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Stellar evolution and nucleosynthesis in 3D hydrodynamic models of stars

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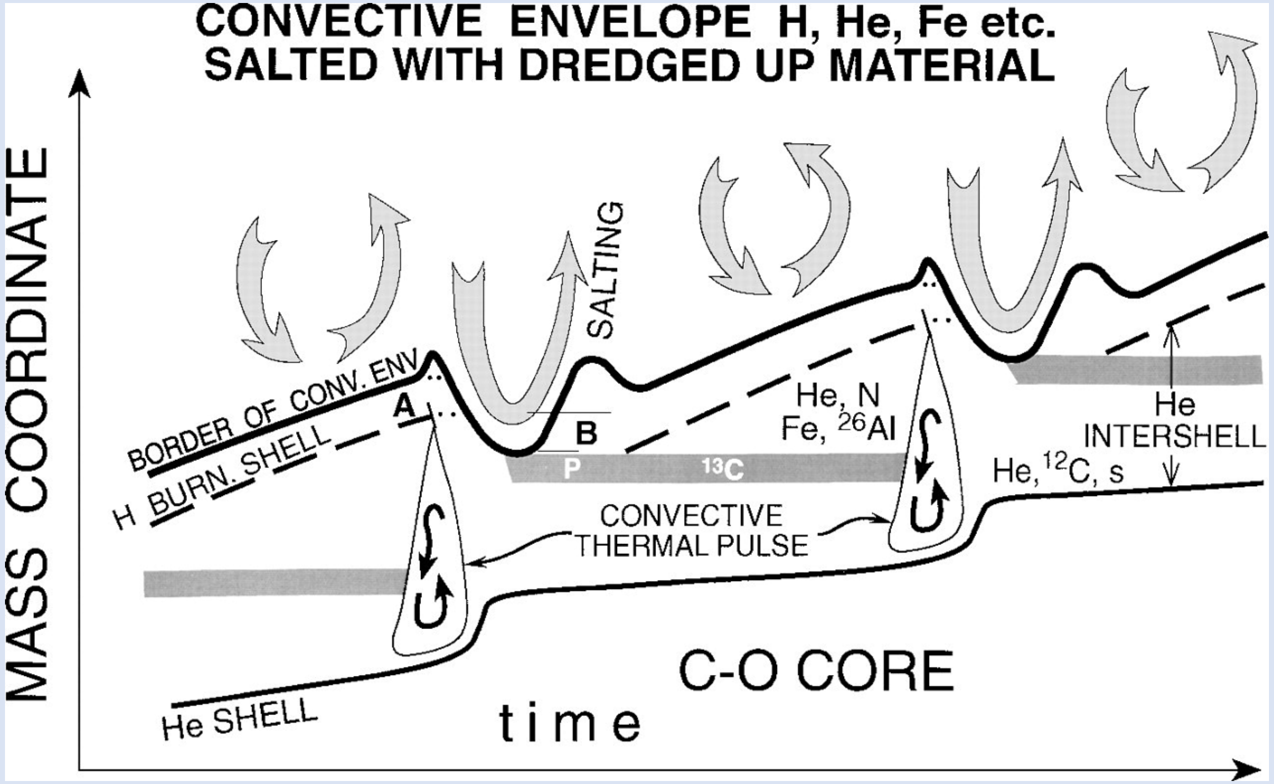
Convective mixing in AGB stars



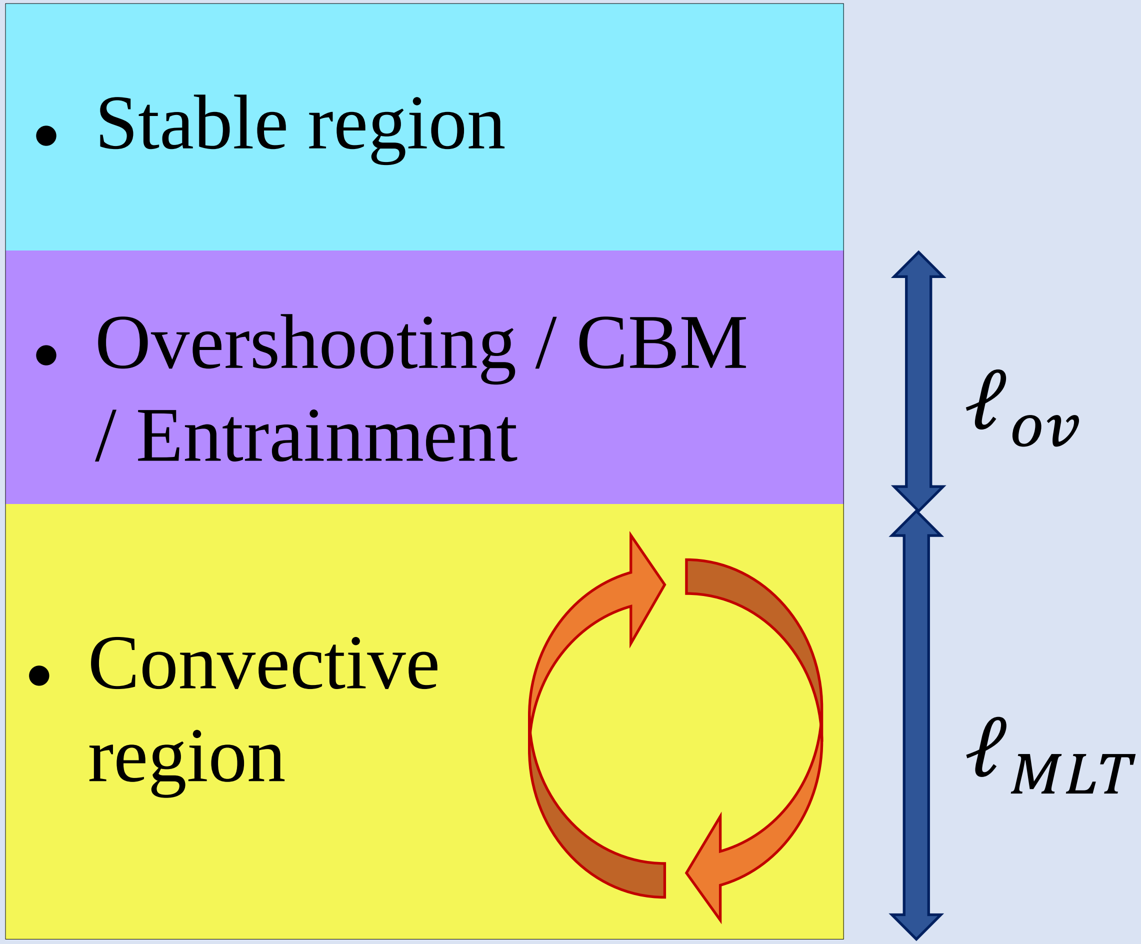
Busso et al. (1999)

- AGB stars have a complex structure: core, He-shell, intershell, H-shell, envelope
- They undergo alternating phases of radiative and convective energy transport: thermal pulses, third dredge up…
- Mixing is important for the formation of a ^{13}C-pocket and consequent s-process nucleosynthesis
- Still many uncertainties about convective mixing: what mechanisms are involved, and how far does convection penetrate?

Current implementation of convection in 1D

1D prescriptions:

- energy transport in convective zone: mixing length theory (MLT) (*Böhm-Vitense 1958*)
- boundary location: Schwarzschild or Ledoux criterion
- overshooting/convective boundary mixing (CBM): penetrative overshoot, exponential decay diffusion, entrainment law…



Convective Boundary Mixing (CBM)

CBM implementations

Penetrative overshoot

$d_{ov} = \alpha_{ov} min[H_P, r_c]$, *Zahn (1991), GENEC*

Same degree of mixing

Extended by fraction of pressure scale height

Exponential decay diffusion

$D = D_0 exp\left[\frac{-2z}{f_{CBM}H_P}\right]$, *Freytag et al. (1996), MESA*

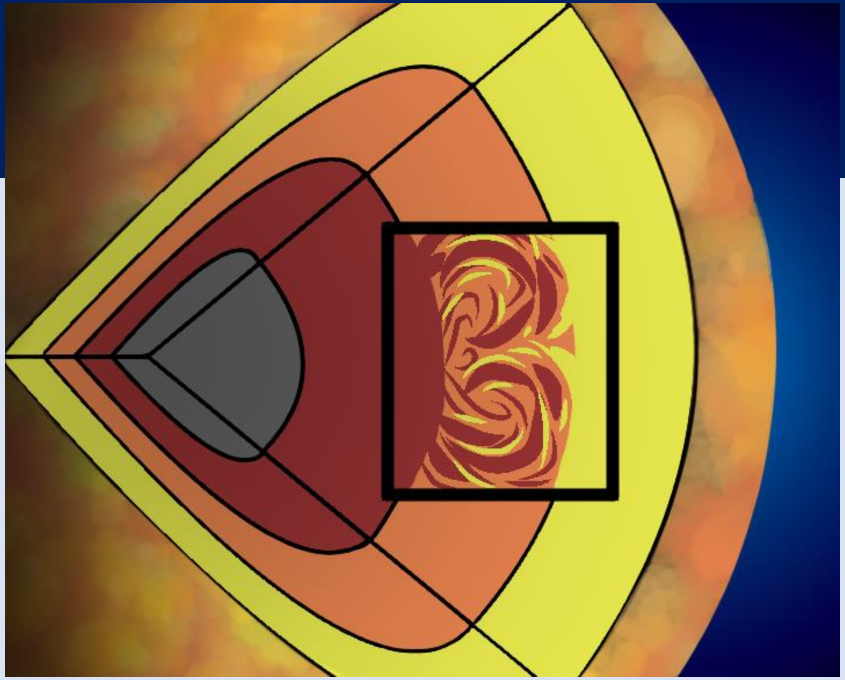
Mixing decreasing exponentially

Mixing continued until cutoff reached

Entrainment law

$\dot{M} = 4\pi r^2 \rho v_c A Ri_b^{-n}$, *Meakin & Arnett (2007), GENEC in Scott et al. (2021)*

3D hydrodynamic models



Modelling a 3D box enclosed in / enclosing a star

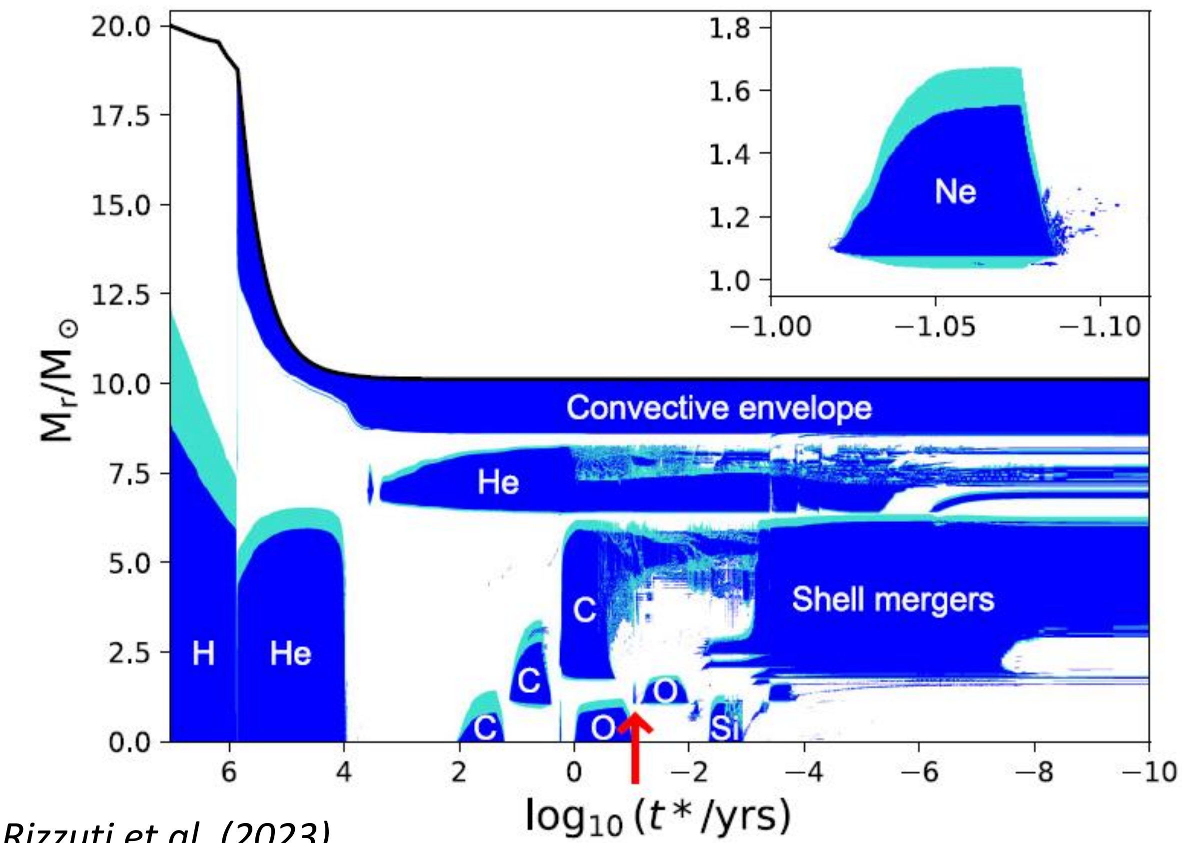
Advantages:

- deviations from spherical symmetry: model fluid instabilities
- can include multi-D processes (convection, rotation, magnetic fields)
- no need to assume prescriptions as in 1D (mixing length theory, convective boundary mixing)
- can use 3D data to constrain 1D parametrization

Disadvantages:

- high computational cost
- limited by fluid dynamical timescales
- cannot simulate full star or entire lifetime
- difficult to compare results to observations

3D simulations of a burning shell



Rizzuti et al. (2023)

Modelling a Ne-burning shell of 20 $M_\odot$ star, $Z_\odot$, with PROMPI code:

- 1D MESA model with extra mixing (expo decay diffusion, *Herwig 2000*)
- 3D spherical “box-in-a-star” of $r = 3.6 - 8.5 \times 10^8$ cm; angle $\sim 26°$
- fuel convection with a 12-isotope network for Ne-burning
- multiple simulations with different resolutions and “boosting factors”
- following the shell untill fuel exhaustion

Convection and fluid motions

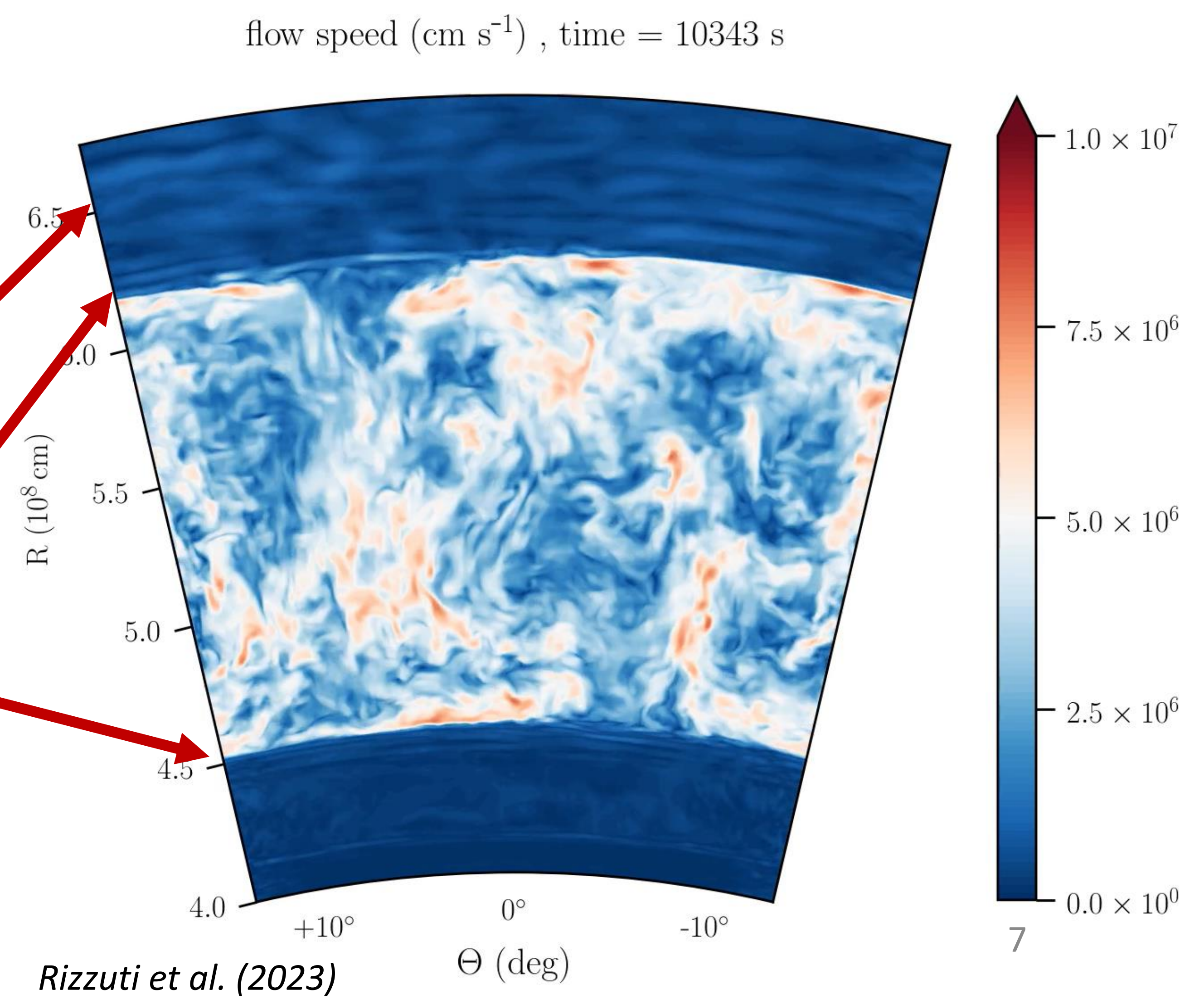
Vertical slice of the cell: velocity magnitude in colour scale.

We can see:

Internal gravity waves

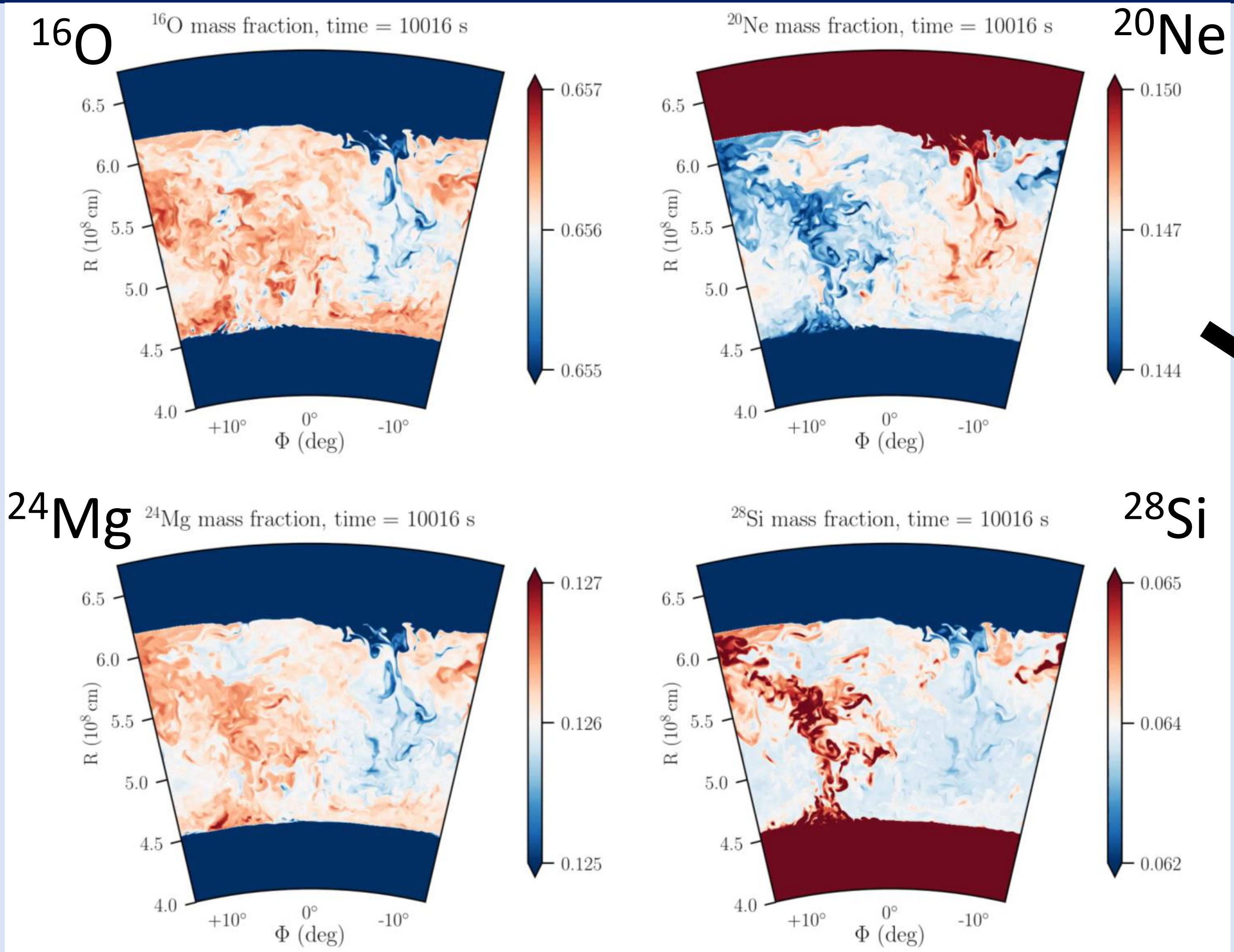
Convective boundary mixing

→ At the boundaries, shear mixing entrains material from stable zones



Rizzuti et al. (2023)

Evolution of the abundances



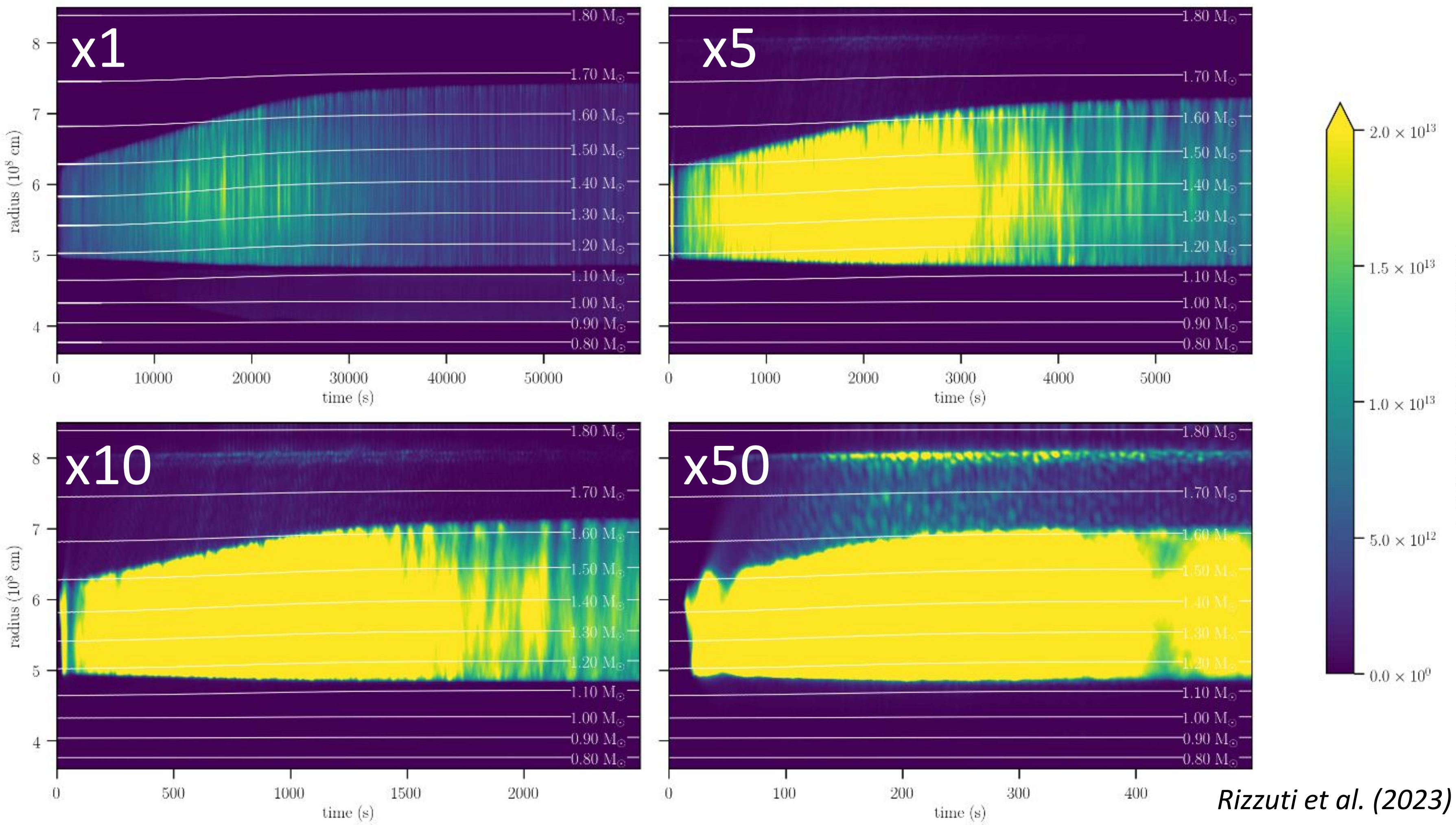
Reflecting the neon burning reactions:

$^{20}Ne(\gamma,\alpha)^{16}O$

$^{20}Ne(\alpha,\gamma)^{24}Mg$

$^{24}Mg(\alpha,\gamma)^{28}Si$

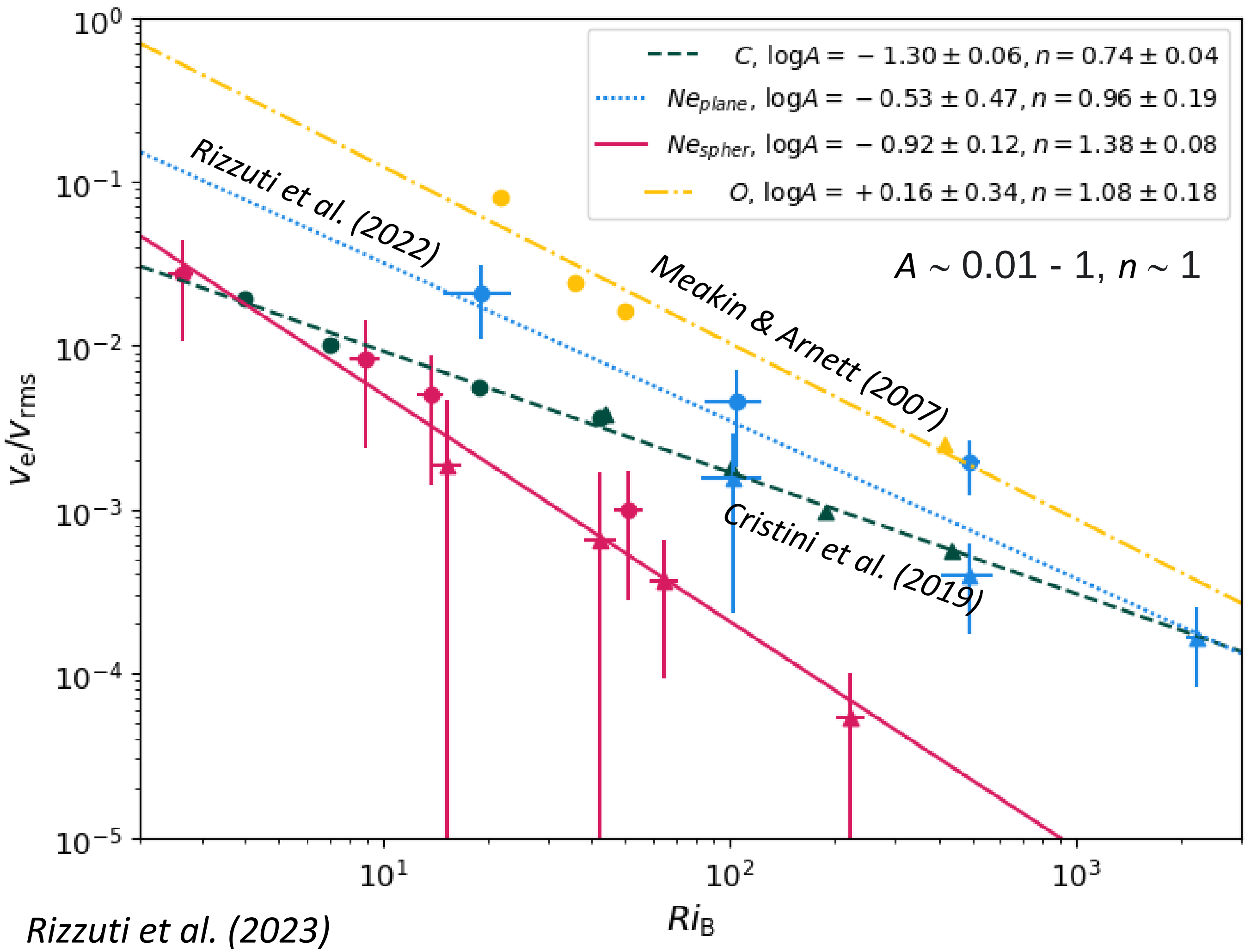
Shell evolution and entrainment



Rizzuti et al. (2023)

- The convective zone grows with time, due to entrainment, until fuel exhaustion
- Convective boundaries are tracked using the abundances
- The entrainment rate is strongly dependent on the boosting factor

Computing the entrainment law



Rizzuti et al. (2023)

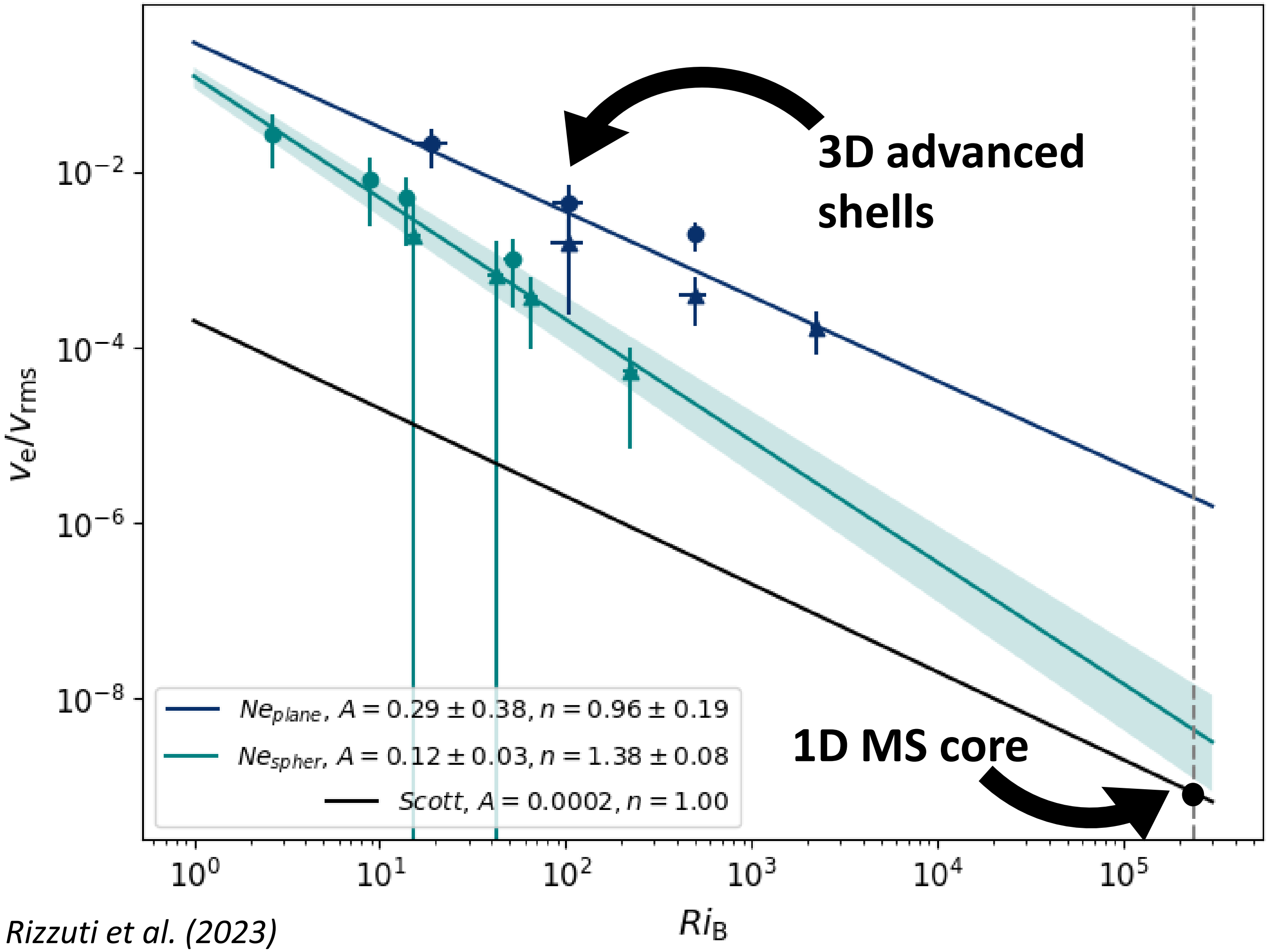
$$E = \frac{v_e}{v_{rms}} = A \cdot {Ri_B}^{-n}$$

(Meakin & Arnett 2007)

- Entrainment rate can be parametrized with a simple law using the "bulk Richardson number", representing the "stiffness" of the boundary
- We can compare hydrodynamic simulations for different burning phases

Implementing entrainment back in 1D models

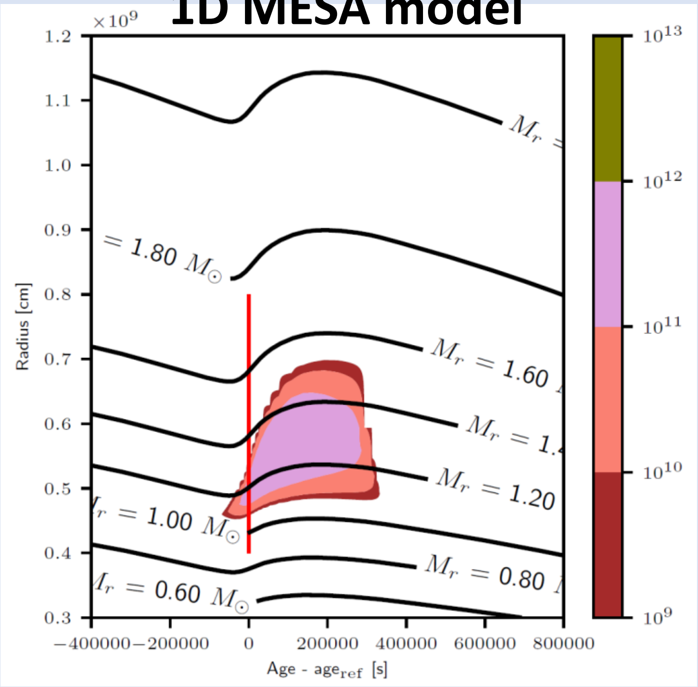
- Entrainment in 1D stellar models as replacement for penetrative overshoot or diffusive CBM
- Scott et al. (2021) with GENEC for MS convective core: calibration of entrainment parameters
- A discrepancy: very different parameter A ~ 0.01 - 1 in 3D vs ~ 10^{-4} in 1D



Rizzuti et al. (2023)

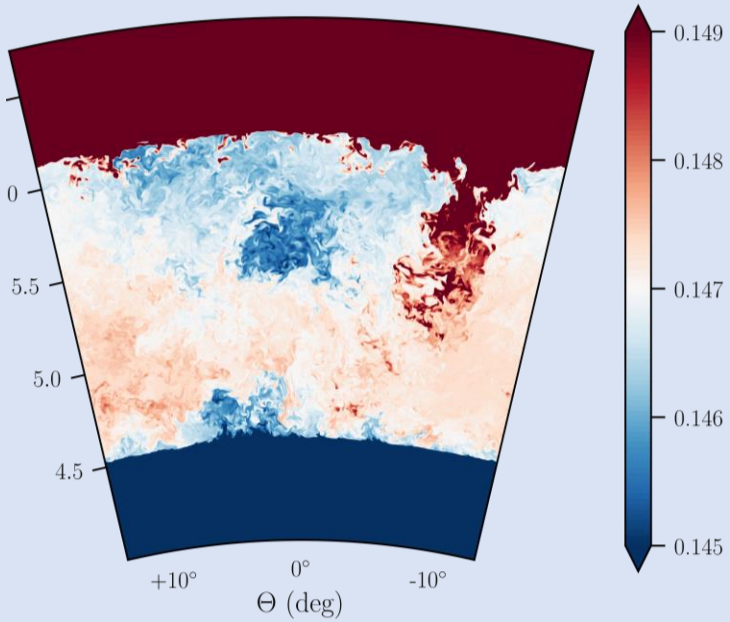
321D: how we have linked 1D and 3D

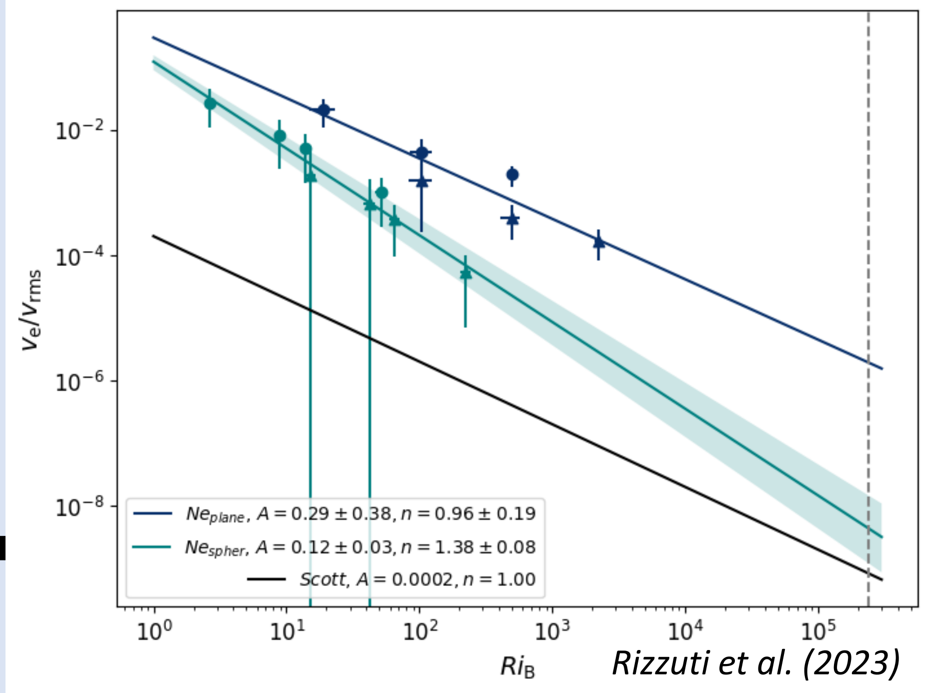
1D MESA model



Initial conditions

3D hydro model





prescription

calibration

Conclusions

- Convective mixing and overshoot affect the structure and evolution of AGB stars, thus need to be better understood
- The interplay between 1D and 3D stellar models improves our knowledge of nucleosynthesis and stellar evolution
- Nuclear reactions can be included and studied in the 3D simulations
- We completed the first 3D simulations of an entire burning phase (Ne-burning shell) measuring convective boundary mixing
- Entrainment can be parametrized, and is approaching convergence between 1D and 3D

For the future: 3D stellar evolution for more stars and phases, including 3D simulations of AGB stars.