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s-process in AGB and super-AGB stars

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- Super-AGB stars
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  - s-process by dredge-out
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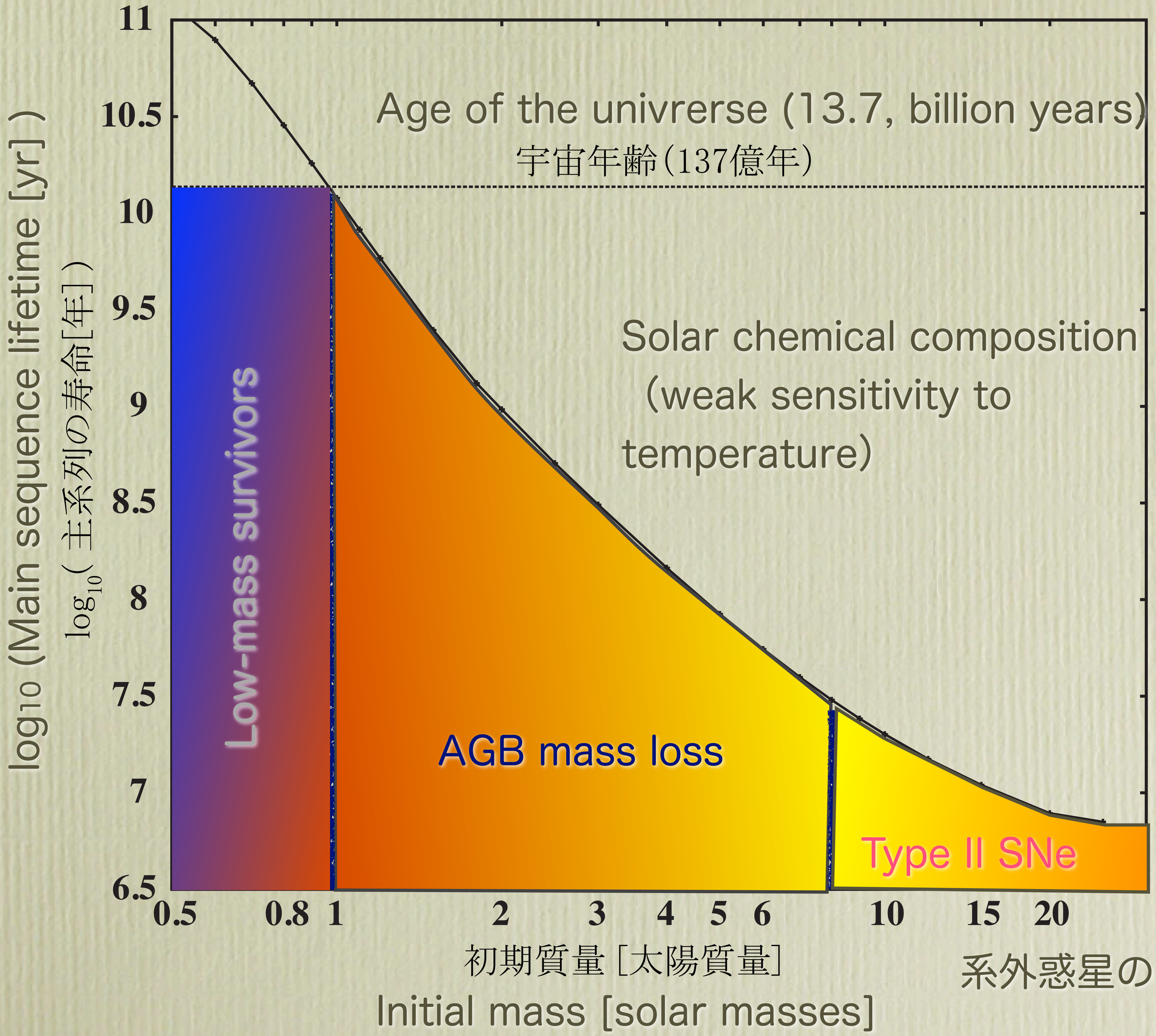
Stellar Evolution and AGB stars

Current situations of stellar evolution

- Standard stellar evolution theory is almost established in one-dimensional framework.
    - Main concern is the application of the mixing length theory (MLT), which is thought to be a crude approximation.
- Simulations with large nuclear reaction network are possible with developing computational capacity.
- 3D hydrodynamical models have been developed in the last decade, mainly focus on convective mixing.
    - Simulations in very short time scale, which cannot be stellar evolution.
- Numerical results are available by MESA code.
    - Updated periodically (Paxton+11,13,15,18).
- Seismology is expected to constrain stellar structure.
    - Kepler to TESS.

Mass - Lifetime relation



系外惑星の事典

Final fate of AGB / SAGB stars

- The key parameters to determine the final fate of intermediate-mass stars are as follows, although they are affected by the uncertainties associated with the input physics.

M_{up}: the minimum initial mass required to ignite carbon.

~7 $M_\odot$ with small metallicity dependence

M_n: the minimum initial mass that forms a neutron star resulting from an electron-capture supernovae.

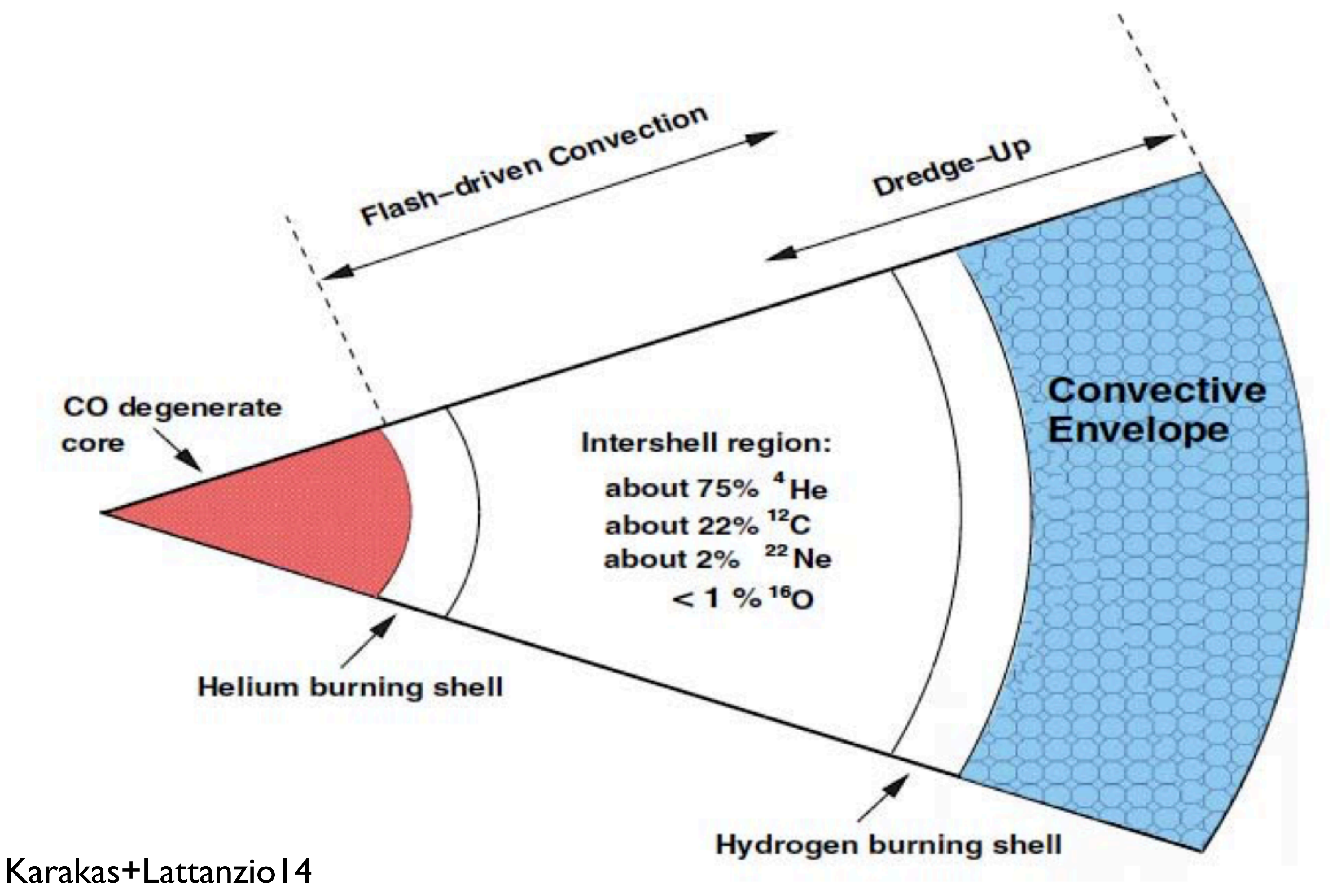
~9 $M_\odot$ with small metallicity dependence

M_{mas}: the minimum initial mass that forms an iron core-collapse supernovae.

~9.5 $M_\odot$ with small metallicity dependence

Gil-Pons+18

Structure of AGB stars

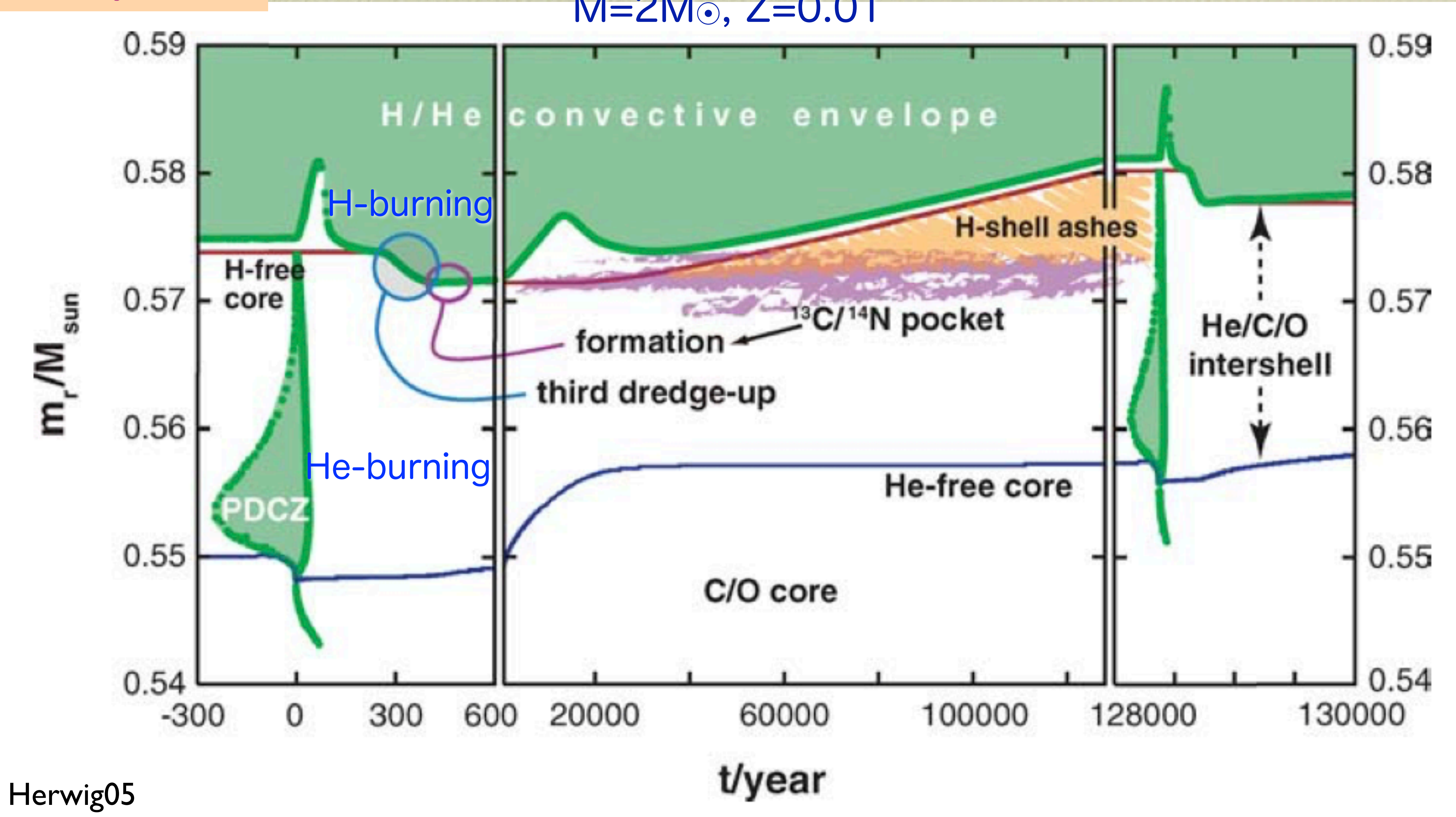


Karakas+Lattanzio14

Standard picture of AGB evolution - 3rd dredge-up and ^{13}C pocket

$$M_r = \int_0^r 4\pi r^2 \rho dr$$

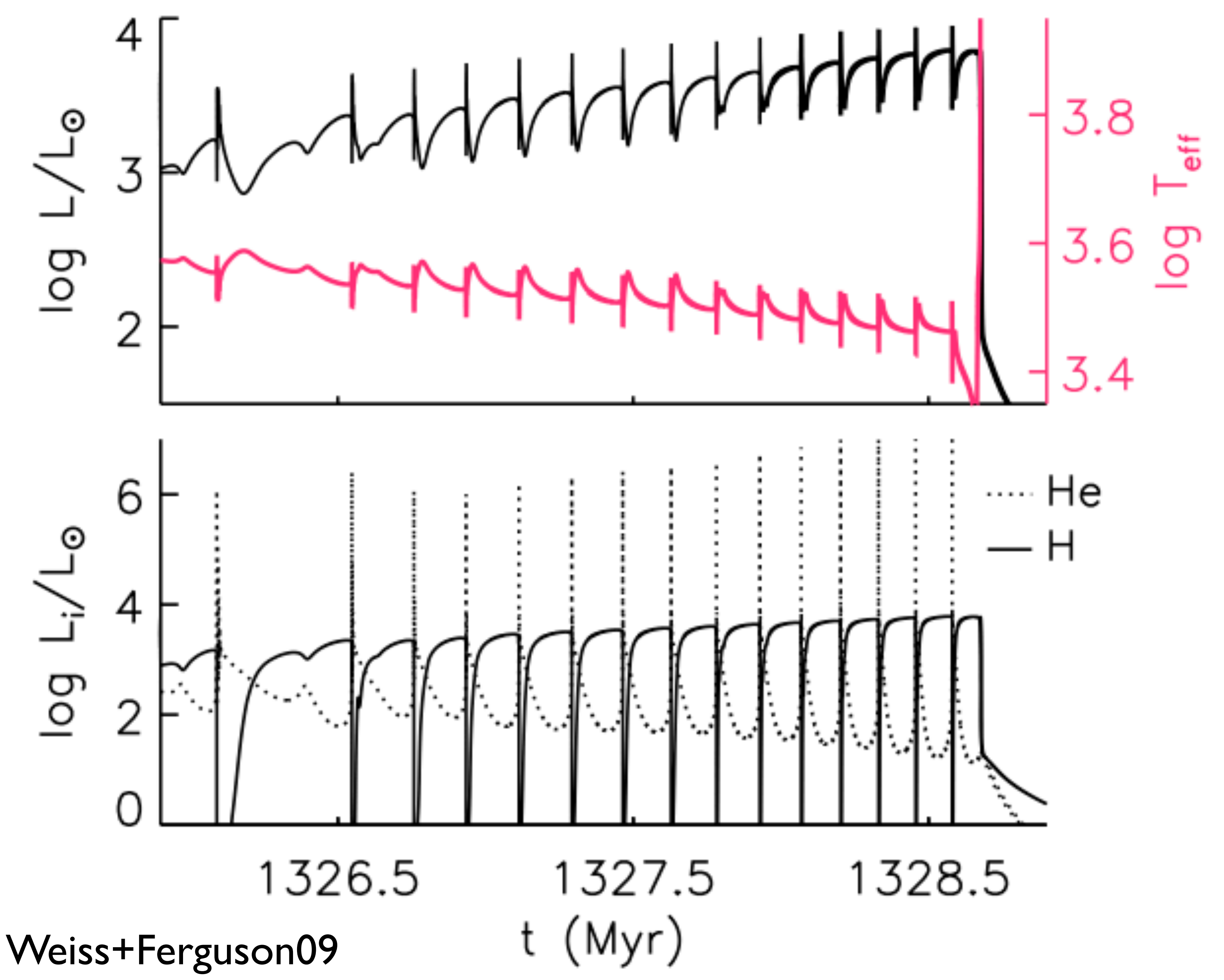
M=2M⊙, Z=0.01



Herwig05

Thermally Pulsating AGB (TPAGB) stars

M=2M⊙, Z=0.02



Weiss+Ferguson09

Keywords for the evolution of (S)AGB stars

Dredge-up

Mixing of nuclear burning products by the convective envelope. “1st”, “2nd”, and “3rd dredge-up” are defined.

Hot Bottom Burning

Nuclear burning (CNO cycles) at the bottom of the convective envelope. Carbon rich stars turn to carbon-normal stars.

Mass Loss

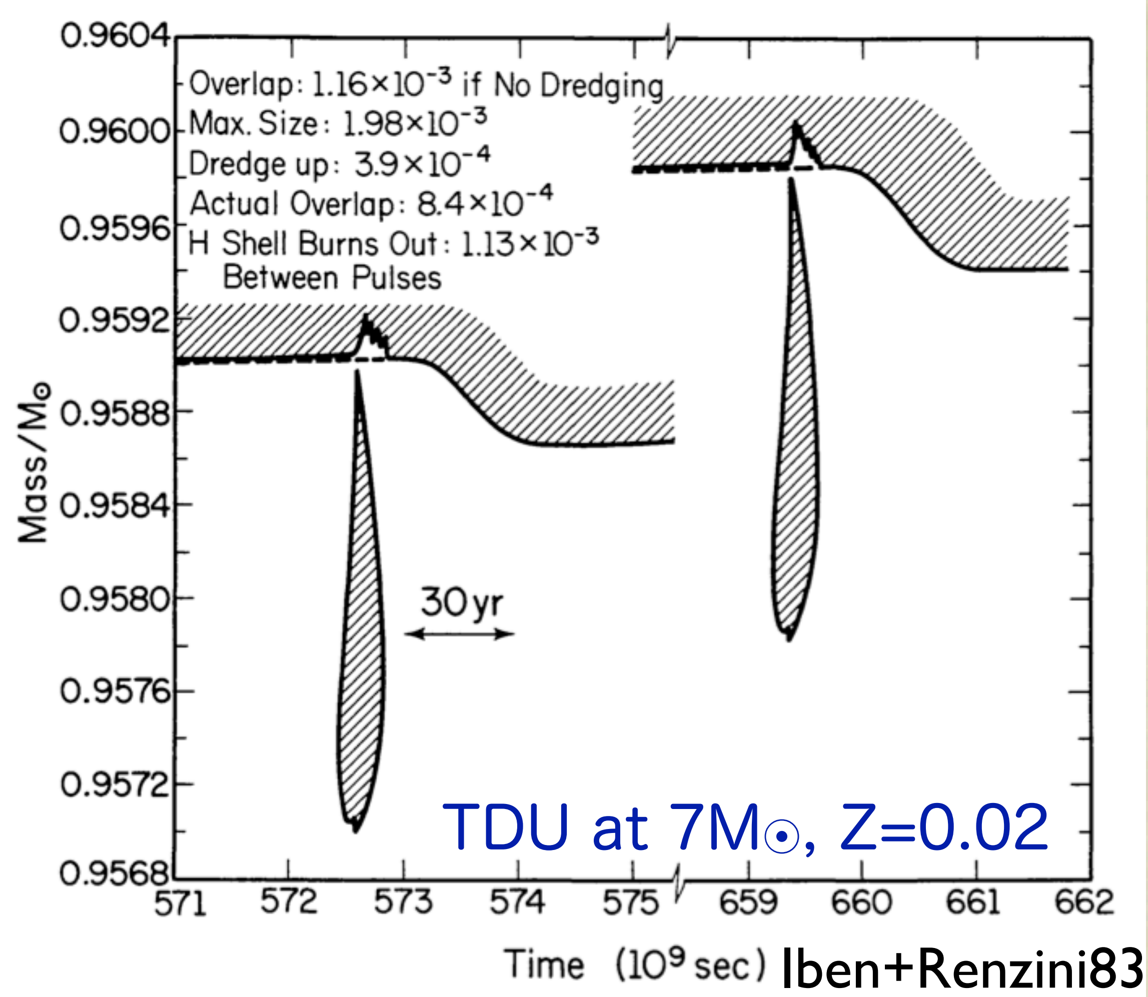
Ejection of the convective envelope. It prevents from the explosion of intermediate-mass stars.

Core Mass

Mass of the hydrogen-exhausted core, also called “He-core”. It determines the characteristics of stellar evolution.

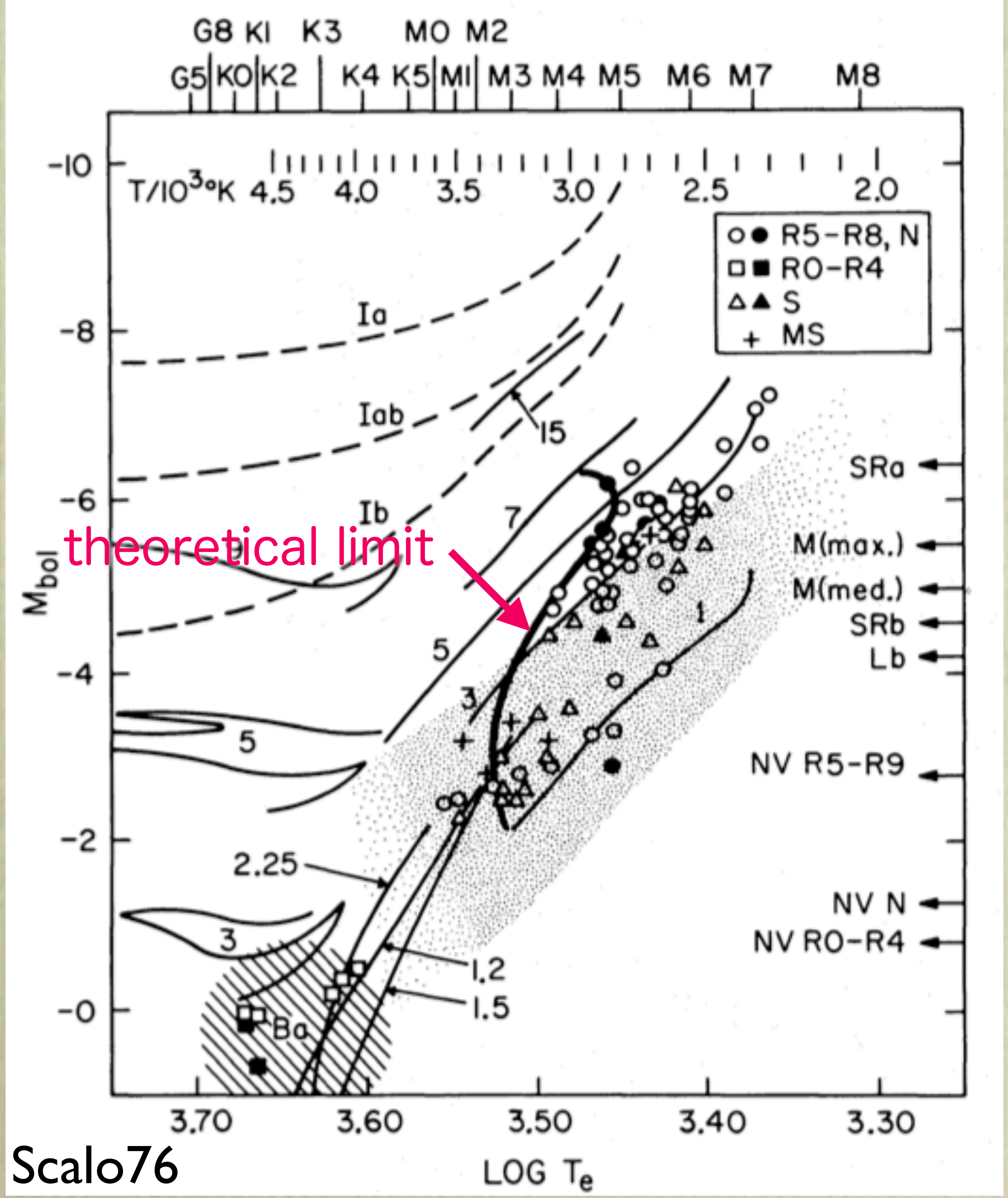
Third Dredge-Up: Carbon Enhancement

- Deepening of convective envelope during the AGB phase (Iben75)
- Observational counterparts: C stars
  - Criteria for TDU
    - Luminosity
    - Helium core mass



TDU at 7$M_\odot$, Z=0.02

Iben+Renzini83



theoretical limit

Scalo76

- Inconsistent with the observations of Magellanic Clouds.
  - M_c needs to be >~0.6$M_\odot$ for TDU to occur (Iben+Renzini83).
  - Carbon star mystery (Iben81)

Latest models find TDU with M_c < 0.6$M_\odot$.

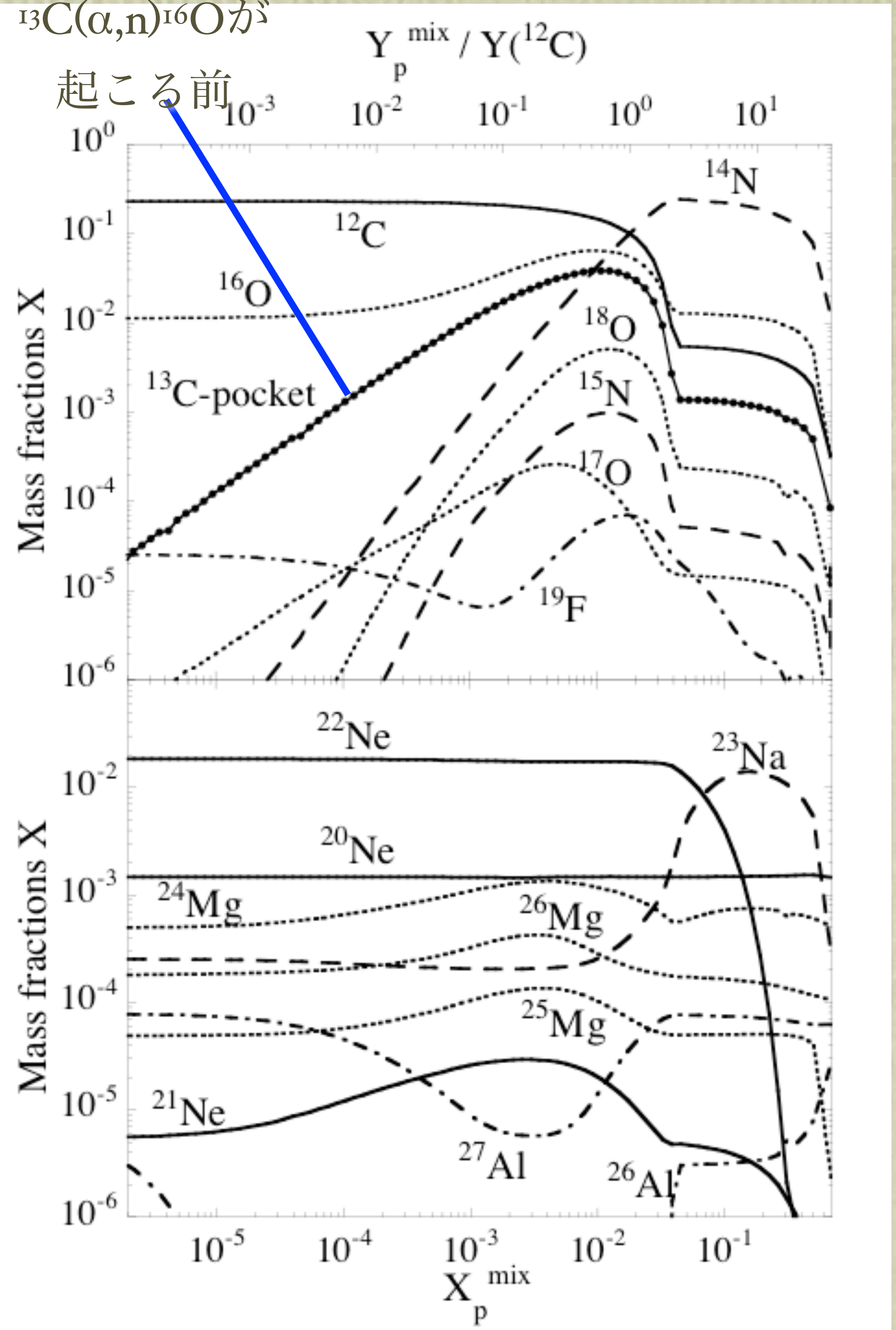
- Weiss+Ferguson09: M_c = 0.508$M_\odot$ for 1.0$M_\odot$

2. s-process

- 中性子捕獲によって合成される元素のうち、中性子捕獲よりもβ崩壊の方が素早く起こるような環境で作られる元素。
- 観測的証拠はAGB星での^{99}Tcの検出。
  - 半減期2.13x10^{5} yrでAGB thermal pulseの周期と同程度
    - 表面で観測されれば、s-processによる合成と表面への輸送の証拠となる。
  - AGB星での検出はMerrill52が最初。
  - 定量的な観測は、Smith+Wallerstein83, Dominy+Wallerstein86など。
- AGB星で作られると考えられており、中性子源は以下の２つの反応によって放出される(Cameron55)。
  - ^{13}C(α,n)^{16}O
    - ^{13}C pocket: TDUの後に表面対流層の底に水素が混入⇒炭素の水素捕獲
  - ^{22}Ne(α,n)^{25}Mg
    - Massive AGB stars (M_c >~ 1 $M_\odot$)のHe対流層で^{14}Nから^{22}Neが作られる。
  - ^{22}Neソースの方が^{13}Cソースよりも高温の環境で機能する。
- ^{13}C pocketの効率はfree parameter
  - opacity? shear mixing? overshooting?

s-process by ^{13}C Pocket

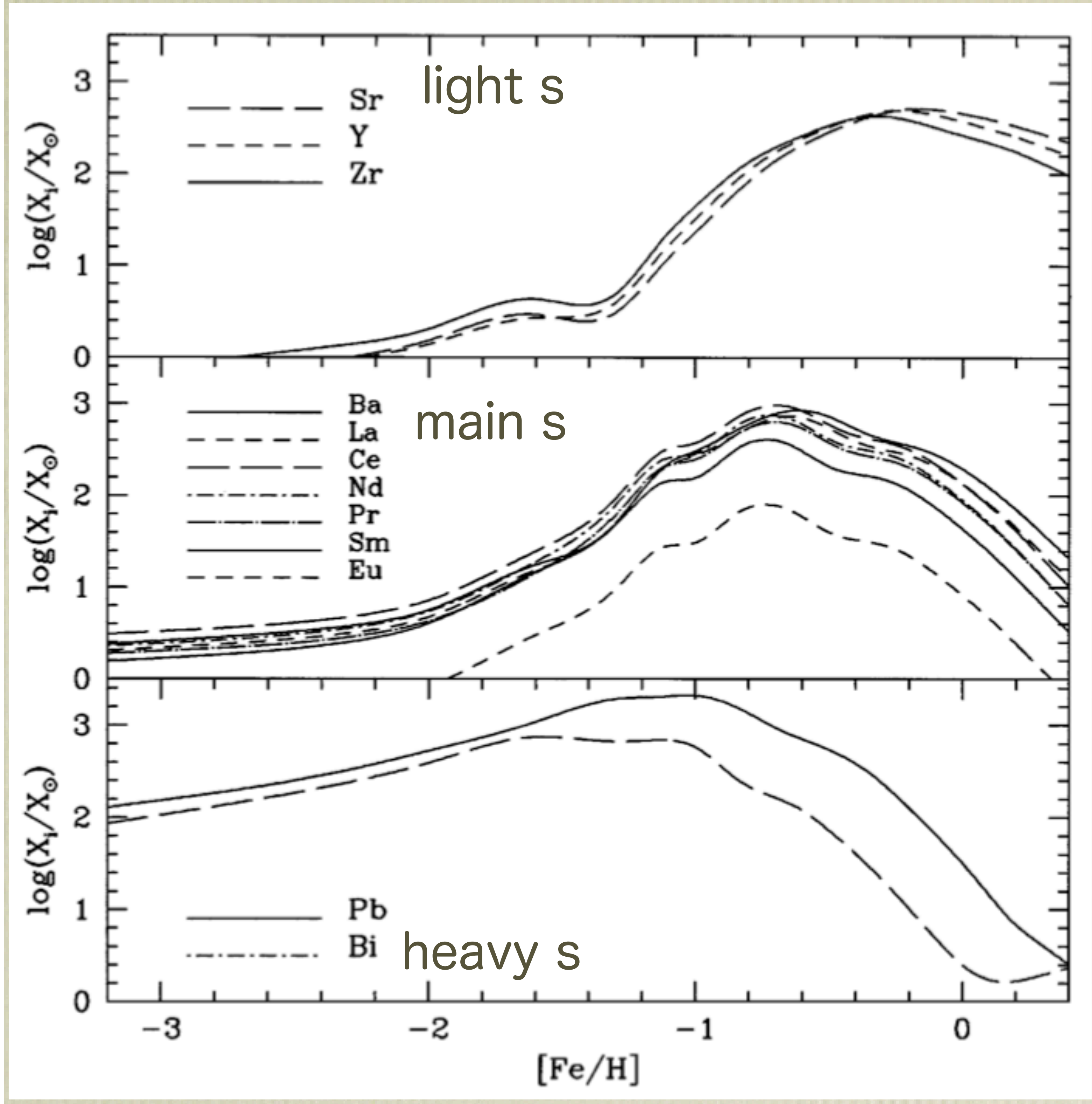
^{13}C pocket内での組成分布



$^{13}C(\alpha,n)^{16}O$が
起こる前

1.5M⊙ model@15th pulse **Goriely+Mowlavi00**

s-processの金属量依存性



light s

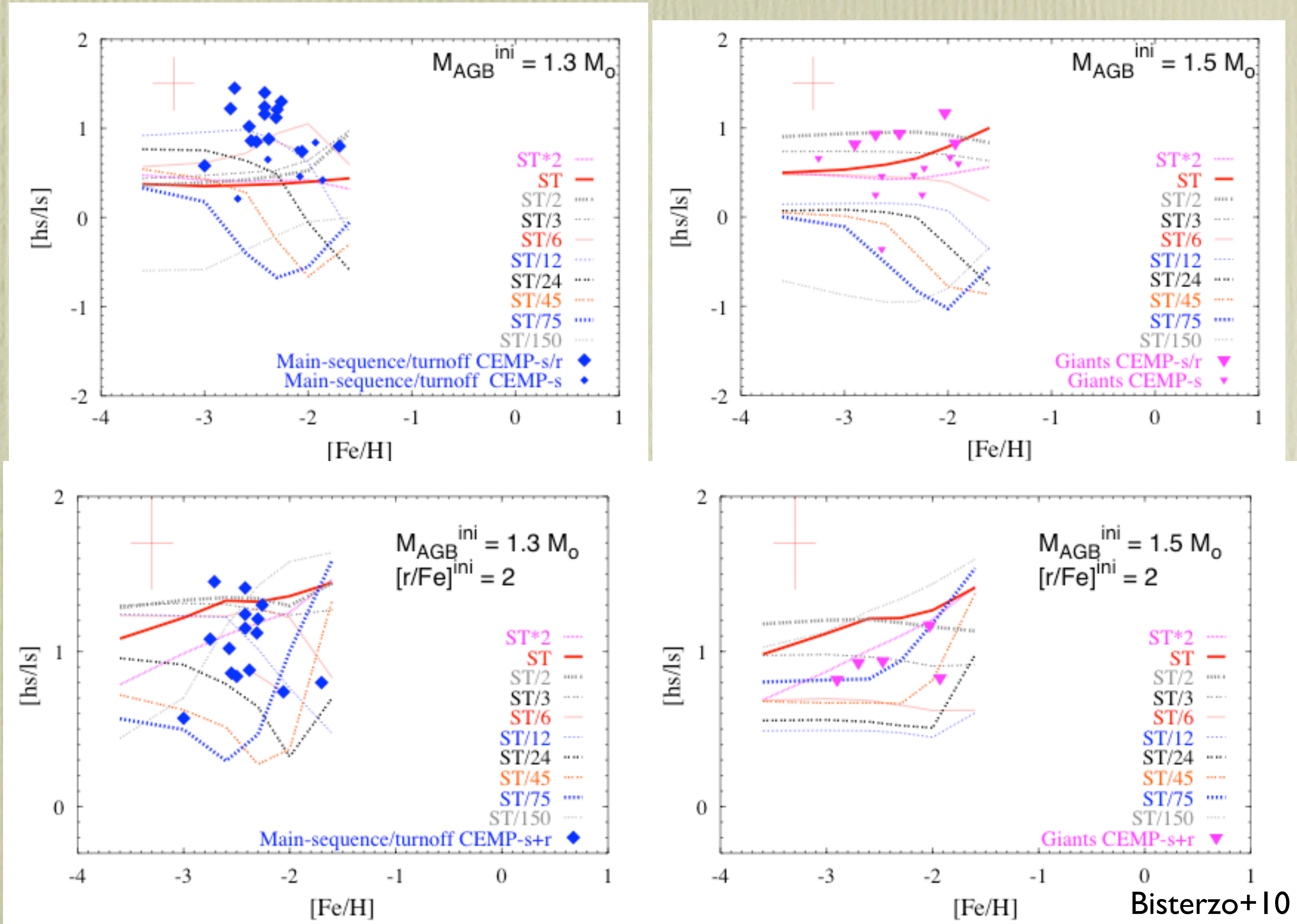
main s

heavy s

2M⊙ model

Busso+99

Parameter Search of ^{13}C Pocket Efficiency



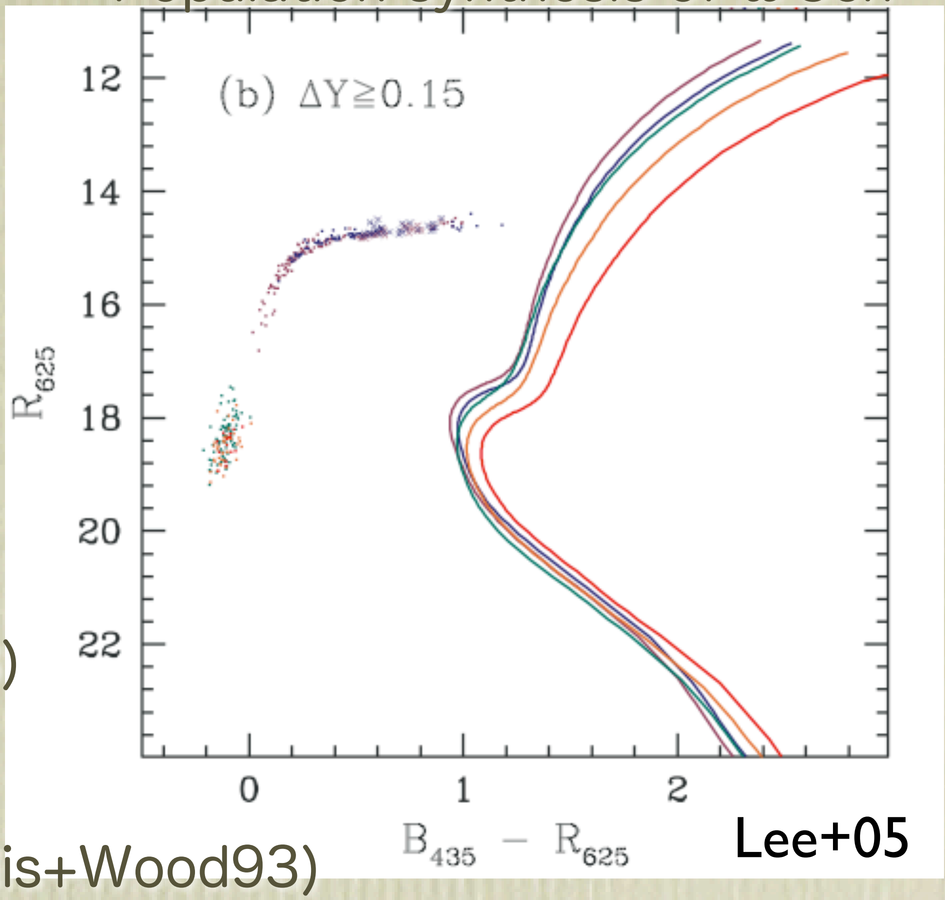
Bisterzo+10

Hot Bottom Burning: CNO Cycle at the Base of Convective Envelope

- Temperature at the bottom of convective envelope becomes high ($T_{BCE} > 50$ MK) at large core mass, where CN cycles operate (Iben75,76).
  - $^{12}C/^{13}C$ approaches a equillibrium value (~3.4) at $T_{BCE} \sim 80$MK (Truran72).
- HBB first discovered in a $7M_\odot$ model(Iben75).
  - Application to chemical evolution models(Iben+Truran78)
  - Determination of the mass range of HBB (Renzini+Voli81)。
    - Occurrence of HBB strongly depends on mixing length parameter ($\alpha = l_{mix}/H_P$)(Iben76).
    - $(\alpha, M_{HBB}) = (2, 3.3M_\odot), (1.5, 4M_\odot), (1, 6.8M_\odot)$ (Renzini+Voli81)
- HBB is prohibited in thin envelope mass(Frost+98, Karakas+Lattanzio07)
  - $M_{crit} = 1.5\ M_\odot$ (Karakas+Lattanzio07)
- No direct evidence of HBB in the observations of AGB stars?
  - N > C confirmed by observation (Smith+Lambert83,85)
  - Metal-poor AGB star: CS30322-023 (Masseron+06)

Mass Loss

Population synthesis of ωCen



Lee+05

- Mechanisms are poorly understood.
- Reimers formula for RGB stars (Reimers75)
  - free parameter η_R = 0.3-1.0
  - effective only for low-mass(~0.8M$_\odot$) giants.

$$\dot{M}_R = -4\times10^{-13}\frac{(L/L_\odot)\,(R/R_\odot)}{(M/M_\odot)}\eta_R \qquad [M_\odot \mathrm{yr}^{-1}]$$

  - consistent with the horizontal branch of GCs.
- Dust-driven mass loss (Bowen+Willson91,Wachter+08)
  - Carbon-dust (SiC) is promising for mass loss.
- Observed mass loss rate for AGB stars (Vassiliadis+Wood93)
  - Period-Luminosity relation in Mira variables
  - Mass loss rate increases at certain luminosity (superwind)。

$$\log \dot{M}_{\mathrm{WR}} = -11.4 + 0.0125\left[P - 100\max\left(\frac{M}{M_\odot} - 2.5\right)\right] \qquad [M_\odot \mathrm{yr}^{-1}] \quad (P[\mathrm{days}])$$

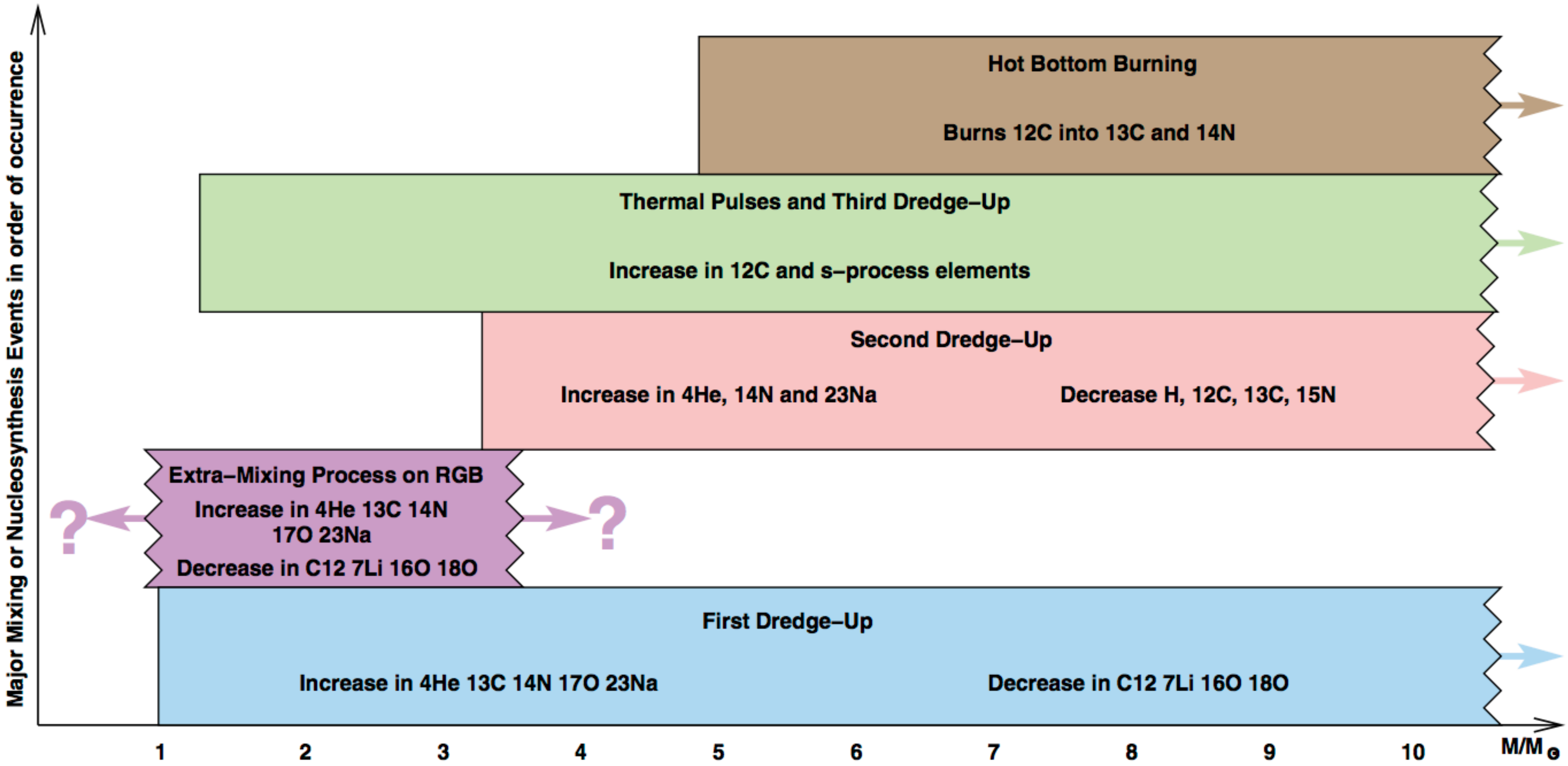
$$\log P = -2.07 + 1.94\log\frac{R}{R_\odot} - 0.9\log\frac{M}{M_\odot} \qquad [\mathrm{days}]$$

  - Planetary nebulae are caused by superwind (dM/dt~10^{-5} M$_\odot$/yr)?

$$\log \dot{M} = -5.65 + 1.05\log\left(\frac{L}{10^5 L_\odot}\right) - 6.3\log\left(\frac{T_{\mathrm{eff}}}{3500\mathrm{K}}\right) \qquad [M_\odot \mathrm{yr}^{-1}]$$

- Mass loss from O-rich AGB stars (van Loon+05)

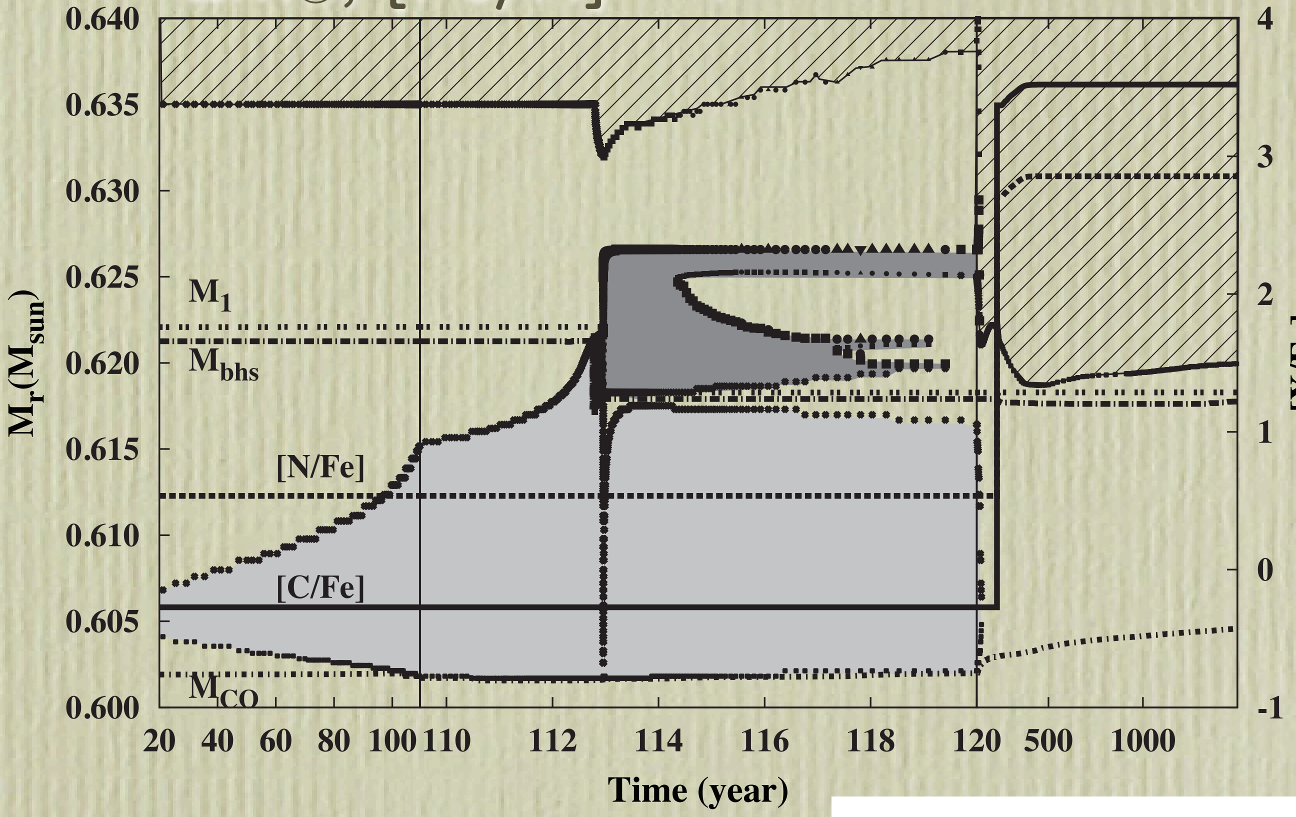
Summary of the events in AGB stars



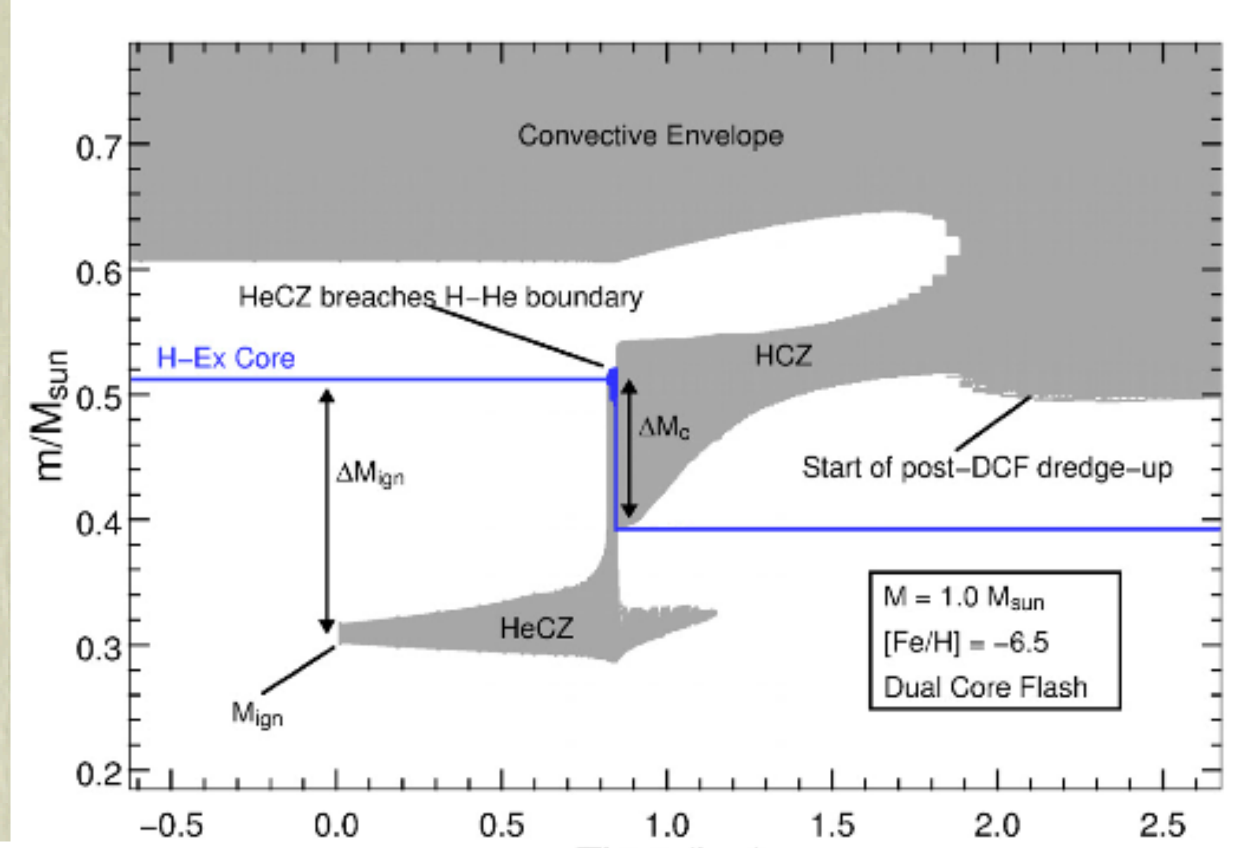
Karakas+Lattanzio14

Extremely Metal-Poor Stars: Hydrogen Ingestion Into the Helium Flash Convective Zone

2M⊙, [Fe/H]=-4

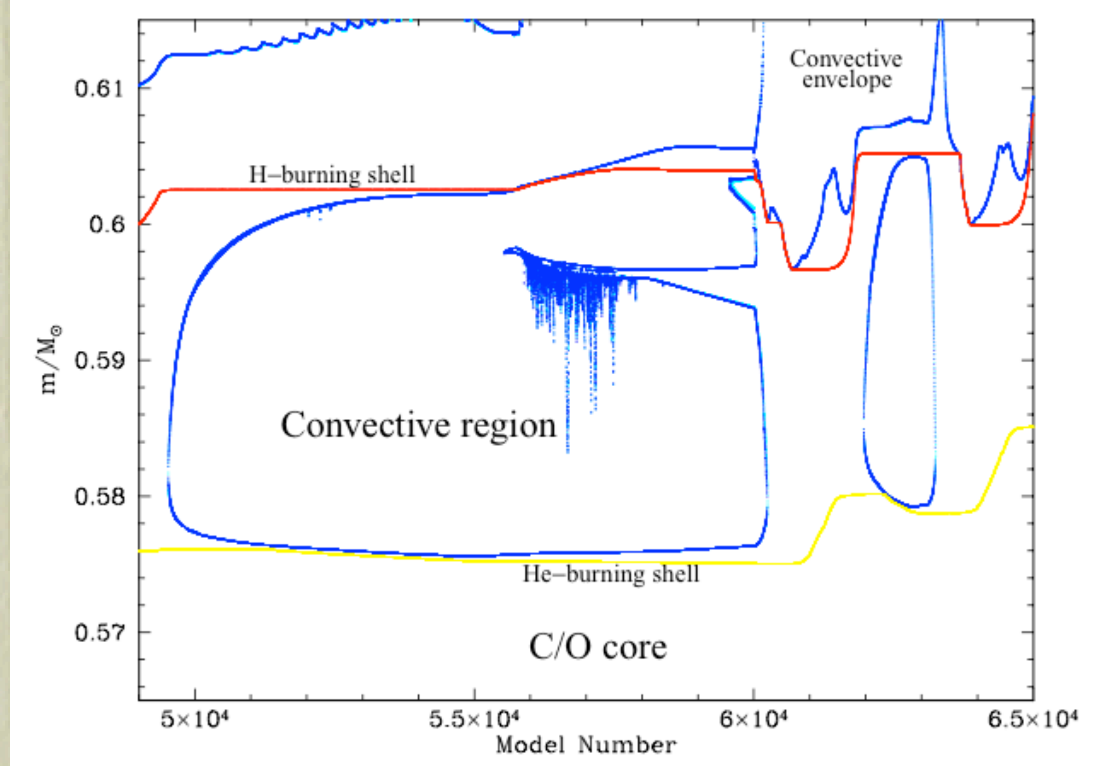


Suda+Fujimoto10



Campbell+Lattanzio08

He対流層への水素の混入。水素層とのentropy barrierが少ないために起こる。水素flashを伴い、その後の表面対流層の侵入によってCNが増大。

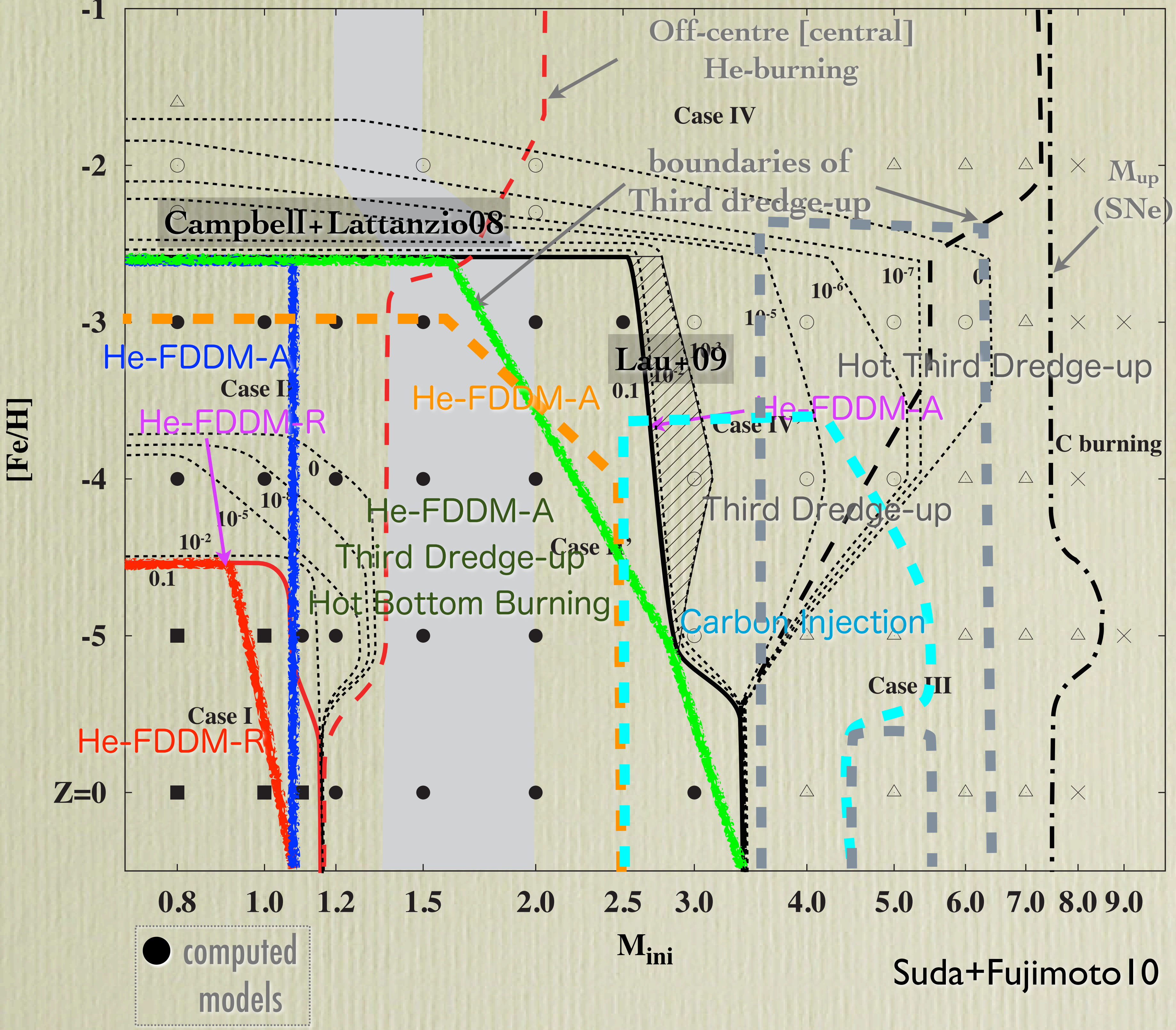


1.5M⊙, [Fe/H]=-3.3

Lau+09

Final Fate of Stellar Evolution

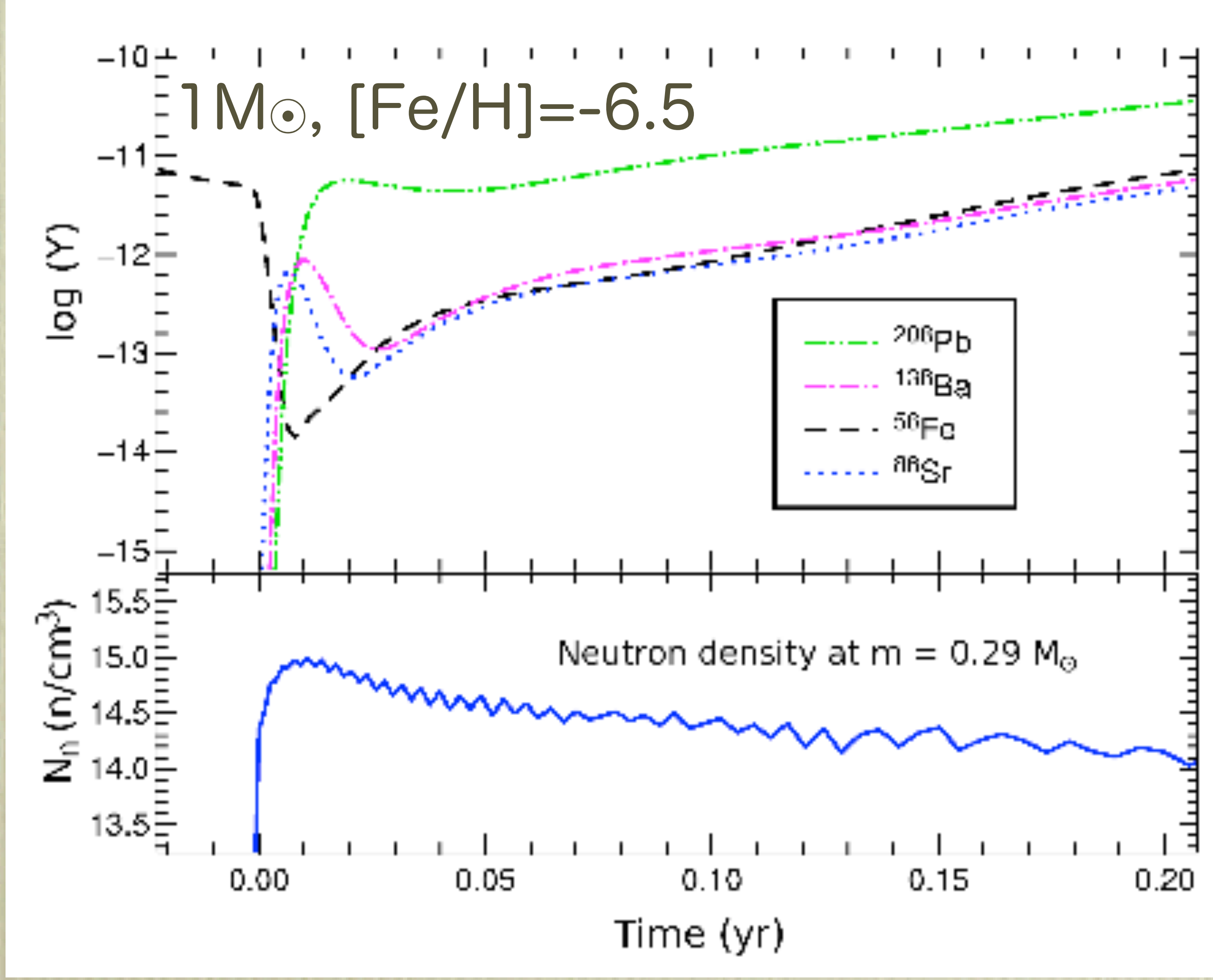
- SF10, CL08, L09のどの計算でも水素混合が起こる境界は似ている。
- 水素混合が起こる[Fe/H]は-2.5--3
- Carbon Injection: He層の炭素が水素層に混入。
- Hot third dredge-up: TDUよりも深いdredge-up。Herwig03でも報告されている。



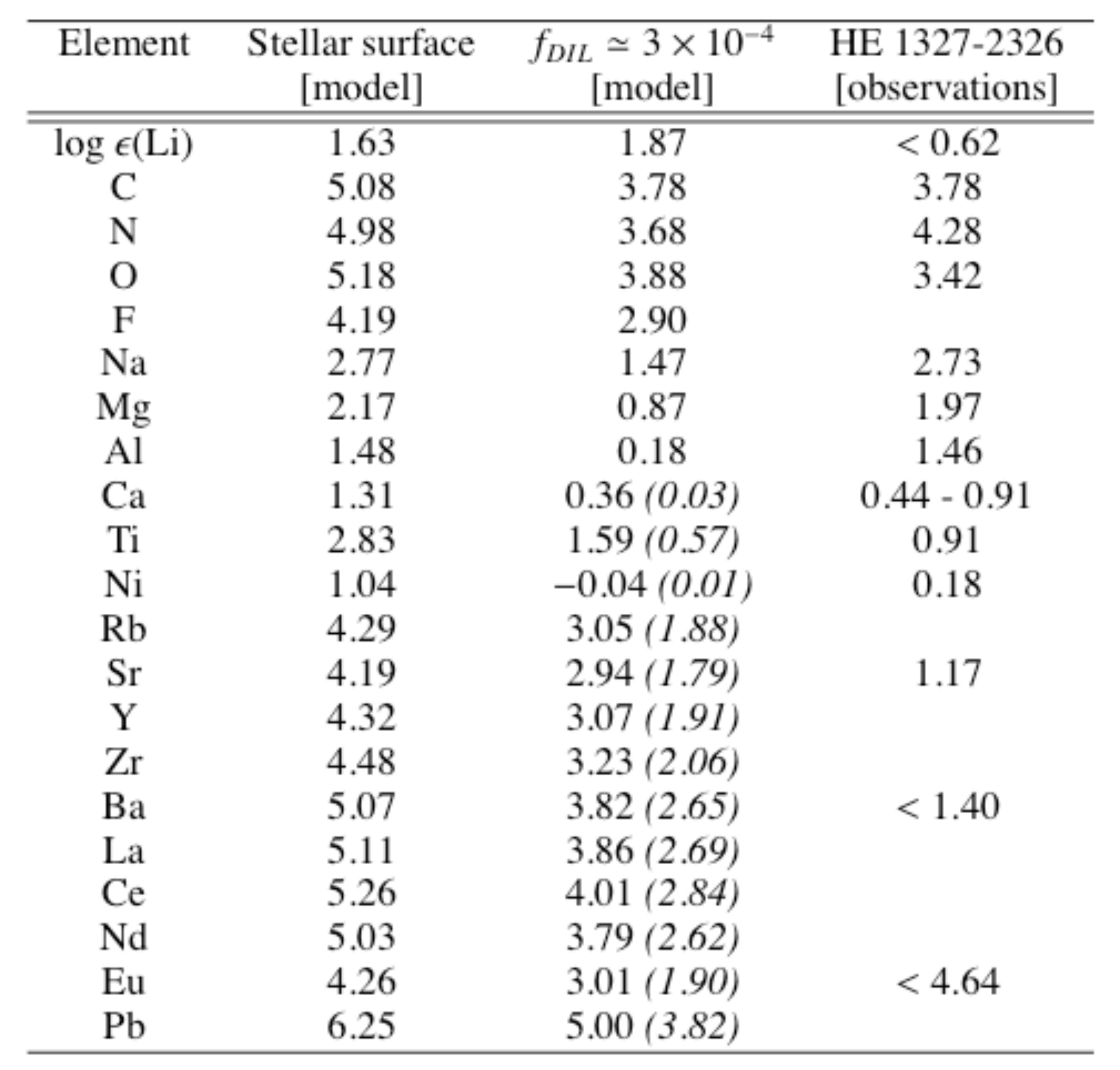
Suda+Fujimoto10

Convective s-process in Extremely Metal-Poor Stars

- He対流層への水素混合によって$^{13}C(\alpha,n)^{16}O$が起こり中性子捕獲反応が進行する(Fujimoto+00, Suda+04)
  - He core flashの場合のpost-processing (Campbell+10)



Campbell+10



Element	Stellar surface [model]	$f_{DIL} \simeq 3 \times 10^{-4}$ [model]	HE 1327-2326 [observations]
log ϵ(Li)	1.63	1.87	< 0.62
C	5.08	3.78	3.78
N	4.98	3.68	4.28
O	5.18	3.88	3.42
F	4.19	2.90	
Na	2.77	1.47	2.73
Mg	2.17	0.87	1.97
Al	1.48	0.18	1.46
Ca	1.31	0.36 *(0.03)*	0.44 - 0.91
Ti	2.83	1.59 *(0.57)*	0.91
Ni	1.04	−0.04 *(0.01)*	0.18
Rb	4.29	3.05 *(1.88)*	
Sr	4.19	2.94 *(1.79)*	1.17
Y	4.32	3.07 *(1.91)*	
Zr	4.48	3.23 *(2.06)*	
Ba	5.07	3.82 *(2.65)*	< 1.40
La	5.11	3.86 *(2.69)*	
Ce	5.26	4.01 *(2.84)*	
Nd	5.03	3.79 *(2.62)*	
Eu	4.26	3.01 *(1.90)*	< 4.64
Pb	6.25	5.00 *(3.82)*	

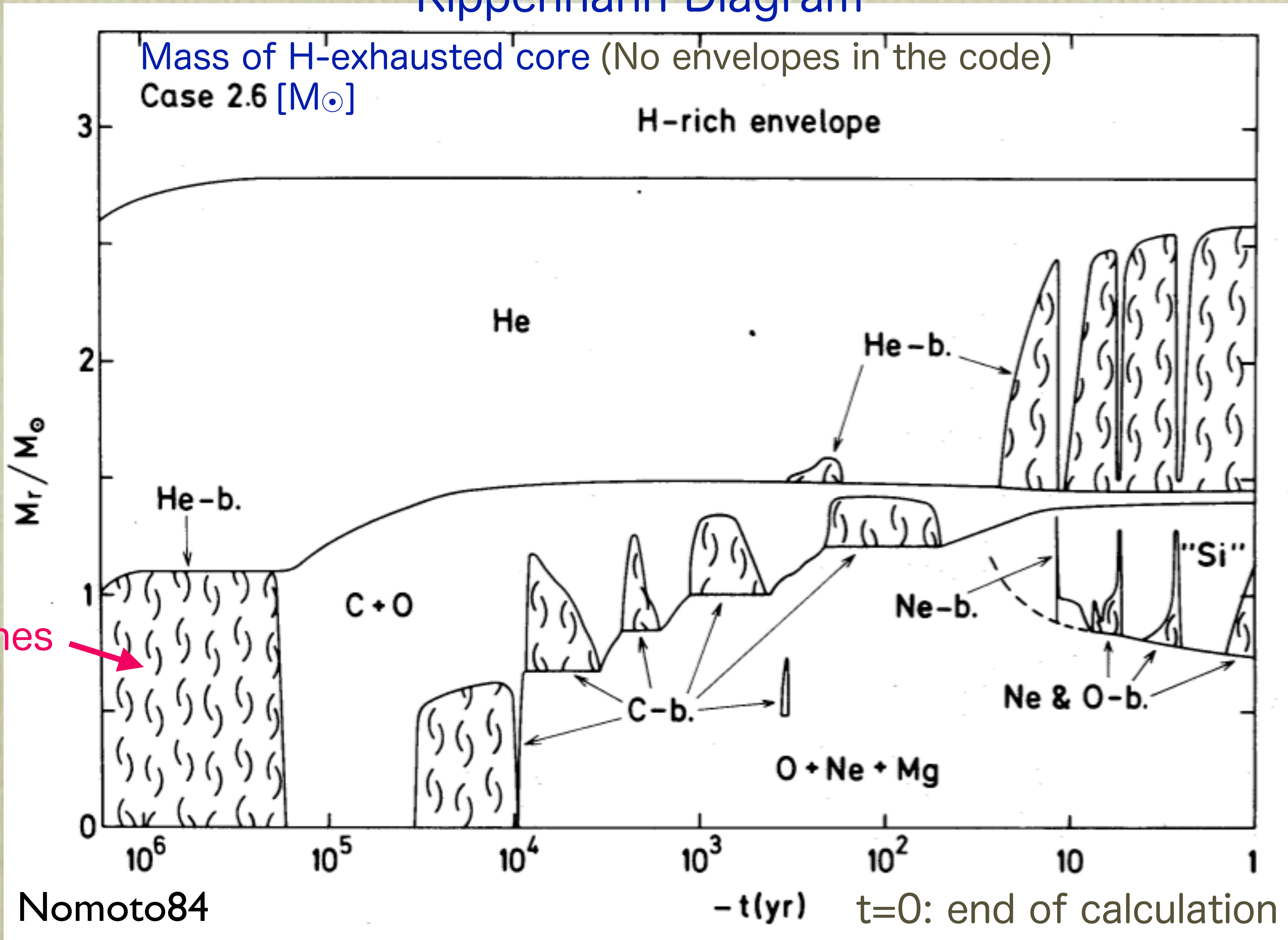
$[X/Fe]_{conv}$ $[X/Fe]_{surf}$

Super-AGB Stars

Super-Asymptotic Giant Branch Stars

- ONeMg core: Miyaji+80, Nomoto84, Nomoto87
- Super-AGB: Garcia-Berro+Iben94, Ritossa+96

Kippenhahn Diagram



Mass of H-exhausted core (No envelopes in the code)

Case 2.6 [M☉]

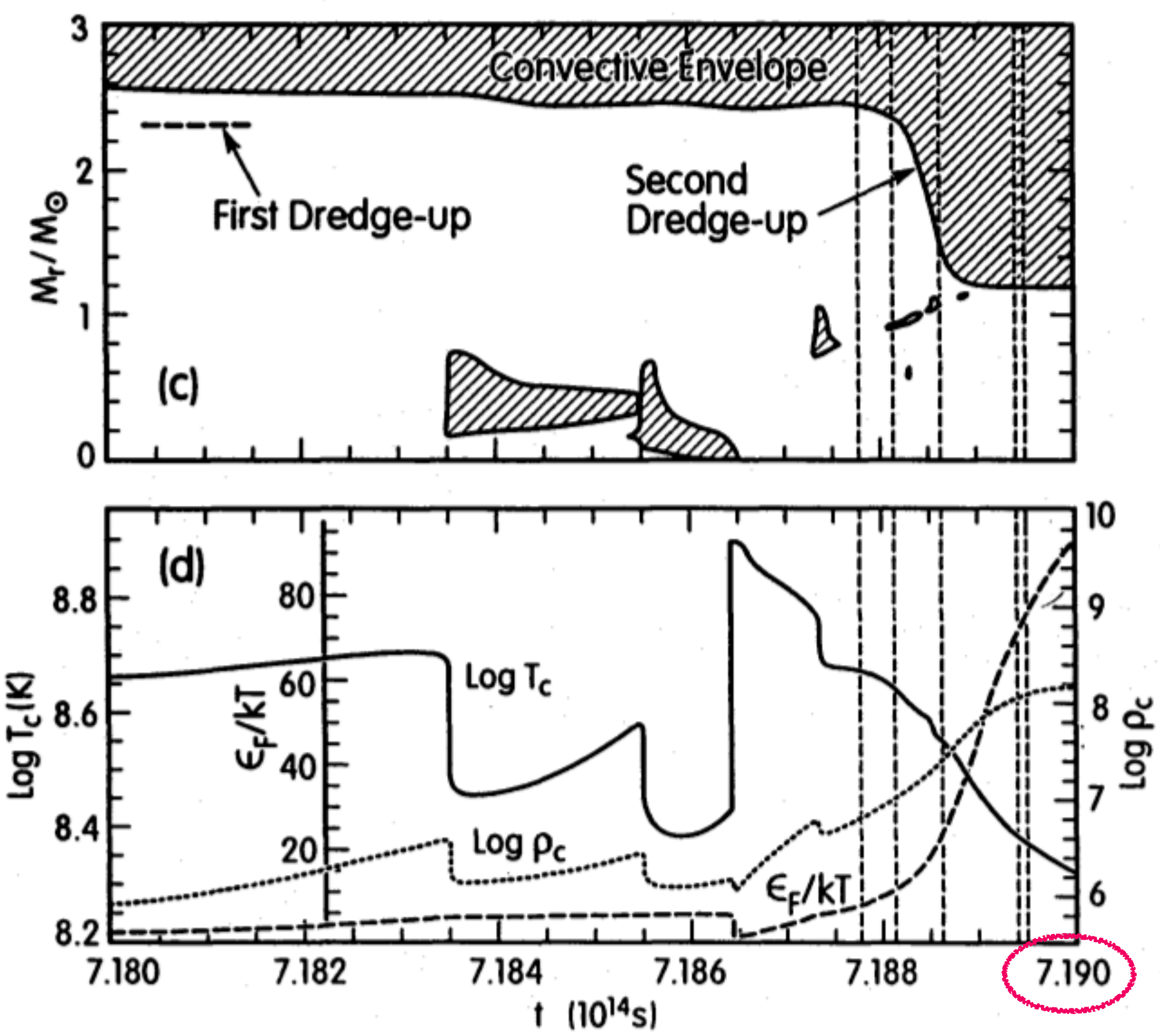
convective zones

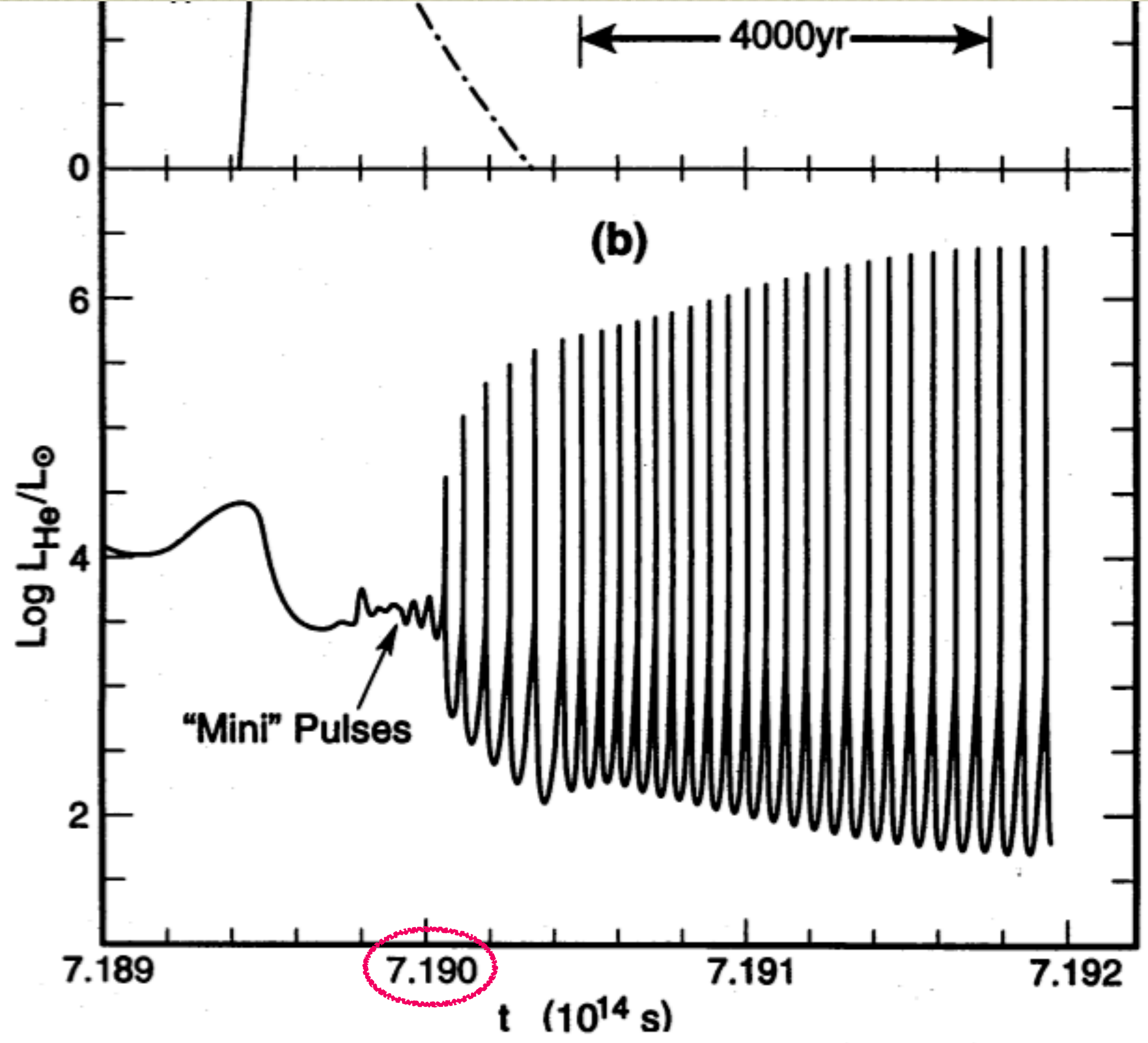
Nomoto84

t=0: end of calculation

Recovery of H-burning and thermal pulses

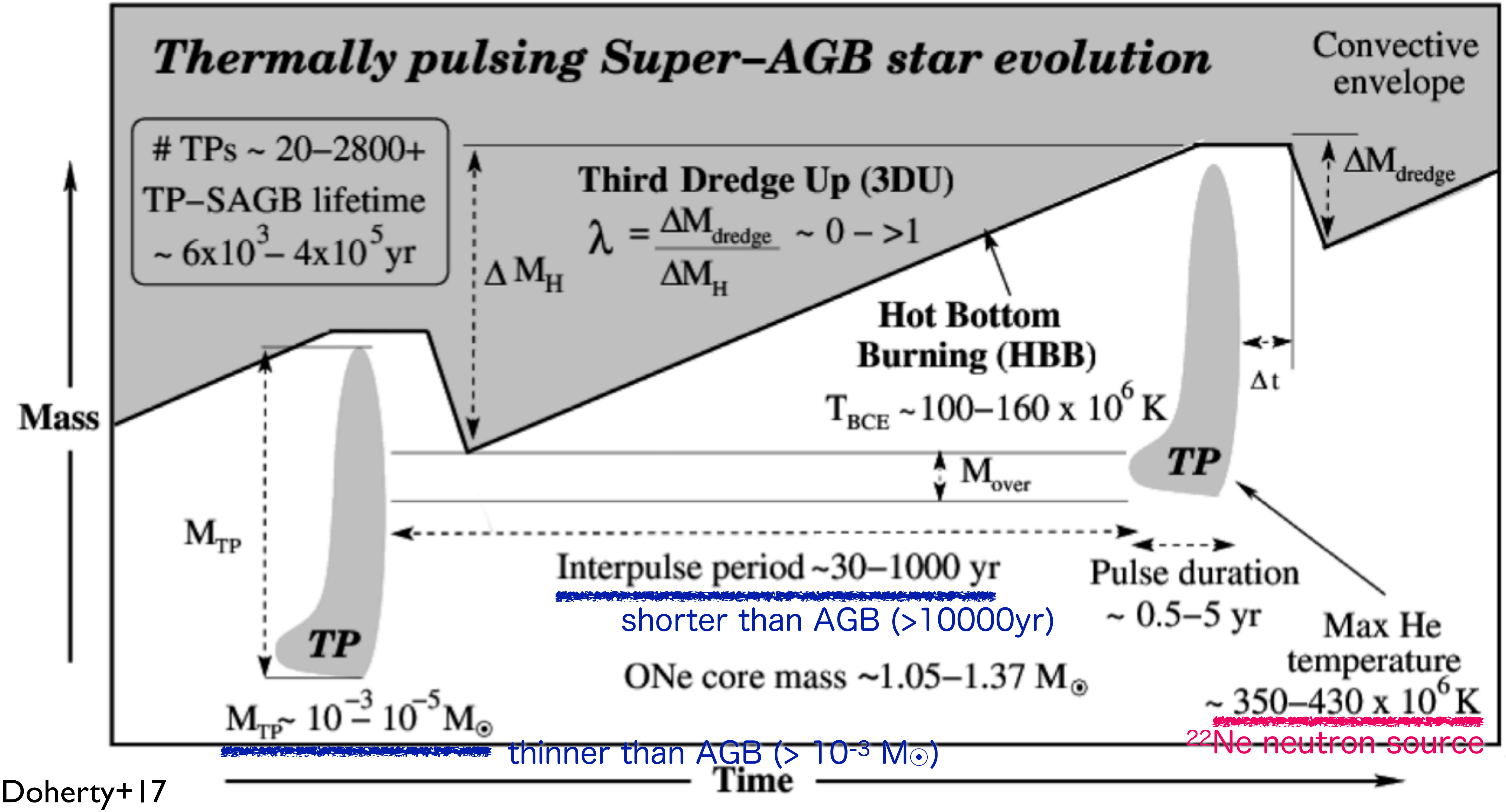
$M=10M_\odot$, $Z=0.02$





Ritossa+96

Summary of SAGB evolution



shorter than AGB (>10000yr)

thinner than AGB (> 10^{-3} $M_\odot$)

^{22}Ne neutron source

Doherty+17

Key parameters for the evolution of SAGB stars

M_{up}

the minimum initial mass required to ignite carbon.

M_n

the minimum initial mass that forms a neutron star resulting from an electron-capture supernovae.

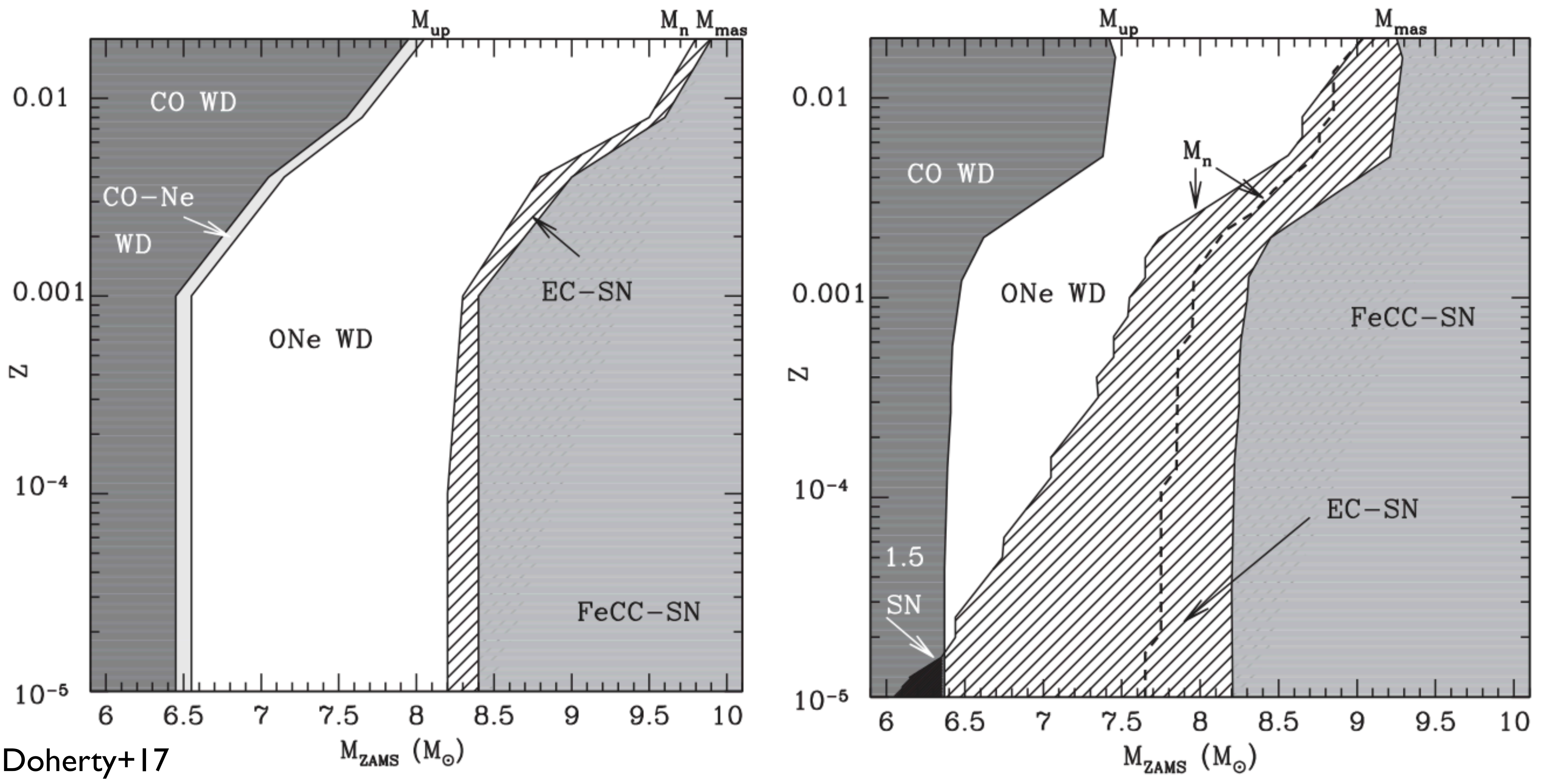
M_{mas}

the minimum initial mass that forms an iron core-collapse supernovae.

λ : Dredge-up parameter

defined by “dredge-up mass by the 3rd dredge-up” / “mass of the growth of core mass during the interpulse phase”. If $\lambda > 1$, core will decrease with time.

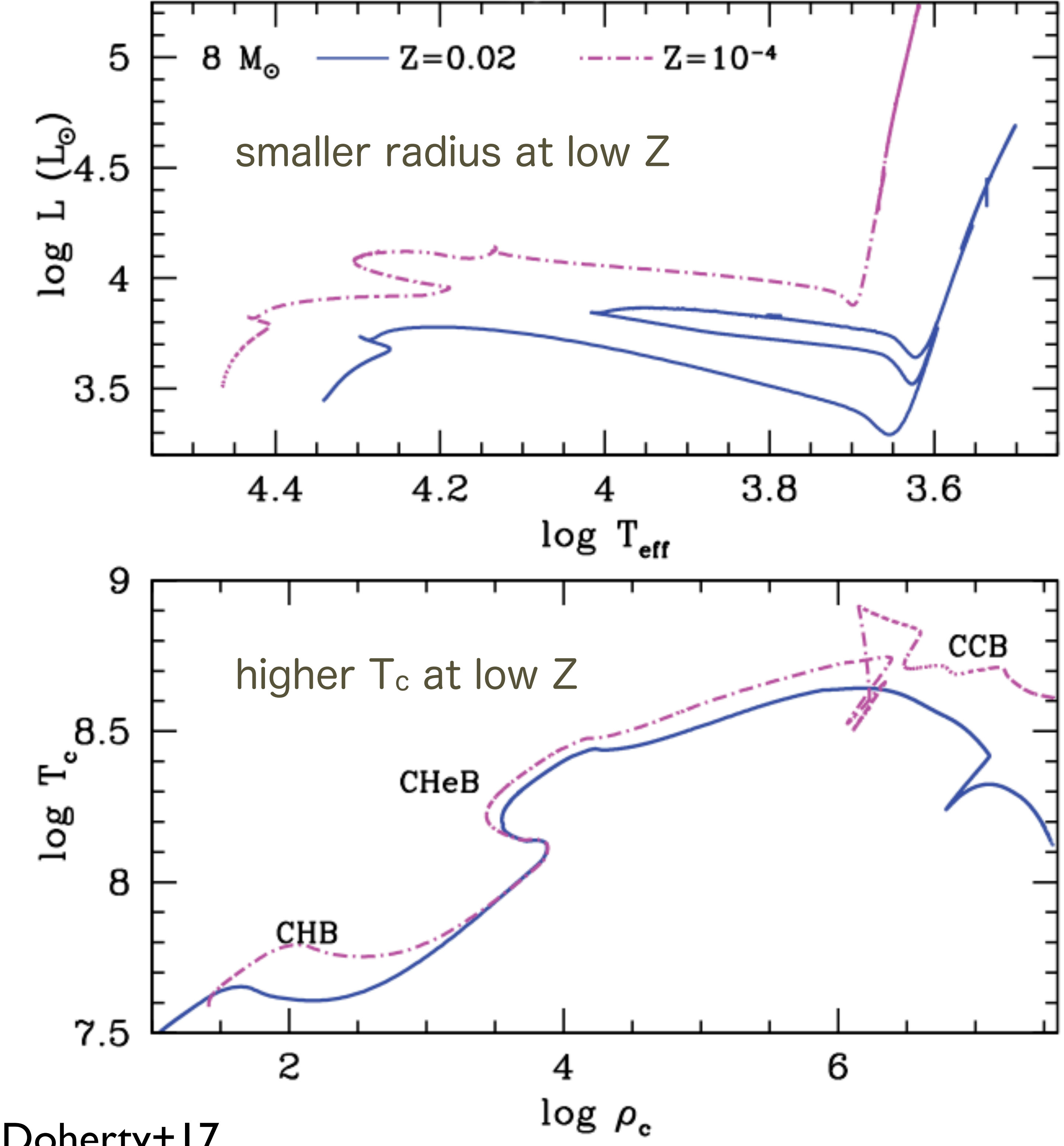
Metallicity dependence of M_{up}, M_n, and M_{mas}



Doherty+17

Evolution to C-burning phase

$M=8M_\odot$, $Z=0.02$ & 10^{-4}



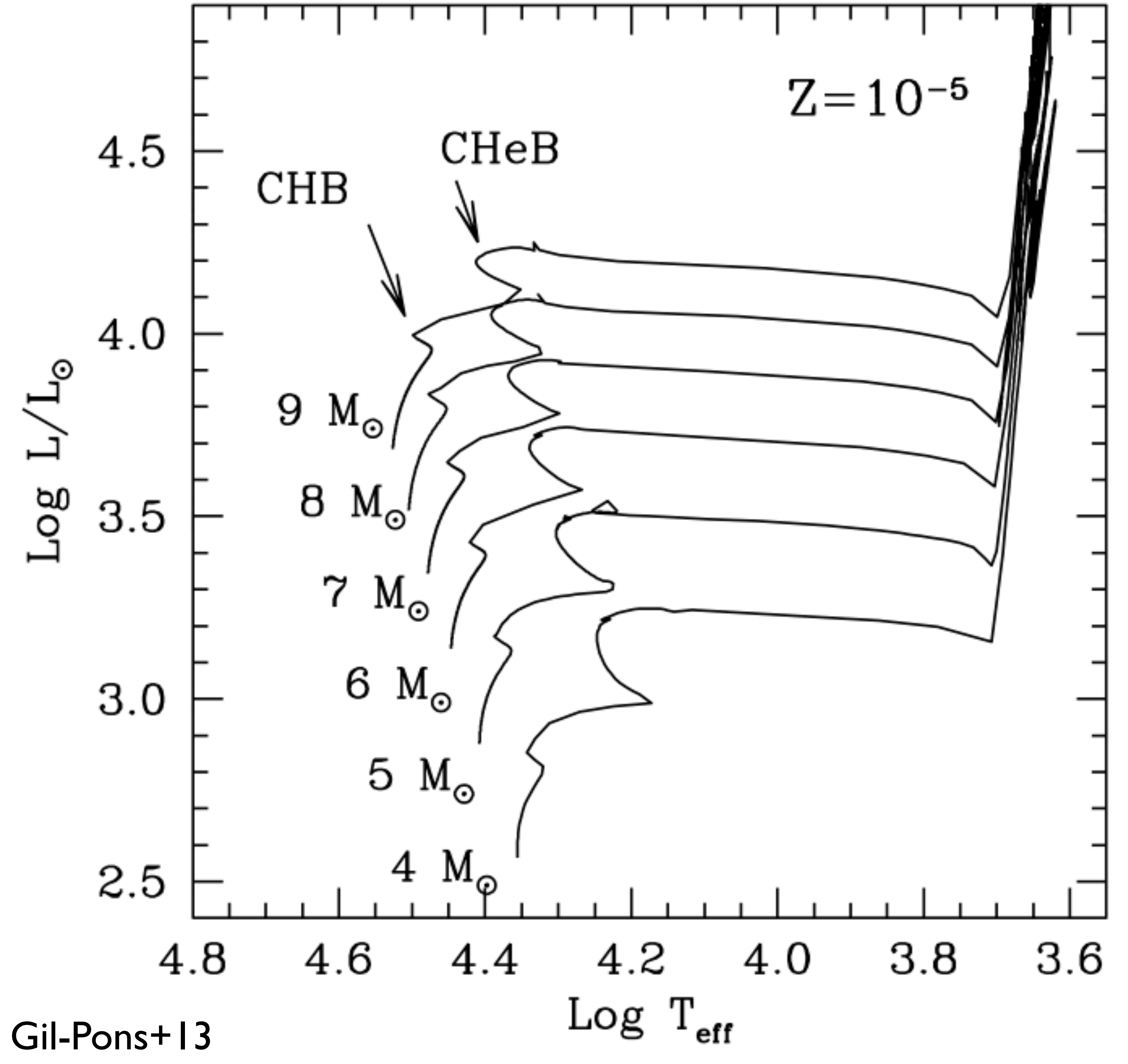
smaller radius at low Z

higher T_c at low Z

Doherty+17

AGB models of low-metallicity stars

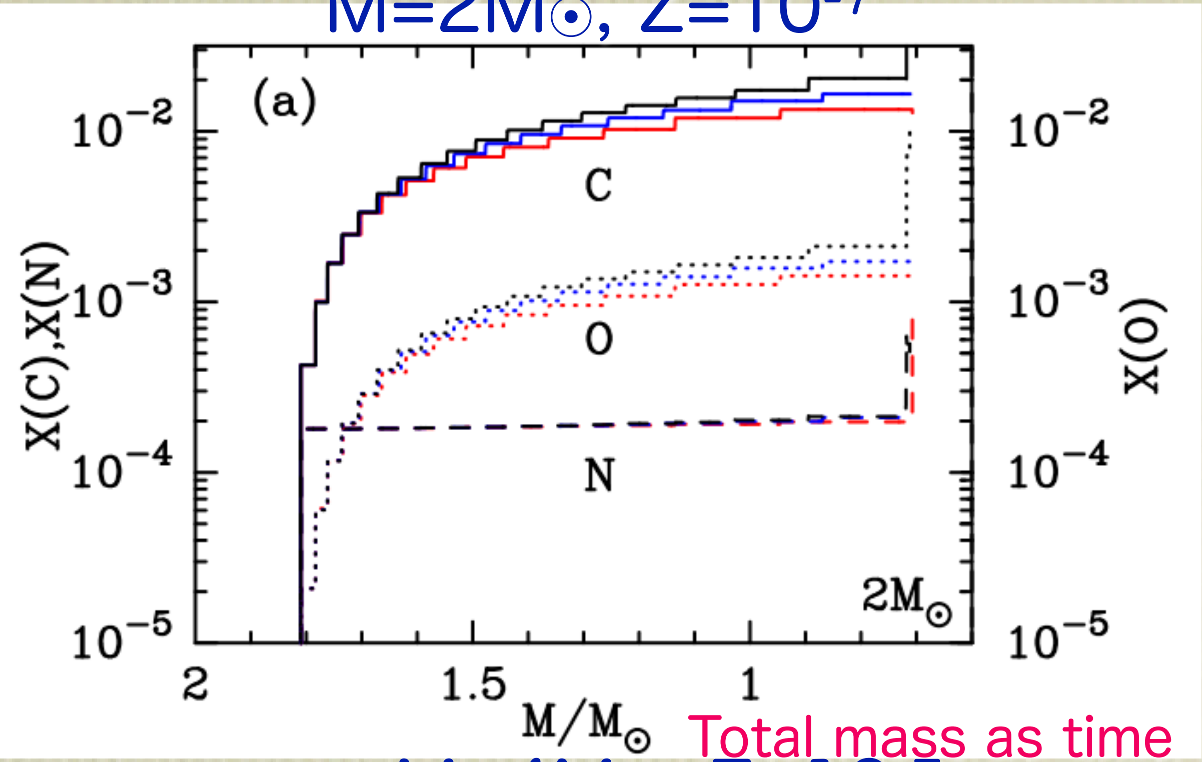
M=4-9M☉, Z=10^{-5}



Gil-Pons+13

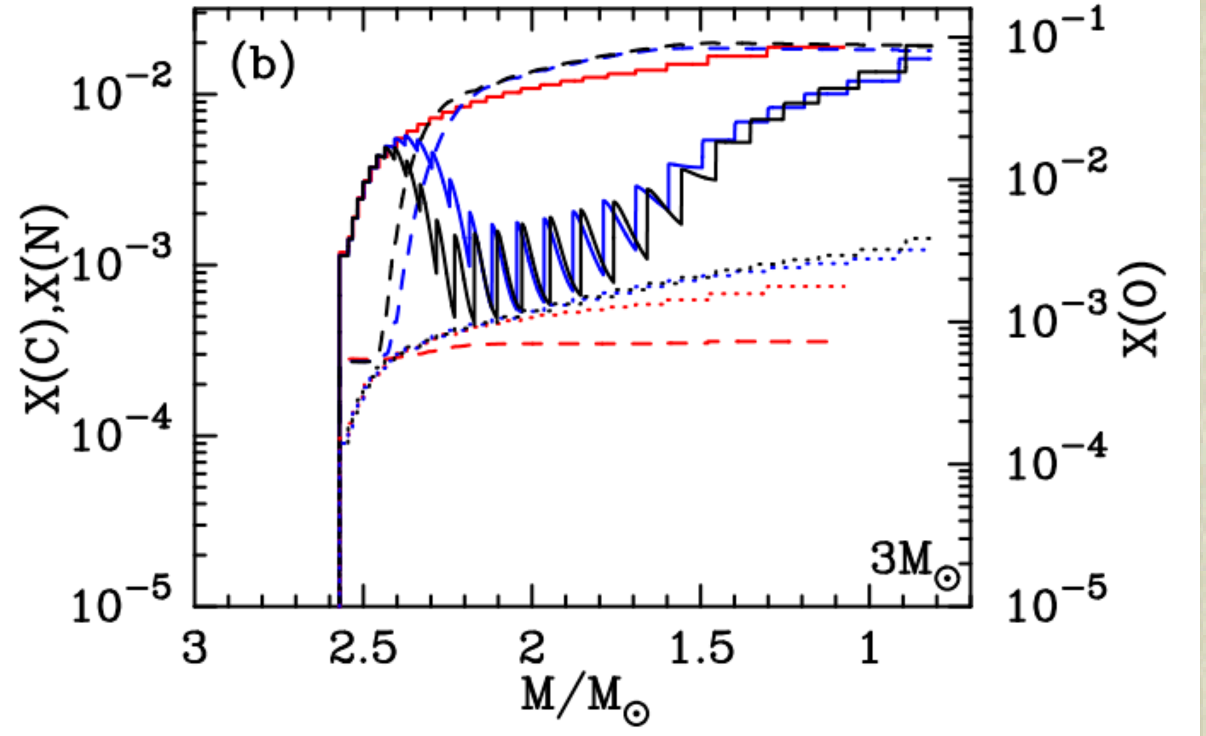
Hot bottom burning and the effect of opacity

M=2M⊙, Z=10^{-7}

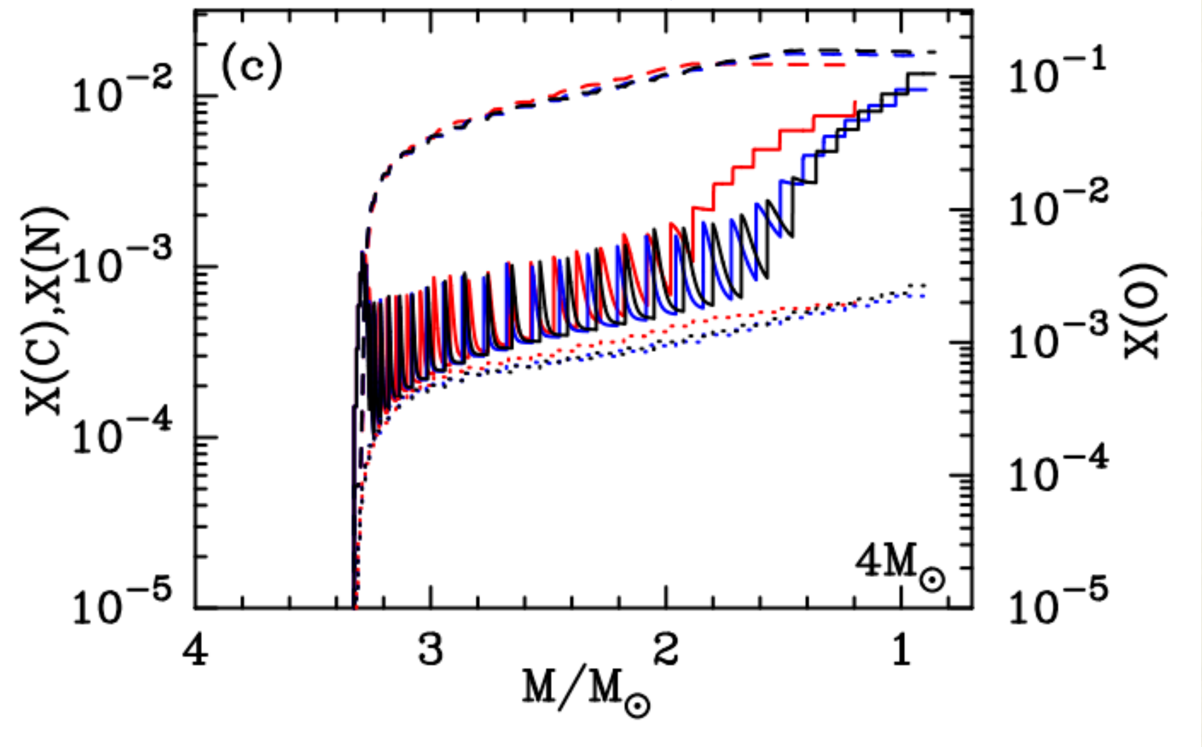


Total mass as time

M=3M⊙, Z=10^{-7}

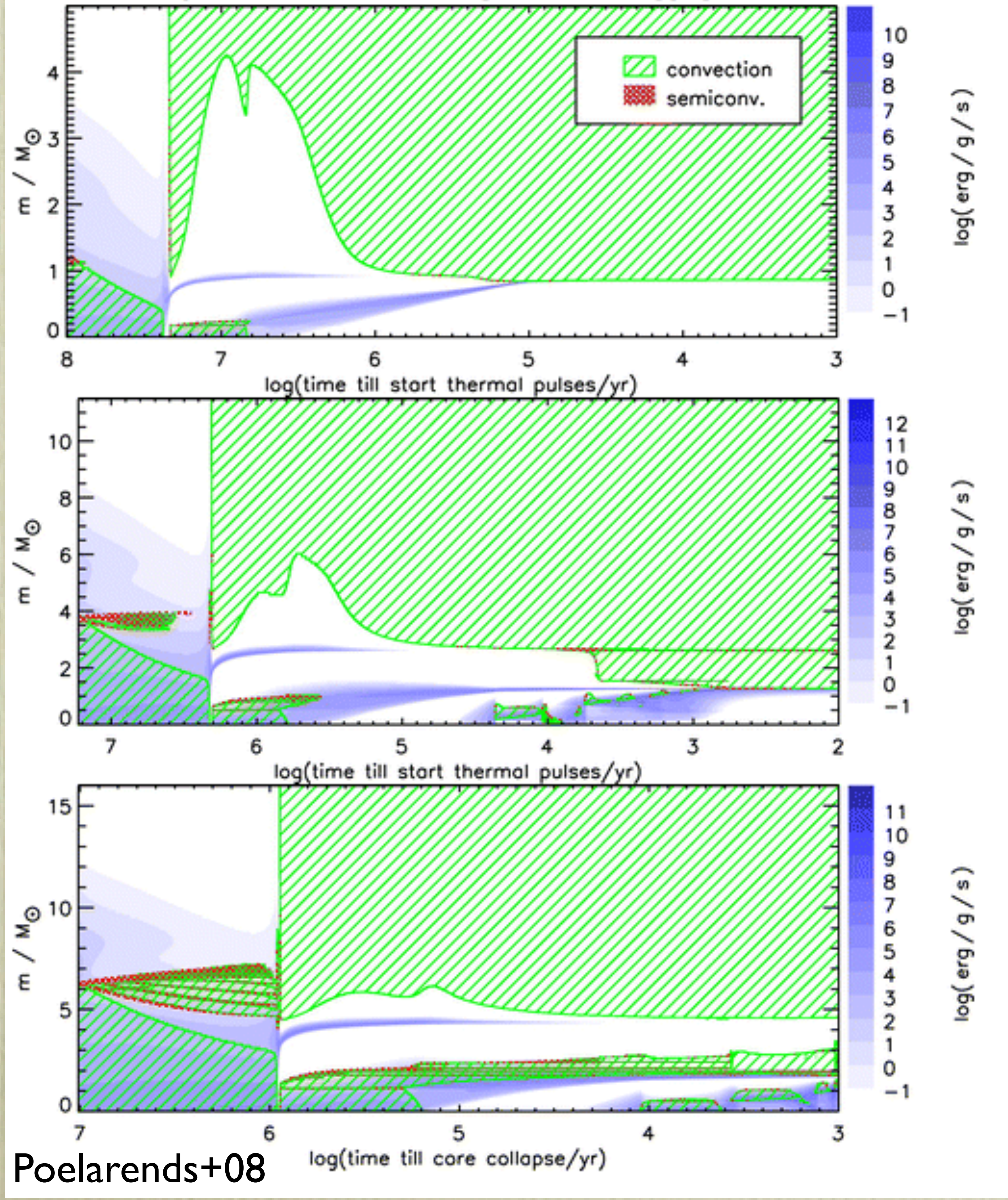


M=4M⊙, Z=10^{-7}

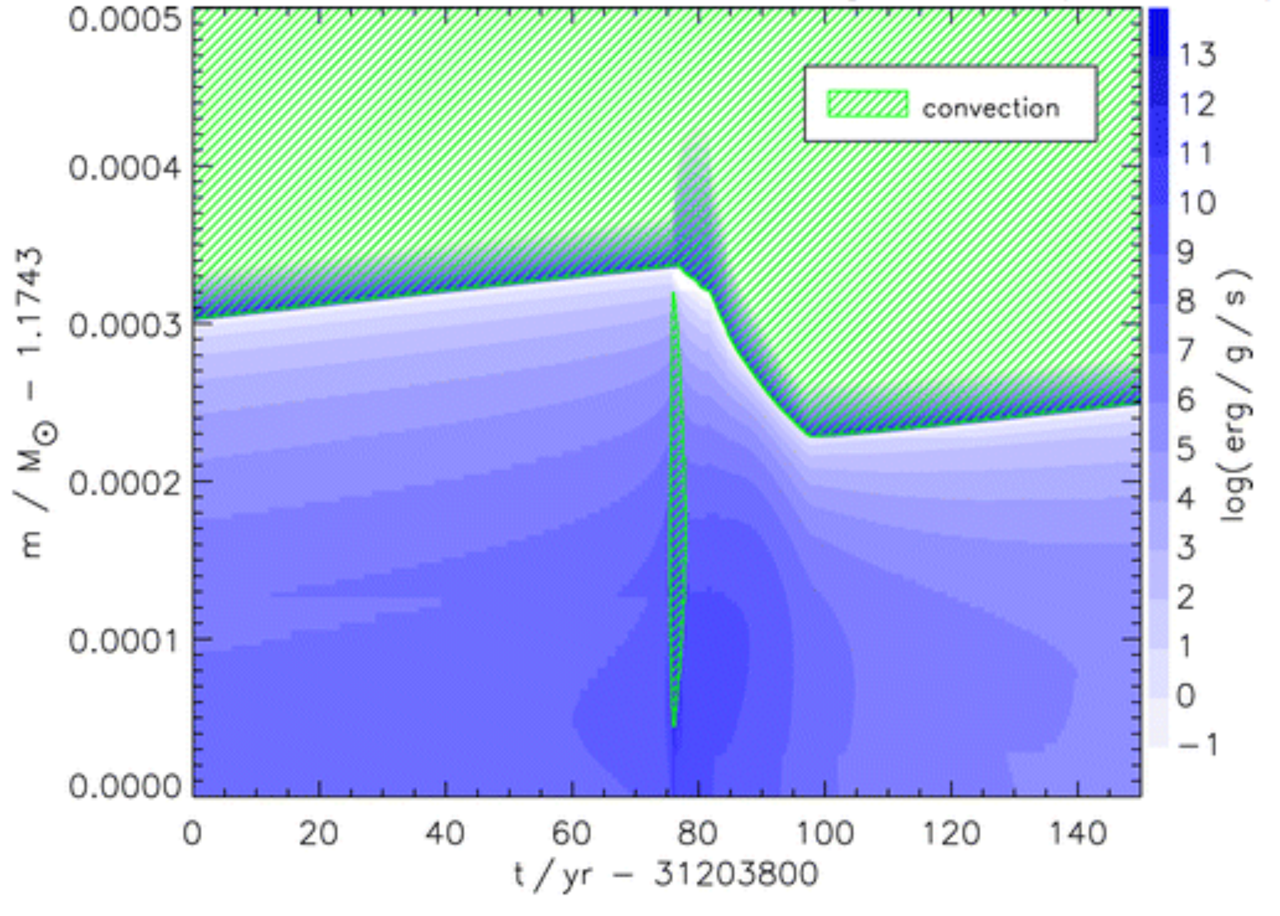


Tashibu+17

Dredge-up parameters



Poelarends+08



s-process in SAGB stars

- Stellar models from Doherty+14a,b
- Nuclear network from Lugaro+14 (324 species)
- neutron source by ^{22}Ne
  - **$N_n \sim 10^{14}$ cm^{-3}**
  - **$\tau \sim 0.04$ mbarn^{-1}**
- production of Kr (Z=36), Rb (37), and light s-process elements (Sr: 38, Y: 39, Zr:40)
- weak Fe dependence due to small τ
- small amount due to small convective shells (5×10^{-4} $M_\odot$)

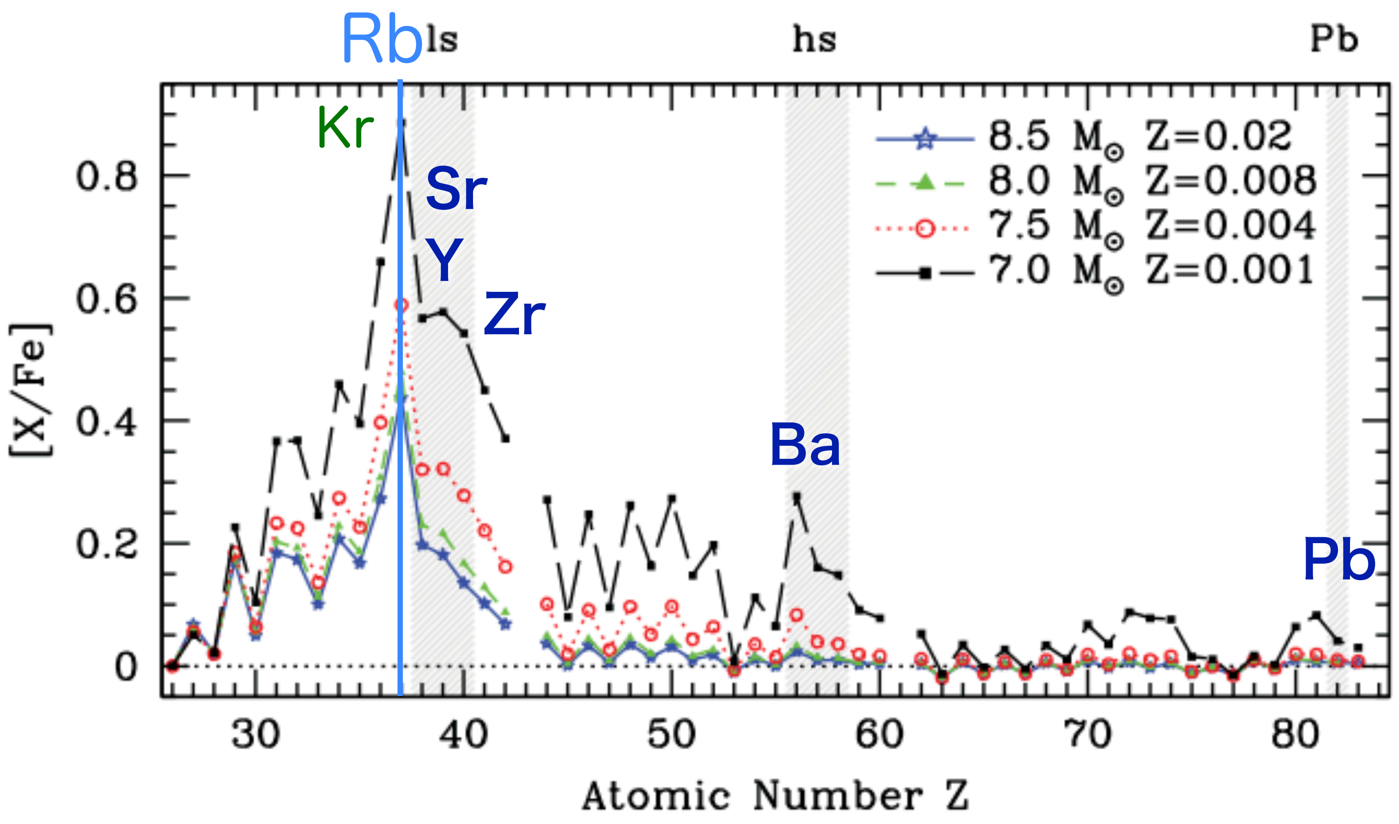


Figure 10. Heavy element nucleosynthesis yields for super-AGB stars for a range of metallicities (in [X/Fe]) all scaled to the solar abundances of Asplund et al. (2009). The breaks in the distribution are for the elements Tc ($Z = 43$) and Pm ($Z = 61$) which have no stable isotopes. The shaded regions represent the elements used to represent the three s-process peaks *ls*, *hs*, and Pb. The maximum production is for the element Rb ($Z = 37$).

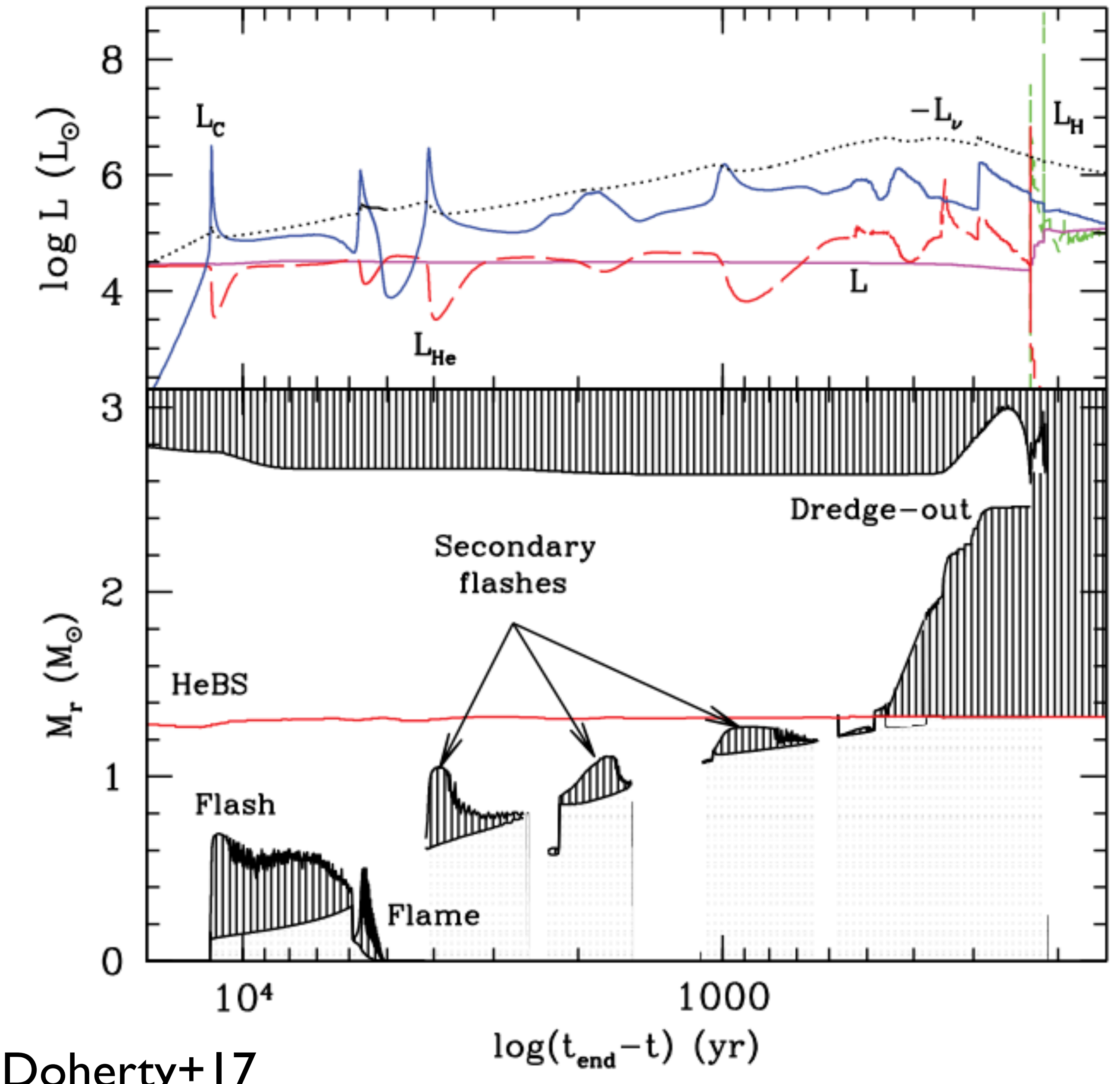
Doherty+17

M_c (He-core mass) ~ 1.15 $M_\odot$, t_{int} (duration of thermal pulses) ~ 6×10^4 yr, N_{pulse} (number of thermal pulses) ~ 100

Dredge-out in SAGB stars

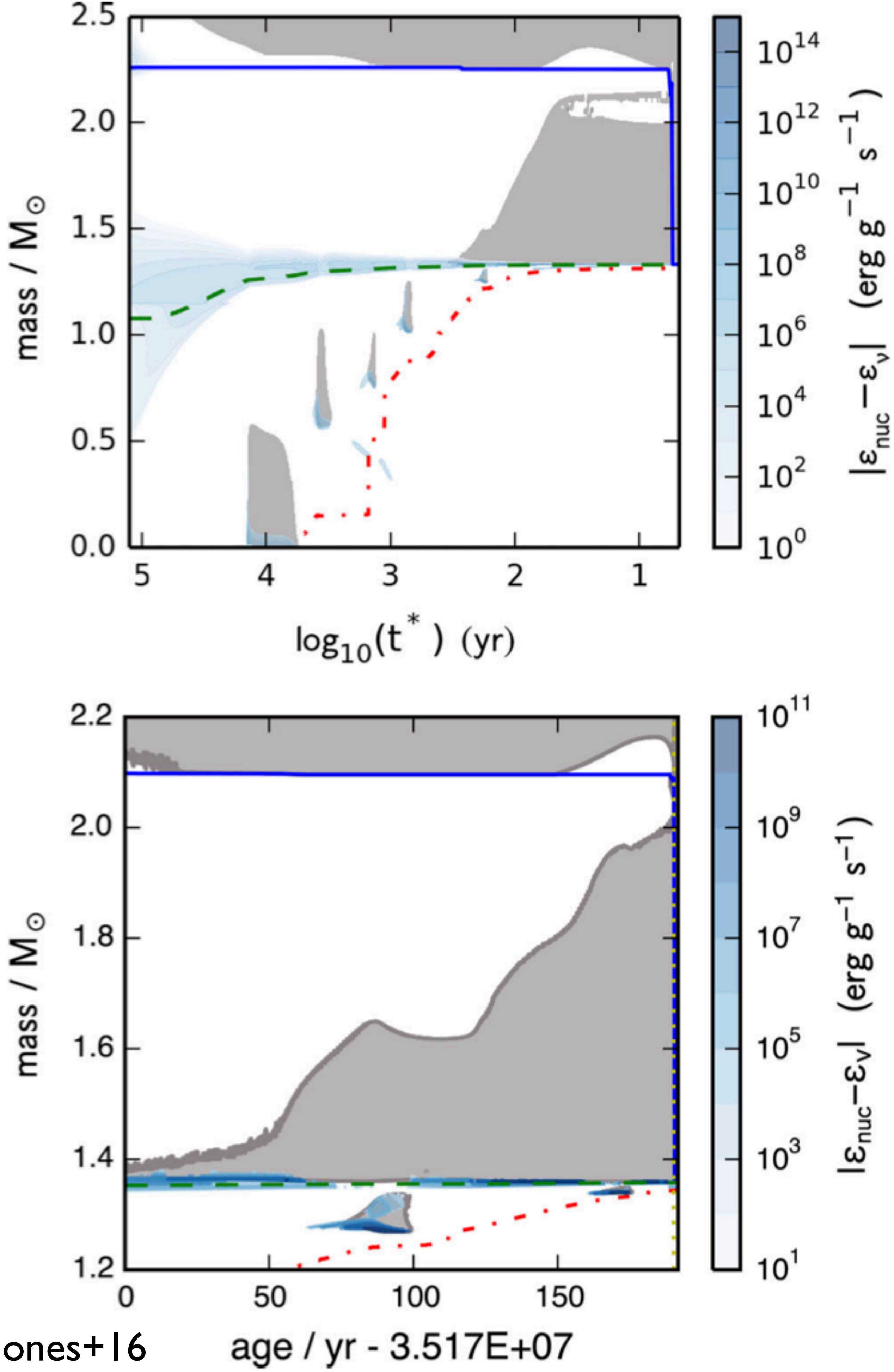
- Envelope is enriched in CNO elements. (Ritossa+99)
- Proton ingestion into He- and C-rich region produces a substantial number of free neutrons by $^{13}C(a,n)^{16}O$.

M=9.5M⊙, Z=0.001



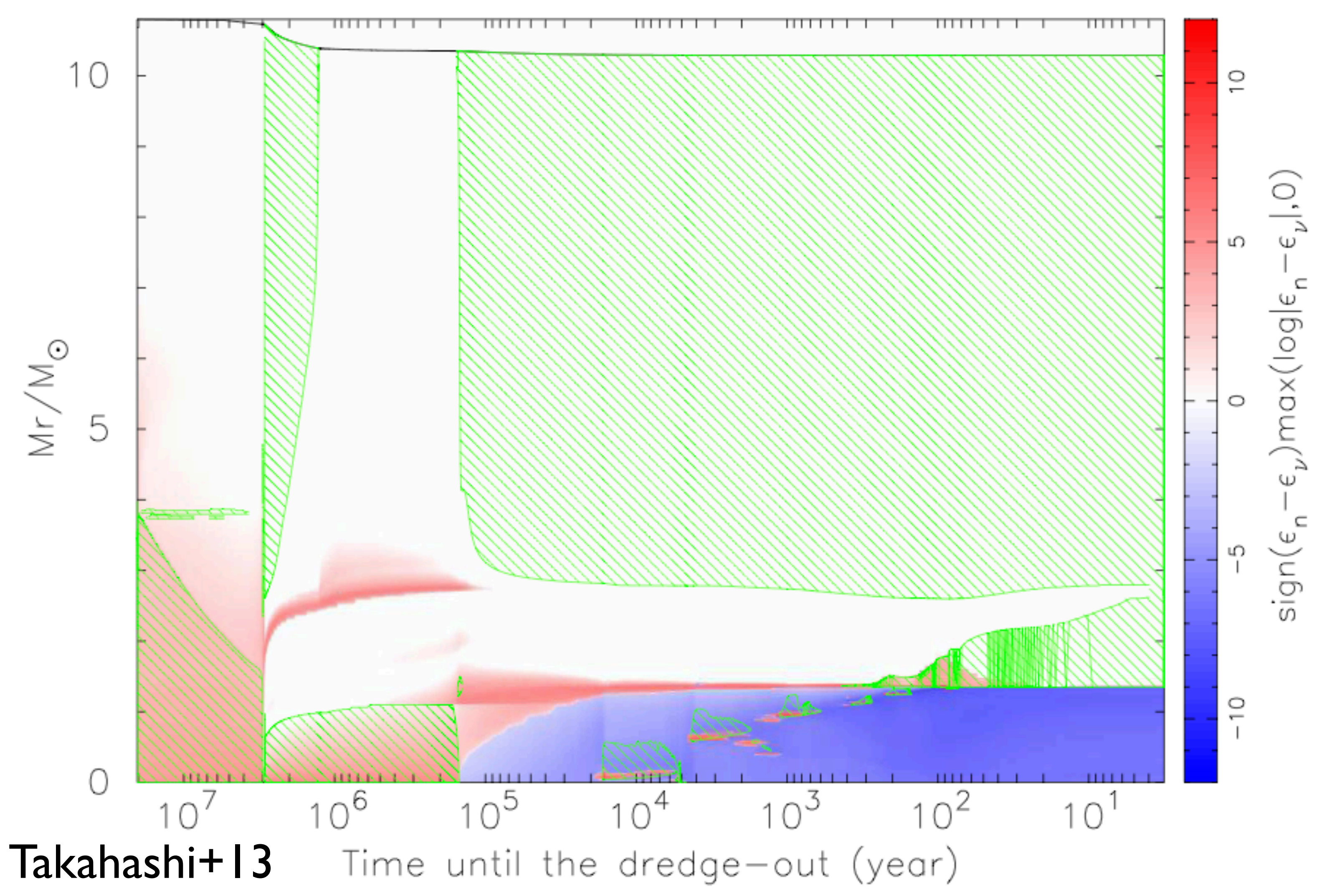
Doherty+17

M=7.5M⊙, Z=0.001

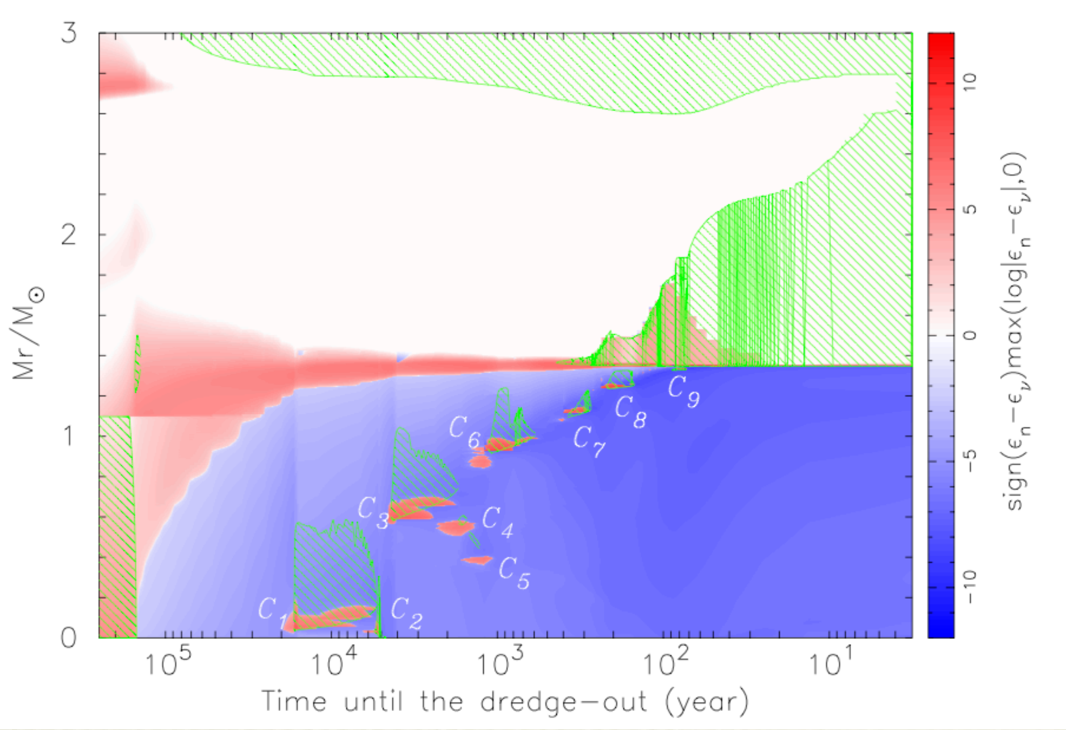


Jones+16

Dredge-out



Takahashi+13



s-process by dredge-out events

- neutron density, Nn = 10^{15} cm^{-3}
  - intermediate n-capture regime (known as ‘i-process’)
  - no calculated yields: 3D simulations, cross sections, etc.
- possible origin of CEMP-s/r (Jones+16)
  - concern is the small intershell mass ($\sim 10^{-4}$ $M_\odot$), even repeated exposure and dredge-up events may not lead to overabundances.
- rejected based on an IMF argument, the relatively few SAGB stars seem unlikely to be a major source of pollution of the CEMP-s/r stars (Abate+16).

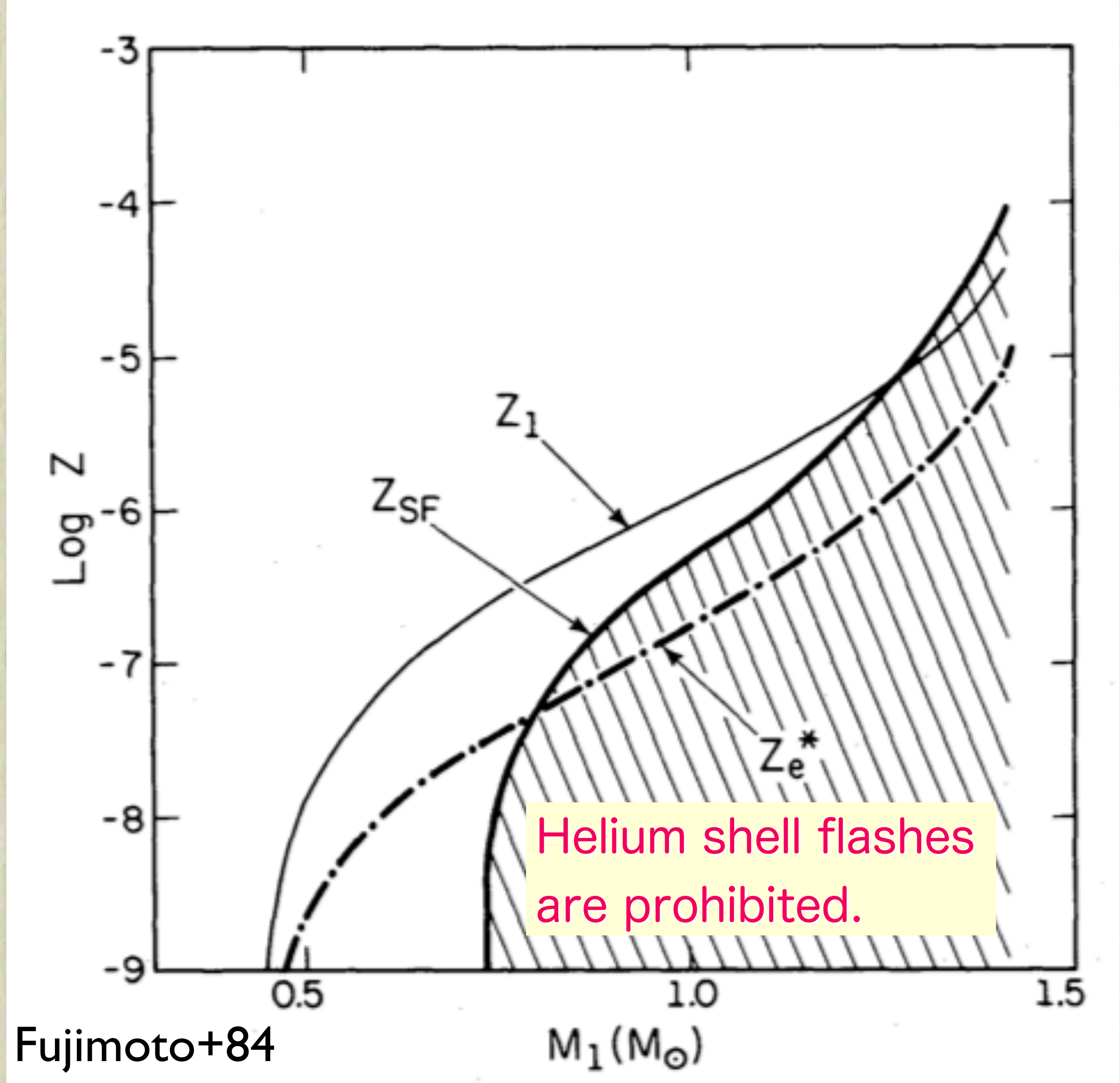
Summary - 4 s-process channels

1. radiative 13C burning
    - “standard” s-process contributed by low-mass AGB stars.
2. convective ^{22}Ne burning
    - small contribution to s-process elements by high-mass AGB and SAGB stars.
3. convective ^{13}C burning by H-ingestion
    - large contribution to s-process elements by low-mass low-metallicity AGB stars.
4. convective ^{13}C burning by C dredge-out
    - potentially large contribution to s-process elements by SAGB stars.

AGB / Super-AGB Stars at Low-Metallicity

Occurrence of SN I1/2

- At low metallicity, He burns in a steady state.
  - No pulse-driven stellar winds are expected.
  - Core mass will grow to have Chandrasekhar mass limit, which leads to supernova explosions.
- SN I1/2 is a thermonuclear explosion (Type I) with a H emission lines in its spectra (Type II).



Helium shell flashes are prohibited.

Fujimoto+84

core mass

Stability of helium shell flashes

F > 0: unstable

F < 0: stable

Stability of helium shell flashes are mainly controlled by

1 $\epsilon_\nu = \left(\frac{\partial \ln \epsilon_n}{\partial \ln T} \right)_\rho$

temperature dependence of nuclear burning rate

2 f: flatness parameter

geometry of He-burning shell,

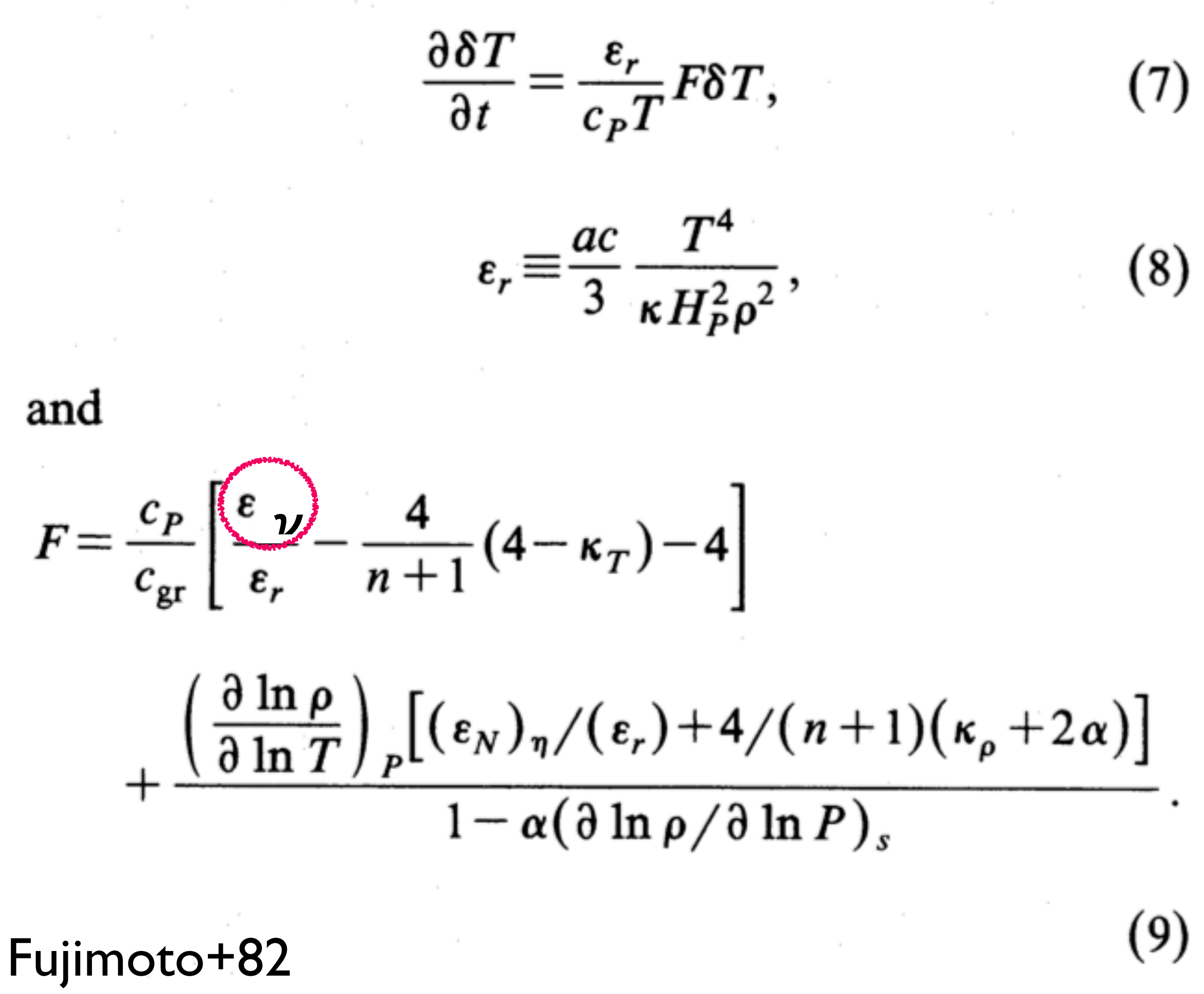
f ~ 0, spherical symmetry, weak flash

f ~ 1, strong flash

3 electron degeneracy

$P \propto \rho^{5/3}$

complete degeneracy, non-relativistic.



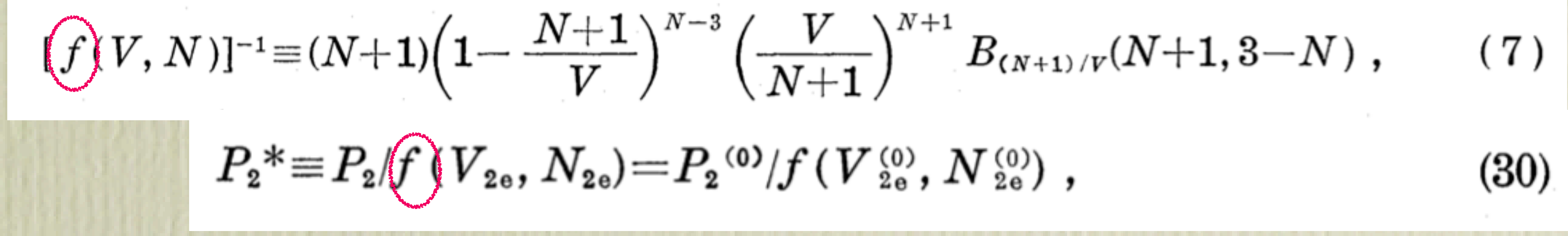
$$\frac{\partial \delta T}{\partial t} = \frac{\varepsilon_r}{c_P T} F \delta T, \qquad (7)$$

$$\varepsilon_r \equiv \frac{ac}{3} \frac{T^4}{\kappa H_P^2 \rho^2}, \qquad (8)$$

and

$$F = \frac{c_P}{c_{\rm gr}} \left[\frac{\varepsilon_\nu}{\varepsilon_r} - \frac{4}{n+1}(4 - \kappa_T) - 4 \right] + \frac{\left(\frac{\partial \ln \rho}{\partial \ln T} \right)_P [(\varepsilon_N)_\eta / (\varepsilon_r) + 4/(n+1)(\kappa_\rho + 2\alpha)]}{1 - \alpha(\partial \ln \rho / \partial \ln P)_s}. \qquad (9)$$

Fujimoto+82



$$[f(V, N)]^{-1} \equiv (N+1)\left(1 - \frac{N+1}{V}\right)^{N-3} \left(\frac{V}{N+1}\right)^{N+1} B_{(N+1)/V}(N+1, 3-N), \qquad (7)$$

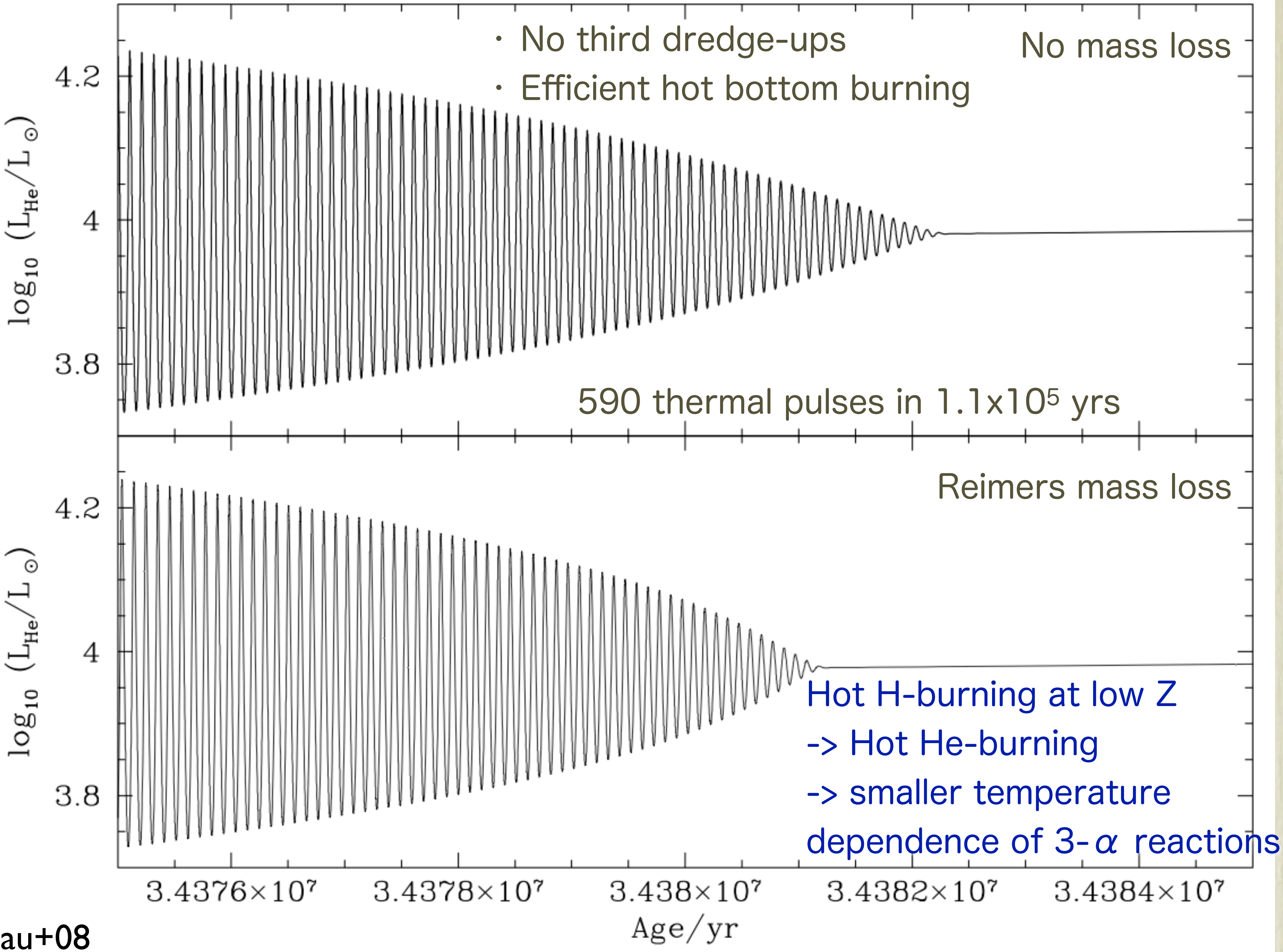
$$P_2^* \equiv P_2 / f(V_{2e}, N_{2e}) = P_2^{(0)} / f(V_{2e}^{(0)}, N_{2e}^{(0)}), \qquad (30)$$

Sugimoto+Fujimoto78

See also Schwarzschild+Harm65, Sackmann77, Yoon+04

End of thermal pulses

M=7M☉, Z=0



- No third dredge-ups
- Efficient hot bottom burning

No mass loss

590 thermal pulses in $1.1\text{x}10^5$ yrs

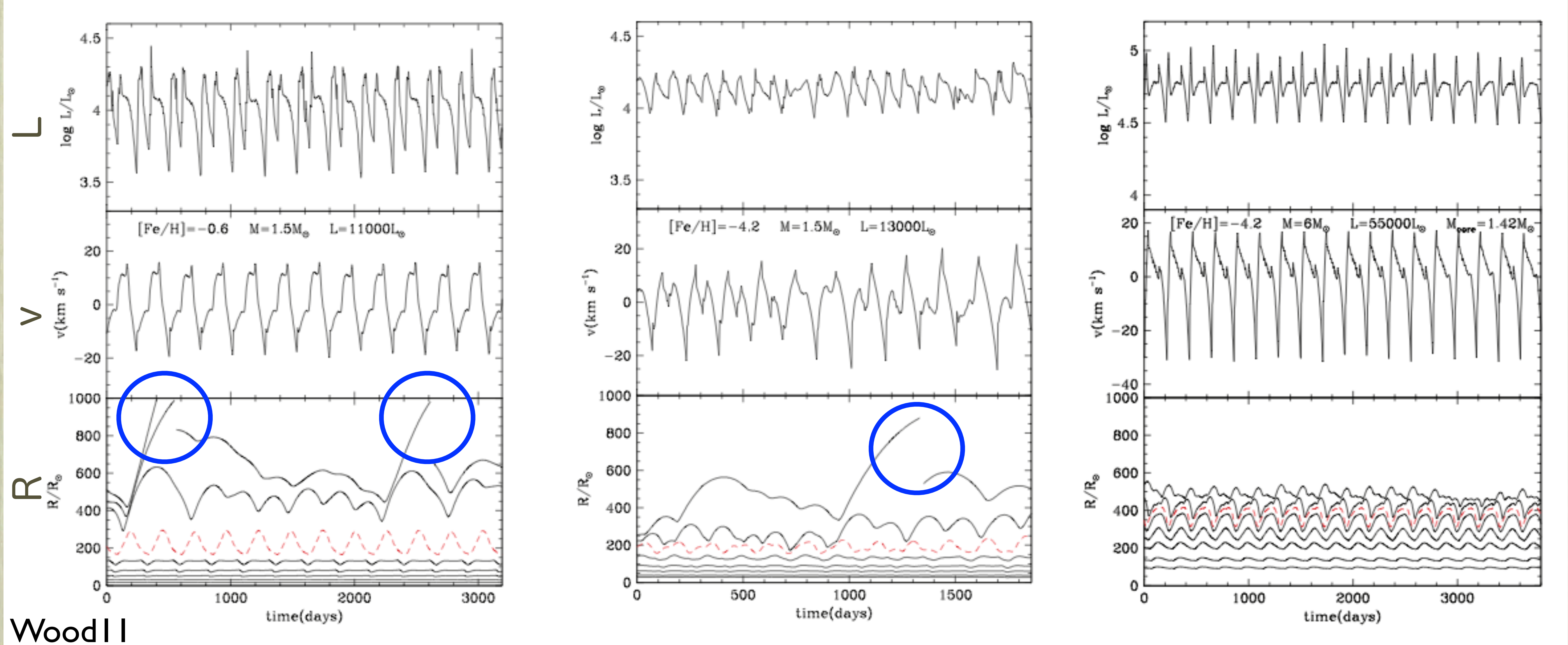
Reimers mass loss

Hot H-burning at low Z
-> Hot He-burning
-> smaller temperature dependence of 3-α reactions

Lau+08

Suppression of Mass Loss during the AGB Phase

$1.5M_\odot$, [Fe/H]=-0.6 $1.5M_\odot$, [Fe/H]=-4.2 $6M_\odot$, [Fe/H]=-4.2



Wood11

Growth of pulsations during the thermal pulses on the AGB phase

Luminosity is increased from 11,000 $L_\odot$ to 13,000 $L_\odot$.

Luminosity is taken for maximum possible value for an AGB star that is not undergoing HBB.