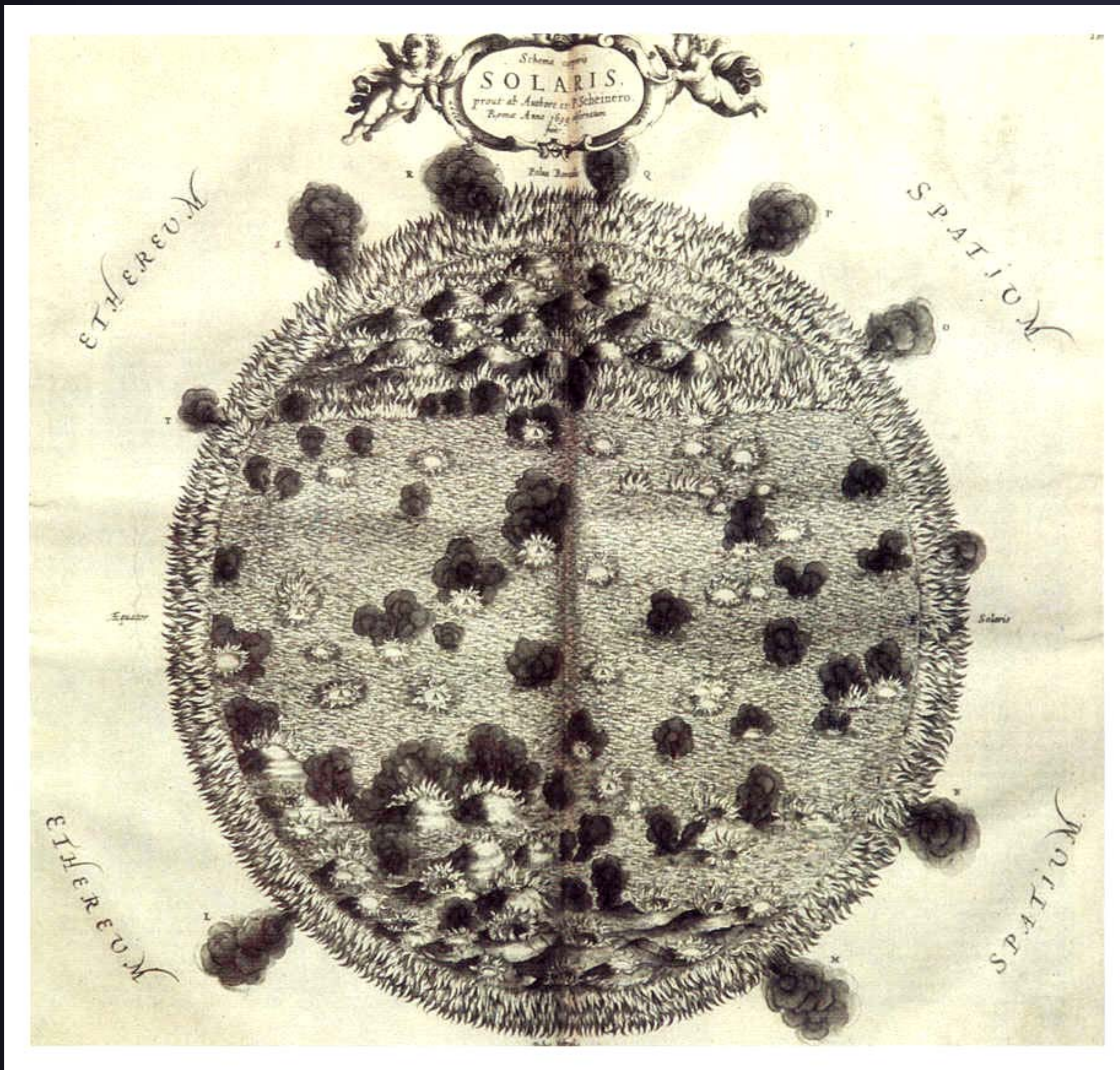
Sunspot magnetic fields

What are Sunspots?



Slag on lava?

Clouds of smoke?

Holes in the Sun ?

Cyclones?

Sunspot structure & dynamics

Umbra

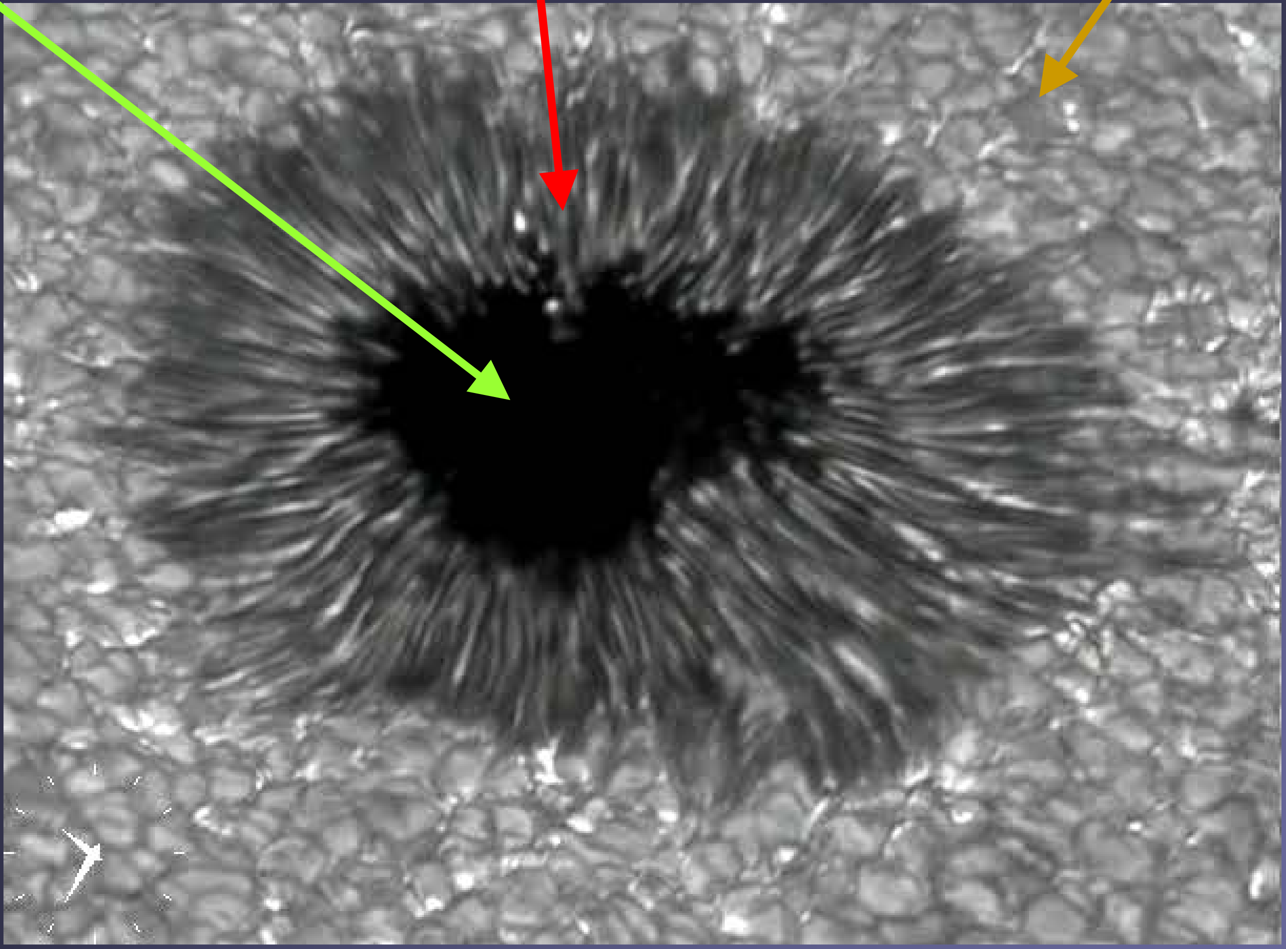
Penumbra

Granule

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

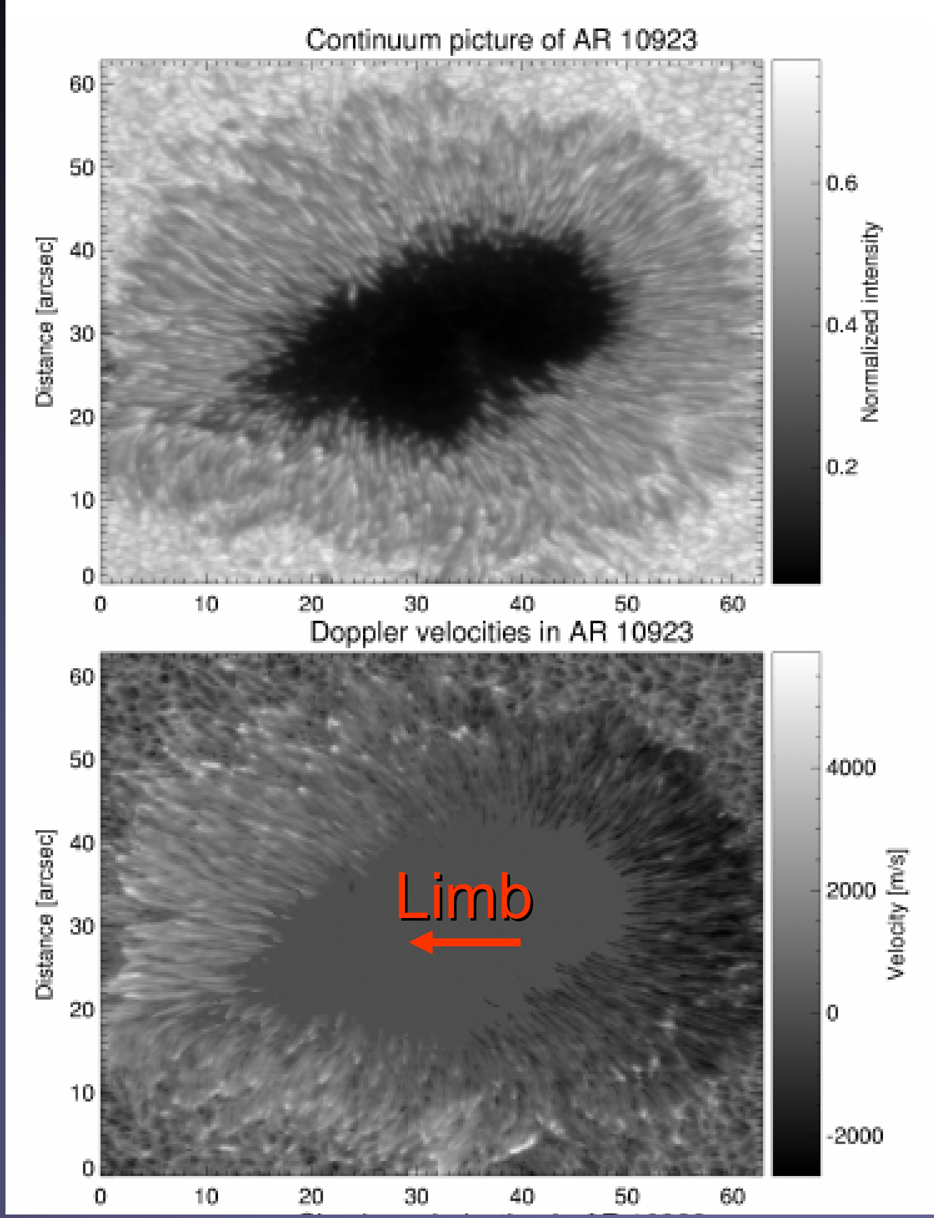
$T_{\mathrm{eff}} \approx 5500$ K

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



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: supersonic

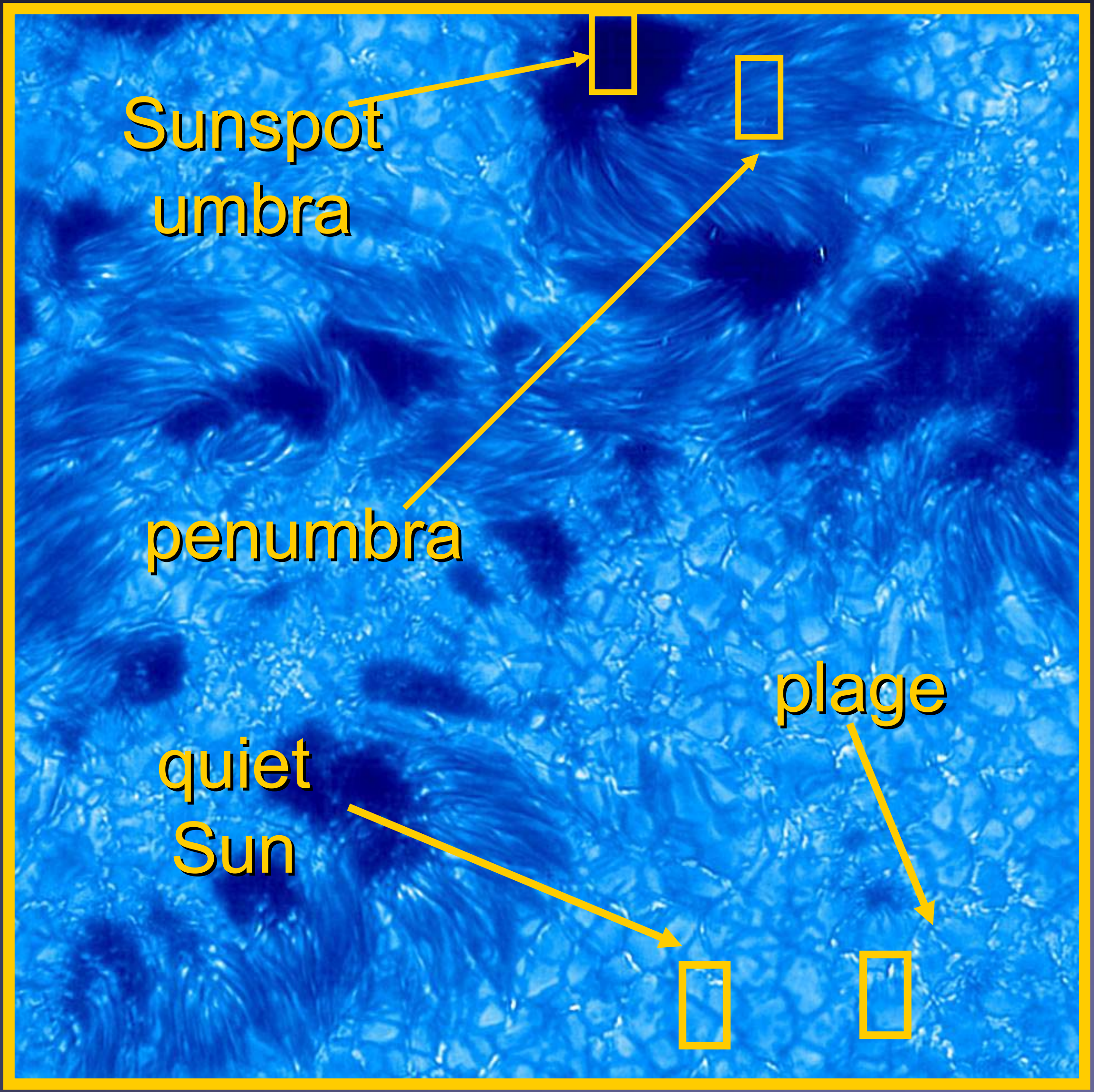


bright: redshift, dark: blueshift

Regimes of solar magnetoconvection

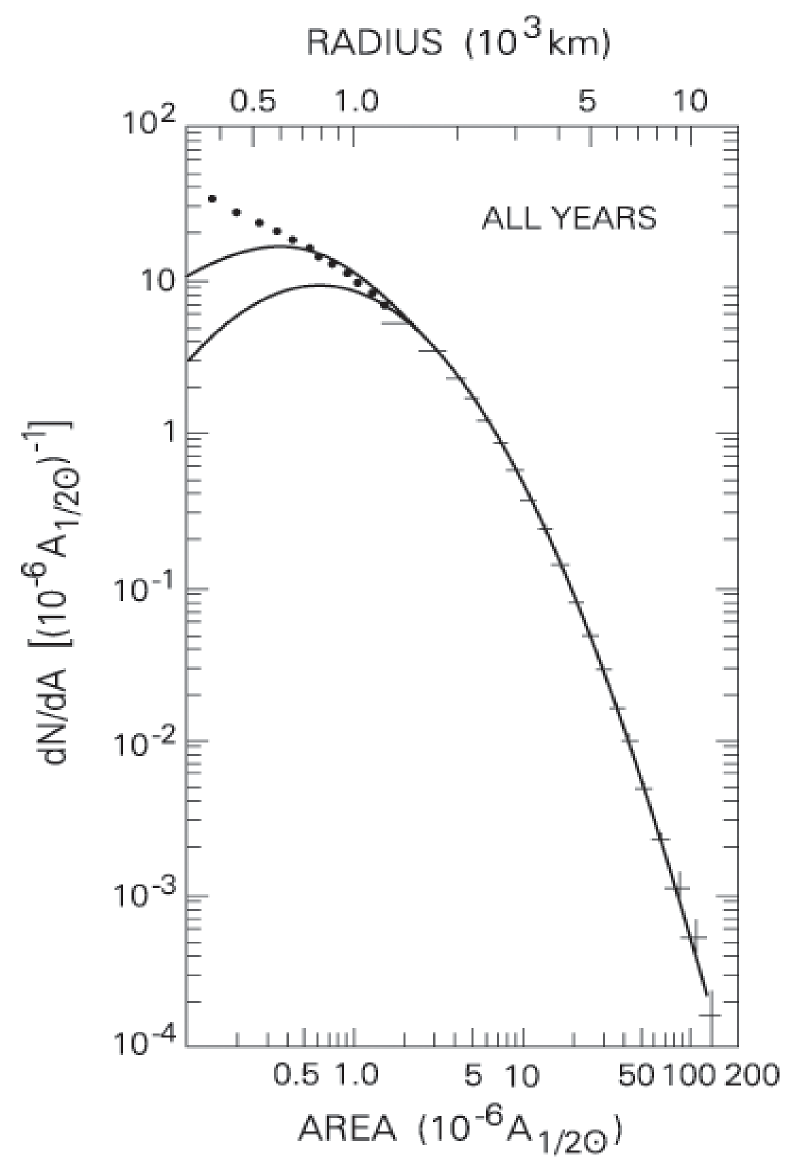
Magnetic activity in cool stars is driven by the interaction of the magnetic field with convection, i.e. magnetoconvection

Sunspots allow us to probe magneto-convection for stronger fields, on larger scales than other magnetic features



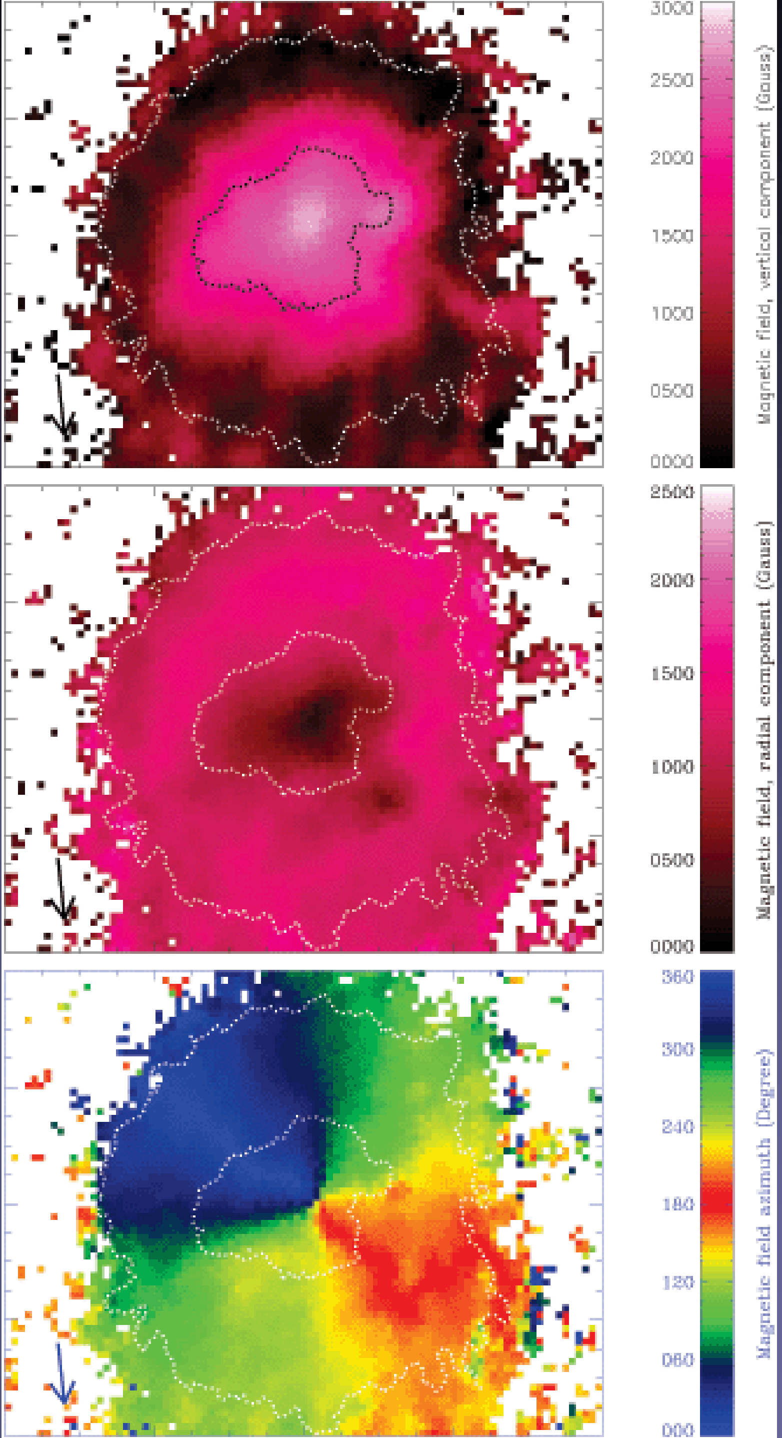
Sunspots, some properties

- Field strength: Peak values 2000-4000 G
- Brightness: umbra: 20% of quiet Sun, penumbra: 75%
- Sizes: Log-normal size distribution. Overlap with pores (log-normal = Gaussian on a logarithmic scale)
- Lifetimes: τ between hours & months: Gnevyshev-Waldmeier rule: $A_{max} \sim \tau$, where A_{max} = max spot area.



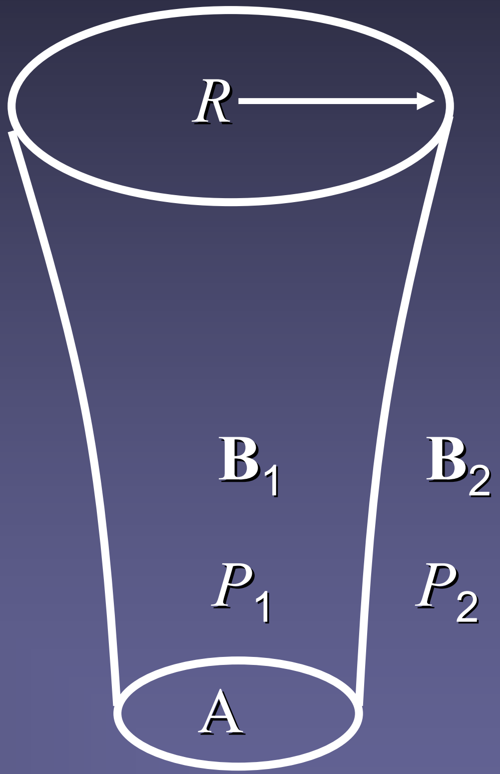
Magnetic structure of sunspots

- B drops steadily from 2000 – 4000 G in umbra towards boundary, $B(R_{spot}) \approx 1000$ G
- At centre, field is vertical. It becomes almost horizontal near R_{spot}
- Regular spots have a field structure similar to a buried dipole



Magnetic flux tubes

- Sunspots are intersections of the solar surface with large magnetic flux tubes
- In CZ and in photosphere most magnetic energy is in concentrated magnetic flux tubes (bounded by topologically simple surface=current sheet)
- Pressure balance: $\frac{B_1^2}{8\pi} + P_1 = P_2 + \frac{B_2^2}{8\pi}$
- Thick flux tubes such as spots, $R > H_P$, where H_P is the pressure scale height, display strong variation across their cross-section. Pressure balance valid only across boundary.



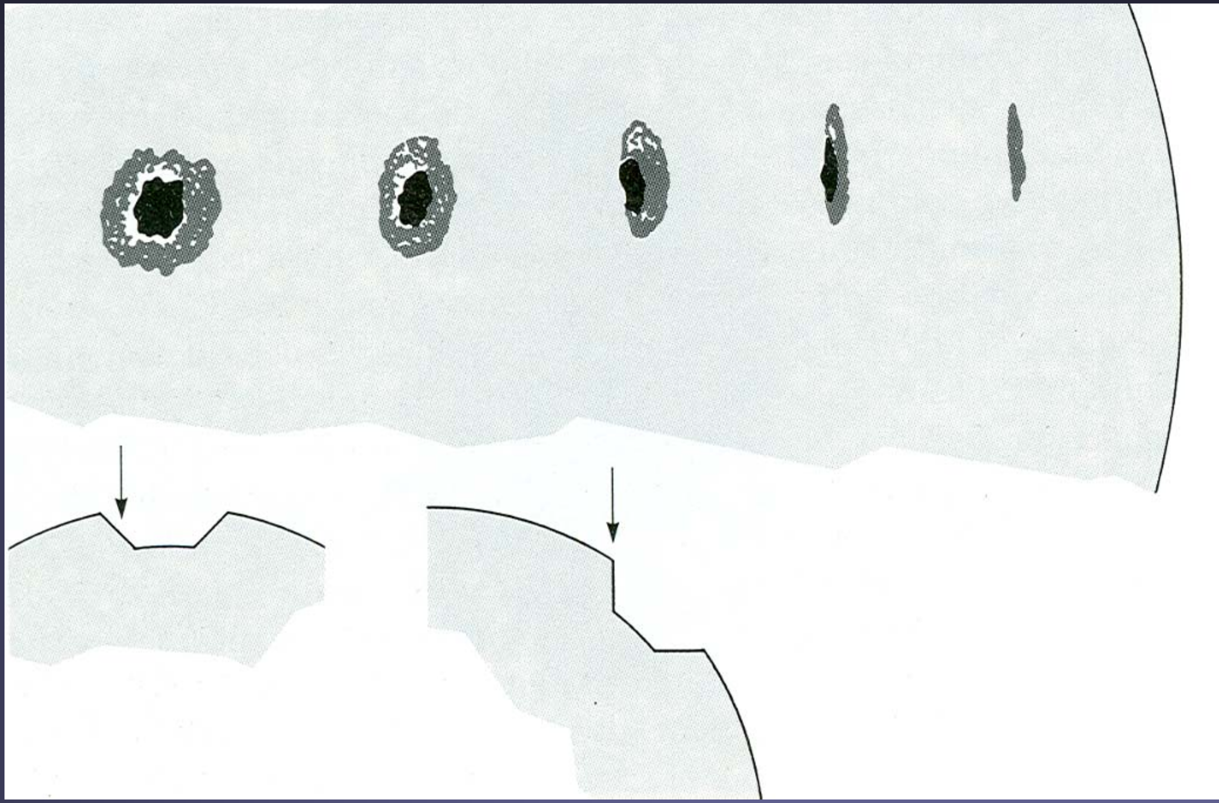
Rump of a flux tube

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

- Correct interpretation by Wilson (18th century).



Other interpretation by e.g. W. Herschell: photosphere is a layer of hot clouds through which we see deeper, cool layers: the true, populated surface of the Sun.

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

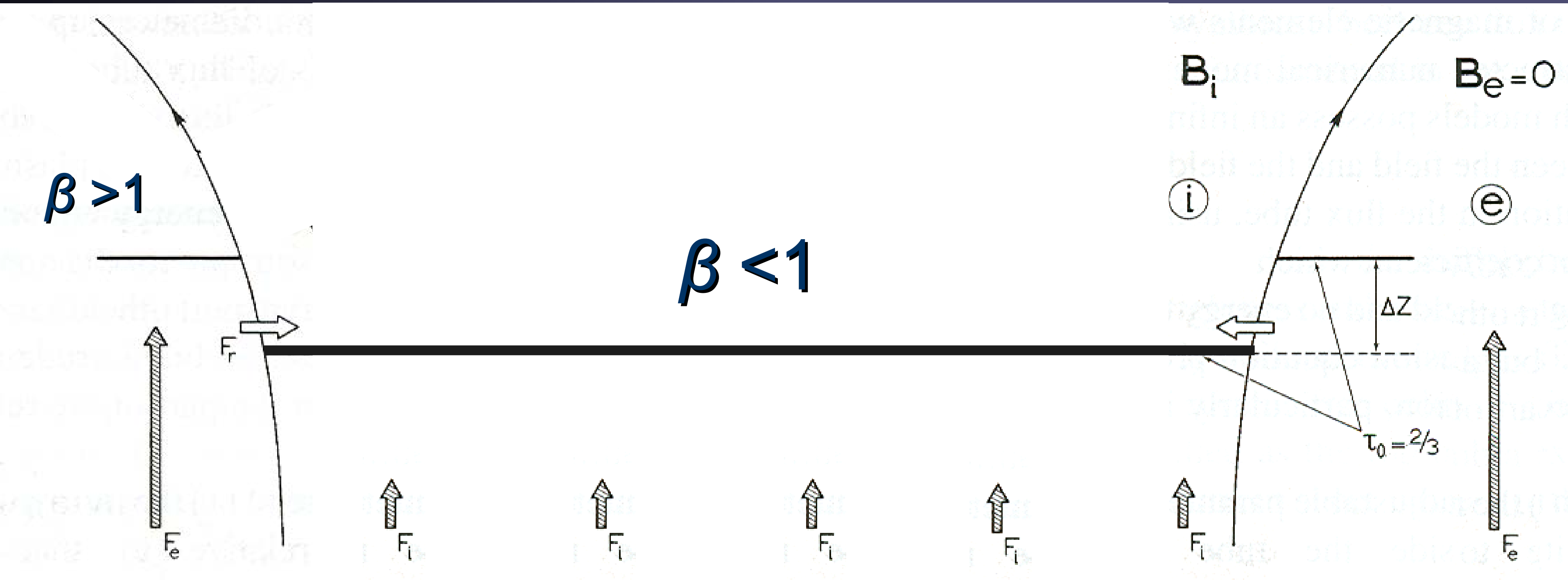
- Darkness: Opacity in the solar photosphere is due to the H^- ion, which depends strongly on temperature. In sunspots temperature is lower ➔ opacity is lower ➔ we see deeper. Responsible for ≈½ of observed effect
- Magnetic field: Magnetic field produces a pressure ~$B^2/8\pi$. Due to pressure balance with surroundings:

$$\frac{B_{\mathrm{spot}}^2}{8\pi} + P_{\mathrm{spot}} = P_{\mathrm{surr}} \rightarrow P_{\mathrm{spot}} << P_{\mathrm{surr}} \rightarrow \rho_{\mathrm{spot}} << \rho_{\mathrm{surr}}$$

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

Why are sunspots dark?

- Basically the strong magnetic field, not allowing motions across the field lines, quenches convection inside the spot.
- Since convection is the main source of energy transport just below the 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)

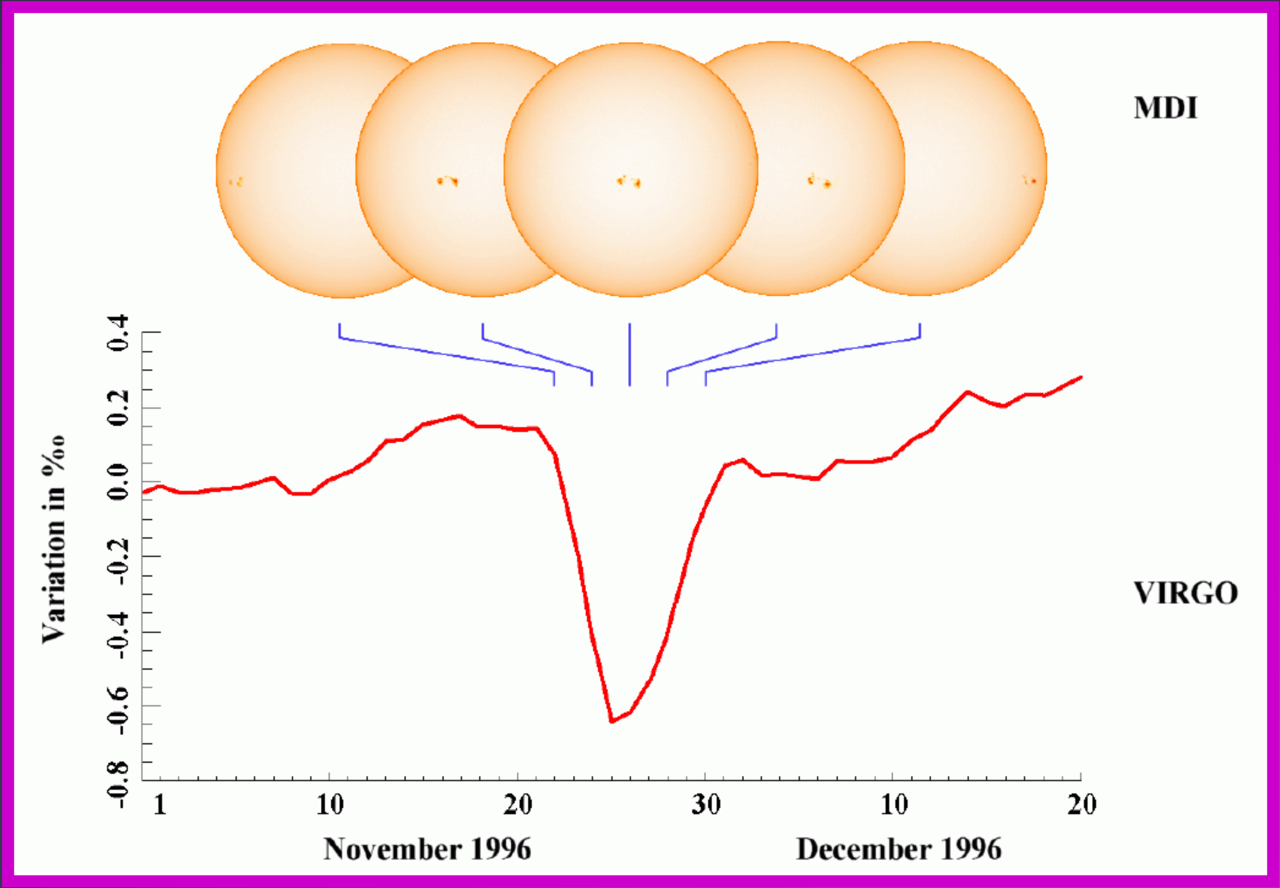
➔ Short diffusive timescale of CZ: blocked heat is redistributed in CZ within 1 month – 1 year (at most only very weak bright rings around sunspots)

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 irradiance during passage of a sunspot group

- The Sun as a whole darkens when spots move across its disc
- I.e. the blocked heat does not reappear somewhere else on a timescale of days to weeks



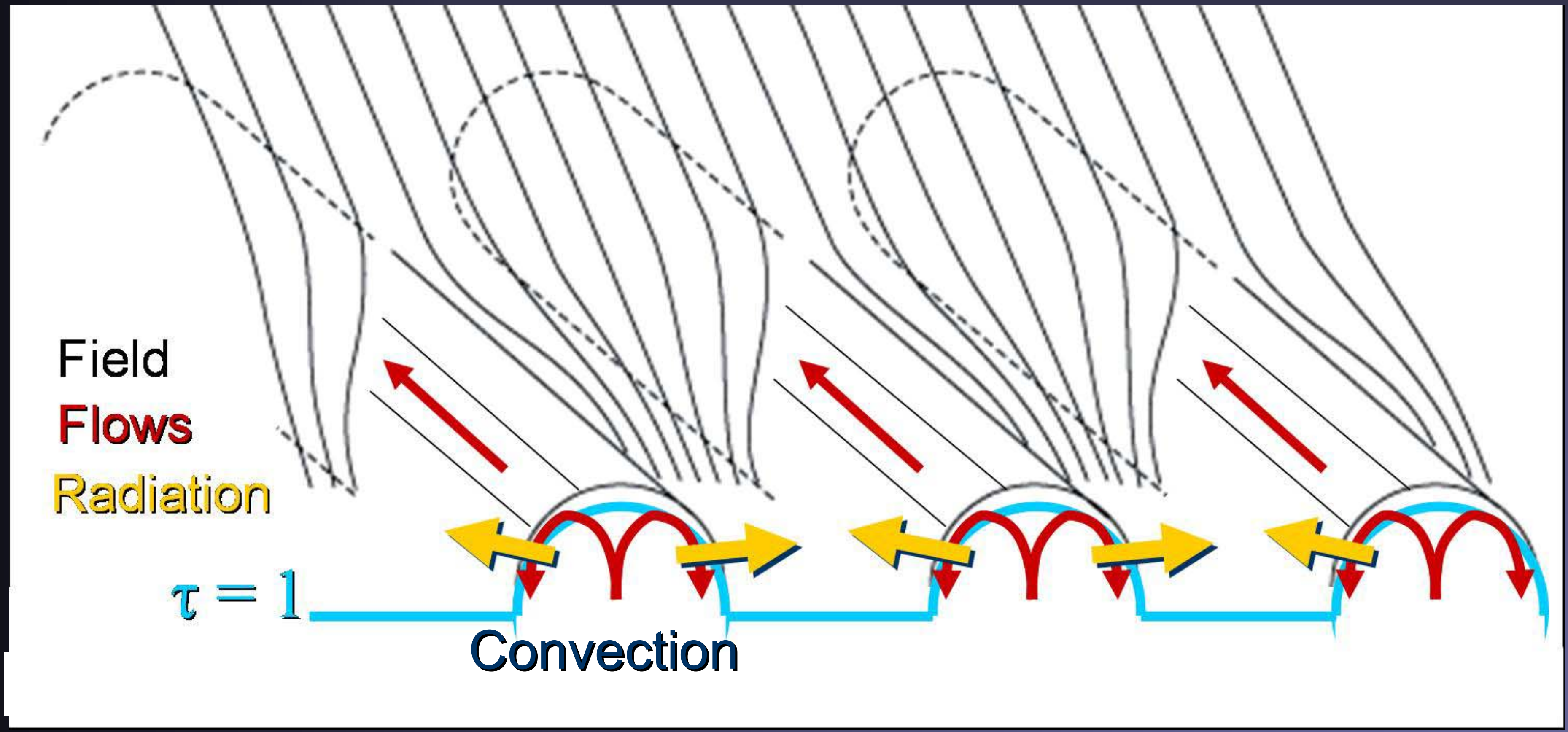
Why are sunspots so bright?

- Sunspot umbra:
  - 20% of photospheric radiative flux
  - 2000-4000 G mainly vertical field
- Sunspot penumbra:
  - 75% of photospheric radiative flux
  - 1000-2000 G complex, more horizontal field
- For both: normal convection completely quenched (Gough & Tayler 1966). Radiation carries <10% of energy from solar interior.

➔ Some form of magnetoconvection must be acting at small scales that transports the missing energy flux

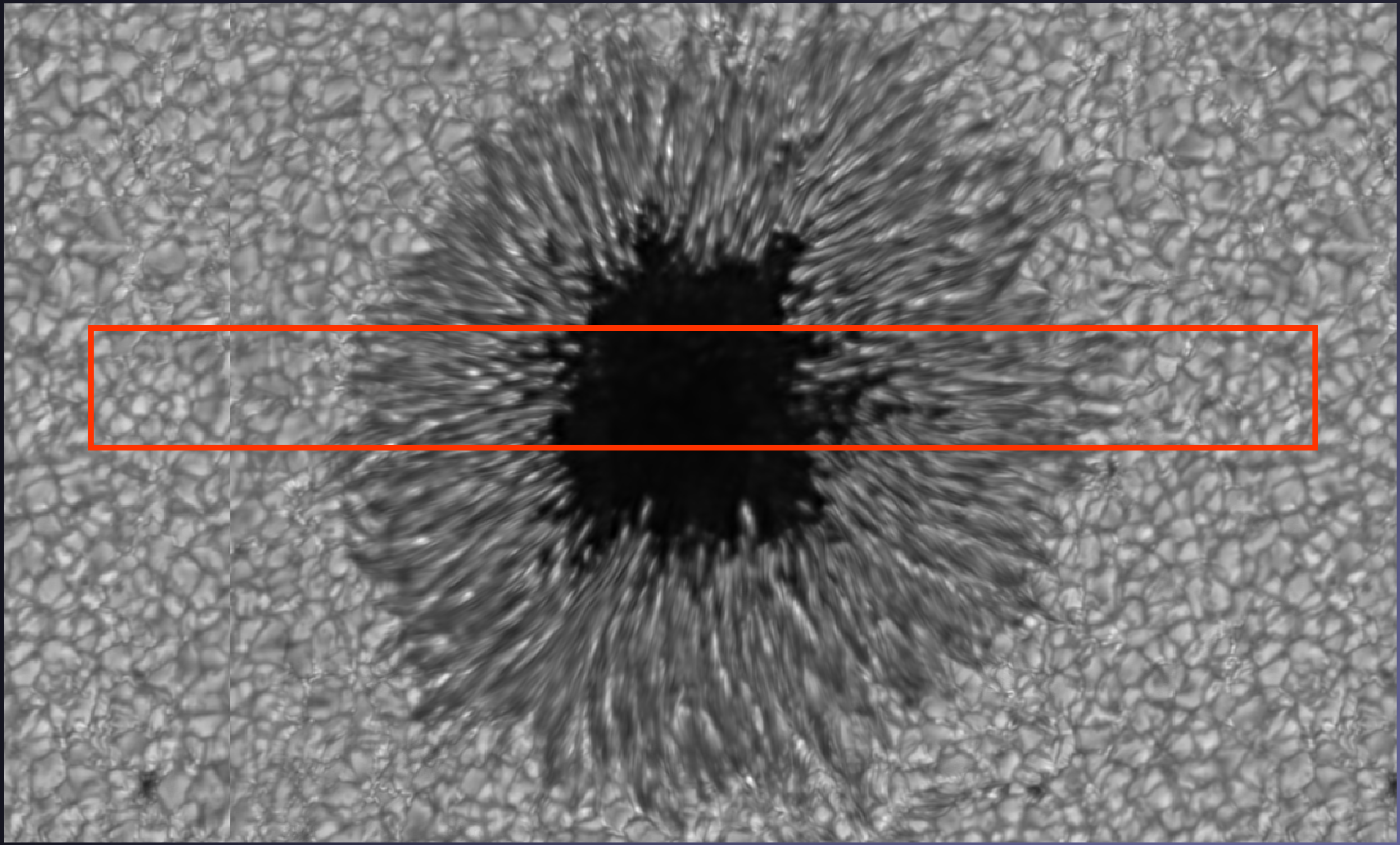
Current view of fine-structure of penumbra

Penumbra is bigger hurdle than umbra (75% of energy flux) and much more controversial



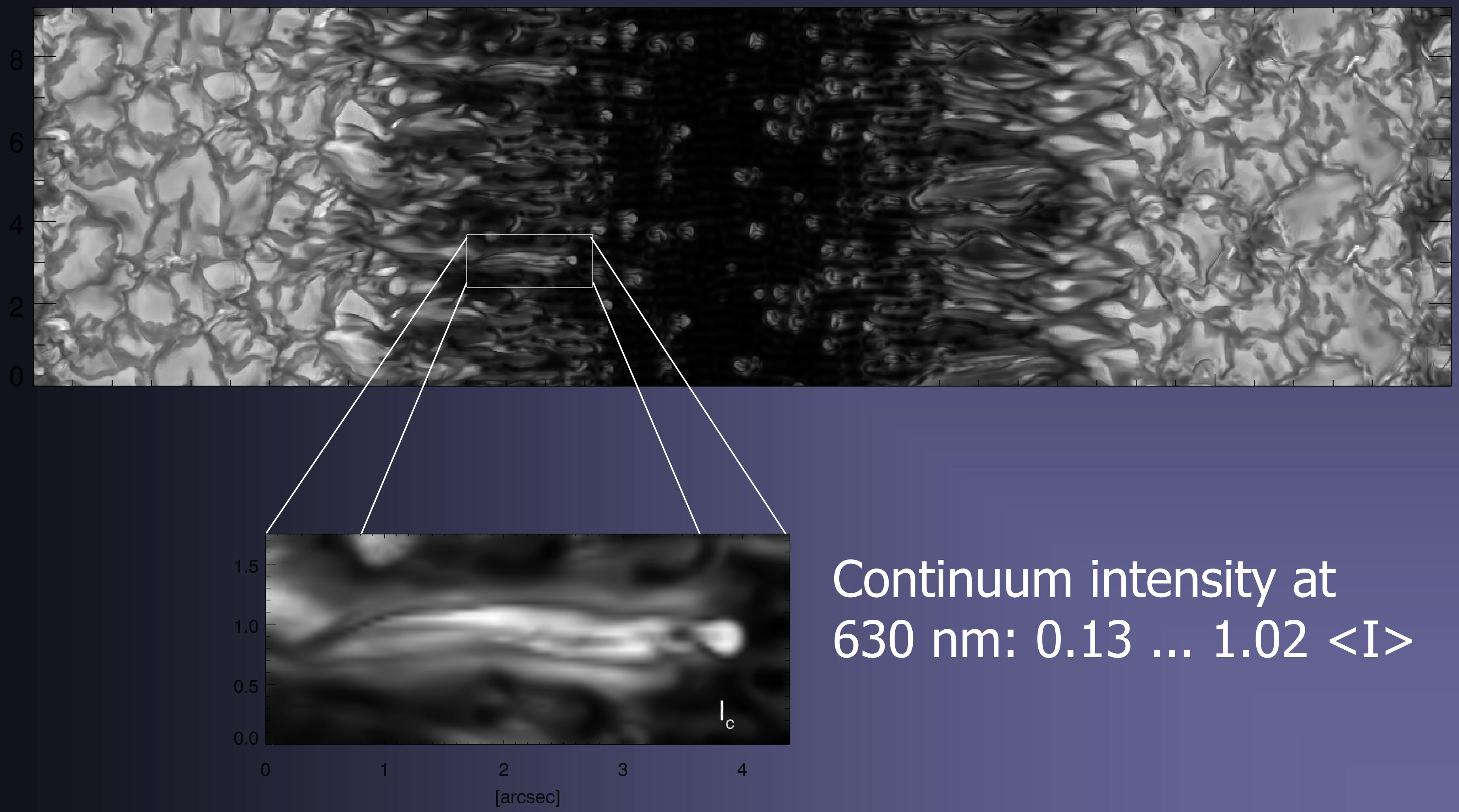
Zakharov et al. 2008, Rempel et al. 2008

MHD simulation of a sunspot



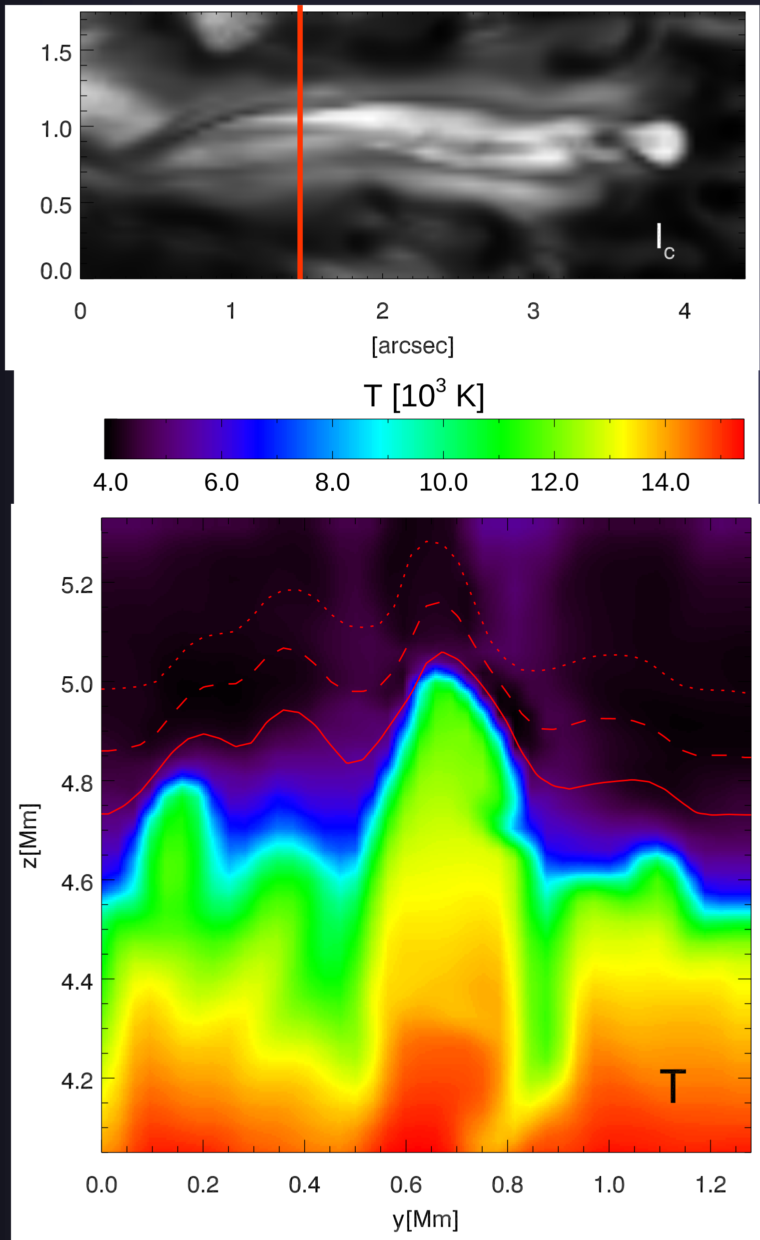
Red box represents the simulation box overlain on image of an observed spot

Detailed structure of a penumbral filament

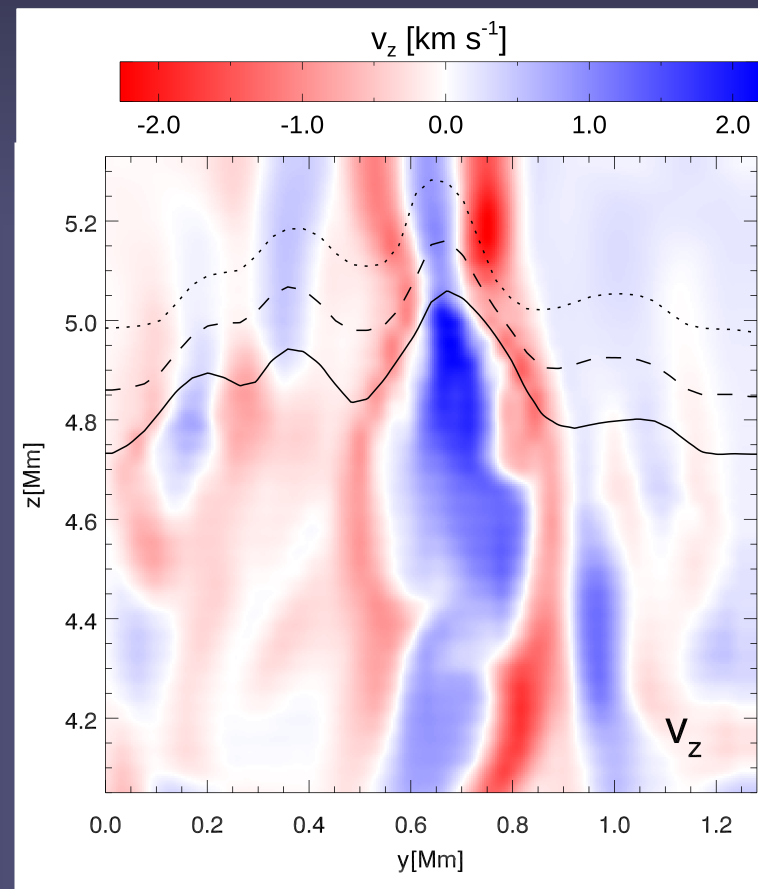


Continuum intensity at 630 nm: 0.13 ... 1.02 <I>

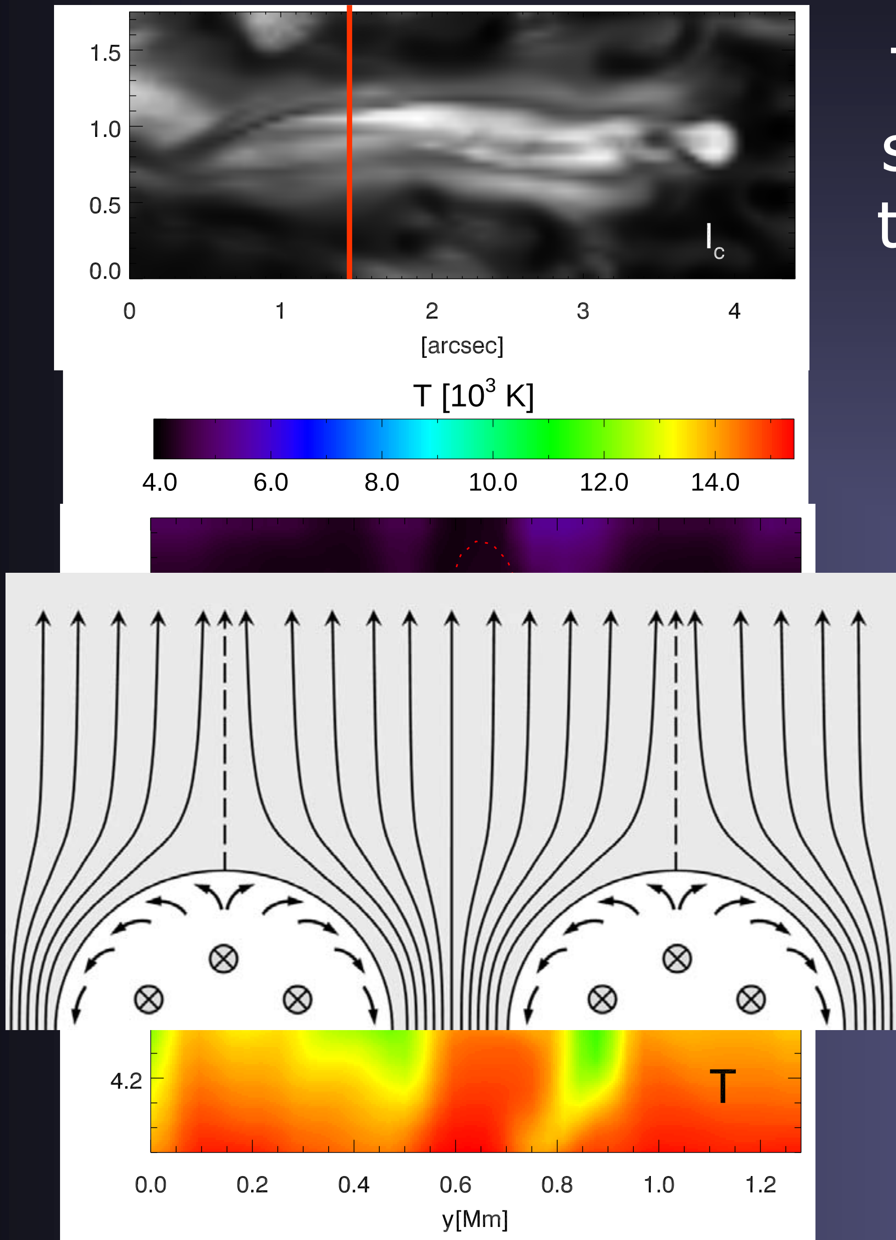
Cuts perpendicular to the filament



The filament is formed by a hot, sheet-like convective upflow that turns over and flows down at the sides of the filament



Cuts perpendicular to the filament



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