Stellar Evolution from the main sequence to the post-AGB phase

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Introduction

I will focus on the lives and death of stars with masses up to about 9 Msun

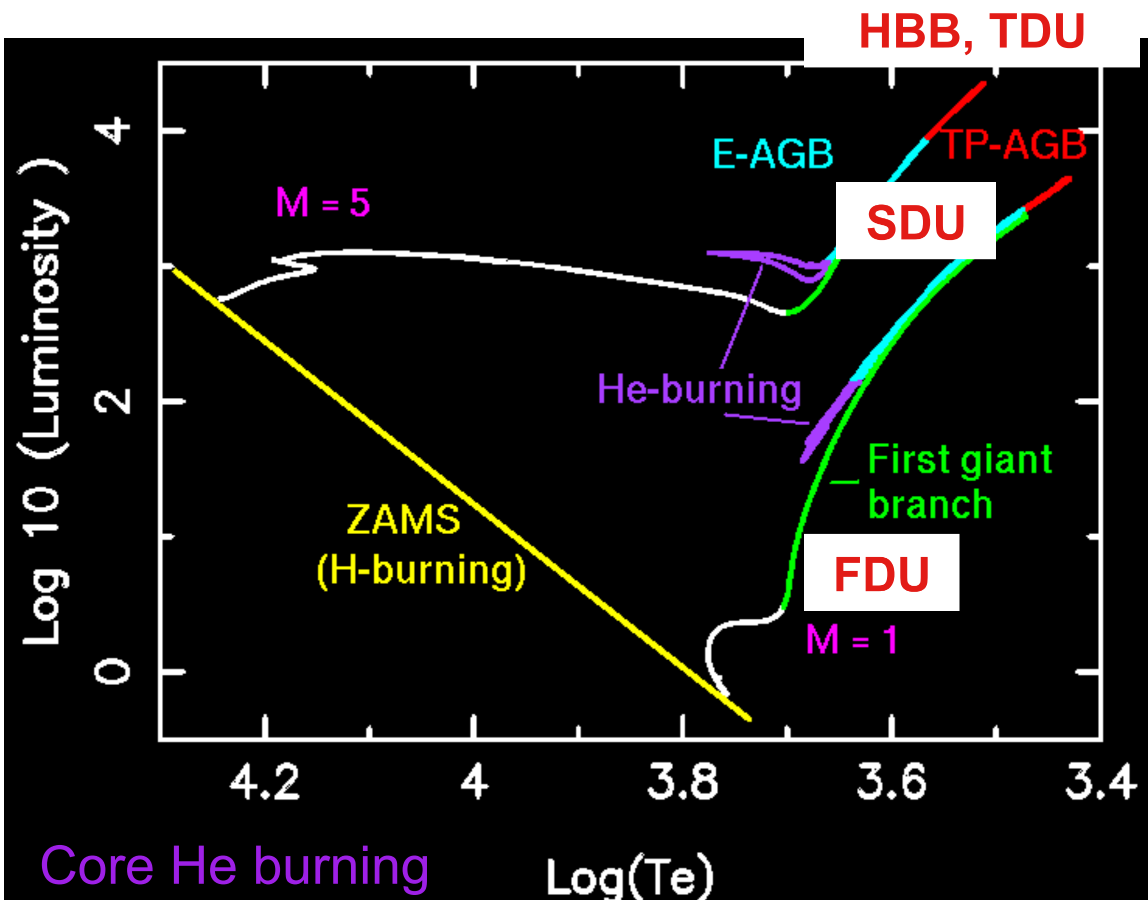
See talks by Meynet and Janka on models of massive stars

Image credit: ALMA (ESO/NAOJ/NRAO); Maercker et al. (2012)

1. Stellar evolution and nucleosynthesis to the asymptotic giant branch

Theoretical evolutionary tracks

Z = Zsolar (0.0142; Asplund et al. 2009)
x-axis: logarithm of the effective temperature
y-axis: logarithm of the radiated luminosity



Core He burning
He to Carbon

Main sequence:
- H to Helium
- t ~ 10^{10} yrs for 1
- ~ 10^{8} yrs for 5

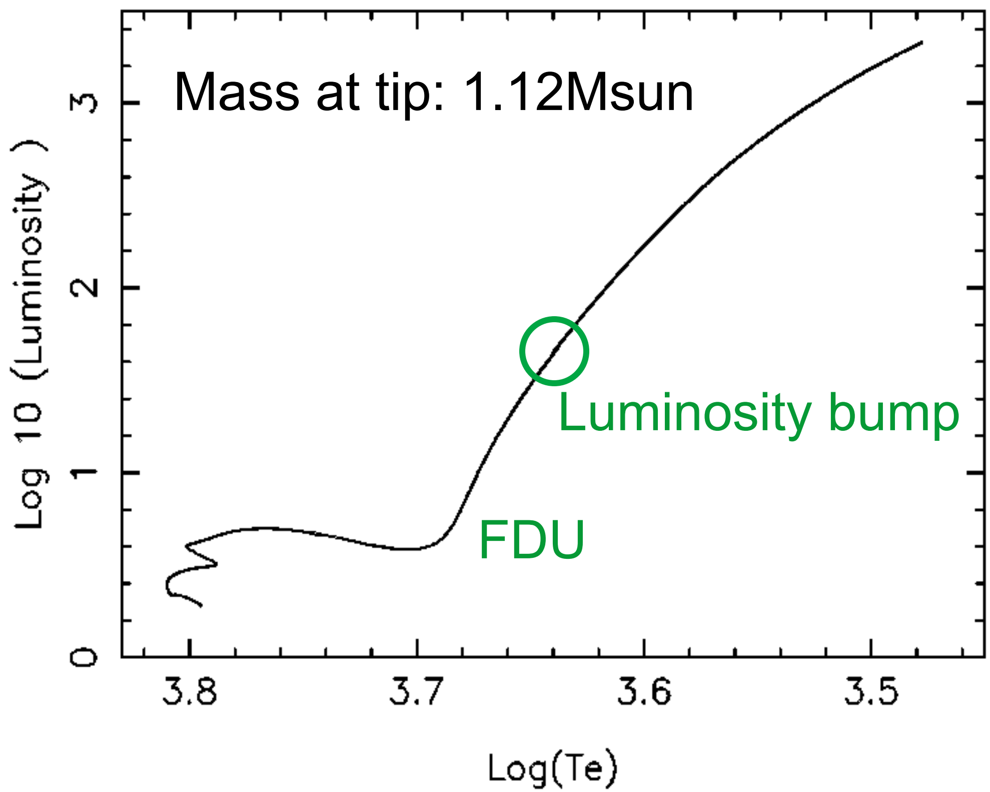
Red Giant Branch:
- core contracts
- outer layers expand

Second giant branch:
- after core He-burning
- giant for second time

Up to the tip of the first giant branch

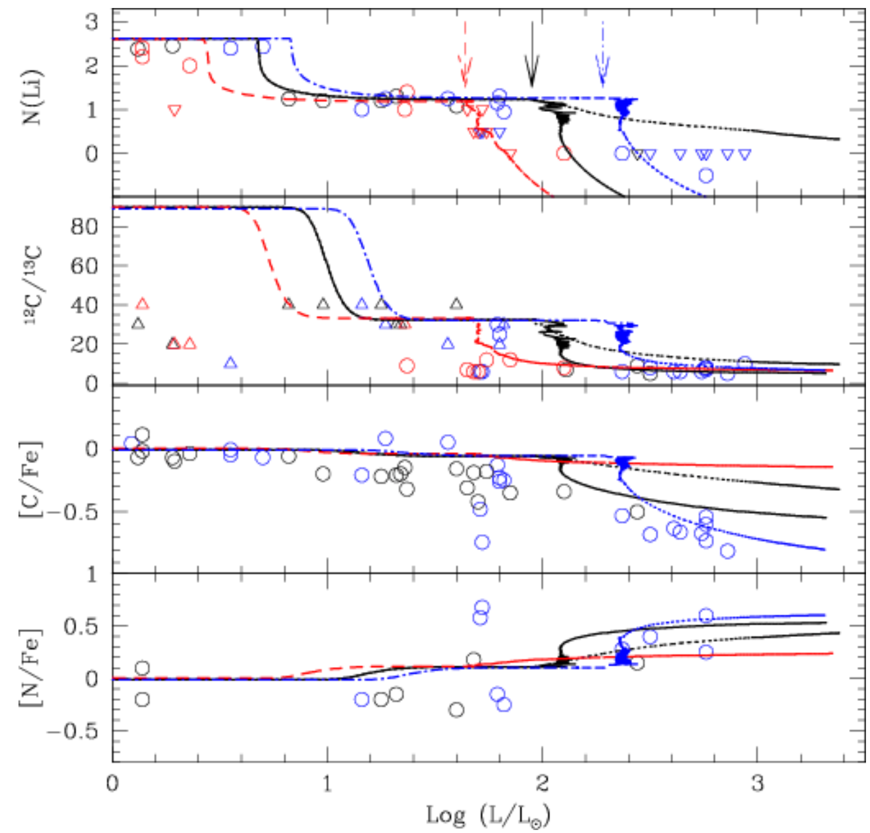
- Envelope convection deepens
- Mixes up material partially processed during the previous main sequence
- Mixing changes surface:
  - Reduction in Li, $^{12}C/^{13}C$ ratio
  - Increases in ^{3}He, N
- Core He-burning ignited at tip of the giant branch
- Mass loss will erode part of the envelope
- Latest Kepler data suggests less mass than than previously thought (Miglio et al. 2012)

Example: 1.25Msun, Z = 0.02 model



Extra mixing in low-mass giant stars

- M < 2Msun
- Standard stellar models: Only *one* mixing event between MS and tip of the first giant branch (FGB)
- The first dredge-up:
- $^{12}C/^{13}C \sim 20$, C/N ~ 1.5
- Disk FGB stars (e.g., Gilroy 1989) have $^{12}C/^{13}C \sim 10$, and C/N ~ 1.0
- GC stars show an anti-correlation of C with luminosity (e.g., in M3; Smith 2002)
- Evidence that some form of chemical transport is acting in low-mass FGB envelopes



From Charbonnel & Zahn (2007)
Models by Eggleton et al. (2008), Charbonnel & Lagarde (2010), Angelou et al. (2011, 2012)

Off-centre Carbon burning

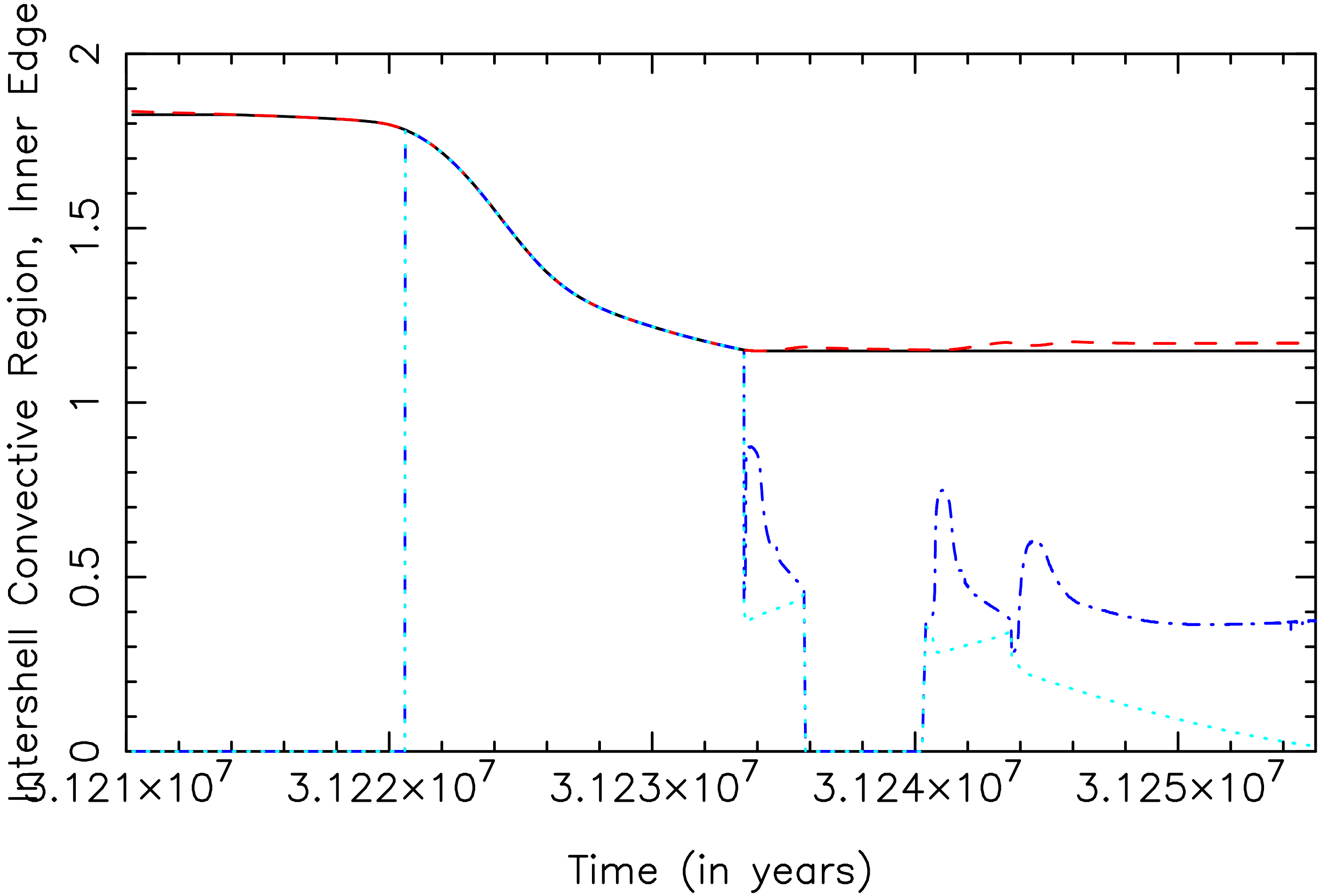
- In the mass range from about 8 to 10Msun, carbon ignition takes place off centre under electron degenerate conditions
- After carbon is ignited, a carbon flame eventually reaches the centre
- The fate of these stars is not well understood
- They may evolve through the thermally-pulsing AGB after the end of core carbon burning with an O-Ne core
- Or explode as electron-capture supernovae if the core mass exceeds ~1.37Msun (Nomoto 1984)

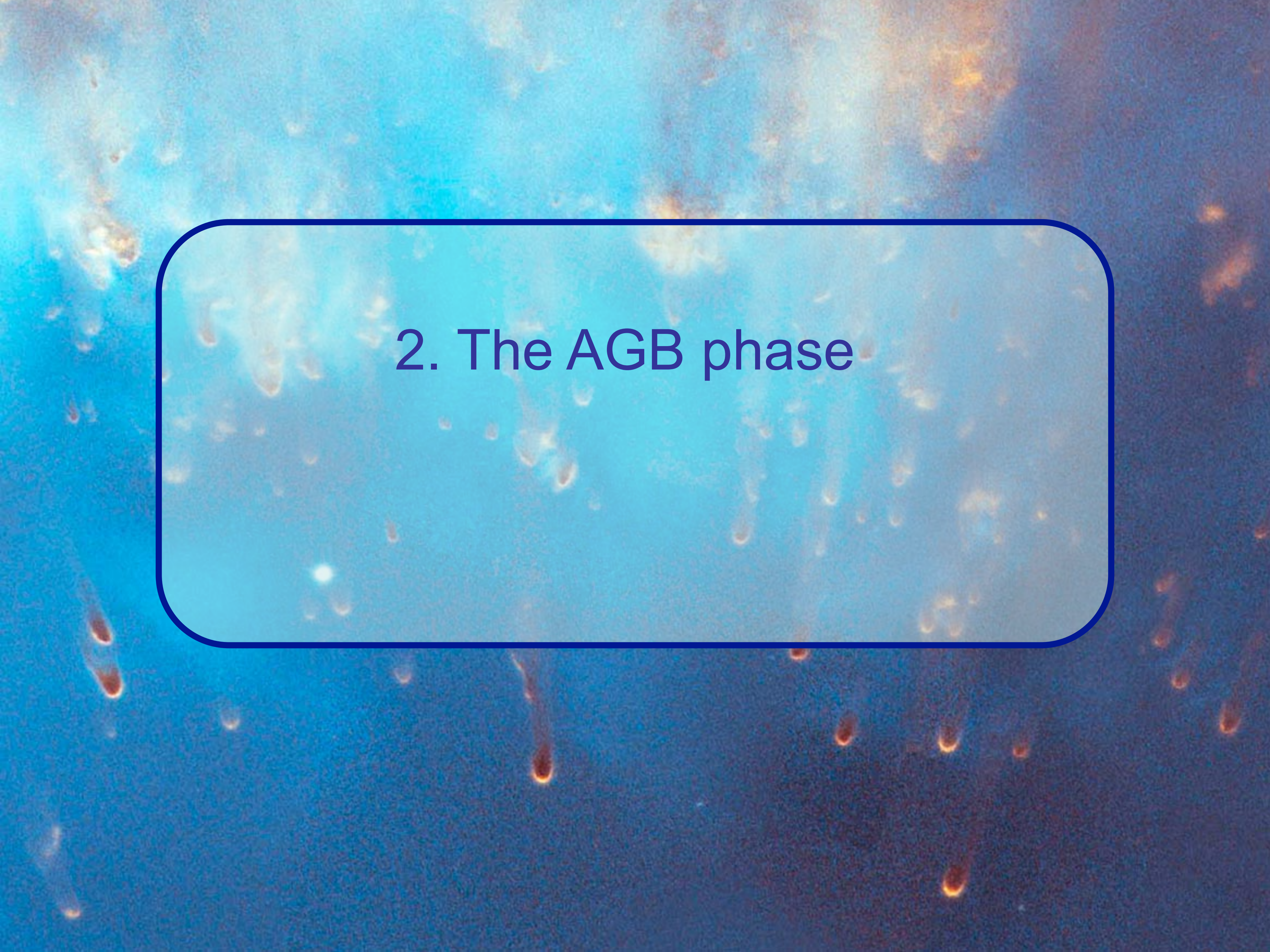
Models by: Siess (2007, 2010), Pumo et al. (2008), Doherty et al. (2010), Karakas et al. (2012), Herwig et al. (2012), Takahashi et al. (2013)

Carbon ignition: 9Msun, Z = 0.02

Maximum temperature peaks at ~950 x 10^6 K.

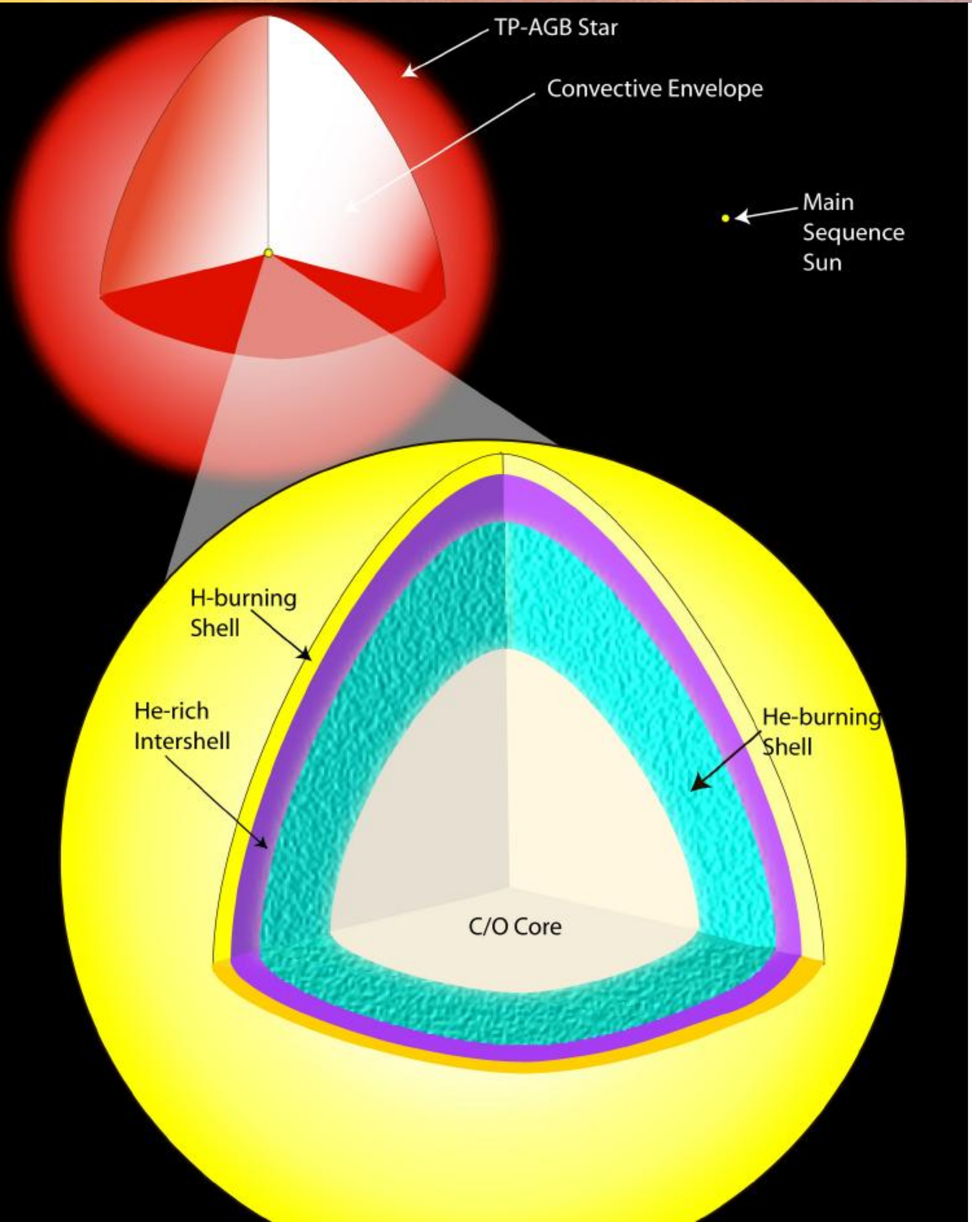
Duration of carbon flashes and central burning ~30,000 years (model from Karakas et al. 2012)





2. The AGB phase

Asymptotic Giant Branch stars



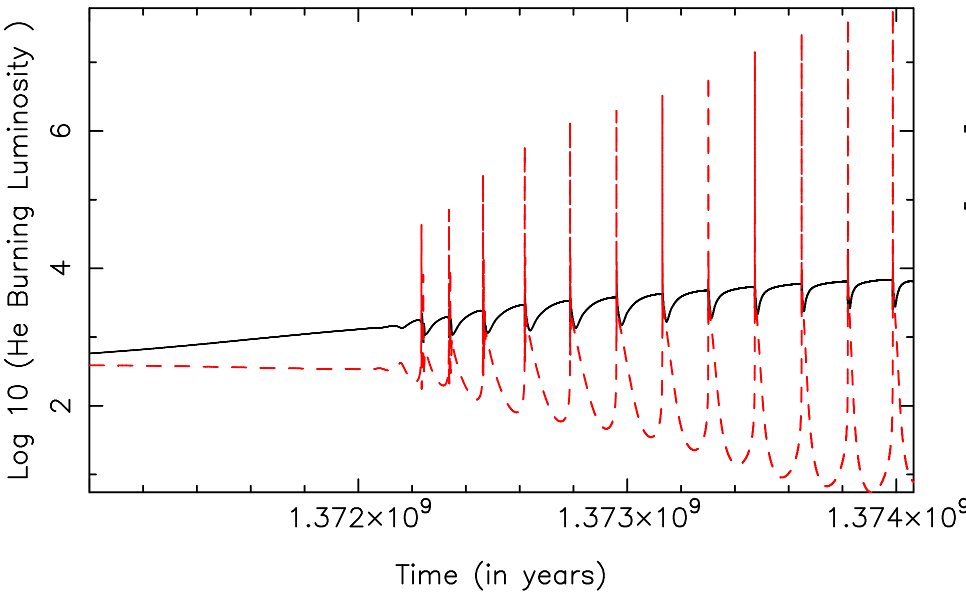
- After core He-burning, the C-O core contracts and star becomes a giant again
- Double-shell configuration
- He-burning shell is thermally unstable and flashes every ~10^5 years
- Rapid, episodic mass loss erodes the envelope

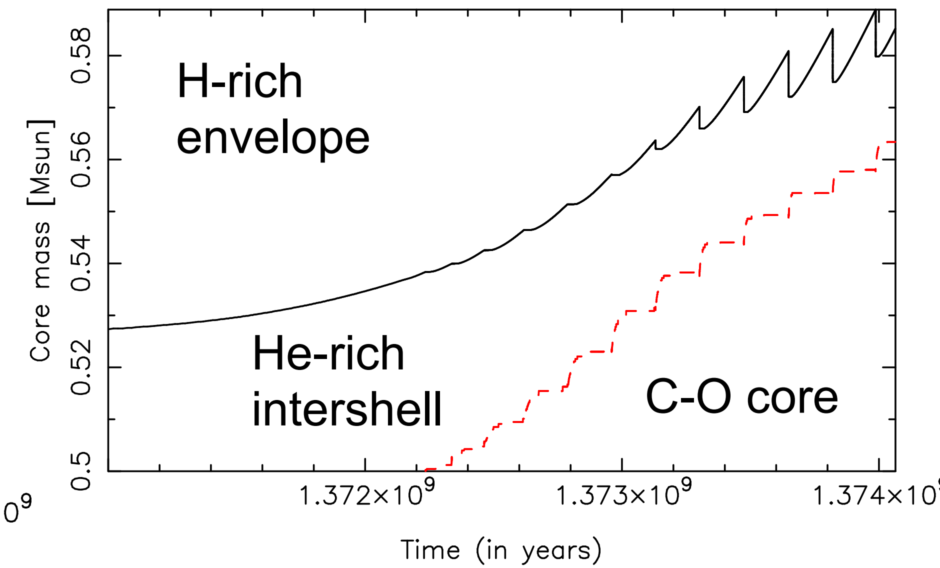
See reviews by Busso et al. (1999) and Herwig (2005)

Evolution during the AGB

- Up to ~10^8 Lsun can be generated by a thermal pulse
- Energy goes into expanding the star
- This allows convection to move inwards (in mass): The third dredge-up
- Mixes material from the He-shell to the surface (e.g., C, F, Ba, Pb)

Typical Galactic C-rich AGB star: 1.8Msun, Z = 0.01

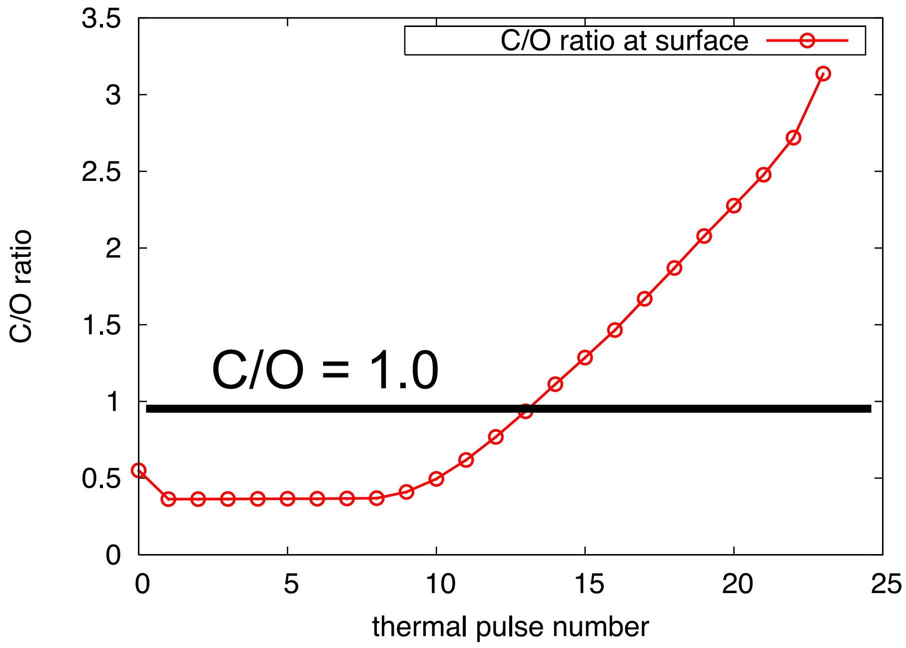


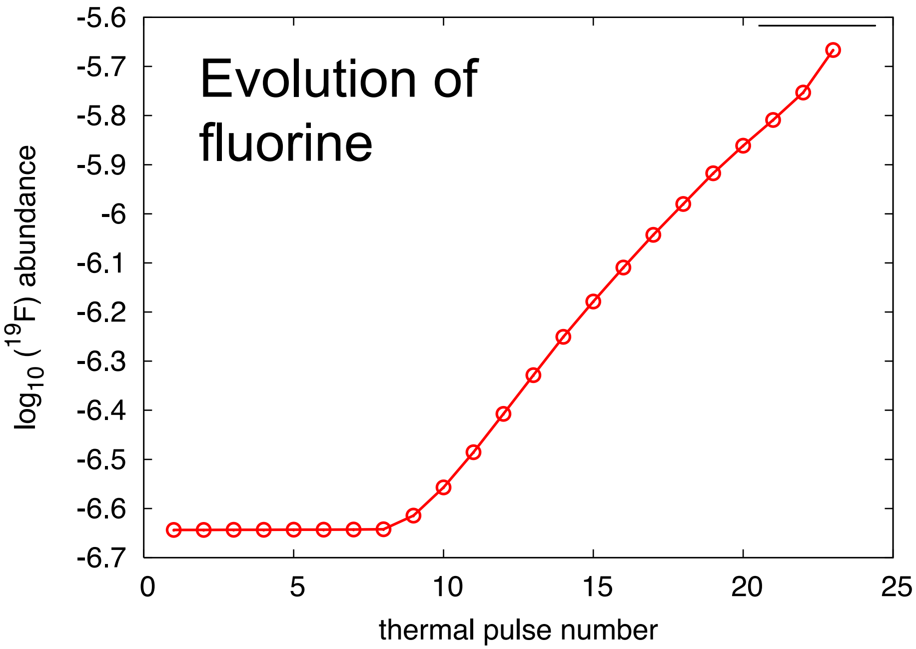


Models from Karakas et al. (2010)

Products of dredge-up

- Inward movement of convection mixes the products of He-shell nucleosynthesis to the envelope
- Repeated process, can happen after each pulse
- This is mostly ^{12}C with some ^{16}O, ^{19}F, ^{22}Ne, ^{23}Na, and maybe even $^{25,26}Mg$



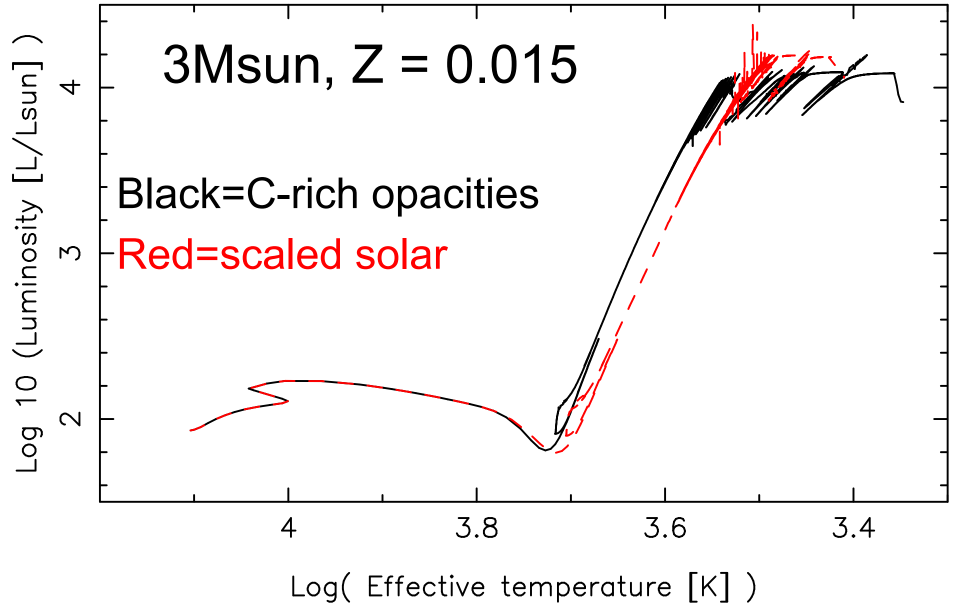


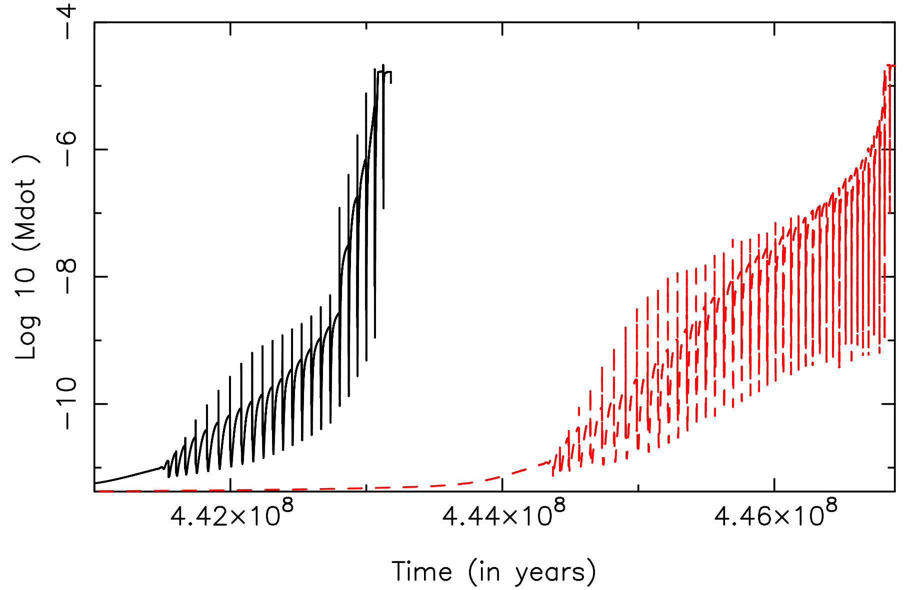
Evolution during the AGB

- Latest models use C-rich low temperature opacities
- This is because as the star becomes carbon rich, the molecular opacity rises (Marigo 2002)
- This leads to a cooling of the outer layers and an expansion

Recent models:

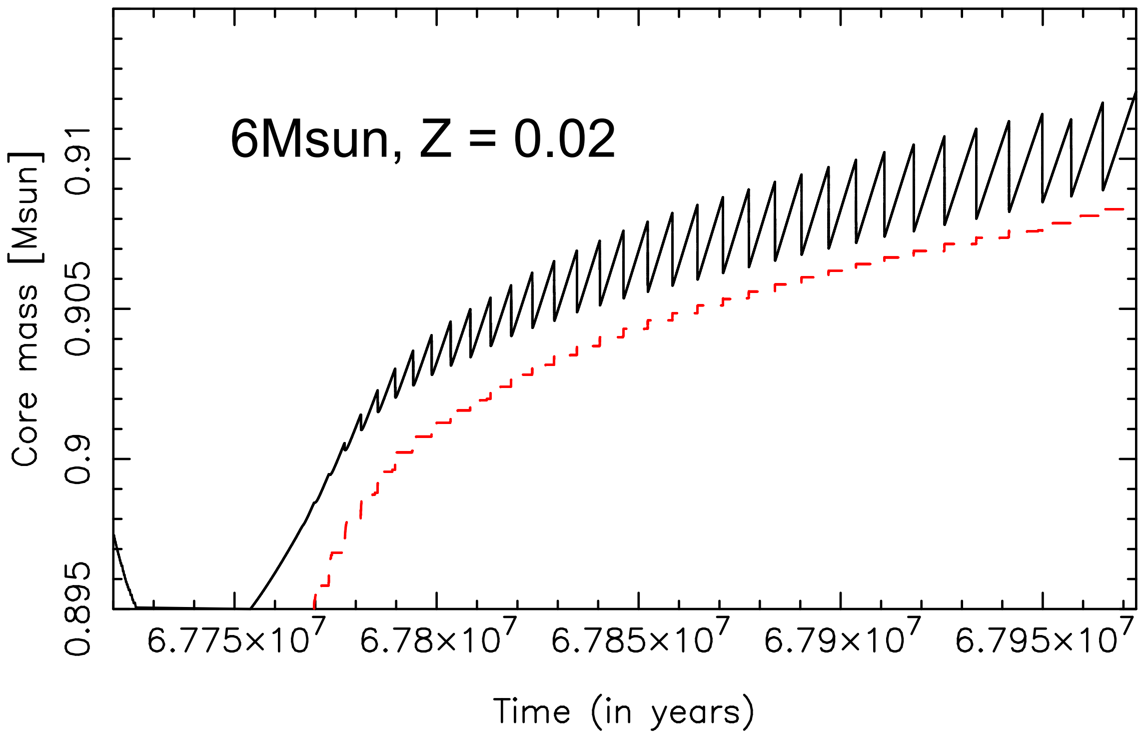
- Cristallo et al. (2009, 2011); Weiss & Ferguson (2009); Ventura & Marigo (2009,2010); Stancliffe (2010); Karakas et al. (2010, 2012); Kamath et al. (2012)





Intermediate-mass AGB stars

- M > 4Msun, depending on Z
- Rare, according to the initial mass function
- Relatively rapid evolutionary timescales (~60Myr for a 6Msun)
- Implicated in the chemical evolution of globular clusters but models suffer from considerable uncertainties (e.g., Ventura & D'Antona 2005)

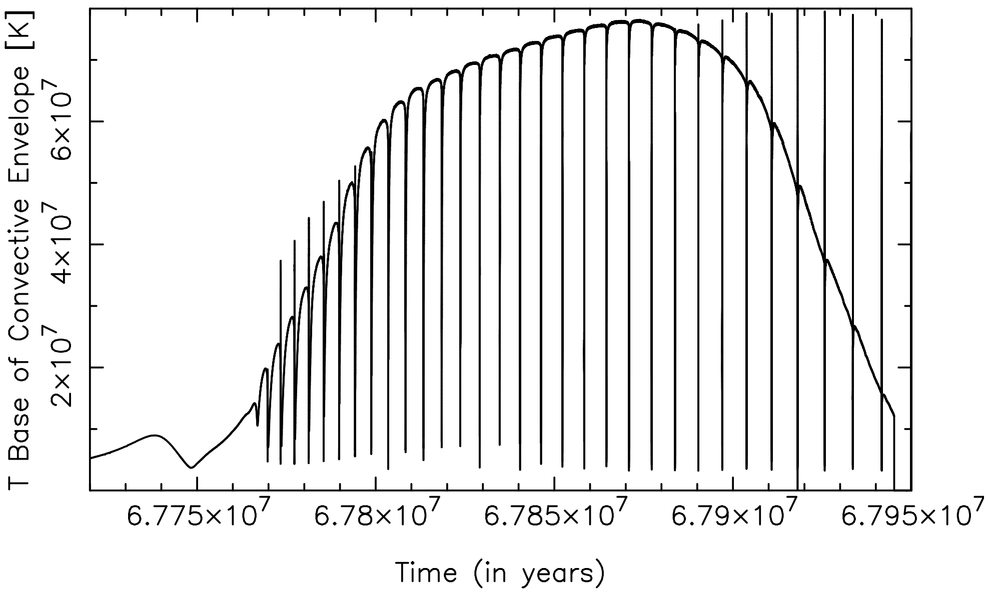


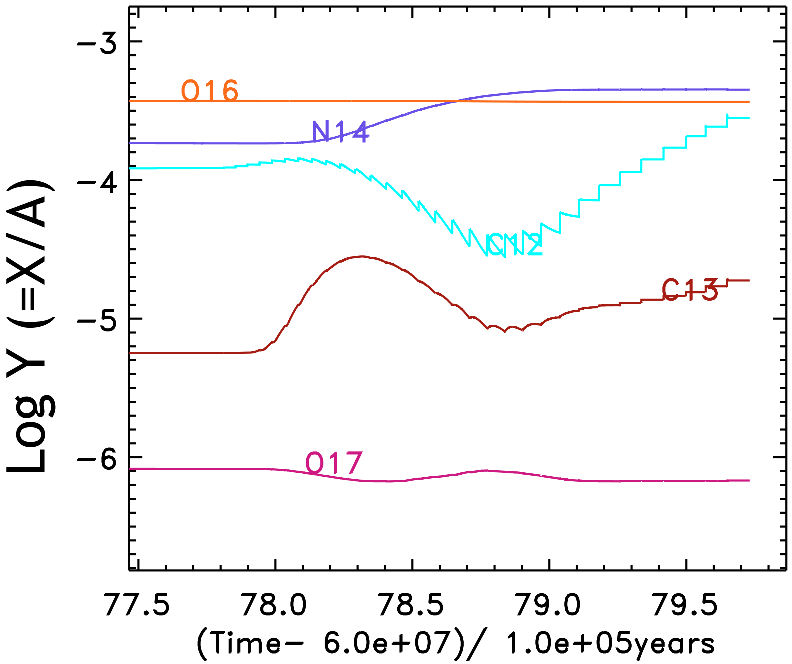
Intermediate-mass AGB stars

Along with TPs and the third dredge-up, these stars also have:

- Second dredge-up: Biggest ΔY (up to 0.1)
- Hot bottom burning: Proton-capture nucleosynthesis at base of envelope (products: N, Na, Al)

Example: 6Msun, Z = 0.02

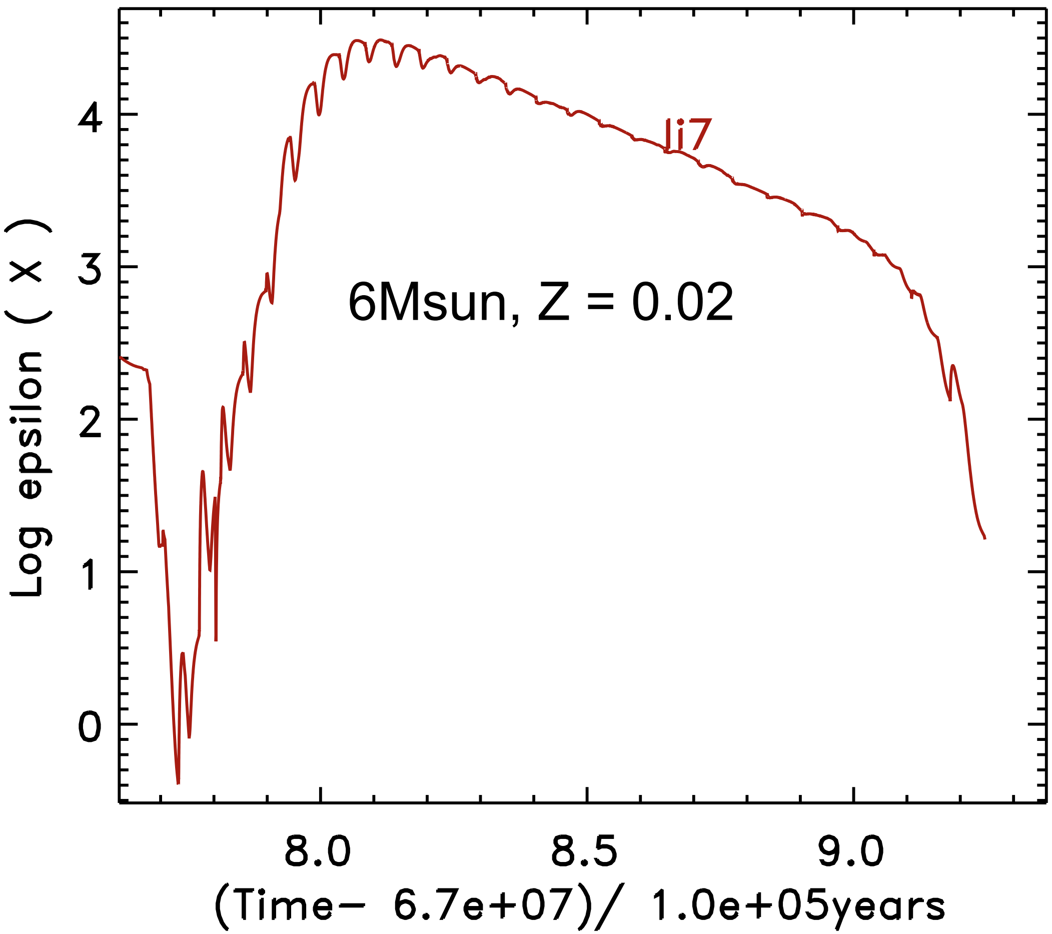




Lithium production

Lithium is produced by the Cameron-Fowler mechanism: ^7Be is transported by convection, where it captures an electron to produce ^7Li

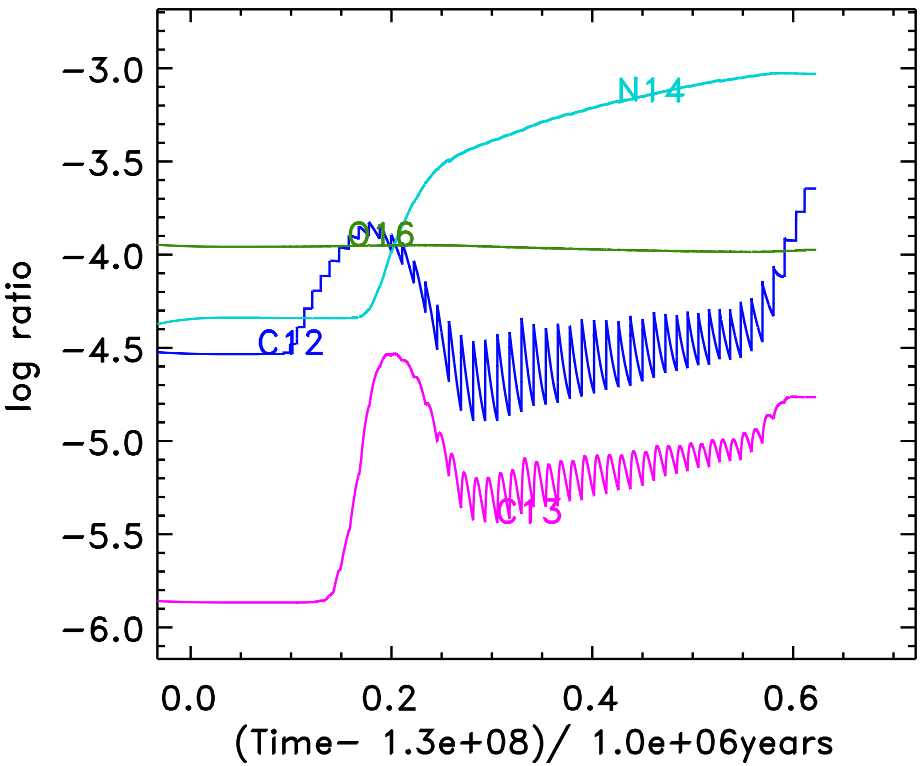
$$\text{Log } \varepsilon(\text{Li})_{max} = \log_{10}(\text{Li/H})+12 = 4.5$$



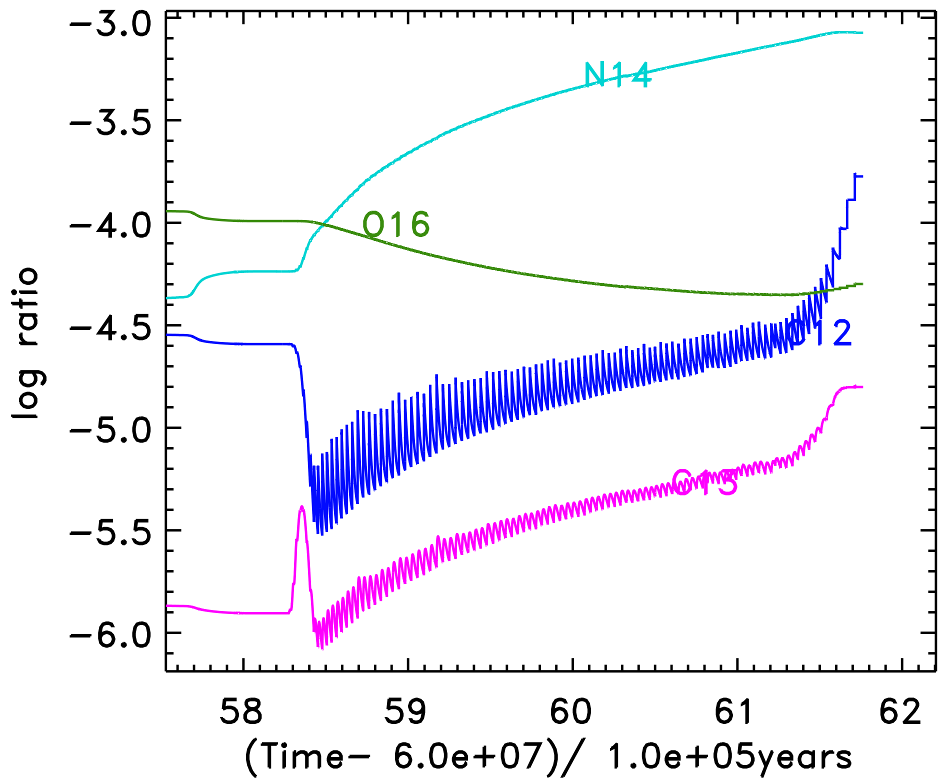
C, N, O isotopes

HBB as a function of stellar mass at the same Z =0.004 ([Fe/H] = -0.7)

M = 4.5Msun, T_{peak} ~ 80 x 10^6 K

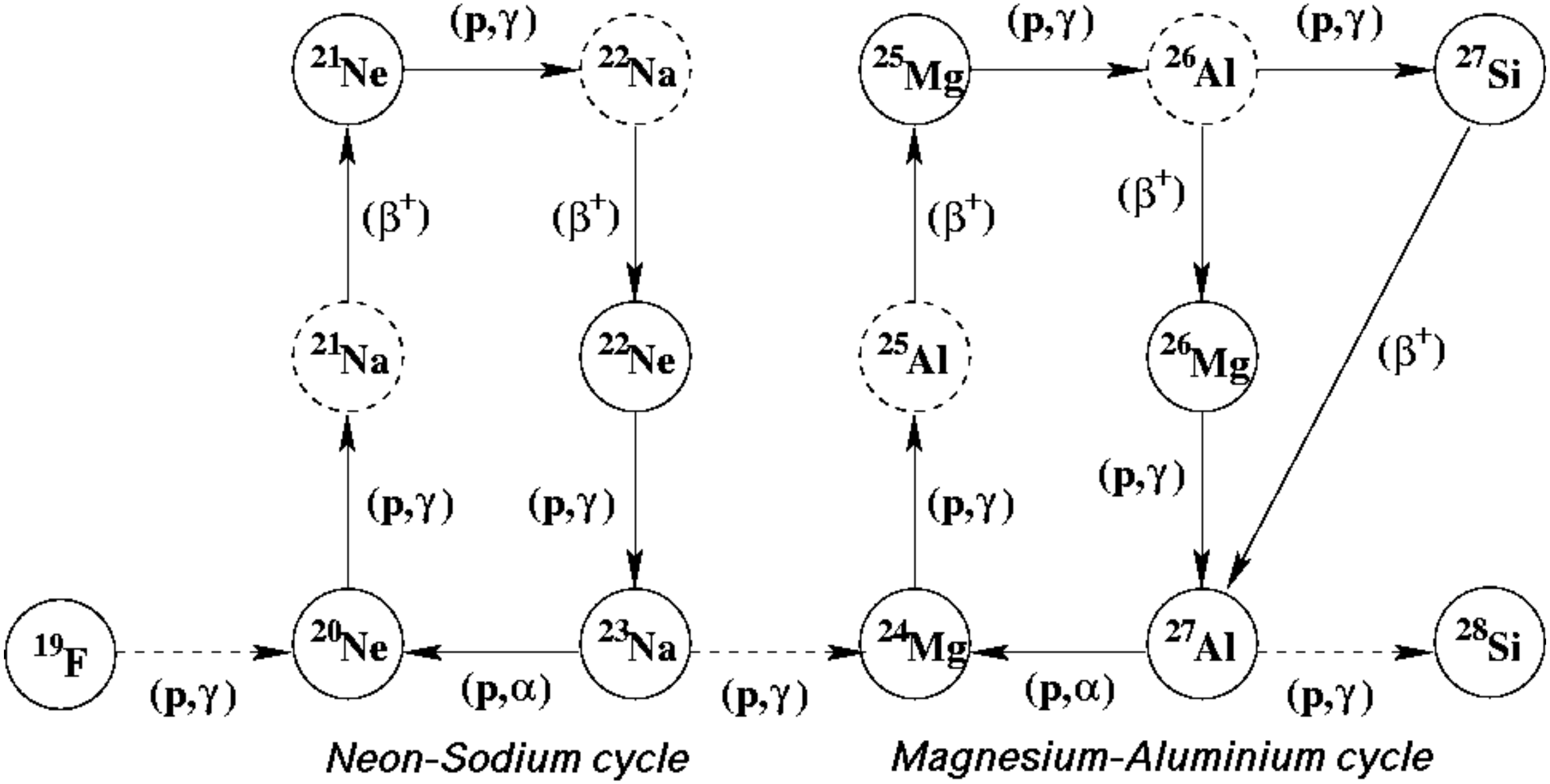


M = 6Msun, T_{peak} ~ 95 x 10^6 K



Advanced H-burning

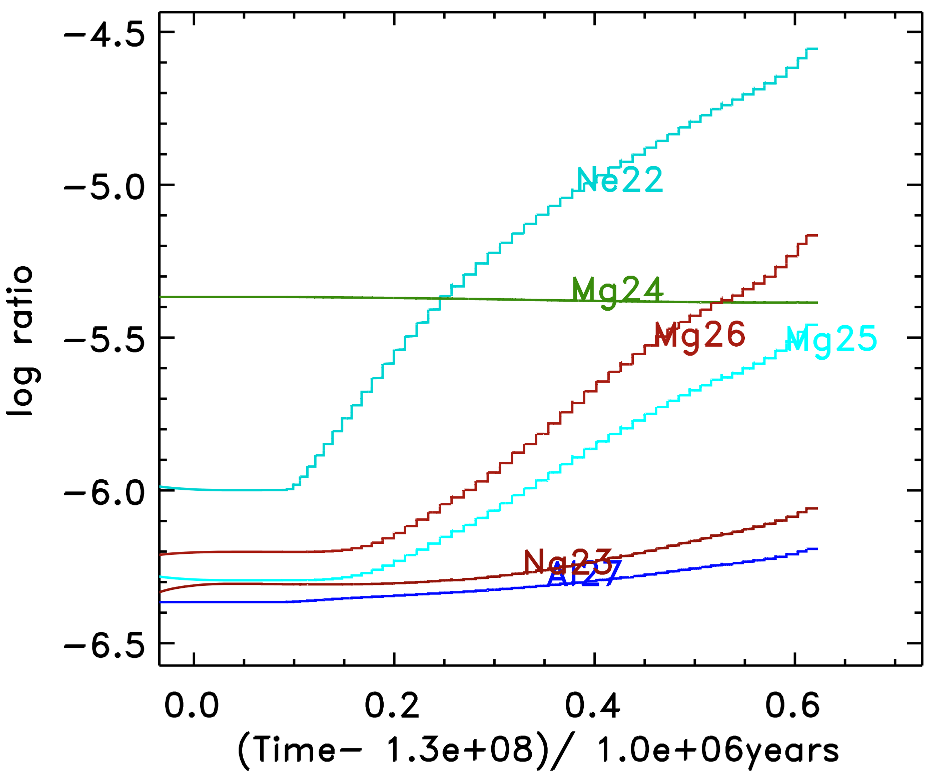
- If the temperature of the H-burning region is sufficiently high proton captures on the isotopes of Ne, Na, Mg, and Al will occur
- Negligible energy production
- Reaction rates highly uncertain for some key reactions (e.g., ^{23}Na + p, Illiadis et al 2010; ^{25}Mg + p, Straniero et al. 2013)



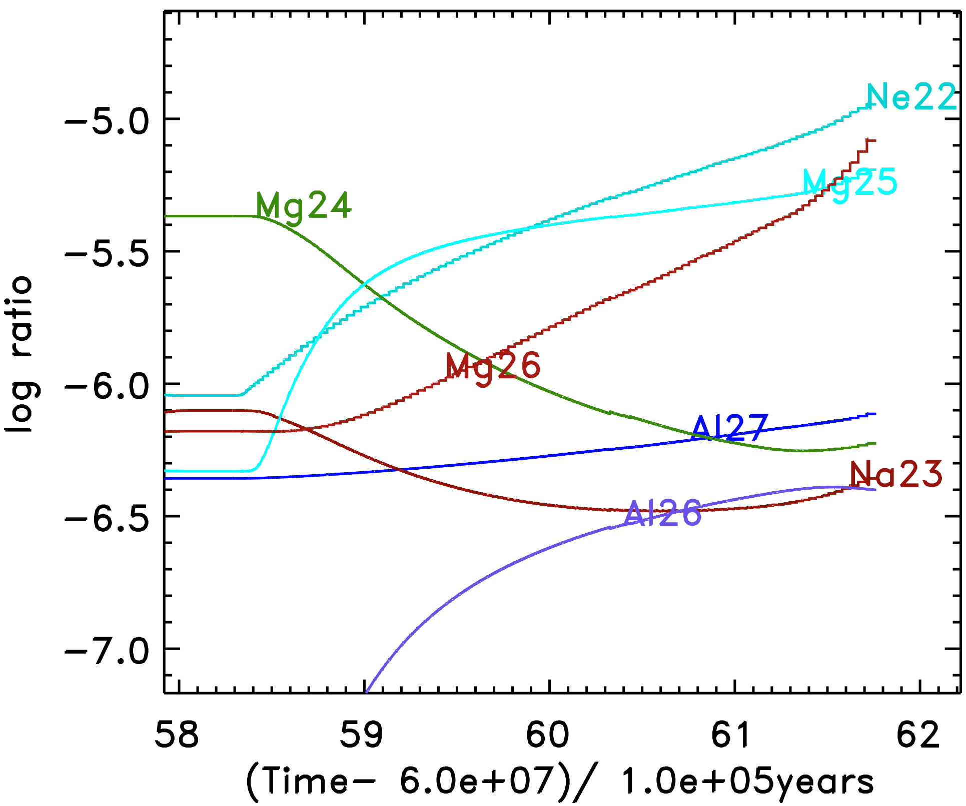
Ne, Na, Mg, Al isotopes

Examining the behaviour in the Z = 0.004 models from before

M = 4.5Msun



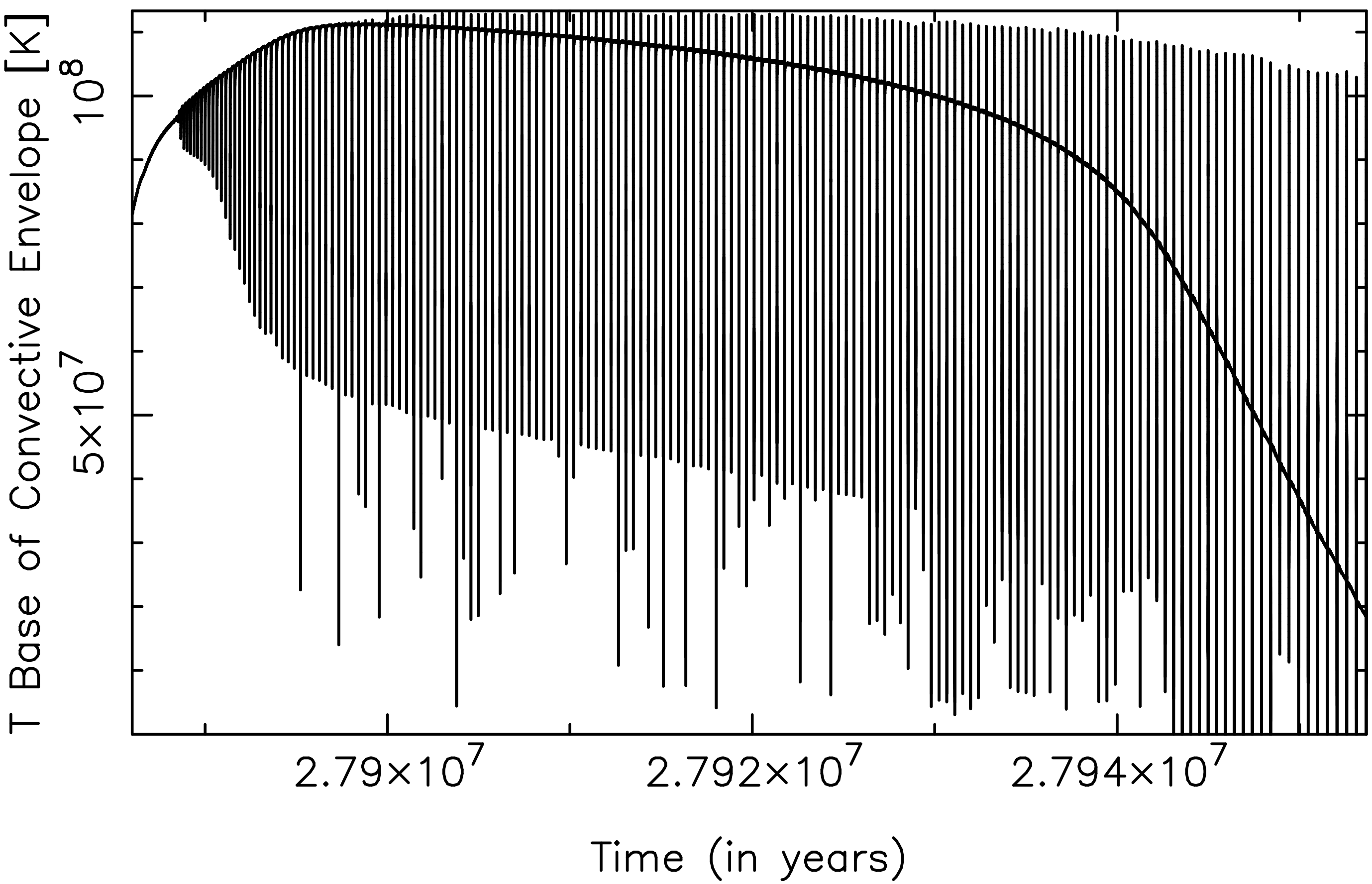
M = 6Msun



Super-AGB stars: the 9Msun

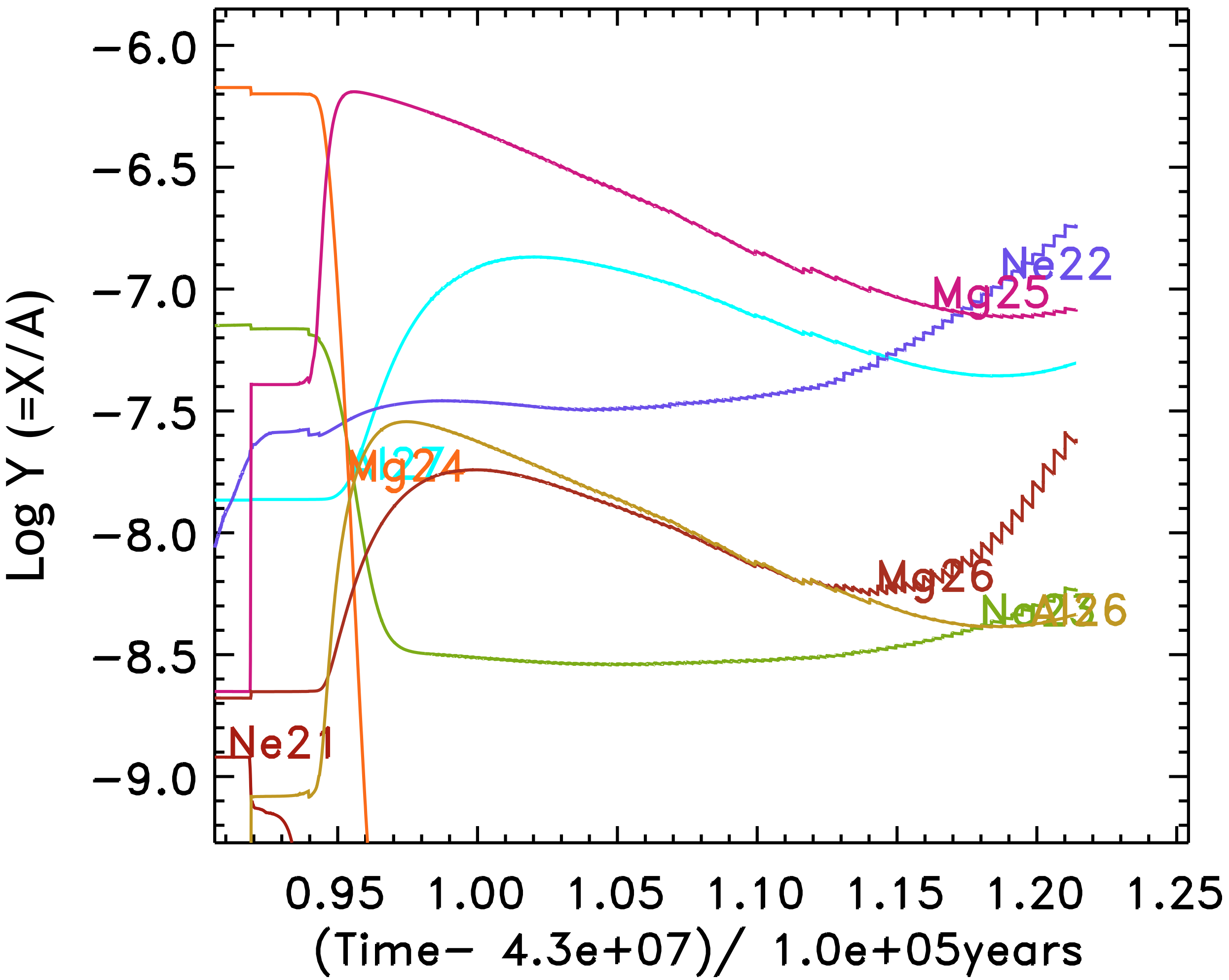
The 9Msun has a core mass of ~1.18Msun, too low to go through electron capture supernovae.

It will produce an O-Ne white dwarf



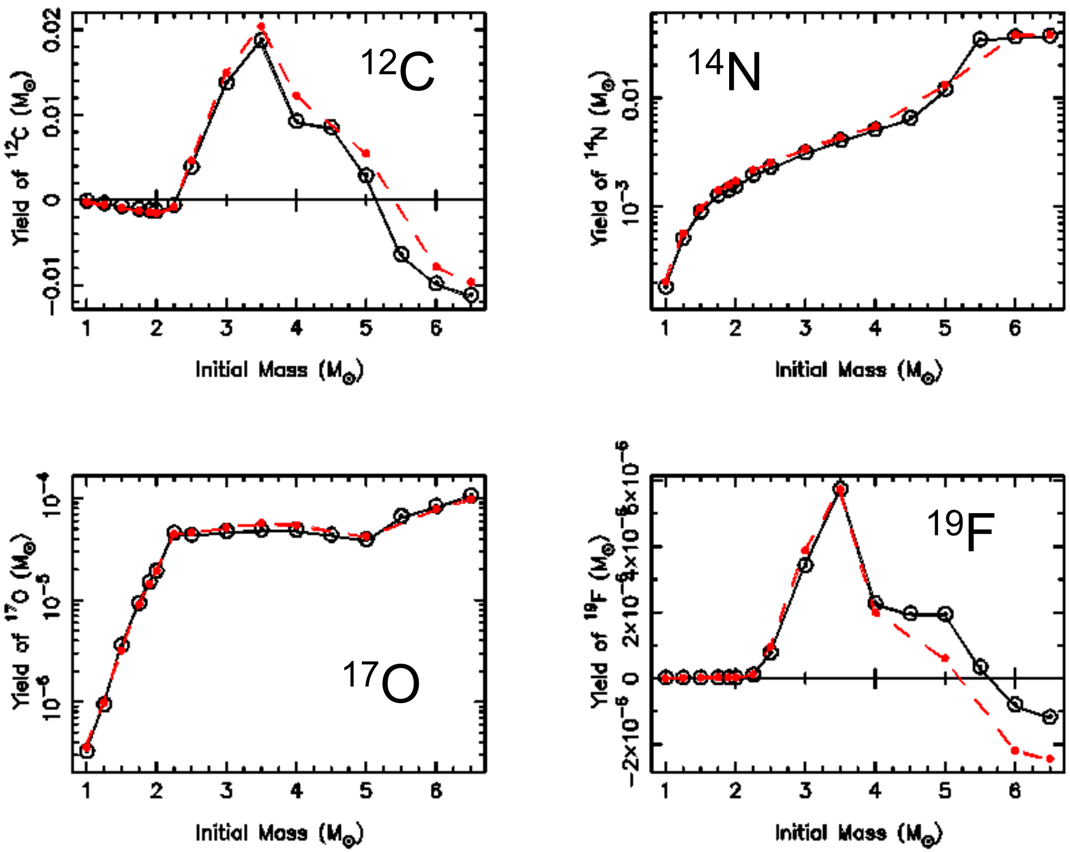
Nucleosynthesis in super-AGB stars

$7M_{sun}$, Z = 0.002 (1/100th solar). Peak temperature ~ 140 x 10^6 K.
This is about as extreme as it gets in an AGB star!



AGB chemical yields

Example: Z = 0.02



- For masses between 1 to 6Msun
- Metallicities Z = 0.02, 0.008, 0.004, 0.0001
- Weighted toward tip of AGB as this is when most mass is lost

Recent models and yields:

- Lagarde, Decressin et al. (2012) – but only two TP-AGB models
- Ventura et al. (2013) – extended mass range but not to the lowest masses

Published in Karakas (2010)

Yields and surface abundances for hydrogen to sulphur

AGB yields: What is lacking

Super-AGB stars not included

- The integrated contribution of 8 to 10Msun stars is currently not well known
- First yields published by Siess (2010) but partly synthetic; see latest paper by Ventura et al. (2013)

Systematic study of the uncertainties

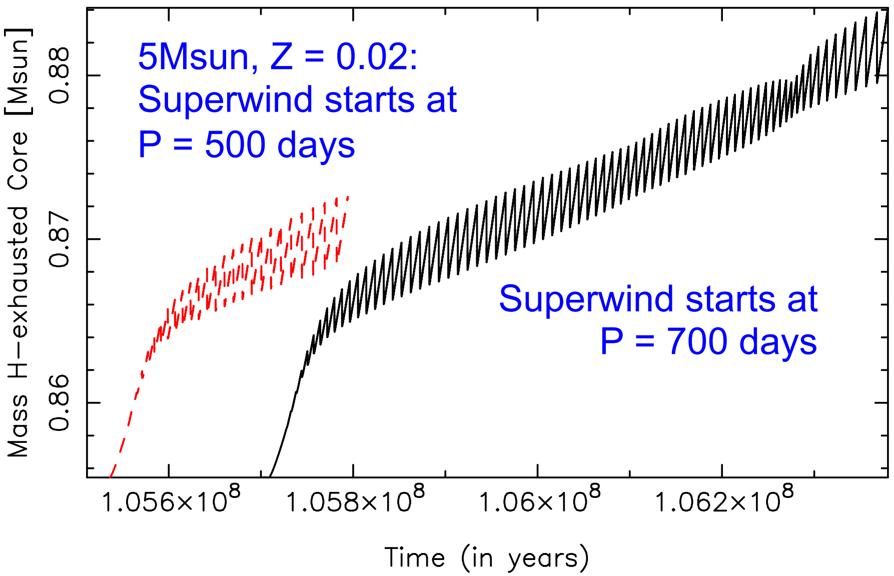
- Convection, mass loss, reaction rates have a huge impact on stellar yield calculations (Ventura & D'Antona 2005; Izzard et al. 2007; Karakas 2010)
- Can impact galactic chemical evolution studies (e.g., Romano et al. 2010)
- But few (no?) systematic studies covering a large range of masses and metallicities

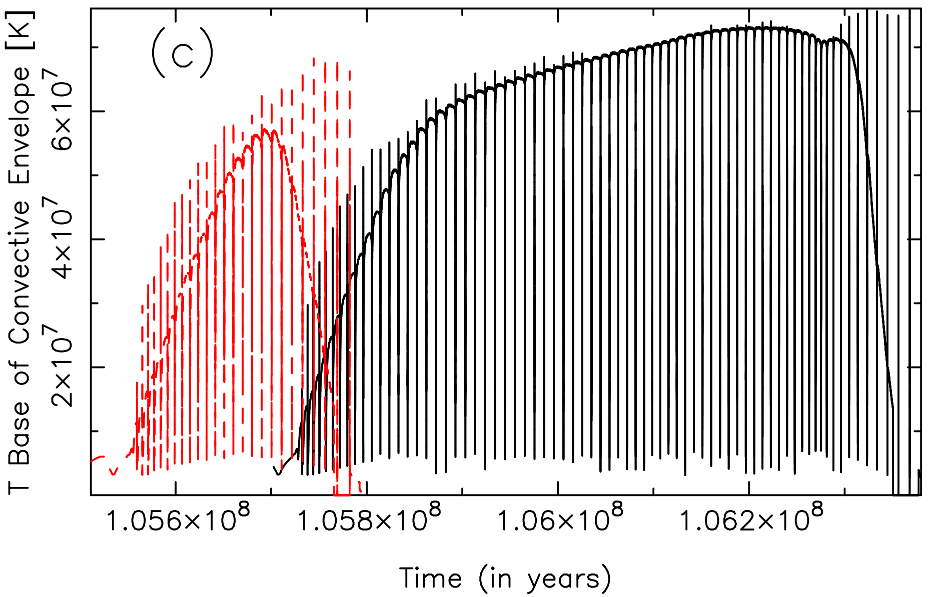
Other physics

- The impact of extra mixing and rotation often ignored but these are starting to be included in yields and chemical evolution studies (e.g., Angelou et al. 2012; Lagarde, Romano et al. 2012)
- Affects of a binary companion mostly ignored (see Izzard et al. 2006)

Uncertainties caused by mass-loss

- We experimented with varying the mass-loss rate in models of 5 to 7Msun, Z = 0.02 ([Fe/H] = +0.14 dex)
- In each case we delayed the onset of the superwind to P ~ 700 days
- We were trying to explain the high [Rb/Fe] abundances observed
- For the effect of reaction rates, see Falk's talk next

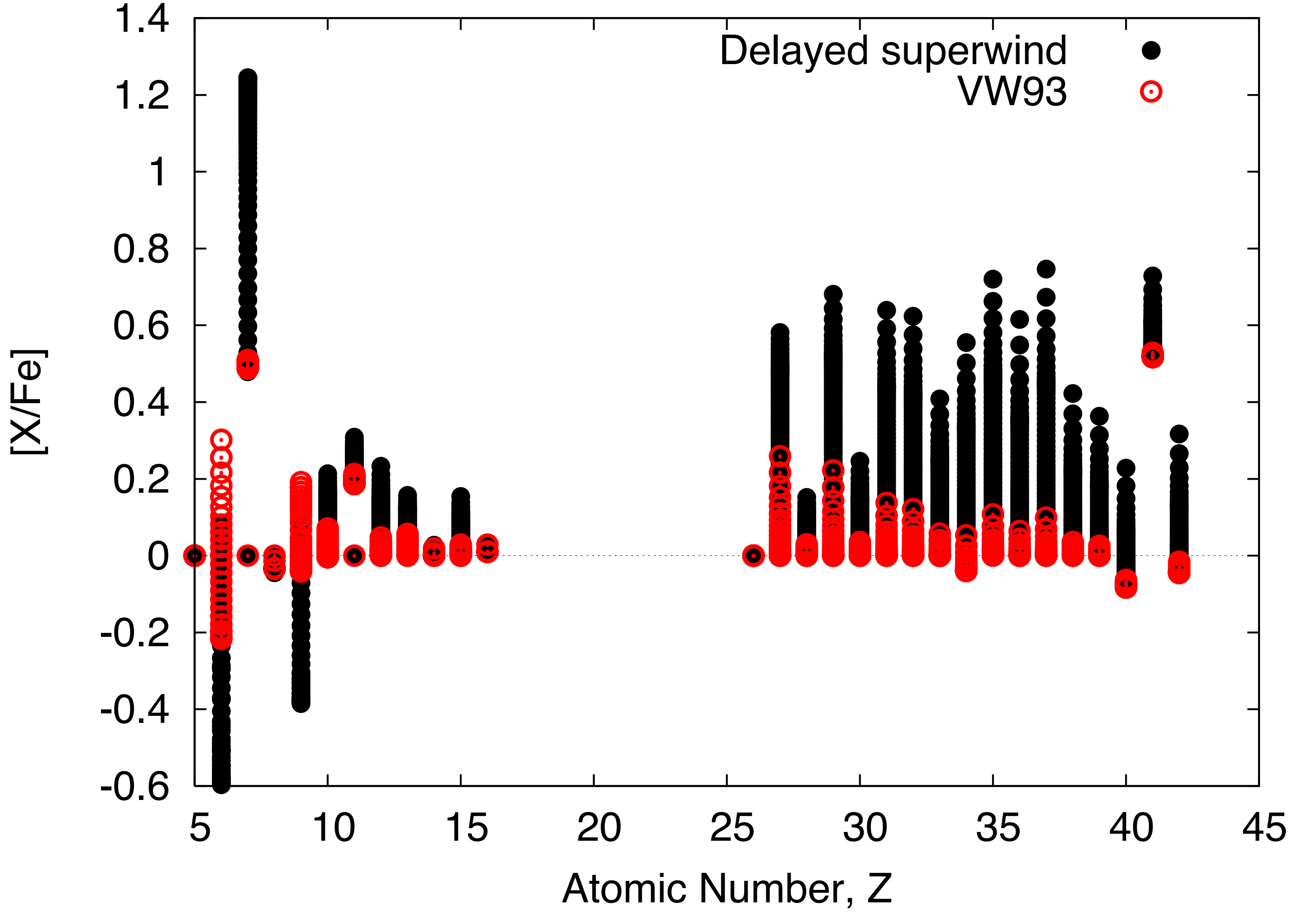




From Karakas et al. (2012)

Effect on nucleosynthesis

Showing nucleosynthesis differences between 5Msun, Z=0.02 with different mass-loss rates:



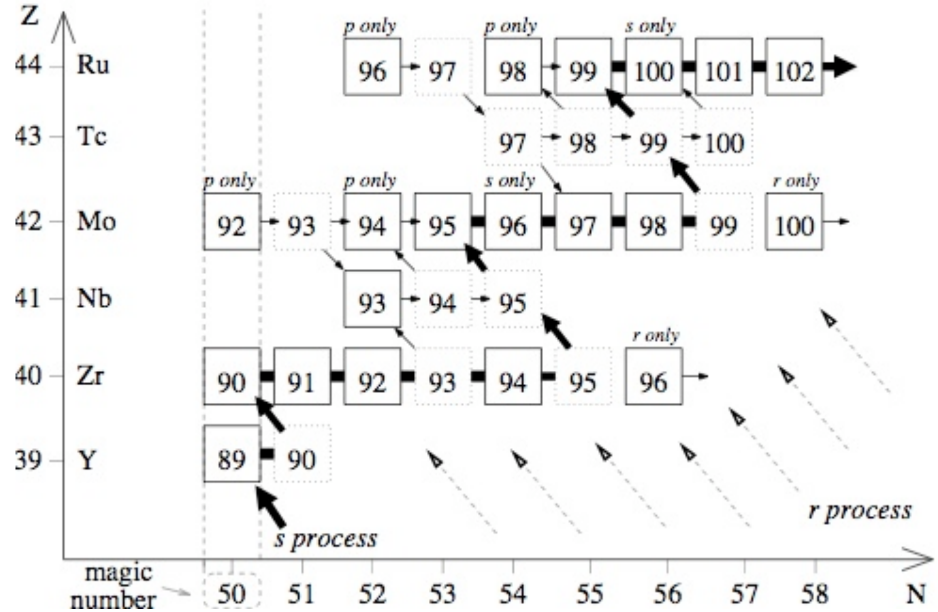
From Karakas et al. (2012)

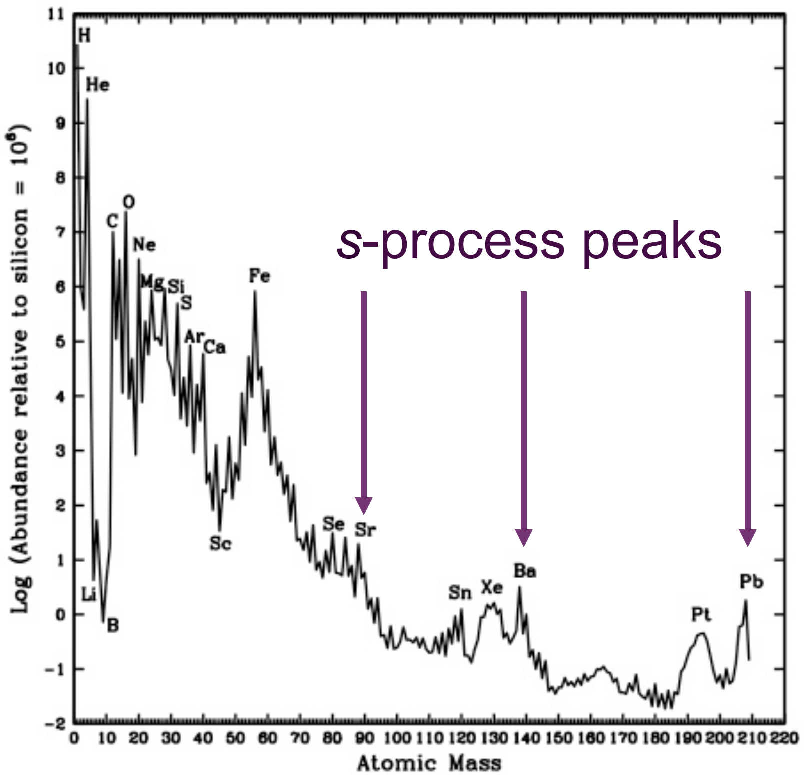
3. Formation of heavy elements by the slow-neutron capture process (s-process)

The slow-neutron capture process

The s-process is responsible for producing half of the heavy elements in the Universe (e.g., Sneden et al. 2008; Lattanzio & Lugaro 2005). Two sites:

1. AGB stars
2. Massive stars





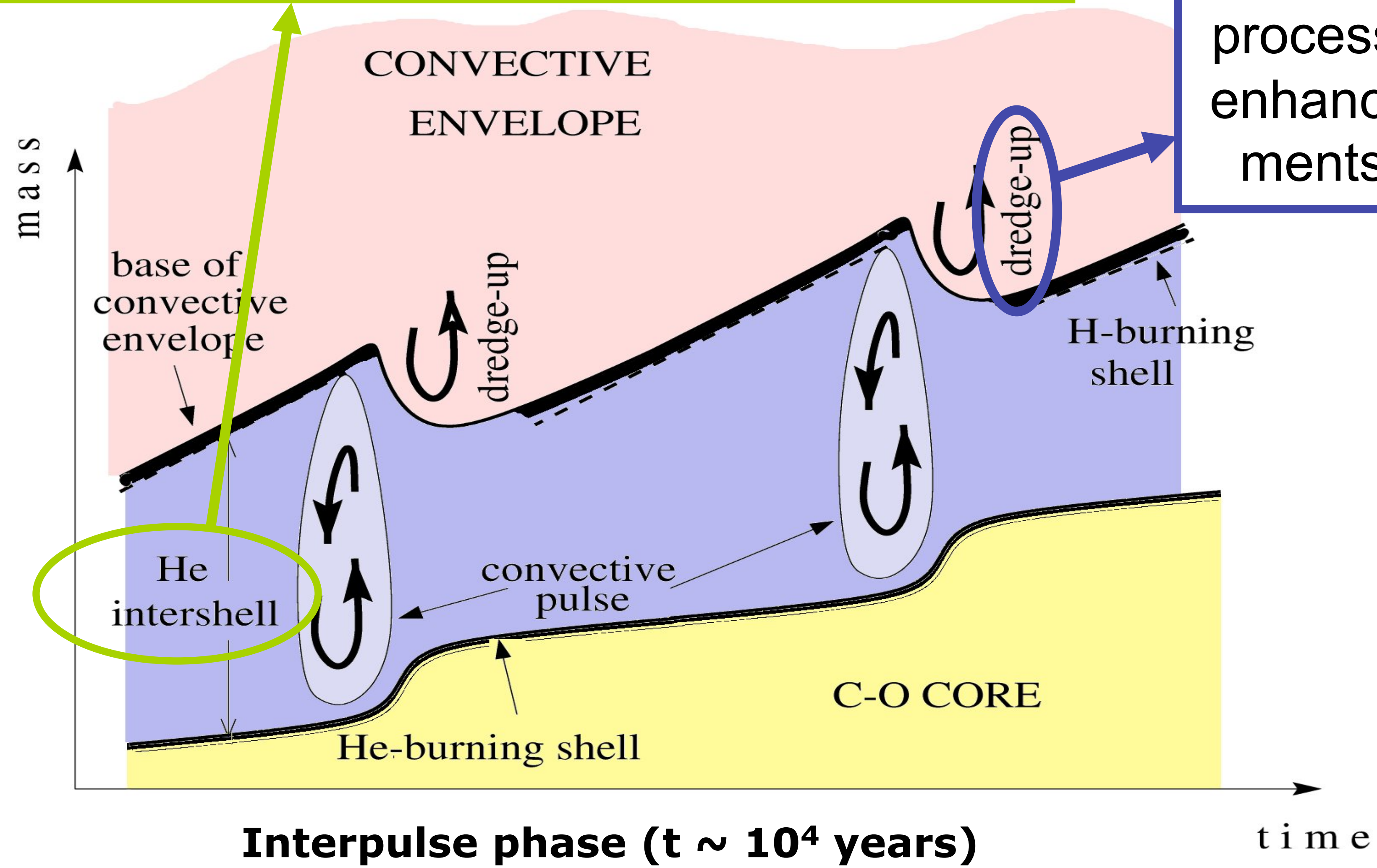
Time scale for n capture << Beta-decay times

Neutrons from $^{13}C(a,n)^{16}O$ and $^{22}Ne(a,n)^{25}Mg$

Where in AGB stars?

^{4}He, ^{12}C, *s*-process elements: Zr, Ba, ...

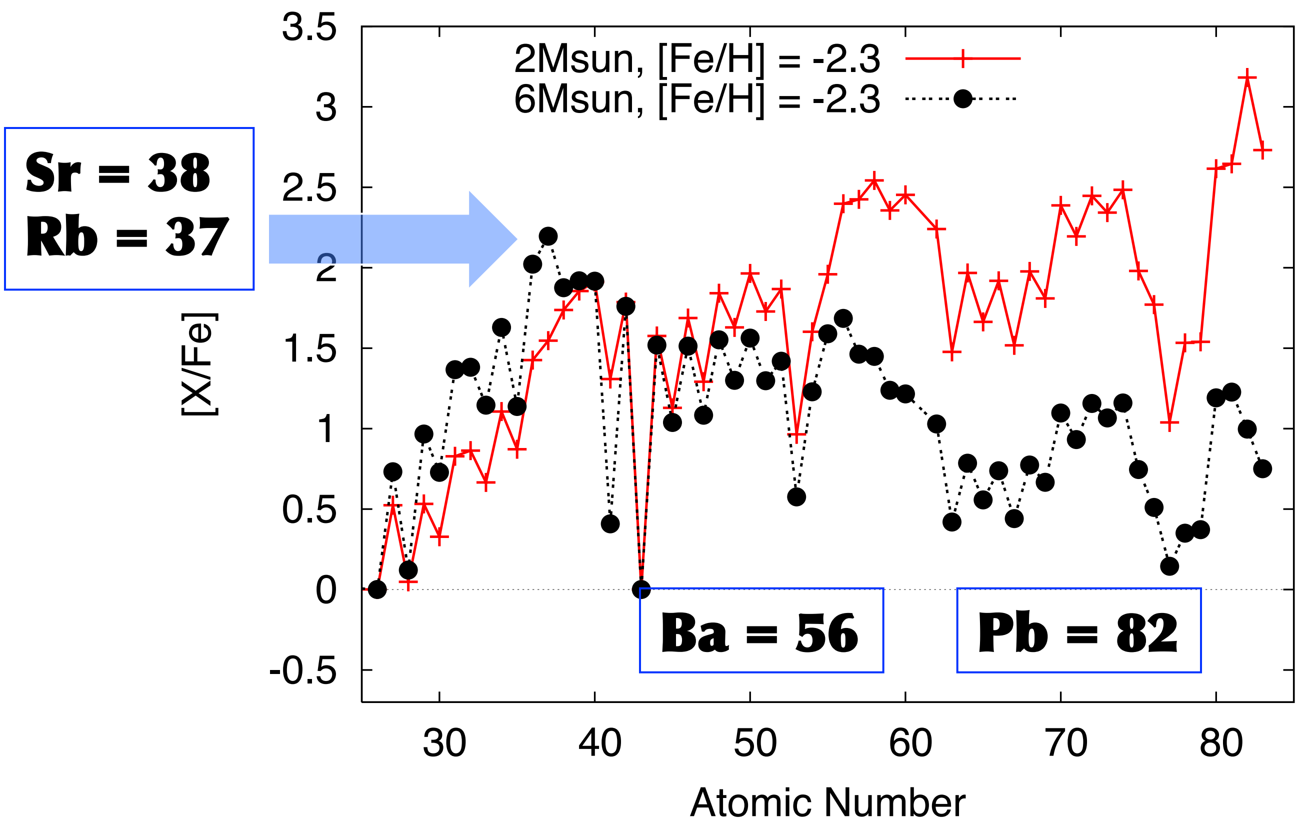
At the stellar surface: C>O, *s*-process enhancements



Interpulse phase (t ~ 10^4 years)

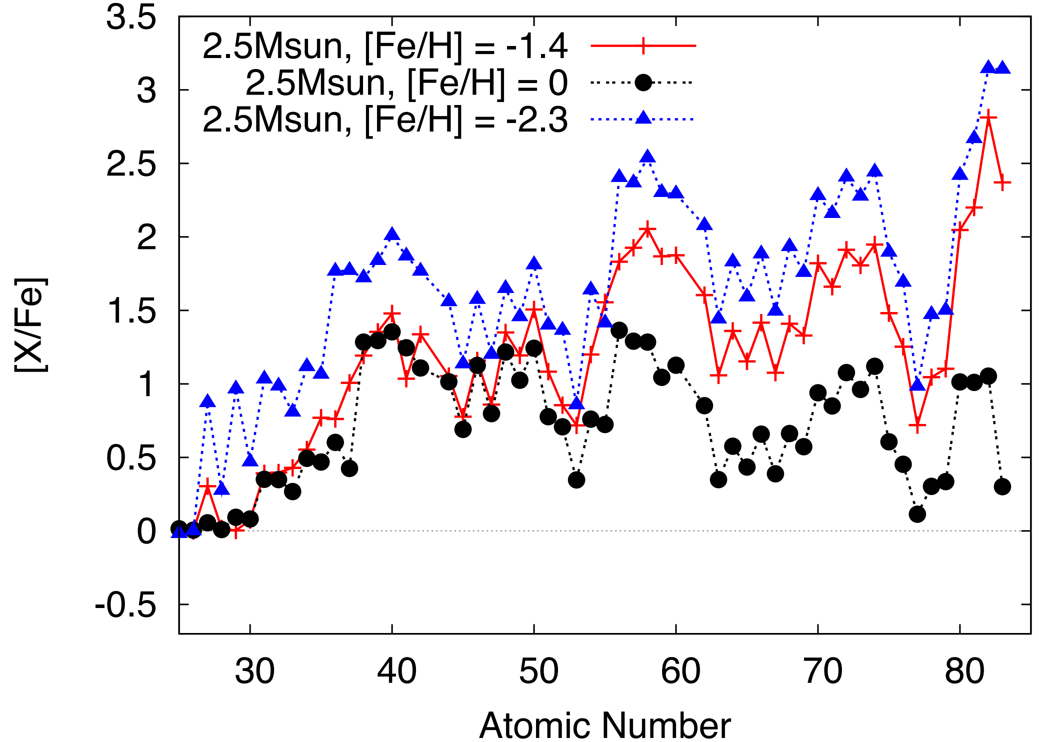
The s-process: The effect of mass

- The s-process in a 6Msun, Z = 0.0001 AGB star produces copious Rb (Z=37) compared to Ba, Pb
- This is because it occurs at high neutron densities: ~10^{13} n/cm^3
- Yields for [Fe/H] = −2.3 are published in Lugaro, Karakas, et al. (2012) for M = 1 to 6Msun



The effect of metallicity

- Few/no s-process yields covering the range from M=1 to ~9Msun for a large range in metallicity
- New s-process models for M =1 to 7Msun models at [Fe/H] = −1.2 (Fishlock et al. 2013, in preparation)
- Cristallo et al. (2011): the FRUITY database (only to 3Msun)
- NuGrid project: aims to publish models and yields for significant range of mass



Double trouble

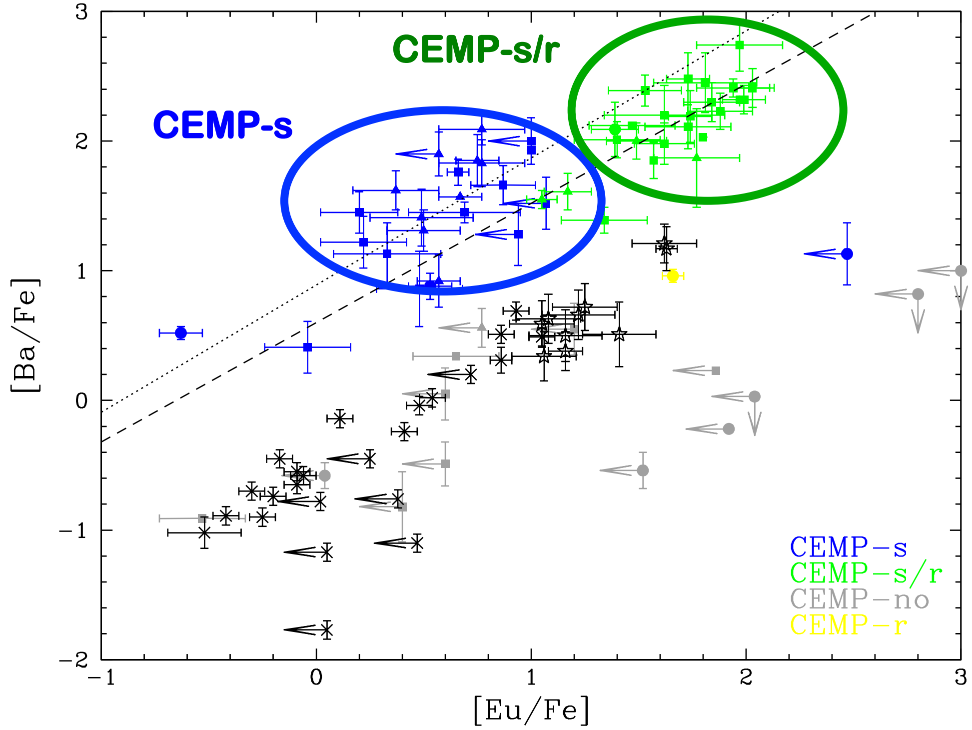
- Simple picture of 1D single stellar evolution
- Adding in a binary companion increases the complexity and uncertainties
- But it must be done because there are a whole range of phenomena that can only be explained by binary stellar evolution:

1. The zoo of carbon-rich stars, e.g., barium/CH, R-type, R Coronae Borealis, J-type (?), carbon-enhanced metal-poor
2. The formation of asymmetrical planetary nebulae (e.g., talks by De Marco, D. Jones, Tyndall)
3. Novae eruptions and interacting binaries (e.g., Tappert, Chesneau, Nicholls)
4. Type Ia supernovae (e.g., Shen, Ruiter)

And the fact that most stars are in binary systems! (All massive O-type stars? e.g., Sana et al. 2012)

Carbon enhanced metal-poor stars

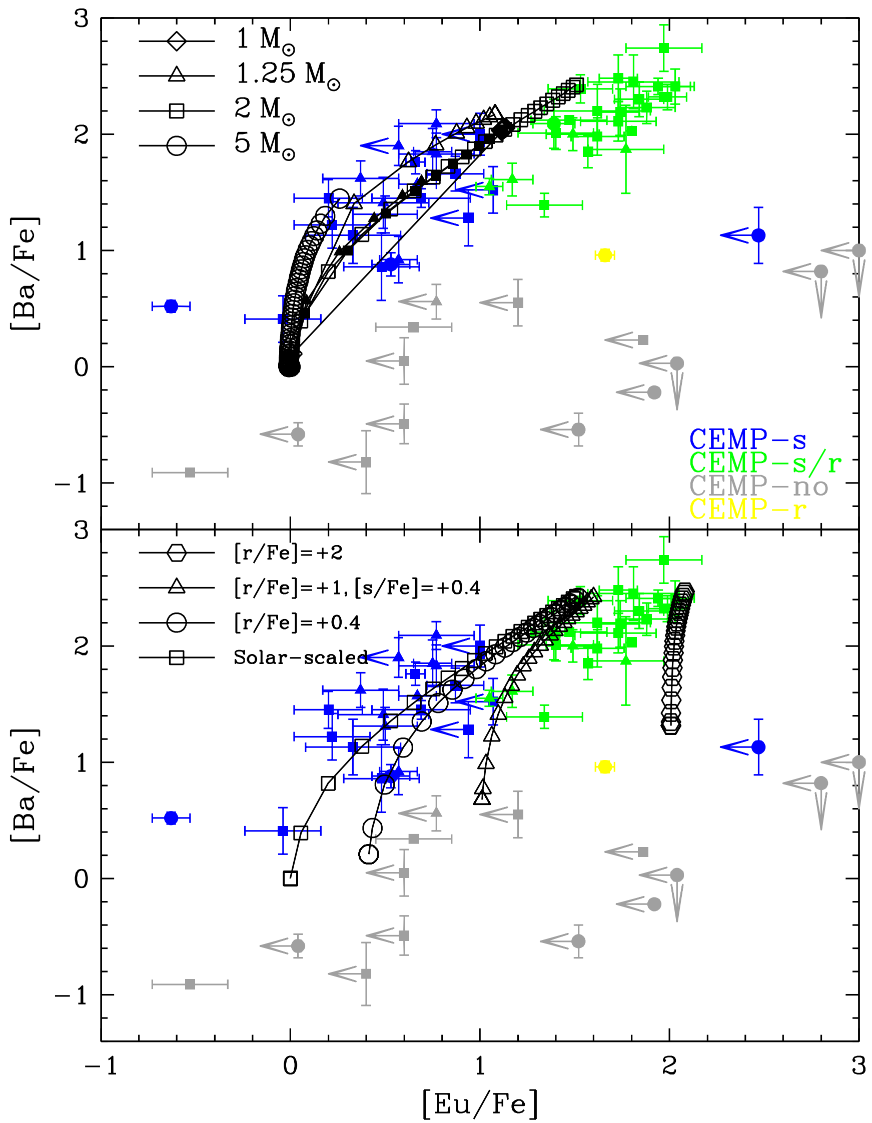
- Roughly 10-20% of old halo stars are C-rich ([C/Fe] > 1; Cohen et al. 2005; Carollo et al. 2011)
- Of these ~2/3 show enrichments in heavier elements (e.g., Aoki et al. 2007)



Using the data and classification of Masseron et al. (2010)

Results: [Ba/Fe] versus [Eu/Fe]

Top panel: **results of different masses, scaled solar initial composition**
Lower panel: **results of variations in the initial composition for the 2Msun Stromlo model (Lugaro et al. 2012)**



Summary

- AGB s-process models fit the CEMP-s data well (e.g., Lugaro et al. 2012; Bisterzo et al. 2010, 2012)
- But the correlation between Ba and Eu of CEMP-s/r group ***not*** reproduced
- However Bisterzo et al. (2012) say otherwise, where the CEMP-rs evolved from a cloud initially seeded with r-process elements

Summary of AGB evolution

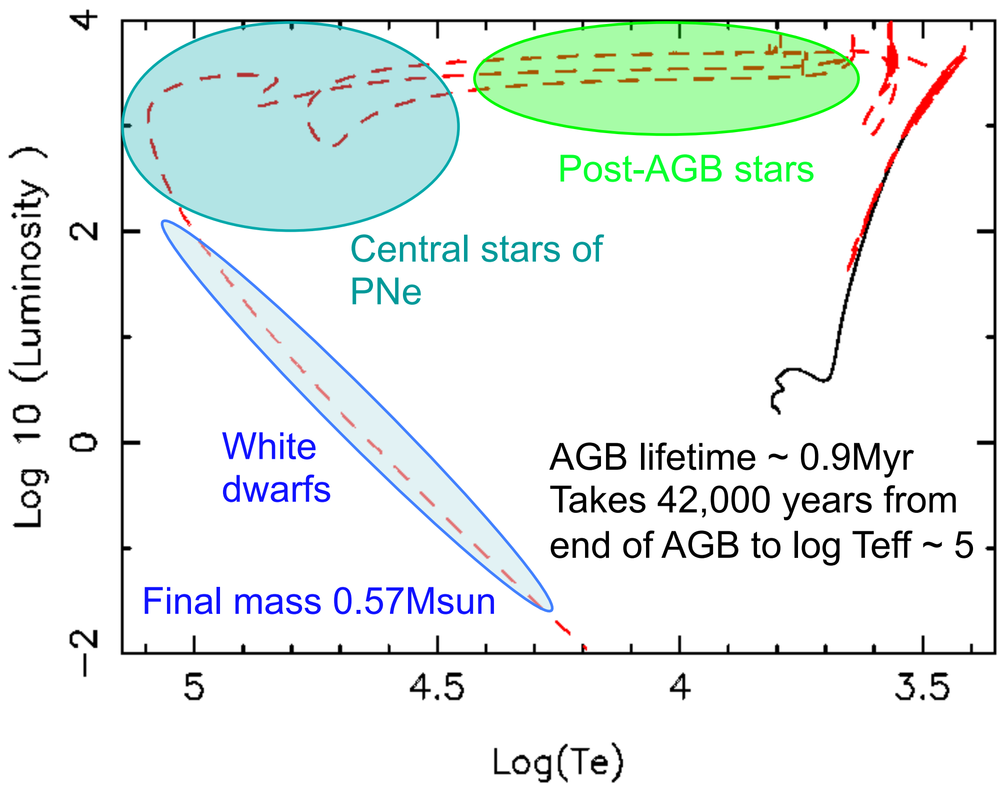
- The mass-loss history on the AGB sets the transitions times of post-AGB objects
- Dredge-up and thermal pulses set the structure and composition of the core
- Low-mass AGB stars (~1.2 to 4 Msun)
  - The third dredge-up dominates nucleosynthesis
  - Mixes He-burning products to the surface e.g., ^{12}C, ^{19}F, s-process elements
- Intermediate-mass and super-AGB stars (~4 to 9Msun)
  - Hot bottom burning occurs alongside the TDU
  - Results in enhancements of ^{4}He, ^{14}N and destruction of C, O
  - Heavy element production?

4. From the post-AGB onwards

After the AGB

- Once the envelope mass drops below ~0.01Msun, the star leaves the AGB
- Evolves at almost constant luminosity toward hotter Teff
- Transition times very rapid (~100 years) for most massive objects → No PN
- Transition times ~10^4 years for low-mass objects
- Mass loss rates are low (~10^{-8} Msun yr^{-1})
- See reviews by van Winkel (2003) and Blöcker (2001)

Example: 1.25Msun, Z = 0.02 model

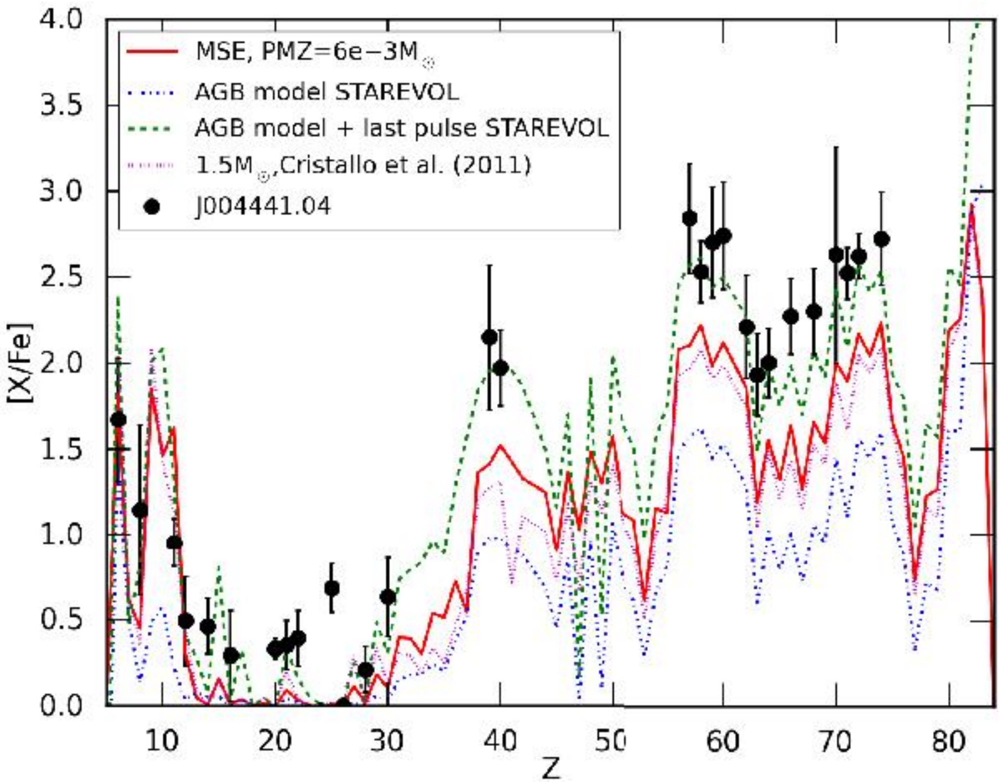


Adapted from Fig. 1; Herwig (2005)

Constraining stellar models with post-AGB stars

- Abundances of post-AGB stars and planetary nebulae are useful tools for stellar evolution and nucleosynthesis studies
- E.g., Bonacic Marinovic et al. (2007); Herwig et al. (2011); de Smedt et al. (2012), Shingles & Karakas (2013)
- Can constrain intershell abundances (e.g., PG 1159 stars), ^{13}C pocket sizes for the s-process

The abundance pattern of the post-AGB star J004441.04 ([Fe/H] = -1.4) in comparison with model predictions.



From De Smedt et al. (2012)

Summary

- Stars with initial masses below ~8Msun evolve through the AGB before losing their envelopes
- The composition of the ejected material is determined by mixing events prior to and during the AGB
- The mass loss history, the occurrence of mixing events, and thermal pulses determine the structure of the remnant core
- As well as the evolution during the post-AGB phase
- Qualitative picture reasonably good, but details remain
- Main uncertainties are mass loss and our lack of understanding of how mixing really works in stars
- Starting to be addressed by multi-D models