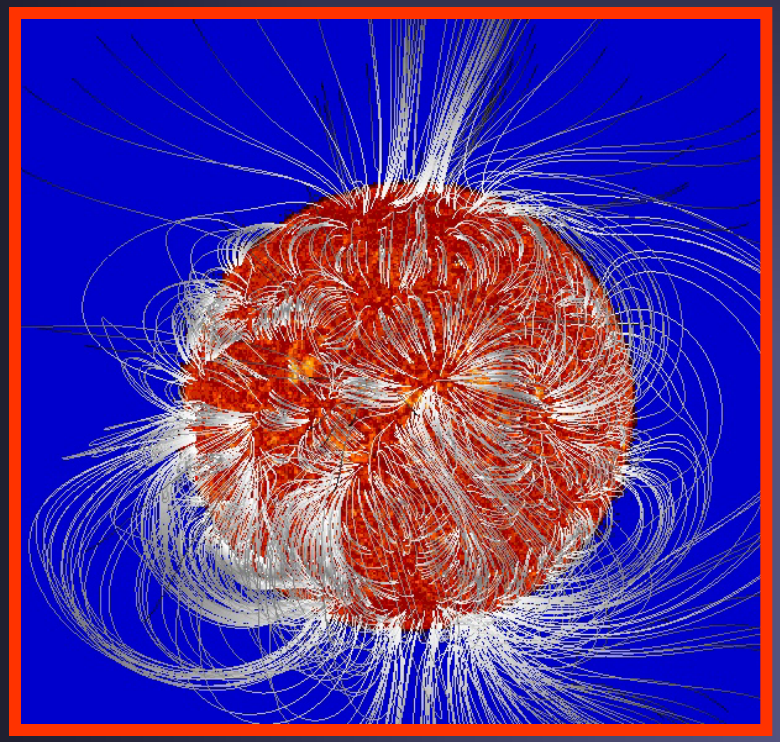
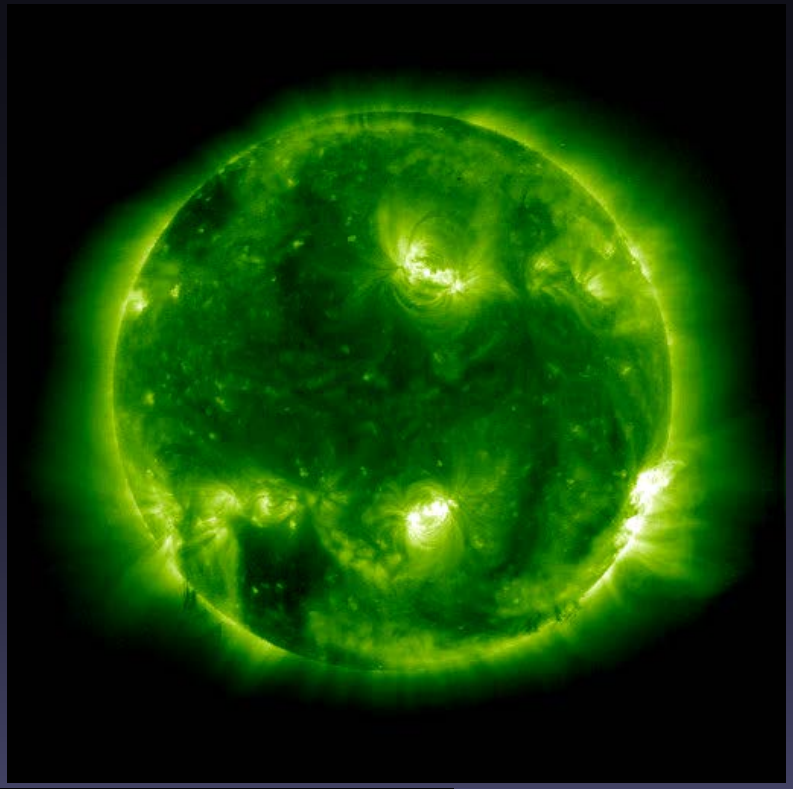
What makes the Sun so active?

Lecture 4: Magnetic Field

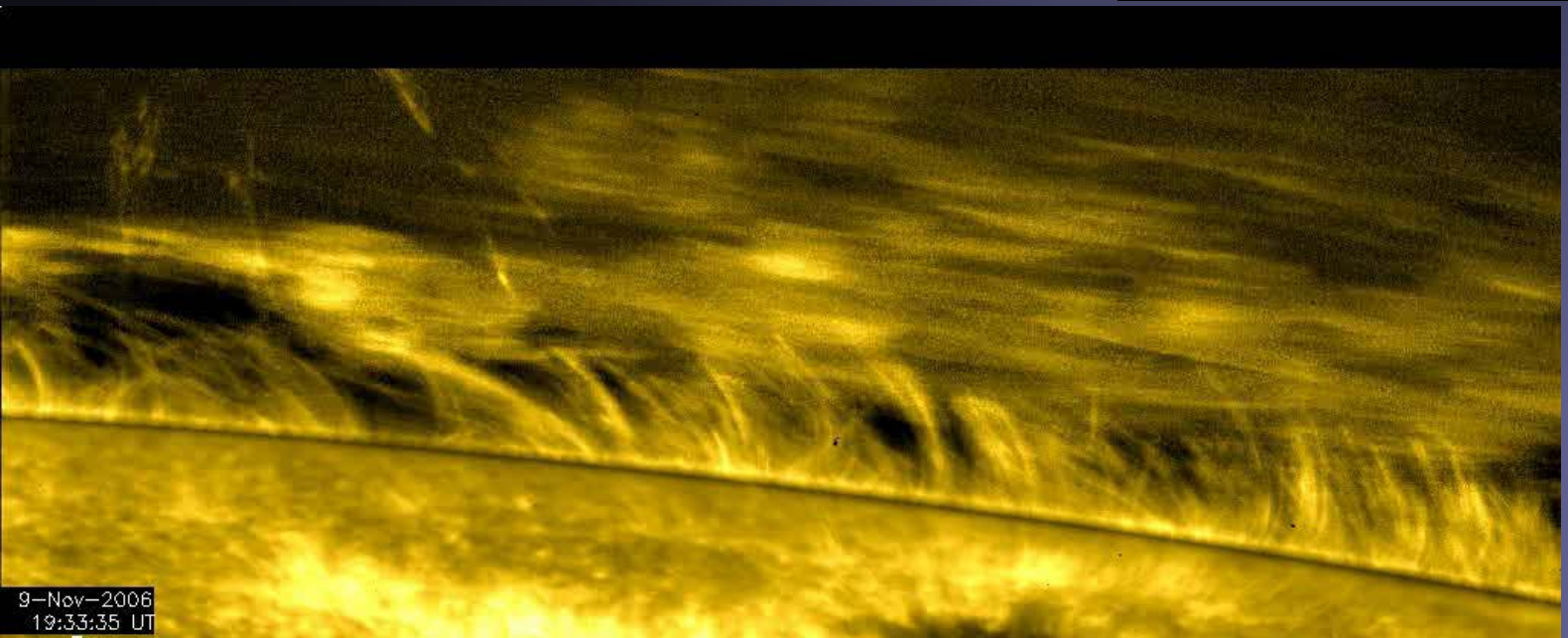


The Dynamic Sun

imaged in radiation showing
gas at 8000 - 50 000 K



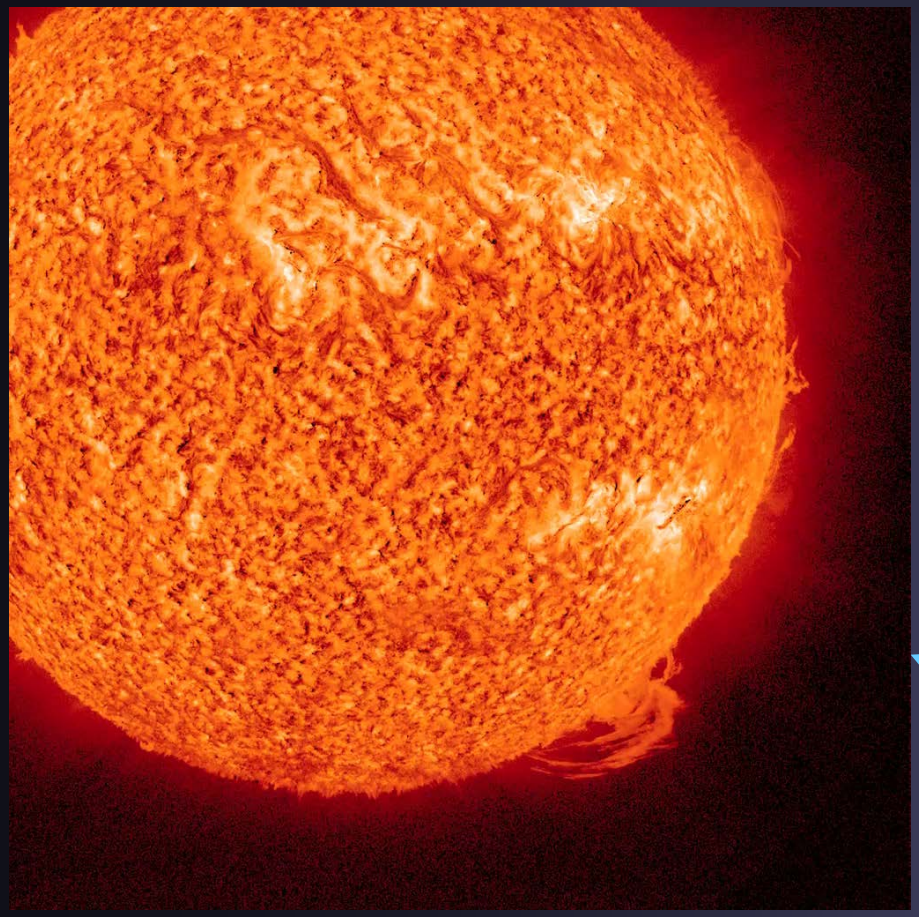
Prominence (Hinode)

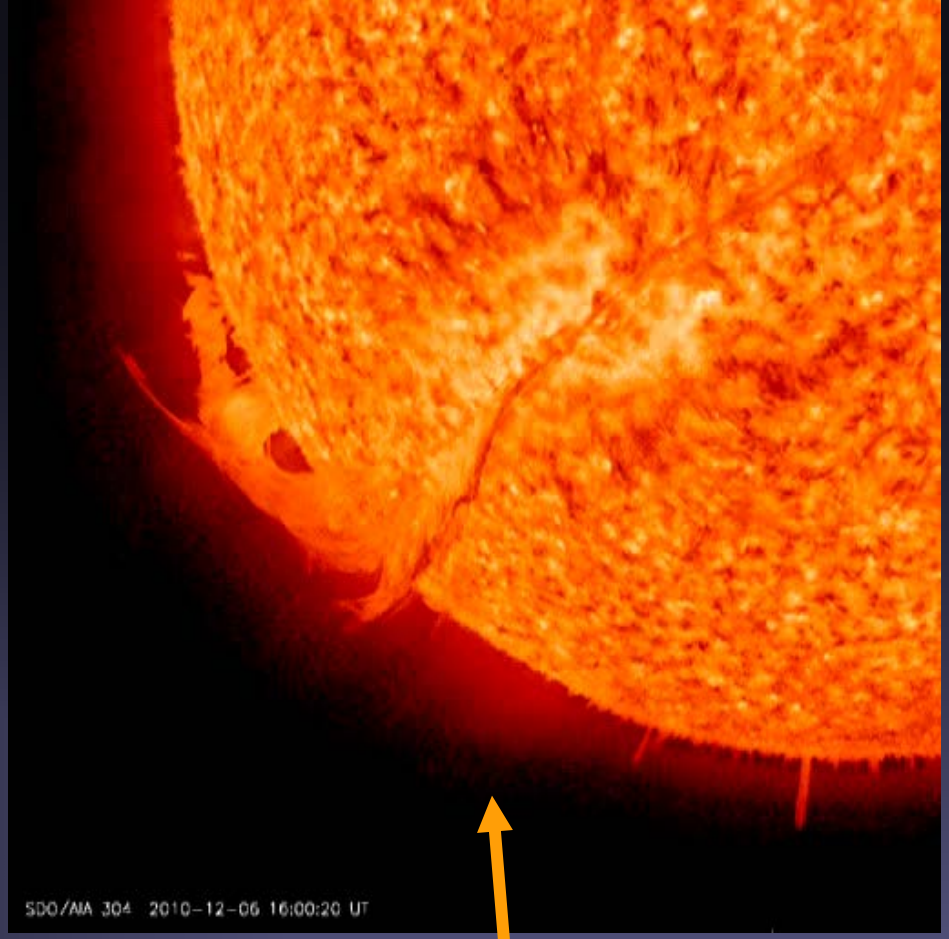


Sun in EUV radiation (SOHO)

The violent Sun

Radiation showing gas at $\approx 10^6$ K

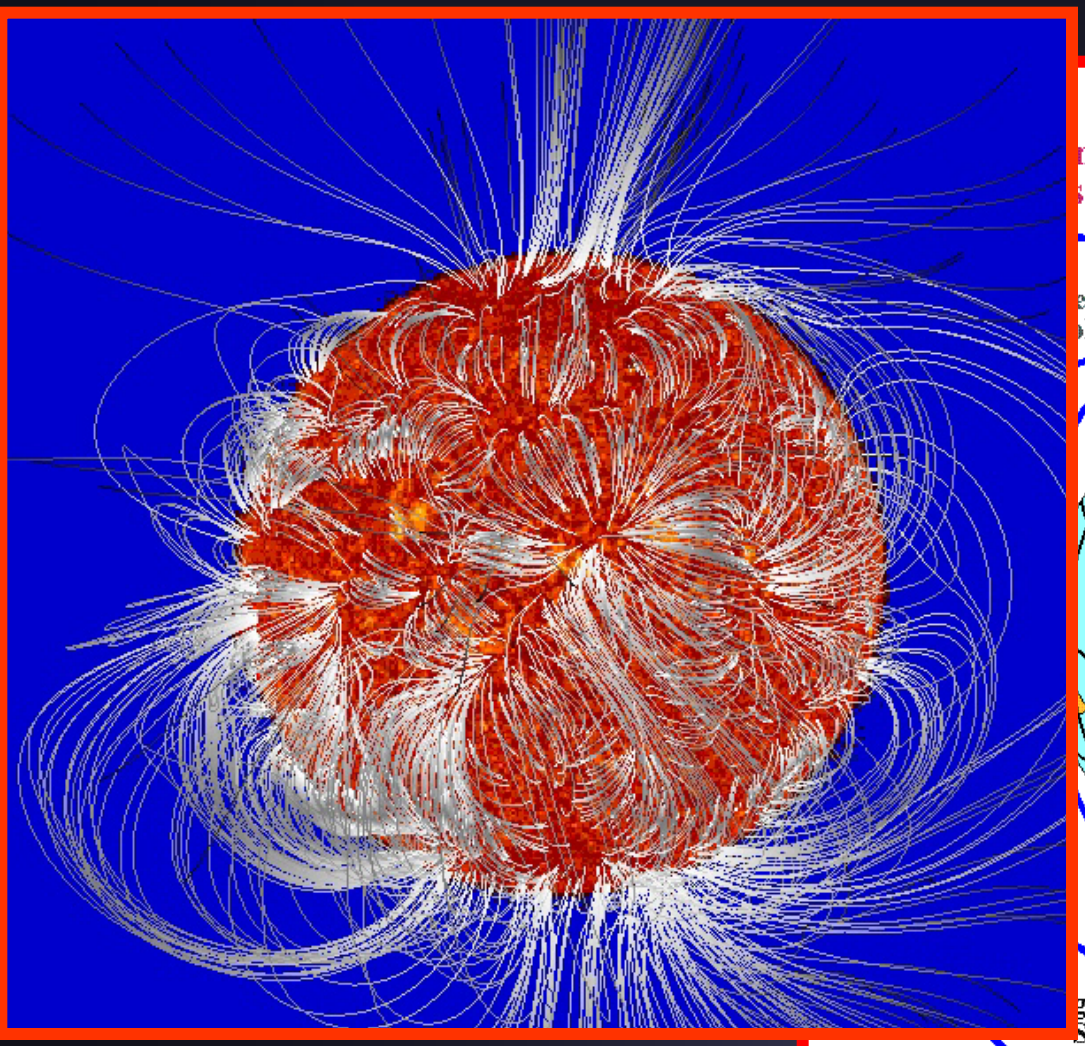


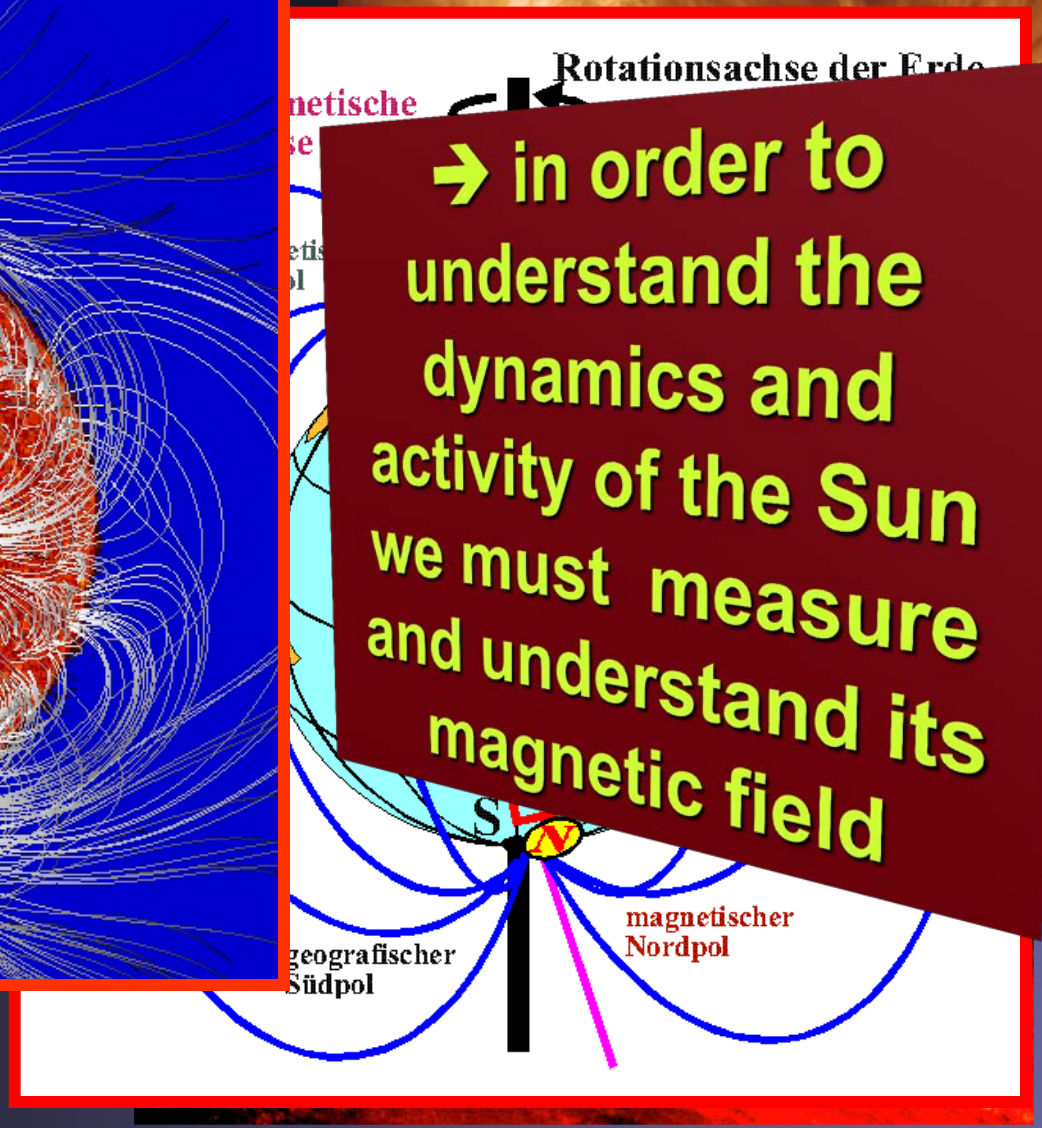


Erupting prominence (SDO)

Failed coronal mass ejection (SDO)

The source of the Sun's activity is the magnetic field





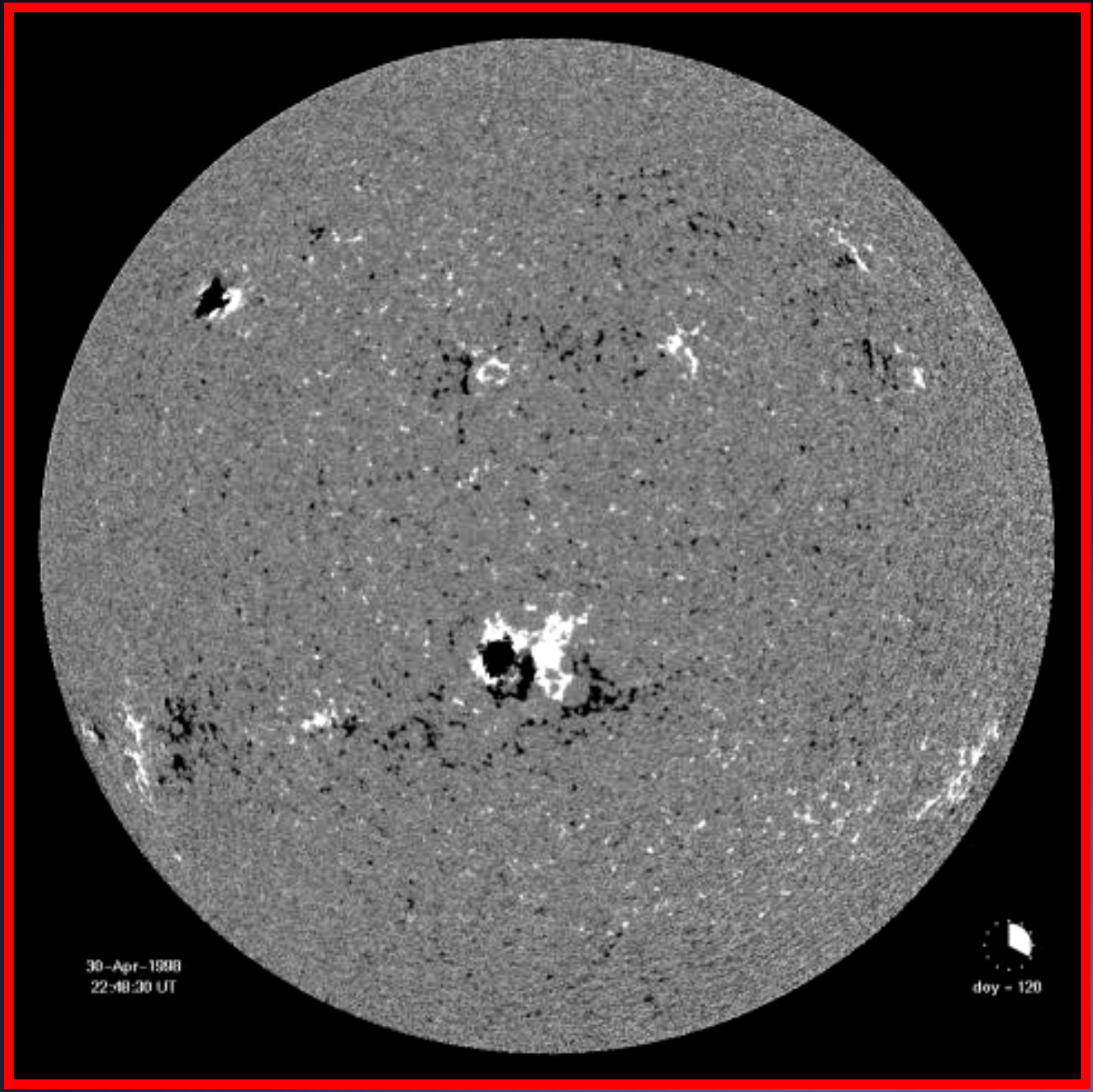
→ in order to understand the dynamics and activity of the Sun we must measure and understand its magnetic field

Thomas Wiegelmann

Measured Magnetic Field at Sun's Surface

Month long sequence of magnetograms (approx. one solar rotation)

MDI/SOHO
May 1998



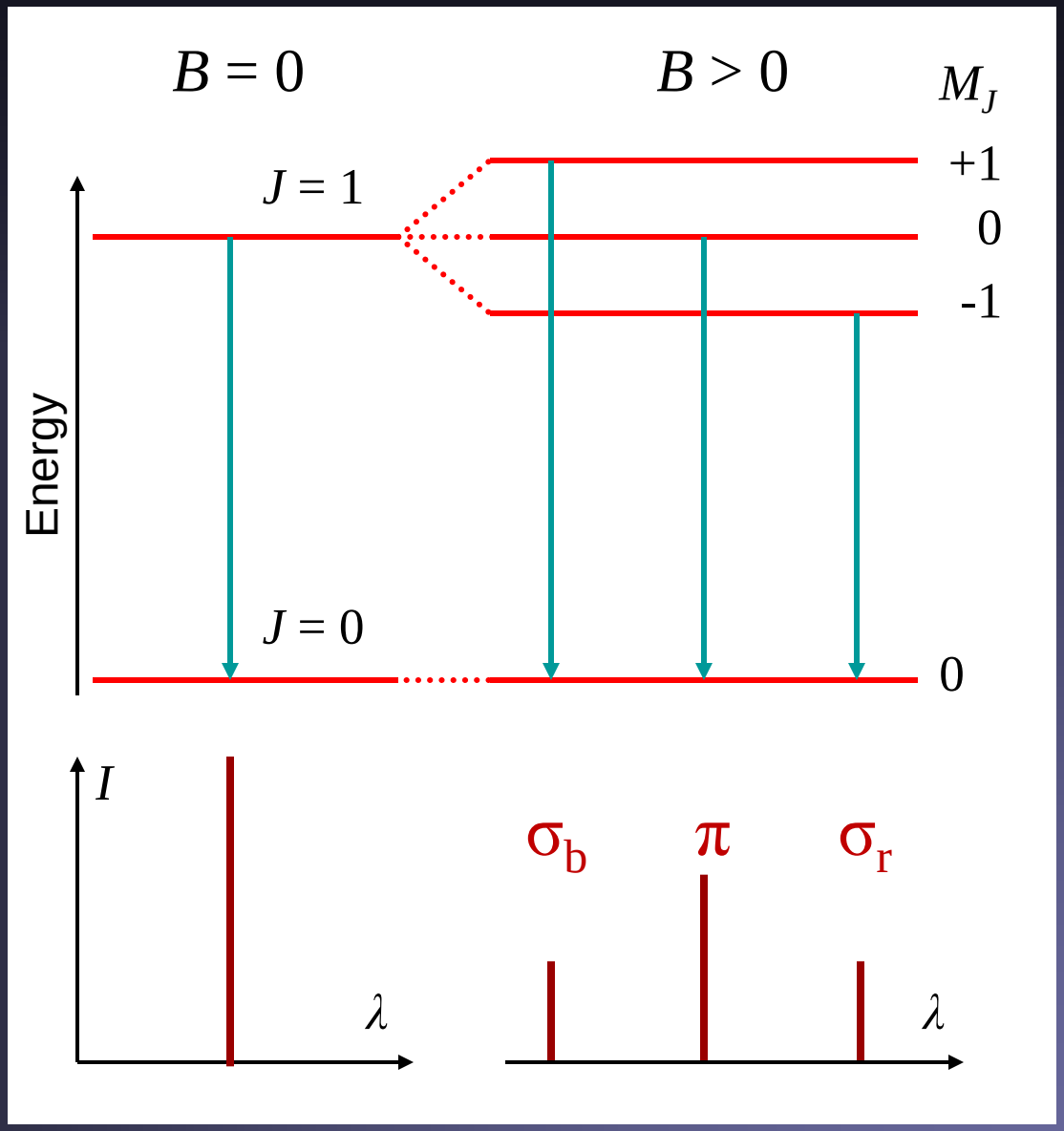
Methods of magnetic field measurement

- Direct methods:
  - Zeeman effect → polarized radiation
  - Hanle effect → polarized radiation
  - Gyroresonance → (polarized) radio spectra
- Indirect methods: Proxies
  - Bright or dark features in photosphere (sunspots, G-band bright points)
  - Ca II H and K plage
  - Fibrils seen in chromospheric lines, e.g. Hα
  - Coronal loops seen in EUV or X-radiation

Zeeman splitting of atomic levels

- In a B-field a level with total angular moment J splits into $2J+1$ sub-levels with different M.
- $E_{J,M} = E_J + \mu_0 g M_J B$
- Transitions are allowed between levels with
  $\Delta J = 0, \pm 1$ &
  $\Delta M = 0\ (\pi), \pm 1\ (\sigma_b, \sigma_r)$
- Splitting is determined by Lande factor g :

  $g(J,L,S) = 1+(J(J+1)+S(S+1)-L(L+1))/2J(J+1)$

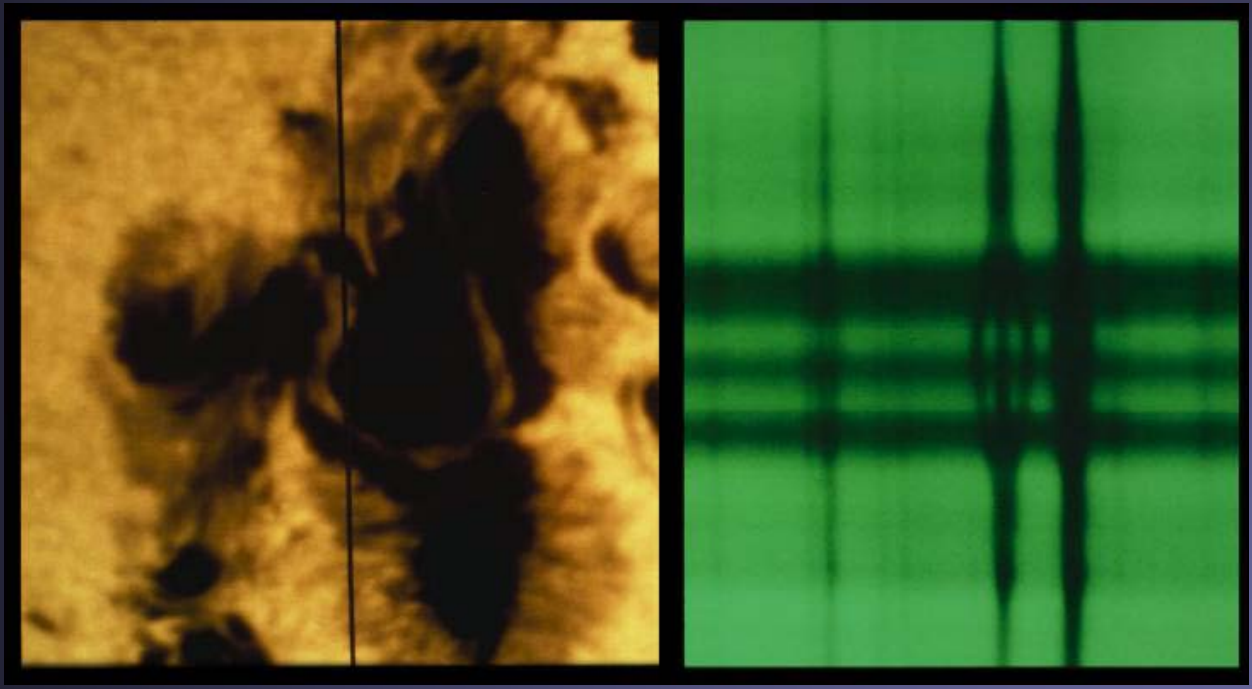


Zeeman diagnostics

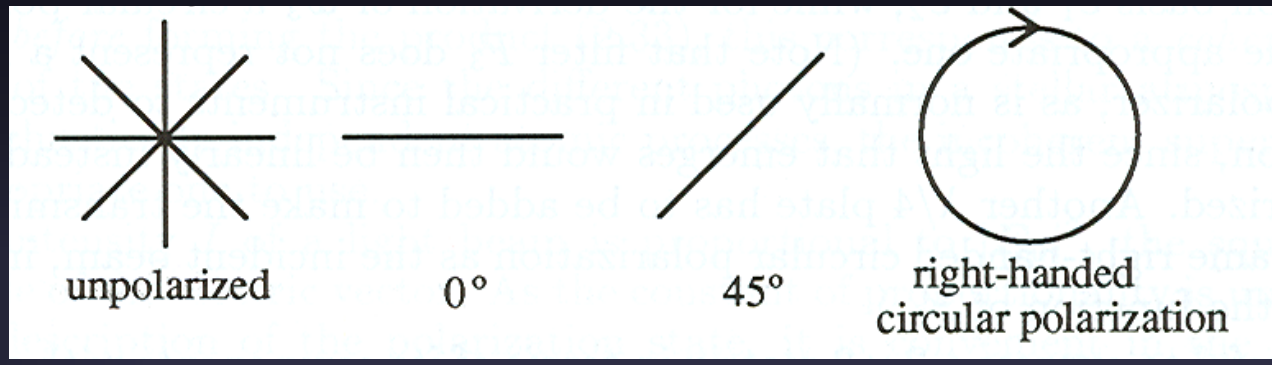
- Direct detection of magnetic field by obs. of magnetically induced splitting and polarisation of spectral lines

- On Sun: Clear Zeeman splitting best seen in sunspots. Outside spots often subtle & difficult to detect in intensity. Better to detect Zeeman effect via its unique polarisation signature

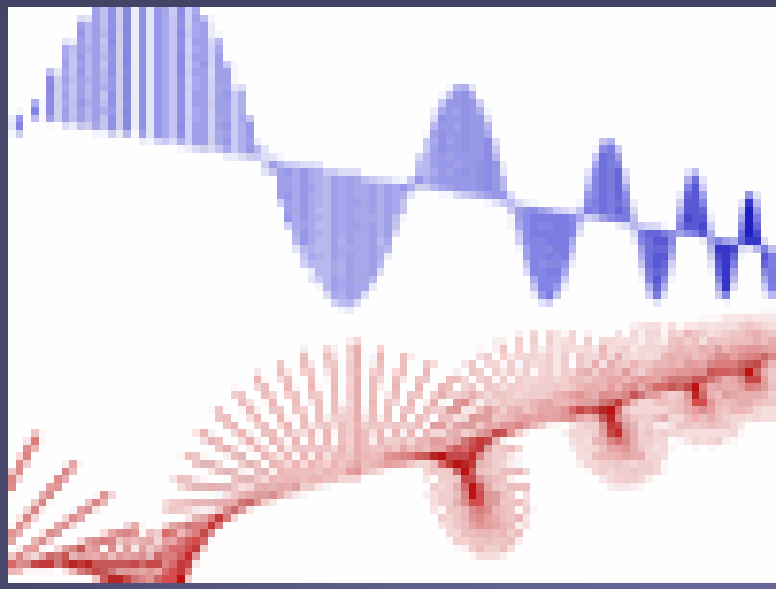
➔ Measurement of polarization is central to measuring solar magnetic fields



Polarized radiation

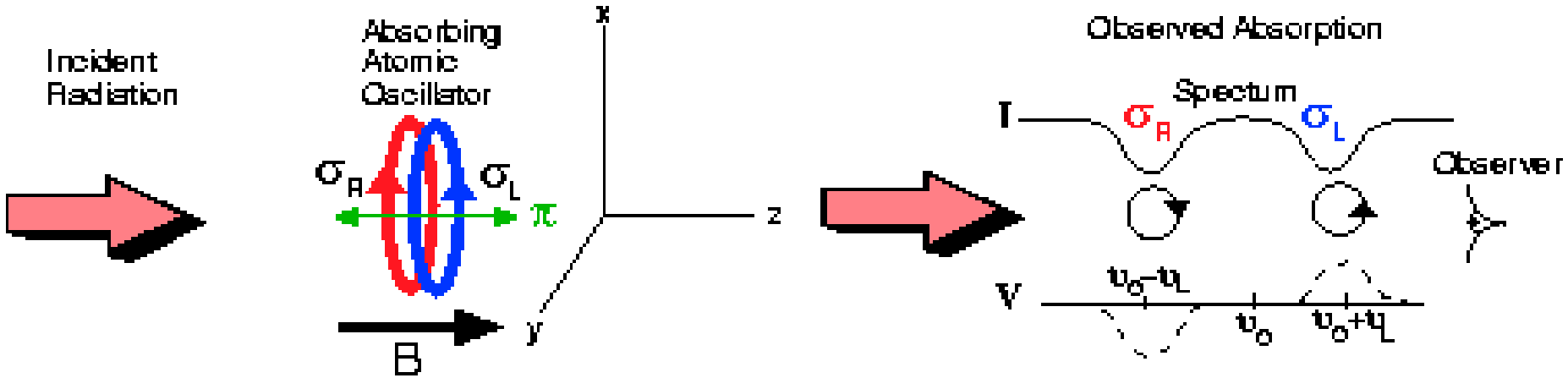


- Polarized radiation is described by the 4 Stokes parameters: I, Q, U and V
- I = total intensity = $I_{lin}(0^o) + I_{lin}(90^o) = I_{lin}(45^o) + I_{lin}(135^o) = I_{circ}(\text{right}) + I_{circ}(\text{left})$
- $Q = I_{lin}(0^o) - I_{lin}(90^o)$
- $U = I_{lin}(45^o) - I_{lin}(135^o)$
- $V = I_{circ}(\text{right}) - I_{circ}(\text{left})$
- Note: Stokes parameters are sums and differences of intensities, i.e. they are directly measurable

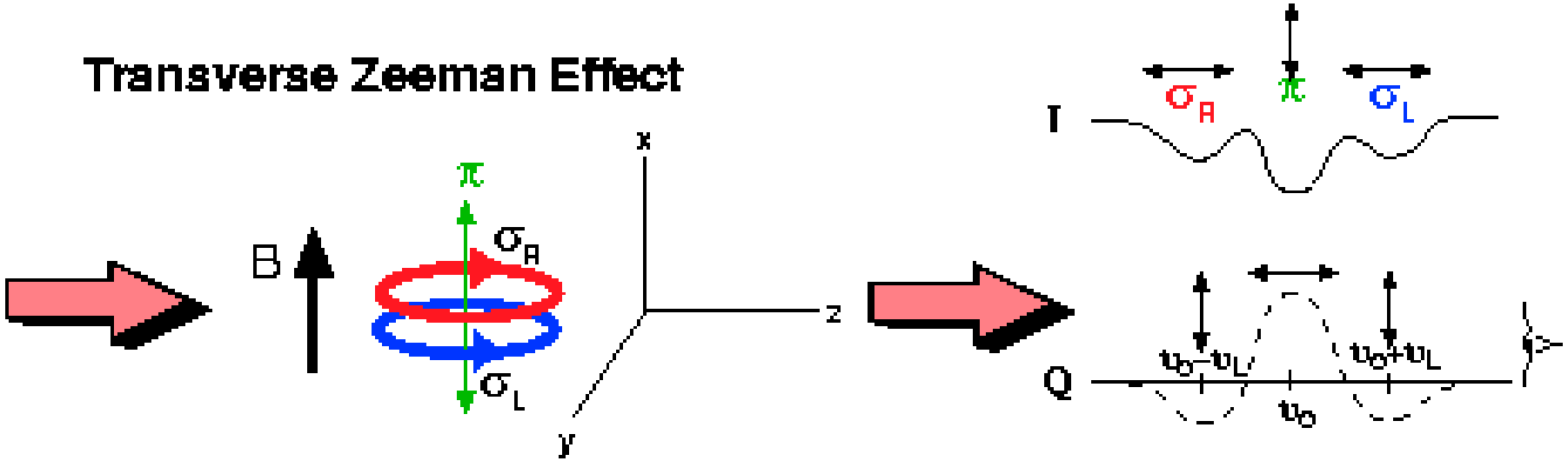


Polarization and Zeeman effect

Longitudinal Zeeman Effect

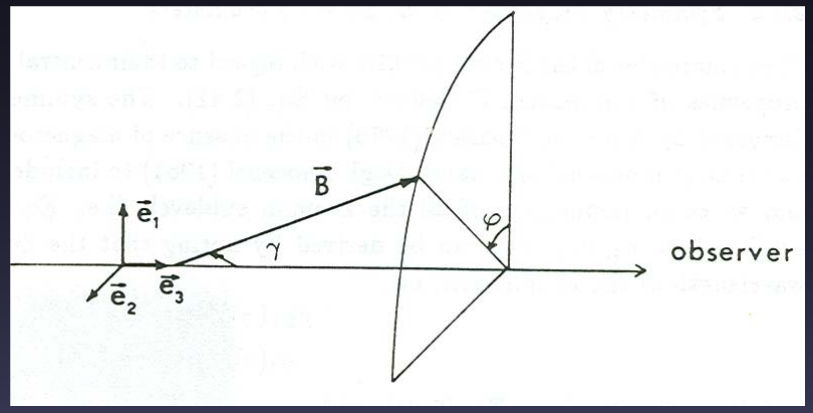


Transverse Zeeman Effect

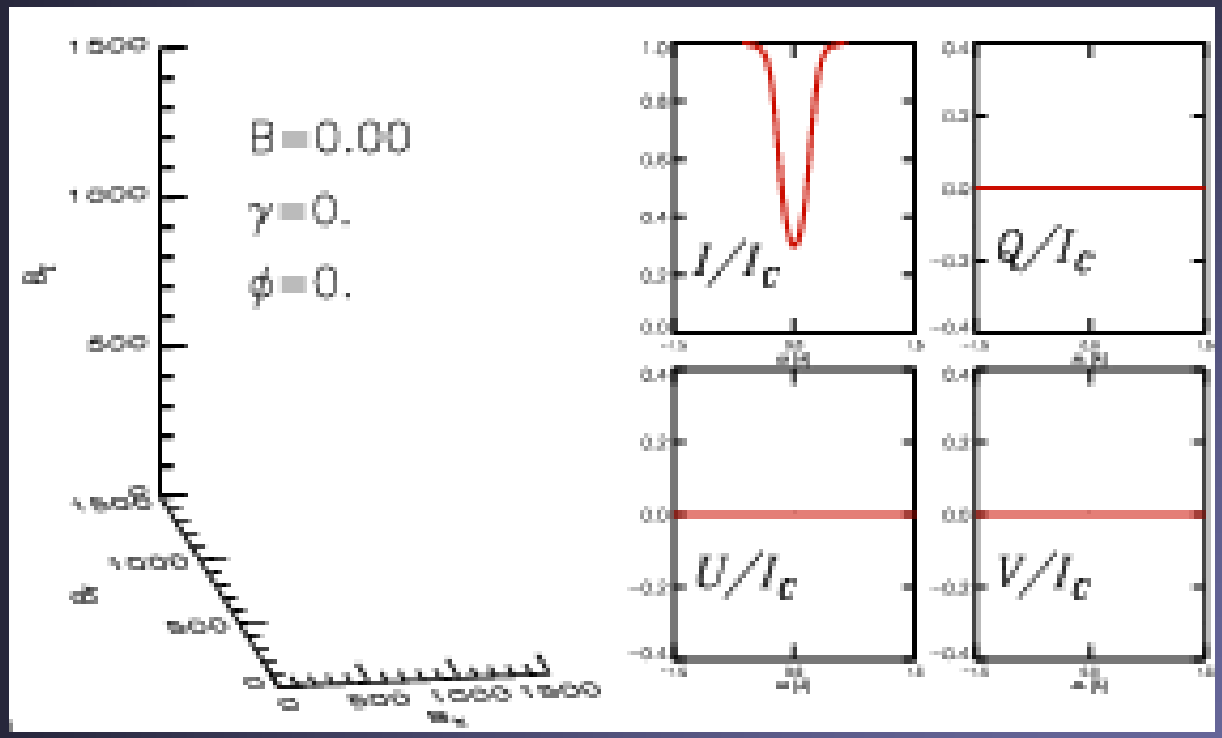


Dependence on B, γ, and φ

- $I \sim \kappa_\sigma(1+\cos^2\gamma)/4 + \kappa_\pi \sin^2\gamma/2$
- $Q \sim B^2 \sin^2\gamma \cos 2\varphi$
- $U \sim B^2 \sin^2\gamma \sin 2\varphi$
- $V \sim B \cos \gamma$



- Q, U: transverse component of B
- V: longitudinal component of B



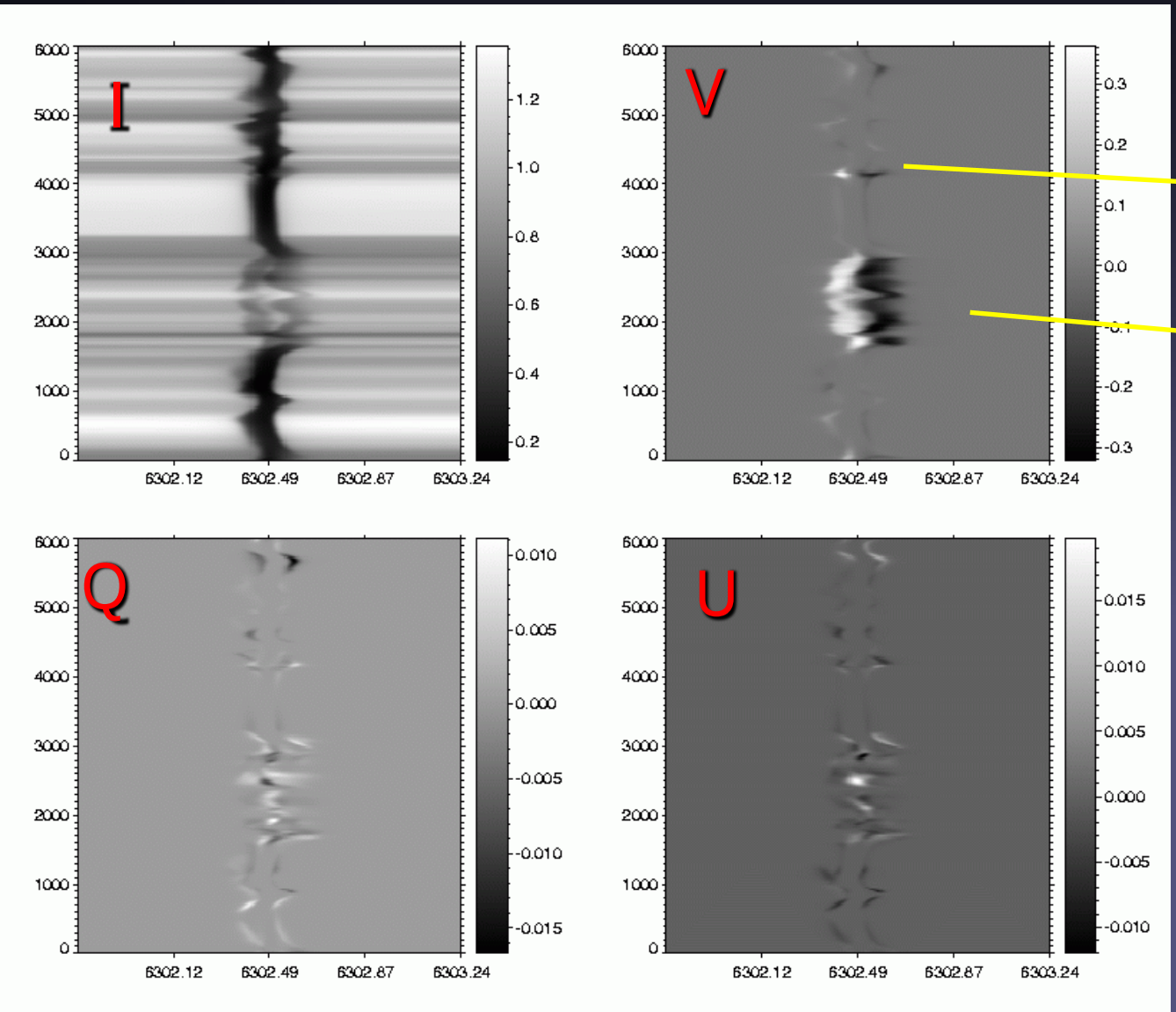
Juanma Borrero

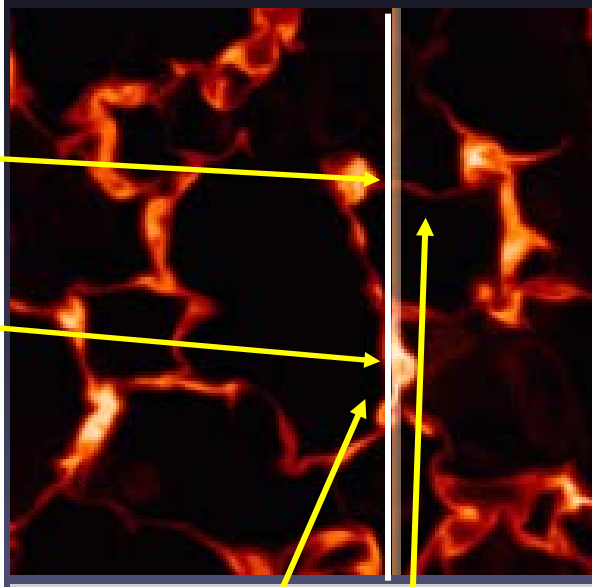
Zeeman polarimetry

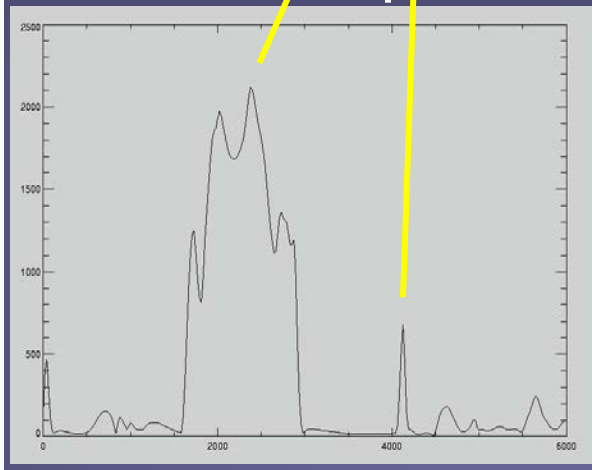
- Most widely used remote sensing technique of astrophysical (and certainly solar) magnetic fields
- Effective measurement of field strength if Zeeman splitting is comparable to Doppler width or more: $B > 200$ G … 1000 G (depending on spectral line) ➔ works best in photosphere and chromosphere
- Splitting scales with λ ➔ works best in IR and visible
- Sensitive to cancellation of opposite magnetic polarities ➔ needs high spatial resolution (even then the smallest-scale magnetic structure is often not resolved)

Zeeman splitting ~ λ^2

Fe I 630.2 nm

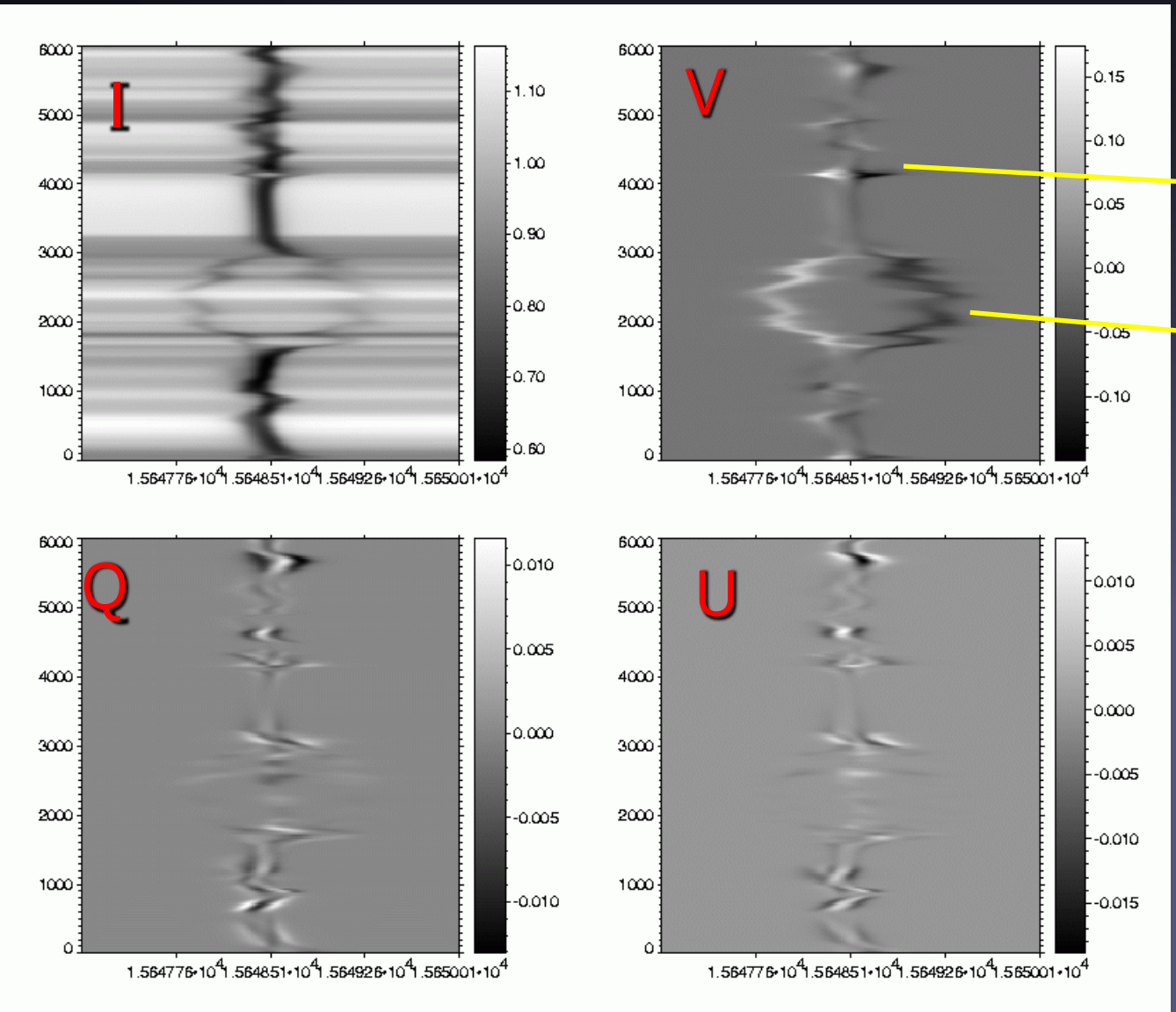


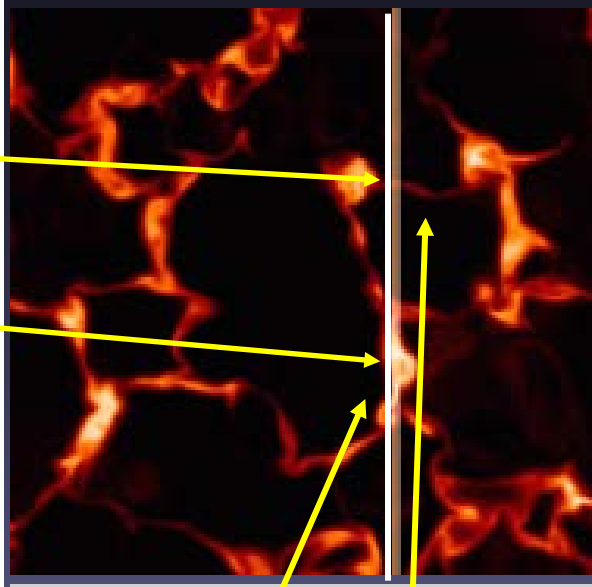


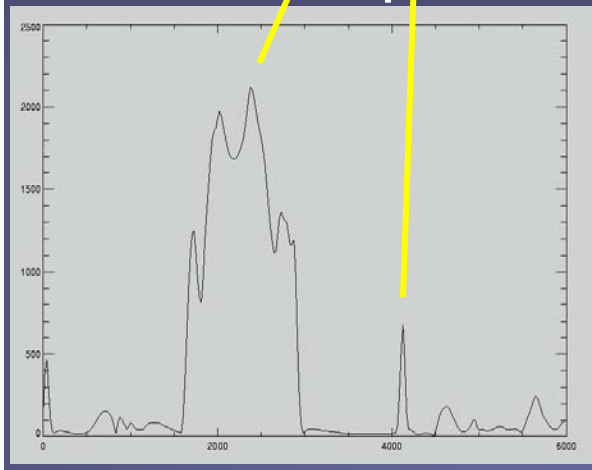


Zeeman splitting ~ λ^2

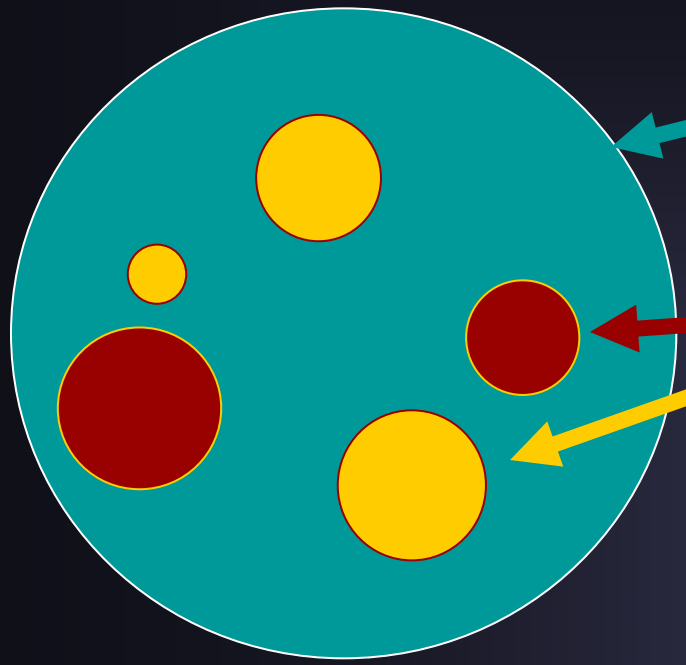
Fe I 1564.8 nm







Unresolved mixed polarity fields

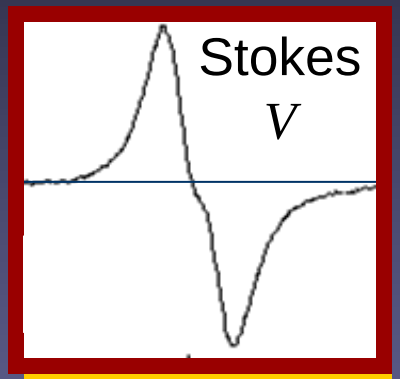


Spatial resolution element with area A_{tot}

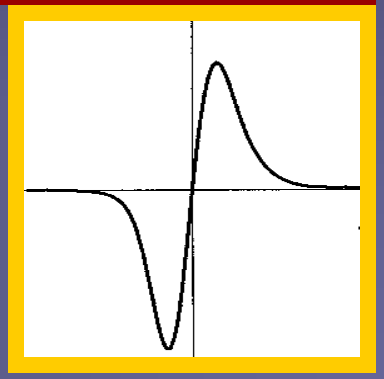
Unresolved magnetic features i with field strength B_i and filling factor

$$f = \sum_i A_i / A_{\mathrm{tot}}$$

= positive polarity magnetic field



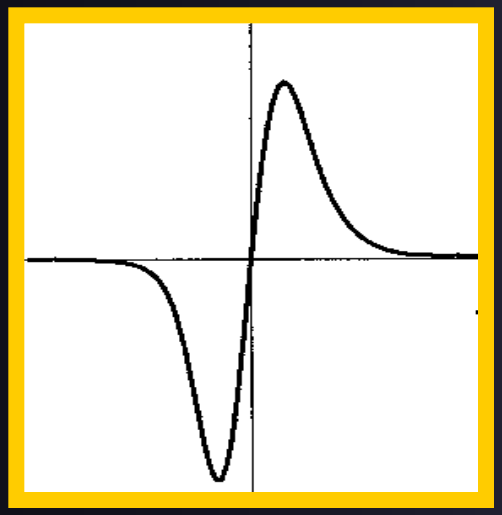
= negative polarity magnetic field



Stokes V signal cancellation

Stokes V signal only samples net magnetic flux ➔ Need high resolution observations to avoid missing part of magnetic flux:

negative polarity magnetic flux = positive polarity magnetic flux



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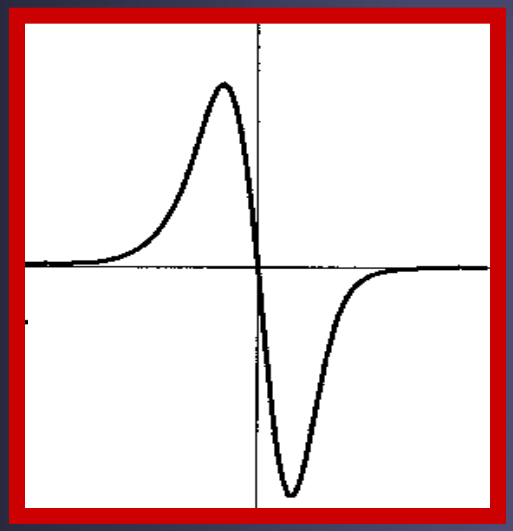

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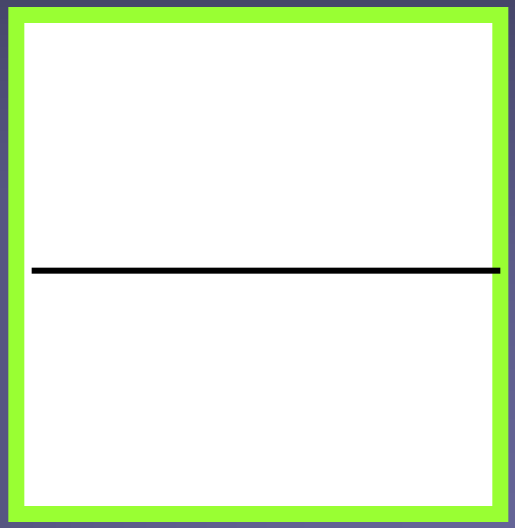
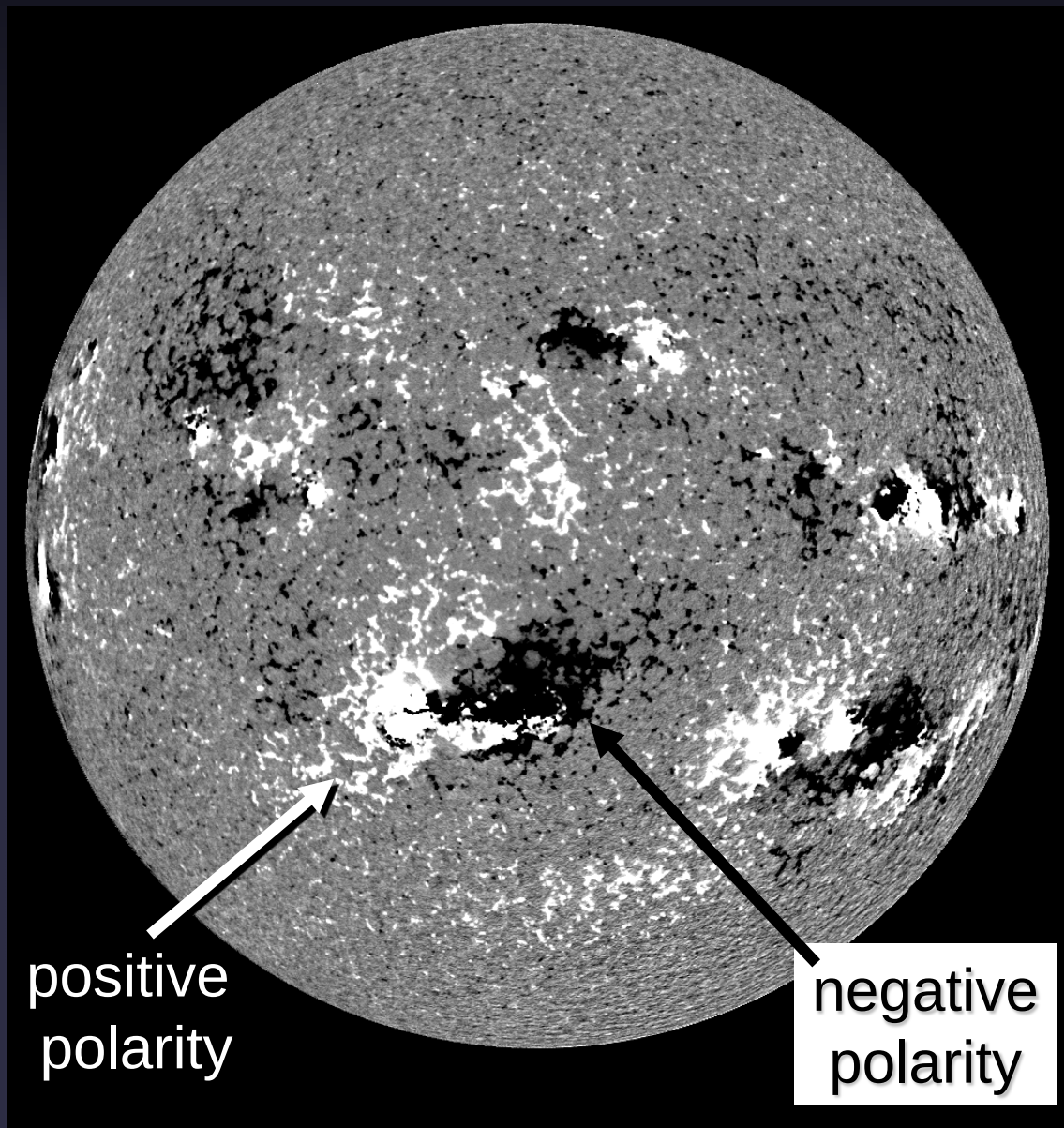
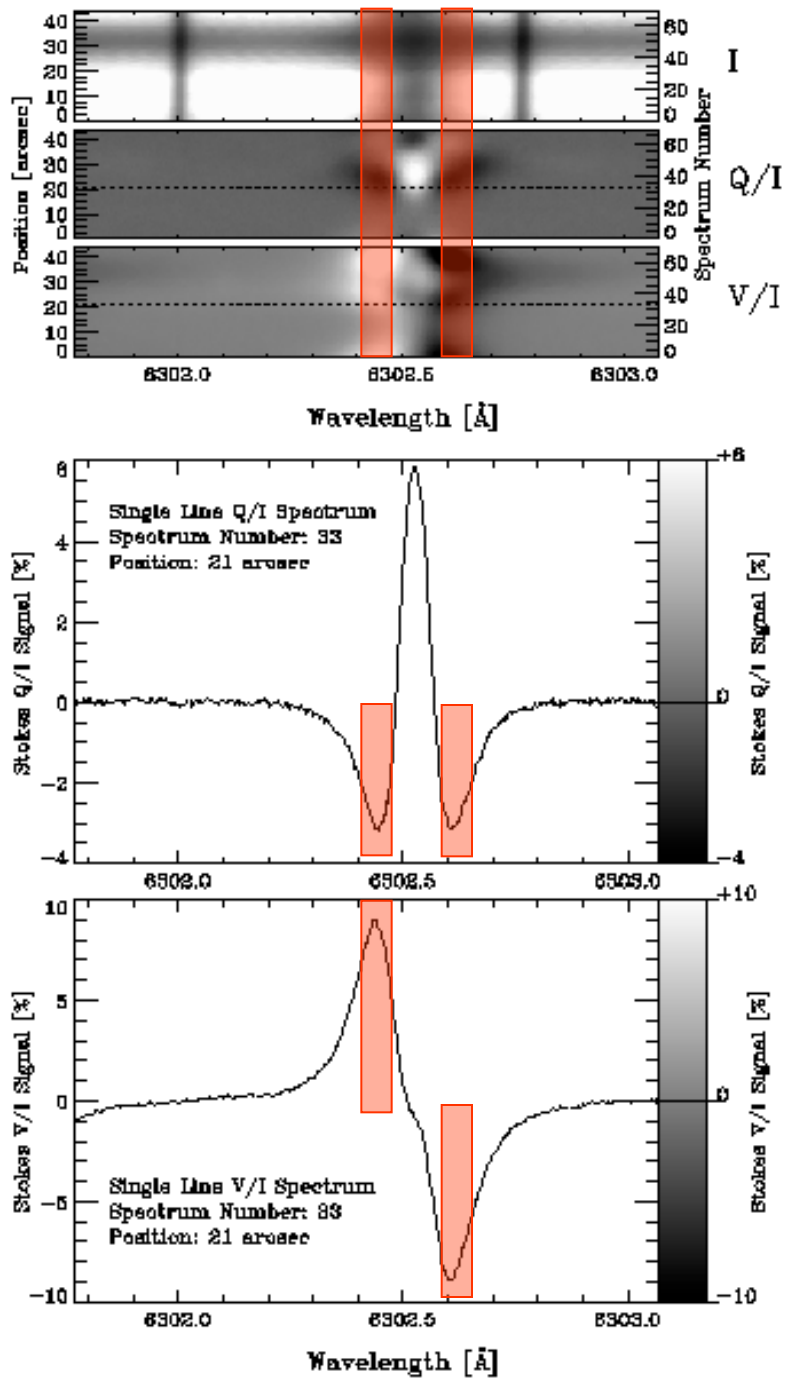


Magnetograms

- Magnetograph: Instrument to make maps of (net circular) polarization in wings of Zeeman sensitive line
- Right: Example of magnetogram obtained by MDI
- Conversion of polarization into magnetic field requires a careful calibration

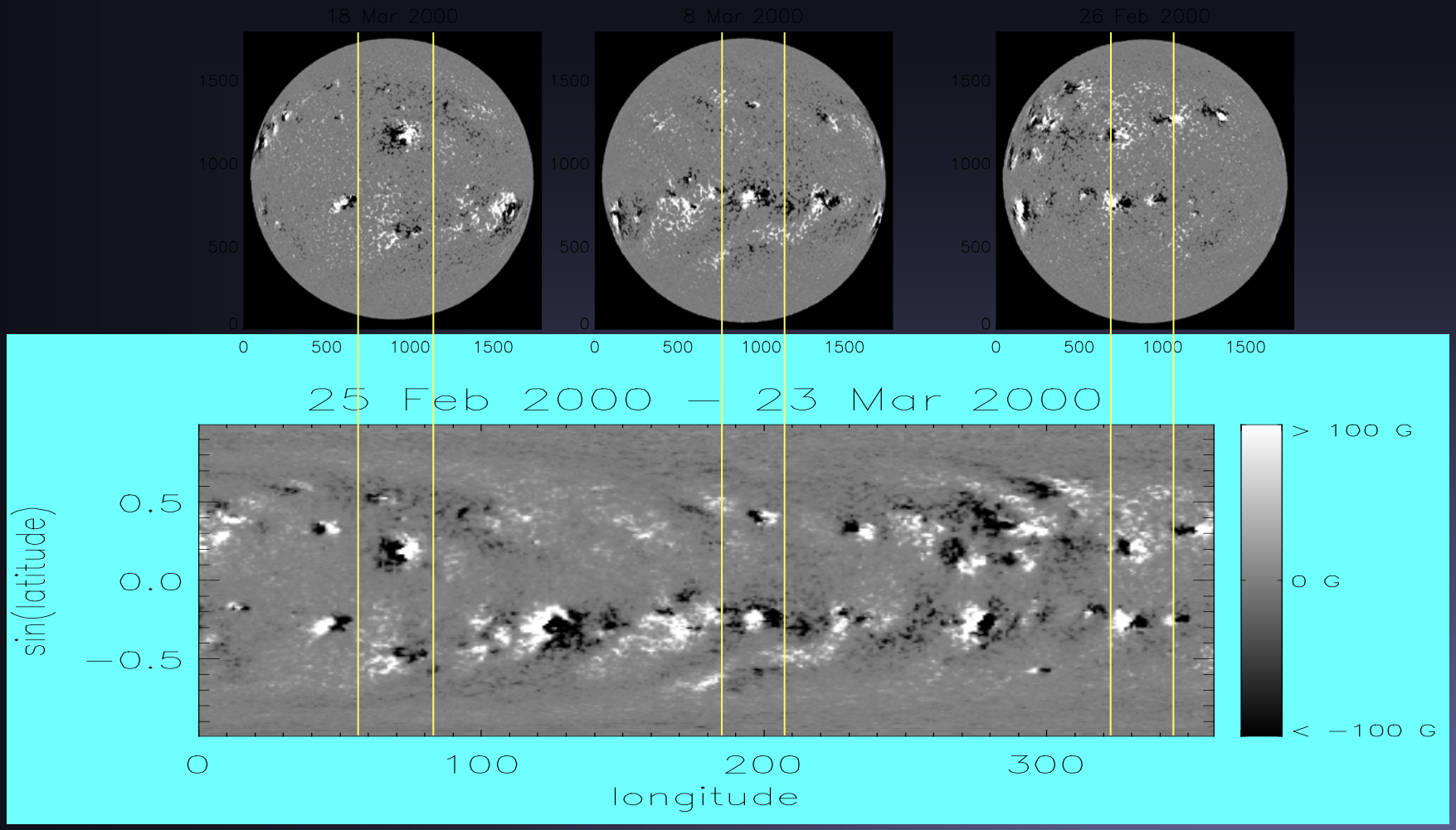




What does a magnetogram show?

- Plotted at left:
  - Top: Stokes I, Q and V along a spectrograph slit
  - Middle: Sample Stokes Q profile
  - Bottom: Sample Stokes V profile
  - Red bars: example of spectral ranges used to make a magnetogram.
  - Often only Stokes V is used (simplest to measure), gives longitudinal component of B.

Synoptic charts



Synoptic charts display radial magnetic flux observed near the central meridian over a period of 27.27 days (= 1 Carrington rotation)

Plasma β

- Plasma β describes the ratio of thermal to magnetic energy density:

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

- $\beta < 1$ ➔ Magnetic energy density dominates and field dictates the dynamics of the gas
- $\beta > 1$ ➔ Thermal energy, i.e. thermal energy density dominates over the magnetic energy density
- β is seen to be important from MHS force-balance Eq. If we neglect gravity and curvature forces, then:

$$\nabla P = \frac{1}{c} B \times (\nabla \times \mathbf{B}) - \rho g \quad \Rightarrow \quad \nabla \left(P + \frac{B^2}{8\pi} \right) = 0$$

Plasma β vs. height in solar atmosphere

Field dominates ← → Gas dominates

B-field follows solar wind flow

Gas follows magnetic field

Gas flows drag field with them

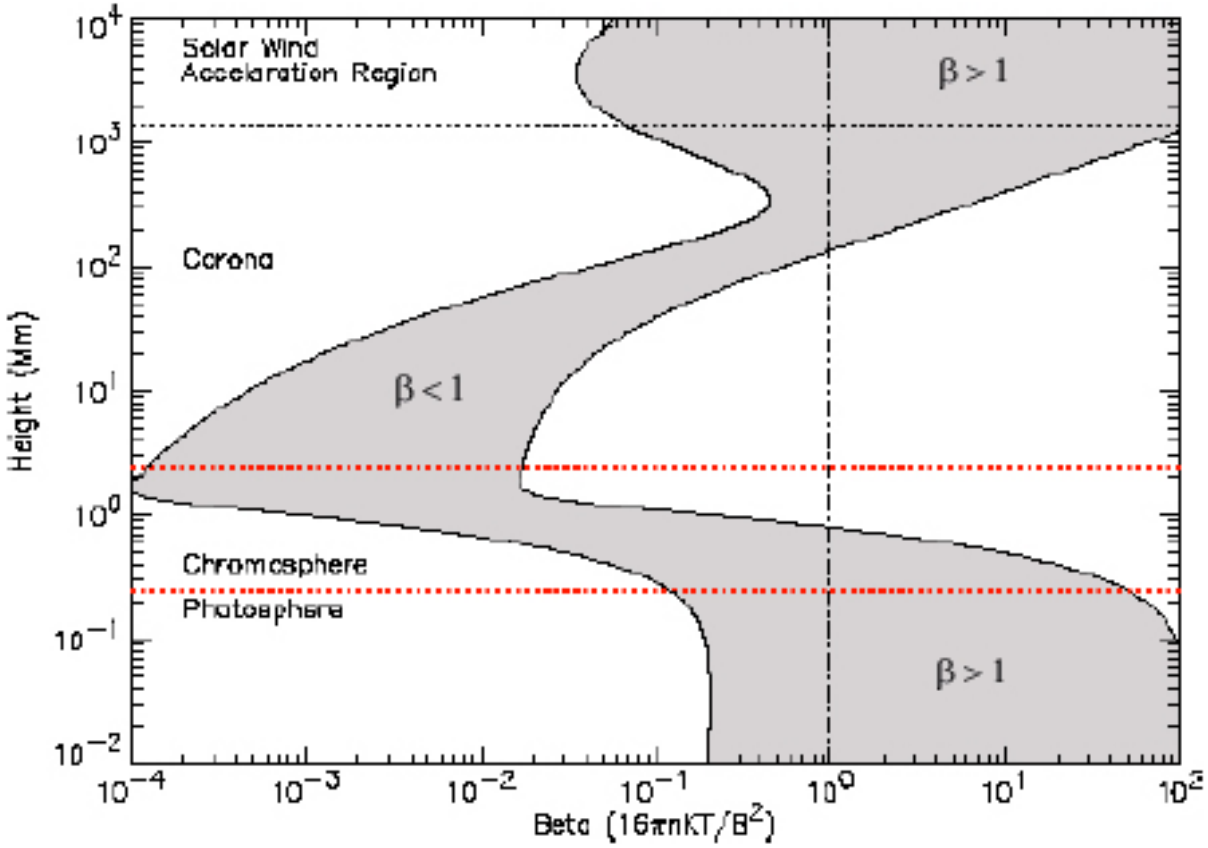


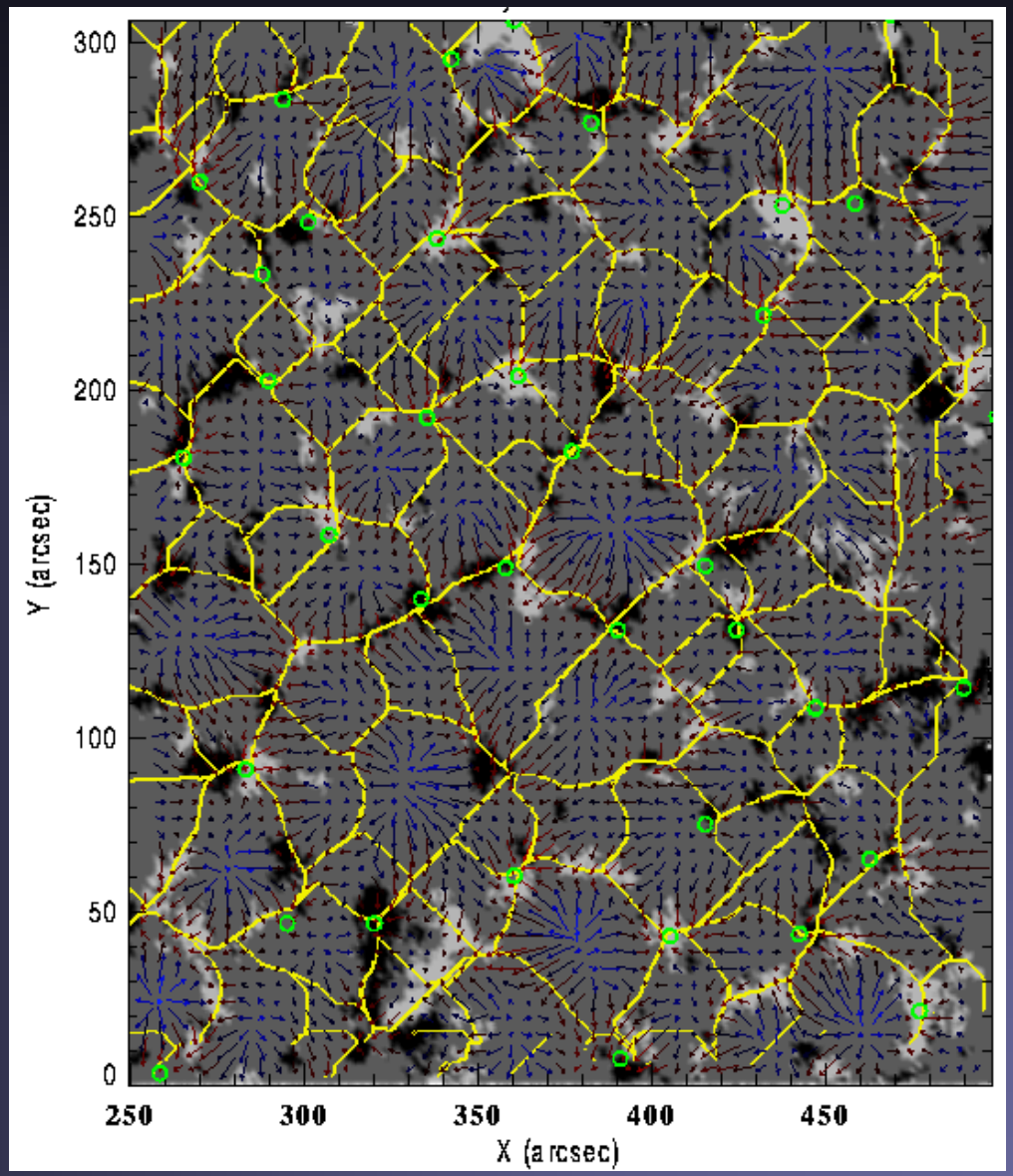
Figure 1. Ratio of gas pressure to magnetic pressure (β) as a function of height[1].

(Gary 2000)

Supergranules and magnetic field

- Magnetogram: black and white (oppos. polarities)
- Horizontal velocity: arrows
- Divergence:
  blue arrows > 0
  dark red arrows < 0
- Supergranule boundaries: yellow
- Magnetic field gathers at edges of supergranules

➔ B swept out by flow of supergranules ($\beta > 1$)



Frozen-in magnetic fields

- Magnetic field is swept to supergranule boundaries ➔ magnetic field is “frozen” into the plasma
- This happens if there are a sufficient number of ionised particles, or equivalently, if the electric conductivity is very high, since charged particles cannot cross field lines (gyration)
- Valid even in photosphere of sunspots (only 10^{-4} of all particles are ionized), due to collisions (very common)

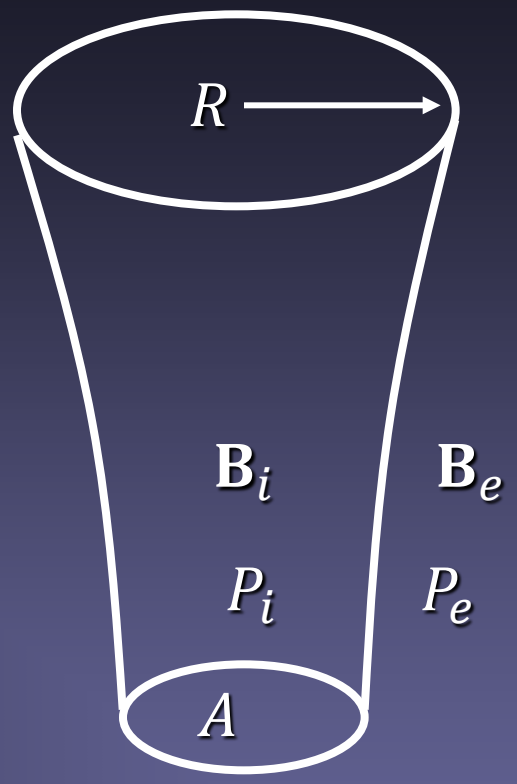
➔ If plasma moves perpendicularly to B-field,

  - $\beta > 1$: it drags the field with it
  - $\beta < 1$: it is stopped by the field

- Flows parallel to the field are unaffected

Magnetic flux tubes

- In convection zone and in photosphere most of magnetic energy is in concentrated magnetic flux tubes: bundles of magnetic field (bounded by topologically simple surface)
- The flux tube has a current sheet at its boundary
- Consider a thin flux tube ($R<H_P$) that is homogeneous inside (no variation of $\mathbf{B}$ and P across cross-section)



Rump of a flux tube

Simplified force balance: pressure balance

- MHS force balance: $\nabla P = \frac{1}{c}\mathbf{j} \times \mathbf{B} - \rho g$ $\left\{ \begin{array}{l} \text{Lorentz force} \\ \text{Gravity} \end{array} \right.$
- Consider a static, vertical, thin magnetic flux tube, FT (typical in lower solar atmosphere):
  - Interior of FT: field $\mathbf{B}_i$, pressure p_i, density ρ_i
  - Exterior of FT: field $\mathbf{B}_e$, pressure p_e, density ρ_e

→ Vertical force balance is independent in the individual components

  - For a vertical field (for each comp): $\nabla p - \rho g = 0$

- Horizontal force balance between the components is then reduced to pressure balance

Pressure balance

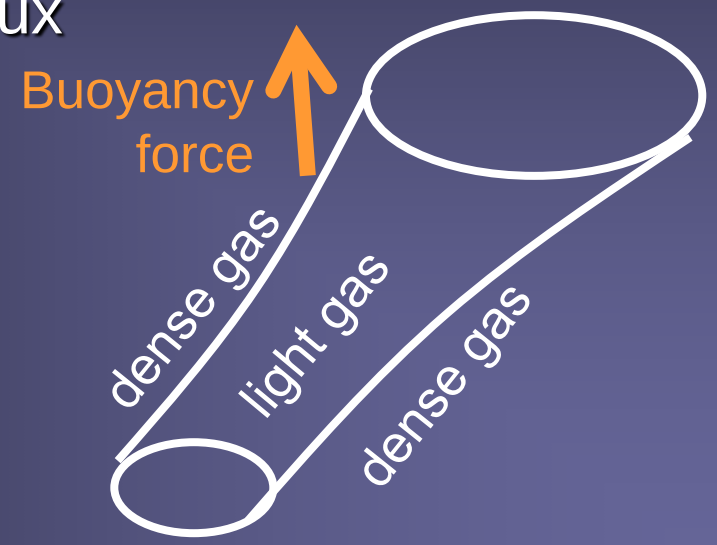
- Pressure balance betw. thin flux tube interior i and exterior e

$$\frac{B_i^2}{8\pi} + P_i = P_e + \frac{B_e^2}{8\pi} \qquad \Rightarrow \qquad \frac{B_i^2}{8\pi} + P_i = P_e \qquad \text{for } B_e = 0$$

- If $B_e = 0$, then $P_i < P_e$. If also $T_i = T_e$, then also $\rho_i < \rho_e$
  - ➔ Magnetic features are evacuated compared to surroundings
  - ➔ Magnetic features are buoyant compared to the surrounding gas

➔ in convection zone: rising magnetic flux tubes keep rising (unless stopped by, e.g. magnetic curvature force) ➔ field cannot be stably stored in convection zone

➔ In atmosphere: strong fields are close to vertical (buoyancy $\sim B^2$)



Pressure balance

- Pressure balance betw. thin flux tube interior i and exterior e

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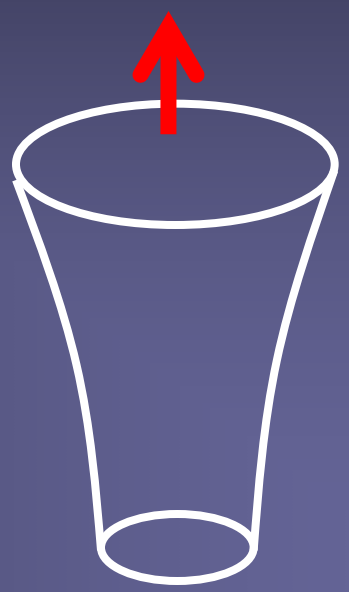


Sunspot structure & dynamics

Umbra

Penumbra

Granule

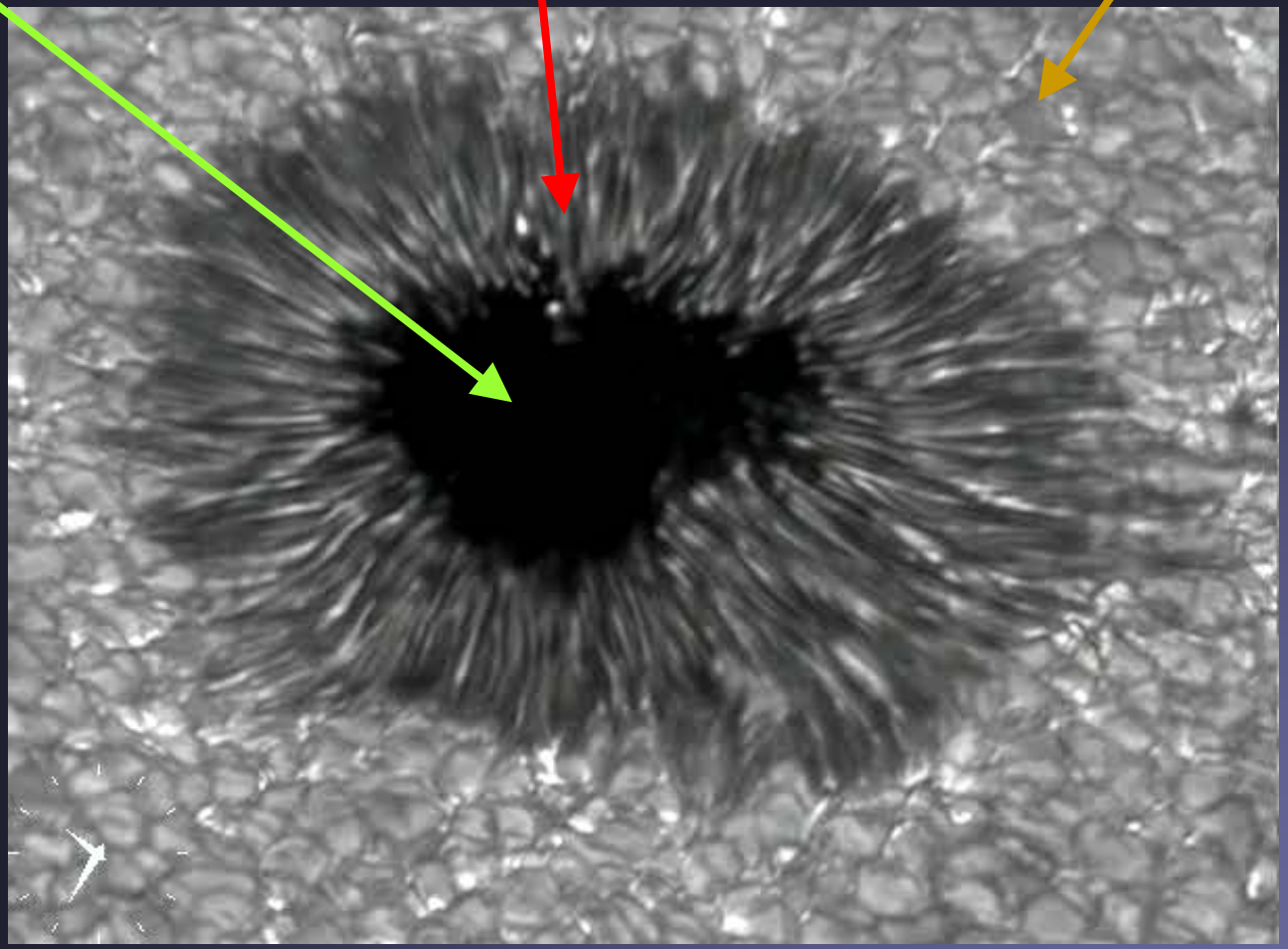
$T_{\mathrm{eff}} \approx 5800$ K

$T_{\mathrm{eff}} \approx 5500$ K

$I_{\mathrm{pen}} = 0.75 I_{\odot}$

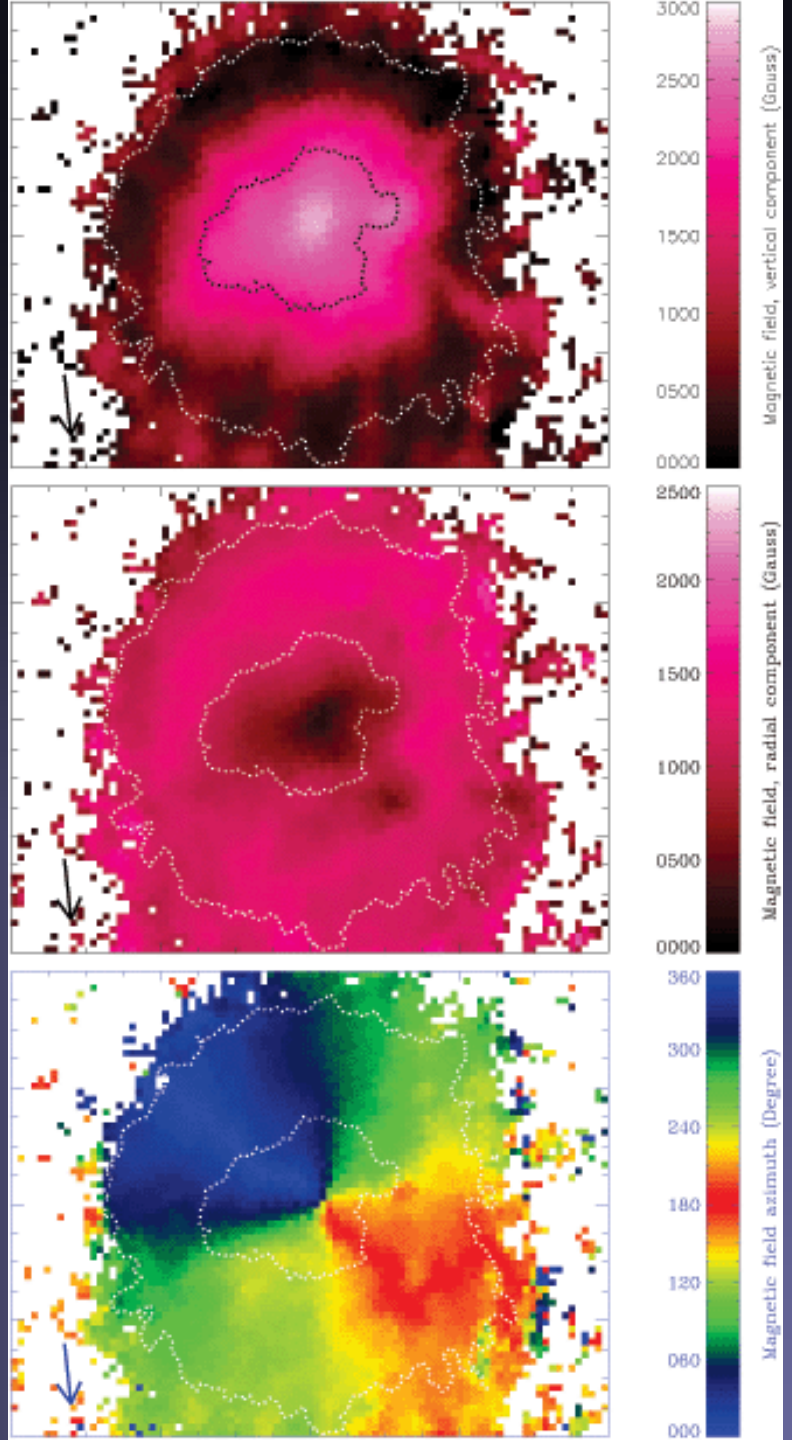
$T_{\mathrm{eff}} \approx 4500$ K

$I_{\mathrm{umb}} = 0.20 I_{\odot}$



Magnetic structure of sunspots

- Peak $B \approx 2000 - 3500$ G (usually in darkest, central part of umbra)
- B drops steadily towards boundary, $B(R_{\mathrm{spot}}) \approx 1000$ G
- At spot centre, field is vertical, but is almost horizontal near R_{spot} .
- Regular spots have a field structure similar to a buried dipole
- These observations miss a lot of the fine-structure inherent in spots

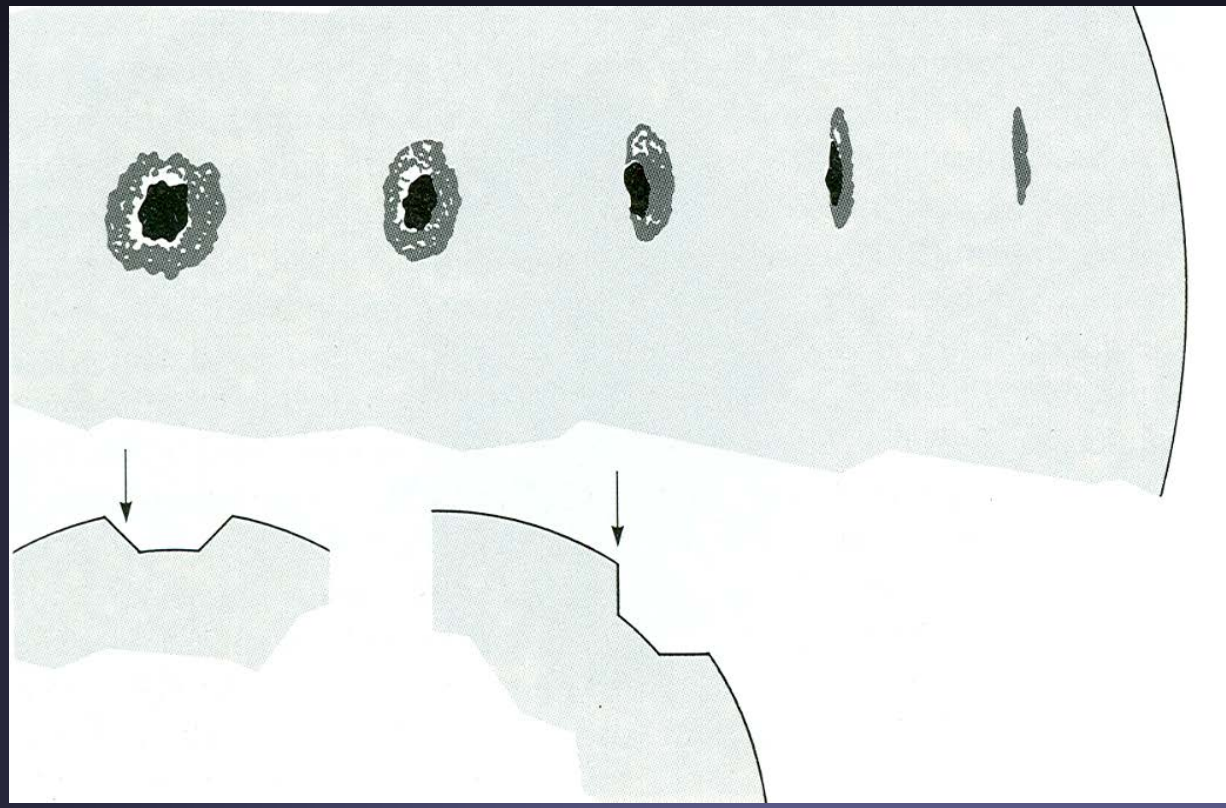


The Wilson effect

- Near the solar limb the umbra and centre-side penumbra disappear

➔ We see 400-800 km deeper into sunspots than in photosphere

- 1st observed and correctly interpreted by Alexander Wilson (1769)



Extension of this interpretation supported by W. Herschel: photosphere is layer of hot clouds. In spots we see deeper, cool layers, to true (populated) surface of Sun

Why do we see deeper inside sunspots, or what causes the Wilson effect?

- Darkness: Opacity in the solar photosphere is due to the H^- ion, which depends strongly on temperature. In sunspots temperature is lower ➔ opacity is lower ➔ we see deeper. Responsible for ≈½ of observed effect

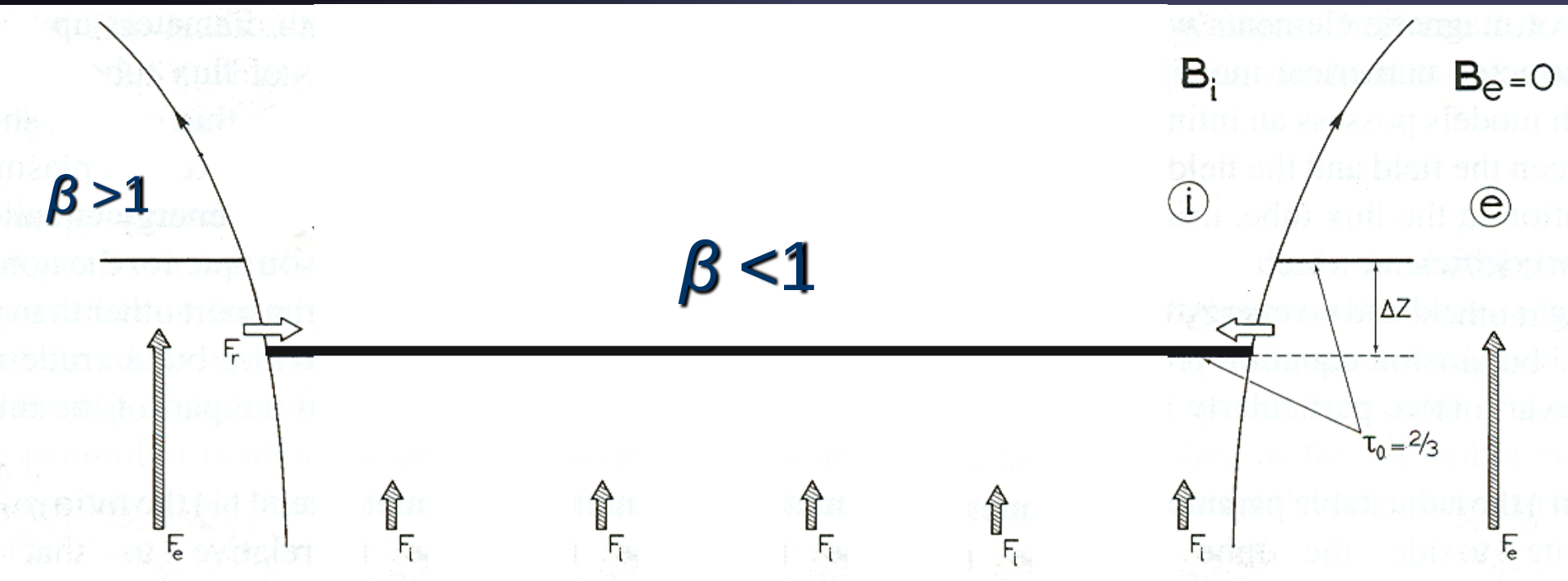
- Magnetic field: B of 2-3 kG produces a large pressure $\sim B^2/8\pi$. Due to pressure balance with surroundings:

$$\frac{B_{\mathrm{spot}}^2}{8\pi} + P_{\mathrm{spot}} = P_{\mathrm{e}} \quad \rightarrow \quad P_{\mathrm{spot}} \ll P_e \quad \rightarrow \quad \rho_{\mathrm{spot}} \ll \rho_{\mathrm{e}}$$

Opacity in spot is decreased. Responsible for remaining ½ of observed effect

Why are sunspots dark?

- Strong nearly vertical magnetic field in umbra leads to plasma $\beta < 1$ ➔ suppresses motions across field lines ➔ quenches most convection inside the spot's umbra
- Since convection is the main source of energy transport just below solar surface, less energy reaches the surface through the spot ➔ dark



Why are sunspots dark? II

- Where does the energy blocked by sunspots go? Spruit (1982)

➔Short diffusive timescale of convection zone (CZ): blocked heat is redistributed in CZ within 1 month – 1 year (i.e. thermal conduction is very effective). Observations confirm lack of significant bright rings around sunspots. Very little of blocked heat is re-radiated immediately.

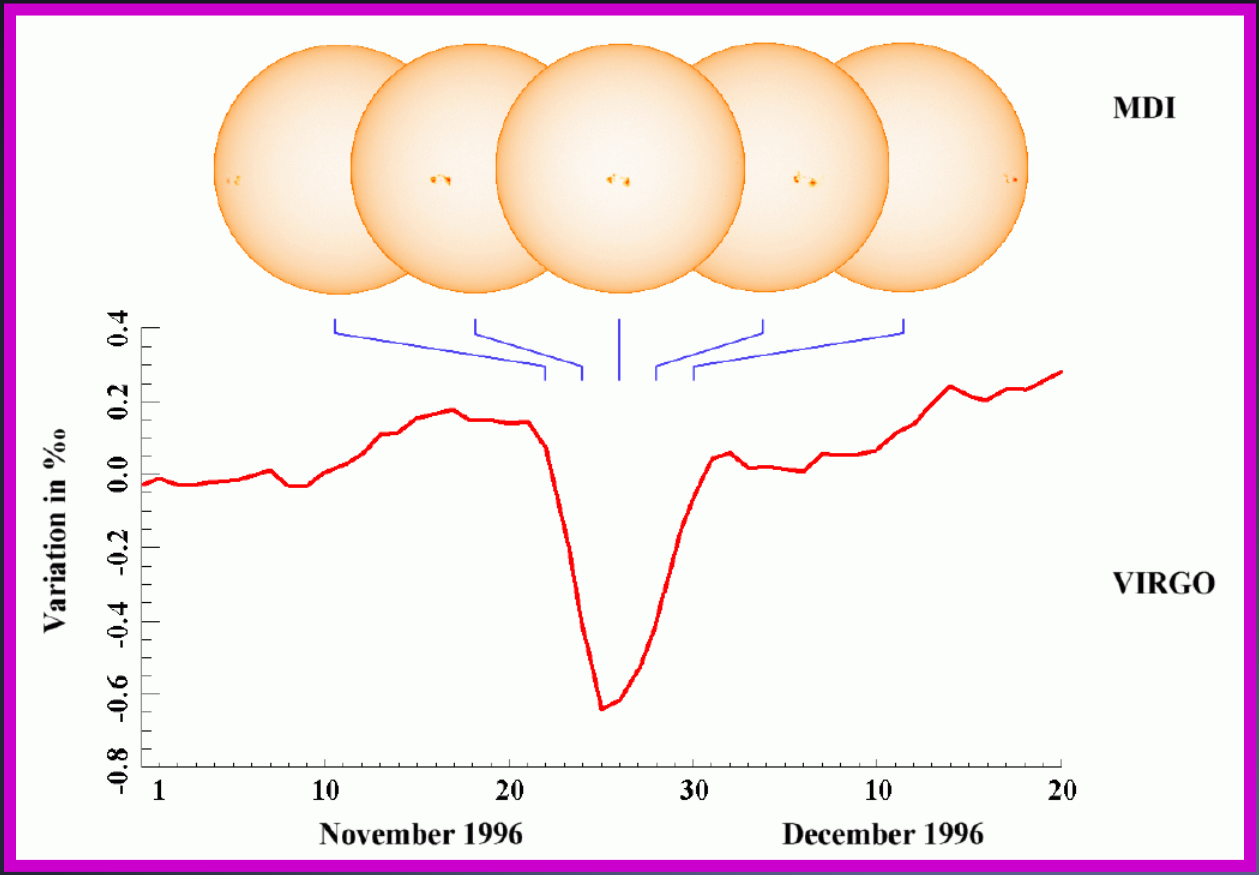
Large heat capacity of CZ: the additional heat does not lead to a measurable increase in temperature

- Long time scale for thermal relaxation of the CZ (Kelvin-Helmholtz timescale): 10^5 years ➔ excess energy is released almost imperceptibly (KH timescale: how long can Sun shine using only its gravitational energy)

Solar brightness and sunspots

- The Sun as a whole darkens when spots move across its disc
- I.e. the blocked heat does not reappear some-where else during spot lifetime

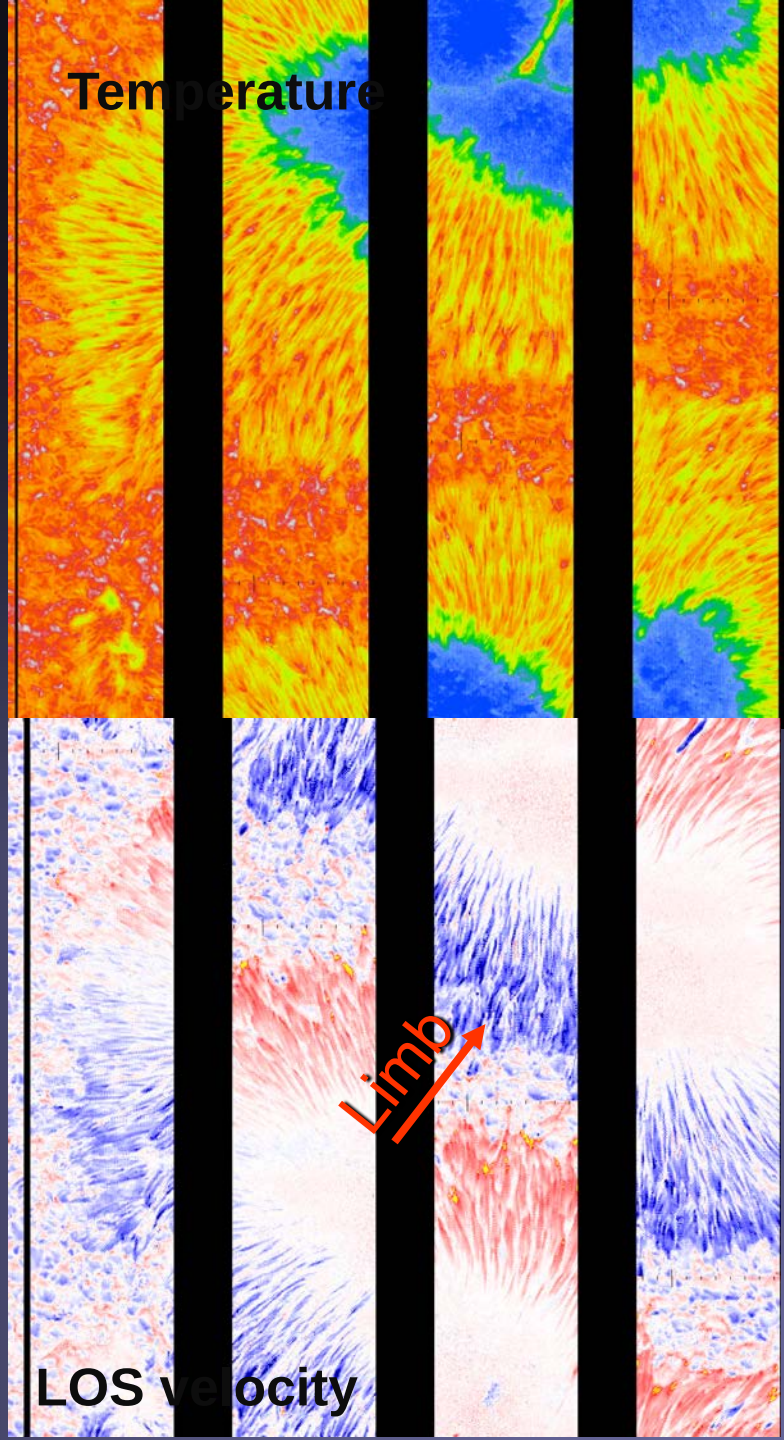
➔ no strong bright rings around spots



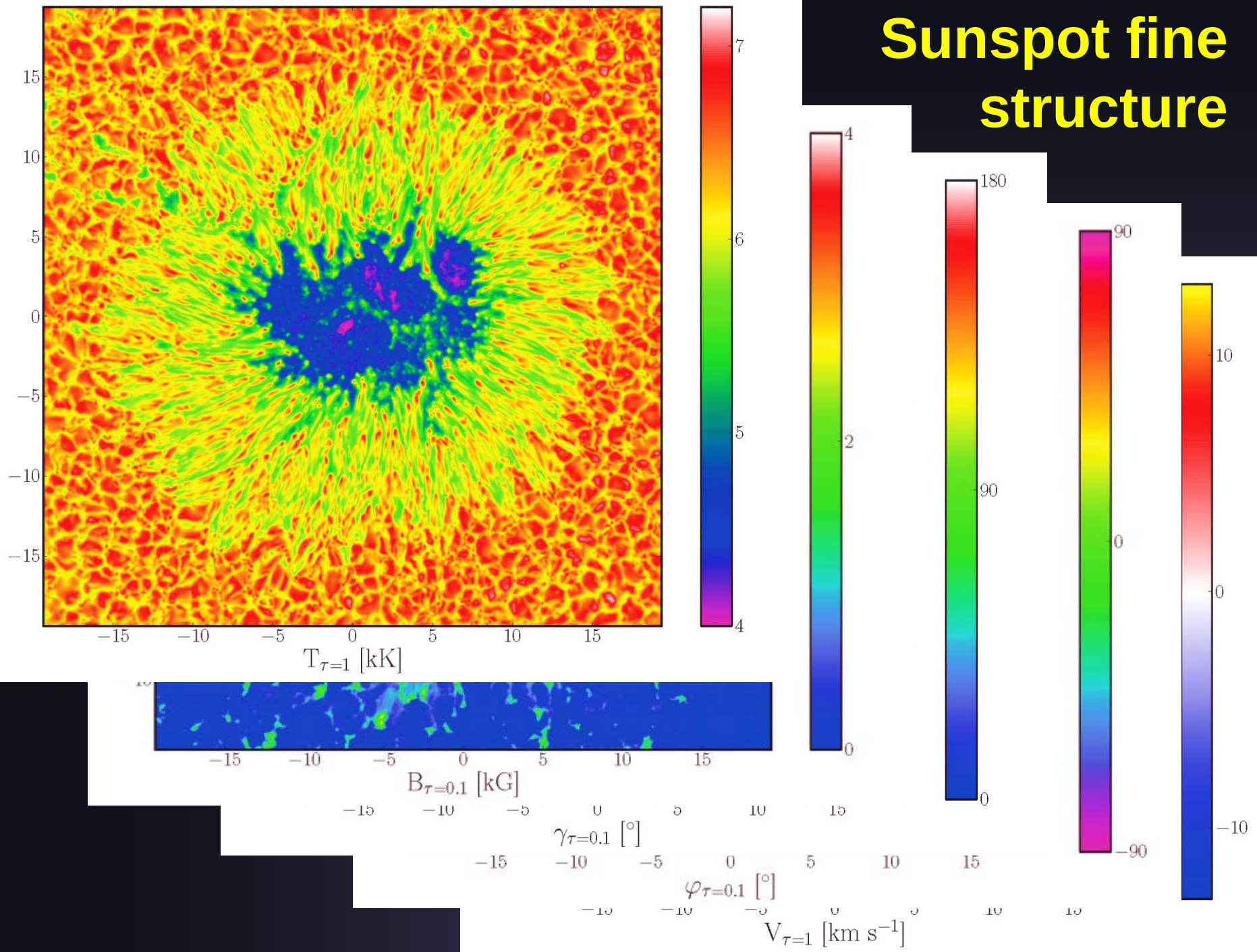
➔ Theory is correct: blocked heat is indeed stored in convection zone to be released later on

Evershed effect

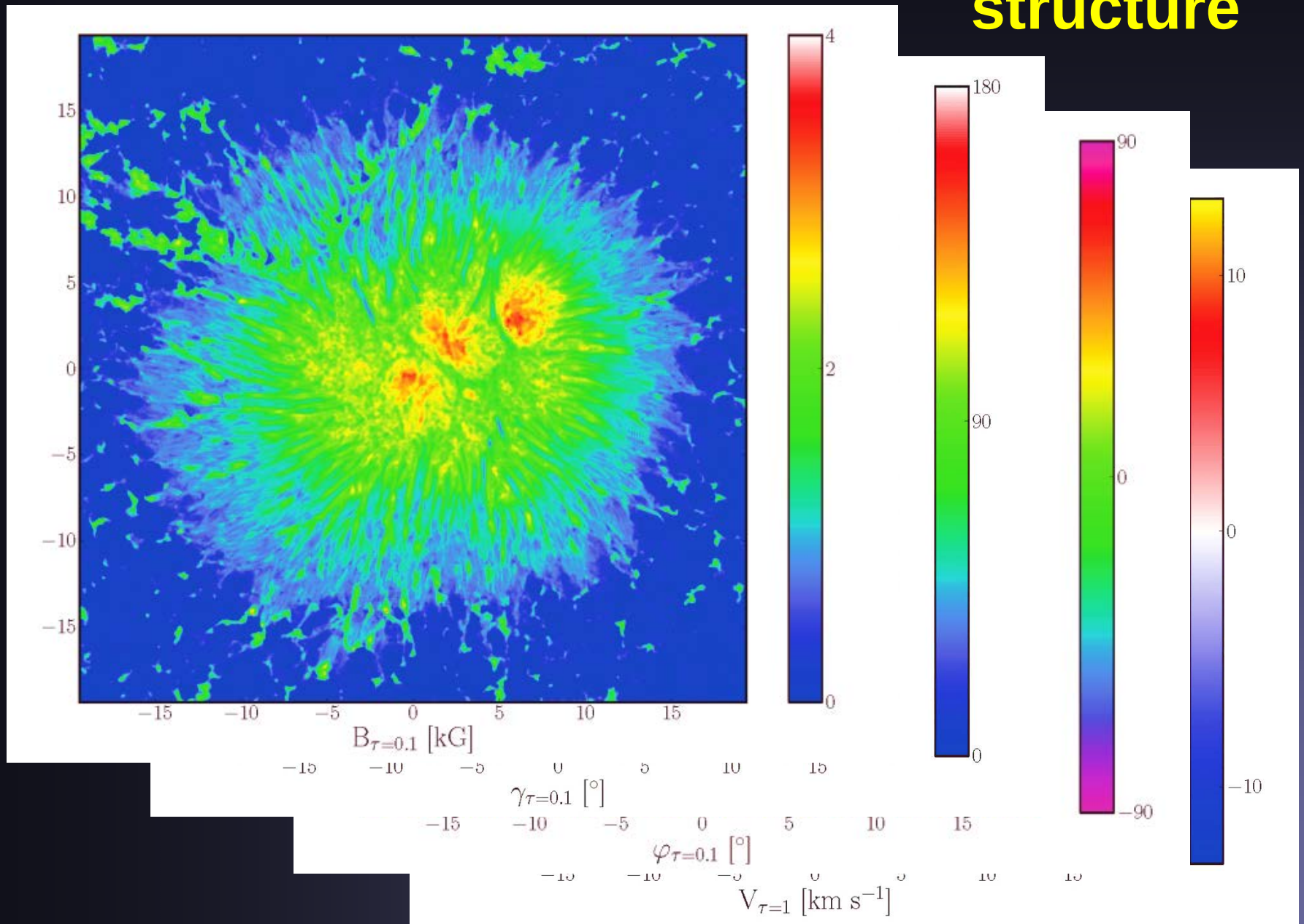
- Observation: Penumbra seen at $\mu<1$ shows
  - on limb side: Doppler red shift
  - on disc side: Doppler blue shift
- Interpretation: horizontal OUTflow of material from inner penumbra to outer
- Low resolution: 1-2 km/s
- High resolution: strongly structured into filaments, strongest flows are supersonic (i.e. > 6-7 km/s)



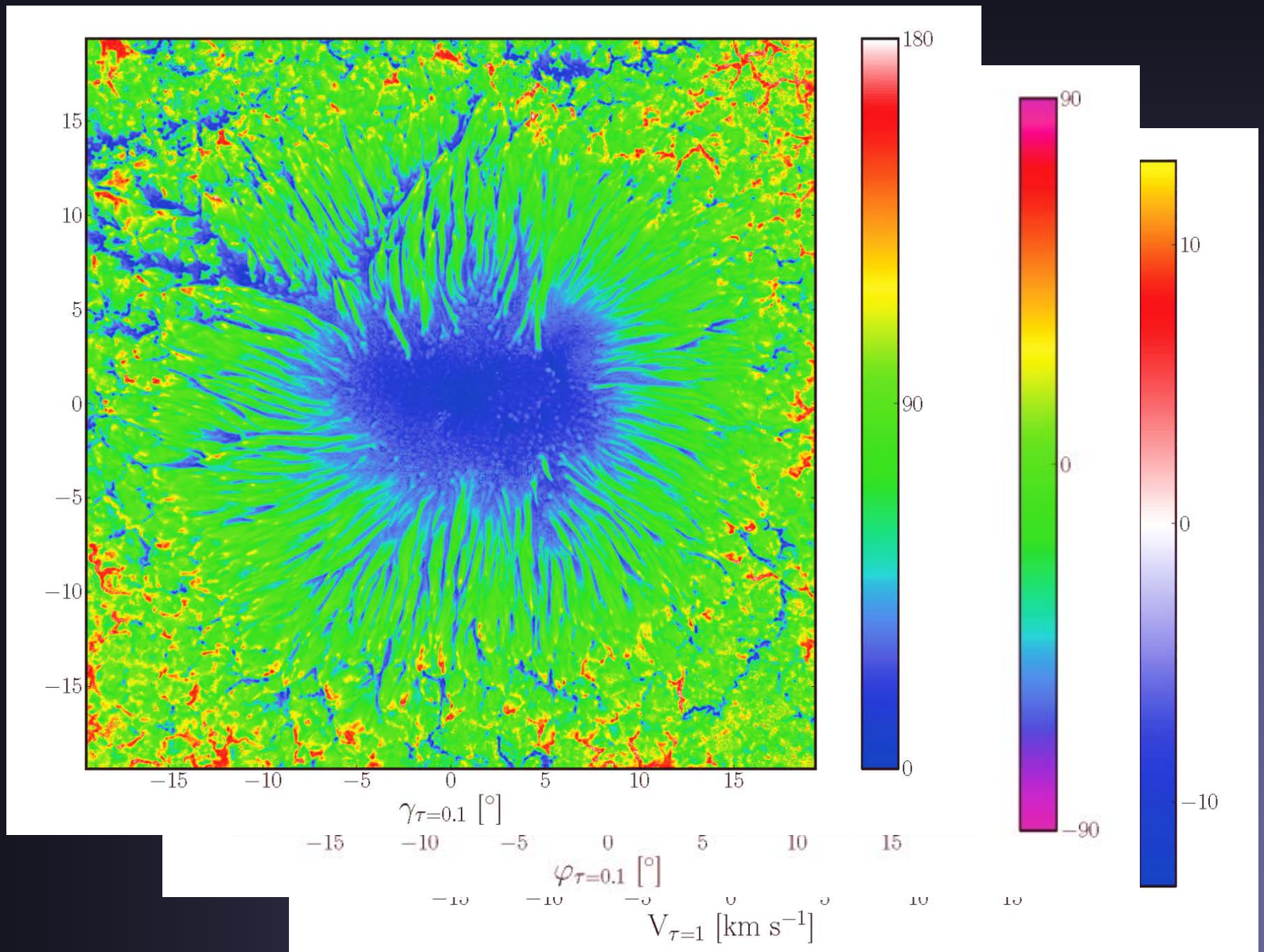
Sunspot fine structure



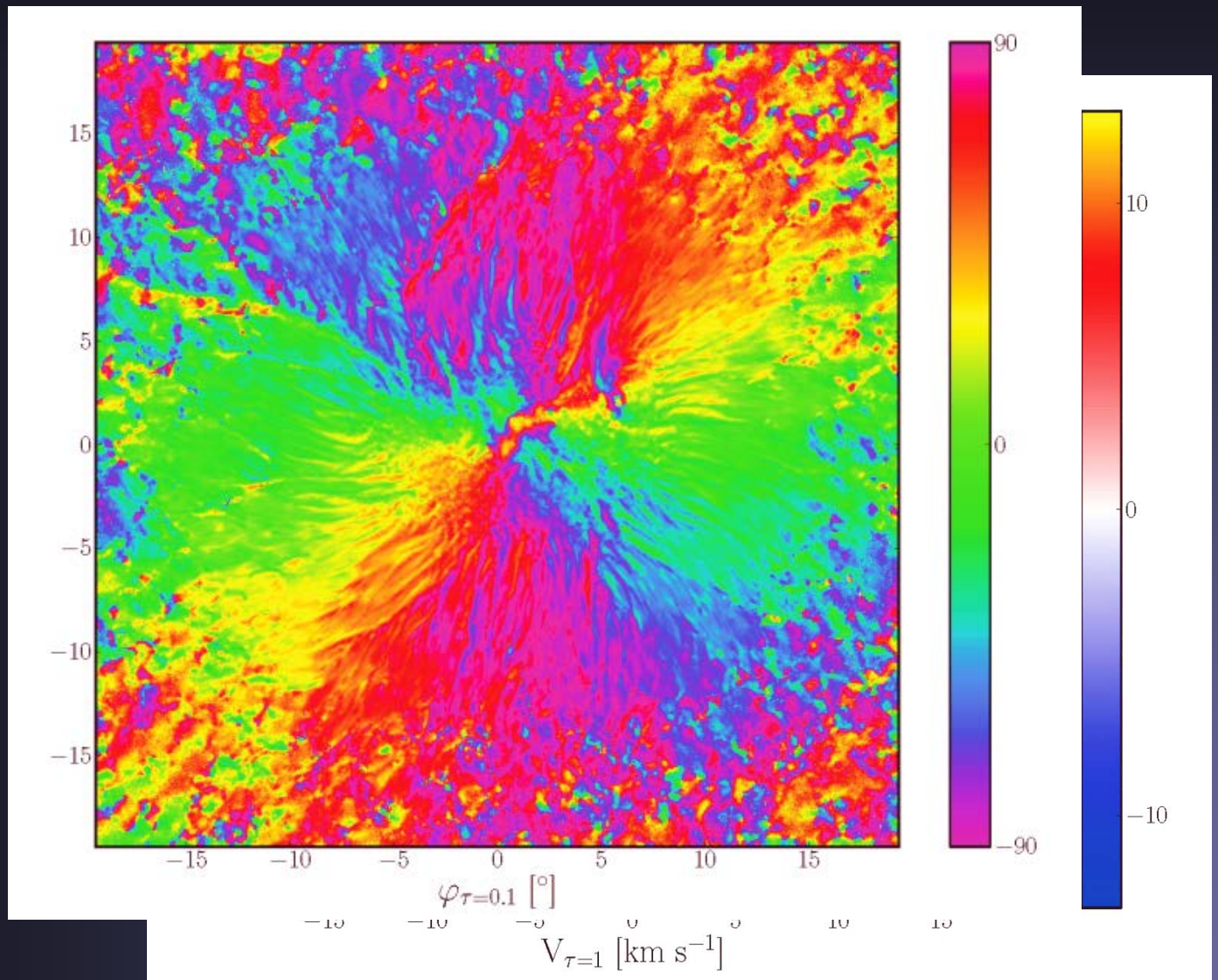
Sunspot fine structure



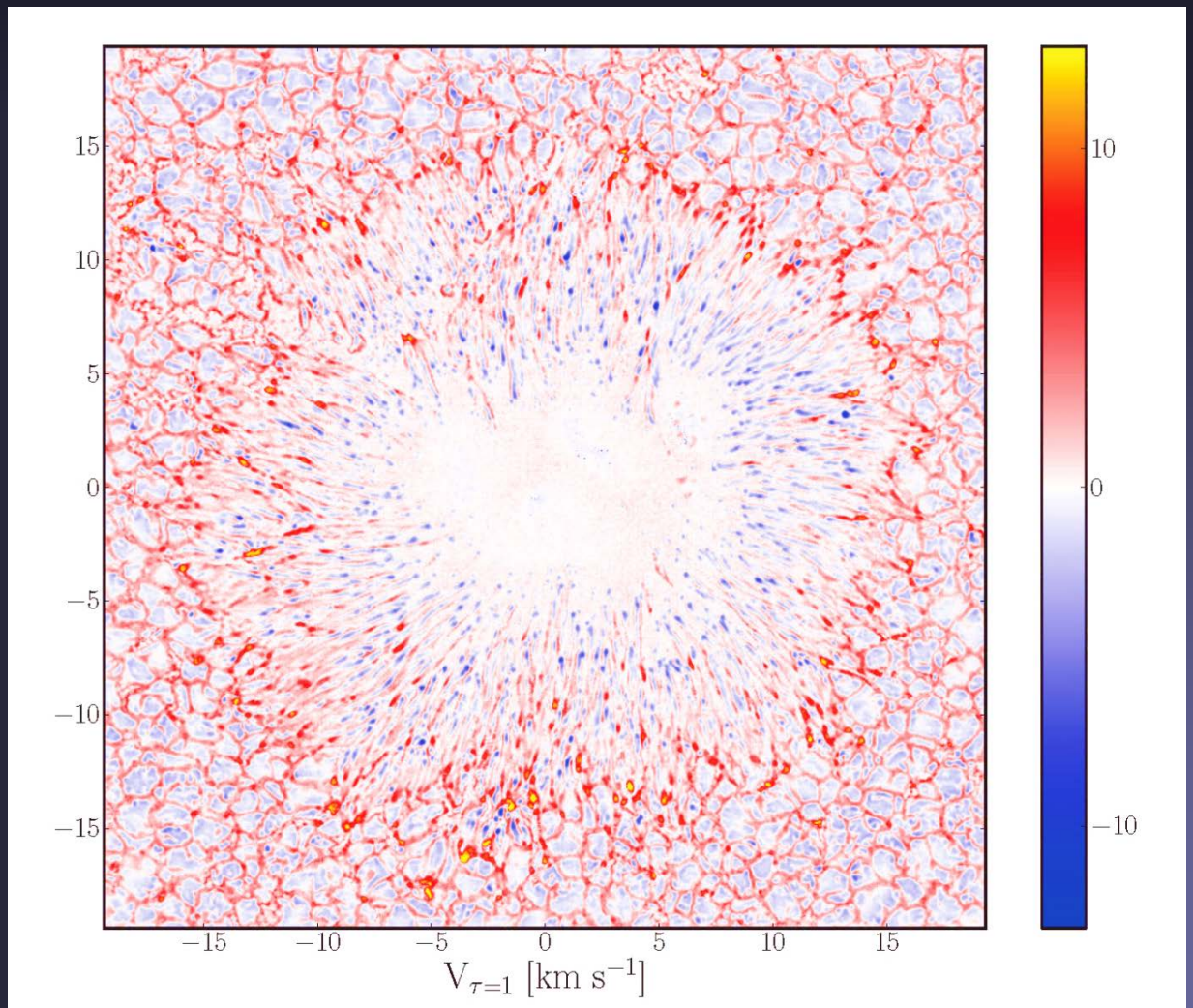
Sunspot fine structure



Sunspot fine structure



Sunspot fine structure

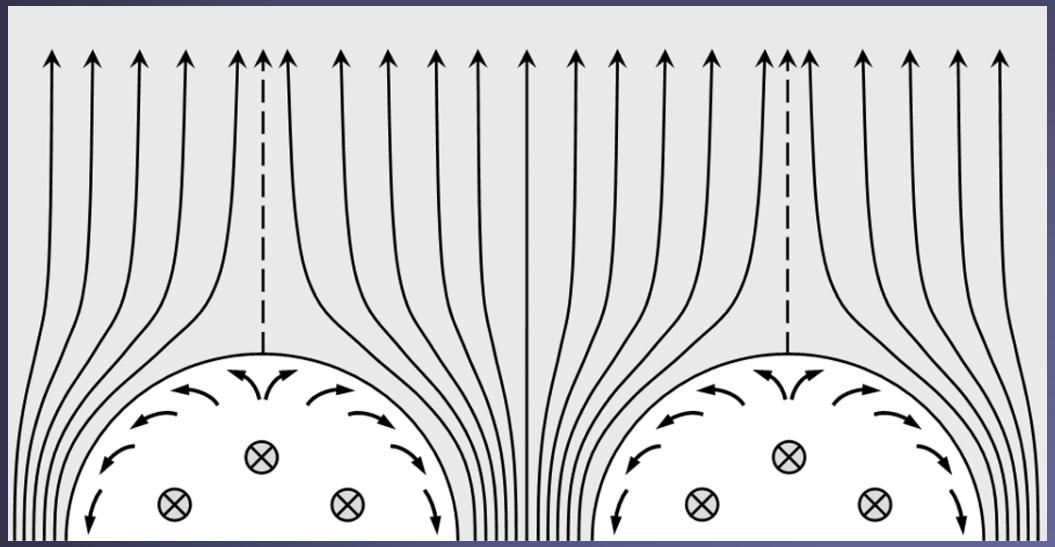


The nature of sunspot fine structure

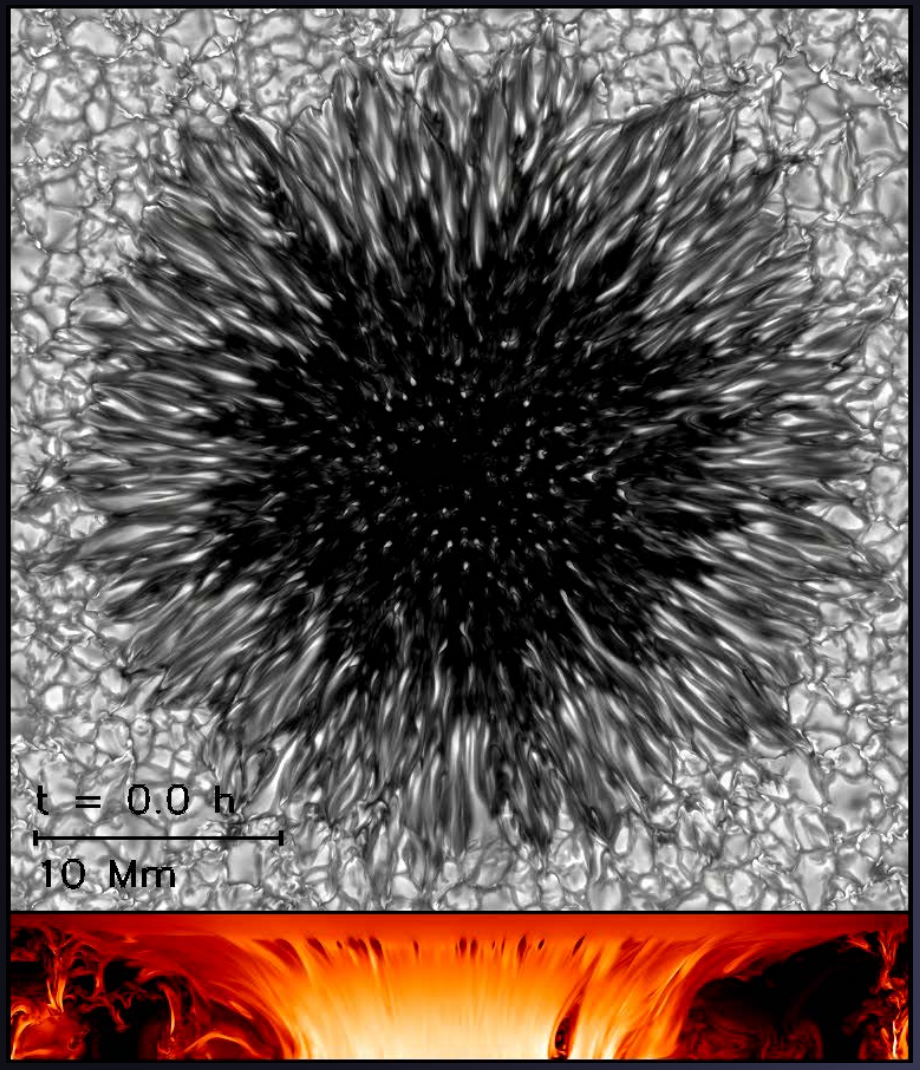
- Today's basic understanding is that all fine structure of sunspots is a manifestation of magnetoconvection

- Magnetoconvection is also responsible for transporting sufficient energy to the surface to keep the spot, in particular the penumbra, bright (75% photospheric)

Umbral dots, penumbral filaments, light bridges are all composed of a hot, point- or sheet-like convective upflow that turns over and flows down at the sides of the structure



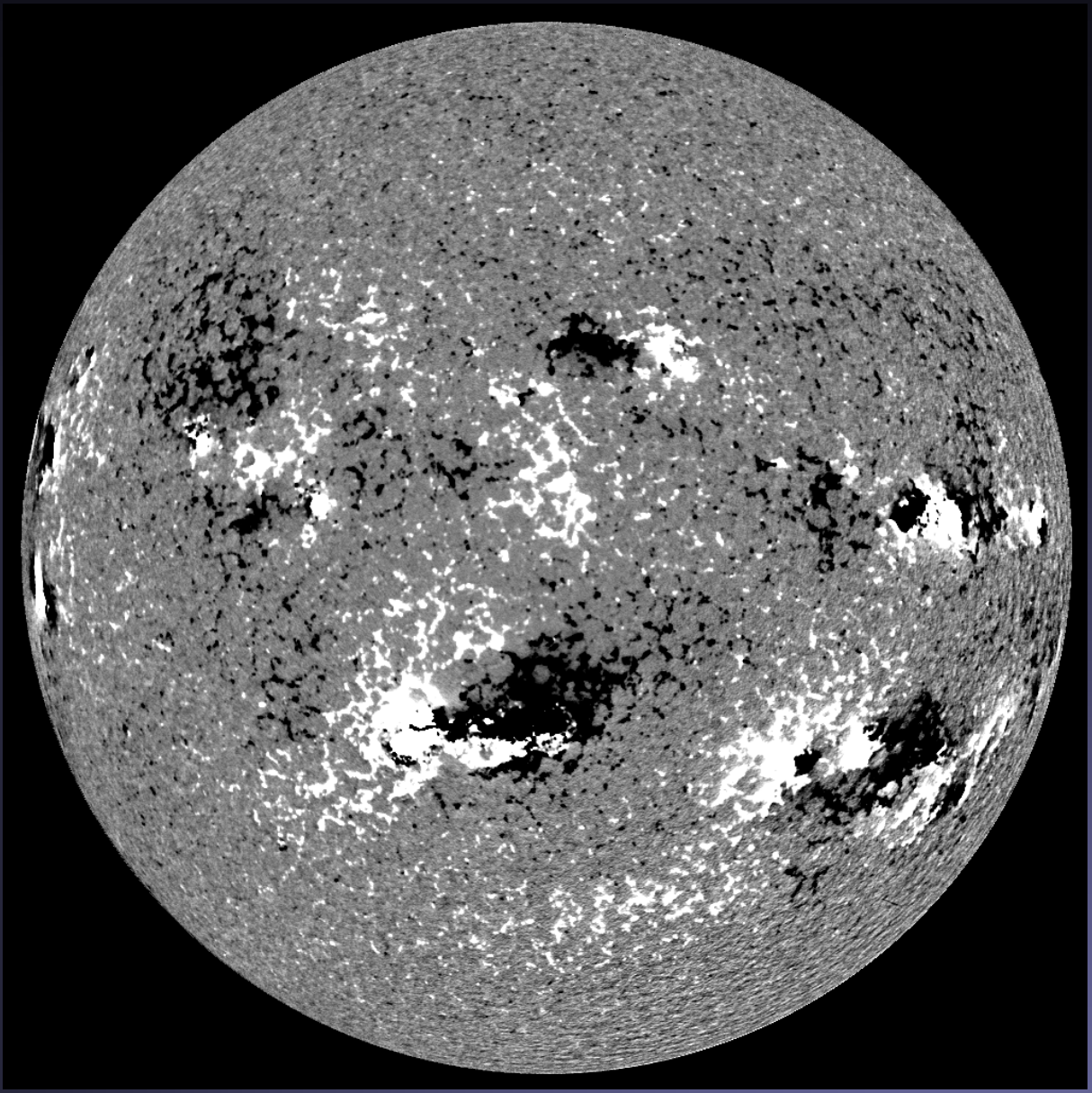
Magnetoconvection in umbra vs. penumbra



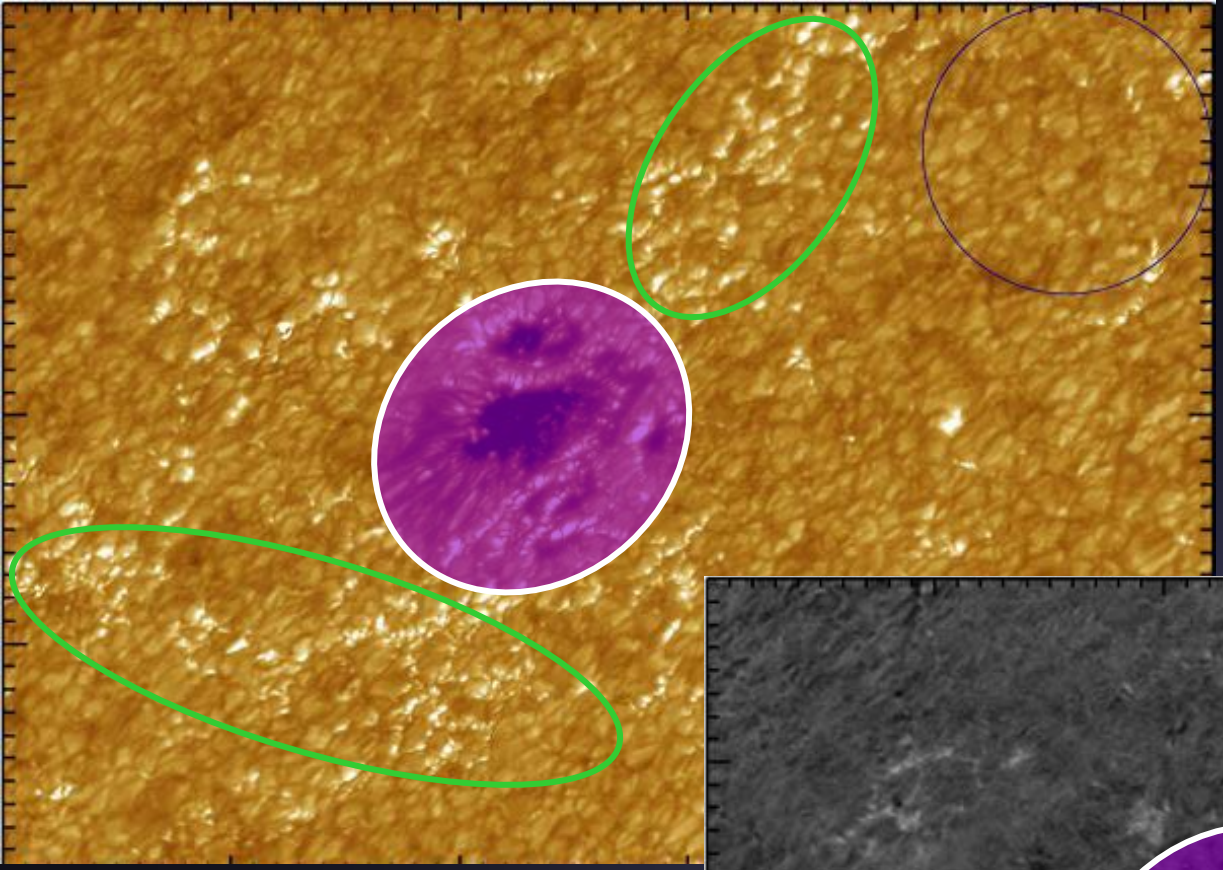
- Umbral magneto-convective features: umbral dots
  - Upwelling of hot gas in nearly vertical field,
  - downflows also in vertical field
  - Connecting the 2: difficult
  - slow, inefficient
- Penumbral magnetocon-vective features: filaments
  - Hot upflow, horizontal flow and cool downflow following inclined field lines
  - Weaker field: more maleable to flows
  - fast, efficient

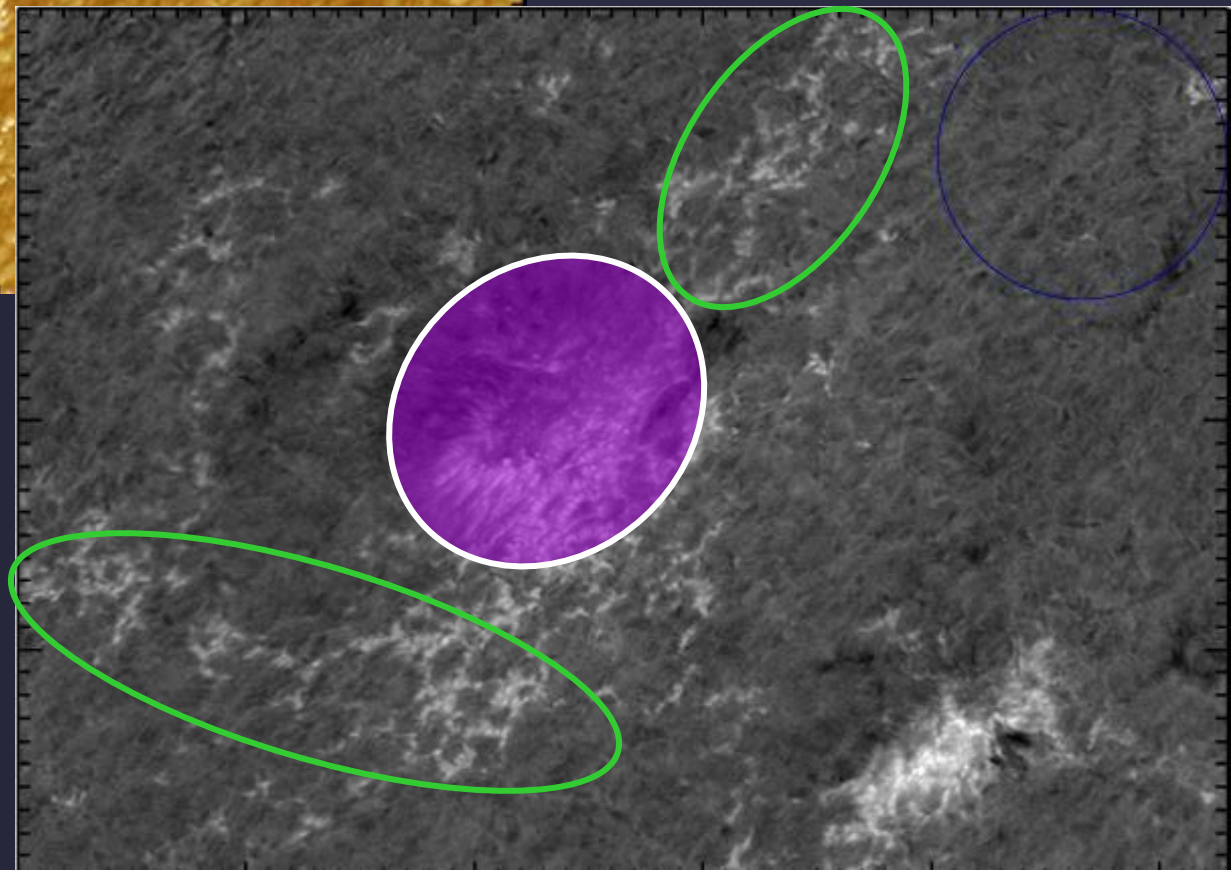
Non-spot fields

- Sunspots cover in general <0.2% of solar surface
- What about the remaining 99.8%?
- What are plage or faculae & network composed of?
- Is there field also in the “empty spaces” between the network elements?



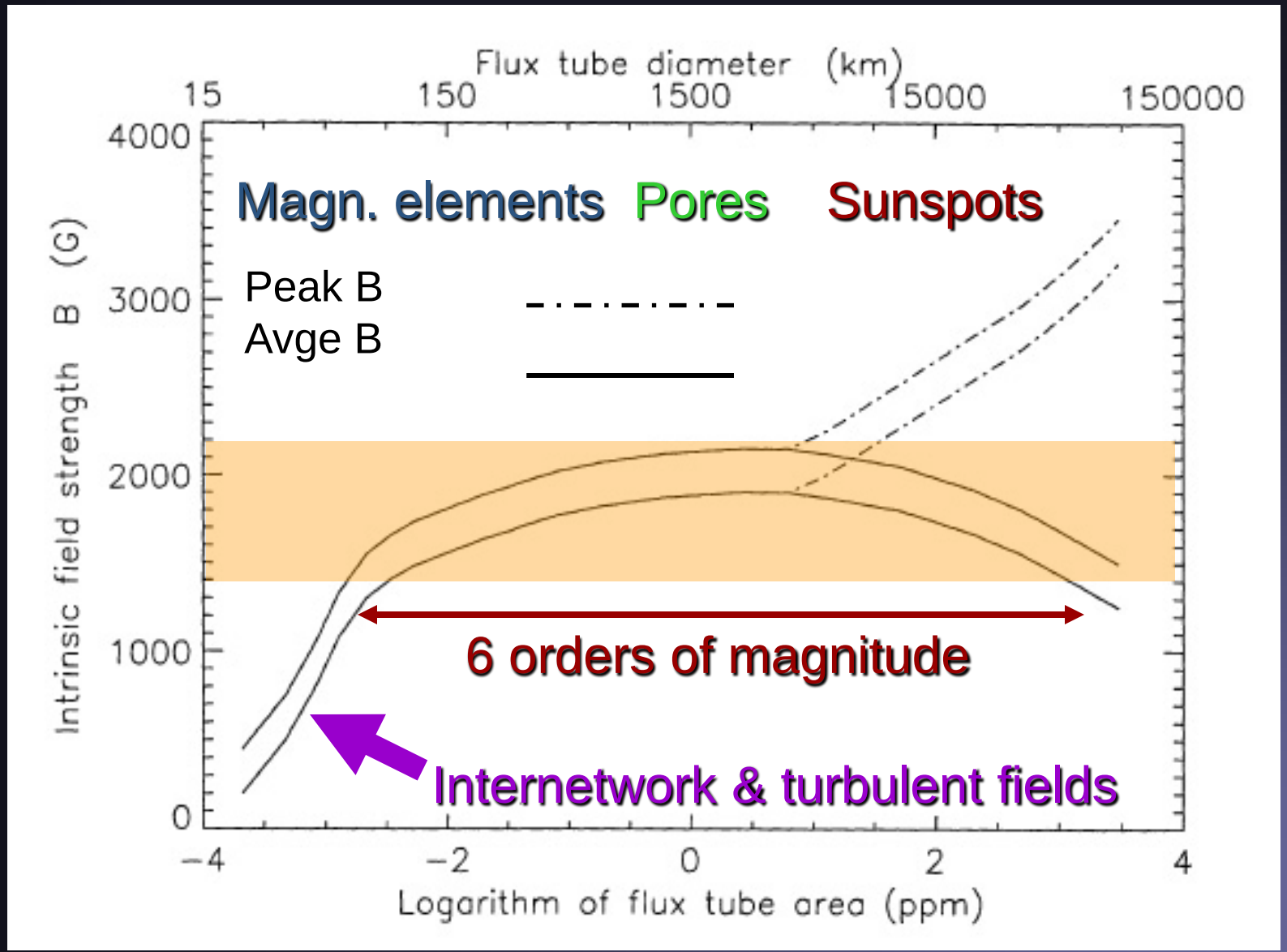
Facular fields



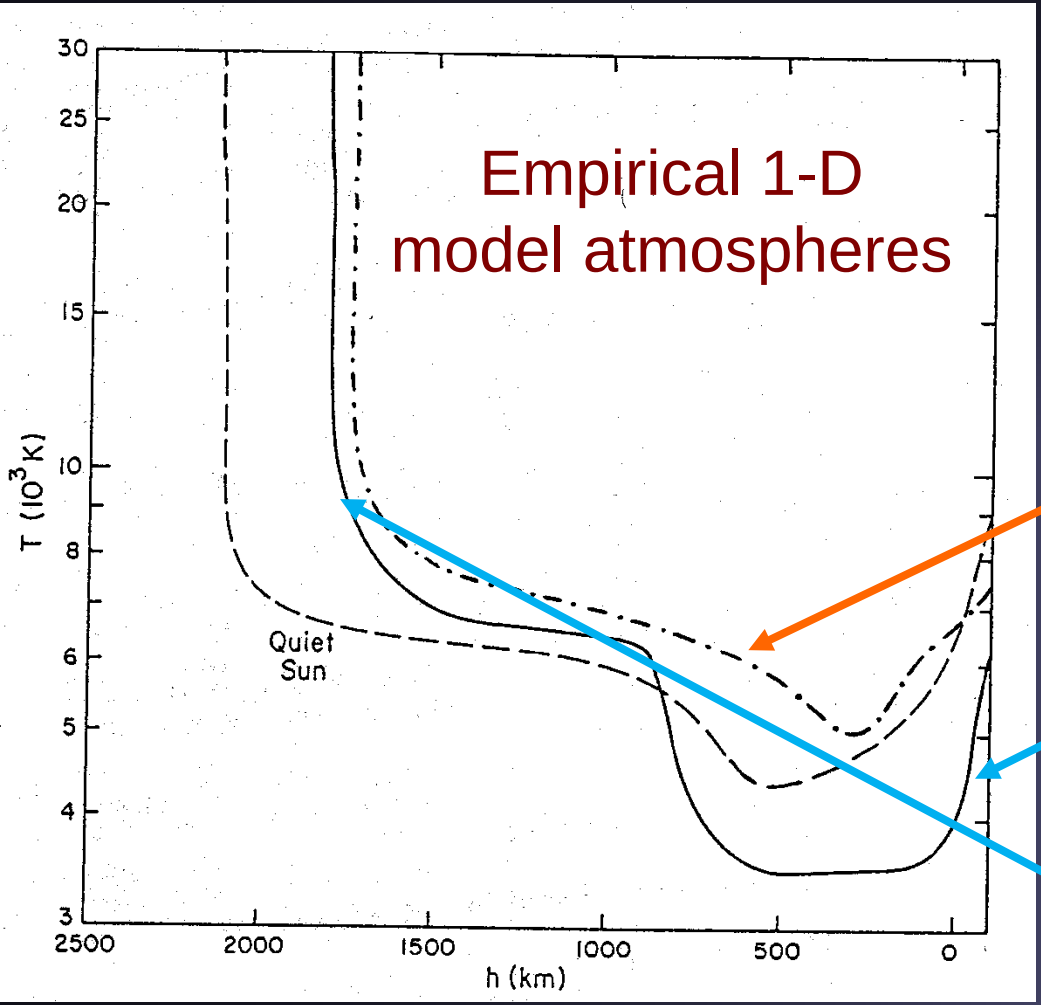


Facular fields are composed of magnetic elements, bright, thin (diameter <300 km) flux tubes or flux sheets

Surprisingly constant field strength



Temperature stratifications of quiet Sun, sunspot, magnetic element



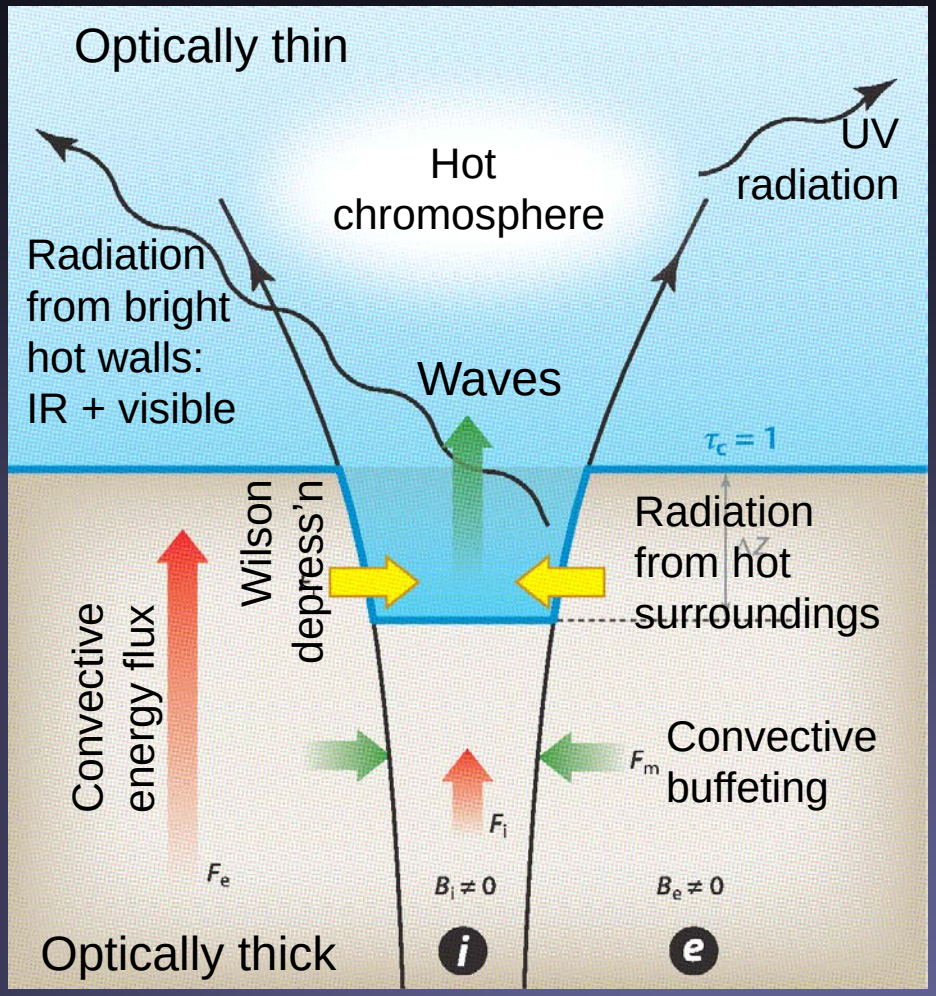
- Dashed: Quiet Sun
- Solid: sunspot
- Dot-dashed: active region plage, magnetic element
- Plage is hottest everywhere above solar surface
- Sunspot cold (dark) in photosphere, but hot (bright) in upper chromosphere & transition region

Magnetic elements: brightness

- Convective energy flux (red arrows) quenched by B-field ➔ heat blocked
- Inflow of radiation into evacuated flux tube through hot walls (yellow arrows). Excess heat flux

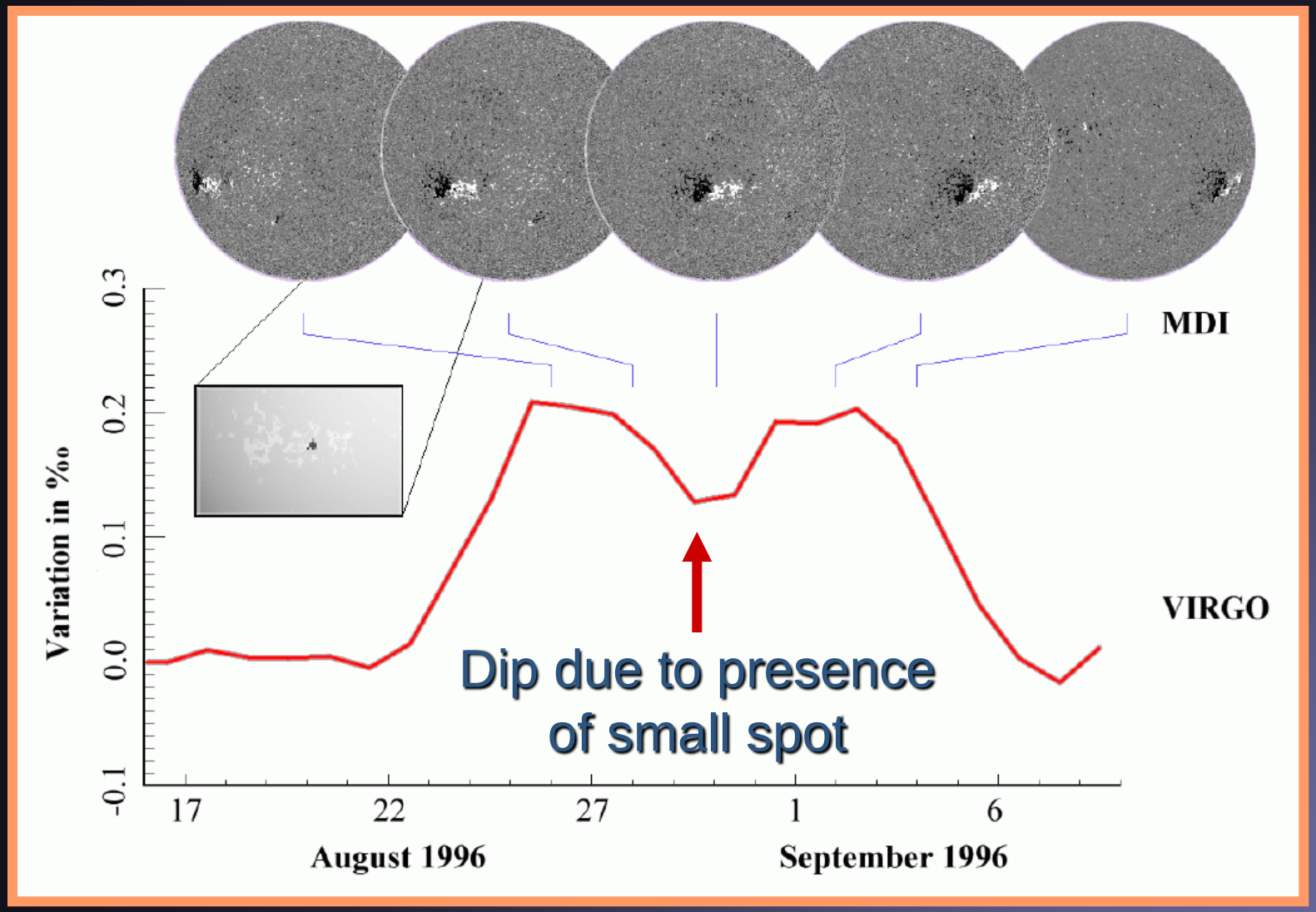
➔Enhanced emission. Inflow wins since FTs are narrow: diameter ≈ Wilson depress

- Excess energy comes partly from deep CZ, which returns to equilibrium on Kelvin-Helmholtz timescale



Field expands with height ➔ upper atmopshere fully magnetic

Faculae lead to brightening of the whole Sun



Why do magnetic elements expand with height?

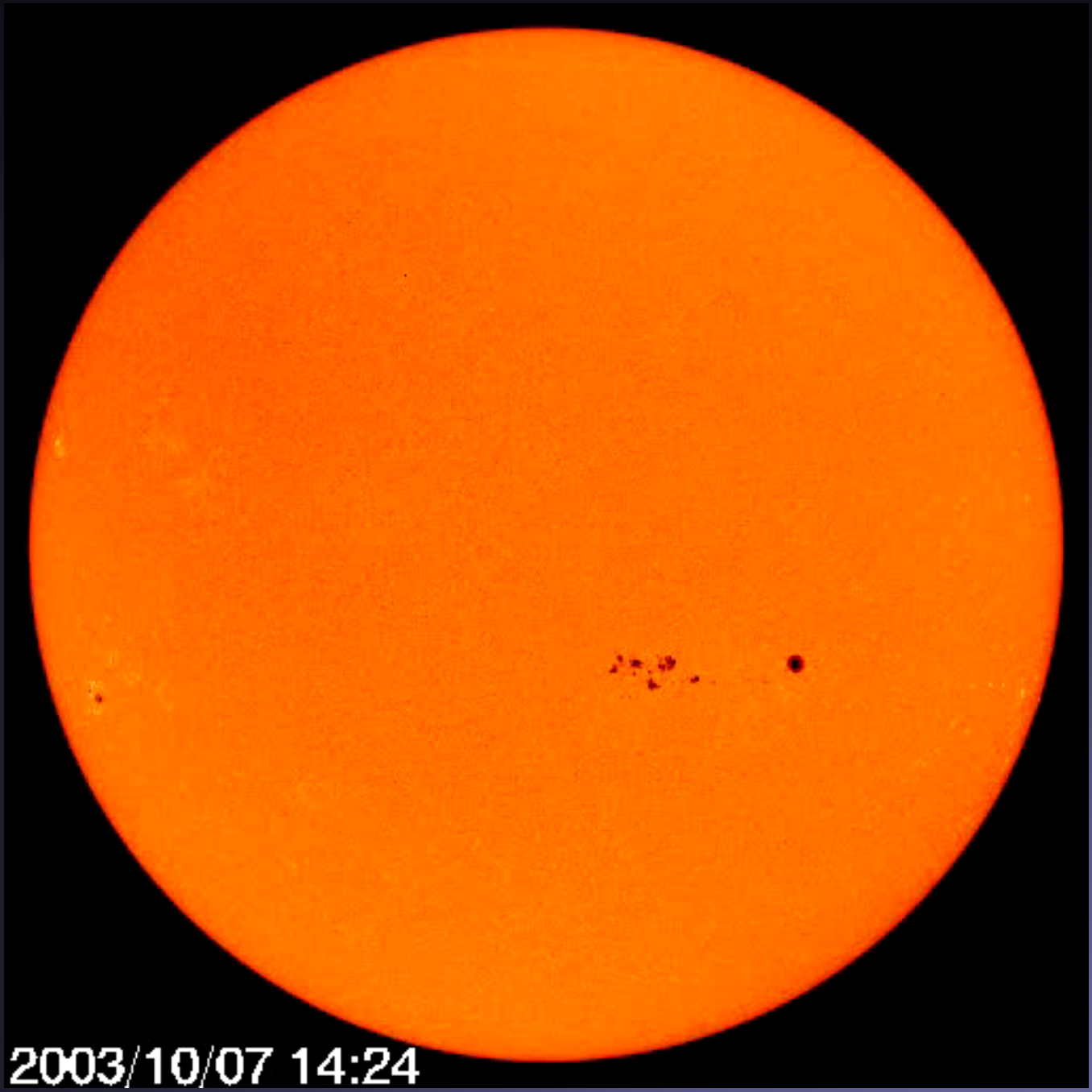
- B-field structure of magn. elements driven largely by
  - horizontal pressure balance: $B^2/8\pi + p = \mathrm{const}$
  - hydrostatic stratification (vertical pressure balance). For an isothermal atmosphere: $p = p_0 \exp(-z/H)$
- Since gas pressure drops exponentially with height (for $T = const.$), so must the field strength: $B = B_0 \exp(-z/2H)$
- Flux conservation: $\mathrm{div}\, B = 0$, or: $\iint B(x,y,z)dxdy = \mathrm{const}$

➔ area A of magnetic flux tube increases exponentially: $A = A_0 \exp(z/H)$

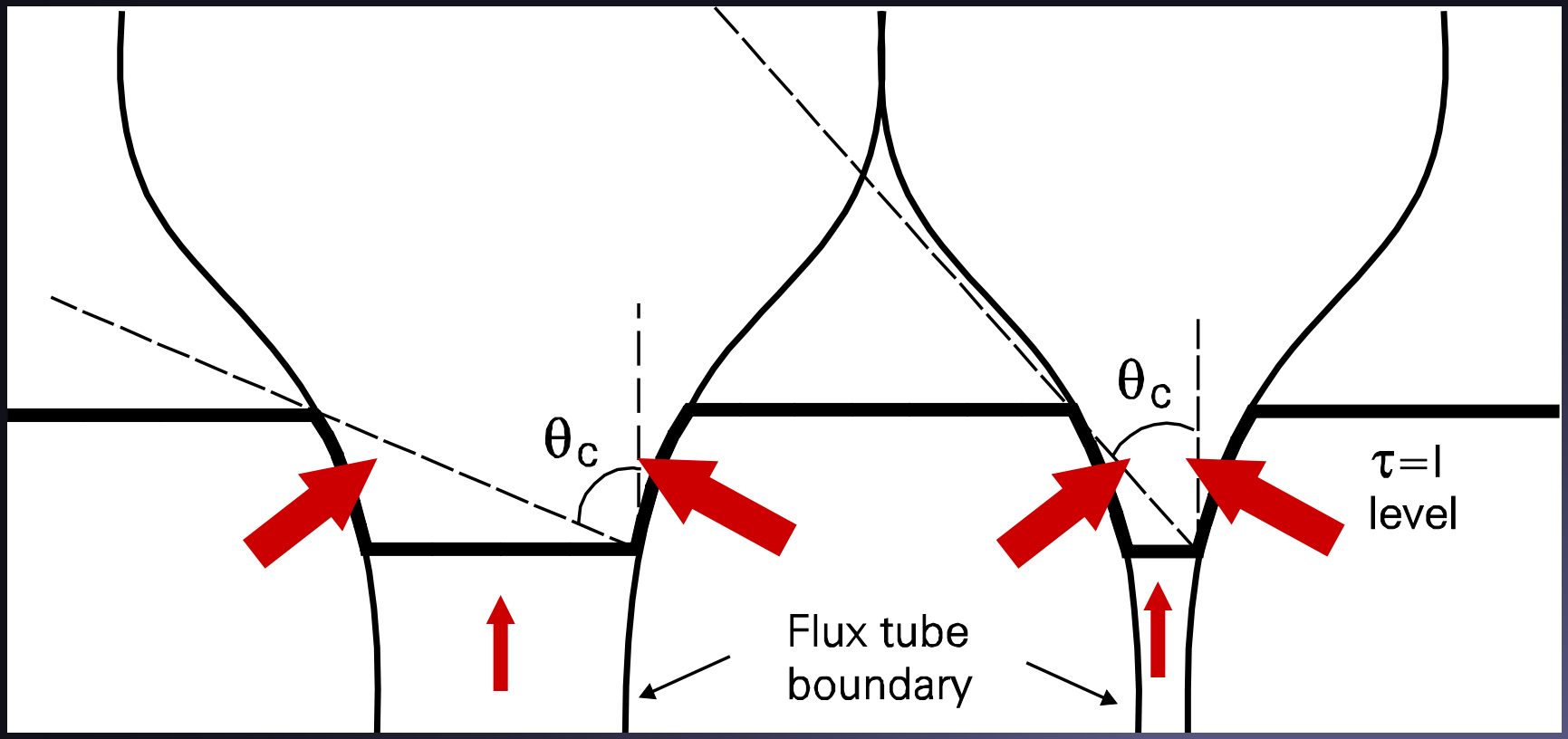
Why are faculae best seen near limb?

The Sun in White Light, with limb darkening removed

MDI on SOHO

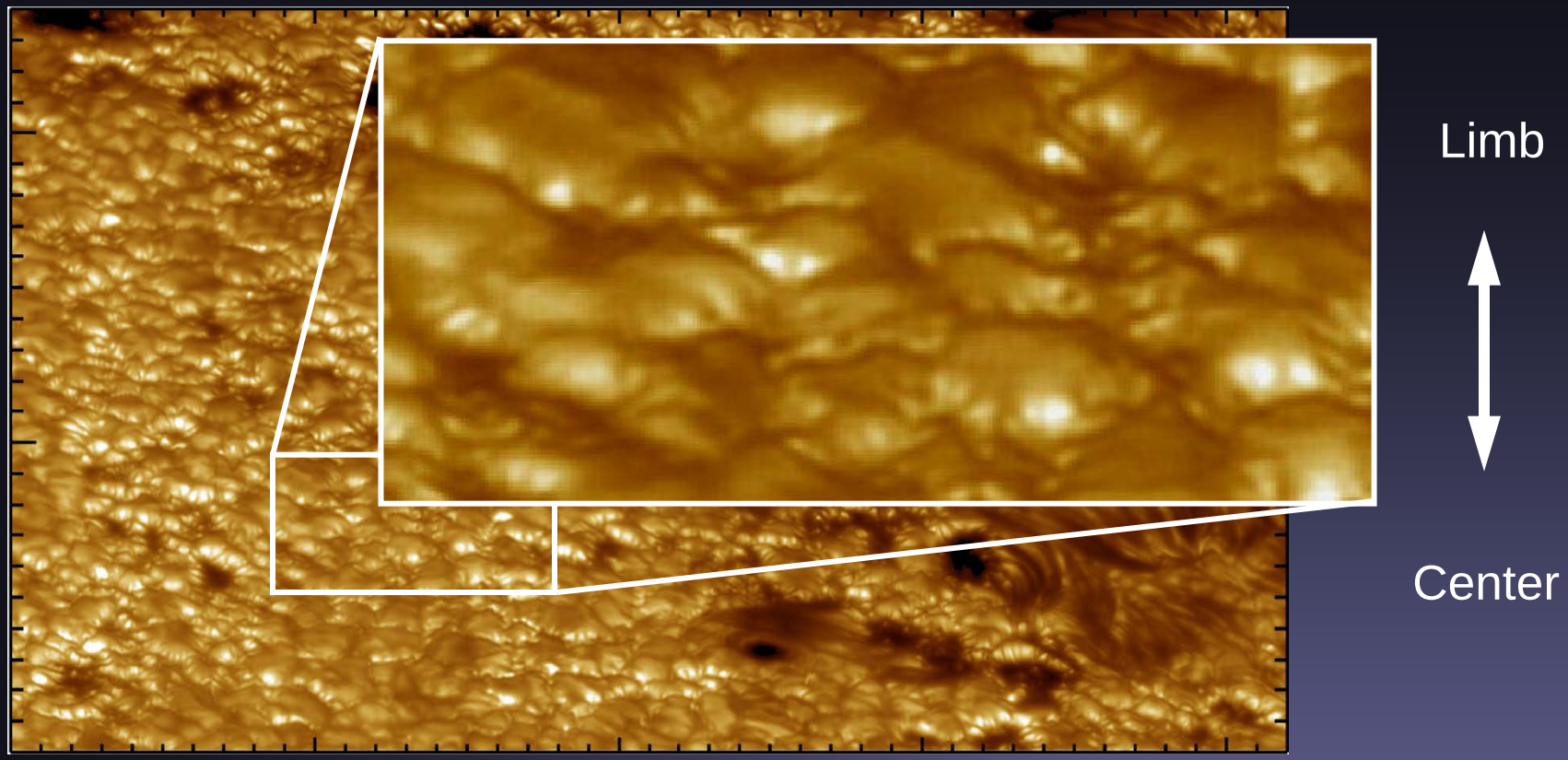


Flux-tube brightening near limb



- FTs are evacuated due to pressure balance → hot walls
- Most energy radiates away from FTs through their hot walls
- FTs appear brightest when hot walls are well seen, i.e. near limb (closer to limb for larger tubes)

Facular brightening



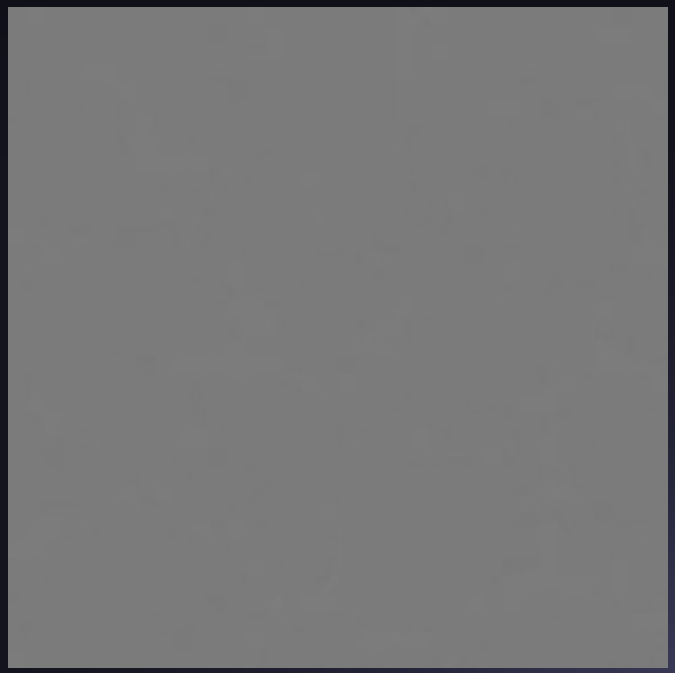
(continuum image: SST, La Palma θ=60° λ=488nm)

High resolution observations reveal 3D appearance of faculae (Lites et al. 2004)

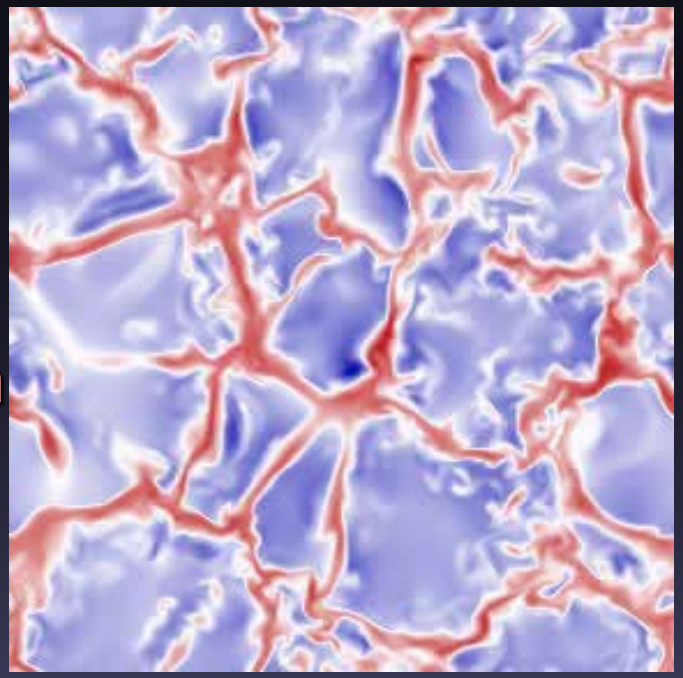
3-D radiation MHD simulations

- Similar to hydrodynamic simulations describing granulation, except that now the full MHD equations need to be solved → Additional complication
- Include realistic radiative transport of energy. Include solar surface to allow comparison with observations
- Suffer from same shortcomings as the HD simulations (too low Reynolds number) etc.

B_z
(Z=0)
>500G
>1000G
>1500G



6 Mm



v_z
(Z=0)

3-D compressible radiation-MHD simulations

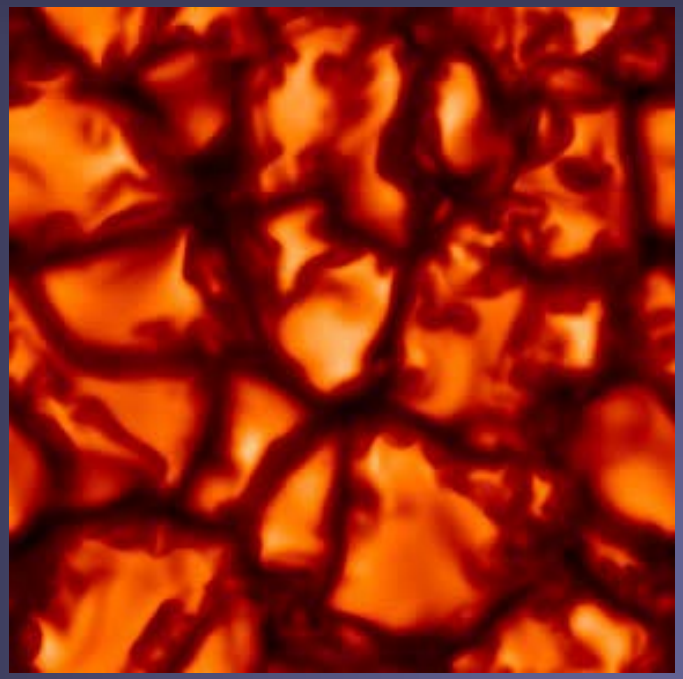
Plage: $B_Z(t=0) = 200$ G

Grid Size: 288 x 288 x 100

Vertical extent: 1.4 Mm

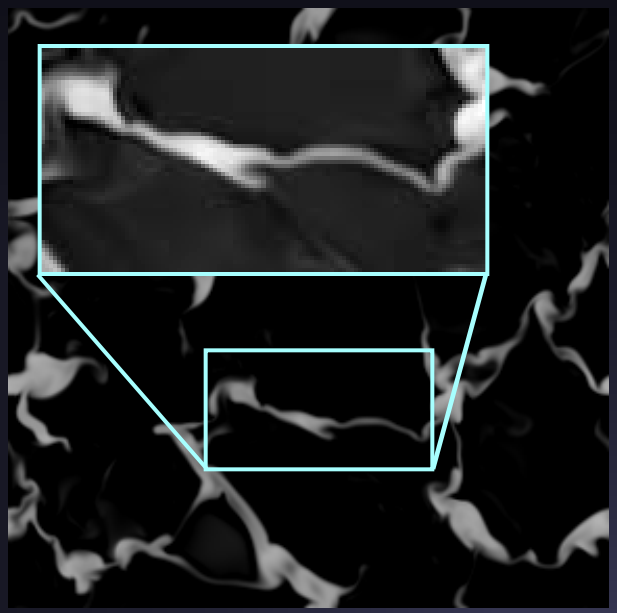
Horizontal extent: 6 Mm

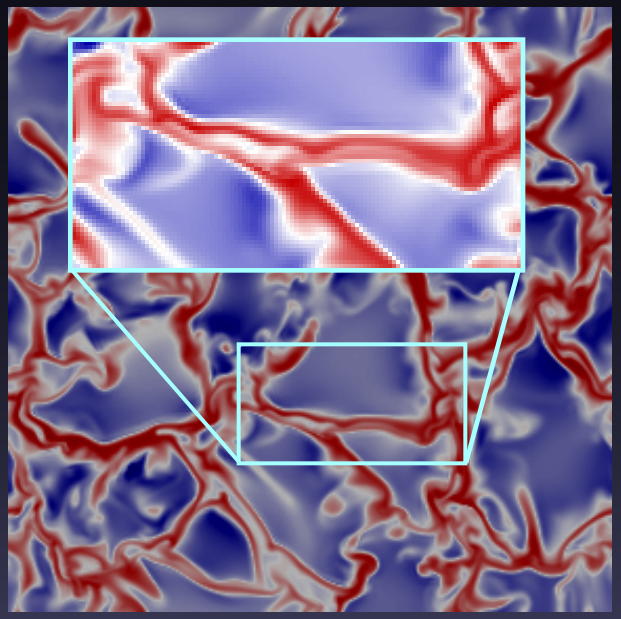
Alexander Vögler et al.



I_c
(Z=0)

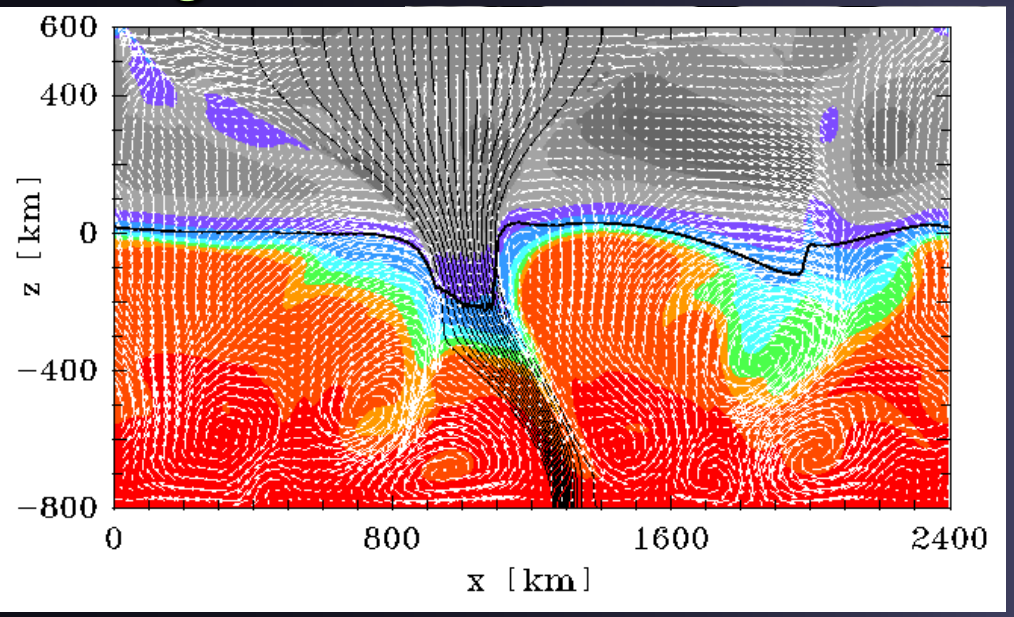
B_z





v_z

Details of thin magnetic



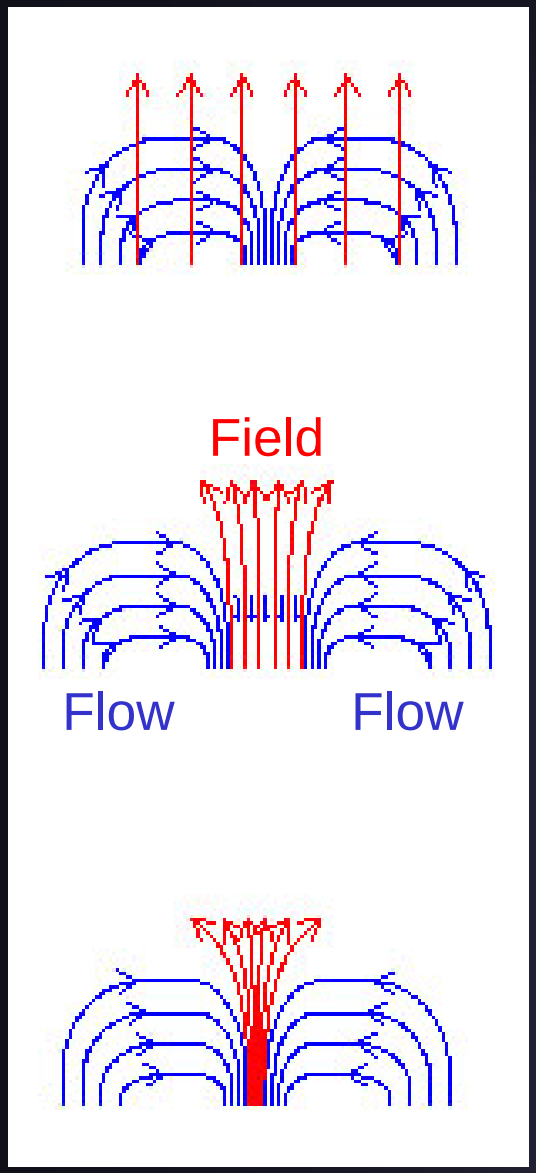
Internal structure of magnetic elements is remarkably well reproduced by thin tube approximation (pressure balance)

I_c

Horizontal cuts near surface level

Vögler et al. 2005

Convective intensification



- Flux advection by horizontal flow (flux expulsion) ➔ Leads to B in equipartition with flow: $\frac{B_{\rm int}^2}{8\pi} = \frac{1}{2} m v_{\rm ext}^2$
- Radiative cooling reduces pressure scale height: $P \sim \exp(-z/Hp)$, $H_p \sim \sqrt{T}$ ➔ down-flow ➔ Evacuation ➔ horizontal pressure imbalance ➔ Excess external gas pressure pushes field together
- ➔ leads to field intensification until $\beta_{\rm int} = \frac{8\pi p_{\rm int}}{B_{\rm int}^2} < 1$ and $\beta_{\rm ext} = \frac{8\pi p_{\rm ext}}{B_{\rm int}^2} \approx 1$

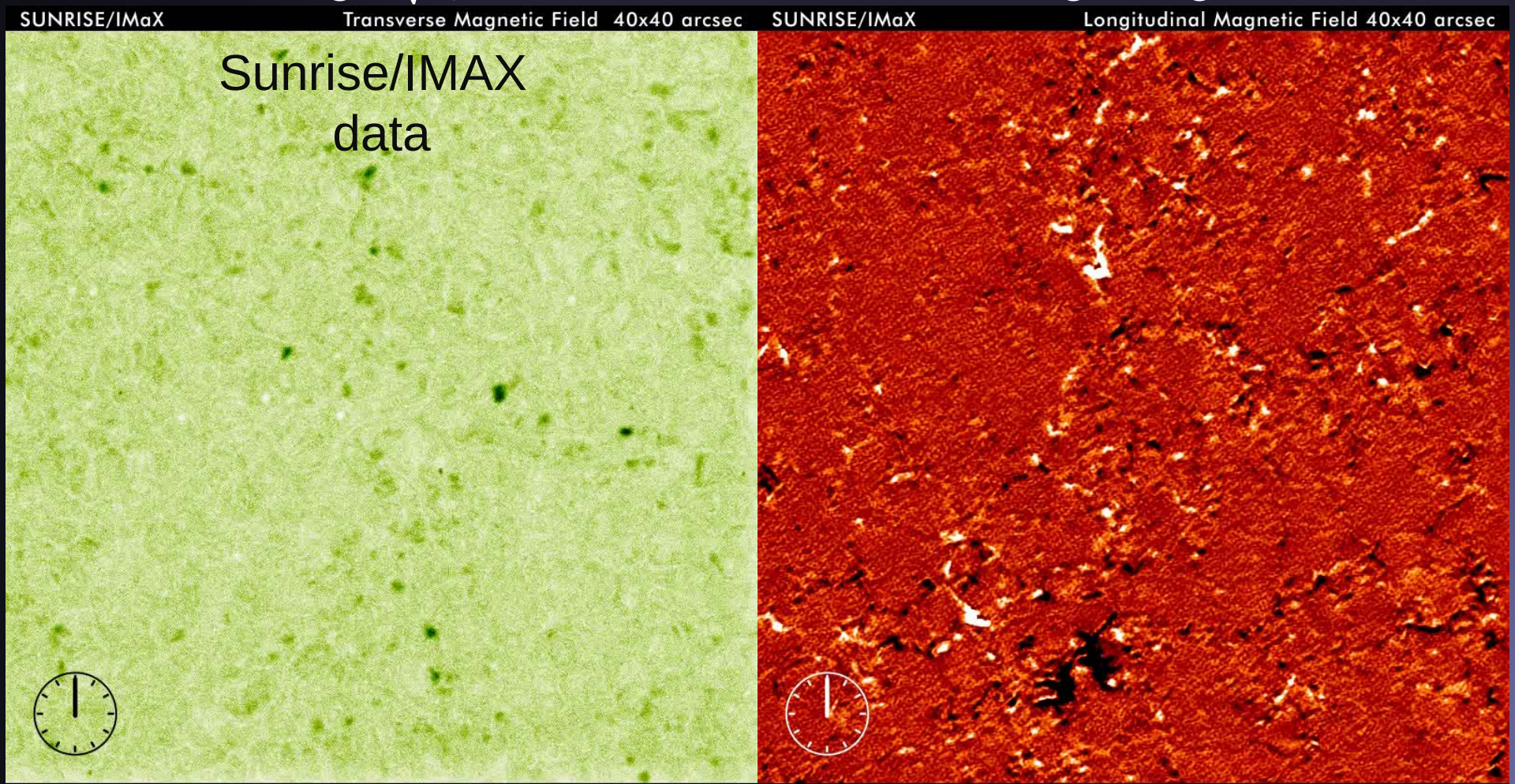
Quiet Sun internetwork: full of horizontal field

Total linear polarization:

dark = large $\sqrt{Q^2 + U^2}$

Stokes V

magnetogram



Sunrise/IMAX data