19th MHD days
2.-4. December 2024
Leibniz Institute for
Astrophysics Potsdam (AIP)

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Sunspot simulations with potential field initial conditions

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Sonnenphysik (KIS)

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GAČR-DFG Project Unveiling the principles of solar magneto-convection
computations using SOLARNET Trans-national Access Program, funded by the EU under grant number 824135

Overview

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- Introduction & Motivation
- Methods & boundary conditions
- Initial conditions
- Parameter study
  - what can go wrong
  - what differences in good simulations
- Example simulation
  - Velocities
  - Flux emergence
- Conclusion

Unit conversion to SI:

$$10\mathrm{kG} = 1\mathrm{Tesla}$$

$$10^{22}\mathrm{Mx} = 10^{14}\mathrm{Weber}$$

Introduction

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- Many high-resolution observations of sunspots exist, particularly of the stable and decaying phase
- Only a few groups attempted radiative magneto-hydrodynamics simulations of sunspots
- Rempel (2009, Science, 325, 171) presented a simulation, that looks like 2 sunspots and has flow directions consistent with observations
- Rempel (2012, ApJ, 750, 62) showed an improved version, standard until today
- Jurčák+ (2020, A&A 638, A28) showed, that the magnetic field distribution of simulations and observations are different, particularly at the umbral boundary B_{ver} and inclinations

Motivation: B_{ver} @ umbral boundary const.

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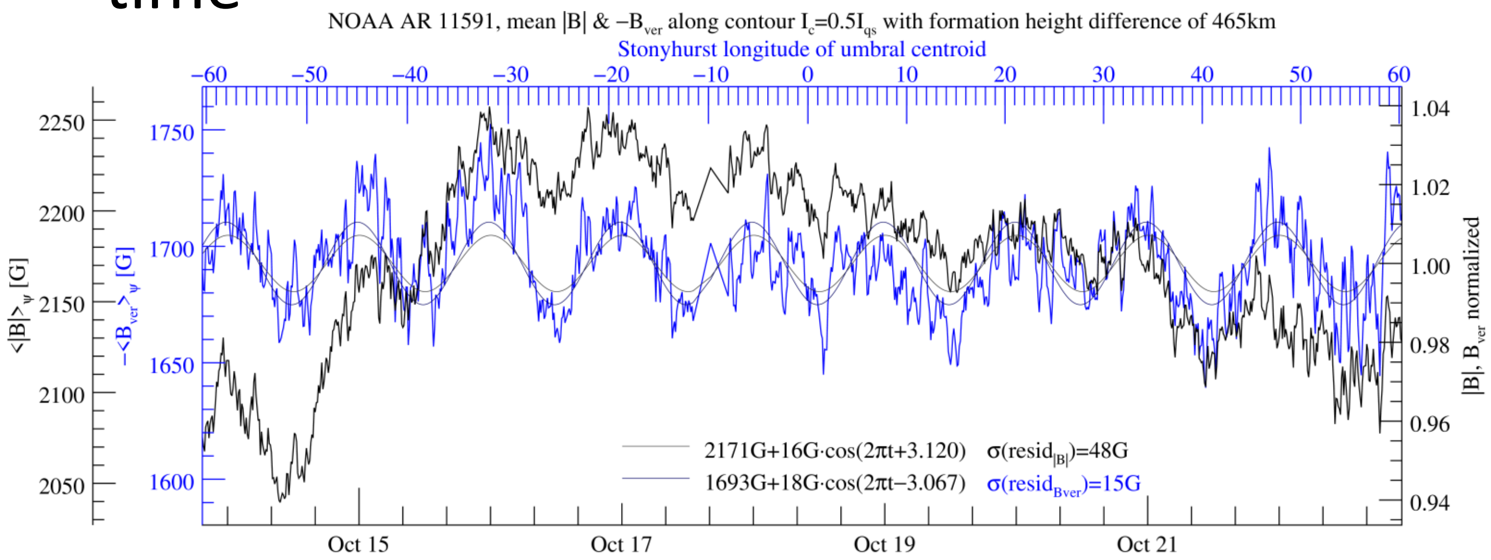
- Jurčák+ (2018, A&A 611, L4) showed that B_{ver} at the umbral boundary is independent of sunspot size and traced the umbral boundaries
- Schmassmann+ (2018, A&A 620, A104) showed that B_{ver} at the umbral boundary is constant in time



Copywrited figure:
Jurčák et al, 2018, A&A 611, L4
Figure 2, bottom panel

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Jurčák et al, 2018, A&A 611, L4
Figure 1

Motivation 2:
Importance of inclination in the penumbra

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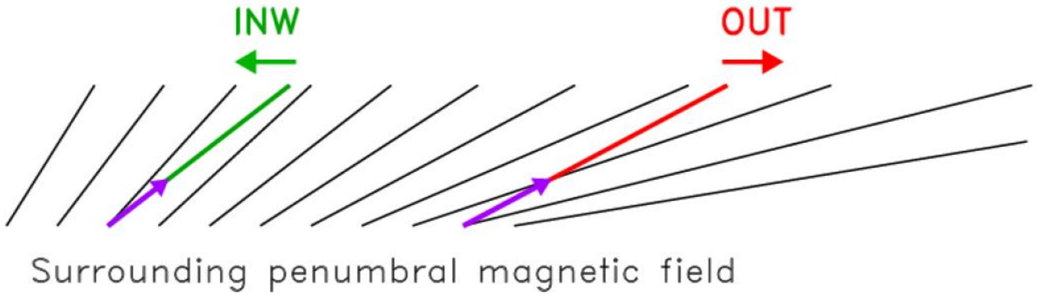
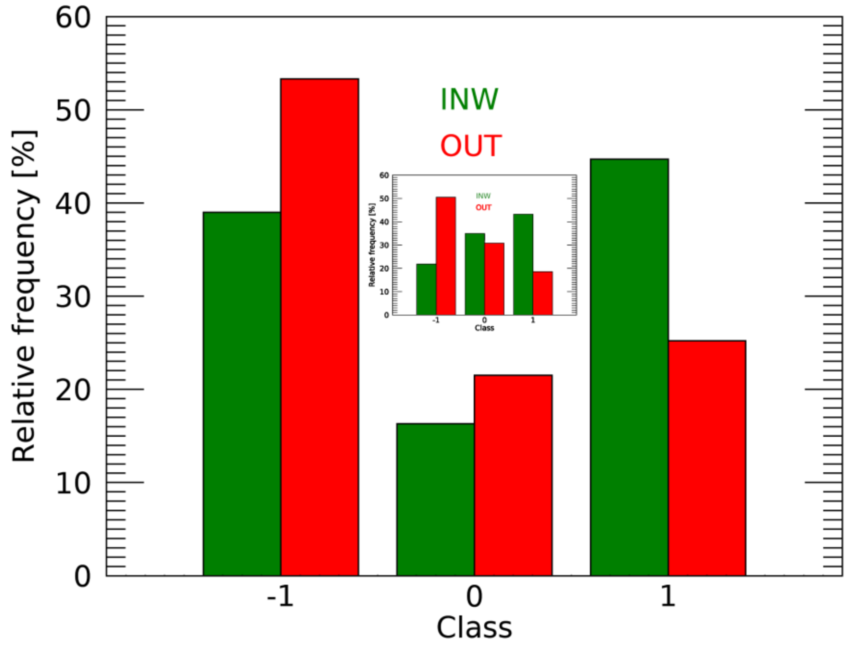
- Sobotka+ (2024, A&A 682, A65) showed that the inclination difference between penumbral grains (PGs) and their surrounding is correlated with their movement direction
- Therefore, if little penumbral-type convection occurs at inclinations typical for the inner penumbra, few PGs have inclinations larger than their surroundings (class 1), and we miss inward-moving PGs. Analysis performed on the continuation of Rempel2012, $\alpha = 2$. The inset shows results from observation for comparison.

  Sobotka+ (2024, A&A awaiting reviewer response)



Class 1: $\gamma_{\mathrm{PG}} > \gamma_{\mathrm{S}}$ Class -1: $\gamma_{\mathrm{PG}} < \gamma_{\mathrm{S}}$



Motivation 3: box height

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- Forcing the field to be more horizontal than natural at the top boundary ($\alpha = 2$) only influences the surface and below, if the box ends close to the surface
- Simulations creating flares & CMEs require higher boxes
- Potential or other force-free field top boundary conditions required

Methods & boundary conditions

Simulation using MURaM radiative MHD code with default settings, in particular:

- Bottom boundary condition: open boundary, symmetric field, called *OSb* in Rempel 2014, ApJ 789, 132, Sec. 2.2
- Potential magnetic field top boundary condition, see Rempel, 2012, ApJ, 750, 62 or Cheung, 2006, PhD thesis

Non-standard MURaM, fixing internal energy per mass in regions with high Alfvén velocity, as used in type I sunspot sim Jurčák+ 2020, A&A, 638, A28

Initial conditions

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- Initial conditions, potential field, based on an idea by Nordlund 2015, Nordita imposed on small-scale dynamo simulation:

$$B_{z,0}(r) = B_0 \exp\left(-\frac{r^2 B_0 \pi}{F_{\mathrm{Gauss}}}\right) - B_{\mathrm{opp}}$$

$$F_{\mathrm{tot}} = \int B_{z,0}\left(\sqrt{x^2+y^2}\right) \mathrm{d}x\,\mathrm{d}y = F_{\mathrm{Gauss}} - B_{\mathrm{opp}} w^2$$

$$B_z = \mathcal{F}^{-1}\left(\mathcal{F}(B_{z,0}) e^{-z|k|}\right)$$

$$B_x = \mathcal{F}^{-1}\left(\mathcal{F}(B_{z,0}) \frac{-ik_x}{|k|} e^{-z|k|}\right)$$

- Varying from $B_0 = 160\,\mathrm{kG},\ B_{\mathrm{opp}} = 0\,\mathrm{G},\ F_{\mathrm{Gauss}} = F_{\mathrm{tot}} = 10^{22}\mathrm{Mx},\ w = 49\,152\,\mathrm{km}$

Parameter study

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Reducing initial field strength

B_0 = 20kG, 40kG, 80kG, 160kG

Subtracting constant vertical offset

B_{opp} =0, 50, 100, 150, 200, 300 G

Increasing width of the box

w = 49 152 km, 98 304 km

Fixing F_{Gauss} or $F_{\mathrm{tot}} = 10^{22}\mathrm{Mx}$

Parameter study, B_0

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Reducing initial field strength

$B_0 = $ 20kG, 40kG, 80kG, 160kG

Subtracting constant vertical offset

$B_{\rm opp} =$0, 50, 100, 150, 200, 300 G

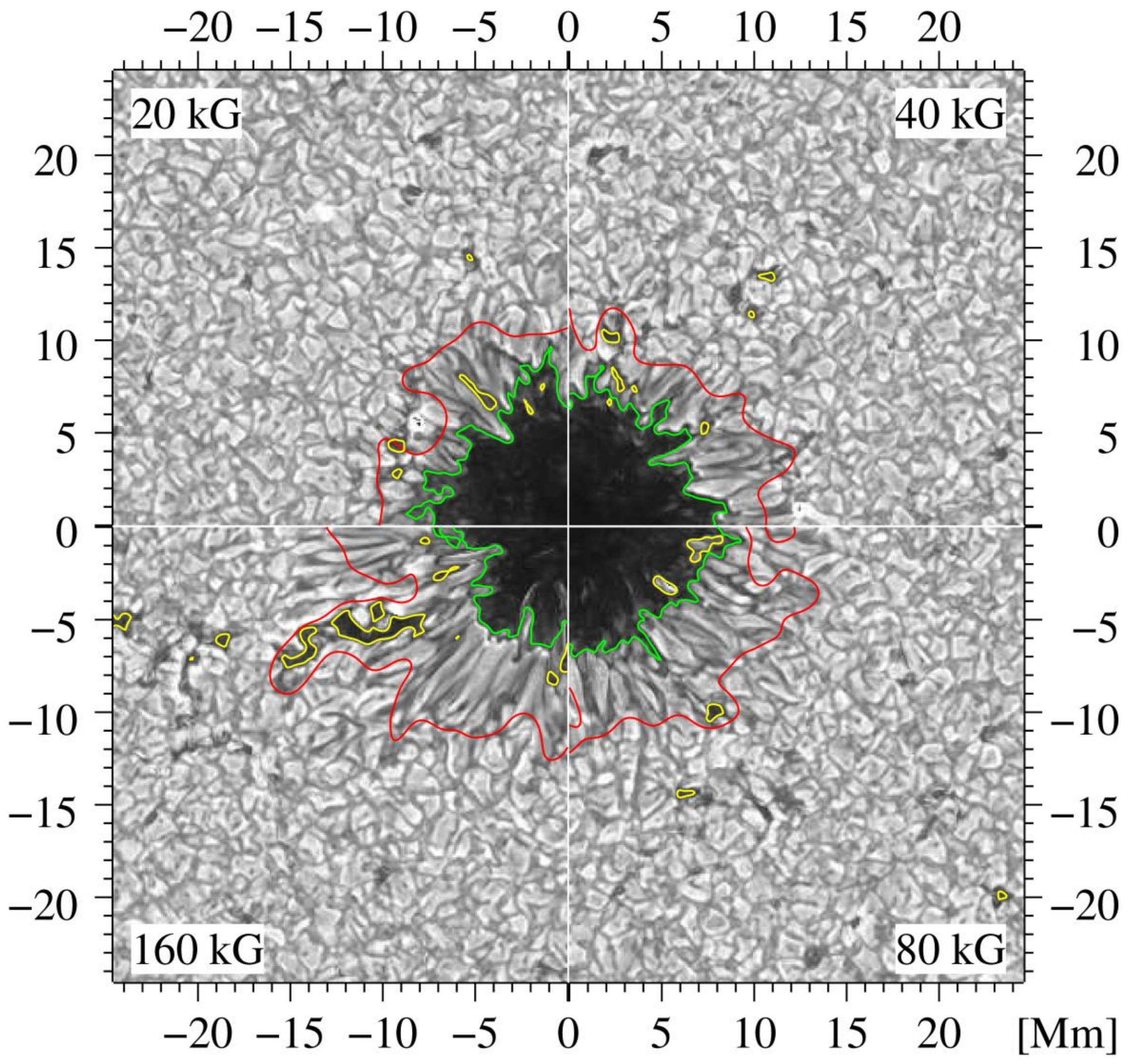
Increasing width of the box

w = 49 152 km, 98 304 km

Fixing $F_{\rm Gauss}$ or $F_{\rm tot} = 10^{22}\,{\rm Mx}$

$B_0 < 160$ kG

results in too narrow a penumbra



Parameter study, increasing F_{Gauss}

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Reducing initial field strength

B_0 = 20kG, 40kG, 80kG, 160kG

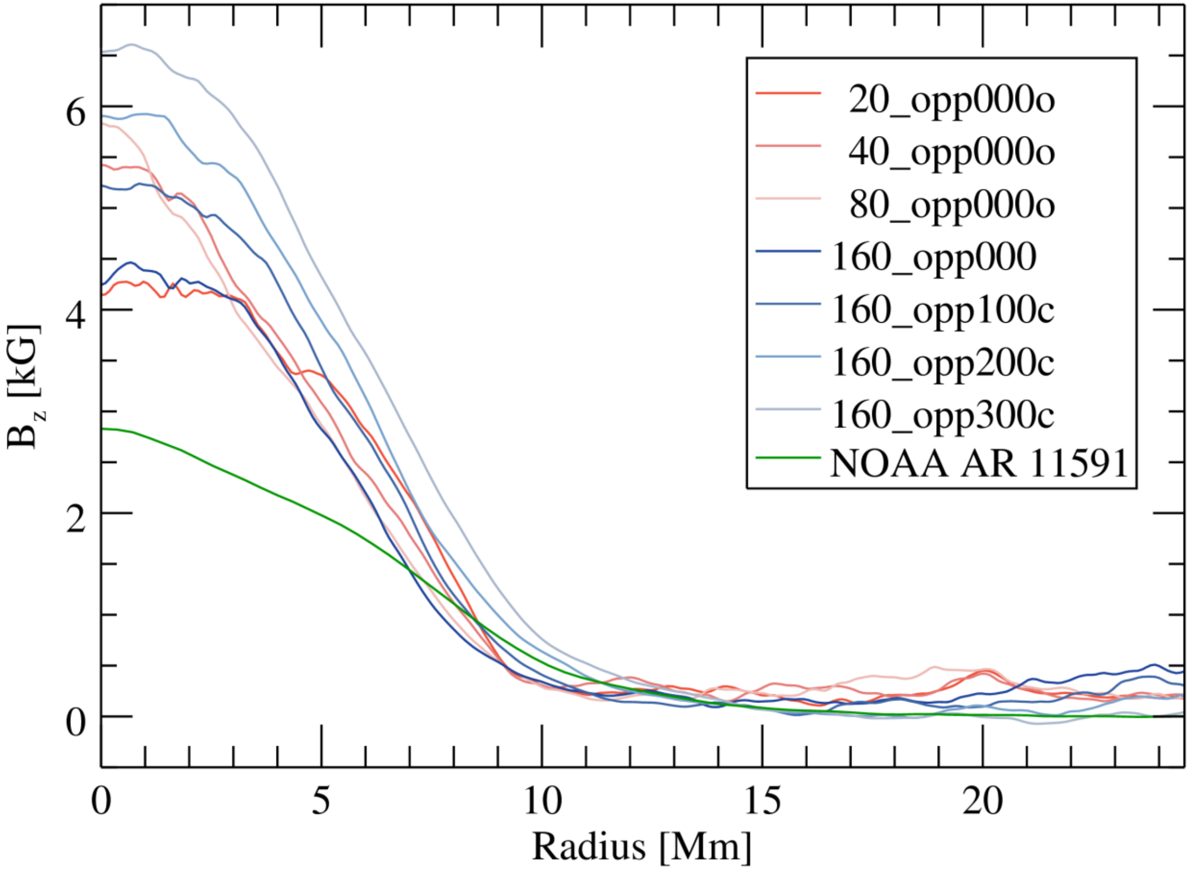
Subtracting constant vertical offset

B_{opp} =0, 50, 100, 150, 200, 300 G

Increasing width of the box

w = 49 152 km, 98 304 km

Fixing F_{Gauss} or $F_{\mathrm{tot}} = 10^{22}\mathrm{Mx}$



$F_{\mathrm{Gauss}} > 10^{22}\mathrm{Mx}$

results in too strong fields in the umbra

Parameter study, decreasing F_{tot}

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Reducing initial field strength

B_0 = 20kG, 40kG, 80kG, 160kG

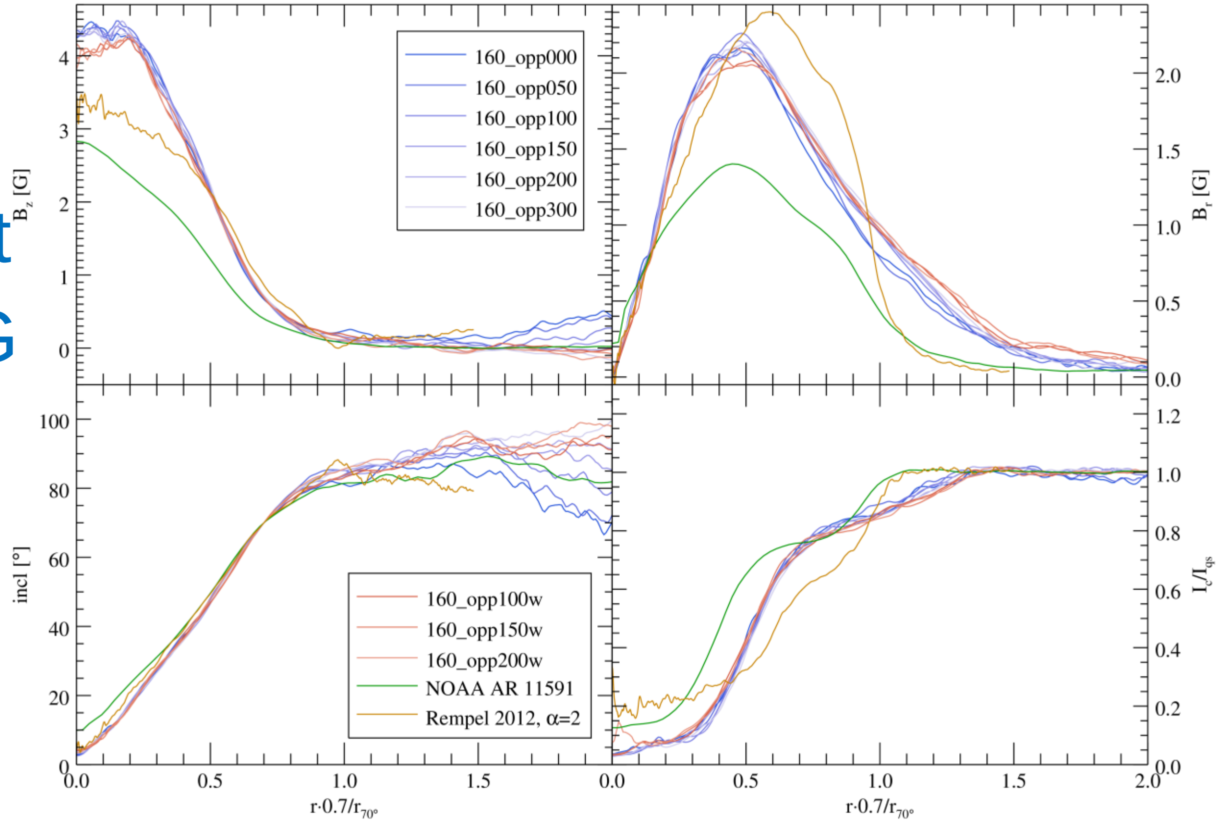
Subtracting constant vertical offset

B_{opp} =0, 50, 100, 150, 200, 300 G

Increasing width of the box

w = 49 152 km, 98 304 km

Fixing F_{Gauss} or $F_{\mathrm{tot}} = 10^{22}\mathrm{Mx}$



Changing B_{opp} with $F_{\mathrm{Gauss}} = 10^{22}\mathrm{Mx}$ changes little within the spot, but dominates outside

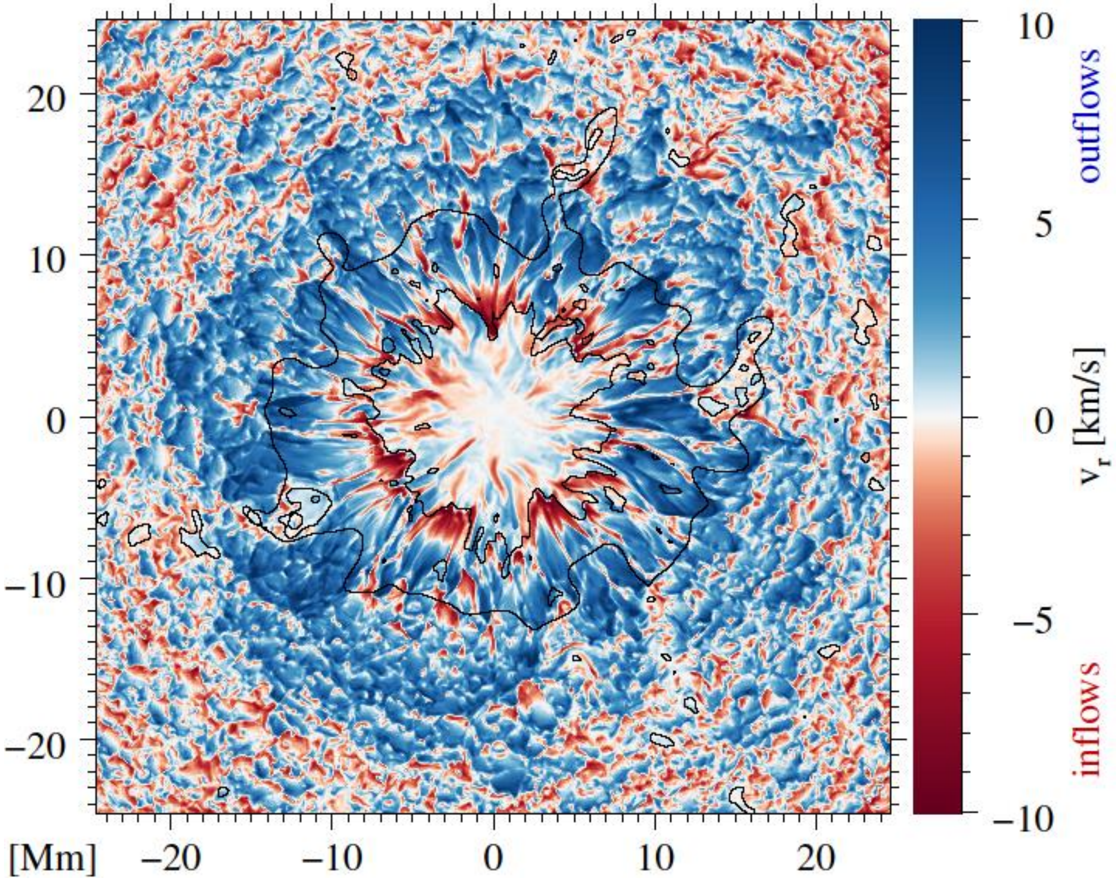
Radial velocities

simulation: $B_0 = 160\,\text{kG},\ B_{\text{opp}} = 0\,\text{G},\ F_{\text{Gauss}} = F_{\text{tot}} = 10^{22}\text{Mx},\ w = 49\,152\,\text{km}$

- Inside the umbra, flows are slow and often associated with waves
- The penumbral filament heads at the umbral boundary show in- and down-flows
- This is more consistent with observations of penumbra formation than with stable sunspots

García-Rivas+ (2024, A&A, 686, A112)

- Also, flux within the spot increases $0.59 \rightarrow 0.65 \cdot 10^{22}$Mx in 3h → 4h



Ongoing flux emergence

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Simulation:

$$B_0 = 160\,\mathrm{kG}, B_{\mathrm{opp}} = 0\,\mathrm{G}, F_{\mathrm{Gauss}} = F_{\mathrm{tot}} = 10^{22}\,\mathrm{Mx}, w = 49\,152\ \mathrm{km}$$

Open video: lout_vel2_flux_1432x1080_h265_crf29.mp4

- very dynamic initial phase
- ongoing flux emergence afterward
- When flux emergence stops, the penumbra gets narrower.
- supporting relation to forming penumbrae

Conclusions

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- Using the potential field approach, $B_0 = 160\mathrm{kG}$ and $\mathrm{F}_{\mathrm{Gauss}} = 10^{22}$Mx, it is possible to create sunspot simulations
- Subtracting a uniform vertical field B_{opp} has little influence on the spot itself, but allows to control B_{ver} outside the spot
- The gas flows in the penumbral filaments of such simulations are more consistent with a forming penumbra, than with a stable sunspot
- Such simulations show ongoing flux emergence

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Thank you for your attention

- Questions?
- Anyone interested in sunspot simulation data?

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And thanks for the funding and access to computing time to

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Choose the video file based on screen size, preferentially 1432x1080 pixel

*.mp4 if the player can handle it
*.mov for QuickTime and other dumb players