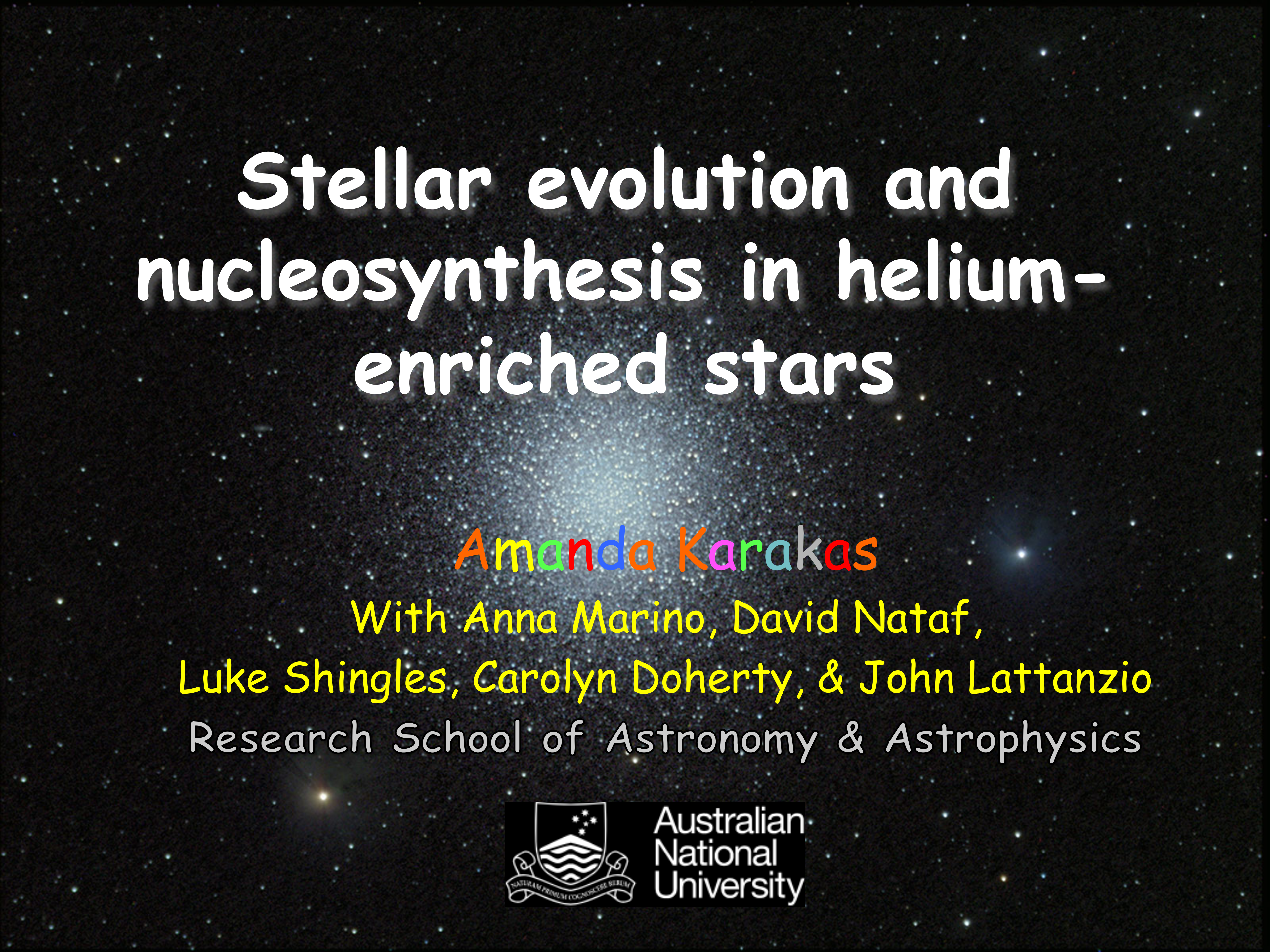

Stellar evolution and nucleosynthesis in helium-enriched stars

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Outline

1. The effect of helium enrichment on the evolution and nucleosynthesis of low-metallicity AGB models

2. The effect of helium enrichment on metal-rich AGB stars

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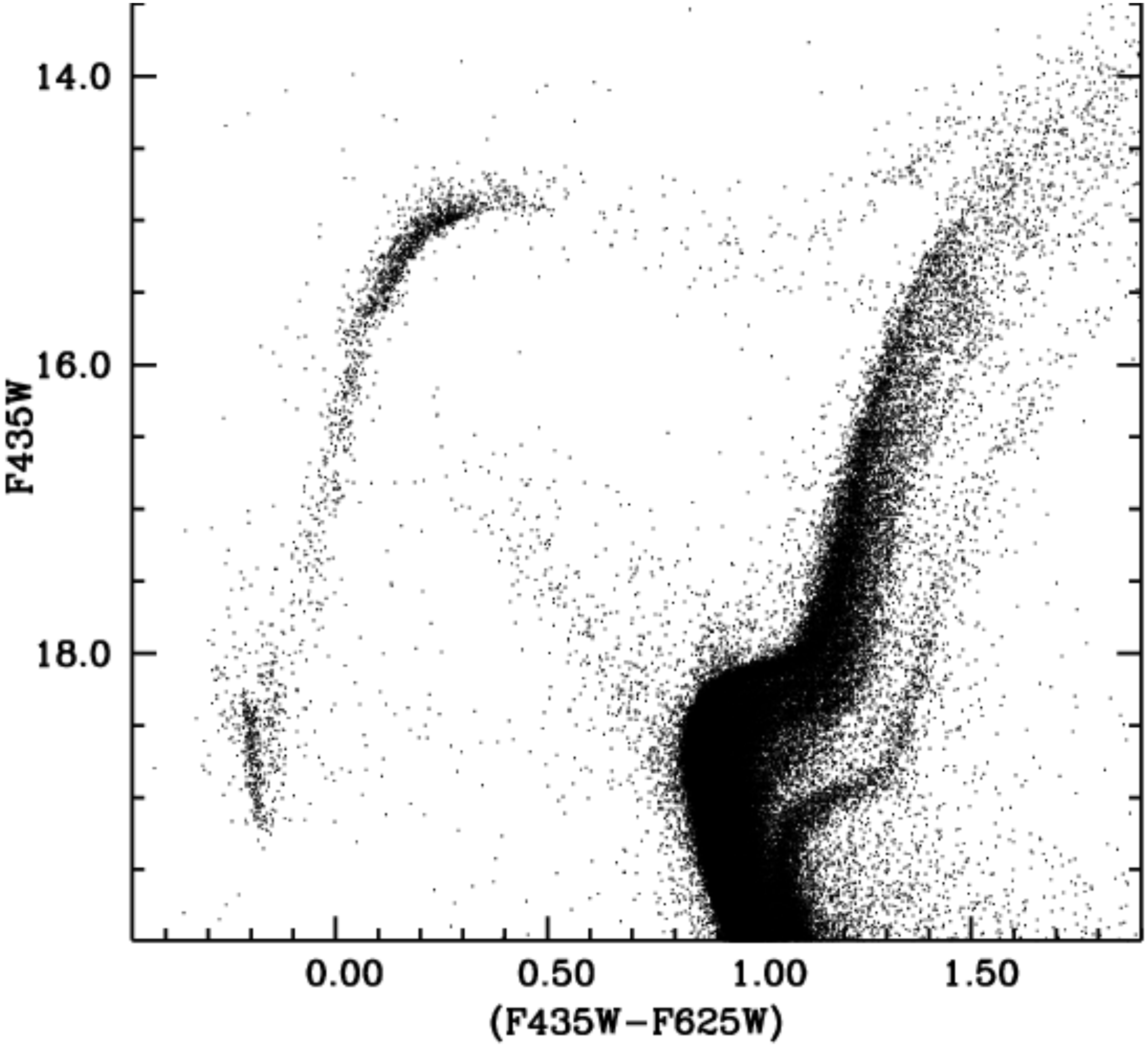
Introduction

- Hubble Space Telescope has revealed sub-populations within galactic globular clusters (e.g., ω Centauri, NGC 2808, M2, …)
- The cause? Variations in iron (Fe), helium (Y), and/or C, N, and O elements
- Some clusters show large variations in helium, from the primordial value of $Y \approx 0.24$ to values higher than 0.40 (i.e., $\Delta Y \sim 0.1$ or more; the solar value ~ 0.28)
- The origin of the multiple populations is unknown
- The origin of the helium is unknown (e.g., massive stars, asymptotic giant branch stars, massive binary stars…)

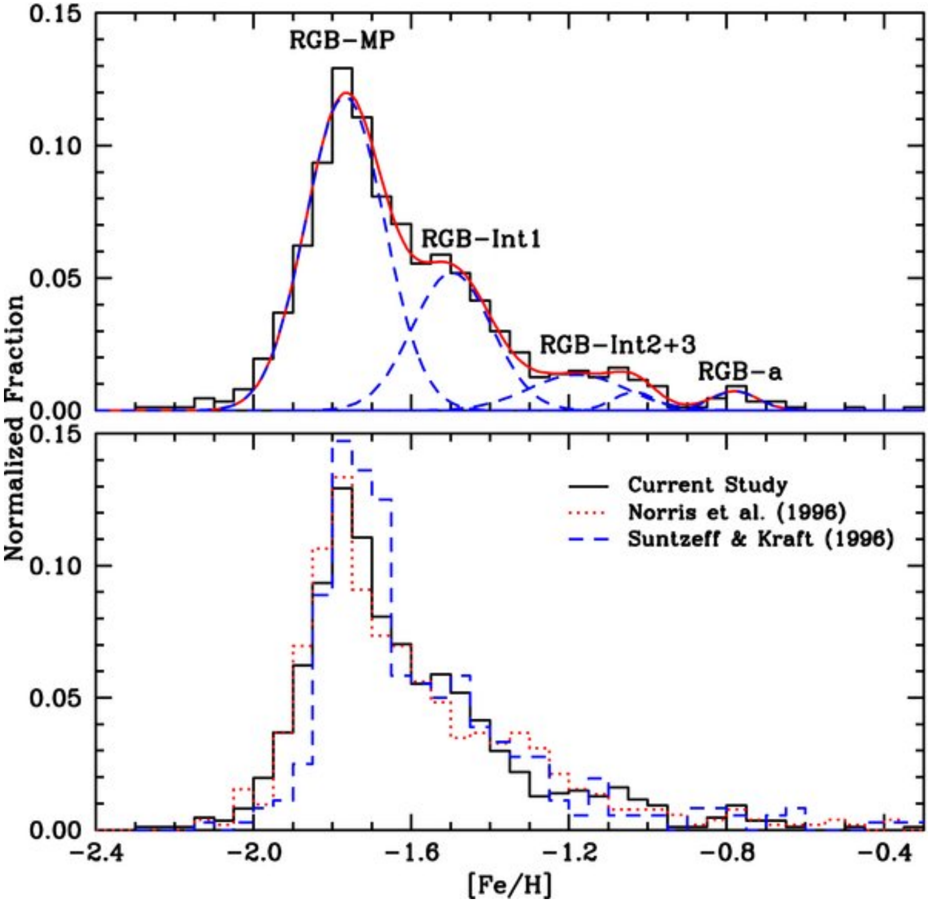
The beast: Omega Centauri

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

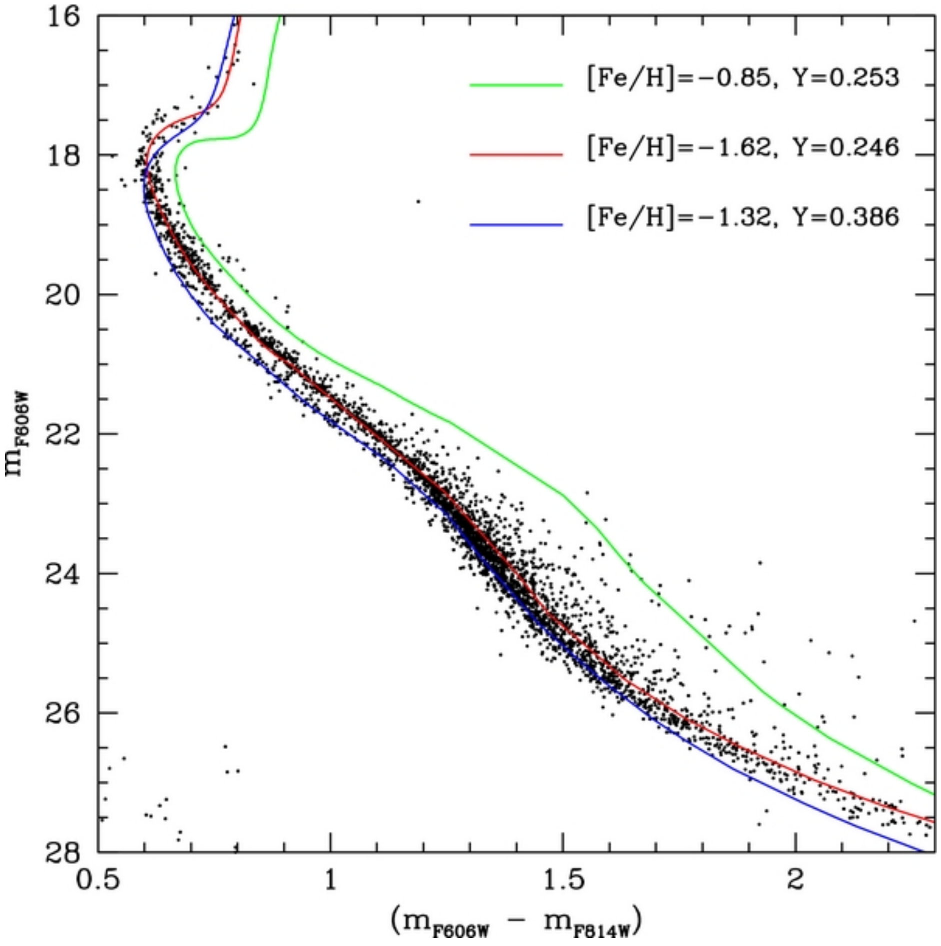


The most extreme example?

Metallicity distribution from Johnson & Pilachowski (2010)



Colour-magnitude diagram from King et al. (2012; also Piotto et al. 2005, Norris 2004, Bedin et al. 2004)



The puzzle of Omega Cen

Omega Cen and M22 show variations in Fe and elements that are produced by the slow neutron capture process (e.g., Norris & Da Costa 1995, Stanford et al. 2007, Da Costa & Marino 2011, Marino et al. 2011, 2012)

The abundances indicate the contribution from low-mass AGB stars (M ≤ 3Msun)
But there are some problems:

1. Low-mass stars evolve slowly
2. Isochrone fitting requires a formation timescale of ≤ 1 Gyr (D'Antona et al. 2011)
3. How did the plateau originate?

How to resolve these problems?

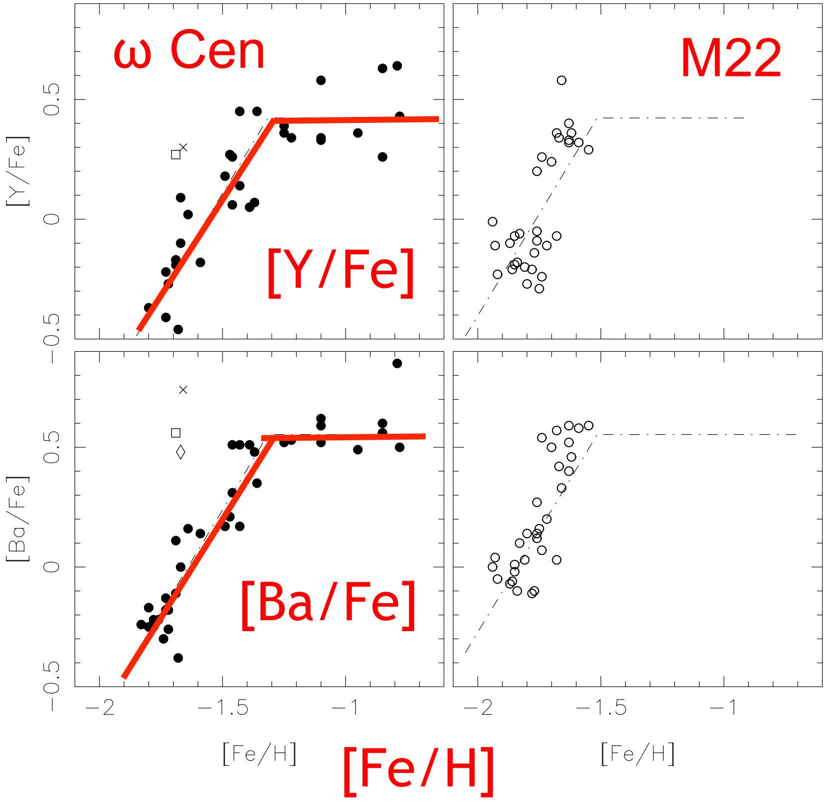
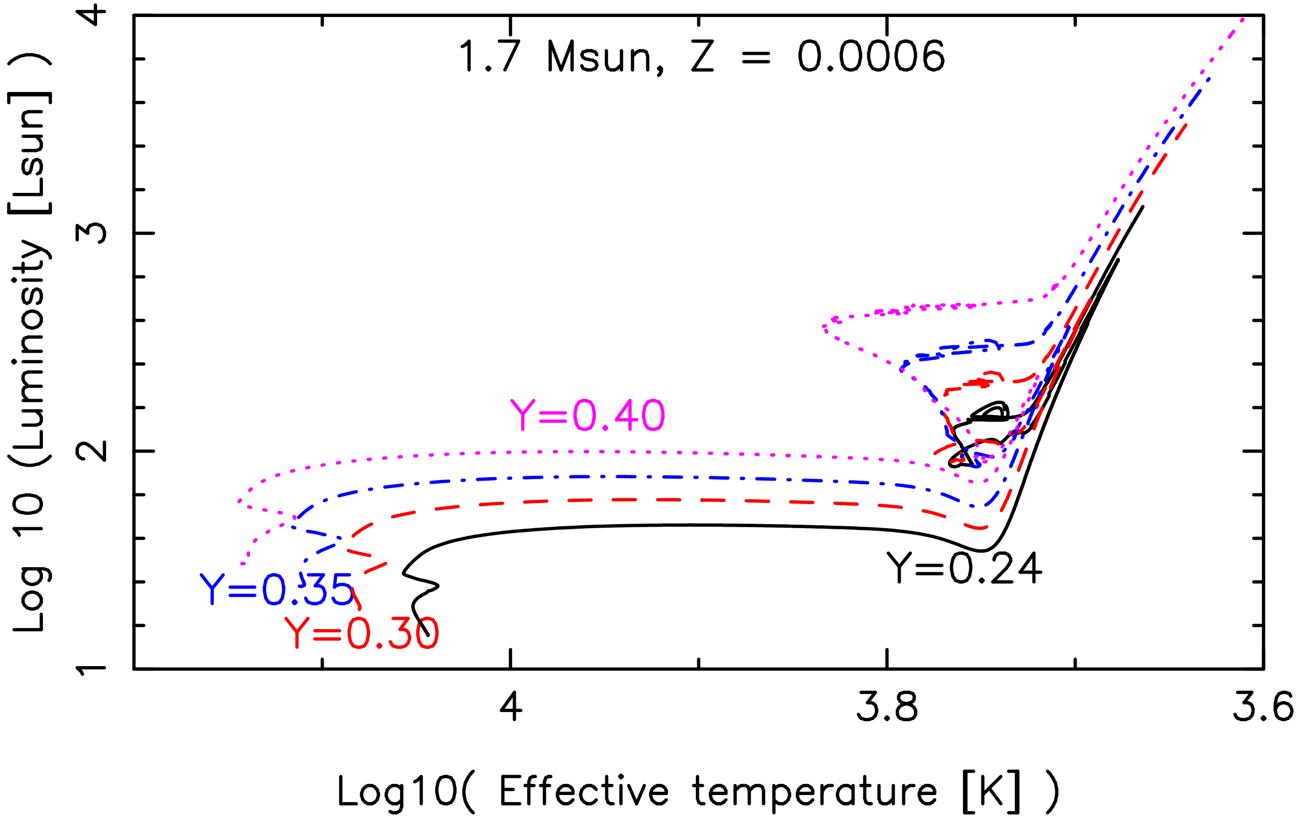


Figure from Gary Da Costa using data from Norris & Da Costa (1995)

Helium-enriched stellar models

- Few studies evolve the stars beyond core helium burning
- What happens to helium-enriched stars on the AGB?
- Evolve models of M = 1.7, 2.4M_{sun}, [Fe/H] = -1.4 with Y = 0.24, 0.30, 0.35, 0.40

From Karakas, Marino & Nataf (2014)



Helium-enriched stellar models

- Helium enrichment shortens the total stellar lifetime according to:

$$\tau_{stellar} \propto M^{-2.69} \times \exp[-5.43(Y-0.24)]$$

- That is, an increase of Y by 0.05 or in mass by 11% will decrease the stellar lifetime by 24%
- Helium-enriched AGB stars not only evolve more quickly than their helium normal counterparts but with bigger cores and hotter burning shells
- Helium-enriched AGB stars of ~2Msun ***will have time*** to contribute to the forming globular cluster

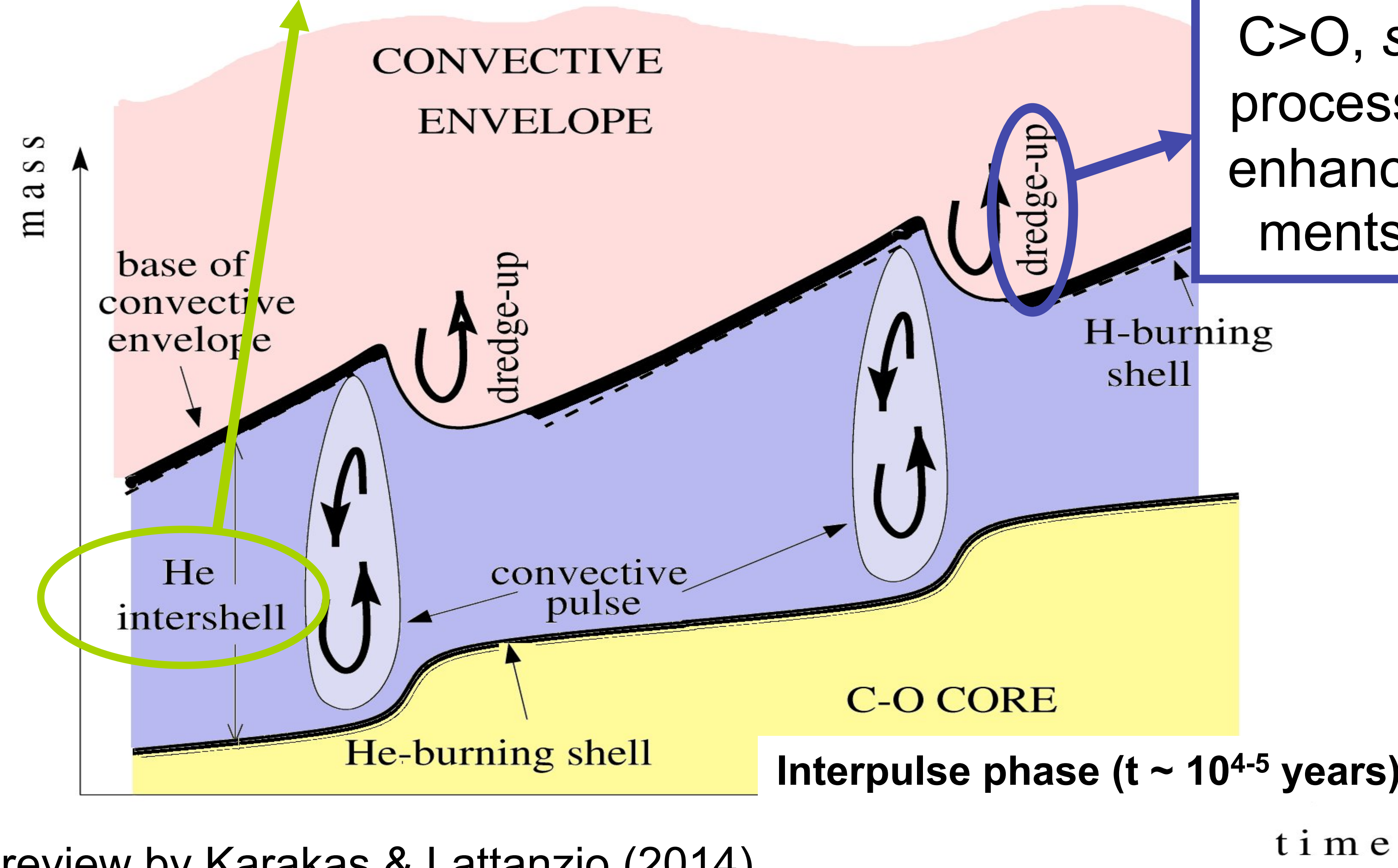
total stellar lifetime of 1.7Msun ~ 1.4 Gyr when Y = 0.24

whereas ~ 560 Myr when Y = 0.40!

Schematic AGB evolution

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

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



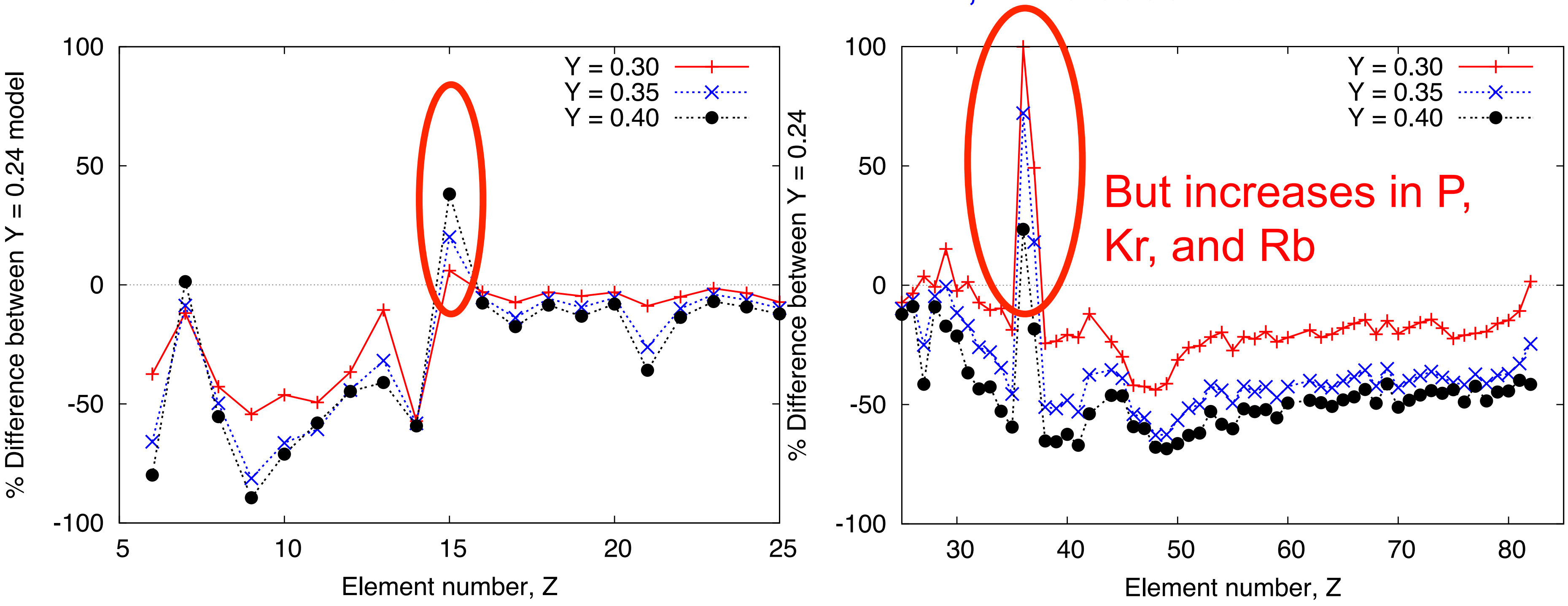
Interpulse phase (t ~ 10^{4-5} years)

See review by Karakas & Lattanzio (2014)

Chemical yields from helium-enriched models

- We find that the stellar yields of helium enriched models are significantly reduced relative to their primordial helium counterparts
- An increase of ΔY = 0.10 at a given mass decreases the yields of C by up ~60%, of F by up to 80%, and decreases the yields of the s-process elements Ba and La by ~45%

Results shown for the M = 2.4Msun, Z = 0.0006 models



But increases in P, Kr, and Rb

From Karakas, Marino & Nataf (2014)

Intermediate-mass AGB stars

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

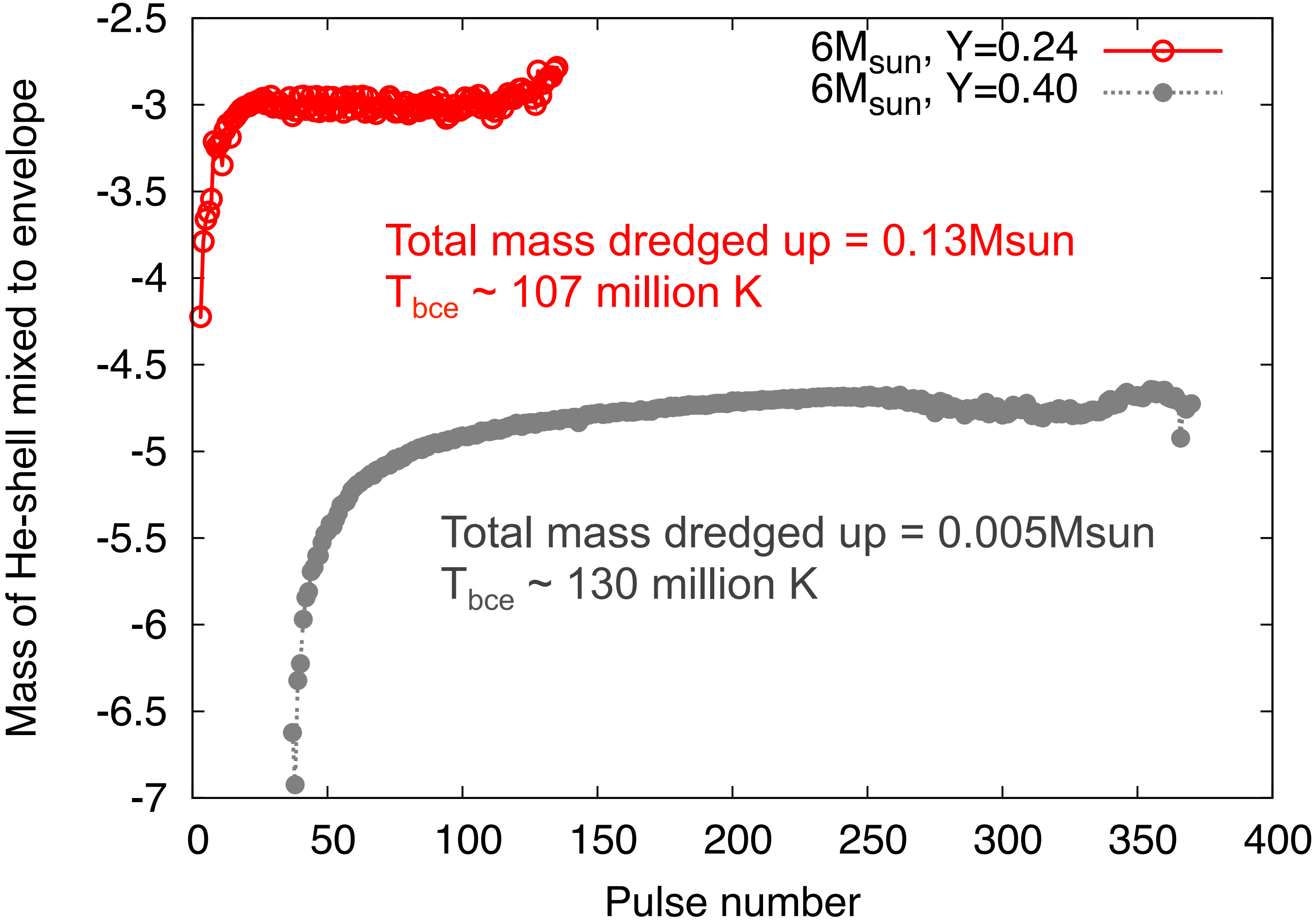
- Second dredge-up: Largest change in ΔY (up to 0.1)
- Hot bottom burning: Proton-capture nucleosynthesis at base of envelope (products: N, Na, Al)

See review by Karakas & Lattanzio (2014)

Helium-rich intermediate-mass models

- M = 3 to 6 M_{sun}, [Fe/H] = -1.4 with Y = 0.24, 0.30, 0.35, 0.40

Shingles, et al. (2014, in preparation)



Total mass dredged up = 0.13Msun
T_{bce} ~ 107 million K

Total mass dredged up = 0.005Msun
T_{bce} ~ 130 million K

Results: The predicted yields of helium

	Y in Ejecta			
Mass:	**1.7**	**2.36**	**3.0**	**6.0**
Y=0.24	0.29	0.30	0.28	0.36
Y=0.3	0.34	0.33	0.33	0.41
Y=0.35	0.37	0.37	0.40	0.45
Y=0.4	0.41	0.43	0.47	0.50

- One barrier to AGB stars producing the multiple-populations in GCs is the helium limit of $Y \leq 0.38$
- Whereas helium enrichments of up to $Y \sim 0.40$ have been inferred for some systems
- We see a small increase in the initial Y of 0.06 leads to a final $Y = 0.41$ in the most massive AGB model

Shingles, L., et al. (2014, in preparation)

Discussion

- We find:
  1) low-mass AGB models with enhanced helium will evolve more than twice as fast, giving them the chance to contribute sooner to the chemical evolution of the forming globular clusters, and
  2) Dredge-up much less material from the He-shell, hence
  3) the stellar yields will be strongly reduced relative to their primordial helium counterparts.

Globular clusters are not the only systems that show strong helium enrichment (e.g., Galactic bulge, elliptical galaxies as a solution to the UV upturn?)

Outline

1. The effect of helium enrichment on the evolution and nucleosynthesis of low-metallicity AGB models

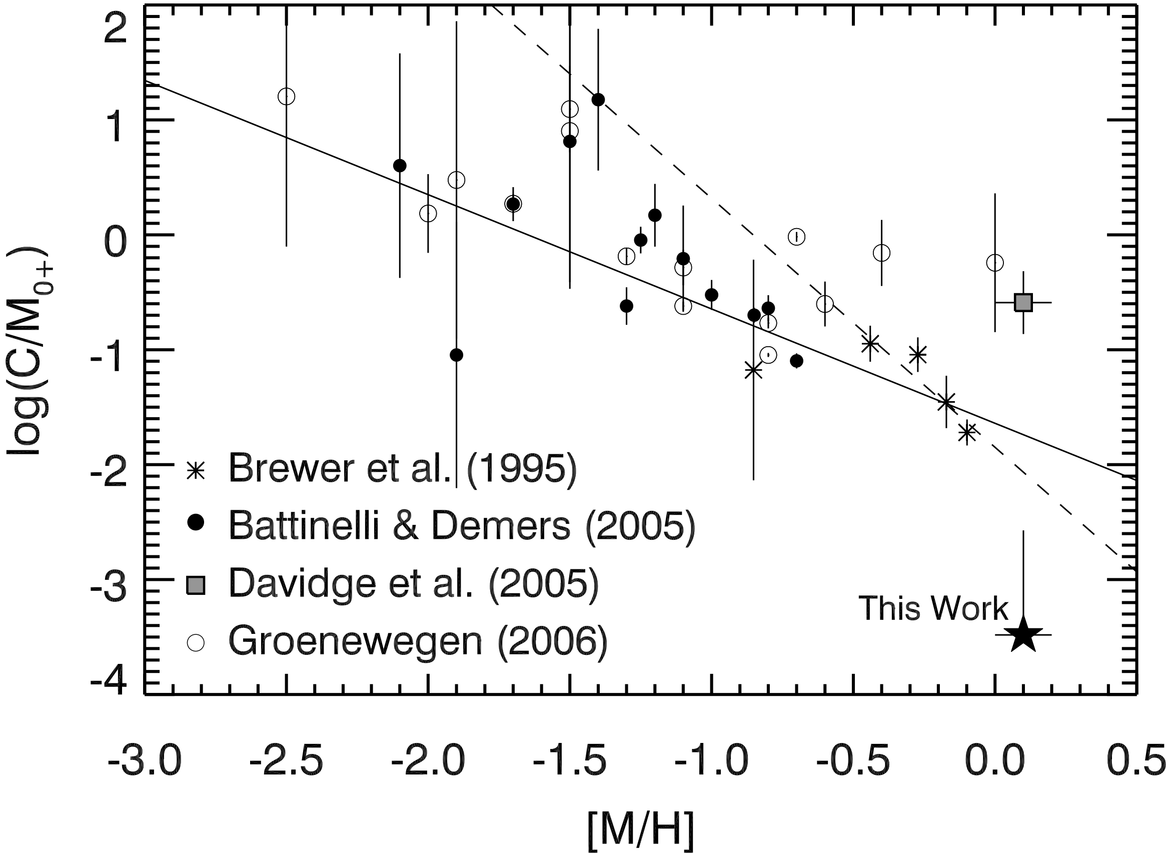
2. The effect of helium enrichment on metal-rich AGB stars

Motivation: The Andromeda Galaxy (M31)

- There are also few carbon stars in the inner region, metal-rich region of M31 (Boyer et al. 2013)
- This has been interpreted as evidence for a metal-rich ceiling to C-star production
- …but [Fe/H] ≈ +0.10 – this is not so high!
- What if helium instead is removing the carbon stars?
- There is evidence of large helium enrichments in the bulge of our Galaxy (Nataf & Gould 2012)

Carbon stars in external galaxies

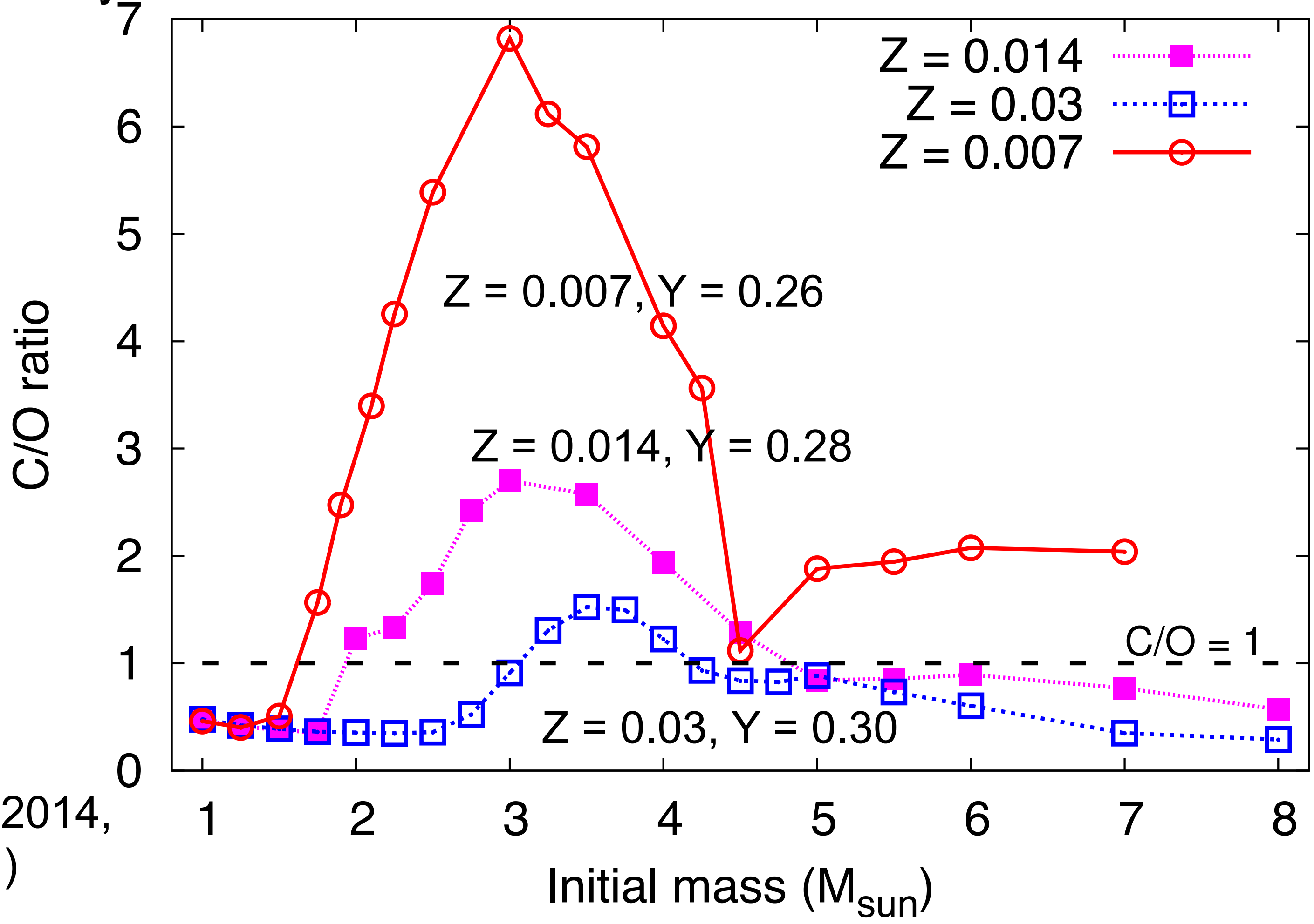
The C/M ratio from Boyer et al. (2013) for five regions of M31 using data from Brewer et al. (1995), as well as nearby galaxies (e.g.,Davidge et al. 2005, Battinelli & Demers 2005, Groenewegen et al. 2006)
The solid line is a fit through all data points, whereas the dashed line is a fit through the Brewer et al. (1995) data only.



Note that the metallicities are not derived directly but estimated from estimates of the metallicity gradient across the disk or bulge

Metal-rich stellar models

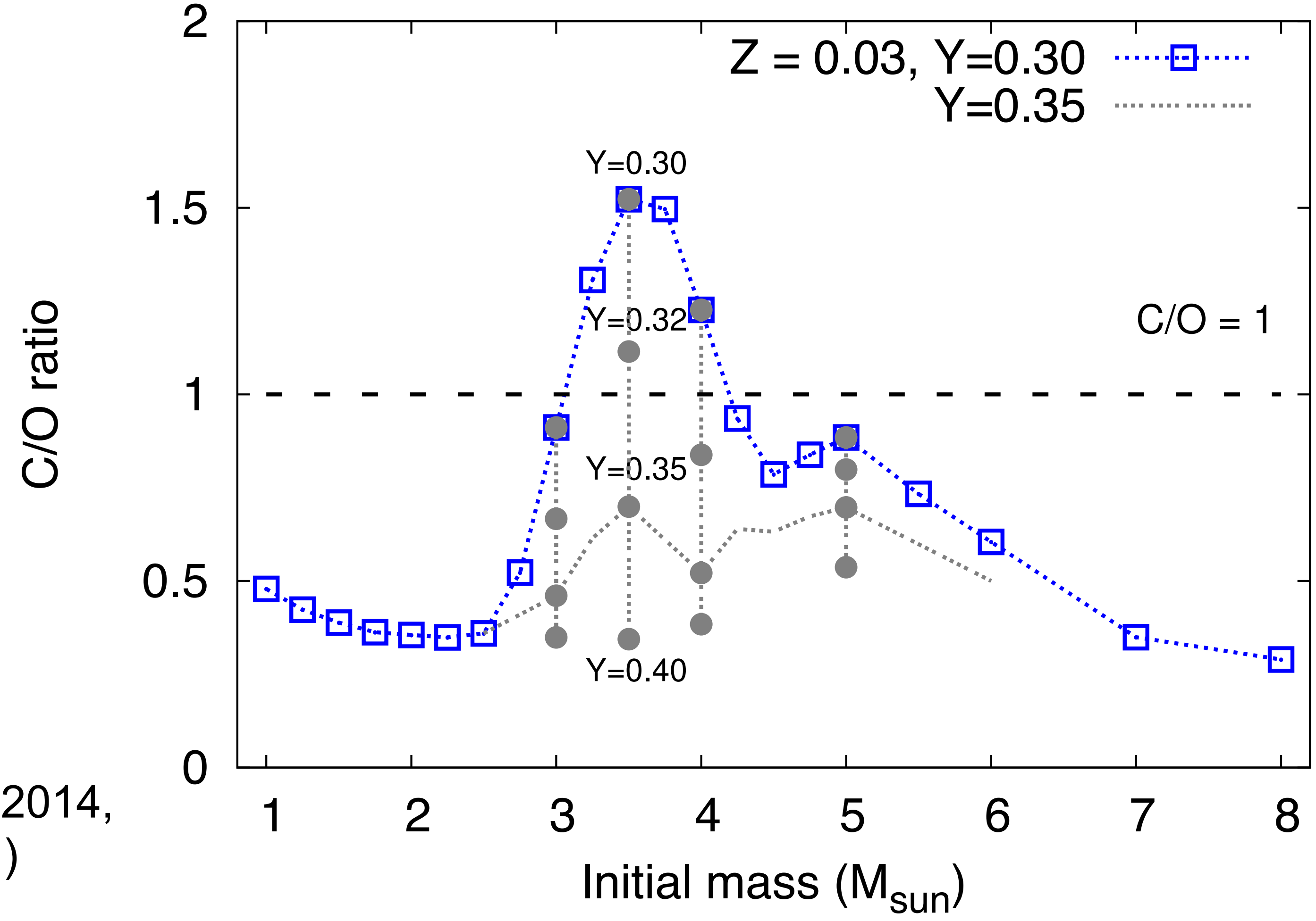
- Boyer et al. (2013) used the Colibri code (Marigo et al. 2013) for interpretation. The metal-rich models are based on extrapolations of solar metallicity detailed AGB models



Karakas (2014, submitted)

Helium-rich metal-rich stellar models

- At Z = 0.03, an increase of ΔY = 0.05 removes carbon stars from the population!



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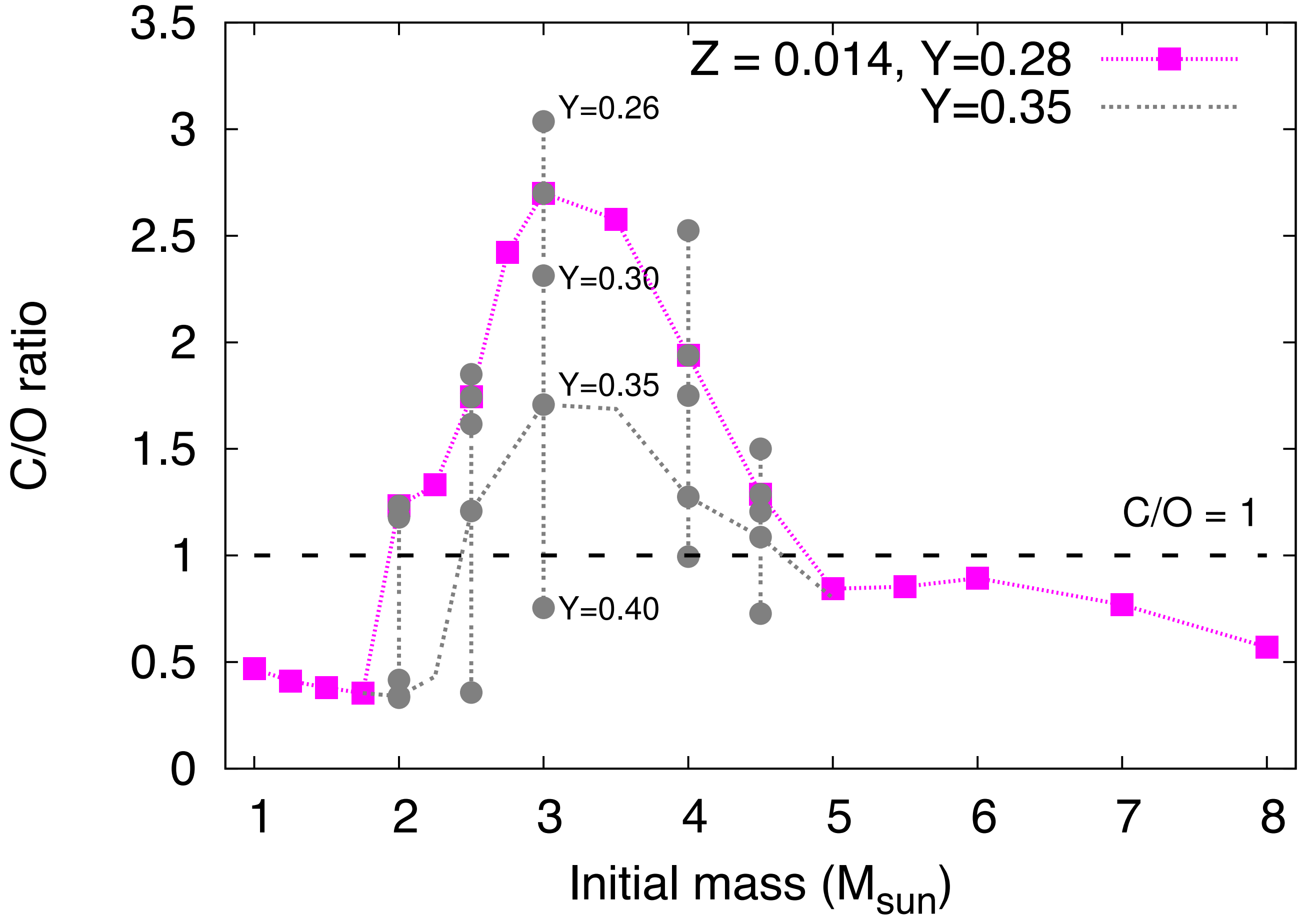
Helium-rich metal-rich stellar models

- At solar metallicity, an increase of ΔY ≥ 0.10 is needed to remove carbon stars from the population
- These results are dependent on uncertain physics such as mass loss and convection



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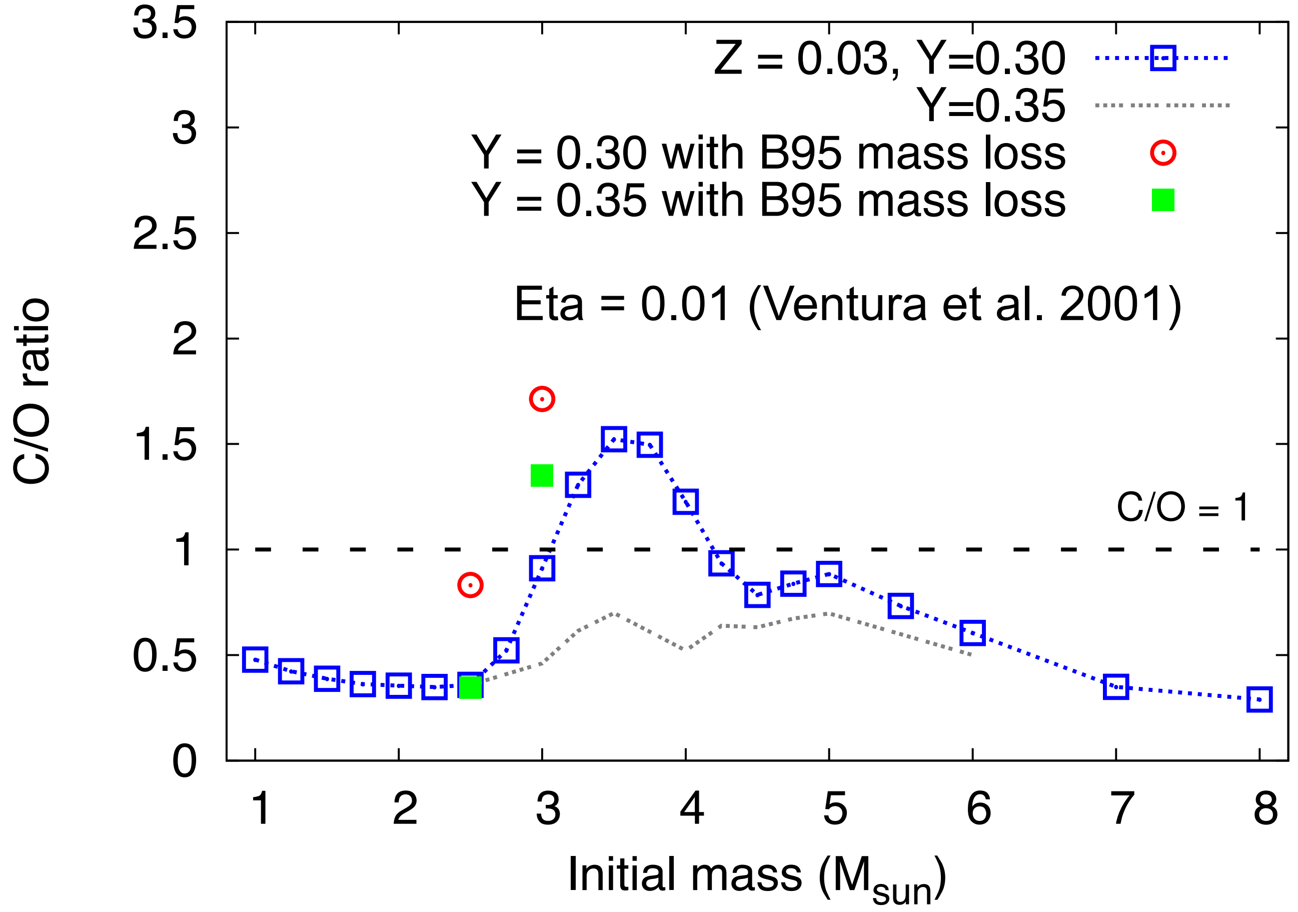
Effect of uncertainties

- Slower mass loss increases the number of TPs → increases the final C/O ratio and lowers the minimum mass for C-star production
- Similar to the effect of overshoot/convective boundary mixing



Karakas (2014, submitted)

Discussion

It may be possible to take the ratio of C/M stars observed in e.g., M31 by Boyer et al. (2013) and infer the level of helium enrichment in the inner regions of galaxies, if the metallicity is well determined

Overall conclusion:

Helium is an important third parameter for stellar nucleosynthesis and yields