# Comparison of stellar hydrodynamic codes

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Motivated by the scarcity of verification and validation efforts with the 3D hydrodynamic codes currently used by the community studying the hydrodynamics of stellar interiors, we have decided to compare the outputs of several major codes used in this field. Code verification is typically done by solving a simple problem and comparing the code's output with a known (semi-)analytical solution. We use a problem that does not have any known exact solution but is directly relevant to the current discussion in the field: turbulent convection and convective mass entrainment from a stably stratified layer. The purpose of this study is to provide the community with estimates of code-to-code spread in quantities such as the convective mass entrainment rate, power spectra of the turbulent convection, velocity profiles, fluxes of enthalpy and kinetic energy, or dissipation rates. We already have test runs performed using the codes FLASH, MUSIC, PROMPI, and SLH and partial implementations in the codes CASTRO, MAESTROex, and xRAGE. The codes differ in the discretisation of the Euler equations, time stepping methods and, in the case of MAESTROex, a low-Mach approximation to the Euler equations is used. Most of the implementations have been done by scientists actively using and developing these codes for their own research. This poster is a summary of the project's current status.

## Test problem

- Convection and mass entrainment from a stably-stratified layer.
- Two fluids with mean molecular weights $\mu_0 = 1.848$ and $\mu_1 = 1.802$.
- Ideal gas equation of state with $\gamma = 5/3$.
- No explicit viscosity or heat diffusivity.
- Convection driven by a time-independent heat source at the bottom of the convective layer.
- Solid-wall boundary conditions at the top and bottom, periodic boundary conditions in the horizontal directions (x, z).
- Standard Cartesian grids: $256^3$, $512^3$, (optionally) $1024^3$.

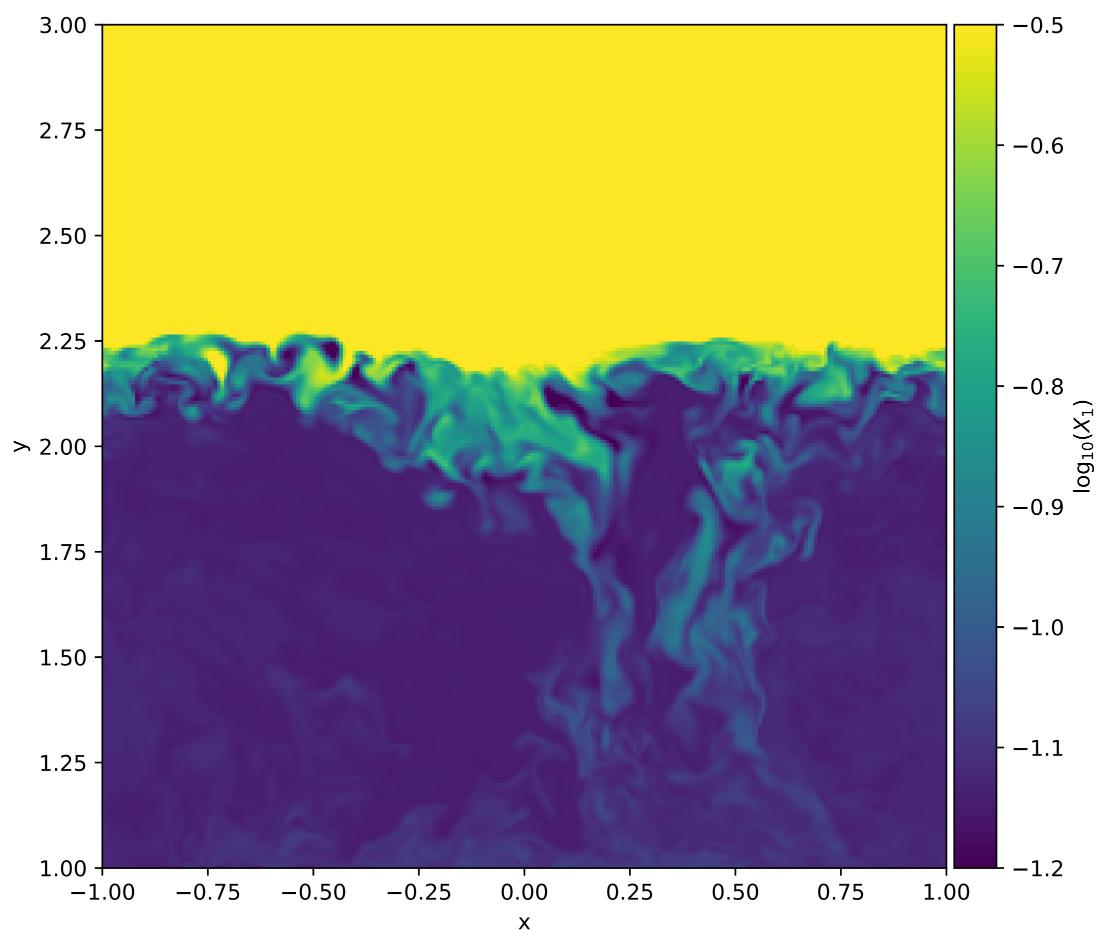


**Fig. 1:** Mass fraction of the lighter fluid initially ocupying the upper half of the domain in a $256^3$ simulation computed with the SLH code. The vertical cross section is visualised approximately 7 convective turnover time scales after the start of the simulation.

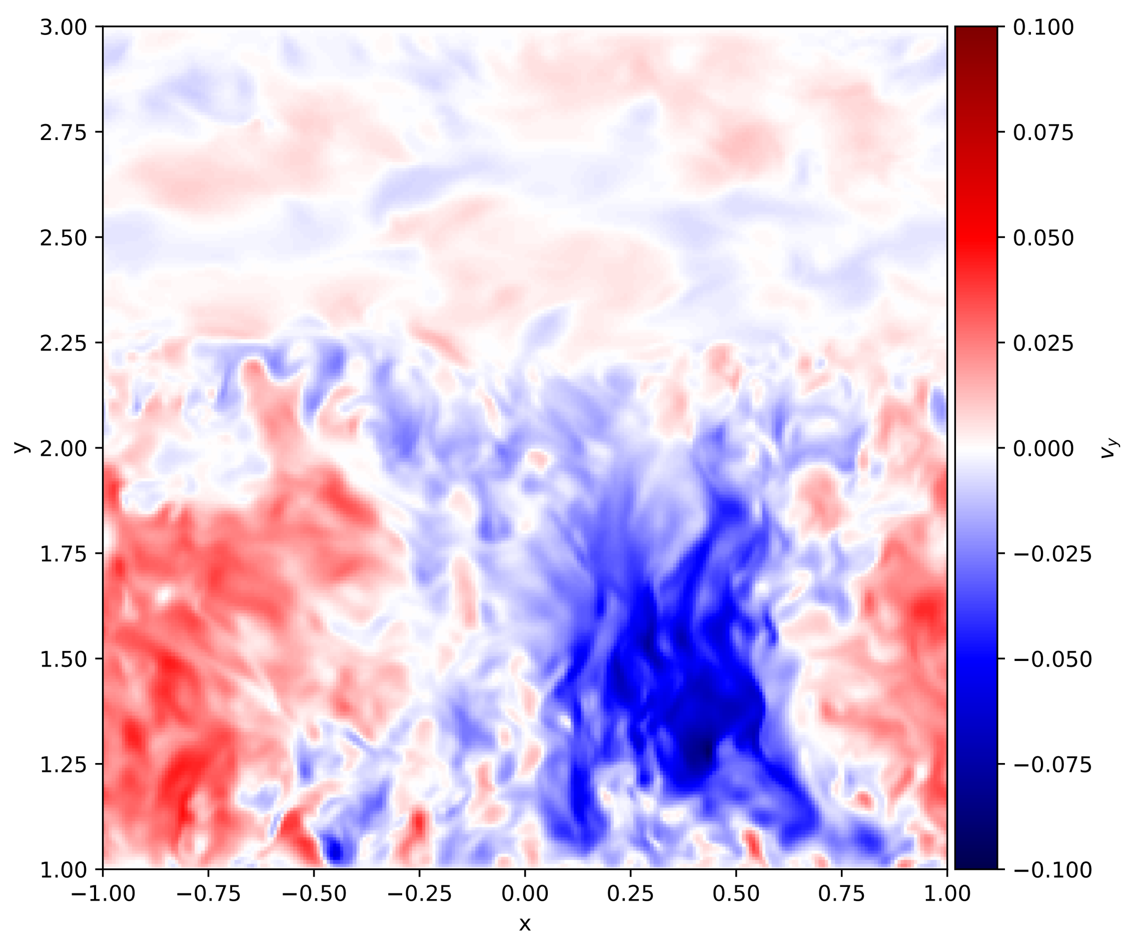


**Fig. 2:** Vertical component of velocity in the same cross section and at the same point in time as in Fig. 1. The relatively slow motions in the stably-stratified layer above $y \sim 2.25$ correspond to internal gravity waves and sound waves.

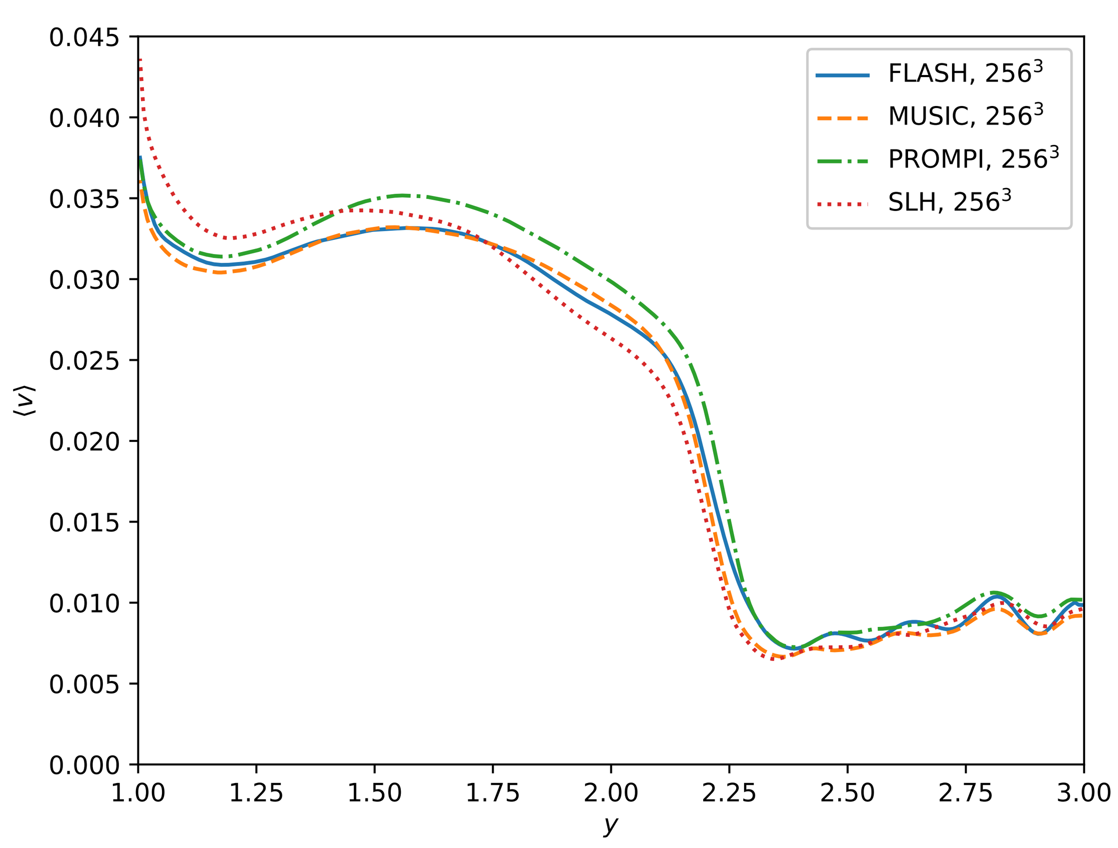


**Fig. 3:** Time- and space-averaged vertical profiles of flow speed extracted from $256^3$ simulations performed with the four codes given in the legend. The drop in velocity close to $y = 2.25$ corresponds to the upper boundary of the convective layer.

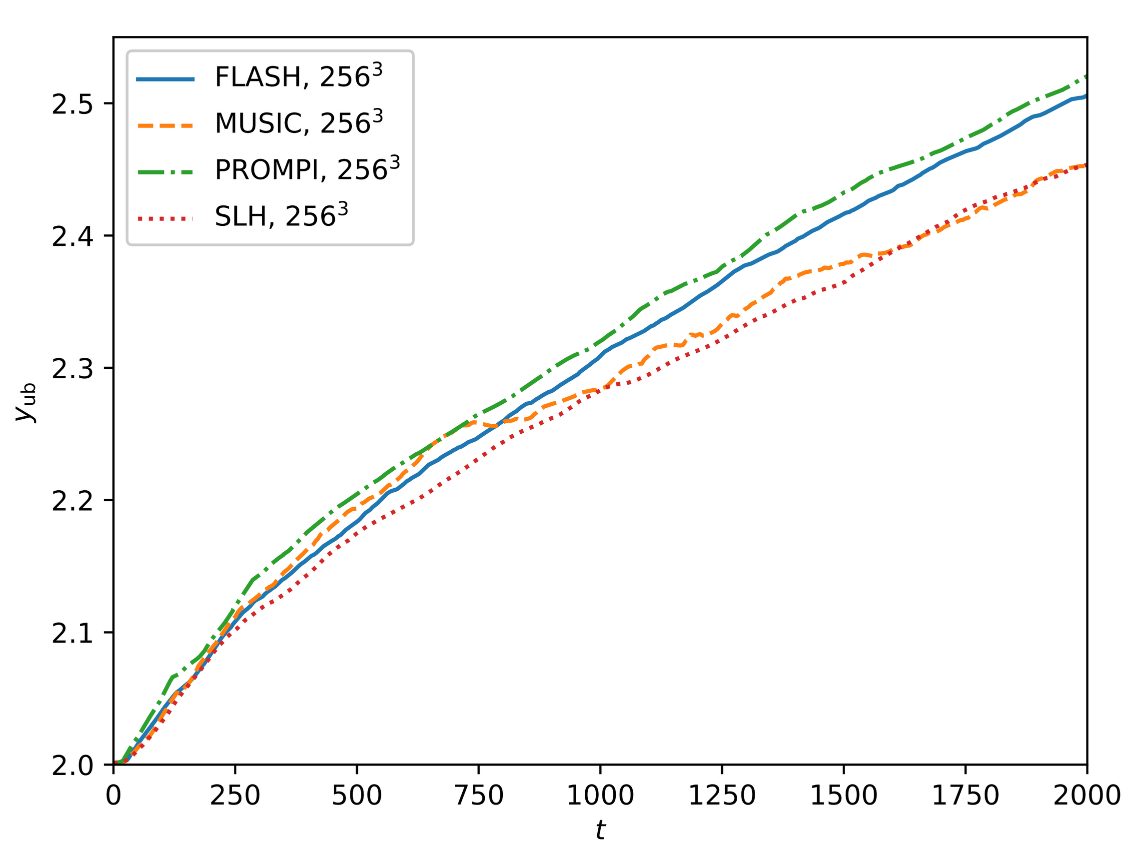


**Fig. 4:** Vertical coordinate $y_{ub}$ of the upper boundary of the convective layer as a function of time. We define $y_{cb}$ by searching for the steepest gradient in spatially-averaged vertical profiles of fluid composition. Convolution is used to smooth out the curves.

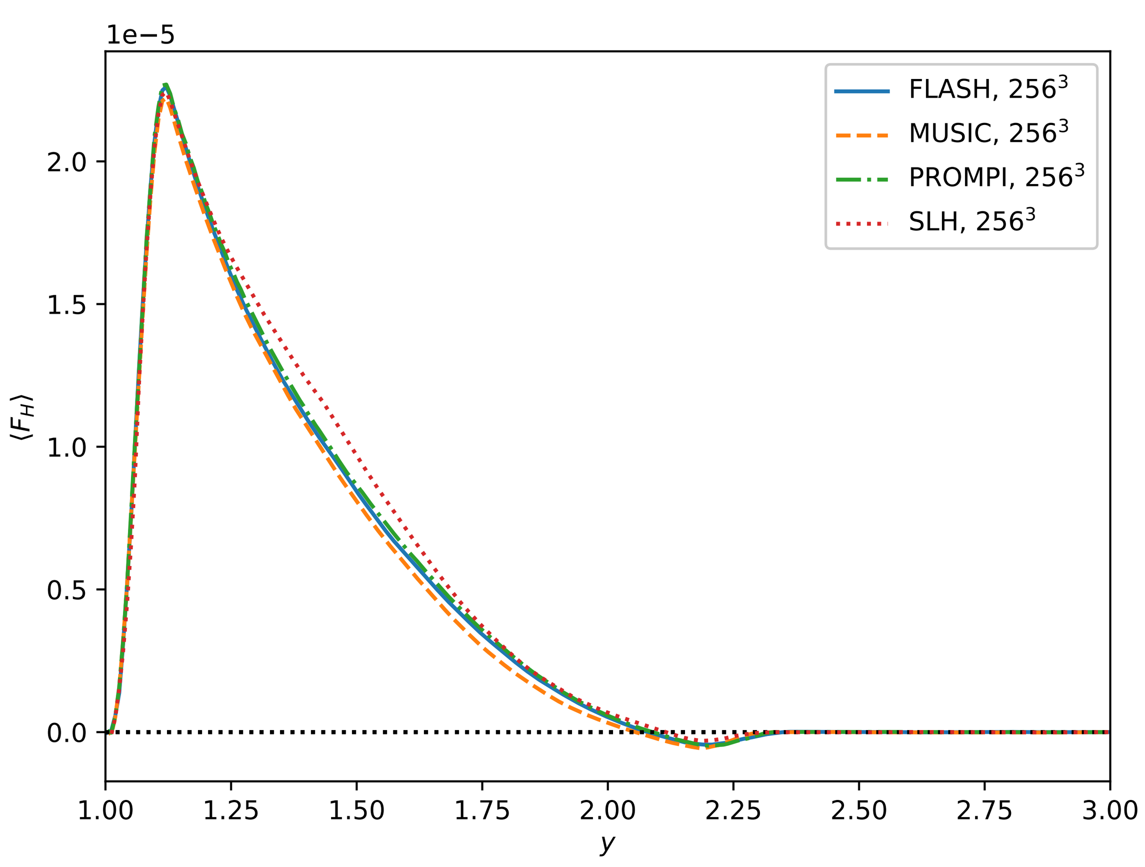


**Fig. 5:** Time- and space-averaged flux of enthalpy as a function of the vertical coordinate $y$. The flux contribution from the horizontally-averaged vertical motion of the stratification is subtracted.

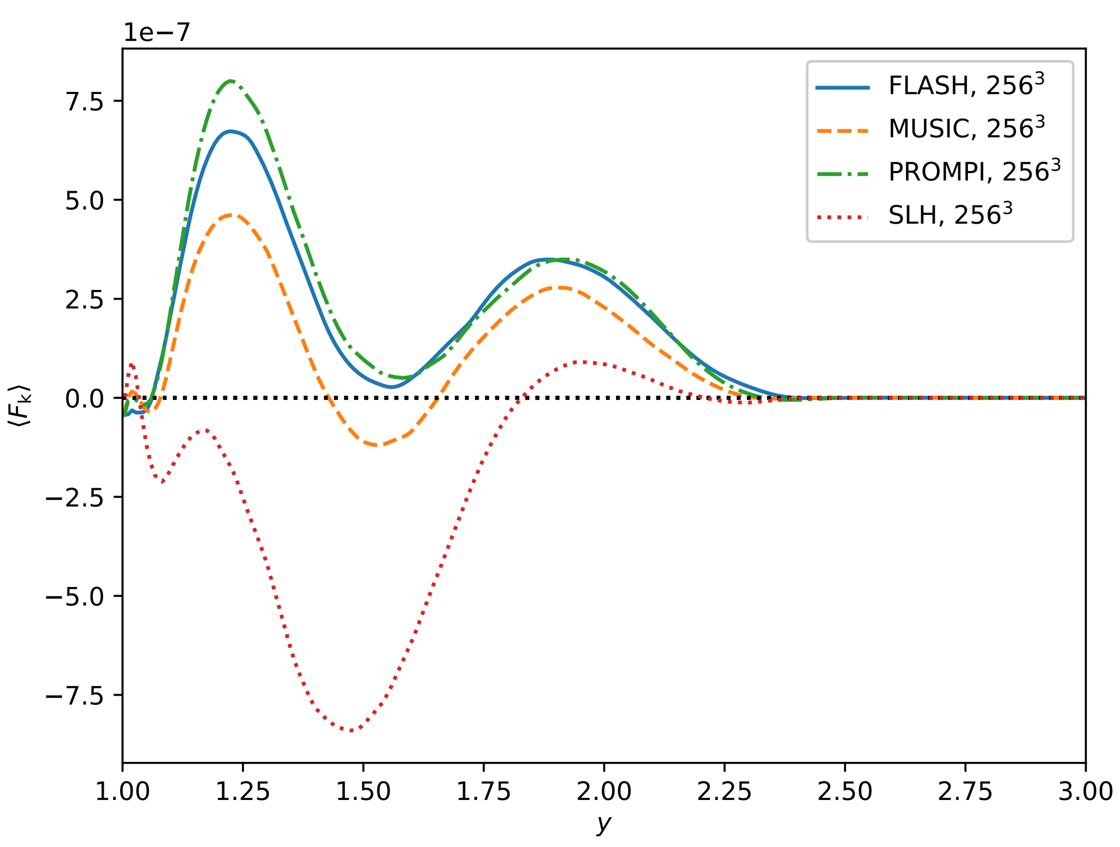


**Fig. 6:** Time- and space-averaged flux of kinetic energy as a function of the vertical coordinate $y$ (note that $\langle F_k \rangle \ll \langle F_H \rangle$, cf. Fig. 5). The flux contribution from the horizontally-averaged vertical motion of the stratification is subtracted. Most of the differences between the first three codes are due to flow intermittency.

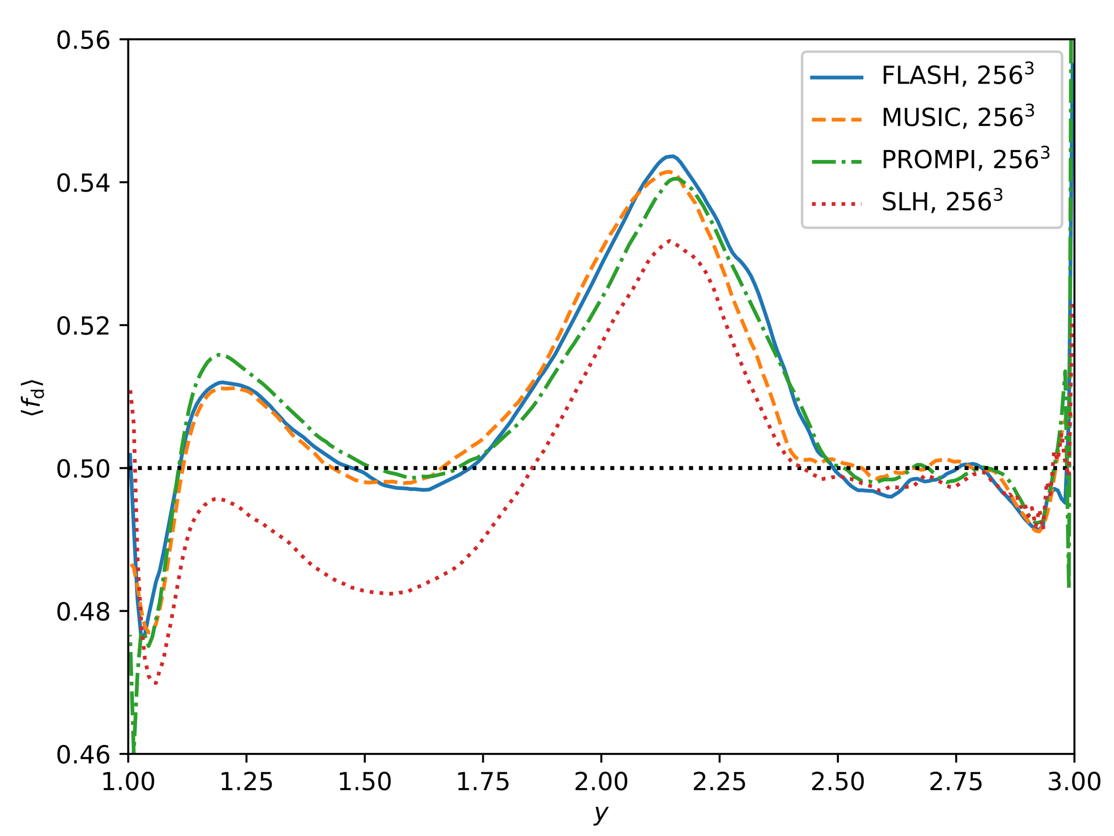


**Fig. 7:** Time- and space-averaged relative geometric area covered by the downflows as a function of the vertical coordinate $y$. The preference for narrow downflows ($\langle f_d \rangle < 0.5$) for $y < 1.8$ in the SLH simulation is likely related to the negative value of $\langle F_k \rangle$ in the same simulation shown in Fig. 6.

## Summary

- Generally good agreement between all four codes (FLASH, MUSIC, PROMPI, SLH) tested so far.
- Rates of convective mass entrainment from the stable layer differ by ~15% between the codes.
- Predictions of SLH differ from those of the other three codes in the flux of kinetic energy and in the small asymmetries between upflows and downflows.
- Comparison of quantities such as numerical dissipation rates or spatial spectra still to be done.
- All codes participating at the moment are based on finite-volume schemes.