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HWB07 - Multidimensional hydrodynamic simulations of stars

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Modelling Stars

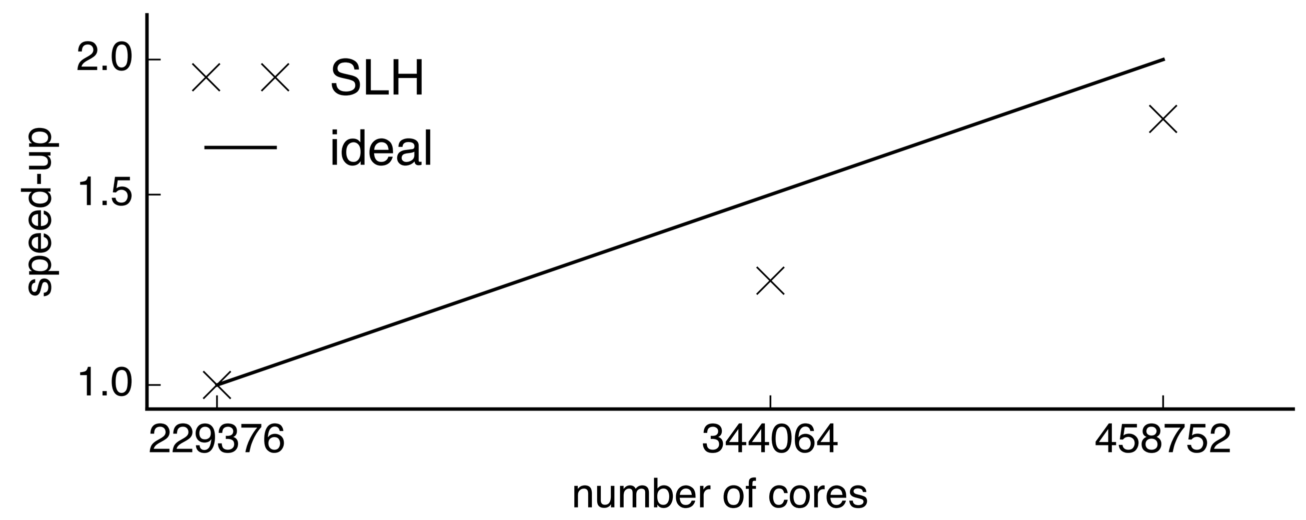
- Time-scale problem (values for the Sun):
  - Nuclear time scale $\tau_{\mathrm{nuc}} = 10^{11}$ years.
  - Free-fall time scale $\tau_{\mathrm{ff}} = 27$ min.
- $\tau_{\mathrm{nuc}} \gg \tau_{\mathrm{ff}} \Rightarrow$ Stellar evolution models are assumed to be spherically symmetric and hydrostatic to make the computation feasible.
- Multidimensional phenomena (turbulent convection, rotation, magnetic fields) are added through simplistic prescriptions.

hydrostatic structure	hydrodynamics
$\nabla P = \rho \vec{g}$	$\partial_t \rho \vec{u} + \nabla \cdot (\rho \vec{u} \otimes \vec{u}) + \nabla P = \rho \vec{g}$

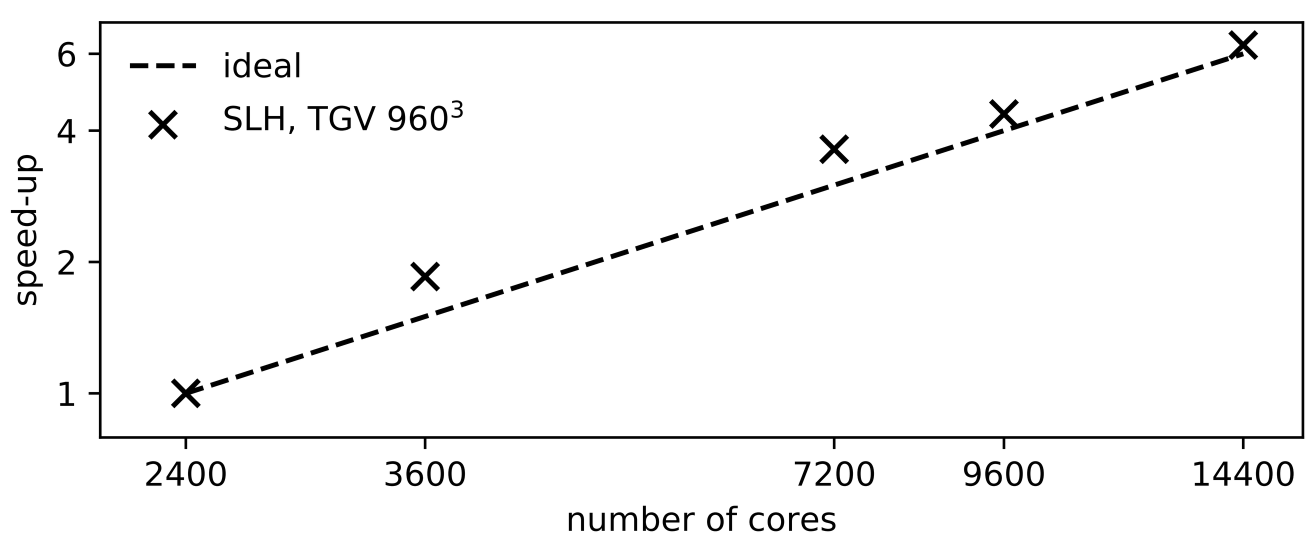
Seven-League Hydro (SLH) Code

- Compressible hydrodynamics in 1D, 2D, and 3D.
- Explicit and implicit time integration.
- Special solvers for all Mach numbers (e.g. AUSM$^+$-up).
- Hybrid (MPI, OpenMP) parallelization.
- Arbitrary curvilinear meshes using a logically rectangular computational mesh.
- Radiation in the diffusion limit.
- General equation of state (fully-ionized ideal gas, radiation, partial degeneracy, Coulomb corrections).
- General nuclear reaction network.
- Self-gravity solvers.

Scaling Tests

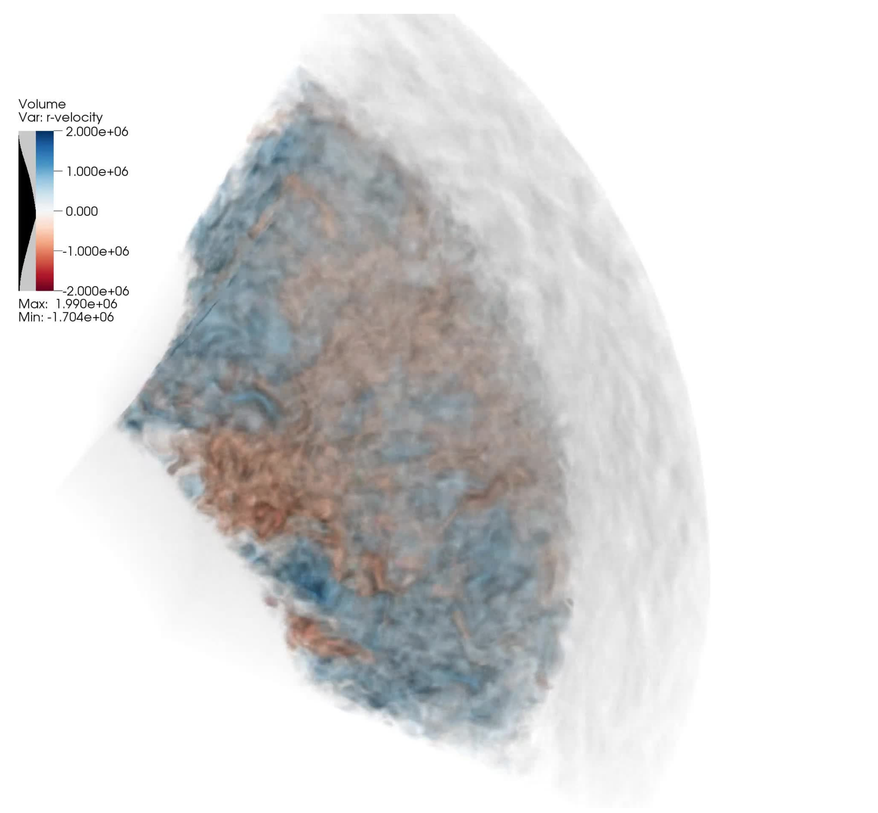


Above: Full-machine tests on JUQUEEN during the 2016 Extreme Scaling Workshop. The runs computed the Taylor-Green vortex on a 2688^3 grid with 16 MPI tasks per node and 4 threads per task.



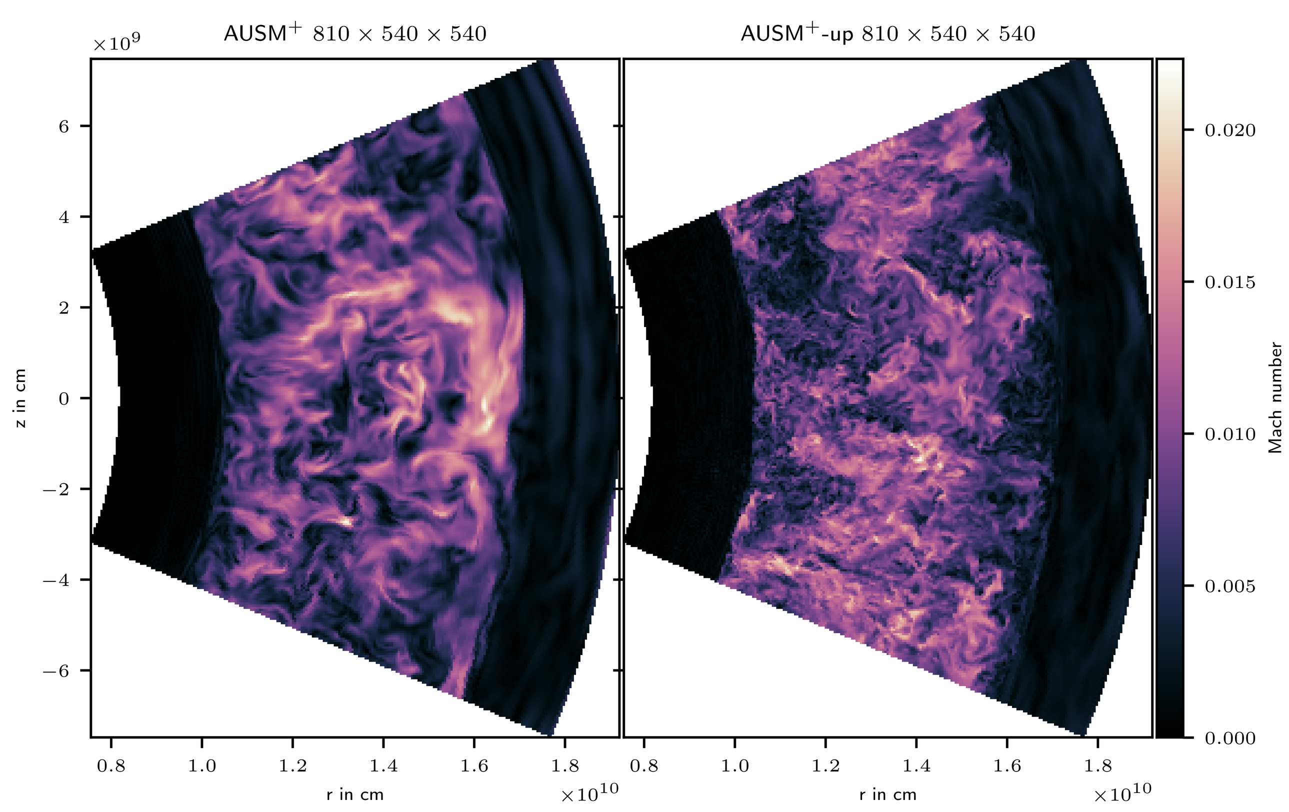
Above: Scaling test using the Taylor-Green vortex computed on a 960^3 grid with pure MPI parallelization on JUWELS.

Case I: Shell Helium Burning



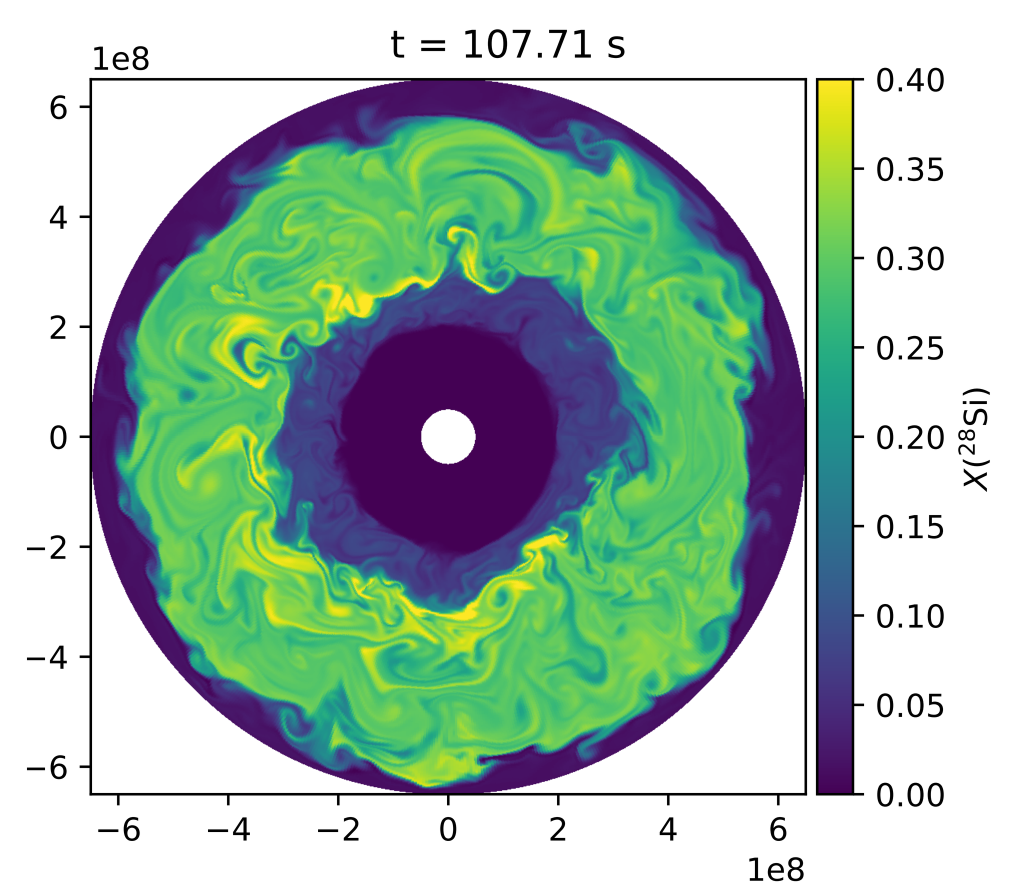
Above: Volume rendering of the radial component of velocity in a 3D SLH simulation of a convective He-burning shell (the high-velocity layer) with a stably-stratified layer on top of it.

- **Goals of the study:**
  - Measure the mixing rate across the upper boundary of a He-burning shell to improve 1D mixing prescriptions for stellar evolution.
  - Investigate the impact of using specialized low-Mach flux functions.
- Model of a 25 $M_\odot$ star after core helium burning: He is burned into C & O in a convective shell.
- Transport of fresh He through the upper convective boundary sustains nuclear burning at the bottom.
- **Numerical challenges:**
  - Low-Mach-number flows in a strongly stratified medium.
  - Mass transport through narrow convective boundary layers.



Left: Mach number distribution in a convective He-burning shell computed on a 810×540^2 spherical-wedge grid with energy generation rate boosted by a factor of 3×10^4. The two simulations have the same initial setup and they only differ in the solver used: the AUSM+ solver not specialized for low-Mach flows (left panel) versus the low-Mach solver AUSM+-up (right panel). The turbulent cascade extends to significantly smaller scales with the low-Mach solver on the same grid.

Case II: Shell Silicon Burning



Above: Distribution of the mass fraction of ^{28}Si during a strong mixing event in a 2D SLH run performed on a 384×768 polar grid. The simulation includes part of the Fe core, a Si-burning shell, an O-burning shell and part of a C-burning shell in a volume comparable to that of the Earth (dimensions on the axes in cm).

- **Goals of the study:**
  - Improve our understanding of convective shell interactions in core-collapse supernova progenitors in terms of their dynamics and of the convective-reactive nucleosynthesis involved.
  - Create improved initial conditions for supernova explosion models by simulating late stages of stellar evolution in 2D and 3D.
- SLH simulations based on a 1D model of a 25 $M_\odot$ star $\sim$2 min before the ultimate core collapse.
- **Multi-physics problem:**
  - 2D and 3D fluid dynamics at typical Mach numbers in the range 10^{-2} to 10^{-1}.
  - Strong self-gravity in the monopole approximation.
  - Equation of state of a partially-degenerate mixture of ideal gas with radiation, including Coulomb corrections.
  - Complex network of nuclear reactions with 21 species advected with the flow.
  - Energy losses via plasma neutrino emission.

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