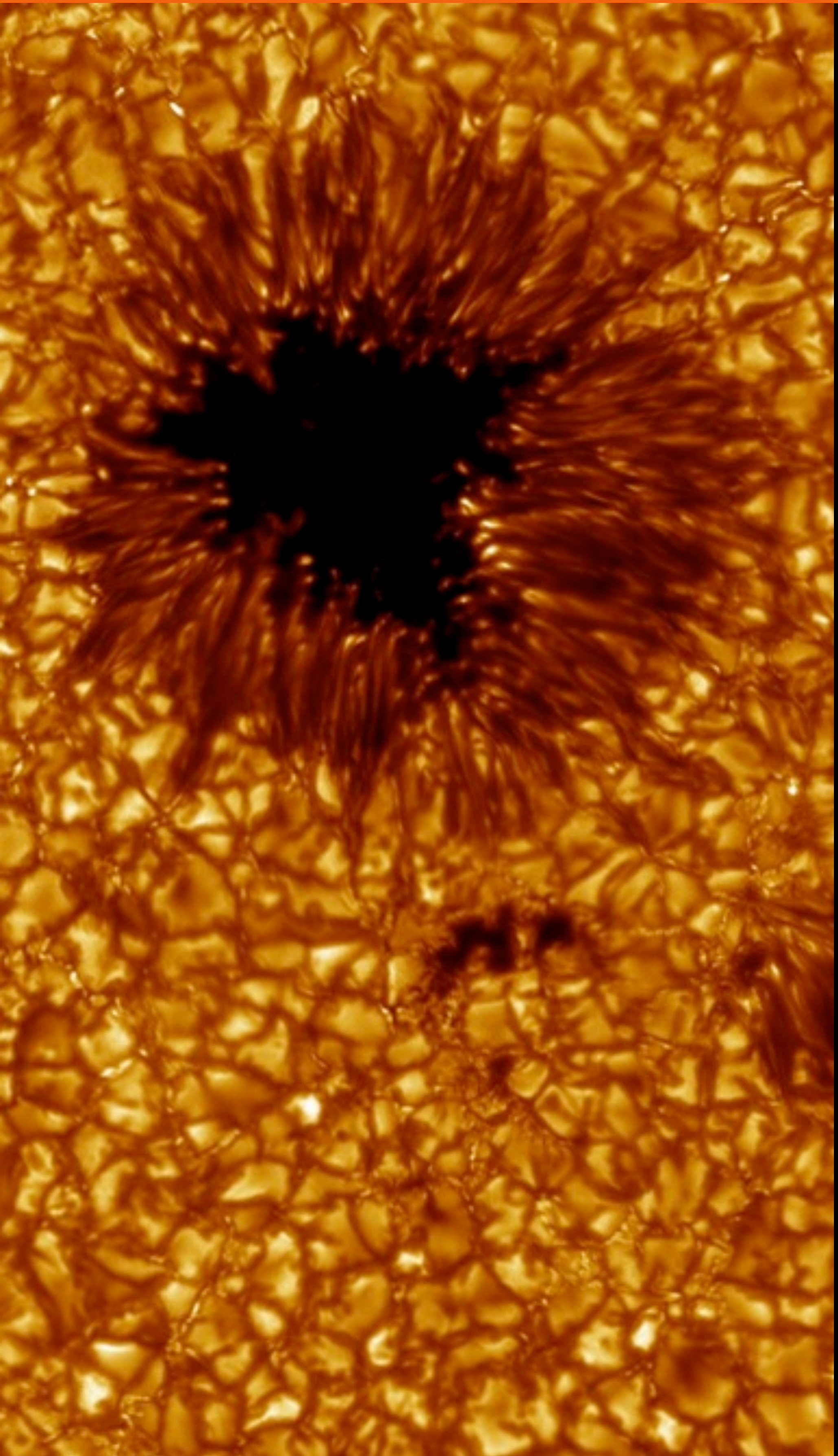
AST5770

Solar and stellar physics

Sven Wedemeyer, University of Oslo, 2023

Magnetic fields on the Sun - Quiz

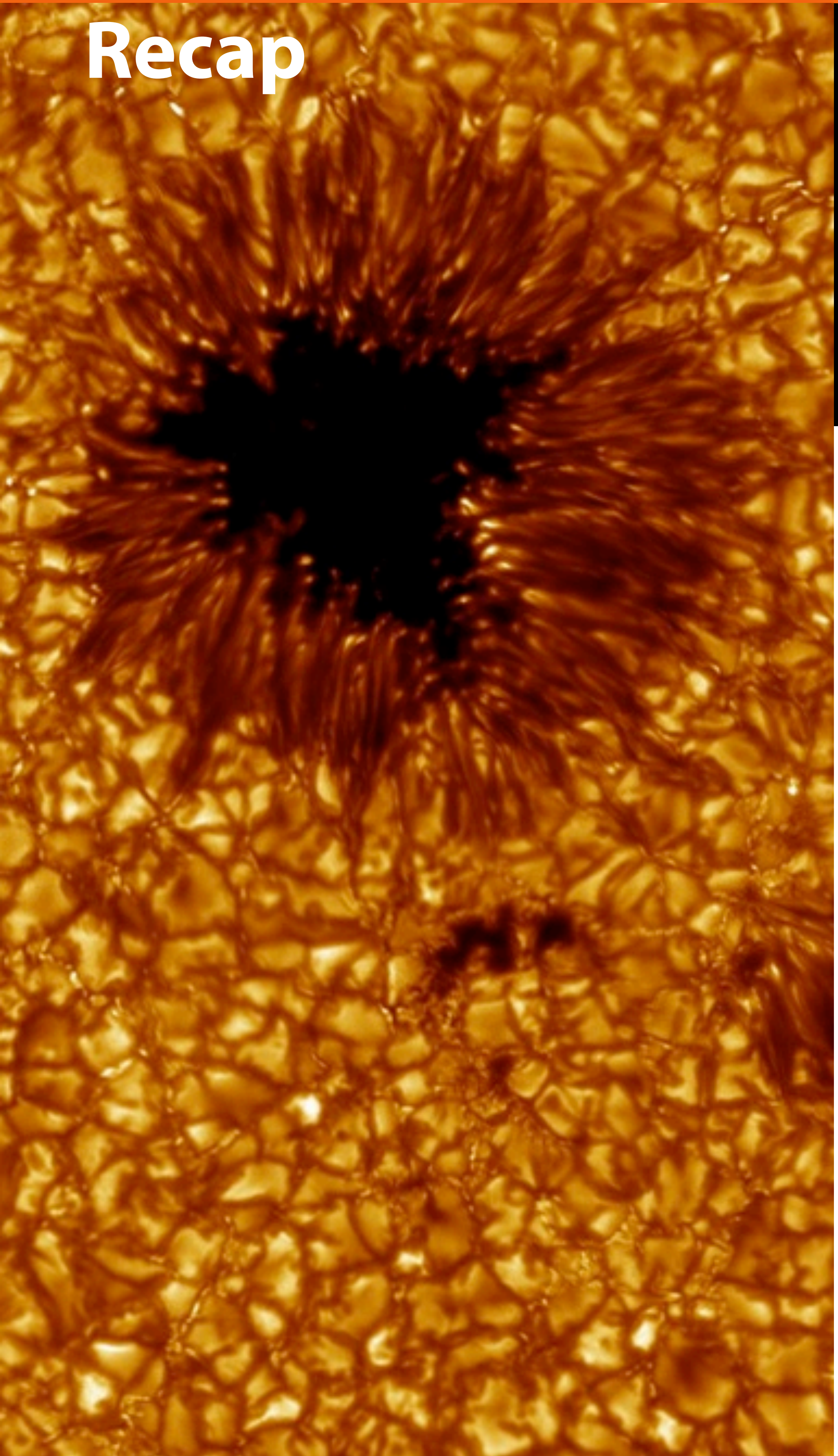


1. Which two major ingredients are needed for a global dynamo to work in a stellar interior?
2. What is the frozen-in condition and why is it important for the magnetic field topology in the solar photosphere?
3. How is plasma-beta defined?
4. What happens if plasma-beta is smaller than 1?
5. Why is the sunspot umbra dark in the photosphere?
6. What is an alpha-sunspot?
7. What is a sea serpent on the Sun?

Discuss in groups of 2-3.

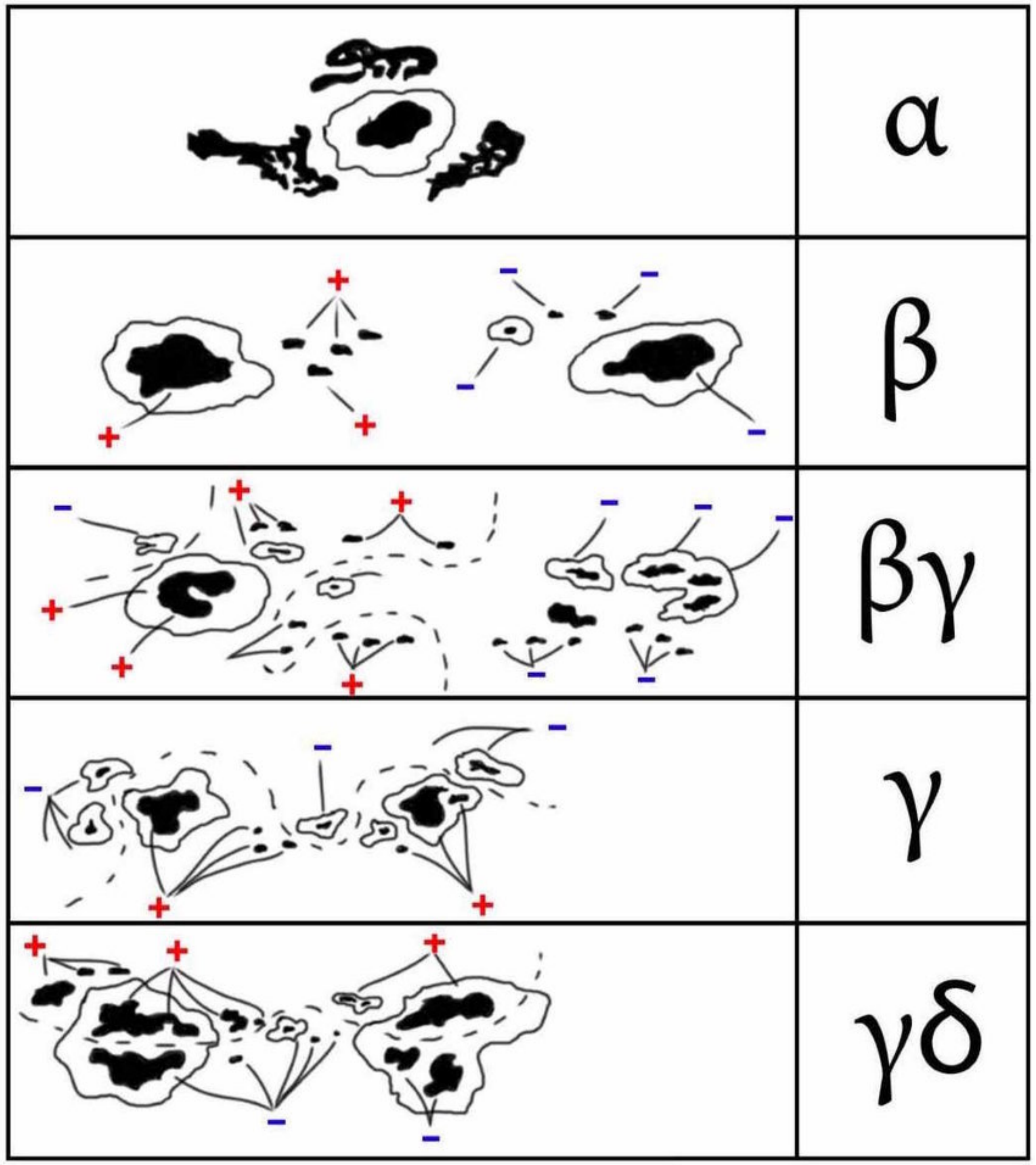
Sunspots

Recap



The Sun's magnetic field has a complicated topology.

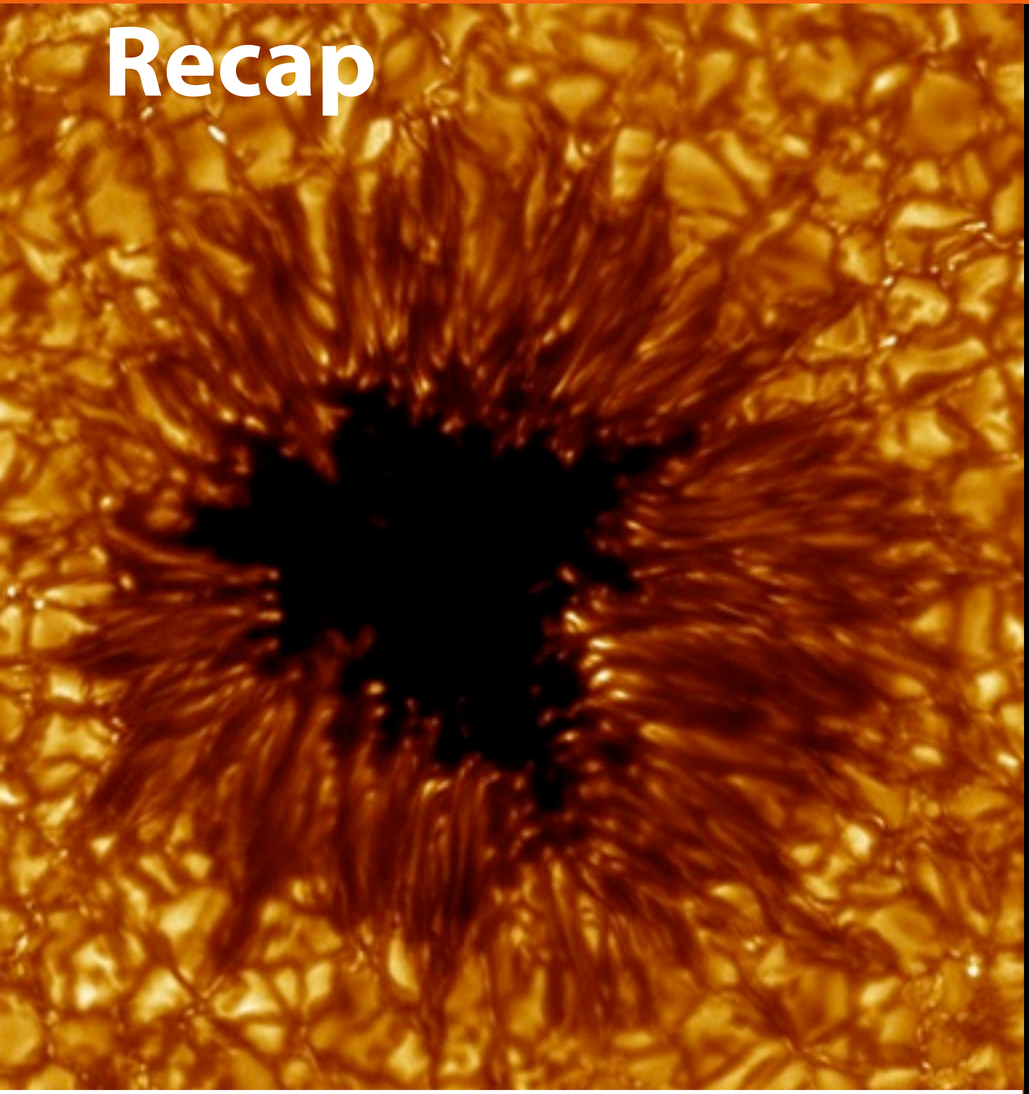
- Sunspot classification from **α to δ** (simple to complex)
- Sizes: a few 10 Mm (3Mm — 60 Mm)
- Lifetimes: hours for small sunspots to (rarely) months
- Lifetime + contained magnetic flux scale with sunspot area

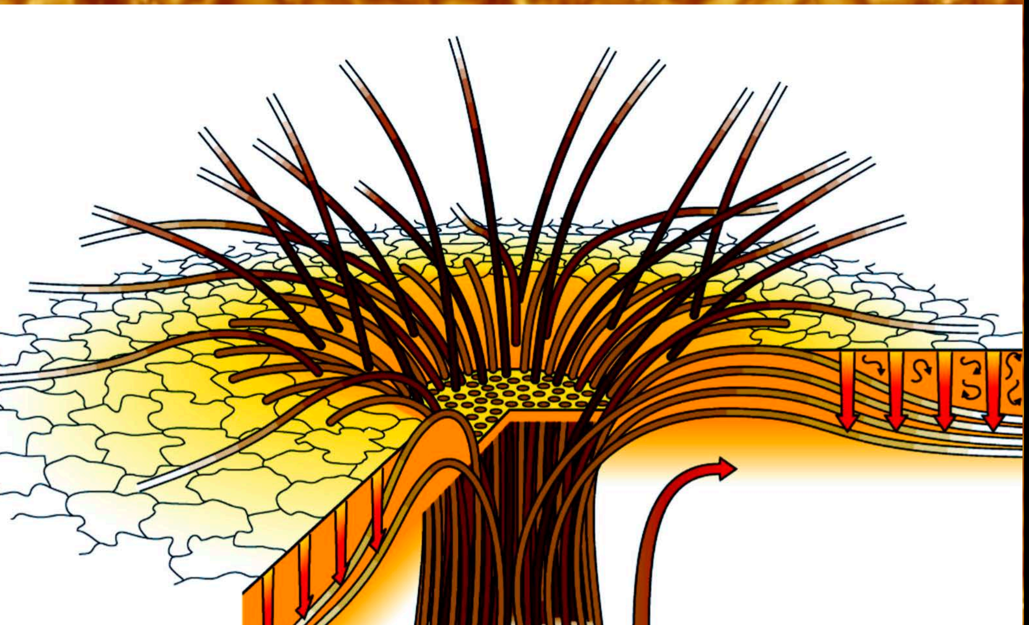


Andrus 2013

Sunspots

Recap





Thomas 2002

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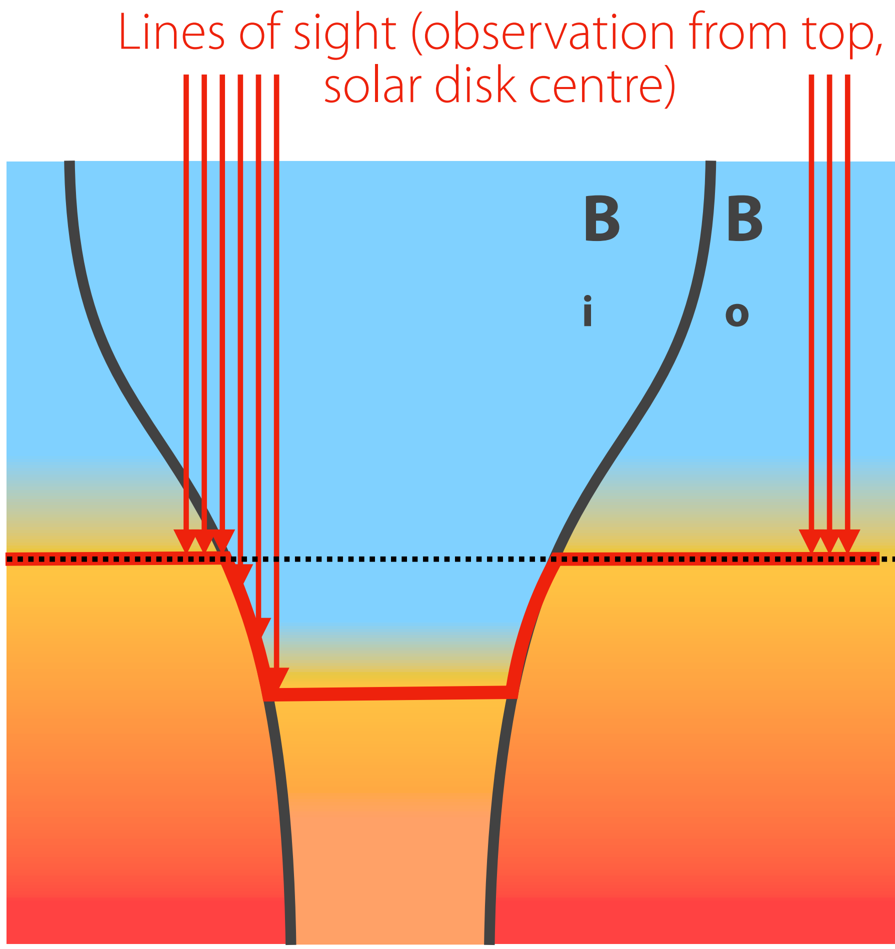
- Sizes: a few 10 Mm (3Mm — 60 Mm)
- Lifetimes: hours for small sunspots to (rarely) months
- Lifetime + contained magnetic flux scale with sunspot area
- Magnetic field strength in **umbra 2-4 kG**
- Magnetic field configuration
  - Mostly vertically aligned in central umbra (photosphere)
  - "**Uncombed penumbra**": Mix of horizontally aligned and inclined magnetic field
- Strong fields inhibit convective energy transport below sunspot
  - Umbra: temperature below 4000K, brightness ~20% of Quiet Sun (appears dark)
- **Evershed flow** = outflows in penumbra along filaments with supersonic components — a result of of magneto-convection and complicated magnetic field structure of the penumbra

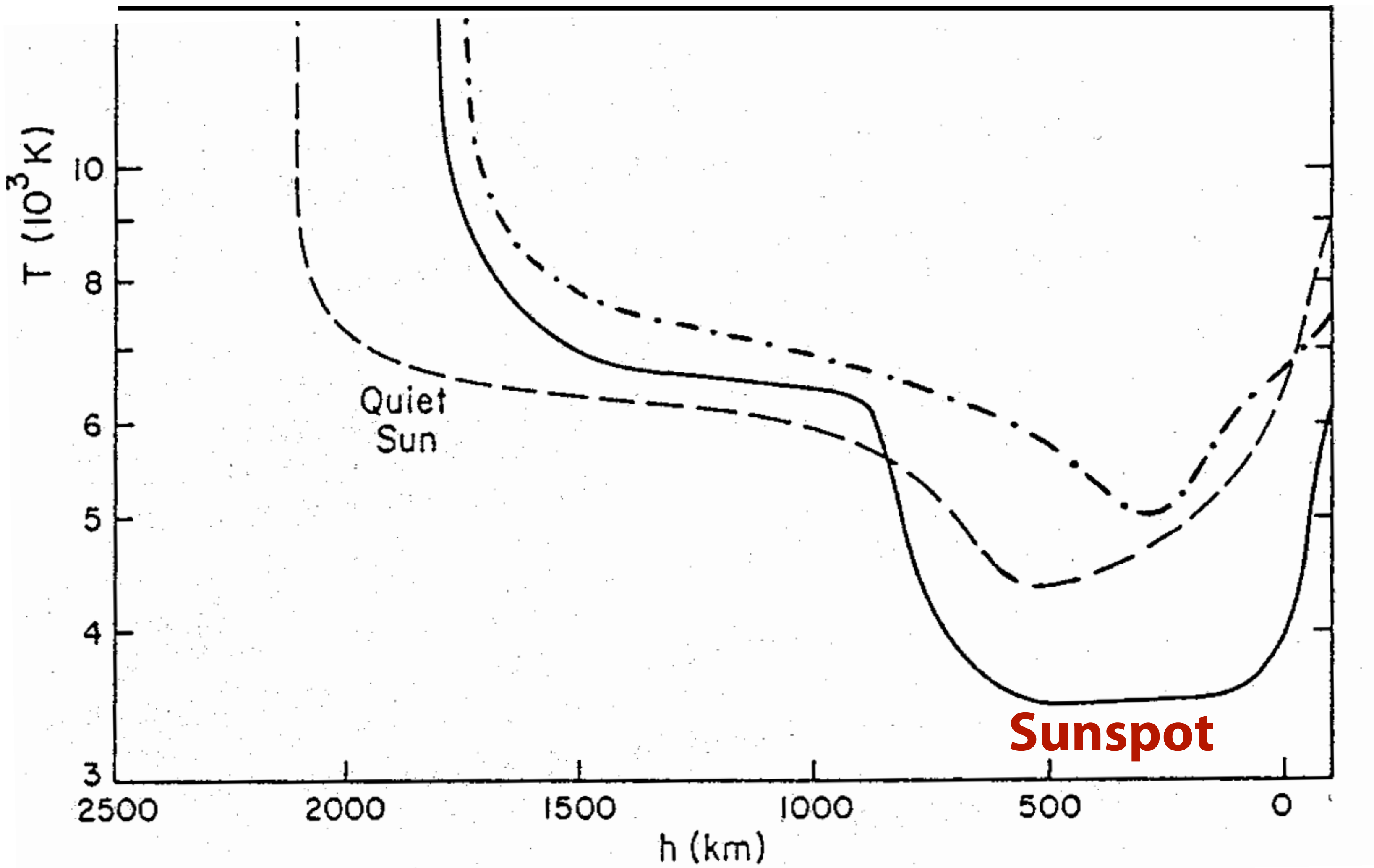
Sunspots

Recap

- Magnetic pressure due to (strong) magnetic field results in lower density and thus lower opacity

➡ **Optical depth lower** inside magnetic field structure than outside (in sunspots: **Wilson depression**)

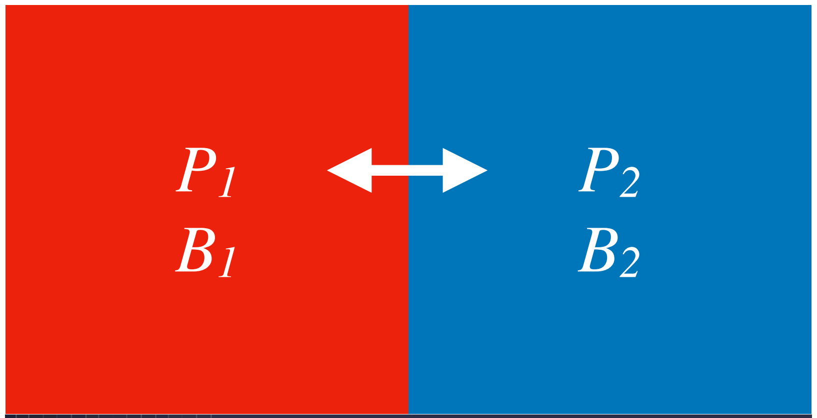




- Temperatures in sunspot umbra much below Quiet Sun values (sunspots appear dark in the photosphere relative to surrounding)
- Sunspot temperatures rise quickly in low chromosphere, surpass Quiet Sun temperatures

Sunspots

Magnetic pressure and equipartition field strength



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

Pressure balance between two different domains (1 and 2):

- Extreme case: $B_2 = 0$ and domain 1 is evacuated ($P_{gas,1}=0$):

  $P_1 = P_2 \Rightarrow B_1^2 / 8\pi = P_2 \qquad (P_2 = P_{gas,2})$

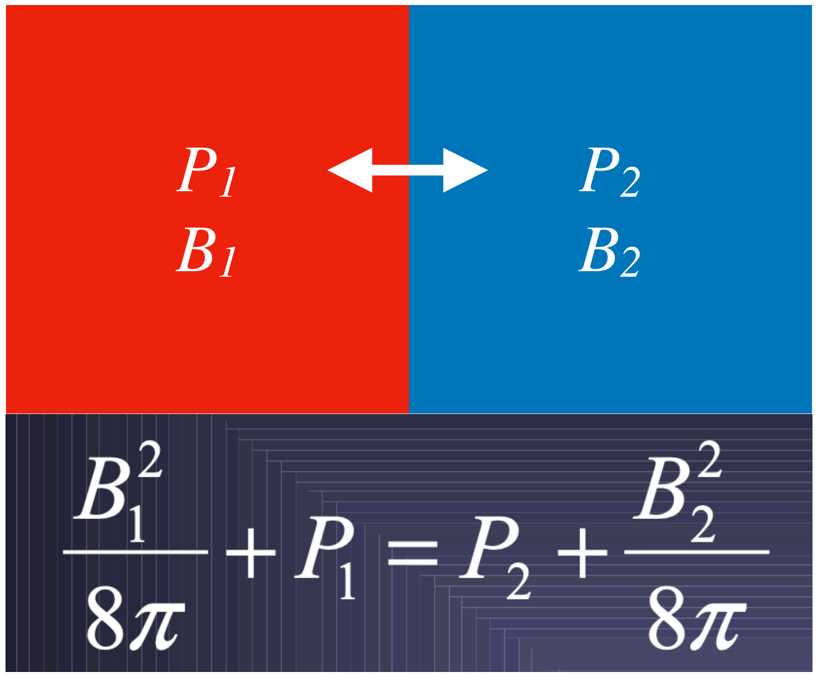
➡ Sets a maximum field strength for region 1 to be in balance with the (surrounding) region 2:

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

Sunspots

Magnetic pressure and equipartition field strength



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- **Pressure in the low photosphere of the Sun $P_2 = 10^5$ dyn cm^{-2} (VAL Model C, 1981)**

	h (km)	m (g cm^{-2})	τ_{500}	T (K)	V (km s^{-1})	n_H (cm^{-3})	n_e (cm^{-3})	P_{total} (dyn cm^{-2})	P_{gas}/P_{total}	σ (g cm^{-3})
43	450	9.378-02	1.017-03	4220	.53	3.989+15	4.516+11	2.569+03	.9949	9.327-09
44	350	2.481-01	5.626-03	4465	.52	9.979+15	1.110+12	6.798+03	.9954	2.334-08
45	250	6.172-01	2.670-02	4780	.63	2.315+16	2.674+12	1.691+04	.9936	5.413-08
46	150	1.433+00	1.117-01	5180	1.00	4.917+16	6.476+12	3.926+04	.9854	1.150-07
47	100	2.118+00	2.201-01	5455	1.20	6.866+16	1.066+13	5.804+04	.9801	1.606-07
4[illegible]	50	3.056+00	4.395-01	5840	1.40	9.203+16	2.122+13	8.274+04	.9748	2.152-07
49	0	4.279+00	9.953-01	6420	1.60	1.166+17	6.433+13	1.172+05	.9702	2.727-07
50	-25	4.991+00	1.683+00	6910	1.70	1.261+17	1.547+14	1.368+05	.9688	2.949-07

Sunspots

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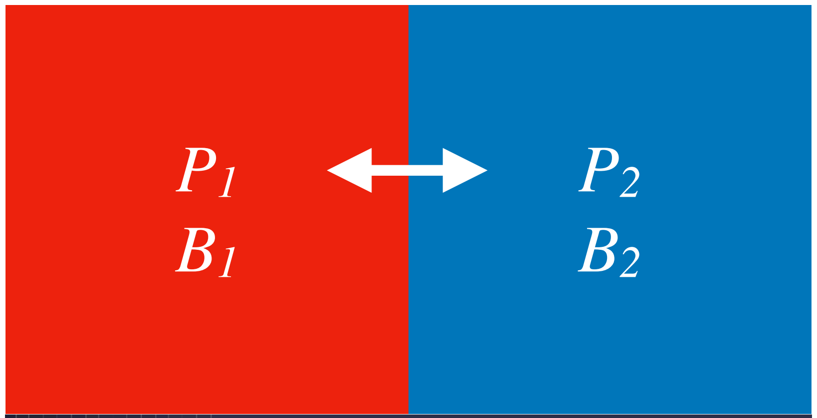

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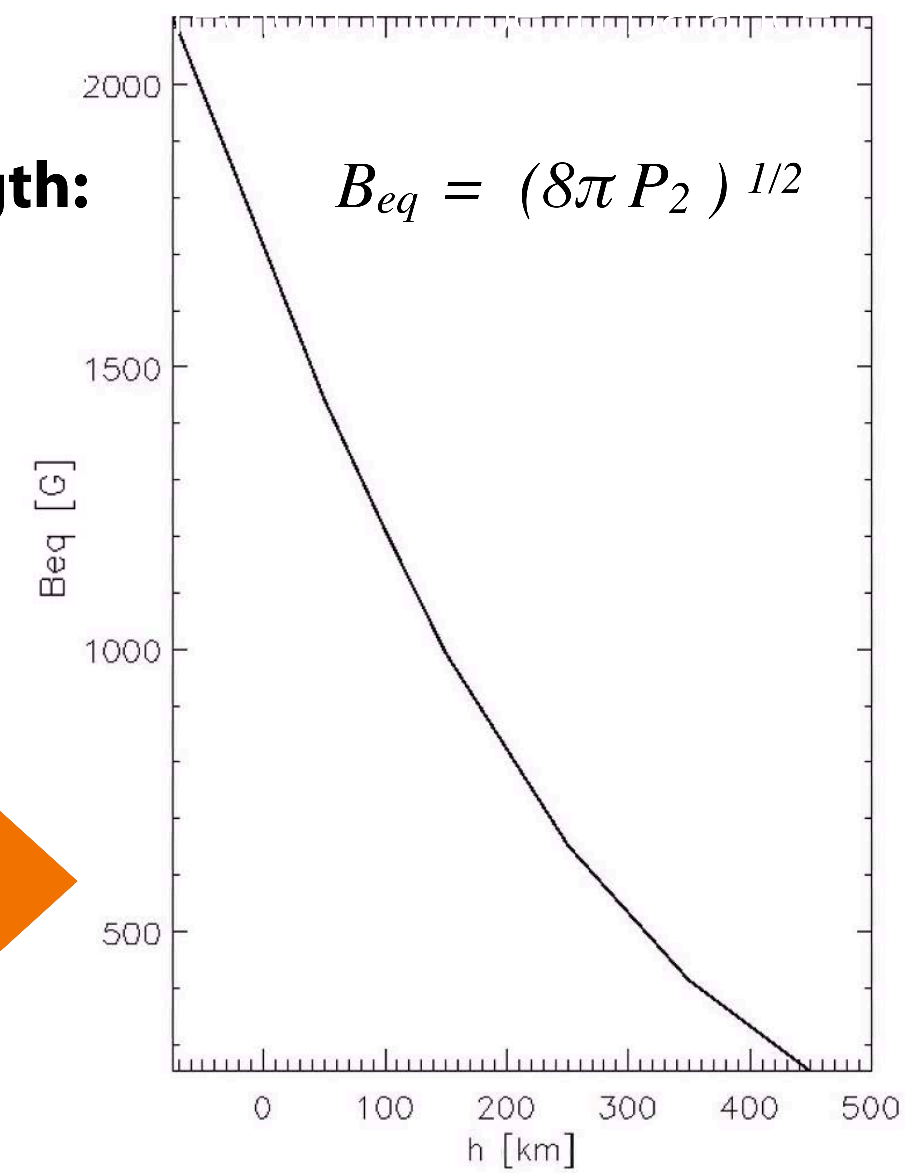
equipartition field strength: $B_{eq} = (8\pi P_2)^{1/2}$



- **Pressure in the low photosphere of the Sun**

➡ **Kilo-Gauss field strengths!**

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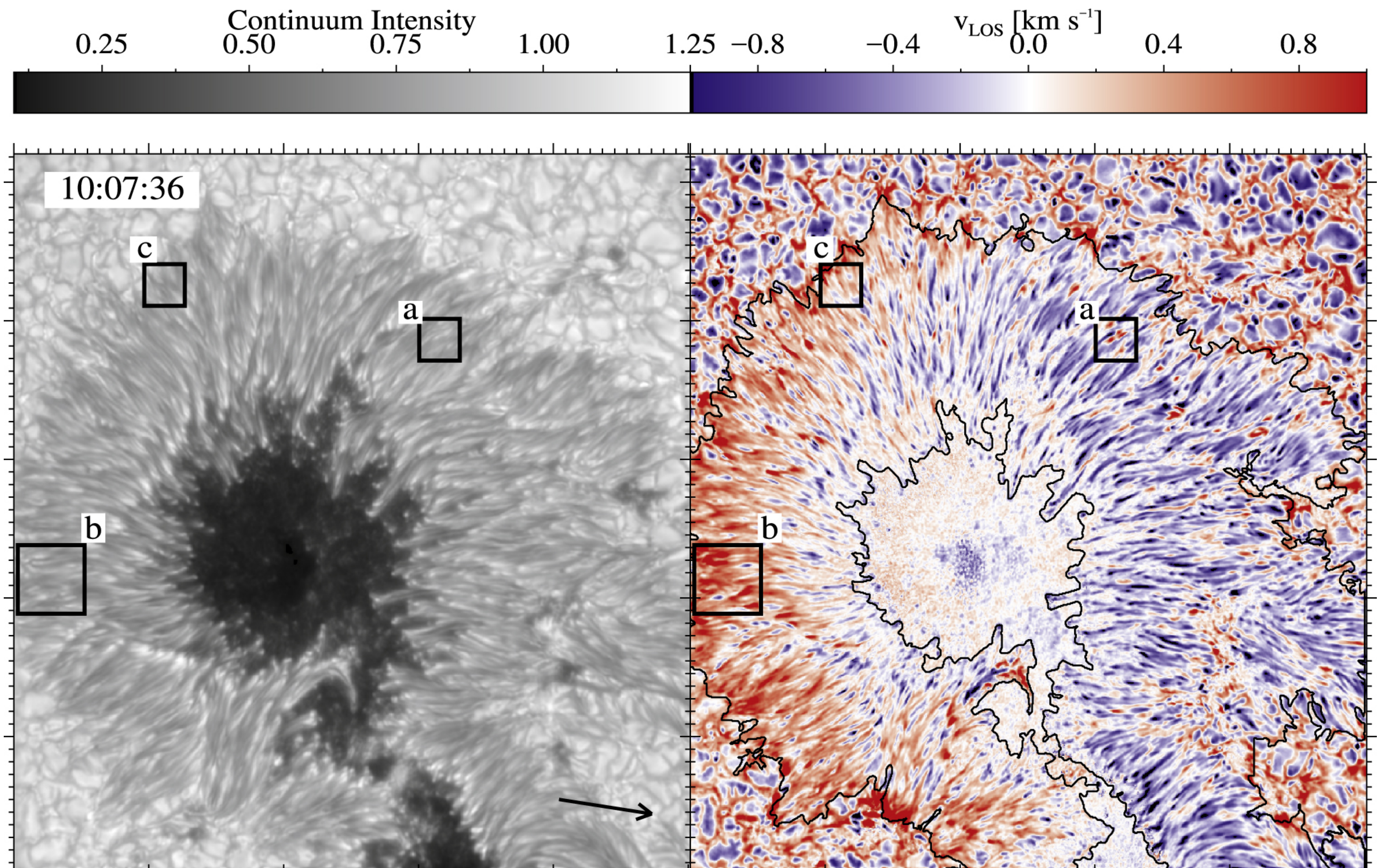
51	-50	5.747+00	3.338+00	7610	1.76	1.317+17	4.645+14	1.575+05	.9697	3.080-07
52	-75	6.534+00	7.445+00	8320	1.80	1.365+17	1.204+15	1.790+05	.9711	3.192-07

Sunspots

Evershed effect / flow



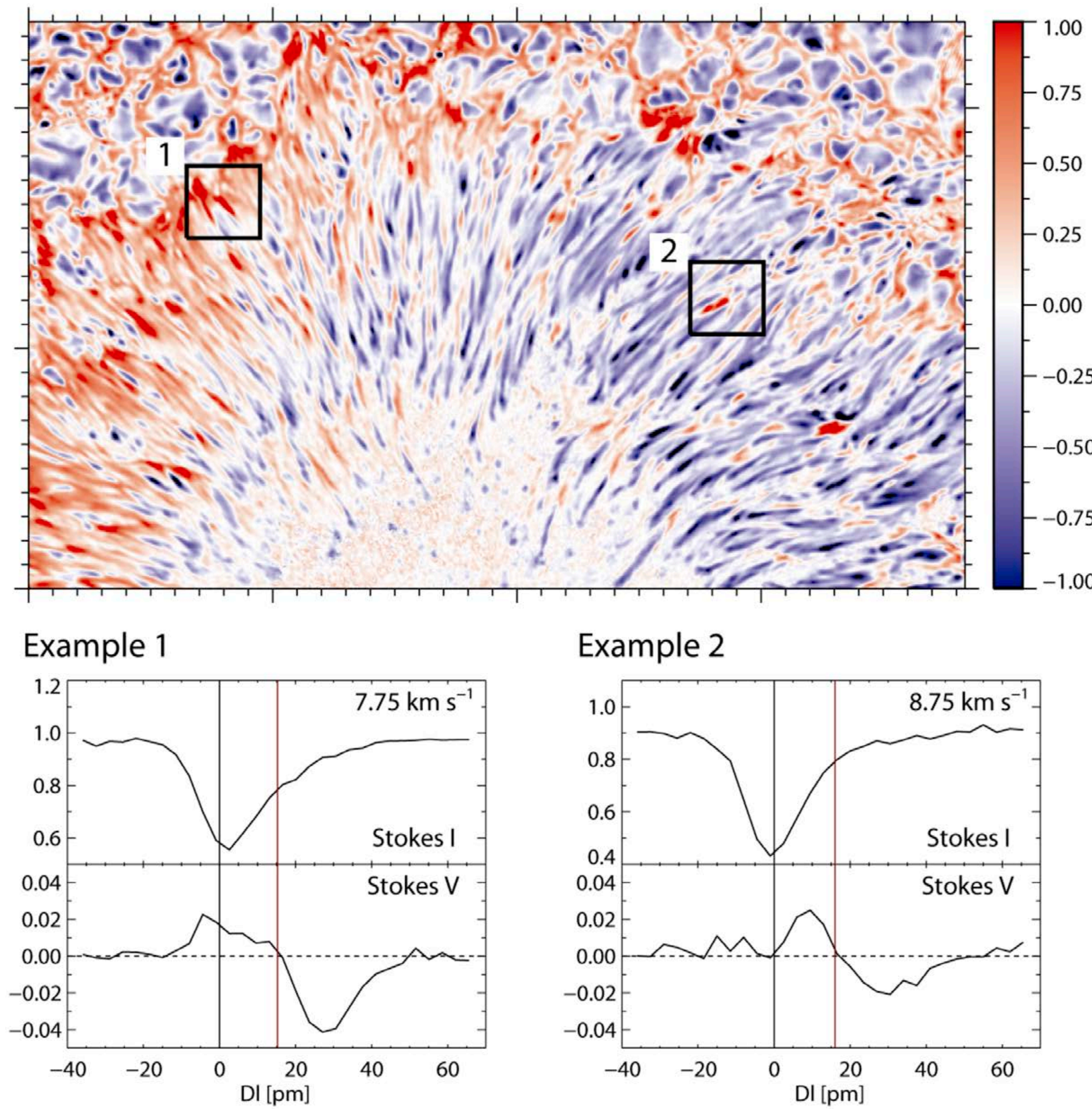
Esteban Pozuelo et al. (2016)

Be aware of project effects depending on the location of the sunspot on the solar disk.

Sunspots

Evershed effect / flow

- Evershed flow = outflows in the penumbra along filaments with nearly horizontal magnetic field
  - Field strengths 1 — 2kG (only slightly larger than average penumbral values)
- First discovered by Evershed (1909) from Dopper-shifted spectral lines in sunspots
- Division in mid-penumbra: most penumbral grains inside move inwards to umbra, those outside move **towards moat**
- **Supersonic** components with velocities ~8 km/s in photosphere, occasionally up to 15-16 km/s
  - Supersonic flows last 1-5min



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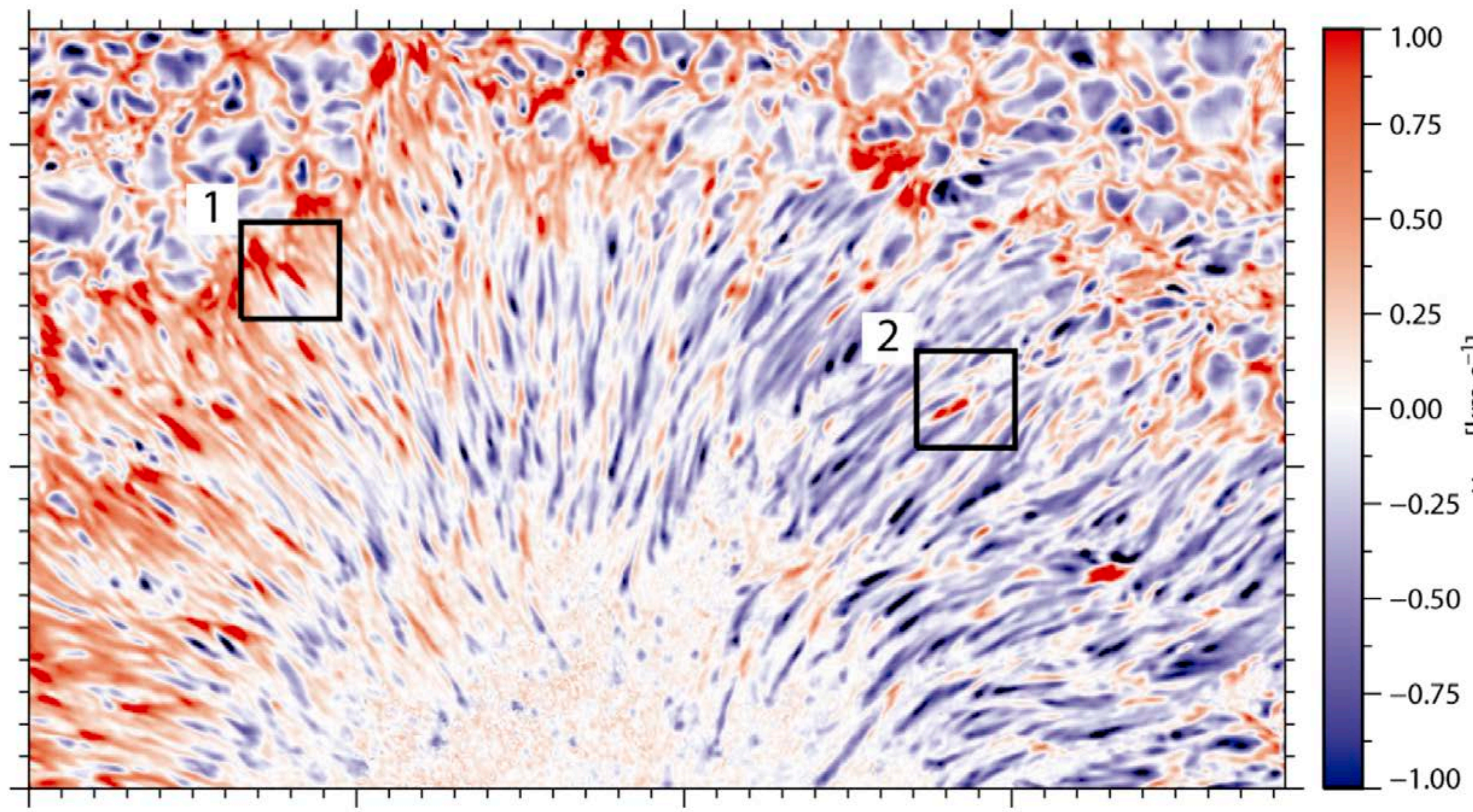


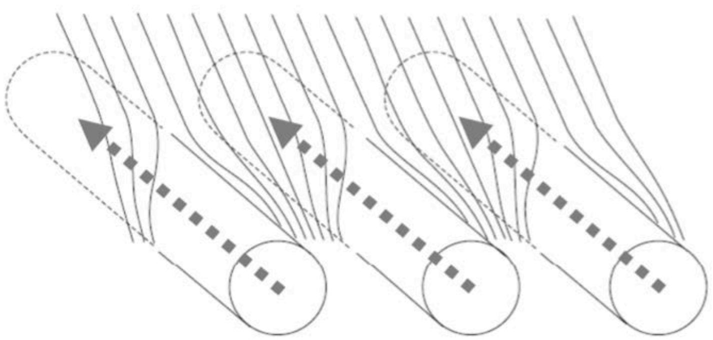
- Rapid decline of flow speed with height (in the photosphere)
- In chromosphere/transition: **Inflow** with higher velocities than the outflows below
  - Known as **inverse Evershed flow.**

Be aware of project effects depending on the location of the sunspot on the solar disk.

Esteban Pozuelo et al. (2016)

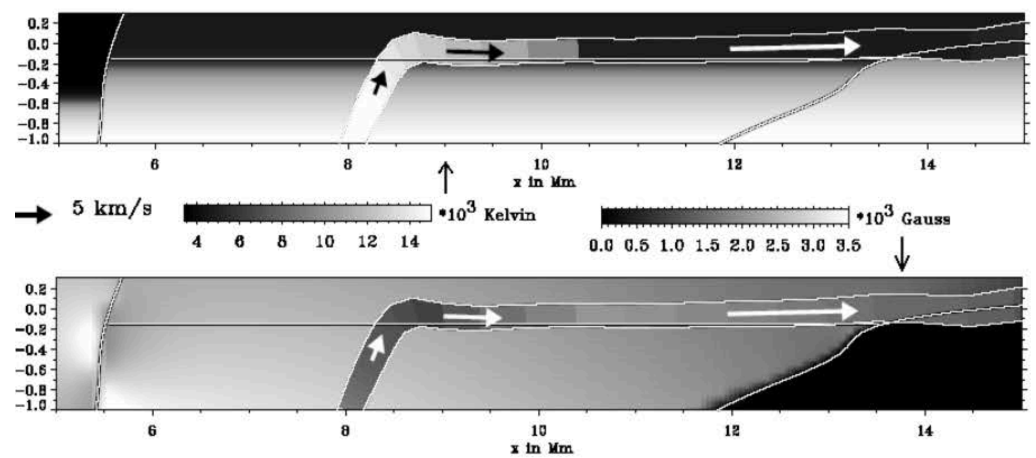
Sunspots

Evershed effect / flow



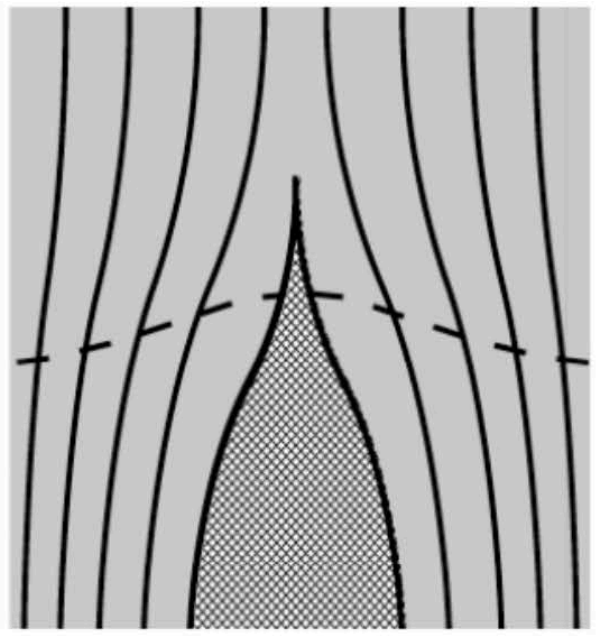
Embedded flux tube model

(e.g., Solanki & Motavon 1993
Schlichenmaier etal 1998)



Gappy model

(e.g., Spruit & Scharmer 2006)



Bright filaments = field free gap = protrusion of convection

- Different models explaining the penumbral structure and flows but typically only accounting for some and not all observed aspects
- Explanation lies in combination of overturning **convection** in competition with strong magnetic field (inhibiting convection when strong, permitting otherwise) and the **complicated magnetic field structure of the penumbra** (horizontal and inclined field)

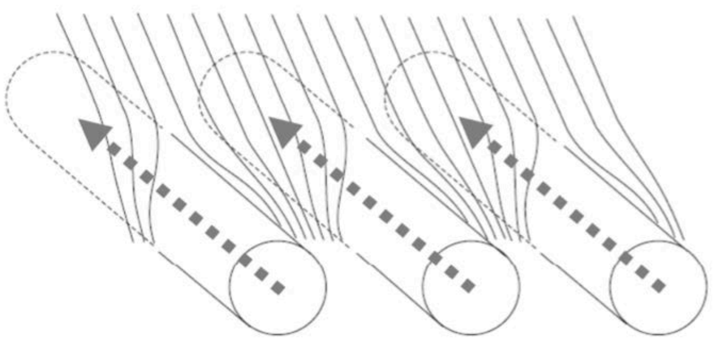
➡ Evershed flow identical to horizontal component of penumbral convection, driven by pressure gradients, flows deflected horizontally through Lorentz-force generated by horizontally stretched magnetic fields

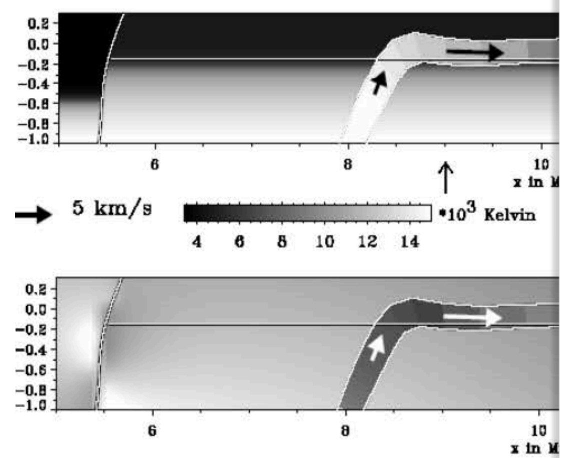
$$\mathbf{F} = q\,(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

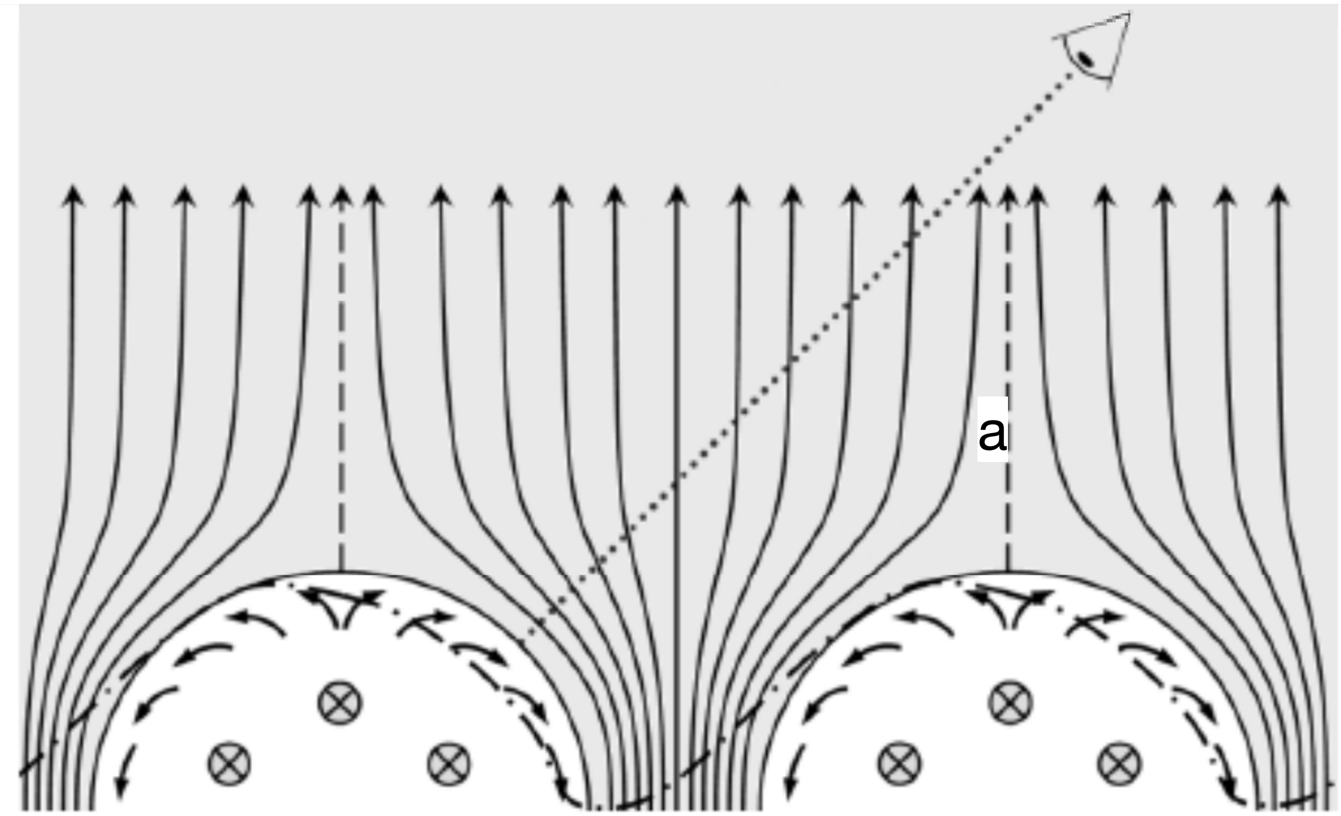
Sunspots

Evershed effect / flow

Embedded flux
(e.g., Solanki & Motav
Schlichenmaier e







V. Zakharov, etal., 2008,
A & A manuscript no. 0266 c ESO

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Sunspots

Bridges and dots

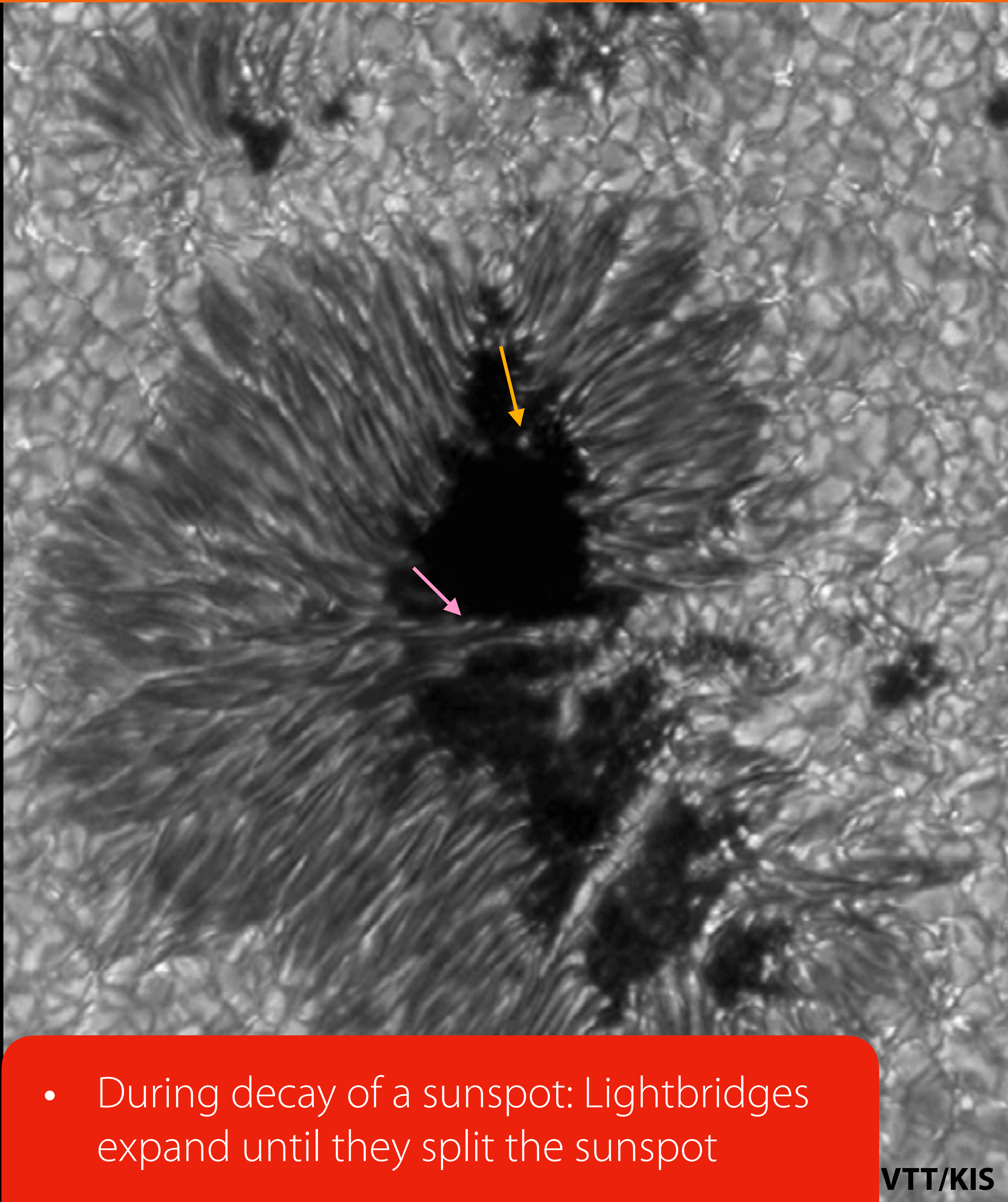
- Strong magnetic fields in umbra inhibit convection — no granulation
- **Decaying sunspots**: magnetic field strength decreases

➡ **Magneto-convection** can prevail again at some locations at first

➡ Visible consequences: **umbral dots** and **light bridges**

- Both have a central dark lane and bright edges
- Light bridges:
  - Extend across umbra, splitting it and connecting penumbra on both sides
  - Blue and redshifted velocities detected!

  ➡ Convection ongoing!



- During decay of a sunspot: Lightbridges expand until they split the sunspot

Sunspots

Bridges and dots

- Strong magnetic fields in umbra inhibit convection — no granulation
- **Forming sunspots**: magnetic field strength at surface still increases

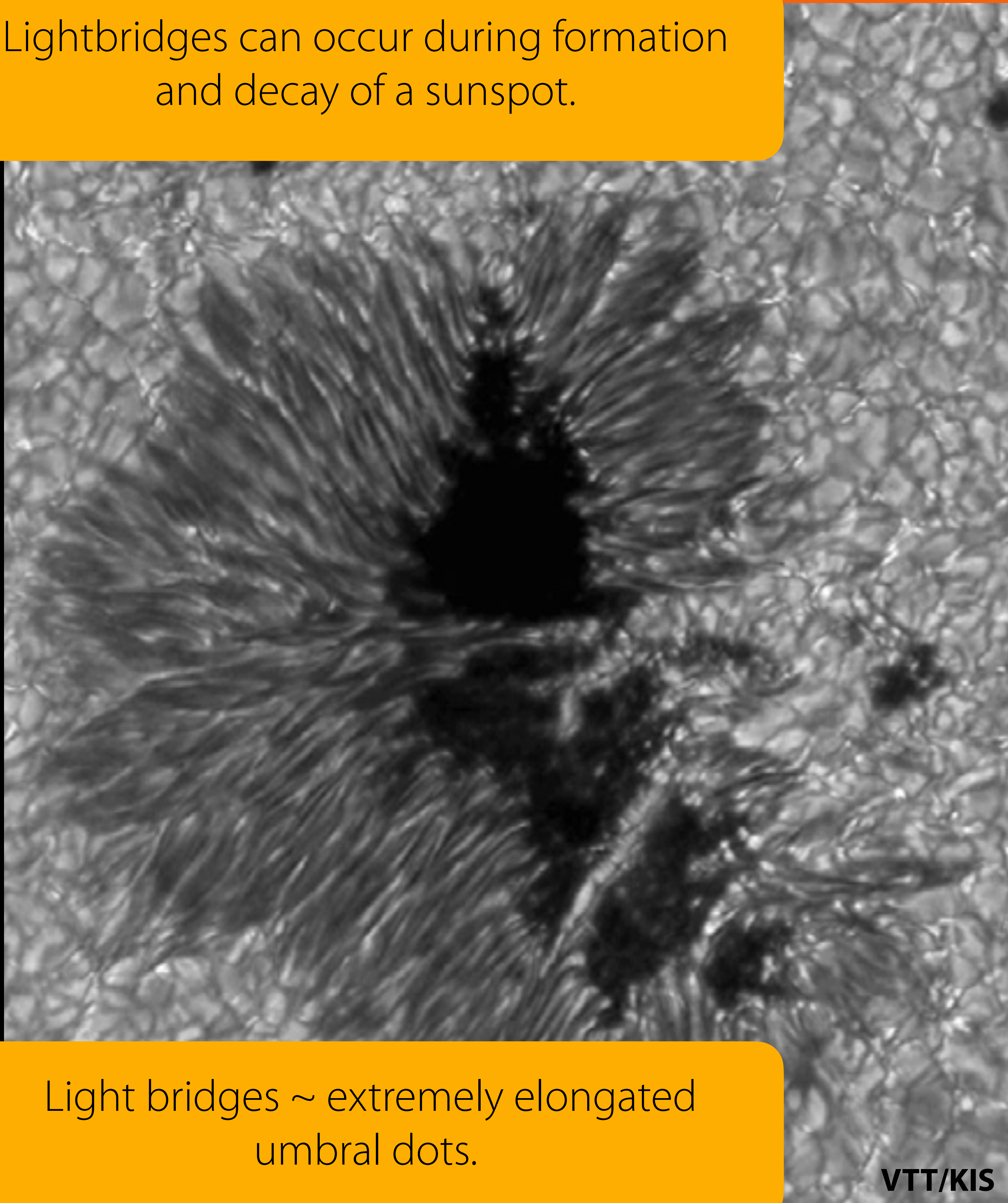
➡ **Magneto-convection** can still prevail at some locations

➡ Visible consequences: umbral dots and light bridges

- Both have a central dark lane and bright edges
- Light bridges:
  - Extend across umbra, splitting it and connecting penumbra on both sides
  - Blue and redshifted velocities detected!

  ➡ Convection ongoing!

Lightbridges can occur during formation and decay of a sunspot.



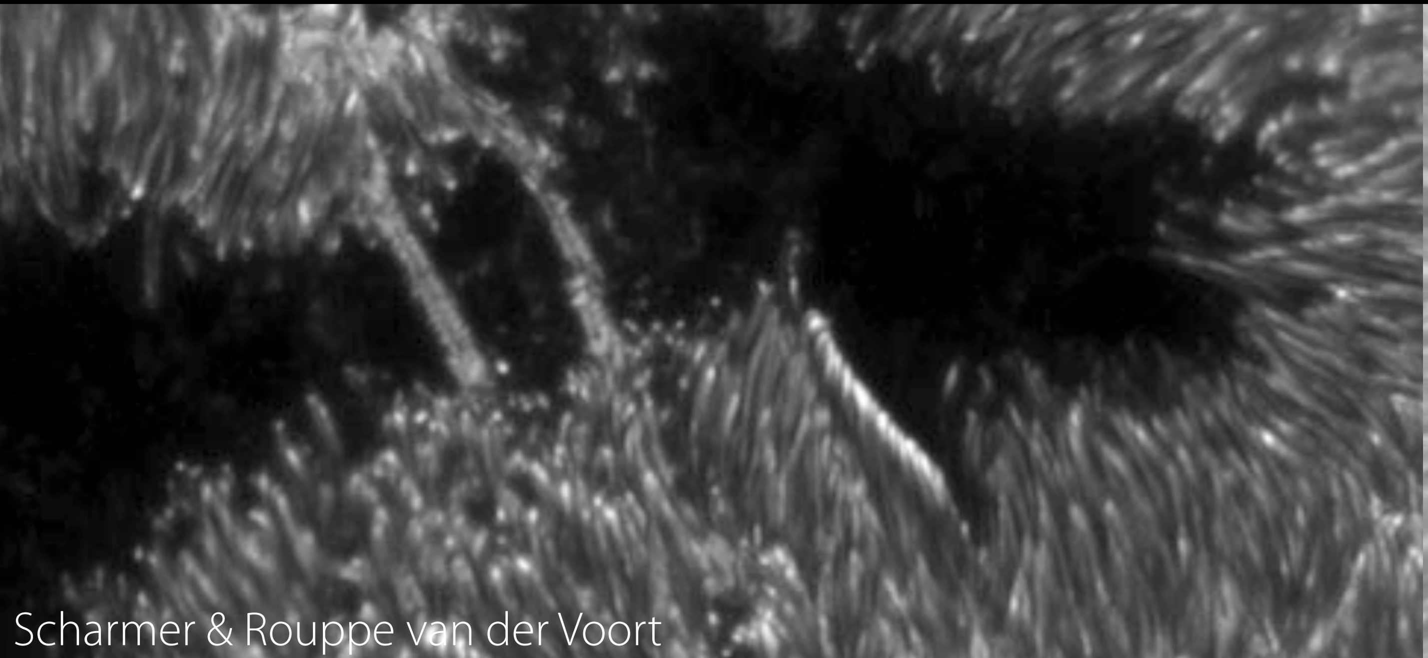
Light bridges ~ extremely elongated umbral dots.

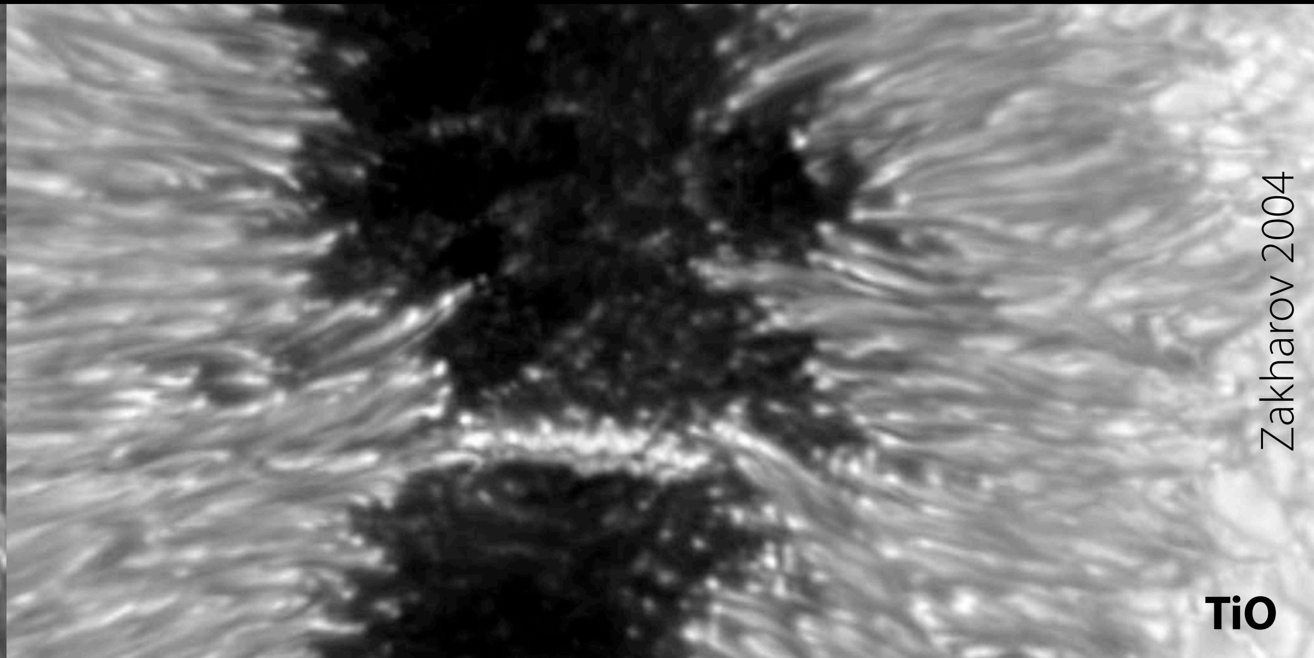
Sunspots

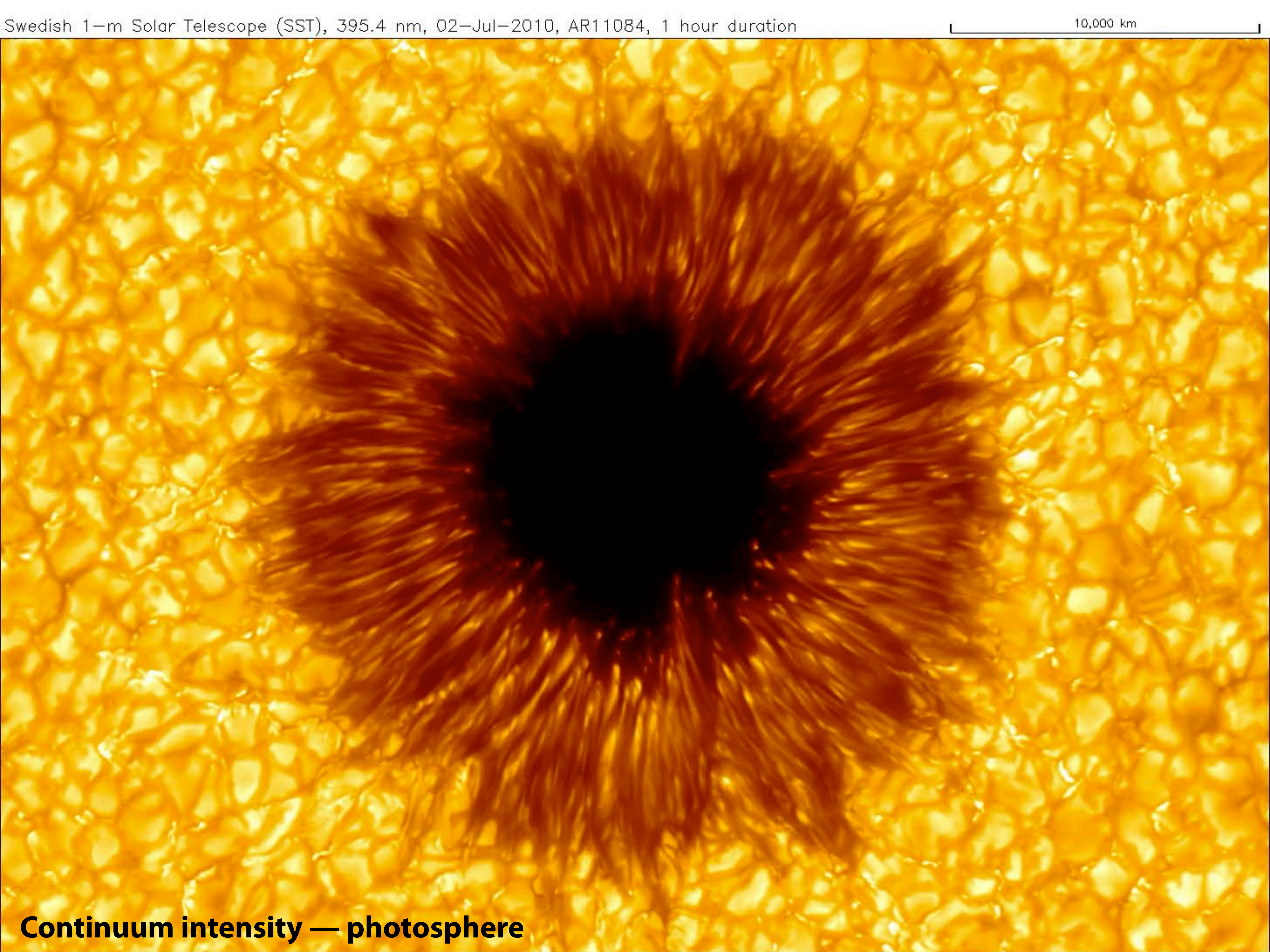
Formation of light bridges and umbral dots

- Formation and evolution of light bridges not fully understood yet.
- Observed aspects:
  - Magnetic field weaker and more inclined than in surrounding umbra
  - Umbral dots form at tip of penumbral filaments, then move into umbra
  - Typical velocities ~ a few 0.1 km/s but also supersonic downflows with up to 10 km/s
- Possible explanation (implied by observations and simulations):
  - Emerging buoyant flux tube with hot gas and weak field below/near surface in connection with sub-photospheric flows; Convective upflow continuously transports horizontal fields to surface and creates a light bridge structure.

➡ Uprising gas with weak field as natural consequence of magnetoconvection in a magnetic flux structure (like a sunspot)



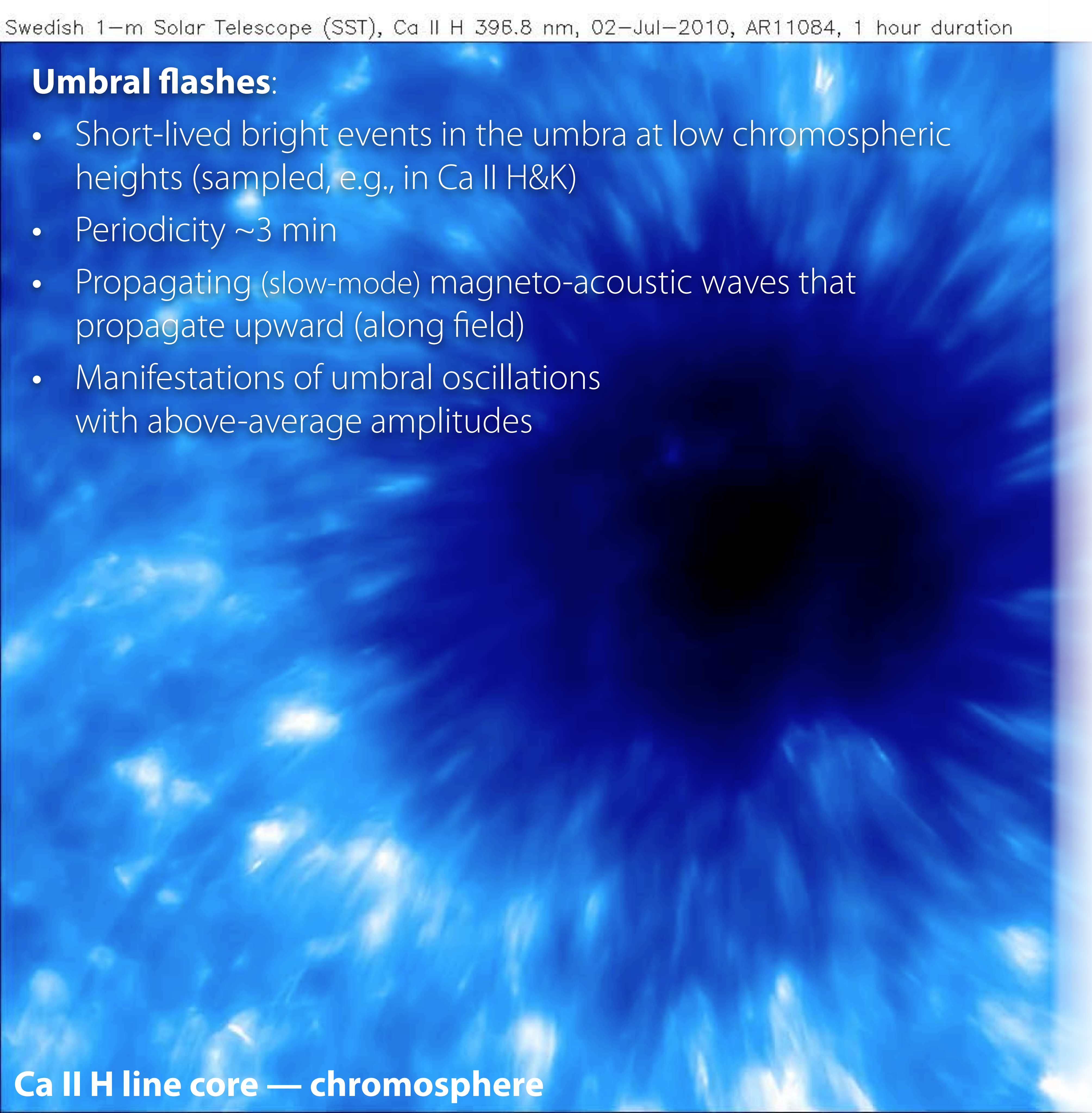


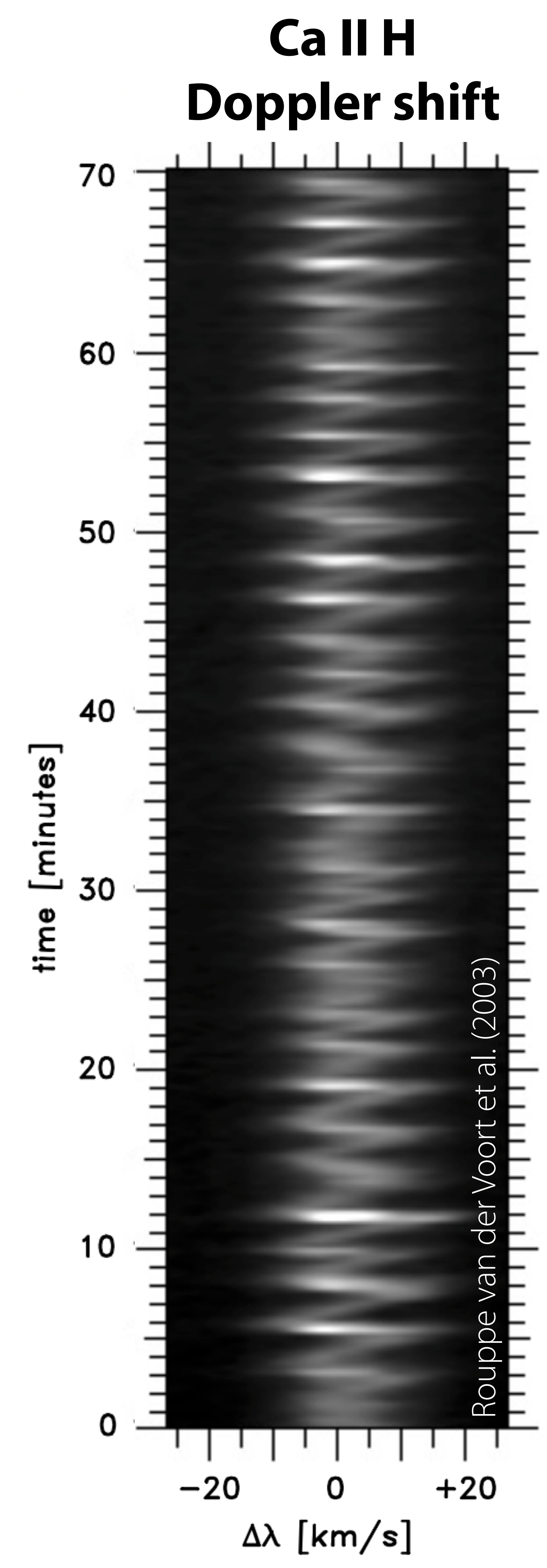


Continuum intensity — photosphere

Umbral flashes:

- Short-lived bright events in the umbra at low chromospheric heights (sampled, e.g., in Ca II H&K)
- Periodicity ~3 min
- Propagating (slow-mode) magneto-acoustic waves that propagate upward (along field)
- Manifestations of umbral oscillations with above-average amplitudes

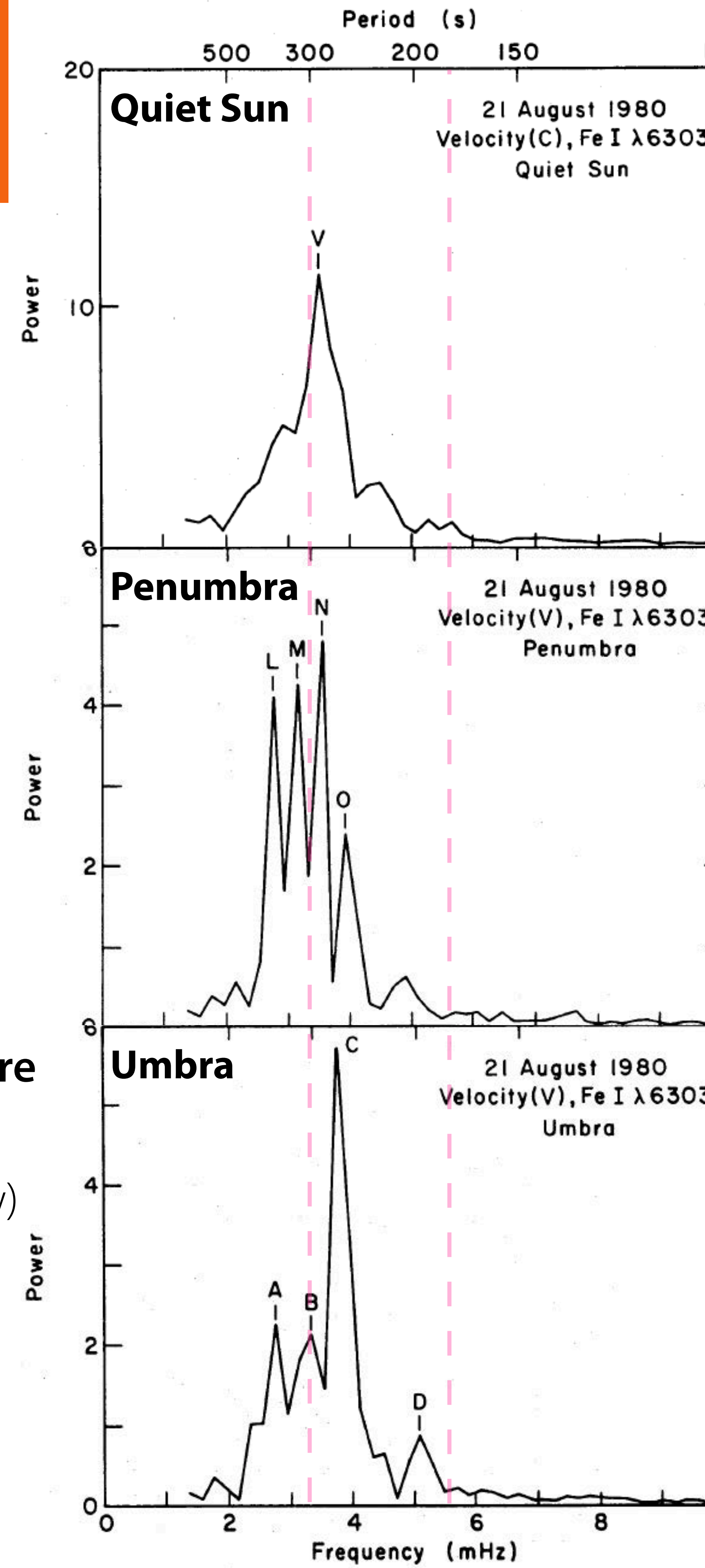




Sunspots

Oscillations and waves

- Stratification/properties in sunspot different than in Quiet Sun (QS) plus influence of strong magnetic field
  ➡ Oscillatory behaviour different in sunspots
    - Umbra: shift towards shorter periods compared to QS
- Three major types of oscillations/waves in sunspots:
- **5-min umbral oscillations — photospheric**
  - Coherent* over a significant fraction of umbra
  - Amplitudes ~0.1km/s (or less)
  - Also in light bridges: periods ~5min period (sometimes sub-min), excited by p-mode leakage from layers below
- **3-min umbral oscillations — upper photosphere/chromosphere**
  - Coherent on smaller spatial scales.
  - Amplitudes exceed several km/s in chromosphere (lower below)
  - Vertically propagating (phase speeds ~ local sound speed)
  - Seen in chromospheric line cores as sawtooth pattern
- **Running penumbral waves**



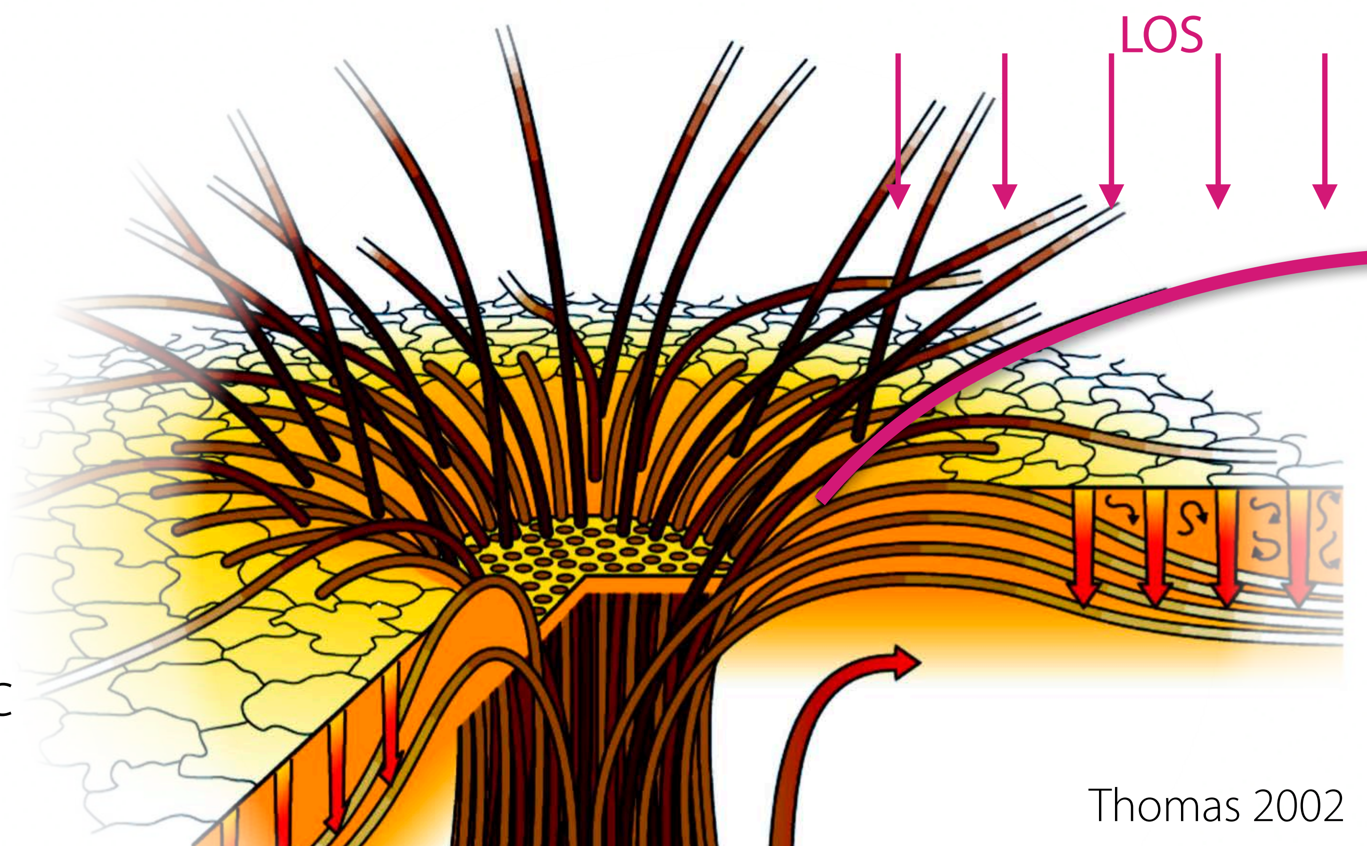
Thomas, Cram & Nye, 1984, ApJ, 285, 368

*coherent waves: constant relative phase

Sunspots

Oscillations and waves

- **Running penumbral waves**
  - Coherent propagating wave fronts, running radially outwards from inner to outer edge of penumbra
  - Clearly visible near the umbra-penumbra boundary (in strong chromospheric lines)
  - Chromospheric phenomenon (but (possibly?) also some photospheric parts with small amplitude)
  - Penumbral waves **guided by inclined magnetic field**
    - Magnetic field inclination increases from the inner to the outer penumbra.
    - Causes increasing apparent path length (projection!) that appears as outward propagation with decreasing velocity.
    - Radial phase speeds of 8–35 km/s, decreasing phase speed with distance.
  - Same underlying physical mechanism umbral flashes: slow-mode magneto-acoustic waves that propagate upward
  - Excited by photospheric umbral oscillations/flashes at low chromospheric levels



Thomas 2002

Sunspots

Simulating sunspots

- Magneto-convection essential for sunspots but a challenging time-dependent problem
- Consistent models needed to explain all observed phenomena
- 3D MHD simulations of two spots with opposite polarity (Rempel et al. 2009)
  - computational box ~100Mm x 50Mm x 6Mm
  - Abs. magnetic field strengths |B| ~ 3-4 kG

Continuum intensity

Rempel et al. (2009)

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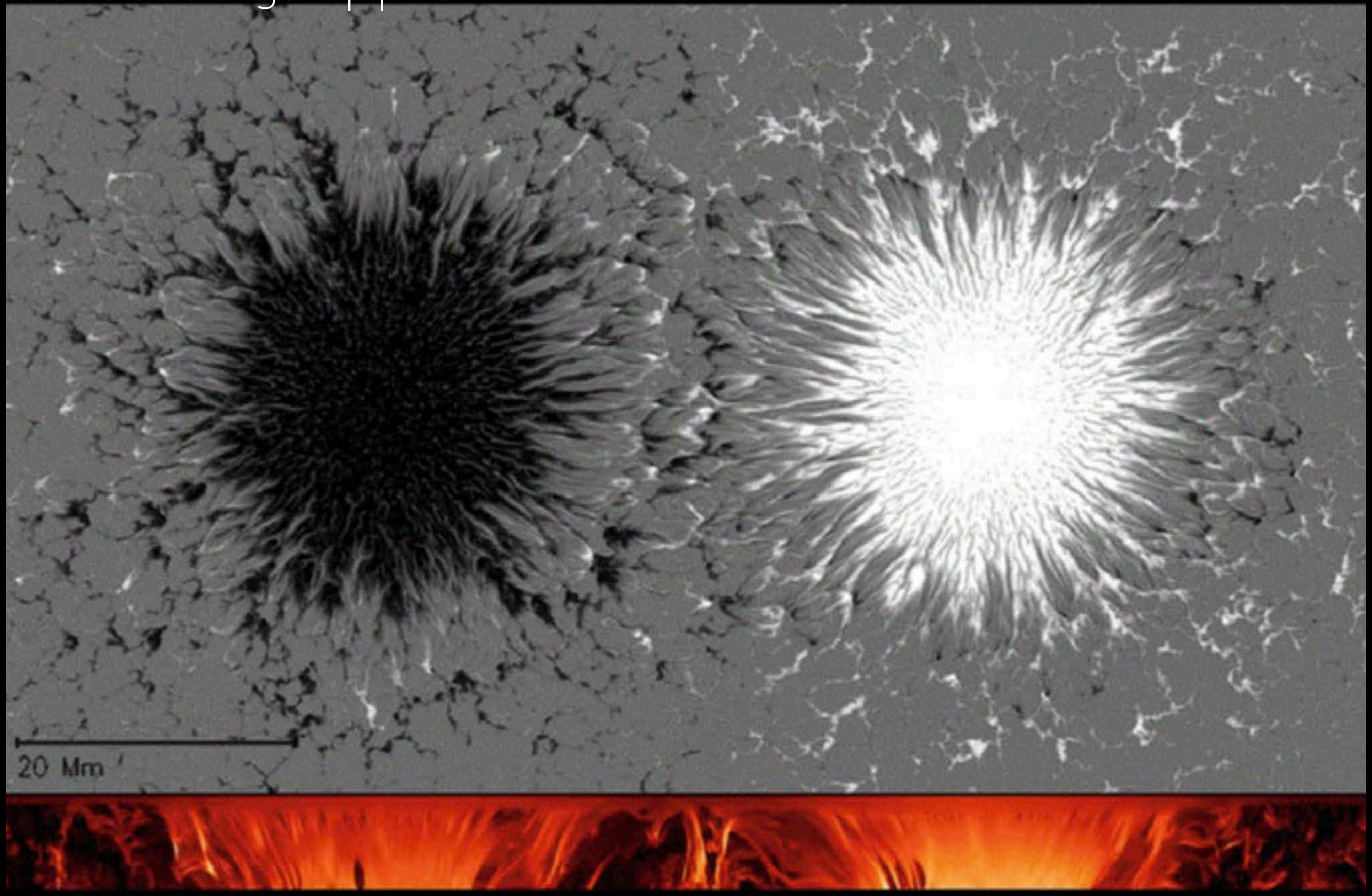
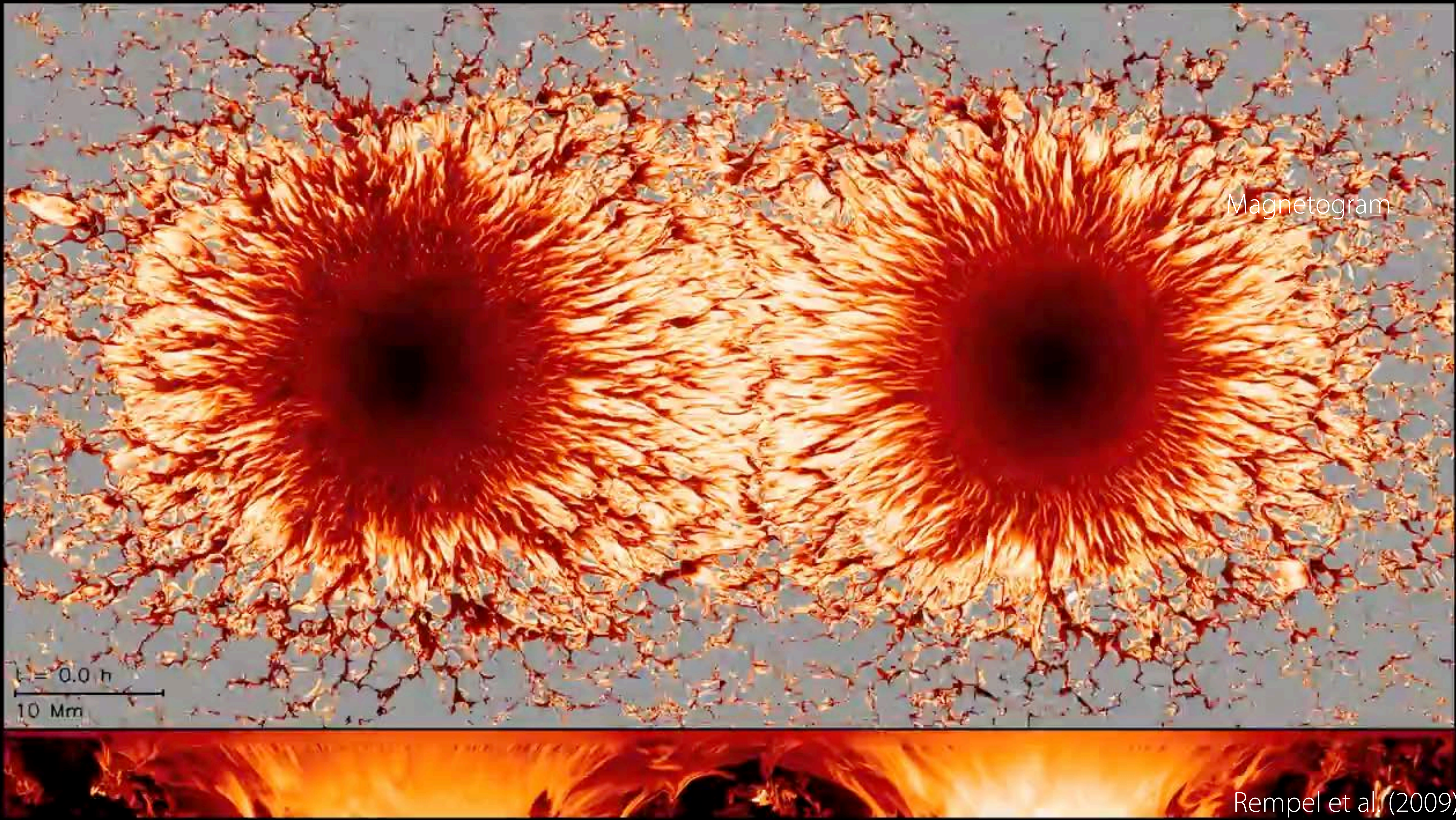


Magnetogram

Rempel et al. (2009)

Sunspots

Simulating sunspots

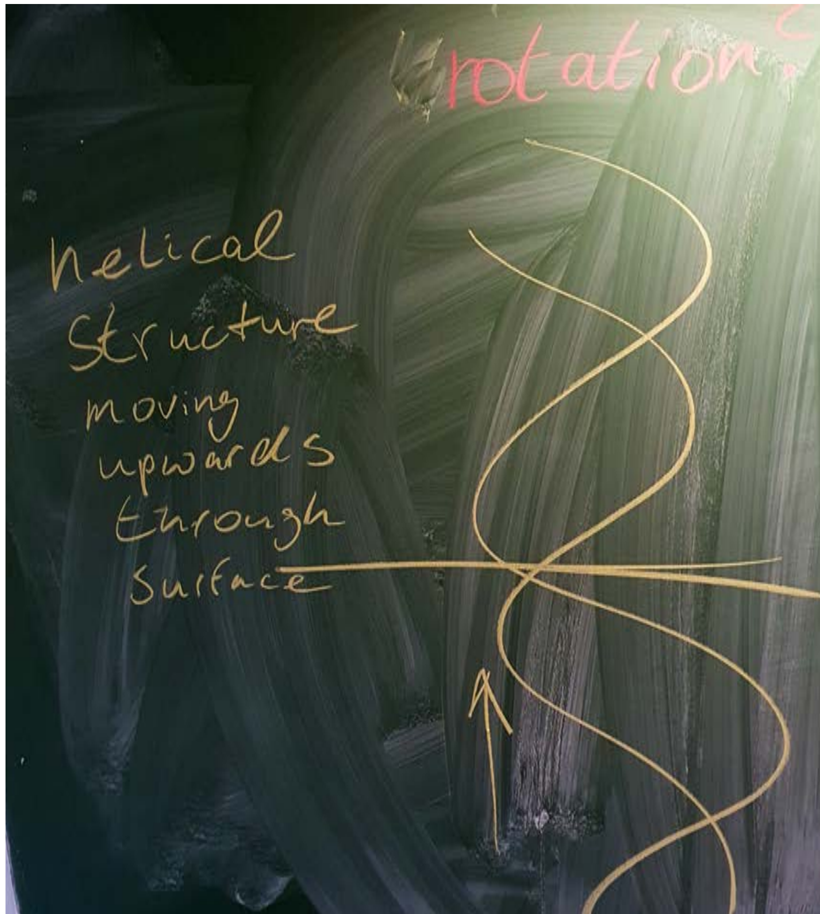


Rempel et al. (2009)

Sunspots

Rotating Sunspots

- **Observations:**
  - Detected already in 1910 (Evershed)
  - Rotation angles up to 540° were measured
  - Rotation angles about umbral center up to 200° over period of 3–5 days
  - Young sunspot groups rotate faster than old spot groups
  - Rotation rates (approx.) in line with helioseismologic measurements
  - Similar ratio of clockwise to counterclockwise rotations in both hemispheres
- **Possible explanations:**
  1. **True rotation** of a magnetic field structure due to forces that act in azimuthal direction
  2. **Apparent rotation** as helically twisted vertical magnetic field structure moves upward through the photosphere



- Rotating sunspots tend to produce more flares accompanied by eruption (more later)