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

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The Evolution of Massive Stars and Formation of Compact Stars: from the Cradle to the Grave
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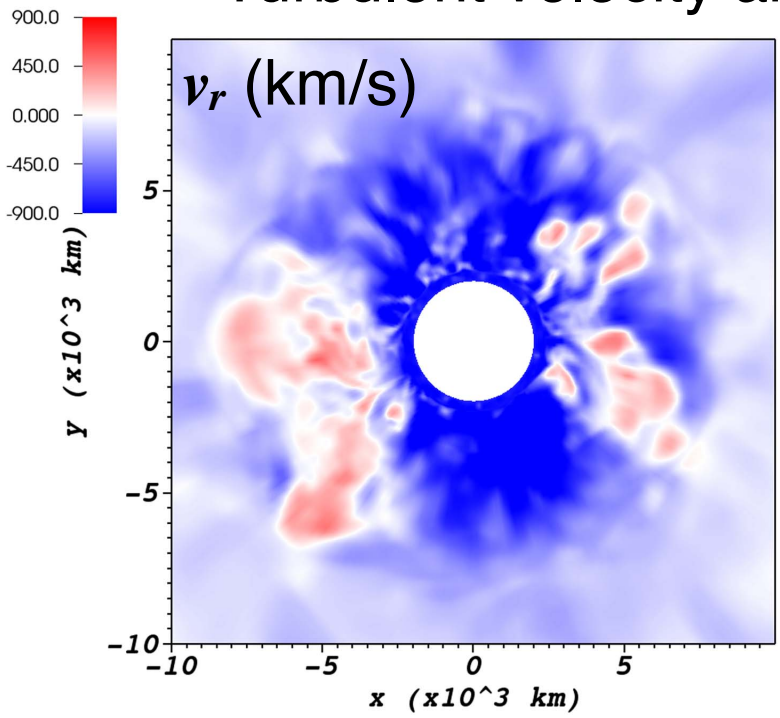
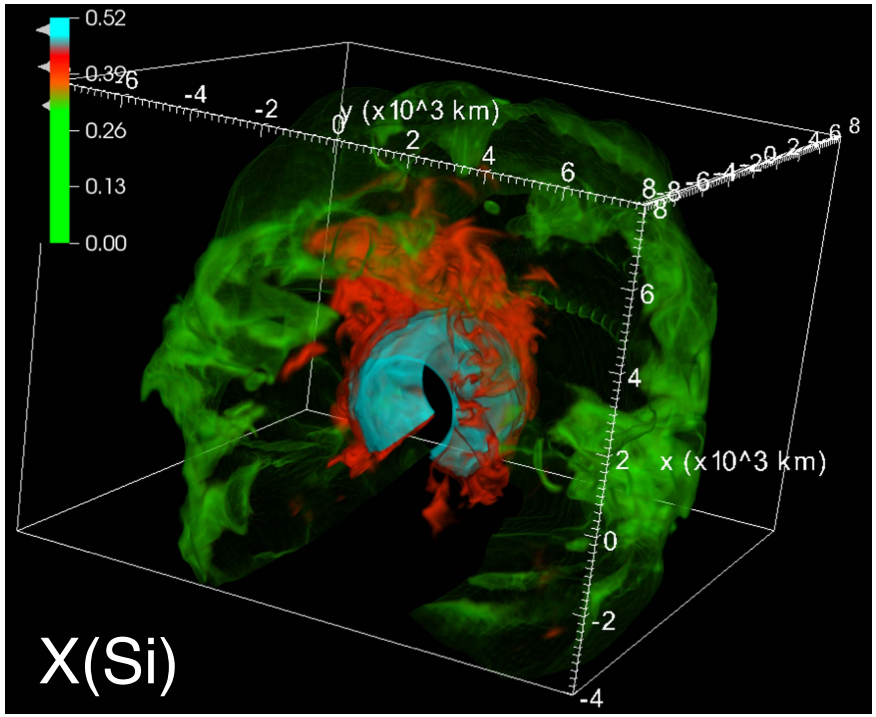
3D Simulations of Shell Burning in SN Progenitors

- 2D and 3D SN simulations with aspherical v_θ perturbations
  (Couch and Ott 2013; Müller and Janka 2015)
- 3D simulations of the Si and Si/O-rich convective layers
  (Couch and Ott 2015; Müller et al. 2016, 2019; Yadav et al. 2019)
- 3D simulations of O shell burning in 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

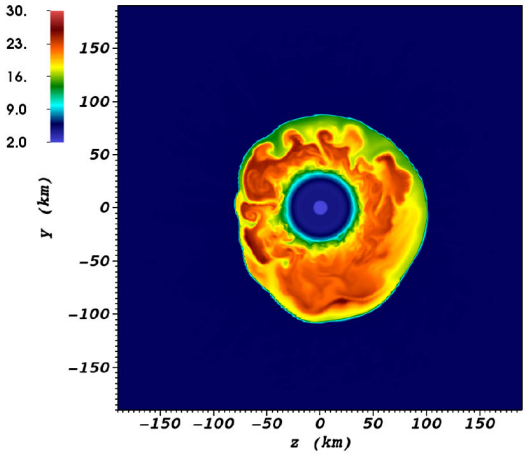




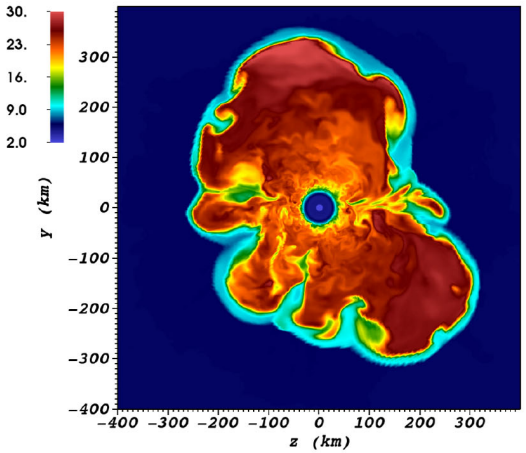
➡ 3D simulation of SN explosion (Müller et al. 2017)

SN Explosion from a 3D Progenitor

- 3D SN explosion simulations using the 3D progenitor models
  - Entropy (400ms)

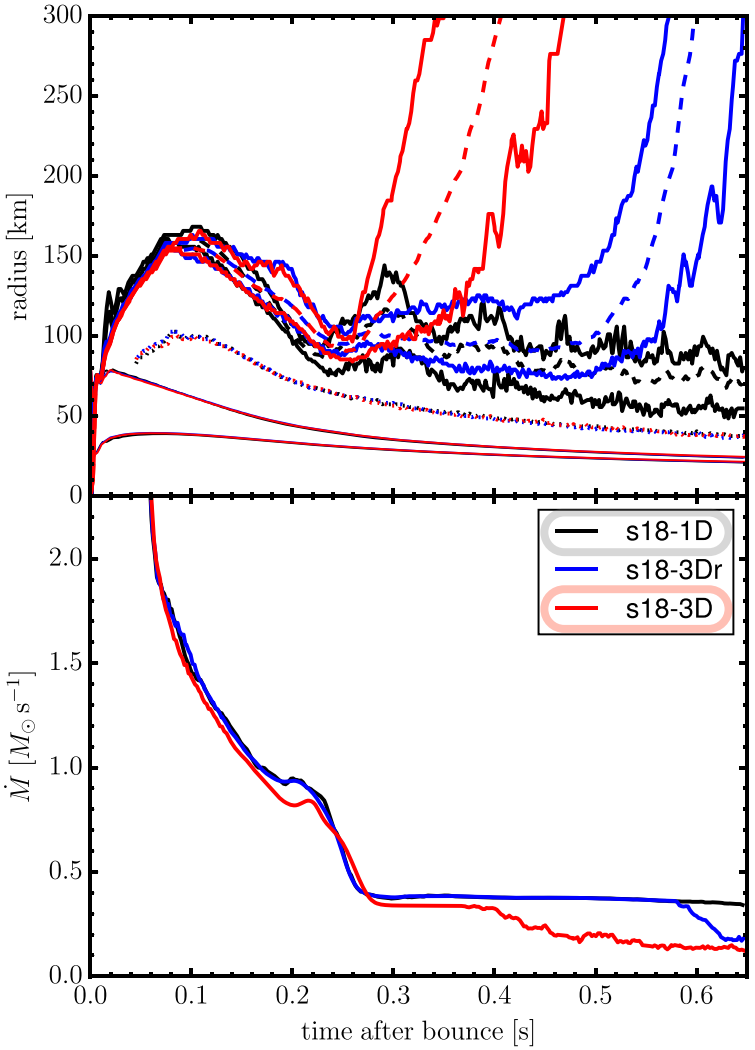


s18-1D



s18-3D

(Müller et al. 2017)



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

➡ **Large-scale asphericity helps triggering SN explosions.**

Multi-D Simulations of Massive Star Evolution

- **3D nuclear hydrodynamics code for Stellar EVolution (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: $r < 10^{10}$ cm, $N_r \times N_\theta = 512 \times 128$ meshes

      ➡ Calculations of the evolution for ~100 s until $T_c = 9\times10^9$ K
    - 3D: $r < 10^{10}$ cm, $N_r \times N_\theta \times N_\phi = 512 \times 64 \times 128$ meshes

      ➡ Calculation of the evolution until $T_c = 10^{10}$ K
  - **Analysis**
    - Turbulent Mach number
    - Si mass fraction distribution
    - Typical scale of the convection (Power spectrum)

Results of 2D Simulations

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

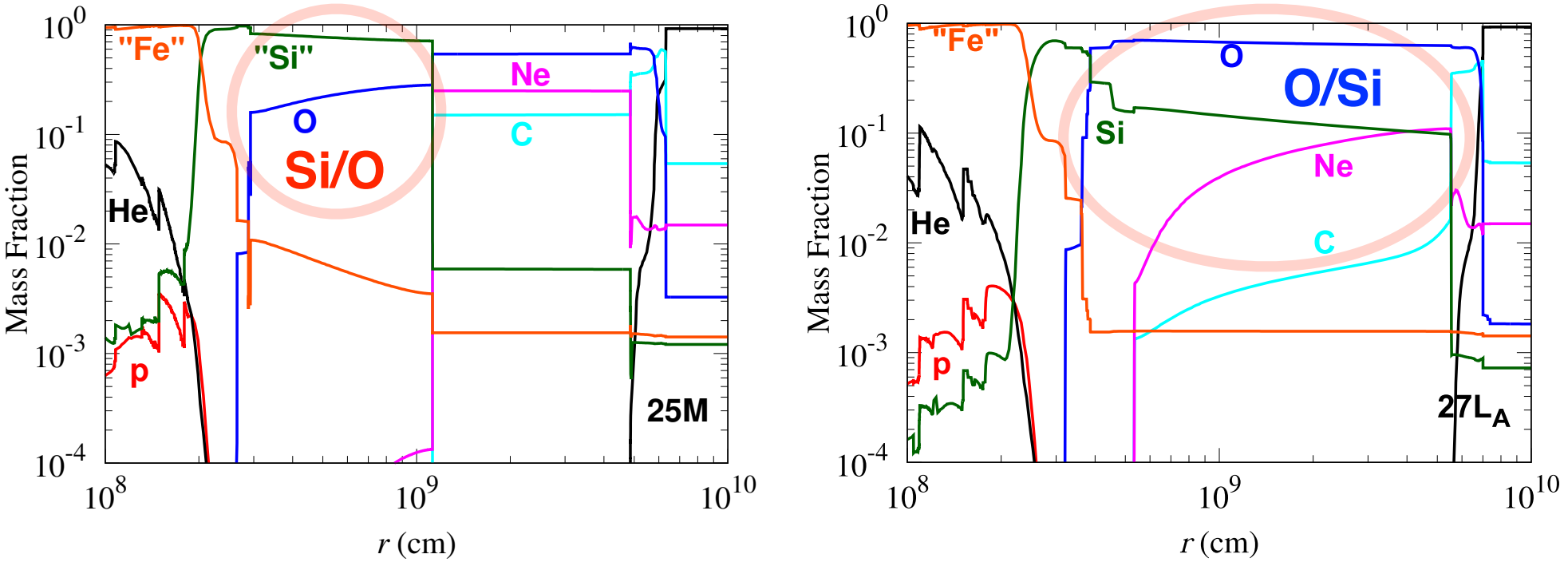
Model	$\langle Ma^2 \rangle_{\rm max}^{1/2}$	$r(\langle Ma^2 \rangle_{\rm max}^{1/2})$	Layer (10^8 cm)	$\ell_{\rm max}$
		Low Ma (< 0.1)		
$13L_A$	0.018	11.6	O/Si	12
$16M_A$	0.015	3.9	O/Si	4
$18M_A$	0.131*	3.1	Si/O	14
$21M_A$	0.134*	3.0	Si/O	8
$23L_A$	0.069	11.5	O/Si	4
		High Ma (> 0.1)		
22L	0.108	9.4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

Mass Fraction Distribution

- Mass fraction distributions of models 25M and $27L_A$

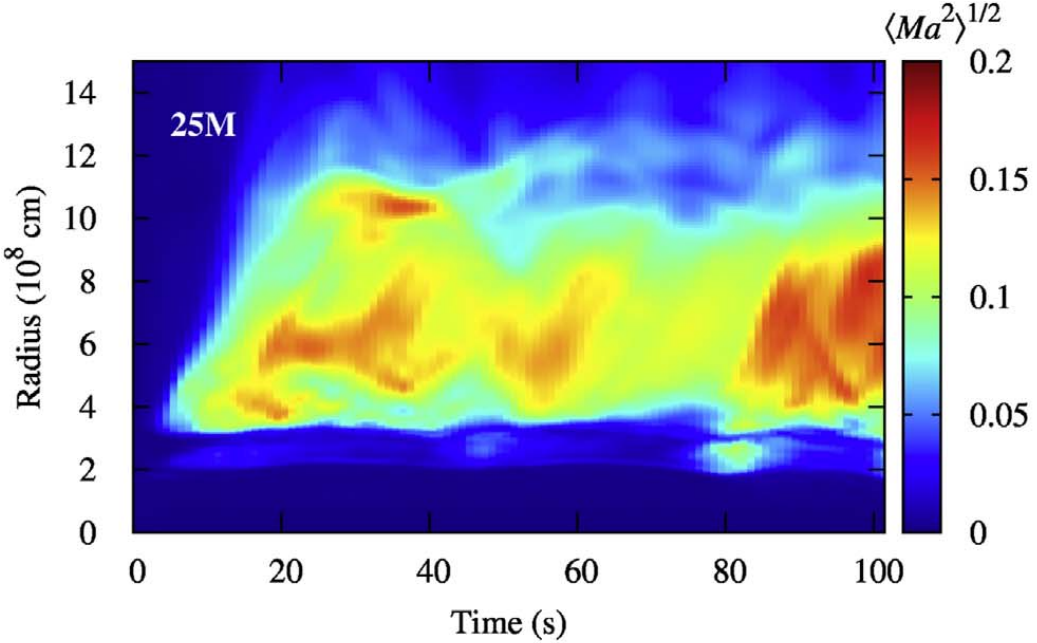


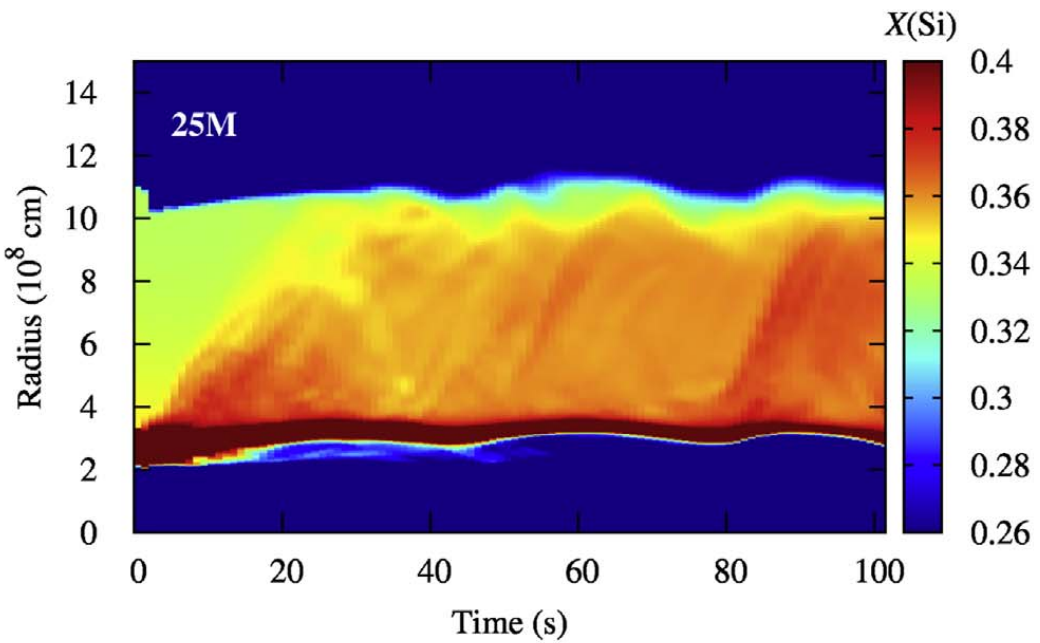
- model 25M → Large Si/O layer
- model $27L_A$ → Large O/Si(/Ne) layer

Time Evolution of Radial Profiles

- 25M (High *Ma* (1))
  - Turbulent Mach number
  - Si mass fraction

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



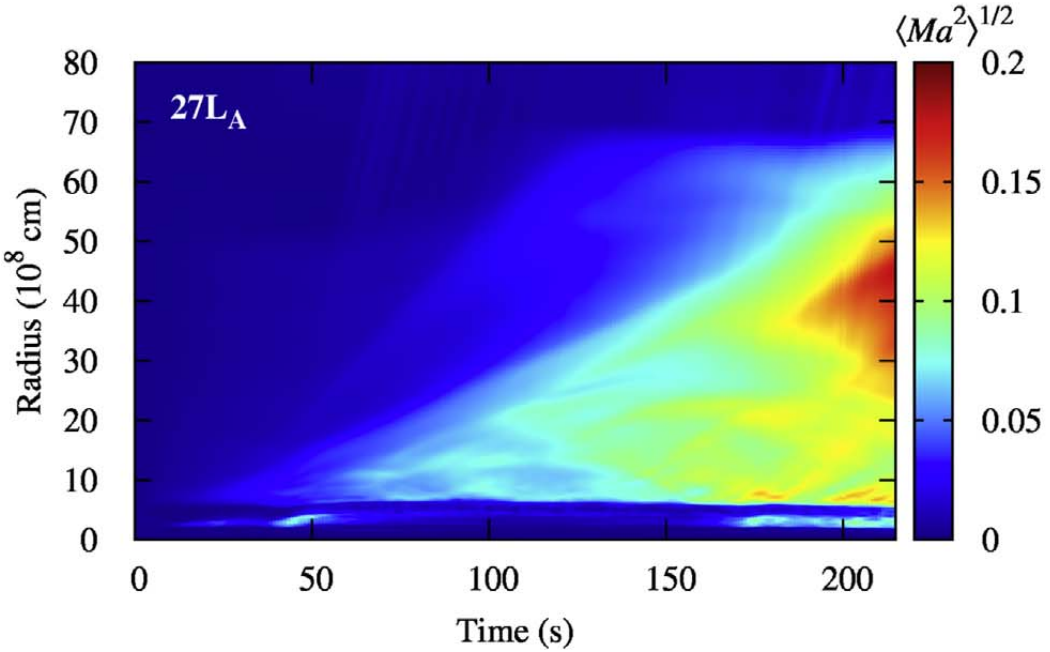


- $\langle \mathrm{Ma}^2 \rangle^{1/2} < 0.16$
- $\ell = 3$ mode dominates
- Si enhancement in $r \sim (4\text{–}11)\times 10^8$ cm
- 22L, 27M, 28L$_A$ → Similar convection features

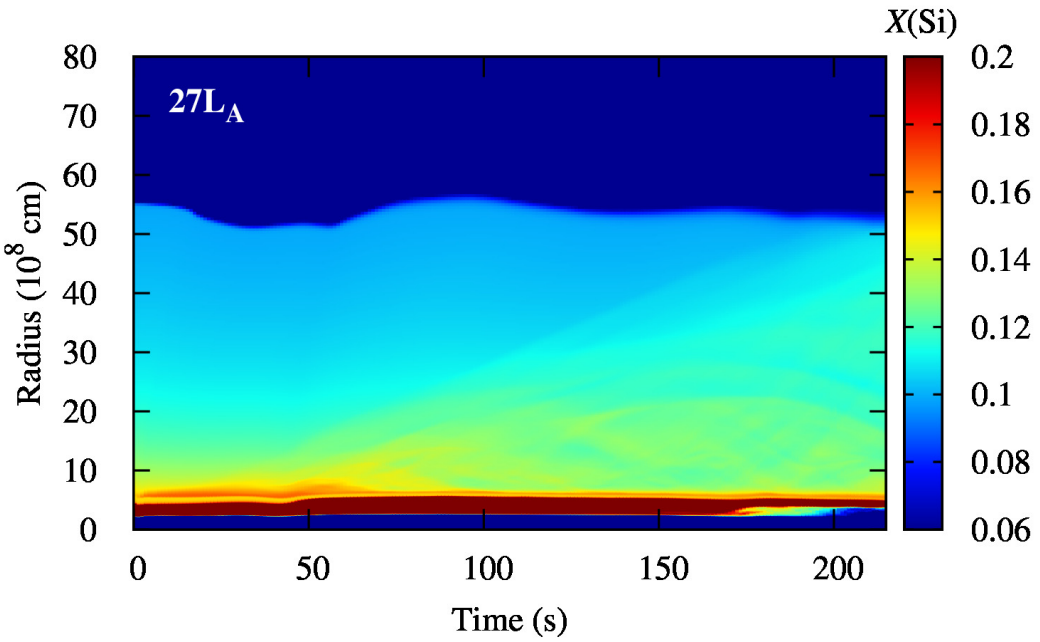
Time Evolution of Radial Profiles

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

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



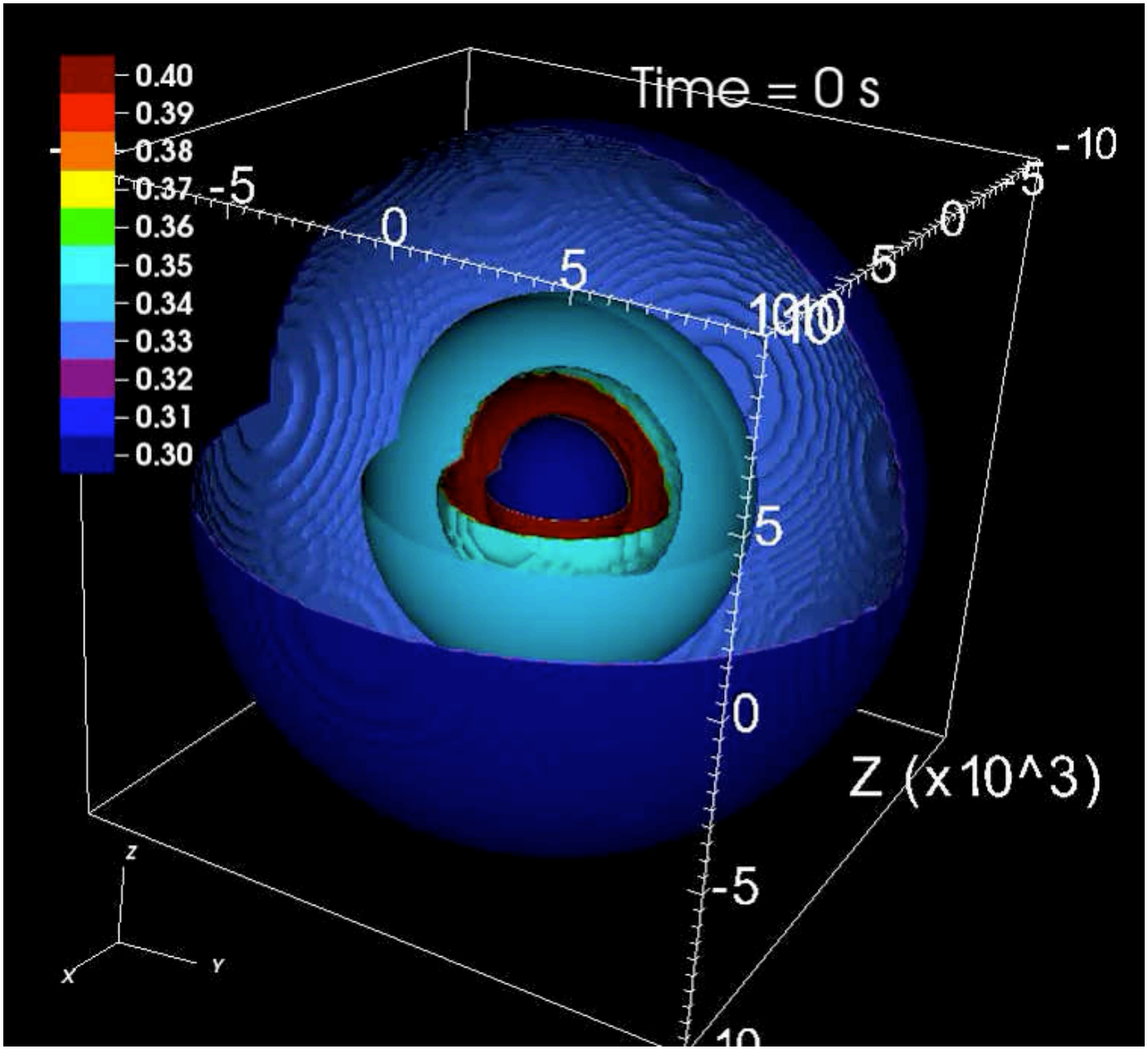
  - Si mass fraction



  - 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

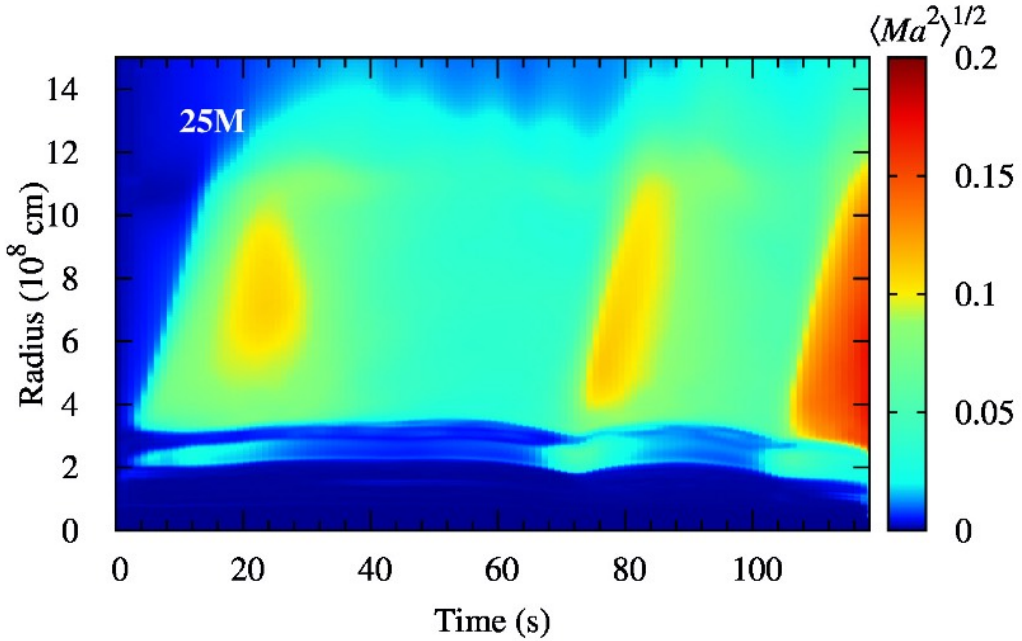
Si mass fraction distribution of model 25M

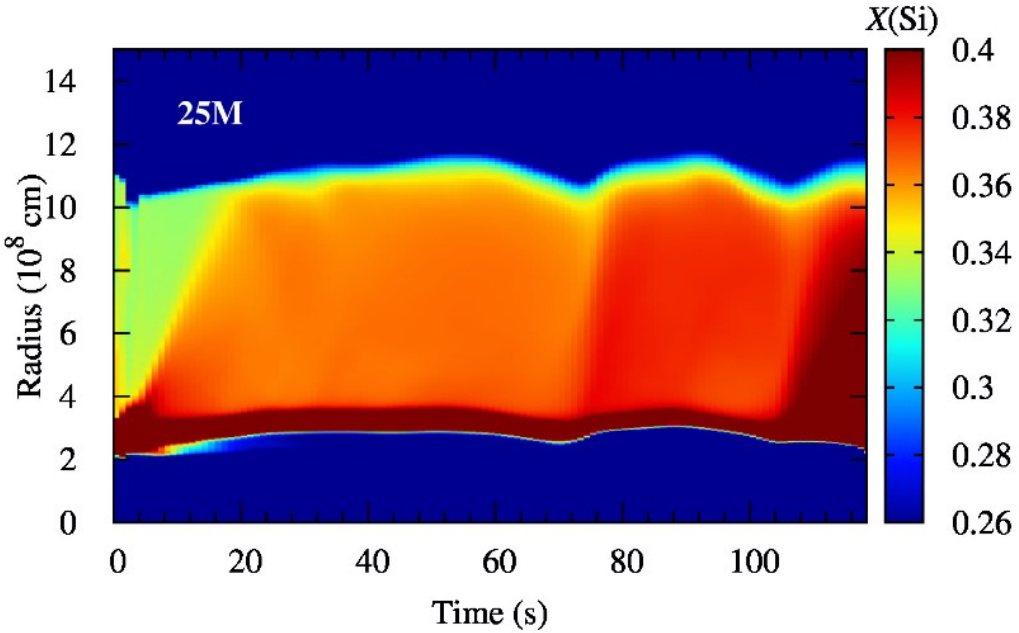


Evolution of model 25M in 3D

- Angle averaged radial profiles
  - Turbulent Mach number
  - Si mass fraction

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

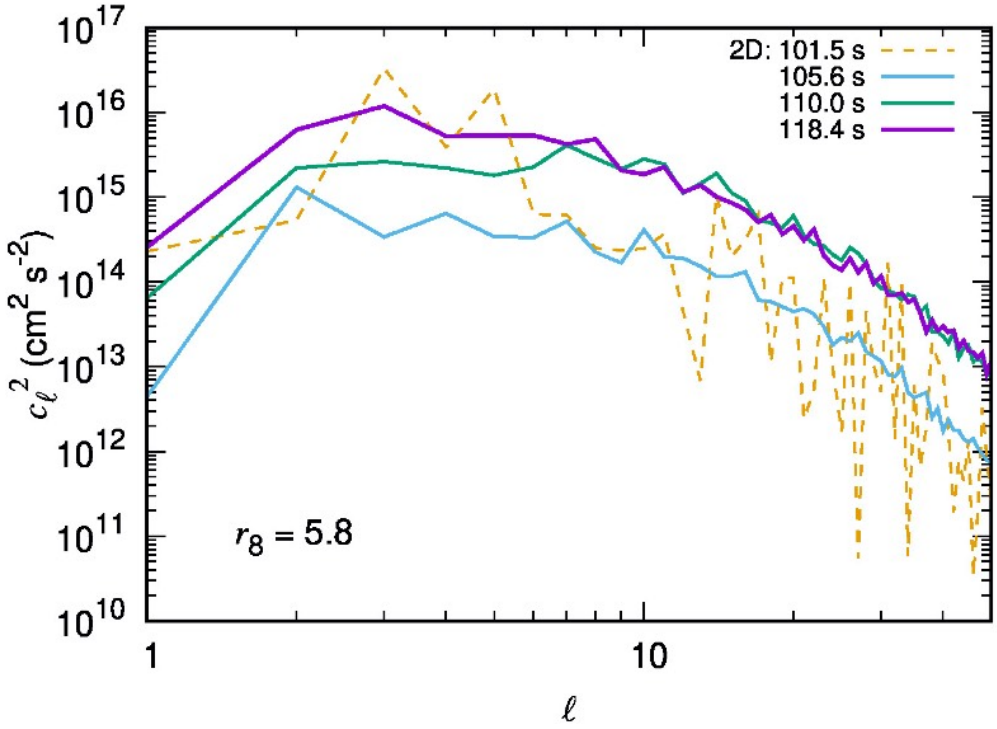




- $\langle Ma^2 \rangle^{1/2}$ ➡ a few to 17%
- Si mass fraction increases by the mixing

Power Spectra of Radial Velocity

- Spectral analysis of radial velocity distributions at 5.8×10^8 cm



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

- $\ell_{\max} = 3$

  ➡ Large-scale convection eddies in 3D

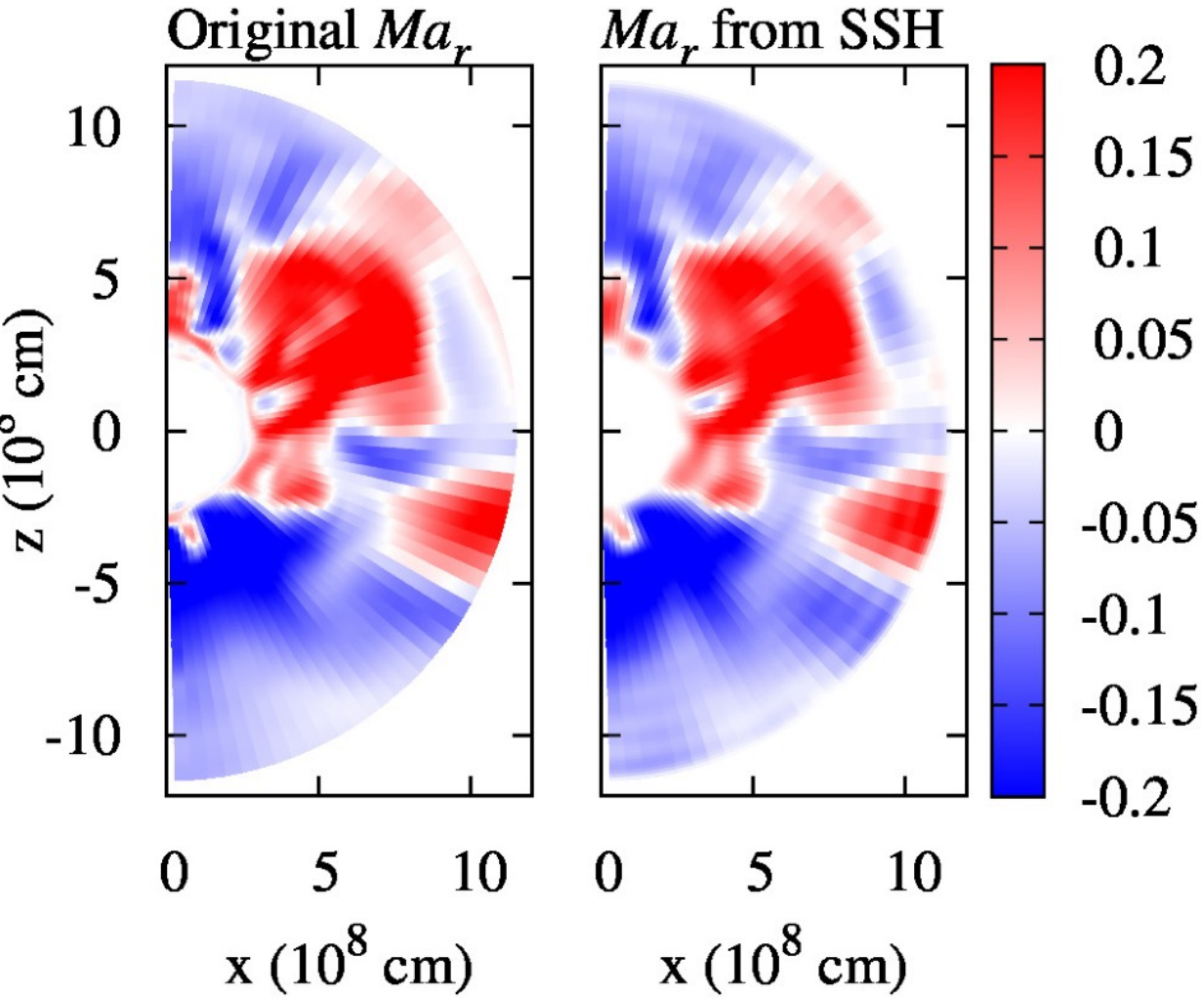
  ⋯ Favorable to SN explosion

  ➡ Connection to 3D simulation of SN explosion

Towards Simulations of SN Explosions

- Scalar spherical harmonics analysis of radial Mach number distribution

(Chatzopoulos et al. 2014)



$n_{\max} = 18$

$\ell_{\max} = 21$

→ Connection to multi-D simulation of SN explosion

Please see **Nakamura-san's poster: P10**

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 $\ell_{\rm max}$.
- 3D hydrodynamics simulation of model 25M
  - ➡ Turbulent Mach number less than 2D
    Large-scale convective motion

Future study

- More simulations with a variety of convective motion