Oxygen in AGB stars and the relevance of planetary nebulae to mapping oxygen in the Universe

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The Cat's Eye Nebula — NGC 6543 HUBBLESITE.org

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Introduction

- Planetary nebulae (PN) are the glowing remnants of the evolution of stars with initial masses between ~0.8 to 8Msun
- PN abundances can reveal both the initial composition as well as the nucleosynthesis that took place during previous evolutionary phases
- PN abundances are also used to track the chemical evolution of galaxies, under the assumption that they reflect the ISM at the time of the PN progenitor's birth
- Is this assumption valid?

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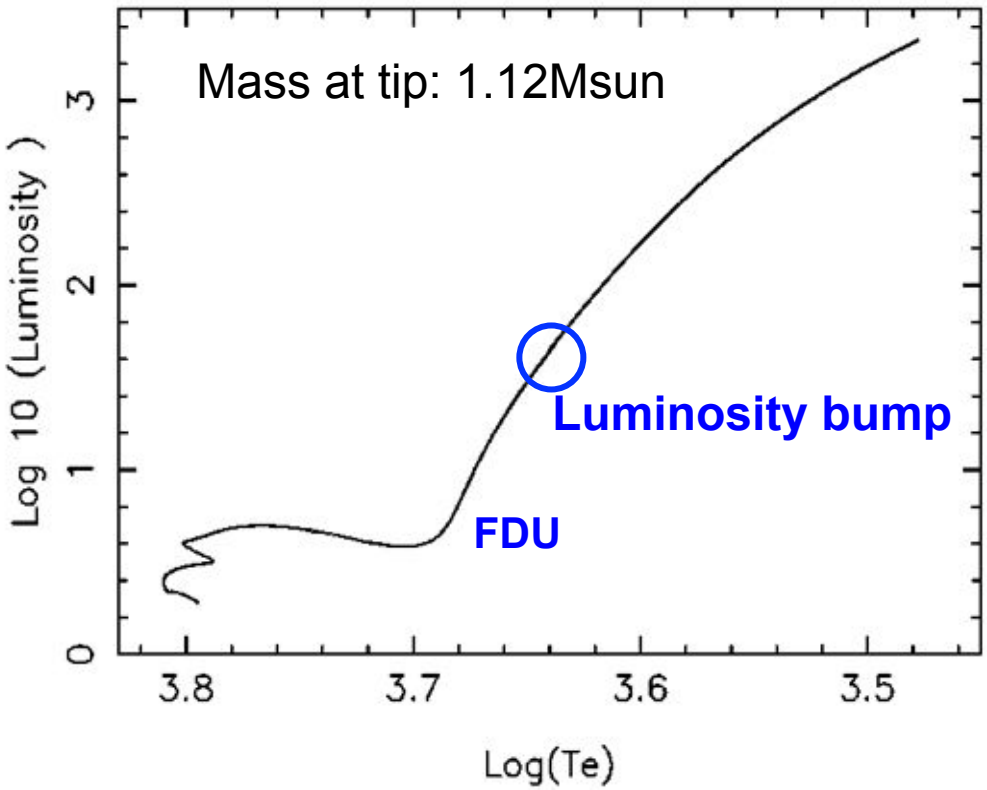
Up to the tip of the first giant branch

- Envelope convection deepens
- Mixes up material partially processed during the previous main sequence
- This is the first dredge-up (FDU)
- Main changes:
  - Reduction in Li, $^{12}C/^{13}C$ ratio
  - Increases in ^{3}He, N
  - Oxygen isotopic ratios altered, depending on initial mass
- Core He-burning ignited at tip of the giant branch
- Mass loss will erode up to 20% of the envelope in ~1Msun stars

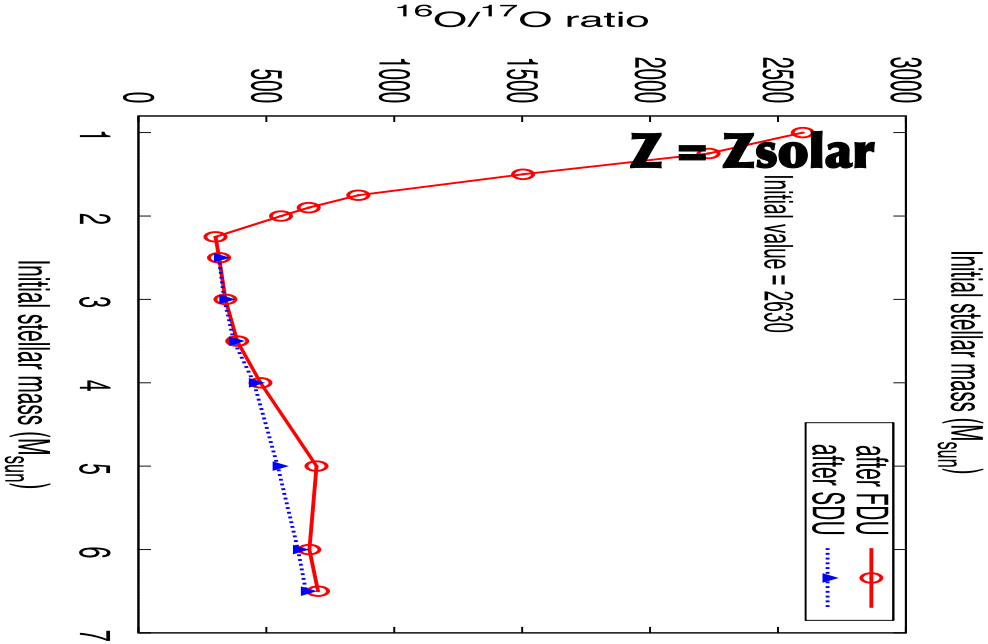
Example: 1.25Msun, Z = 0.02 model



→ Mass loss on RGB may not be this efficient, according to latest Kepler data of old open clusters (Miglio et al. 2012)

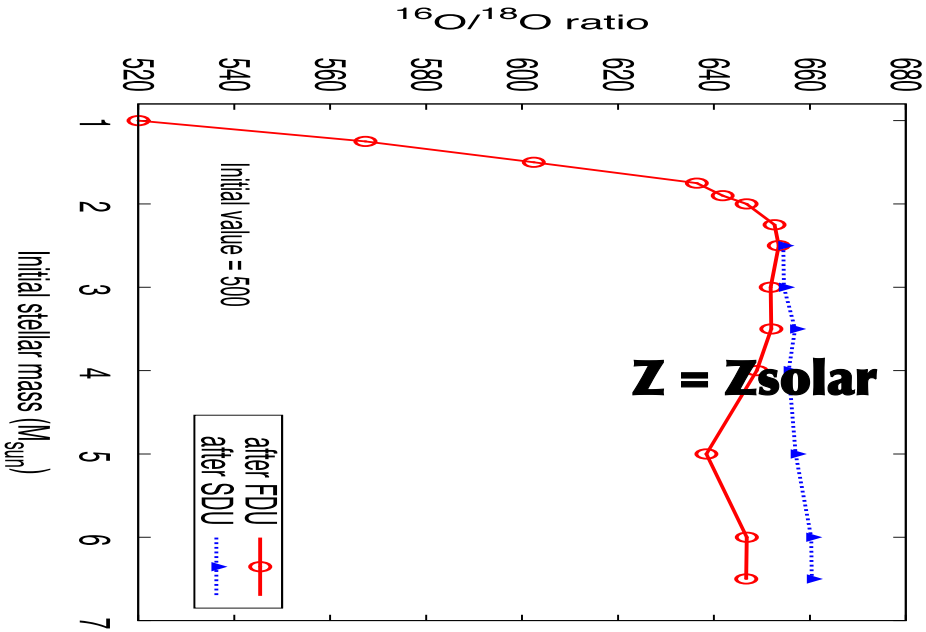
Oxygen isotope ratios after FDU

- Mixes up material partially processed during the previous main sequence
- Oxygen isotope ratios: $^{16}O/^{17}O$ can decrease by up to 80% whereas $^{16}O/^{18}O$ increases by ~30% (e.g., Boothroyd & Sackmann 1997)



$^{16}O/^{17}O$ ratio at surface after FDU (red) and SDU (blue)

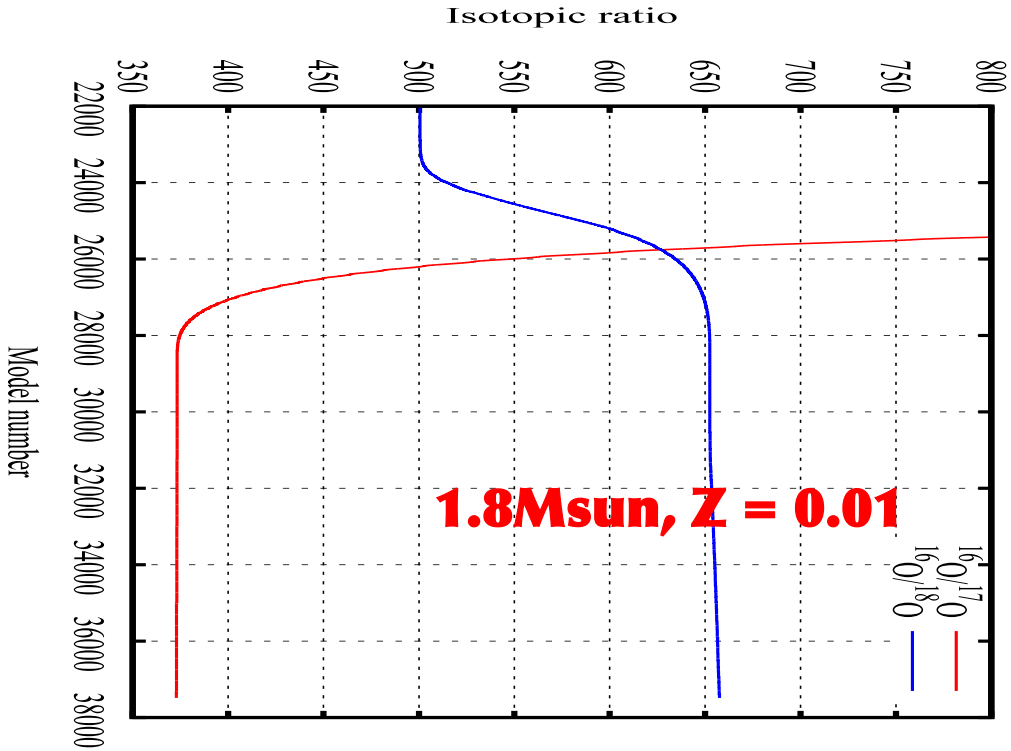
Data from Karakas & Lattanzio (2007)



$^{16}O/^{18}O$ ratio at surface after FDU (red) and SDU (blue)

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
- The first dredge-up:
- $^{12}C/^{13}C$ ~ 20, C/N ~ 1.5
- Disk FGB stars (e.g., Gilroy 1989) have $^{12}C/^{13}C$ ~ 10, and C/N ~ 1.0
- Evidence that some form of chemical transport is acting in low-mass FGB envelopes
- Mechanism? Thermohaline mixing currently favoured

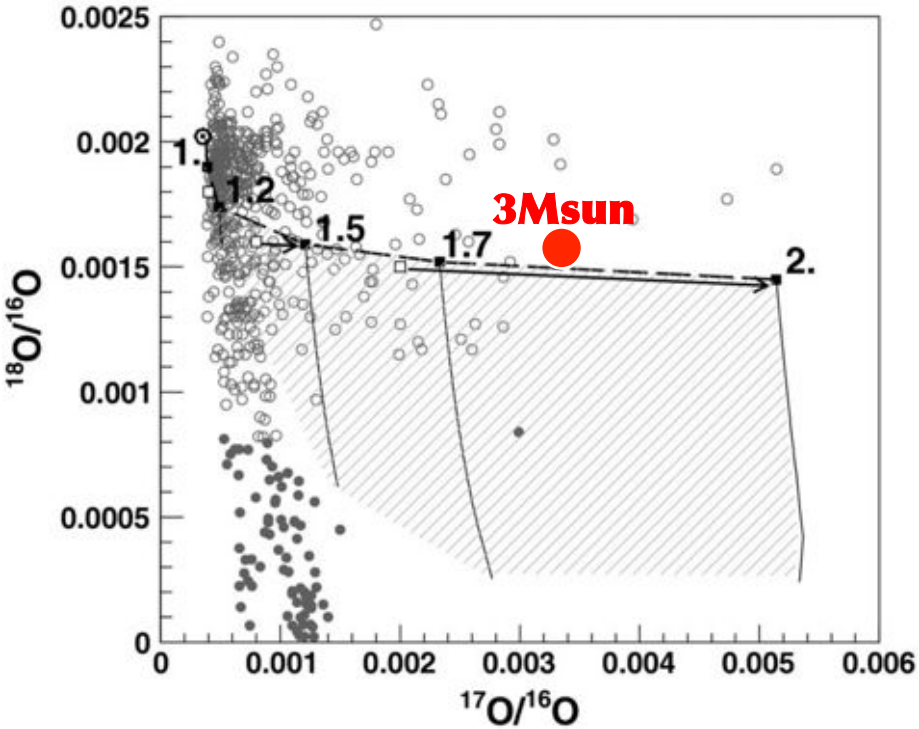


Almost no change from thermohaline mixing (Richard Stancliffe, private communication)

See also Charbonnel & Zahn (2007), Eggleton et al. (2008), Stancliffe et al. (2009)

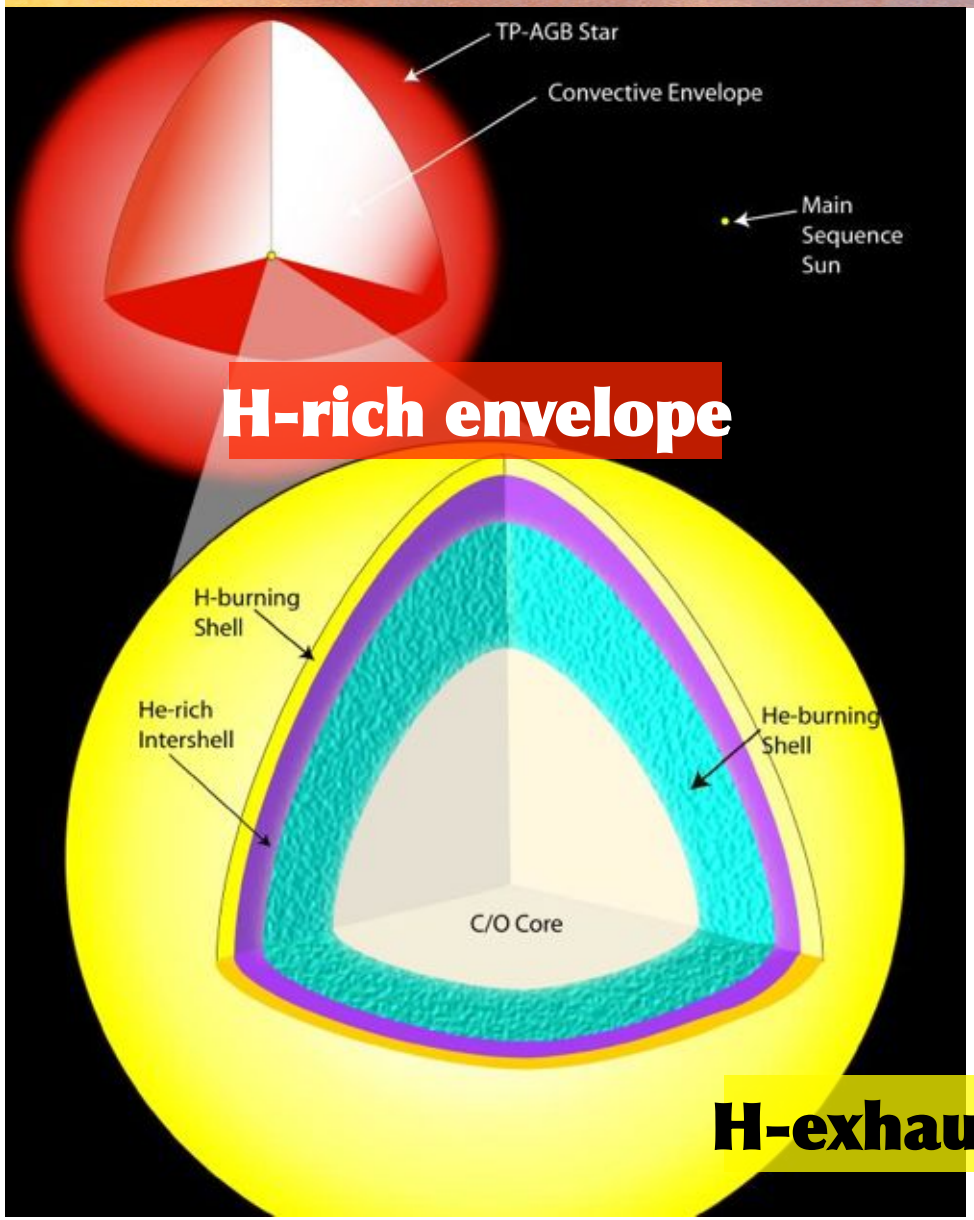
Extra mixing in low-mass giant stars

- Other mechanisms have been proposed including rotation (Charbonnel & Lagarde 2010) and magnetic buoyancy (e.g., Busso et al. 2007)
- However the models are still parametric and need to be calibrated
- This is difficult to do for the oxygen isotope ratios
- This is because there are few observations of real stars (Harris et al. 1987, 1988)
- Instead, calibration is based on presolar oxide grains (e.g., Palmerini et al. 2011) ➔ difficult to know where these grains came from!



From Palmerini et al. (2011)

Asymptotic Giant Branch stars



- The asymptotic giant branch is the last nuclear burning phase for stars with mass < 8Msun
- AGB stars are cool (~3000 K) evolved giants, spectral types M, S, C
- It is during the AGB where the products of nucleosynthesis reach the stellar surface
- Many AGB stars are observed to be losing mass in dense outflows of material

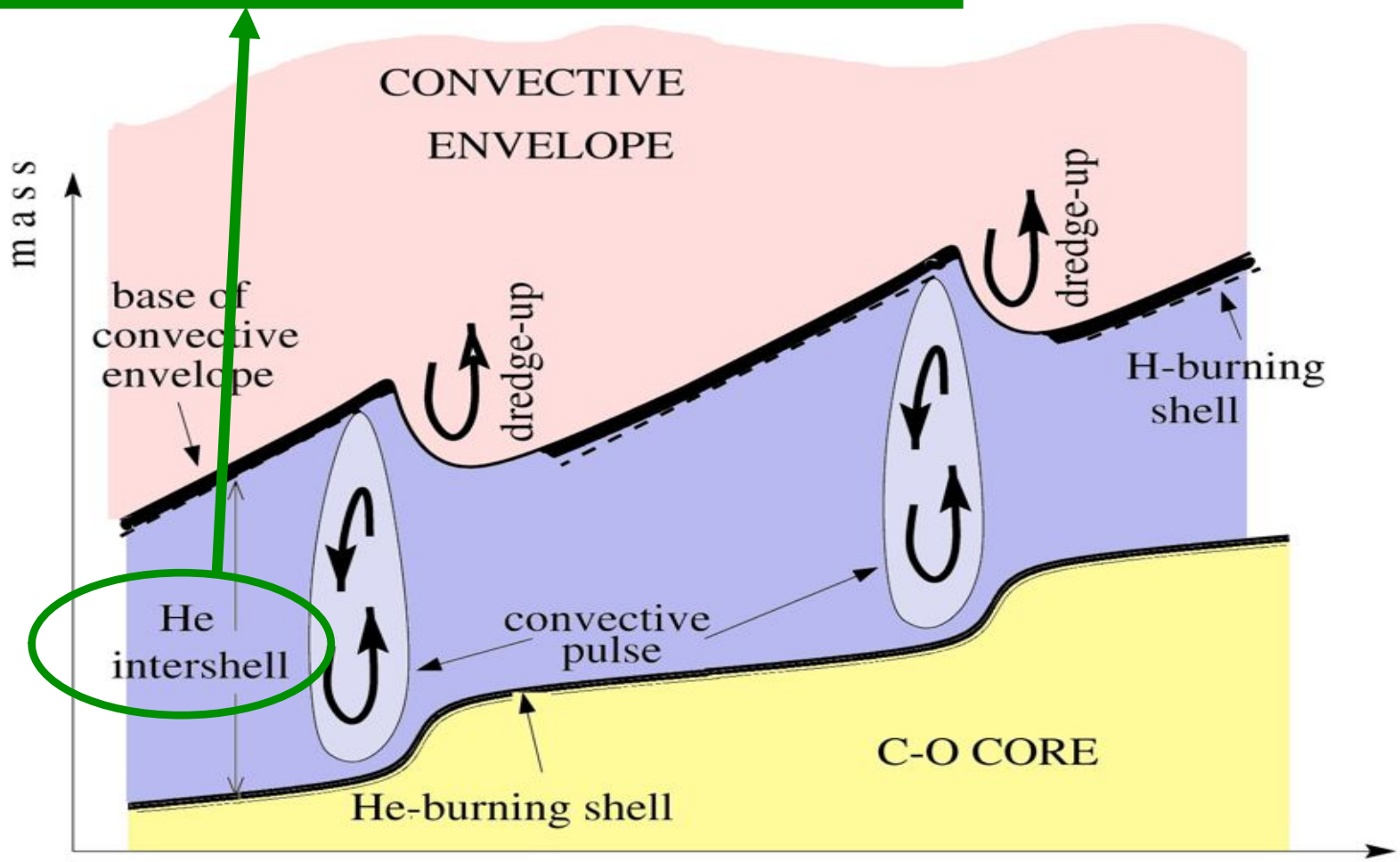
➔ Enriching the interstellar medium

➔ Progenitors of planetary nebulae

➔ Review by Herwig (2005, ARAA)

Where in AGB stars?

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



Interpulse phase (t ~ $10^{3\text{-}5}$ years)

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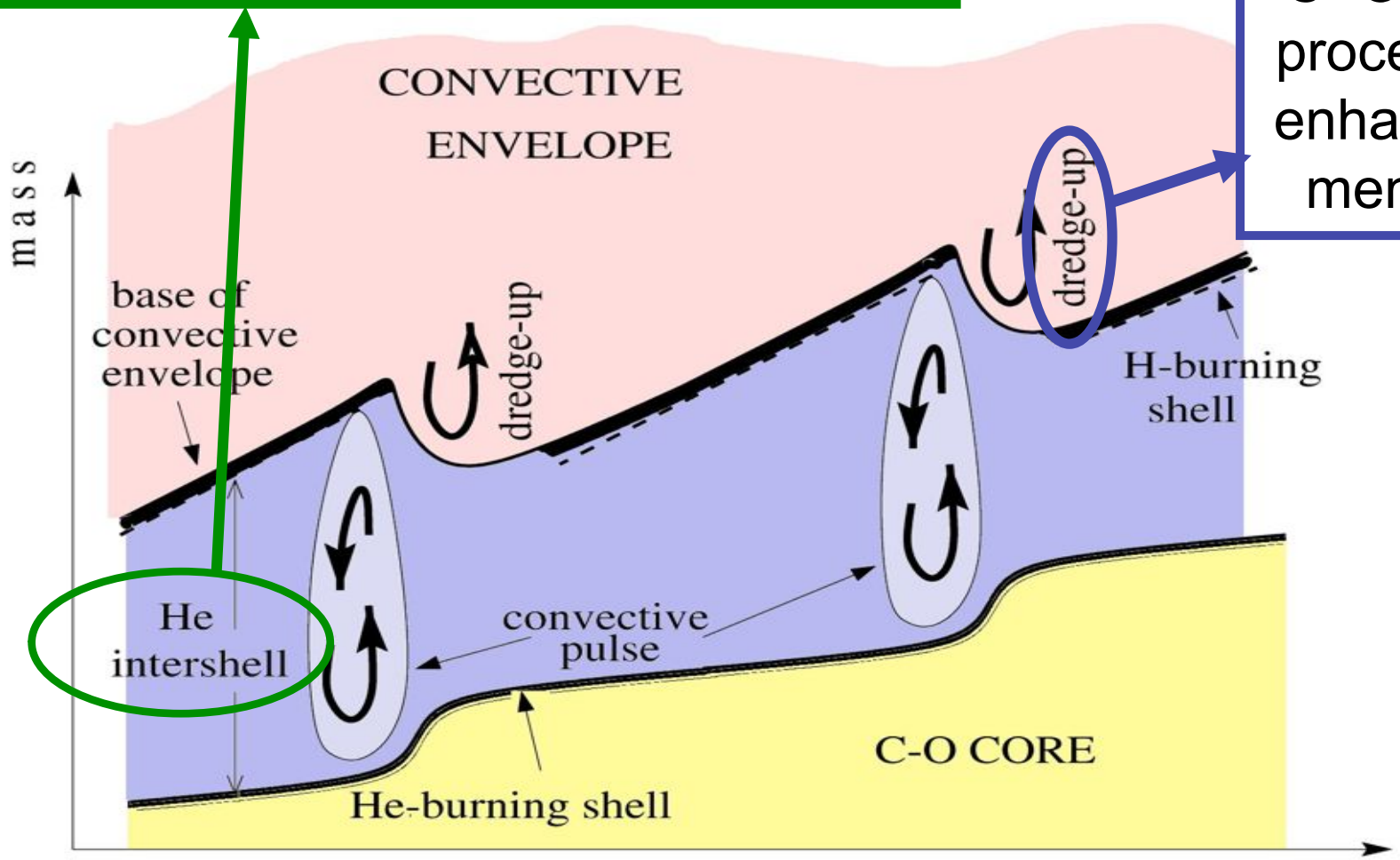
^{4}He, ^{12}C, *s*-process elements: Ba, Pb,...

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



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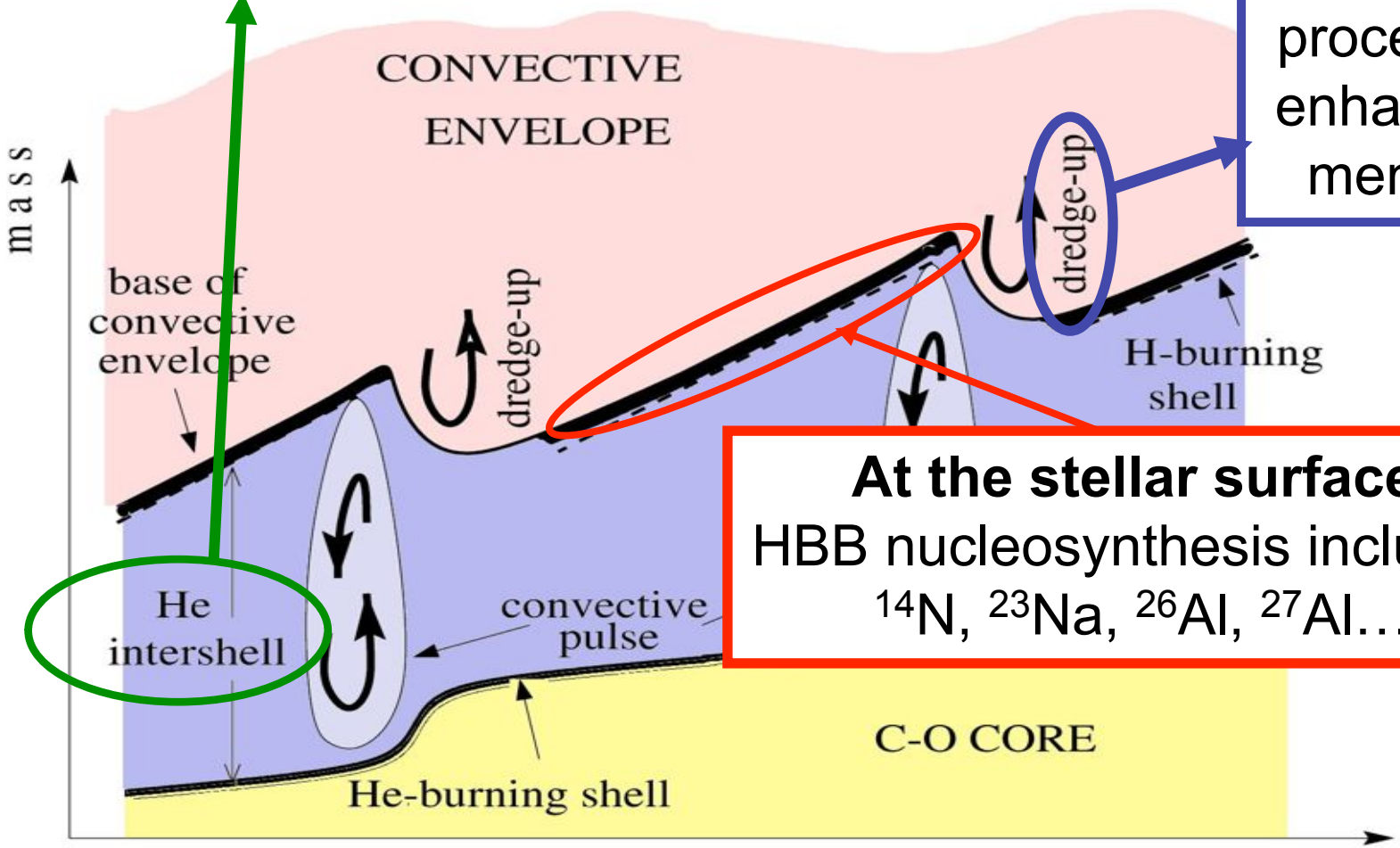
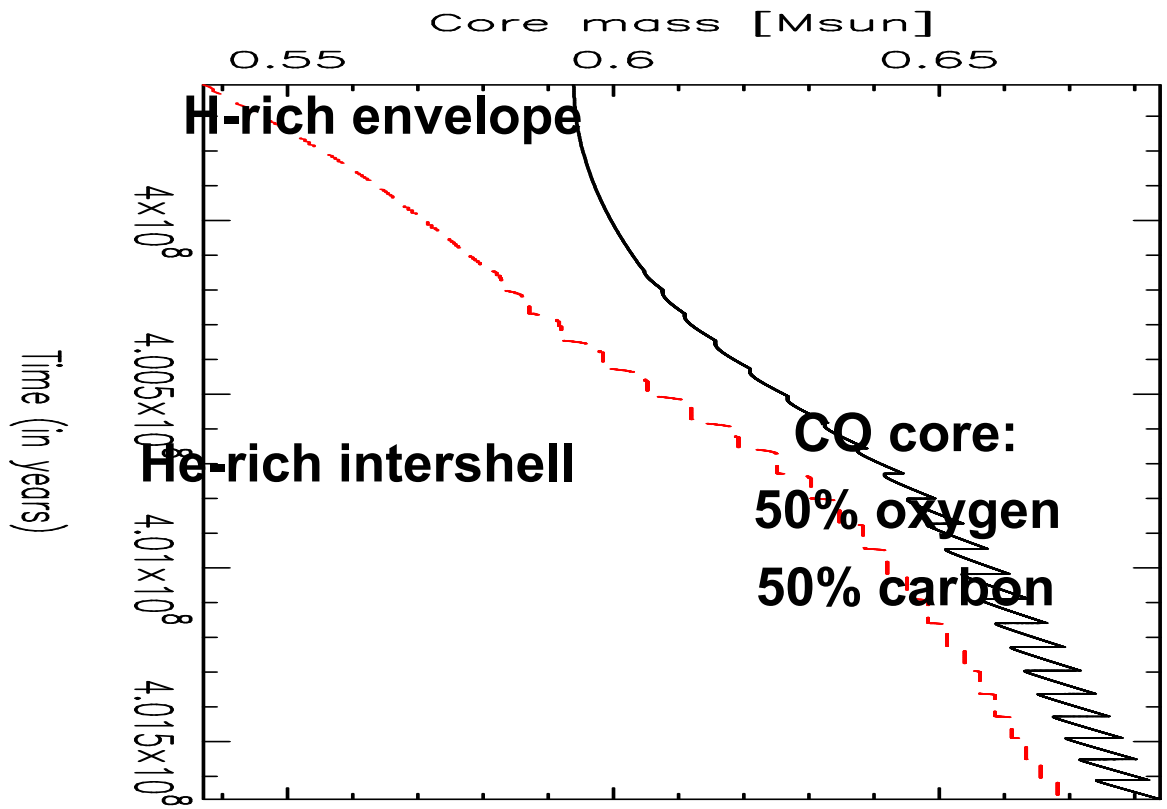


At the stellar surface: HBB nucleosynthesis including ^{14}N, ^{23}Na, ^{26}Al, ^{27}Al…

Interpulse phase (t ~ $10^{3\text{-}5}$ years)

He-shell instabilities

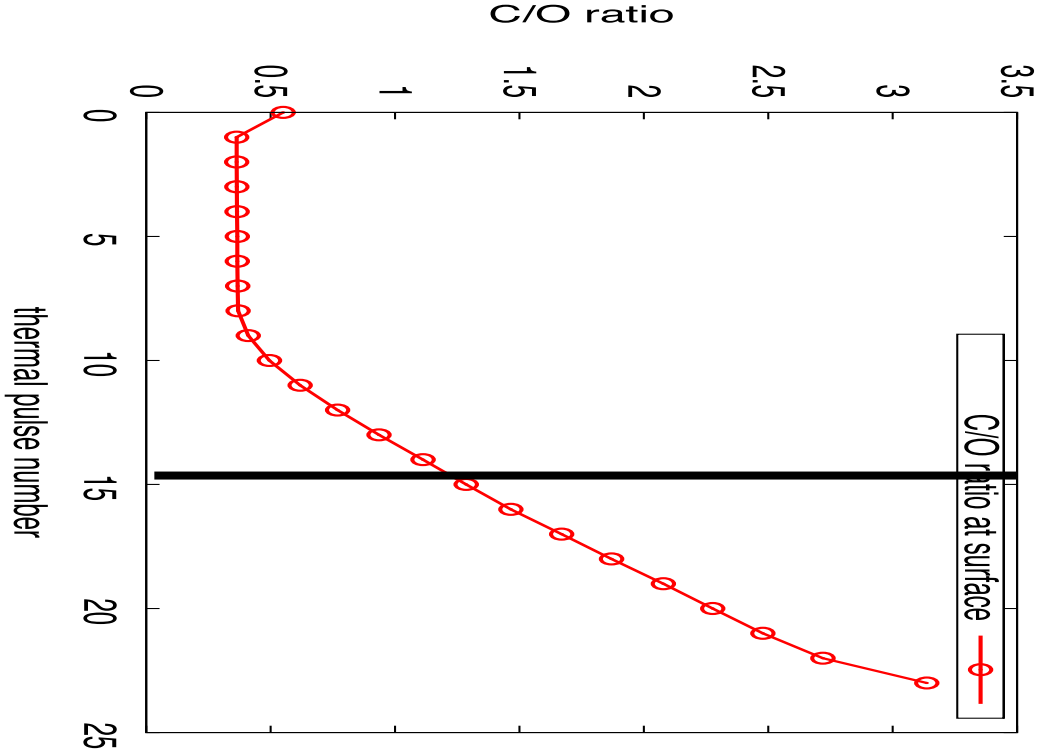
- AGB stars experience instabilities of the He-shell
- Stellar evolution models predict that each He-shell flash produces ^{12}C, along with some ^{22}Ne and ^{16}O (few % by mass)
- Nucleosynthesis is primary (does not strongly depend on Z)



3Msun, Z = 0.01 model AGB star

Third dredge-up and carbon production

- After each He-shell flash, the base of the envelope may "dredge" into the intershell region ➔ third dredge-up
- This can lead to carbon star production, where C/O > 1 at the stellar surface
- Correlated with an enrichment of heavy elements (s-process)



Standard picture:

Dominant process in stars between ~1.2 to 4Msun

➔These stars are NOT expected to produce or destroy much O

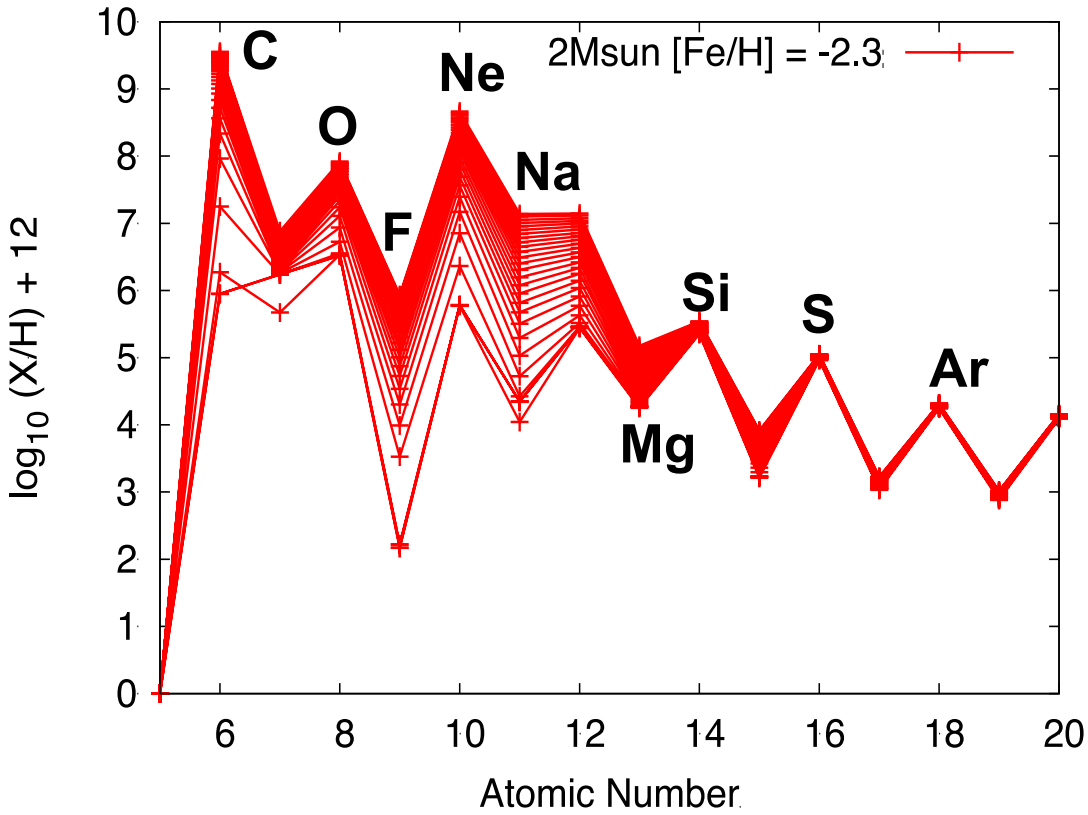
➔Except perhaps at low metallicity

Low-mass AGB stars and PN

- Stars with masses less than ~1.2Msun: experience the FDU and extra-mixing on the first giant branch → no third dredge-up
- And are therefore expected to stay *O-rich*, where C/O < 1
- For the PN that these stars stars make, the elemental O should reflect the initial for a wide range of metallicities
- For stars with masses between ~1.2 to 4Msun: the third dredge-up can cause the stars to become C-rich
- Important source of carbon and carbonaceous dust in galaxies (e.g., Sloan et al. 2008)
- Caveat: Some fraction of PNe formed via binary interaction (e.g., ~20% or more? Miszalski et al. 2009, De Marco 2009)
- Binary evolution can truncate the AGB before many TDU episodes occur (or it occurs at the tip of the first giant branch)
- Avoiding carbon star formation

Low metallicity evolution

At very low metallicity ([Fe/H] ~ -2.3 or log(O/H) + 12 ~ 6.5), the progenitor AGB star can produce significant amounts of oxygen



From a 2Msun stellar model:

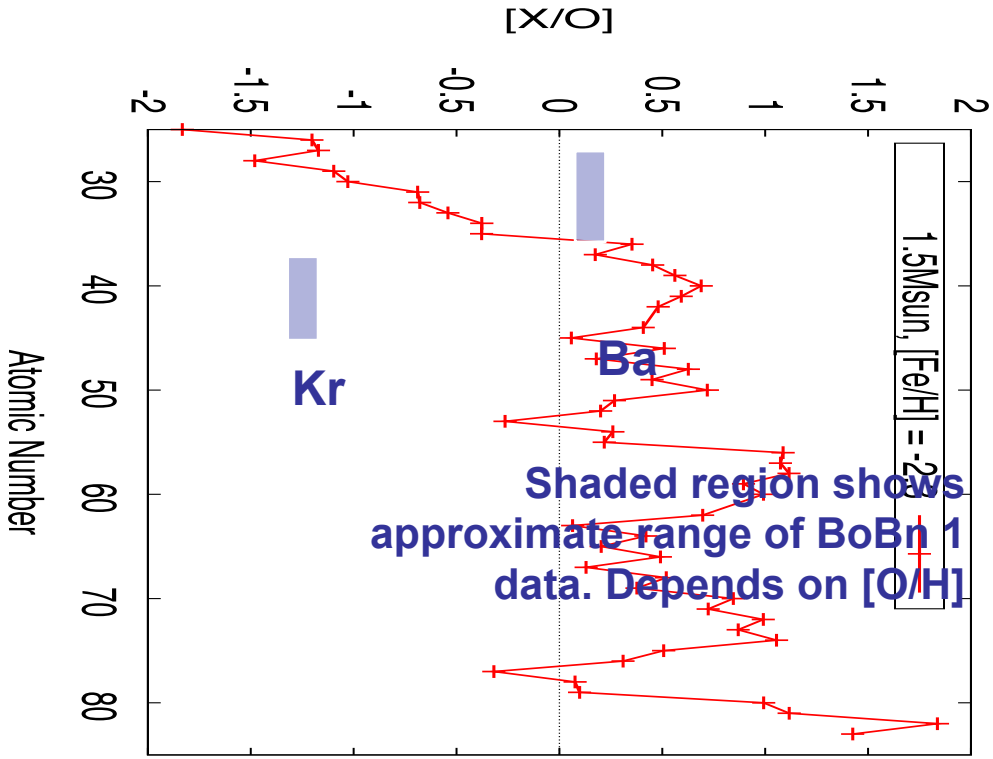
1. Final log e(O) ~ 8, from 6.5
2. Would have the oxygen of a more metal-rich object with halo kinematics
3. Oxygen is primary from He-shell; final abundances does not depend strongly on initial

Even a 0.9Msun, [Fe/H] = -2.3 model has a final surface oxygen: log e(O) ~ 7.5

Karakas (2010, MNRAS) and Lugaro et al. (2012, ApJ)

Low metallicity PN

- There are a few PN found in low-metallicity environments (e.g., BoBn 1, Otsuka et al. 2010)



The model:

1. Z = 0.0001 or [Fe/H] = -2.3
2. Alpha-enhanced + r-process enriched initially
3. The carbon, oxygen, fluorine and heavy element abundances best fit by a ~1.5Msun, Z = 10^{-4} model
4. Present day PN evolved from a star that accreted material from a previous AGB star

The log (O/H) varies between 7.74 (CELs) to 8.23 (ORLs): the CEL oxygen value matches the theoretical model best

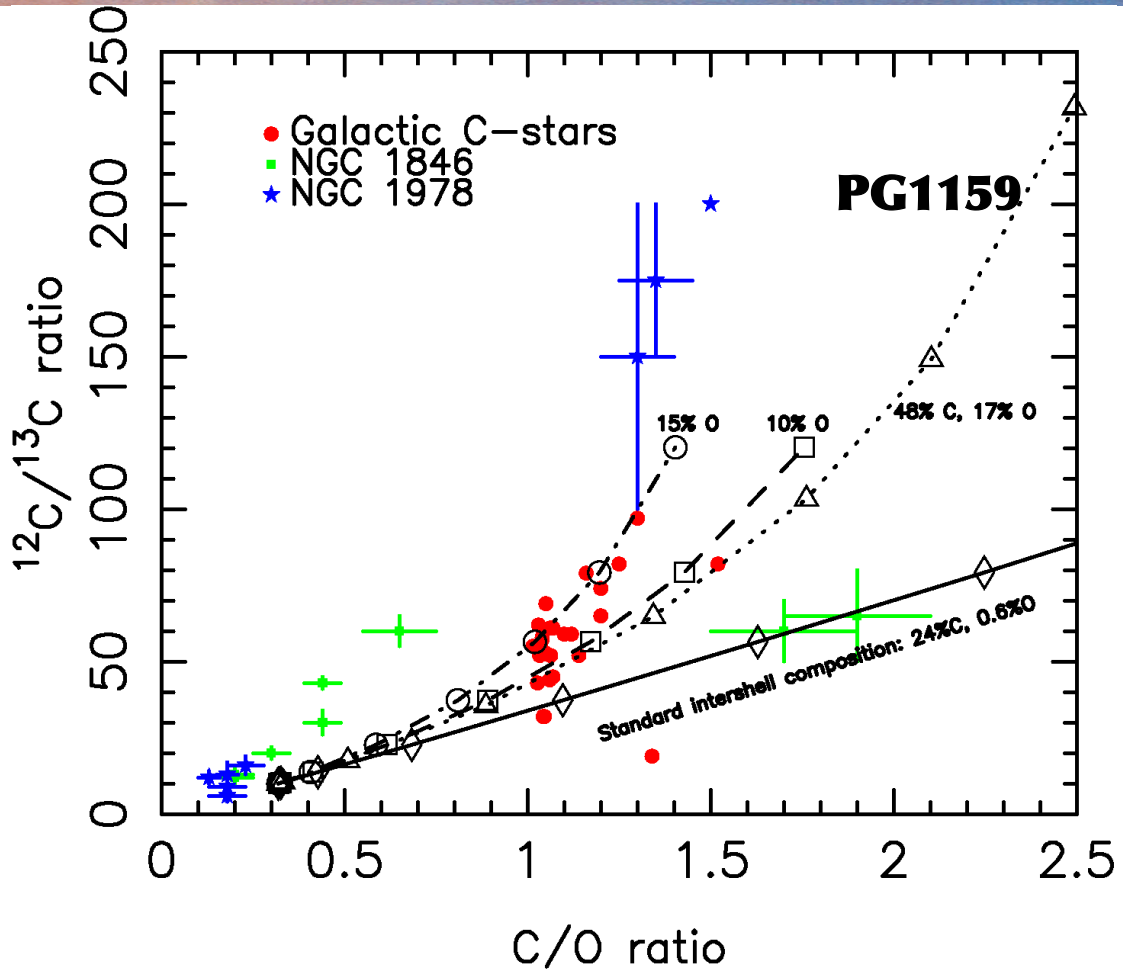
Using model data from Lugaro, Karakas, et al. (2012)

Evidence for oxygen enrichment

- There is some evidence that low-mass stars produce oxygen
- The best evidence comes from the abundances of rare H-deficient PG 1159 class of post-AGB stars
- Result of late He-shell flash that mixes the remaining H-rich envelope
- Abundances (Werner & Herwig 2006):
  - 2-20% (by mass) oxygen → compared to ~1% in standard models
  - 15-60% (by mass) carbon → compared to ~25% " " "
- Theoretically motivated by convective overshoot into C-O core (e.g., Herwig 2000)
- Still unclear if this is a unique signature of a late He-shell flash during the post-AGB phase
- Or, if this is occurs during the thermally-pulsing AGB phase

Increasing Oxygen in the Intershell

- What happens if O increases during the AGB phase?
- Explore this using a toy model that increases the ^{12}C and ^{16}O content of the intershell
- Based on calculations of a 1.8Msun, Z = 0.01 model
- Final O abundance increases by up to a factor of 3

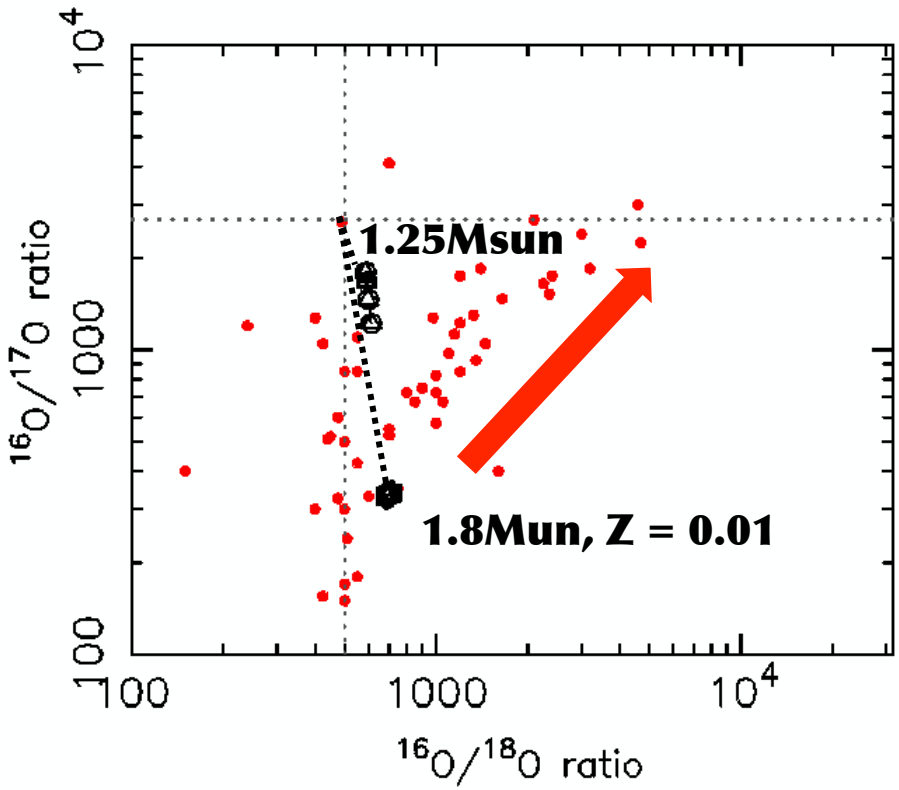


From Karakas, Campbell & Stancliffe (2010)

See also data for LMC clusters (Kamath, Karakas & Wood (2012)

Oxygen Isotope ratios in evolved stars

- Figures includes oxygen isotope data from G-K giants, barium stars, MS, S and, C type AGB stars (Harris et al. 1984, 1987, 1988)
- Predicted oxygen isotope ratios during the AGB are shown for two low-mass models; AGB evolution shows little shift from FDU values (Karakas et al. 2010)



Predicted ratios show little evolution during AGB

Does the observational data shows evidence for ^{16}O enrichment?

Error bars not shown but are substantial

In comparison to PNe abundances

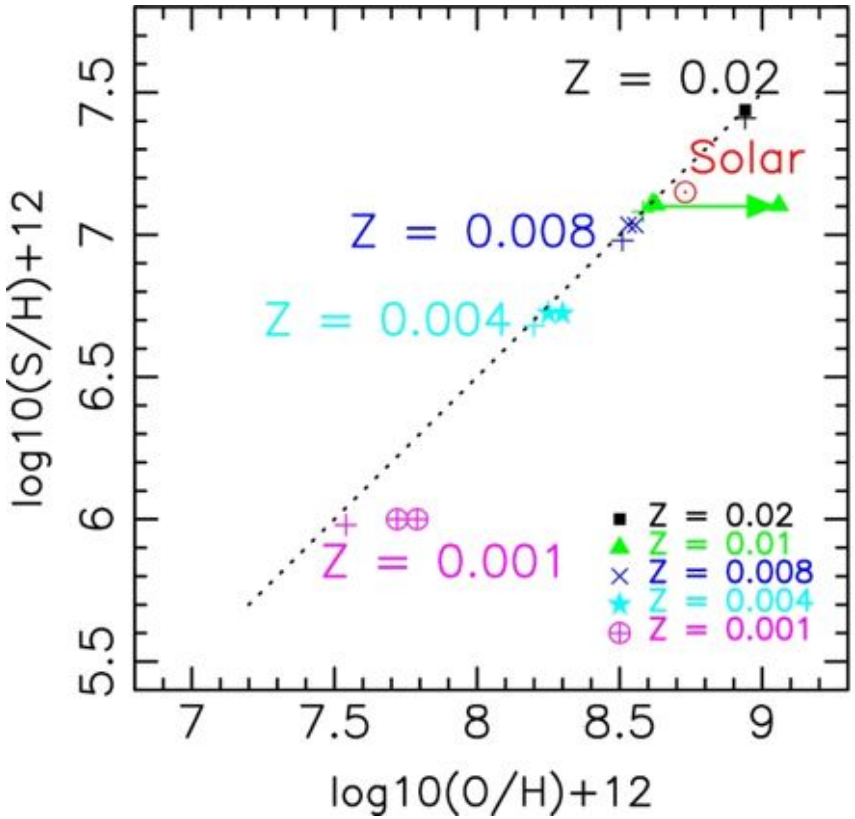
- Low-mass evolution increases the surface abundances of C, N, (F), Ne (e.g., Karakas 2010)
- And possibly O
- Sulphur, chlorine, argon also observed in PNe
- But AGB evolution not expected to alter these elements

➔ Sulphur abundances PNe show depletions compared to HII regions

➔ The sulphur anomaly

➔ See Henry et al. (2012)

➔ S is not a good metallicity indicator for the moment



Final surface abundances of O versus S of stellar models of various metallicities (from Henry et al. 2012)

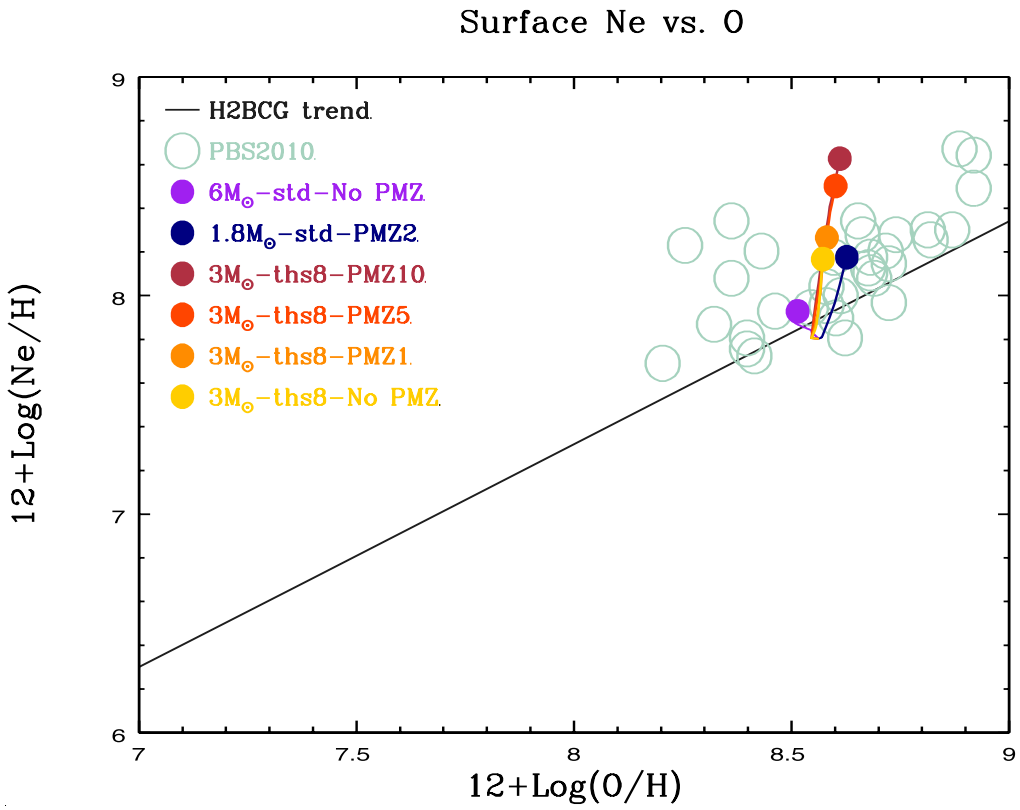
Masses:

1.5Msun at Z = 0.001

1.8Msun, Z = 0.01, with increased O

In comparison to PNe abundances

- If we compare theoretical models to observational data from Pottasch & Bernard-Salas (2010)
- With the HII region trend from Milingo et al. (2010)
- Small variations in oxygen
- The amount of neon enrichment is dependent upon the details of mixing and the initial stellar mass
- The spread in Ne well explained by theoretical models of AGB stars



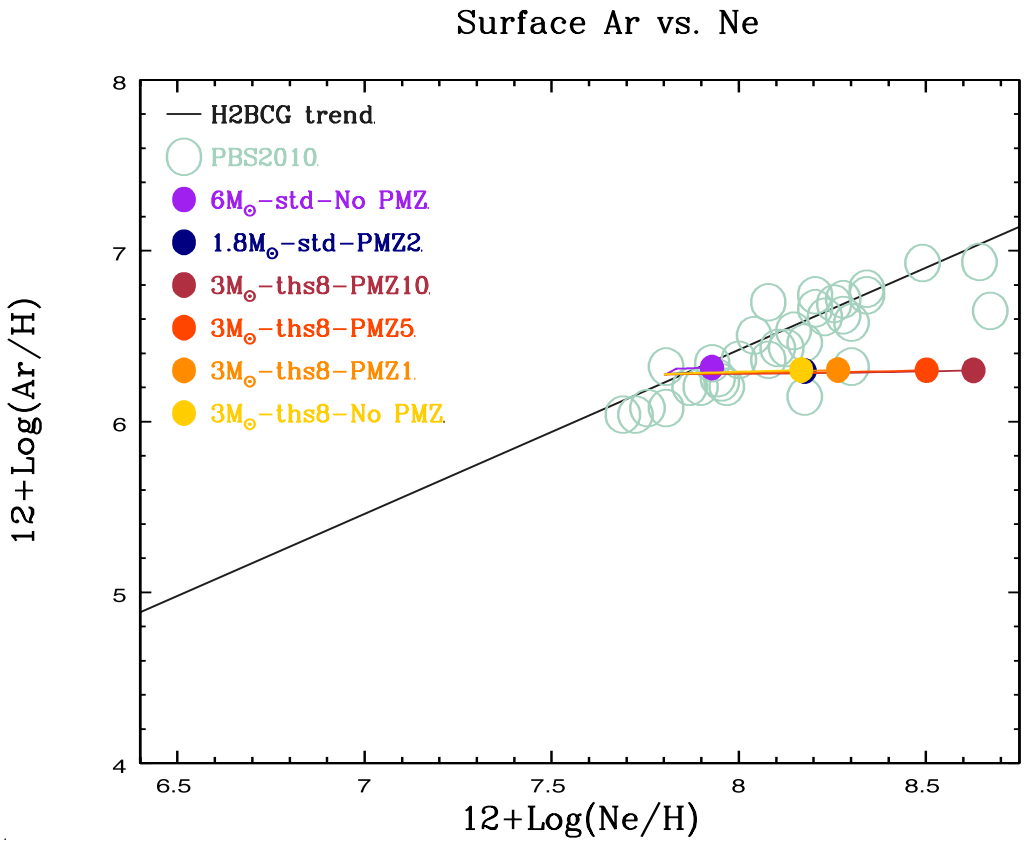
Plot from Luke Shingles (PhD student, ANU)

In comparison to PNe abundances

- Observational data from Pottasch & Bernard-Salas (2010)
- With the HII region trend from Milingo et al. (2010)
- We see that variations in stellar mass produce no change to argon

➔ Demonstrates that argon is an excellent metallicity indicator

➔ Also the case in low-metallicity AGB stars (e.g., data from Lugaro et al. 2012)



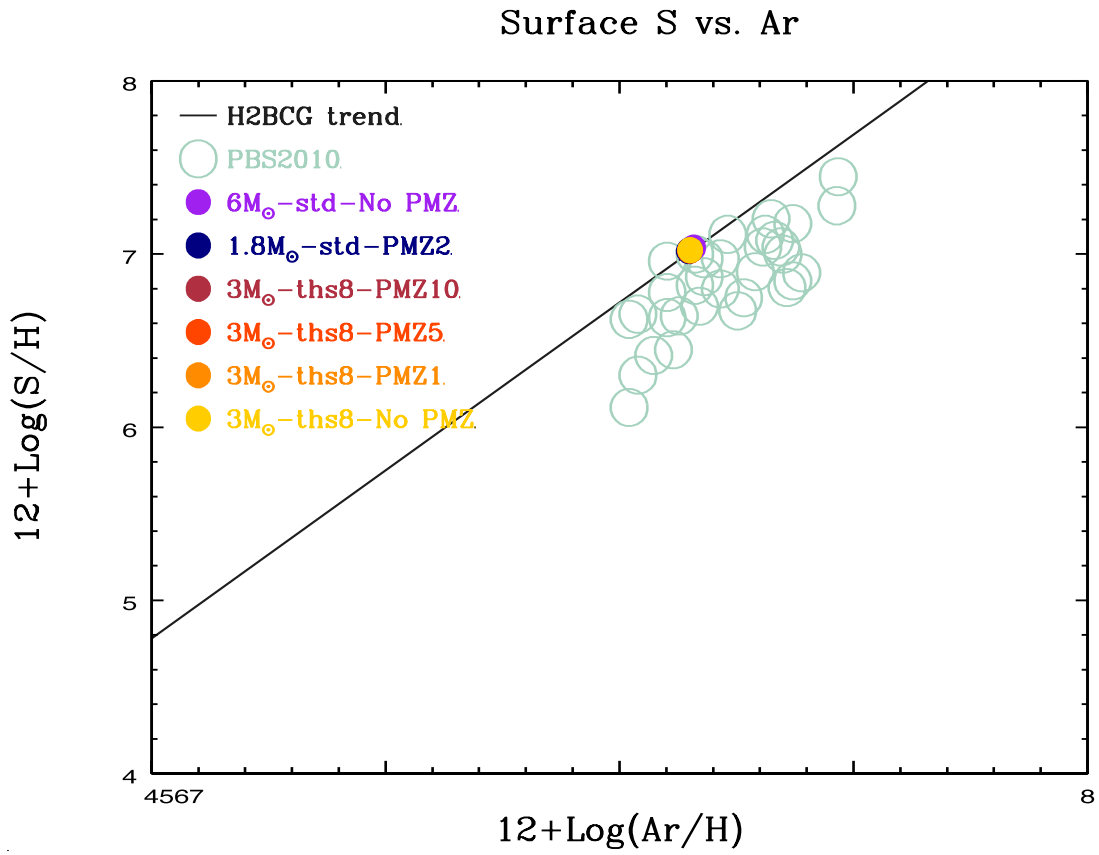
Plot from Luke Shingles (PhD student, ANU)

In comparison to PNe abundances

- Highlighted by plotting argon versus sulphur
- Note the low S in the observational data, compared to the trend line for HII regions

➔ Cause of the sulphur anomaly still not clear

➔ Probably caused by inability to account for populations of ionization stages about S^{+2} (see Henry et al. 2012)



Plot from Luke Shingles (PhD student, ANU)

Zn also suggested as a good metallicity indicator for PNe, but there are still few observations (e.g., Dinerstein & Geballe 2001)

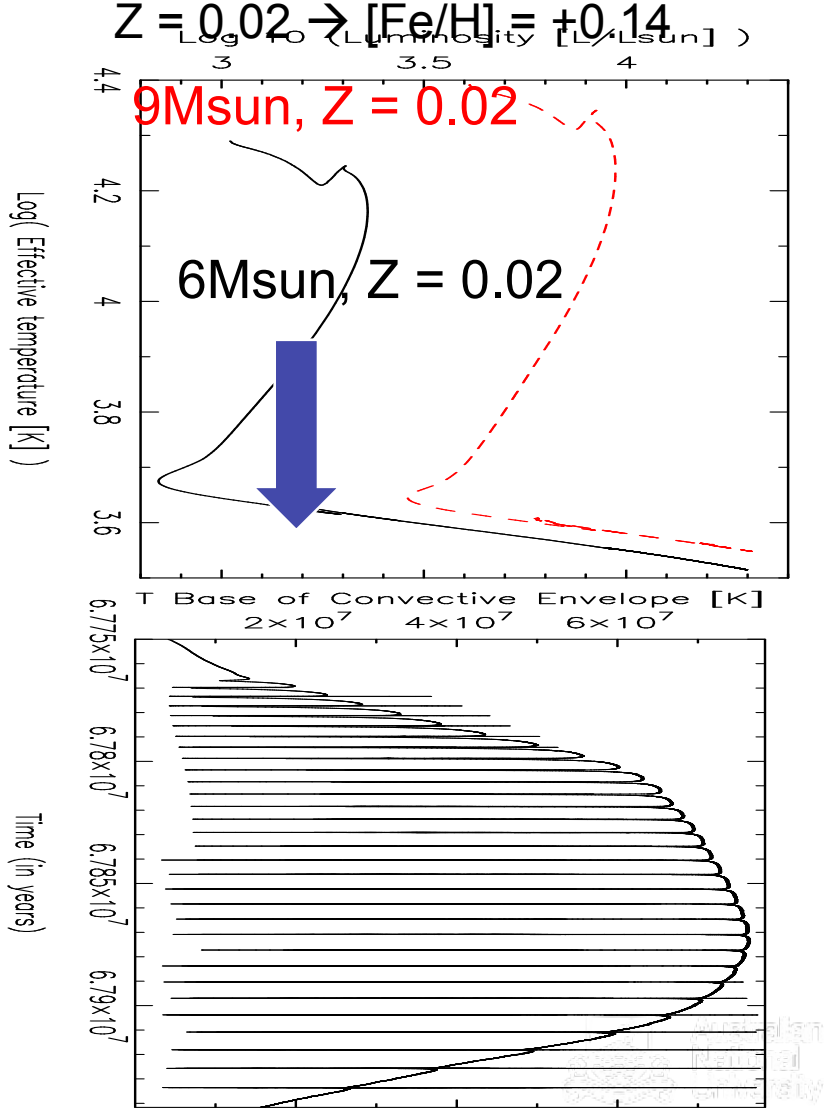
Intermediate-mass AGB stars

- M > 4, these stars have:
- Second dredge-up: burning material during early AGB
- Hot bottom burning: Proton-capture nucleosynthesis at base of envelope (products: He, N, Na)
- Rare, owing to initial mass function considerations
- Relatively rapid evolutionary timescales (~100Myr for a 5Msun)
- Final core masses: ~0.8 to 1.2Msun
- Evolve too fast to form PNe?

$$[X/Fe] = \log(X/Fe)_{star} - \log(X/Fe)_{sun}$$

Example evolutionary tracks:

Z = 0.02 → [Fe/H] = +0.14

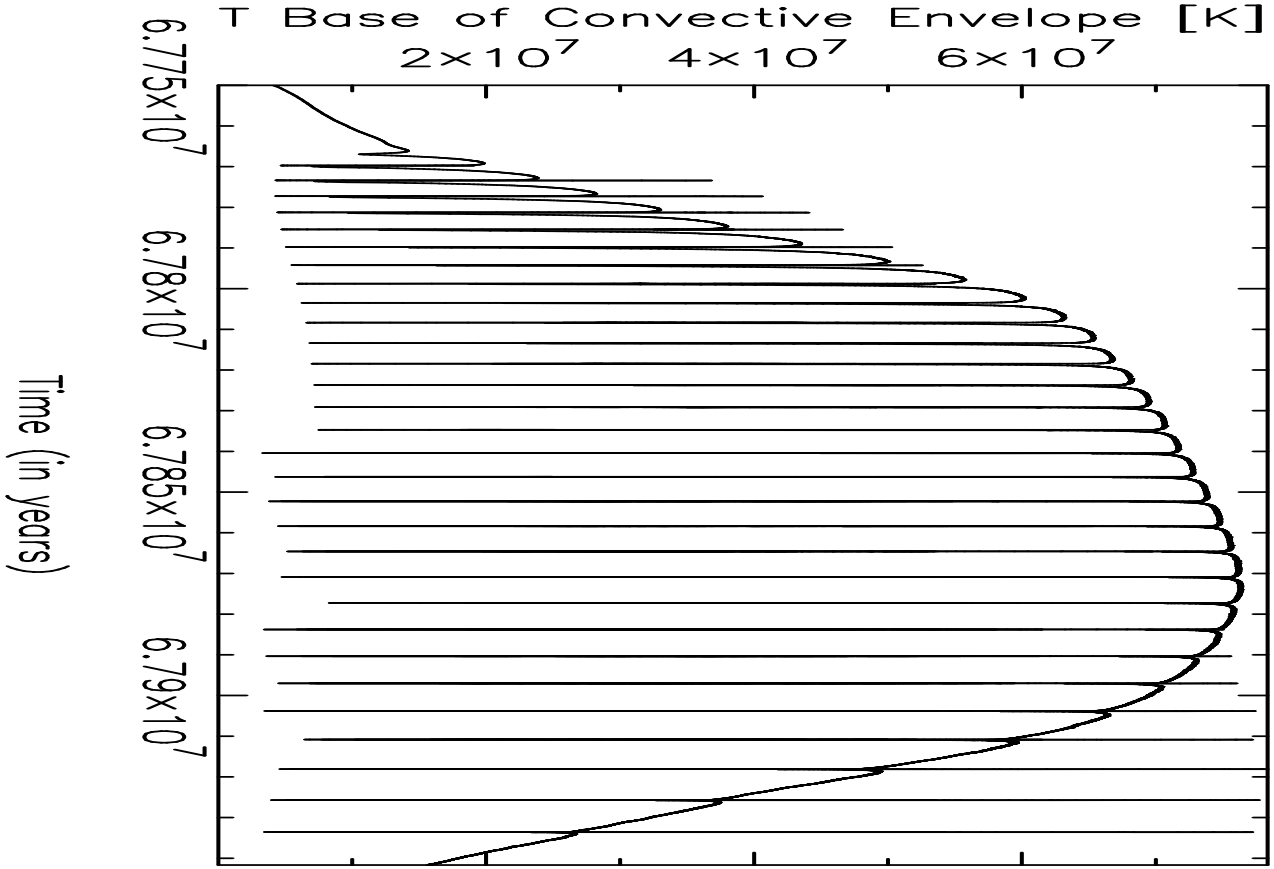


Oxygen destruction

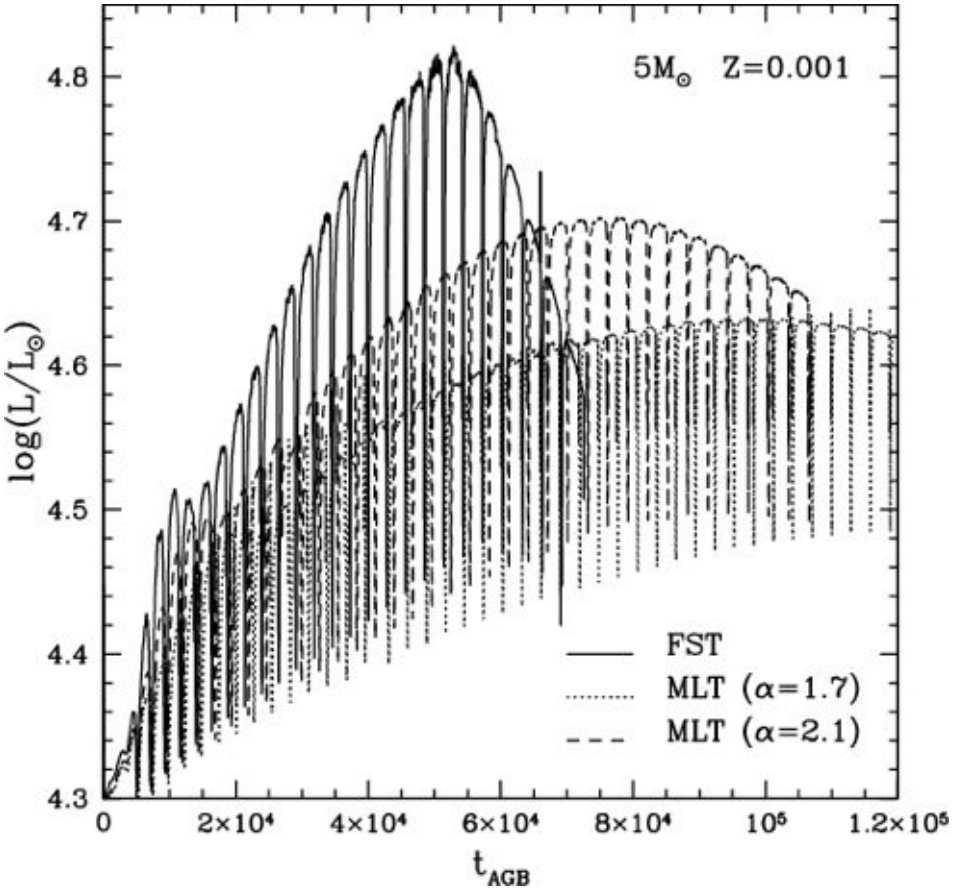
$6M_{sun}$, solar composition. Peak temperature ~ 80 x 10^6 K

How much O is destroyed? Up to [O/Fe] = −0.25 dex

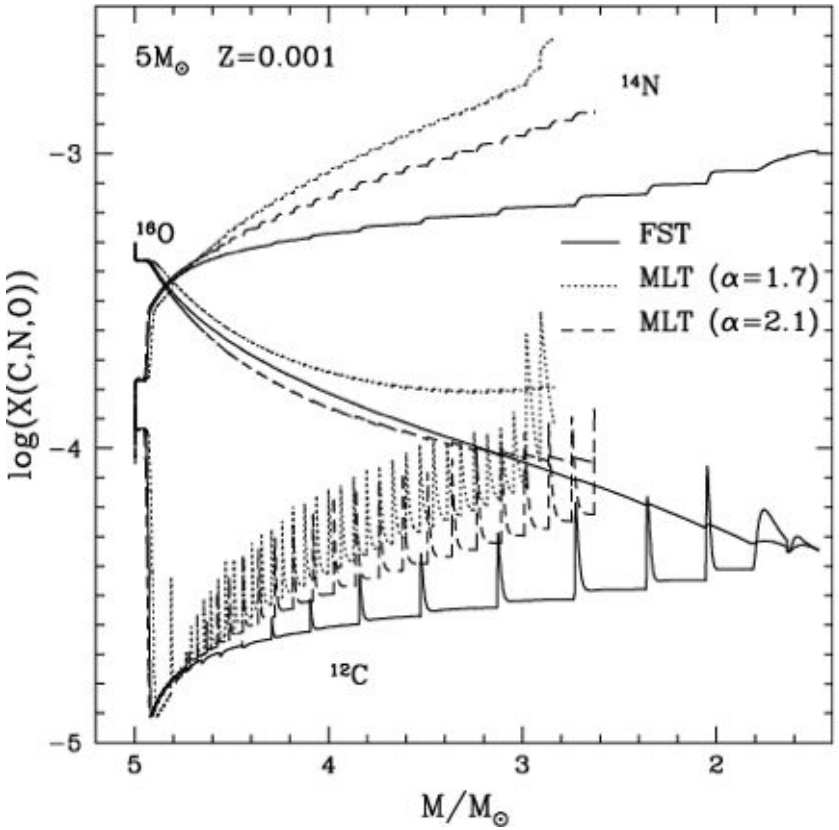
Depends on mass-loss rate and duration of HBB (Karakas et al. 2012)



Uncertainties caused by convection



Surface luminosity as a function of time for three convective prescriptions

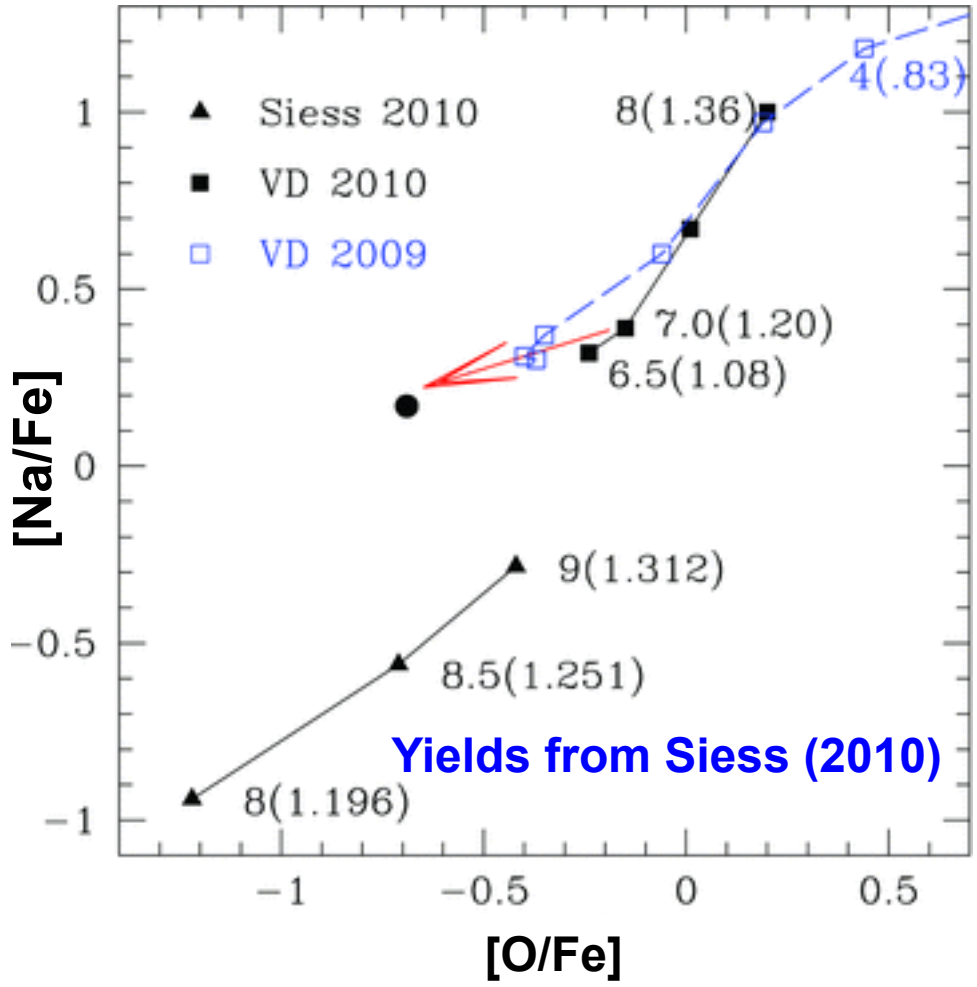


Surface CNO abundances as a function of total mass

From Ventura & D'Antona (2005)

Implications

- Short-lived AGB stars with lifetimes < 100 Myr
- Means that they can quickly pollute the interstellar medium of forming galaxies and star clusters
- Have been implicated in the chemical evolution of globular clusters (e.g, Gratton et al. 2004)
- But theoretical models are not well constrained by observations
- And depend upon many uncertainties (e.g., convection, mass loss, reaction rates)



From Ventura & D'Antona (2011)

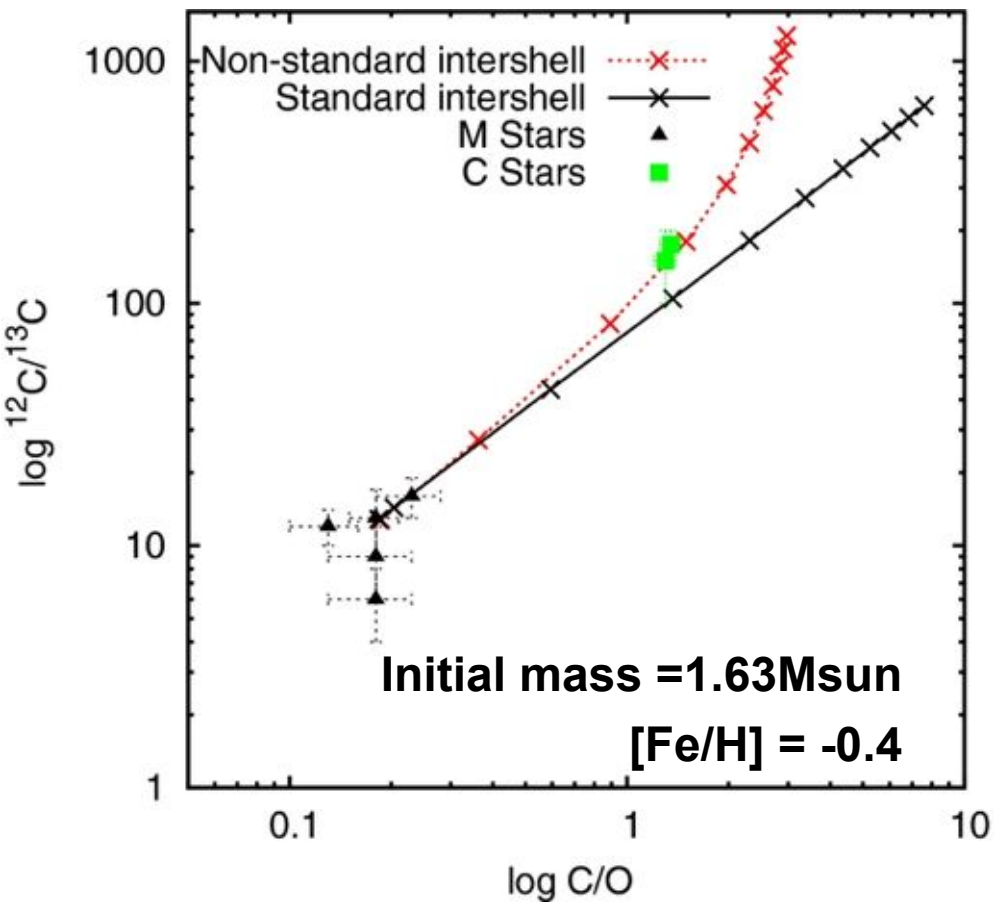
Summary

- Low to intermediate-mass stars are not theoretically expected to be net producers of oxygen
- Except under certain conditions
  - Late thermal pulses during the post-AGB that mix into the CO core – or do these occur during the AGB too?
  - Substantial oxygen is produced at low metallicities
- Oxygen in PNe should reflect the initial, except for low Z PN
- Oxygen isotope ratios altered by mixing events
- Hard to constrain mixing models because few observations
- Intermediate-mass stars with masses above 4Msun can destroy oxygen during the AGB
- Substantial model uncertainties → the amount of oxygen destruction is not well constrained

The LMC cluster NGC 1978

- The abundances of AGB stars in the LMC cluster NGC 1978 also show evidence for O enrichment:
- **Black line**: shows model with a standard intershell composition
- **Red line**: shows the model with increased ^{12}C (40%) and ^{16}O (15%) content of the intershell
- Observational data from Lederer et al. (2009)

- Note the cluster NGC 1846 does not show evidence for O enrichment (although has a similar [Fe/H])



From Kamath, Karakas & Wood (2012)