321D modelling of the interplay between turbulence and nuclear reactions in massive stars: shell mergers

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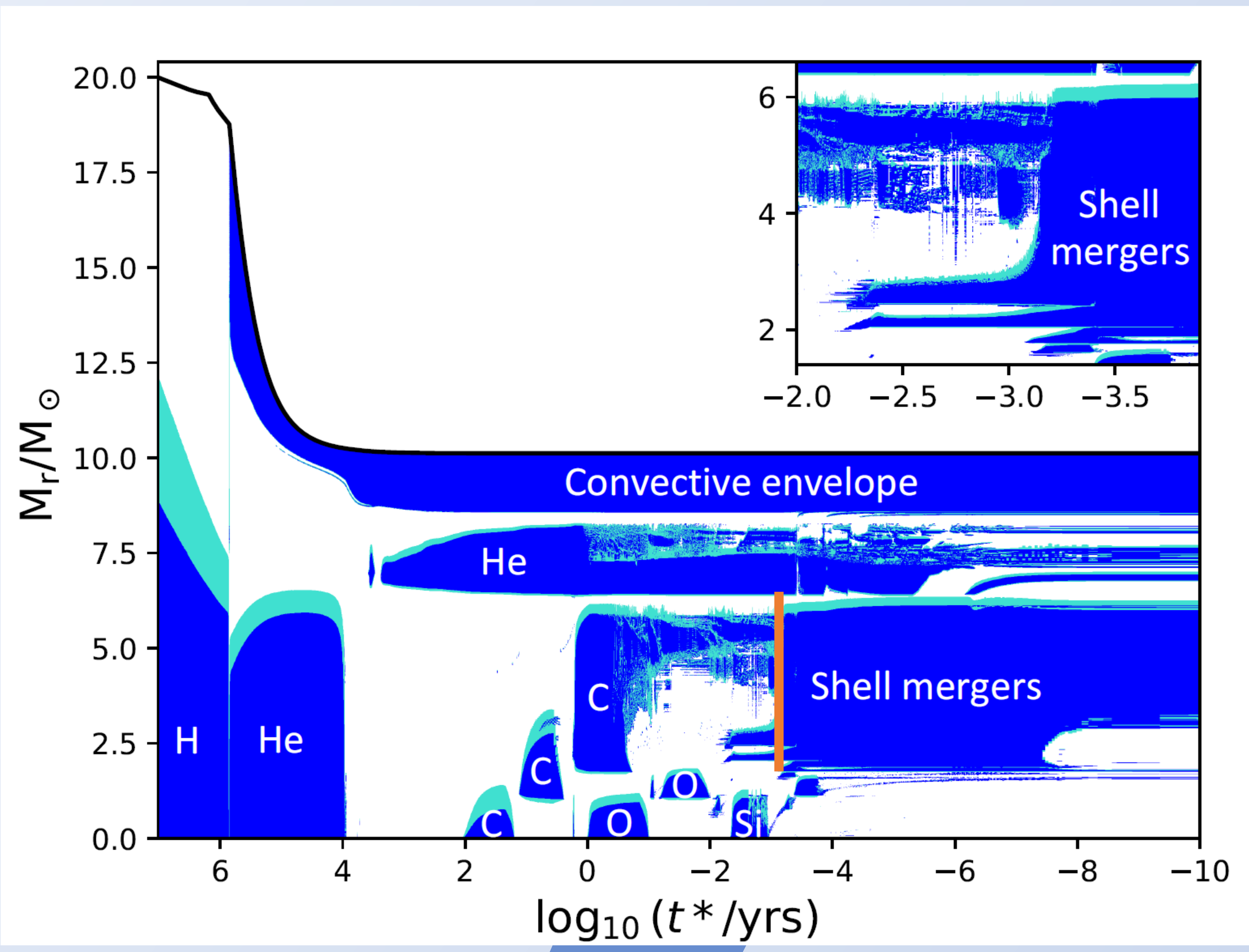
The modelling of massive stars is affected by uncertainties linked to multi-dimensional processes. 3D hydrodynamics simulations can reproduce these 3D processes in stellar interiors and guide the improvement of 1D stellar evolution models (321D loop). We present here 321D modelling of a C-Ne-O shell merger in the late phases of a massive star. We find signification deviations from spherical symmetry and homogeneity, which may lead to unique nucleosynthesis and affect the fate of the star.

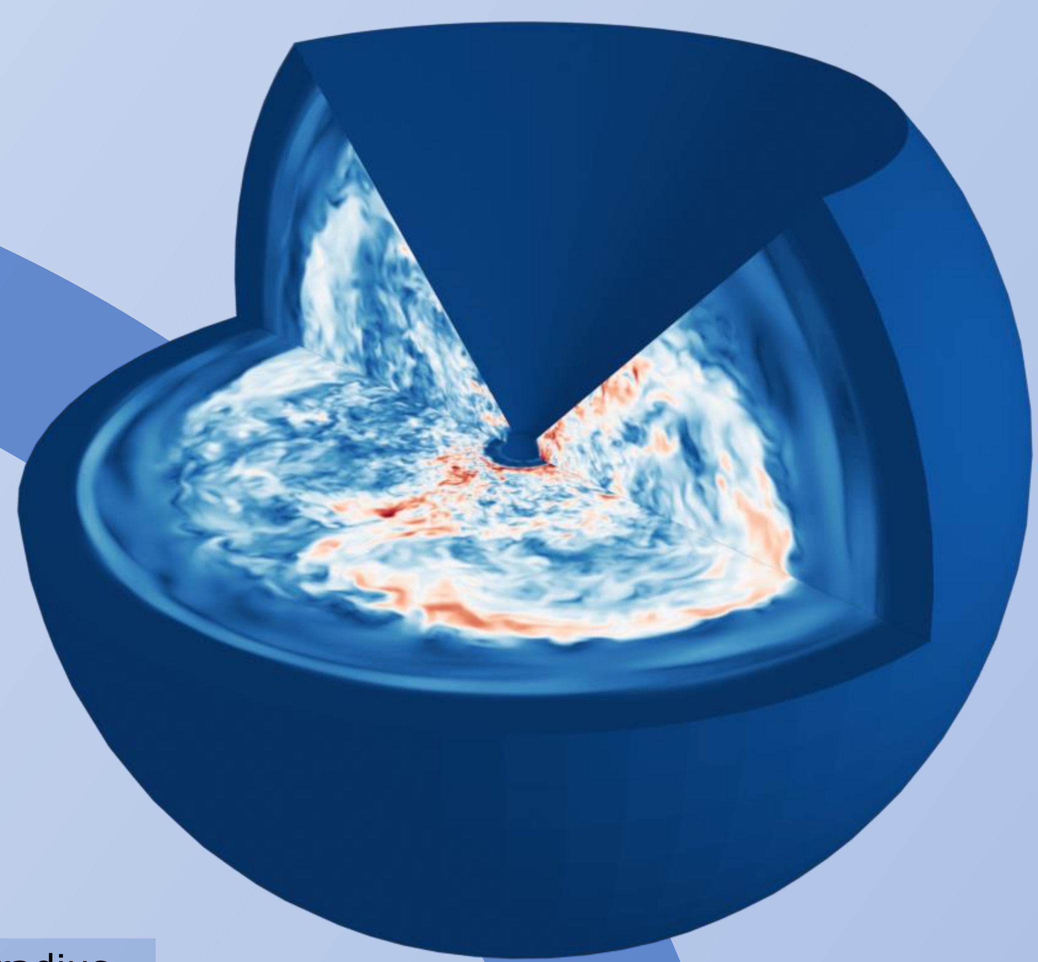
Structure evolution diagram of the 1D input stellar model



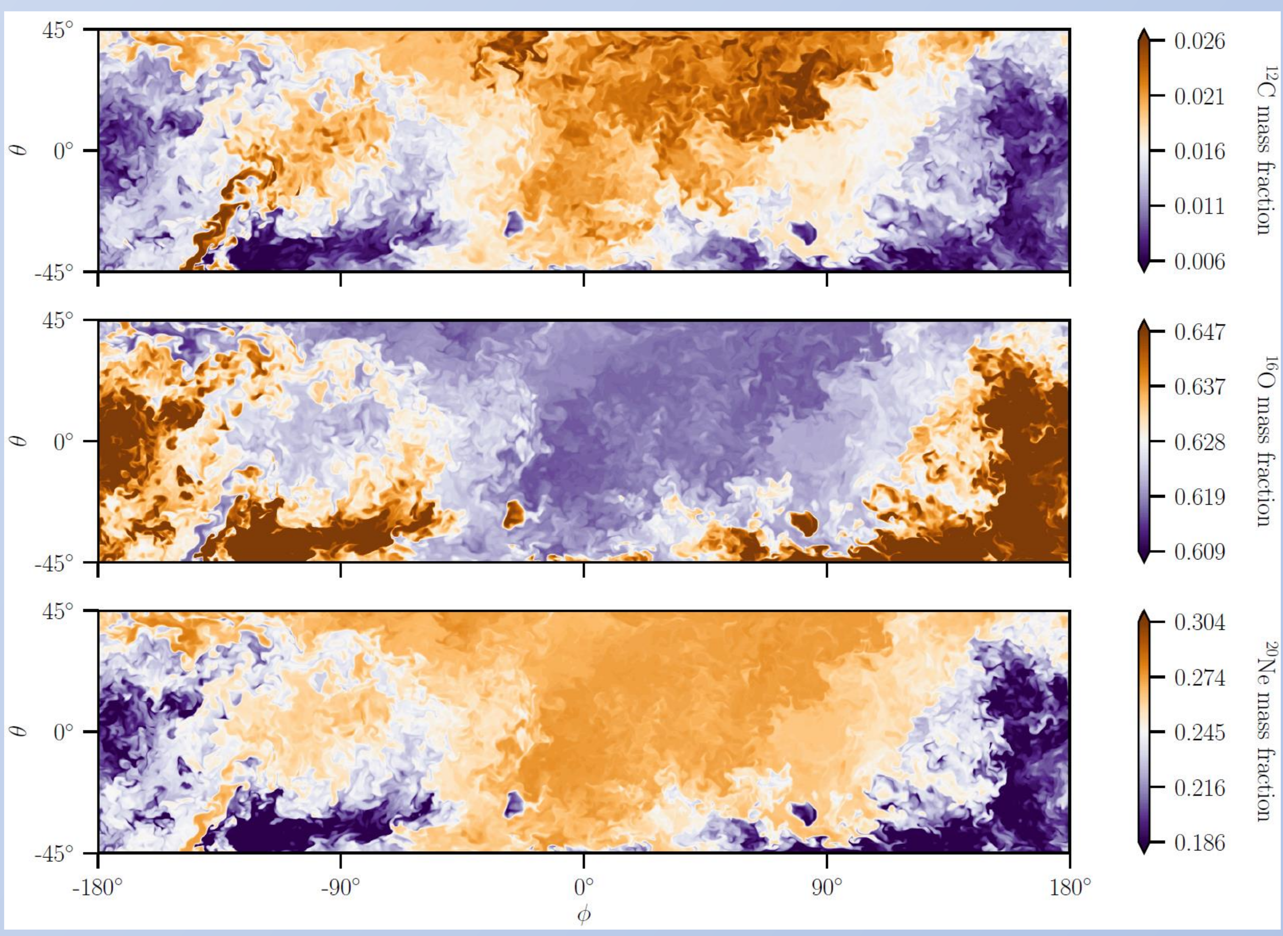
We computed a set of 3D hydrodynamics simulations of a triple-shell merger in a 20 $M_\odot$ star with the PROMPI code (1D input MESA model shown on the left).

The nuclear reaction network includes n, p, ^{4}He, ^{12}C, ^{16}O, ^{20}Ne, ^{23}Na, ^{24}Mg, ^{28}Si, ^{31}P, ^{32}S, ^{56}Ni.

Representation of the 3D computational domain (~2π) comprising equatorial and vertical planes. Colour shows speed.



Angular cross-sections showing abundance fluctuations at fixed radius, spanning 2σ around the mean value (a360n1024 at 1500 s).



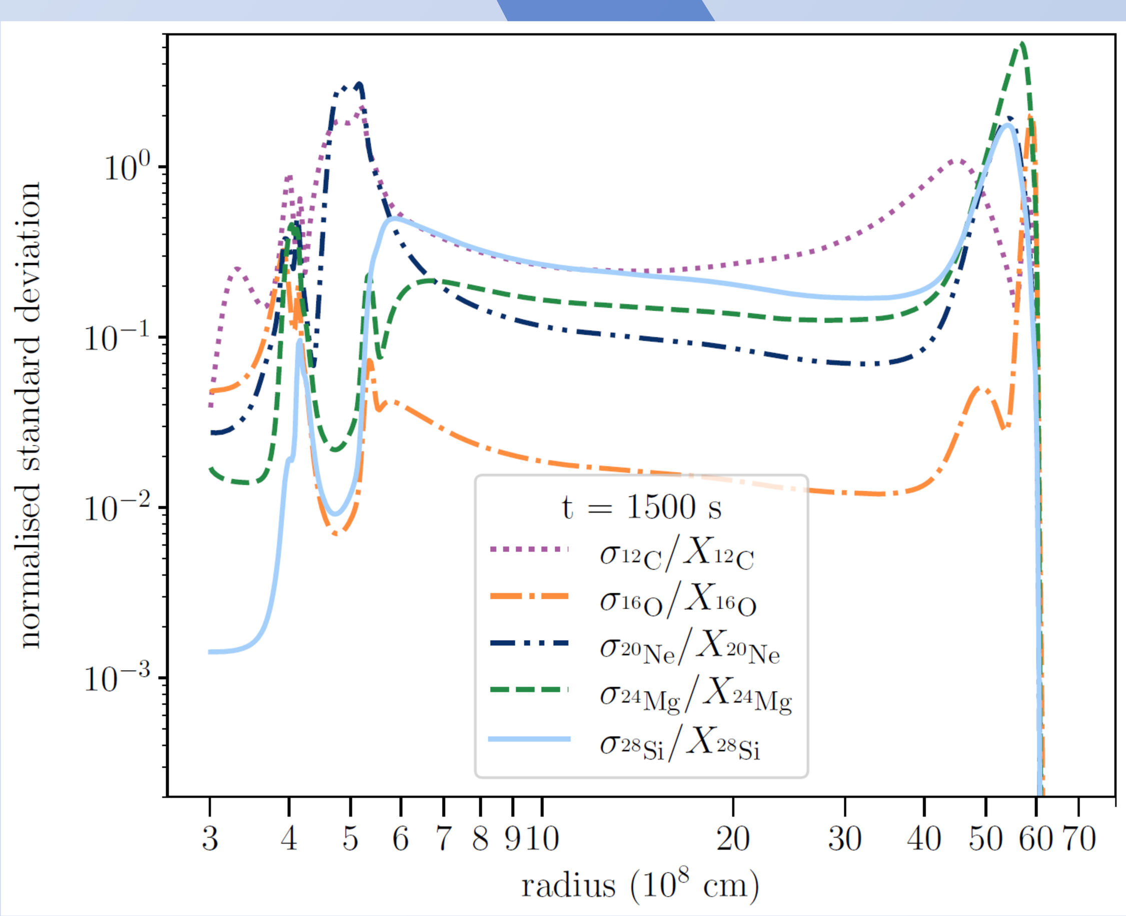
<u>Key Points</u>:

- We can now simulate shell mergers and the related nucleosynthesis in 3D.
- 3D simulations of shell mergers show key similarities and differences compared to the 1D input model.
- Shell mergers create unique conditions that can change both the structure and nucleosynthesis of massive stars.

In the 1D input MESA model, three convective burning shells merge: C, Ne and O, starting with a C-Ne shell merger.

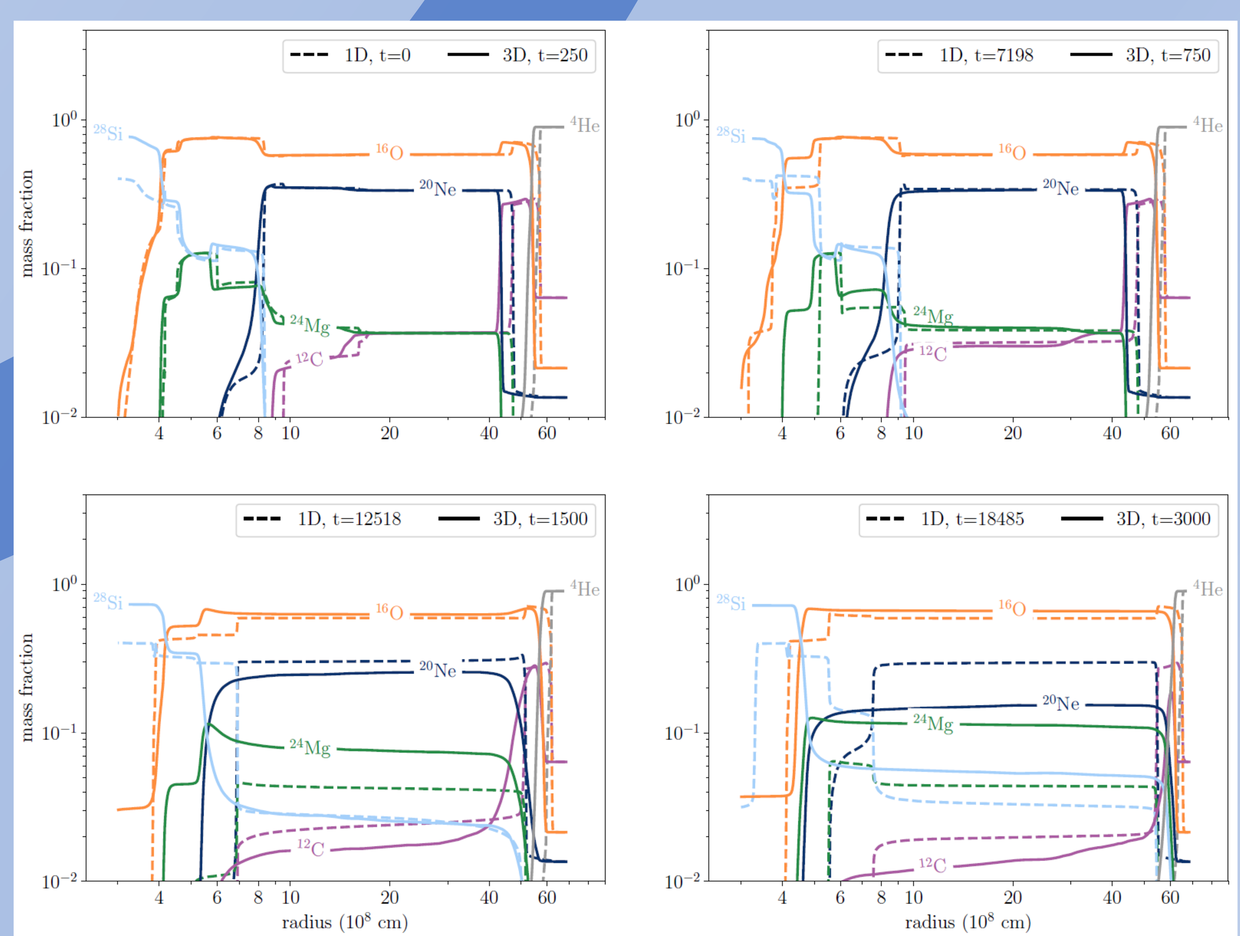
In the 3D simulation, the C-Ne shell merger also occurs (around 1000s, see figure below). However, instead of a further merger with the O-shell (as in 1D), the O-shell weakens and never merges (see t=3000s).

Normalised standard deviation profiles for composition



Shell mergers are dynamic events that create unique nucleosynthesis condition characterised by high a Damköhler number (Da = $t_{mixing}/t_{nuclear}$ ~ 1). In such events, chemical composition is not spherically-symmetric (see figure above), let alone homogeneous (see left figure).

Time evolution of the angularly-averaged chemical composition in both 1D and 3D models.



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<u>**Acknowledgments**</u>: RH acknowledges support from the World Premier International Research Centre Initiative (WPI Initiative), MEXT, Japan and the IReNA AccelNet Network of Networks (National Science Foun- dation, Grant No. OISE-1927130). WDA acknowledges support from the Theoretical Astrophysics Program (TAP) at the University of Arizona and Steward Observatory. CG has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant No. 833925). The University of Edinburgh is a charitable body, registered in Scotland, with Registration No. SC005336. CG, RH, and CM acknowledge ISSI, Bern, for its support in organizing collaboration. This article is based on work from the ChETEC COST Action (CA16117) and the European Union's Horizon 2020 research and innovation programme (ChETEC-INFRA, Grant No. 101008324). The authors acknowledge the STFC DiRAC HPC Facility at Durham University, UK (Grants ST/P002293/1, ST/R002371/1, ST/R000832/1, ST/K00042X/1, ST/H008519/1, ST/ K00087X/1, and ST/K003267/1).

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