HITS
Heidelberg Institute for Theoretical Studies

HITS
Heidelberg Institute for Theoretical Studies

# Comparison of five stellar-hydrodynamic codes on a turbulent convection problem

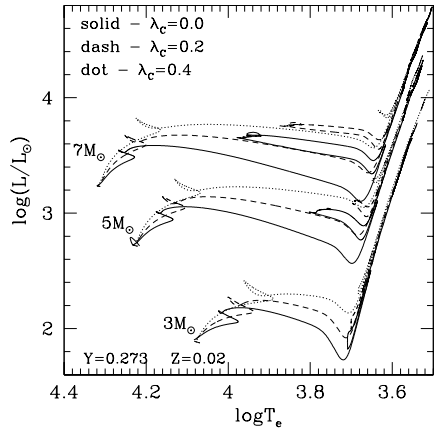
R. Andrassy[1], J. Higl[1], H. Mao[2], M. Mocák, D. G. Vlaykov[3], I. Baraffe[3,4], S. W. Campbell[5], T. Constantino[3], P. V. F. Edelmann[6], T. Goffrey[7], T. Guillet[3], F. Herwig[8,9], R. Hirschi[10,11], L. Horst[1], G. Leidi[1,12], J. Pratt[13], F. K. Röpke[1,14], P. Woodward[2,9]

[1] HITS, [2] U of Minnesota, [3] U of Exeter, [4] ENS de Lyon, [5] Monash U, [6] LANL, [7] U of Warwick, [8] U of Victoria, [9] JINA, [10] Keele U, [11] Kavli IPMU, [12] ARI at ZAH Heidelberg, [13] Georgia State U, [14] ITA at ZAH Heidelberg

17 June 2021

# Why study stellar convection?

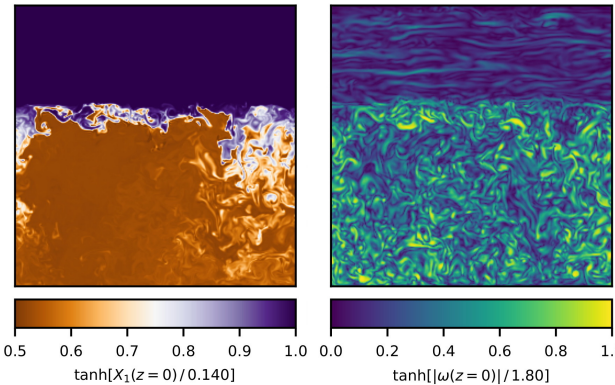
- Convection influences all stars.
- Convective boundary mixing (CBM) – a large uncertainty in 1D models of stellar evolution.
- Numerous 2D and 3D simulation efforts to better understand the dynamics of convective boundaries (e.g. Meakin&Arnett 07, Viallet+13, Gilet+13, Woodward+15, Lecoanet+16, Jones+17, Pratt+17, Mocák+18, Cristini+19, Horst+20).
- **Would the codes agree on all relevant quantities if they were to solve the same complex but well-posed problem?**




Cassisi 04: Evolution of intermediate-mass stars with different assumptions about the extent of convective boundary mixing.

# Test problem

- Inspired by the oxygen-shell simulations of Jones+17 and Andrassy+20.
- Simplifications:
  - Plane-parallel geometry.
  - Ideal gas EOS.
  - Two fluids: $\mu_0 = 1.848$ in the convective layer and $\mu_1 = 1.802$ in the stable layer.
- Inviscid Euler equations with no radiative diffusion.



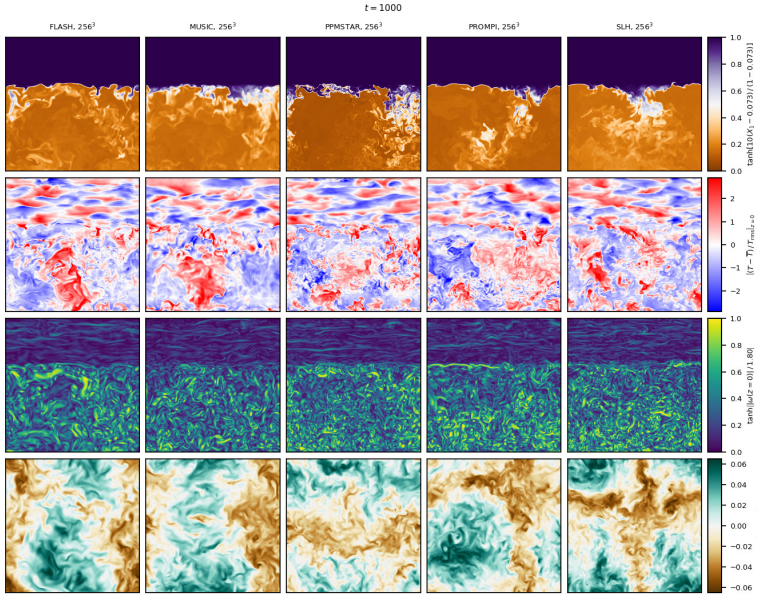

Stratification: $\frac{\rho_{\rm bot}}{\rho_{\rm top}} = 77.3$, $\frac{\rho_{\rm bot}}{\rho_{\rm top}} = 19.8$.

# Five 3D hydrodynamic codes

- FLASH (Fryxel+00)
  - unsplit PPM + HLLC, time-explicit
- MUSIC (Viallet+11,13,16, Goffrey+17)
  - Van Leer 74 scheme, staggered grid, time-implicit
- PPMstar (Woodward+15,19)
  - PPM+PPB, time-explicit
- PROMPI (Fryxel+91, Meakin&Arnett 07)
  - PPM, time-explicit
- SLH (Miczek 13, Edelmann 14, Edelmann+21)
  - PPM + AUSM+-up, time-implicit and time-explicit

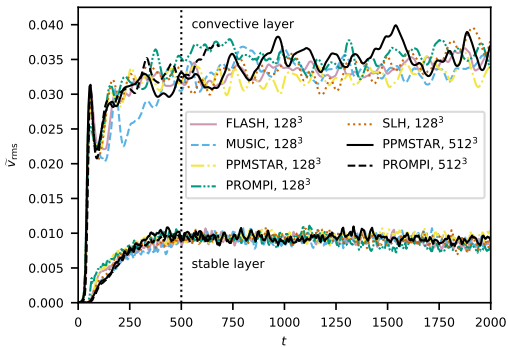
# Simulations and outputs

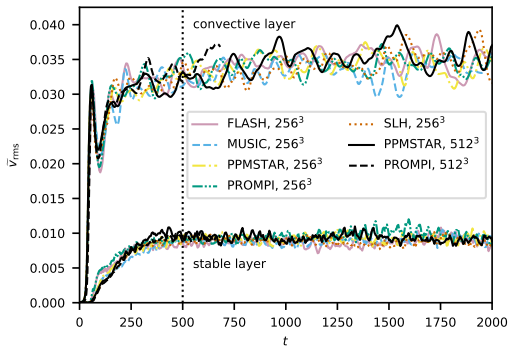
- $128^3$, $256^3$, and $512^3$ uniform Cartesian grids.
- Long runs to gather statistics ($\approx 25\tau_{conv}$, 400 output intervals).
- Outputs:
  - 3D data cubes.
  - 2D slices.
  - 1D averages.
  - Kinetic energy spectra.
- All data products and analysis and setup tools will be published.


$t = 1000$
FLASH, $256^3$
MUSIC, $256^3$
PPMSTAR, $256^3$
PROMPI, $256^3$
SLH, $256^3$
$\tanh[5(0.6(\lambda_2 - 0.073)/(1 - 0.073)]$
$(T - \overline{T})/T_{rms}|_{z=0}$
$\tanh[|\omega|z = 0|]/1.80]$
$v_y|y = 1.7)$

# Evolution of bulk rms velocity

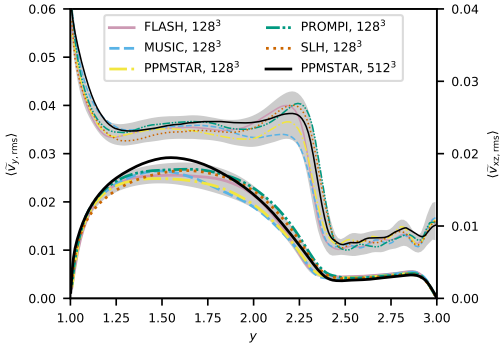
- Significant statistical variation.
- All simulations ($128^3$ to $512^3$) statistically agree.

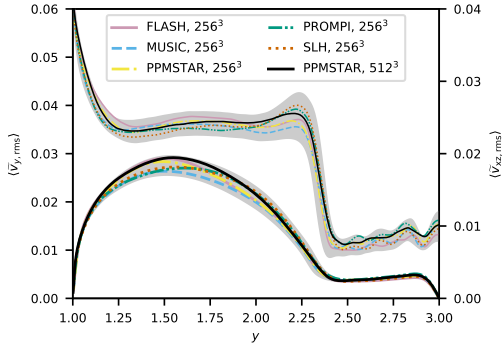


# Velocity profiles

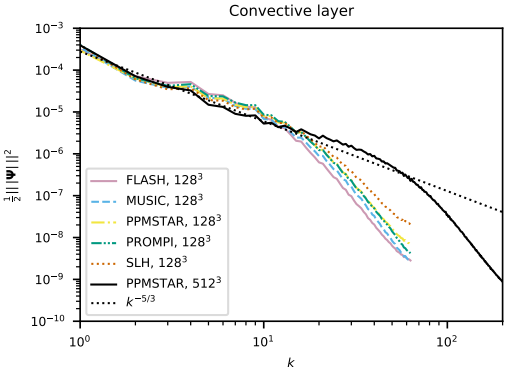
- Run-to-run differences compatible with statistical variation.

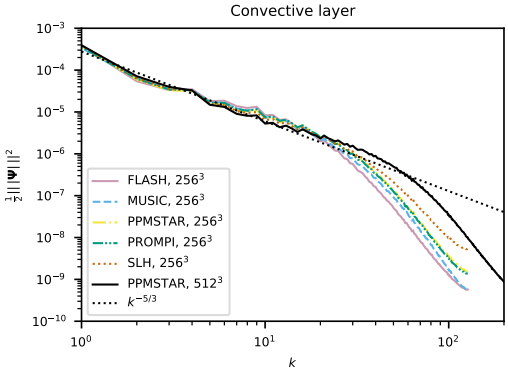


# Kinetic energy spectra: convective layer

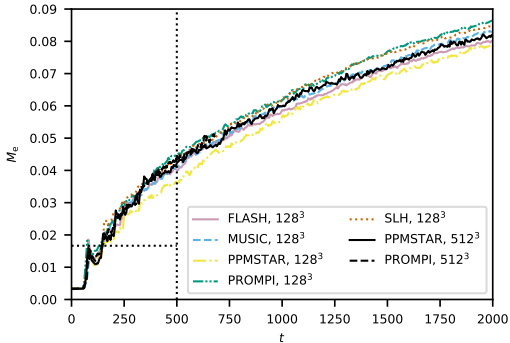
- All five codes converge to Kolmogorov's $-\frac{5}{3}$ law in the midplane of the convective layer.

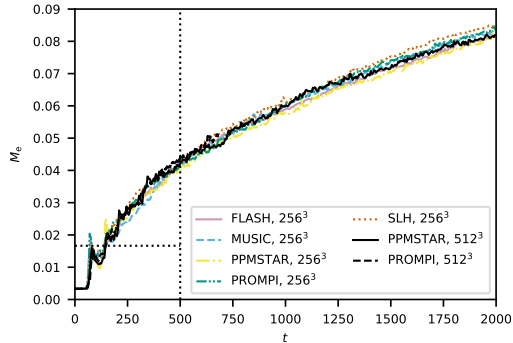


# Convective mass entrainment

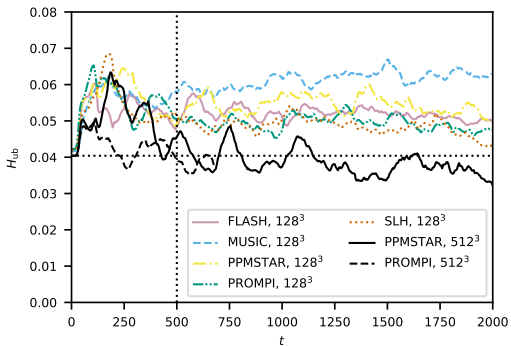
- Code-to-code differences comparable with the statistical variation on the $256^3$ grid.

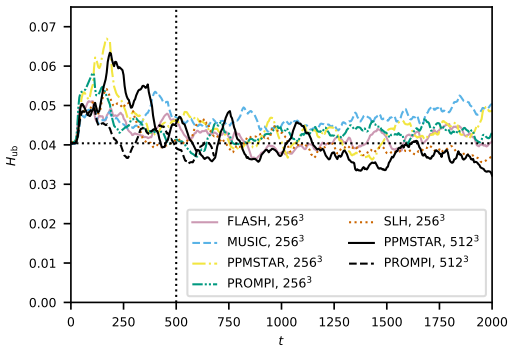


# Thickness of the convective boundary

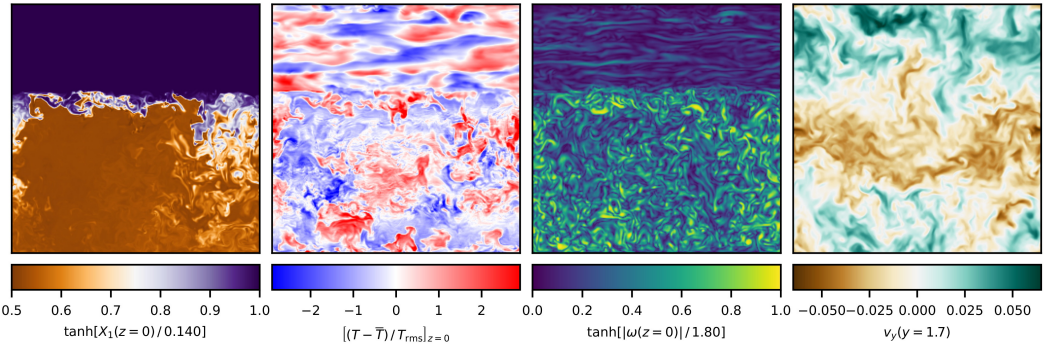
- Boundary under-resolved on the $128^3$ grid.
- $256^3$ runs approach convergence.



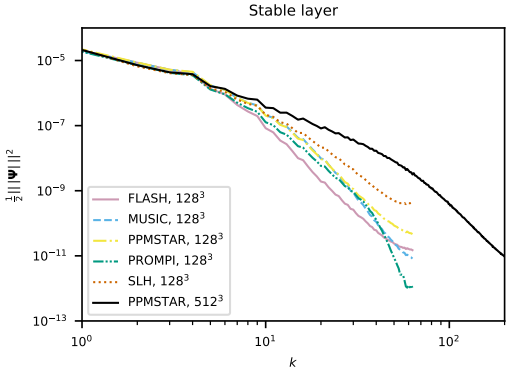
# Summary and conclusions

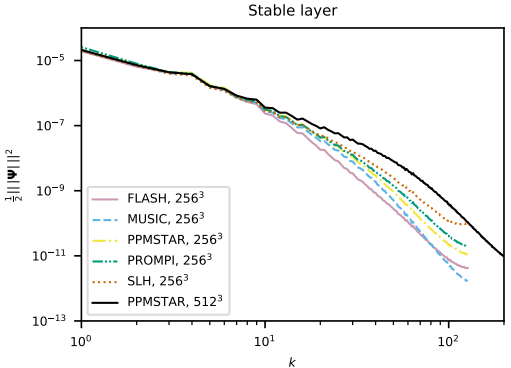
- Complex test problem: turbulent convection with mass entrainment.
- Simplified physics and geometry ⇒ applicable to many codes.
- Excellent agreement between FLASH, MUSIC, PPMstar, PROMPI, and SLH on a $256^3$ grid.
- All data products and analysis and setup tools will be published.



# Kinetic energy spectra: stable layer

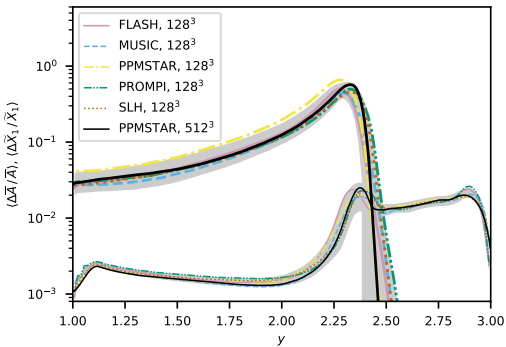
- No theoretical prediction, but convergence observed for horizontal wavelengths $\gtrsim 26$ grid cells.

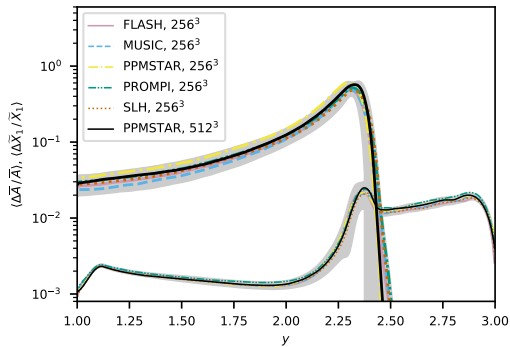


# Fluctuations

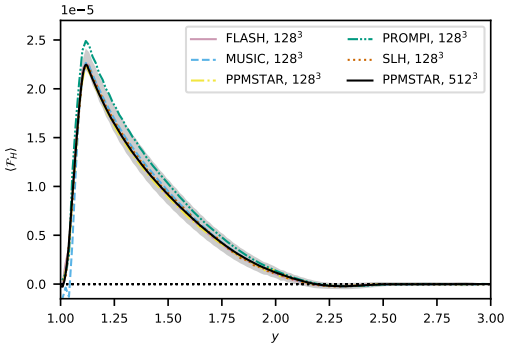
- Run-to-run differences compatible with statistical variation.

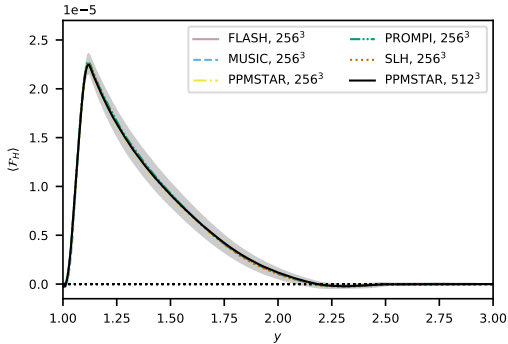


# Flux of enthalpy

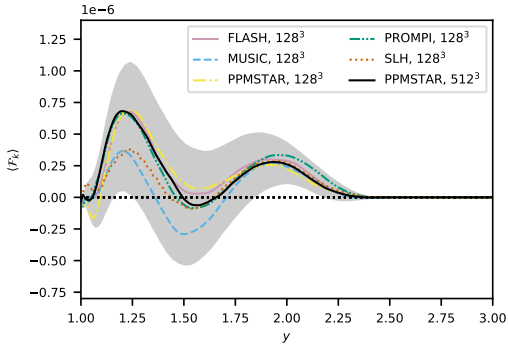
- Differences of only **1.3%** in $\max\langle F_H \rangle$ on the $256^3$ grid.

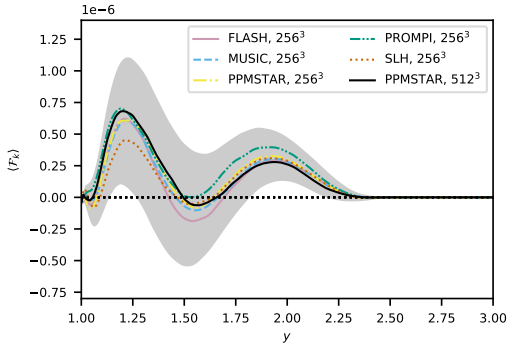


# Flux of kinetic energy

- Small quantity ⇒ large statistical variation.



# Downflow filling factor

- Convection close to perfect up-down symmetry ⇒ large statistical variation.