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

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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

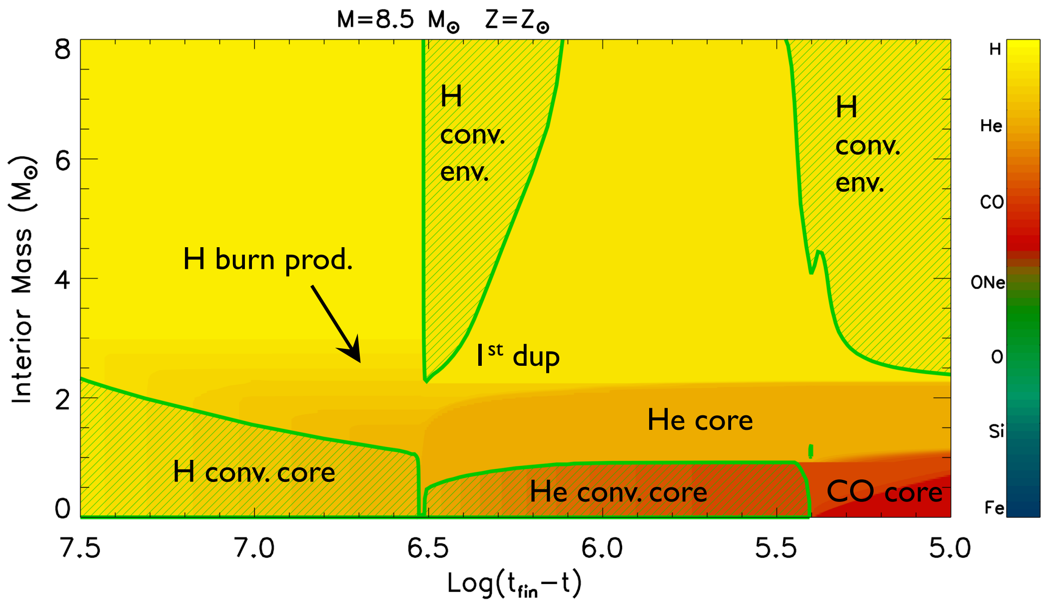
In spite of such astrophysical relevance, their evolutionary properties as well as their final fate (CO-WD, ONe-WD, Electron Capture Supernova, Core Collapse Supernovae) are scarcely studied

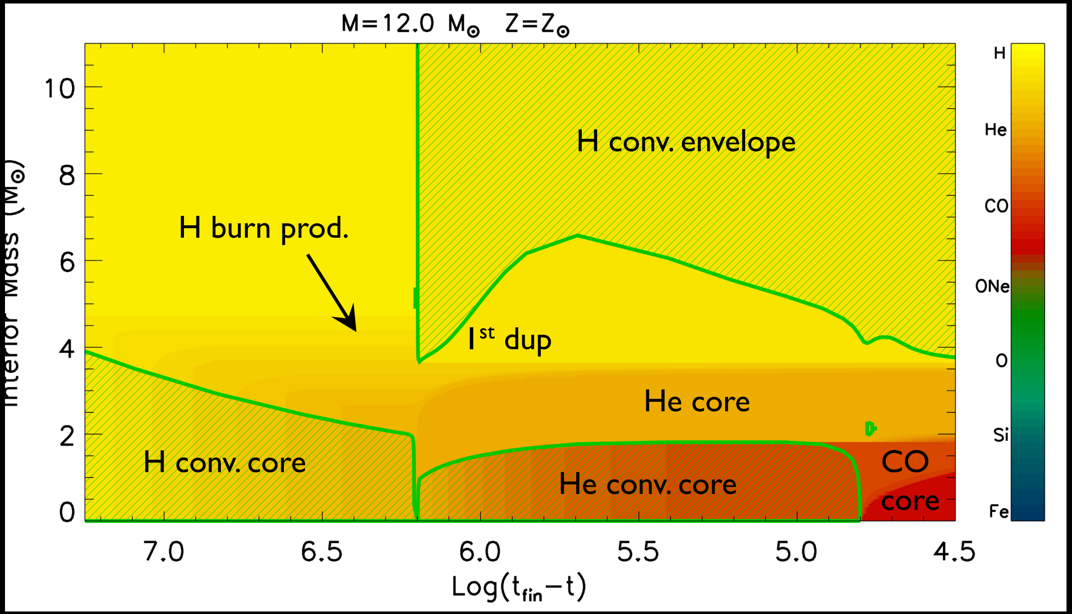
The main reason for the paucity of homogenous, detailed and comprehensive studies of the evolution of these stars is that the computation of their full evolution is extremely challenging

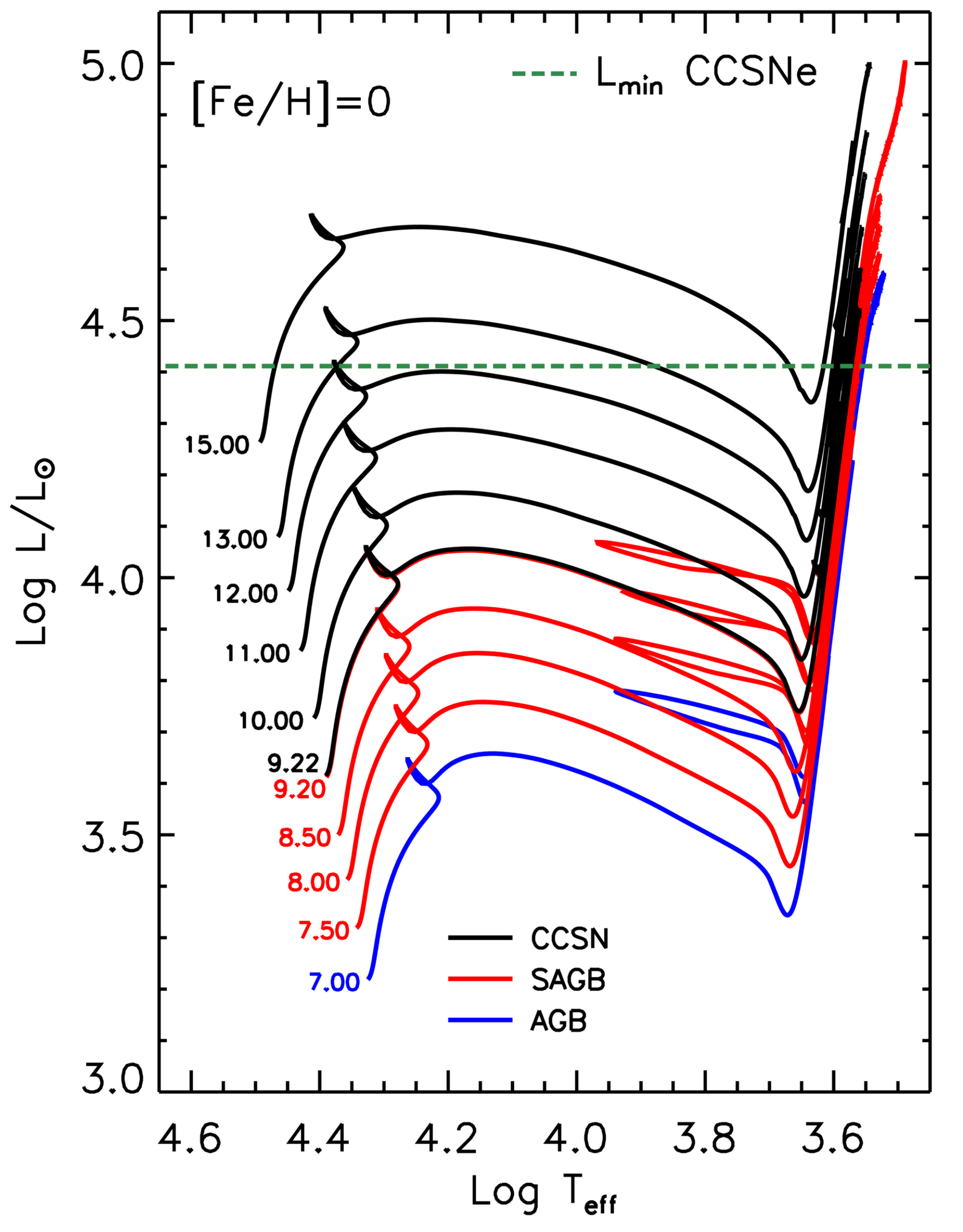
In the last 20 years we developed and continuously improved our stellar evolution code FRANEC that is characterized by features that make it perfectly suited for the calculation of the most challenging evolutionary phases, like those of the stars in the range 7-15 $M_\odot$

In this talk I will present an overview of the complete evolution of solar metallicity, non-rotating, stars in the mass interval 7-15 $M_\odot$

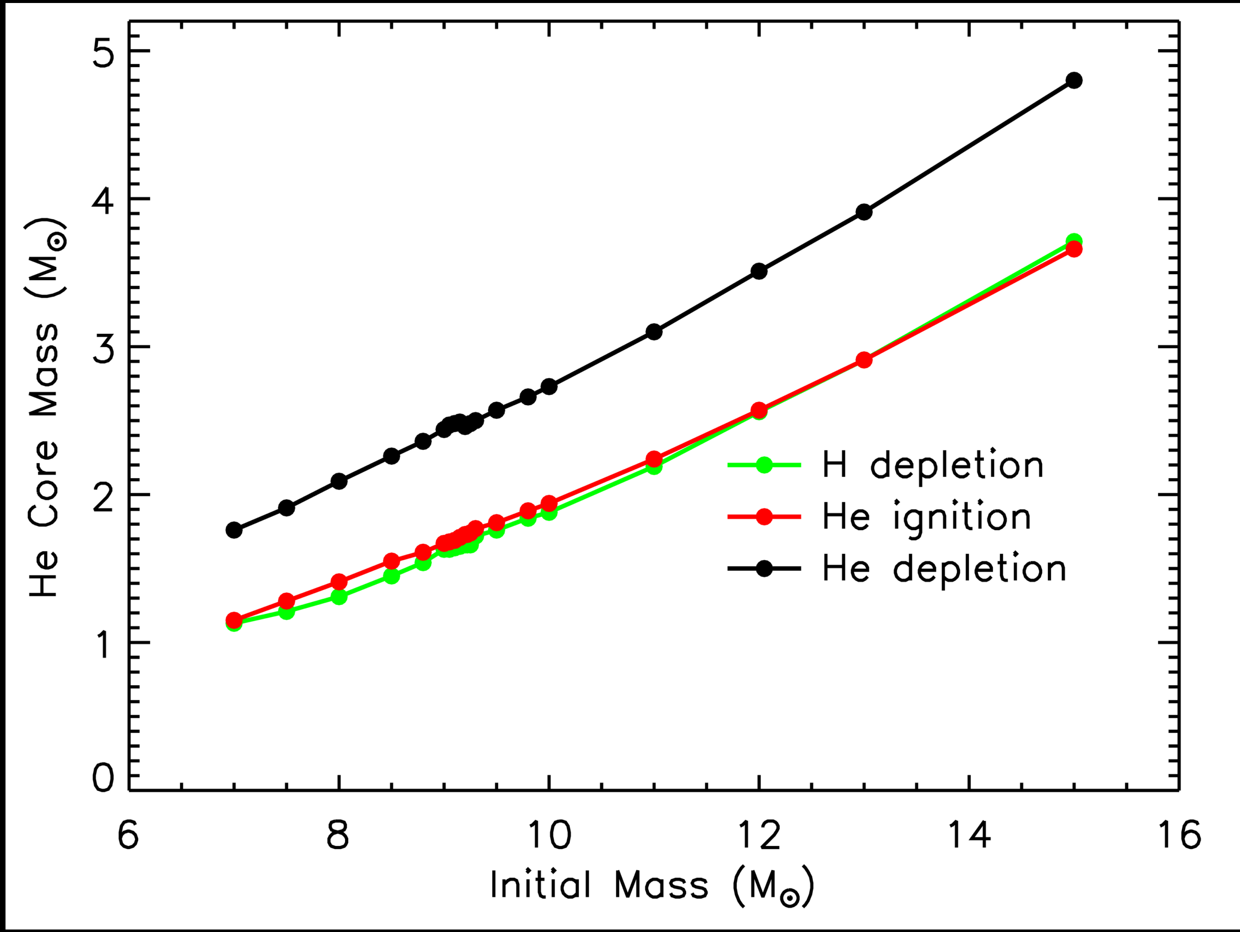
Core H- and Core He-burning

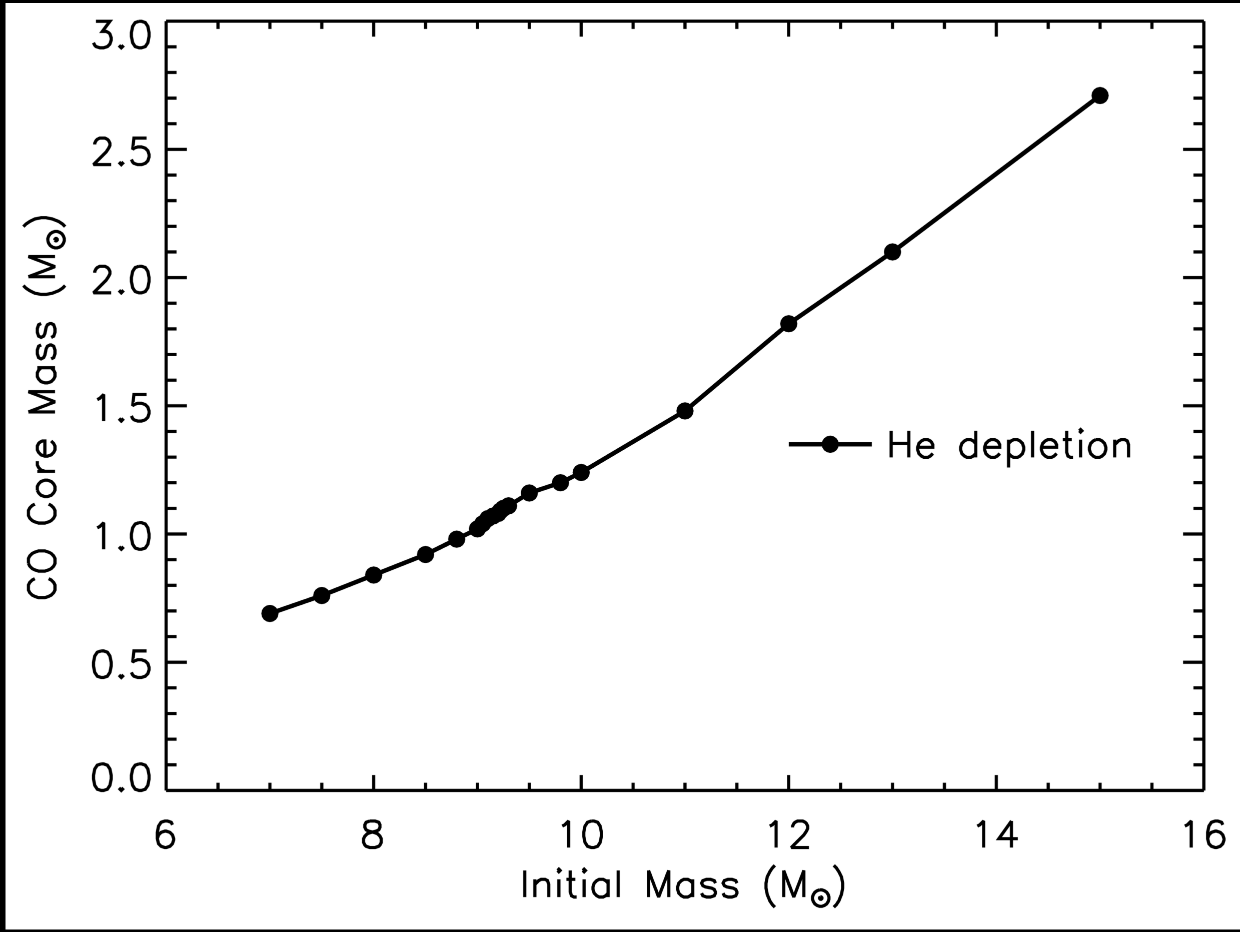






Core H- and Core He-burning





Evolution after Core He burning

Increase of the CO core mass and quenching of the H burning shell due to the advancing He burning shell

Energy loss from the central zones due to the neutrino emission

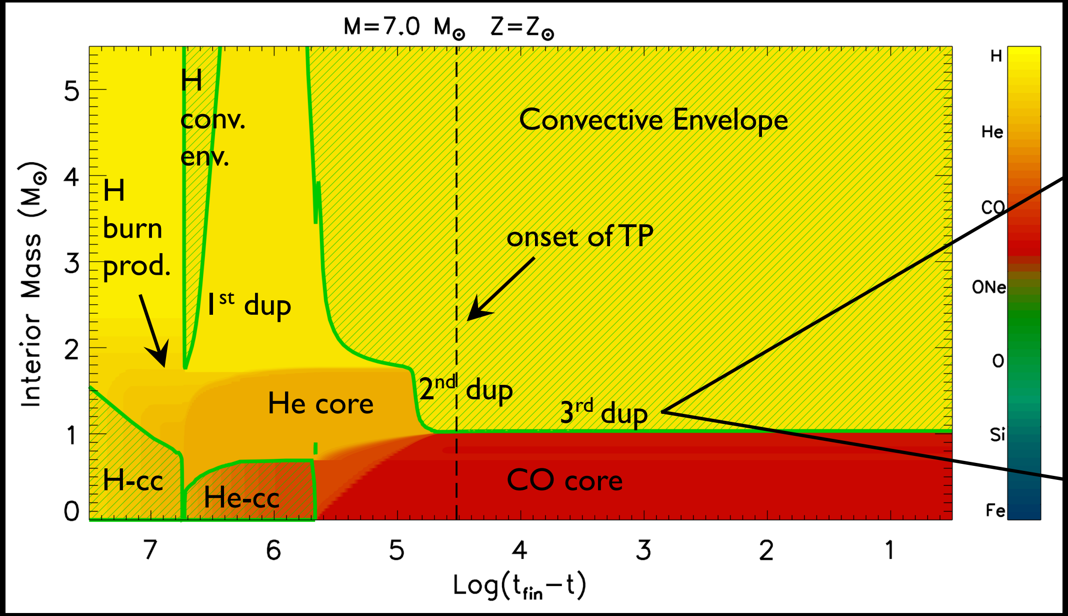
Energy deposition in the CO core due to compressional heating induced by the advancing He burning shell

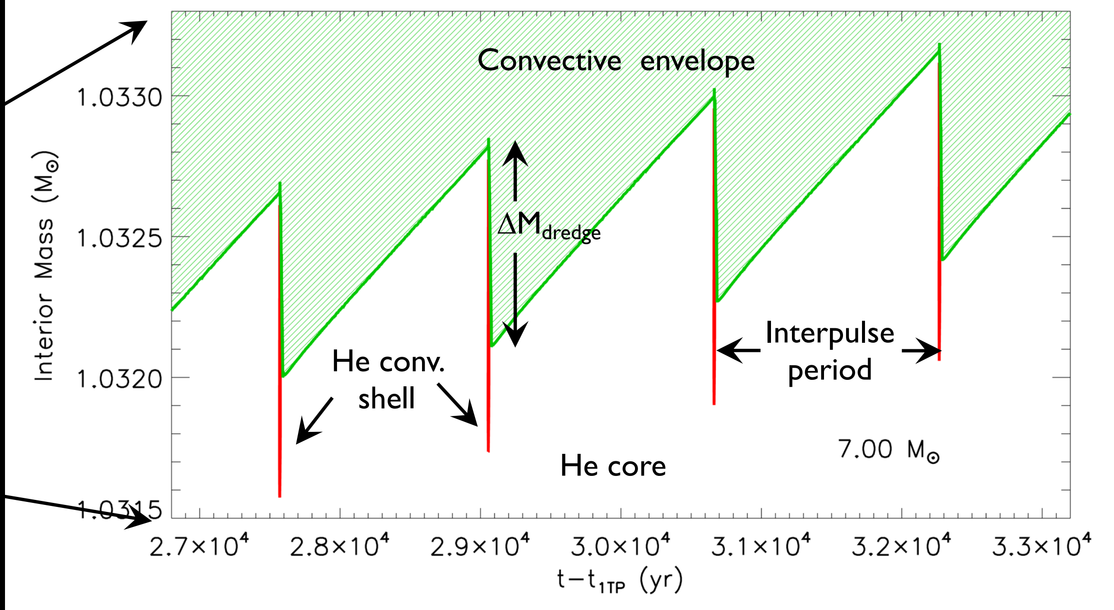
Progressive penetration of the convective envelope that may eventually lead to the 2nd dredge up

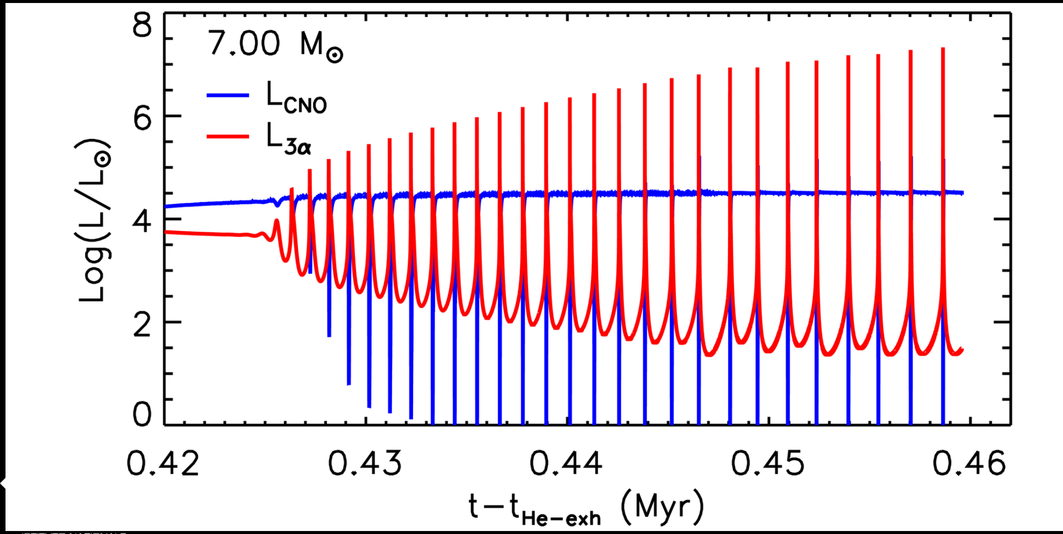
Interplay and timing of these processes and final fate of the star depend on the CO core mass

Stars with M ≤ 7 $M_\odot$

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





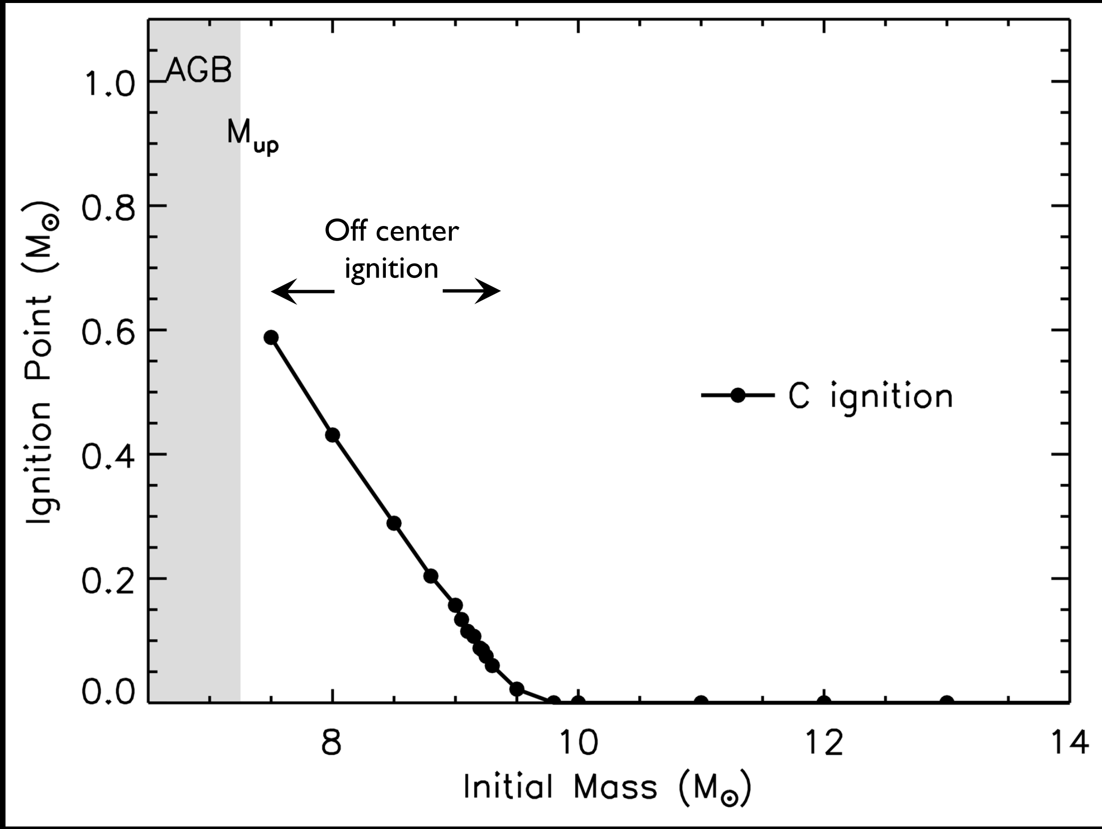


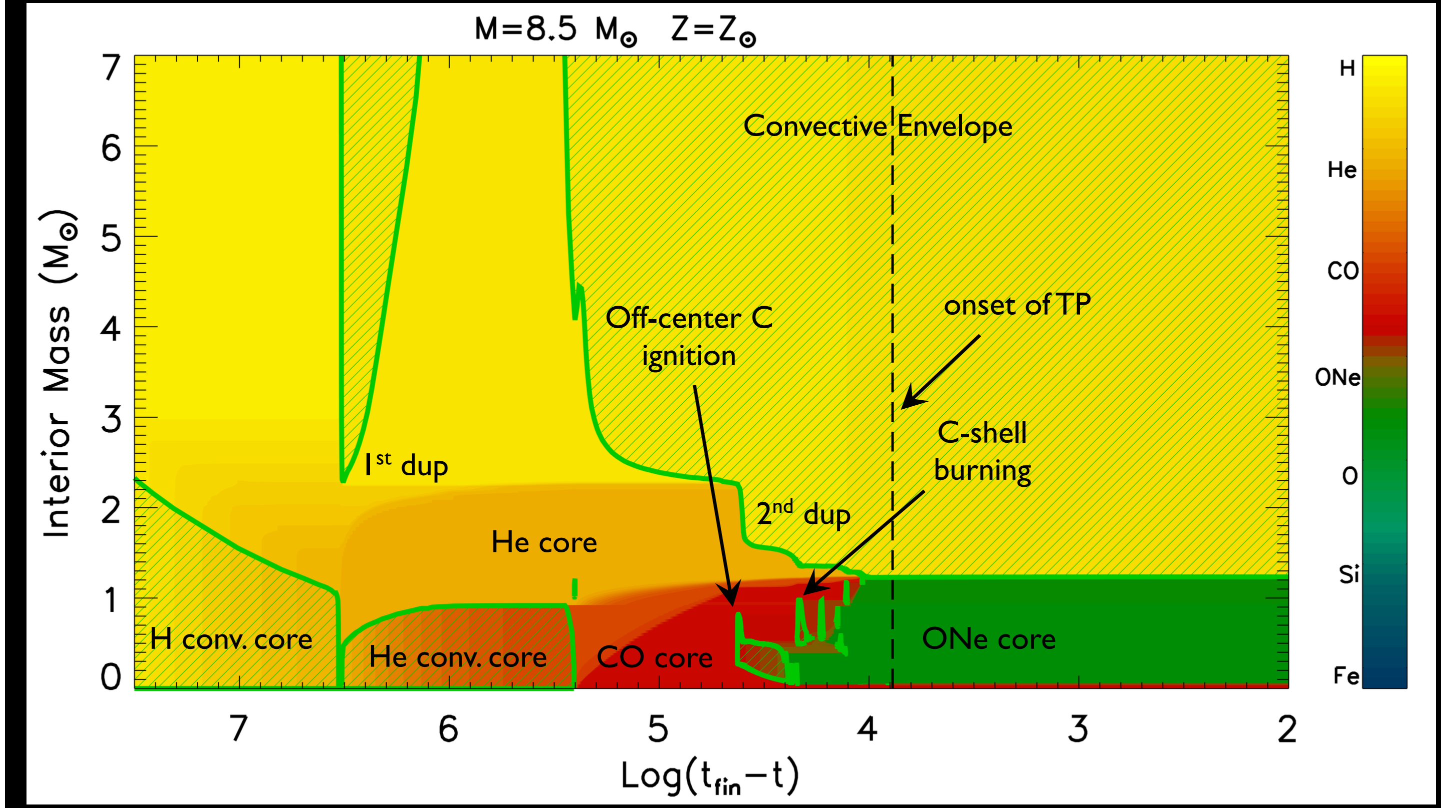
Stars with M ≤ 7 $M_\odot$ end their life as planetary nebulae with CO-WD

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

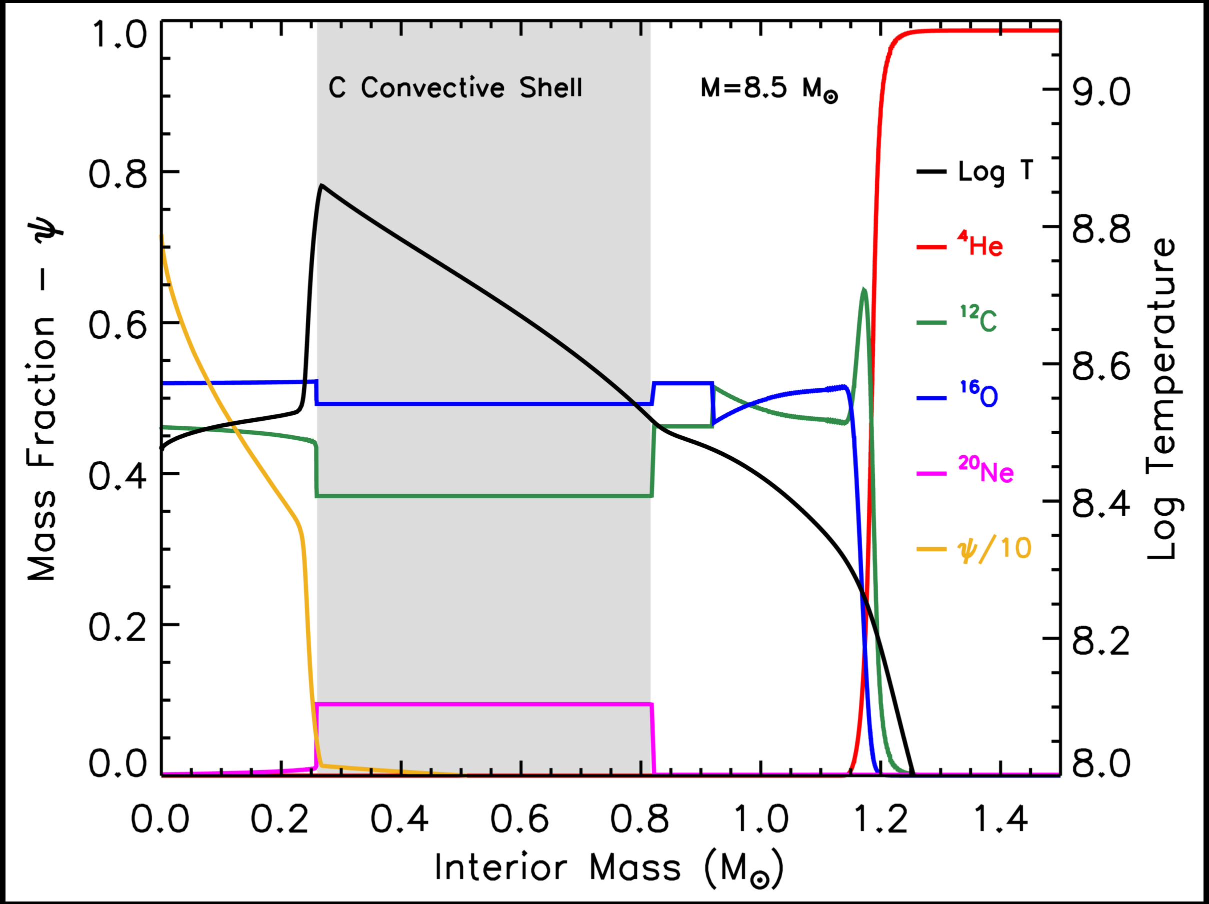
Off-center C-ignition in stars with 7.5 ≤ $M/M_\odot$ ≤ 9.5



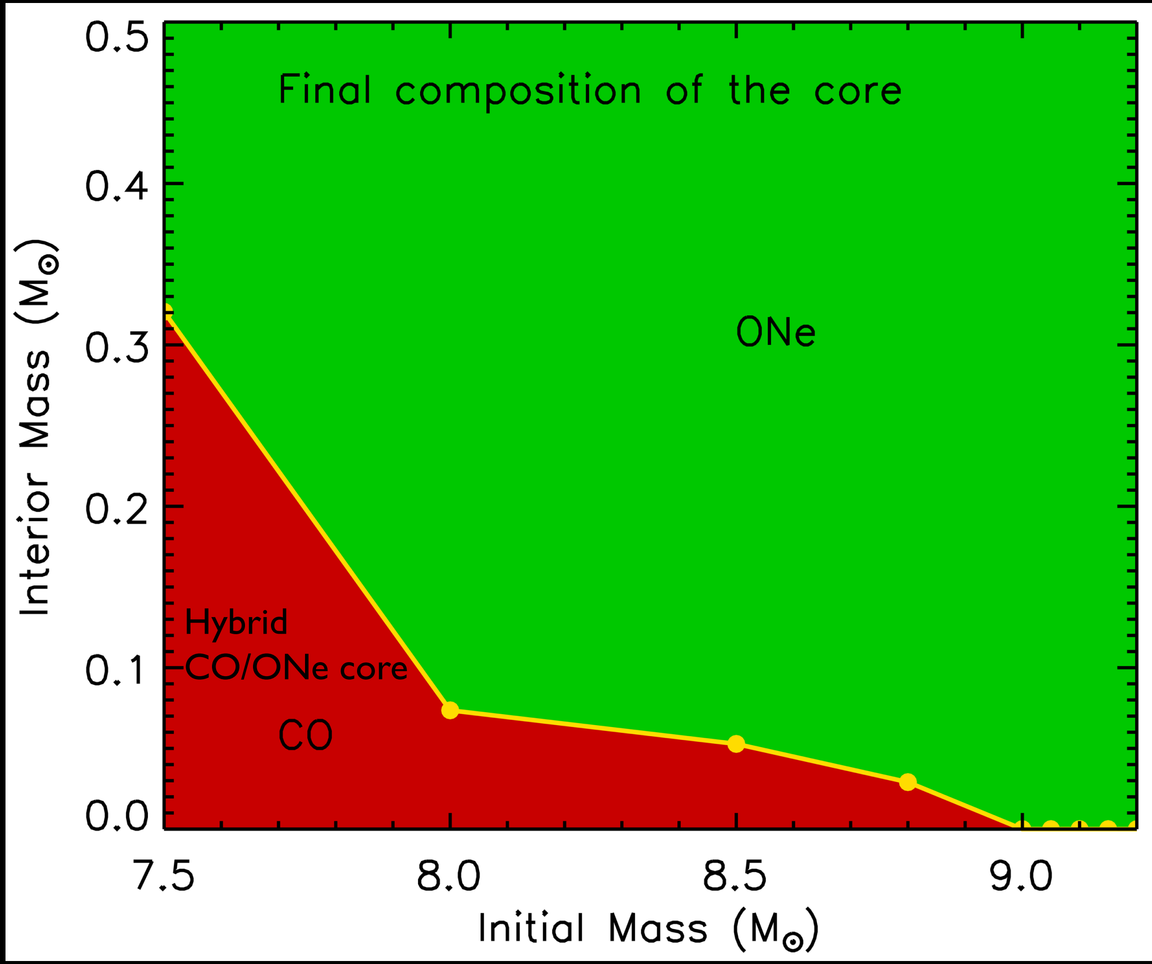


Stars with M ≥ 7.5 $M_\odot$

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



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



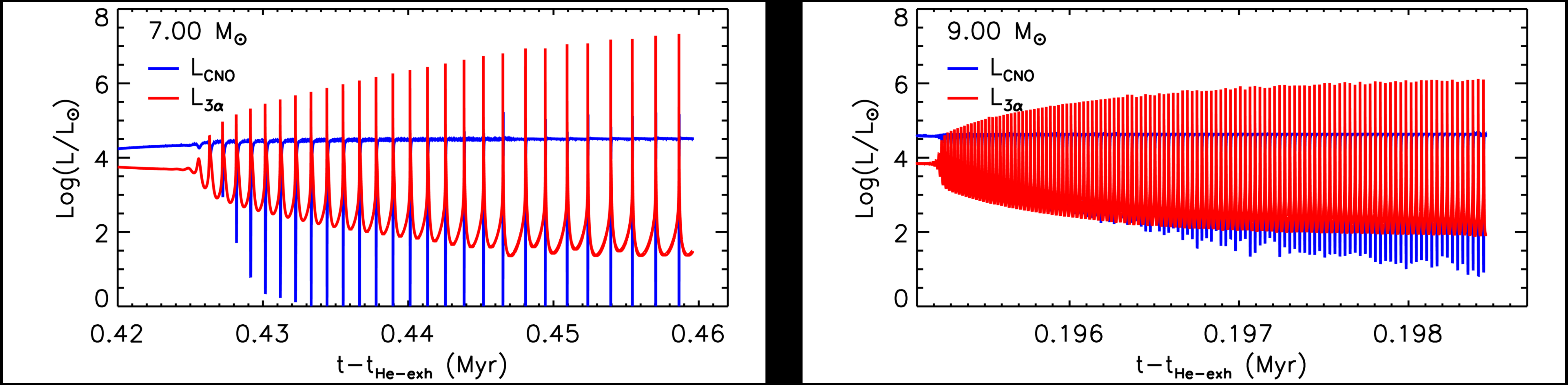
Stars with 7.5 $M_\odot \leq M \leq 9.2\ M_\odot$

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

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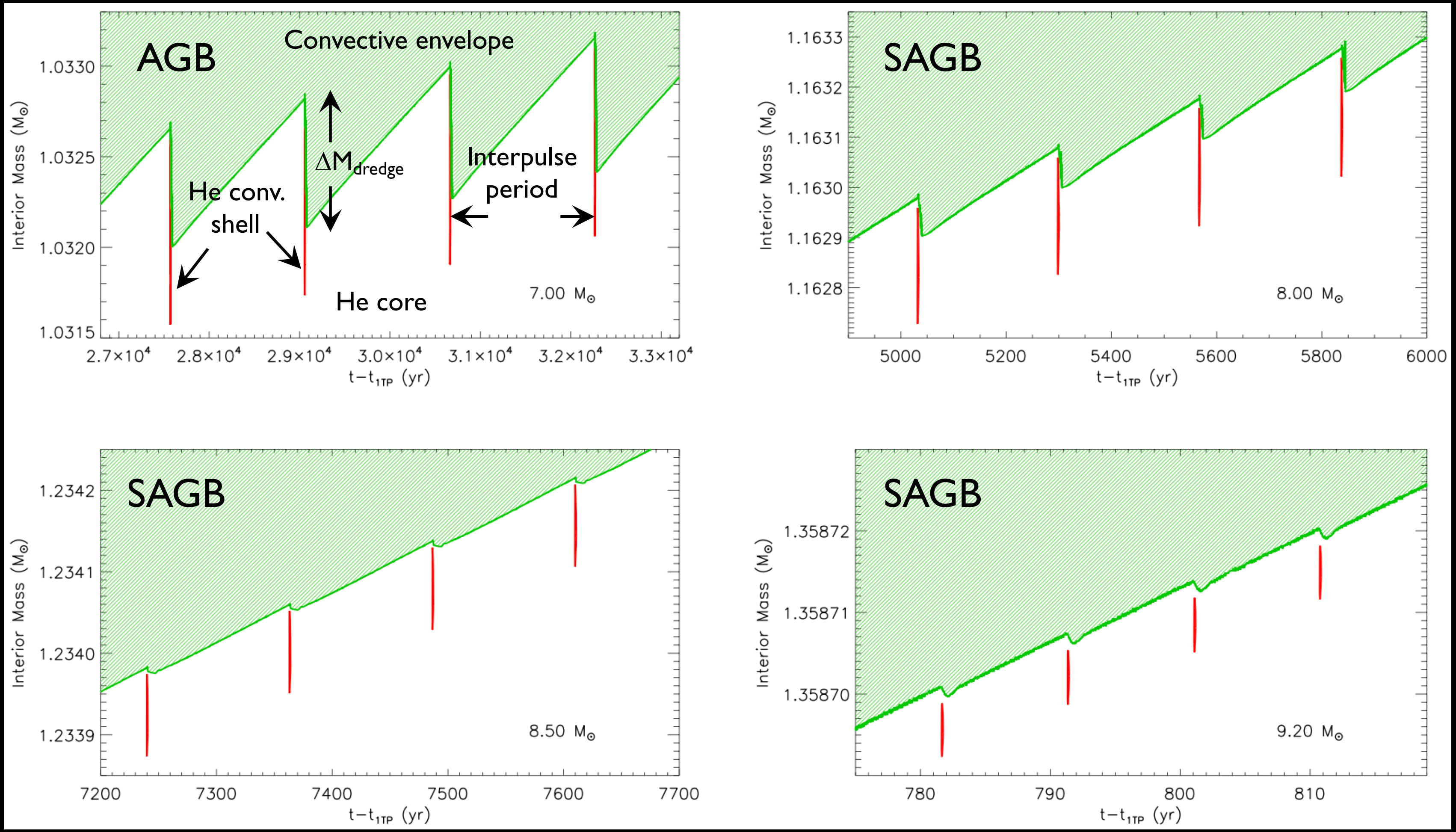
Stars with 7.5 $M_\odot \leq M \leq 9.2\ M_\odot$



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

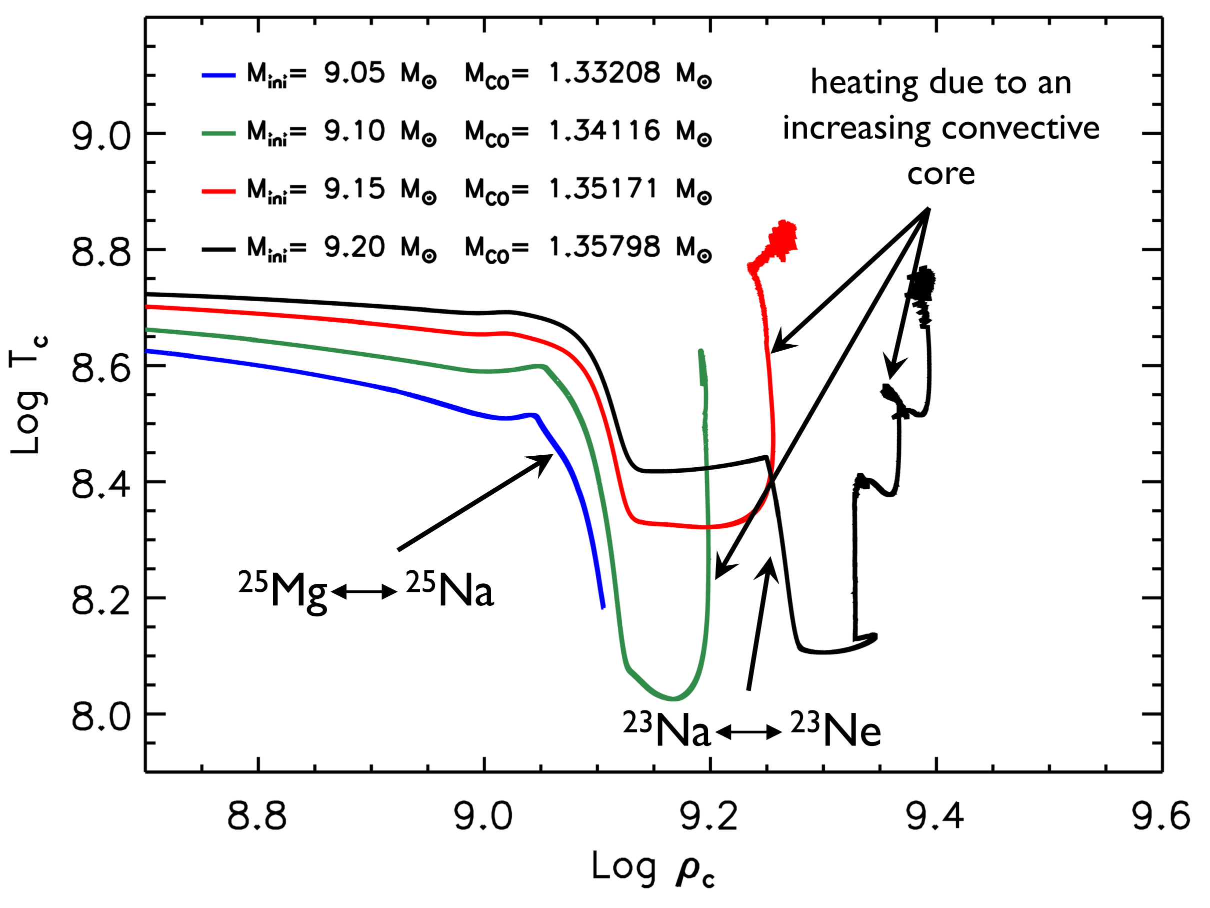
Stars with 9.05 $M_\odot \leq M \leq 9.20\ M_\odot$

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

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

In radiative environment → Cooling

In convective environment → Cooling/Heating



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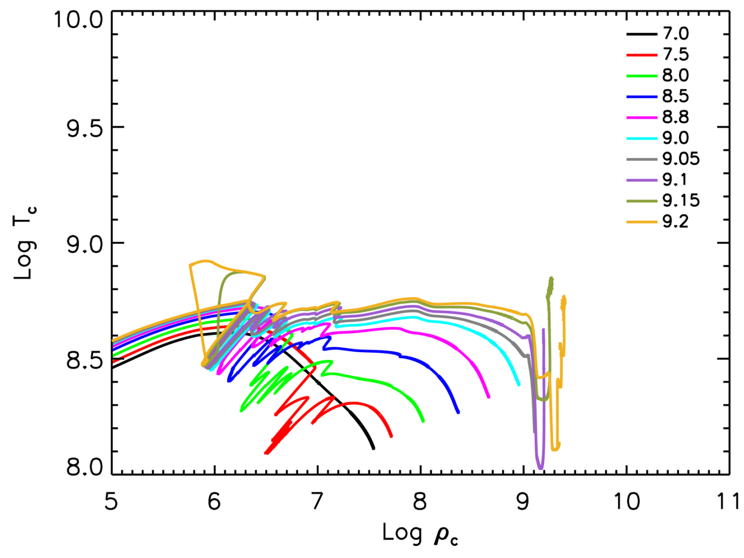
Stars with 7.5 $M_\odot \leq M \leq 9.2\ M_\odot$: Final Fate

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



M	#TPs
7.50	23
8.00	25
8.50	67
8.80	81
9.00	116
9.05	170
9.10	159
9.15	193
9.20	102

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

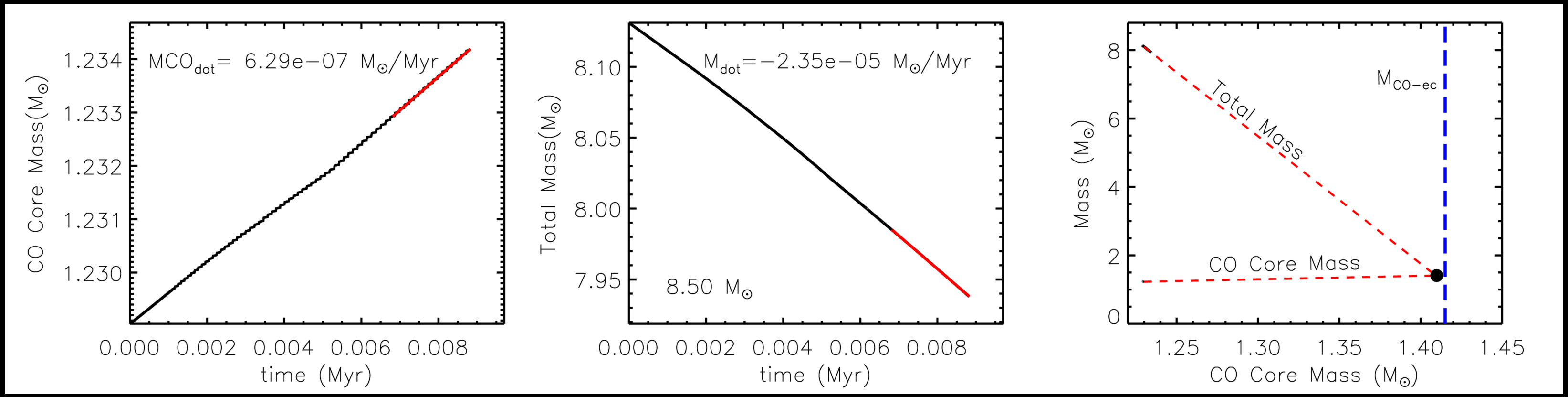
Central density approaches the threshold (~9.6) for electron capture $^{20}\mathrm{Ne}(e^-,\nu)^{20}\mathrm{F}$ → Potential explosion as Electron Capture Supernova (ECSN)

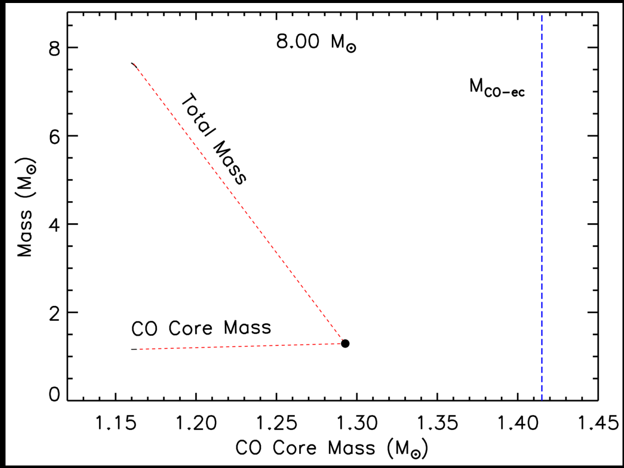
Complete removal of the H-rich envelope before the activation of $^{20}\mathrm{Ne}(e^-,\nu)^{20}\mathrm{F}$ → ONe-WD

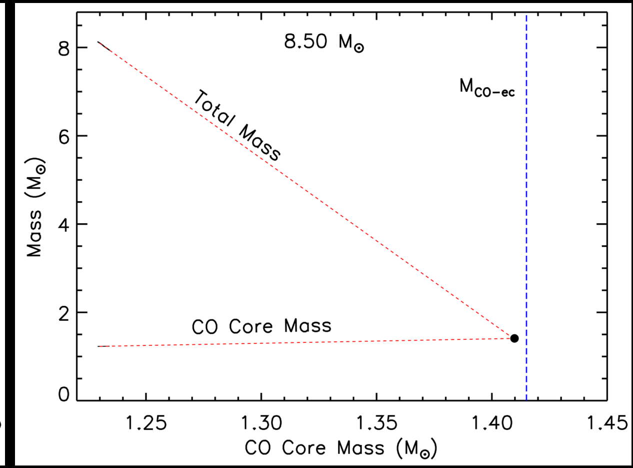
A self consistent determination of the final fate would require the calculation of several thousands of TPs that is not feasible at present → estimate of the final fate by means of "extrapolated" evolutions

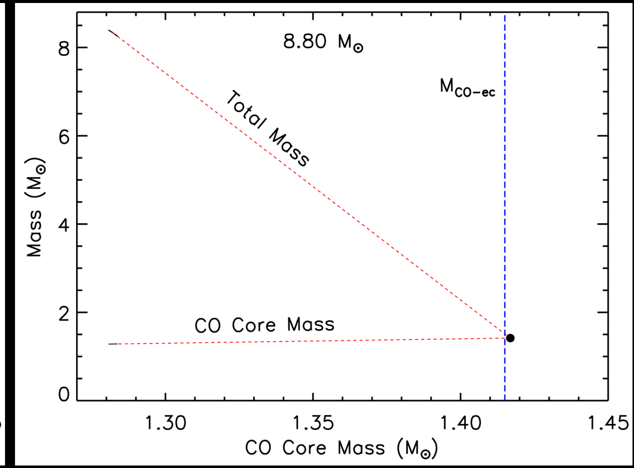
Stars with 7.5 $M_\odot \leq M \leq 9.2\ M_\odot$: Final Fate

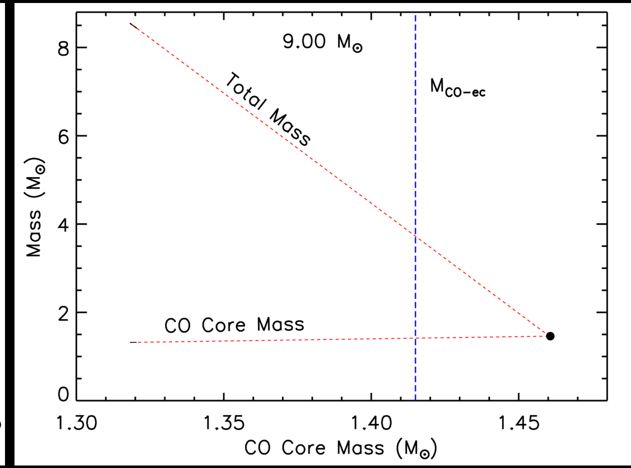
Linear regression of the quantities over the last few TPs and extrapolations at late times











ONe-WD | ECSN | ECSN | ECSN

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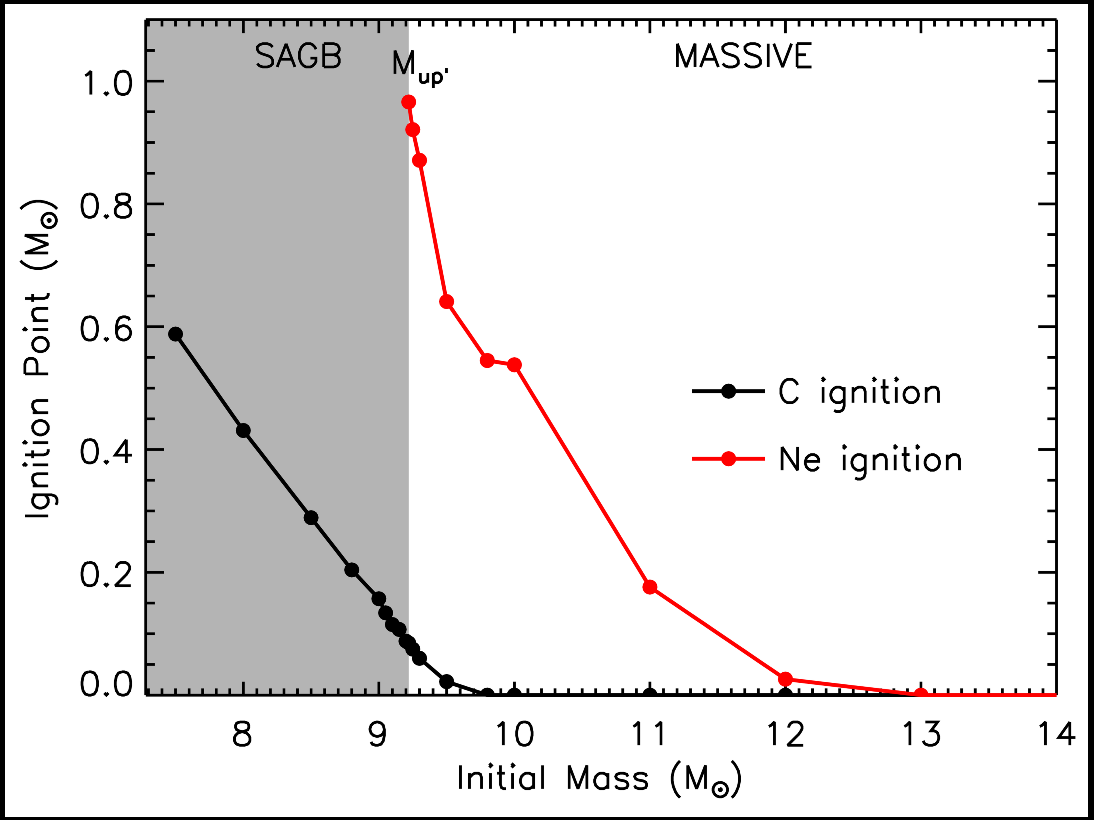
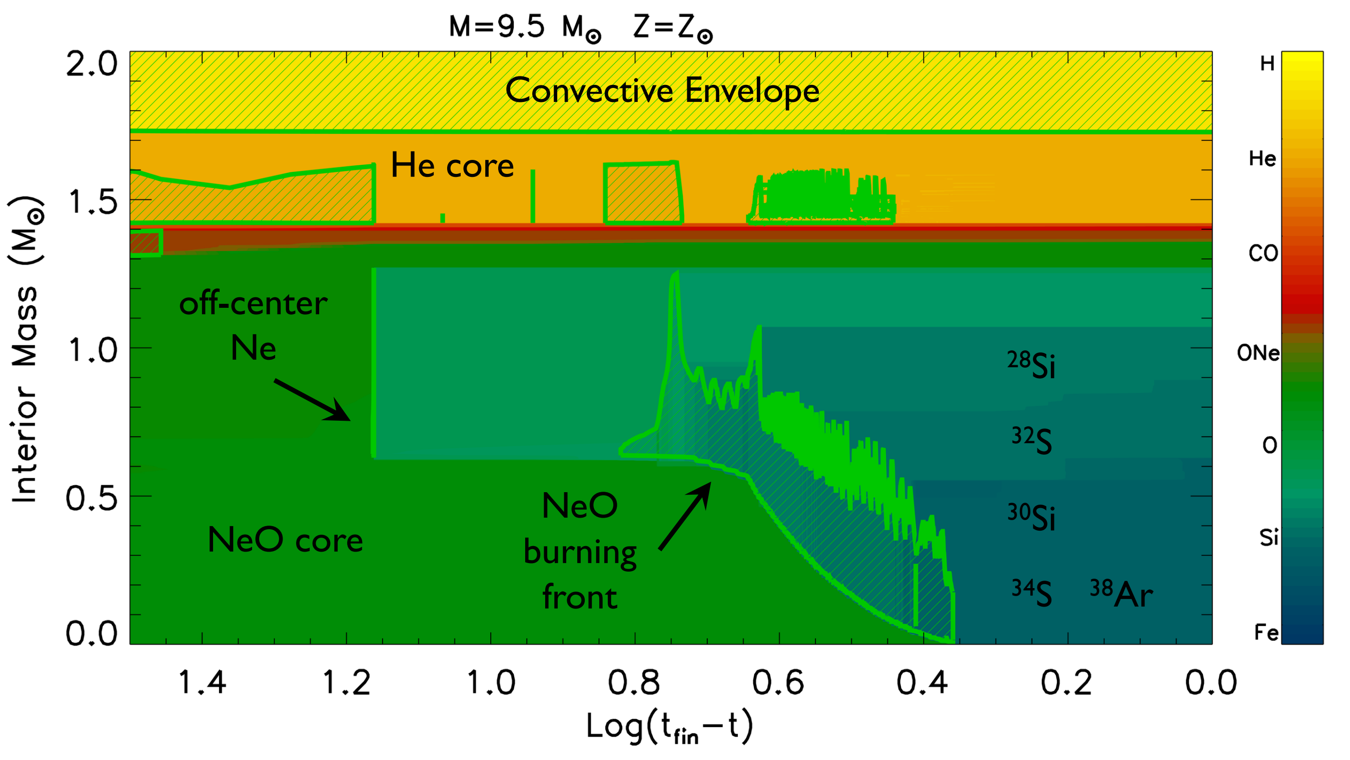
Stars with $M \geq 9.22\ M_\odot$

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

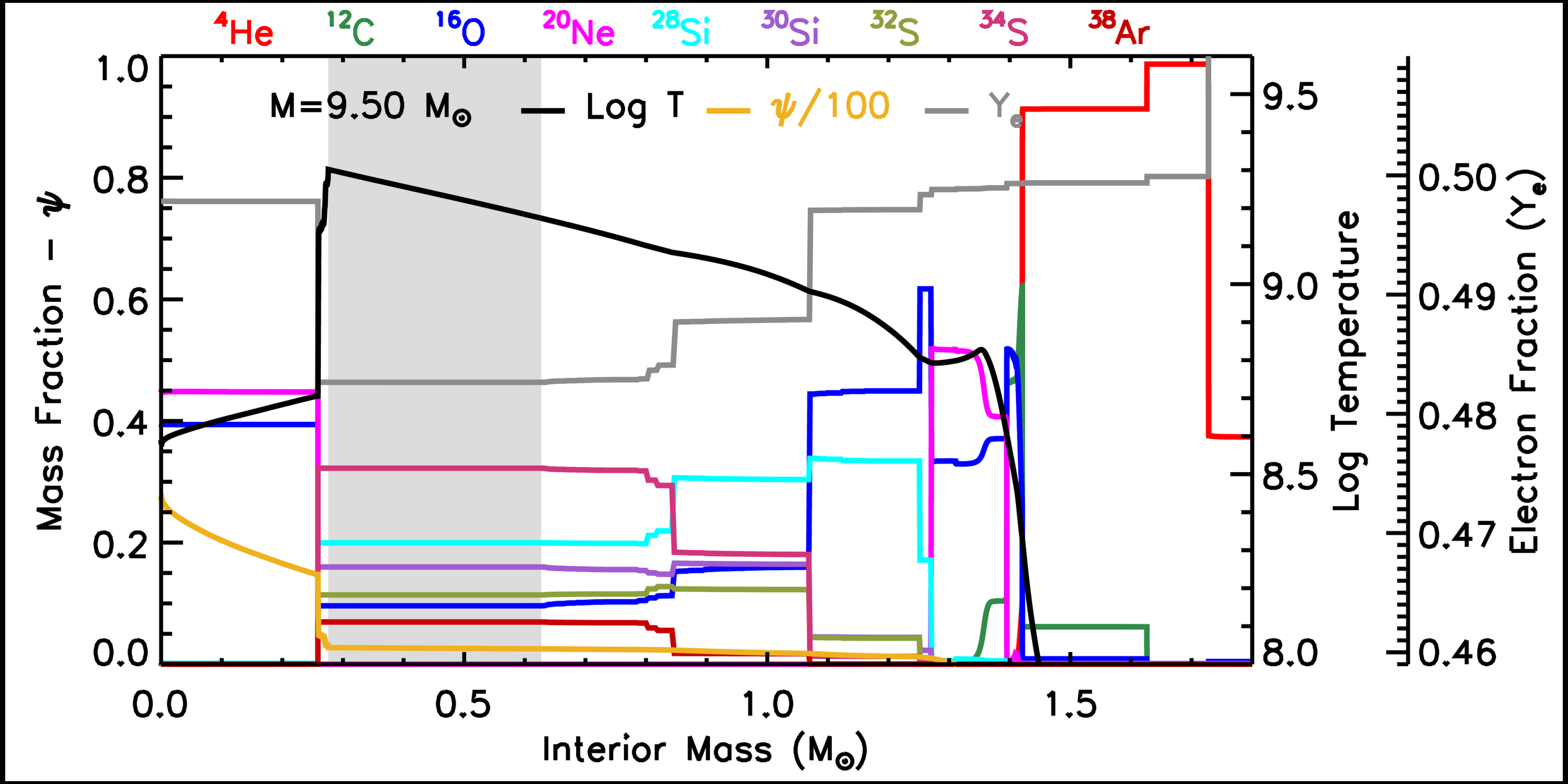
Off-center Ne-ignition in stars with $9.22 \leq M/M_\odot \leq 12$





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

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, therefore the chemical composition left by the Ne/O burning tends to be dominated by less neutron rich isotopes as the initial mass of the star increases

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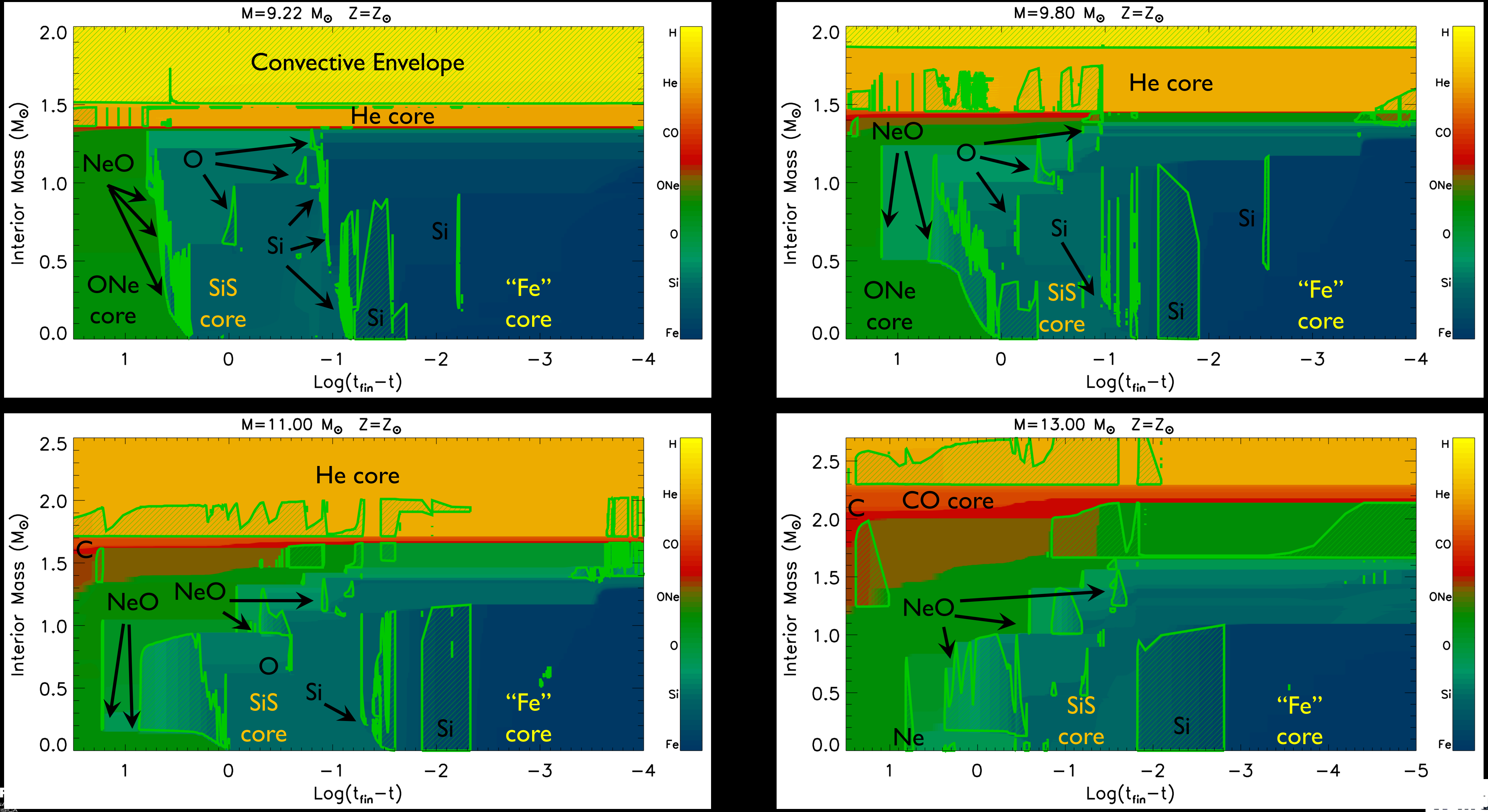
Stars with $M \geq 9.22\ M_{\odot}$

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



Summary and Conclusions

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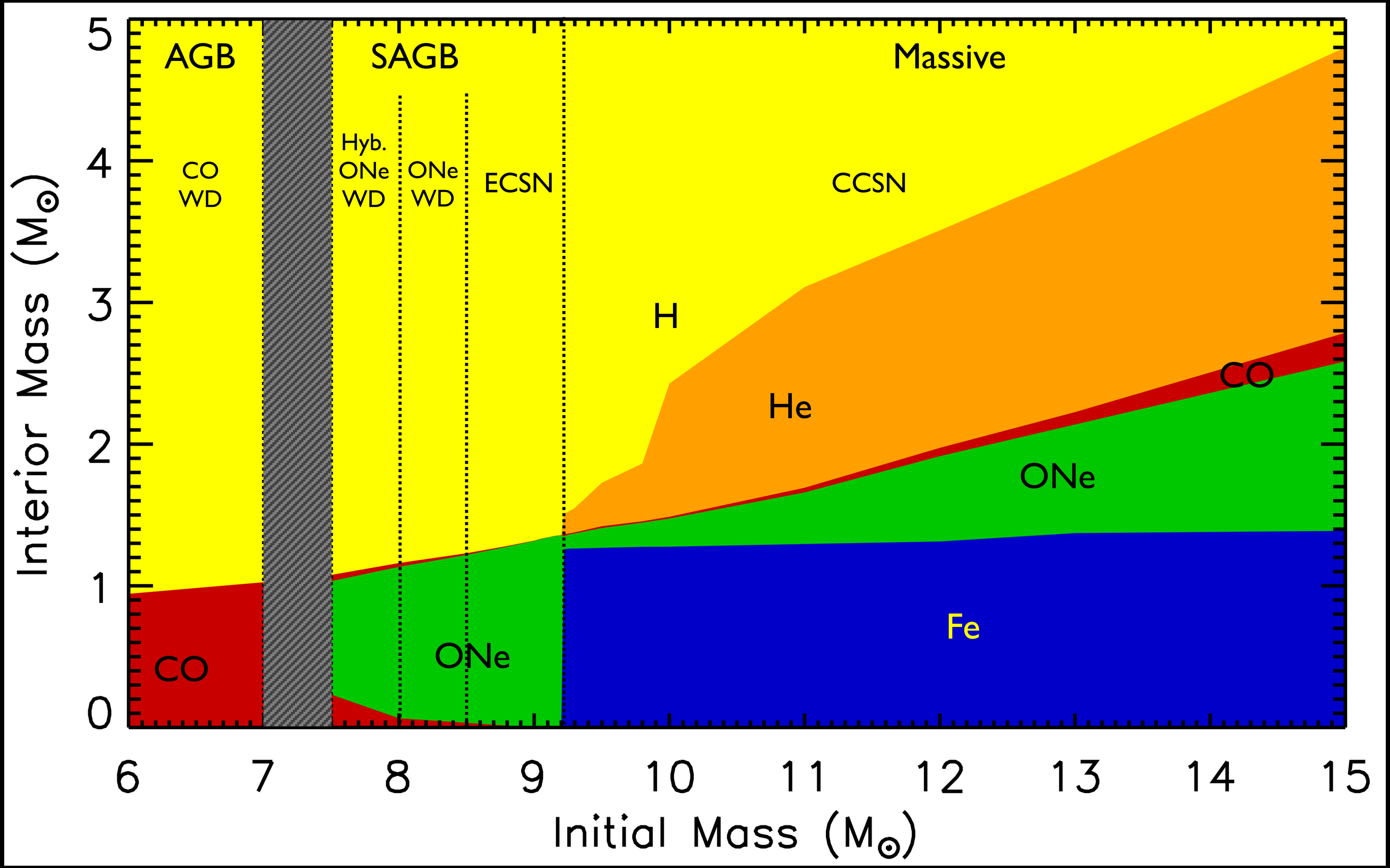

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