# Recent advances in the physics of sunspots and starspots

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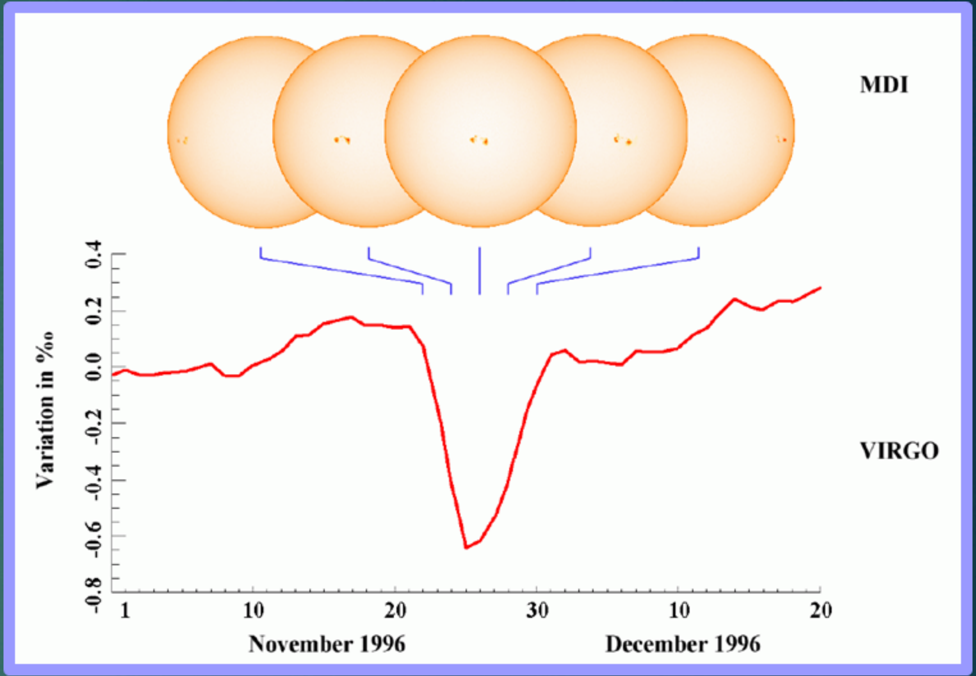
WITH HELP FROM MAYUKH PANJA AND YVONNE C. UNRUH

# Why should the PLATO community ~~care~~ worry about sunspots and starspots?

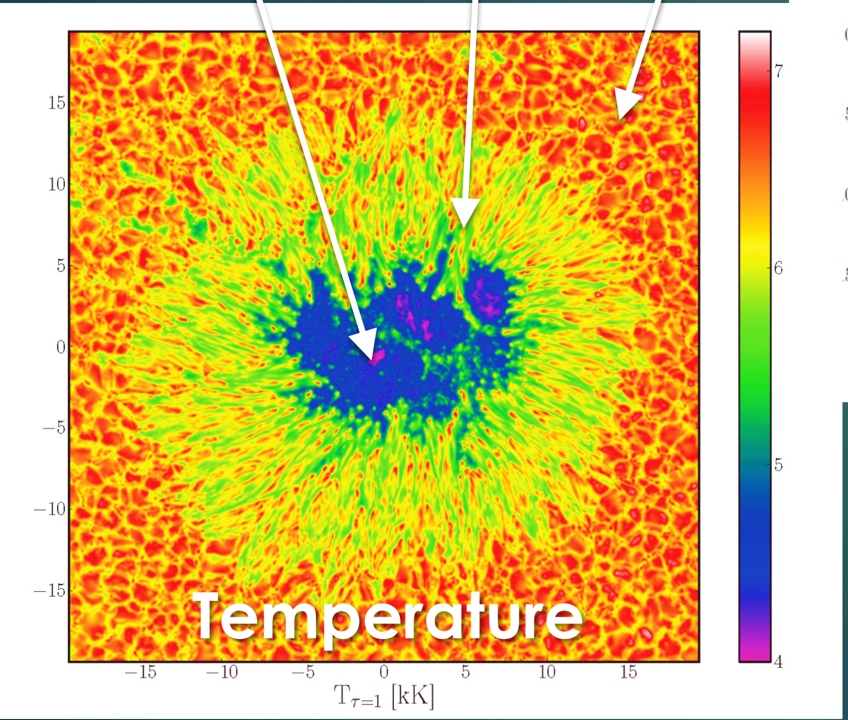
- They are a pain in the neck!
  - Even for our rather inactive Sun, spots regularly produce dips as deep as a transiting Earth
  - Sunspots never come alone: where there is a spot, there is plage → starspots, stellar plage?
  - Together they affect Intens+veloc variability, spectrum, limb-darkening, and luminosity

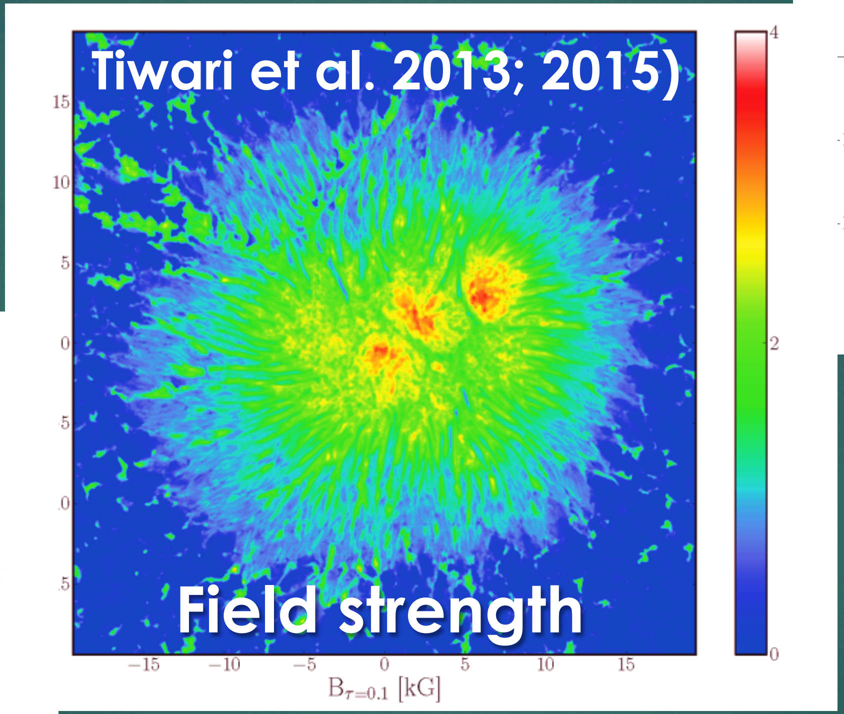


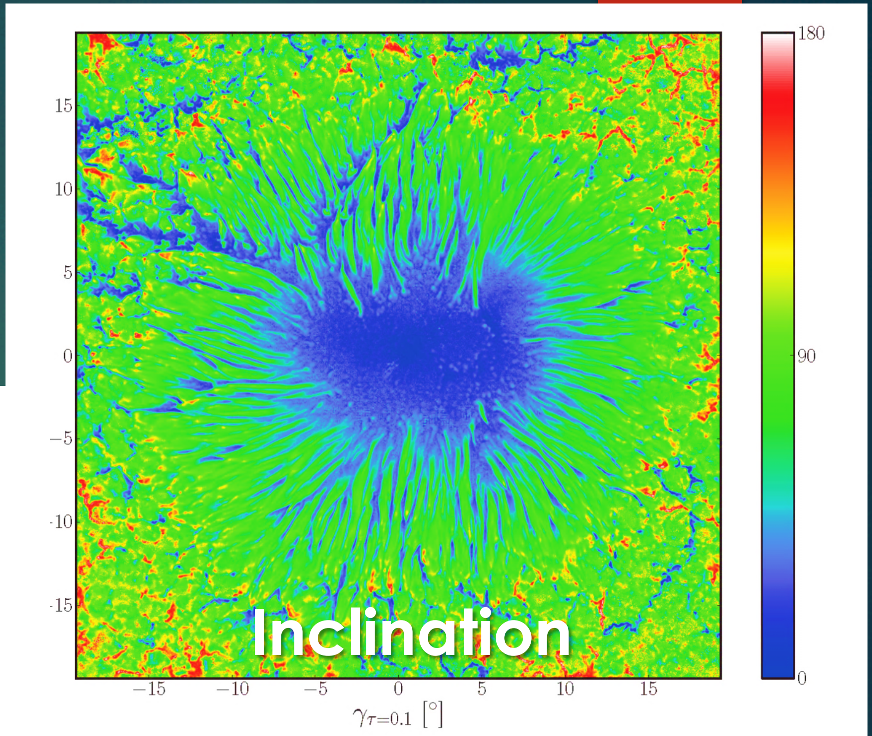

- They are great fun!
  - Spots are most prominent example of magnetoconvection at work
  - They are a prime way of constraining solar and stellar dynamos
  - PLATO will place firmer constraints on starspot properties & hence stellar dynamos

# At the hearts of active regions: Sunspots

Umbra Penumbra Granule (quiet Sun)




Sunspots are large (?) magnetic flux tubes, concentrations of field that expand with height

**Quiet Sun:**

$T_{eff} \approx 5800$ K $\quad B < 100$ G

**Penumbra:**

$T_{eff} \approx 5500$ K $\quad B \approx$ 1-2 kG

$I_C \approx 0.75\, I_C$ (quiet Sun)

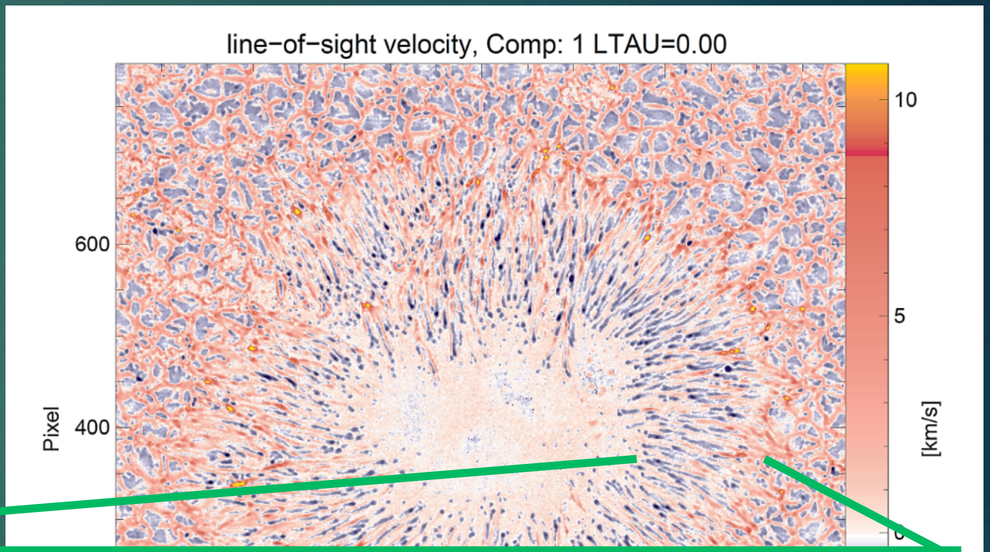
**Umbra:**

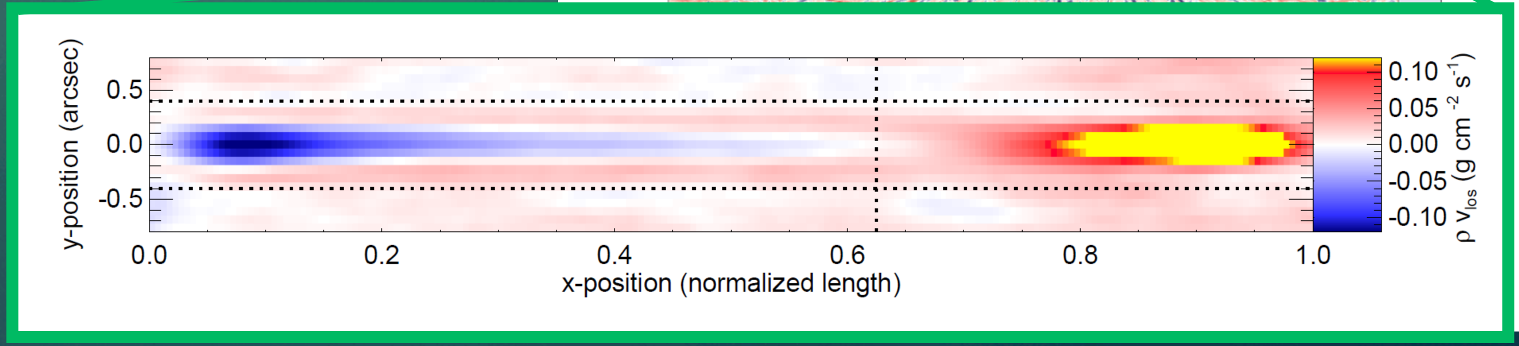
$T_{eff} \approx 4500$ K $\quad B \approx$ 3-4 kG

$I_C \approx 0.2\, I_C$ (quiet Sun)

# Magnetoconvection: why are sunspots so bright?

- The magnetic field in sunspots reduces convective energy transport, but does not completely quench it, as simple theory requires → sunspots are too bright!
- Both, penumbra and umbra host convective features carrying the energy that spots radiate
  - Umbra: umbral dots
  - Penumbra: penumbral filaments
- The elongated cells of overturning magneto-convection in penumbra are particularly effective at transporting energy




Zakharov+ 08, Scharmer+ 11, Tiwari+ 13

# Sunspot simulations

- Radiation MHD simulations of sunspots are quite mature  (MuRAM code, Rempel+09,15)
- They agree well with the observational picture of overturning magnetoconvection in umbrae and penumbrae (Rempel+ 09)

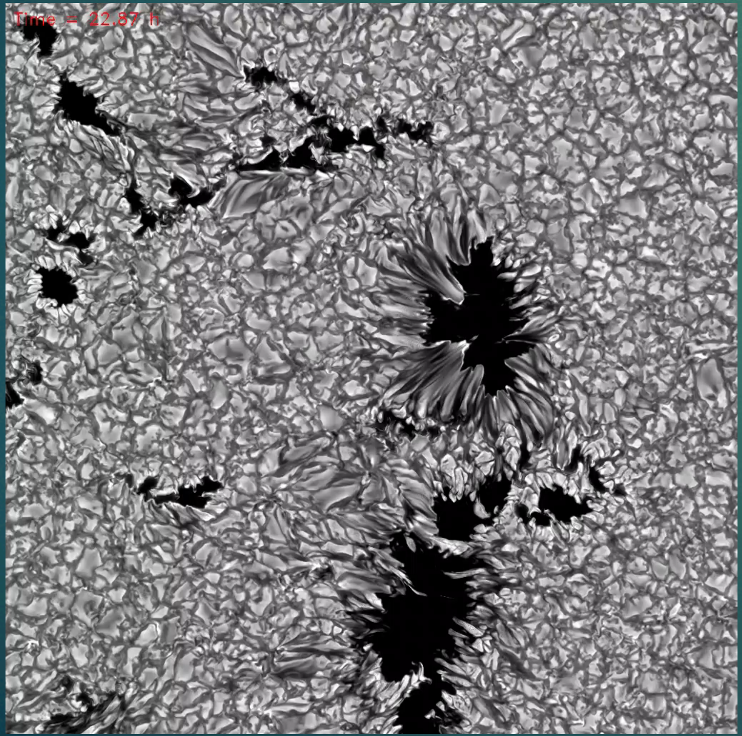
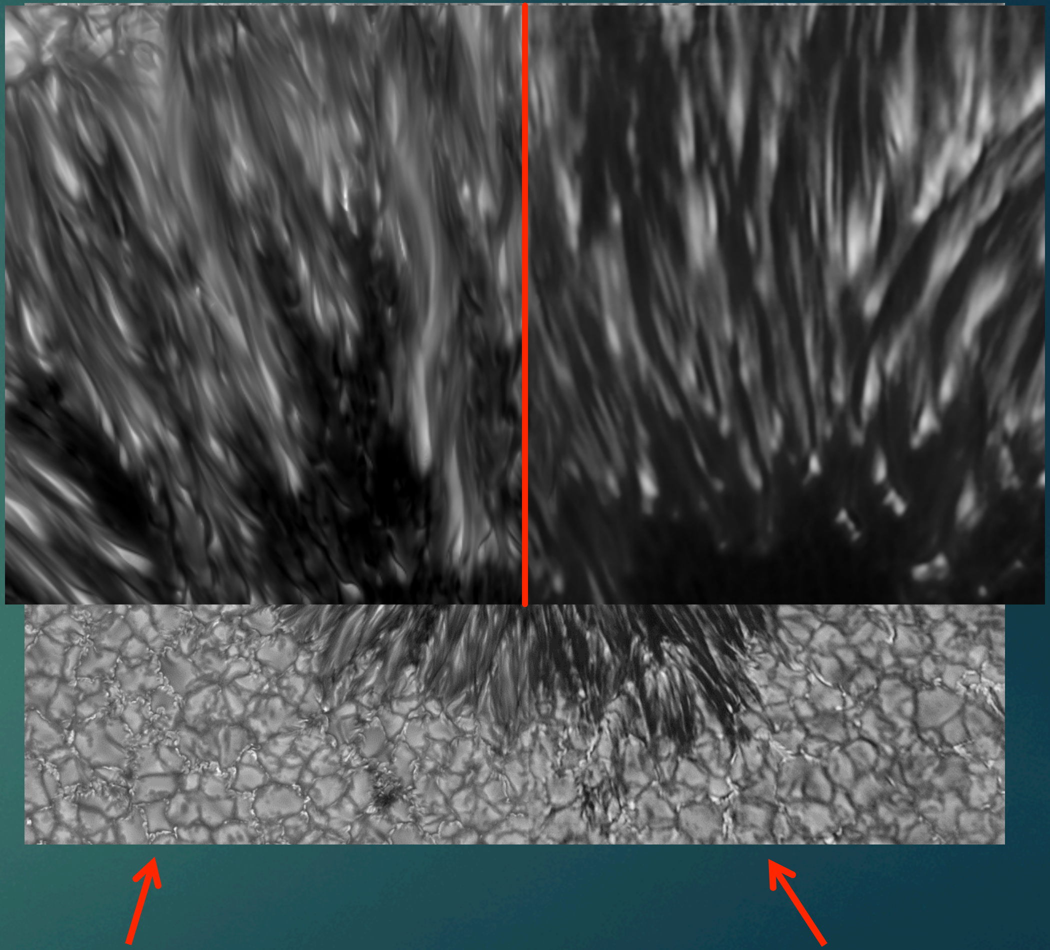


Figure by M. Rempel

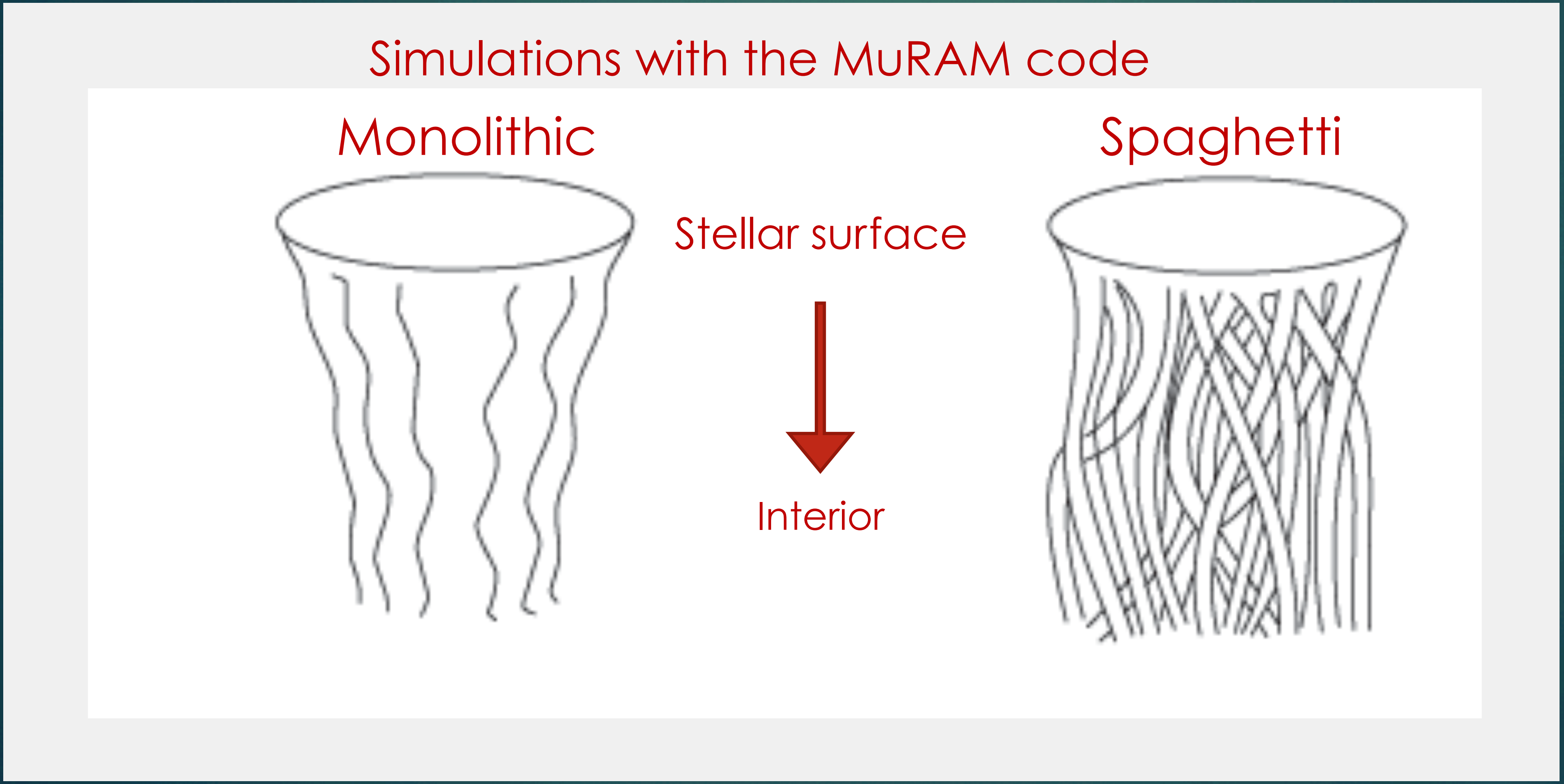


MuRAM Simulation
(M. Rempel/HAO)

G-band observation
(F. Wöger/NSO)

# Single large flux tubes or spaghetti?

Very much an open question: subsurface structure of sunspots:
Are spots monolithic or a spaghetti of smaller flux tubes (Parker 1979)?

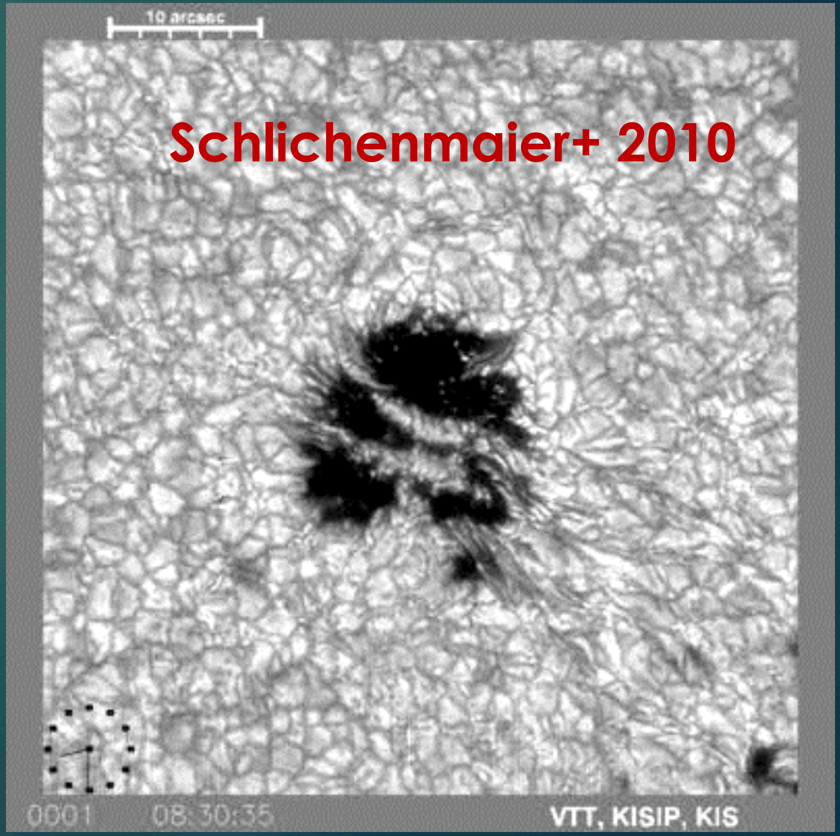



Structuring of sub-surface layers of an initially monolithic sunspot due to the fluting instability (15 h of simulations)

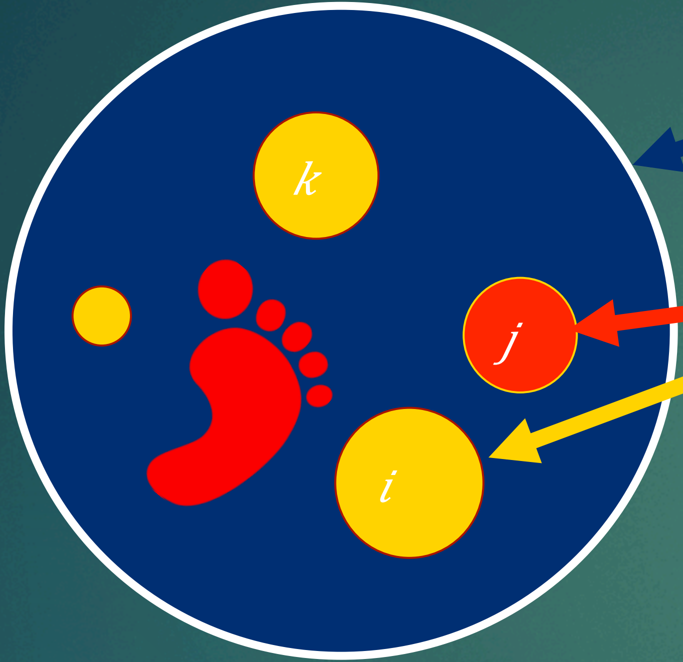
Panja et al. in prep.

# Birth and death of sunspots

- Still many open questions on birth and death of spots
- Often related to the processes driving formation and dissolution of the penumbra
- Mysteriously, the chromosphere layers appear to play an important role in penumbra formation (Shimizu 2012, Romano+ 2014, Murabito+ 2016)
- Also, exact physics of the dissolution process not clear yet. Old spots break up, but probably flux is also carried away on small scales (unipolar moving magnetic features)



# Cancellation of Stokes *V* signals




Spatial resolution element

Unresolved magnetic features with **magnetic flux** $\Phi_i = B_i A_i$ , where

$B_i = B$ in element $i$

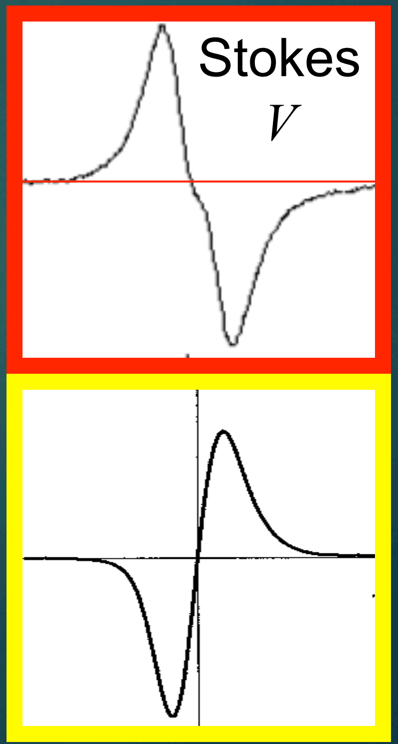
$A_i =$ area of elem. $i$

Field pointing towards observer

= positive polarity magnetic field

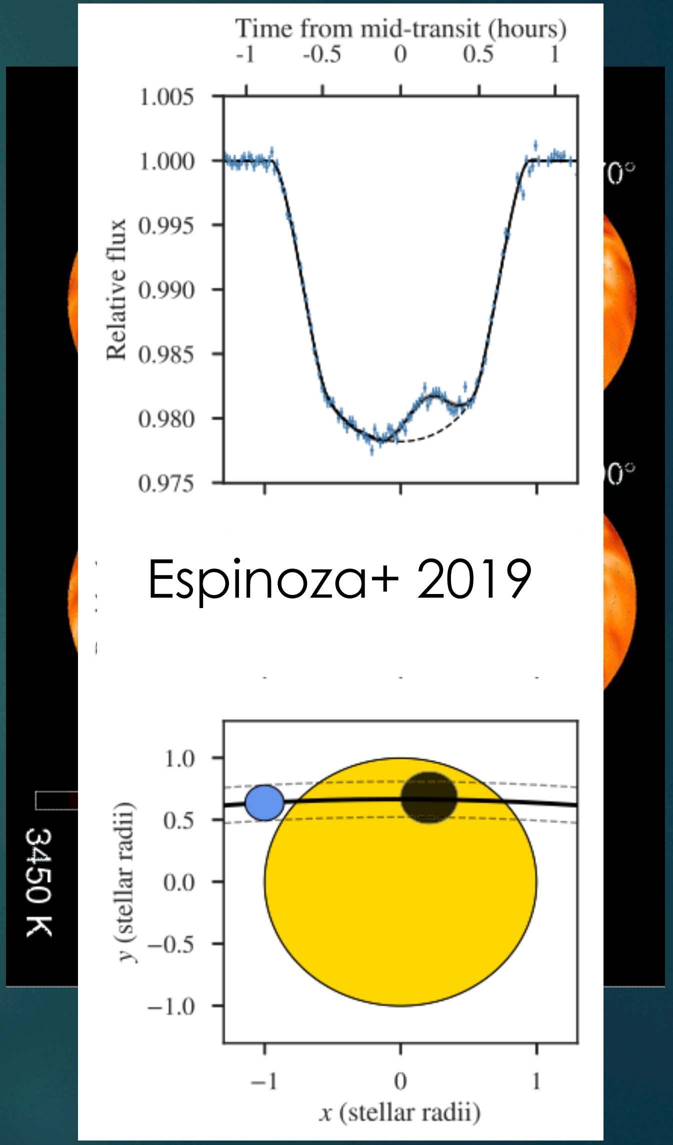
Field pointing away from observer

= negative polarity magnetic field



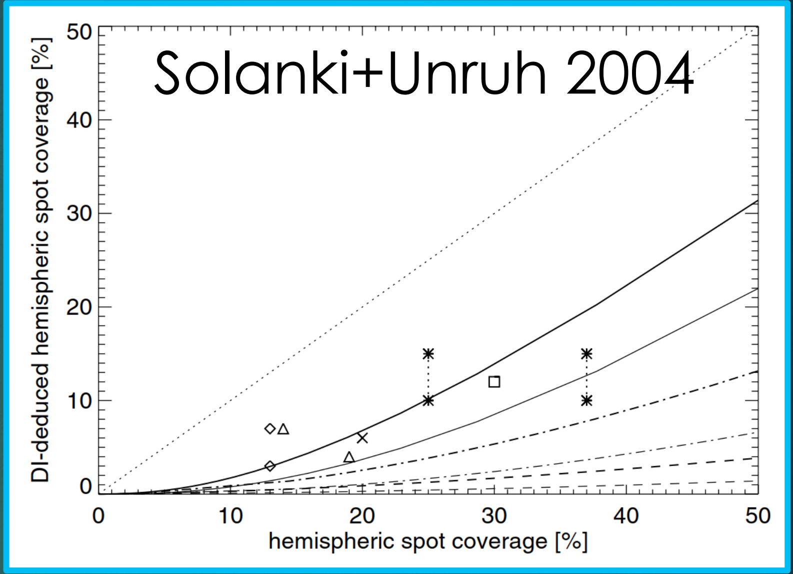
# Starspot observations: techniques

- Techniques for detecting and studying starspots:
  - **Photometric time series:** provide info on location, contrast and size of (1-2 large) spots (Vogt 1981), often with some degeneracy (multiple wavelengths help)
  - **Doppler Imaging and Zeeman Doppler Imaging** (Semel 1989; Donati+ 1997): potentially more accurate determination of shapes, sizes, contrasts, even magnetic fields (ZDI). Works best for rapidly rotating stars (young stars, close binaries)
  - **Molecular bands:** allow determining true area coverage by spots and their temperatures (by using line ratios)
  - **Transit profile mapping:** maps spot locations, sizes and (if spectra are used) contrasts (e.g., Mancini+13, Morris+18, Espinoza+19)



# Starspot observations: challenges

- Starspots are generally unresolved: spectral info is required to distinguish area from brightness contrast
- Starspots are dark, so that most spectral lines do not sense their internal properties well (e.g. magnetic vector, true brightness, flows)
- For all observational techniques, it is not clear which combination of umbra, penumbra, quiet star is sensed: umbra alone, umbra + penumbra, other?
- Various methods find different spot coverages: E.g. molecular lines ≫ DI → is DI missing small spots, or do the techniques sense penumbra in different ways?




Assuming log-normal distribution of starspot sizes reconciles areas obtained from DI and from molecular lines

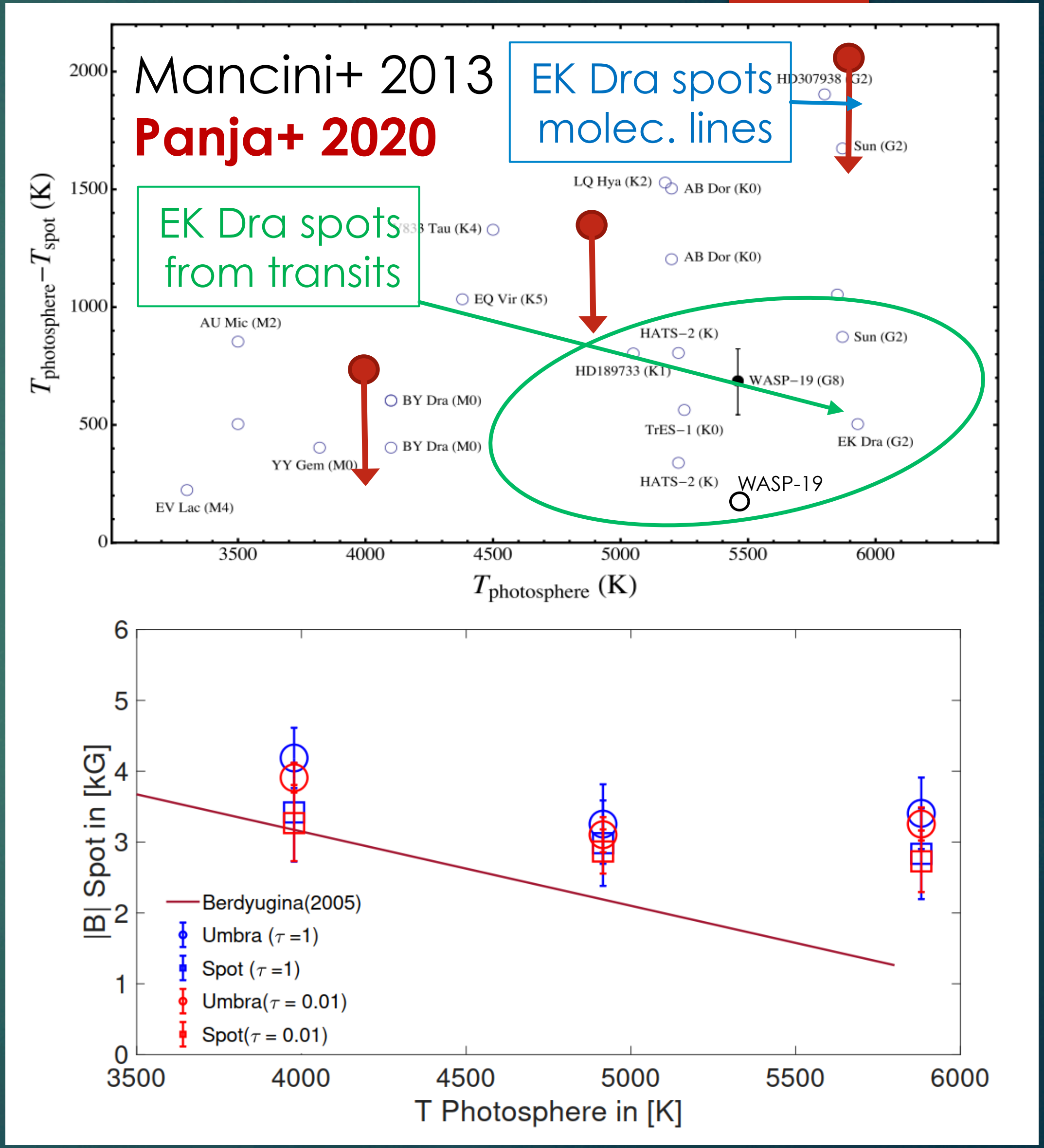
# Starspot simulations

- 1st radiation MHD simulations of starspots
- Rectangular geometry chosen to save computing time. Catches main physics well (compare Rempel+ 2009a, b)
- Disadvantage: ratio of penumbra/umbra area is 1-2 compared to 4-5 typical of sunspots → spot-averaged properties are similar to umbral properties
- Box scaled to cover similar number of granules: G-star box has ~10 times larger area than M-star box

See poster by Mayukh Panja et al.

# Starspot simulations vs. observations

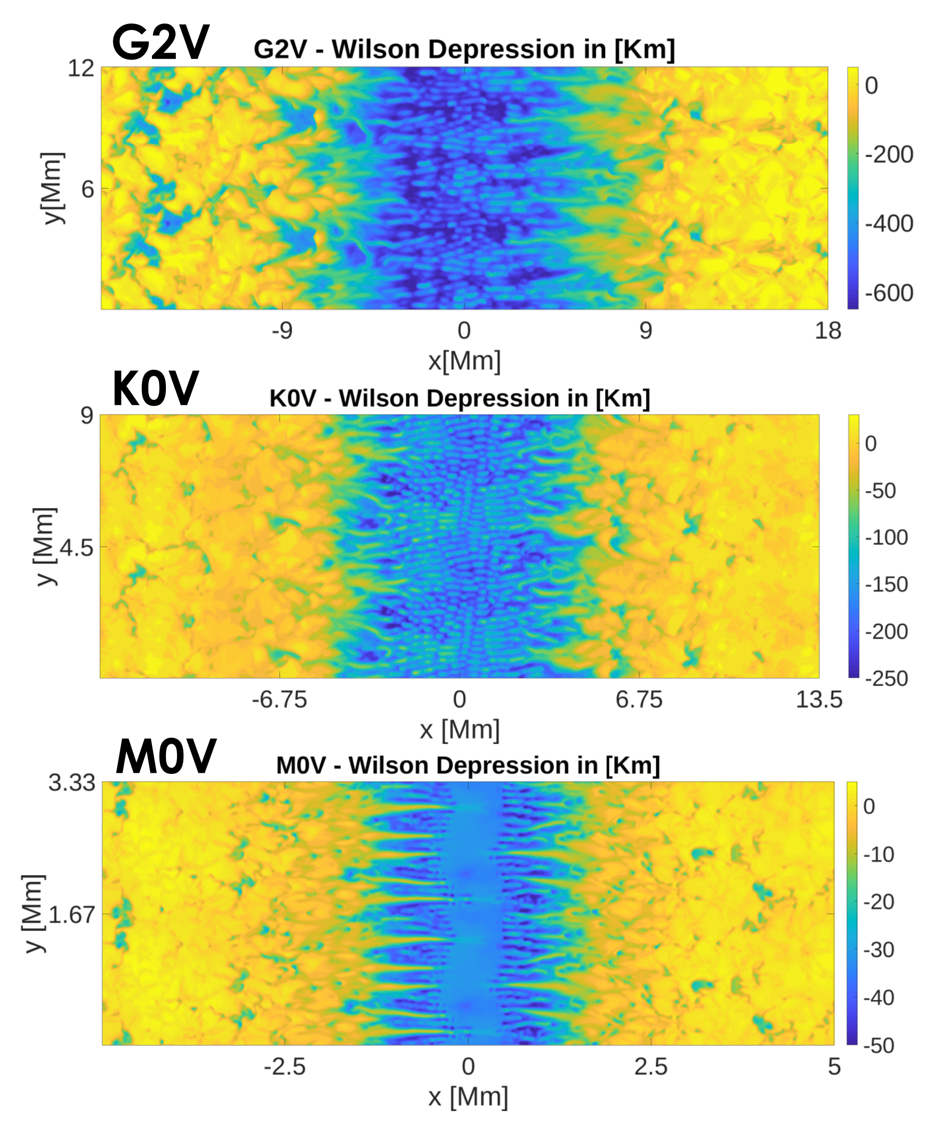
- Simulated intensity contrast of starspots reproduce measurements collated by Berdyugina 2005
- Transits give lower temperature contrasts than other techniques (bigger influence of penumbra?)
- Simulated B are larger, likely because
  - ZDI etc. underestimate spot B values, especially for dark spots
  - too small penumbral areas in the simulations (penumbra = low field)
- New simulations of circular starspots now running



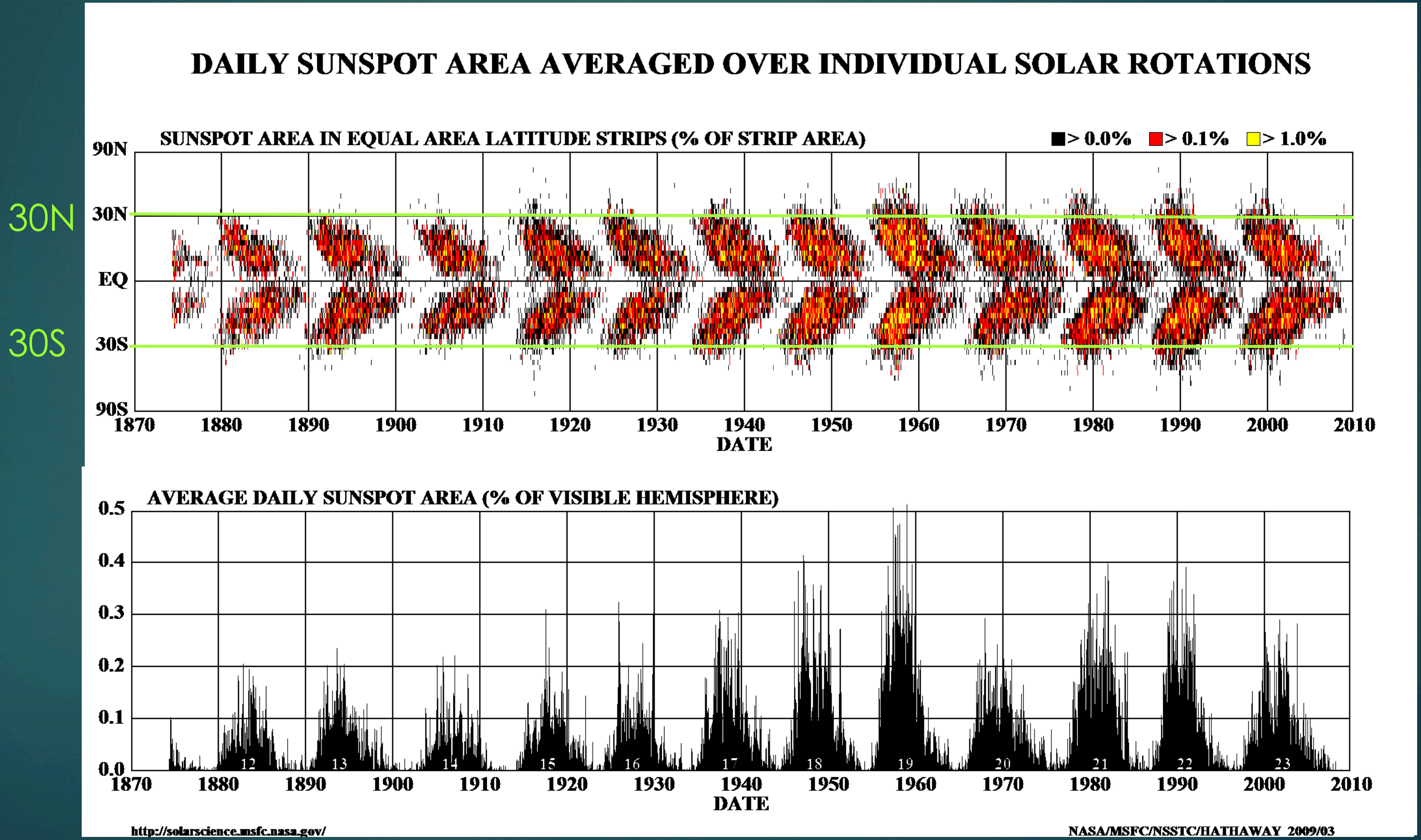
# Starspot simulations: explanations

- Dependence of spot properties on $T_{eff}$ likely is mainly due to:
  - Lower $T_{eff}$ → radiation becomes increasingly important below surface → quenching of convection by a strong magnetic field has a smaller effect on the energy transport & hence on brightness of spot on M star
  - Larger pressure at M-star surface → M-star can support larger umbral field strength
  - Pressure scale height decreases rapidly from early G to M stars → Wilson depression decreases by factor of >10 → B in M spot is not as large as it could be

See also poster by M. Panja et al.

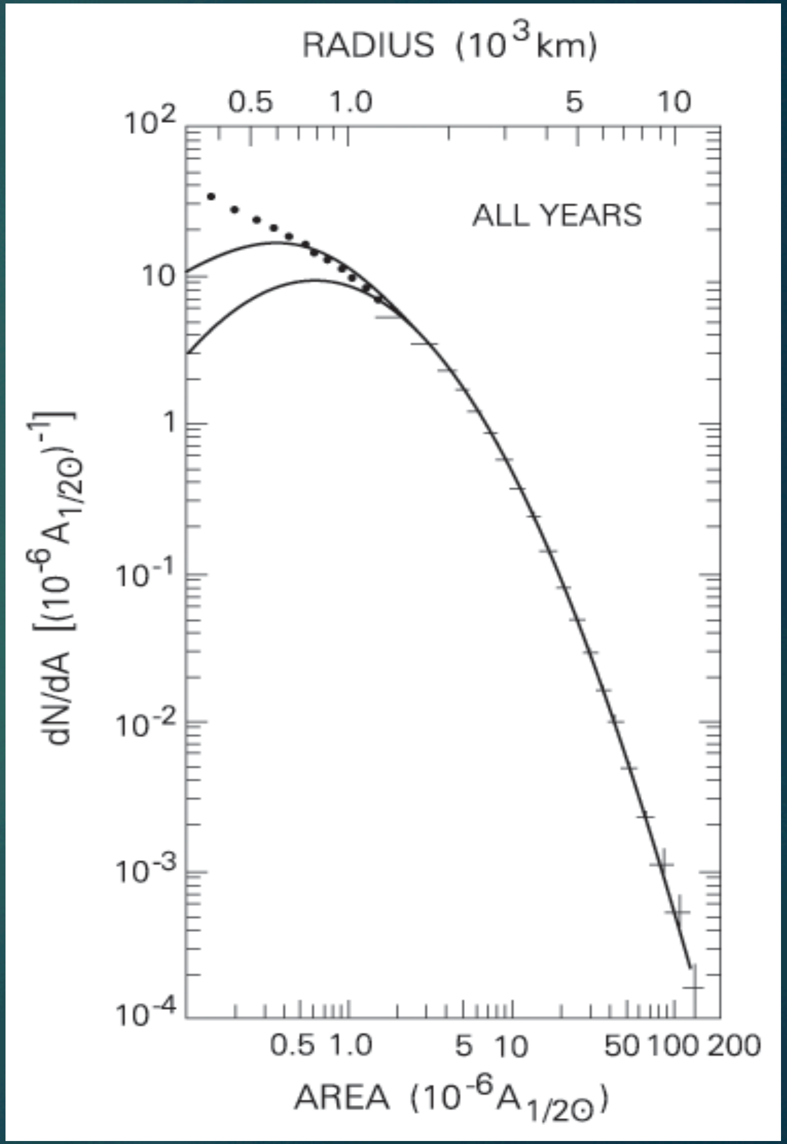


# The sunspot cycle and the butterfly diagram: Spörer's law



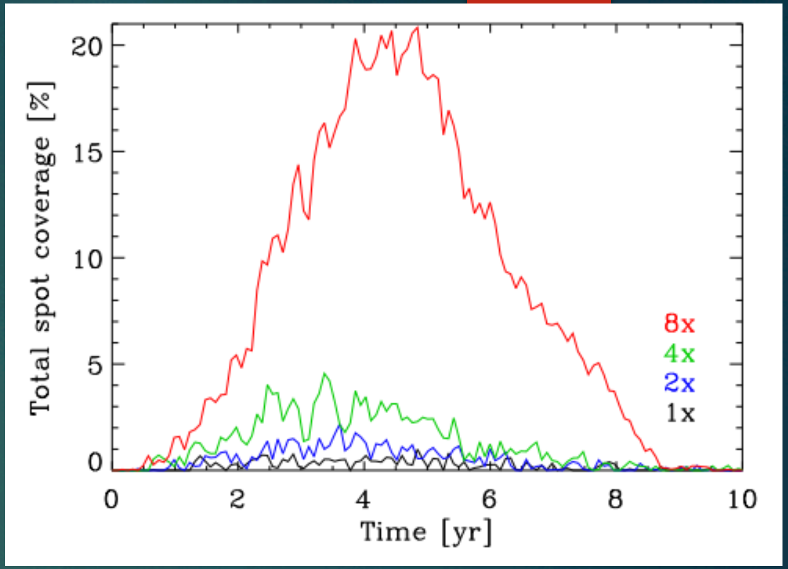
# Sunspot statistics ↔ starspots

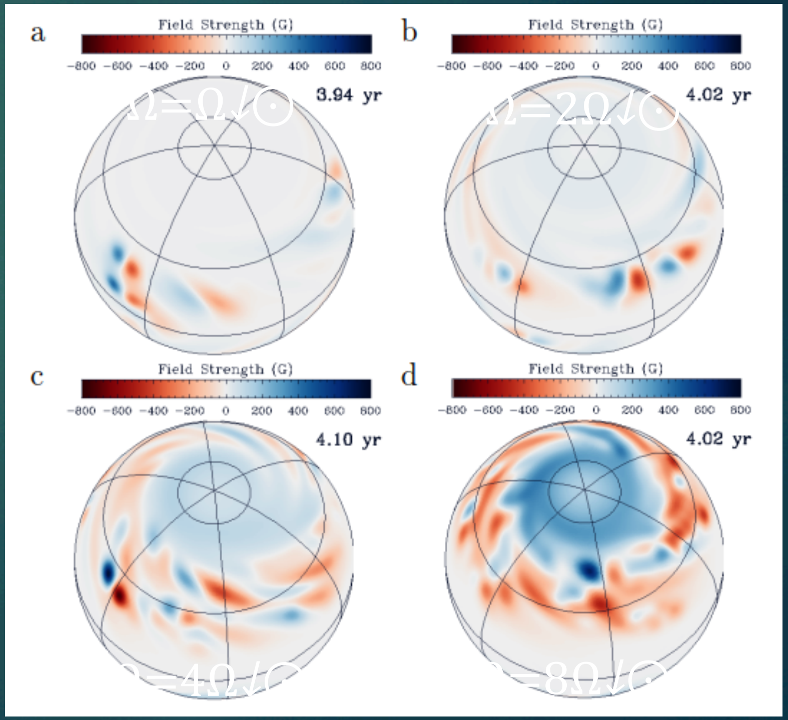
- Sunspot sizes: Log-normally distributed (= Gaussian on a logarithmic scale) ↔ starspots: distribution unknown; active stars appear to have larger spots
- Lifetimes: hours–months; Gnevyshev-Waldmeier rule: Liftetime ~ max spot area ↔ starspots: irregular light curves of inactive Kepler stars → spot lifetimes similar to solar. Regular light curves of variable Kepler stars: possibly longer lifetimes
- Spatial distribution: within ±30↑∘ of equator, following the butterfly diagram, with leading spot of a group closer to equator according to Joy's law ↔ starspots: depends strongly on rotation rate



# Starspot positions and evolution

- Simulations magnetic flux on G2V stars at different rotation rates (emerging flux ~ rotation rate), assume solar paradigm
- Take into account emergence of field through CZ & evolution on surface with surface flux transport simulation
- Star with $\Omega=\Omega_\odot$ displays solar properties
- More rapidly rotating stars show flux settling at higher latitudes and at $\Omega=8\Omega_\odot$ producing a polar spot
- Spot coverage increases quicker than rotation rate and reaches 20% in fastest rotator, similar to coverages found from molecular lines in active stars (O'Neal+ 2004, 2006)
- Next step: compute Kepler light curves




Isik et al. 2018

# Summary

- We know infinitely more about sunspots than about starspots
- In spite of huge advances in understanding sunspots there are a number of open questions regarding their sub-surface structure, formation and disappearance
- Difficult to get clear information on starspots from observations
- MHD simulations open a new channel to getting properties and physics of starspots
- Further work is underway

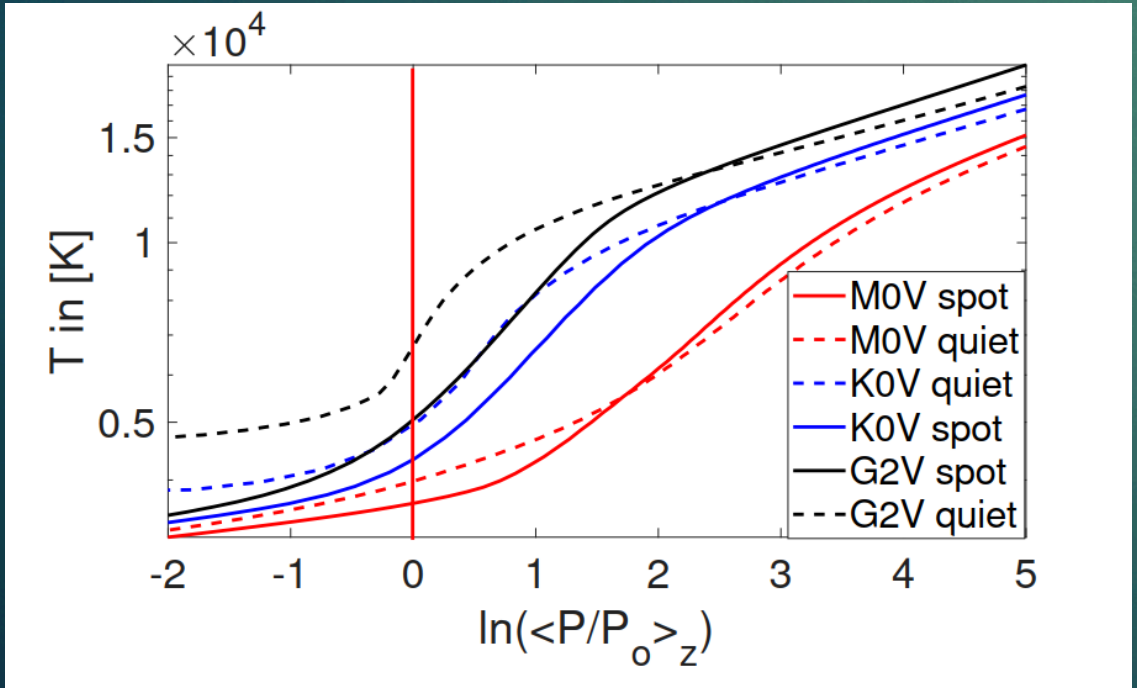
MuRAM simulation by M. Cheung

# Thank you for your attention

# not clear how much time: 20 min with discussion? → 15 min talk

- Needed: 11 – 12 slides
- Now: 17 – 2 = 15 slides

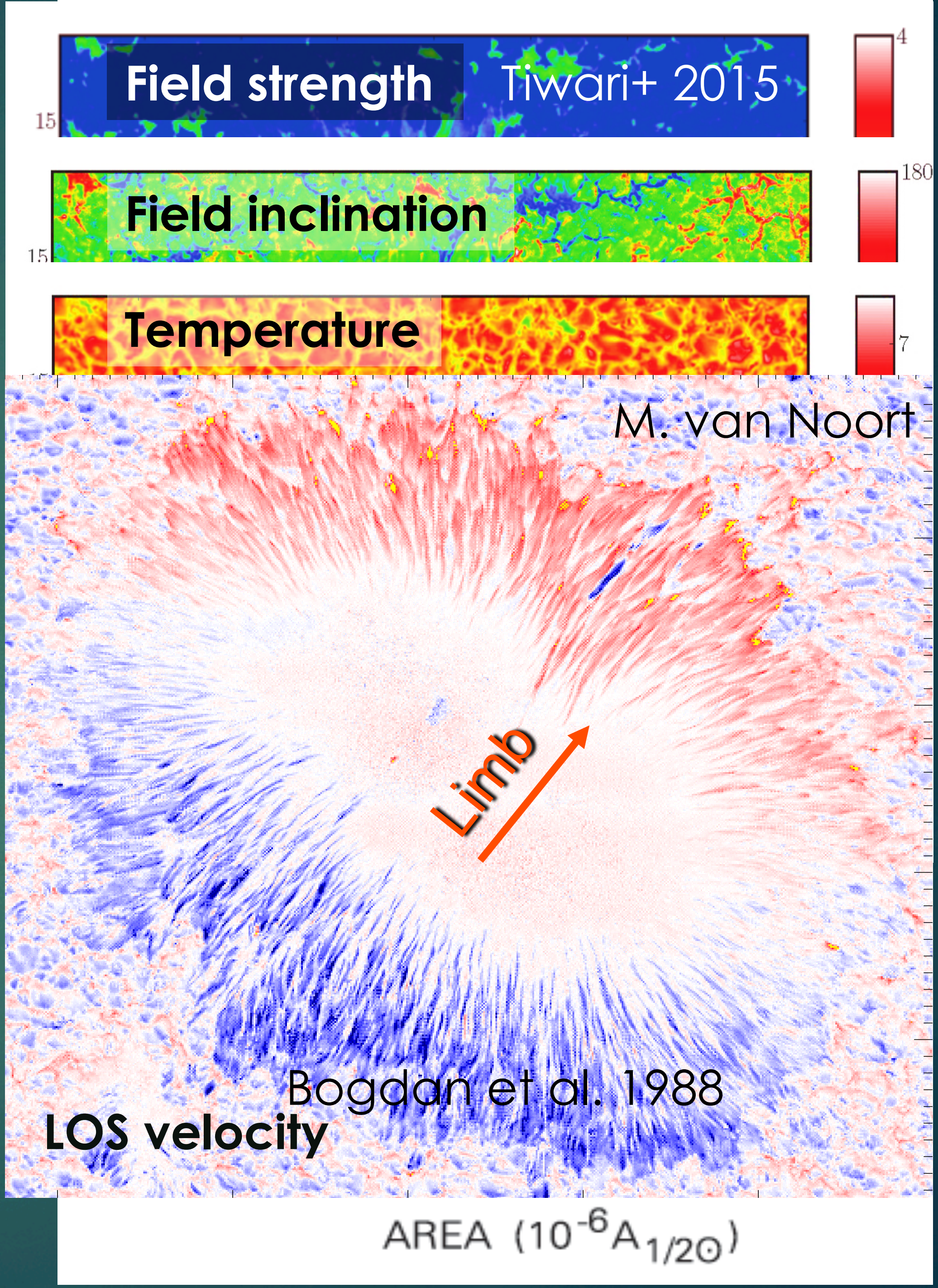
# Sunspot lifetimes



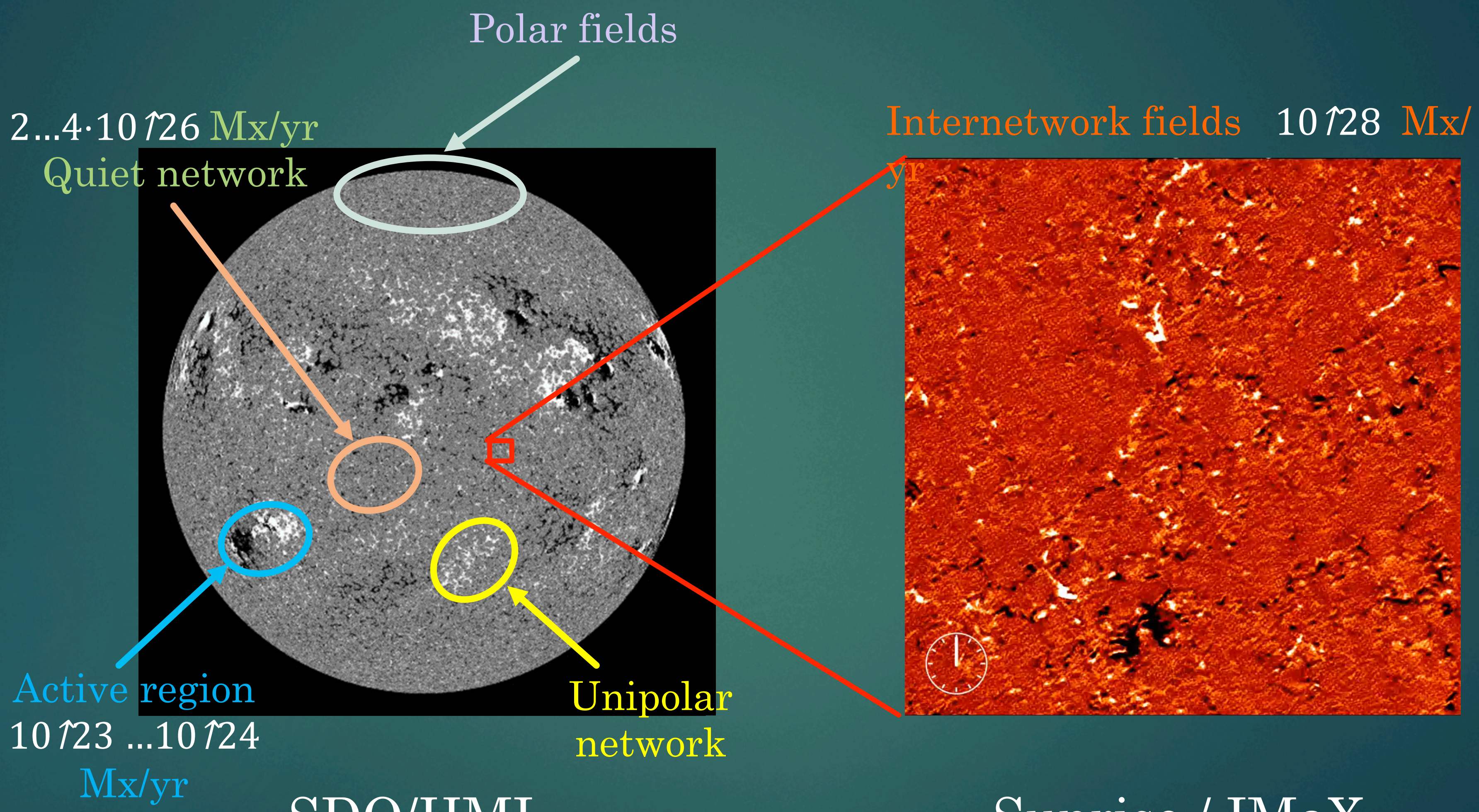
×10^4
1.5
1
0.5
T in [K]
-2
-1
0
1
2
3
4
5
ln(<P/Po>z)
M0V spot
M0V quiet
K0V quiet
K0V spot
G2V spot
G2V quiet

# Sunspots

- Field: $B_{\max}$ = 2500–4500 G; vertical in umbra, nearly horizontal at outer edge
- Brightness: umbra: 20% of quiet Sun, penumbra: 75%
- Evershed flow: horizontal, radially outwards directed flow. Averaged speeds: 1−2 km/s, locally 10km/s
- Sizes: Log-normally distributed (= Gaussian on a logarithmic scale)
- Lifetimes: hours–months: Gnevyshev-Waldmeier rule: Liftetime ~ max spot area



# Large and small magnetic features




SDO/HMI

Sunrise / IMaX

# At the hearts of active regions: Sunspots

Umbra

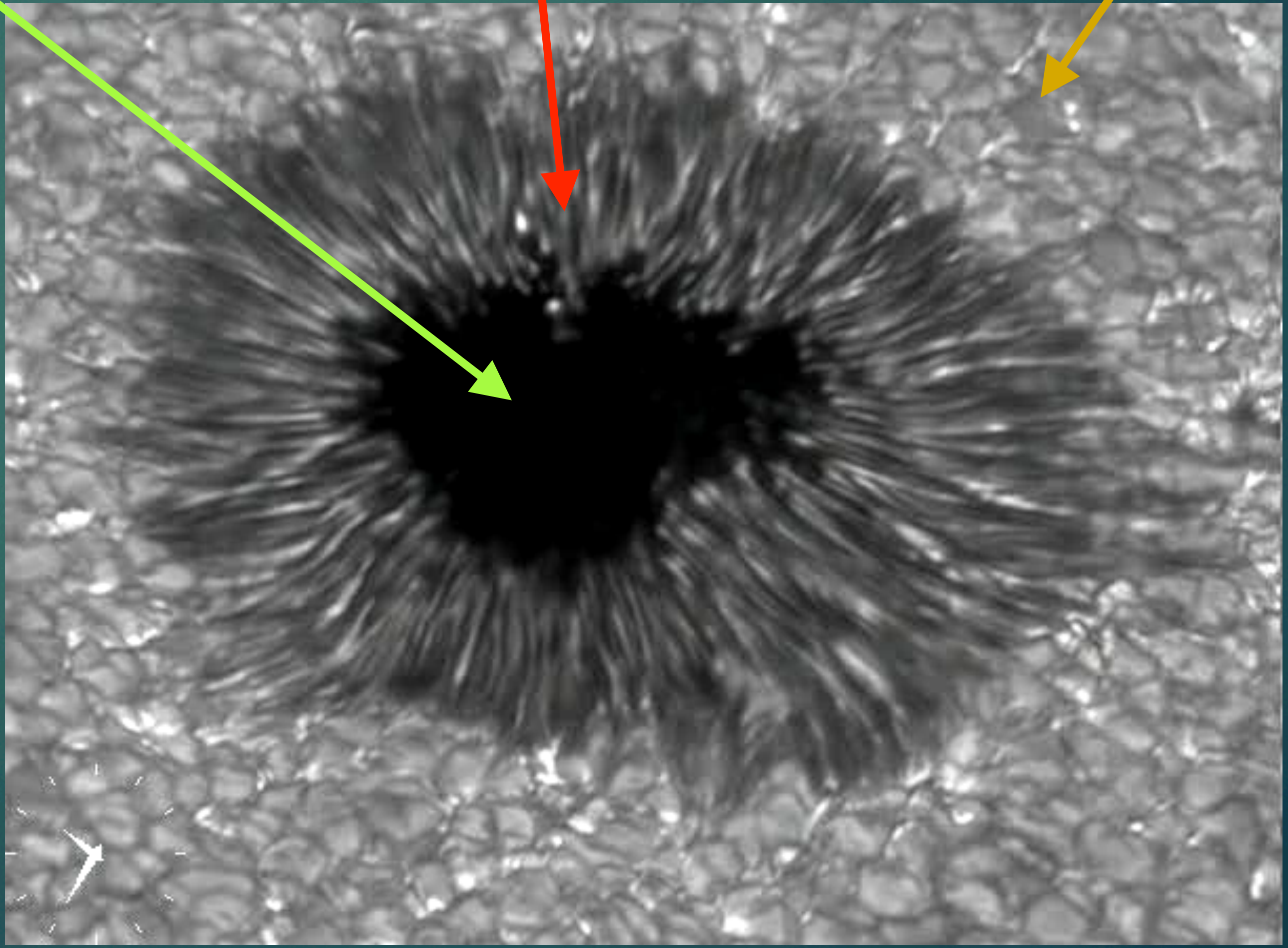
Penumbra

Granule

$T_{\mathrm{eff}} \approx 5800$ K
$B < 100$ G

$T_{\mathrm{eff}} \approx 5500$ K
$B \approx$ 1-2 kG

$T_{\mathrm{eff}} \approx 4500$ K
$B \approx$ 3-4 kG



# Sunspots

Umbra

Penumbra

Granules + lanes

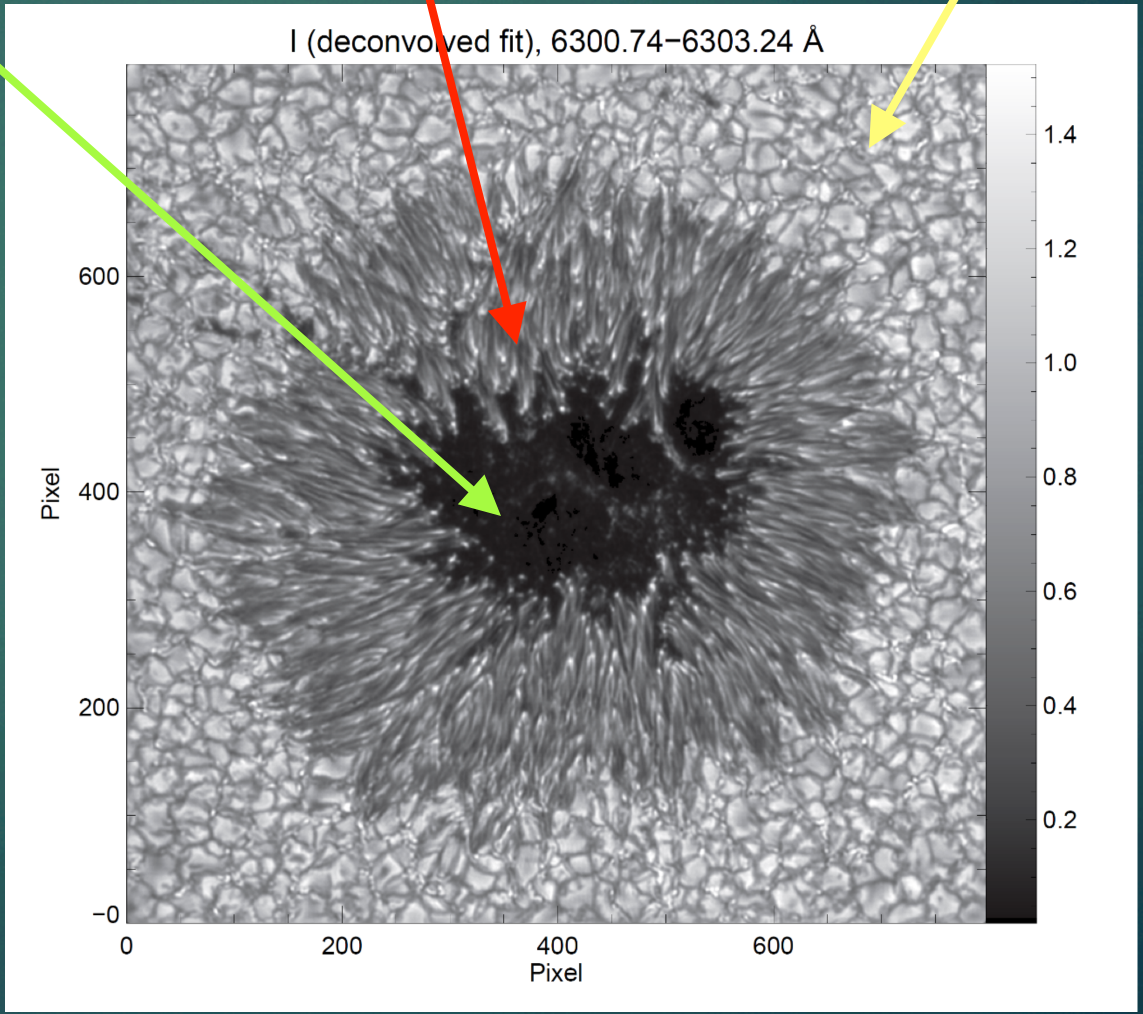
$T_{\rm eff} \approx 5800$ K

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

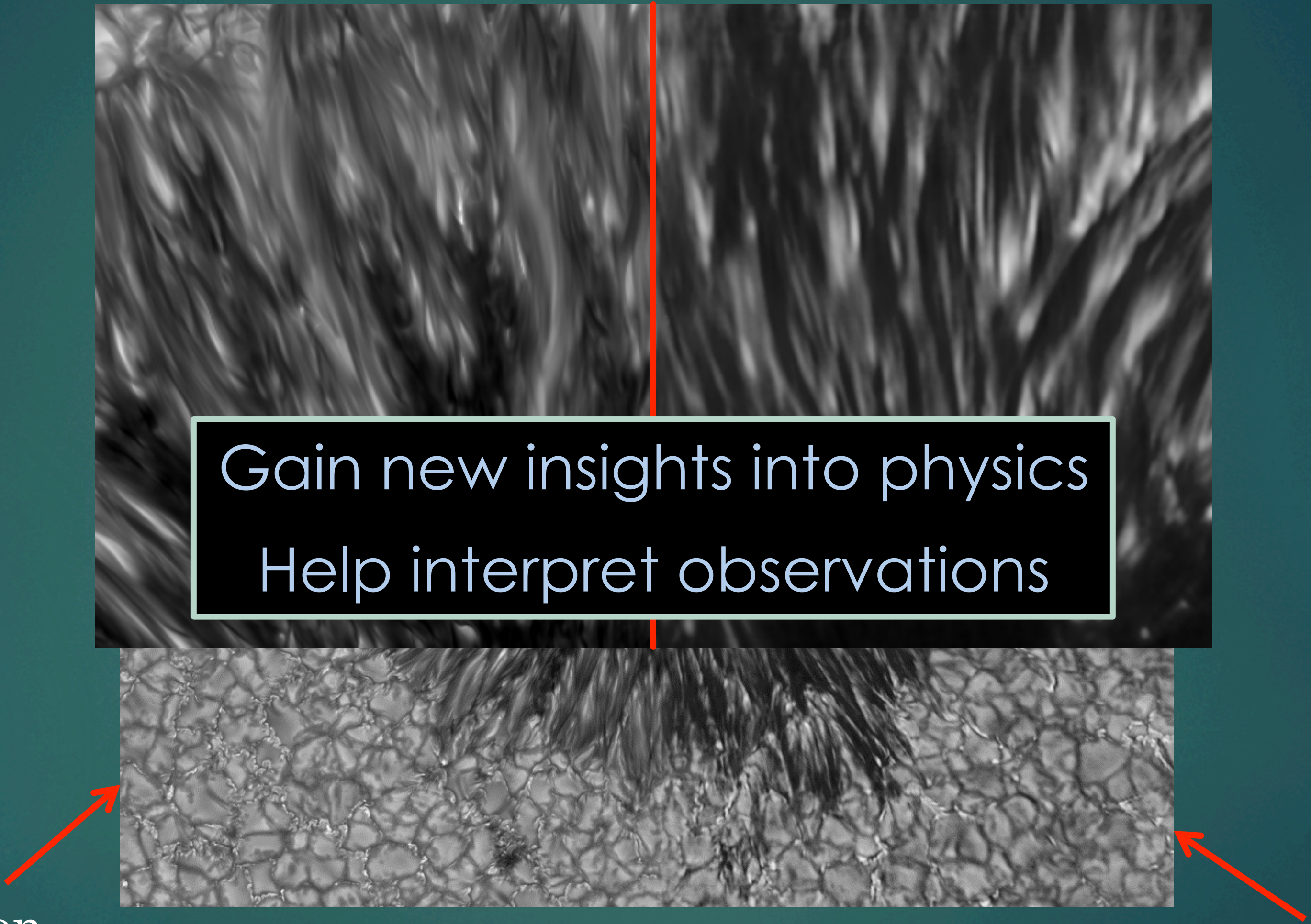
$I_{\rm pen} = 0.75 I_{\odot}$

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

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



# Simulation or observation?



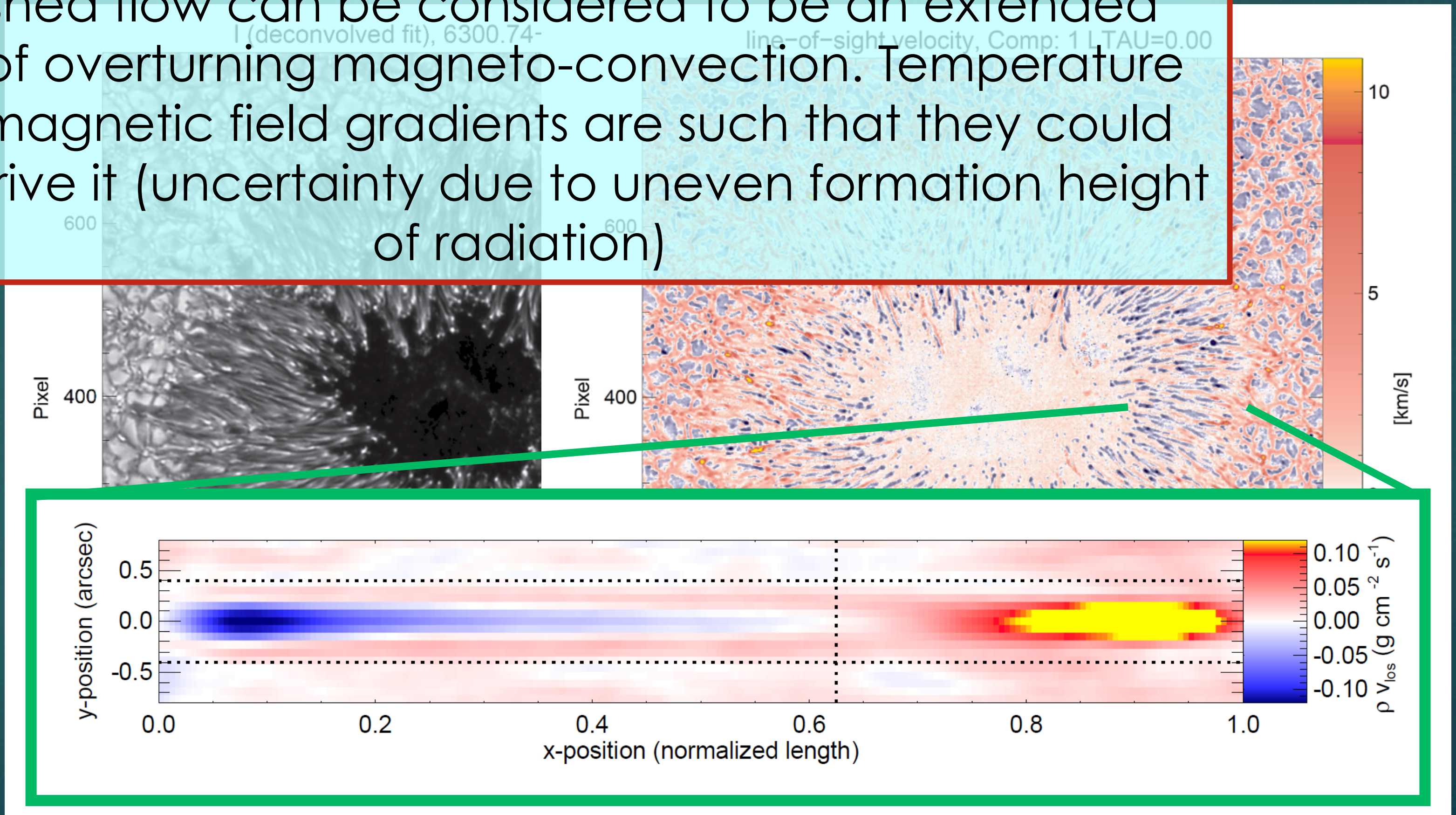

Simulation
(M. Rempel/HAO)

G-band observation
(F. Wöger/NSO)

# Evershed effect with sources and sinks

- Plots of intensity, magn. inclination, LOS velocity at $\tau$=1 obtained from 2-D inversions (van Noort 2012) from Hinode/SP data (Tiwari et al. 2013; 2015)

Evershed flow can be considered to be an extended form of overturning magneto-convection. Temperature and magnetic field gradients are such that they could both drive it (uncertainty due to uneven formation height of radiation)



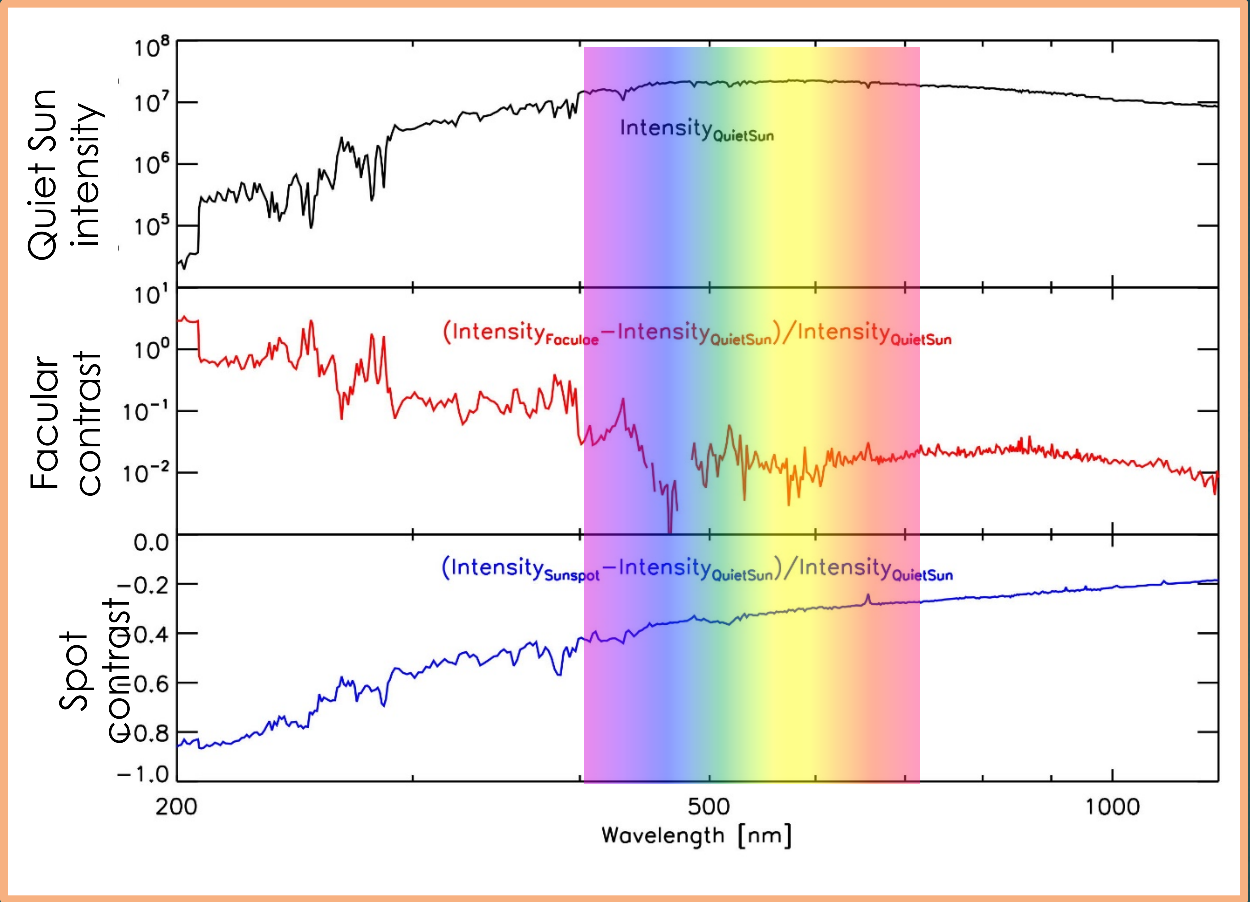
# Spectra

**Sun:**
**UV** dominated by facular brightening

**IR** dominated by spot darkening

**Visible:** mixture of both (depends on timescale

Spectra computed from 1D models (Unruh+ 1999; Shapiro+ 2010; 2015; Tagirov+ 2018) & from 3D models (Norris+ 2017)




Quiet Sun Intensity

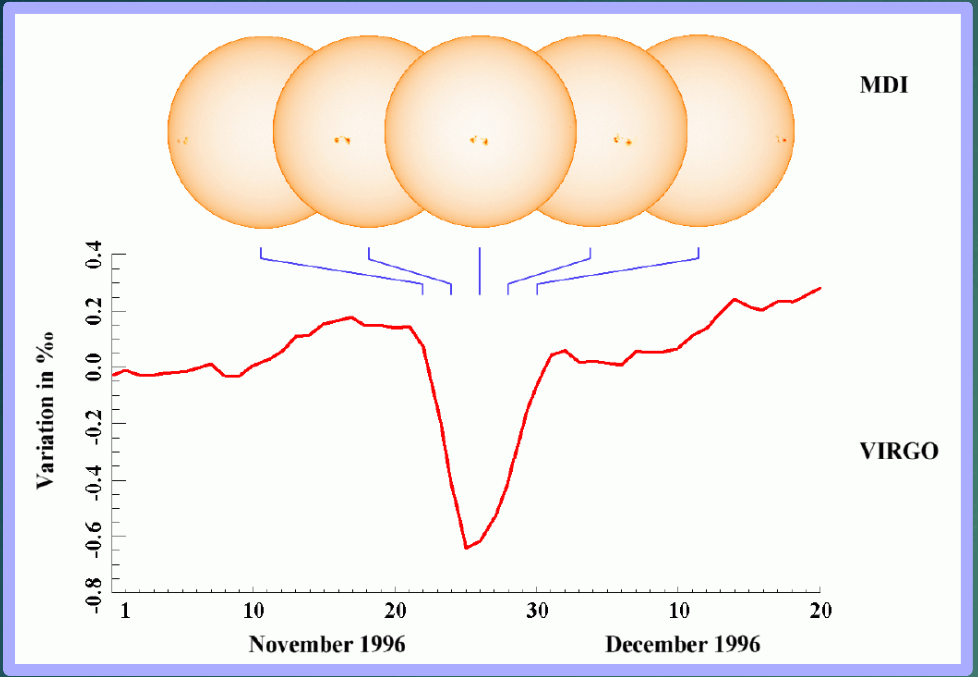
Plage + network contrast

Sunspot contrast

Shapiro+ 2015

**Other stars:** Depends on spectral type and activity level
Low activity G+K stars behave qualitatively like the Sun
Highly active stars tend to be spot dominated in the visible

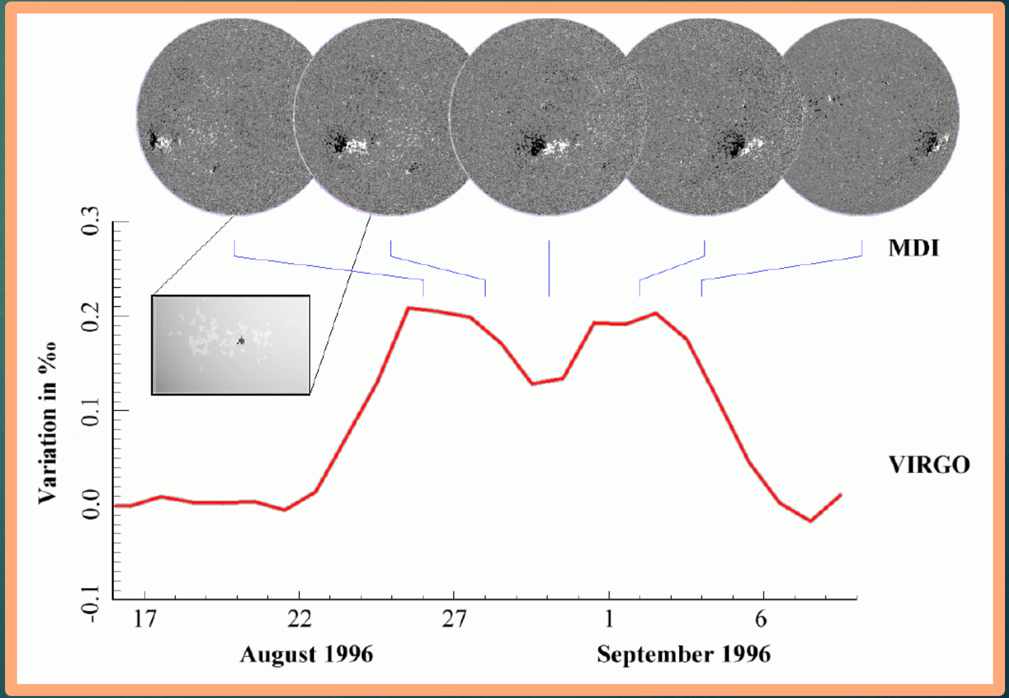
# TSI: effect of  sunspots and faculae




Sunspots produce a global darkening of the Sun, while faculae lead to a brightening (Foukal & Lean 1996; Fligge+ 2000; Krivova+ 2003)

Starspots → darkening of their host stars (amount depends on spectral type)

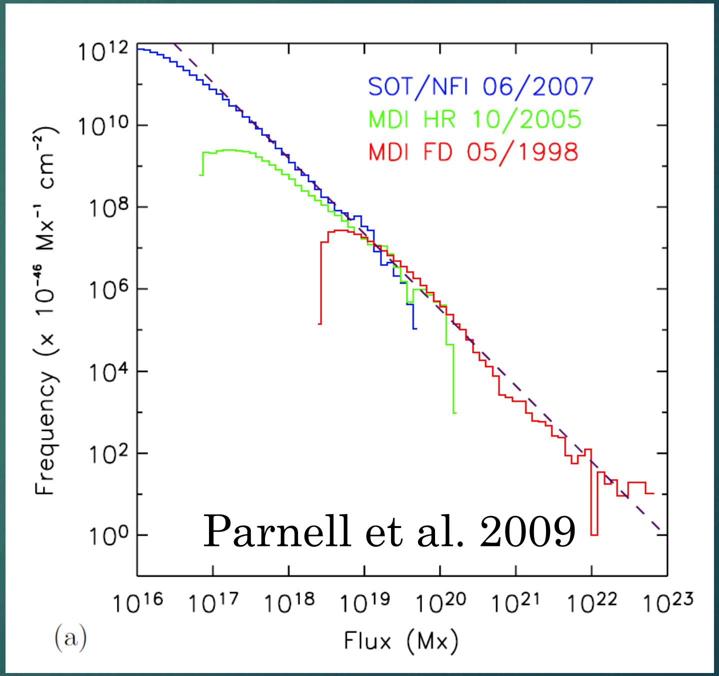
Effect of faculae (even the sign) depends on spectral type (Beeck+ 2015)



# How much magnetic flux in different types of features?

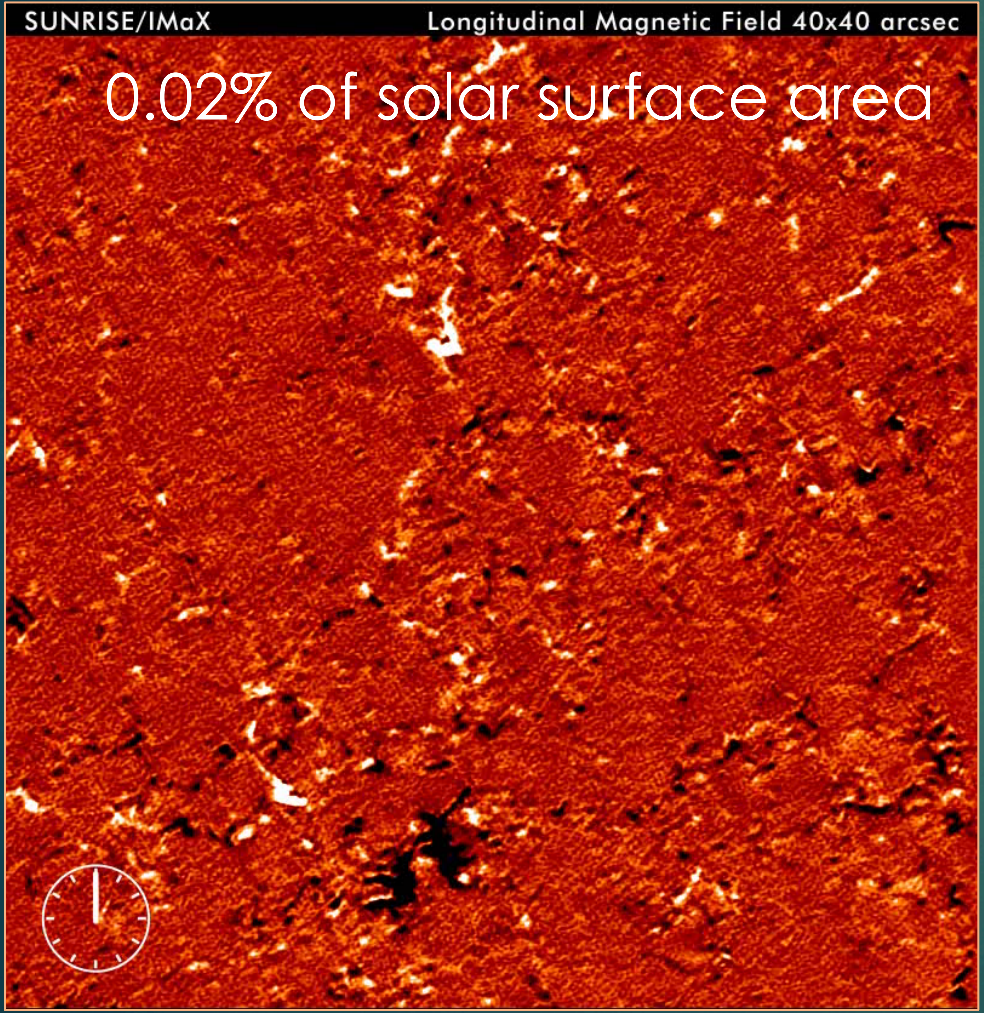
- PDFs of QS magnetic fluxes have been derived by Stenflo & Holtzreuter 2002, Khomenko+ 2003, Dominguez Cerdena+ 2006, Martinez Gonzalez+ 2008, Bühler+ 2013, etc.

- Parnell+ 2009: single power law of -1.85 covers frequency of features with fluxes from $10^{17}$ to $10^{22}$
- Does a single power law mean that all magnetic features have same source?
- Also: Sun had different activity in 1998, 2005 and 2007). Should power laws be different at the top end?




Magnetic flux per feature

# From the Sun to the stars




$B_{LOS}$ from Sunrise I / IMaX

Sun (detail)

Sun-like Star

- Stars poorly resolved ➔ at best largest scales of field
- S/N is generally low
- *Q,U* hard to measure
- But many stars, with different parameters
- 1st cool-dwarf B-field: Robinson+ 80, 1st Stokes *V* : Donati+90