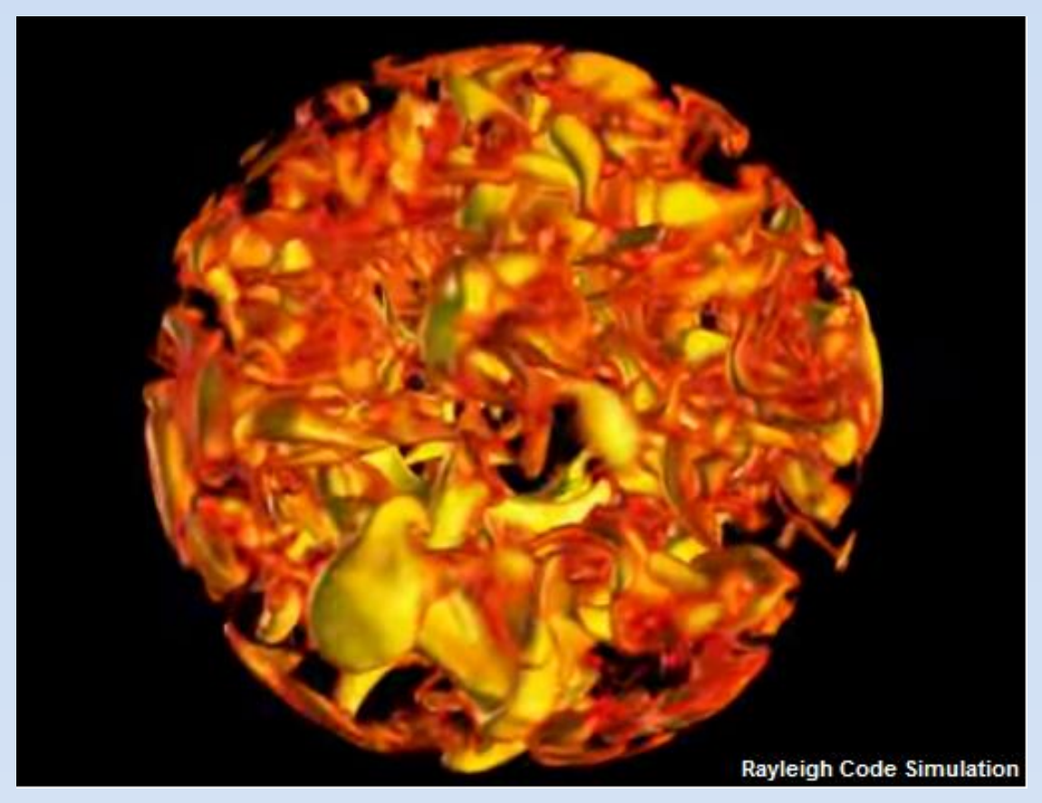
Examining the Impact of Prandtl Number and Heat Transport Models on Convective Amplitudes

Bridget O’Mara*, Kyle Augustson, Nicholas Featherstone, Mark Miesch
Regis University* 3333 Regis Blvd. Denver, CO 80221
HAO, Boulder, CO

Abstract


Rayleigh Code Simulation

Turbulent motions within the solar convection zone play a central role in the generation and maintenance of the Sun's magnetic field. This magnetic field reverses its polarity every 11 years and serves as the source of powerful space weather events, such as solar flares and coronal mass ejections, which can directly affect artificial satellites and power grids. The structure and inductive properties are linked to the amplitude (i.e speed) of convective motion. Using the NASA Pleiades supercomputer, a 3D fluids code simulates these processes by evolving the Navier-Stokes equations in time and under an anelastic constraint. This code imitates the fluxes describing heat transport in the sun. The theories behind the radiative, entropy, and kinetic energy flux have been well established, yet past models simulating the conductive and granulation fluxes have not produced results matching observations from the sun. New models implement a revised granulation flux at the sun’s surface. Results comparing the behavior of convection with and without the new model will be presented, as well as the behavior of convection with a varying prandtl number.

Motivation

- Convection is a fundamental process that occurs often and regularly in everyday life
- The convection in the sun contributes to the generation of magnetic fields, which cause space weather events such as CMEs and Solar Flares
- Recent observational and modeling results suggest that an overestimation of the convective amplitude

Background

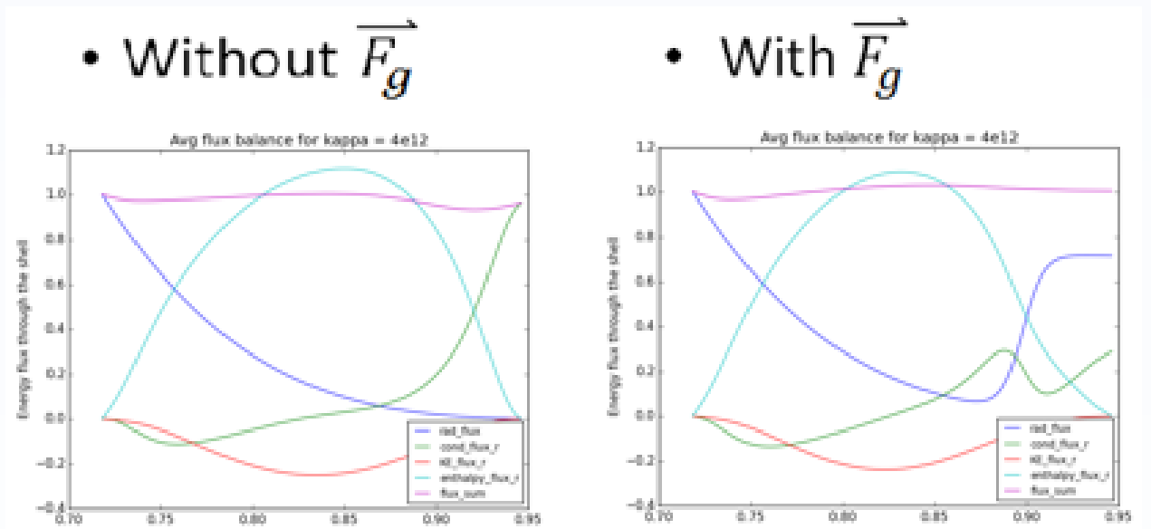
- Previous models of surface convection use the following conservation of energy equation:

$$\frac{\partial E}{\partial t} = -\nabla \cdot \left(\overrightarrow{F_{rad}} + \overrightarrow{F_e} + \overrightarrow{F_k} + \overrightarrow{F_{cond}}\right)$$

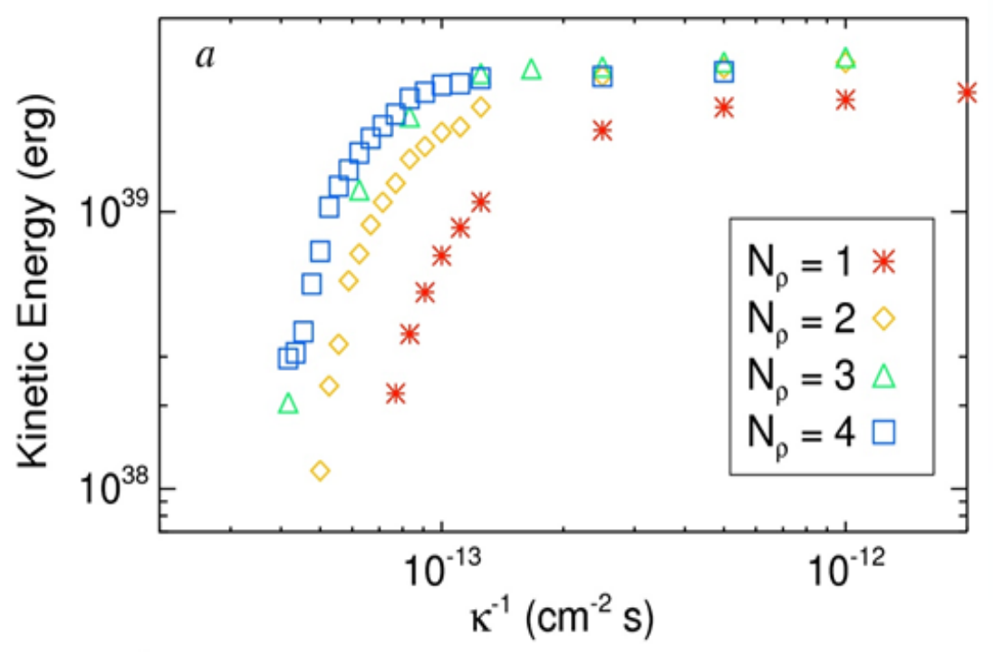
- In this model, $\overrightarrow{F_{cond}} \propto -\kappa \frac{dS}{dr}$, where

$\kappa = thermal\ diffusivity$, $(\kappa_{sun} \sim 10^7, \kappa_{model} \sim 10^{12})$

- As κ decreases, v_{rms} increases, and no longer matches observations of the sun
- A new model replaces $\overrightarrow{F_{cond}}$ with $\overrightarrow{F_g} + \overrightarrow{F_{cond}}$ as flux representing the small scale surface convection on the sun (where $\overrightarrow{F_g} = granulation\ flux$)
- Advantage: $\overrightarrow{F_g}$ $is\ not\ proportional\ to\ -\kappa \frac{dS}{dr}$, so we can decrease κ without raising v_{rms}



- We run tests with a decreasing κ for both models and observe the differences
- Generally, we expect to see increasing v_{rms} and kinetic energy (KE) with decreasing κ

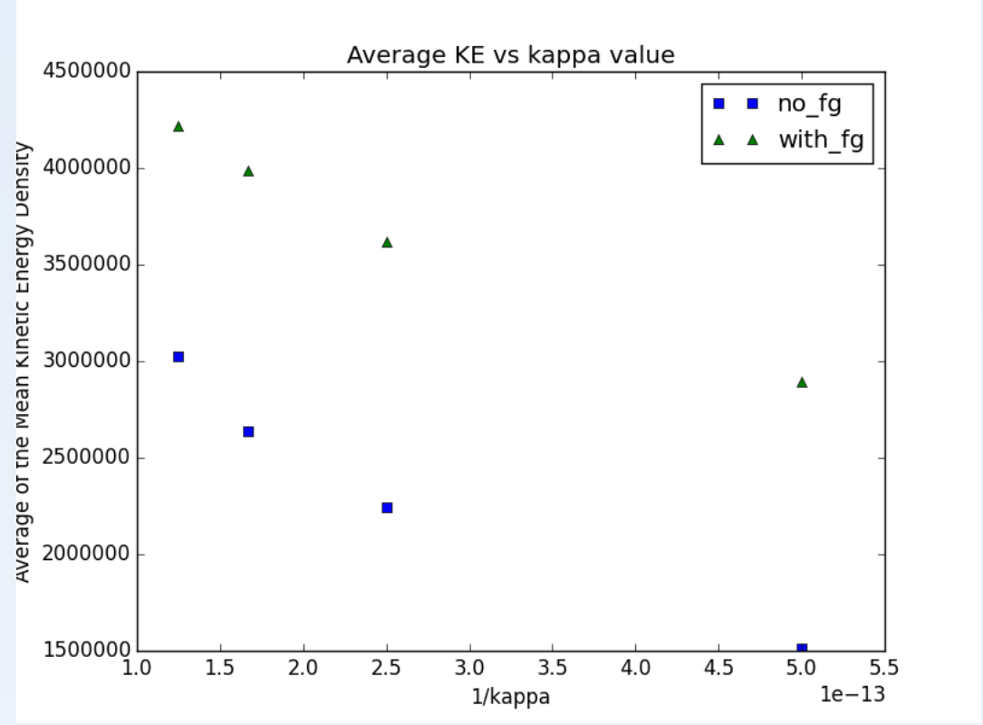


Methods

- Using the NASA’s Pleiades supercomputer, we solve the Navier Stokes equations in time under an anelastic constraint to model the small scale convection ($\overrightarrow{F_{cond}}$ for old model, $\overrightarrow{F_g} + \overrightarrow{F_{cond}}$ for new model)
- Navier Stokes equations:
  - Based on the conservation of mass, momentum, and energy equations
- Anelastic constraint:
  - $\nabla \cdot (\hat{\rho}\vec{v}) = 0$
- The output is used to analyze the convective amplitude and structure and the heat transport by convection

Initial Results

- KE decreases with decreasing κ
- Not expected…



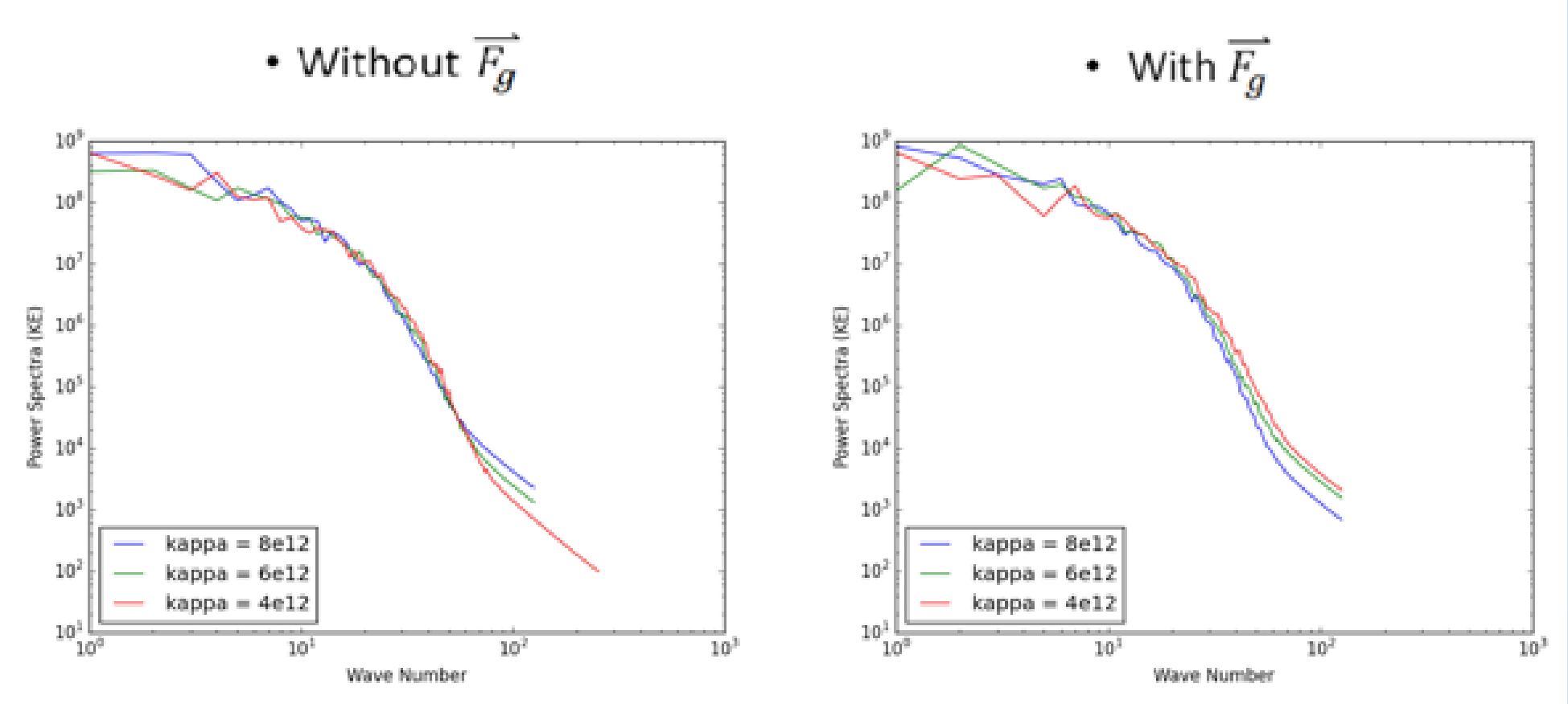
Prandtl Number Tests

- To understand the decrease in KE we look at the Prandtl number
- The Prandtl number equals the ratio between viscous and thermal diffusivity

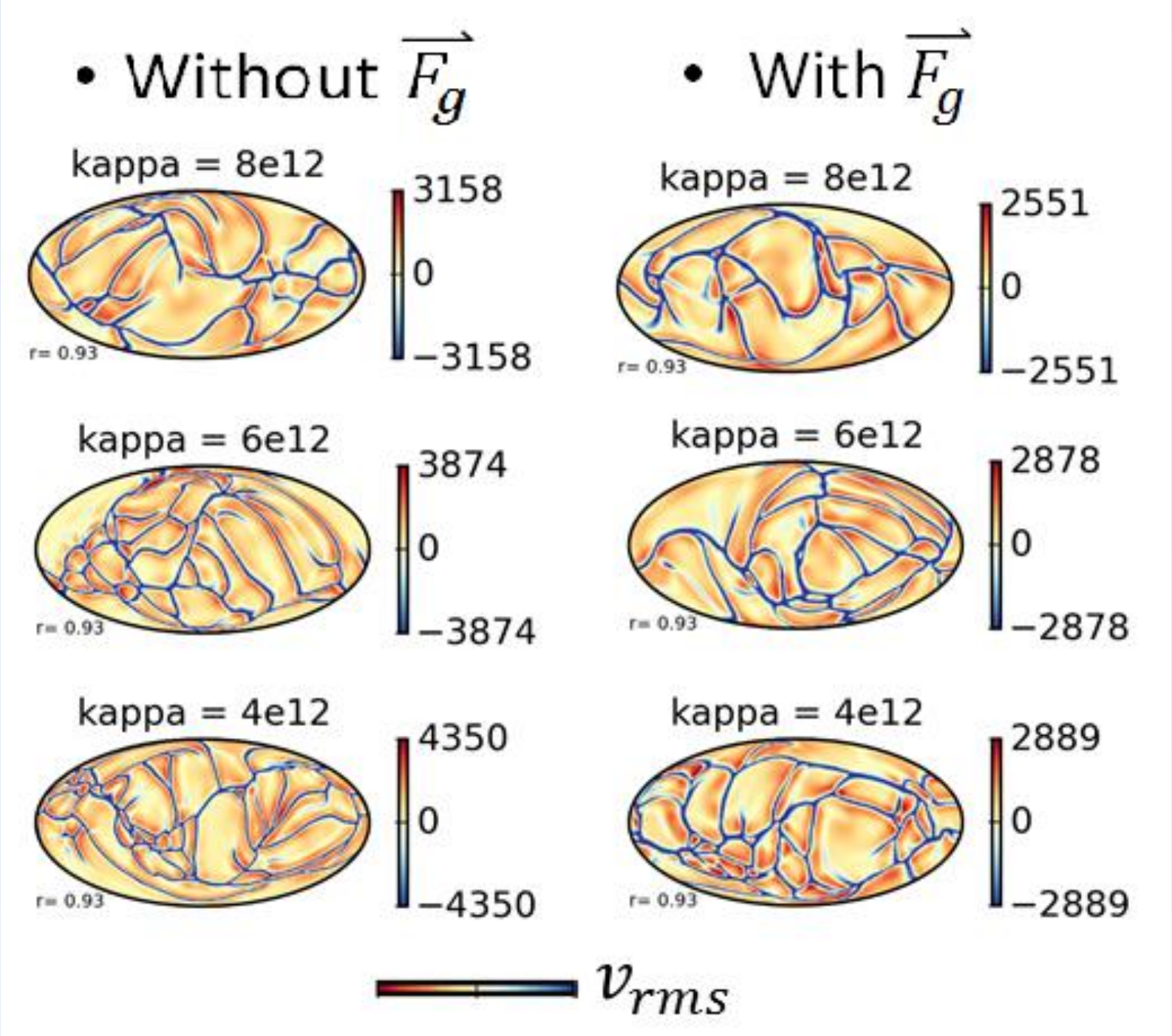
$$P_r = \frac{\nu\ (viscous)}{\kappa\ (thermal)}$$

- We run tests to see the differences between a changing and constant P_r
- For changing values, ν is constant as κ changes
- For constant values, $\nu = \kappa$ (so $P_r = 1$)

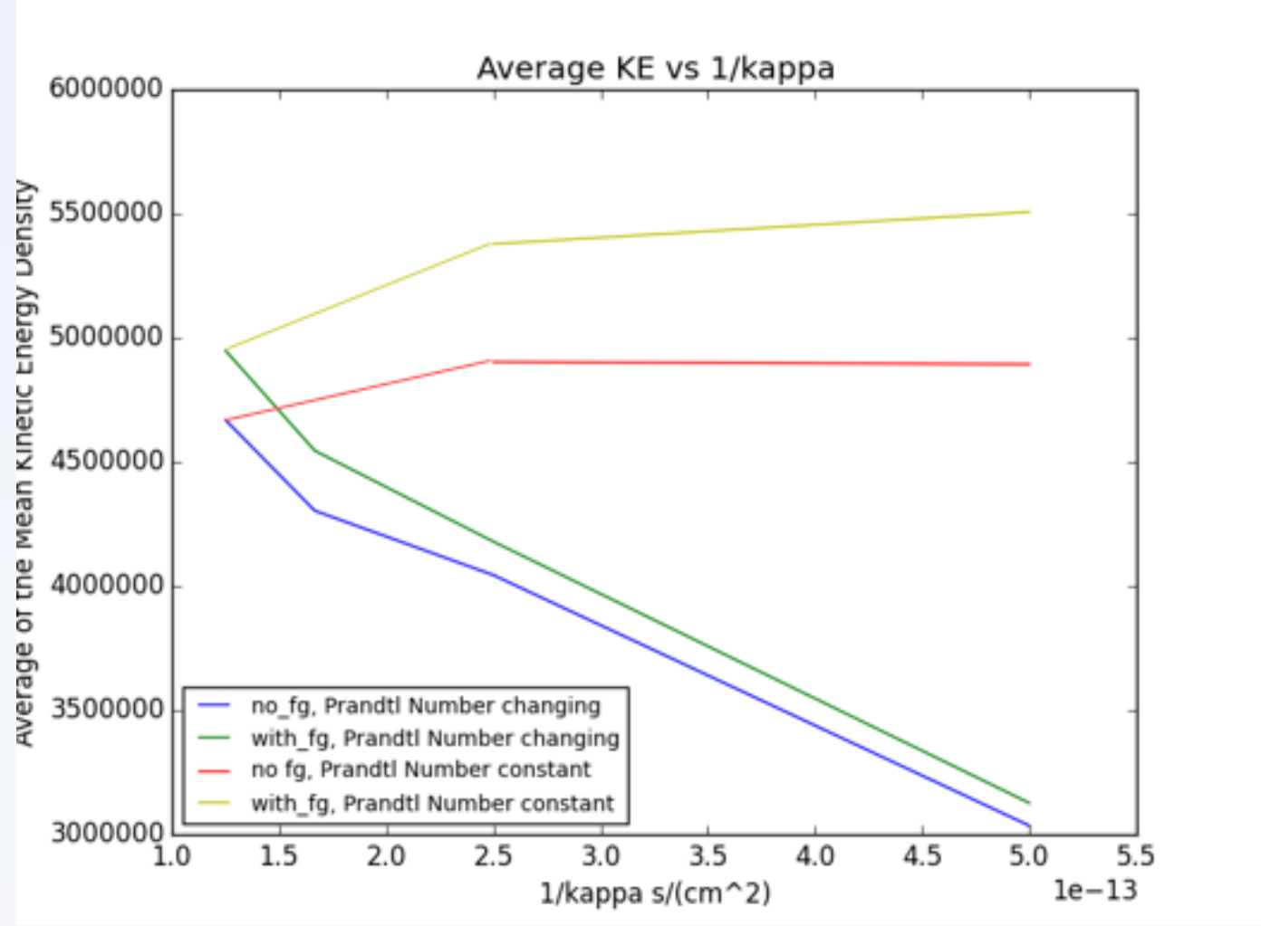
Results

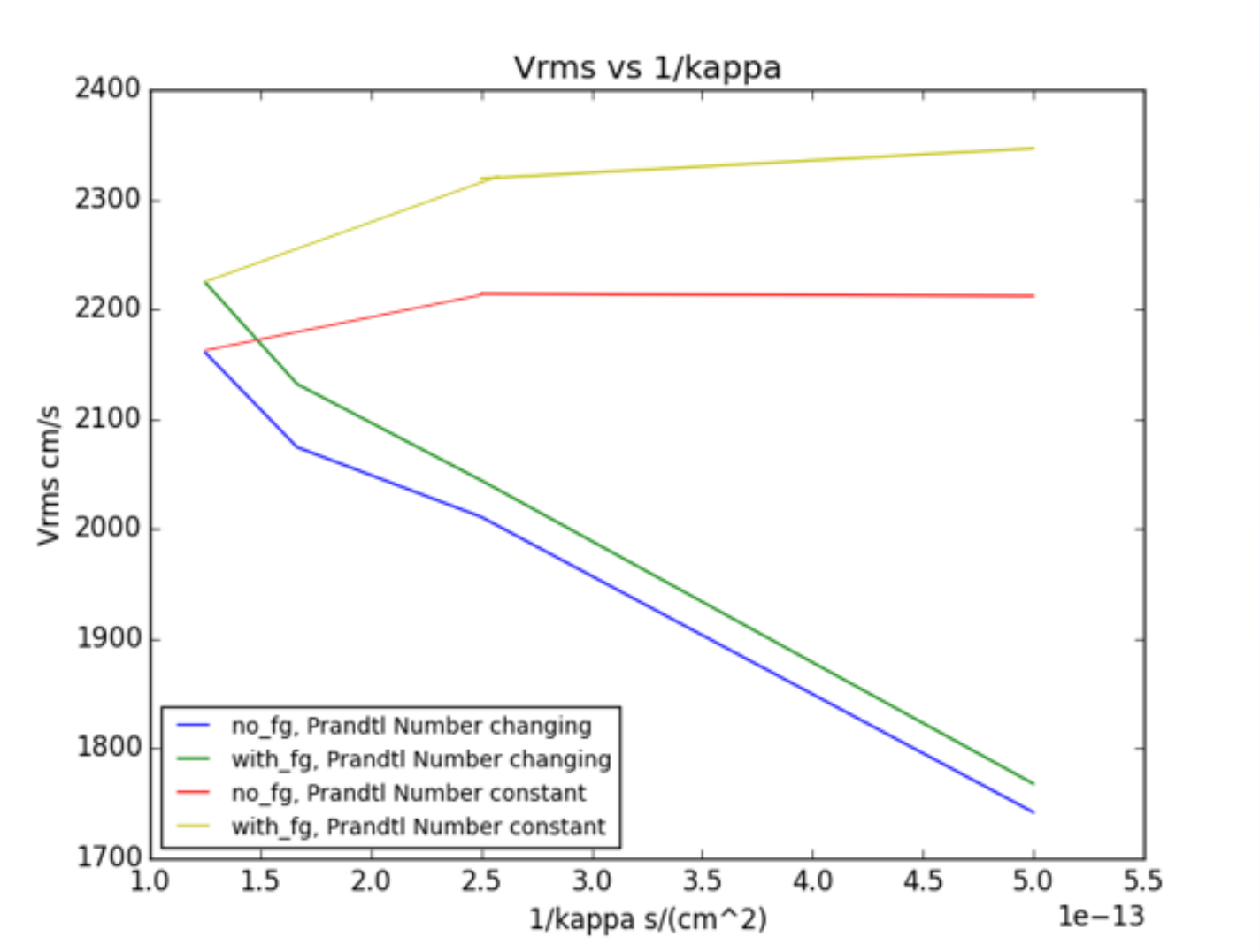


- Spectra graphs for both models show similar trends



- v_{rms} and convective structure show similar behavior with decreasing κ in both models





- KE and v_{rms} increase with constant P_r
- KE and v_{rms} decrease with changing P_r

Conclusion

- The structure and amplitude of deep convection is similar for both models of surface convection considered (conduction and fixed-flux)
  - Suggests that deep convection is not very sensitive to the details of the surface convection
- The Prandtl number makes a big difference on the convective amplitude!
  - As κ is decreased, holding P_r constant, v_{rms} increases
  - As κ is decreased, holding ν constant (increasing P_r), v_{rms} decreases! (surprise!)
  - The second situation (increasing P_r) is very promising because v_{rms} in current convection simulations might be too big and the real κ of the Sun is very small

Next Steps

Testing the following Hypothesis:

- $T'\ in\ the\ middle\ of\ the\ convection\ zone, increases\ as\ you\ decrease\ \kappa$.
- Where $\overrightarrow{F_e} \propto v_{rms}T' \approx F_\odot$
- If true, explains decreasing v_{rms} with increasing Prandtl number

Acknowledgements

Thanks to the NSF REU program, LASP and HAO, and a special thanks to Erin Wood and Marty Snow