MAX PLANCK INSTITUTE
FOR SOLAR SYSTEM RESEARCH

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 (convective conundrum...)
  - Flux emergence and spot formation

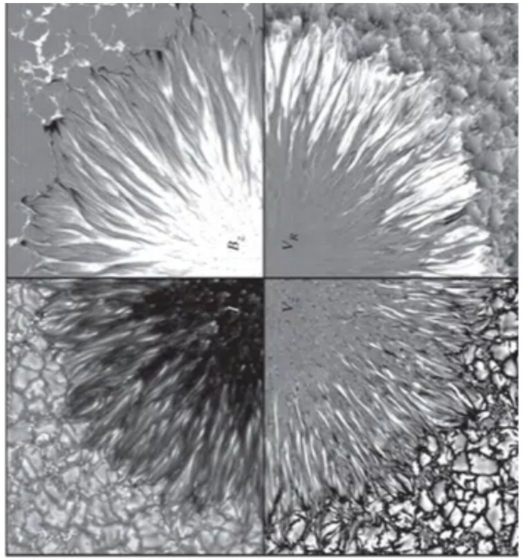
Modeling stellar atmospheres

The data

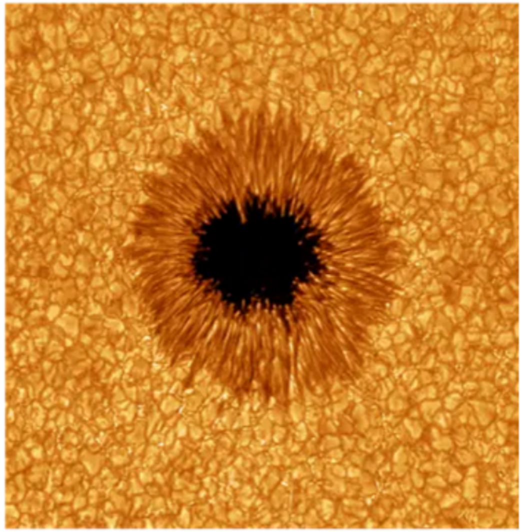
- Sun – reference star – resolved, excellent observations of spots, faculae, plages, filigree, bright points...
- Other stars – (mostly) point source, spectral and temporal info only

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 τ=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.



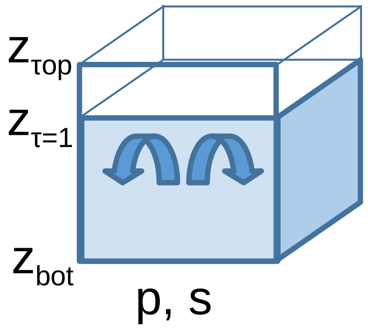
(a)

(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/

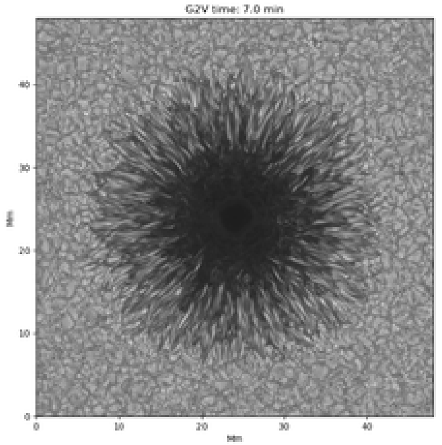
What’s new now?

MURaM setup



Models of spots *(Bhatia+2024 arXiv:2412.16921)*

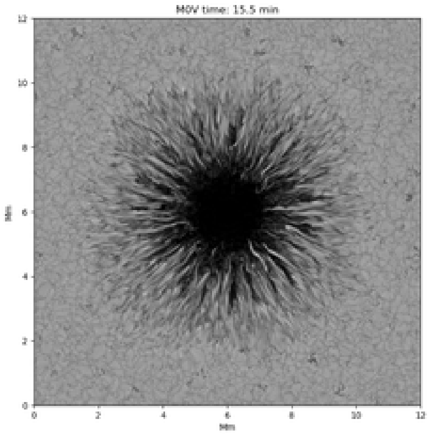
- First stellar spot simulations by Panja+2020 – **starting point**
- Round spot simulations following the approach of Rempel+2015
- Initial models from existing SSD simulations (Bhatia+2022)
- FreeEoS (Irvin 2012) – easily incorporate different metallicities
- RT with 4 opacity bins instead of gray
- Synthetic spectra using MPS-ATLAS – ODF approach with updated linelists (Witzke+2021)

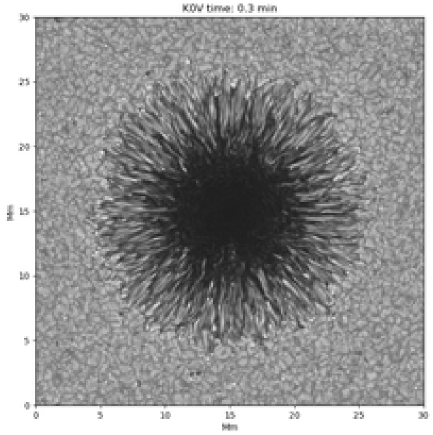


Simulation setup: Initial SSD run → spot introduced

- → 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



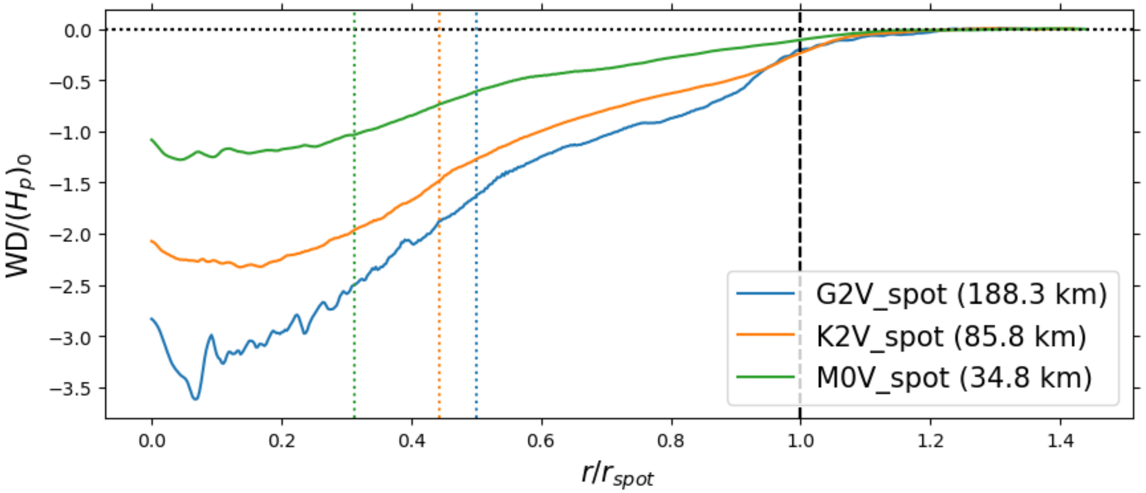


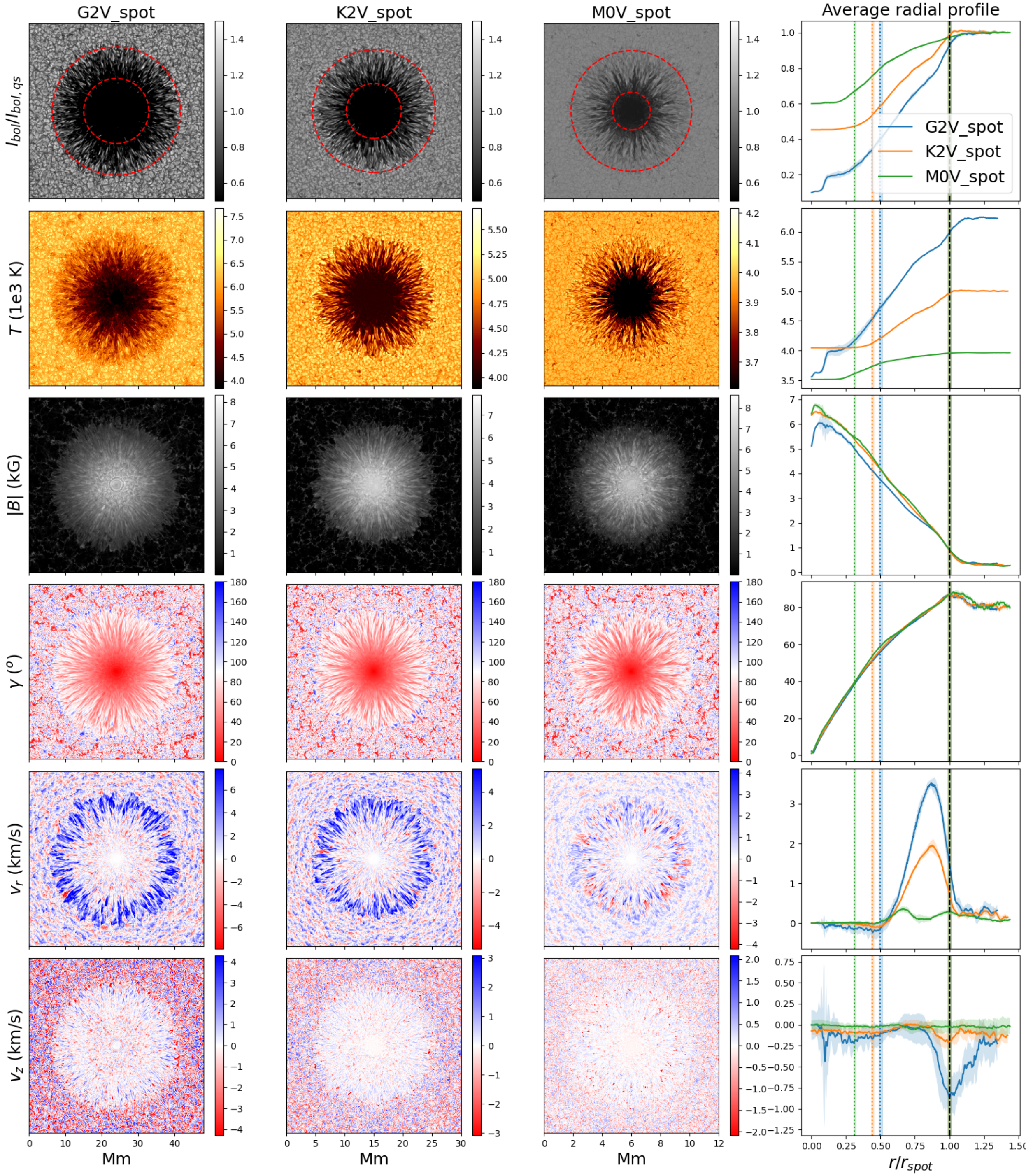
Surface properties

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

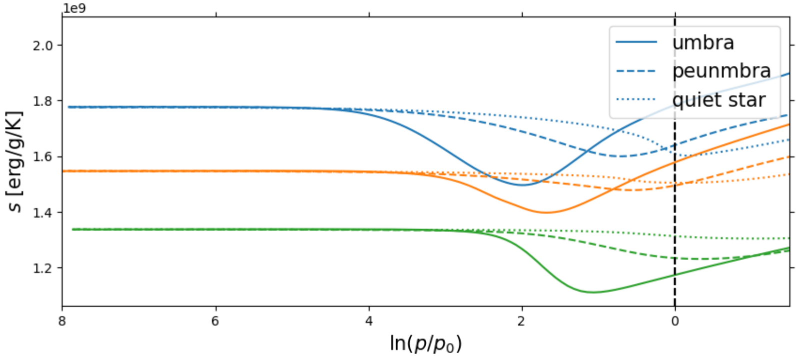
Radial trends of surface quantities

- 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

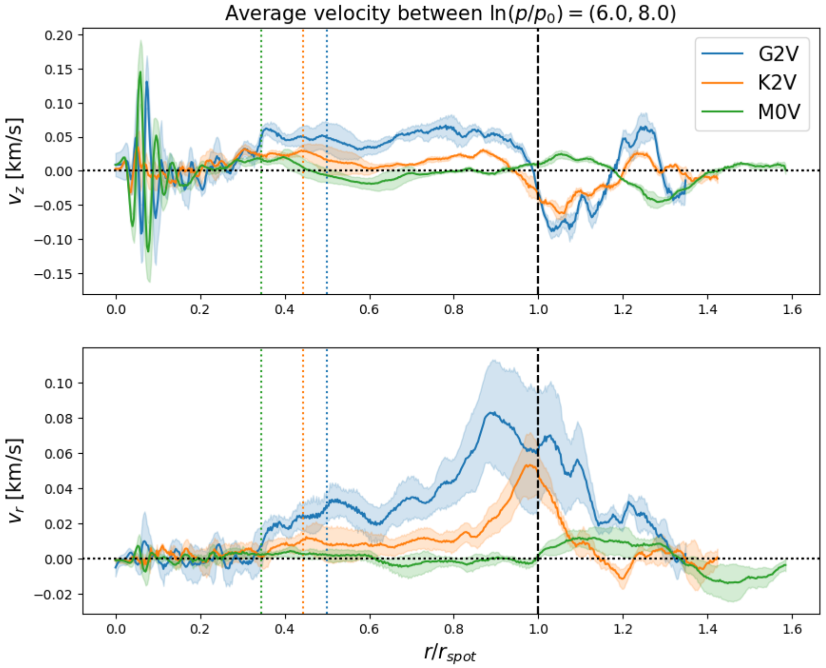


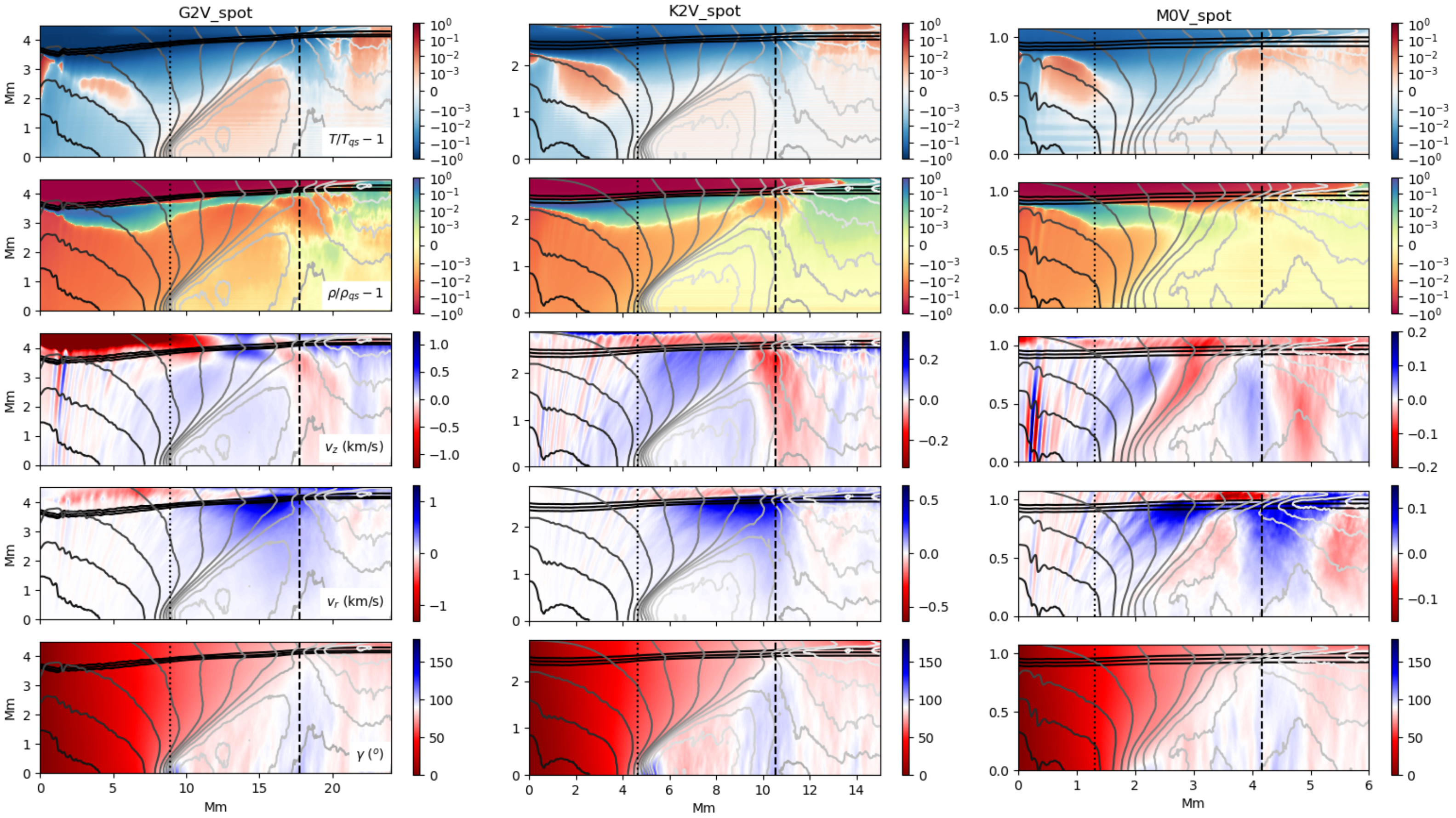


Structure



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

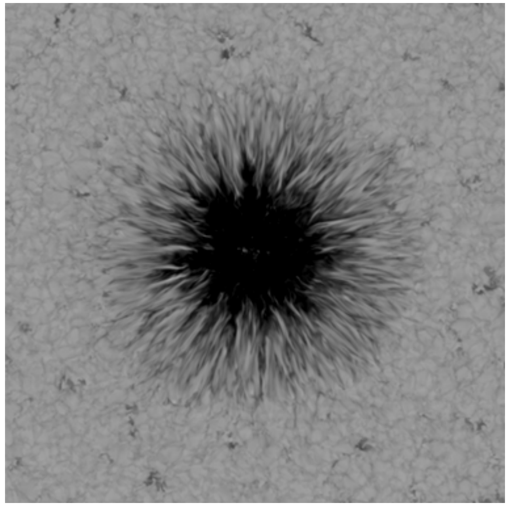
- Umbral trunk: reduced T, ρ
- T excess below penumbra, corresponding v_z and v_r structure indicate ringed convection (*see left plot as well*)
- Structure in G2V and K2V spot rather similar, M0V spot no so much (multiple rings vs. single ring, but may be influenced by box size)
- Inclinations shows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

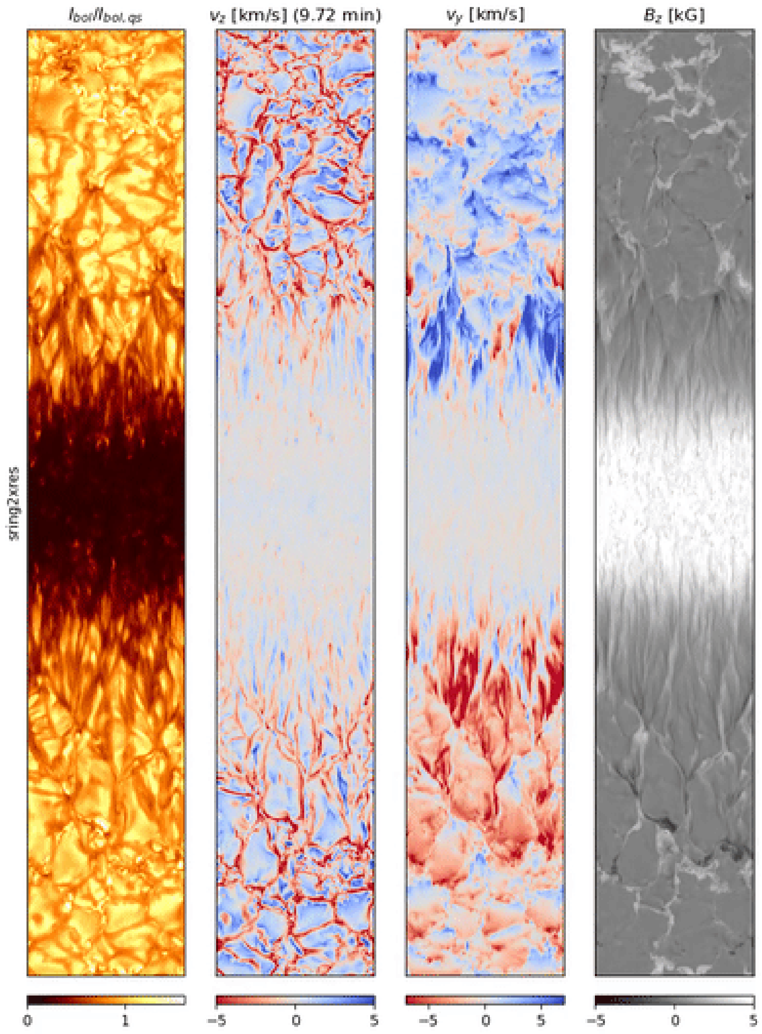
Conclusion

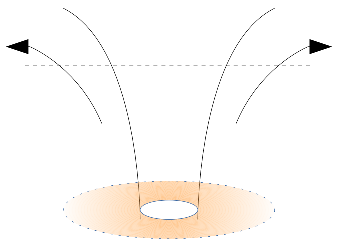
- First realistic 3D rMHD round starspot simulations *Bhatia+2024 arXiv:2412.16921*
- Intensity contrast, Evershed flow decreases with T_{eff}
- Convective and thermodynamic structure rather similar

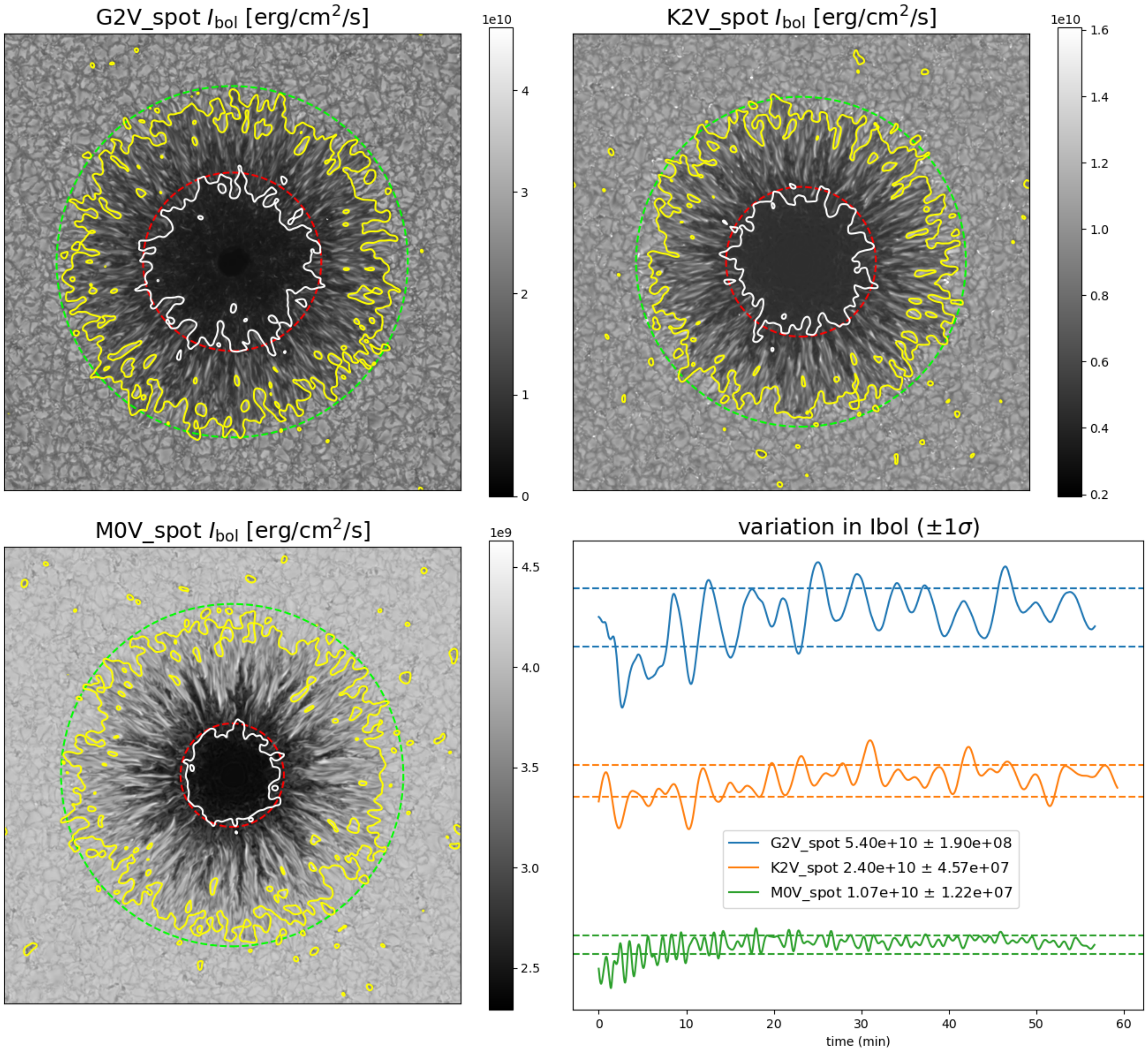
Next steps

- Spectra – broadband, CLV, line profiles *Smitha+2024 arXiv:2411.14056*
- Cooler M-dwarf spots (M4V)
- Physically motivated BC for penumbra formation (entropy ring?) - spots with chromospheres
- 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