Lecture 14

AST5770

Solar and stellar physics

Sven Wedemeyer, University of Oslo, 2023

Measuring magnetic fields in stellar atmospheres

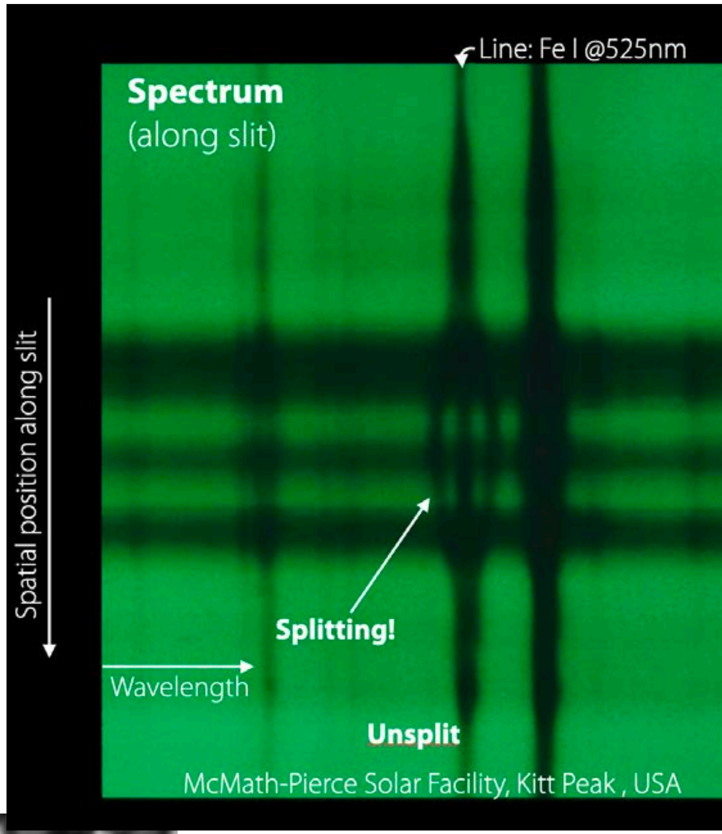
Measuring magnetic fields

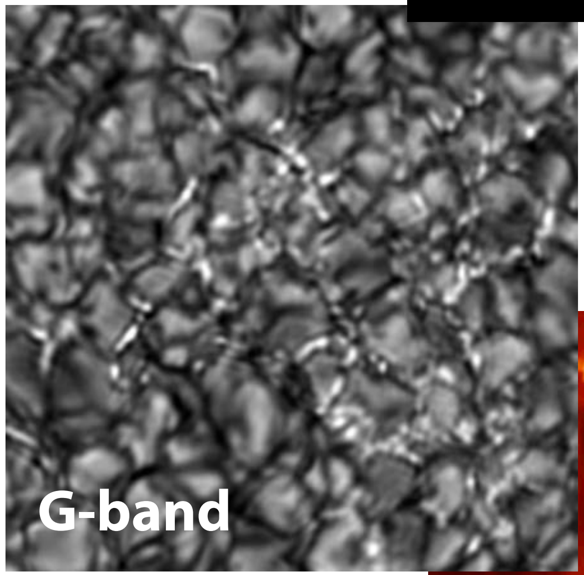
Methods of magnetic field measurement

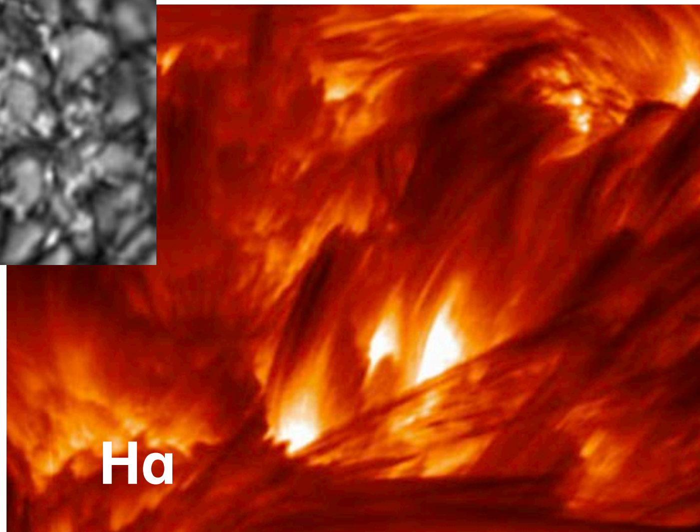
- **Direct methods:**
  - Zeeman effect — polarized radiation
  - Hanle effect — polarized radiation (scattering)
  - Gyroresonance — radio spectra

- **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
Slit across a sunspot



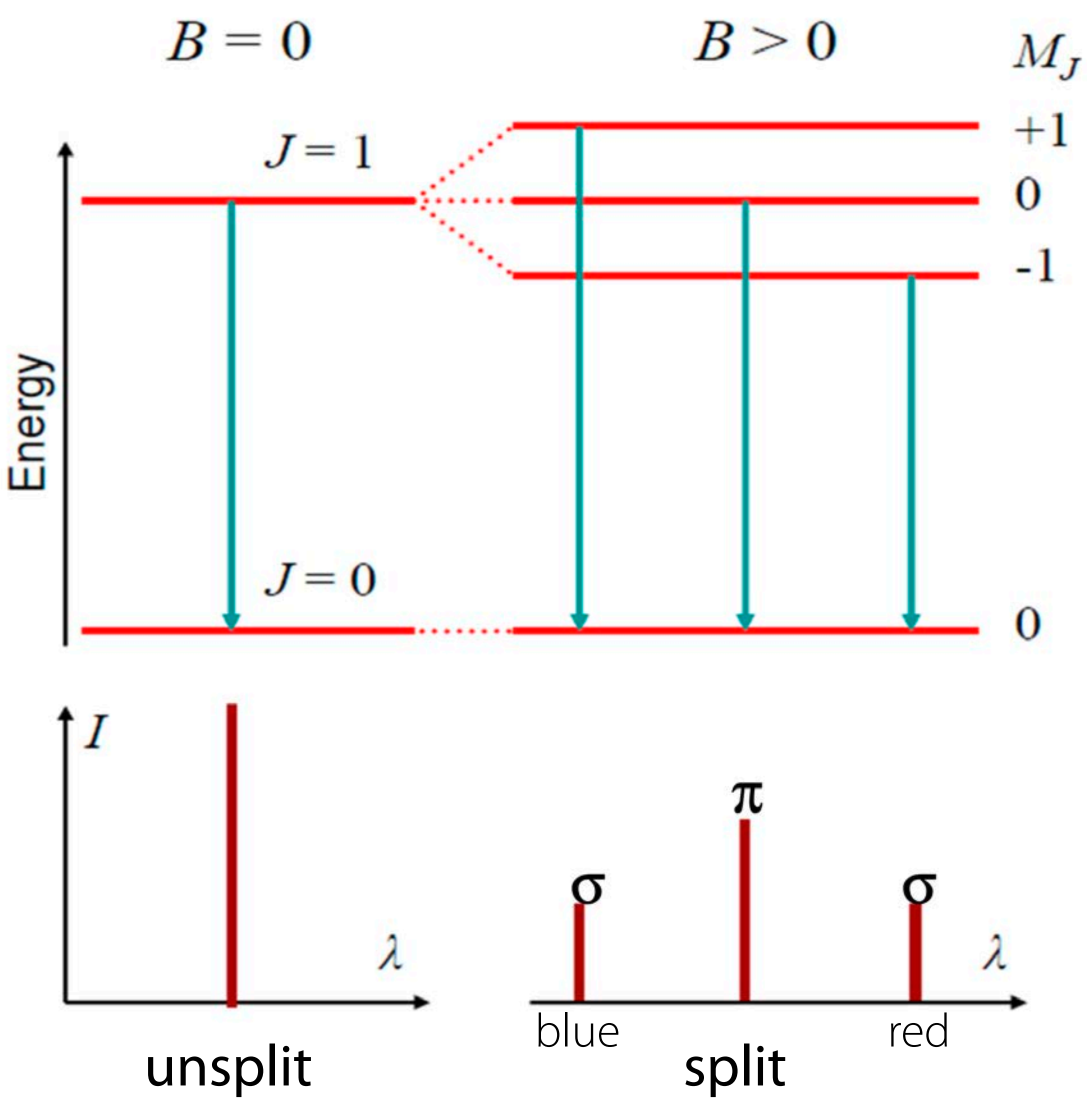




Measuring magnetic fields

Zeeman diagnostics

- Splitting of atomic energy in presence of magnetic field
  - Total angular moment j splits into $2J+1$ sub-levels with different M_J.
  - Transitions allowed between levels with $\Delta J = 0, \pm 1$ & $\Delta M_J = 0\ (\pi), \pm 1\ (\sigma_b, \sigma_r)$
- Splitting depends on strength and orientation of magnetic field (wrt line of sight)
- Observation perpendicular to mag. field $\vec{B}$: three components:
  - π component linearly polarized parallel to $\vec{B}$
  - σ components are linearly polarized perpendicular to $\vec{B}$
  - No information about the direction of magnetic field vector $\vec{B}$



π component at original wavelength

L is the total orbital moment of the electrons
S is the spin quantum number
J is the total angular momentum
M_J is the magnetic quantum number: -J,…,J

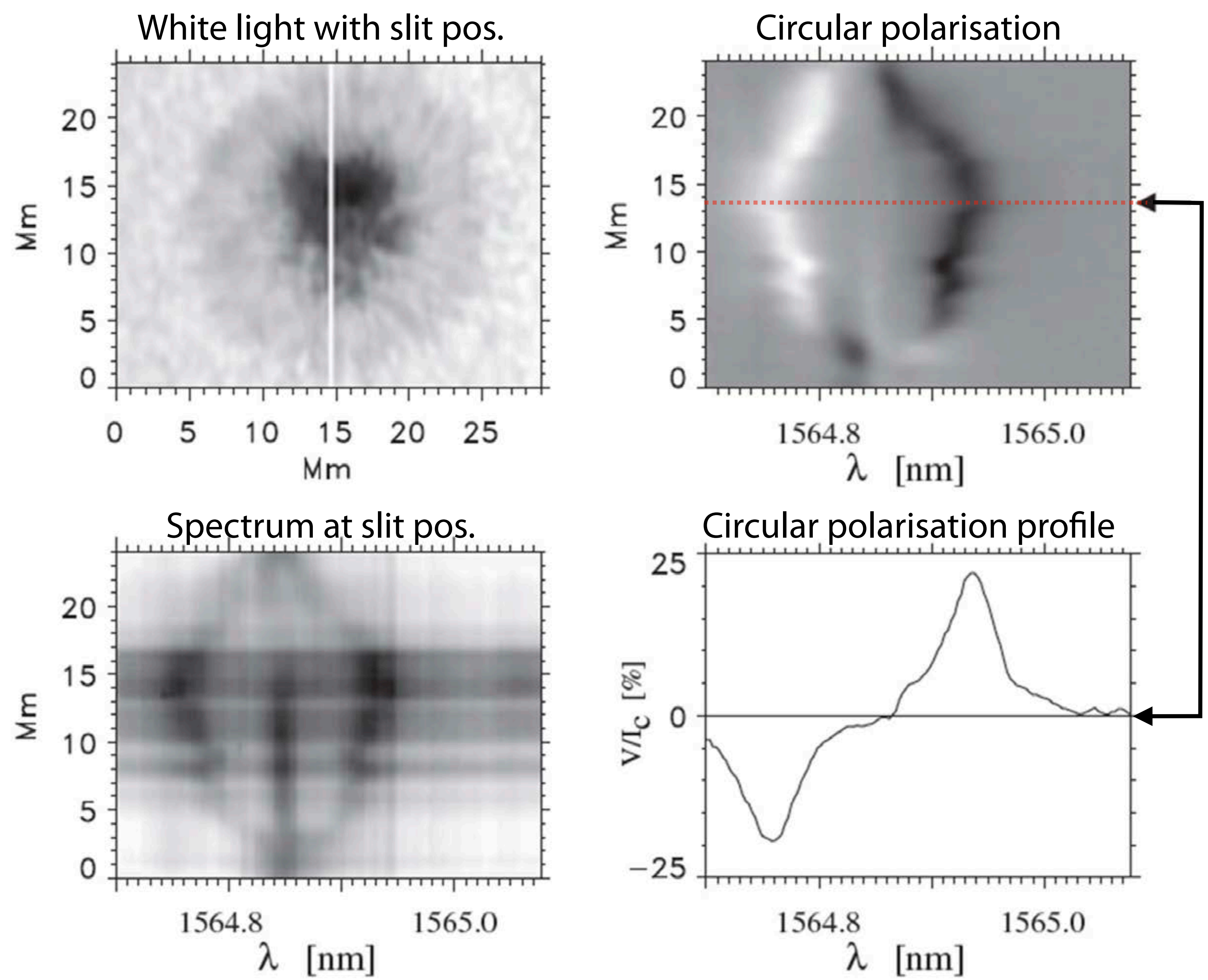
Measuring magnetic fields

Zeeman diagnostics

➡ Zeeman effect allows direct detection and measurement of magnetic field

- Note: Zeeman effect can be subtle and difficult to measure
- BUT: Unique **polarisation** signature in addition to change of spectral line shape/split
- Measurement of polarization is central to measuring solar magnetic fields

Zeeman splitting and circular polarization of the infrared Fe I line at 1564.8 nm



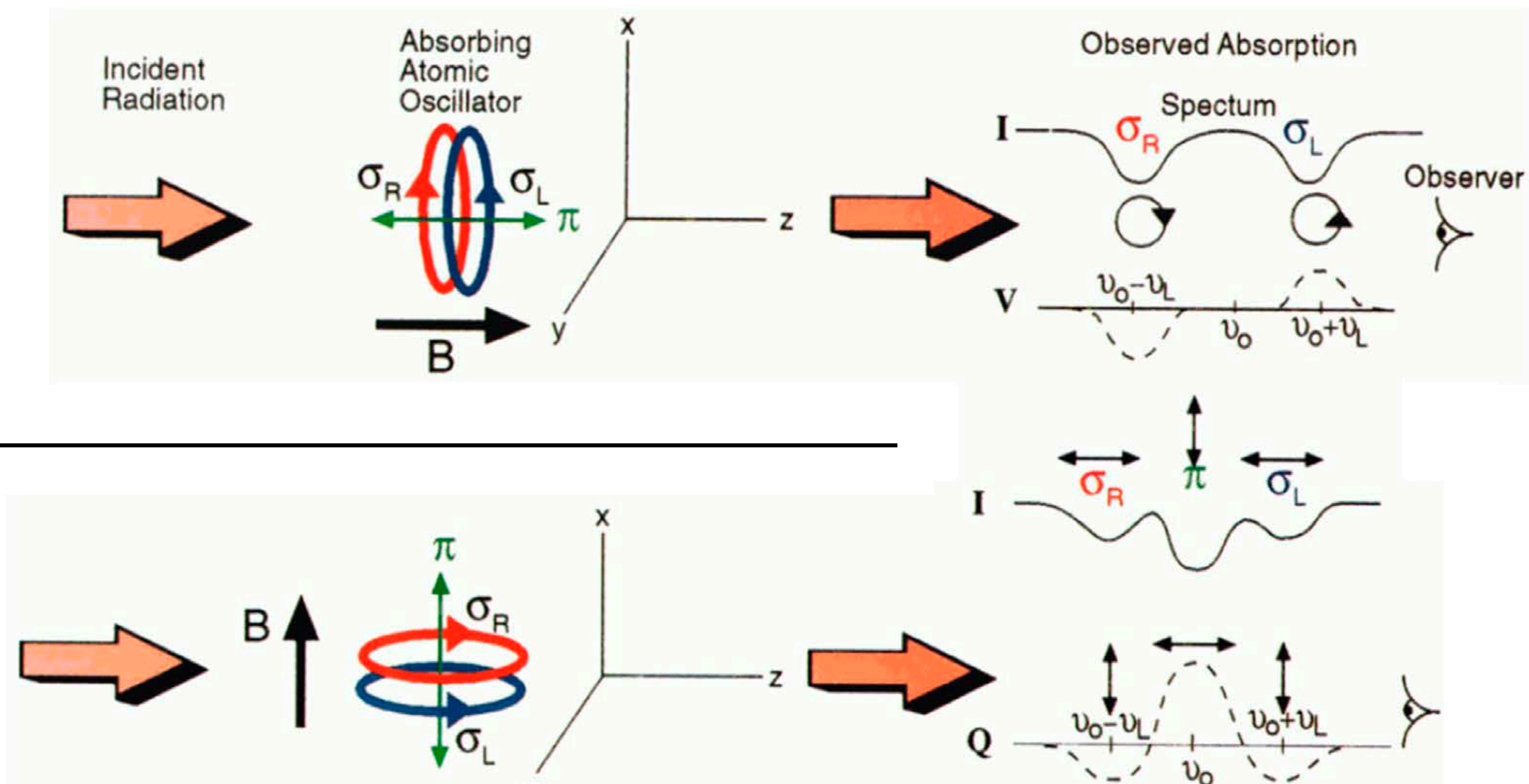
German Vacuum Tower Telescope, Tenerife (1999)

Measuring magnetic fields

Zeeman diagnostics

Longitudinal Zeeman Effect

- Absorption of right- and left circularly polarized light at shifted frequencies corresponding to Zeeman σ components; no absorption of π component



Stokes parameters

$$I = I_{\leftrightarrow} + I_{\updownarrow}$$

$$Q = I_{\leftrightarrow} - I_{\updownarrow}$$

$$U = I_{\nearrow} - I_{\nwarrow}$$

$$V = I_{\circlearrowright} - I_{\circlearrowleft}$$

(from B.Lites, 2000)

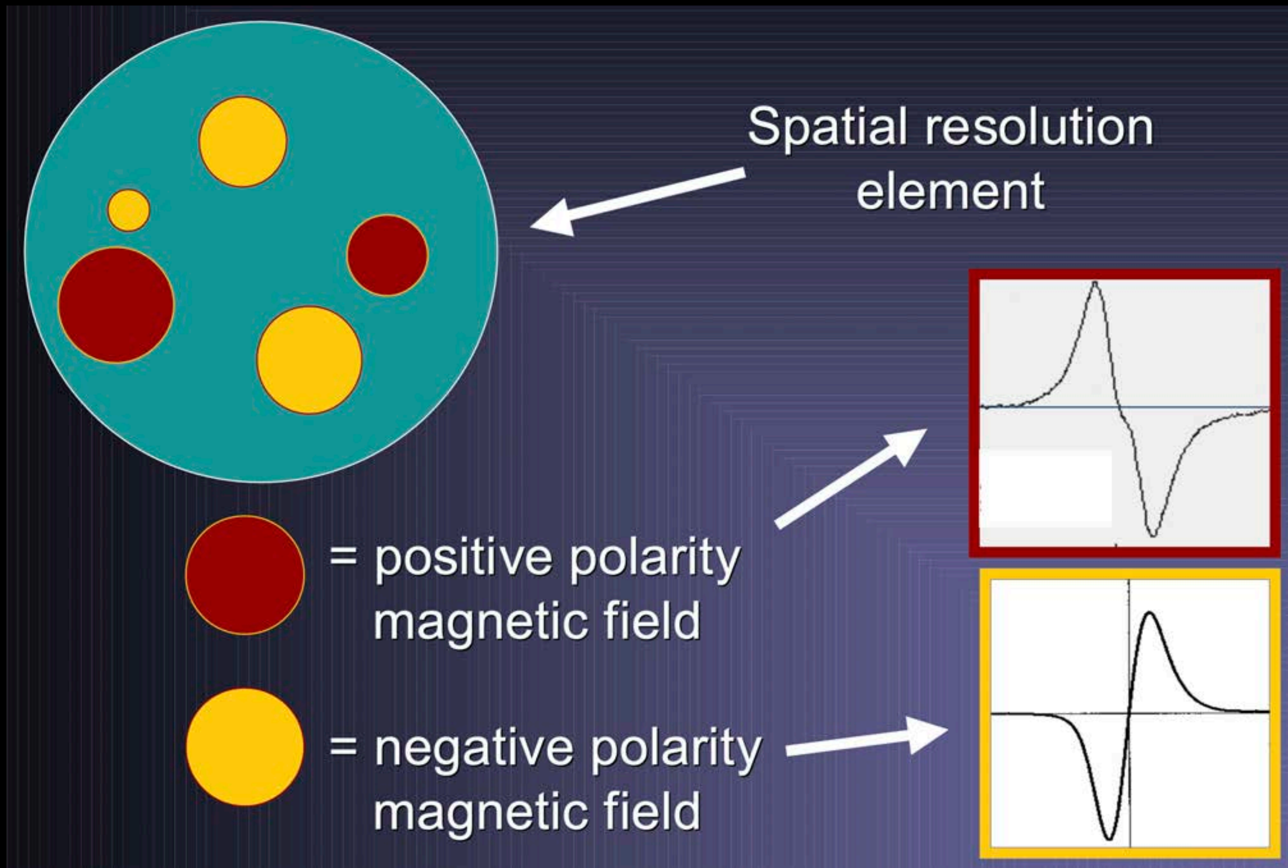
Transverse Zeeman Effect

- Absorption for all components $(\sigma^+, \pi, \sigma^-)$ with intensity ratios 1/4 : 1/2 : 1/4
- Stokes U = 0

Measuring magnetic fields

Zeeman polarimetry

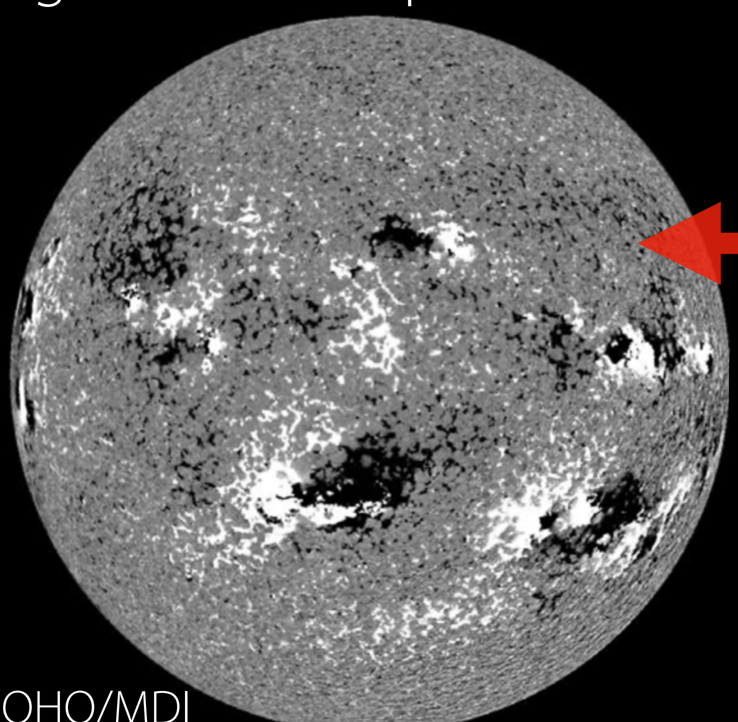
- Most used remote sensing of astrophysical (and certainly solar) magnetic fields
- Effective measurement of field strength if Zeeman splitting is comparable to Doppler width or more: B > 200 G ... 1000 G (depending on spectral line)
- Works best in photosphere
- Splitting scales with wavelength — works best in IR
- Sensitive to cancellation of opposite magnetic polarities — needs high spatial resolution



Measuring magnetic fields

Magnetograms

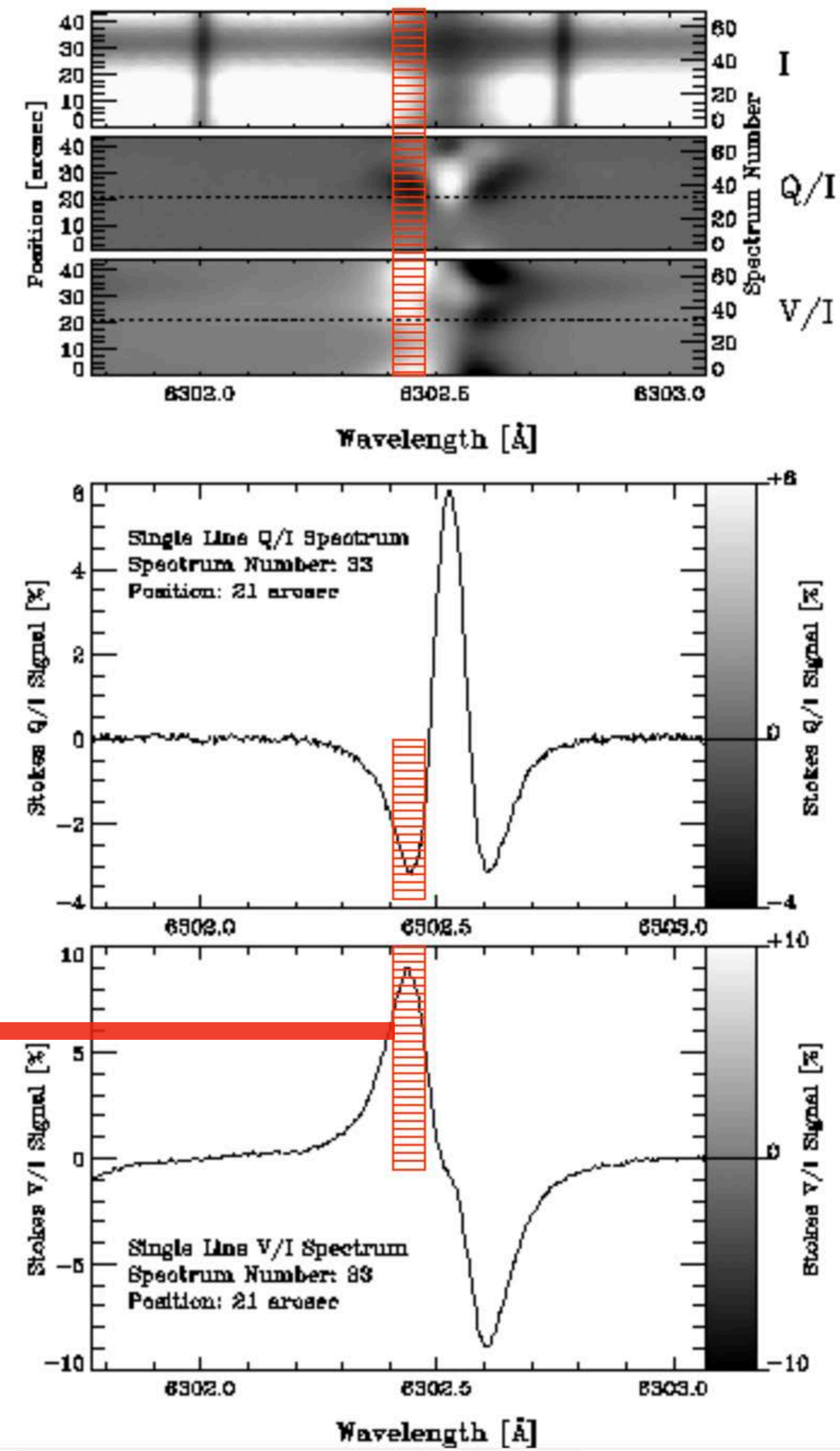
- Magnetograph = Instrument that makes maps of (net circular) polarisation in wing of Zeeman sensitive line.
- Conversion of polarisation into magnetic field requires a careful calibration.
- Usually only Stokes **V** is used (simplest to measure),
- Provides longitudinal component of **B**.



Stokes I, Q and V along spectrograph slit

Stokes Q profile

Stokes V profile



$I = I_{\leftrightarrow} + I_{\updownarrow}$

$Q = I_{\leftrightarrow} - I_{\updownarrow}$

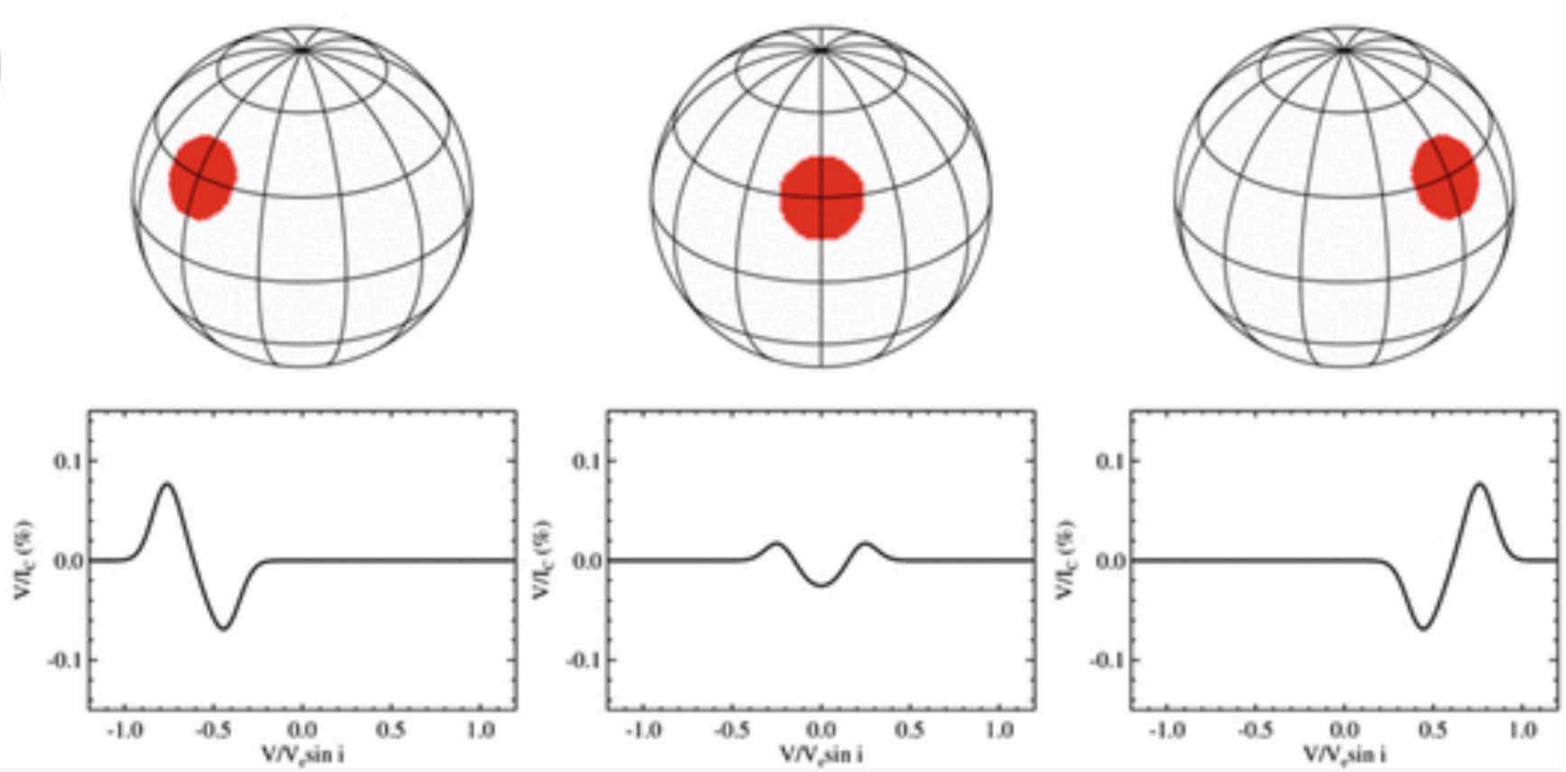
$U = I_{\nearrow} - I_{\nwarrow}$

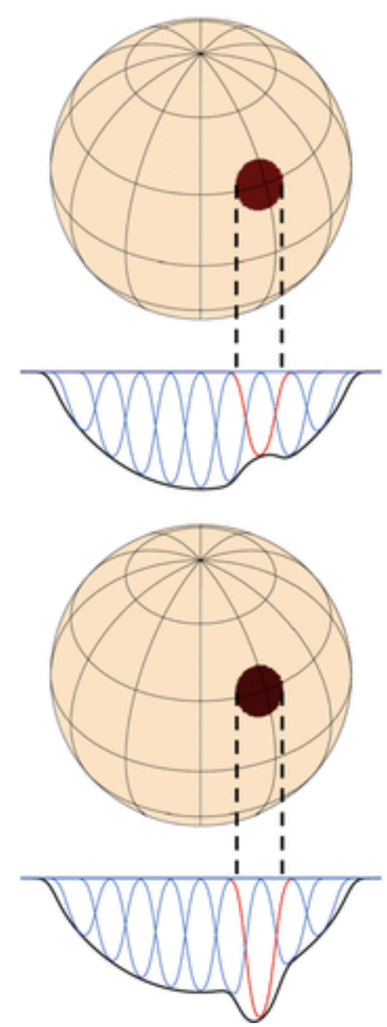
$V = I_{\circlearrowright} - I_{\circlearrowleft}$

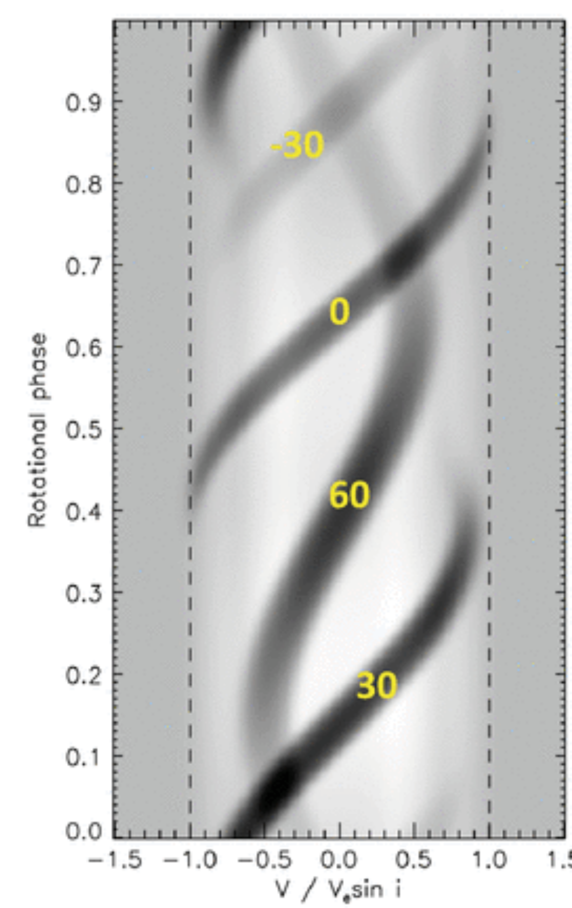
Measuring magnetic fields

Zeeman Doppler Imaging (ZDI)

- Derives magnetic field information from Zeeman splitting of spectral lines from spatial unresolved observations
- As function of time over stellar rotation period(s)
- Requires observations over a sufficient number of nights
- Data then used to reconstruct the stellar surface as it rotated
- Mapping the star's surface



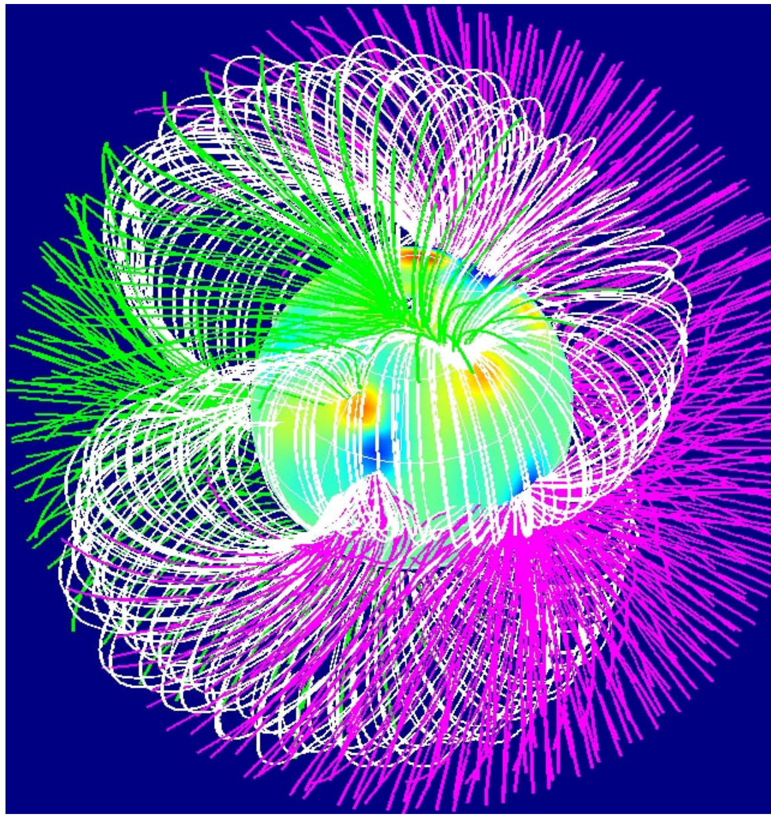




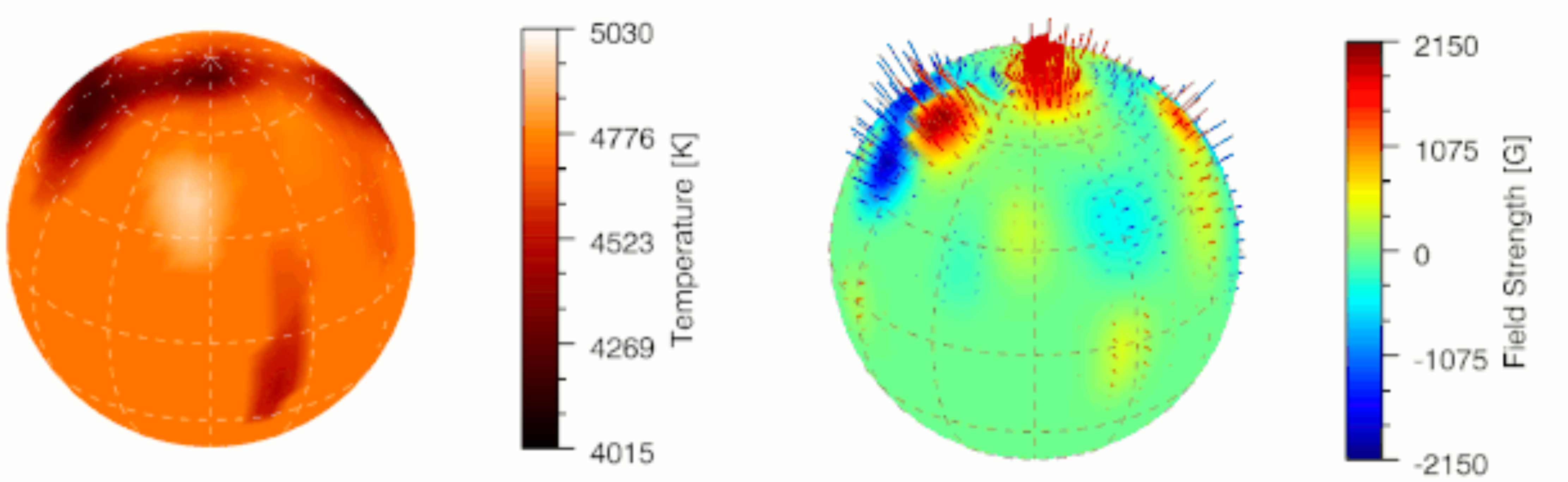
Measuring magnetic fields

Zeeman Doppler Imaging (ZDI)

- ZDI: observational constraints for dynamos in Sun-like stars
- Commonly used: Problem: Latitude degeneracy -
  - ZDI cannot always distinguish the hemisphere in which the starspots are located
  - Uncertain north–south distribution of starspot active latitudes
  - Limits constraints of dynamo theory !
- Alternative measurements via direct interferometric imaging



Example: II Pegasi A (HD 224085)

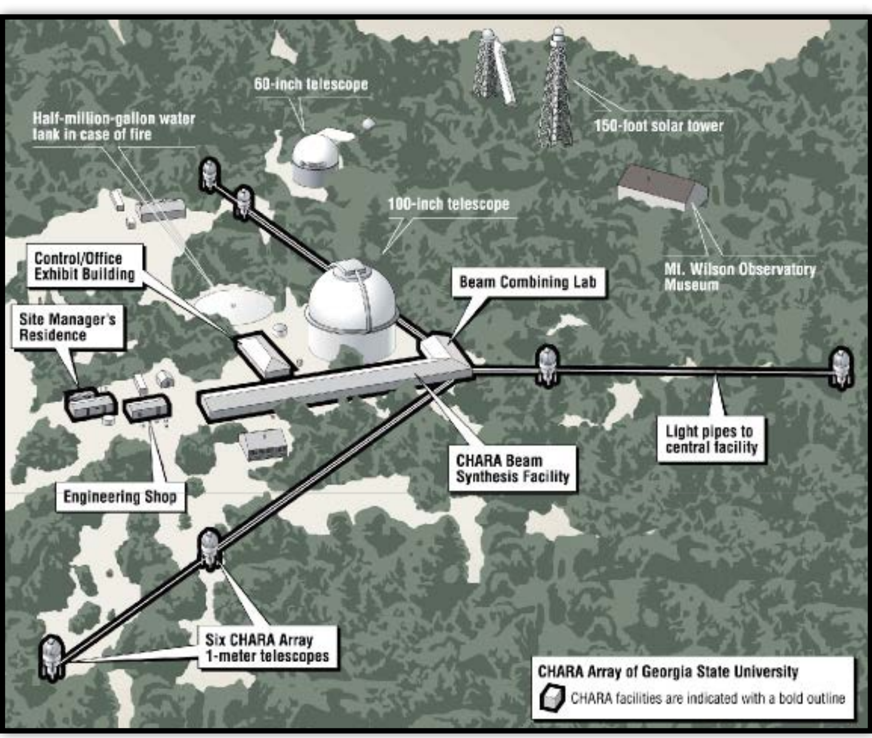


Strassmeier/AIP

Measuring magnetic fields

Direct interferometric imaging

- Works only for stars with significant angular extent in the sky (physical size vs. Distance)
  ➡ Few examples so far (limited by achievable angular resolution)
  - Observation with CHARA of **ζ Andromedae** (Roettenbacher et al 2016)
    - K-type cool giant star (15 times larger than Sun)
    - Observations in 2011 and 2013 over several consecutive days to cover the star's rotation period



CHARA, USA: array of 6 telescopes

Table 1 | Parameters of ζ And

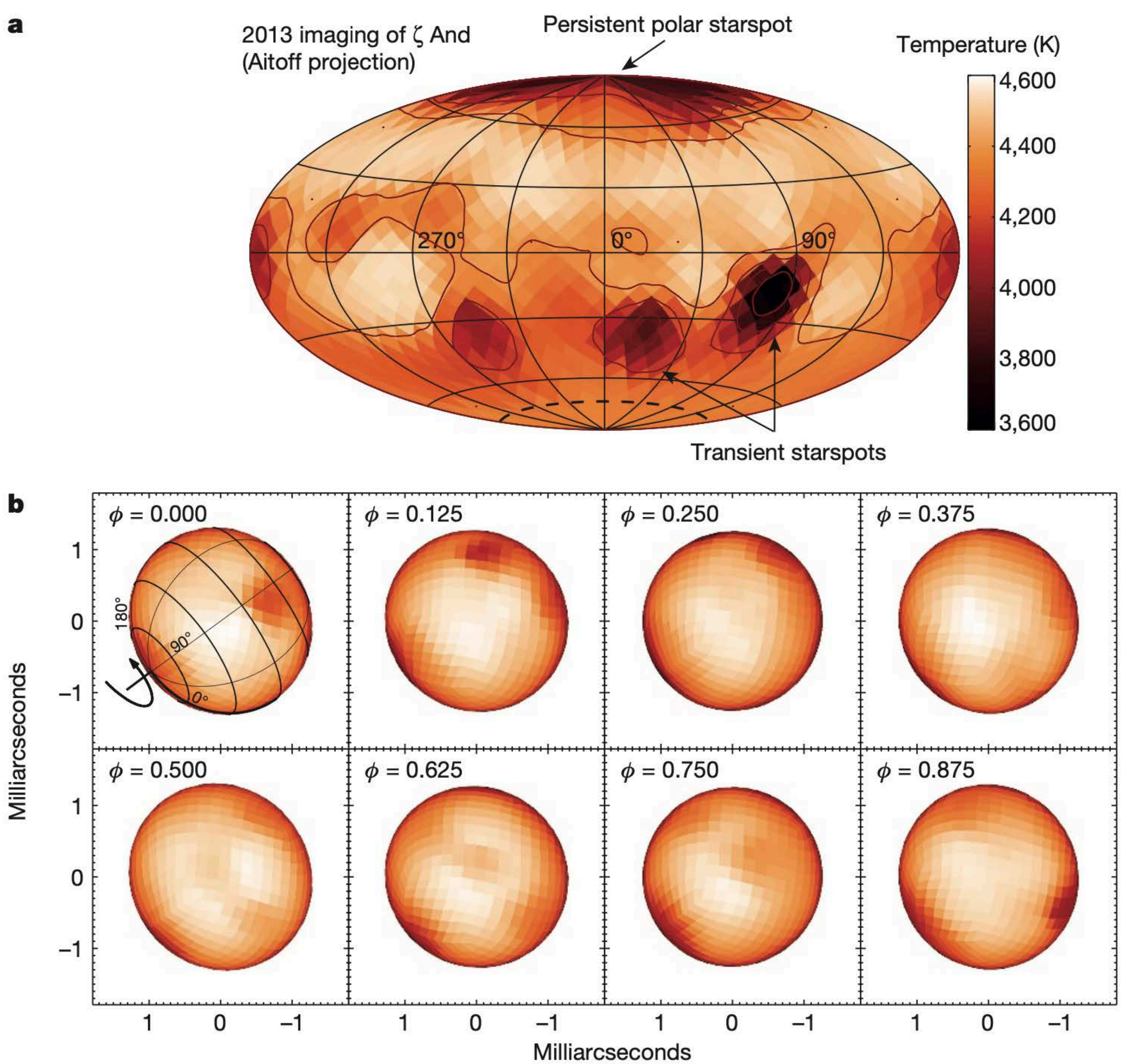
Measured parameter	Value
Angular polar diameter, θ_{LD} (mas)	2.502 ± 0.008
Polar radius ($R_\odot$)	15.0 ± 0.8
Oblateness (major to polar axis)	1.060 ± 0.011
Inclination, i (°)	70.0 ± 2.8
Pole position angle (°, E of N)	126.0 ± 1.9
Values from the literature	
Distance, d (pc)	17.98 ± 0.83 (ref. 29)
Effective temperature, T_{eff} (K)	4600 ± 100 (ref. 9)
Luminosity, log $L/L_\odot$	1.98 ± 0.04 (ref. 9)
Primary mass ($M_\odot$)	2.6 ± 0.4 (ref. 9)
Secondary mass ($M_\odot$)	~ 0.75 (ref. 9)
Iron metallicity [Fe/H]/[Fe/H]$_\odot$	-0.30 ± 0.05 (ref. 9)

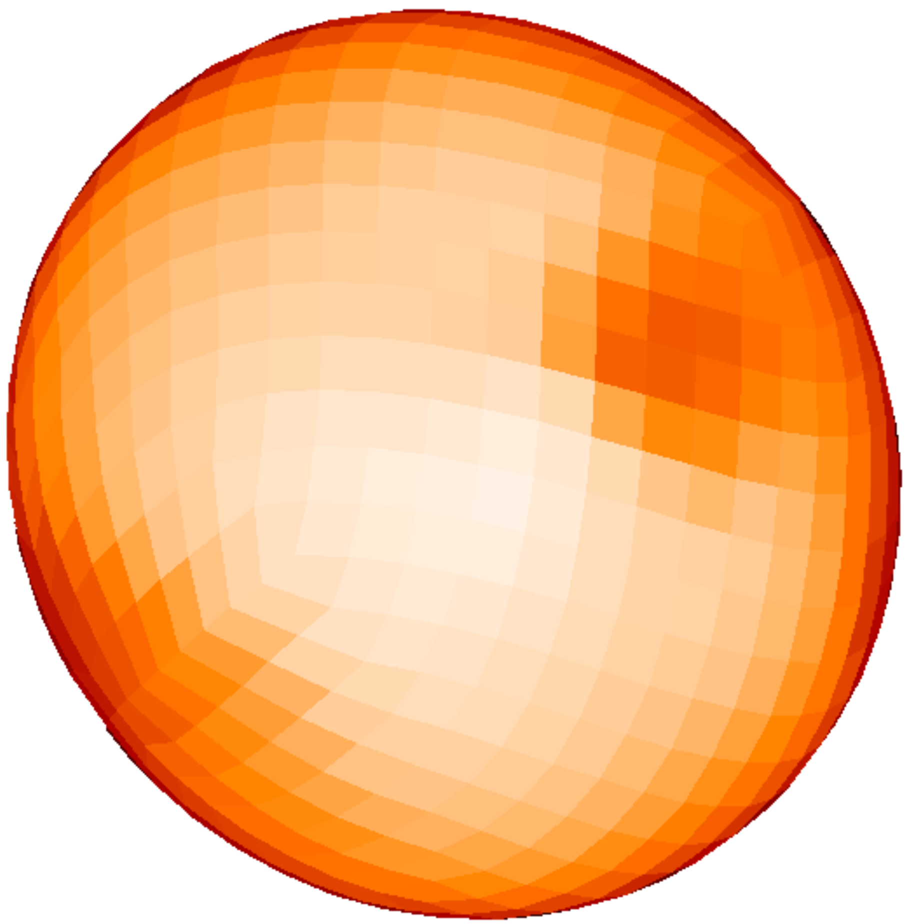
Measuring magnetic fields

Direct interferometric imaging — ζ Andromedae

Time sequence of interferometric images

➡Time-dependent model of the star's surface





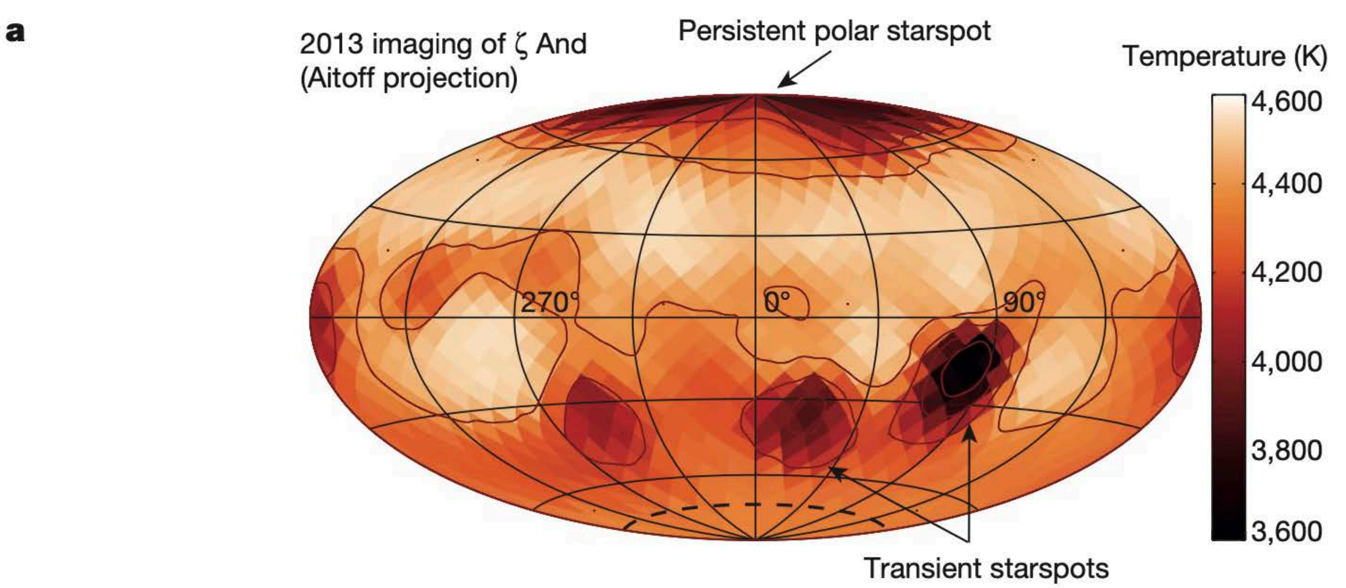
- Dark polar spot seen in both observation epochs but lower-latitude spot structures in both hemispheres do not persist between observations

Roettenbacher et al 2016

Measuring magnetic fields

Direct interferometric imaging — ζ Andromedae

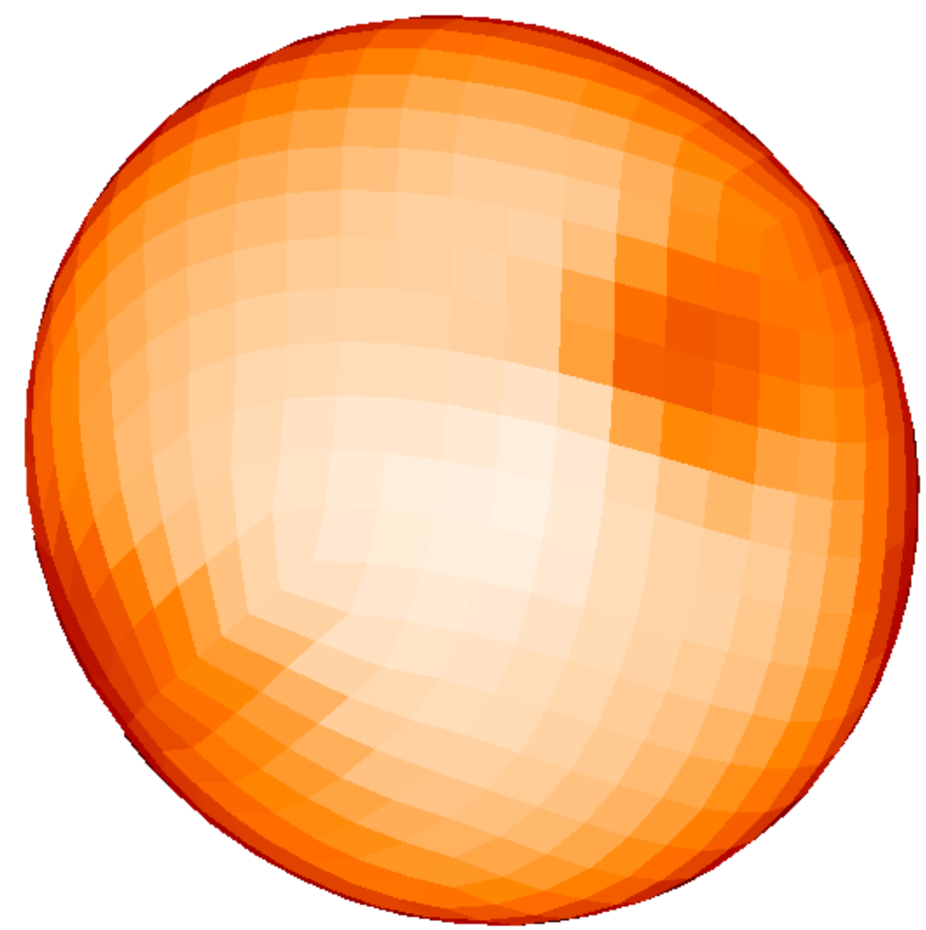
Time sequence of interferometric images



(Potential) problem:

- Conclusion: Inferred magnetic field configuration difficult to produce with a global dynamo
- Is there enough data for this conclusion?
- Interferometry is challenging but promising
- **Can provide important constraints on stellar dynamos and the resulting magnetic fields!**

➡Time-dependent model of the star’s surface



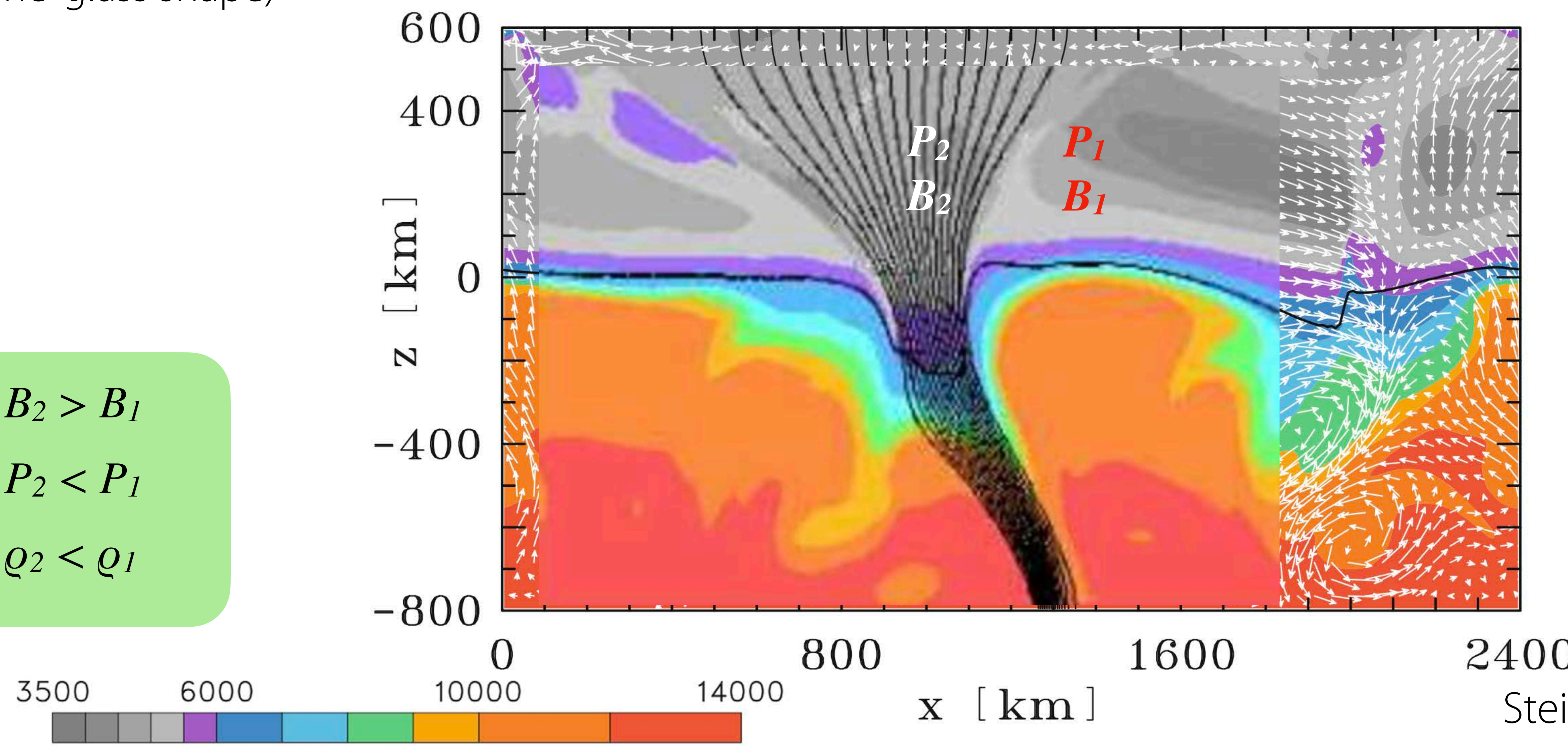
Dark polar spot seen in both observation epochs but lower-latitude spot structures in both hemispheres do not persist between observations

Magnetic field in the solar atmosphere

Magnetism

Magnetic pressure

- Ionised gas (plasma) in motion — electric and magnetic fields need to be considered
- Additional contributions from magnetic pressure inside magnetic flux concentration
- **Magnetic pressure** $P_m = B^2 / 8\pi$
- Pressure balance $\Longrightarrow$ lower gas pressure inside the flux concentration than outside
- Gas pressure of surrounding drops with height $\Longrightarrow$ Magnetic structure funnels out (wine-glass shape)



- $B_2 > B_1$
- ➡ $P_2 < P_1$
- ➡ $\varrho_2 < \varrho_1$

Steiner

Magnetism

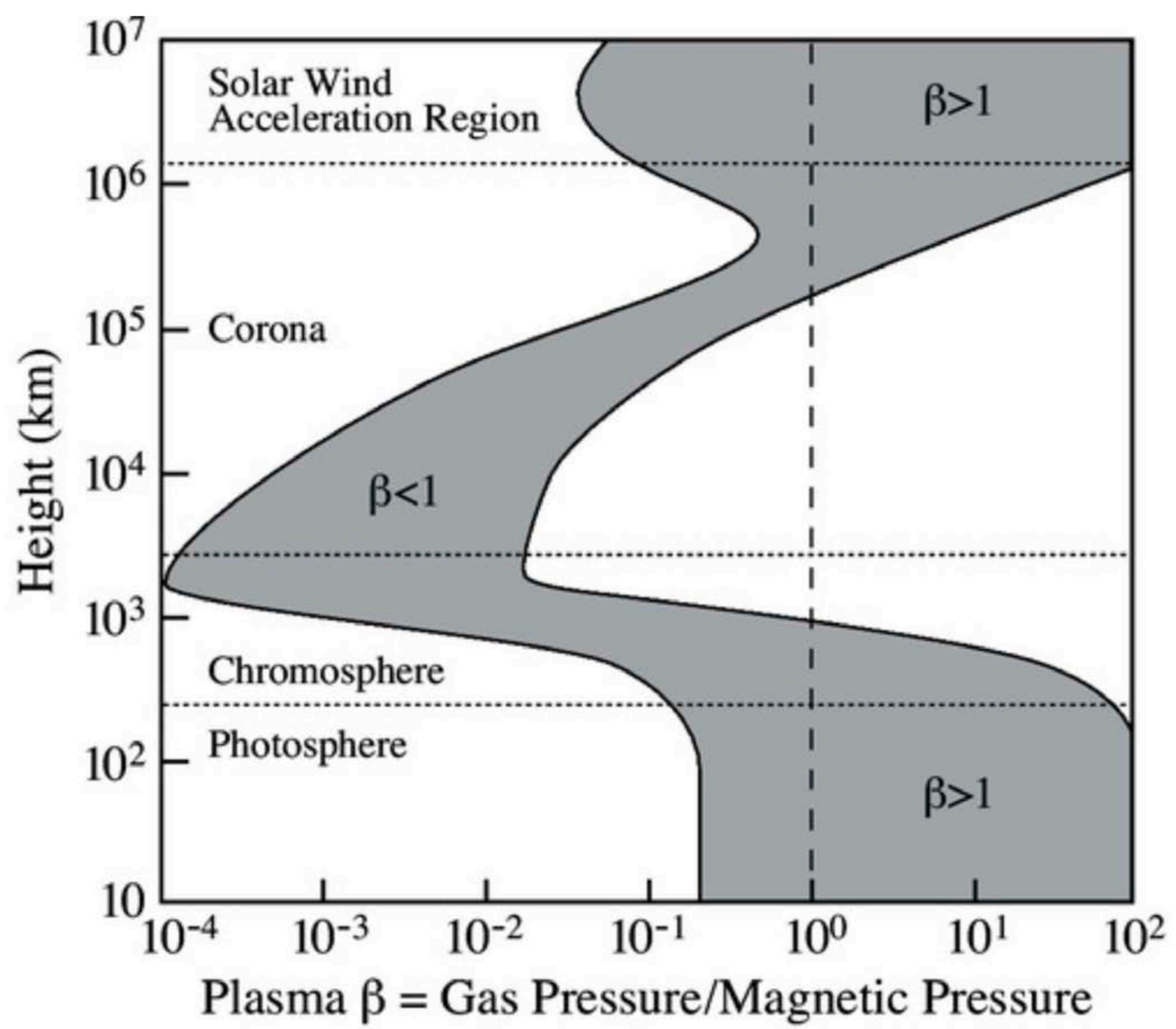
Plasma-Beta

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

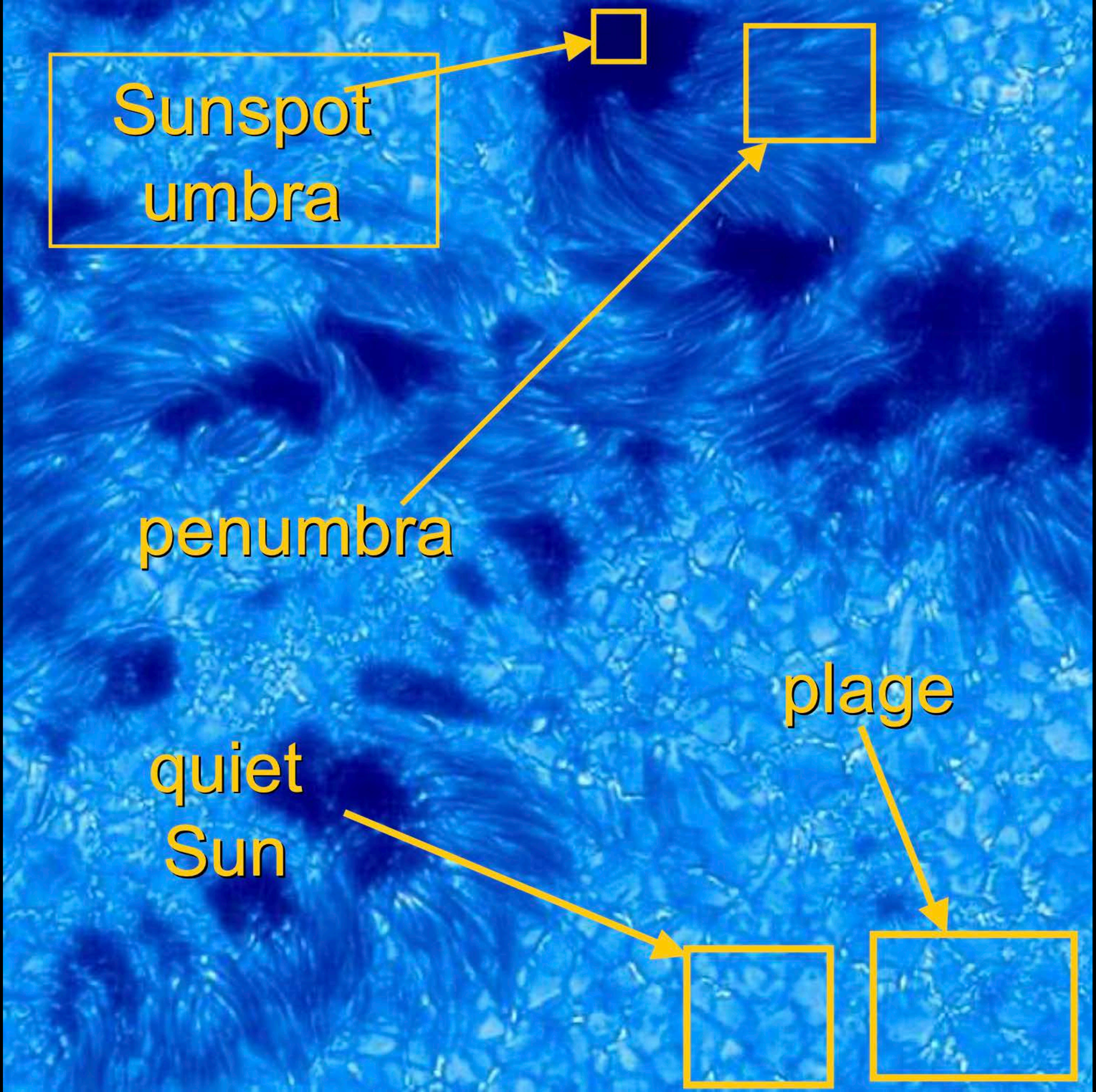
$$\beta = \frac{P_g}{P_m} = \frac{8\pi P_g}{B^2}$$

- **β < 1: Magnetic field dominates** and dictates the dynamics of the gas
- **β >1: Thermal gas dynamics dominate** and forces the field to follow — The magnetic field is **frozen-in.**

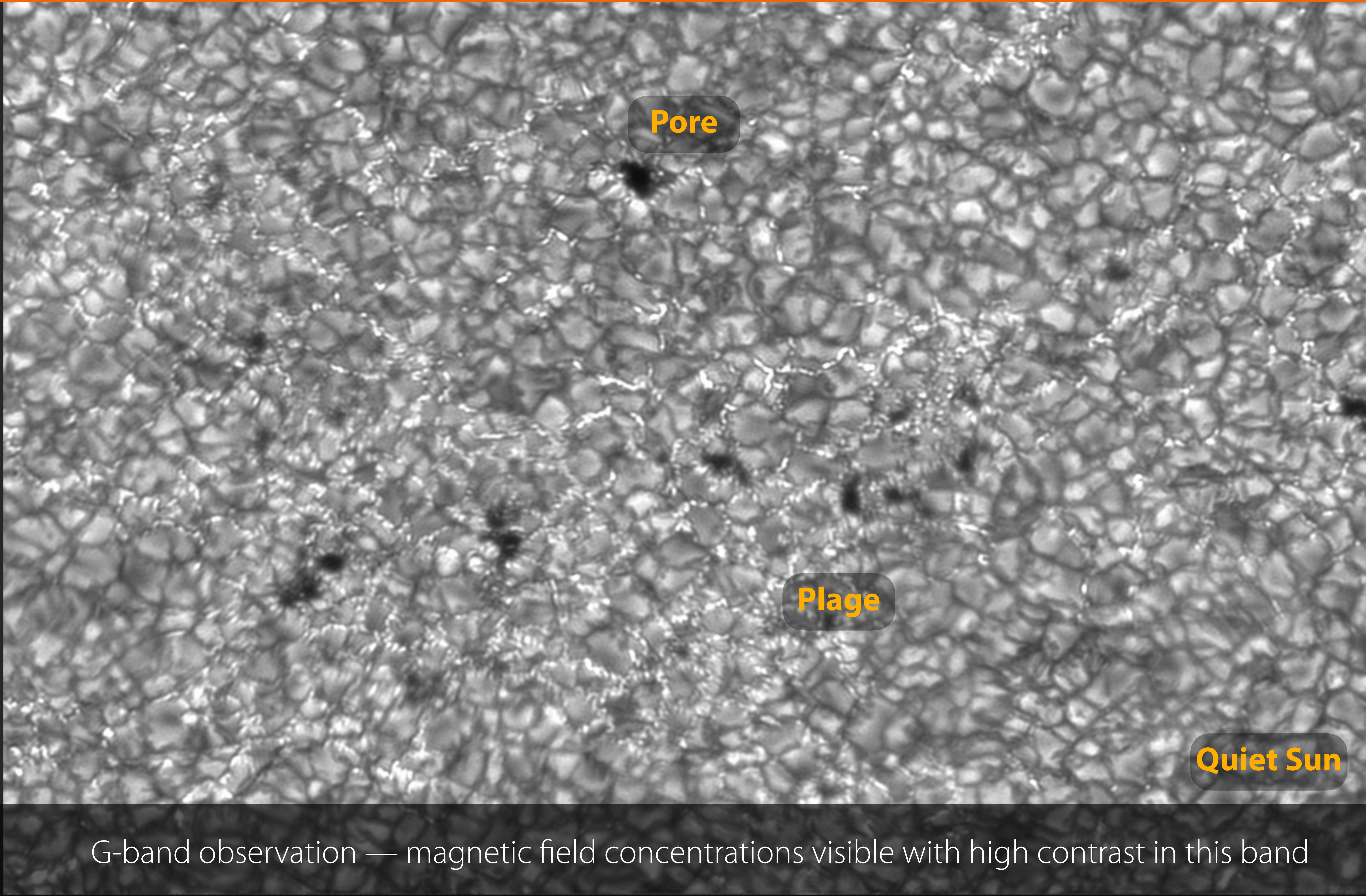
- β is a local quantity but the typical range of values changes with radius:
  - Convection zone: β >1
  - Lower atmosphere (outside strong magnetic field concentrations): β >1
  - Chromosphere: transition to β < 1
  - Corona: β <<1



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


Sunspot
umbra
penumbra
quiet
Sun
plage

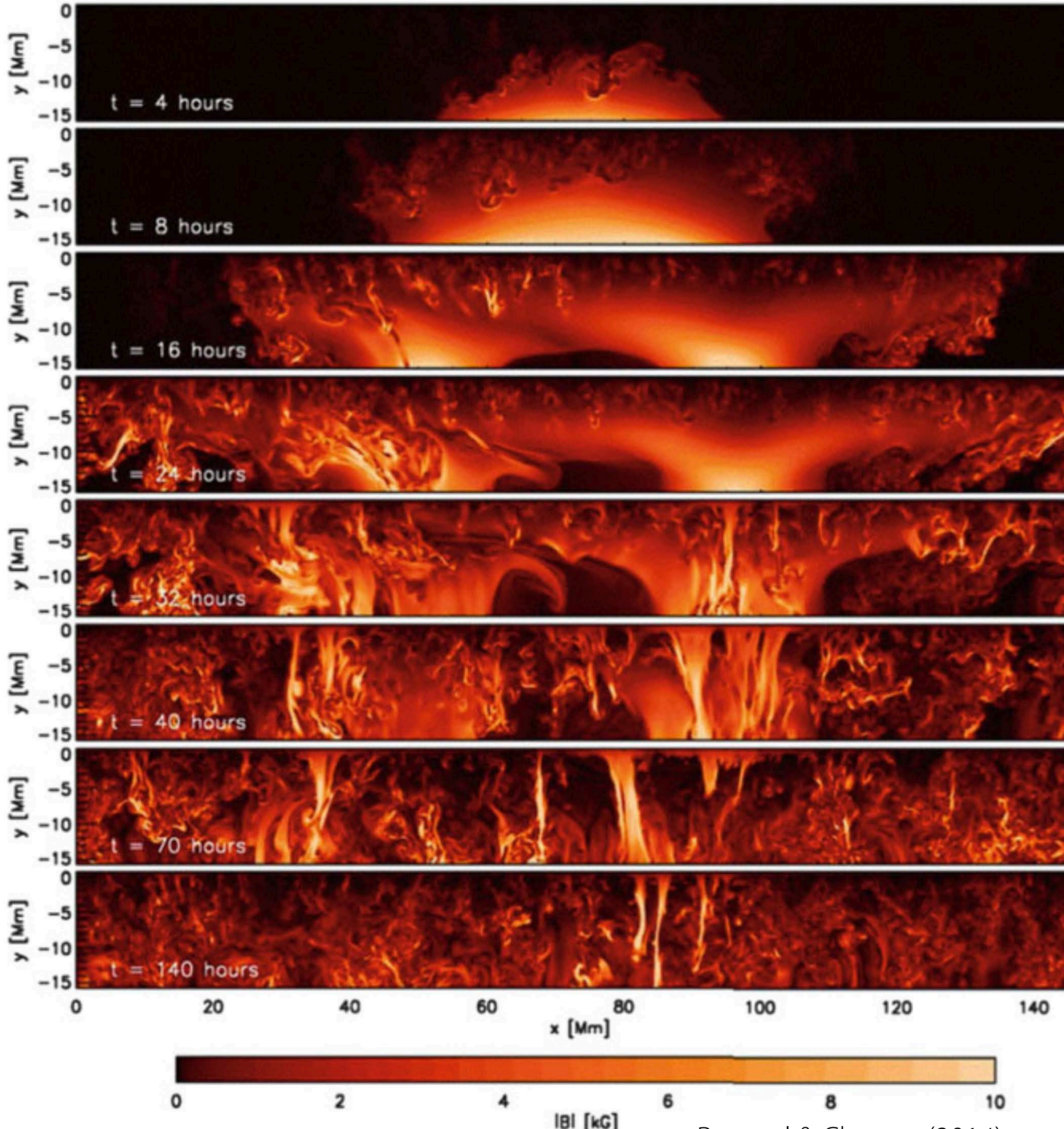
Magnetic field in the solar atmosphere



G-band observation — magnetic field concentrations visible with high contrast in this band

Mag. field

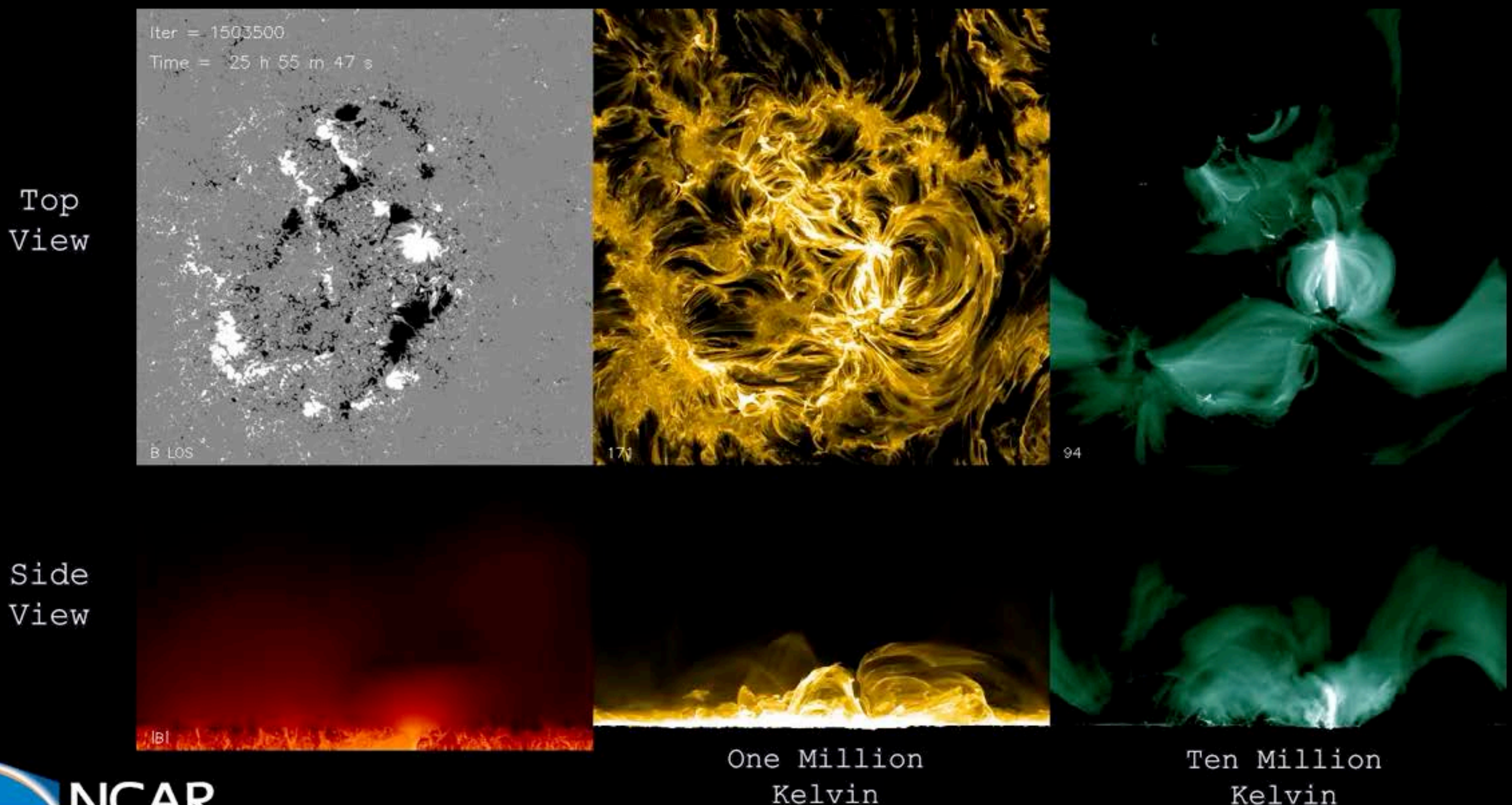
Flux emergence



Rempel & Cheung (2014)

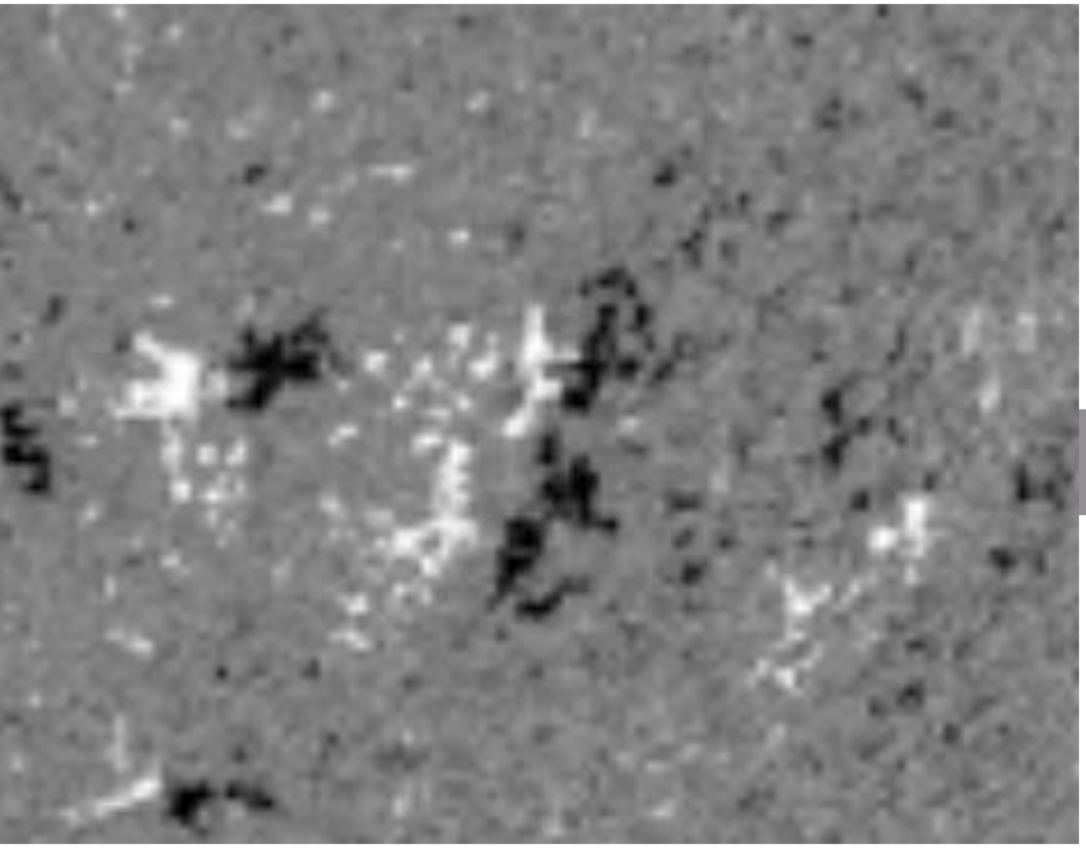
Magnetic field in the solar atmosphere

Flux emergence

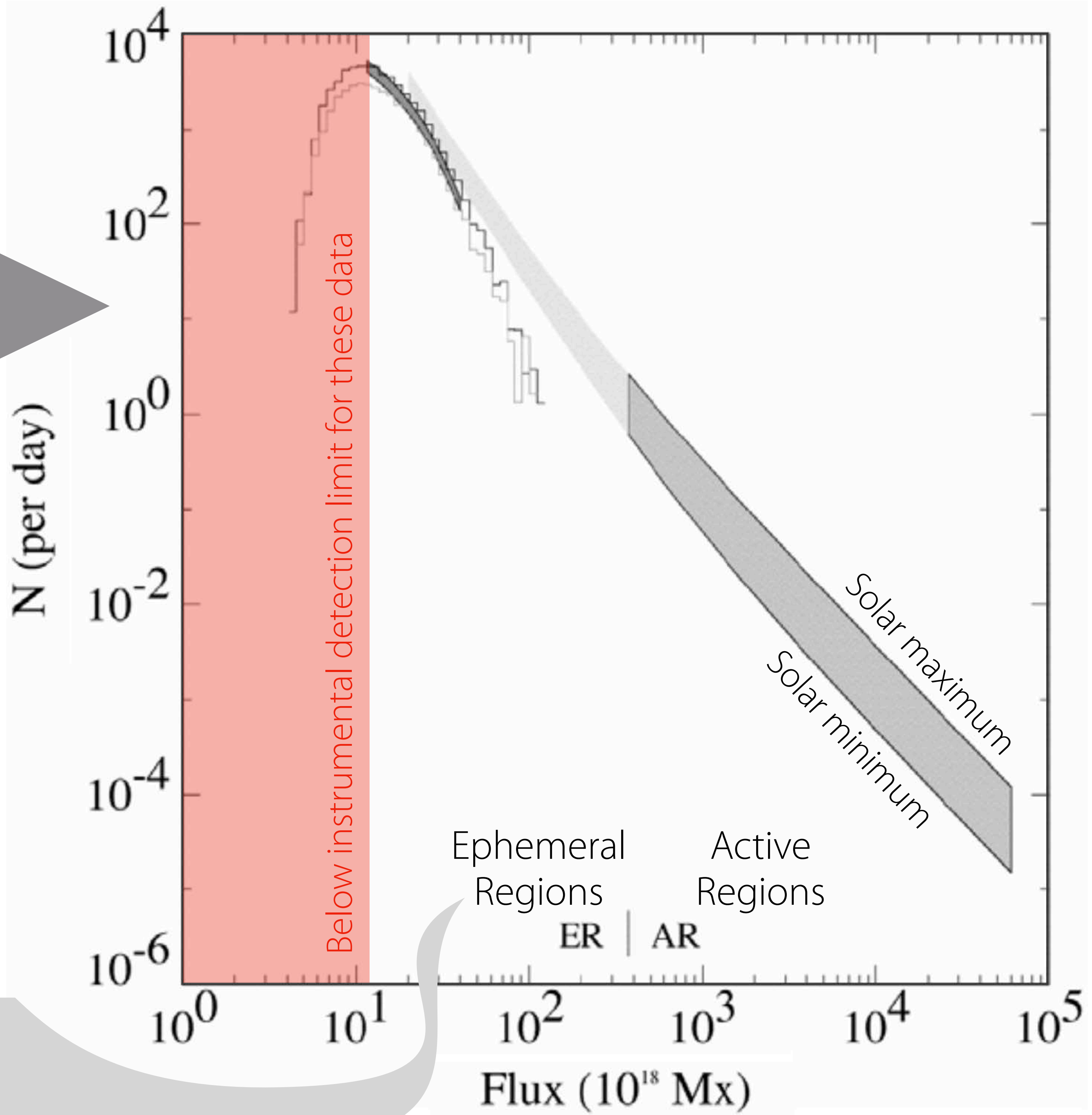


Magnetic field in the solar atmosphere

Flux emergence



Emergence rate of bipolar regions per (unsigned) flux

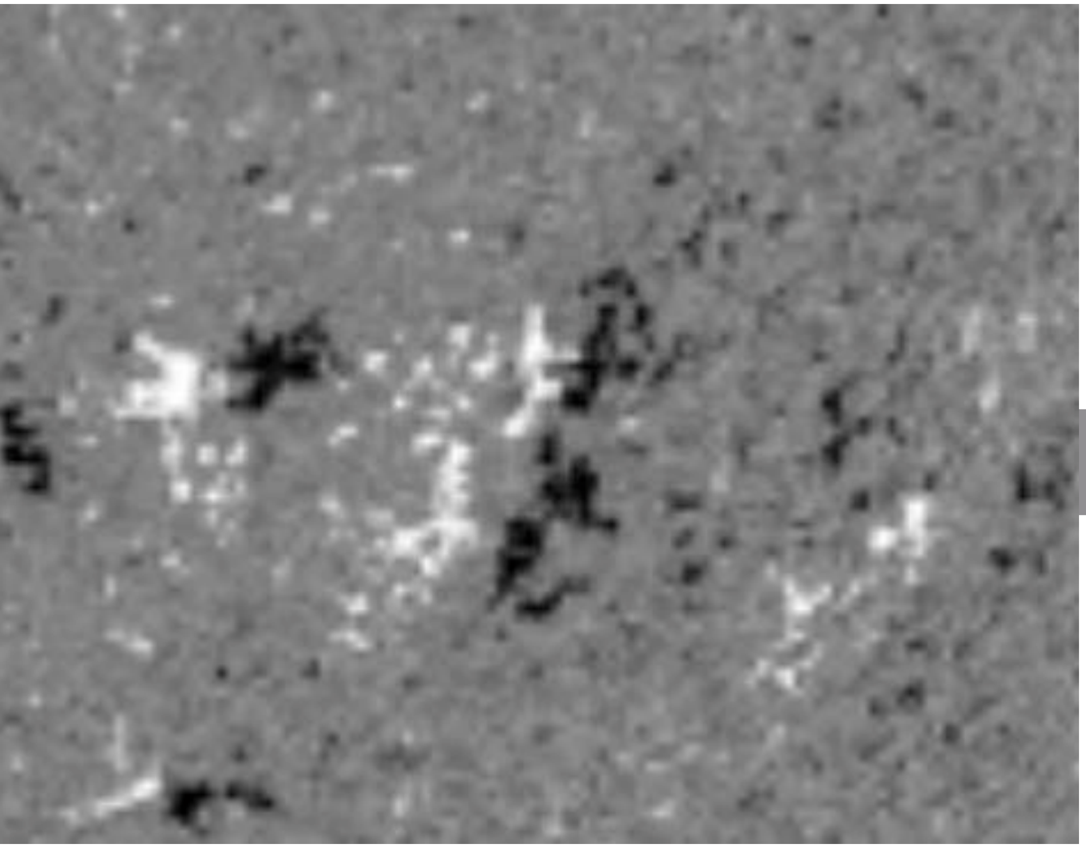


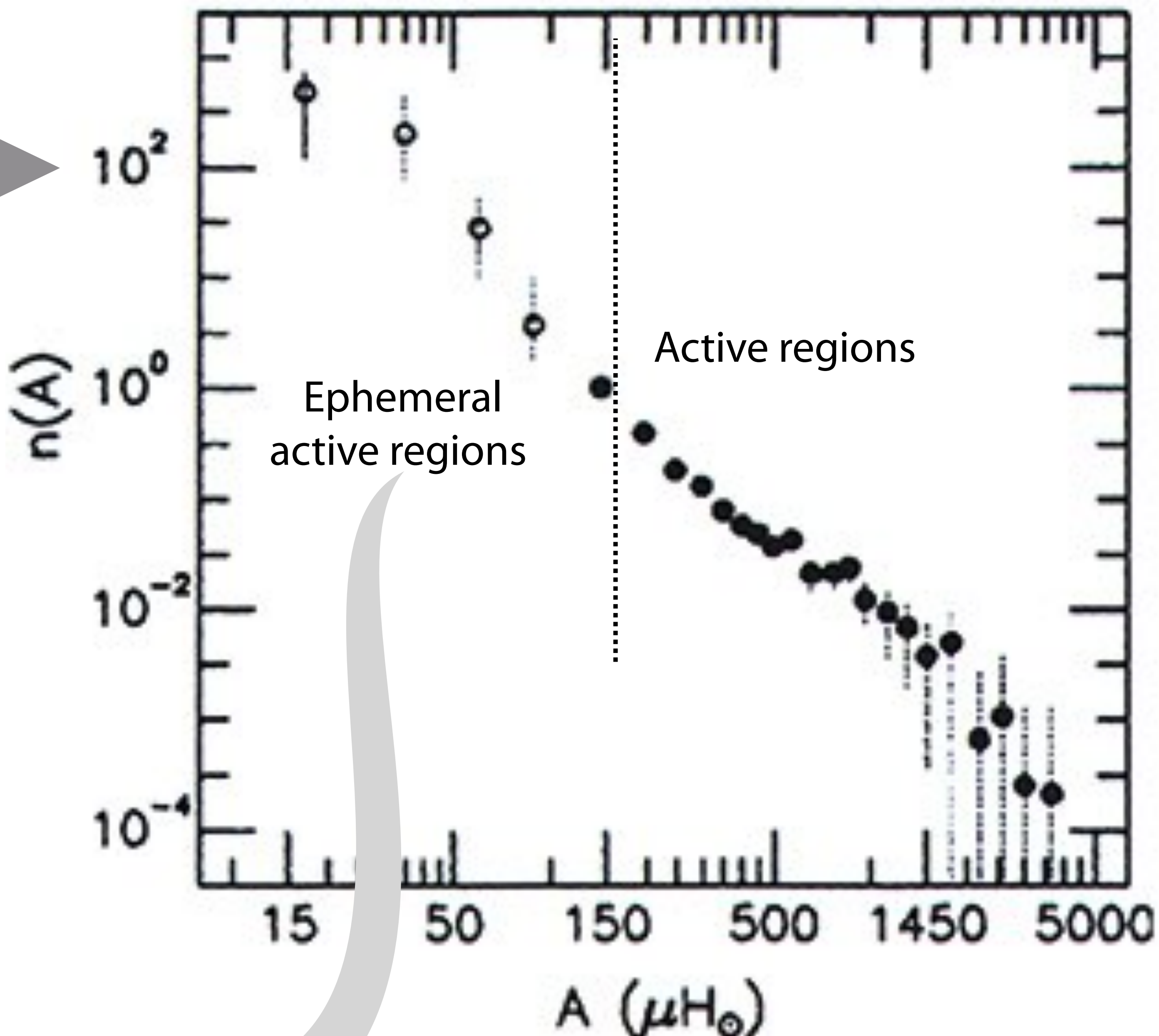
- Emergence of bipolar regions with a large range of contained magnetic flux
  - Many regions with little flux, fewer with a lot of flux
- Varies over solar cycle

Ephemeral regions = short-lived, small bipolar regions (do not develop sunspots)

Magnetic field in the solar atmosphere

Flux emergence





millionths of a hemisphere (μH⊙)

Martin (2018)

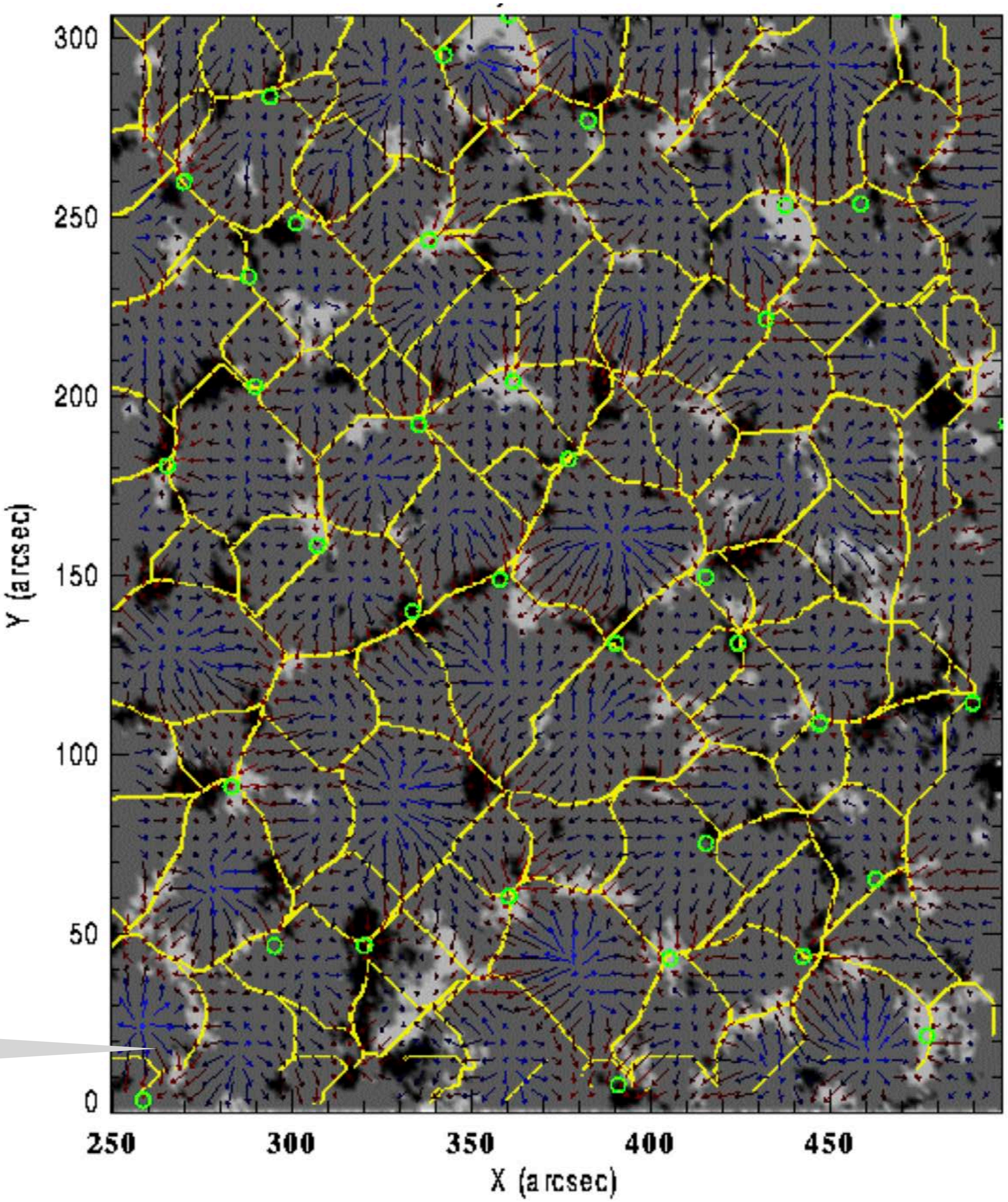
- Emergence of bipolar regions with a large range of contained magnetic flux
    - Many regions with little flux, fewer with a lot of flux
- Varies over solar cycle

Ephemeral regions = short-lived, small bipolar regions (do not develop sunspots)

Magnetic field in the solar atmosphere

Advection — supergranulation scales

- Magnetic field emerges to the surface
- Away from strong fields (sunspots): **High plasma-β** in the photosphere
- **Frozen-in** magnetic field
- Field is advected with the photospheric velocity field towards the **edges of supergranules**
- Concentrated there, resulting in stronger magnetic flux concentrations
- Observable as **magnetic network**
- Encloses **inter-network regions**

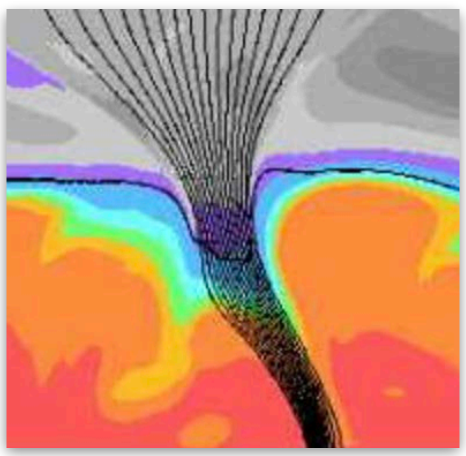


- Magnetogram (grayscale)
- Horizontal flow field (arrows)
- Supergranule boundaries: yellow

Magnetic field in the solar atmosphere

Advection — granulation scales

- Advection into intergranular lanes (downflow lanes between granules)
- Concentration into stronger flux concentrations but fewer than in the network



Granulation image, Fe I 630.25 nm line

Overlaid magnetogram contours 30, 50, 70 and 90 G

(Domınguez Cerdena et al., 2003)