Investigating the Role of Diffusivities in Solar Convection Modeling

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KEY POINTS:

- **We simulate several sets of non-rotating, solar-like convection zones with varying functional forms of the thermal and momentum diffusivity that are routinely used to represent the effects of subgrid scale motion.**
- **Regardless of the functional form employed the diffusivity profiles, all systems achieve a 'free-fall' scaling in which diffusive effects are subdominant**
- **We find that alternative formulations of diffusivity lead to different distributions of turbulence in depth throughout the shell.**

Motivation

- Convection is pervasive in stellar interiors and is integral to the generation of stellar dynamos.[1]
- Our current understanding of the underlying processes deep in the solar convection zone (CZ) is from numerical models.
- Many numerical models employ various functional forms for the viscosity and thermal diffusivity[2],[3]

How does changing the form of diffusivities affect our solar convection models?

Numerical Model

This work was performed using the **Rayleigh**[4] code. This code solves the anelastic MHD equations in a rotating spherical shell. Each model employs a polytropic background state that corresponds closely to solar models. For all simulations performed **ν = κ** where $\nu(r) = \nu_{top}\left(\frac{\rho}{\rho_{top}}\right)^{n}$ for n = 0, -0.5, -1. The domain of the simulations span from the base of the convection zone (CZ) to 0.97R$_\odot$, with density varying by a factor of 55 between the upper and lower CZ.

Reynolds Number

$$Re = \frac{\text{Viscous Time}}{\text{Advective Time}}$$

How turbulent is the system?

Flux Rayleigh Number

$$Ra_F = \frac{\text{Thermal Diffusion Time} * \text{Viscous Time}}{(\text{Free Fall Time})^2}$$

How strong is the thermal forcing?

The free-fall limit occurs when inertia balances buoyancy which leads to the scaling,

$$Re \sim Ra_F^{1/3}$$

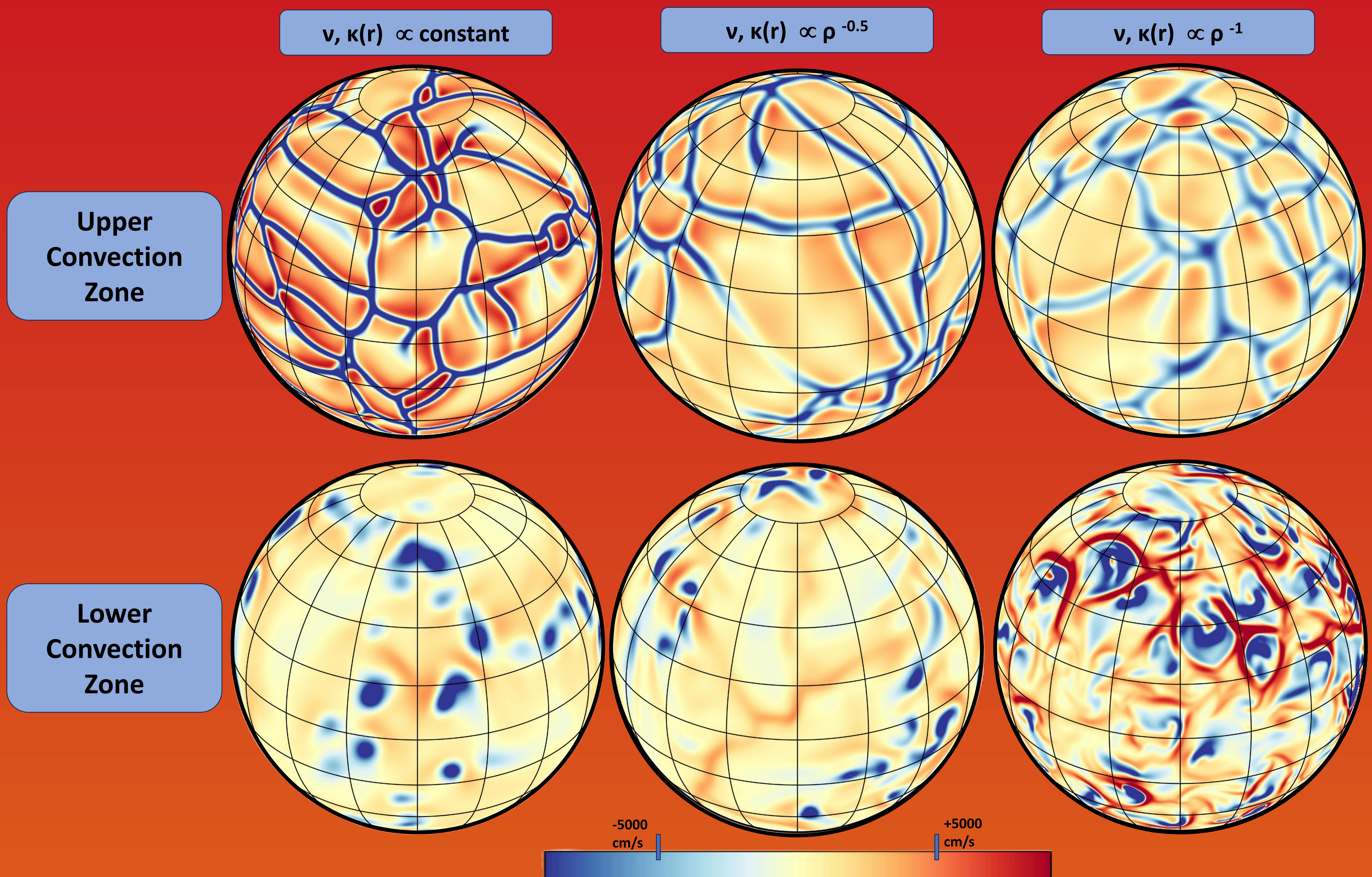

Figure 1. Shown are radial velocity profiles realized under three different prescriptions for the diffusivity. For constant diffusivity, the system is more turbulent near the top of the shell but for variable diffusivity the turbulence is concentrated at the bottom of the shell despite how similar each model scales.

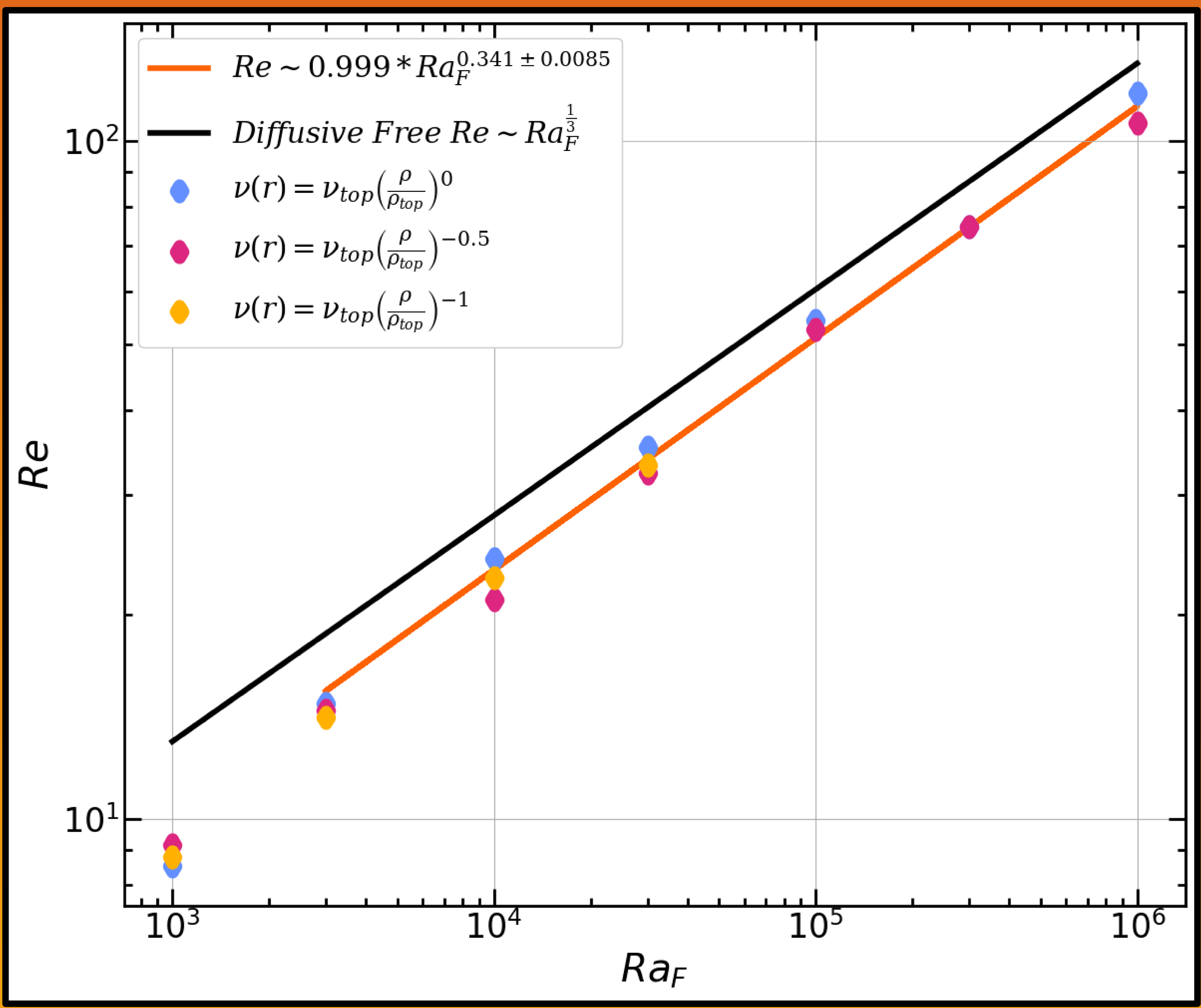

Figure 2. Reynolds number as a function of the Flux Rayleigh number for 18 different cases. The orange line indicates a fit to all the data with $Ra_F > 10^3$. The black line is a reference line that indicates the 'free-fall' scaling between Re and Ra_F which closely matches the slope of our data.

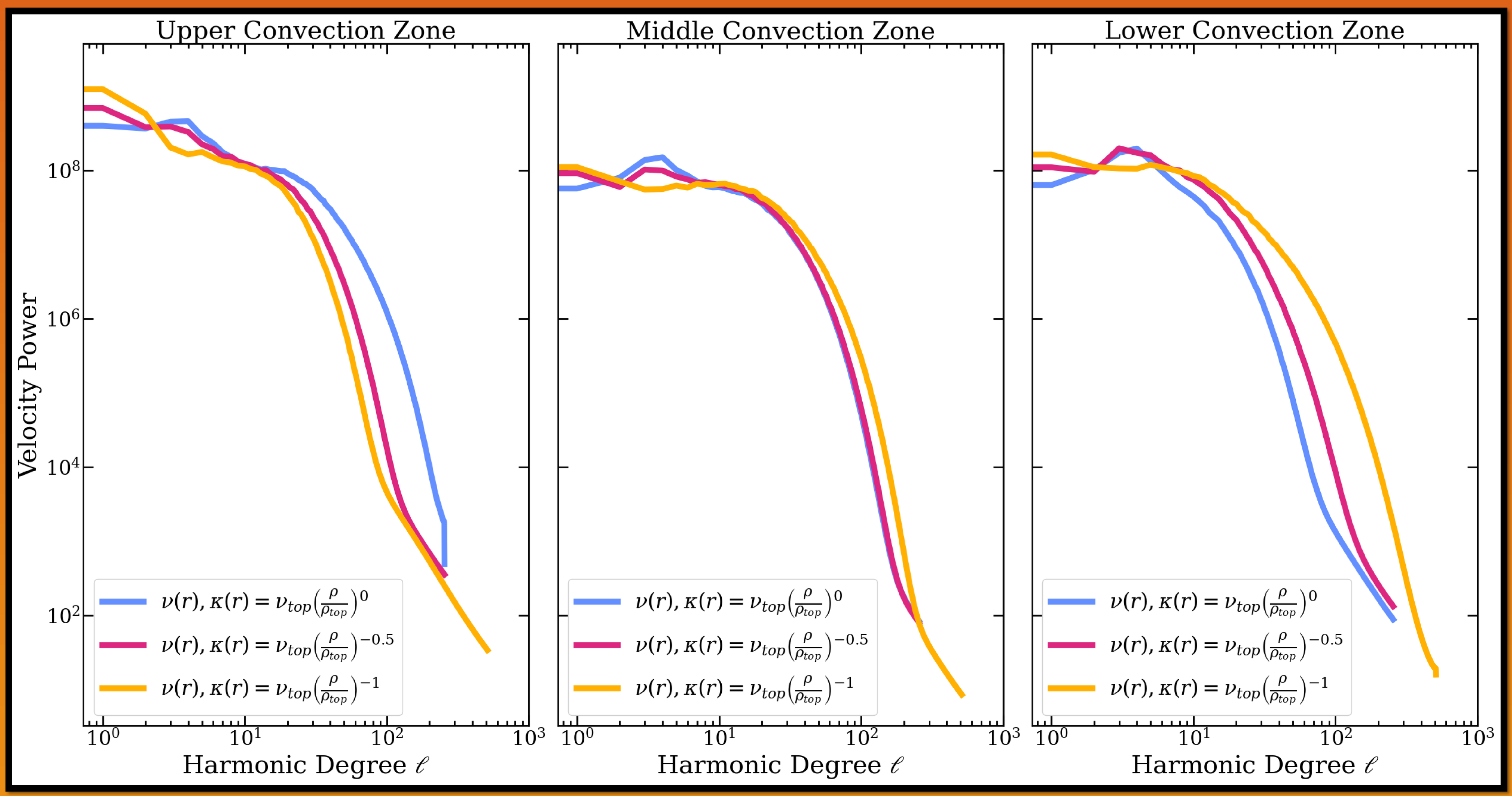

Figure 3 Time averaged velocity power spectra for 3 regions inside our simulations: The upper convection zone, middle convection zone, and lower convection zone (from left to right). For constant diffusivity there is more small-scale power at the top of the shell rather than at the bottom of the shell for the variable diffusivities.

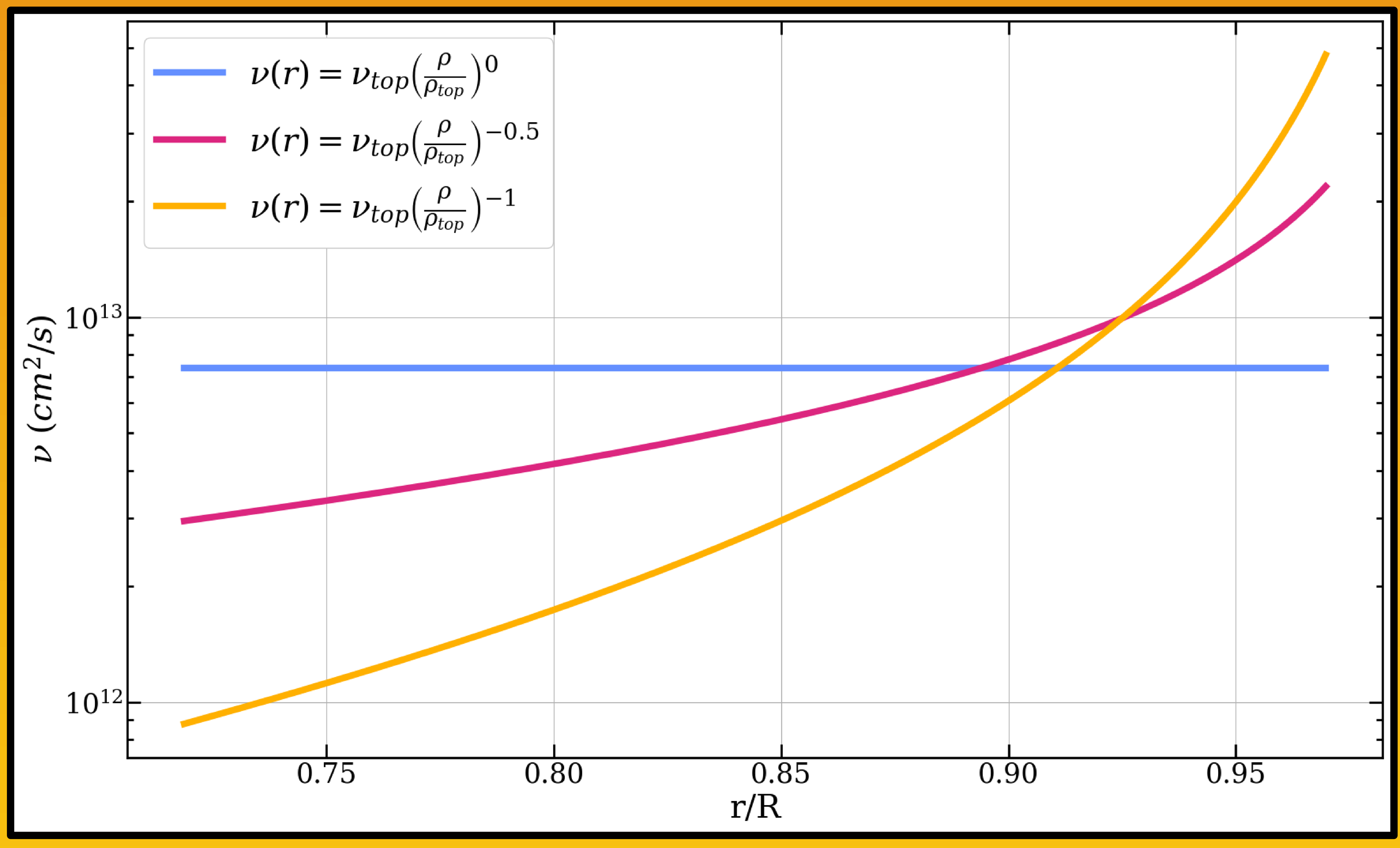

Figure 4. The viscosity (and thermal diffusivity) as a function of radius in our simulations. Each curve represents a different functional form employed in the three sets of simulations performed.

Conclusion and Future Work

- We find that regardless of the functional form of viscosity or thermal diffusivity, the Reynolds number scales with the Rayleigh number scale in a similar manner for all simulations.
- While each set of simulations scale similarly, the result of different diffusivity leads to varying flow patterns based on how viscosity varies with depth leading to different signatures within the velocity spectra.
- Further work will explore rotating cases and magnetism.

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