Nucleosynthesis and yields from low and intermediate-mass stars

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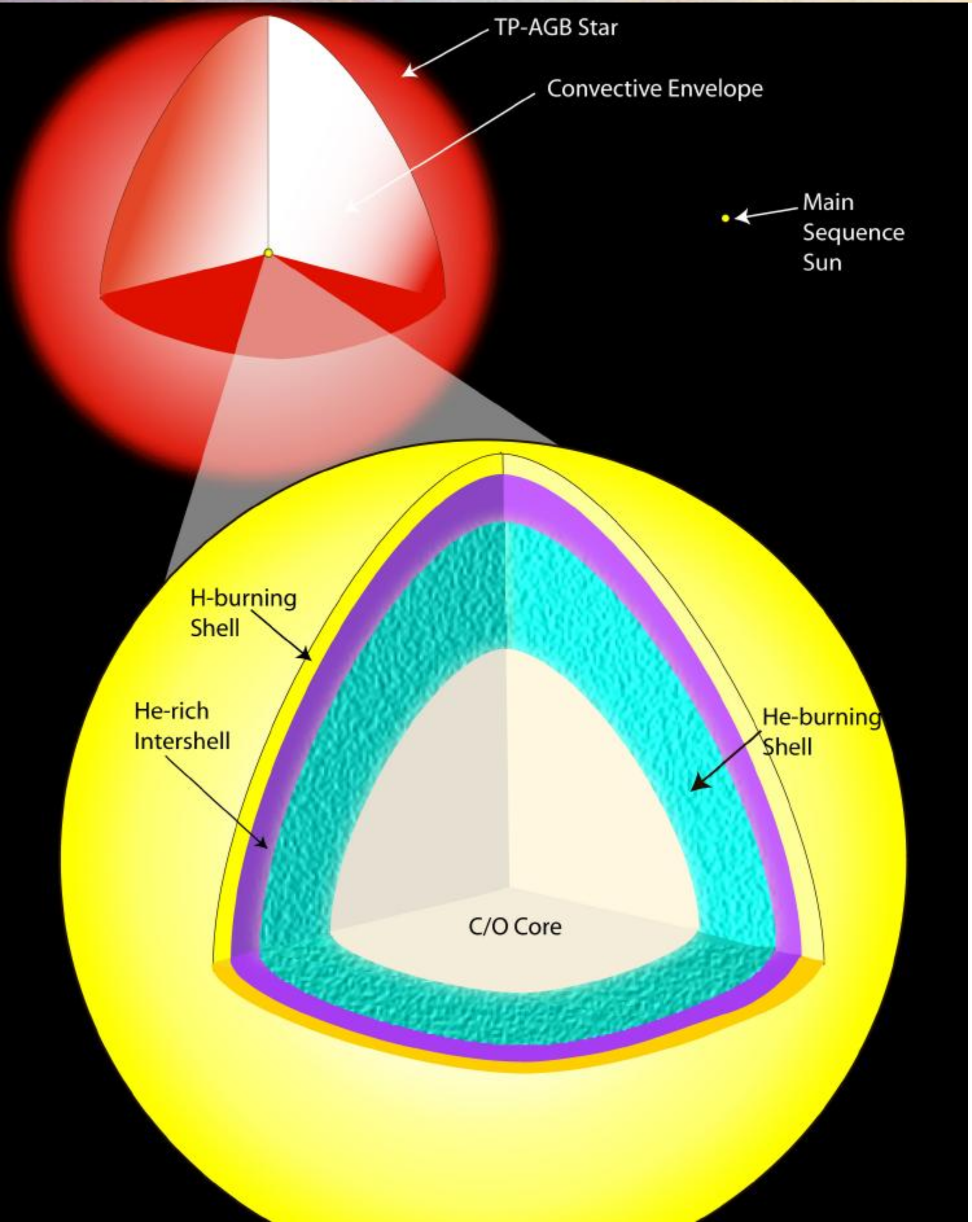
Asymptotic Giant Branch Stars



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

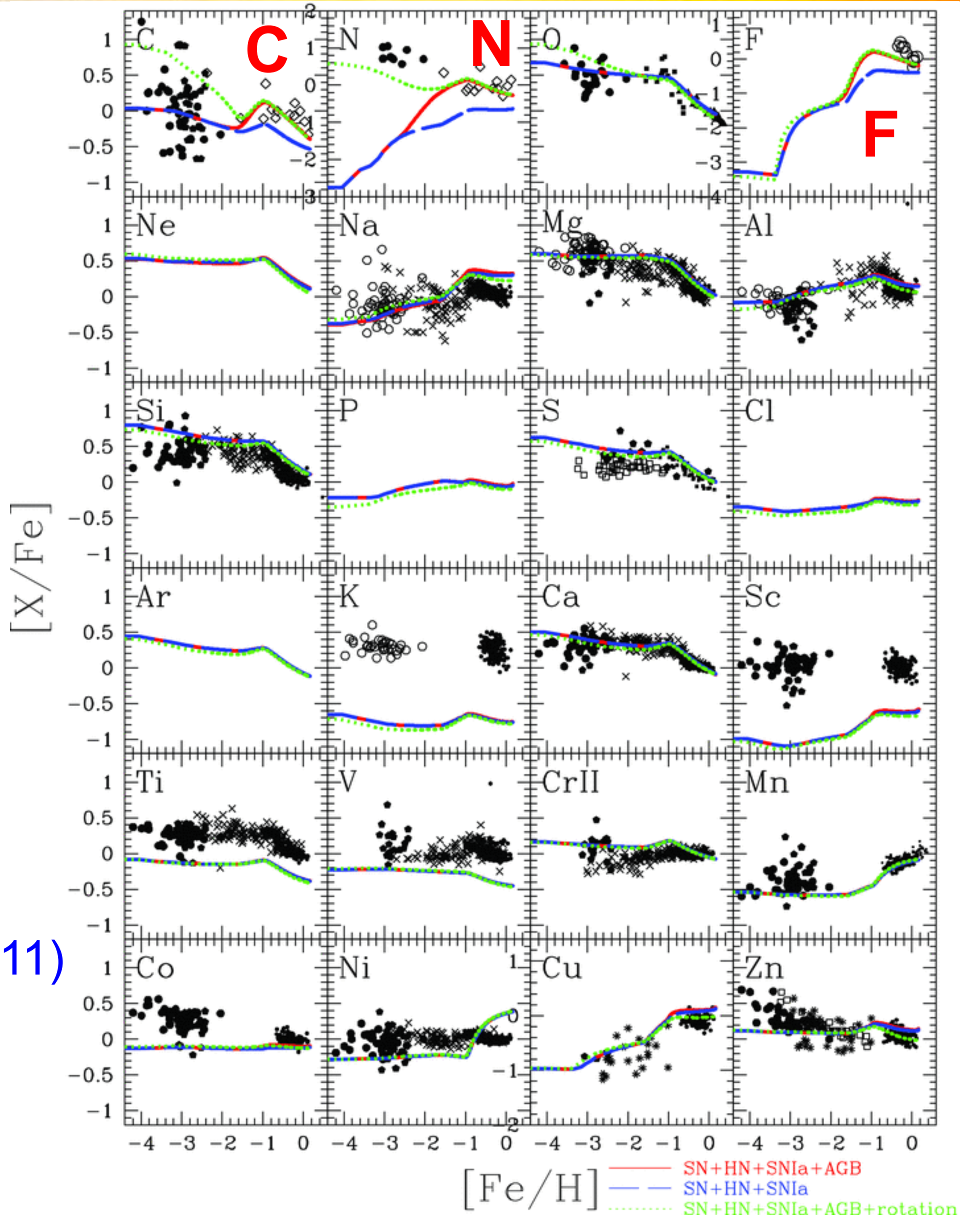
- After core He-burning, the C-O core contracts and the star becomes a giant again
- Double-shell configuration
- He-burning shell is thermally unstable and flashes every $\sim 10^4$ years
- Rapid, episodic mass loss erodes the envelope

Reviews by Karakas & Lattanzio (2014) and Herwig (2005)

The contribution of AGB stars

Low and intermediate-mass stars are important factories for :

- Li, C, N, F (e.g., Romano et al. 2010)
- Neutron-rich isotopes of C, O, Ne, Mg, Si
- Half of all heavy elements including Sr, Y, Ba, Pb (e.g., Bisterzo et al. 2014)

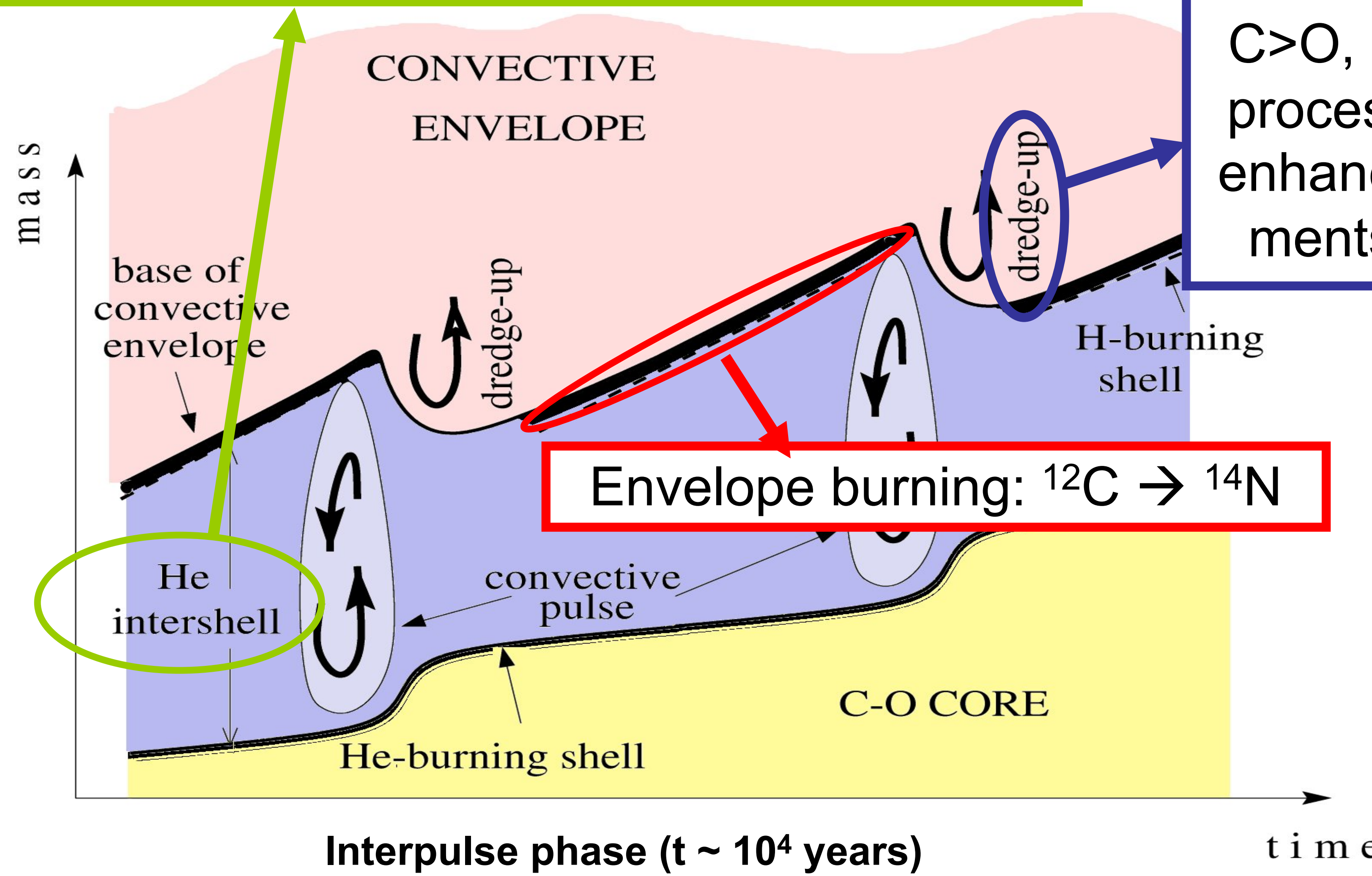


Evolution of elements in the solar neighbourhood

From Kobayashi, Karakas, & Umeda (2011)

Schematic AGB evolution

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



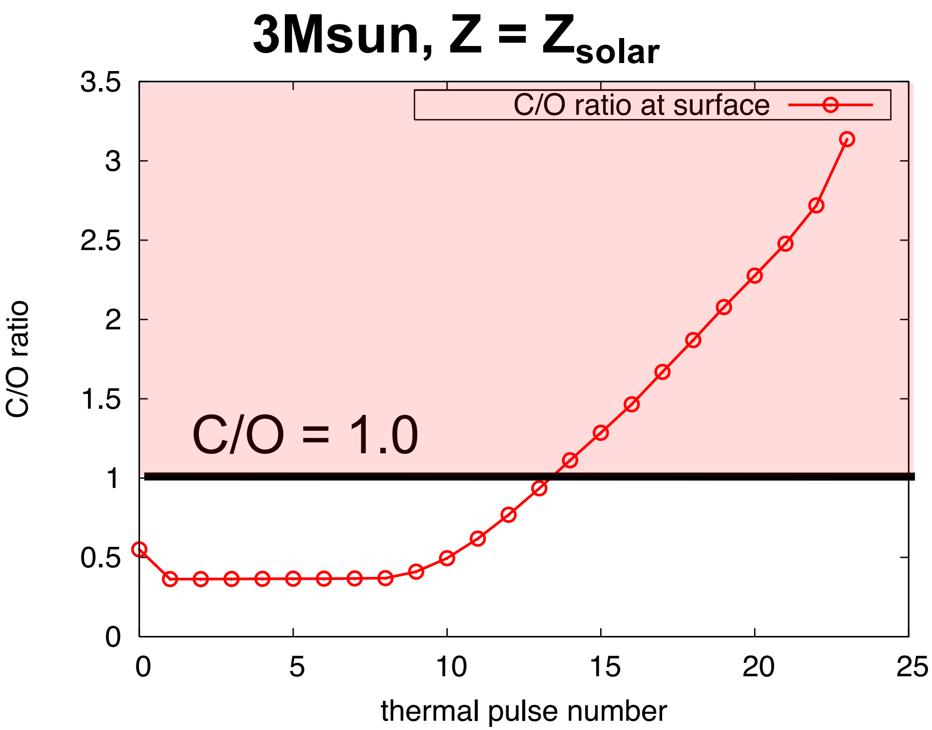
At the stellar surface: C>O, *s*-process enhancements

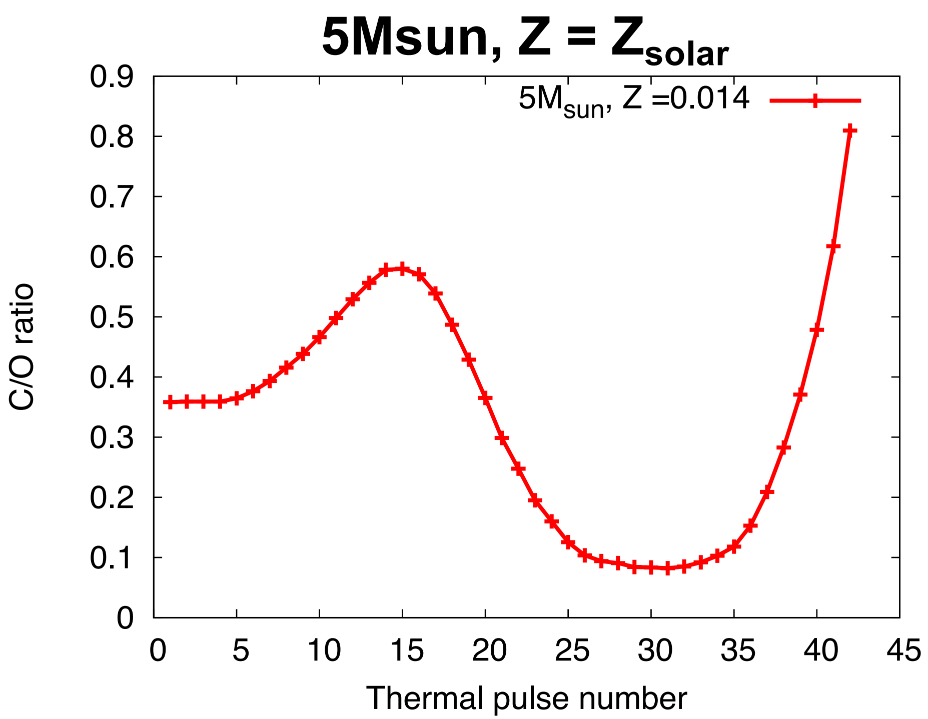
Envelope burning: $^{12}C \rightarrow ^{14}N$

Interpulse phase (t ~ 10^4 years)

Nucleosynthesis

- **C/O > 1**: ~1.5 to 4.5M_{sun} for Z = Z_{solar} (here Z = 0.014)
  - Third dredge-up: helium shell mixed into the envelope (e.g., ^{12}C, s-elements)
- **C/O < 1**: M < 1.5Msun and M > 4.5M_{sun} for Z = Z_{solar}
  - M < 1.5Msun: first dredge-up ONLY
  - M > 4.5Msun: Hydrogen burning at base of convective envelope (e.g., ^{14}N)





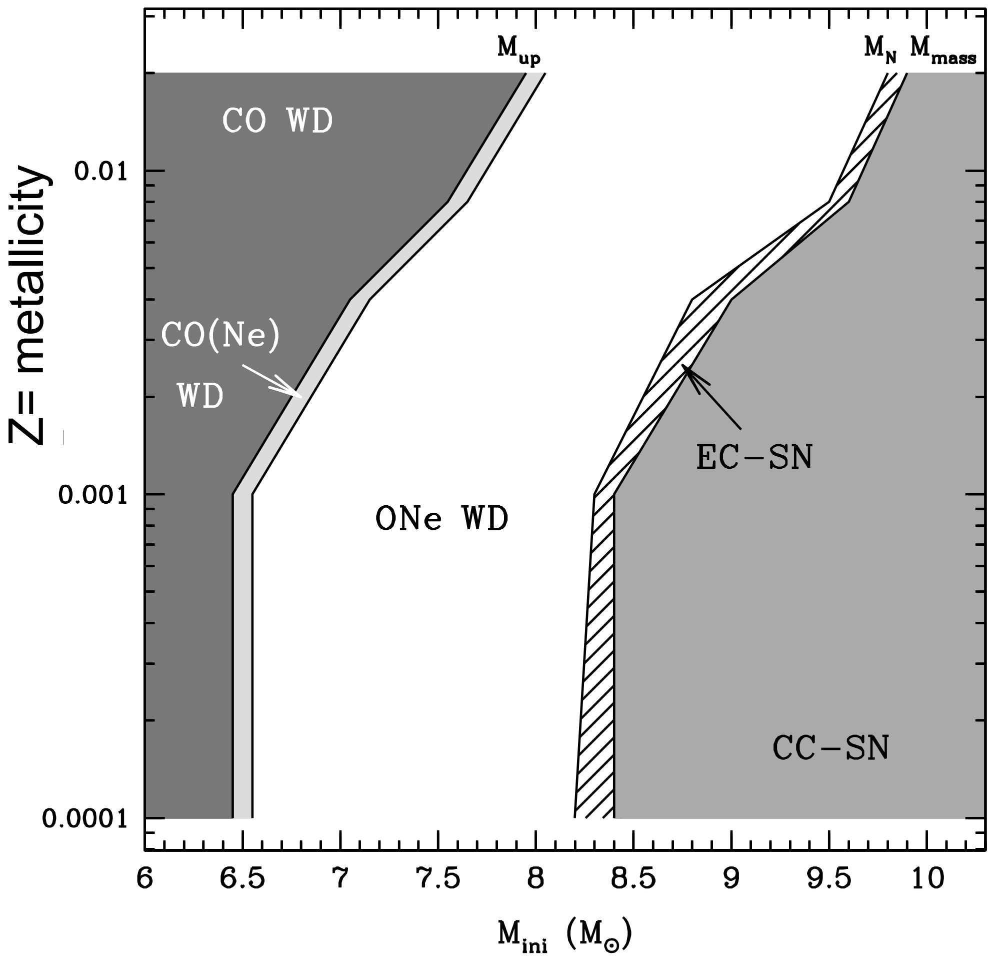
Super-AGB stars

- M ≥ 8Msun (for $Z = Z_{solar}$) up to 10Msun

→ Core carbon burning before ascending the AGB

→ Super-AGB stars → ONe cores

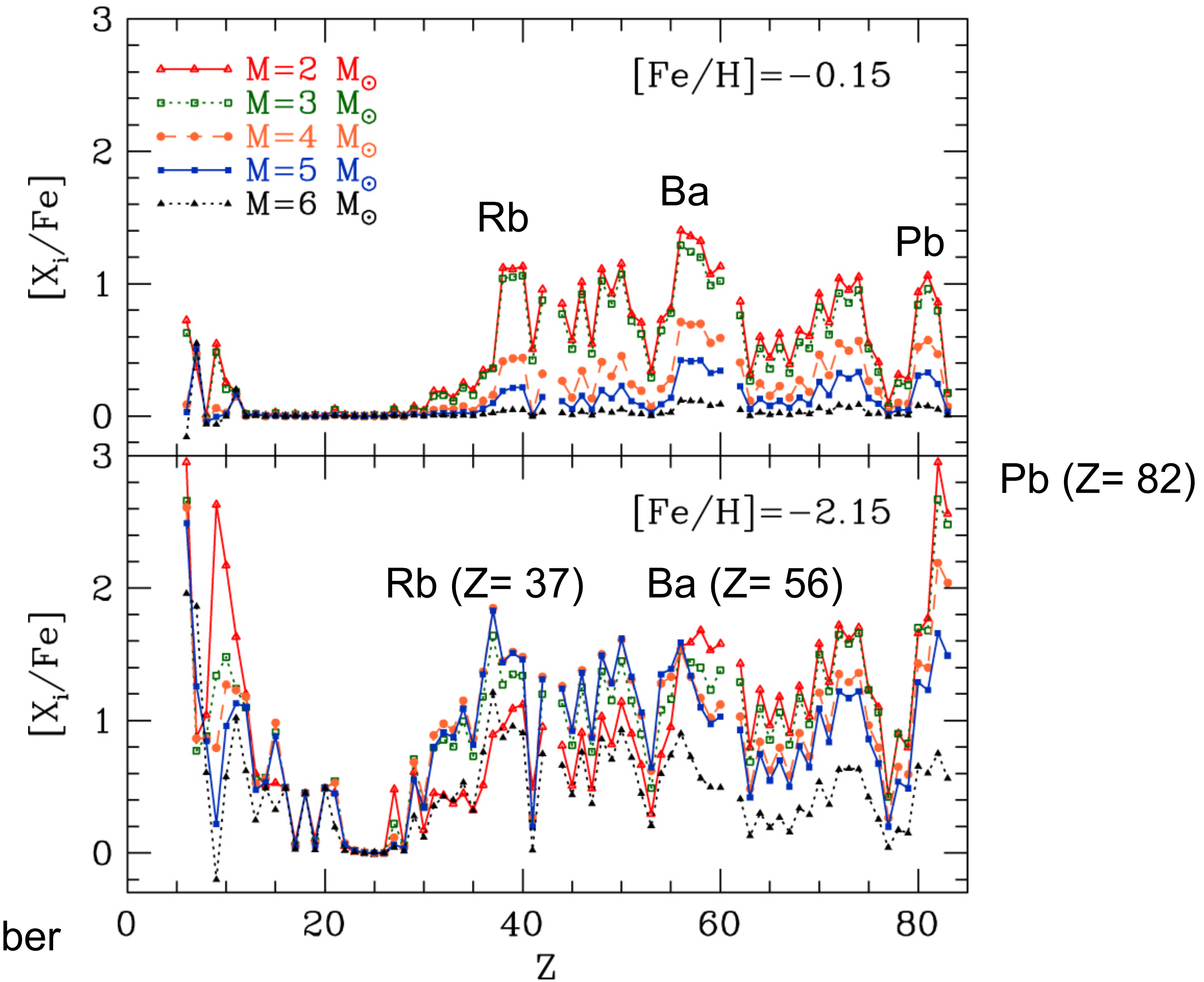
- Hot bottom burning: C/O < 1
- Maybe they can produce Type Iax supernovae? (Denissenkov et al. 2015; Kobayashi et al. 2015)
- Electron capture supernova? If so do they make *r*-process elements? (Wanajo et al. 2015)



See review by Doherty et al. (2017)

AGB surface abundances

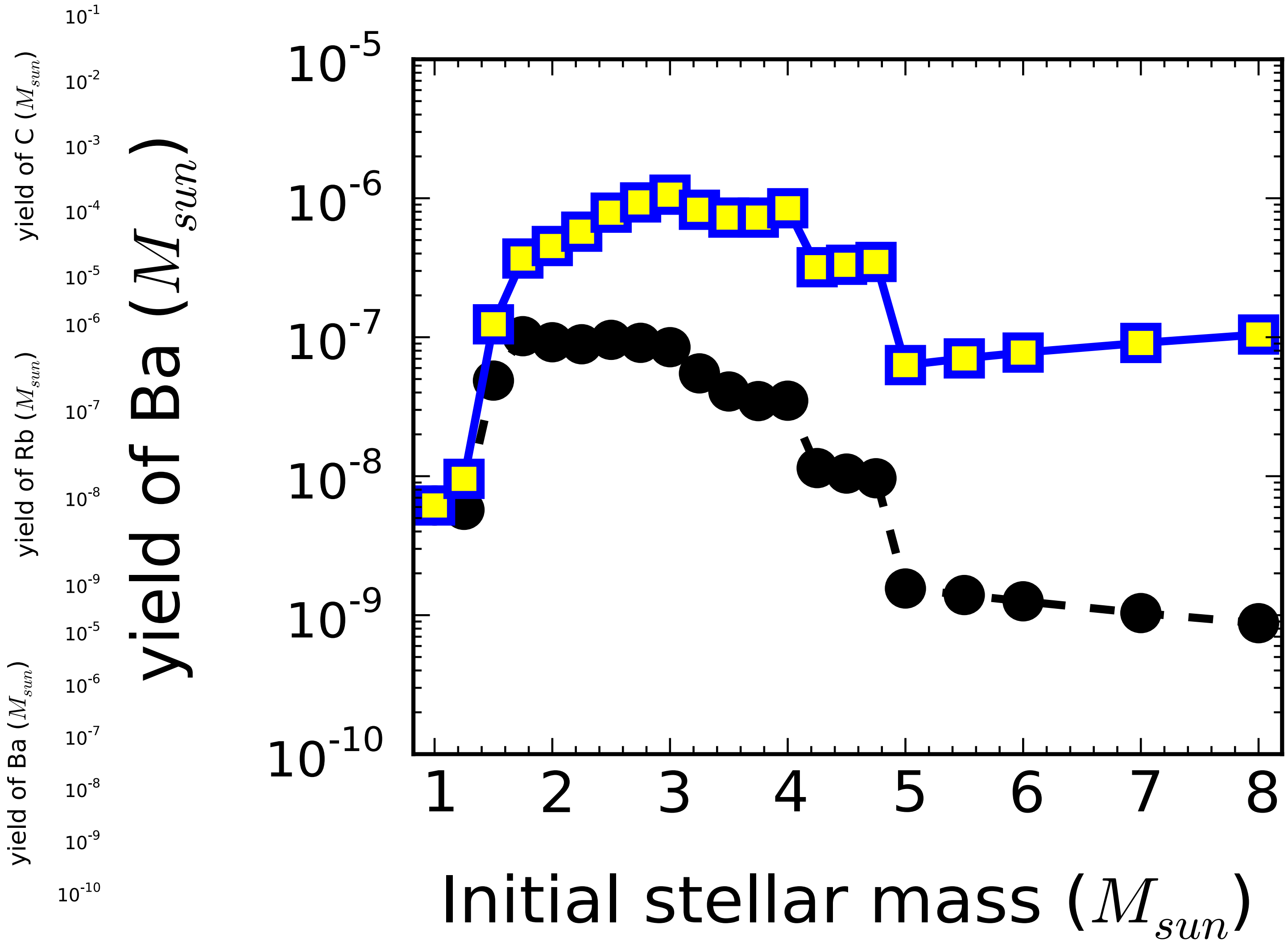
FRUITY database: From Cristallo et al. (2015)



Z = proton number

AGB chemical yields

Example: [Fe/H] = 0 (solar) from Karakas & Lugaro (2016)



Yield = amount of an isotope ejected into the ISM over the star's lifetime

Black dots = weighted by an IMF

Yields of s-process elements

- **FRUITY database:** Cristallo et al. (2011, 2015) yields for 1-3Msun for a range of metallicities; few intermediate-mass models up to 6Msun
- **Our group:** Lugaro et al. (2012); Fishlock et al. (2014), Karakas & Lugaro (2016) yields of 1 to ~6-8Msun for [Fe/H] = -2.3, -1.2, -0.3, 0.0, +0.3
- **NuGrid/MESA:** Pignatari, Herwig et al. (2016) for Z = 0.01 and 0.02 for limited masses
- **At very low metallicities:** Bisterzo et al. (2010), Campbell et al. (2010) and Cruz et al. (2013) but no tabulated yields

What is lacking? Yields for low metallicity for all masses. Super-AGB yields.

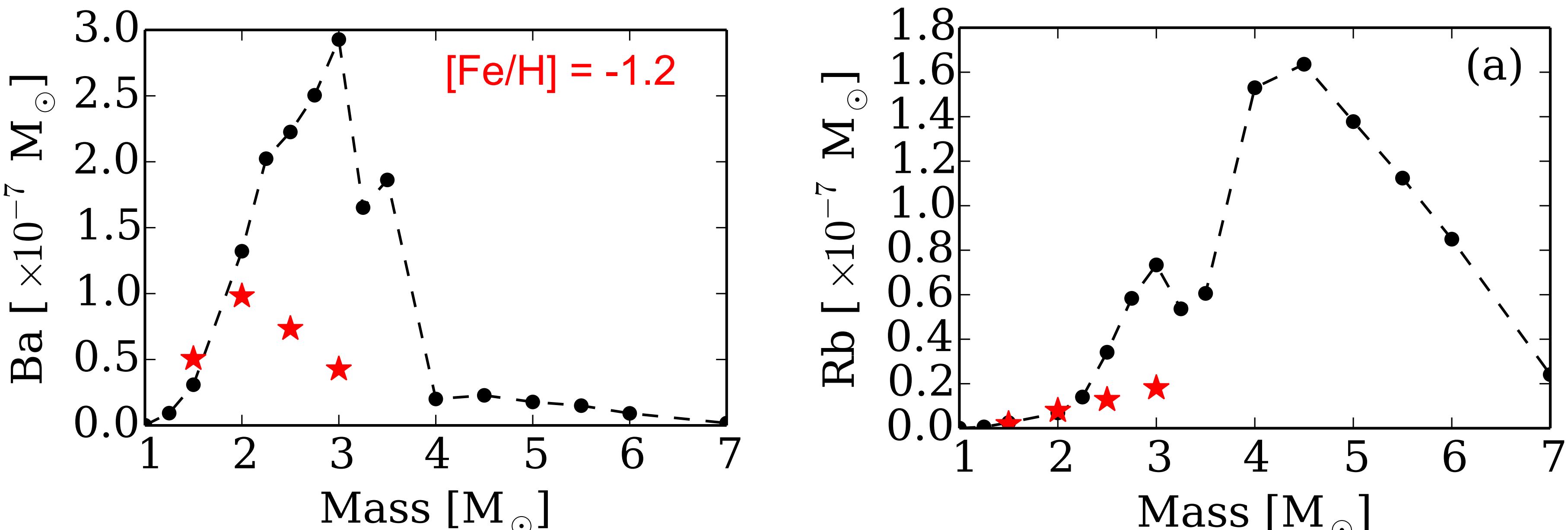
Yields of s-process elements

Light s-process (Y, Sr, Zr, Rb) versus heavy s-process elements (Ba, La, Nd)

- Light s-process – particularly Rb – are strongly produced in massive (3-8Msun) AGB stars with short lifetimes (< 100Myr)
- Heavy s-process produced in lower mass AGB stars with longer lifetimes

→ Elements trace different star formation histories and processes in galaxies

Black points: Fishlock et al. 2014; **Red stars:** FRUITY/Cristallo



Open questions

1. How does the s-process operate inside AGB/post-AGB stars?
2. What is the site(s) of the i-process and how much influence does it have on GCE?
3. What mechanism(s) drives extra mixing in red giant envelopes?
4. How does a binary companion change stellar yields for low and intermediate-mass stars?
5. How do stellar modelling uncertainties (e.g., mass-loss, mixing, rotation, nuclear reaction rates) affect the yields?
6. The rise of the s-process in the Galaxy – when?

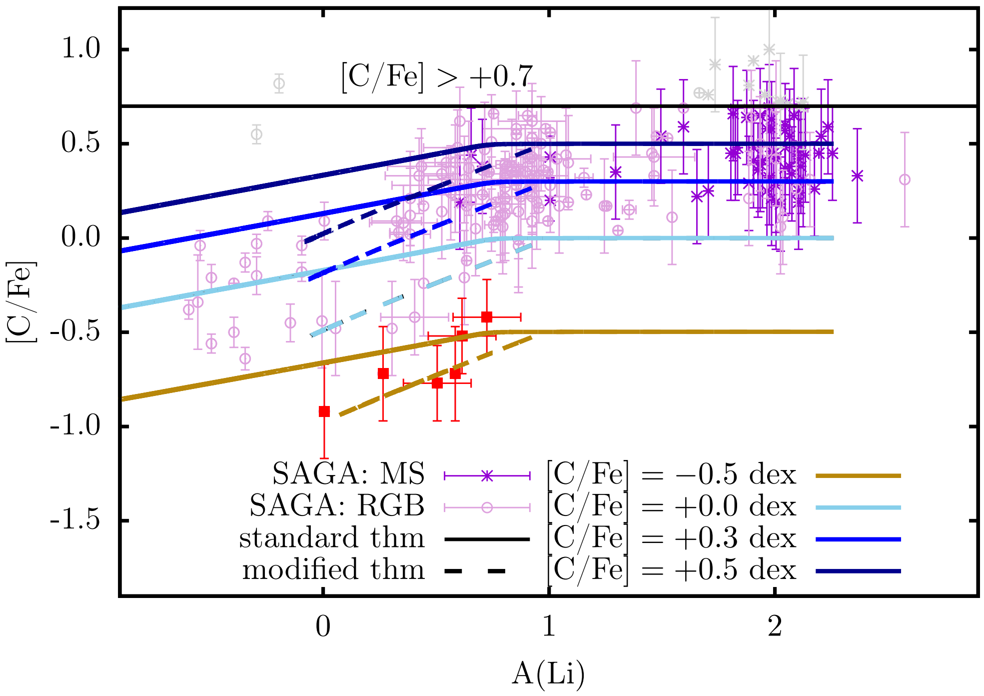
Extra mixing in red giant stars

- Thermohaline mixing seems to be a viable candidate on the RGB but tweaking of the model is needed (e.g., Henkel, Karakas & Lattanzio 2017, in press)

Thermohaline mixing in very metal-poor stars of [Fe/H] ≈ -3

Models: M = 0.8Msun, [Fe/H] =-3, evolved to tip of RGB

Plot by Kate Henkel (PhD student, Monash University)



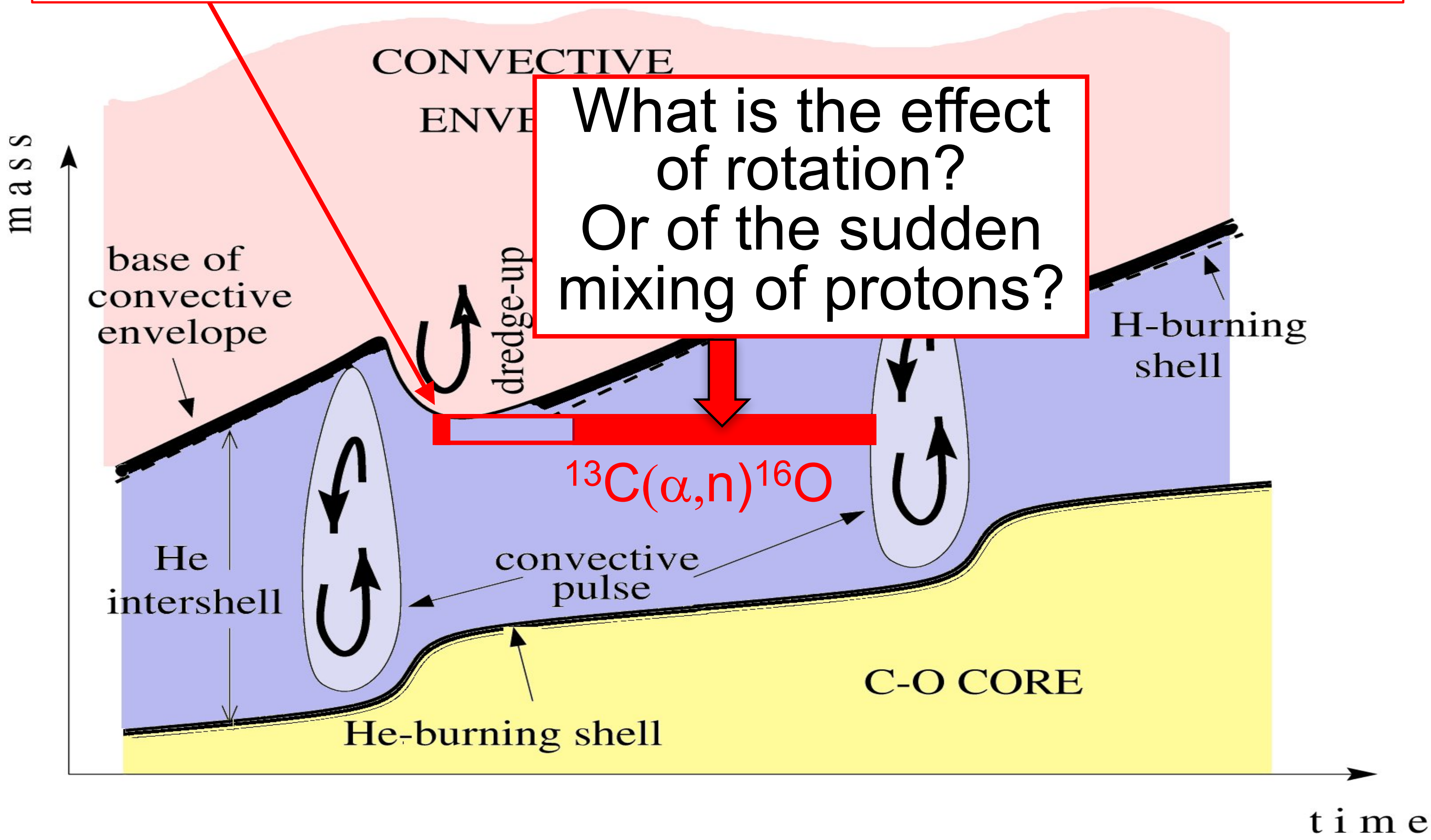
- What about on the AGB? CEMP-s stars show $^{12}C/^{13}C \sim 4$ when low-Z AGB models predict >> 100

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

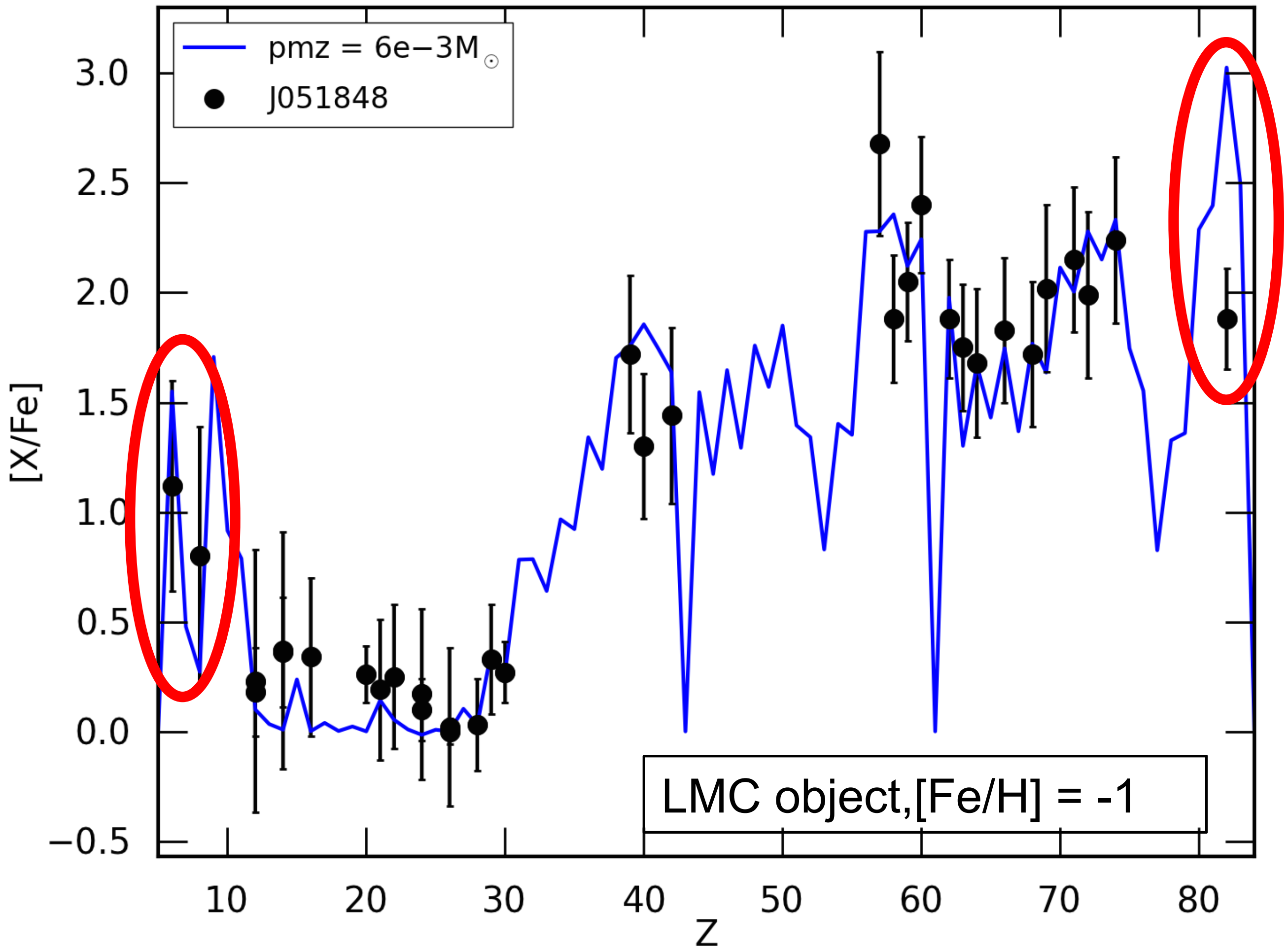
Neutrons are produced ^{13}C pockets – we don't know how these form!



Post-AGB stars in the Magellanic Clouds

- 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)

Figure from Kenneth De Smedt



Two issues:

1. The low C/O ratio, given the HUGE s-process enrichment
2. The low Pb

- Low Pb is found in 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)

Beyond the standard model of nucleosynthesis

- Proton ingestion episodes into a carbon and helium-rich region will produce neutrons
- This produces ^{13}C pockets when the rate of proton ingestion is slow → What if it's fast? e.g., into a convective region

→ *Burst of neutron production above what we find in s-process models*

→ *The intermediate or "i-process" (Cowan & Rose 1977)*

The *i*-process

- Is the *i*-process responsible for the neutron-capture pattern in post-AGB stars?

(Herwig et al. 2011; De Smedt et al. 2012, 2014; Lugaro et al. 2015)

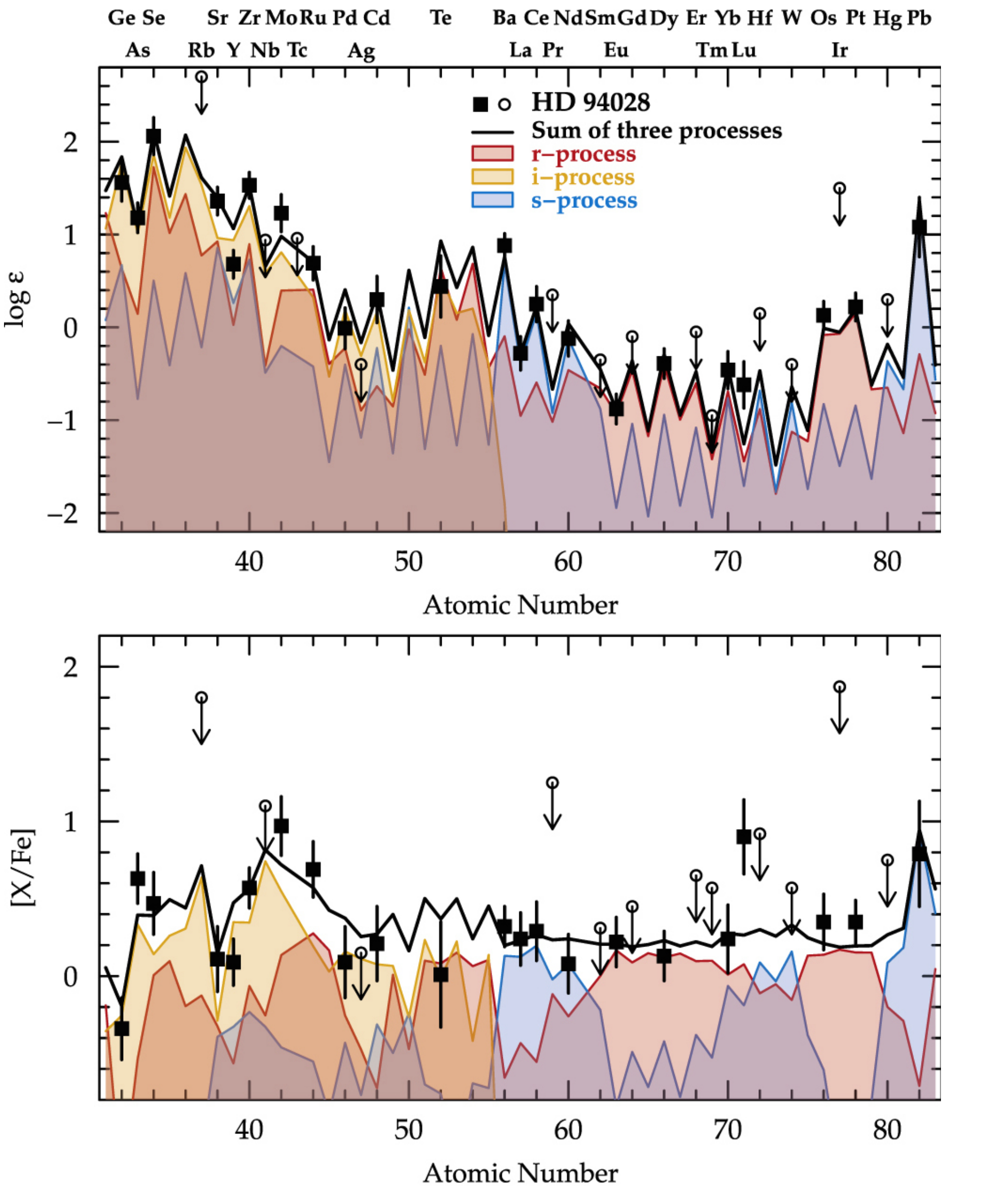
- What about the origin of the CEMP s/r stars?

(Lugaro et al. 2012; Dardelet et al. 2015; Jones et al. 2016)

→ Ubiquitous in metal-poor stars throughout the Galaxy?

→ Roederer et al. (2016)

HD 94028 from Roederer et al. (2016)



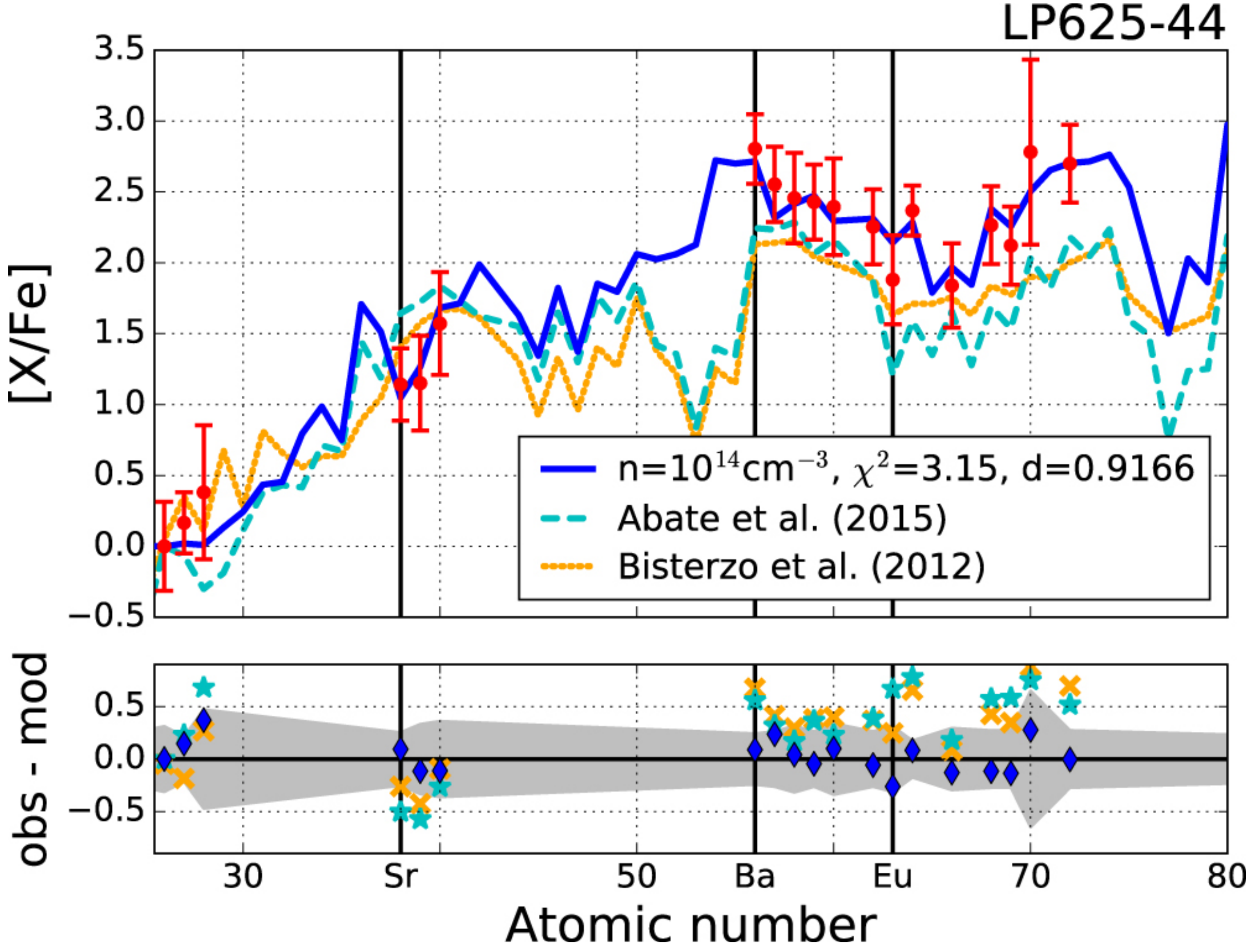
What are the site(s) of the *i*-process?

- There are quantitative problems fitting *s*-process predictions to observations in low-mass, low-metallicity post-AGB stars (e.g., de Smedt et al. 2012, 2014)
- Perhaps super-AGB stars > 6-8Msun, also of low metallicity (Jones et al. 2016)
- New predictions suggest *i*-process a better fit to CEMP s/r stars (Hampel et al. 2016) than an *s*-process (Abate et al. 2015a,b, 2016; Lugaro et al. 2012)

How will the i-process affect the (early) chemical evolution of the Galaxy?

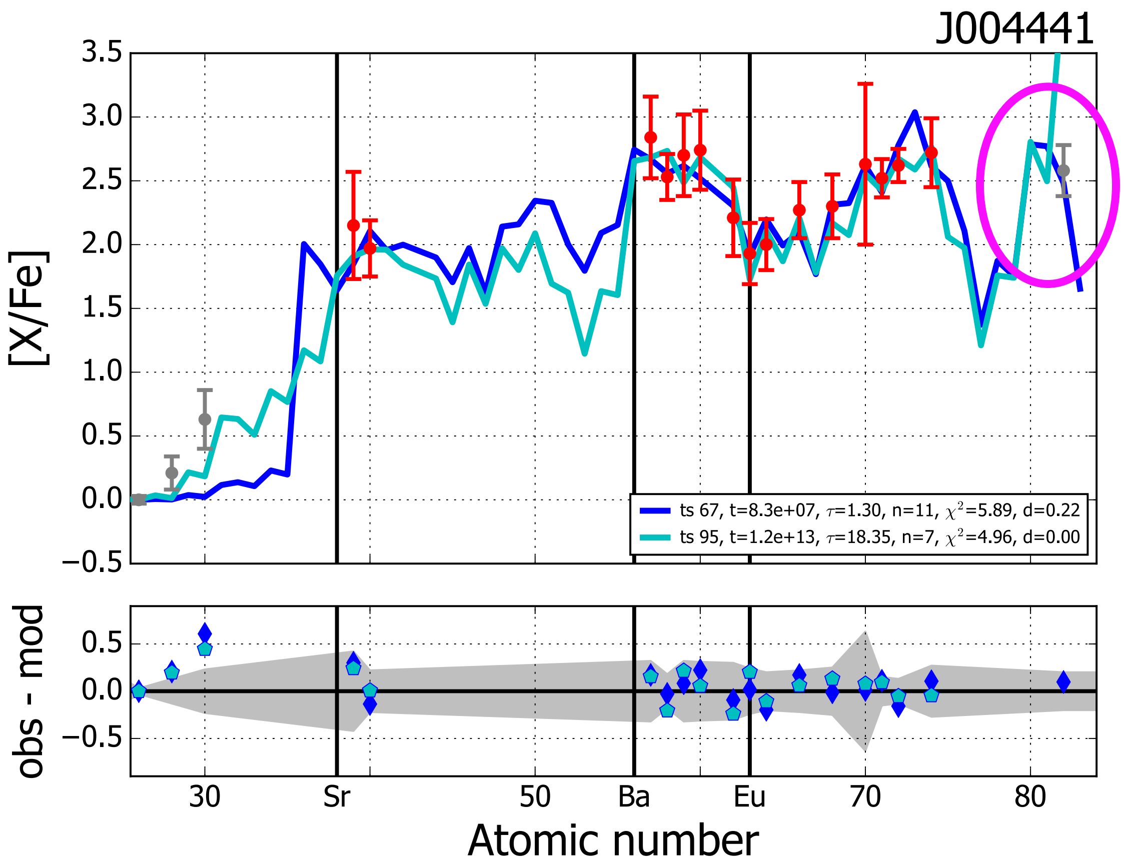
CEMP-*r/s* should be CEMP-i?

- Best-fitting model for CEMP-*s/r* star LP625-44 from Hampel et al. (2016)



The *i*-process in post-AGB stars

- Neutron densities on the order of ~10^{11} n/cm^3 operating not in equilibrium can produce a pattern that matches
- Plot by Melanie Hampel (PhD student, Monash Uni)



The binary problem

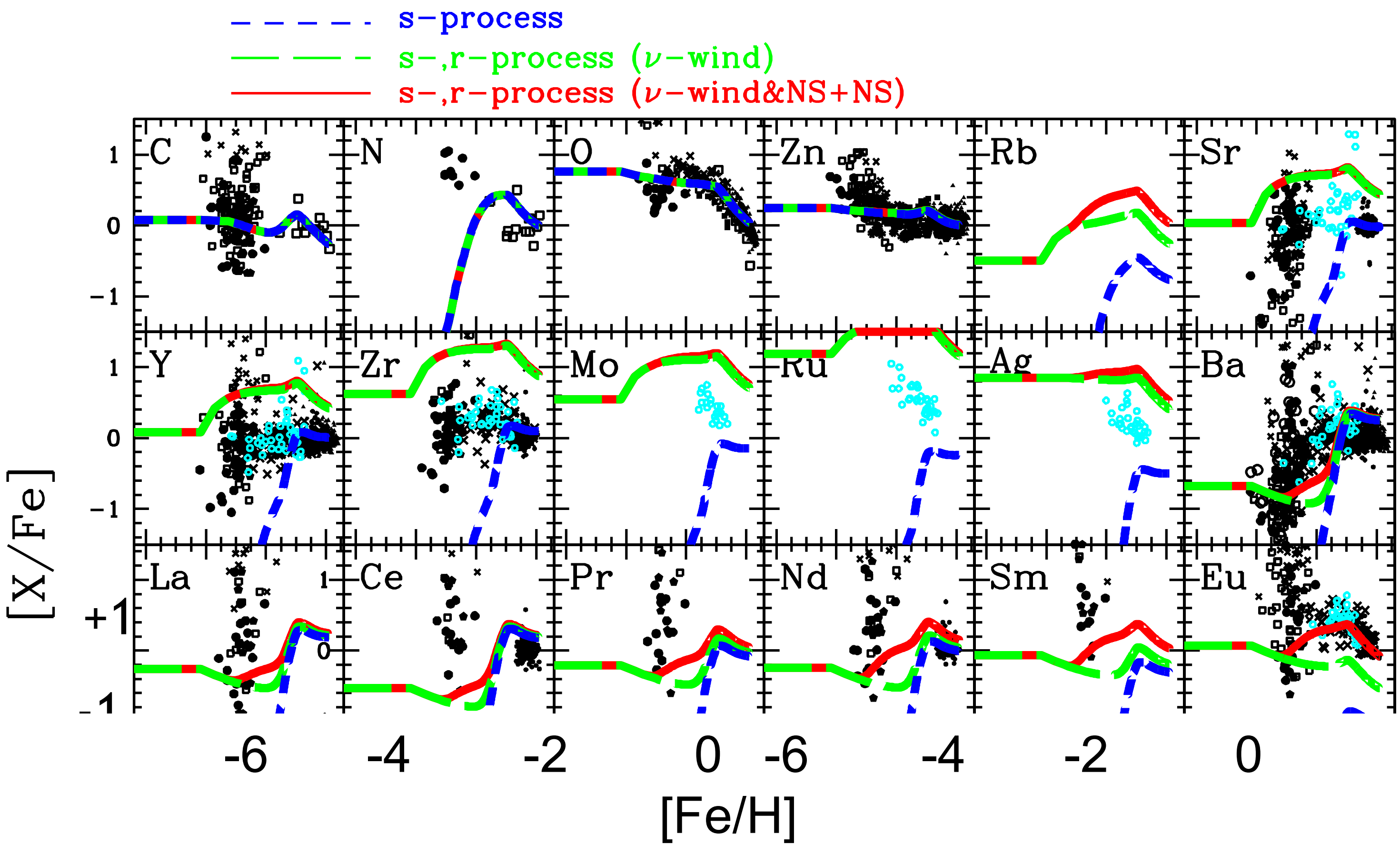
- The effect of binaries on AGB yields has been considered a problem for a while now
- But we don't know how model this accurately

→ Binary evolution results in a zoo of outcomes (Type Ia, novae, R Cor Borealis, sub-dwarf B, CEMP, Ba stars…)

Consider:

- All O stars are binaries (Sana et al. 2012)
- Binary fraction of G dwarfs is ~50%
- Does this mean that most (or all?) intermediate-mass of M > 3Msun are in binaries? How many will interact?
- We need better statistics (e.g., De Marco & Izzard 2017, Moe & De Stefano 2017)

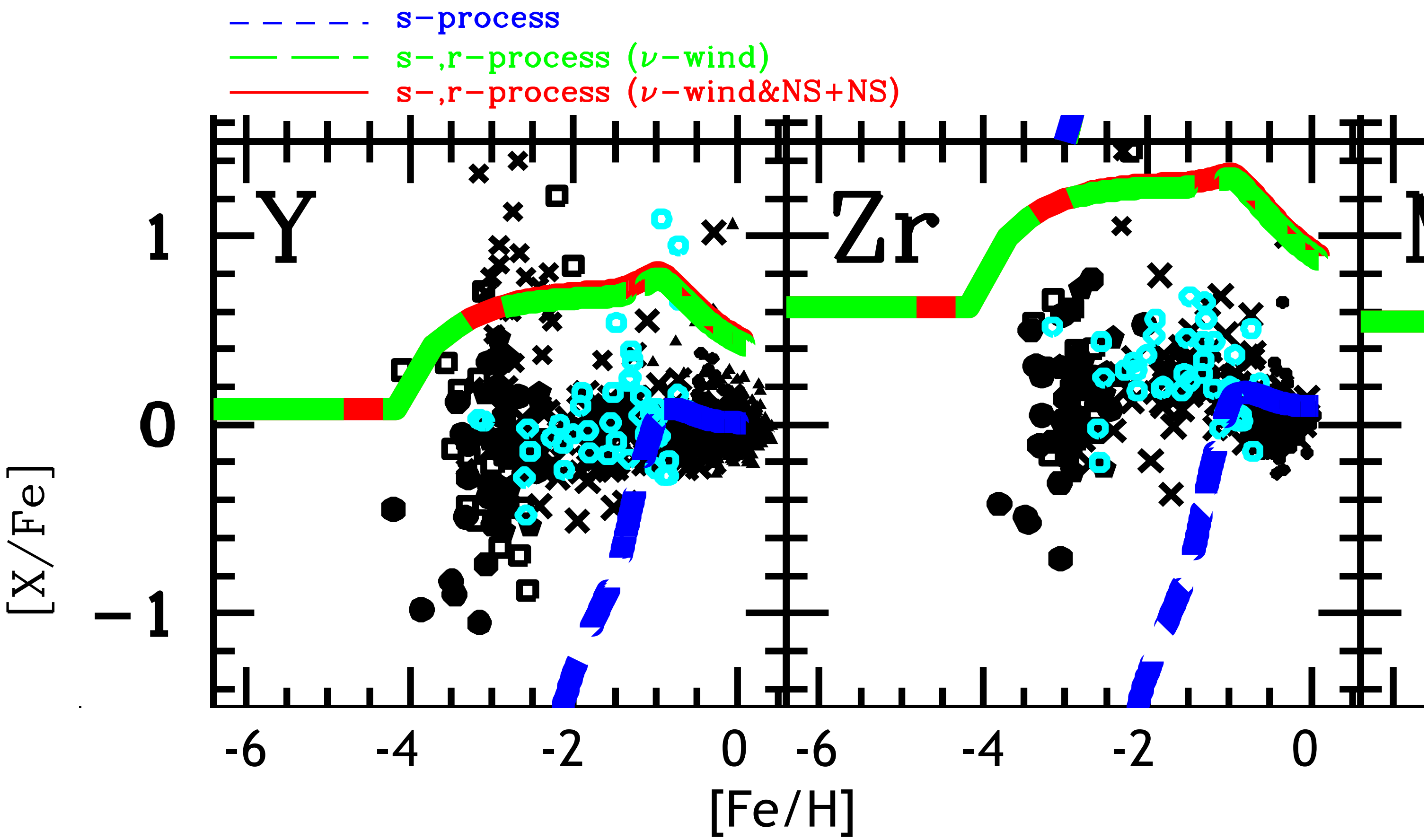
Evolution of elements in the Universe



For some elements, the s-process alone can produce the solar composition

This is not true for low metallicities (i.e., the early Universe)

Evolution of elements in the Universe



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Summary

- With available yields, we are now making quantitative chemical evolution predictions including heavy elements
- Which is 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)
- New observations test our models of the s-process
- What is the site of the i-process and it's contribution GCE?
- Nuclear uncertainties affecting r-process likely important for i-process as well
- Need yield tables to include the effects of binaries

Conferences in Australia this year

Upcoming conferences in Australia

- "*A celebration of CEMP and a Gala of Galah*", Nov 13-17 2017, Monash University, Melbourne, Australia
  - https://indico.fnal.gov/conferenceDisplay.py?confId=13478
- John Lattanzio's 60th birthday conference, Oct 29 – Nov 4, 2017, Port Douglas, Queensland
  - http://www.ast.cam.ac.uk/~gmh/JL60th/index.html

New theory postdoc at Monash University

New theory postdoc at Monash University to work with me, John Lattanzio, Chiaki Kobayashi and Maria Lugaro on chemical evolution and/or heavy-element nucleosynthesis, funded by an Australian Research Council grant

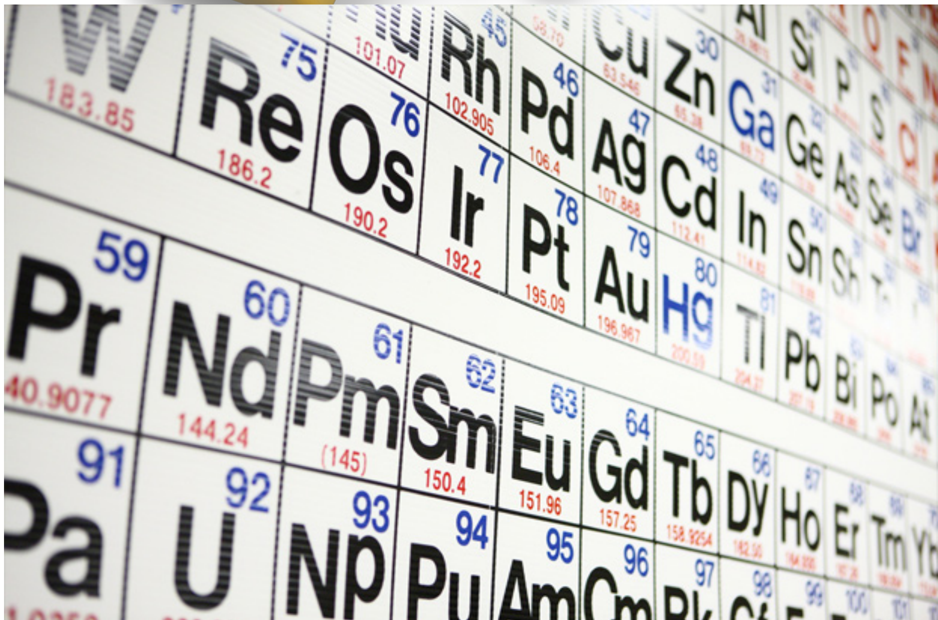
→ Will be advertised on the AAS job register 1 August 2017

→ Closing date 30 September 2017. Email me if interested.

Production of heavy elements

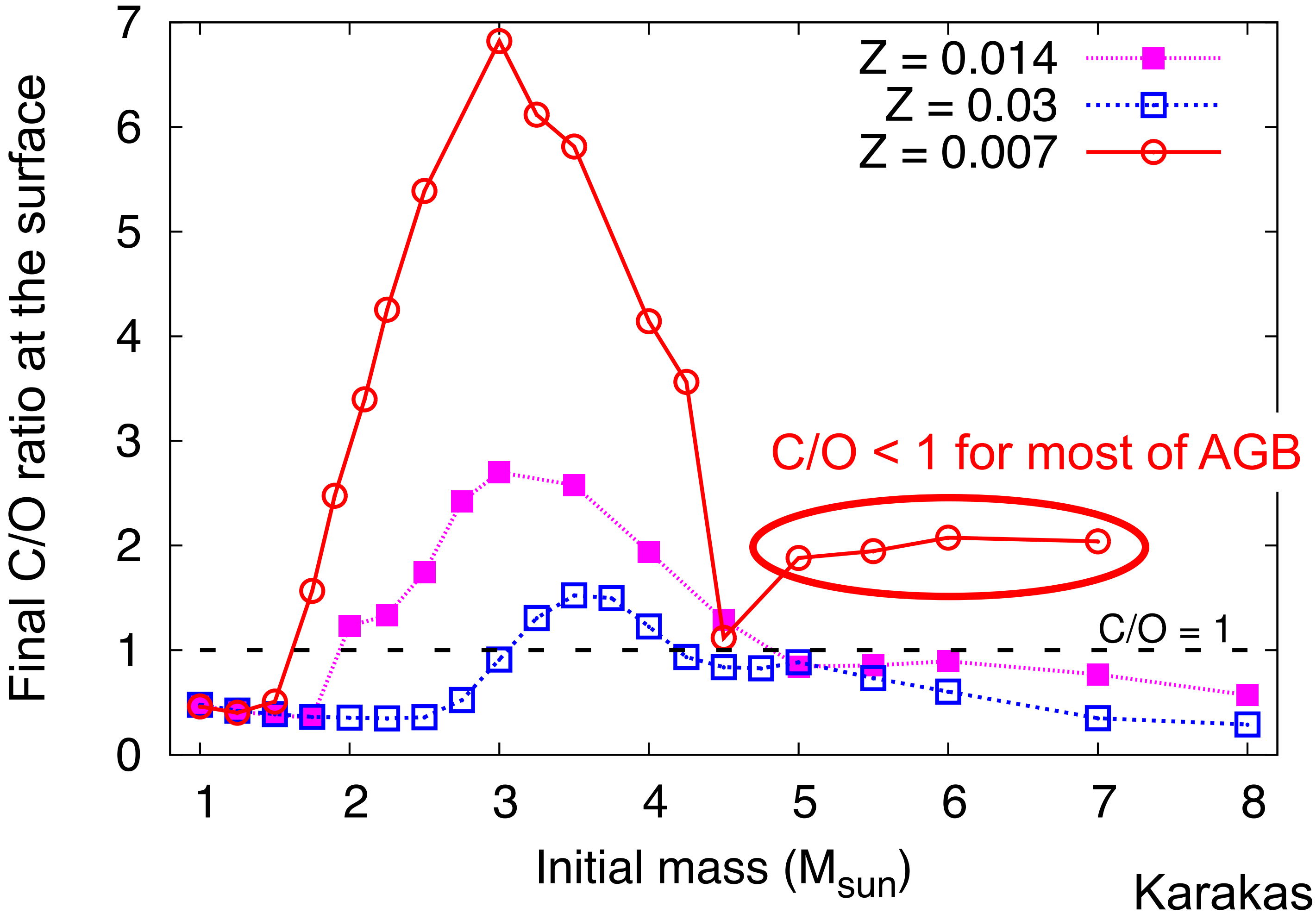
- Heavy elements: heavier than iron (Fe)
- Most heavy nuclei are formed by neutron addition onto Fe-peak elements
- Two processes:
  - *r-process* (rapid neutron capture)
  - *s-process* (slow neutron capture)

Reviews by
Kaeppeler et al. (2011)
Meyer (1994)



Effect of metallicity

Galactic thin-disk metallicities: [Fe/H] = -0.3, 0.0, +0.3



Karakas (2014)