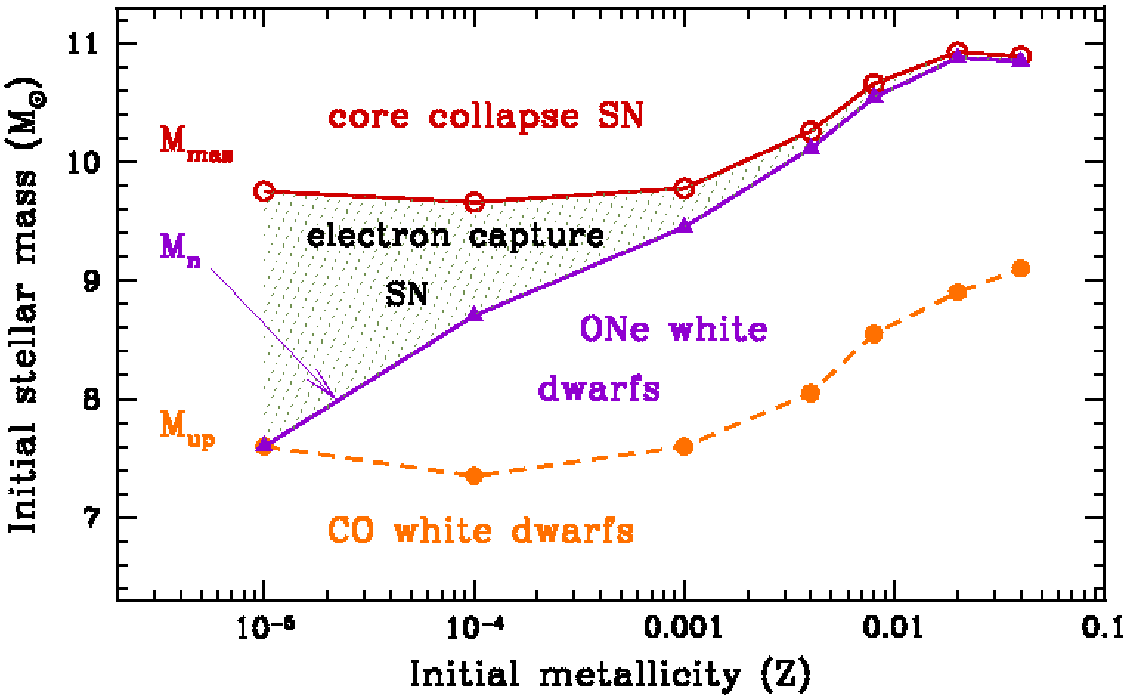
Pre-SN evolution of Super AGB stars



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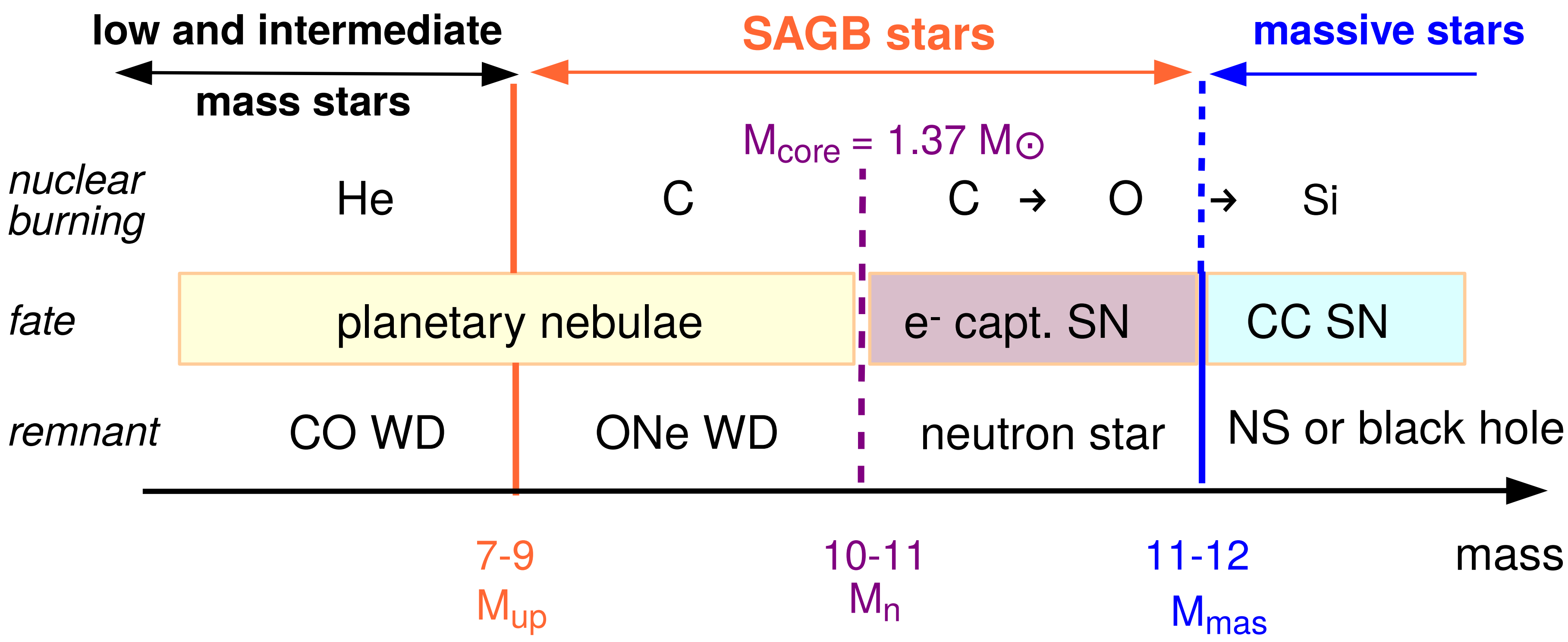
Who are SAGB stars

- B type stars on the main sequence
- massive counterparts of AGB stars
- ignite carbon but do not proceed to further nuclear burning stages
- responsible for the formation of ONe white dwarfs
- may explode as electron capture SN (EC-SN)



Evolution up to C-ignition

Standard evolution up to C ignition

- convective H core burning
- followed by 1DUP

  no 1DUP below $Z \leq 0.001$

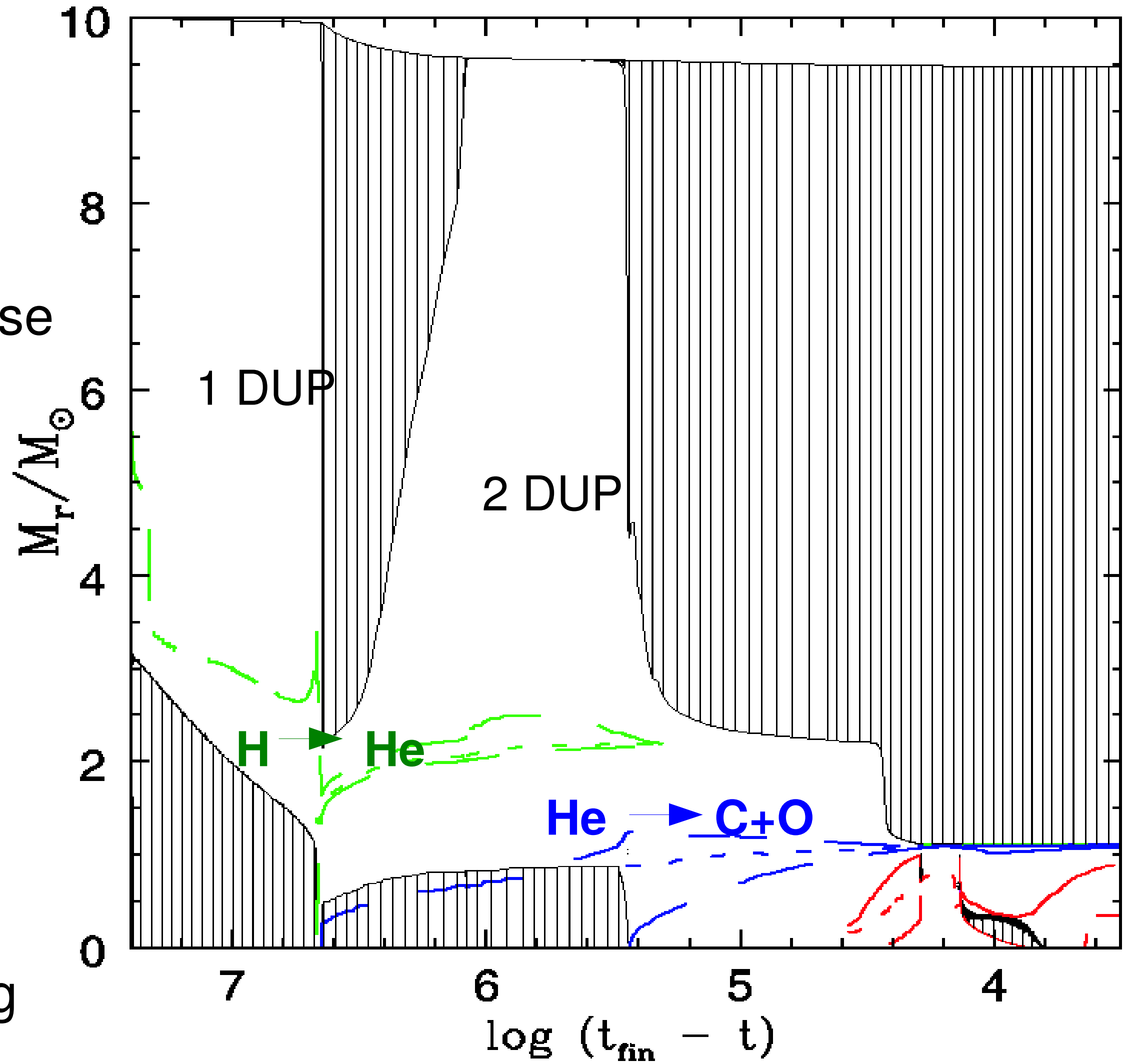
- chemical signatures similar to those of lower mass stars

↗	$^{3,4}He$, ^{13}C, ^{14}N
↘	$^{12}C/^{13}C$

- standard core He burning phase

2DUP

→ before, during or after C burning



M = 10 , Z = 0.02

Carbon burning

proceeds in 2 steps

1) carbon flash

off center C ignition at $T_{max} \sim 6.10^8$ K

partial degeneracy $\eta \sim 2$- 3

flash short lived (<few 1000 yr) and energetic $10^6 < L_C/L_\odot < 2.10^8$

2) flame

C re-ignites at lower $\eta \sim 1$

instability develops in regions where carbon was partially burnt

peak luminosity lower : no quenching

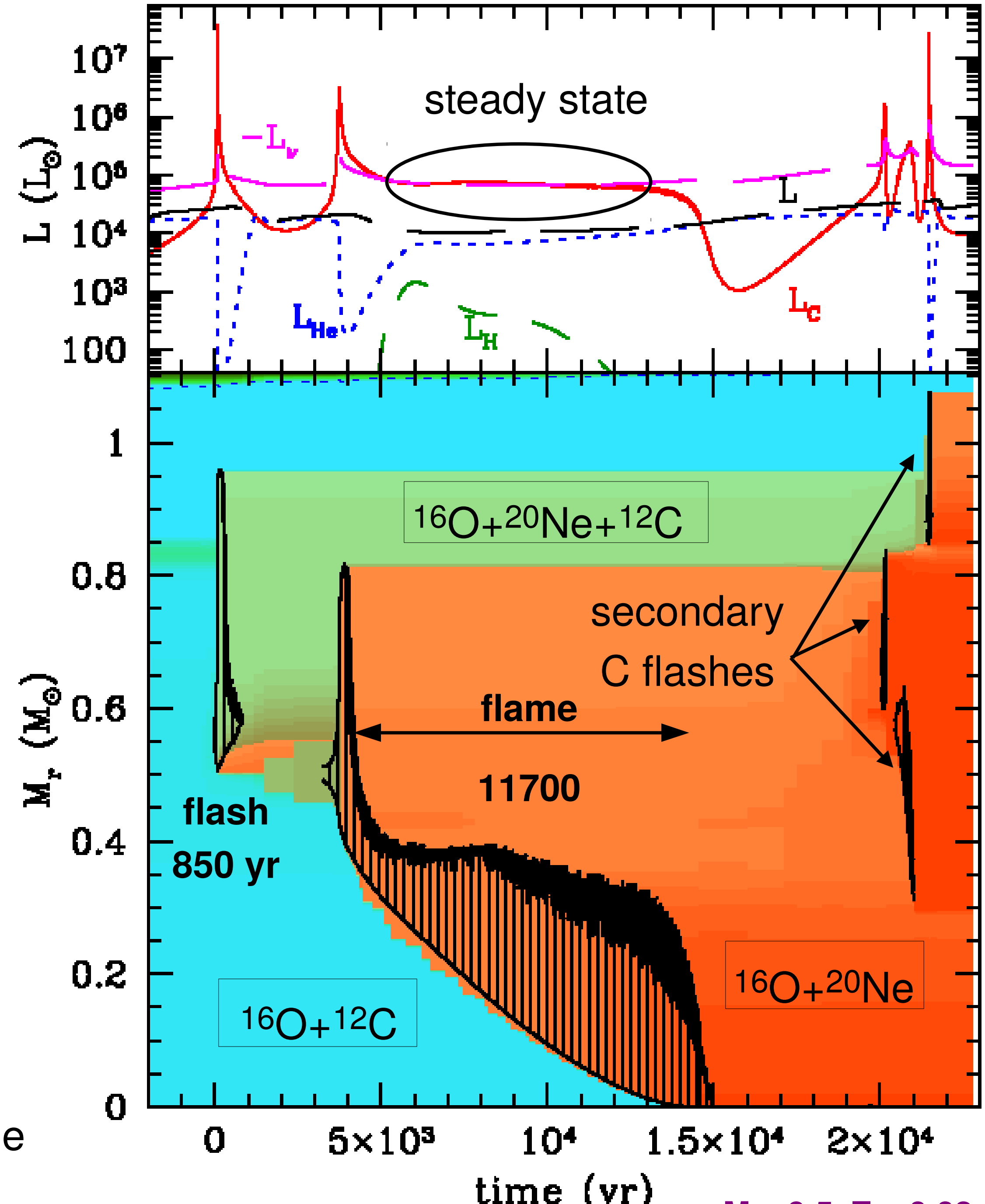
steady state : energy generated by C burning is carried away by neutrinos :

$$L_C = - L_\nu$$

surface decoupled : $L \sim L_{He}$

Extra mixing can quench the flame

→ talk by *Farmer*



M = 9.5, Z = 0.02

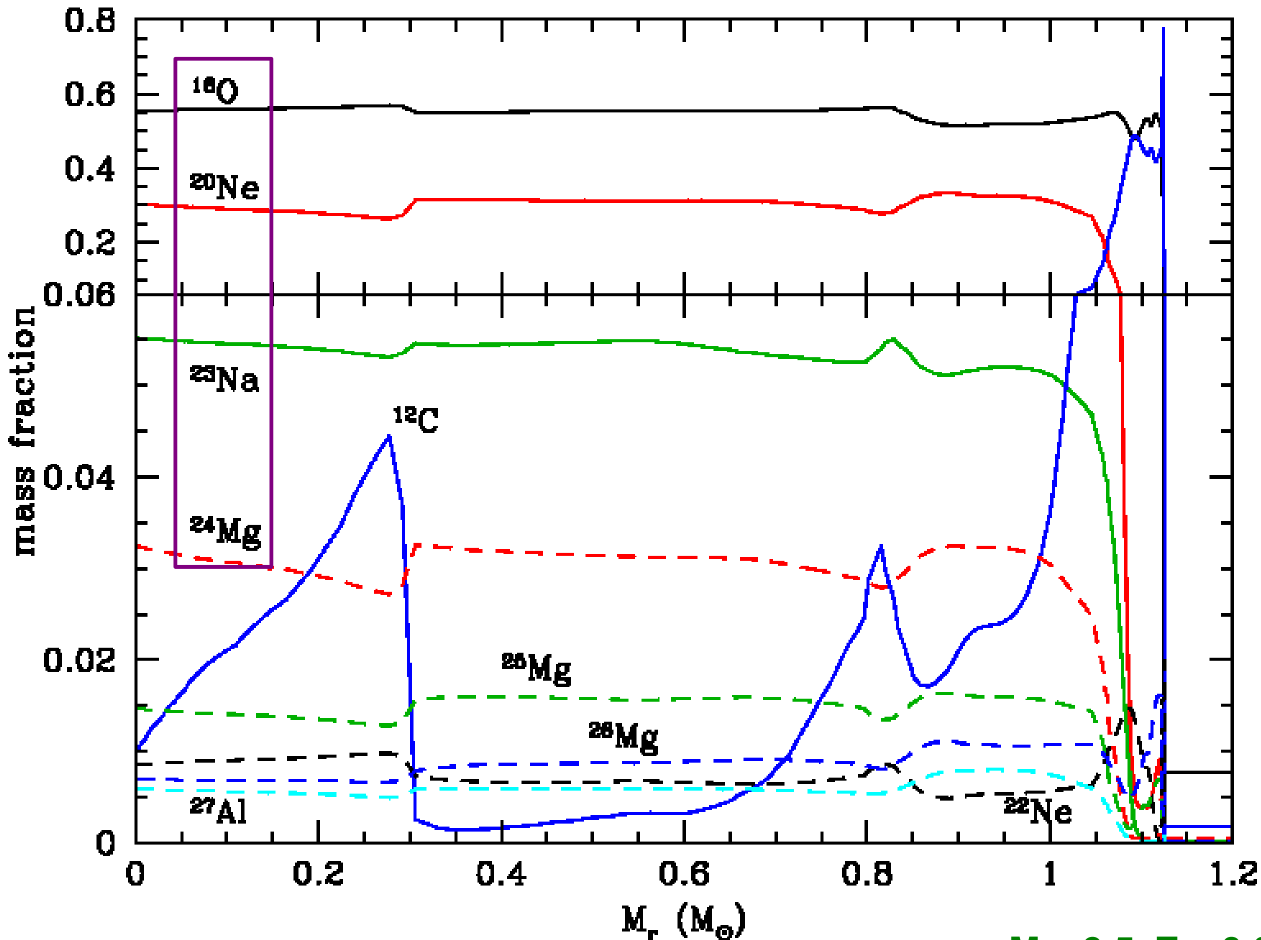
Core composition at the end of C burning

main reactions

$^{12}C\ (^{12}C, p)\ ^{23}Na$
$^{12}C\ (^{12}C, \alpha)\ ^{20}Ne$
$^{16}O\ (\alpha, \gamma)\ ^{20}Ne$

secondary reactions

$^{22}Ne\ (\alpha, n)\ ^{25}Mg$
$^{22}Ne\ (\alpha, \gamma)\ ^{26}Mg$
$^{23}Na\ (p, \alpha)\ ^{20}Ne$
$^{23}Na\ (p, \gamma)\ ^{24}Mg$
$^{26}Mg\ (p, \gamma)\ ^{27}Al$



M = 9.5, Z = 0.02

(n, γ) reactions ➔ production of ^{13}C, ^{17}O, ^{21}Ne, ^{26}Mg, s-process

Presence of **unburnt ^{12}C** in the core

Extra mixing can alter the core composition

Evolution as a function of initial mass

C-burning characteristics

when M_{zams} ↗

degeneracy η ↘

$M_{C,igni}$ ↘ L_{flash} ↘ dt_{flame} ↘

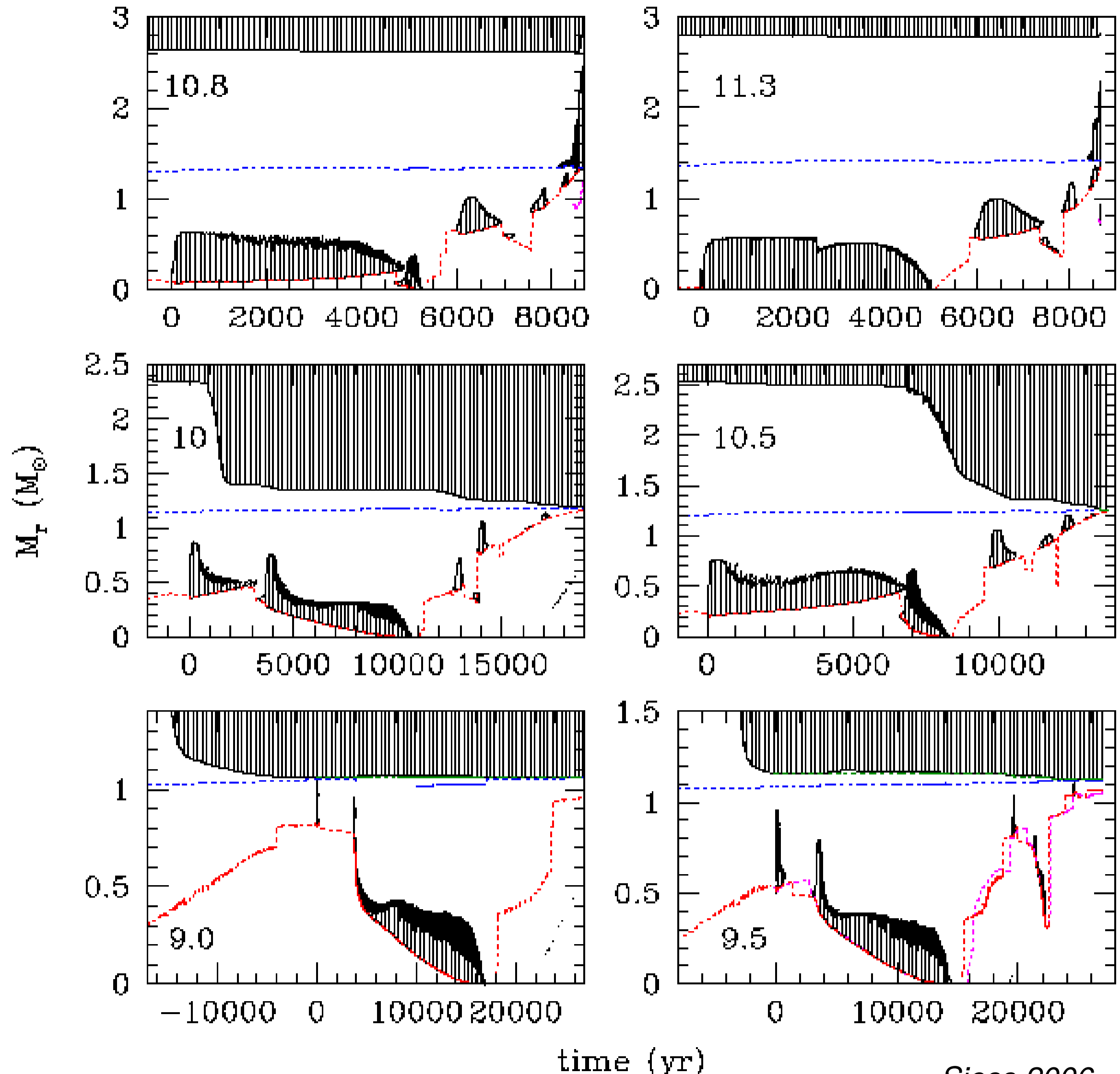
2DUP

when M_{zams} ↗

2DUP occurs later and is deeper : reaches top HeBS

↗ ^{4}He, ^{13}C, ^{14}N

↘ H, ^{12}C, ^{16,18}O



Siess 2006

aborted carbon burning in lower mass SAGB (*Doherty et al 2012*)

dredge-out in the most massive SAGBs

Z = 0.02 models

The dredge-out phenomenon

In the *most massive SAGB* stars, near the *end of C-burning*

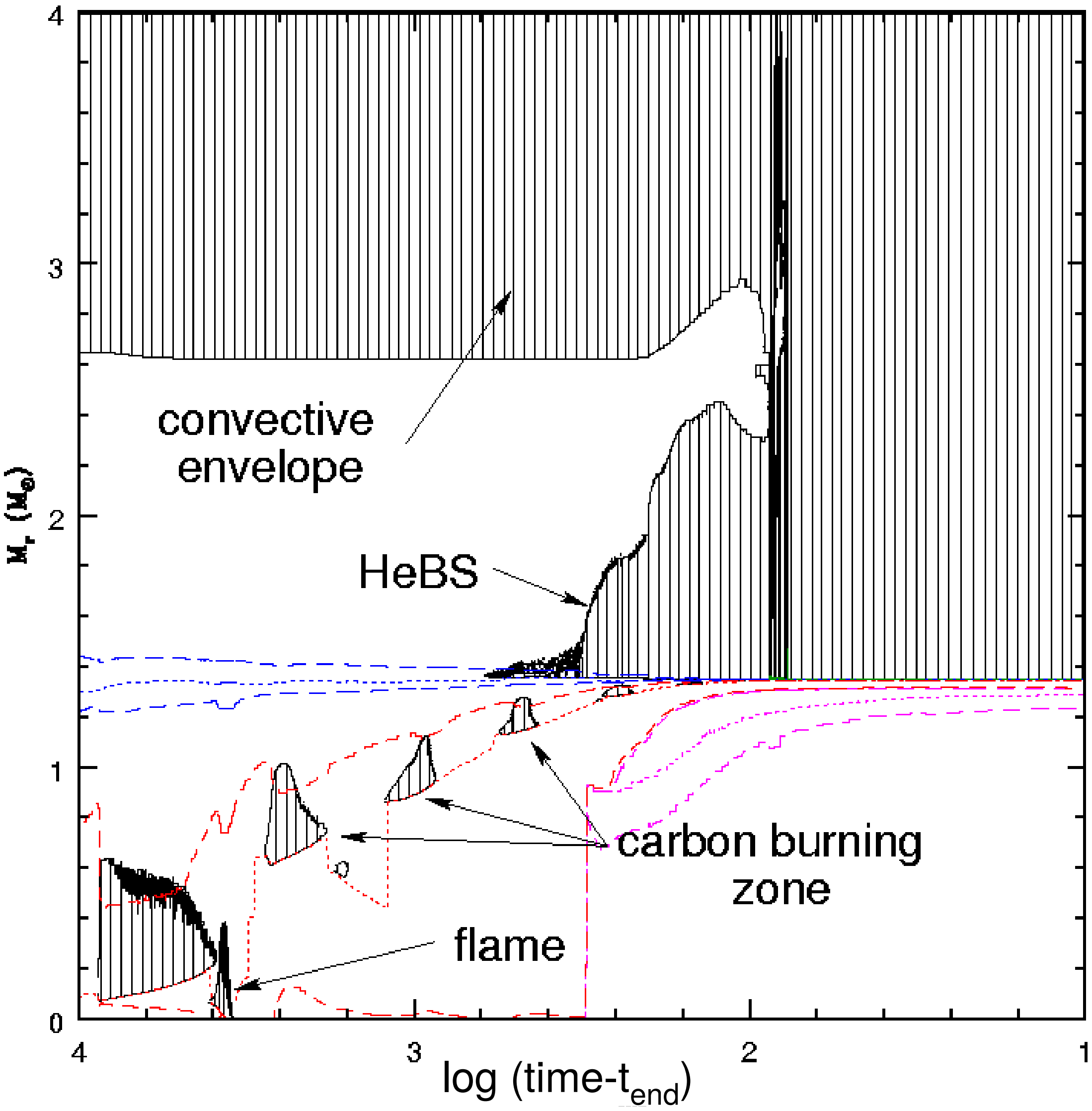
1) convection develops in the HeBS

2) the He driven convective zone moves outward

3) merges with the envelope

Consequences

- envelope pollution ↗ ^{4}He, ^{12}C, ^{14}N
- proton injection, new elements ?
  → *Ritter*
- decrease in the core mass



M = 10.8 , Z = 0.02

Siess 2006

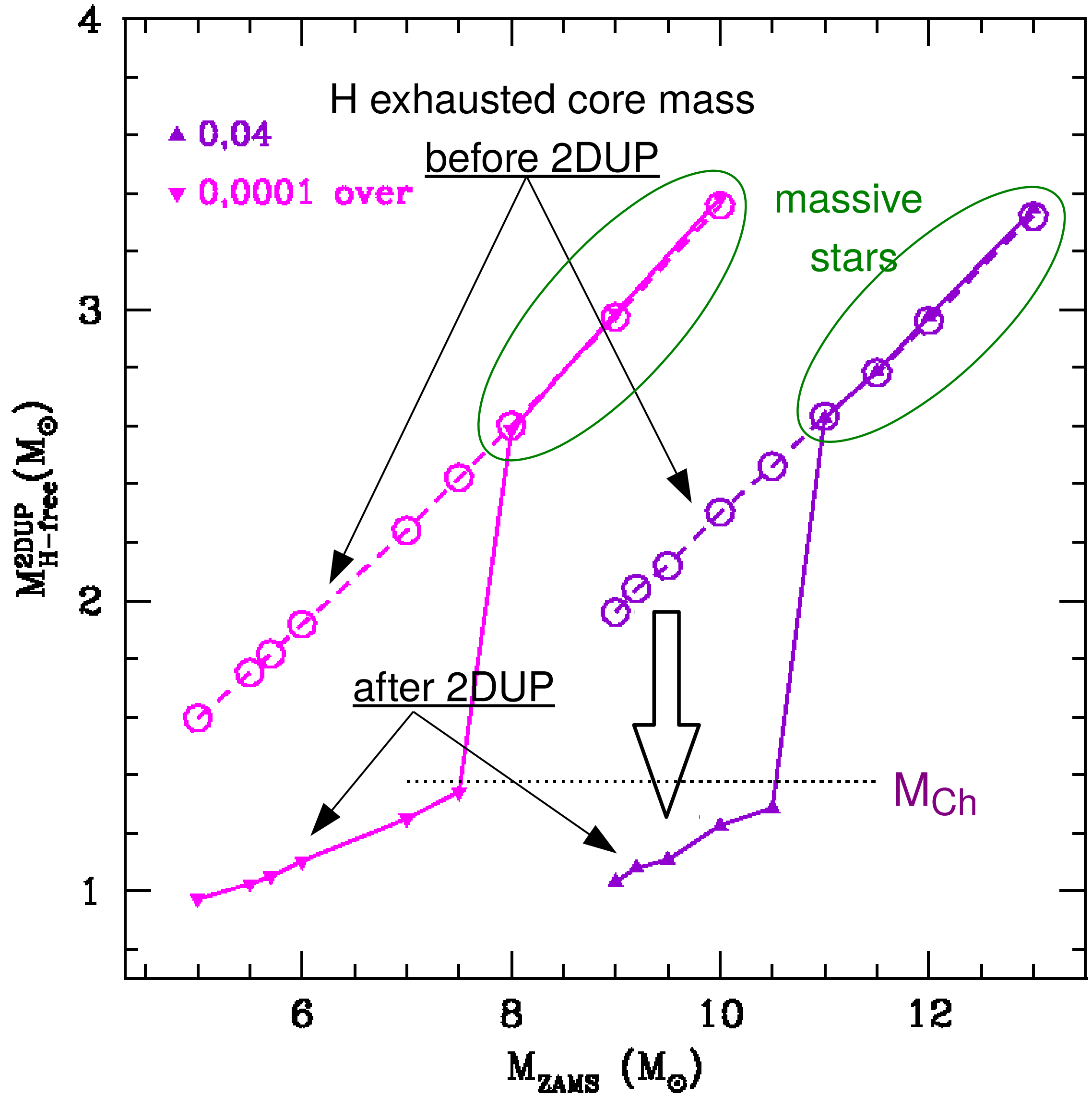
About the second dredge-up

the fate of the star is intimately related to the 2DUP

the 2DUP provokes a reduction of H-depleted core mass $M_{H\text{-free}}$ below the Chandrasekhar limit M_{Ch}

Massive stars do not experience 2DUP and have $M_{core} > M_{Ch}$

SAGB : most massive stars that still undergo 2DUP



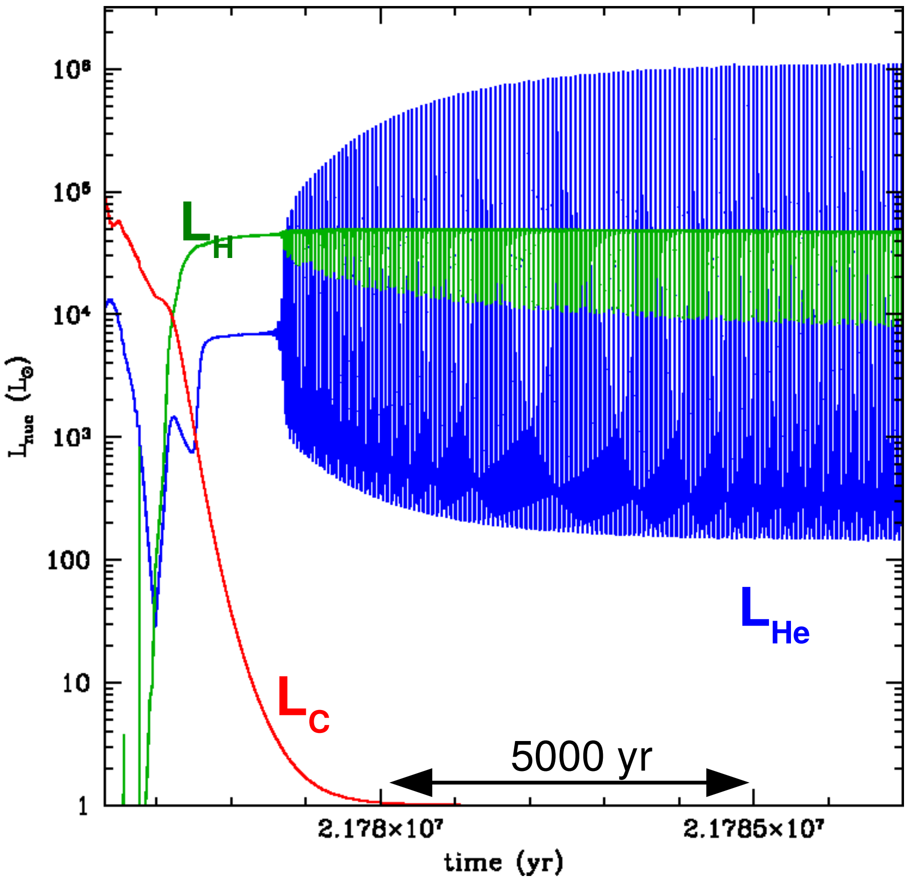
Siess 2007

The thermally pulsing SAGB phase

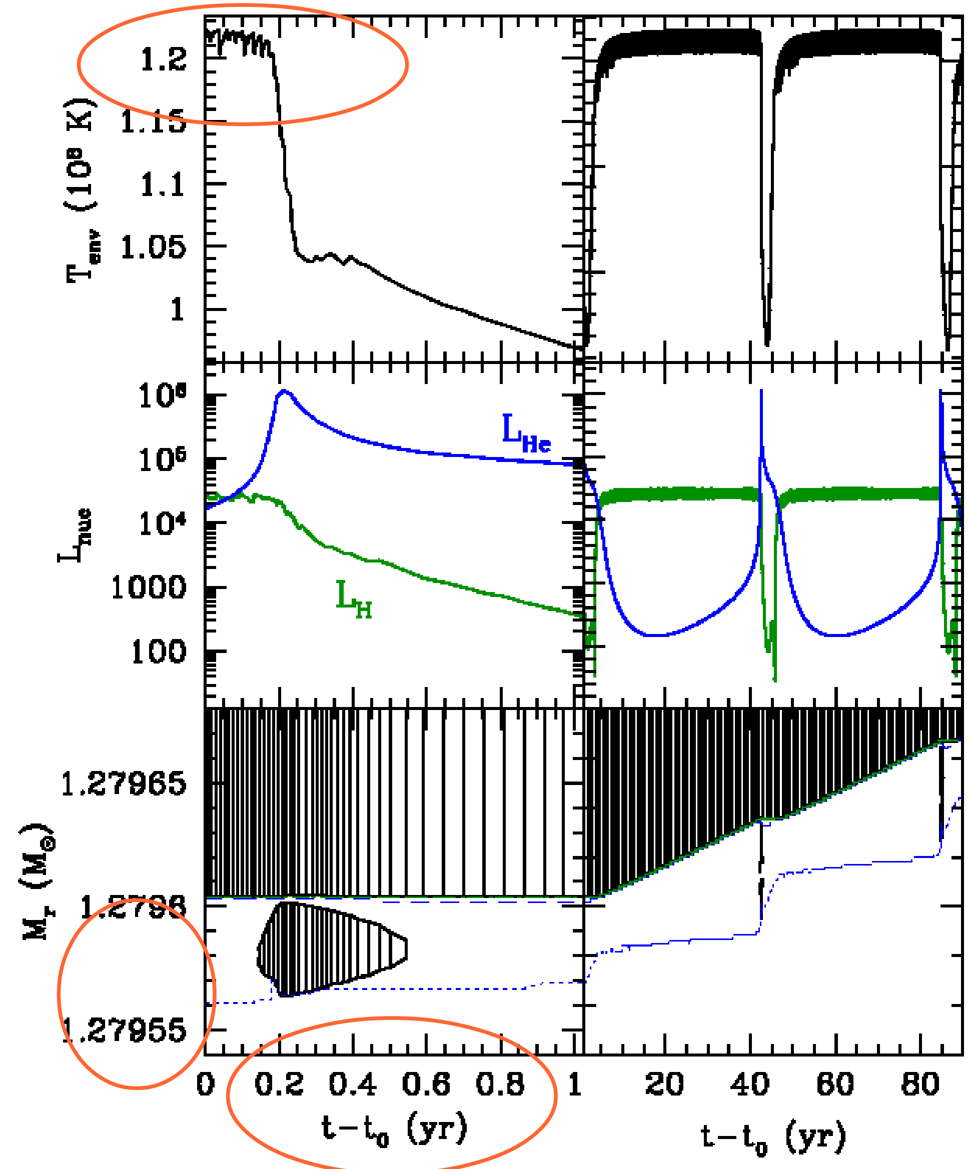
L_{He} < few 10^6 $L_\odot$

T_{env} very high

pulse & interpulse duration short



M = 10.5 , Z = 0.02



Scale !

M = 10.5 , Z = 0.02

TP-SAGB : comparisons

pulses

weak : $L_{He} \sim 10^6 L_\odot$

small : $M_{pulse} < 2\ 10^{-4} M_\odot$

short lived ~ few yr

interpulse : < few 100 yr

<u>very high</u> temperatures

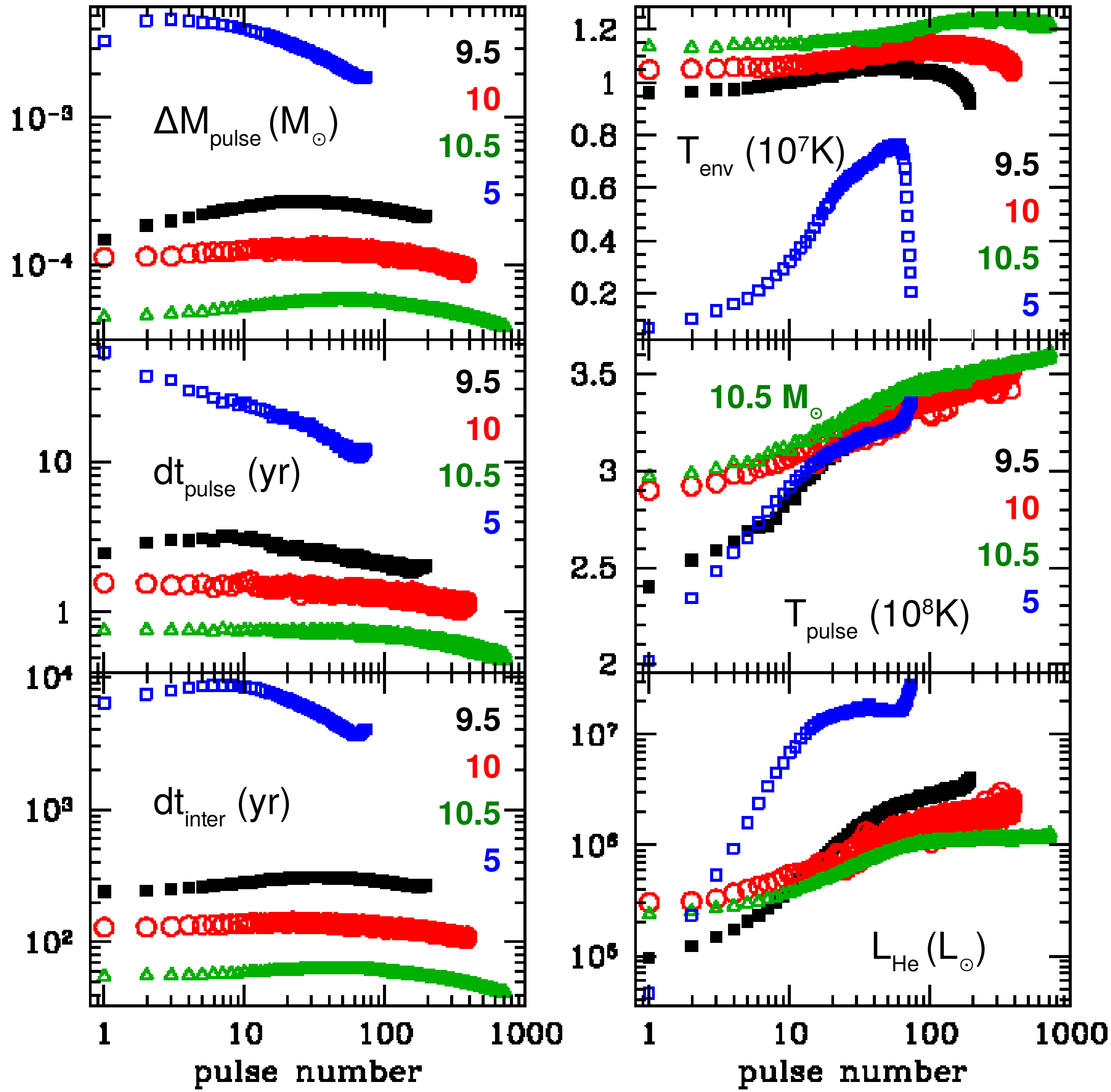
at the base of the

- pulse (> 3.3 10^8K)
- envelope (> 1.3 10^8K)

many pulses ~ 300-3000 !

nucleosynthesis

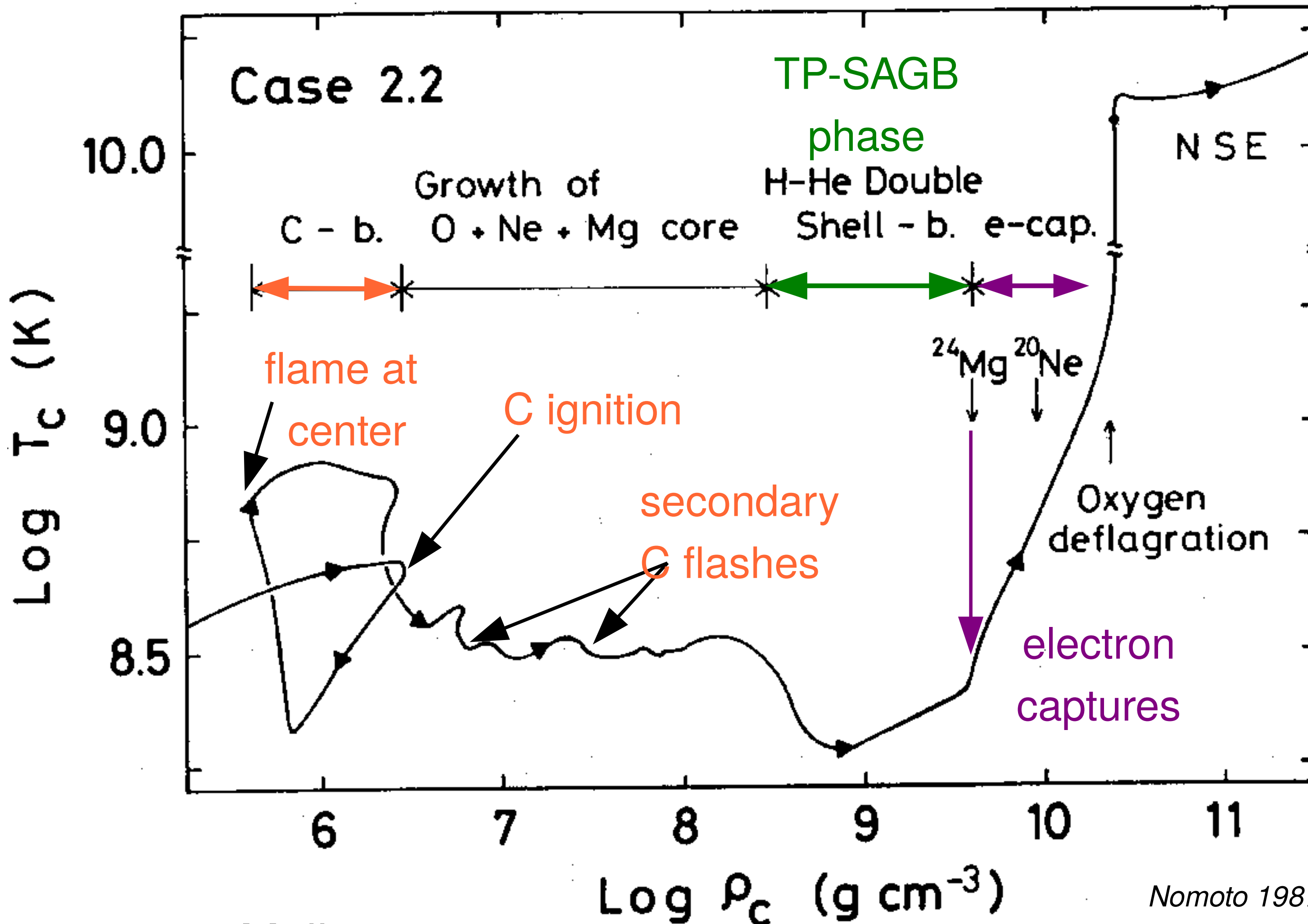
→ talks by *Doherty*, *Karakas*



5 $M_\odot$ - 9.5 $M_\odot$ - 10 $M_\odot$ - 10.5 $M_\odot$ Z = 0.02

The explosive fate of SAGB stars

- electron captures start on ^{27}**Al** when $M_{core} \approx 1.37\ M_\odot$
- then proceed on ^{25}**Mg**, ^{23}**Na**, ^{20}**Ne**
- convection and URCA process → *Schwab*
- core collapses
- oxygen ignites
- core reaches NSE
- SN explosion & formation of a neutron star → *Muller*



Nomoto 1987

Mass range of SAGB stars

$M_{up} \leq M_{zams} \leq M_{mas}$

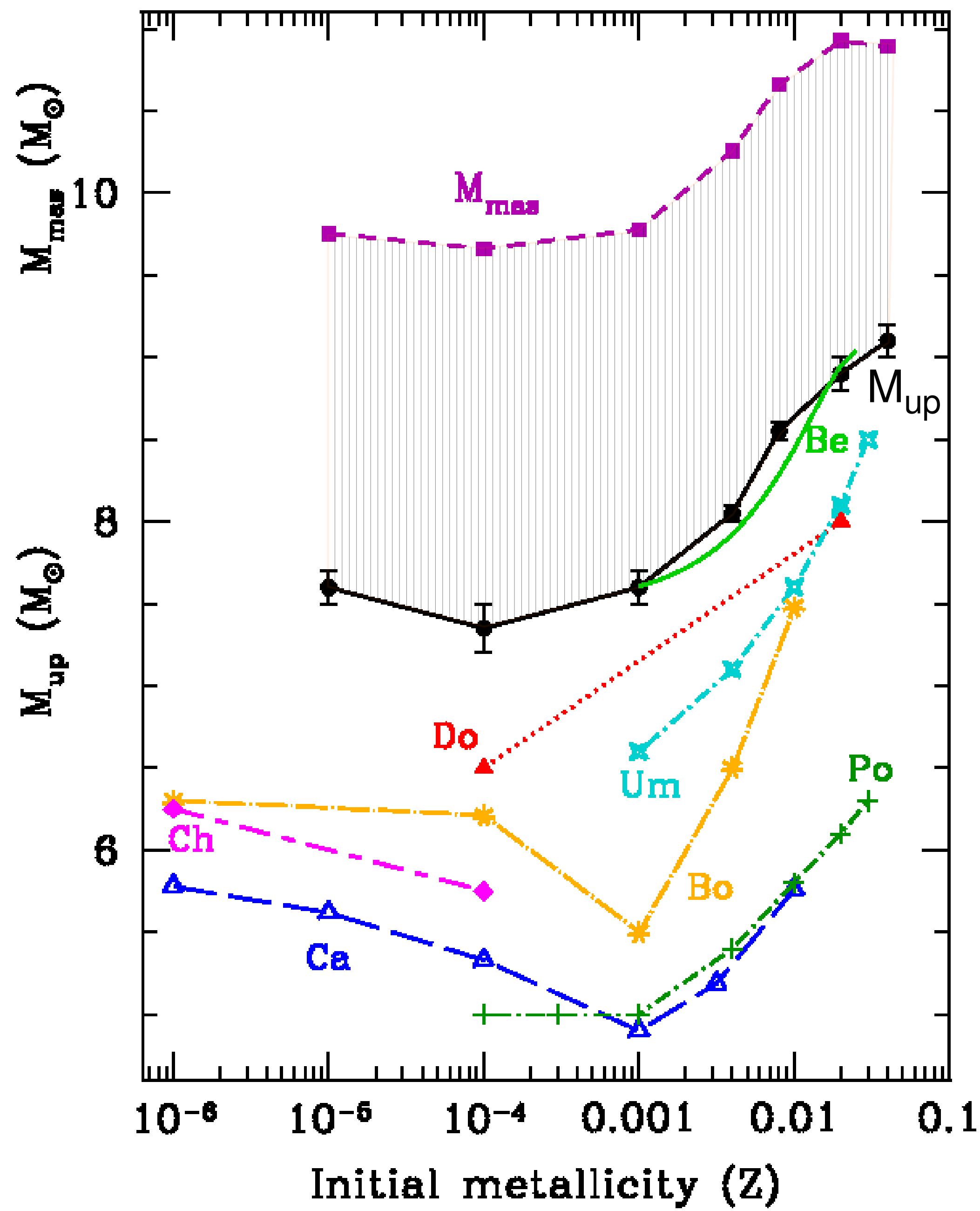
M_{up} minimum mass for C ignition

M_{mas} minimum mass for no 2DUP

Large uncertainties in M_{up} :

treatment of core He burning

M_{up} and **M_{mas}** ↘ with *Z* due to opacity effects (T, L ↗ with ↘ *Z*) and at very low *Z*, CNO burning less efficient



Siess 2007

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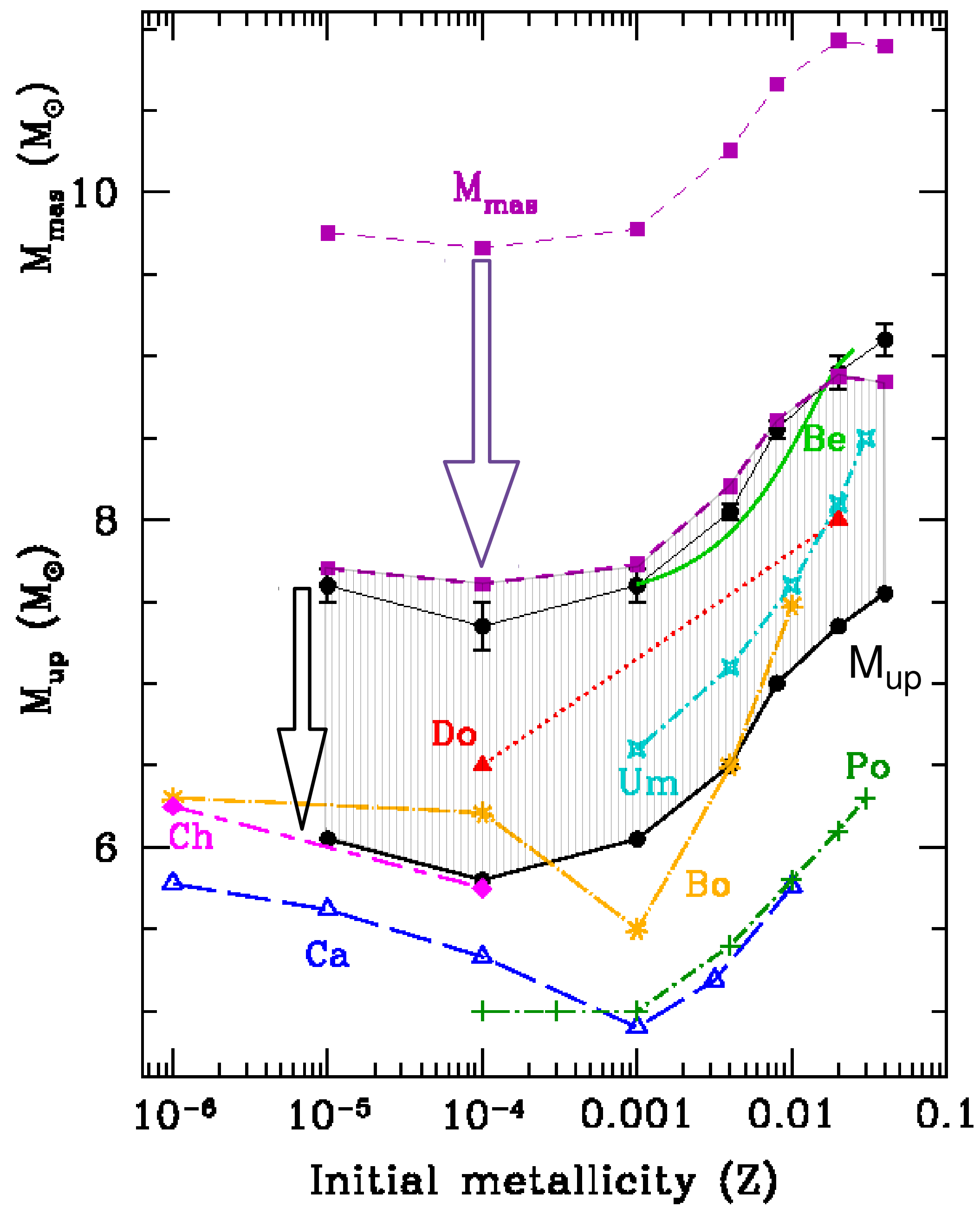
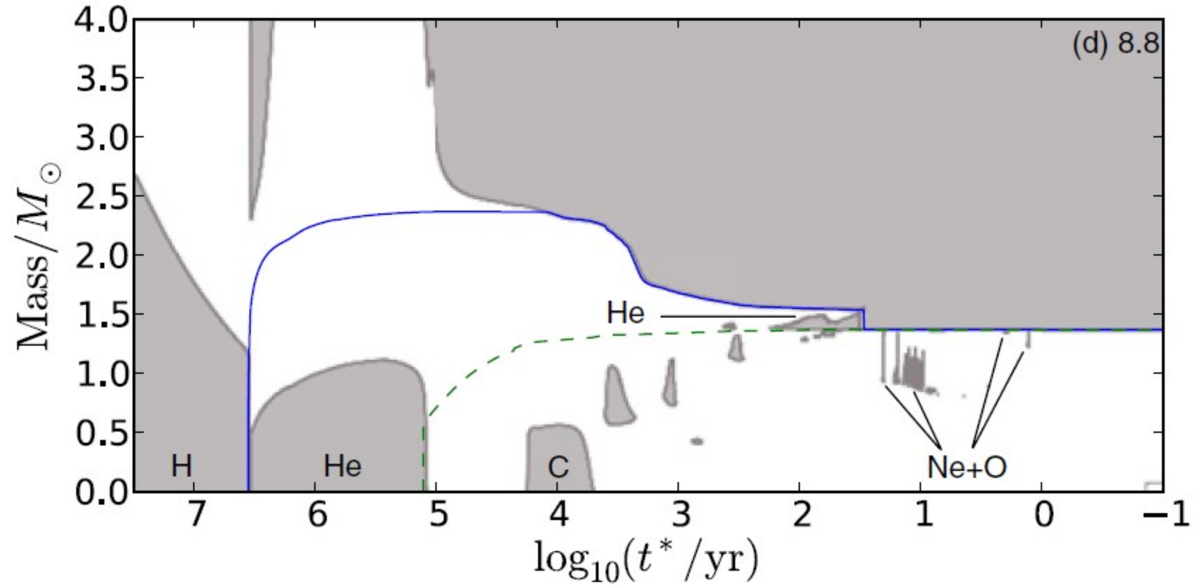
Large impact of overshooting reduces M_{up} and M_{mas} by ~ 2 $M_\odot$



Siess 2007

The initial mass of electron capture supernovae

At the end of C burning, some stars have a core mass close to 1.37 $M_\odot$ and do not enter the SAGB phase.
They ignite Ne off center and some of them will evolve towards EC-SN



Jones et al 2013

→ talk by *Nomoto*

The star goes SN if the core mass reaches $M_{core}^{final} = M_{core}^{2dup} + \Delta M_{core} = 1.37 M_\odot$

The increase of the core mass during the TP-SAGB phase ΔM_{core} depends on

- mass loss rate $\dot{M}_{loss}$: poorly known for SAGBs, Z dependence ?
- core growth rate $\dot{M}_{core}$: depends on 3DUP efficient, badly constrained

Mass range for EC supernovae

For each ($\dot{M}_{core}$, $\dot{M}_{loss}$) we determine how much mass is accreted on the core

$\Delta M_{core} = f(\zeta)$ with $\zeta = \langle \dot{M}_{loss} \rangle / \langle \dot{M}_{core} \rangle$

efficient 3DUP $\zeta \gg 1$: $M_n \rightarrow M_{mas}$

→ no SAGB go ECSN

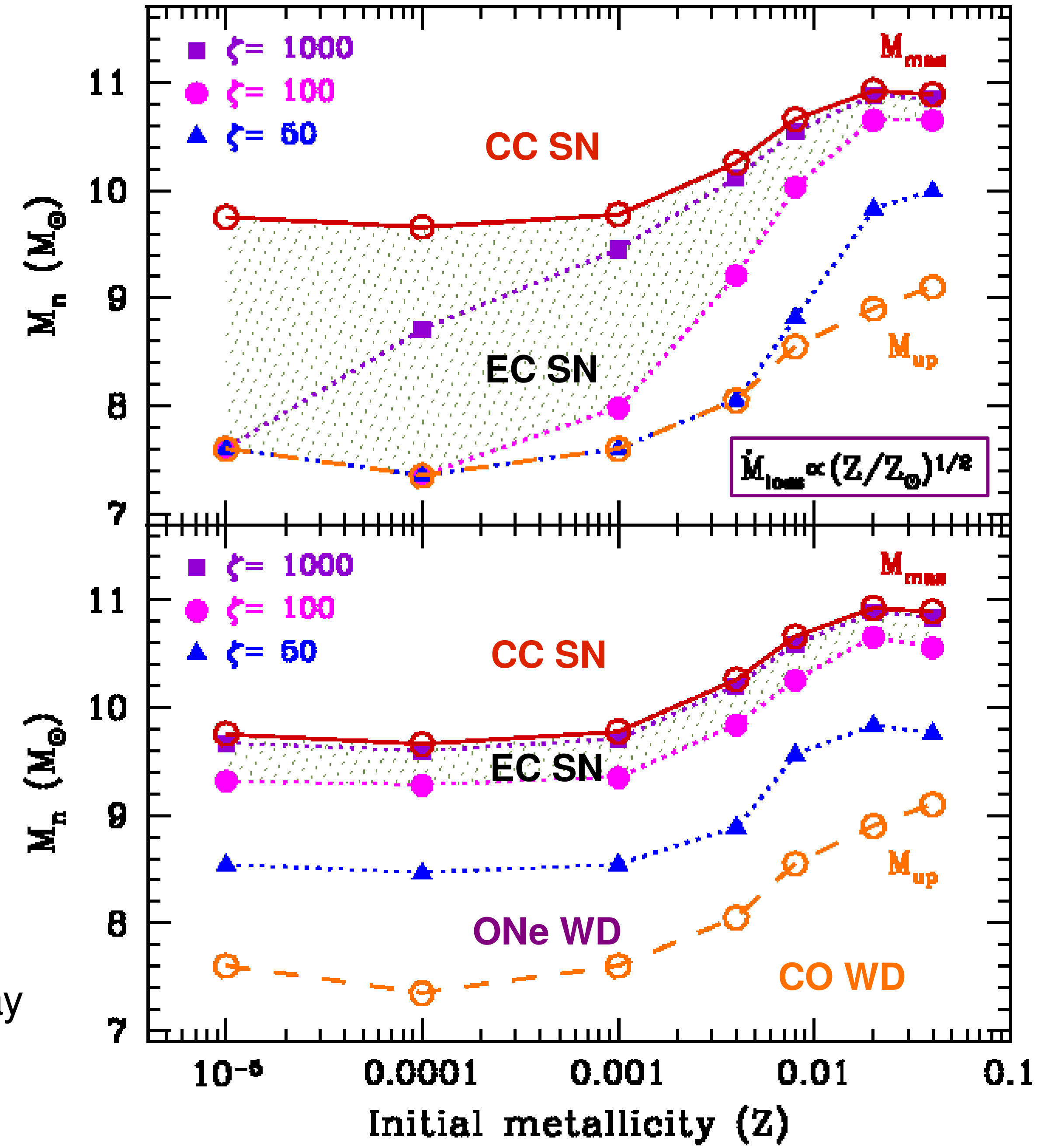
weak mass loss $\zeta \sim 1$: $M_n \rightarrow M_{up}$

→ all SAGB evolve into ECSN

Metallicity dependent mass loss

if $\dot{M}_{loss}$ ↘ with ↘ Z then ζ ↘

→ many low metallicity SAGB stars may then evolve into EC SN

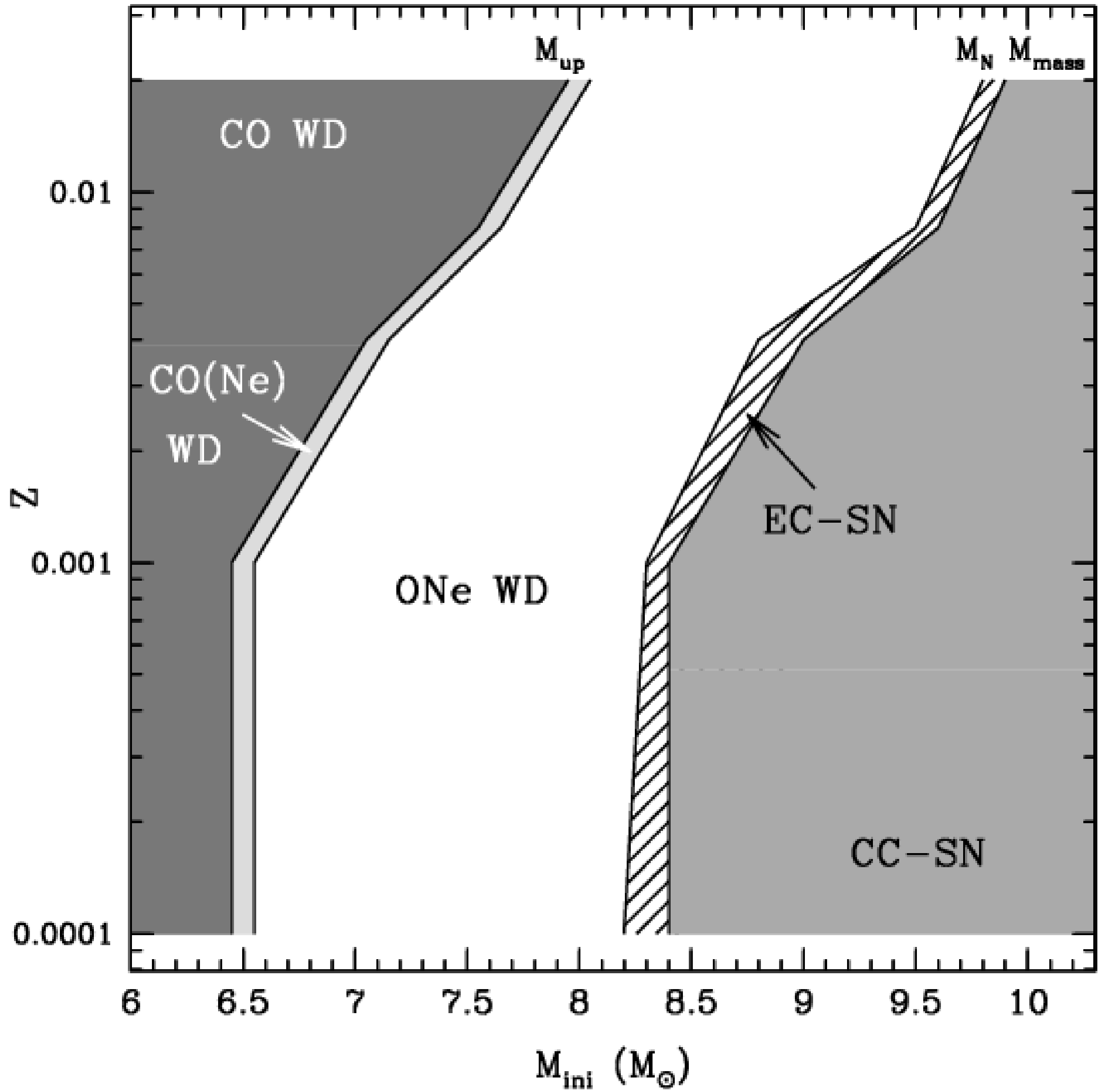


Realistic models including the full TP-SAGB evolution and using the Vassiliadis and Wood mass loss rate with no metallicity dependence indeed indicates that

the mass range of single SAGB star evolving towards electron capture is very narrow

$\Delta M_{EC} \sim 0.2\text{-}0.3\ M_\odot$

→ binaries evolution may be a more promising channel



Doherty et al 2014

The binary path to EC SN

The classical

CV-like picture

1 - RLOF mass transfer (late case BB)

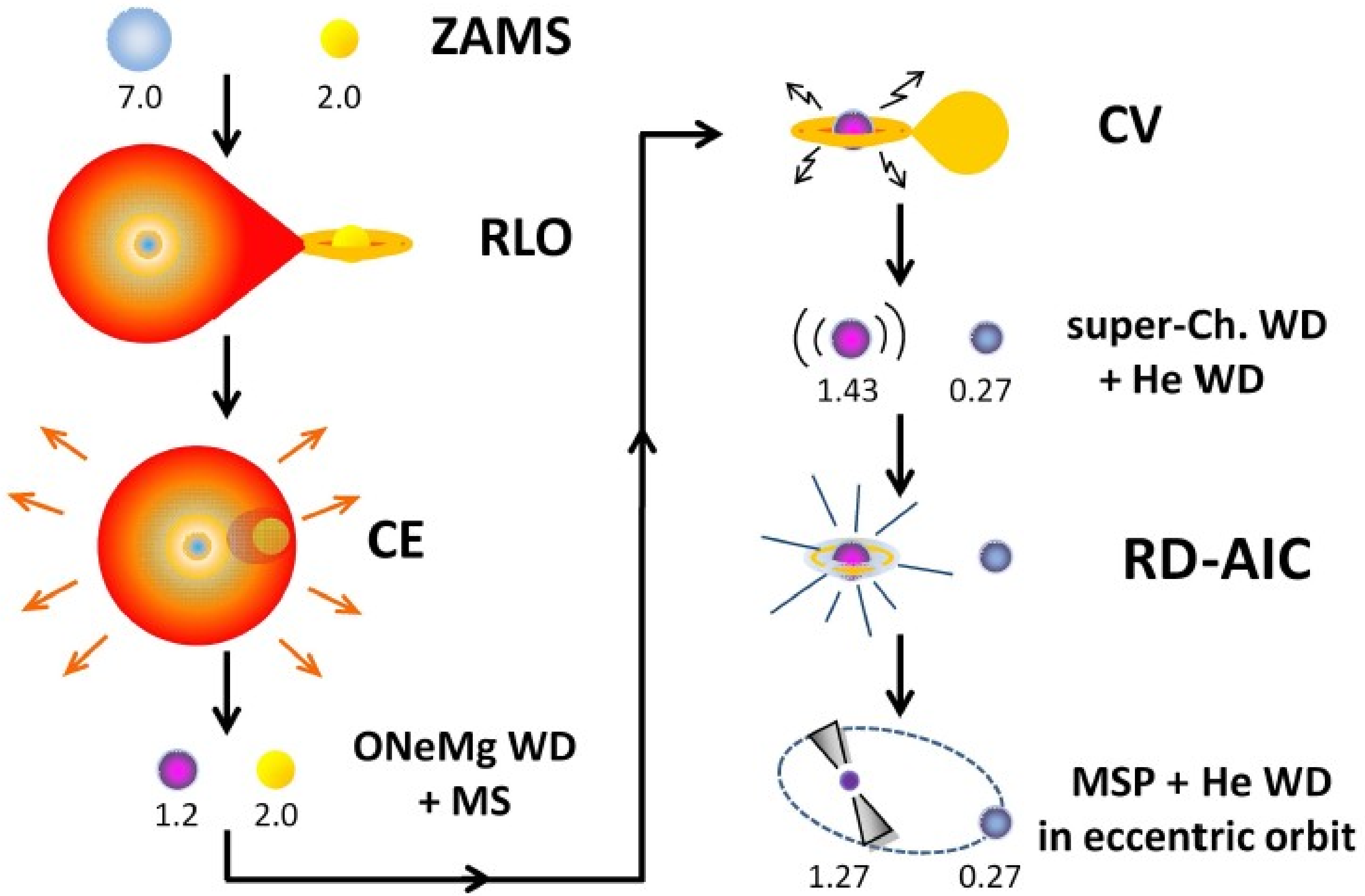
2 - Common envelope evolution

3 – X-ray CV

4 – ONe WD reach M_{ch}

5 – explosion : accretion induced collapse

6 – formation of a milli-second pulsar

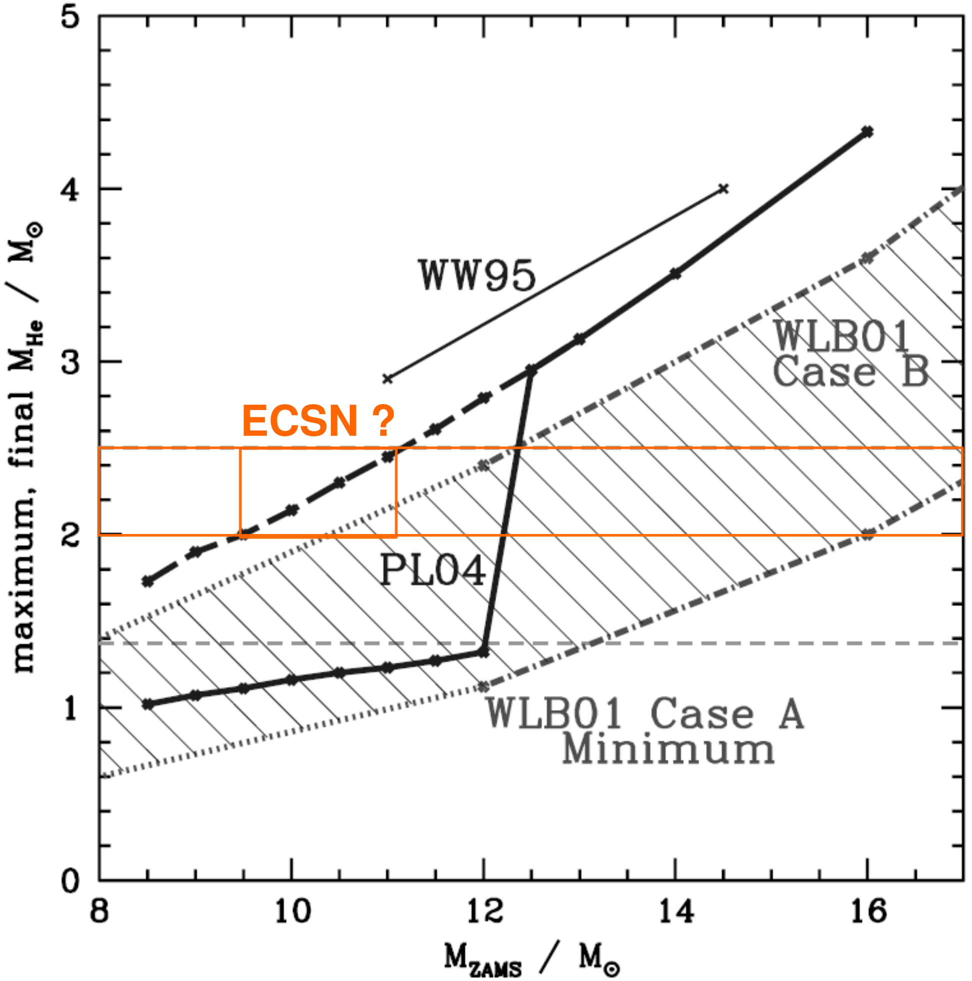


Freire & Tauris (2014)

The alternative binary path

The idea (*Podsiadlowski et al 2004*) is to prevent the 2DUP from occurring by removing the envelope of the SAGB during binary interaction.

If the mass of the He core remains $2 < M_{He\text{-}core}/M_{\odot} < 2.5$, then the star can potentially evolve into an EC-SN *(Nomoto 1984)*



Binary interaction will modify the evolution of the helium core and alter its C/O ratio, spin velocity so the evolution may differ from that of an isolated He core

Podsiadlowski et al 2004

Open questions

Who are the progenitors of EC-SN ?

- single star progenitors rare, what about binary channel → *Eldridge, Petermann*
- where is the transition between EC-SN and CC SN → *Nomoto*

What is the structure of the progenitor

- How extra-mixing impacts the core composition → *Farmer, Ritter*
- and the subsequent explosion ?

How do EC-SN explode ?

- 3D simulations → *Muller, Hix*
- What is the role of the URCA process → *Schwab*
- Will the explosion imprint a low kick to the neutron star ?

What are the observational signatures of EC-SN

- What is the rate of EC-SN, Were they more frequent in the past ? → *Ruiter*
- What is the contribution of ECSN to the galactic chemical evolution → *Travaglio*
- What kind of light curve shall we expect (type IIP?) → *Moriya*
- Are EC-SN the site for a rich nucleosynthesis ? → *Chieffi, Hix, Qian, Sieverding*

A laboratory for physics :

- EOS of dense neutron rich matter → *Brown's talks, Toki*
- Nuclear reactions rates → *Martinez-Pinedo*