Precollapse Shell Burning in the Si and O-rich Layers in Massive Stars

Yoshida et al. 2021, ApJ 908, 44

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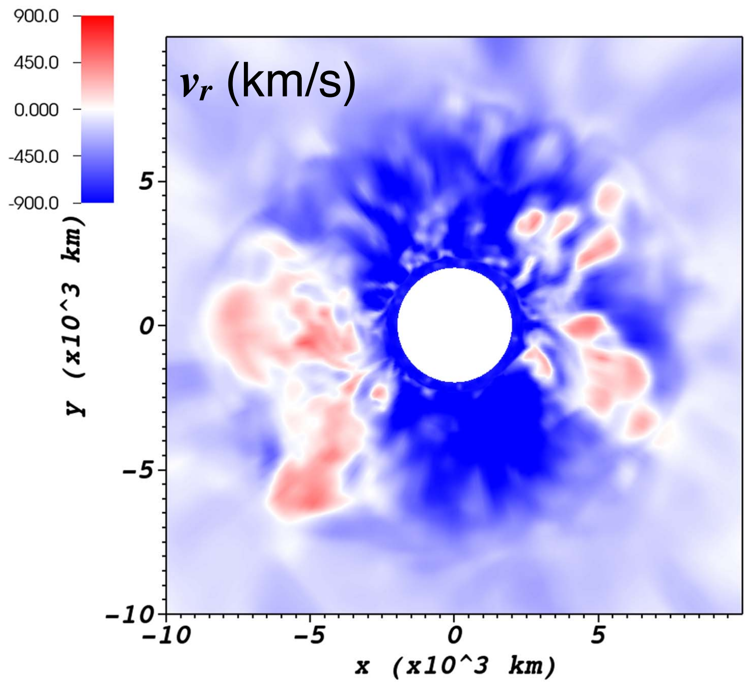
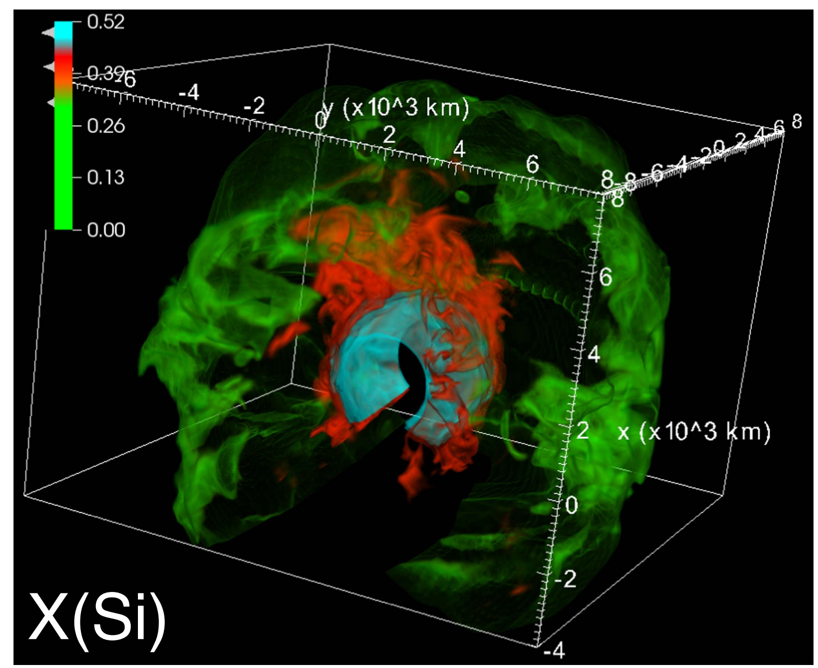
Nuclear burning in massive stars: towards the formation of binary black holes
July 26th, 2021, YITP, Kyoto University and Monash University

3D Simulations of Shell Burning in SN Progenitors

- Aspherical structure of SN progenitors affects the explosion of SNe.
  (e.g., Couch & Ott 2013; Müller & Janka 2015)
- 3D simulations of Si or O/Si-rich convective layers in precollapse stars
  (e.g., Couch & Ott 2015; Müller et al. 2016)

➡ Convective motion with high Mach number and a large scale
(e.g., Müller et al. 2016; , Yadav et al. 2020; Yoshida et al. 2019, 2021a,b)



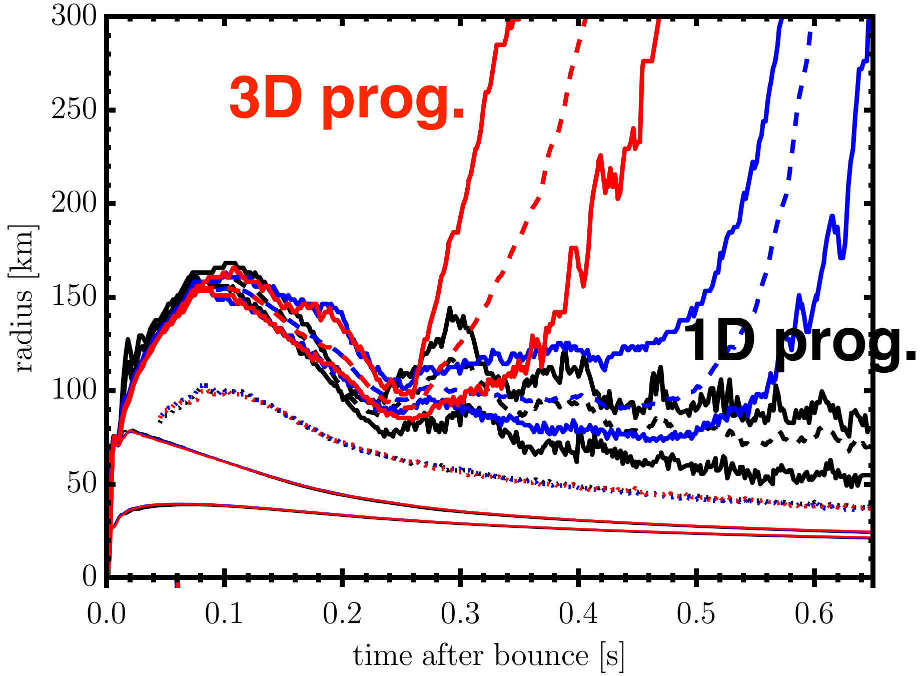


(Müller et al. 2016)

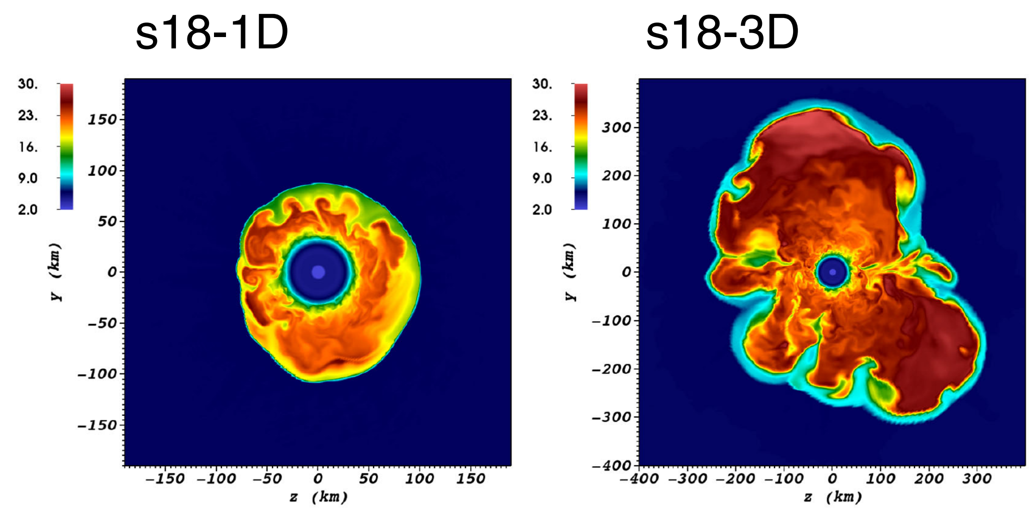
3D Simulations of Shell Burning in SN Progenitors

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

(Müller et al. 2017, 2019; Bollig et al. 2021)



- Entropy (400ms) (Müller et al. 2017)



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

- Increasing 3D simulations of convective layers in precollapse stars
  - Large convective layers (Yoshida et al. 2021a; Fields & Couch 2020, 2021)
  - Merging of convective layers (Yadav et al. 2020)
  - Rotating effects (Yoshida et al. 2021b; McNeill & Müller 2021)
  - Magnetic field (Varma & Müller 2021)

3D Simulations of Shell Burning in SN Progenitors

This study

- 3D hydrodynamics simulations of the O/Si-rich layer of a 27 $M_\odot$ precollapse star (model 27L$_A$) for ~200 s

  → Properties of convective motion in the O/Si-rich layer

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

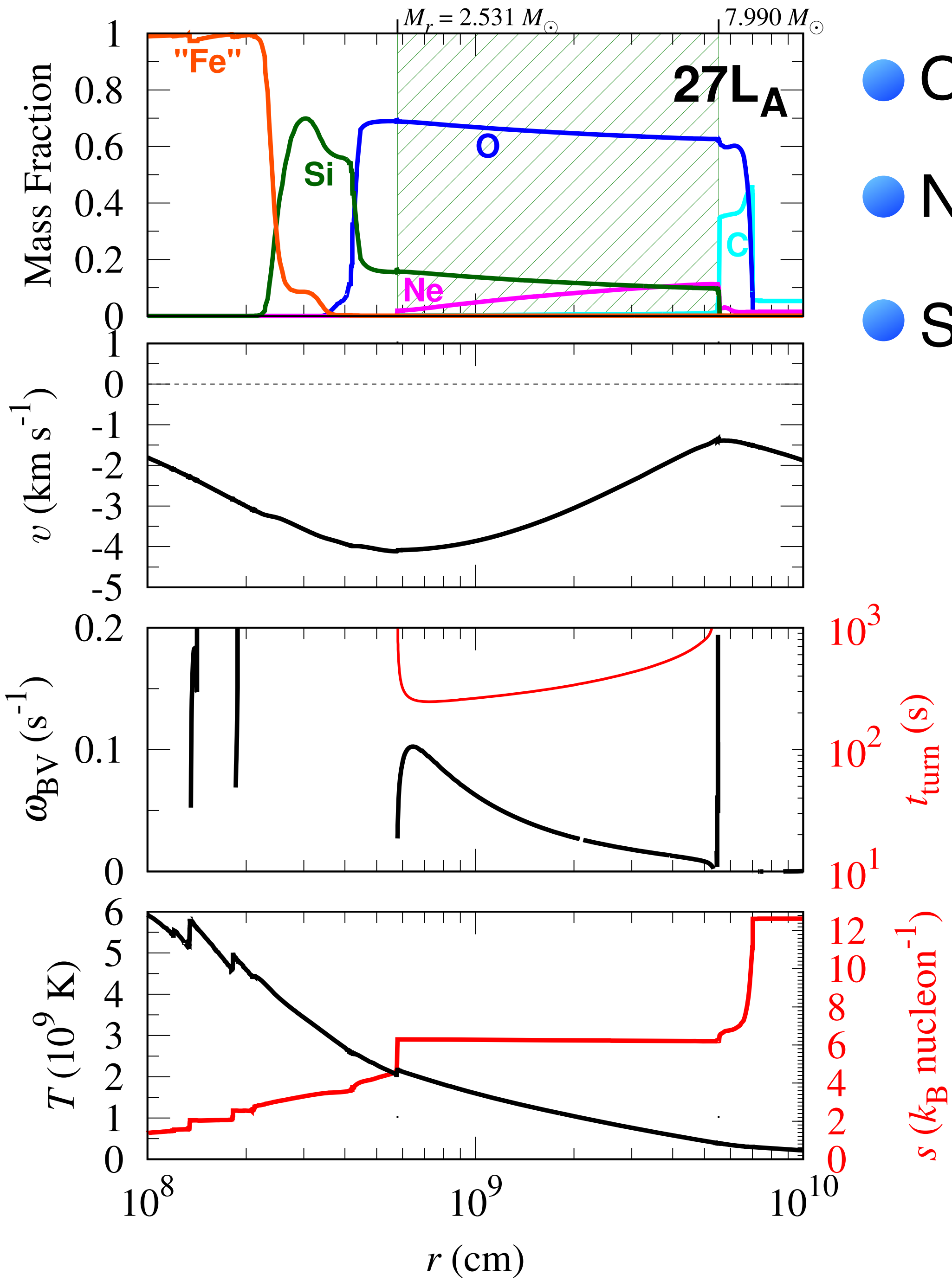
  (Yoshida et al. 2019, 2021a,b)

  A branch of **3DnSNe** (e.g. Takiwaki et al. 2016, Nakamura et al. 2016, Kotake et al. 2018)

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

    NSE is assumed in $T > 5\times10^9$ K.
  - Tabulated EOS of Helmholtz (Timmes & Swesty 2000)
  - Neutrino cooling (Itoh et al. 1996)
  - $N_r \times N_\theta \times N_\phi = 512 \times 64 \times 128$ **meshes**

Initial Structure of Model $27L_A$



- O/Si/Ne layer in r = (5.8 - 60)×10^8 cm
- Ne shell burning at the bottom
- Si and O shell burnings occur below the O/Si/Ne layer

$$\omega_{BV} = \sqrt{-\frac{GM_r}{r^2}\frac{\delta}{H_P}\left(\nabla_{ad} - \nabla + \frac{\varphi}{\delta}\nabla_\mu\right)}$$

$$t_{turn} = r_{cv}/v_{cv,MLT}$$

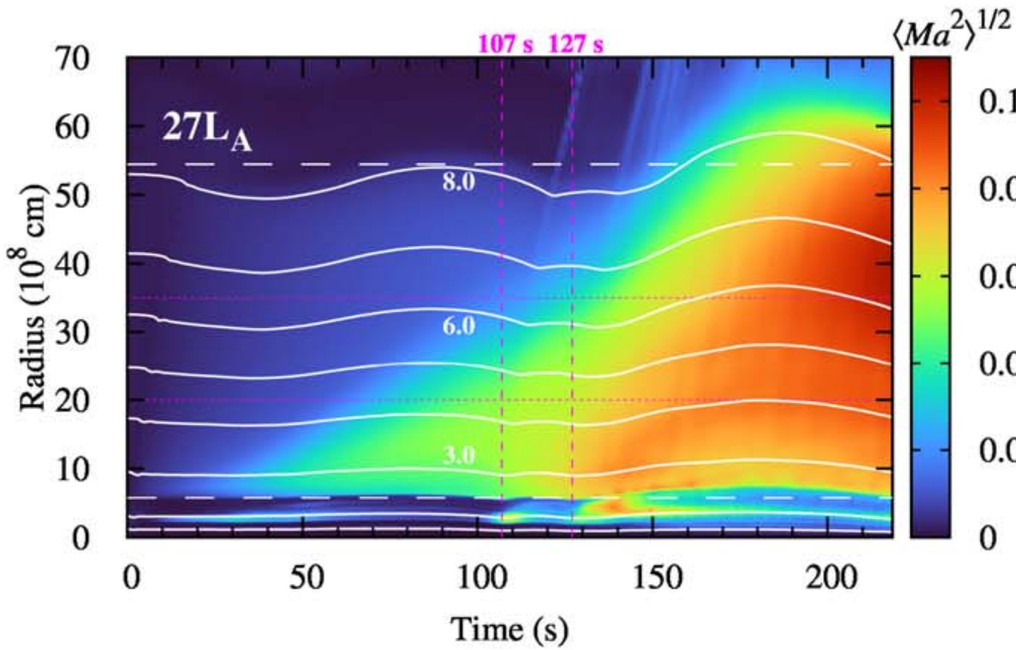
Model 27L$_A$: Turbulent Velocity

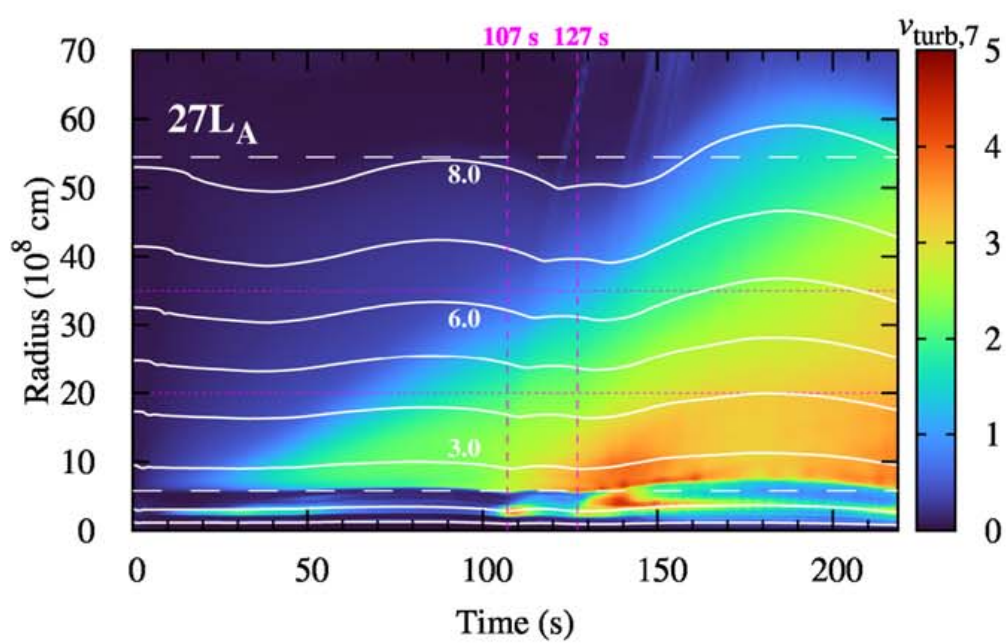
- Angle averaged radial profiles
  - Turbulent Mach number

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

  - Turbulent velocity

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

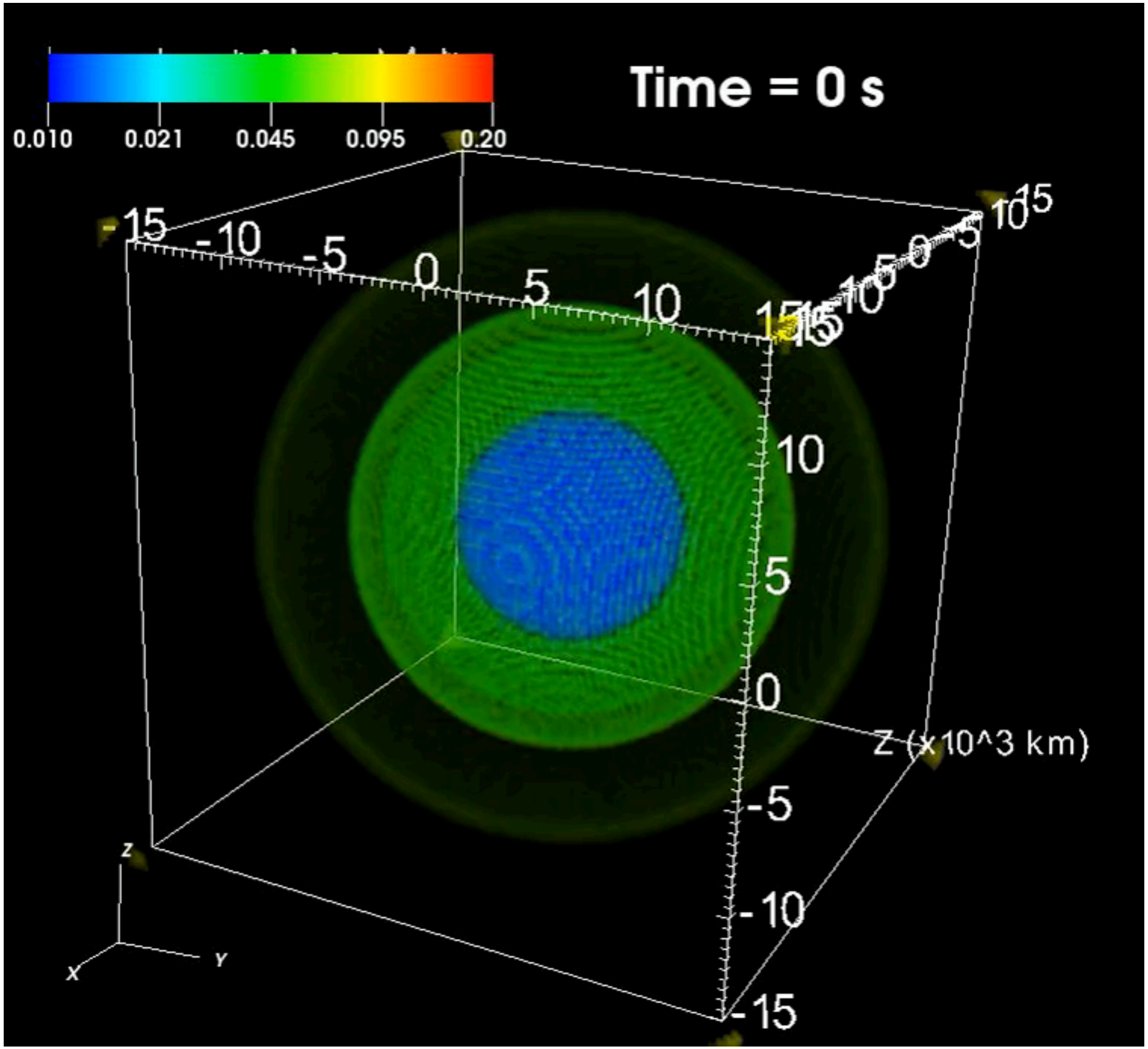




- High turbulence region extends with time.
- High turbulence velocity with $\langle \mathrm{Ma}^2 \rangle^{1/2} \sim 0.1$ appears in the O/Si/Ne layer.
- $v_{\mathrm{turb,max}}$ = 3.8×10^7 cm s^{-1} at the last time step

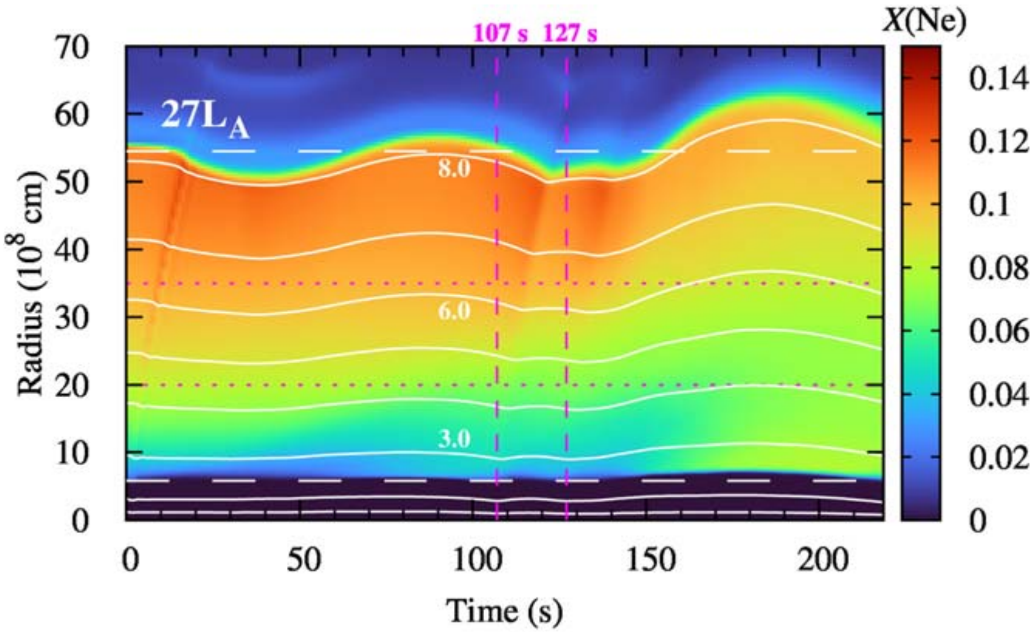
Neon Mass Fraction

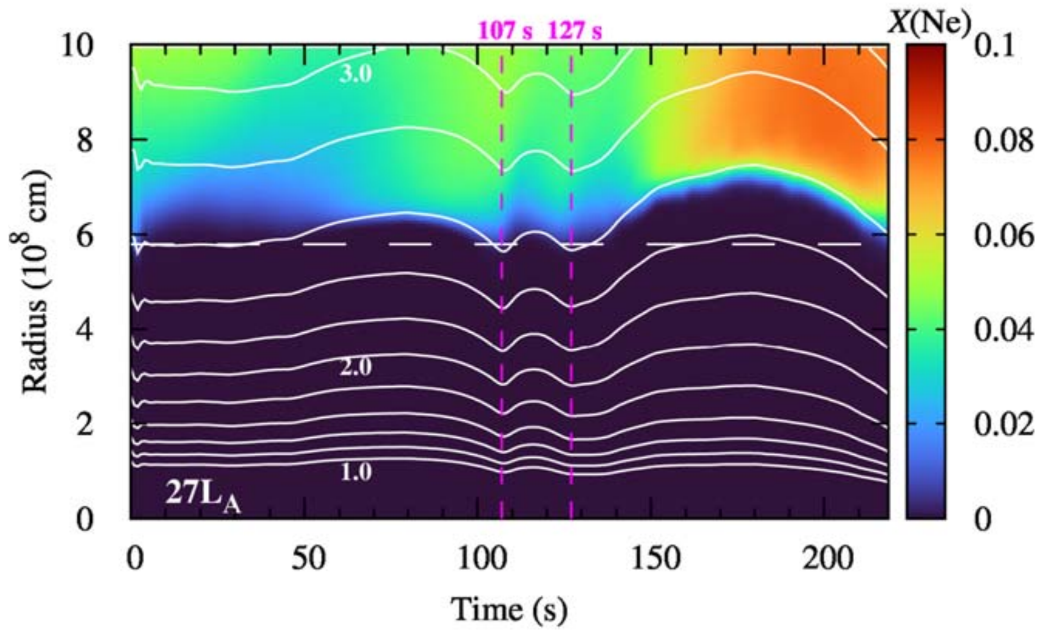
- 3D color contour map of the Ne mass fraction



Neon Mass Fraction

- Time evolution of the angle-averaged radial profiles
  - The whole region
  - Close to the lower boundary

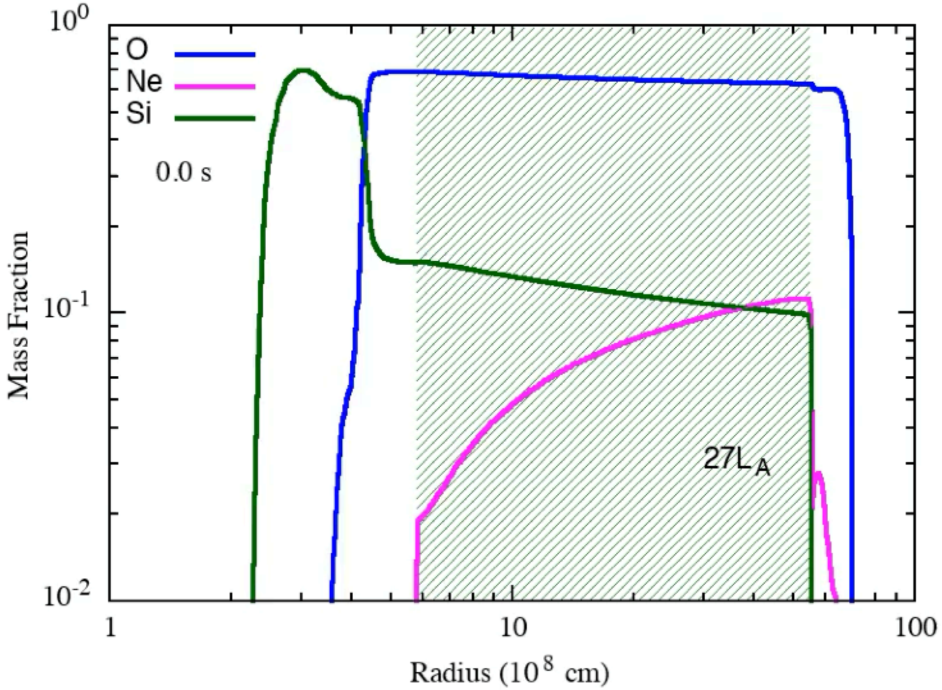


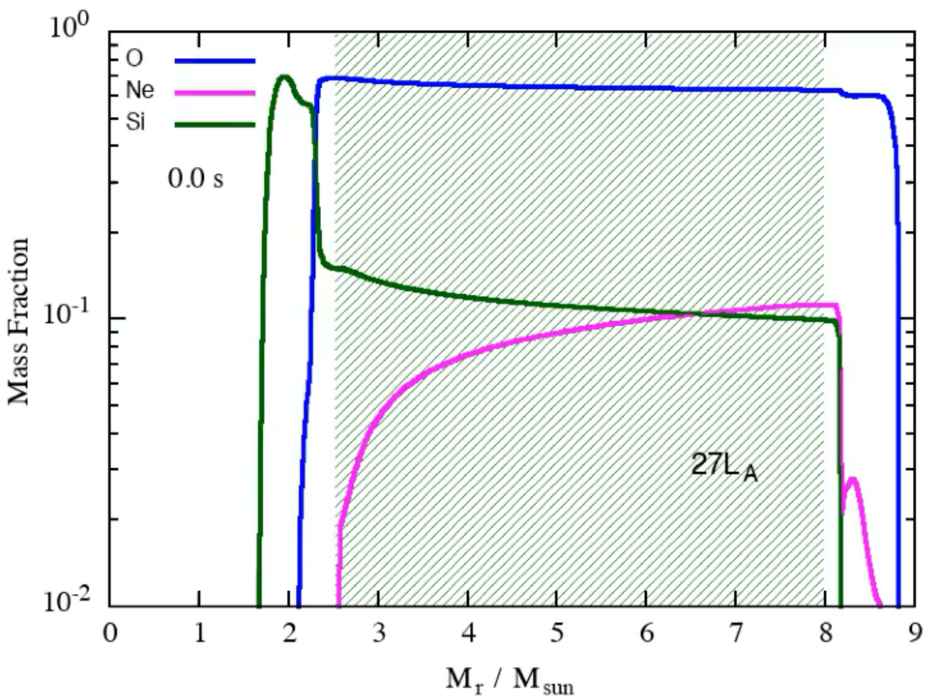


- Decrease in the Ne mass fraction by Ne shell burning in the region close to the lower boundary

- The Ne mass fraction is homogenized through inflows.

Angle-Averaged Mass Fractions





O, Ne, Si mass fractions

Thick lines: angle averaged value

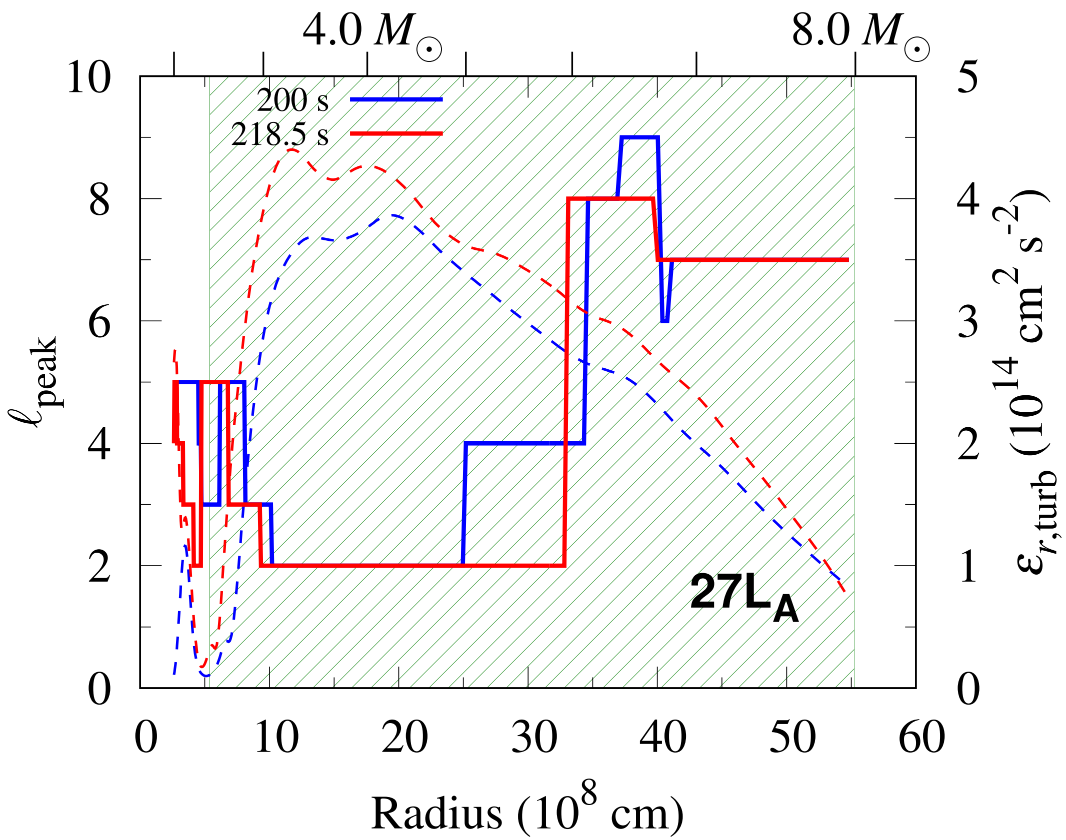
Thin lines: angular dispersion

- Strong turbulence by shell burning
  - ➡ Radial homogenization
  - ➡ Larger angular dispersion

- As turbulence weakens
  - ➡ Angular dispersion becomes smaller.

Power Spectrum of Radial Turbulent Velocity

- Power spectrum of the radial turbulent velocity



$$c_\ell^2(r) = \sum_{m=-\ell}^{\ell} \left| \int (v_r - \langle v_r \rangle) Y^*_{lm}(\theta, \phi) d\Omega \right|^2$$

$$\epsilon_{r,\mathrm{turb}}(r) = \frac{1}{8\pi} \sum_\ell c_\ell(r)^2$$

$$\langle \ell_{\mathrm{peak}} \rangle = \frac{\int \ell_{\mathrm{peak}}(r) \rho(r) \epsilon_{r,\mathrm{turb}}(r) r^2 dr}{\int \rho(r) \epsilon_{r,\mathrm{turb}}(r) r^2 dr}$$

$$\langle \ell_{\mathrm{peak}} \rangle = 3.56$$

- High turbulent velocity region

  ➡ Large scale (low mode: $\ell \sim 2 - 4$) turbulence dominates.

Summary

- Aspherical structure of the Si/O-rich convective layer in SN progenitor gives a favorable effect to SN explosions.

- 3D hydrodynamics simulations of the O/Si/Ne layer of a 27 $M_\odot$ precollapse star (model $27L_A$) for ~200 s
  - Episodic shell burnings of O and Ne
    - ➡ Turbulent mixing with $\langle \mathrm{Ma}^2 \rangle^{1/2} \sim 0.1$ and small ℓ_{peak} in the O/Si/Ne-rich layer.
      Favorable to SN explosion
    - ➡ Mass fraction distribution
      - ➡ More homogeneous in the radial distribution
        Inhomogeneous in the angular direction

- Application to multi-D SN explosion simulations
  - ➡ Si/O-rich convective layer of a 25 $M_\odot$ model

    See Nakamura-san's short talk/poster