Hydrodynamic Simulations of Stellar Interiors

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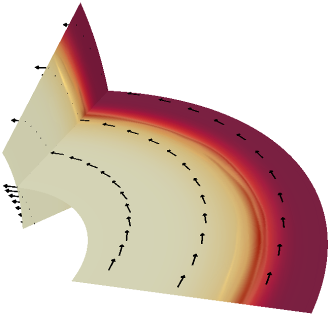


(shear instability in a rotating star)

Heidelberg Institute for
Theoretical Studies

HITS

The Problem of Modeling Stellar Evolution

- Stellar evolution simulations are needed to understand involved processes
- Problem: Dynamical processes faster than nuclear ones

$$\textit{hour} \approx \tau_{\rm dyn} \ll \tau_{\rm nuc} \approx 10^{15}\tau_{\rm dyn}$$

- High computational costs:
  – Stars need to be treated as 1D objects

↯ Many aspects are multidimensional (e.g. convection)

→ 1D codes rely on uncertain parametrization

Approach: Multidimensional Hydro Simulations

- Restrict multi-D simulation to smaller parts of a star

→ Use results to improve the 1D treatment of the complete star

Our Tool: The SLH Code

- Gas flow in star described by Euler equations
- Implicit time stepping beneficial in low-Mach regime as $\Delta t \sim 1/M_{ref}$
- Finite Volume scheme + impl. time steps lead to system of coupled non-linear equations for $U_i = (\rho, \rho\vec{u}, \rho E)_i$ at cell i

$$\left.\begin{aligned} \partial_t \rho + \nabla(\rho\vec{u}) = \vec{0} \\ \partial_t(\rho\vec{u}) + \nabla\left(\rho\vec{u}\vec{u}^T\right) + \nabla P = \vec{g} \\ \partial_t(\rho E) + \nabla(\vec{u}(\rho E + P)) = \rho(\vec{u}\vec{g}) \end{aligned}\right\} \overset{FV+impl.time}{\longrightarrow} \underbrace{f\left(U\right)}_{\text{nonlinear function}} + U_i = 0$$

- Number of equations to solve: $N_{equ} = N_{cells} \cdot N_{cons}$
- Entries in Jacobian for Newton-Raphson solver:

$$N_{entry} = N_{cells} \cdot (4N_{dim} + 1) \cdot N_{cons}^2$$

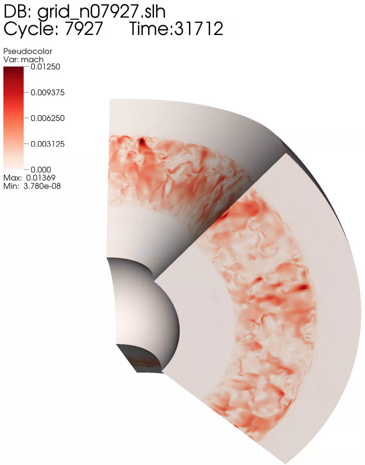
- For typical 3D simulation this requires $\sim$ 325GB of memory

$\rightarrow$ **Need for HPC facilities**

Convective Helium-Shell Burning

- 3D setup constructed from 1D stellar evolution models
- ^{4}He, ^{12}C, ^{16}O advected with fluid flow + nuclear burning
- Implicit time stepping allows to cover several days of physical time

→ Amount of overshooting at convective boundaries influences stellar evolution

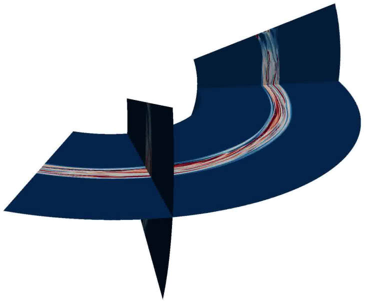


Mach number of the convective motion is color coded. Simulation performed on the JUQUEEN Supercomputer in Jülich, Germany consuming about 2×10^{6}CPUh.

Shear Instability in a rotating Star

- Mapping of underlying 1D model to 3D while preserving *shellular rotation*
- Simulation from onset until quenching of instability

→ Amount of mixing and resulting angular velocity profile may be used to improve 1D description of rotation



Richardson number is color coded. Blue color represents stable regions. Simulation performed on the JUQUEEN Supercomputer in Jülich, Germany consuming about 6×10^6CPUh.