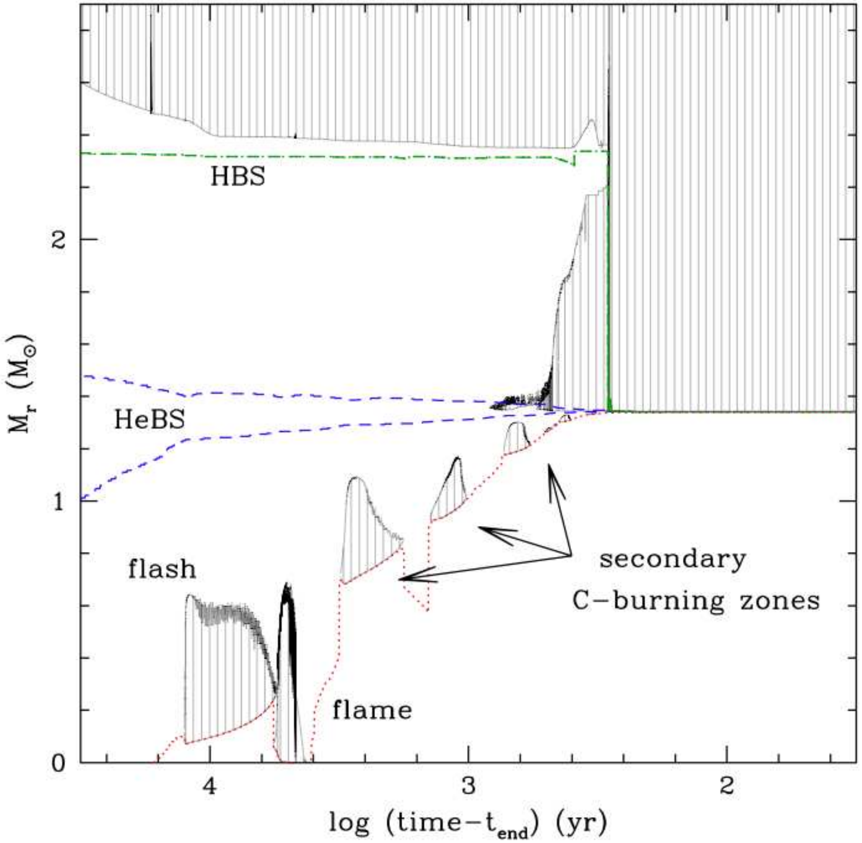
Super-AGB Stars

Understood, Unknown and Uncertain Physics



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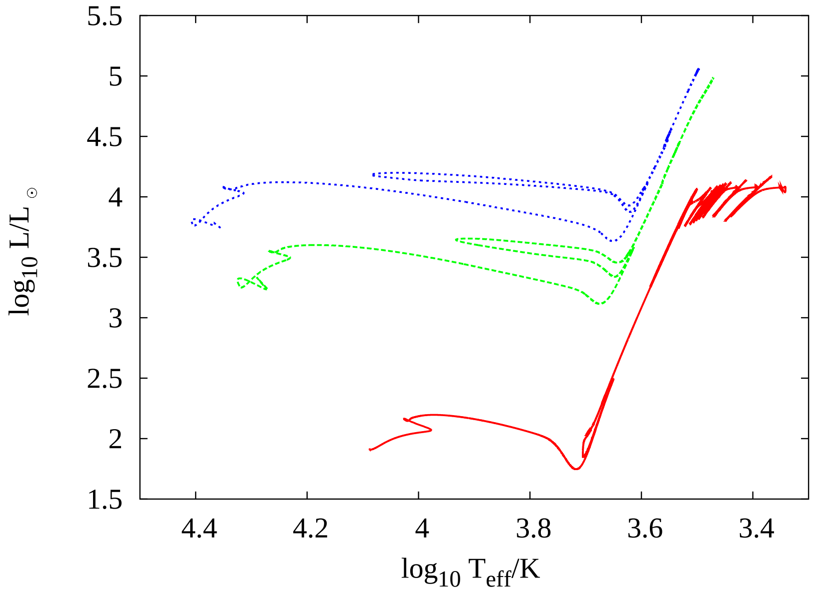
Outline

- The Understood: overview of stellar evolution
- The Unknown: missing physics
- The Uncertain: the role of S-AGBs

Part I: The Understood

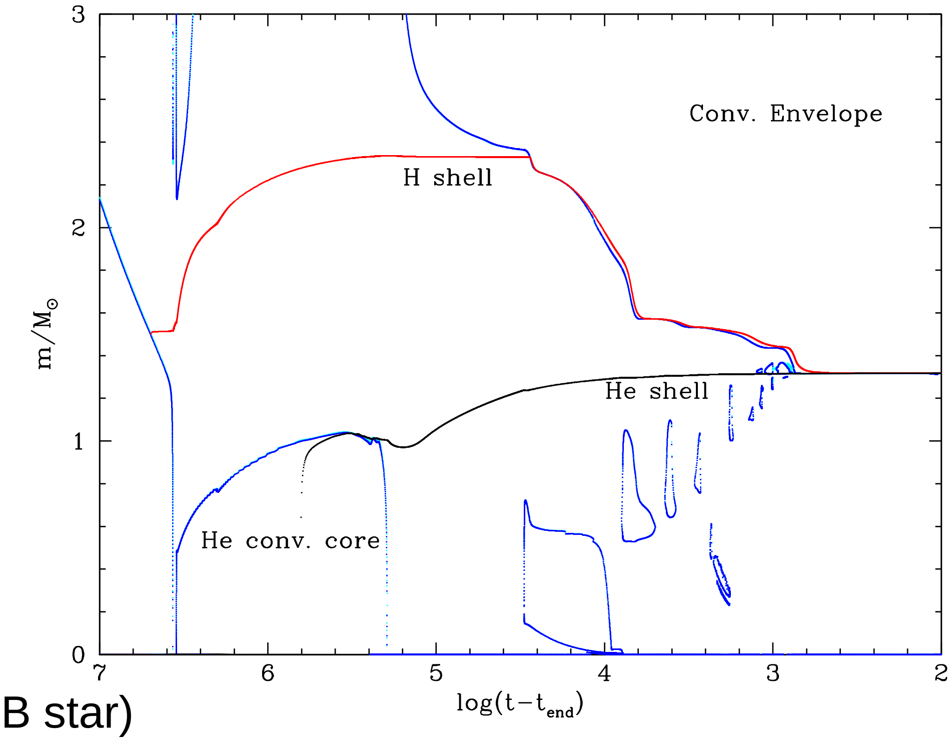
Stellar Evolution 101

- Super-AGB stars are the more massive counterparts of AGB stars
- They are massive enough to ignite carbon under partially degenerate conditions
- Do not proceed to further stages of nuclear burning
- Responsible for the production of ONe white dwarfs or may explode as SN



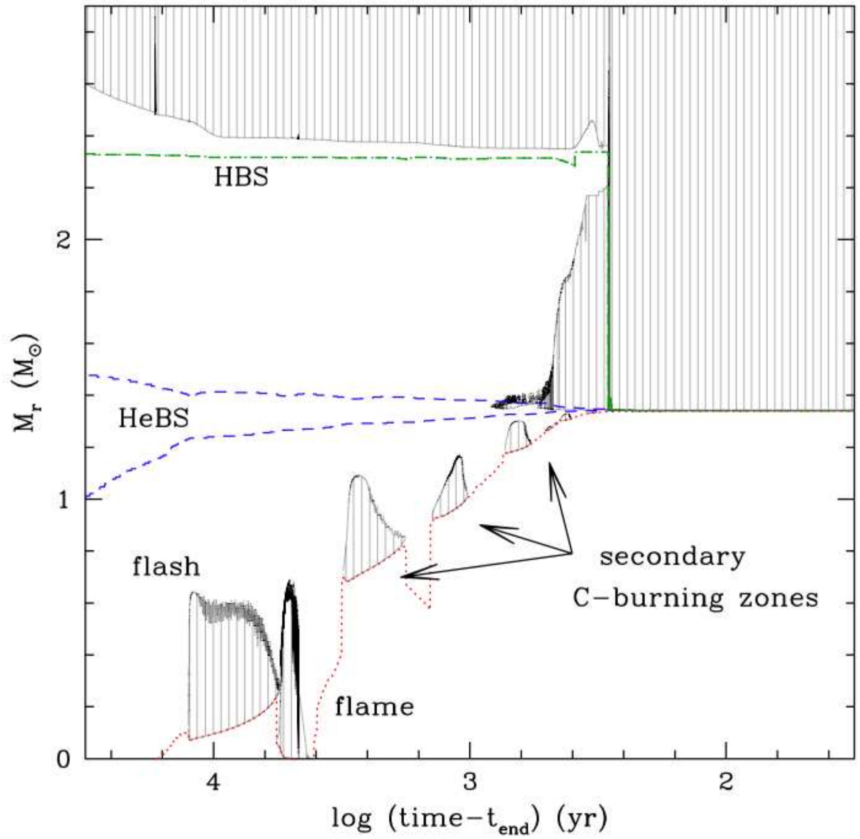
Stellar evolution 101

- Second dredge-up reduces core mass below Chandrasekher mass
- In more massive models, He-driven convective zone can connect with the convective envelope – dredge-out
- Core is hot enough that carbon ignites
- M_{up} – minimum mass for C-ignition (maximum mass for an AGB star)
- M_{mass} – transition mass for core-collapse SN



Carbon burning

- C ignites in partially degenerate conditions
- Carbon flash, drives convective zone – high C abundance
- Flash is weaker in more massive stars – less degenerate
- C-burning flame propagates to the centre – $X_c \leq 0.08$
- Subsequent C-burning zones



Siess (2007)

Carbon burning flame

- Steady state processes. ν carry away the energy produced by C-burning
- Energy release heats surrounding material, allows flame to burn inwards
- Computationally difficult – requires high spatial and temporal resolution
- Δr less than 1km, $5 \times 10^{-5} \leq \delta t \leq 40$ yr
- Models follow theory of Timmes & Woosley (1992) and Timmes et al. (1994)

TP-SAGB

- After 2^{nd} dredge-up, C burning slowly dies out
- H- and He-burning shells pushed close together
- Star enters a thermally pulsing phase just like a 'normal' AGB star
- Pulses are quite weak $\mathrm{L}_{\mathrm{He}}^{\mathrm{max}}$ around 10^6 $L_\odot$
- Base of convective envelope in H-burning shell – Hot Bottom Burning

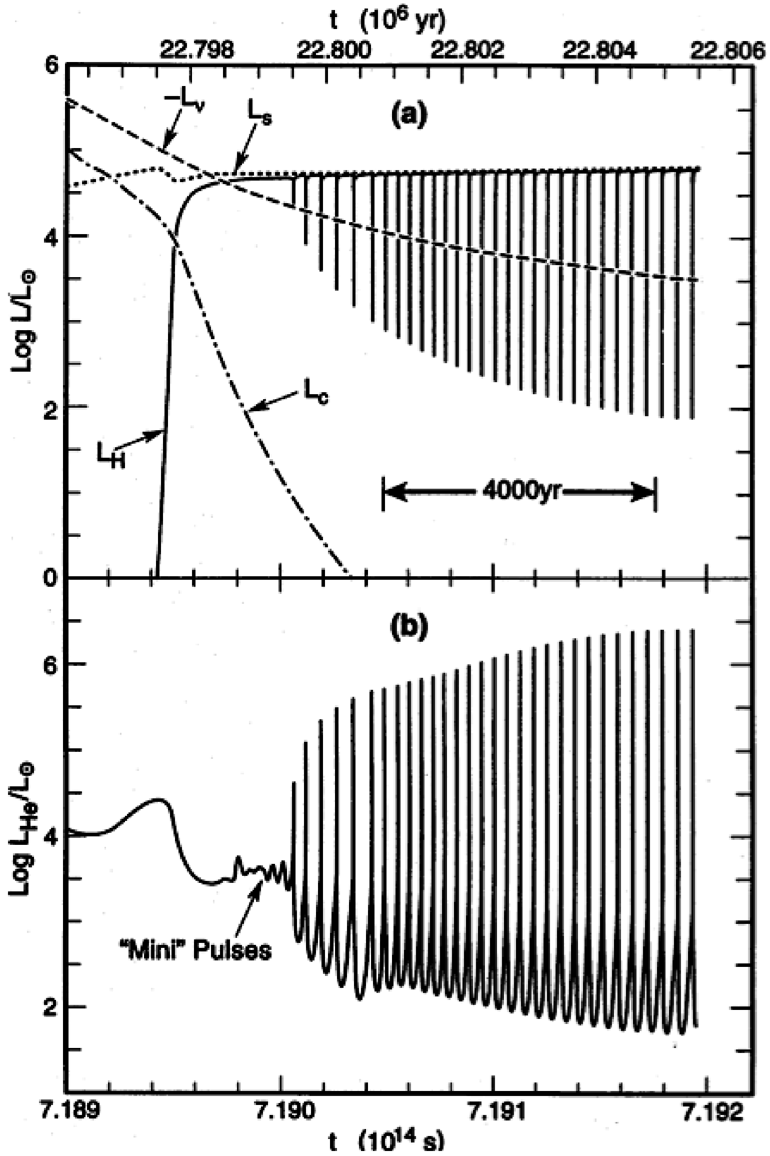


Image: Ritossa et al. (1996)

End of the TP-SAGB

- TP-SAGB characterised by strong mass loss
- Core may grow to beyond the Chandresekhar mass
- Third dredge-up may inhibit core growth
- Competition between these processes determines final fate
- Either have a massive ONe white dwarf or an electron-capture supernova
- M_{n} – the transition mass between these two fates

Metallicity Dependence

- Both $M_{\rm up}$ and $M_{\rm mass}$ decrease with metallicity
- Upturn between $Z = 10^{-4}$ and $Z = 10^{-5}$
- Due to a decrease in core size during MS – less CNO burning
- Metallicity may also affect mass-loss during the TP-SAGB
- More on primordial models in talks by Gil-Pons & Lau

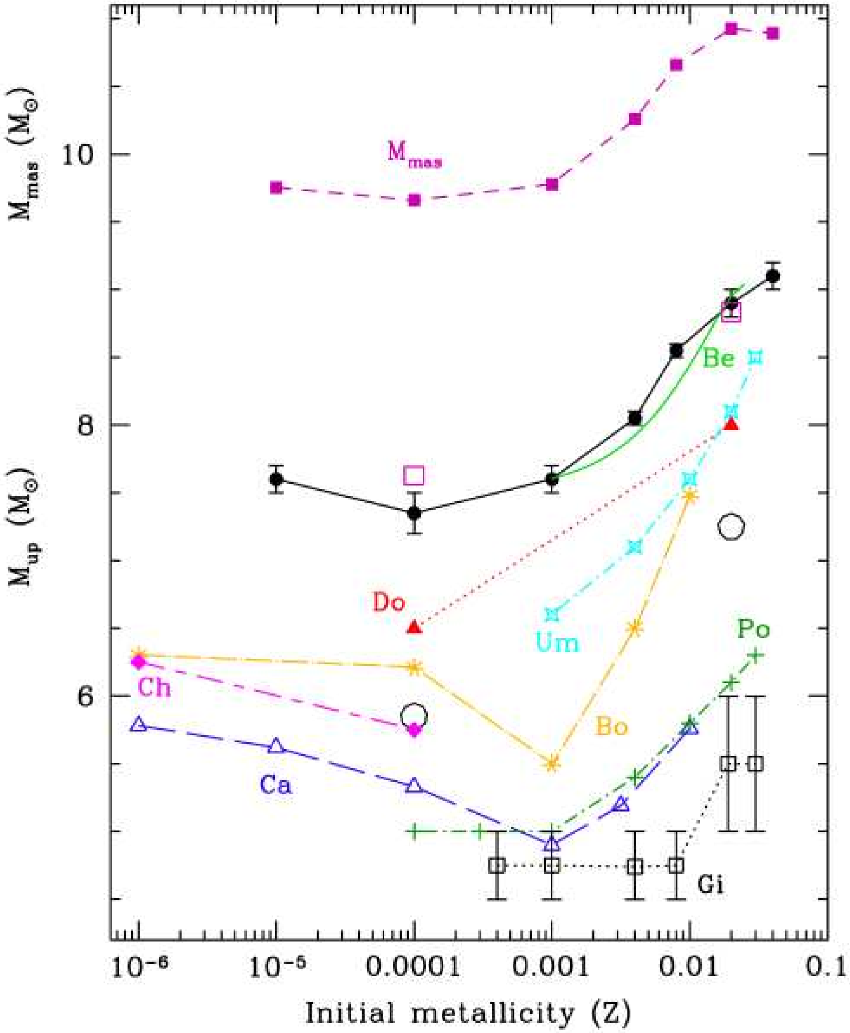


Image: Siess (2007)

Part II: The Unknown

Convection

- Problem both prior to TP-SAGB and during it
- Convection during core He burning determines core masses
- Convection also determines pulse strengths & third dredge-up
- Physics problem: Schwarzchild/Ledoux, inclusion of overshooting
- Computational boundaries: How to treat them

Assessing uncertainty

- Overshooting versus no overshooting – seems to suggest that overshooting reduces $M_{\rm up}$ by 1.5-2 $M_{\odot}$ (Gil-Pons et al. 2007, Siess 2007)
- Need to test different physics and also examine numerical prescriptions
- Can observations help us to constrain the core He-burning phase?

Third dredge-up

- Intimately related to the convective prescriptions
- Dredge-up efficiency λ varies from code-to-code
- Siess (2007) $\lambda = 0$, Poelarends et al. (2007) $\lambda = 0.5$, Doherty & Lattanzio (2006) $\lambda = 0.7$
- Maybe not so important for nucleosynthesis
- Crucial to the issue of which stars will explode – dredge-up inhibits core growth

Mass Loss

- TP-AGB stars are characterised by high mass loss
- The mechanism is not well understood – and even less so for the SAGBs!
- Which rates should we use???
- It's a matter of (slightly longer) life or (violent) death!

Mass Loss Prescriptions

- de Jager et al. (1988) – used for massive stars
- Vasilliadis & Wood (1993) – based on Mira pulsation period, popular among AGB modellers
- van Loon et al. (2005)

$$\log \dot{M} = -5.65 + 1.05 \log \left(\frac{L}{1000\mathrm{L}_\odot} \right) - 6.3 \log \left(\frac{T_{\mathrm{eff}}}{3500\mathrm{K}} \right)$$

- Or do we need some theoretical insight to the mass loss?

Mass Loss	Type	Approx. Rate $M_\odot(yr^{-1})$
Reimers ($\eta = 1$)	Red giants	5×10^{-6}
Reimers ($\eta = 4$)	Red giants	2×10^{-5}
Schröder & Cuntz	Supergiants	1×10^{-5}
van Loon	AGB/RSG	3×10^{-5}
Blöcker	AGB	6×10^{-3}
V&W93	AGB	4×10^{-5}
de Jager		1×10^{-6}

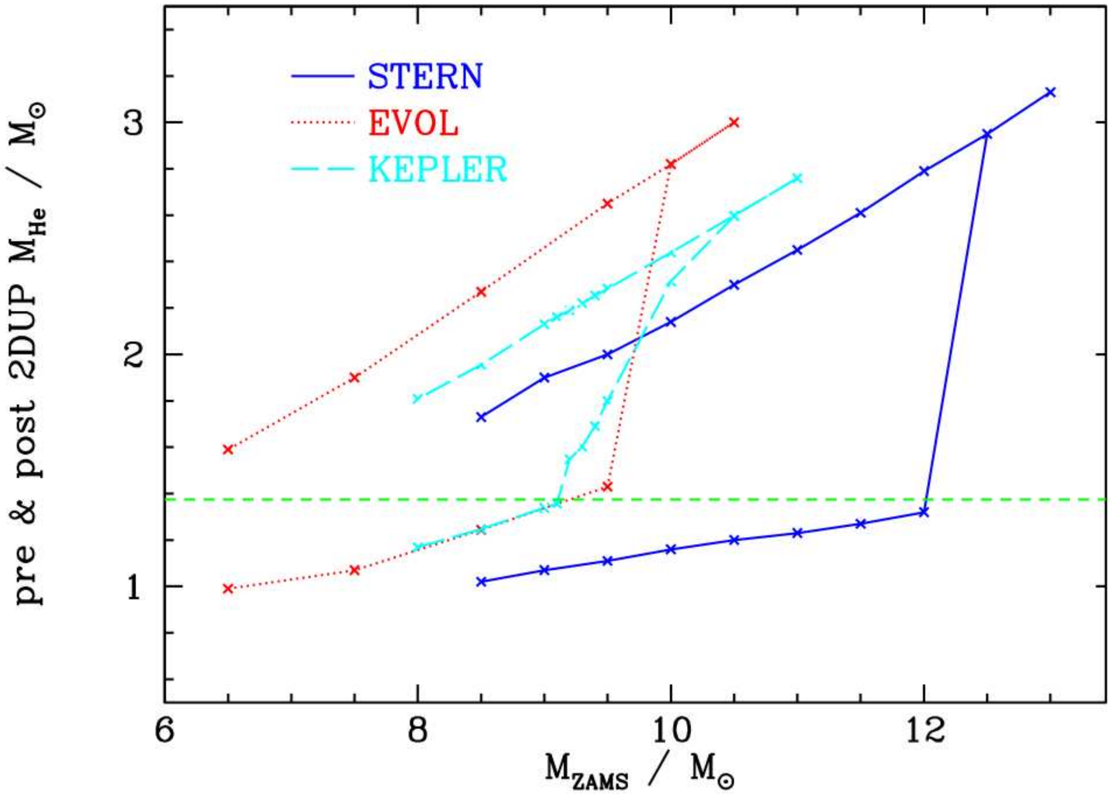
Adapted from Poelarends et al. (2007)

The Synthetic Approach

- Avoid computationally demanding, detailed modelling
- Use fits to existing models, or extrapolations to these
- Advantanges: very quick, allows easy variation of parameters
- Disadvantages: Only as good as the input models
- Examples: Izzard & Poelarends (2006), Poelarends et al. (2007), Siess (2007)

Computational uncertainties

- How well do different codes agree?
- Two issues: different numerical techniques versus different input physics
- Poelarends et al. (2007) used 3 different codes to model SAGB stars
- Find that semiconvection & overshooting are the biggest uncertainties



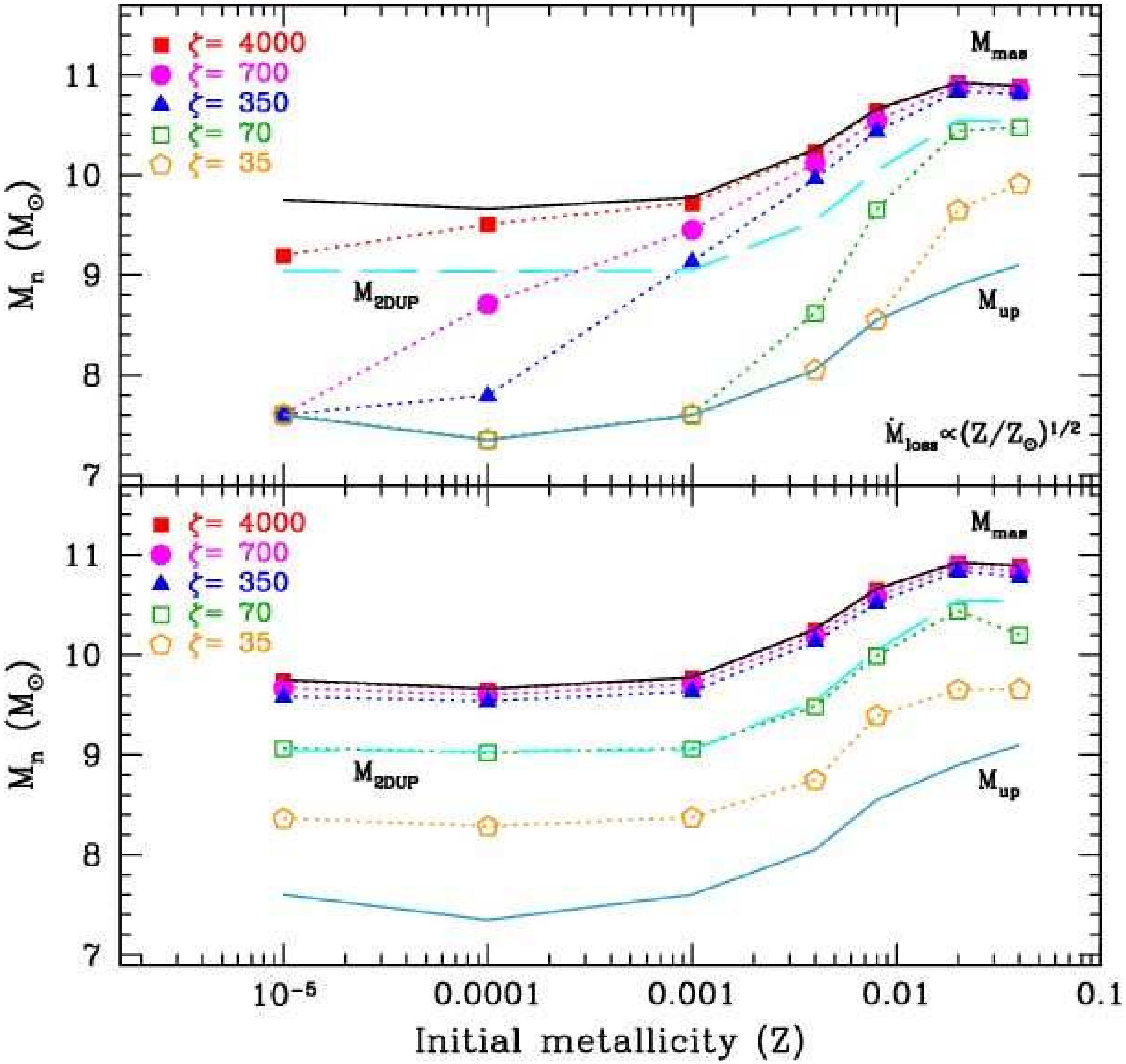
Part III: The Uncertain

S-AGB nucleosynthesis

- Not significant contributors to GCE through HBB at $Z = 0.02$ – Izzard & Poelarends (2006)
- Based on limited calibration and large extrapolation
- More detailed (and time consuming!) modelling is needed
- Explosive nucleosynthesis? r-process? (Ning et al. 2007)
- What about in binary systems – ONe novae

S-AGB contribution to SNe

- Observational evidence points to low mass progenitors for several supernovae
- Theoretical predictions strongly dependent on mass loss and dredge-up
- Poelarends et al. (2007) conclude that ECSN account for 4% of local SN at $Z = 0.02$
- Firm upper limit of 20% based on modelling uncertainties


ζ= 4000
ζ= 700
ζ= 350
ζ= 70
ζ= 35
M_{mas}
M_{2DUP}
M_{up}
$\dot{M}_{loss} \propto (Z/Z_\odot)^{1/2}$
M_n ($M_\odot$)
11
10
9
8
7
10^{-5}
0.0001
0.001
0.01
0.1
Initial metallicity (Z)

Conclusions

- Evolution of SAGBs is fairly well known up to the end of C-burning
- Need for more detailed modelling of TP-SAGB phase
- Understanding of mass loss is crucial – both theoretical and observational input needed
- Without this, it is hard to say what role these stars can play.