UNIVERSITÀ DEGLI STUDI DI TRIESTE

Keele University

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Nucleosynthesis in 3D stellar evolution models

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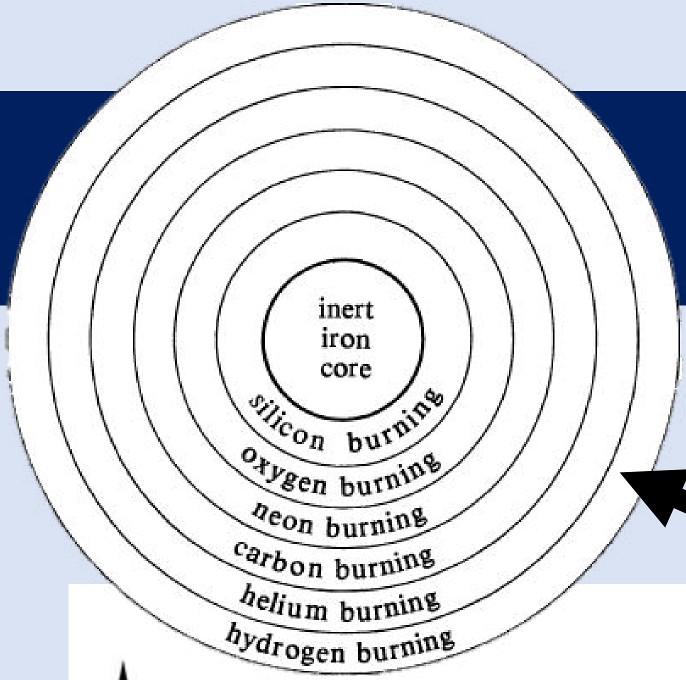
Why is stellar modelling important?

sdo.gsfc.nasa.gov

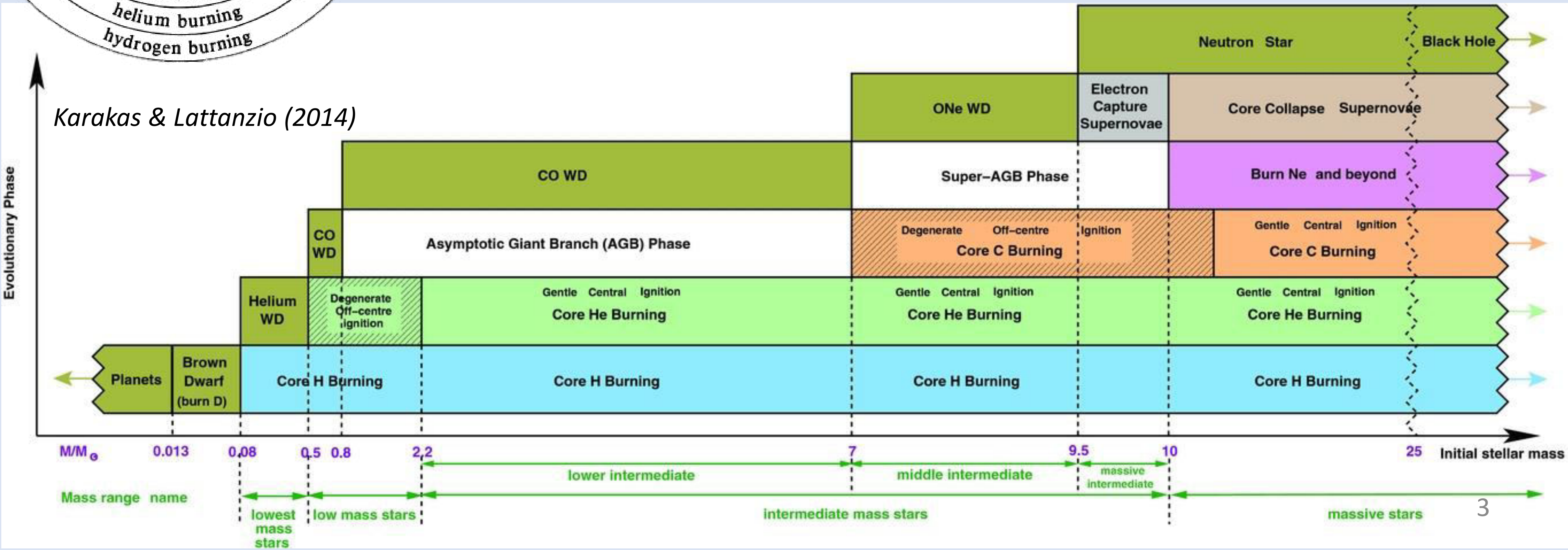
Explaining and predicting stellar lives (and deaths) affects:

- observations (stellar parameter estimations, isochrone fitting, asteroseismology…)
- supernova progenitor studies
- neutron star and black hole physics
- **nuclear reaction rates**
- **stellar nucleosynthesis**

A star's life: nuclear burning phases



- The life of a star: a sequence of nuclear burning phases
- A progression in time, but also in space:
the onion-ring structure

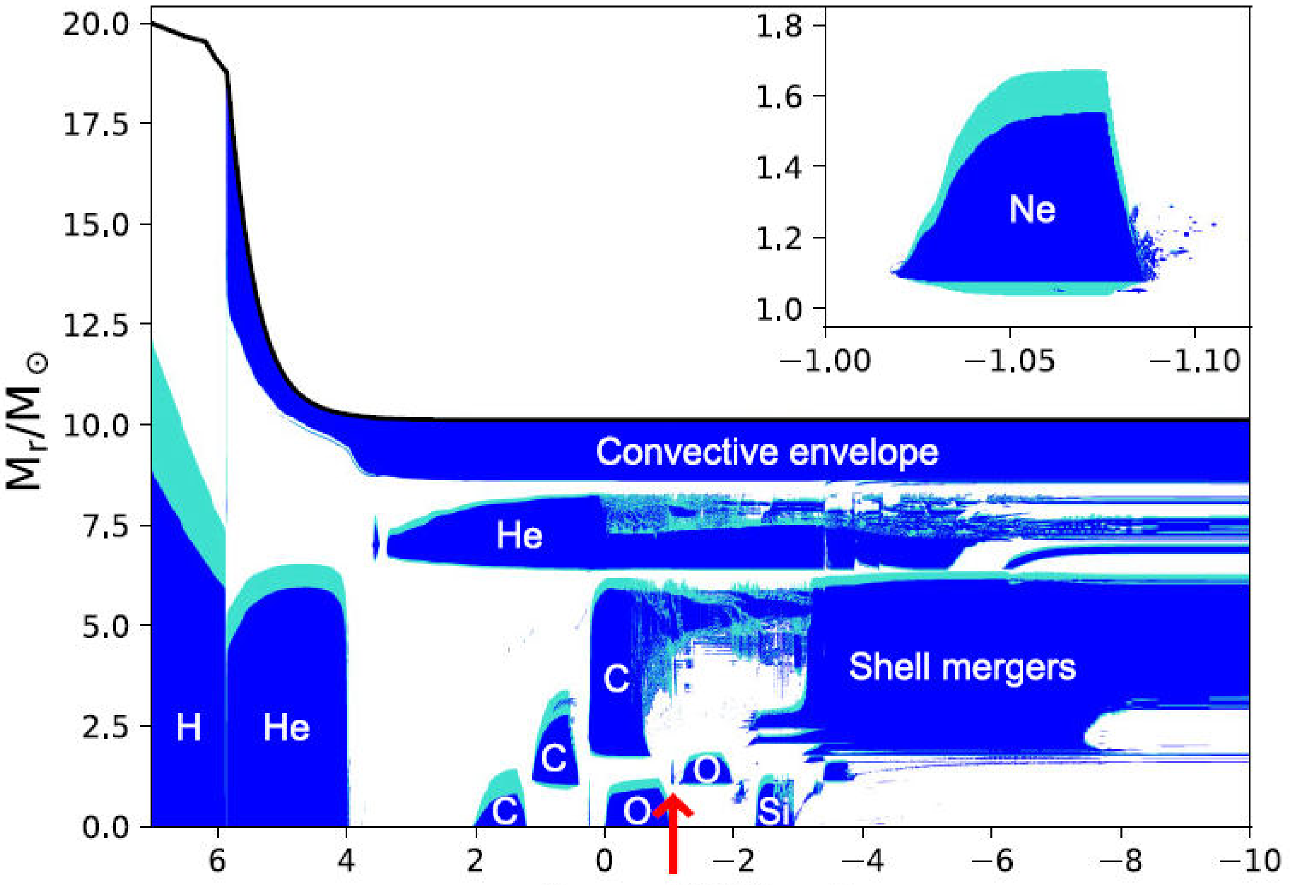


Karakas & Lattanzio (2014)

1D stellar evolution models

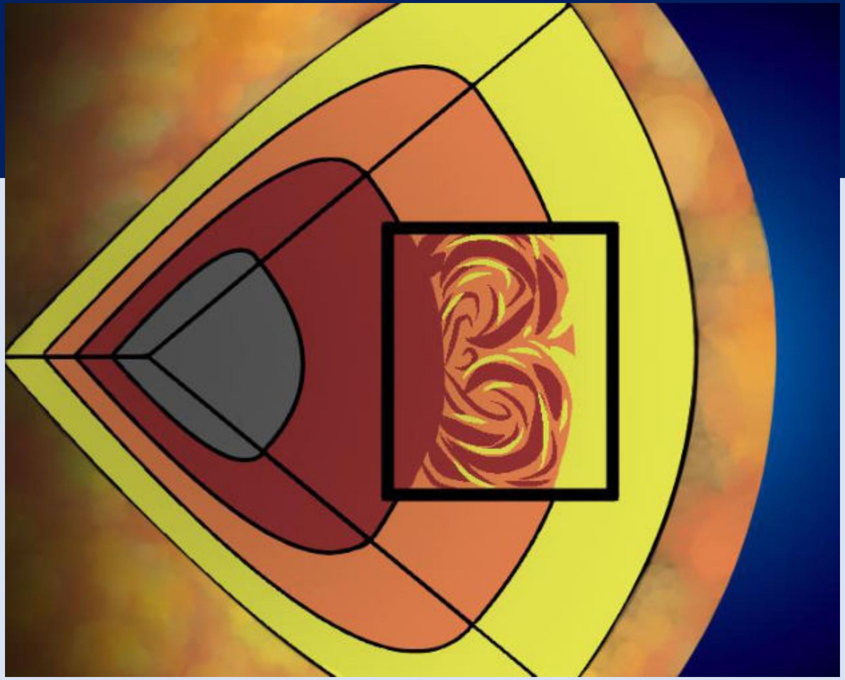
Advantages:
- can model the full star and cover the entire lifetime
- easily compared to obsevations
- can explore mass and metallicity

Disadvantages:
- assuming spherical symmetry
- parametrized physics for multi-D processes: mass loss, convection, rotation, magnetic fields, opacity, binarity (and their interplay)



Rizzuti et al. (2023)

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

321D: the link between 1D and multi-D

1D models:

- spherical symmetry
- assuming prescriptions / parametrizations
- subjected to uncertainties

Initial conditions

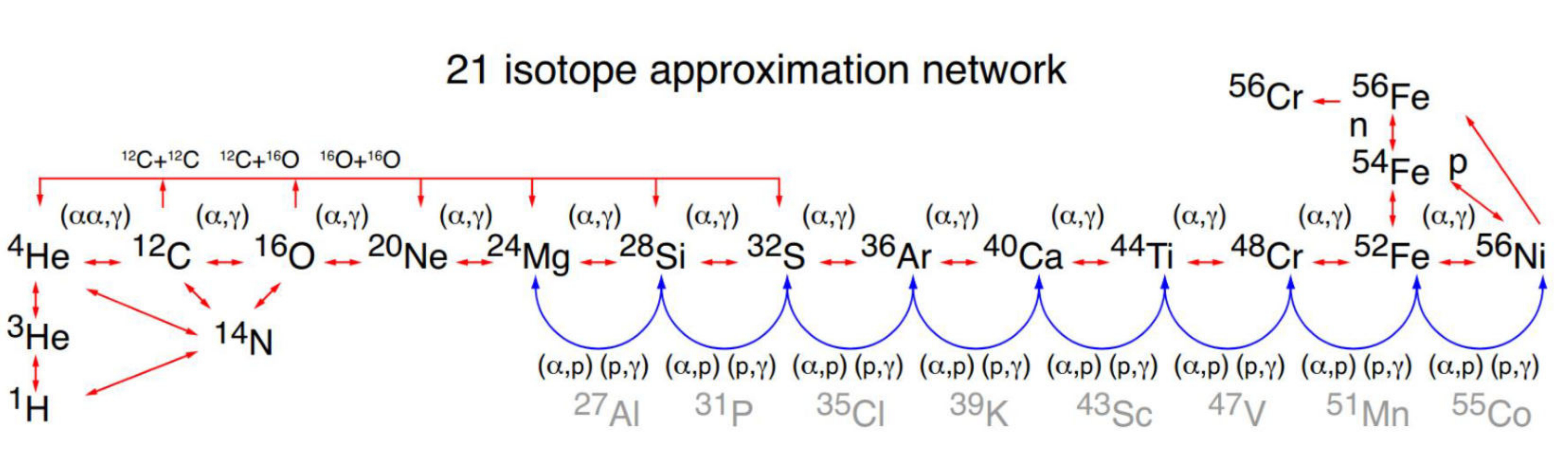
multi-D models:

- break the symmetry
- small space extension
- short timescale (hrs)

improve theoretical prescriptions / estimate coefficients

Nuclear burning in 1D models

- 1D MESA models can use a simple 21-isotope network
- It covers all burning phases, hydrogen- to silicon-, but with approximations
- Larger networks are available, but no one is perfect

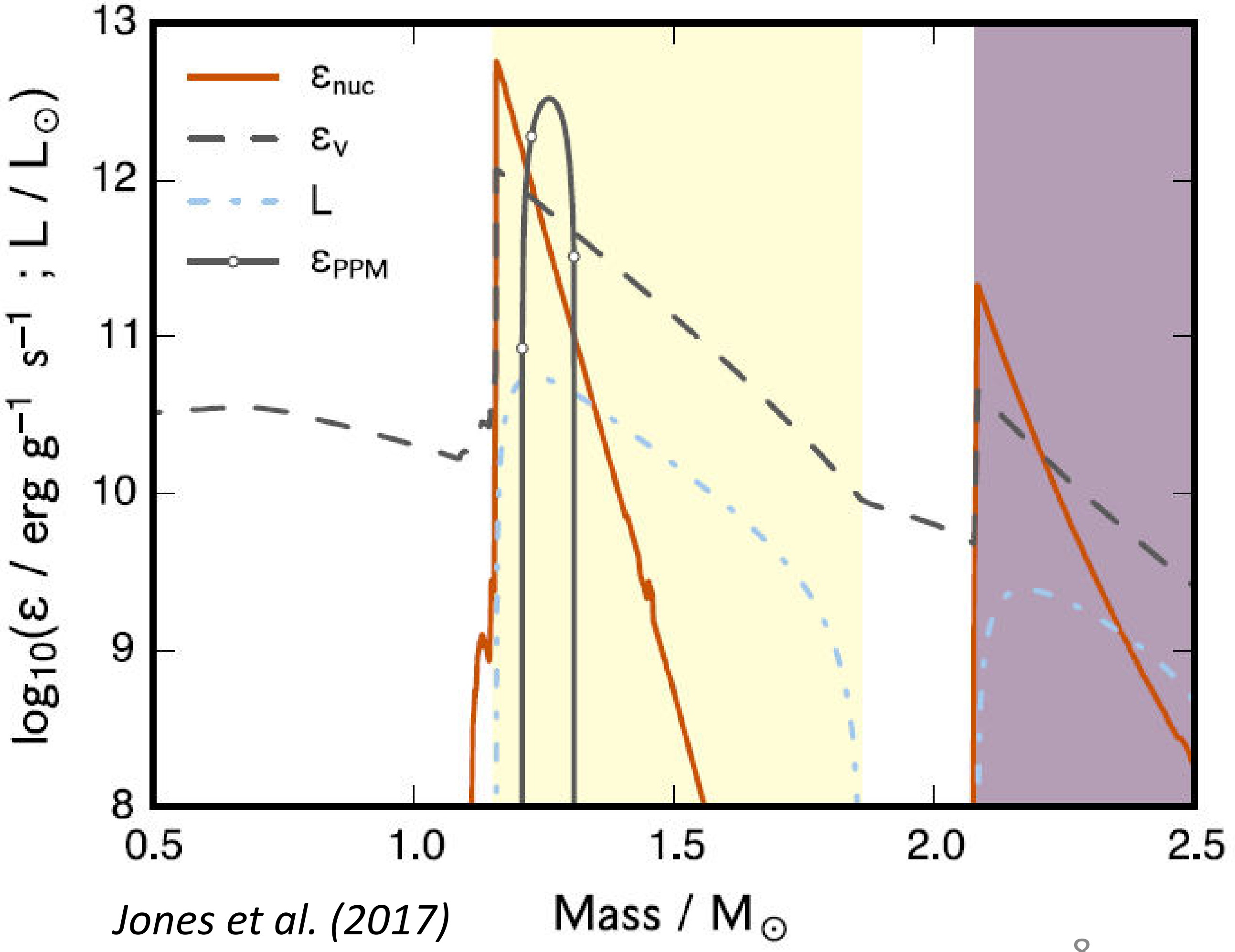


Timmes, cococubed.com

Nuclear burning in 3D models

- Need to consider the computational cost
- Time-independent: fixed heating profile from 1D model
- Time-dependent: explicit set of isotopes and nuclear reactions

→ more accurate, but more expensive!



Jones et al. (2017)

A simple network for 3D models

- We use a 12-isotopes nuclear burning routine:

  → n, p, ^{4}He, ^{12}C, ^{16}O, ^{20}Ne, ^{23}Na, ^{24}Mg, ^{28}Si, ^{31}P, ^{32}S, ^{56}Ni

- Energy generation reactions for different environments:

  →He-burning: $^{4}\mathrm{He}(2\alpha,\gamma)^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}(\alpha,\gamma)^{20}\mathrm{Ne}$;

  →C-burning: $^{12}\mathrm{C}(^{12}\mathrm{C},\alpha)^{20}\mathrm{Ne}$; $^{12}\mathrm{C}(^{12}\mathrm{C},p)^{23}\mathrm{Na}$; $^{23}\mathrm{Na}(p,\alpha)^{20}\mathrm{Ne}$; $^{23}\mathrm{Na}(p,\gamma)^{24}\mathrm{Mg}$;

  →Ne-burning: $^{20}\mathrm{Ne}(\gamma,\alpha)^{16}\mathrm{O}$; $^{20}\mathrm{Ne}(\alpha,\gamma)^{24}\mathrm{Mg}$; $^{24}\mathrm{Mg}(\alpha,\gamma)^{28}\mathrm{Si}$

  →O-burning: $^{16}\mathrm{O}(^{16}\mathrm{O},\alpha)^{28}\mathrm{Si}$; $^{16}\mathrm{O}(^{16}\mathrm{O},p)^{31}\mathrm{P}$; $^{31}\mathrm{P}(p,\alpha)^{28}\mathrm{Si}(\alpha,\gamma)^{32}\mathrm{S}$

- For normalization: ^{56}Ni
- Assuming: the latest rates of the JINA-REACLIB database

JINA-CEE

The PROMPI 3D Hydrodynamical Code

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla} \cdot (\rho\, \boldsymbol{v}) = 0;$$

$$\rho \frac{\partial \boldsymbol{v}}{\partial t} + \rho\, \boldsymbol{v} \cdot \boldsymbol{\nabla} \boldsymbol{v} = -\boldsymbol{\nabla} p + \rho\, \mathbf{g};$$

$$\rho \frac{\partial E_{\mathrm{t}}}{\partial t} + \rho\, \boldsymbol{v} \cdot \boldsymbol{\nabla} E_{\mathrm{t}} + \boldsymbol{\nabla} \cdot (p\, \boldsymbol{v}) = \rho\, \boldsymbol{v} \cdot \mathbf{g} + \rho(\epsilon_{\mathrm{nuc}} + \epsilon_{\nu});$$

$$\rho \frac{\partial X_{\mathrm{i}}}{\partial t} + \rho\, \boldsymbol{v} \cdot \boldsymbol{\nabla} X_{\mathrm{i}} = R_{\mathrm{i}},$$

PROMPI : Meakin, Arnett+ 2007-onwards
PROMETHEUS : Fryxell, Mueller, Arnett 1989
PPM method : Colella & Woodward 1984

- PROmetheus MPI (domain decomposition)
- finite-volume, time explicit, Eulerian, PPM implementation
- Helmholtz eos, general nuclear reaction network
- Cartesian, spherical or cylindrical geometry
- reflective or periodic boundary conditions, shell gravity, velocity damping...

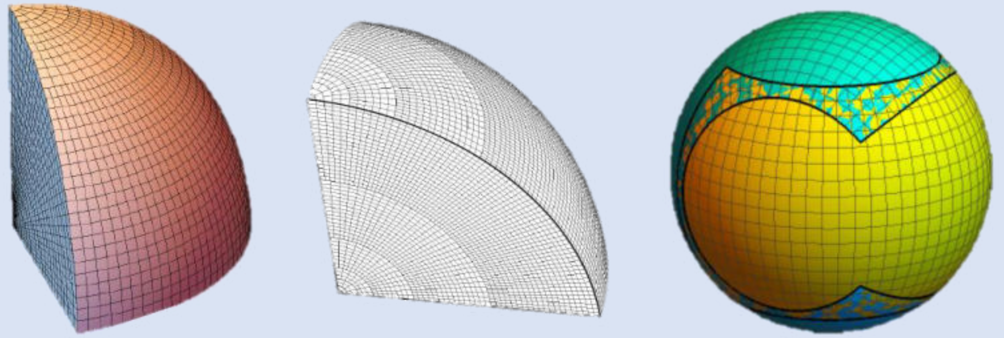
Possible choices for a setup

First of all, the physics of the problem:

→ stellar mass, age, metallicity, core or burning layers…

Then:

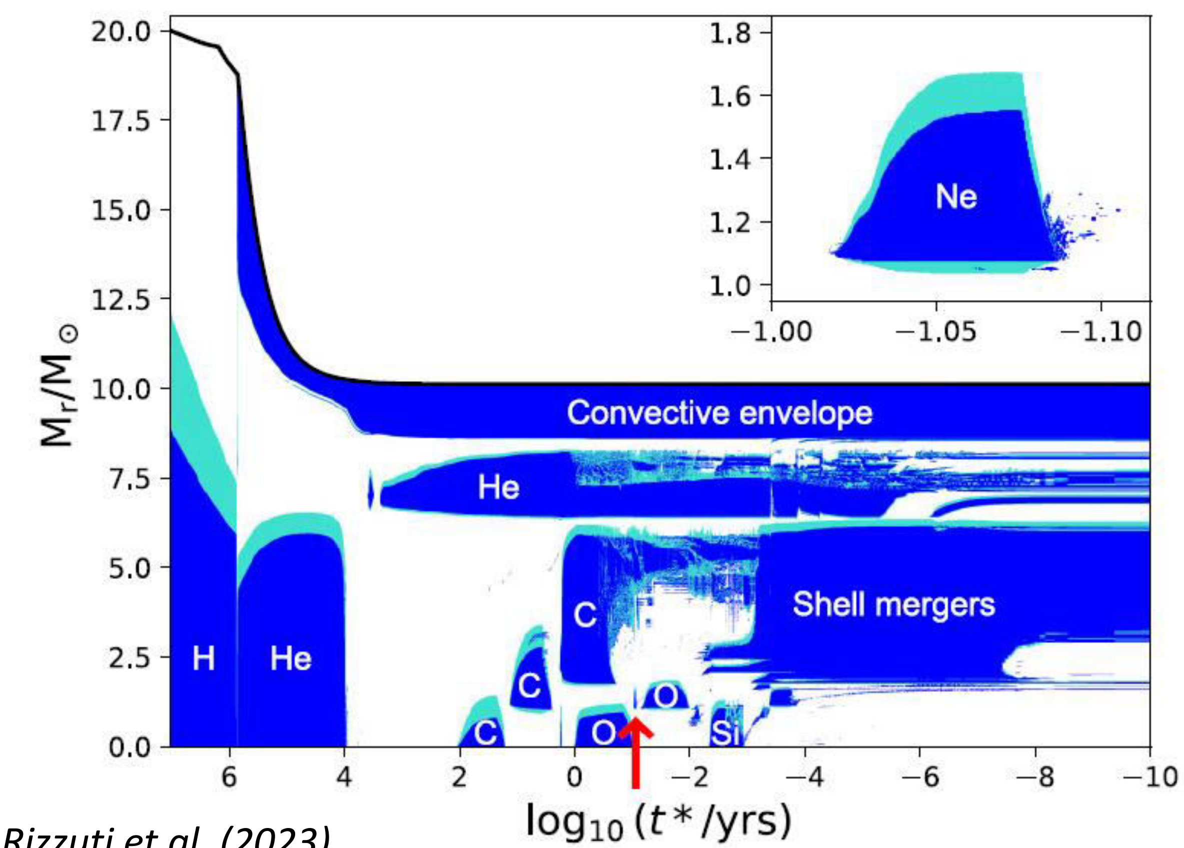
- Initial conditions from a 1D stellar evolution model
- Problem geometry and resolution: plane-parallel, spherical…
    → be careful with singularities



- Boundary conditions: periodic, reflective…
- Gravity: constant, polynomial…
- Energy generation and nuclear network

Muller (2020)

3D simulations of a neon-burning shell



Rizzuti et al. (2023)

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

- 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-isotopes network for Ne-burning
- multiple simulations with different resolutions and "boosting factors"
- following the shell untill fuel exhaustion

Convection and fluid motions

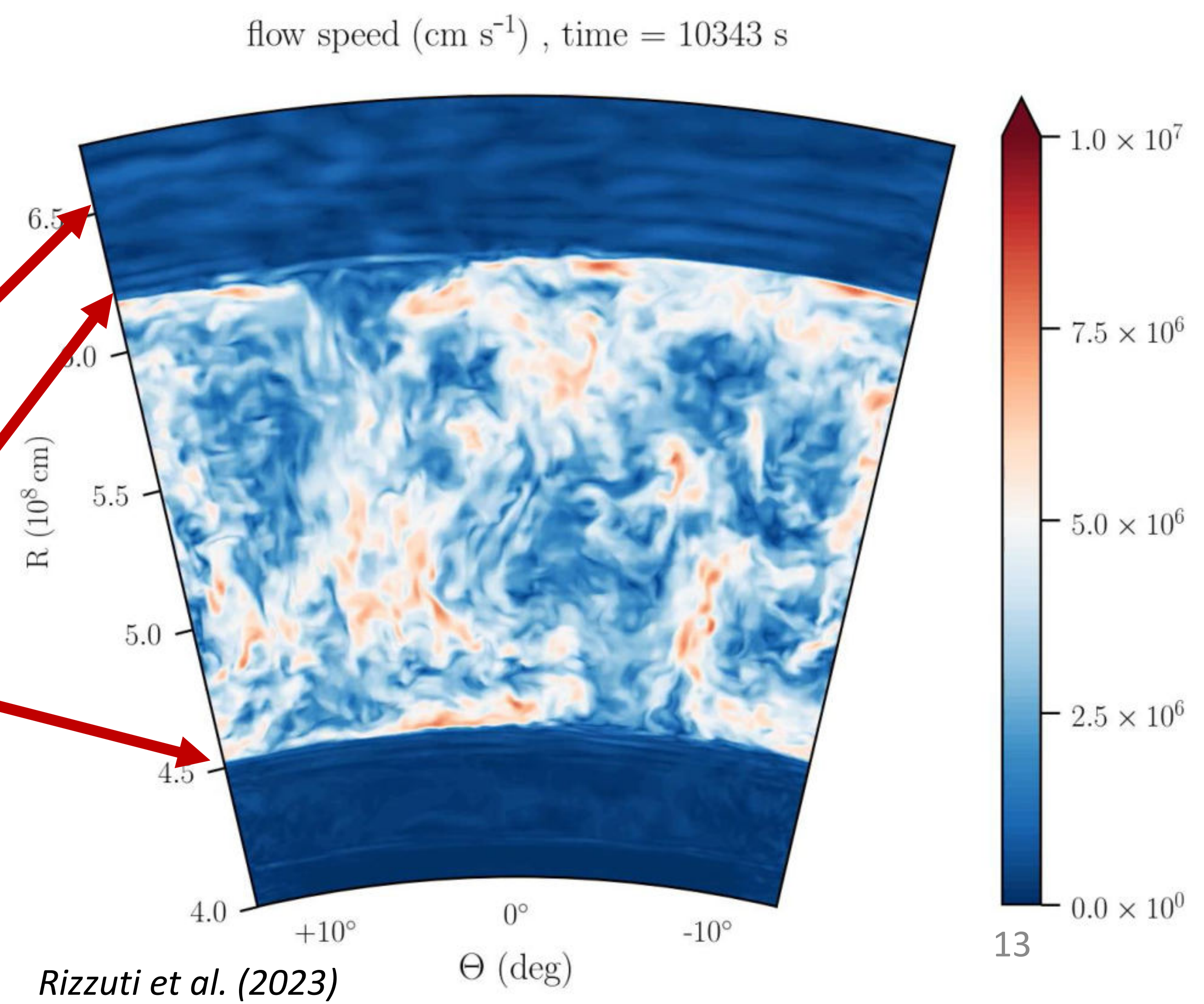
Vertical slice of the cell: velocity magnitude in colour scale.

We can see:

Internal gravity waves

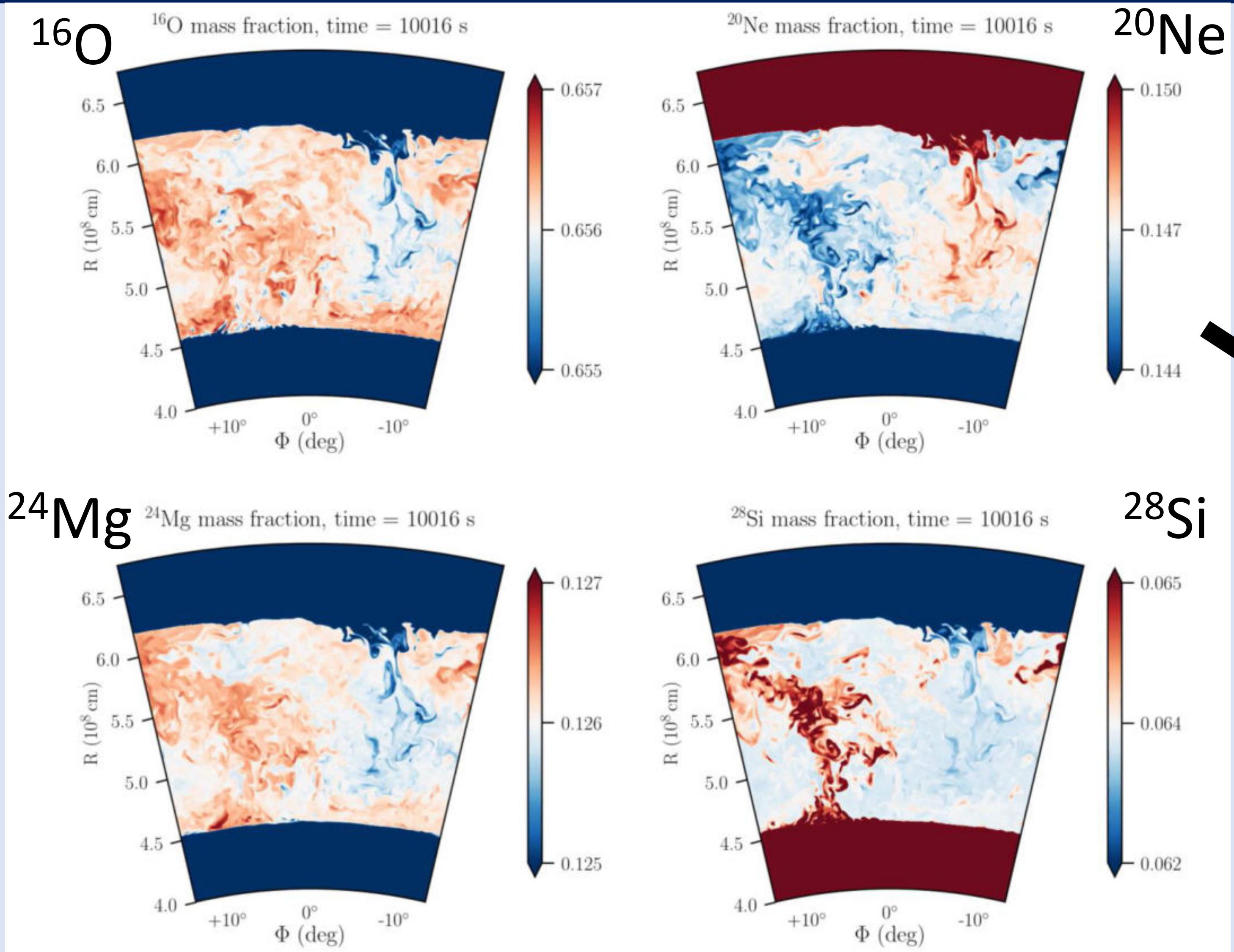
Convective boundary mixing

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



Rizzuti et al. (2023)

Evolution of the abundances



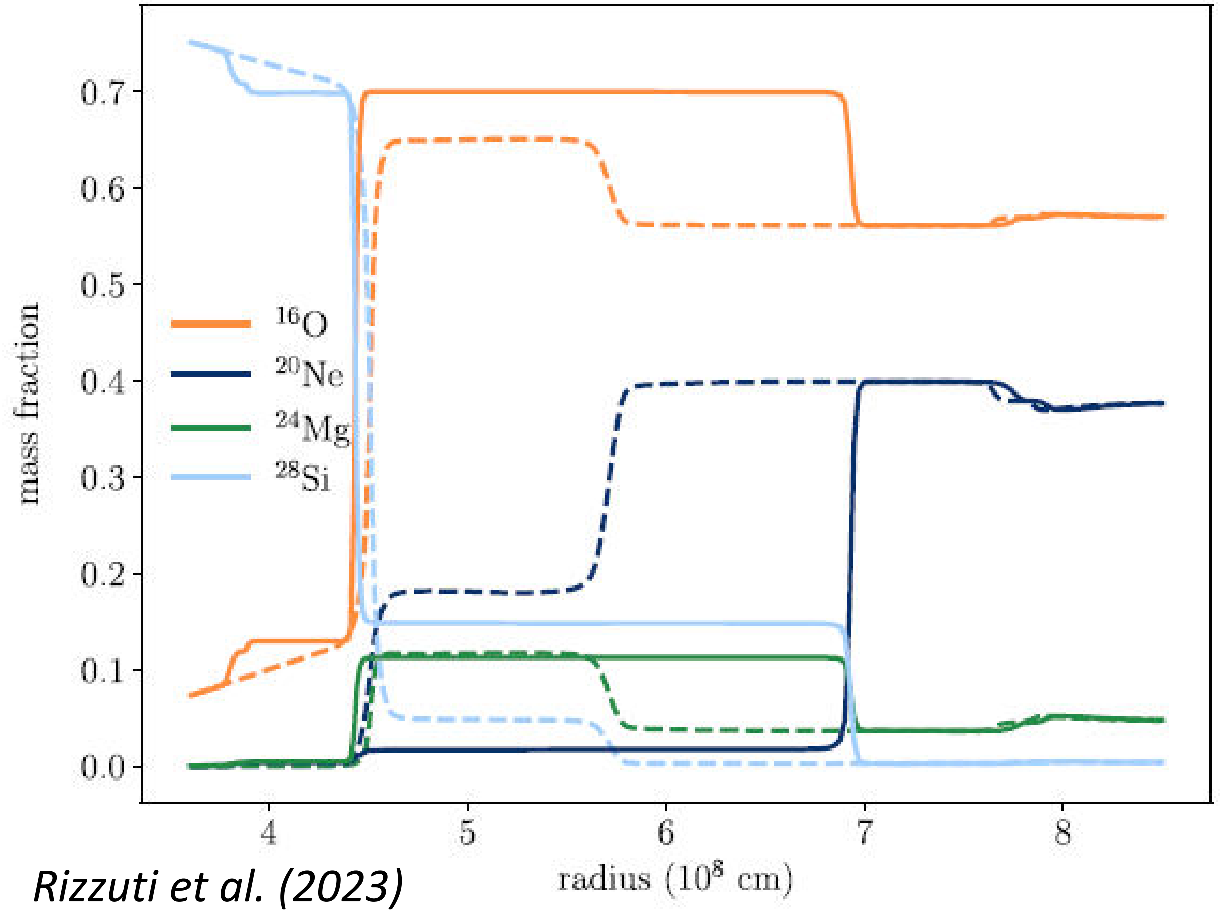
Reflecting the neon burning reactions:

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

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

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

The radial abundance profiles

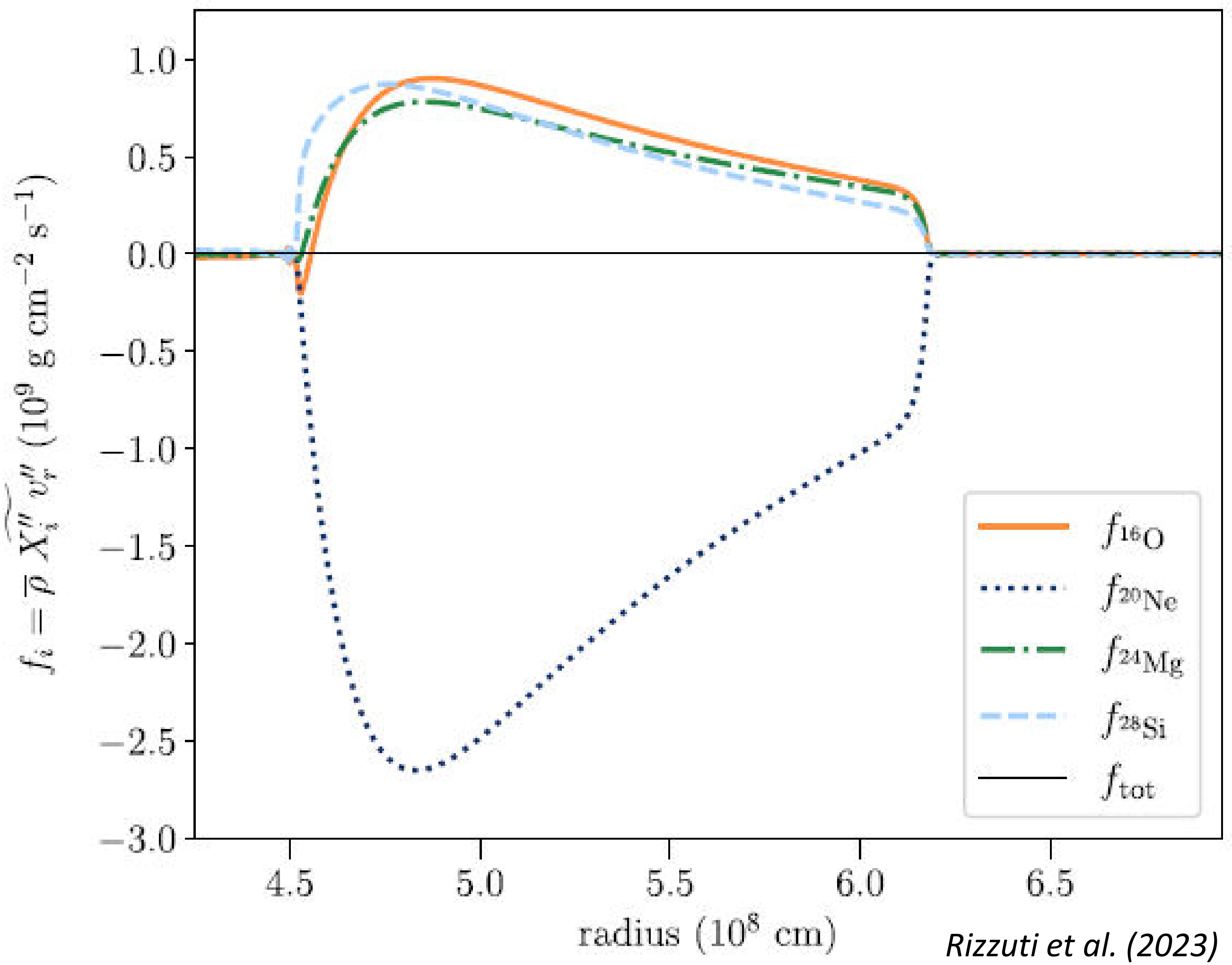


Rizzuti et al. (2023)

- We plot horizontally-averaged abundance profiles
- This way, we can study the abundance distribution and evolution: start (dashed) to end (solid)
- A plateau: the well-mixed convective zone

→ a useful way of defining the convective boundaries

The transport of species across layers



Rizzuti et al. (2023)

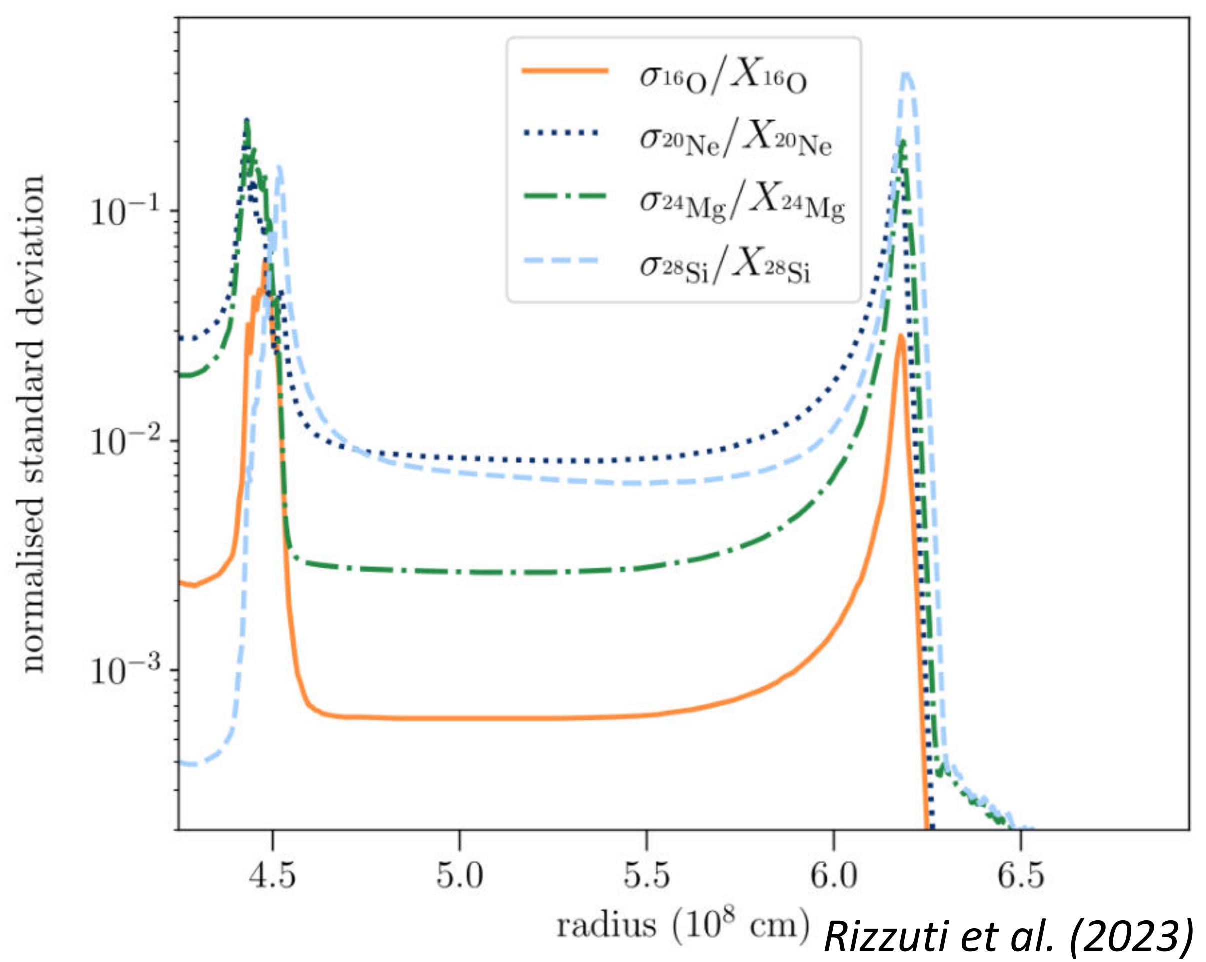
- Studying the radial flux profiles for each species
- Neon consumed: strong negative flux (downward)
- O, Mg, Si produced: positive fluxes
- Transported inside the convective zone by turbulent motions

Deviations from the spherical symmetry

Abundance variances:

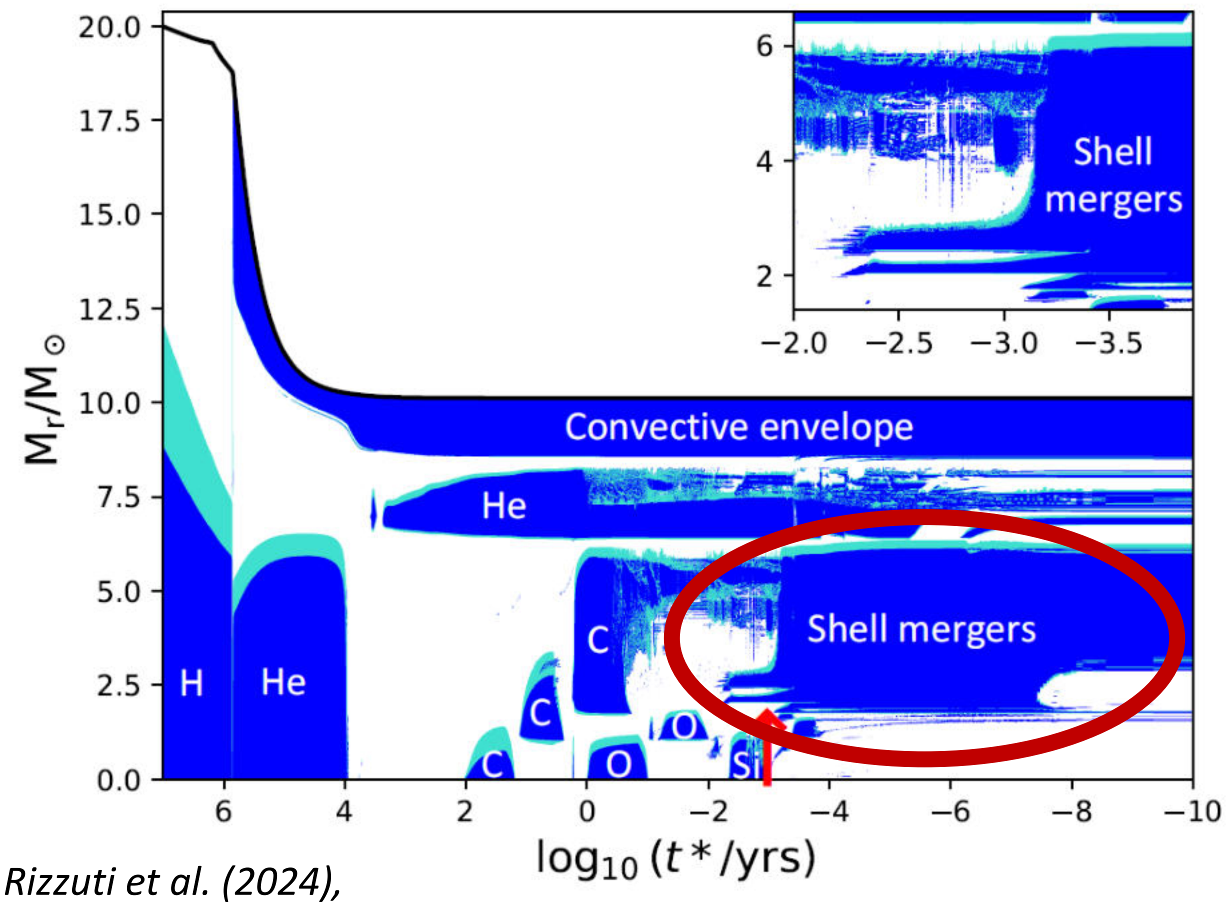
- flat in the convective zone: well-mixed
- peaks at the boundaries: strong mixing
- non-zero central variance: deviations from spherical symmetry

→ that's why we do 3D stellar models



Rizzuti et al. (2023)

3D simulations of a shell-merging event



Rizzuti et al. (2024), in preparation

Shell merging: going beyond the onion-ring model

Do they really occur?

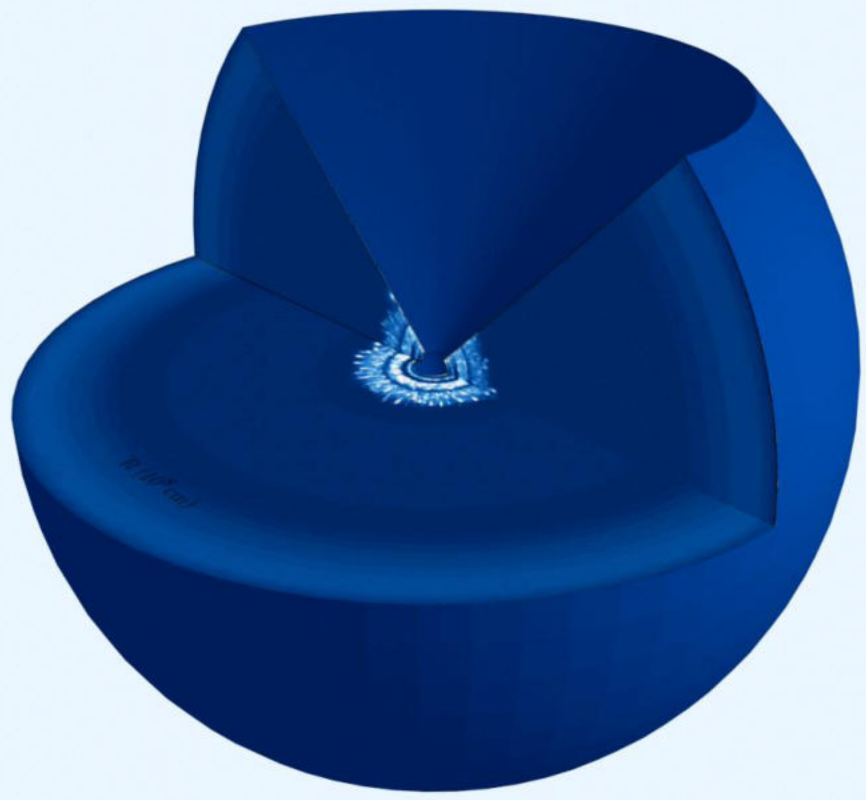
- O, Ne and C-shell mergers have been reported for a long time (*Rauscher et al. 2002; Tur, Heger & Austin 2007*)

Peculiar nucleosynthesis:

- C-O merging shells as source of odd-Z elements ^{31}P, ^{35}Cl, ^{39}K, ^{45}Sc *(Ritter+18)*
- explosive nucleosynthesis across merged shells: γ-process (*Roberti+2023*)

Towards a 4π setup geometry

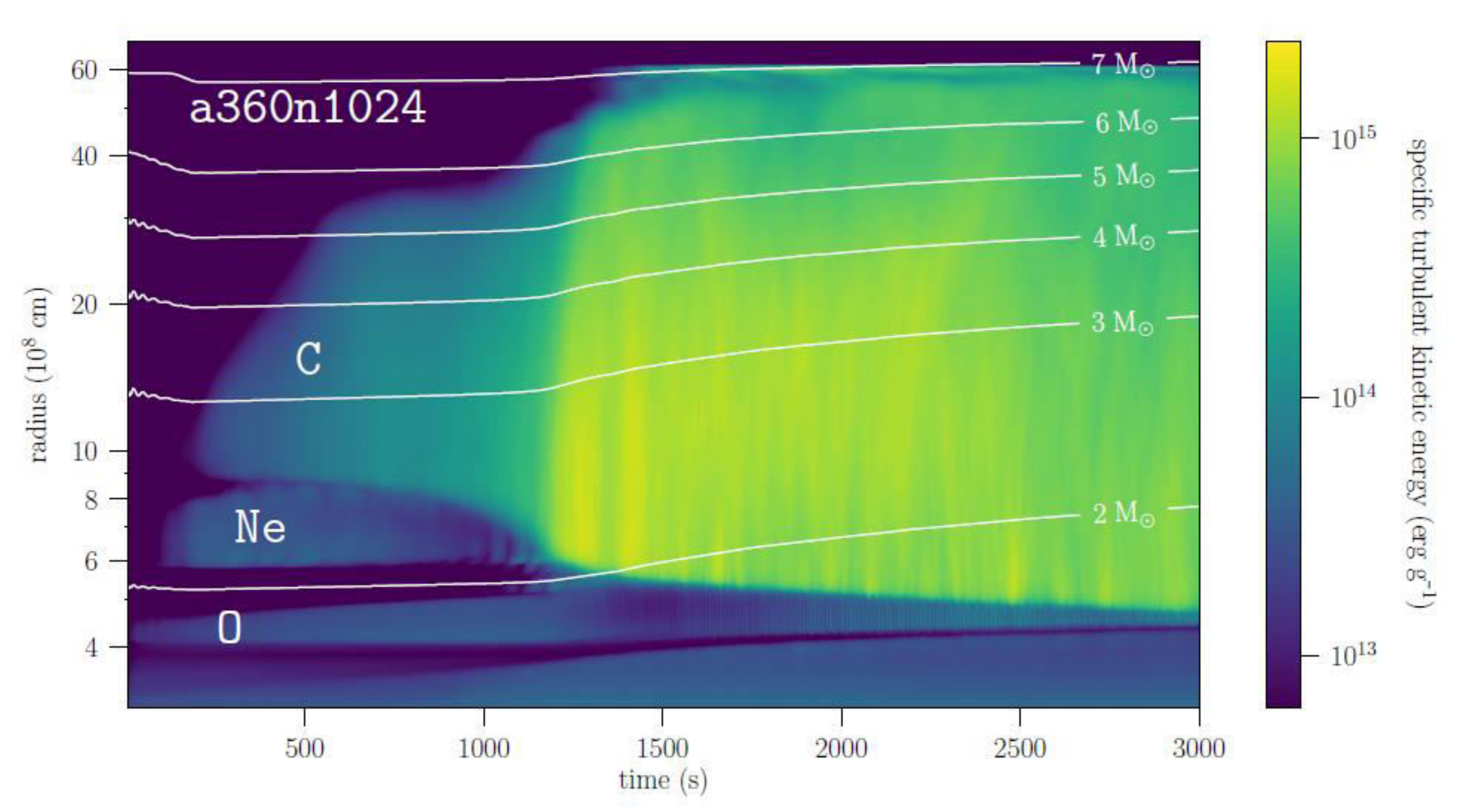
- From 1D MESA model: 20 $M_{\odot}$, $Z_{\odot}$
- Nearly-4π geometry: 360° x 90°
- Merging event of C-, Ne- and O-burning shells
- Nuclear burning with a 12-isotope network
- Nominal energy generation (no boosting)
- Formation of one large convective zone
- Very strong dynamical features



Rizzuti et al. (2024), in preparation

Kinetic evolution of the merging shells

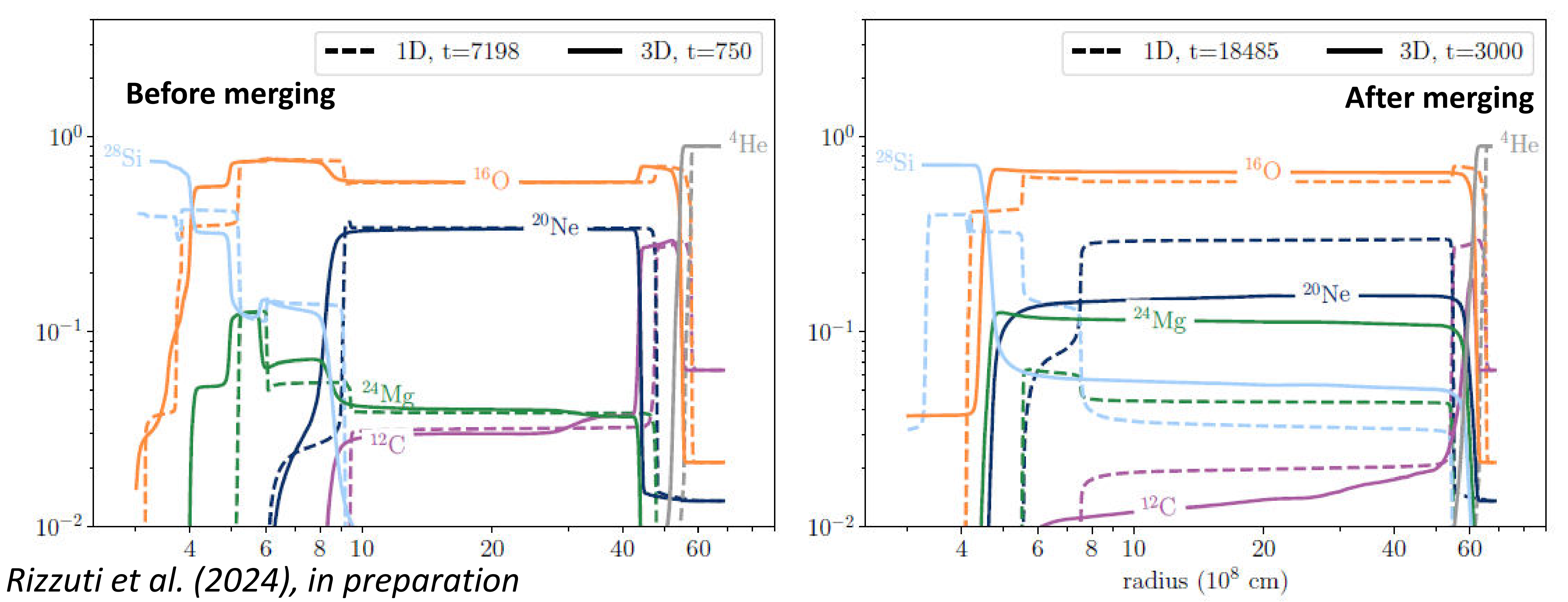
- Three individual shells before the merging
- Merging event of C- and Ne-burning shells at 1200 s
- Sudden rise in kinetic energy
- Comparison with the 1D: no merging with the oxygen shell; faster timescale



Rizzuti et al. (2024), in preparation

Chemical abundance differences: 1D vs 3D

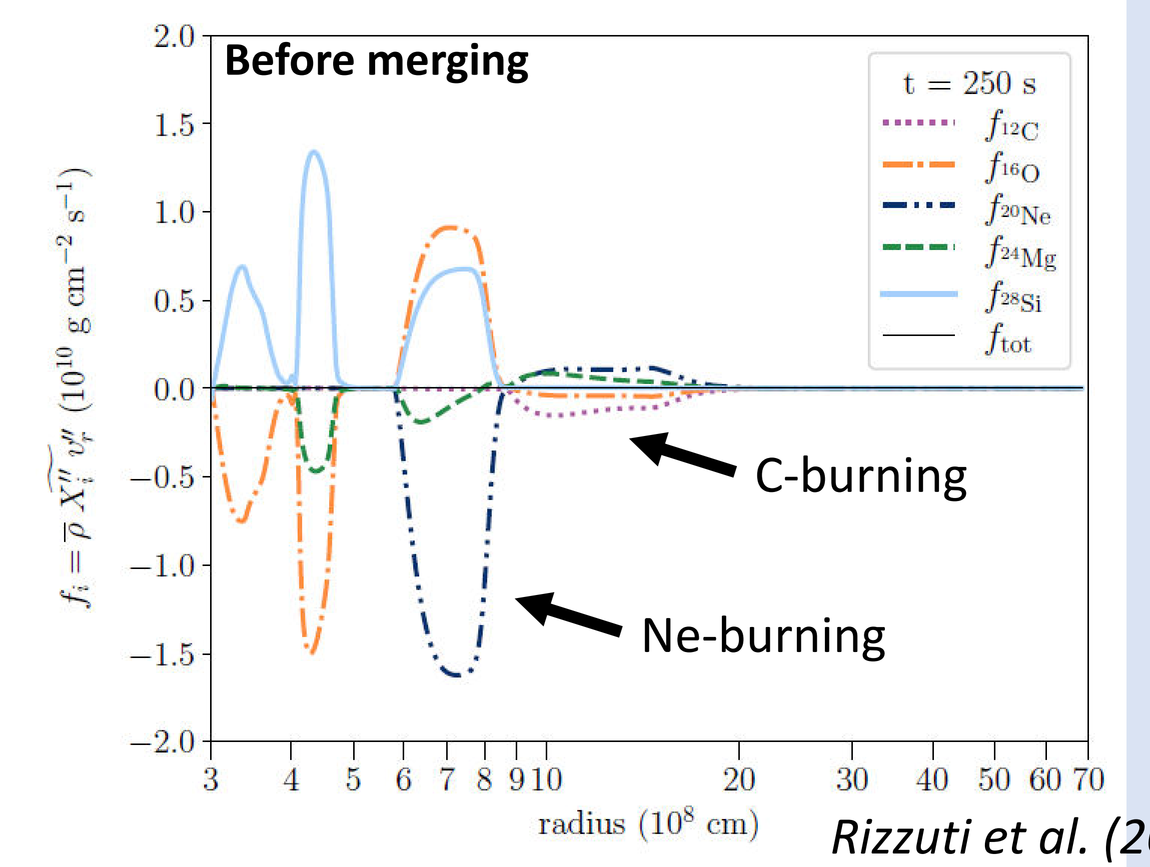
- Different location of the convective zones: the 3D structure is different
- Different final mass fractions: the 3D composition is different

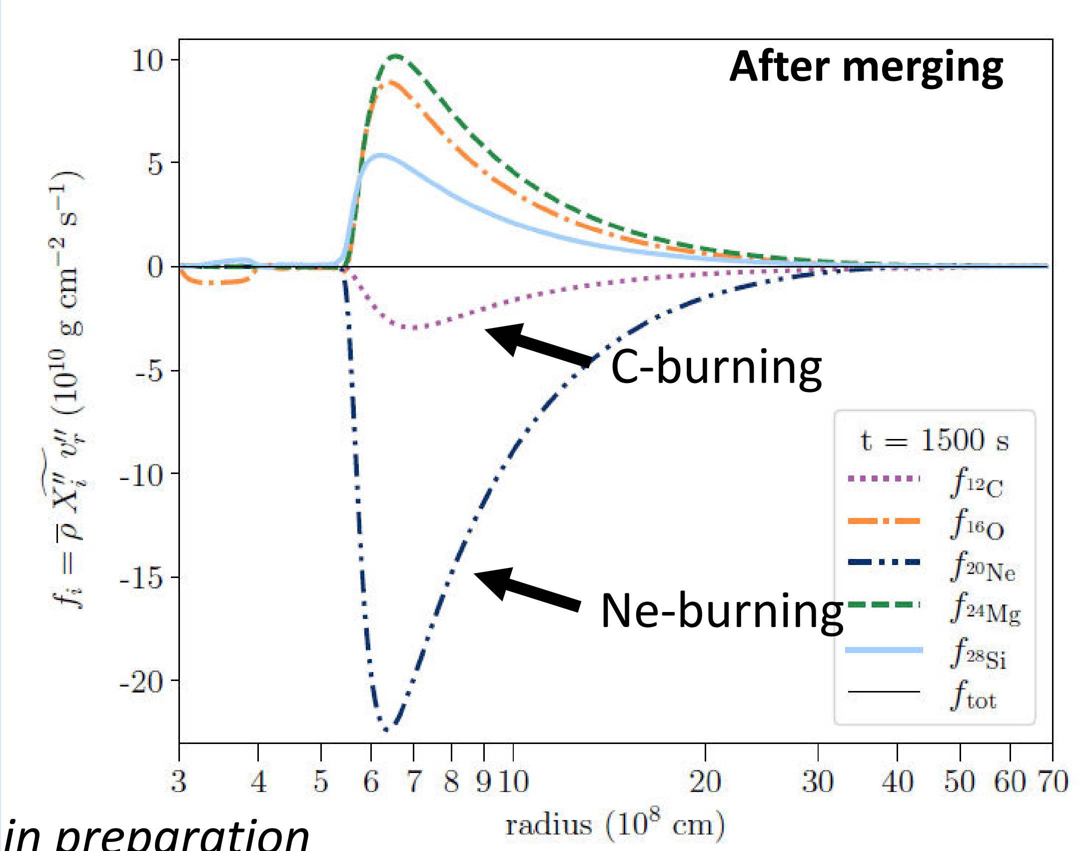


Rizzuti et al. (2024), in preparation

Transport of species and nucleosynthesis

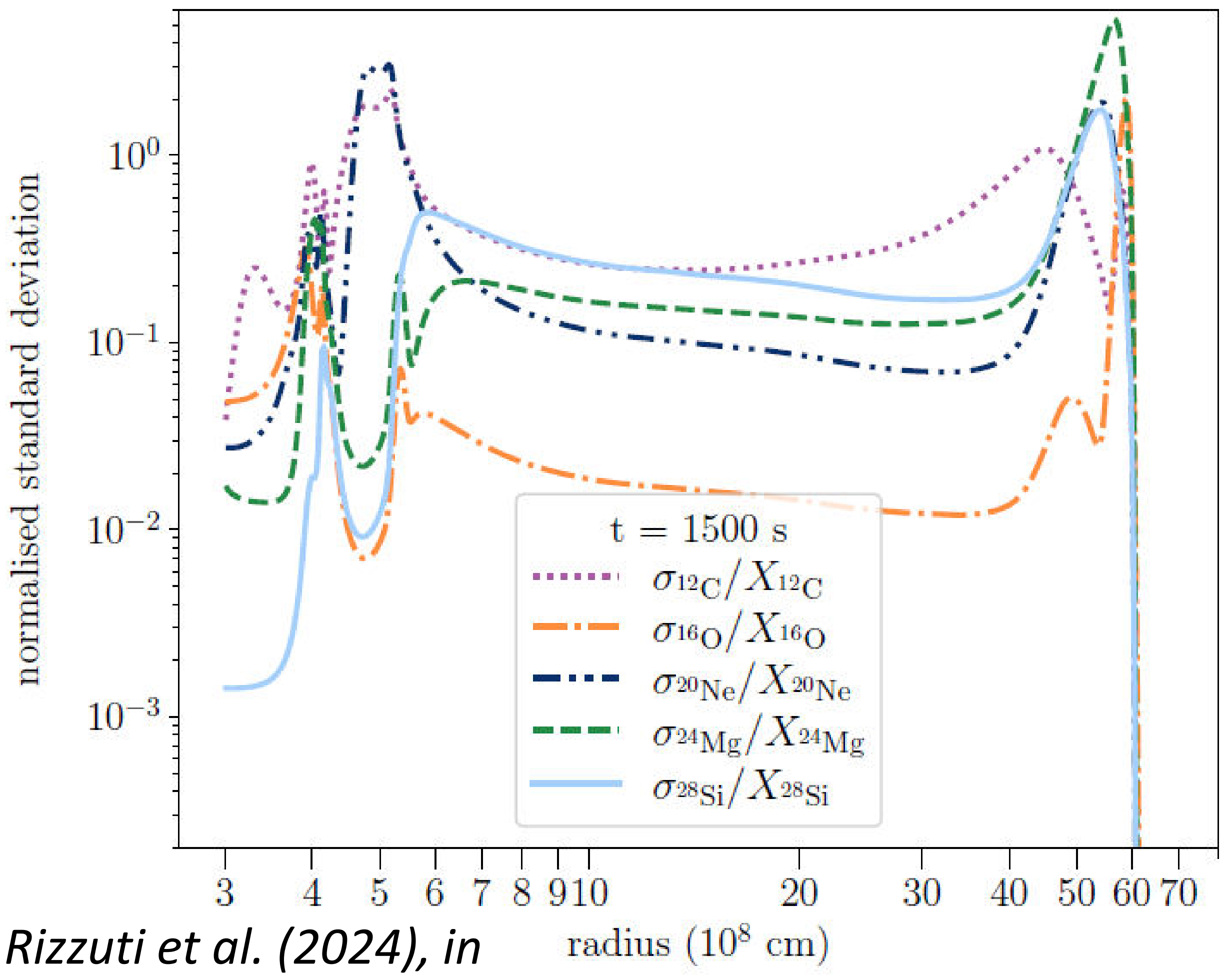
- Simplified scenario: positive/negative flux represents production/destruction of species
- After the merging: only one convective zone, with largely enhanced C- and Ne-burning





Rizzuti et al. (2024), in preparation

Deviations from the spherical symmetry



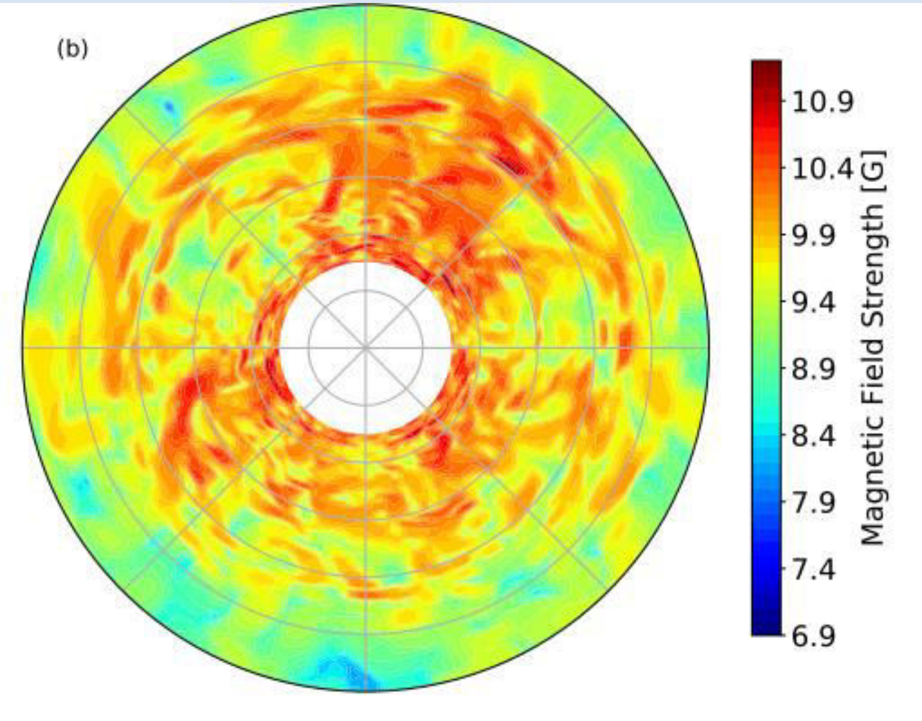
Rizzuti et al. (2024), in preparation

- After the merging, strong horizontal dispersion of species (even up to 300%)
- Ashes Ne, Mg, Si average dispersion 10-30%
- Effect of the very strong dynamics
- Different from "quiet" burning phases such as Ne-burning shell simulations

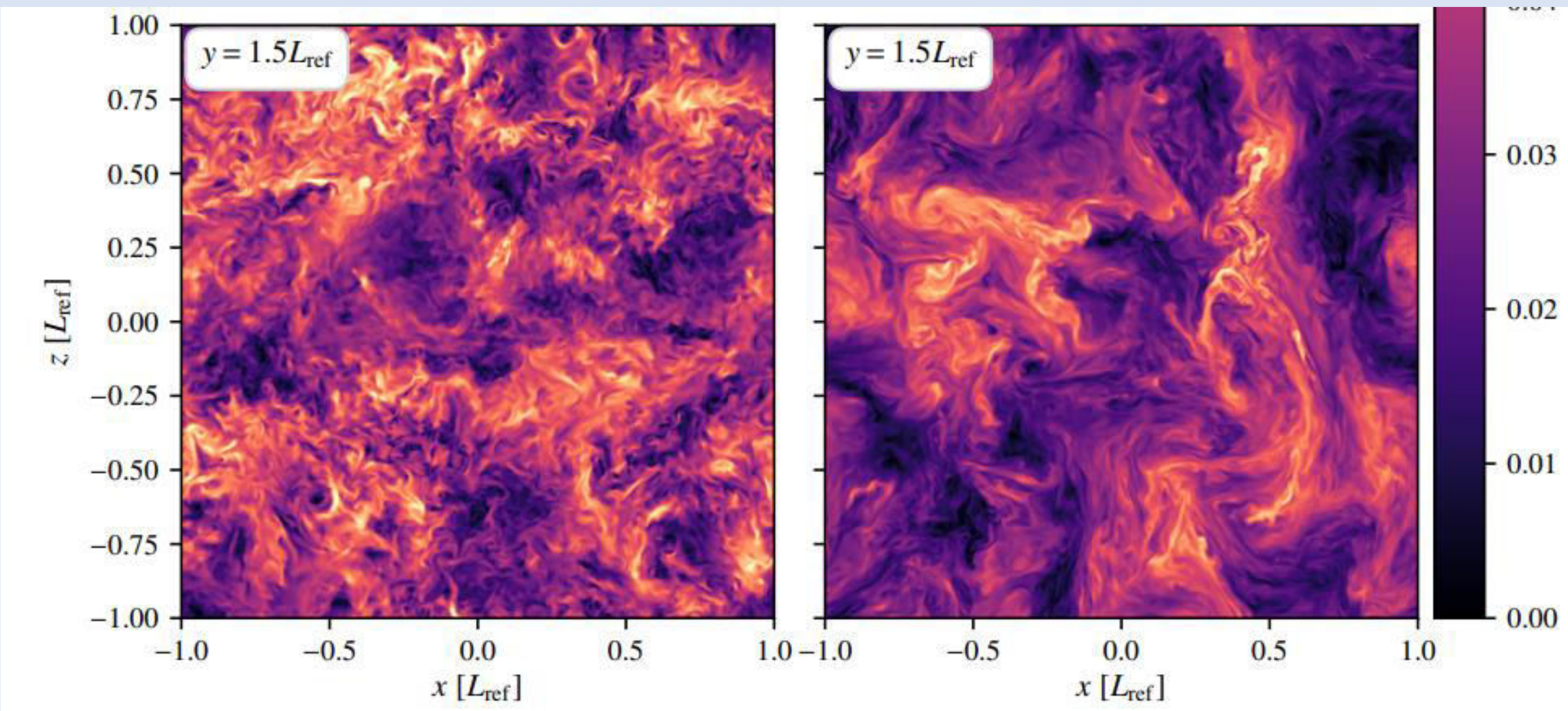
What remains to be done?

Future prospects:

- build a library of 3D burning phases (H-core, He-core…)
- extend the nuclear network (e.g. Si-burning)
- add magnetic fields, rotation…



Varma & Muller 2021



Leidi et al. 2023

Conclusions

- The interplay between 1D stellar models and 3D hydrodynamical models pushes forwards our knowledge of nucleosynthesis and stellar evolution
- Nuclear reactions and chemical abundances can be included and studied in the 3D simulations
- ‘‘Quiet’’ burning phases (e.g. Ne-burning) can be now studied in 3D simulations with nuclear reactions, until fuel exhaustion
- Shell mergers provide a peculiar environment for nucleosynthesis and stellar evolution: 3D can help constrain and improve the 1D

For the future: 3D stellar evolution, 3D nuclear astrophysics, non-symmetric nucleosynthesis, extension to other phases