# ChETEC-INFRA SNAQs: February 2022

# 3D hydrodynamics simulations of massive stars with the PROMPI code

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# Outline

- Modelling stars: 1D vs 3D
- Setup choices and the PROMPI code
- A new set of Ne-shell simulations
- Kinematics and abundance profiles
- Evolution of the convective boundaries
- From 3D to 1D : parametrizing the entrainment law
- Conclusions

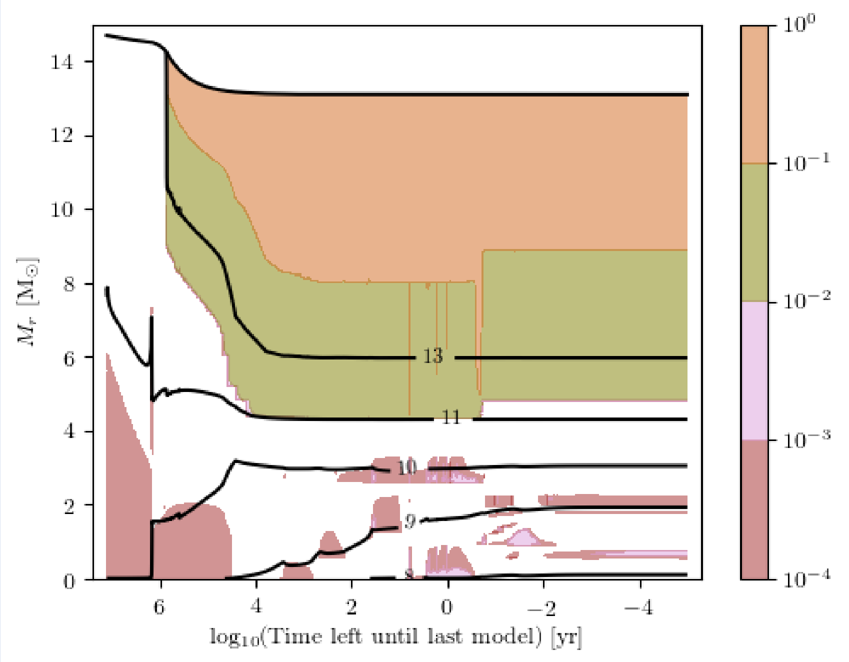
# Stellar evolution models: the limits of 1D

**Advantages:**
- can model the full star
- can cover the entire lifetime
- easily compared to obsevations
- can explore mass and metallicity
- used for progenitor models

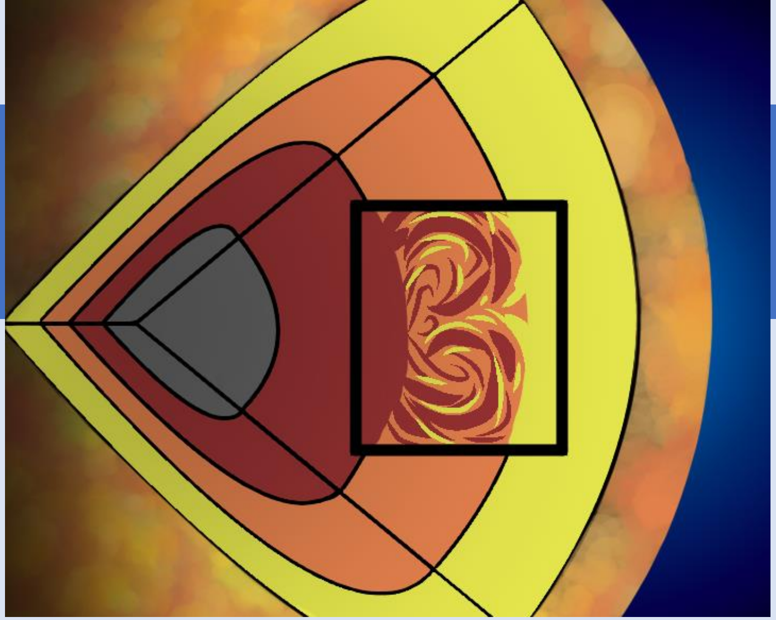
**Disadvantages:**
- spherical symmetry assumed
- parametrized physics for multi-D processes
- cannot model turbulence

**What's missing?**

- self-consistent physical descriptions of mass loss, convection, rotation, magnetic fields, opacity, binarity (and their interplay)



# 3D hydrodynamics models



Modelling a 3D box enclosed in / enclosing a star

**Advantages:**

- deviations from spherical symmetry
- can model fluid instabilities
- can include naturally 3D processes (convection, turbulence) without assuming any prescription

**Disadvantages:**

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

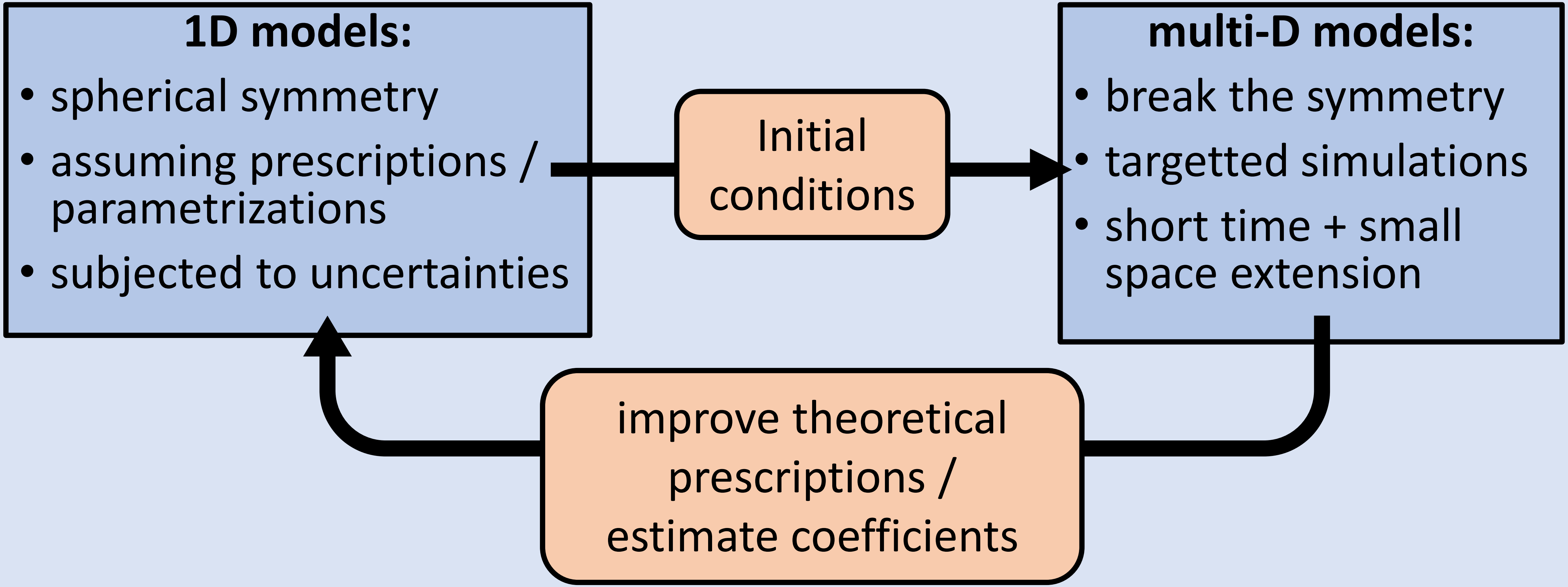
# Why employ hydrodynamics models?

**Multi-D processes can be reproduced:**

- Convection, rotation, magnetic fields
- No need to assume prescriptions as in 1D e.g. mixing length theory (MLT), convective boundary mixing (CBM)

  → possible to use 3D data to constrain 1D parametrization
- Turbulent mixing leading to convection
- Turbulent entrainment at convective boundaries
- Internal gravity waves

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

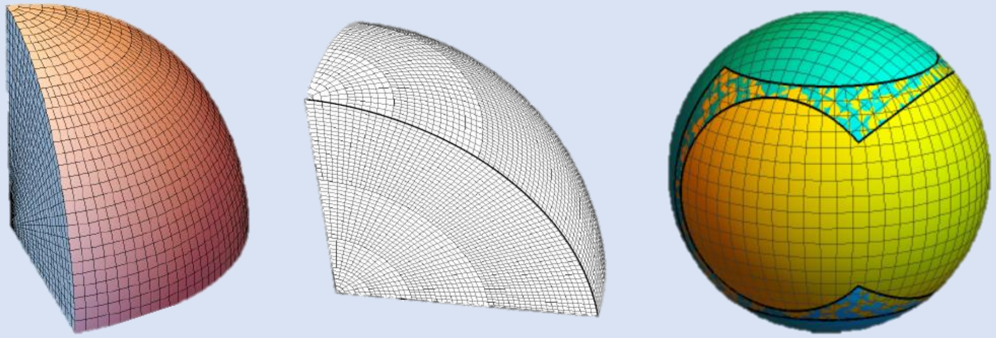


# Possible choices for a setup

First of all, the physics of the problem:
→ stellar mass, age, 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…

Muller (2020)

# The PROMPI 3D Hydrodynamics Code

PROMPI solves the Euler equations (inviscid approximation) by:

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

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

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

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

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

- PROmetheus MPI
- finite-volume, time explicit, Eulerian, PPM implementation
- domain decomposition for parallel computing (MPI)
- Cartesian, spherical or cylindrical geometry
- reflective or periodic boundary conditions, velocity damping

# Simulations of a neon-burning shell

Modelling a 3D cell in the Ne-shell of 15 $M_\odot$ star with PROMPI:

- Plane-parallel "box-in-a-star" of $(0.64 \times 10^8\ \mathrm{cm})^3$
- Multiple simulations with different resolutions (mesh size) and nuclear energy generation rates ("boosting factors")

We focus on reproducing/studying:

- Turbulent convection
- Convective boundary mixing
- Turbulent entrainment

| resolution → boosting ↓ | $128^3$ | $256^3$ | $512^3$ | $1024^3$ |
|---|---|---|---|---|
| **x 1** | | | Ex1 | |
| **x 10** | lrez | mrez | Ex10 | vhrez |
| **x 100** | | | Ex100 | |
| **x 1000** | | | Ex1000 | |

# Kinematic study: velocity movie

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

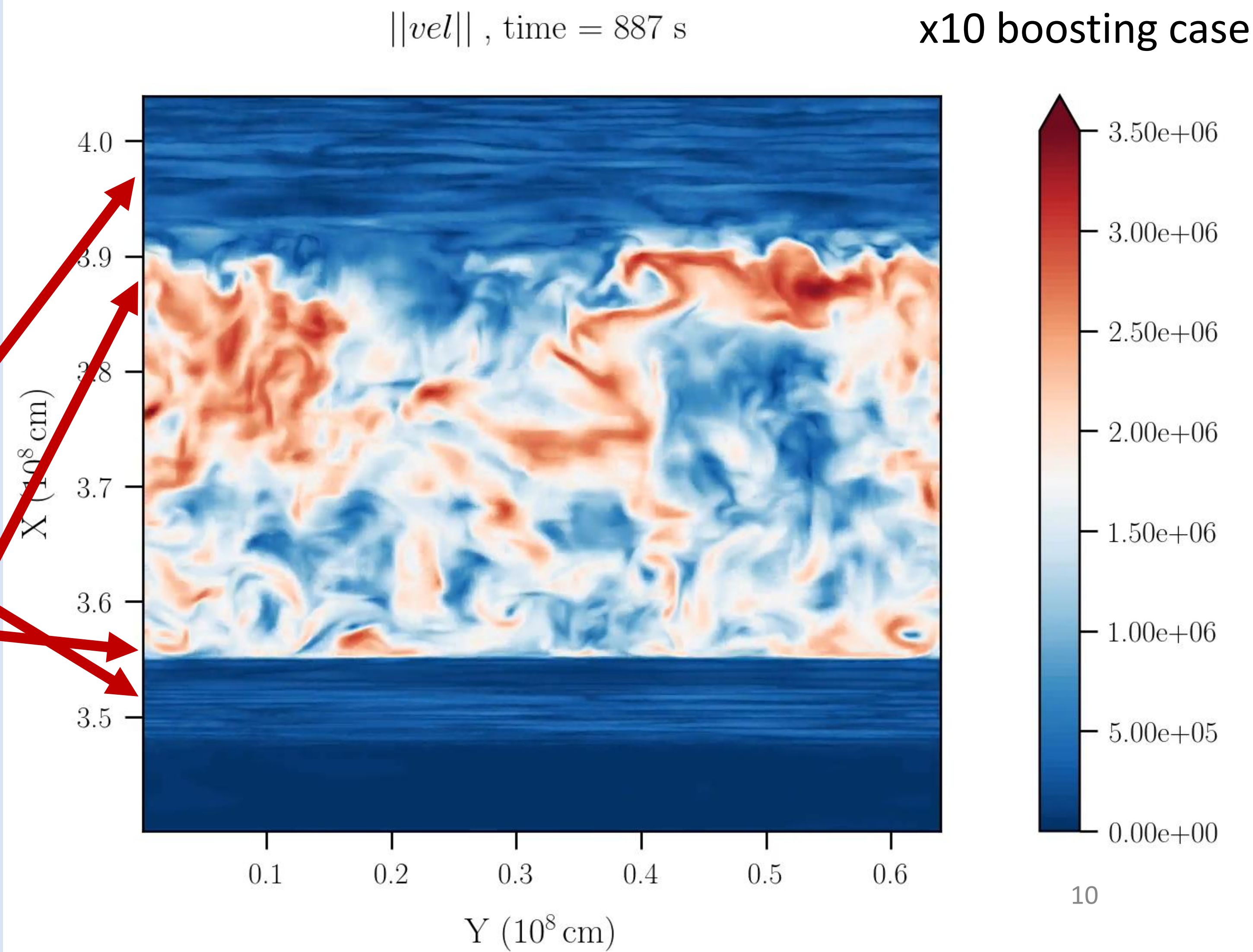
We can see:

Internal gravity waves

Boundaries

→ Boundaries are moving!

x10 boosting case



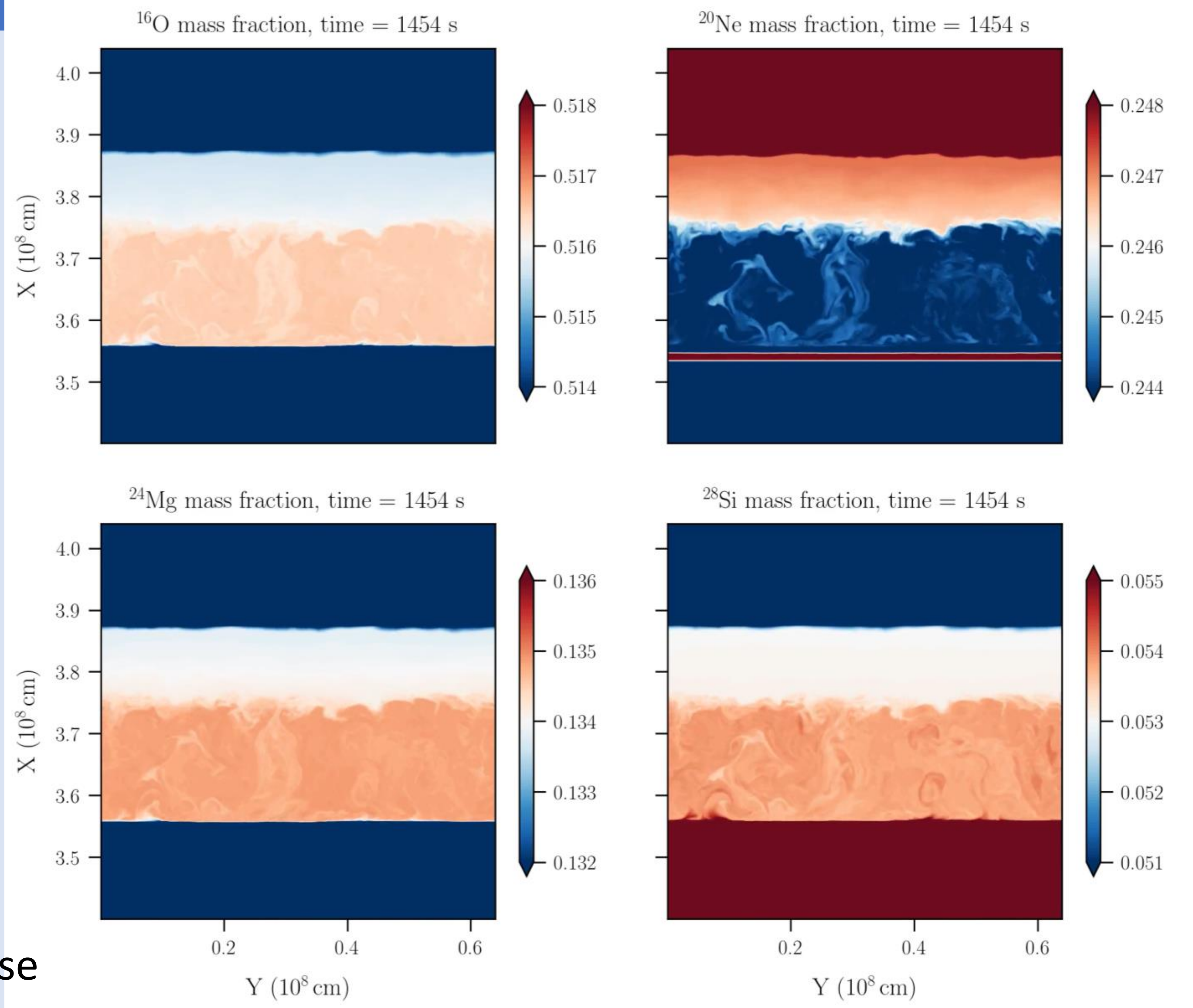
# Chemical study: abundance movies

$^{16}O$ $^{20}Ne$

→ $^{20}Ne(\gamma,\alpha)^{16}O$

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

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

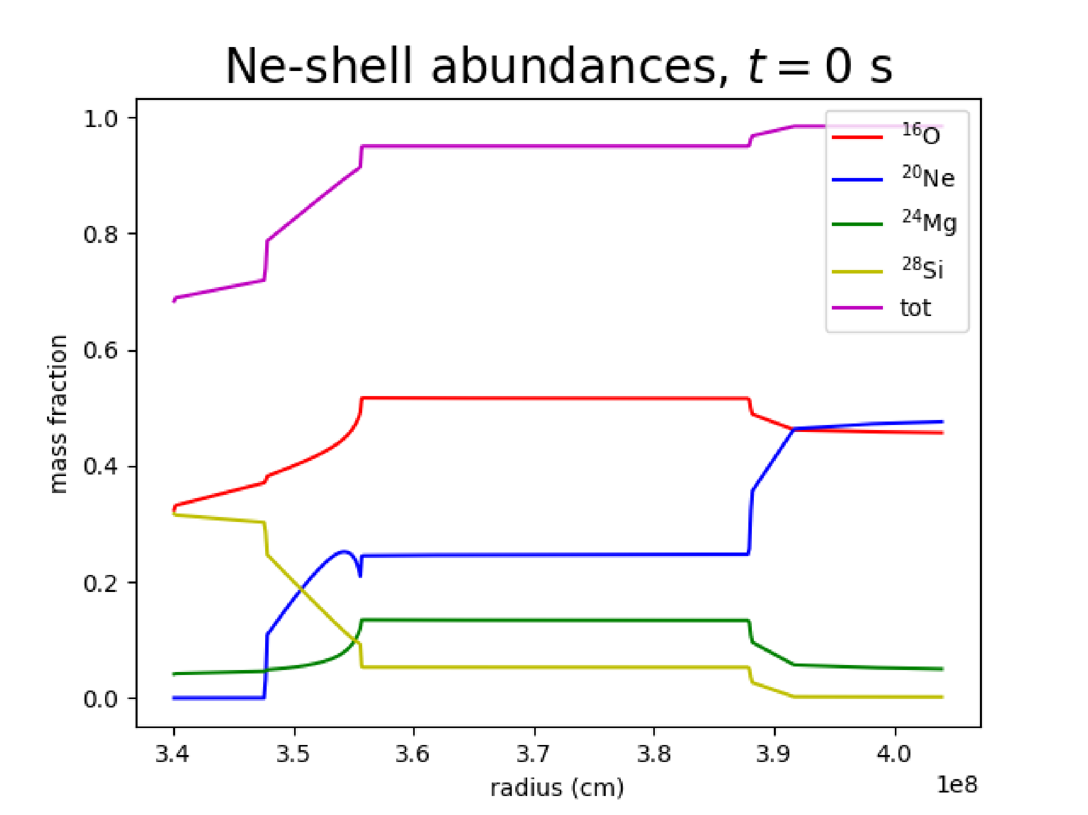


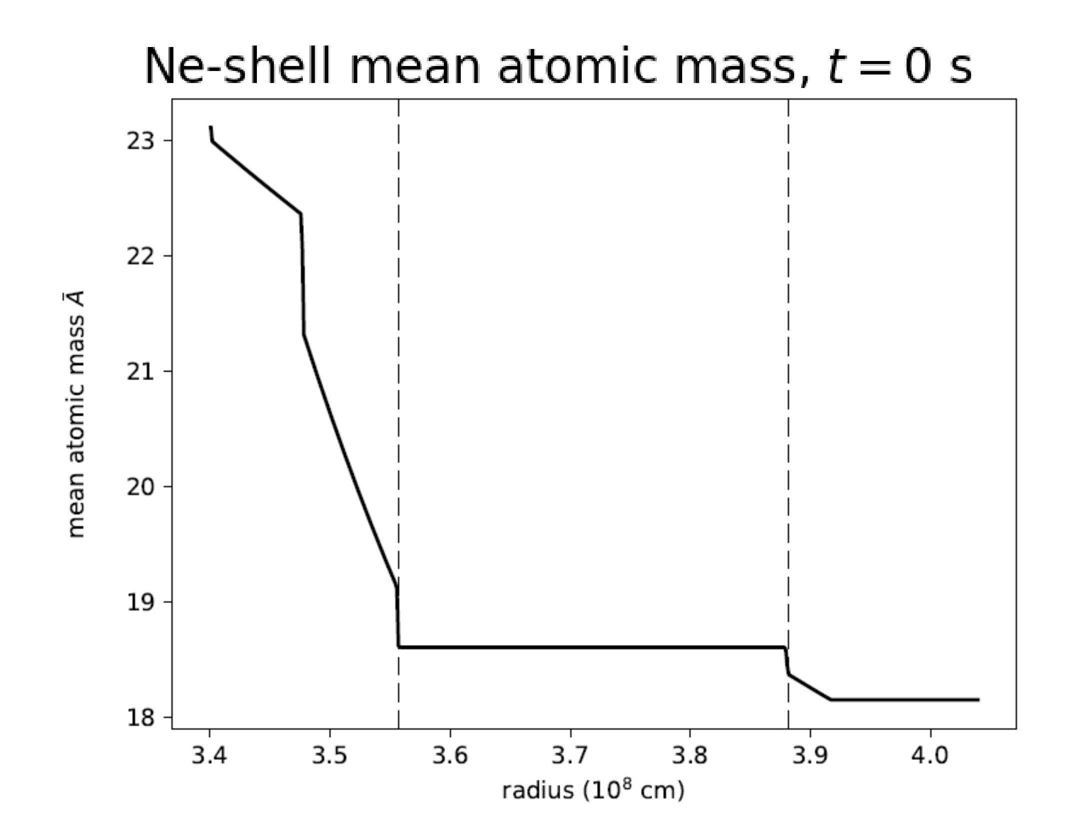

$^{24}Mg$ $^{28}Si$

x1 boosting case

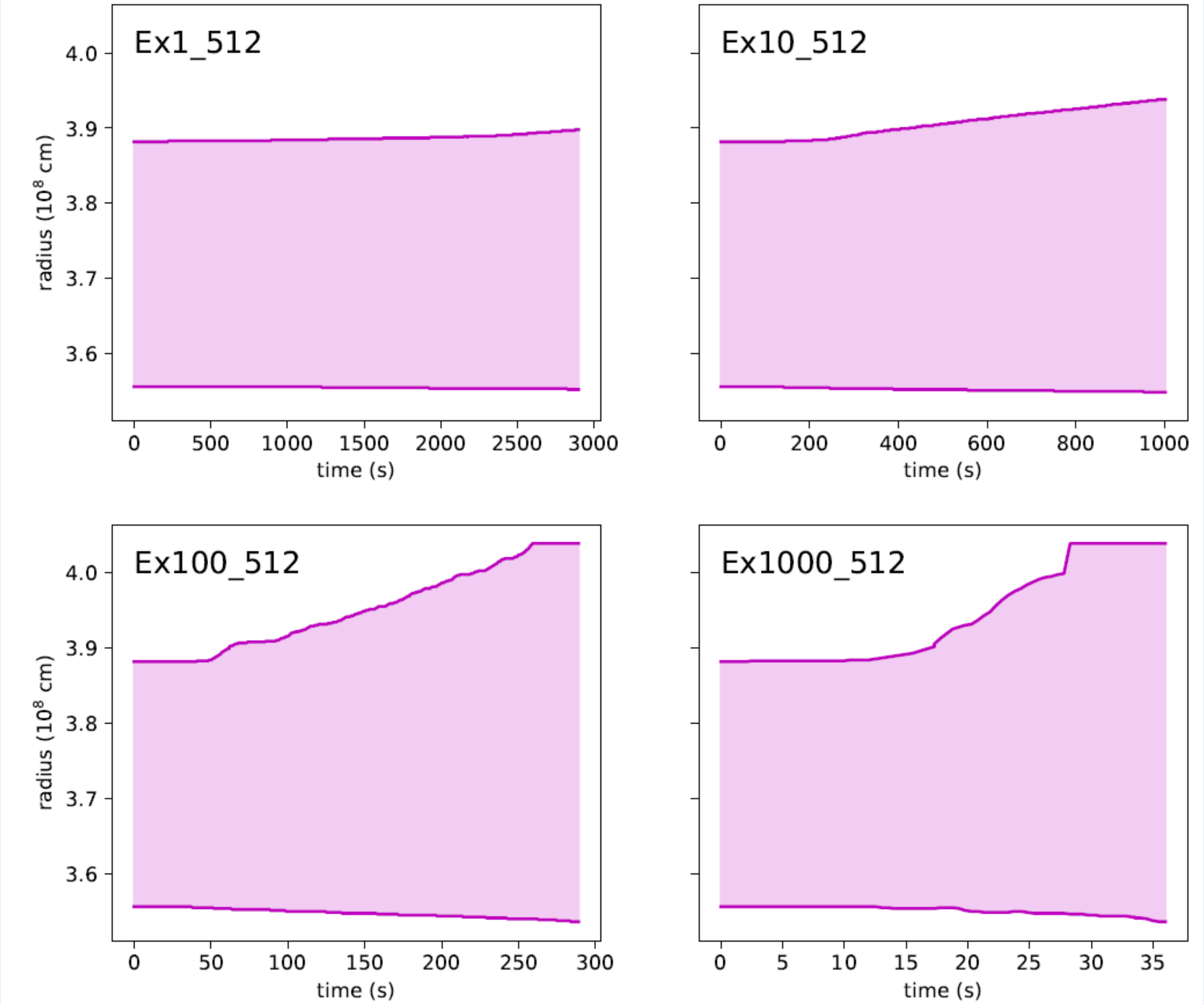
# Abundance profiles

- We study the mass fraction of the most abundant isotopes
- The profiles are used to define the convective boundaries



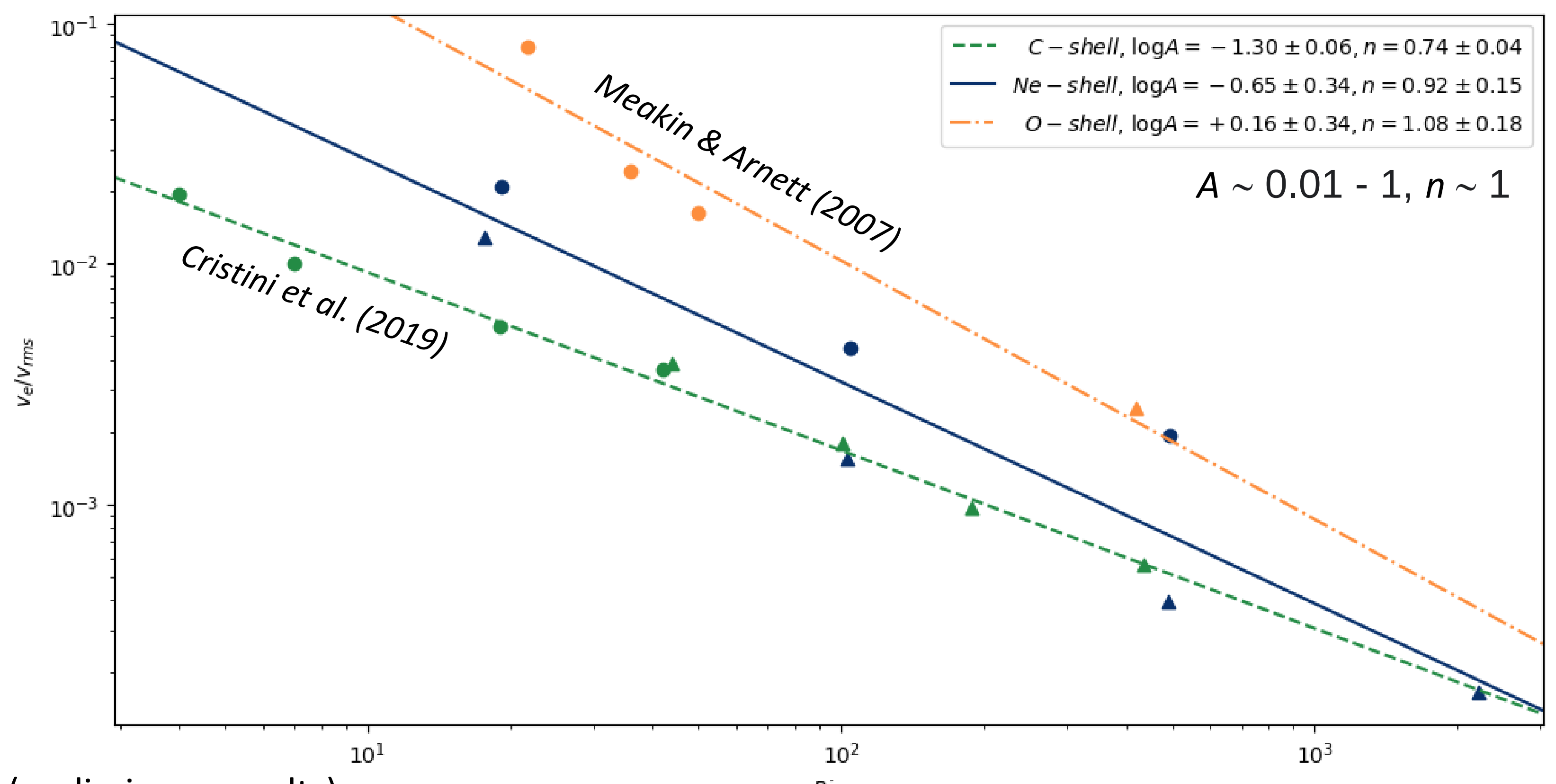
# Evolution of the boundary locations




- The location of the boundaries moves with time, because the convective zone is growing: this is entrainment
- The entrainment rate is strongly dependent on the boosting factor
- The entrainment rate is not dependent on the resolution

# Computing the entrainment law

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




(preliminary results)

- Entrainment rate can be parametrized with a simple law using the “bulk Richardson number”, representing the “stiffness” of the boundary
- Then the law can be used to improve convection in 1D models

1D → 3D → 1D

# Conclusions

- 3D hydrodynamics codes like PROMPI reproduce turbulent flow for short timescales but with great accuracy
- The interaction between nuclear burning and turbulent flow can be studied in unprecedented detail
- We completed the first detailed 3D simulations of the Ne-shell: different resolutions and luminosity boosting factors
- The entrainment rate is correlated to the boosting factor and can be parametrized with a law useful for 1D

For the future:
- build a library of burning shells with the PROMPI code (C- and O-shells already present in the literature)
- complete the loop 1D → 3D → 1D and continue → …