321D Modelling of Massive Stars: Nuclear Burning Shell Interactions Open New Nucleosynthesis Pathways

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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 massive stars and the variety of shell interactions (mergers) we find in our latest 321D-guided stellar evolution models. These lead to unique nucleosynthesis and affect the fate of the star.

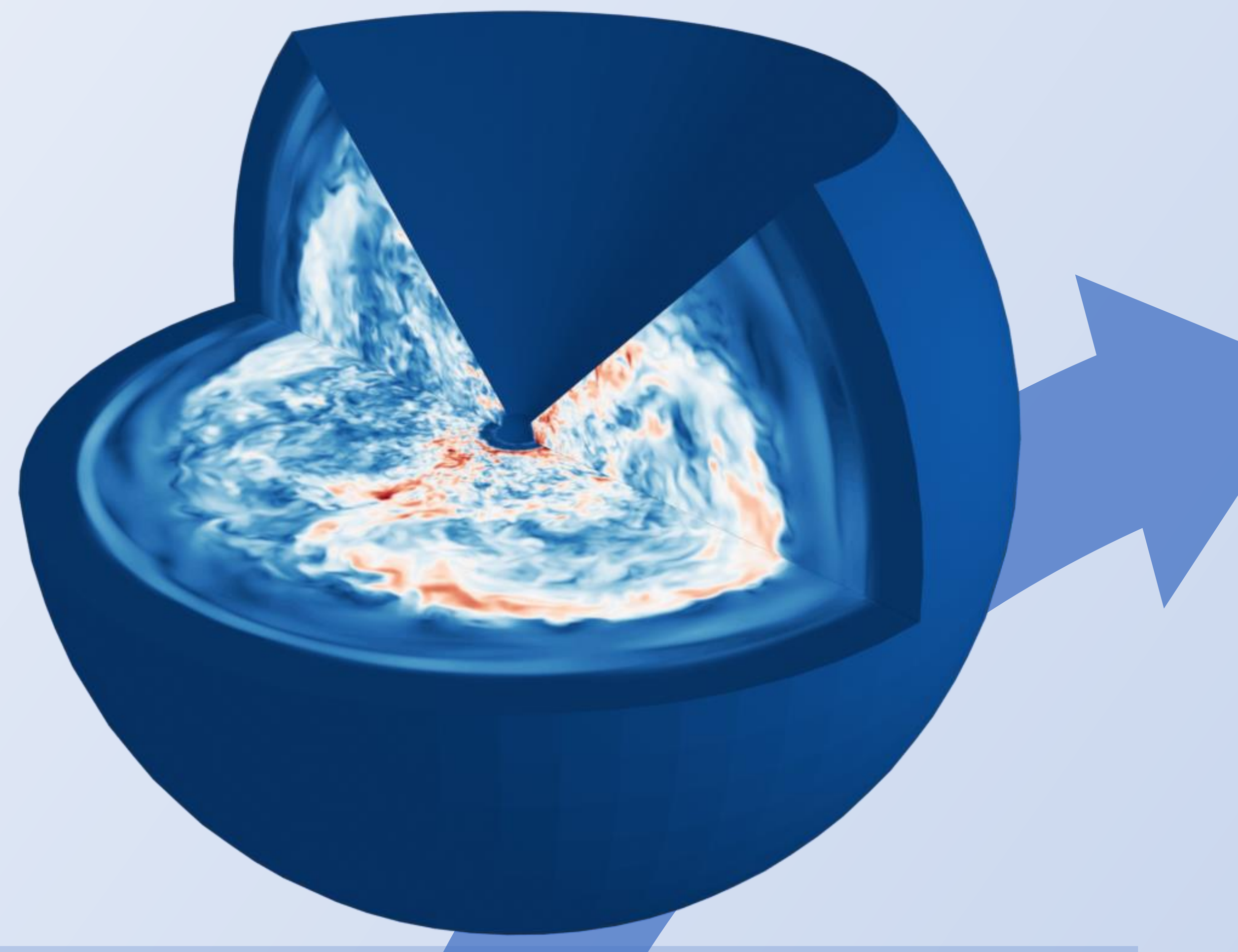

Fig. 1: Representation of a 3D computational domain (~2π) comprising equatorial and vertical planes. Colour shows flow speed. Taken from Rizzuti et al (2024).

We computed a range of 3D hydrodynamics simulations of nuclear burning shells: carbon (Cristini et al 2017, 2019) neon (Rizzuti et al 2023) and silicon (Varma et al, ArXiV2608.04954) as well as shell mergers (see Fig. 1, Rizzuti et al 2024) with the PROMPI code (Meakin & Arnett 2007) using initial conditions from 1D MESA or GENEC stellar evolution models, see e. g. in Fig. 4). 3D simulations include up to 25 nuclides.

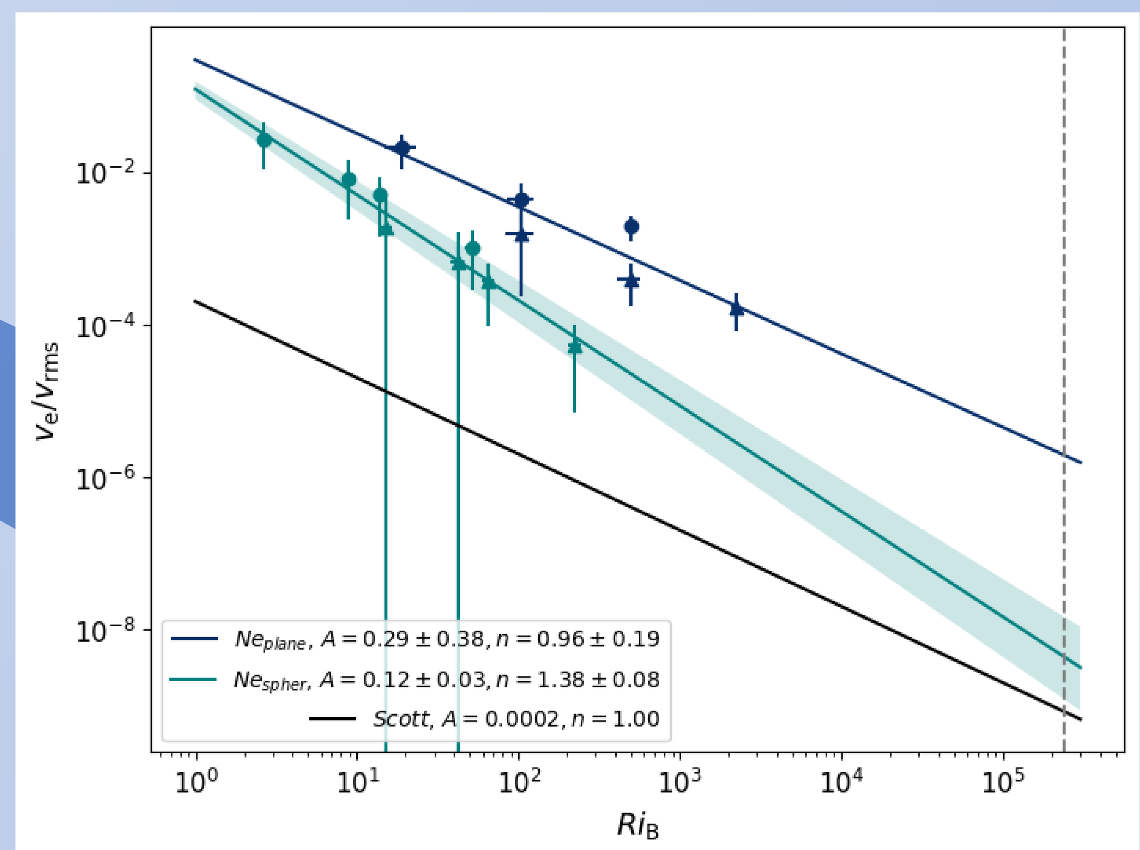

Fig. 2: Fitting of entrainment law parameters using the results of 3D simulations as well as analysis of 1D models (Scott et al 2021, SH21). Taken from Rizzuti et al (2023).

Key Points:

- We can use 3D simulations to guide 1D stellar evolution modelling (321D loop).
- Our latest 321D-guided models encounter a wide range of shell interactions/mergers.
- Shell mergers create unique conditions that change the structure, fate and nucleosynthesis of massive stars.

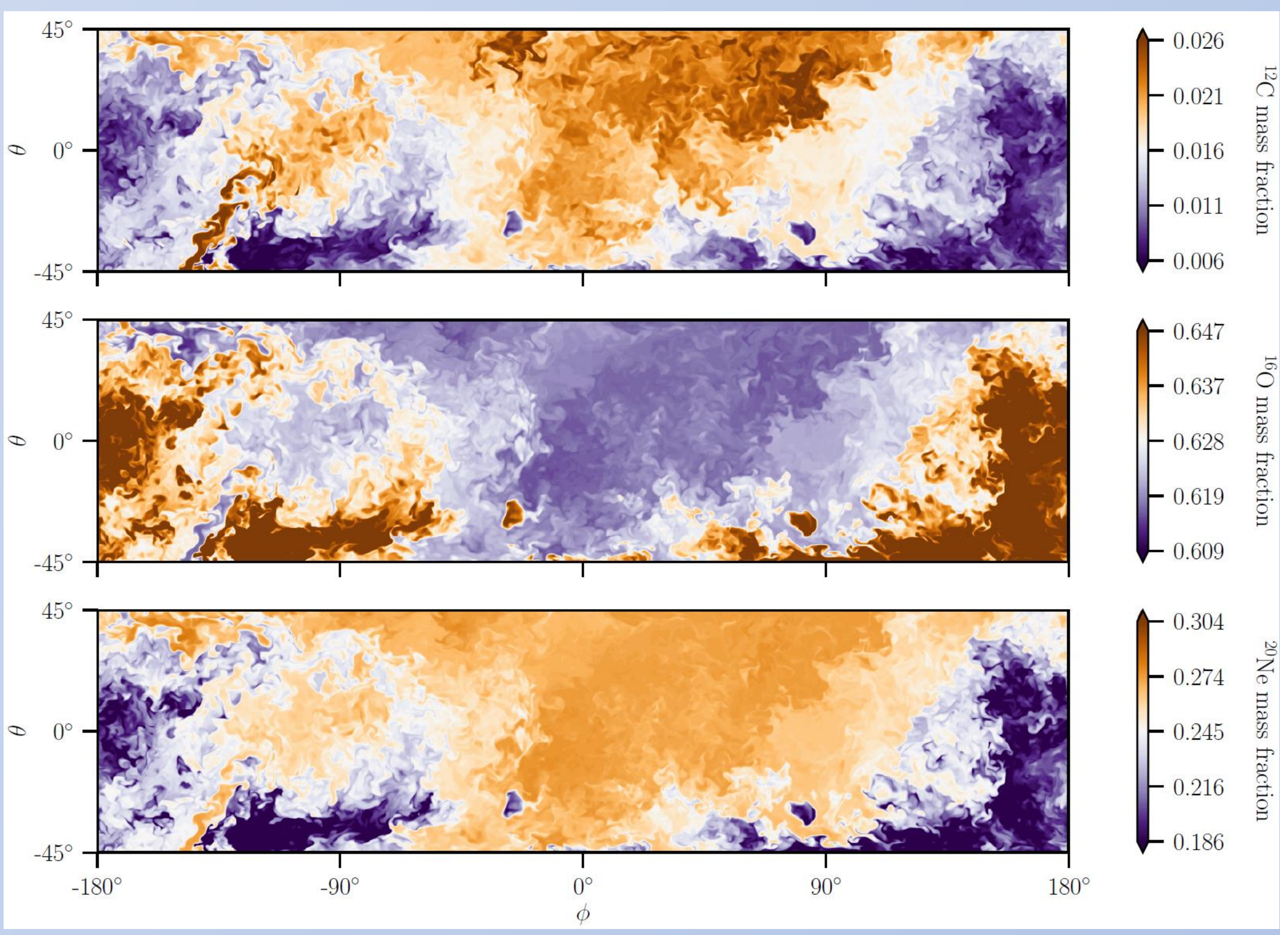

Fig. 3: Angular cross-sections showing abundance fluctuations at fixed radius, spanning 2σ around the mean value (a360n1024 simulation from Rizzuti et al 2024 at 1500 s).

Combining 3D simulations and theory (entrainment law), we can guide new prescriptions for convective boundary mixing (CBM) in 1D stellar evolution codes (321D loop). Using our new 321D-guided CBM prescription (called SH21), we computed a new grid of 1D stellar evolution models (Whitehead et al 2026) and a comparison grid (called f0p02).

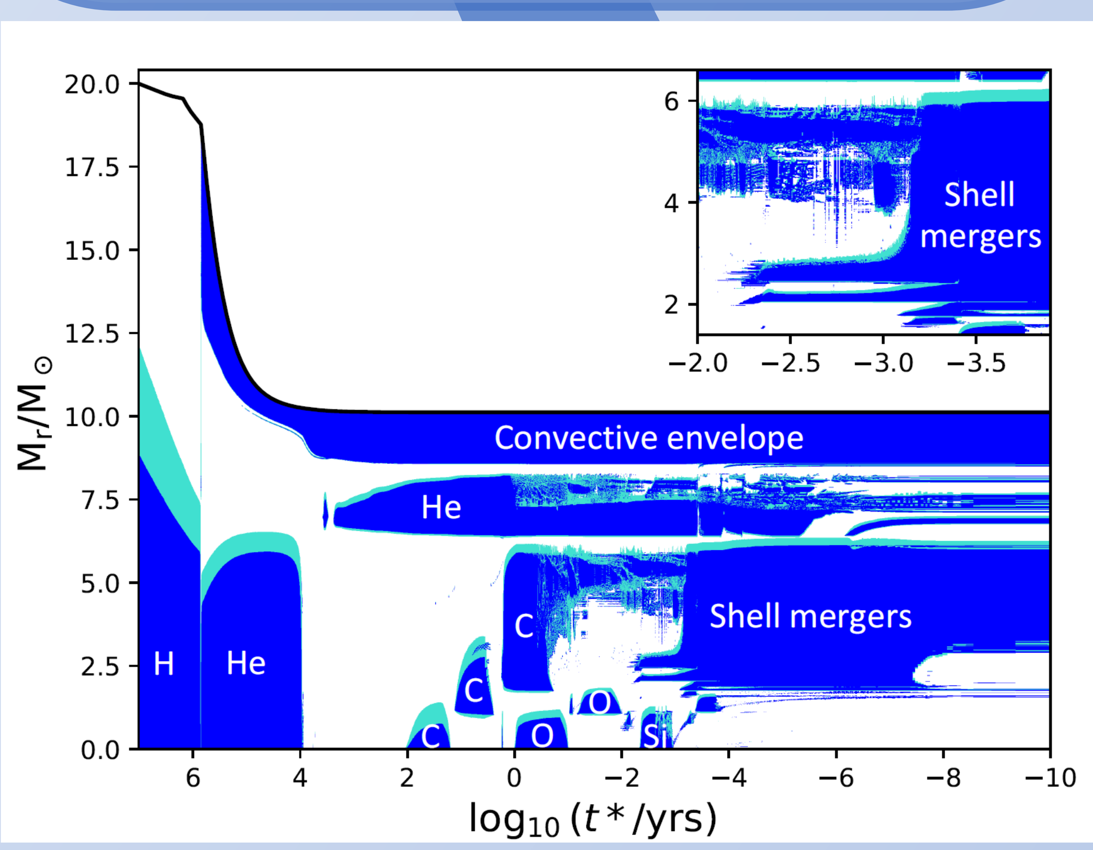

Fig. 4: Structure evolution diagram of a 1D stellar model experiencing a C-Ne-O shell merger. Blue regions are convective. Cyan regions show CBM regions. Taken from Rizzuti et al (2024).

Shell mergers are dynamic events that create unique nucleosynthesis conditions characterised by high a Damköhler number (Da = $t_{mixing}/t_{nuclear}$ ~ 1). In such events, chemical composition is not spherically-symmetric (see Fig. 3) and deviate from the traditional 1D onion-like picture of massive stars.

Table 3. Properties of the SH21 grid at the pre-SN stage (columns 1-14): model codename, CO-core mass (M_{CO}), effective temperature (Log T_{eff}), radius (Log R), luminosity (Log L), interaction type, total final mass (M_{fin}), total lifetime (τ), central entropy (s_c), mass of the carbon-free core M_{C-free}, compactness parameter measured at a mass coordinate of 2.5 $M_\odot$ ($\xi_{2.5}$) and the mass derivative (μ_4), mass coordinate (M_4) and $M_4\mu_4$, all calculated at the mass coordinate where the entropy per nucleon $s = 4$.

Name	M_{CO} [$M_\odot$]	Log(T_{eff}) [K]	Log(R) [$R_\odot$]	Log(L) [$L_\odot$]	Interactions	M_{fin} [$M_\odot$]	τ [Myr]	s_c [$\frac{k_B}{baryon}$]	M_{C-free} [$M_\odot$]	$\xi_{2.5}$	μ_4 [$\frac{M_\odot}{1000\,km}$]	M_4 [$M_\odot$]	$M_4\mu_4$ [$\frac{M_\odot^2}{1000\,km}$]
10SH21	2.282	3.579	2.800	4.871	C-Ne-O	9.435	27.179	0.704	2.265	0.041	0.047	1.685	0.080
11SH21	2.734	3.577	2.852	4.968	C-Ne-O	10.196	23.526	0.757	2.615	0.084	0.050	1.552	0.078
12SH21	3.222	3.577	2.894	5.050	C-Ne-O	11.142	20.770	0.809	3.024	0.110	0.041	1.734	0.071
13SH21	3.702	3.578	2.926	5.117	C-Ne-O	11.944	18.601	0.883	3.019	0.164	0.053	1.868	0.100
14SH21	4.254	3.577	2.959	5.182	C-Ne-O	12.174	16.870	0.971	3.157	0.247	0.069	2.032	0.140
15SH21	4.787	3.581	2.978	5.236	C-Ne-O	13.243	15.545	1.040	3.560	0.391	0.104	2.225	0.231
16SH21	5.212	3.583	2.996	5.276	C-Ne-O	13.791	14.252	1.044	3.674	0.389	0.111	2.181	0.242
17SH21	5.634	3.585	3.006	5.305	C-Ne-O	14.862	13.180	1.032	4.032	0.376	0.103	2.189	0.226
18SH21	6.026	3.587	3.018	5.338	C-Ne-O	15.136	12.276	0.995	4.181	0.293	0.083	2.062	0.171
19SH21	6.481	3.589	3.027	5.365	C-Ne-O	15.142	11.495	1.002	4.406	0.317	0.086	2.130	0.184
20SH21	1.778	3.574	3.234	5.716	He-C H-He	16.948	10.833	0.717	1.778	$\sim 0^{1}$	0.040	1.413	0.056
21SH21	7.417	3.589	3.082	5.475	Multiple	18.644	10.246	0.763	2.129	0.135	0.069	1.620	0.111
22SH21	8.005	3.589	3.169	5.649	Multiple	16.883	9.731	0.860	2.252	0.177	0.082	1.690	0.139
23SH21	8.373	3.597	3.171	5.683	Multiple	19.725	9.286	0.991	2.659	0.301	0.096	1.943	0.186
24SH21	9.068	3.597	3.102	5.543	Multiple	18.190	8.875	0.813	4.066	0.208	0.073	1.686	0.122
25SH21	9.383	3.598	3.121	5.586	H-He He-C C-Ne	18.256	8.521	0.961	2.313	0.279	0.101	1.915	0.194
30SH21	3.162	3.601	3.158	5.673	He-C C-Ne-O	22.977	7.182	0.803	2.513	0.130	0.066	1.582	0.104
35SH21	2.714	3.621	3.175	5.786	He-C C-Ne-O-Si	19.570	6.346	0.701	2.635	0.083	0.040	1.473	0.058
40SH21	4.589	3.623	3.220	5.885	He-C	23.085	5.715	0.989	2.912	0.338	0.126	2.000	0.251
45SH21	5.351	3.626	3.264	5.984	He-C	26.039	5.248	1.078	3.737	0.464	0.148	2.190	0.323

Table 1 (Table 3 from Whitehead et al 2026): Key properties of the SH21 models with in particular the types of shell interactions/mergers found in the models.

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
- Cristini A., Hirschi R., Meakin C., Arnett D., Georgy C., Walkington I., 2019, MNRAS, 484, 4645
- Scott L., Hirschi R., Georgy C., Arnett W. D., Meakin C., Kaiser E. A., et al., 2021, MNRAS, 503, 4208
- Rizzuti F., Hirschi R., Arnett W. D., Georgy C., Meakin C., Murphy A. StJ., Rauscher T., Varma V., 2023, MNRAS, 523, 2317
- Rizzuti F., Hirschi R., Varma V., Arnett W. D., Georgy C., Meakin C., Mocák M., Murphy A. StJ., Rauscher T., 2024, MNRAS, 533, 687
- Whitehead E., Hirschi R., Varma V., Mueller B., Rizzuti F., Georgy C., Arnett W. D., 2026, MNRAS, 546, 2245

Acknowledgments: This work is guided by the 3D hydrodynamic simulations run on the DiRAC Memory Intensive service (Cosma8) at Durham University, managed by the Institute for Computational Cosmology on behalf of the STFC DiRAC HPC Facility (www.dirac.ac.uk). The DiRAC service at Durham was funded by BEIS, UKRI and STFC capital funding, Durham University and STFC operations grants. DiRAC is part of the UKRI Digital Research Infrastructure. EW acknowledges receipt of an STFC postgraduate studentship. BM acknowledges support from the Australian Research Council through Discovery Project DP240101786. BM acknowledges computer time allocations from Astronomy Australia Limited's ASTAC scheme and the National Computational Merit Allocation Scheme (NCMAS). Some of this work was performed on the Gadi supercomputer with the assistance of resources and services from the National Computational Infrastructure (NCI), which is supported by the Australian Government, RH acknowledges support from the World Premier International Research Centre Initiative (WPI Initiative), MEXT, Japan, the IReNA AccelNet Network of Networks (National Science Foundation, grant no. OISE-1927130) and the Wolfson Foundation. FR is a fellow of the Alexander von Humboldt Foundation. FR acknowledges support by the Klaus Tschira Foundation, by the INAF Mini grant 2024, 'GALoMS – Galactic Archaeology for Low Mass Stars' (1.05.24.07.02), and by the National Recovery and Resilience Plan (NRRP), funded by the European Union–NextGenerationEU, Project 'Cosmic POT' (PI: L. Magrini) Grant Assignment Decree no. 2022X4TM3H by the Italian Ministry of University and Research (MUR).

Watch the merger movie!

Link to Whitehead et al (2026)