Simulations of stellar spots

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Why care about starspots?

All stars are magnetic

(let's just focus on cool main sequence stars for this talk)

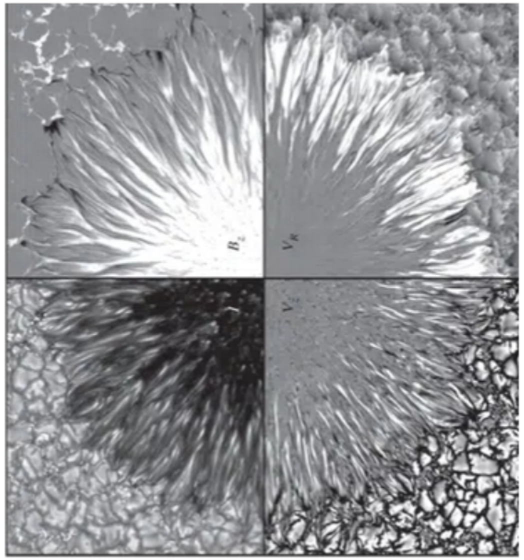
- Observations
  - Photometric variability – starspots/faculae vs. exoplanetary transits
  - Chromospheric variability – S-index, connection to stellar dynamo
  - (Zeeman)-Doppler imaging, interferometry – brightness inhomogeneities

- Theory implications
  - Stellar dynamos, relations between activity, rotation (weakened braking...)
  - Influence on convection (flux blocking, convective conundrum...)
  - Flux emergence and spot formation

Modeling stellar atmospheres

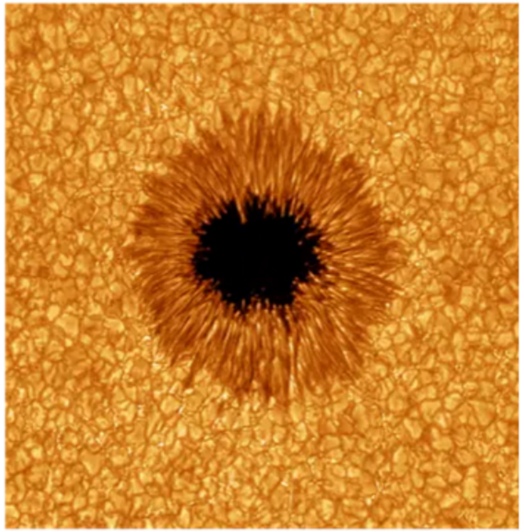
- **The data**
  - Sun – reference star – resolved, excellent observations of spots, faculae, plages, filigree, bright points...
  - Other stars – (mostly) point source, spectral and temporal info only

- **Stellar atmosphere models**
  - Realistic treatment of convection – good match with solar obs.
  - Stellar grids exist (e.g. STAGGER, CO5BOLD) – resource for self-consistent convective structure, associated spectra
  - Recent studies with fields as well, plage-like (Beeck+ 2015, Salhab+ 2018) as well as spots (Rempel+ 2008-2015, Panja+ 2020)



(b)

At the $\tau=1$ level clockwise: I, B_z, v_R and v_z. The range shown is 0.3...1.5$I_\odot$ for I, ±2.5 kG for B_z, ±8 km/s for v_R, ±2 km/s for v_z.



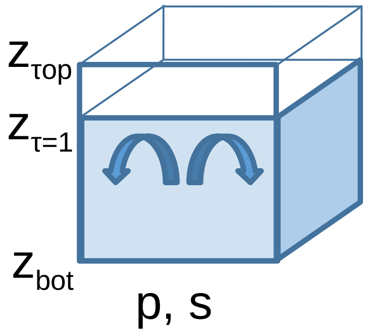
(a)

(a) Image of AR NOAA 1084 taken on July 2, 2010 in TiO (706 nm) filter from Big Bear Solar Observatory from https://www.bbso.njit.edu/nst_gallery.html . (b) simulated sunspot from Rempel 2012b, Phil. Trans. R. Soc. A (reproduced with permission; copyright 2012 Royal Society).

https://nso.edu/telescopes/dkist/csp/magnetoconvection-dynamo/

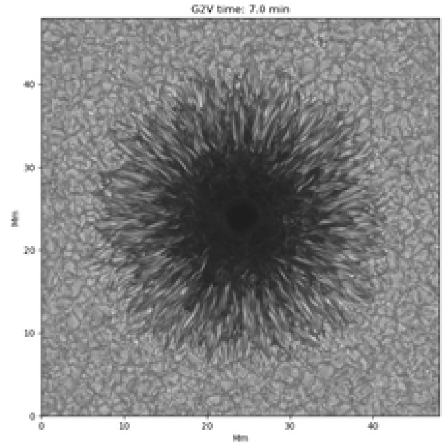
What's new now?

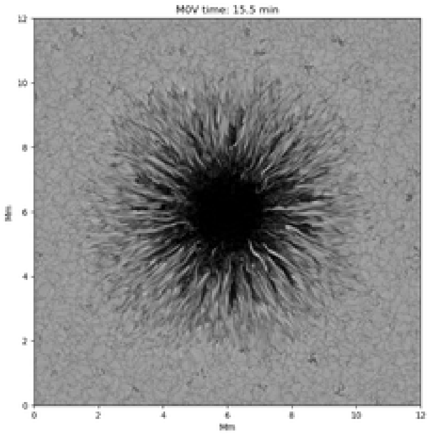
MURaM setup

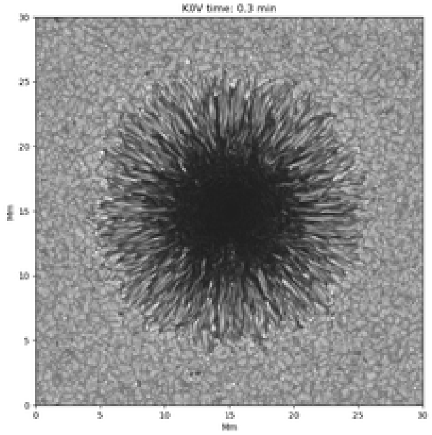


- **Models of spots** *(Bhatia+2024 arXiv:2412.16921)*
  - First stellar spot simulations by Panja+2020 – **starting point**
  - Round spot simulations following the approach of Rempel+2015
  - Initial models from existing SSD simulations (Bhatia+2022)
  - FreeEoS (Irvin 2012) – easily incorporate different metallicities
  - RT with 4 opacity bins instead of gray
  - Synthetic spectra using MPS-ATLAS – ODF approach with updated linelists (Witzke+2021)
- **Simulation setup**: Initial SSD run → spot introduced
- → evolve away initial transient → increase resolution
- → multibin RT → analyze!

Star	L_X, L_Z (Mm)	dx, dz (km)	g_{surf} (cm/s^2)	T_{qs} (K)	T_p/T_{qs}	T_u/T_{qs}
G2V	48, 4.50	46.9, 15.6	2.74×10^4	6092 ± 8	0.89	0.70
K2V	30, 2.88	29.3, 9.80	4.06×10^4	4856 ± 4	0.93	0.83
M0V	12, 1.07	11.72, 3.92	6.70×10^4	3858 ± 1	0.97	0.89



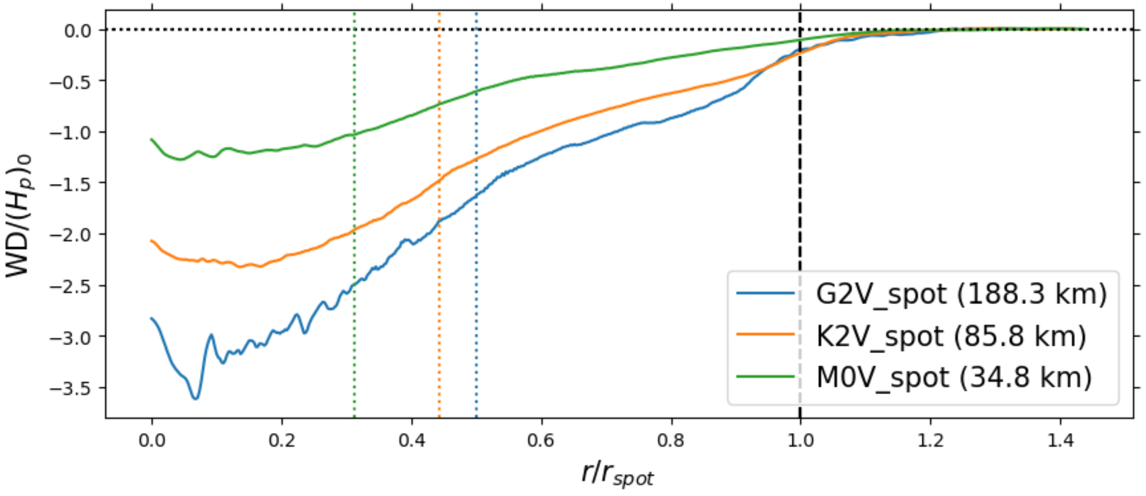


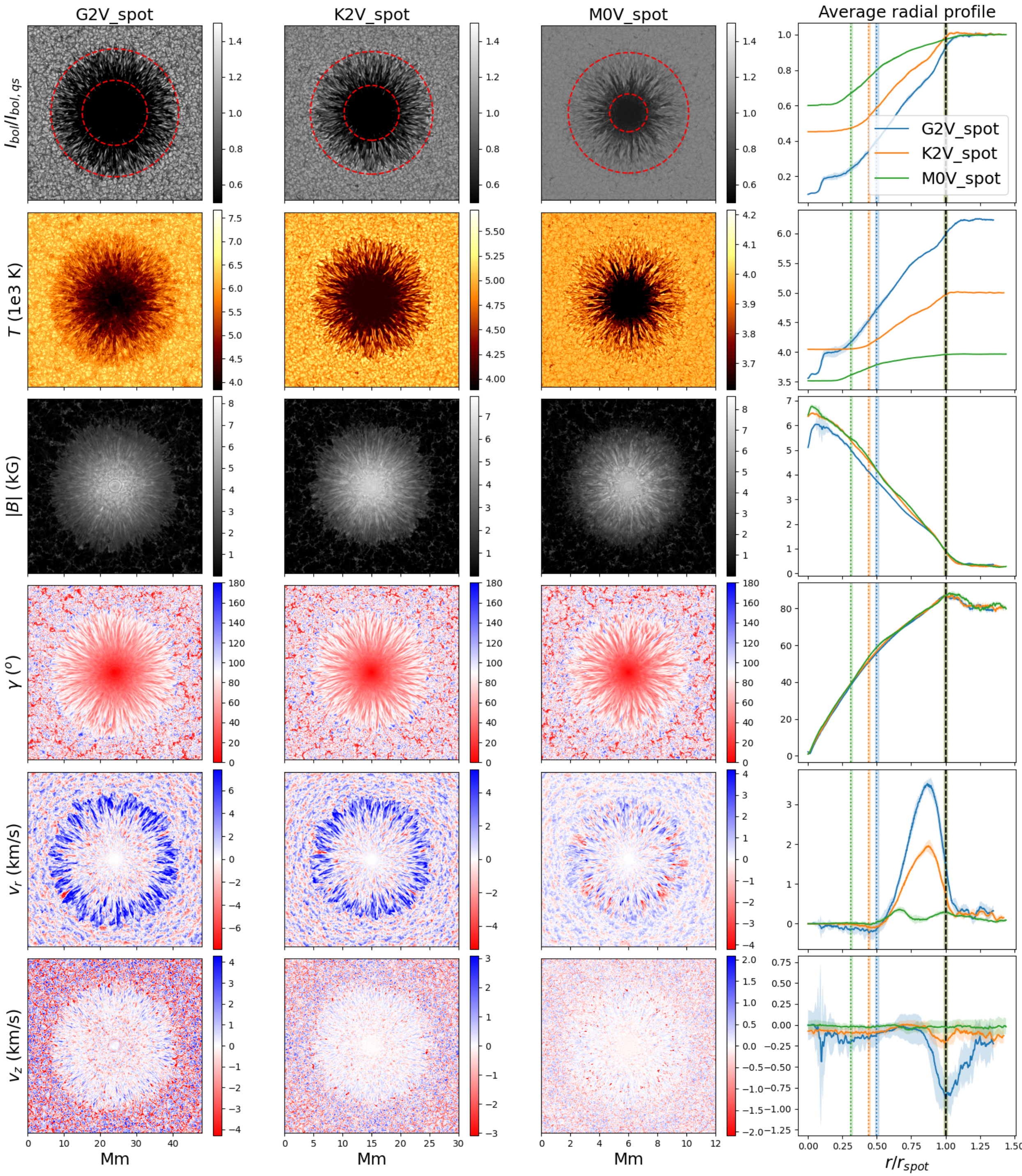


Surface properties

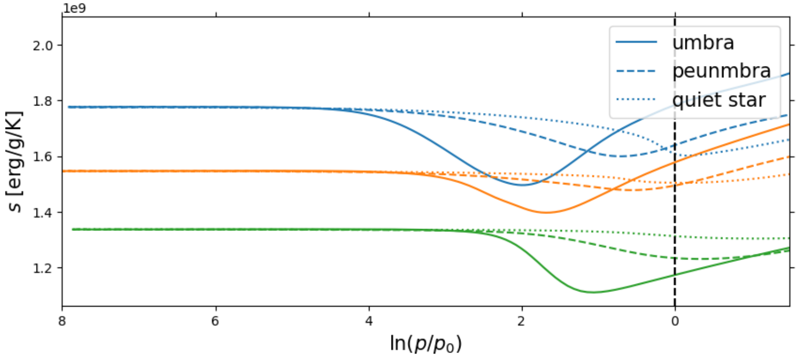
- Cases: G2V, K2V, M0V
- Setup: same field strength, scaled with H_p, ($1.5xB_h$ at top boundary)

- *Radial trends of surface quantities*
- Trend in I_{bol}, T, v_r (Evershed) with T_{eff}
- B and γ rather similar
- Trend in v_z with T_{eff} at spot boundary
- Wilson depression scale with spectral type

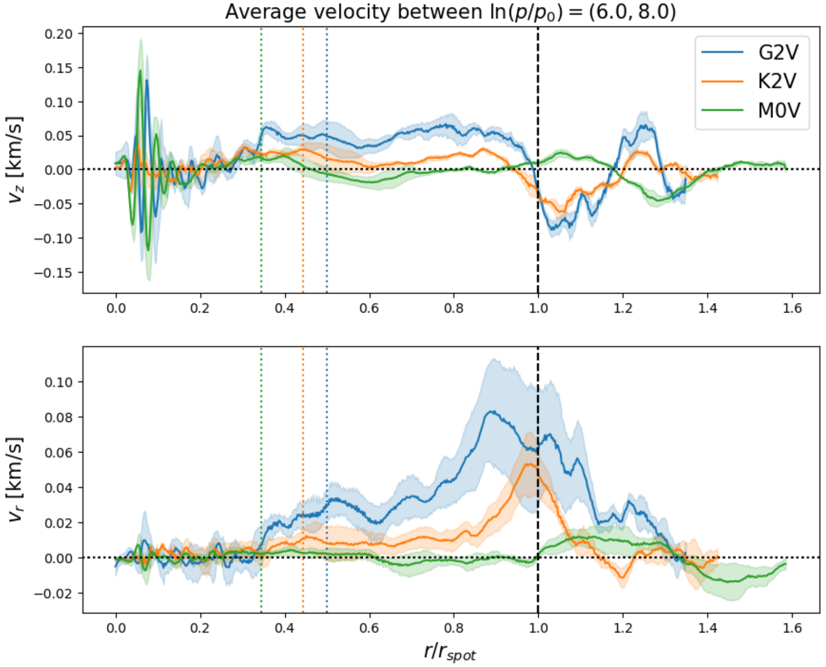


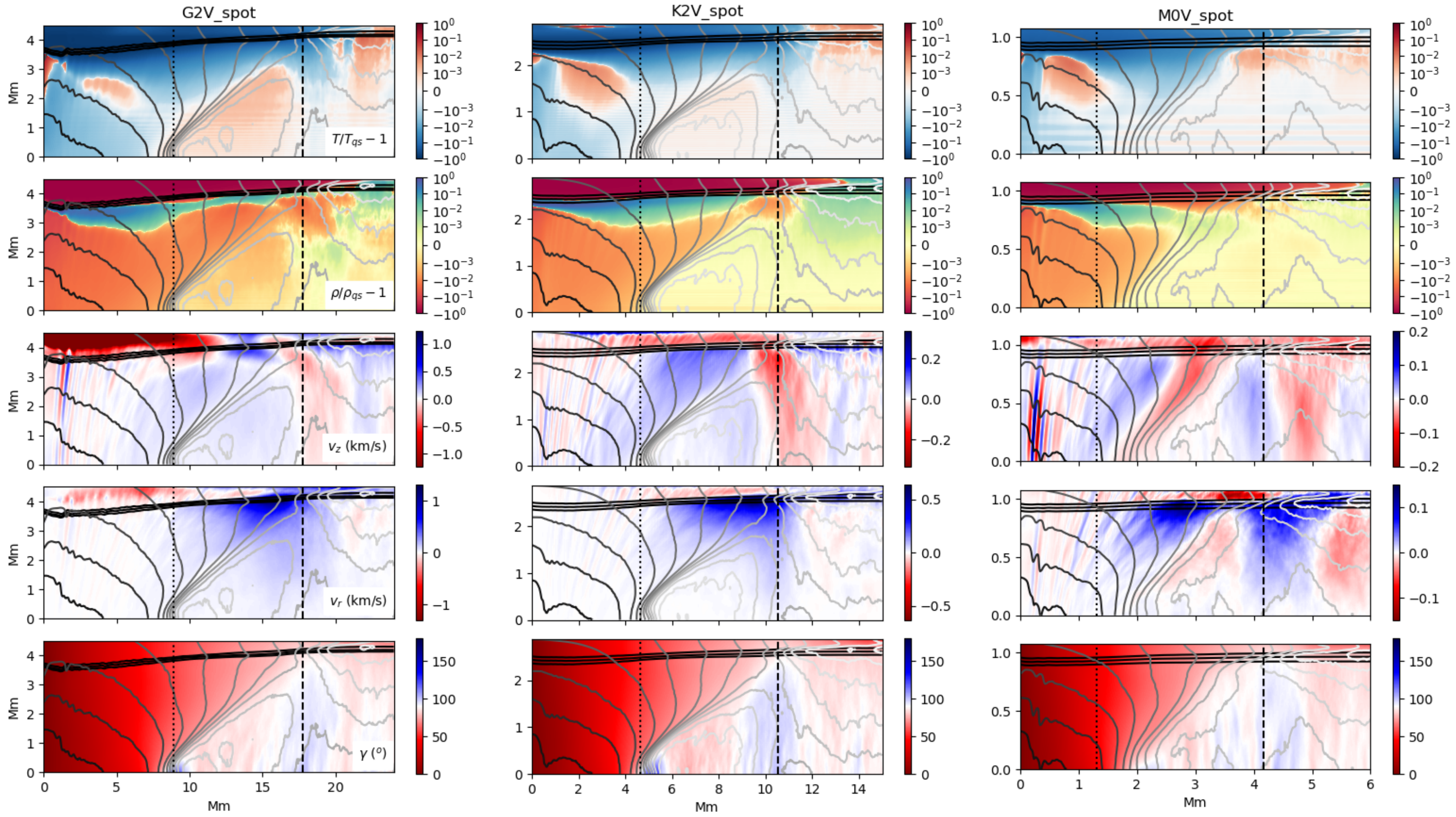


Structure



Entropy structure different in umbra, penumbra, QS – gradient indicates stable stratification near surface – depth ~ T_{eff}





Azimuthal averages different in umbra and penumbra, relative to QS

- Umbral trunk: reduced T, ρ
- T excess below penumbra, corresponding v_z and v_r structure indicate ringed convection (*see left plot as well*)
- Structure in G2V and K2V spot rather similar, M0V spot no so much (multiple rings vs. single ring, but may be influenced by box size)
- Inclinations shows how field is carried down in downflow lanes

Penumbra formation

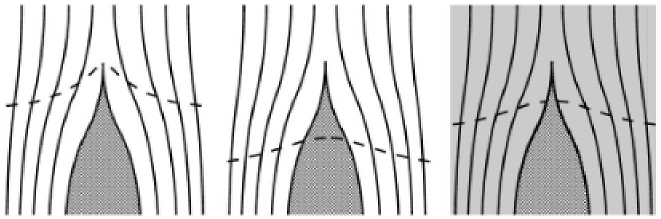


Fig. 3. Gaps (hatched) in a magnetic field near the solar surface (vertical cross-sections). Dashed lines indicate the continuum $\tau = 1$ level. The two neighboring flux bundles spread out horizontally above the surface, forming a cusp at some height above $\tau = 1$. *Left*: cusp is located below $\tau = 1$, corresponding to an umbral dot. The surface around the gap is brightened by the radiative heat flux. The observed field strength is reduced due to the displacement of field lines by the gap. *Middle*: a wide gap that would be seen as a field-free "canal" or umbral light bridge. *Right*: the case of a penumbral filament in the proposed model is like a light bridge, but with an additional horizontal field component (indicated by shading) along the filament.

Gappy penumbra (Spruit & Scharmer, 2006)

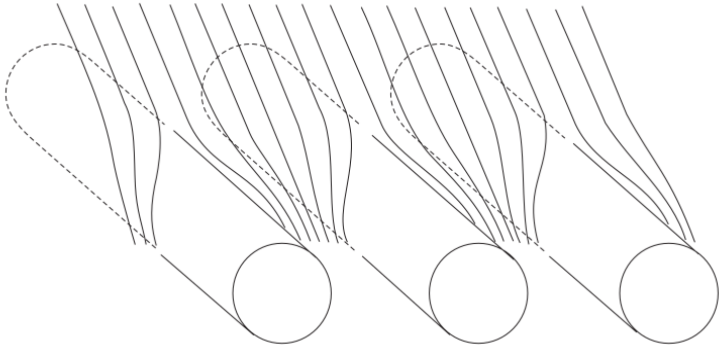


Fig. 3.7. Sketch of the local fine-scale structure of the magnetic field in sunspot penumbrae. The field is composed of two components, a flux-tube component, represented by the horizontal cylinders, and a more inclined magnetic field, indicated by the field lines threading their way between the flux tubes at an angle.

Embedded flux tube (Solanki 2003)

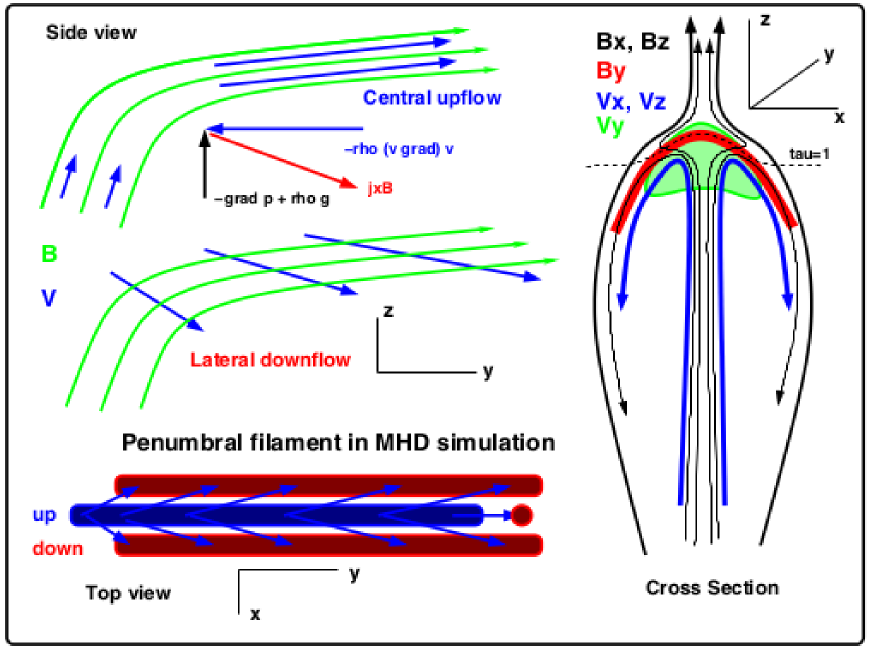
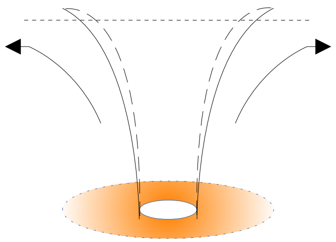
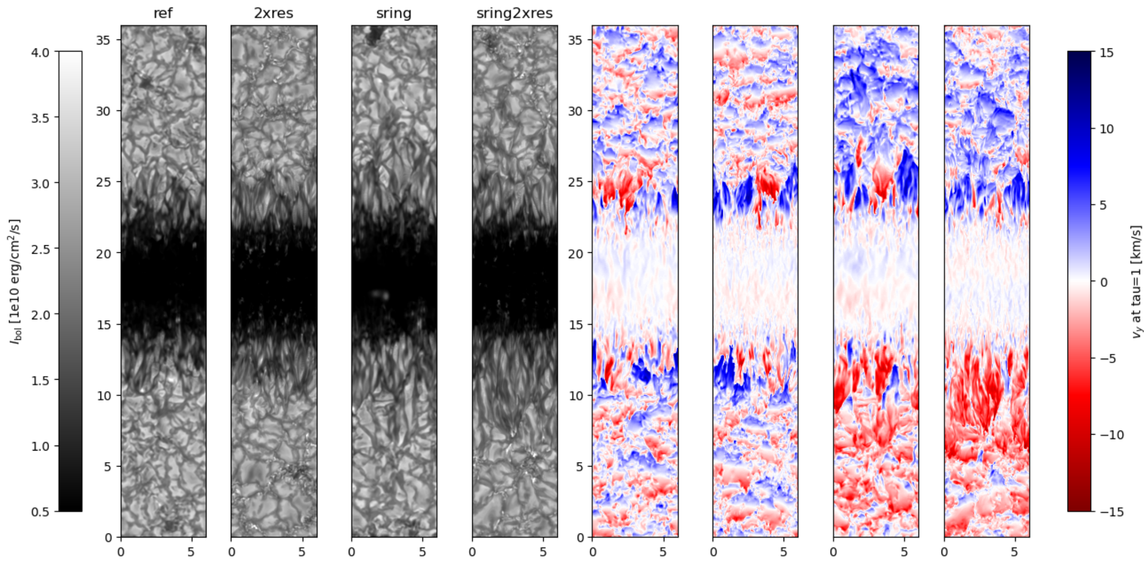


Figure 22. Diagram summarizing the basic field and flow structure of a penumbral filament as present in the numerical simulation. We present a schematic side, top, and cross-section view. x and z denote the horizontal and vertical direction perpendicular to the filament, y denotes the direction along the filament away from the spot center. In the central upflow regions, the flow and field are well aligned, while the flow submerges mostly horizontal field lines in lateral downflow regions. Overall, filaments have a reduced field strength, but they contain a core with a non-vanishing vertical field component. Some of the associated flux continues upward; some of the flux returns downward within the filament cavity. Depending on the position of the $\tau = 1$ level the latter might become visible as inverse polarity flux. The strong subsurface shear of the Evershed flow induces a strong horizontal field component that is concentrated along the $\tau = 1$ surface. This leads to strongly magnetized Evershed flow channels in the visible layer, while the field strength is significantly reduced in the subsurface layers.

Magnetoconvection in a penumbra (Rempel 2012)

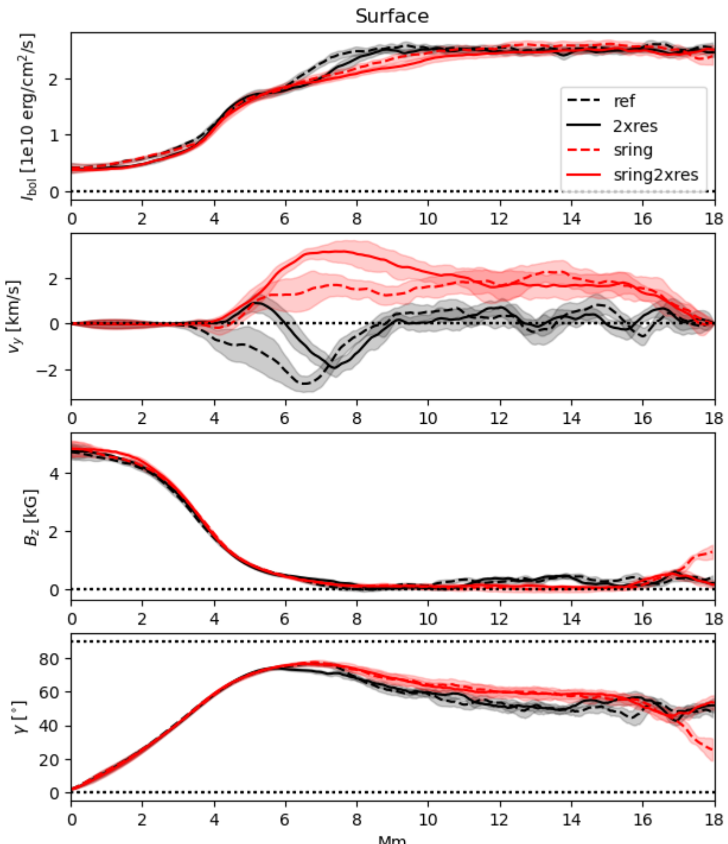
Penumbra formation

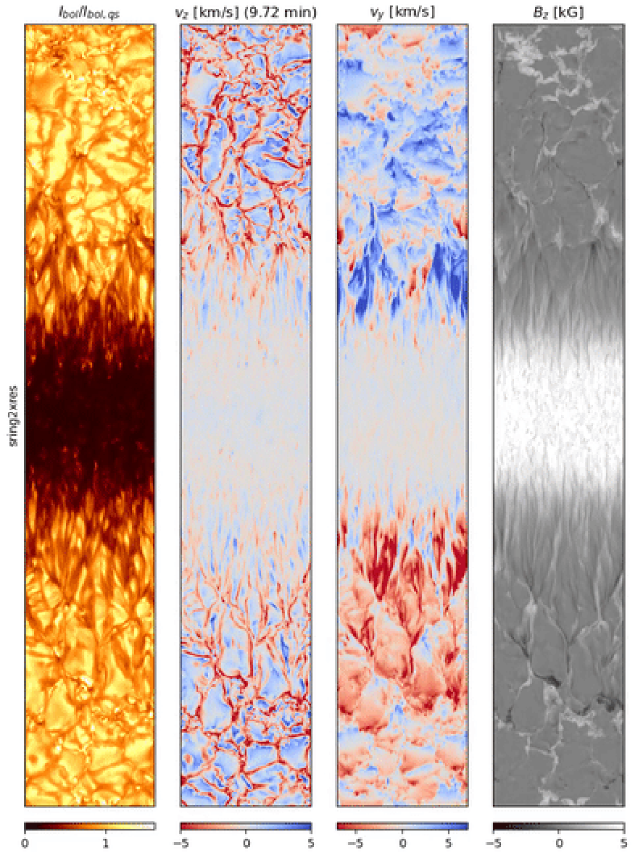


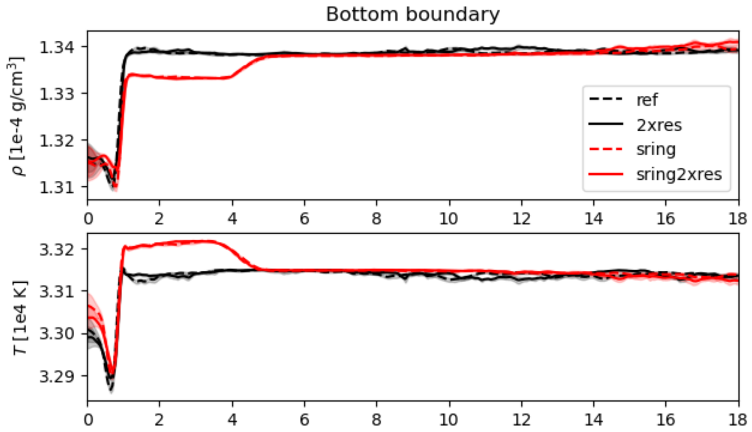


Our idea: slight entropy excess surrounding the umbral trunk near the bottom boundary

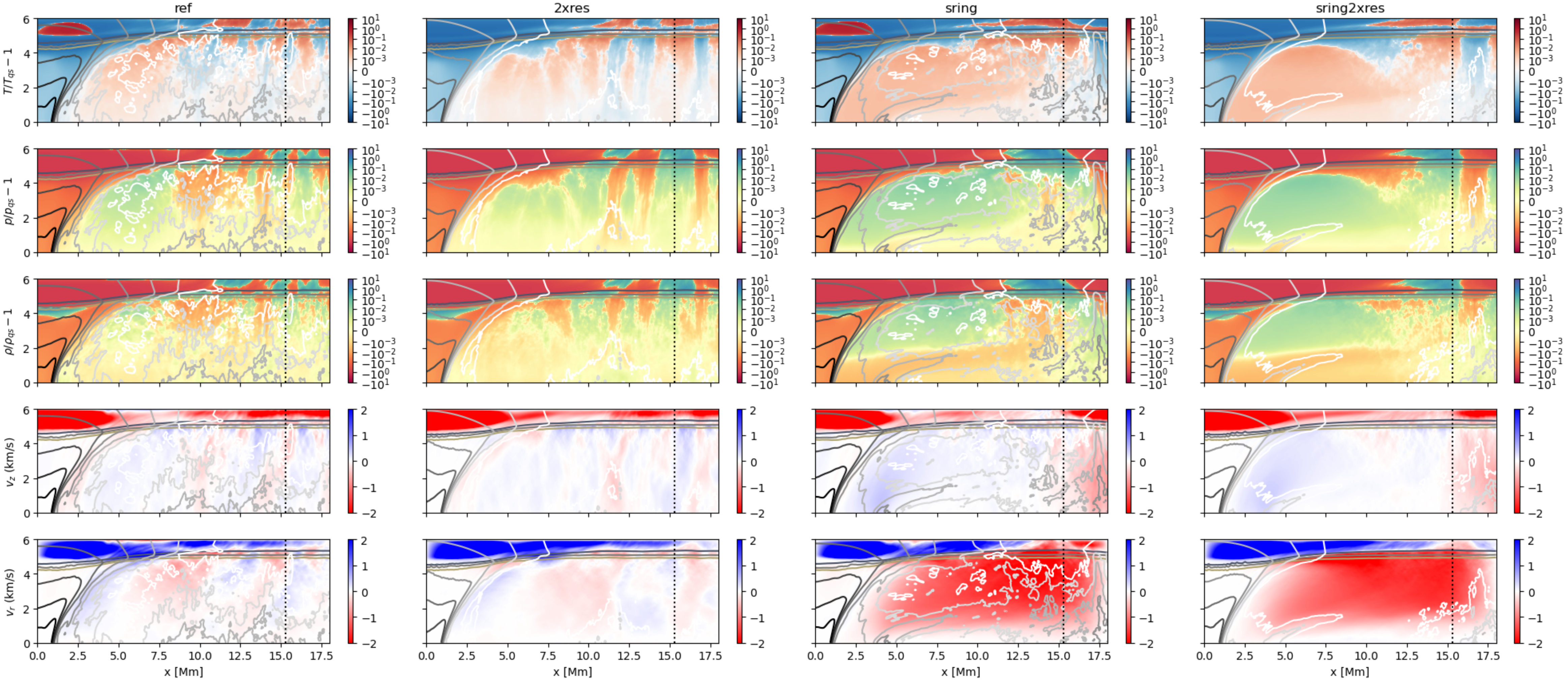
- Better penumbral extent
- Correct Evershed flow
- More horizontal fields in the penumbra







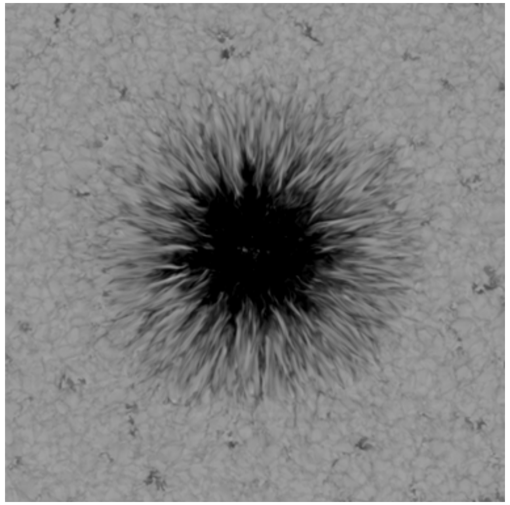
Penumbra formation: vertical structure

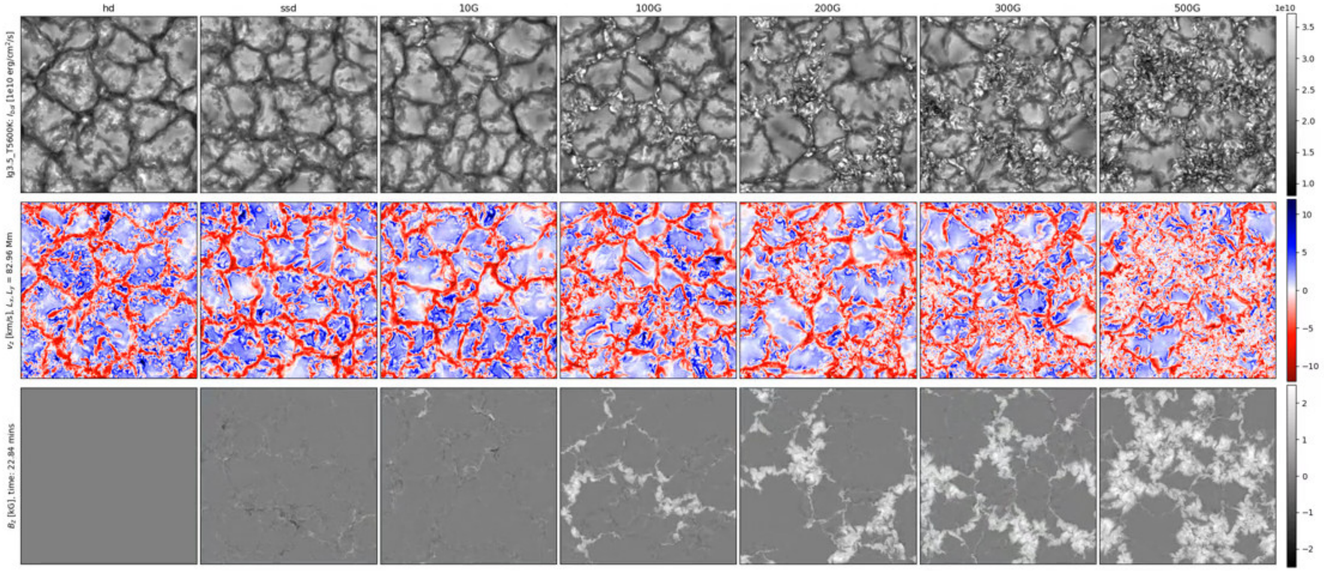


Large-scale clockwise circulation under the penumbra – Low T, high rho flows under the penumbra compresses plasma above and increases the curvature in the umbral trunk – more horizontal fields

Conclusion

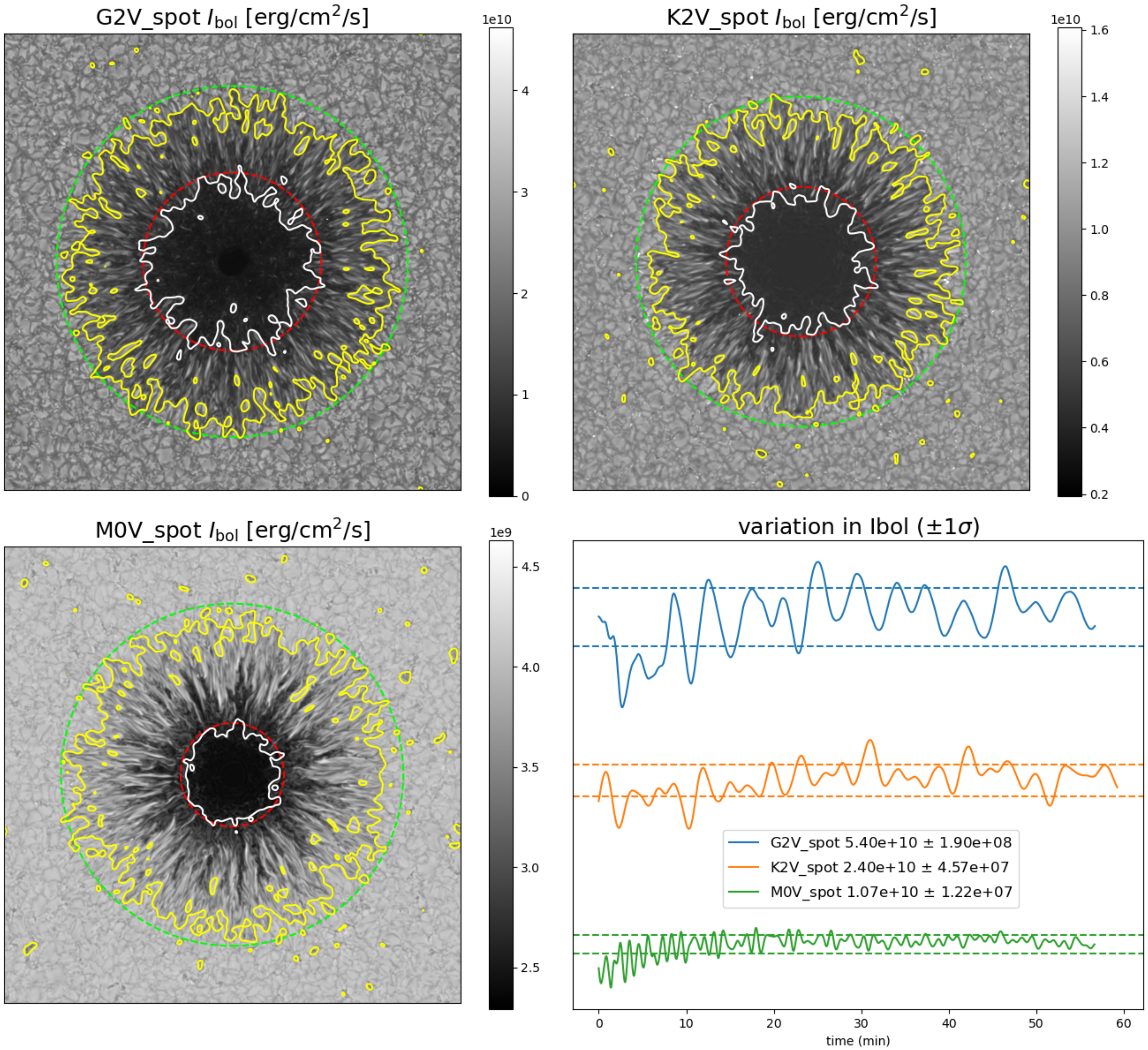
- First realistic 3D rMHD round starspot simulations *Bhatia+2024 arXiv:2412.16921*
- Intensity contrast, Evershed flow decreases with T_{eff}
- Convective and thermodynamic structure rather similar between stars
- Penumbra formations with entropy results shows promising results – work in progress - see Aswathi's poster for more ideas!





Next steps

- Spectra – broadband, CLV, line profiles *Smitha+2024 arXiv:2411.14056*
- Cooler M-dwarf spots (M4V)
- Spots with chromospheres (more details in poster by Aswathi Krishnankutty)
- Subgiants!
- Cool movies :) (most important)



Intensity contours:

G2V: I_u/I_{qs} = 0.35, I_p/I_{qs} = 0.8

K2V: I_u/I_{qs} = 0.50, I_p/I_{qs} = 0.9

M0V: I_u/I_{qs} = 0.65, I_p/I_{qs} = 0.965

QS region: $0.2L_x$ x $0.2L_y$ region in the corner