Metal-rich AGB models and yields

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Outline

- Introduction
- Brief review of yields available from AGB stars including heavy elements
- Brief detour into the effect of helium on stellar yields and minimum mass for C burning
- Yields from new metal-rich AGB models
- Summary

The Cycle of Matter

How do stars produce and recycle the elemental building-blocks of life?

What stars?

- Stars that will have died in 13.7Gyr → M > 0.8Msun
- Here we have been focusing on stars between roughly 6-10Msun → super-AGB stars and EC supernova
- What are their chemical yields?

Credit: HST public archive

The origin of the elements

Ideally, we want to know the origin and evolution of all elements in the Universe

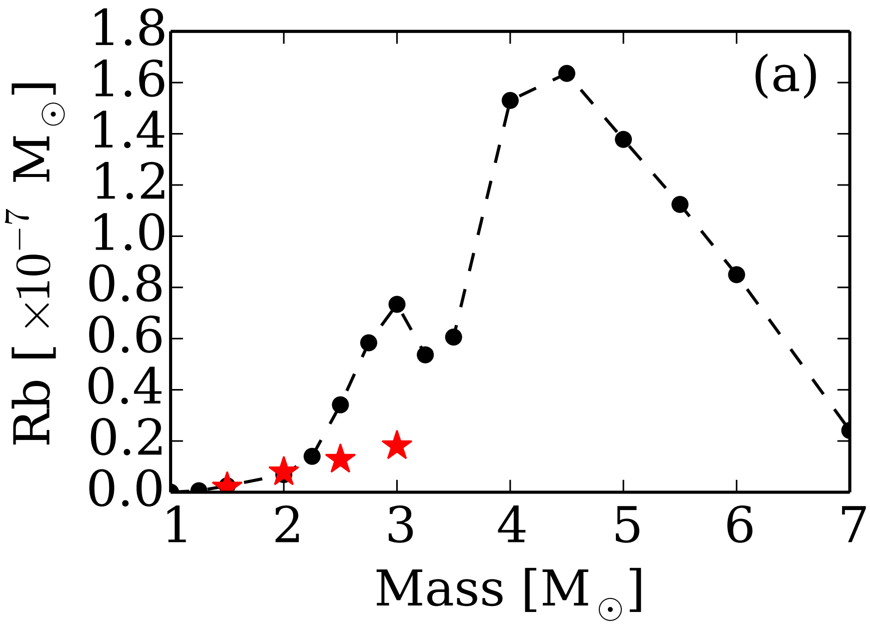
To do this we need to have accurate predictions of nucleosynthesis yields from all contributing sources, including AGB stars

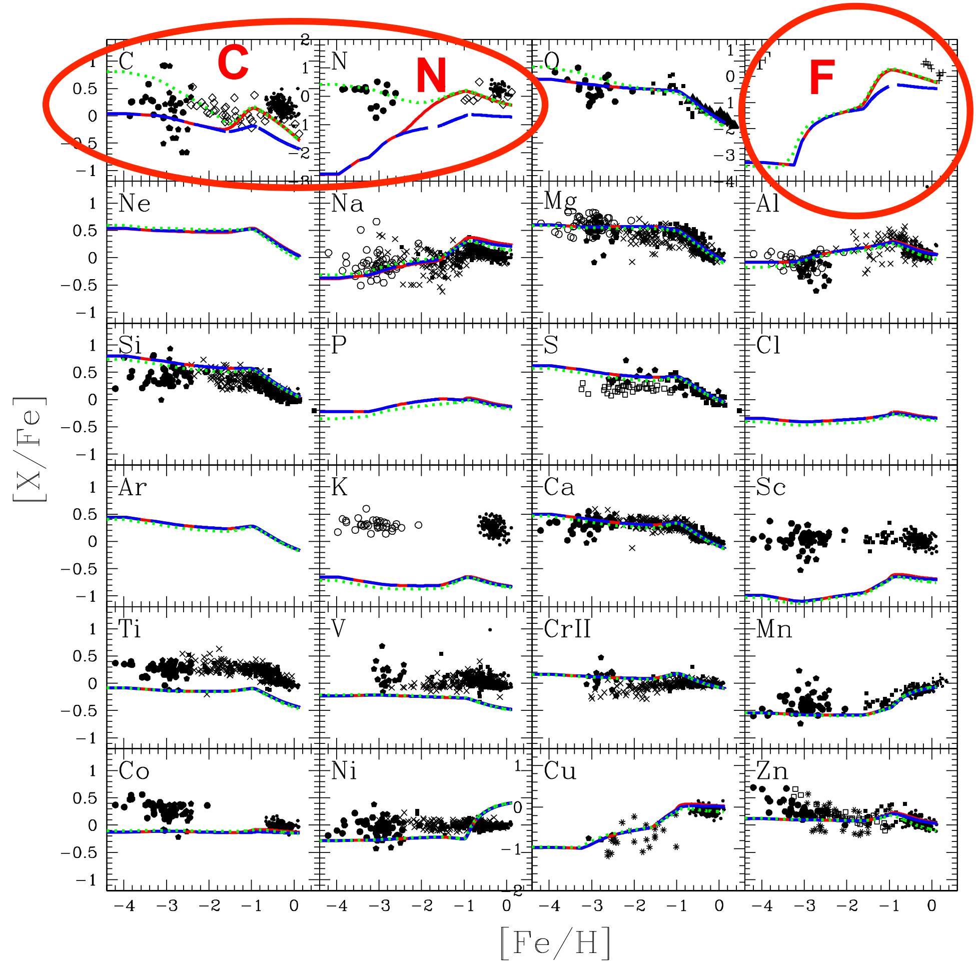
One substantial stellar uncertainty is the lack of AGB yields for heavy elements

Credit: HST public archive

Evolution of elements in the Universe

Yields of 1-7Msun models of [Fe/H] = -1.2
From Fishlock, Karakas et al. (2014, ApJ)





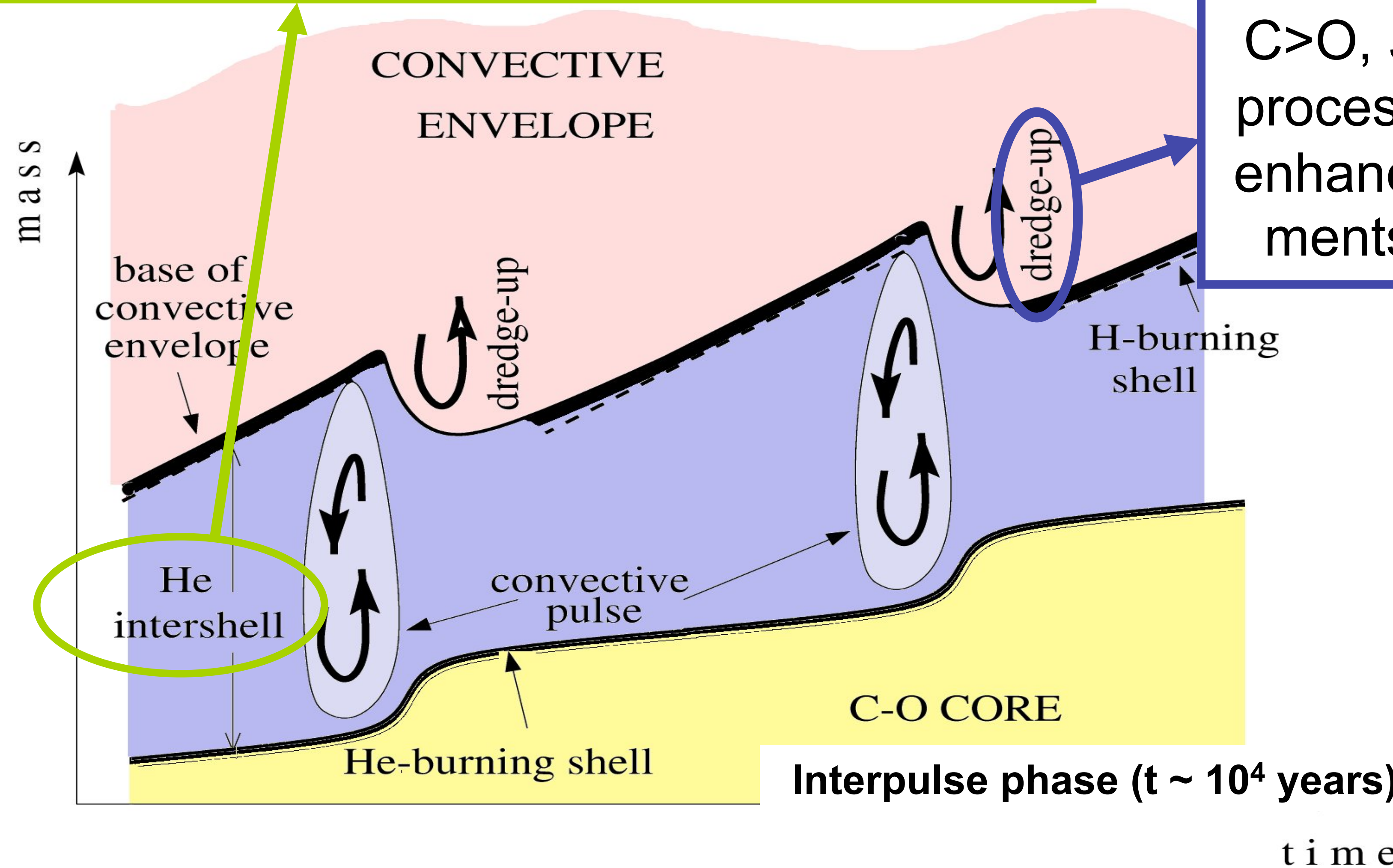
Review of AGB yields available in
Karakas & Lattanzio (2014)

Kobayashi, Karakas, & Umeda (2011)
using yields from Karakas (2010)

Schematic AGB evolution

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

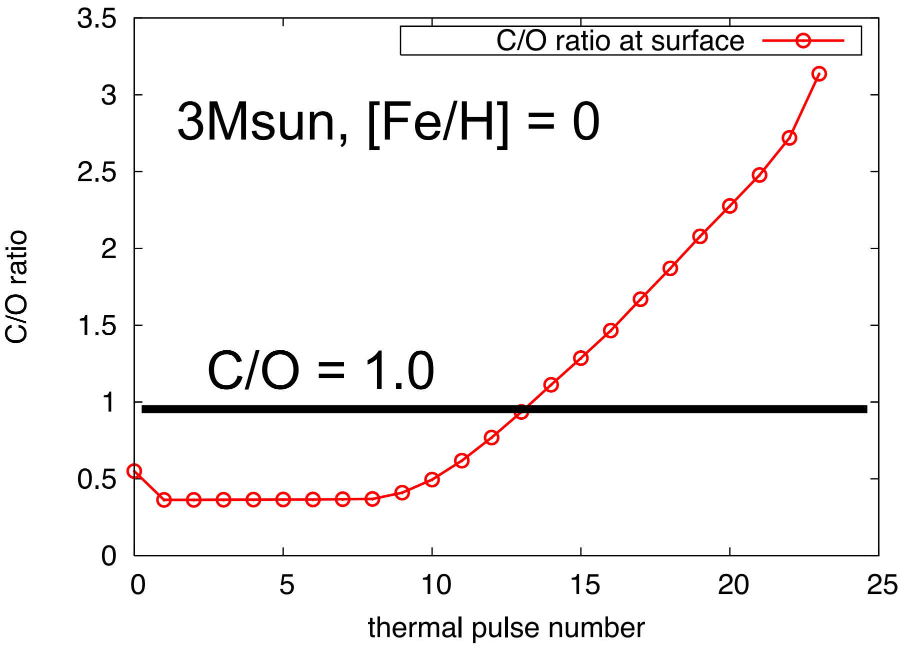
At the stellar surface: C>O, *s*-process enhancements



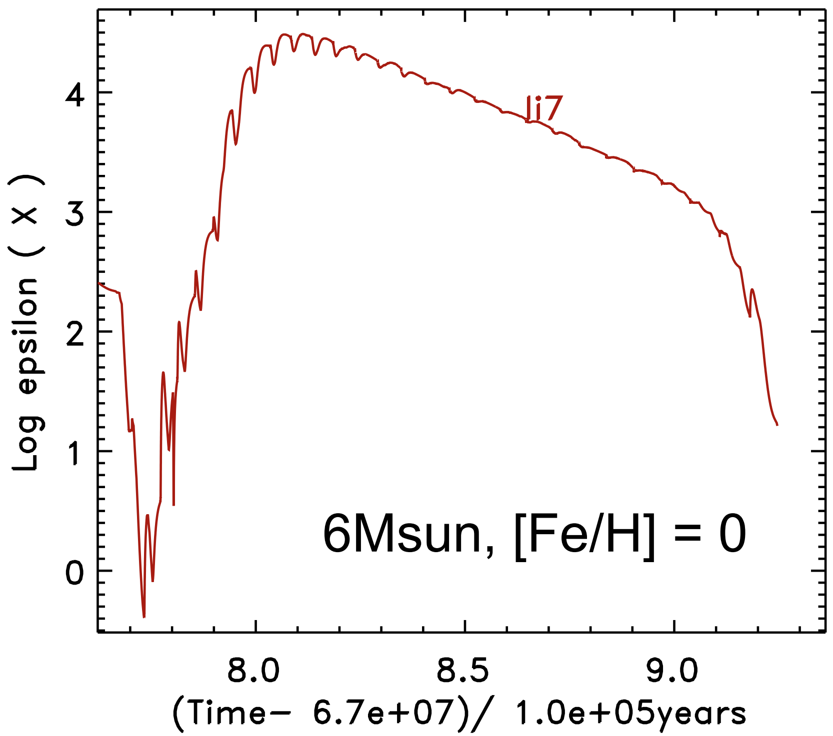
Interpulse phase (t ~ 10^4 years)

Nucleosynthesis

- Inward movement of convection mixes the products of He-shell nucleosynthesis to the envelope (^{12}C, ^{19}F, s-process)
- Envelope burning in M ≥ 4Msun, depending on Z (e.g., ^{7}Li, ^{13}C, ^{14}N, ^{23}Na, $^{26,27}Al$)

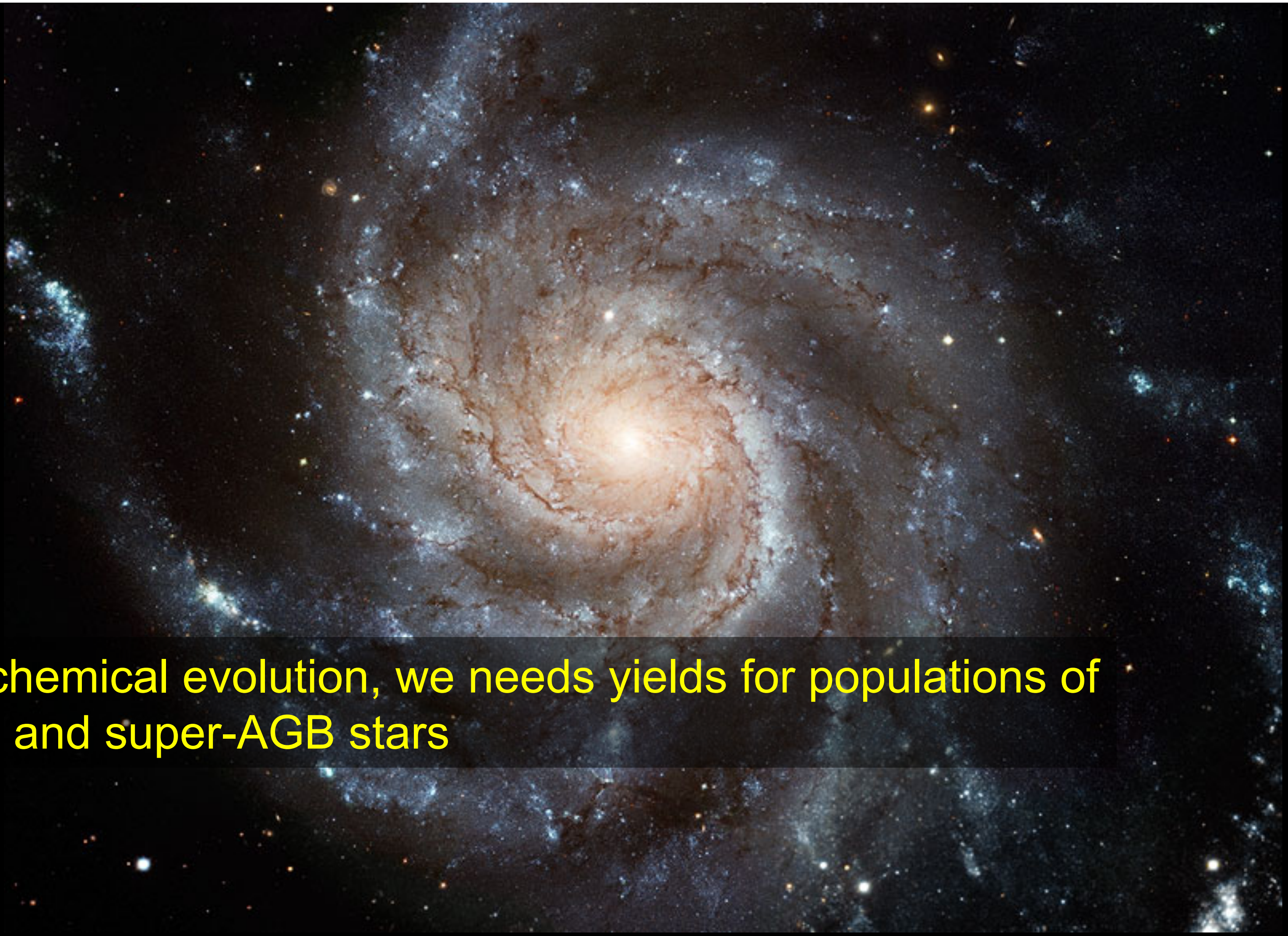


Log ε(Li)$_{max}$ = log$_{10}$(Li/H)+12 = 4.5



Galactic archaeology

How to disentangle the vast quantity of information from current and future stellar abundance surveys? (e.g., HERMES, LAMOST, GAIA-ESO…)



For chemical evolution, we needs yields for populations of AGB and super-AGB stars

So what yields are available?

AGB stellar yields

Including heavy s-process elements

- **Lugaro et al. (2012)**: Surface abundances with a low metallicity [Fe/H] = -2.3 for models from 1 to 6Msun
- **Fishlock et al. (2014)**: Yields with a metallicity of [Fe/H] = -1.2 for models with 1 to 7Msun
- **Karakas et al. (2014)** and **Shingles et al. (2015)**: Yields with a metallicity of [Fe/H] = -1.4 for models between 1 to 6Msun, including the effect of helium enrichment

AGB stellar yields

Including heavy s-process elements:

- **FRUITY database:** Cristallo et al. (2011) and Straniero et al. (2014) yields for 1-3Msun for a large range of metallicities; an increasing number of intermediate-mass models up to 6Msun → but weak or no HBB
- **NuGrid/MESA:** Pignatari, Herwig et al. (2013, ApJ, submitted) for Z = 0.01 and 0.02 (Ritter's talk)
- **At very low metallicities:** Campbell et al. (2010) and Cruz et al. (2013) but no tabulated yields

What is lacking? Low metallicities, super-AGB stars, full grid of solar metallicity yields

The effect of helium on stellar yields

Colour-magnitude diagram using HST photometry from Cassisi et al. (2009; see also Bellini et al. 2009)

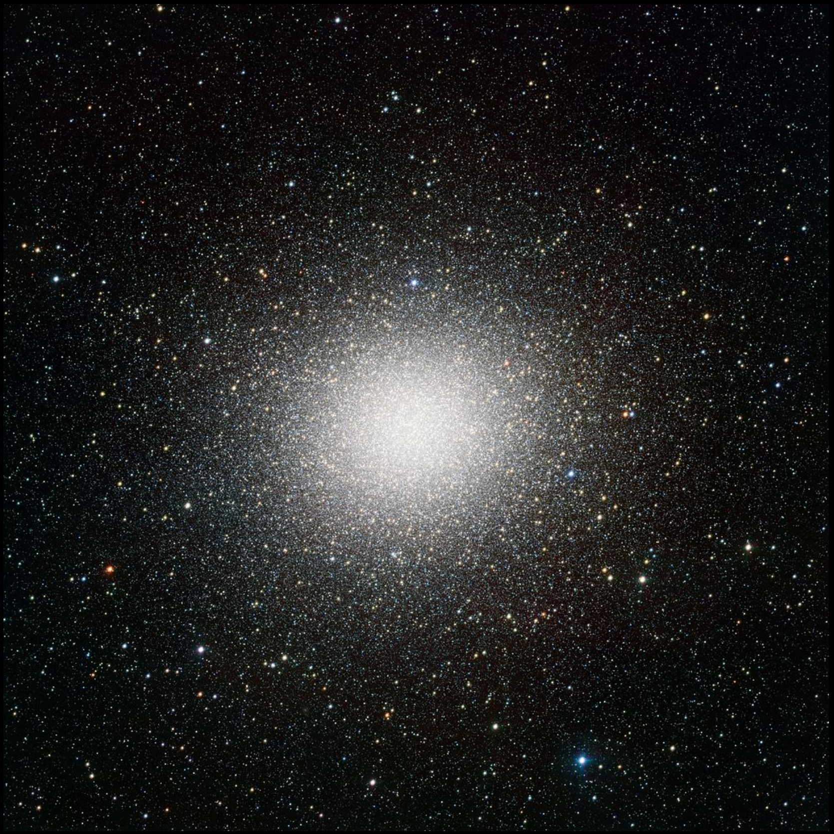
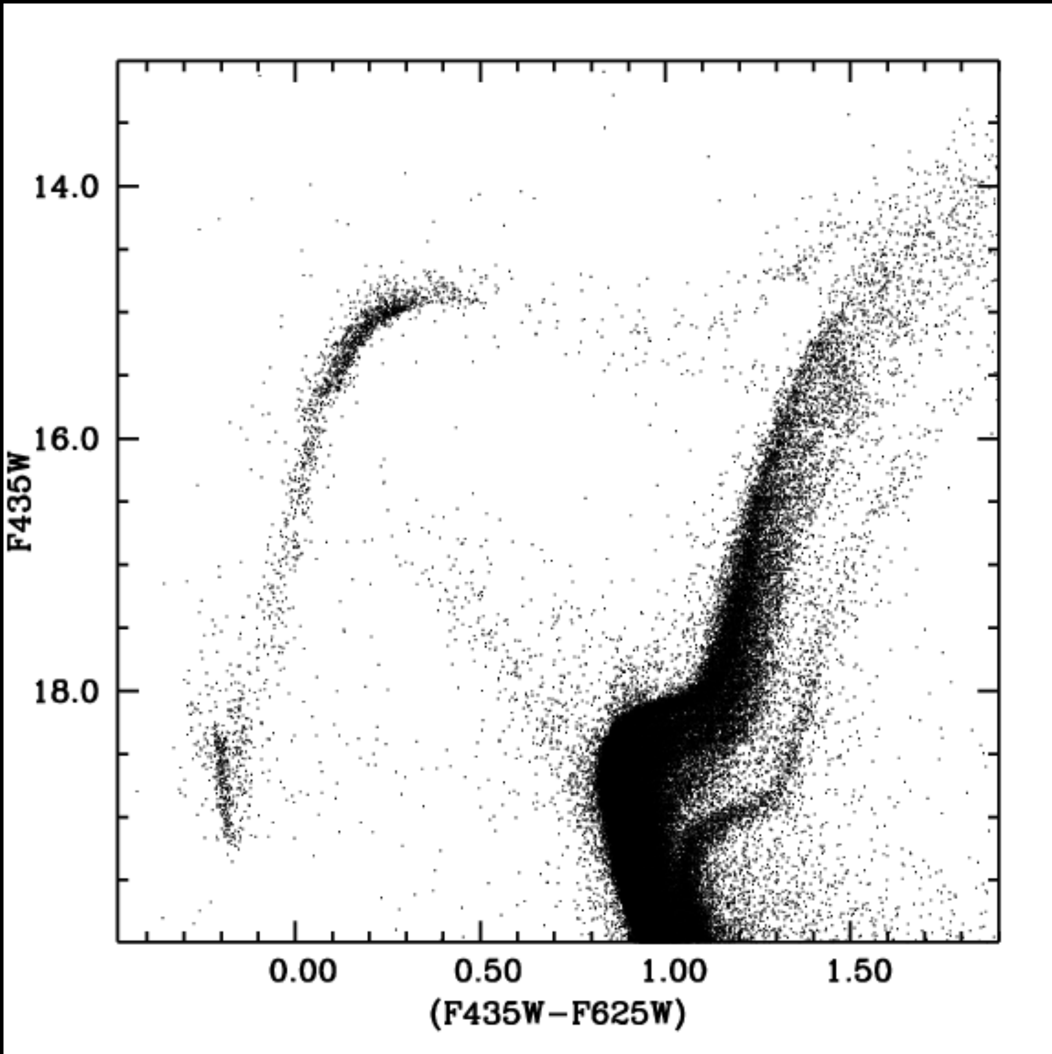


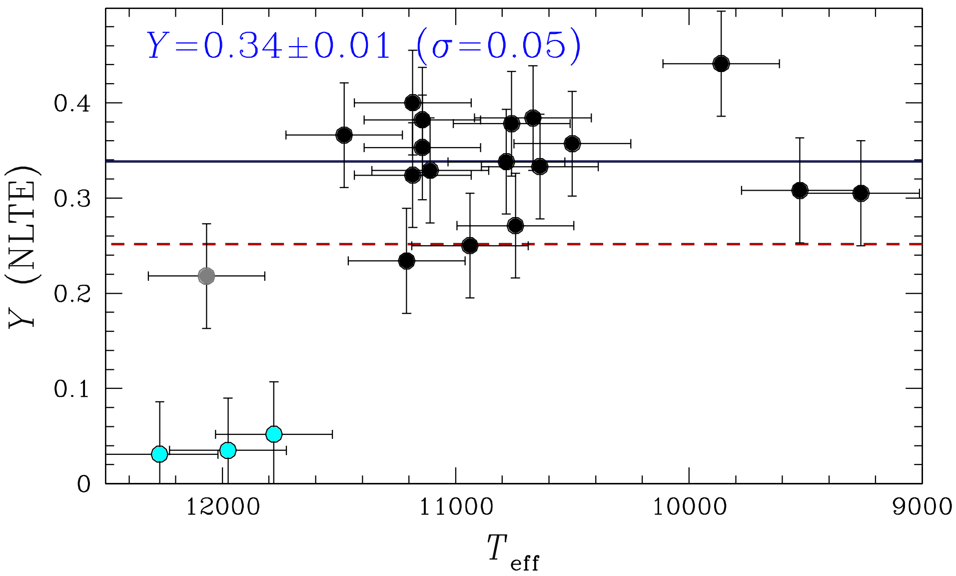
Image credit: ESO



Helium enrichments in globular clusters

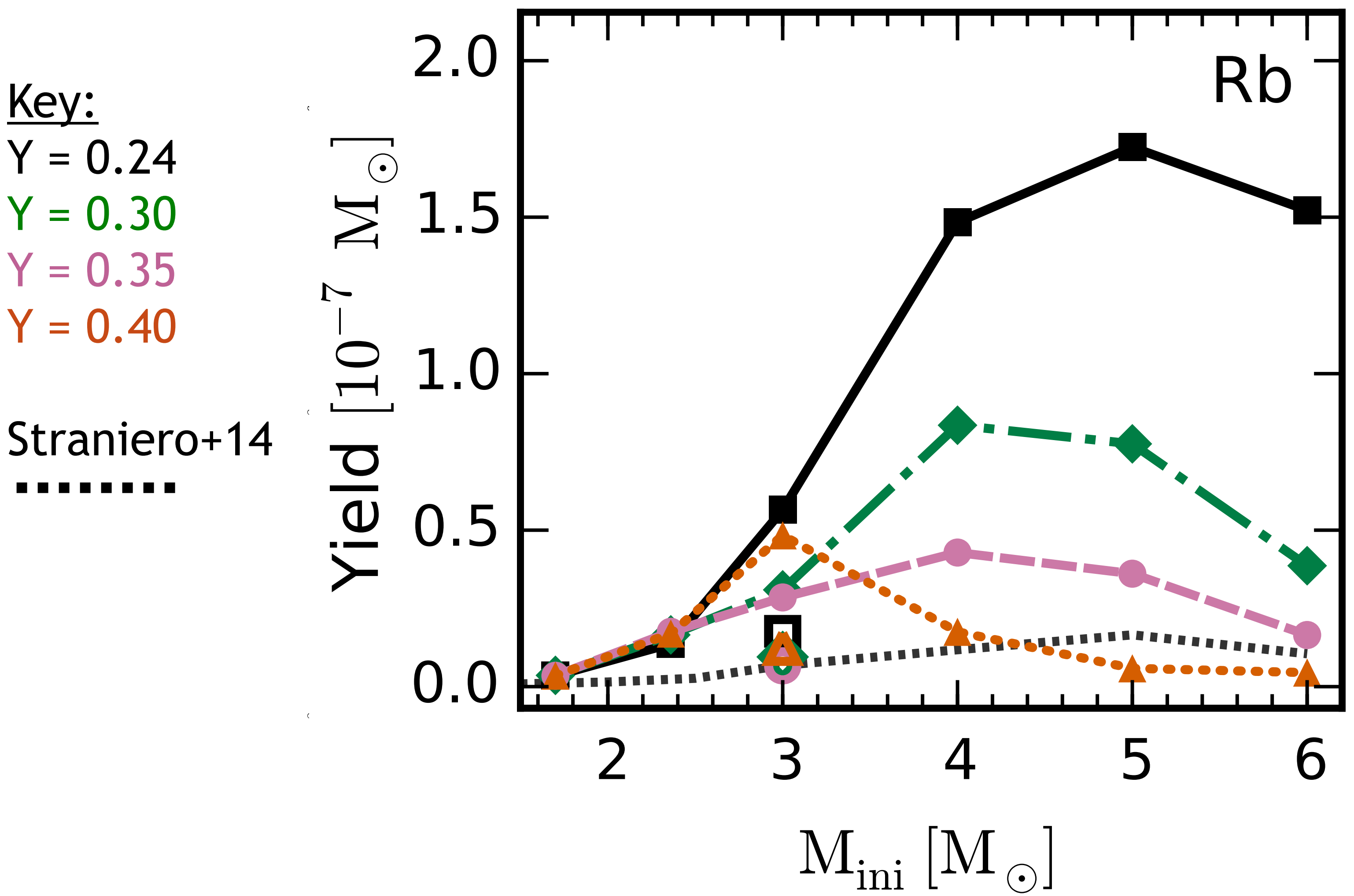
- Hubble Space Telescope has revealed sub-populations within globular clusters (e.g., ω Centauri, NGC 2808, M2)
- Caused by variations in Fe, helium (Y), and/or C, N, and O elements
- Some clusters show large variations in helium, from the primordial value of Y ≈ 0.24 to values higher than 0.40 (i.e., ΔY ~ 0.1 or more; the solar value ~ 0.28)

Direct evidence for helium: Marino et al. (2014) measured helium in horizontal branch (HB) stars in NGC 2808



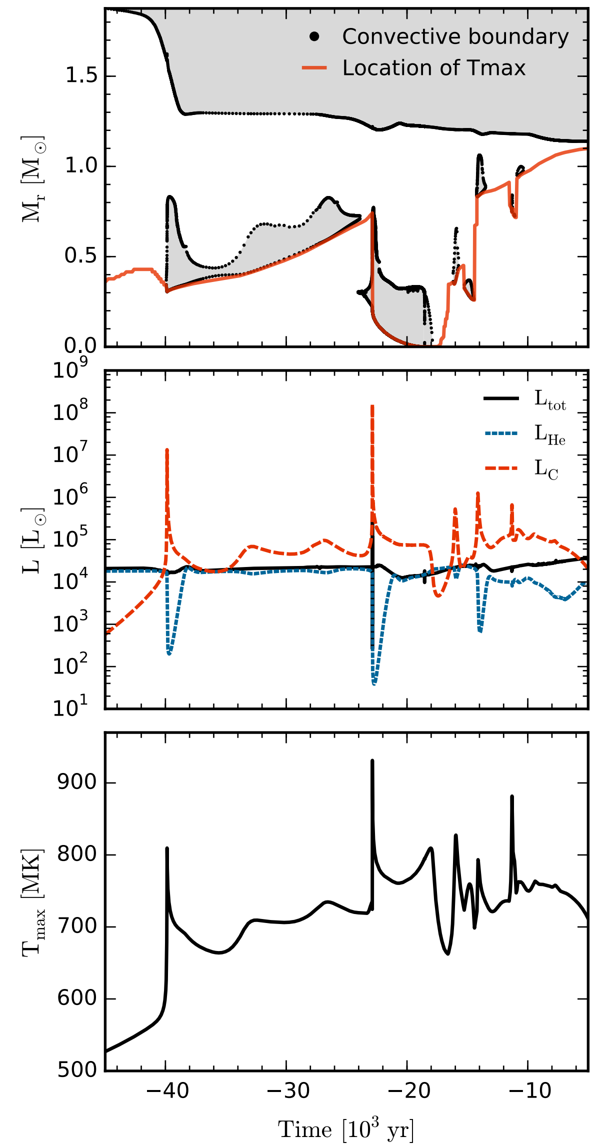
Yields from intermediate-mass models

Helium enrichment will reduce the yields of s-process elements at all masses (Shingles et al. 2015, MNRAS)



Carbon burning in helium enriched models

- We find the minimum mass for M_{up} (carbon burning) drops to ≈ 4-5Msun when Y ≥ 0.35
- Down from M > 6Msun when Y = 0.24
- We will therefore make more neutron stars from lower mass progenitors
- What are the implications for neutron star formation in GCs?



From Shingles et al. (2015):

Showing results for a 5Msun model

What about for solar metallicity?

Preliminary results:

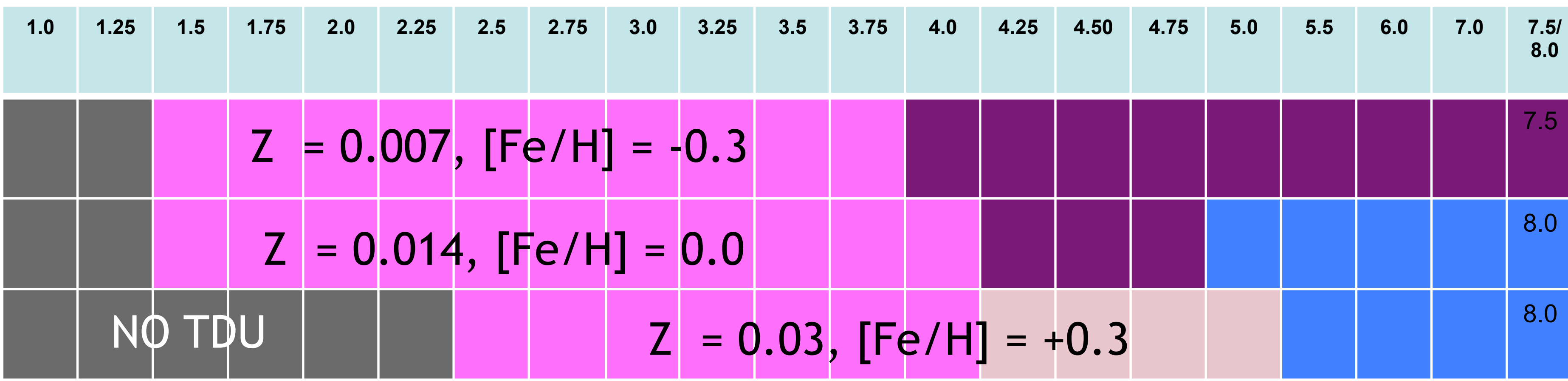
Z = 0.014; canonical value is Y ~ 0.28

Y/M	5.5	6.0	6.25	6.50	6.75	7.0	7.5	7.75	8.0
0.28	CO	CO	CO	CO	CO	CO	CO	CO	CO(Ne)
0.35	CO	CO	CO	CO	CO(Ne)	ONe	ONe	ONe/ electron capture?	ONe/ electron capture
0.40	CO	CO(Ne)	ONe	CO(Ne)	ONe	ONe/ electron capture?	Electron capture	Electron capture	Core collapse ?

Metal-rich and solar metallicity yields

- New grid of yields with three metallicities: [Fe/H] = +0.3, 0.0, -0.3, based on models from Karakas (2014)

Grid of models:



Key: Pink squares → third dredge up; final C/O > 1
Purple squares → HBB and dredge-up, final C/O > 1
Blue squares → HBB and dredge-up, final C/O < 1
Light pink squares → dredge-up but final C/O < 1
Dark grey squares → no TDU and final C/O < 1

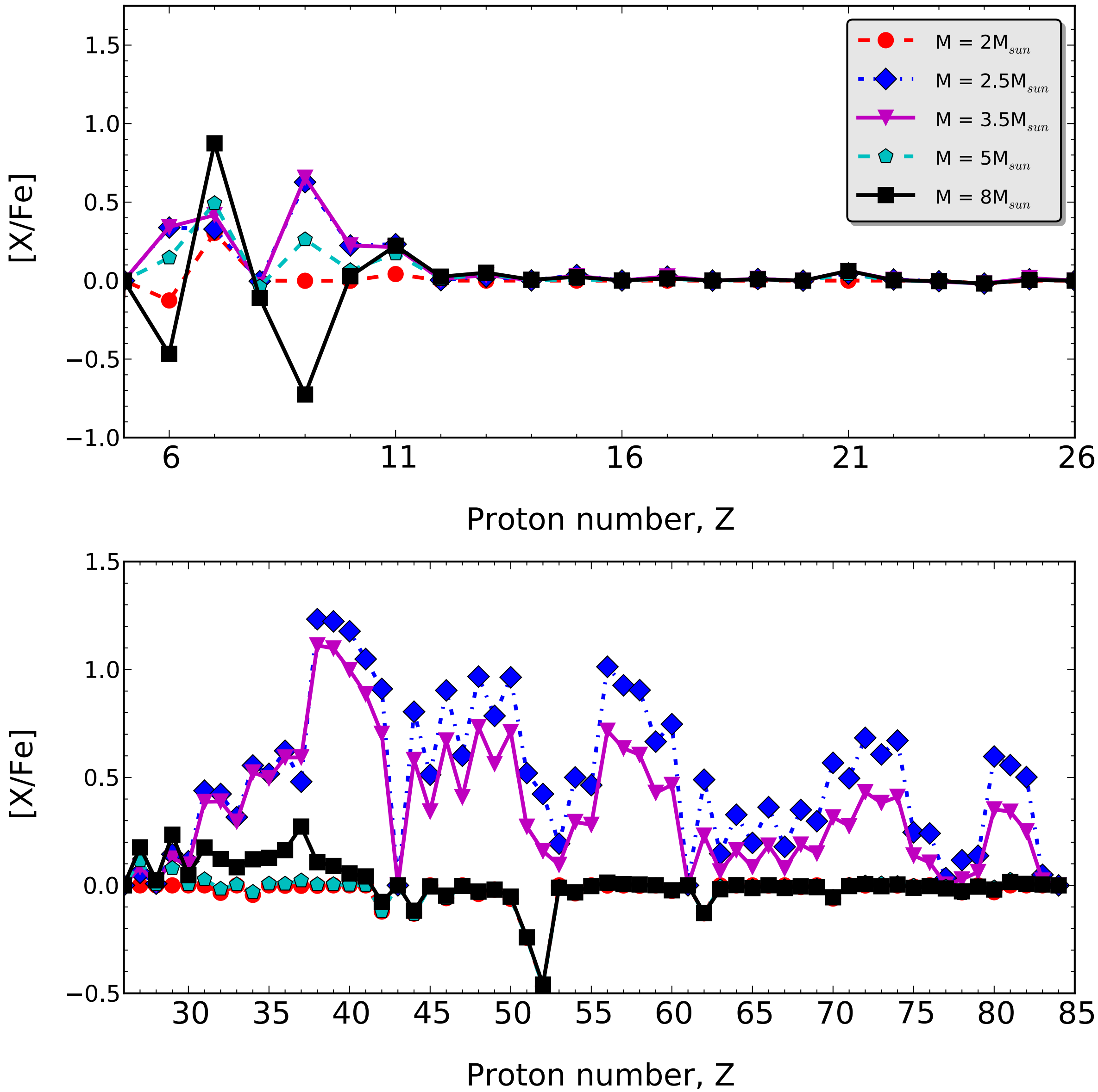
Yields of new metal-rich AGB models

- The CO core limit model is 8Msun for Z = 0.014, 0.03 and 7Msun for Z = 0.007 → and the remnant will be a hybrid CO(Ne) core
- We include one super-AGB model of 7.5Msun, Z = 0.007, which experiences complete C-burning
- Full s-process nucleosynthesis for each (M, Z) combination shown in previous table

Karakas & Lugaro (2016, ApJ submitted)

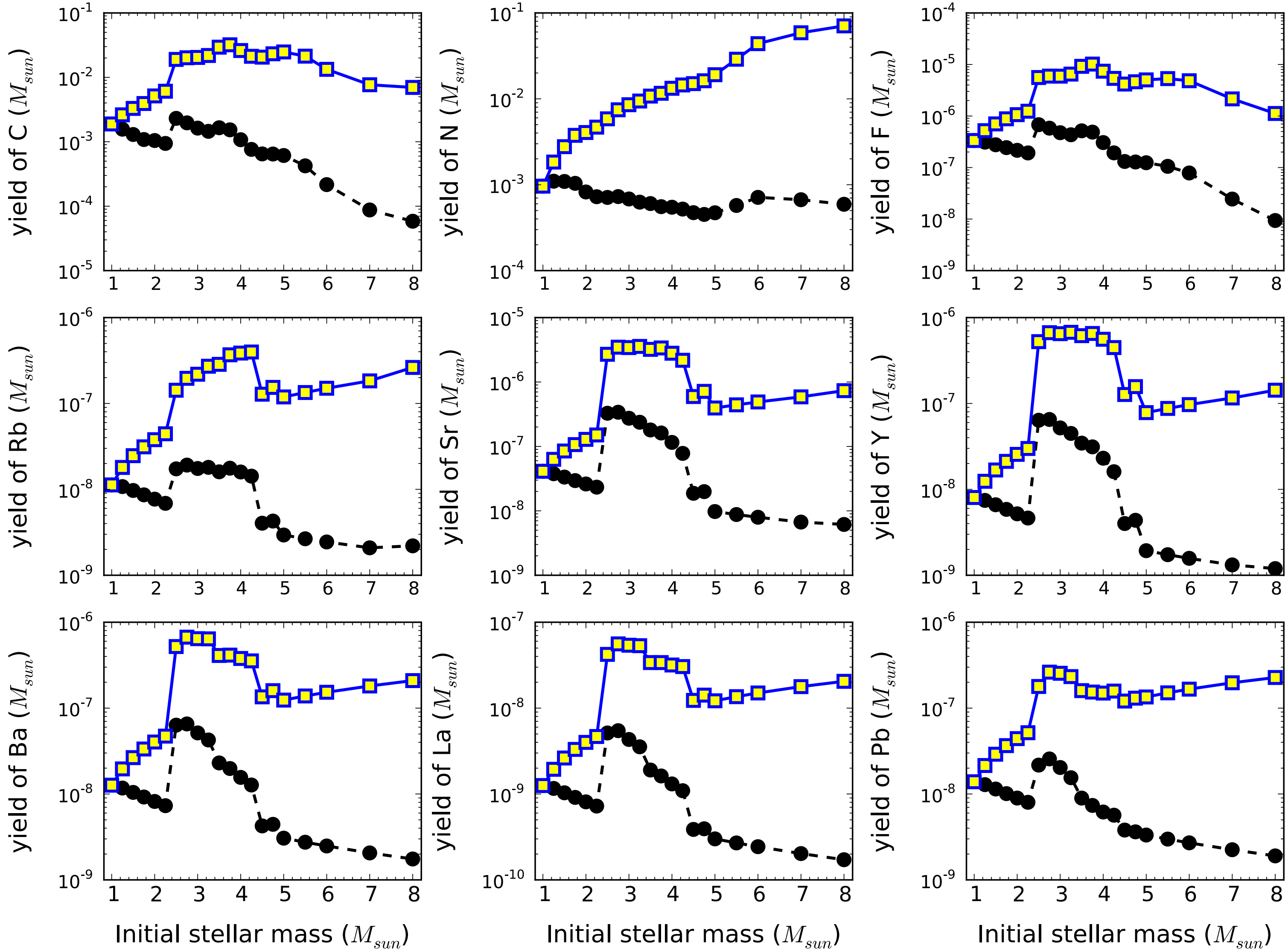
Results: Super-solar metallicity models

Z = 0.03,
[Fe/H] = +0.3



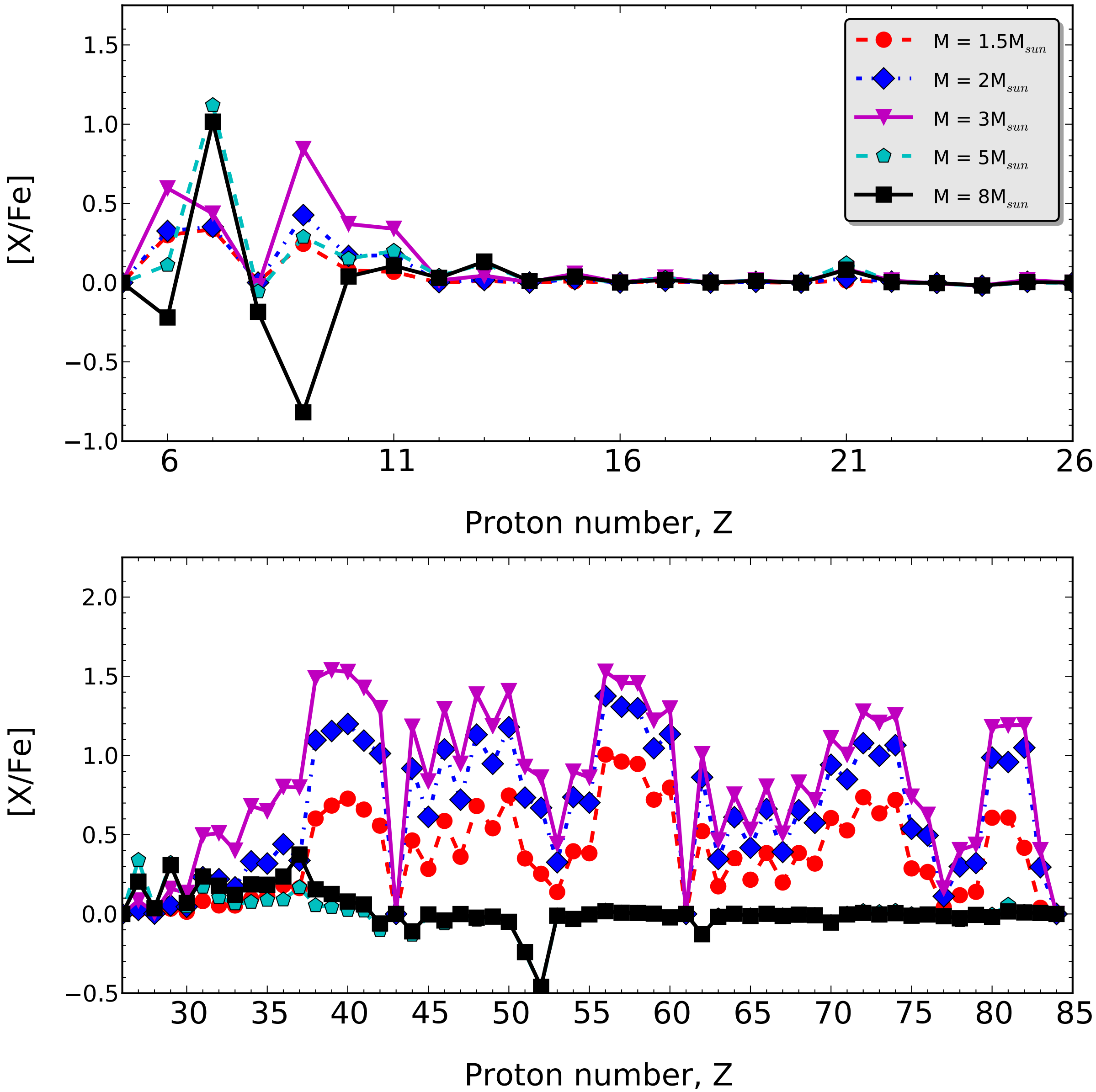
Results: Yields of super-solar models

Z = 0.03, [Fe/H] = +0.3



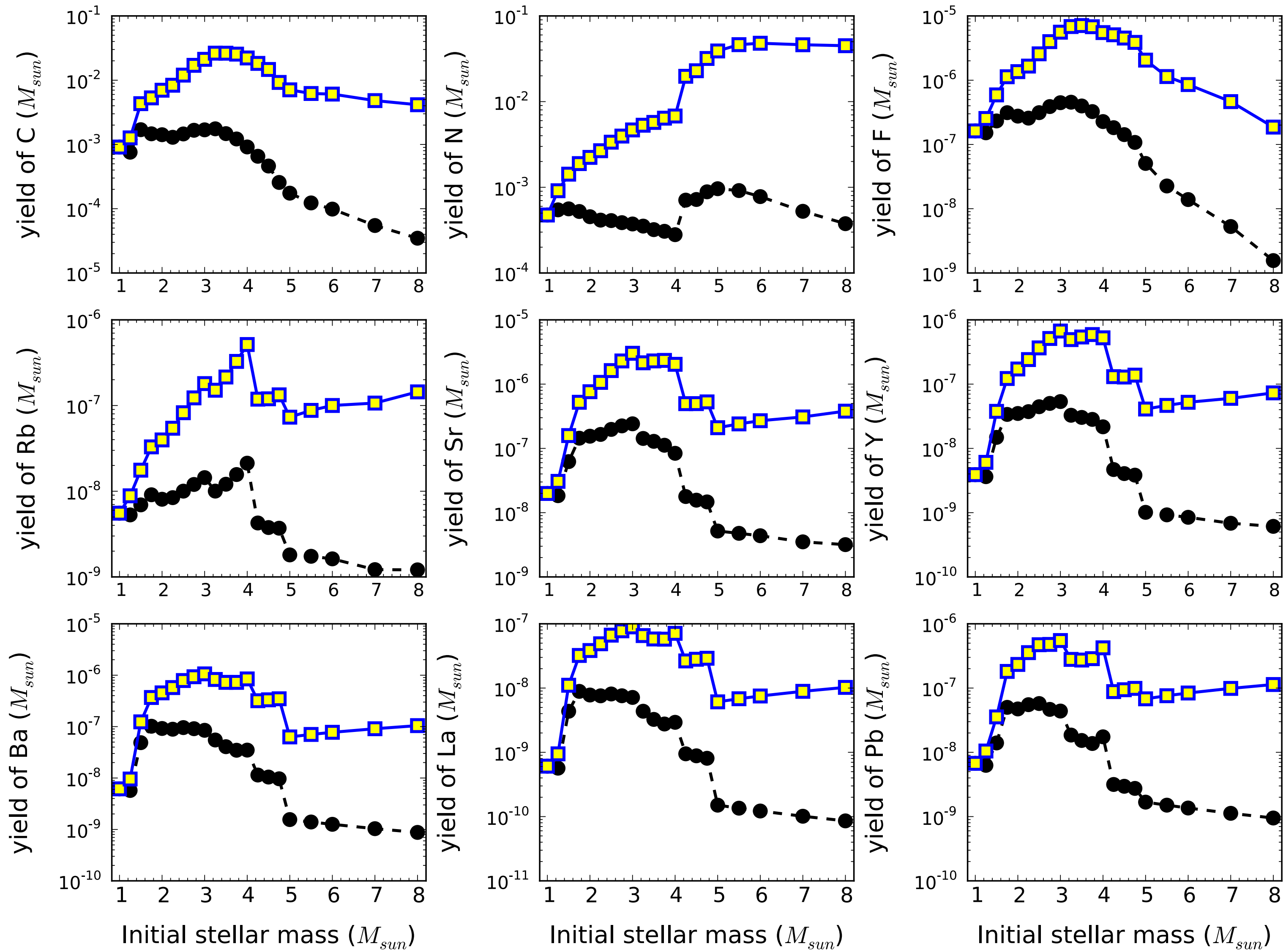
Results: Solar metallicity models

Z = 0.014,
[Fe/H] = 0



Results: Yields of solar metallicity models

Z = 0.014, [Fe/H] = 0

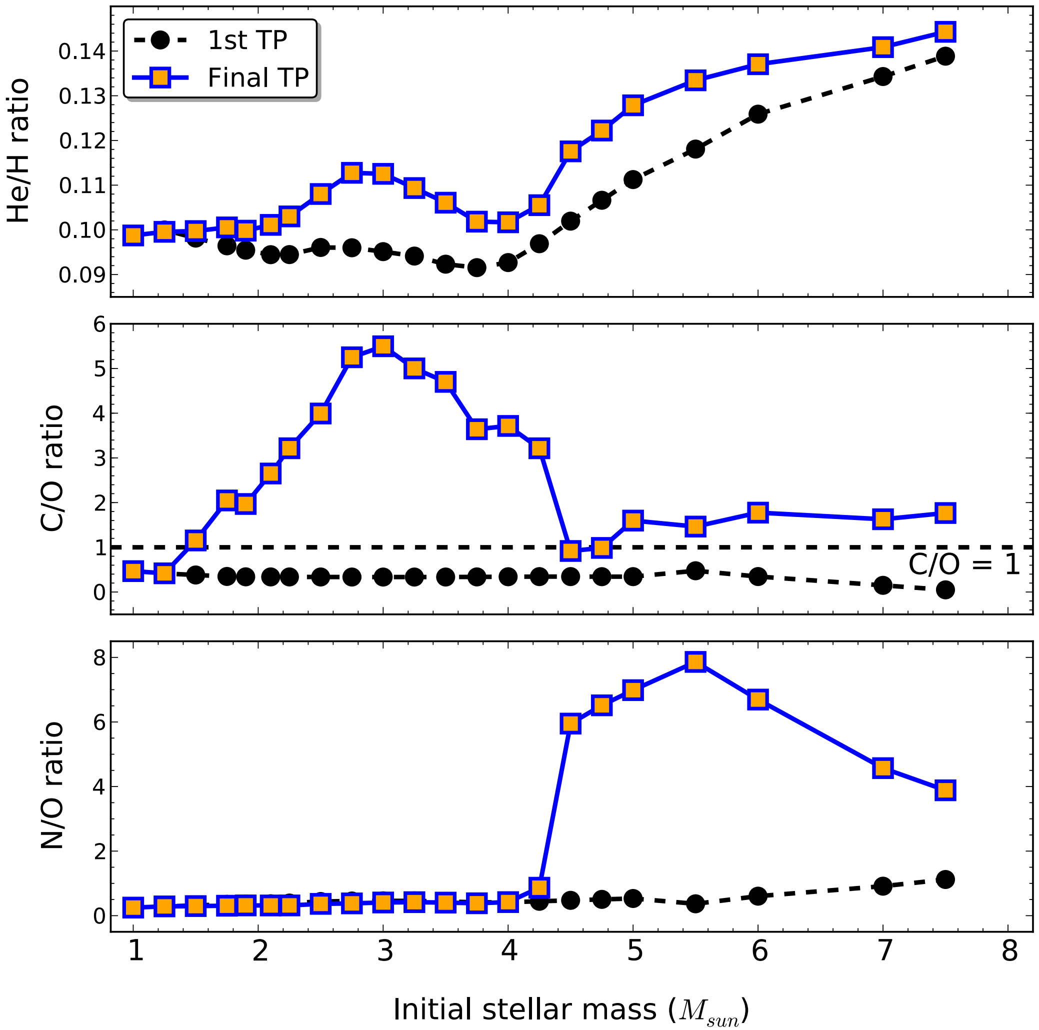


Results: Lower metallicity Z = 0.007 models

- We predict that all stars over 1.25Msun will eventually become C-rich
- Although the C-rich phase will be brief for models with hot bottom burning

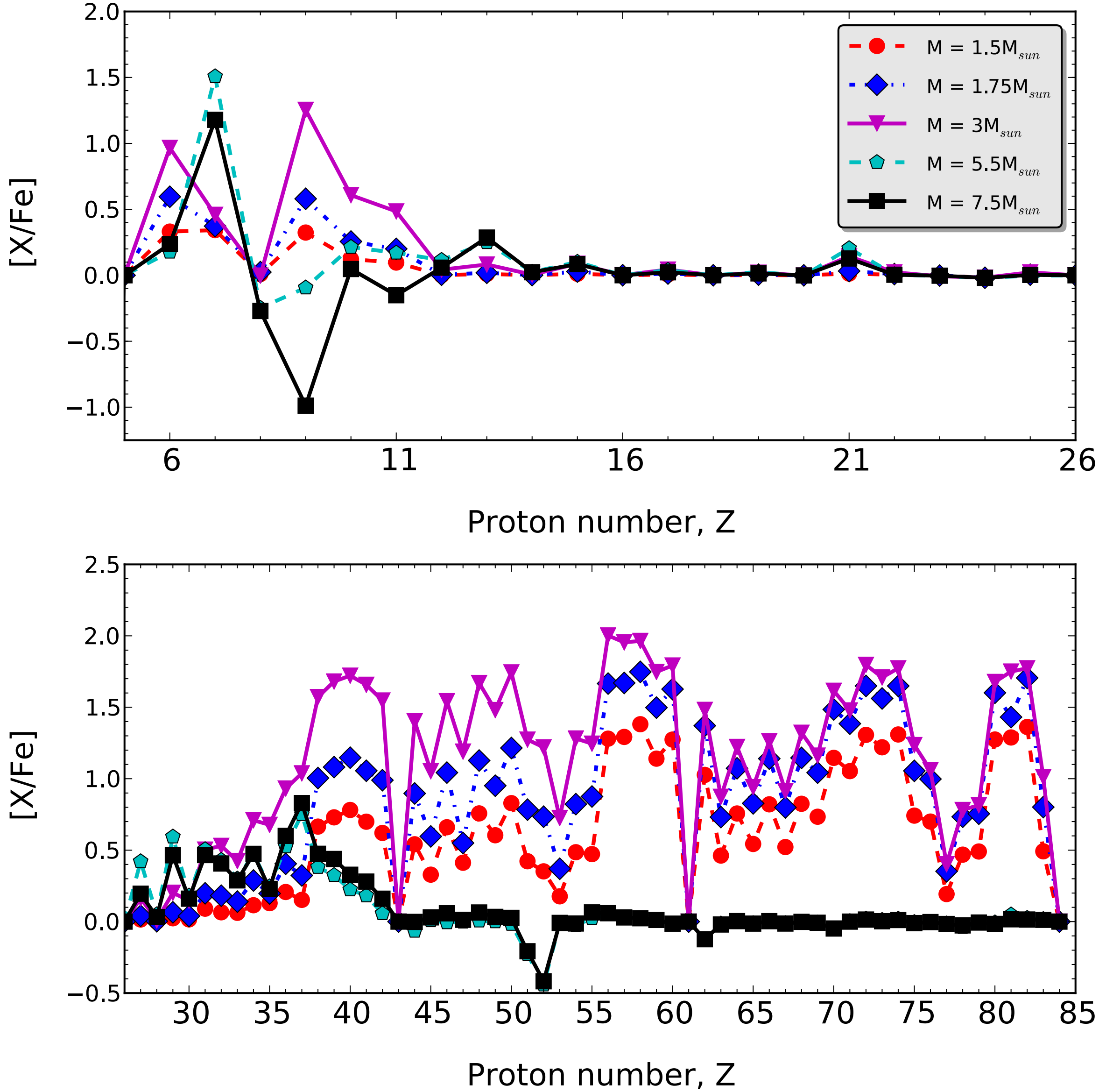
→ This is the metallicity of the Large Magellanic Clouds

→ There are many AGB stars and their progeny here for comparison, with known distances

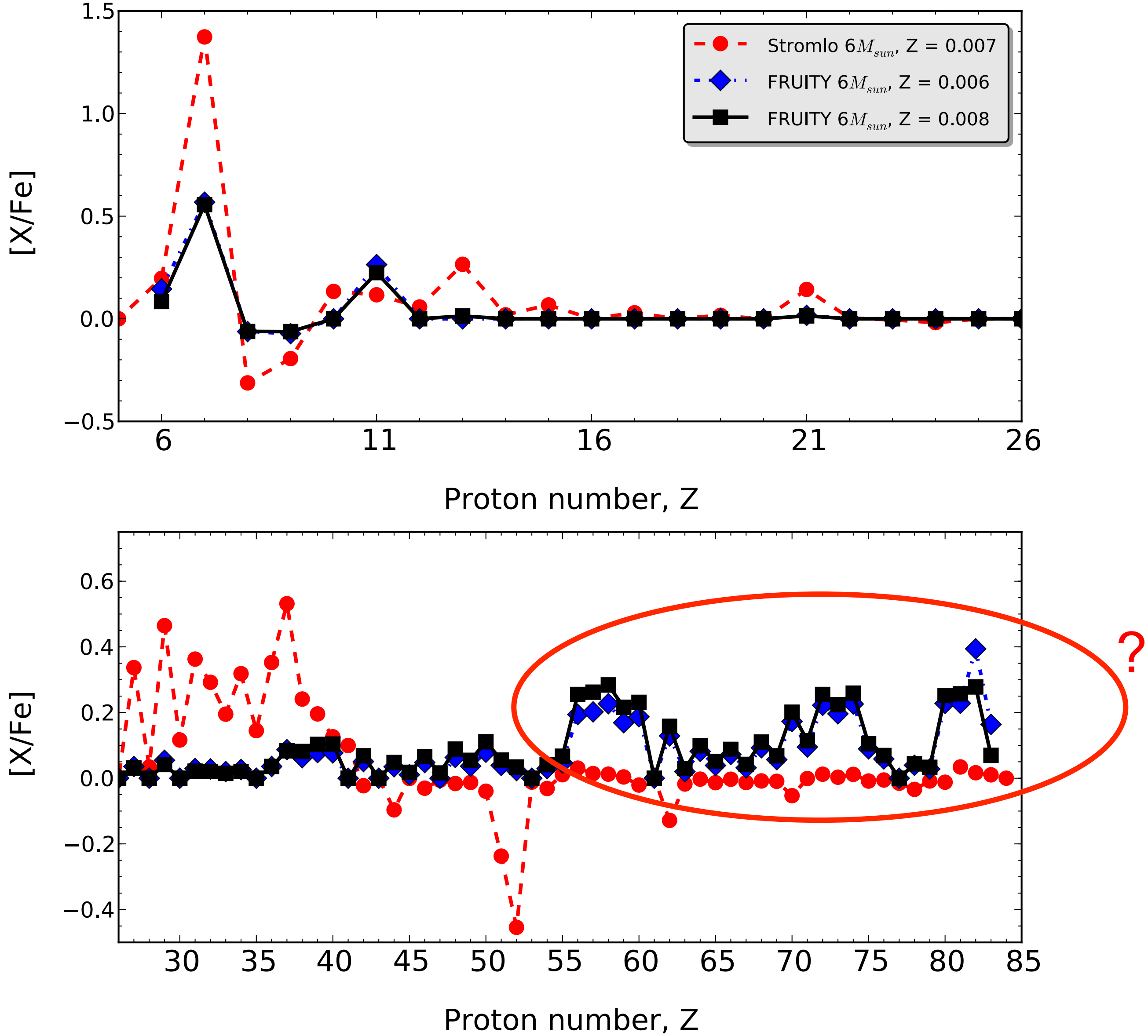


Results: LMC-metallicity models

Z = 0.007,
[Fe/H] = -0.3



Results: Comparison to FRUITY models

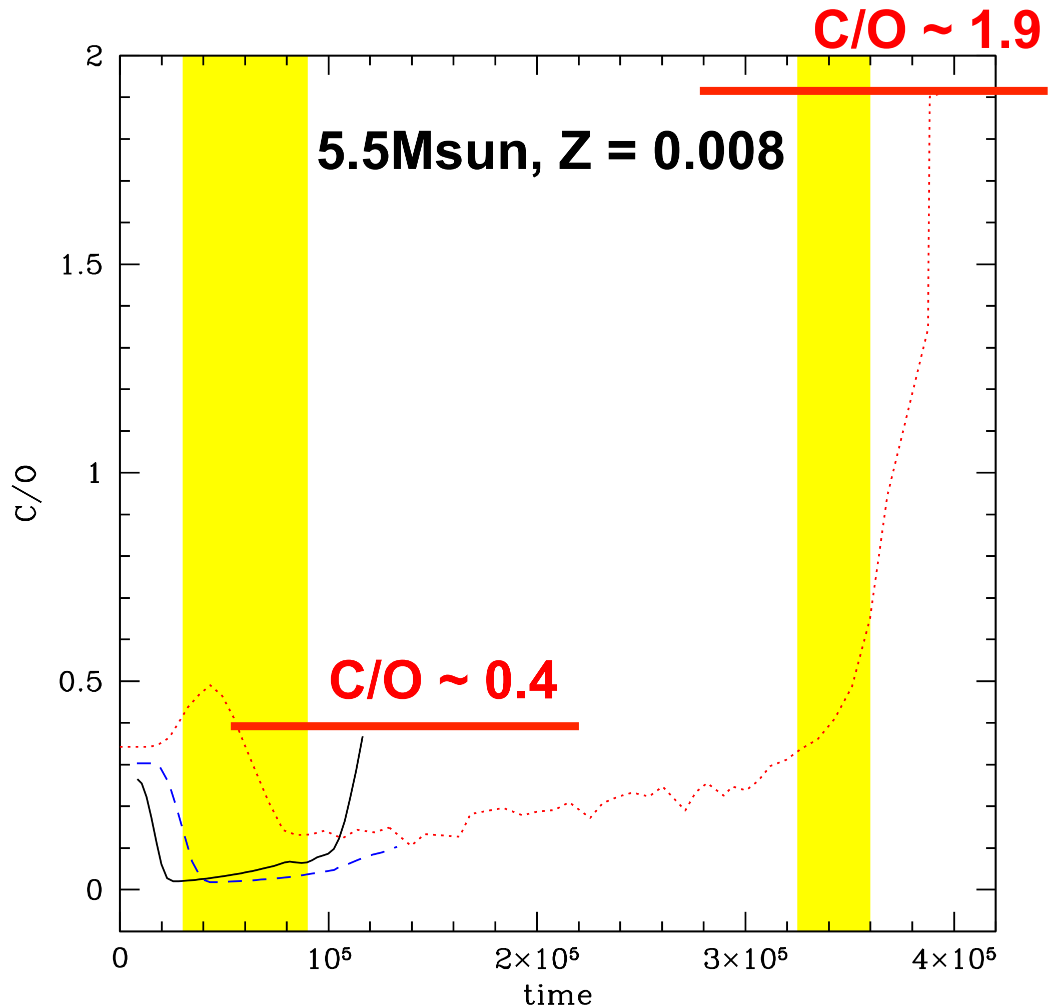


Uncertainties from convection

- Blue/Black lines: Ventura/ ATON models
- Red: Karakas models

Observations needed to constrain C/O in stars with HBB

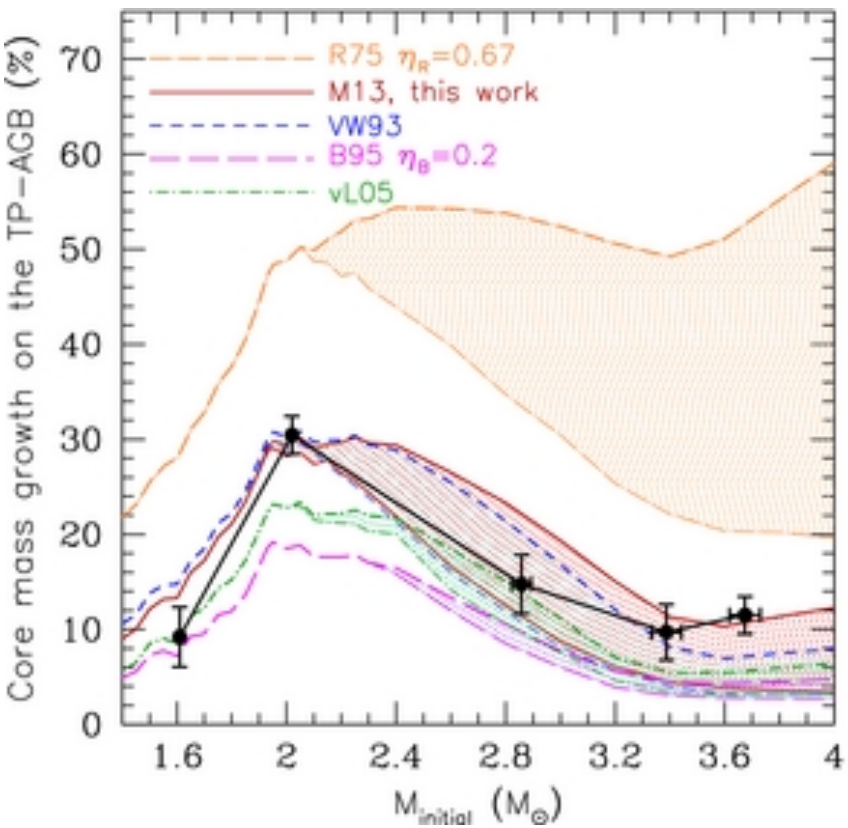
- Van Loon et al. (1999) show TDU occurs, agreeing with the Stromlo predictions
- But C/O ratios in McSaveney et al. (2007) are closer to Ventura's models

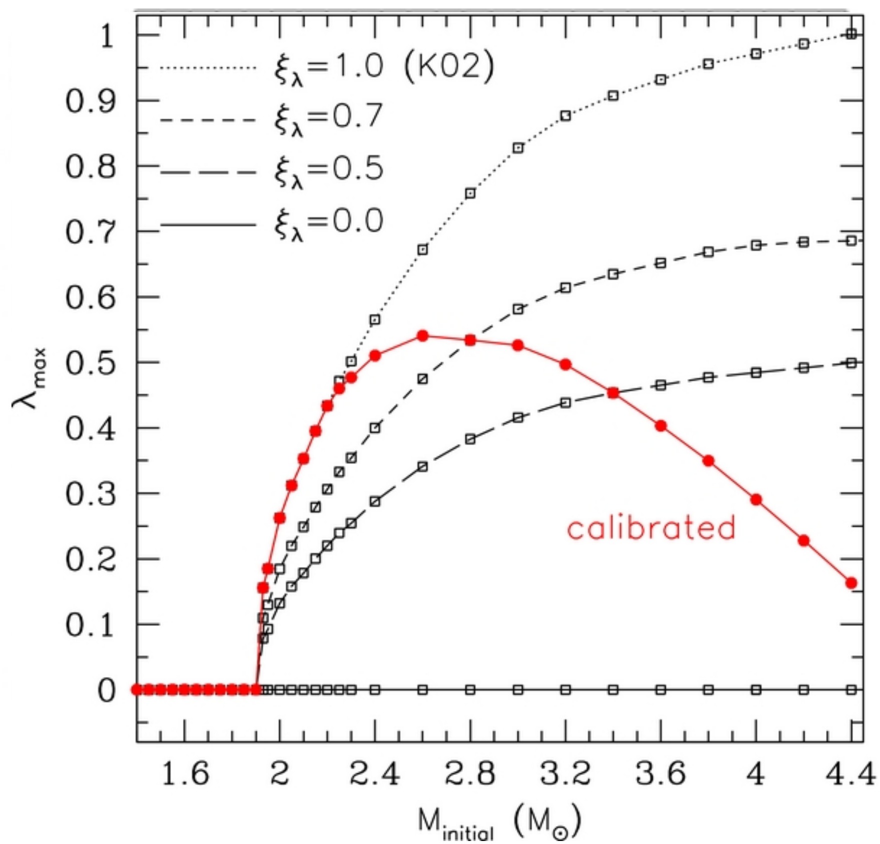


From Ventura et al. (2015)

Constraints on core mass growth

- Kalirai et al. (2014) used WDs in open clusters to try and constrain core mass growth in intermediate-mass AGB stars
- Including amount of third dredge-up and mass loss rates





Wish list

Intermediate-mass AGB models need the most improvement. Here is a short wishlist. More ideas welcome!

- *Observations of the most massive AGB stars (e.g. bright AGB stars in nearby galaxies with rich AGB populations, e.g. M31, MCs etc)*
- *Can we disentangle super-AGB from RSGs and normal AGB stars?*
- *Accurate mass-loss rates for the brightest AGB stars. Is using Vassiliadis & Wood 93 ok? What about in super-AGB stars?*
- *Can we use post-AGB stars to constrain intermediate-mass AGB stars? Probably not but useful for M < 4Msun*

Summary

- Helium enrichment will have as big an effect on the maximum mass for carbon burning as convective overshoot → important in some places
- We present new AGB nucleosynthesis models of AGB stars covering the full mass range for three metallicities
- We provide surface abundances for elements, isotopic ratios and yields for each (M, Z) combination
- Intermediate-mass AGB models between different groups show the largest discrepancy. We need to fix this. Implies issues with super-AGB models probably much much worse…