Burning Questions in Stellar Evolution:

Exploring Uncertainties in Mixing & Key Nuclear Reaction Rates

by

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work done with Mounib El Eid at the

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Outline

1. How stellar models are constructed and the main uncertainties in stellar evolution calculations.

2. Powerful constraints on our parameter choices: direct link to observations
   a. $^{16}O/^{17}O$ surface abundances of low-mass Red Giant stars.
   b. Blue loops in intermediate-mass stars

3. Evolution during the SAGB phase: uncertainties in C-rate & mixing

4. Conclusions & Future work

Evolutionary Code

- Models are constructed using a Lagrangian 1D **hydrodynamic evolutionary code** that solves the partial differential equations describing stellar structure & evolution on an adaptive grid.
- Updated input physics (equation of state, opacities, nuclear reaction rates..)

Uncertainties

- Convection is described within the framework of the local 1D MLT. So the treatment of **convective boundaries** includes free parameters which need to be constrained by observations.
- Existing uncertainties in the evaluation based on experimental grounds of certain key **nuclear reaction rates** at the low energies encountered in stars. These uncertainties propagate into the stellar models affecting their fidelity and the nucleosynthesis yields.

Treatment of convective boundaries: Overshooting

$$\frac{dX_i}{dt} = \frac{\partial}{\partial M_r}\left[(4\pi r^2 \rho)^2 \boxed{D} \frac{\partial X_i}{\partial M_r}\right]$$

D = 0 in radiative zones

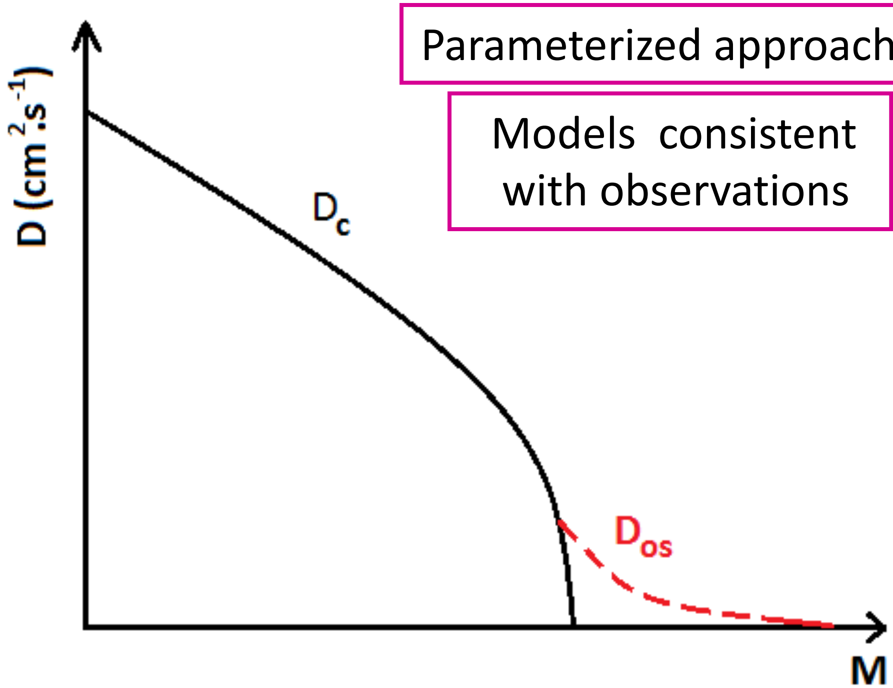
D ≠ 0 in convective zones calculated according to the MLT

D at **convective boundaries** given by:

$$D_{os}(z) = D_c e^{\frac{-2z}{fH_p}} \qquad z = |r_0 - r|$$

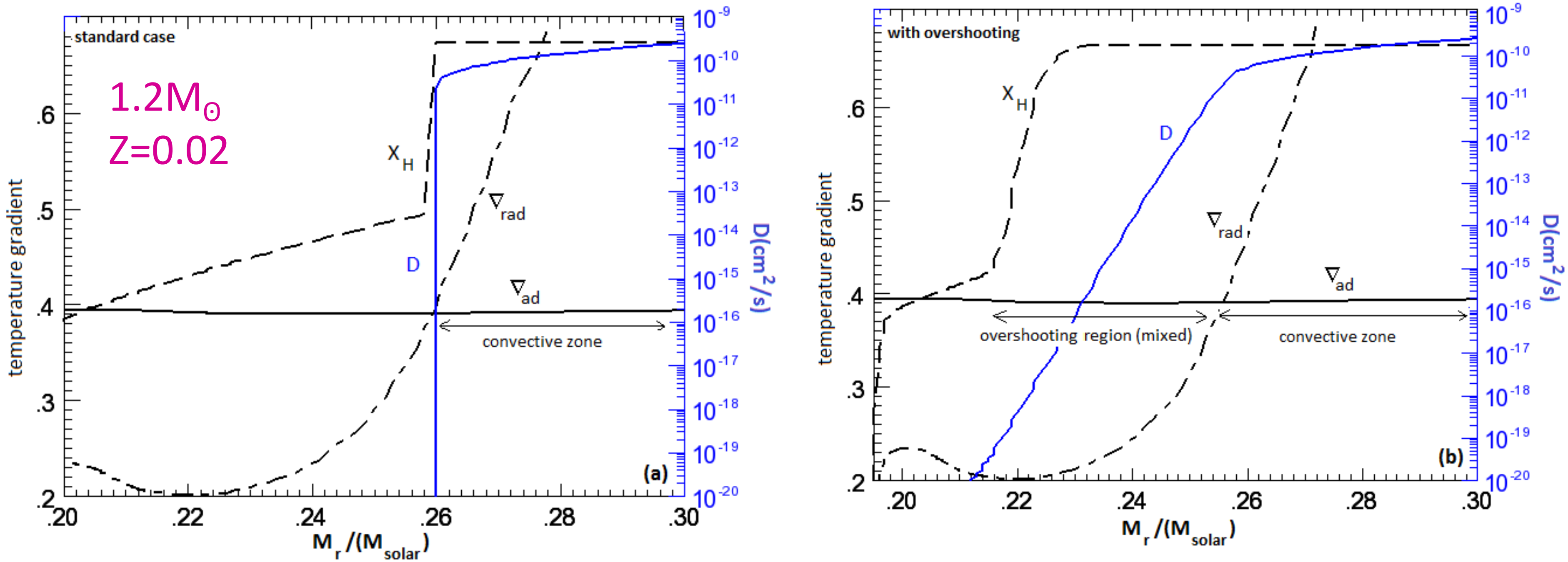
(Freytag et al. 1996)

f is dependent on the stellar parameters and the evolutionary phase

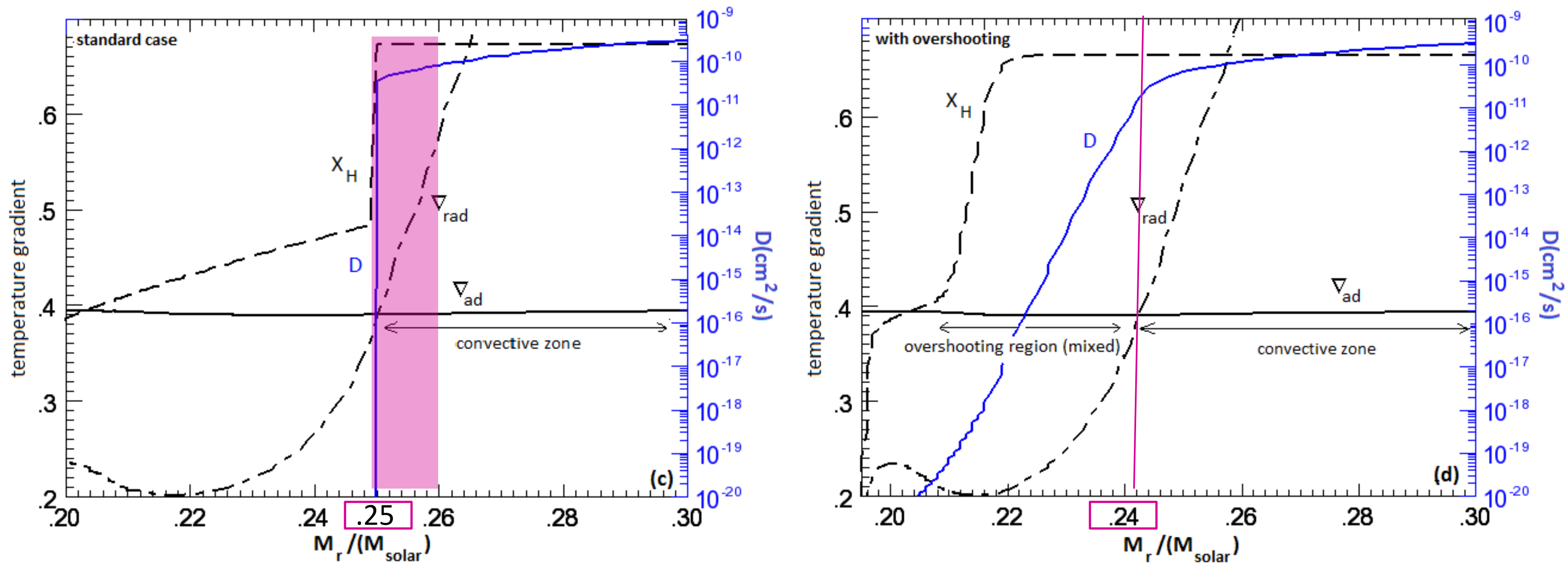


Parameterized approach

Models consistent with observations



3x10^5 years later..

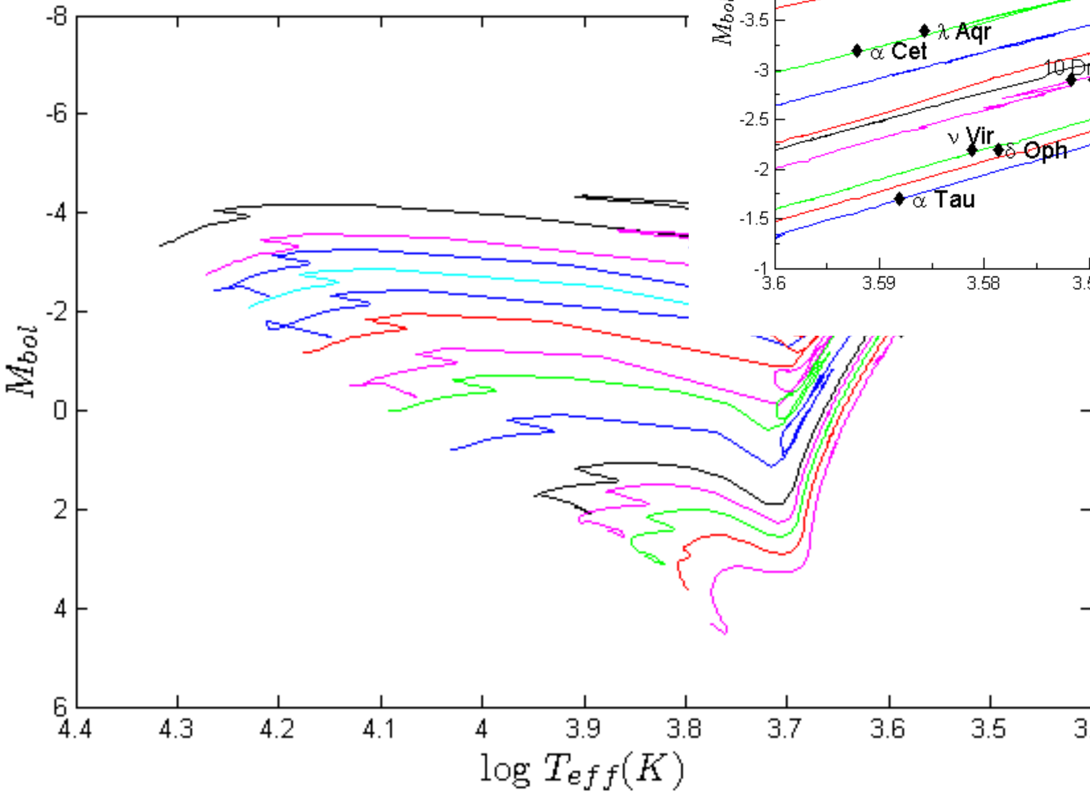


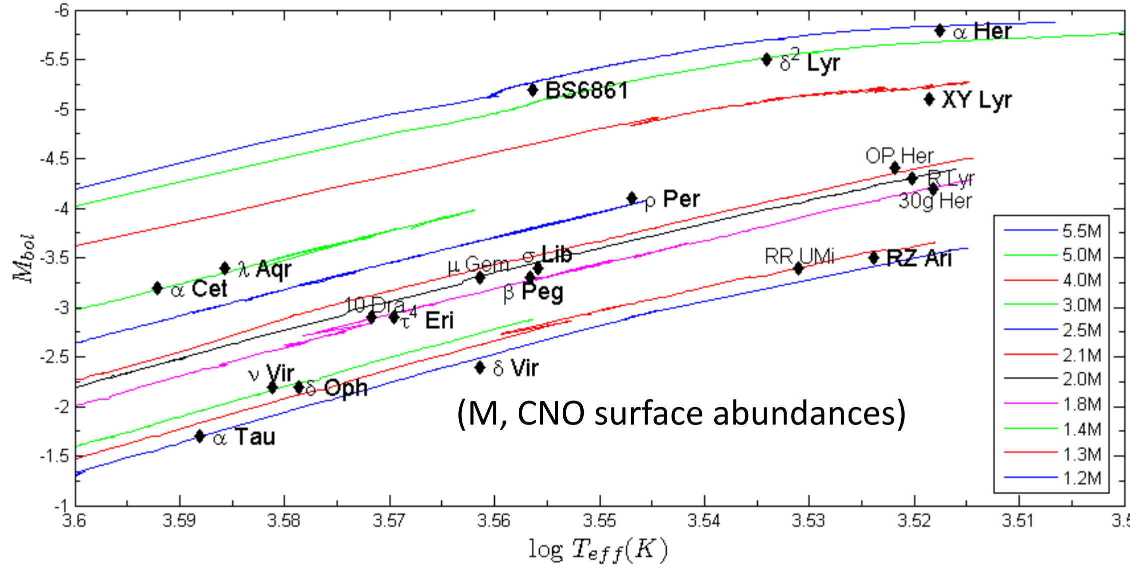
why do we need overshooting (I)

$^{16}O/^{17}O$ surface abundances in low-mass red giant stars

Masses & Surface Abundances (I): Observational data

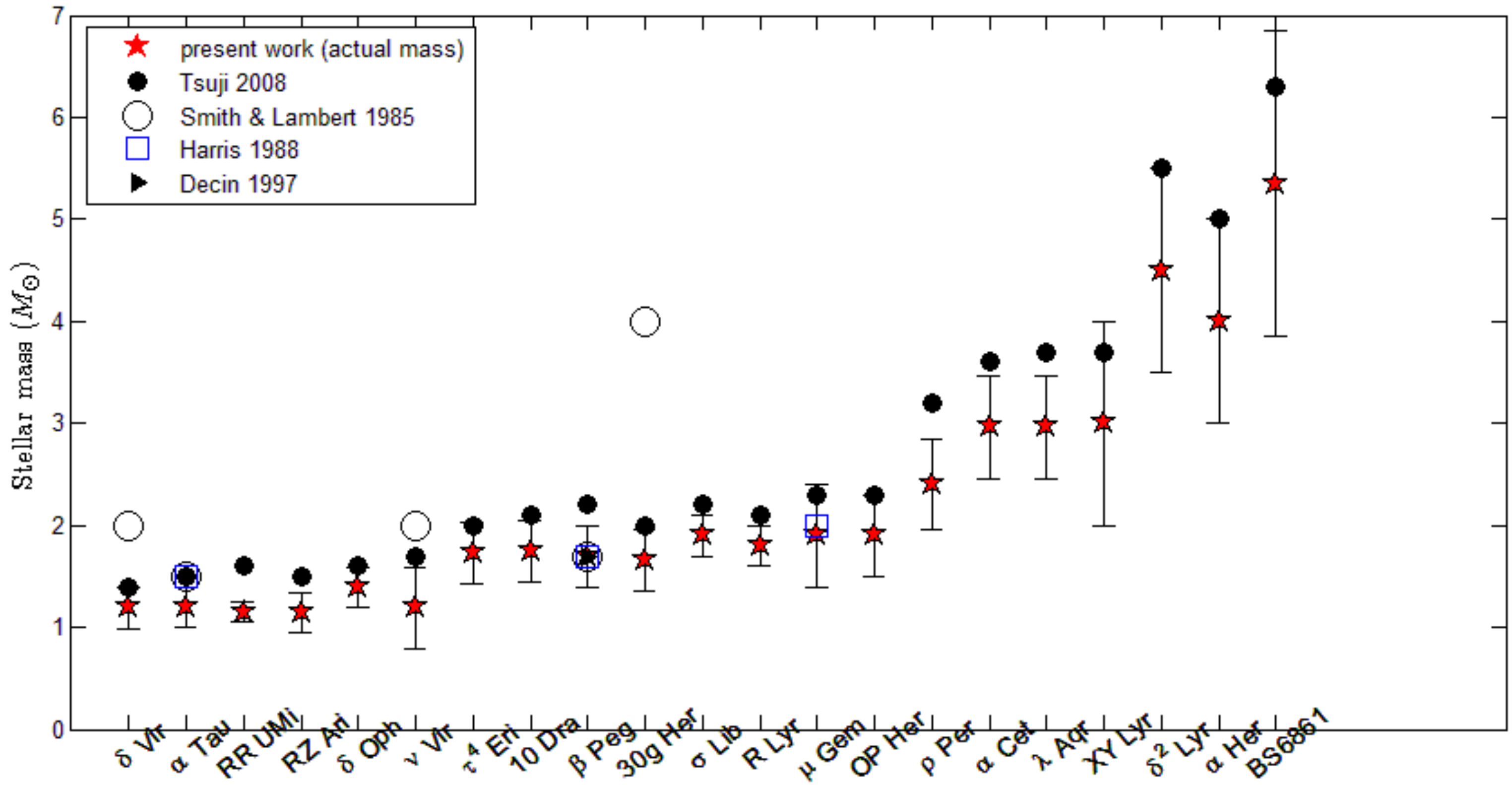
Observational data by Tsuji (2008)





Halabi, G. M. & El Eid, M. 2015, MNRAS, submitted and under revision

Masses & Surface Abundances (II): Mass Determination

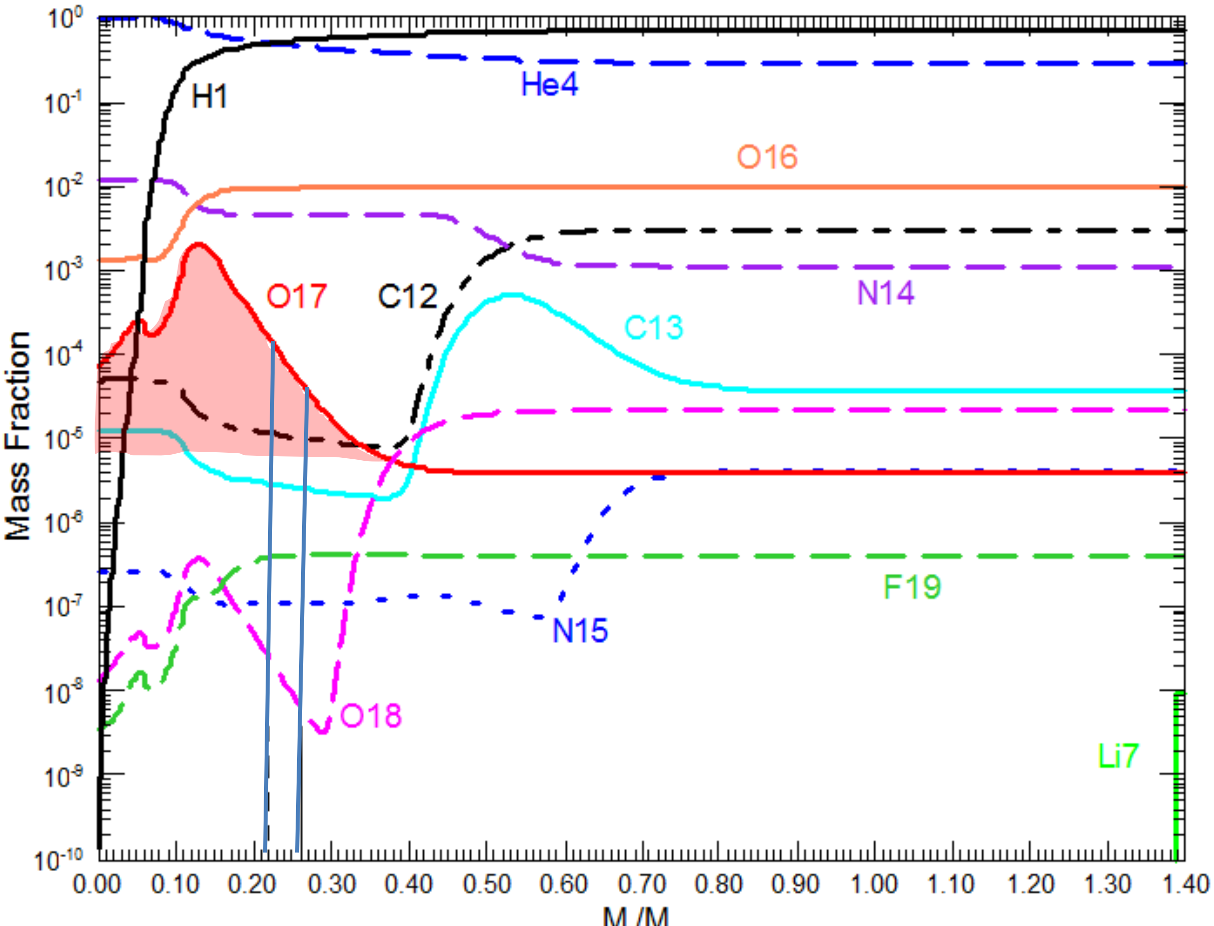


- Mass-loss taken into account
- Lower error bars than Tusji (2008)

Halabi, G. M. & El Eid, M. 2014, MNRAS, submitted and under revision

Masses & Surface Abundances (III): Abundance Profiles

Abundance profiles after H-burning, before FDUP



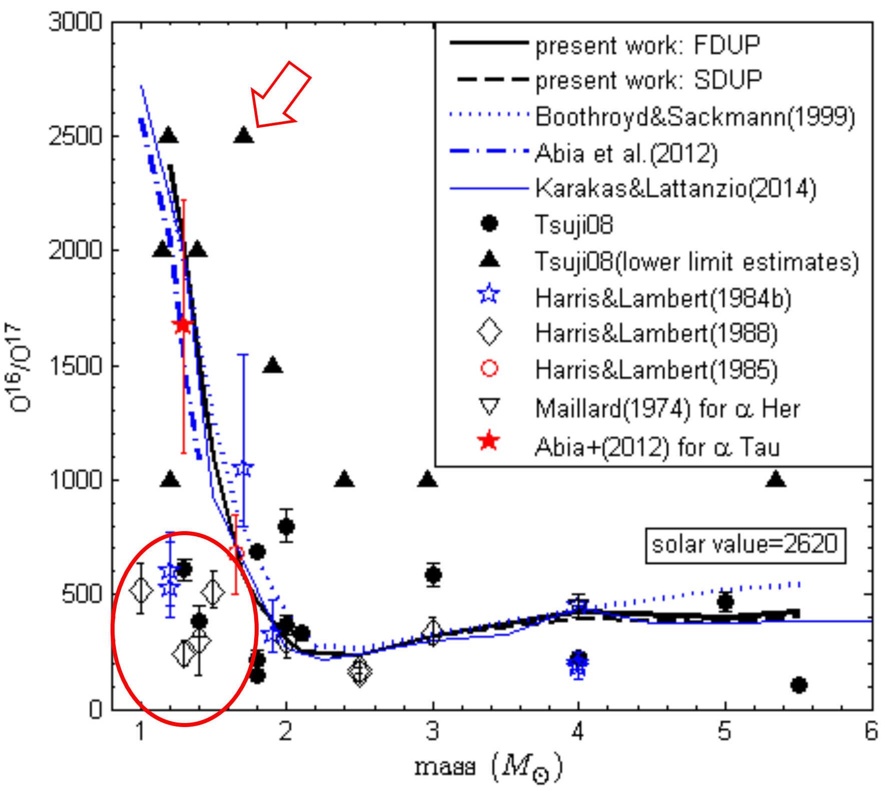
$^{16}O/^{17}O$

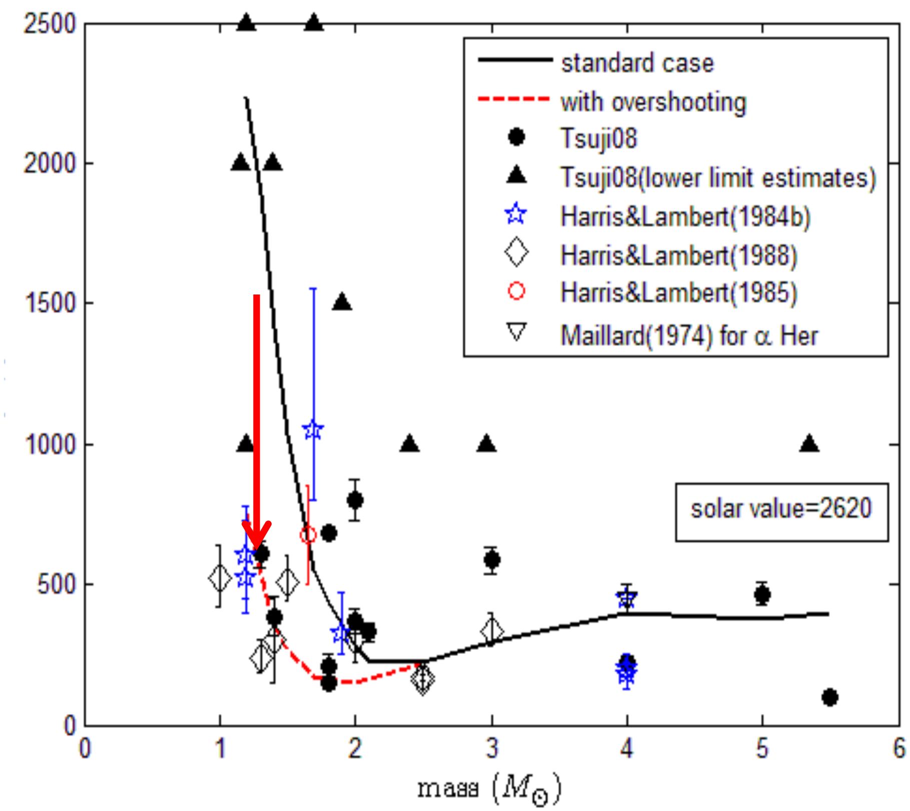
Critical indicator of the depth of convective mixing.

$1.4M_\odot$

$Z=0.02$

Masses & Surface Abundances (IV): Surface Abundance of $^{16}O/^{17}O$





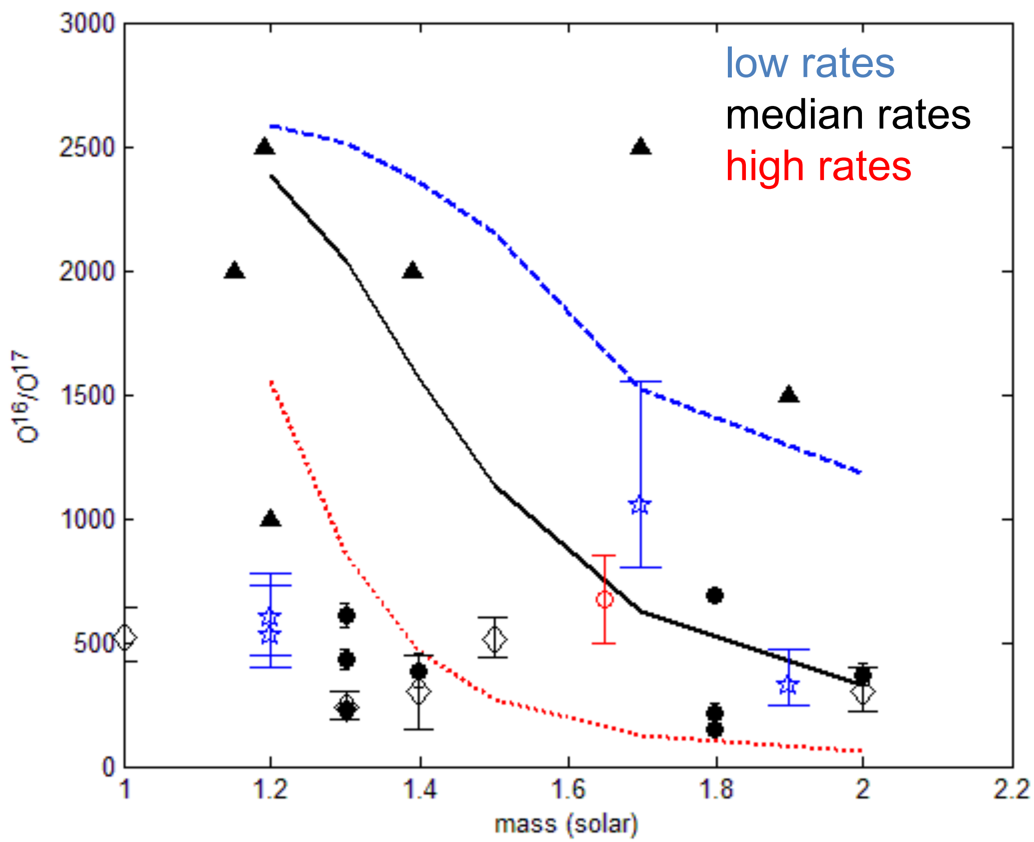
Direct evidence that overshooting is needed in low mass stars

Halabi, G. M. & El Eid, M. 2015, MNRAS, submitted and under revision

Masses & Surface Abundances (V): Surface Abundance of $^{16}O/^{17}O$: Rate uncertainties

The Sallaska et al. (2013) compilation of p-capture reaction rates is based on a Monte Carlo simulation.

The rates have statistically well-defined uncertainties (Longland 2012; Iliadis et al. 2014).



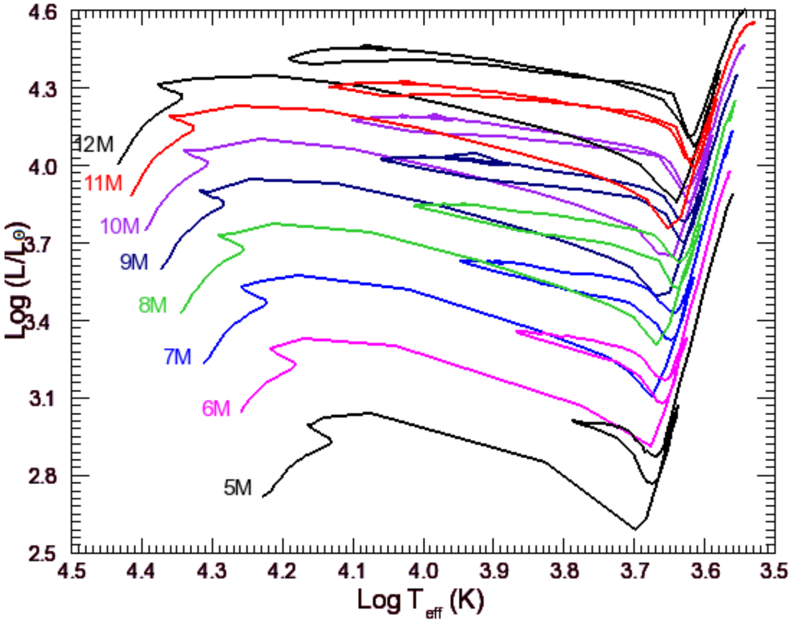
Standard case

why do we need overshooting (II)

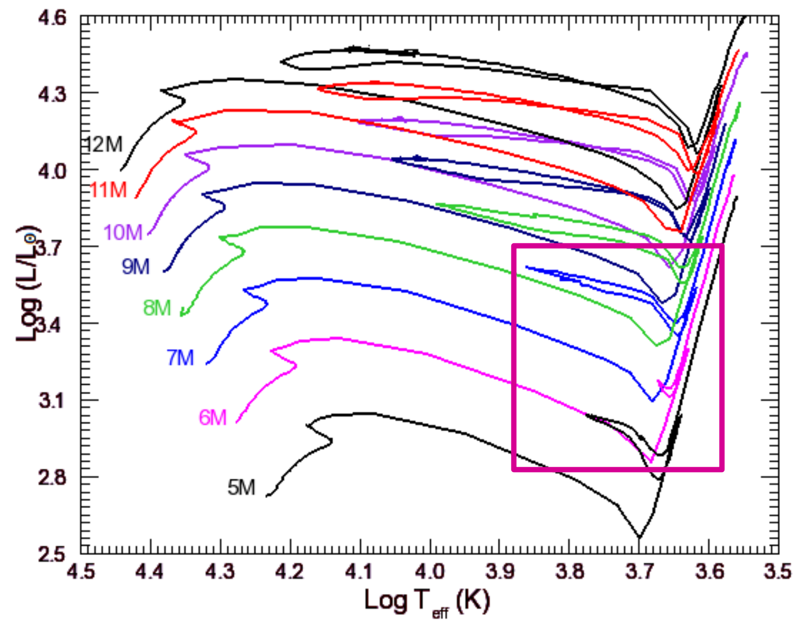
Blue loops in intermediate mass stars

Blue Loops (I): The effect of $^{14}N(p,\gamma)^{15}O$ reaction rate

Same input physics except the $^{14}N(p,\gamma)^{15}O$ reaction rate which controls H-burning by the CNO cycle:



Old rate (NACRE)
(Angulo et al. 1999)
overestimated



New rate: Experimental data by Imbriani et al. (2005) and Marta et al. (2011) provided a rate **lower** than NACRE by about 50% at stellar temperatures.

Halabi, G. M., El Eid, M. & Champagne, A. 2012, ApJ, 761, 10

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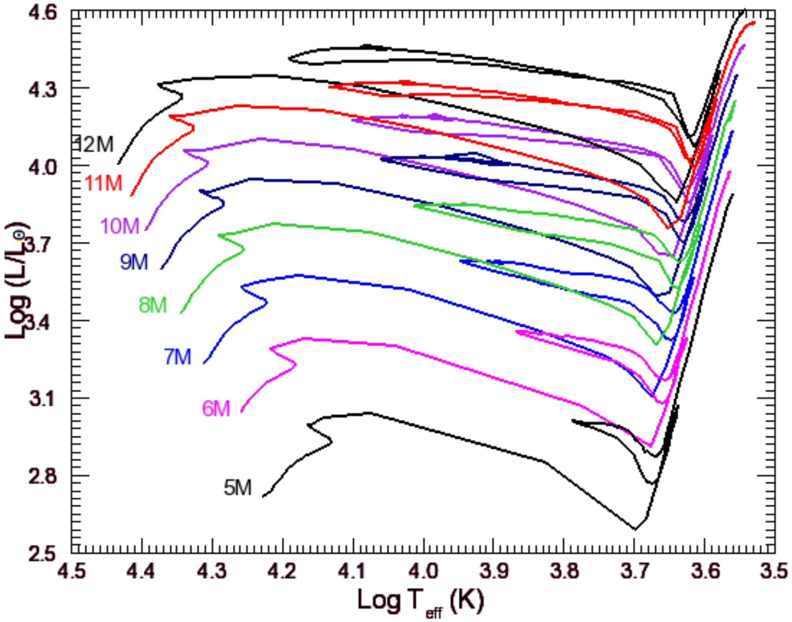

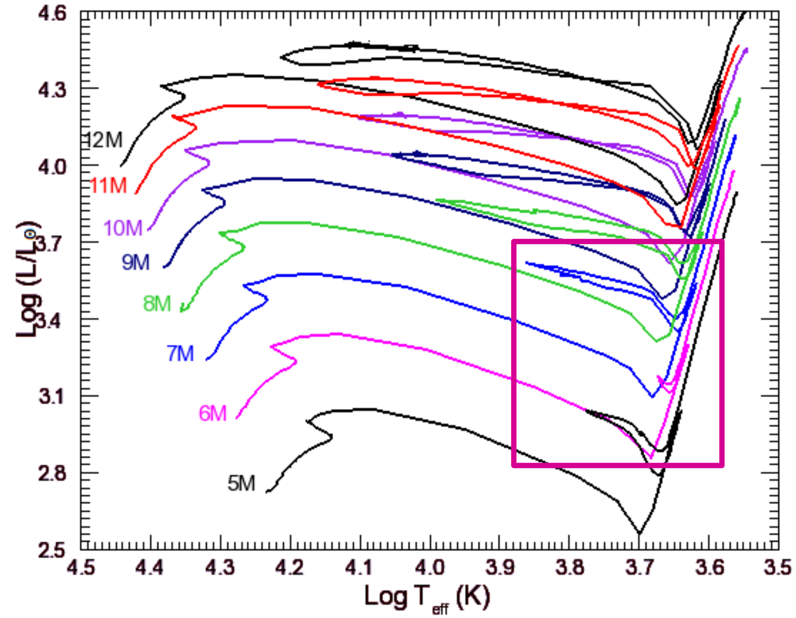

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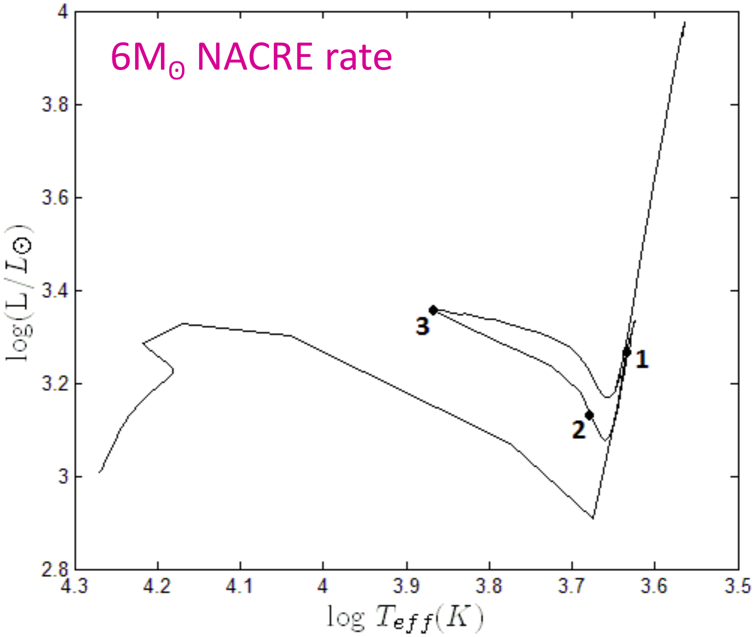
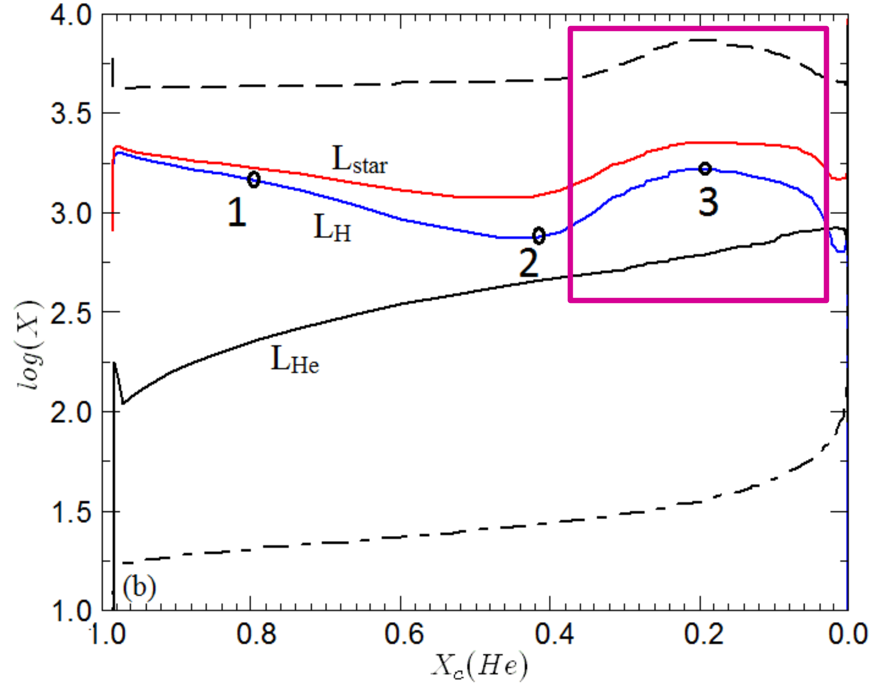
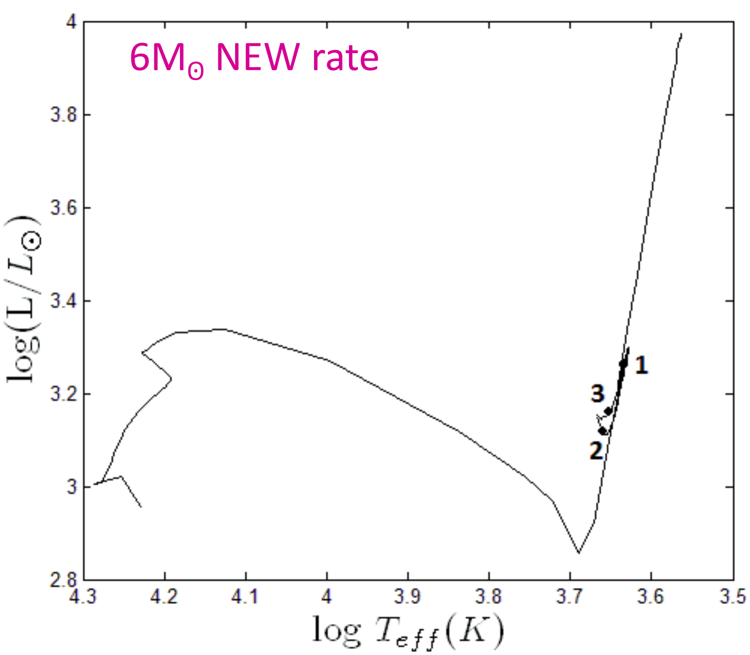
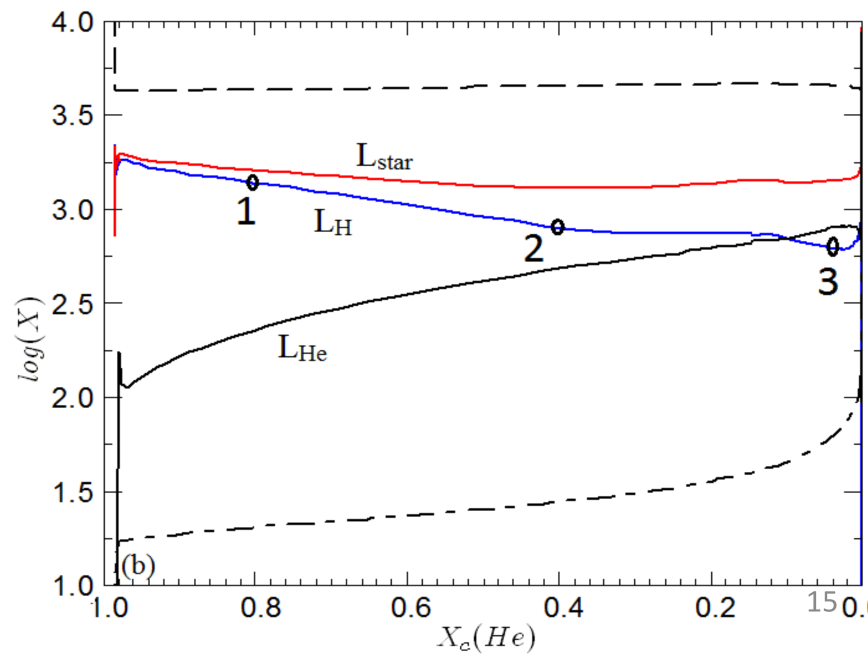
Blue loops are the region in the HRD where **Cepheids** are observed, whose astrophysical and cosmological importance are well-known.

Halabi, G. M., El Eid, M. & Champagne, A. 2012, ApJ, 761, 10

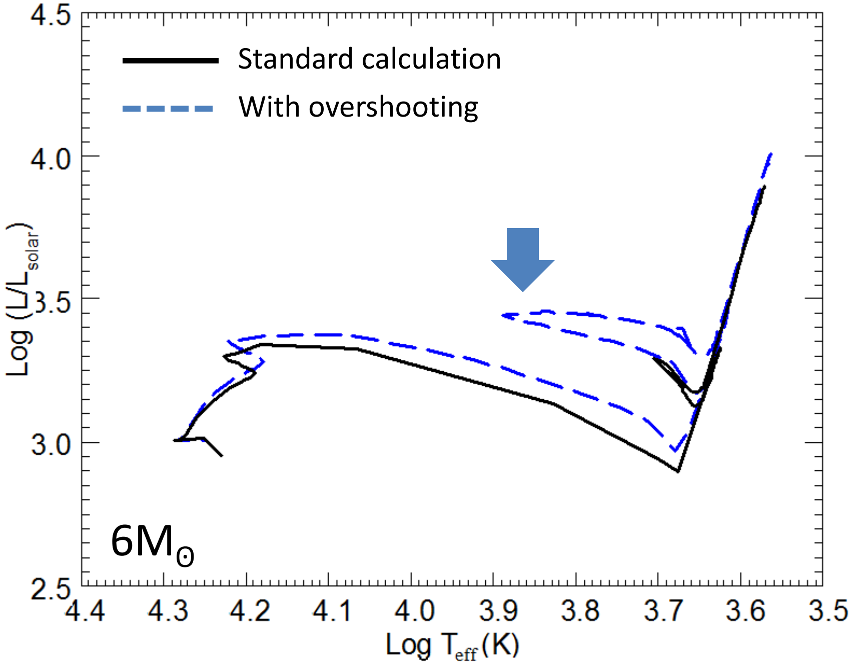

6M⊙ NACRE rate
log(L/L⊙)
log $T_{eff}(K)$
1
2
3

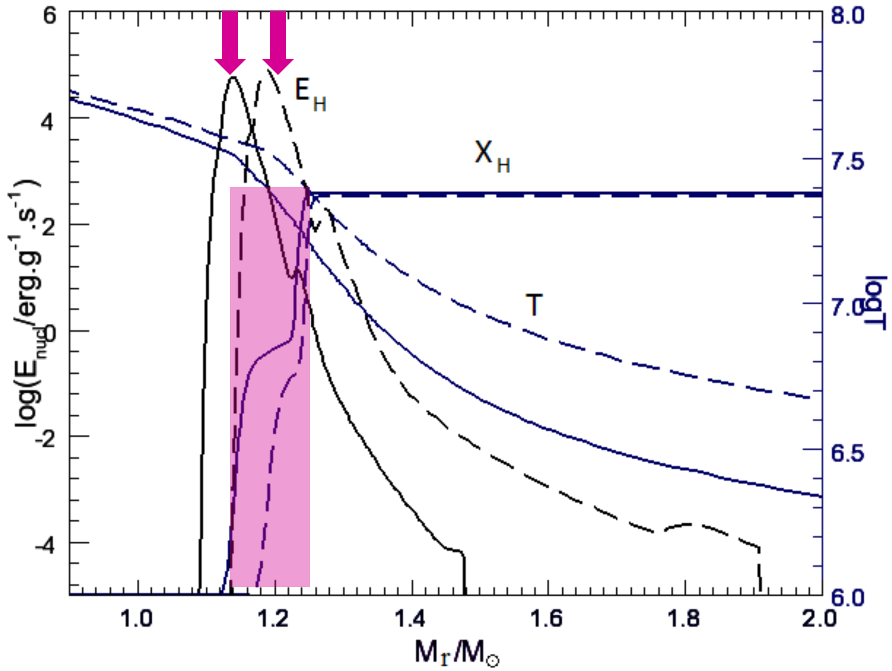

L_{star}
L_H
L_{He}
1
2
3
(b)
log(X)
$X_c(He)$


6M⊙ NEW rate
log(L/L⊙)
log $T_{eff}(K)$
1
2
3


L_{star}
L_H
L_{He}
1
2
3
(b)
log(X)
$X_c(He)$

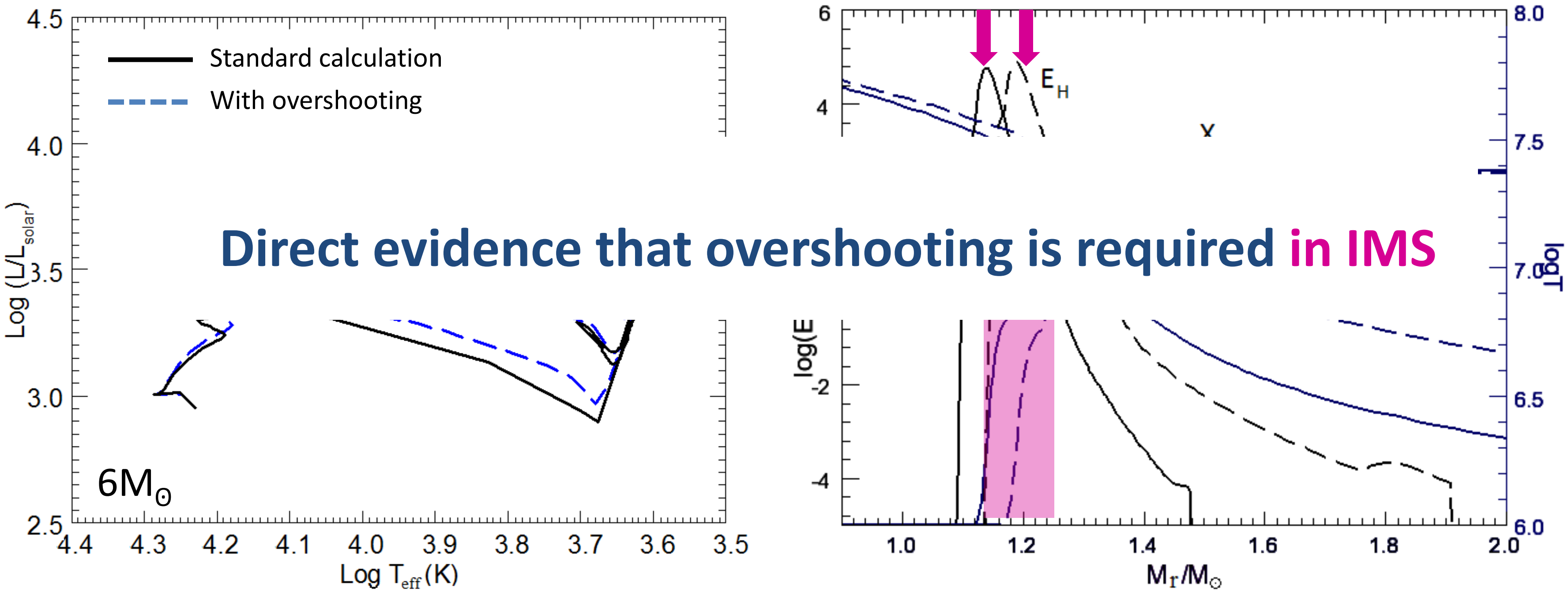
Blue Loops (II): Effect of core & envelope overshooting





- **Core overshooting** pushes the H-shell out in mass and establishes higher temperatures in the H-shell region.
- **Envelope overshooting** causes a deeper penetration of the H-profile (closer to the H-shell source).
- The H-shell burning is more efficient and the extension of the loop is **restored**.

Blue Loops (II): Effect of core & envelope overshooting



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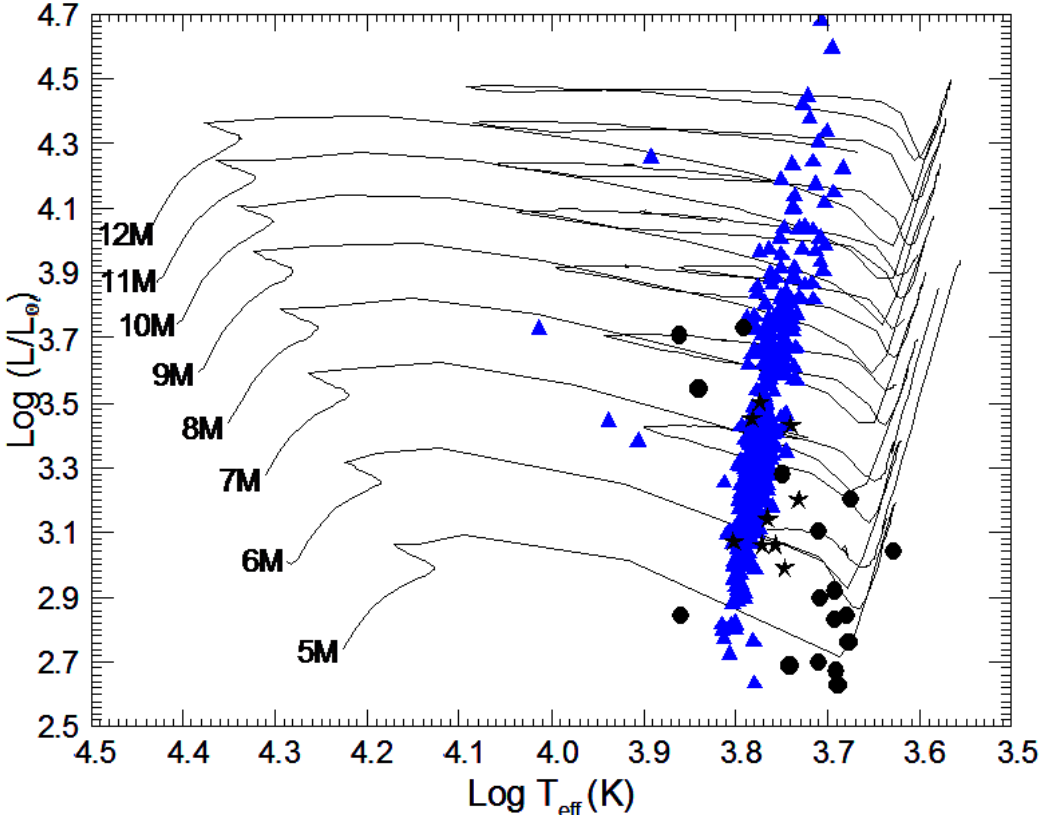
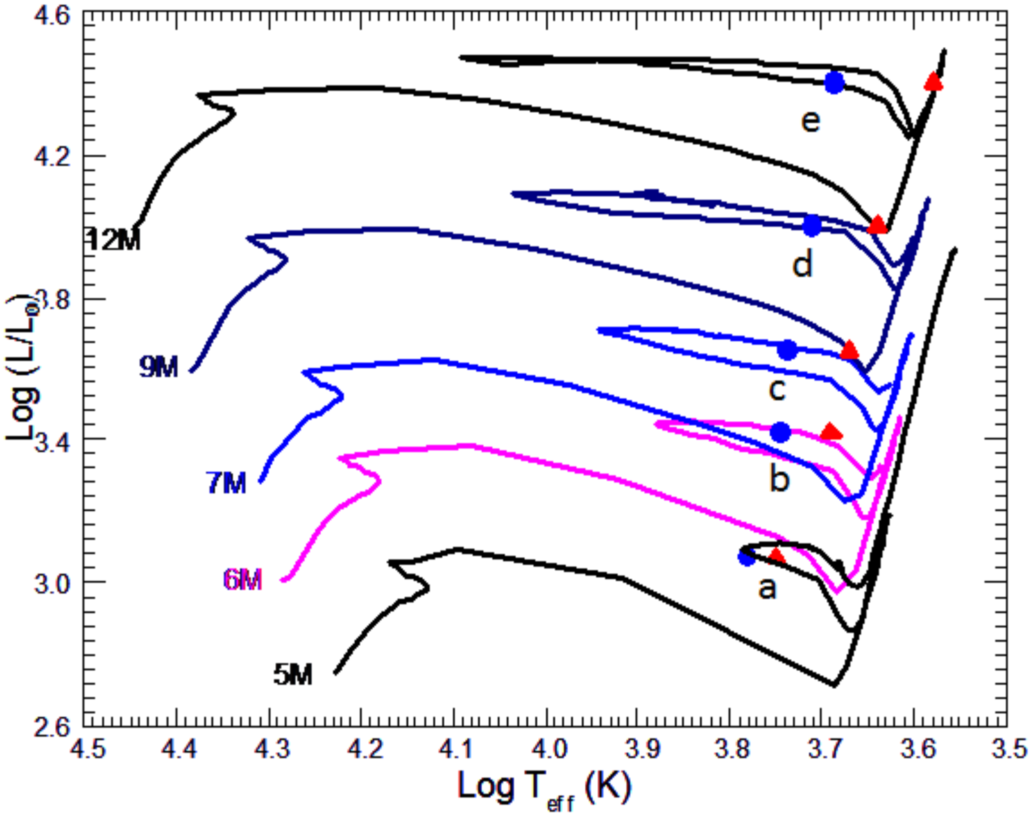
Blue Loops (IV): Restored Loops
Comparison with observations



Including observed Cepheids by
Fernie et al. (1995) and Schmidt (1984).

Halabi, G. M. 2014, AIP 1595, 264

Blue Loops (V): Restored Loops
Comparison with observations

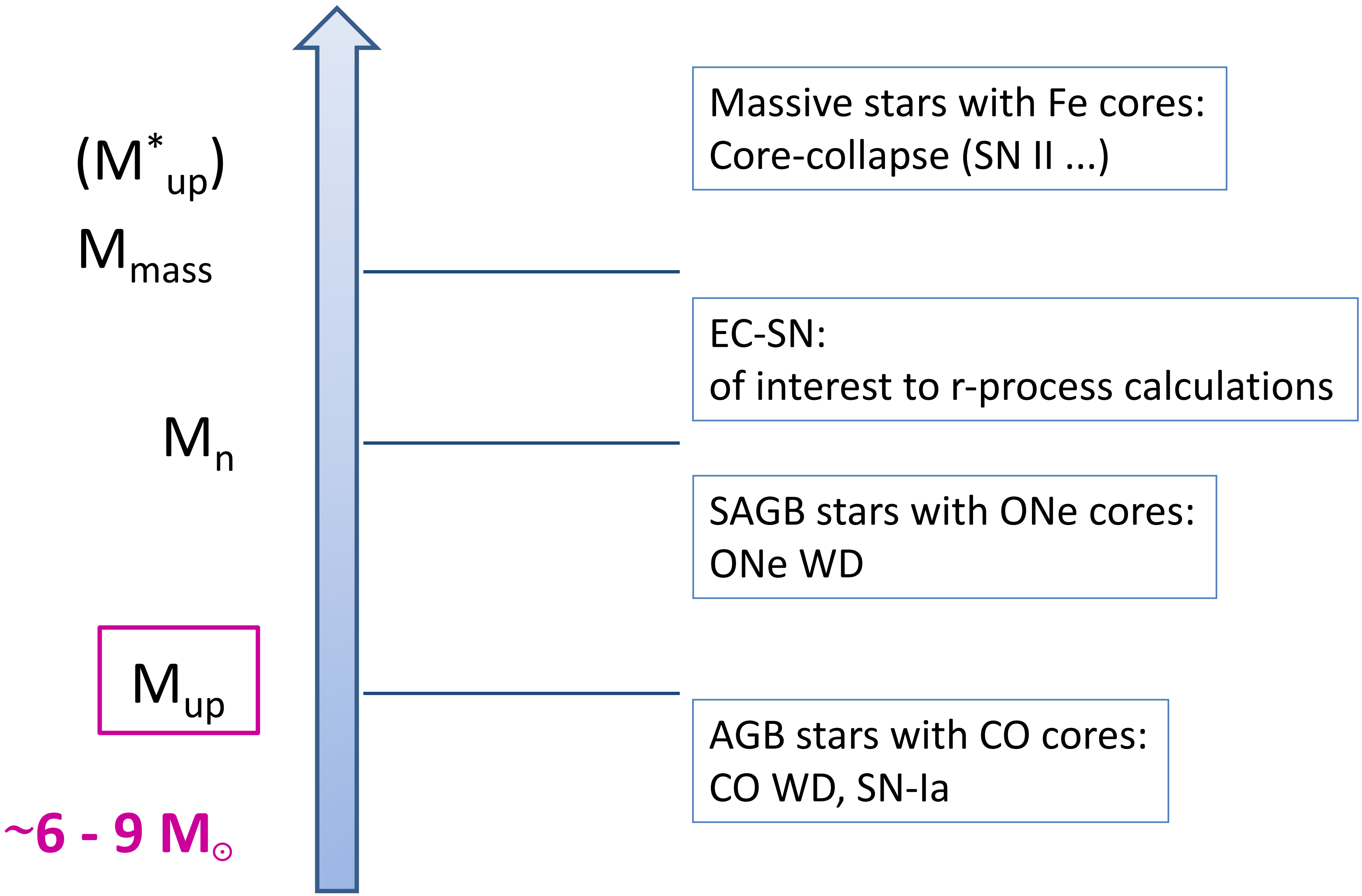


label	$M/M_\odot$	$M_{RGB}/M_\odot$
a	5	4.96
b	6.25	5.92
c	7	6.87
d	9	8.73
e	11	11.3

Predicted properties of galactic and magellanic classical Cepheids observed in the SDSS filters (Criscienzo et al. 2012).

Halabi, G. M. 2014, AIP 1595, 264

The SAGB phase:
Effect of C-rate & Overshooting


(M*up)
Mmass
Mn
Mup
~6 - 9 M⊙
Massive stars with Fe cores:
Core-collapse (SN II ...)
EC-SN:
of interest to r-process calculations
SAGB stars with ONe cores:
ONe WD
AGB stars with CO cores:
CO WD, SN-Ia

Importance of M_{up}

Astrophysical consequences

- Important for the **theory of novae outbursts** in cataclysmic variables when these stars belong to close binary systems
- Mass limits of **WDs** and their progenitors
- Mass limits of **SNe** and their progenitors
- Chemical **yield of massive AGB stars** and enrichment of ISM.
- For the **SNe Rates**: SNIa explosion requires a CO WD growing to the Chandrasekhar mass, which is favoured with a higher M_{up}
- A lot of **debate** over M_{up}
- ...

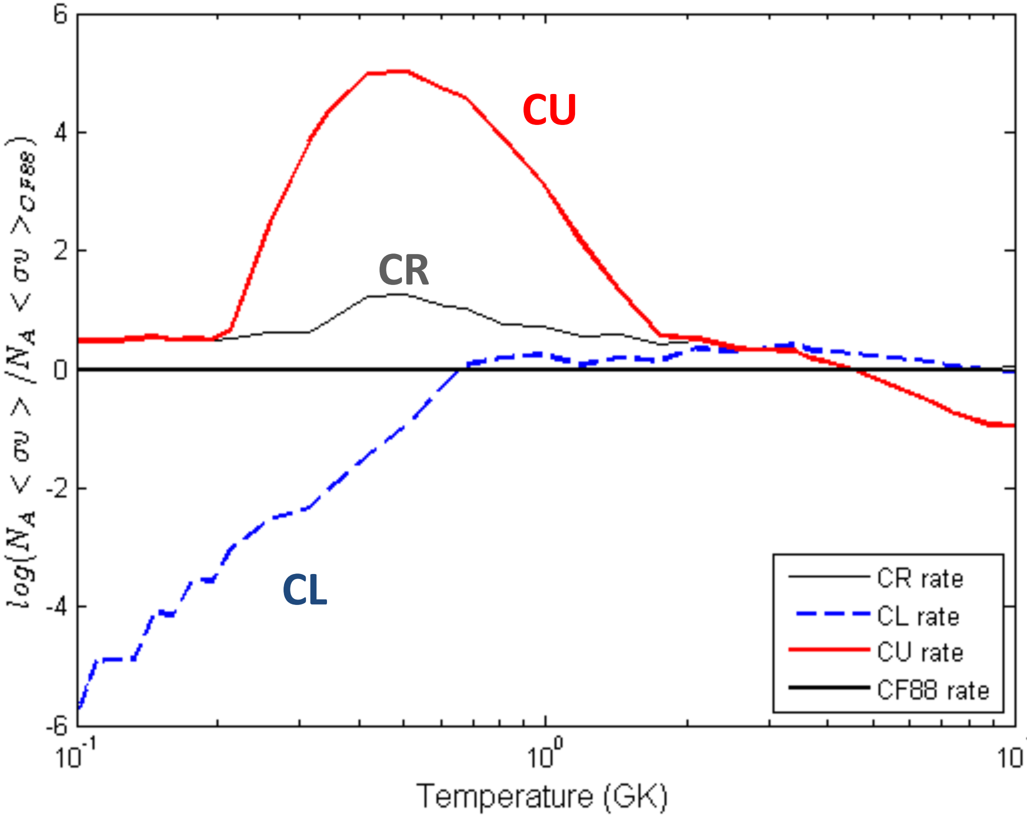
What affects M_{up} ?

- $\boxed{\text{Rates: eg. } ^{12}C+^{12}C}$ (Chen et al. 2014)
- $\boxed{\text{Convective mixing}}$ (Doherty et al. 2014; Denissenkov et al. 2014)
- Metallicity (Becker & Iben 1979; Siess 2008; Meng et al. 2008)
- Binarity
- Rotation
- Mass-loss
- …

Evolution during the SAGB phase (I): C-burning rate

Caughlan & Fowler (1988): **CF88 rate**

Pignatari et al. (2013):



Recommended rate (CR)
Pronounced $^{12}C+^{12}C$ **resonance structure** reported in the p and α channels, at $E_{cm} = 2.138\ MeV$ (Spillane+ 2007)

Upper limit (CU)

Possible **strong cluster resonance**

at E_{cm} = 1.5MeV (Perez-Torres+2006)

Lower limit (CL)

Existence of a **hindrance term** for low energy fusion processes (Jiang+ 2007)

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The dependence of the evolution of Type Ia SN progenitors on the C-burning rate uncertainty and parameters of convective boundary mixing

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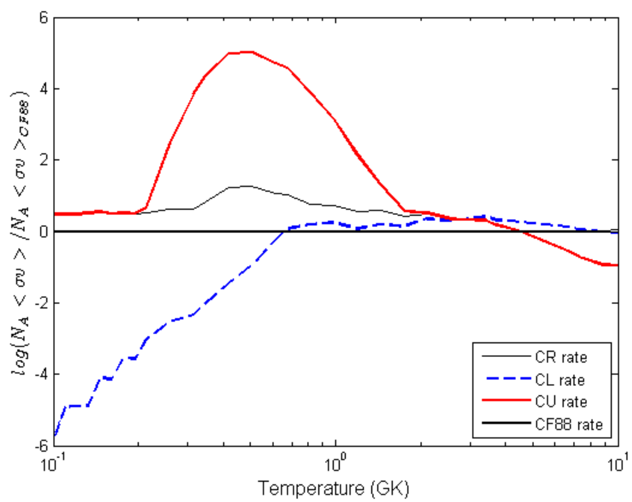
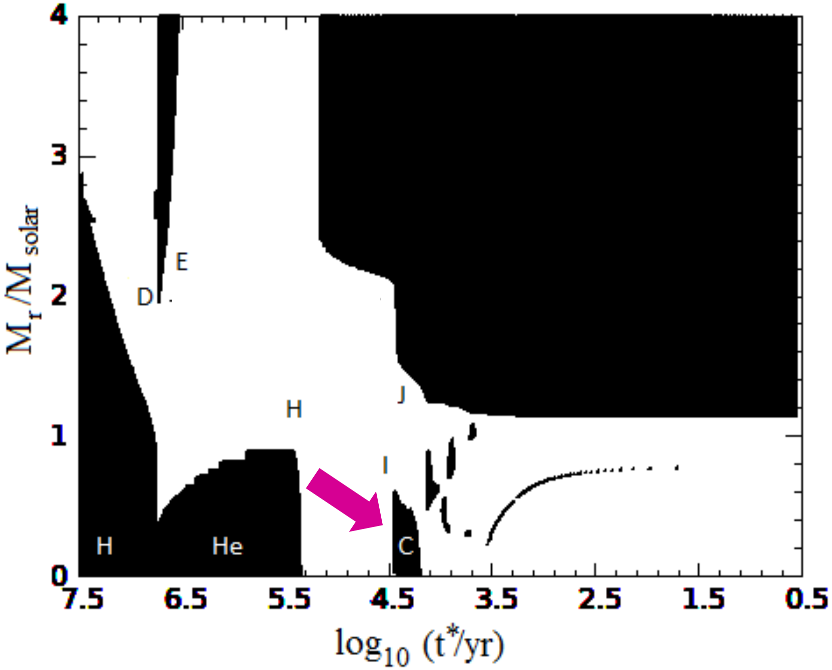
[2]The Joint Institute for Nuclear Astrophysics, Notre Dame, IN 46556, USA
[3]Kavli Institute for Theoretical Physics and Department of Physics, Kohn Hall, University of California, Santa Barbara, CA 93106, USA

et al. (NACRE; Angulo et al. 1999). We vary the CBR by applying a multiplicative factor (0.01, 0.1, 1, 100 and 1000) to its standard recommended value. The nuclear physics of the $^{12}C+^{12}C$ rate has

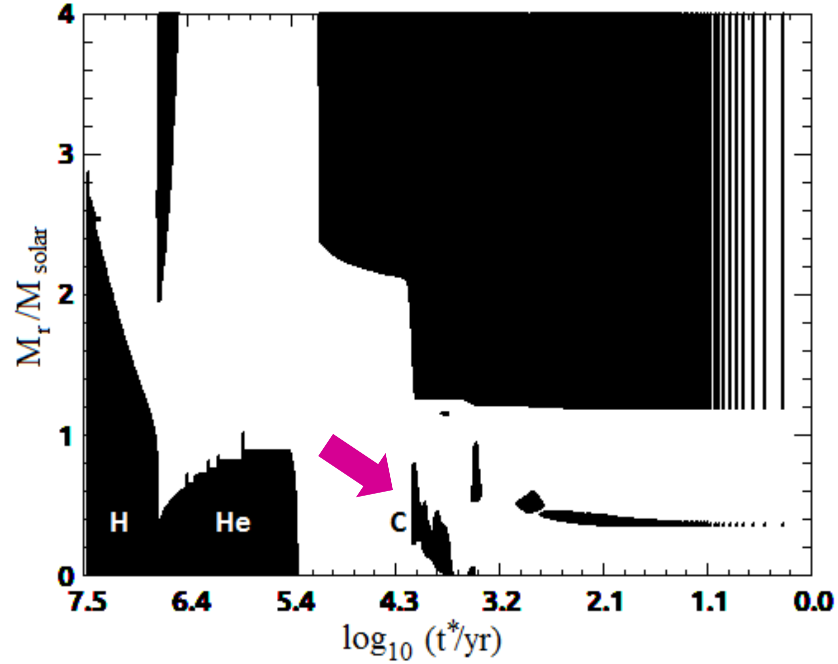


Evolution during the SAGB phase (II): Dependence on the C-burning rate

$9M_{\odot}$



with the **CR** rate



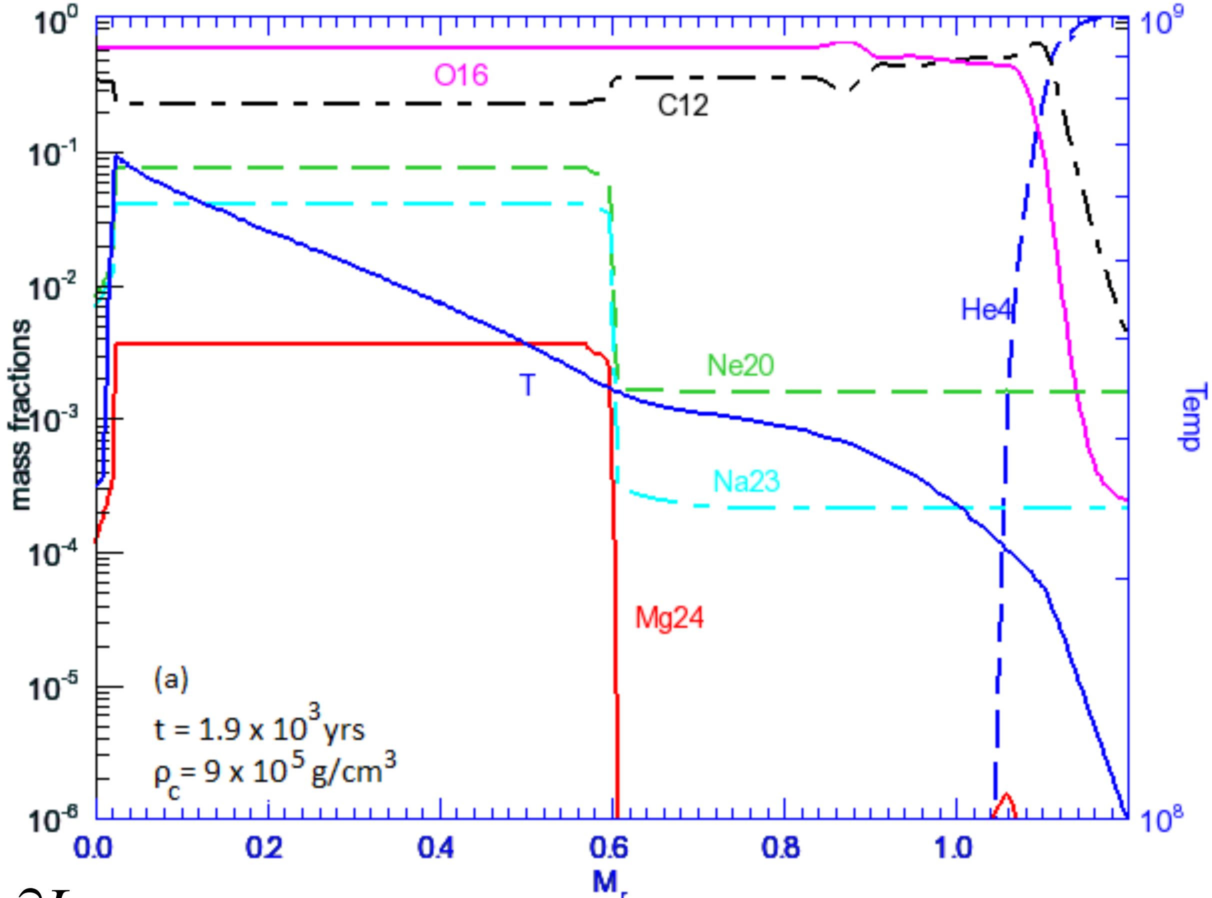
with the **CF88** rate

- Carbon ignites at $T \sim 7 \times 10^8$ K very close to the center, at mass shell $0.07M_{\odot}$
- Burning proceeds in a convective core

- Carbon ignites remarkably off-center, at mass shell $0.23M_{\odot}$
- The temperature gradient drives the energy flux to propagate inwards, fueled by convection

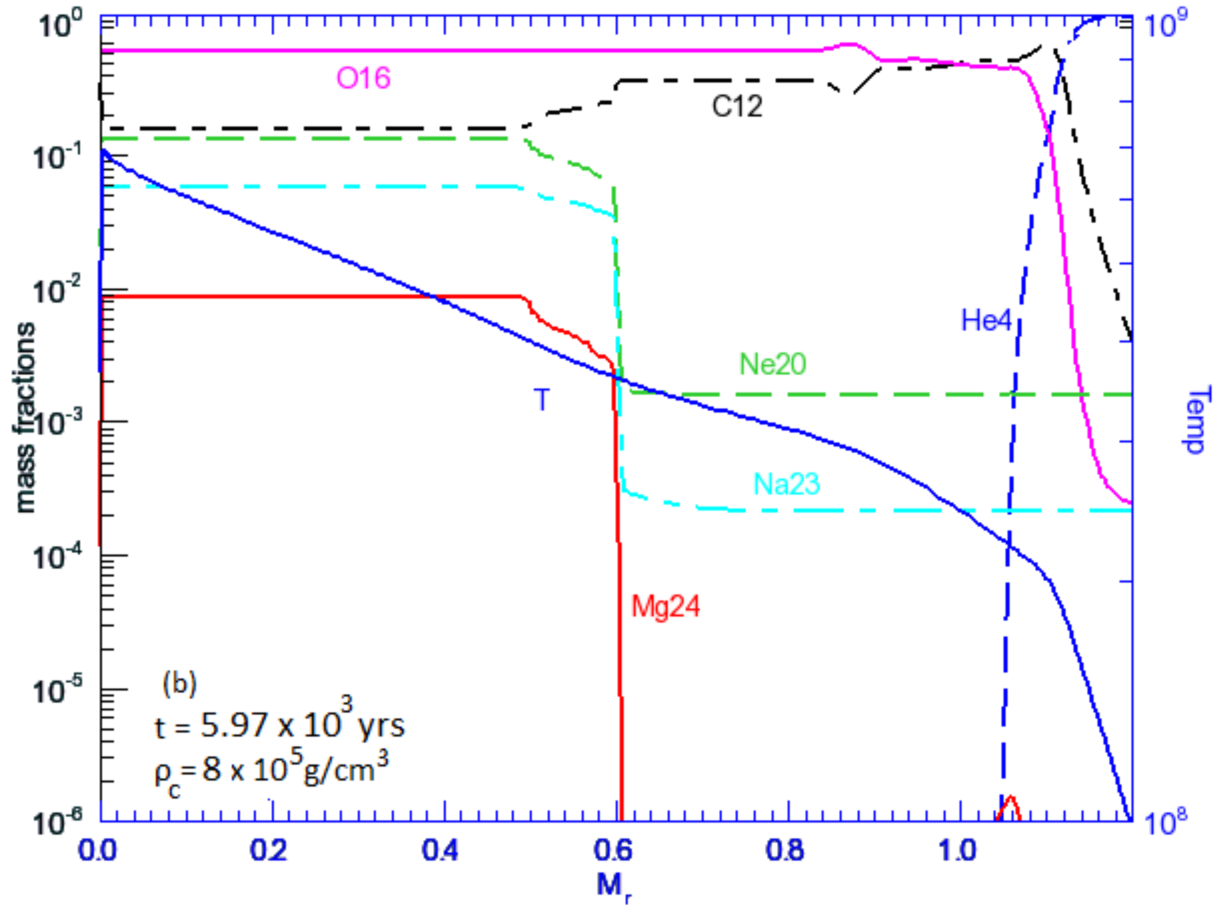
Halabi, G. M. & El Eid, M. 2015, AIP, 1645, 339

Evolution during the SAGB phase (III): C-burning mechanism with the CR rate



$$\frac{\partial L}{\partial M_r} = \varepsilon_{nuc} - \boxed{\varepsilon_{\nu}}$$

Evolution during the SAGB phase (III): C-burning mechanism with the CR rate



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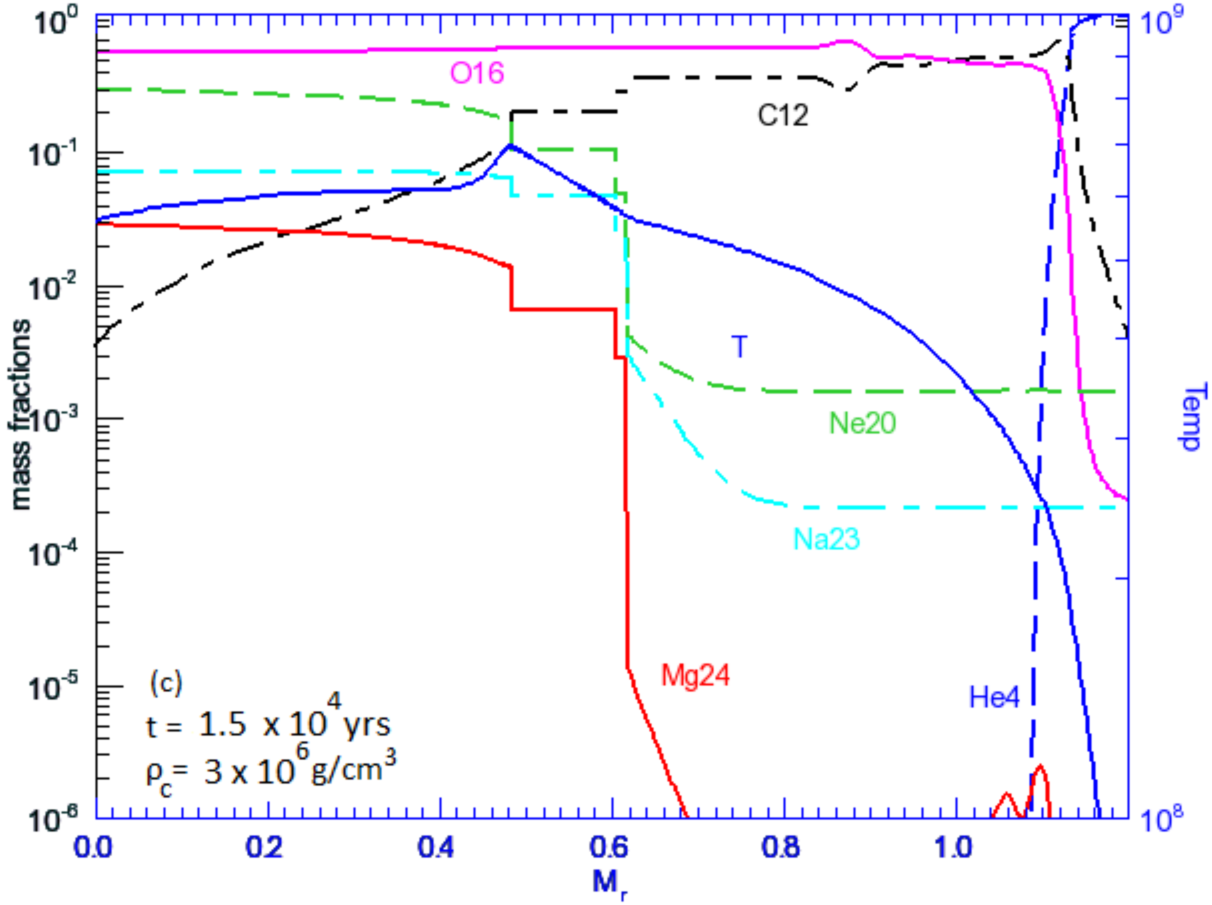

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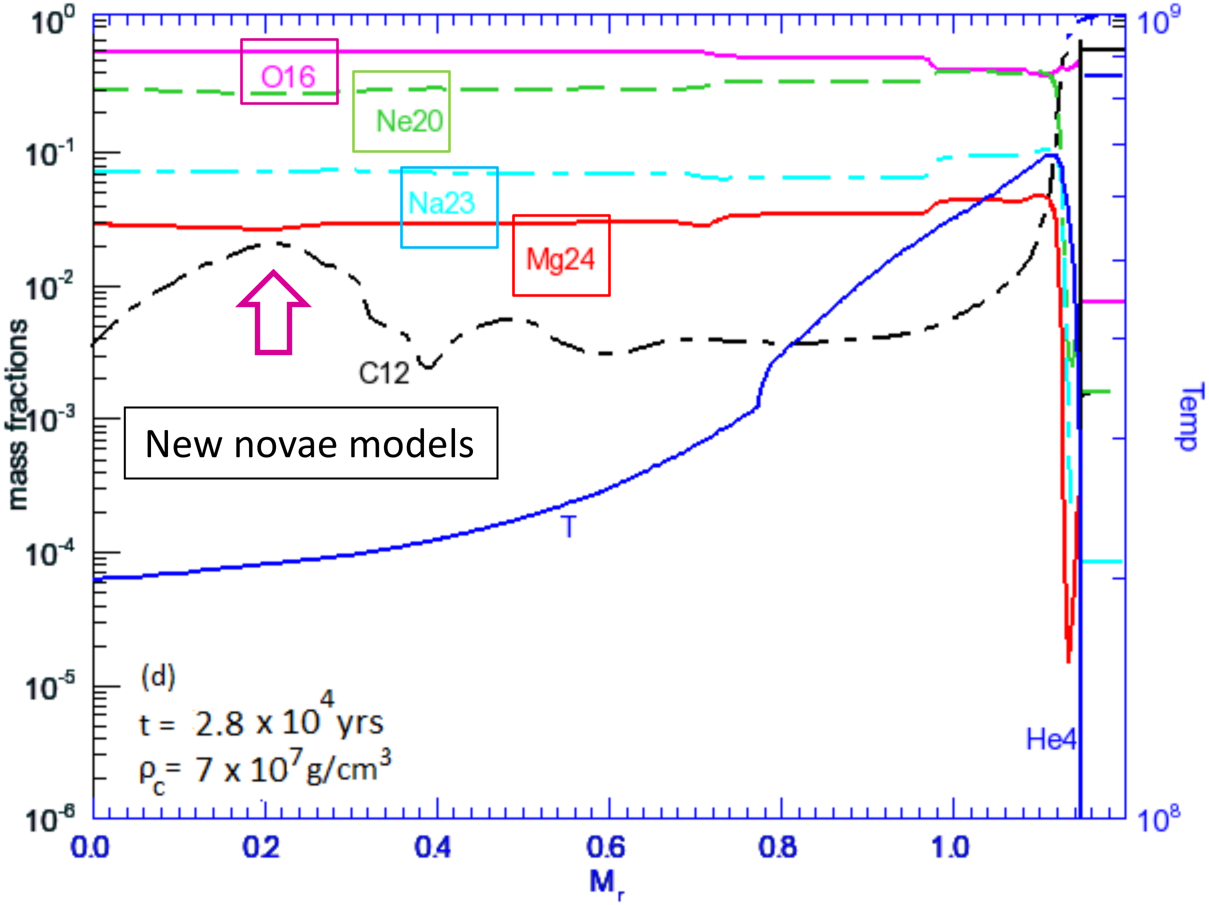
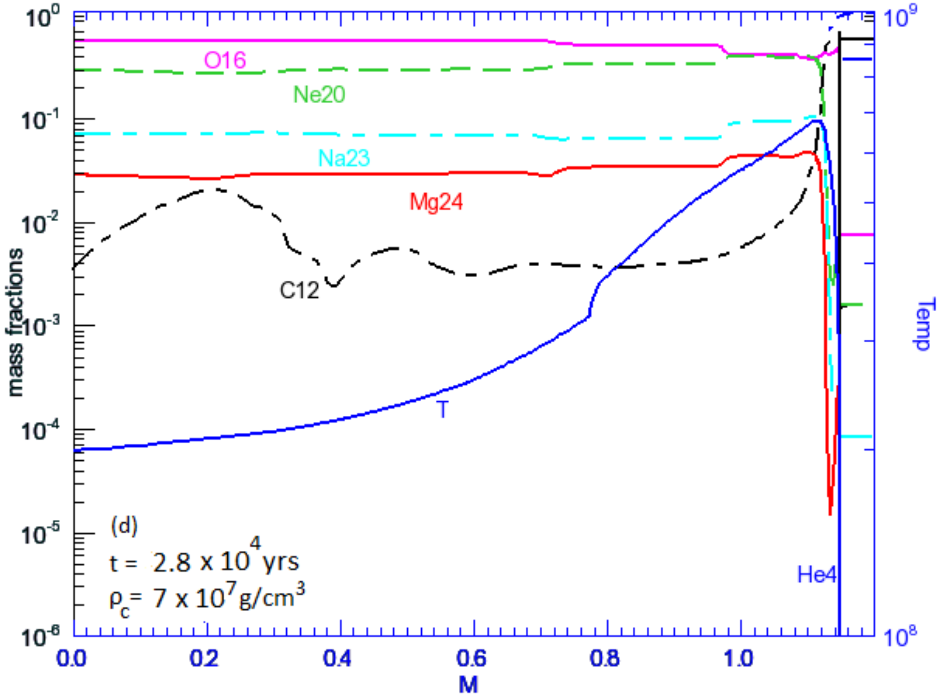


Halabi, G. M., El Eid & J. Jose, in preparation

Evolution during the SAGB phase (III): C-burning mechanism with the CR rate



X_{12}^{min} = 0.015 (Gutierrez et al. 2005) thermonuclear disruption

M_{ONe}	ΔM_{CO}	M_{CO}	X_{12}^{max}	$M_r(X_{12}^{max})$	$^{12}C_c$
1.122	0.025	1.147	0.021	0.215	0.0035

^{24}Mg	$^{16}O_c$	$^{20}Ne_c$	$^{23}Na_c$	$^{4}He_{top}$	$^{1}H_{top}$
0.029	0.57	0.299	0.0725	0.383	0.6

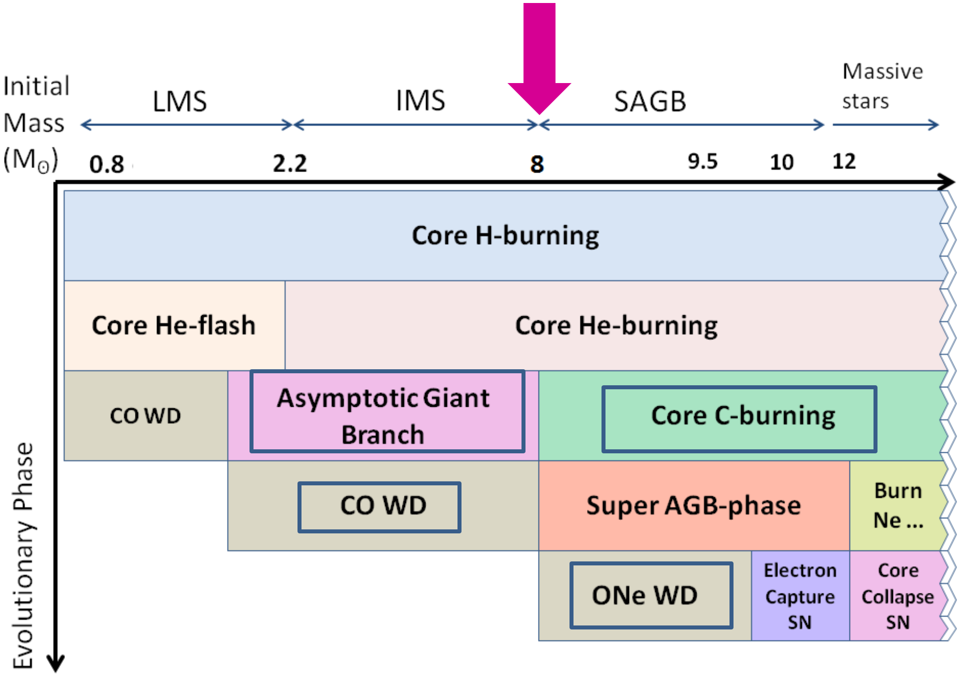
Halabi, G. M., El Eid & J. Jose, in preparation

Evolution during the SAGB phase (IV): Effect of C-rate & overshooting on M_{up}

Rate	M_{up} (Standard mixing)	M_{up} (Core overshooting)
CF88	$8.5\ M_\odot$	$8\ M_\odot$
CR	$8.3\ M_\odot$	$7.5\ M_\odot$
CU	$7\ M_\odot$	--
CL	$9\ M_\odot$	--

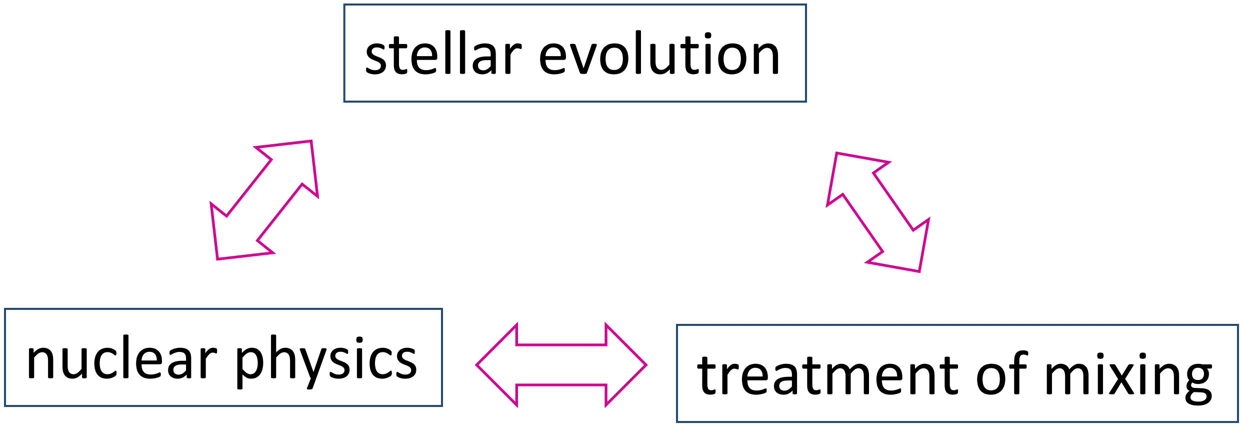
Core overshooting constrained from study on blue loops

Consistent!



Halabi, G. M. & El Eid, M. 2015, AIP, 1645, 339

Conclusion **1**



Understanding this connection based on the underlying physics.

Conclusion **2**

Complicated models

input **parameters**
(treatment of instabilities like convection)
Mechanism is used (**overshooting**)

Dramatic **consequences** on the details of evolution & nucleosynthesis

Blue loops, $^{16}O/^{17}O$
powerful constraints on our parameter choices

Direct **link** to observations!

Conclusion **3**

State-of-the-art nuclear reaction rates:
C-burning, CNO, s-process network

I investigated their **uncertainties** on details of evolution & nucleosynthesis

+

Mass-loss carefully considered and taken into account

Conclusions could be drawn based on how well models match observations

Future Work

- **s-process nucleosynthesis**.

1. Factors affecting the amount of ^{13}C
2. Efficiency of the diffusion process
3. Constraining amount of ^{13}C based on observations.

   (CNRS project in intensive collaboration with Bradley Meyer, Clemson University, SC).

- The new C-burning rate will be further investigated in **novae simulations.** Consequences on novae outbursts in binary systems, SN Ia rates..

  (Project in collaboration with Jordi Jose, Barcelona).

  (Halabi, El-Eid, Jose (2015), in preparation).

1866

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الجامعة الأميركية في بيروت

Thank you