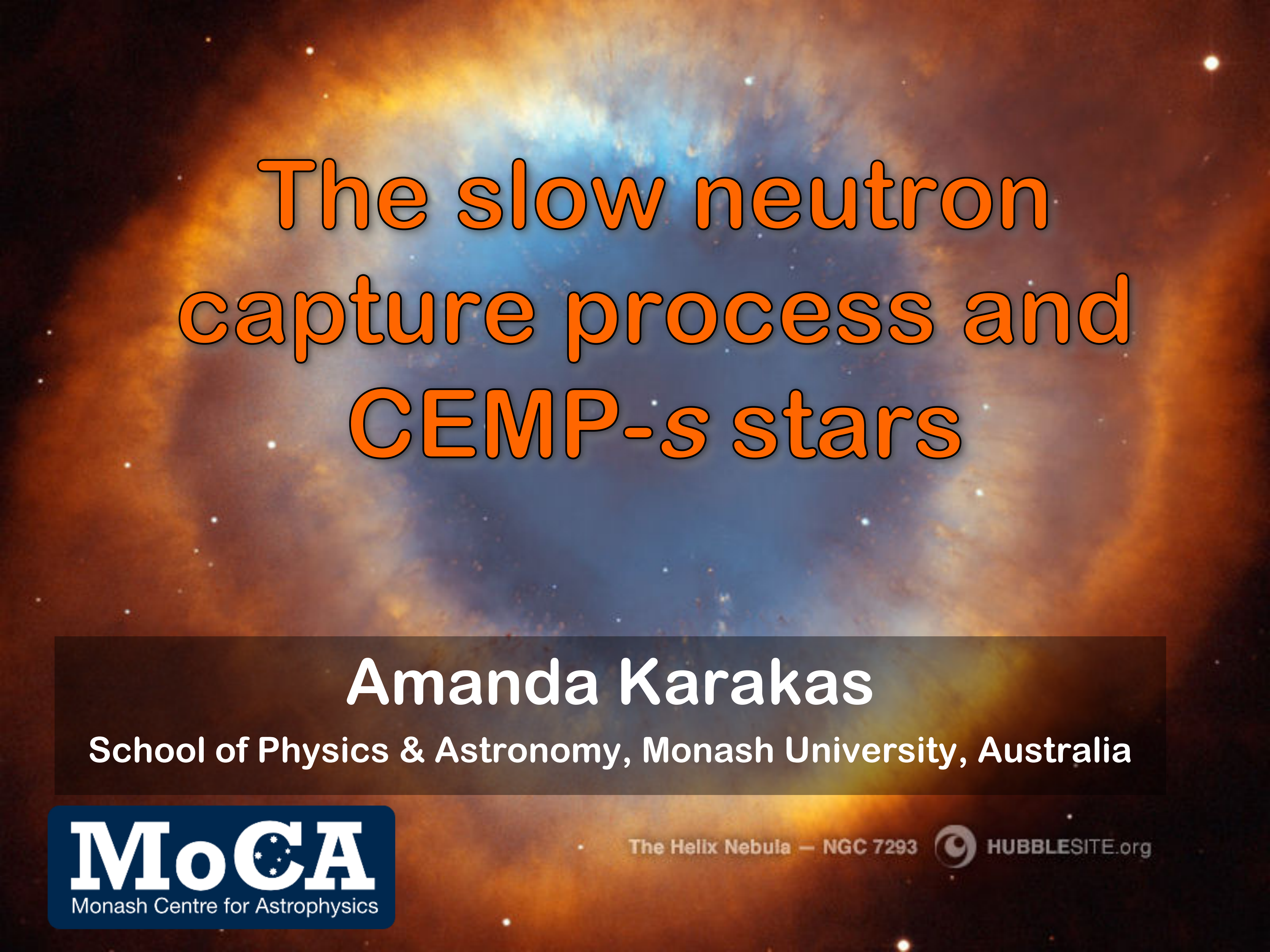

The slow neutron capture process and CEMP-*s* stars

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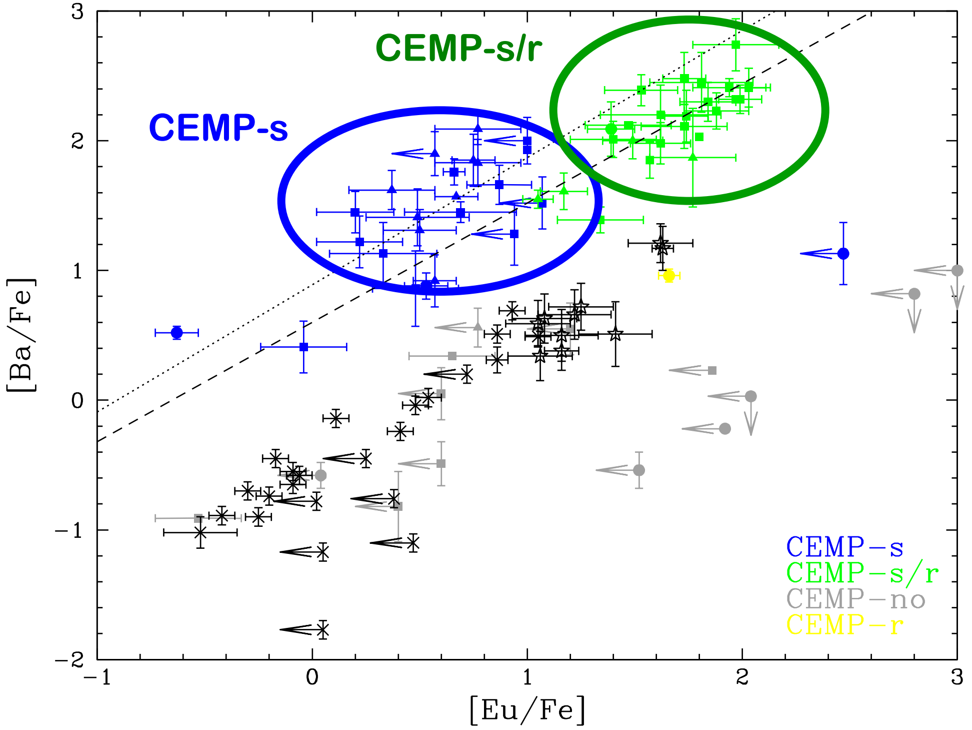
The Helix Nebula — NGC 7293 HUBBLESITE.org

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), with CEMP-s defined in Beers & Christlieb (2005)



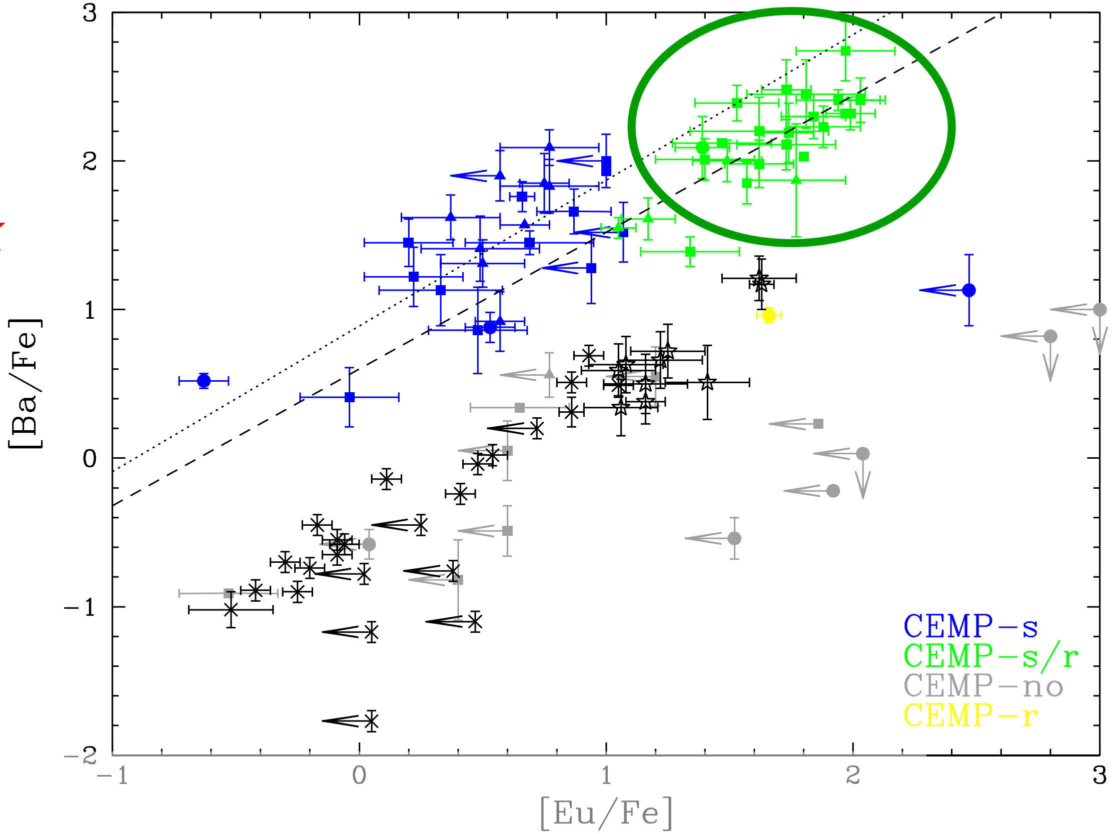
Using the data and classification of Masseron et al. (2010)

The puzzle of the CEMP-s/r stars

- About 50% of CEMP stars with an s-process signature also show an enrichment in r-process elements

→ *See Melanie Hampel's talk*

CEMP-s/r

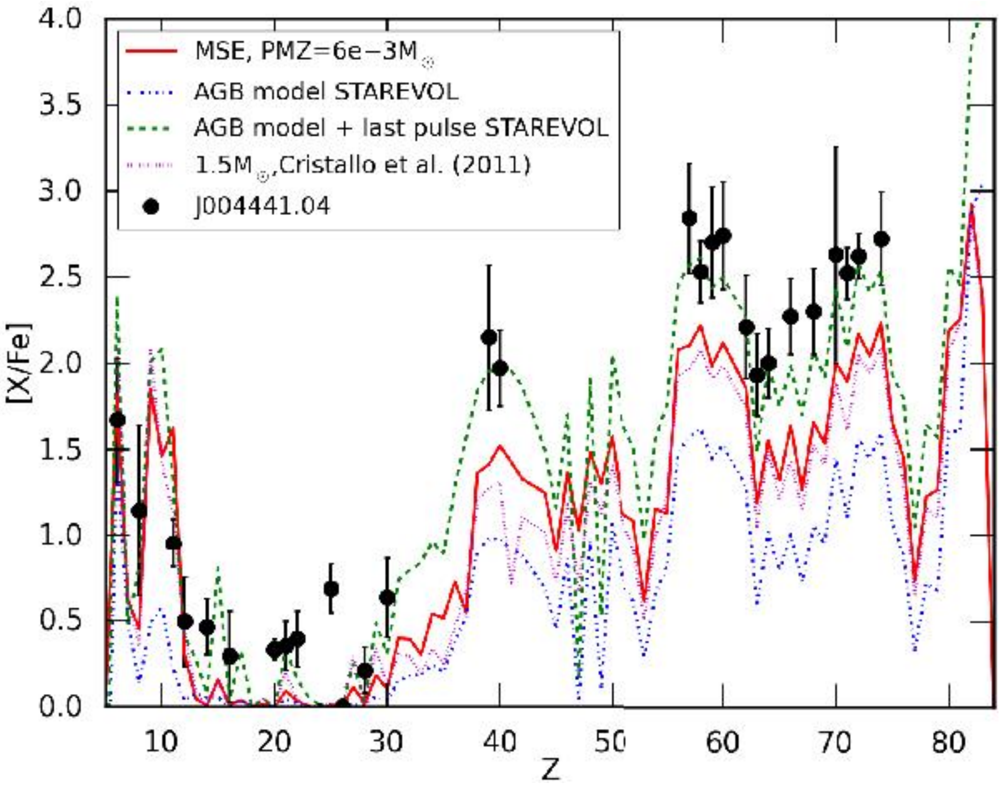


Definition of CEMP s/r:

- [Eu/Fe] > 1
- [Ba/Eu] > 0 but lower than for CEMP-s
- Appear distinct from CEMP-s (e.g., talks by Beers, Aoki etc)

The “other” CEMP-s stars

- In the Small and Large Magellanic Cloud, a population of very s-process enriched post-AGB stars have been discovered
- These are also metal-poor ([Fe/H] < -1) and carbon-rich

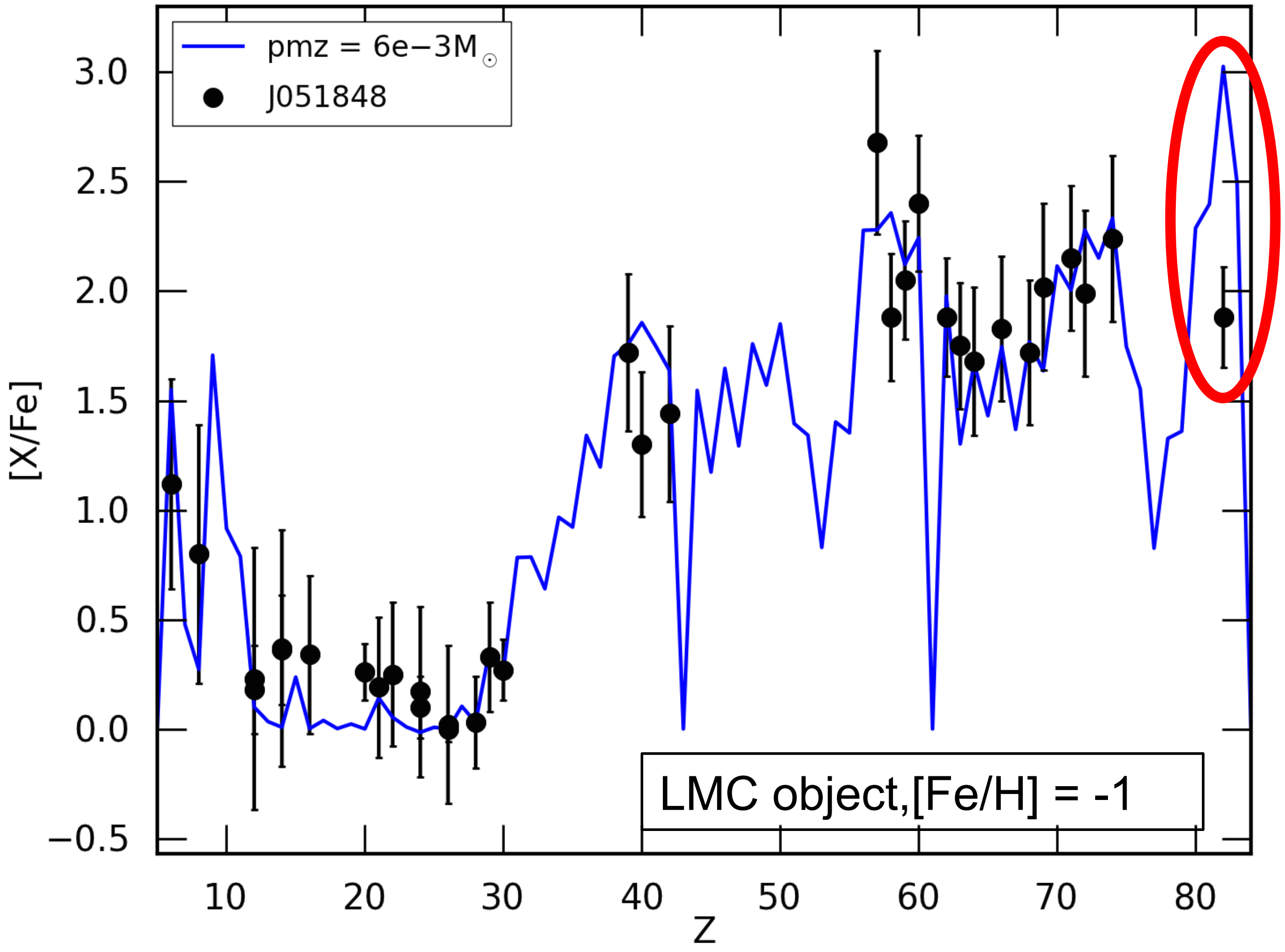


The abundance pattern of the post-AGB star J004441.04 ([Fe/H] = -1.4) in comparison with model predictions from various groups

From De Smedt et al. (2012)

The “other” CEMP-s stars

- Evolved from stars of low-mass of ~1.3Msun with [Fe/H] ≲ -1 (De Smedt et al. 2012, 2014, 2016; van Aarle et al. 2013)



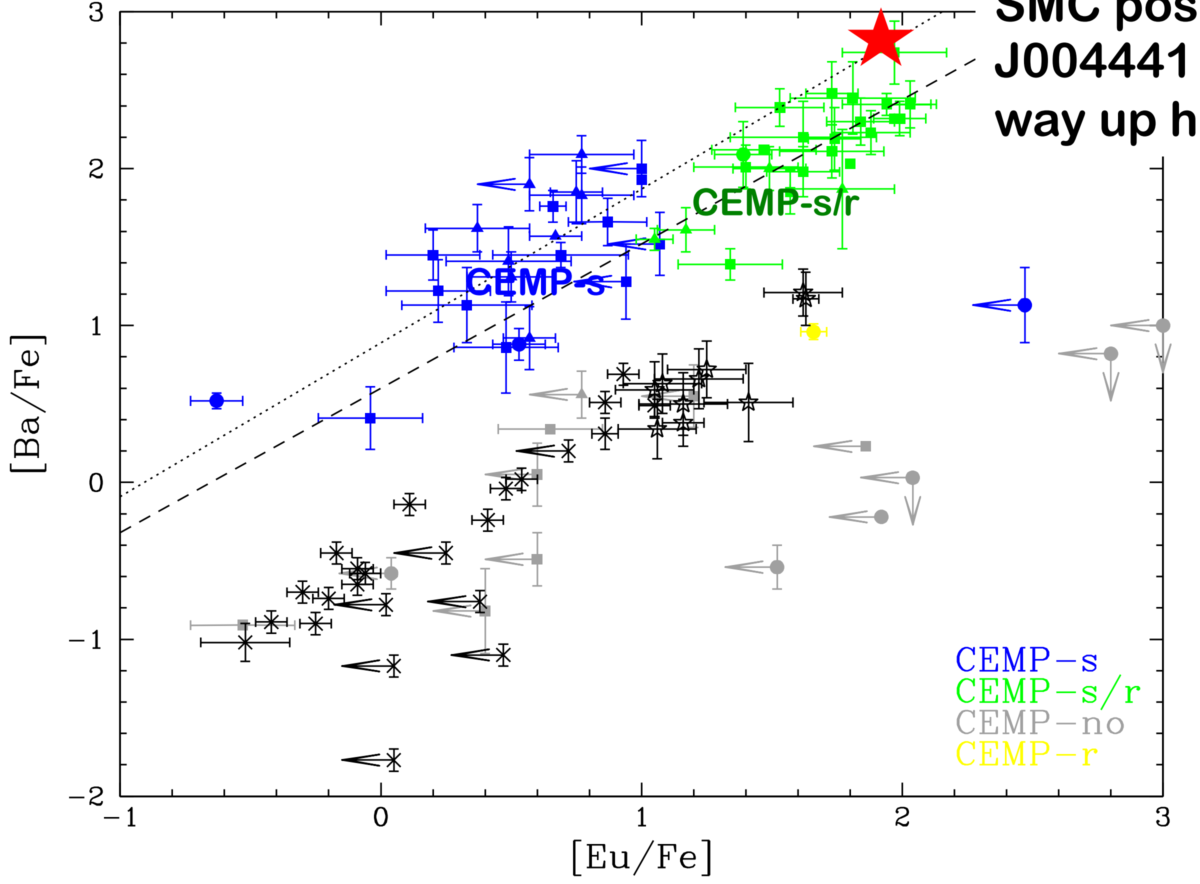
Puzzles:

- Low Pb is found in **ALL** stars with [Fe/H] < -0.7
- Can the low Pb be explained by variations in ^{13}C pocket sizes? (e.g., Trippella et al. 2016)
- Or is it an “i-process” (Lugaro et al. 2015)

Figure from Kenneth De Smedt

CEMP post-AGB stars

- Where are they on the Ba/La-Eu diagram?



SMC post-AGB J004441 sits all the way up here!!

[C/Fe] = 1.67,
[O/Fe] = 1.14 (!),
[Mg/Fe] = 1.16 (!),
[La/Fe] = 2.84,
[Eu/Fe] = 1.93,
[W/Fe] = 2.72 …

This is a self-enriched star…

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

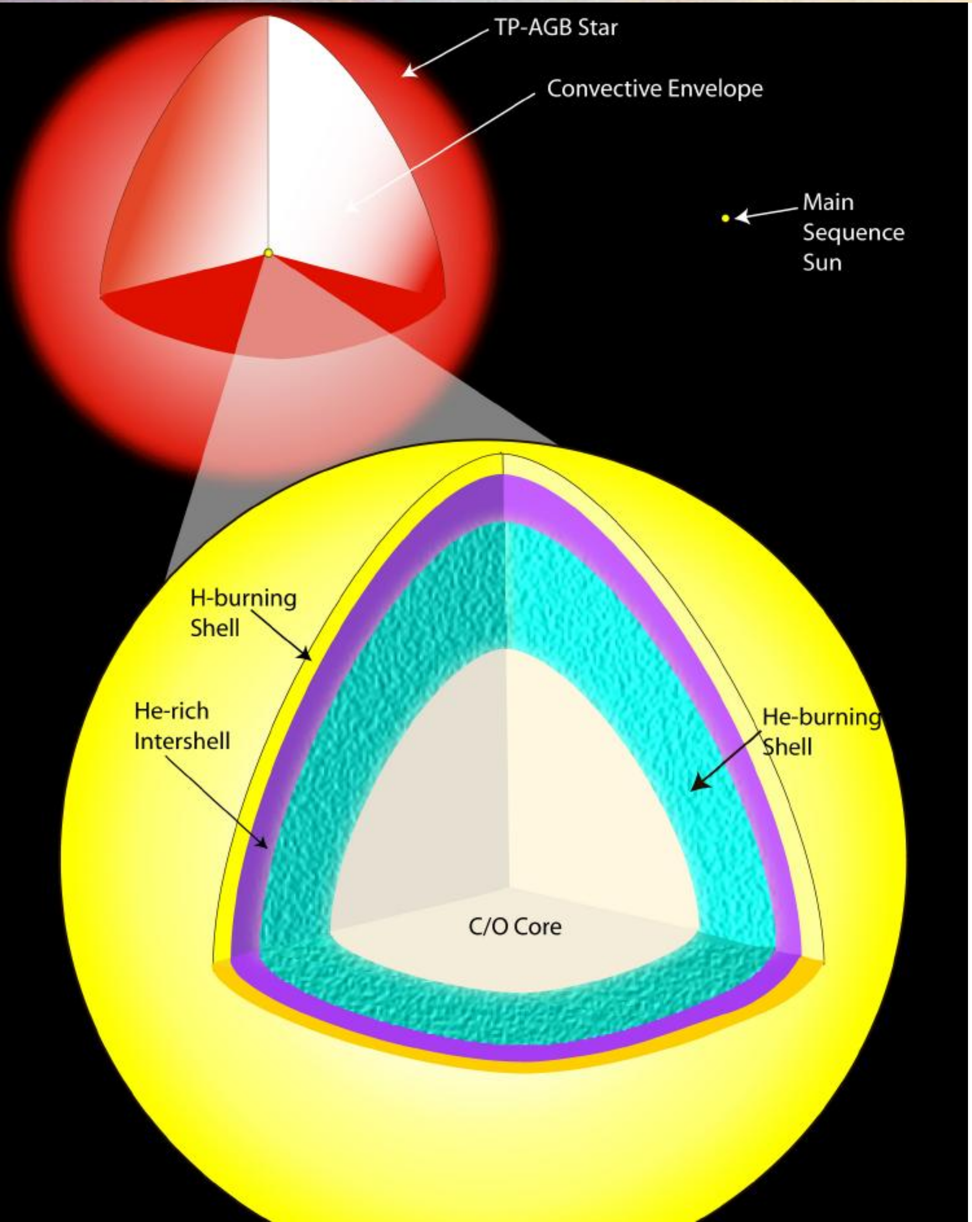
Where is the s-process made?

- When neutrons are released in the He-burning shell via (α,n) reactions. Where?
- Any star (it seems) where proton ingestions occur in a He-burning region
- This includes:

1. AGB stars
2. RGB stars undergoing core He-flash (e.g., Campbell)
3. Massive stars (e.g., Banerjee)

- The s-process also occurs in (rotating) massive stars (e.g., talk by **Choplin**, and papers by Frischknecht, Pignatari)

Asymptotic Giant Branch Stars



Asymptotic Giant Branch stars:
($0.8 \lesssim M/M_{sun} \lesssim 8$)

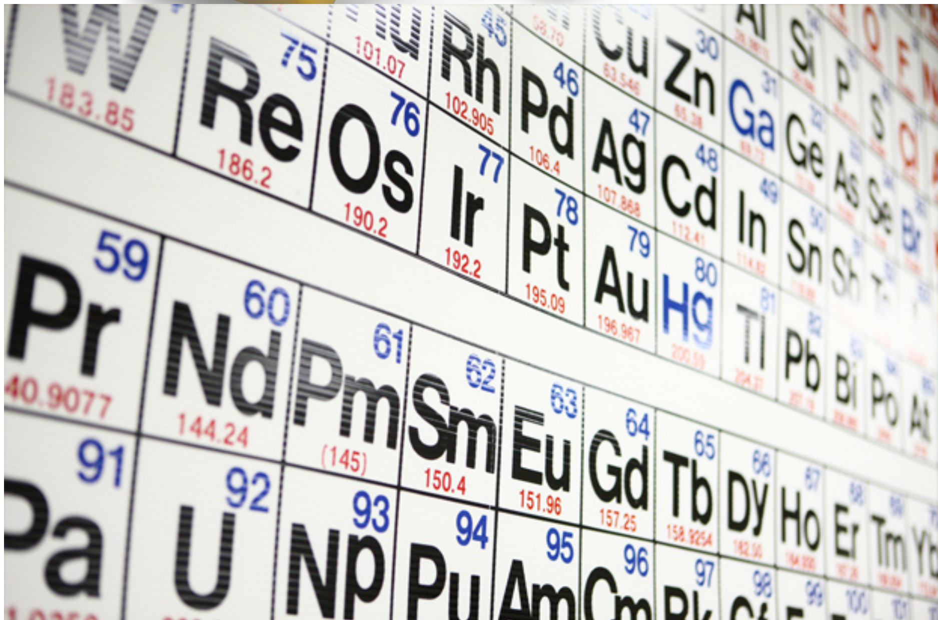
- After core He-burning, the C-O core contracts and the star becomes a giant again
- Double-shell configuration
- He-burning shell is thermally unstable and flashes every ~10^4 years
- Rapid, episodic mass loss erodes the envelope

Reviews by Karakas & Lattanzio (2014)

Production of heavy elements

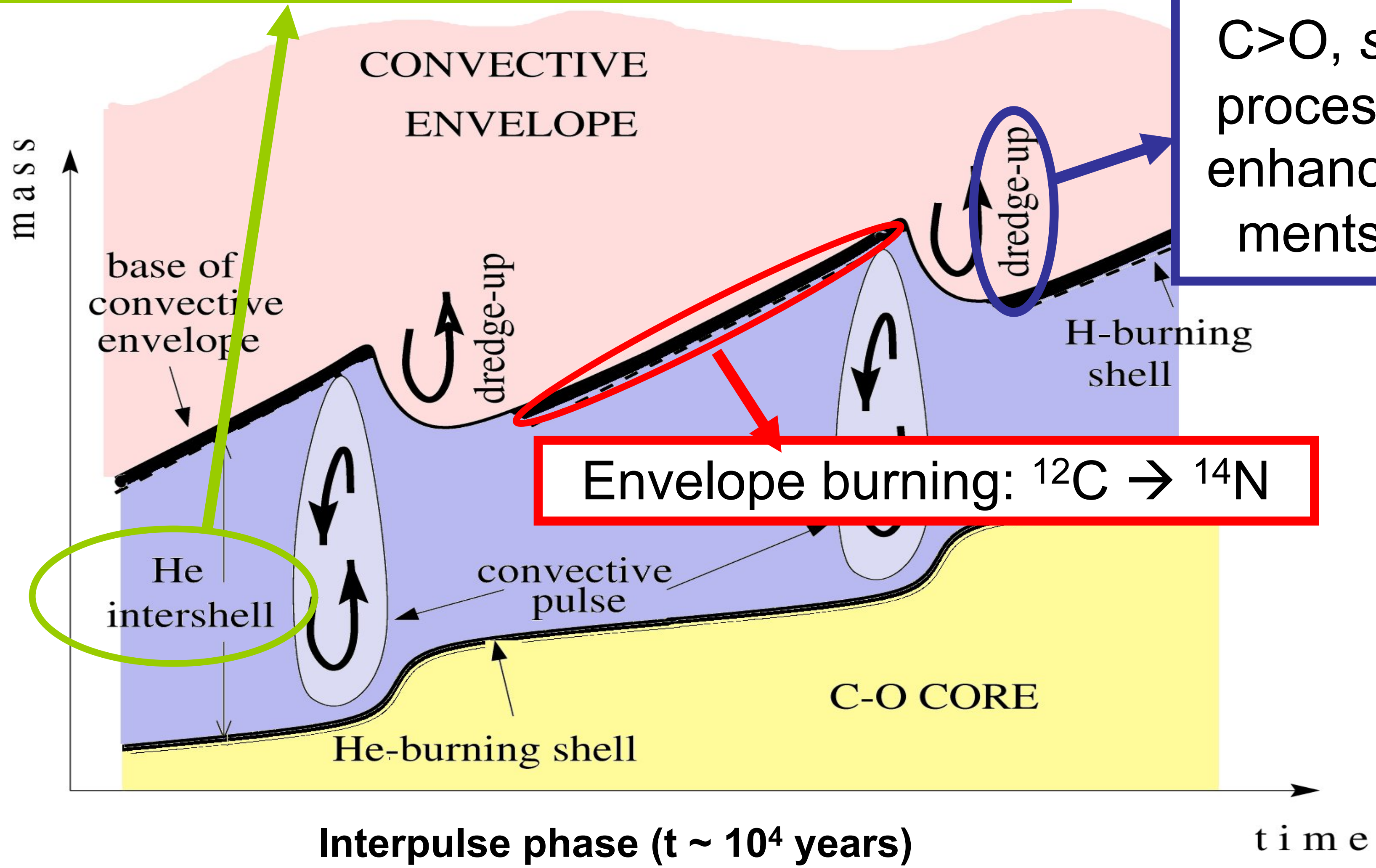
- Heavy elements: heavier than iron (Fe)
- Most heavy nuclei are formed by neutron addition onto Fe-peak elements
- Two processes:
  - *r-process* (rapid neutron capture)
  - *s-process* (slow neutron capture)

Reviews by Busso, Gallino & Wasserburg (1999); Kaeppeler et al. (2011); Meyer (1994)



Schematic AGB evolution

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



Envelope burning: ^{12}C → ^{14}N

...

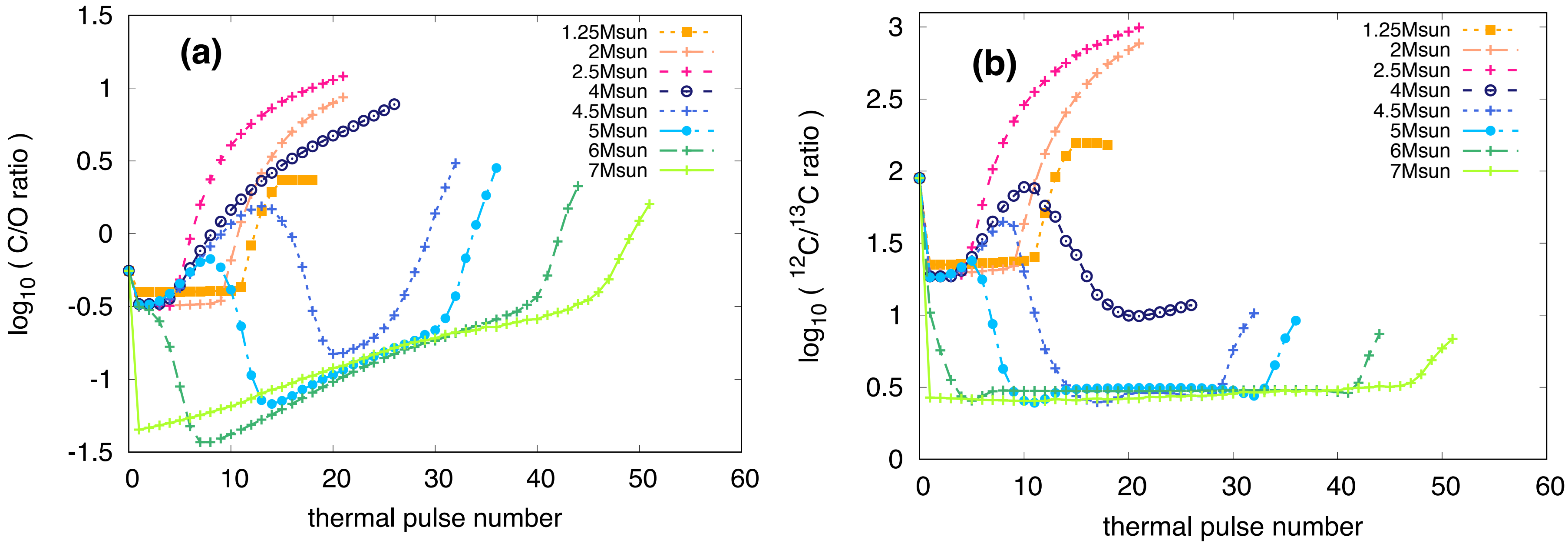
At the stellar surface: C>O, *s*-process enhancements

Interpulse phase (t ~ 10^4 years)

Nucleosynthesis

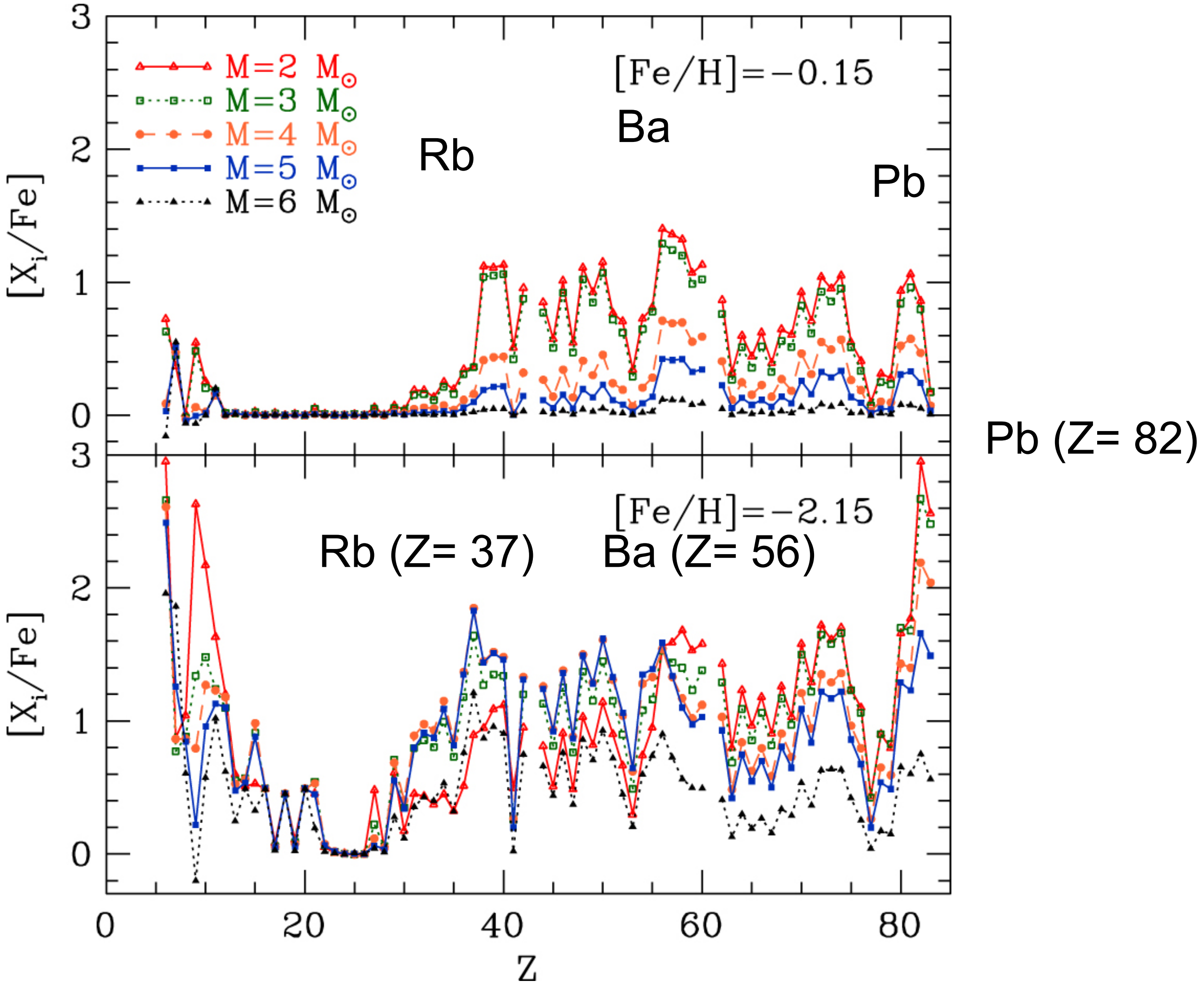
- **Low-mass:** ~0.9 to 2.5M_{sun} for [Fe/H] = -2.3 → CEMP
  - Third dredge-up: helium shell mixed into the envelope (e.g., ^{12}C, s-elements)
- **Intermediate-mass:** $M \gtrsim 3\ M_{sun}$ for [Fe/H] = -2.3 → NEMP
  - Hydrogen burning at base of convective envelope (e.g., ^{14}N)
  - Plus third dredge-up, which produces primary C and N

Models of [Fe/H] = -0.7 (Karakas et al. 2017, in prep)



The s-process: Effect of metallicity

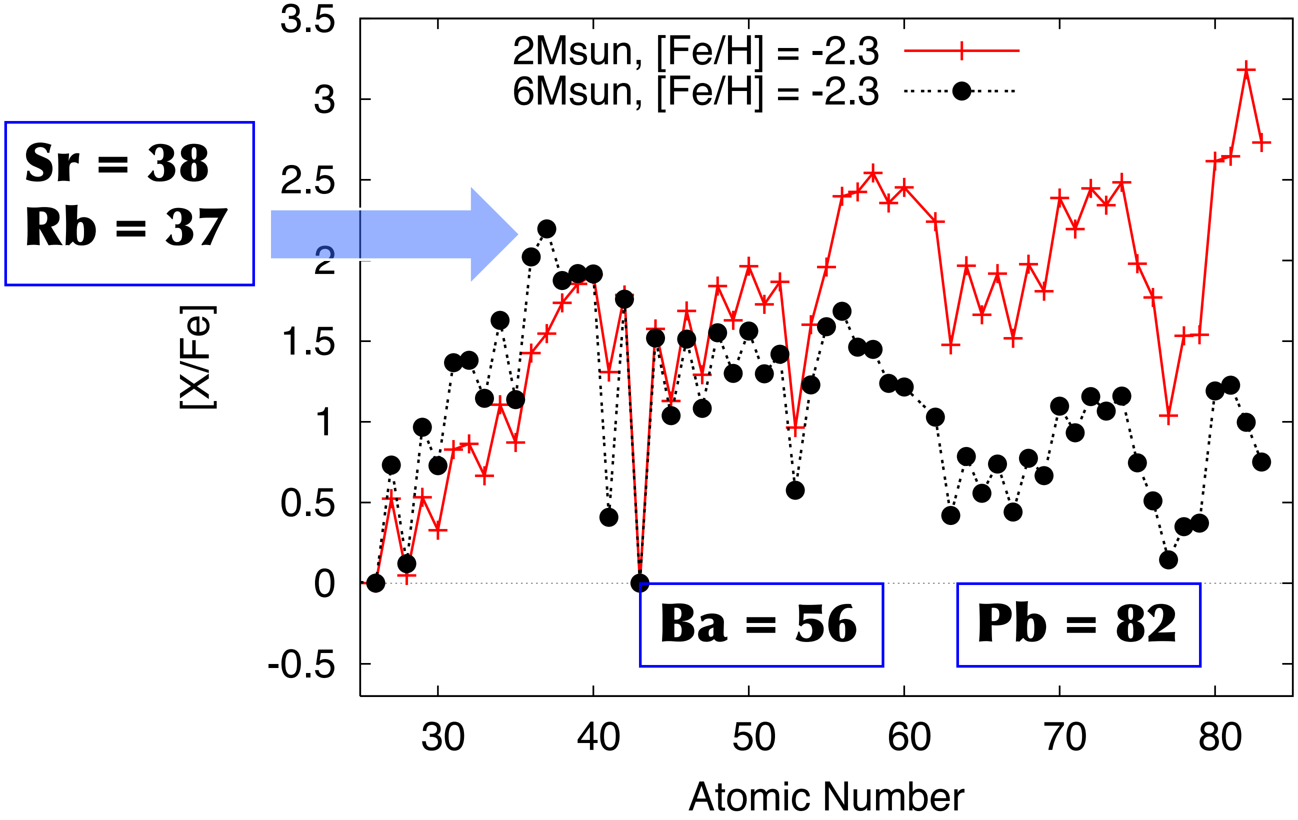
FRUITY database: From Cristallo et al. (2015); also AGB models by Bisterzo et al. (2010) and NuGrid collaboration (e.g., Pignatari et al. 2016)



Z = proton number

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



Sr = 38
Rb = 37

Ba = 56

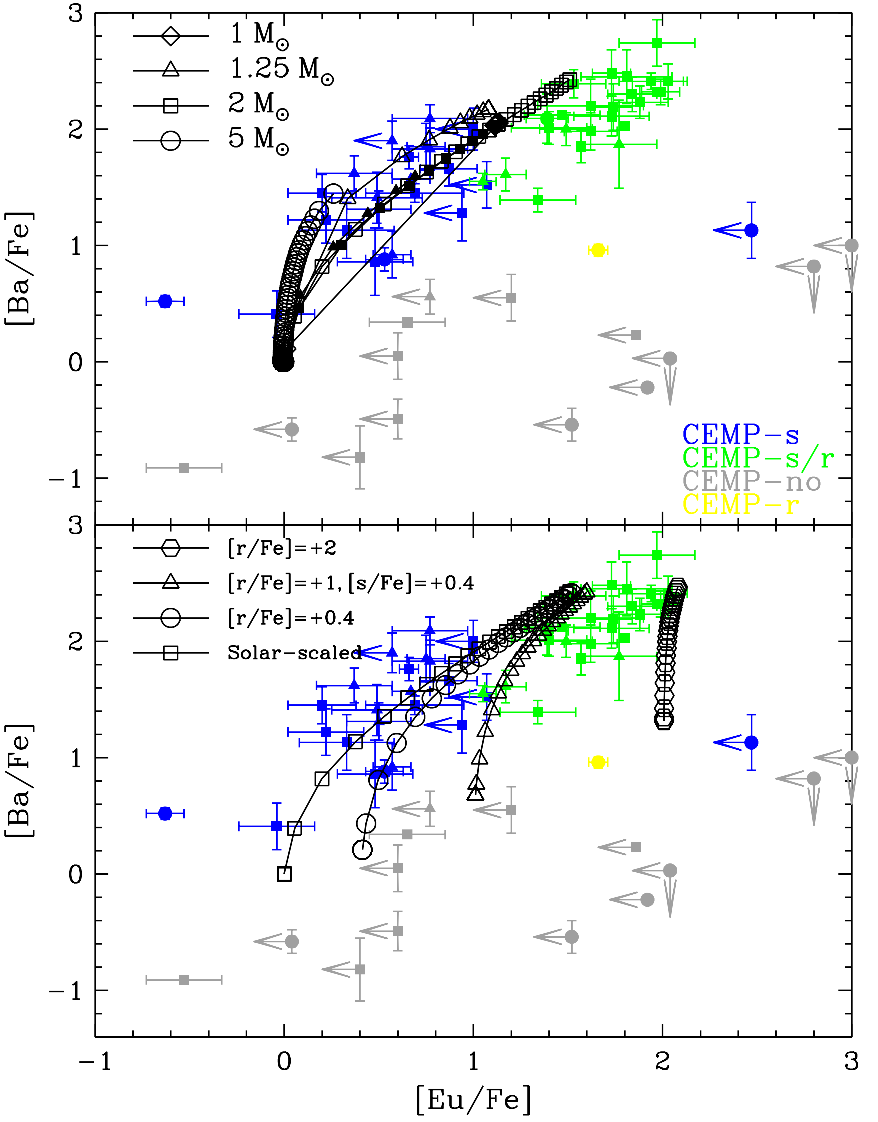
Pb = 82

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**

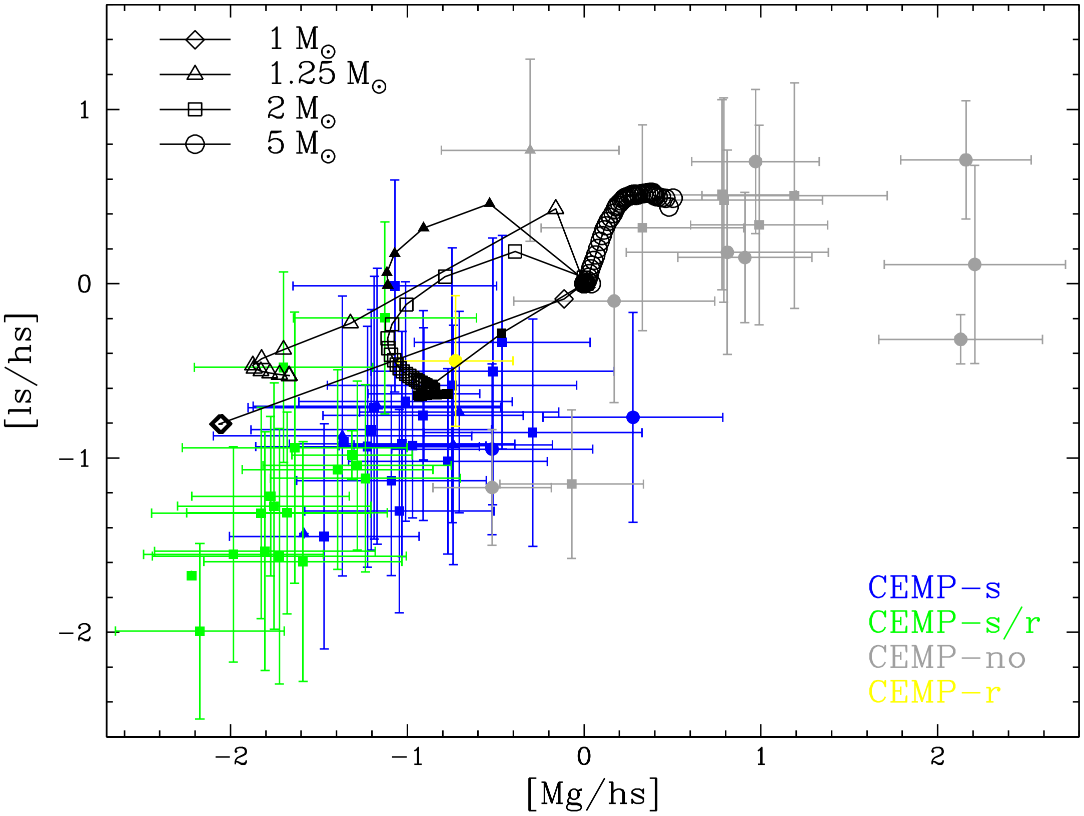
Summary:

- All models produce Ba and Eu with the prediction lines following the trend of the CEMP-s group
- AGB models do not produce the high [Eu/Fe] seen in the CEMP-s/r stars
- Increasing the initial [r/Fe] produces same final [Ba/Fe]
- Correlation between Ba and Eu of CEMP-s/r group ***not*** reproduced



Results: [ls/hs] versus [Mg/hs]

- Use “intrinsic” indicators, elemental ratios that only include elements produced in AGB stars
- Almost independent of model uncertainties (third dredge-up, mass loss, accretion, mixing processes)
- All our AGB models produce [ls/hs] > -1, similar to CEMP-s
- This is a basic fact about the s-process and comes from neutron-capture cross sections
- CEMP-s/r have the lowest [ls/hs] and [Mg/hs] values

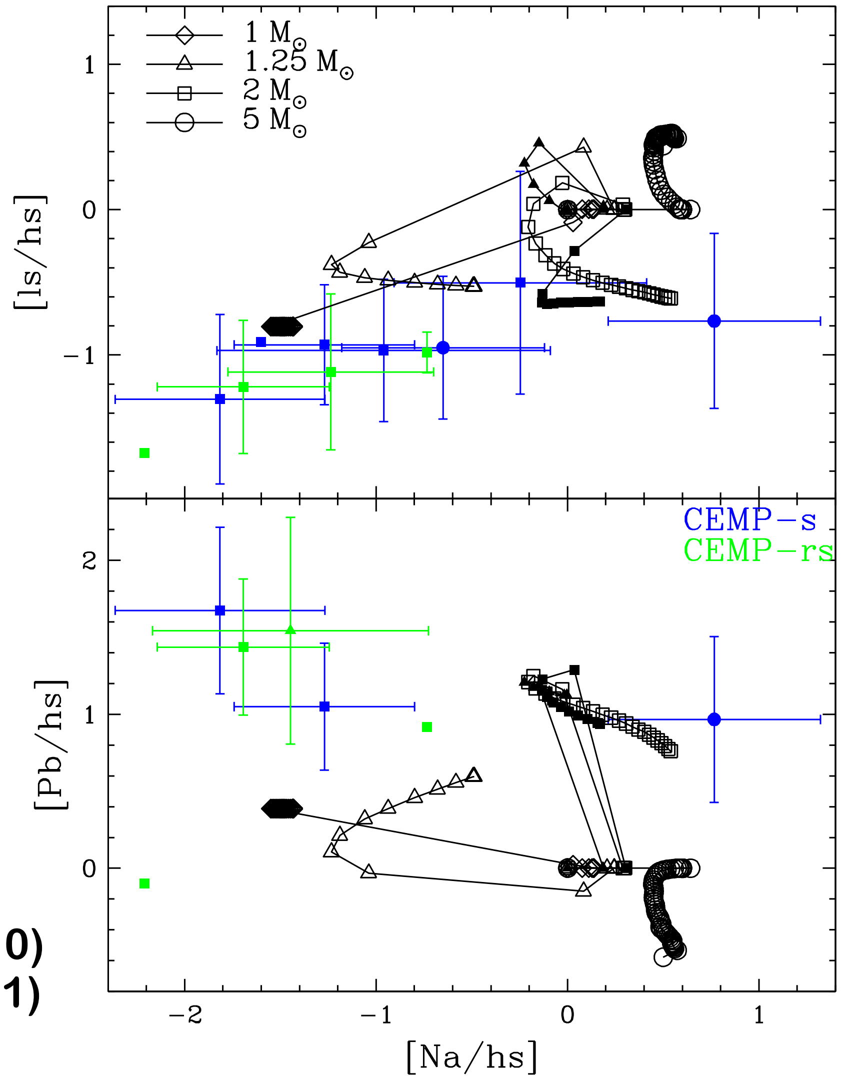


CEMP data from Masseron et al. (2010). Data for *ls* is taken from the SAGA database (Suda et al. 2008)

ls = light *s*-process elements (Sr, Y, Zr), hs = heavy s elements (Ba, La, Ce)

Results: Sodium and fluorine

- Models where ^{13}C burns radiatively provide a good match to the overall composition of CEMP-s stars in terms of their [Mg/hs], [ls/hs], and [Pb/hs]
- But produce too much Na and F with respect to the heavy s-process elements
- Could be related to the formation of the ^{13}C pocket (and ^{14}N pocket)
- Leads to Na production via ^{14}N(a,γ)^{18}O(a,γ)^{22}Ne in intershell then ^{22}Ne(p,γ)^{23}Na



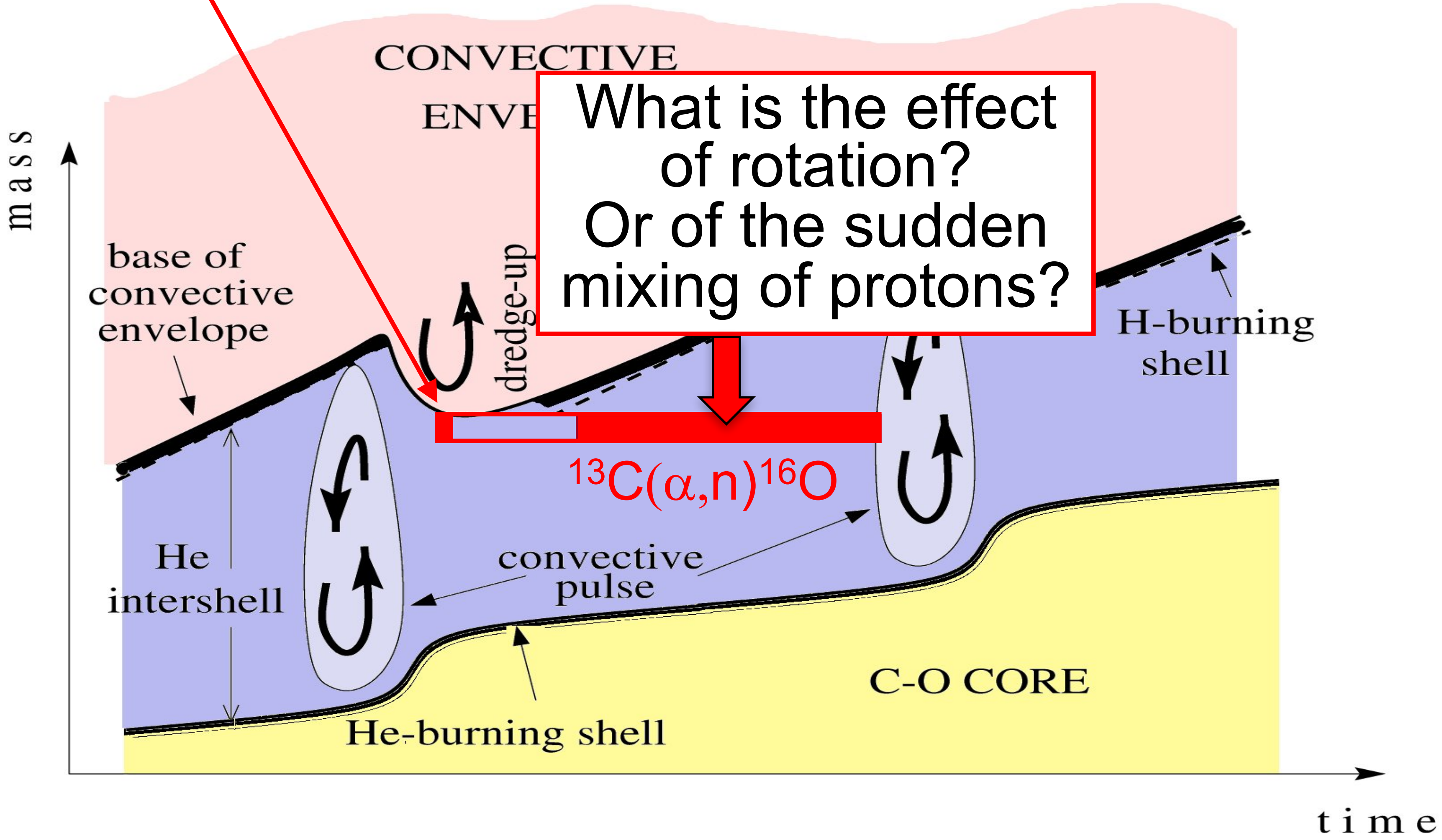
CEMP data from Masseron et al. (2010)
Data for Na from Lucatello et al. (2011)

The s-process in AGB stars

- How well do we really understand the operation of the s-process in AGB stars?
- This is a different question to the *accuracy of yields*, which depend on other modelling uncertainties (e.g., mass loss)

Neutron production is still poorly understood

Neutrons are produced ^{13}C pockets – we don't know how these form!



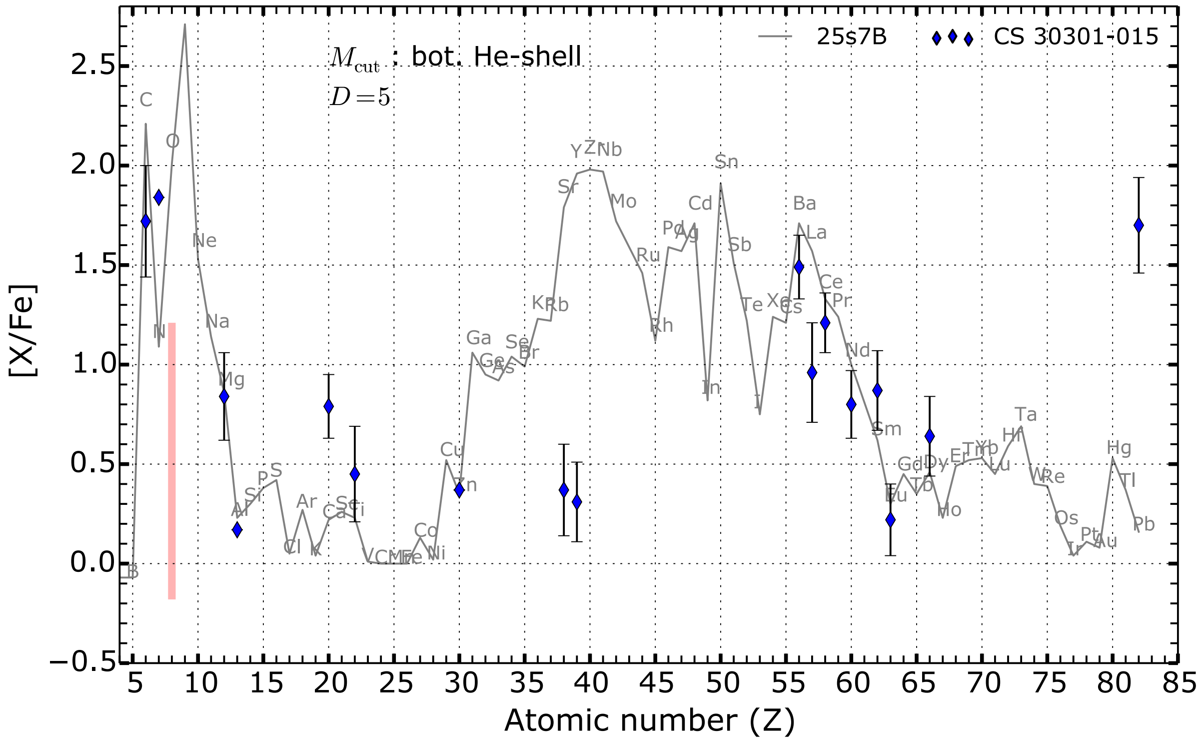
What is the effect of rotation?
Or of the sudden mixing of protons?

$^{13}C(\alpha,n)^{16}O$

CEMP-s are mostly binaries

- But some of them appear single (Hansen et al. 2016)
- Are these non-binary CEMP-s formed by forming from material polluted by a massive star? *Talk by Choplin*
- *Answer, yes (?) at least for some (3/4) but not all*

Figure from Choplin et al. (2017)



Summary

- With available yields, we are now making quantitative chemical evolution predictions including heavy elements
- The new yields are timely, given the release of stellar abundance data from surveys for 100,000+ stars (e.g., GAIA-ESO survey; Galah in Australia, De Silva et al. 2015; K2 mission, e.g. Huber et al. 2016)
- Low-mass, low-metallicity AGB stars match composition of CEMP-s stars well but not CEMP-s/r (→ is it ‘i-process’?)
- New observations test our models of the s-process
- What is the origin of “Single” CEMP-s stars?
- What process is behind the post-AGB stars found in the Magellanic Clouds?