Evolution, Nucleosythesis and Final Fate of Stars in the Mass Range 7-15 $M_\odot$

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Lorenzo Roberti, Konkoly Observatory, Hungary

Ken’ichi Nomoto, IPMU – The University of Tokyo, Japan

Motivation

In the general picture of stellar evolution stars in the transition between AGB stars and Massive Stars have mass in the range 7-10 $M_\odot$

Stars in the mass range 7-10 $M_\odot$ constitute ~40% (by number) of the stars with $M \geq 7\ M_\odot$ therefore a proper knowledge of how they evolve and die is crucial for many astrophysical subjects

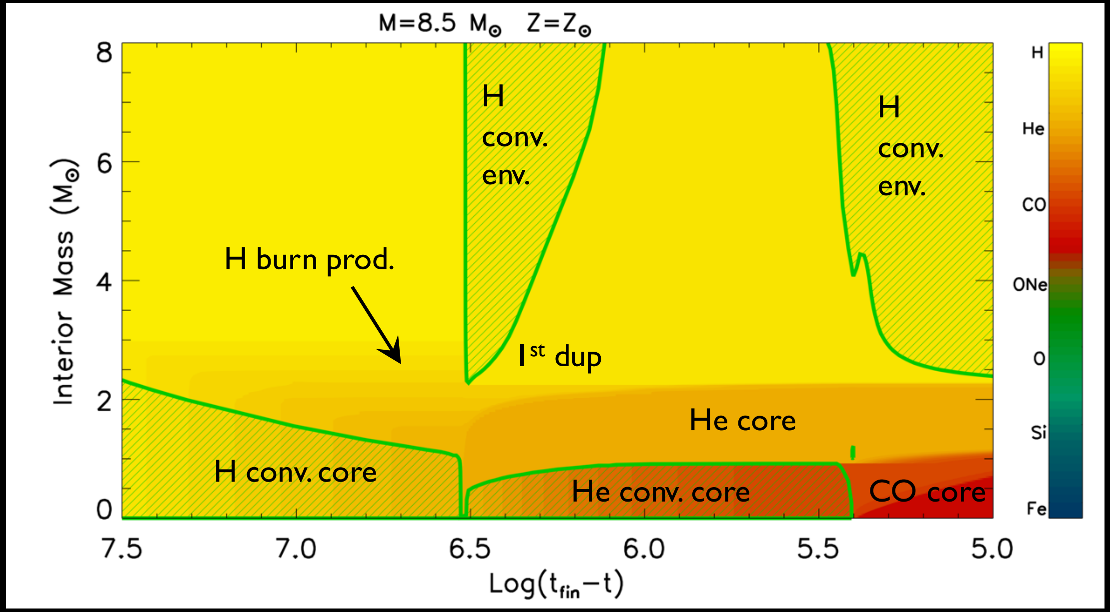
In spite of such astrophysical relevance, their evolutionary properties as well as their final fate (CO-WD, ONe-WD, Electron Capture Supernova, Core Collapse Supernovae) are scarcely studied

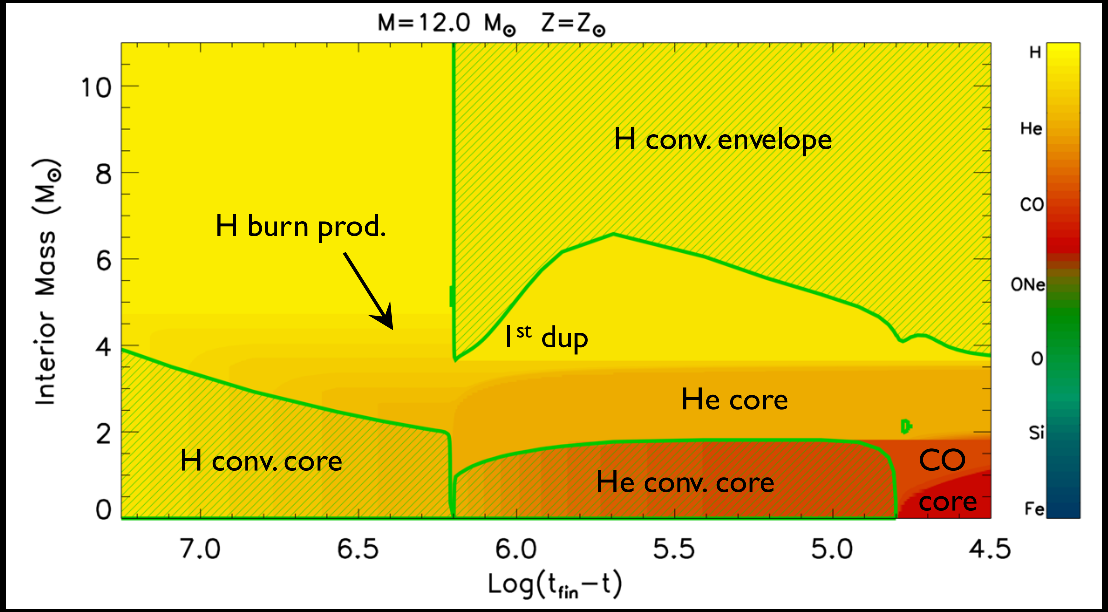
The main reason for the paucity of homogenous, detailed and comprehensive studies of the evolution of these stars is that the computation of their full evolution is extremely challenging

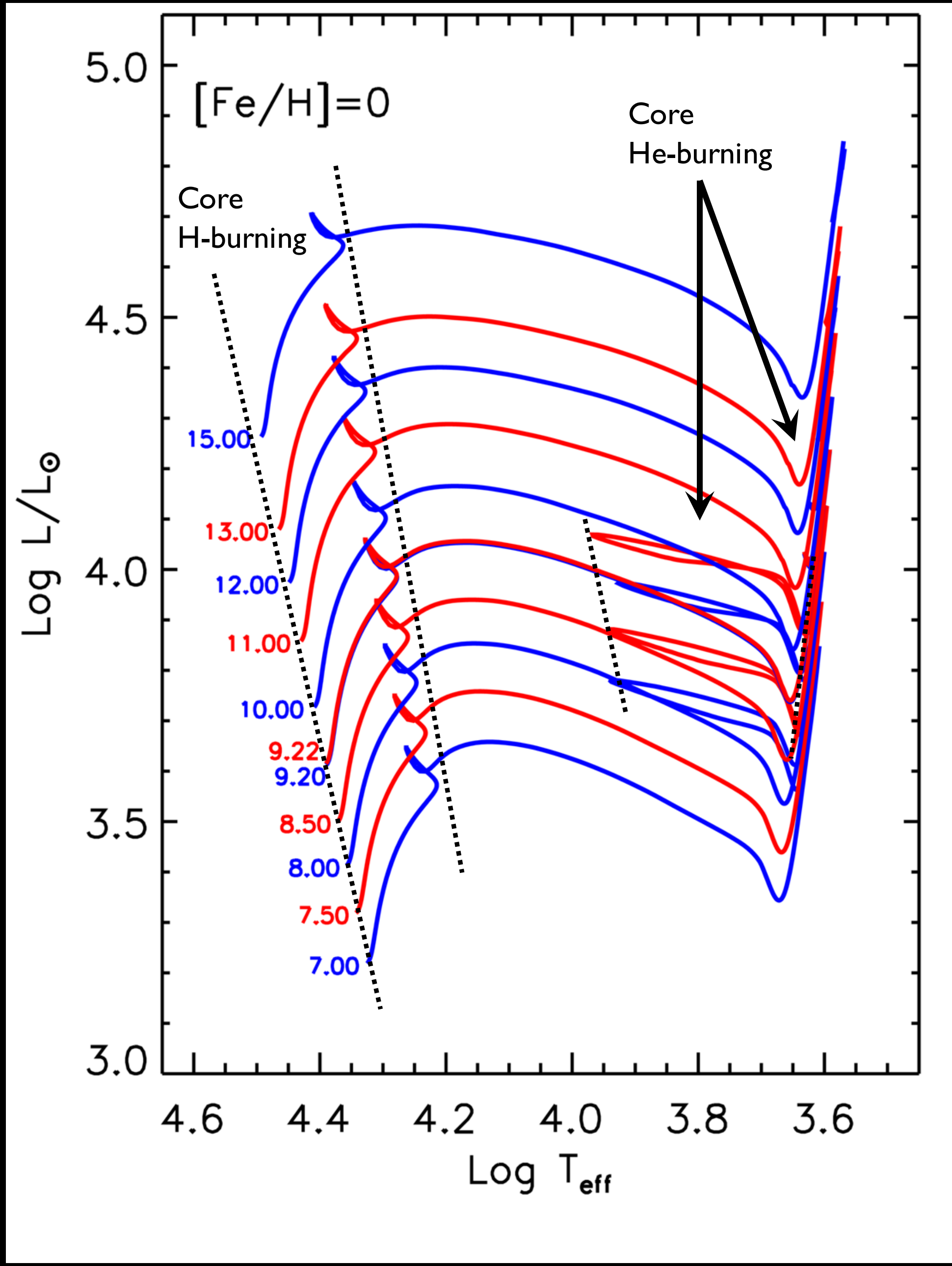
In the last 20 years we developed and continuously improved our stellar evolution code FRANEC that is characterized by features that make it perfectly suited for the calculation of the most challenging evolutionary phases, like those of the stars in the range 7-15 $M_\odot$

Overview of the complete evolution, nucleosynthesis and final fate of solar metallicity, non-rotating, stars in the mass interval 7-15 $M_\odot$

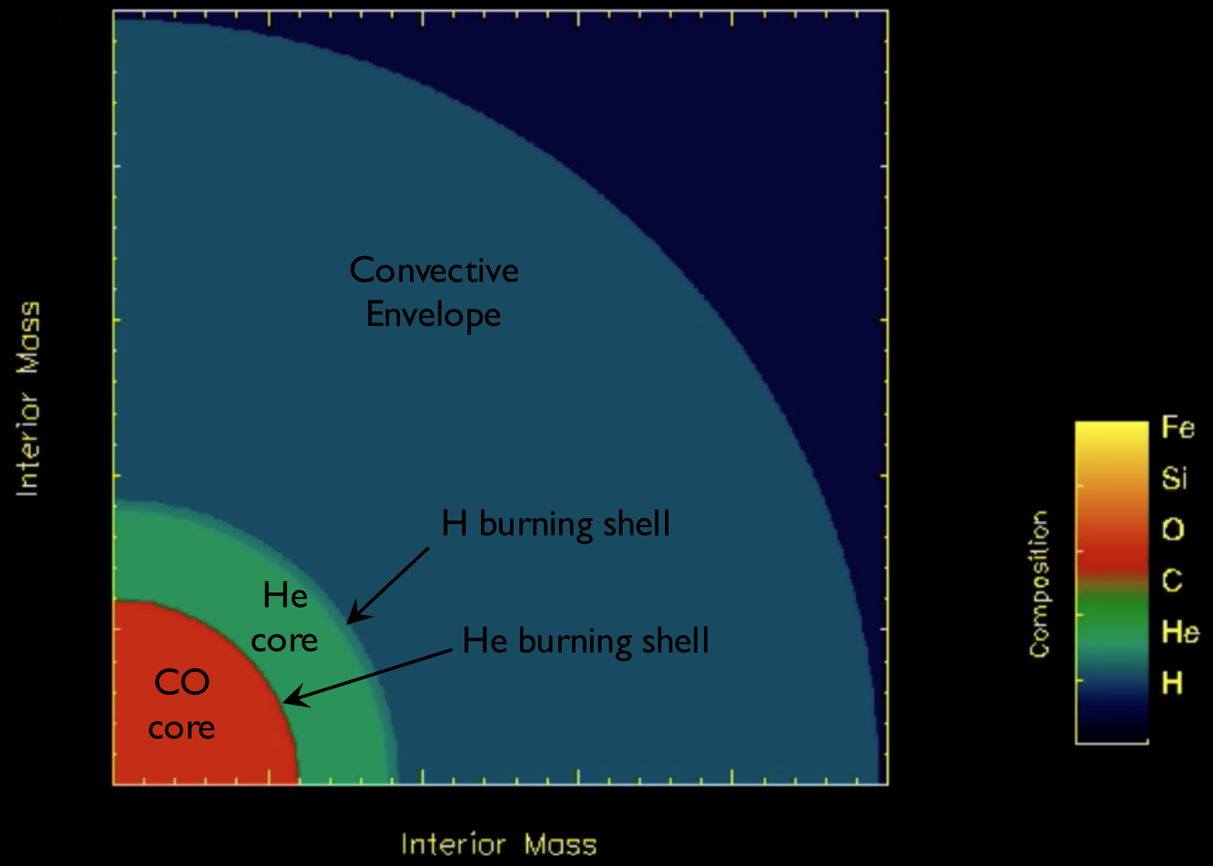
Core H- and Core He-burning



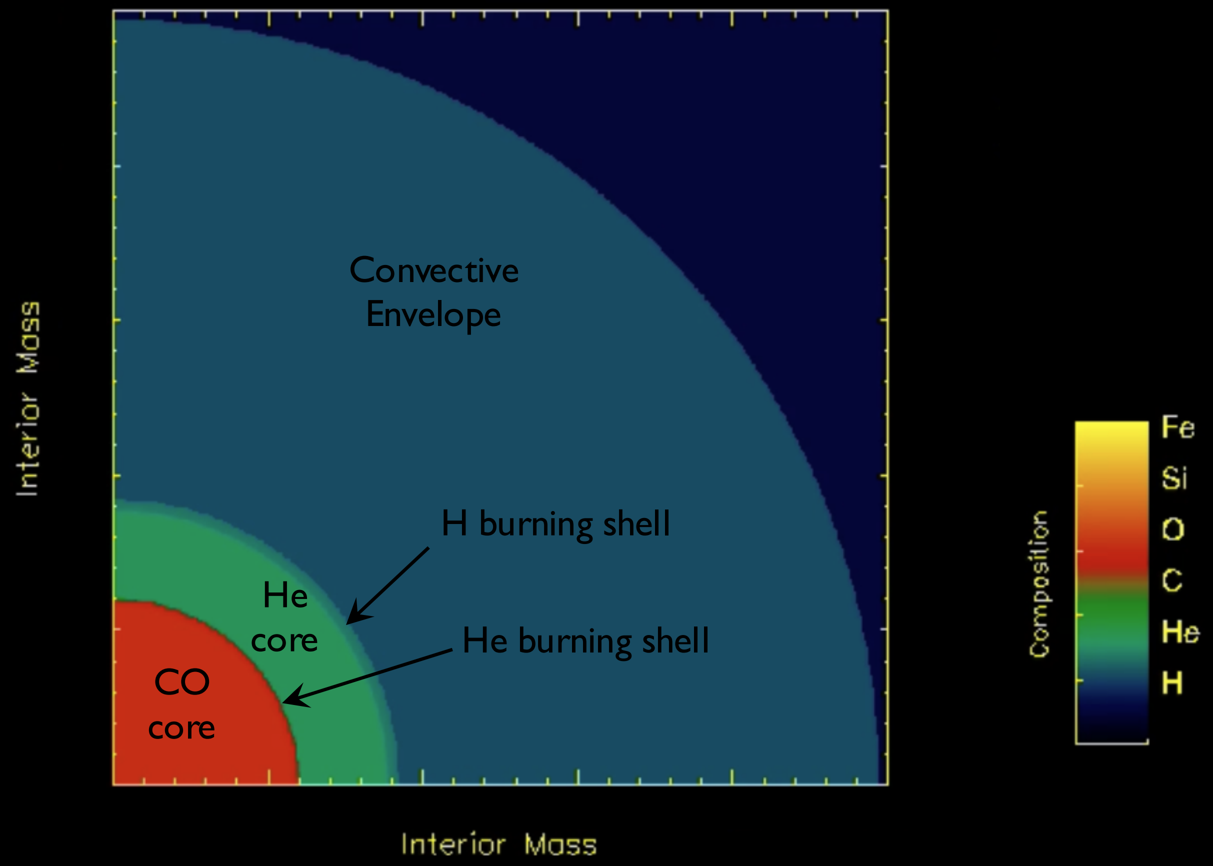




Structure after core He depletion



Evolution after core He depletion



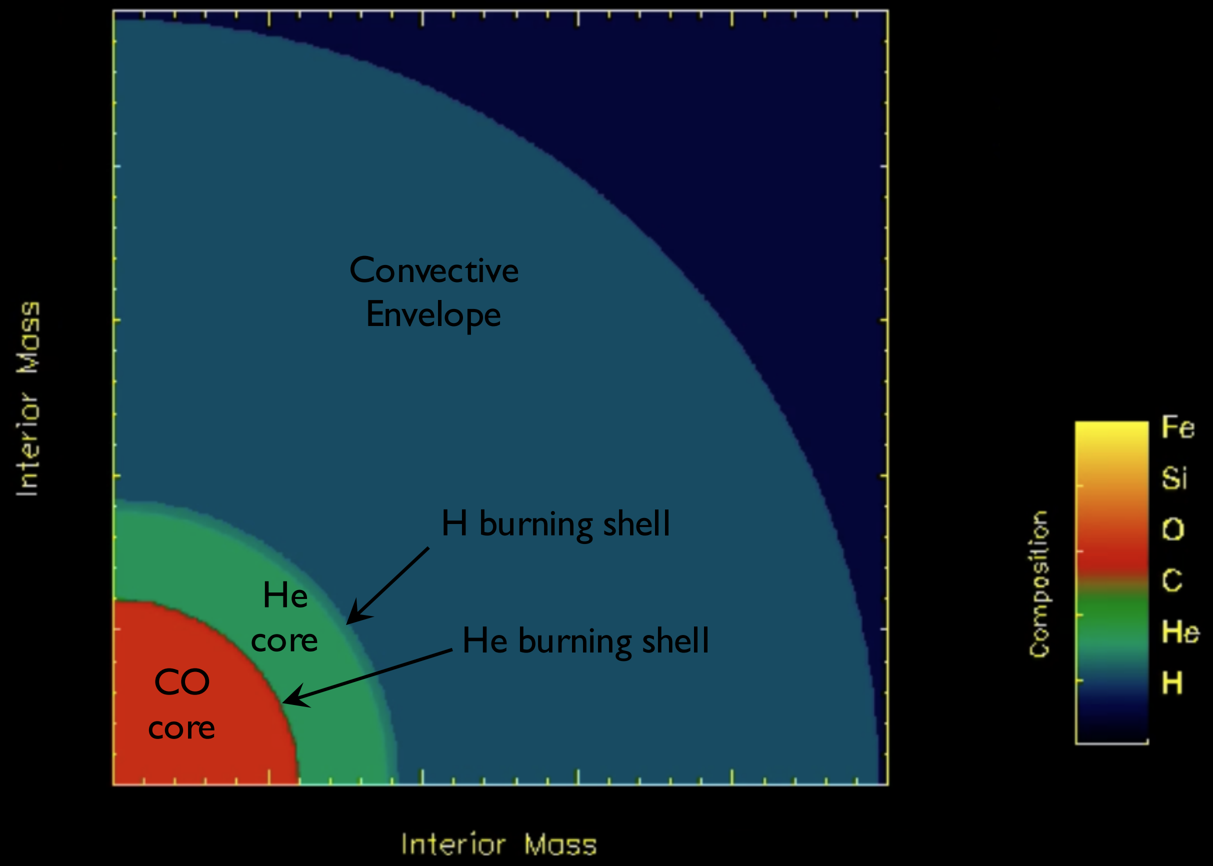
Increase of the CO and switching off of the H burning shell due to the shift outward of the He burning shell

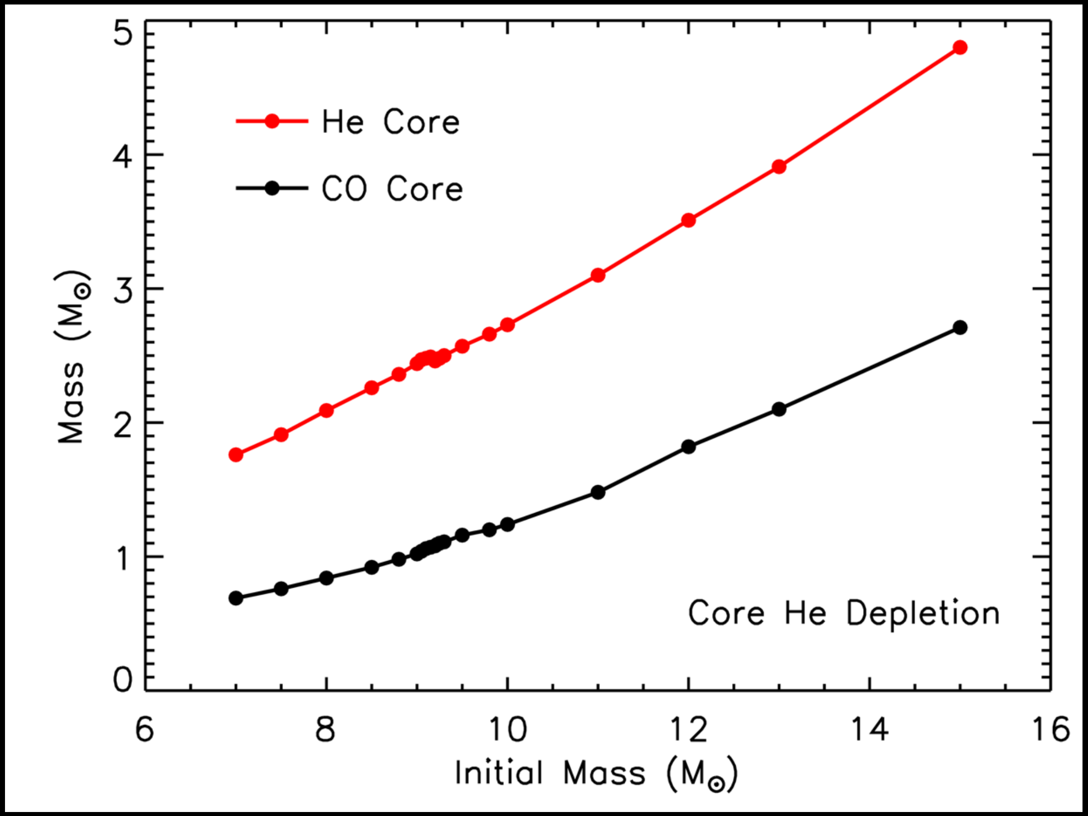
Energy loss from the central zones due to the neutrino emission

Energy deposition in the CO core due to compressional heating induced by the advancing He burning shell

Progressive penetration of the convective envelope that may eventually lead to the 2nd dredge up

Evolution after core He depletion



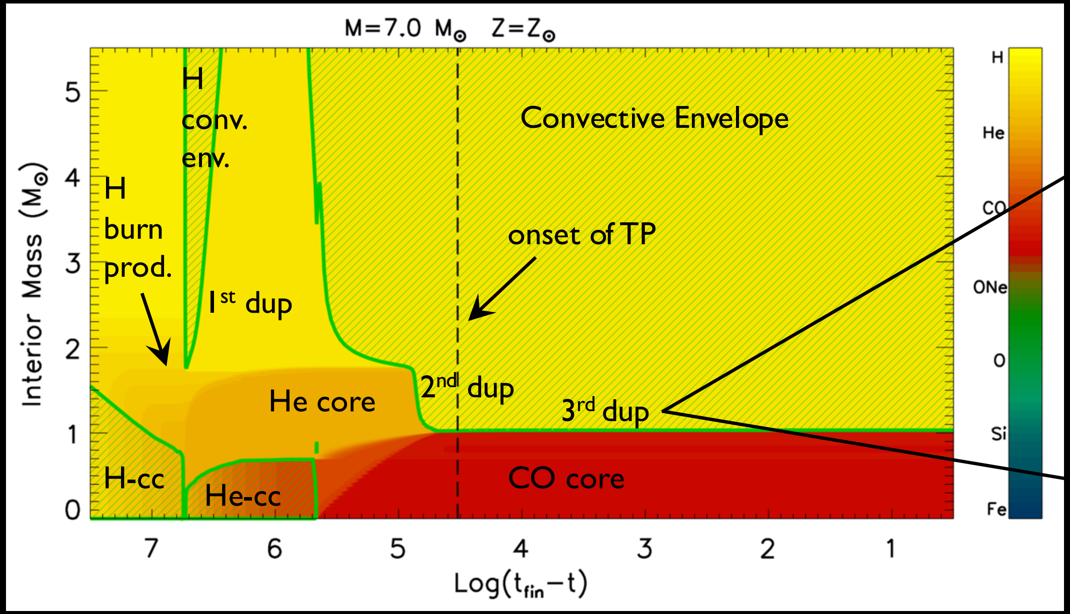


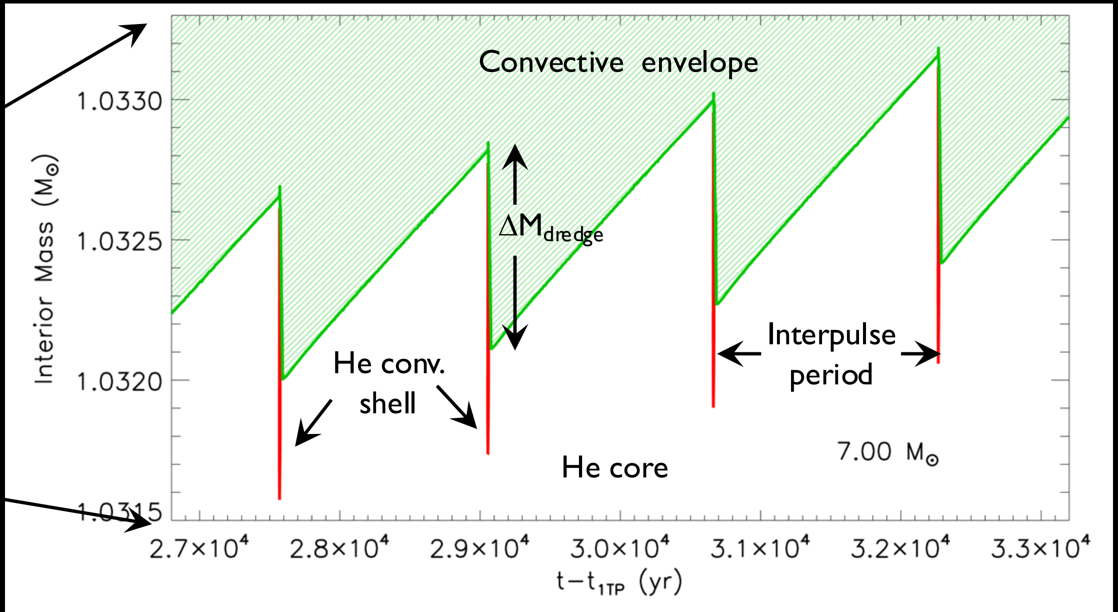
Interplay and timing of these processes drive the following evolution of the star

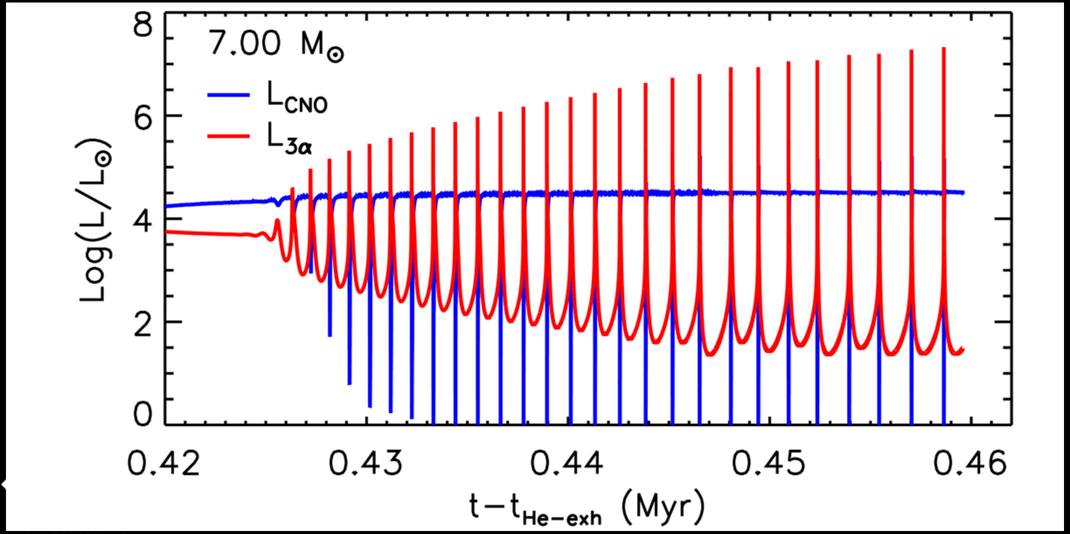
They depend on the CO core mass and therefore on the initial Mass

Stars with M $\leq$ 7 $M_\odot$

In stars with M $\leq$ 7 $M_\odot$ the temperature does not reach the threshold value for the ignition of C burning







Mass loss becomes very efficient during the TP-AGB phase. After few tens of TPs the envelope is lost

Stars with M $\leq$ 7 $M_\odot$ end their life as planetary nebulae with CO-WD

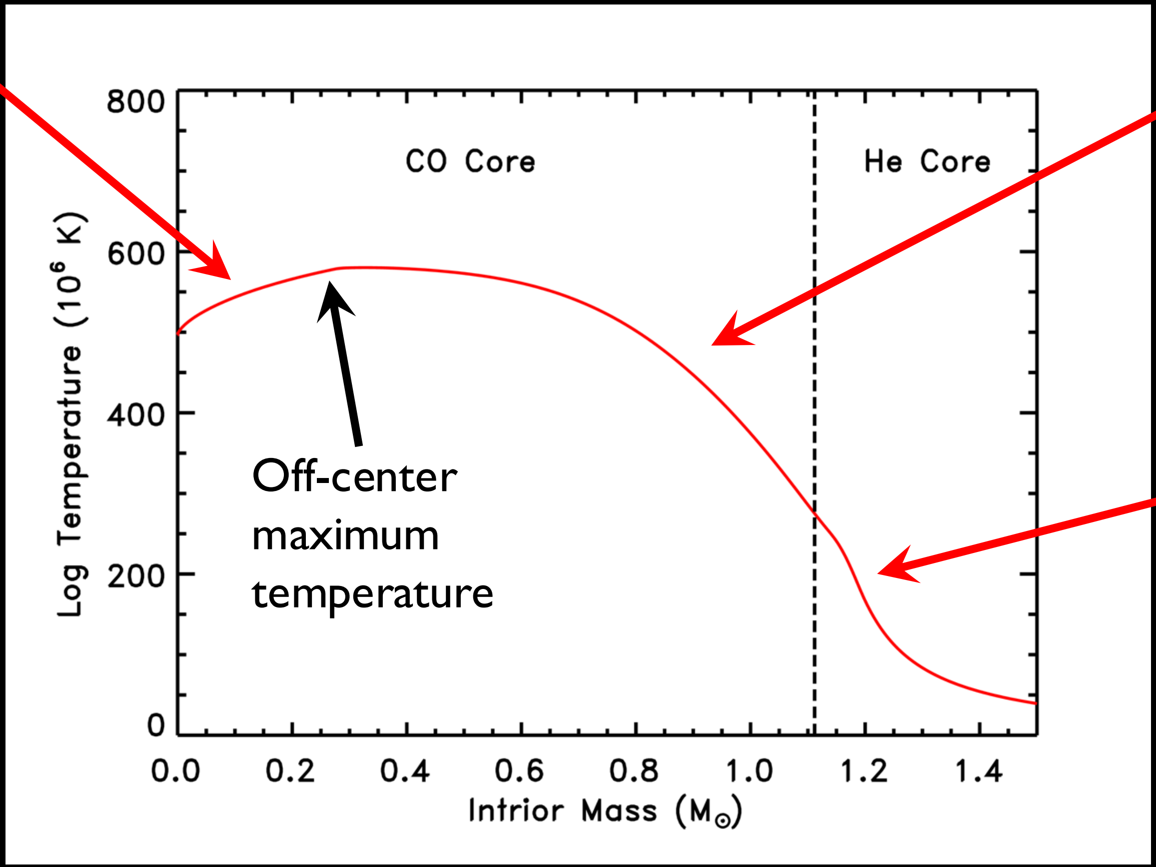
Stars with M $\geq$ 7.5 $M_\odot$

In stars with M $\geq$ 7.5 $M_\odot$ the temperature reaches the threshold value for the ignition of C burning

Off-center C-ignition in stars with 7.5 $\leq M/M_\odot \leq$ 9.5

Energy loss from the central zones due to the neutrino emission

Energy deposition in the CO core due to compressional heating induced by the advancing He burning shell

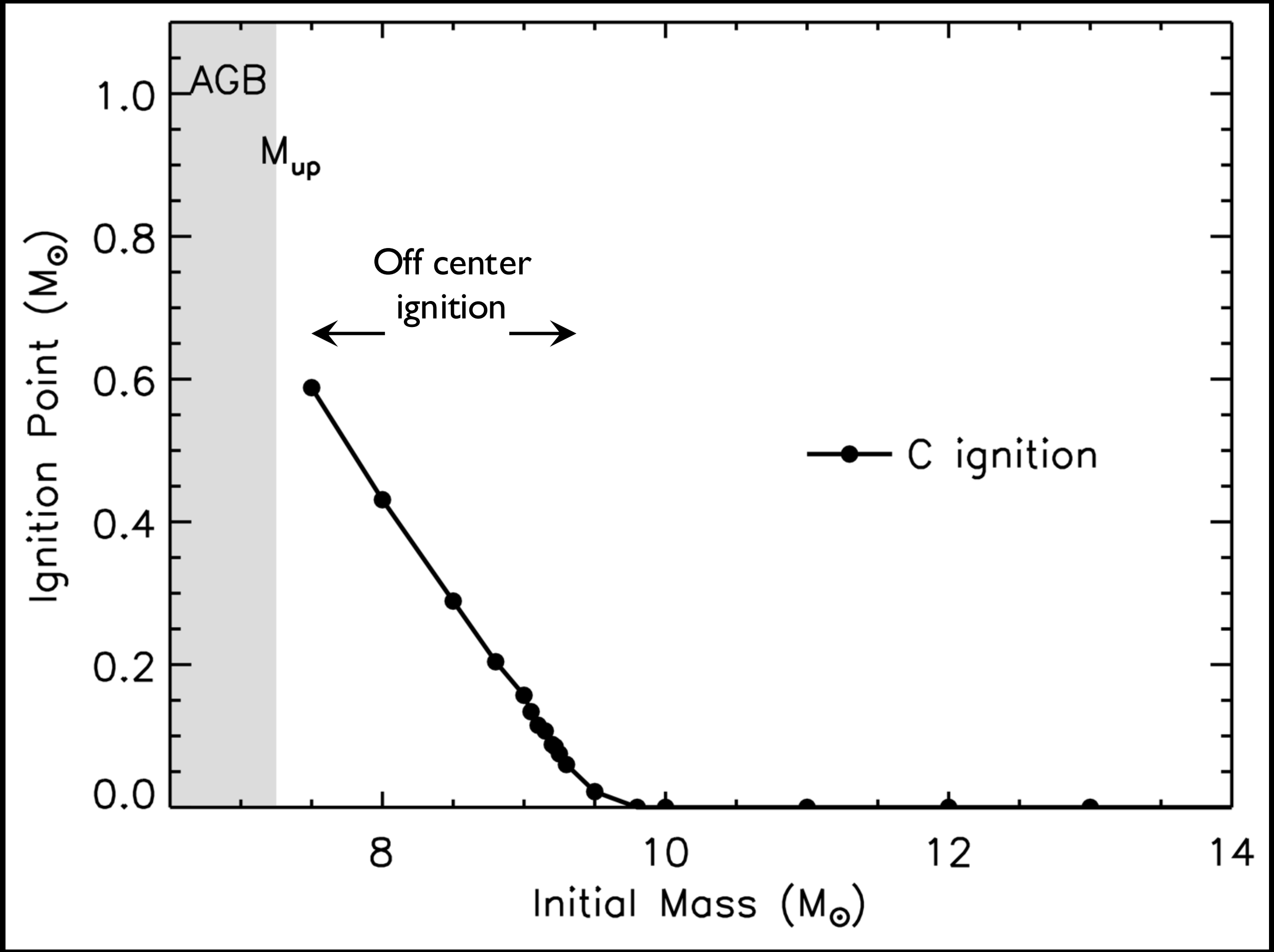


He burning shell

Stars with M ≥ 7.5 $M_\odot$

In stars with M ≥ 7.5 $M_\odot$ the temperature reaches the threshold value for the ignition of C burning

Off-center C-ignition in stars with 7.5 ≤ $M/M_\odot$ ≤ 9.5



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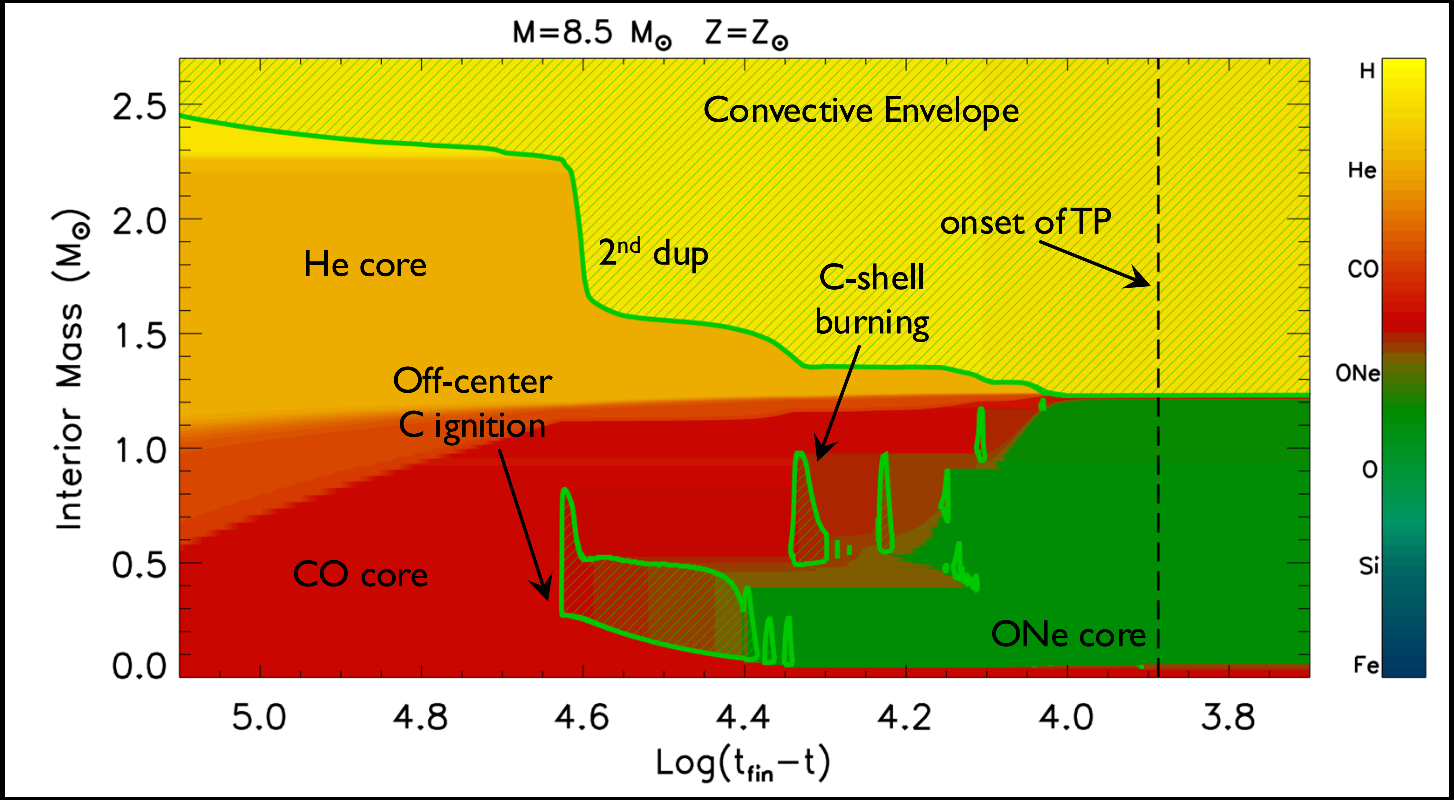

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Stars with $M \geq 7.5\ M_\odot$

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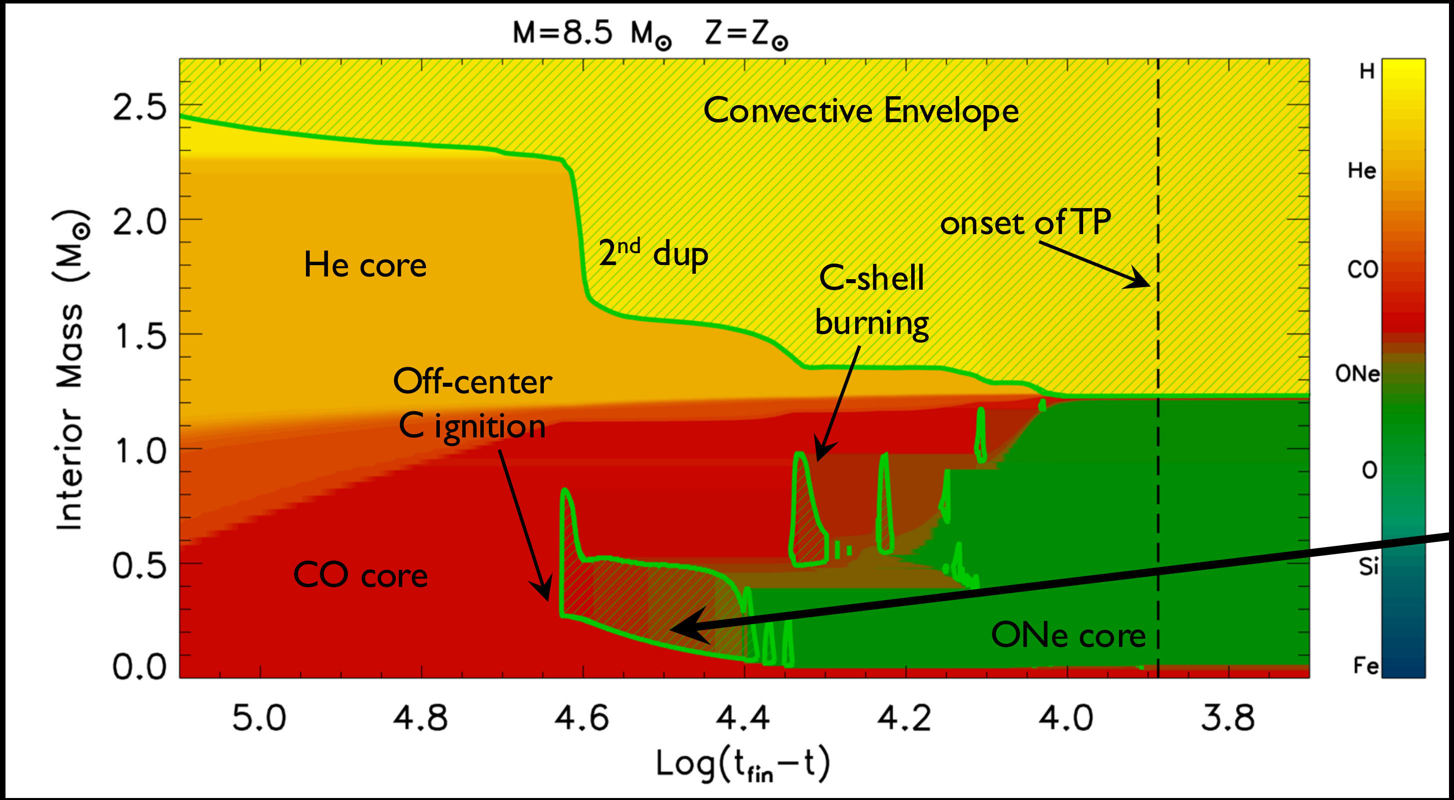
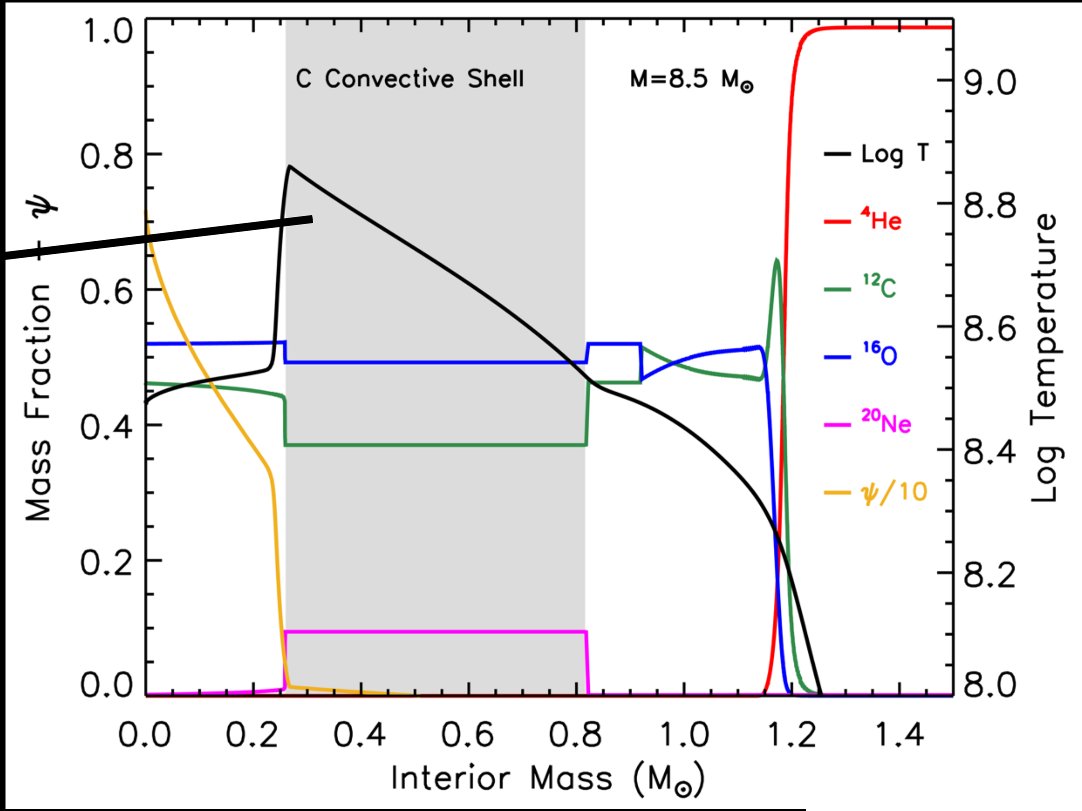
Off-center C-ignition in stars with $7.5 \leq M/M_\odot \leq 9.5$



The propagation of the C burning front inward is driven by the heat transfer from the hotter (convective) burning zone to the cooler radiative one below



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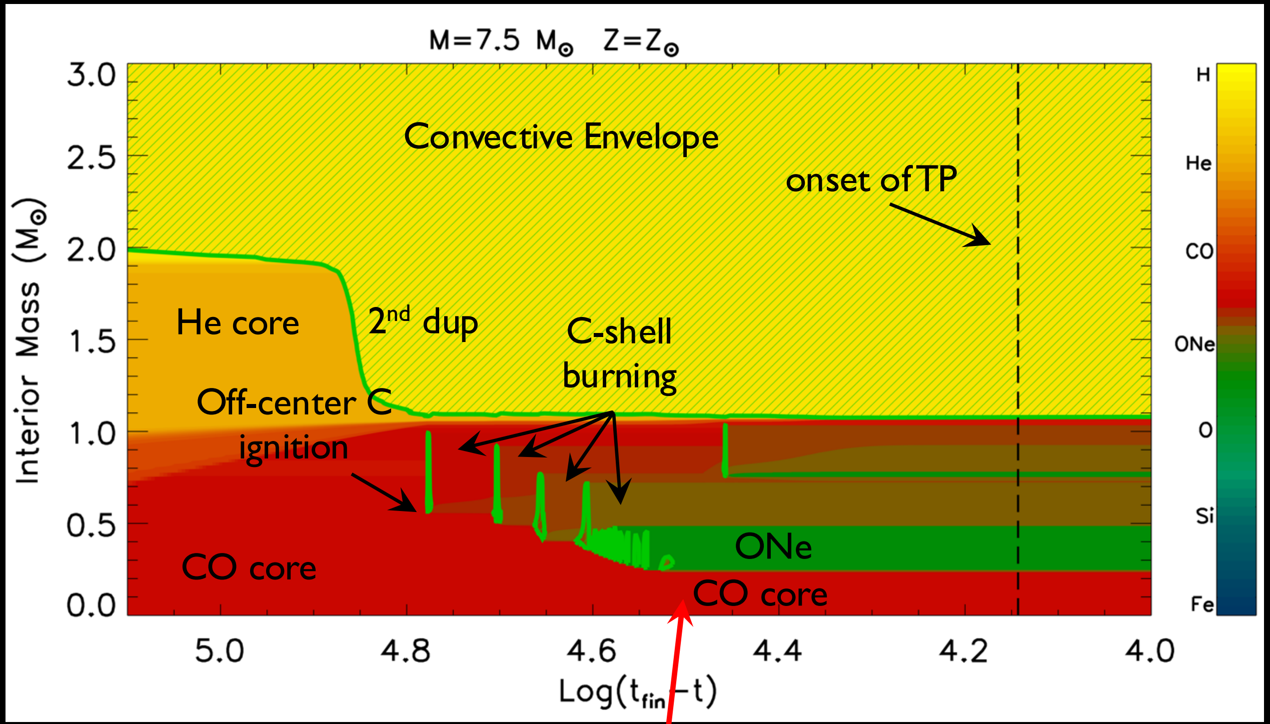
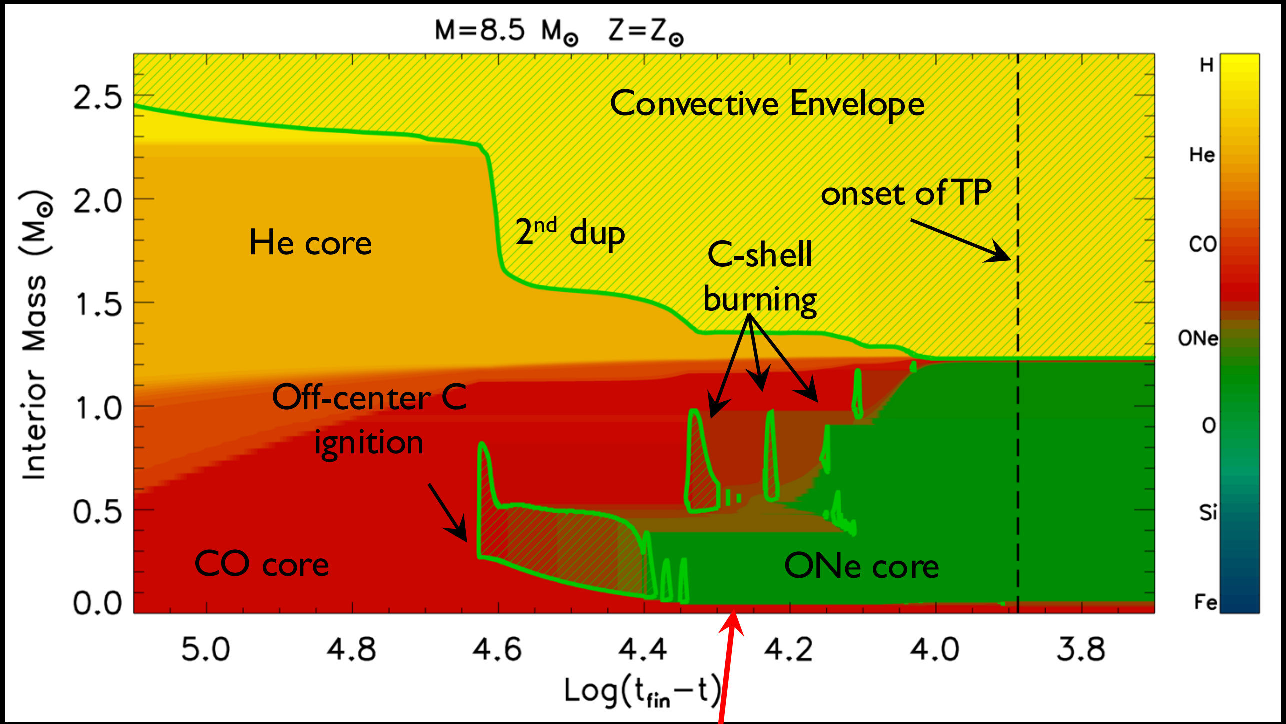
Stars with M ≥ 7.5 $M_\odot$

Some amount of ^{12}C remains unburnt in the lower mass models – Hybrid CO/ONe core

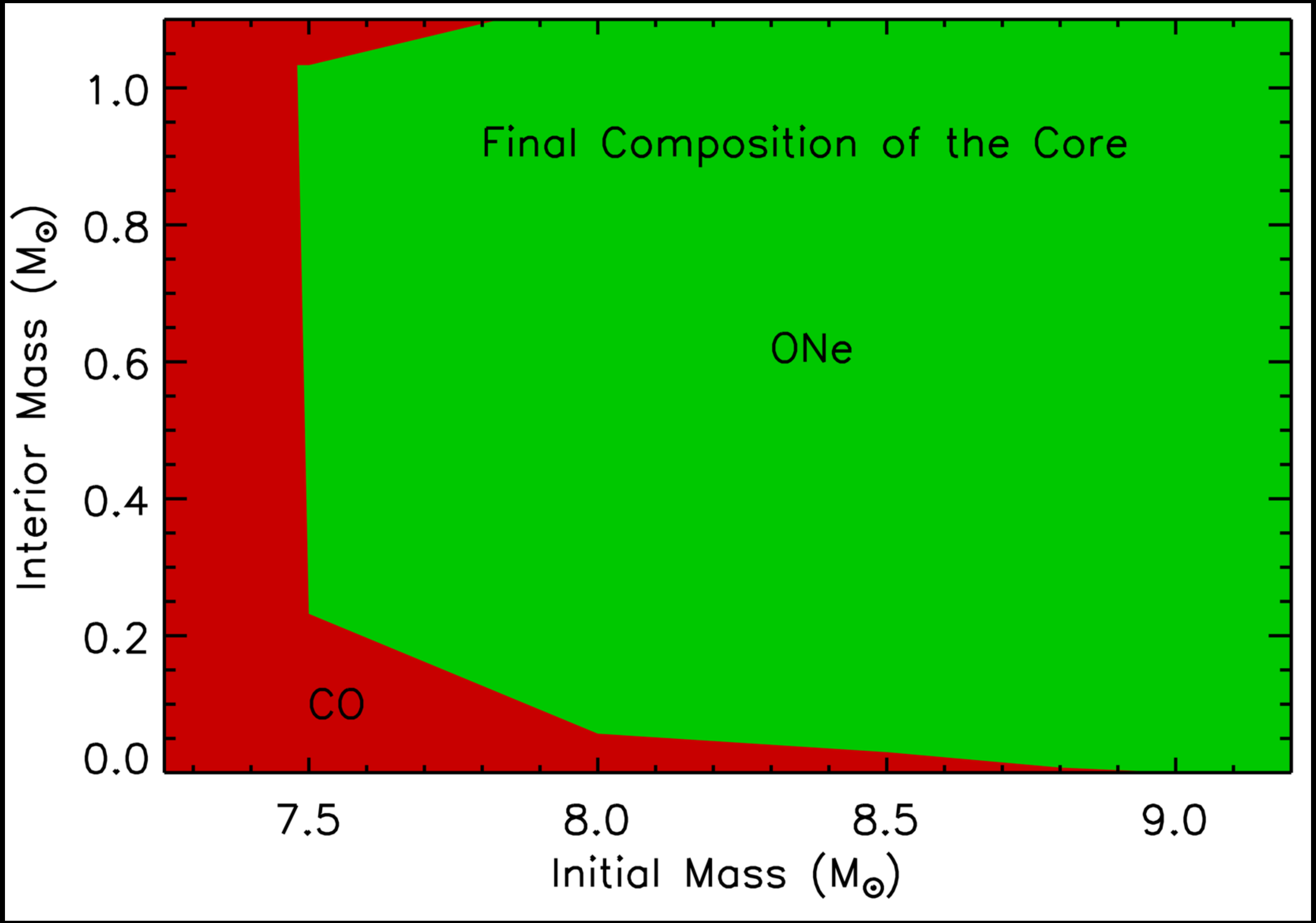




CO unburnt

CO unburnt

Stars with M ≥ 7.5 $M_{\odot}$



Stars in the range ~7.5-8.2 $M_{\odot}$ form Hybrid CO/ONe cores → implications for SNIa explosion

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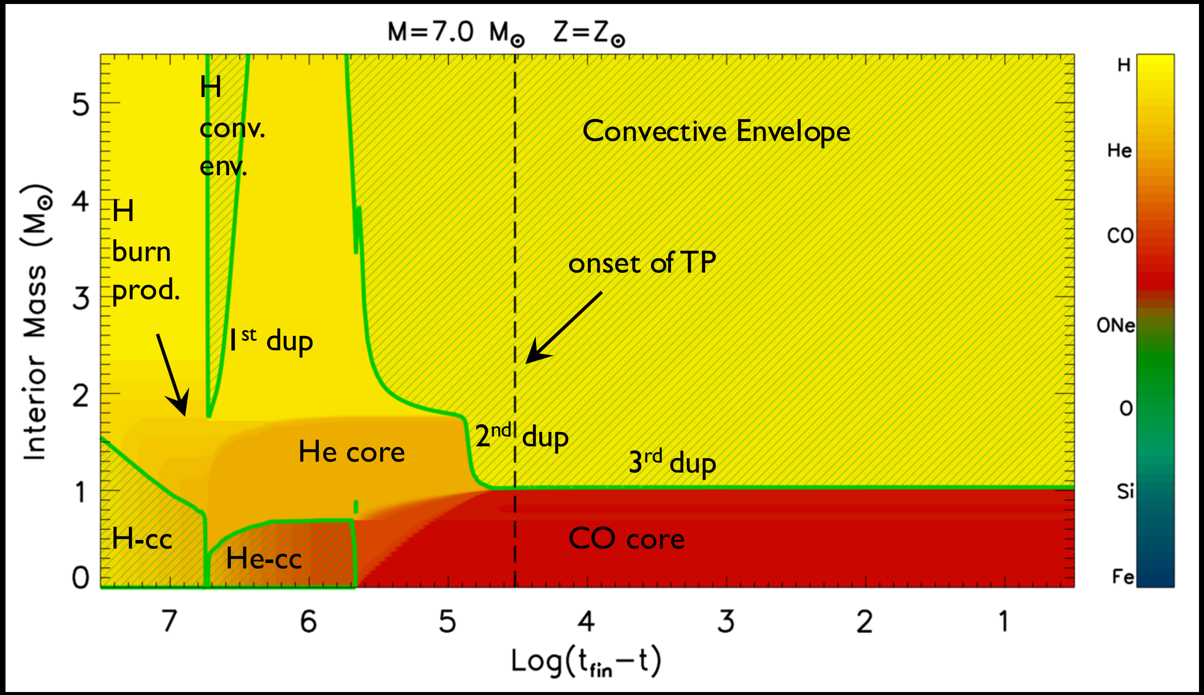
Stars with 7.5 $M_\odot \leq M \leq 9.2\ M_\odot$

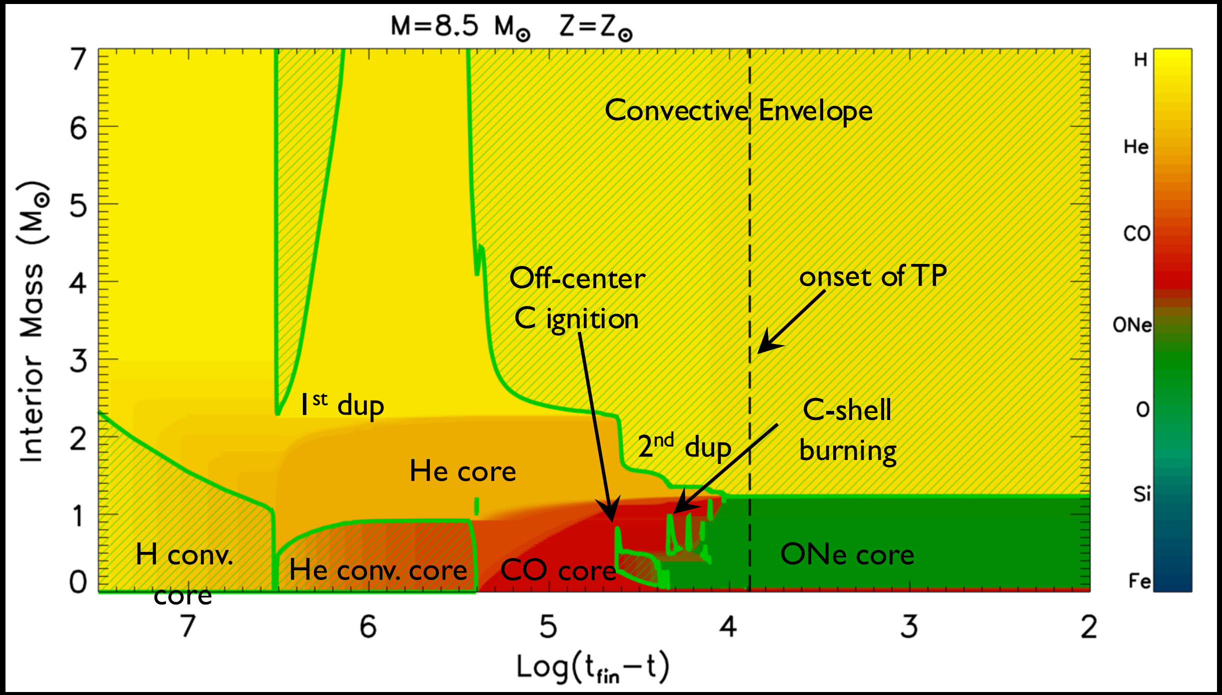
In stars with initial mass 7.5 $M_\odot \leq M \leq 9.2\ M_\odot$ the temperature in the ONe core does not reach the threshold for the Ne ignition

These stars enter the TP-SAGB phase

AGB



SAGB



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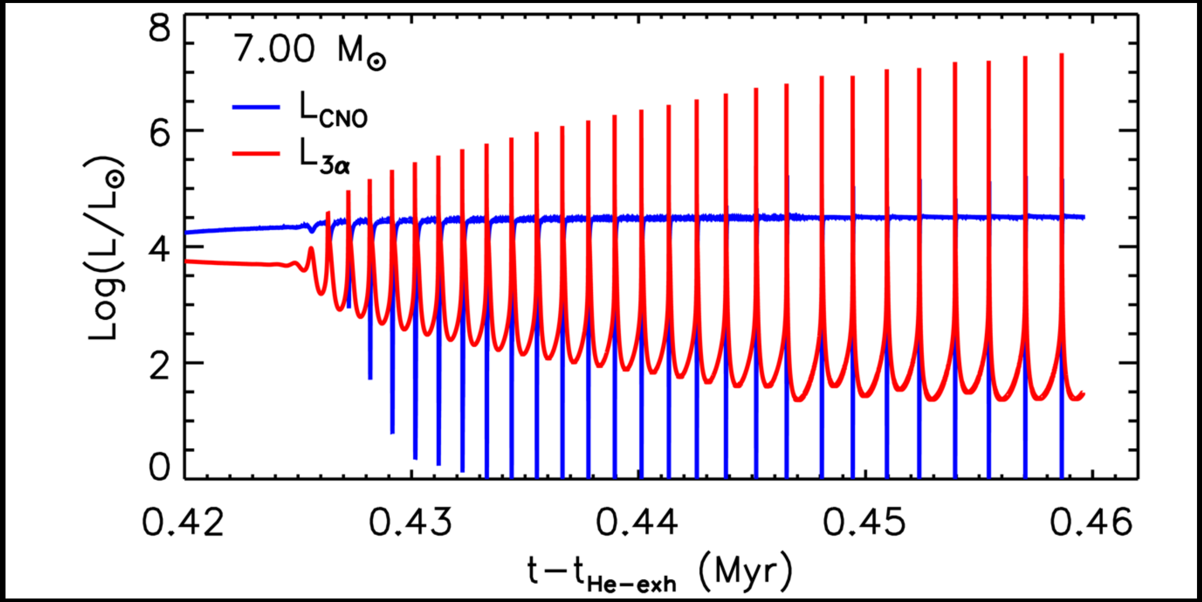
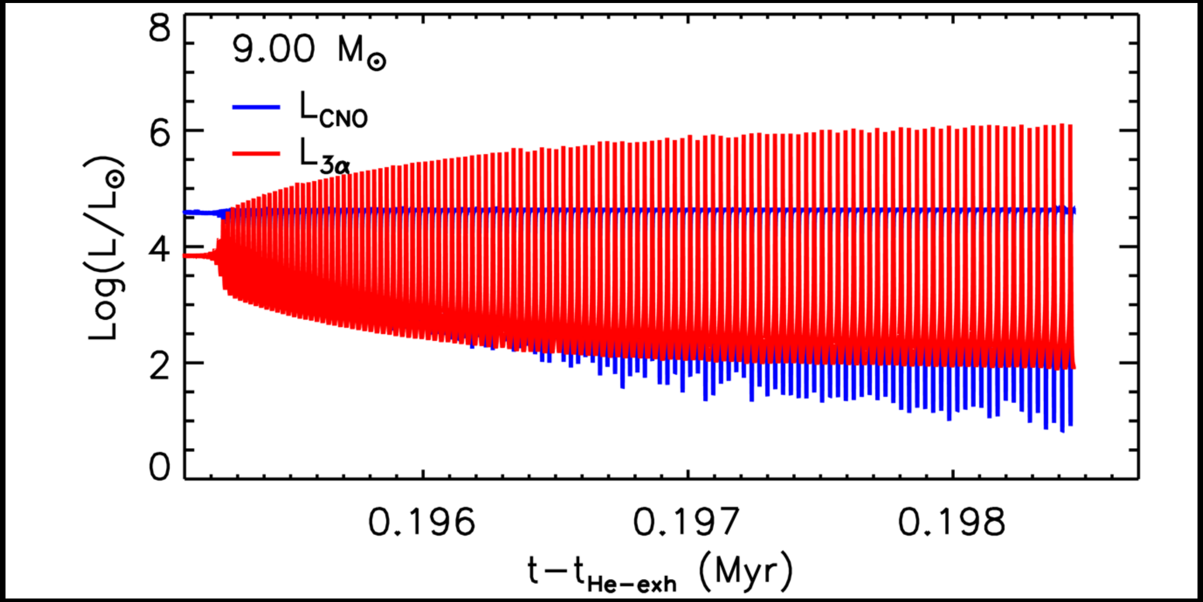
These stars enter the TP-SAGB phase

Moving from AGB stars to SAGB stars the maximum He luminosity reached during each thermal pulse decreases while the frequency of the TPs increases. The reason is that in SAGB the stars the core is larger and hotter

AGB



SAGB



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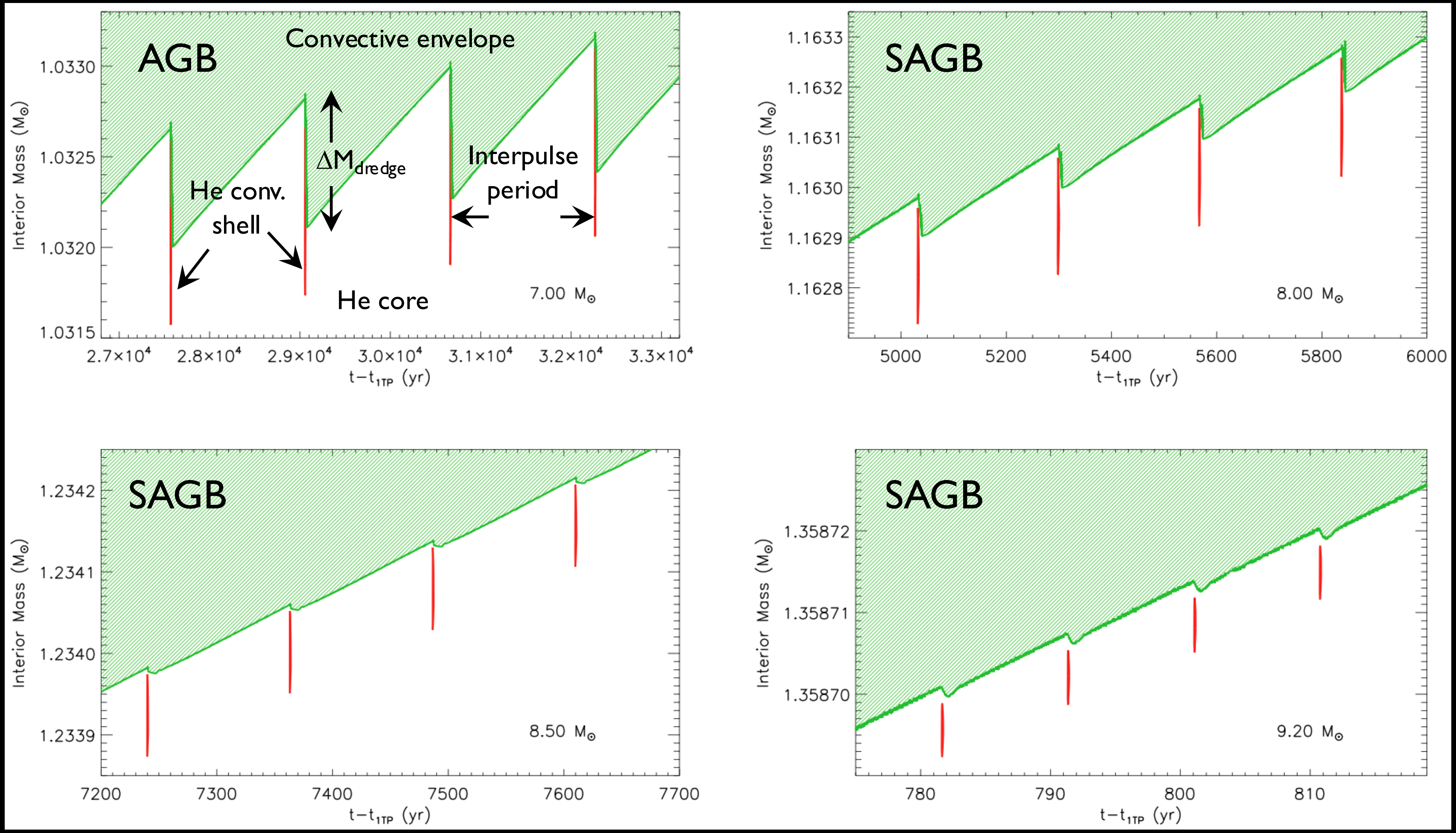
Stars with 7.5 M⊙ ≤ M ≤ 9.2 M⊙



- Reduction of the size of the He convective shell
- Reduction of the interpulse time
- Disappearance of the 3rd dup

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Stars with 9.05 $M_\odot \leq M \leq 9.20\ M_\odot$

In stars with initial mass 9.05 $M_\odot \leq M \leq 9.20\ M_\odot$ the central density increases enough that the Fermi energy exceeds the threshold value for the electron captures on a number of nuclear species that are quickly followed by the beta decays → URCA process

$$N(A,Z) + e^- \rightarrow M(A,Z-1) + \nu$$

$$M(A,Z-1) \rightarrow N(A,Z) + e^- + \bar{\nu}$$

Energy released

$$E_{\rm ec} = Q_{\rm nuc} - E_{\nu,{\rm ec}} + \mu_{\rm e}$$

$$E_\beta = -Q_{\rm nuc} - E_{\nu,\beta} - \mu_{\rm e}$$

$$[{\rm MeV}]$$

→

$$\epsilon = r_{\rm ec} E_{\rm ec} + r_\beta E_\beta \qquad [{\rm MeV}\ g^{-1}\ s^{-1}]$$

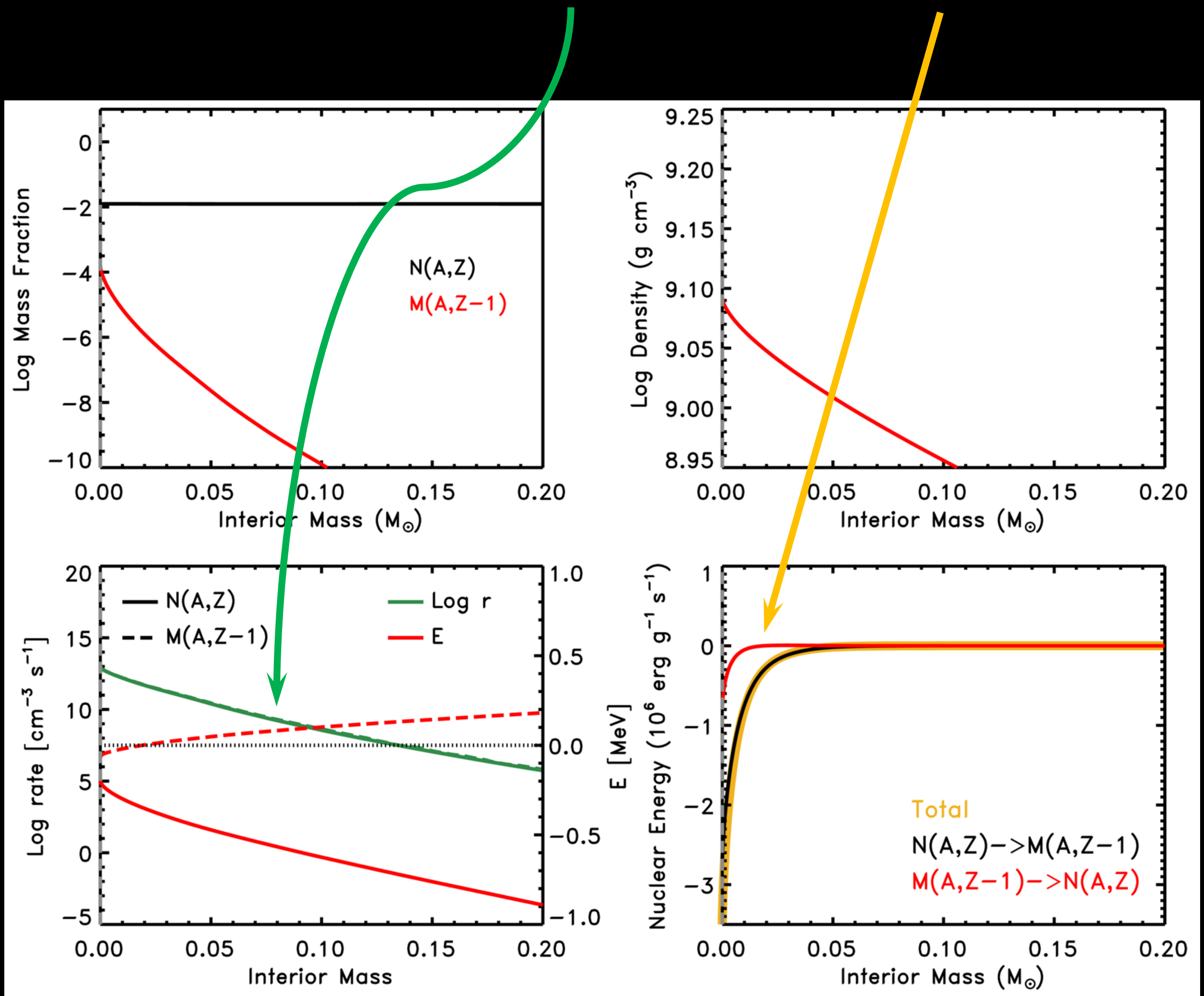
When the two reactions are in equilibrium

$$r_{\rm ec} = r_\beta$$

$$\epsilon = -r\left[E_{\nu,{\rm ec}} + E_{\nu,\beta}\right]$$

Stars with $9.05\ M_\odot \le M \le 9.20\ M_\odot$

In radiative environment equilibrium is achieved → $r_{\rm ec} = r_\beta$ $\quad \epsilon = -r\,[E_{\nu,\rm ec} + E_{\nu,\beta}]$ → Cooling



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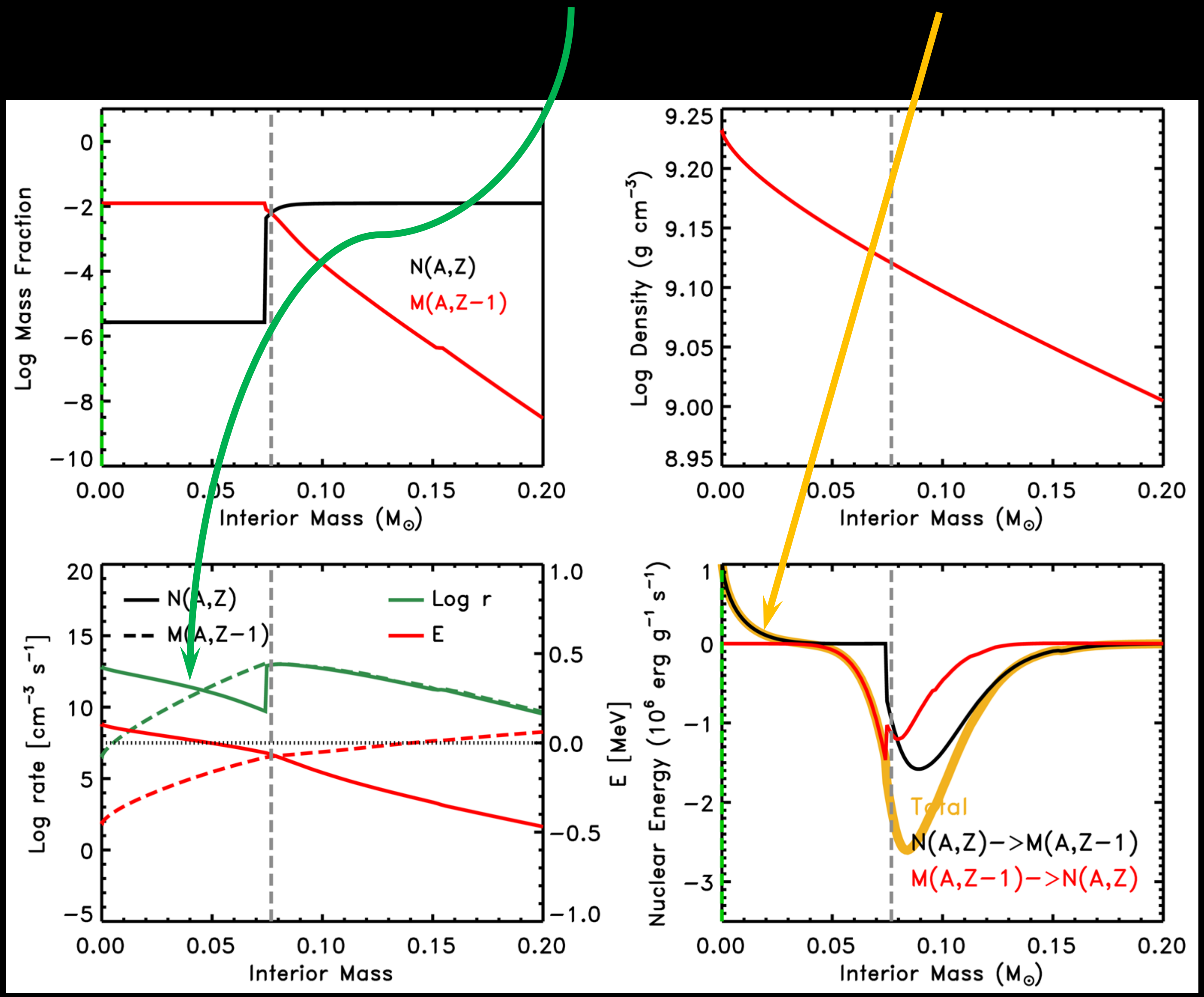
Stars with 9.05 $M_\odot \leq M \leq$ 9.20 $M_\odot$

In convective environment NO equilibrium is achieved → $r_{ec} \neq r_\beta$ $\epsilon = r_{ec}E_{ec} + r_\beta E_\beta$ → Heating / Cooling

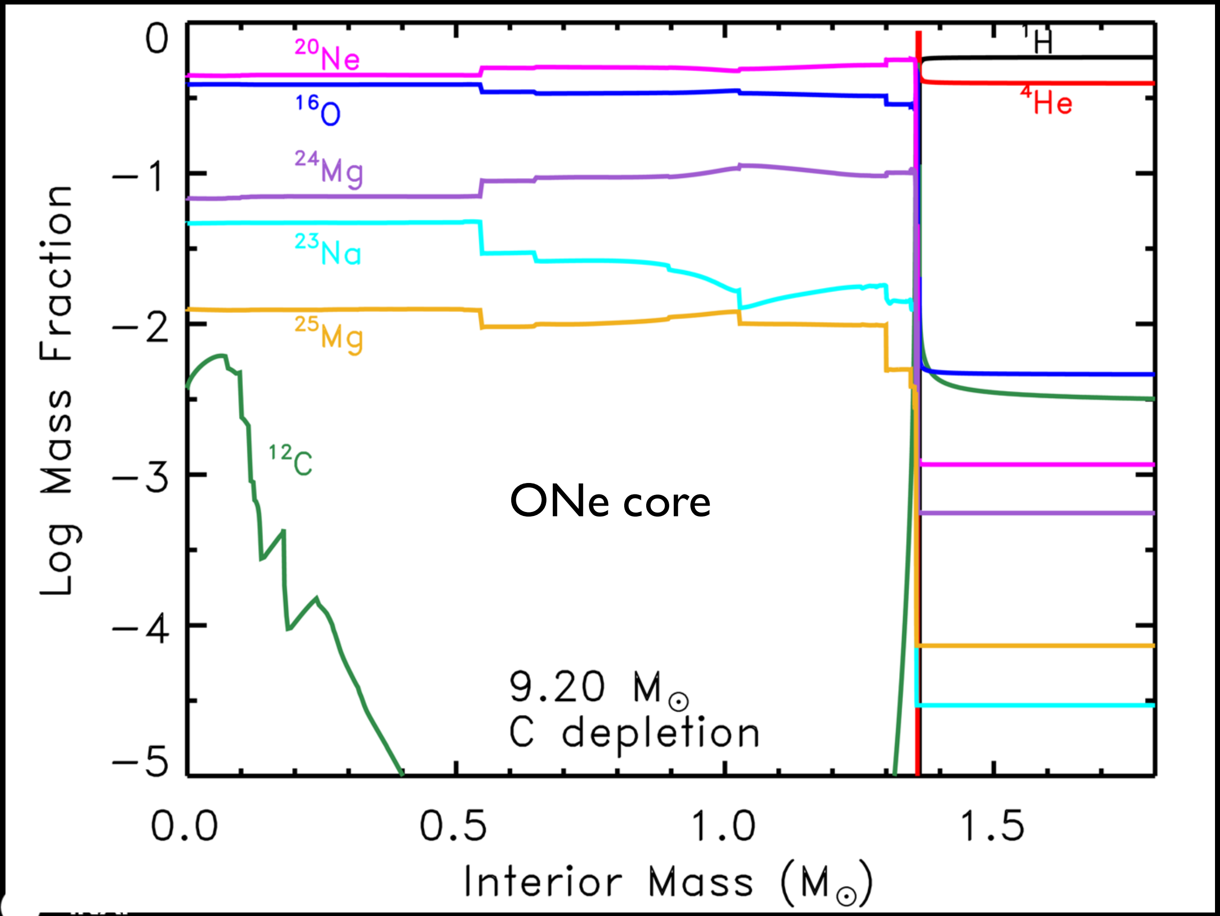


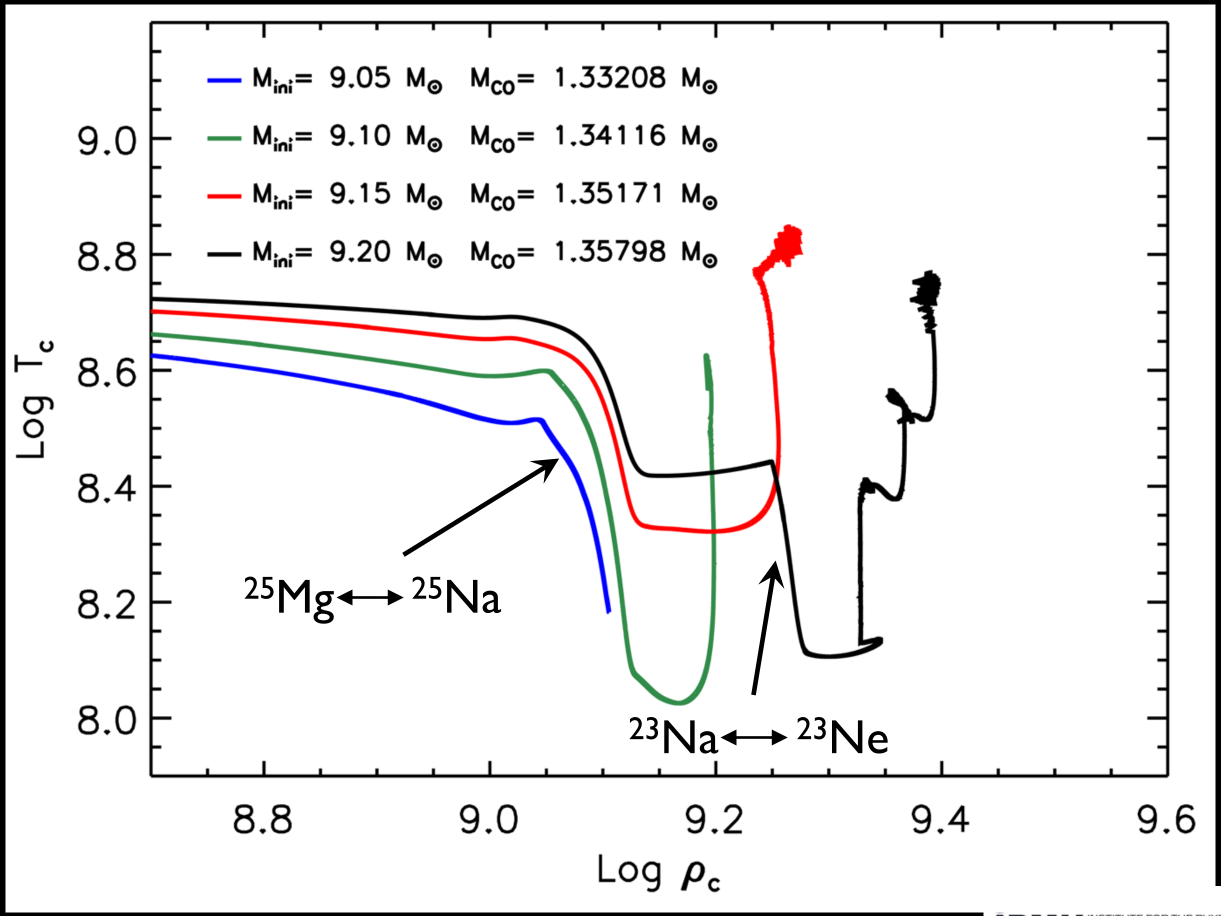
Stars with 9.05 $M_\odot \leq M \leq 9.20 M_\odot$

Two URCA pairs that induce some effect on the evolution

$^{25}\mathrm{Mg}(e^-,\nu)^{25}\mathrm{Na}$ $^{23}\mathrm{Na}(e^-,\nu)^{23}\mathrm{Ne}$

$^{25}\mathrm{Na}(\beta^-,\bar{\nu})^{25}\mathrm{Mg}$ $^{23}\mathrm{Ne}(\beta^-,\bar{\nu})^{23}\mathrm{Na}$





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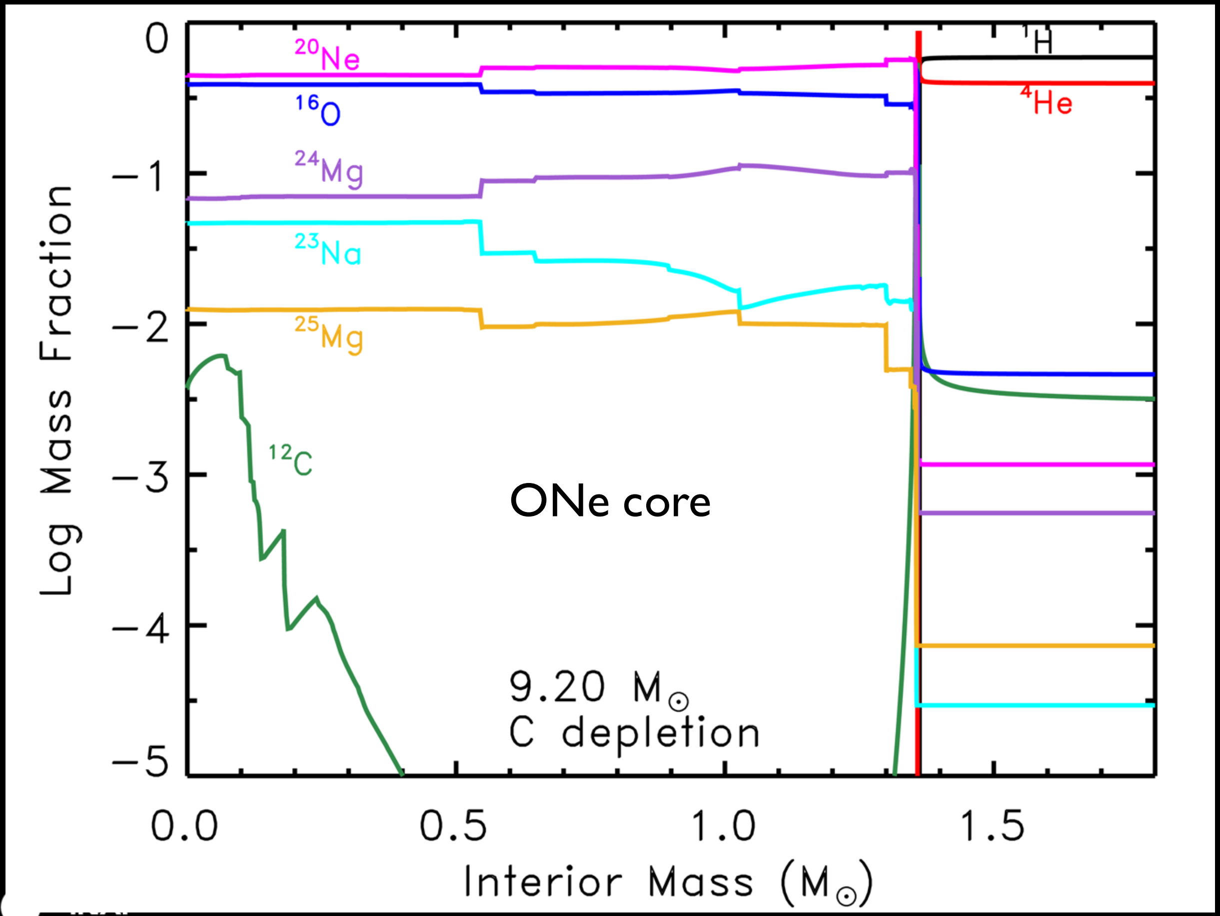
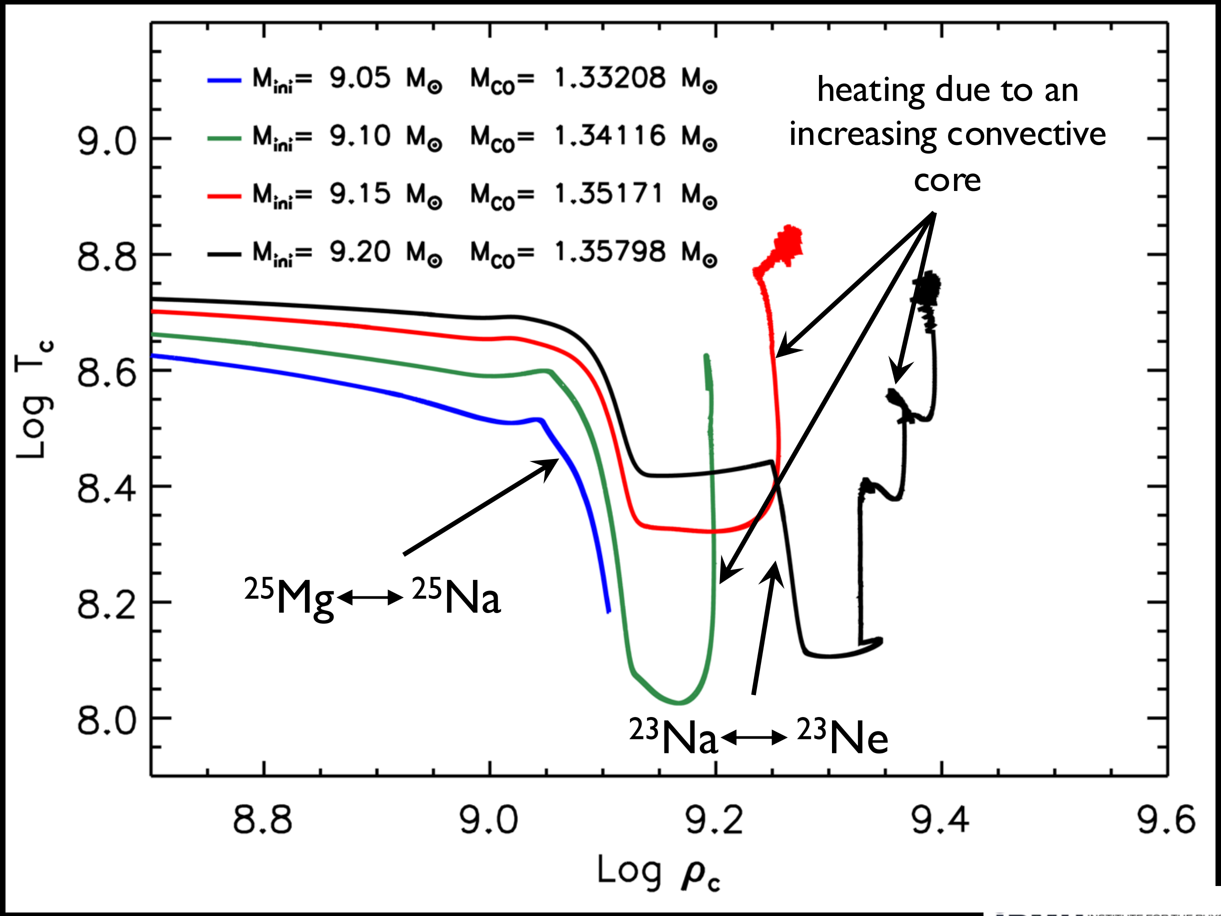
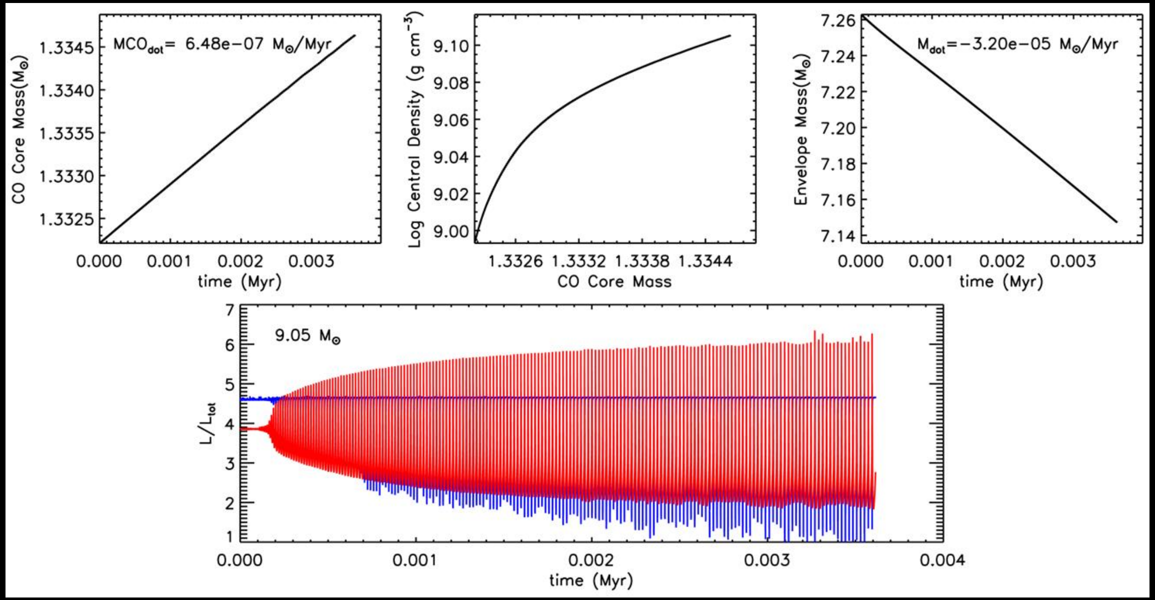




Stars with 7.5 $M_\odot \leq M \leq 9.2\ M_\odot$: Final Fate

Progressive increase of the central density due to the increase of the CO core during TP-SAGB phase

Progressive reduction of the H-rich envelope due to stellar wind



The final fate is the result of the competition between these two phenomena

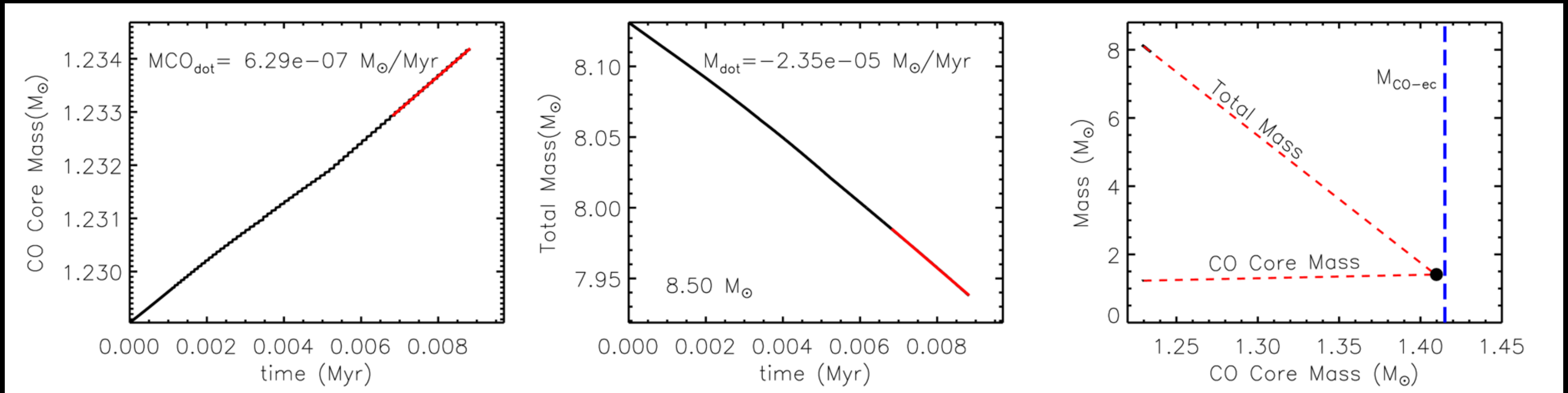
Central density approaches the threshold (~9.6) for electron capture $^{24}\mathrm{Mg}(e^-,\nu)^{24}\mathrm{Na}$ → Electron Capture Supernova

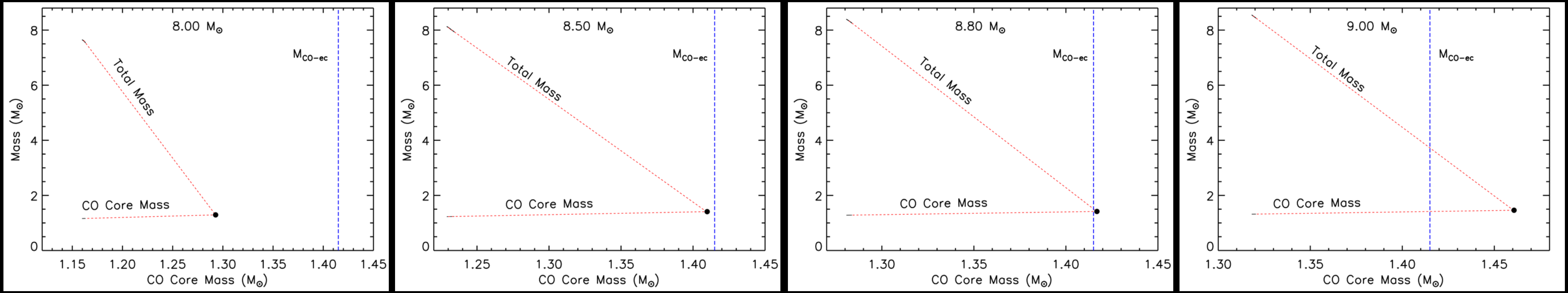
Complete removal of the H-rich envelope before the activation of $^{24}\mathrm{Mg}(e^-,\nu)^{24}\mathrm{Na}$ → ONe-WD

A self consistent determination of the final fate would require the calculation of several thousands of TPs that is not feasible at present → estimate of the final fate by means of "extrapolated" evolutions

Stars with 7.5 $M_\odot \leq M \leq 9.2\ M_\odot$: Final Fate

Linear regression of the quantities over the last few TPs and extrapolations at late times





ONe-WD   ECSN   ECSN   ECSN

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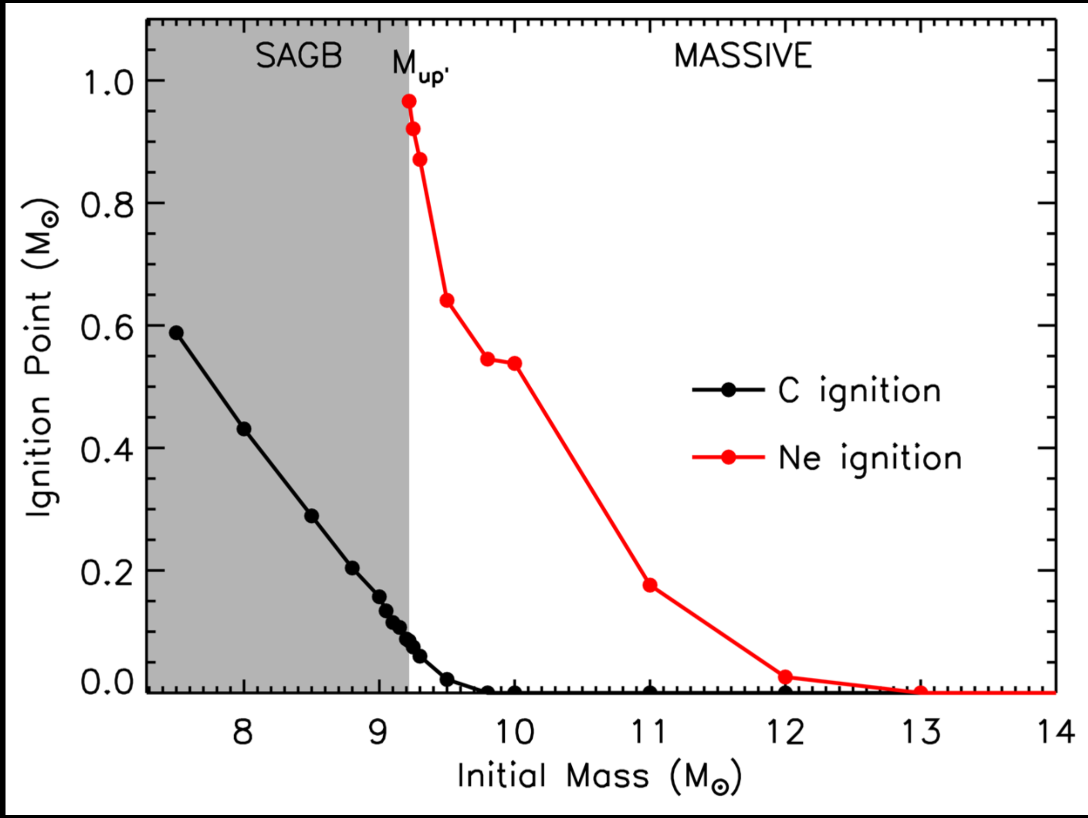
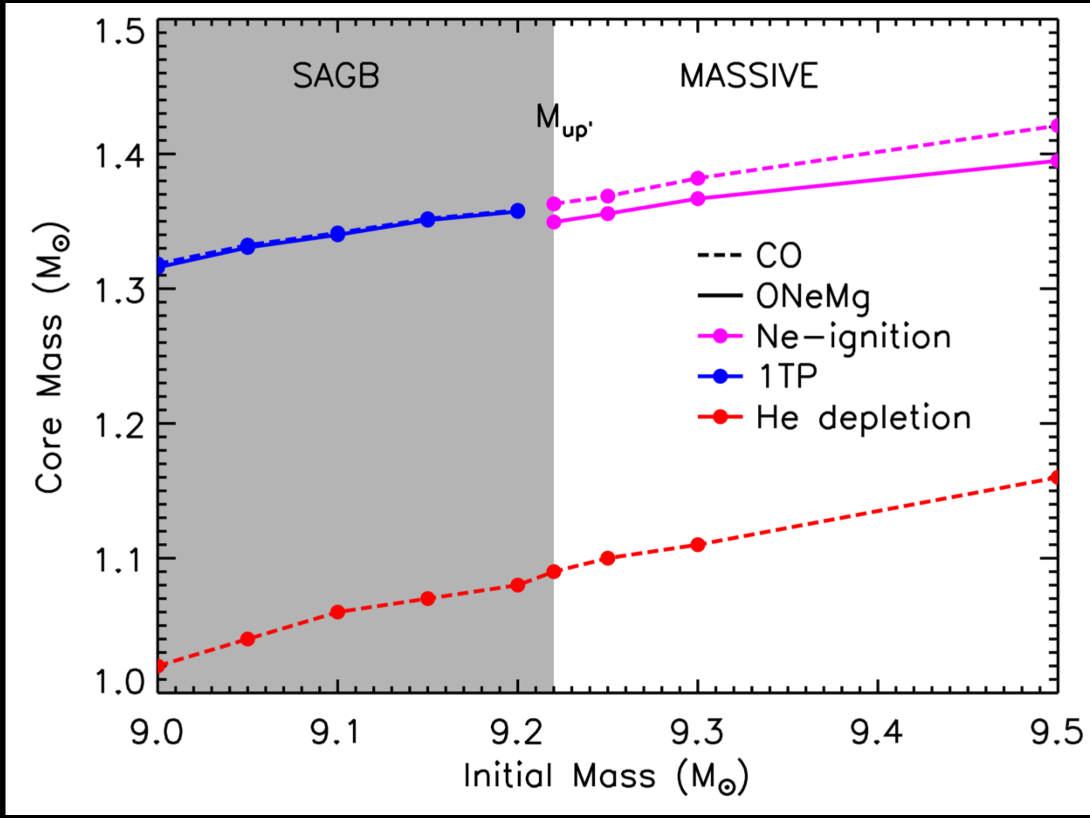
Stars with M ≥ 9.22 $M_\odot$

In stars with M ≥ 9.22 $M_\odot$ the temperature reaches the threshold value for the ignition of Ne burning

Off-center Ne-ignition in stars with 9.22 ≤ $M/M_\odot$ ≤ 12

Minimum CO core for Ne-ignition M_{CO}=1.363 $M_\odot$ - M_{ONe}=1.349 $M_\odot$





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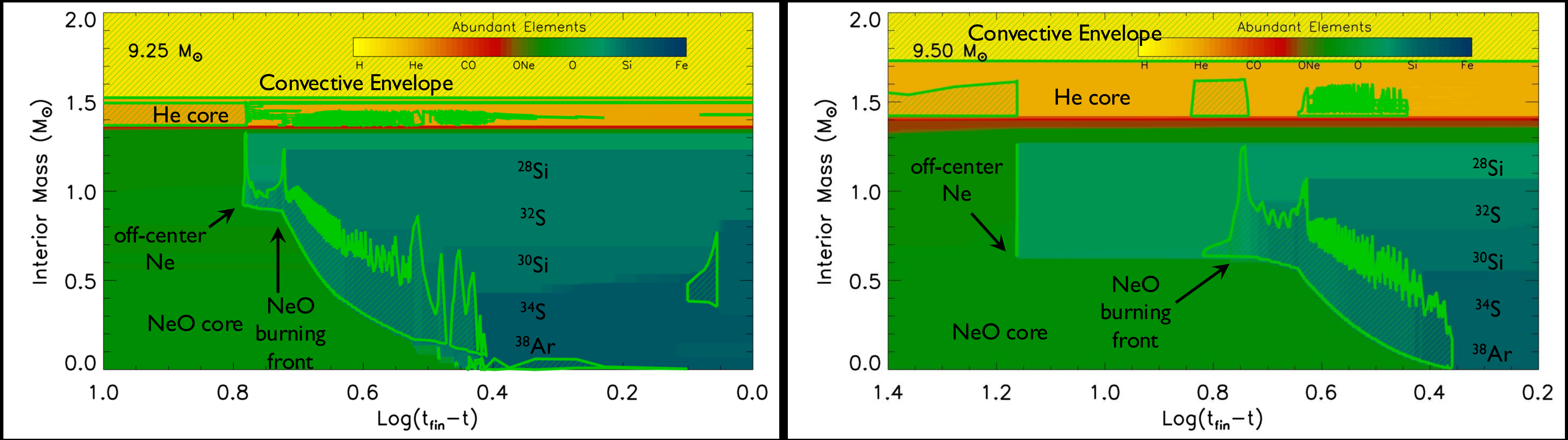
Stars with $M \geq 9.22\ M_\odot$

Ne ignition in a degenerate environment induces a progressive increase of T and L

A convective zone is formed

Temperature increases to the threshold value for O ignition



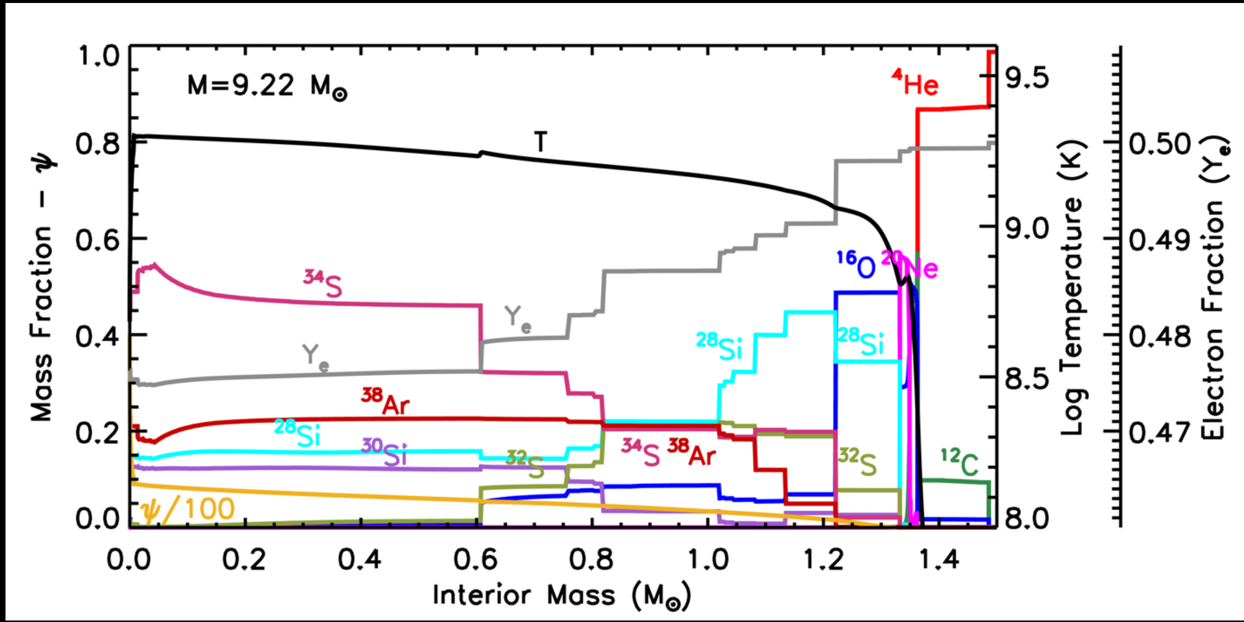
Because of the efficient electron captures, the main products of the off-center Ne/O burning within the convective shell are ^{34}S, ^{28}Si, ^{30}Si and ^{32}S

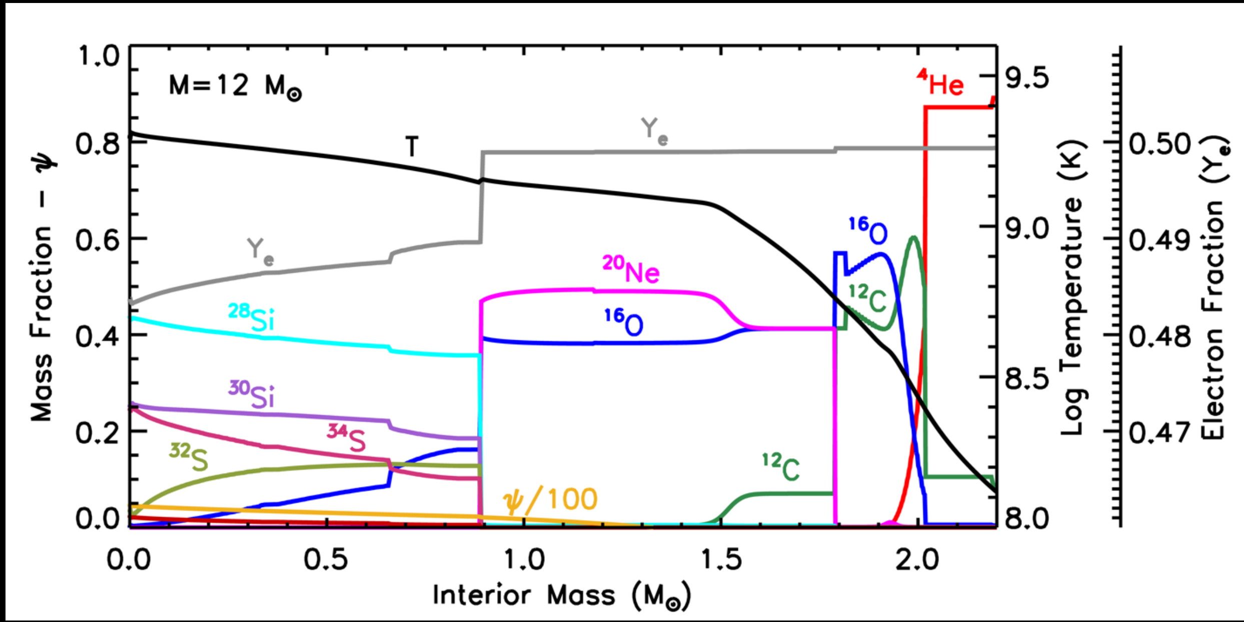
The efficiency of the electron captures, however, decreases as the initial mass of the star increases

Stars with M ≥ 9.22 $M_\odot$

At variance with off- center C burning, no hybrid core is formed as a result of the off- center Ne ignition. All of the stars that ignite off-center Ne burning form an O-depleted core; i.e., in all of these models, the ONe burning front reaches the center

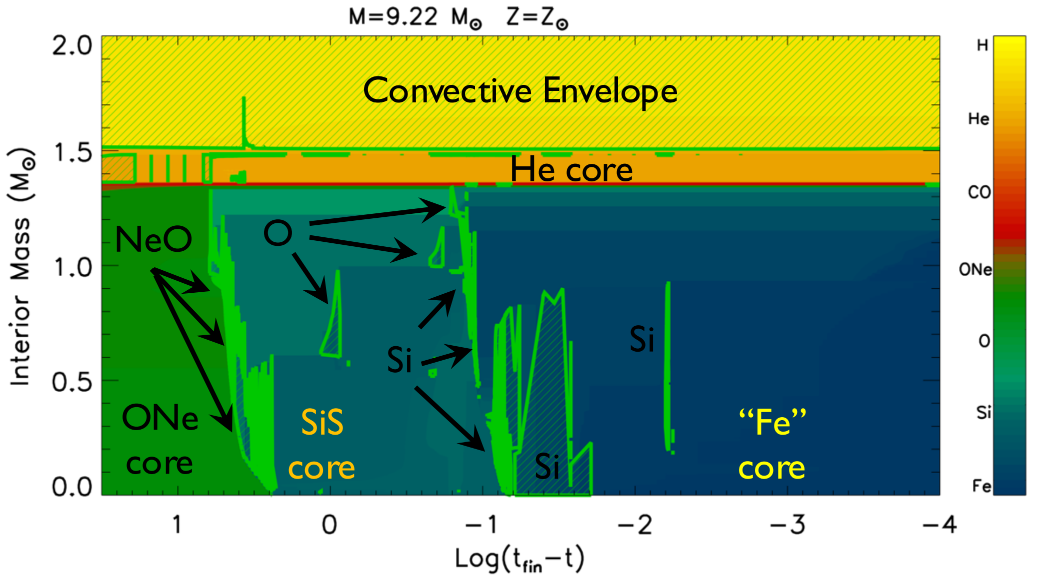
Chemical composition of the O-exhausted core strongly depends on the initial mass

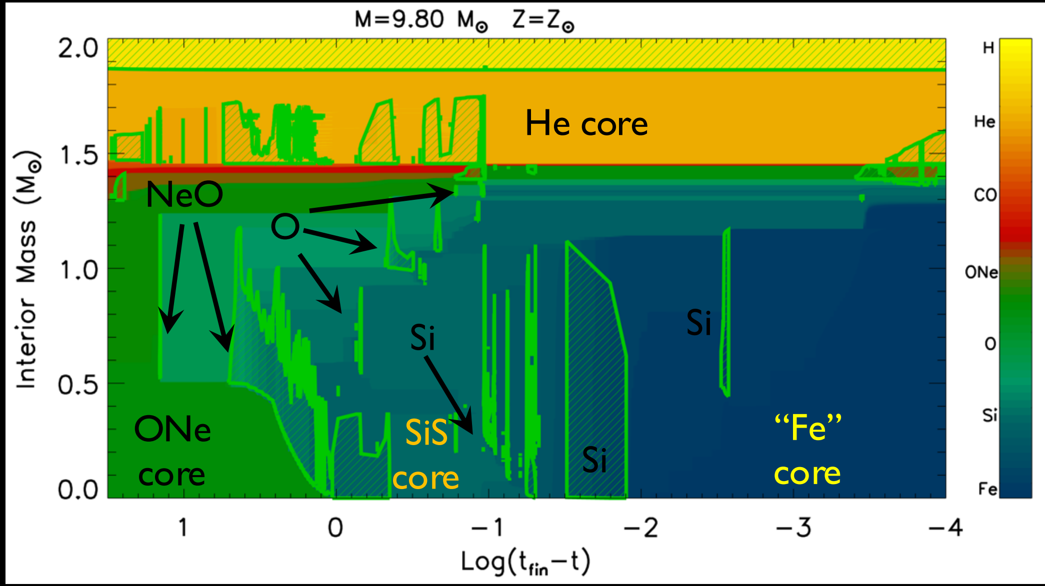


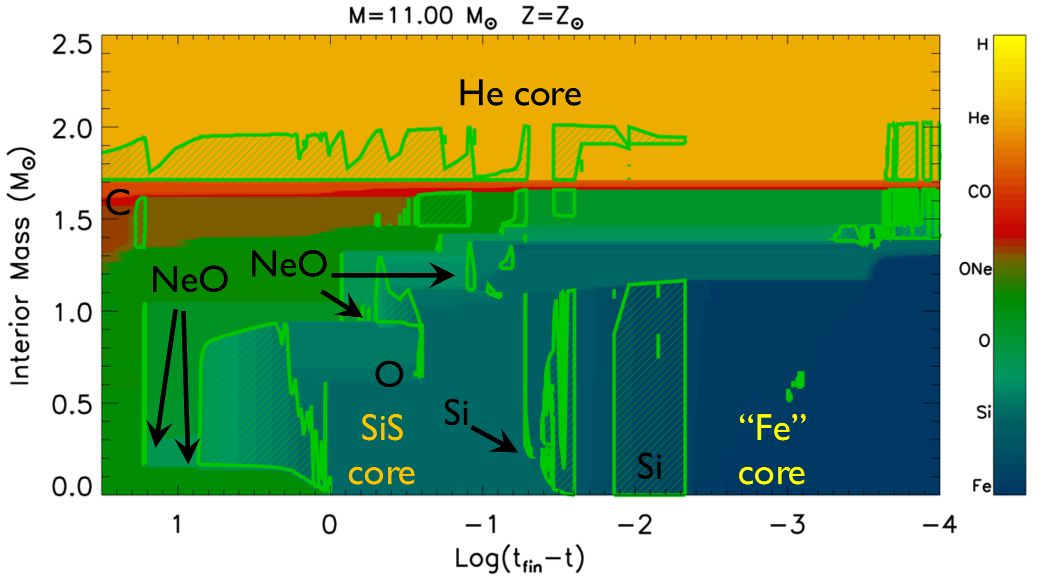


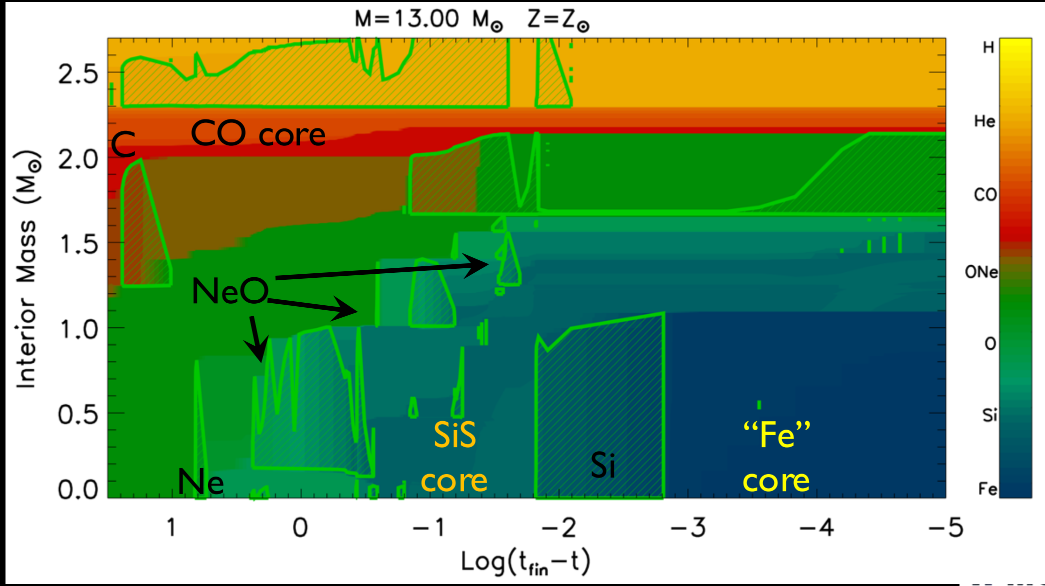
Stars with $M \geq 9.22\ M_\odot$

All the stars that ignite NeO, ignite also Si burning (off-center or centrally), form a "Fe" core and explode as CCSNe









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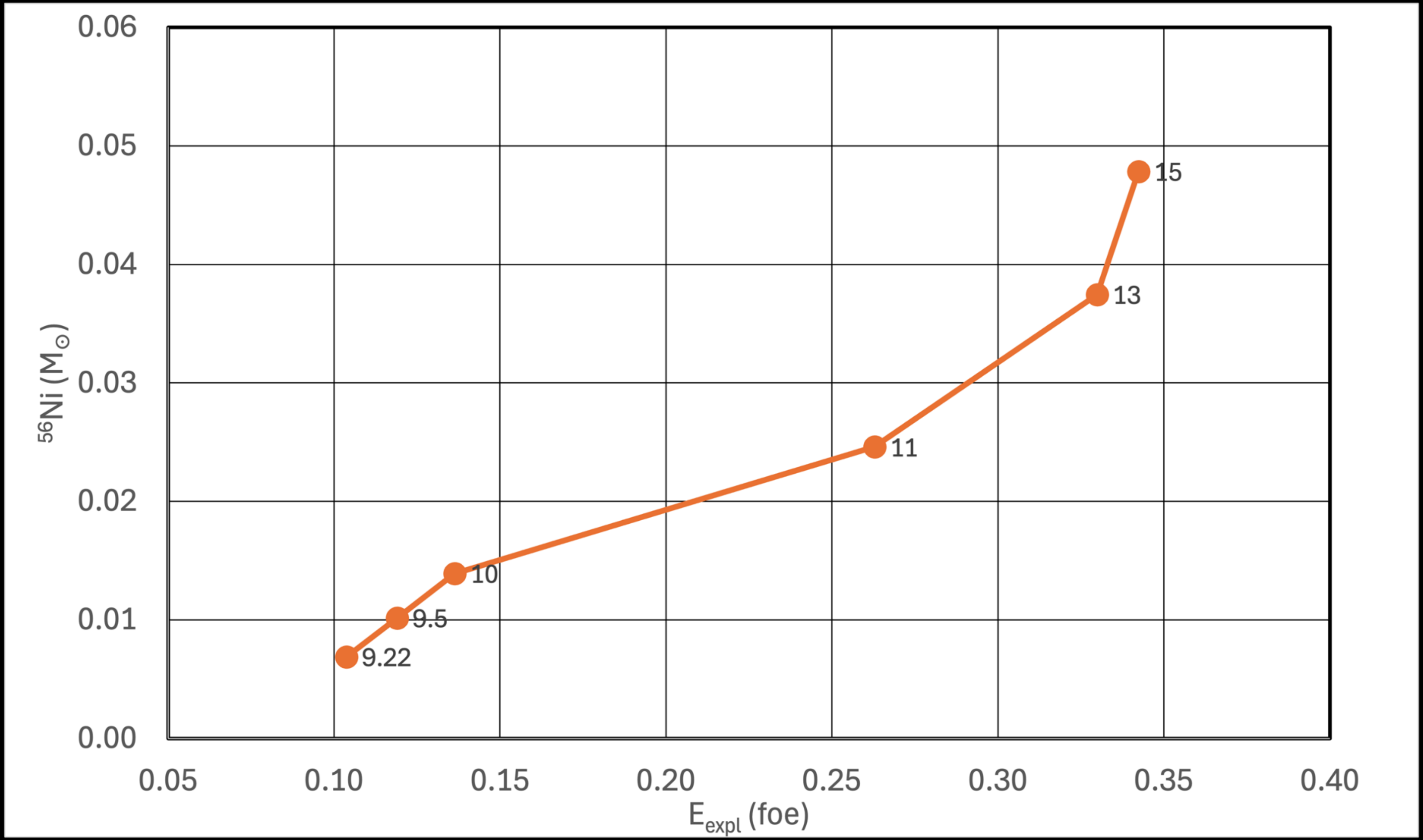
CCSN Explosion

Explosions computed by means of the HYPERION code (Limongi & Chieffi 2020)

Parameters of explosions from Burrows+2024



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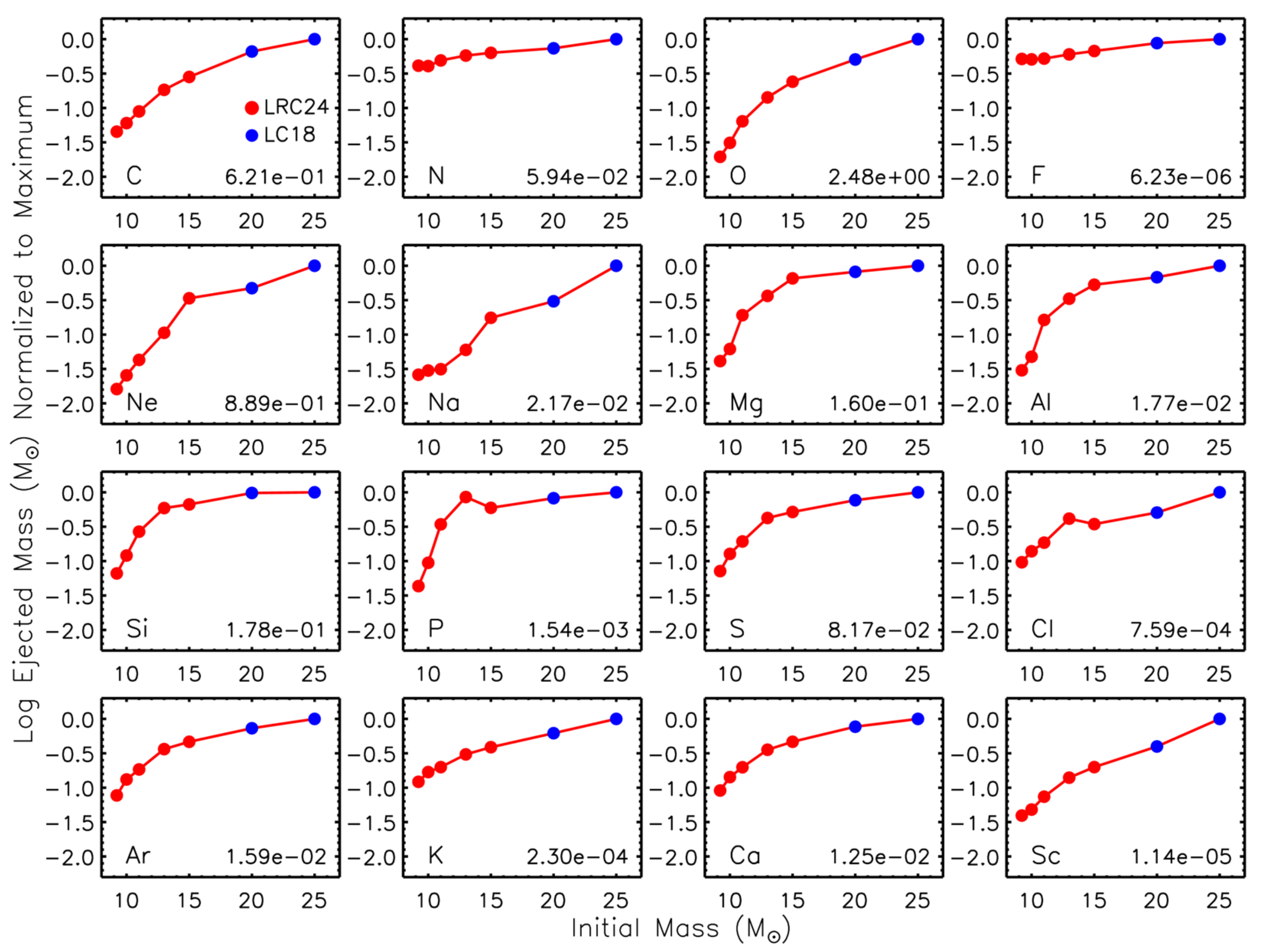
CCSN Explosion: The Chemical Composition of the Ejecta

Yields for stars smaller than ~12 $M_\odot$ not available in literature



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Extrapolation below ~13 $M_\odot$ can be dangerous for most of the elements

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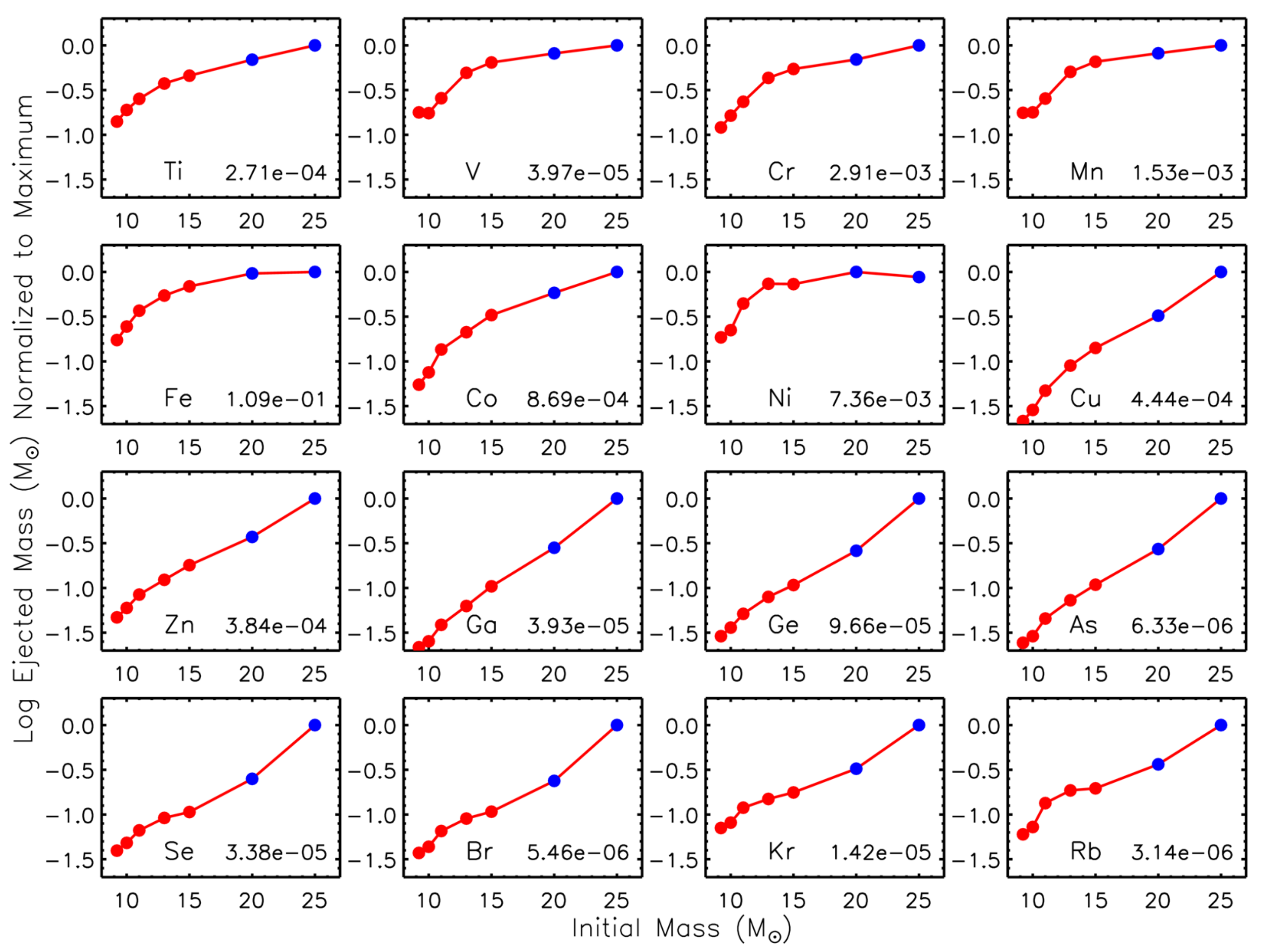

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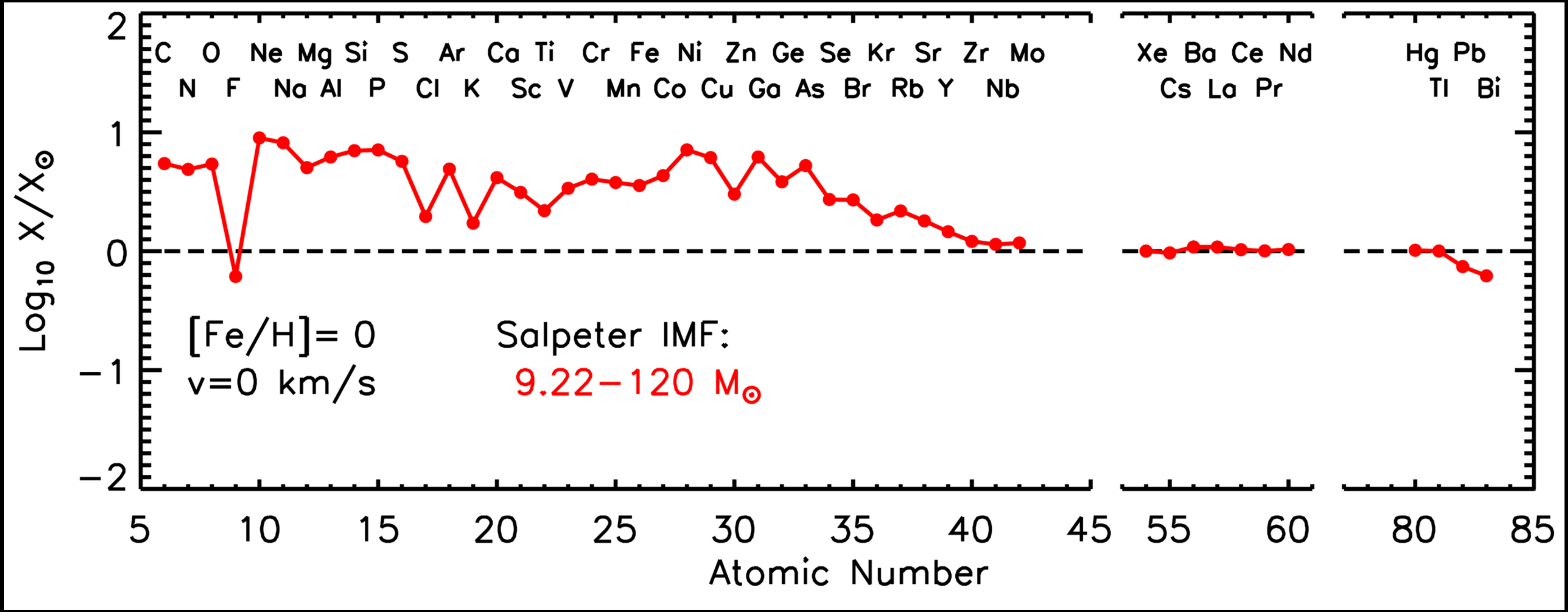
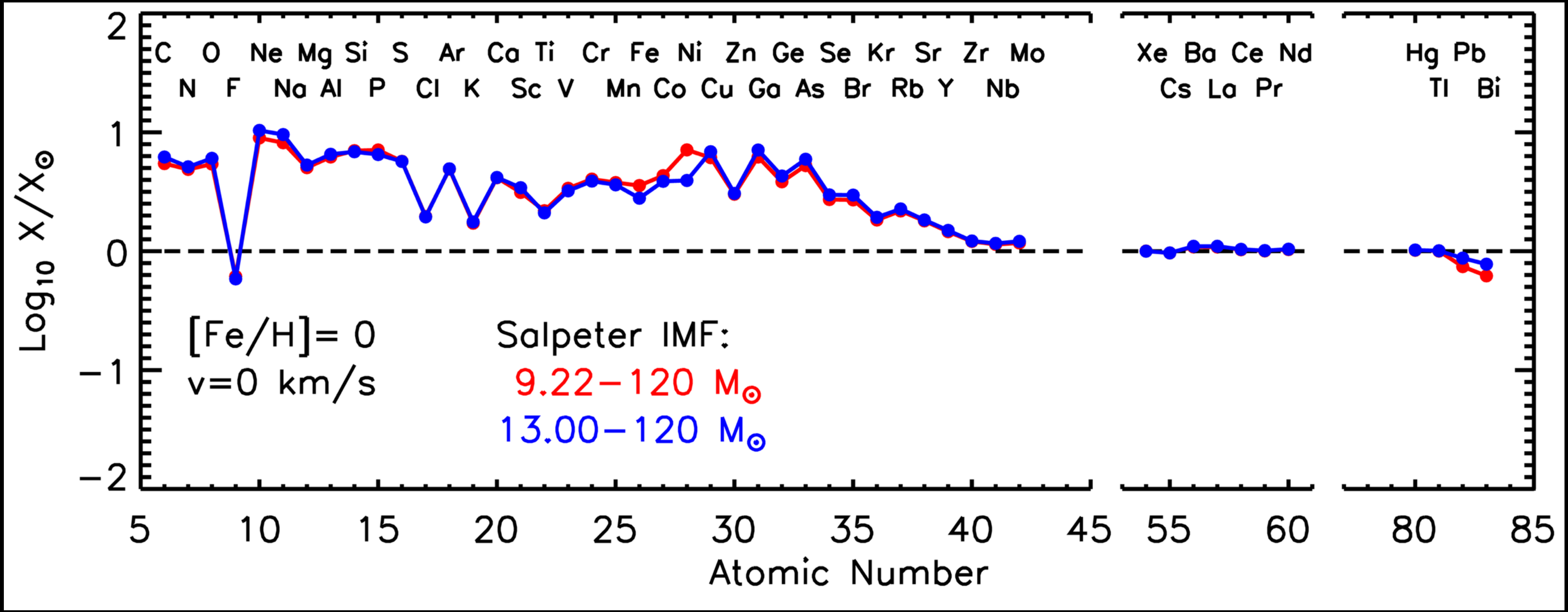
CCSN Explosion: Averaged Yields



CCSN Explosion: Averaged Yields

The high number of stars in the mass interval 9.22-13 $M_{\odot}$ is compensated by the small amount of ejected masses



The actual contribution of these stars to the chemical evolution of the galaxies could be investigated only in the context of the GCE models

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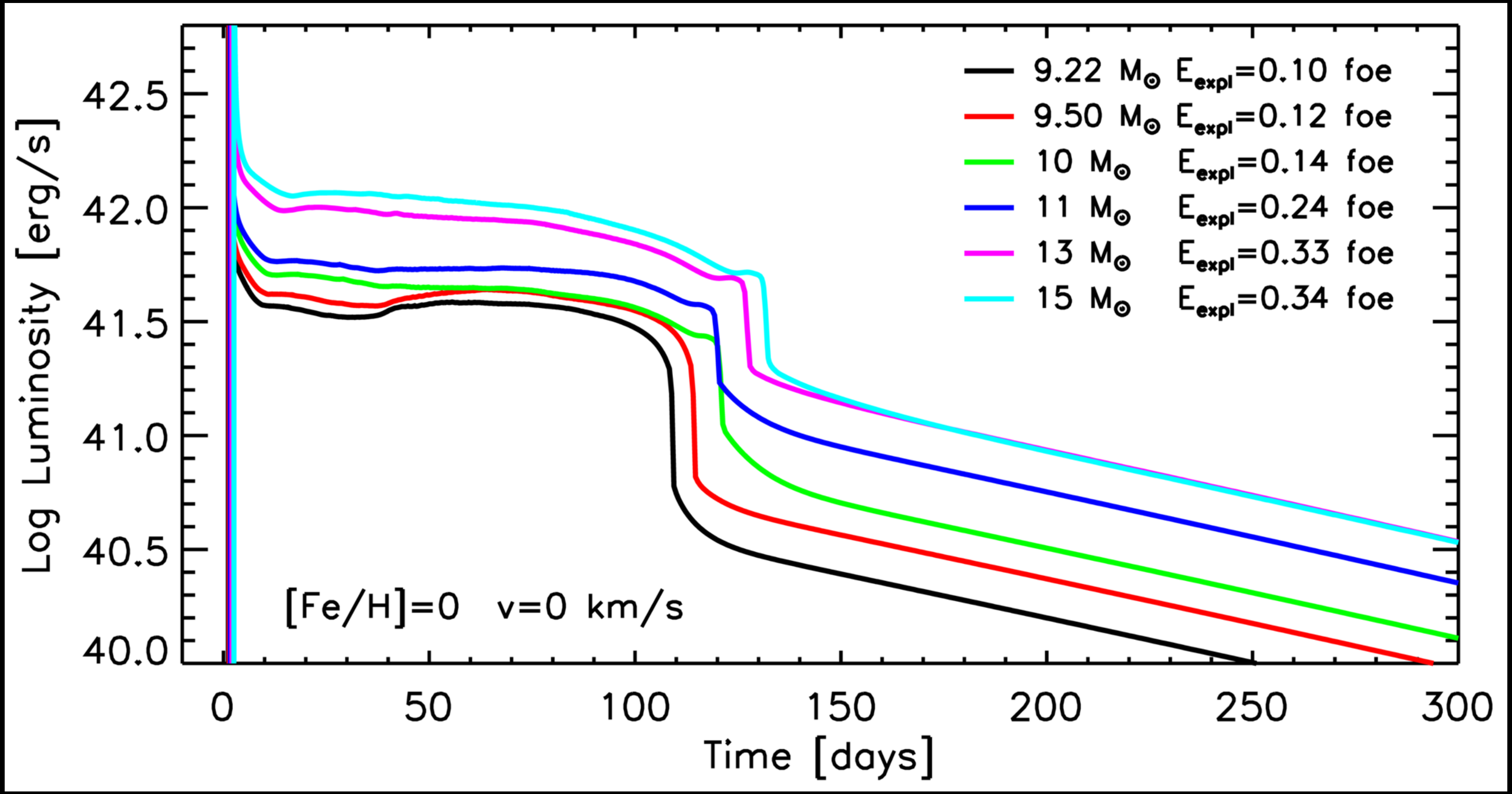
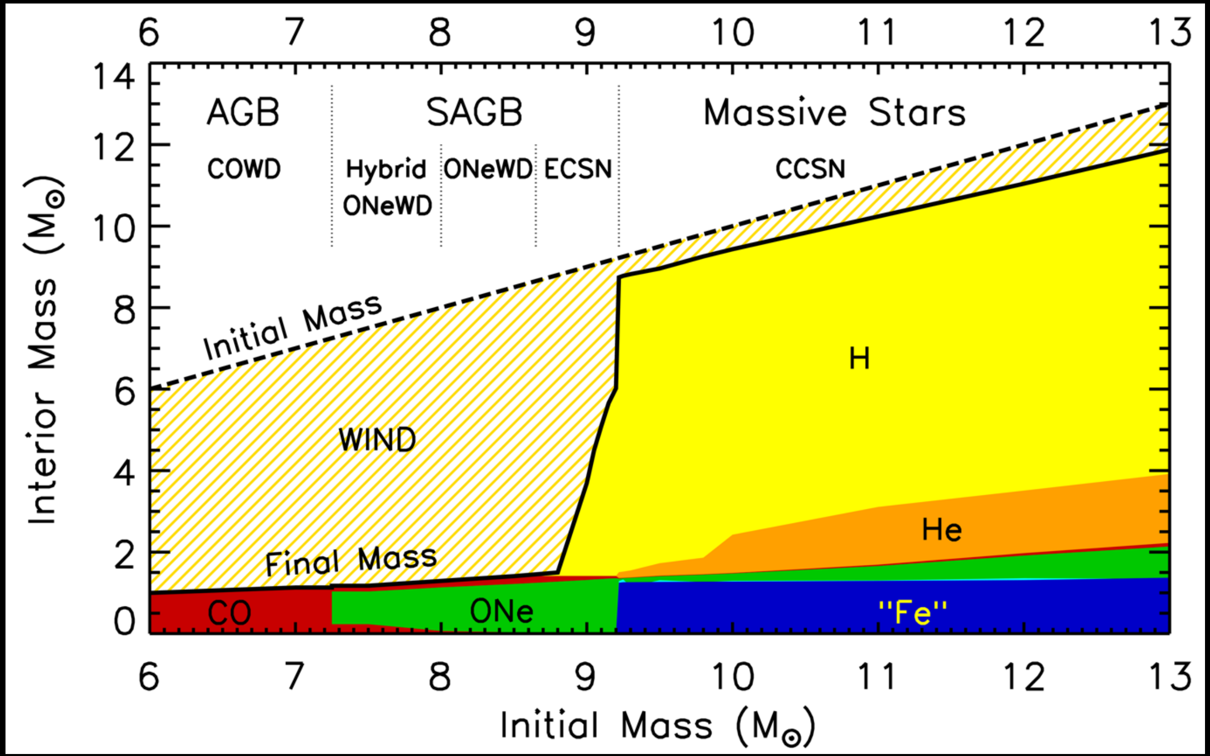
CCSN Explosion: Optical Display - The Light Curves



Light curves computed by means of the HYPERION code (Limongi & Chieffi 2020)

Luminosity and length of the Plateau increase with the progenitor mass

Summary and Conclusions



Limongi, Roberti & Chieffi (2024)

The ejected masses decrease substantially for stars with M<13 $M_\odot$ – Extrapolation dangerous

The high number of stars in the mass interval 9.22-13 $M_\odot$ is compensated by the small amount of ejected masses

Diversity of the optical display both luminosity and duration of the plateau

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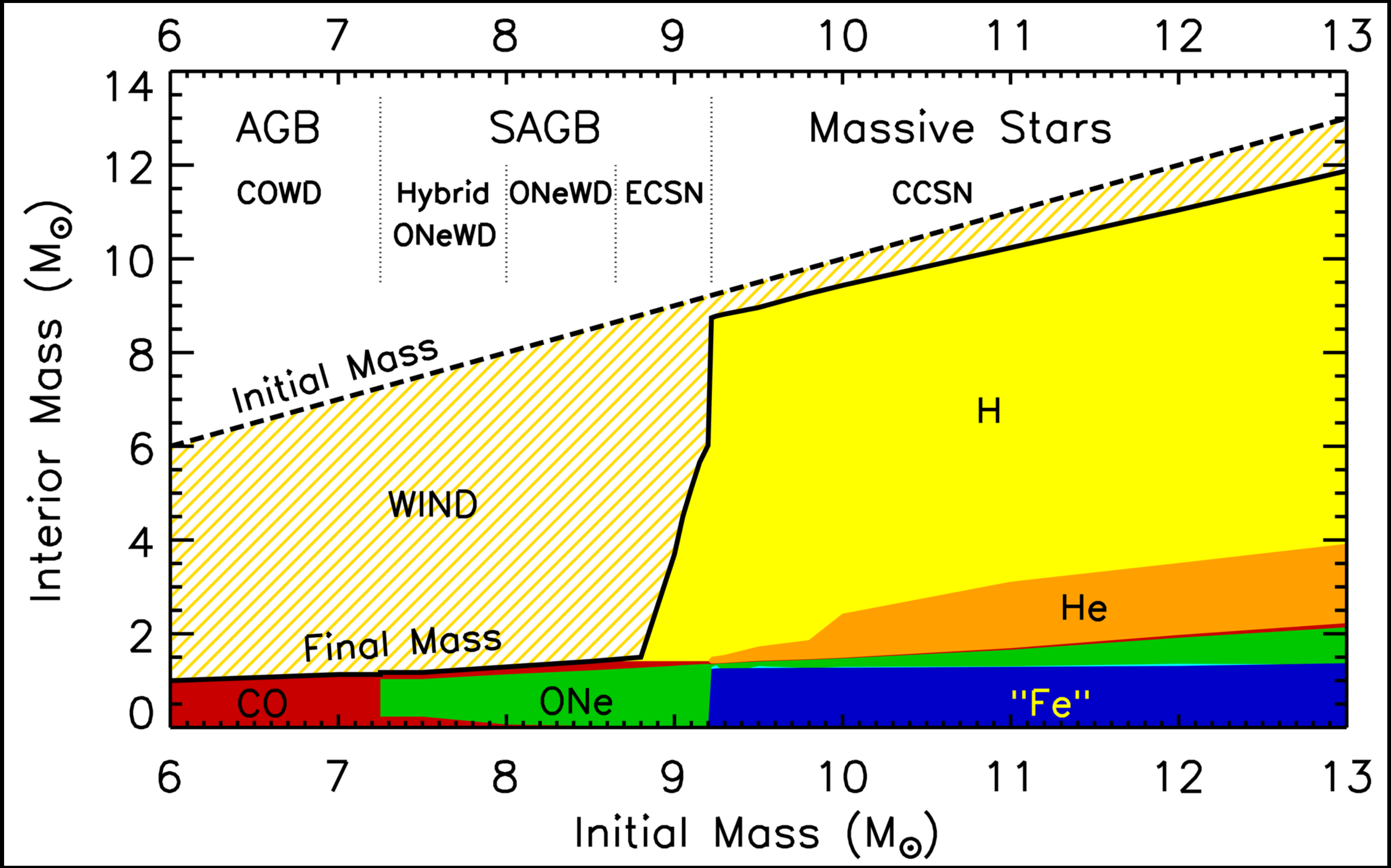
Summary and Conclusions



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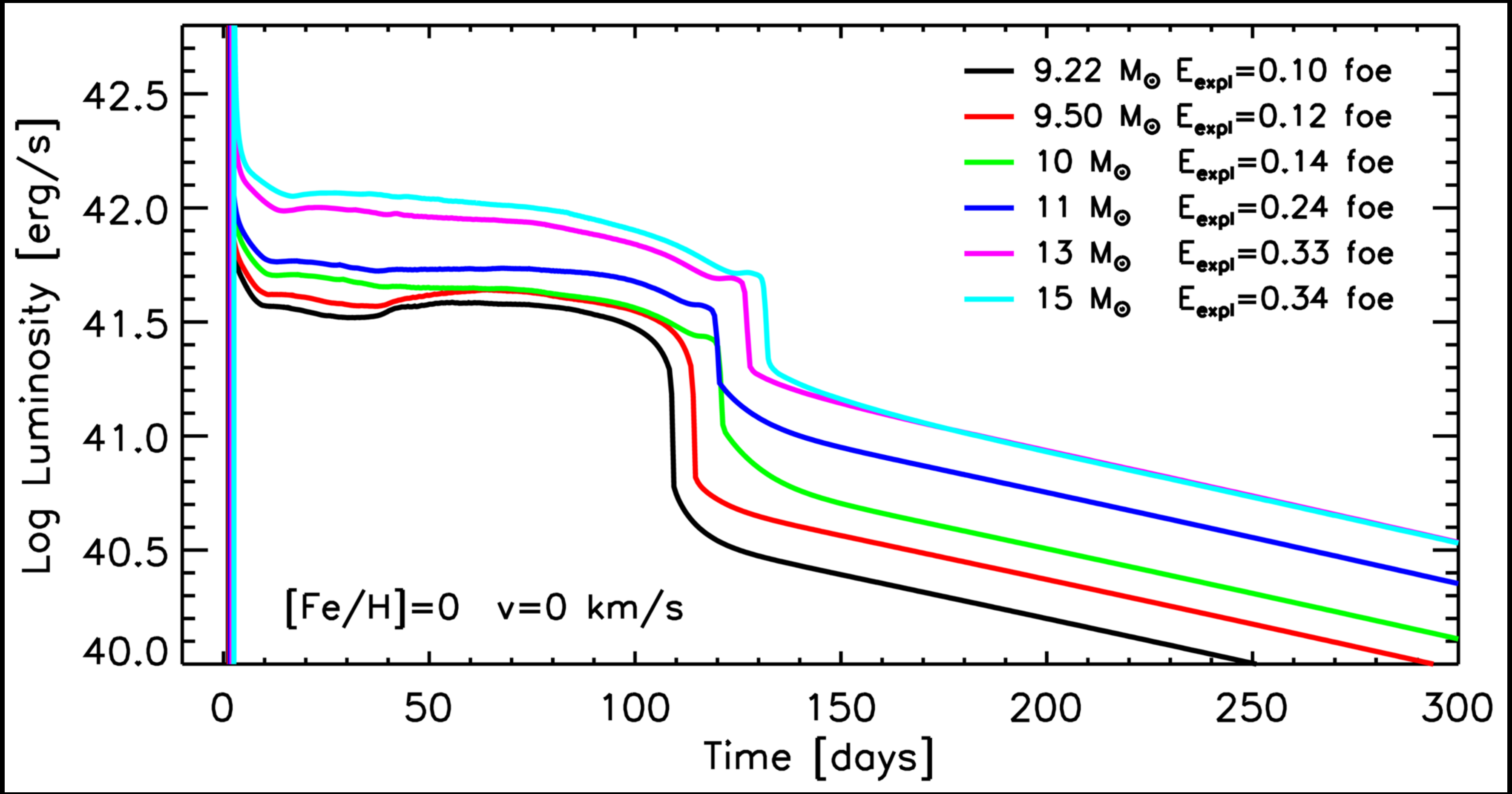
CCSN Explosion: Optical Display - The Light Curves



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