Super-AGB stars
Lives, deaths & element production

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Overview

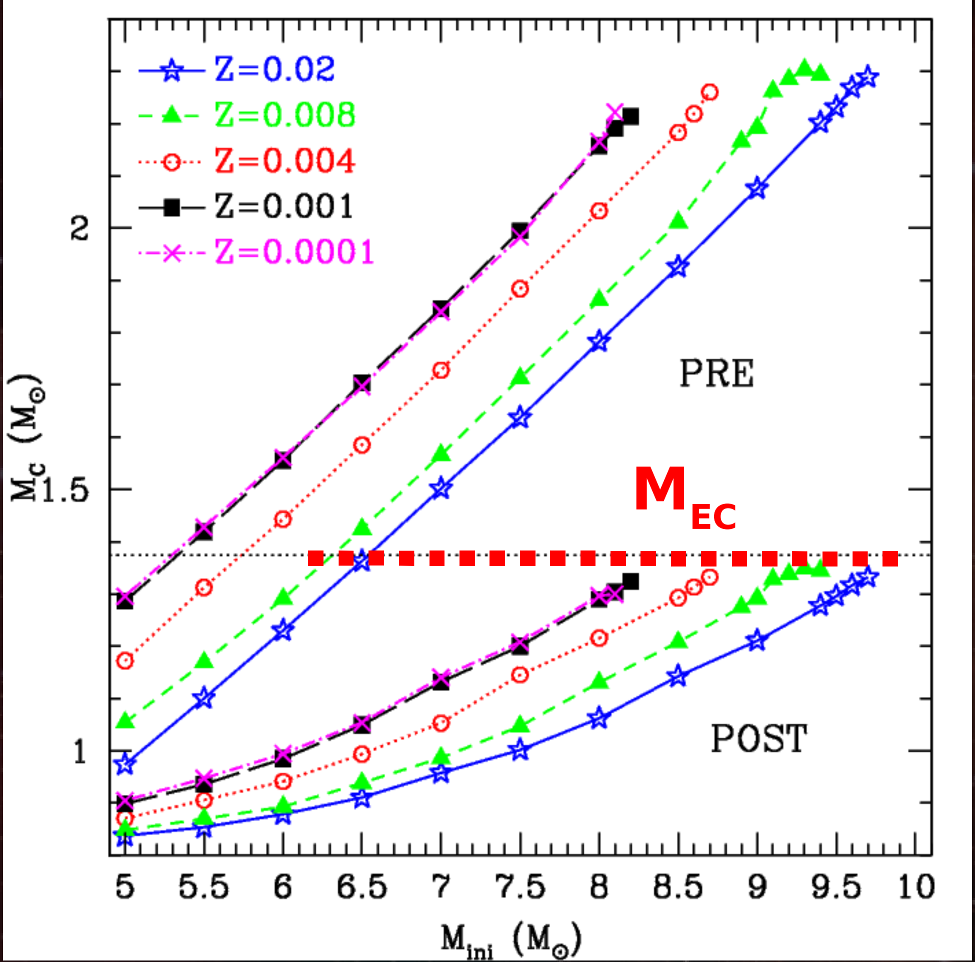
Final Fates - Initial-to final mass relation

- Core growth rate
  - third dredge up
- Mass loss
  - Low Temperature opacities
  - Low metallicity
  - Fe peak instability and envelope ejection

Element production - Nucleosynthesis

Summary and Conclusion

The Final Fates "Race"



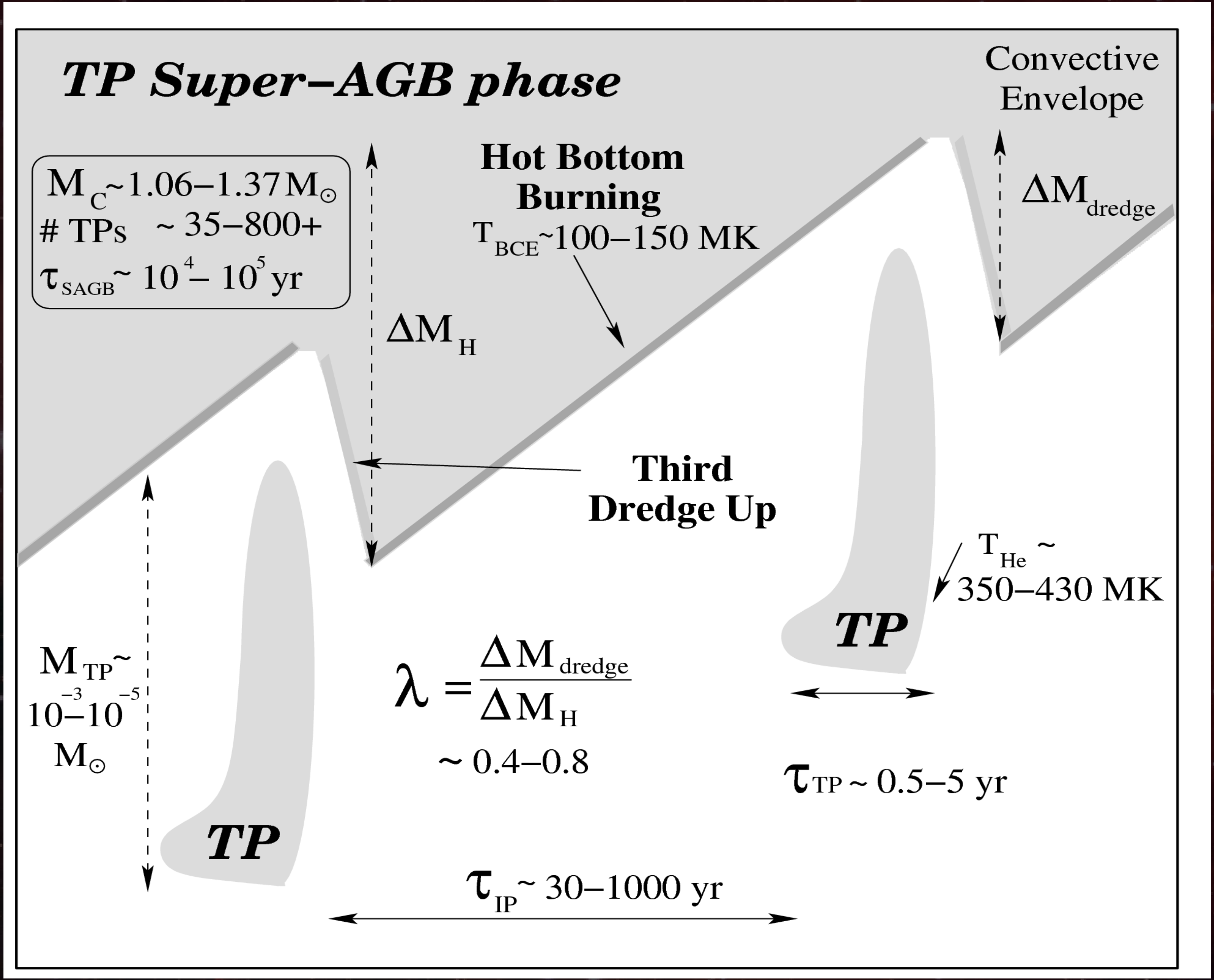
If Post 2DU $M_c > M_{Ch}$
(Massive star)

Post 2DU core mass

If M_c reaches M_{Ch} ≈1.375 M⊙ then an EC-SN will occur

Competition between mass loss and core growth determines fate

TP Super–AGB phase



$M_C \sim 1.06–1.37 M_\odot$
$\#$ TPs ~ 35–800+
$\tau_{SAGB} \sim 10^4 – 10^5$ yr

Convective Envelope

Hot Bottom Burning
$T_{BCE} \sim 100–150$ MK

ΔM_H

ΔM_{dredge}

Third Dredge Up

$T_{He} \sim$ 350–430 MK

TP

TP

$M_{TP} \sim 10^{-3}–10^{-5} M_\odot$

$$\lambda = \frac{\Delta M_{dredge}}{\Delta M_H} \sim 0.4–0.8$$

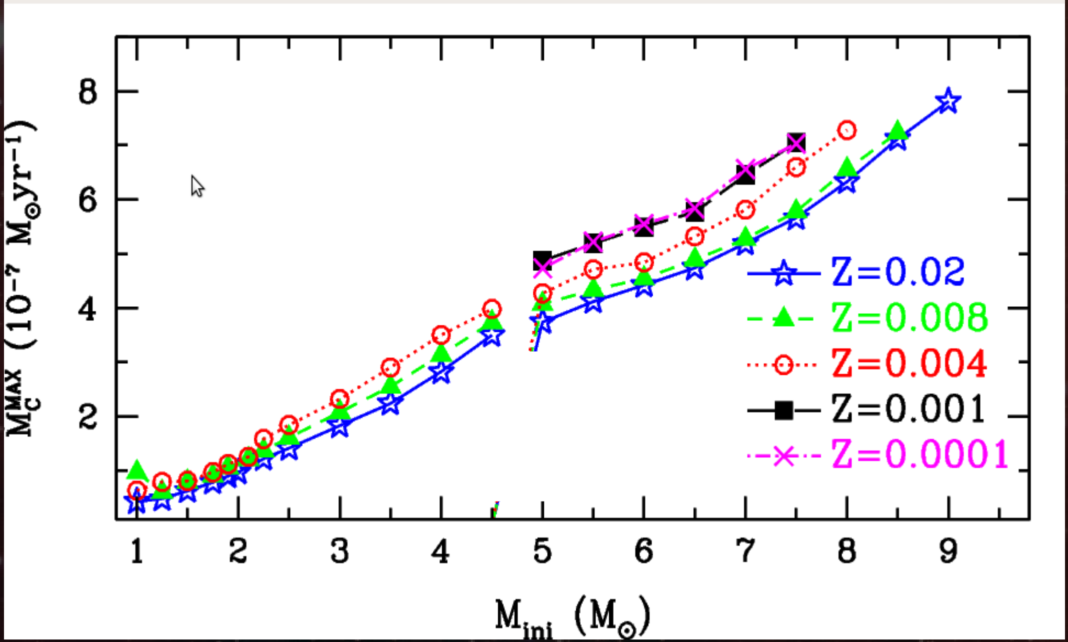
$\tau_{TP} \sim 0.5–5$ yr

$\tau_{IP} \sim 30–1000$ yr

Core growth rate

The core growth is determined by the H-burning shell

Faster core growth rate in the more massive and metal rich stars



Core growth rate as a function of initial mass

A strong anti-correlation between core growth rate and core radius with lower metallicity models having slower core growth rates by virtue of their more condensed structure.

~ $\Delta M_C \approx 5 \times 10^{-7}\ M_\odot/\text{yr}$

EFFECTIVE core growth also depends on 3DU

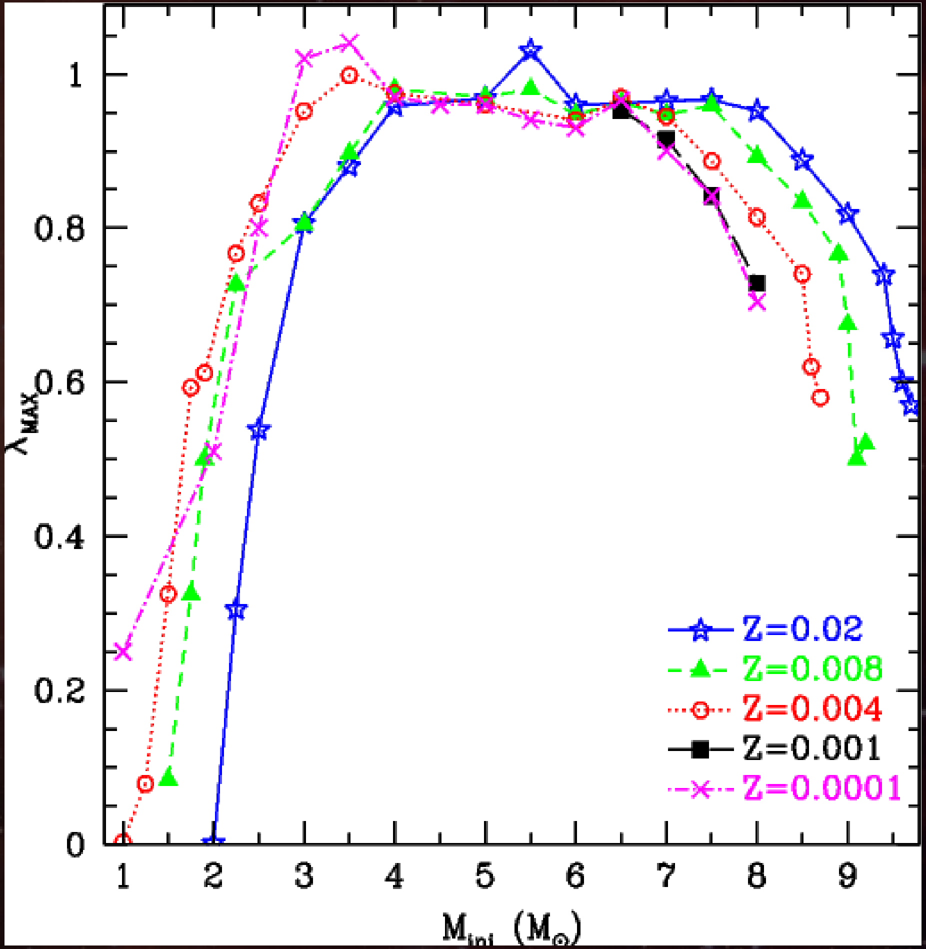
Third dredge-up (3DU) ?

We find efficient 3DU with lamda values close to unity

But 3DU efficiency varies widely between different groups calculations.

e.g Siess 2010, Ventura et al. 2013 find no 3DU

Obs. Evidence - Rb (s-process) is 3DU product observed in O-rich AGBs in LMC & SMC (Garcia-Hernandez 2006,2009)

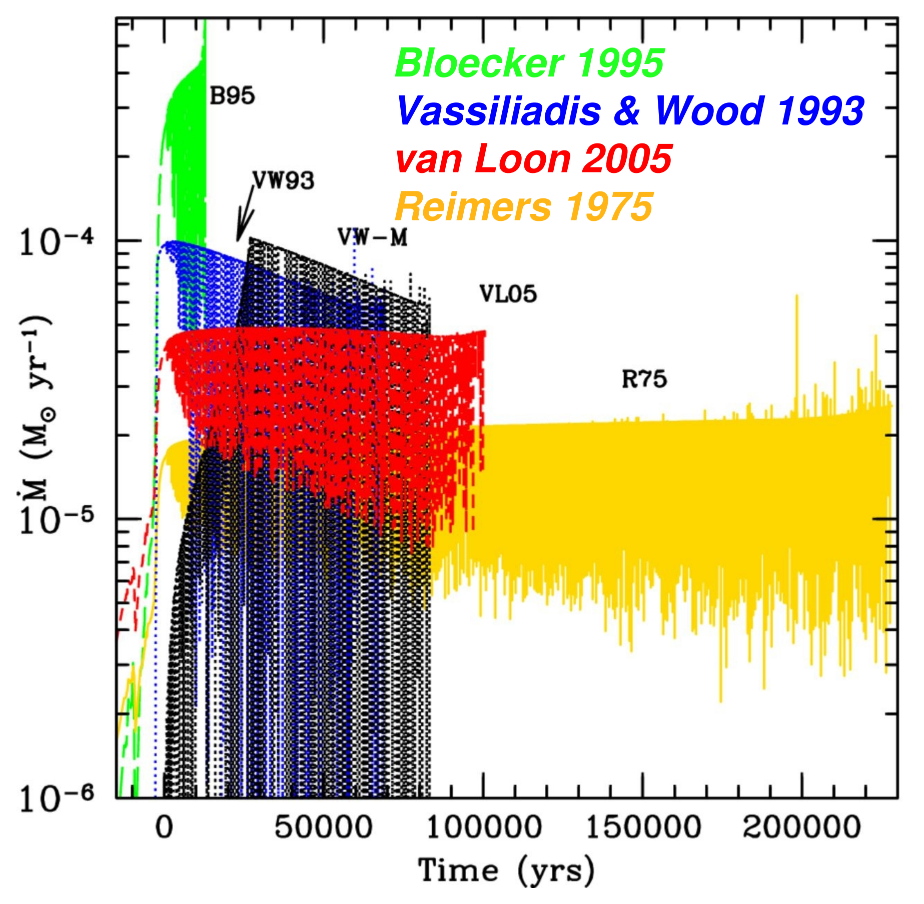


Mass loss rates

Mass loss in super-AGB stars assumed to be a combined process involving the levitation of material by radial pulsations, followed by formation of grains and then radiation pressure on these grains drives the wind

The uncertainty in mass-loss rate increases at lower metallicity!

We use the (relatively rapid mass-loss rate) from Vassiliadis & Wood (1993) & do not apply an explicit metallicity scaling.



Commonly used mass loss prescriptions for the super-AGB phase. 8.5 Msun Z=0.02 t= 0 corresponding to 1st thermal pulse

Doherty el al 2014a

Variable compostion
low temperature molecular opacity

When the C>O ratio in the stellar envelope exceeds unity this changes the molecular chemistry

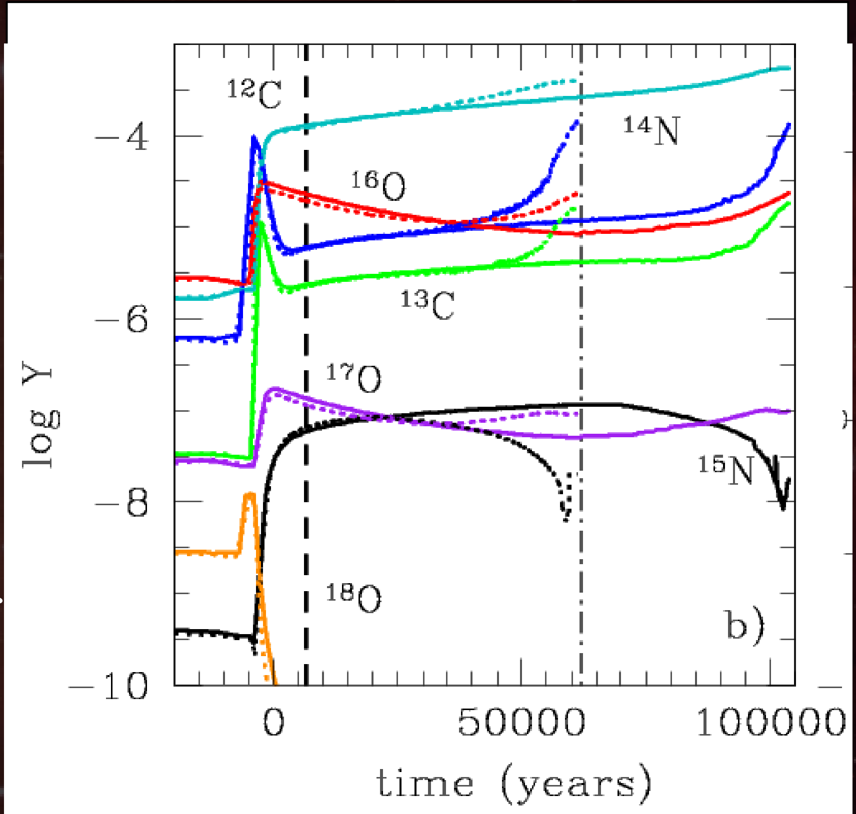
* increased opacity
* more cool/extended evelope
* drives more massive mass loss

All massive Super-AGB stars become Carbon rich (C/O > 1) at the start of the TP-SAGB phase from either:

- Dredge-out events
- Corrosive second dredge up

We expect then no metallicity dependence on the mass loss

BUT see also Wood 2011 weak pulsations at low Z = no super-wind !



Evolution of the surface abundance of CNO isotopes for a 7.5 Msun Z=0.0001 model.

t= 0 corresponding to 1st thermal pulse

Doherty el al 2014b

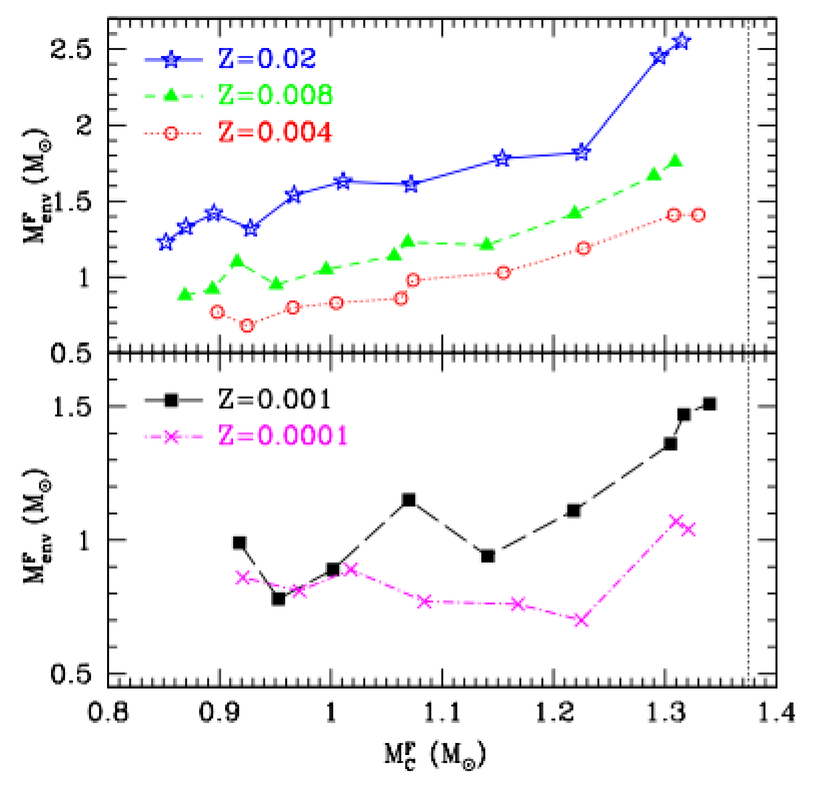
Fe-peak opacity instability

1-D stellar evolution models have convergence issues near the end of the AGB phase

For super-AGB stars up to ~ 2.5 M⊙ of envelope remains

More envelope for more massive/metal rich stars

Radiation pressure in the envelope so high, that it supplies all the pressure support required by the model, forcing gas pressure to < 0 near the base envelope. Code cannot converge to a solution (Wood & Faulkner1986) Local Lum exceeds the Eddington luminosity.



Final envelope mass remaining vs final core mass

Ejection of entire remaining envelope?

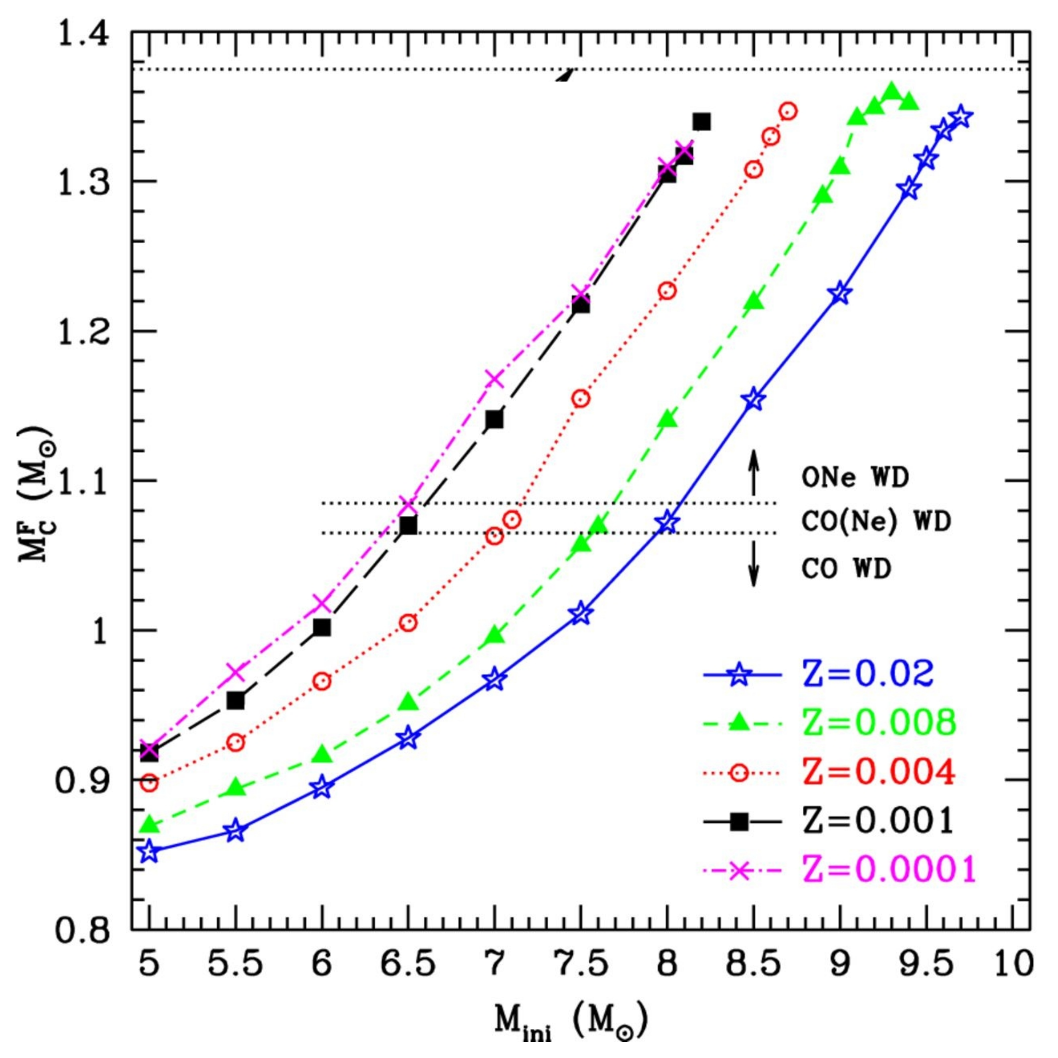
Initial-Final mass relation

Grid of (single, non rotating) super & massive AGB stars models along the TP-(S)AGB phase (MONSTAR)

Small core growth ~ 0.01 -0.03 M_{sun} during (S)AGB phase

Includes 3 types of massive white dwarfs ONe,CO(Ne)* &CO WDs

Lower metallicity stars leave more massive WDs for the same initial masses.



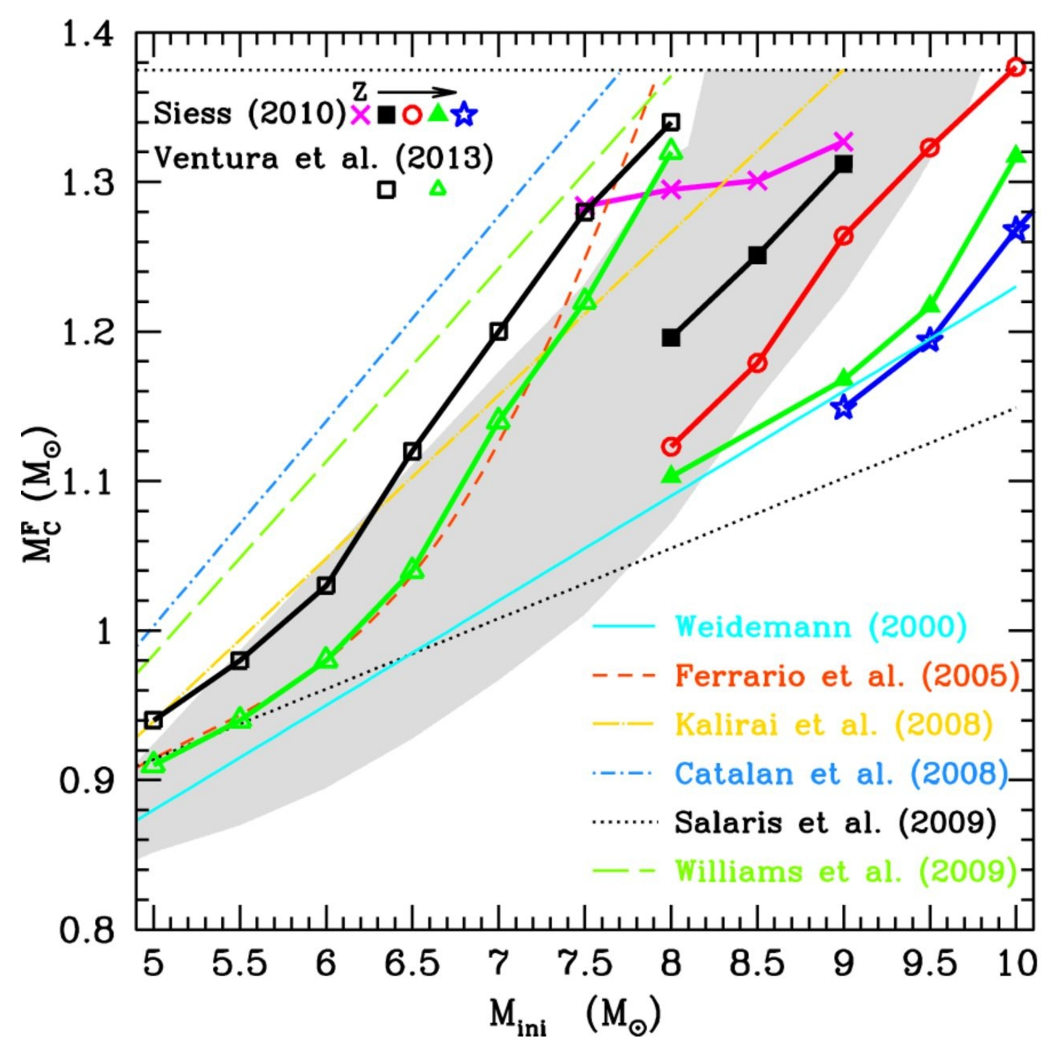
* CO(Ne) white dwarfs (Doherty +. 2010, Denissenkov +2013, Chen +l2014, Farmer + 2015

Comparison - observations/other models

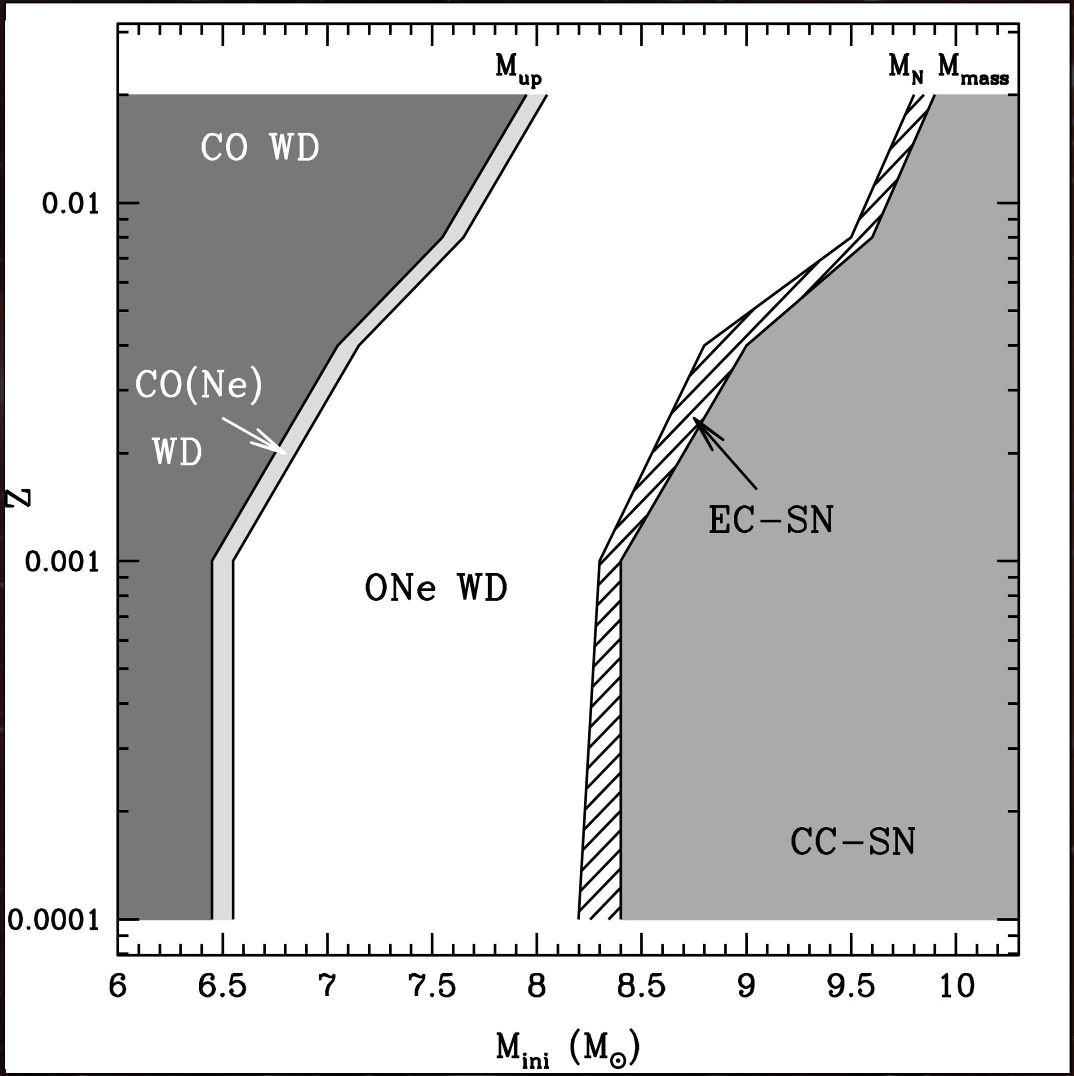
We compared our predictions to observationally derived IFMRs

Large spread in results with maximum mass of WD ranging ~7.6 - 10+ M_{sun}

Large variation in results between difference model predictions (Siess 2010 & Ventura et al 2013) primarily due to differences in treatment of convective boundaries during core He burning



Super-AGB star Supernovae?



M_{up} ,M_n and $M_{mass,}$ CC=Core Collapse,
EC=Electron capture   Doherty el al 2015

Very fine ~ 0.1- 0.2M_{sun} mass range of EC-SN

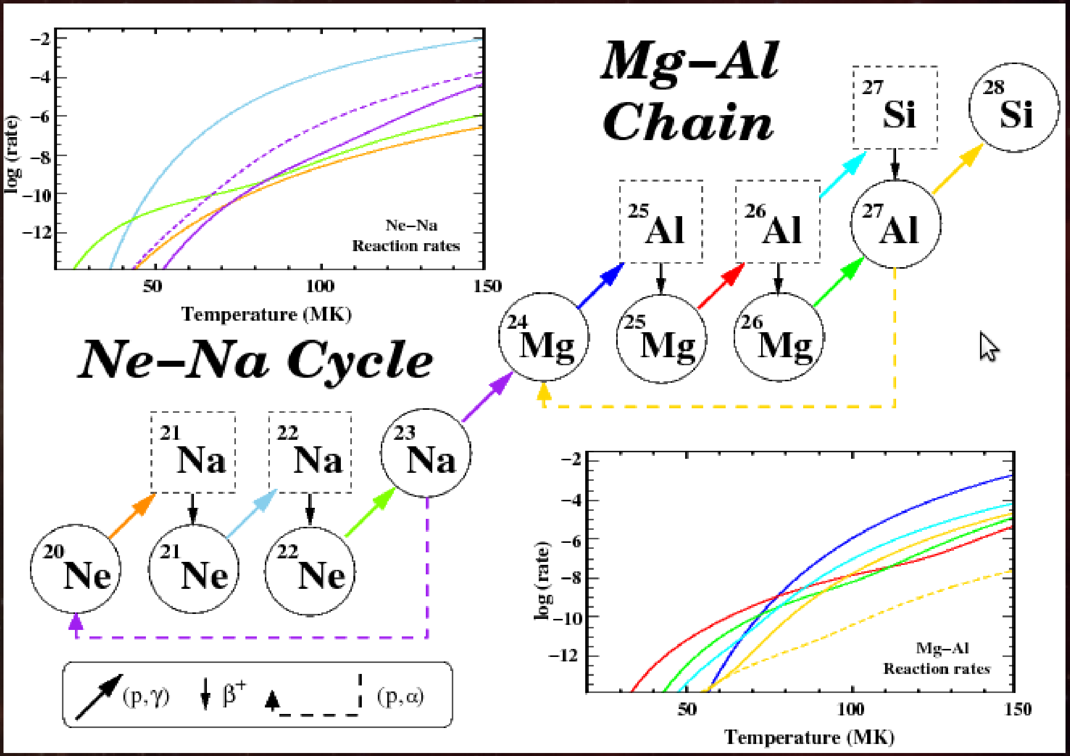
Weighted by a Kroupa Initial Mass function **~ 2 to 5 %** of all Type II SN will be EC-SN

At high metallicity our results compare well with parametric studies by Poelarends et.al 2008 & Siess 2007

At low metallicity, because we do not apply at Z mass loss scaling we find far fewer EC-SN.

Hot bottom burning

Very high temperatures
at the base of the
convective envelope
100-150 MK
High enough for p
captures
* CNO
* Ne-Na
* Mg-Al-Si
* potentially Ar-K



Hot bottom burning produces ^{4}He,**^{7}Li**, ^{13}C, **^{14}N**, ^{17}O, ^{23}Na, **^{25}Mg**, **^{26}Al**
Galactically important*

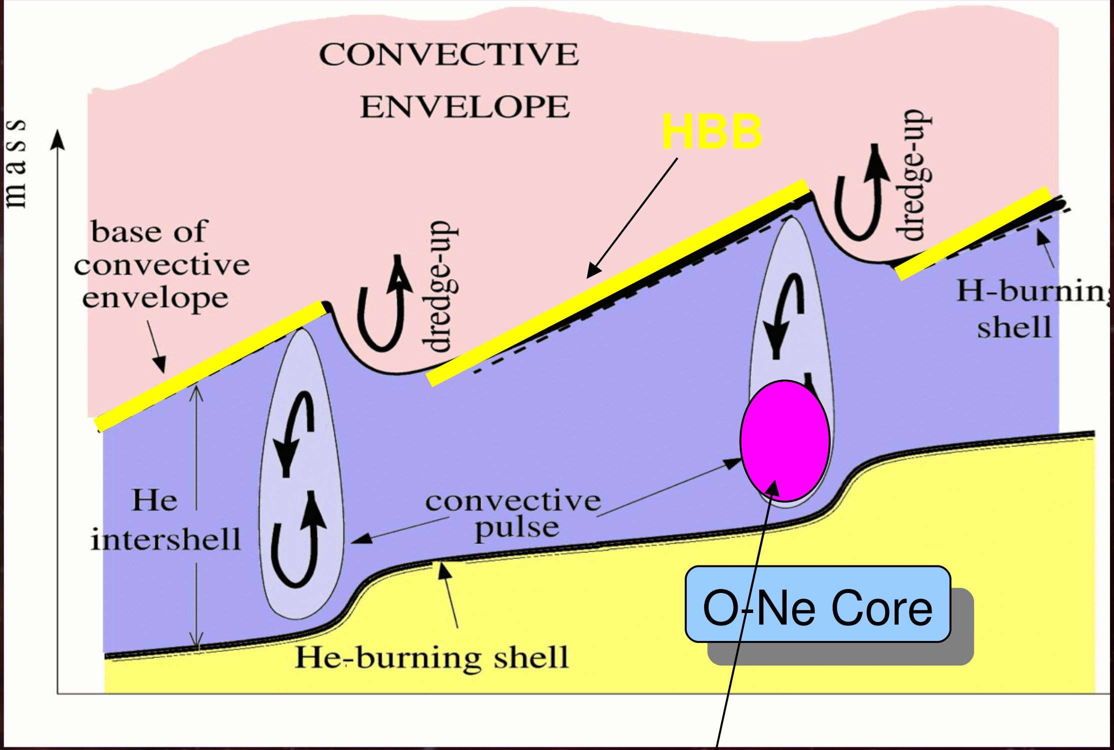
Doherty el al 2014b

Heavy element nucleosynthesis

Helium burning is activated during the thermal pulse making a variety of elements, primarily ^{12}C, ^{16}O, ^{22}Ne, ^{25,26}Mg and s-process elements.
3DU events then mix this material to the surface

Massive AGB stars make substantial amounts of Rb & light s elements
e.g. van Raii et al 2012

Neutrons from reaction
$^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$



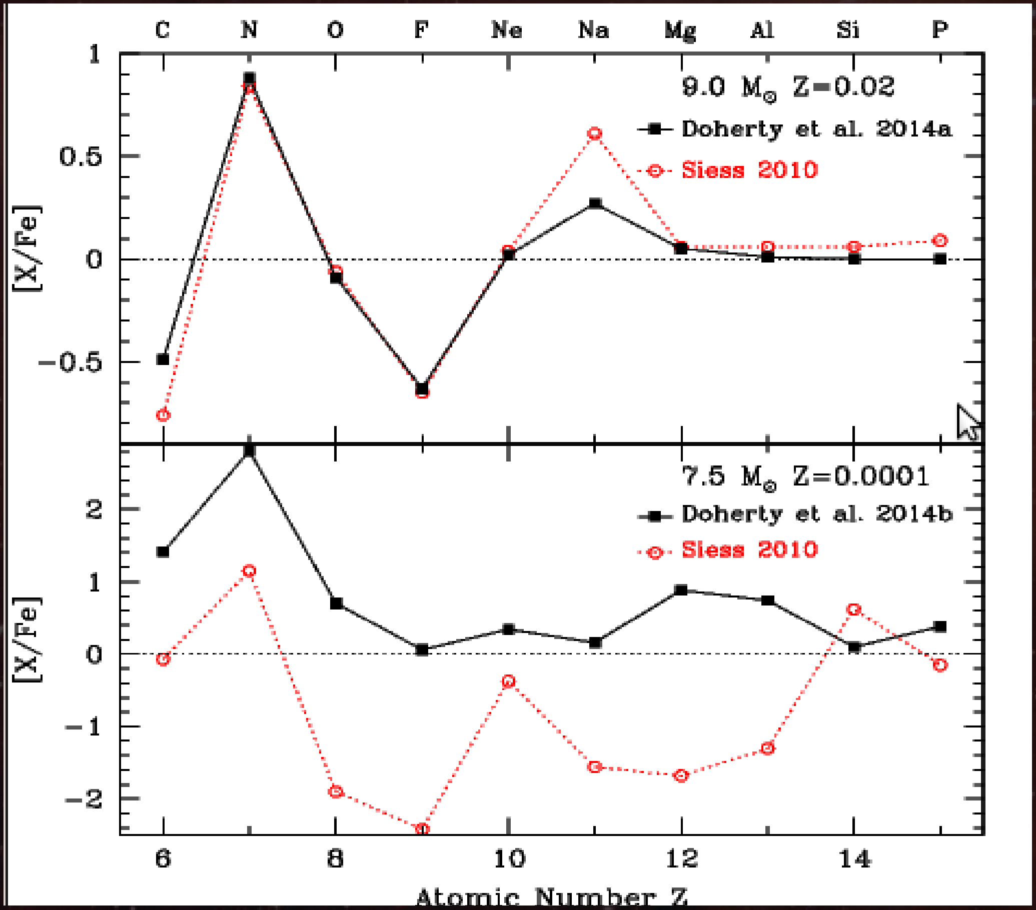
Lugaro 2005

Heavy element production

Dredge out events (Ritossa et al 1999, Siess 2006, Gil-Pons & Doherty 2010) in massive super-AGB stars may be another source of heavy elements

Nucleosynthesis signatures?

At high metallicity, super-AGB stars nucleosynthesis is dominated by HBB and results from different groups are suprising similar



At low metallicity corrosive 2DU and 3DU may play an important role (and results diverge)

2DU : ^{4}He, ^{23}Na

HBB products:

^{7}Li, ^{13}C, (^{14}N) ^{17}O, ^{25}Mg, ^{27}Al

3DU products:

(^{14}N), ^{22}Ne, ^{26}Mg, *g* (s-process proxy)

Conclusions

Most (single) super-AGB stars end life as ONe WDs

The mass width of (single) stars which undergo EC-SN is about 0.1-0.2 M_{sun}

~ 2 to 5 % of all gravitational collapse SN will be EC-SN

Mass loss at low Z & Fe peak opacity instability

3DU not (very) important for nucleosynthesis at high metallicity

Low metallicity 3DU / Dredge-out/2DU important