Mass and Metallicity Dependence of Massive Star Evolution

Takashi Yoshida

吉田 敬

Department of Astronomy, University of Tokyo

Collaborators

Hideyuki Umeda, Shinpei Okita, Koh Takahashi

Formations of Compact Objects: from the cradle to the grave

March 7, 2012, Waseda University

Introduction

- **Massive stars ($M_{\rm init} \gtrsim 10\ M_\odot$)**

  ⇐ **Progenitors of supernovae**

  Core structure ⇒ **Explosion mechanism**

  Final mass, surface composition

  ⇒ **Supernova types (II, IIn, Ib, Ic)**

  Variety of supernovae (Super-luminous, faint)

  ⇐ **Initial mass, metallicity**

  Rotation, magnetic field, ...

- **Very massive stars**

  135 - 265 $M_\odot$ WN5h stars in R136 cluster

  ⇒ $M_{\rm init} = 165 - 320\ M_\odot$

Introduction

- **Updating massive star evolution code**
  - **Evolution sequence**
  - **Initial mass dependence of final mass, (He, CO, Fe) core masses (M_{init} = 10 - 300$M_{\odot}$, Z=0.02)**
  - **Comparison with models in other groups**
  - **Metallicity dependence (Z=10^{-4} - 0.02)**
  - **Supernova explosions evolved from very massive stars**

Massive Star Evolution Code

- Stellar evolution model

→ Based on Saio code

(Saio, Nomoto, and Kato 1988; Umeda & Nomoto 2008)

From H burning to the onset of core-collapse

- Mass loss rate

Main-sequence → Vink et al. (2001) $\propto Z^{0.69}$, $Z^{0.64}$

Red giant → de Jager et al. (1988)

(Metallicity dependence: $\propto Z^{0.64}$)

Wolf-Rayet stars → Nugis & Lamers (2000)

(Metallicity dependence: Vink & de Koter 2005)

- Convection criterion

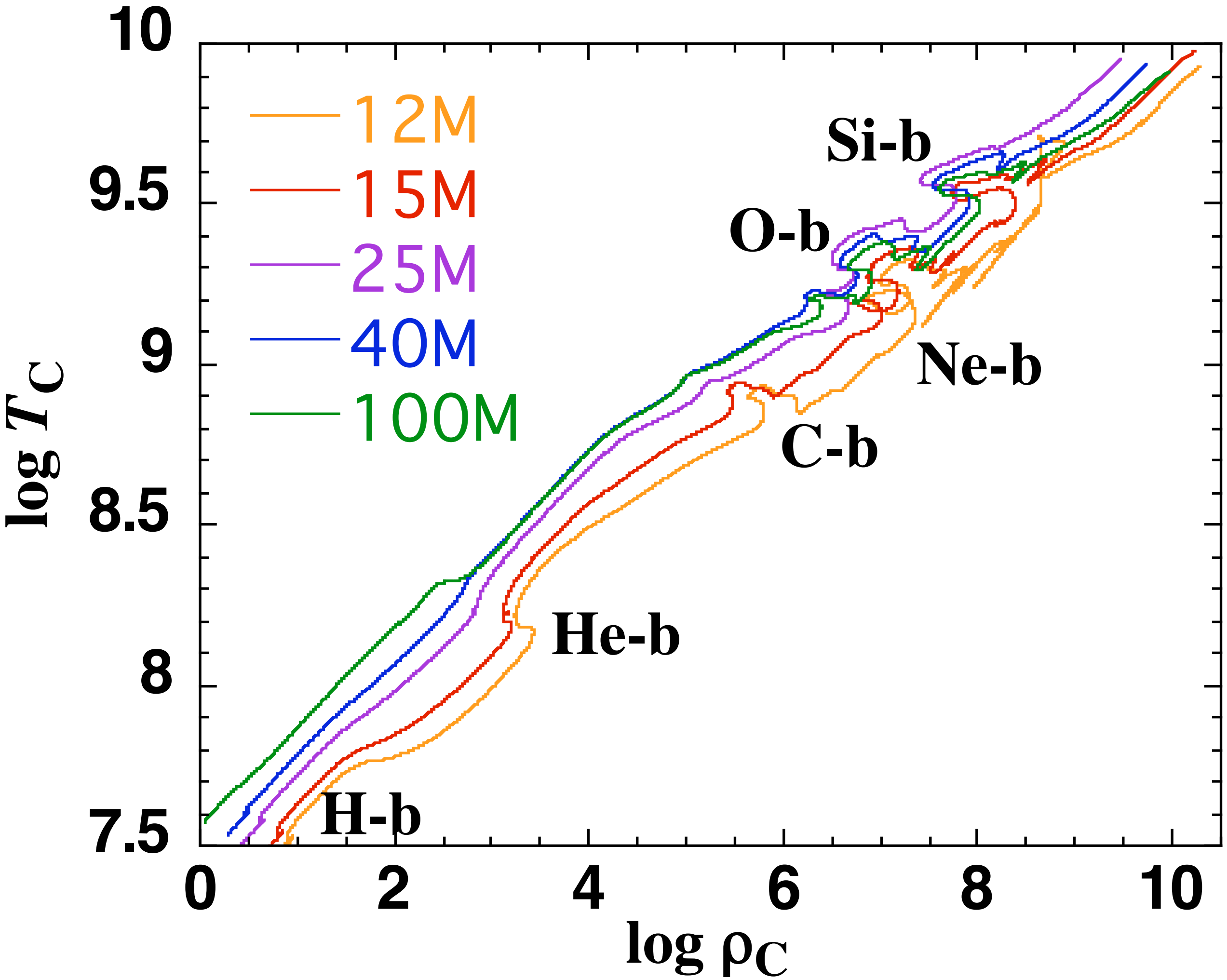
→ Schwarzschild criterion

Massive Star Evolution Code

- **Stellar evolution model**
  - **EOS and neutrino energy loss rate**
    → **Adopted from Umeda & Nomoto (2005)**
  - **Nuclear reaction network**
    → **282 species of nuclei from *n*, ^{1}H to Br**
    - **Thermonuclear reaction rates**
      → **JINA reaclib (Cyburt et al. 2010)**
      $^{12}C(\alpha,\gamma)^{16}O$ rate: 1.5×CF88
    - **Weak interaction rates**
      → **Langanke & Martinez-Pinedo (2001)**
      Oda et al. (1994)
      Fuller, Fowler, & Newman (1985)
      Takahashi & Yokoi (1984)

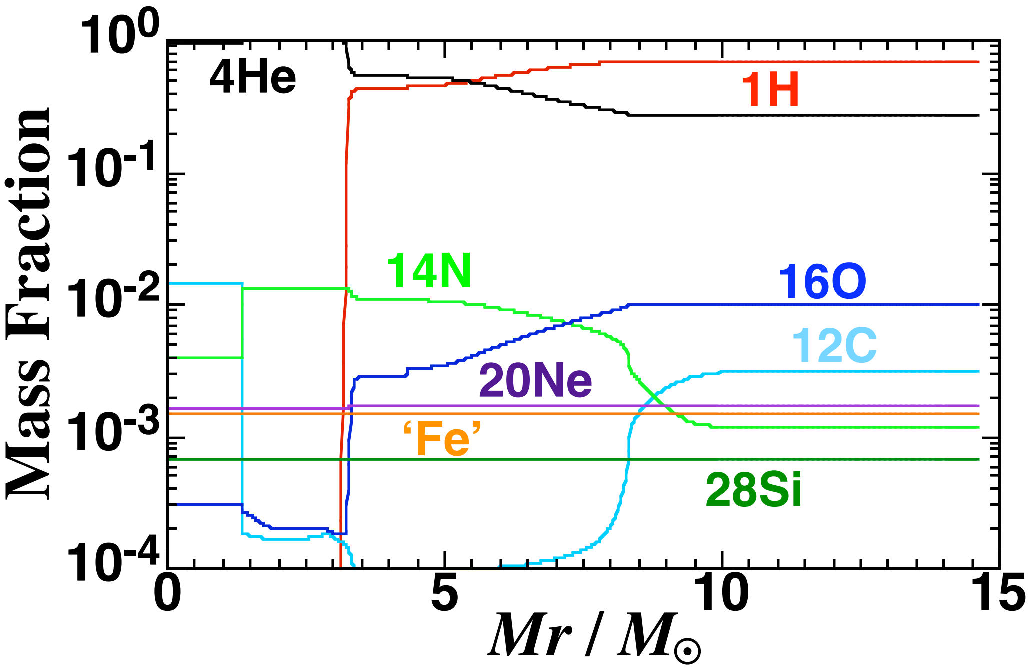
log ρ_C-log T_C Diagram

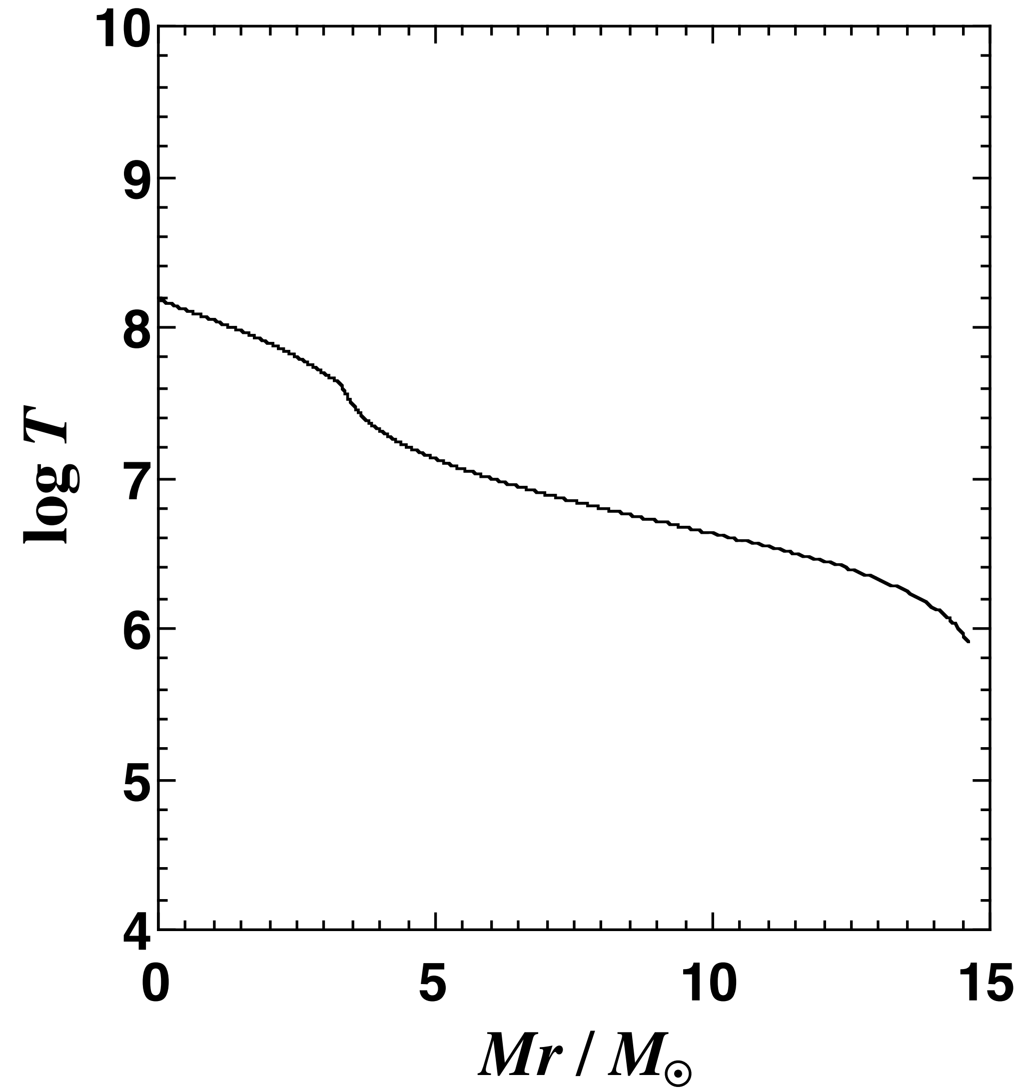
- Z=0.02 stars



Evolution of 15 $M_\odot$, Z=0.02 Star

- **H-exhaustion**

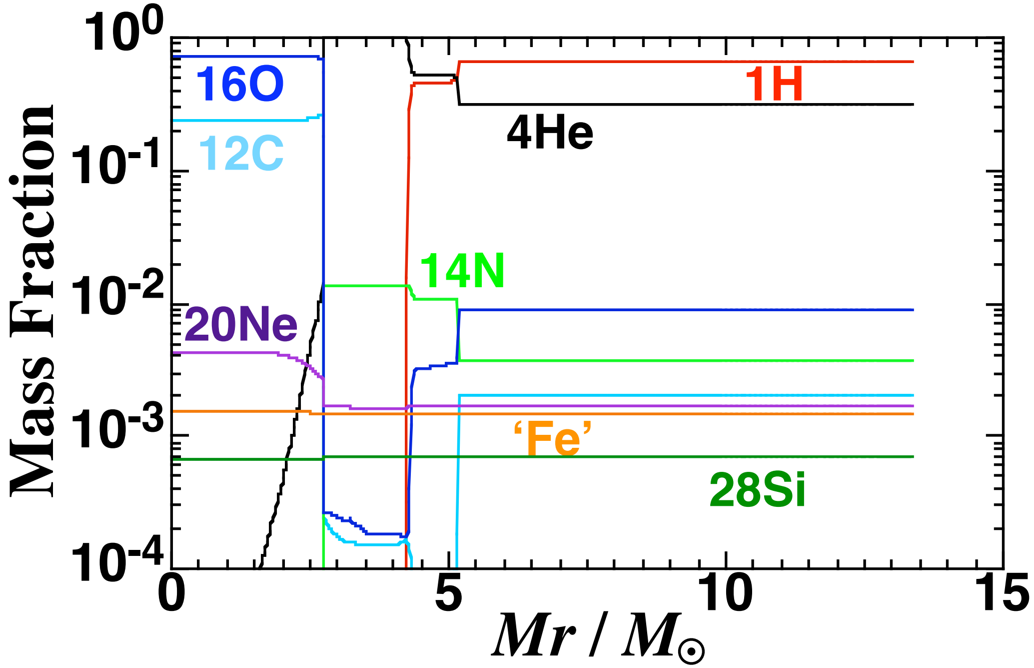


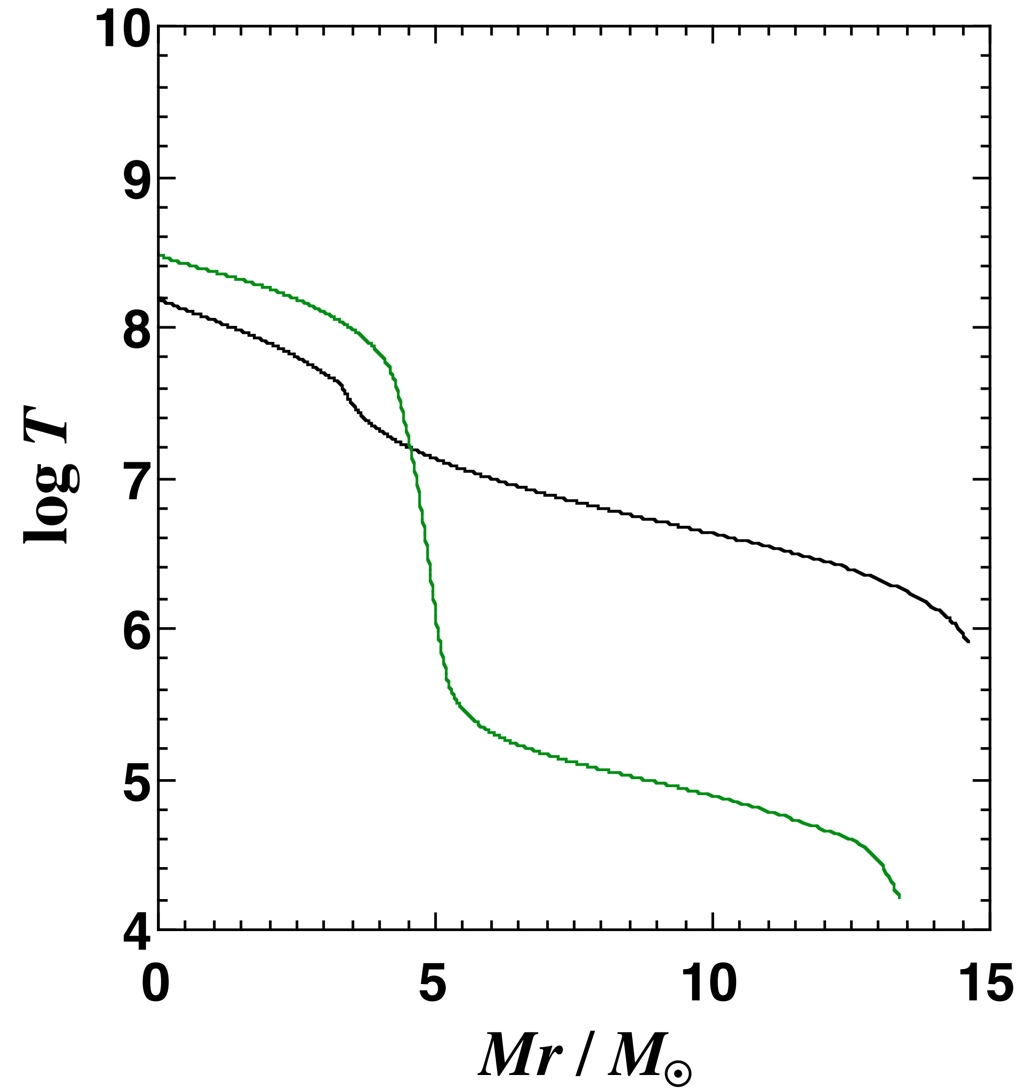


- M = 14.9 $M_\odot$

Evolution of 15 $M_\odot$, Z=0.02 Star

- He-exhaustion

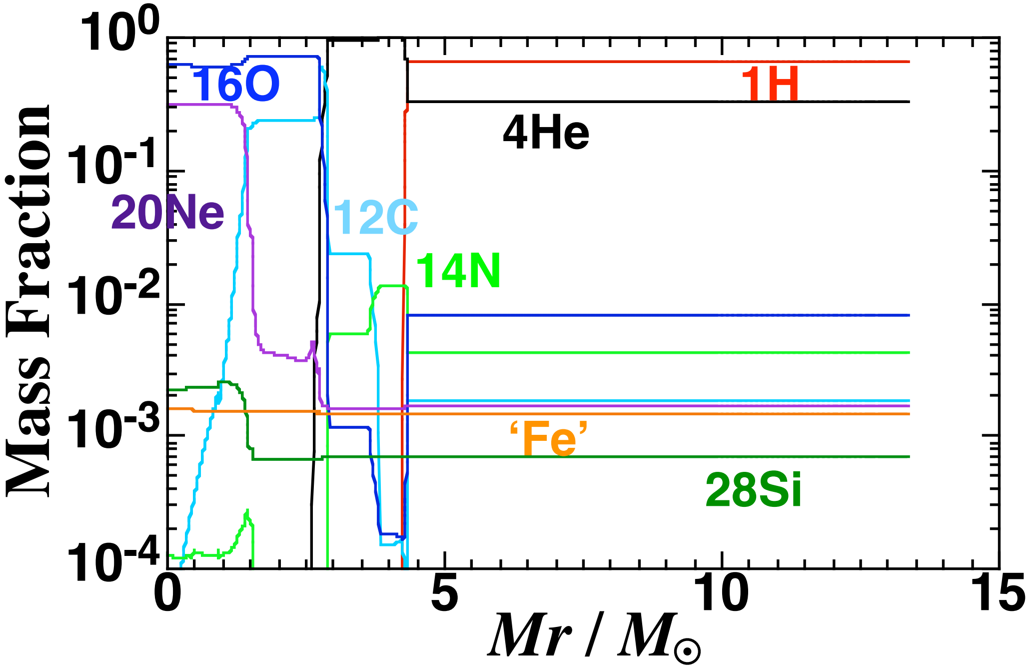


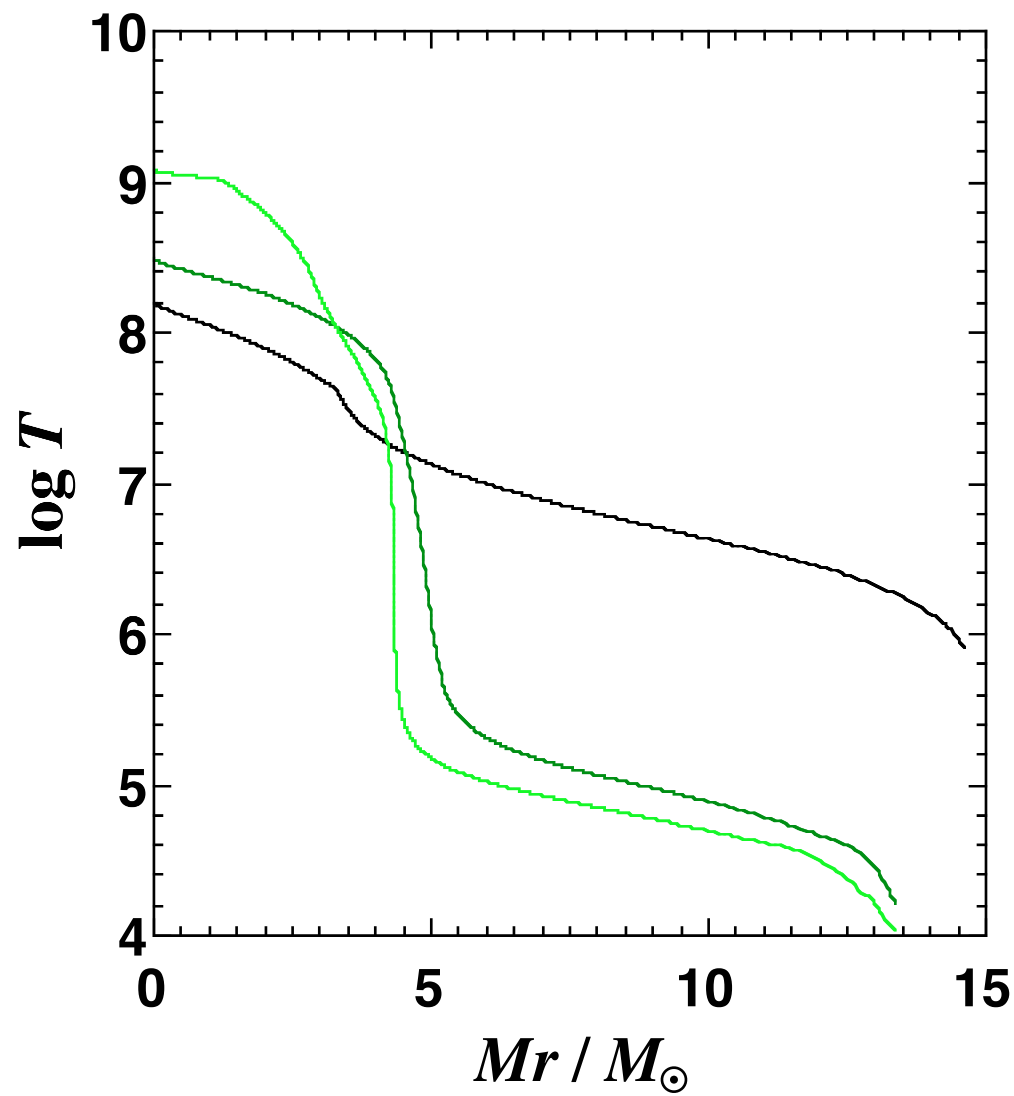


- M = 13.6 $M_\odot$

Evolution of 15 $M_\odot$, Z=0.02 Star

- **C-exhaustion**

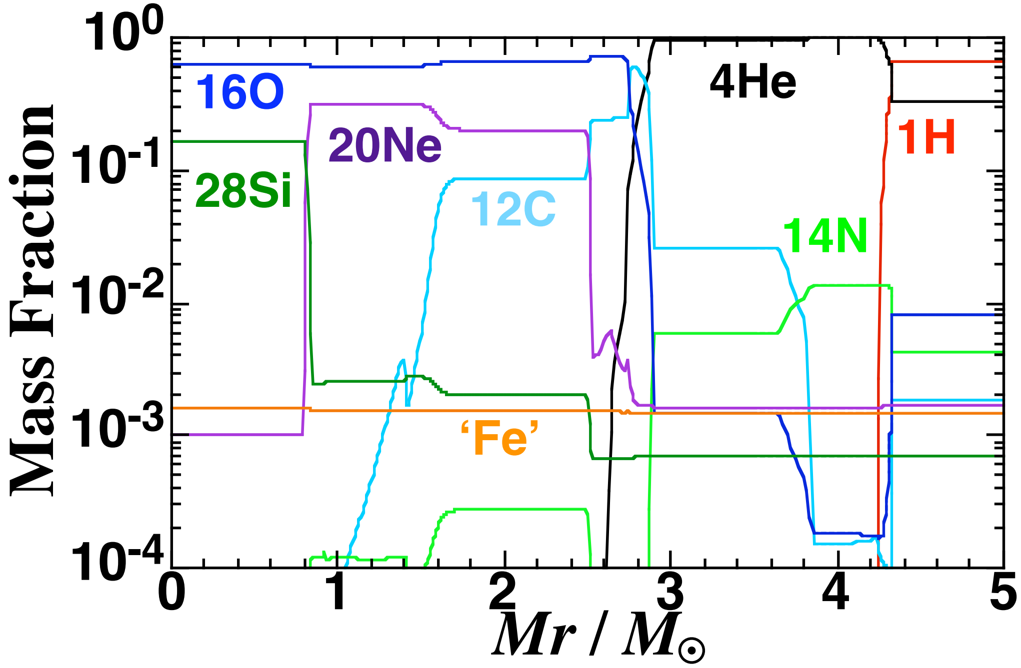


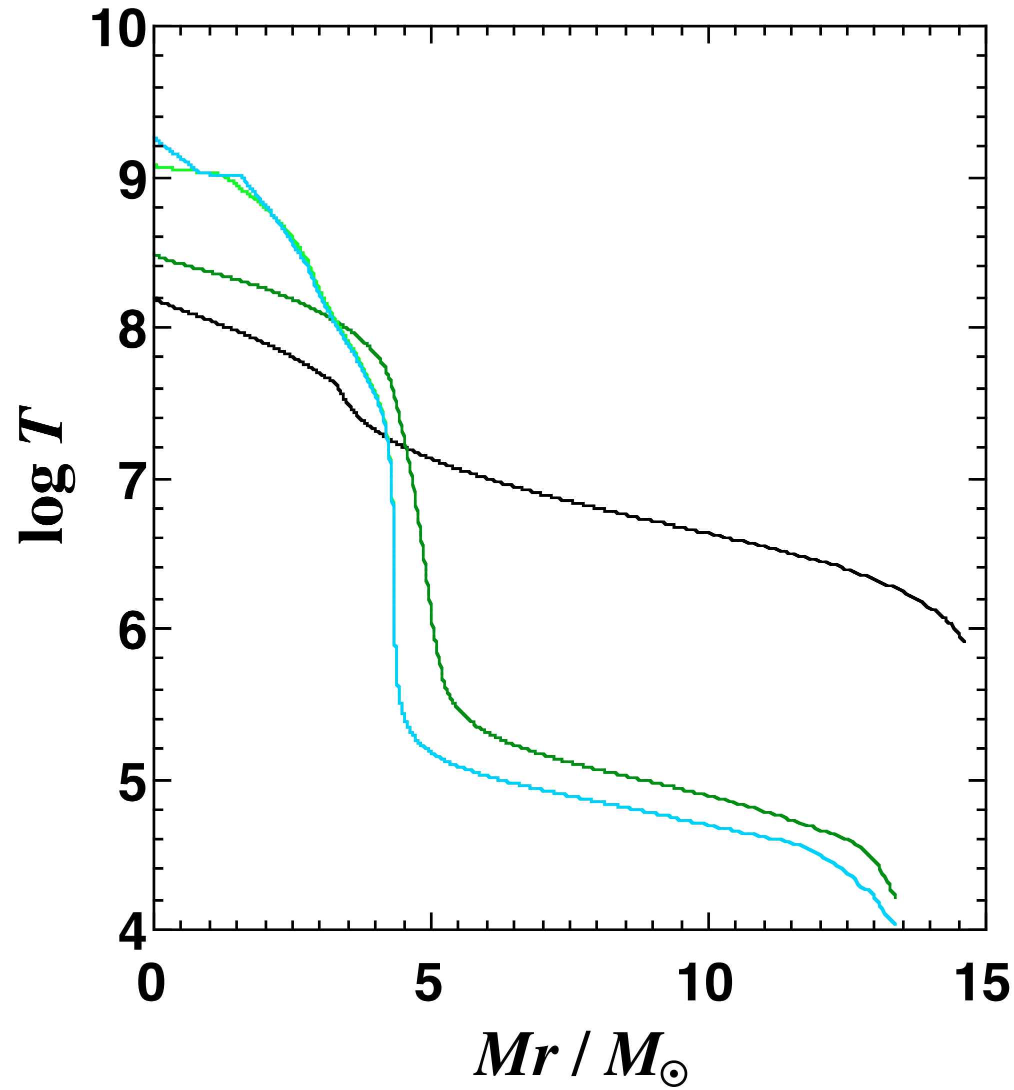


- M = 13.6 $M_\odot$

Evolution of 15 $M_\odot$, Z=0.02 Star

Ne-exhaustion

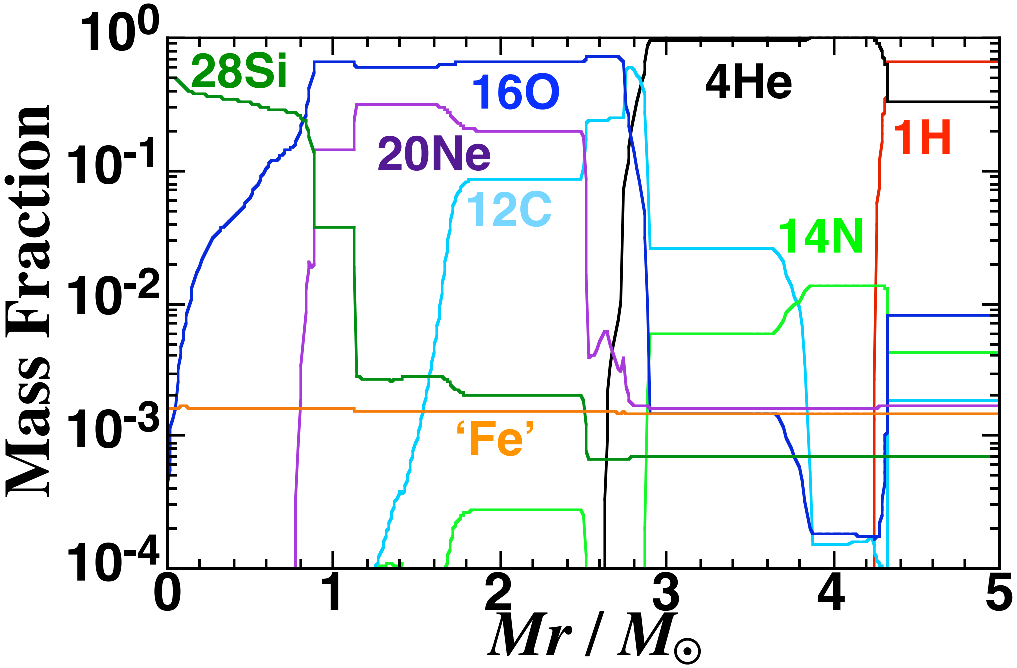


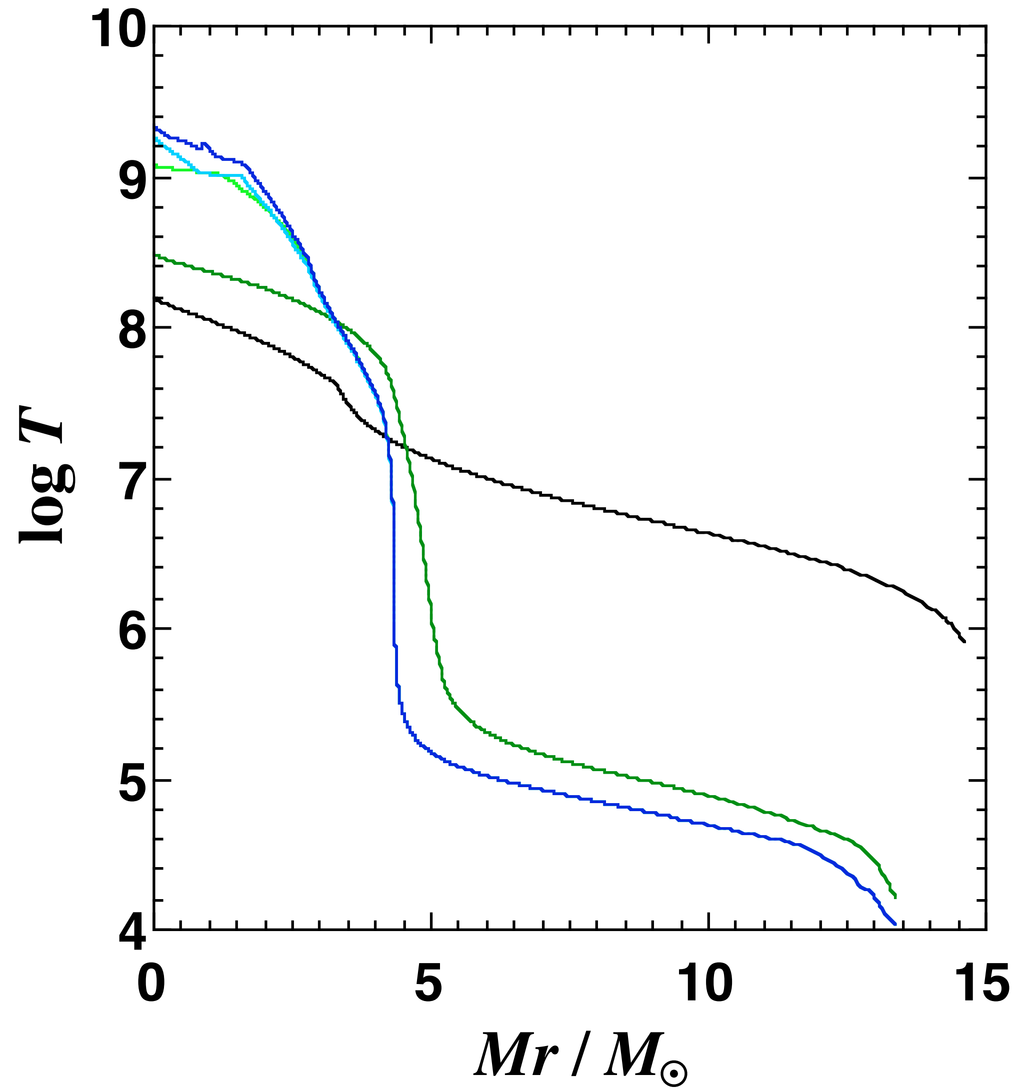


- $M = 13.6\ M_\odot$

Evolution of 15 $M_\odot$, Z=0.02 Star

O-exhaustion

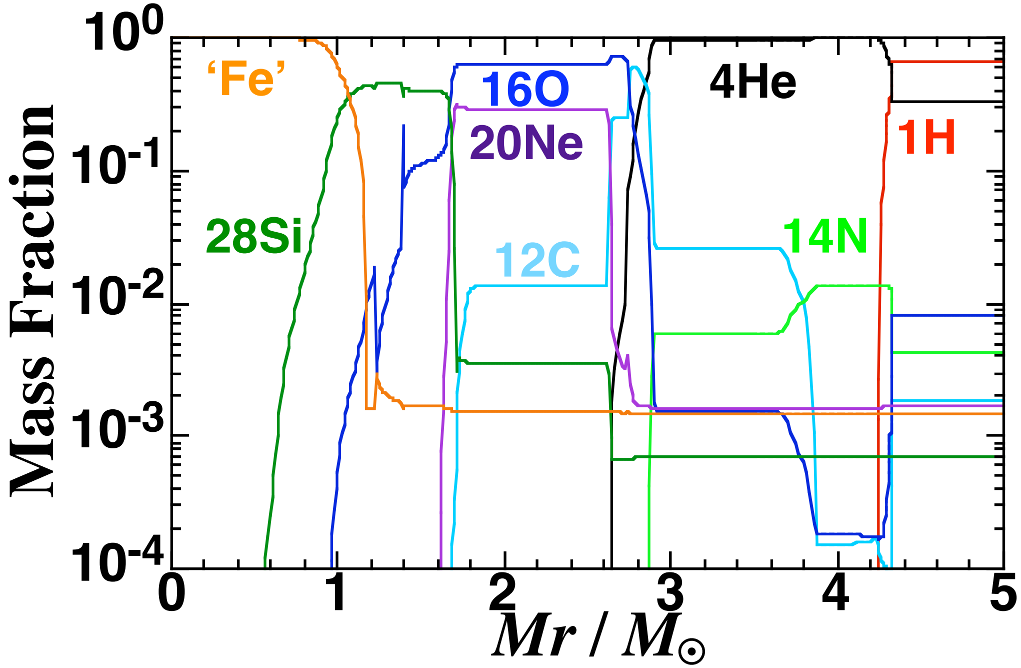


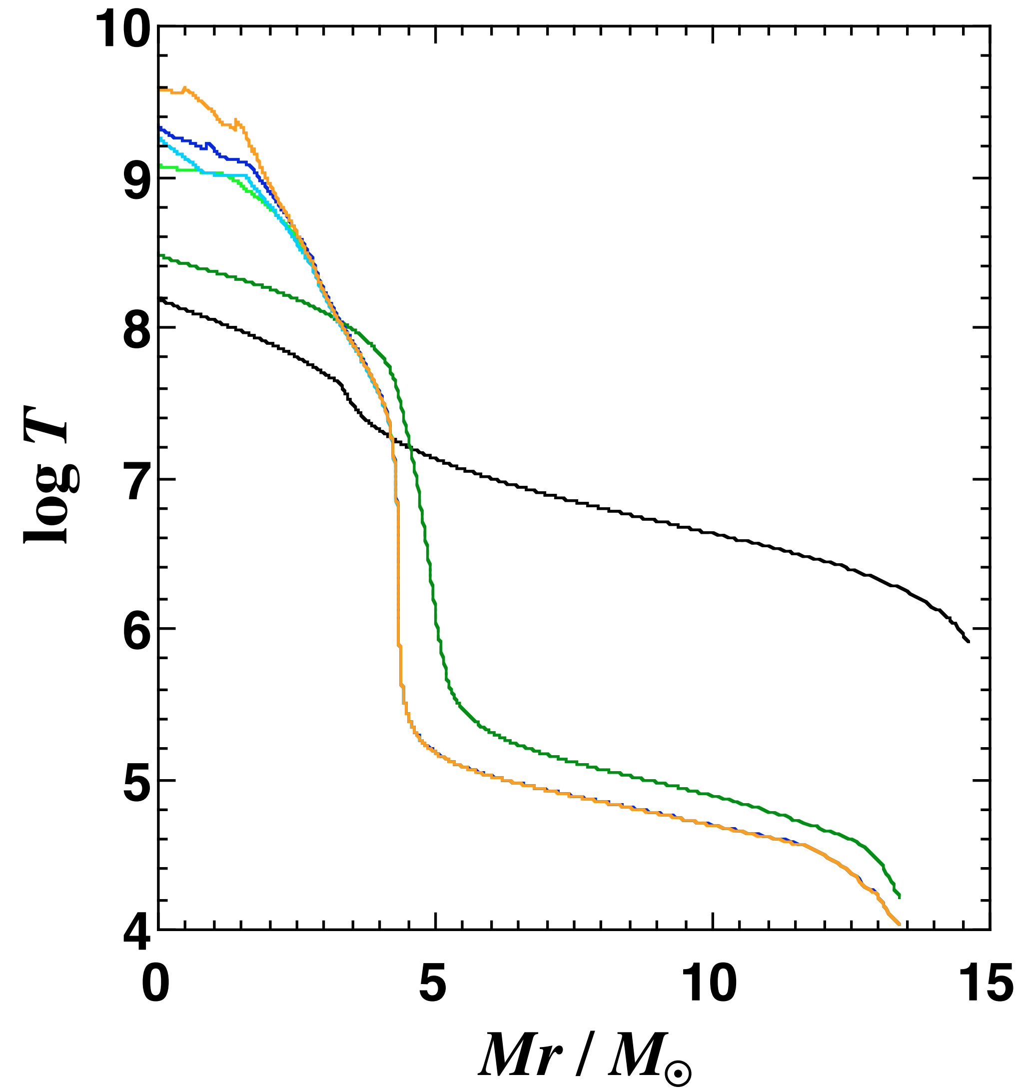


- M = 13.6 $M_\odot$

Evolution of 15 $M_\odot$, Z=0.02 Star

- Si-exhaustion

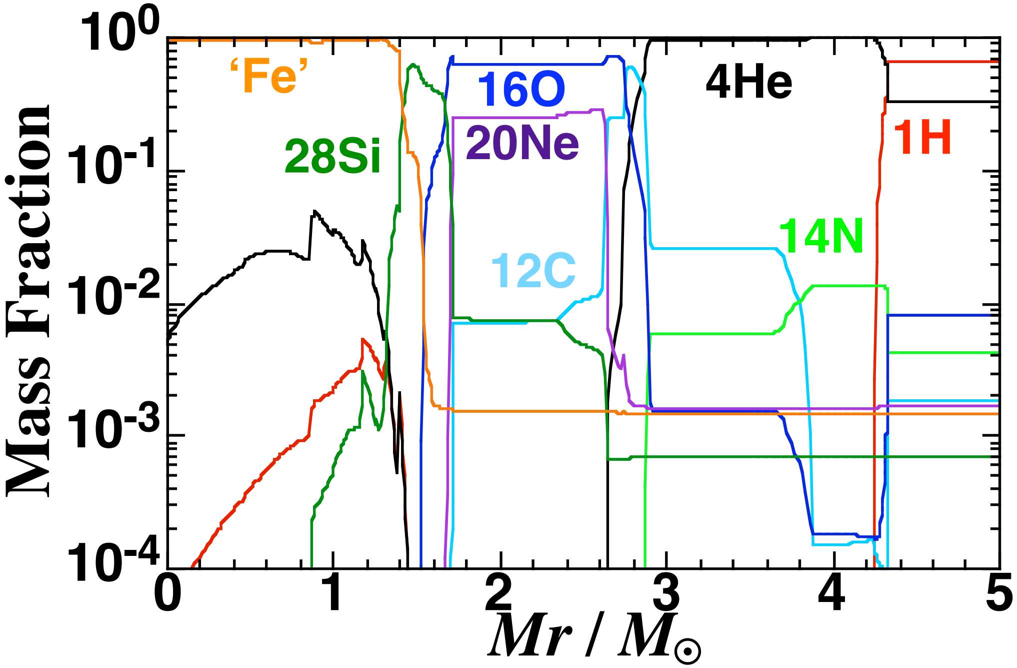


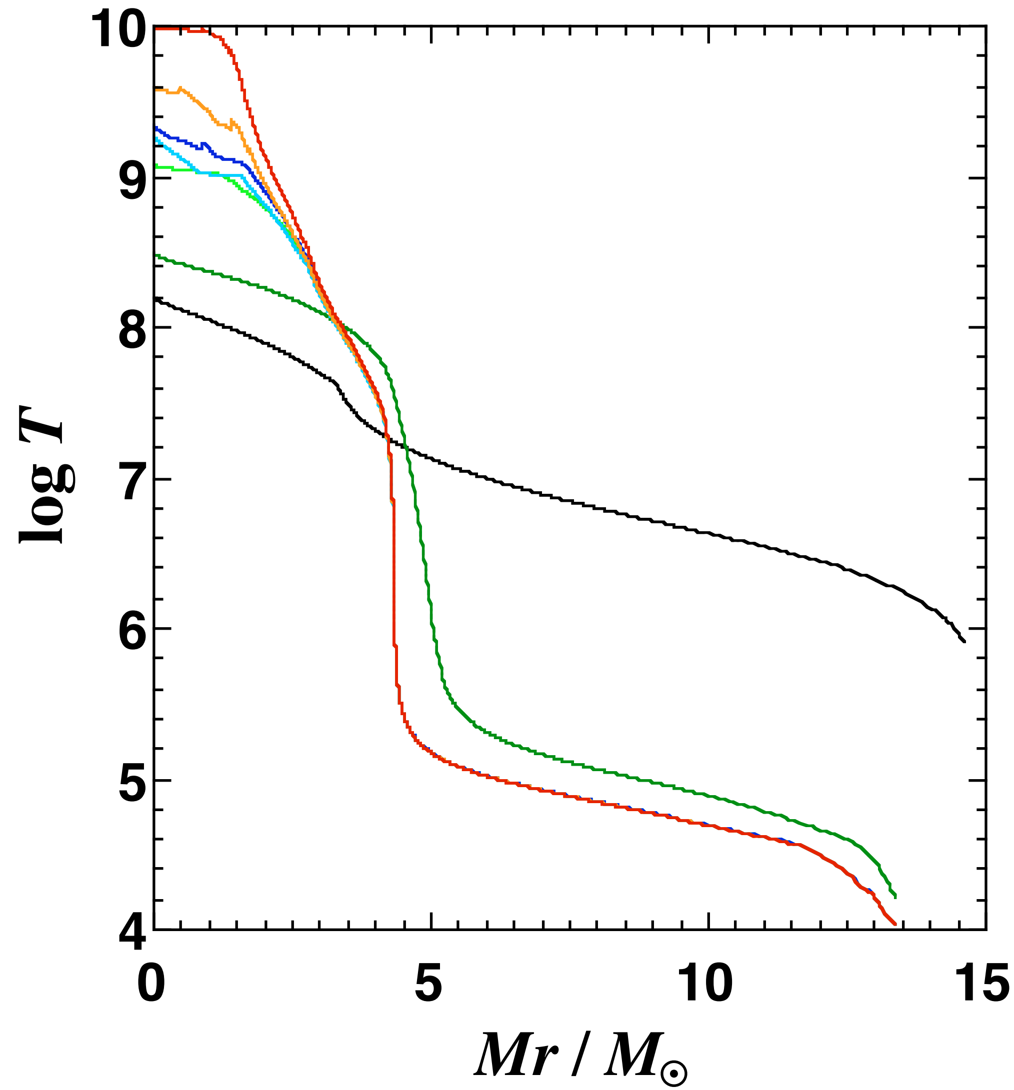


- M = 13.6 $M_\odot$

Evolution of 15 $M_\odot$, Z=0.02 Star

- **Core collapse**

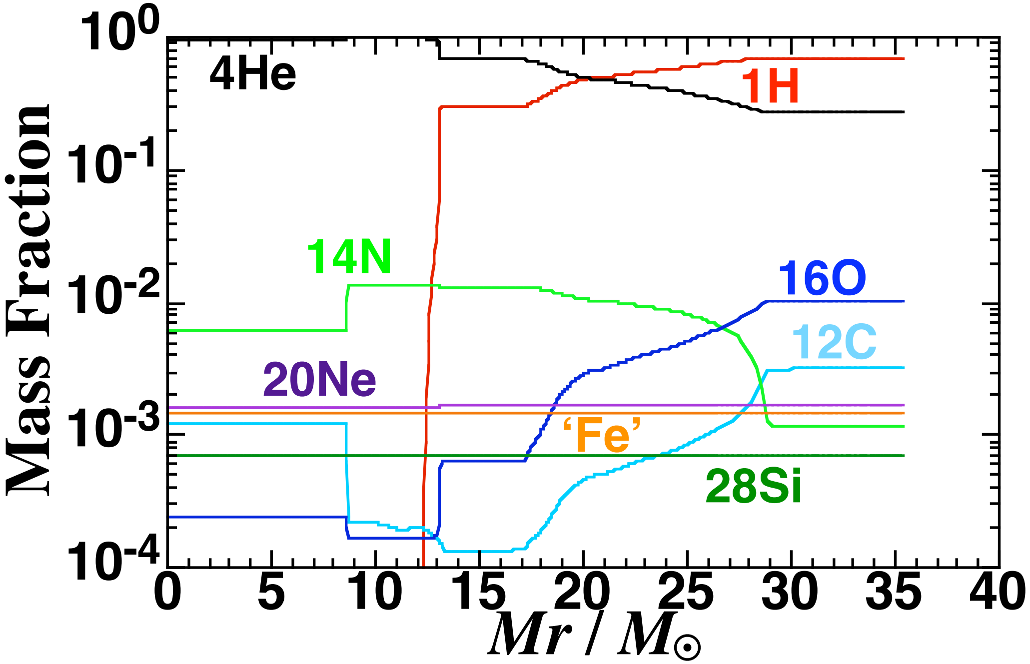


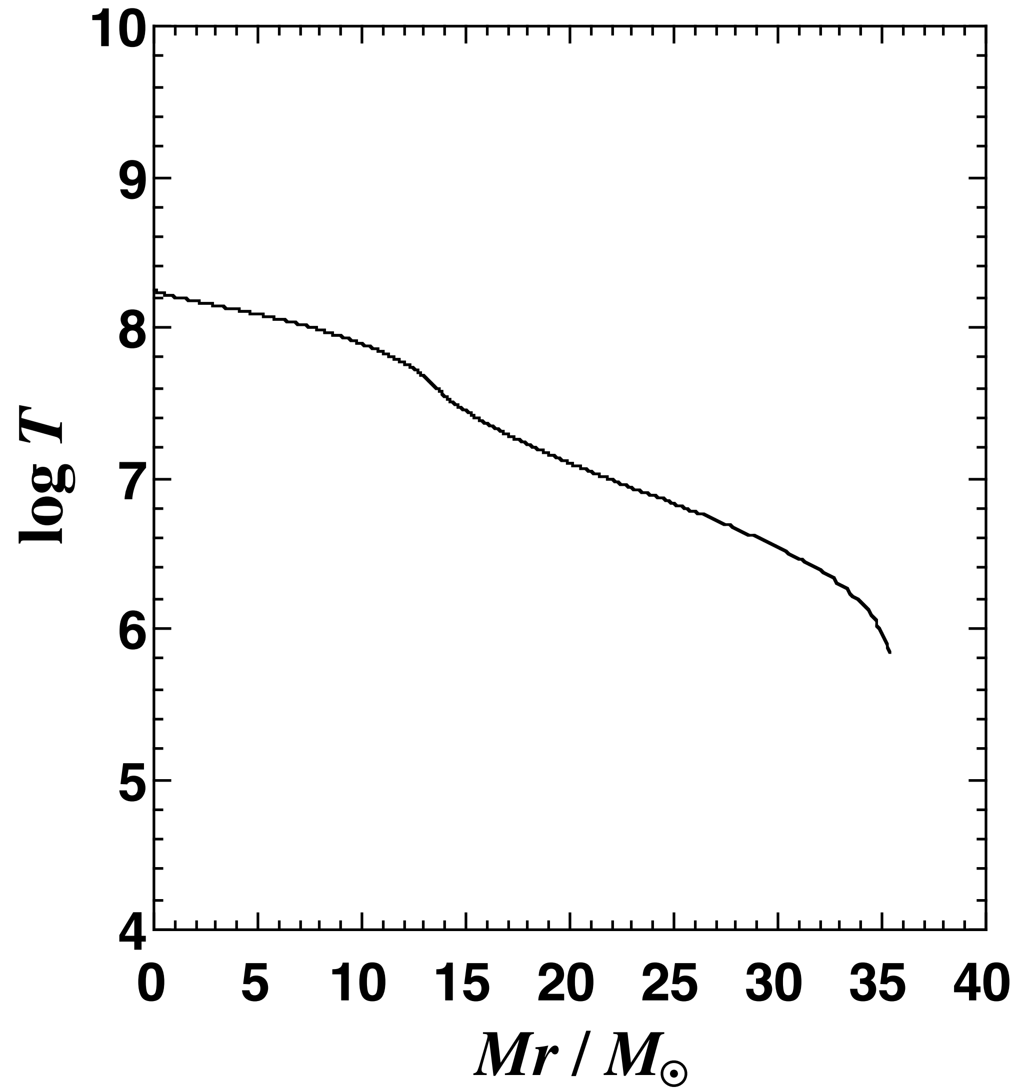


- $M_f = 13.6\ M_\odot$
- $M_{\rm He\ core} = 4.23\ M_\odot$
- $M_{\rm CO\ core} = 2.64\ M_\odot$
- $M_{\rm Fe\ core} = 1.38\ M_\odot$

Evolution of 40 $M_\odot$, Z=0.02 Star

- H-exhaustion

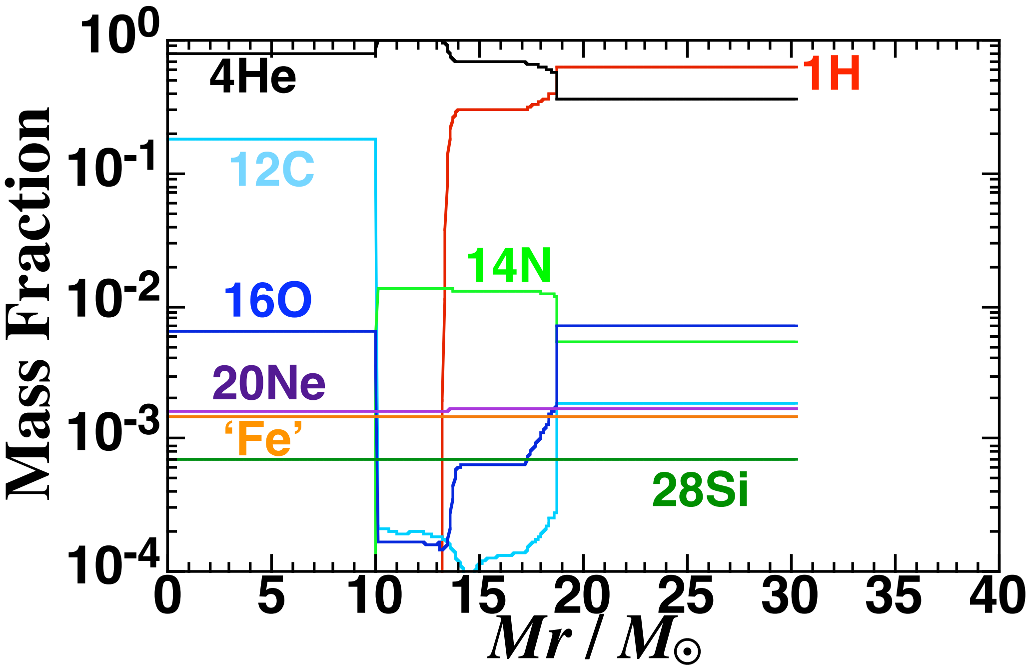


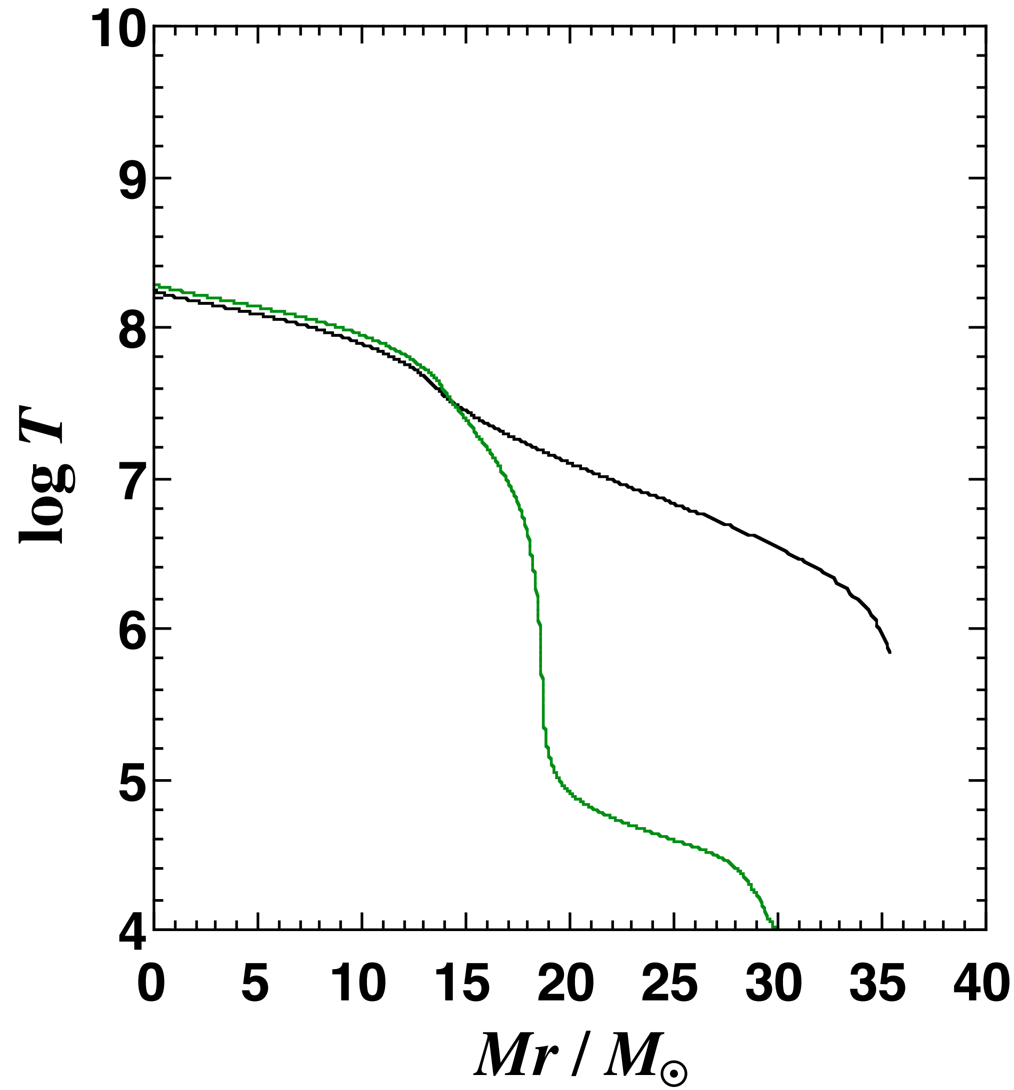


- M = 36.1 $M_\odot$

Evolution of 40 $M_\odot$, Z=0.02 Star

- **He-burning**

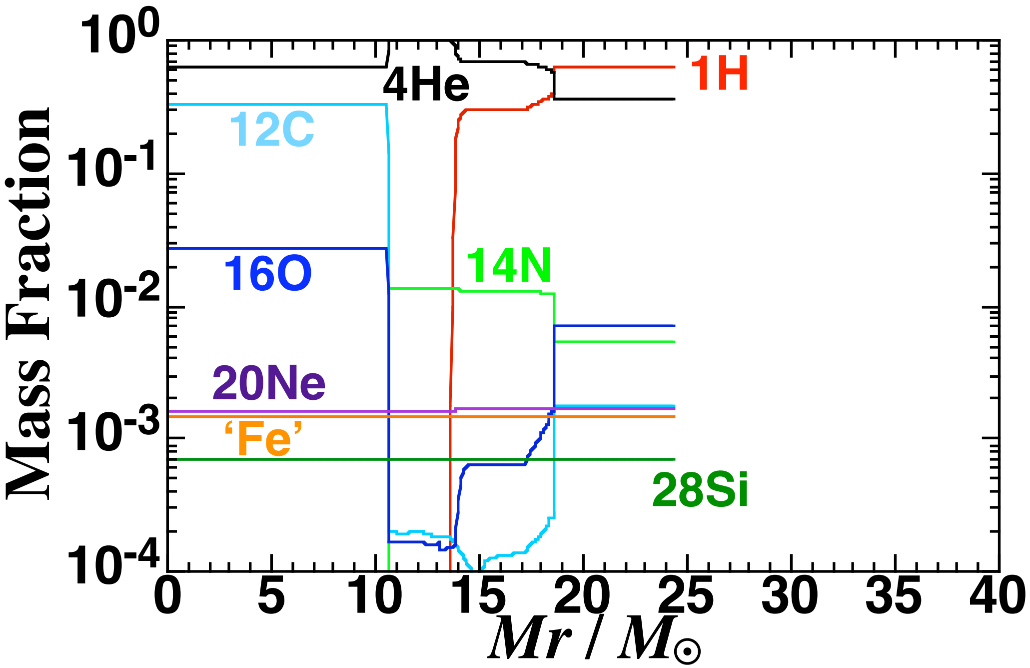


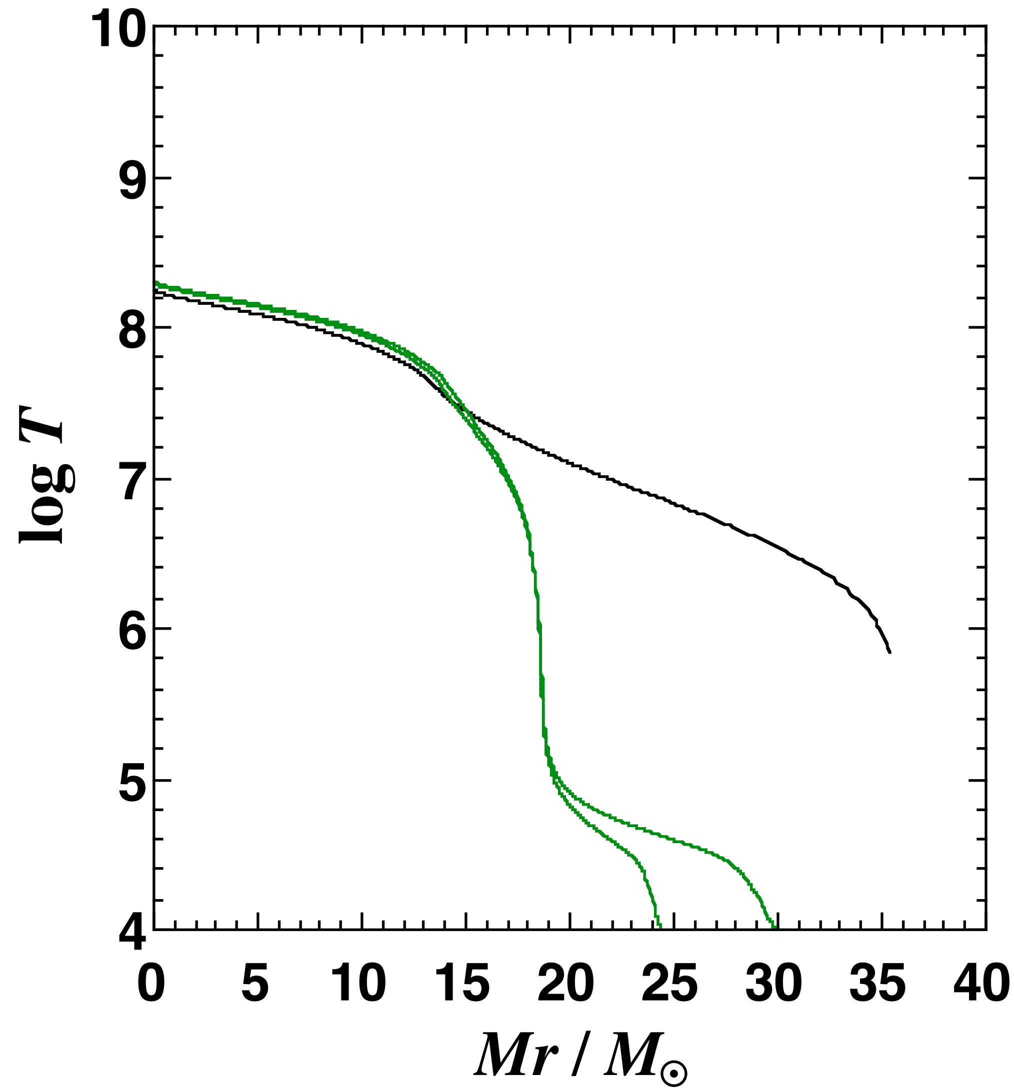


- M = 30.9 $M_\odot$

Evolution of 40 $M_\odot$, Z=0.02 Star

- **He-burning**

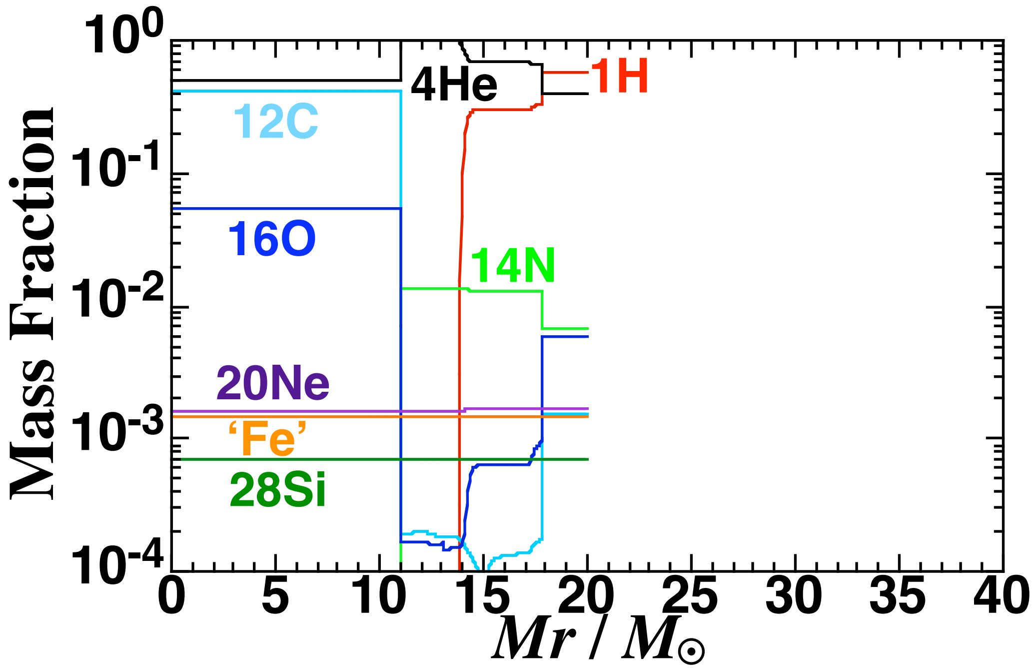




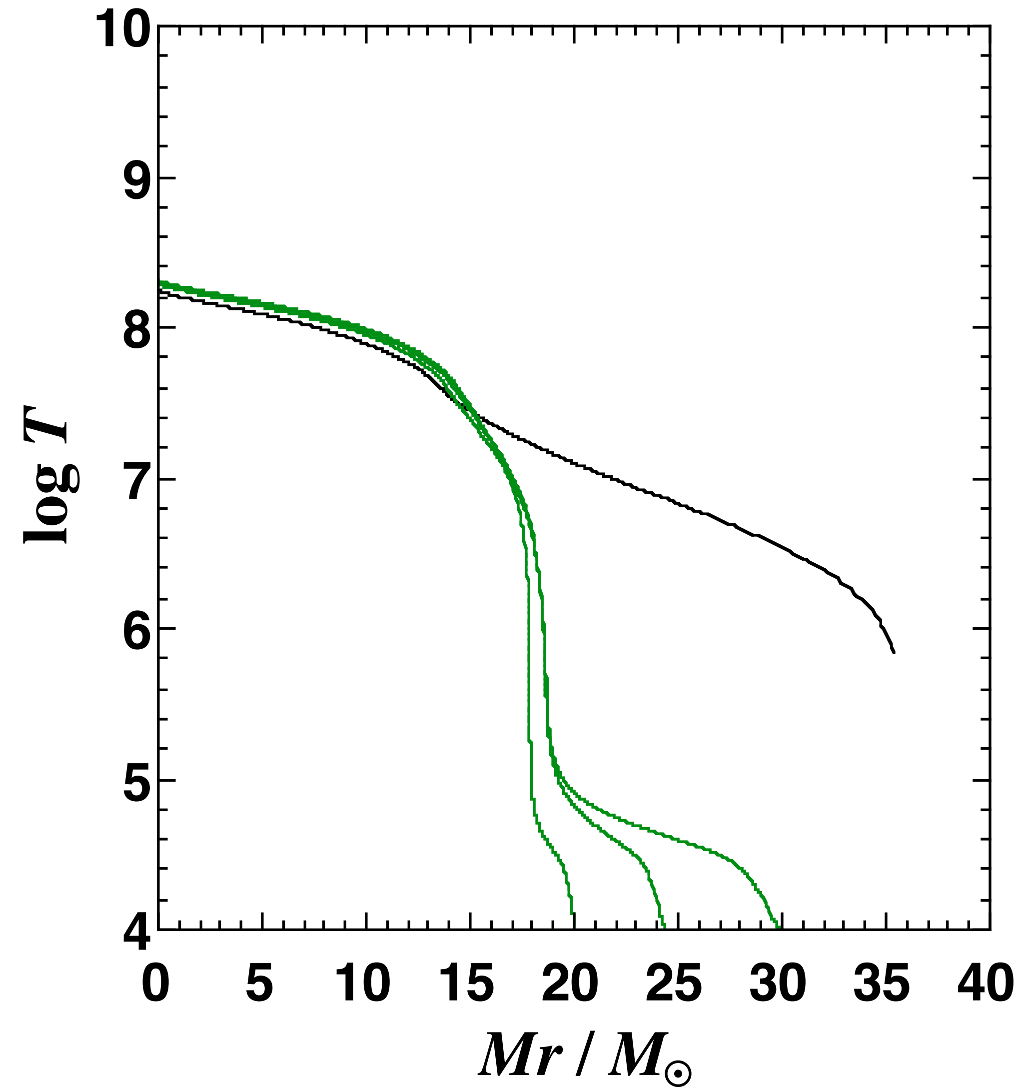
- $M = 24.8\ M_\odot$

Evolution of 40 $M_\odot$, Z=0.02 Star

- **He-burning**

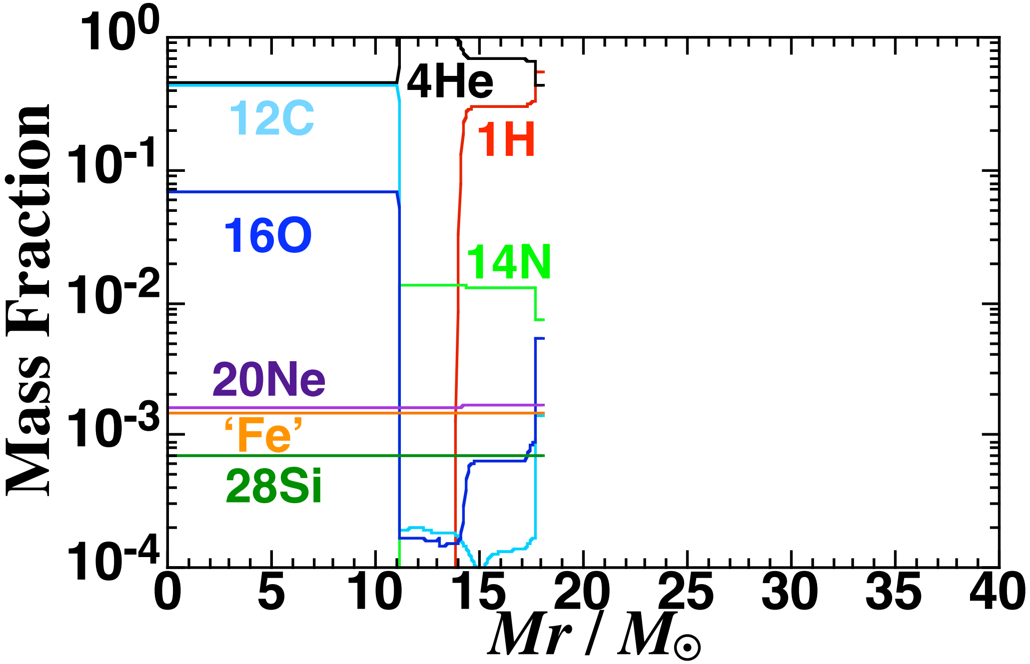


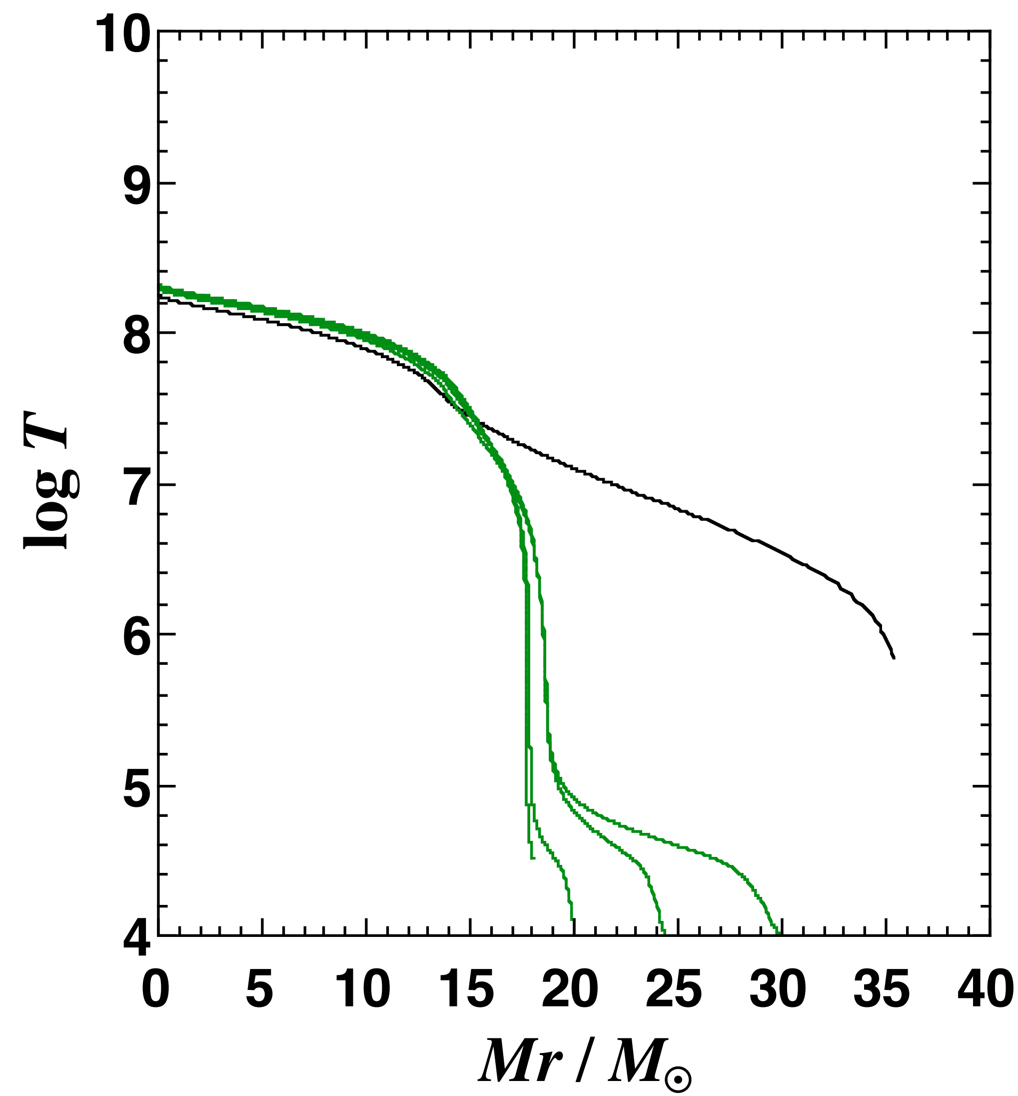
- M = 20.4 $M_\odot$



Evolution of 40 $M_\odot$, Z=0.02 Star

- **He-burning**

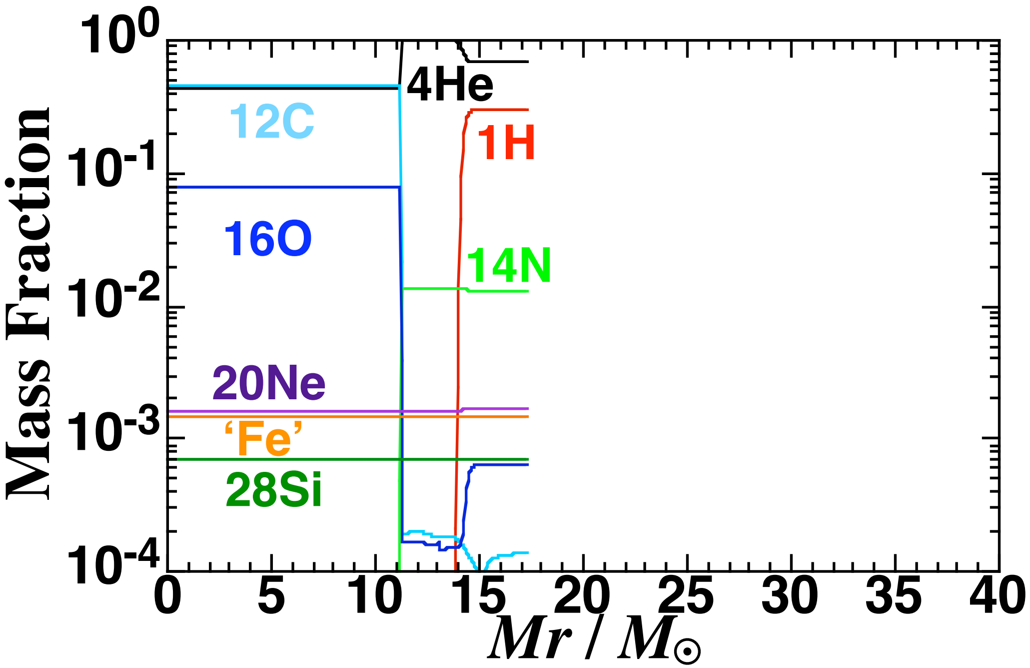


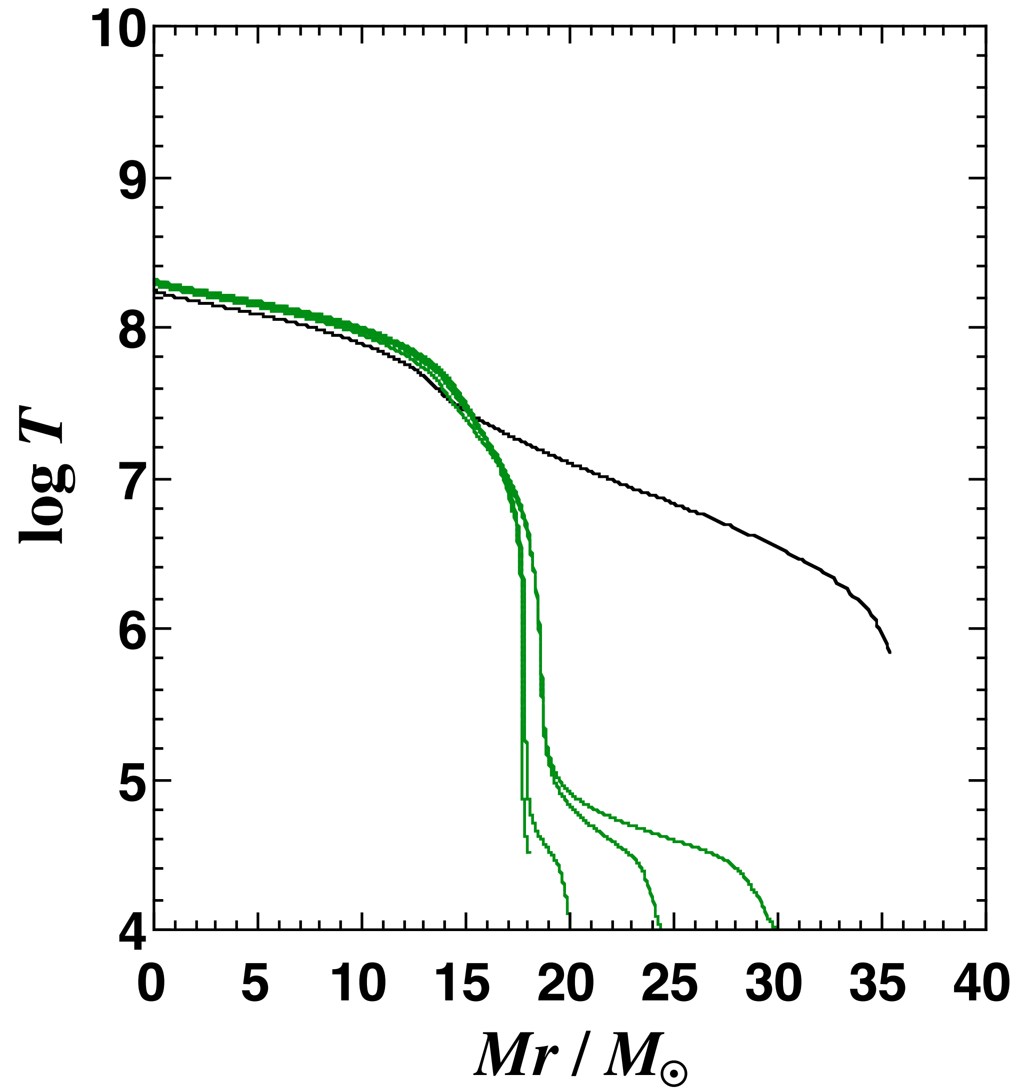


- $M = 18.4\ M_\odot$

Evolution of 40 $M_\odot$, Z=0.02 Star

- **He-burning**

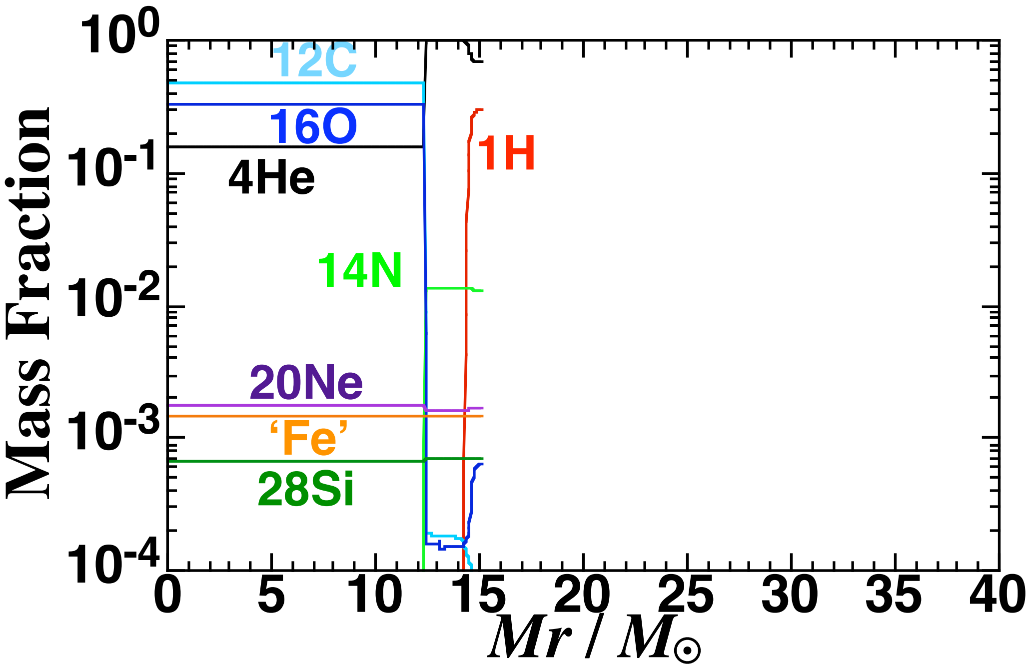


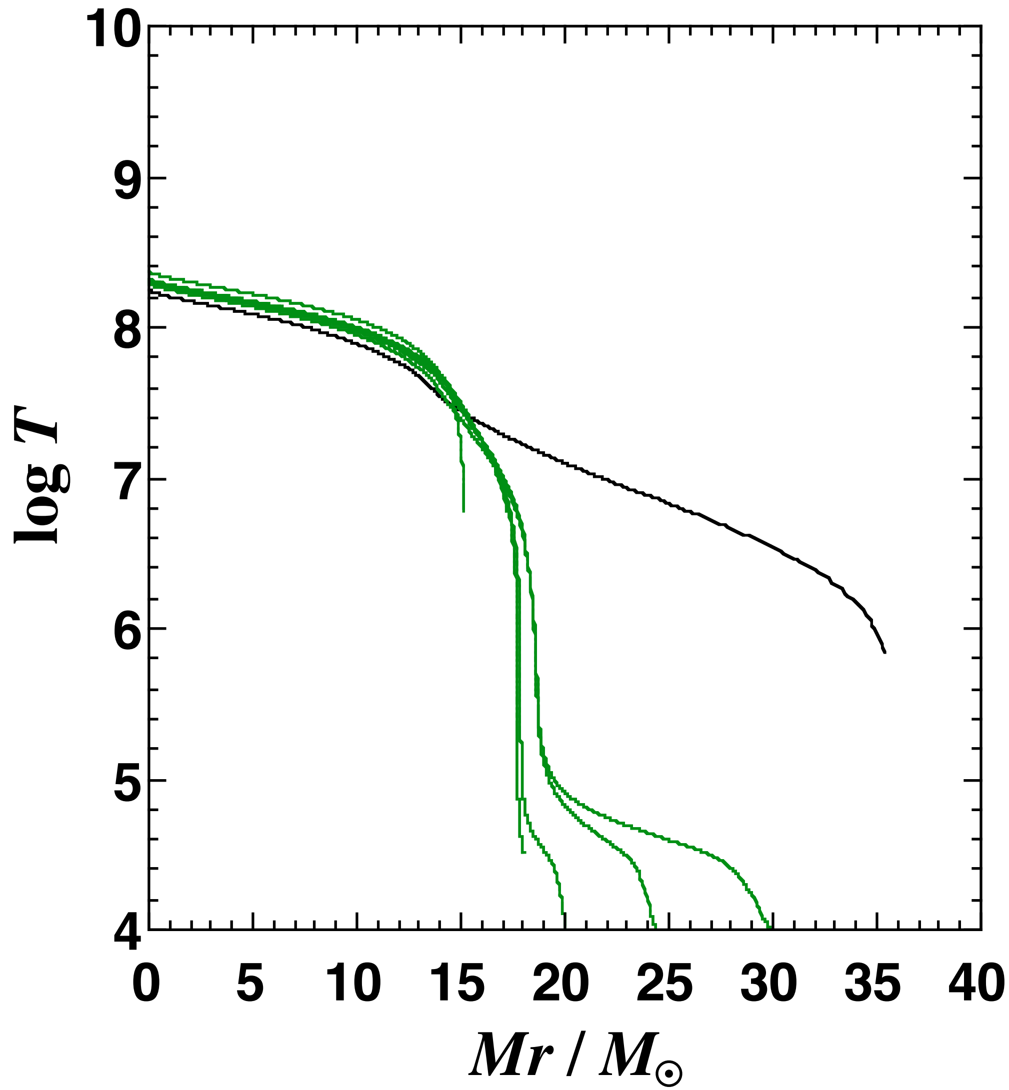


- $M = 17.6\ M_\odot$

Evolution of 40 $M_\odot$, Z=0.02 Star

- **He-burning**

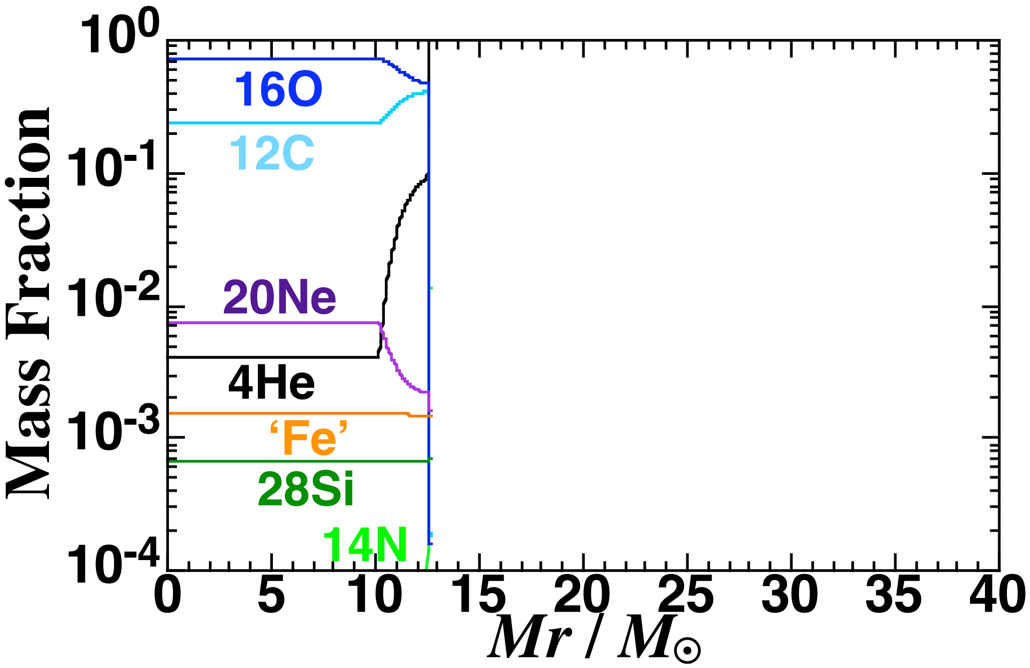


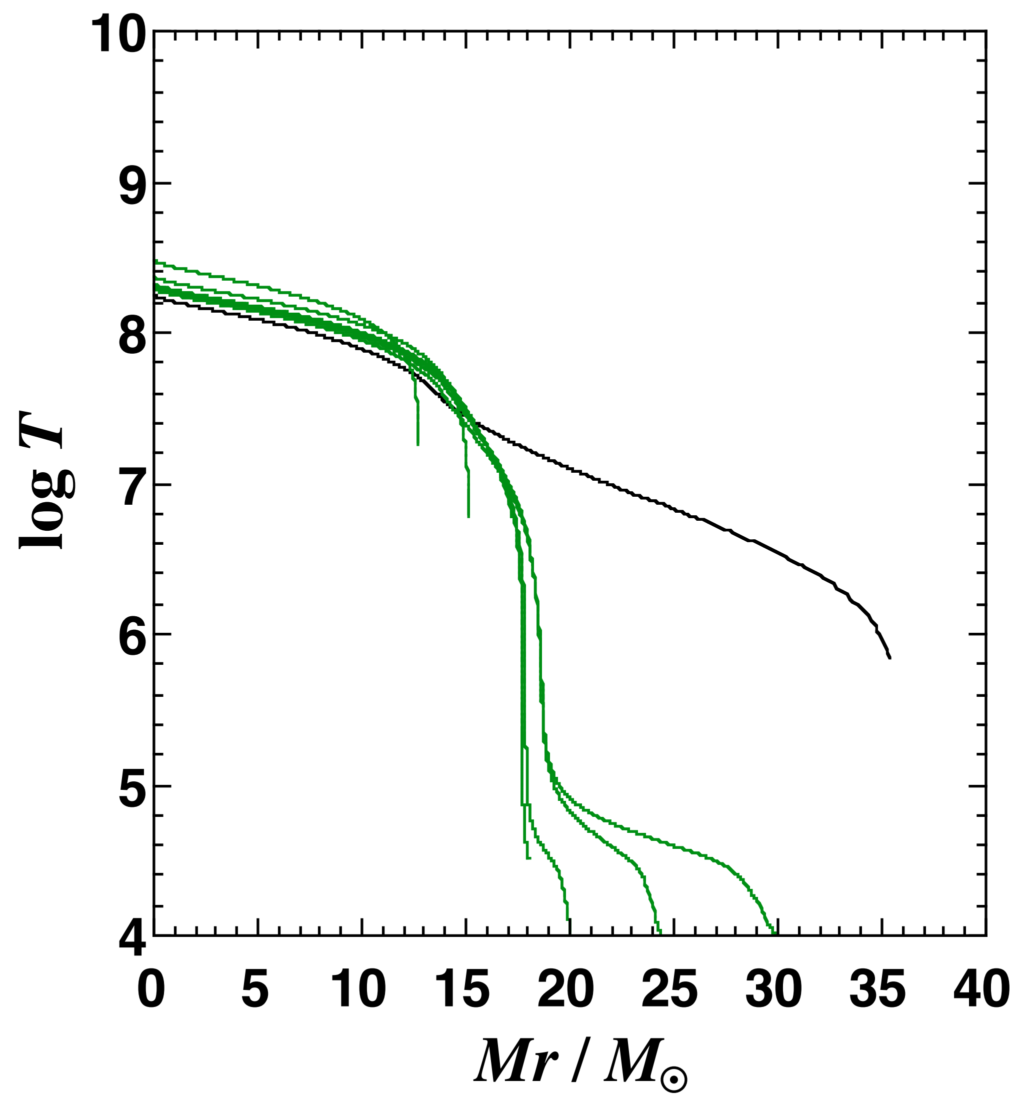


- $M = 15.2\ M_\odot$

Evolution of 40 $M_\odot$, Z=0.02 Star

- **He-burning**

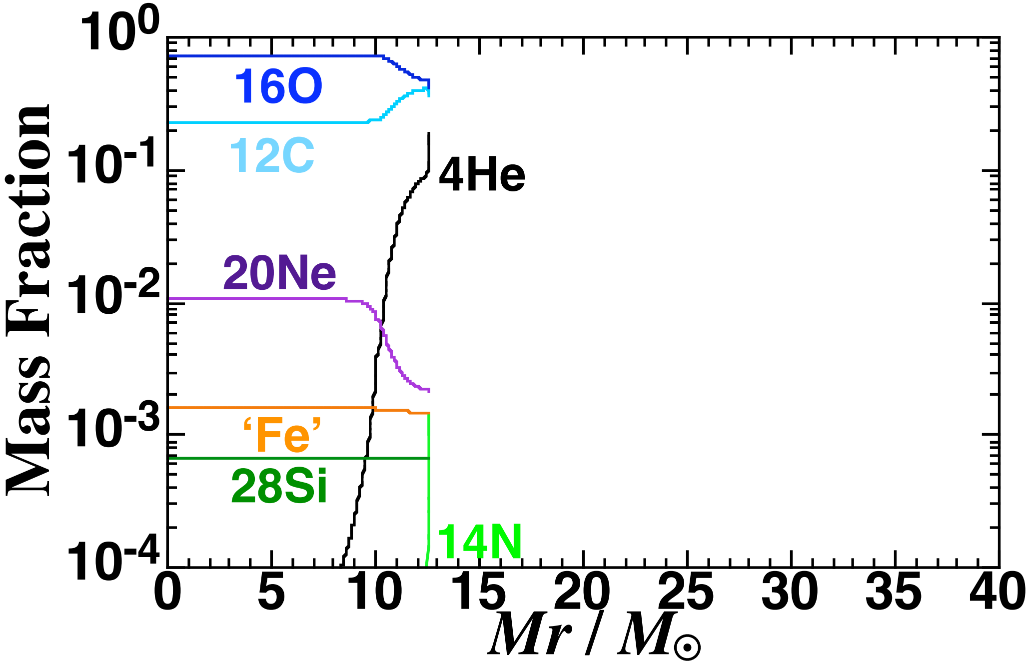


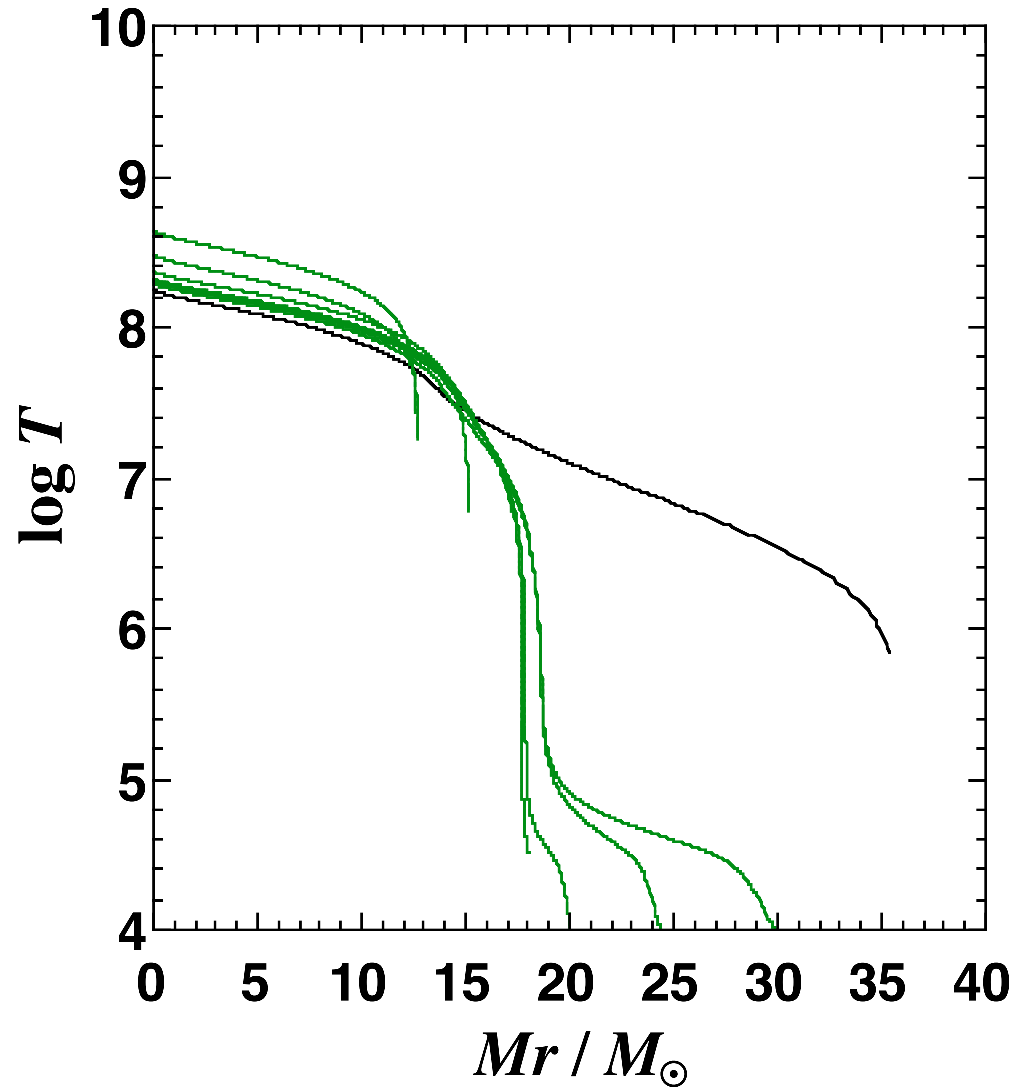


- M = 12.7 $M_\odot$

Evolution of 40 $M_\odot$, Z=0.02 Star

- **He-exhaustion**

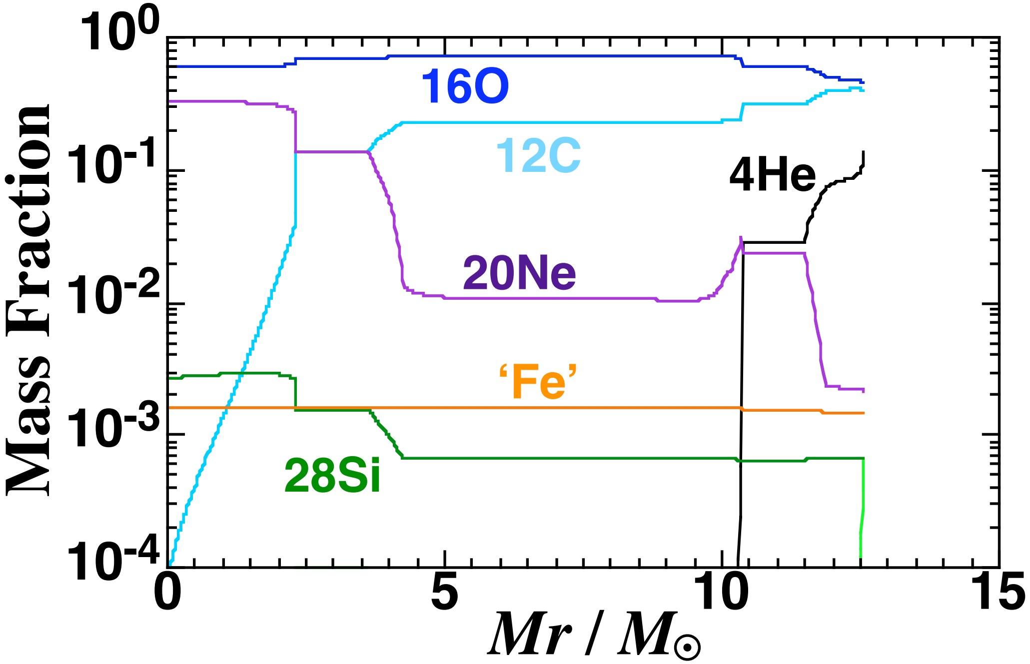




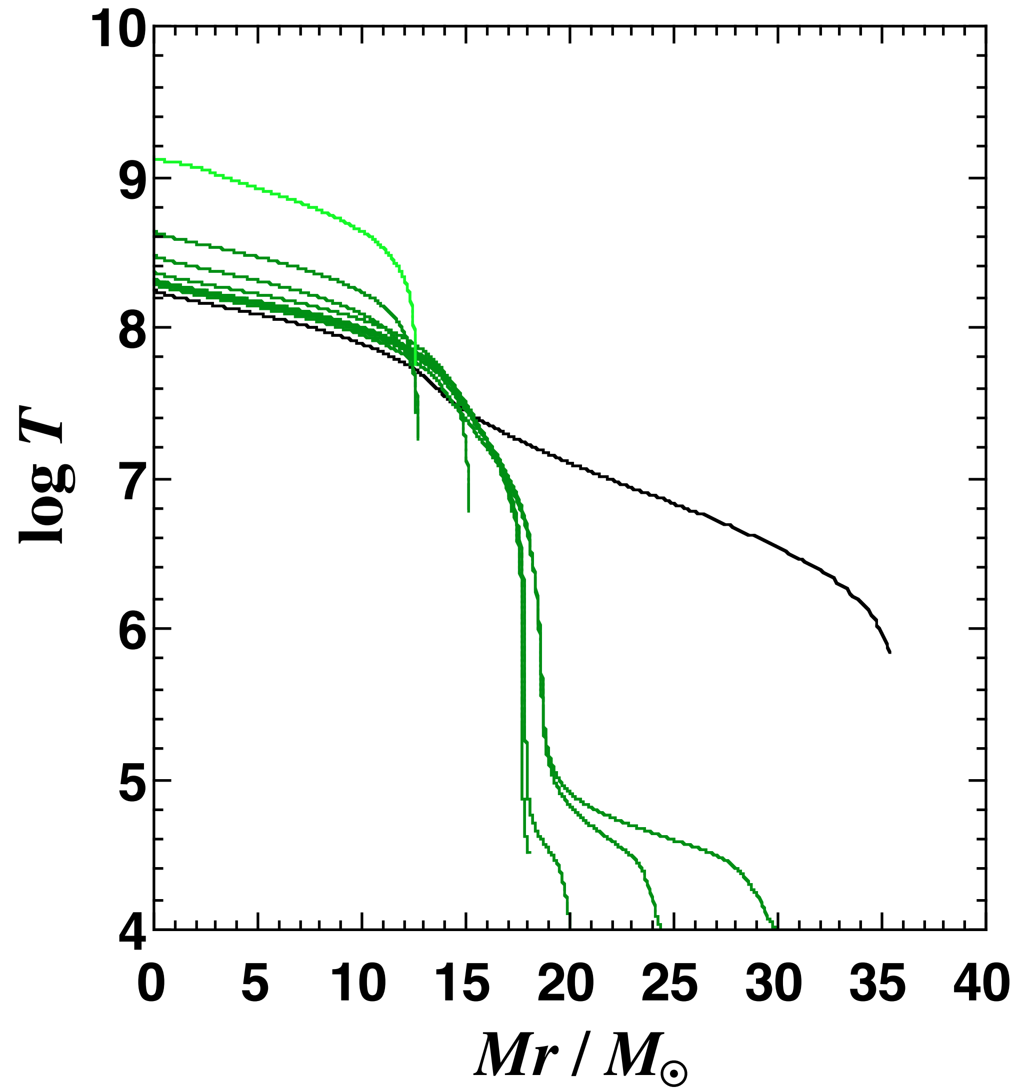
- $M = 12.6\ M_\odot$

Evolution of 40 $M_\odot$, Z=0.02 Star

- C-exhaustion

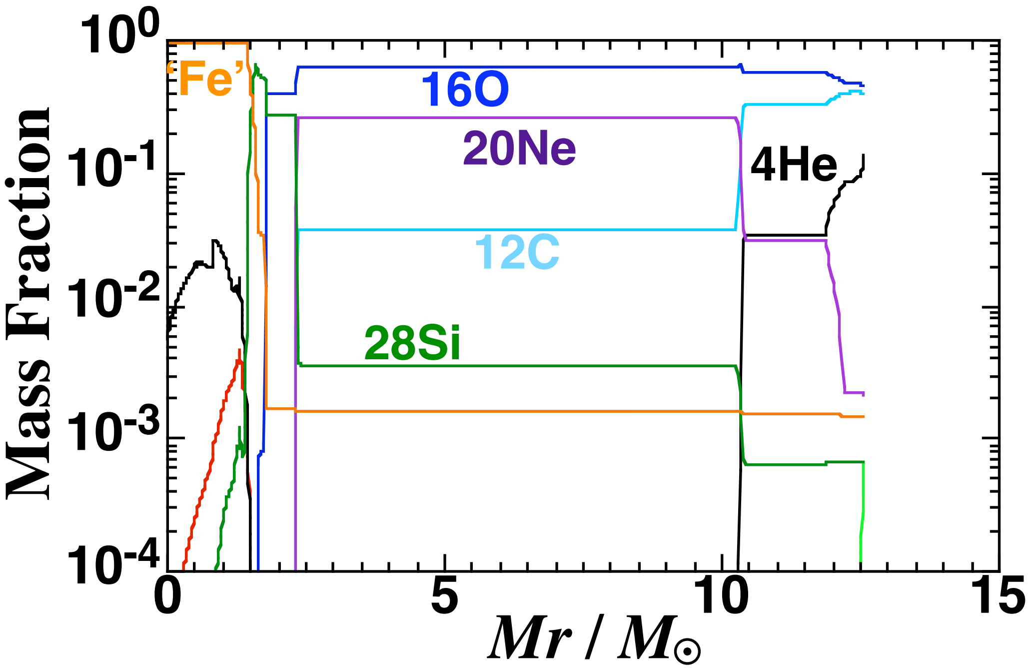


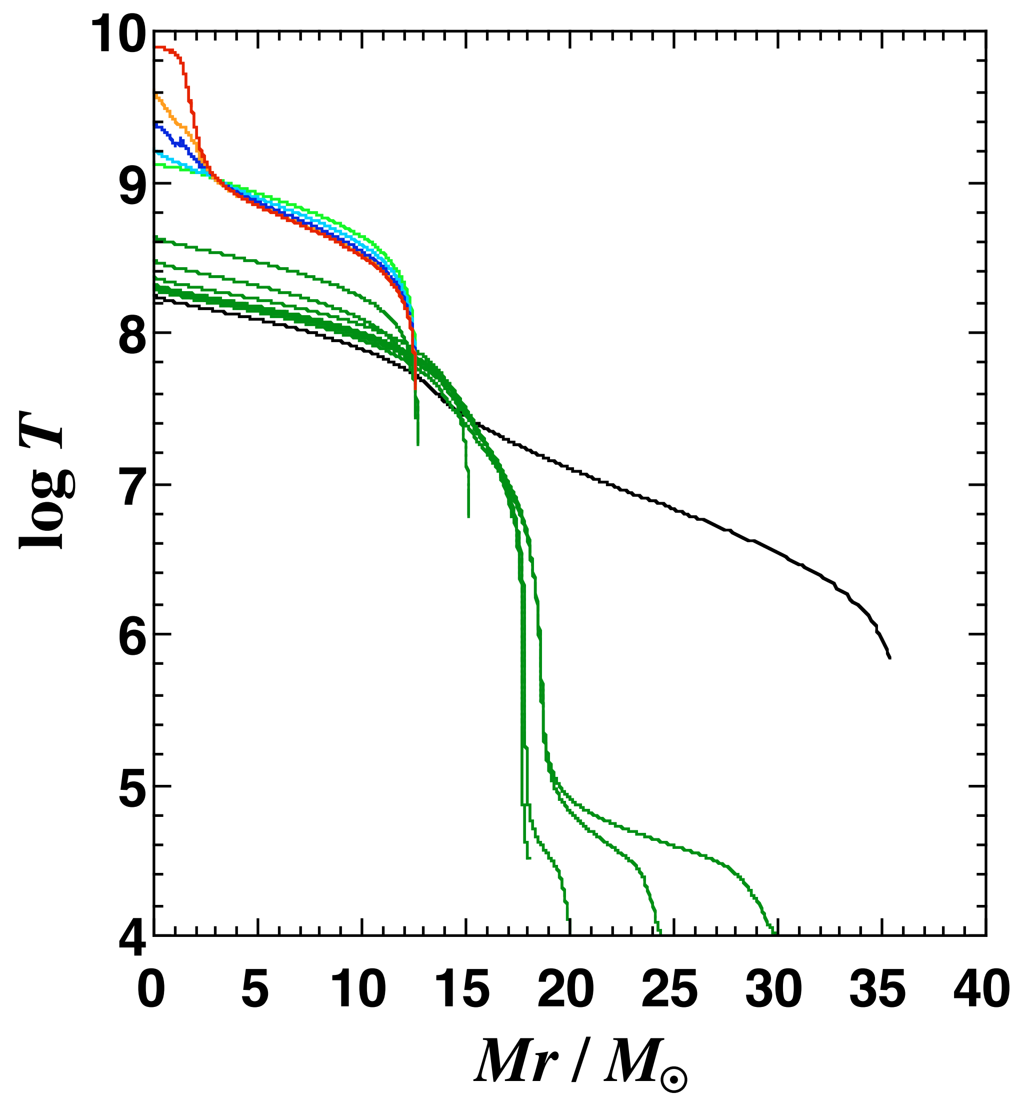
- M = 12.6 $M_\odot$



Evolution of 40 $M_\odot$, Z=0.02 Star

- Core collapse





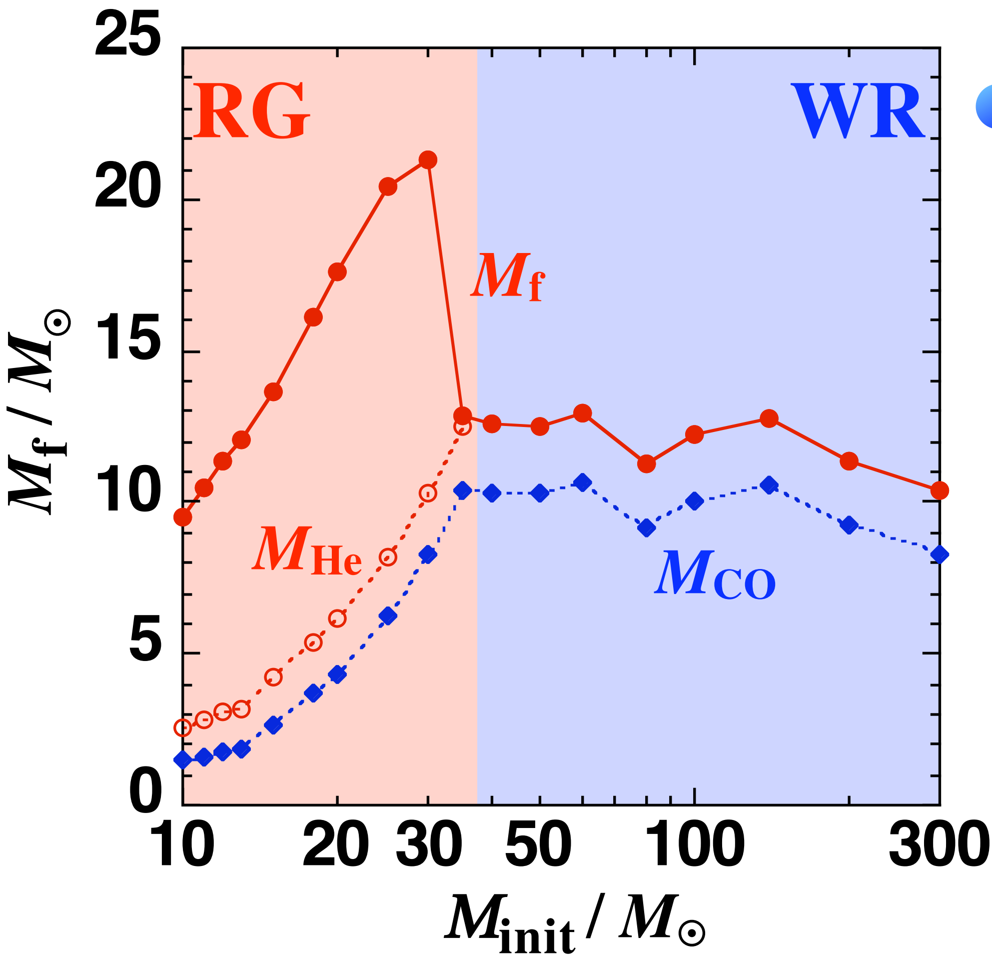
- $M_f = 12.6\ M_\odot$
- $M_{\rm CO\ core} = 10.3\ M_\odot$
- $M_{\rm Fe\ core} = 1.47\ M_\odot$

Final Mass

- **Initial mass dependence (Z=0.02)**

M_{He}: The largest mass coordinate satisfying X(H) < 10^{-3}

M_{CO}: The largest mass coordinate satisfying X(He) < 10^{-3}



- **M_{init} < 40 $M_\odot$**

  ➡ **Red giants**

  M_{init} ↗ ➡ M_{He}, M_{CO} ↗

  M_f < 22 $M_\odot$

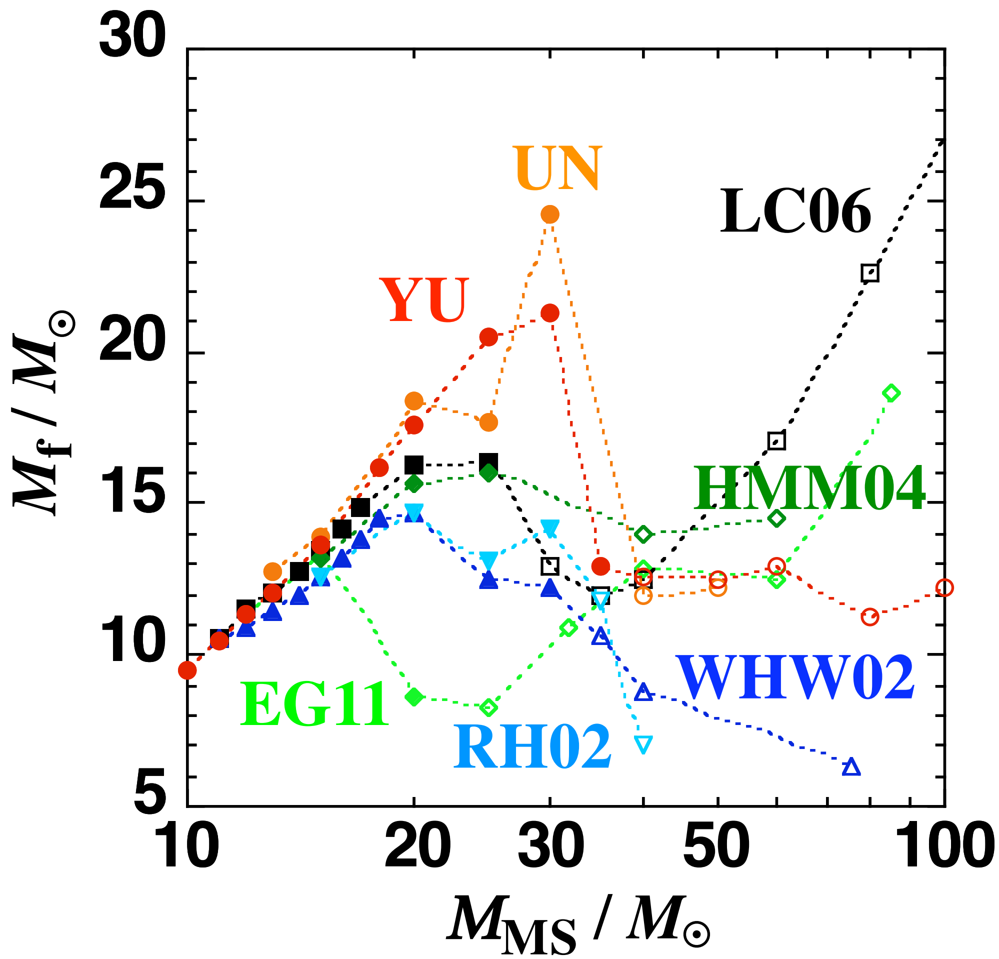
- **M_{init} > 40 $M_\odot$**

  ➡ **Wolf-Rayet stars**

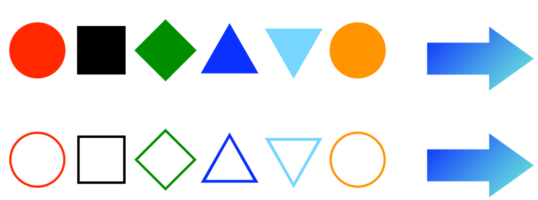
  M_{CO} ~ 10 $M_\odot$

Final Mass

- Comparison with models in other groups (Z=0.02)



YU: This study
UN: Umeda & Nomoto (Nomoto et al. 2006, etc.)
LC06: Limongi & Chieffi (2006)
HMM04: Hirschi, Meynet, Maeder (2004)
WHW04: Woosley, Heager, Weaver (2002)
RH02: Rauscher, Heger, Hoffman, Woosley (2002)
EG11: Ekstrom et al. 2011

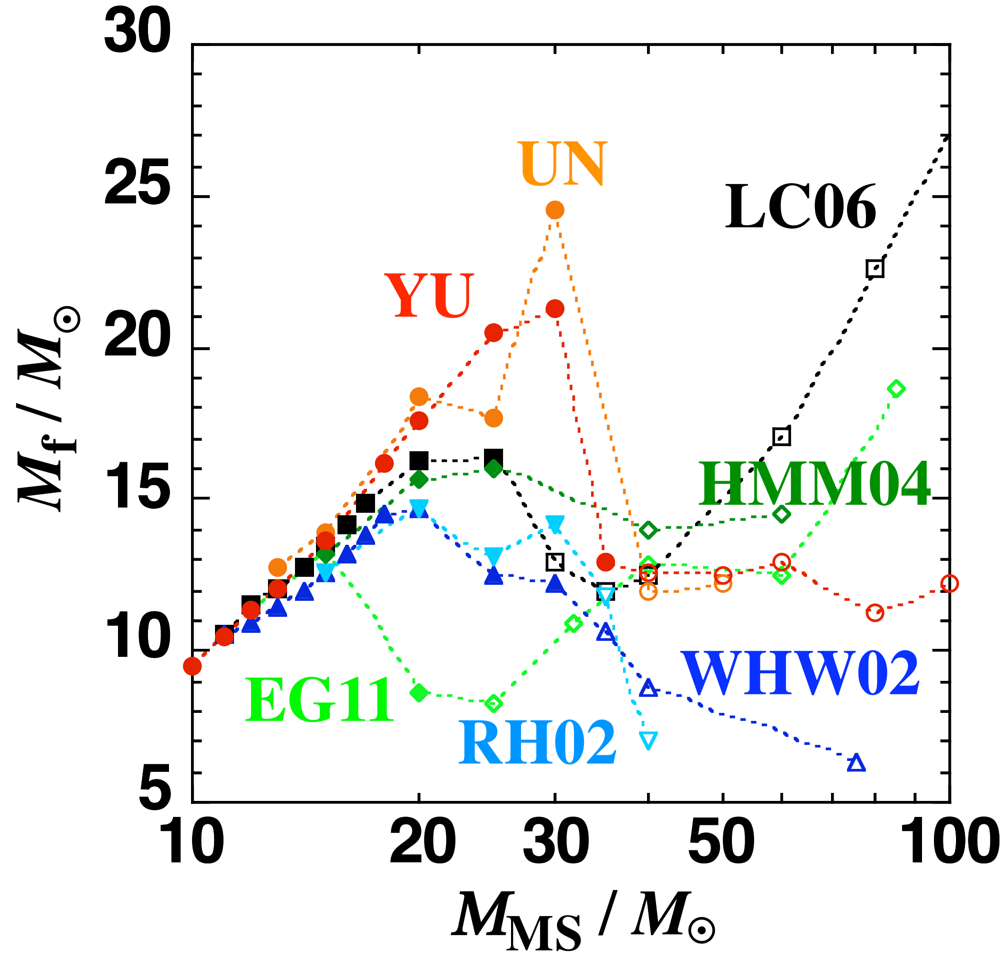


Red giants

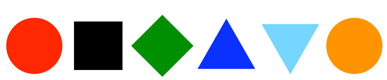
Wolf-Rayet stars

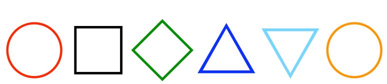
Final Mass

- Comparison with models in other groups (Z=0.02)



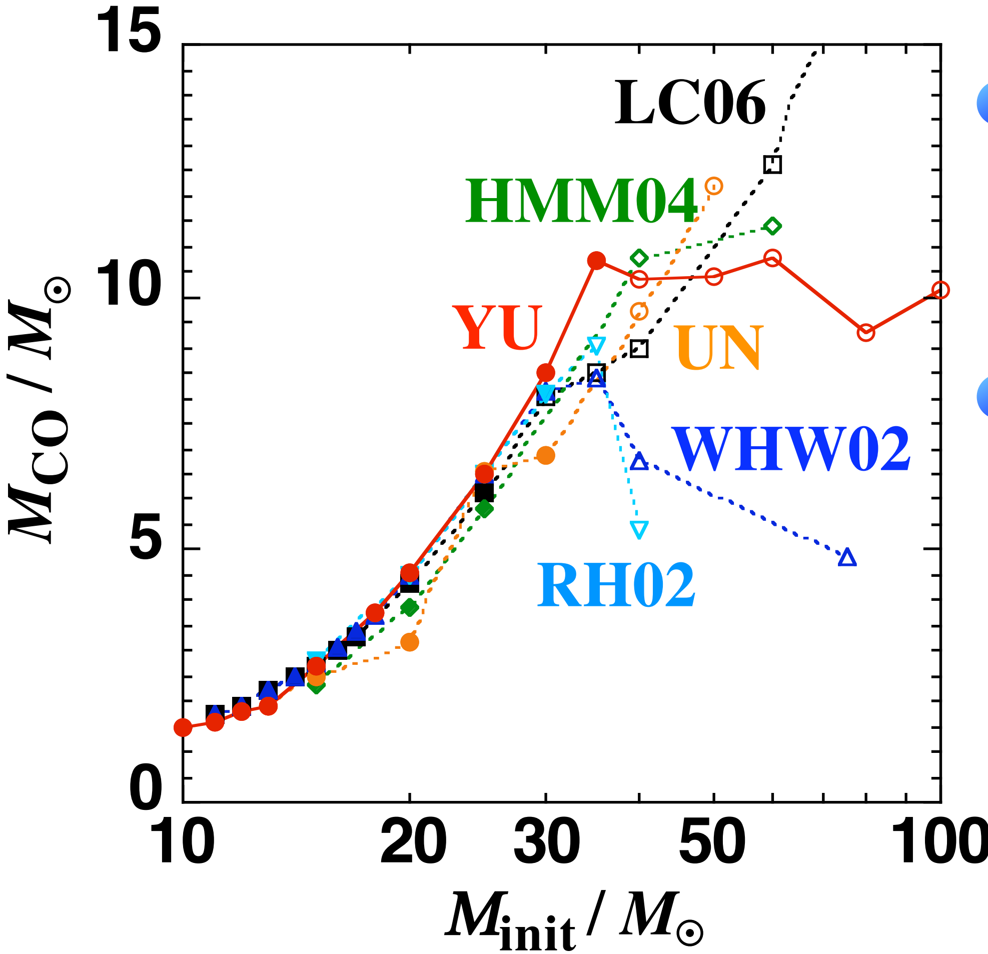
- $M_{init} < 20\ M_\odot$
  - → Small model dependence
- $20 < M_{init} < 40\ M_\odot$
  - → Large model dependence
- $M_{init} > 30 - 40\ M_\odot$
  - → Evolution to WR stars

 → Red giants

 → Wolf-Rayet stars

CO Core Mass

- Comparison with models in other groups (Z=0.02)



- $M_{init} < 30\ M_\odot$
  ➡ **Small dependence**

- $M_{init} > 30\ M_\odot$
  ➡ **Core mass is influenced by the evolution before C-burning.**

  Mainly mass loss

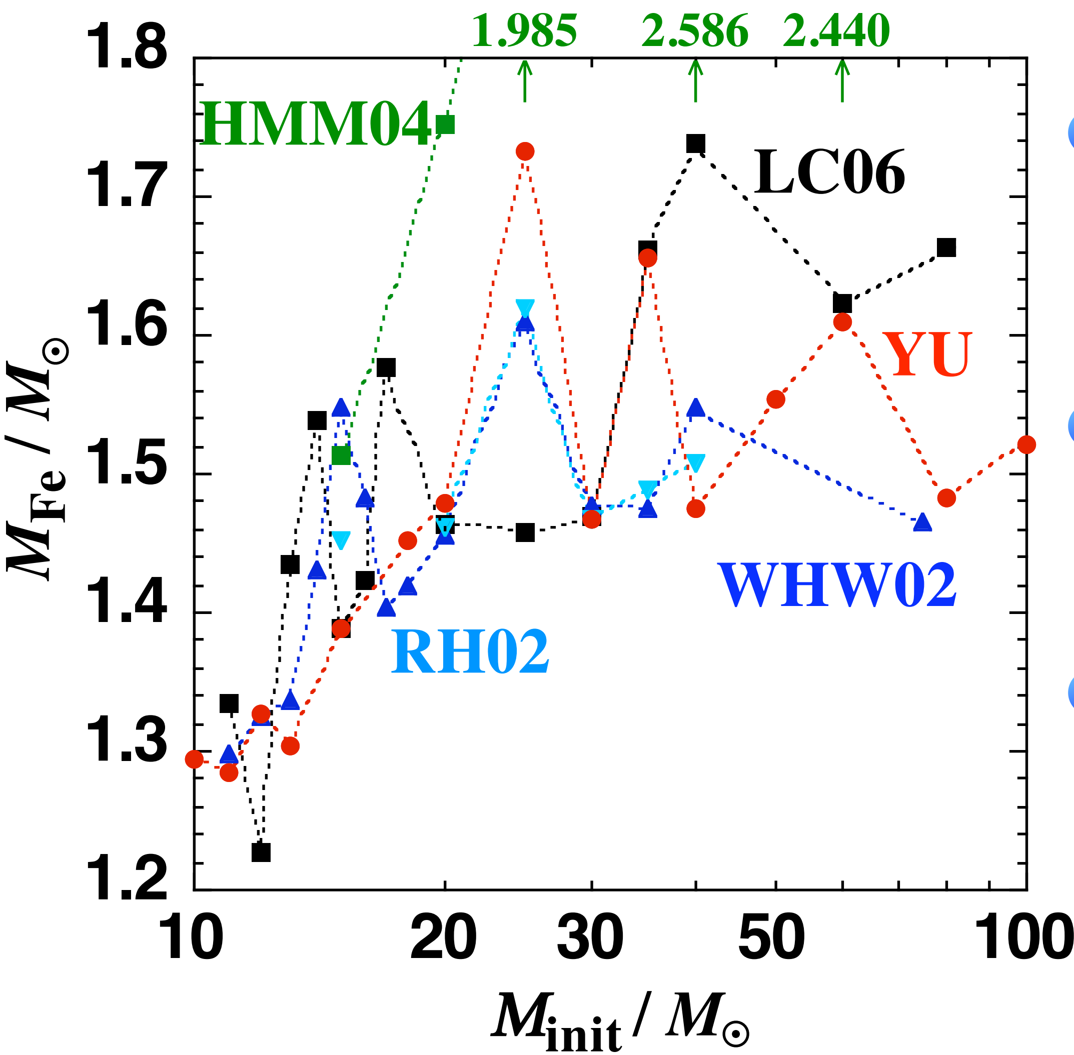
●■◆▲▼● ➡ **Red giants**

○□◇△▽○ ➡ **Wolf-Rayet stars**

Fe Core Mass

- **Fe core**

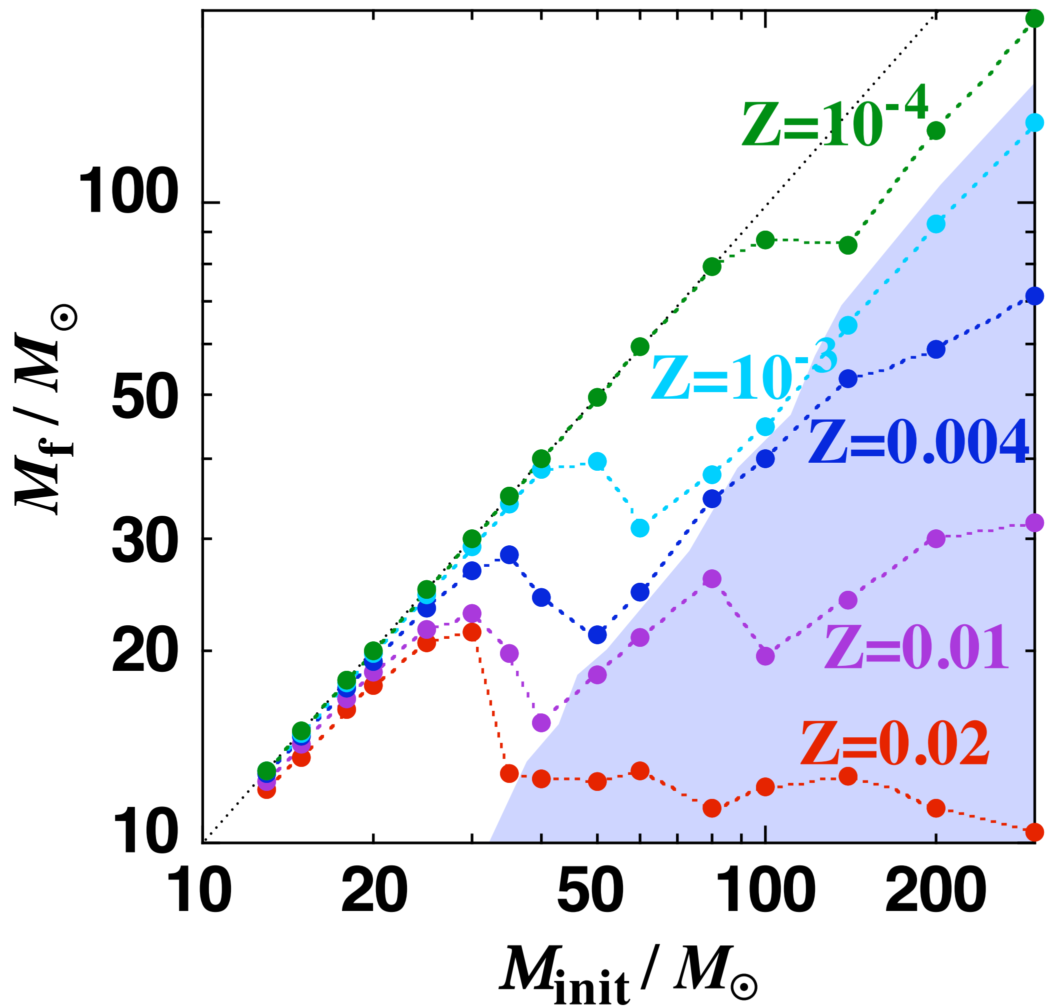
  ➡ The largest mass coordinate satisfying X(Ti-) > 0.5



- **Complex mass dependence in every model...**
- **1.3 $M_\odot < M_{Fe} < 1.6\ M_\odot$ for most models**
- **25 $M_\odot$ model??**

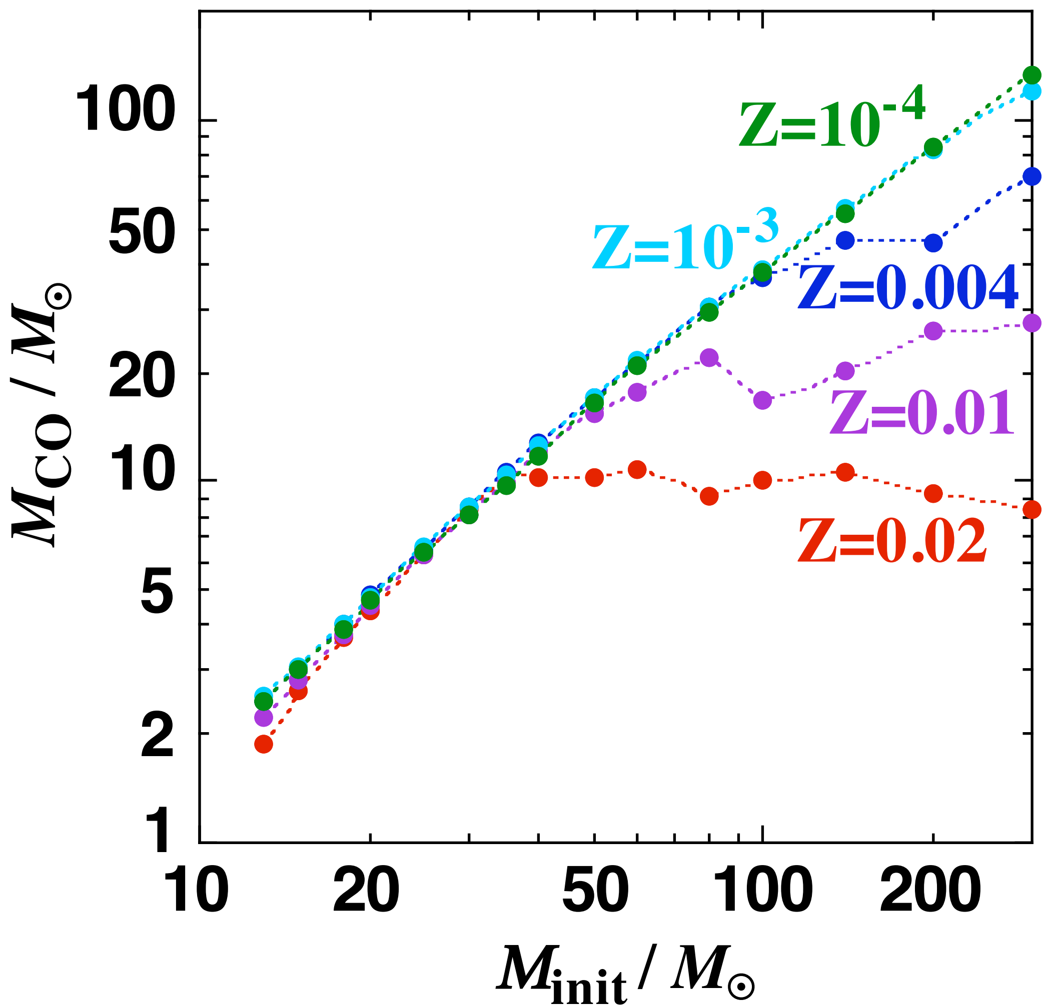
Mass & Metallicity Dependence of Final Mass

TY, Okita, & Umeda (2012) in prep.



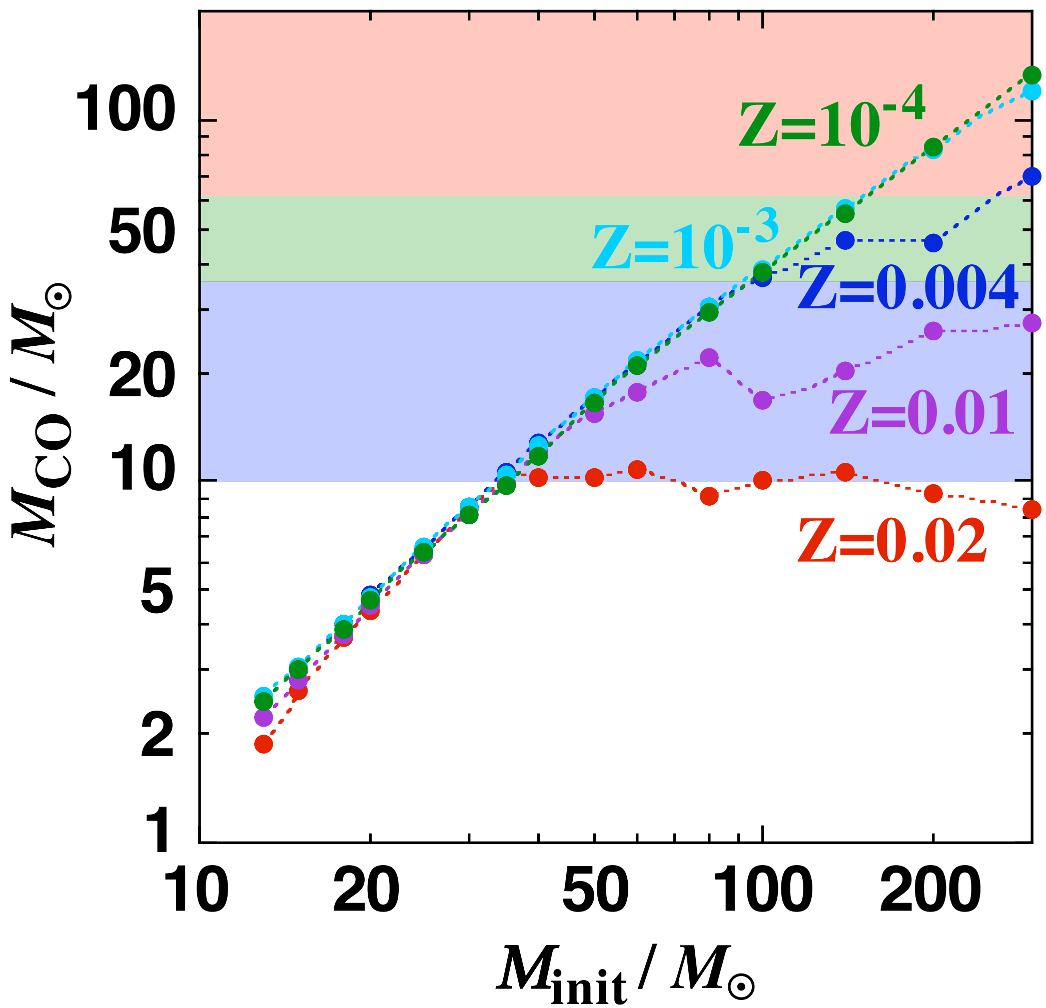
- **Blue shaded region**
  - ➡ WR stars → SNe Ic
- $Z=0.02$
  - ➡ Evolution to WR for $M_{\rm init} > 40\ M_\odot$
- WR stars ➡ $Z > 0.001$
- $Z=10^{-4}$
  - ➡ Very small mass loss

Mass & Metallicity Dependence of CO Core



- $M_{init} < 40\ M_\odot$
  → Small Z dependence
- Z=0.02
  → $M_{CO} \sim 10\ M_\odot$ (WR) for $M_{init} > 40\ M_\odot$
- $M_{init} > 140\ M_\odot$, Z<0.004
  → Very large CO core
  → PISN

Mass & Metallicity Dependence of CO Core



PISN

$M(^{56}Ni) > 3M_\odot$ for CCSN ($E_{ex,51} > 20$)

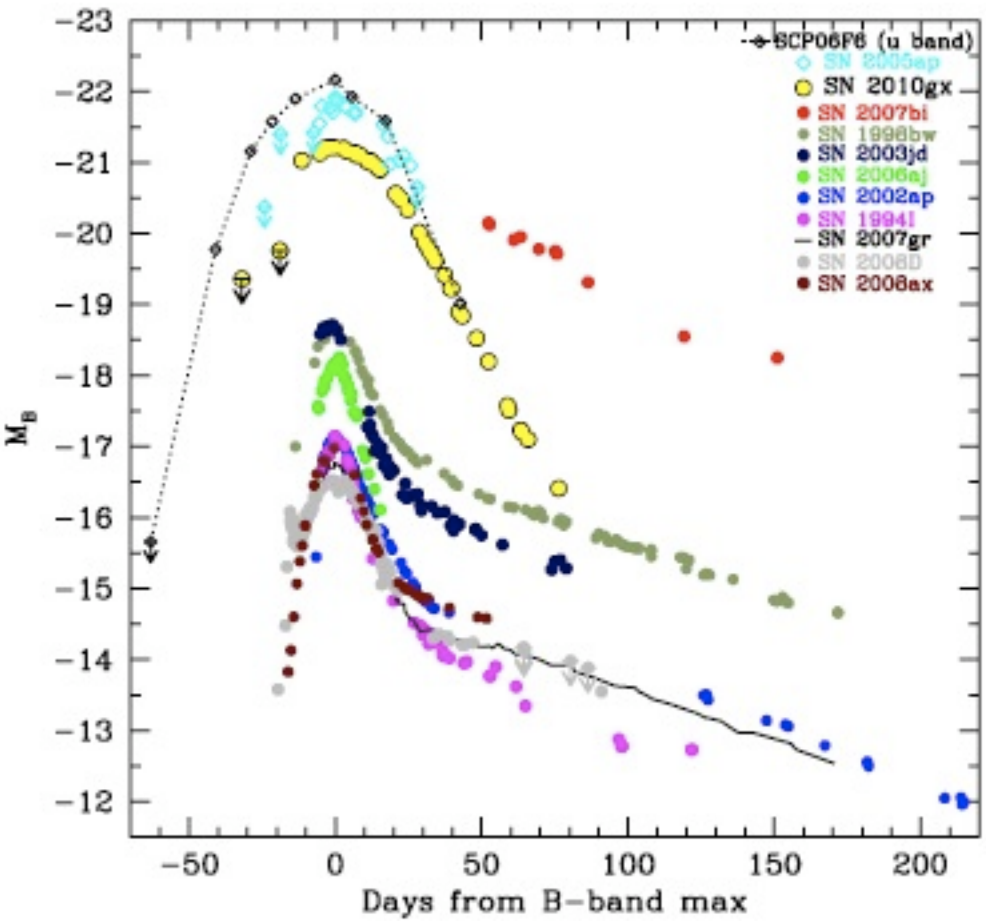
$M(^{56}Ni) > 1M_\odot$ for CCSN ($E_{ex,51} > 10$)

(Heger & Woosley 2002; Umeda & Nomoto 2002, 2008)

- $M_{init} > 40 - 100\ M_\odot$, $Z > 0.001$ stars

→ Possibility of super-luminous type Ic supernovae

Super-Luminous SNe Ic



Pastorello et al. (2010)

- **SN 2007bi**
  - ➡ $M(^{56}\mathrm{Ni}) \sim 3 - 7\ M_\odot$
  - **PISN?** (Gal-Yam et al. 2009)
  - **CCSN?** (Moriya et al. 2010)
- **SN 2010gx, (SN 2005ap)** (Quimby et al. 2011)
  - ➡ $M(^{56}\mathrm{Ni}) \sim 1\ M_\odot$
  - **Rapid light curve decrease**
  - **Explosion mechanism?**

SNe Ic from very massive stars

- **Progenitor:** $M_{\mathrm{init}} = 110\ M_\odot$, $Z = 0.004$ **star → WR star**
  - ➡ ^{56}**Ni amount**

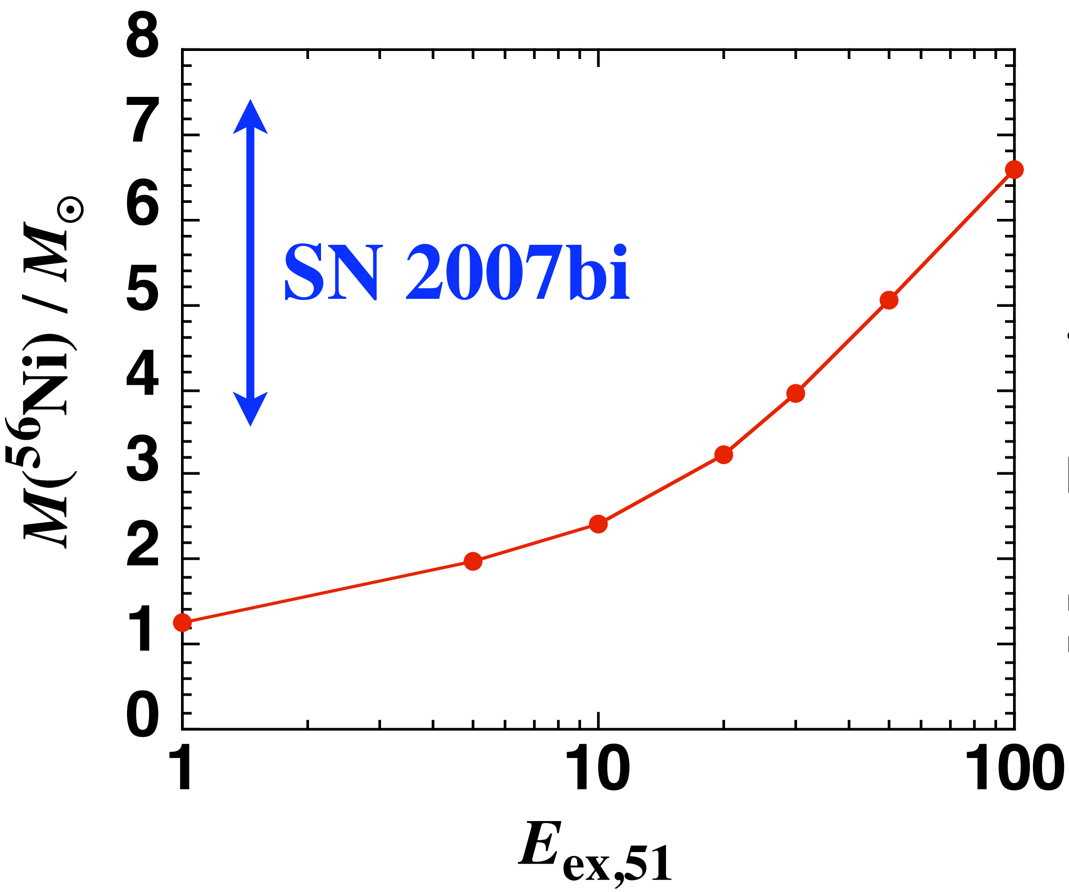
^{56}Ni Production in a SN with $M_{\rm init} = 110 M_\odot$

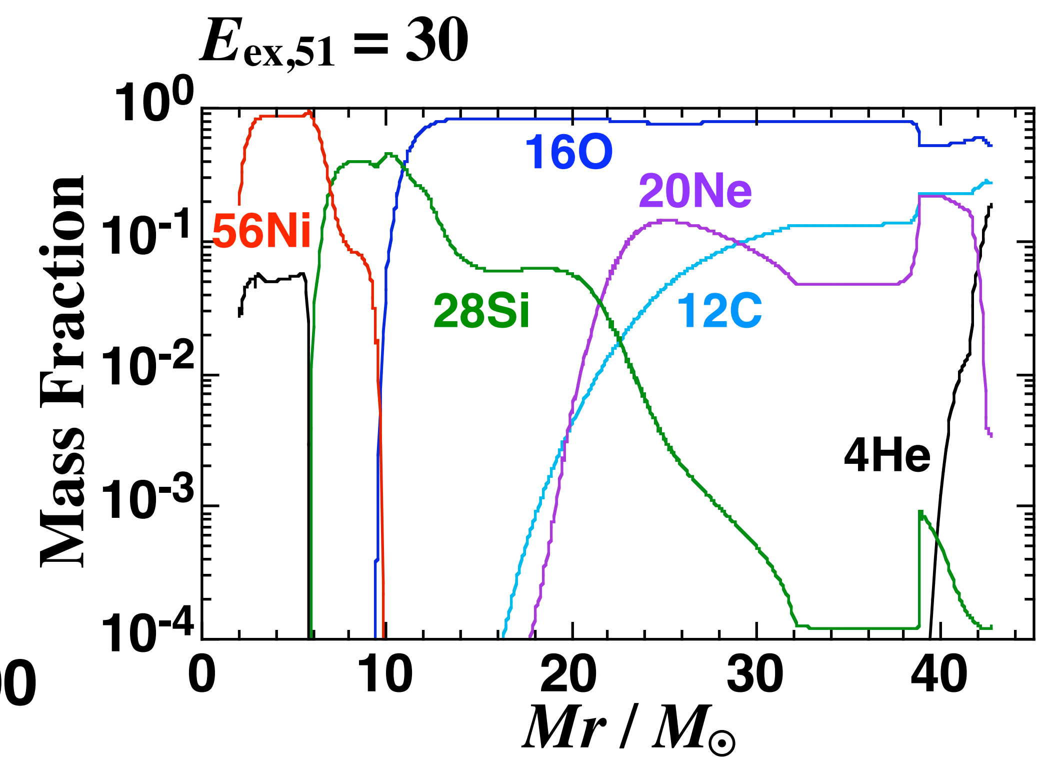
TY, Okita, & Umeda (2012) in prep.

- $M_{\rm init} = 110\ M_\odot$, $Z = 0.004$ star

→ WO star: $M_{\rm f} = 43.2\ M_\odot$, $M_{\rm CO} = 38.2\ M_\odot$

Spherical CC SN Ic





- $E_{\rm ex,51} > 20$ → ^{56}Ni amount appropriate for SN 2007bi

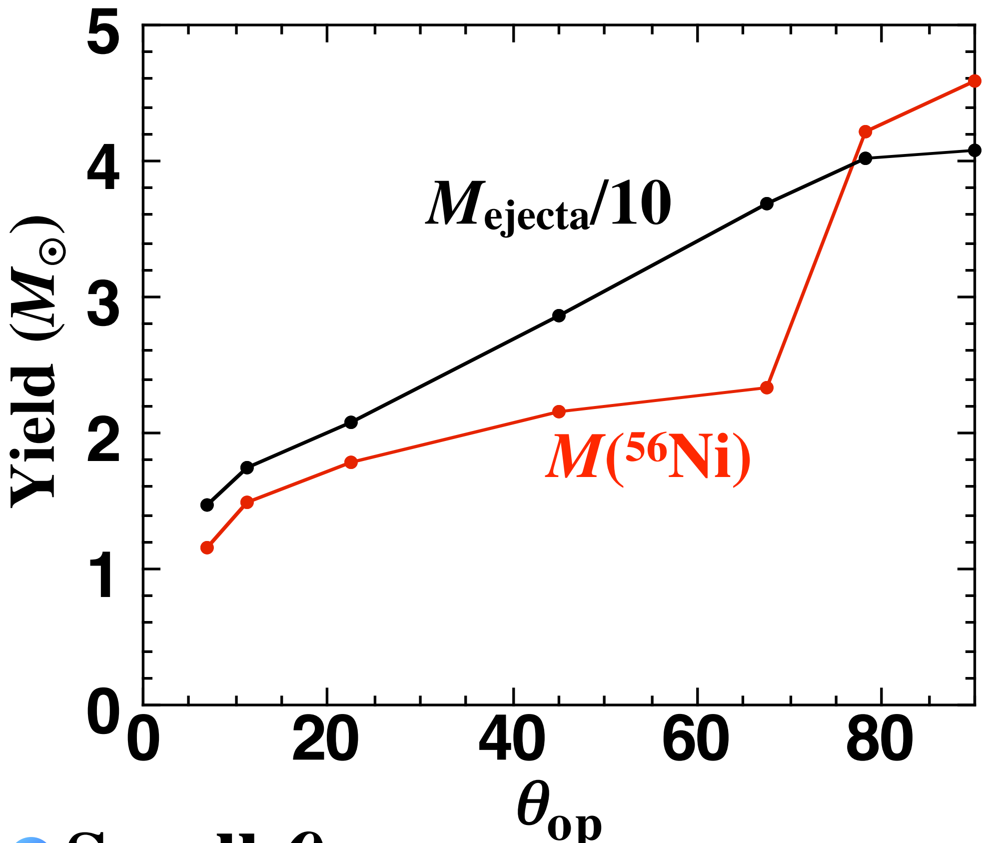
^{56}Ni Production in a SN with $M_{init} = 110 M_\odot$

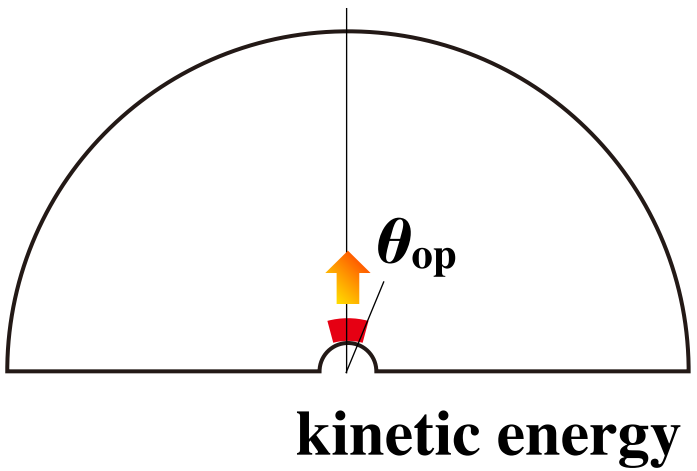
TY, Okita, & Umeda (2012) in prep.

- $M_{init} = 110\ M_\odot$, $Z = 0.004$ star

  ➡ WO star: $M_f = 43.2\ M_\odot$, $M_{CO} = 38.2\ M_\odot$

  Axisymmetrical CC SN Ic, $E_{ex,51} = 30$





- Small θ_{op}

  ➡ Small amounts of ^{56}Ni and total ejecta

Conclusions

Updating massive star evolution code

- **Mass dependence ($Z = 0.02$)**

  $M_{init} < 40\ M_\odot$ → Red giants

  $M_{init} > 40\ M_\odot$ → Wolf-Rayet stars: $M_f \sim 10\ M_\odot$

  Effect of mass loss → Smaller than models in other groups

  Iron core → Mass dependence is complicated

- **Metallicity dependence**

  Evolution to Wolf-Rayet stars → $Z \geqq 0.001$

  $M_{init} > 40$ - $100\ M_\odot$, $Z > 0.001$ stars

  → Possibility of super-luminous SNe Ic

- **Supernova evolved from $M_{init} = 110\ M_\odot$, $Z = 0.004$ star**

  Spherical SN Ic with $E_{ex,51} > 20$

  → ^{56}Ni amount appropriate for SN 2007bi

  Axisymmetrical SN Ic → Smaller amount of total ejecta and ^{56}Ni