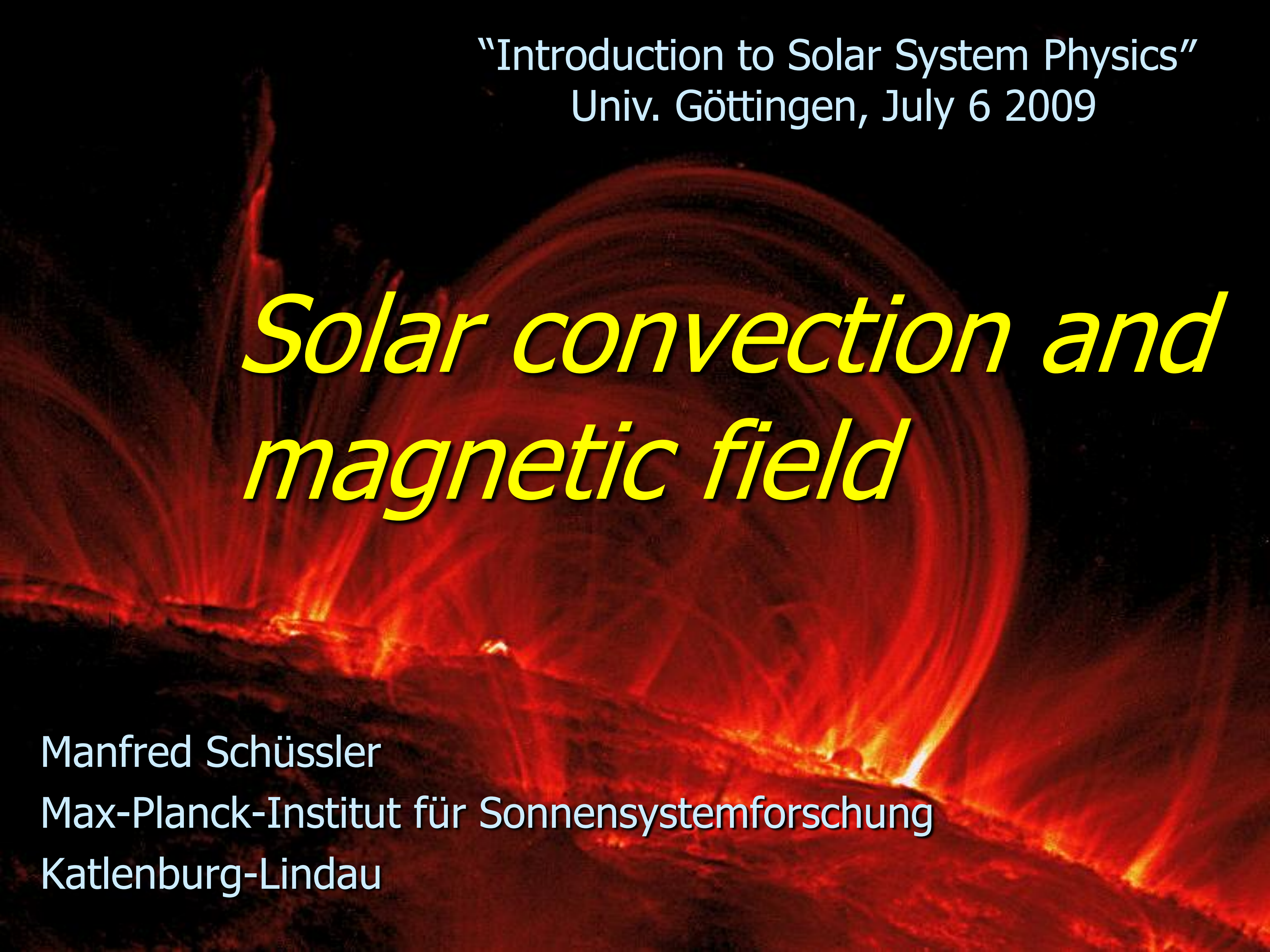
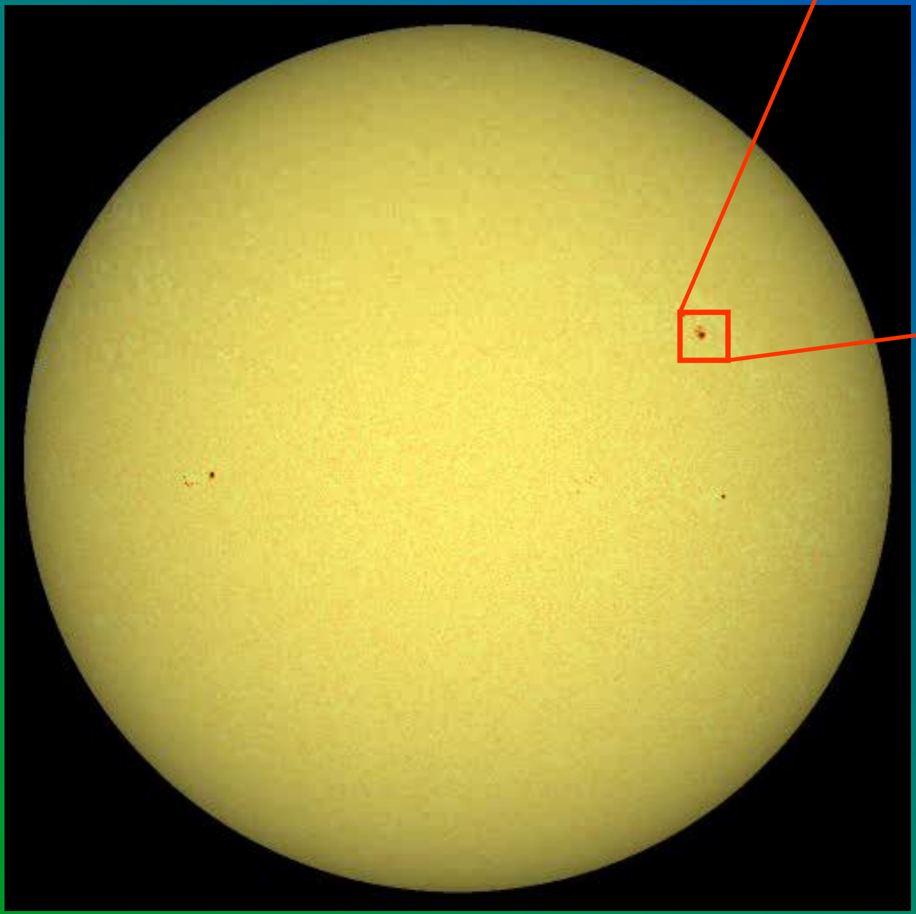


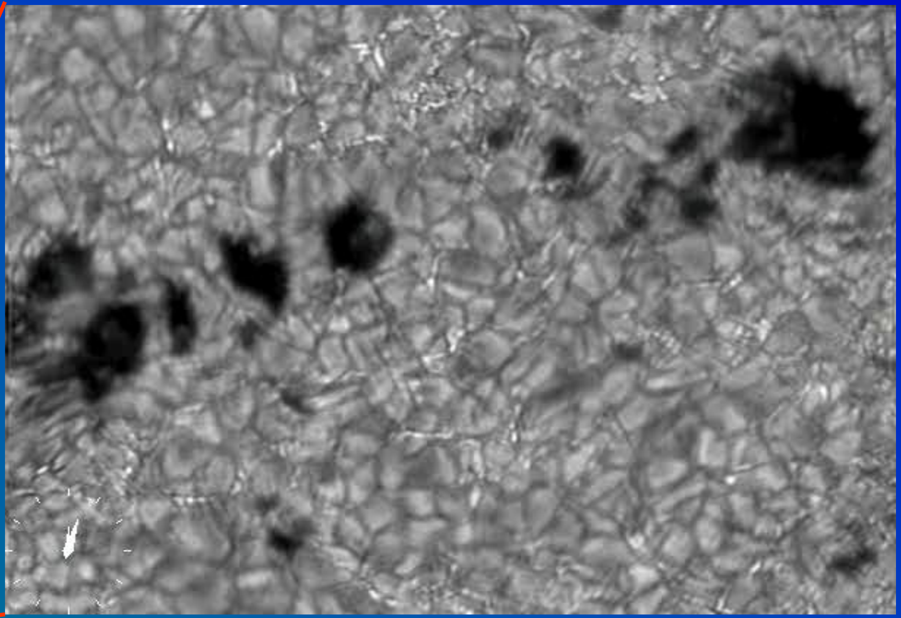
"Introduction to Solar System Physics"
Univ. Göttingen, July 6 2009

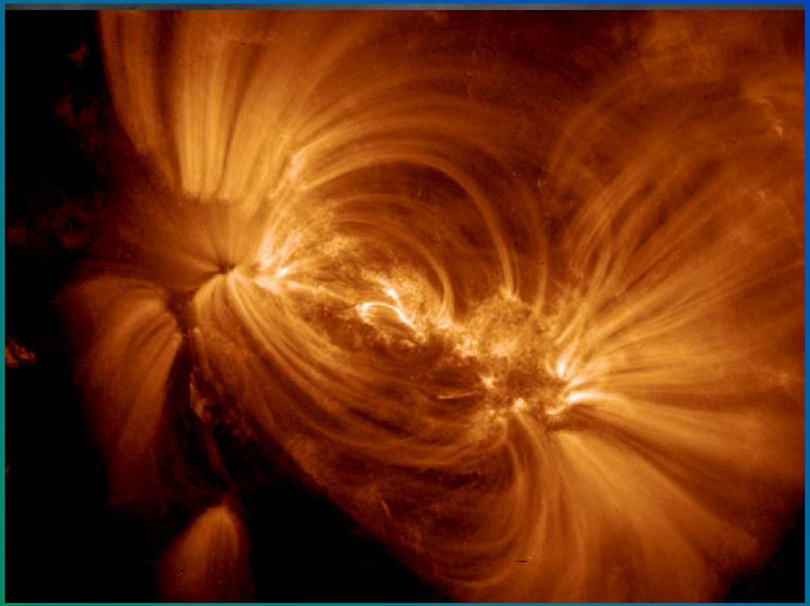
Solar convection and magnetic field

Manfred Schüssler
Max-Planck-Institut für Sonnensystemforschung
Katlenburg-Lindau

Convection & magnetism: closely related







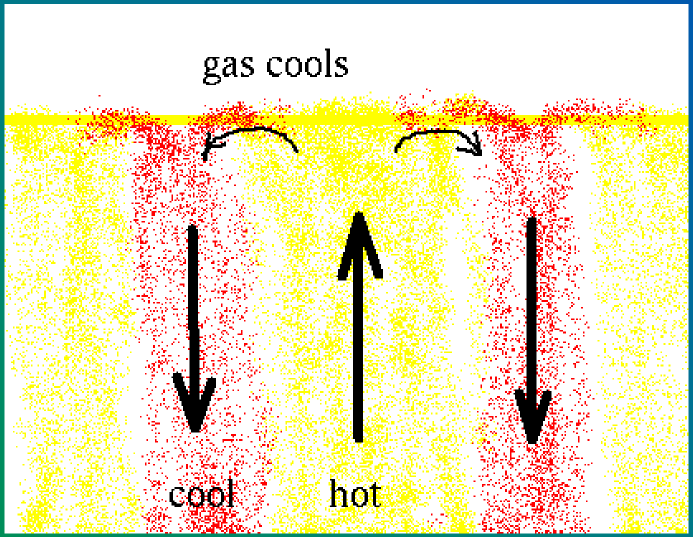
Outline

1) Basic physics of convection
2) Numerical simulation of convection
3) Overview of solar magnetism
4) Surface magneto-convection
5) Deep convection zone field & dynamo

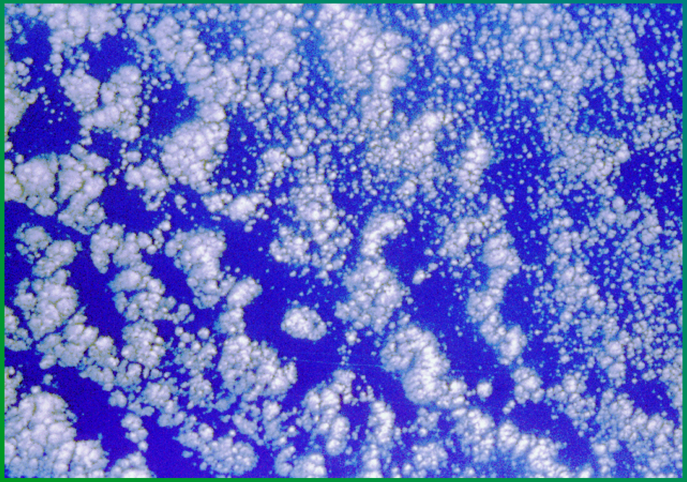
The solar convection zone

- 200 Mm thick layer in turbulent motion
- Velocities range from 100 m/s (bottom) to 10 km/s (top)
- Energy flux nearly completely transported by convective motion

What is convection?

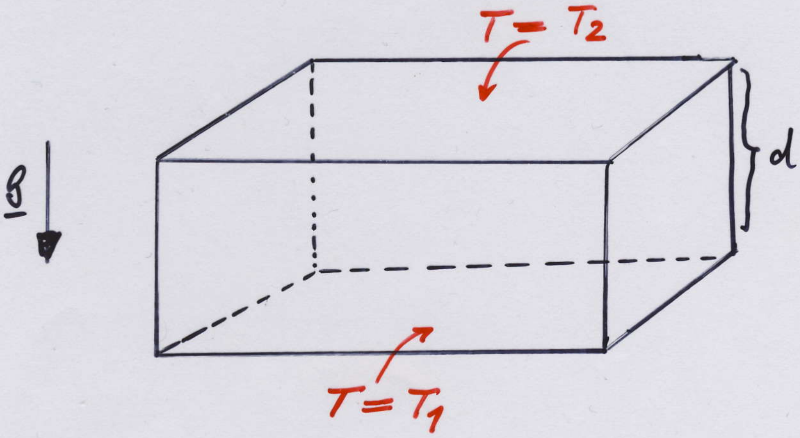


- Flow driven by thermal buoyancy
- Convective instability



➔ Viewgraphs...

Laboratory Convection
(Rayleigh-Bénard conv.)



$\Delta T = T_2 - T_1 > 0$

„fluid in a box"

Conducted flux : $F_z \propto k \dfrac{dT}{dz} = \dfrac{k \, \Delta T}{d}$

Hydrostatic equil., fluid static for $\Delta T < \Delta T_c$

Instability for $\Delta T \geq \Delta T_c$

Rayleigh number :

$\odot : \mathcal{R} \sim 10^{23}$

$$\mathcal{R} = \frac{\alpha g \, \Delta T \, d^3}{\nu \, \kappa} \geq \mathcal{R}_c \simeq 1700.$$

α : expansion coefficient [conv. buoyancy-driven]
ν : (kinematic) viscosity

→ 2D rolls :

$\mathcal{R}\uparrow$: bifurcations → chaos

$$\frac{\partial T}{\partial t} + \underline{v} \cdot \underline{\nabla} T = \kappa \, \underline{\nabla}^2 T$$

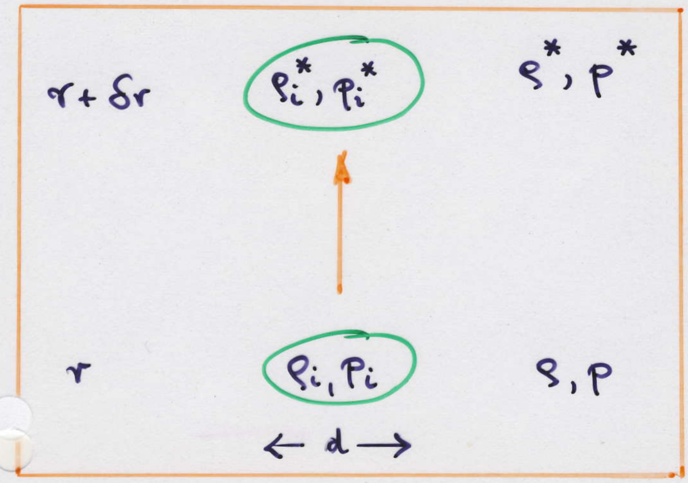
Stars : $\kappa = \kappa_{RAD}$

for $\mathcal{R} \geq \mathcal{R}_c$ is convection „more efficient":

Nusselt No. $\quad Nu = \dfrac{F_{conv}}{F_{diff}(\underline{v} = \underline{0})} > 1$

3. CONVECTIVE INSTABILITY

HERE : „BLOB THEORY" → FLUCTUATIONS OF AN AVERAGE STATE



$$d \ll H_p, \quad \delta\rho/\rho \ll 1$$

BLOB TIMESCALE : $\tau_i = d/v$

THERMAL " : $\tau_{th} = d^2/\eta_R$

DYNAMICAL " : $\tau_{dyn} = d/c_s$

$\tau_i \ll \tau_{th} \quad \Rightarrow \quad S_i = S_i^*$ (ADIABATIC)

$\tau_i \gg \tau_{dyn} \quad \Rightarrow \quad p_i^* = p^*$ (NO PRESSURE FLUCTUATIONS)

$$\boxed{\text{INSTABILITY :} \quad \rho_i^* < \rho^*}$$

(BUOYANCY)

$$\Rightarrow \quad \rho_i^* - \rho^* = \left[\left(\frac{d\rho}{dr}\right)_{ad} - \frac{d\rho}{dr} \right] \cdot \delta r < 0$$

EQ. OF STATE $\quad p = \mathcal{R}\rho T/\mu \quad \& \quad p_i^* = p_i$:

$$\Rightarrow \quad \boxed{\frac{dT}{dr} < \left(\frac{dT}{dr}\right)_{ad} + \frac{T}{\mu}\left[\frac{d\mu}{dr} - \left(\frac{d\mu}{dr}\right)_{ad} \right]}$$

$\frac{d\mu}{dr} \neq 0$ → COMPOSITION CHANGES (STELLAR INTERIORS)

→ IONIZATION (STELLAR ENVELOPES)

→ CONSIDER SEPERATELY

SCHWARZSCHILD CRITERION

$$\frac{dT}{dr} < \left(\frac{dT}{dr}\right)_{ad} \qquad \frac{1}{H_p} \equiv -\frac{1}{p}\frac{dp}{dr} \quad \text{pressure scale height}$$

REWRITE: $$\frac{dT}{dr} = \frac{T}{p} \underbrace{\frac{d\ln T}{d\ln p}}_{\nabla} \cdot \frac{dp}{dr} = -\frac{T}{H_p}\nabla$$

→ INSTABILITY FOR $\boxed{\nabla > \nabla_{ad}}$

ideal gas, no ionization : $\nabla_{ad} = \frac{\gamma-1}{\gamma} = 0.4 \ (\gamma = \frac{5}{3})$

RELATION TO ENTROPY GRADIENT

$$TdS = pdV + dE$$

ASSUME IDEAL GAS $\quad dE = c_v dT, \quad p = R\rho T$

+ USE $(dS)_{ad} = 0 \qquad R = c_p - c_v$

⇒ ... EXERCISE ...

$$\frac{dS}{dr} = \frac{c_p}{T}\left[\frac{dT}{dr} - \left(\frac{dT}{dr}\right)_{ad}\right] < 0 \text{ for inst.}$$

→ CONVECTIVE INSTABILITY

⟺ ENTROPY DECREASES OUTWARD

[ENTROPY SINK : STELLAR SURFACE]

- COMPOSITION CHANGE, NO IONIZATION

$\Rightarrow \left(\frac{d\mu}{dr}\right)_{ad} = 0$ $\qquad \boxed{\frac{dT}{dr} < \left(\frac{dT}{dr}\right)_{ad} + \frac{T}{\mu}\frac{d\mu}{dr}}$

LEDOUX CRITERION

HE-ENRICHED CORE $\Rightarrow d\mu/dr < 0 \Rightarrow$ STABILIZING μ-GRADIENT

- IONIZATION, NO COMPOSITION CHANGES

$\Rightarrow \mu(T,p)$ GIVEN FUNCTION (EXT. & INT.)

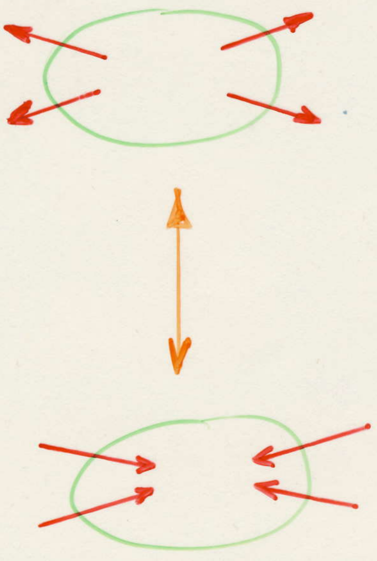
$$\left[\frac{dT}{dr} - \left(\frac{dT}{dr}\right)_{ad}\right] \cdot \underbrace{\left[1 - \left(\frac{d\ln\mu}{d\ln T}\right)_p\right]}_{X_p > 0 \text{ ALWAYS}} < 0$$

$\boxed{\frac{dT}{dr} < \left(\frac{dT}{dr}\right)_{ad}}$ SCHWARZSCHILD CRITERION $\left[\frac{dS}{dr} < 0\right]$

- SEMICONVECTION [EARLY-TYPE STARS]

$$\left(\frac{dT}{dr}\right)_{ad} + \frac{T}{\mu}\left(\frac{d\mu}{dr}\right) < \frac{dT}{dr} < \left(\frac{dT}{dr}\right)_{ad}$$

DYNAMICALLY STABLE, BUT FREE ENERGY AVAILABLE



$T_i > T_e \rightarrow$ RADIATIVE COOLING

$\rightarrow \rho_i > \rho_{i,ad}$

OVERSTABLE OSCILLATIONS,

GROWING AMPLITUDES

τ_μ RELEVANT

$T_i < T_e \rightarrow$ RADIATIVE HEATING

$\rightarrow \rho_i < \rho_{i,ad}$

- **„NABLA" - NOTATION**

$\boxed{\ln p}$ AS NON-DIMENSIONALIZED COORDINATE TECHN. CONVENIENT

$$\frac{dT}{dr} = \frac{T}{p}\underbrace{\frac{d\ln T}{d\ln p}}_{\nabla}\cdot\frac{dp}{dr} \underset{\text{HYD. EQU.}}{=} -\frac{T\varrho g}{p}\nabla \underset{H_p = \mathcal{R}T/\mu g}{=} -\frac{T}{H_p}\nabla$$

$$\boxed{\begin{array}{ll} \text{LEDOUX}: & \nabla > \nabla_{ad} + \nabla_\mu \\ \text{SCHWARZSCHILD}: & \nabla > \nabla_{ad} \end{array}}$$

$\nabla_\mu = \frac{d\ln\mu}{d\ln p}$ (ideal gas)

- **CRITERIA ARE SUFFICIENT AND NECESSARY**

LEBOVITZ (1966) FULL LINEAR STABILITY ANALYSIS

- **4 GRADIENTS**

RADIATIVE ENERGY TRANSPORT : $\nabla = \nabla_{rad} = \frac{3\kappa\varrho H_p}{4ac\,T^4}\,\frac{L(r)}{4\pi r^2}$

ADIABATIC STRATIFICATION : $\nabla = \nabla_{ad} = (\gamma-1)/\gamma$

„BLOB GRADIENT" WITH RADIATIVE EXCHANGE : $\nabla_i > \nabla_{ad}$

RELATION IN A CONVECTIVE REGION :

$$\boxed{\nabla_{rad} \underset{\text{CONVECTION MIXES}}{>} \nabla \underset{\text{DRIVER}}{>} \nabla_i \underset{\text{ENERGY EXCHANGE (DAMPING)}}{>} \nabla_{ad}}$$

- **FORMAL STABILITY ANALYSIS** :

→ REVIEW BY P. LEDOUX in

E.A. SPIEGEL & J.P. ZAHN,

„PROBLEMS OF STELLAR CONVECTION",

LECTURE NOTES IN PHYSICS 71, p.87

SPRINGER (1977)

„EXPLODING GRANULES"
& GRANULE SIZES

$p' > 0$

→ ACCELERATION OF HORIZ. FLOW

→ BUOYANCY BRAKING

→ UPFLOW CHOKED

→ COOLING BY RADIATION

SUBSONIC → $0 \approx \underline{\nabla} \cdot (\varrho \underline{u}) = \dfrac{\partial \varrho v_z}{\partial z} + \dfrac{1}{r} \dfrac{\partial}{\partial r} (r \varrho v_r)$

$$\left.\begin{array}{l} v_r \sim k \cdot r \\ v_z \sim \text{const.} \\ \varrho(z) \end{array}\right\} \quad \frac{\varrho v_z}{H_\varrho} = \frac{2 \varrho v_r}{r} \quad \Rightarrow \quad \boxed{R = 2 H_\varrho \left(\frac{v_r}{v_z} \right)}$$

- $\dfrac{v_r}{v_z}$ ↑ WITH SIZE OF THE STRUCTURE

- p' ↑ TO DRIVE INCREASING u_h

  → BUOYANCY BRAKING CHOKES UPFLOW

- GRANULES CANNOT EXCEED A CRITICAL SIZE

  ($v_z = 2$ km/s , $v_r = c_s \approx 10$ km/s

  SUN: $R \lesssim 10 H_\varrho \approx 2000$ km)

- STELLAR GRANULES SCALE WITH H_ϱ

  (DRAVINS & NORDLUND, 1990)

4. MIXING LENGTH DESCRIPTION

CONVECTION AS MIXTURE OF BLOBS WHICH MOVE VERTICALLY OVER A DISTANCE ℓ (THE MIXING LENGTH) AND DISSOLVE

[PRANDTL (1925), BIERMANN (1948), ÖPIK (1950), BÖHM-VITENSE (1953)]

TYPICALLY $\boxed{\ell = \alpha \cdot H_p}$, $\alpha = O(1)$

AIM: CALCULATE ENERGY FLUX AND MEAN QUANTITIES

(∇; S; ΔT, v of BLOBS, ...)

TEMPERATURE DIFFERENCE: [ignore factors of $O(1)$]

$$\Delta T = \left[\left(\frac{dT}{dr}\right)_i - \frac{dT}{dr}\right] \cdot \delta r = (\nabla - \nabla_i)\, T\, \frac{\delta r}{H_p} = (\nabla - \nabla_i)\, T \alpha$$

CONVECTIVE FLUX: [ERGS $\cdot$ CM^{-2} $\cdot$ S^{-1}]

$$F_c = \Delta T \cdot \rho c_p \cdot v = \rho c_p v T (\nabla - \nabla_i) \alpha$$

VELOCITY: [ACCELERATION BY BUOYANCY]

$$\ddot{\delta}_r = -g\, \Delta\rho / \rho = g\, \chi_p\, \Delta T / T = g \chi_p (\nabla - \nabla_i) \frac{\delta r}{H_p}$$

$\Rightarrow$ (BLOB HOMOGENEOUS) $\dot{\delta}_r^2 = \frac{g \chi_p}{H_p} (\nabla - \nabla_i)\, \delta_r^2$.

$$\Rightarrow \quad \boxed{v = \left[\frac{g \chi_p}{H_p} (\nabla - \nabla_i)\right]^{1/2} \cdot \ell}$$

stabil:

$$\omega^2 = -\frac{g\delta}{H_p} = N^2$$

Brunt-Väisälä

$$\omega^2 \sim \frac{10^4 \cdot 10^{-6}}{10^{10}} \sim 10^{12}$$

CONVECTIVE FLUX:

$$\boxed{F_c = \rho c_p T (g \chi_p H_p)^{1/2} \alpha^2 (\nabla - \nabla_i)^{3/2}} \sim$$

$\tau \sim 2\pi \cdot 10^6 \sim 2$ Monate

ENERGY FLUX:

$$F_{RAD} + F_c = L_\odot / 4\pi r^2$$

- $\nabla_i = \nabla_a \Rightarrow$ READY , $\nabla(r)$ DETERMINED
- $\nabla_i > \nabla_a$ DUE TO RADIATION $\rightarrow \dots \rightarrow$ CUBIC EQUATION
- TYPICAL VALUES IN DEEP CONVECTION ZONE:

$$\nabla - \nabla_a \approx 10^{-5} \ll 1$$
$$\Delta T \approx 2\,K \ll T$$
$$v \approx 100\,m/s \ll c_s$$

$\rightarrow$ CONVECTION IS VERY „EFFICIENT"

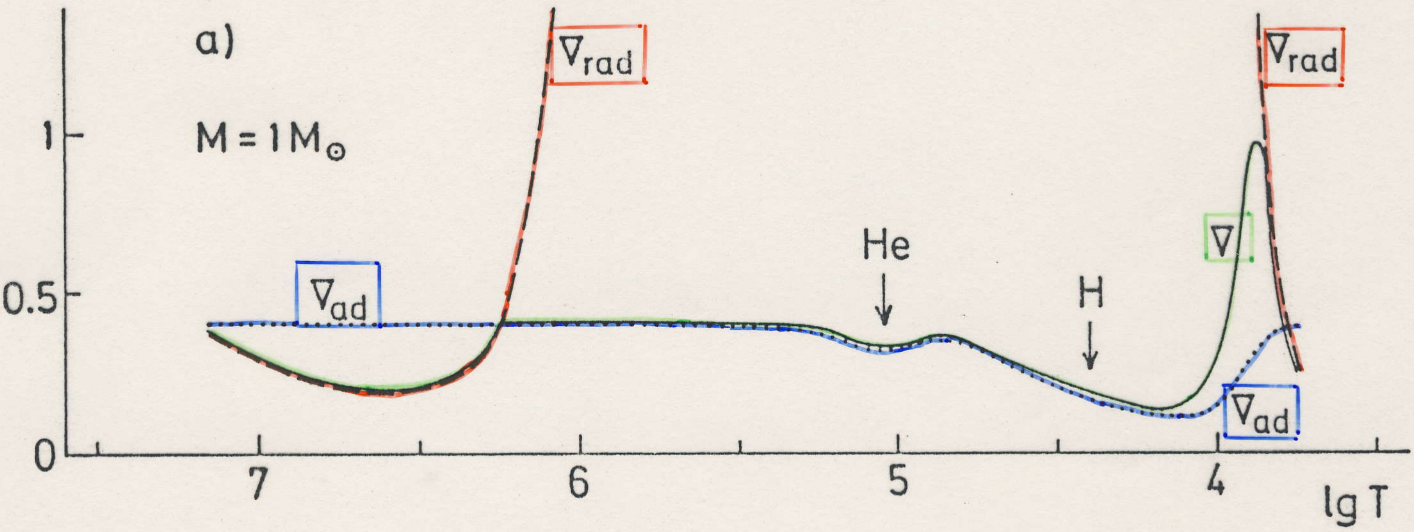
- ... AND NEAR THE SURFACE

$$\nabla - \nabla_a \approx 0.6$$
$$\Delta T \approx 2000\,K$$
$$v \approx 2\,km/s$$

$\rightarrow$ ASSUMPTIONS BECOME INVALID

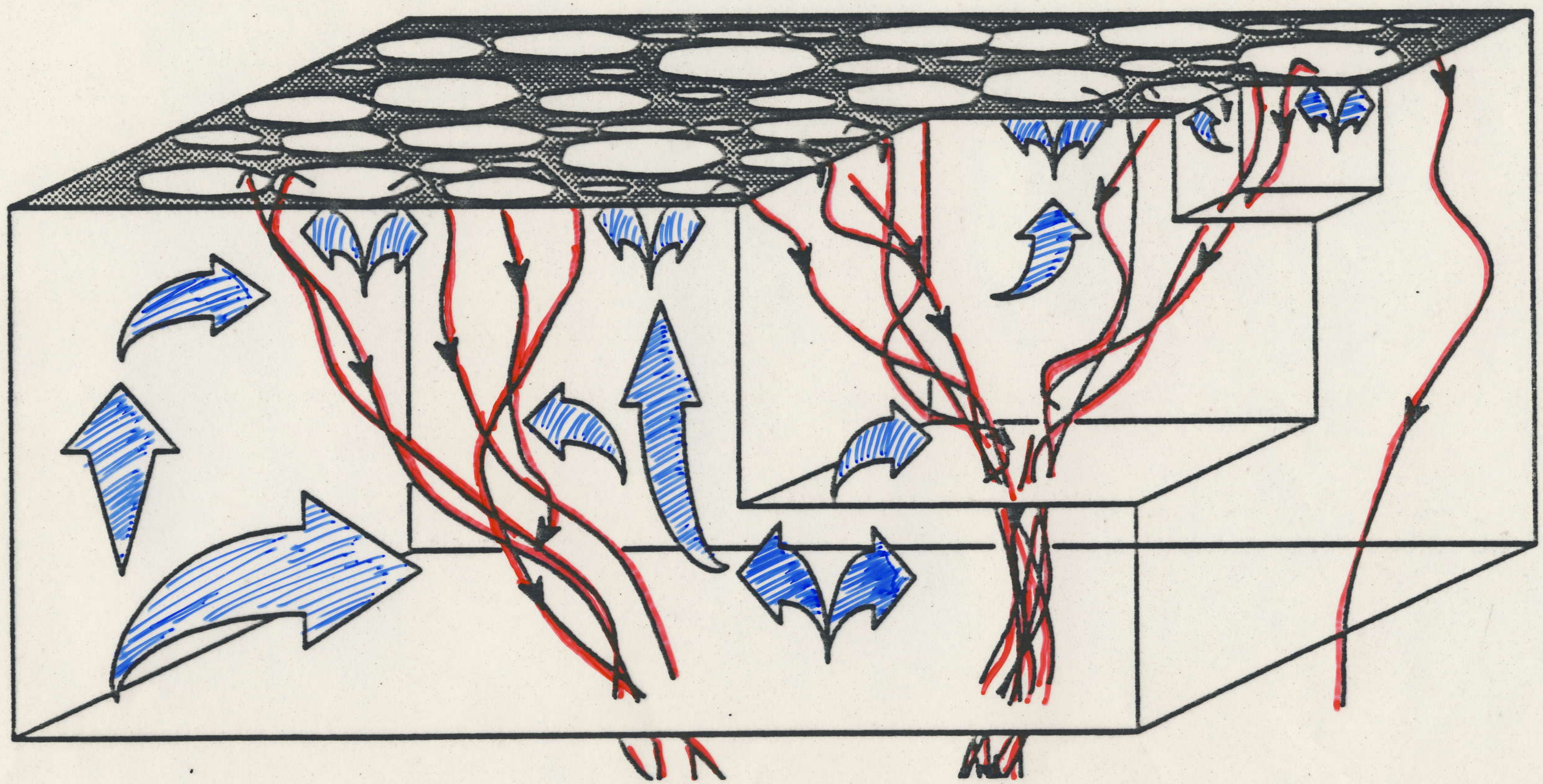
- MIXING LENGTH DESCRIPTION
  $\approx$ TURBULENT DIFFUSION OF ENTROPY WITH $\eta \sim v \cdot \ell$
- IONIZATION (H, He) REDUCES ∇_{ad} (LATENT HEAT)
  $\rightarrow$ DESTABILIZING
- DRAWBACKS OF M.L.D. :
  - LOCAL (NO OVERSHOOT)
  - ADJUSTABLE PARAMETERS (NO PREDICTIONS)
  - EFFECTIVELY INCOMPRESSIBLE, NEGLECTS PRESSURE FLUCTUATIONS, STATIFICATION (BOUSSINESQ - APPROX.)
    (INAPPLICABLE TO OBSERVABLE SURFACE FLOWS)

∇_{RAD}, ∇_{AD}, ∇ IN A STANDARD MIXING LENGTH MODEL OF THE SOLAR CONVECTION ZONE



(SPECULATIVE) PICTURE OF SOLAR CONVECTION : INVERSE CASCADE

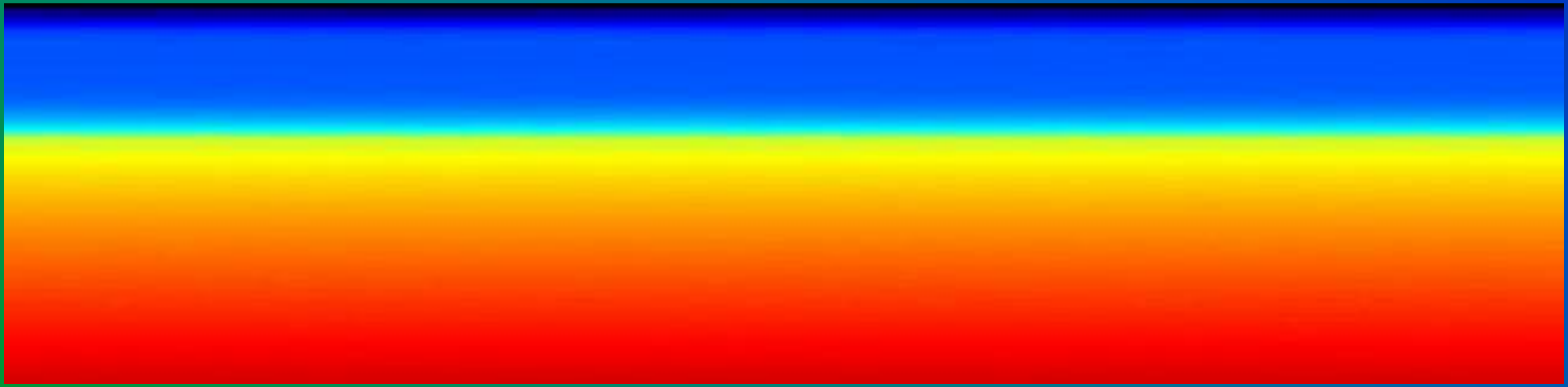
(SPRUIT ET AL., 1990)



FILAMENTARY DOWNDRAFTS MERGE (DUE TO HORIZ. FLOWS ON LARGER SCALES,) DRIVEN BY THE ENTROPY DEFICIT OF THE DOWNDRAFTS THEMSELVES)

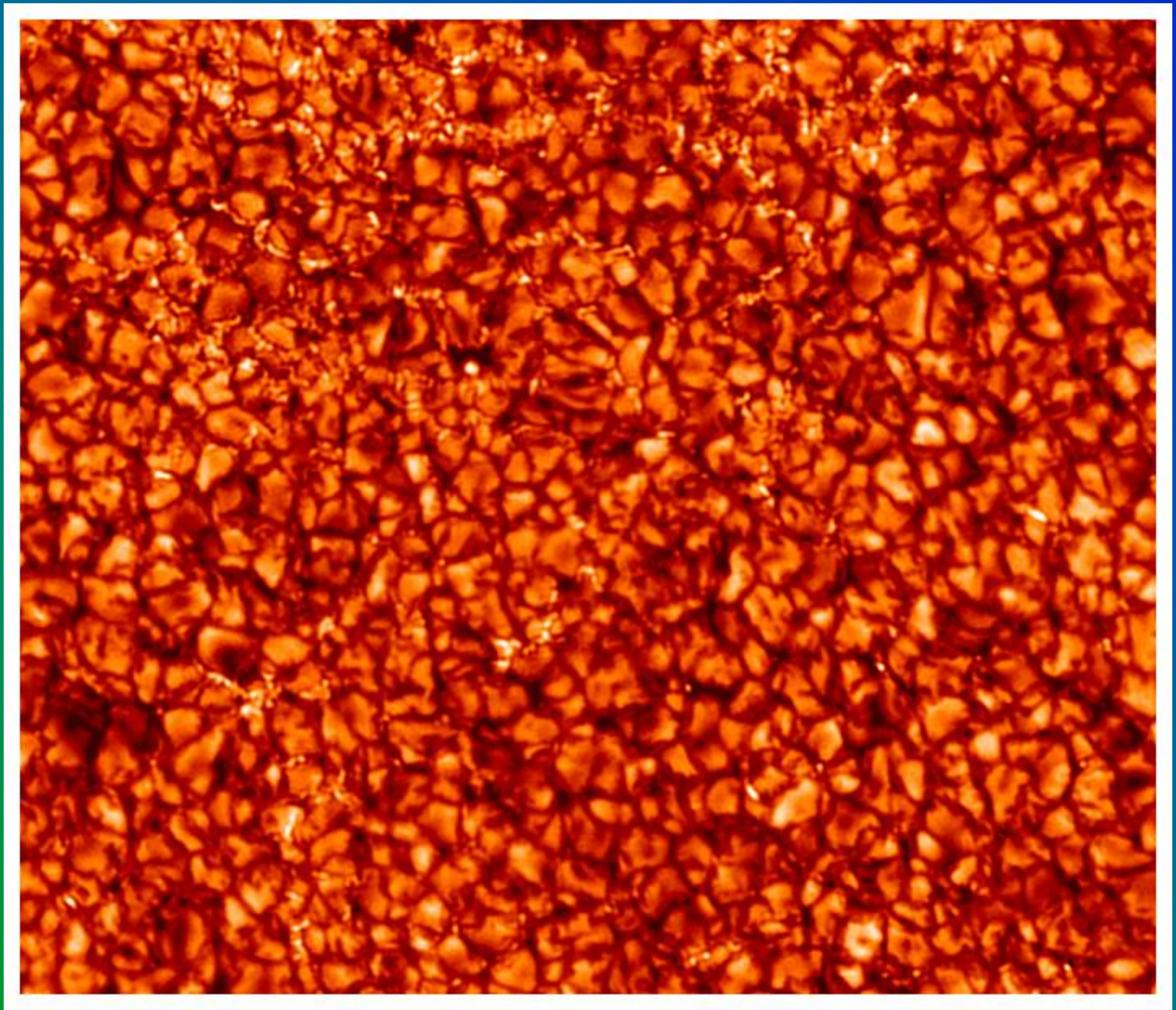
23

Onset of convection: 2D simulation

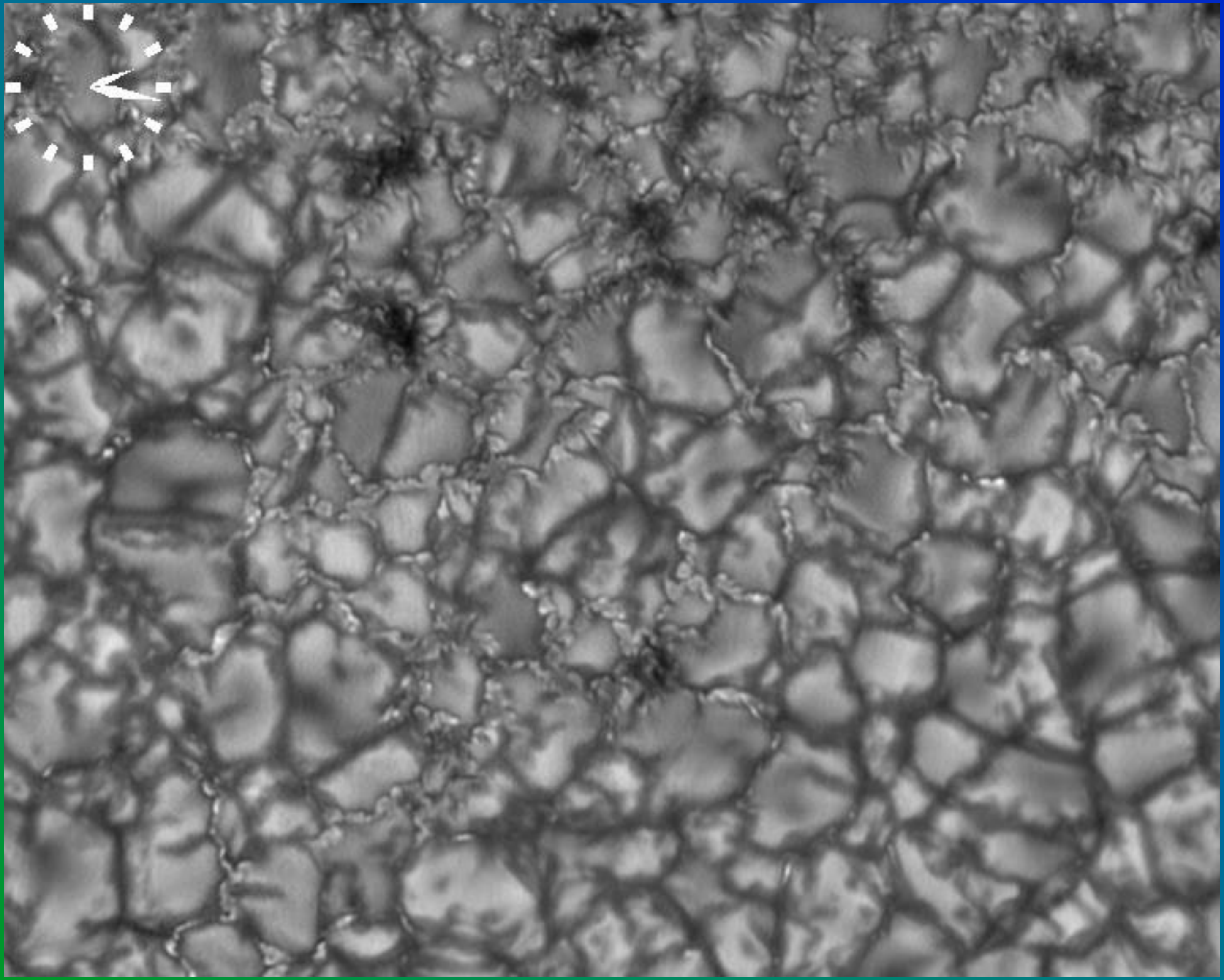


Colours: temperature

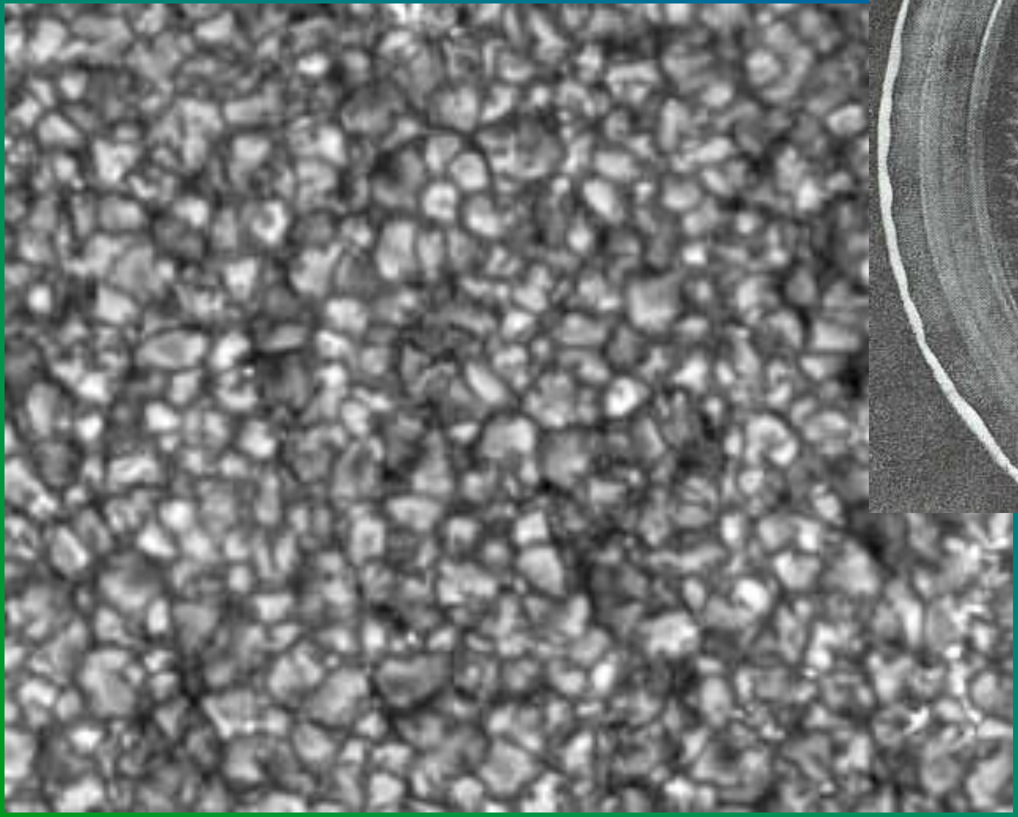
Granulation: Solar surface convection

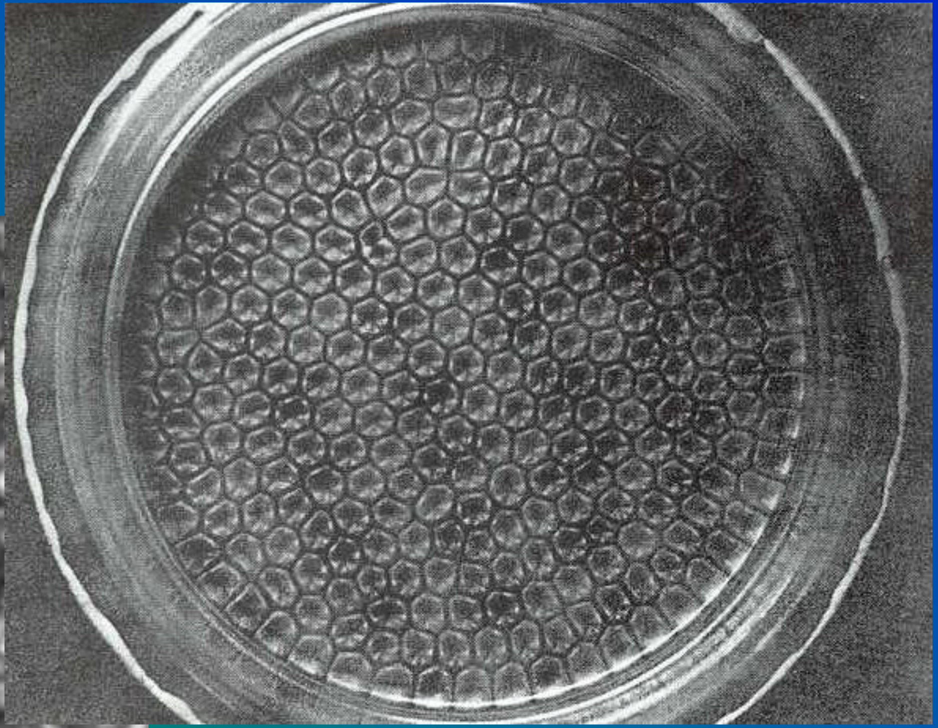


Solar granulation

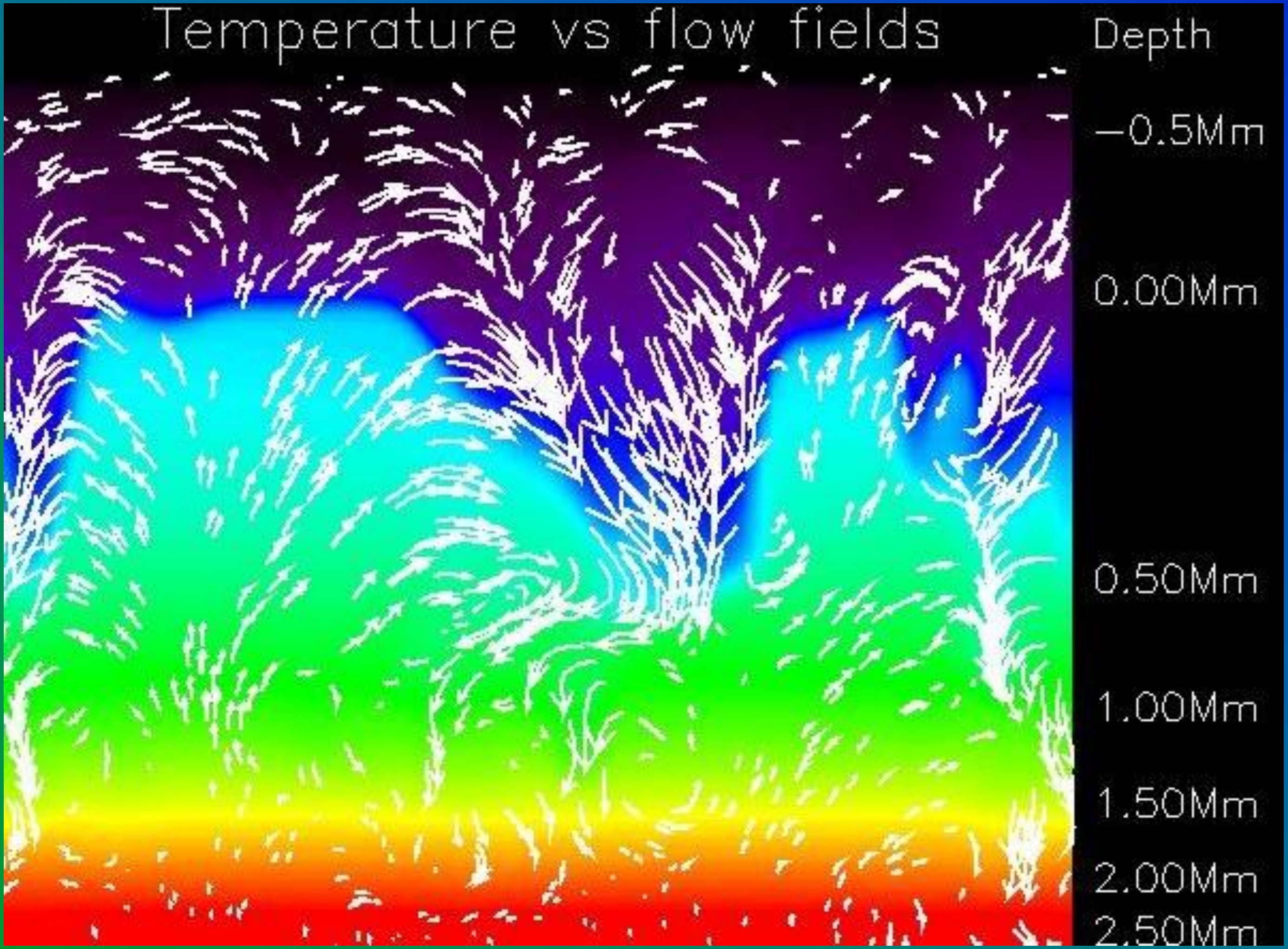


Granulation und laboratory convection

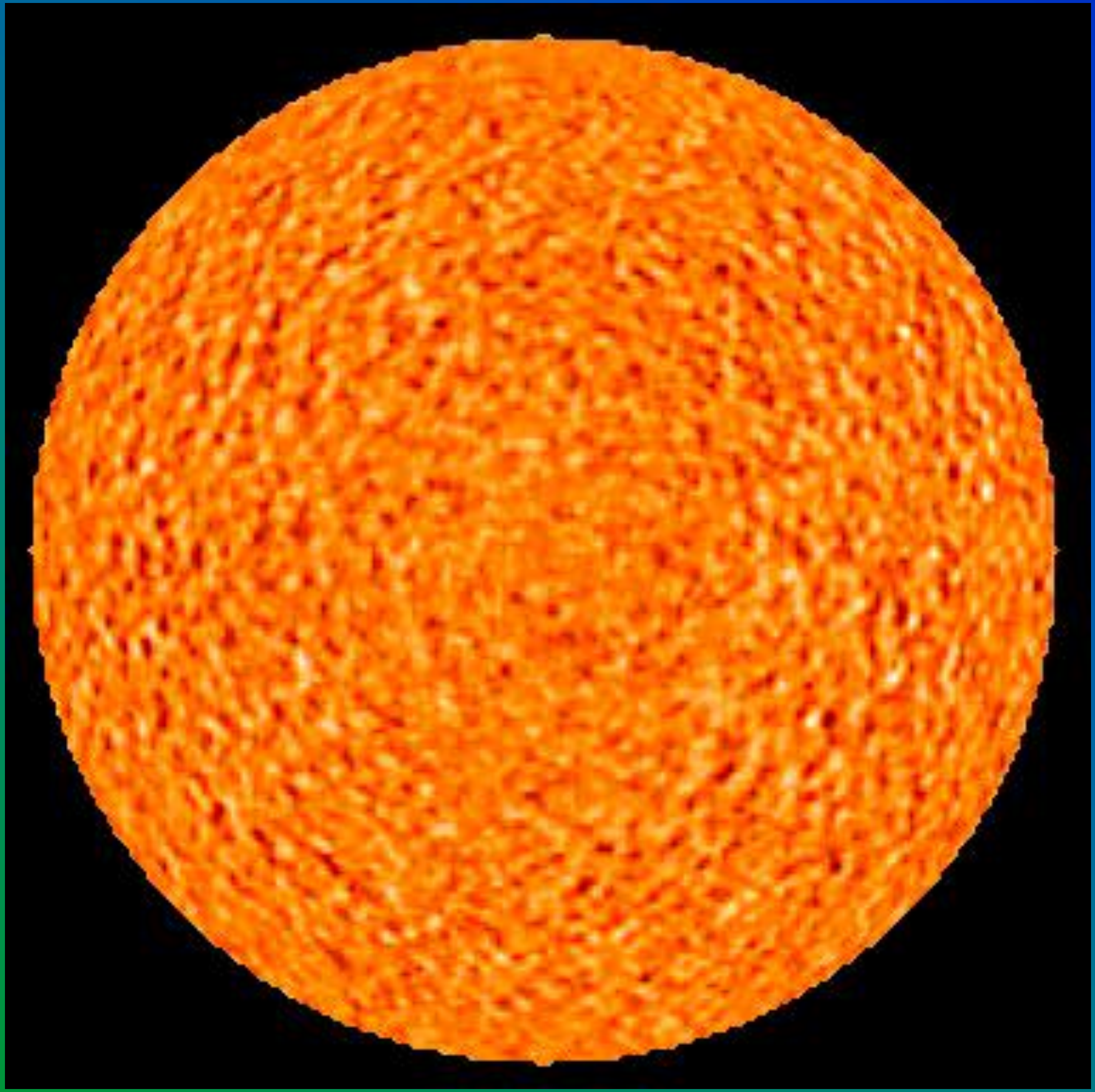




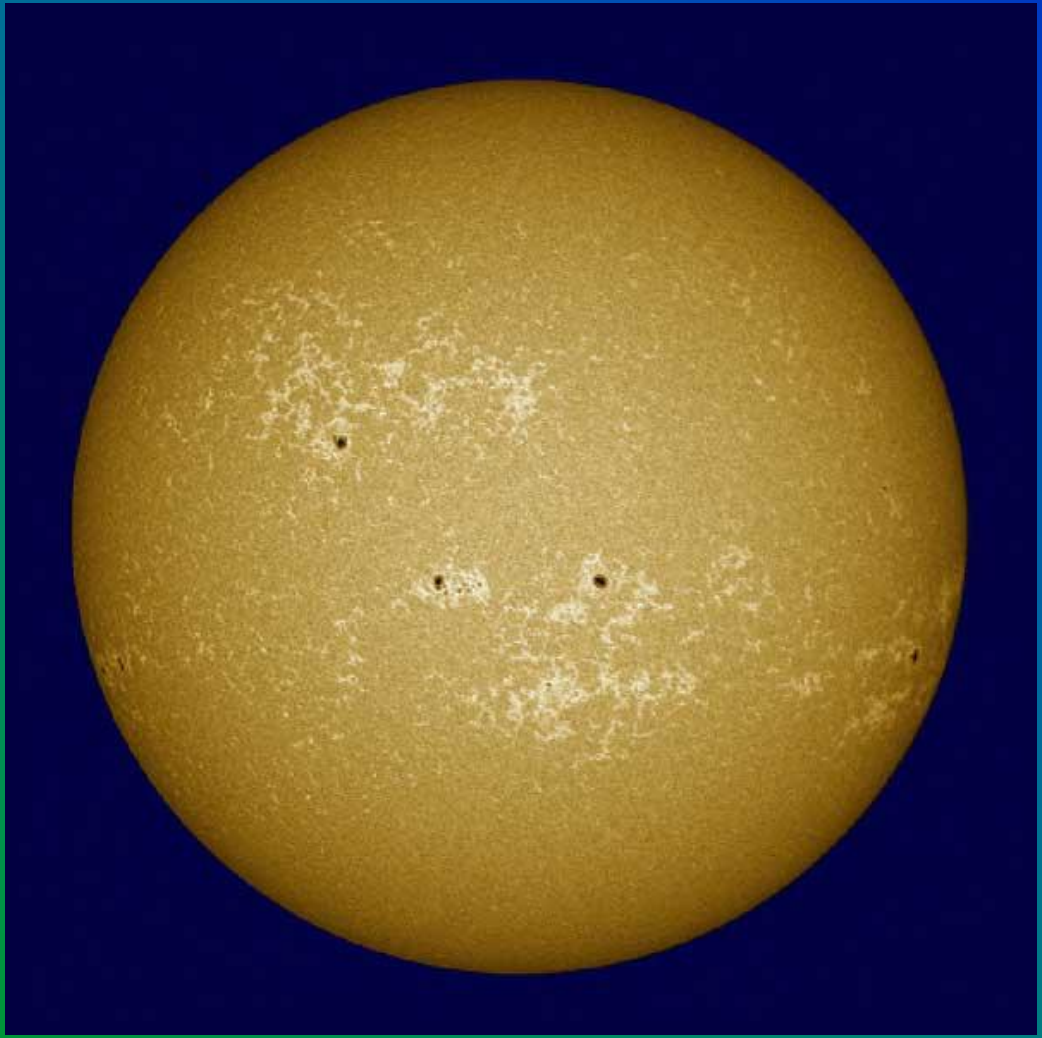
Granulation as a convective phenomenon



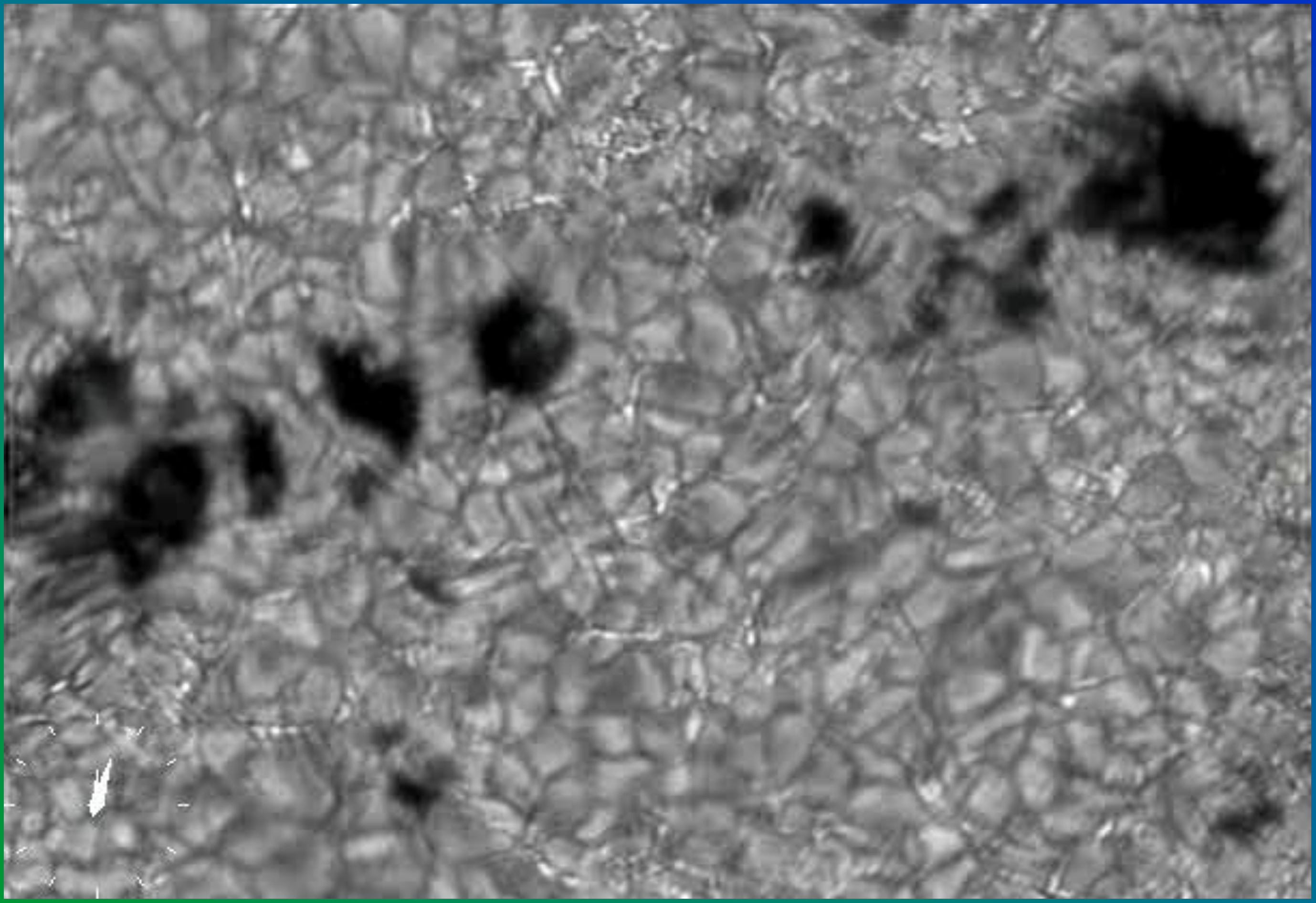
Supergranulation



Supergranulation and magnetic field: the Ca^+ network



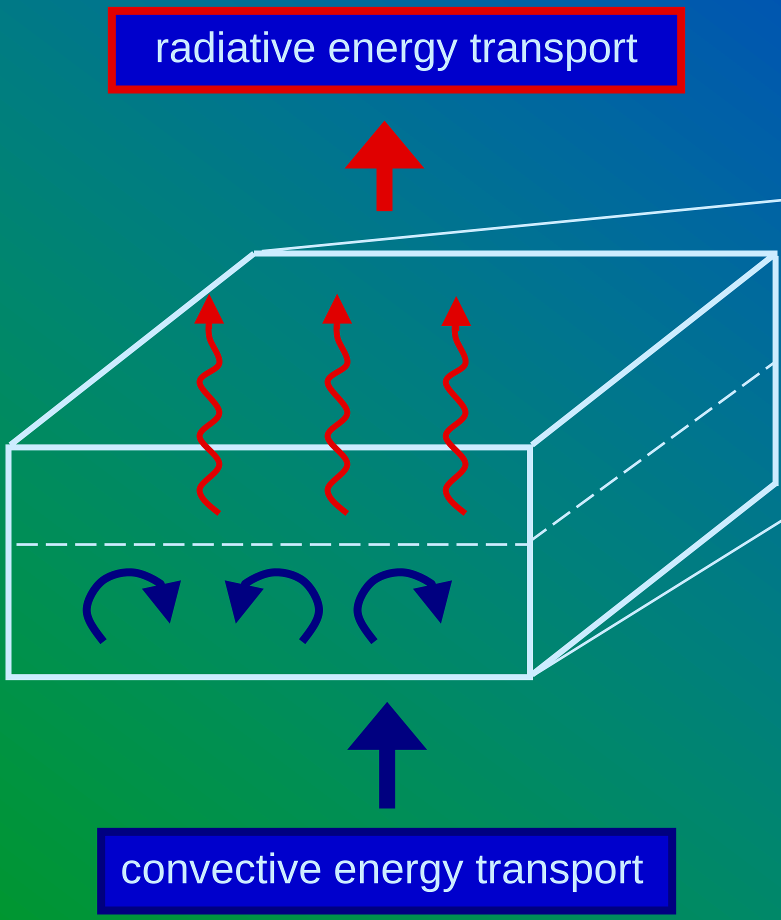
Granulation, sunspots, & small-scale magnetic field

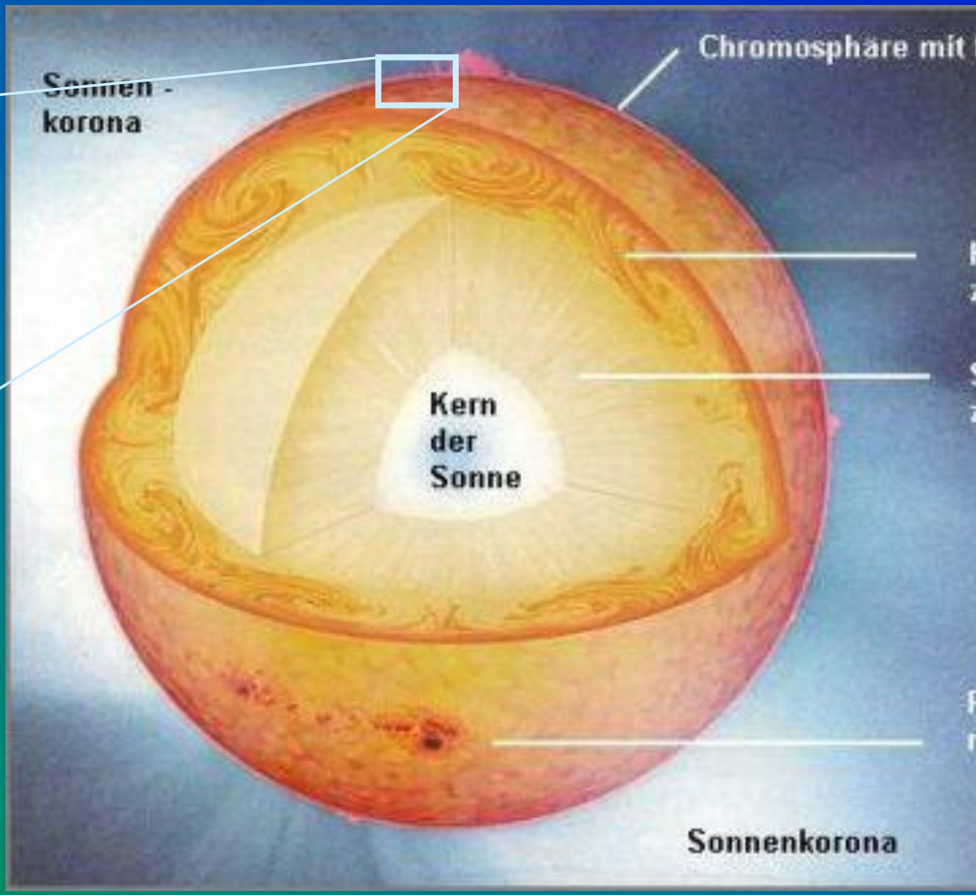


‘Realistic’ solar simulations

- elaborate physics: partial ionization, radiation, compressible, open box, transmitting boundaries, spectral line diagnostics (Stokes profiles)
- + : approximation to solar conditions
- + : direct comparison with observations
- – : computational restrictions (box size, resolution)
- – : Reynolds numbers much below solar values

Approach: Local simulation box including photosphere





The MURaM code: equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

Continuity equation

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \left(\rho \mathbf{u}\mathbf{u} + \left(p + \frac{|\mathbf{B}|^2}{8\pi} \right) \underline{\mathbf{1}} - \frac{\mathbf{B}\mathbf{B}}{4\pi} \right) = \rho \mathbf{g} + \nabla \cdot \underline{\tau}$$

Momentum equation

$$\begin{aligned} \frac{\partial e}{\partial t} &+ \nabla \cdot \left(\mathbf{u} \left(e + p + \frac{|\mathbf{B}|^2}{8\pi} \right) - \frac{1}{4\pi} \mathbf{B} (\mathbf{u} \cdot \mathbf{B}) \right) \\ &= \frac{1}{4\pi} \nabla \cdot (\mathbf{B} \times \eta \nabla \times \mathbf{B}) + \nabla \cdot (\mathbf{u} \cdot \underline{\tau}) + \nabla \cdot (\chi \rho \nabla \frac{e}{\rho}) \\ &+ \rho (\mathbf{g} \cdot \mathbf{u}) + Q_{rad} \ , \end{aligned}$$

$$Q_{rad} = -\nabla \cdot \mathbf{F} = 4\pi\rho \int \kappa_\nu (J_\nu - S_\nu) d\nu$$

Energy equation

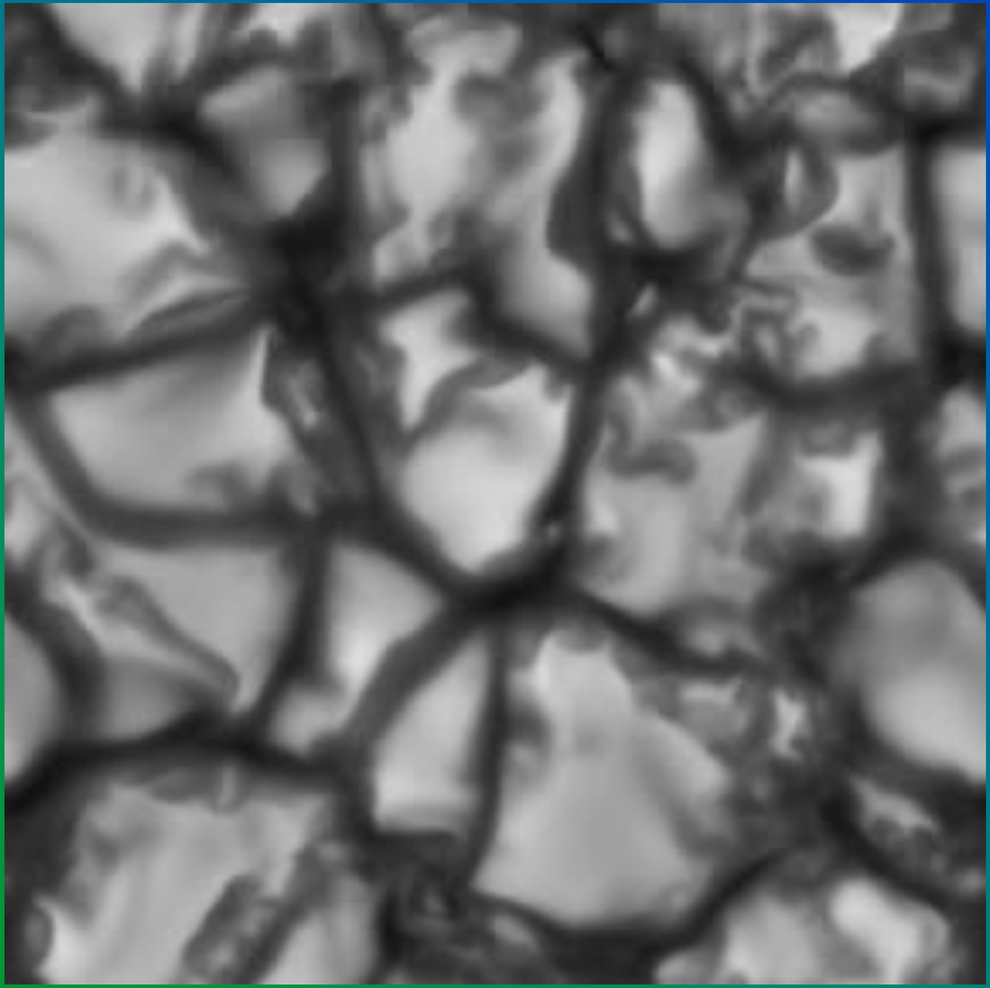
$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{B} - \mathbf{B}\mathbf{u}) = -\nabla \times (\eta \nabla \times \mathbf{B}) \ .$$

Induction equation

$$\frac{dI_\nu}{ds} = -\kappa_\nu \rho (I_\nu - S_\nu)$$

Radiative Transfer Equation

Computer-simulated convection

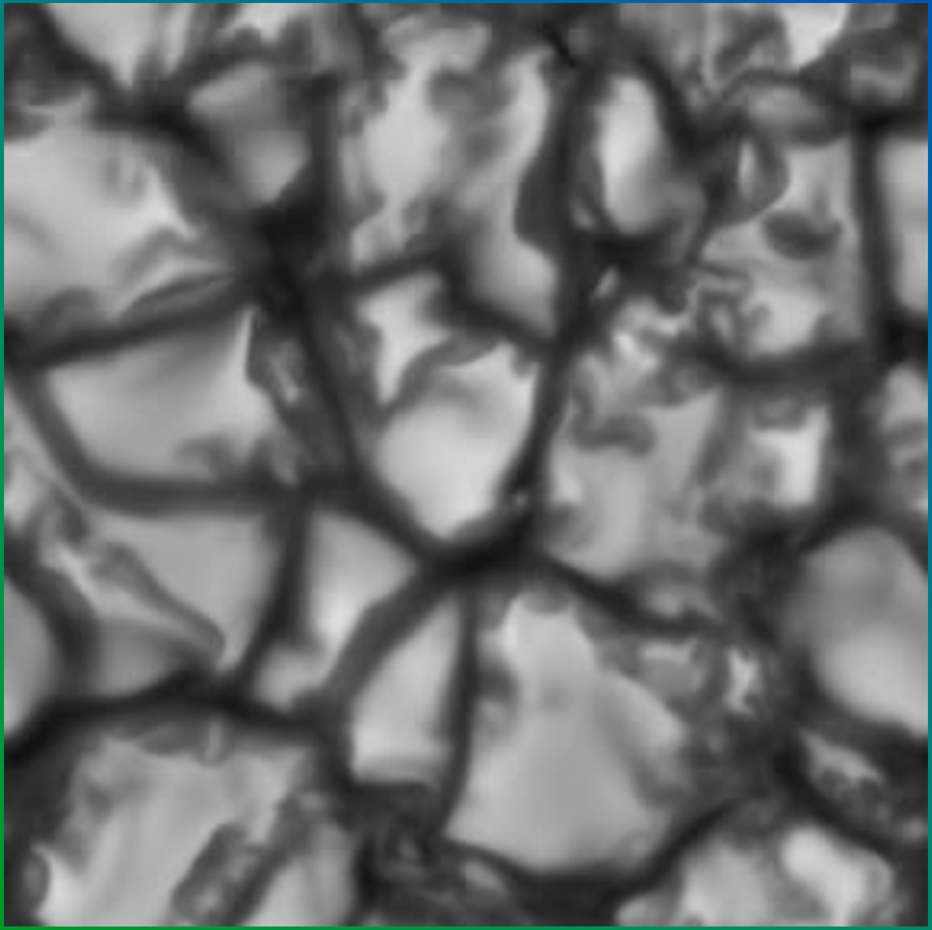


Emerging intensity

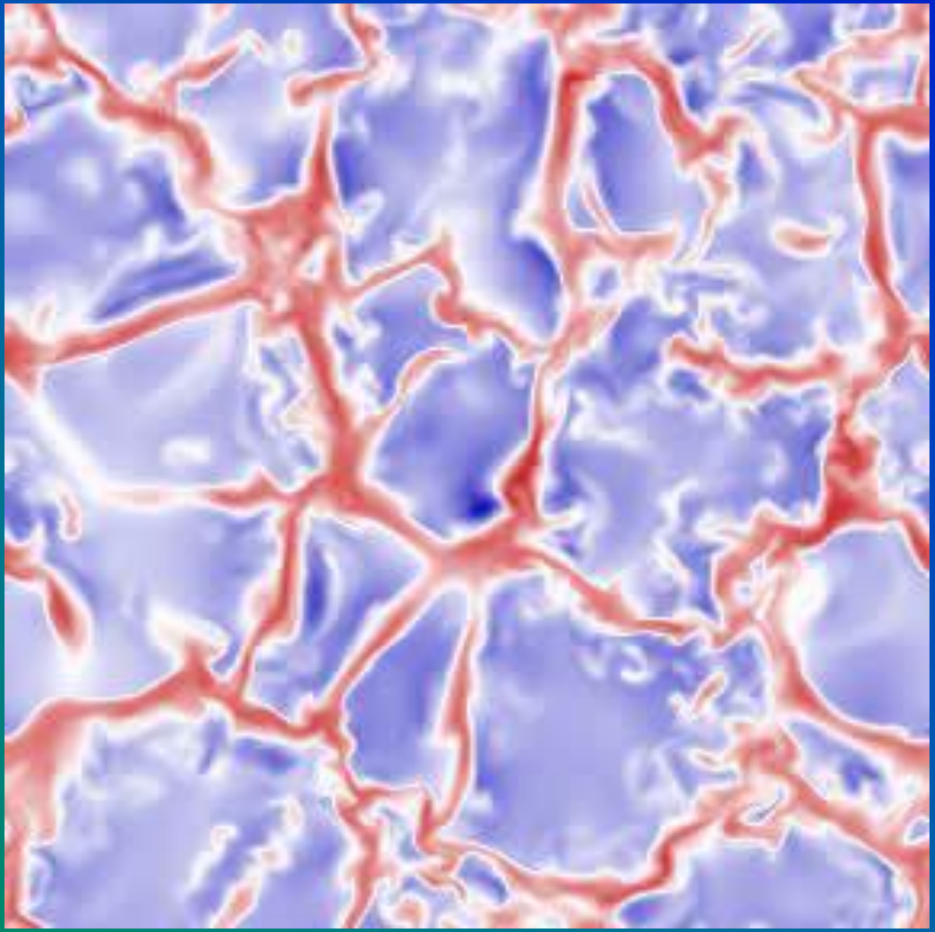
- realistic simulation
- ionization, rad. transfer
- 3D, 288×288×100 mesh
- 6 Mm × 6 Mm × 1.4 Mm
- granulation

Vögler et al. (2005)

Computer-simulated convection



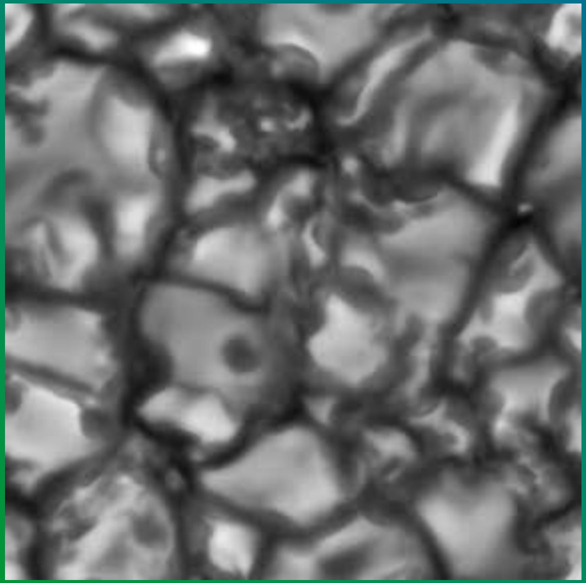
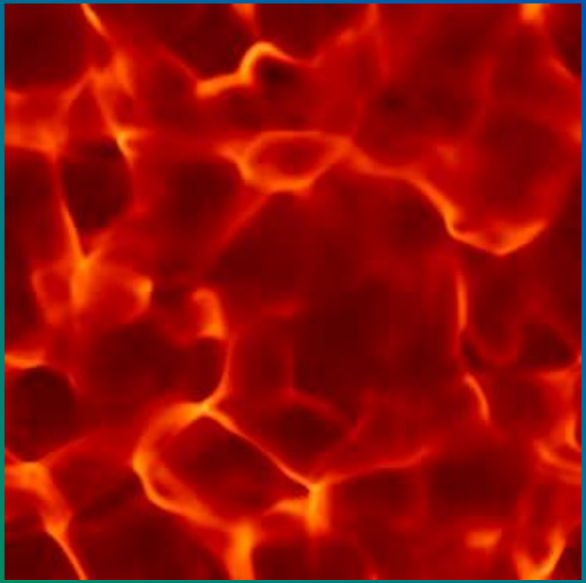
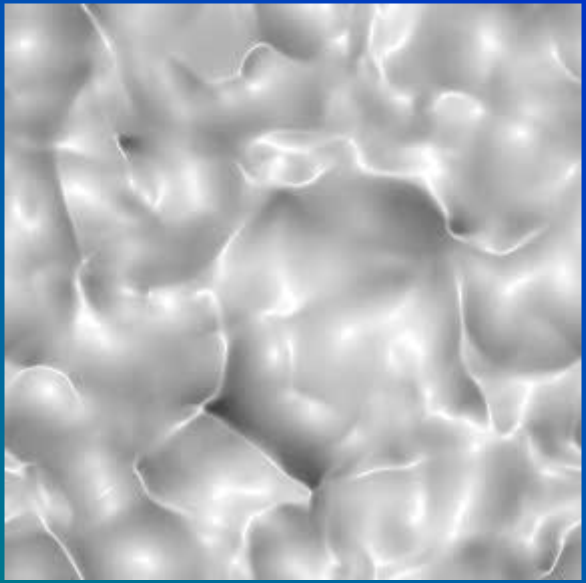
Emerging intensity



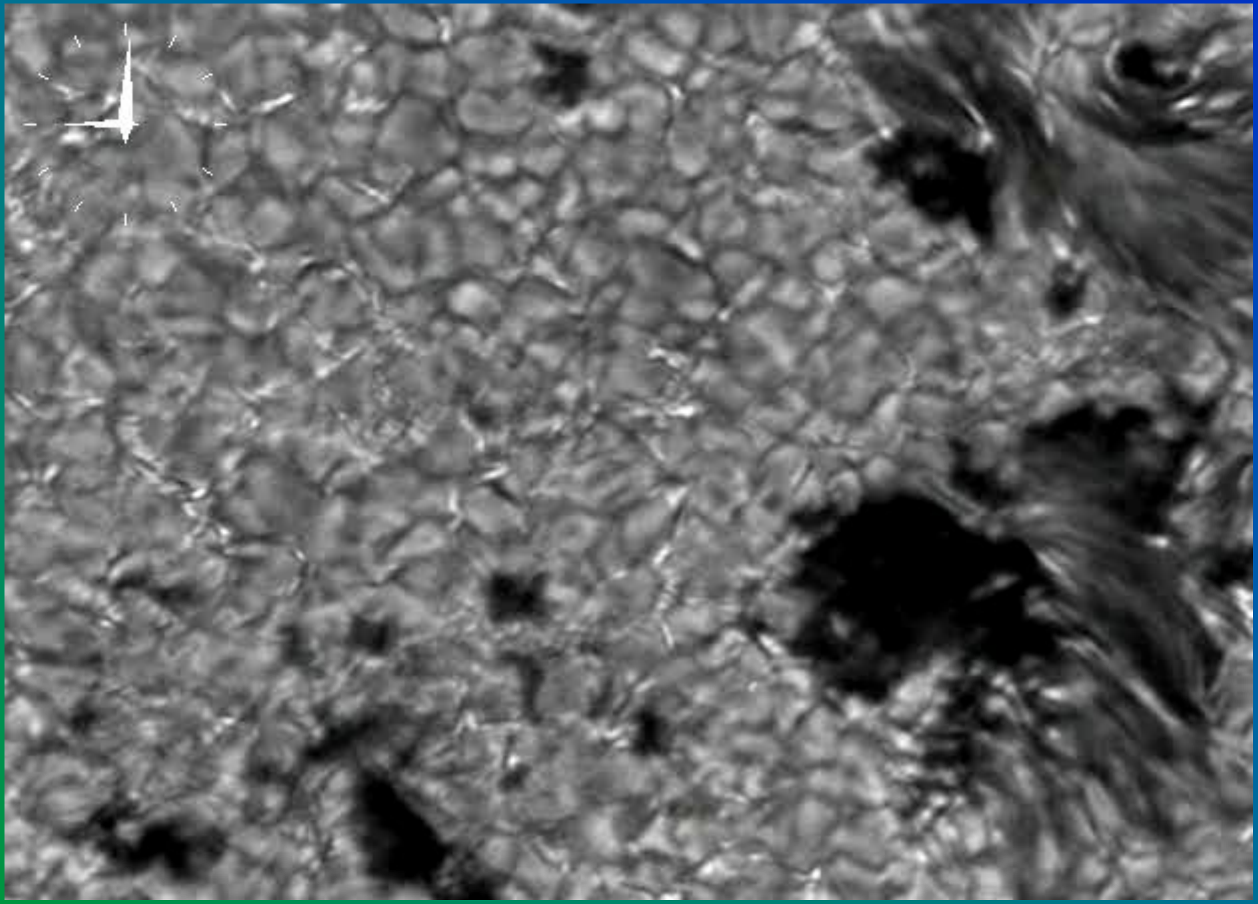
Vertical velocity
(red: down, blue: up)

Computer-simulated convection

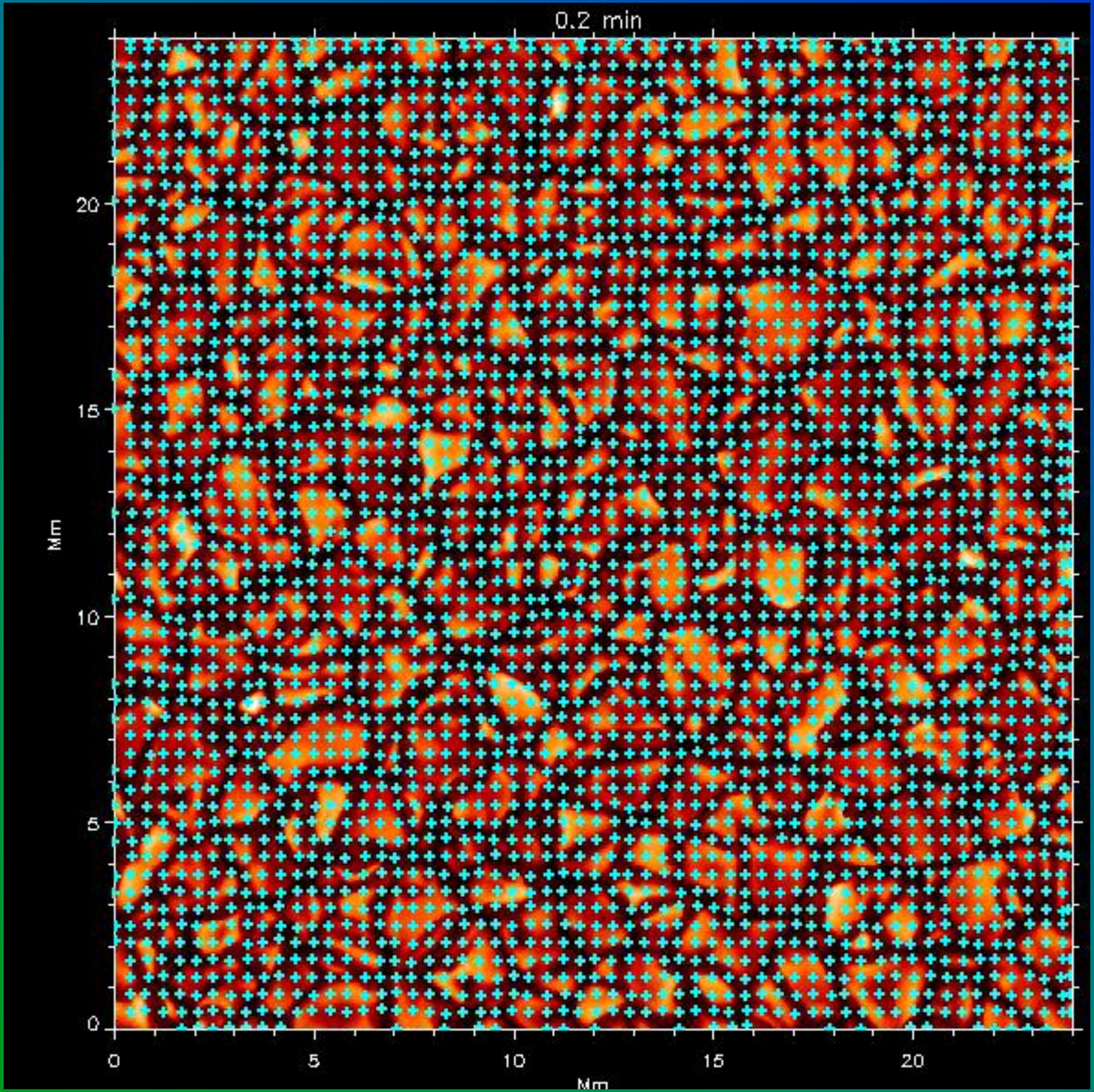
Upper photosphere

"Mesogranulation" ?

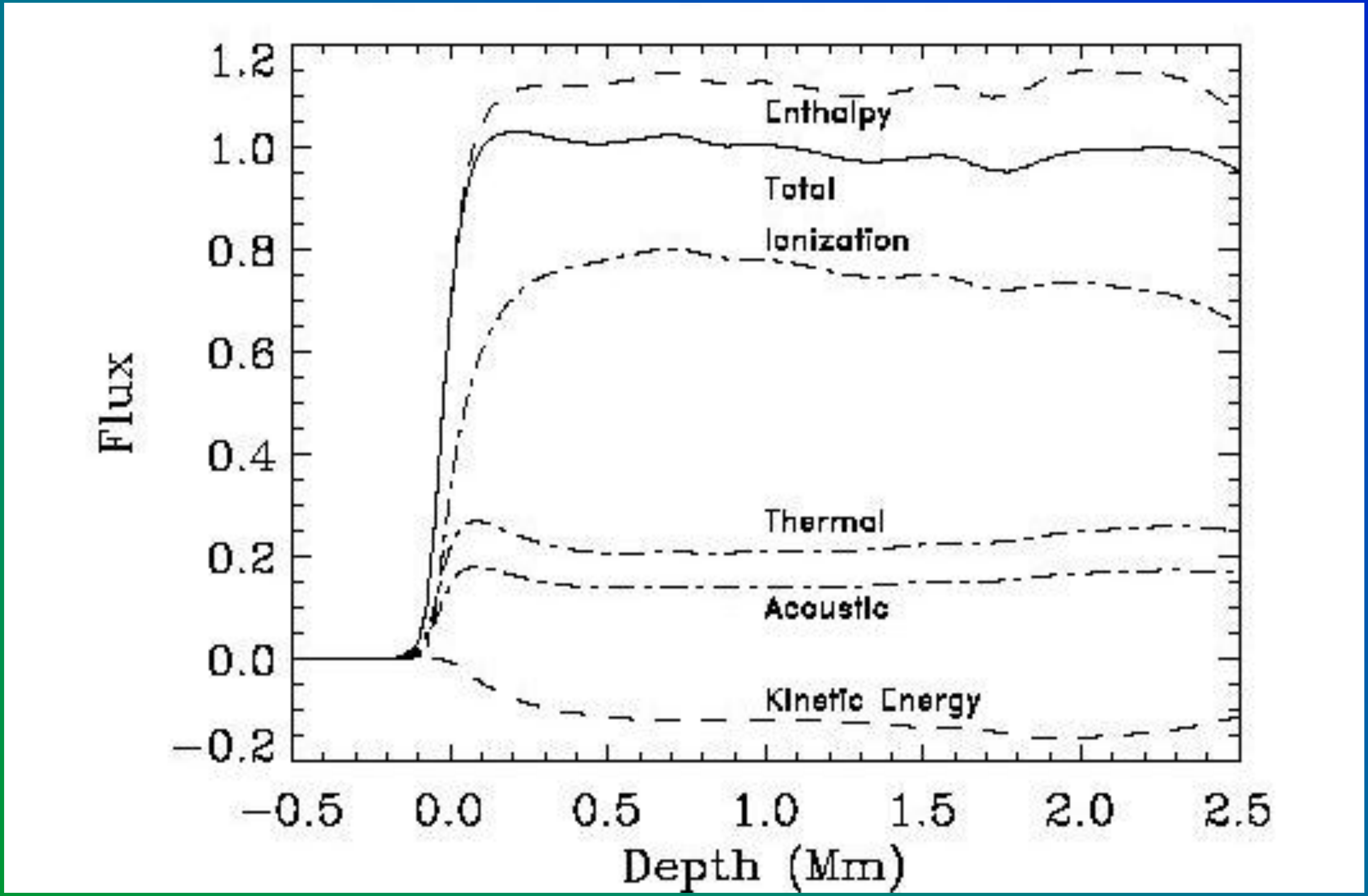


Simulated long-lived convective downflows



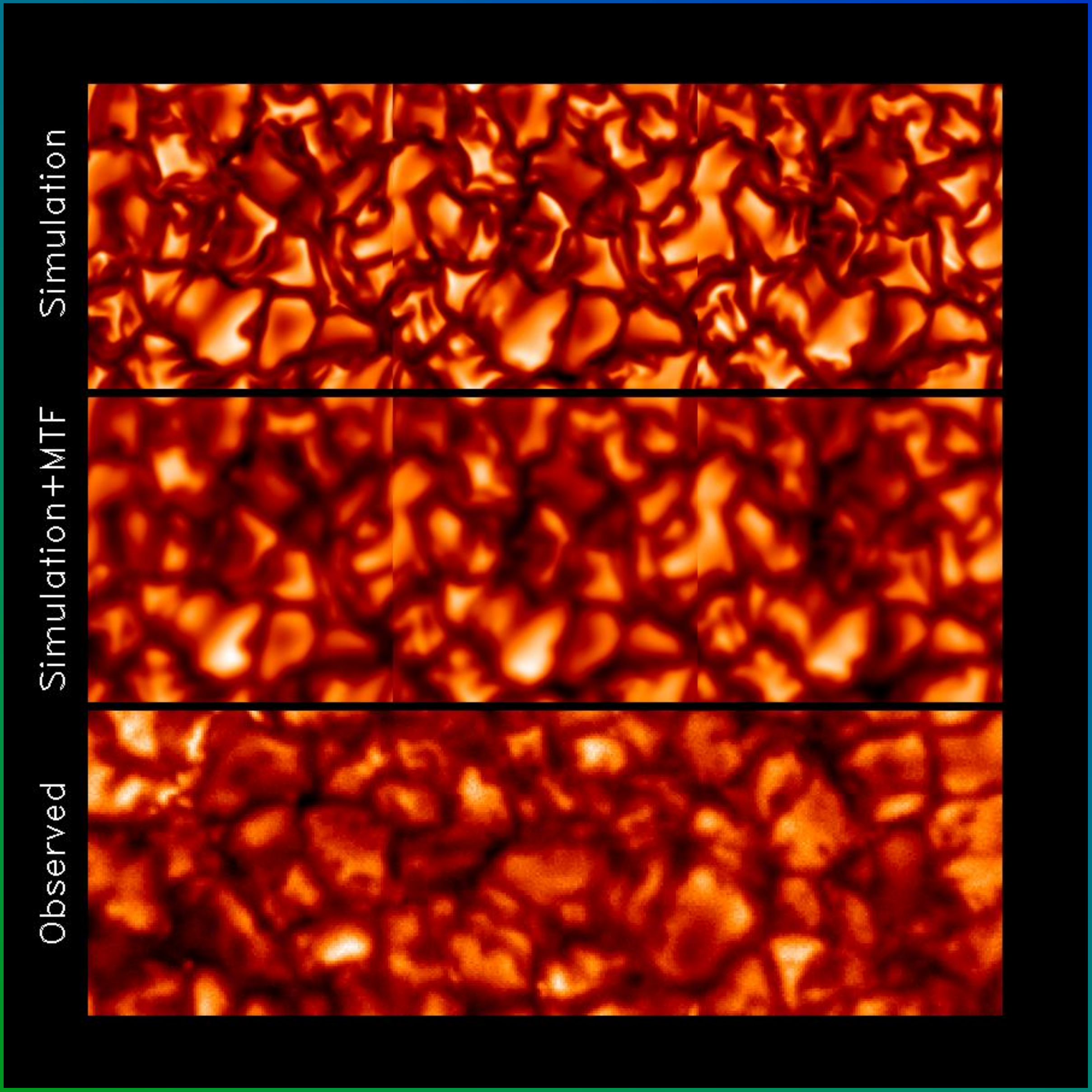
Virtual "corks" are carried by the horizontal flow. They accumulate in downflow regions.

Averaged energy fluxes in a simulation of solar convection



Stein & Nordlund, 2000

Simulation and observation

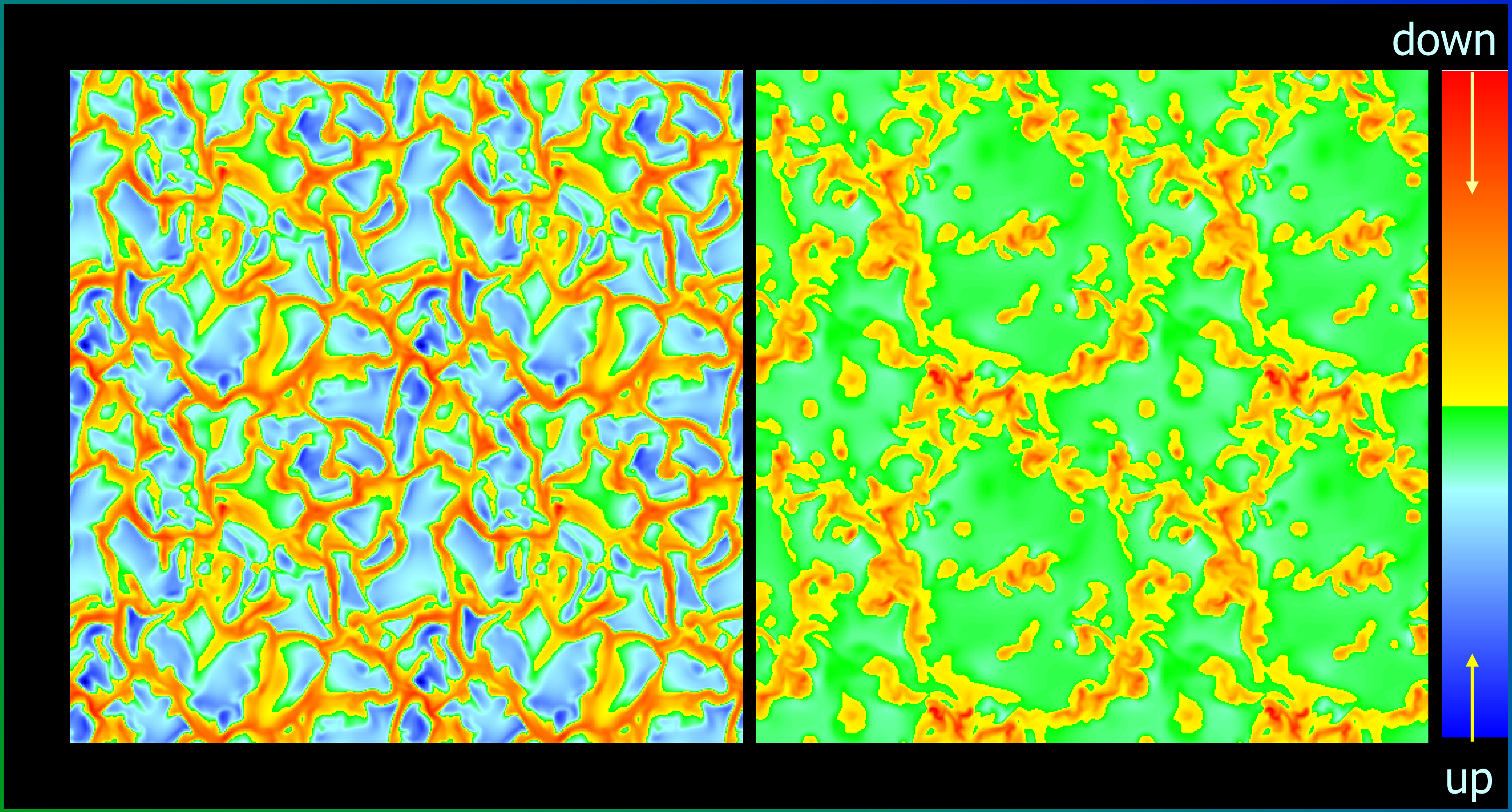


Simulation (original)

Simulation (smoothed)

Observation

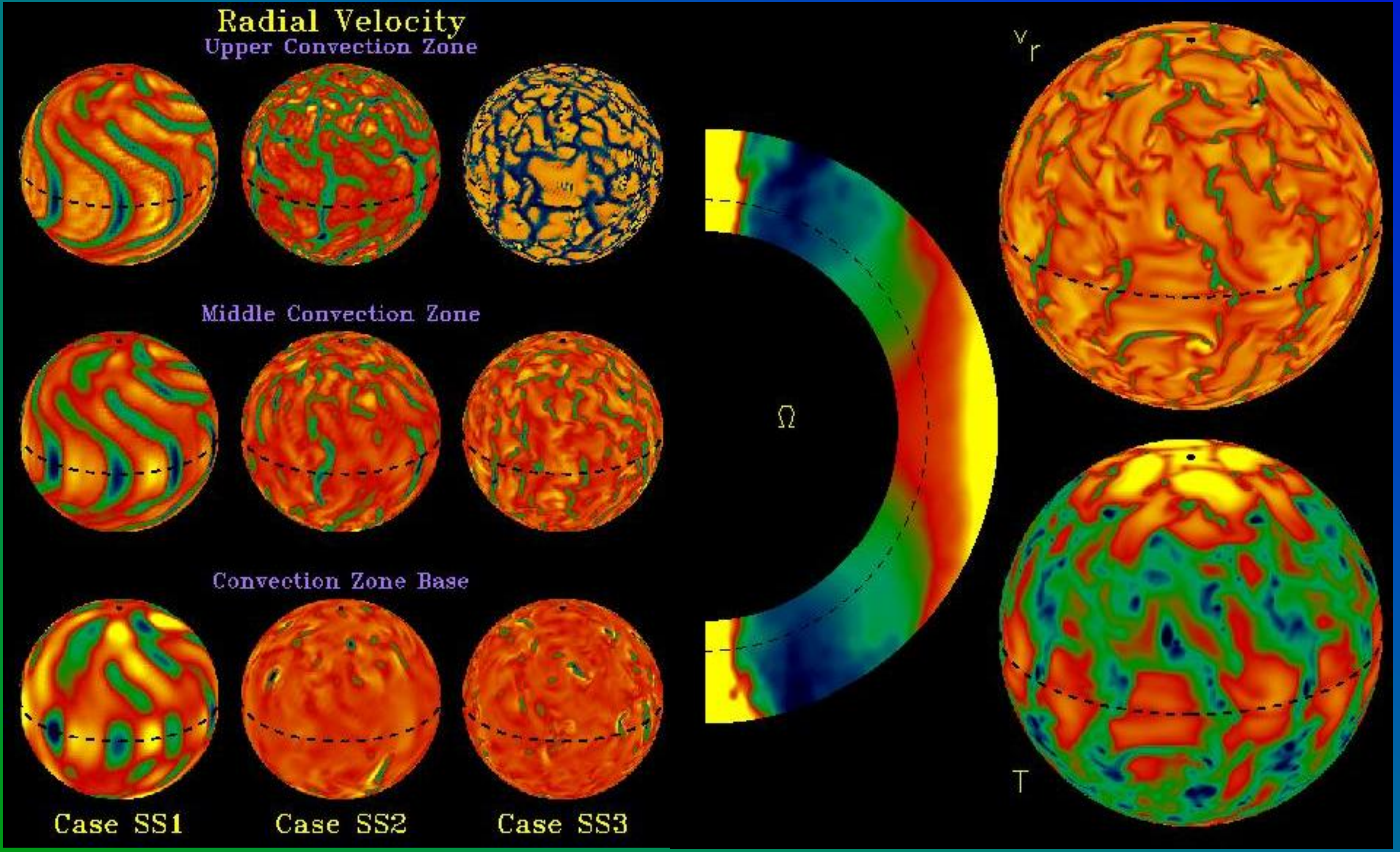
Change of downflow topology



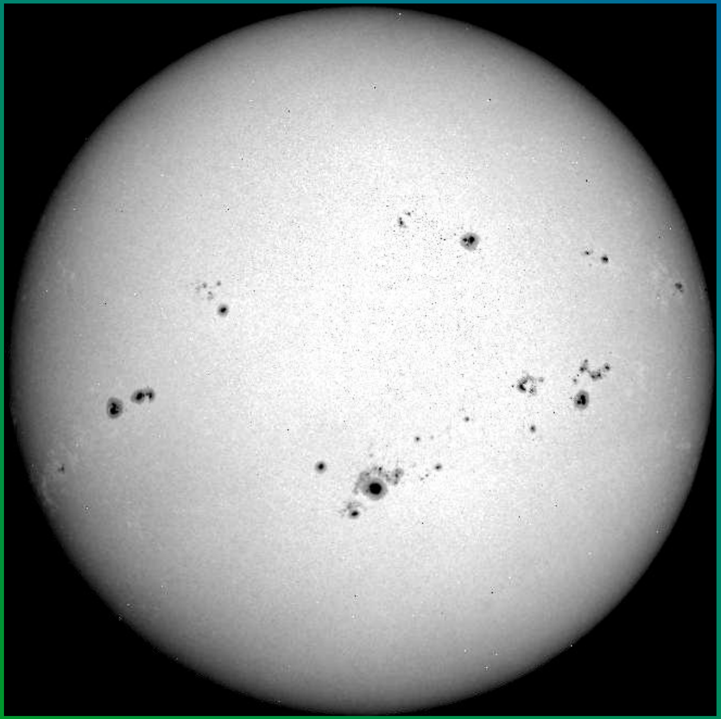
Stein & Nordlund, 1998

Simulated convection in a solar-like spherical shell

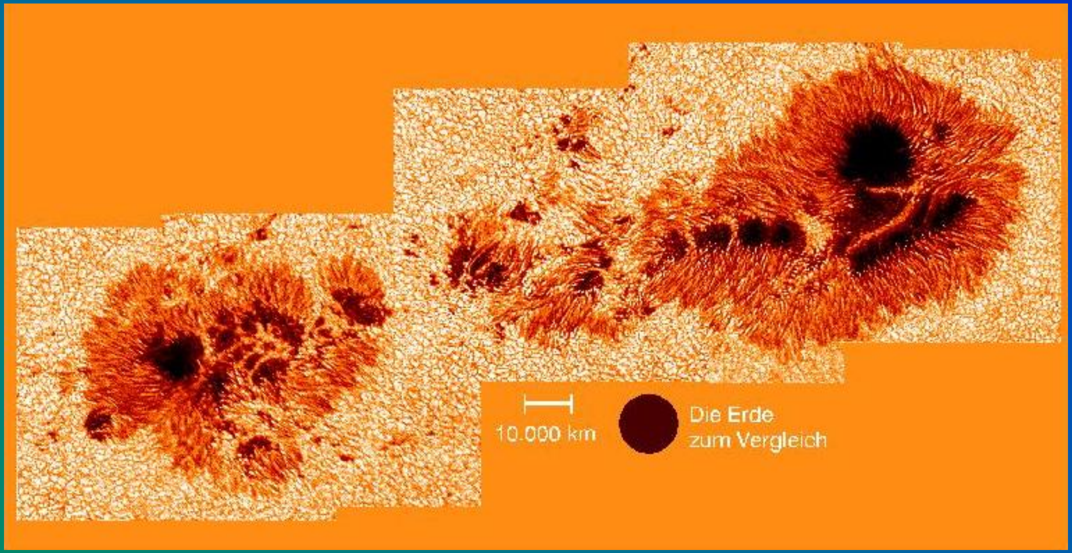
Miesch 1998



Magnetic fields on the Sun

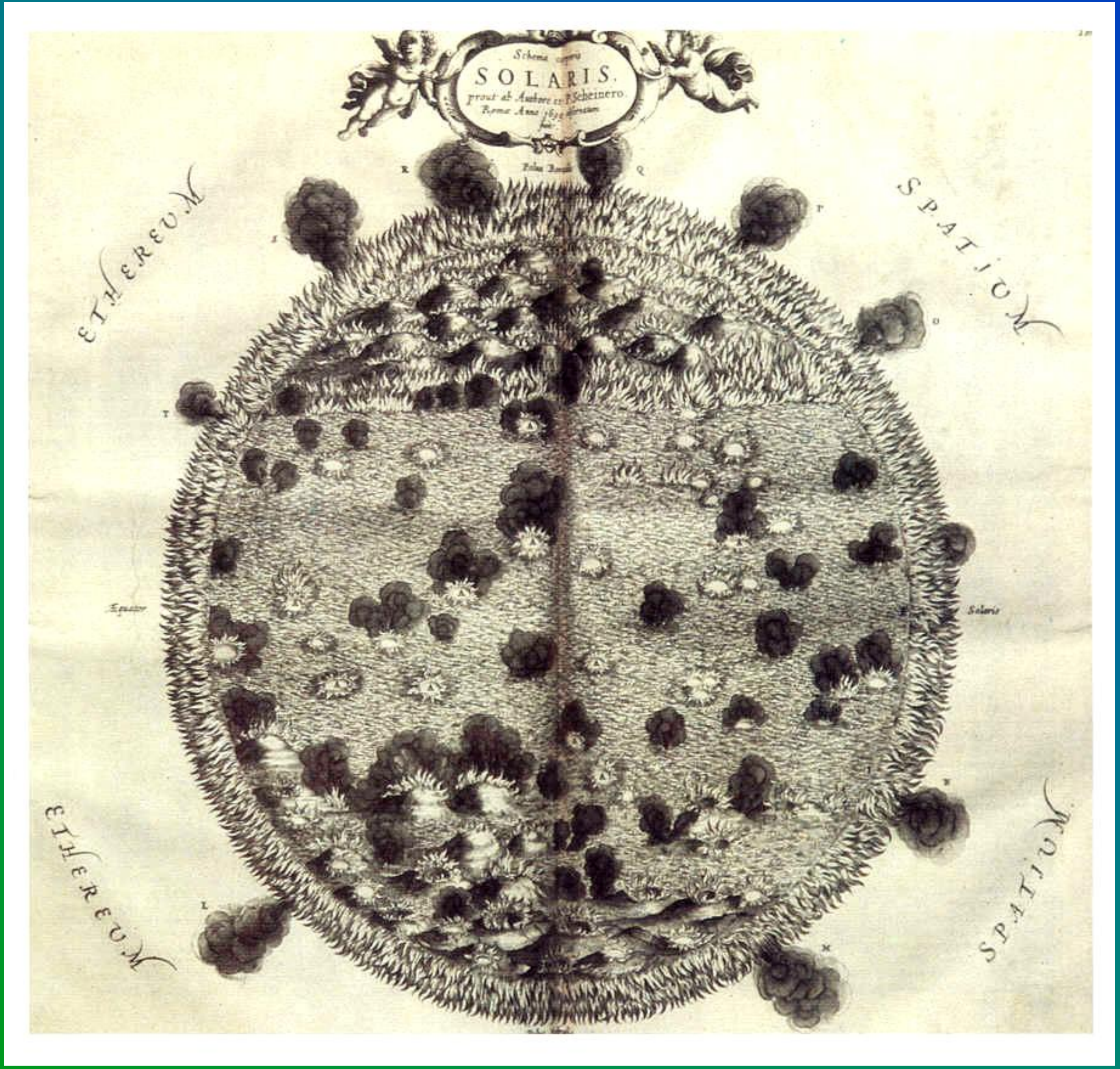


Sunspots



A large sunspot group

What is the nature of sunspots?

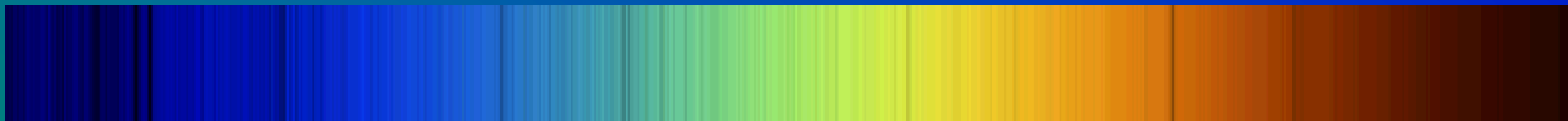


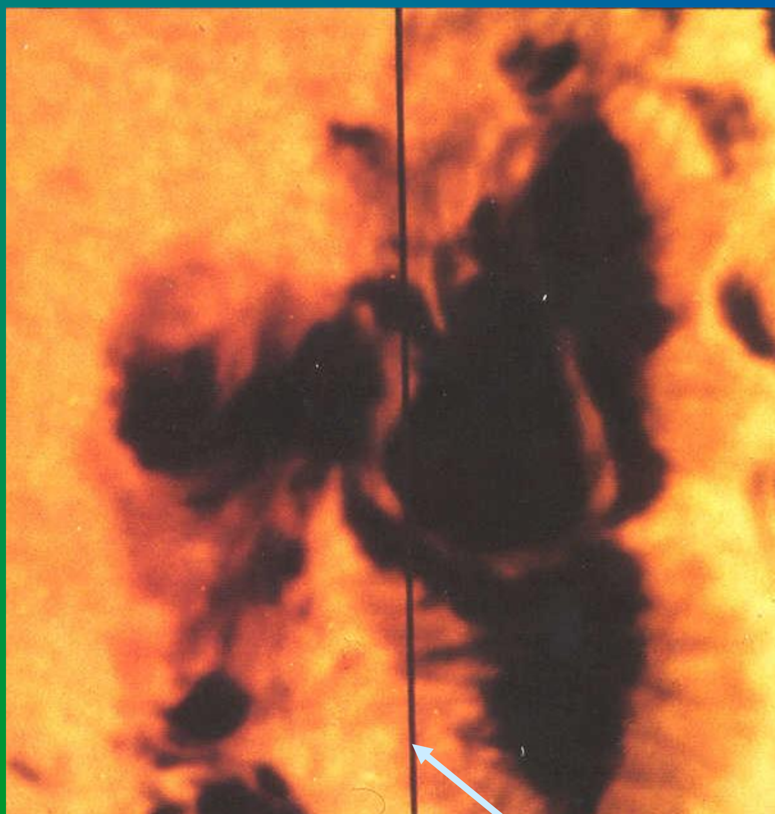
Smoke clouds ?

Holes ?

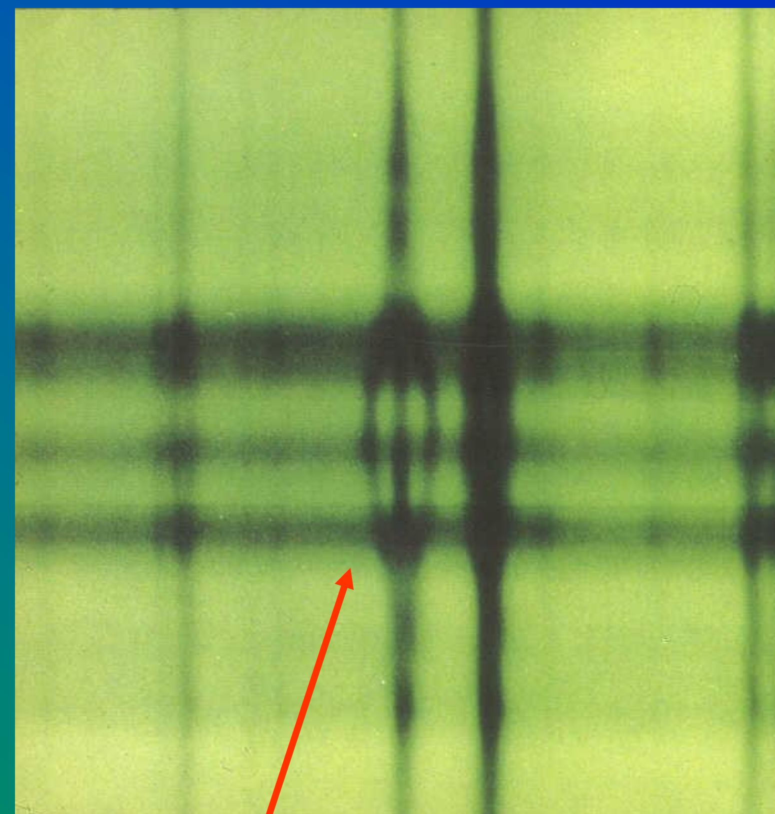
Tornadoes ?

The magnetic nature of sunspots



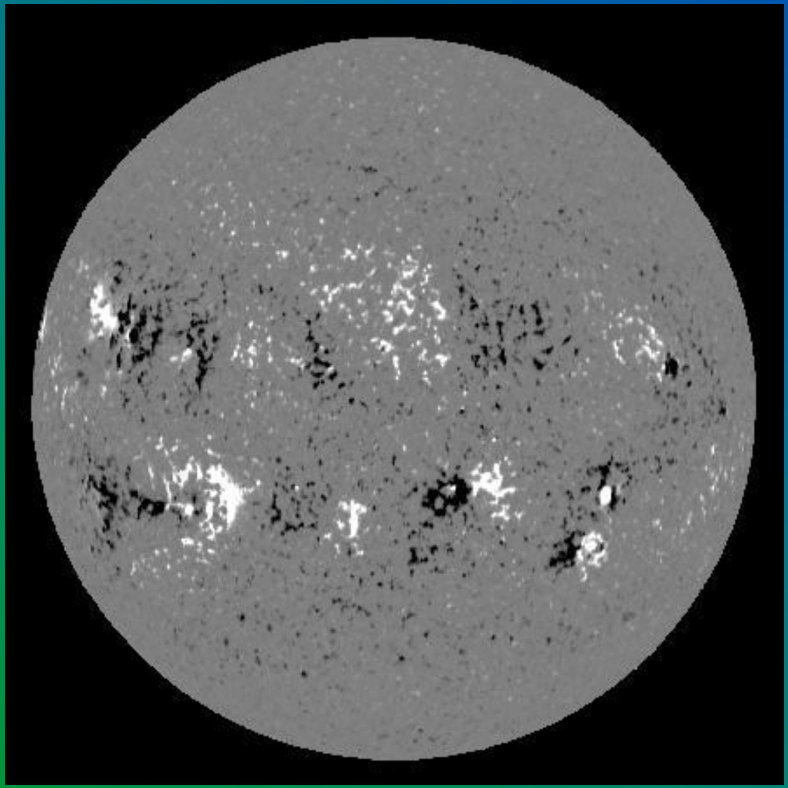


Sunspot with spectrograph slit

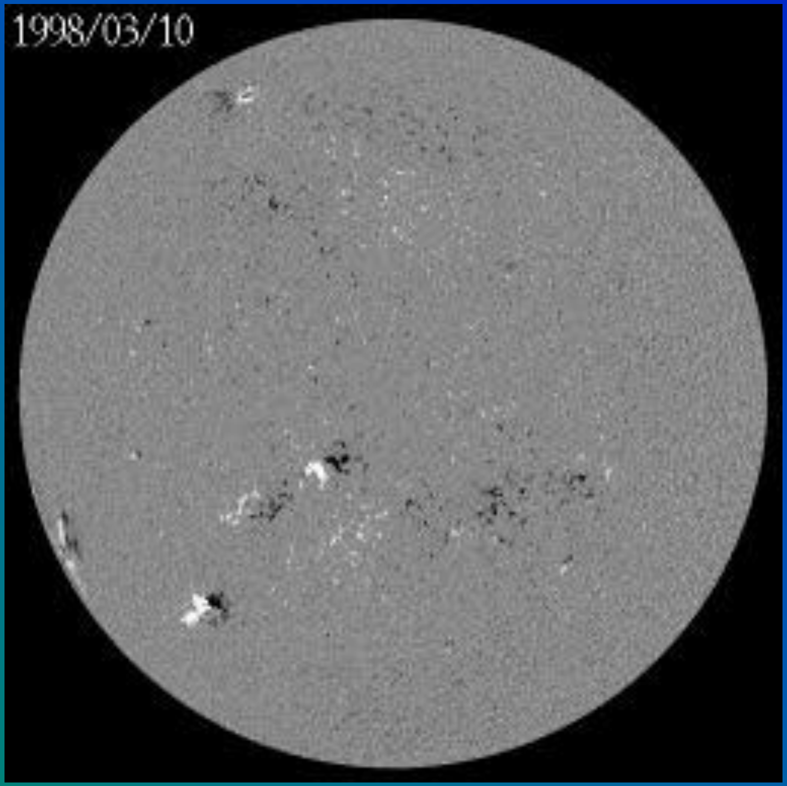


Magnetically split spectral line

Magnetic variability

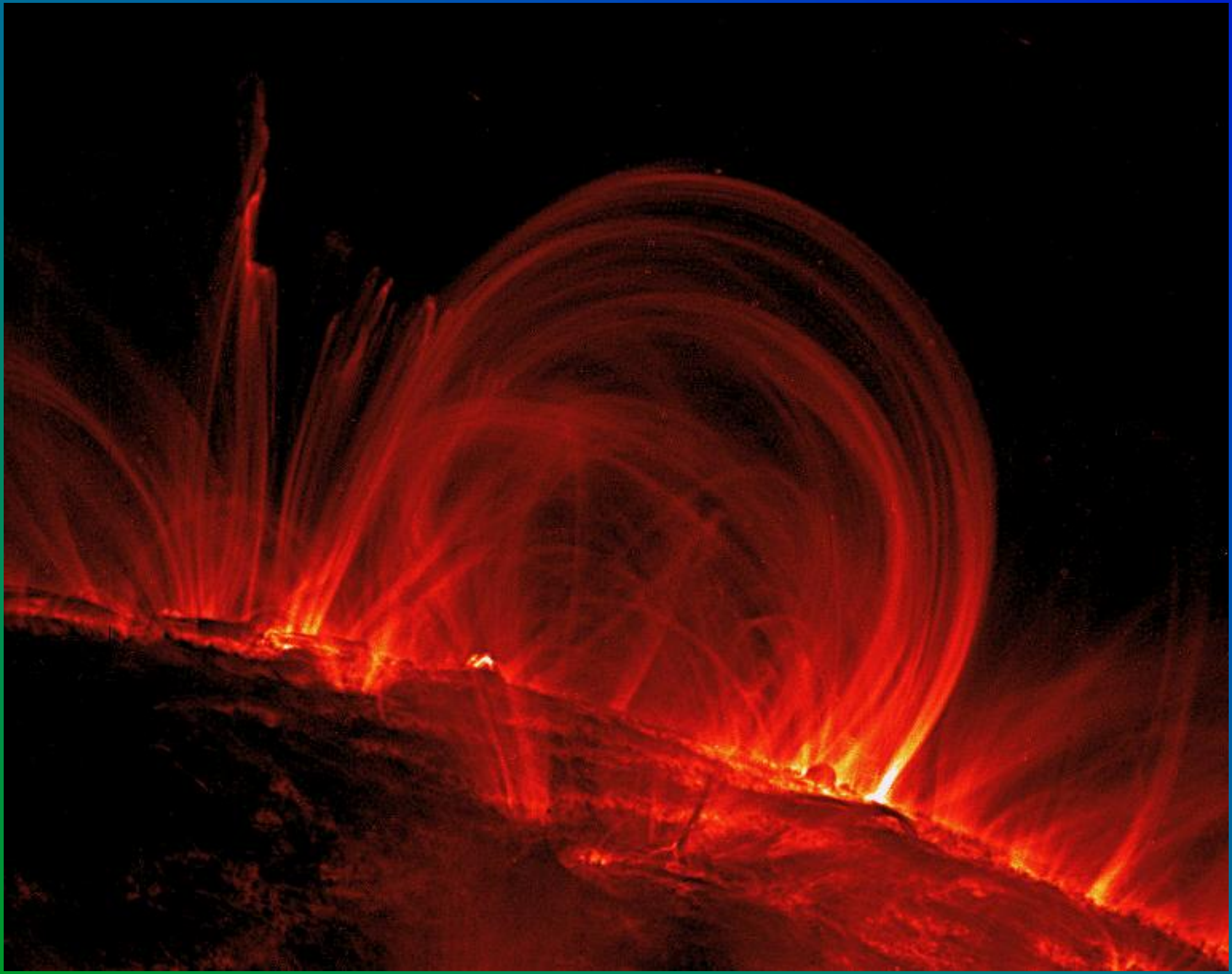


Full-disk magnetogram

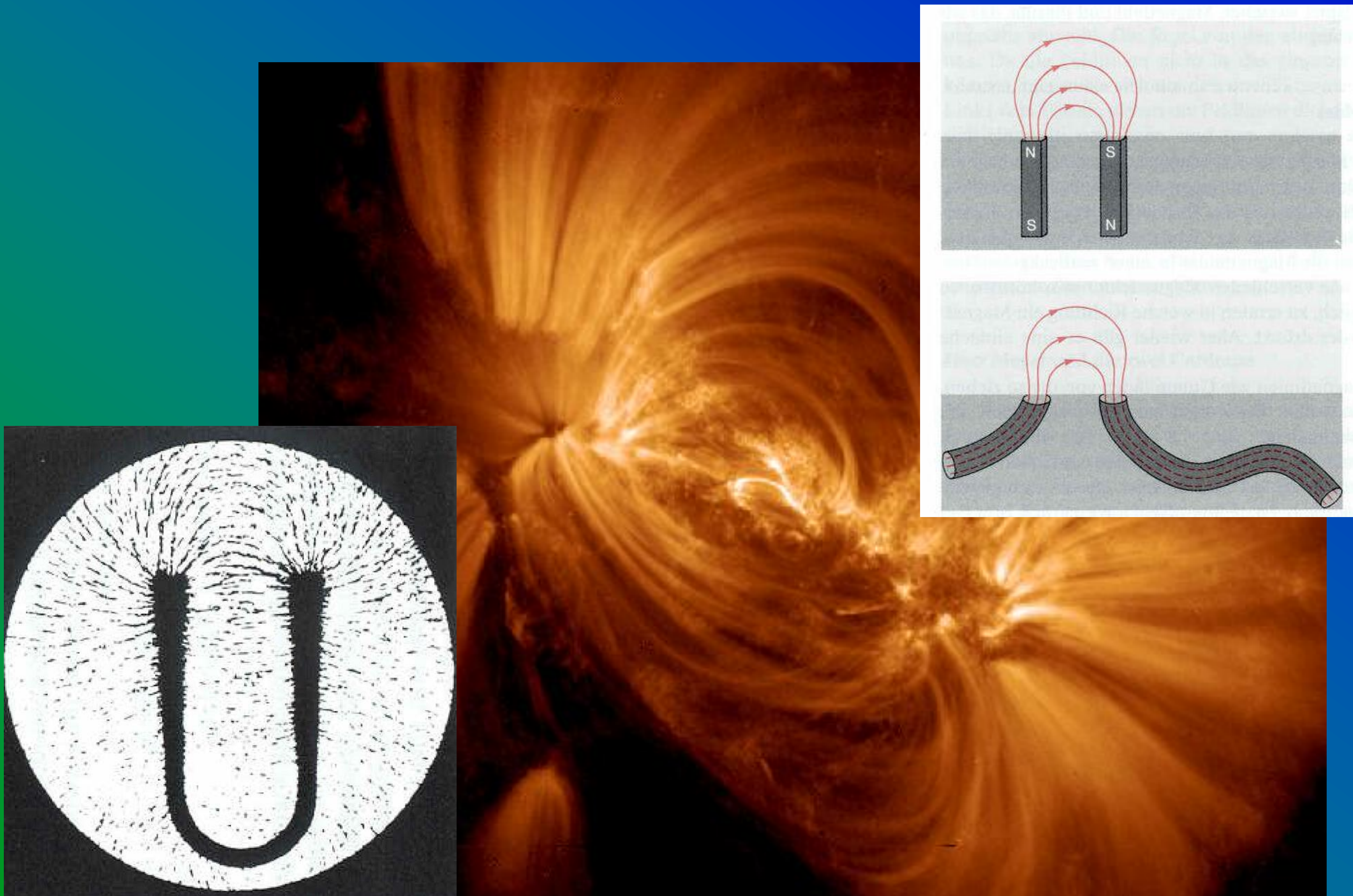


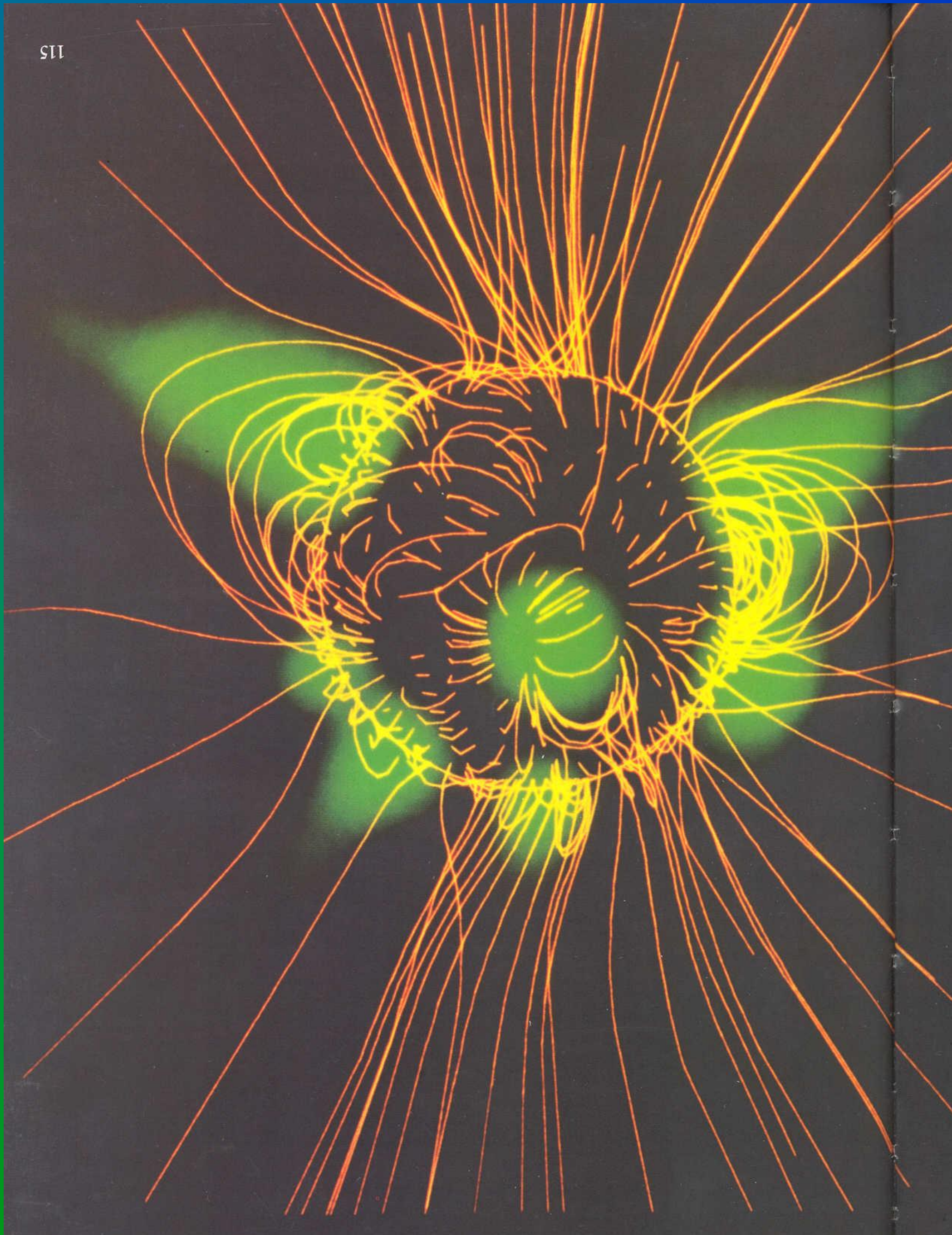
Magnetic patterns on the rotating Sun

Hot plasma draws magnetic field lines...



Hot plasma draws magnetic field lines...





The solar magnetic field…

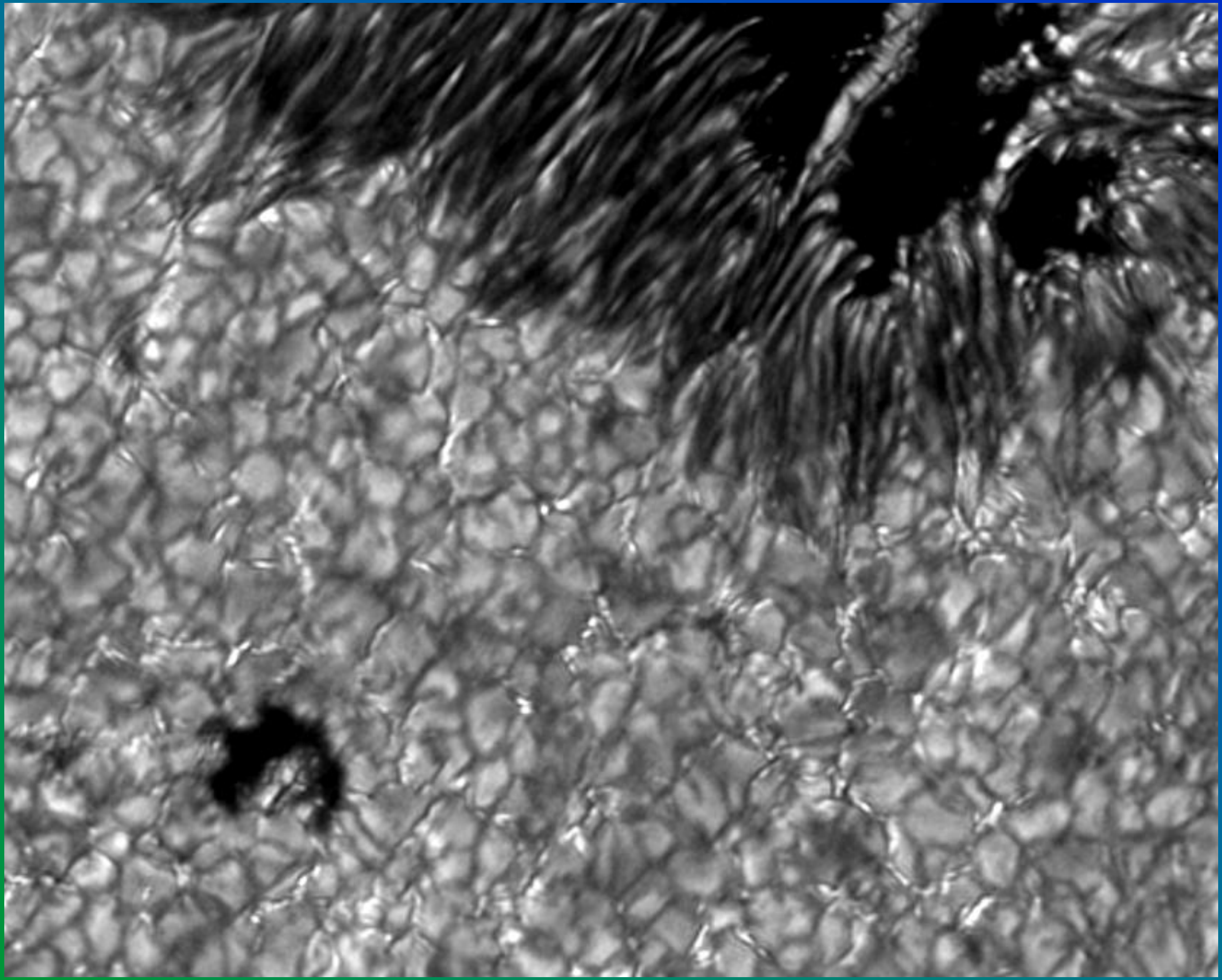
… continues into interplanetary space.

Its variability in the course of the 11-year cycle and its long-term modulation...

- affects cosmic rays,

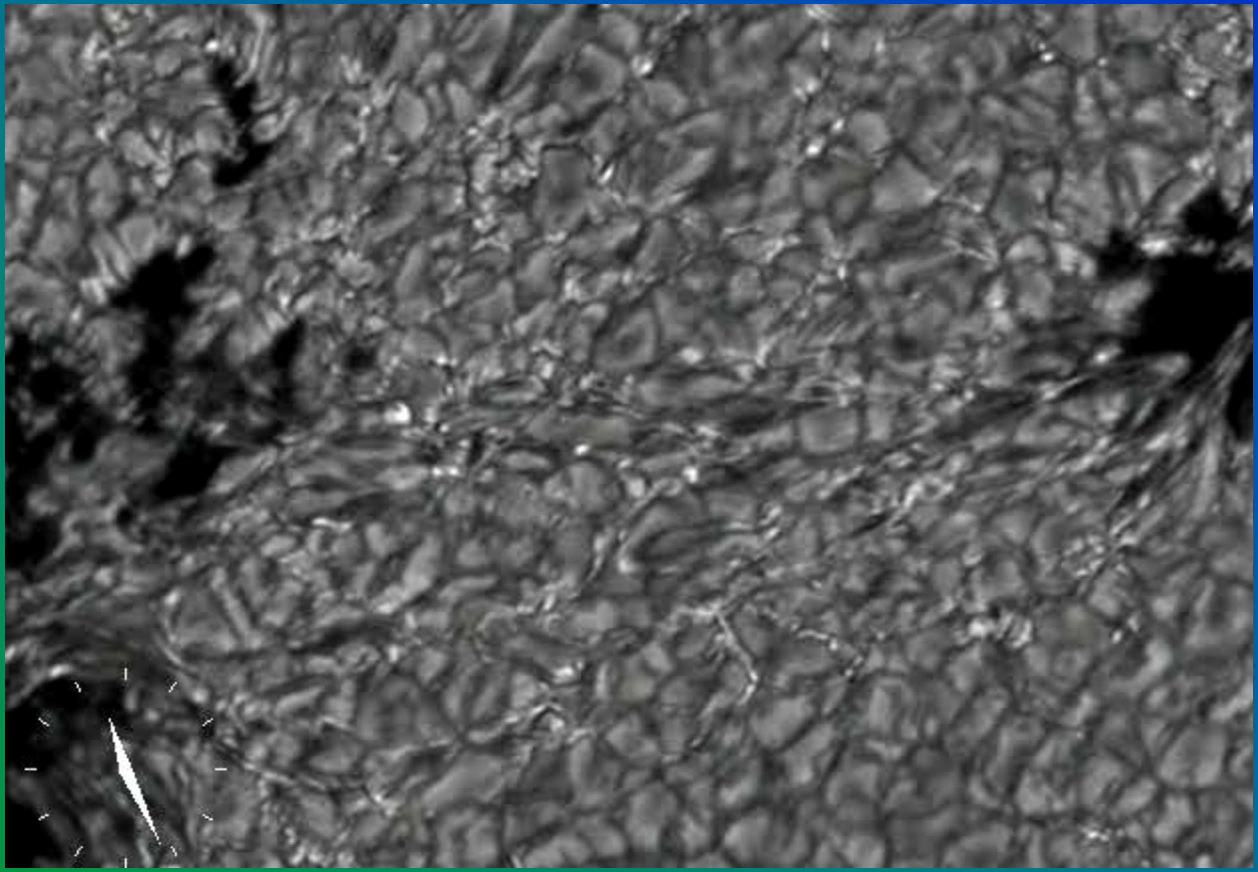
- perturbs the terrestrial magnetic field.

G-band observations



KIS/VTT, Obs. del Teide, Tenerife

G-band observations



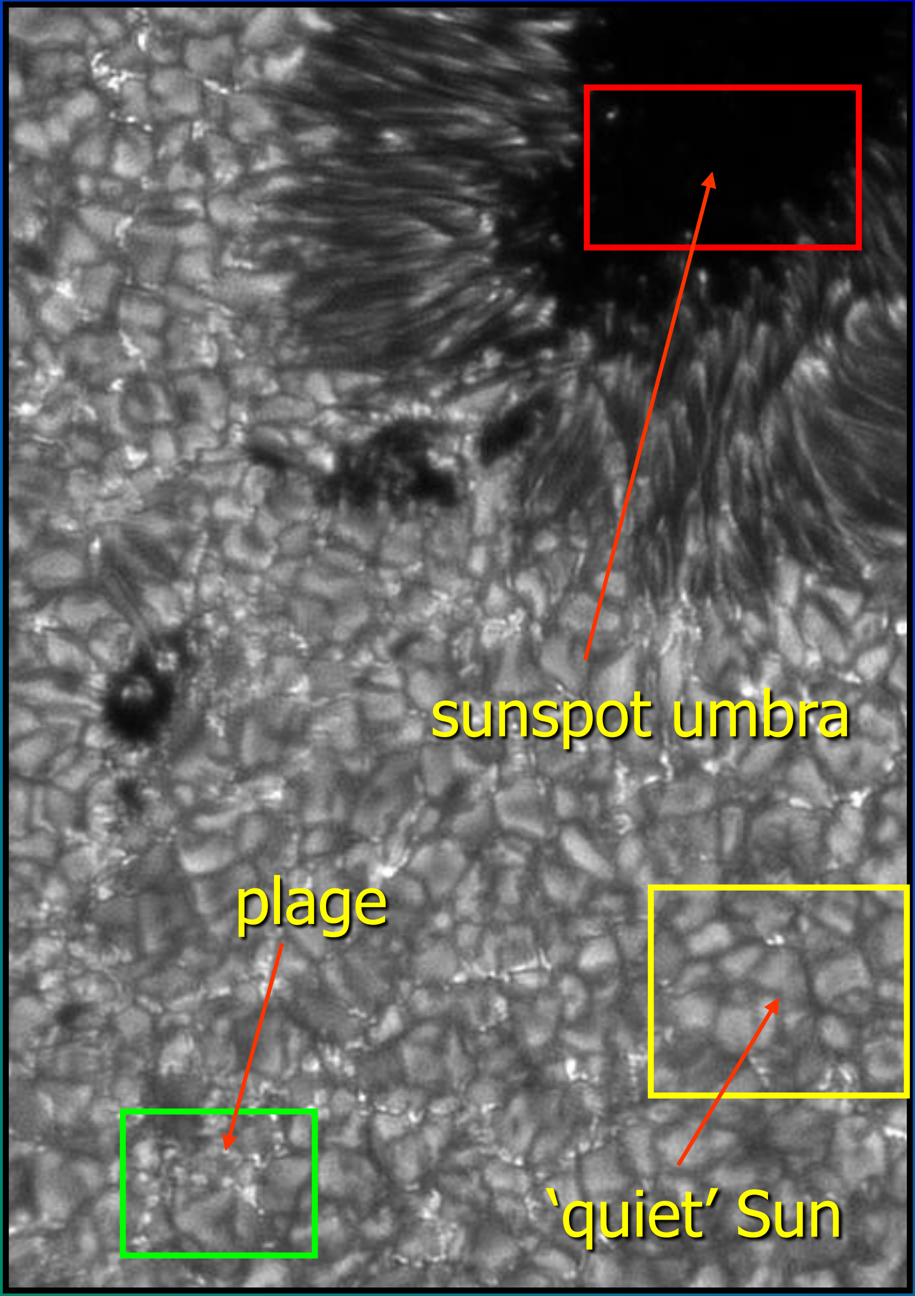
Dutch Open Telescope, Obs. del Roque de los Muchachos, courtesy P. Sütterlin

What is magneto-convection?

- Interaction between convective flows and magnetic field in an electrically well-conducting fluid
- High Reynolds numbers: nonlinear dynamics, structure and pattern formation
- Interference with convective energy transport

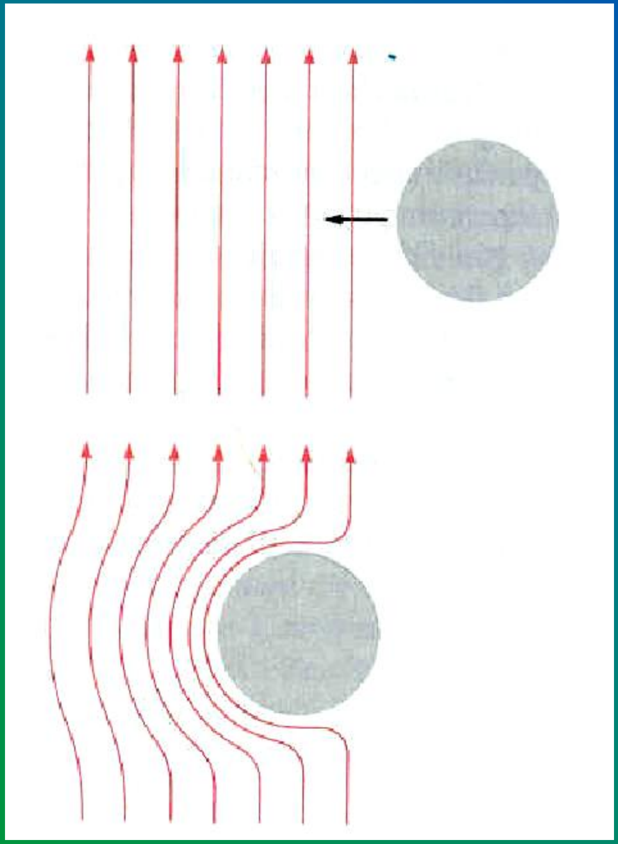
Regimes of solar magneto-convection

- <B> increases: quiet Sun → plage → → umbra
- horizontal scale of convection decreases
- convective energy transport decreases

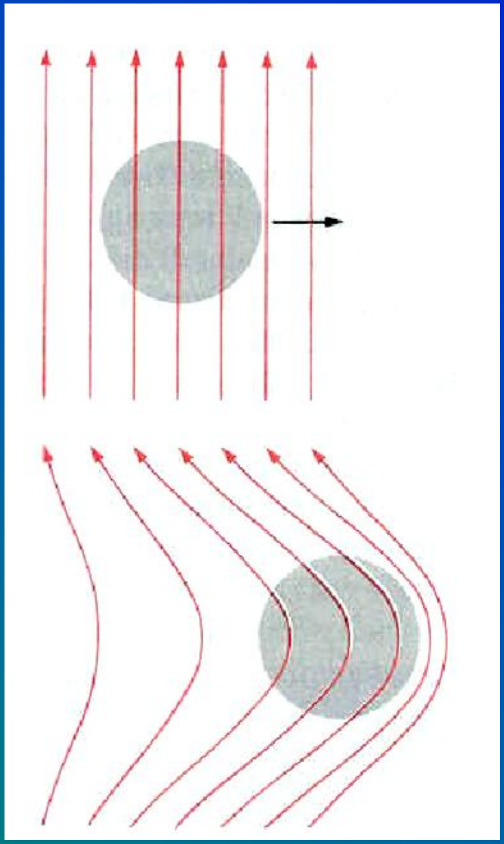


T. Berger, SVST 12 May 1998, Obs. del Roque de los Muchachos
Adapted from a figure by Thierry Emonet, Univ. Chicago

Good electrical conductors : “frozen field”

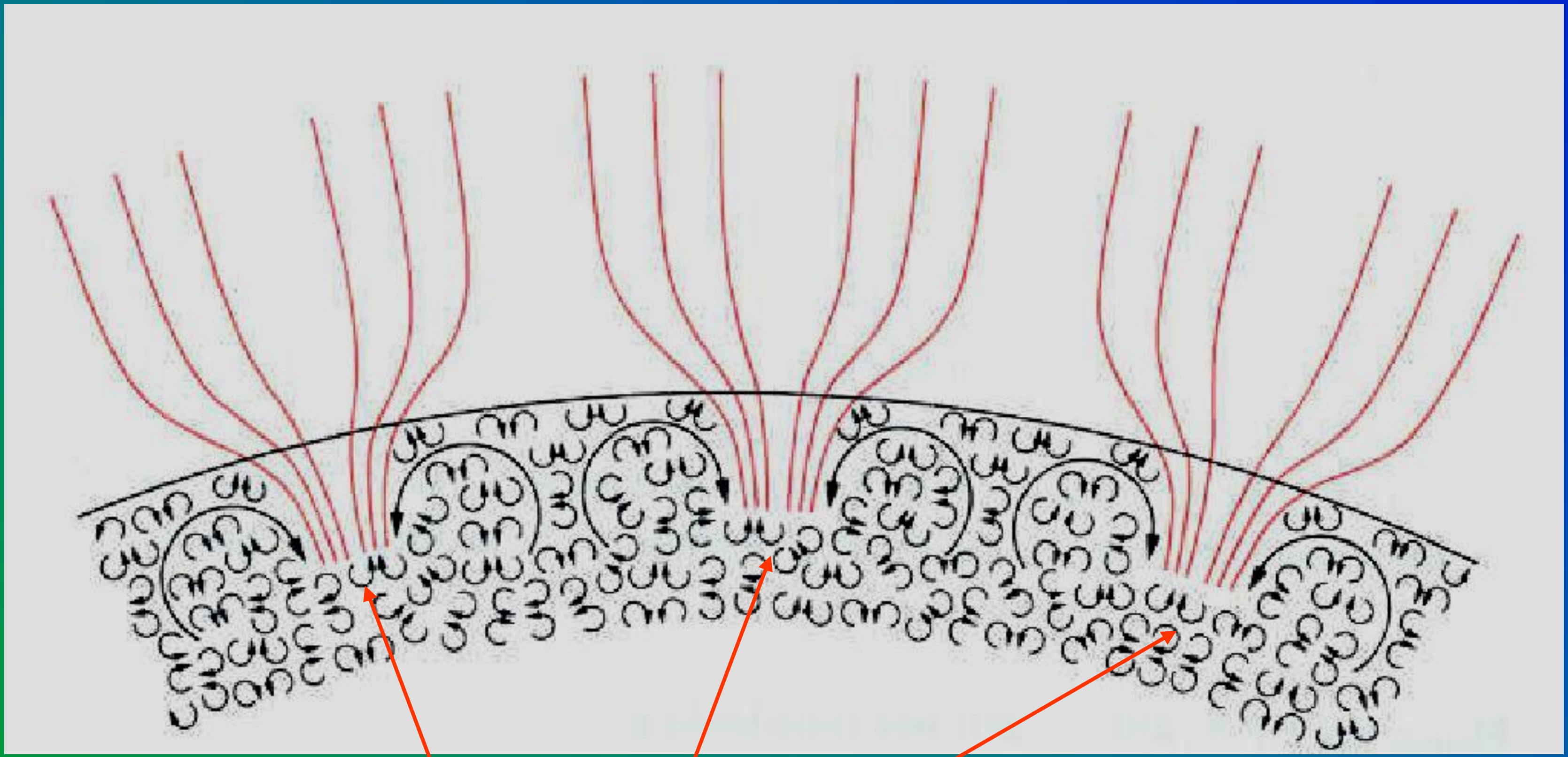


Initially field-free volumes remain field-free



Magnetic flux through a given volume remains constant

“Frozen field” in the Sun

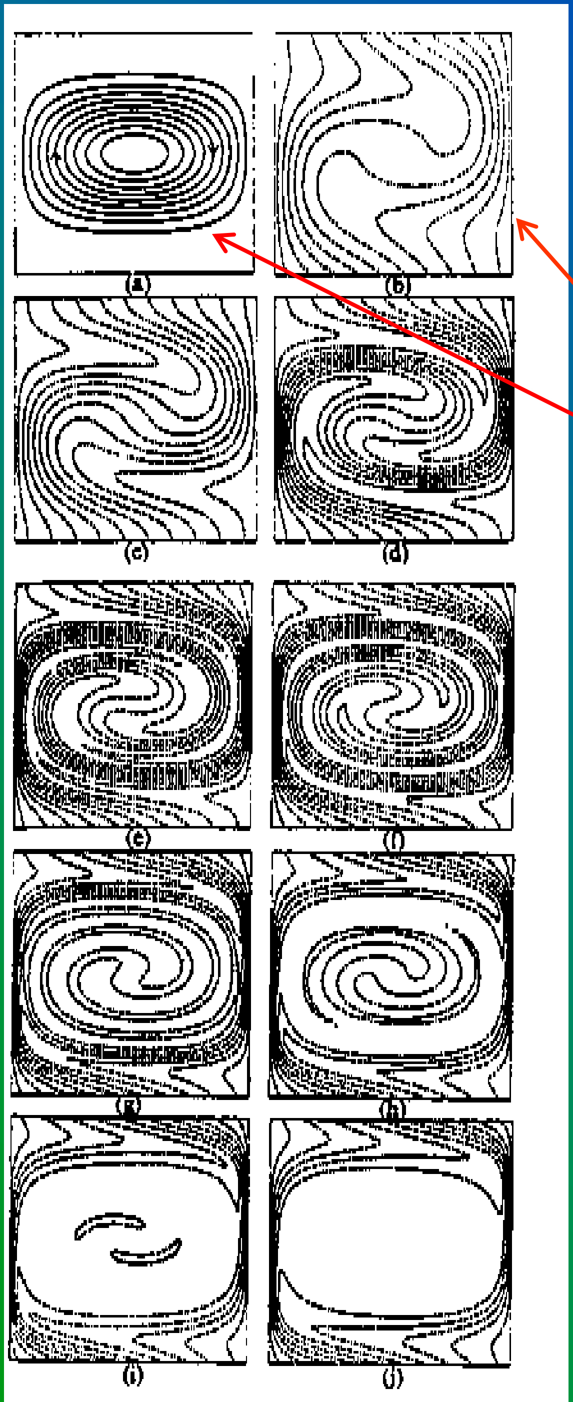


Magnetic flux is transported to the downflow regions of the convective flow patterns

“magnetic network”

Simulation of flux expulsion

(Weiss, 1966)



b: final state for $Re_m = 40$

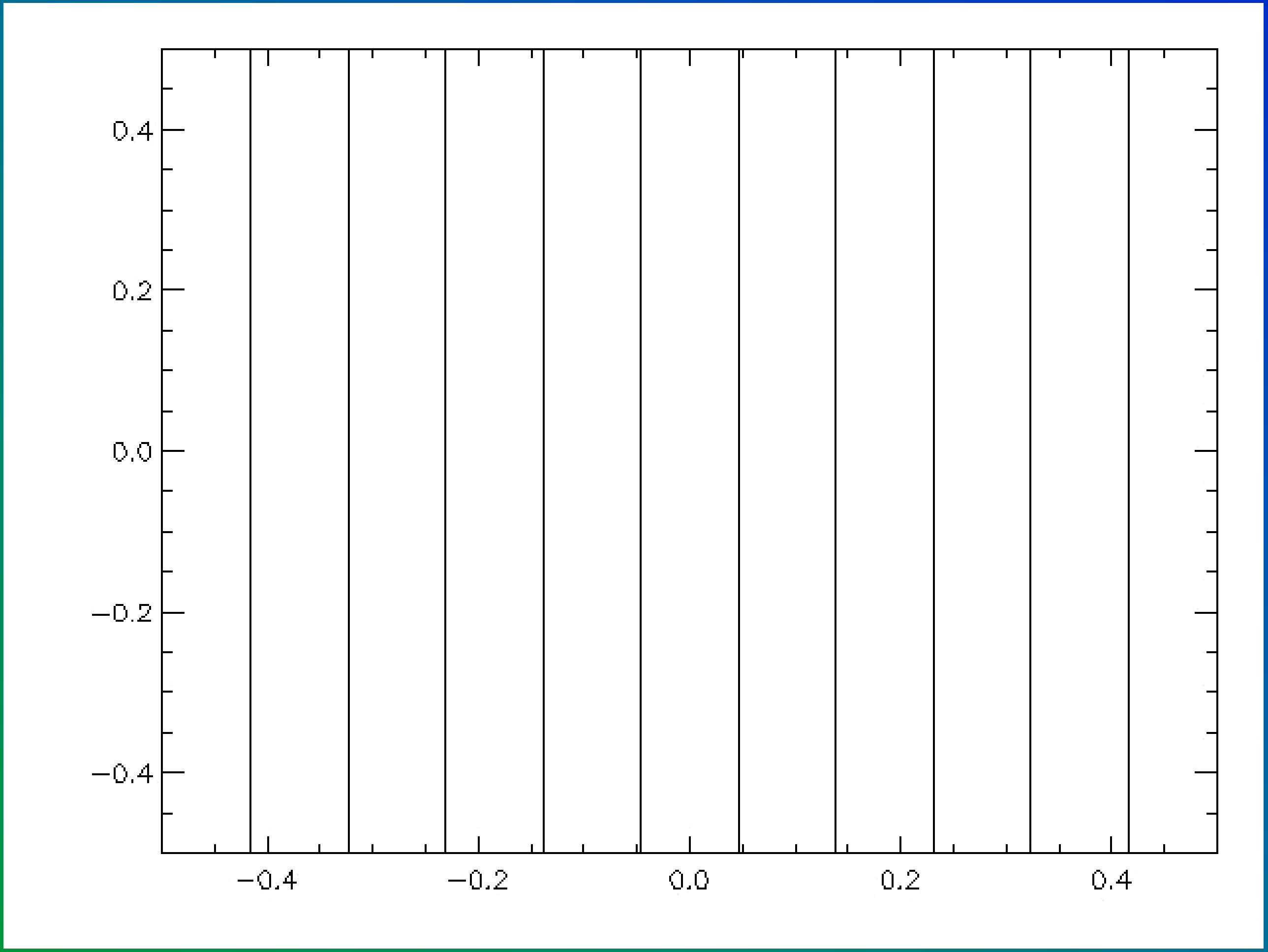
a: streamlines of the fixed velocity field

c-j: time evolution for $Re_m = 1000$

- evolution of an initially vertical magnetic field under the influence of a fixed flow field
- kinematic, 2D
- the magnetic flux is expelled from the area of closed streamlines and concentrated in narrow sheets

Flux expulsion and intermittency

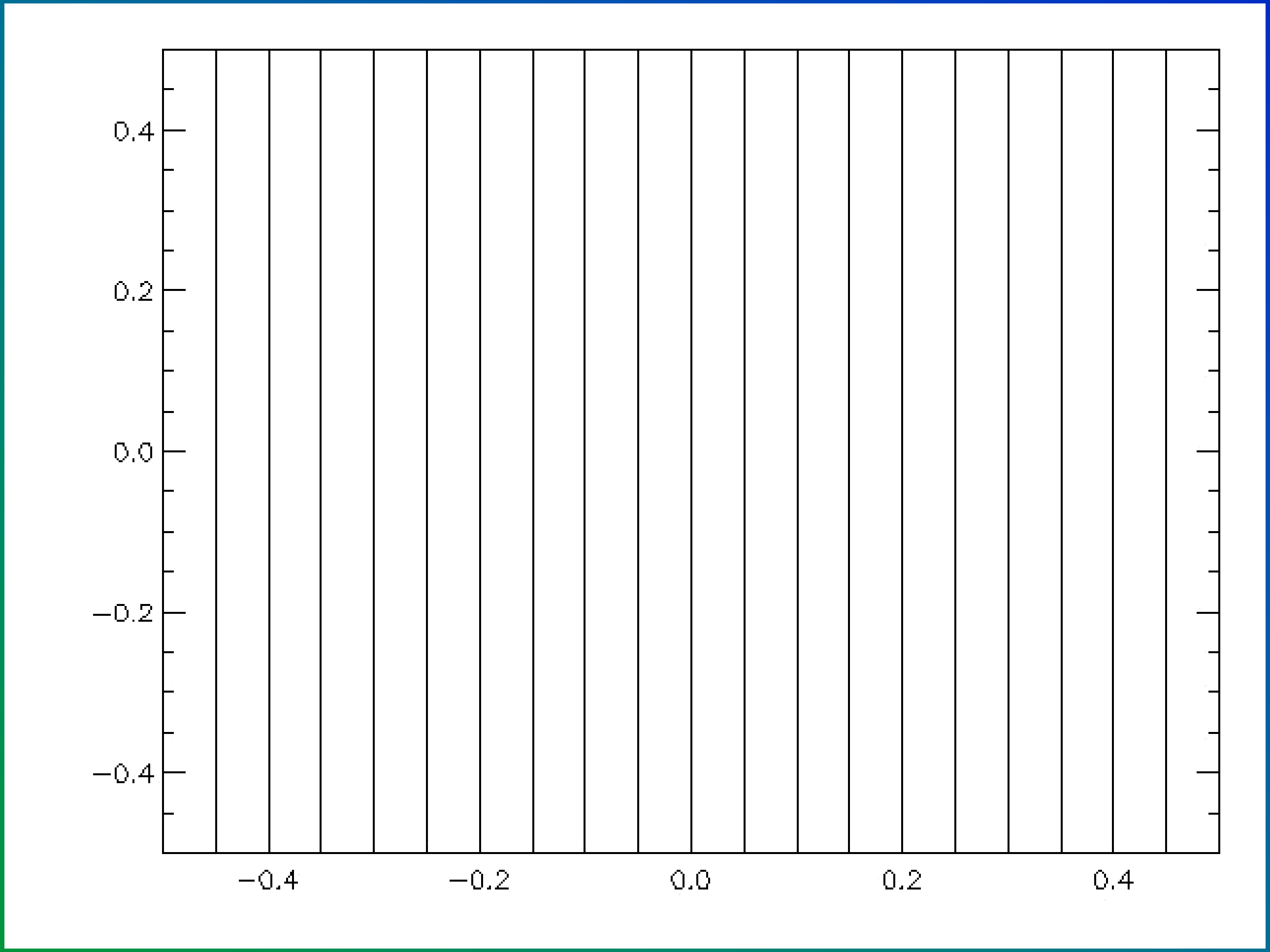
- N.O. Weiss (1964): *first simulations*



(Hupfer, KIS Freiburg, 2001)

Flux expulsion and intermittency

- N.O. Weiss (1964): *first simulations*



(Hupfer, KIS Freiburg, 2001)

B_0 = 200 G (plage): time evolution

horizontal cuts near τ=1
6000 km × 6000 km × 1400 km
288 × 288 × 100 grid points

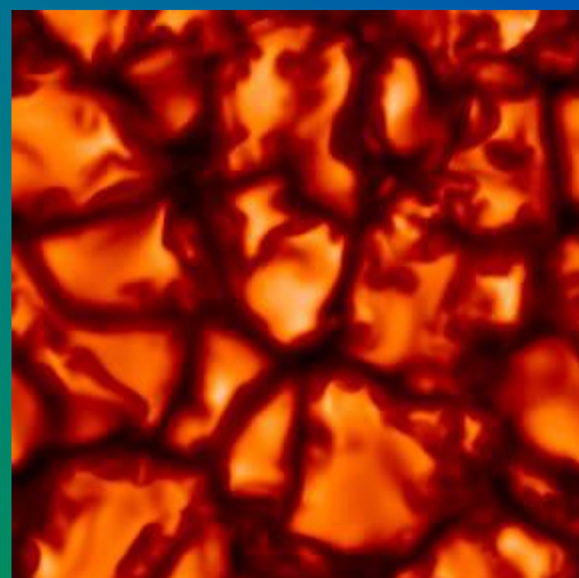
up down

vertical magnetic field

-1.3 0 +2.2

[kG]

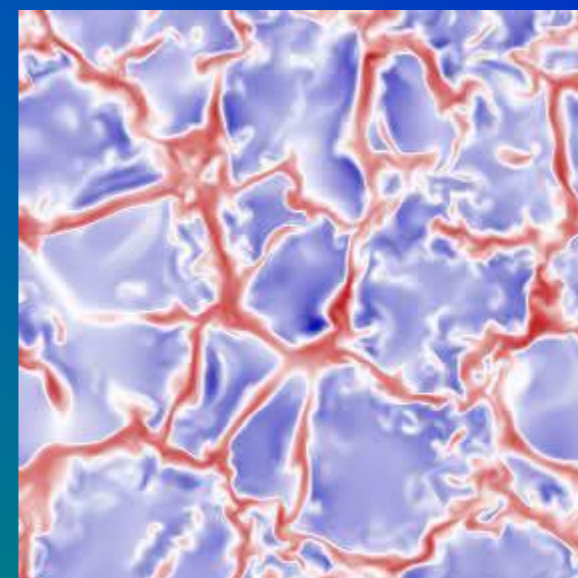
brightness



0.6 1.0 1.5

I/<I>

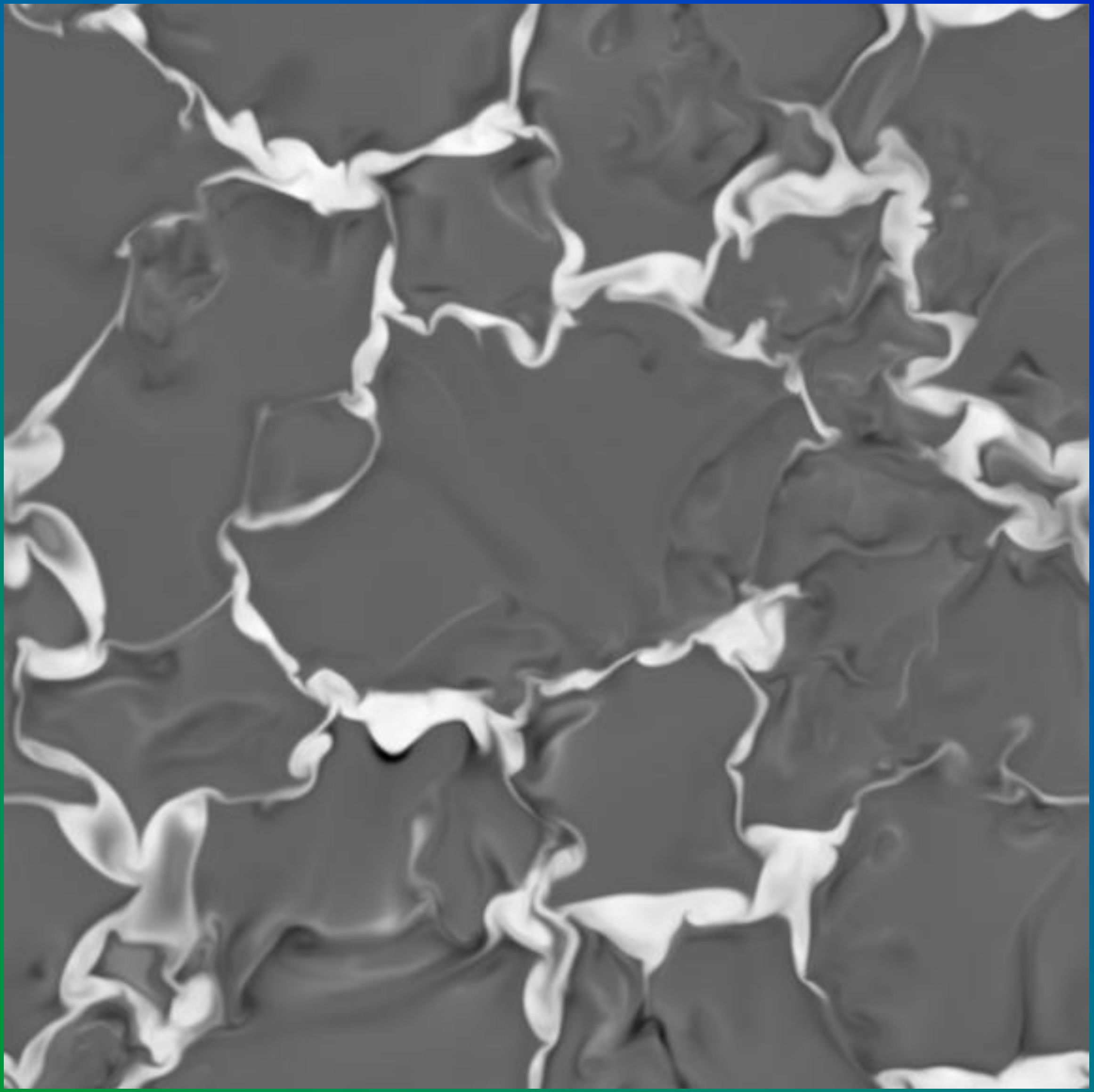
vertical velocity



-10 0 +10

[km/s]

B_0 = 200 G (plage)



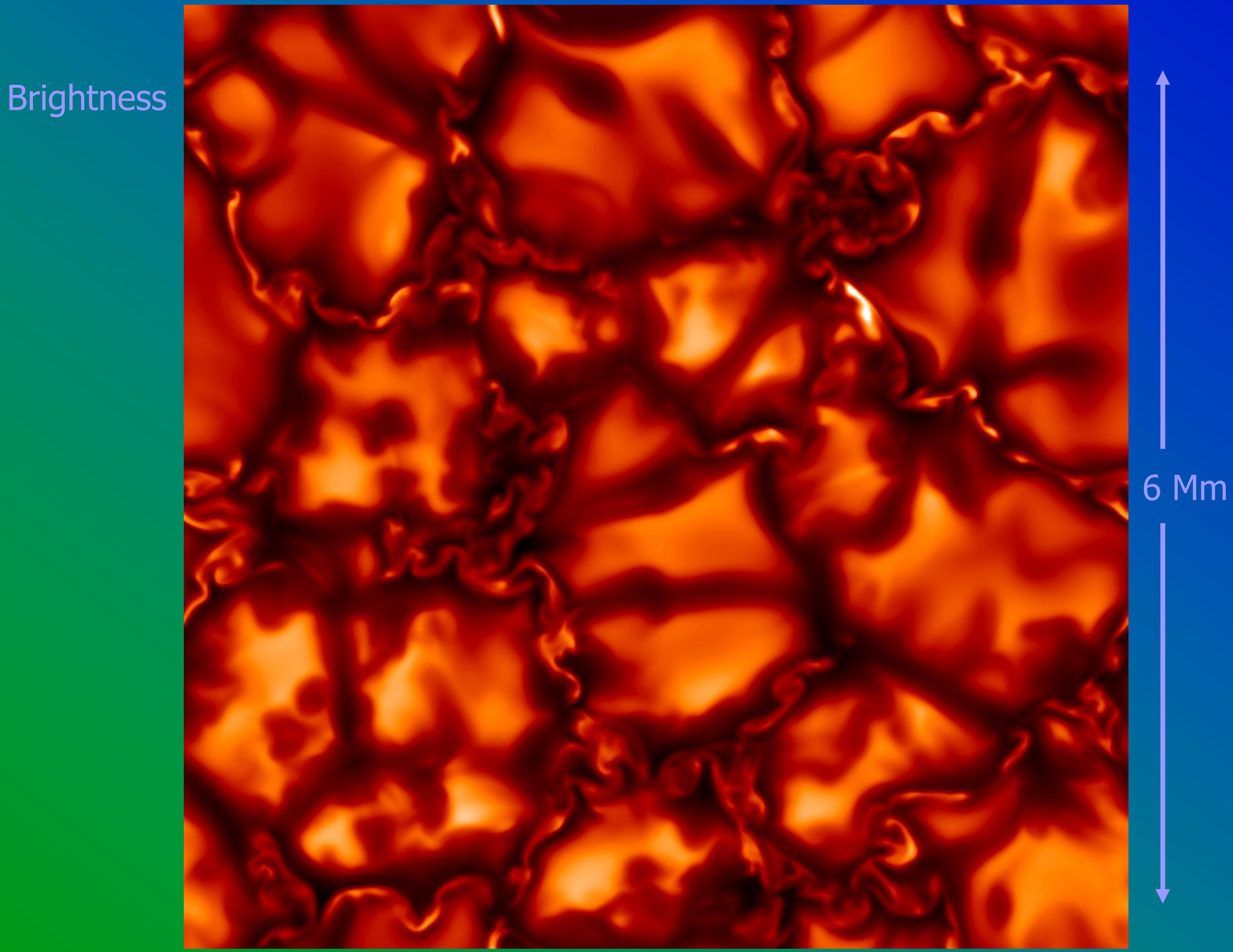
+2 kG

-2 kG

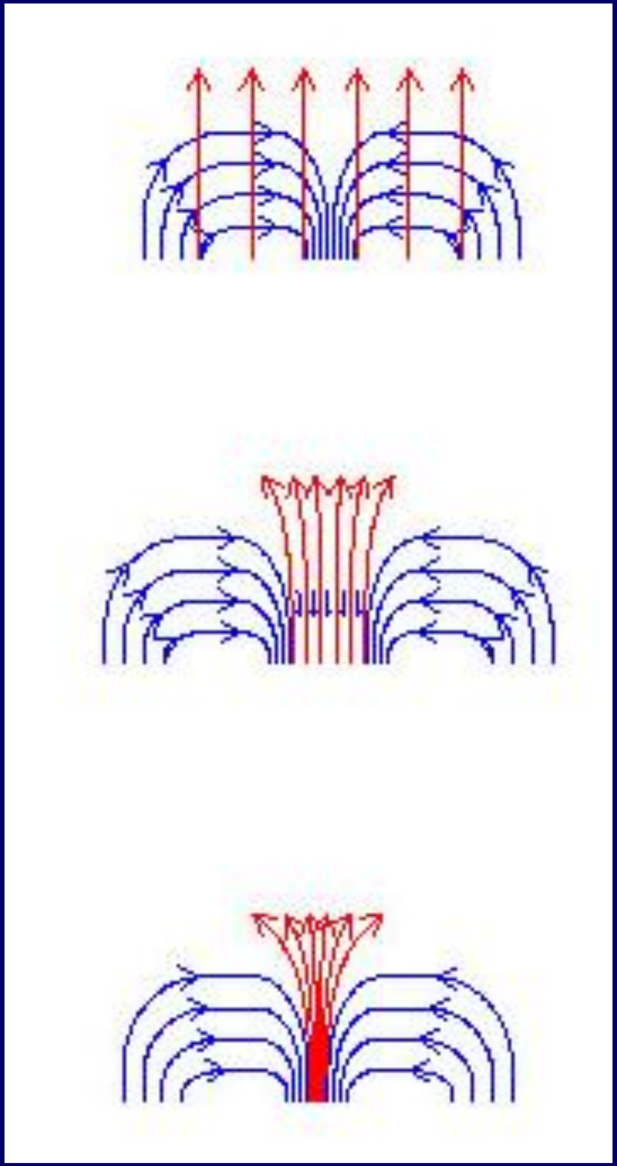
Vertical magnetic field component

6 Mm

B_0 = 200 G (plage)

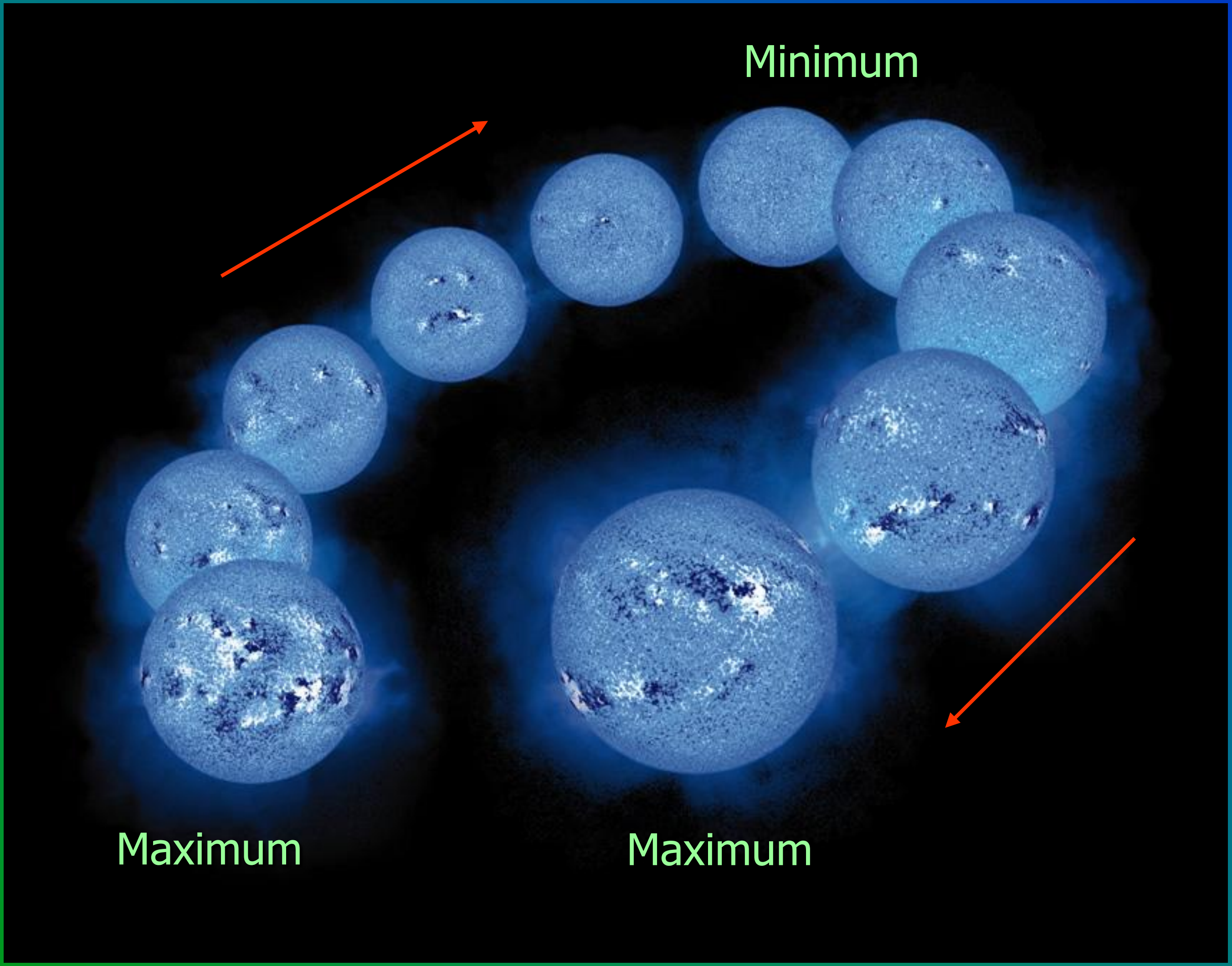


Convective intensification



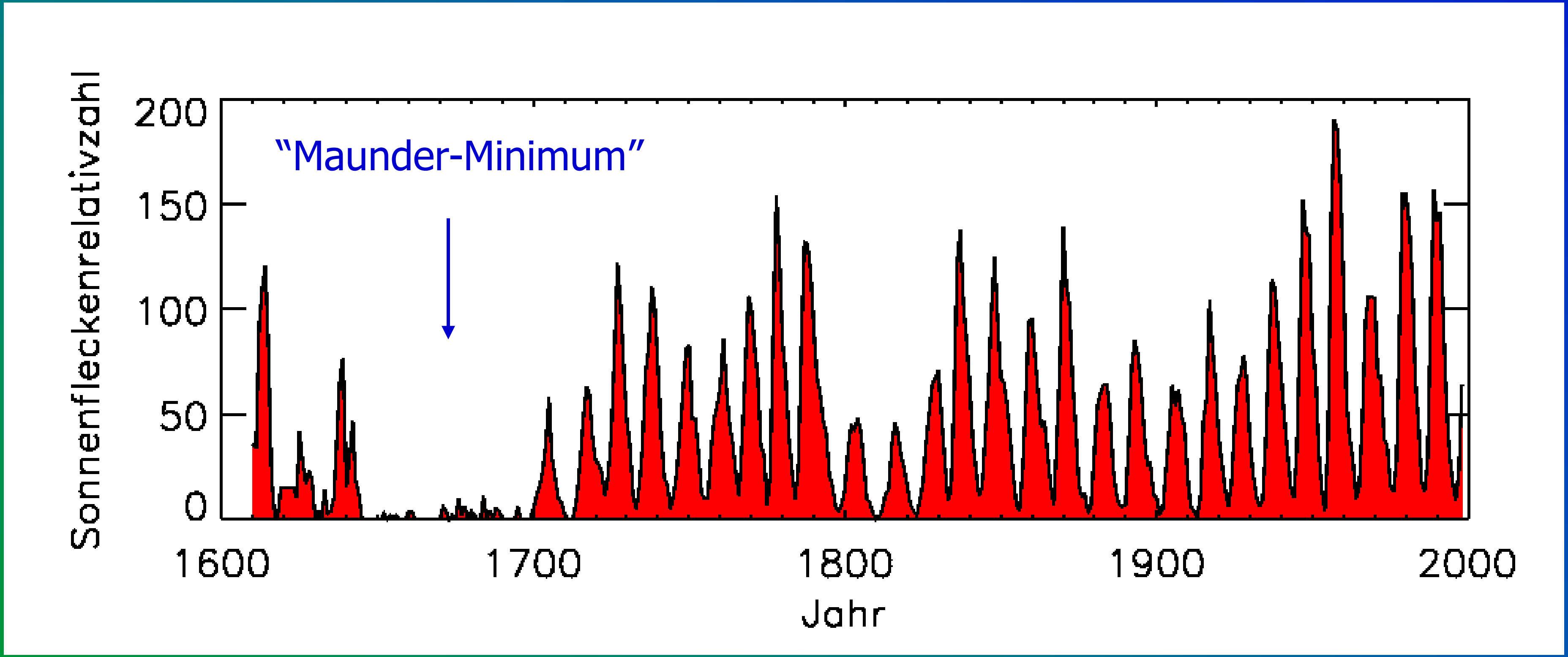
- Flux advection by horizontal flow (flux expulsion)
- Suppression of convection, cooling and downflow
- Evacuation, field intensification

The magnetically variable Sun



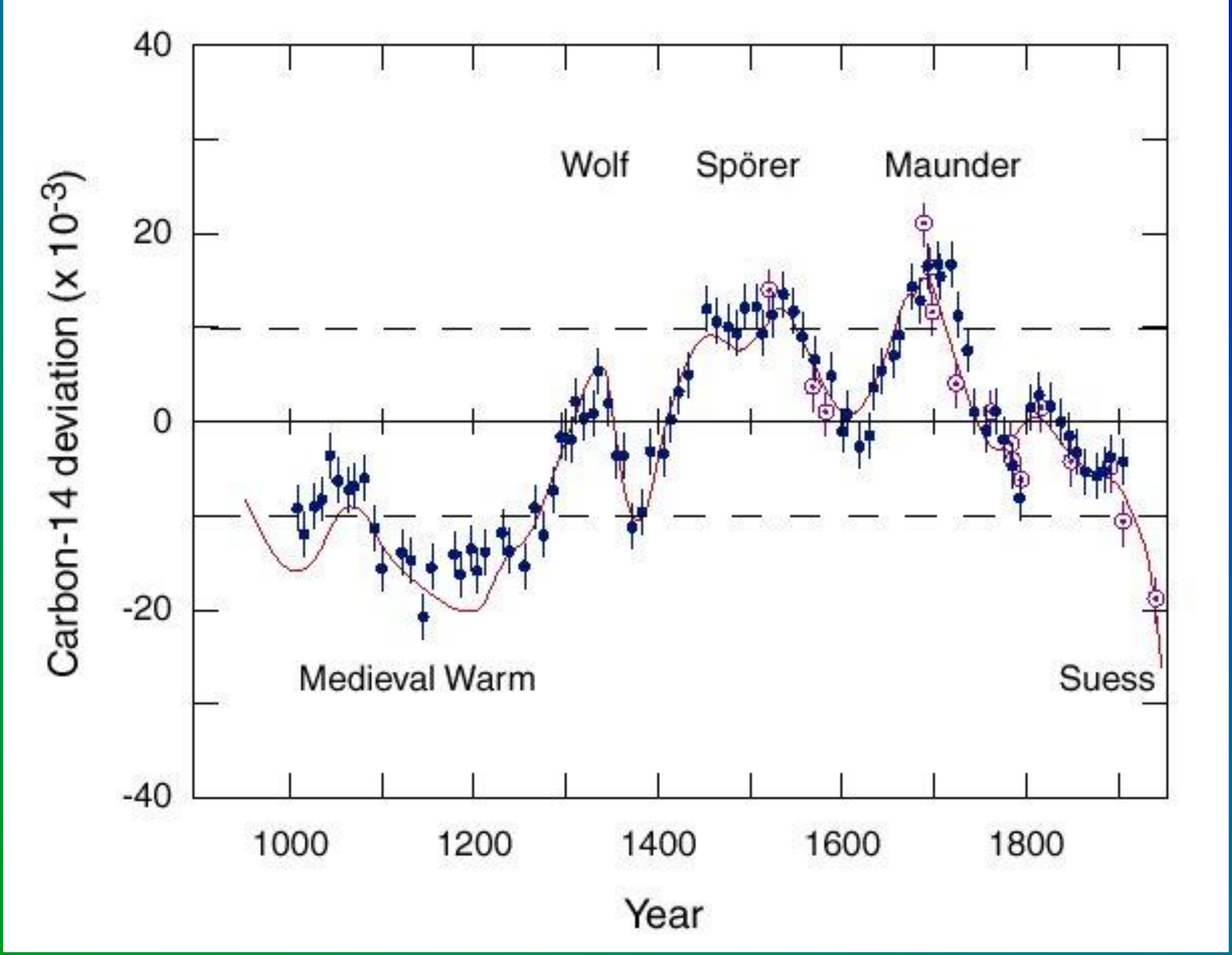
11-year cycle of magnetic activity and surface flux

The 11-year solar cycle

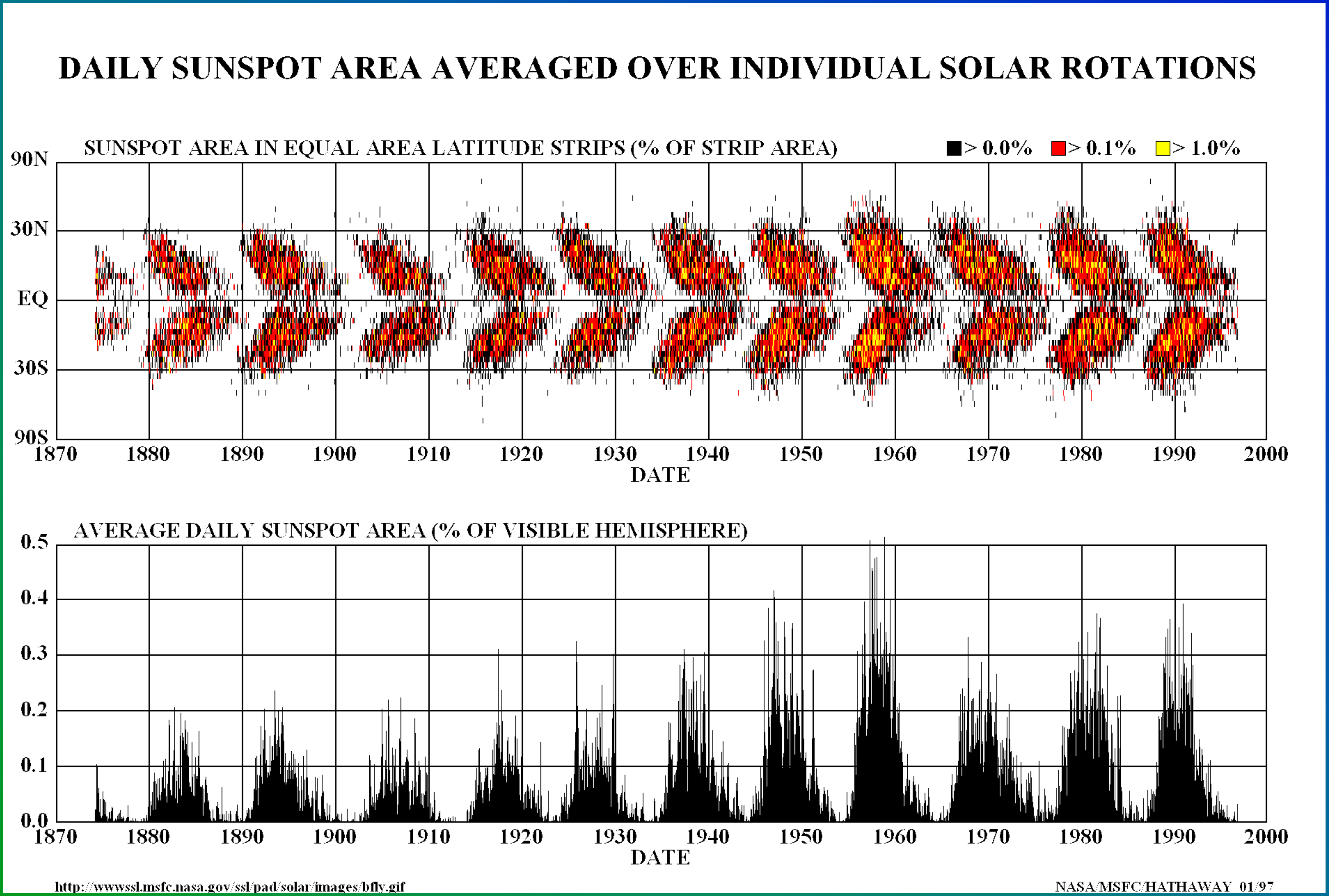


Solar magnetic activity varies with a period of roughly 11 years. Long-term variations are superposed upon this cycle.

^{14}C: Solar activity back to AD 1000



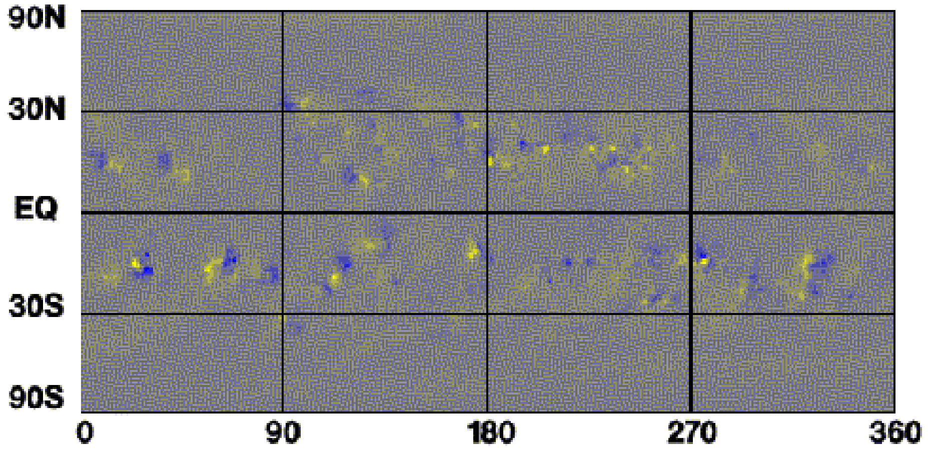
Butterfly diagram



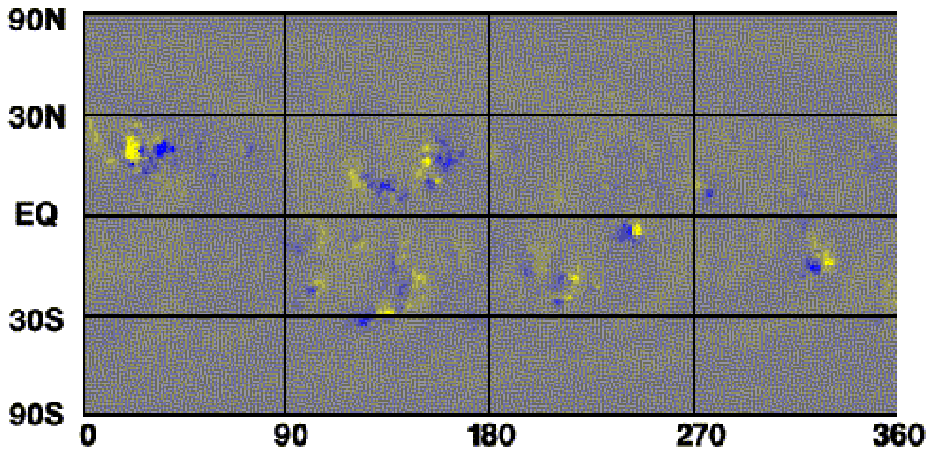
Hale's Polarity Law:

The polarity of the leading spots in one hemisphere is opposite that of the leading spots in the other hemisphere and the polarities reverse from one cycle to the next.

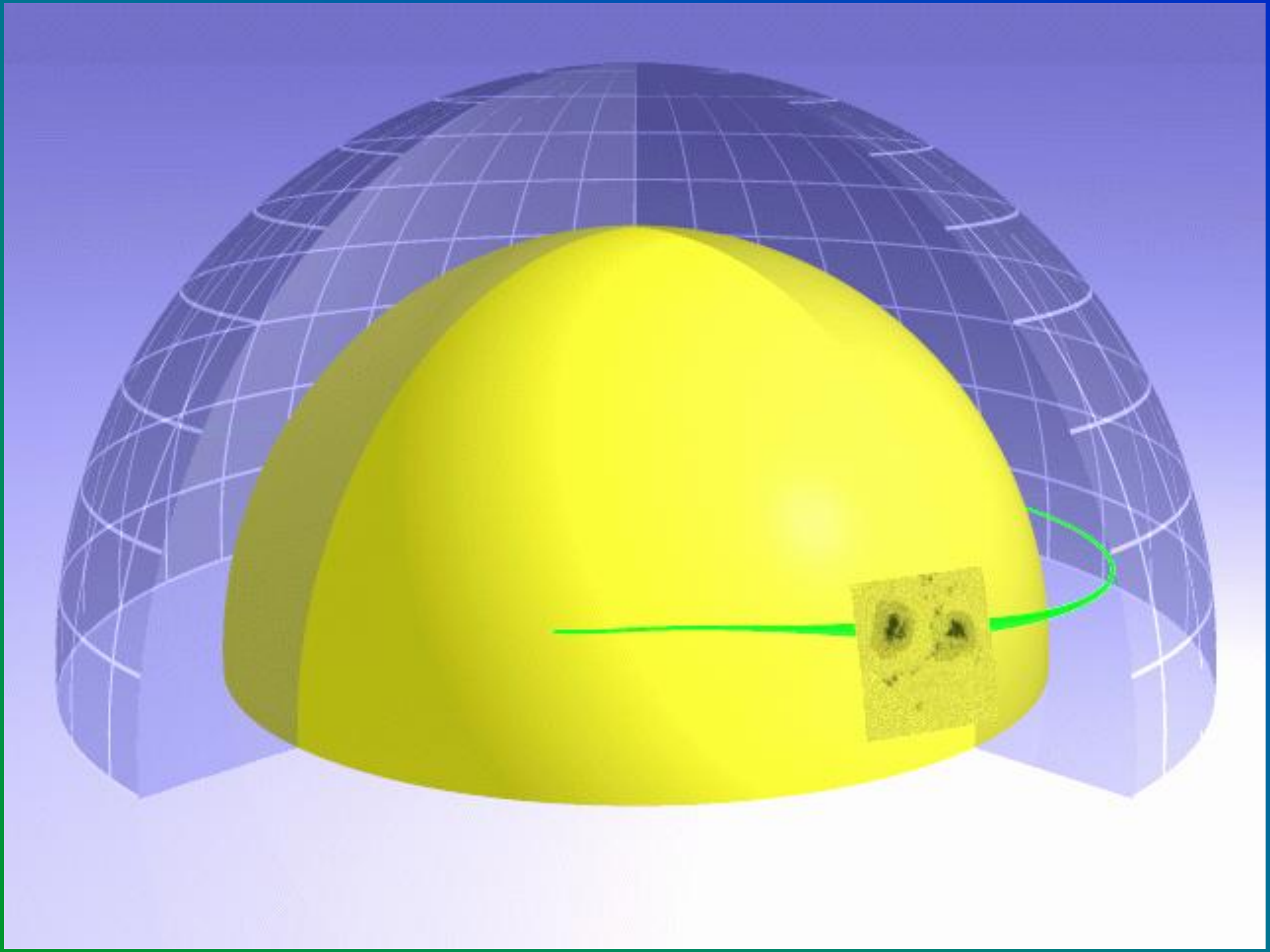
Cycle 21 Maximum



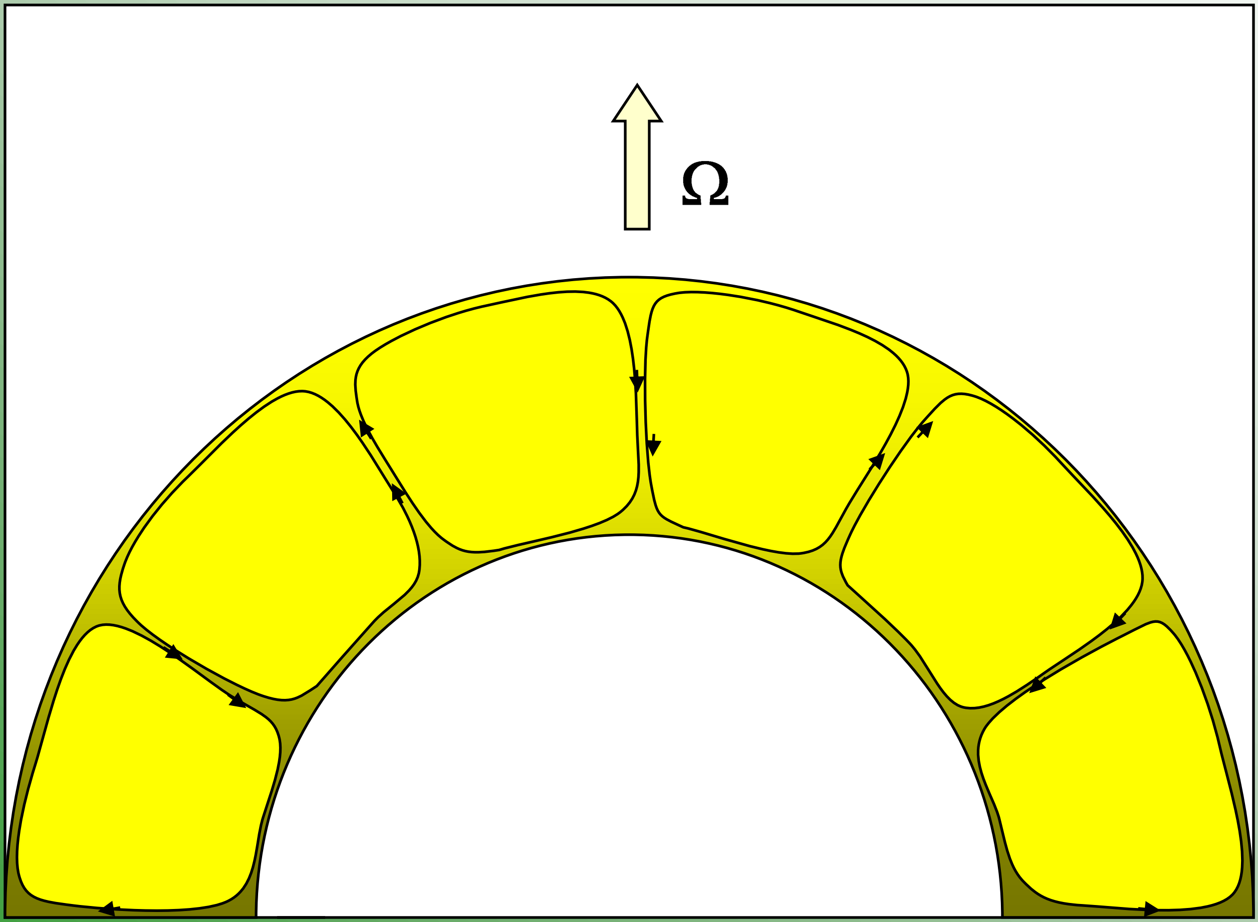
Cycle 22 Maximum



Where do the surface fields come from?



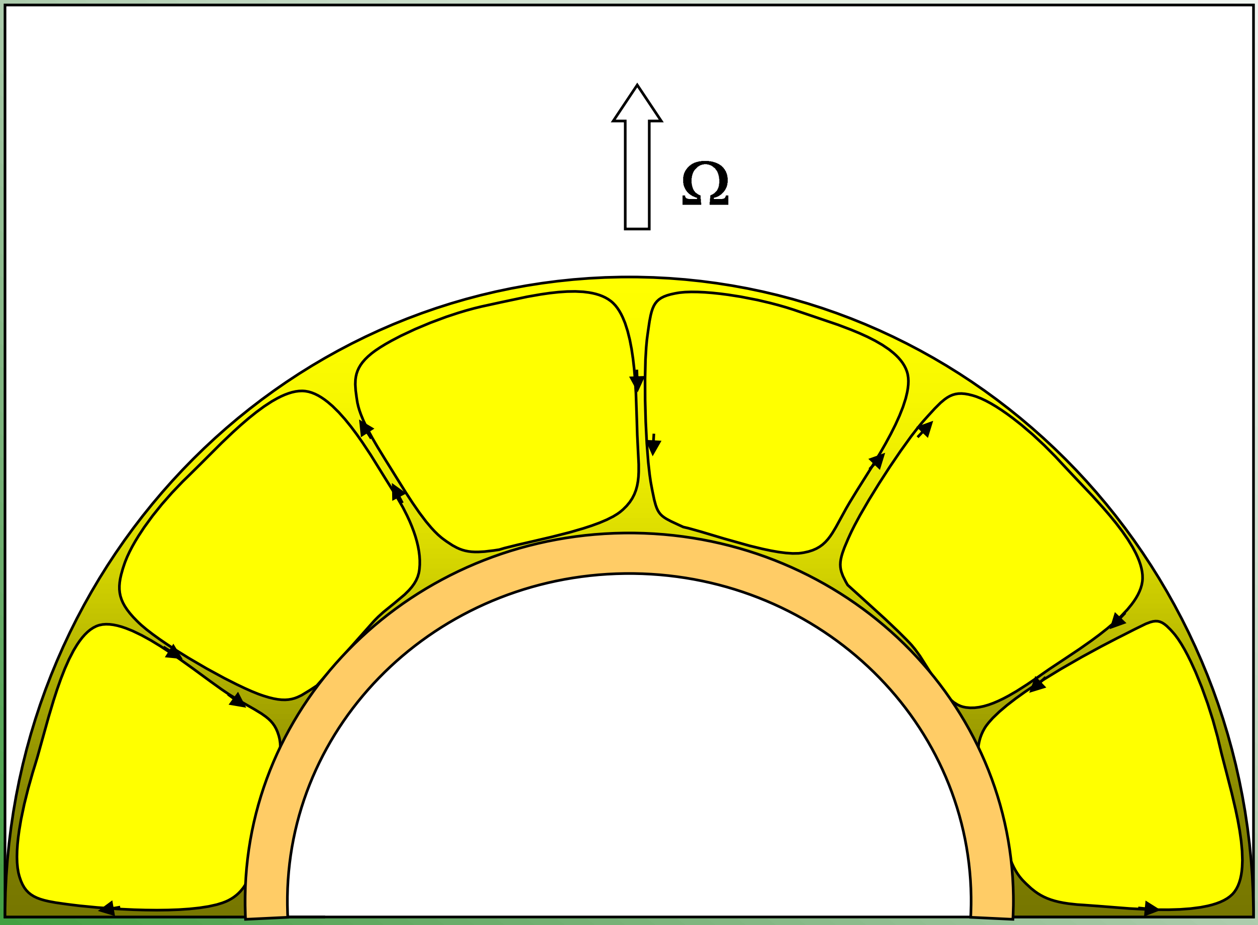
Origin of sunspots



1

•Convection zone

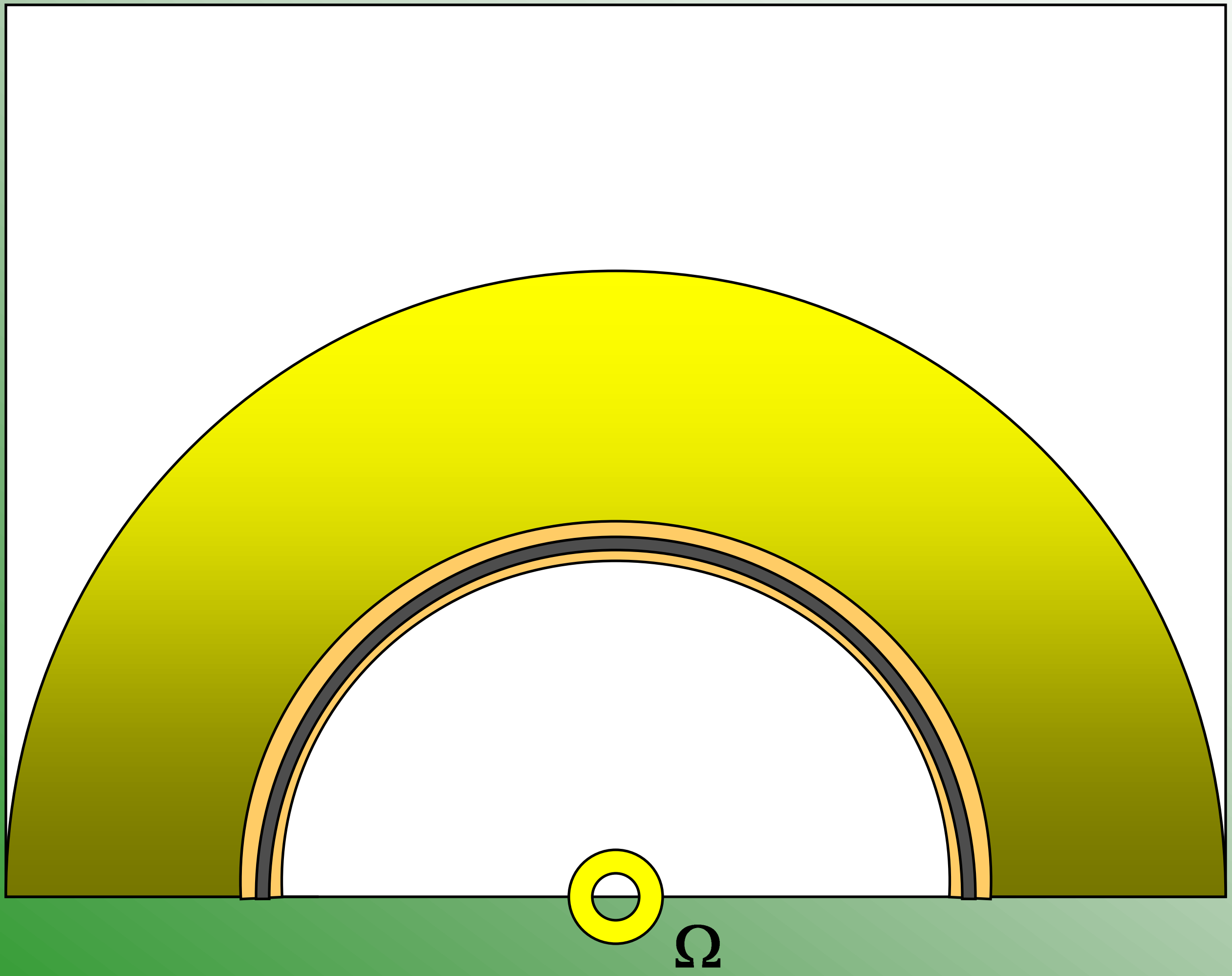
Origin of sunspots



2

•**Overshoot layer**

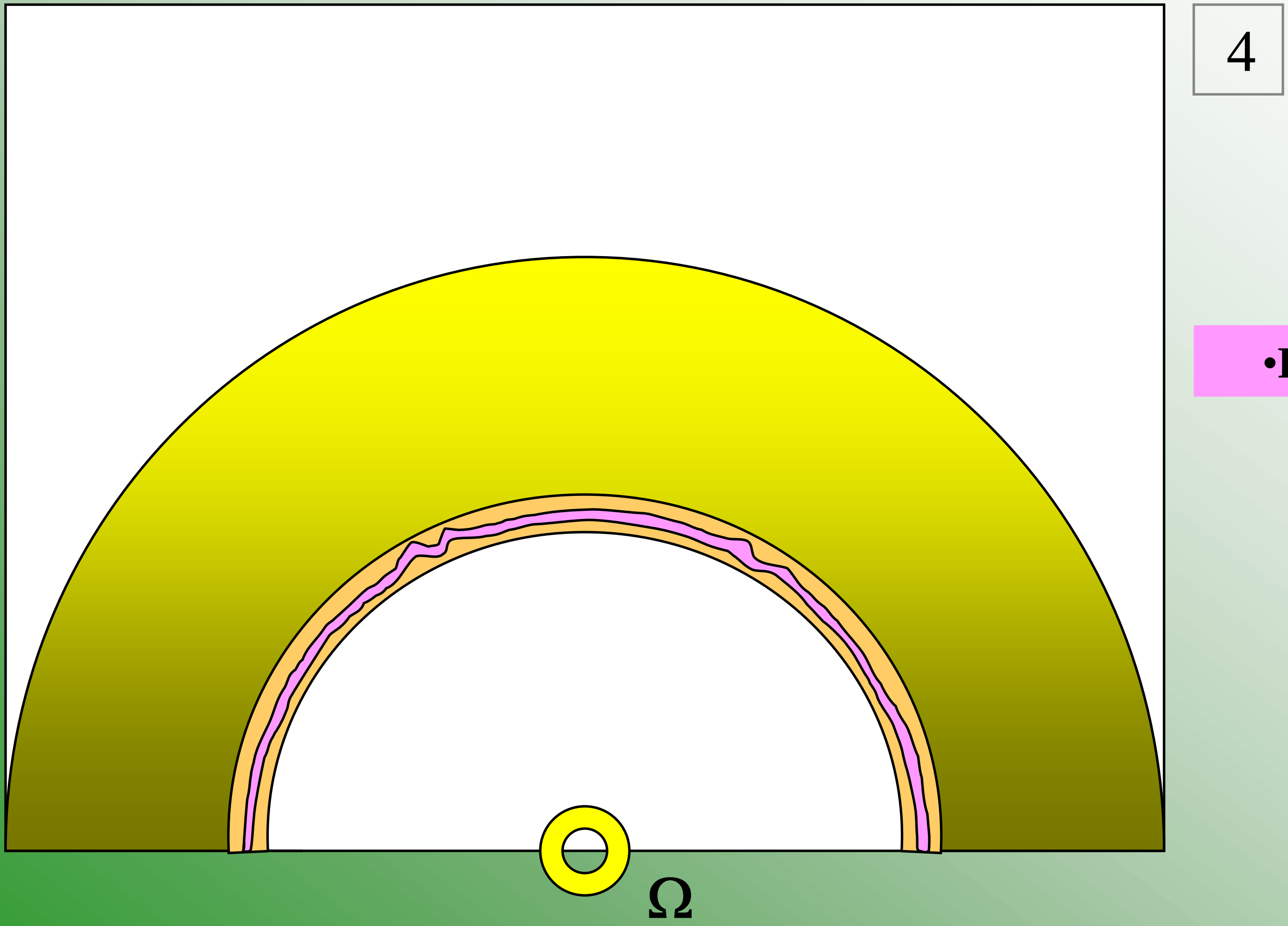
Origin of sunspots



3

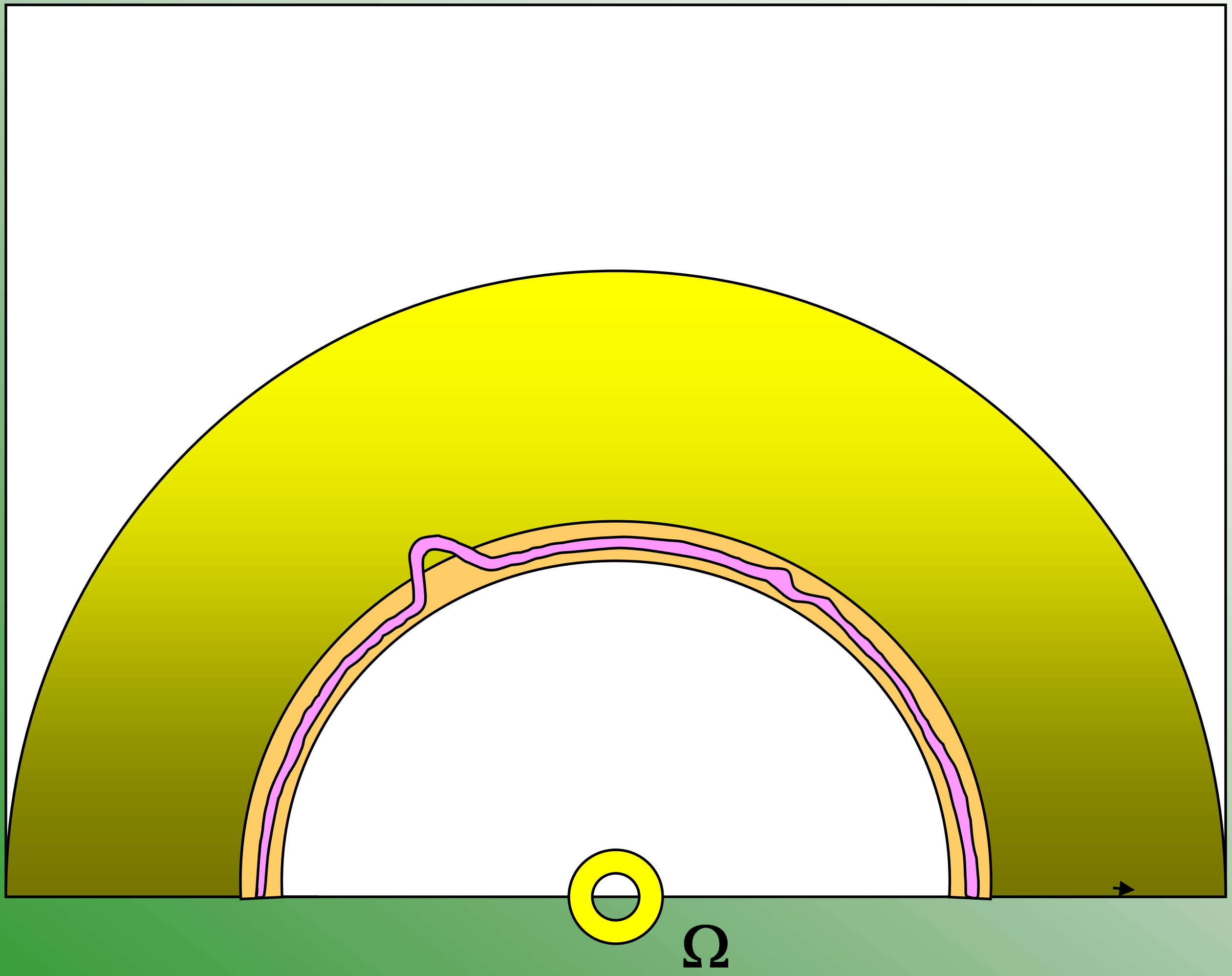
•Magnetic flux tube

Origin of sunspots



•Parker instability

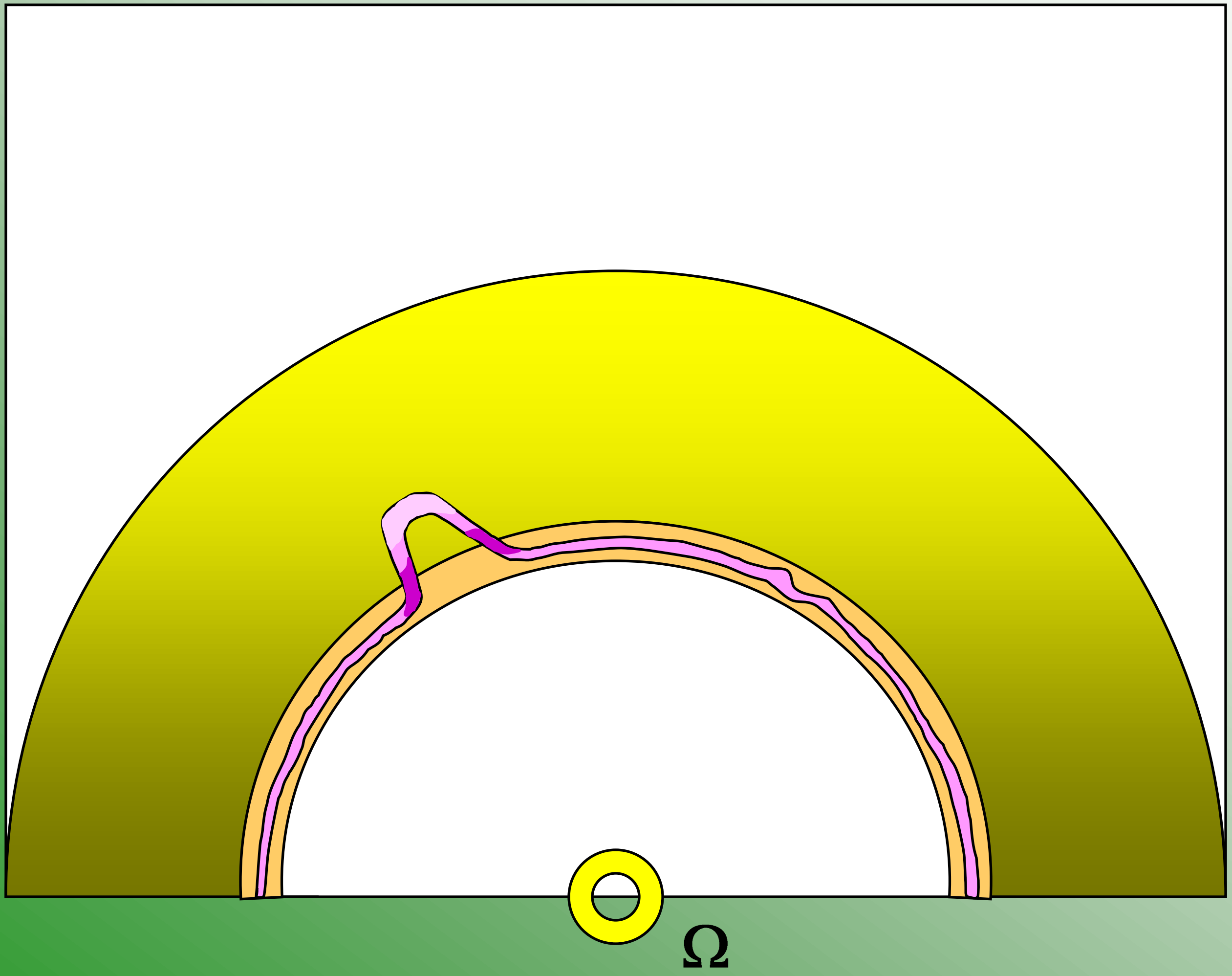
Origin of sunspots



5

•**Magnetic buoyancy**

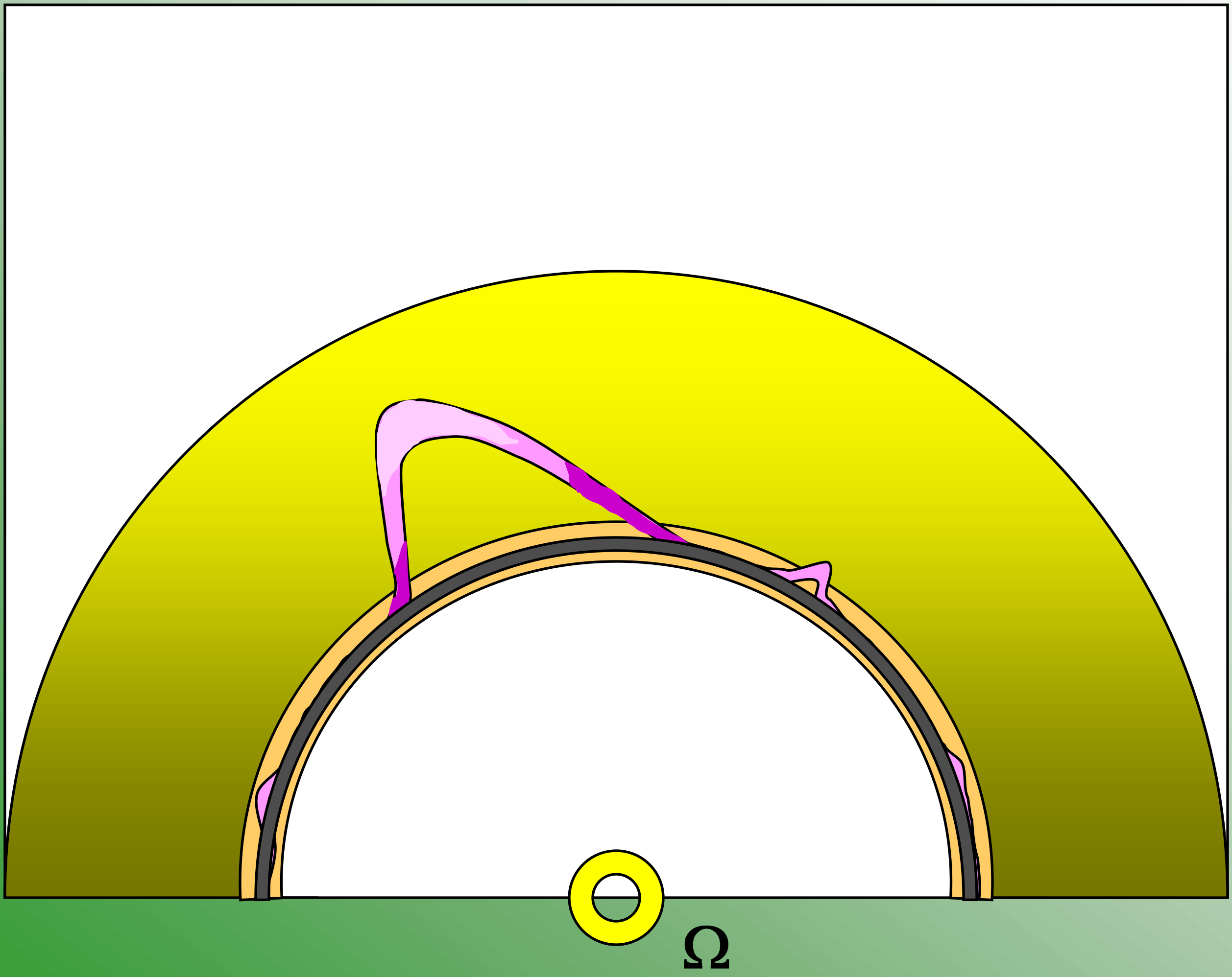
Origin of sunspots



6

•**Magnetic buoyancy**

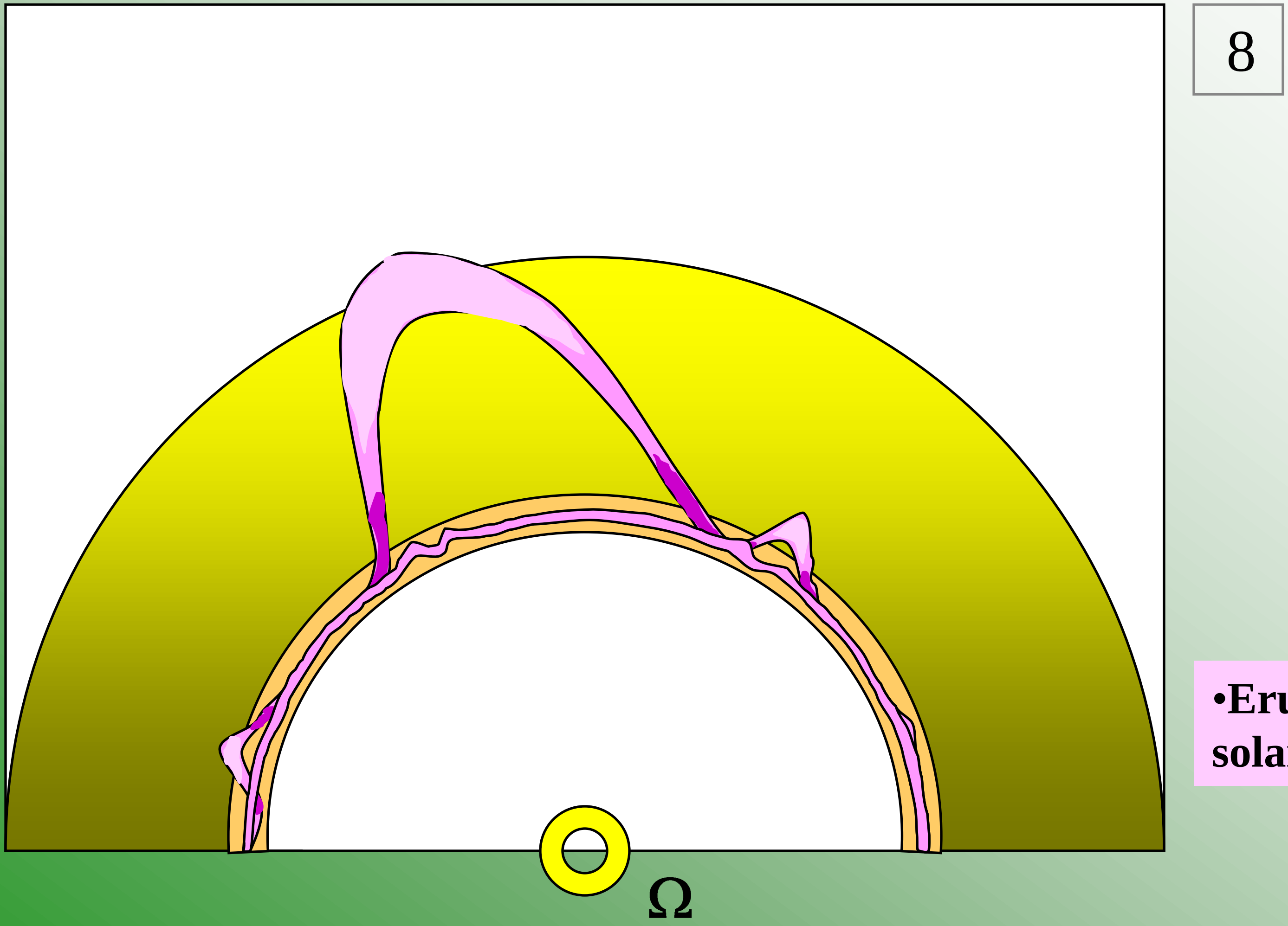
Origin of sunspots



7

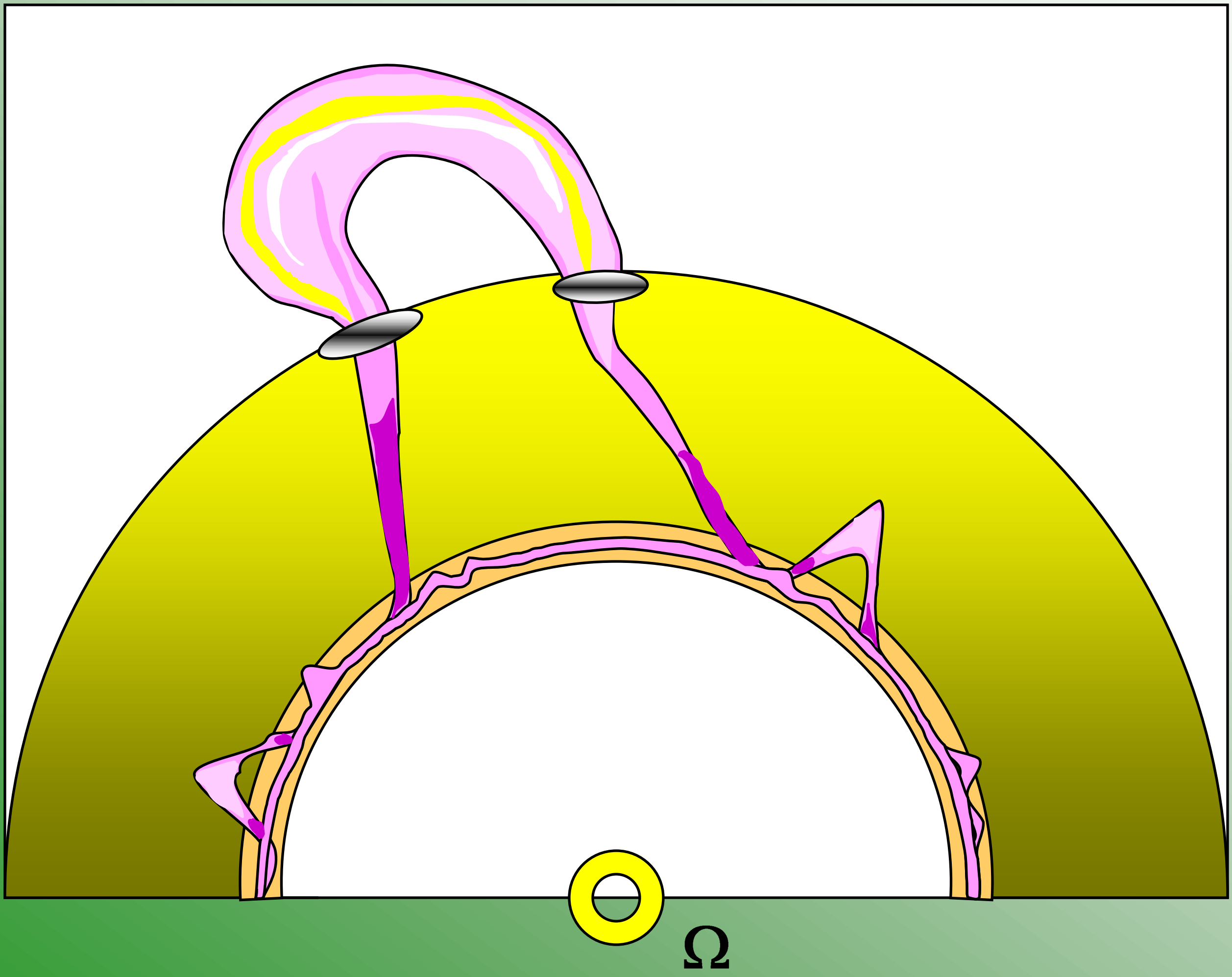
• **Tube expansion and decreasing field strength**

Origin of sunspots



•Eruption at the solar surface

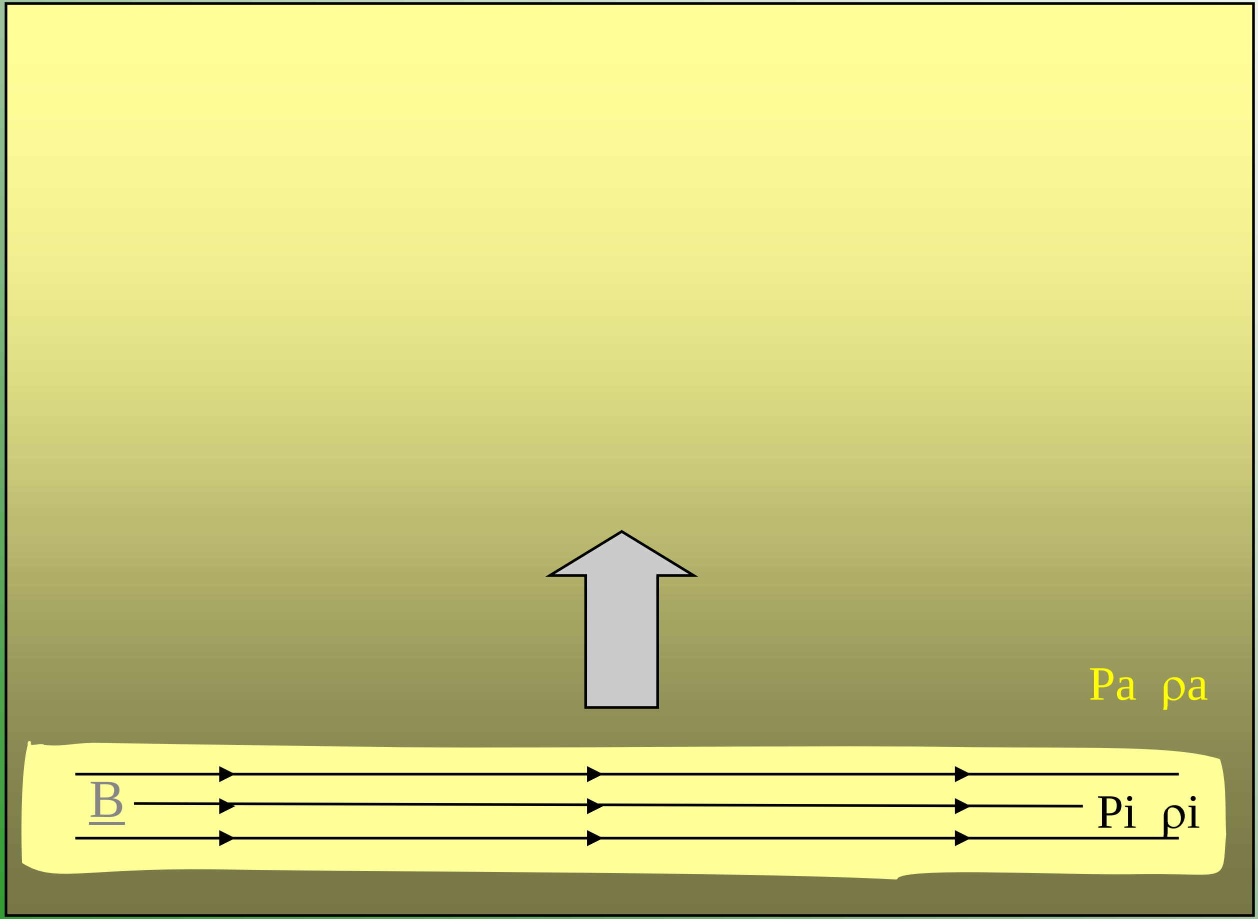
Origin of sunspots



9

•Formation of a bipolar sunspot pair/group

Magnetic buoyancy of a flux tube



Pressure equilibrium

$$\mathbf{Pa = Pi + B^2/8\pi}$$

$B \neq \mathbf{0} \Rightarrow P_i < P_a$

$\Rightarrow \rho_i < \rho_a$

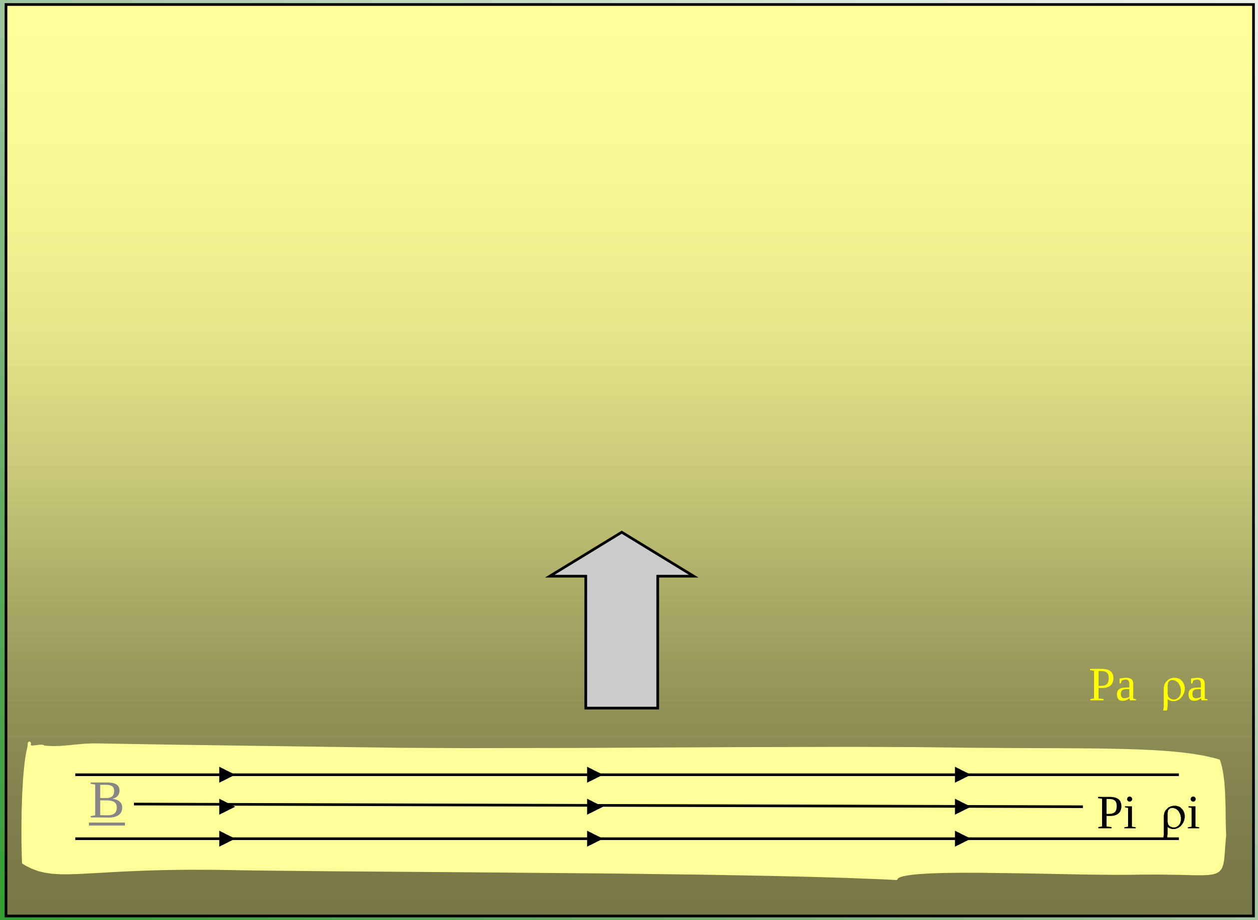
$\Rightarrow$ **buoyancy**

P_a ,ρ_a **external pressure, density**

P_i ,ρ_i **internal pressure, density**

Parker instability

Magnetic buoyancy of a flux tube



Pressure equilibrium

$$\mathbf{Pa = Pi + B^2/8\pi}$$

B $\neq$ **0** $\Rightarrow$ Pi < Pa

$\Rightarrow$ ρi < ρa

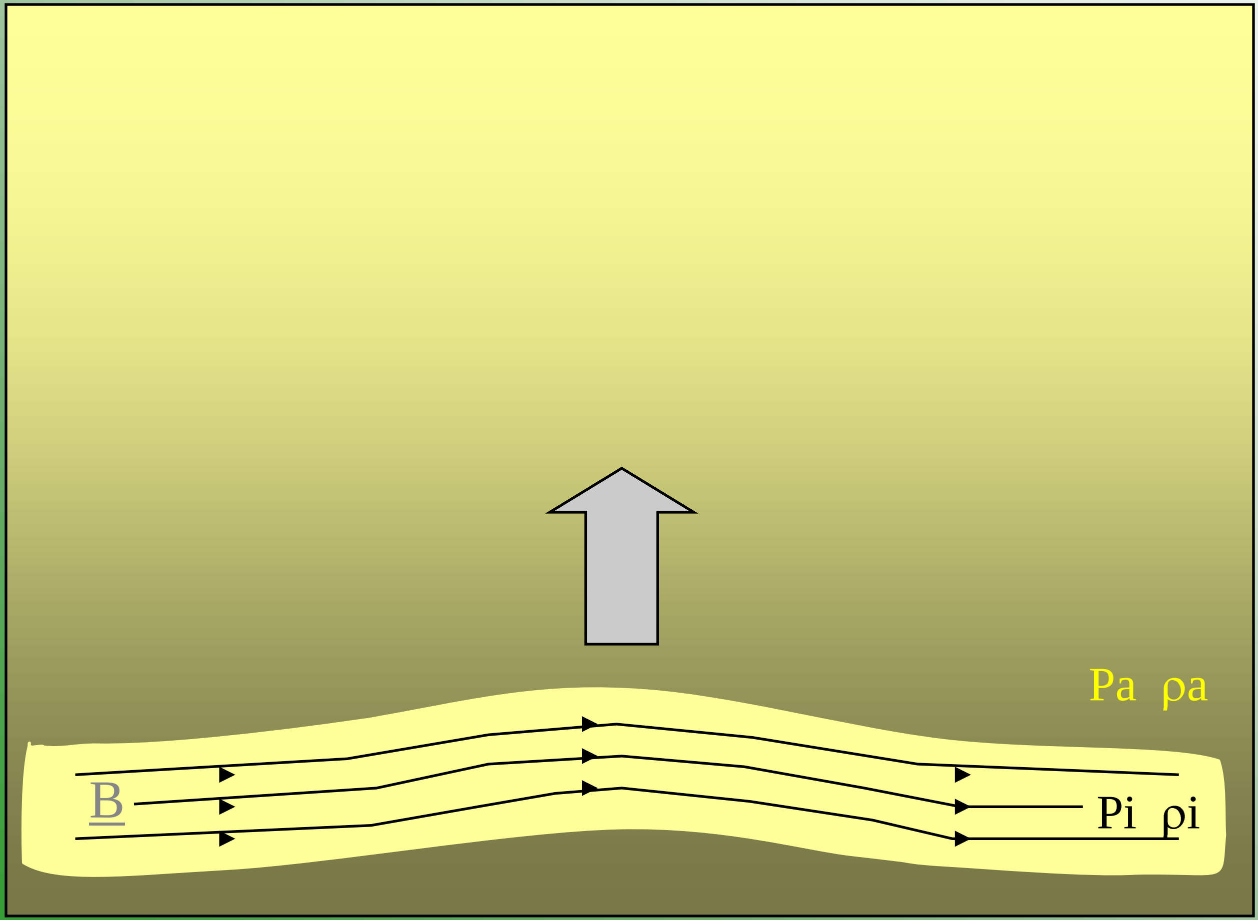
$\Rightarrow$ **buoyancy**

Pa ,ρa **external pressure, density**

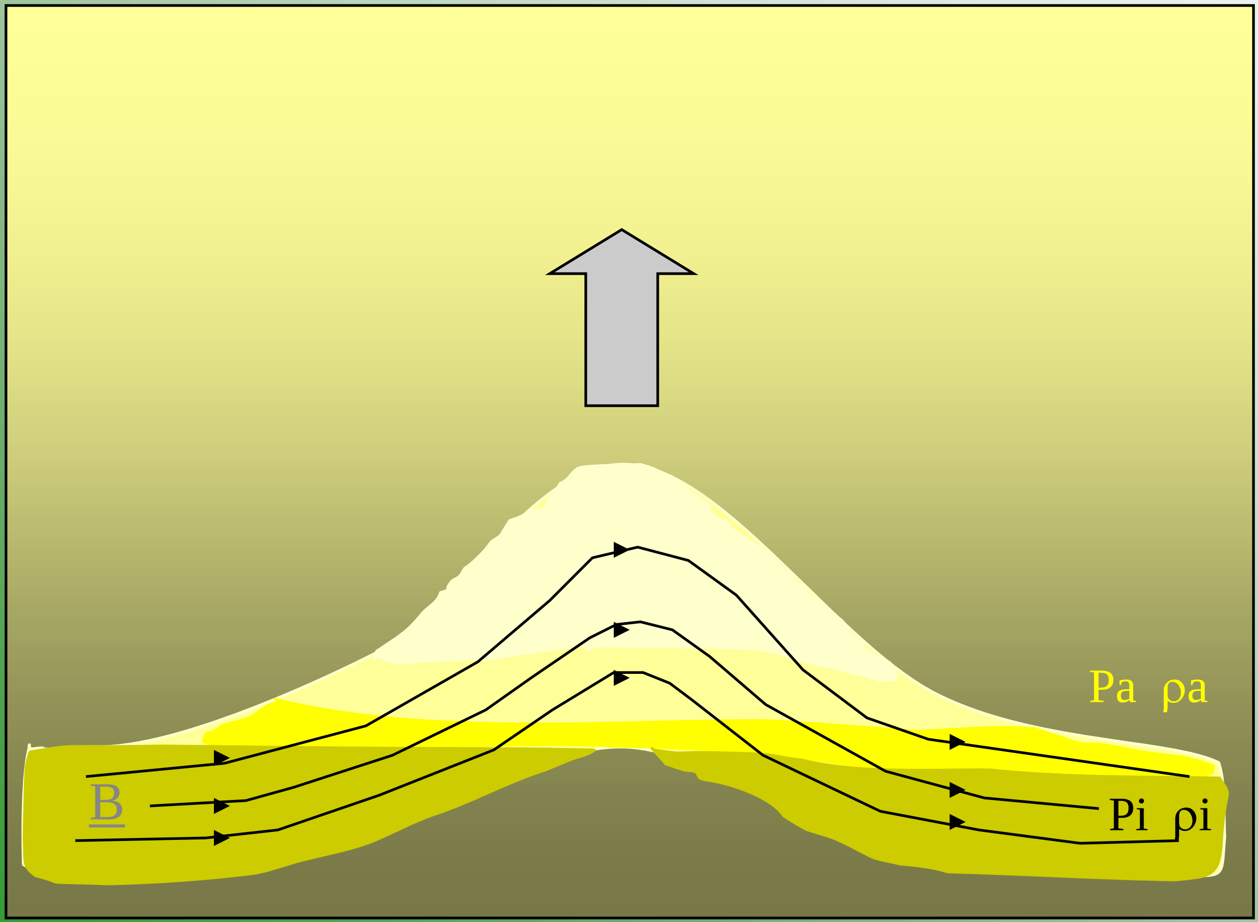
Pi ,ρi **internal pressure, density**

Parker instability

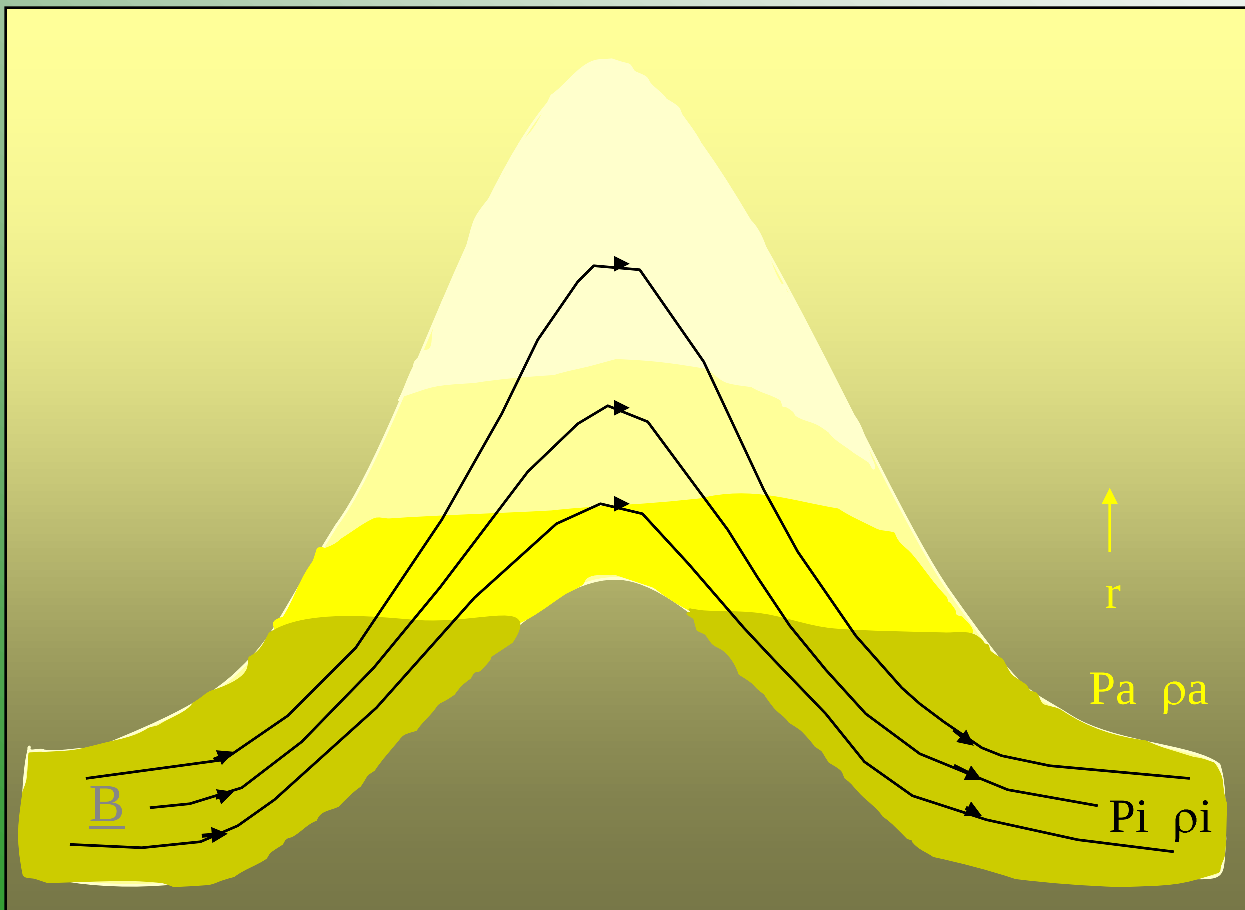
Magnetic buoyancy of a flux tube



Magnetic buoyancy of a flux tube



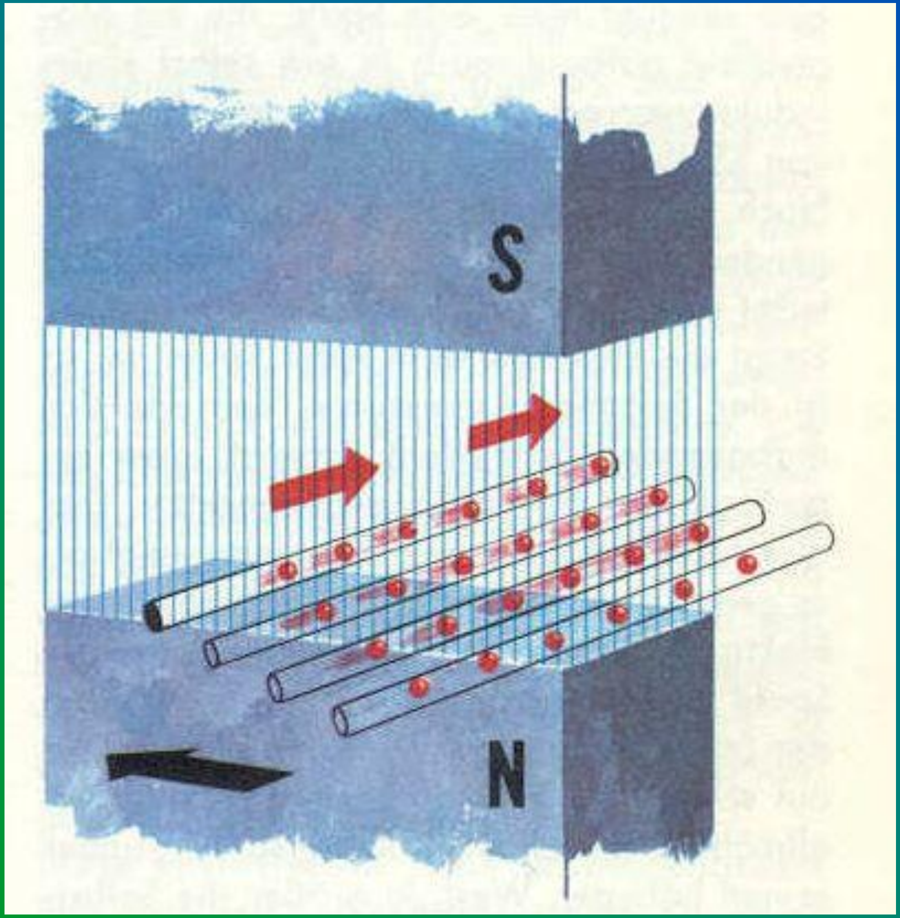
Magnetic buoyancy of a flux tube



Generation of magnetic flux...

- ... requires an electrically conducting medium
  - ➔ plasma (ionized gas)
- ... requires fluid motion for induction
  - ➔ convective flows
  - ➔ (differential) rotation
- ... how is the field maintained against dissipation?
  - ➔ (self-excited) dynamo process

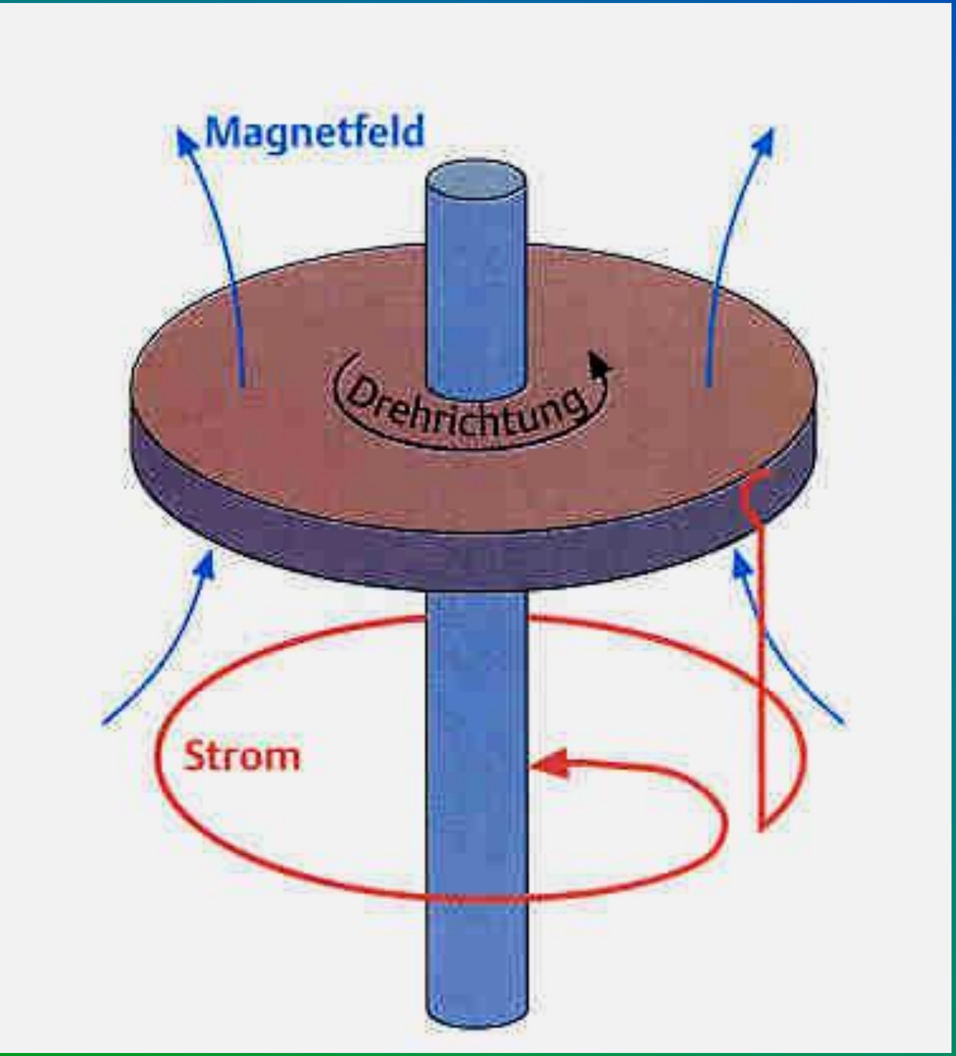
The induction principle



- Conductor moving in a magnetic field
- perpendicular electrical field and force
- electrical current
- new magnetic field
- Lenz´s rule!

  (no perpetuum mobile)

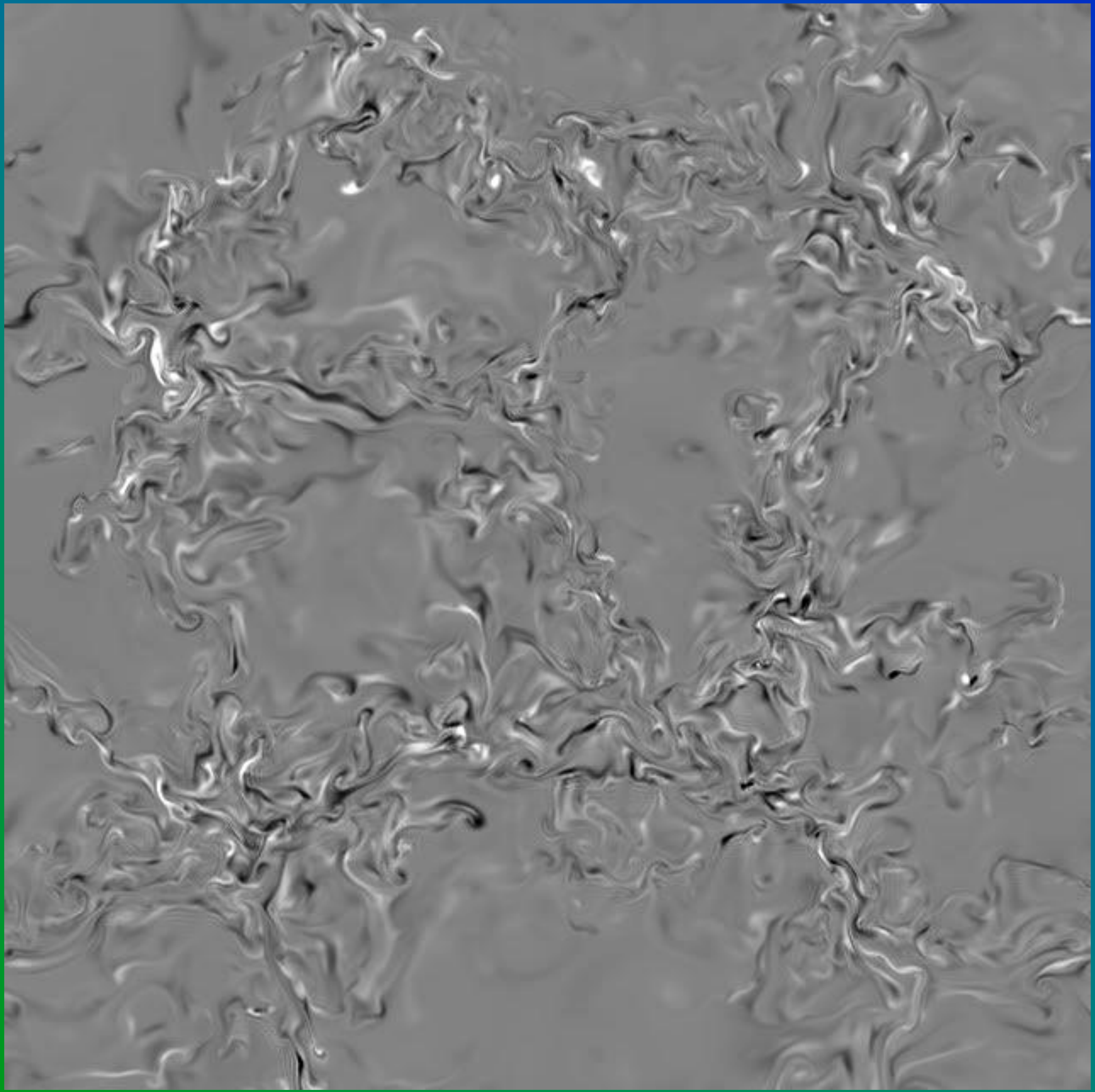
A simple dynamo



Initially weak "seed field"

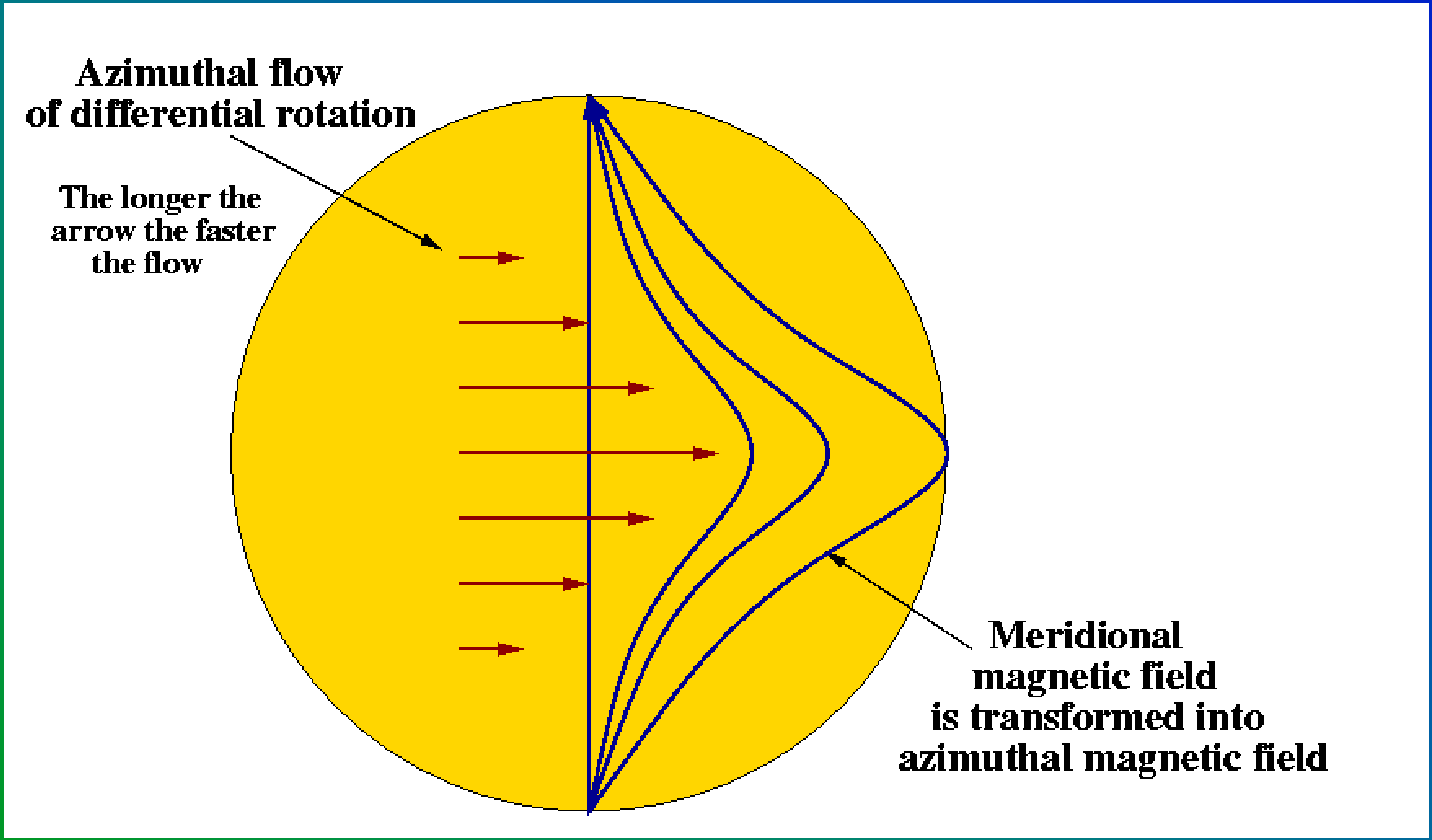
- ➔ Rotation induces electrical field between axis and edge
- ➔ Current closed by wire
- ➔ Current generates a magnetic field which amplifies the seed field
- ➔ Sun: no isolated wires
- ➔ "homogeneous dynamo"

Local dynamo

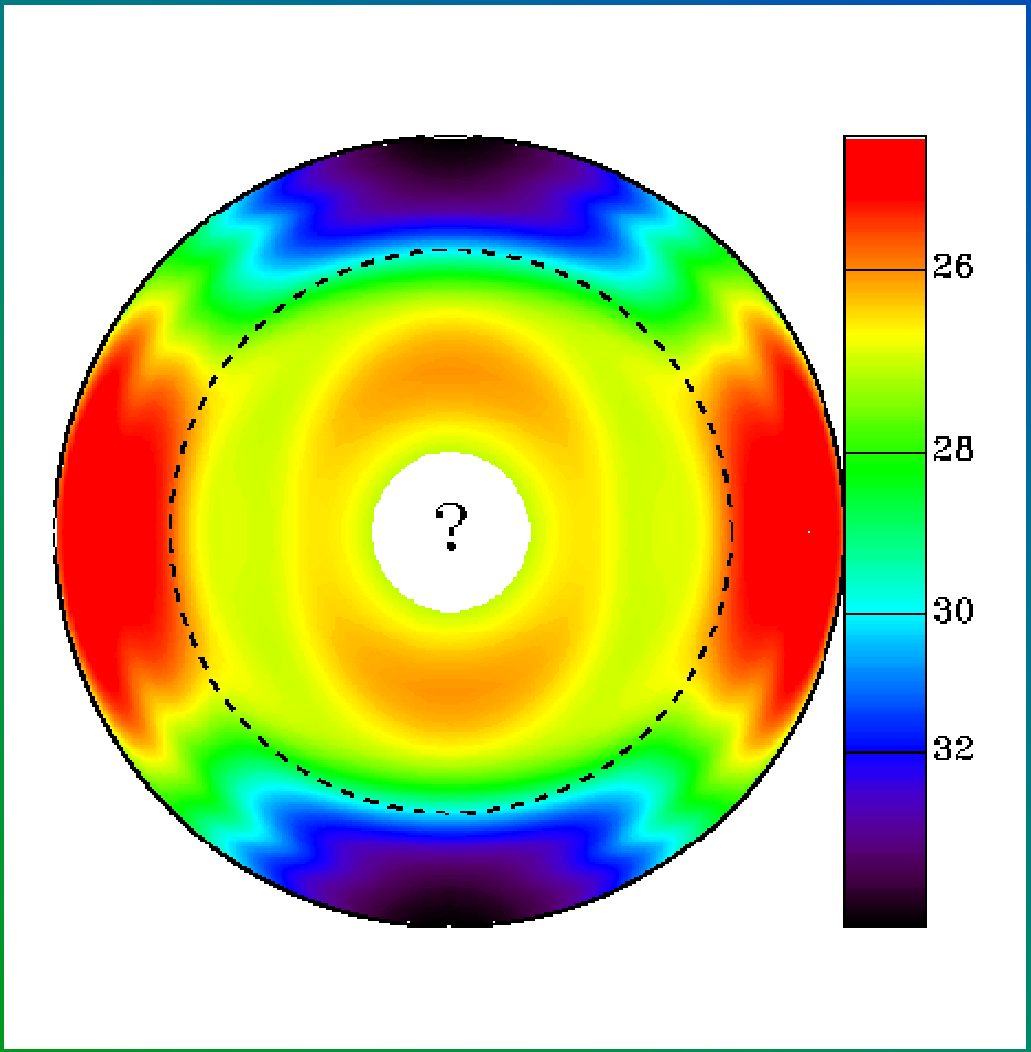


Vögler & Sch. 2007

Differential rotation generates azimuthal (toroidal) magnetic field

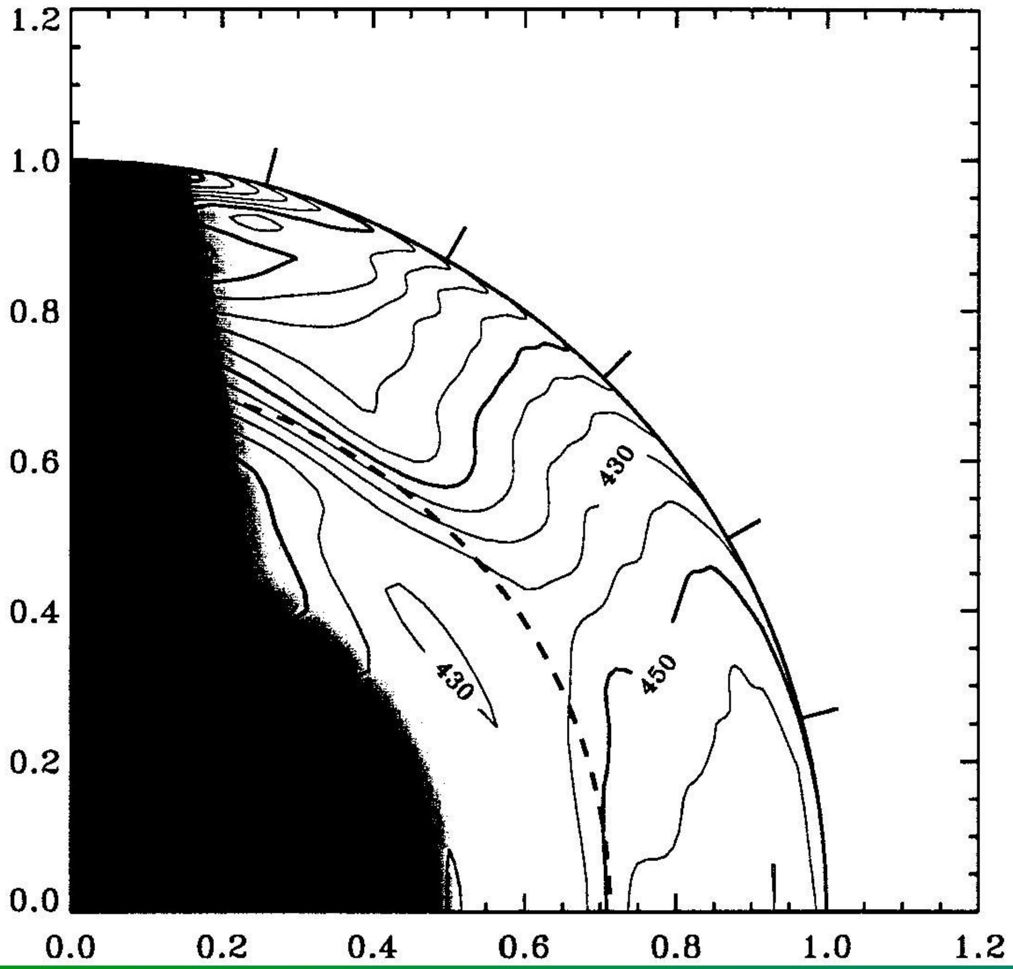


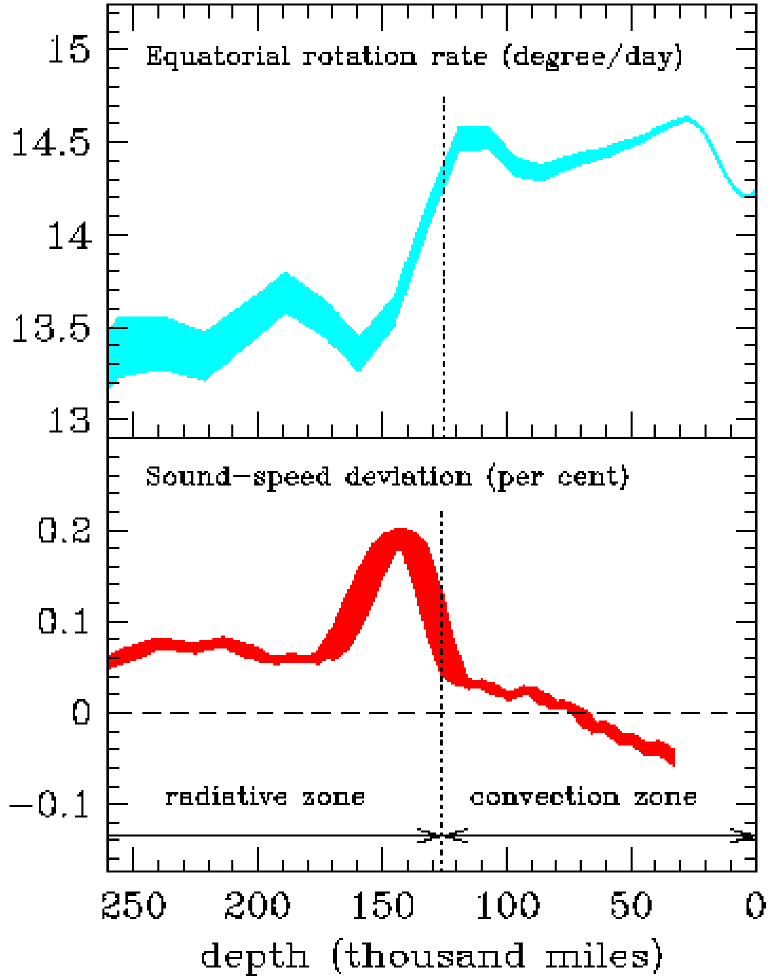
Internal rotation of the Sun as determined by helioseismology



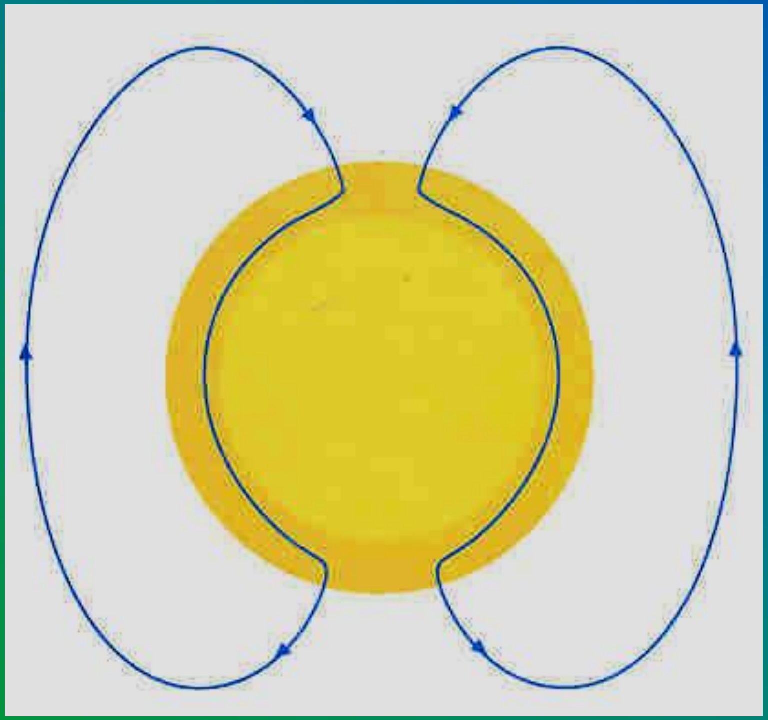
- Convection zone rotates similar to surface
- Core rotates nearly rigidly
- Steep transition at the bottom of the convection zone; width ~2% R_{sun}
- Region of strongest shear ➔ Dynamo!

Internal rotation of the Sun as determined by helioseismology



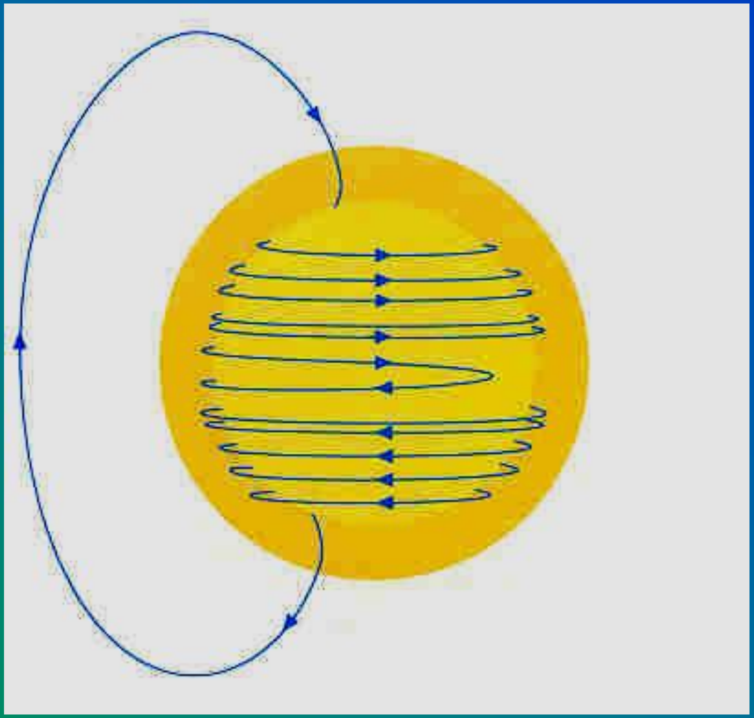


The solar dynamo (1)

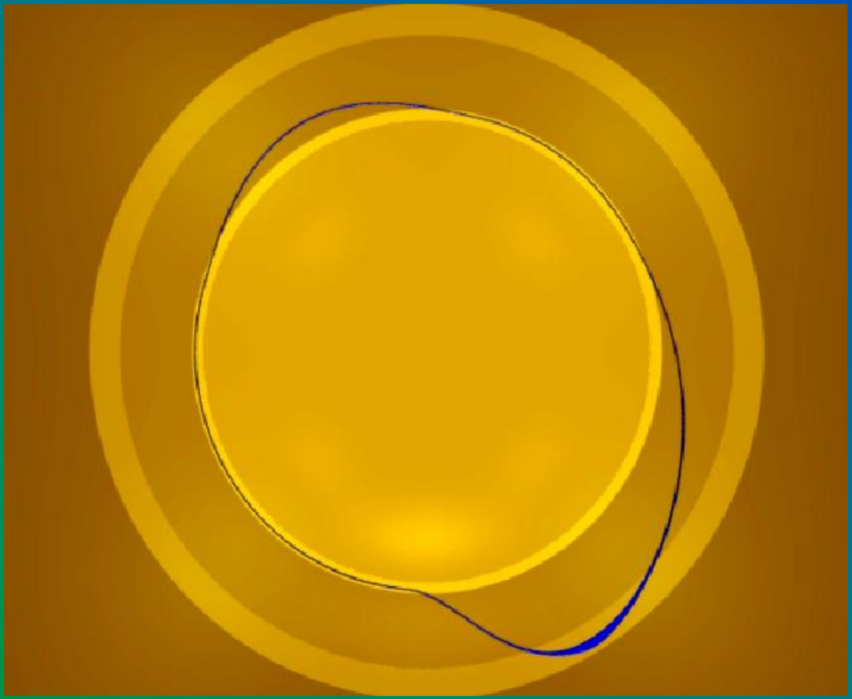


Dipol field in the convection zone

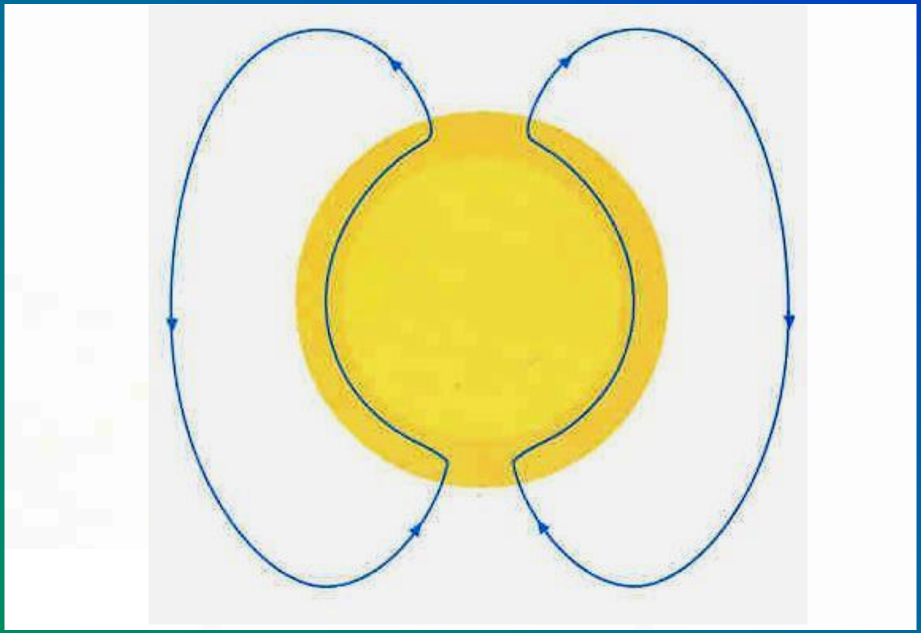
Winding up of the field by differential rotation
→ strong toroidal field



The solar dynamo (2)

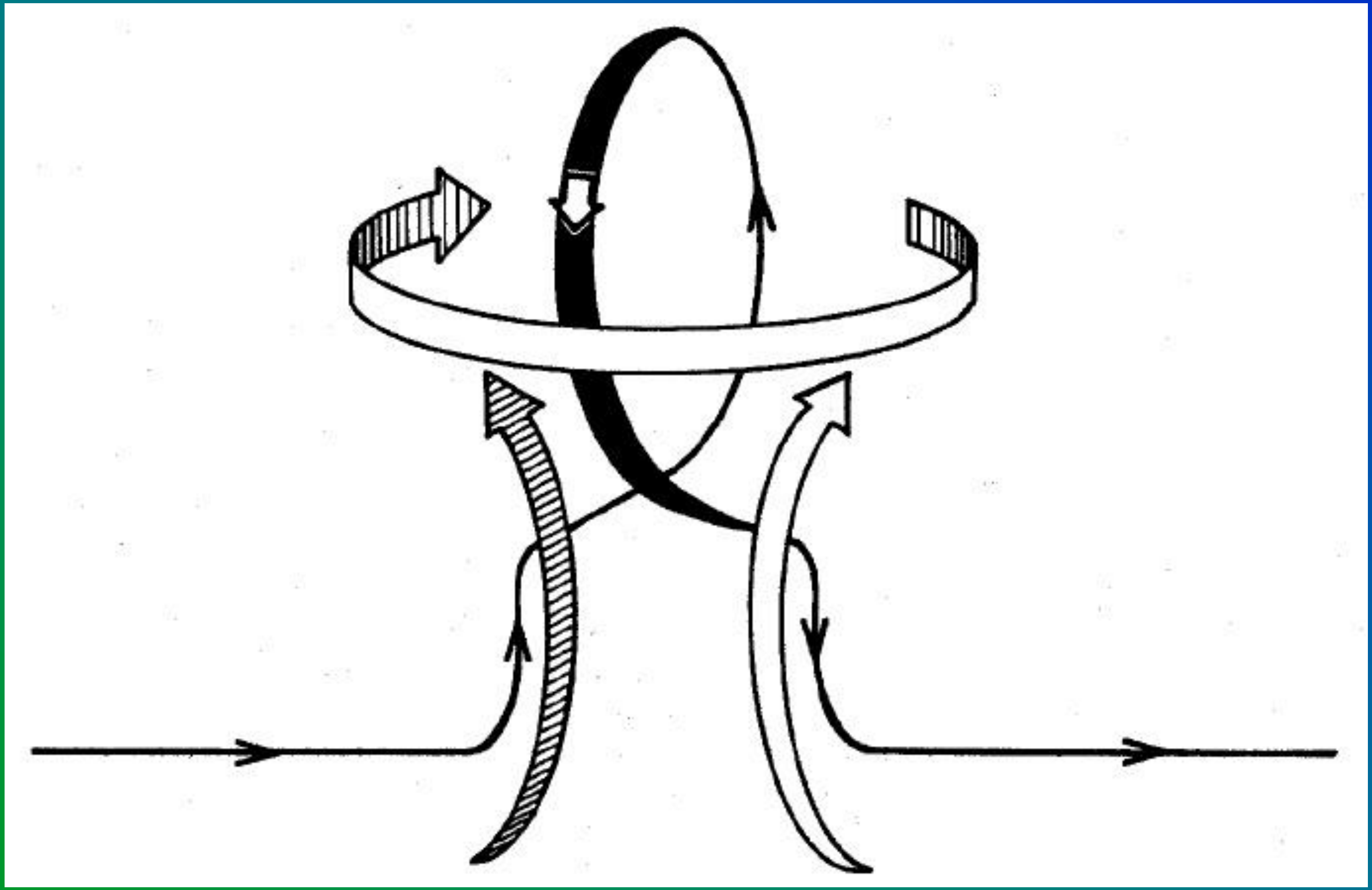


Twist of the erupting field
by Coriolis force
➔ reversed dipole field

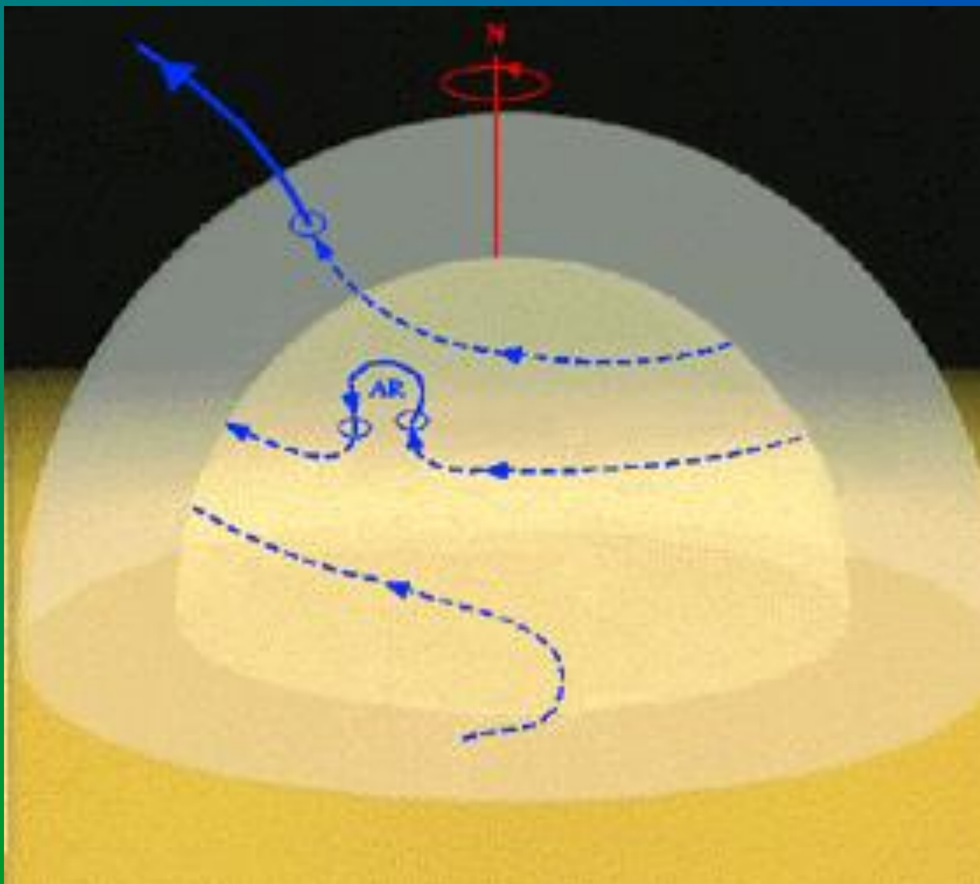


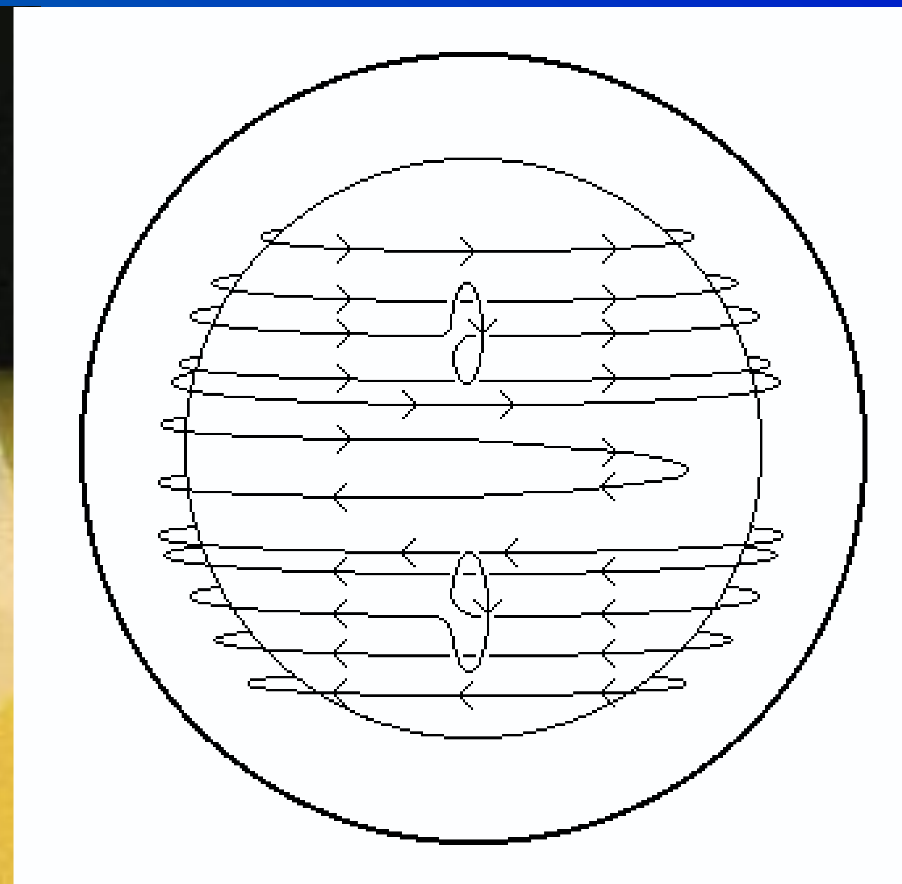
Rise and eruption of
magnetic flux tubes
➔ sunspots

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

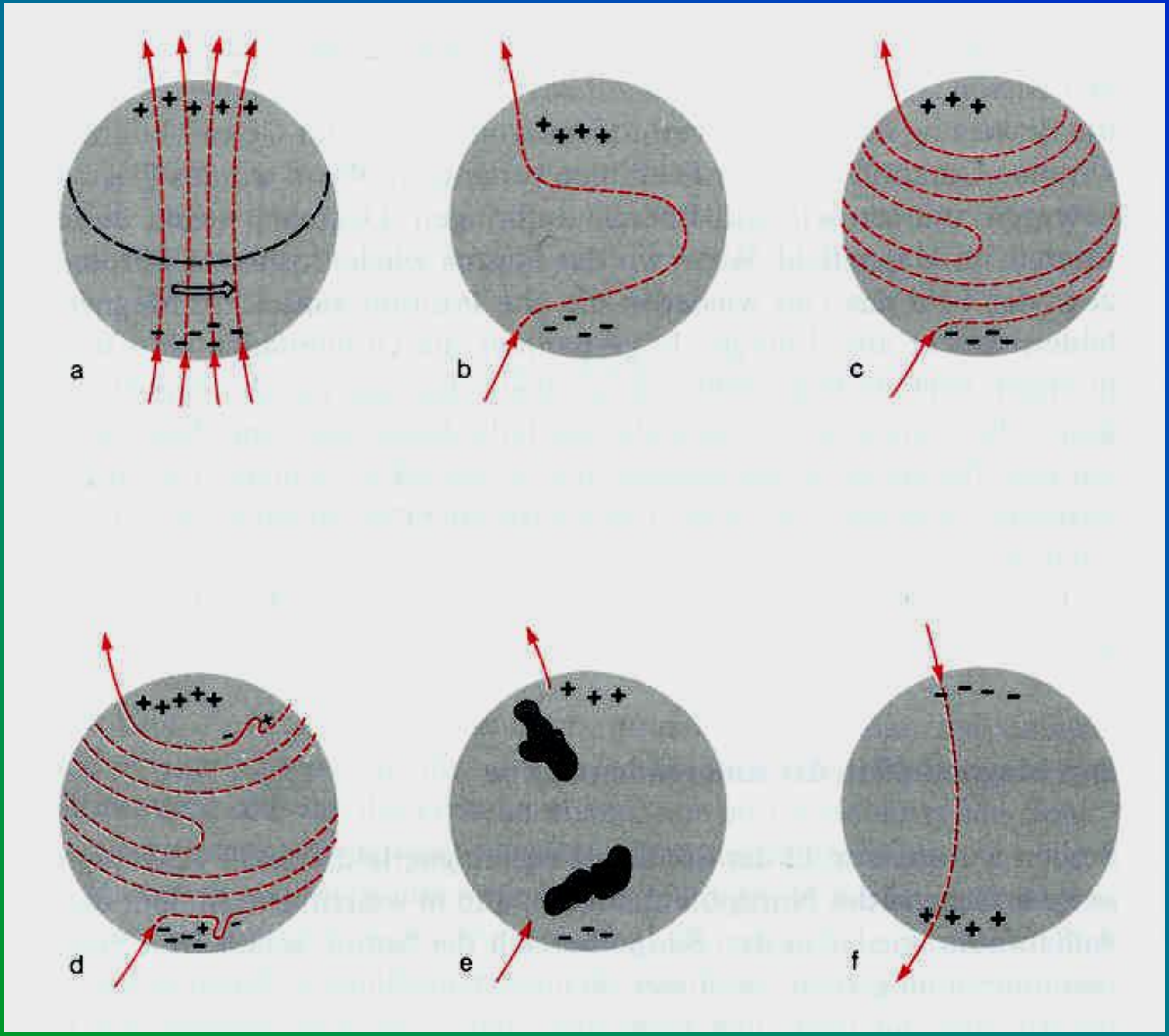


Reversal of the meridional field

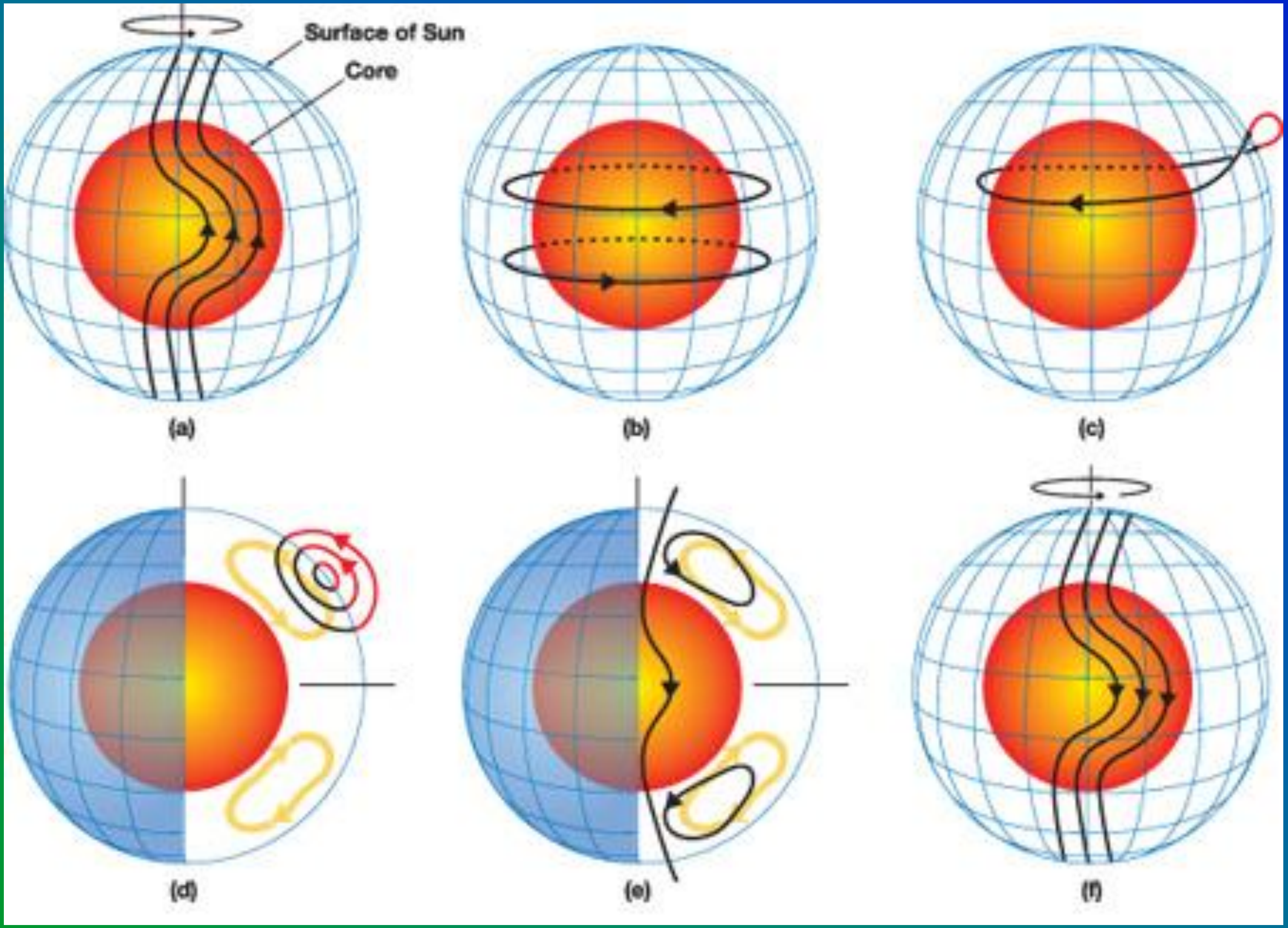




Reversal of the meridional field



Flux transport dynamo scheme



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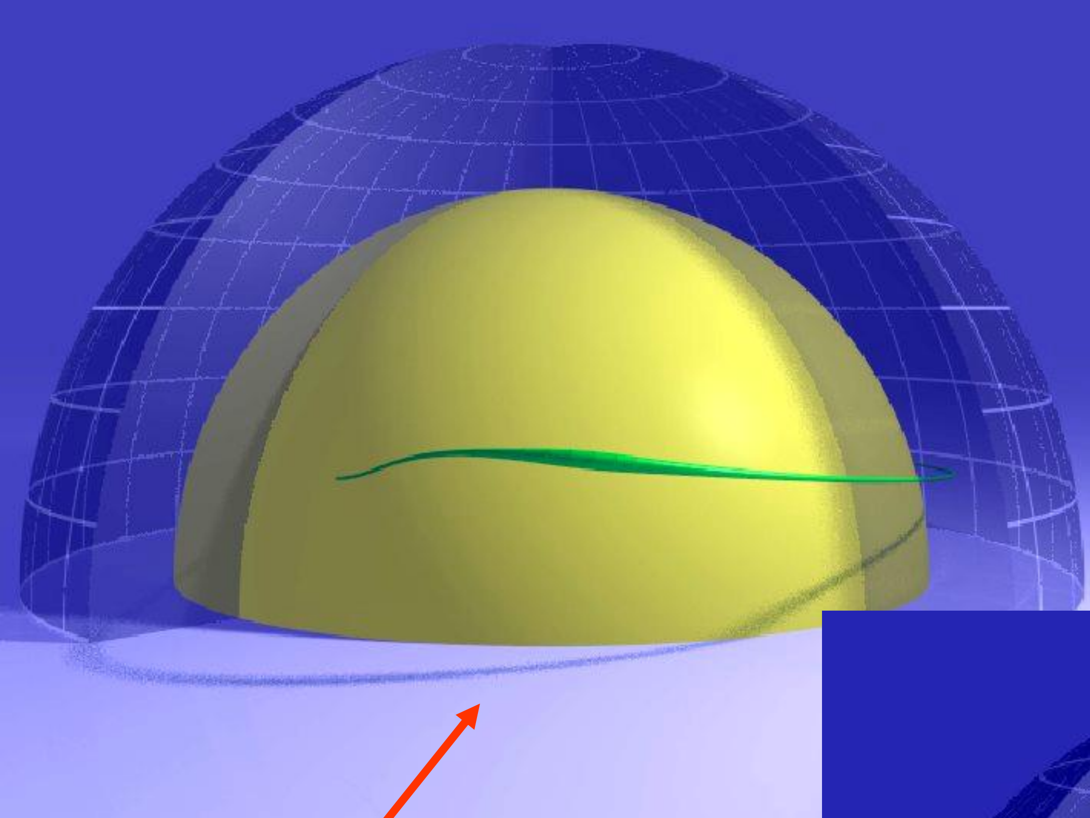
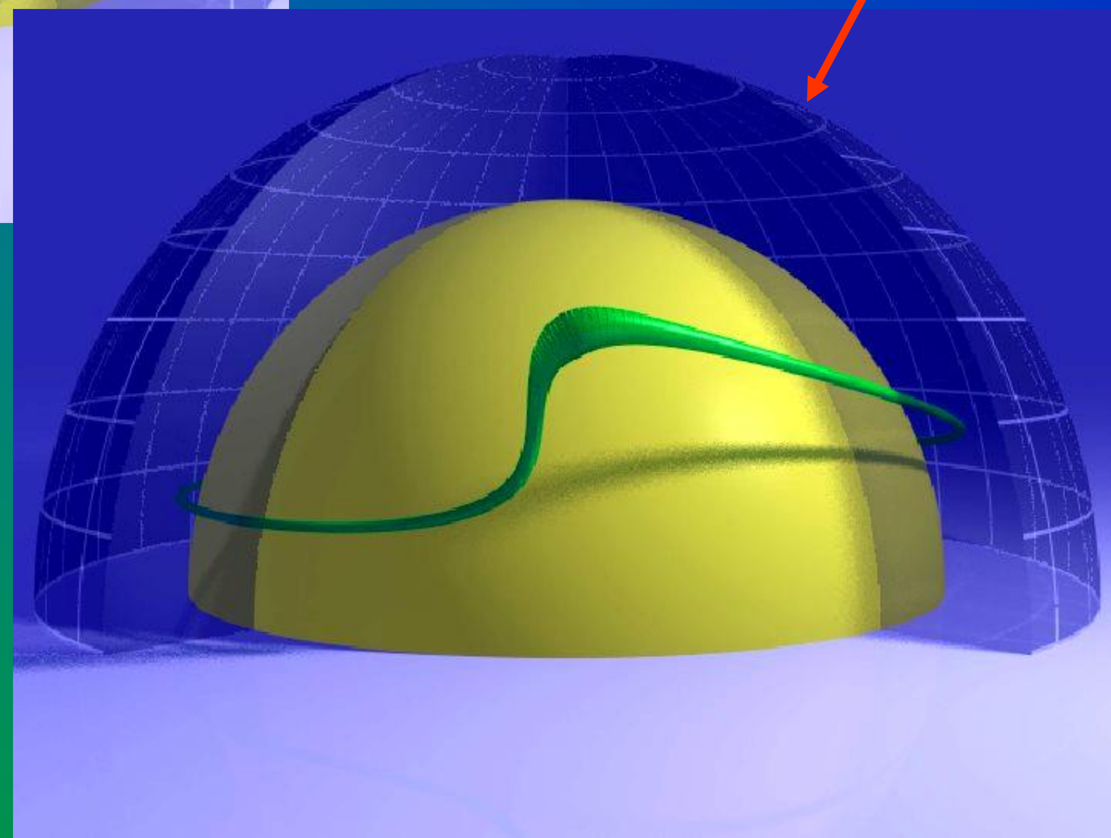


B = 1 Tesla

B = 10 Tesla



The end...