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Current Status of Massive Star Evolution

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Current Status

A03: Astrophysics Project

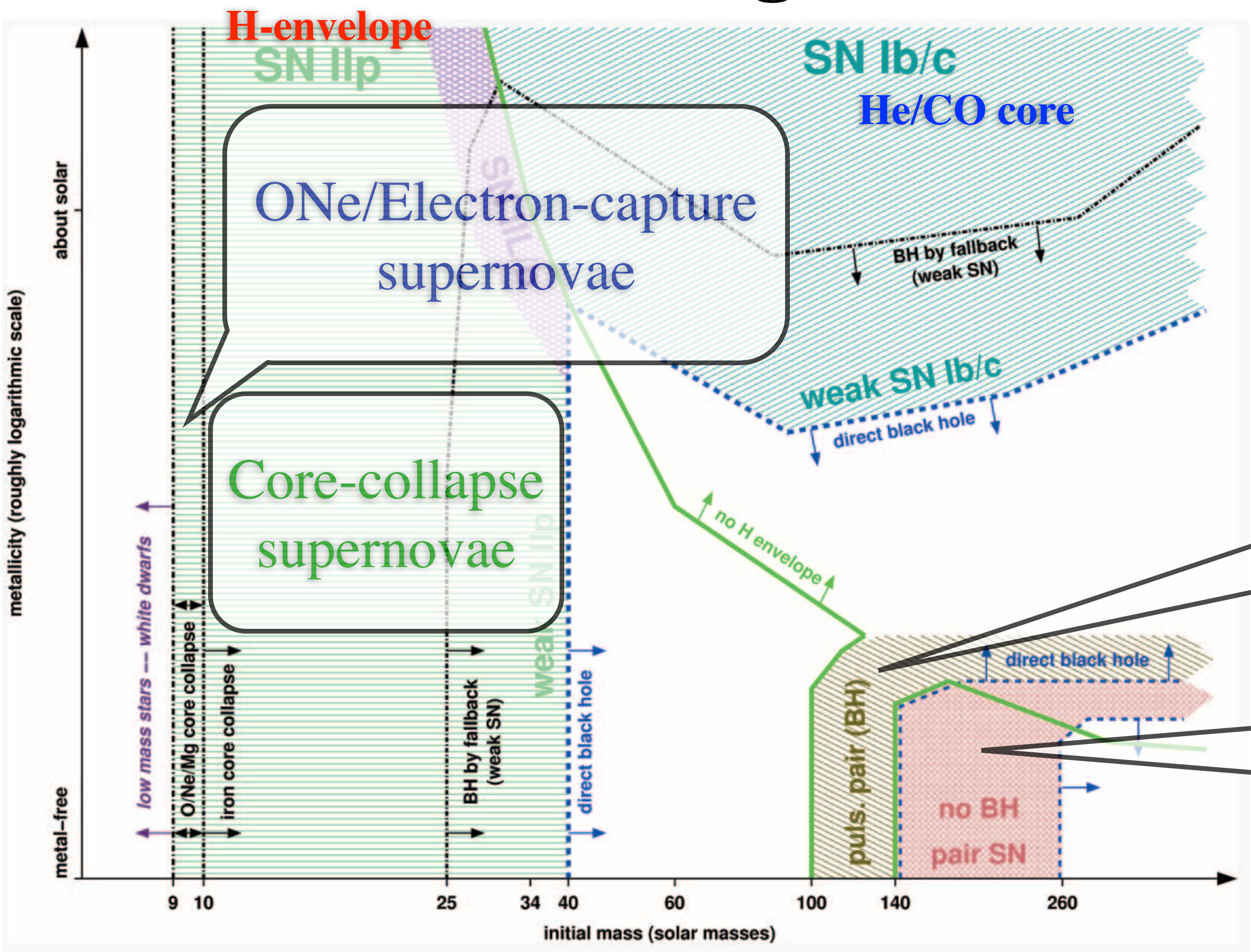
- **Massive star model** (TY & Umeda 2011, Umeda, TY & Takahashi 2012)
  - **Wide ranges of main-sequence (MS) mass M_{MS} and metallicity Z**
  - **Effect of stellar rotation**

- **Current status**
  - **Very massive stars ($M_{\mathrm{MS}} \gtrsim 100\ M_\odot$) as a progenitor for super-luminous supernova (SLSN)**
    - **Pulsational pair-instability (PPI) supernova**
    - **Aspherical core-collapse SNe from very massive stars**
  - **Progenitor for electron-capture supernova (Poster A03-P27: Takahashi, TY & Umeda)**
  - **Evolution of rotating massive star (test calculation)**

    $M_{\mathrm{MS}}=15\ M_\odot$, $Z=0.02$, $v_{\mathrm{rot}}=200$ km/s star model

Massive Stars as Progenitors for Supernovae

(Heger & Woosley 2003)



Pulsational pair-instability supernovae

Pair-instability supernovae

SLSN?

- **Massive Stars → Progenitors for supernovae**

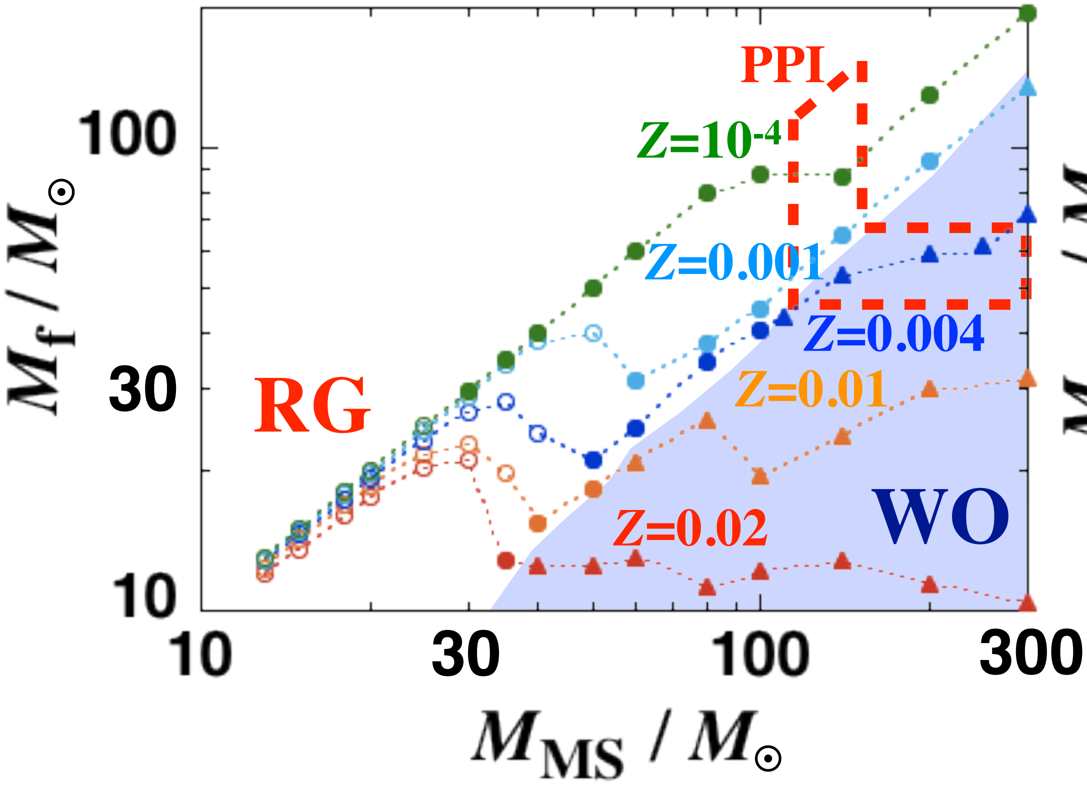
  → Progenitor structure is important for supernova explosions.

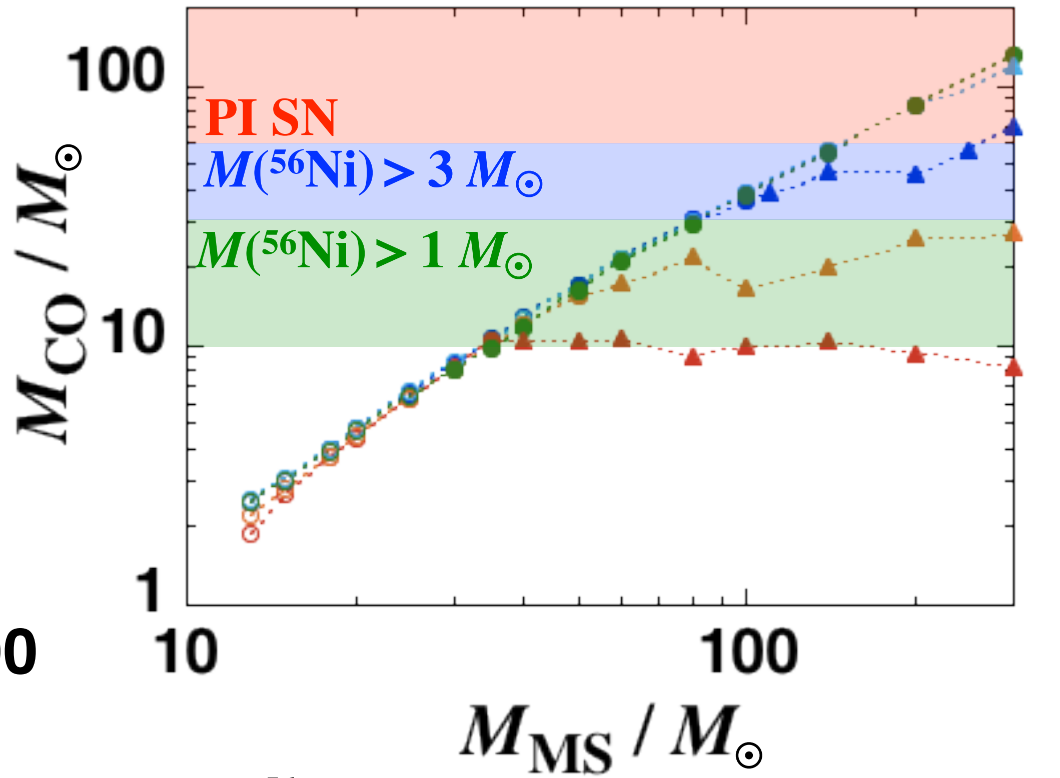
Stellar Type and Final Mass of Massive Stars

Stellar evolution until C-burning

$M_{MS} = 13 - 300\ M_\odot$, $Z = 10^{-4} - 0.02$

(Umeda, TY & Takahashi 2012, *PTEP* 01A302; TY, Okita & Umeda, in prep.)





^{56}Ni mass is supposed from the results of Umeda & Nomoto (2008)

Very massive stars ($M_{MS} > 100\ M_\odot$)

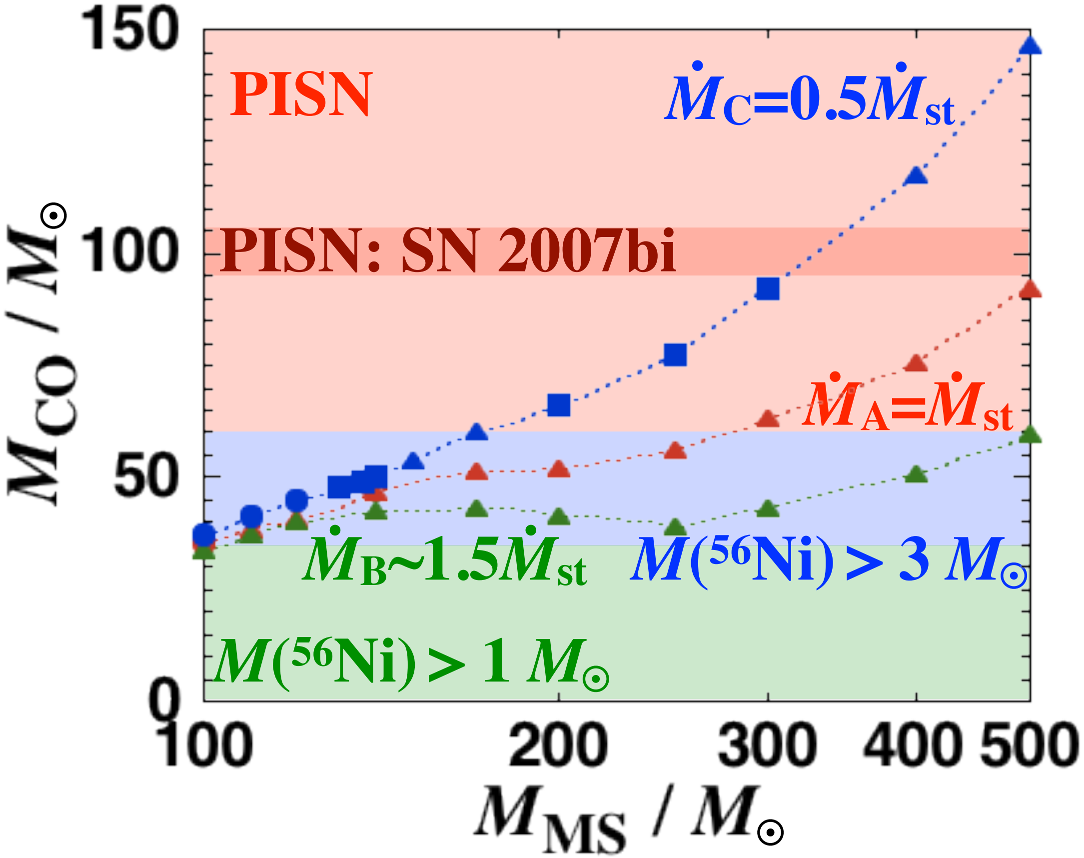
- $0.001 \lesssim Z < 0.01$ → **WO stars with large CO core**
  Possibility for Type Ic super-luminous (SL) SNe
- $Z \lesssim 0.001$ → **Type II(n?) SLSNe or Type Ic SLSNe through PPI**

CO Core Mass of Very Massive Stars

- Some SLSNe may have evolved from very massive stars.

  Stellar evolution calculation for M_{MS} = 100 - 500 $M_\odot$ and Z=0.004.

  (TY & Umeda 2011, *MNRAS* 412, L78)



- Three cases of mass loss rates

  $\dot{M}_A$: standard ($\dot{M}_{st}$)

  $\dot{M}_B \sim 1.5\ \dot{M}_{st}$

  (WR stars: Crowther 2007)

  $\dot{M}_C = 0.5\ \dot{M}_{st}$

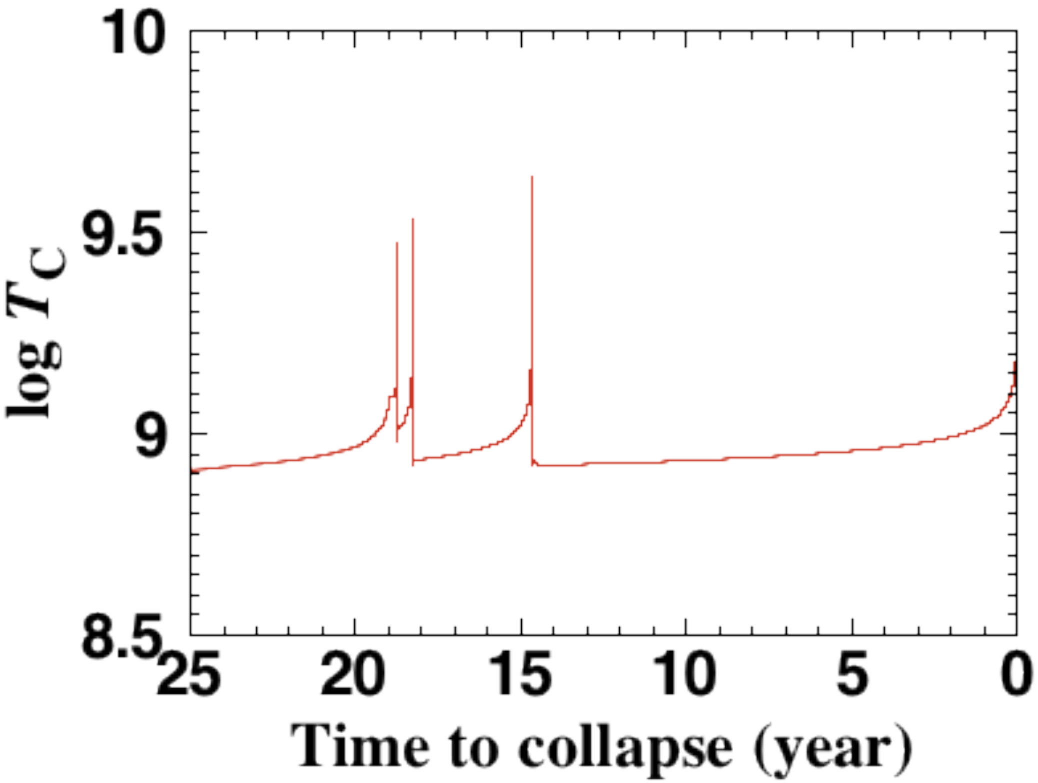
  (e.g., Discussion in Hirschi 2008, Pulse et al. 2008)

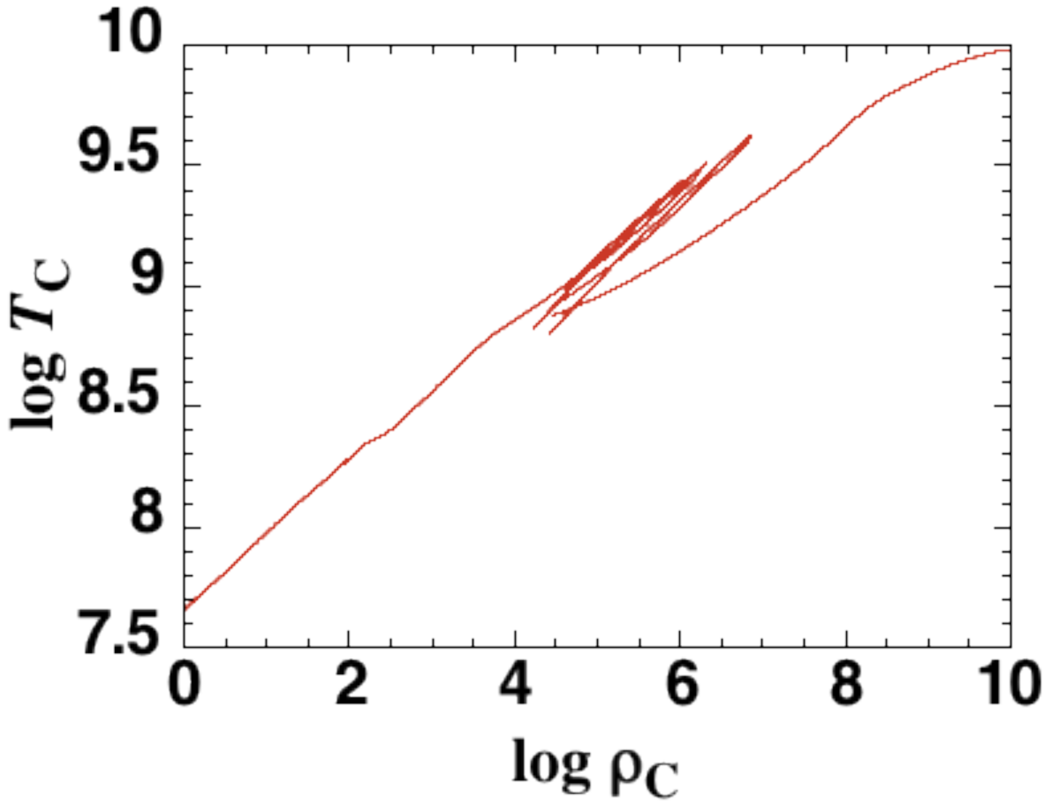
- Core-collapse SN Ic with $M(^{56}Ni)>3M_\odot$ → A: 110 < M_{MS} < 270 $M_\odot$
- SLSN 2007bi is a candidate of ~100$M_\odot$ pair-instability SN (Gal-Yam et al. 2009)

  → M_{MS} > 300 $M_\odot$ with small mass loss (C)

Pulsational Pair-Instability

- $M_{MS} = 250\ M_\odot$, Z=0.004 → $M_f = 61.1 M_\odot$ (TY, Okita & Umeda, in prep.)





- Pulsational pair-instability occurs in stars with $M_{CO} \sim$ 40-60 $M_\odot$ (e.g., Heger & Woosley 2002, Umeda & Nomoto 2008)
- After some pulsations, the star collapses to become SN.
- Eruptive mass loss will be included in a future study. (e.g., Woosley et al. 2007, Chatzopoulos & Wheeler 2012)

Aspherical SN Explosion of Very Massive Stars

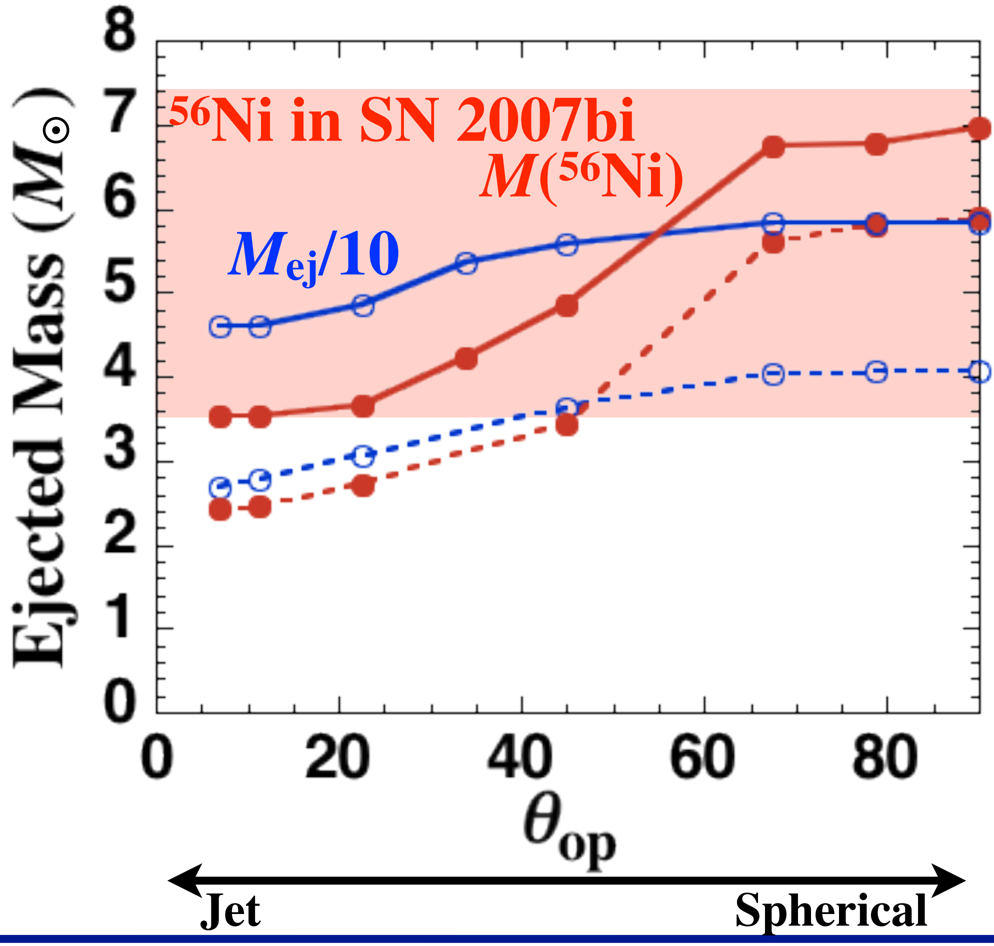
- SLSN 2007bi ➡ $M(^{56}\mathrm{Ni}) = 3.5$ - $7.4\ M_\odot$ (TY, Okita & Umeda, in prep.)

  Pair-instability SN or Core-collapse SN?

- Explosive nucleosynthesis during aspherical core-collapse SN explosion

  Solid lines: M_f=61.1$M_\odot$, M_{CO}=56.2$M_\odot$, E=7×10^{52} erg (M_{MS}=250$M_\odot$)

  Dashed lines: M_f=43.1$M_\odot$, M_{CO}=38.8$M_\odot$, E=5×10^{52} erg (M_{MS}=110$M_\odot$)



- Smaller θ_{op} ➡ Smaller $M(^{56}\mathrm{Ni})$

- More massive progenitor
  Larger explosion energy

  ➡

  Aspherical SN explosion reproduces $M(^{56}\mathrm{Ni})$ of SN 2007bi.

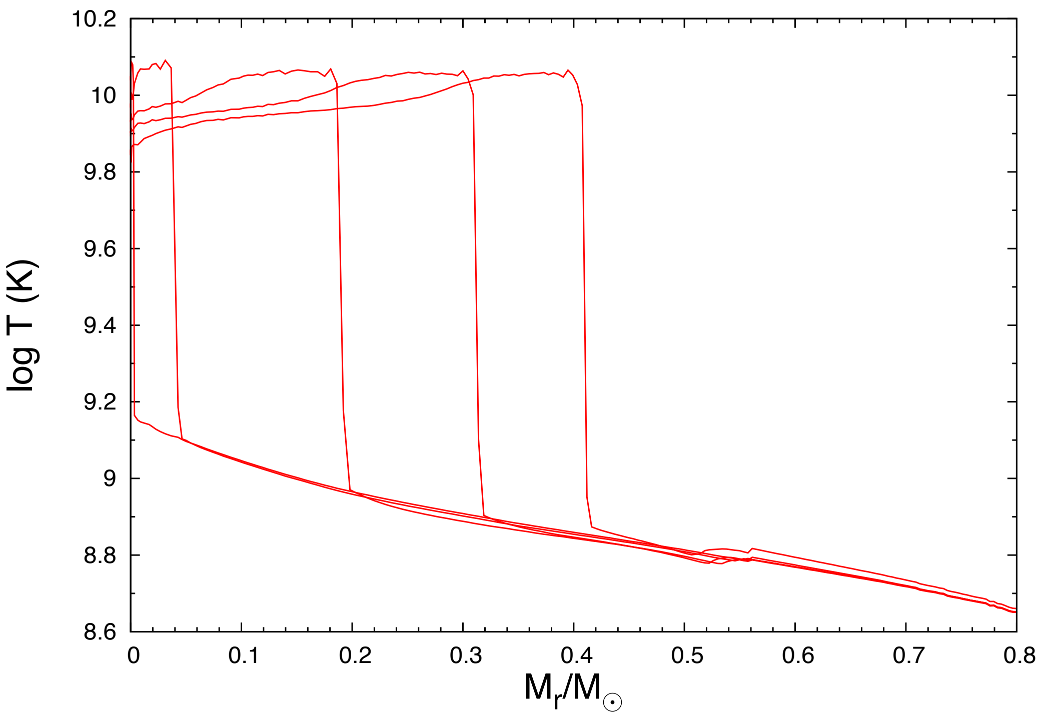
Progenitor for Electron-Capture Supernova

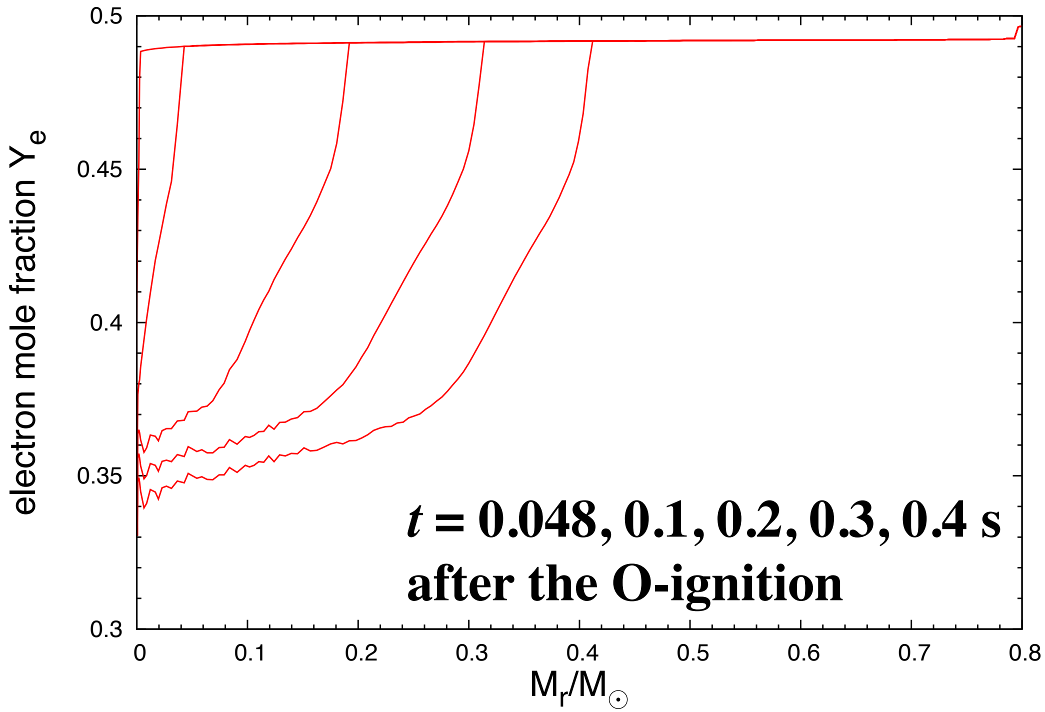
Lower mass limit of supernova → Electron-capture SN (ECSN)

- **Evolution of a progenitor for ECSN** **(Takahashi, TY & Umeda, in prep.)**

  Propagation of deflagration front

  → ***Material behind the front becomes to nuclear statistical equilibrium.***





Next Step → **Hydrodynamical simulation of SN explosion**

For details, please see Poster A03-P27

Core collapse of an ONe core: The progenitor of ECSN

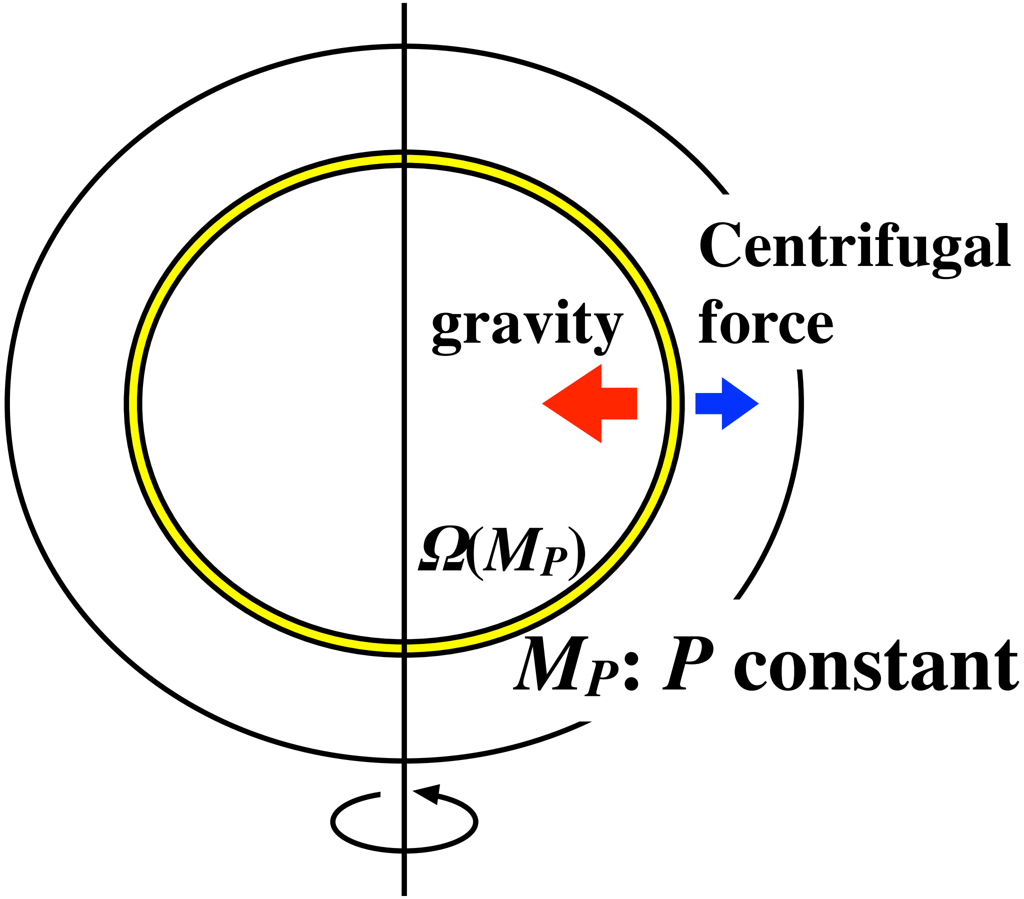
Takahashi, TY, & Umeda

Rotating Star Model

- Mass coordinate as isobar $M_r \rightarrow M_P$
  (e.g., Endal & Sofia 1976, Meynet & Maeder 1997, Heger, Langer, & Woosley 2000)

  ➡ Radius r_P is determined from the volume enclosed by isobar surface

$$r_P = \left(\frac{3}{4\pi} V_P\right)^{1/3}$$



$$r(r_0,\theta) = r_0\{1 - \varepsilon(r_0)\, P_2(\cos\theta)\}$$

$$\frac{\partial P}{\partial M_P} = -\frac{G M_P}{4\pi r_P^4} f_P$$

$$\frac{\partial r_P}{\partial M_P} = \frac{1}{4\pi r_P^2 \bar{\rho}}$$

$$\frac{\partial \ln \bar{T}}{\partial \ln P} = \min\left(\nabla_{ad}, \nabla_{rad} \frac{f_T}{f_P}\right)$$

$$\frac{\partial L_P}{\partial M_P} = \varepsilon_{nucl} - \varepsilon_\nu + \varepsilon_{grav}$$

$$\dot{M}(\Omega) = \dot{M}(\Omega = 0)\left(\frac{1}{1 - v/v_{crit}}\right)^{0.43}$$

$$\dot{J} = j_{env} \dot{M}$$

f_T, f_P: Correction factors

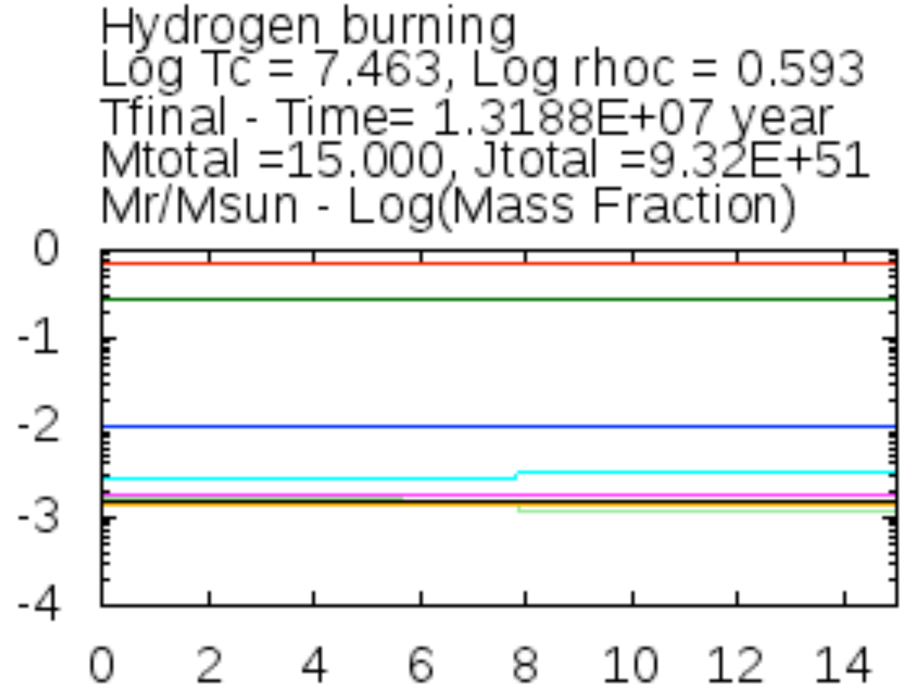
- Transport of angular momentum and rotation-induced mixing are also taken into account.

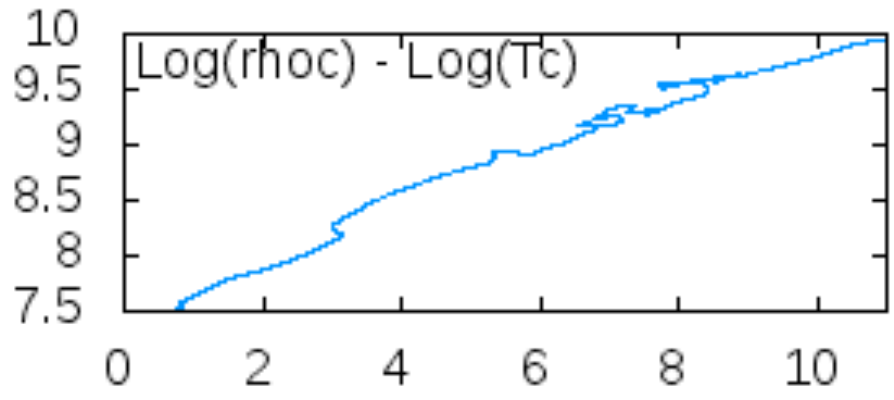
(Heger, Langer, & Woosley 2000)

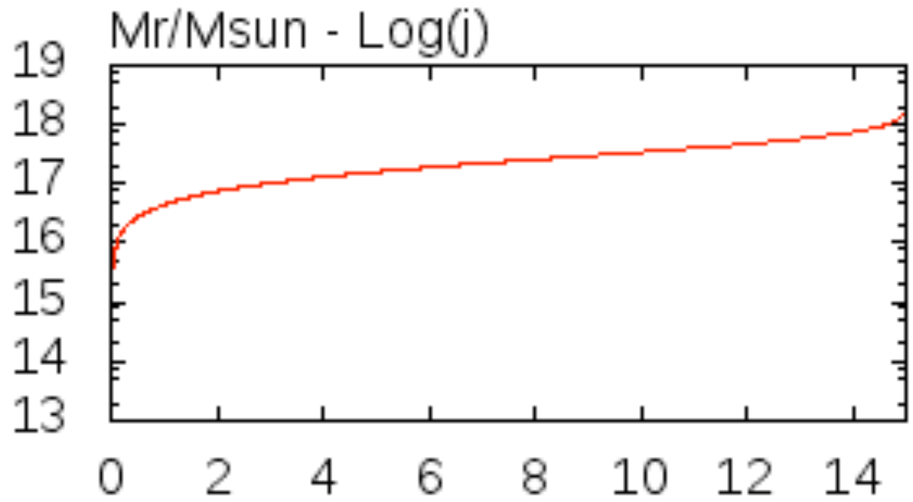
Rotating Massive Star

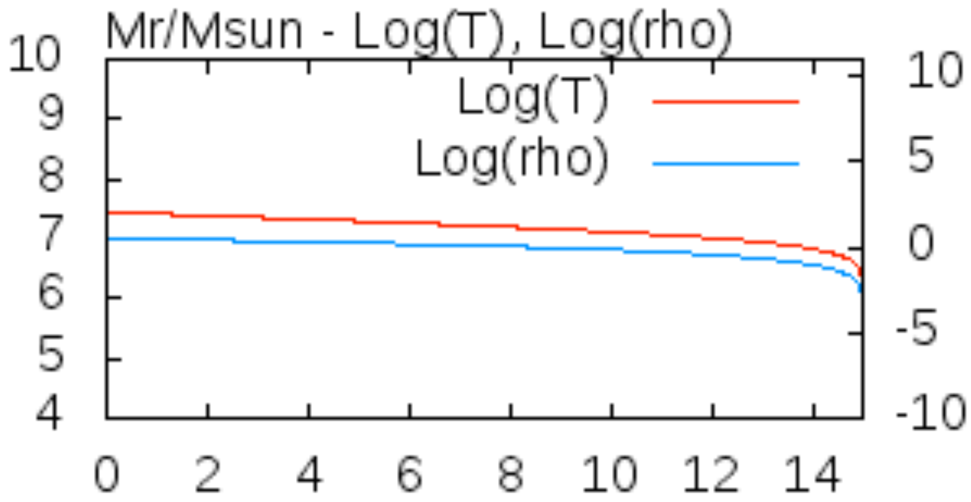
$M_{\rm MS}$=15$M_\odot$, Z=0.02, $v_{\rm rot}$=200 km s^{-1}

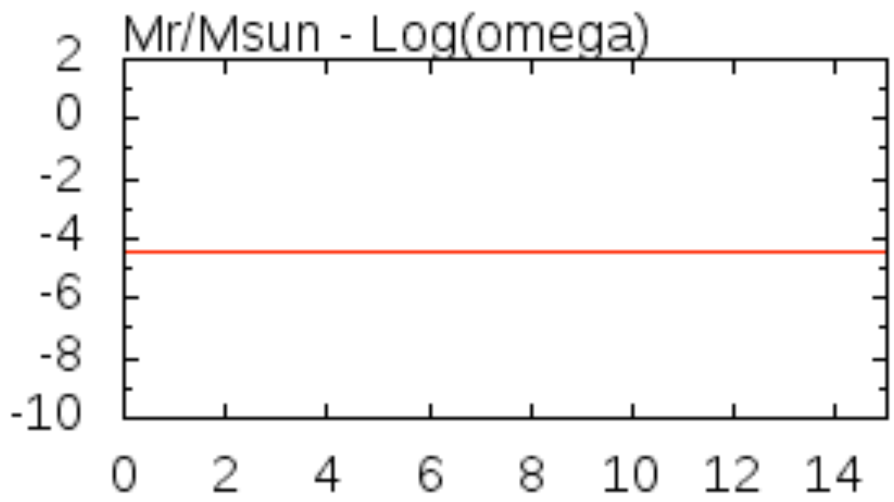
^{1}H,^{4}He,^{12}C,^{16}O,^{20}Ne,“Si”,“Fe”



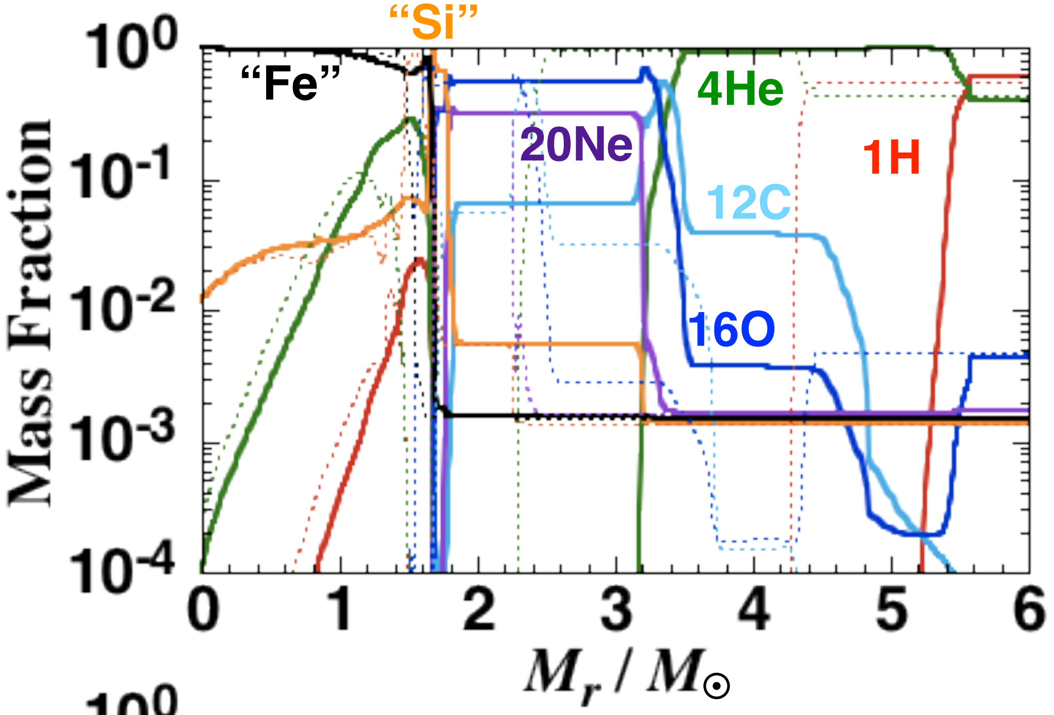


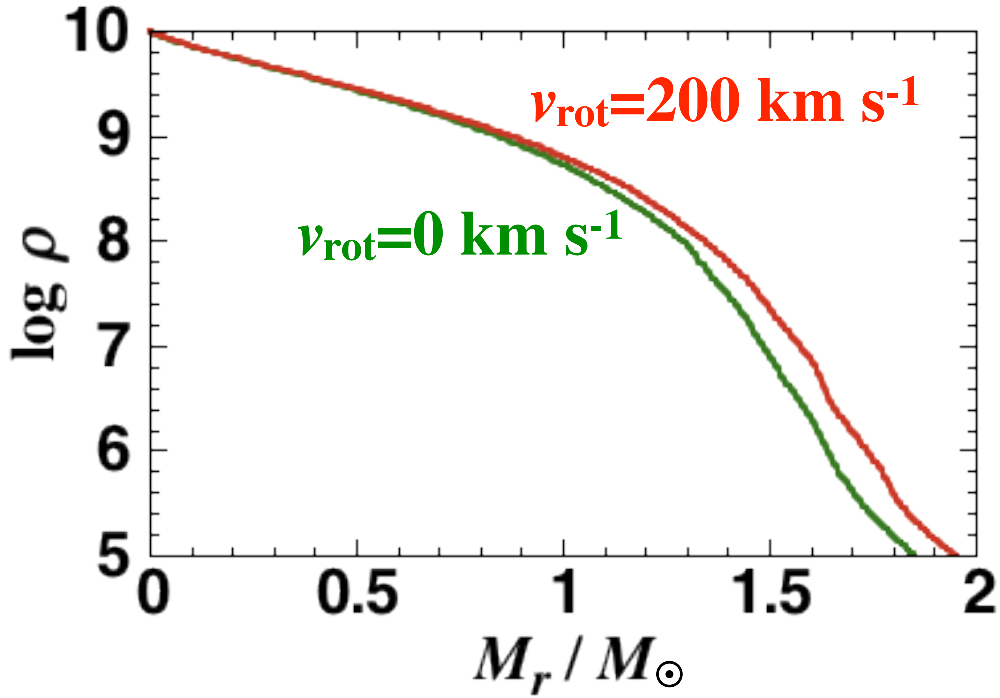


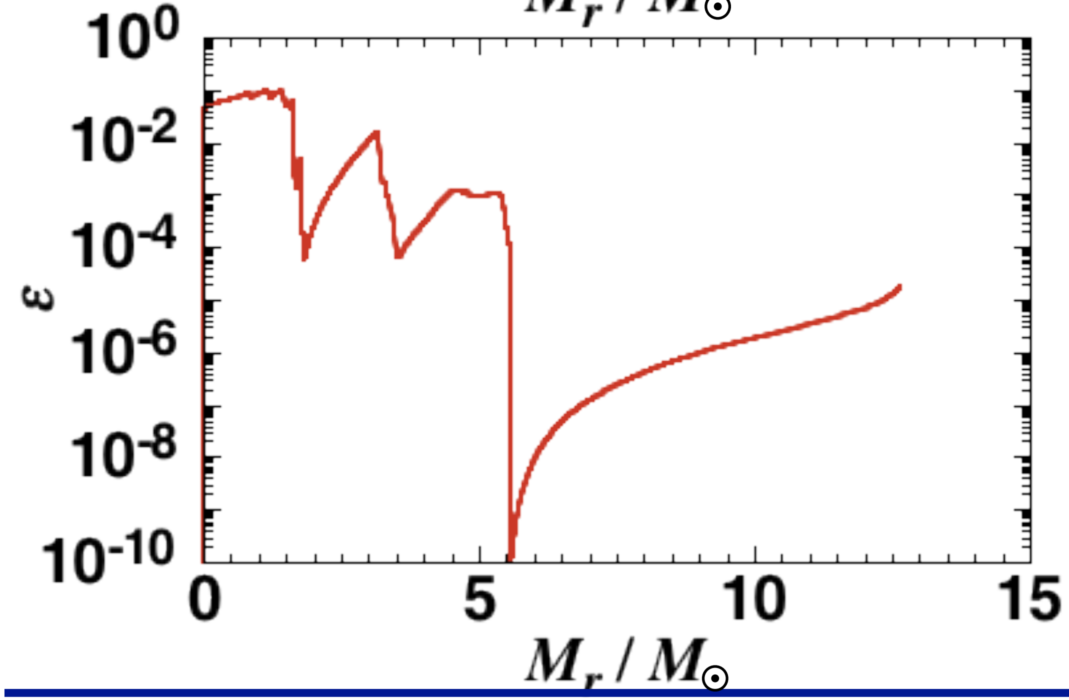




15 $M_\odot$, Z=0.02 v_{rot}=200km s^{-1} Star







Rotating (non-rotating) star

- M_f = 12.7 (13.9) $M_\odot$
- $M_{\mathrm{He\ core}}$ = 5.28 (4.27) $M_\odot$
- $M_{\mathrm{CO\ core}}$ = 3.18 (2.27) $M_\odot$
- $M_{\mathrm{Fe\ core}}$ = 1.66 (1.47) $M_\odot$

$$r(r_0,\theta) = r_0\{1 - \varepsilon(r_0)\, P_2(\cos\theta)\}$$

Summary

- **Massive star evolution model** (TY & Umeda 2011, Umeda, TY & Takahashi 2012)
  - **Very massive stars ($M_{MS} \gtrsim 100\ M_\odot$) for super-luminous SNe (SLSNe)**

    $0.001 \lesssim Z < 0.01$ → WO stars with large CO core
    Possibility for Type Ic SLSNe

    $Z \lesssim 0.001$ → Type II(n) SLSNe or Type Ic SLSNe through PPI

  - **Aspherical core-collapse SN explosion for SLSN 2007bi**

    110, 250$M_\odot$ models with large explosion energy

    → ^{56}Ni amount consistent with SN 2007bi

- **Evolution of ONe core to become ECSN**

  Up to deflagration by the ignition of O-burning

  See Poster A03-P27, Takahashi, TY & Umeda

- **Rotating massive star model**

  Test of 15 $M_\odot$, v_{rot} = 200 km/s model up to the onset of core-collapse