Simulations of convection in massive stars: 321D loop approaching convergence

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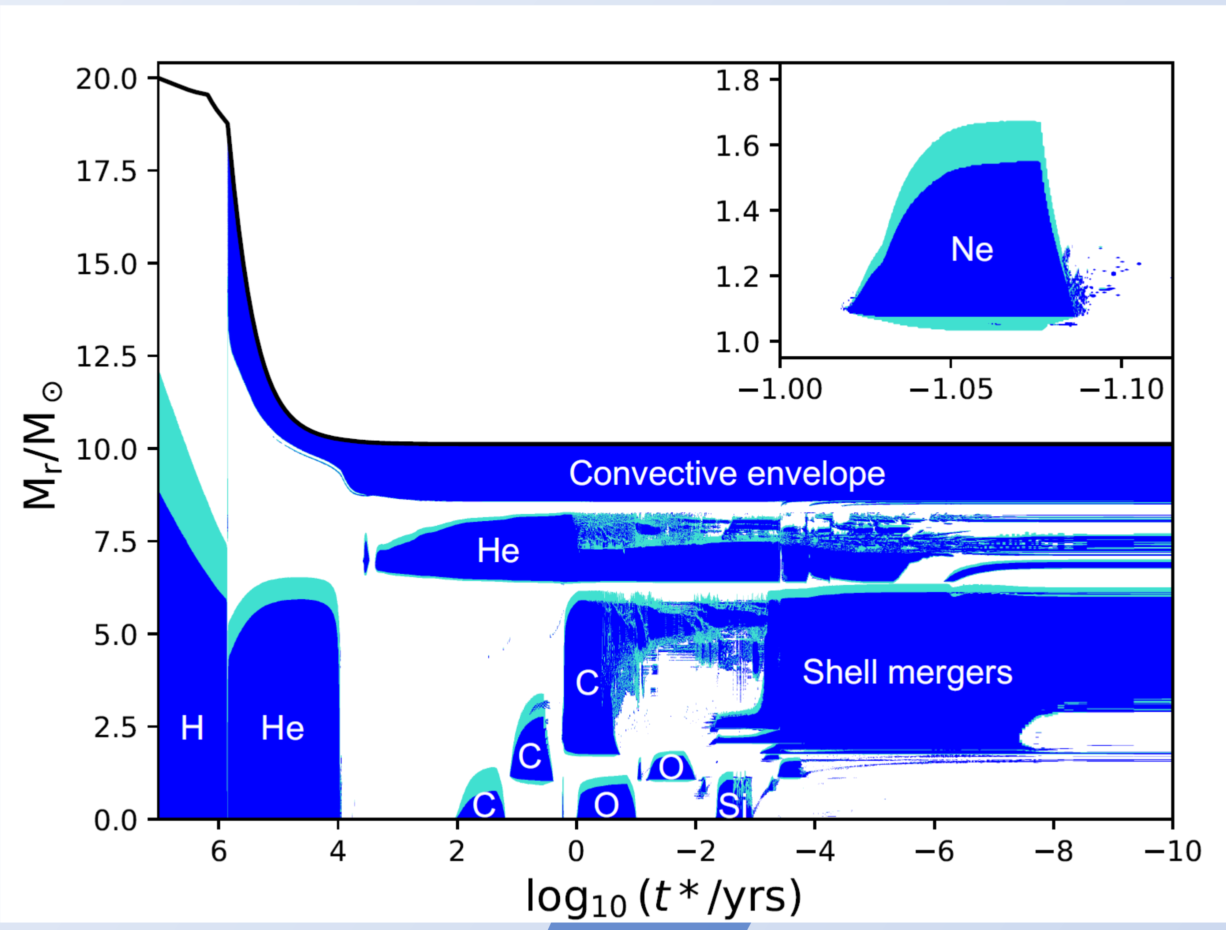
The modelling of massive stars is affected by uncertainties linked to multi-dimensional processes. 3D hydrodynamics simulations can reproduce these 3D processes in stellar interiors and guide the improvement of 1D stellar evolution models (321D loop). We completed the second 321D loop and 3D and 1D models are now apporaching convergence. This will improve predictions of the fate and impact of massive stars.

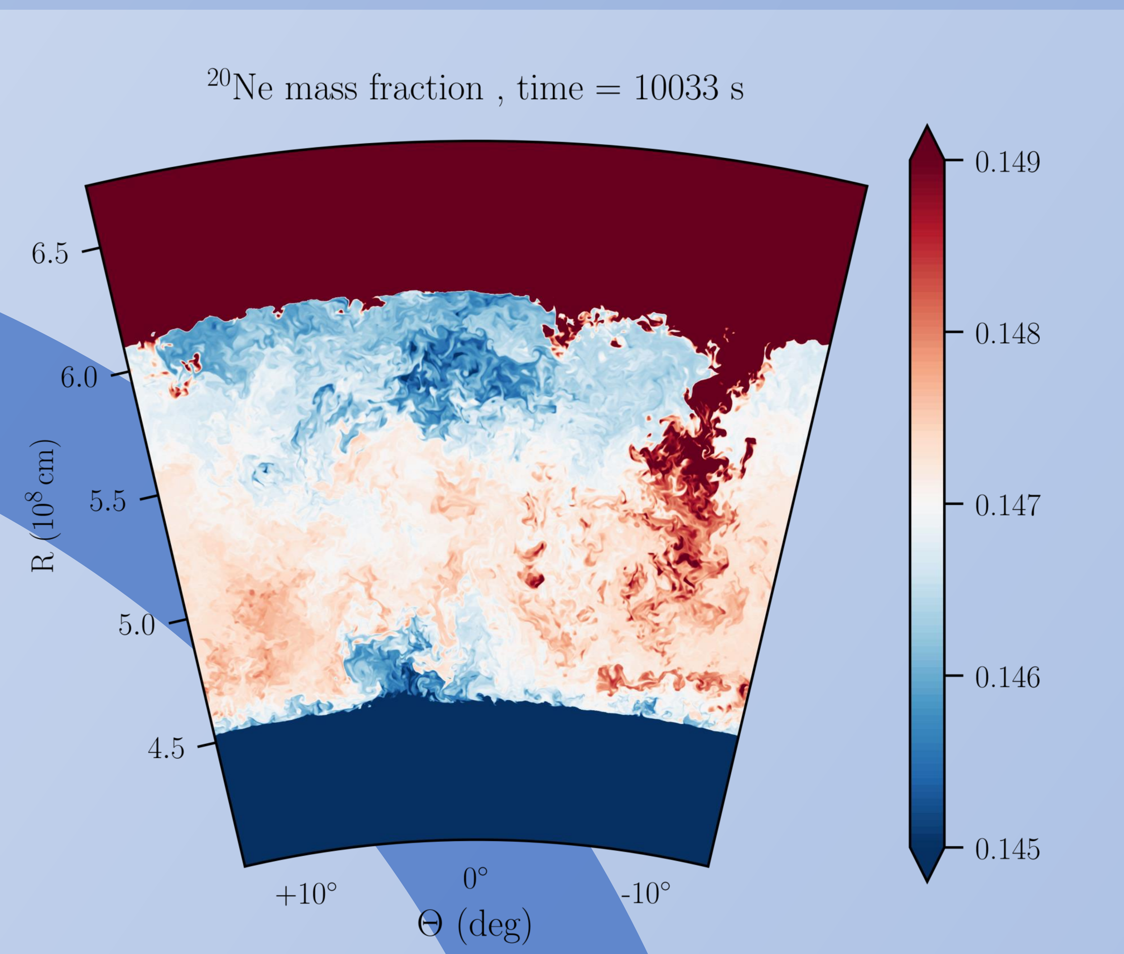
Structure evolution diagram of a 1D stellar evolution model

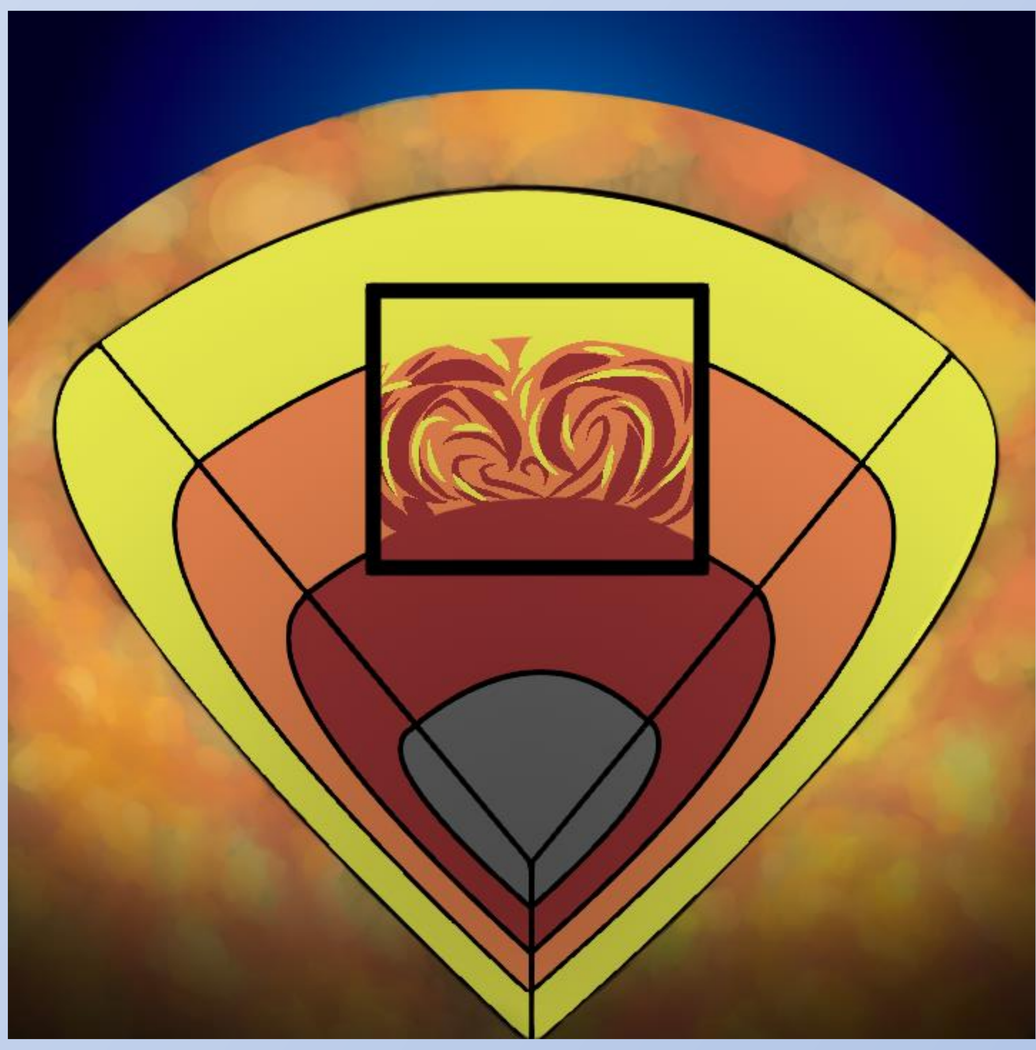


We computed a set of 3D hydrodynamics simulations of a neon-burning shell in a 20 $M_\odot$ star with the PROMPI code. The simulations follow the box/wedge-in-a-star approach.

Convection is driven by the energy released by nuclear reactions involving ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si.

Cross section of the ^{20}Ne mass fraction in the 3D model





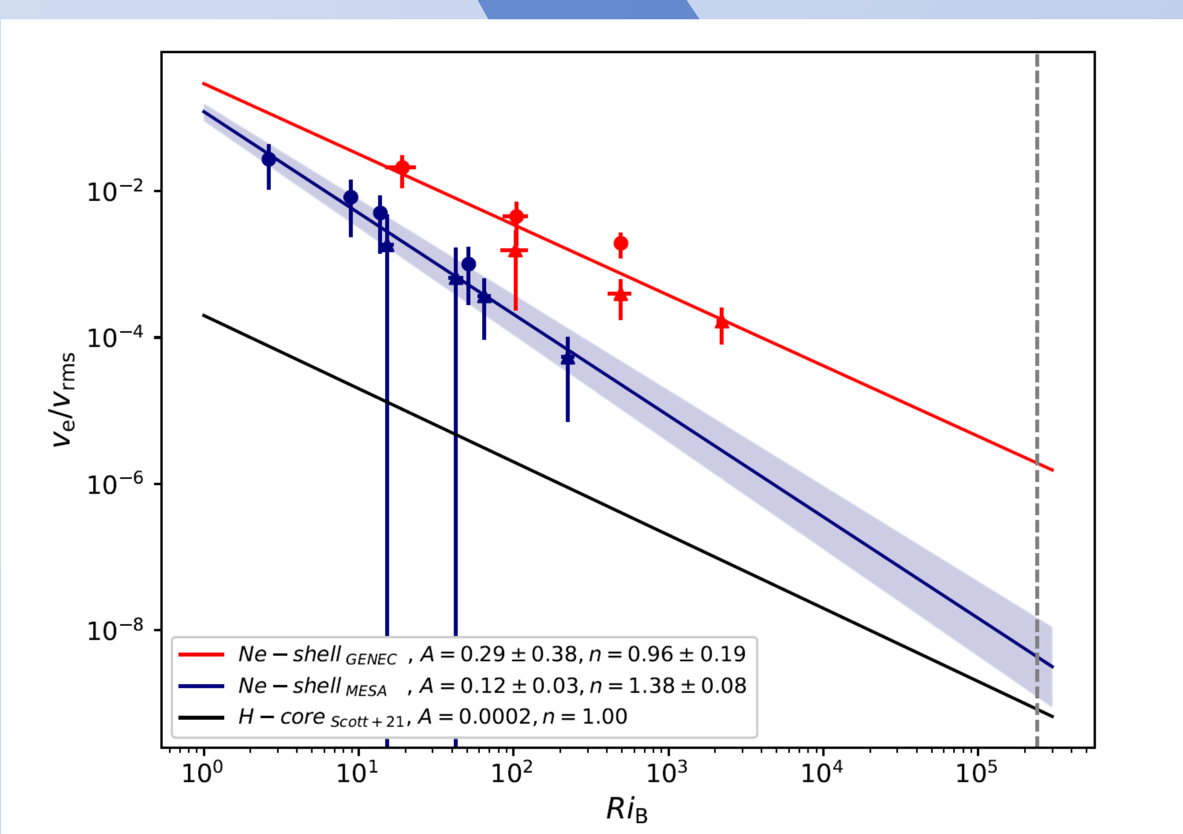
Key results:

- We completed the first burning stage in 3D (bottom-right figure).
- The growth of the convective zone is similar in 1D and 3D demonstrating that 1D & 3D models approach convergence.
- The entrainment law parameters derived are also compatible with observations of main-sequence stars.

The mixing near the convective boundaries entrains material from the stable regions into the convective zone, that grows with time. This phenomenon is known as *entrainment*.

The growth rate of the convective zone depends on the convection and boundary properties.

Entrainment rate versus bulk Richardson number from 3D

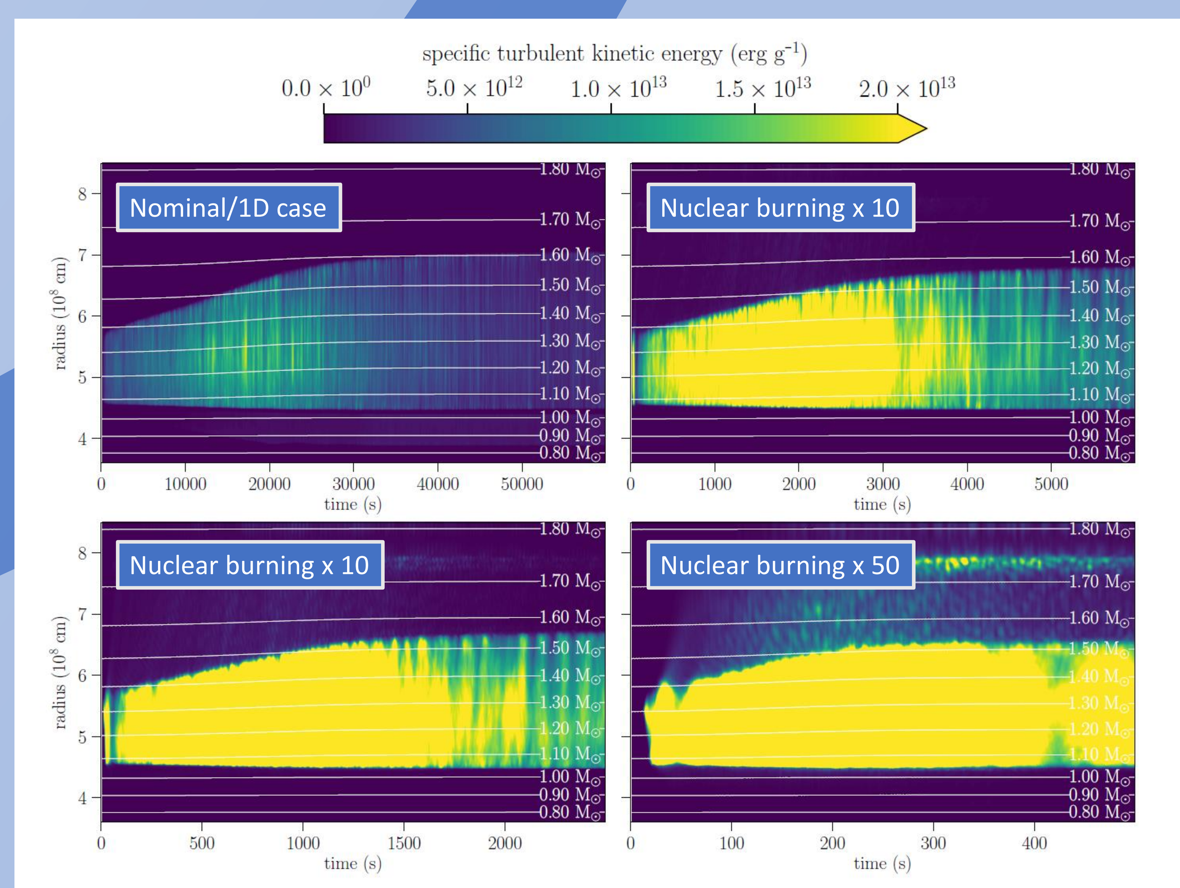


The entrainment rate can be parametrized as a function of the bulk Richardson number:

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

We estimate the value of parameters A = 0.12, n = 1.38, and compare them to previous studies of different stellar phases.

Time evolution of the specific kinetic energy in 3D



Bibliography: Meakin C. A., Arnett D., 2007, ApJ, 667, 448

- Cristini A., Meakin C., Hirschi R., Arnett D., Georgy C., Viallet M., Walkington I., 2017, MNRAS, 471, 279
- Jones S., Andrassy R., Sandalski S., Davis A., Woodward P., Herwig F., 2017, MNRAS, 465, 2991
- Mocák M., Meakin C., Campbell S. W., Arnett W. D., 2018, MNRAS, 481, 2918
- Cristini A., Hirschi R., Meakin C., Arnett D., Georgy C., Walkington I., 2019, MNRAS, 484, 4645
- Horst L., Hirschi R., Edelmann P. V. F., Andrássy R., Röpke F. K., 2021, A&A, 653, A55
- Scott L., Hirschi R., Georgy C., Arnett W. D., Meakin C., Kaiser E. A., et al., 2021, MNRAS, 503, 4208
- Rizzuti F., Hirschi R., Georgy C., Arnett W. D., Meakin C., Murphy A. StJ., 2022, MNRAS, 515, 4013
- Rizzuti F., Hirschi R., Arnett W. D., Georgy C., Meakin C., Murphy A. StJ., Rauscher T., Varma V., 2023, MNRAS, 523, 2317

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