



Fine Structure and Dynamics of the sub-Surface Shear Layer

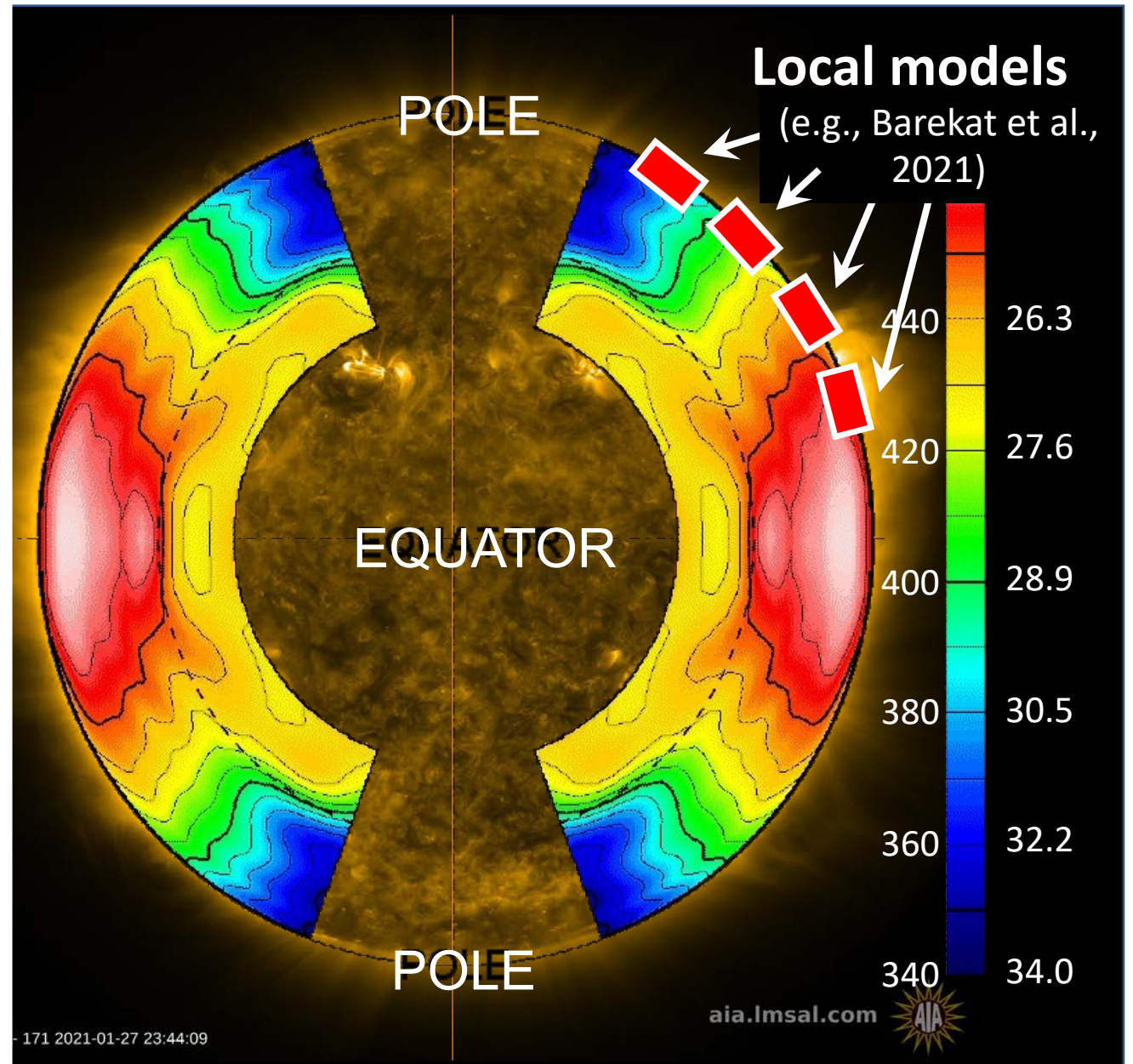
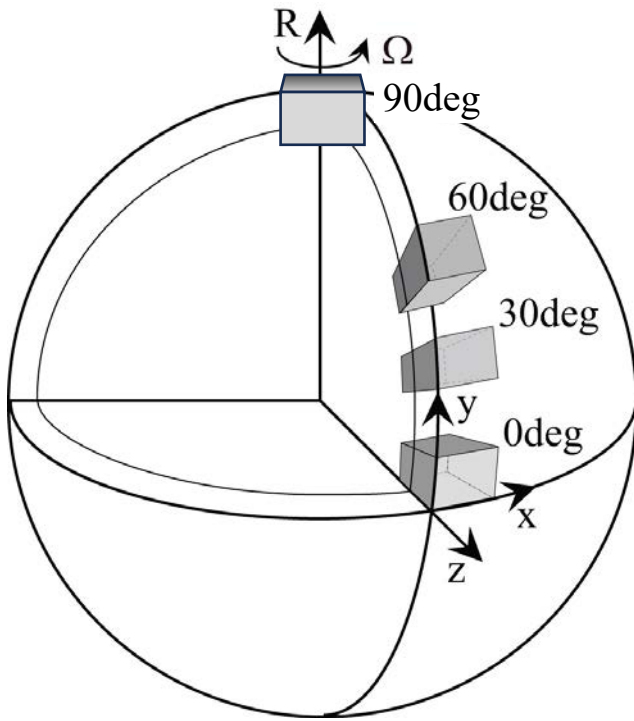
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NASA Ames Research Center, USA

COFFIES Community Workshop Series

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Observations of the Differential Rotation & Near Surface Shear Layer



Modeling of the solar rotation

☀ **Compressible plasma flows in a highly stratified medium**

☀ **3D multi-group radiative energy transfer between the fluid elements**

☀ **A real-gas equation of state**

☀ **Ionization and excitation of all abundant species**

☀ **Small-scale turbulence**

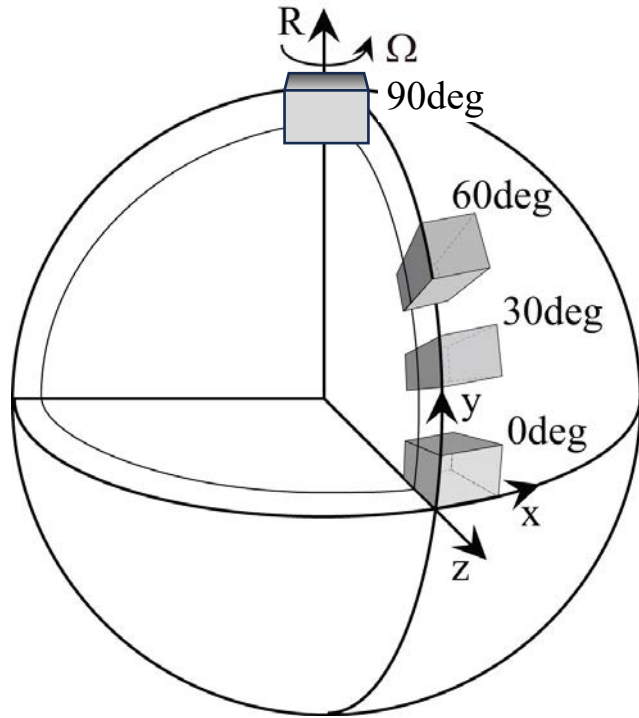
☀ **Magnetic effects**

☀ **Rotation**

StellarBox code (Wray et al., 2015; 2018)

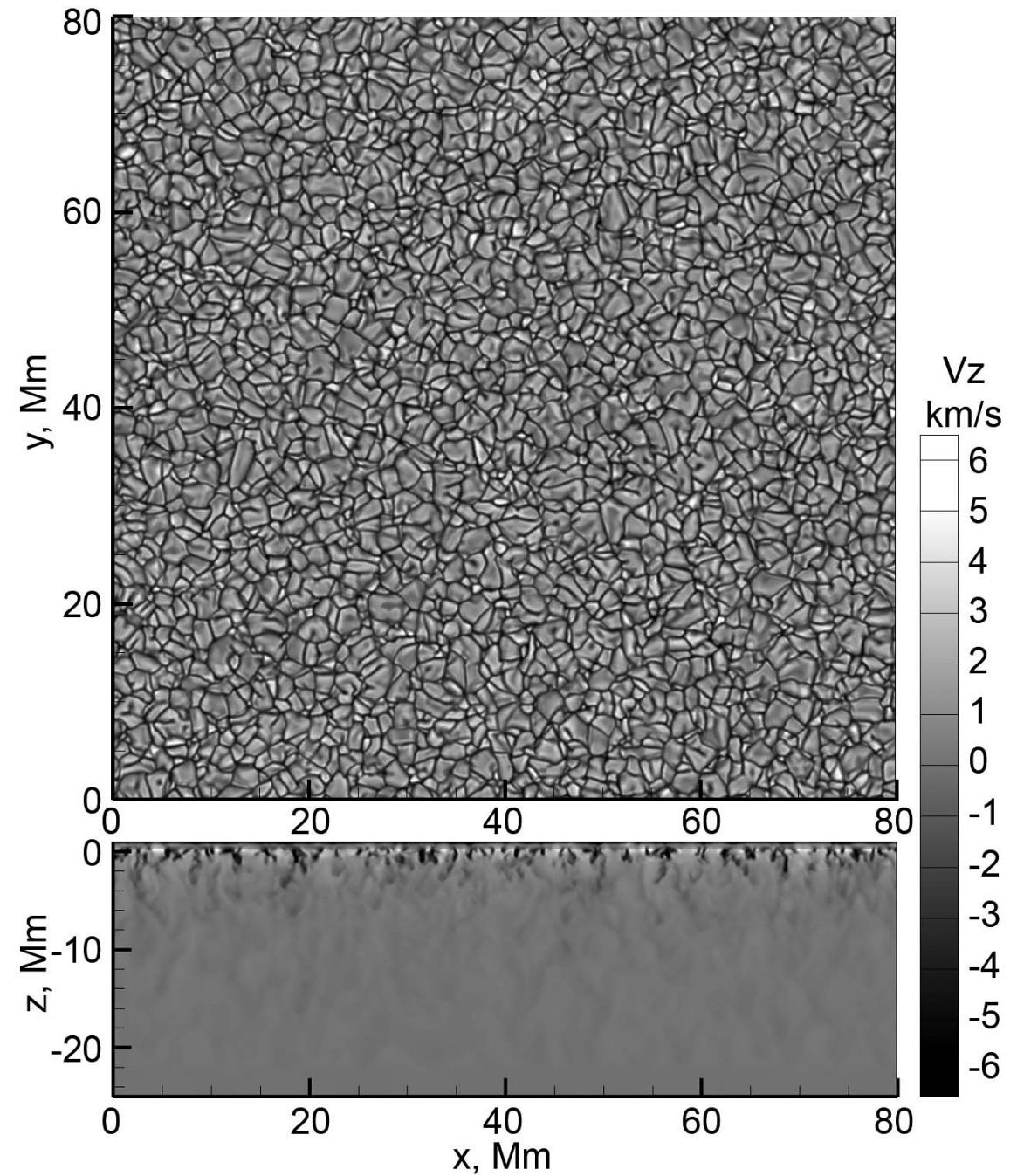
- ✓ 3d rectangular geometry
- ✓ Fully conservative compressible
- ✓ Fully coupled radiation solver:
 - LTE using 4 opacity-distribution-function bins
 - Ray-tracing transport by Feautrier method
 - 18 rays (2 vertical, 16 slanted) angular quadrature
- ✓ Non-ideal (tabular) EOS
- ✓ 4th order Padé spatial derivatives
- ✓ 4th order Runge-Kutta in time
- ✓ Different Turbulence models
 - LES: Smagorinsky model (including its dynamic form)
 - DNS + Hyperviscosity approach
 - MHD subgrid models

Modeling of the solar rotation in a local computational domain

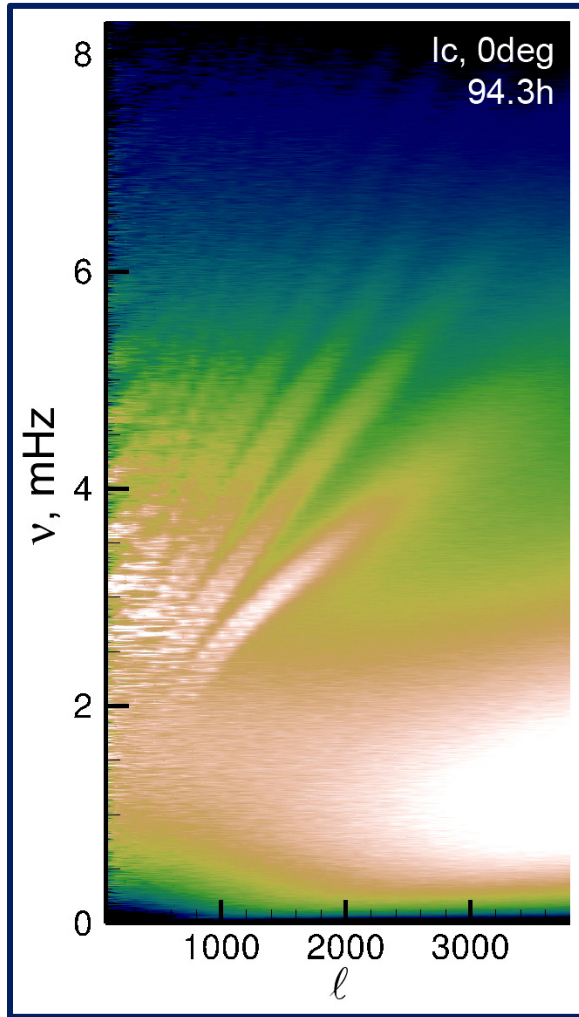


Scheme of the computation box location relative to the Sun's equator and rotation axis.

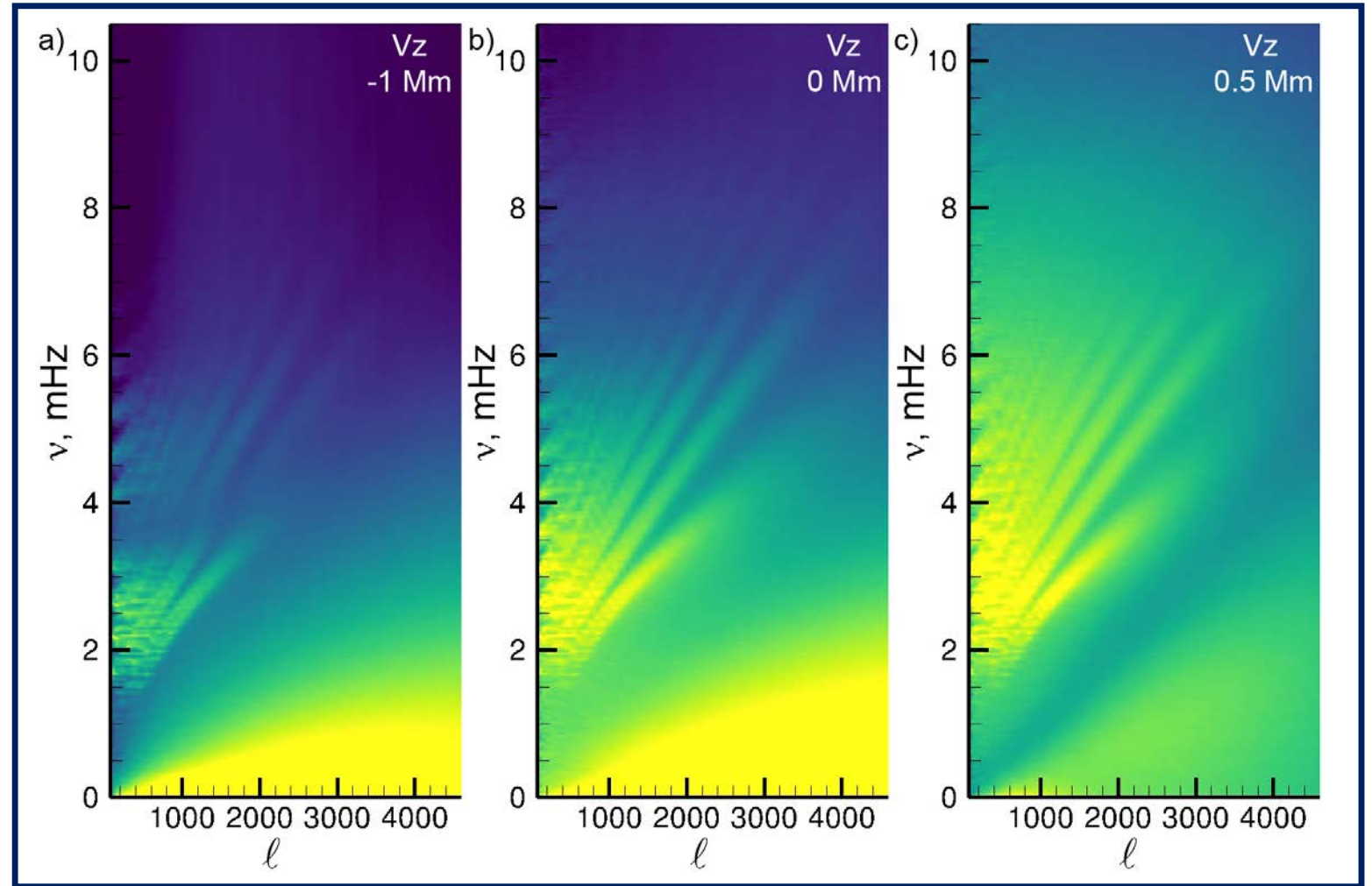
Snapshot of the vertical velocity at the solar photosphere and a vertical slice through the computational domain.



Rotational splitting in the oscillation power spectra (l - ν diagrams)



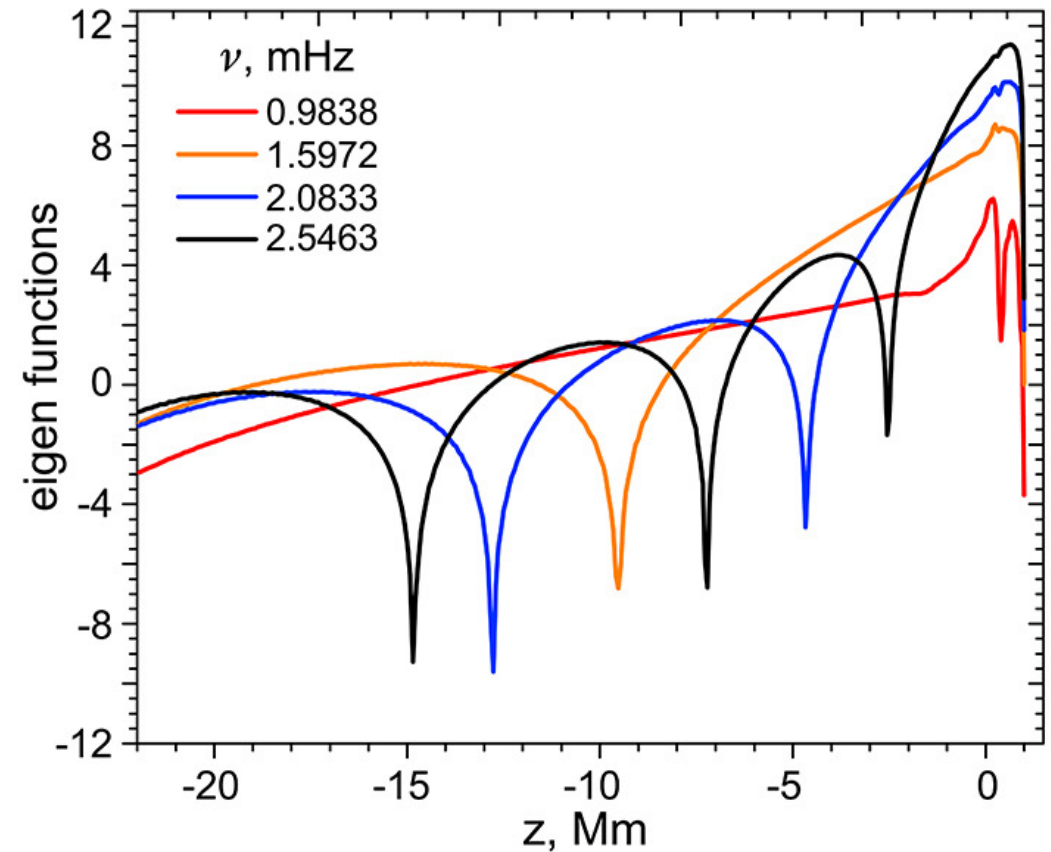
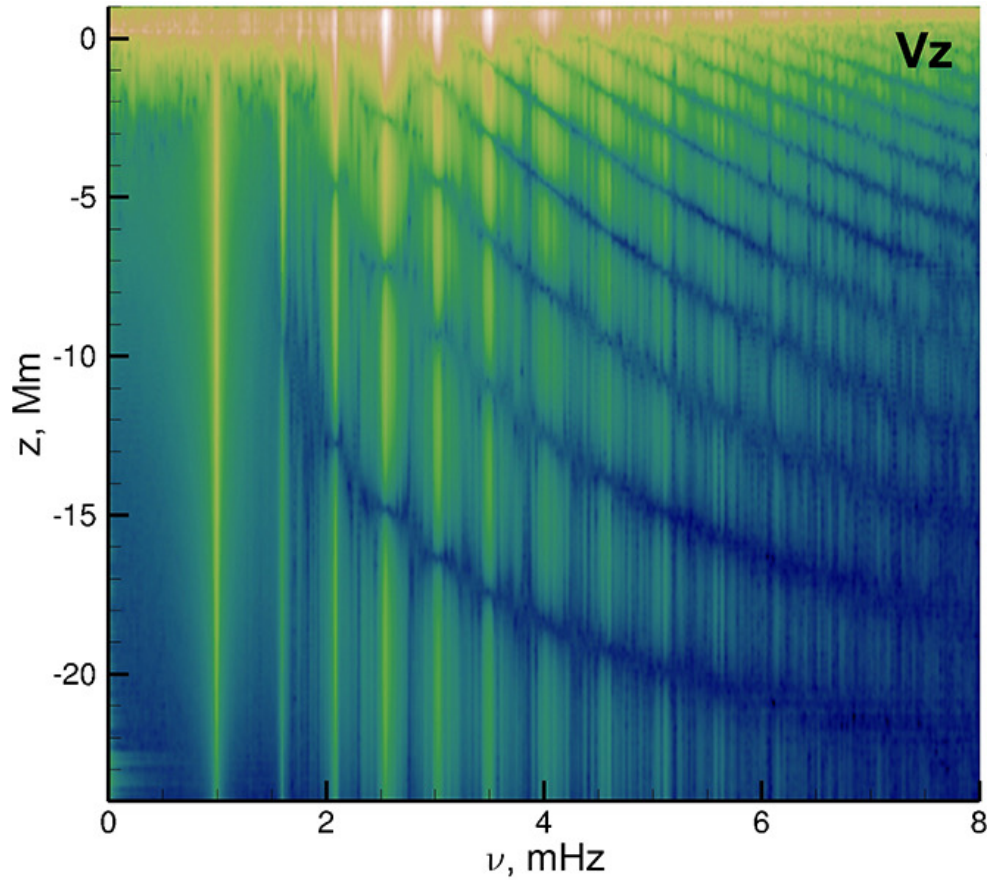
The l - ν diagram is computed using 94.3 hours-long time-series of the continuum intensity (Fe I, 6173Å) at the disk.



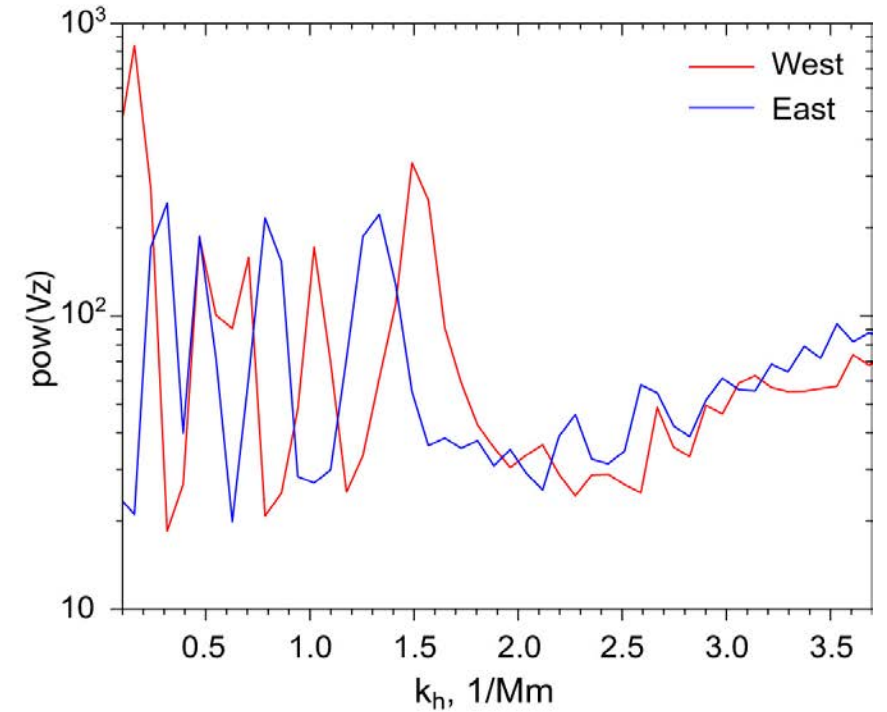
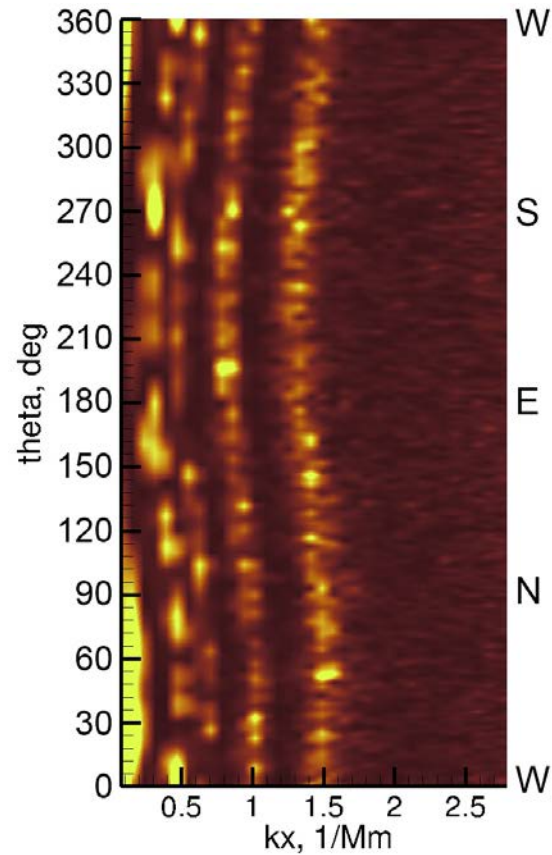
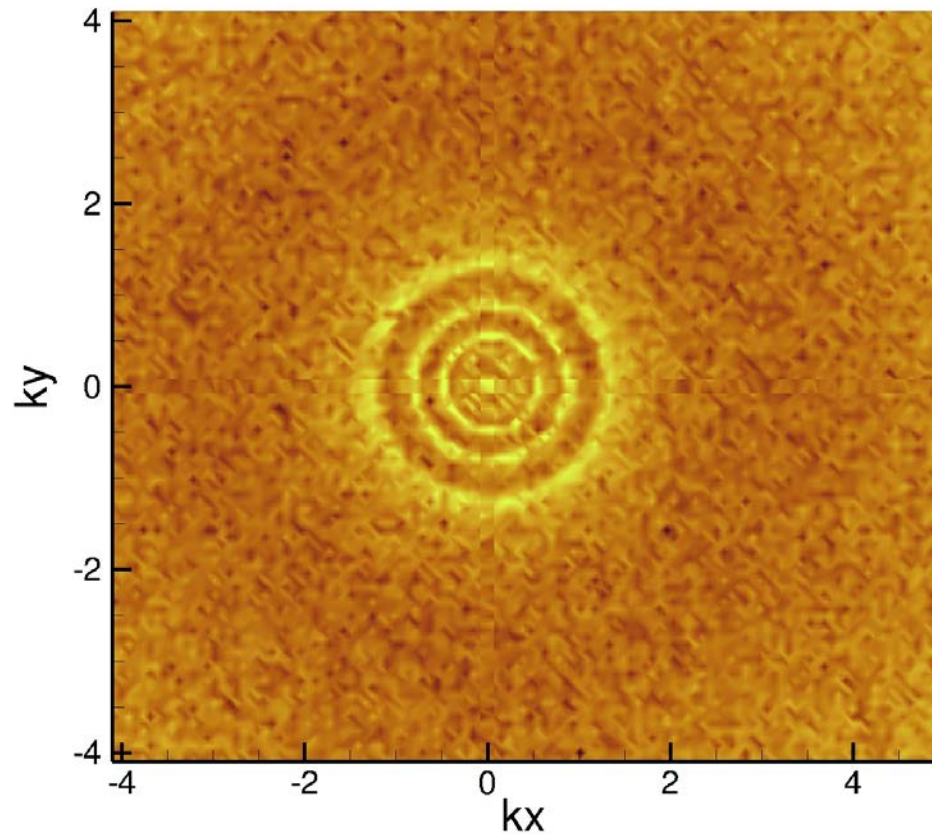
The l - ν diagram is computed from the 24 hour-long time-series of the vertical velocity at different layers above and below the solar surface.

Solar oscillations – distribution of the oscillation amplitude with depth – radial eigenfunctions (p-modes)

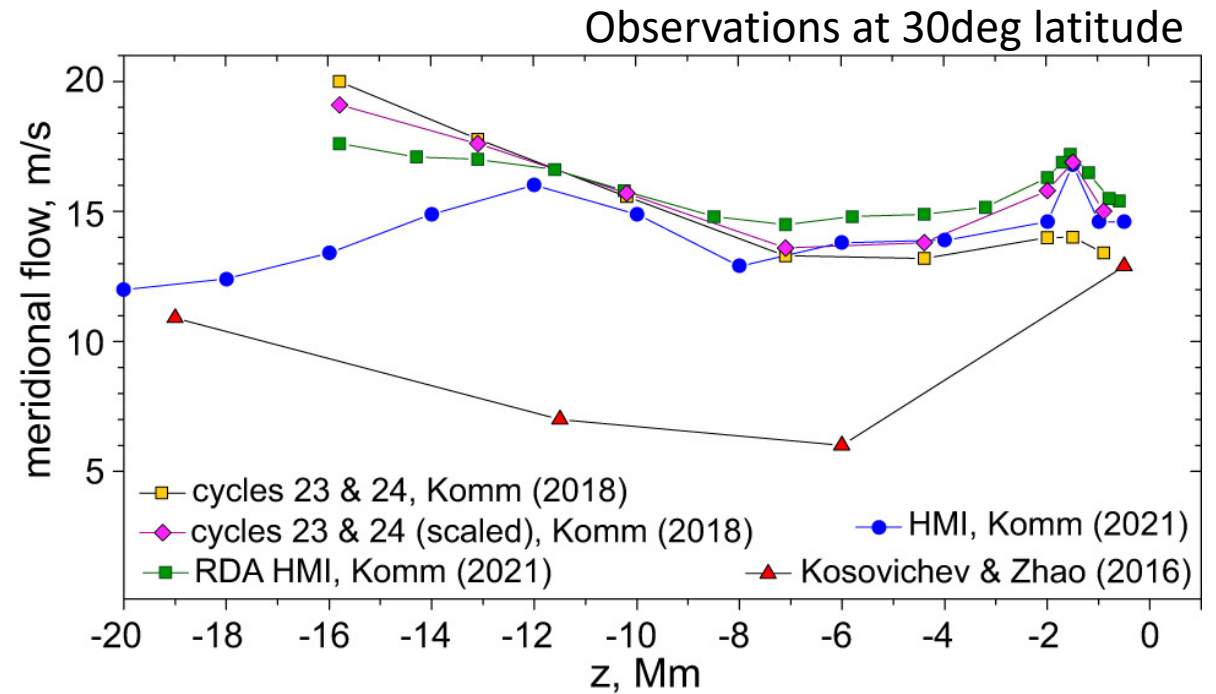
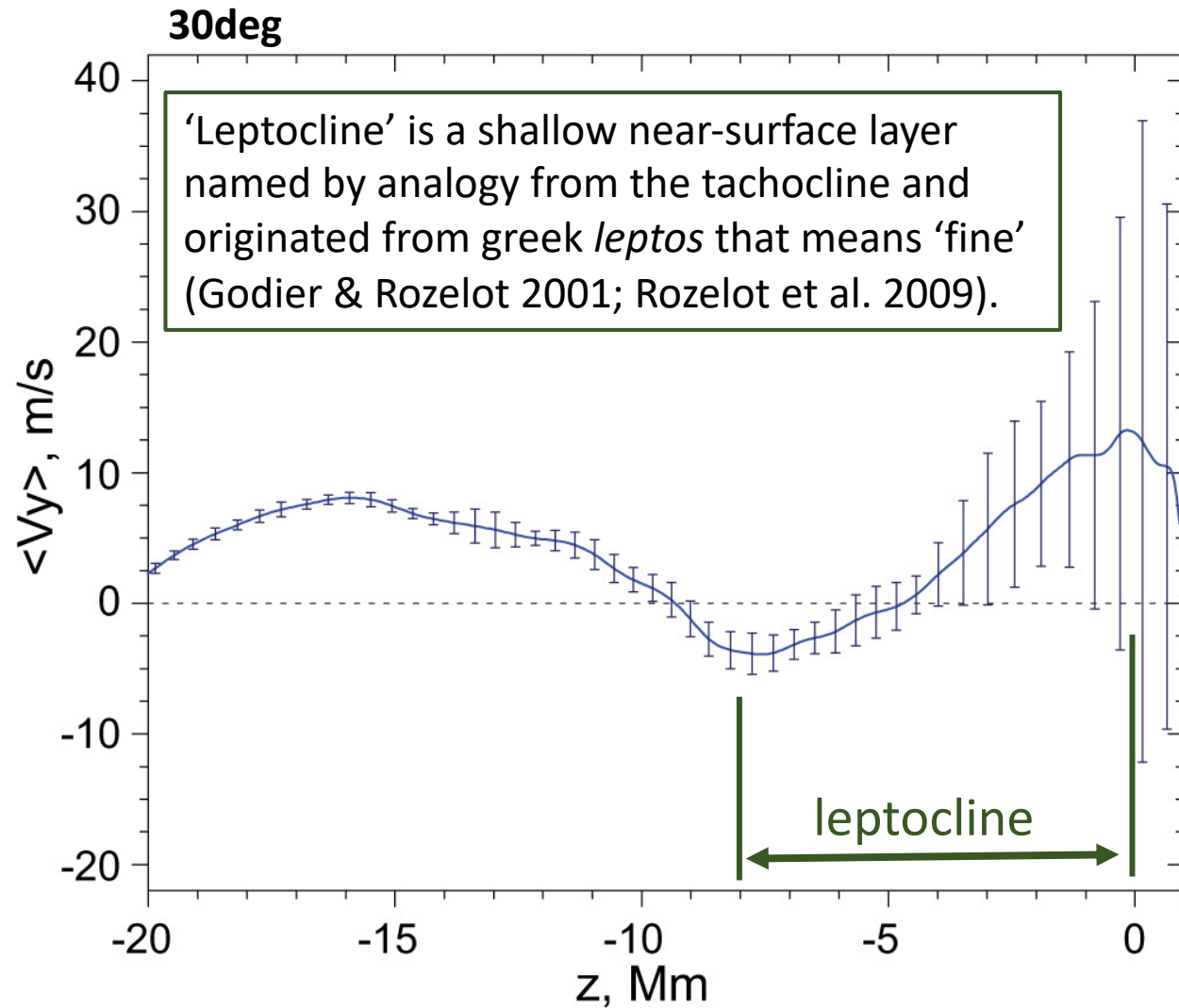
Sun



Effects of Rotation on Ring Diagram Analysis



Meridional Flows

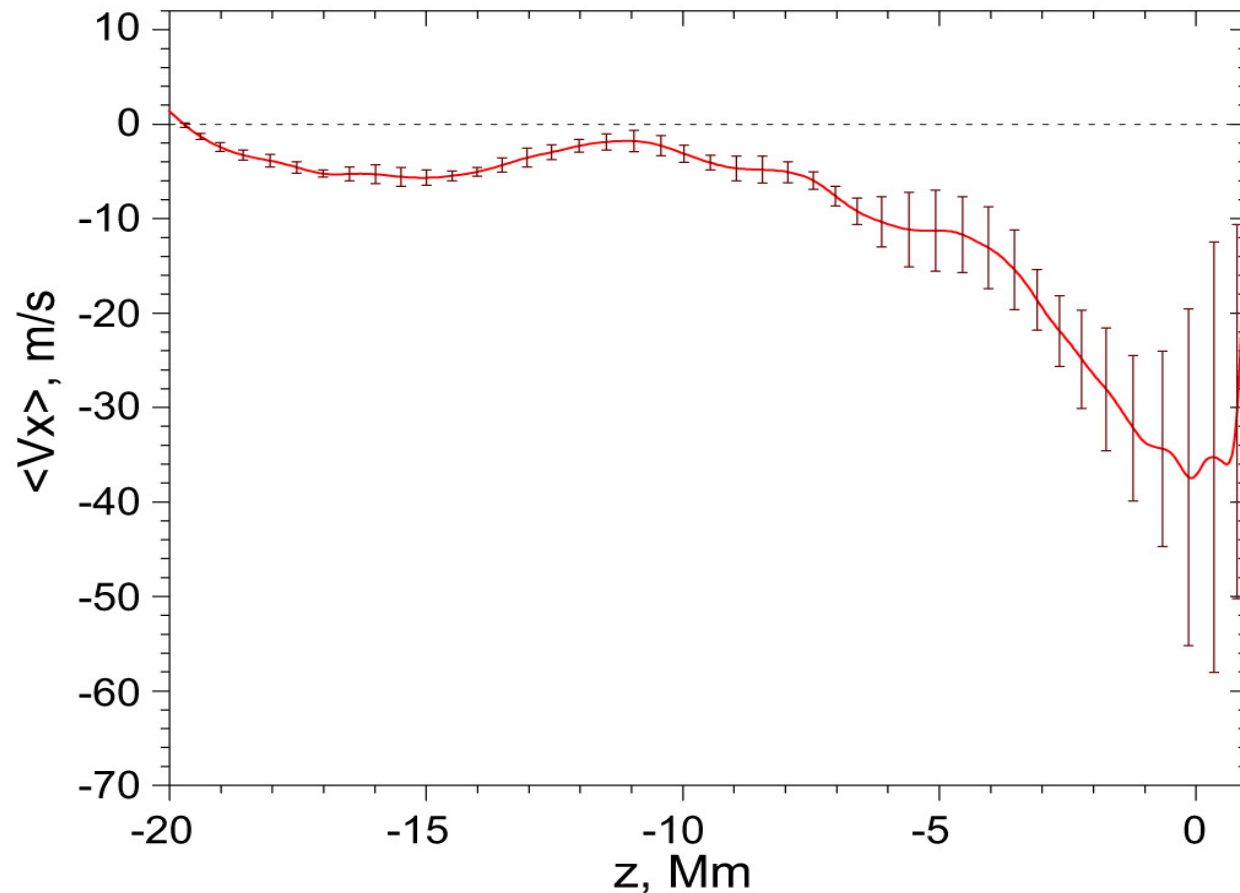


Helioseismic inferences of the meridional circulation at 30 degrees latitude.

Mean radial profile of the meridional flow component of the flow velocity at 30 degrees latitude. The vertical bars show 1σ velocity deviations from the mean values. Radial profiles are obtained by averaging a 24-hour series of simulation data.

Kitiashvili et al., 2023

The model reveals a shallow subsurface layer with radial differential rotation, corresponding to the leptocline



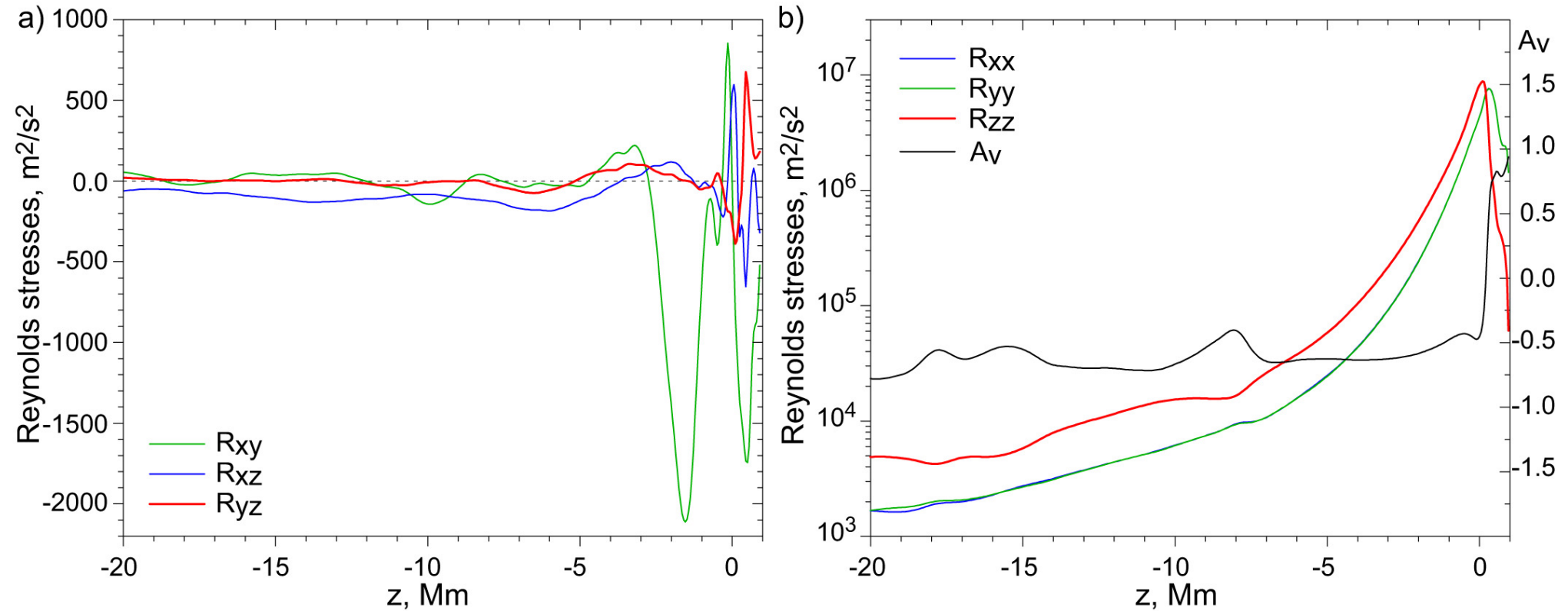
First signatures of the leptocline was detected by Deubner, Ulrich & Rhodes (1979)

Recent studies:
Global helioseismology
Reiter et al., 2020
Local helioseismology
Komm et al. 2021

Mean radial profile of deviation of the azimuthal flow speed from the imposed rotational velocity at 30 degrees latitude. The vertical bars show 1σ velocity deviations from the mean values. Radial profiles are obtained by averaging a 24-hour series of simulation data.

Kitiashvili et al., 2023

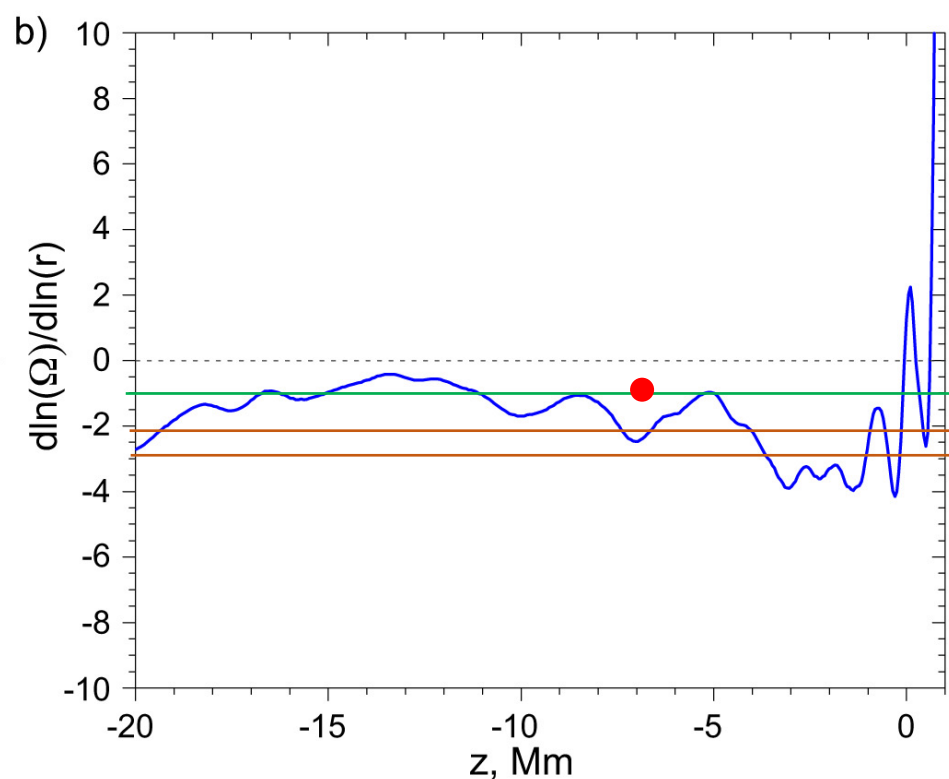
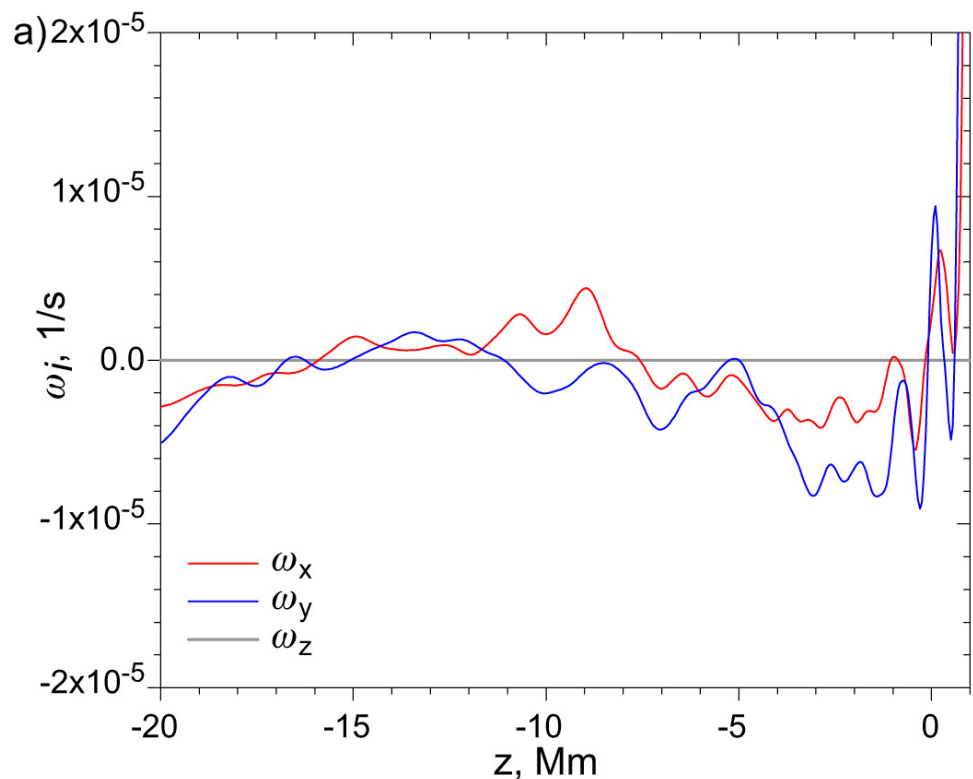
Subsurface dynamical structure of the outer layers of the convection zone shows a sharp increase of turbulent anisotropic Reynolds stresses



Mean radial profiles of a) off-diagonal Reynolds stresses, and b) diagonal Reynolds stresses and the anisotropy parameter, A_V (black curve). Radial profiles are obtained by averaging a 24-hour series of simulation data.

$$A_V = (R_{xx} + R_{yy} - 2R_{zz})/V_{rms}^2$$

Subsurface dynamical structure of upper layers of the convection zone



$$d\ln\Omega/d\ln(r) \sim -1$$

Corbard & Thompson,
2002

Barenkat et al., 2014

$$d\ln\Omega/d\ln(r) \sim -2.8$$

Reiter et al., 2020
(high-degree inversions)

$$d\ln\Omega/d\ln(r) \sim -2.13$$

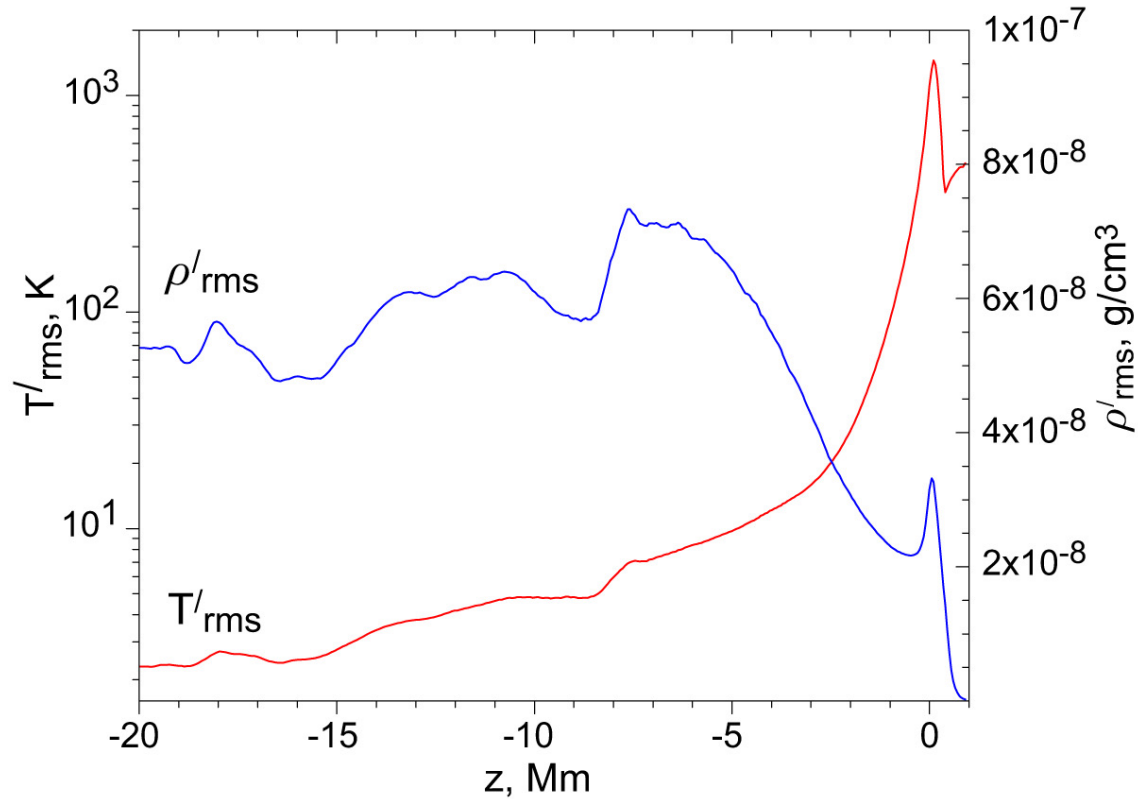
Reiter et al., 2020
(intermediate-degree
inversions)

$$d\ln\Omega/d\ln(r) \sim -0.95 \text{ at depth of 7Mm}$$

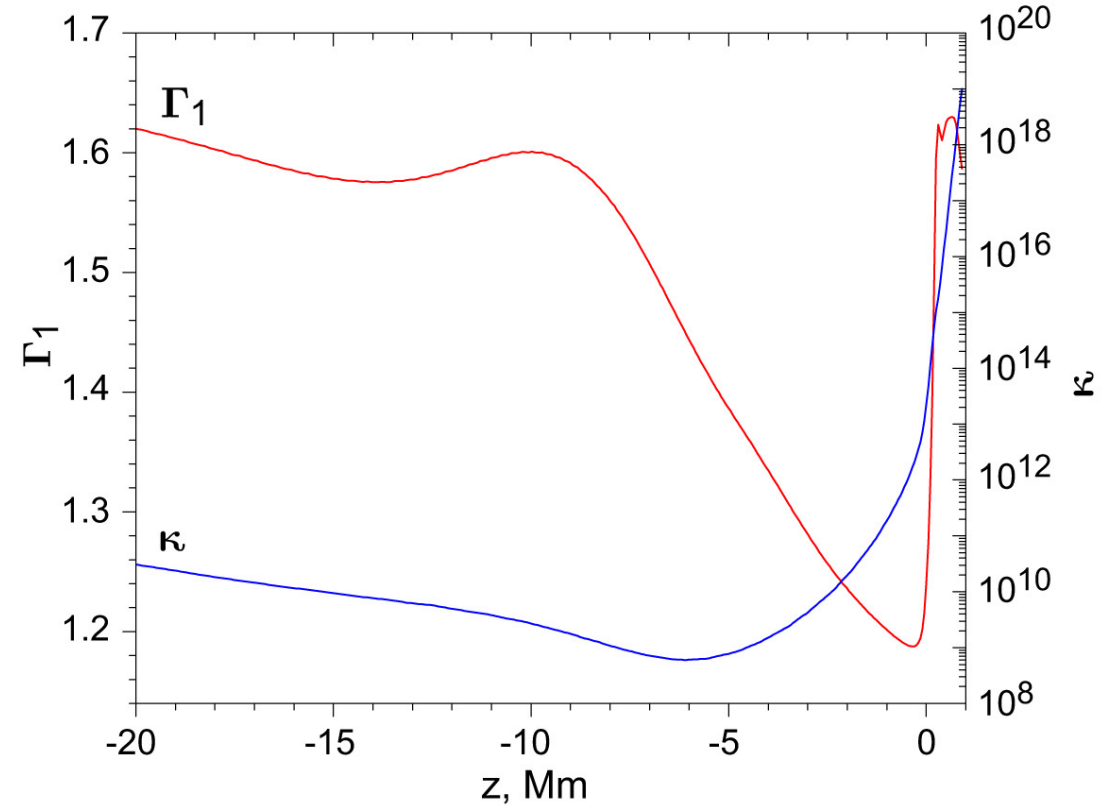
Antia & Basu et al., 2022

Mean radial profiles of a) the vorticity components, and b) the radial gradient of the local solar rotation rate. Radial profiles are obtained by averaging a 24-hour series of simulation data.

Thermodynamic structure of the upper layers of the convection zone shows enhanced variations of temperature and density in the leptocline, located in the H and HeI ionization zones

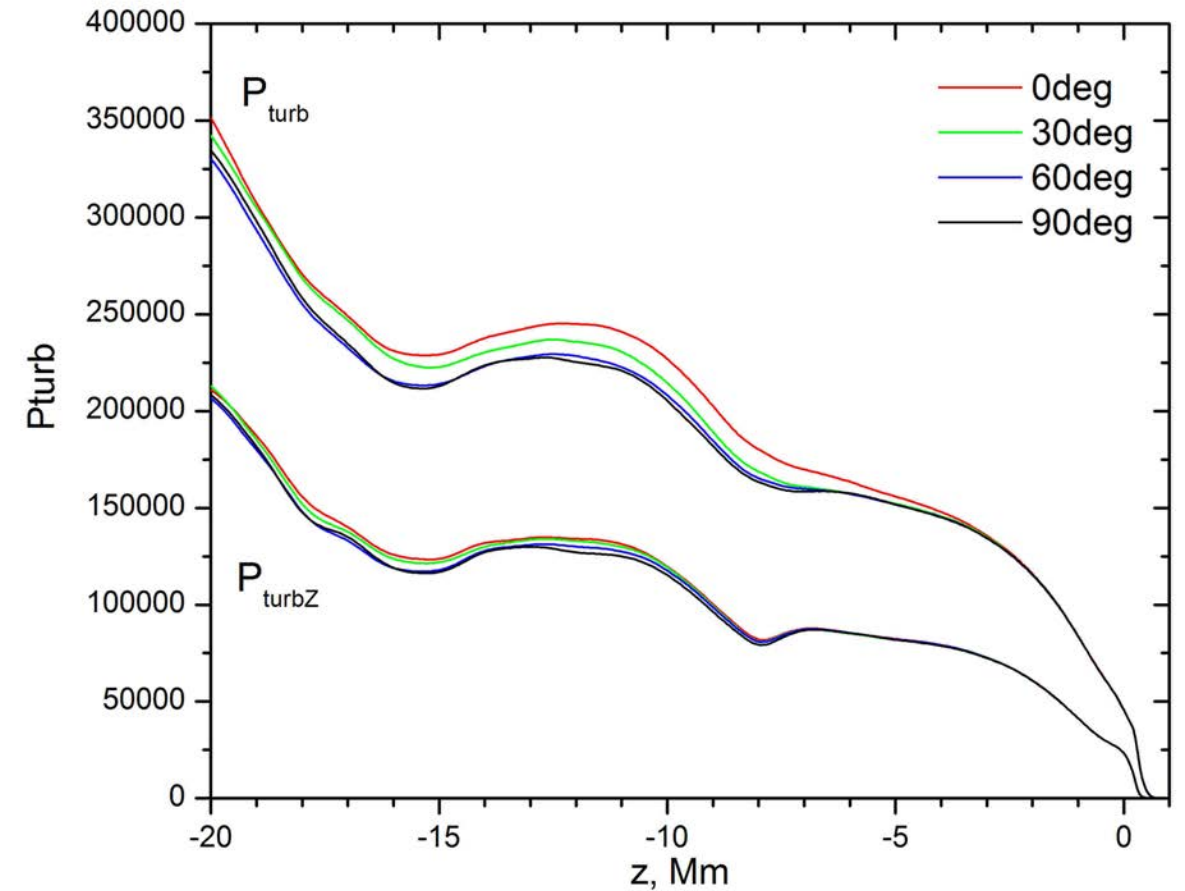
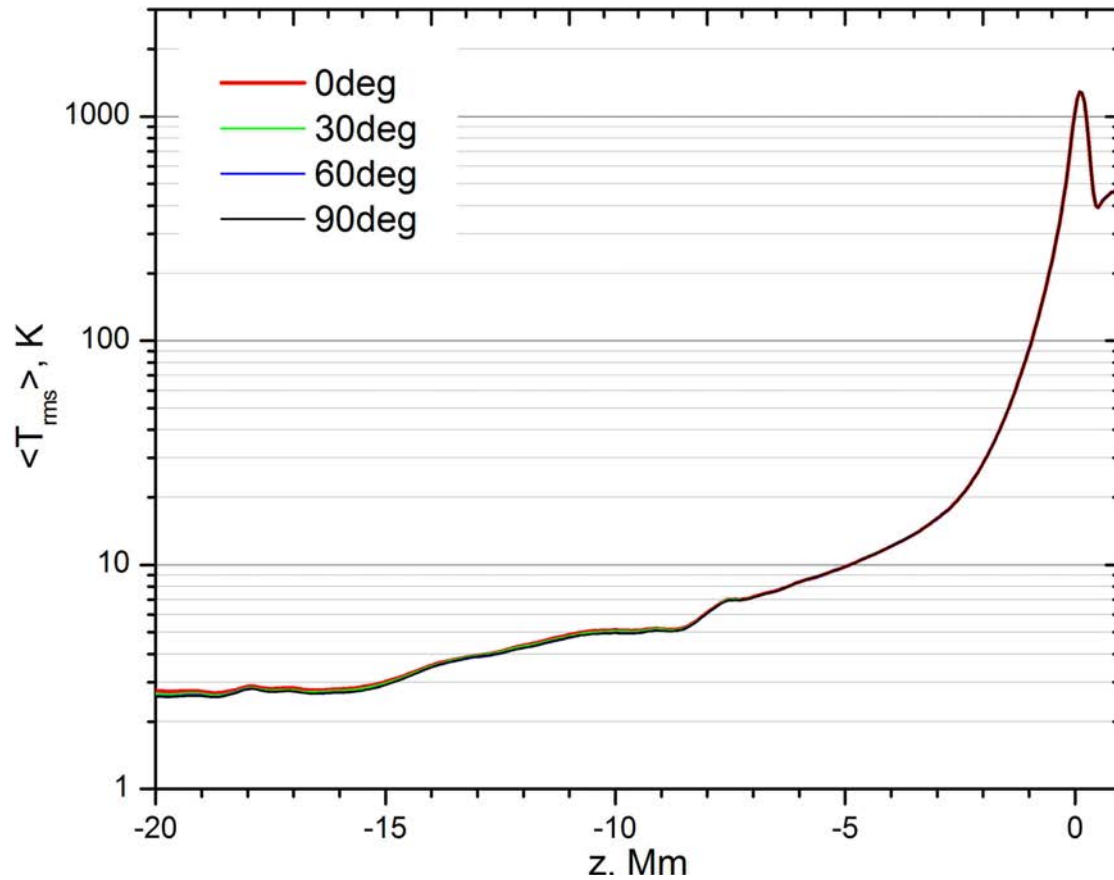


Radial profiles of the temperature perturbations, T'_{rms} (red curve), and density perturbations, ρ'_{rms} (blue curve).

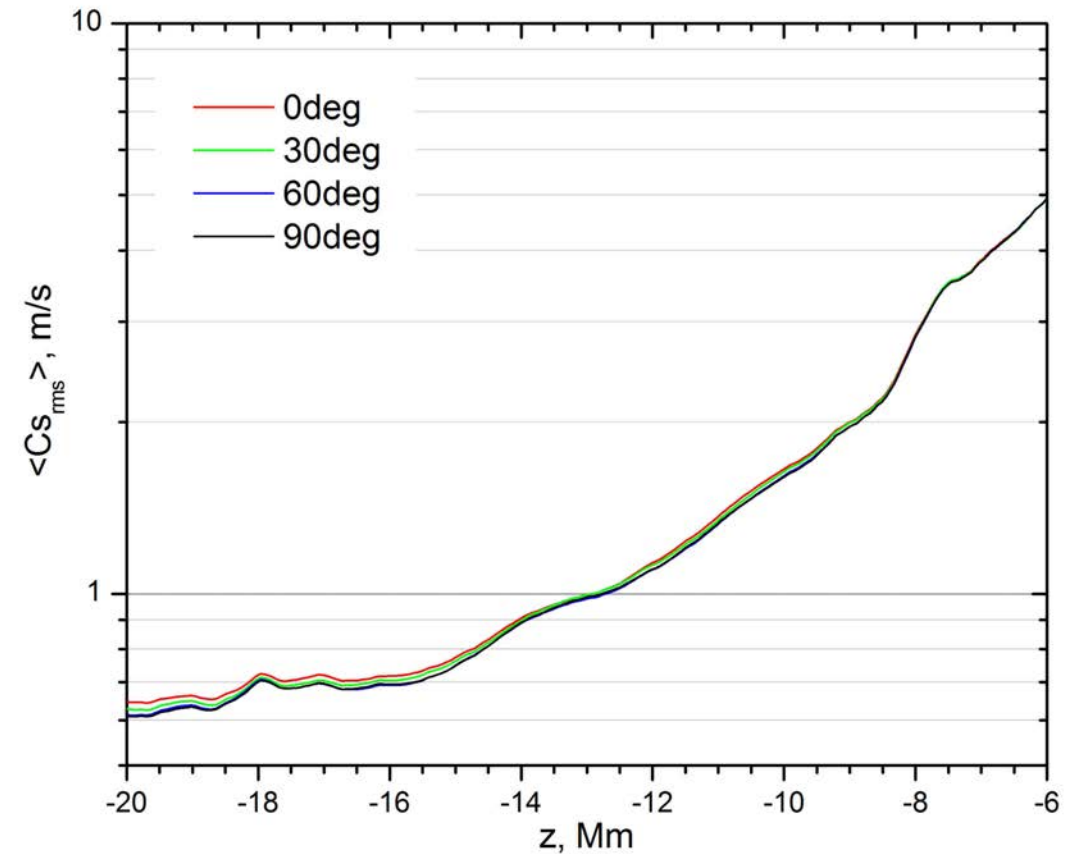
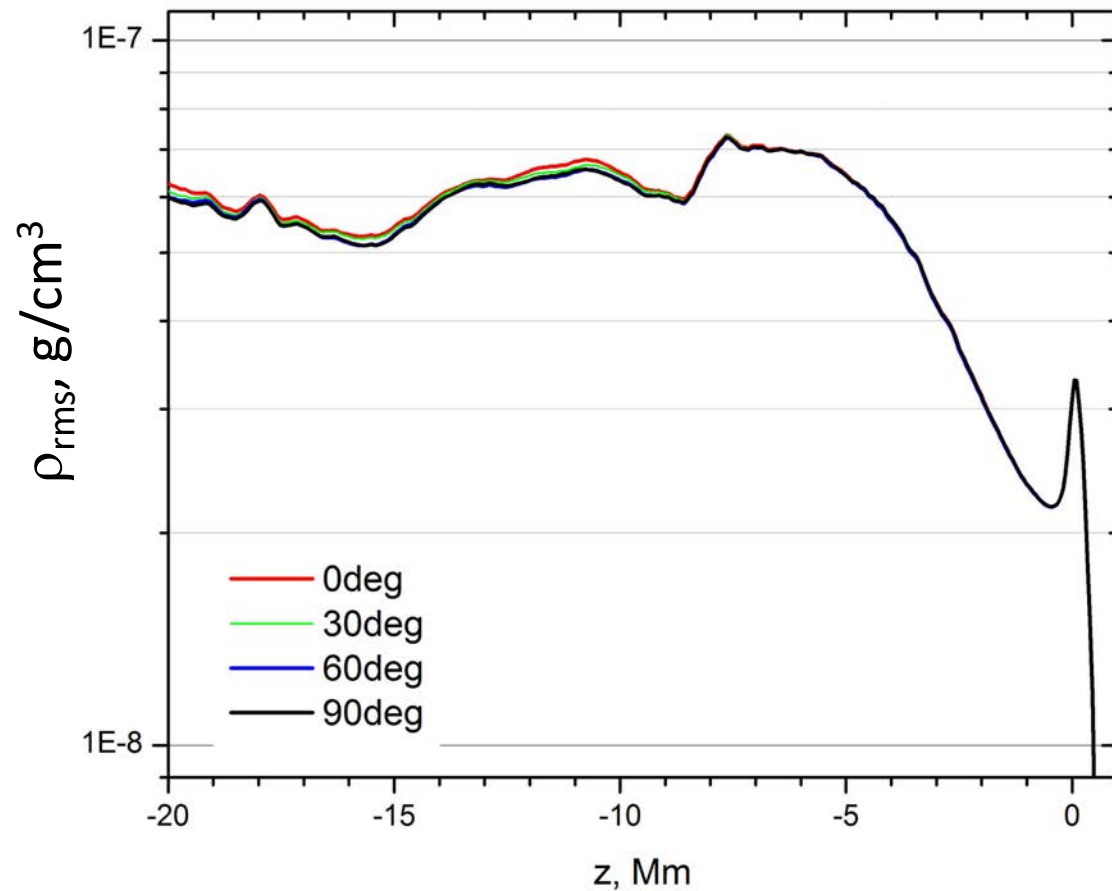


Radial profiles of the adiabatic index, Γ_1 (red curve) and the heat conductivity, κ (blue curve).

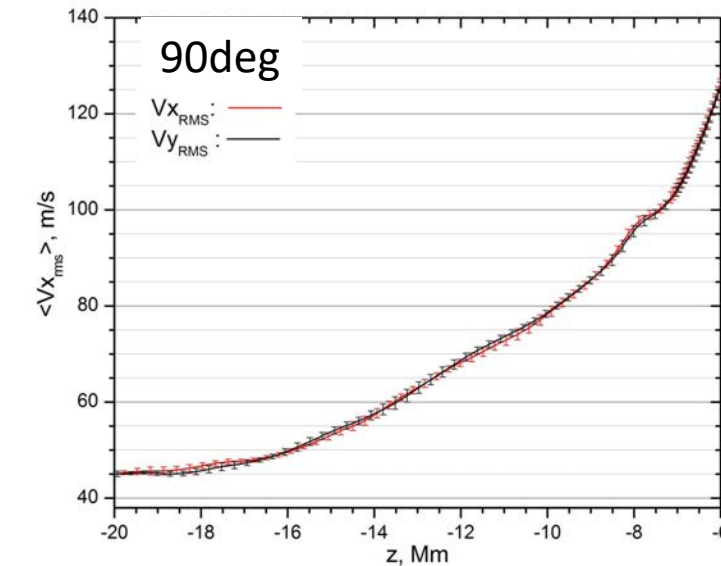
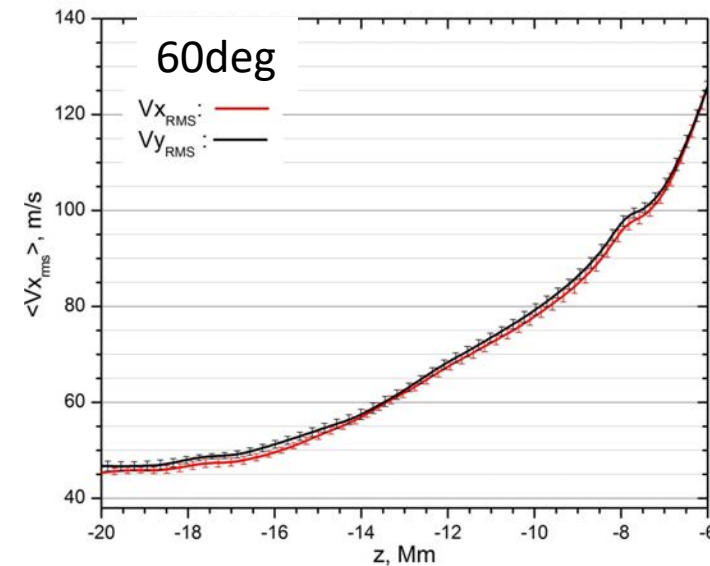
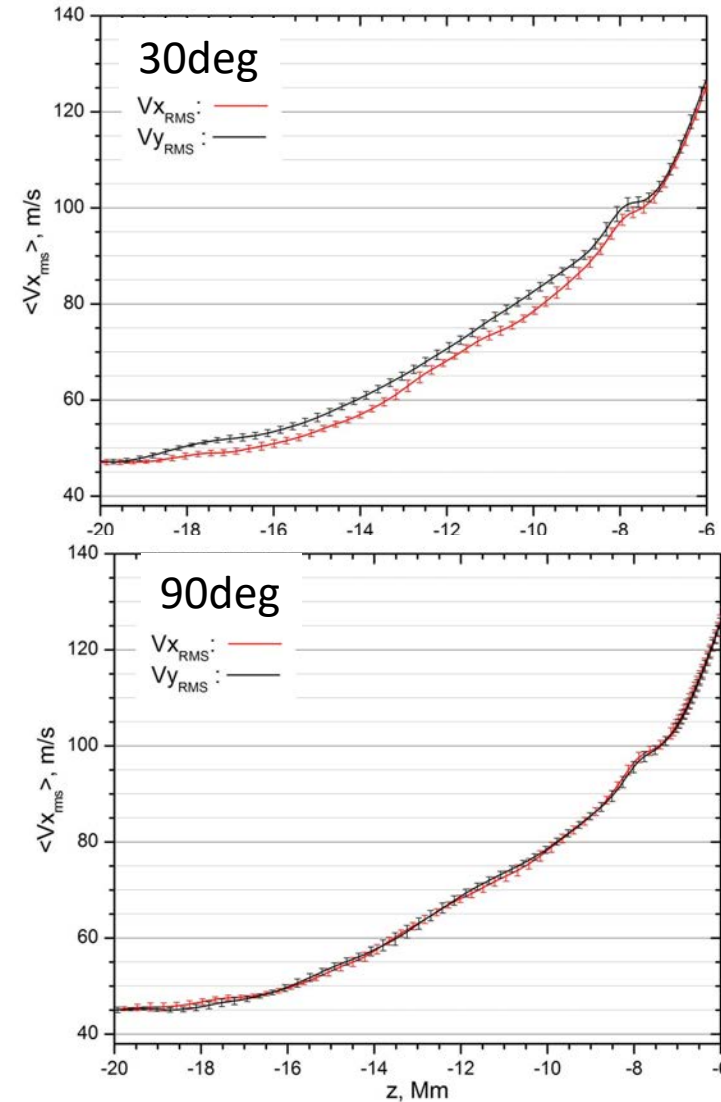
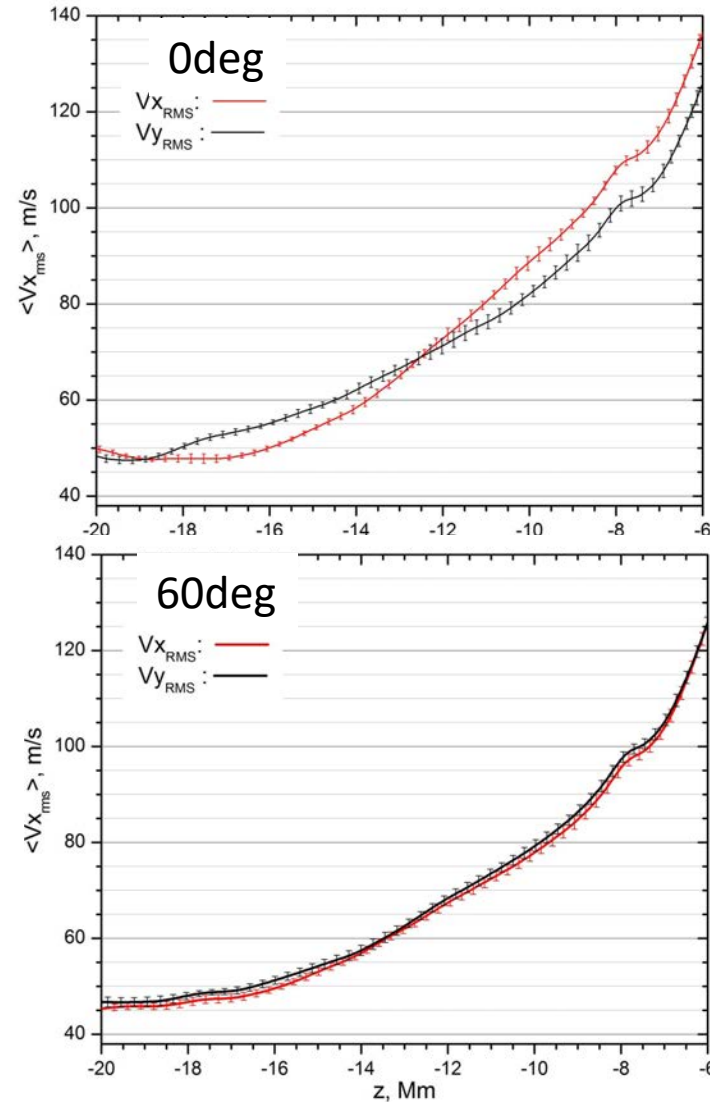
Effect of the Coriolis force on Thermodynamic Structure of Subsurface Flows



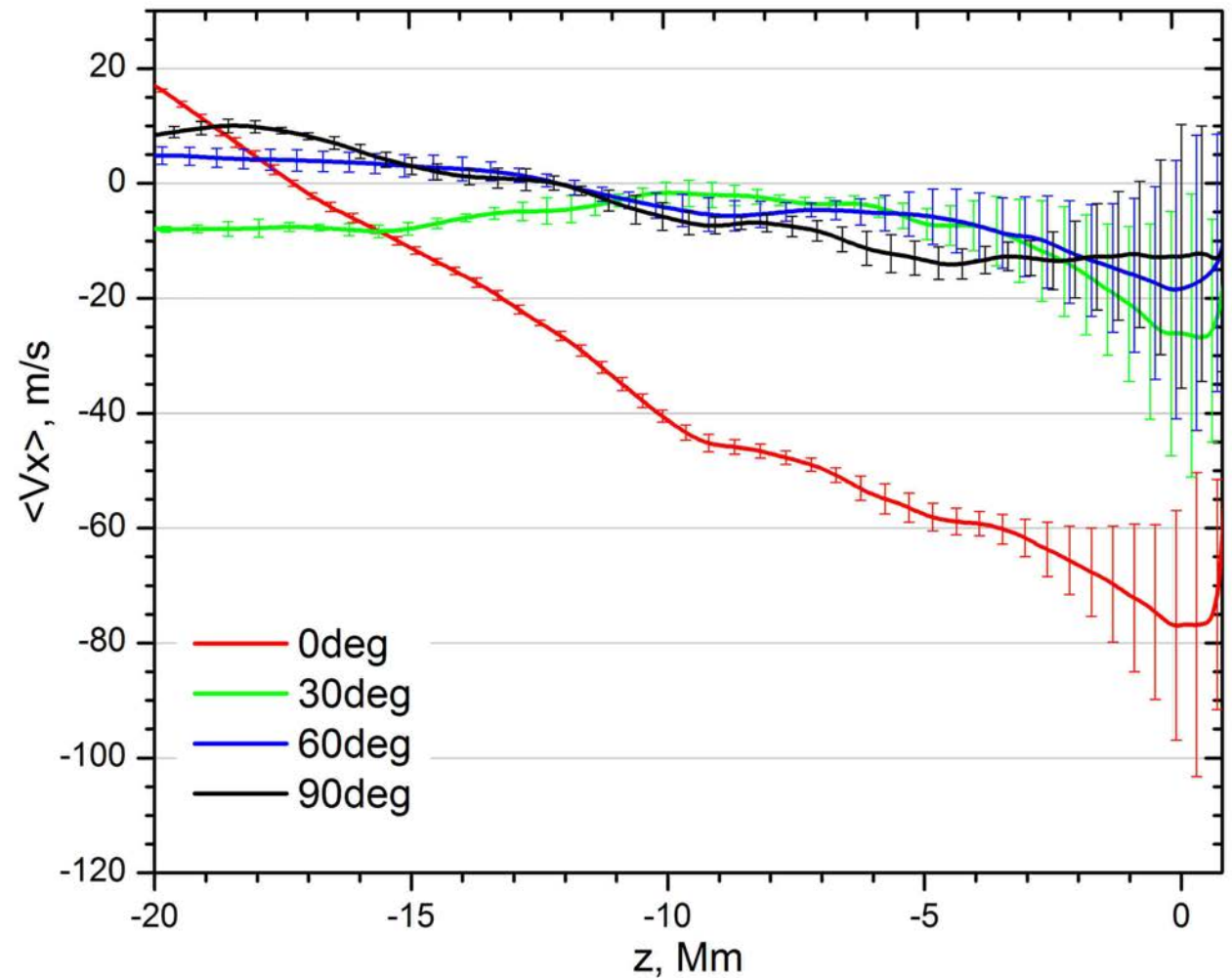
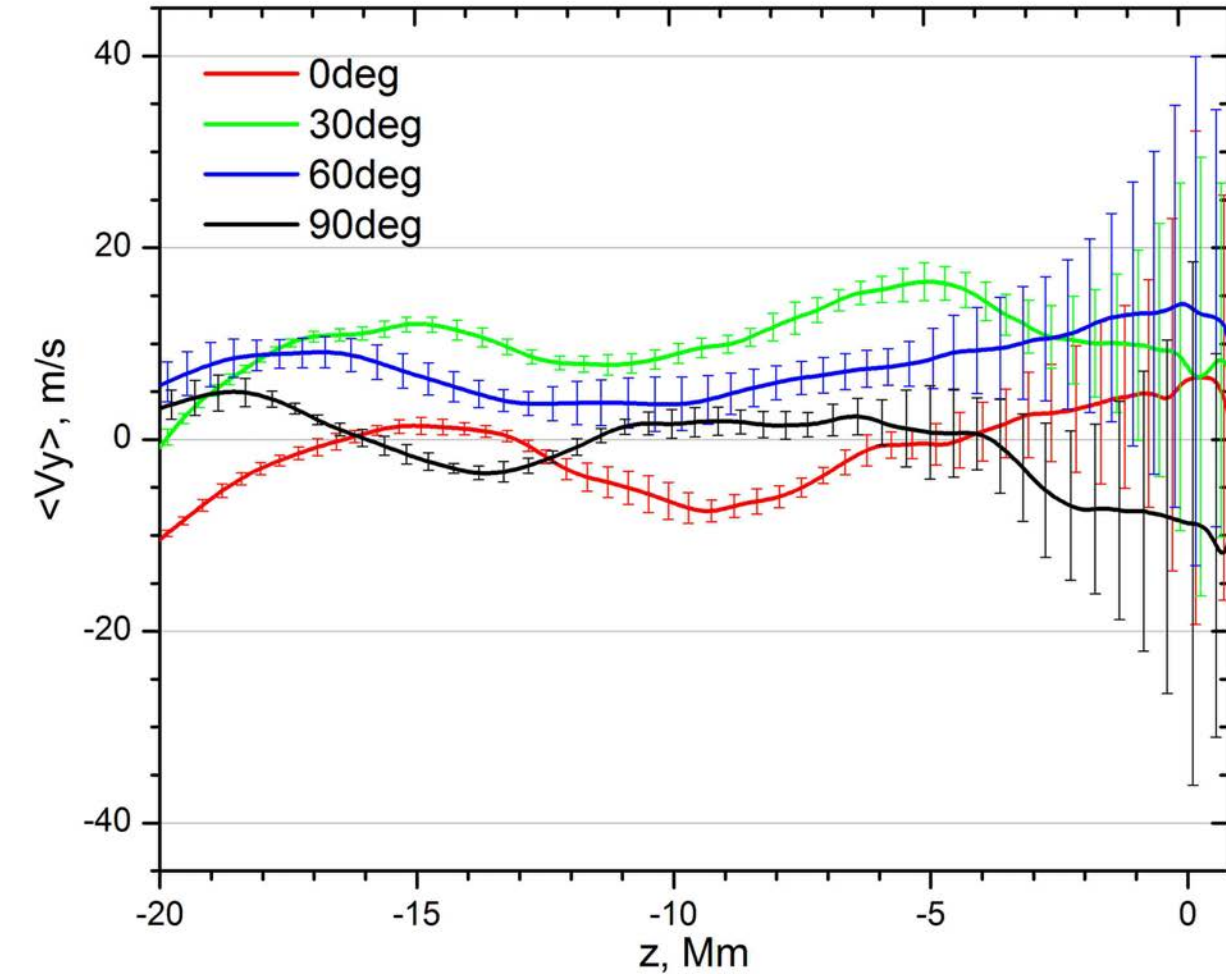
Effect of the Coriolis force on Thermodynamic Structure of Subsurface Flows



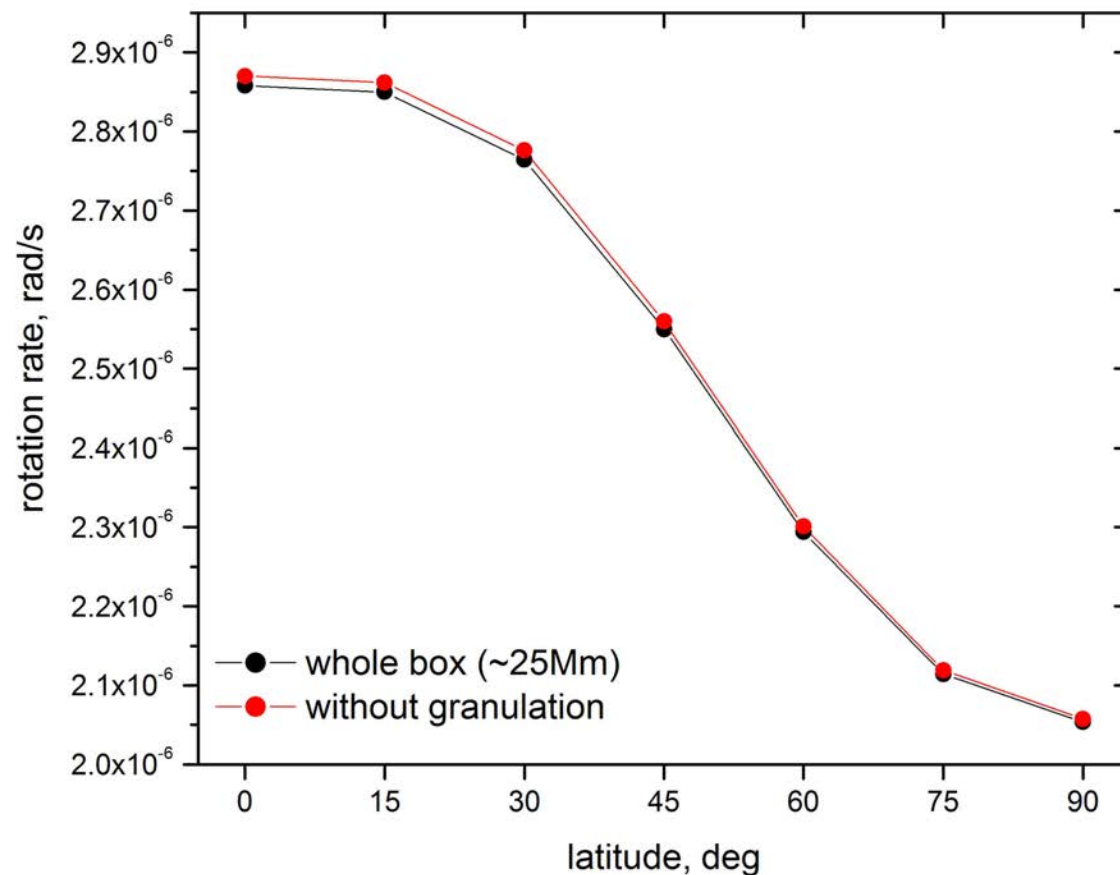
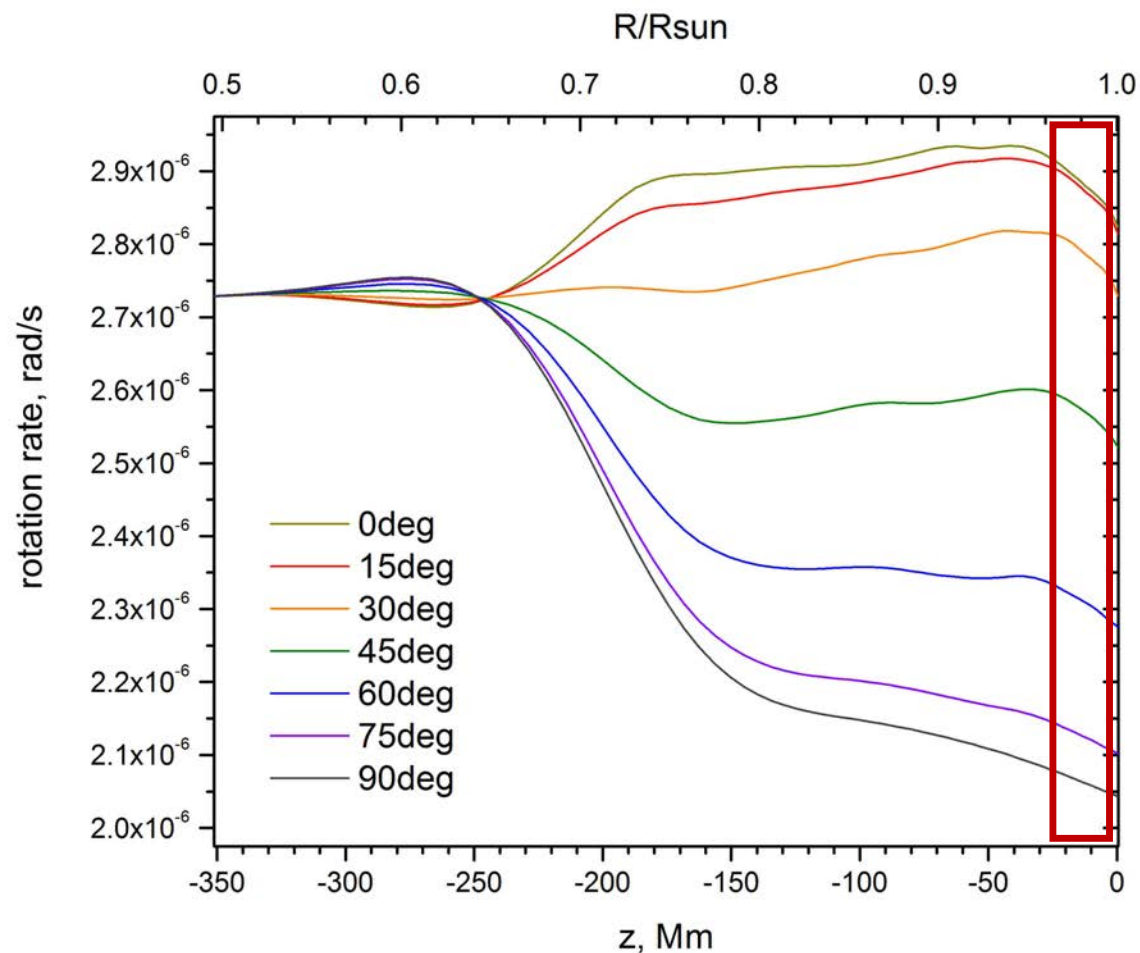
Effect of the Coriolis force on subsurface flows



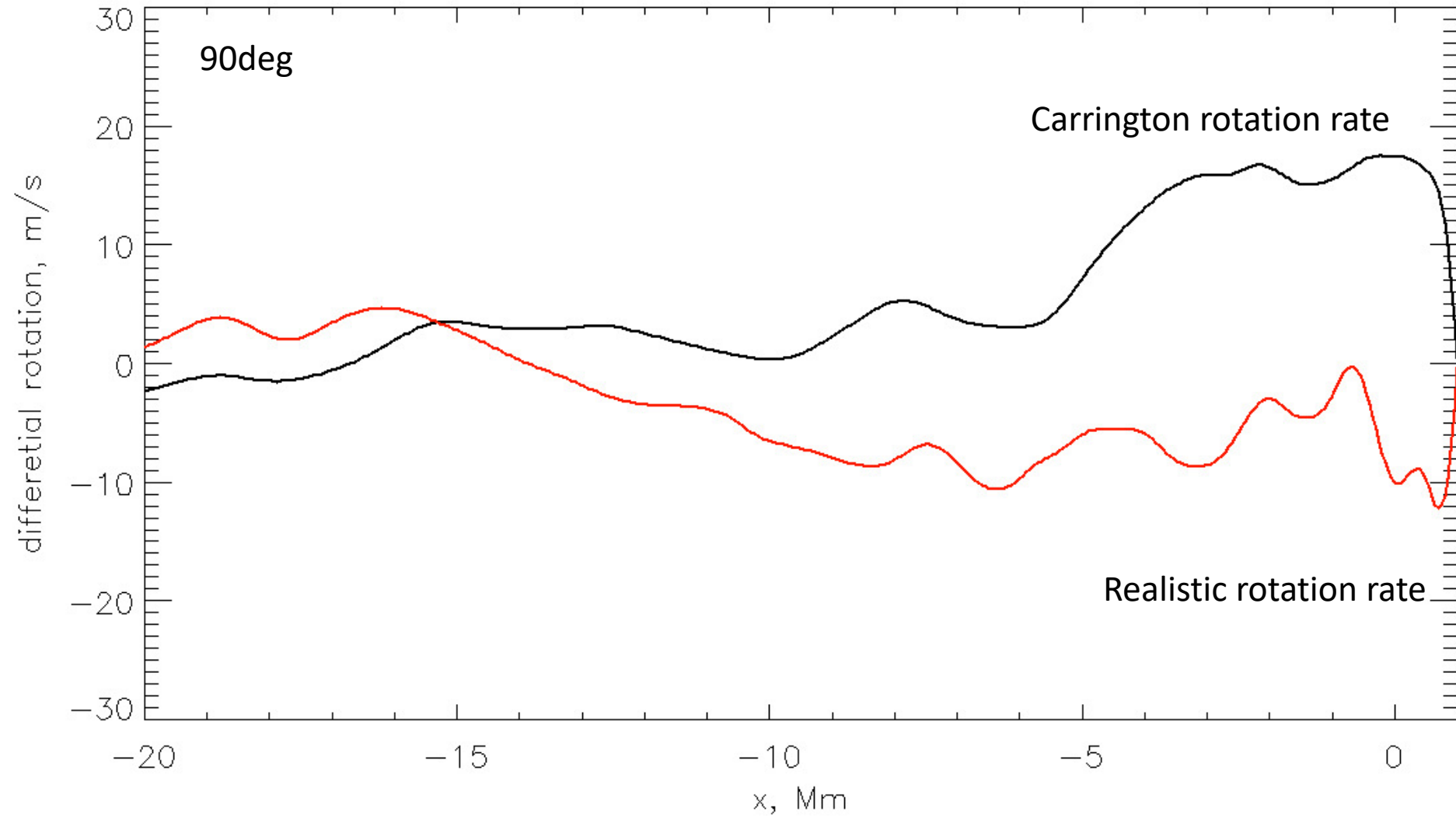
Effect of the Coriolis Force on the Meridional Flows and Differential Rotation



Global Helioseismic Inferences of the Solar Differential Rotation



Differential Rotation: Northern Pole



Conclusions

- ❖ The simulations reveal the development of radial differential rotation and formation of a shallow ~ 10 Mm-deep substructure of the Near-Surface Shear Layer – the leptocline – associated with a steep radial gradient of the angular velocity, changes in the thermodynamic and structural properties of the convection, and the bottom of the hydrogen ionization zone.
- ❖ The leptocline constitutes the upper part of the Near-Surface Shear Layer. The interface between the leptocline and deeper layers is characterized by overshooting downdrafts, which may intensify the turbulent mixing below the leptocline layer.
- ❖ Our results show that the Near-Surface Shear Layer is not uniform with a constant rotational gradient, but it has an important shallow substructure – the leptocline.
- ❖ The self-formed meridional flows are characterized by poleward mean motions near the photosphere and weak reverse flows at depths of 5 – 10 Mm. The bottom of the reverse flows corresponds to the bottom of the leptocline layer and the hydrogen ionization zone. This structure resembles a double-cell meridional circulation previously found on the whole-convection-zone scale.
- ❖ The Coriolis force effect is most noticeable mainly below the leptocline, where the Rossby number decreases significantly compared to the near-surface layers.

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