Extremely Metal-Poor Asymptotic Giant Branch Stars

The 13th Torino Workshop on AGB Stars & the 3rd Perugia Workshop on Nuclear Astrophysics
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Credits: NASA

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But...

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- Not directly observed yet, but many observational constraints on their existence:

a)detection of metals in Ly-α forest spectra of distant QSOs

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It is crucial to study the evolution and nucleosynthesis of EMP stars!

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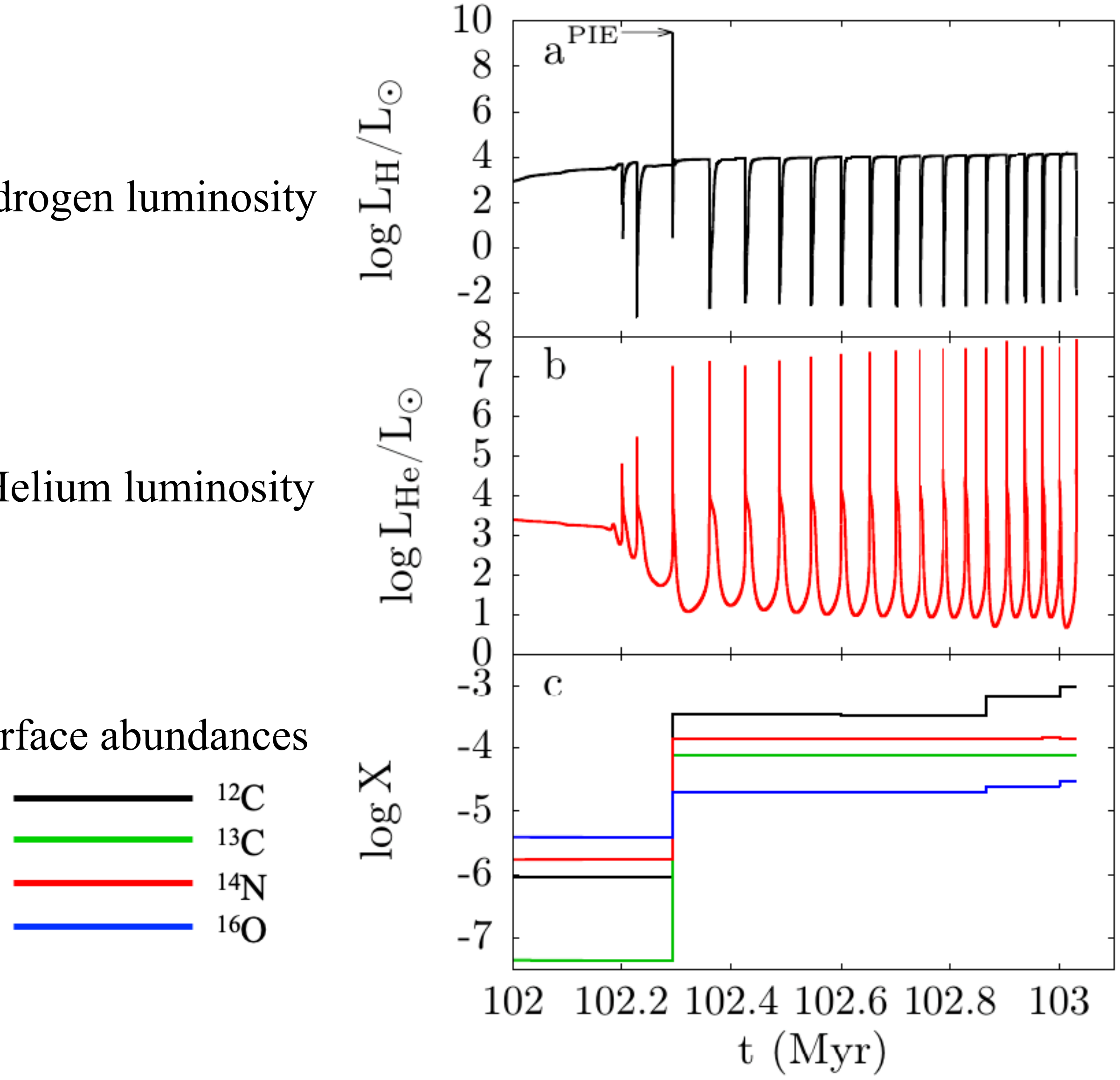
$M = 2\ M_\odot$, $Z = 10^{-5}$, PIE

Hydrogen luminosity

Helium luminosity

Surface abundances



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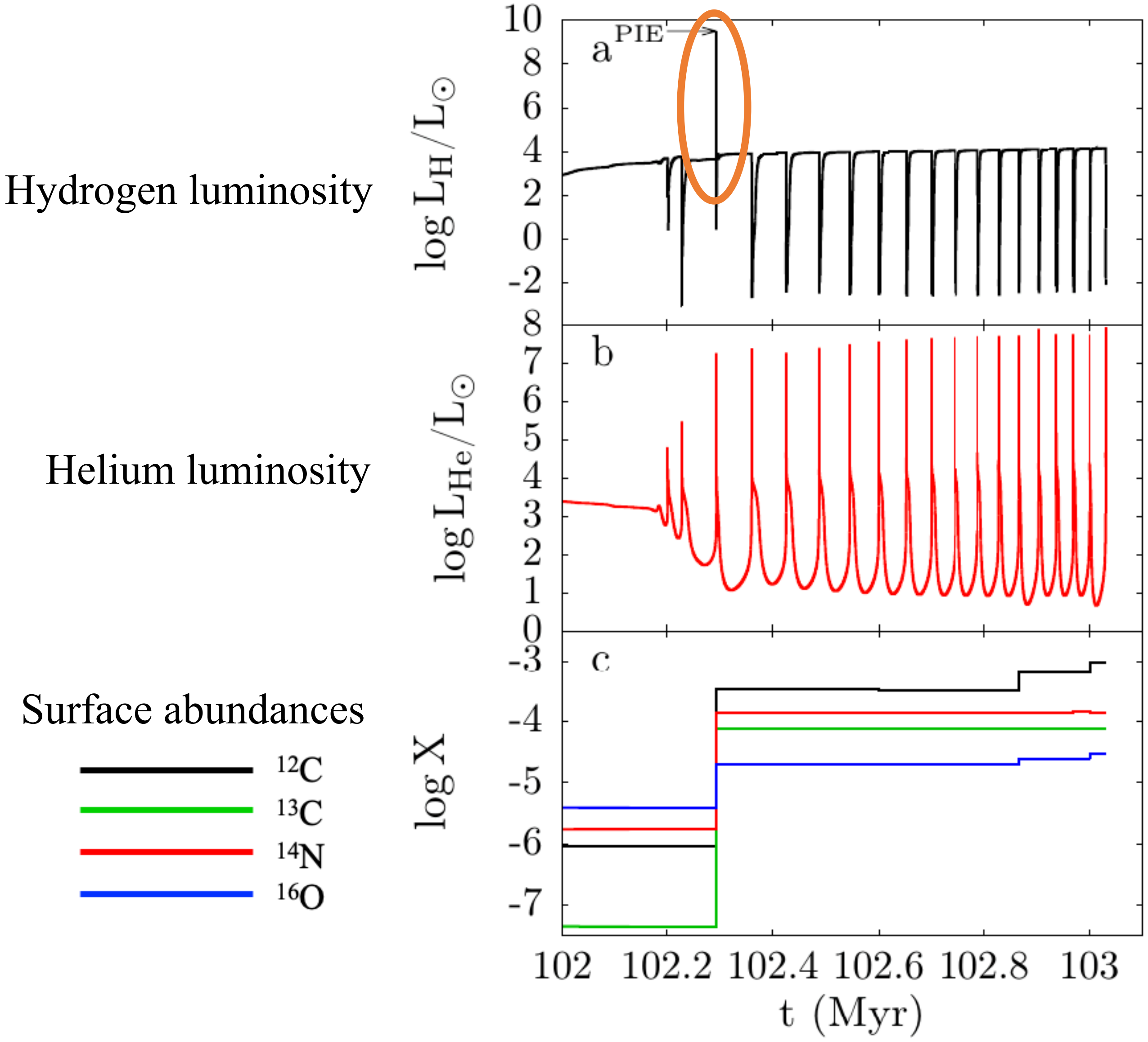
- Proton Ingestion Episode at the beginning of the TP-AGB phase



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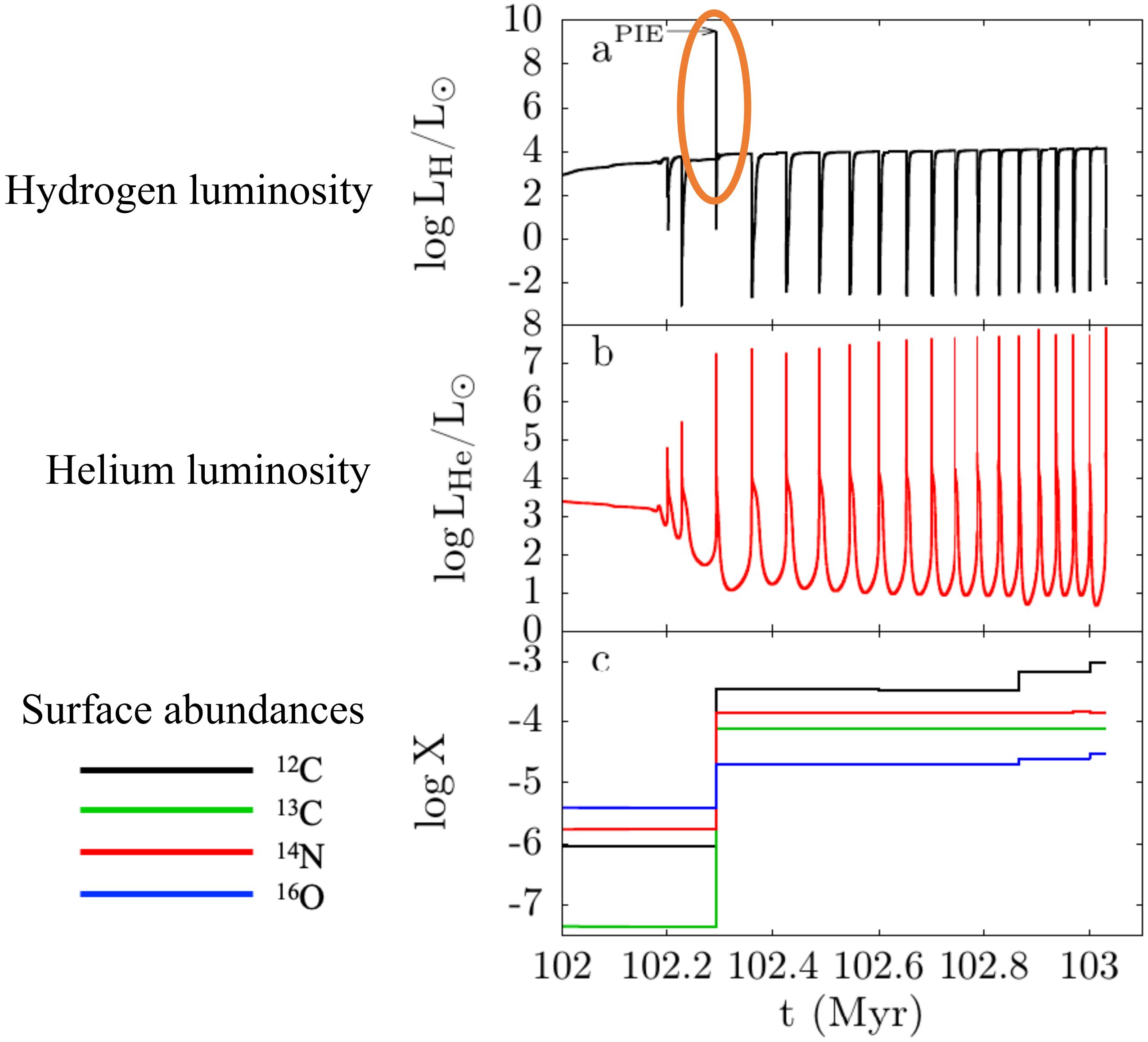

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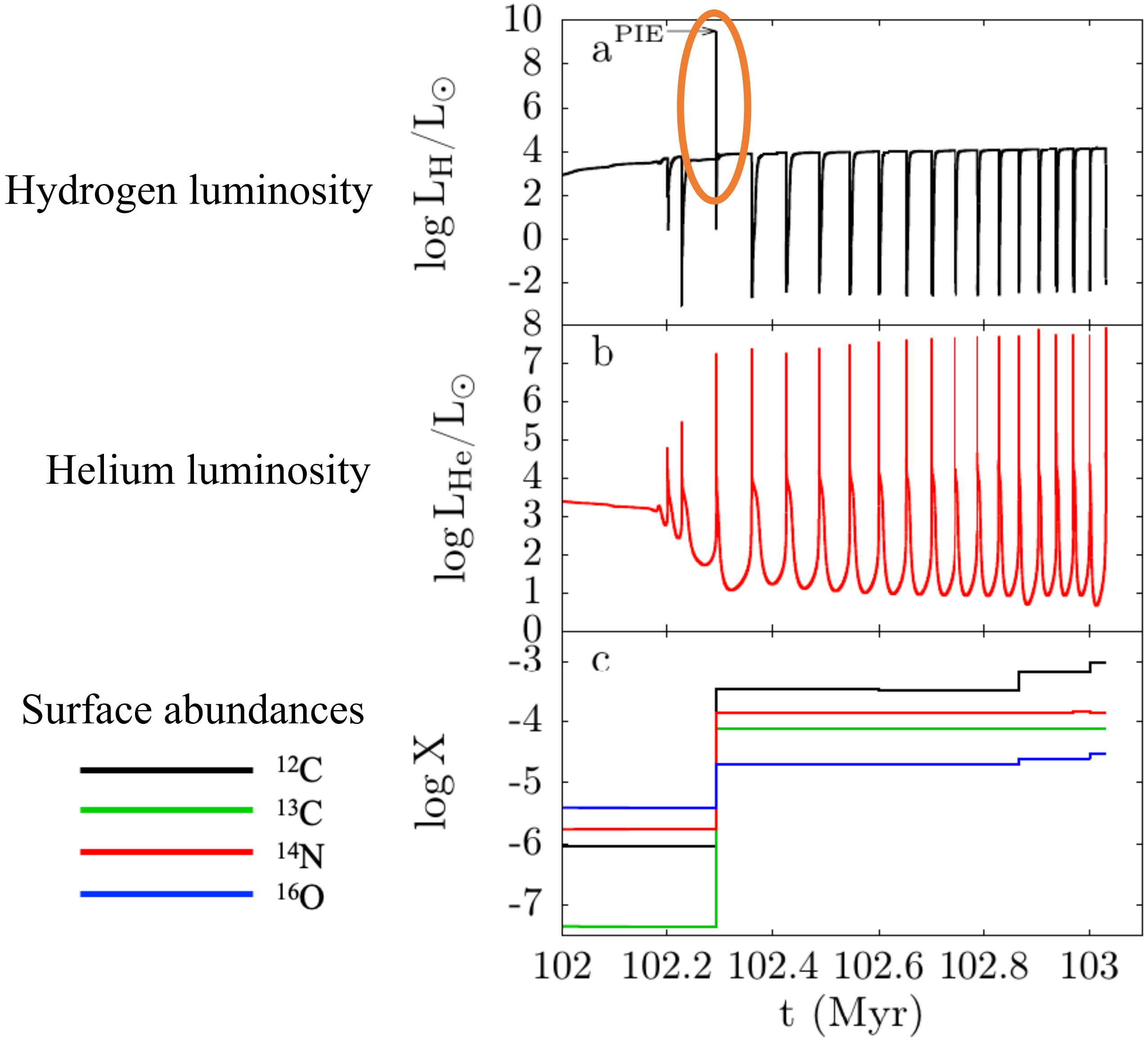

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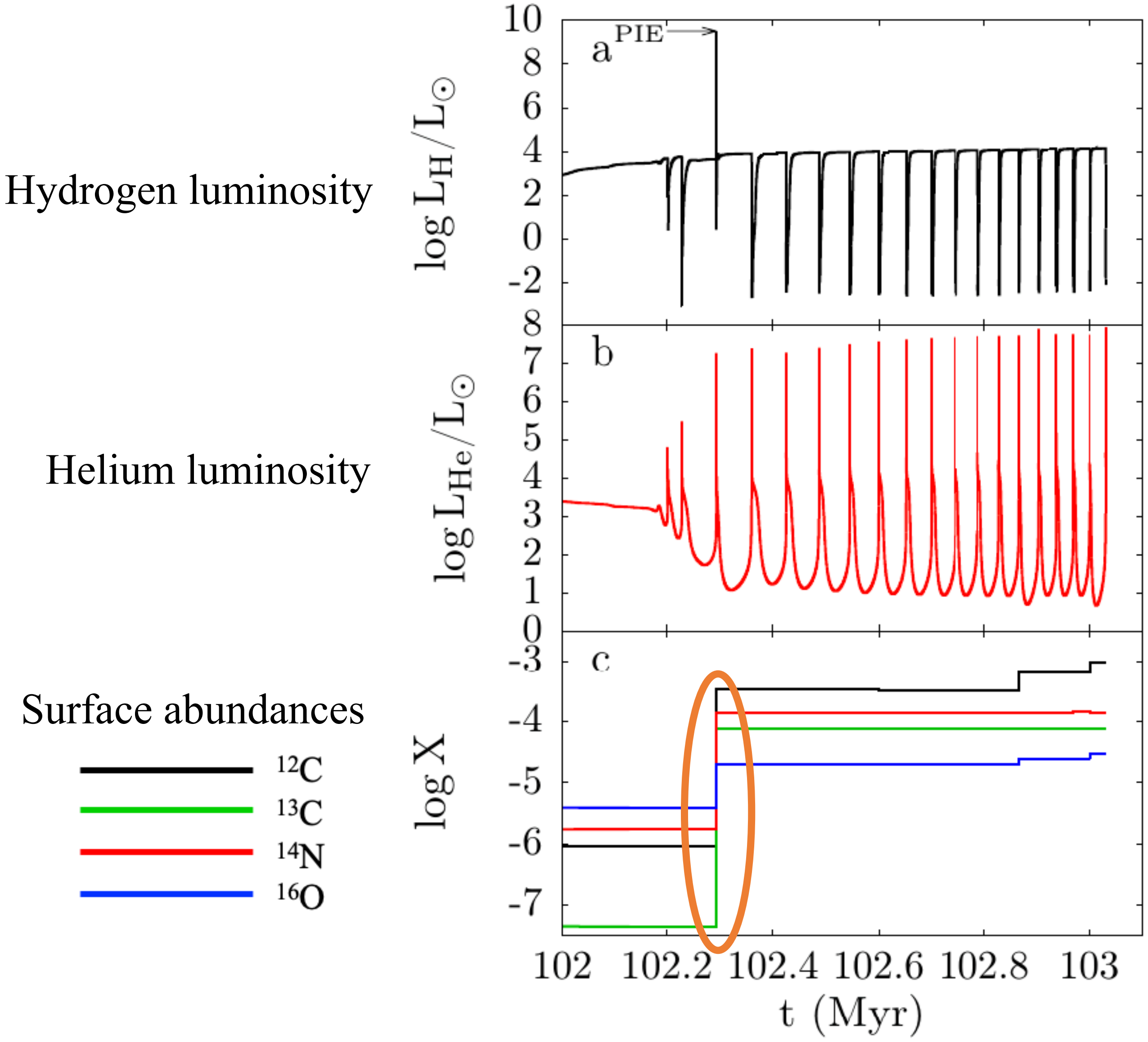
- At the subsequent TDU, all the surface main CNO abundances are raised from one to three orders of magnitude



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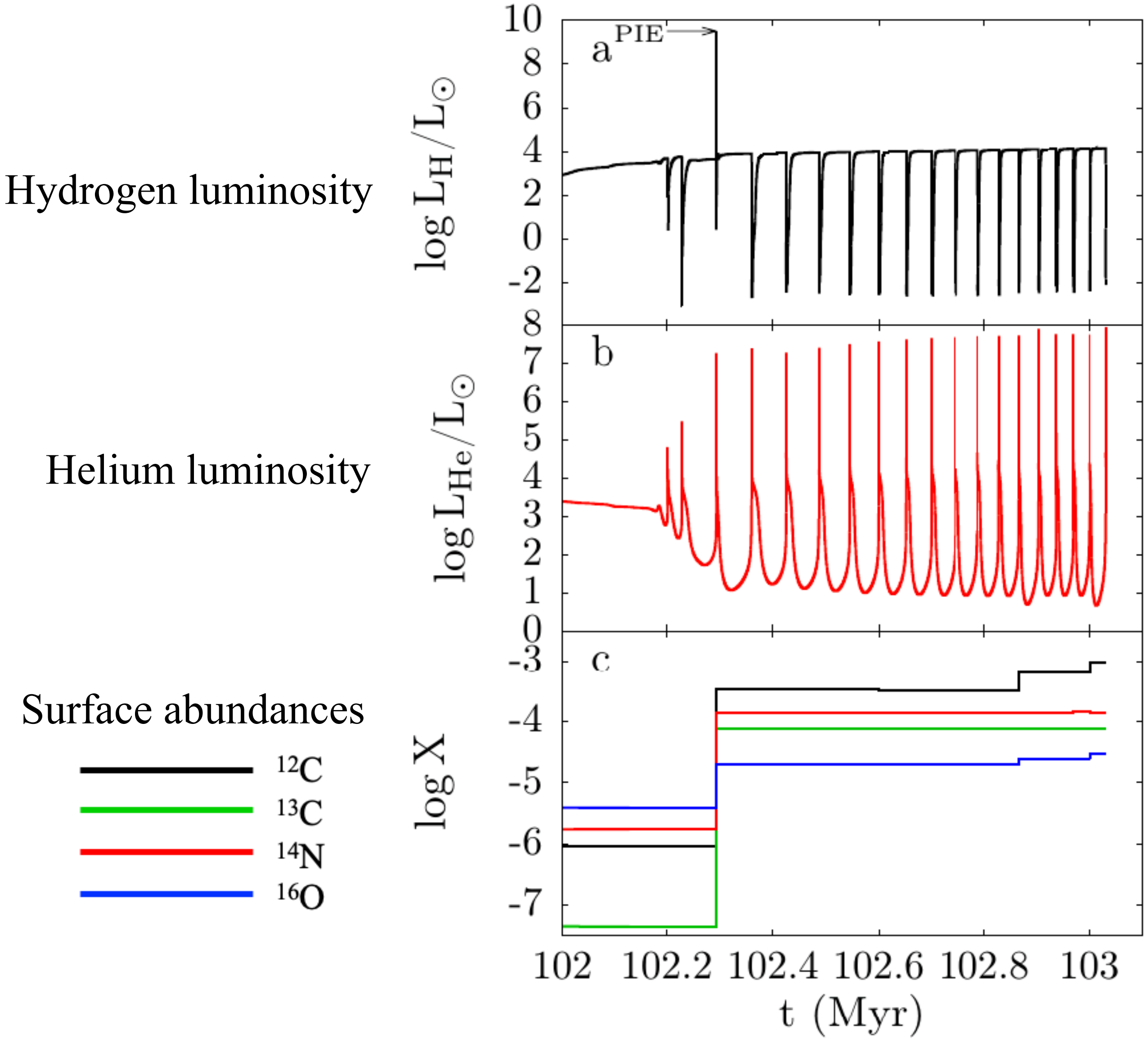
- At the subsequent TDU, all the surface main CNO abundances are raised from one to three orders of magnitude
- But what happens inside the star during a PIE?



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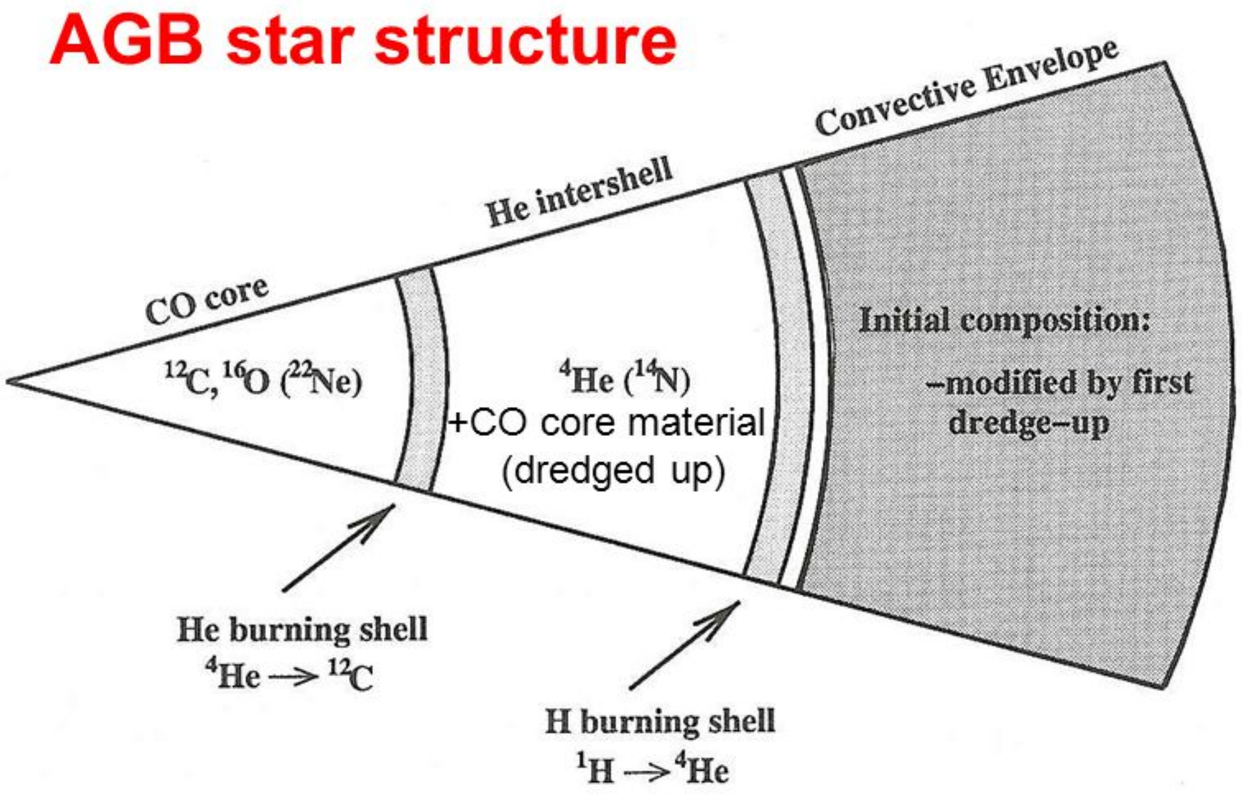
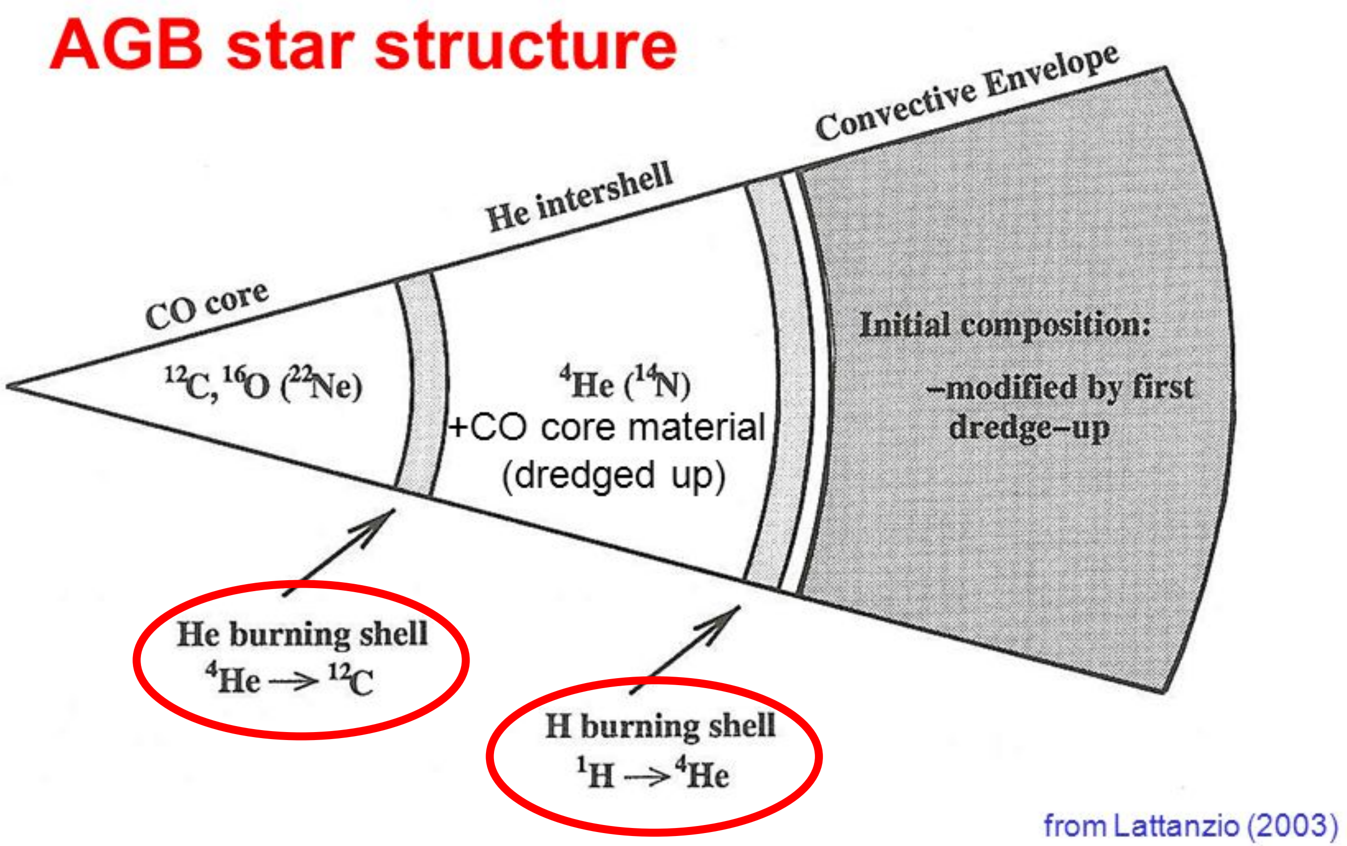
AGB and PIE



from Lattanzio (2003)

AGB and PIE

- The star has now a double shell structure, with the two shells advancing alternatively



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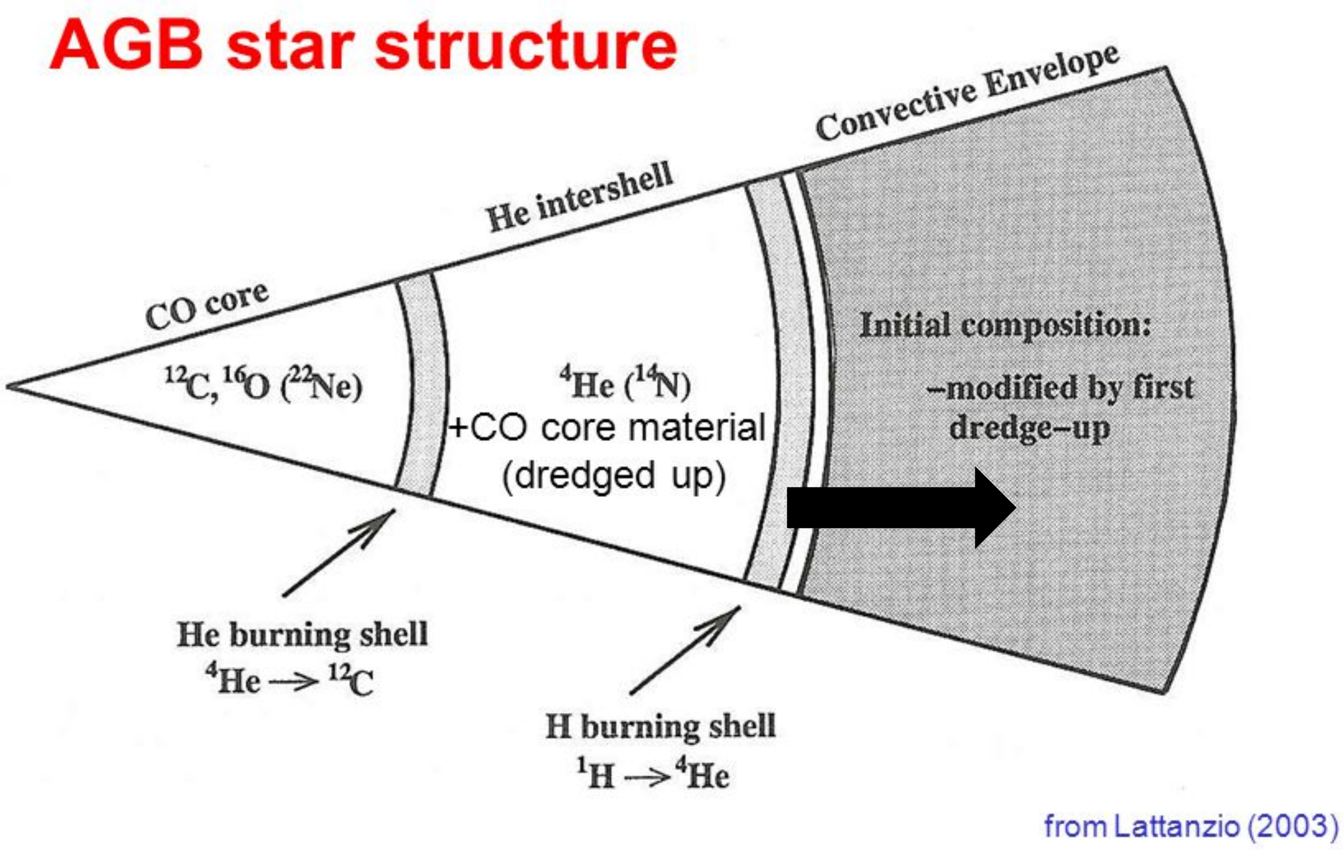

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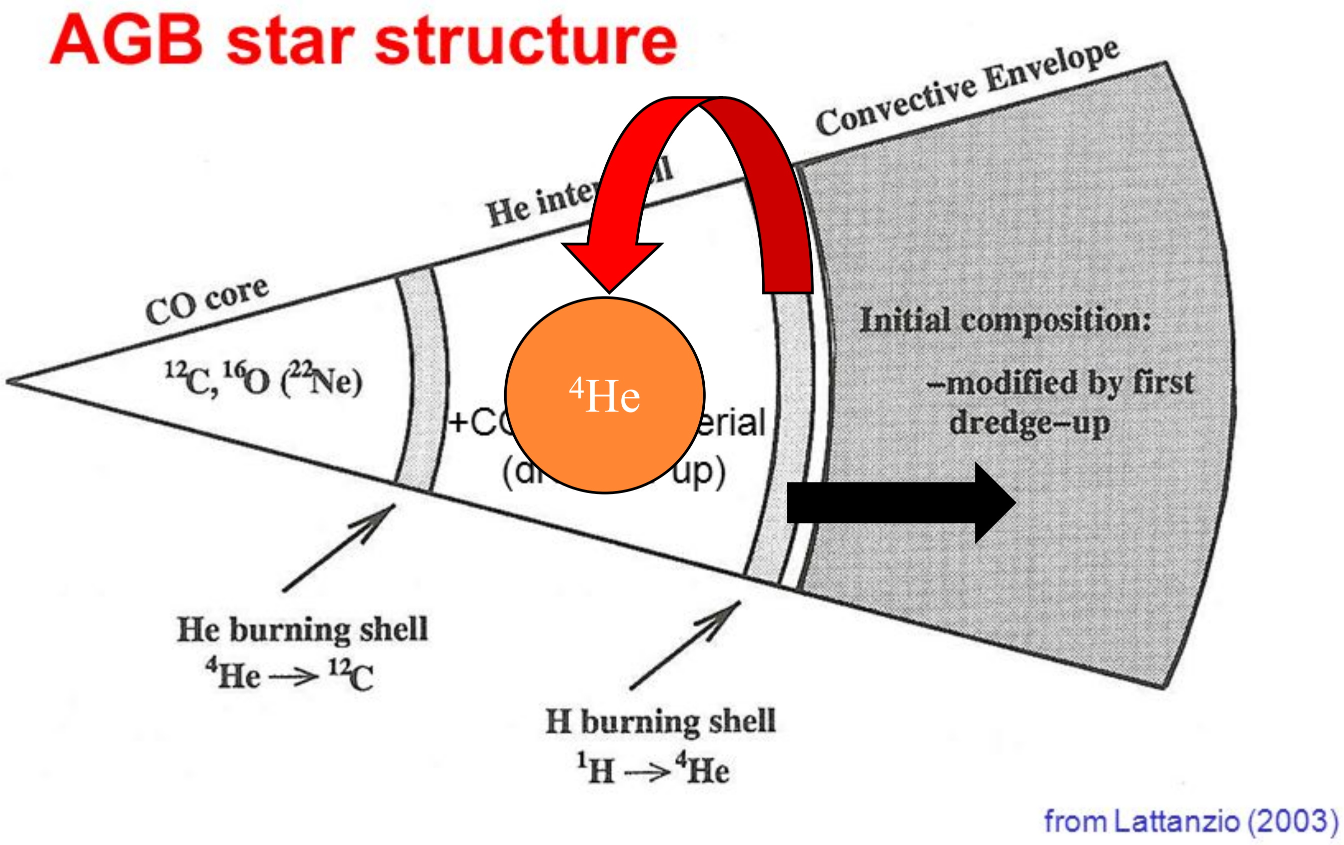
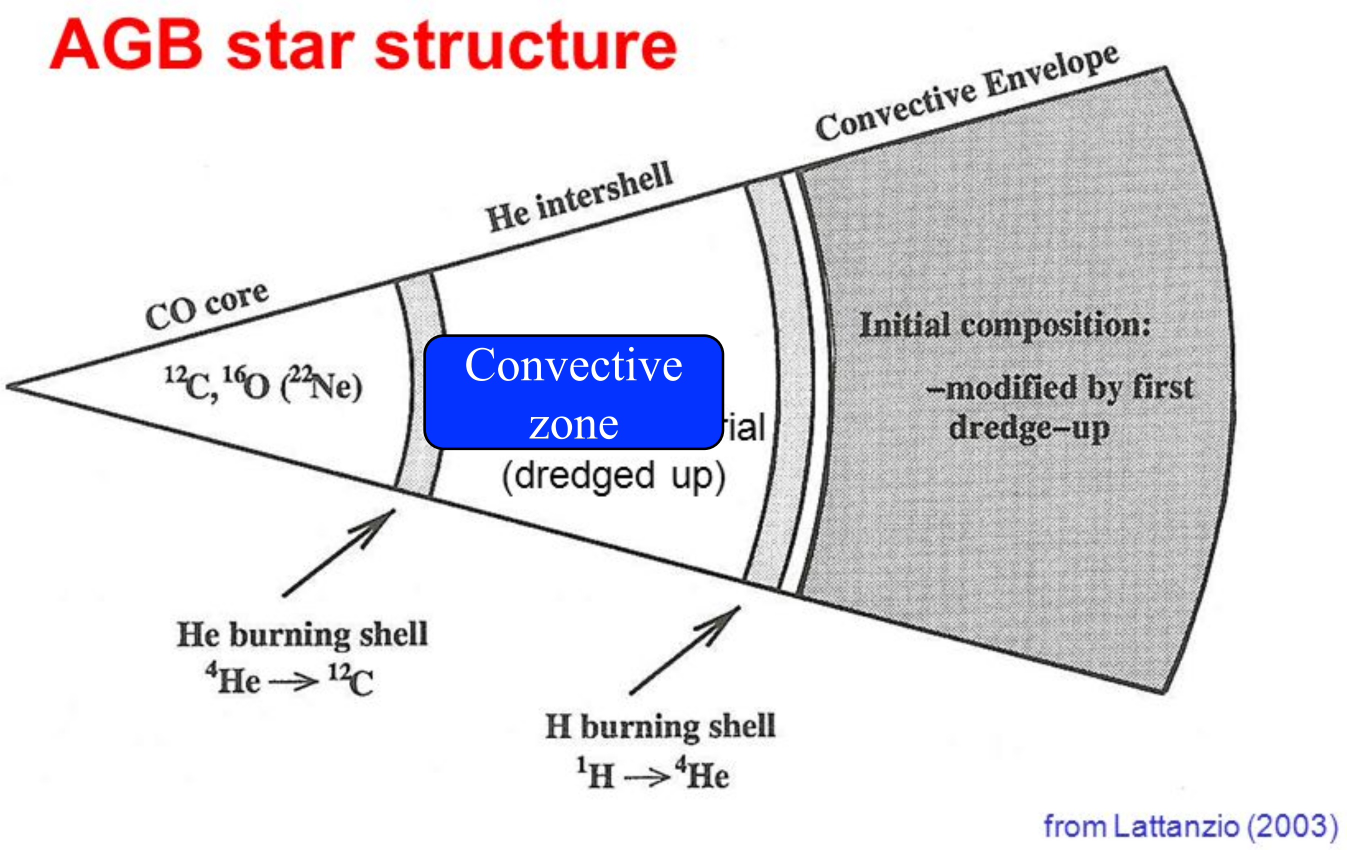


AGB and PIE

- The star has now a double shell structure, with the two shells advancing alternatively
- Thermal Pulse



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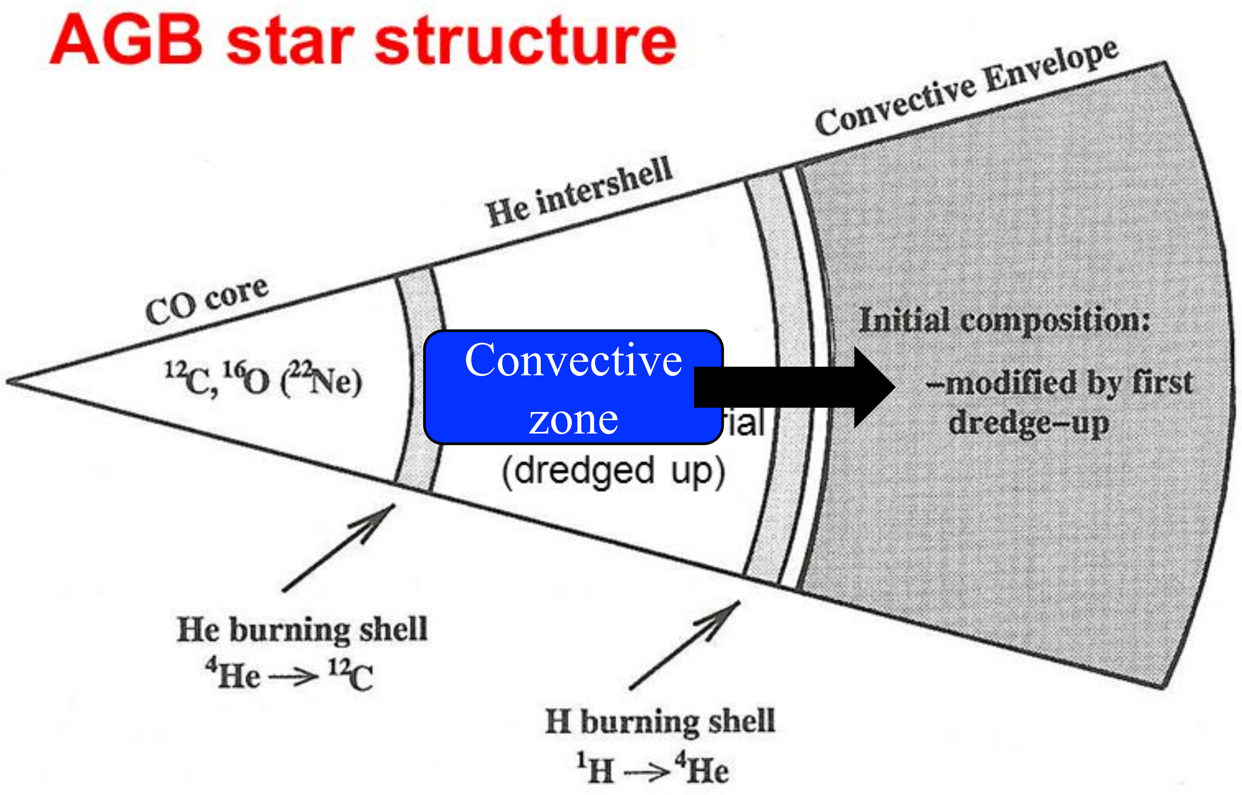

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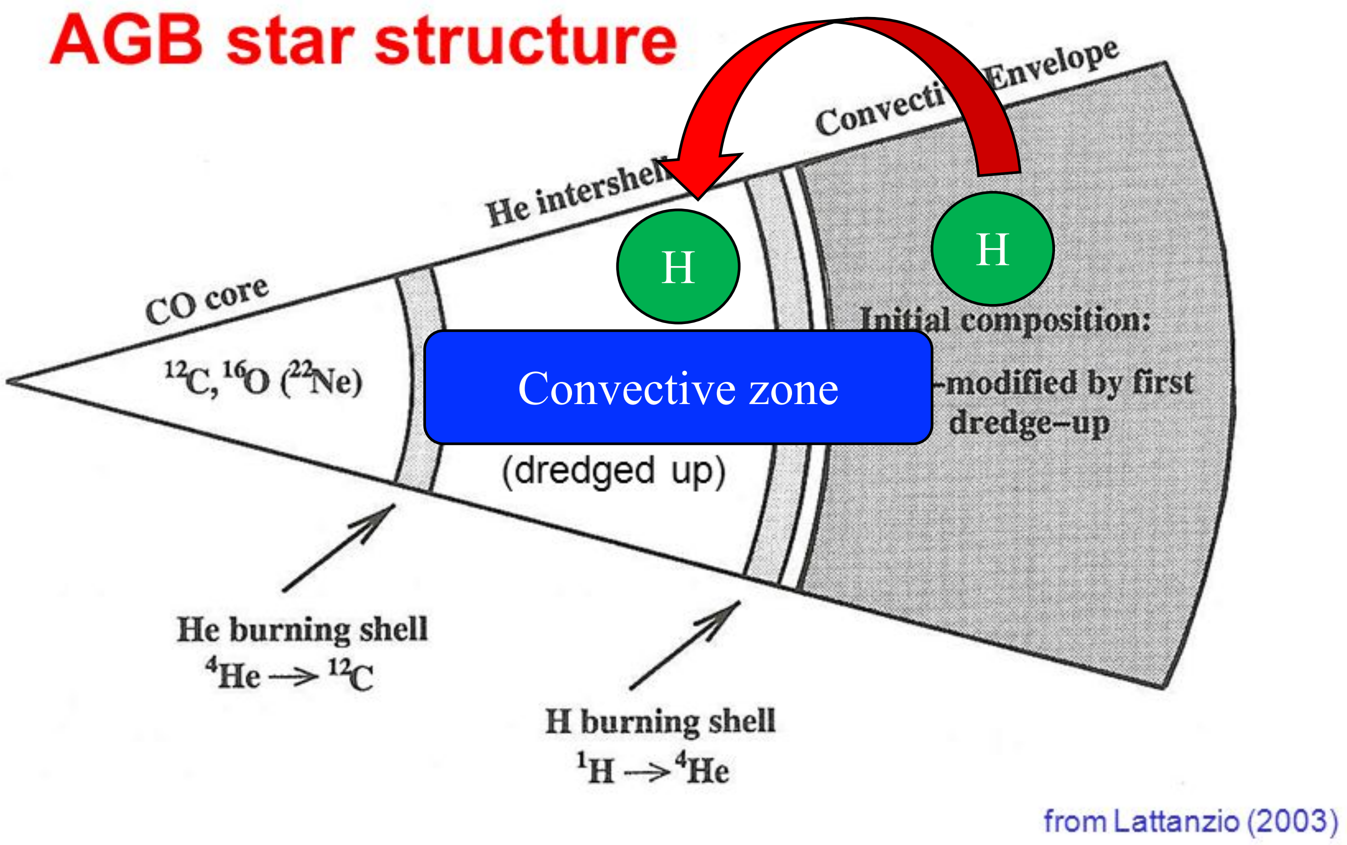

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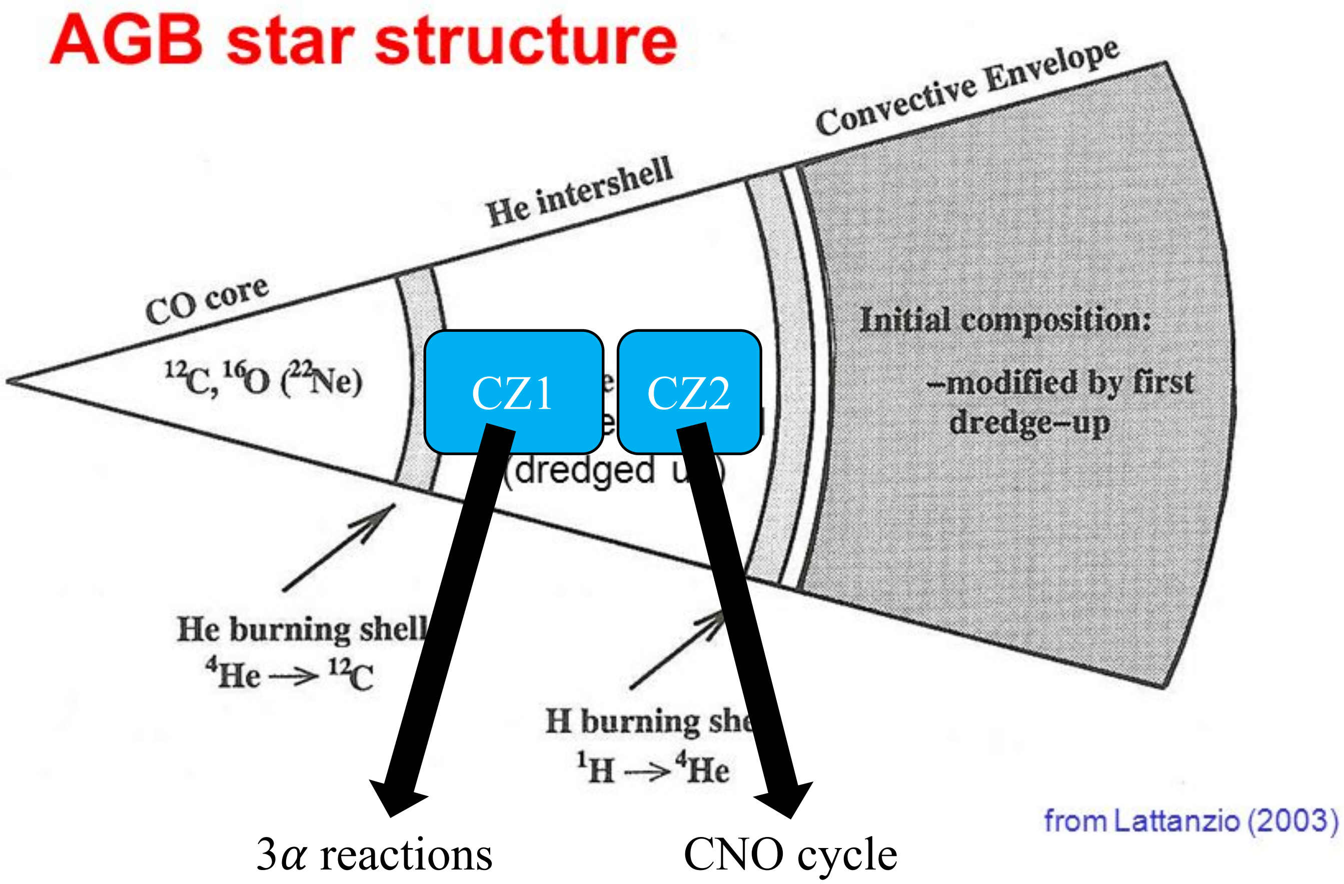

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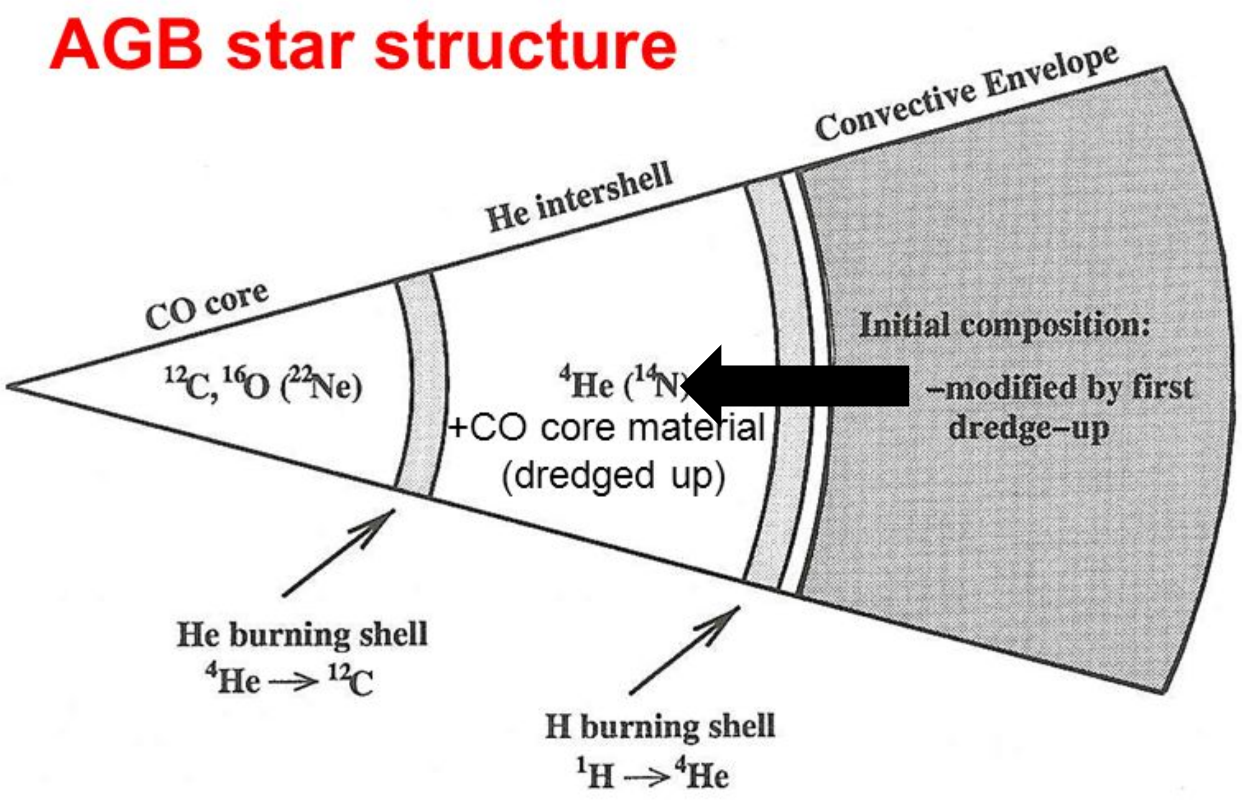

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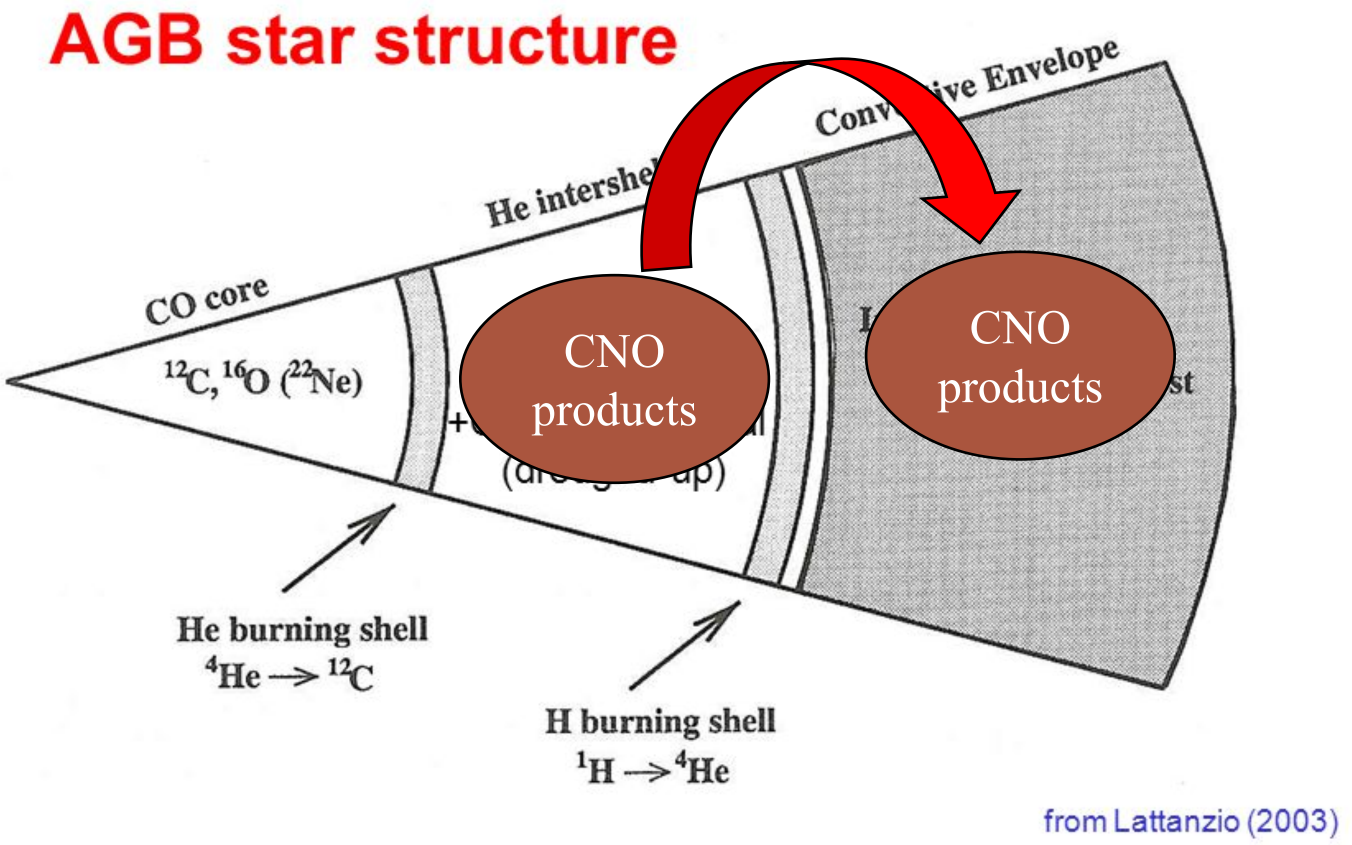
- Splitting of the convective zone into two separate convective regions
- TDU

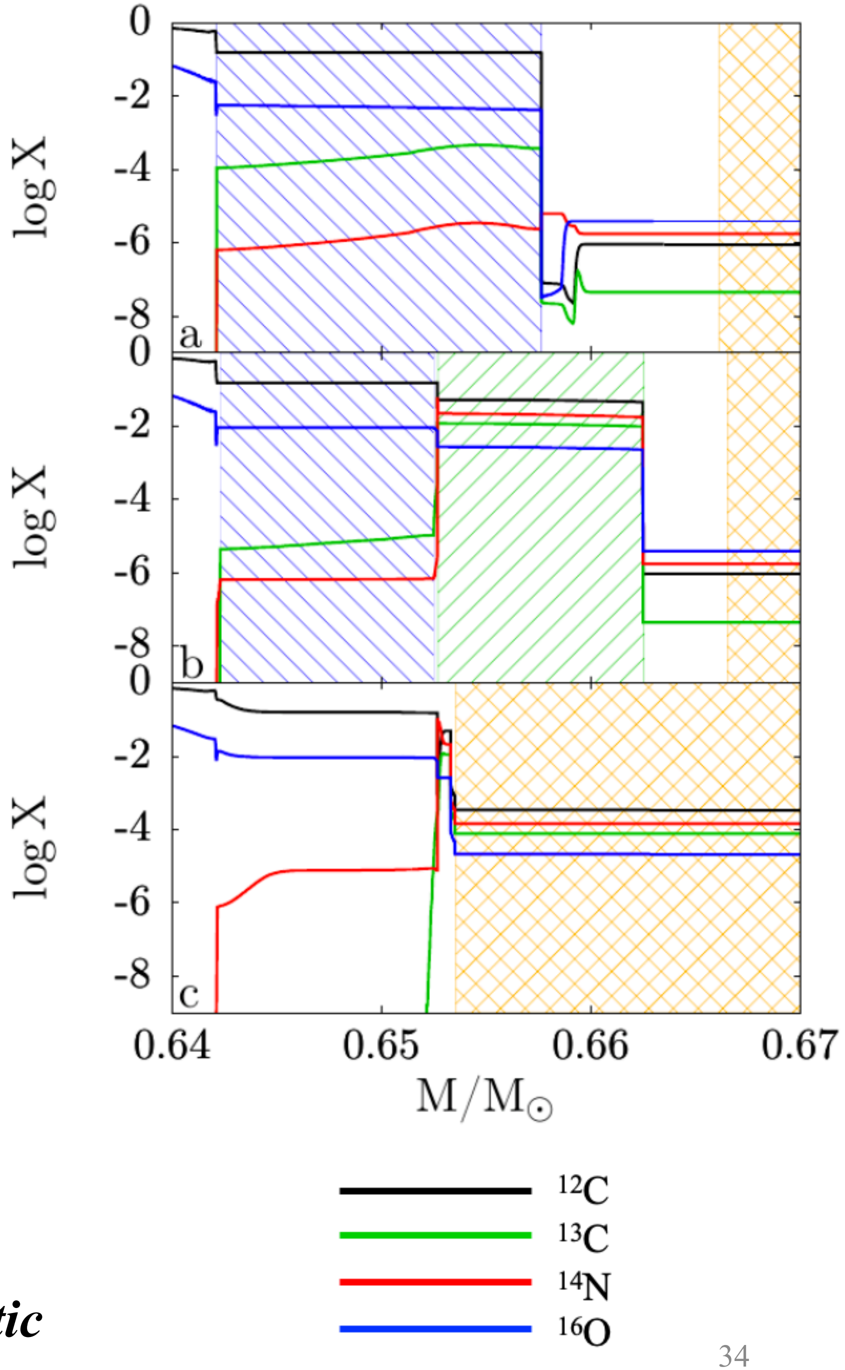


M = 2 M$_\odot$, Z = 10^{-5}, PIE: CNO

Before the PIE

PIE at maximum luminosity

TDU at maximum penetration



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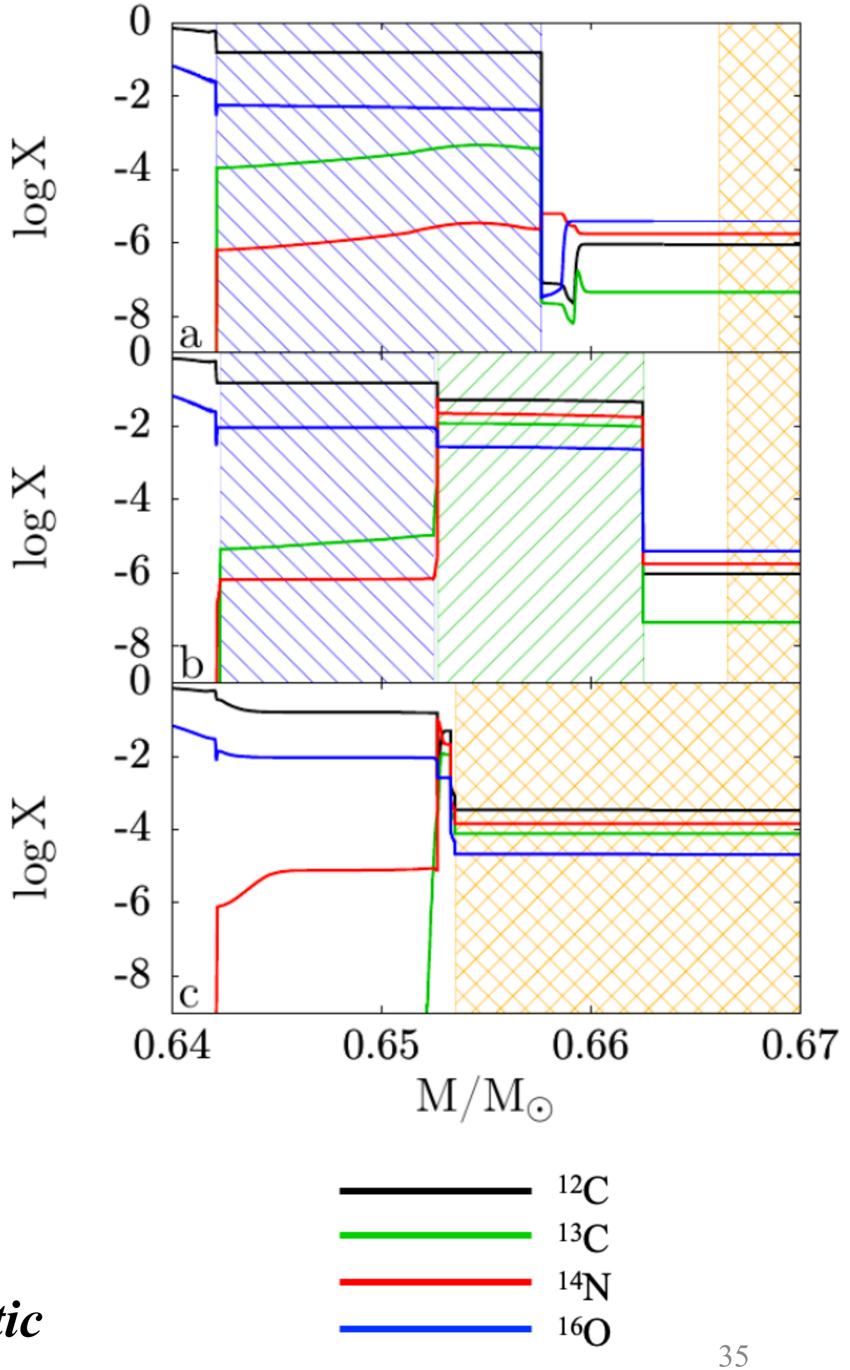

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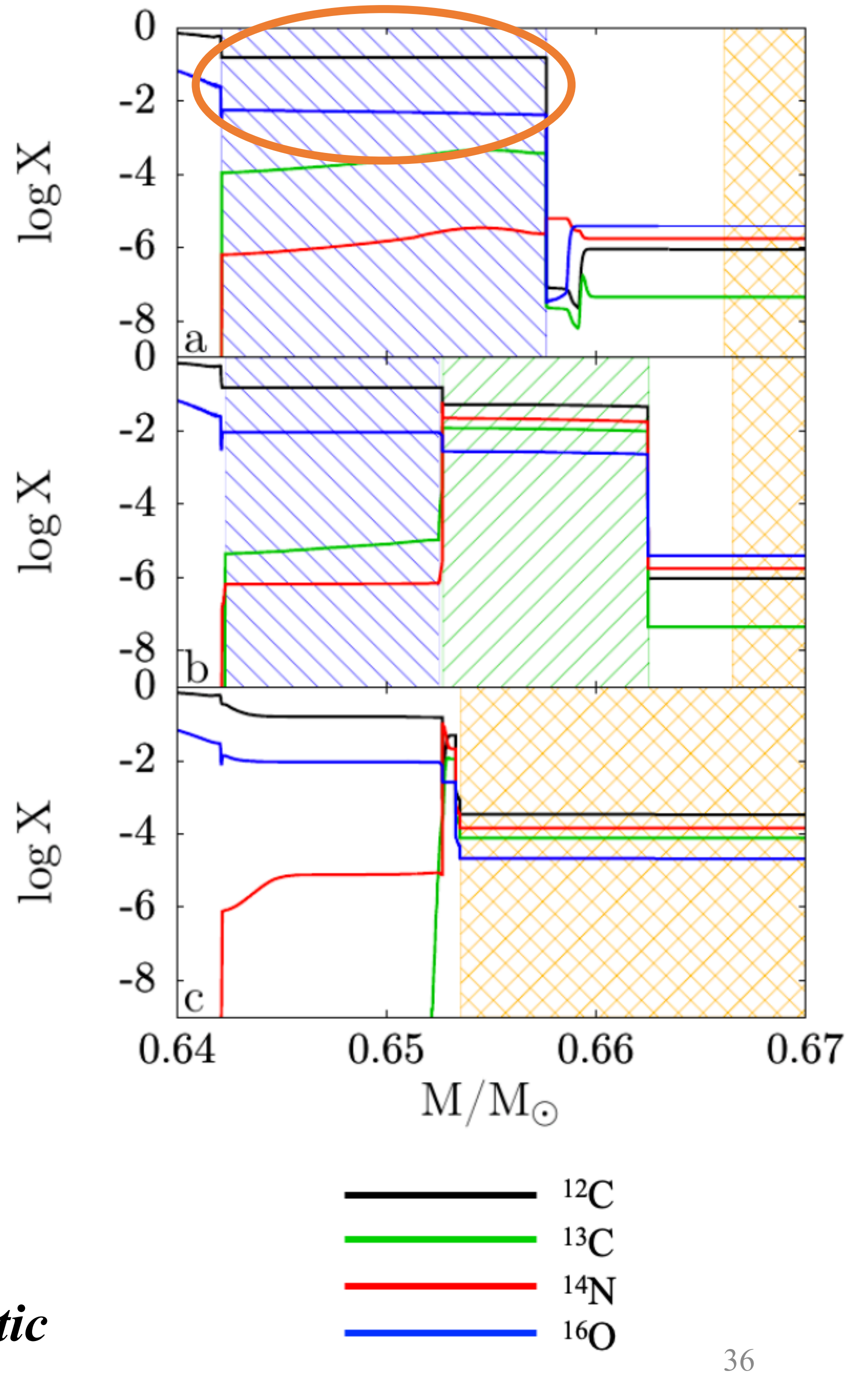

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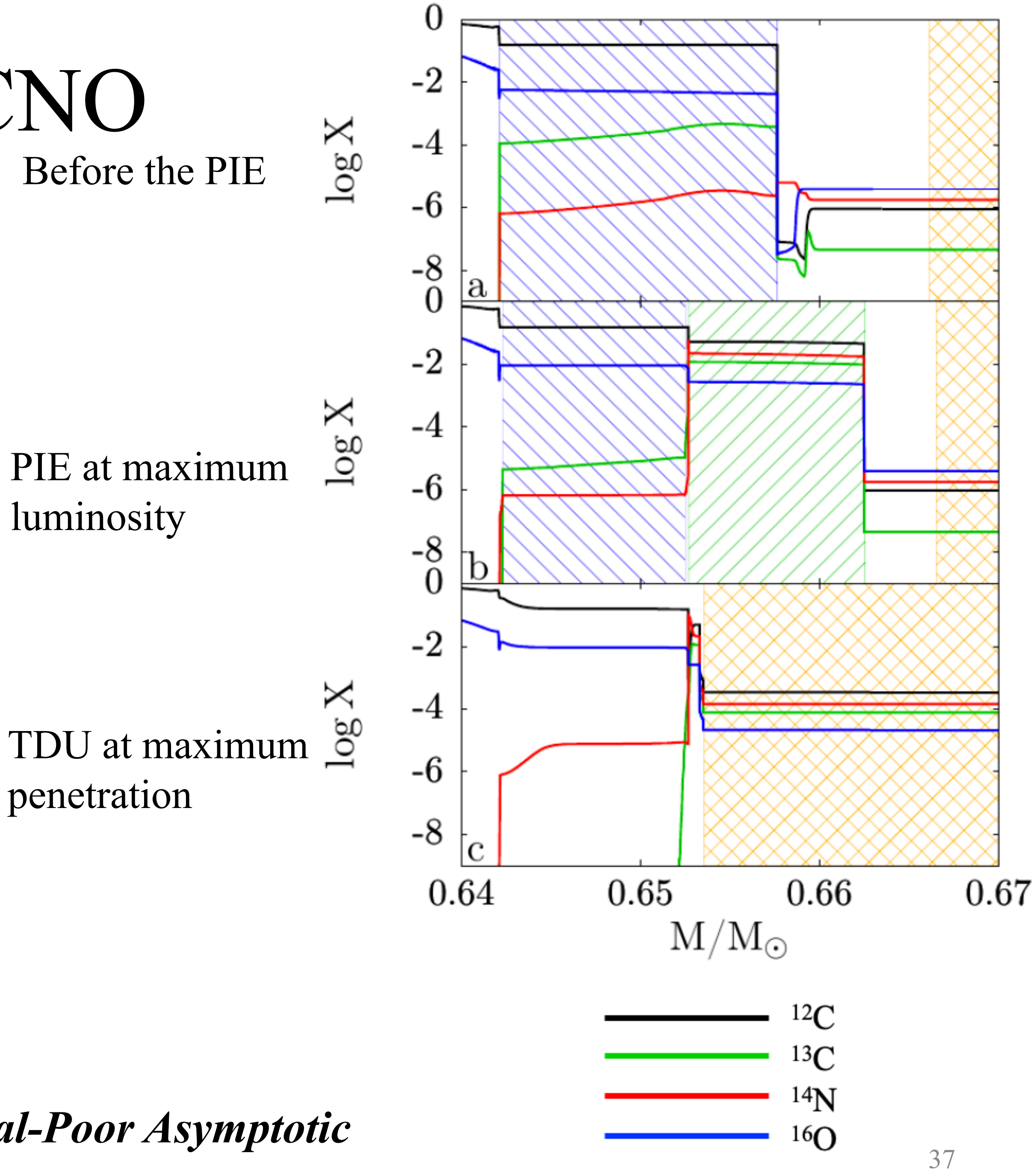

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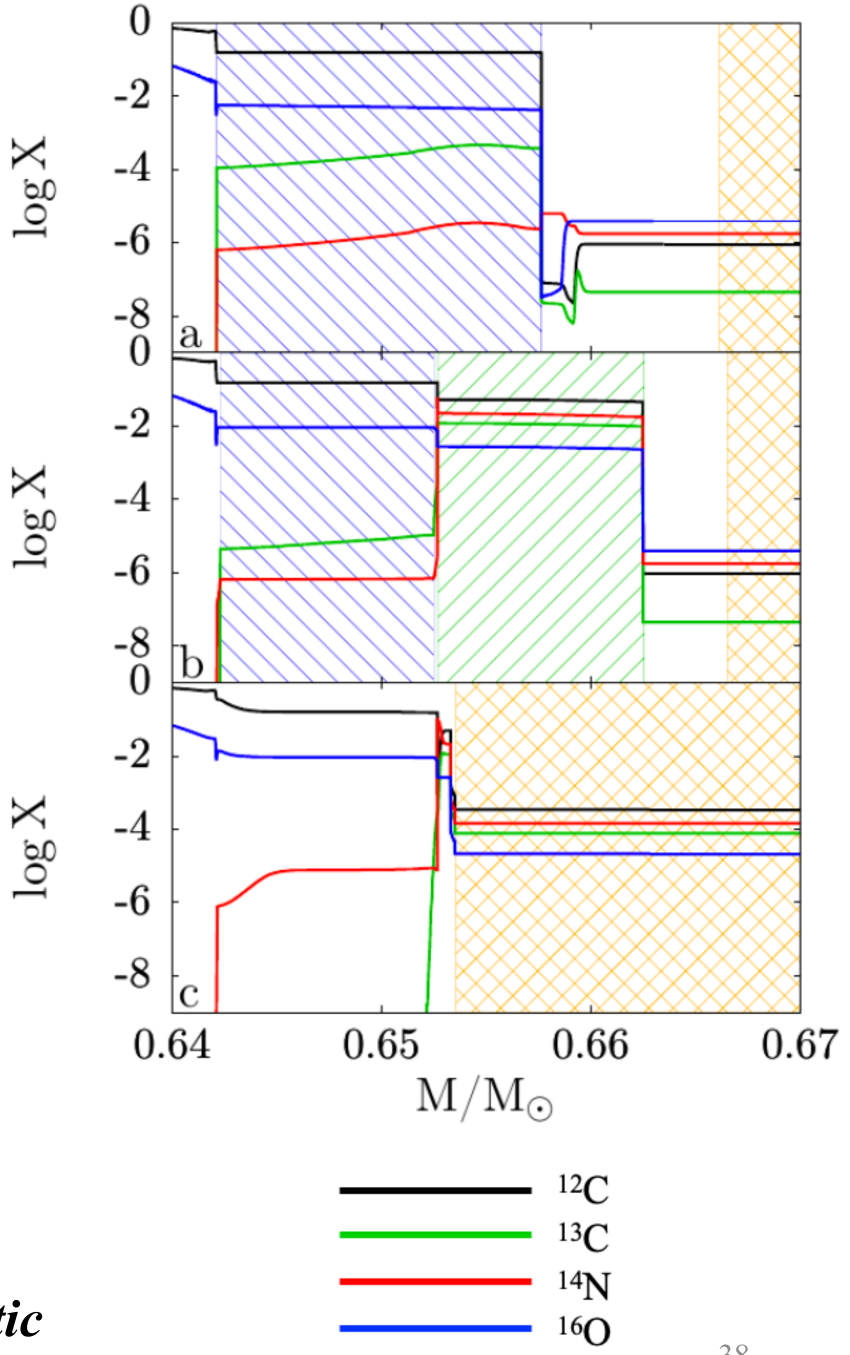

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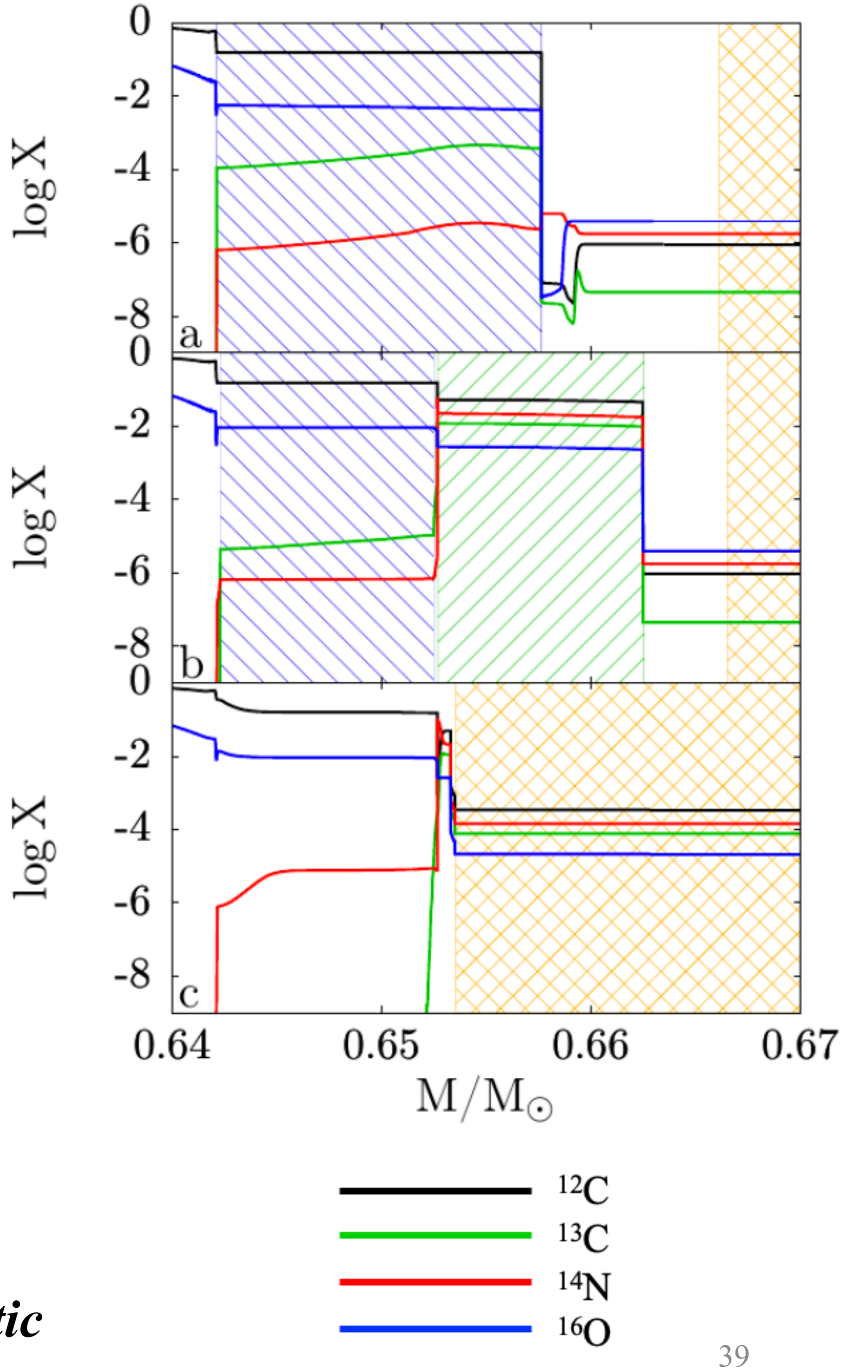

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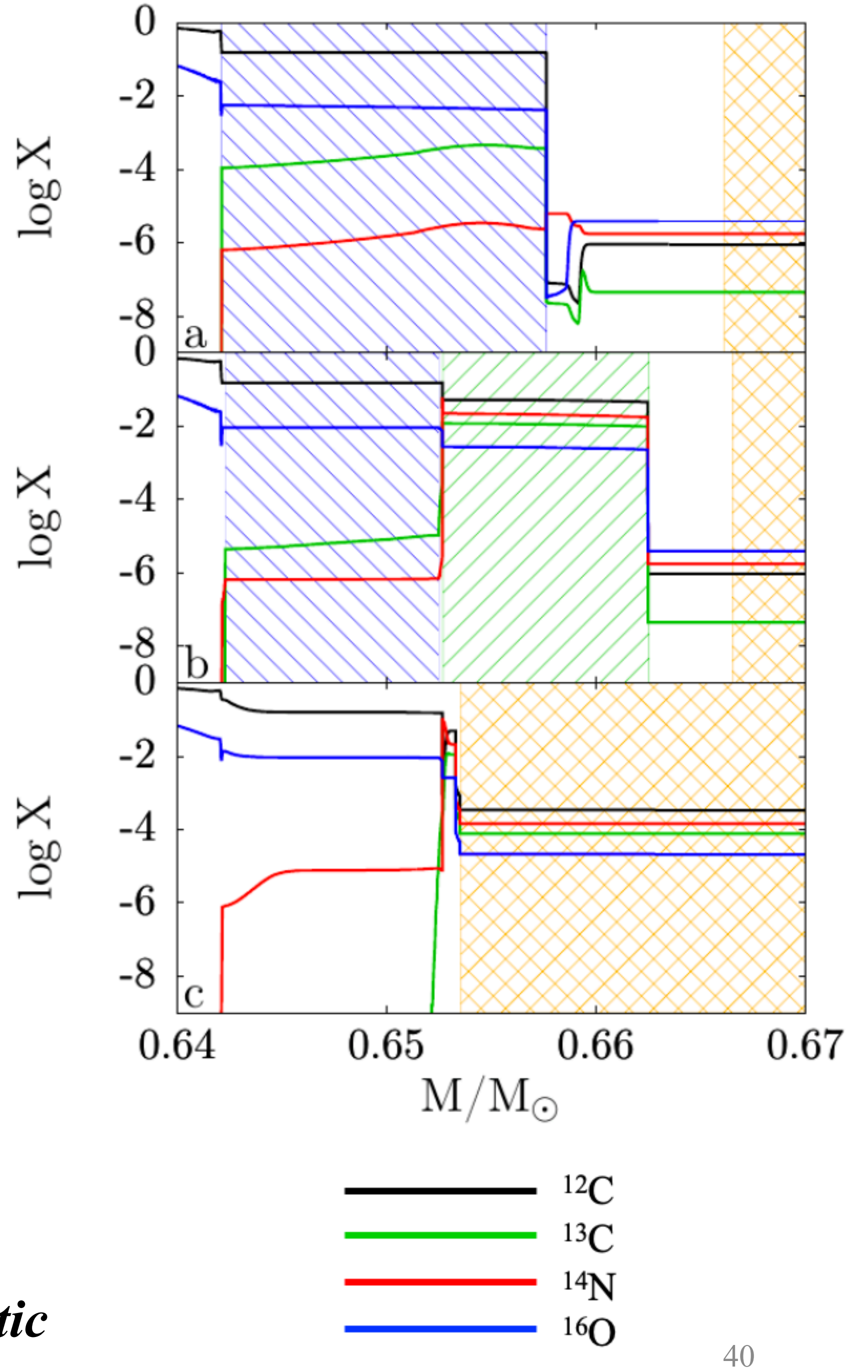

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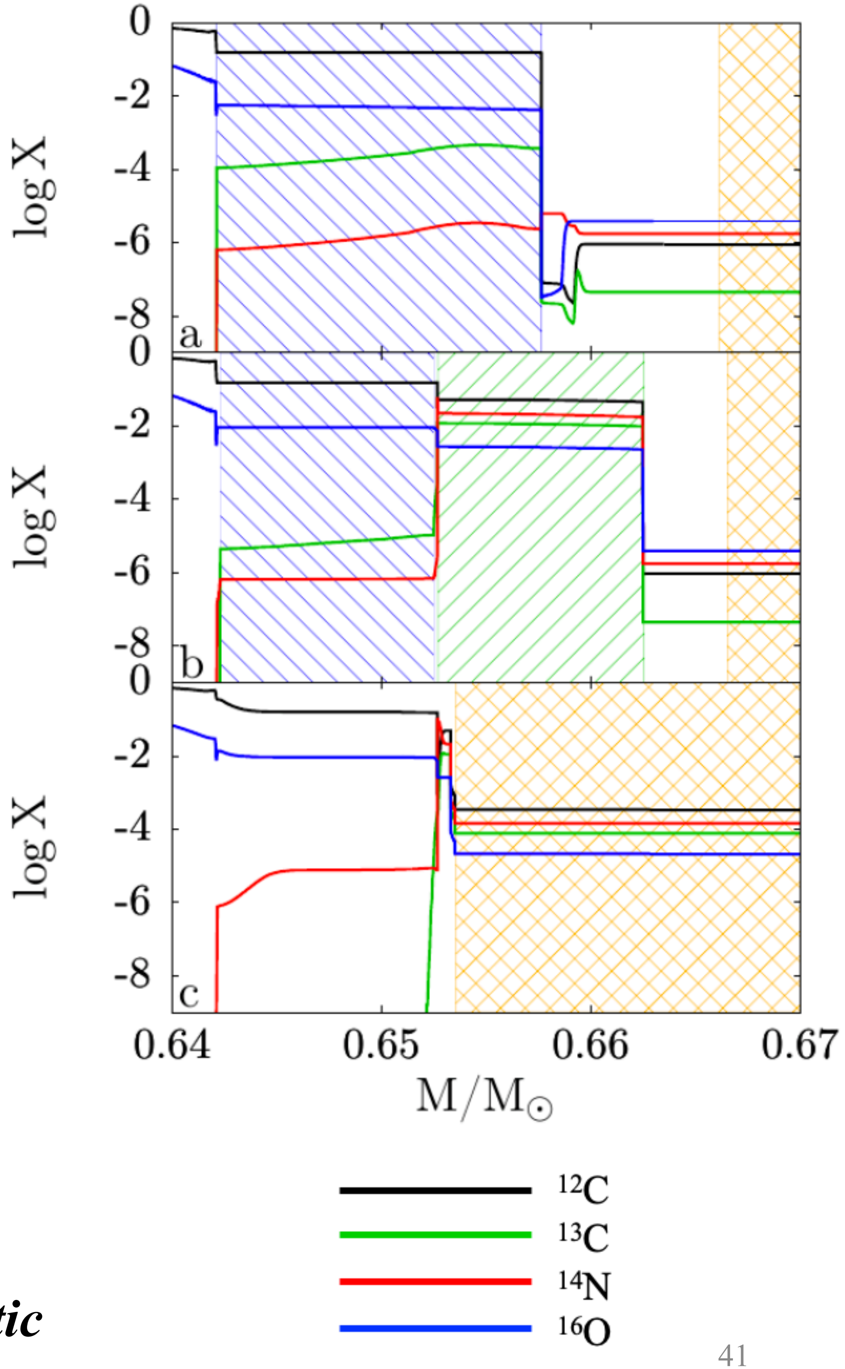

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Before the PIE

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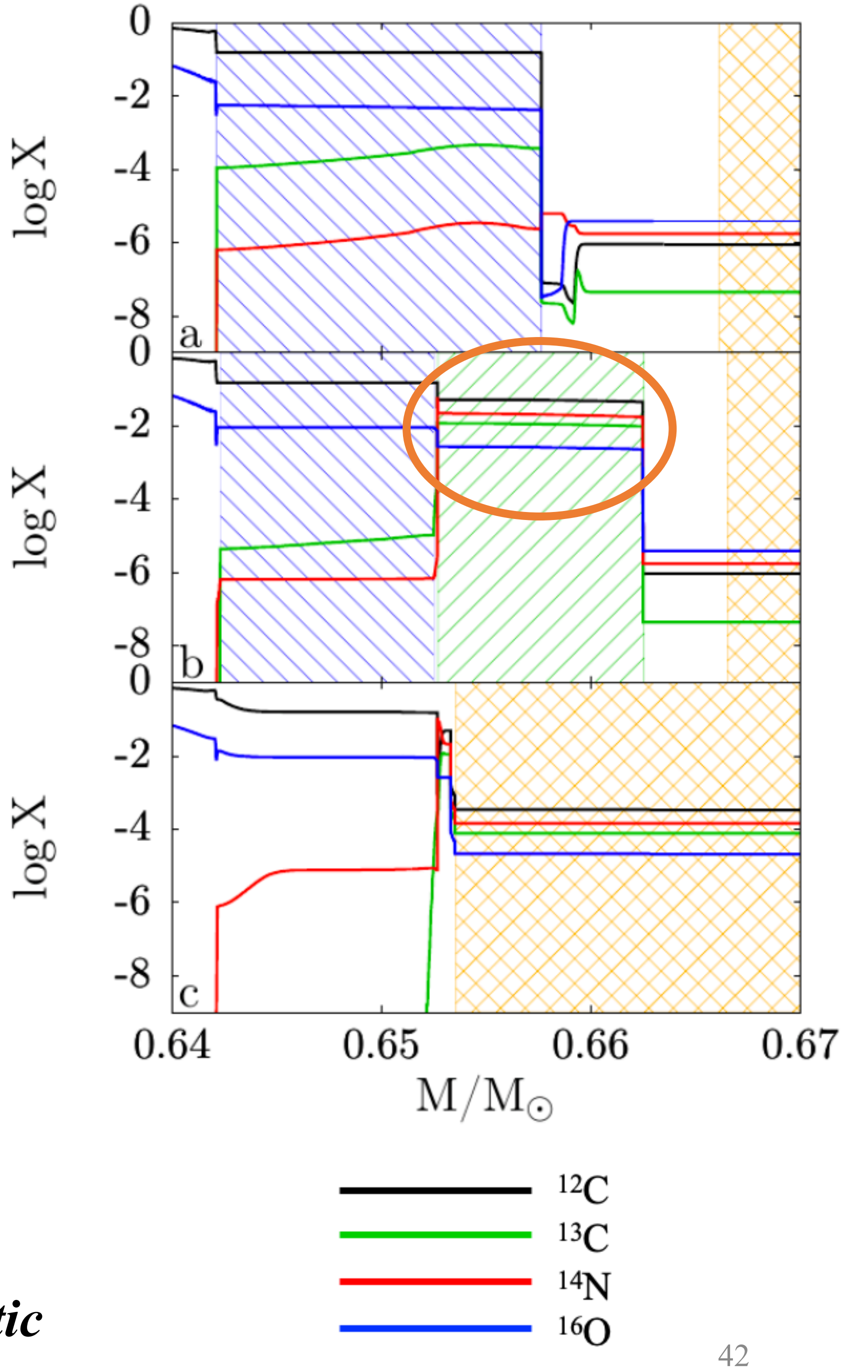

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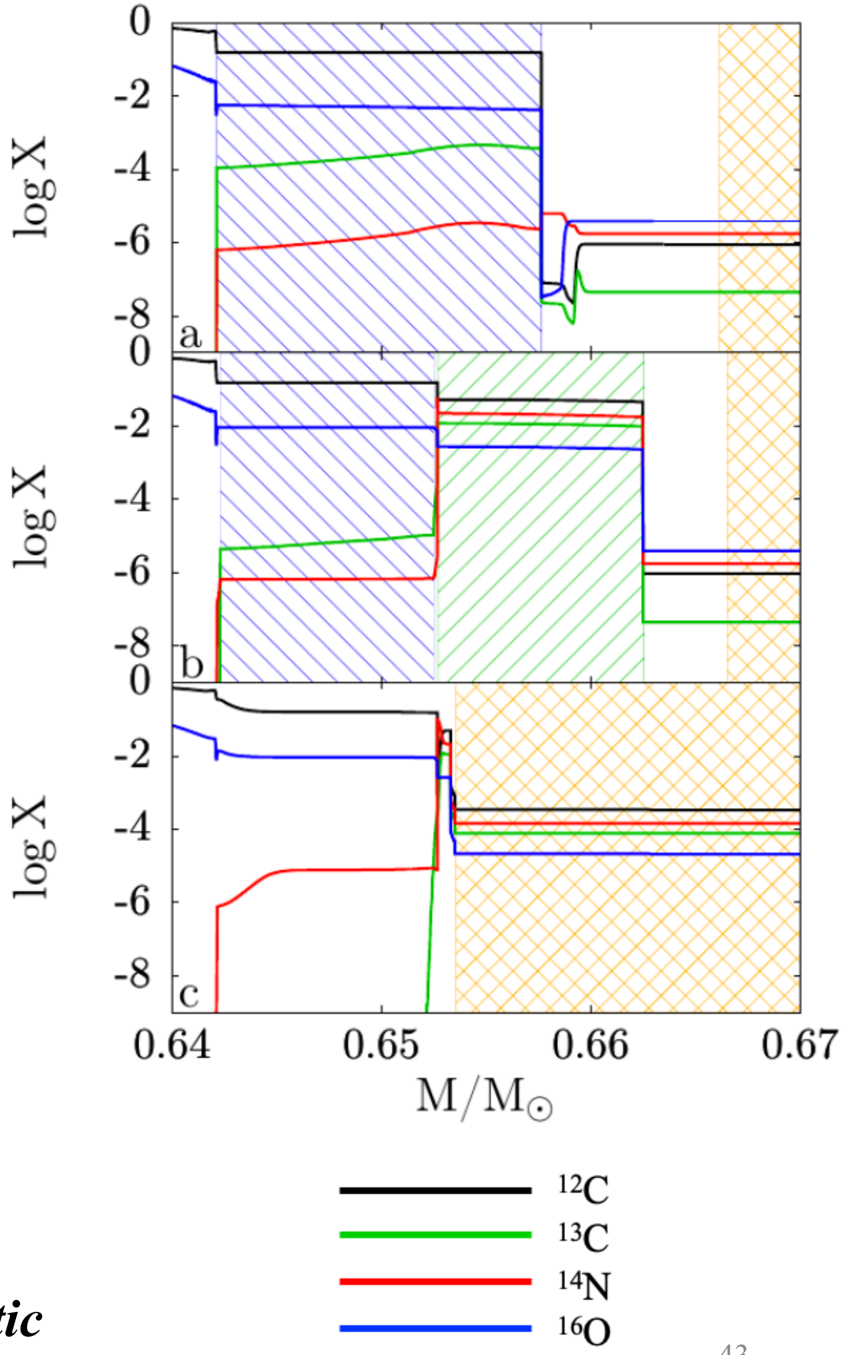

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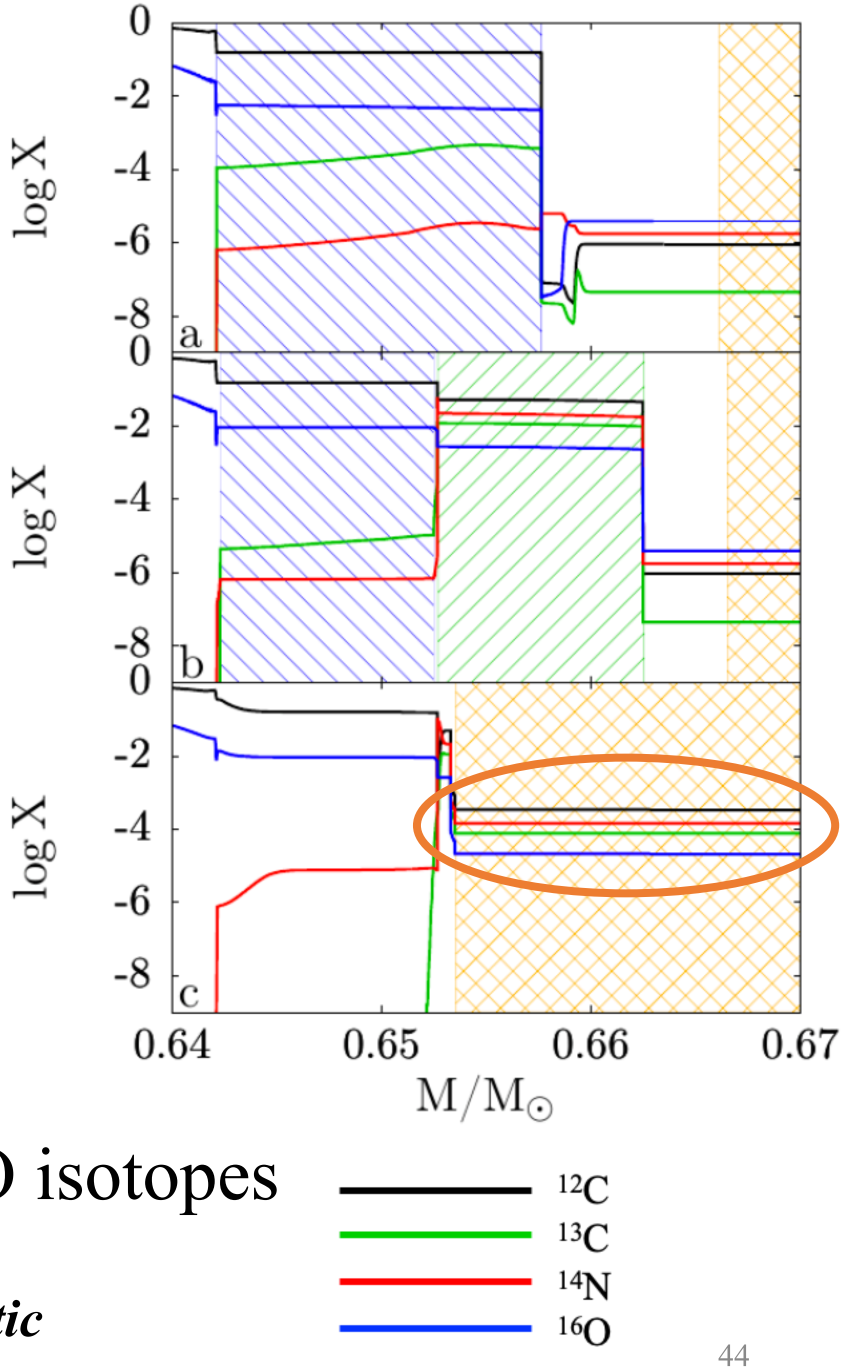
- d)penetration of the convective envelope ➡ TDU and surface enrichment in CNO isotopes

Before the PIE

PIE at maximum luminosity

TDU at maximum penetration



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$M = 2\ M_\odot$, $Z = 10^{-5}$, PIE: ^7Li

Before the PIE

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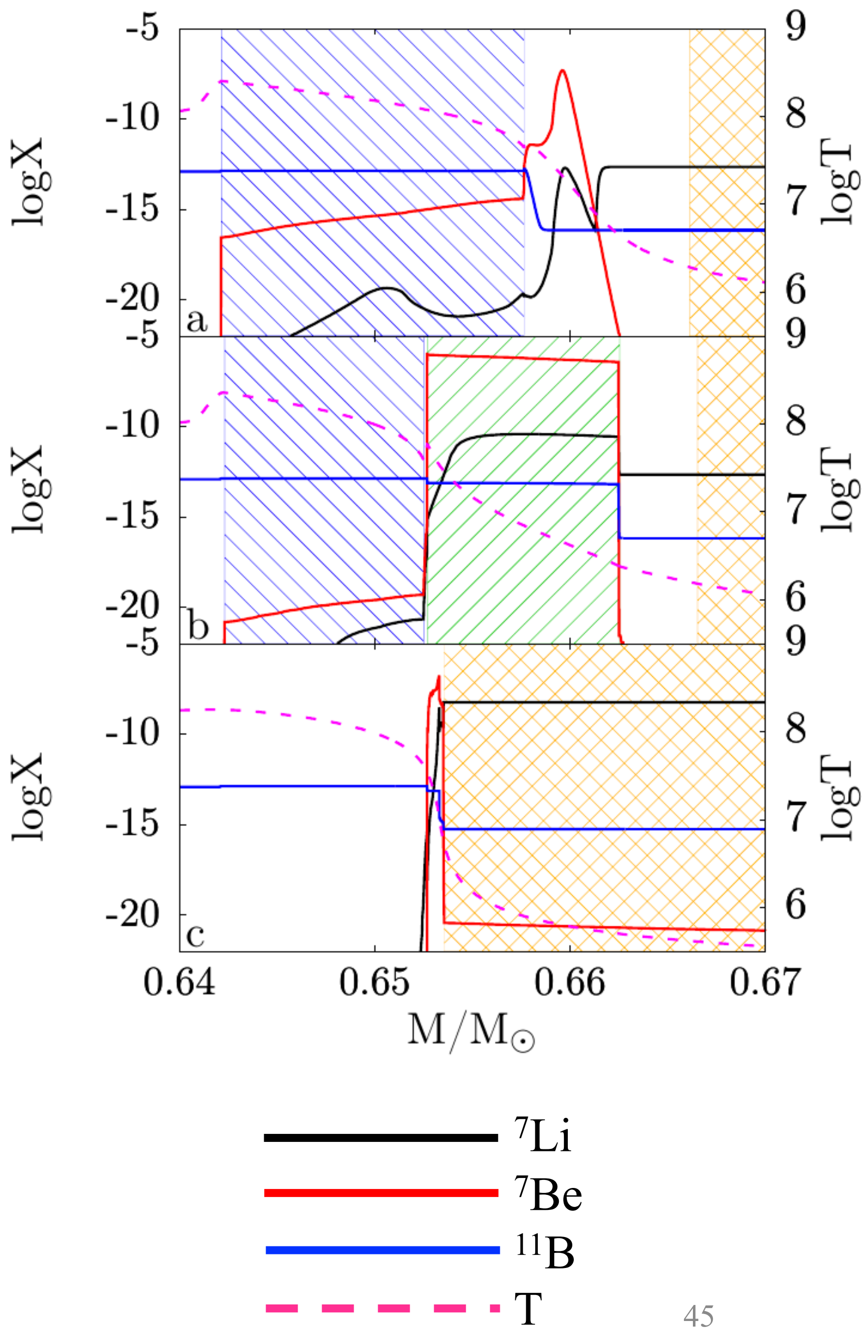


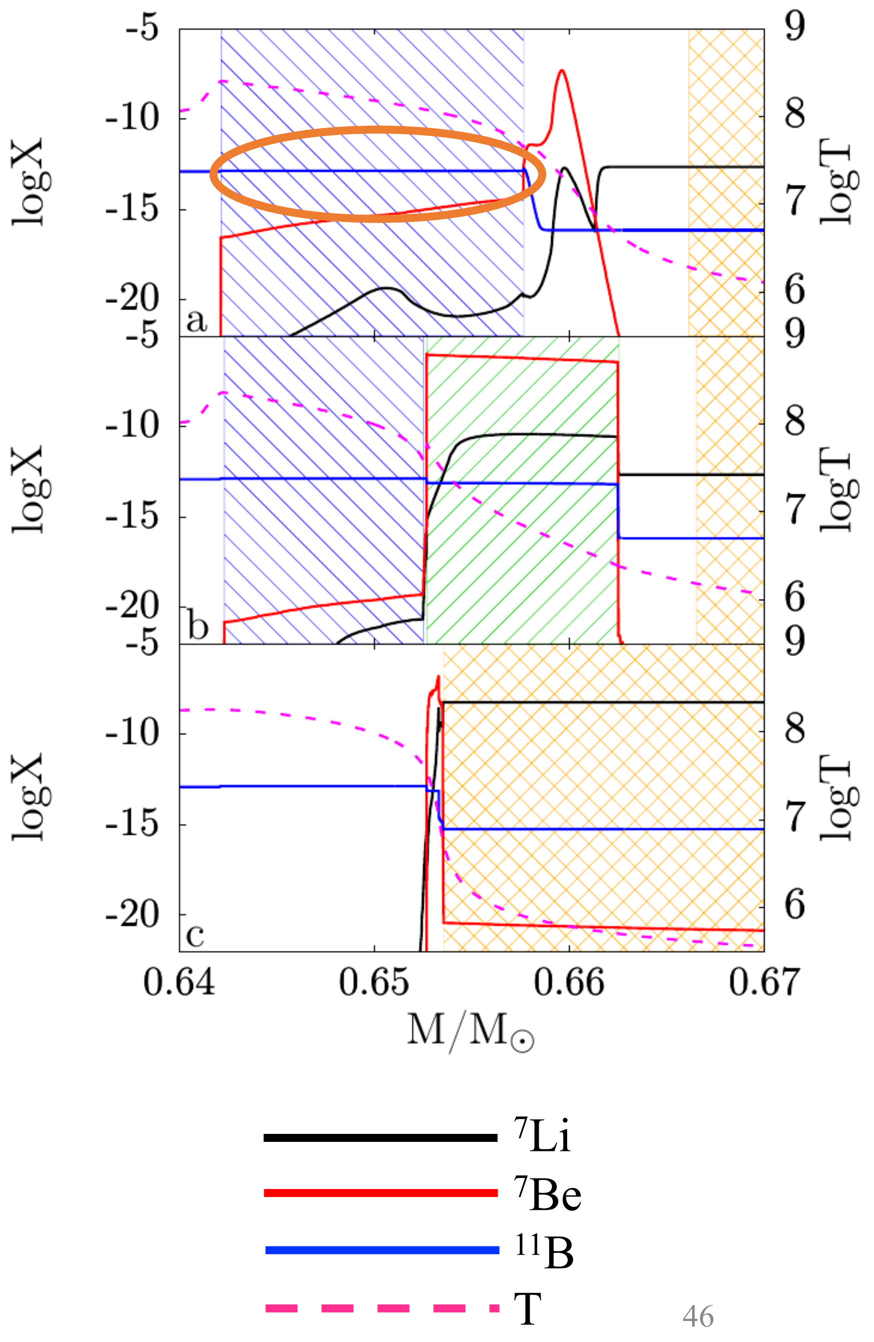
$M = 2\ M_\odot$, $Z = 10^{-5}$, PIE: ^7Li

- a) ^{11}B is produced via $^7Li(\alpha, \gamma)^{11}B$ and $^7Be(\alpha, \gamma)^{11}C(\beta^+, \nu)^{11}B$

Before the PIE

PIE at maximum luminosity

TDU at maximum penetration



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- b) ^{7}Be is produced via $^{3}He(\alpha, \gamma)^{7}Be$

Before the PIE

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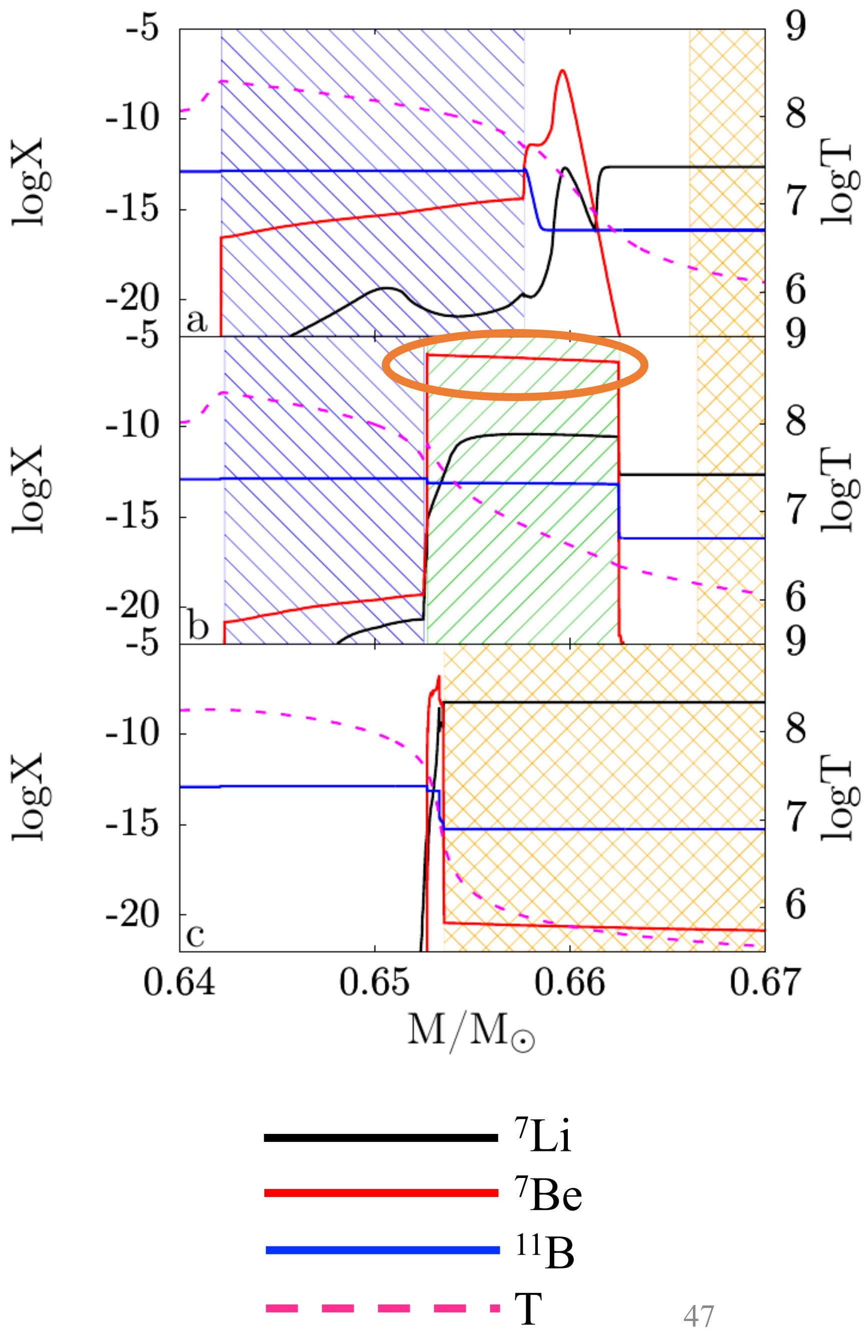

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- b) ^7Be is produced via $^3He(\alpha, \gamma)^7Be$
- c) Production of ^7Li via $^7Be(e^-, \nu)^7Li$ ($T \lesssim 20$ MK)

Before the PIE

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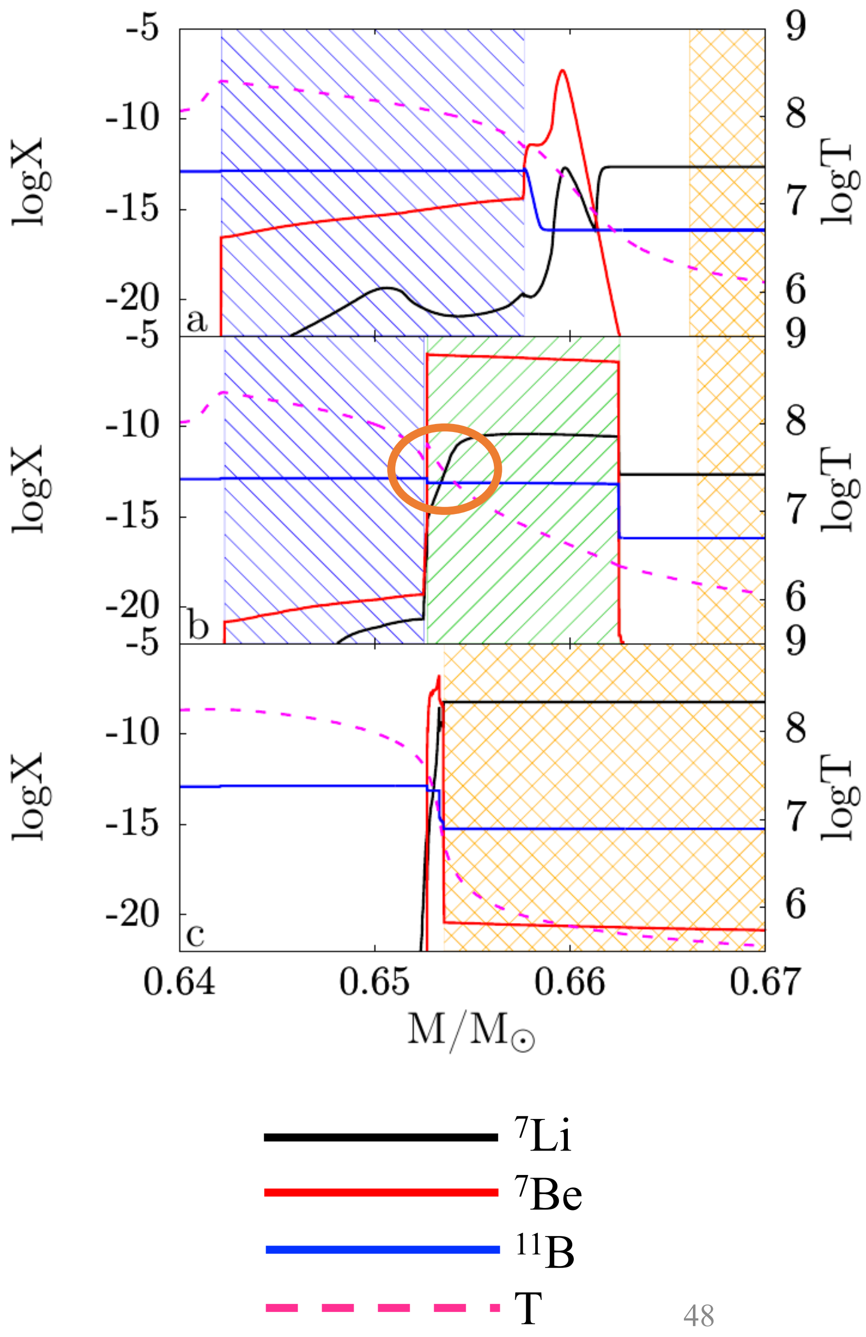

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- a) ^{11}B is produced via $^7Li(\alpha, \gamma)^{11}B$ and $^7Be(\alpha, \gamma)^{11}C(\beta^+, \nu)^{11}B$
- b) ^7Be is produced via $^3He(\alpha, \gamma)^7Be$
- c) Production of ^7Li via $^7Be(e^-, \nu)^7Li$ ($T \lesssim 20$ MK)
- d) Surface ^7Li mass fraction grows from $\approx 10^{-13}$ to $\approx 10^{-8}$

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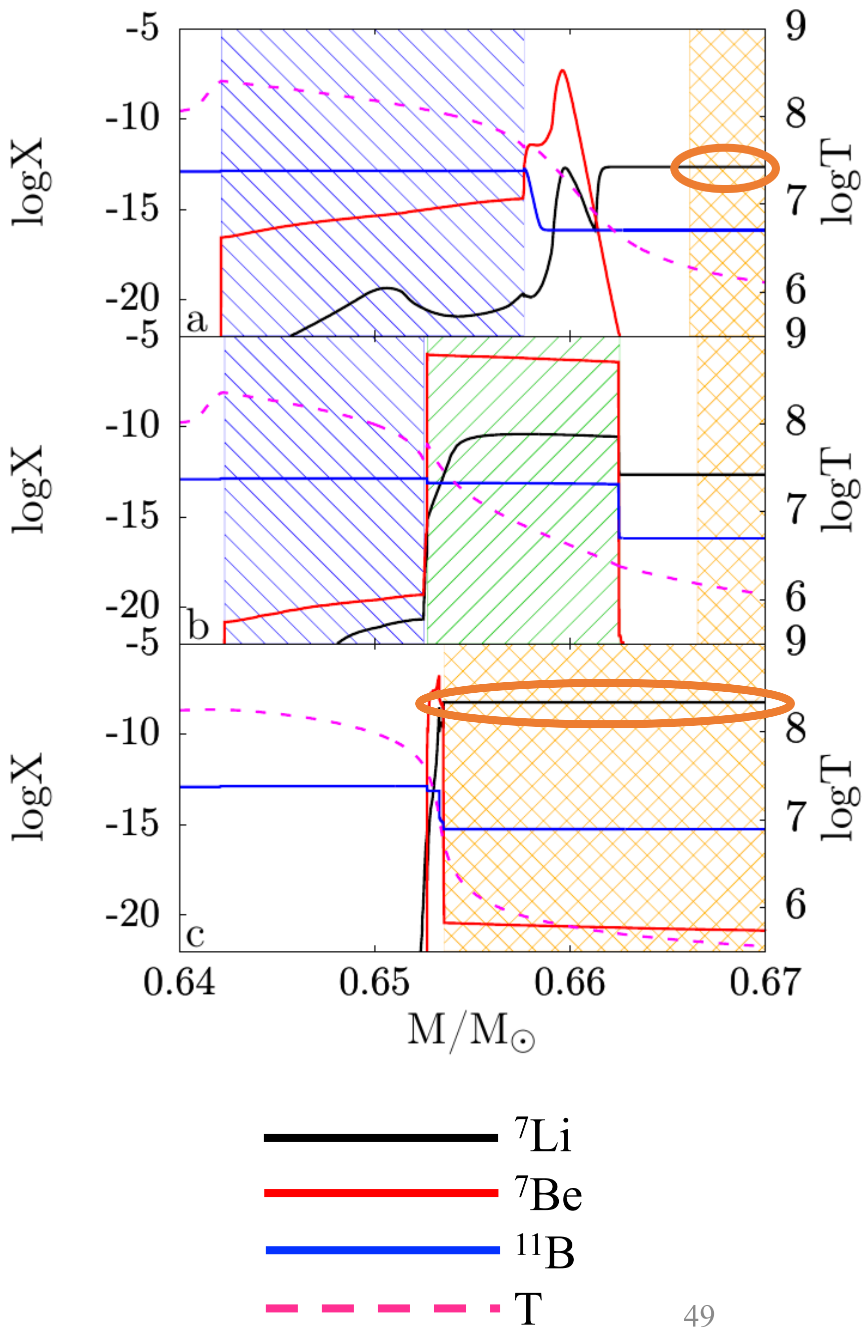

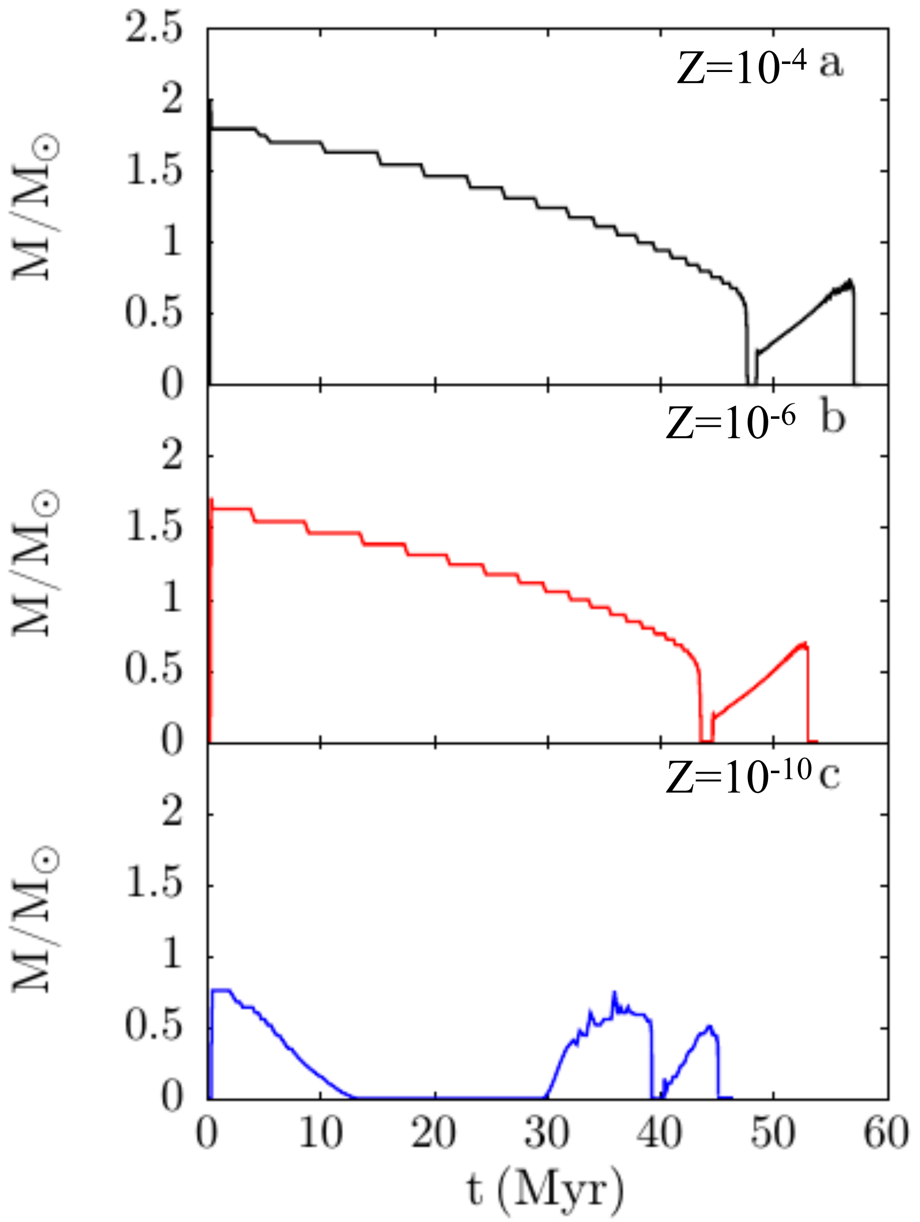

M = 6 M☉, different Z

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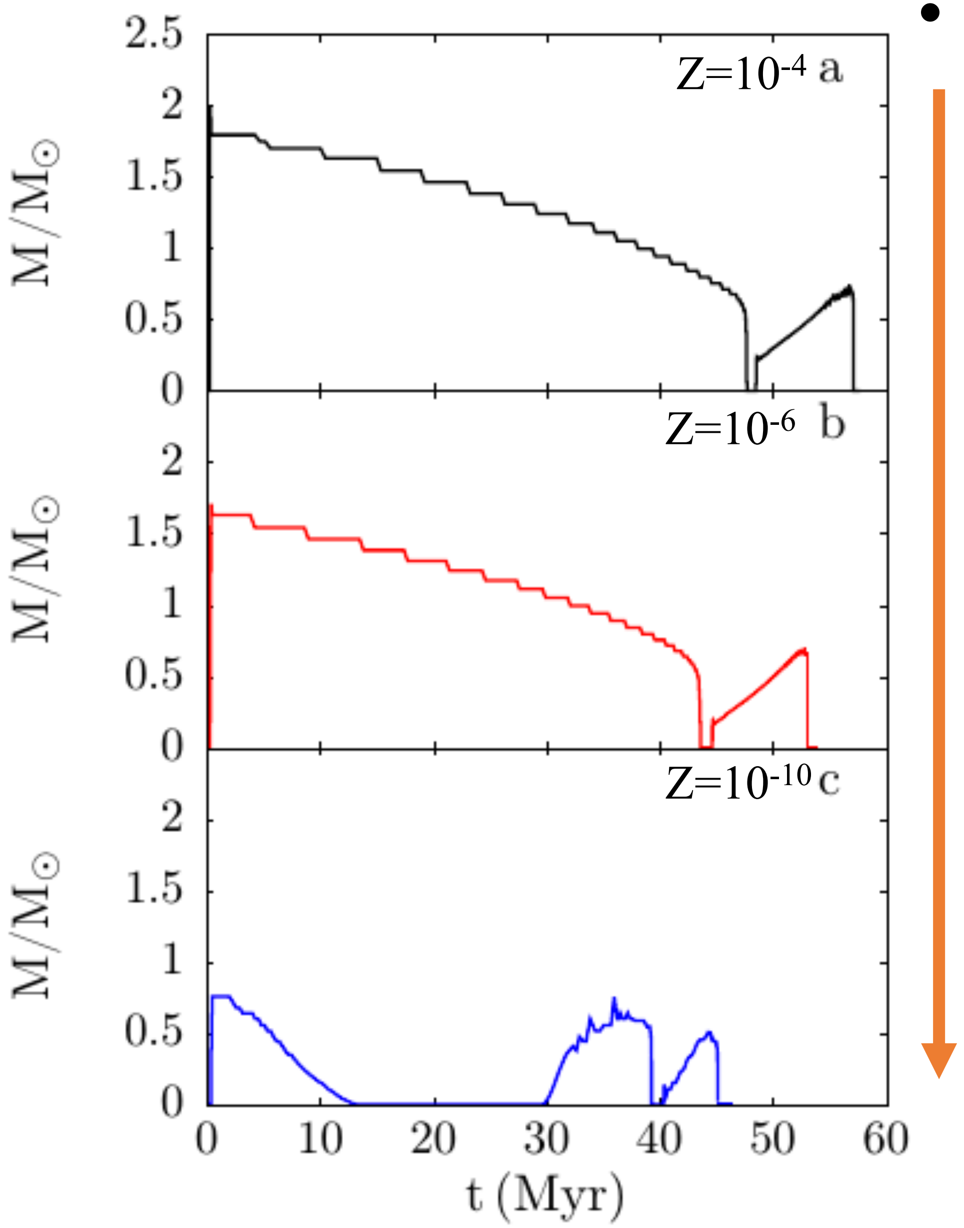

- Progressive reduction of core masses at each convective episode as Z decreases (more compact structures)

$M = 6\ M_\odot$, different Z

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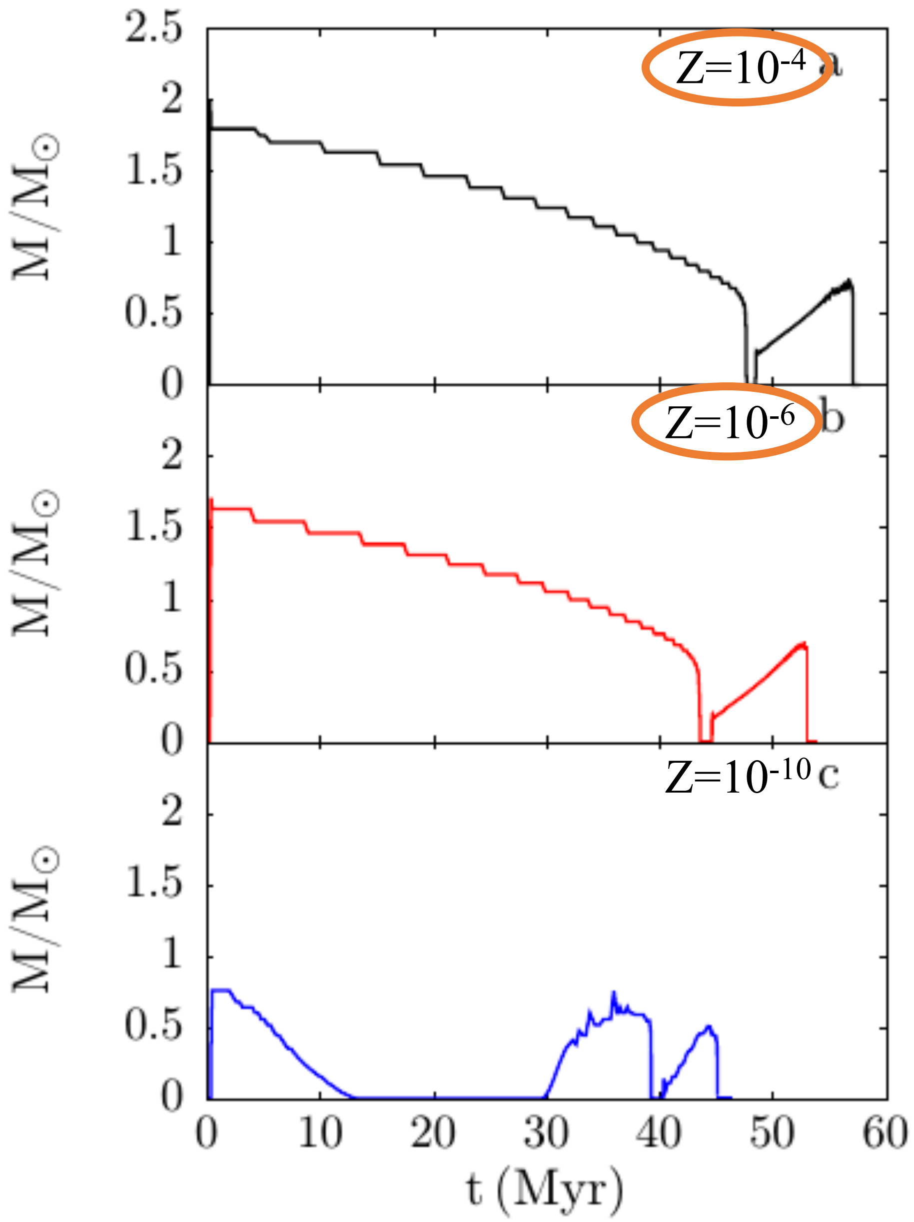

- Progressive reduction of core masses at each convective episode as Z decreases (more compact structures)
- Two convective episodes (CNO cycle and He burning) in $Z=10^{-4}$ and $Z=10^{-6}$

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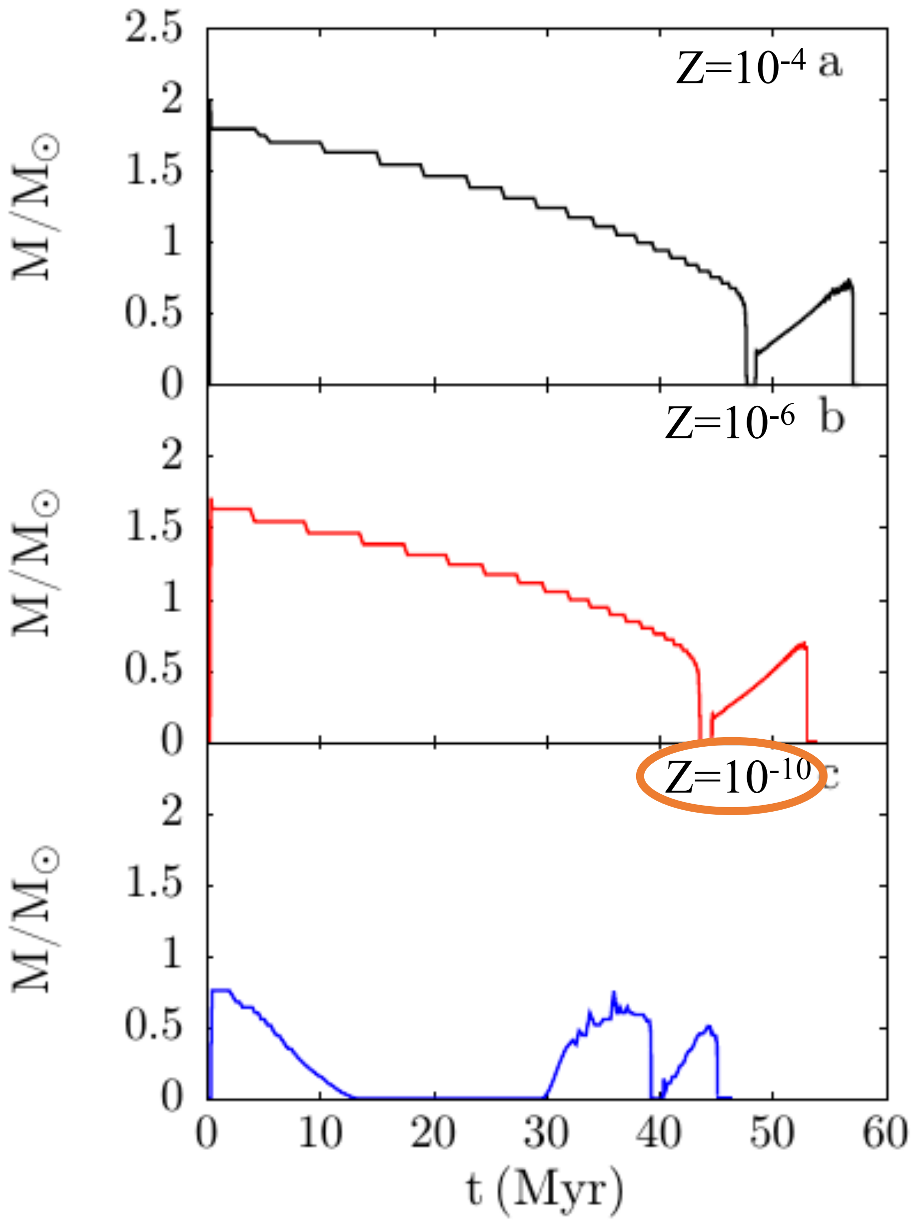

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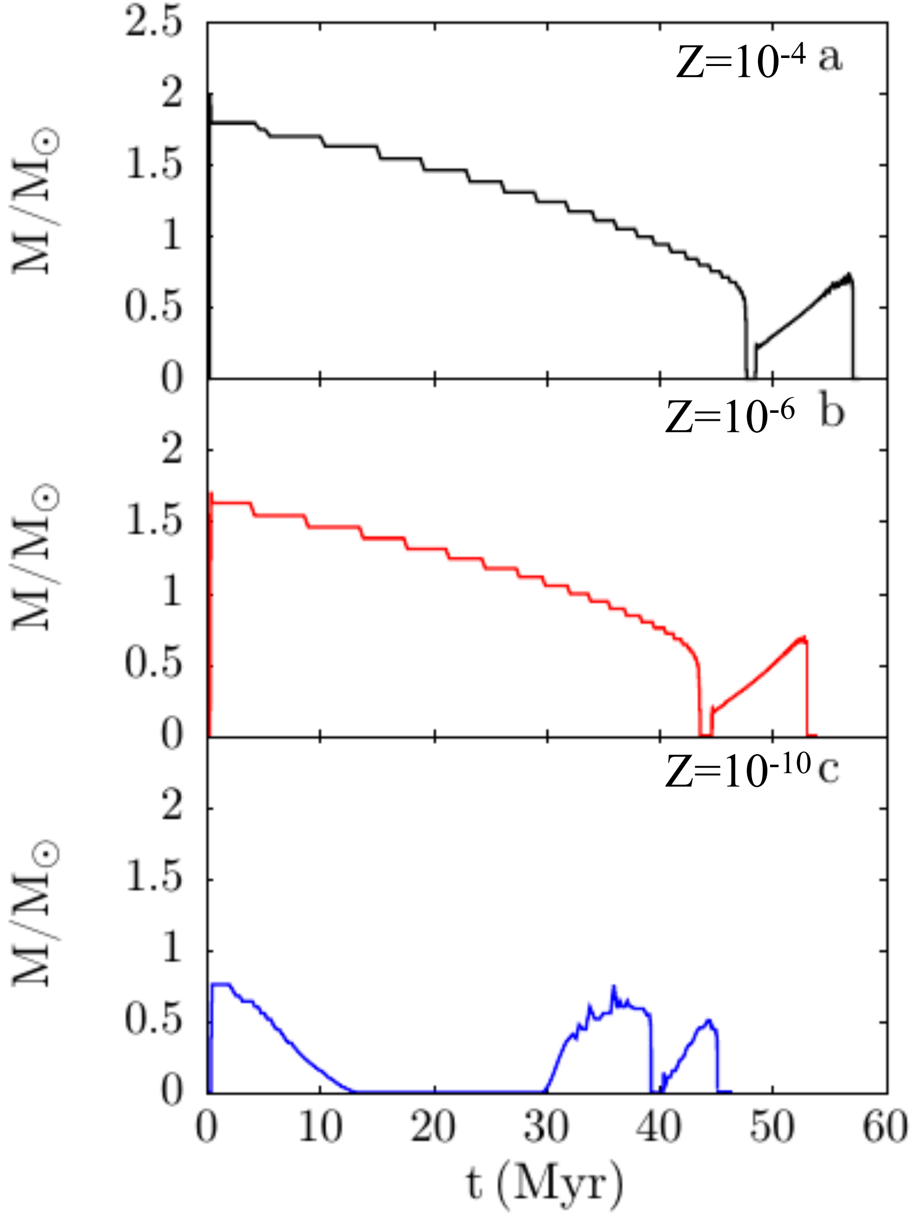

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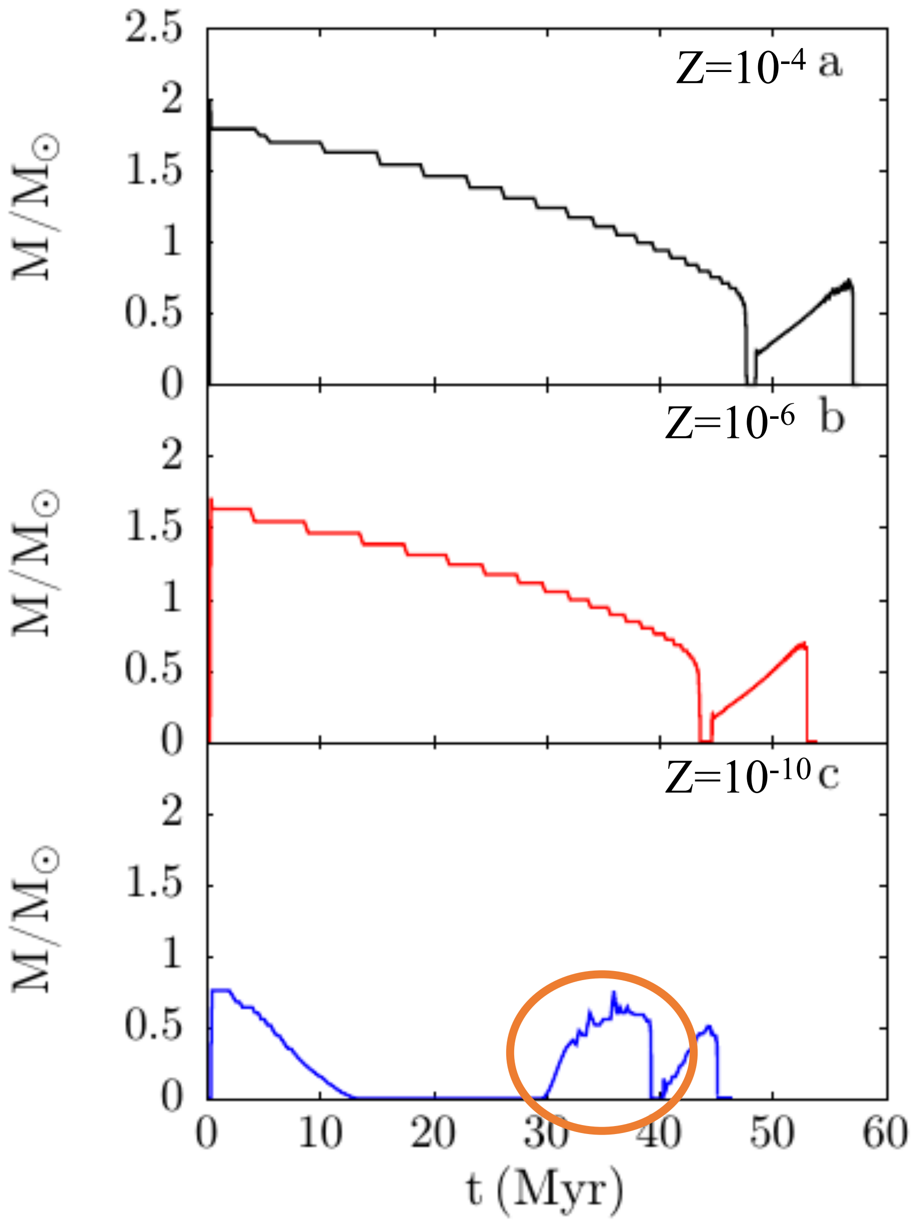

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- When CNO central abundance reaches $\approx 2\times10^{-10}$, CNO cycle is activated and a second convective episode appears

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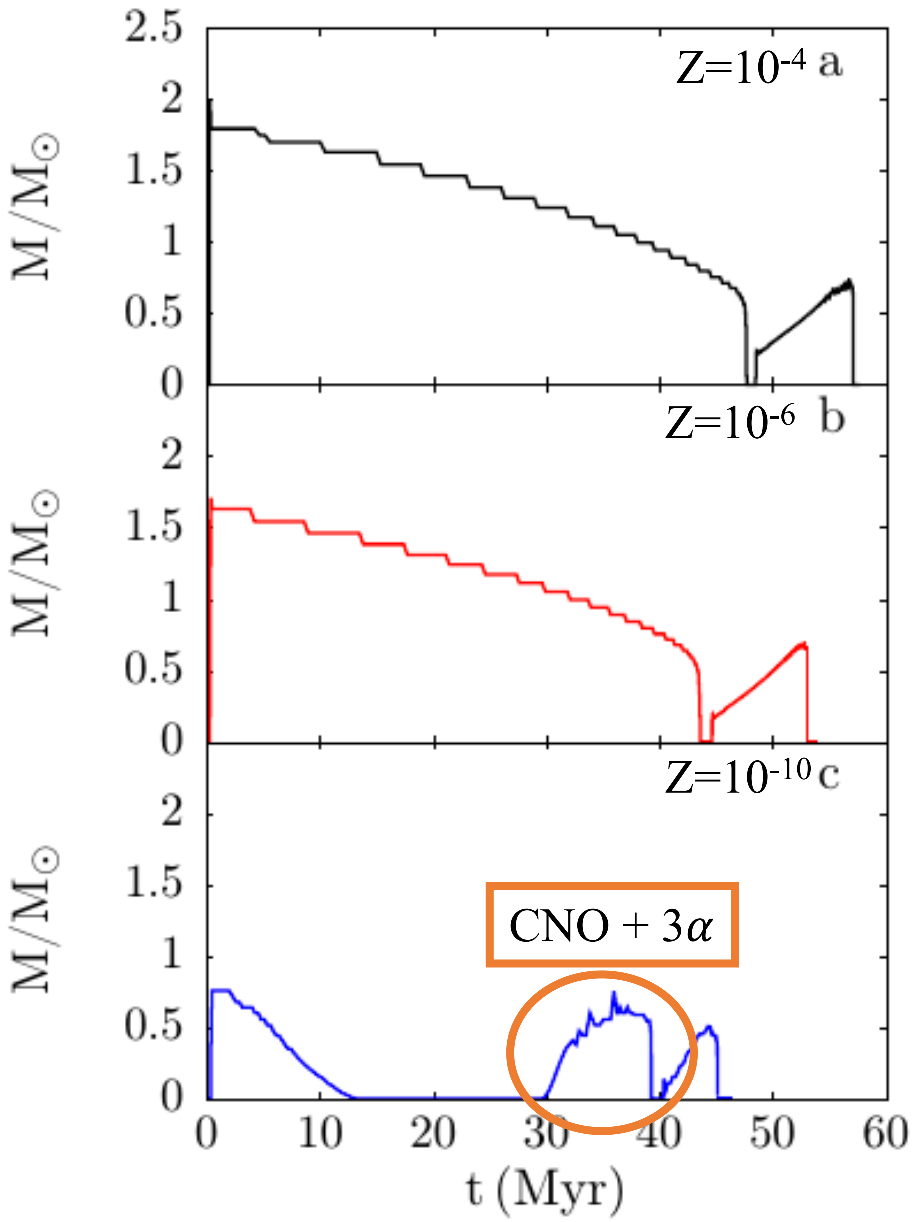

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- When CNO central abundance reaches $\approx 2\times10^{-10}$, CNO cycle is activated and a second convective episode appears ➡ CNO + 3α

$M = 6\ M_\odot$, different Z

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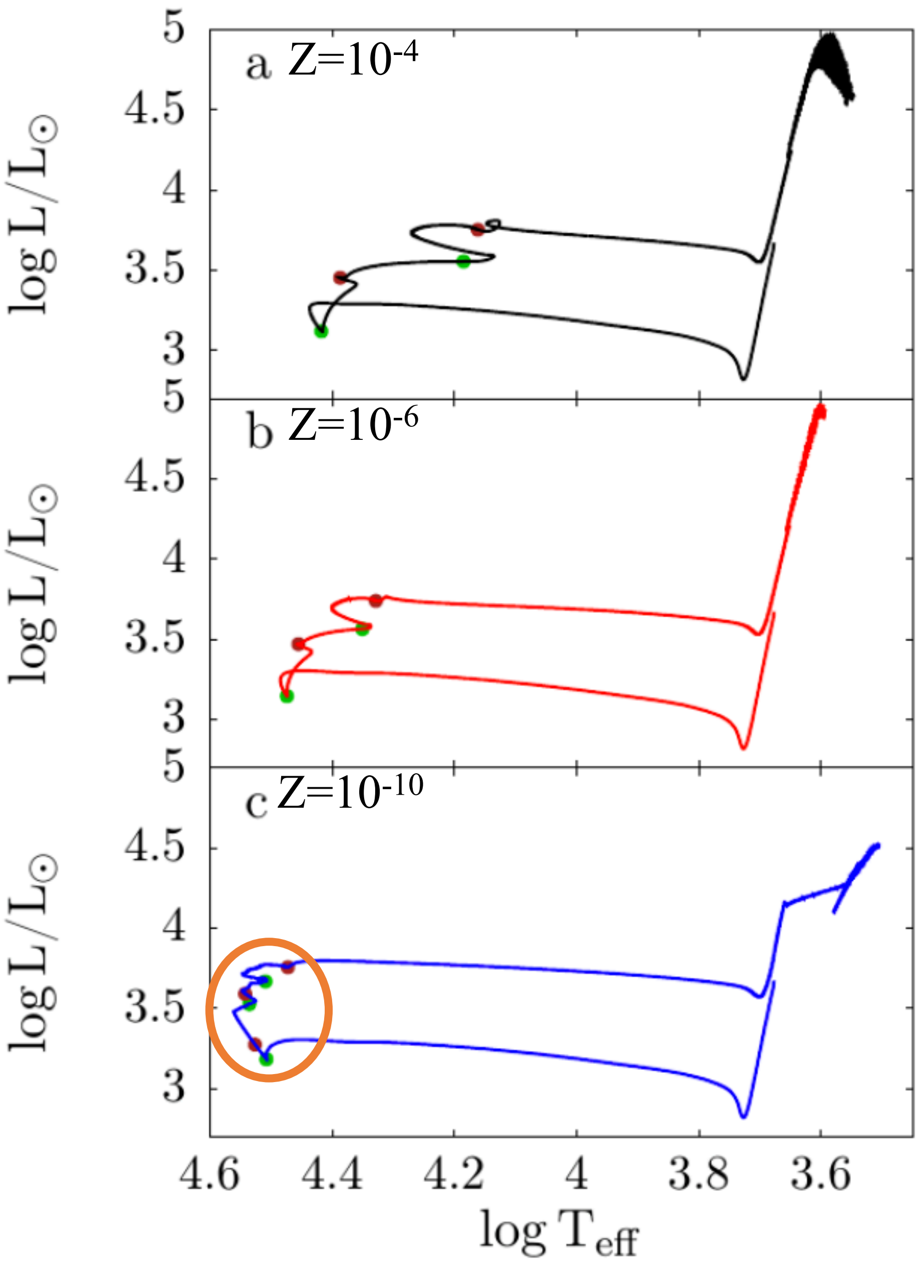

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- The star contracts until it reaches $T \approx 10^8$ K and 3α reactions take place producing ^{12}C
- When CNO central abundance reaches $\approx 2\times10^{-10}$, CNO cycle is activated and a second convective episode appears ➡ CNO + 3α
- This leaves a footprint in the HR diagram

$M = 6\ M_\odot$, different Z

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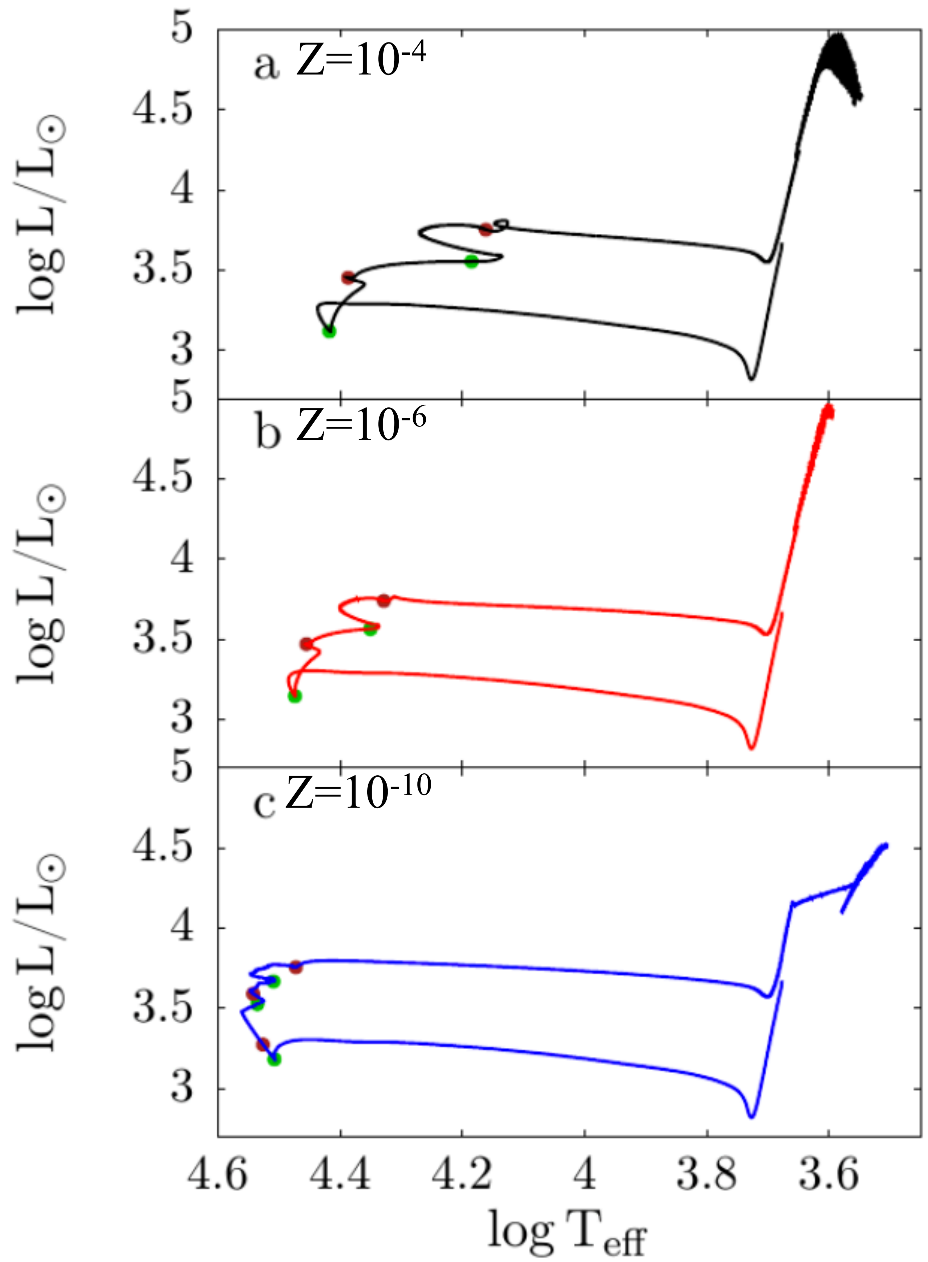

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- Metal-poor stars are hotter than metal-rich stars

$M = 6\ M_\odot$, different Z

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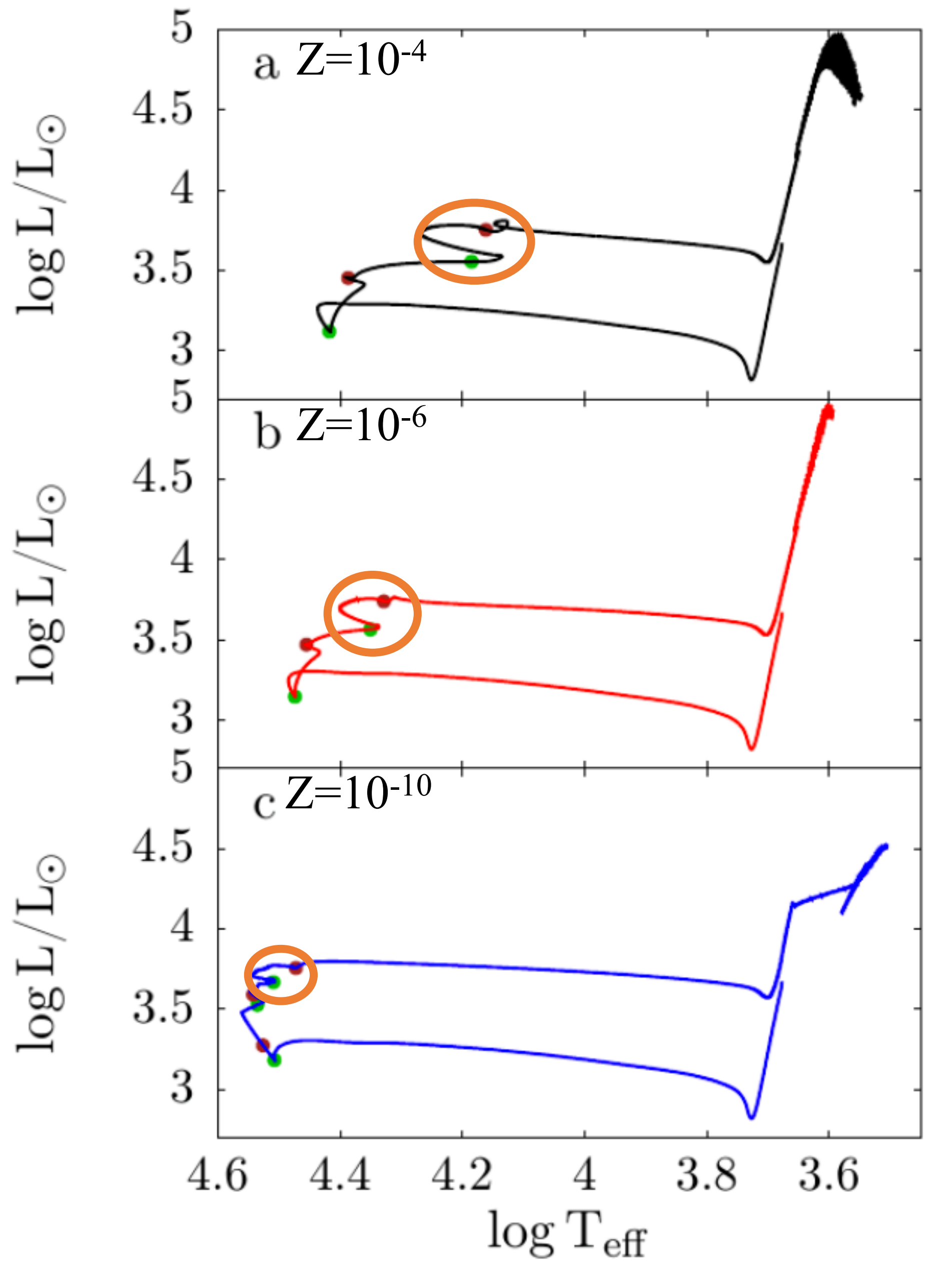

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- When CNO central abundance reaches $\approx 2\times10^{-10}$, CNO cycle is activated and a second convective episode appears ➡ CNO + 3α
- This leaves a footprint in the HR diagram
- Metal-poor stars are hotter than metal-rich stars ➡ He burning in the blue part of the HR diagram

Cirillo, M.; Piersanti, L.; Straniero, O. *Extremely Metal-Poor Asymptotic Giant Branch Stars*, Universe 2022, 8, 44

M = 6 $M_\odot$, different Z: SDU

M = 6 $M_\odot$, different Z: SDU

Cirillo, M.; Piersanti, L.; Straniero, O. *Extremely Metal-Poor Asymptotic Giant Branch Stars*, Universe 2022, 8, 44

	$Z = 10^{-4}$		$Z = 10^{-6}$		$Z = 10^{-10}$	
	Before	**After**	**Before**	**After**	**Before**	**After**
H	7.50×10^{-1}	6.51×10^{-1}	7.50×10^{-1}	6.50×10^{-1}	7.50×10^{-1}	6.14×10^{-1}
^{4}He	2.50×10^{-1}	3.49×10^{-1}	2.50×10^{-1}	3.50×10^{-1}	2.50×10^{-1}	3.86×10^{-1}
^{12}C	1.74×10^{-5}	8.21×10^{-6}	1.74×10^{-7}	5.35×10^{-7}	1.74×10^{-11}	8.78×10^{-8}
^{13}C	1.97×10^{-7}	3.66×10^{-7}	1.97×10^{-9}	2.58×10^{-9}	1.97×10^{-13}	1.29×10^{-12}
^{14}N	4.90×10^{-6}	2.69×10^{-5}	4.90×10^{-8}	3.87×10^{-7}	4.90×10^{-12}	1.45×10^{-9}
^{16}O	4.25×10^{-5}	3.19×10^{-5}	4.25×10^{-7}	2.19×10^{-7}	4.25×10^{-11}	1.81×10^{-10}
CNO	4.46×10^{-6}	4.60×10^{-6}	4.46×10^{-8}	8.59×10^{-8}	4.46×10^{-12}	7.43×10^{-9}

$M = 6\ M_{\odot}$, different Z: SDU

Cirillo, M.; Piersanti, L.; Straniero, O. *Extremely Metal-Poor Asymptotic Giant Branch Stars*, Universe 2022, 8, 44

	$Z = 10^{-4}$		$Z = 10^{-6}$		$Z = 10^{-10}$	
	Before	**After**	**Before**	**After**	**Before**	**After**
H	7.50×10^{-1}	6.51×10^{-1}	7.50×10^{-1}	6.50×10^{-1}	7.50×10^{-1}	6.14×10^{-1}
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CNO	4.46×10^{-6}	4.60×10^{-6}	4.46×10^{-8}	8.59×10^{-8}	4.46×10^{-12}	7.43×10^{-9}

- In the $Z = 10^{-4}$ model, the surface abundances of ^{12}C and ^{16}O decrease, while those of ^{13}C and ^{14}N increase, but the total number of C+N+O nuclei is almost conserved

$M = 6\,M_\odot$, different Z: SDU

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	$Z = 10^{-4}$		$Z = 10^{-6}$		$Z = 10^{-10}$	
	Before	After	Before	After	Before	After
H	7.50×10^{-1}	6.51×10^{-1}	7.50×10^{-1}	6.50×10^{-1}	7.50×10^{-1}	6.14×10^{-1}
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- In the $Z = 10^{-6}$ model, the surface abundance of ^{12}C increases after the SDU

$M = 6\ M_\odot$, different Z: SDU

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	$Z = 10^{-4}$		$Z = 10^{-6}$		$Z = 10^{-10}$	
	Before	**After**	**Before**	**After**	**Before**	**After**
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- In the $Z = 10^{-6}$ model, the surface abundance of ^{12}C increases after the SDU ➡ **new phenomenon**!

$M = 6\ M_{\odot}$, different Z: SDU

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	$Z = 10^{-4}$		$Z = 10^{-6}$		$Z = 10^{-10}$	
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- In the $Z = 10^{-10}$ model, all the surface abundances of the CNO isotopes increase after the SDU (^{12}C mass fraction becomes ≈ 5000 times higher after the SDU)

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- Enhancement of C+N+O in the envelope

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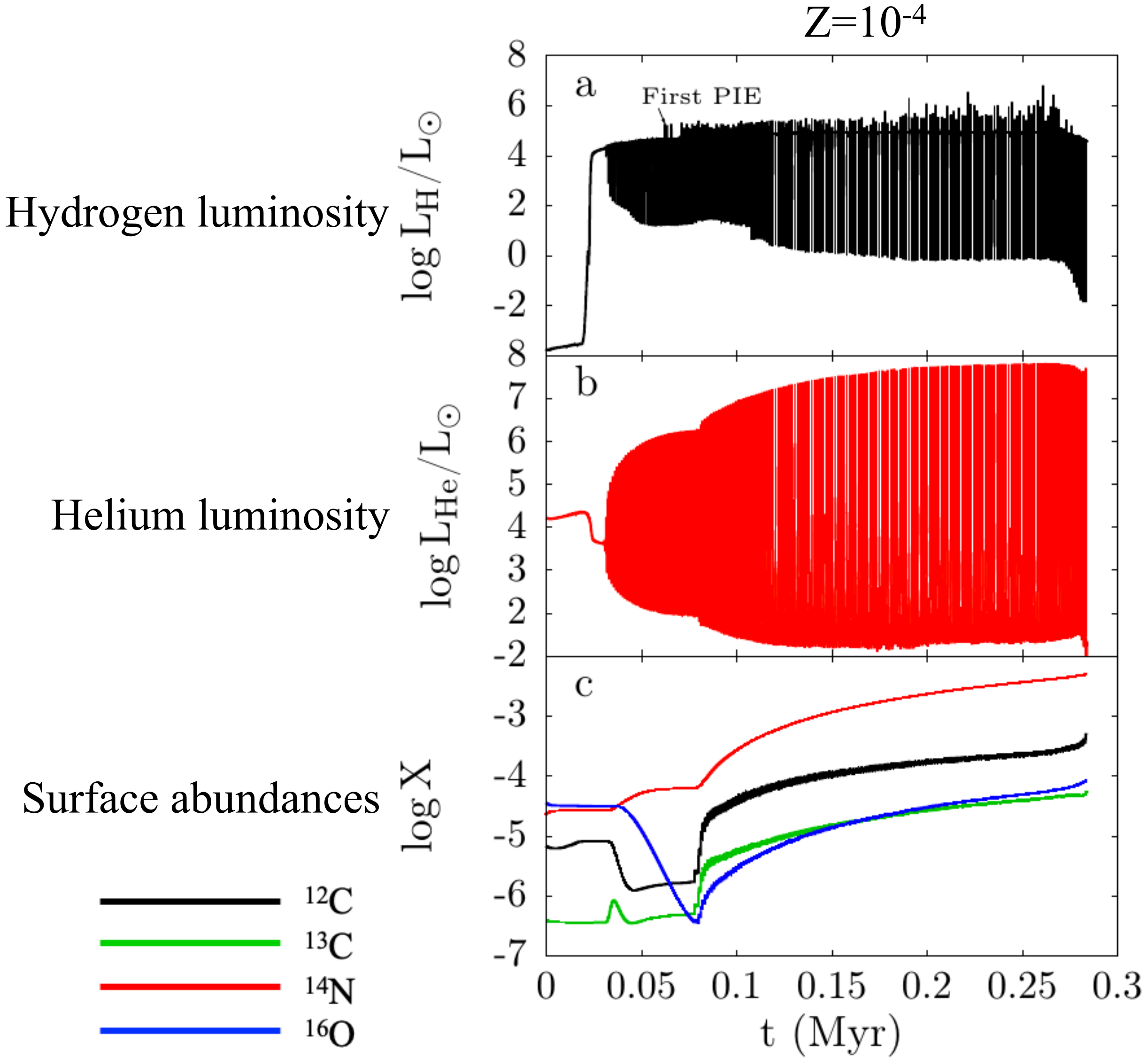
- This is a consequence of the coexistence of core-H and He burning
- Enhancement of C+N+O in the envelope ➡ efficiency of the shell-H burning increases

M = 6 M$_\odot$, different Z: TP-AGB



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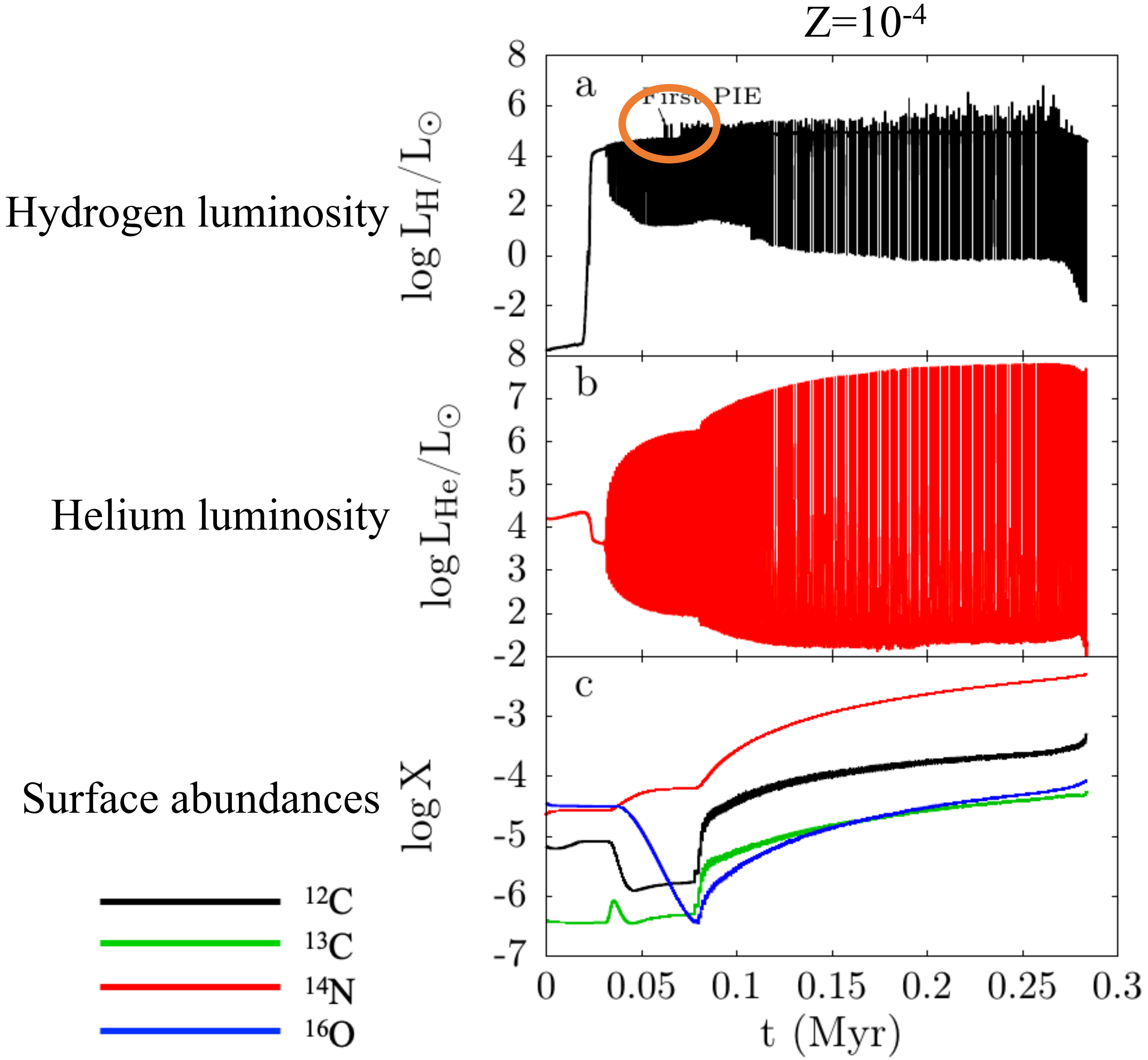
$M = 6\ M_\odot$, different Z: TP-AGB

- H-flash or PIE



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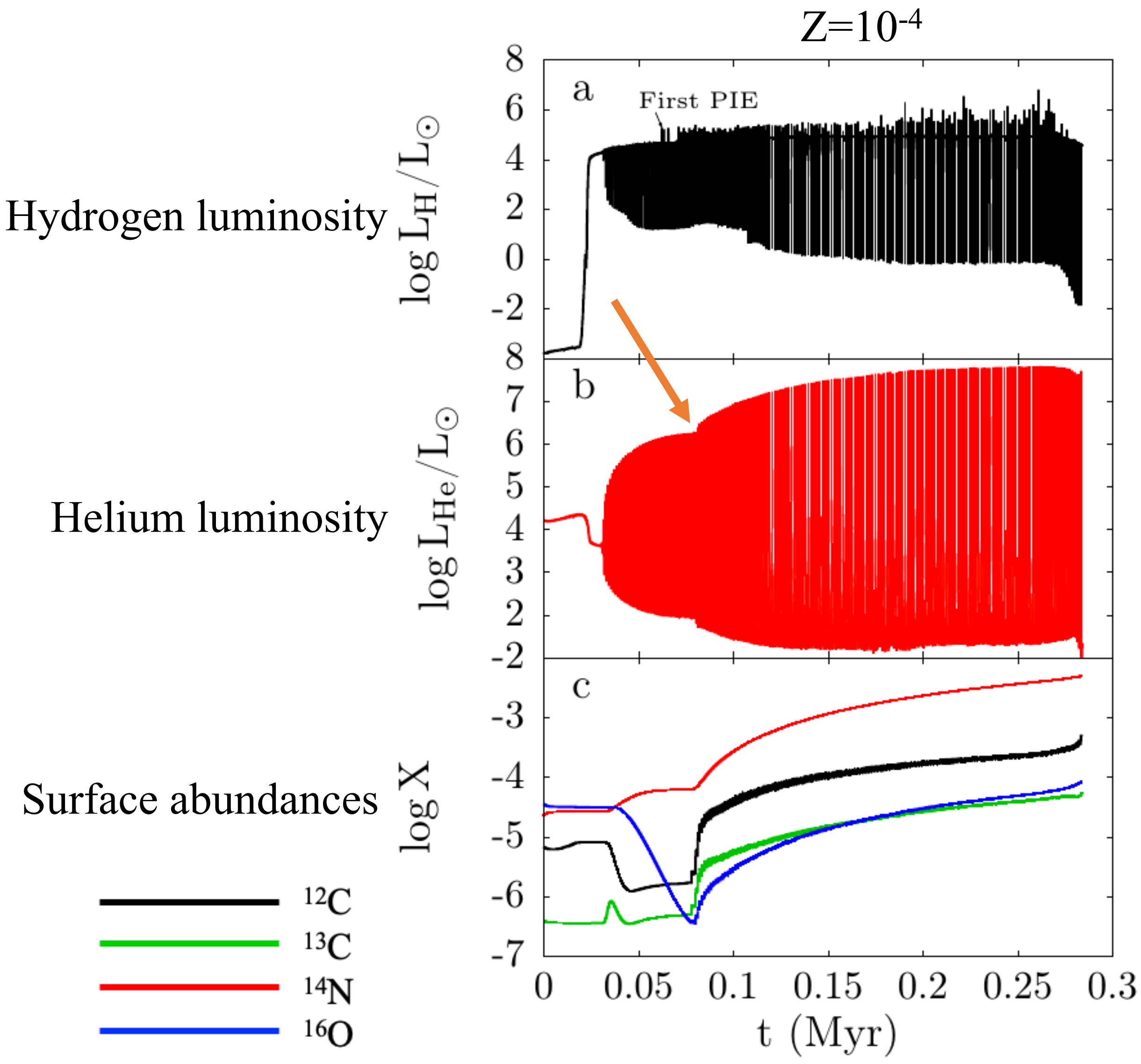
M = 6 $M_\odot$, different Z: TP-AGB

- H-flash or PIE
- The occurrence of the first PIE leads to stronger TPs (helium luminosity)



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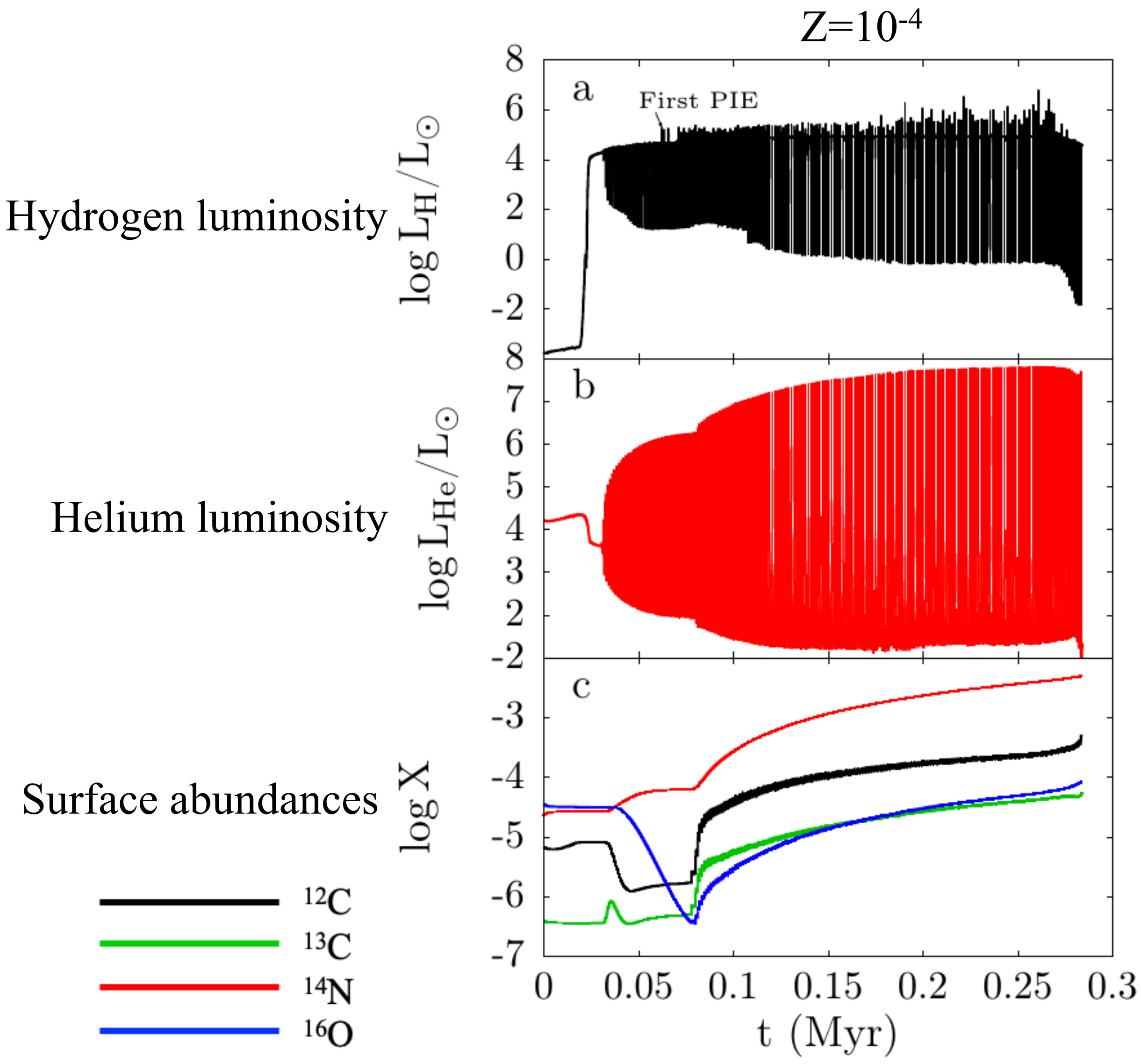
M = 6 $M_\odot$, different Z: TP-AGB

- H-flash or PIE
- The occurrence of the first PIE leads to stronger TPs (helium luminosity)
- The subsequent TPs are followed by TDUs



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$M = 6\ M_\odot$, different Z: TP-AGB

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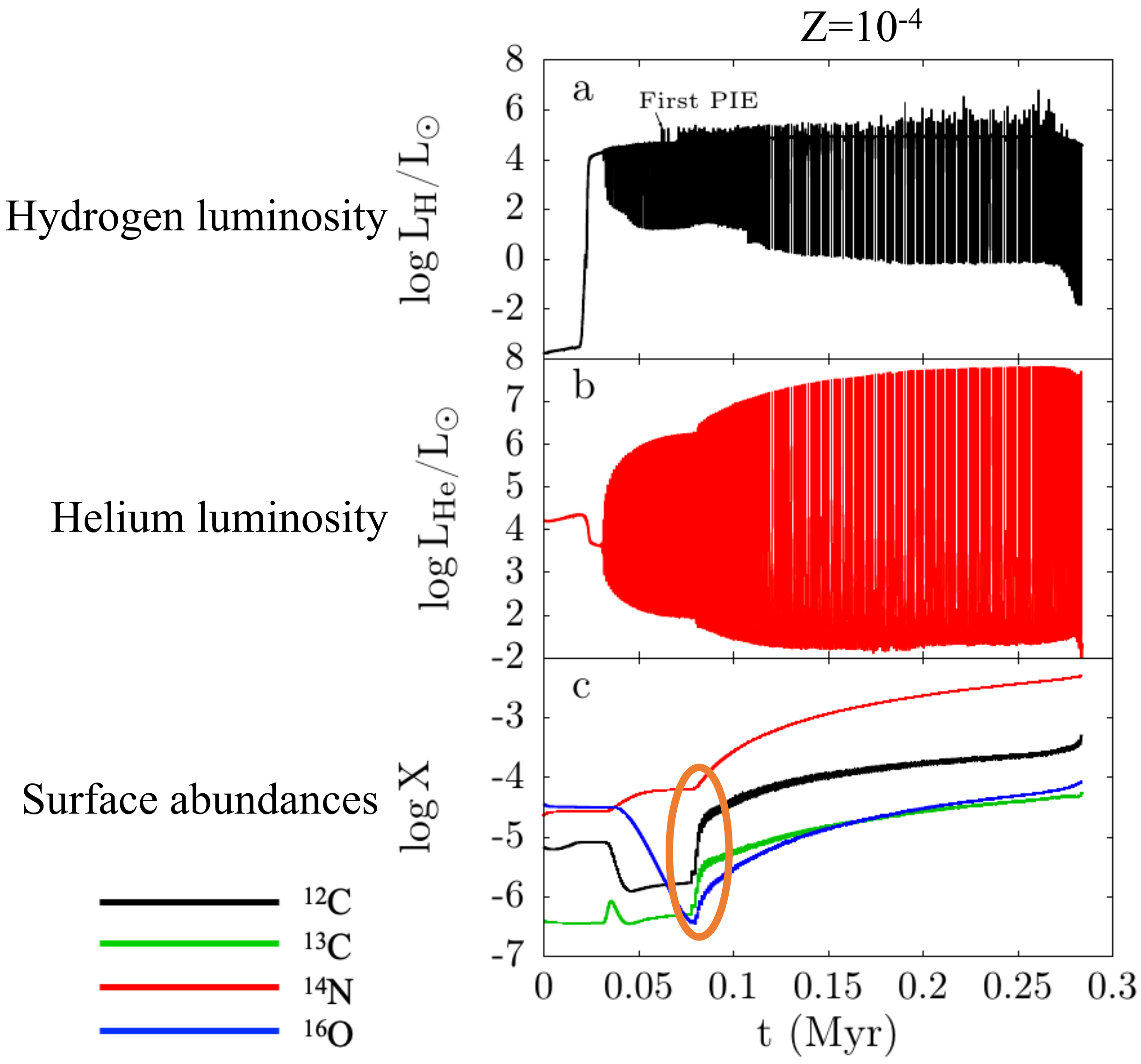
- The subsequent TPs are followed by TDUs ➡ surface enrichment in 3α and CNO products



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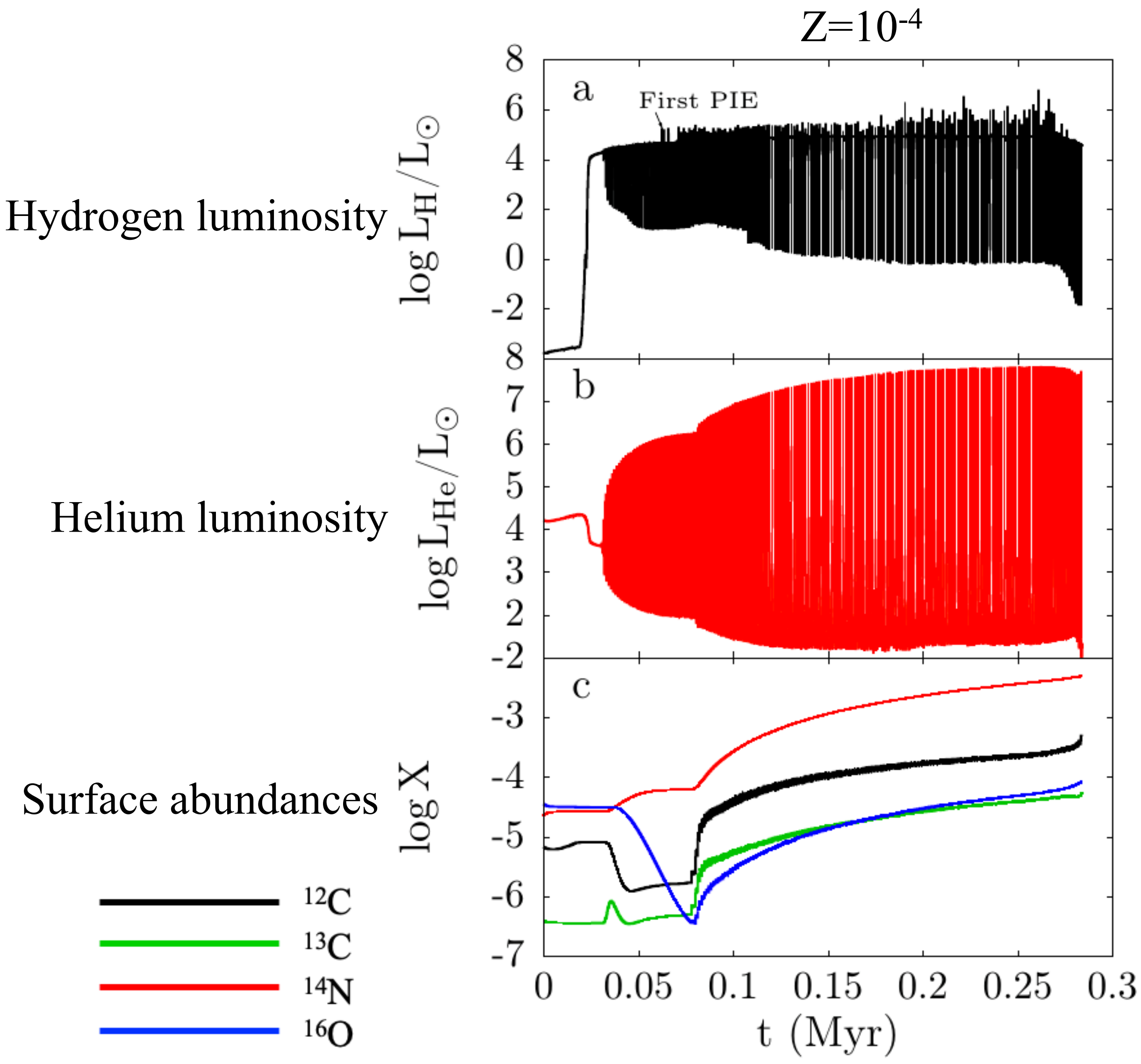
M = 6 $M_\odot$, different Z: TP-AGB

- H-flash or PIE
- The occurrence of the first PIE leads to stronger TPs (helium luminosity)
- The subsequent TPs are followed by TDUs ➡ surface enrichment in 3α and CNO products
- ^{12}C and $^{16}O \longrightarrow {}^{14}N$



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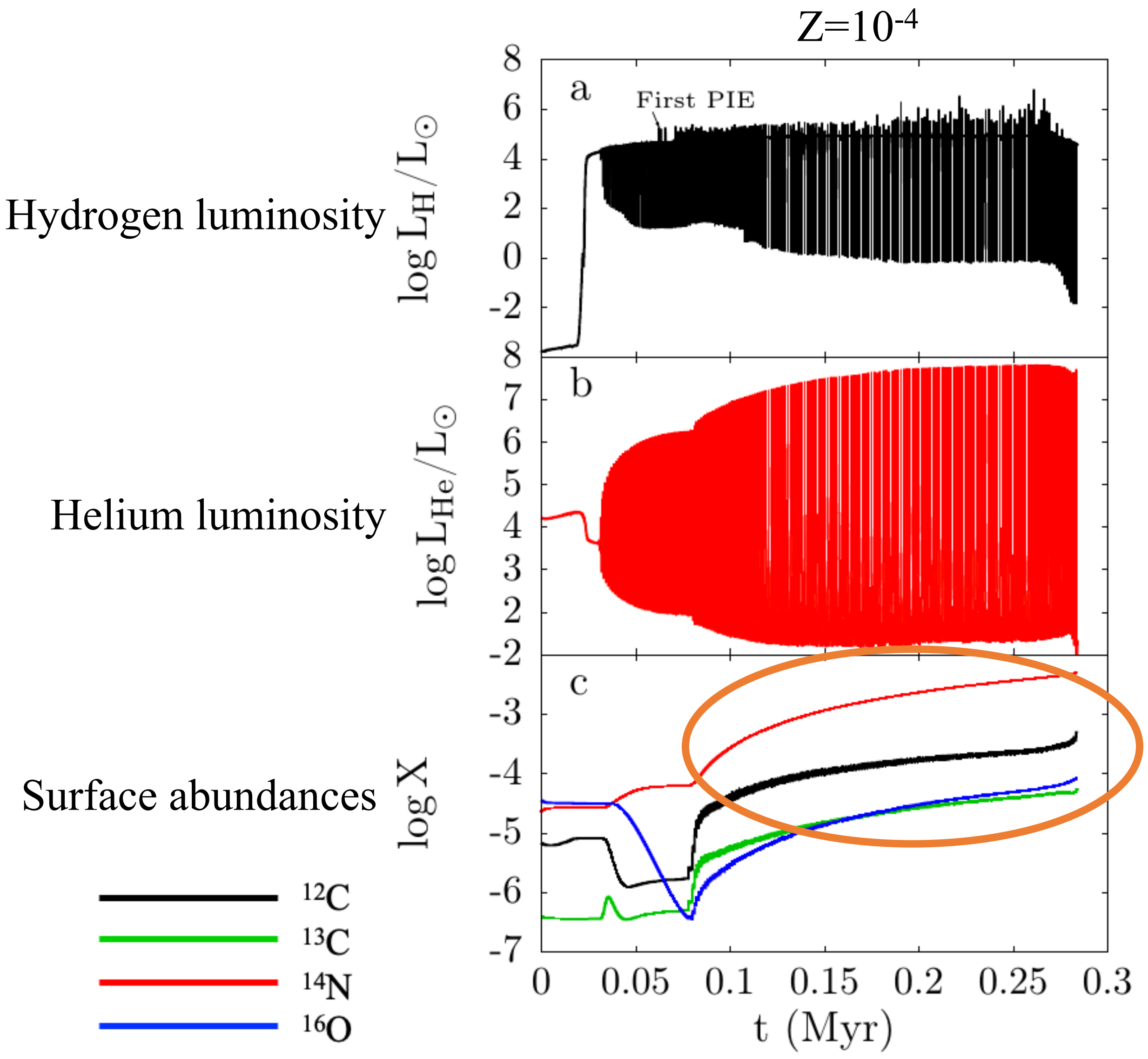
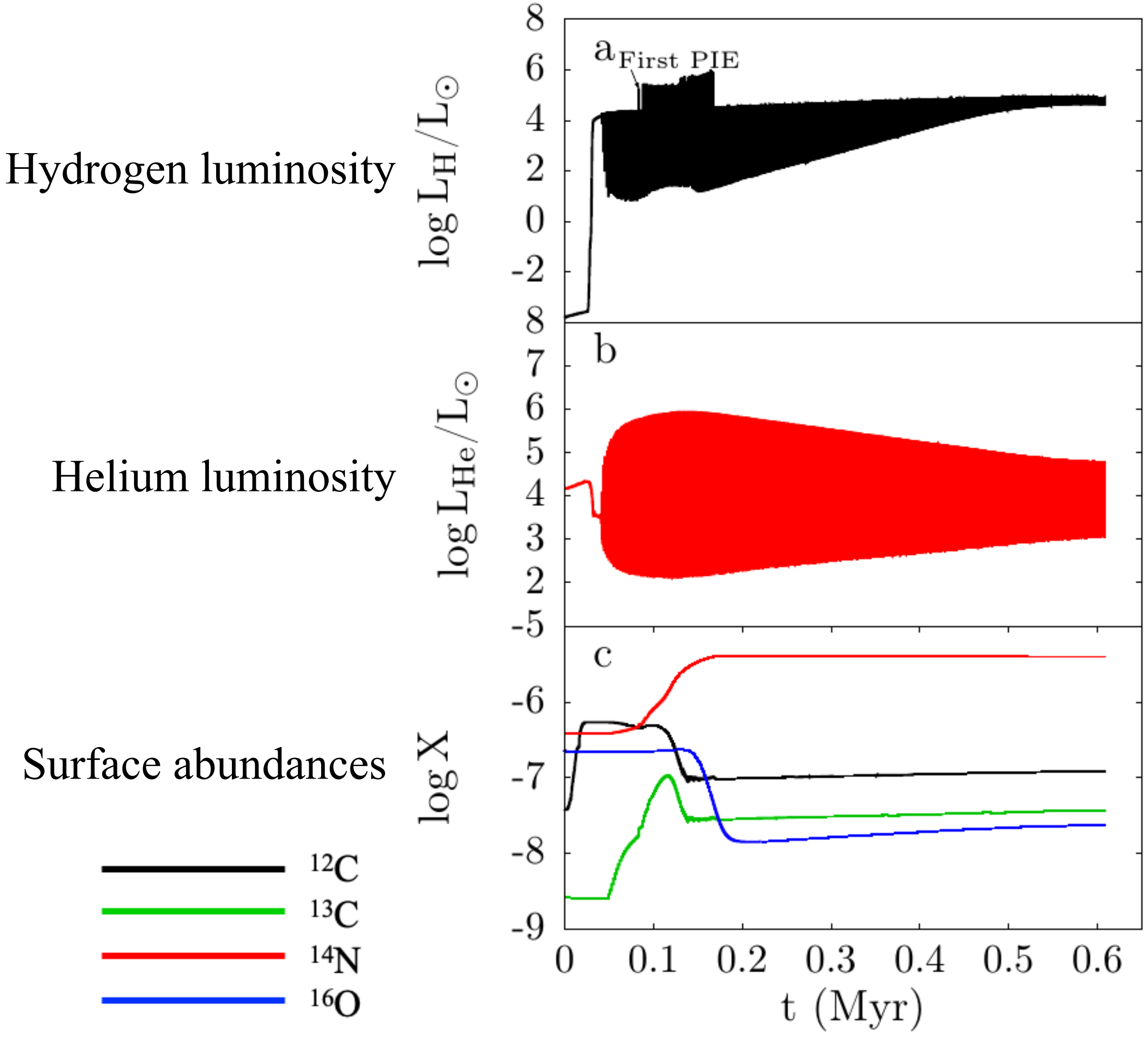
- The occurrence of the first PIE leads to stronger TPs (helium luminosity)
- The subsequent TPs are followed by TDUs ➡ surface enrichment in 3α and CNO products
- ^{12}C and $^{16}O \longrightarrow {}^{14}N$ ➡ HBB



Cirillo, M.; Piersanti, L.; Straniero, O. ***Extremely Metal-Poor Asymptotic Giant Branch Stars*****, Universe 2022, 8, 44**

M = 6 $M_\odot$, different Z: TP-AGB

Z=10^{-6}



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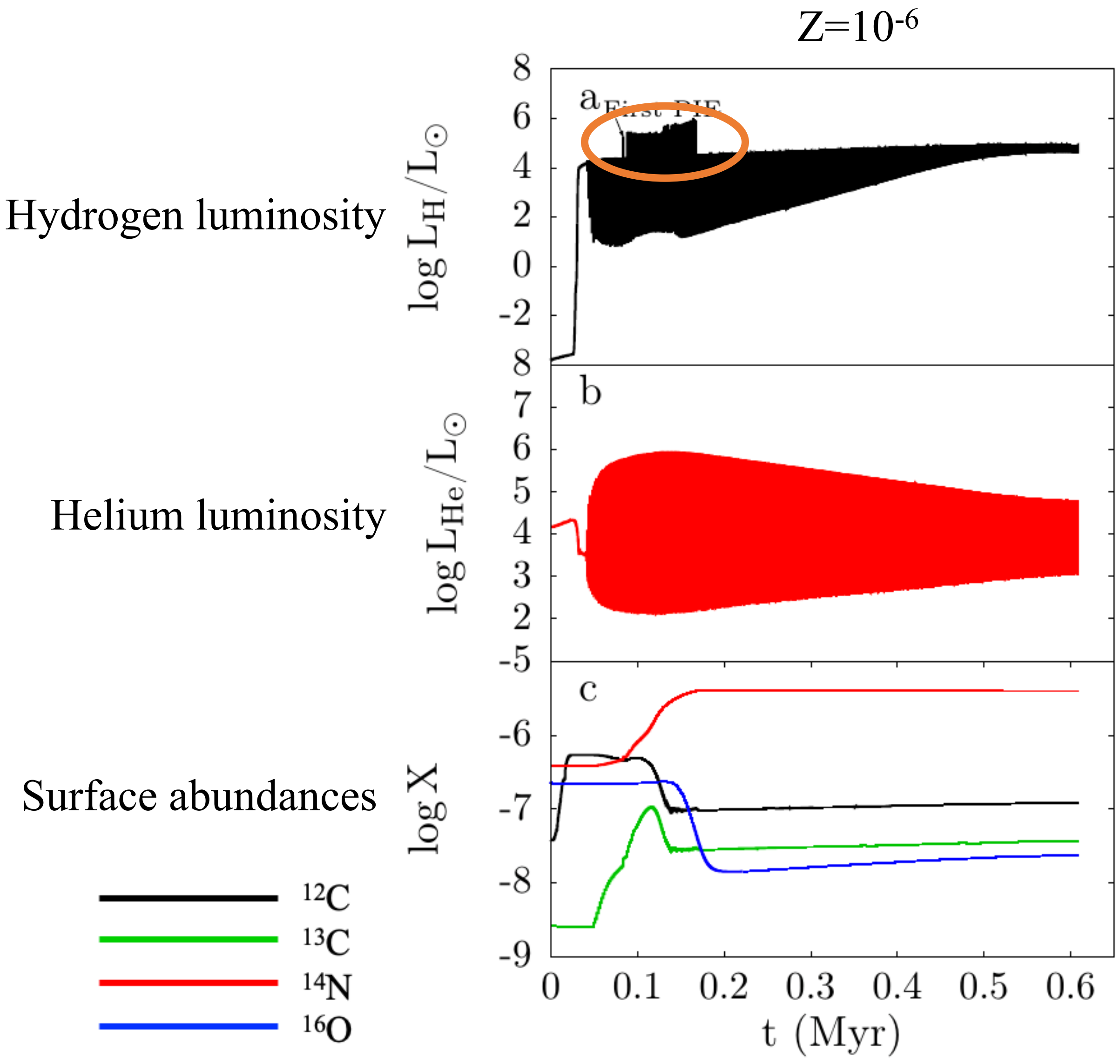

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- PIEs hampered by low metallicity
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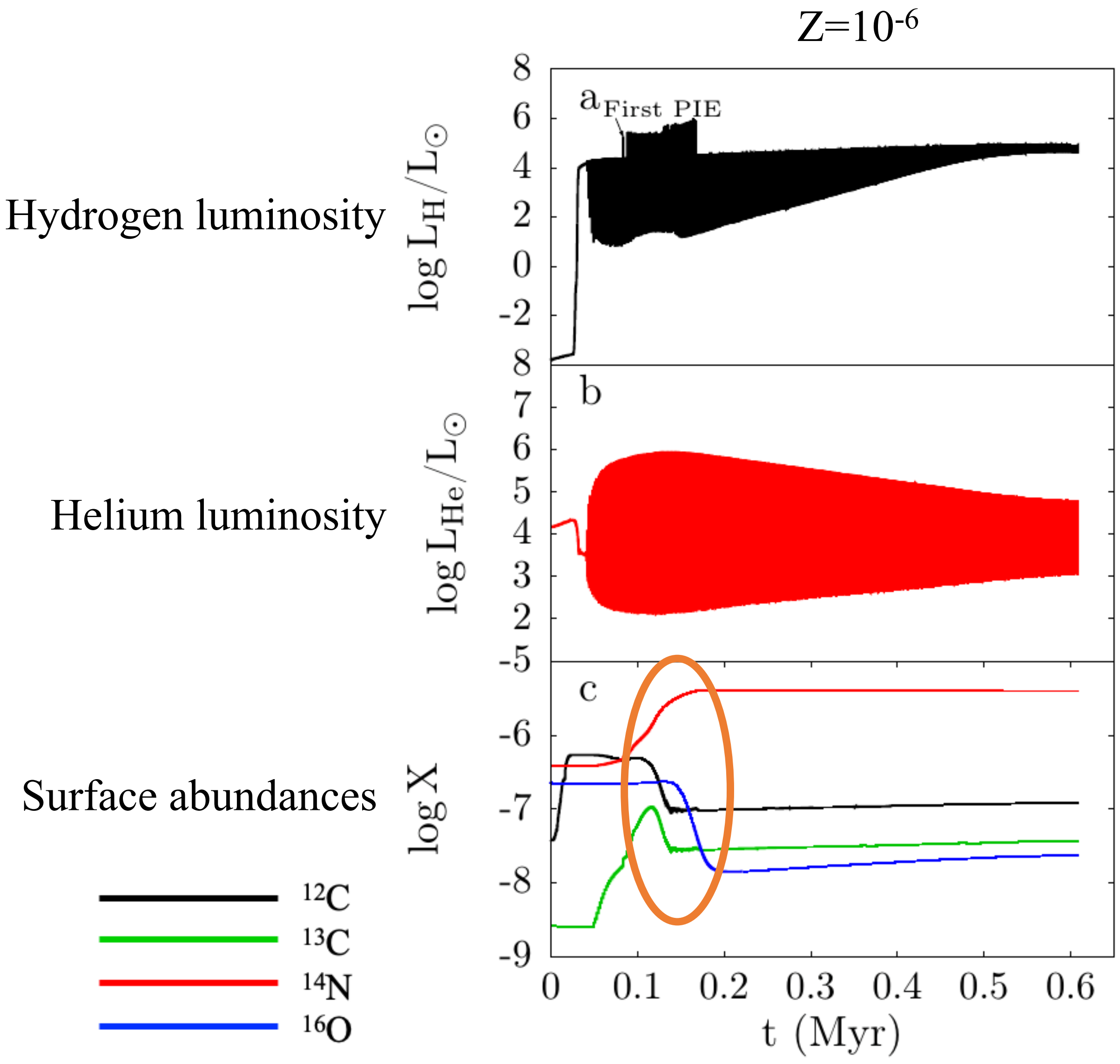

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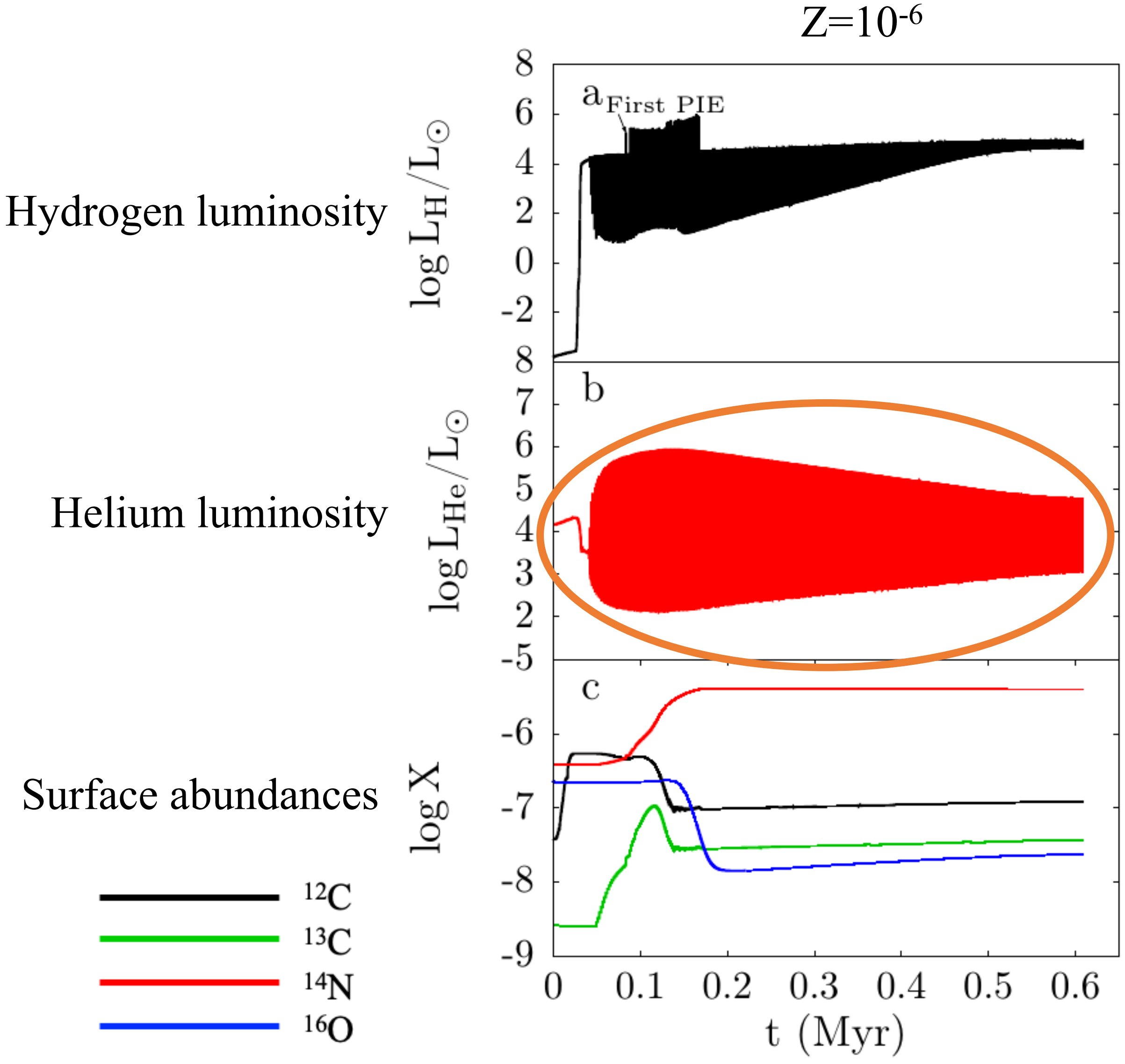

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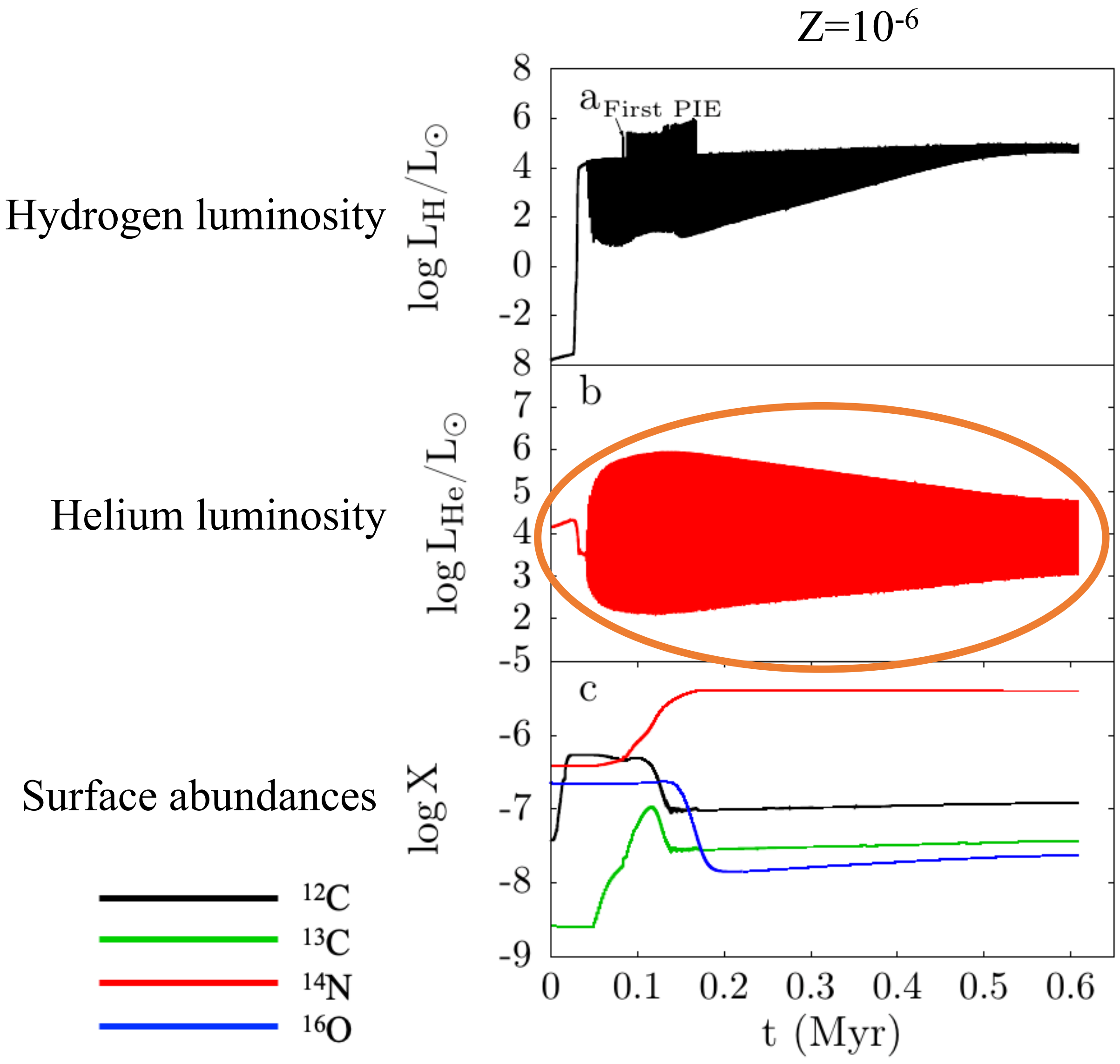

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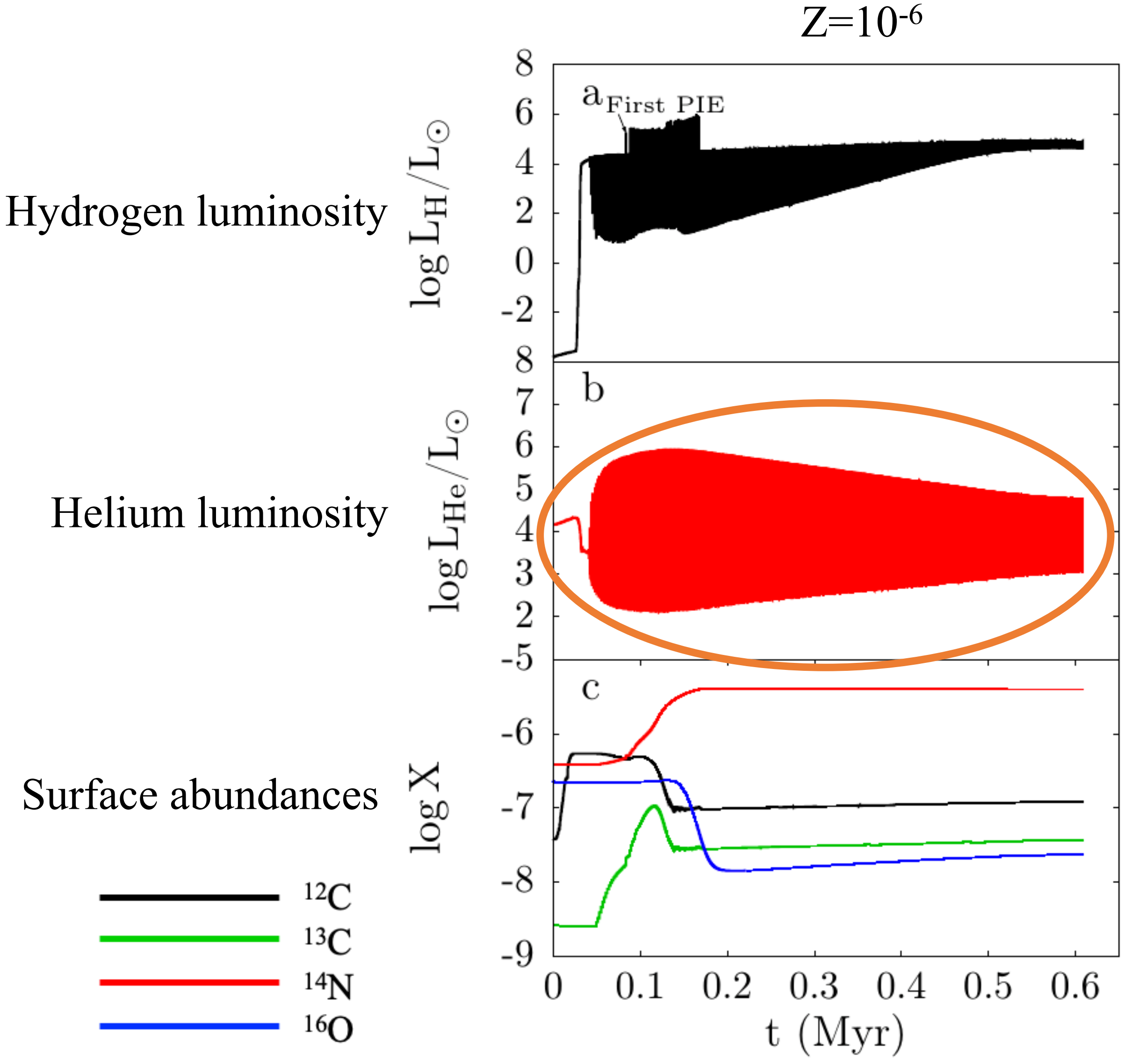

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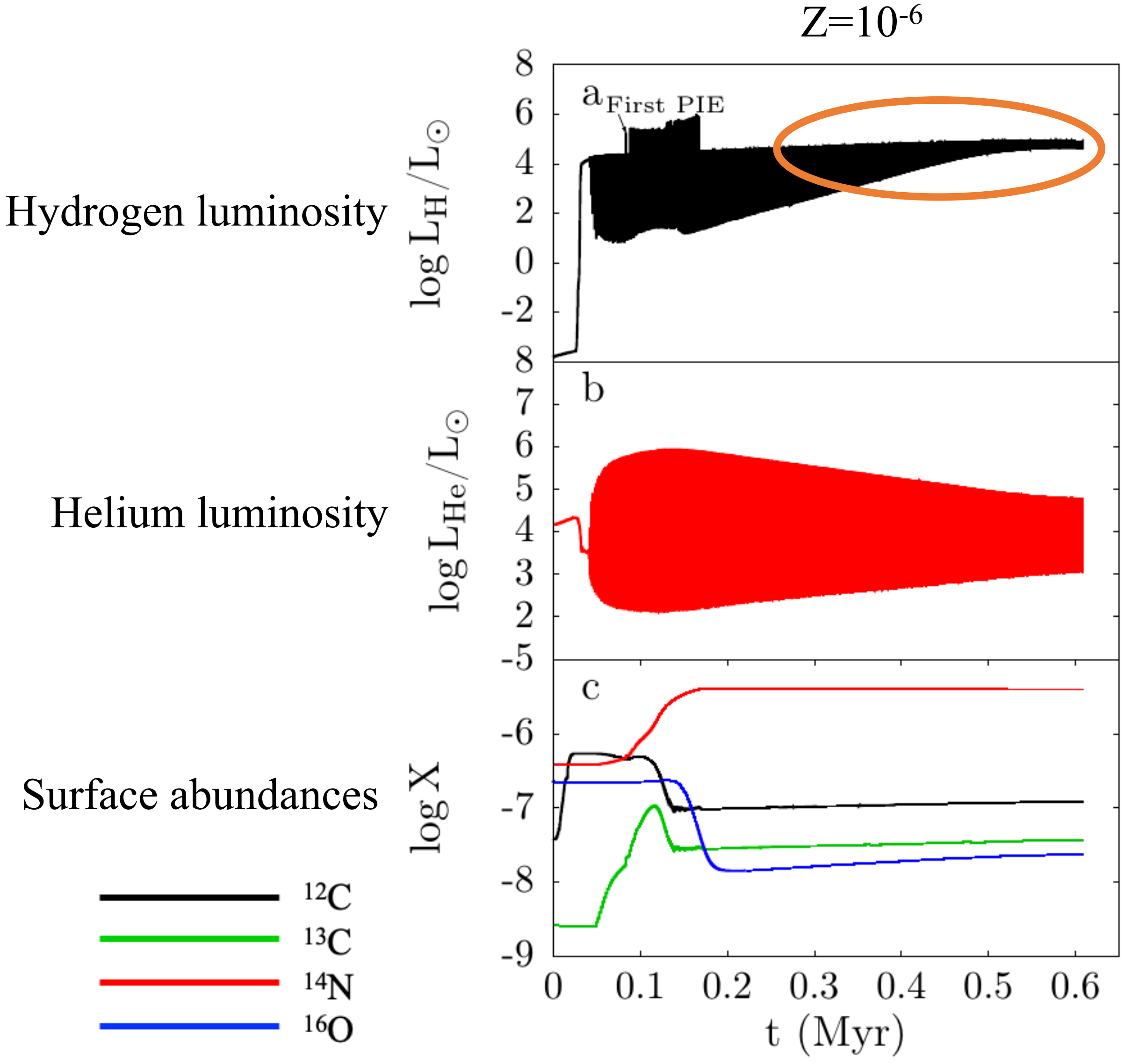

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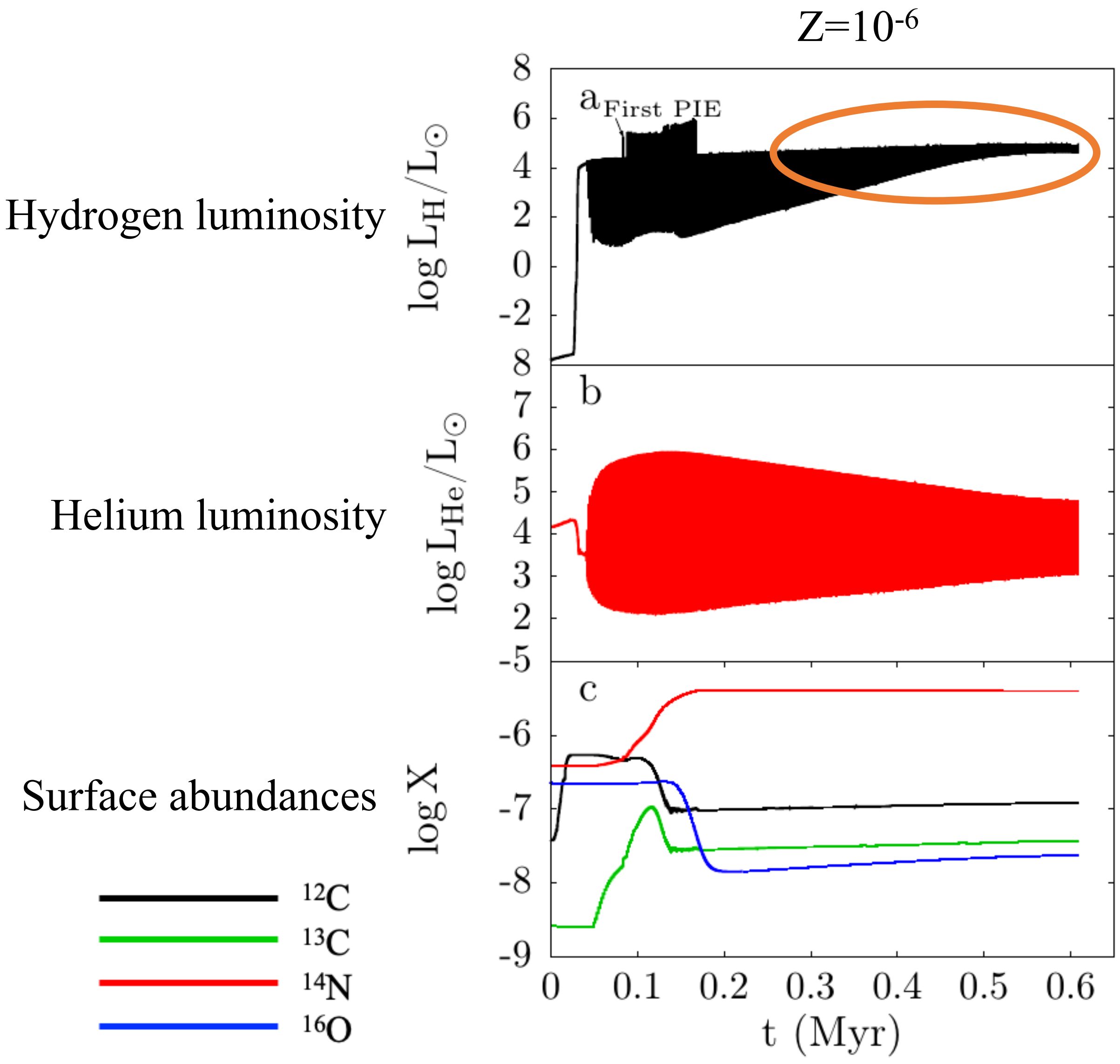

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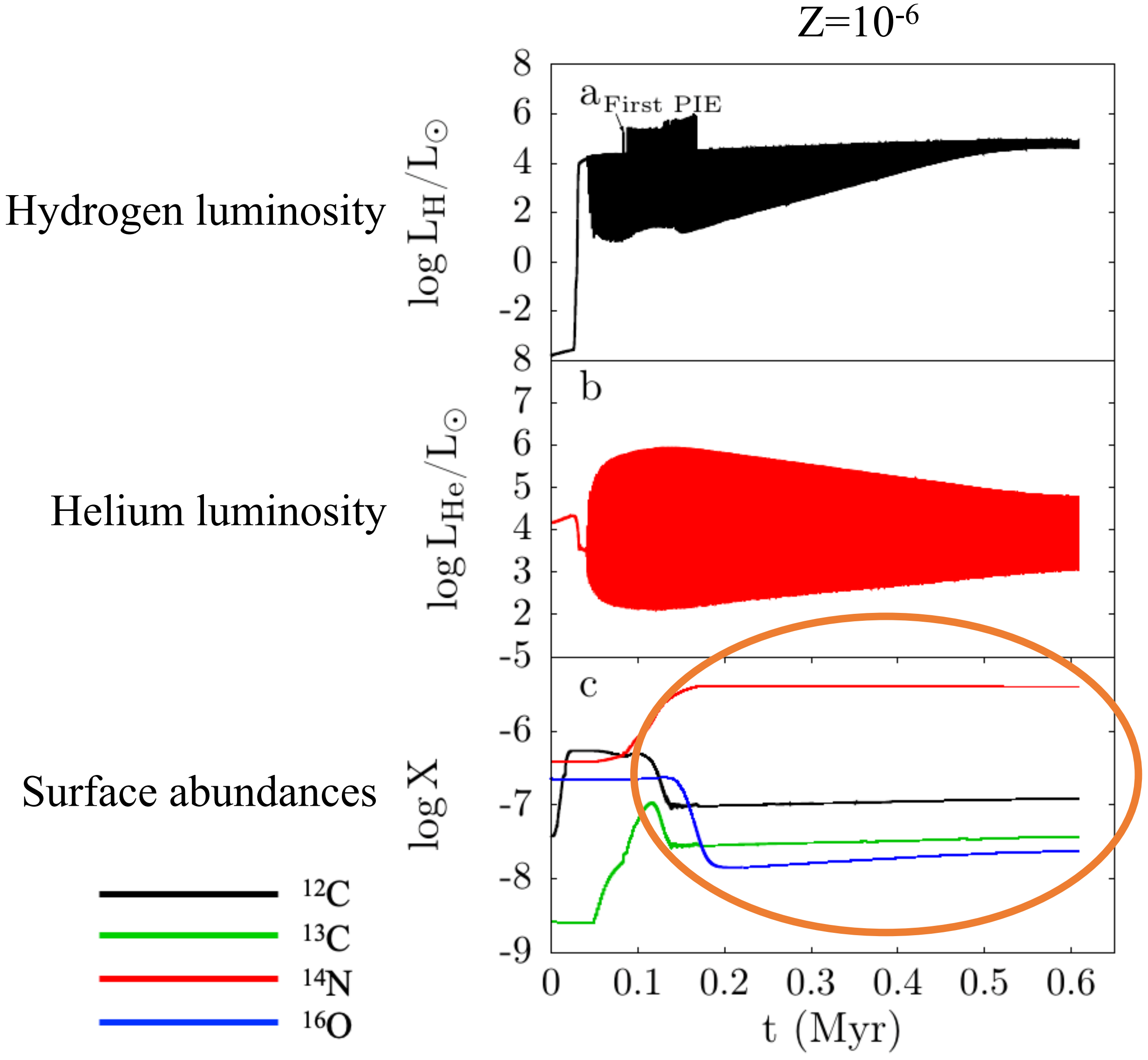
- Moderate HBB and CNO equilibrium



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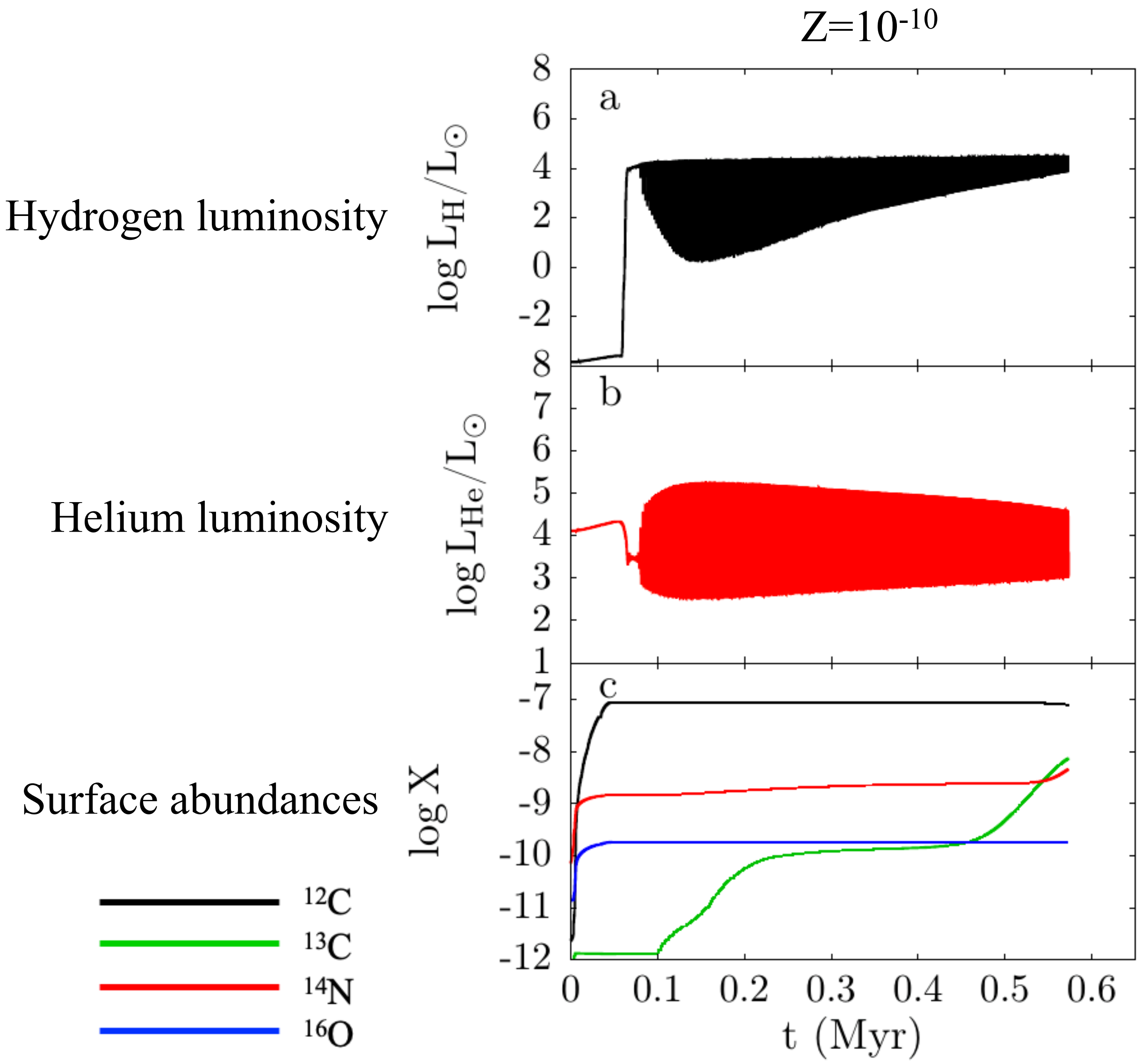

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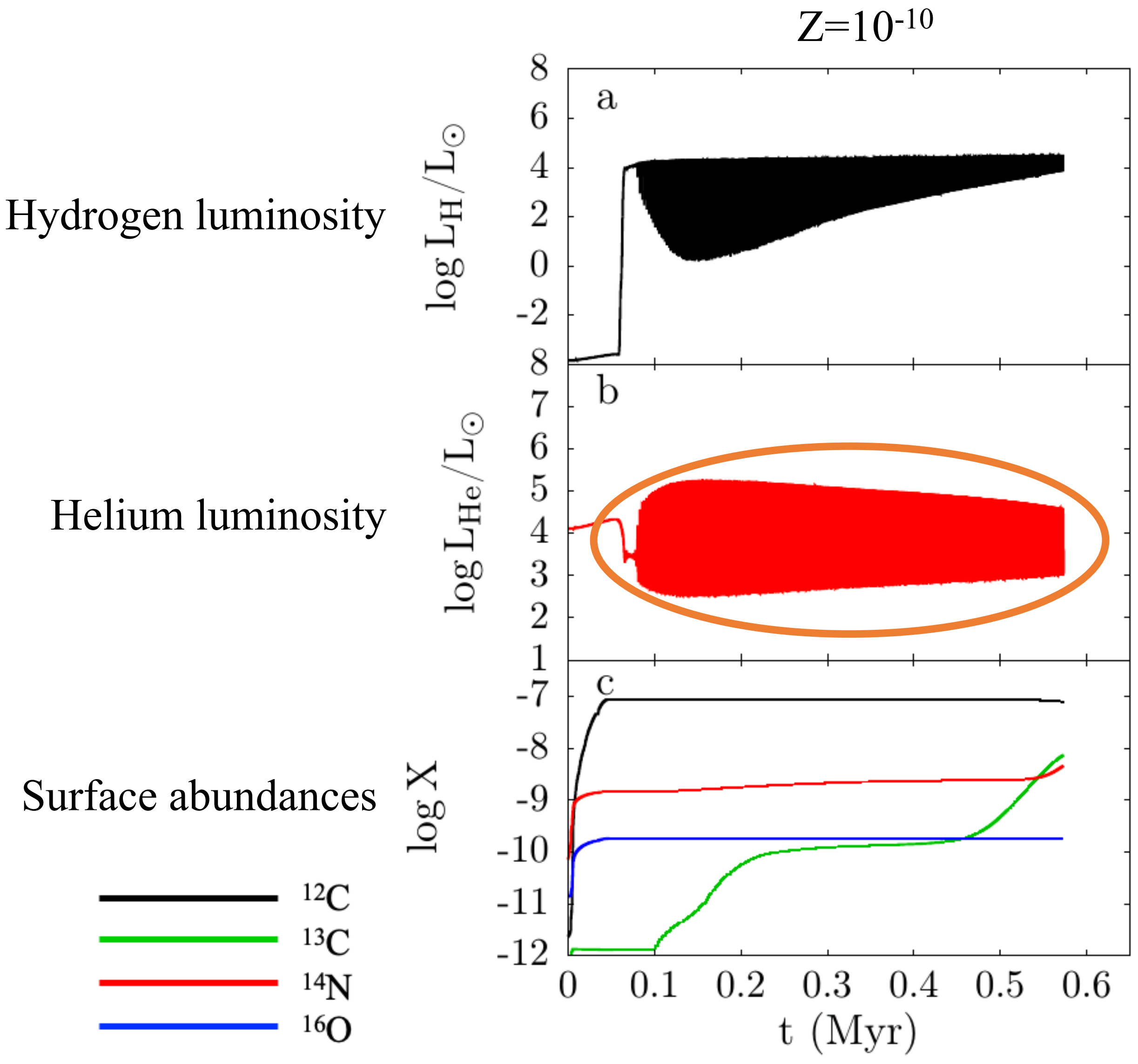

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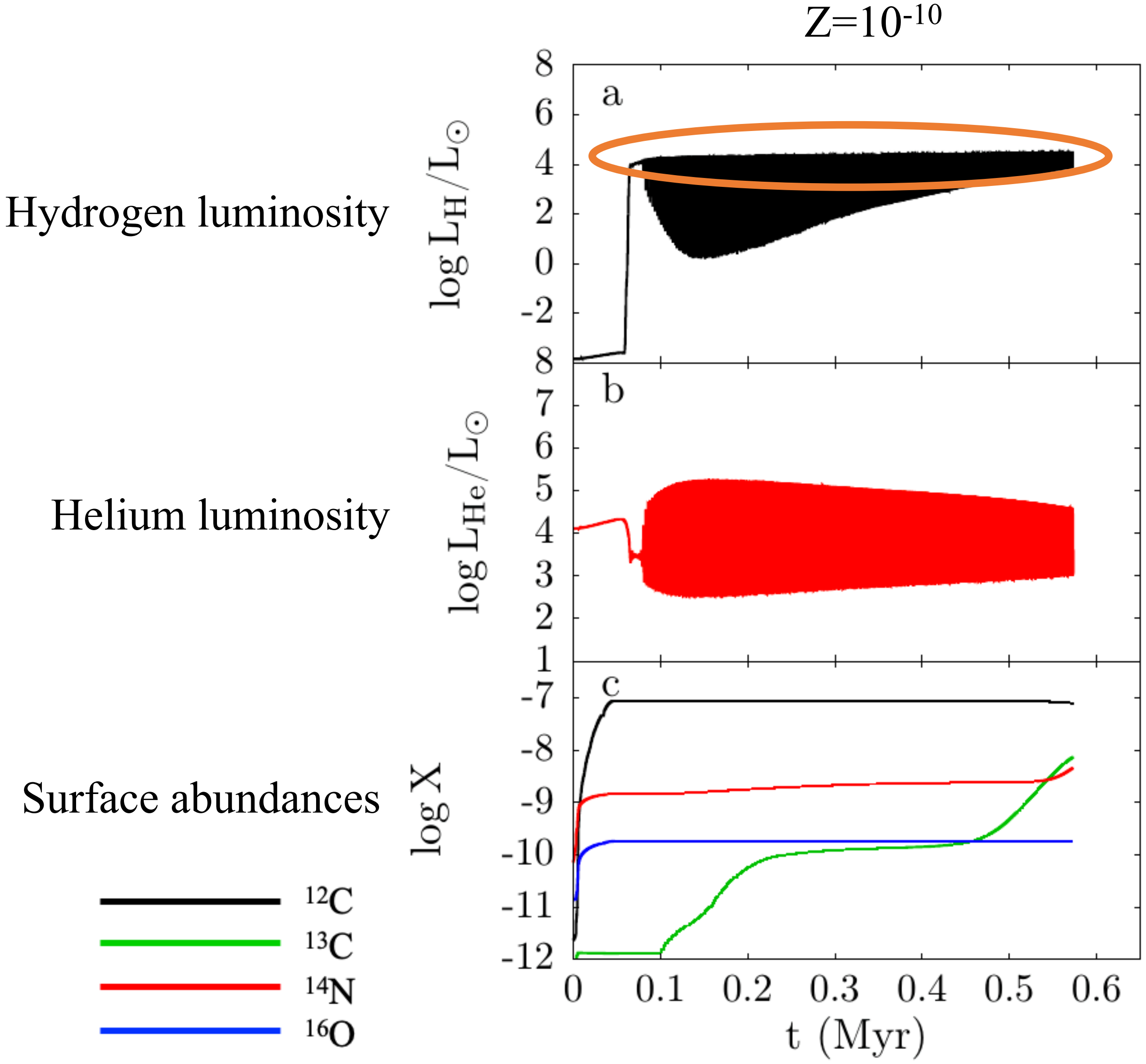

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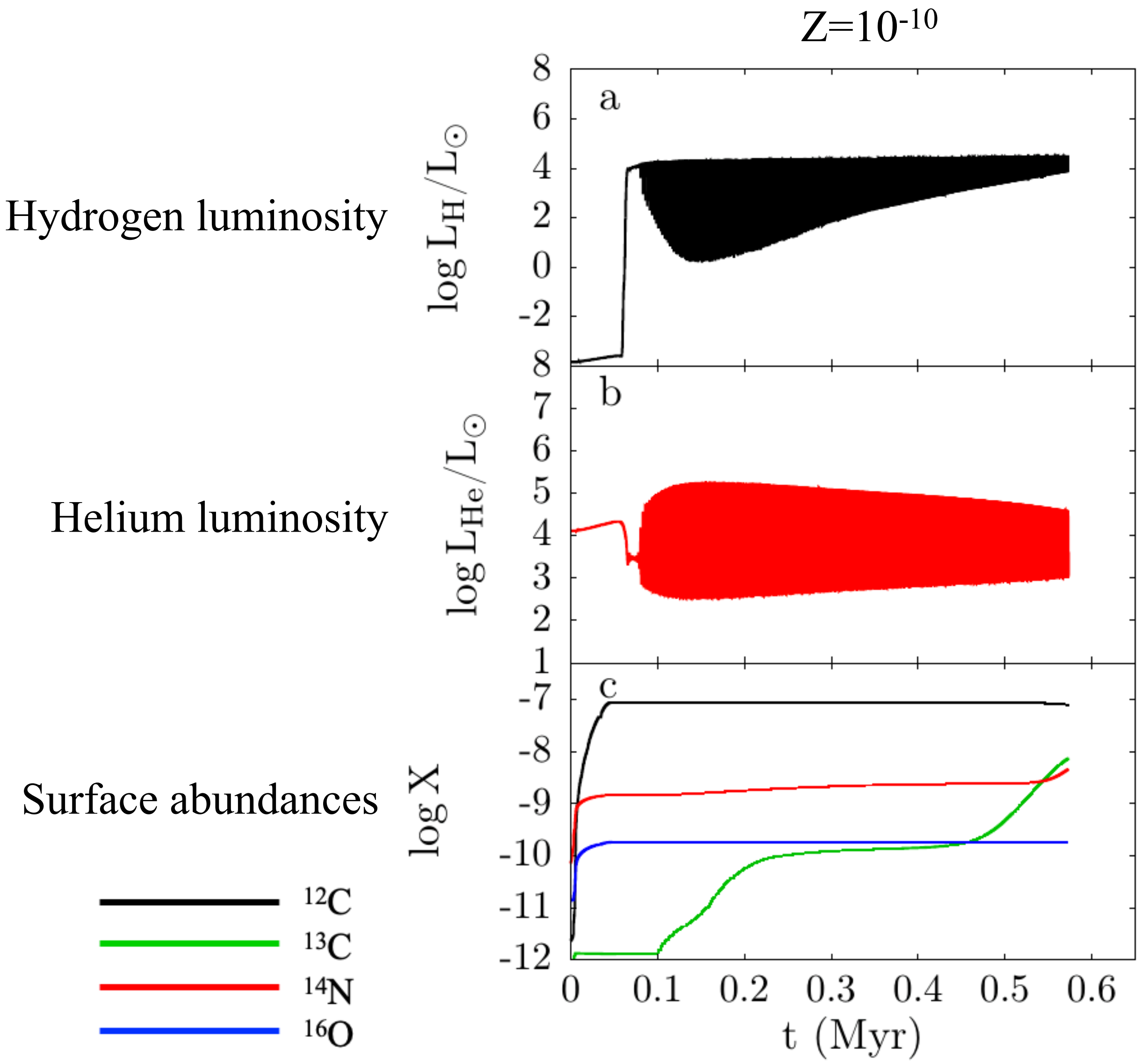

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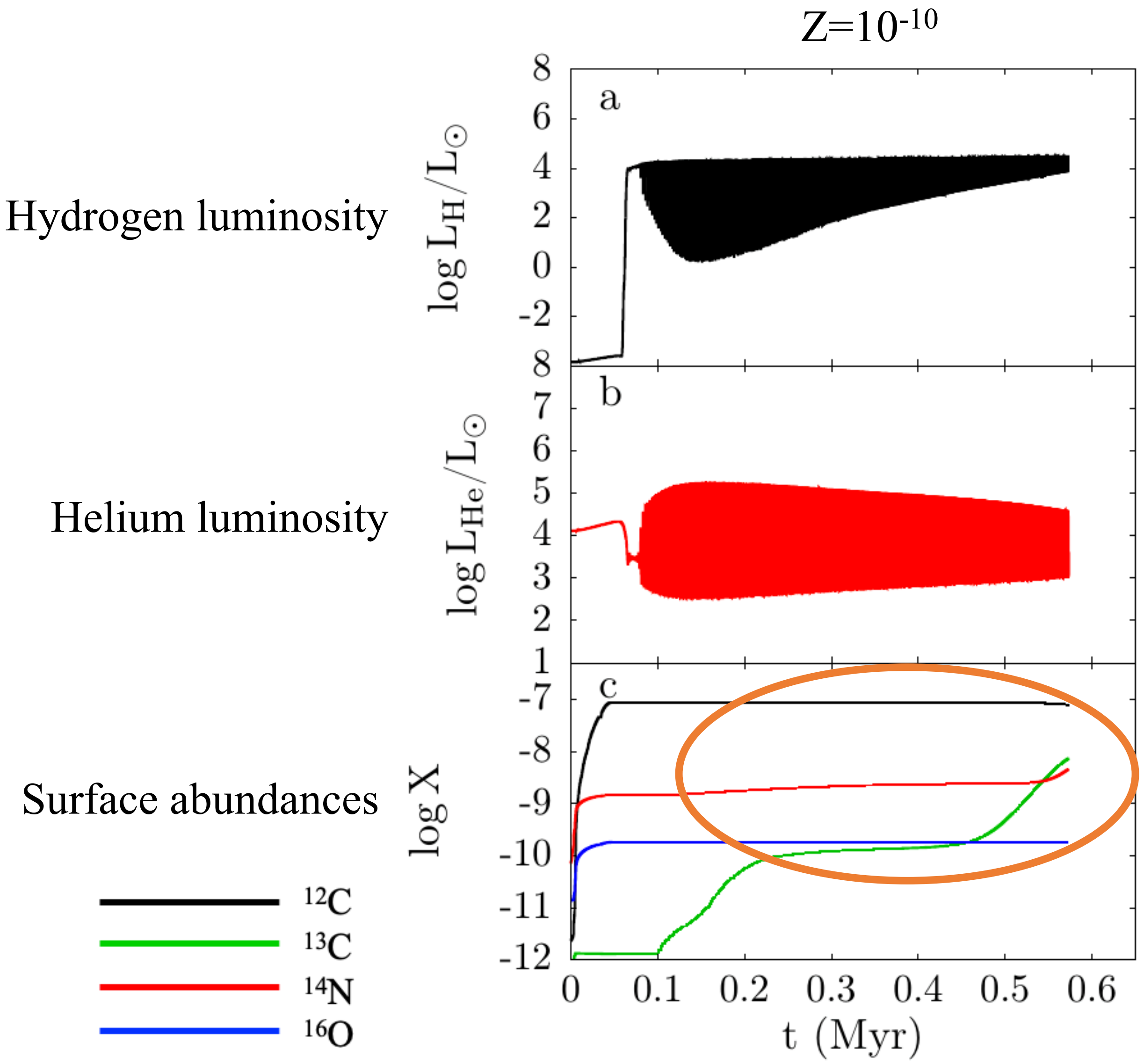

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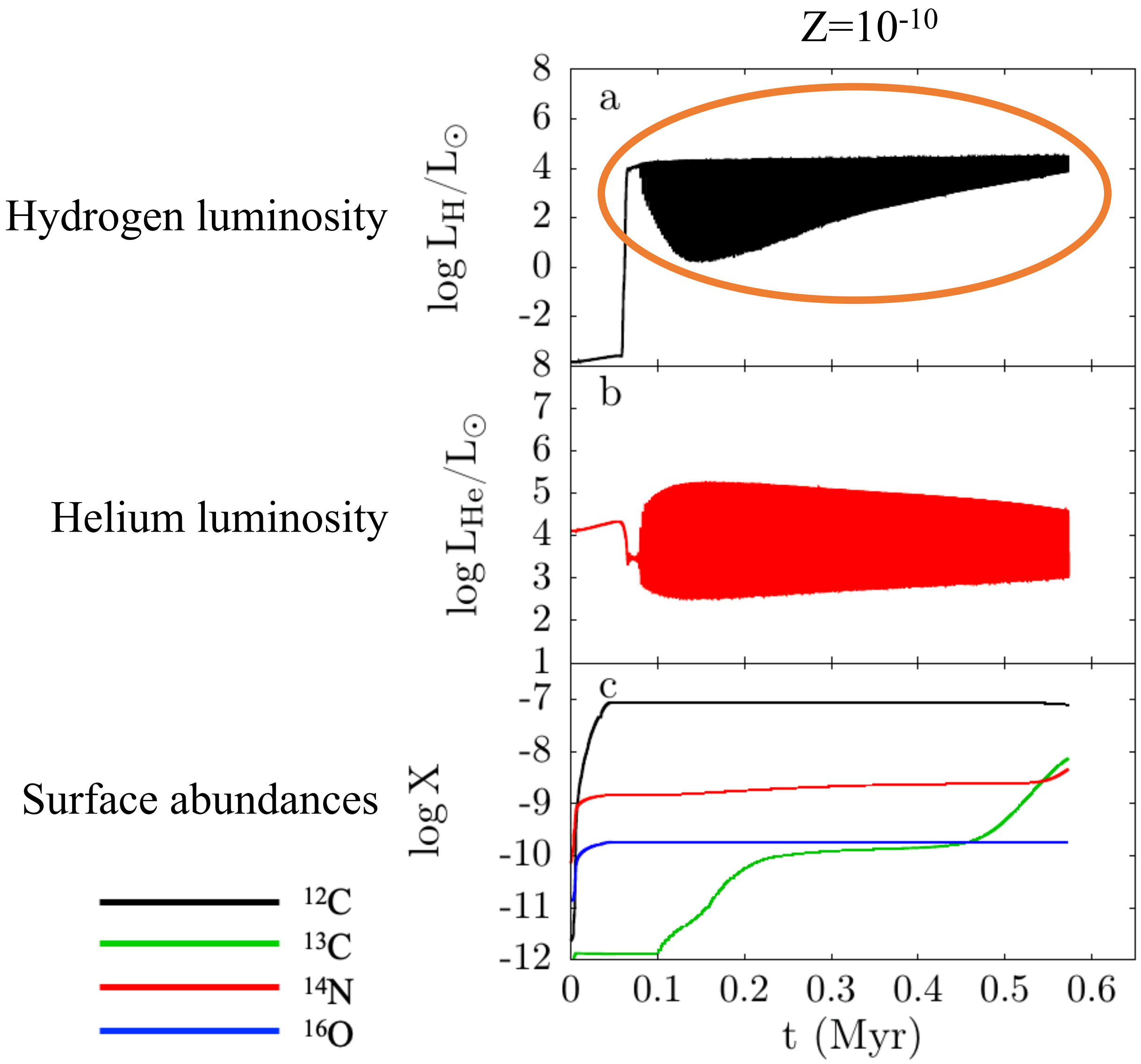

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Conclusions and ongoing activity

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- One model with $M = 2\ M_\odot$ and $Z = 10^{-5}$
- Three models with $M = 6\ M_\odot$ and $Z = 10^{-4}$, 10^{-6} and 10^{-10}
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- Ongoing activity: full grid of models of EMP stars with $1\ M_\odot \leq M \leq 20\ M_\odot$ and $3.1\times10^{-4} \leq Z \leq 10^{-10}$ in order to investigate their main properties and peculiar phenomena like Proton Ingestion Episode

THANKS FOR YOUR ATTENTION!

Cirillo, M.; Piersanti, L.; Straniero, O. *Extremely Metal-Poor Asymptotic Giant Branch Stars*, Universe 2022, 8, 44

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Equation of state

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- In metal-poor stars convection is able to mix regions with different chemical compositions, leading to thermal runaways and thus reducing the characteristic timescales with respect to more metal-rich stars
- The reduction of the burning timescales influences the main physical quantities of the star ➡ coupling physics, burning and mixing affects the evolution of the whole structure

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log T = 6.5

EOS	Main properties	Temperature range
Straniero and Prada Moroni	1)Completely ionized matter 2)Deviations from perfect gas (electron degeneracy, pair production, relativistic effects and Coulomb interactions) taken into account 3)Ideal for advanced burning phases and high temperatures and densities	$6 < \log T < 10$
Opal	1)Partially ionized matter 2)More accurate than Saha equation of state because of the treatment of all excited states, taking into account many-body effects and Coulomb interactions 3)Ideal for atmospheric layers and low temperatures and densities	$3.3 < \log T < 8.3$

Both equations of state are needed!