Multi-Dimensional Simulations of Oxygen-shell Burning Just before the Core-Collapse of Massive Stars

Yoshida, Takiwaki, Kotake, Takahashi, Nakamura, & Umeda, ApJ 881, 16 (2019)

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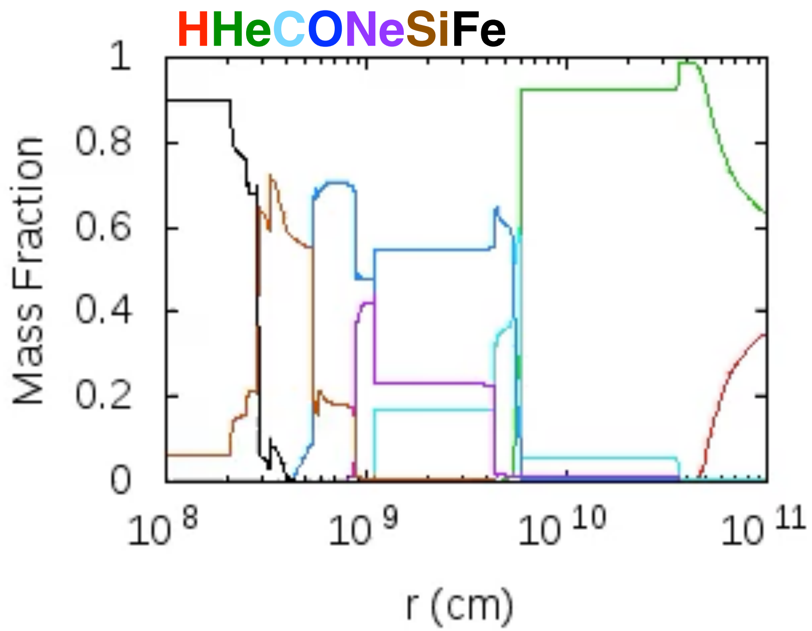
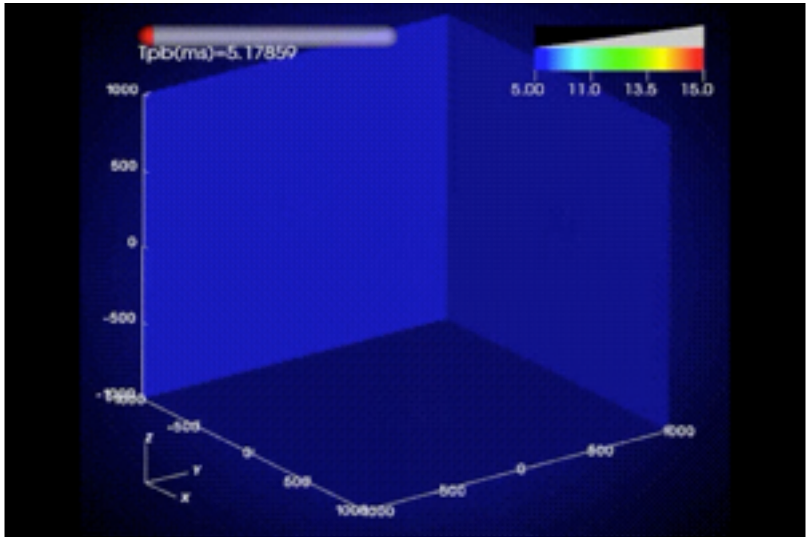
Multi-dimensional Modeling and Multi-Messenger observation from Core-Collapse Supernovae
October 22, 2019, Fukuoka University

Asphericity of SN Progenitors

- From massive star evolution to supernova explosion



1D stellar evolution

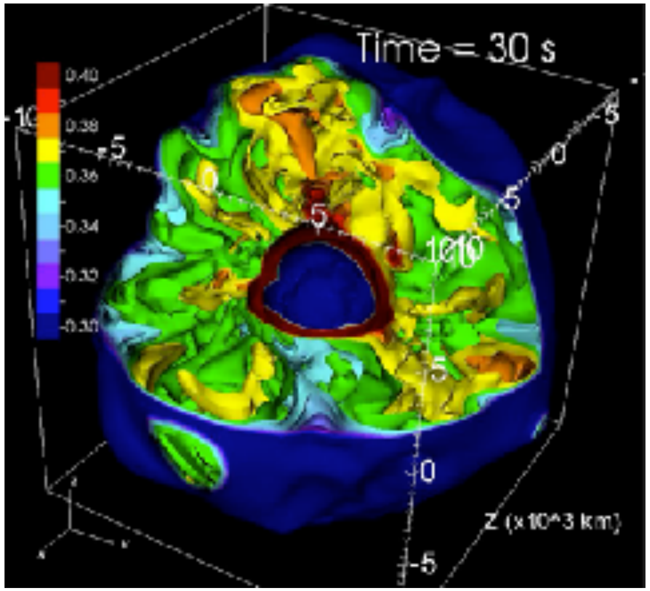


(Nakamura et al. 2014)

3D simulation of SN explosion

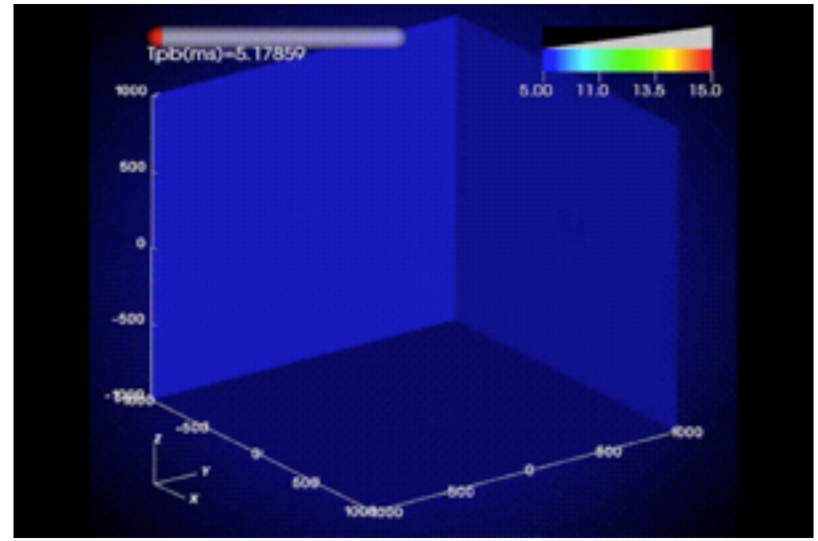
Asphericity of SN Progenitors

- From massive star evolution to supernova explosion



(Yoshida et al. 2019)

3D stellar evolution



(Nakamura et al. 2014)

3D simulation of SN explosion

- Aspherical structure of SN progenitor affects the explosion of SNe.

(e.g., Couch and Ott 2013; Müller and Janka 2015)

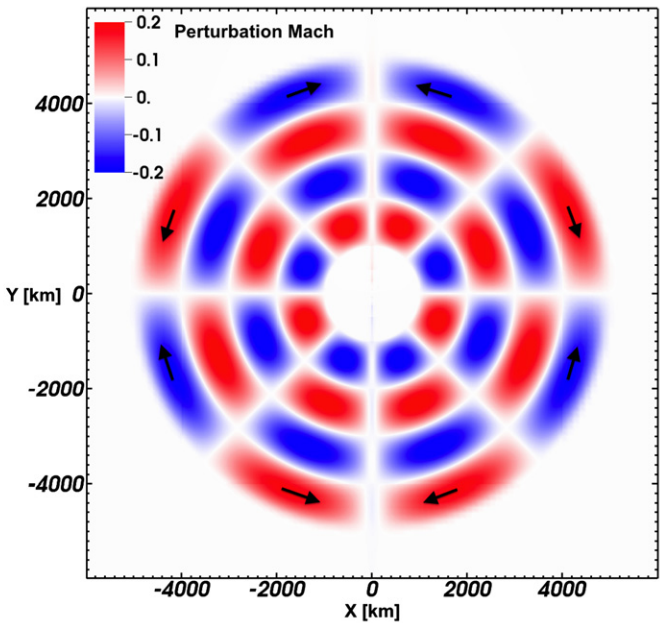
→ Multi-D massive star evolution in the collapsing stage

(e.g., Couch and Ott 2015; Müller et al. 2016, 2019; Yadav et al. 2019)

Asphericity of SN Progenitors

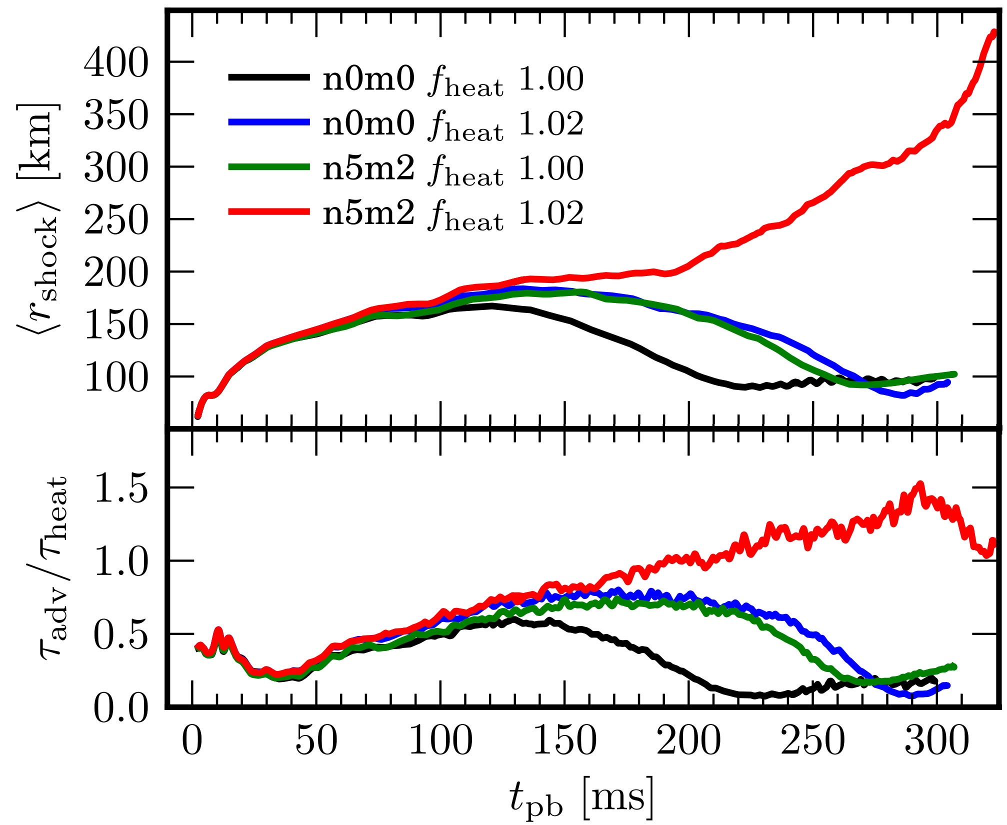
- Couch and Ott (2013)
  - v_θ perturbations in the Si/O layer of a 15 $M_\odot$ star (s15-2007)

➡ 3D SN explosion simulation (leakage for ν)



n5m2: M_{pert} = 0.2

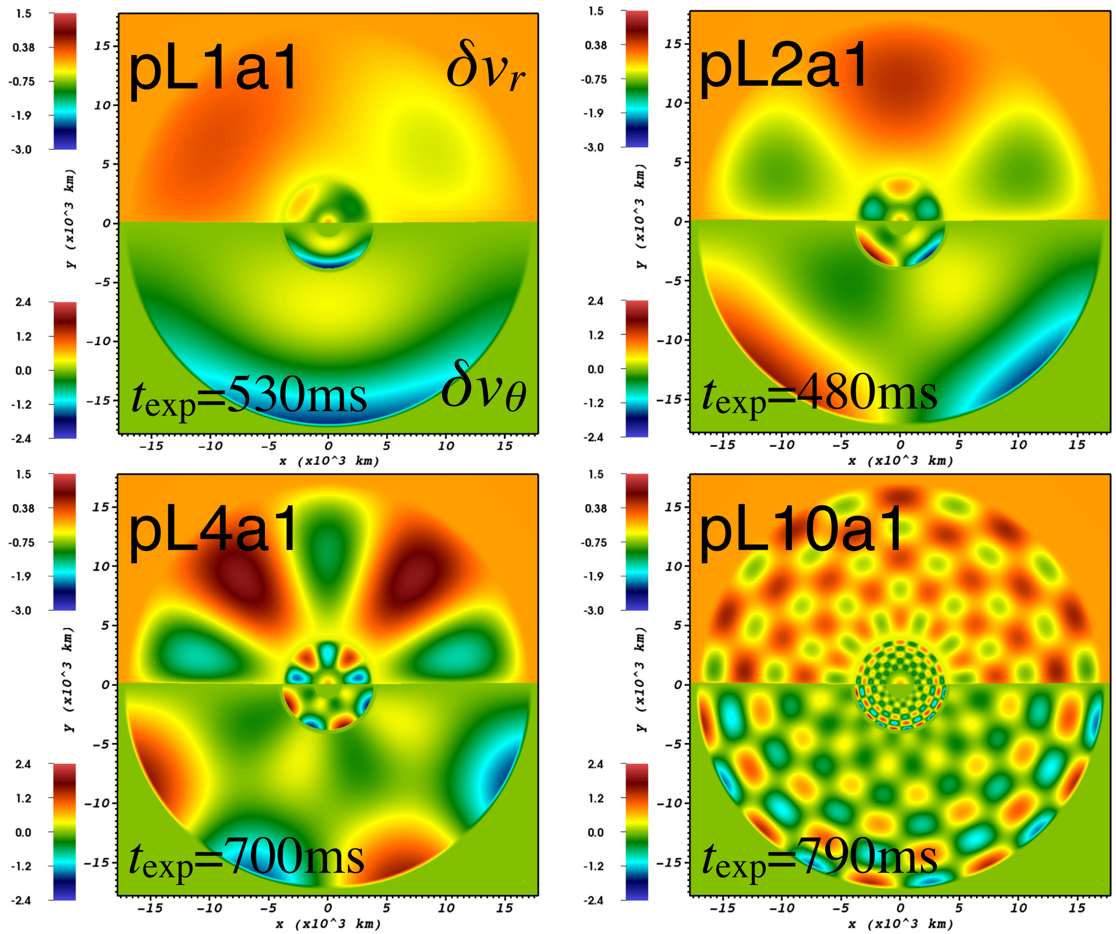
Triggering a SN explosion



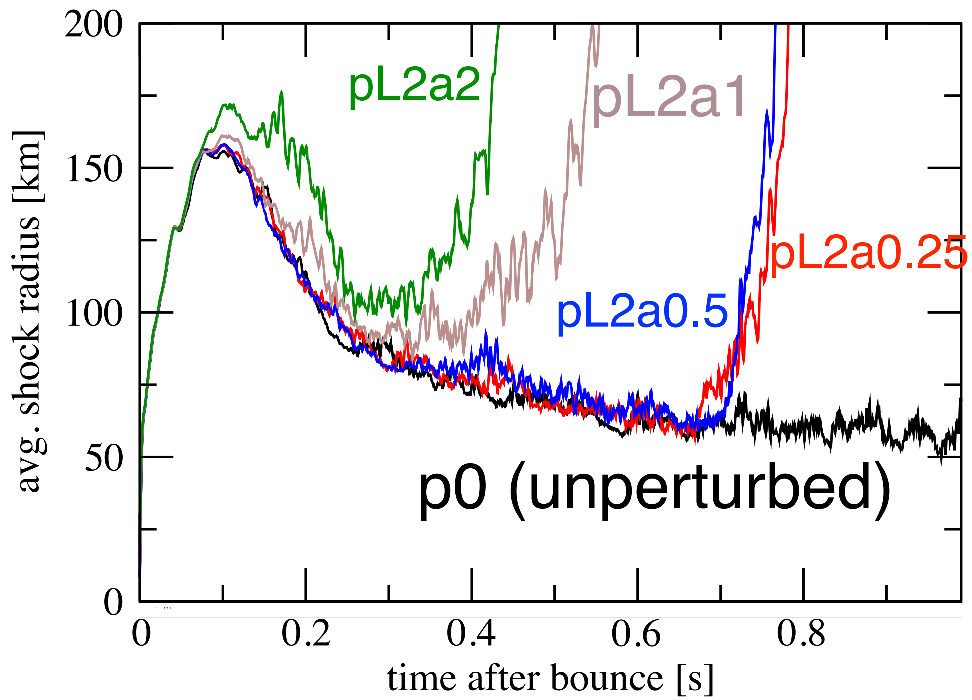
Asphericity of SN Progenitors

- Müller and Janka (2015)
  - various ν (ρ) perturbations in ~10^9 cm of a 15 $M_\odot$ star (s15-2007)

    ➡ 2D SN explosion simulations



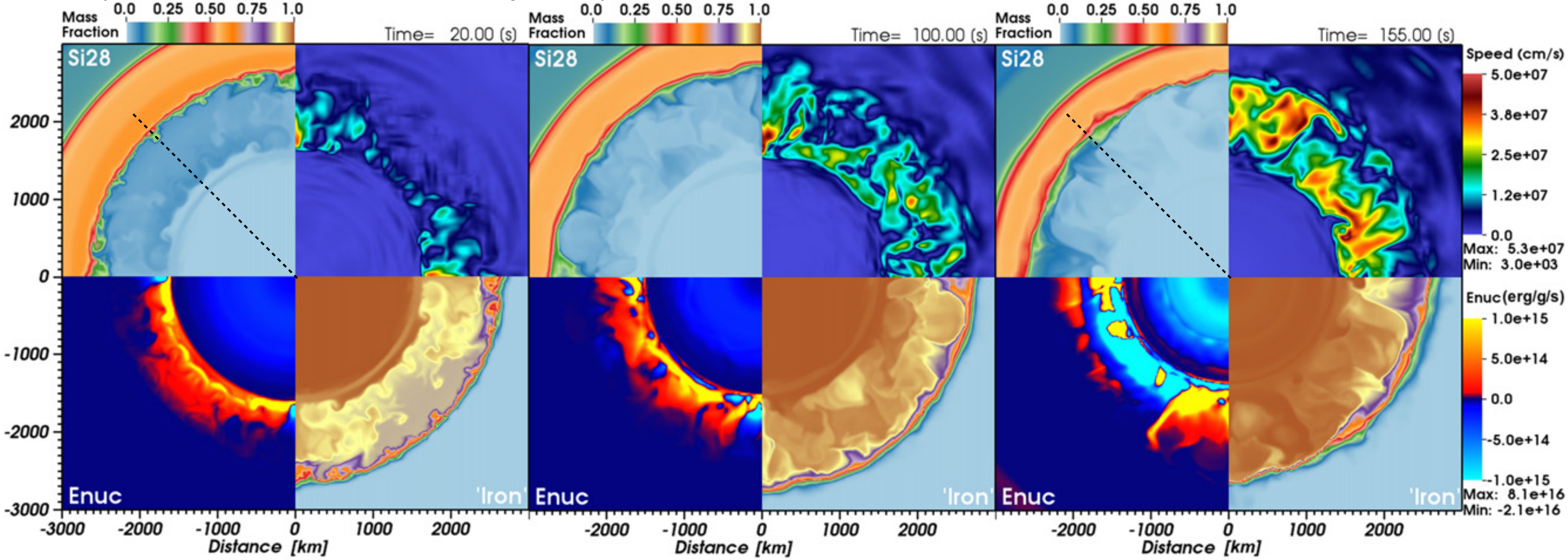
10^8 cm s^{-1}



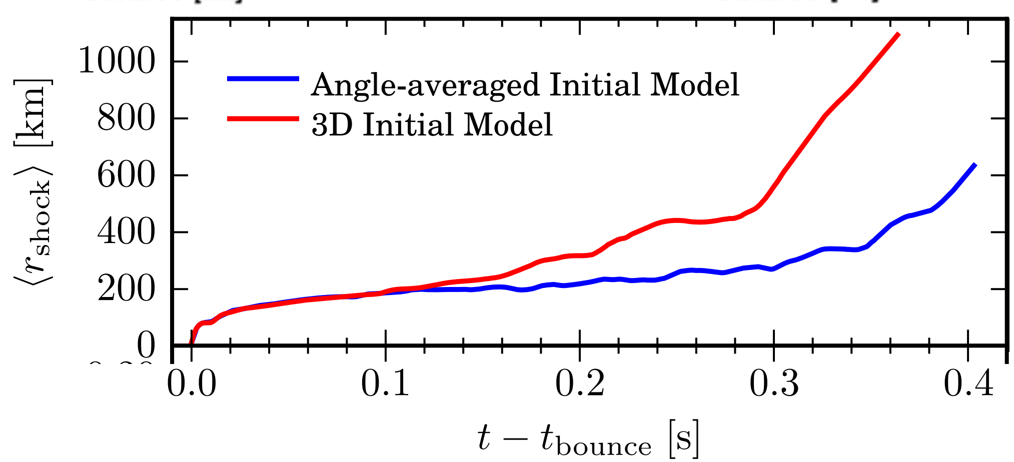
- Large-scale modes are preferred.

3D Simulation of a SN Progenitor

- 3D simulation of the Si layer of a 15 $M_\odot$ star for ~155 s (Couch et al. 2015)
  (one octant of the full 3D sphere)



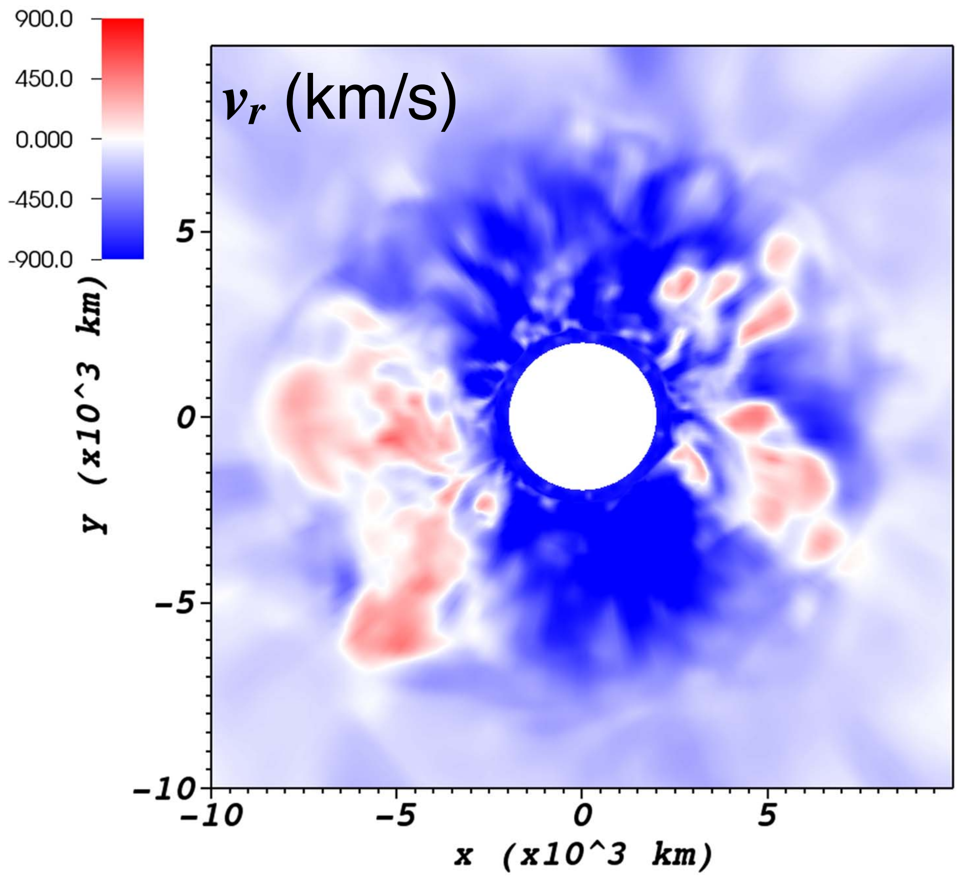
Explosion properties

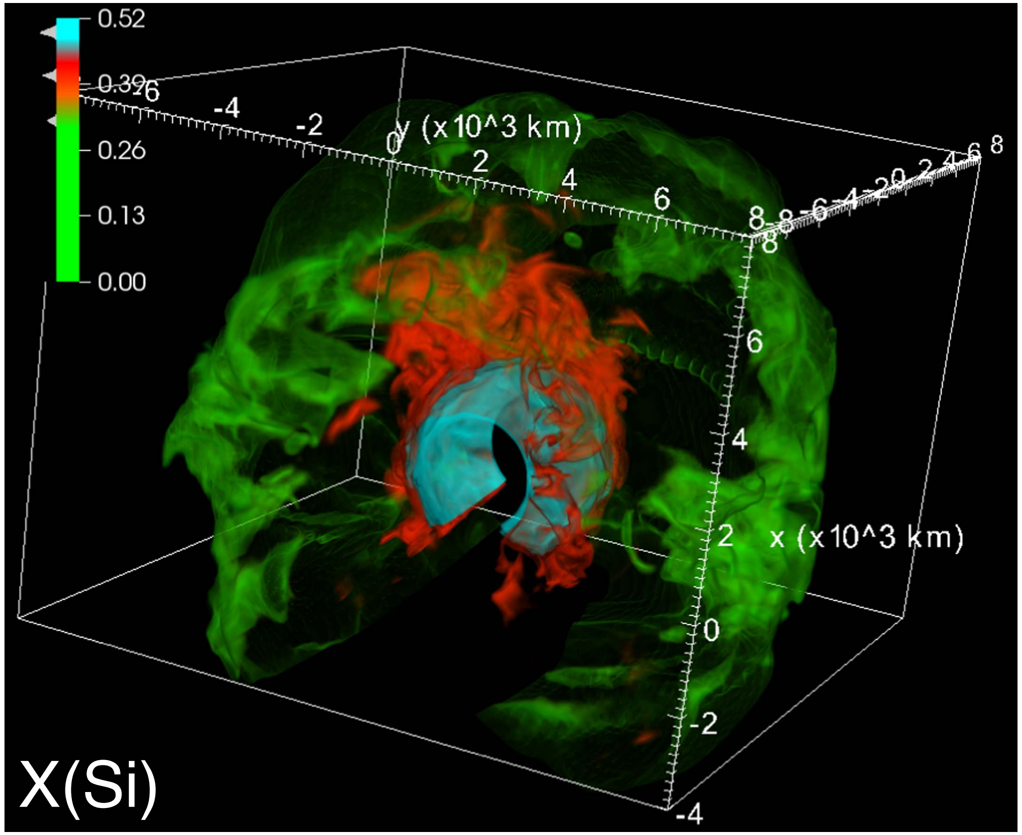


3D Simulation of O/Si layer in a SN Progenitor

- 3D simulation of the O/Si convective layer of a 18 $M_\odot$ star for ~300 s (Müller et al. 2016)

Turbulent velocity and Si mass fraction at 293.5 s





→ 3D SN explosion simulation (Müller et al. 2017)

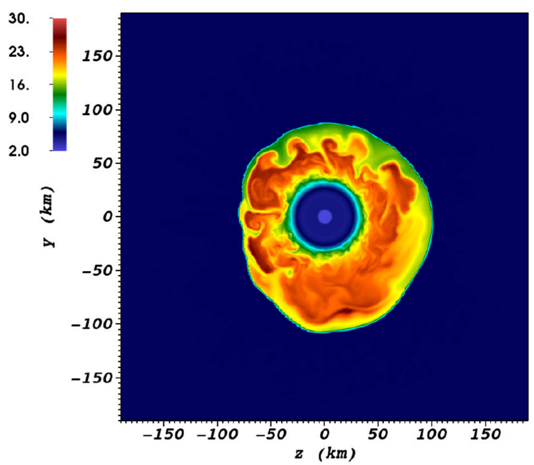
SN Explosion from a 3D Progenitor

- 3D SN explosion simulations using the 3D progenitor model

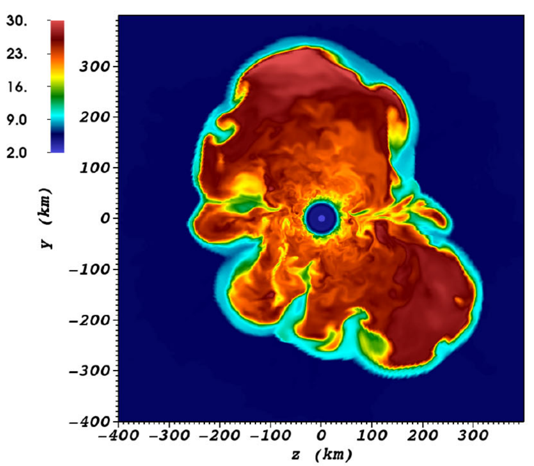
(Müller et al. 2017)

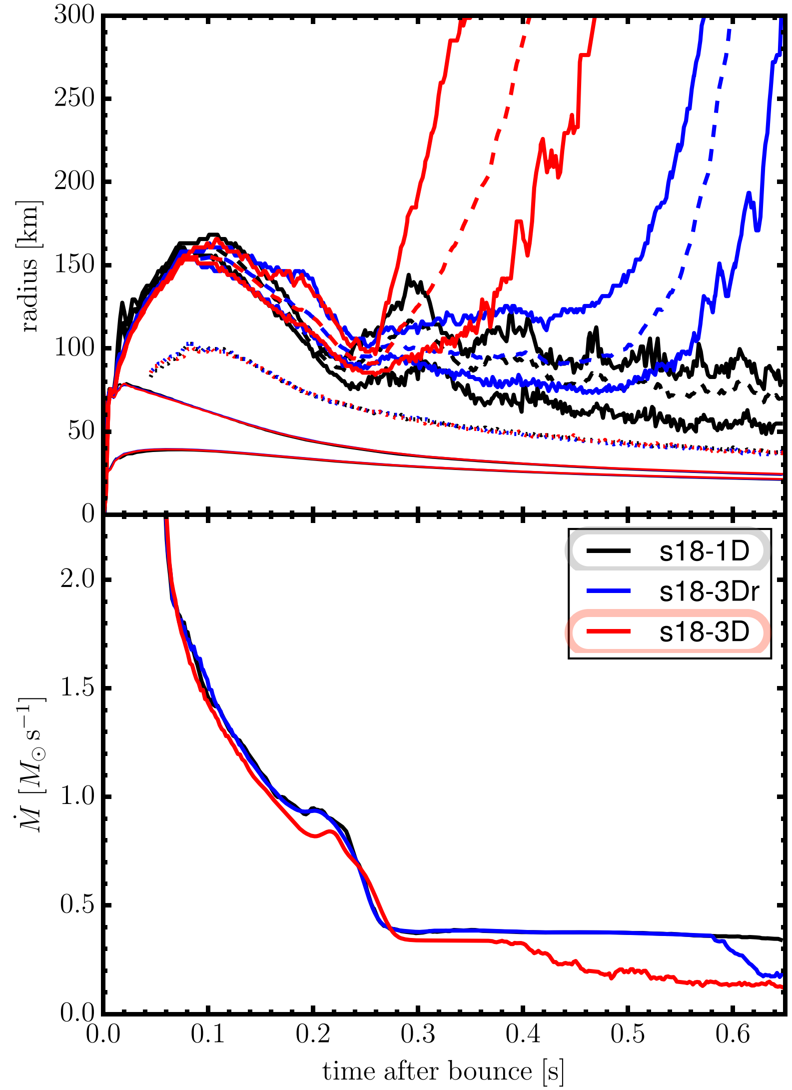
- Entropy (400ms)

s18-1D



s18-3D





➡ Triggering explosion at ~330 ms for the 3D progenitor model

Multi-D Simulations of Massive Star Evolution

- **3D n**uclear hydrodynamics code for **S**tellar **EV**olution (**3DnSEV**)

  A branch of **3DnSNe** (e.g., Takiwaki et al. 2016, Nakamura et al. 2016)

  - Nuclear reaction network of 21 species of nuclei (aprox21)

    (Paxton et al. 2011)

    Nuclear statistical equilibrium is assumed in $T > 5\times10^9$ K
  - Tabulated EOS of Helmholtz (Timmes & Swesty 2000)
  - Neutrino cooling (Itoh et al. 1996)
  - 2D: $N_r \times N_\theta = \mathbf{512 \times 128}$ **meshes**

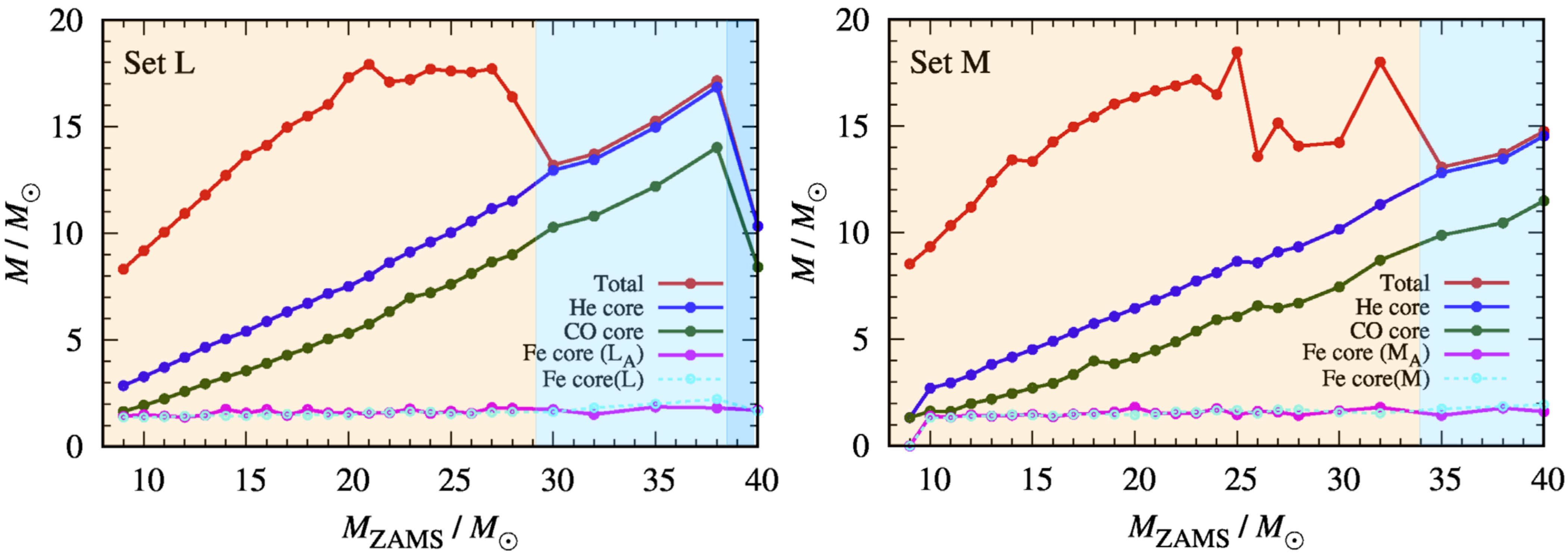
    3D: $N_r \times N_\theta \times N_\phi = \mathbf{512 \times 64 \times 128}$ **meshes**

    ➡ Calculations of the evolution for ~100 s until $T_c = 9\times10^9$ K

Analysis

- Turbulent Mach number
- Si mass fraction distribution
- Typical scale of the convection

1D Massive Star Evolution



- Set L → Stern-like (large) overshoot

  Set M → Genec-like (moderate) overshoot

- Sets L_A and M_A → Overshoot is also taken in advanced stages.

  → Larger M_{He} and M_{CO} of model L for a given M_{ZAMS}

- We look for stellar models having a wide O and Si-rich layer.

Results of 2D Simulations

- 11 models having a “large” SiO-coexisting layer

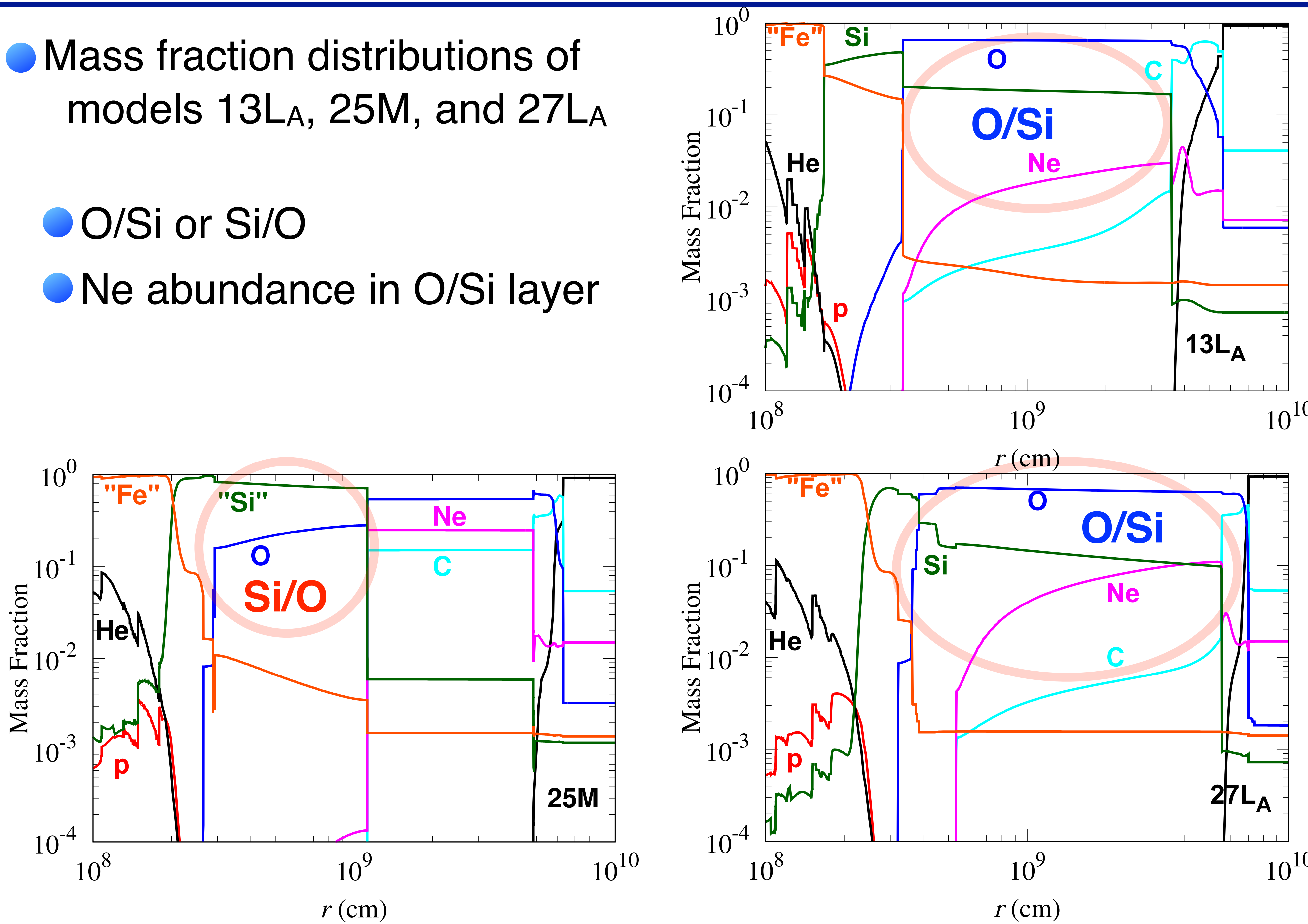
Model	$\langle Ma^2\rangle^{1/2}_{\rm max}$	$r(\langle Ma^2\rangle^{1/2}_{\rm max})$	Layer (10^8 cm)	$\ell_{\rm max}$
		Low Ma (< 0.1)		
$13\mathrm{L_A}$	0.018	11.6	O/Si	12
$16\mathrm{M_A}$	0.015	3.9	O/Si	4
$18\mathrm{M_A}$	0.131*	3.1	Si/O	14
$21\mathrm{M_A}$	0.134*	3.0	Si/O	8
$23\mathrm{L_A}$	0.069	11.5	O/Si	4
		High Ma (> 0.1)		
22L	0.108	9.4	Si/O	2
25M	0.160	5.8	Si/O	3
$27\mathrm{L_A}$	0.179	45.0	O/Si	2
27M	0.134	4.7	Si/O	10
$28\mathrm{L_A}$	0.117	5.3	Si/O	8
28M	0.369	14.6	O/Si	2

$\langle Ma^2\rangle^{1/2} > 0.1$ is achieved only in a few seconds before the last step.

- We will show convection properties of models 25M, and $27\mathrm{L_A}$.

Mass Fraction Distribution

- Mass fraction distributions of models 13L$_A$, 25M, and 27L$_A$
  - O/Si or Si/O
  - Ne abundance in O/Si layer

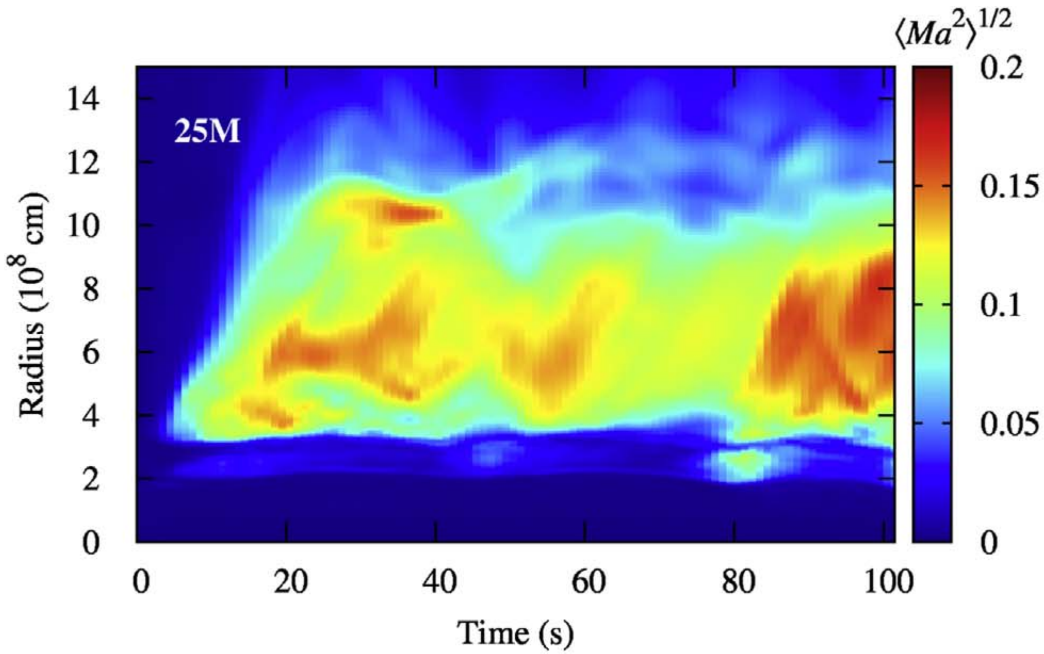


Time Evolution of Radial Profiles

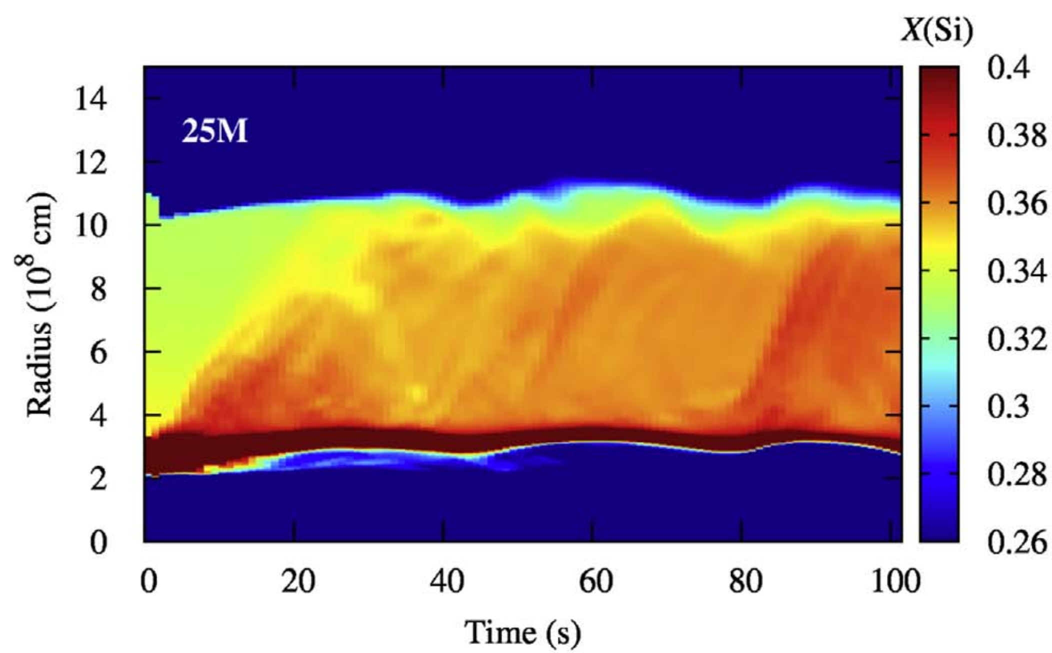
- 25M (High *Ma* (1))

- Turbulent Mach number

$$\langle Ma^2 \rangle^{1/2}(r) = \left[\frac{\int \rho[(v_r - \langle v_r \rangle)^2 + v_\theta^2 + v_\phi^2] d\Omega}{\int \rho c_s^2 d\Omega} \right]^{1/2}$$



- Si mass fraction

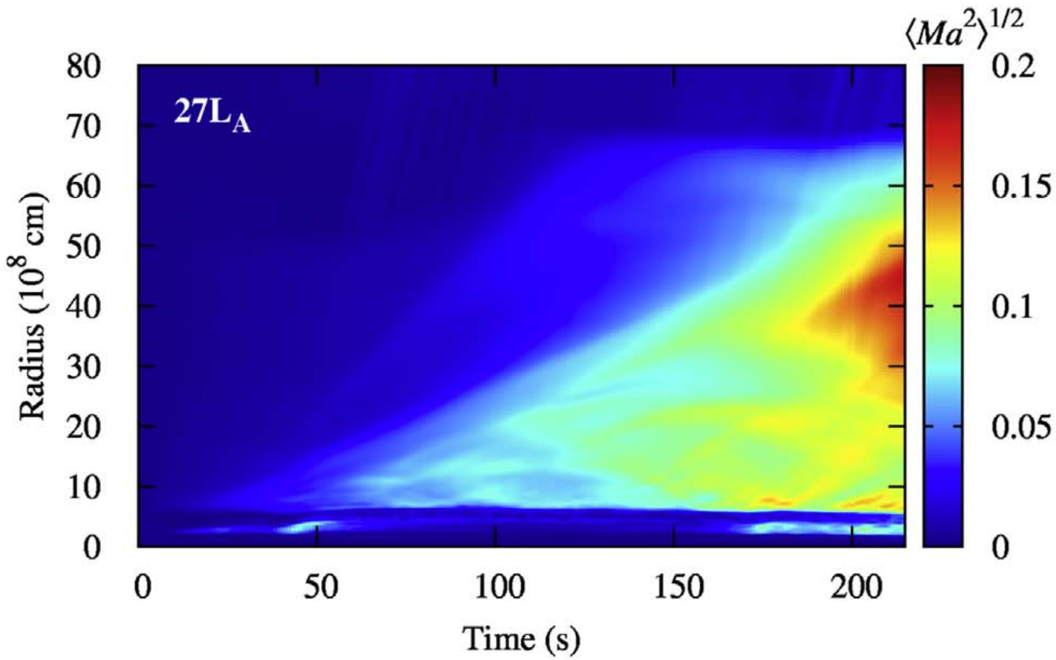


- $\langle \mathrm{Ma}^2 \rangle^{1/2} < 0.16$
- $\ell = 3$ mode dominates
- Si enhancement in $r \sim (4\text{–}11) \times 10^8$ cm
- 22L, 27M, $28L_A$ → Similar convection features

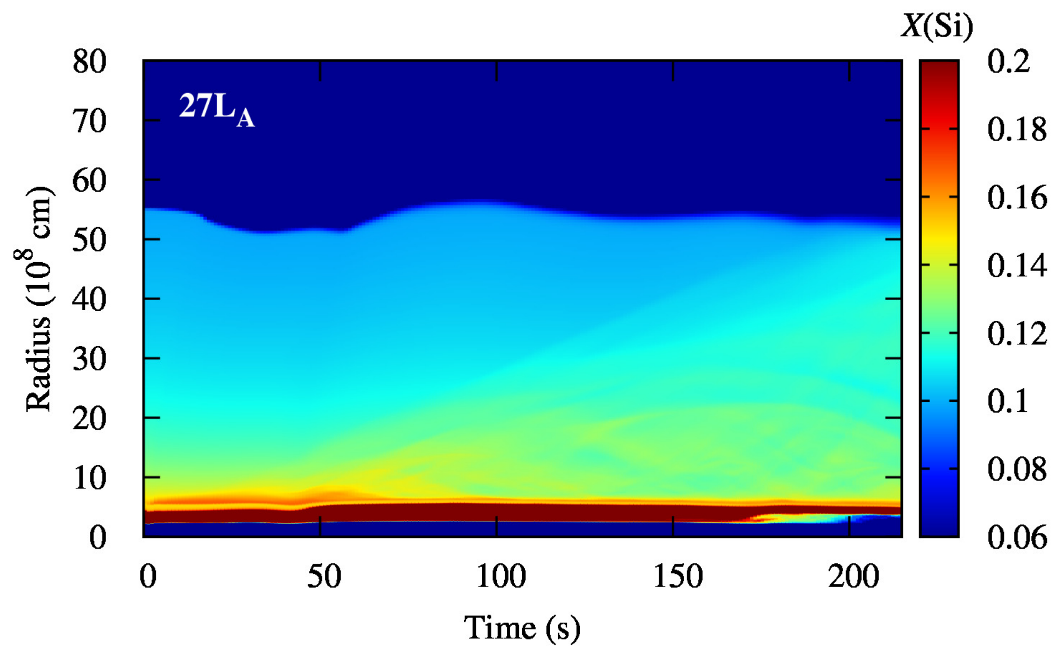
Time Evolution of Radial Profiles

- $27L_A$ (High *Ma* (2))
  - Turbulent Mach number

$$\langle Ma^2\rangle^{1/2}(r) = \left[\frac{\int \rho[(v_r - \langle v_r\rangle)^2 + v_\theta^2 + v_\phi^2]d\Omega}{\int \rho c_s^2 d\Omega}\right]^{1/2}$$



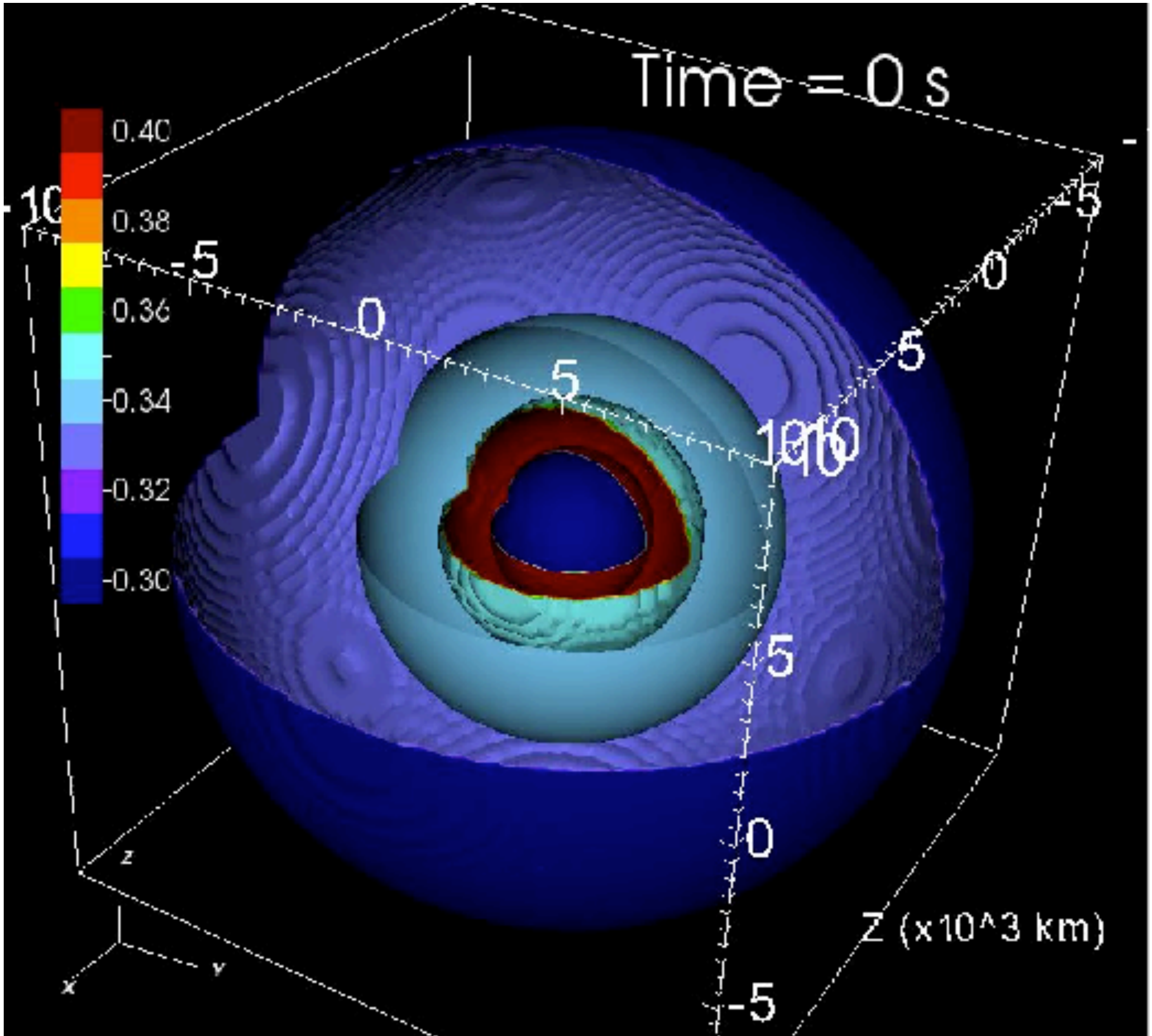
  - Si mass fraction



- Turbulent Mach number increases with time in the O/Si layer.
- $\ell = 2$ mode dominates at the last step.
- Convection region increases (mixing with Ne).
- 28M ➡ Similar convection feature

3D Simulation of Model 25M

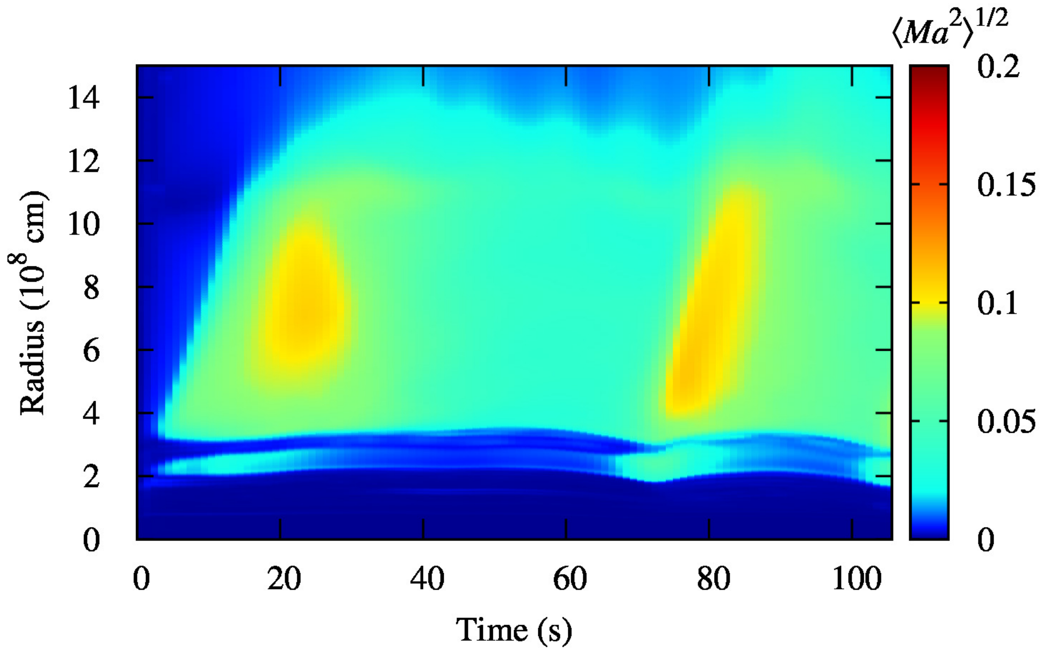
Si mass fraction distribution of model 25M



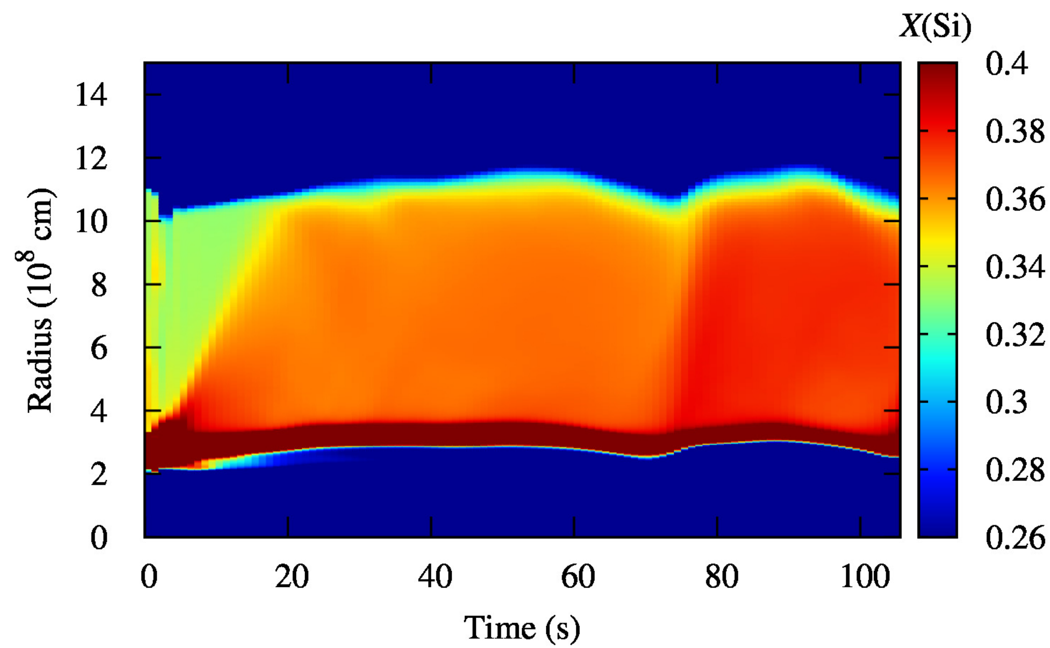
Evolution of model 25M in 3D

- Angle averaged radial profiles
  - Turbulent Mach number

$$\langle Ma^2 \rangle^{1/2}(r) = \left[\frac{\int \rho [(v_r - \langle v_r \rangle)^2 + v_\theta^2 + v_\phi^2] d\Omega}{\int \rho c_s^2 d\Omega} \right]^{1/2}$$



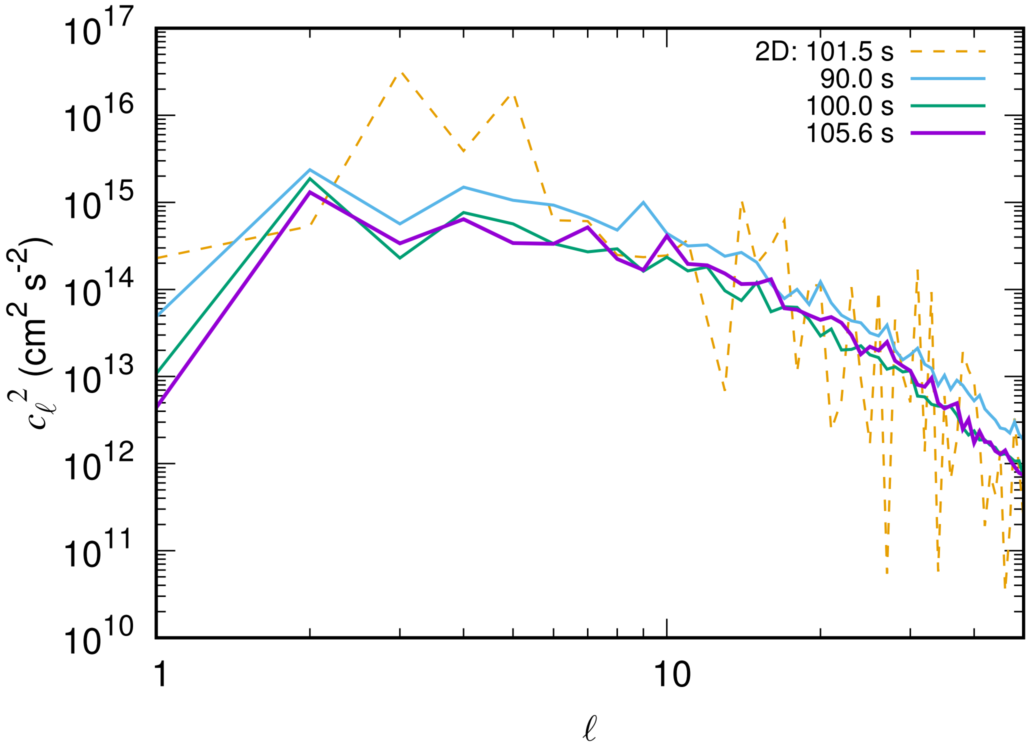
  - Si mass fraction



- $\langle \mathrm{Ma}^2 \rangle^{1/2}$ → a few to 10%: lower than the 2D result
- Si mass fraction increases by the mixing

Power Spectra of Radial Velocity

- Spectral analysis of radial velocity distributions at 5.8×10⁸ cm



$$c_l^2 = \sum_{m=-l}^{l} \left| \int (v_r - \langle v_r \rangle) Y_{lm}^*(\theta, \phi) d\Omega \right|^2$$

- $\ell_{\max} = 2$

➡ Large-scale convection eddies in 3D

⋯ Favorable to SN explosion

➡ Connection to 3D simulation of SN explosion

Summary

- Aspherical structure of SN progenitor affects the explosion of SNe.
  - O-shell burning in a large O and Si-rich layer

    ➡ High turbulent velocity and large-scale convective eddies

    ➡ **Asphericity helps triggering SN explosion.**

Multi-D hydrodynamics simulations in O and Si-rich layer of massive star models for ~100 s before the core-collapse

- 2D hydrodynamics simulations for 11 massive star models
  - Models ***having a large O and Si-rich layer and large mass***

    ➡ Convective motion with $\langle Ma^2 \rangle^{1/2} \sim 0.1$ and small $\ell_{\rm max}$.

    Favorable to SN explosion

- 3D hydrodynamics simulation of model 25M

  ➡ Turbulent Mach number lower than 2D

  Large-scale convective motion