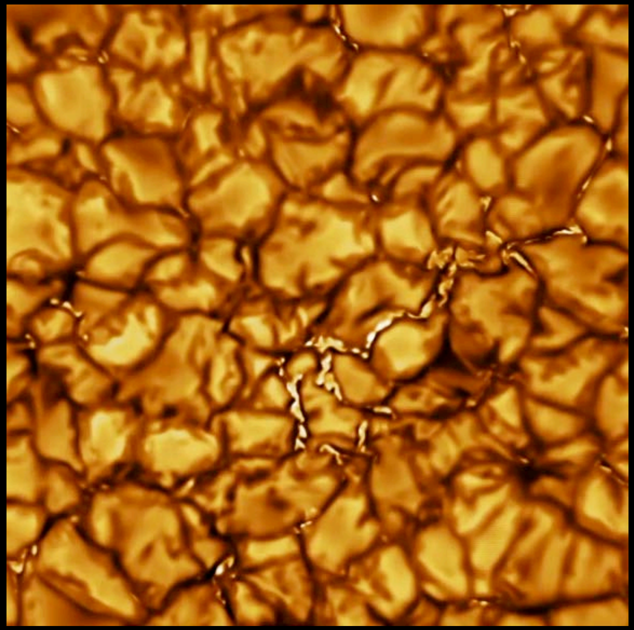


NASA/SDO - Tom Bridgman et a

Magnetism

Captured through different scientific missions

- Ground-based instruments (on Earth)
  - Begin with Galileo Galilei and the refracting telescope (1611)
  - “Solar Tower” in Meudon (France)
  - Swedish Solar Telescope (SST) and THEMIS spectro-palorimeter (Canary)
  - Daniel K. Inouye Solar Telescope (DKIST) in Hawaii …



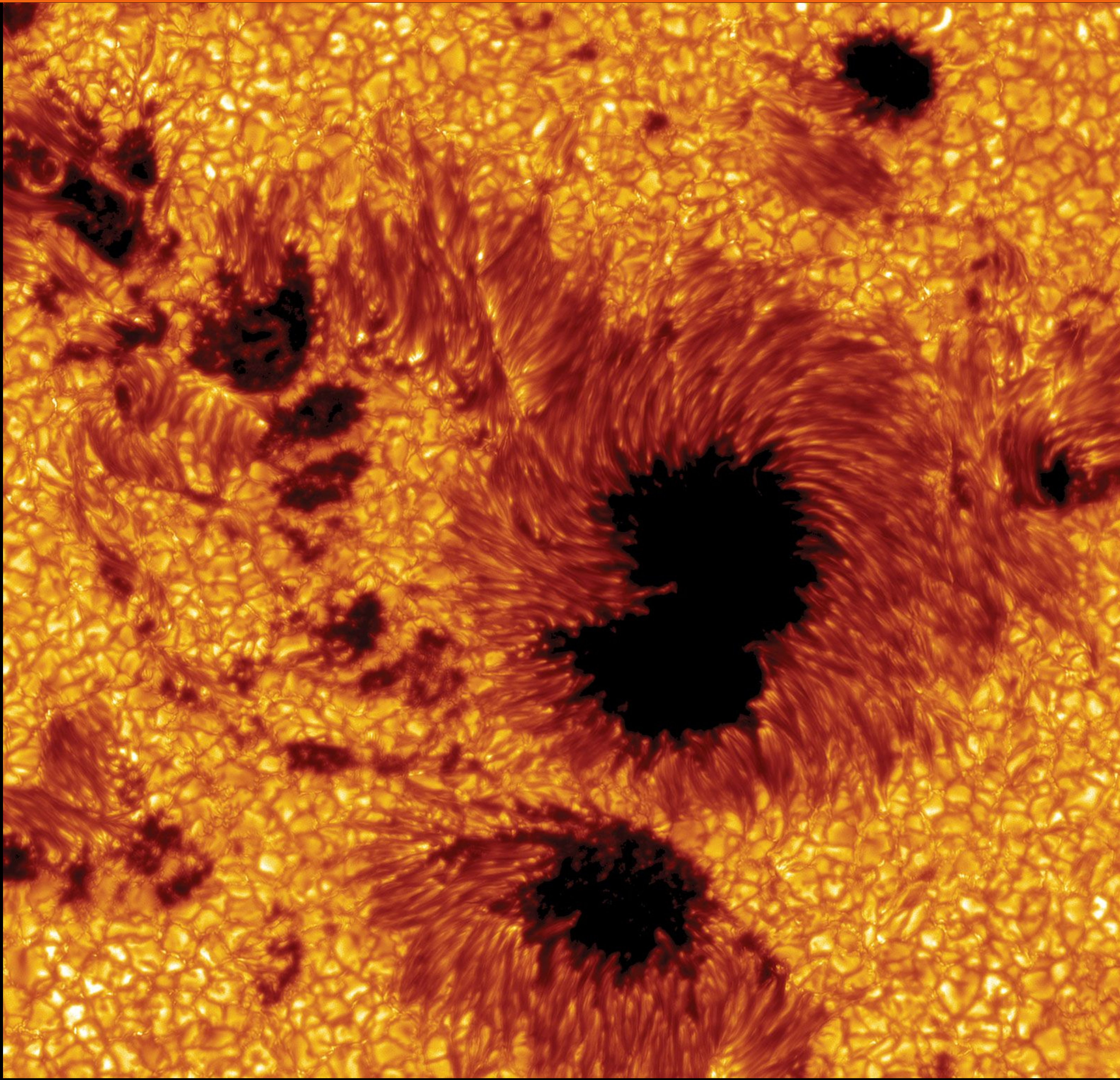
NSO DKIST

- Space missions
  - “Remote sensing” observations, especially for UV, X and γ-lights
  - “In situ” measurement of the ambiant magnetised wind of particules
  - Ex : SOHO, SDO, HINODE, Solar Orbiter, Parker Solar Probe…

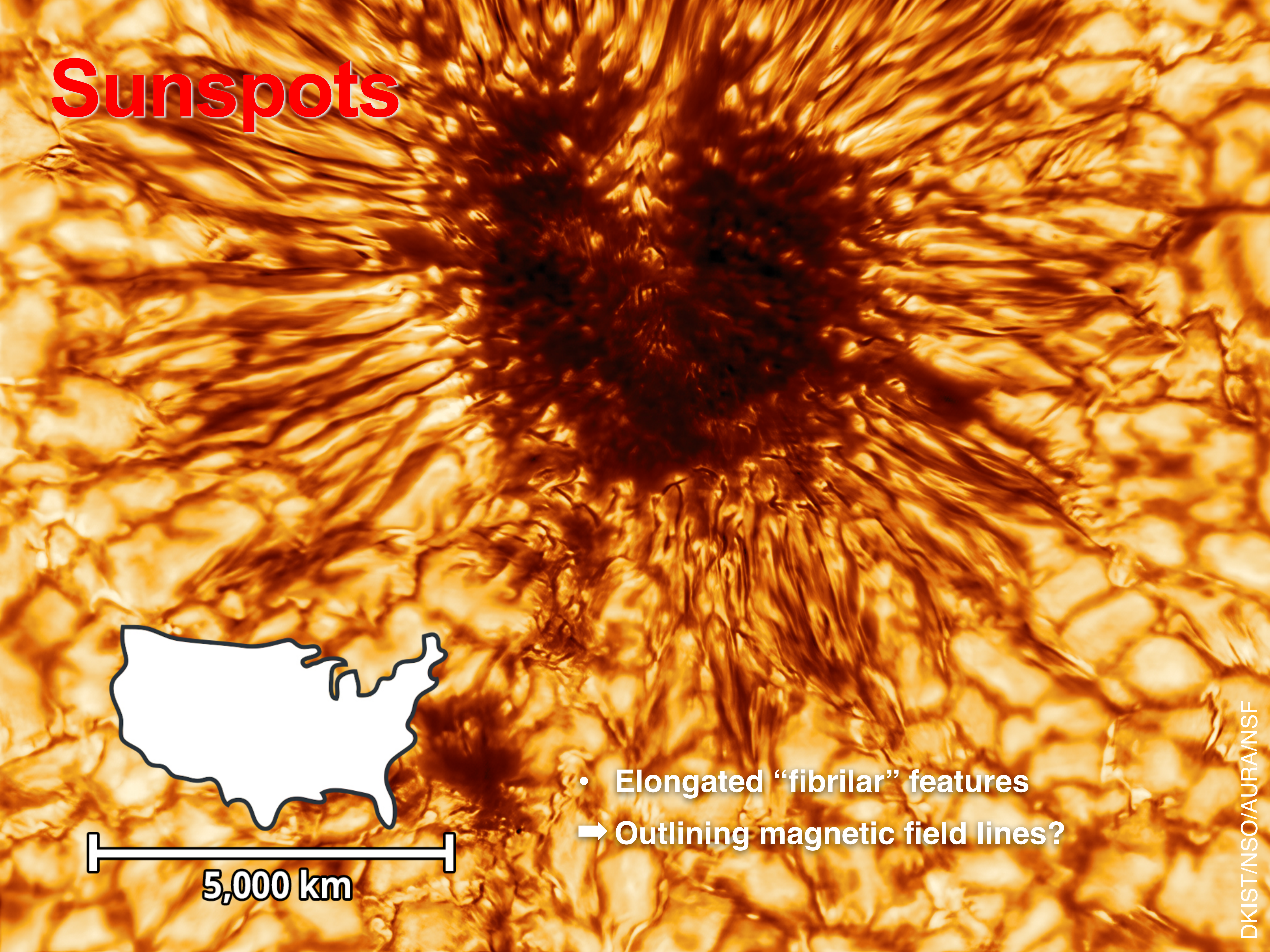
Magnetism

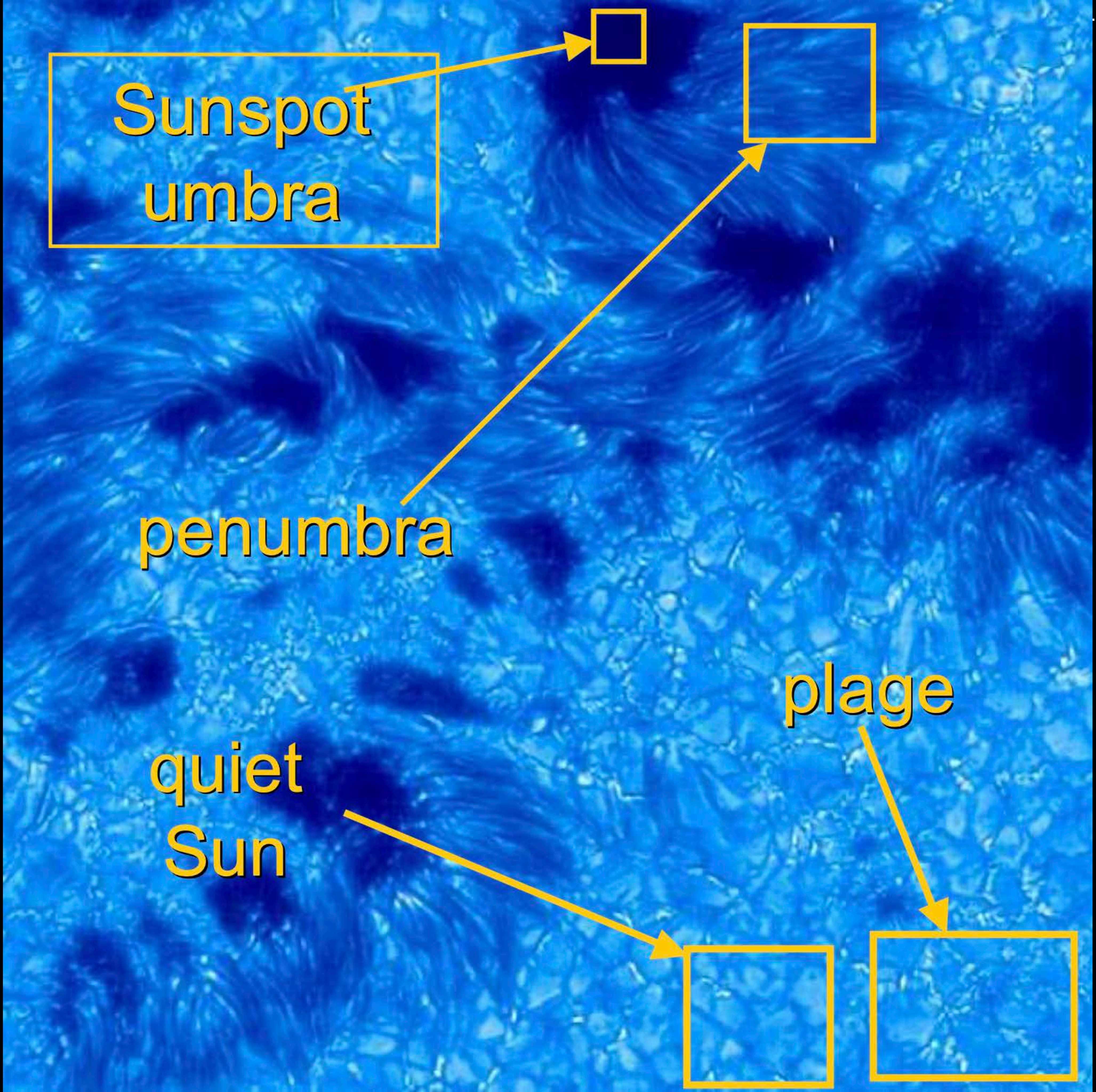
On the Sun

- 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


Sunspots
5,000 km
• Elongated “fibrilar” features
➡ Outlining magnetic field lines?
DKIST/NSO/AURA/NSF

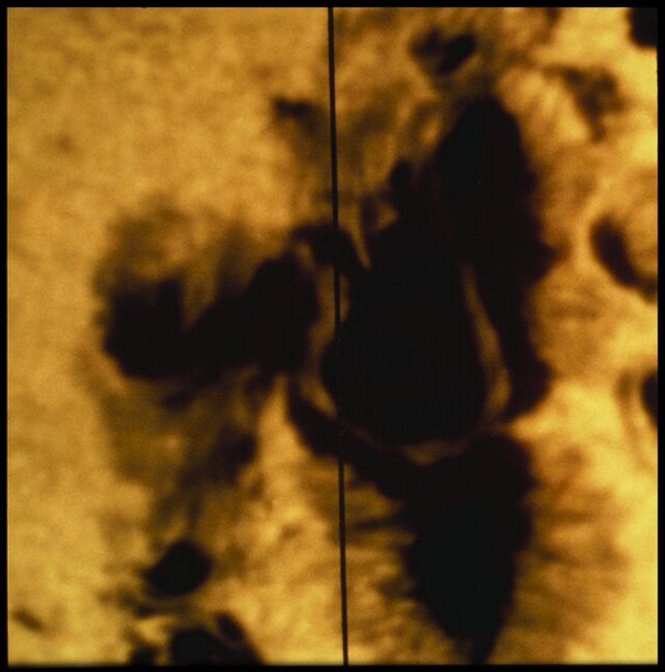


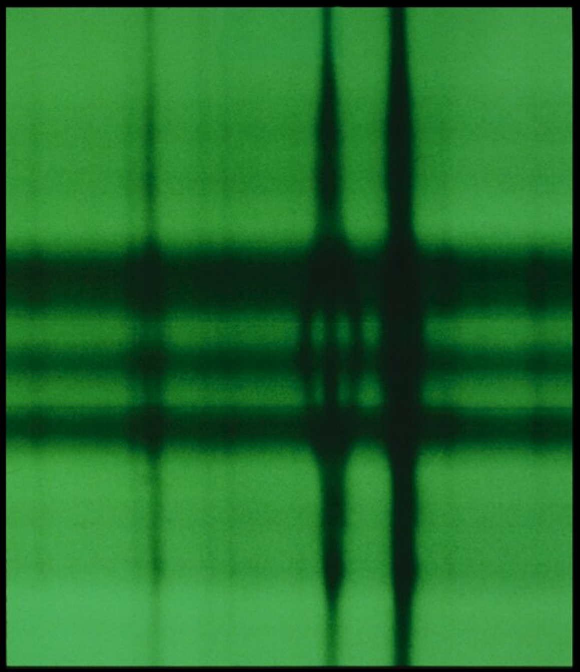
S. Wedemeyer
Q. Noraz

Magnetism

How to quantify it?

Kitt Peak National Observatory, NSO/AURA/NSF
See also Reiners et al. (2012)





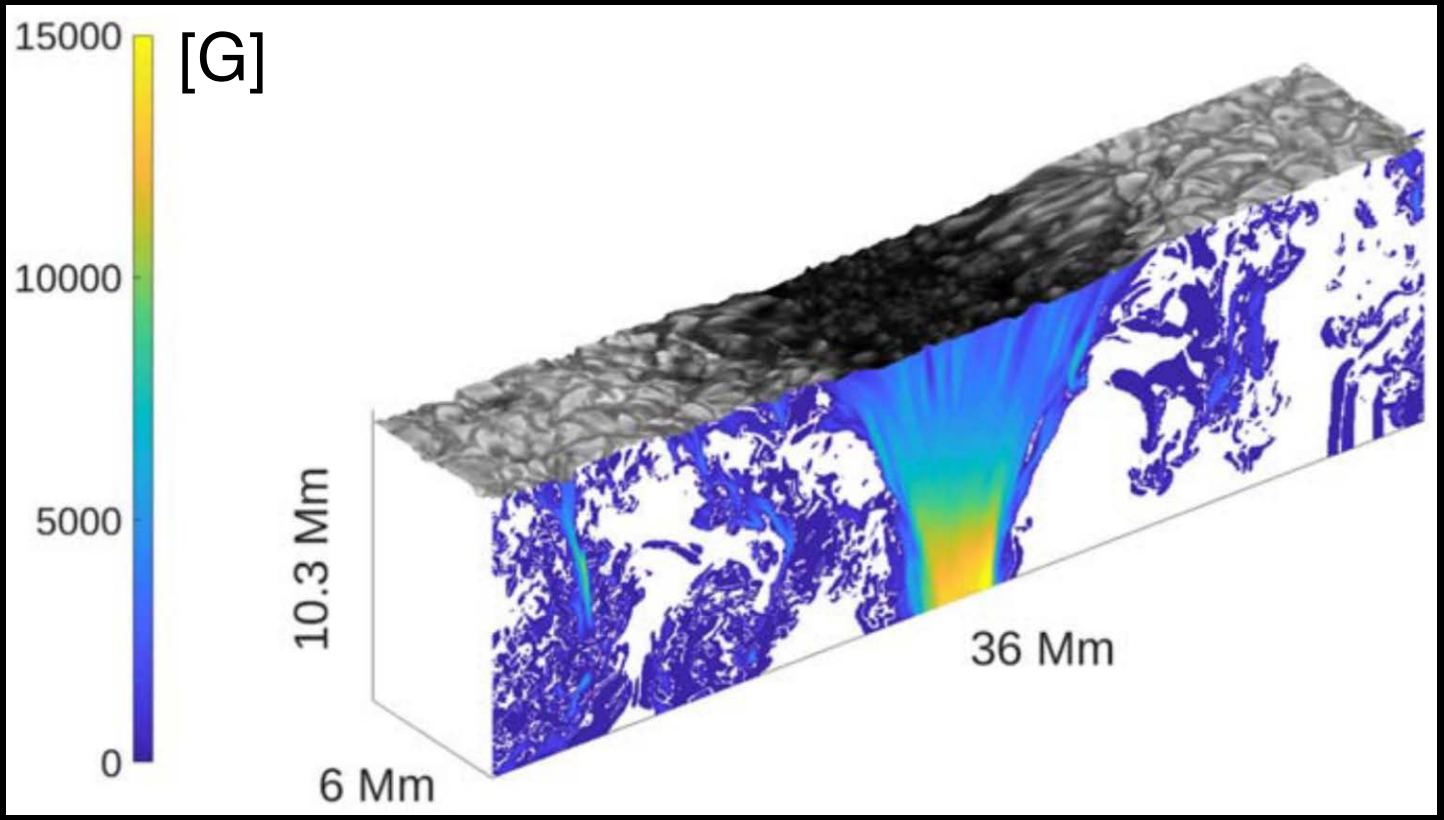
Through measurements :

Zemman effect on atomic rays

$\Delta\lambda = 46.67\, g_L\, \lambda_0^2\, |B|$

help from reconstruction/simulations:

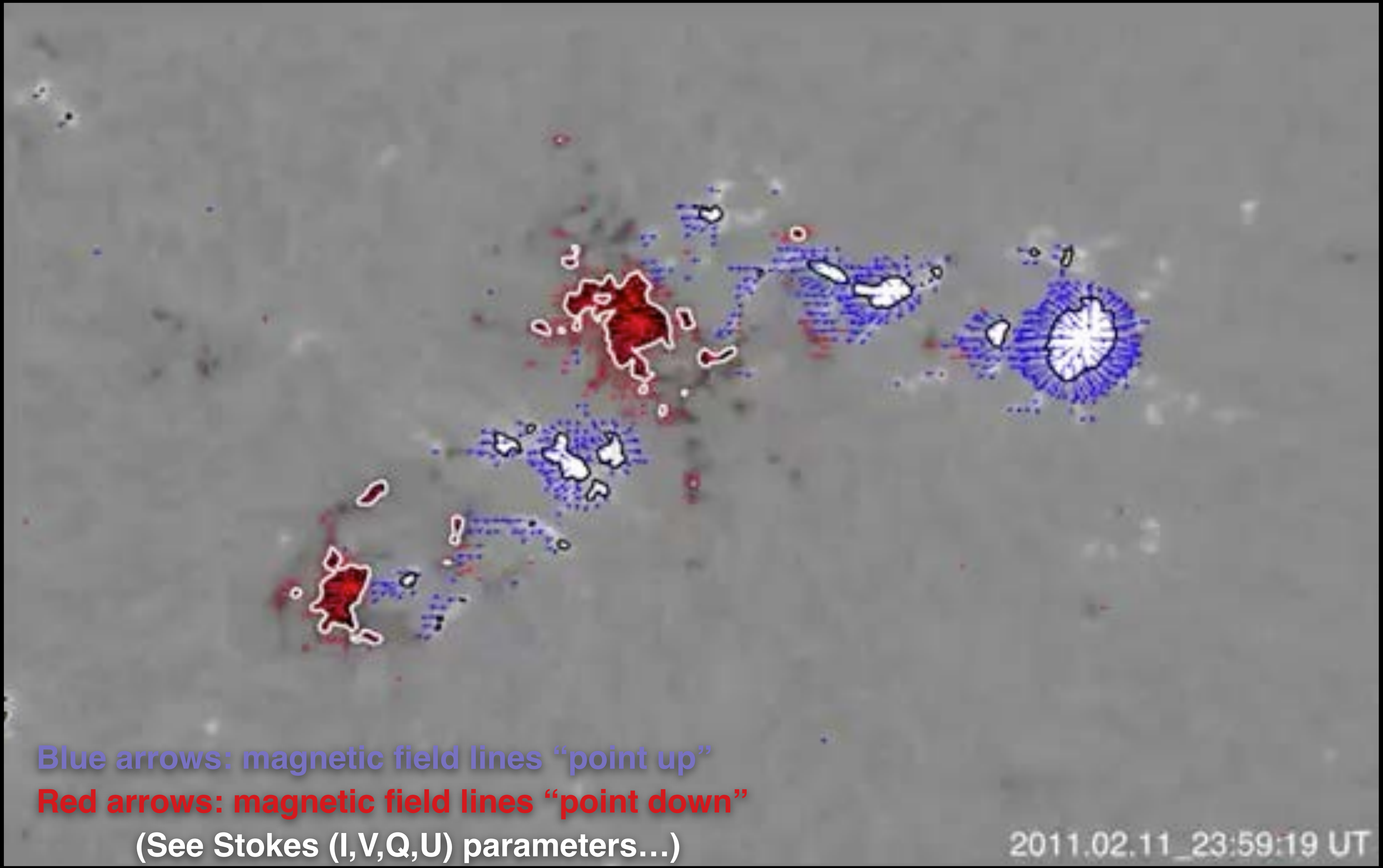
here Panja et al. (2020)



Magnetism

Photospheric magnetograms

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



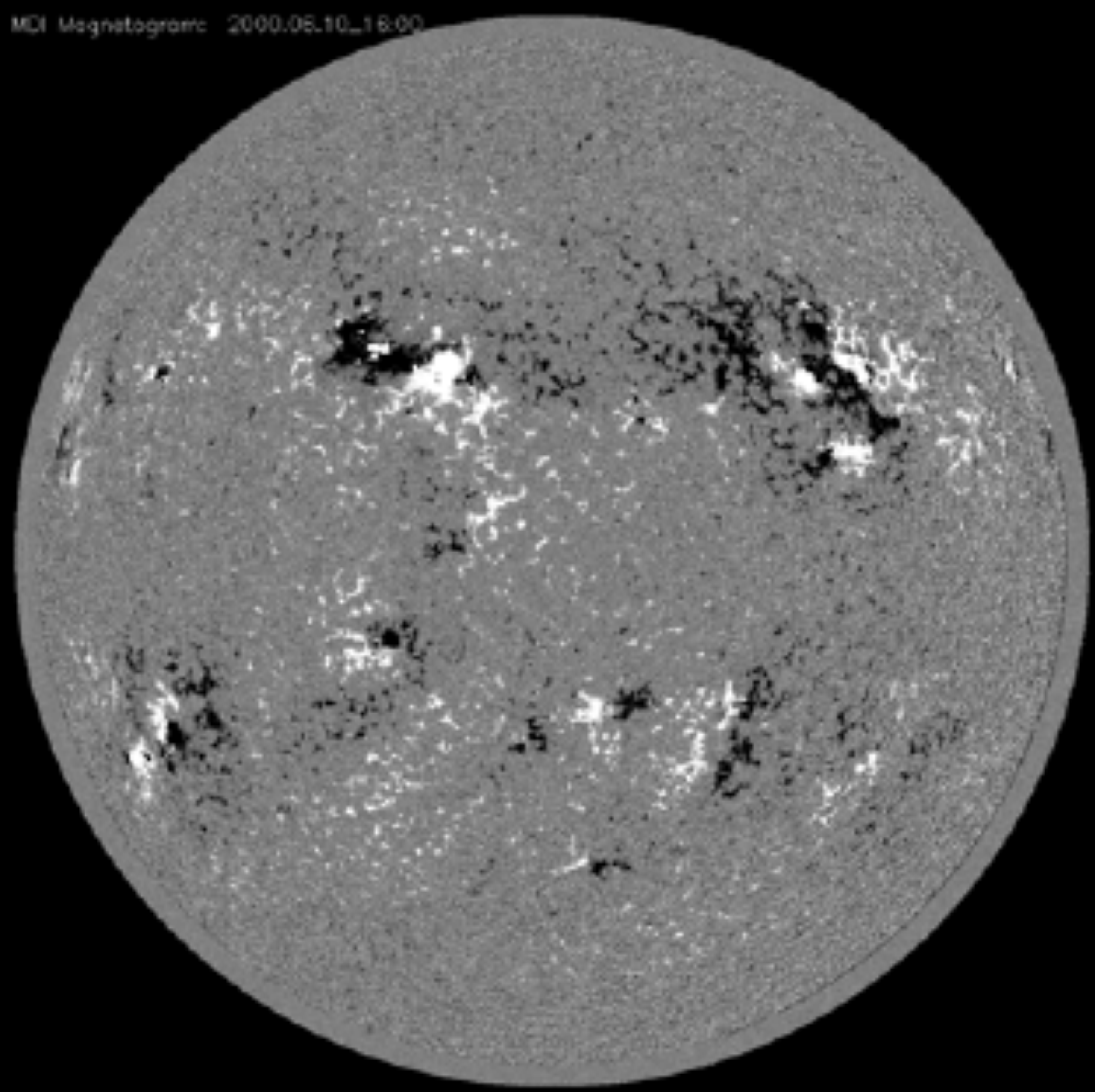
Observation follows target region, removing effect of solar rotation

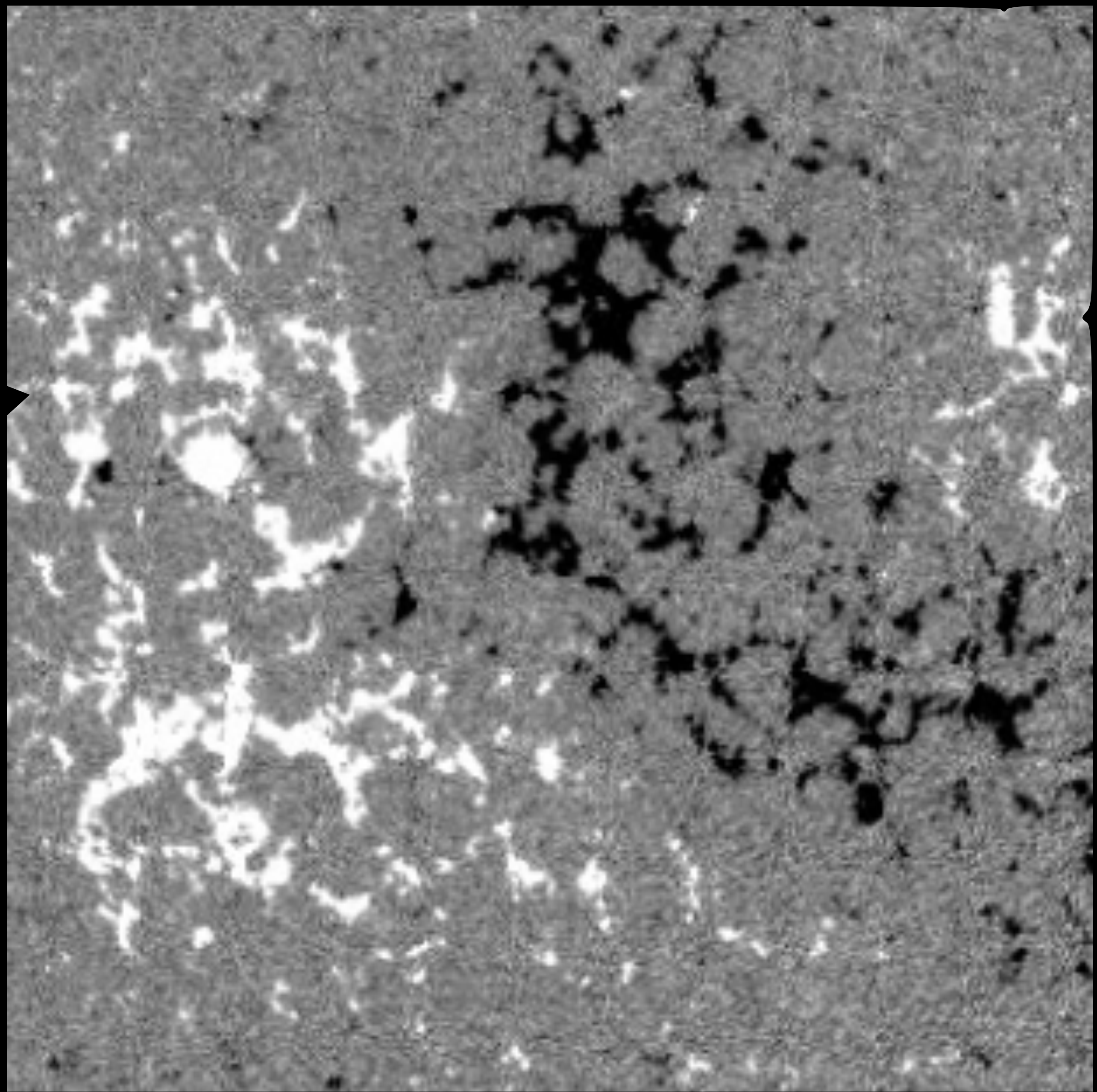
NASA/SDO - HMI

Magnetism

Photospheric magnetograms

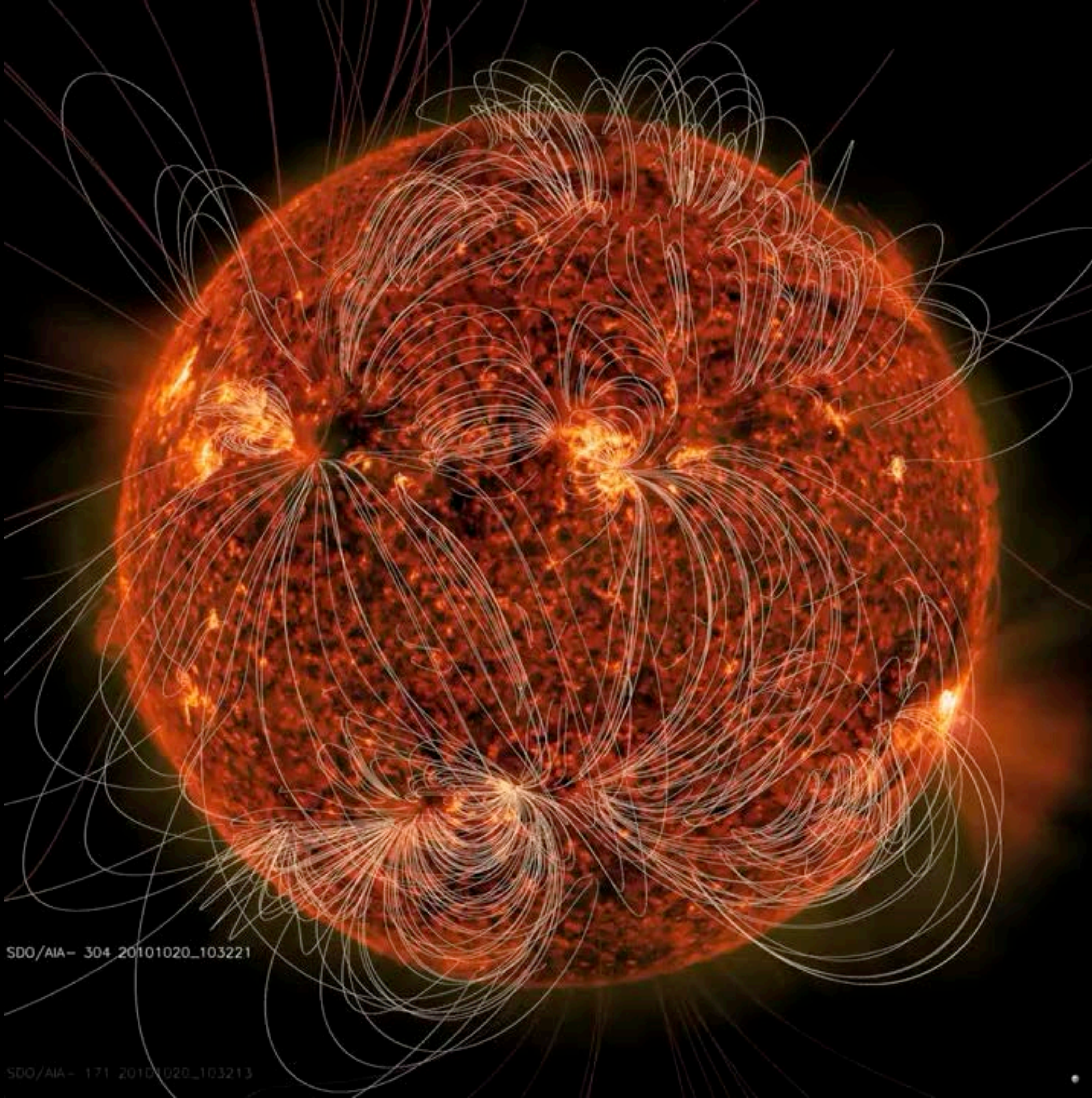
- Active regions, bi-polarity systematic east-west orientation opposite in the south





NASA/SDO - HMI

UiO - S. Wedemeyer
Q. Noraz



NASA/SDO - HMI

Magnetism

So far — Radiative-Hydrodynamic Equations

- Hydrodynamic equations:
  - Conservation of mass (density): (*mass* continuity equation) $$\partial_t \rho = -\boldsymbol{\nabla} \cdot (\rho \boldsymbol{v}),$$
  - Conservation of momentum: $$\partial_t \rho \boldsymbol{v} = -\boldsymbol{\nabla} \cdot (\rho \boldsymbol{v}\boldsymbol{v} + \underline{\tau}) - \boldsymbol{\nabla} p + \rho \boldsymbol{g},$$
  - Conservation of energy: $$\partial_t e = -\boldsymbol{\nabla} \cdot (e\boldsymbol{v}) - p\boldsymbol{\nabla} \cdot \boldsymbol{v} + q_{\mathrm{rad}} + q_{\mathrm{visc}},$$

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

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

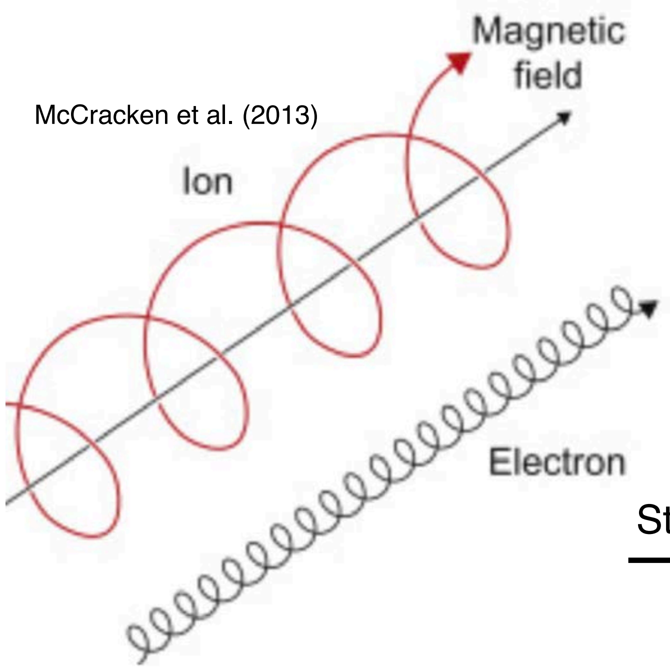
- Equation of state $P = c_s^2 \rho = \frac{\rho k_B T}{\ldots}$ perfect gas approximation

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

Magnetism

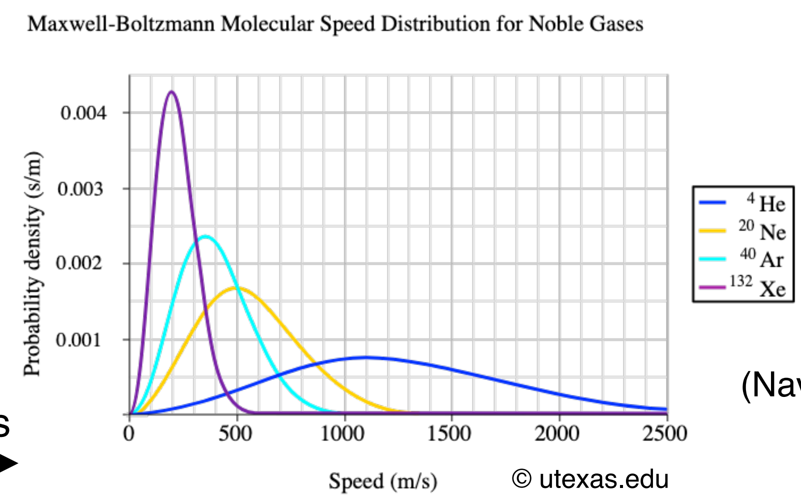
From particules to MHD

McCracken et al. (2013)



Particules approach

Statistical Physics



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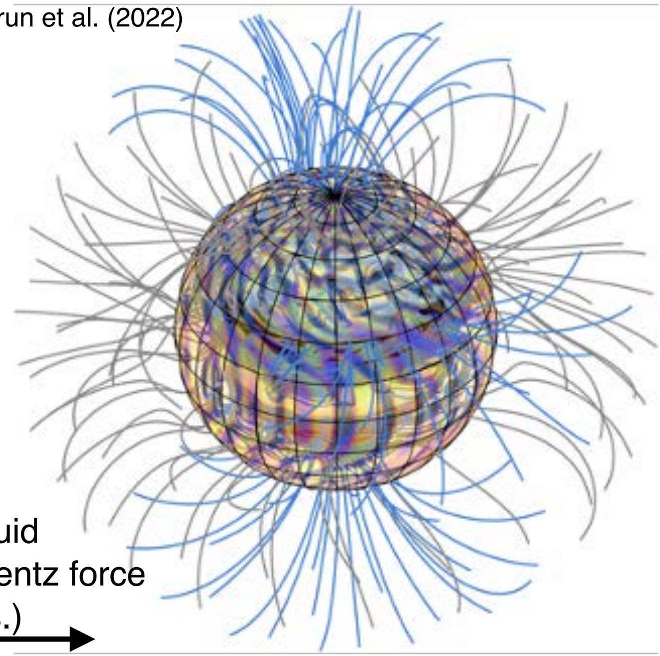
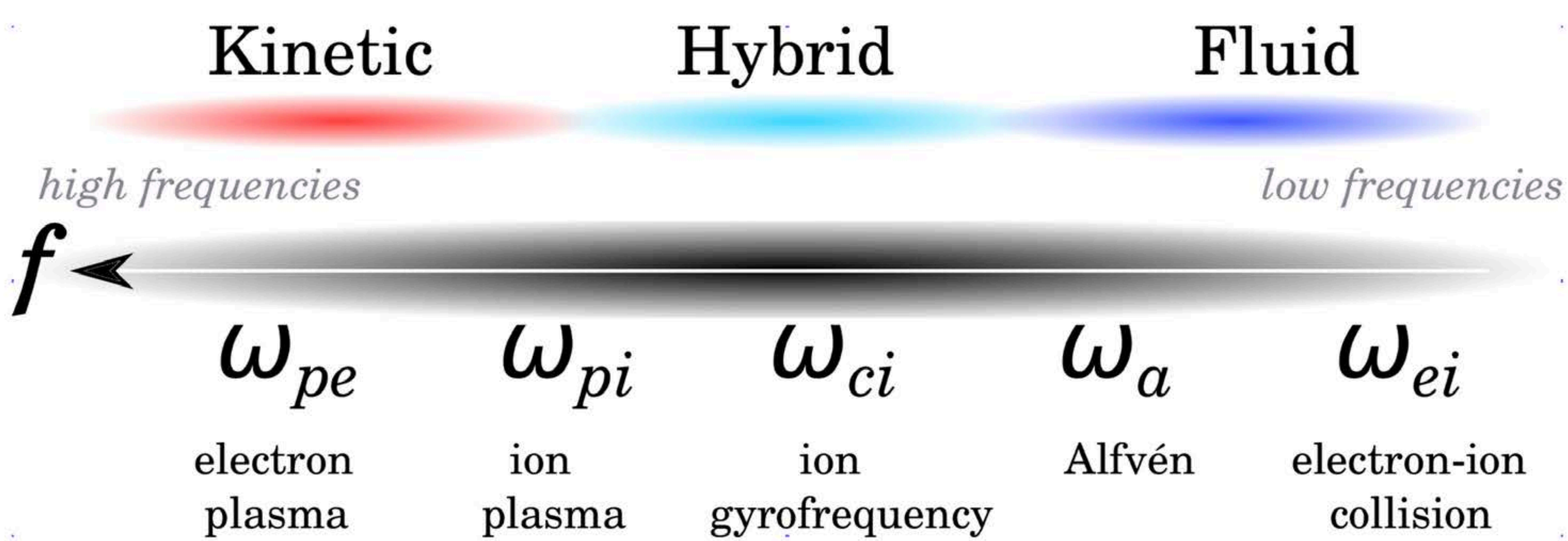
Continuous fluid
(Navier-stockes, Lorentz force
Maxwell Eqs.)

Brun et al. (2022)





Larger spatial/temporal scales

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 interactio
between the magnetic field and the plasma

j^2/σ: Ohmic dissipation

q: heat flux due to particle conduction

L_r: net radiation

Magnetism

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Equation of state	$p = \frac{k_B}{m} \rho T \quad \left(= \frac{\tilde{R}}{\tilde{\mu}} \rho T \right)$
Induction equation	$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$
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

$$\frac{d\rho}{dt} + \rho \mathbf{\nabla} \cdot \mathbf{v} = 0$$

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

$$\frac{\rho^\gamma}{\gamma - 1} \frac{d}{dt}\left(\frac{p}{\rho^\gamma}\right) = -\mathbf{\nabla} \cdot \mathbf{q} - L_r + j^2/\sigma + F_H$$

$$p = \frac{k_B}{m} \rho T \quad \left(= \frac{\tilde{R}}{\tilde{\mu}} \rho T\right)$$

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

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

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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 (see "Drude model"…)

  $$\sigma = n_e e^2 \tau_{ei} / m_e$$

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

- **Magnetic diffusivity** η

  $$\eta = 1/(\mu\sigma)$$

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

- **Charge conservation:** MHD "charge continuity equation"

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

  $$\varrho_q = q\, n$$
  $$\varrho_q \boldsymbol{v} = \boldsymbol{j}$$

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

- **Ohm's law:**
  (From Lorentz force of a large number of particules, 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 $\mathbf{j} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B})$

Magnetism

Generalized Ohms Law (For a plasma that consists of a mix of electrons, protons and neutral atoms)

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

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

Momentum Equation

- Conversation of momentum — the MHD equation of motion

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

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

Magnetism

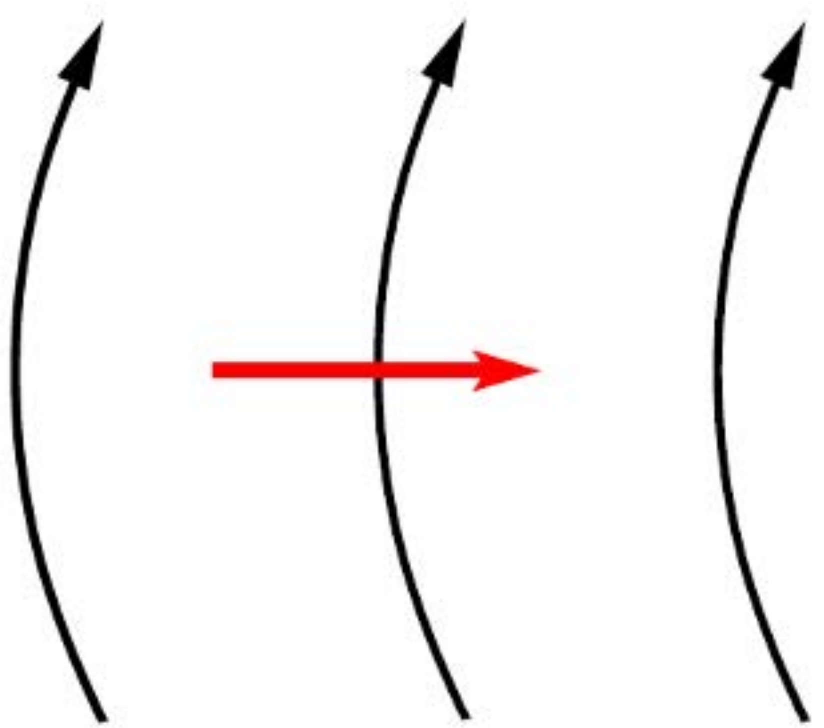
Magnetic pressure

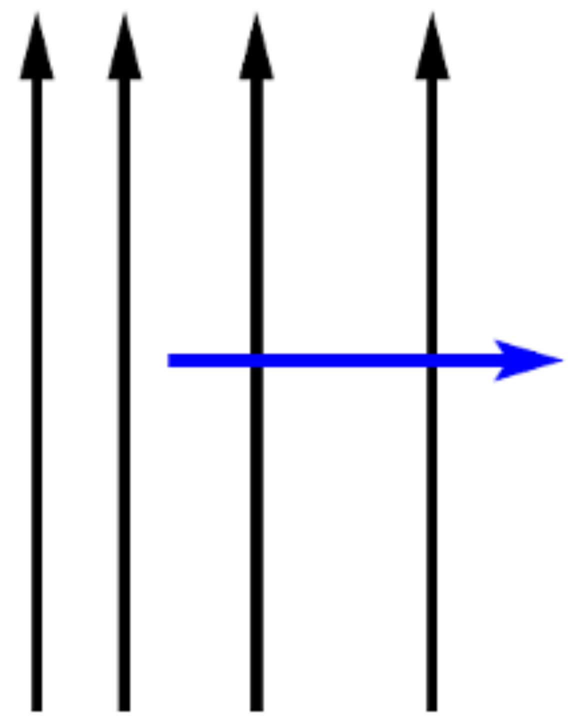
$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B} + \mathbf{F}_g + \mathbf{F}_v$$

Lorentz force $$\vec{j} \wedge \vec{B} = \frac{\overrightarrow{(\vec{B} \cdot \vec{\nabla})\vec{B}}}{\mu_0} - \vec{\nabla}\left(\frac{B^2}{2\mu_0}\right)$$

magnetic tension

magnetic pressure





Magnetism

Force-free fields

- Magnetic field configuration for which Lorentz force is zero ($j \times B = 0$) called **force-free**

$$\rho\left(\frac{\partial \vec{v}}{\partial t} + (\overrightarrow{v \cdot \vec{\nabla}})\vec{v}\right) = \rho\vec{g} - \vec{\nabla}p + \vec{j} \wedge \vec{B}$$

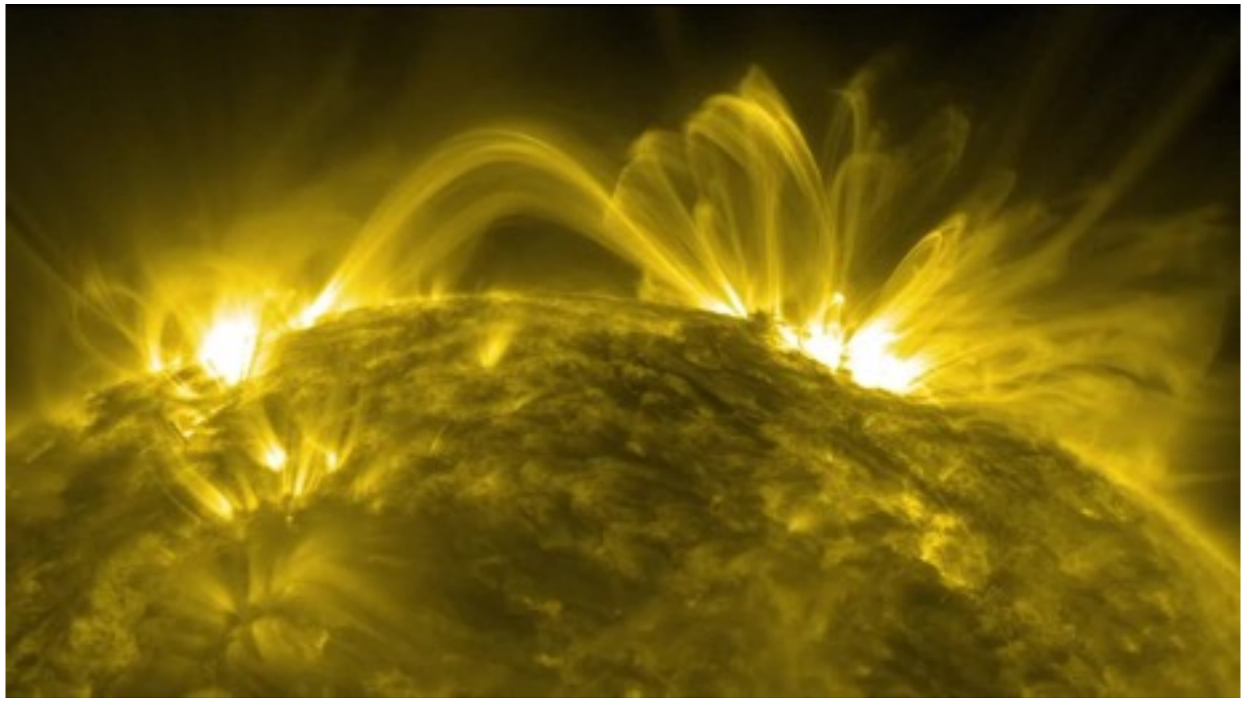
Static   high in the atmosphere   β << 1

$$\vec{j} \wedge \vec{B} = 0$$

$$\vec{\nabla} \wedge \vec{B} = \mu_0 \vec{j}$$

$$\alpha = \frac{\mu_0 j}{B}$$

$$\boxed{\vec{\nabla} \wedge \vec{B} = \alpha \vec{B}}$$

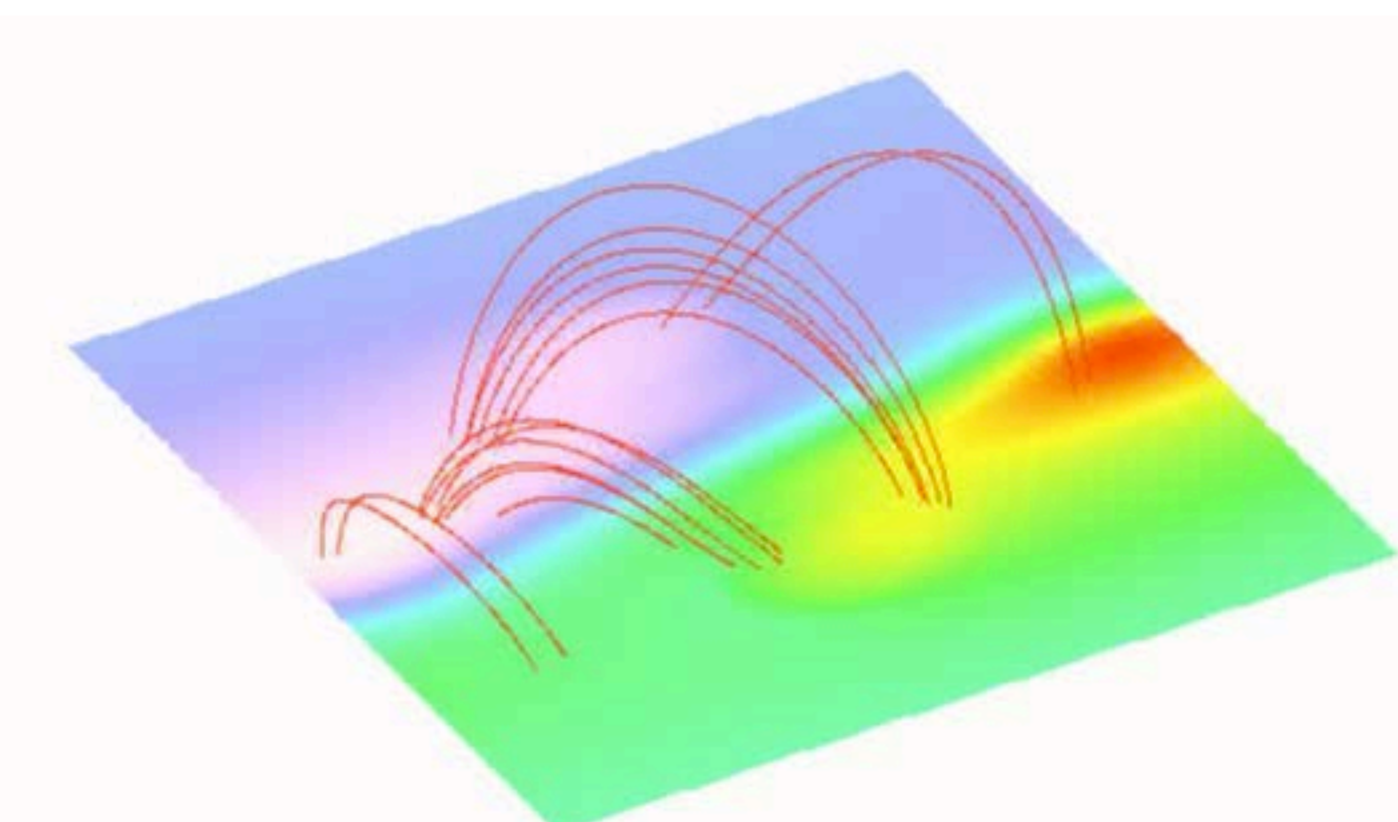


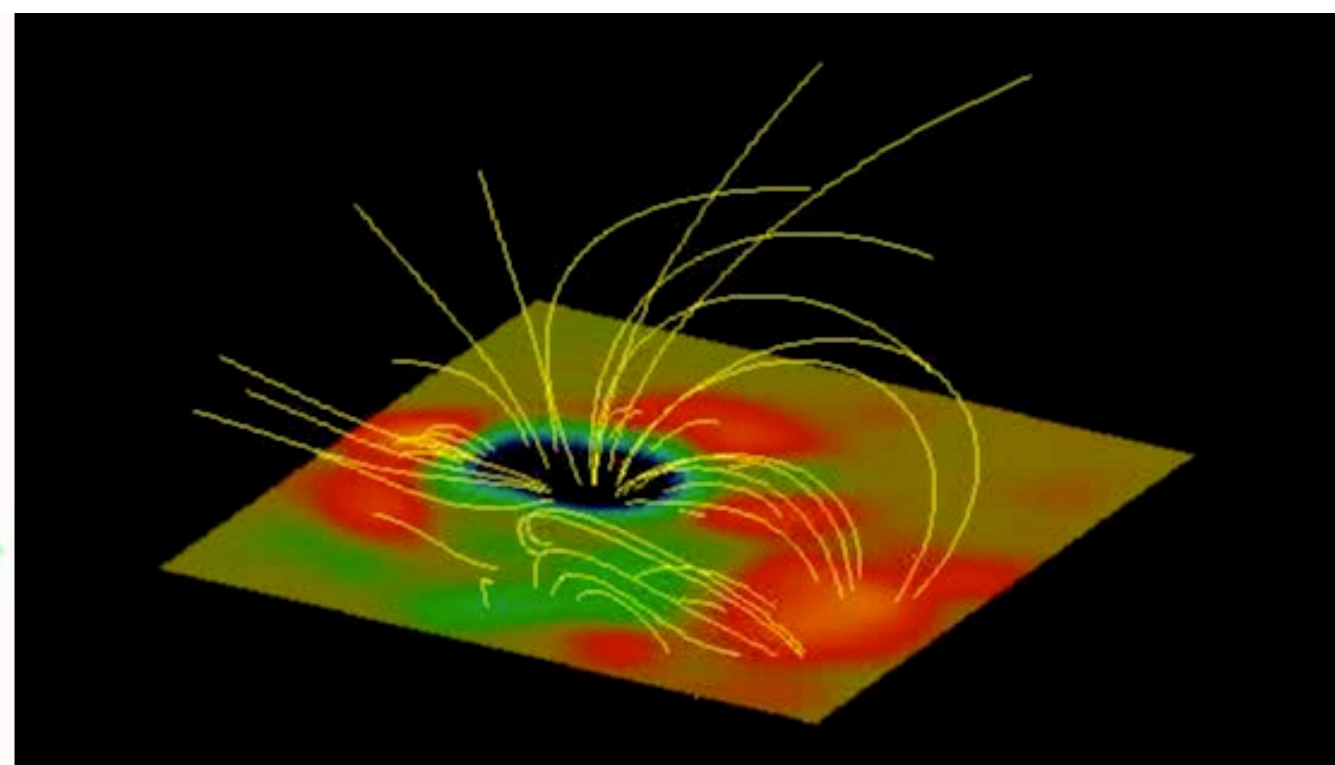
AIA/SDO

Magnetism

Force-free fields

- Magnetic field configuration for which Lorentz force is zero ($j \times B = 0$) called **force-free**
- **Example 1:** magnetic tension and pressure are in balance
- **Example 2:** potential magnetic field configuration with no electric current
  $\mathbf{j} = \mathbf{0} \rightarrow \nabla \times \mathbf{B} = \mathbf{0} \rightarrow \quad \mathbf{B} = \boldsymbol{\nabla}\Psi \qquad \Psi$: magnetic (scalar) potential





Potential magnetic field extrapolation

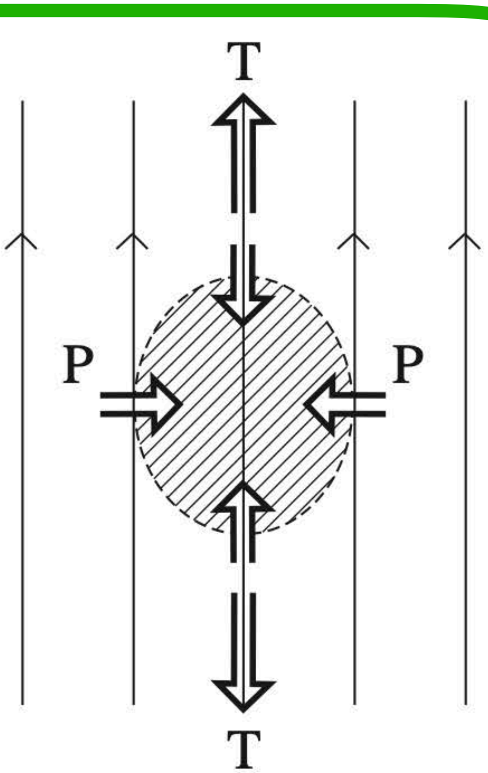
See Alissandrakis (1981) ; Wiegelmann

Magnetism

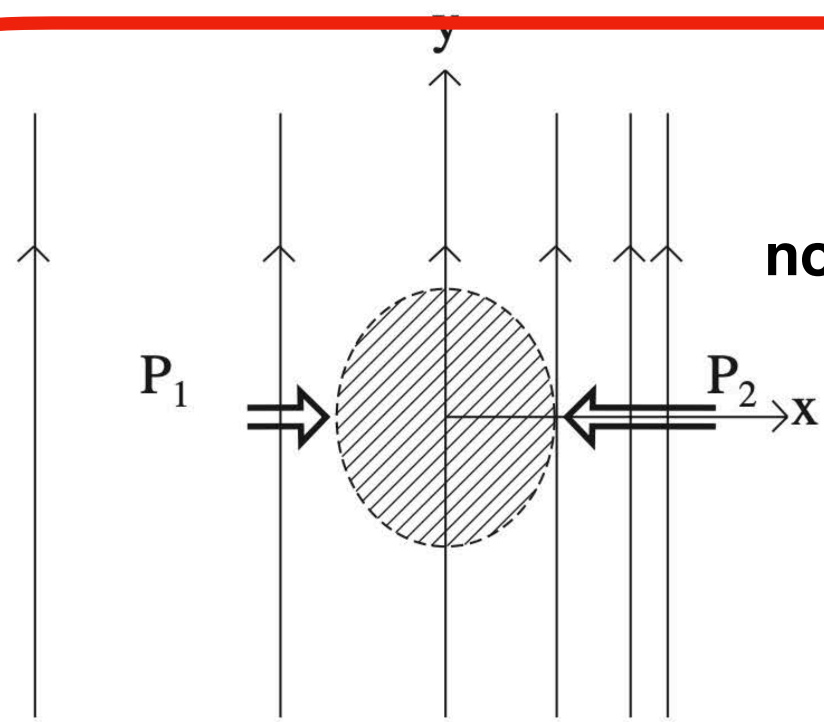
Magnetic pressure

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

- 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
    μ_0: magnetic permeability in vacuum
  - In cgs units $P_{\text{mag}} = \frac{B^2}{8\pi}$ cgs units: P in dyn/cm², B in G



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



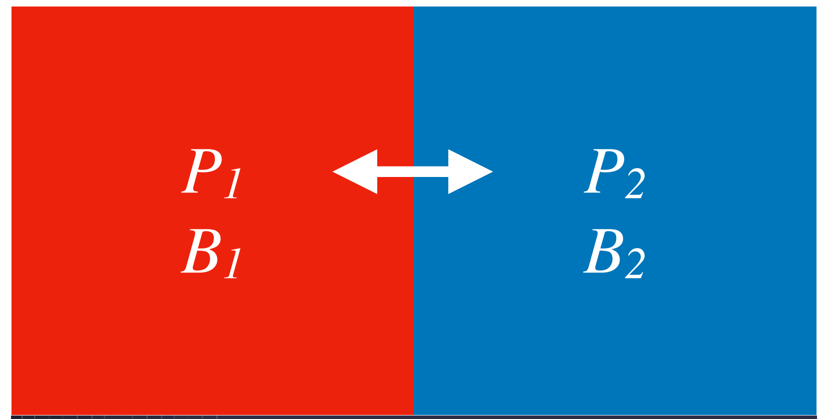
non-uniform field:
$dB/dx > 0$

Imbalance:
$P_2 > P_1$

Priest (2014)

Magnetism

Magnetic pressure

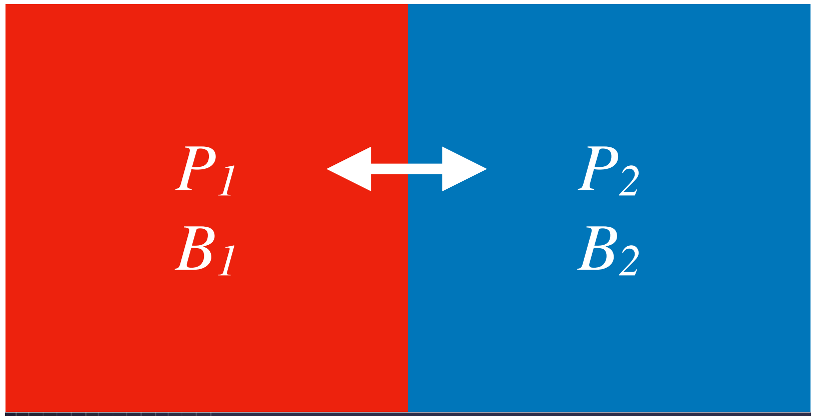


$$\frac{B_1^2}{8\pi} + P_1 = P_2 + \frac{B_2^2}{8\pi}$$

- **Pressure balance** between two different plasma domains (1 and 2):
- If $B_2 = 0$:
  - Extreme case: Component 1 is evacuated: $P_1 = 0 \;\Rightarrow\; B_1^2 / 8\pi = P_2$
  - Sets a maximum field strength for region 1 to be in balance with the (surrounding) region 2: **equipartition field strength** $B_{eq} = (8\pi P_2)^{1/2}$
  - 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!)

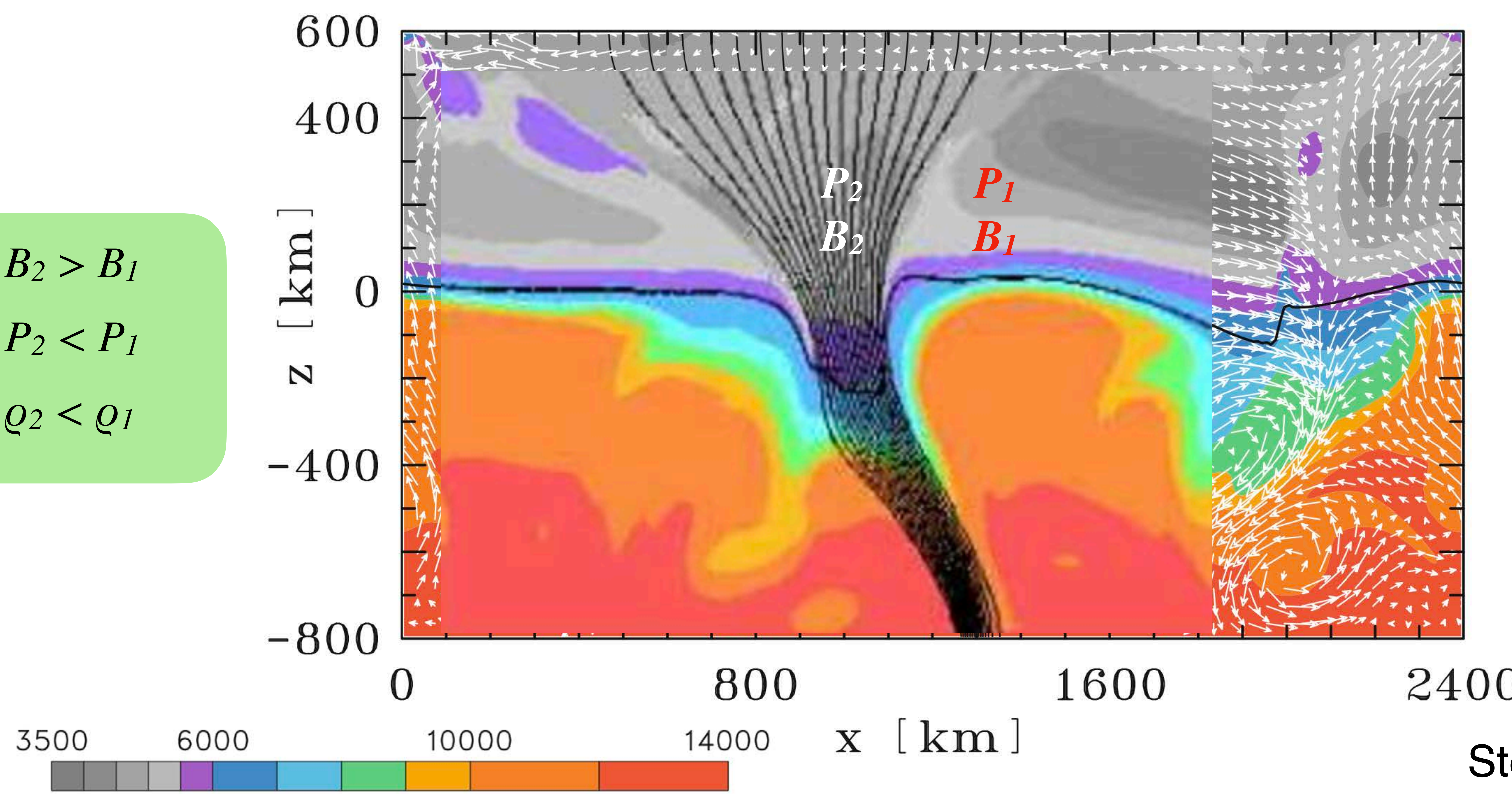
  ➡ Magnetic features (here 1) are buoyant compared to the surrounding gas.
- In the convection zone:
  - Lower density inside magnetic flux bundles compared to surrounding plasma
  - Magnetic flux bundle becomes buoyant and rises towards the surface (down the gradient) unless stopped by other forces

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

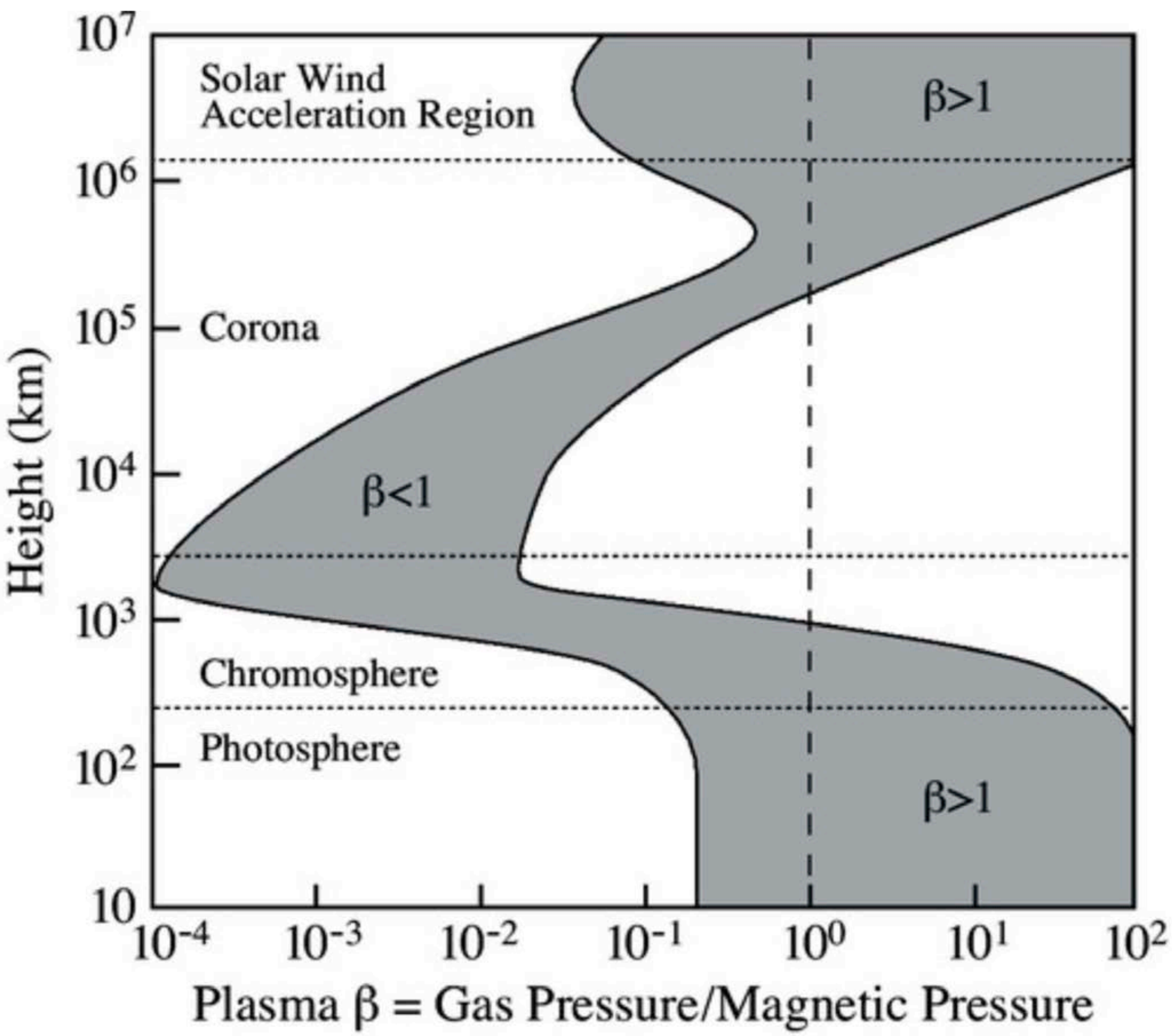
Magnetism

Plasma-Beta

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

$$\beta = \frac{P_g}{P_m} = \frac{8\pi P_g}{B^2} \quad (cgs)$$

- **β < 1: Magnetic field dominates** and dictates the dynamics of the gas
- **β >1: Thermal gas dynamics dominate** and forces the field to follow (—> If **ideal-MHD,** the magnetic field does not diffused and is said **"frozen-in"** the plasma.)
- 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



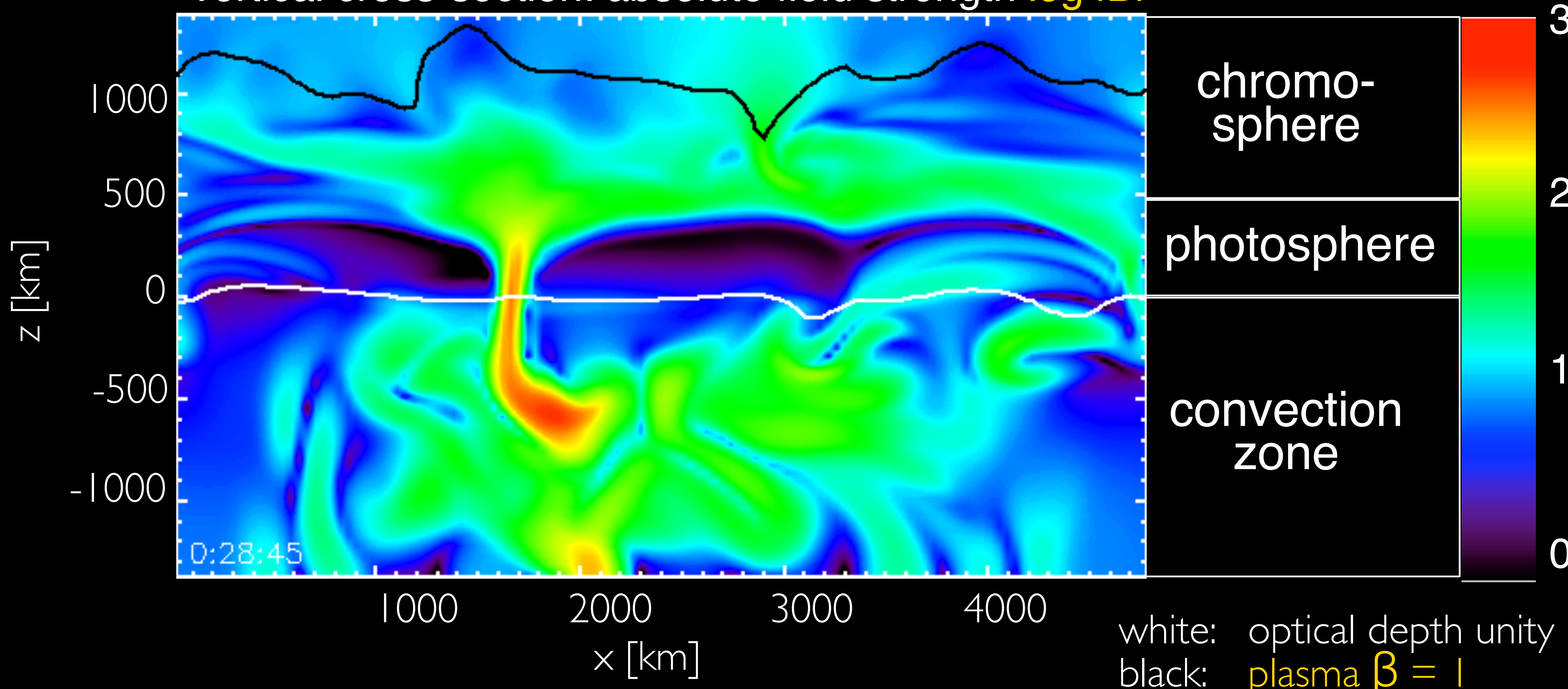
K.R. Lang, Tufts University; Adapted from G. Allen Gary, Solar Physics 203, 71-86 (2001).

Magnetism

Plasma-Beta

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

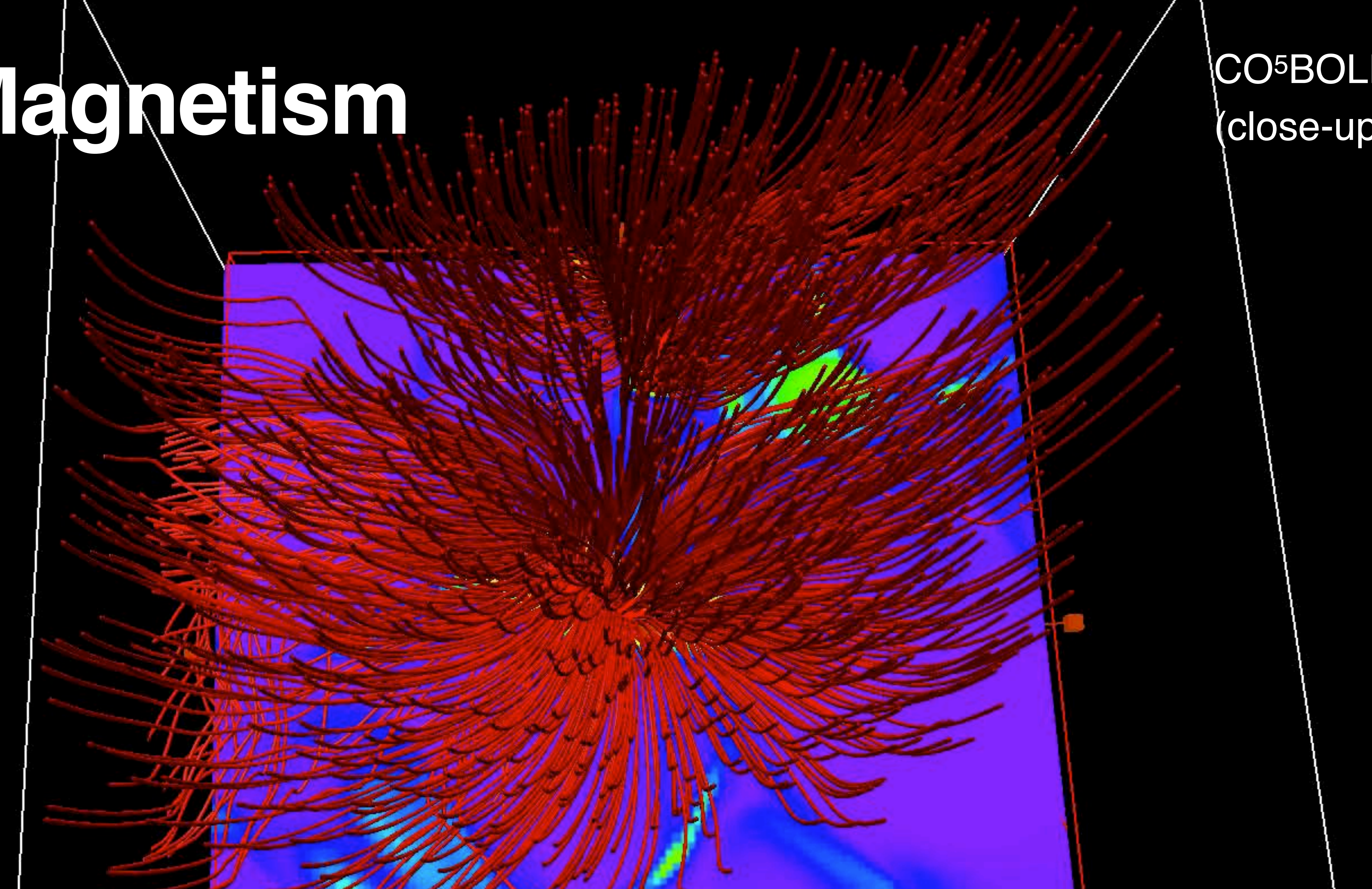
vertical cross-section: absolute field strength log |B|



$|B_0| = 10$ G

Schaffenberger, Wedemeyer, Steiner, Freytag (2005)

Magnetism

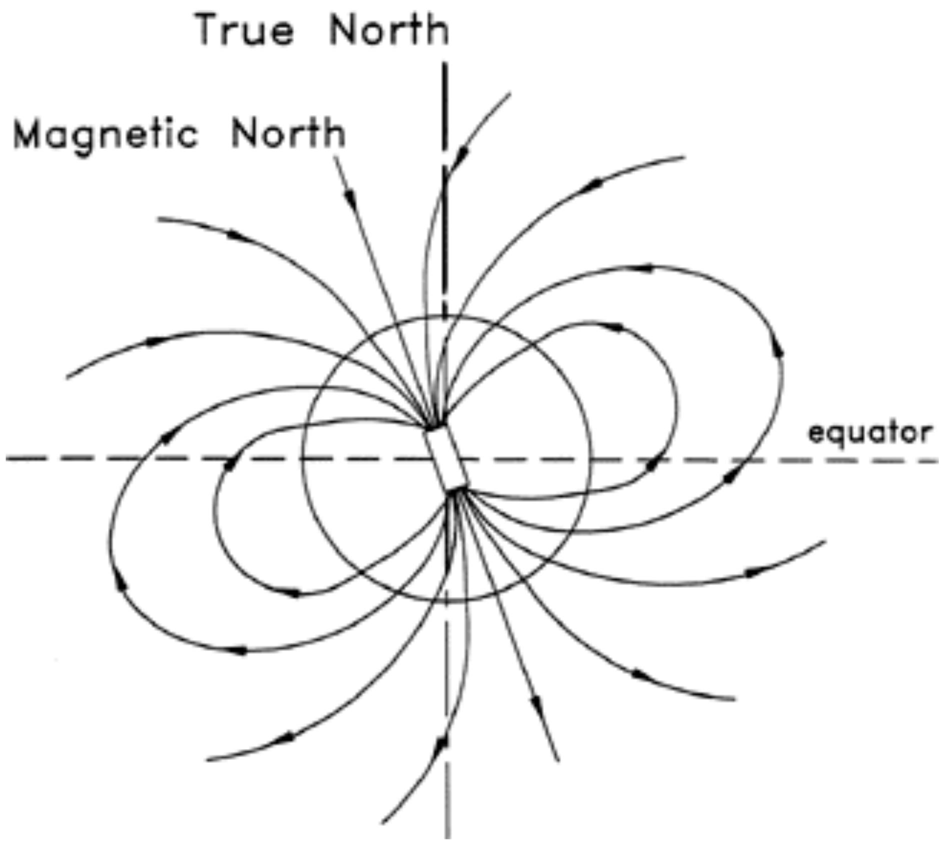


- Complicated field structure with rotating and/or swaying subgroups
- Continuous reorganisation of structure
- More complicated than individual “flux tubes”

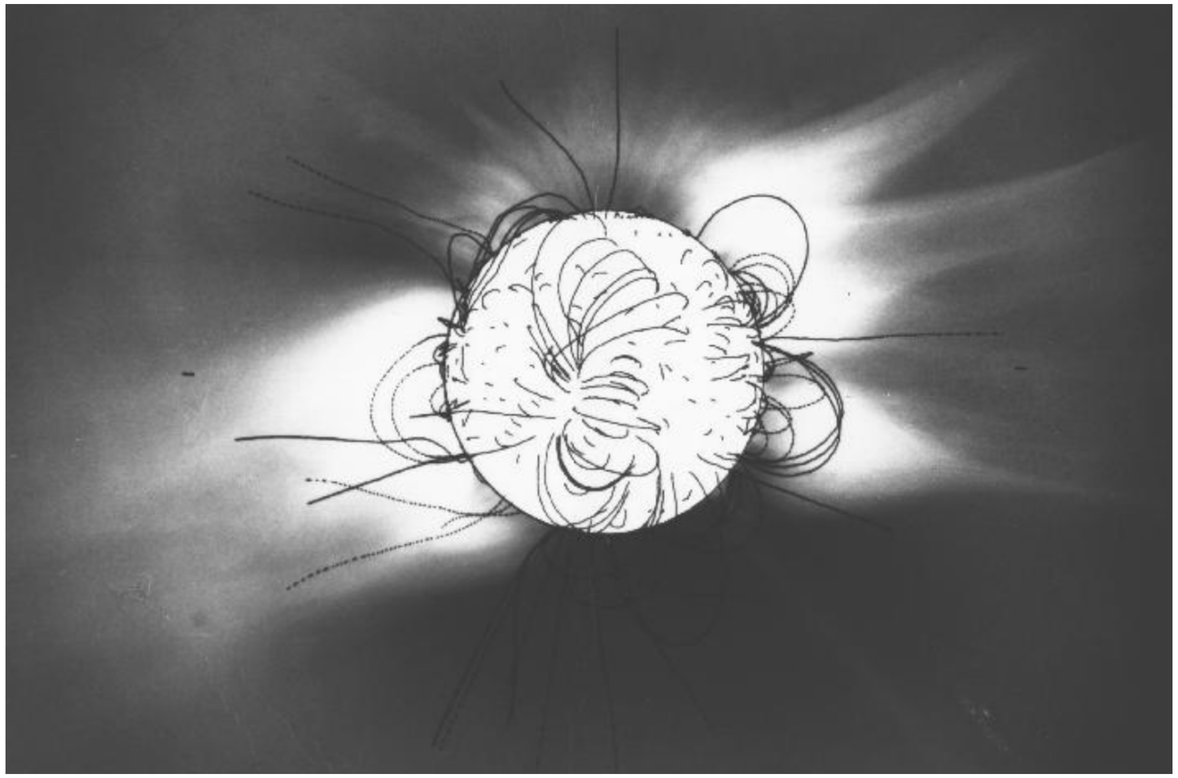
Magnetism

Global magnetic field configurations

Earth — dipole field



Sun — more complicated

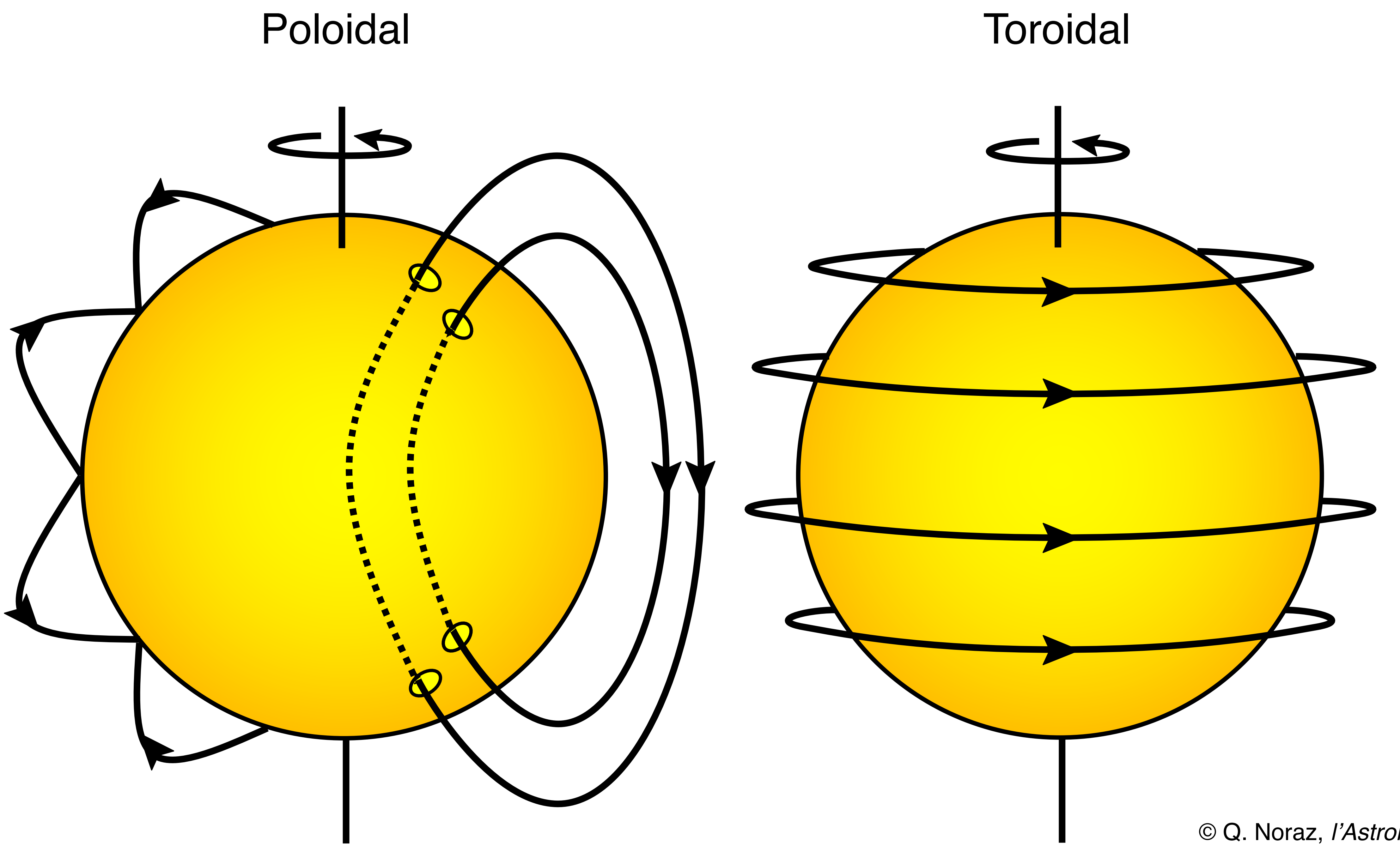


- Like Earth, also the Sun is permeated by a dipole field but with much more complicated additional field geometry that changes over time (solar cycle)

https://solar.physics.montana.edu/ypop/Spotlight/Magnetic/Images/magnetic_earth.gif

Magnetism

Global magnetic field configurations



Multi-pole
(here “hexadecapole”,
see also spherical harmonics for details…)

dipole

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

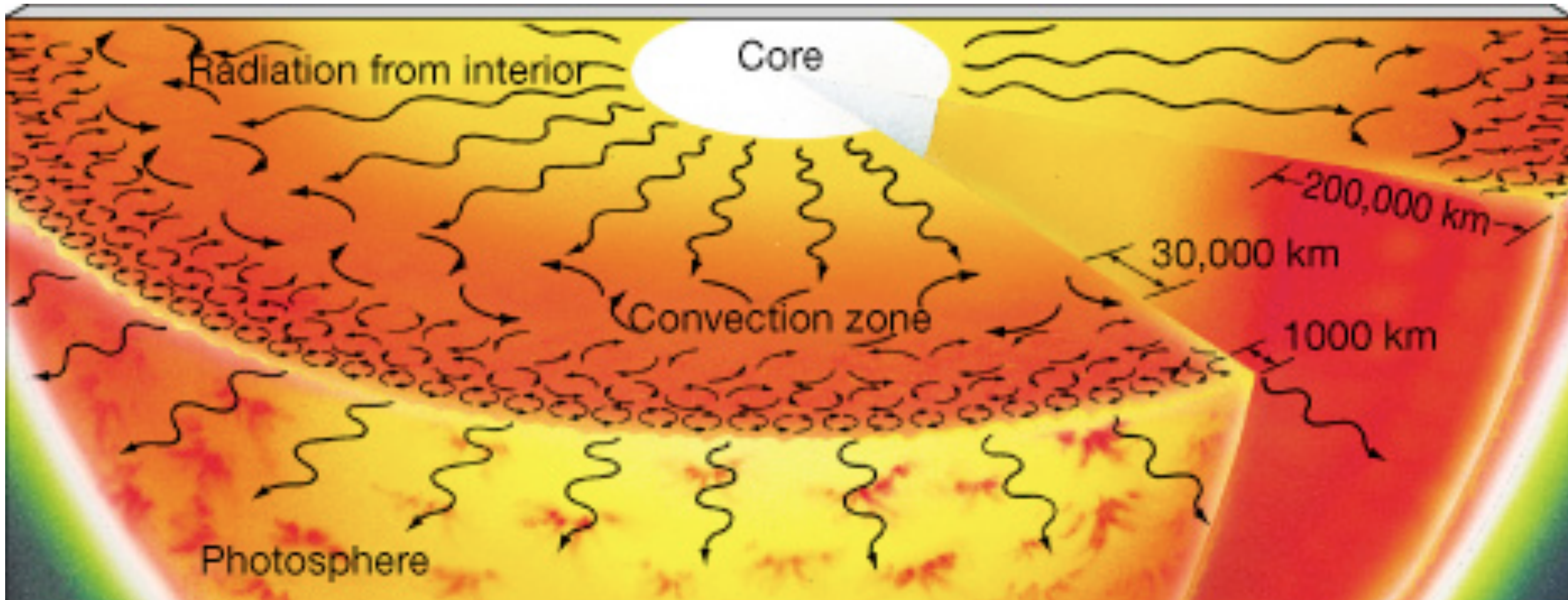
The solar dynamo

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 induces 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
- Magnetic field decays on time scales much shorter than the Sun's life time

➡ **New field is generated** continuously



Dynamo

Induction equation

Dynamo effect:
The ability of a conductive fluid (plasma) to amplify and maintain a magnetic field against its ohmic dissipation.

Convert kinetic energy into magnetic energy

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

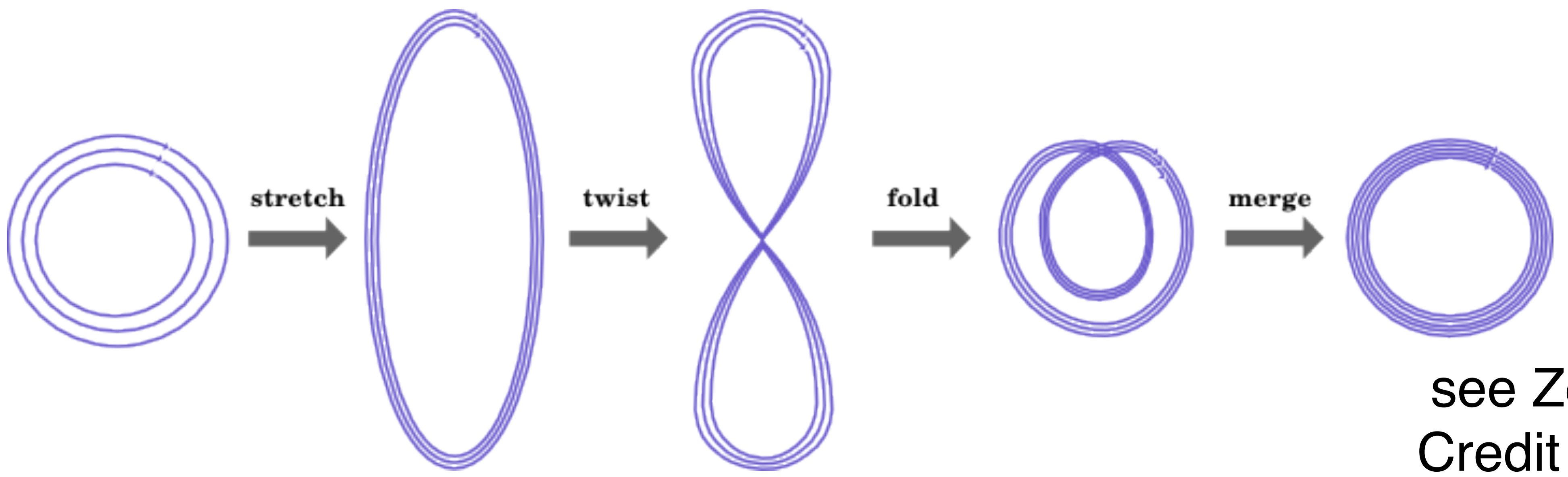
$$Rm = \frac{vL}{\eta} \sim \frac{\text{induction or advection of a magnetic field due to the motion of a conducting medium}}{\text{magnetic diffusion}}$$

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

Dynamo

Fast & Small-Scale

- SFT mechanism: ***stretch-twist-fold***



see Zeldovich et al. 1983
Credit : Jennifer Schooner

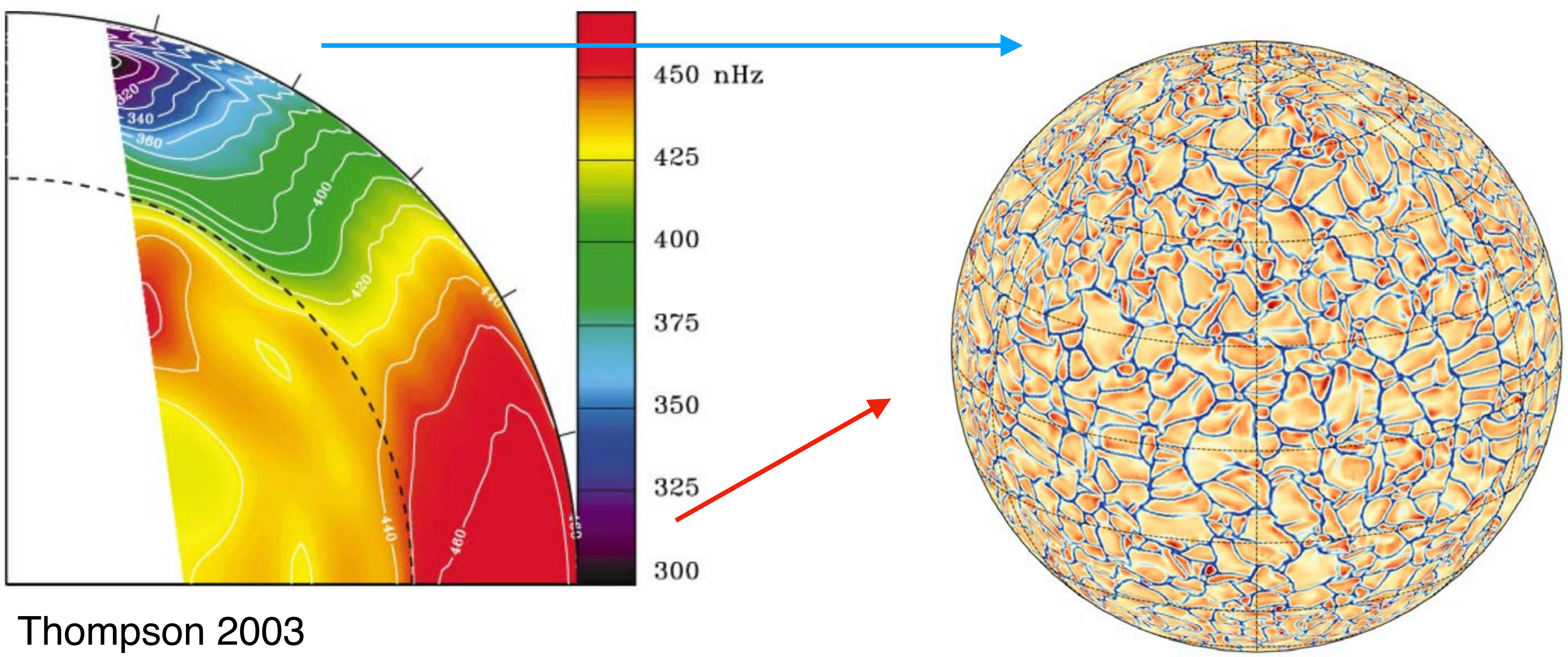
- Rm >> 1 : frozen-in field
- Stretch : increase radius of loop (V=cte)
  -> section decreases, B increases (Maxwell-flux)
- Twist/fold : increases magnetic tension
- Merge : Relaxation of magnetic geometry with reconnection ($\eta \neq 0 \rightarrow R_m \neq \infty$)

=> **Magnetic energy increased,** for a final geometry similar to the initial one

Dynamo

Large-scales : Ω-effect (Omega effect)

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



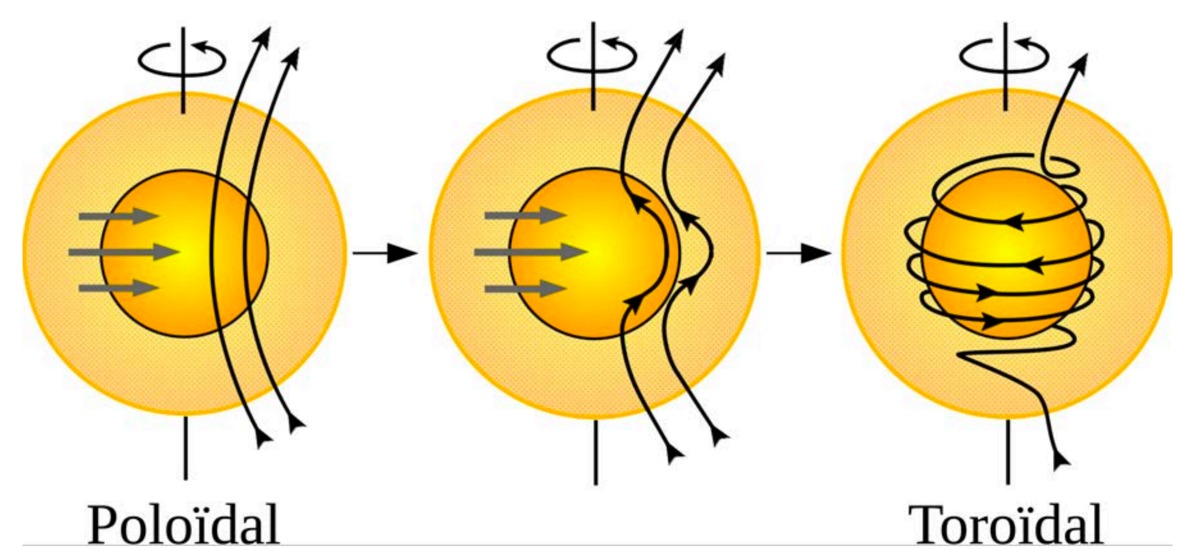
Thompson 2003

Differential Rotation (DR)

- Radiative interior: solid-body rotation
- Convective envelope: differential rotation with slow poles and a fast equator

Ω-effect

Noraz+22



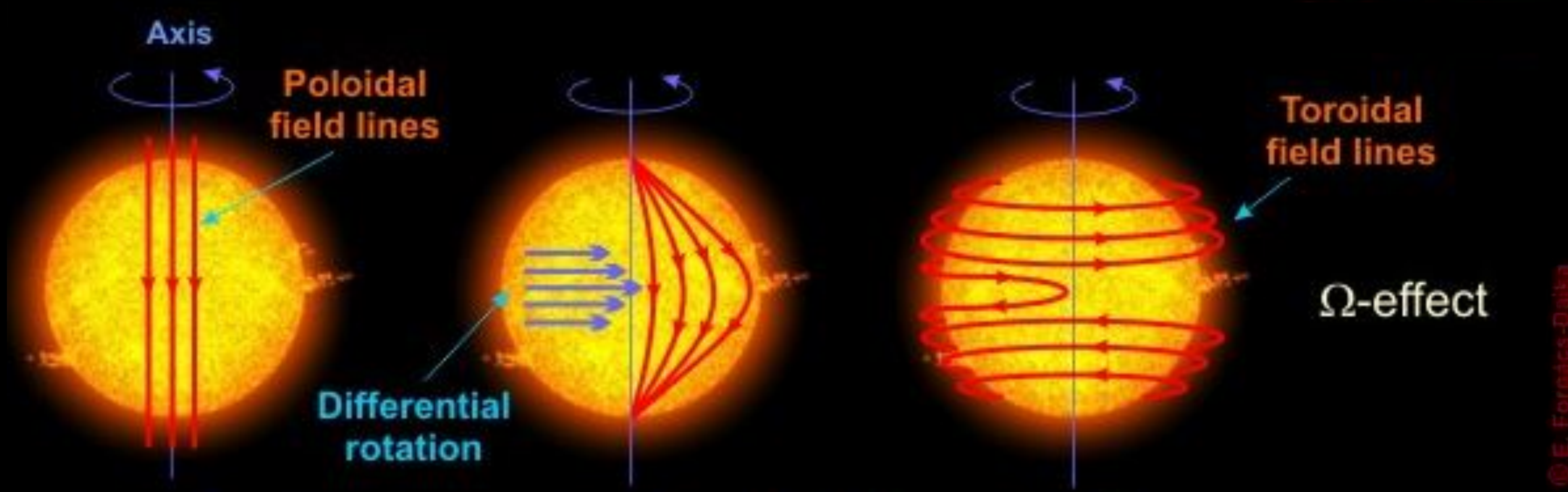
Dynamo

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**

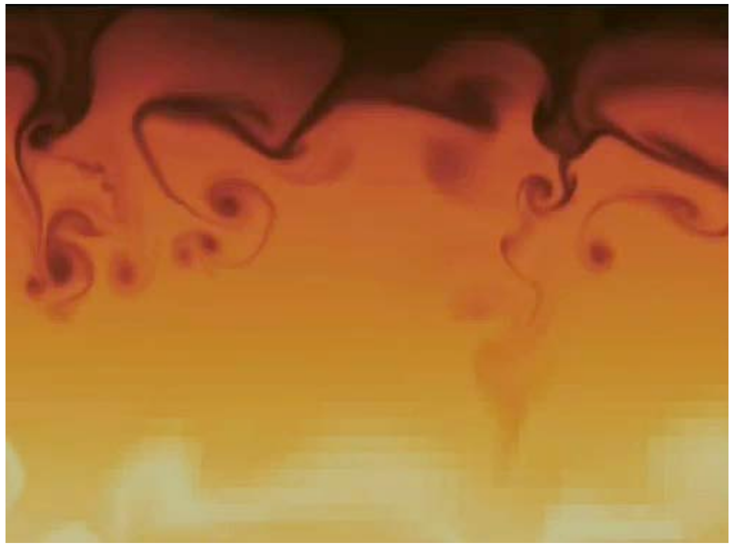
➡ Creates magnetic flux strands in the azimuthal (toroidal) direction in shallow depths and low latitudes



Dynamo

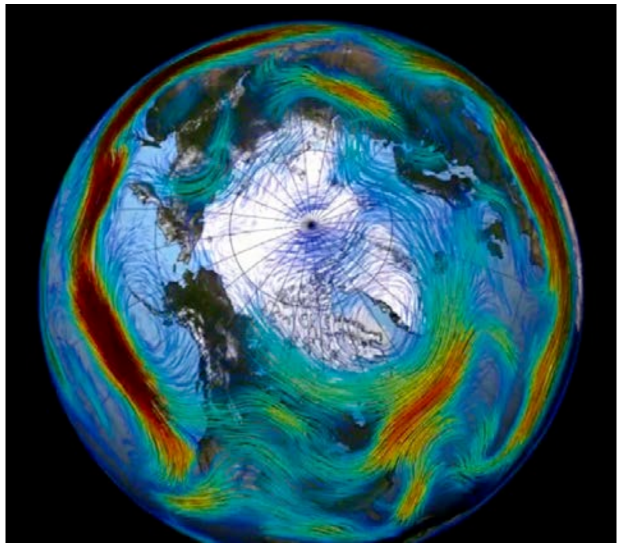
Large-scale : α-effect (Alpha effect)

Convection



© M. Delorme, Dyablo-WholeSun

Rotation



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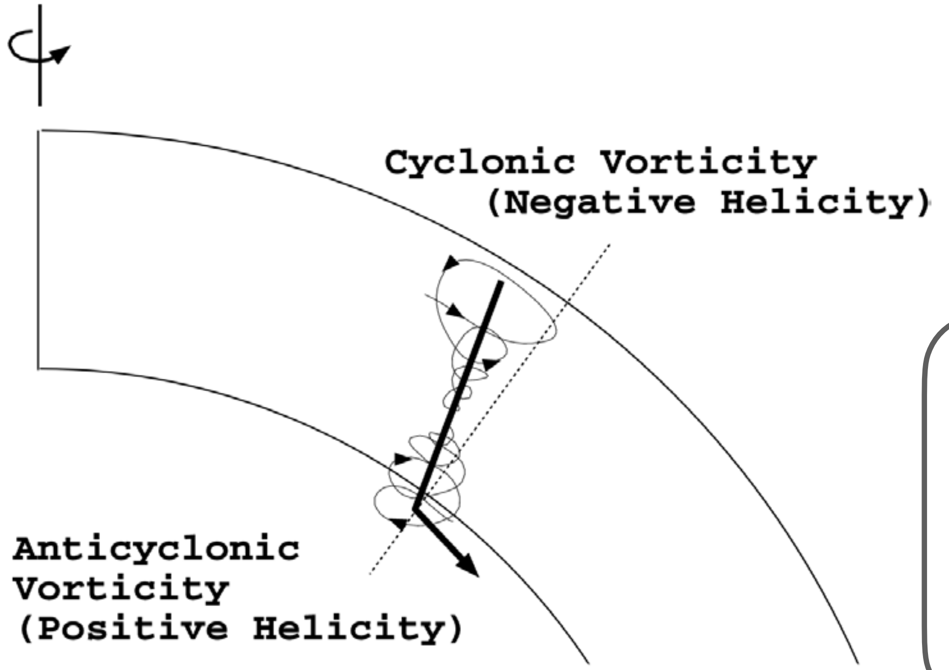


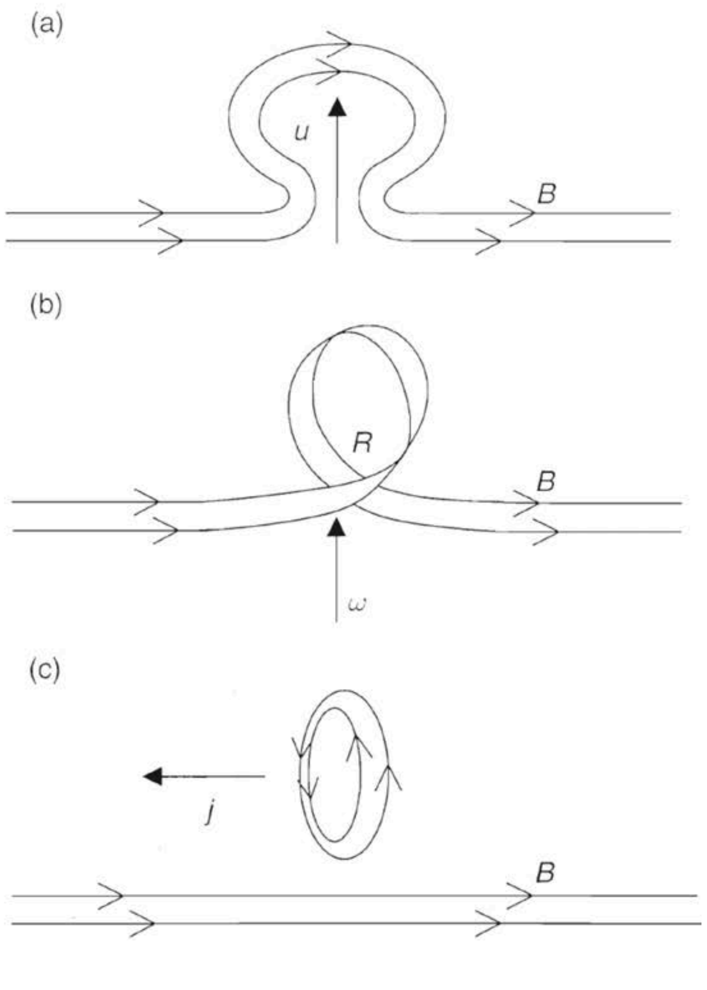
Miesch et al. (2000)

velocity $\boldsymbol{u}$

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

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

$\longrightarrow$



Parker 1955

Dynamo

Large-scale : α-effect (Alpha effect)

- High gas pressure (deep) in the convection zone: $P_g >> P_m \Rightarrow \beta >> 1$

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

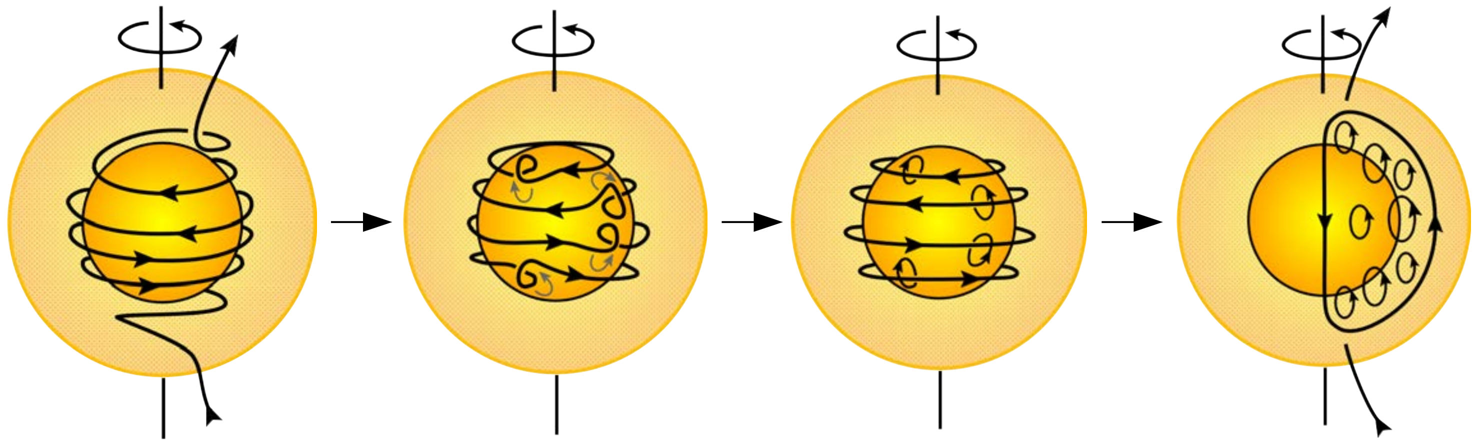
  ➡ Toroidal magnetic field gets partially dragged along by the moving plasma

- Solar rotation induces **Coriolis force** (ω x v) on convective motions
- 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

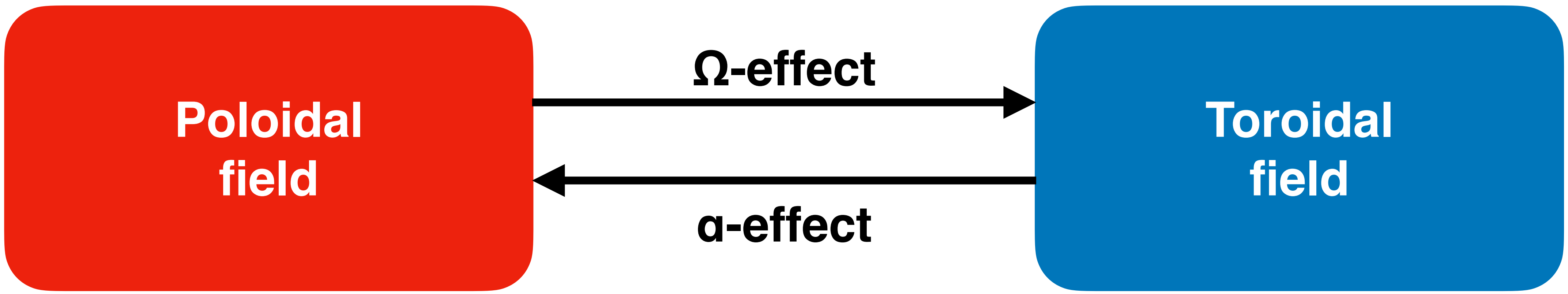
  ➡ **Generates a large scale poloidal magnetic field** (Parker 1955).



Noraz+22

Dynamo

α and Ω



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

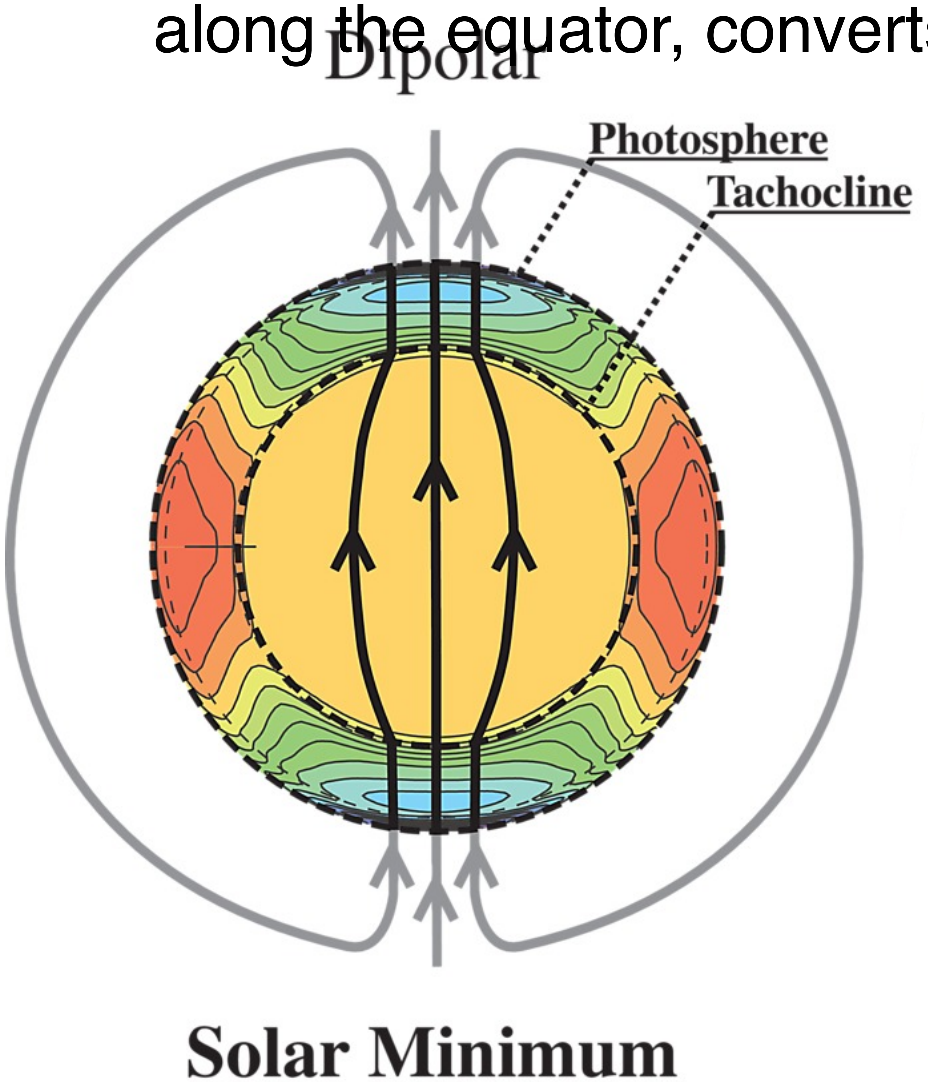
- generates magnetic activity (e.g., sunspots) during **solar (activity) maxima**

- **Solar cycle**: Change between these extreme configurations, forming a solar activity cycle
  - 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.

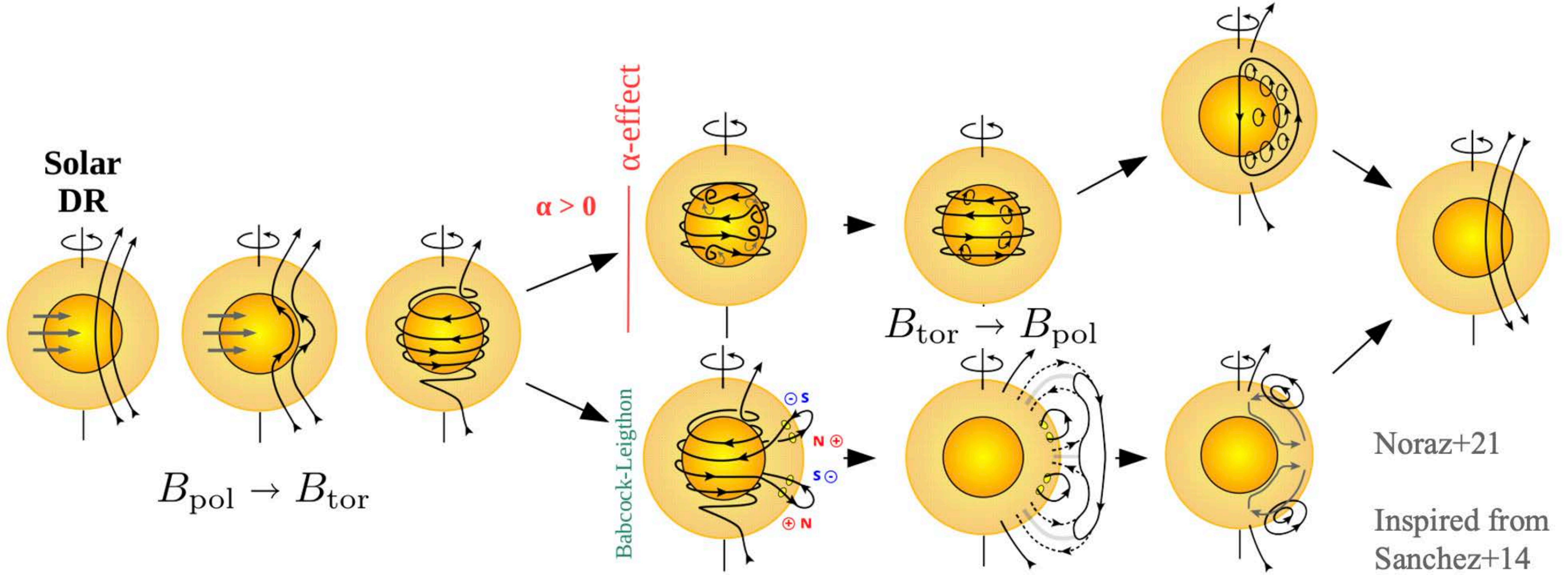


Higgins, Paul (2012): Schematic of the Solar Dynamo. figshare. Figure. https://doi.org/10.6084/m9.figshare.102

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
- Toroidal generation either with ***α*-effect or Babcock-Leighton**

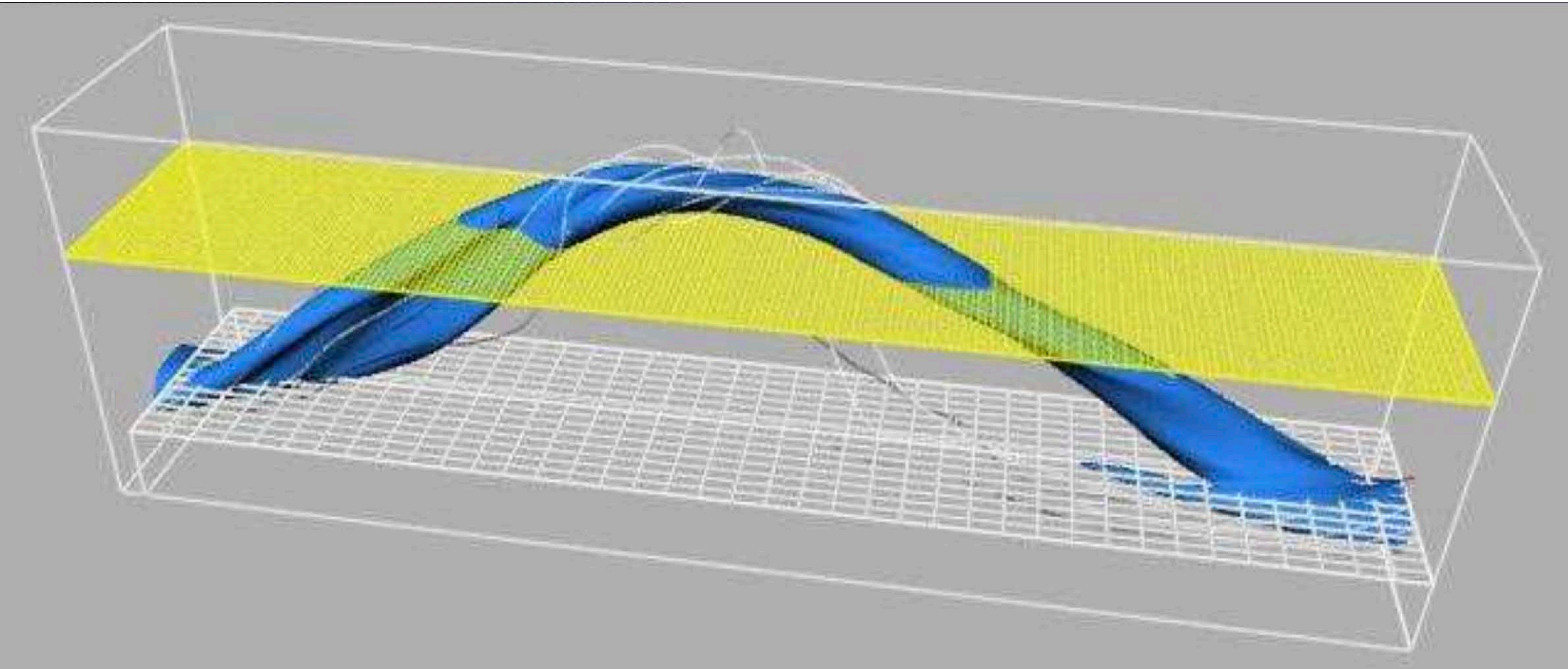


Dynamo

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

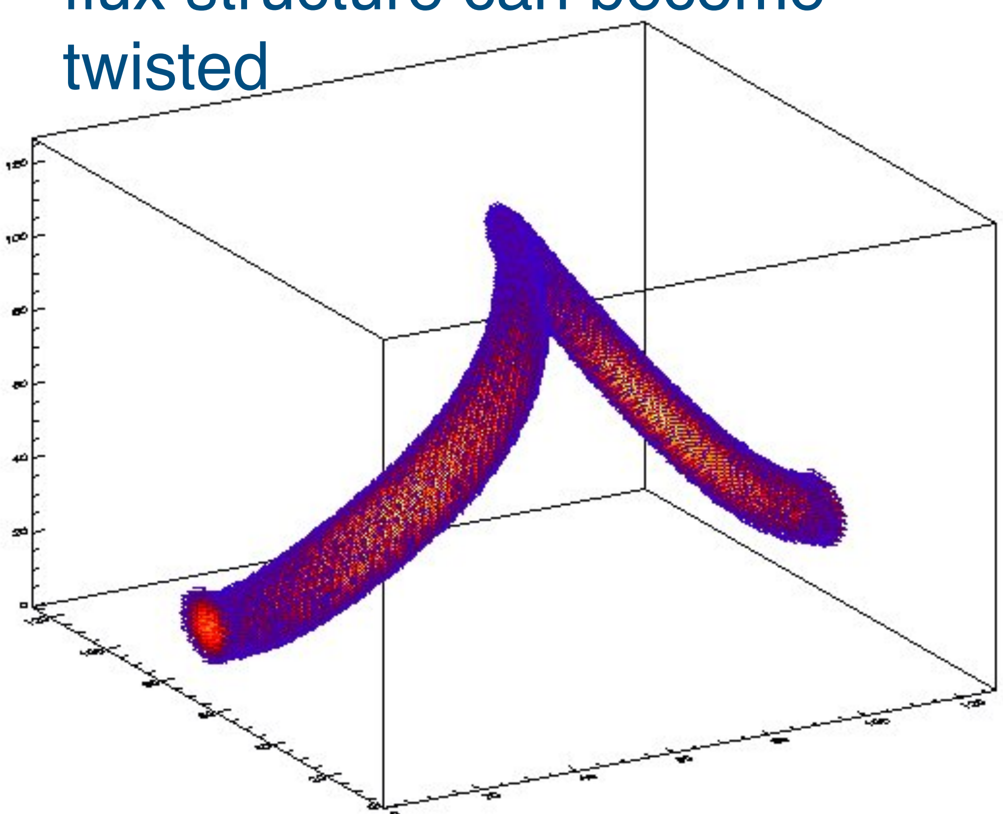
➡ Magnetic flux rope becomes **buoyant, rises upwards** (Parker instability)

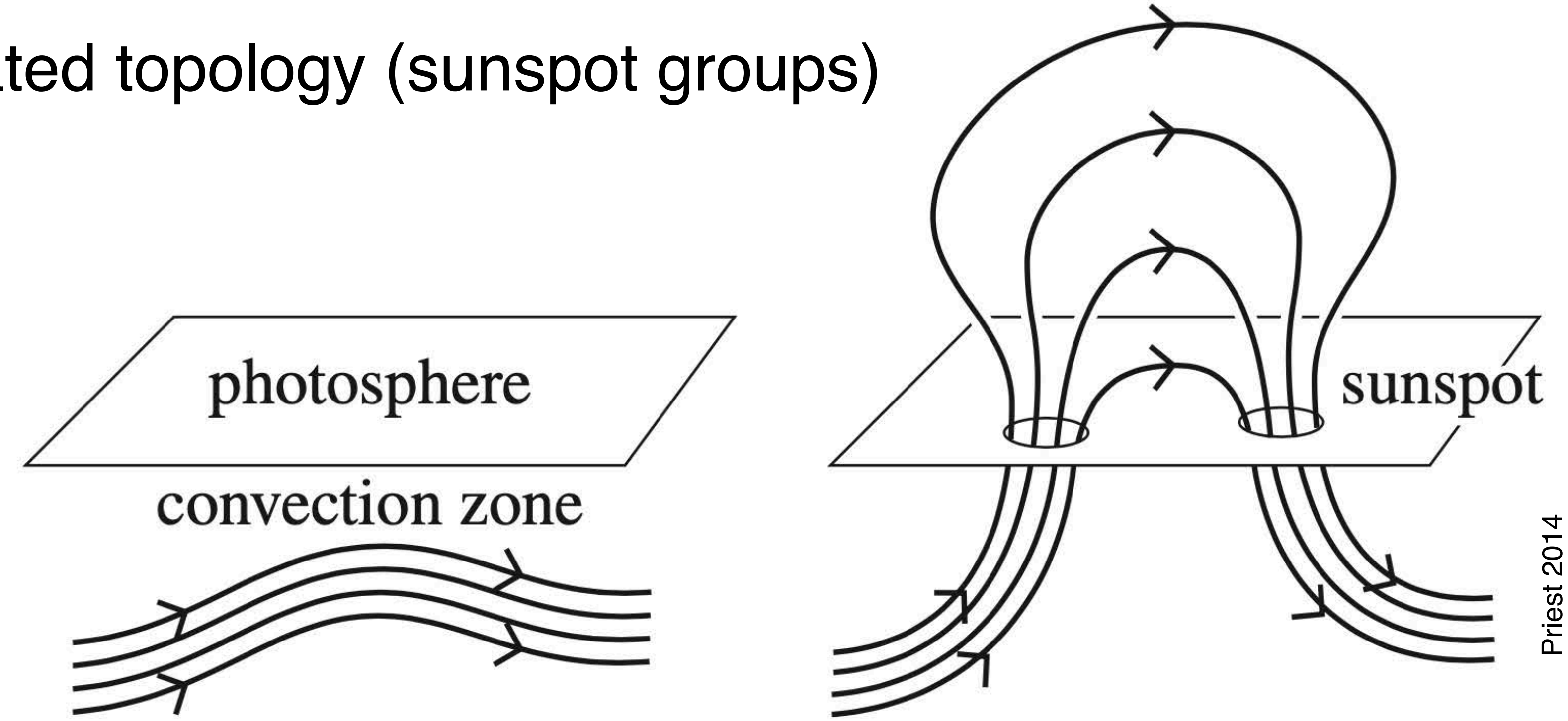


Dynamo

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

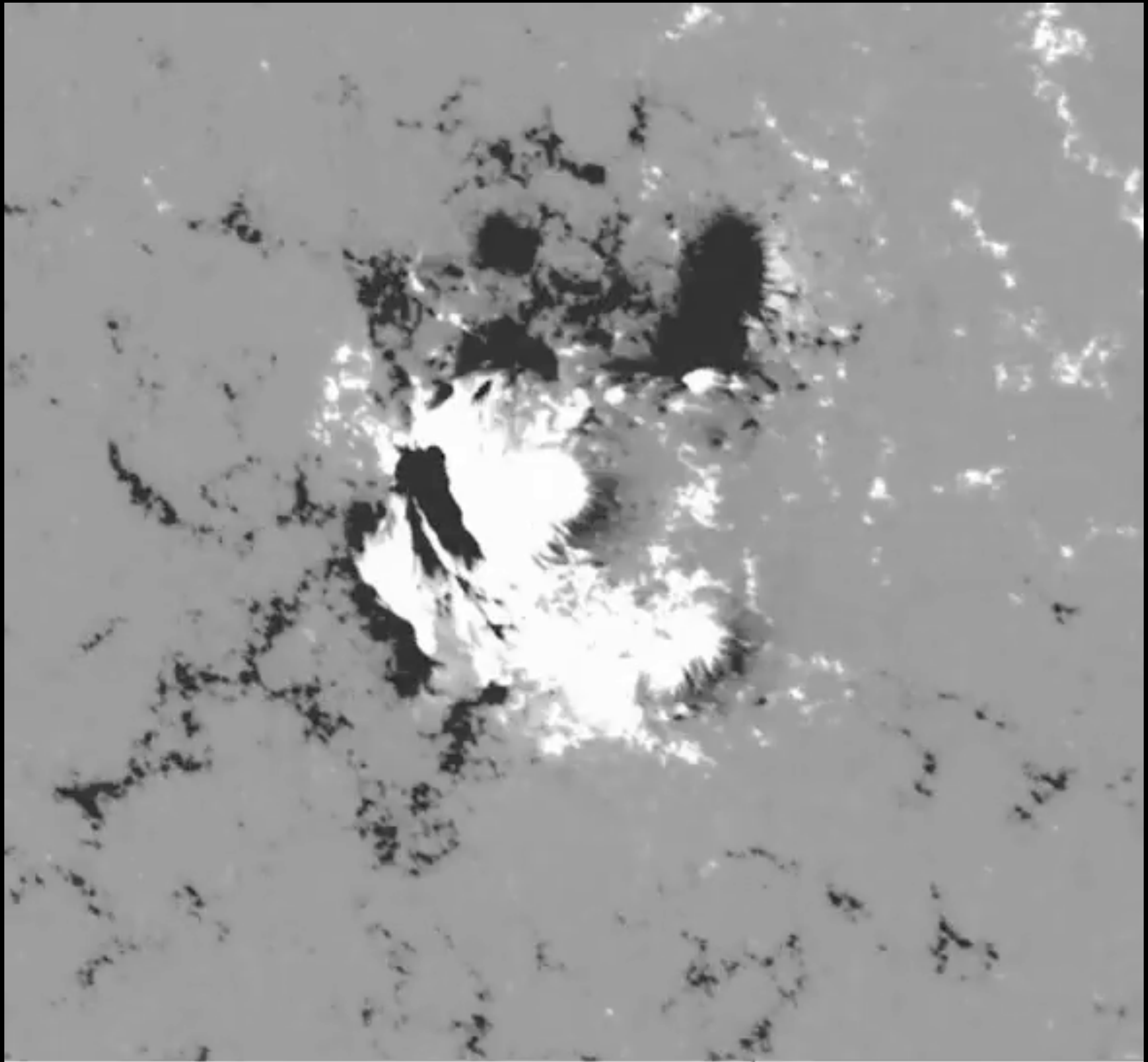
Dynamo

Magnetic fields at the surface — Active Regions

Dynamo

Magnetic fields at the surface — Active Regions

- Magnetogram (HMI)



Dynamo

Overview

- 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

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

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

- Plasma motions must convert meridional (poloidal) magnetic field into an azimuthal (toroidal) magnetic field, and vice versa (Large-scale).
- **Induction** has to overcome magnetic diffusion (large magnetic Reynolds number)

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.