重力崩壊型超新星の下限質量と ONeMg超新星

(Low mass core-collapse SNe & ONeMg SNe)

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素核宇融合による計算基礎物理学の進展

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Introduction

- **Supernovae from Massive Stars**
  - **Pair Instability SNe (M ~ 140-300$M_\odot$**
  - **Iron core collapse (M > ~ 10$M_\odot$**
  - **ONeMg SNe ~ 8-10$M_\odot$?**

Iron core collapse ($M > \sim 10 M_\odot$

- **What is the lowest mass for Iron CCSN?**
- **Is the lowest mass progenitor something special?**
  - **Iron core mass is minimum? So What?**

ONeMg SNe ~ 8-10$M_\odot$?

- 1D Explosion succeeded !(Electron capture SN)
  - Chandrasekhar critical Mass = 1.47 $(Y_e/0.5)^2 M_\odot$
- But, , ,
  - Only one (relatively old) progenitor model
    - なぜなら、計算が大変（super-AGB star; thermal pulses）
  - Mass range seems very narrow
    - maybe no range (?
      - ちょっと重いとNeが燃え、ちょっと軽いと ONeMgコアが 1.47 $(Y_e/0.5)^2 M_\odot$ に成長する前に（super-AGB星として）外層を失って白色矮星のまま終わる。

Poelarends et al. 2008 ApJ 675, 614

3 codes : no ECSN for E-code

Model	M_i	pre-2DU	post-2DU	comments	fate
S5.0	5.0	0.91	0.84	14 TP	CO WD
S8.5	8.5	1.73	1.02	10 TP	CO WD
S9	9	1.90	1.07	30 TP	ONe WD
S9.5	9.5	2.00	1.11		ONe WD
S10	10	2.14	1.16	55 TP	ONe WD
S10.5	10.5	2.30	1.20		ONe WD
S11	11	2.45	1.23		ONe WD
S11.5	11.5	2.61	1.27	15 TP	ONe WD
S12	12	2.79	1.32	dredge-out	ECSN
S12.5	12.5	2.95	2.95	dredge-out	CCSN
S13.0	13	3.13	3.13	Ne ignition	CCSN
S16.0	16	4.33	4.33	Ne ignition	CCSN
E10.5	10.5	3.00	3.00	Ne ignition	CCSN
E0099	9.0	2.15	1.17	$f_{over} = 0.004$	
K8	8.0	1.808	1.168		ONe WD
K8.5	8.5	1.955	1.247		ONe WD
K9	9.0	2.130	1.338		ONe WD
K9.1	9.1	2.161	1.357		ECSN
K9.2	9.2	2.190	1.548	Ne ignition	CCSN
K9.3	9.3	2.221	1.603	Ne ignition	CCSN
K9.4	9.4	2.253	1.690	Ne ignition	CCSN
K9.5	9.5	2.283	1.799	Ne ignition	CCSN
K10	10.0	2.439	2.315	Ne ignition	CCSN
K10.5	10.5	2.598	2.596	Ne ignition	CCSN
K11	11.0	2.759	2.759	Ne ignition	CCSN

8-10M$_\odot$ ≠ ONeMg SNe

Massive Star Evolution
$M_{ini} \geqq 10 M_{\odot}$

Yoshida & Umeda 2012

Massive Star Evolution Code (Yoshida & Umeda 2010~

- Stellar evolution model

→ Based on Saio code (e.g., Saio, Nomoto, and Kato 1988)

From H burning to 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)

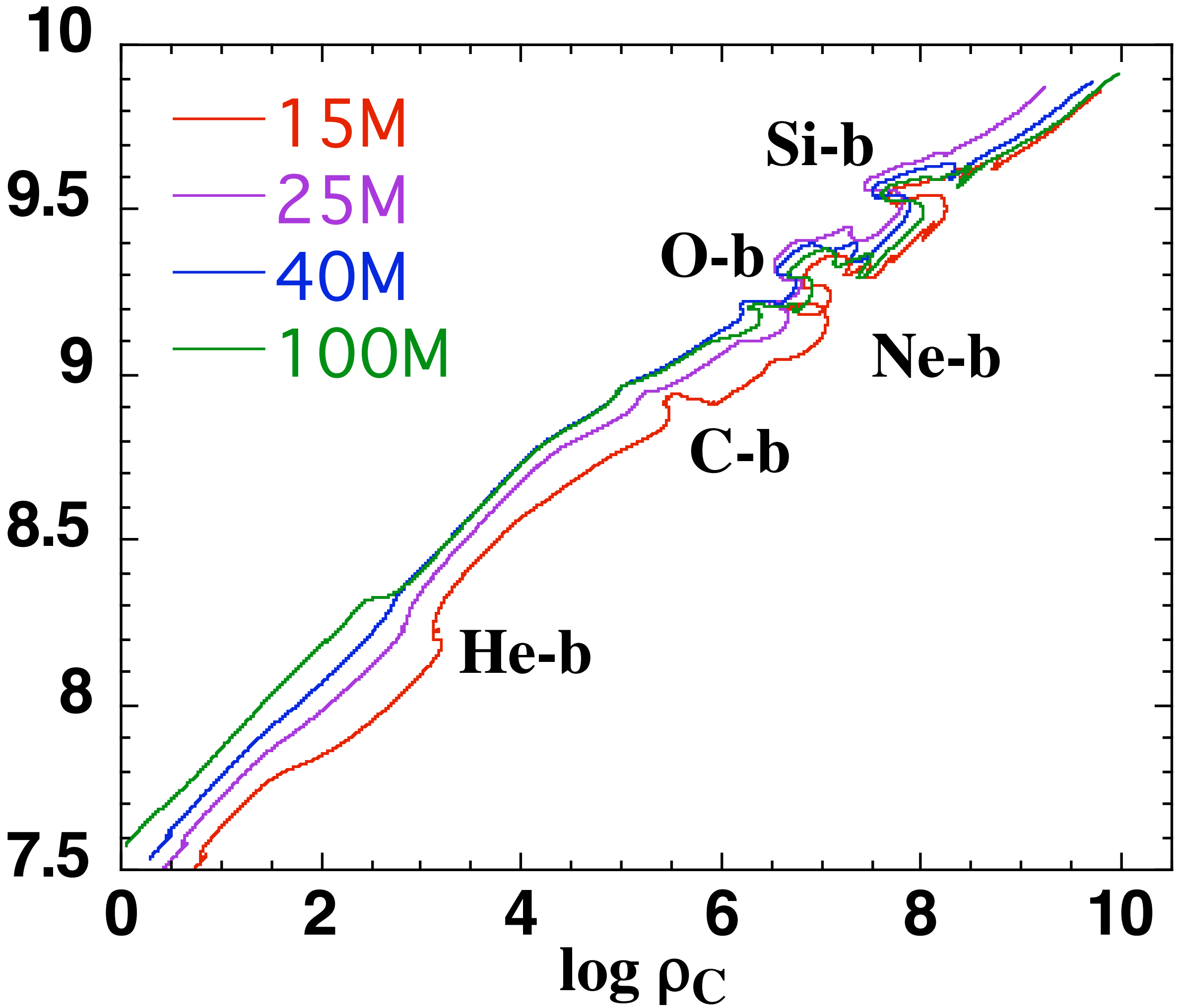
- Convection criterion

→ Schwarzschild criterion

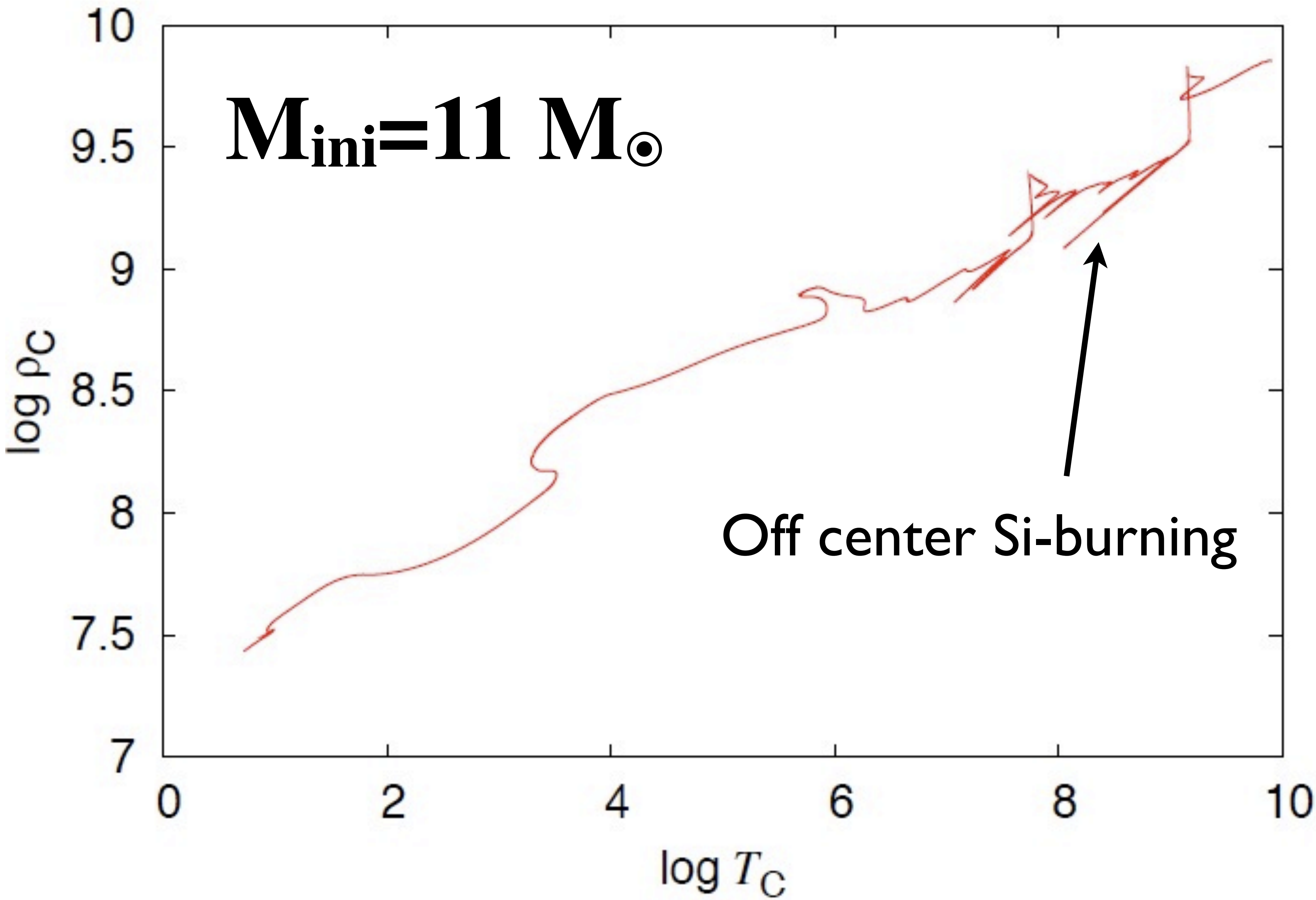
- Dynamical evolution is included (hopefully?).

log ρ_C-log T_C Diagram

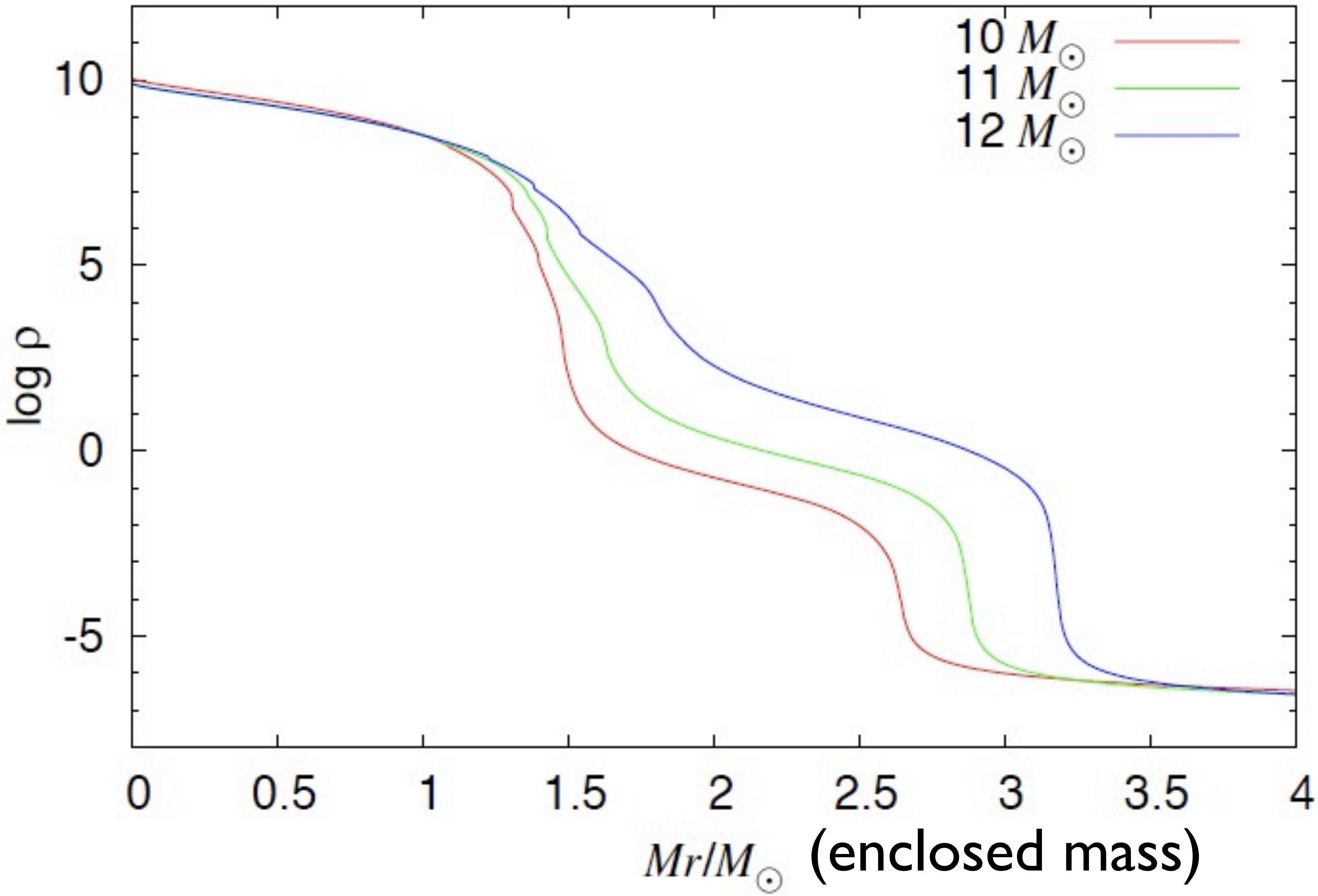
- Z=0.02 stars



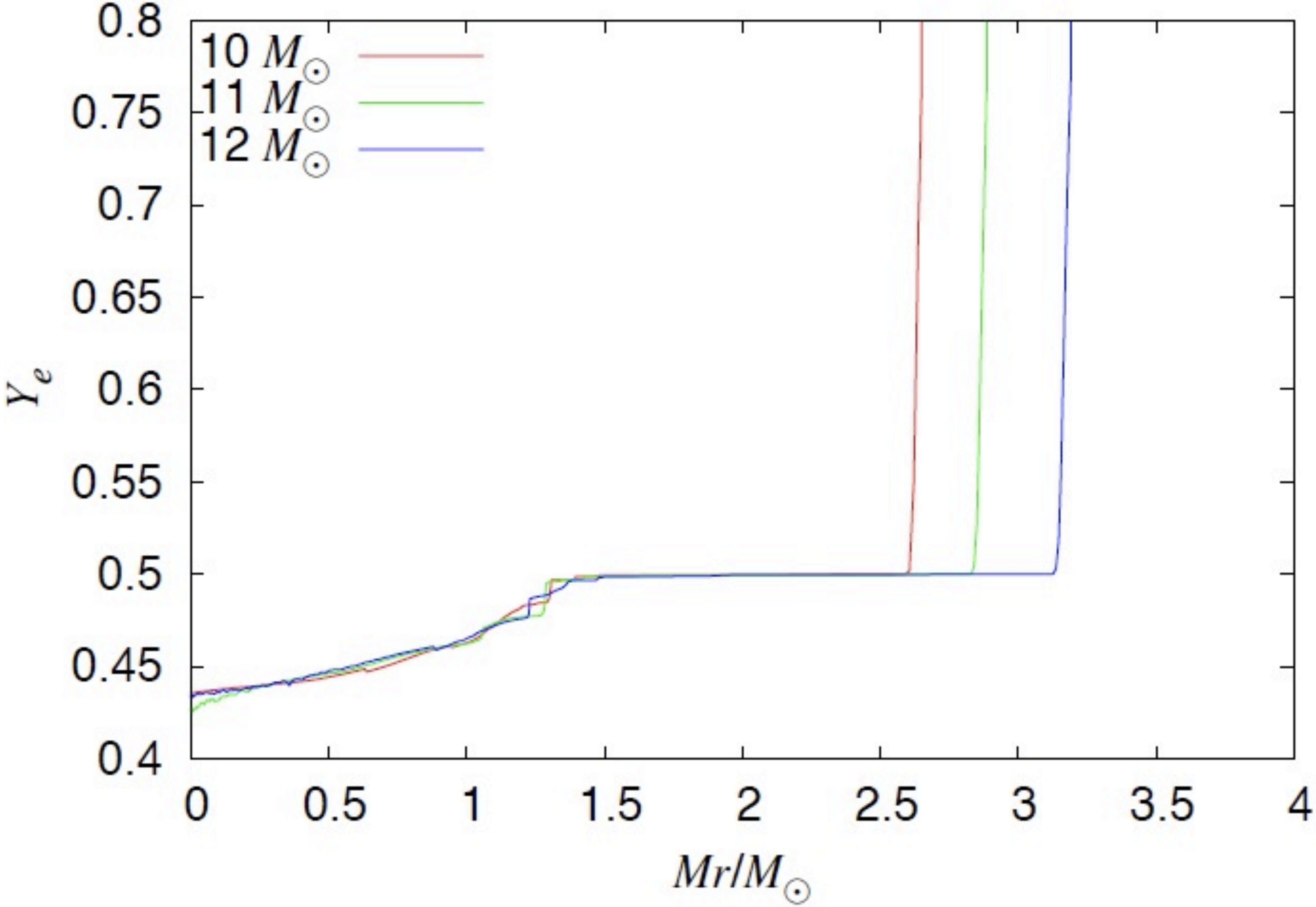
$$\mathbf{M_{ini}=10,\ 11,\ 12\ M_{\odot}}$$



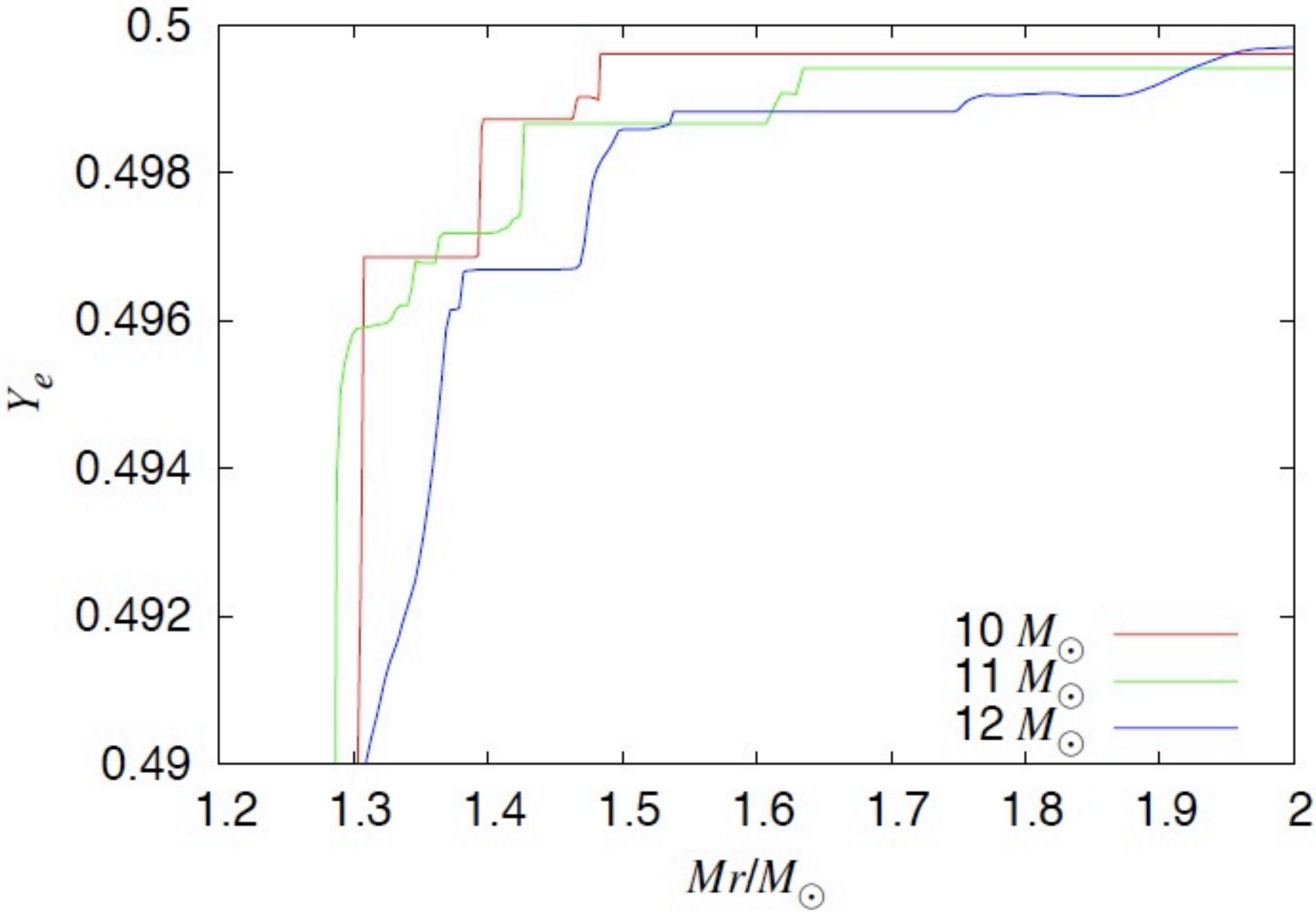
Mini=11 M⊙
Off center Si-burning
log ρC
log TC
10
9.5
9
8.5
8
7.5
7
0
2
4
6
8
10


10 $M_\odot$
11 $M_\odot$
12 $M_\odot$
log ρ
10
5
0
-5
0
0.5
1
1.5
2
2.5
3
3.5
4
$Mr/M_\odot$ (enclosed mass)

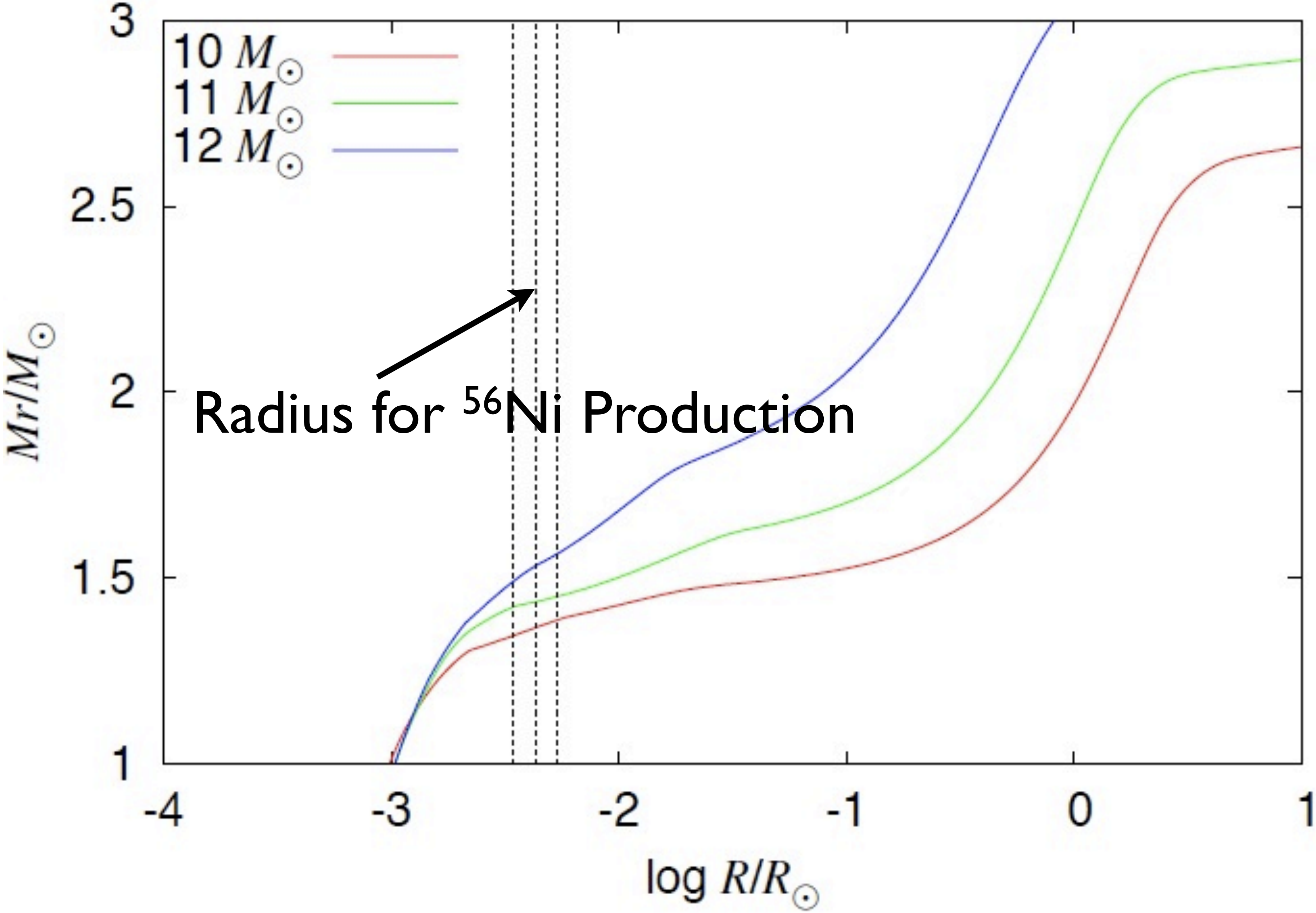
He-core Mass (単調増加）



definition of Fe-core --- ambiguous



$E_{exp}=4 R^3 a T^4/4$ with $T=5\times10^9$K



M_r for ^{56}Ni production

For $E_{exp} = E_{51} \times 10^{51}$ erg

===== 10 M ==== 11 M ==== 12 M ===

E51 = 0.5; 1.344, 1.421, 1.488

E51 = 1.0; 1.365, 1.436, 1.532

E51 = 2.0; 1.388, 1.450, 1.566

Mass cut (Neutron star mass for M(^{56}Ni)=0.07)

===== 10 M ==== 11 M ==== 12 M ===

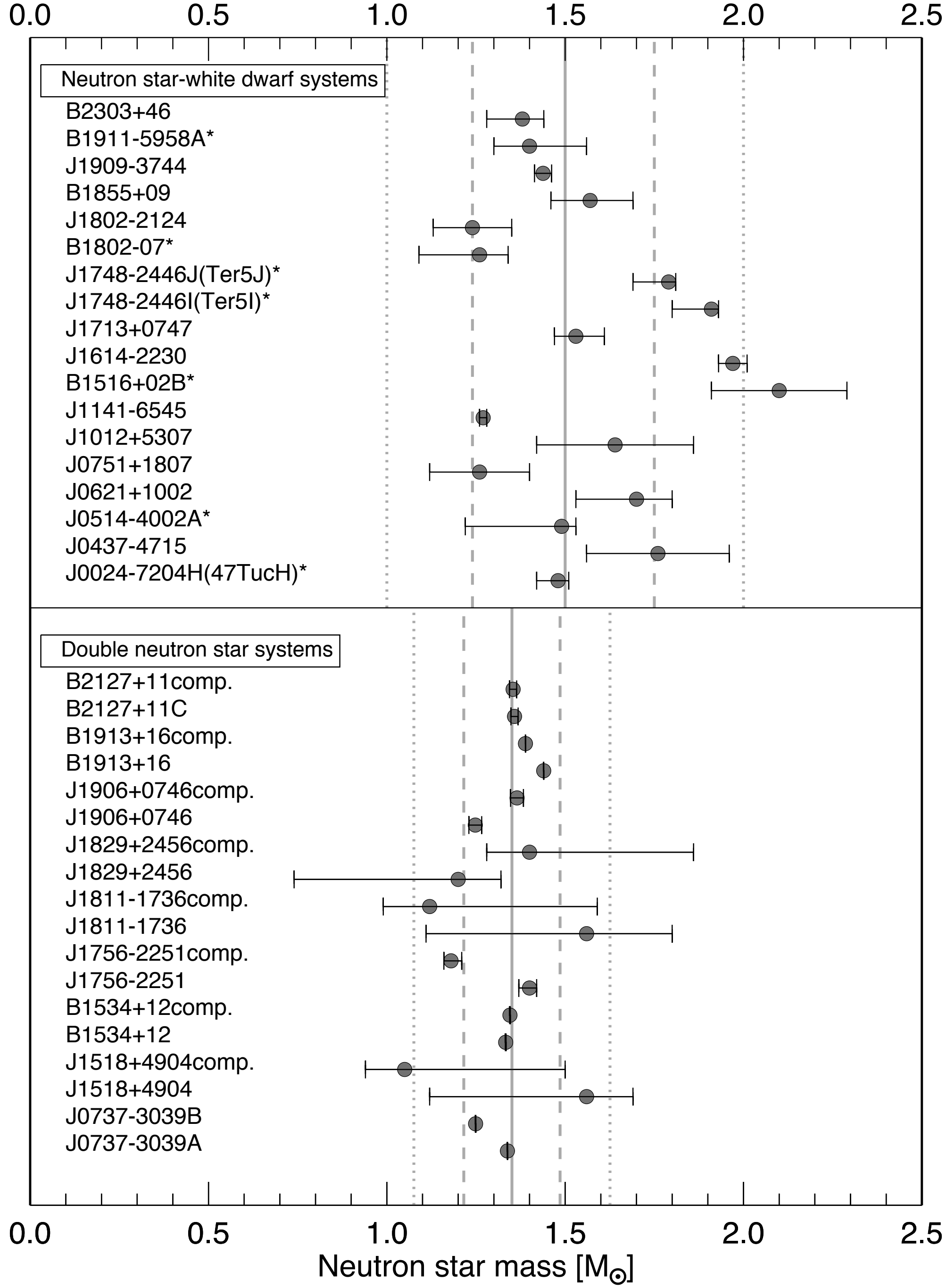
E51 = 0.5; 1.274, 1.351, 1.418

E51 = 1.0; 1.295, 1.366, 1.462

E51 = 2.0; 1.318, 1.380, 1.496

Neutron star mass observation (arXiv:1011.4291)

Minimum
~ 1.2$M_\odot$

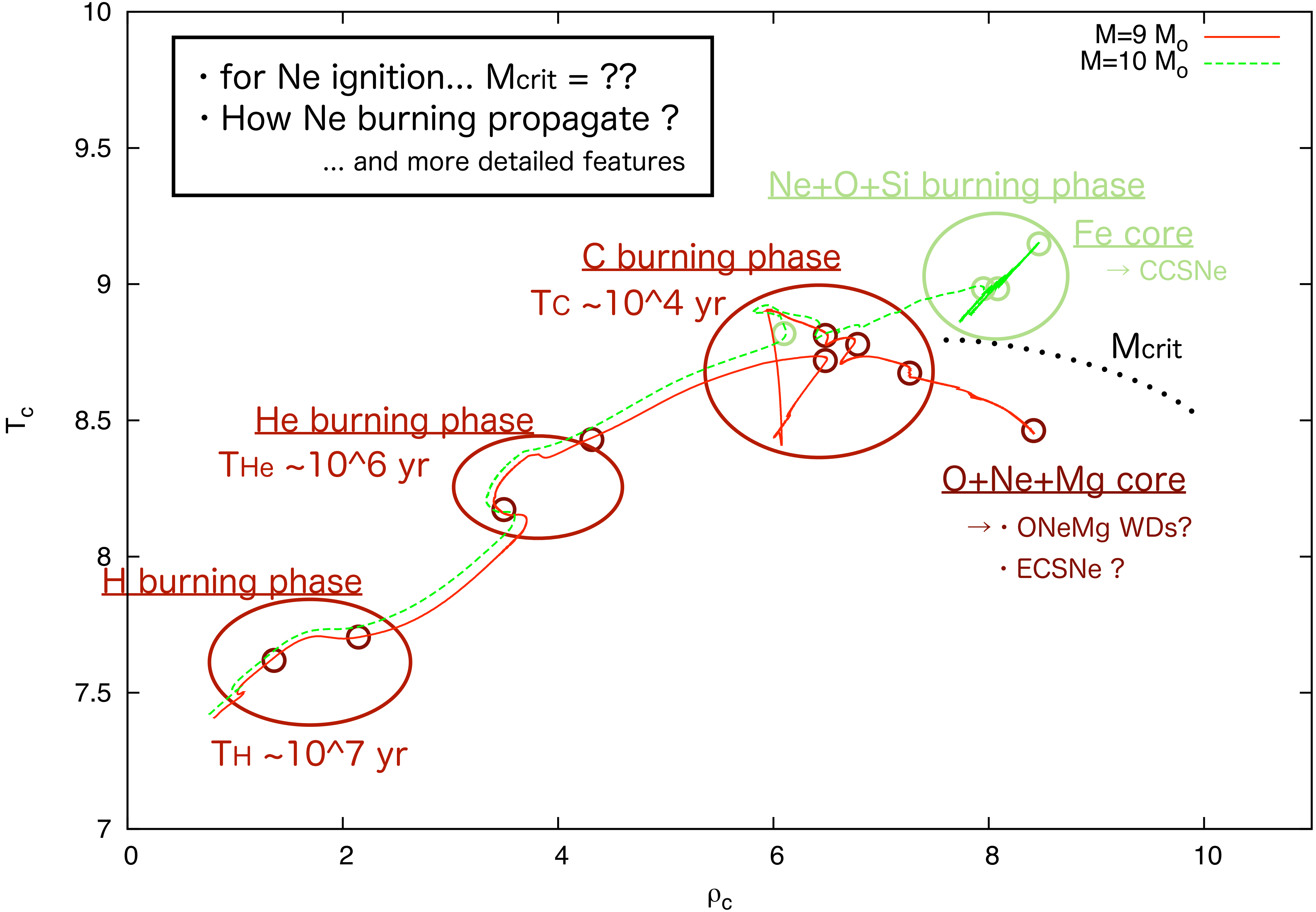


$M_{ini} < 10M_{\odot}$

ONeMg core formation

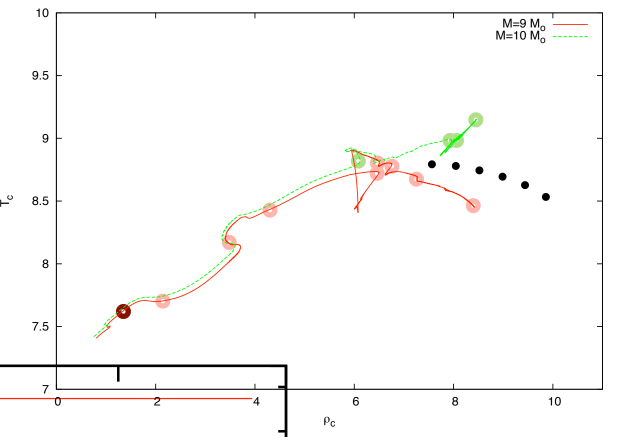
Takahashi, Umeda & Yoshida

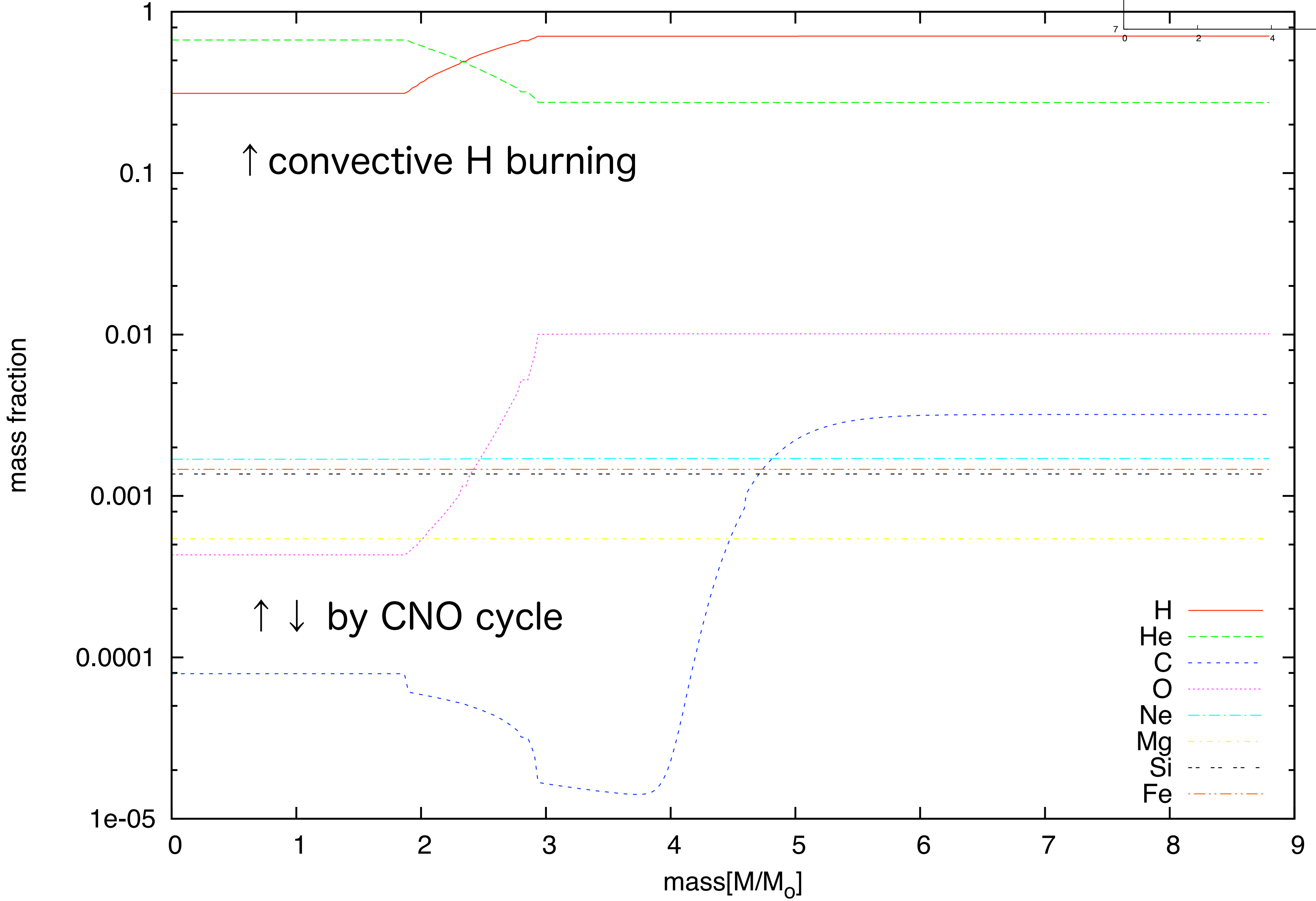
Core evolutions



Core evolutions for 9Mo

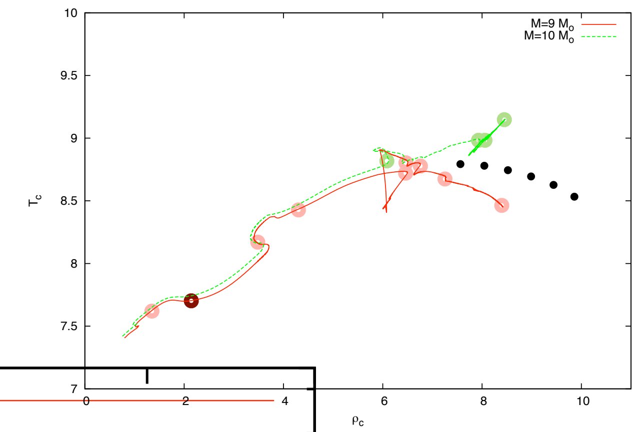
1. core H burning





Core evolutions for 9Mo

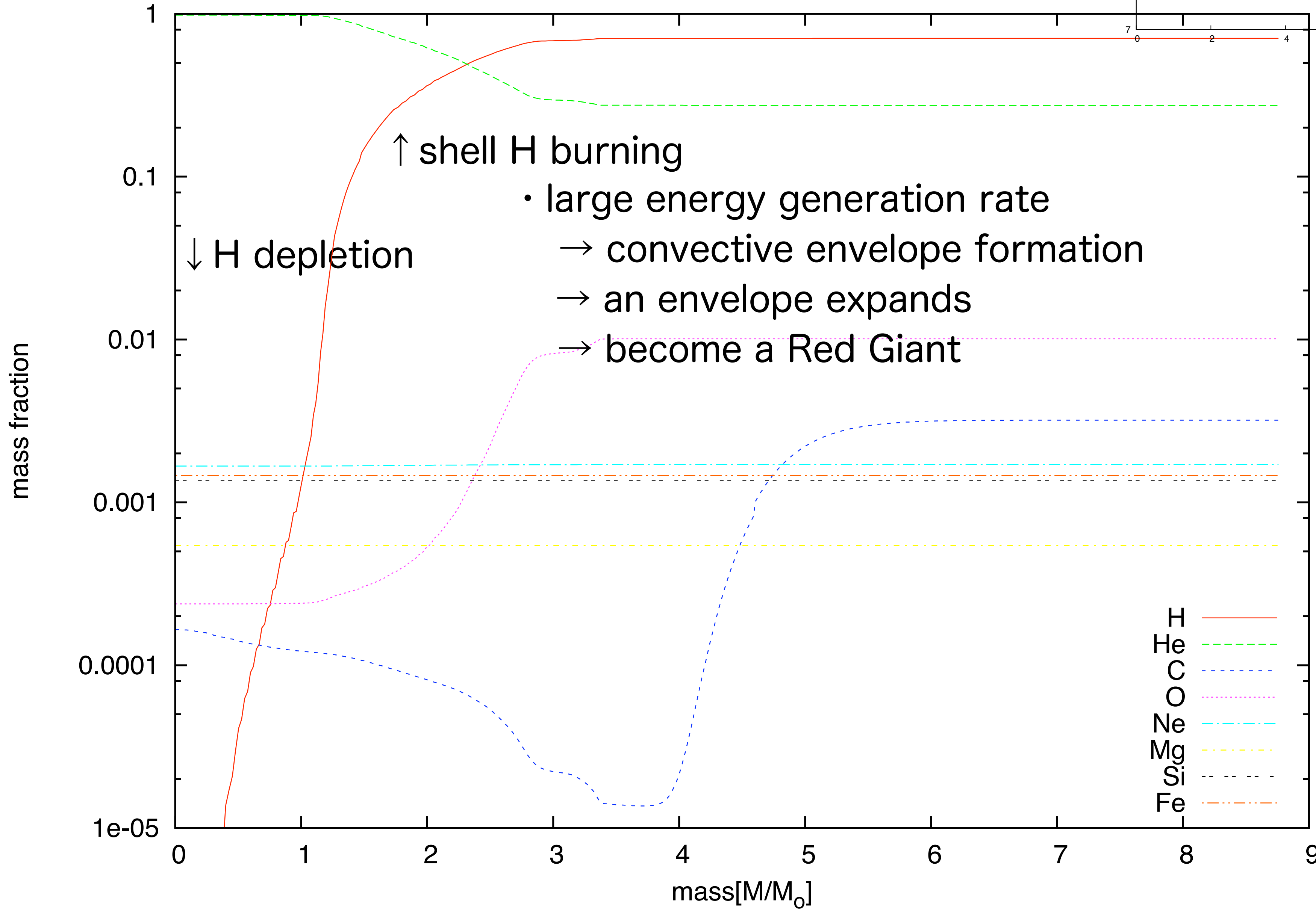
2. shell H burning



↑ shell H burning

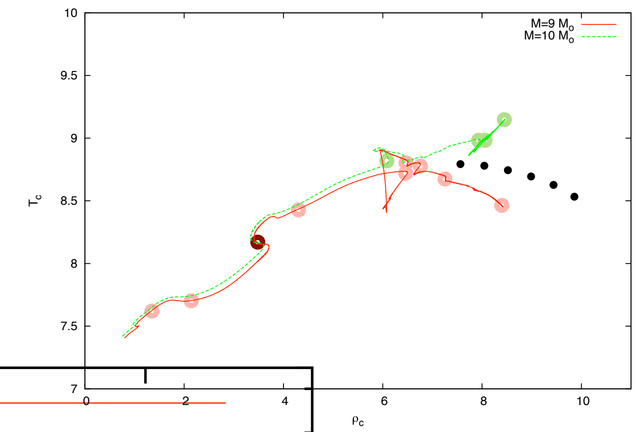
- large energy generation rate
  → convective envelope formation
  → an envelope expands
  → become a Red Giant

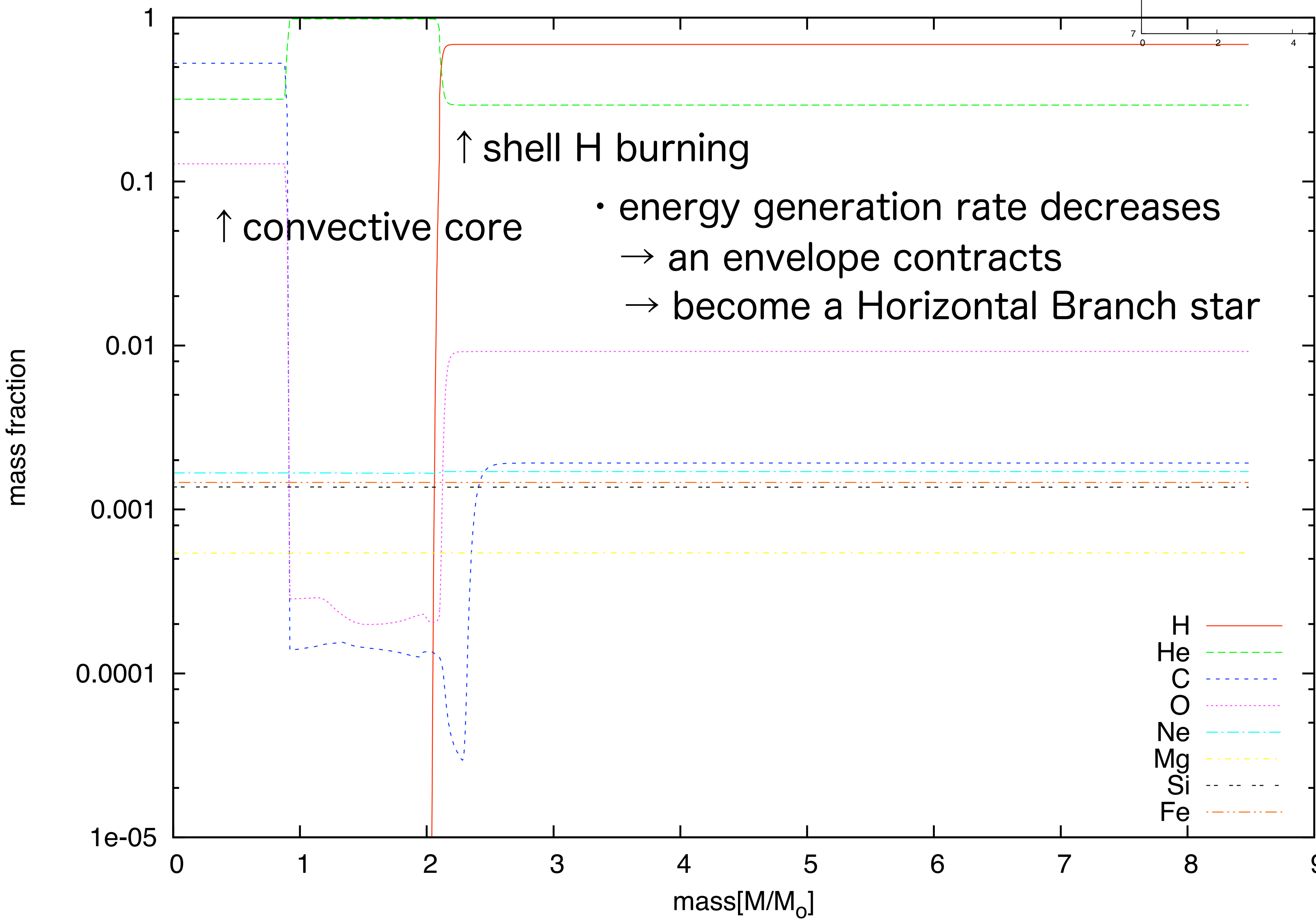
↓ H depletion



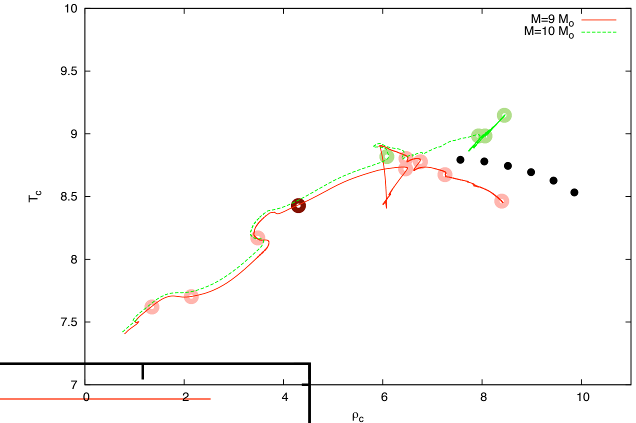
Core evolutions for 9Mo

3. core He burning

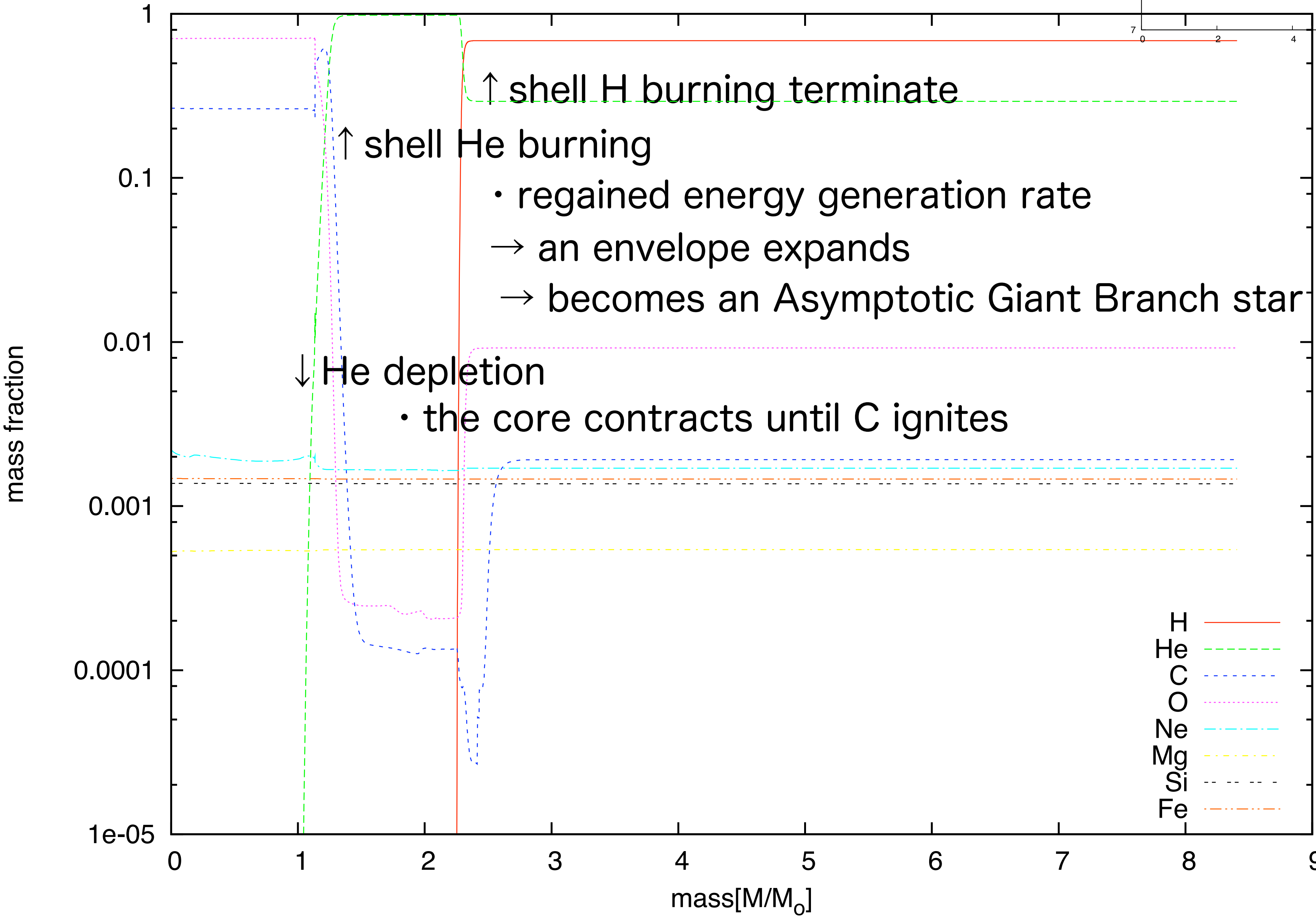




Core evolutions for 9Mo



4. shell He burning



↑ shell H burning terminate

↑ shell He burning

・regained energy generation rate

→ an envelope expands

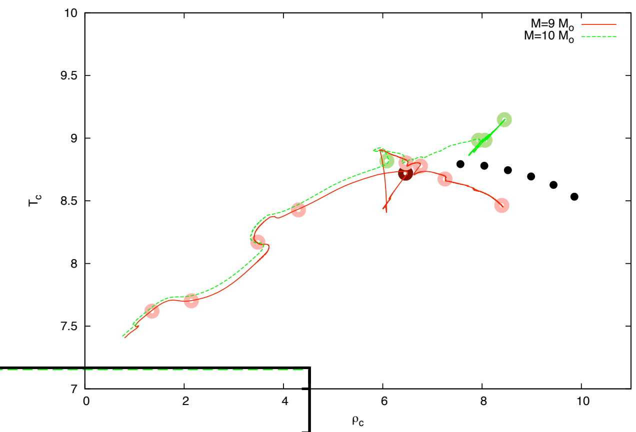
→ becomes an Asymptotic Giant Branch star

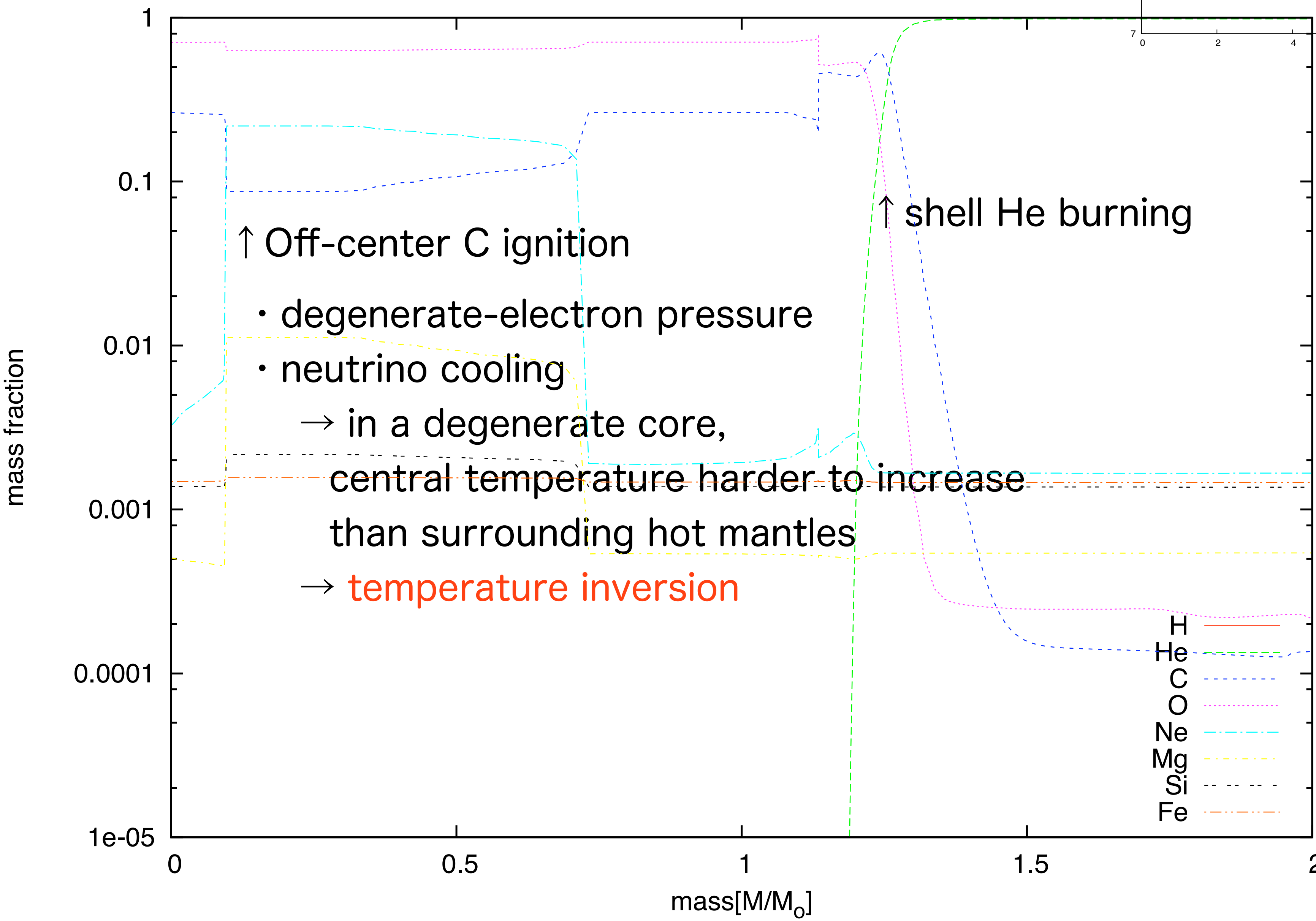
↓ He depletion

・the core contracts until C ignites

Core evolutions for 9Mo

5. Off-center C ign.





↑ shell He burning

↑ Off-center C ignition

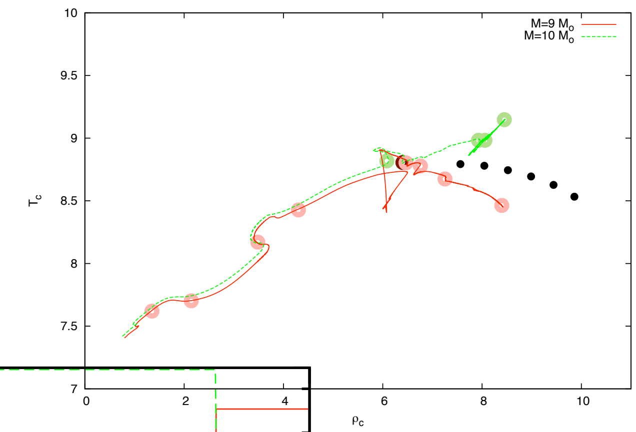
- degenerate-electron pressure
- neutrino cooling

→ in a degenerate core, central temperature harder to increase than surrounding hot mantles

→ temperature inversion

Core evolutions for 9Mo

6. C front propagation

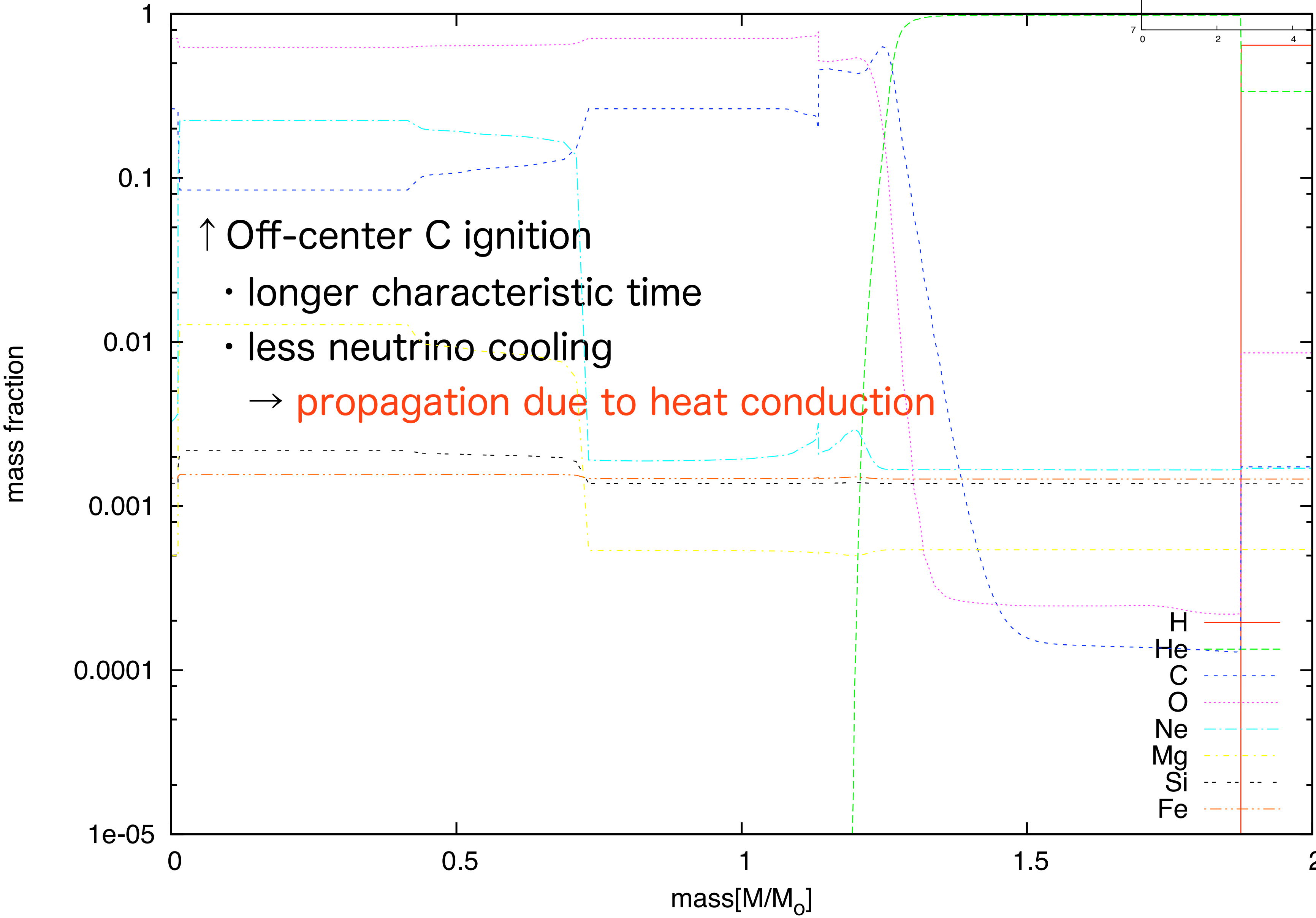


↑ Off-center C ignition

・longer characteristic time

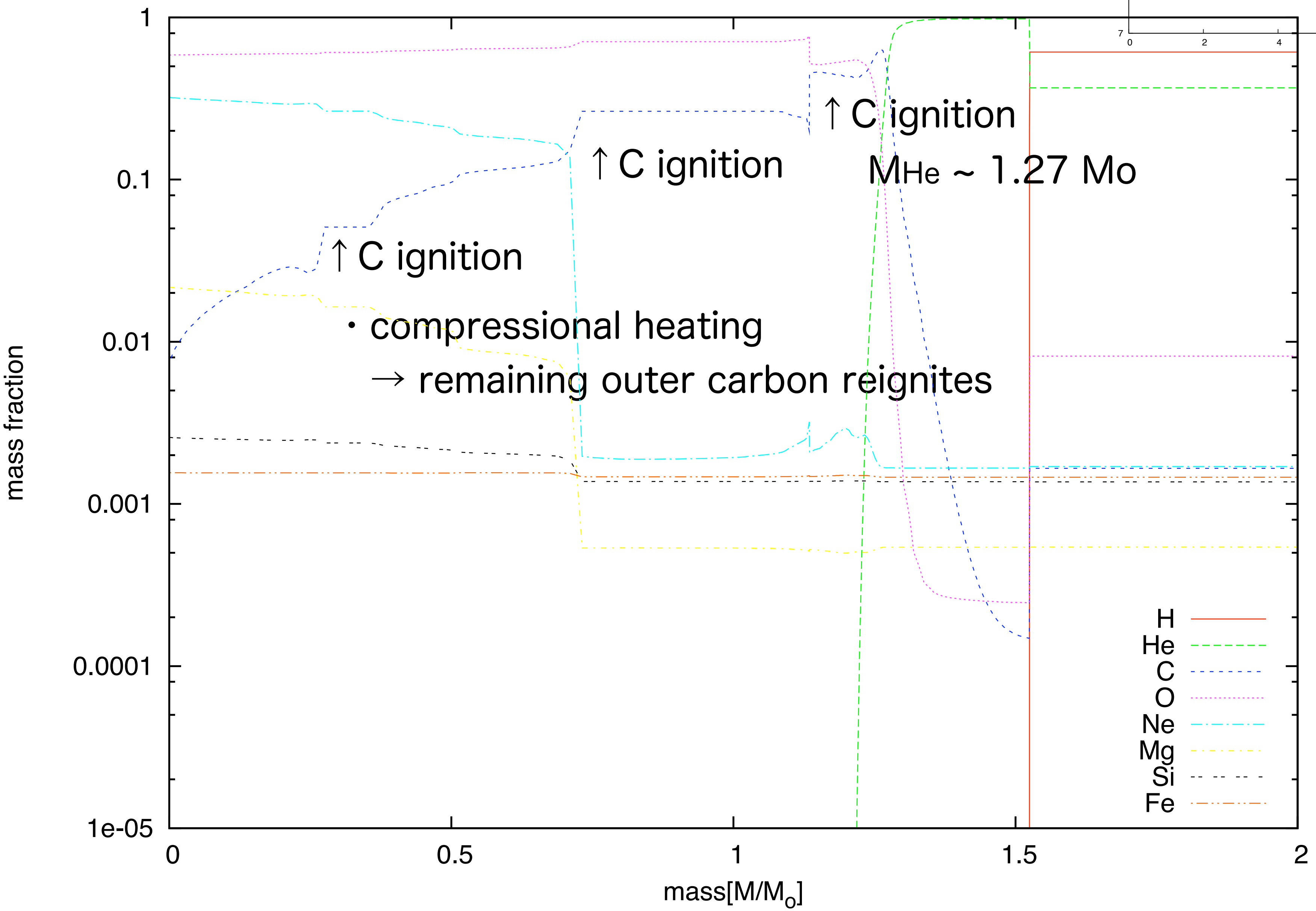
・less neutrino cooling

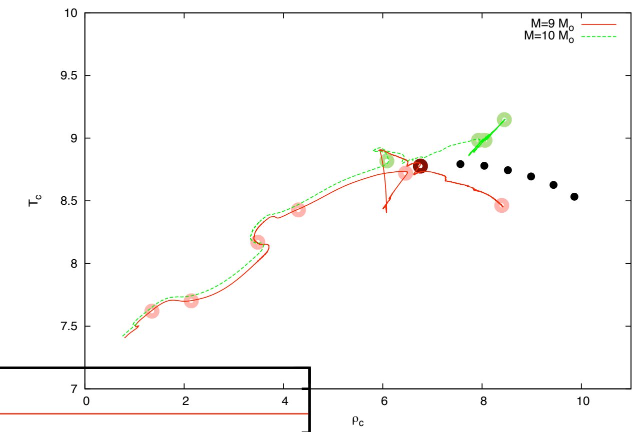
→ propagation due to heat conduction



Core evolutions for 9Mo

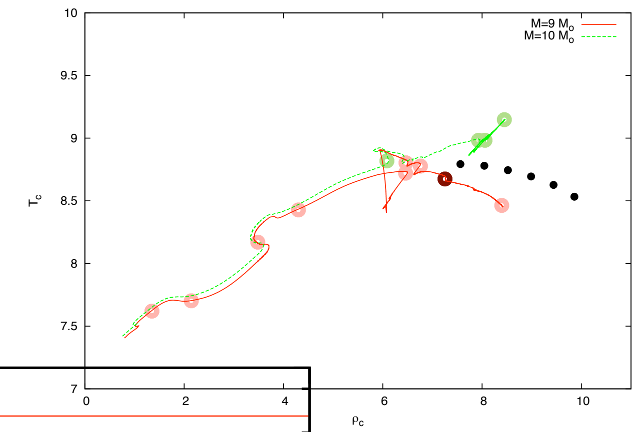
7. Several C burnings

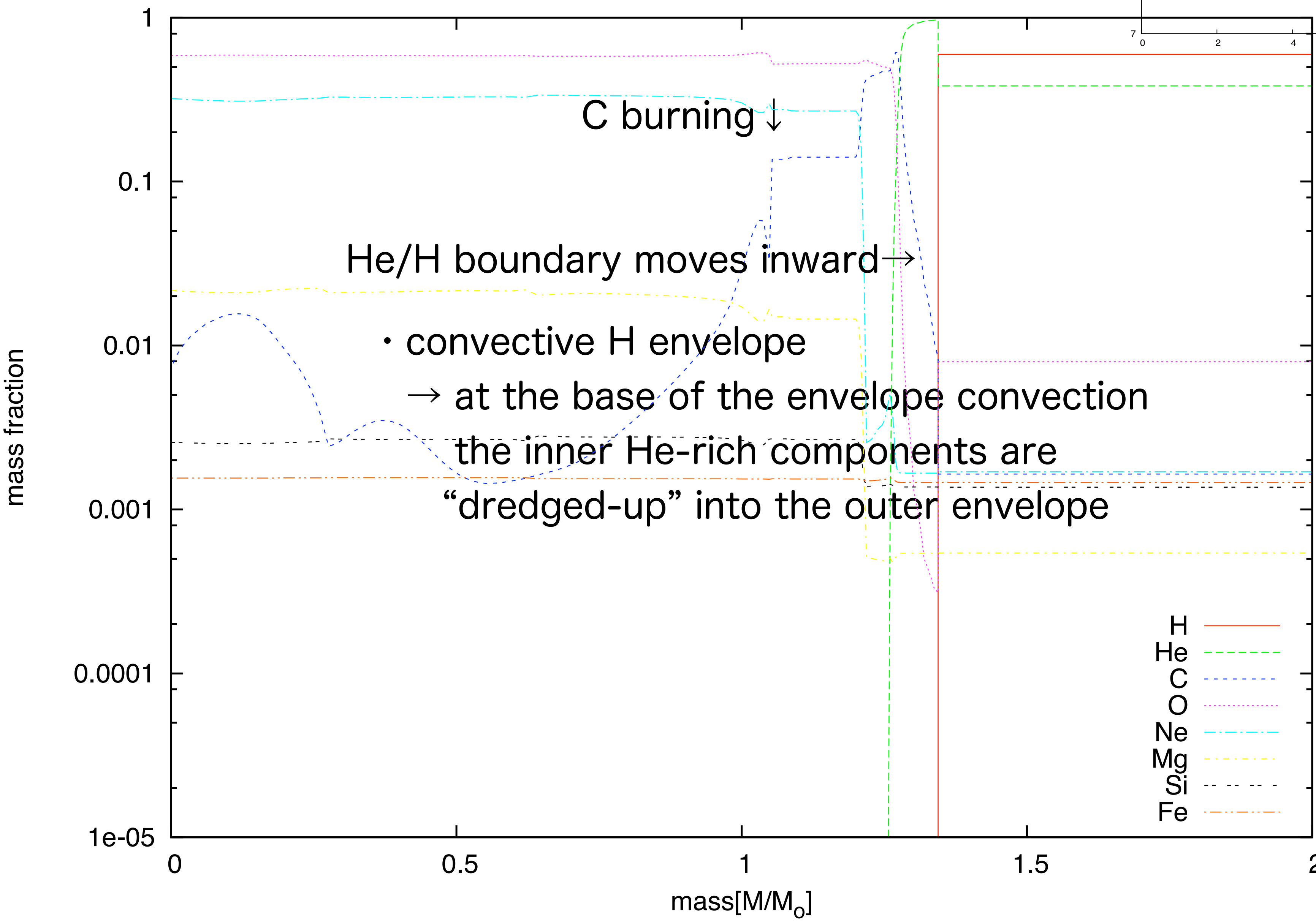




Core evolutions for 9Mo

8. the 2nd Dredge UP





C burning↓

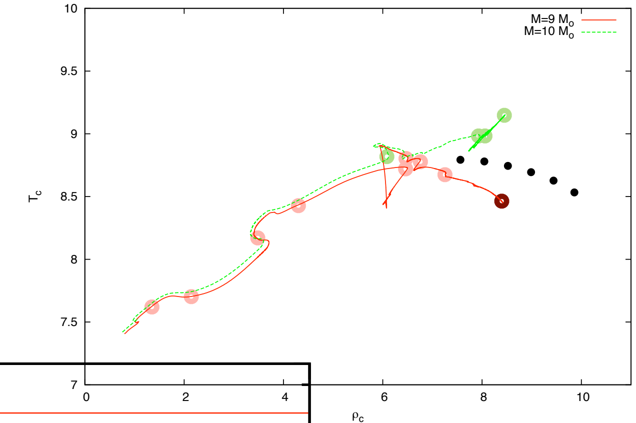
He/H boundary moves inward→

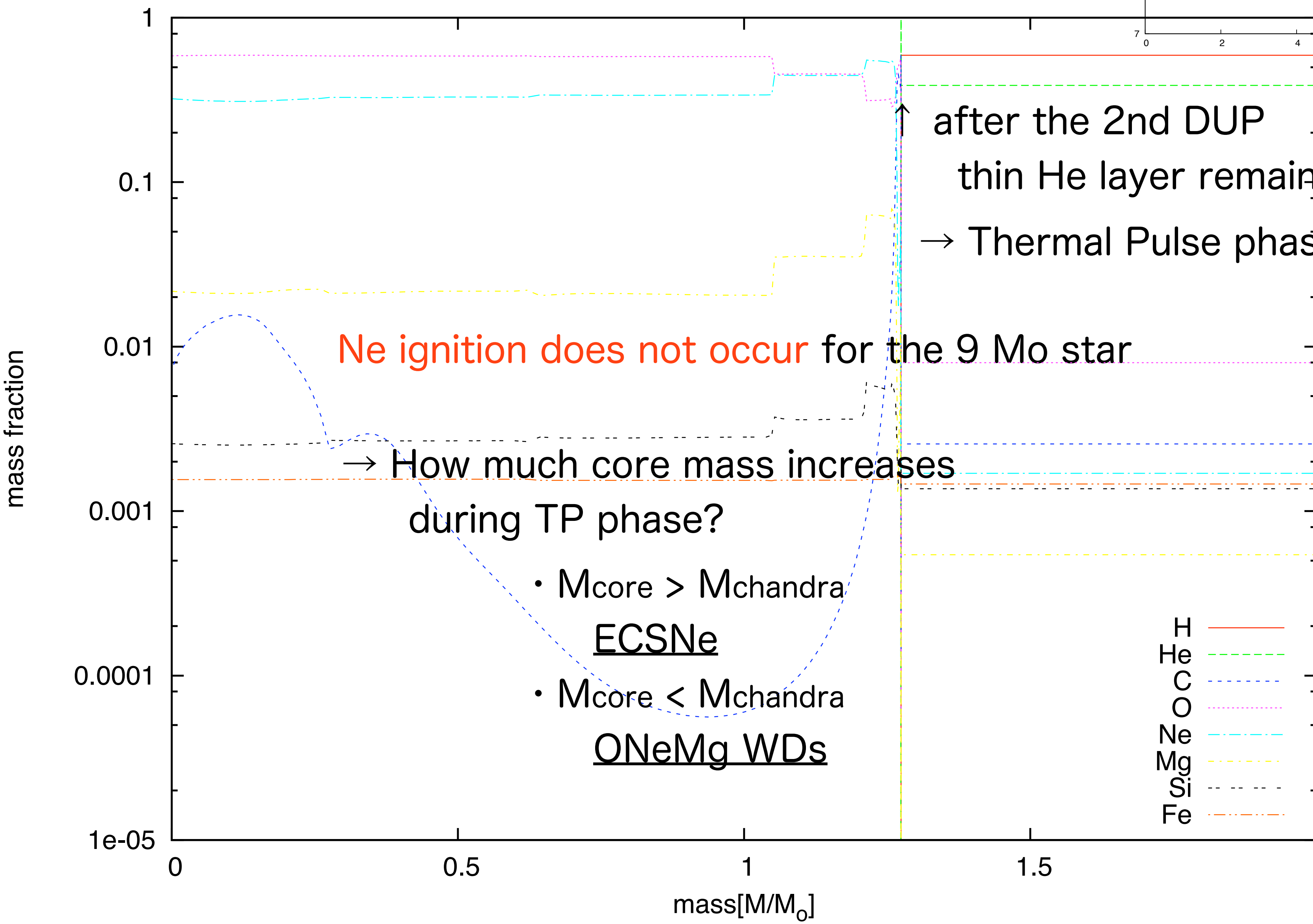
- convective H envelope

  → at the base of the envelope convection the inner He-rich components are “dredged-up” into the outer envelope

Core evolutions for 9Mo

9. O+Ne+Mg core





↑ after the 2nd DUP

thin He layer remains

→ Thermal Pulse phase

Ne ignition does not occur for the 9 Mo star

→ How much core mass increases during TP phase?

- Mcore > Mchandra
  <u>ECSNe</u>
- Mcore < Mchandra
  <u>ONeMg WDs</u>

Core mass @2nd dredge up