The s-process

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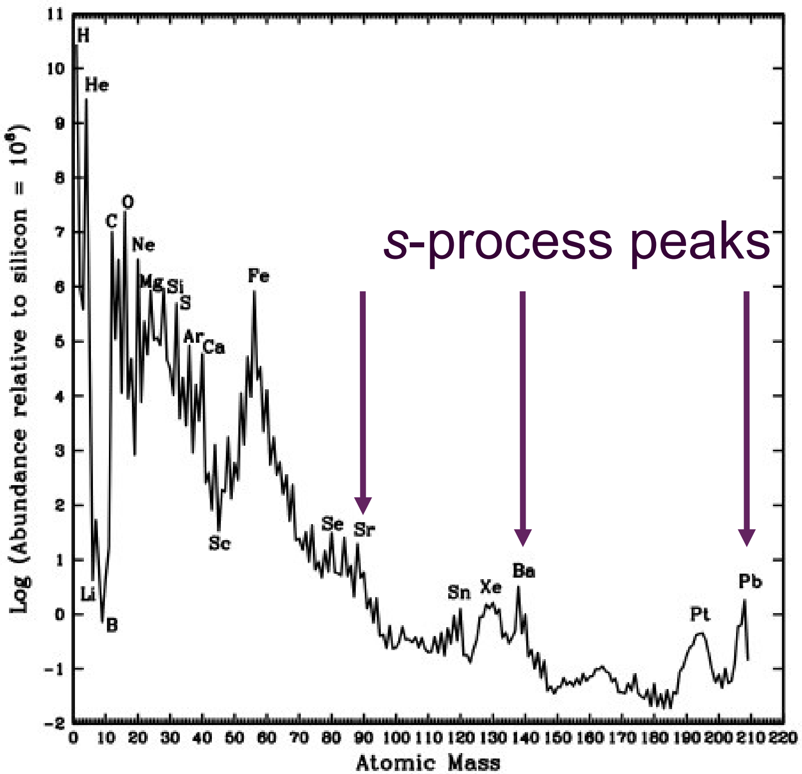
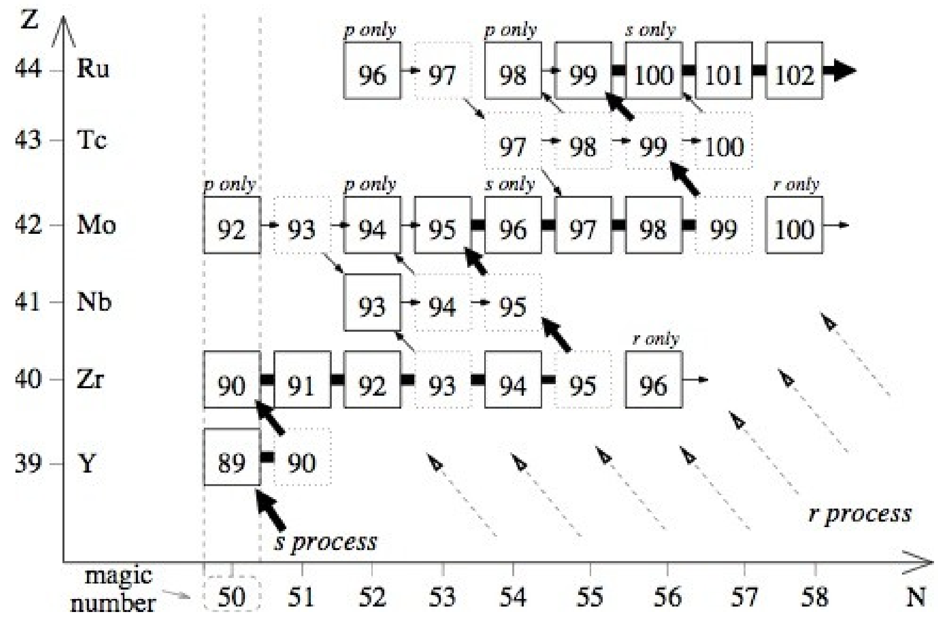
The slow-neutron capture process

The *s* process is responsible for the production of about half the abundances of elements heavier than iron in the Galaxy. See reviews by Sneden et al. (2008) and Lattanzio & Lugaro (2005)





During the *s* process: $N_n \sim 10^7$ n/cm^3

In general, time scale (n,g) << t_b

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

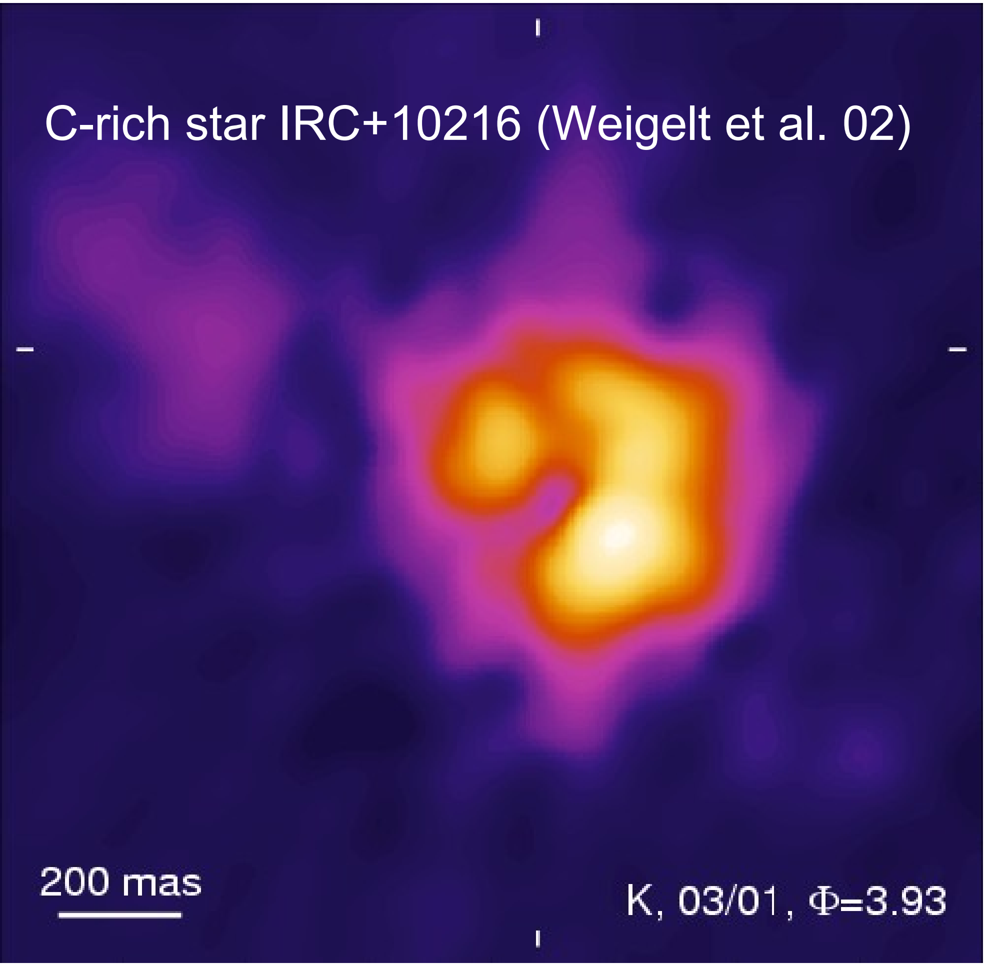
Sites of the *s*-process

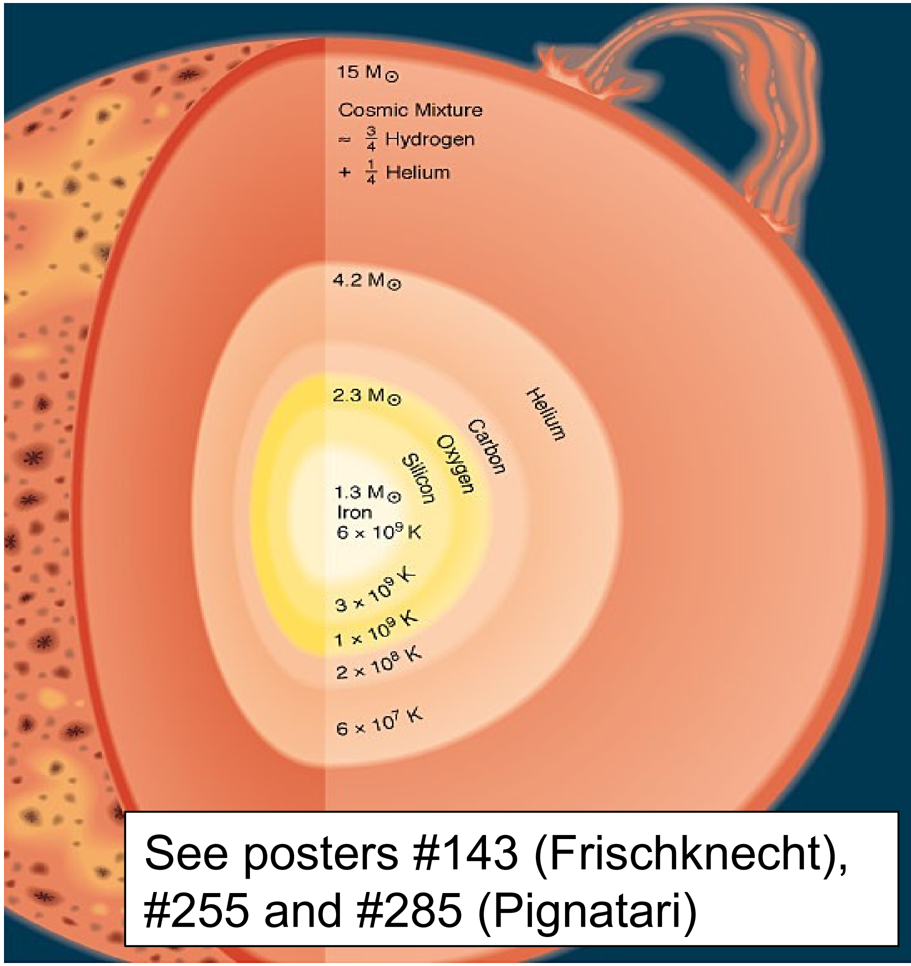
AGB stars (0.8 to 8Msun)

He-shell burning

Massive stars (> 12Msun)

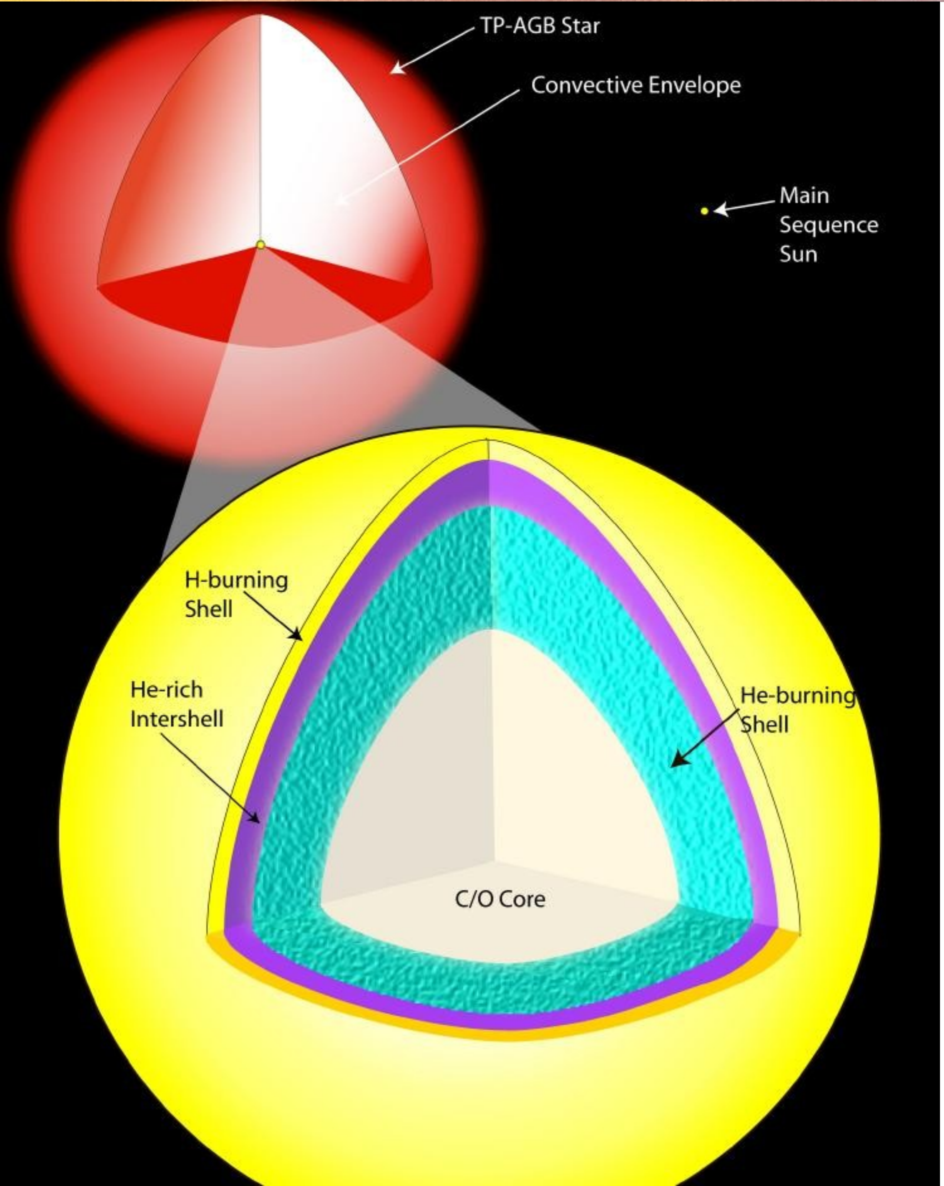
Core & shell He and C-burning





See posters #143 (Frischknecht), #255 and #285 (Pignatari)

Asymptotic Giant Branch stars



- Cool, evolved giants (spectral types M, MS, S, SC, C)
- He-burning shell is thermally unstable and flashes every ~10^5 yrs
- Following a thermal pulse, mixing episodes may enrich envelope with He-shell material
- Rapid, episodic mass loss erodes the envelope
- Known since the 1950s that low-mass AGB stars make heavy elements via the *s*-process

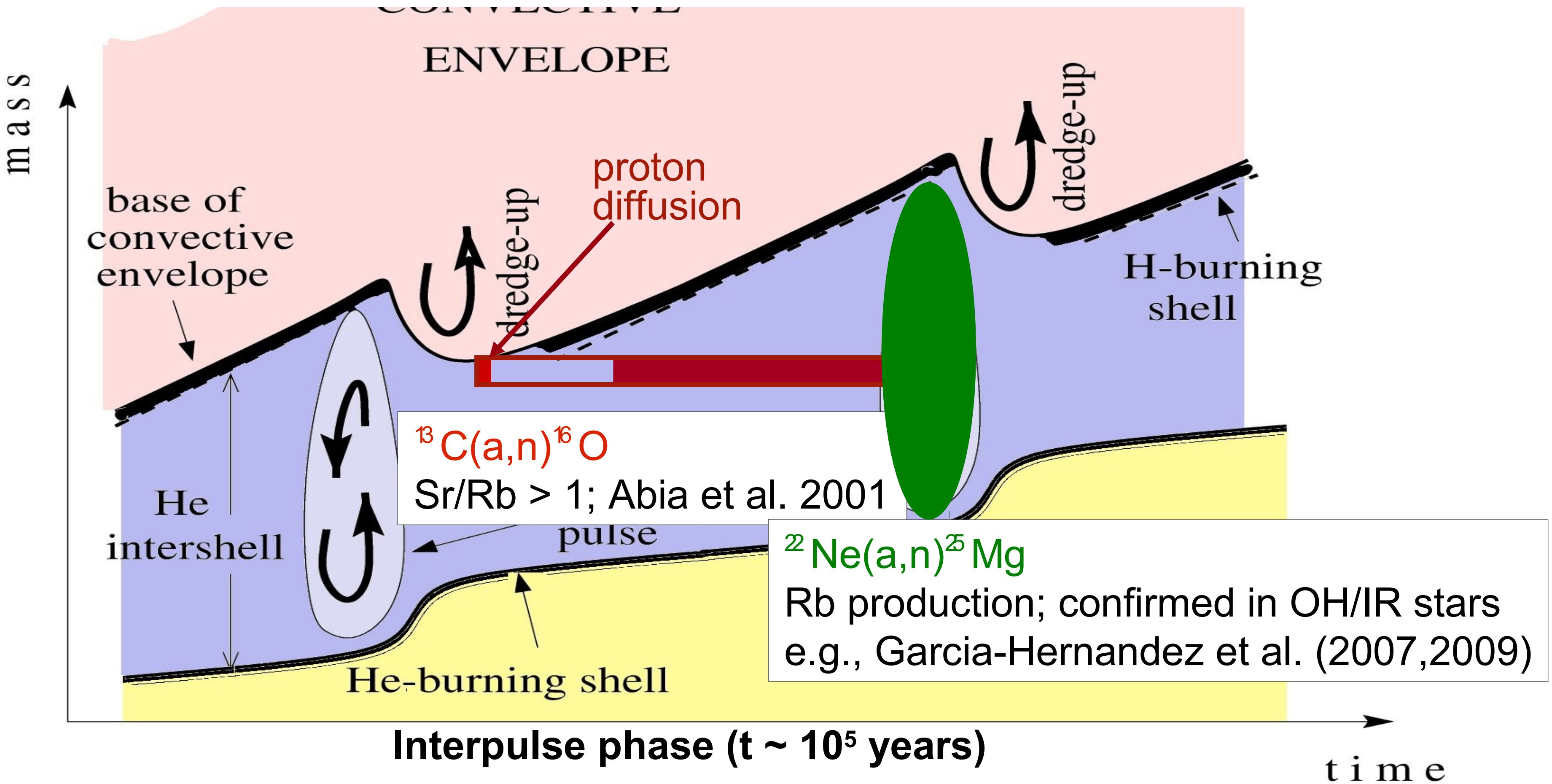
See reviews by Busso, Gallino & Wasserburg (1999) and Herwig (2005; this conference)

The neutron sources in AGB stars

Low mass AGBs
Lower temperature
Radiatively, between TPs

~4.5 M_{sun}

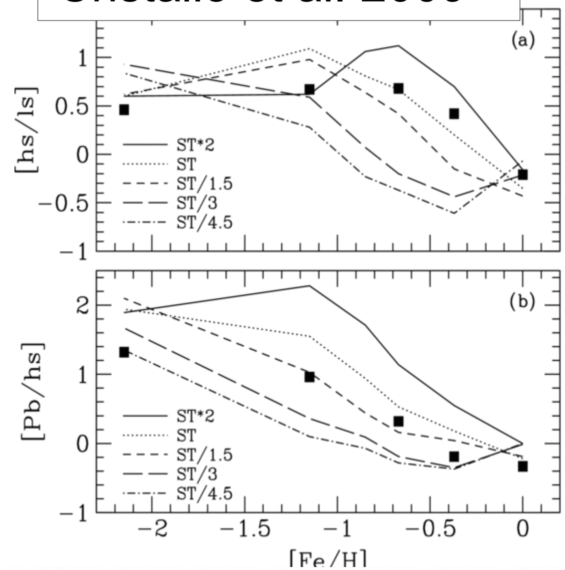
Intermediate mass AGBs
Higher temperature
Convectively, during TPs

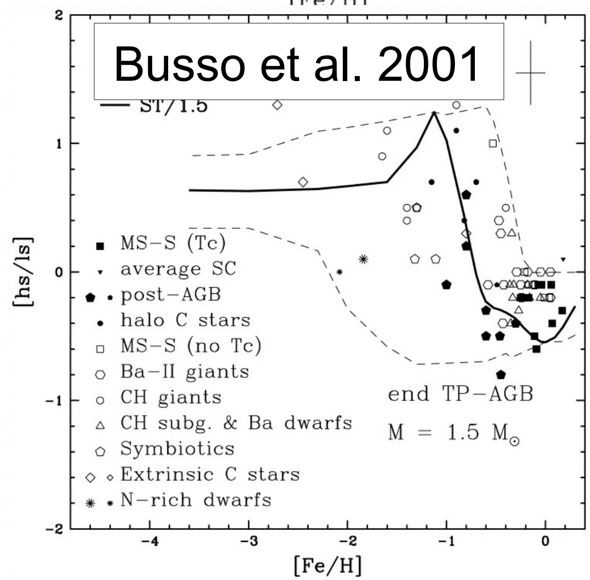


Latest theoretical *s*-process calculations

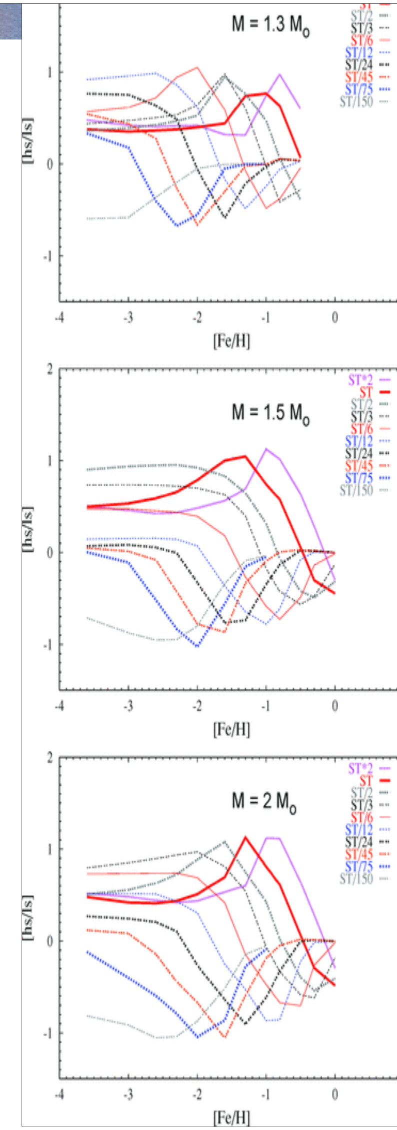
- Bisterzo et al. (2010): predictions for a range of stellar masses and metallicities (see poster #338)
- Using Gallino's updated post-processing code
- Based on model extrapolations for [Fe/H] < -1, but the [hs/ls] ratio predictions should be robust
- Cristallo et al. (2009): very detailed model calculations of 2Msun stars of various Z (including Z = 0.0001)
- Using the latest input physics (see his talk, this session)
- Also Church et al. (2009), Karakas et al. (2009) and Lau (poster #172)
- And NuGrid yields (Herwig talk)

Cristallo et al. 2009



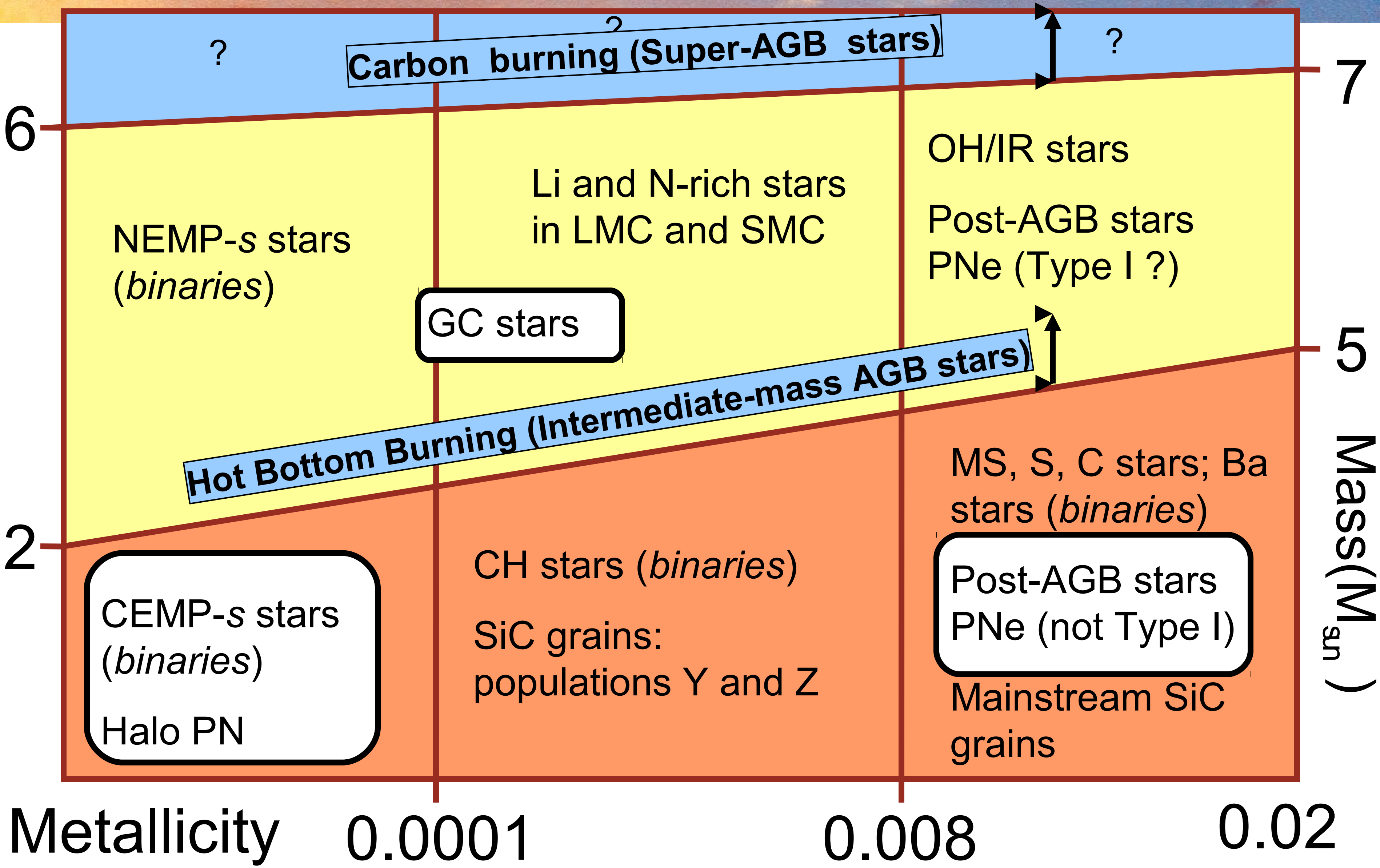


Bisterzo et al 2010



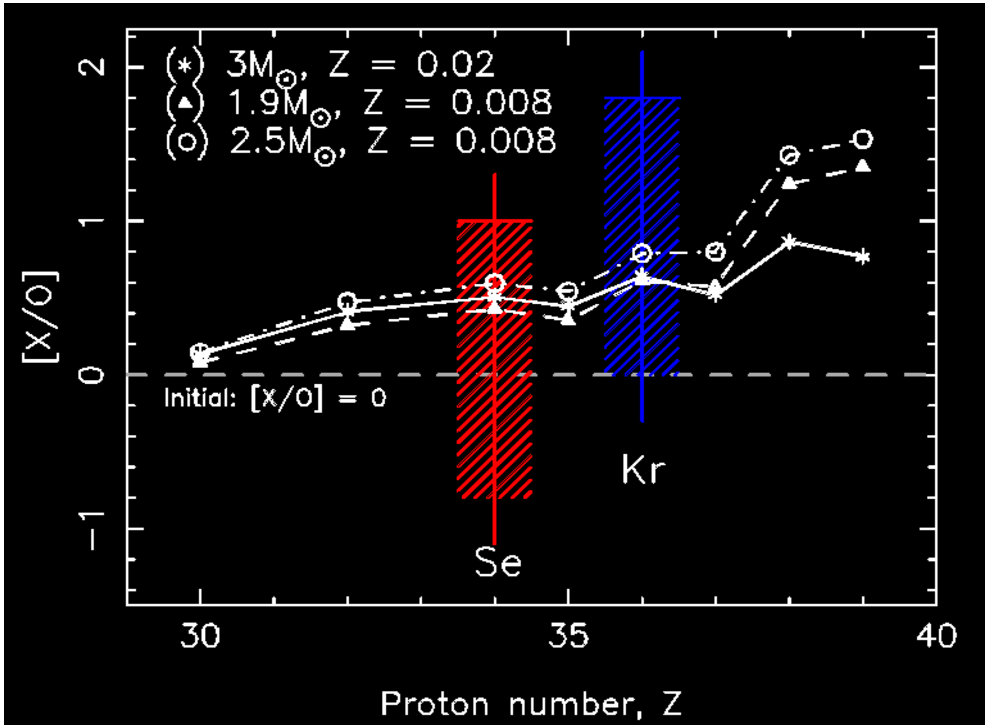
Observations of the *s* process in AGB stars

(dwarfs/giant stars in thin/thick disk, halo, bulge, other galaxies)



The s-process in planetary nebulae

- Neutron capture elements are detected in planetary nebula (PN) spectra
- Sterling & Dinerstein (2008): Determined Se, Kr abundances for a sample of 120 PN
- Sharpee et al. (2007): Detected Br, Rb, Xe, Ba, Pb in PN spectra
- Uncertainties are being reduced by improvements in atomic data (Sterling et al. '09)

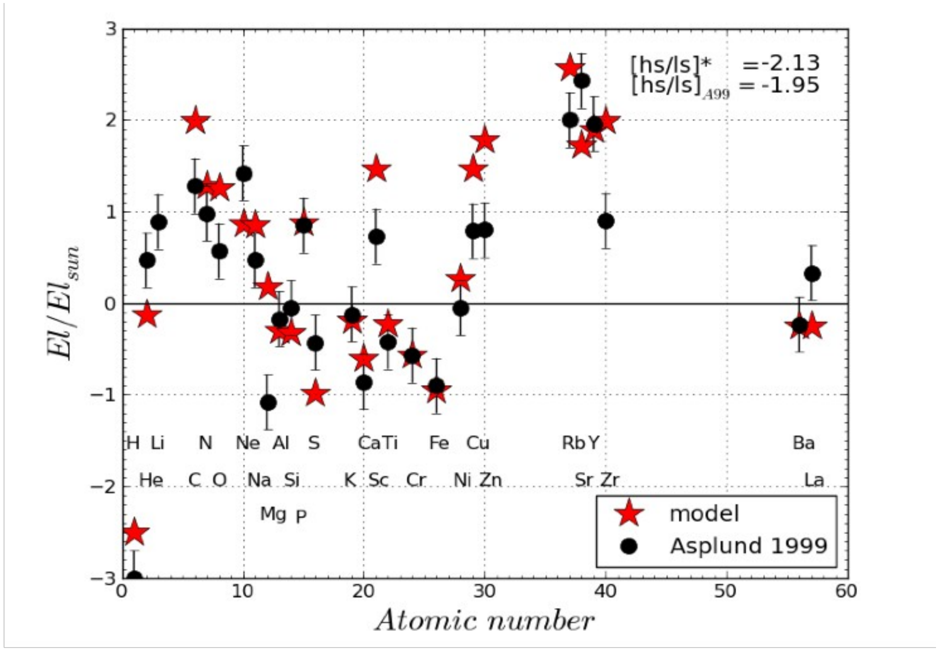


- There are also a few PN found in the halo (e.g., K548 in M15 and BoBn 1 in the Halo; Zjilstra et al. 06)
- S-process elements are being looked for in low-Z PN (Otsuka et al. '10)
- Provides a complimentary data set to the CEMP star abundances?

Karakas & Lugaro (2010)

The s-process in post-AGB objects

- Sakurai's object is a post-AGB object evolving on human timescales
- It likely experienced a “very late TP” (Werner & Herwig 06)
- Detailed spectroscopic analysis (Apslund et al. 99) shows a low ratio of heavy s to light s-process elements ([hs/ls])
- Standard 1D stellar evolution do produce results consistent with the observed



Herwig et al. (2010, submitted, poster#224)

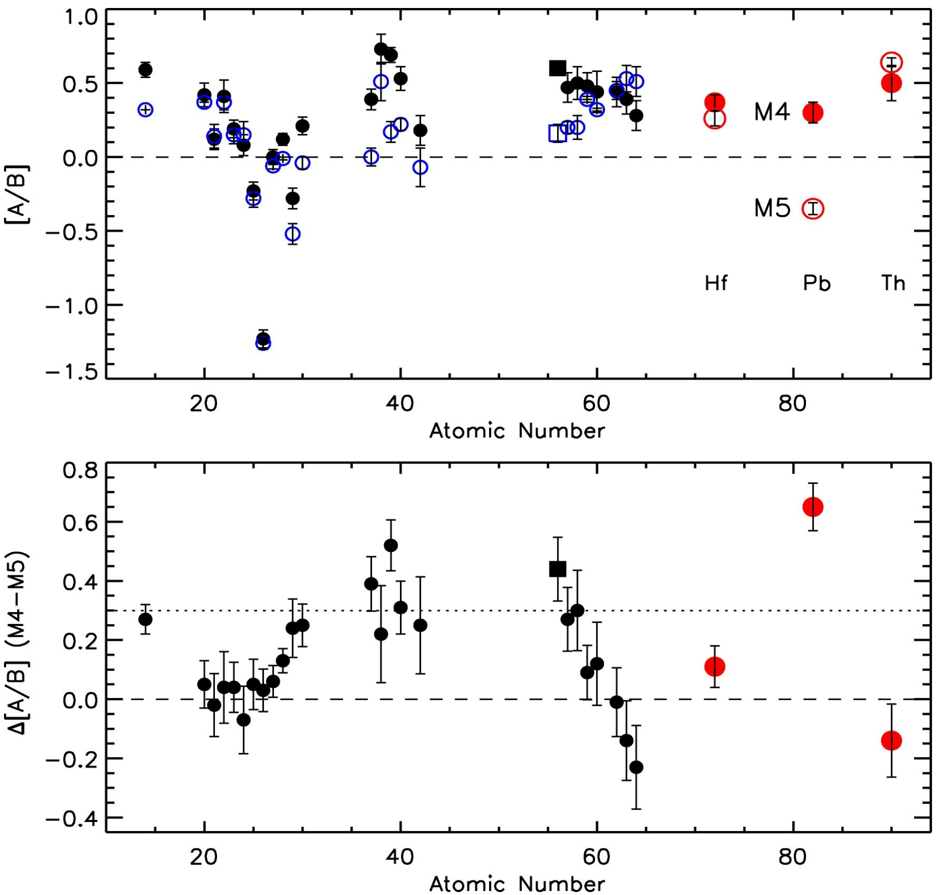
Cristallo talk on s-process in low-Z AGB models

- Guided by 3D simulations of He-shell convection
- Assume that the ingestion process of H into the He-rich region leads to an entropy barrier after some delay time that the convection zone splits
- Leads to significantly higher neutron densities (~10^{15} neutrons per cm^3)
- That can reproduce most of the key abundance trends

Heavy elements in Globular Clusters

- Abundances of s and r-process elements provide insight into stellar nucleosynthesis processes in the early Galaxy
- M4 shows larger abundances of s-process elements Rb, Ba, La, and Pb compared to M5
- With M4 receiving a higher concentration of the s-process enriched gas
- Did AGB stars produce the Rb, Ba, La, and Pb in M4?
- There is no star-to-star scatter in the heavy elements

M4 and M5: same metallicity, [Fe/H] ~ -1.2



From Yong et al. (2008)
See also Poster #145 (Worley)

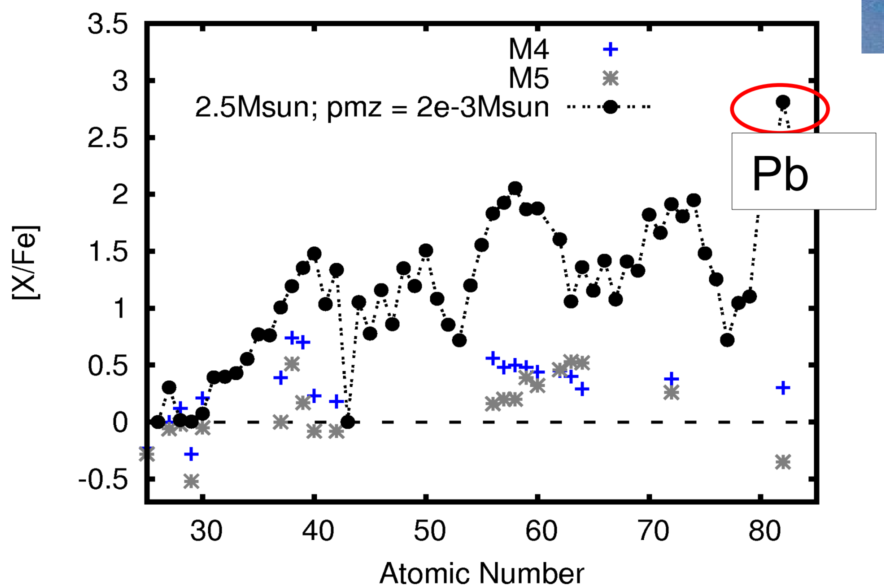
Did AGB stars produce the heavy elements?

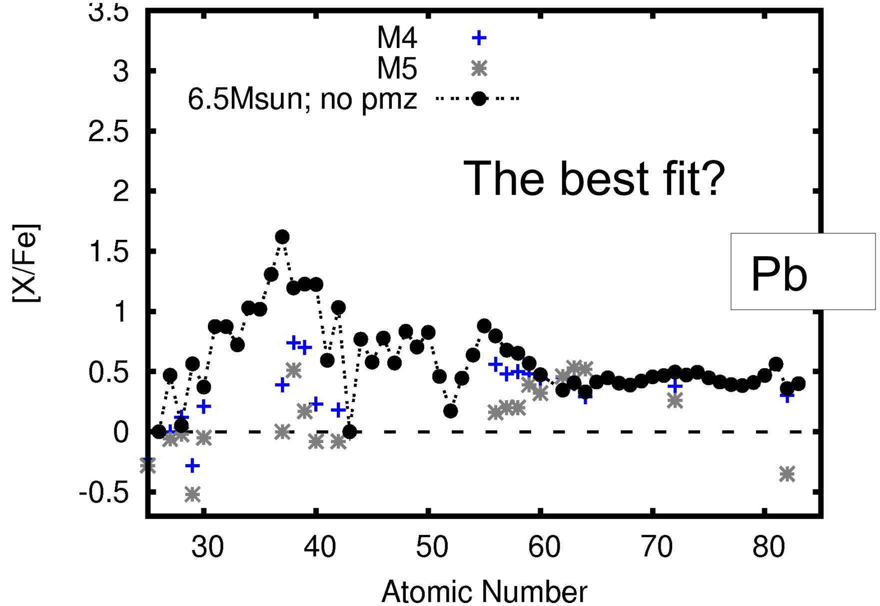
- Use AGB models of [Fe/H] = -1.4 to test this idea
- M = 1.25, 2.5, 3.5, 5, 6.5Msun
- Alpha and r-process enhanced initial abundances
- In the lower mass models, the $^{13}C(a,n)^{16}O$ source dominates
- In the 5 and 6.5Msun models, neutrons are released by the $^{22}Ne(a,n)^{25}Mg$ reaction

Results for the 2.5Msun and 6.5Msun models:

– 2.5Msun produces too much Pb

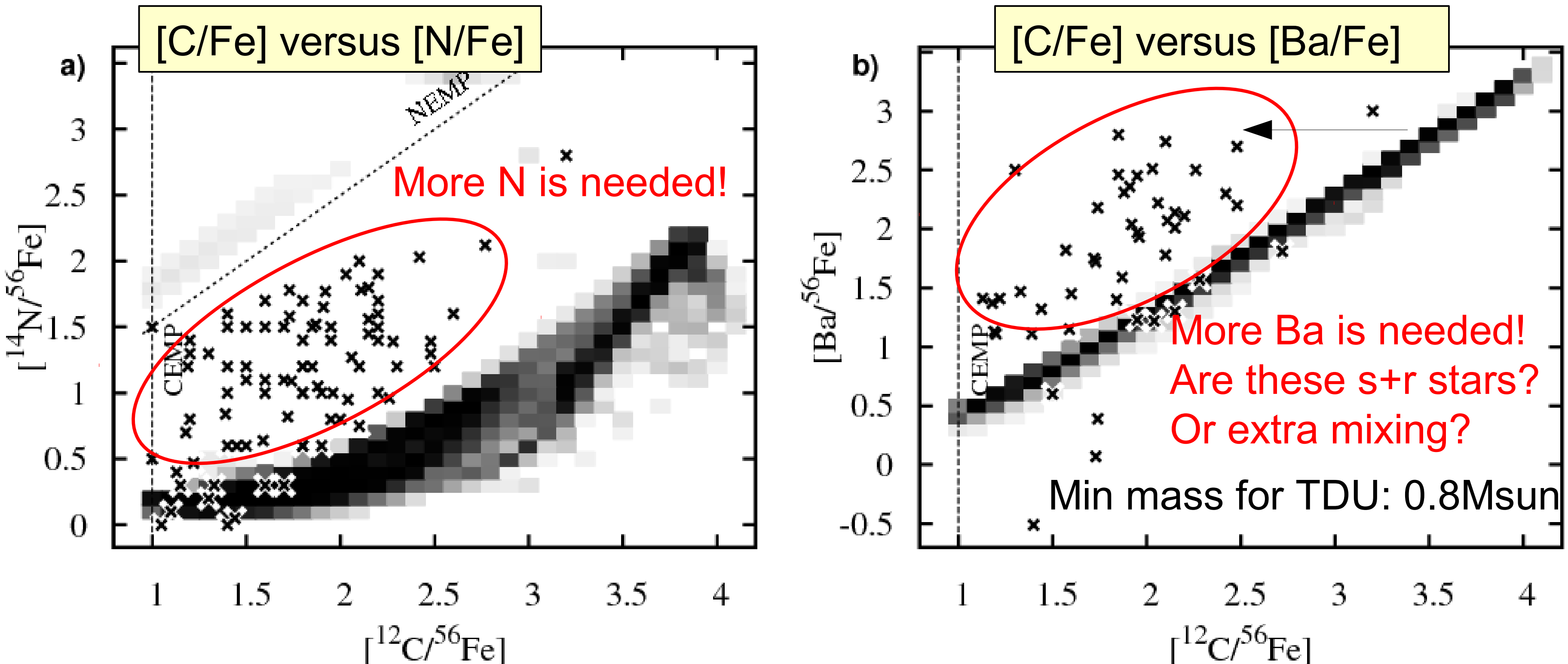
A chemical evolution model is needed to test the idea further





Carbon enhanced metal-poor (CEMP) stars

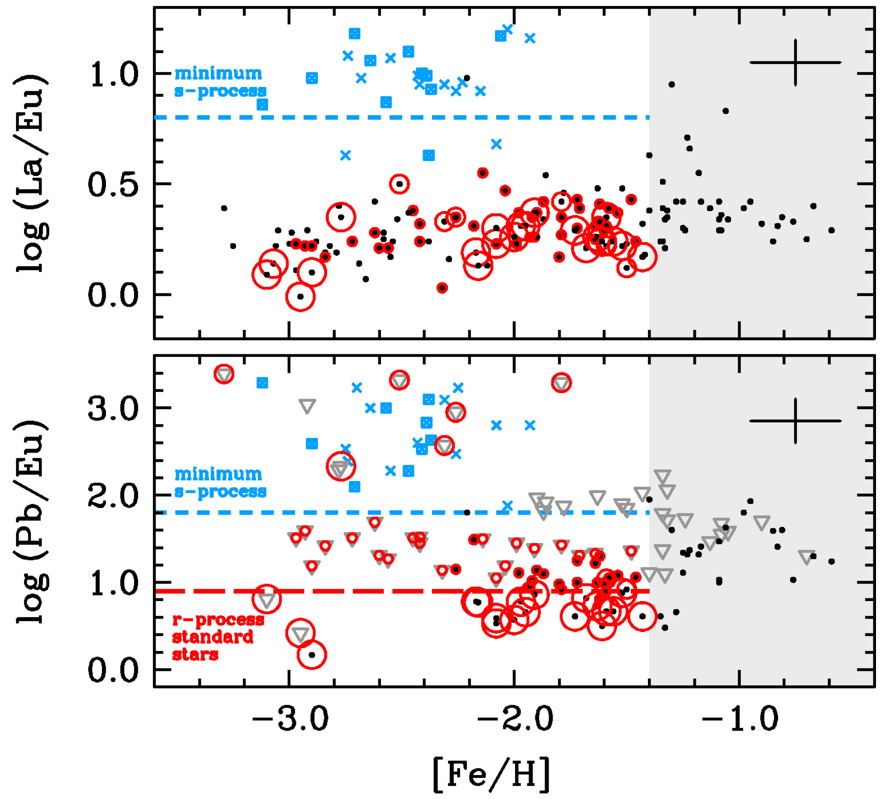
- Stellar population synthesis is useful a tool to explore AGB model uncertainties
- Izzard et al. (2009) constructed binary population synthesis models to try and explain the fraction of CEMP(*s*) stars at around [Fe/H] ~ -2.3
- Varied inputs such as the initial mass function, mass transfer efficiencies, and the efficiency of TDU mixing in AGB models
- The correlation between C and Ba in the best fit model:



The s-process can help us understand the r-process

- Roederer et al. (2010, ApJ submitted, poster #54) have derived neutron-capture abundances for 161 metal-poor stars
- Guided by low-metallicity AGB models, the Pb/Eu ratio can be used identify stars with any s-process
- Can also help determine the onset of the s-process in the Galaxy (see also Simmerer et al. 2004)
- Suggest no significant s-process gas until [Fe/H] ~ -1.4
- Identify a dispersion of abundance ratios (e.g., La/Eu, Ba/Eu) among elements produced by the r-process
- Cautions against using e.g., La/Eu alone as discriminant against s- or r-process

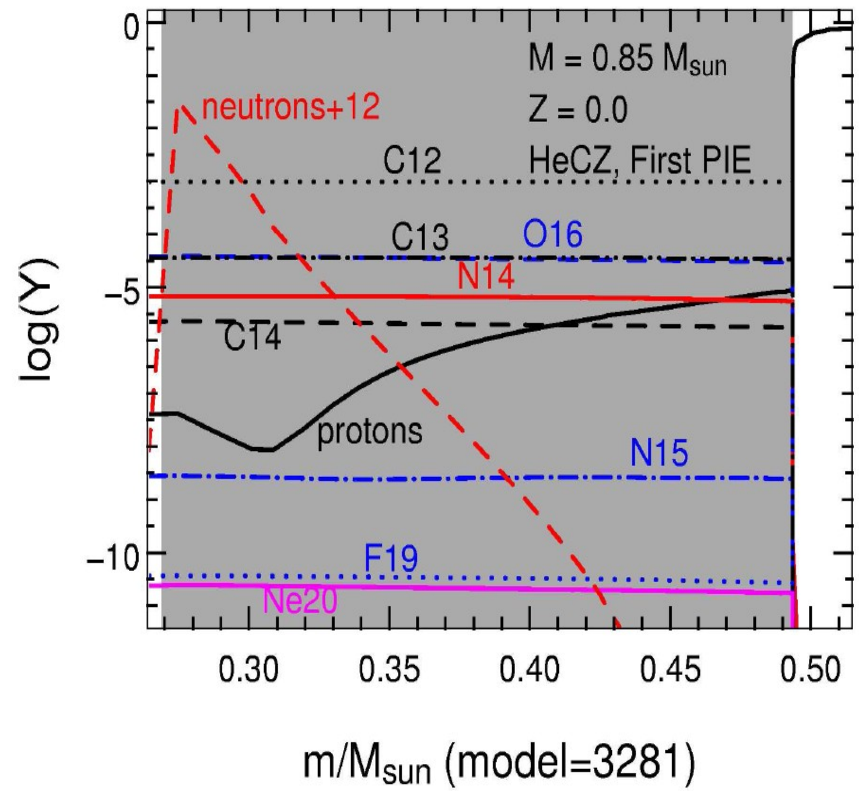
From Roederer et al. (2010)



Neutron superburst in primordial low-mass stars

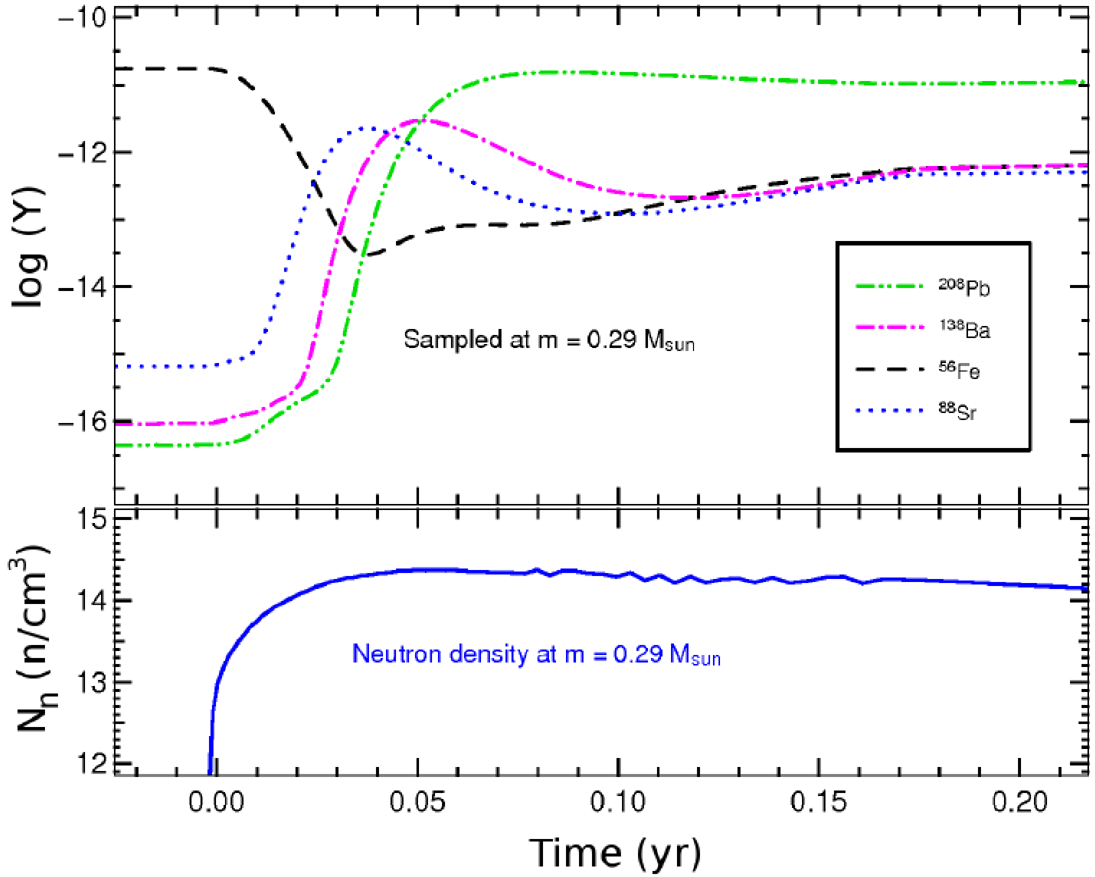
- Calculations show that heavy elements are produced and mixed to the surface in primordial low-mass red giant branch stars
- Speculated by Fujimoto et al. (1990)
- Production occurs during the core He-flash
- Mixing between the flash-driven convective layers and envelope occurs
- Neutron flux remains above $\sim 10^{13}$ n/cm^3 for a few years! Neutron exposure $\sim 10^2$ mbarn^{-1}
- Compare to low-Z AGB model which have up to a few tens of mbarn^{-1}
- S-process in equilibrium produces Ba and Pb

Campbell, Lugaro & Karakas (2010, submitted)
Model has 1Msun, [Fe/H] = -6.5



Neutron superburst in primordial low-mass stars

Campbell, Lugaro & Karakas (2010, A&A Letters, submitted)
Open questions: Did these stars even form in the first place??



Summary

- AGB stars are important contributors to the chemical evolution of heavy elements produced by the s-process
- The latest theoretical models provide a reasonable description of s-process nucleosynthesis
- But uncertainties remain, including the formation mechanism and extent of ^{13}C pockets in AGB stars
- Puzzling observations still need to be addressed e.g., heavy elements in GC stars (AGB?) & did low-mass stars form at [Fe/H] ~ -6.5 and produce heavy elements?
- Most of our problems are based on our lack of understanding of how mixing really works in evolved stars
- Multi-D hydro models can be used as a guide to constrain the 1D stellar evolution models along with observations