Evolution, Explosion and Nucleosynthesis of PopIII Massive Stars

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work in collaboration with

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Evolution, explosion and nucleosynthesis of zero metallicity massive stars (Limongi & Chieffi 2012)

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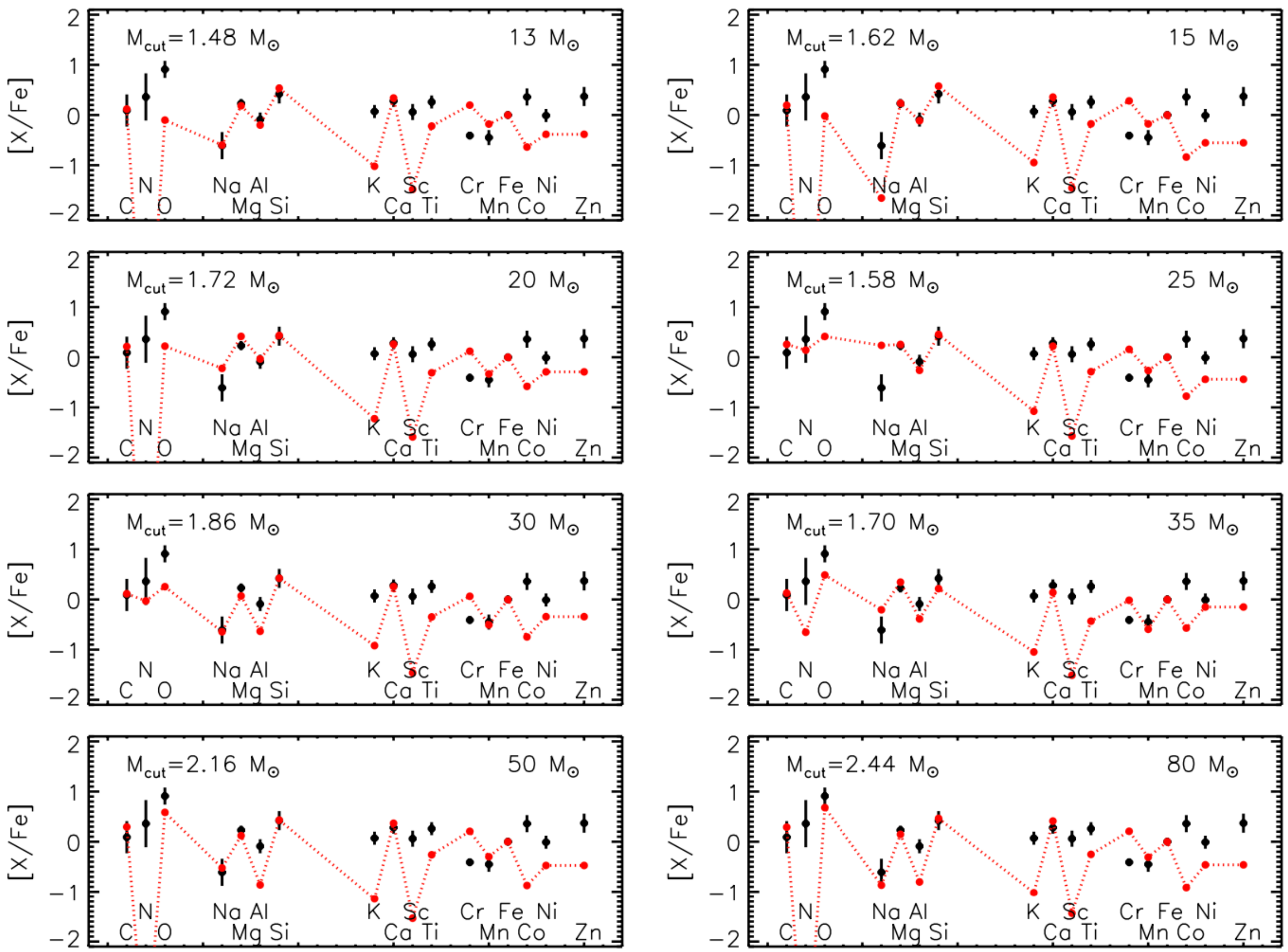

Figure 7. Best fit to the observed abundances of the average star (Cayrel et al. 2004) obtained with the present set of models following the procedure described in the text.

The Stellar Models

Presupernova Evolution from the preMS up to the onset of the iron core collapse

Initial Masses ($M_\odot$): 15, 25

Initial Metallicity Z=0

Element	Mass Fraction
^{1}H	0.7550
^{2}H	$3.8507\ 10^{-5}$
^{3}He	$2.4916\ 10^{-5}$
^{4}He	0.2449
^{7}Li	$8.4564\ 10^{-10}$

Fields+ 2020, Coc+ 2013

Initial Rotation Velocities (km/s): 0, 150, 300, 450, 600, 700, 800

Stellar Evolution Code: FRANEC (Chieffi & Limongi 2013, Limongi & Chieffi 2018)

The FRANEC code in a nutshell

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$$\frac{\partial P}{\partial M} = -\frac{GM}{4\pi R^4} f_P$$

$$\frac{\partial R}{\partial M} = \frac{1}{4\pi \rho R^2}$$

$$\frac{\partial T}{\partial M} = -\frac{GMT}{4\pi R^2 P} \nabla \frac{f_T}{f_P}$$

$$\frac{\partial L}{\partial M} = \varepsilon_n + \varepsilon_g + \varepsilon_\nu$$

$$\frac{\partial Y_i}{\partial t} = \left(\frac{\partial Y_i}{\partial t}\right)_{\rm nuc} + \frac{\partial}{\partial m}\left[\left(4\pi\rho r^2\right)^2 \left(D_{\rm mix} + D_{\rm semi} + D_{\rm rot}\right)\left(\frac{\partial X_i}{\partial m}\right)\right]$$

$$\rho \frac{d}{dt}\left(r^2\omega\right) = \frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4 \omega U\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho D_{\rm shear} r^4 \frac{\partial \omega}{\partial r}\right)$$

Meridional Circulation — Shear Instabilities

(4^{th} order → 4 ODE solved by means of a relaxation method)

- FULL COUPLING of all EQUATIONS
- INCLUSION OF ROTATION:
  - Shellular Rotation (Meynet & Maeder 1997)
  - Transport of Angular Momentum due to shear instabilities and meridional circulation (Advection/Diffusion equation, Meynet & Maeder 2000)
  - Coupling of Rotation and Mass Loss
- MASS LOSS:
  - OB: Vink et al. 2000,2001
  - RSG: de Jager 1988+Van Loon 2005 (Dust driven wind)
  - WR: Nugis & Lamers 2000
  - Supra Eddington Mass Loss
  - Mechanical mass loss due to rotation
- TWO NUCLEAR NETWORKS:
  - 380 iso (n-^{209}Bi) H/He Burning
  - 524 iso (n- ^{209}Bi) Advanced Burning

Chieffi & Limongi 2013, ApJ, 764, 21
Limongi & Chieffi 2018, ApJS)
Roberti, Limongi & Chieffi (in prep.)

Explosions

Explosions induced by a thermal bomb

Hydro Code: HYPERION (Limongi & Chieffi 2020)

1D Lagrangian Hydro Code, PPM, Riemann Solver, Flux Limited Diffusion Radiation Transport, Nuclear Burning, Nuclear EoS at NSE

$$\frac{\partial \rho}{\partial t} = -4\pi\rho^2 \frac{\partial r^2 v}{\partial m}$$

$$\frac{\partial v}{\partial t} = -4\pi r^2 \frac{\partial P}{\partial m} - \frac{Gm}{r^2}$$

$$\frac{\partial E}{\partial t} = -\frac{\partial}{\partial m}\left(4\pi r^2 v P + L\right) + \epsilon$$

$$\frac{\partial Y_i}{\partial t} = \sum_j c_i(j)\lambda_j Y_j + \sum_{j,k} c_i(j,k)\rho N_{\rm A} < \sigma v >_{j,k} Y_j Y_k$$

$$+ \sum_{j,k,l} c_i(j,k,l)\rho^2 N_{\rm A}^2 < \sigma v >_{j,k,l} Y_j Y_k Y_l \qquad i = 1, ..., N$$

$$L = -\left(4\pi r^2\right)^2 \frac{\lambda a c}{3\kappa} \frac{\partial T^4}{\partial m}$$

Explosion parameters calibrated on SN1987A:

Explosion energy: 2 foe

Deposition time: 0.01 s

Deposition zone: 0.01 $M_\odot$

Non-Rotating Models – Core H Burning

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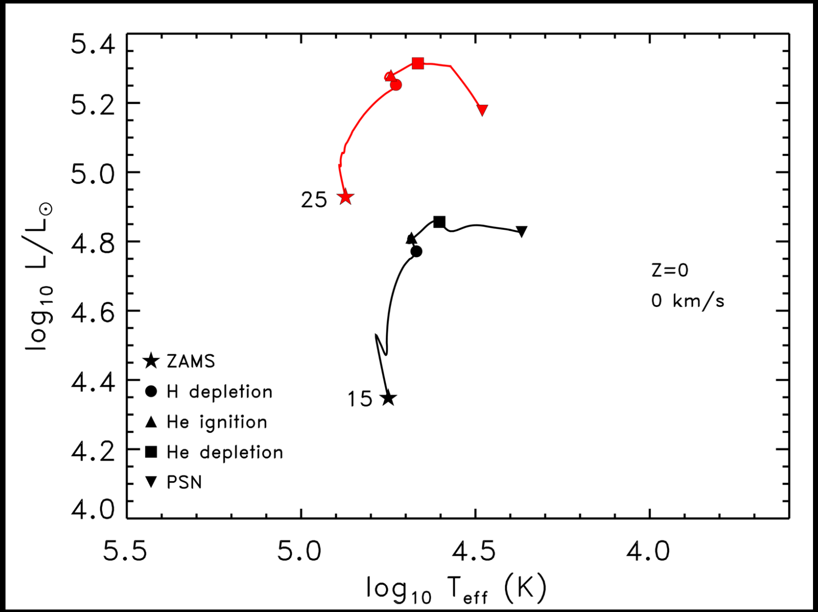
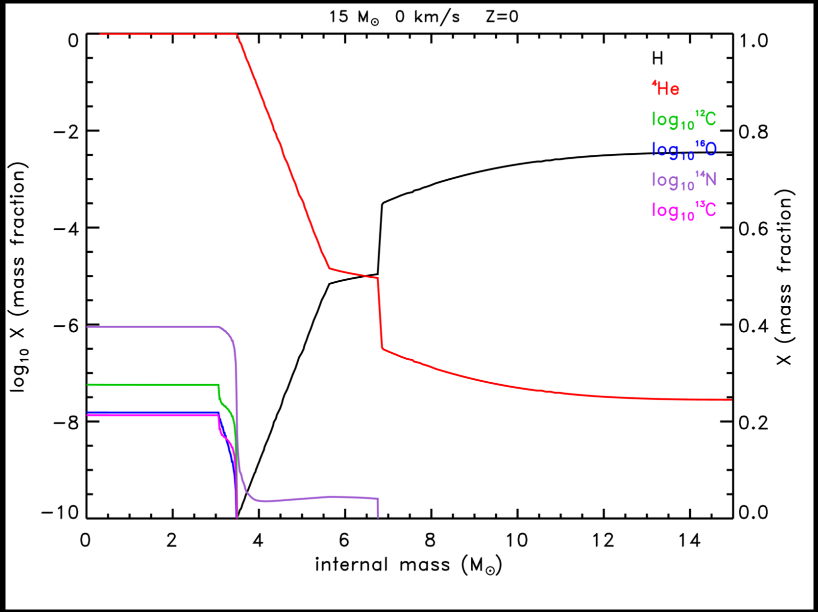
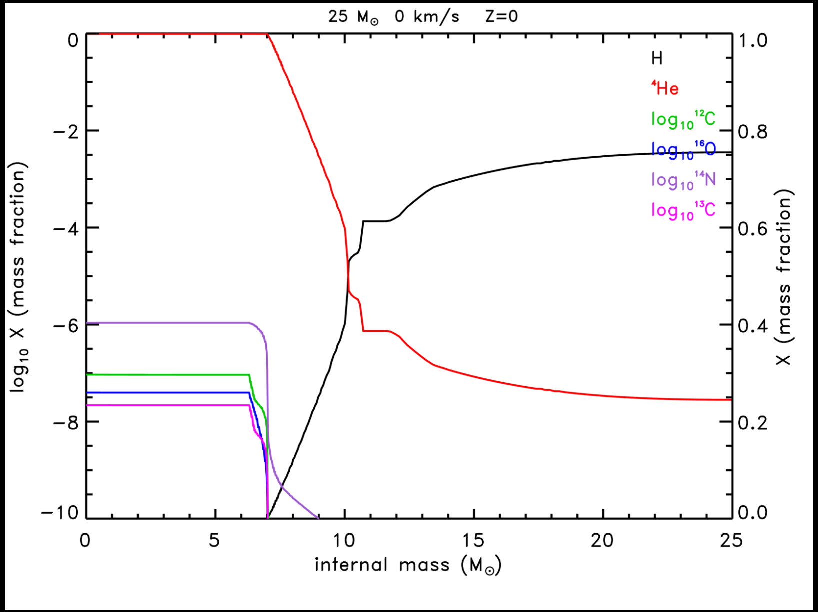
- low opacity → evolution as BSGs
- negligible mass loss → evolution at constant mass
- no CNO → H burning at high temperature (some ^{12}C production by partial activation of 3α required)
- $^{14}N \sim 10^{-6}$ in mass fraction at core H depletion in both models

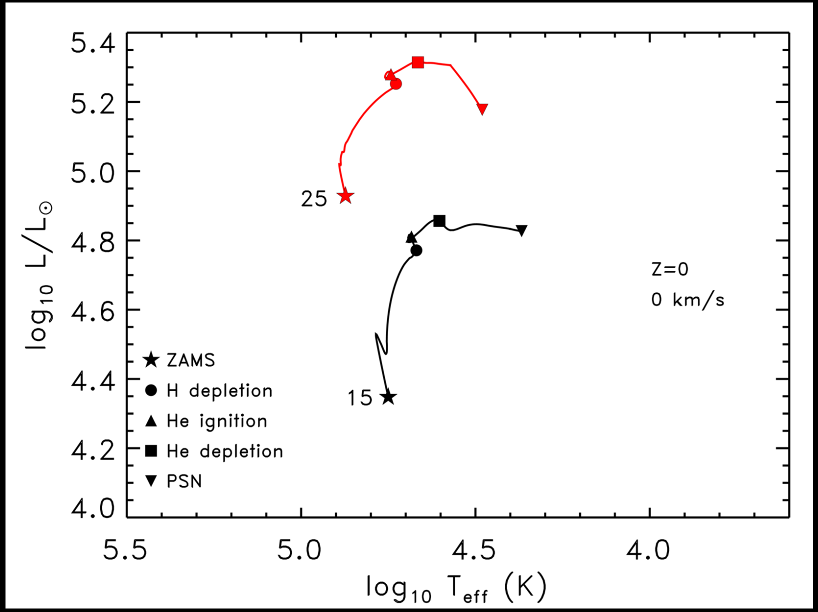


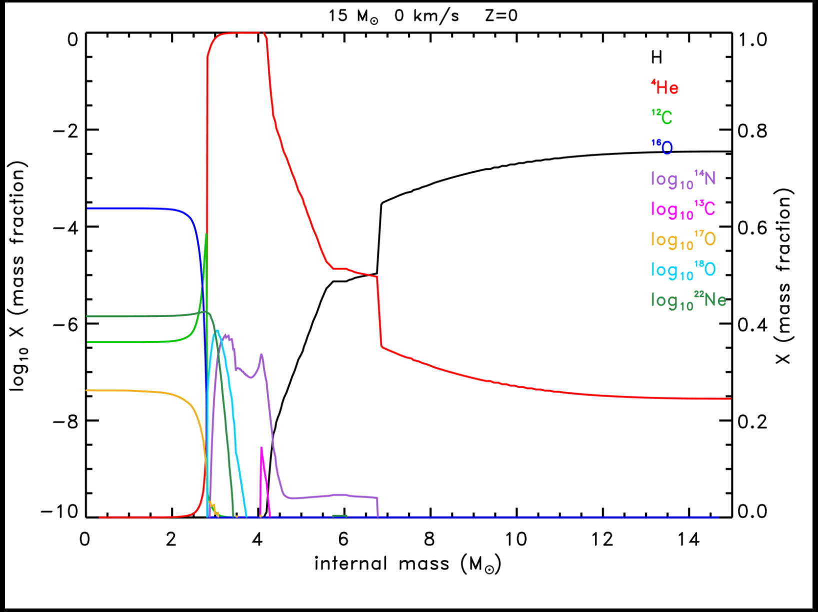


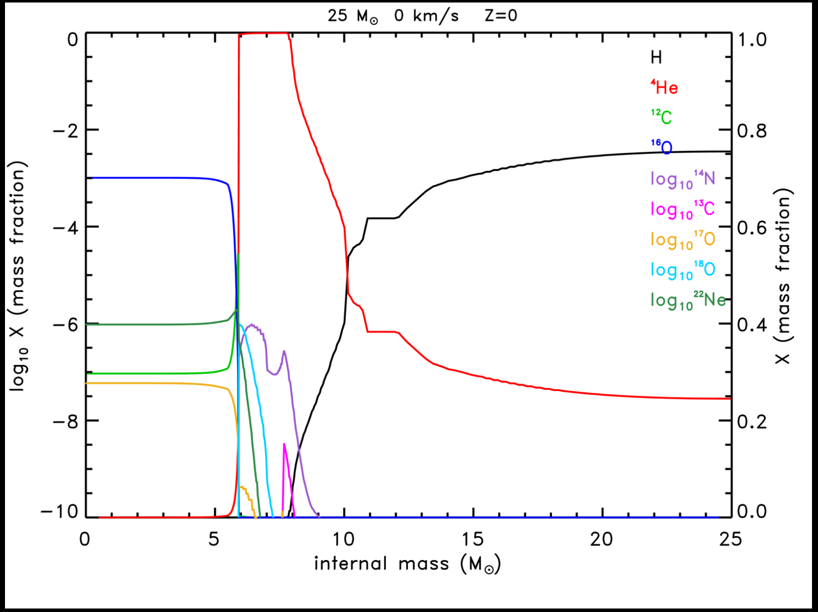


Non-Rotating Models – Core He Burning

- ignite and burn He as BSGs
- negligible mass loss → evolution at constant mass
- physical evolution of the He core in core He burning does not depend on the initial metallicity
- ^{14}N left by H burning fully converted into ^{22}Ne part of which constitutes a neutron source through the ^{22}Ne(α,n)^{25}Mg reaction
- the low abundance of ^{22}Ne and the lack of seeds nuclei (mainly ^{56}Fe) prevents an efficient s-process nucleosynthesis → a negligible quantity of heavy elements are produced





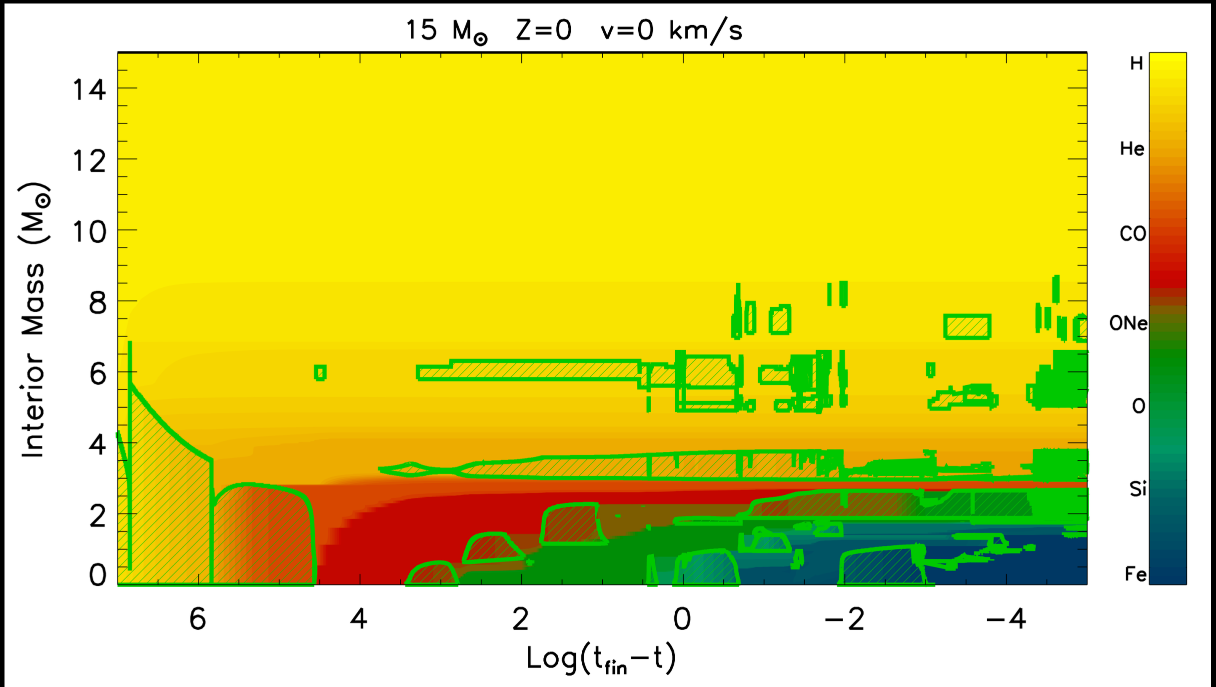


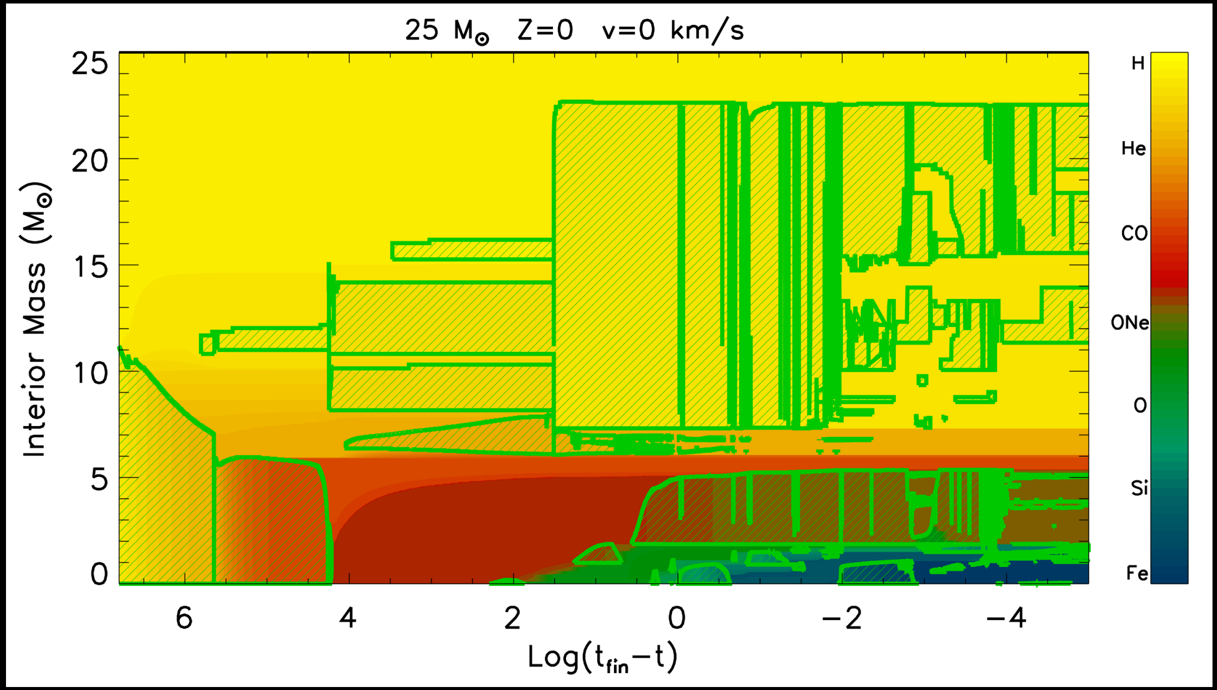
Non-Rotating Models – Advanced Burning Stages

- evolution of the CO core does not depend on the initial metallicity

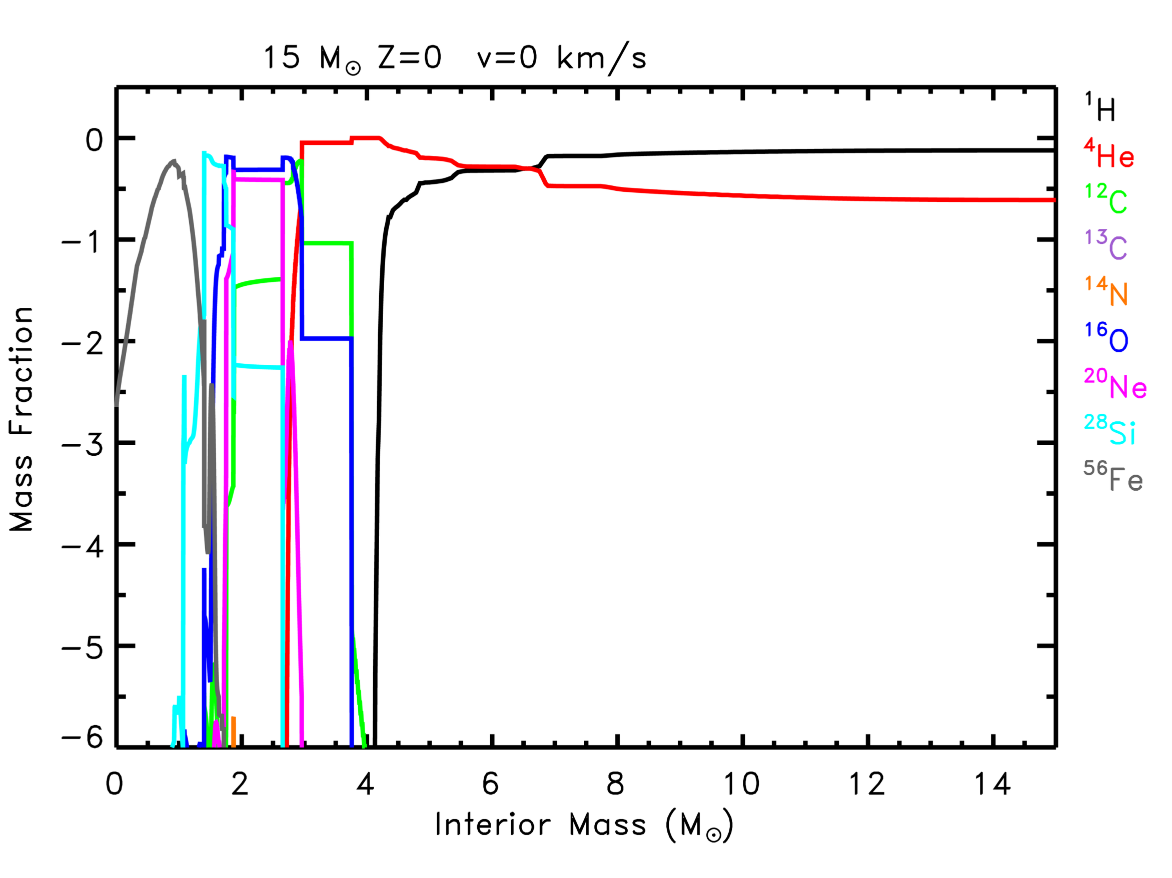
- typical evolution of a massive star: four major burning, C, Ne, O, Si; 1 to 4 C convective shells and 1 to 3 convective episodes for each of the Ne, O and Si shell burning; formation of iron core

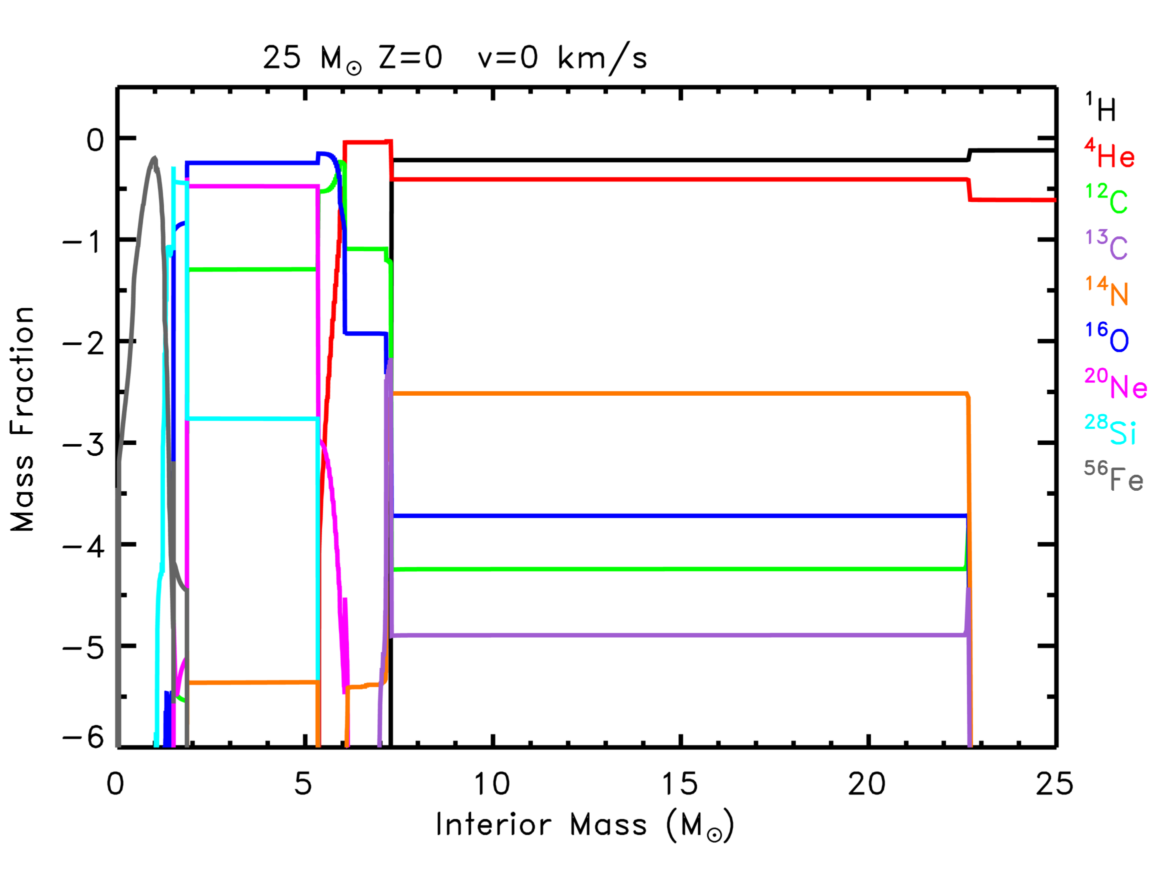
- Merging of the He and H convective shells (in the 25 $M_\odot$) due to low entropy barrier → primary ^{14}N production (and in general of all the CNO nuclei)



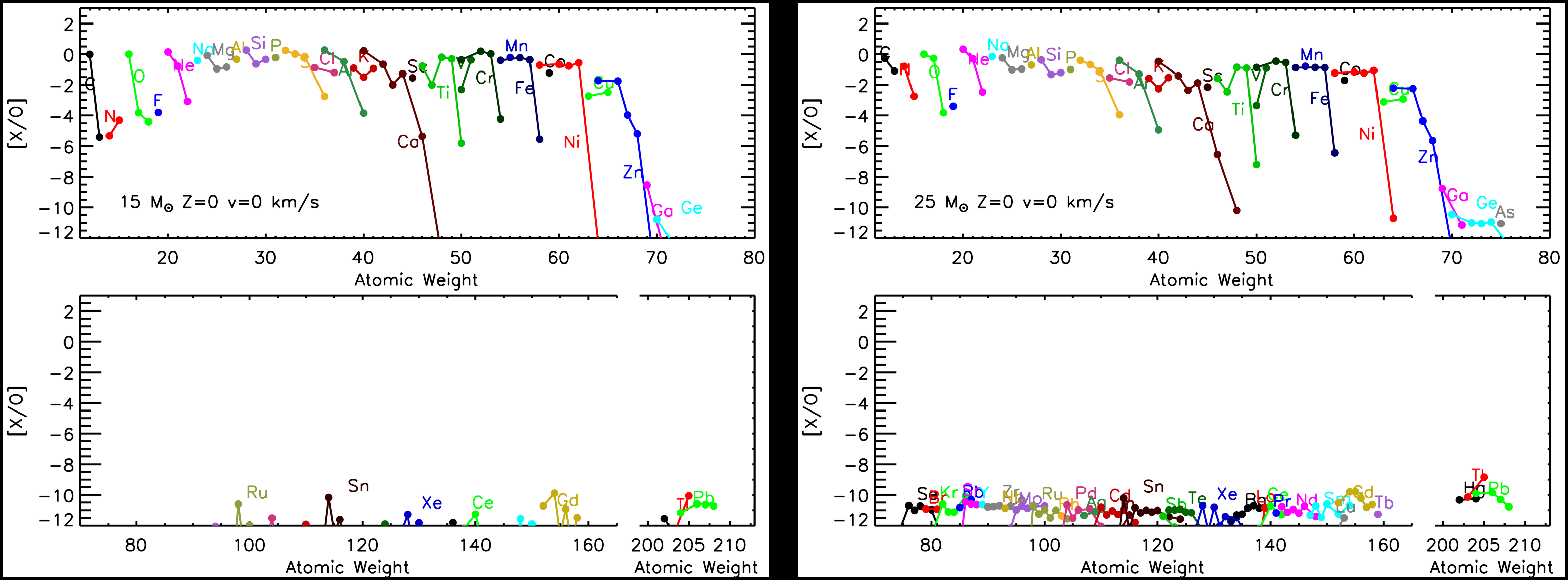


Non-Rotating Models – Presupernova Composition

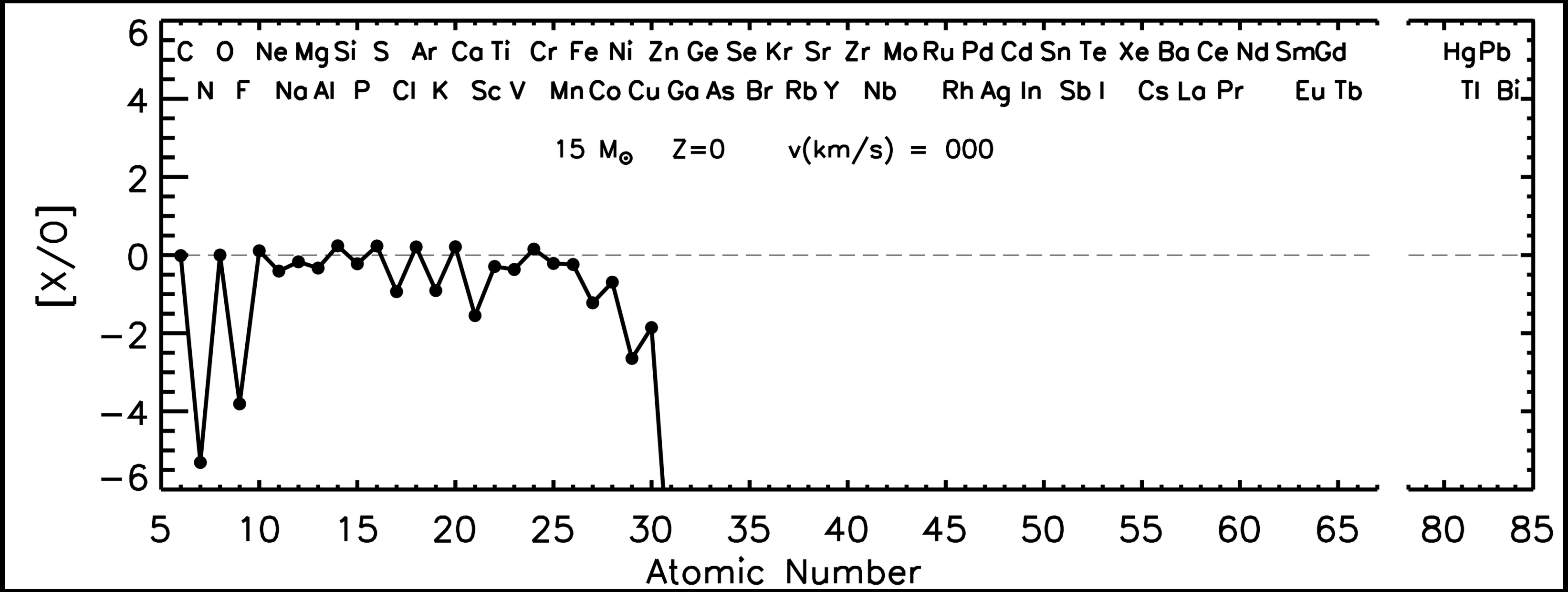


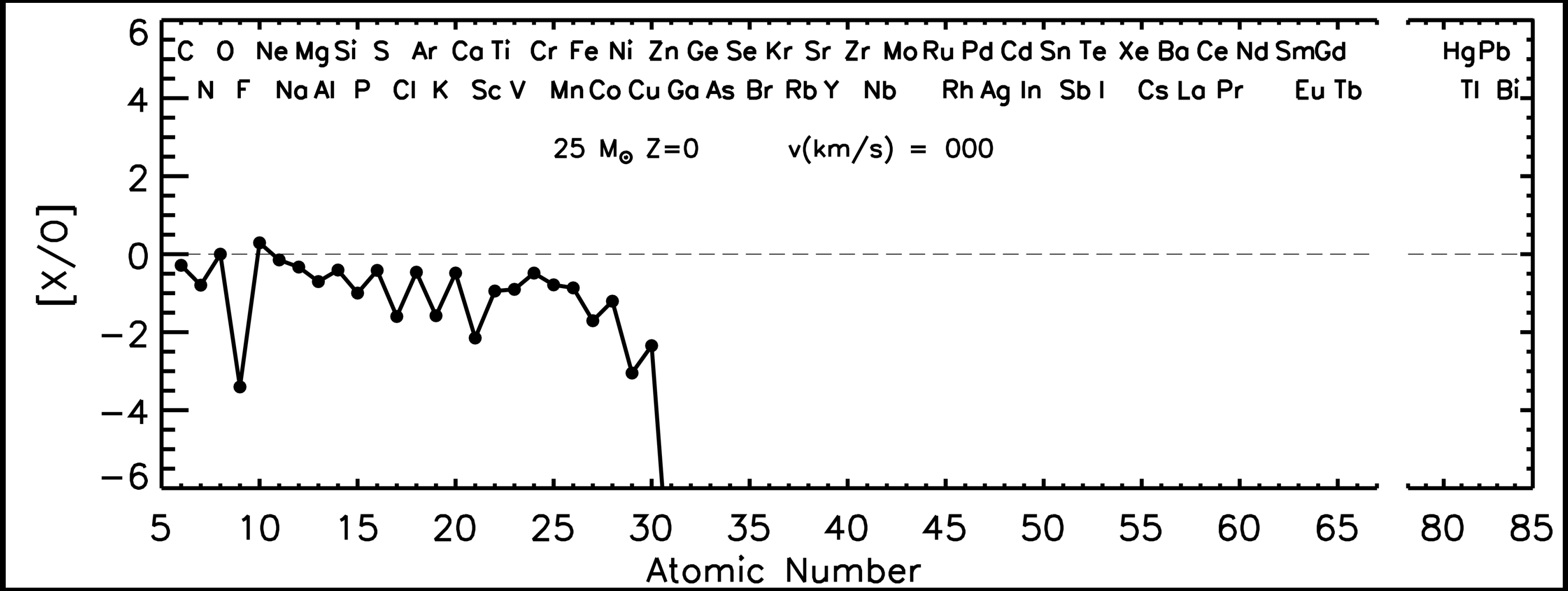


Non-Rotating Models – Chemical Composition of the Ejecta



Non-Rotating Models – Chemical Composition of the Ejecta





The Effect of Rotation

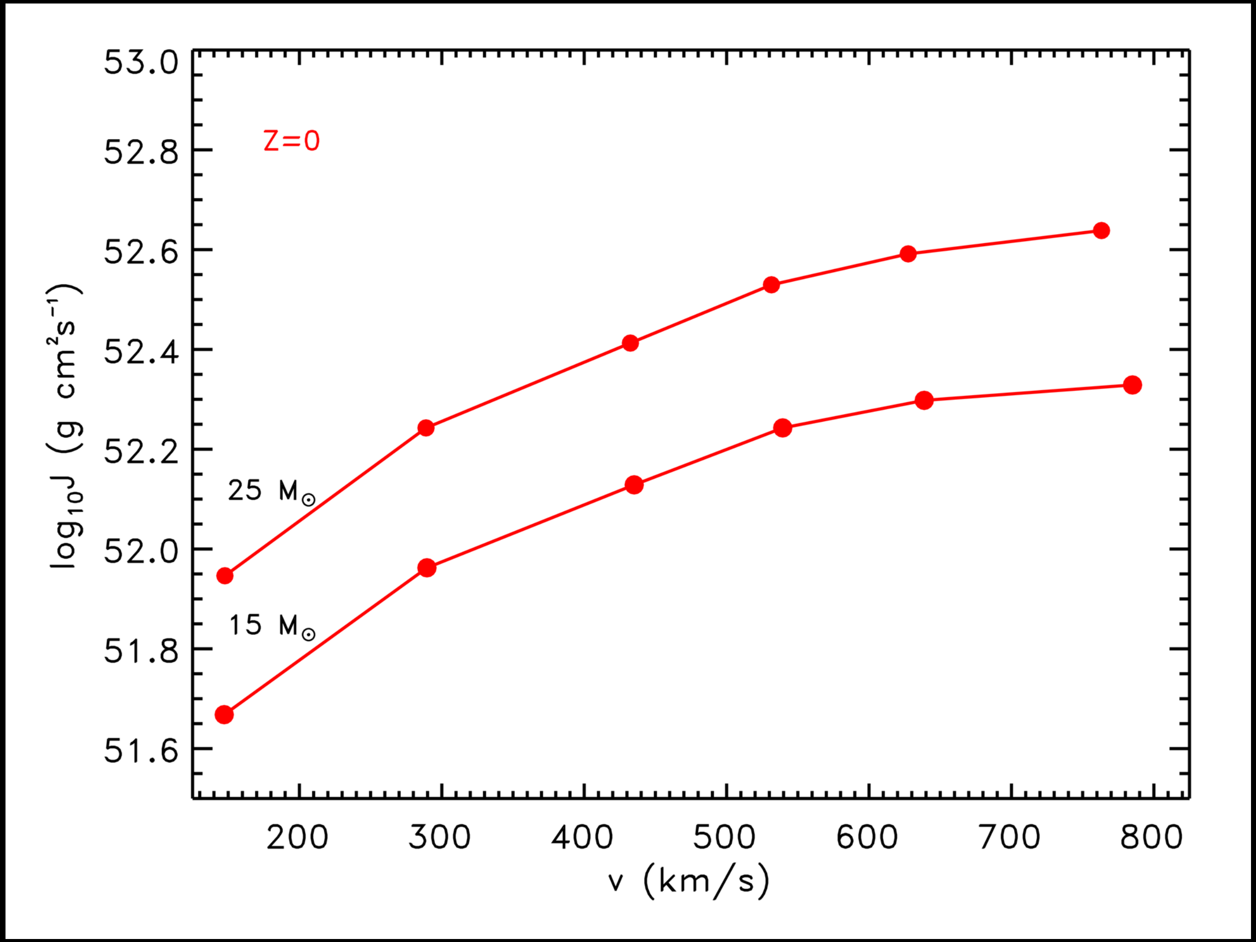
- Drives some mixing in layers that would otherwise be in radiative equilibrium
- Forces stronger and faster inflation mainly because of the centrifugal force

↓

- Peculiar nucleosynthesis
- Larger cores
- More compact interior structures
- Increased mass loss

Rotating Models

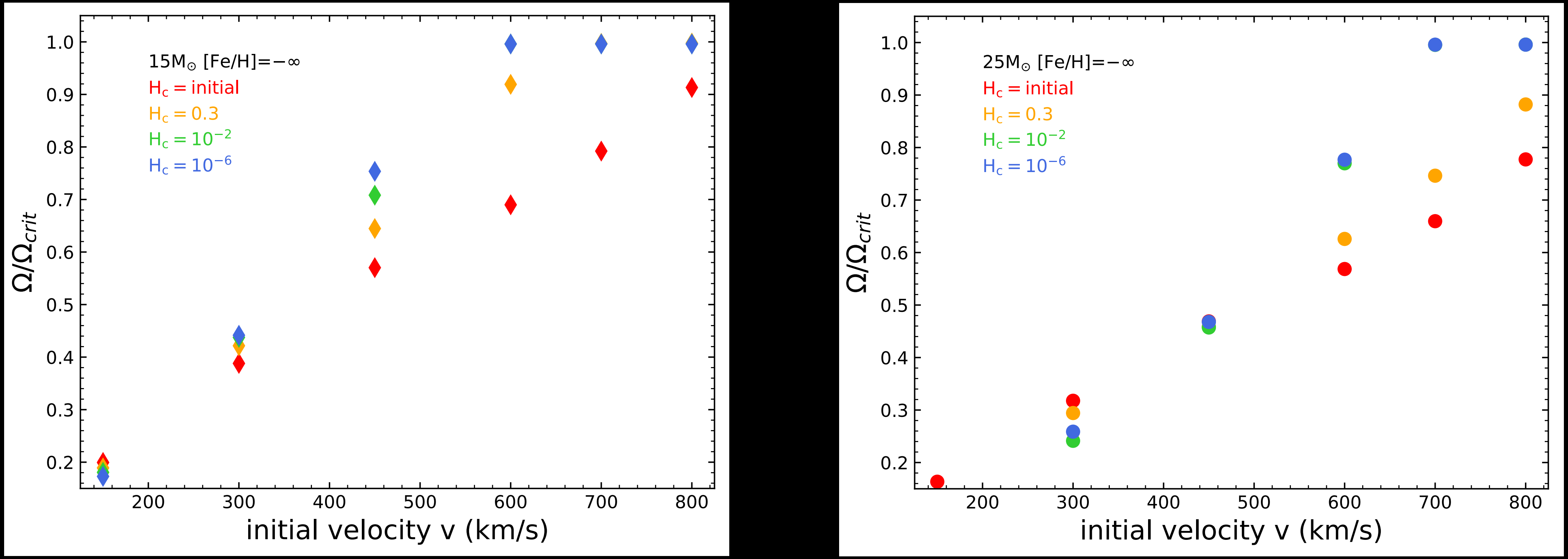
Angular momentum increases as the initial mass increases and as the initial metallicity increases (larger radii)



Rotating Models – Core H Burning

ω/ω_{crit} increases during core H burning. It reaches ~1 for the fastest rotating models due to

- efficient angular momentum transport from the interior to the surface
- lack of efficient angular removal from the surface because of negligible mass loss



- Modest amount of mass loss: ω/ω_{crit} ~1 reached toward the end of core H burning

Rotating Models – Core H Burning

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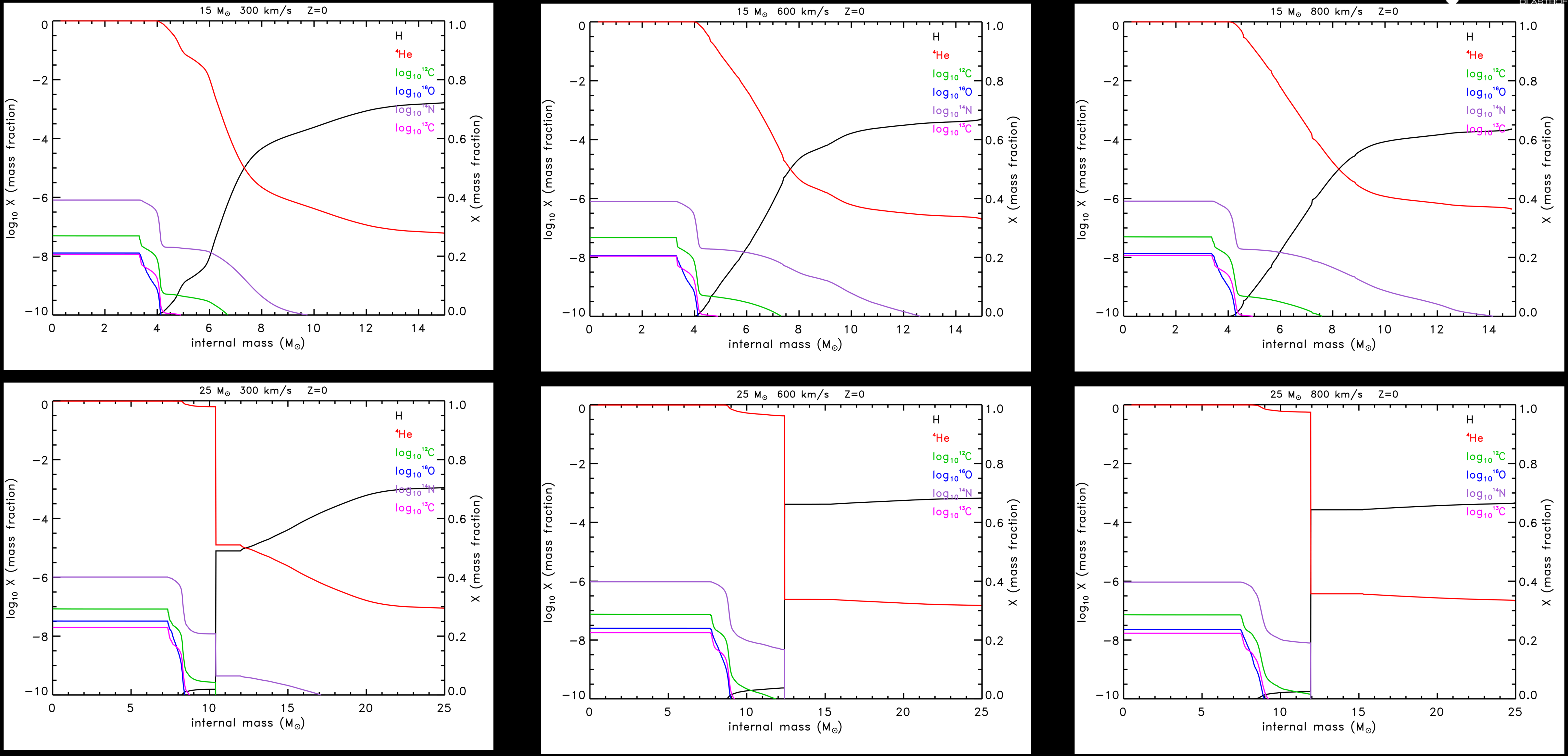
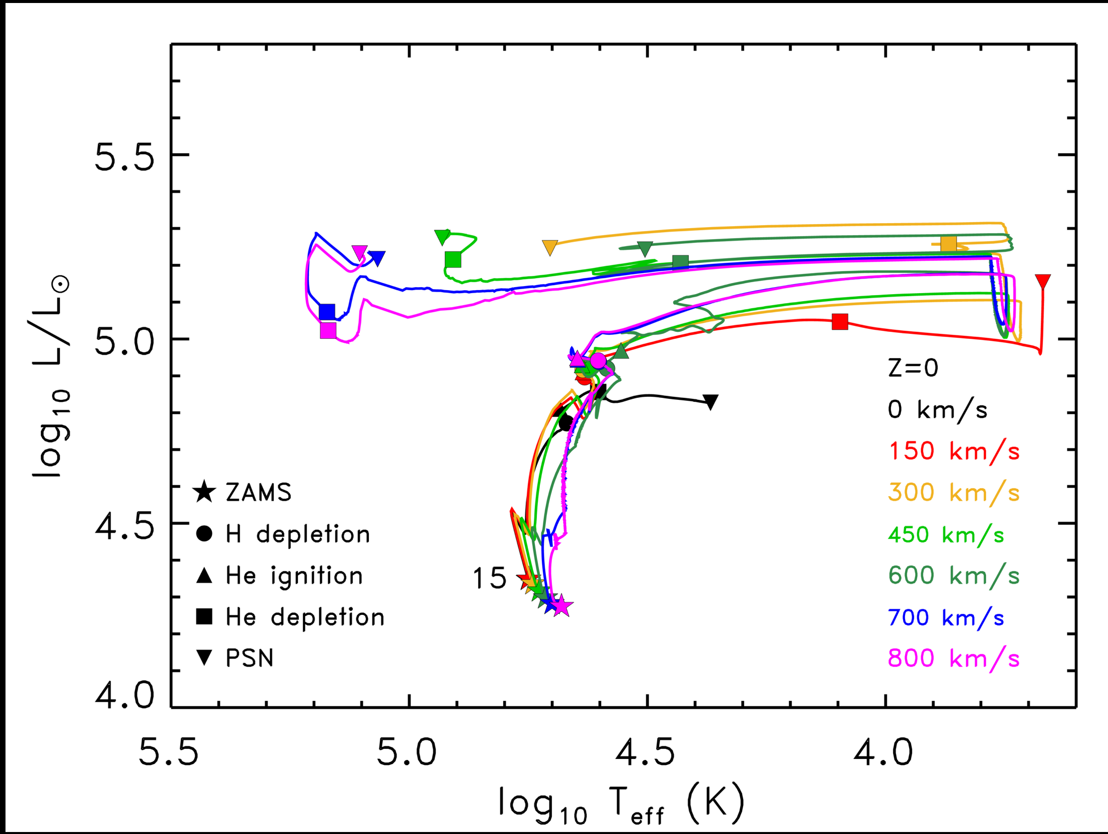


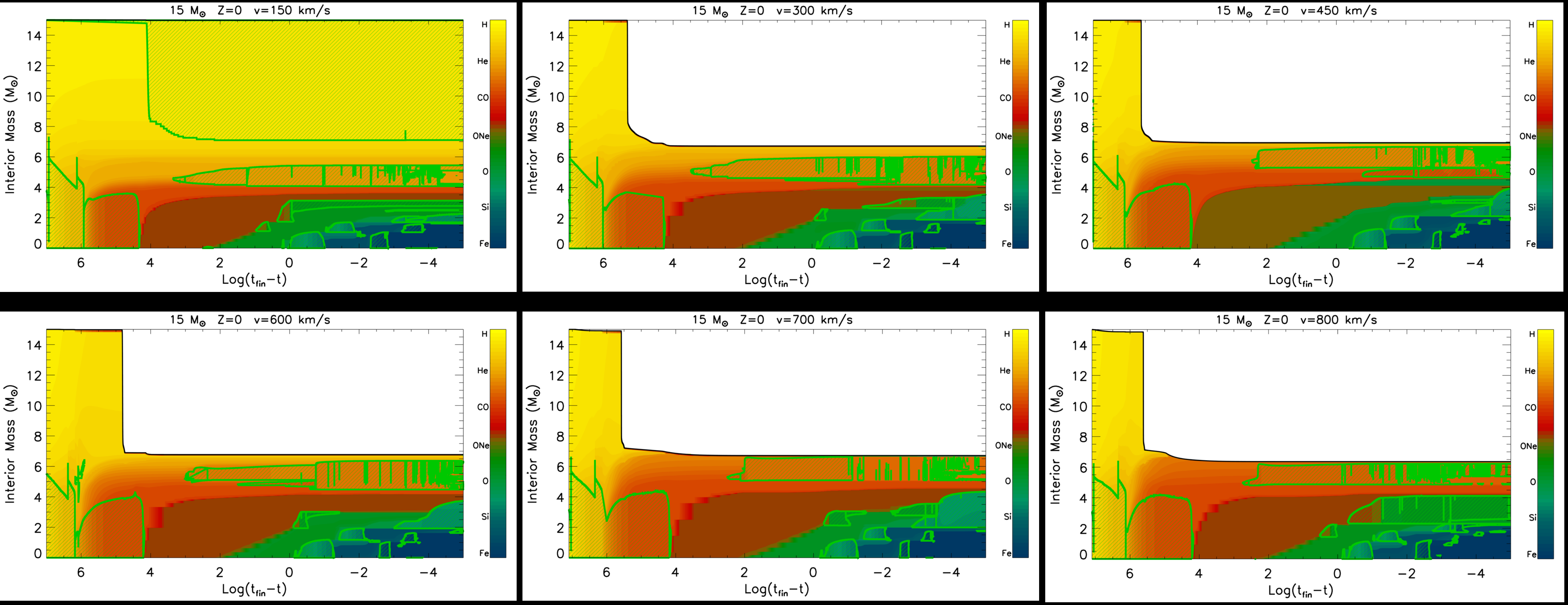
- No quasi-homogeneous mixing in spite of the high $\boldsymbol{\omega/\omega_{crit}}$
- $^{14}N \sim 10^{-6}$, $^{13}C \sim 10^{-8}$, $^{12}C/^{13}C \sim 7$ in mass fraction at core H depletion in every model

Rotating Models – Core He Burning

- All models become RSGs
- Approach the Eddington luminosity
- Loose most of the H-rich envelope
- Become BSGs (150 km/s is the only exception)



Rotating Models – Convective History

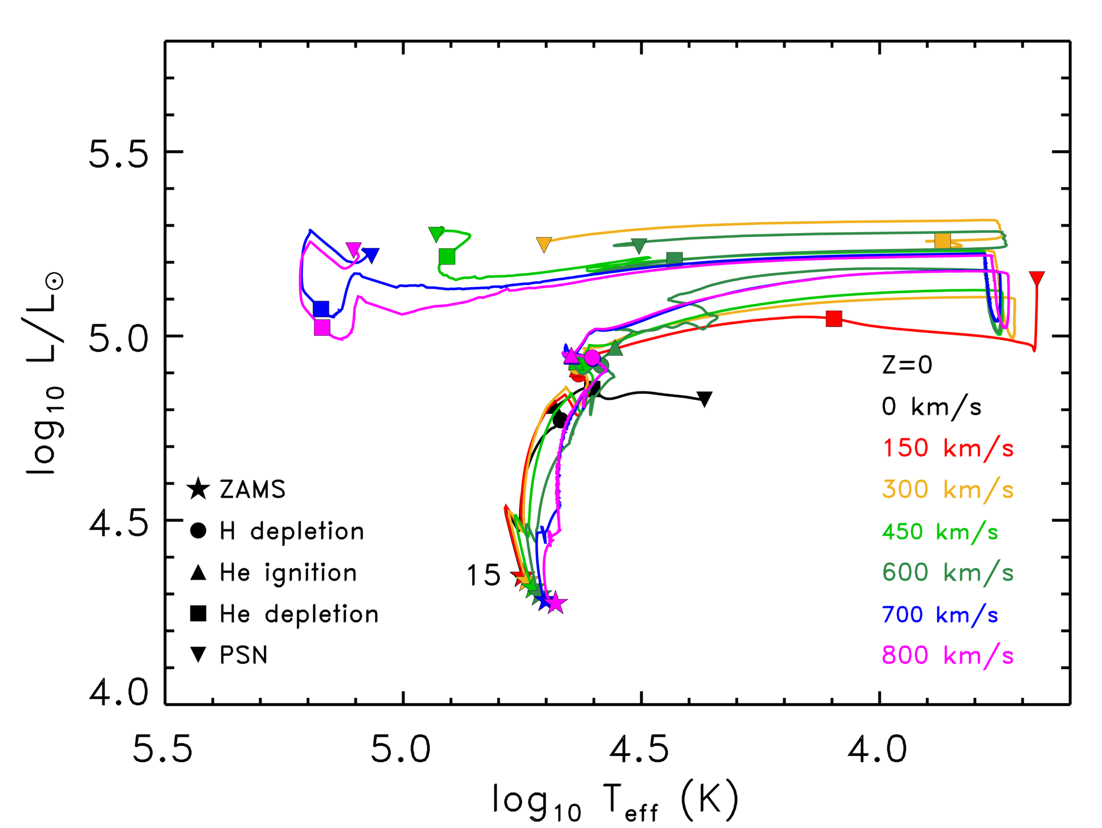


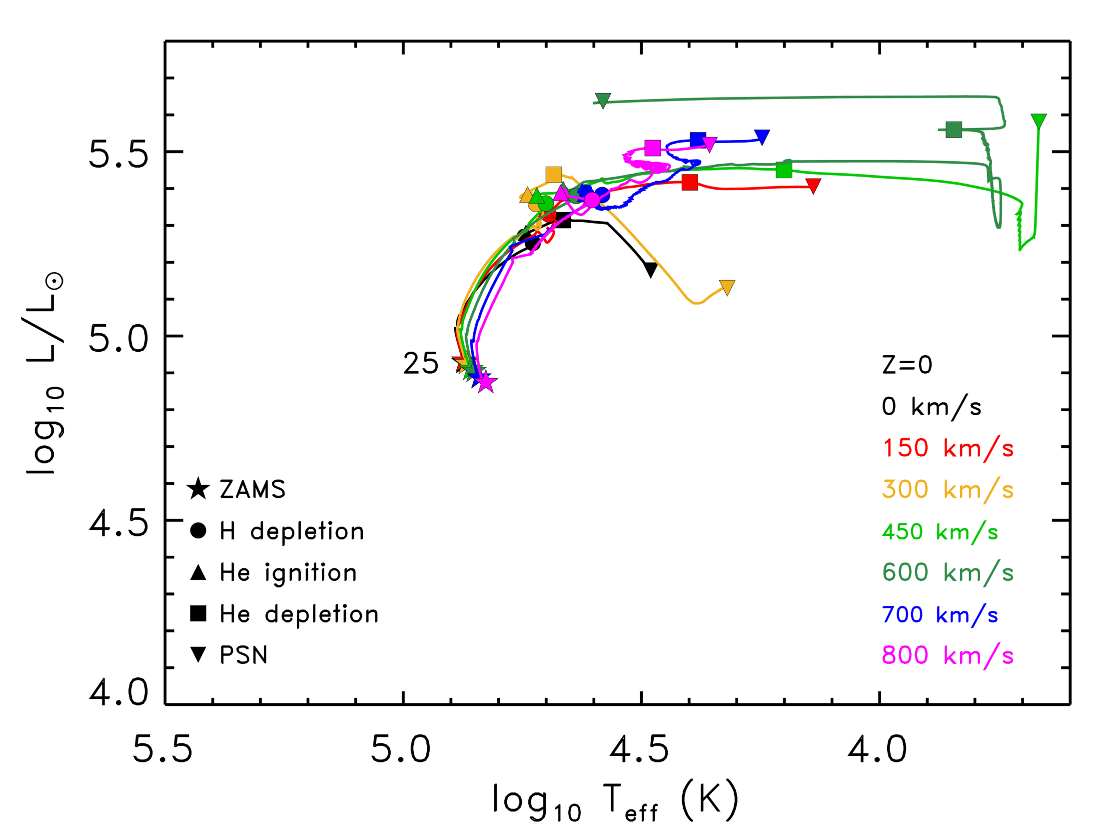
- All the models with v>150 km/s become loose all the H rich envelope and become BSGs
- No H-convective shell is formed → No H/He shell merging can occur

Rotating Models – Core He Burning

- All models become RSGs
- Approach the Eddington luminosity
- Loose most of the H-rich envelope
- Become BSGs (150 km/s is the only exception)

- Non monotonic behavior with initial velocity
- Complex interplay between the effects of rotation and the convective shells





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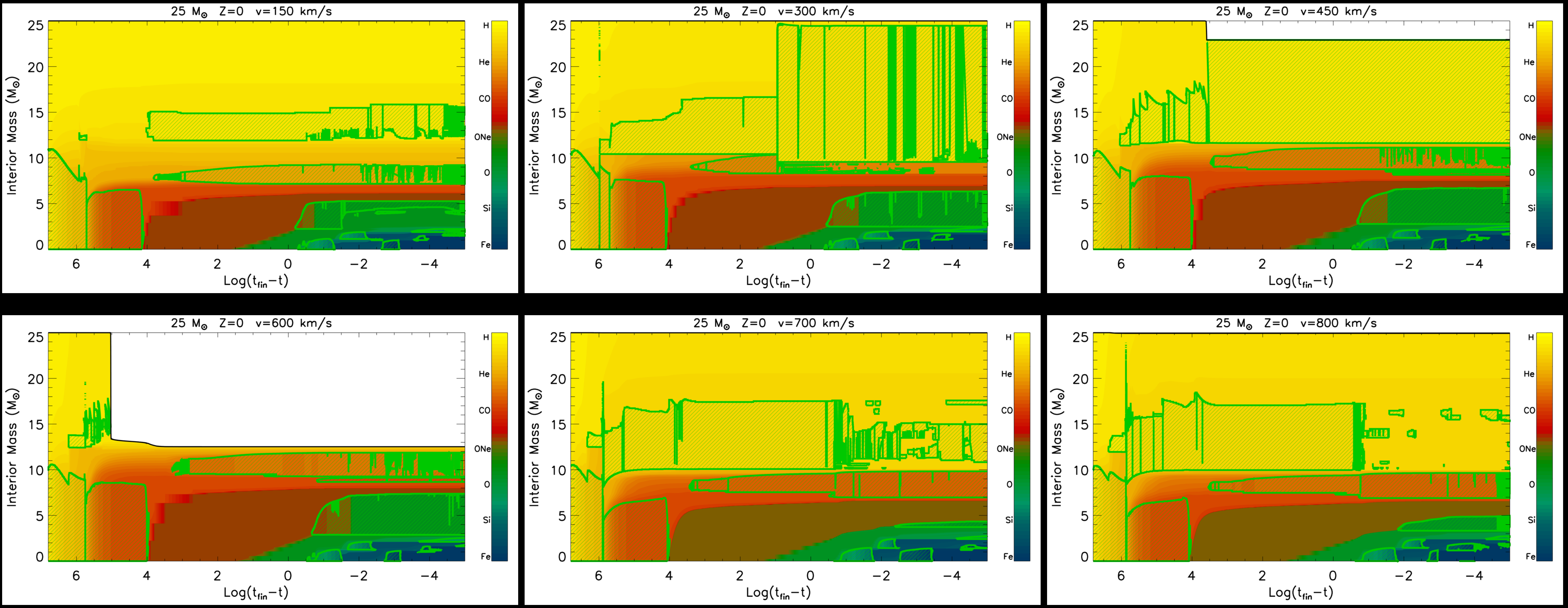
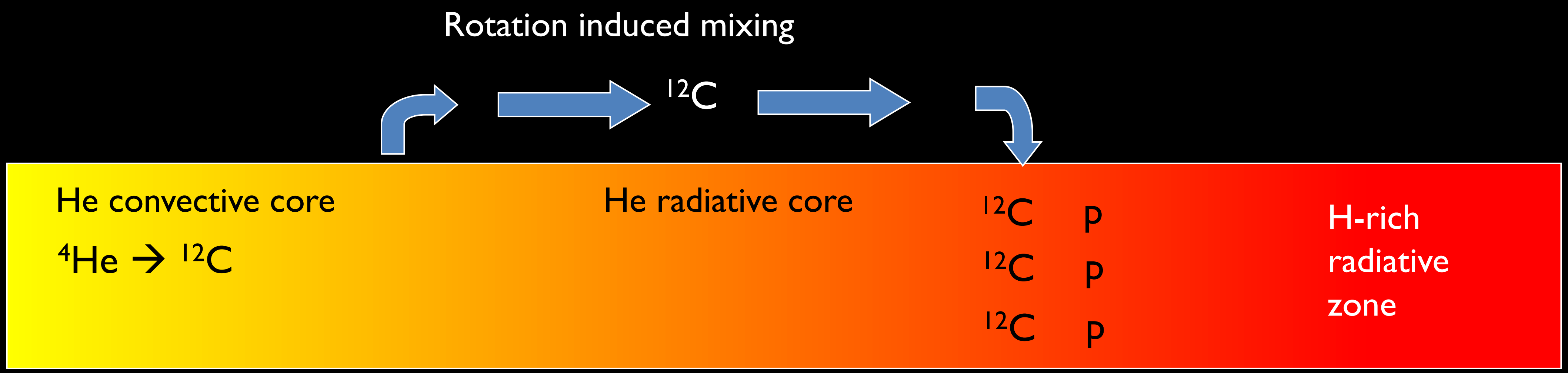


- H/He interaction only in the 300 km/s case
- Extended H convective shell in the fast-rotating stars

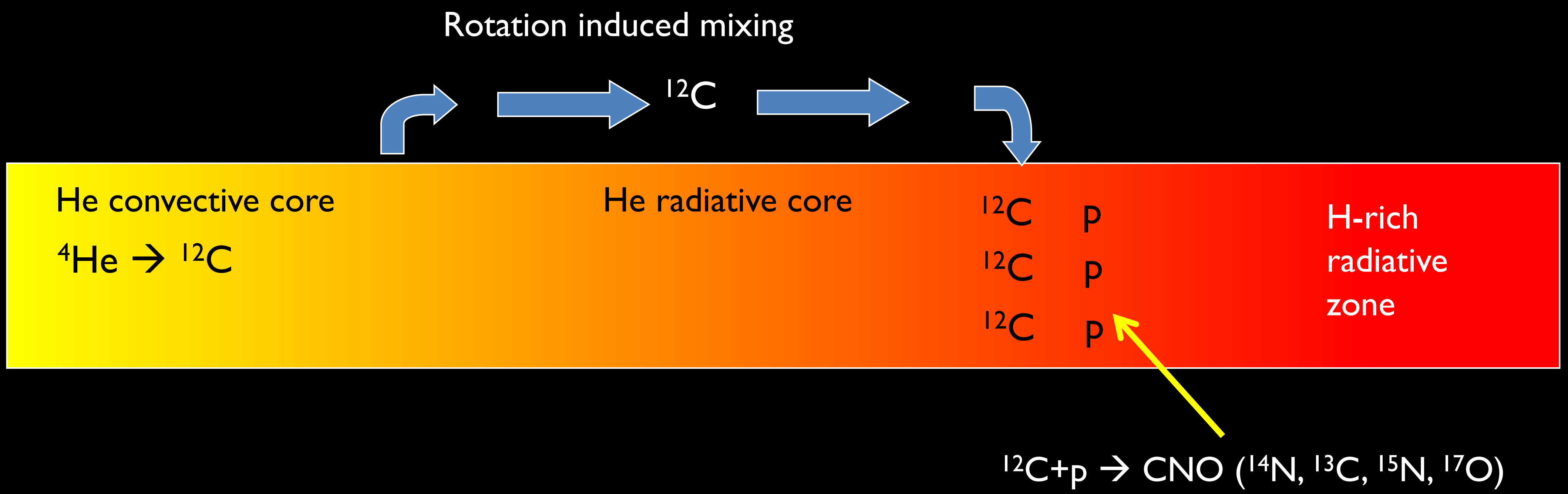
Rotating Driven Mixing

- ^{12}C synthesized in the He convective core diffuses up to the tail of the H-burning shell



Rotating Driven Mixing

- ^{12}C synthesized in the He convective core diffuses up to the tail of the H-burning shell
- ^{12}C is converted into CNO nuclei whose abundances are enhanced (the most abundant being ^{14}N)



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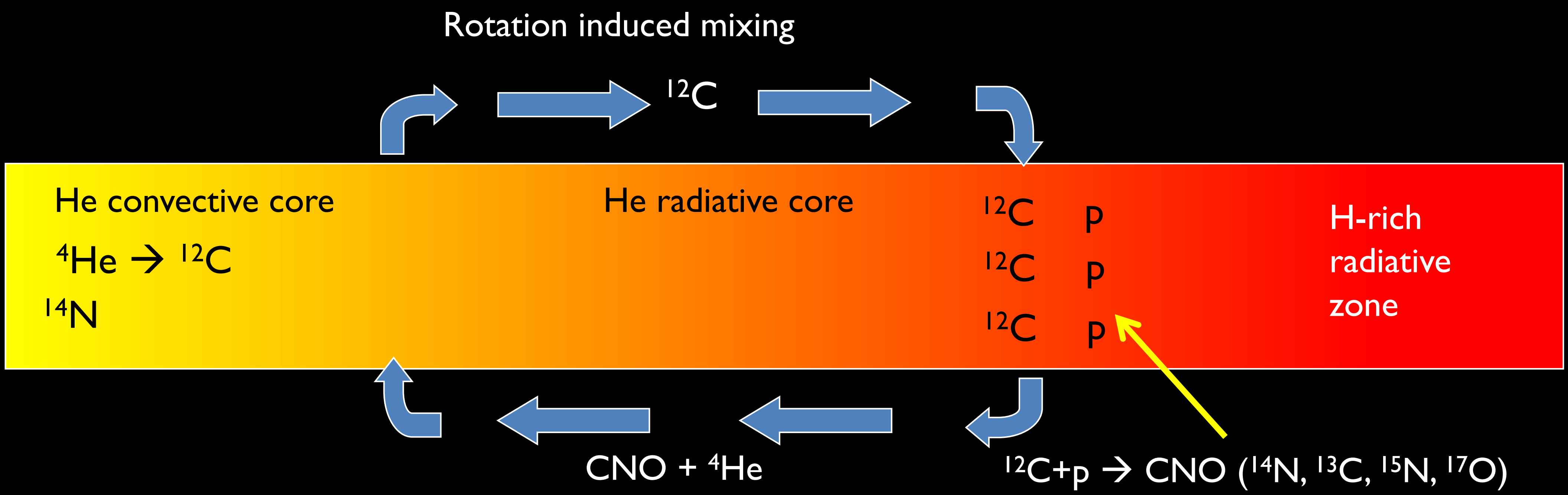
- ^{12}C is converted into CNO nuclei whose abundances are enhanced (the most abundant being ^{14}N)
- The fresh CNO nuclei, and in particular ^{14}N, plus fresh He, are brought back toward the center.



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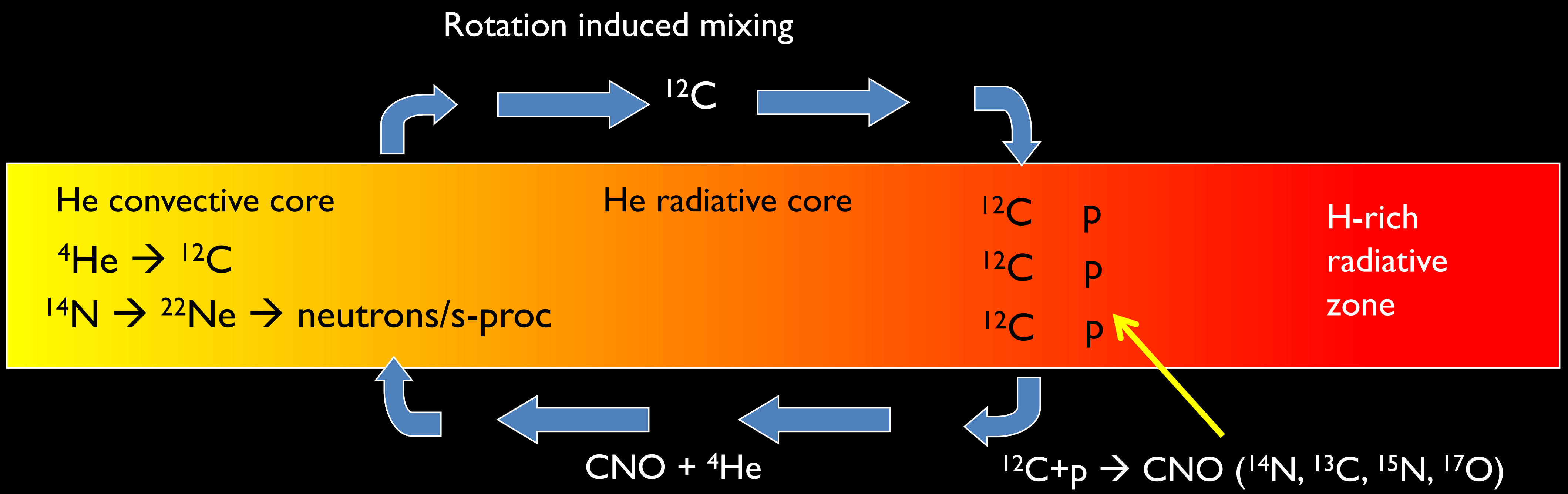
- The ^{14}N that diffused back to the center is quickly converted into ^{22}Ne that becomes an efficient primary neutron source → in principle s-process nucleosynthesis can be activated



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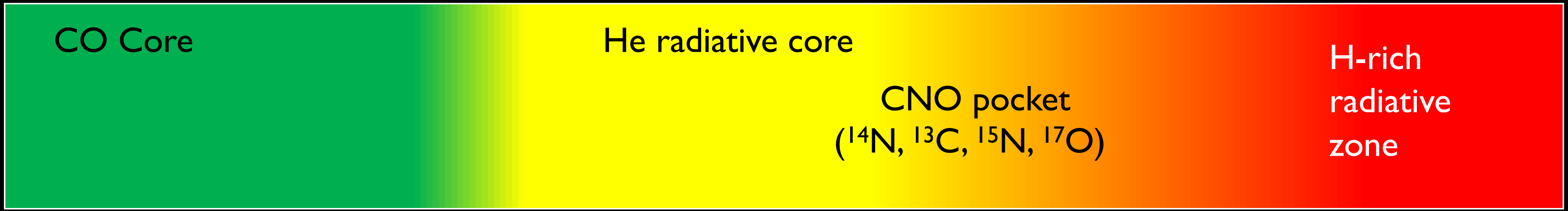
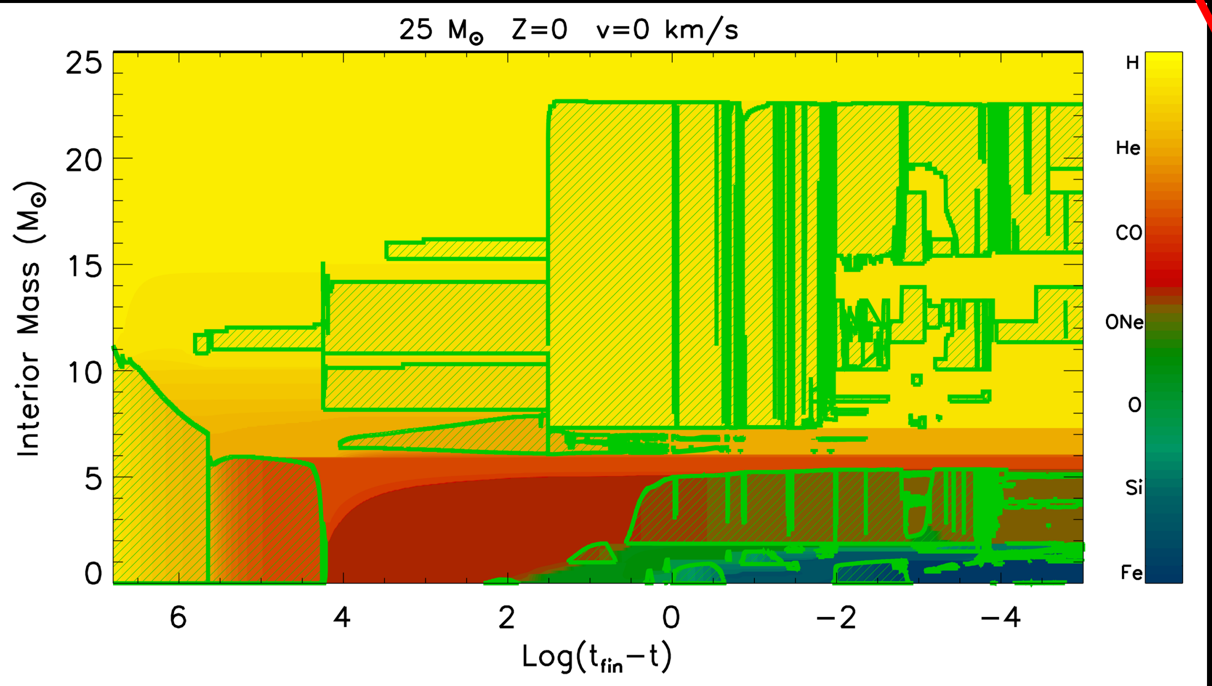
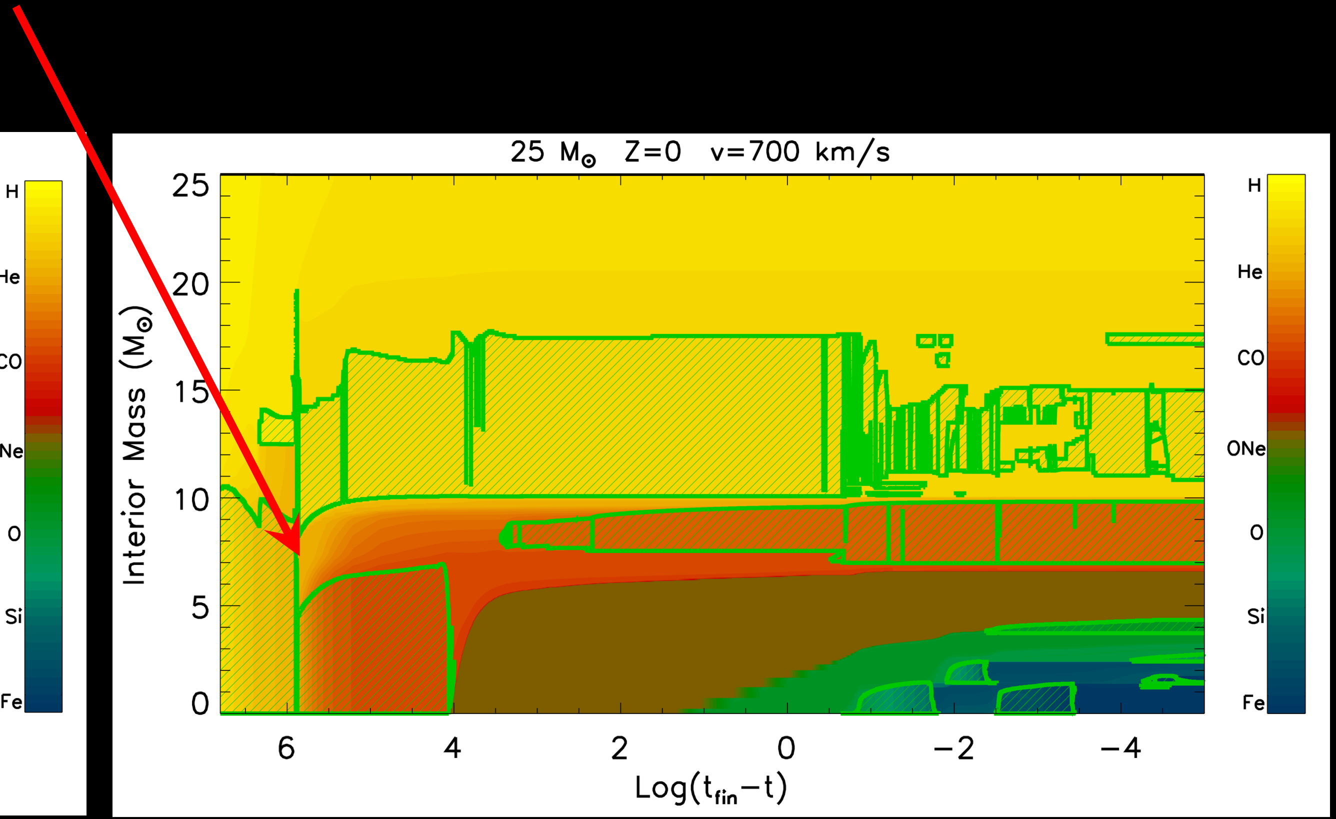
- The fresh CNO nuclei, and in particular ^{14}N, plus fresh He, are brought back toward the center.
- The ^{14}N that diffused back to the center is quickly converted into ^{22}Ne that becomes an efficient primary neutron source → in principle s-process nucleosynthesis can be activated
- Formation of a CNO (^{14}N, ^{13}C, ^{15}N, ^{17}O) pocket in the radiative layers of the He core



Rotating Driven Mixing

- During core He burning rotation driven mixing brings fresh ^{12}C up to the tail of the H-shell





In the two fast rotating 25 $M_\odot$ models the diffused ^{12}C reaches values of $\sim 10^{-4}$ in mass fraction where the H mass fraction is $\sim 10^{-4}$

Rotating Driven Mixing

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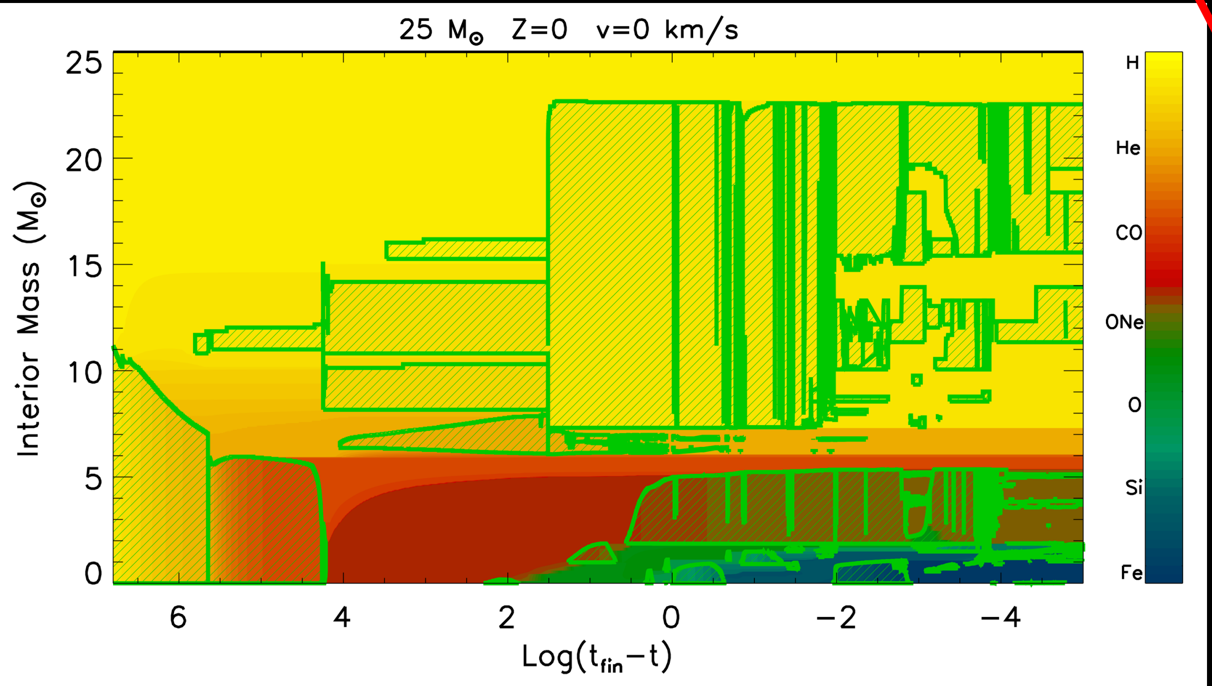
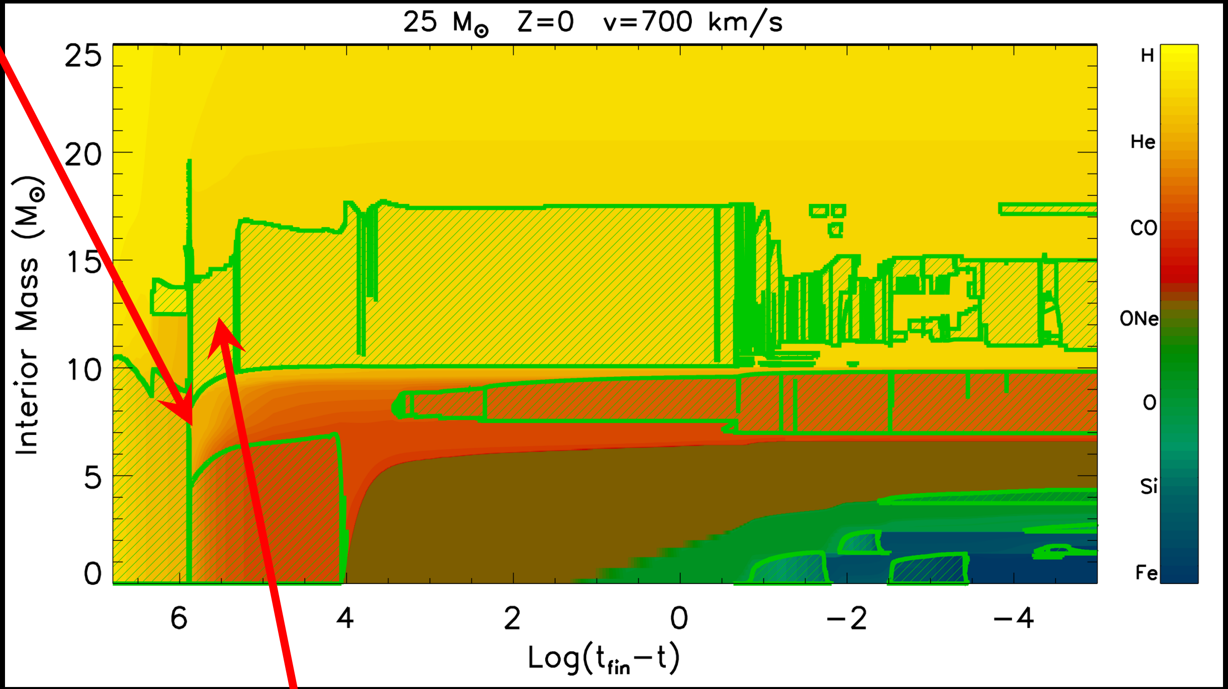


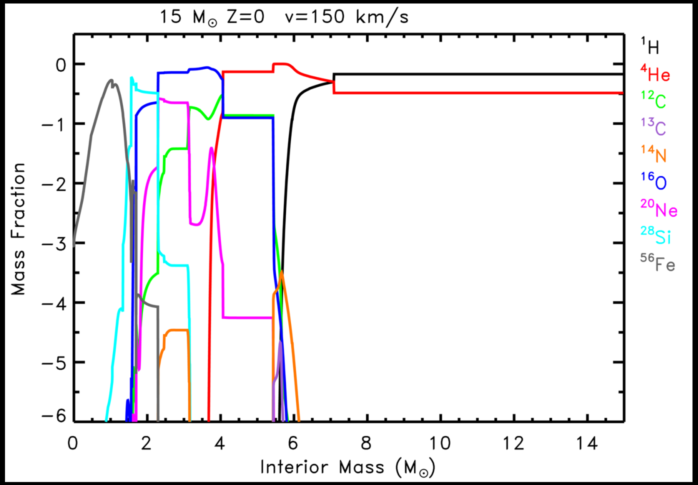


In the two fast rotating 25 $M_{\odot}$ models the diffused ^{12}C reaches values of ~10^{-4} in mass fraction where the H mass fraction is ~10^{-4}

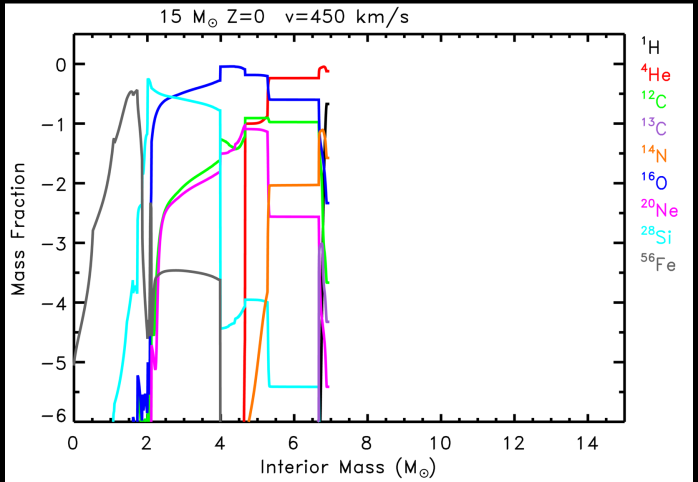
This phenomenon induces the development of an extended H convective shell

Rotating Models – Presupernova Composition

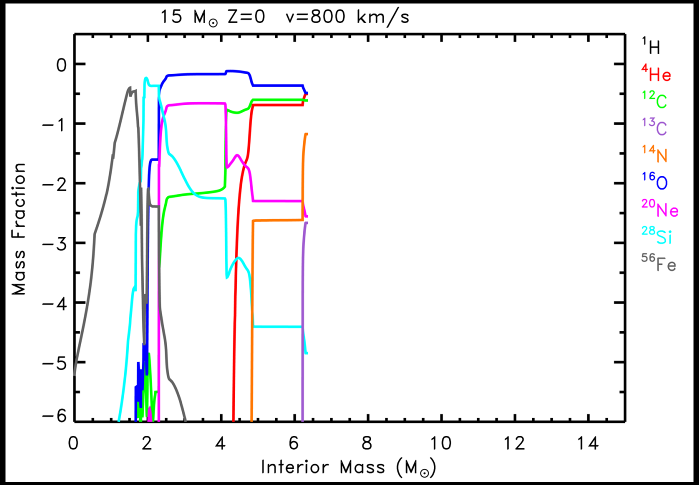
RSG



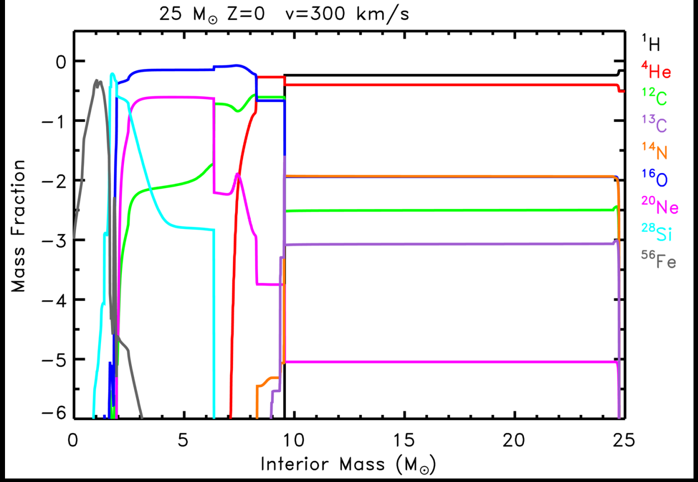
Eddington → BSG



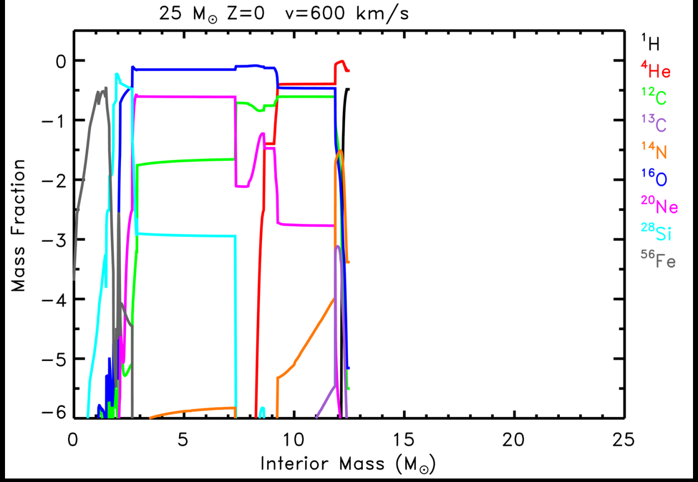
Eddington → BSG



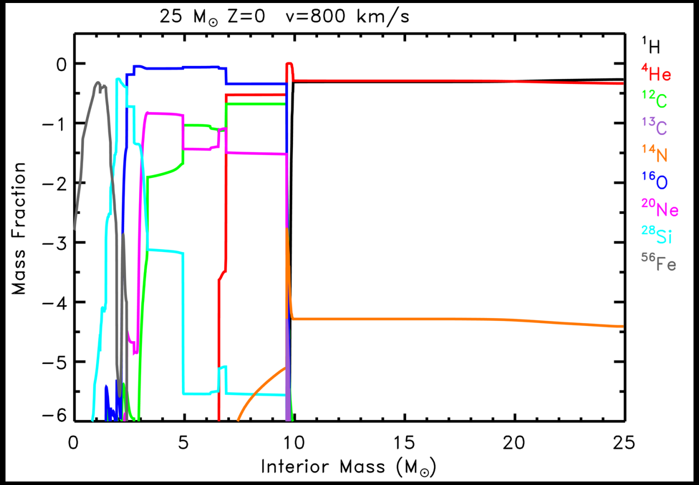
merging H/He



Eddington → BSG



extended H conv. shell



Rotating Models – Composition of the Ejecta

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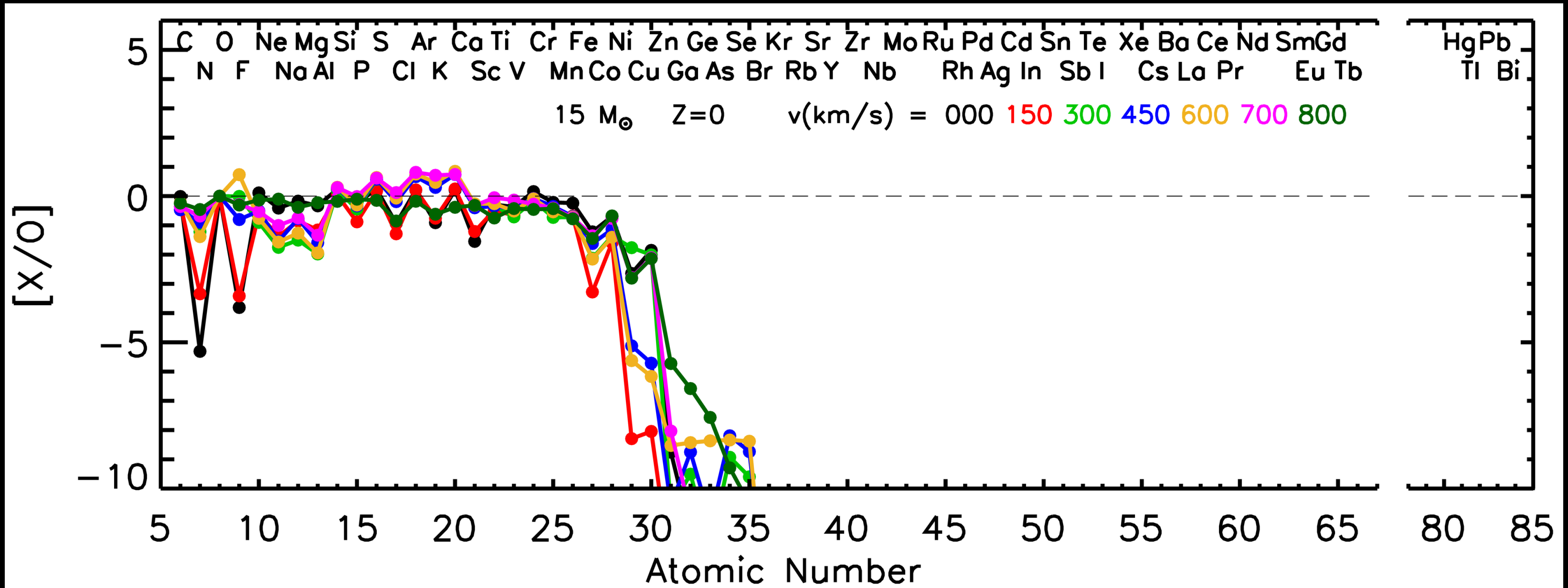

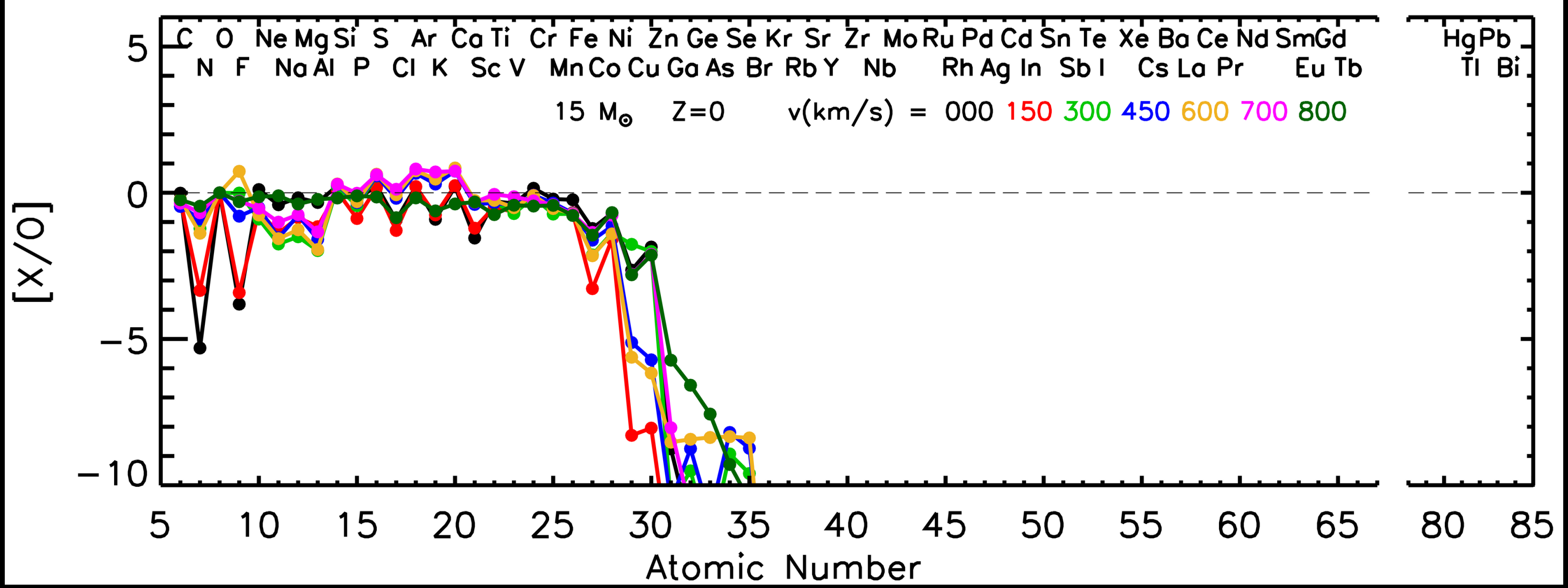

Summary and Conclusions

Evolution of non-rotating PopIII stars characterized by:

- Negligible mass loss → constant mass → BSGs
- H burning at high Temperature
- Abundance of ^{14}N, and in general of the CNO nuclei, independent on mass
- Merging of He and H convective shells in a given mass interval (see also Limongi & Chieffi 2012)
- Large ^{14}N production in models where H- and He-convective shells merge
- Lack of seeds nuclei (Fe) → negligible s-process elements production in spite of the high ^{14}N abundance

Evolution of rotating PopIII stars characterized by:

- No homogenous mixing even in the fastest rotating models
- Abundance of ^{14}N, and in general of the CNO nuclei, independent on mass and rotation velocity
- RSG evolution for some models → high mass loss due to approach to the Eddington luminosity
- No H/He convective shells merging (with only one exception)
- Non monotonic behavior due to a complex interplay between rotation and convective shells
- Large ^{14}N and ^{19}F production due to rotation driven mixing
- Negligible production of s-process elements as in the non-rotating case