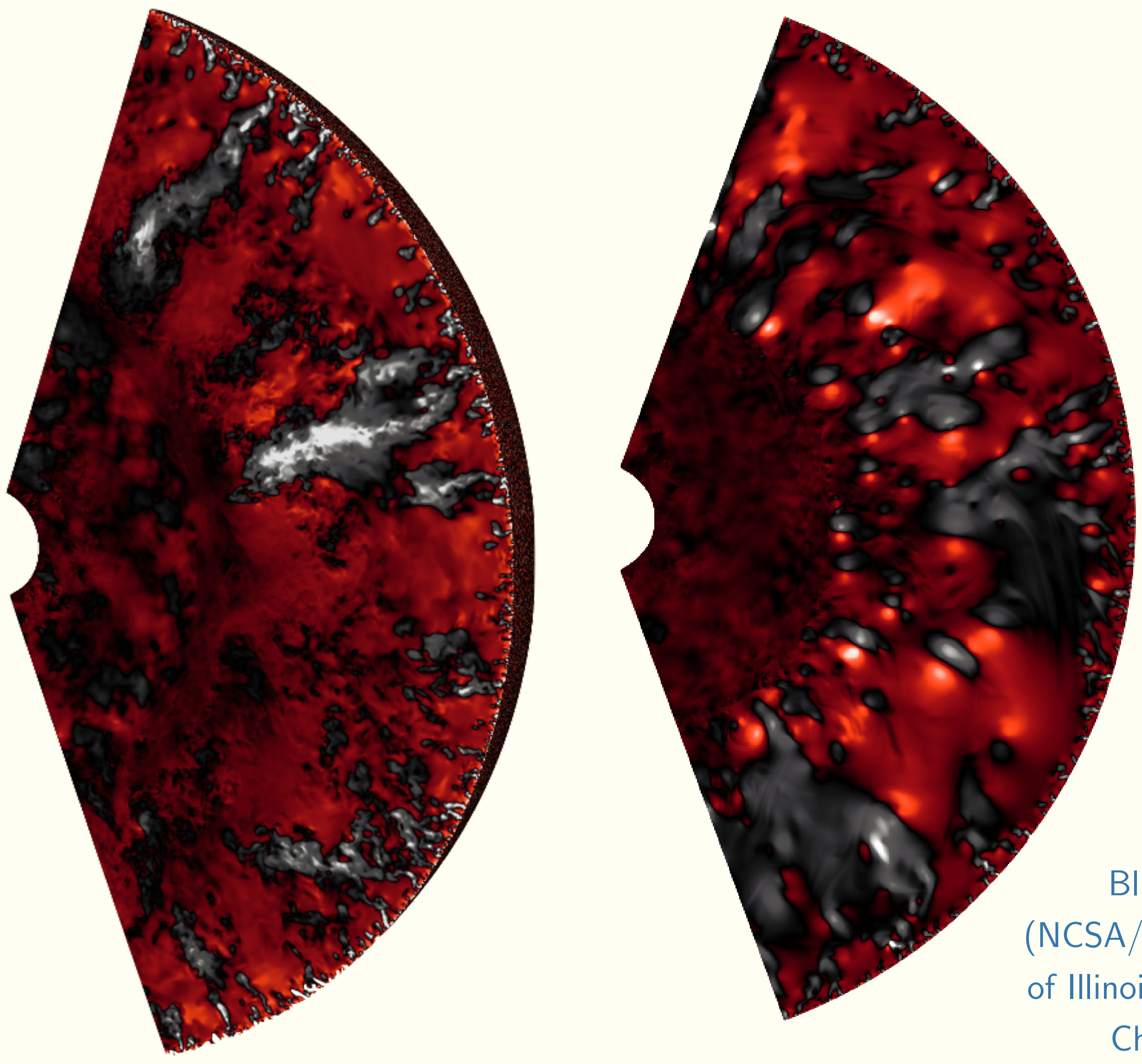
A comparison of the filling factor in hydrodynamic simulations of pre-main-sequence stars

Mary Geer Dethero (GSU), Jane Pratt (GSU), Isabelle Baraffe (Exeter), and the MUSIC Team



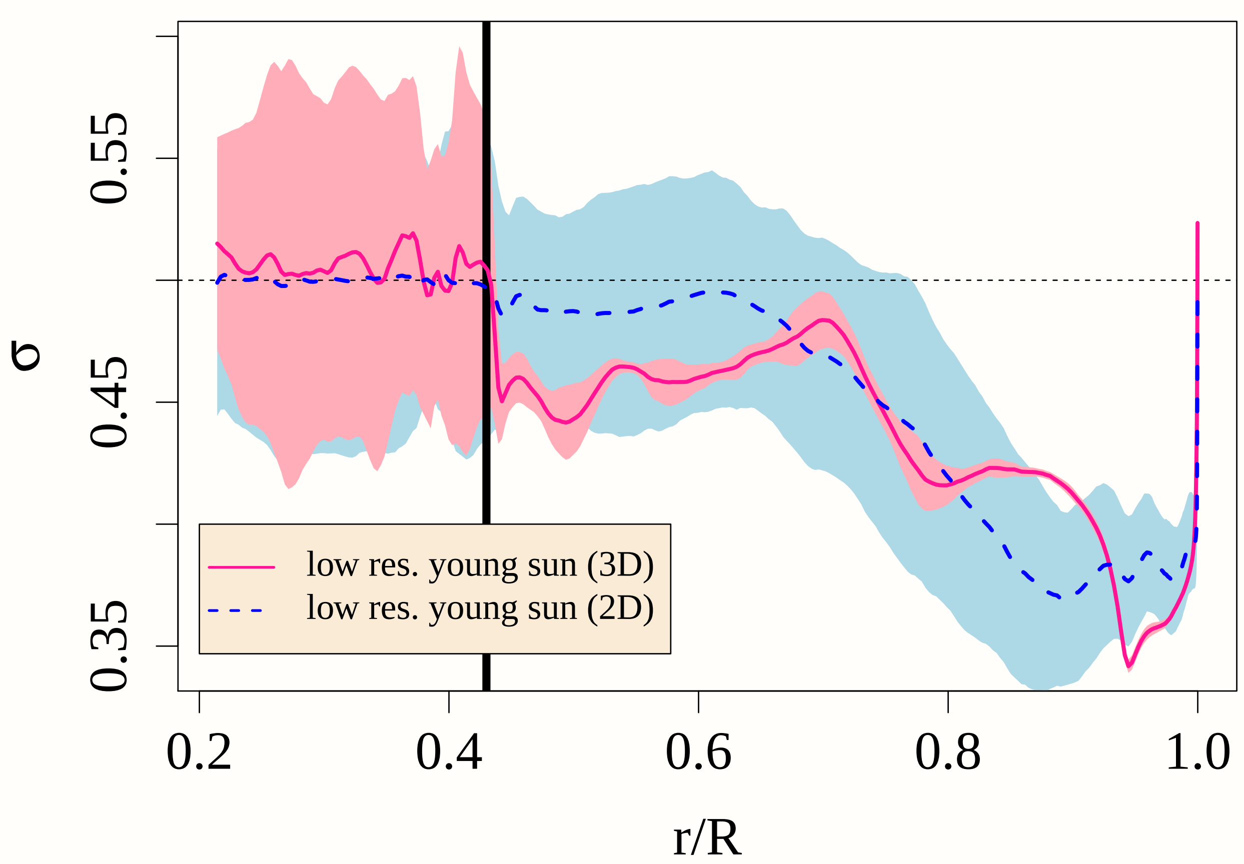
Run on Blue Waters (NCSA/University of Illinois Urbana-Champaign)

Radial velocity in 3D (left) and 2D (right) hydrodynamic simulations of a pre-main-sequence star.

Motivation

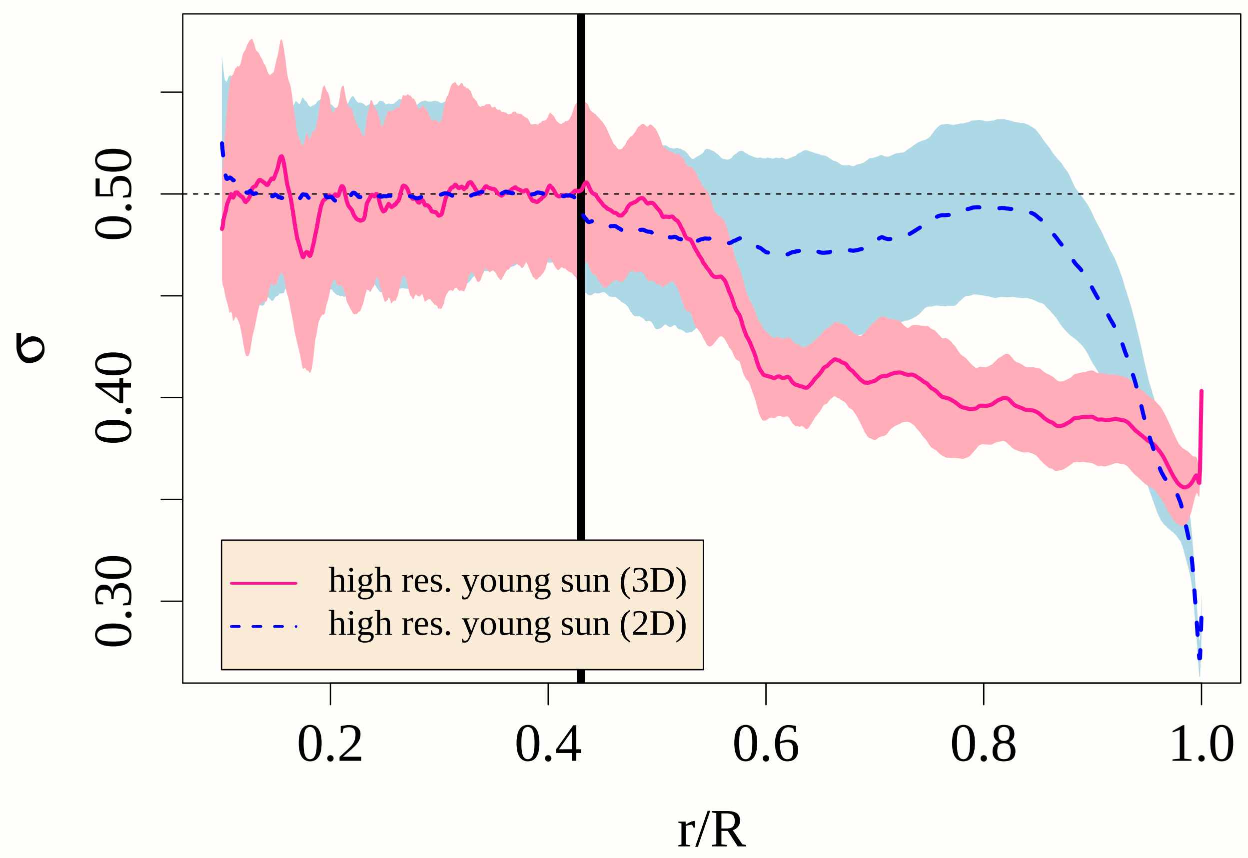
- Convective overshooting may depend on the shape, size, number, and geometrical structure of plumes that reach the boundary of the convectively unstable region.
- These properties are expressed in a basic way in the *filling factor* (defined in Zahn A&A 1991, Canuto & Dubovikov ApJ 1998).
- We define a simple filling factor $\sigma(r)$ as the volume at depth r occupied by plumes moving radially inward, divided by the total volume at depth r.
- We produce realistic, hydrodynamic simulations of a pre-main sequence star, called "the young sun", using the `MUSIC` code (for details of these simulations, see Pratt et al. A&A 2016,2017,2020).
- **Questions: How does the filling factor change throughout the convection zone? Is this different for stars with different sizes of convection zone, or in different stages of evolution?**

The filling factor in the young sun



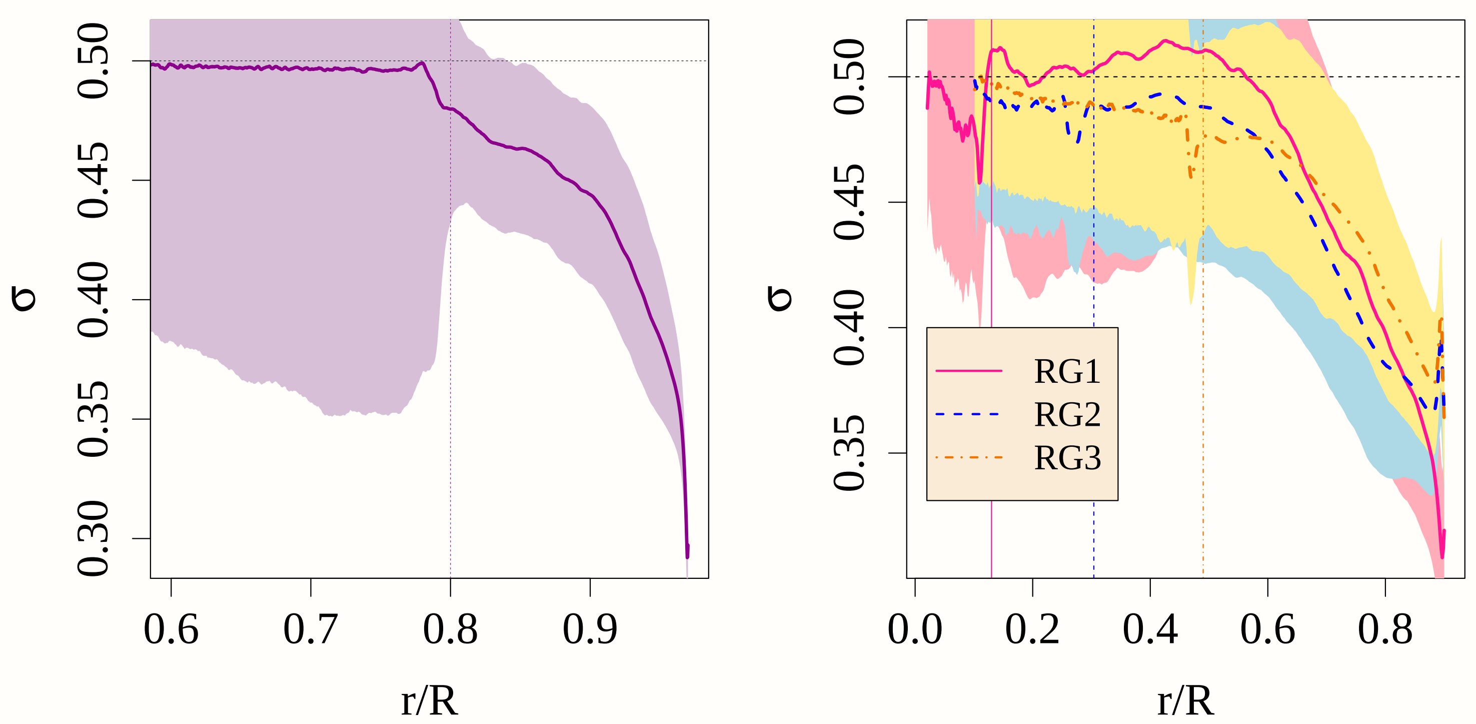
- We compare the filling factors for a 2D and a 3D simulation of the young sun that are identical except for dimensionality.
- The black vertical line indicates the position of the convective boundary in the deep stellar interior. The shaded regions indicate one standard deviation above and below the average lines.
- The statistics represent a much longer time in 2D ($> 100\tau_{\rm conv}$) than in 3D ($\sim 3\tau_{\rm conv}$), but the 3D data is in the range of the 2D data.
- We define resolution for a simulation of global stellar convection using the pressure scale height at the convective boundary $H_{p,\rm CB}$ and the grid spacing in the simulation Δr. Here both simulations have $H_{p,\rm CB}/\Delta r = 72$.

Higher resolution 3D simulation results



- Here we examine simulations of the young sun with a resolution ~ 3.5 times higher at $H_{p,\rm CB}/\Delta r = 258$.
- Again the statistics represent a much longer time in 2D ($> 60\tau_{\rm conv}$) than in 3D ($\sim 4\tau_{\rm conv}$).
- Differences between 2D and 3D simulations exist, but it is not clear that they are statistically significant.
- Near the bottom of the convection zone, the 3D line is well within the range of the 2D data.

Filling factors in main-sequence and post-main-sequence stars



- For comparison we examine the filling factor for (left) a main-sequence star ($2.5M_\odot$, $H_{p,\rm CB}/\Delta r \sim 240$, $40\tau_{\rm conv}$) and 3 stars on the RGB ($3M_\odot$, $H_{p,\rm CB}/\Delta r \sim 55$, $> 70\tau_{\rm conv}$).
- There is a similar drop in the filling factor from the bottom of the convection zone toward the surface of each star.

Summary & Future Work

- This is a preliminary study of the filling factor in realistic simulations of stars.
- We find the (time averaged) filling factor for the inflows is usually less than ~ 0.5, in agreement with the observations of Canuto & Dubovikov (ApJ 1998). This can be violated (see simulation RG1, the red giant with a very deep convection zone).
- Near the surface in our simulations, the filling factor typically approaches 1/3, agreeing with observations of solar surface convection (e.g. Nordlund, Stein, and Asplund LRSP 2009). Resolution of the near-surface dynamics is challenging, and boundary treatment can effect this.
- The filling factor increases toward 1/2 near the bottom of the convection zone.
- These observations appear to apply to stars with convection zones of different size, at different stages of stellar evolution, and regardless of the simulation details such as dimensionality and resolution.
- Similarities between 2D and 3D filling factors at the bottom of the convection zone imply that other aspects of the shape of convective structures may be important for characterizing convective boundary mixing.
- In the future we will look at the filling factor in a broader set of stars, as well as the relationship between the filling factor and the overshooting length.