The slow neutron capture process

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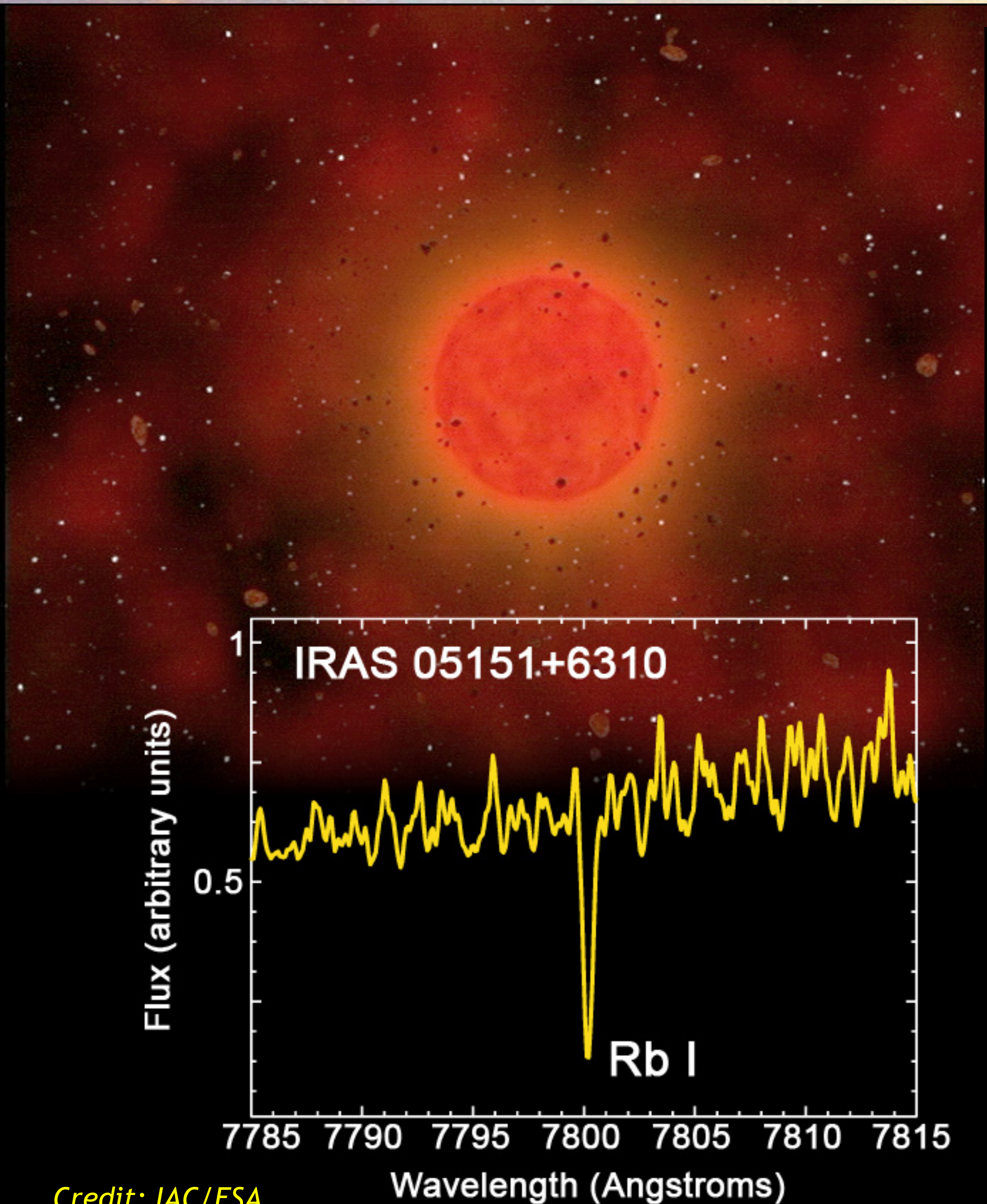
Outline of Lectures

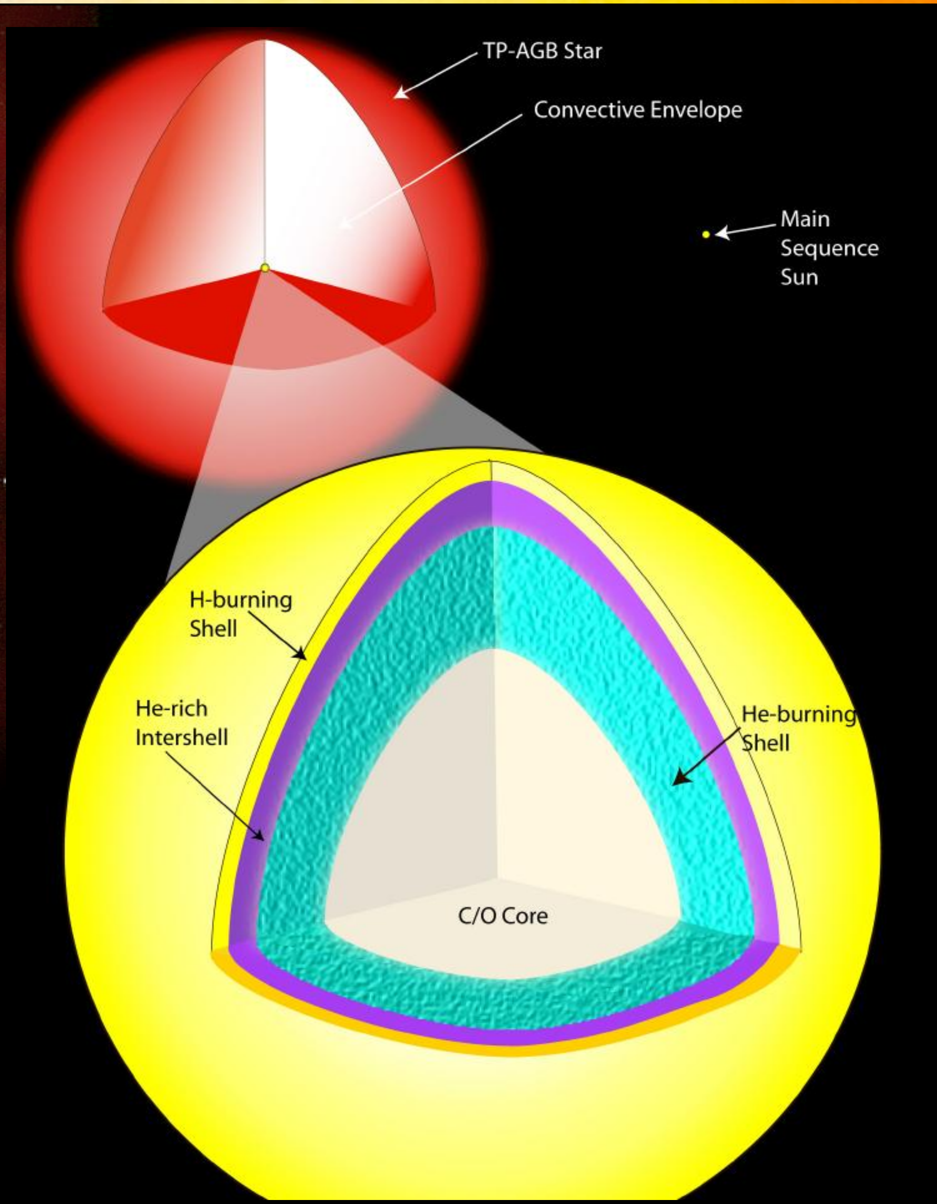
I'm giving three lectures, which will be broken down into the following components:

1. Introduction – some basics
2. Nucleosynthesis prior to the asymptotic giant branch (AGB) phase
3. The evolution and nucleosynthesis of AGB stars
4. The slow neutron capture process

AGB stars as element factories

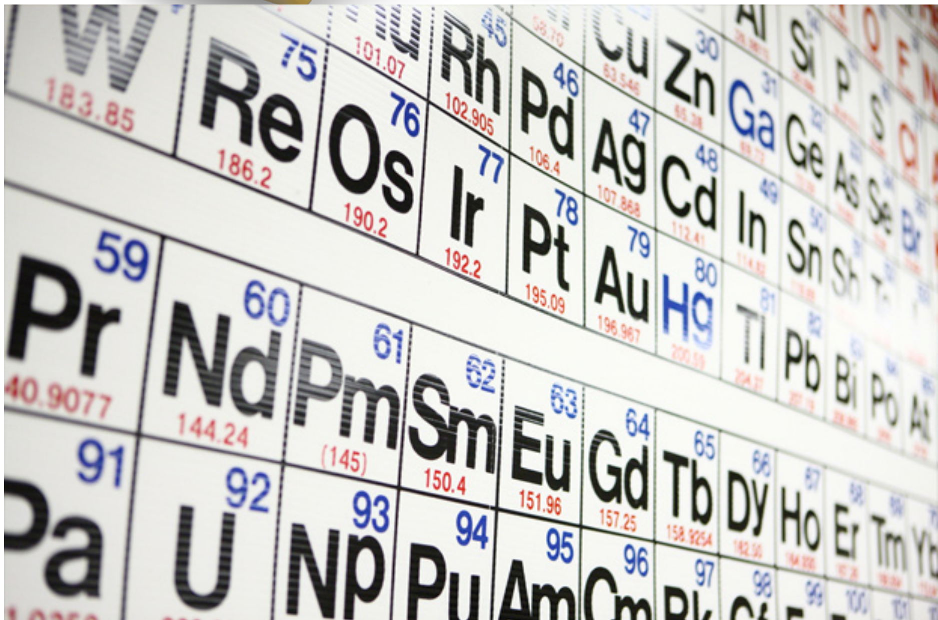


Credit: IAC/ESA



Production of heavy elements

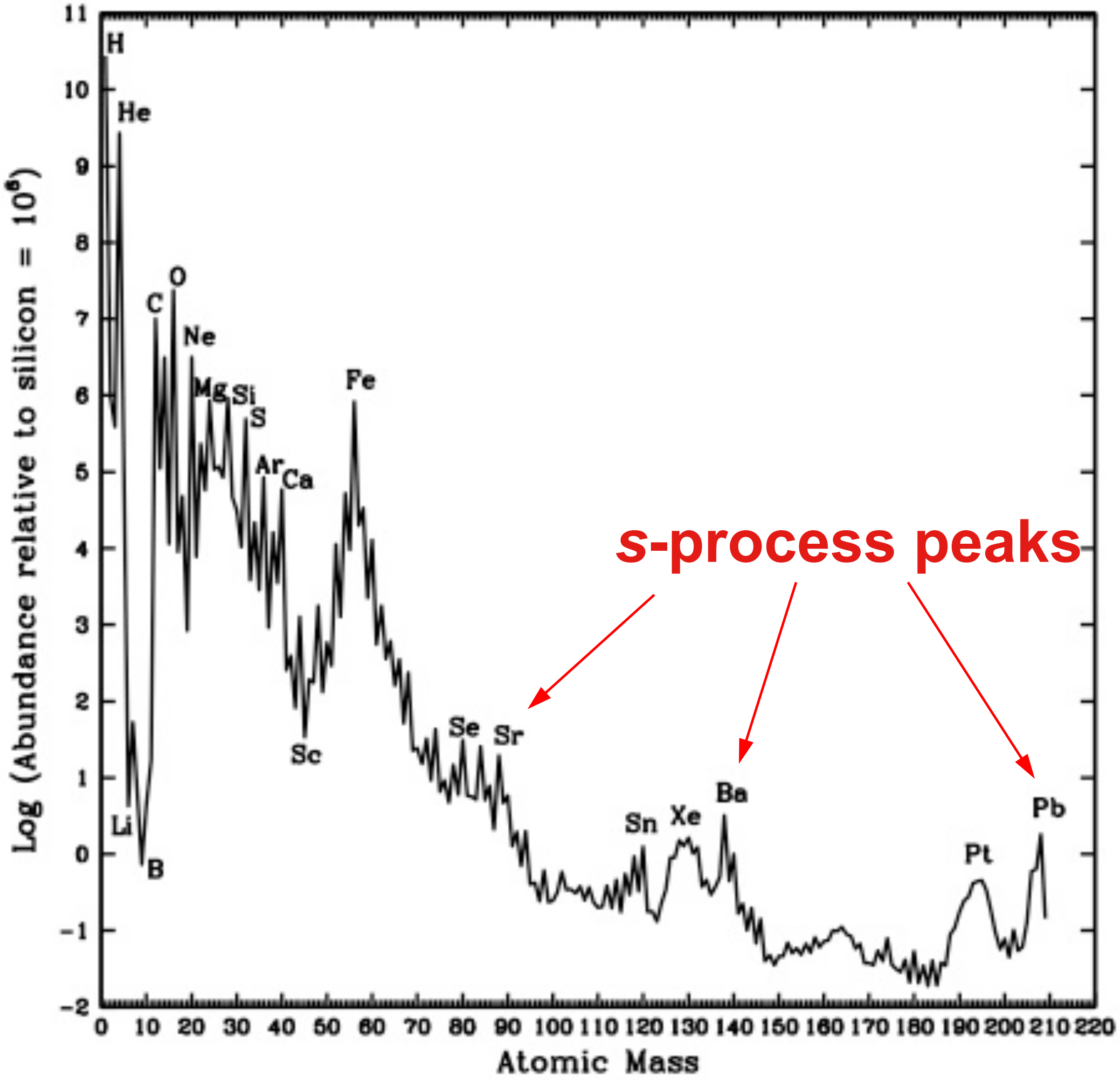
- By heavy elements we mean heavier than iron (Fe)
- Z is large → the electrostatic repulsion inhibits fusion reactions
- Most heavy nuclei are formed by neutron addition onto Fe-peak elements
- Two processes:
  - *r-process* (rapid neutron capture)
  - *s-process* (slow neutron capture)



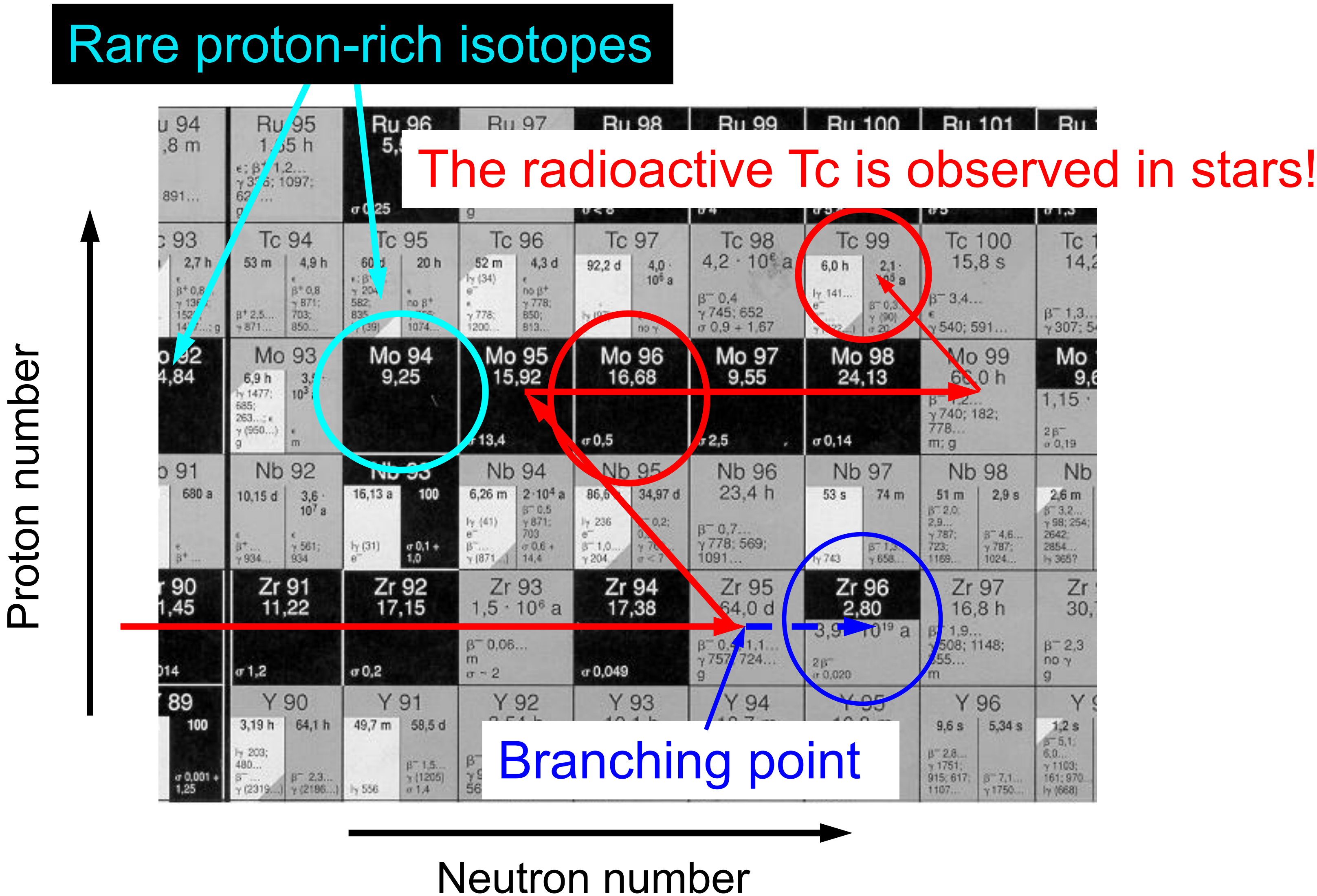
References:

Meyer (1994), Sneden, Cowan & Gallino (2008)

The distribution of heavy elements



Making heavy elements



Magic Numbers

- Analogous to the behaviour of atomic physics, where certain electron configurations are very stable
- Such elements are inert (e.g., noble gases, He, Ne, Ar)
- Similar behaviour seen in nuclear physics for isotopes with full neutron shells: neutron magic numbers
- nuclei with a magic number of neutrons n = 50, 82, 126 (for lighter elements n = 2, 8, 20, 28)
- A nuclei composed of a magic number of protons AND neutrons is very stable, doubly magic e.g. ^{16}O, and ^{208}Pb with p = 82 and n = 126
- Closed-shell nuclei are very stable against neutron capture and have low neutron-capture cross sections
- Act as bottlenecks, seen as s-process peaks
- The r-process peaks produced when very unstable nuclei decay to nuclei with a magic number of neutrons
- Note that ^{56}Ni, made in abundance by SN, is doubly magic!

The slow neutron capture-process

- Add neutrons slowly, so that unstable nuclei generally have time to β-decay before capturing another neutron
- That is, $\tau_{beta\text{-}decay} << \tau_{neutron\text{-}capture}$
- Produces nuclei along the "valley of beta-stability"
- Start with Fe-peak elements as they are very abundant, a typical path is:

$$^{56}Fe(n,\gamma)^{57}Fe(n,\gamma)^{58}Fe(n,\gamma)^{59}Fe$$

- What happens at ^{59}Fe? (half life ~ 44 days) → branching point: Choice between decaying to ^{59}Co or capturing a neutron to form ^{60}Fe
- The isotopic component of all elements between Sr and Pb have an important contribution from the s-process

Which stars make s-process elements?

1. AGB stars
   - AGB stars are observed to be rich in carbon and heavy elements produced by the s-process, including the unstable element Tc
   - The discovery of Tc in the atmosphere of an AGB star by Merrill (1952) was the first confirmation that stars make heavy elements
   - **Famous review**: Burbidge, Burbidge, Fowler & Hoyle (1957): B^2FH

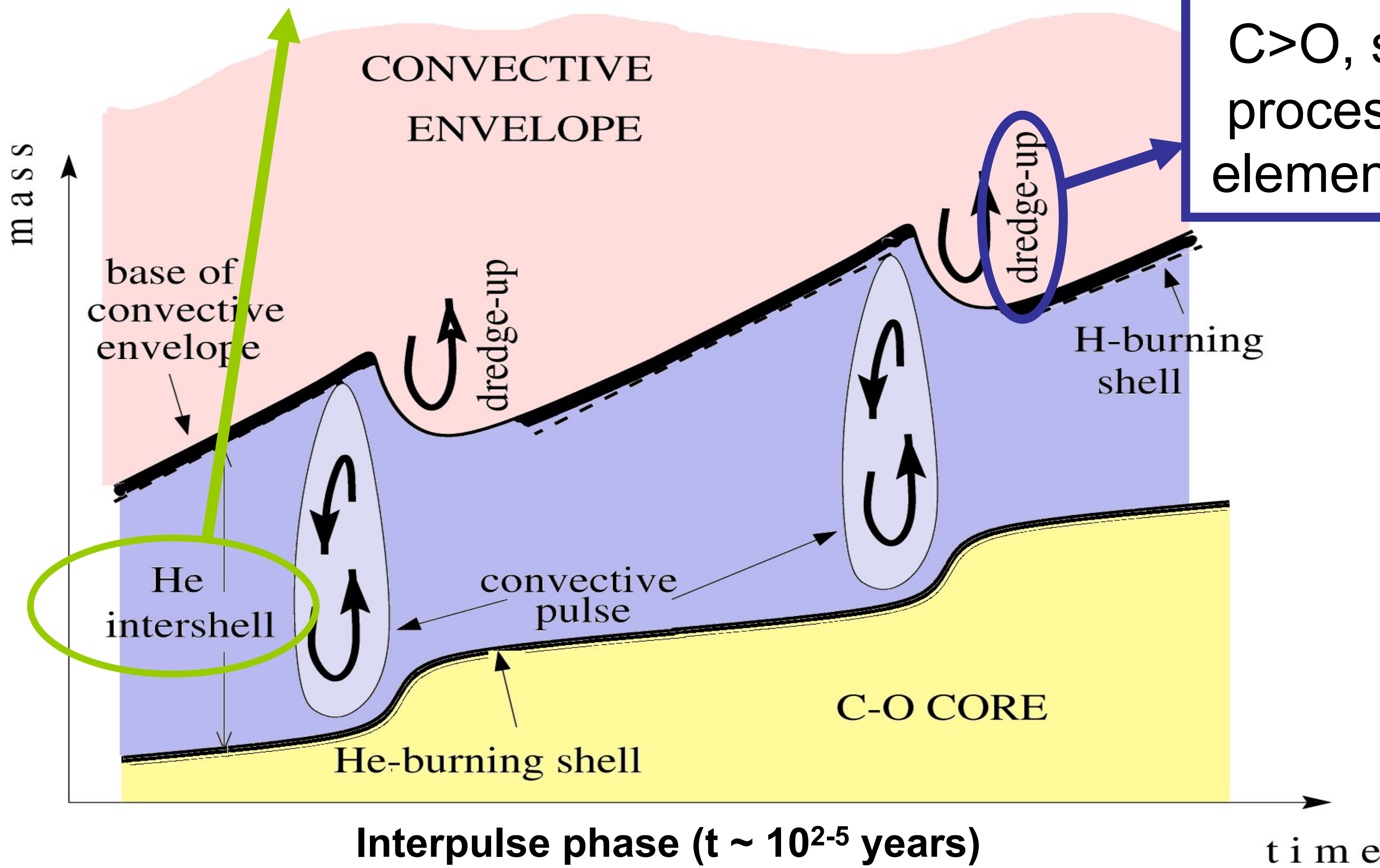
1. Massive stars
   - The He and C-burning shells of massive stars also make heavy elements via the s-process
   - Weak s-process, elements from Zn to Sr
   - Little production in metal-poor massive stars, unless rotation is significant
   - **References**: The et al. (2000), Pignatari et al. (2010), Frischknecht et al. (2012, 2016)

AGB nucleosynthesis

...

^{4}He, ^{12}C, ^{19}F, *s*-process elements: Zr, Ba, ...

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



Interpulse phase (t ~ $10^{2\text{-}5}$ years)

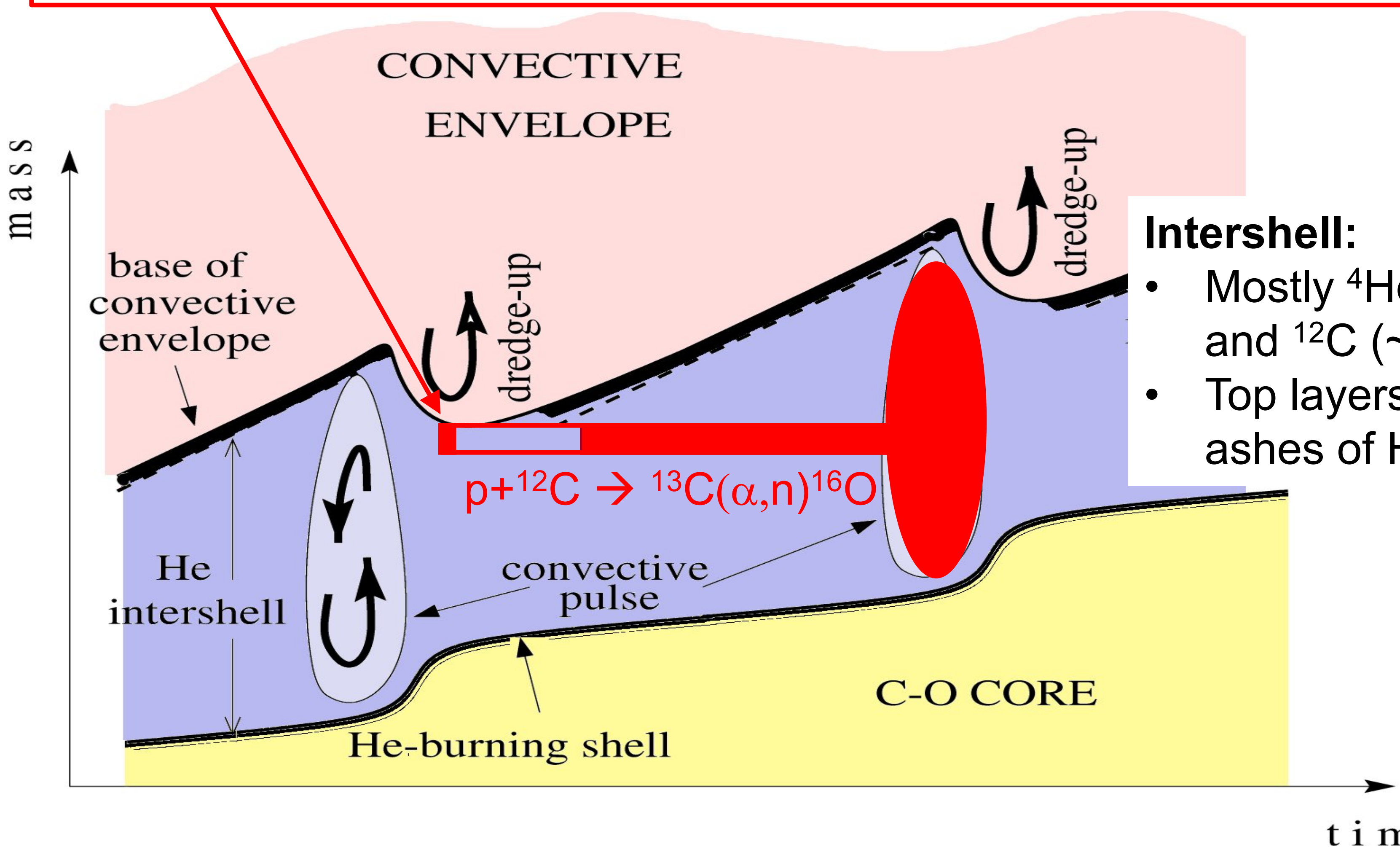
The s-process in AGB stars

- AGB stars observed to be enriched in s-process elements are mostly of low mass, between ~1 to 3Msun
- How does the s-process occur?
- The trick is making free neutrons!
- These come from the $^{13}C(\alpha, n)^{16}O$ reaction
- He-shell is ashes of H-burning: 98% He, 2% ^{14}N, some ^{13}C
- Models have shown that the amount of ^{13}C is not enough to account for s-process enhancement of S and C-type stars
- We still do not understand how stars produce enough ^{13}C in a He-burning region to activate this reaction

References: Busso, Gallino & Wasserberg (1999), Käppeler et al. (2011), Karakas & Lattanzio (2014)

The s-process

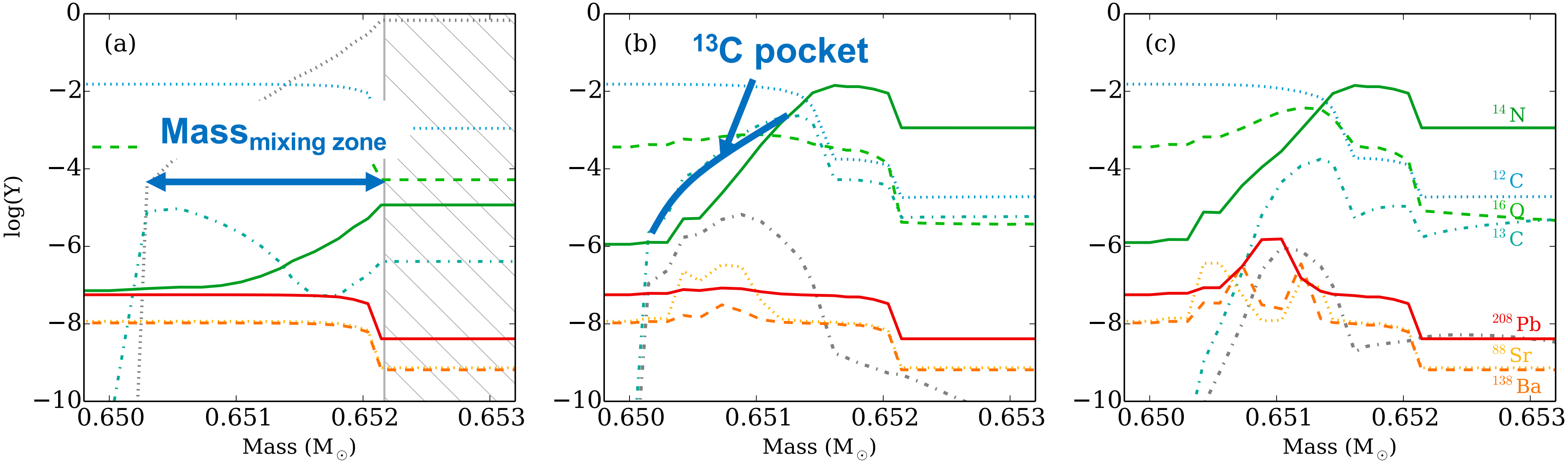
Neutrons are released in ^{13}C pockets – these form by mixing *a bit* of hydrogen into the intershell



Intershell:

- Mostly ^4He (~75%) and ^{12}C (~25%)
- Top layers are ashes of H-burning

The s-process



Composition of the interhsell in a 2Msun, Z = 0.001 model:

a) Protons mixed into the intershell over Mass$_{mixing\ zone}$.

b) The formation of the ^{13}C pocket; peak neutron flux.

c) Pb is created at the expense of Ba; ^{13}C abundance below that of ^{14}N → no more neutrons.

From Fishlock, Karakas et al. (2014)

Neutron sources: ^{22}Ne source

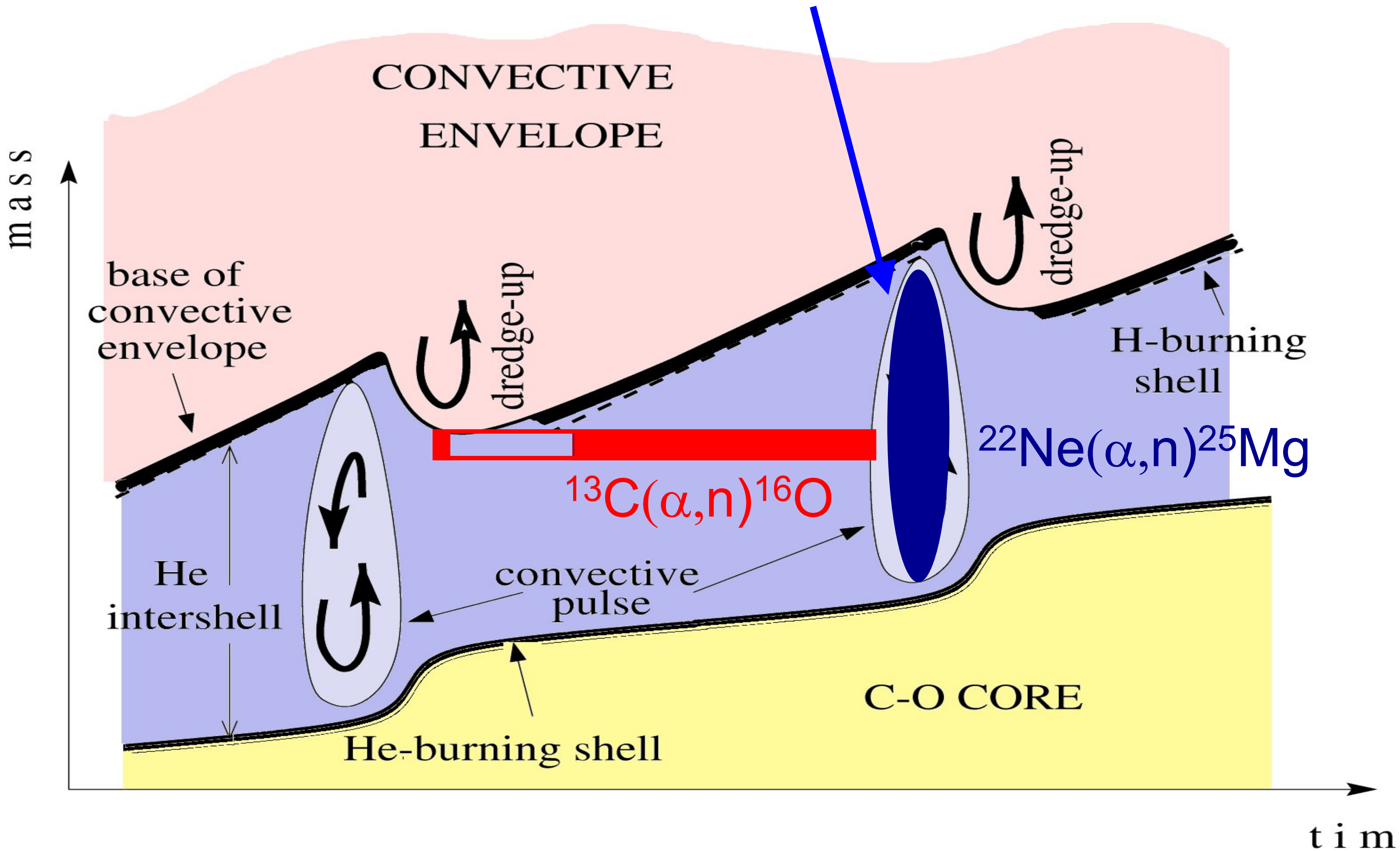
- The other neutron source is

  $^{14}N(\alpha,\gamma)^{18}F\ (\beta^{+}\nu)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$

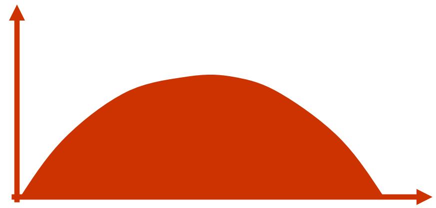
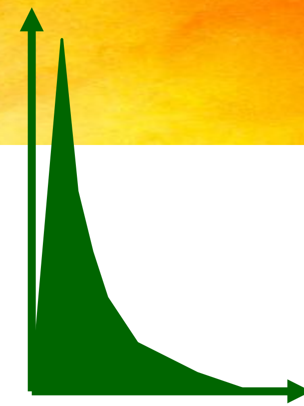
- Plenty of ^{14}N left over from CNO cycling to produce the ^{22}Ne
- Occurs in stars when the temperature of the He-burning region exceeds about 300 x 10^{6} K, under convective conditions
- Intermediate-mass AGB or super-AGB stars (~4 to maybe 10Msun)

Neutron production

Extra burst of neutrons from the $^{22}Ne(\alpha,n)^{25}Mg$ reaction, which takes place during thermal pulses



Theoretical models

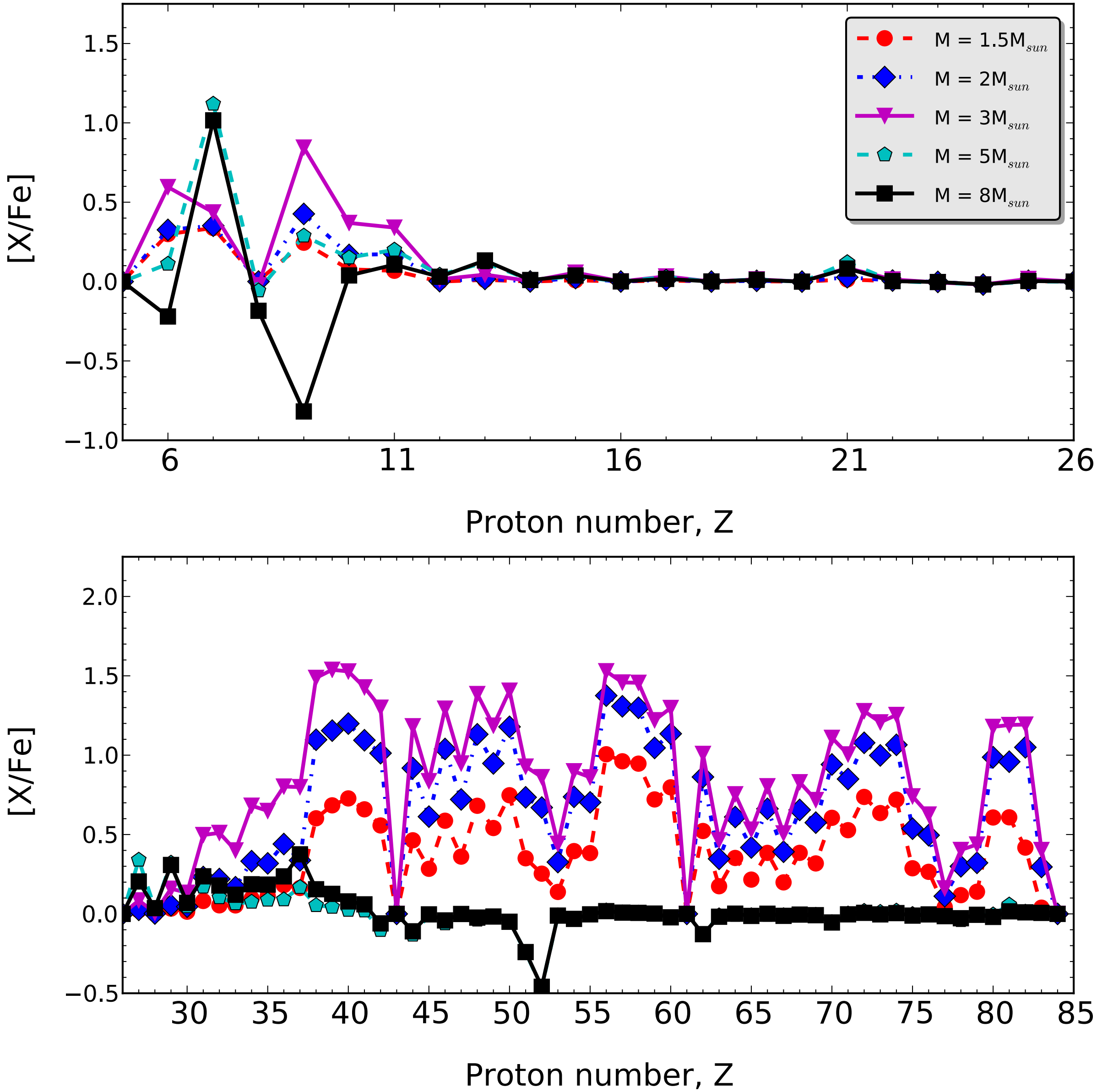
Typical neutron density profile in time:	 Low mass	 Intermediate mass
Neutron source	^{13}C(a,n)^{16}O	^{22}Ne(a,n)^{25}Mg
Maximum neutron density	10^8 n/cm^3	10^{13} n/cm^3 ?
Timescale	10,000 yr	10 yr
Neutron exposure	0.3 mbarn^{-1}	0.02 mbarn^{-1}

(at solar metallicity)

The s-process in solar-metallicity models

Z = 0.014,
[Fe/H] = 0

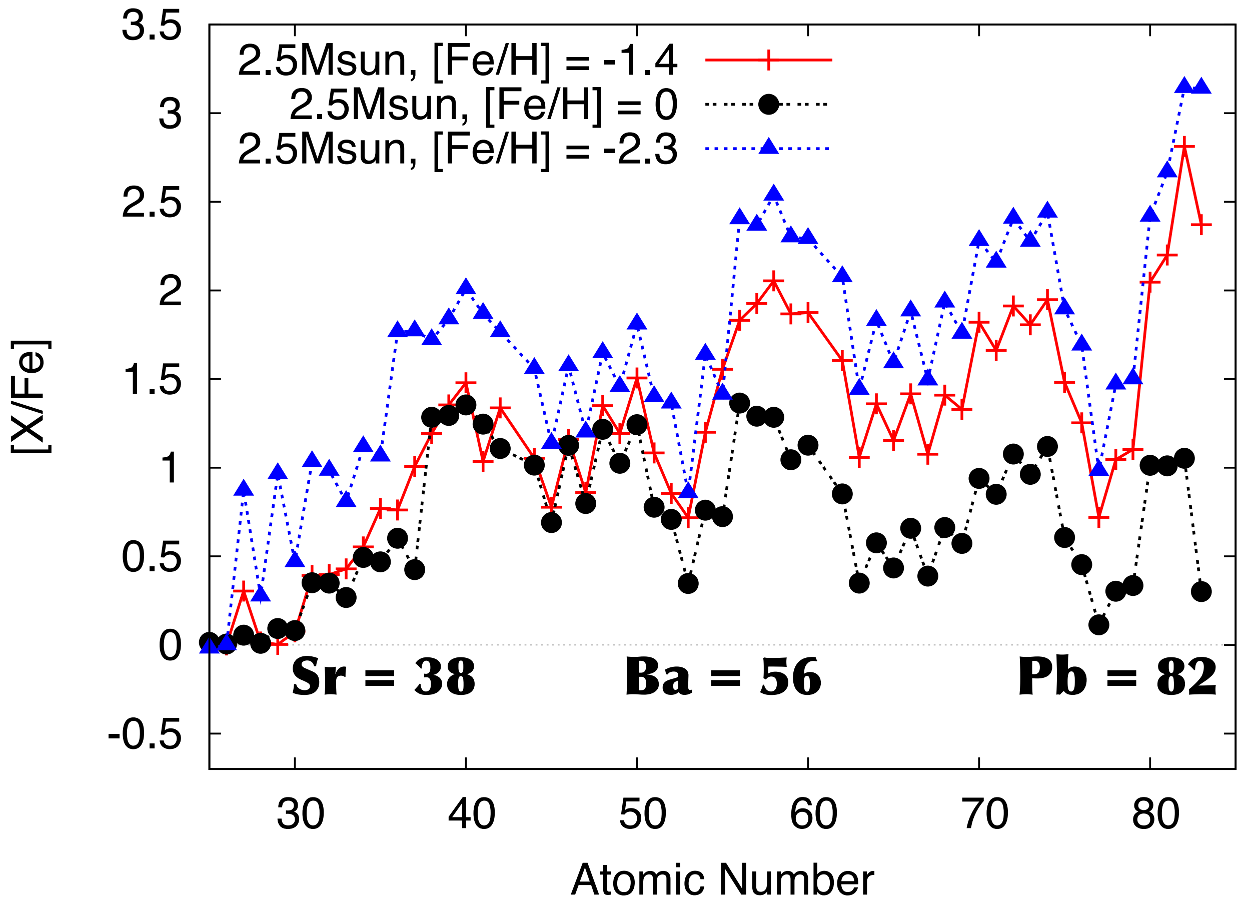
Similar to the bulk metallicity of the disk of our Galaxy



From Karakas & Lugaro (2016)

The s-process: The effect of metallicity

Decrease in metallicity results in more s-process elements at the 2nd peak (Ba, La), then at the 3rd (Pb)



e.g., see also Gallino et al. (1998), Busso et al. (2001)

Intrinsic s-process indicators

- [ls/Fe] = light s-process elements (e.g., Y, Sr, Zr) where [ls/Fe] = ([Y/Fe] + [Sr/Fe] + [Zr/Fe]) / 3
- [hs/Fe] = heavy s-process elements, typically choose 2-4 elements (e.g., Ba, La, Ce; Bisterzo et al. 2010, Lugaro et al. 2012)
- Then the ratio [ls/hs] are indicators of elements only produced in AGB stars (unlike Fe)
- These intrinsic ratios are mostly independent of AGB modelling uncertainties including mass loss, third dredge-up, and binary mass transfer
- Instead, they constrain the nucleosynthesis occurring in the deep layers of the star and trace the metallicity

Intrinsic s-process indicators

- [ls/Fe] = light s-process elements (e.g., Y, Sr, Zr) where [ls/Fe] = ([Y/Fe] + [Sr/Fe] + [Zr/Fe]) / 3
- [hs/Fe] = heavy s-process elements, typically choose 2-4 elements (e.g., Ba, La, Ce)
- Example for 3Msun models of different metallicity:

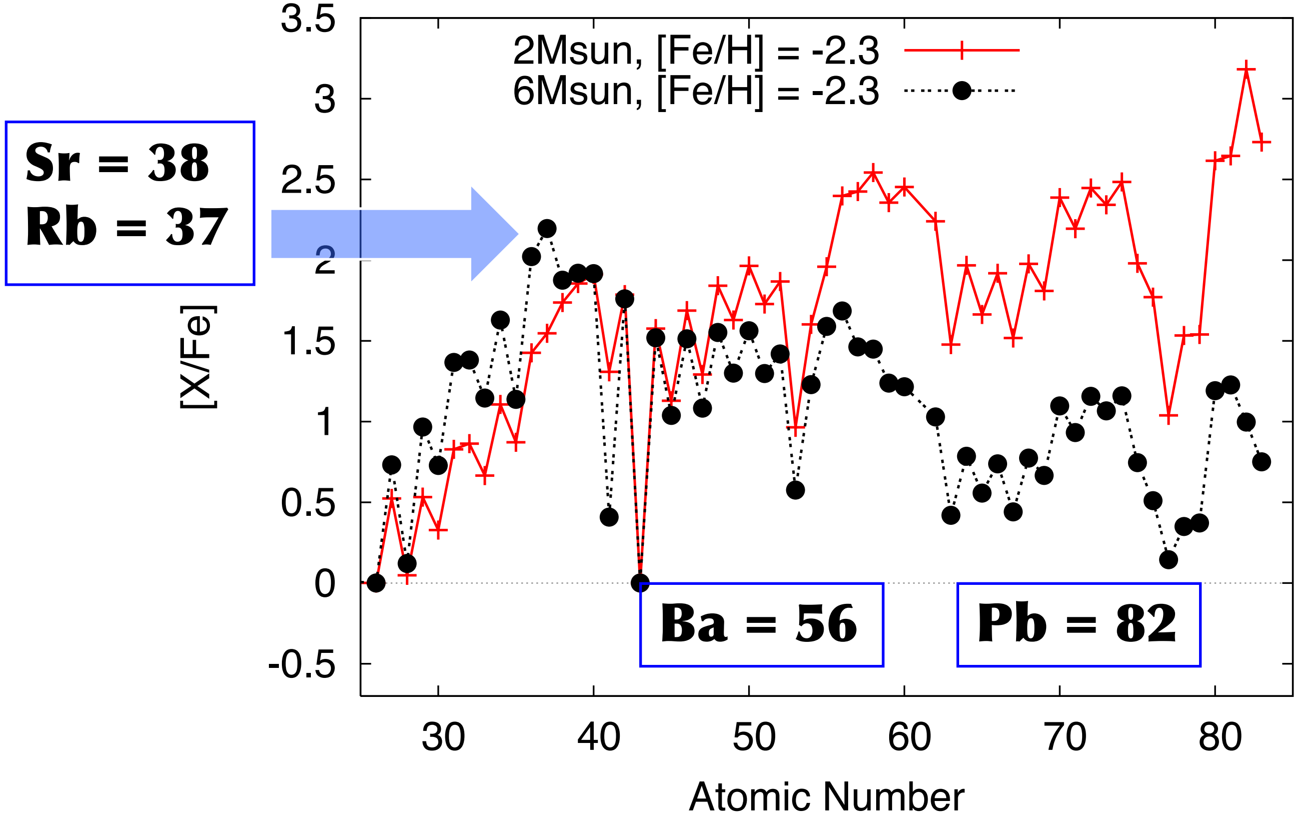
[Fe/H]	[Rb/Zr]	[ls/Fe]	[hs/Fe]	[hs/ls]	[Pb/hs]
+0.3	-0.57	1.16	0.92	-0.24	-0.39
0.0	-0.73	1.47	1.44	-0.03	-0.28
-0.3	-0.69	1.64	1.96	0.32	-0.20

- Compare to a 5Msun, [Fe/H] = – 0.3:

[Fe/H]	[Rb/Zr]	[ls/Fe]	[hs/Fe]	[hs/ls]	[Pb/hs]
-0.3	0.48	0.26	0.03	-0.23	0.00

The s-process: Why range 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
- Figure: Yields for [Fe/H] = −2.2 from Lugaro et al. (2012) for M = 1 to 6Msun

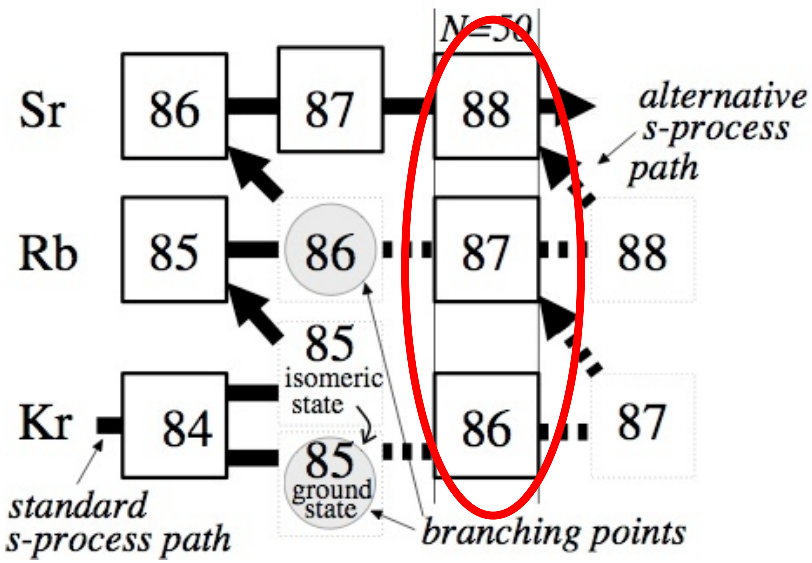


Neutron density indicators

At high neutron densities, two branching points open that allow rubidium to be produced. At N_n=5 x 10^8 n/cm^3 ~80% of the flux goes through ^{85}Kr, and the branching at ^{86}Rb opens to make ^{87}Rb

1. ^{85}Rb has a high σ = 240 mb (30 keV)
2. ^{87}Rb is magic, has a low σ = 15 mb (30 keV)

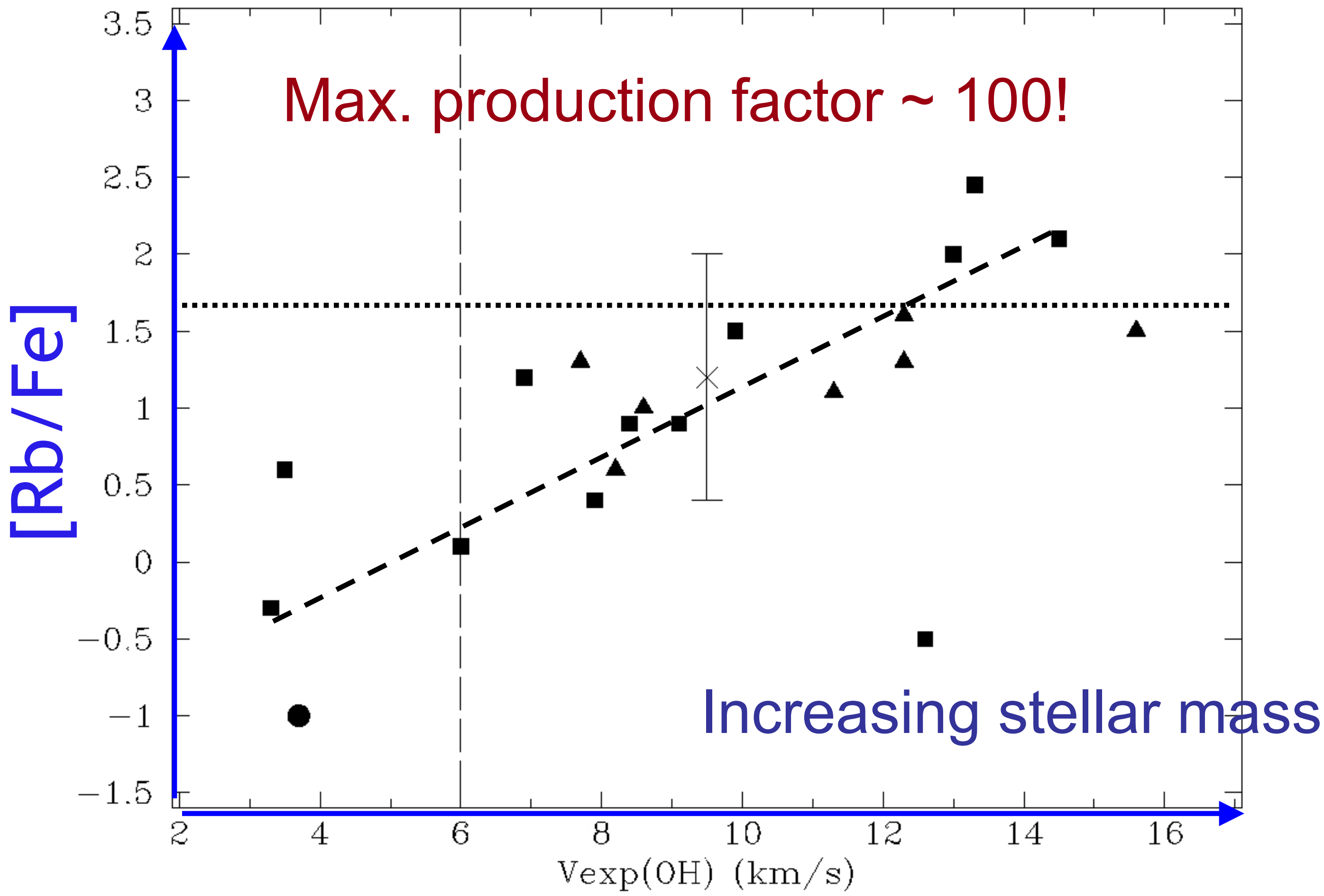
→ Rb in AGB stars in an indicator of the neutron density!



^{86}Kr, ^{87}Rb, and ^{88}Sr are all magic, with low neutron capture cross sections
In low-mass stars: ^{88}Sr produced
In massive AGB: ^{87}Rb

Zr,Sr/Rb > 1 → low-mass AGB
Zr,Sr/Rb < 1 → > 4Msun AGB

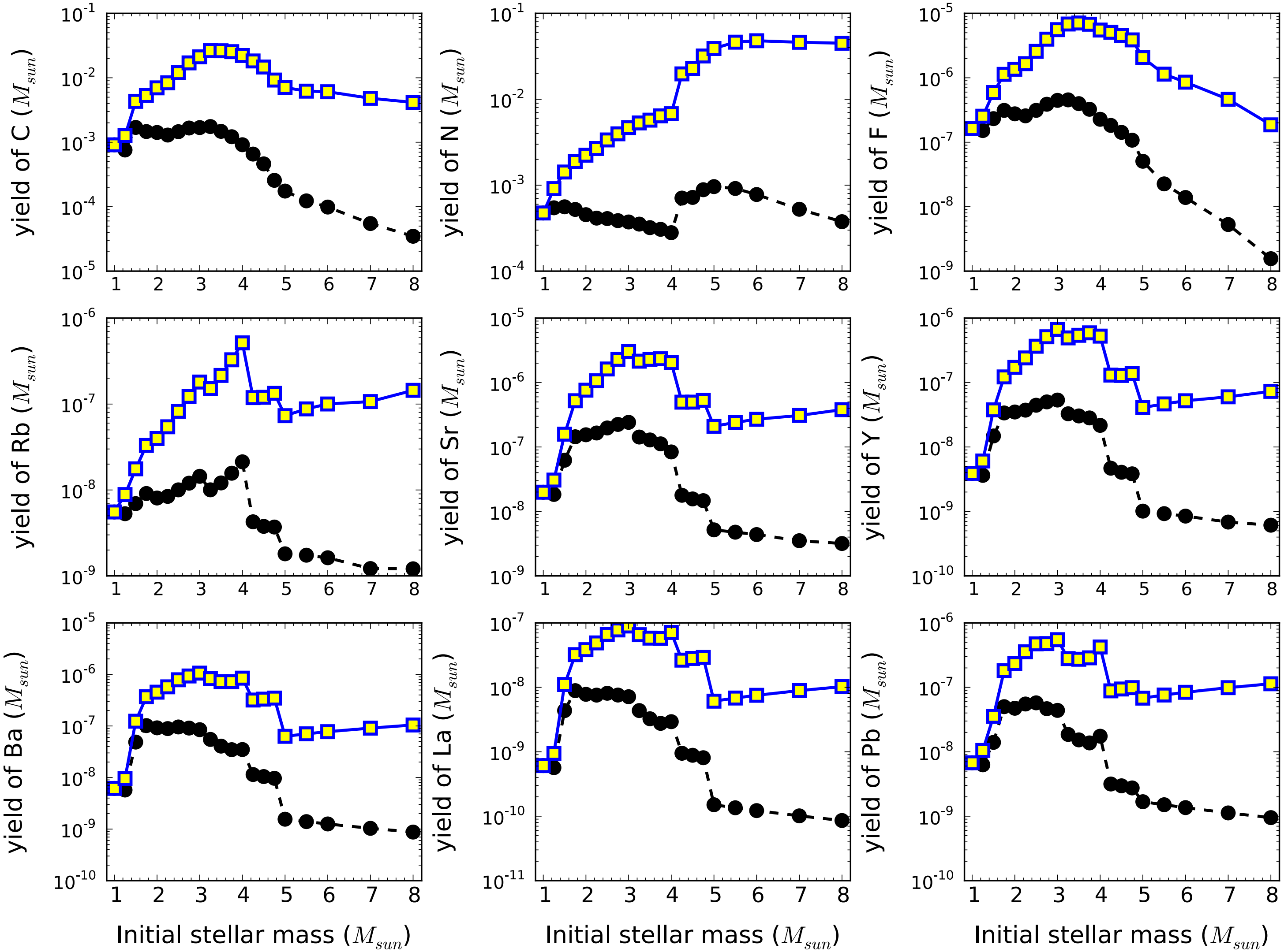
Rubidium in bright AGB stars



From D. A. Garcia-Hernandez et al. (2006, Science)
See models by Karakas et al. (2012), van Raai et al. (2012)

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

AGB chemical yields

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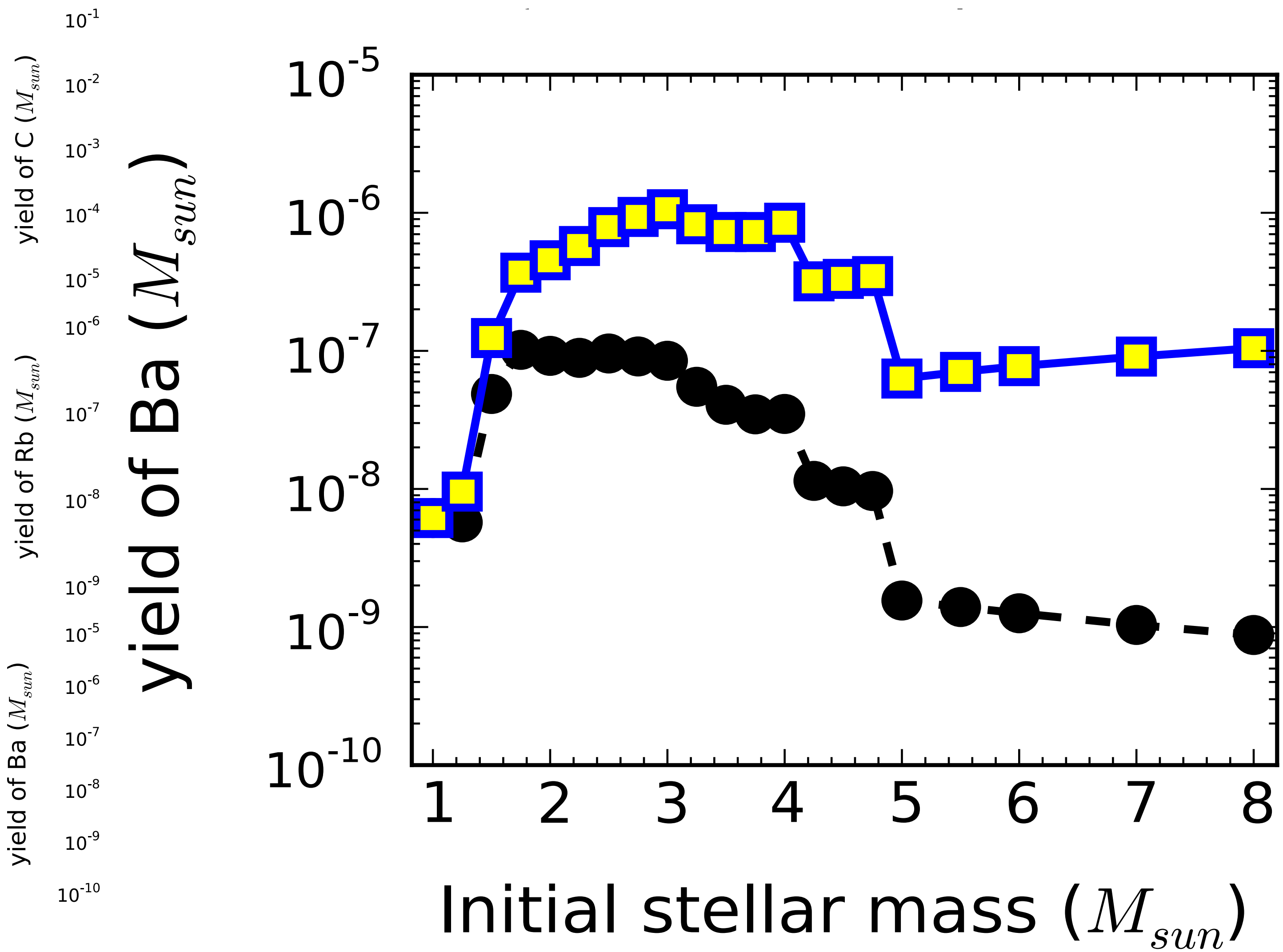
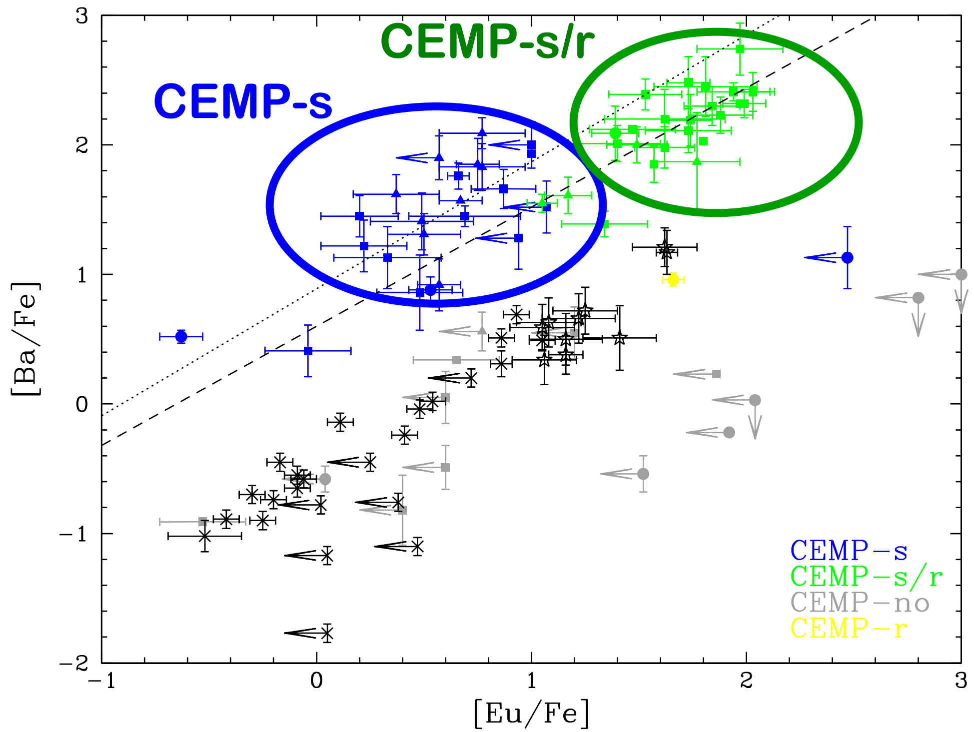


Yield = amount of an isotope ejected into the ISM over the star's lifetime

Black dots = weighted by an IMF

Carbon enhanced metal-poor stars

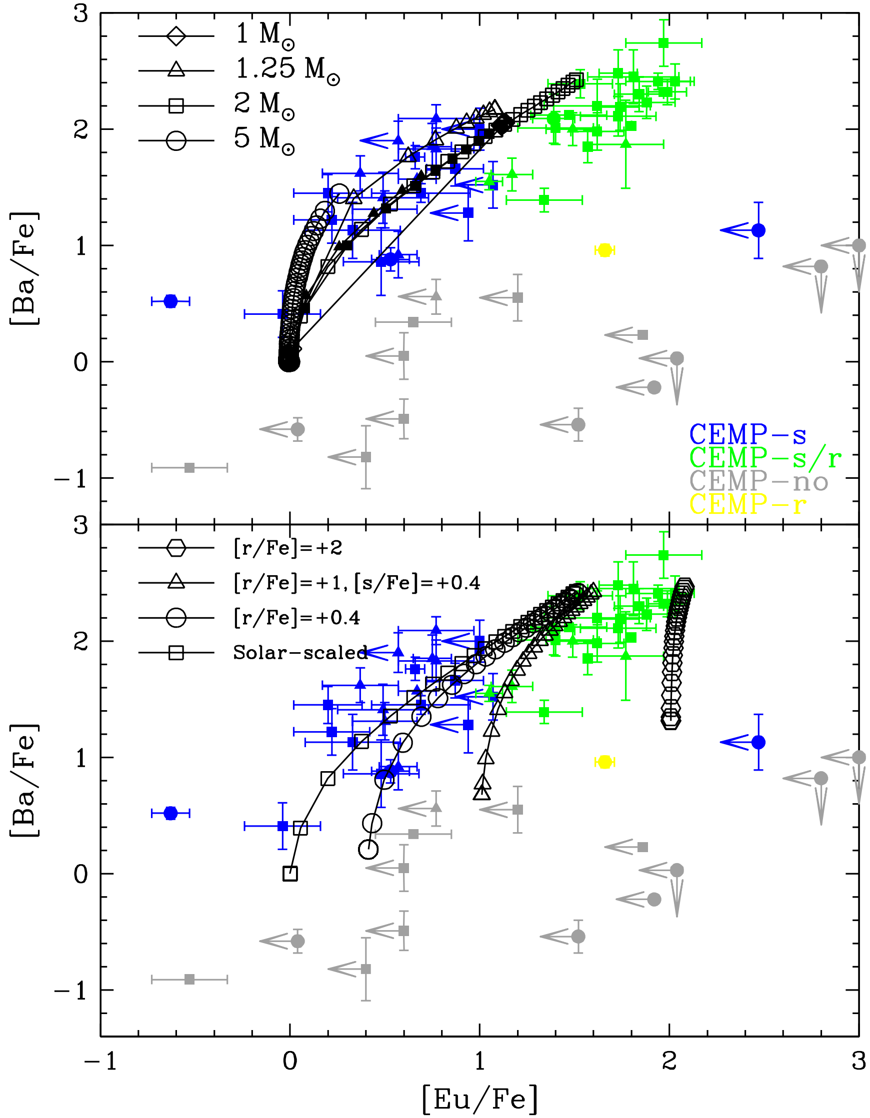
- Next few slides from Lugaro, Karakas et al. (2012)
- Roughly 10-20% of old halo stars are C-rich ([C/Fe] > 1; reviews by Beers & Christlieb 2005, Frebel & Norris 2015)
- Of these ~2/3 show enrichments in heavier elements (e.g., Aoki et al. 2007)



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

[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**

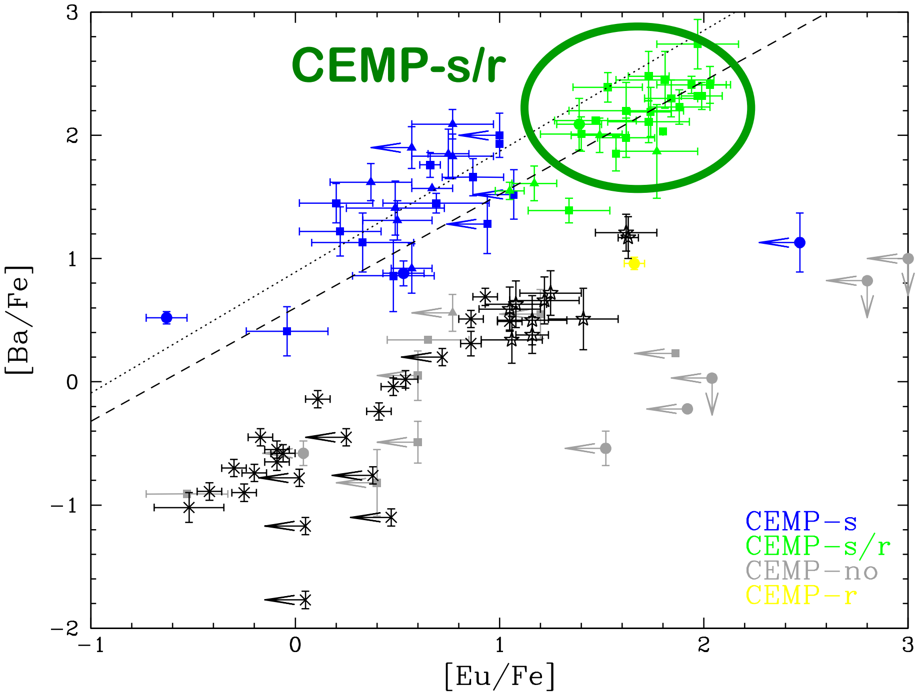


Summary:

- 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

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
- It is puzzling how CEMP-s/r could have formed in such large numbers
- Given that the s and r-processes are thought to occur in independent events
  - s-process (AGB stars)
  - r-process (supernnovae?)

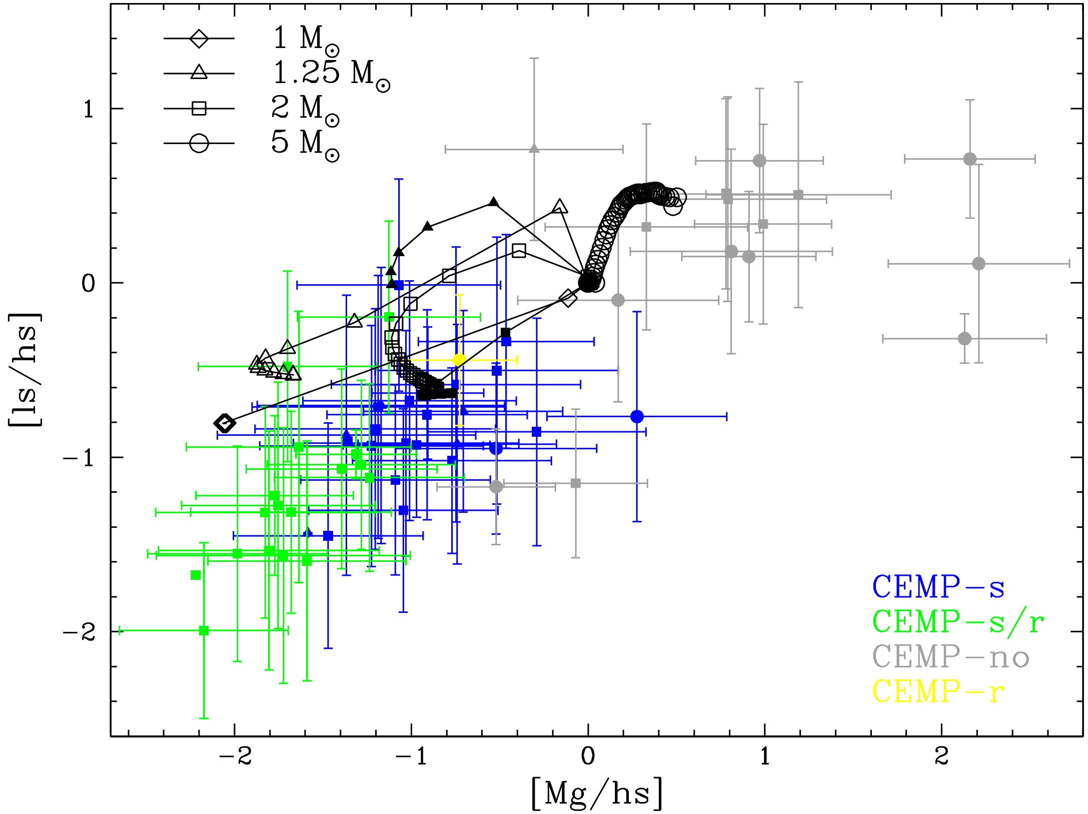


Definition of CEMP s/r:

- [Eu/Fe] > 1
- [Ba/Eu] > 0 but lower than for CEMP-s (0.9 c.f. 0.6)
- Appear distinct from CEMP-s

[ls/hs] versus [Mg/hs]

- Use "intrinsic" indicators, elemental ratios that only include elements produced in AGB stars
- 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

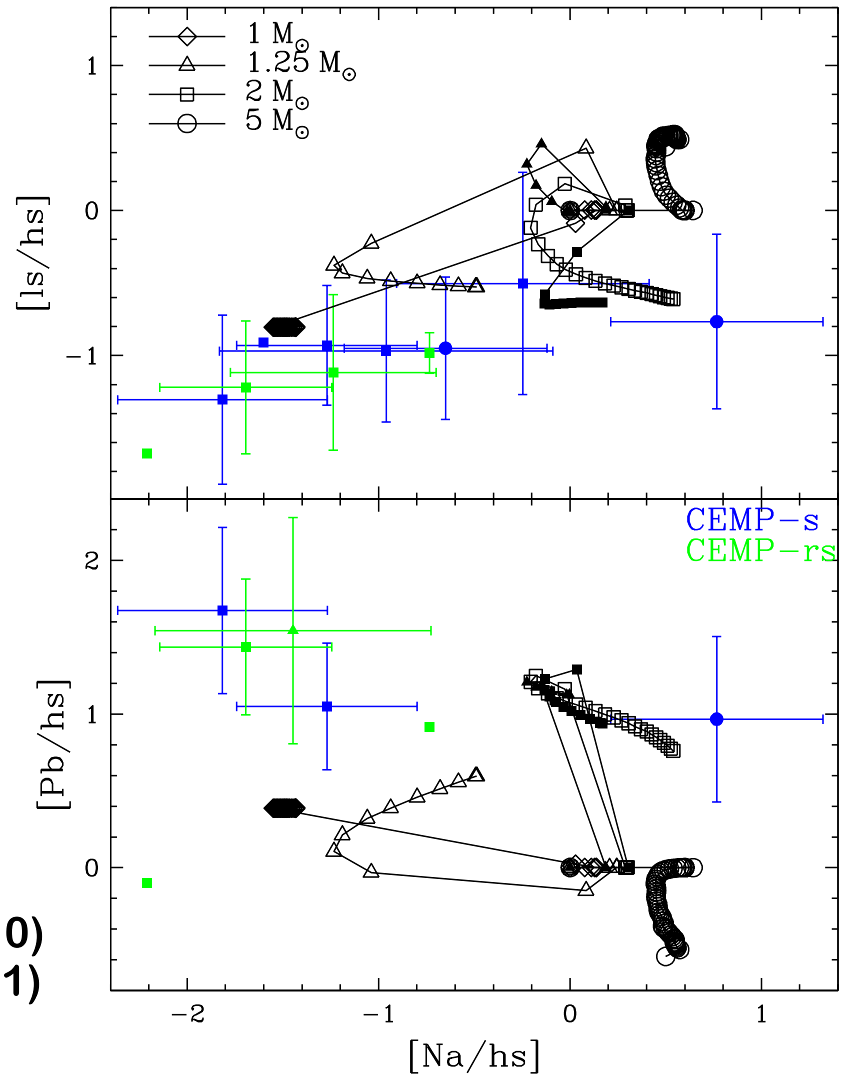


CEMP data from Masseron et al. (2010). Data for *ls* is taken from the SAGA database (Suda et al. 2008)

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

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 $^{14}N(a,\gamma)^{18}O(a,\gamma)^{22}Ne$ in intershell then $^{22}Ne(p,\gamma)^{23}Na$

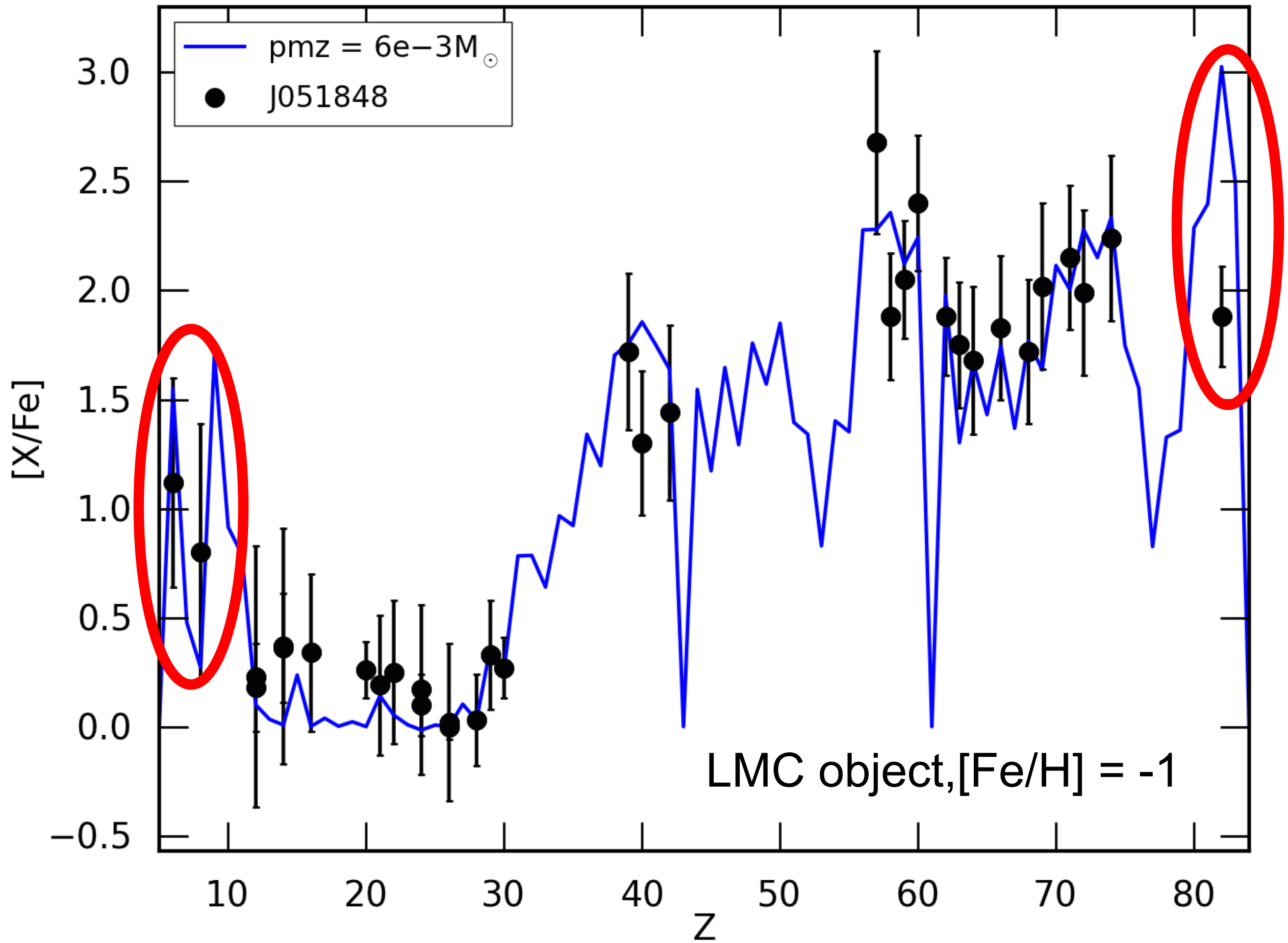


CEMP data from Masseron et al. (2010)
Data for Na from Lucatello et al. (2011)

Problems with theoretical picture

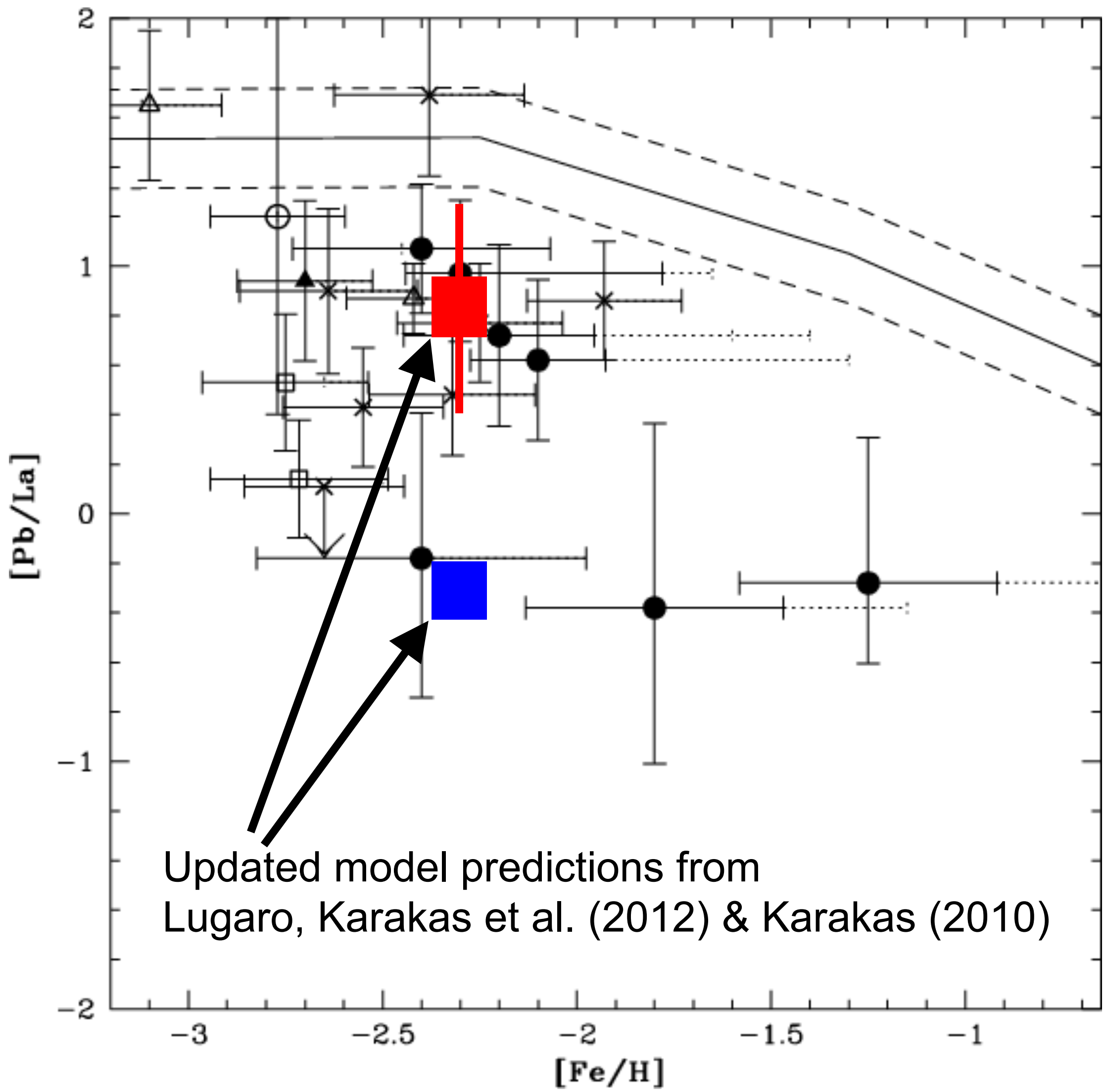
Post-AGB stars: Evolved from stars of low-mass, 1-1.5Msun at relatively low metallicity, [Fe/H] ~ -1 (e.g., De Smedt et al. 2014; van Aarle et al. 2013)

Figure from Kenneth De Smedt



What about carbon-enhanced metal-poor stars?

- [Pb/La] from a selection of CEMP stars. From Van Eck et al. (2003)

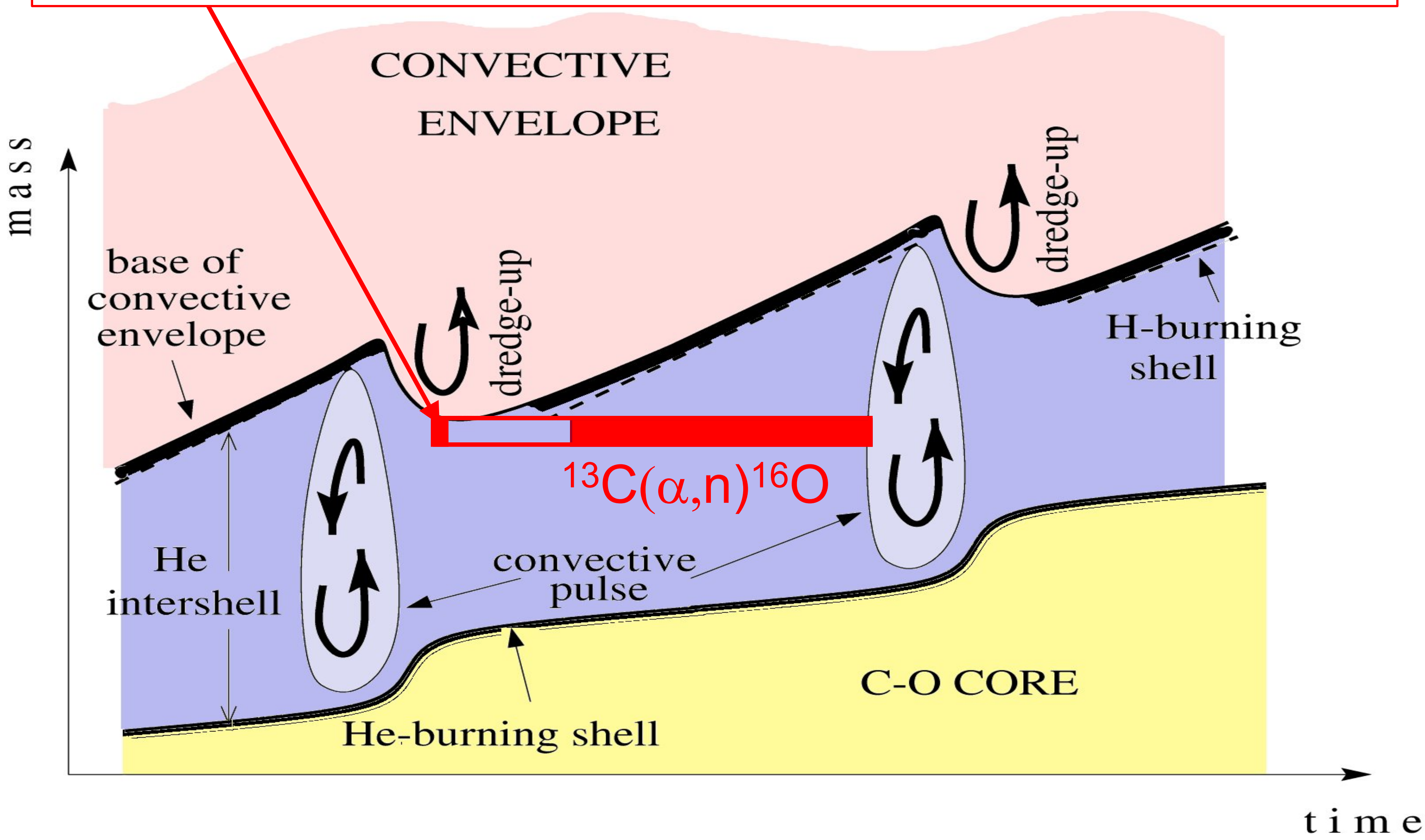


2Msun, [Fe/H] = -2.3
→ Produces CEMP-type composition
→ Low neutron density

6Msun, [Fe/H] = -2.3
→ Does not produce a CEMP
→ High neutron density

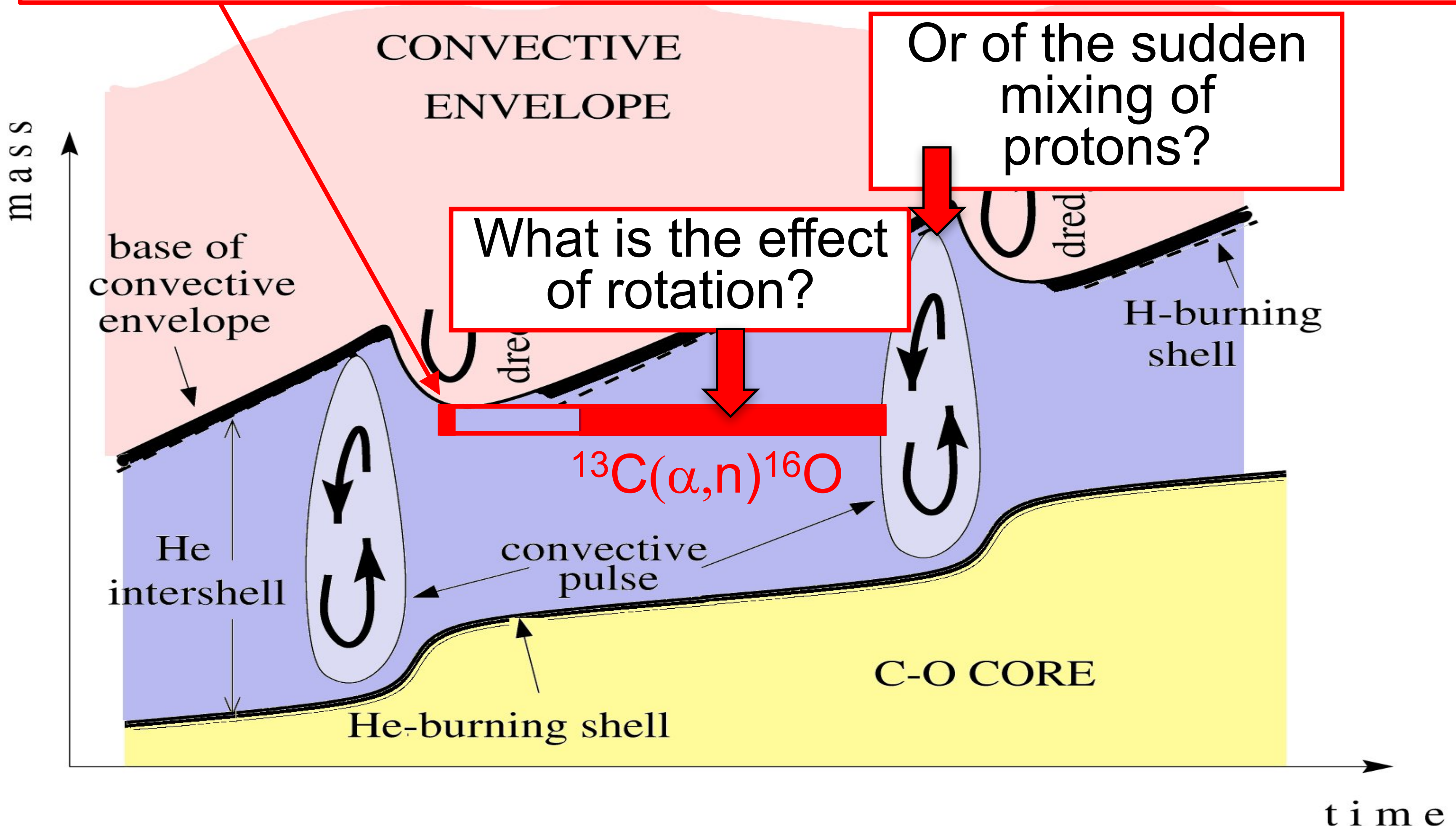
Neutron production is still poorly understood

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



Neutron production is still poorly understood

How much hydrogen is need to make a ^{13}C pocket? We don't really know. This is a big uncertainty in models of the s-process



The intermediate process

Neutron flux determines whether we have an s or r-process:

- r-process: $n_n > 10^{20}$ n/cm^3
- s-process: $n_n < 10^{13}$ n/cm^3

During the *r* process:
Time scale (n,g) << τ_β

During the *s* process:
Time scale (n,g) >> τ_β

- What about in between?
- Theoretically, we know that proton ingestion into a He-burning region will produce neutron densities of ~10^{15} n/cm^3 (Campbell, Lugaro & Karakas 2010)
- There was no evidence that such behaviour was found in nature, until recently

The i-process

HD 94028 from Roederer et al. (2016)

- Do proton ingestion episodes produce an i-process in post-AGB stars?

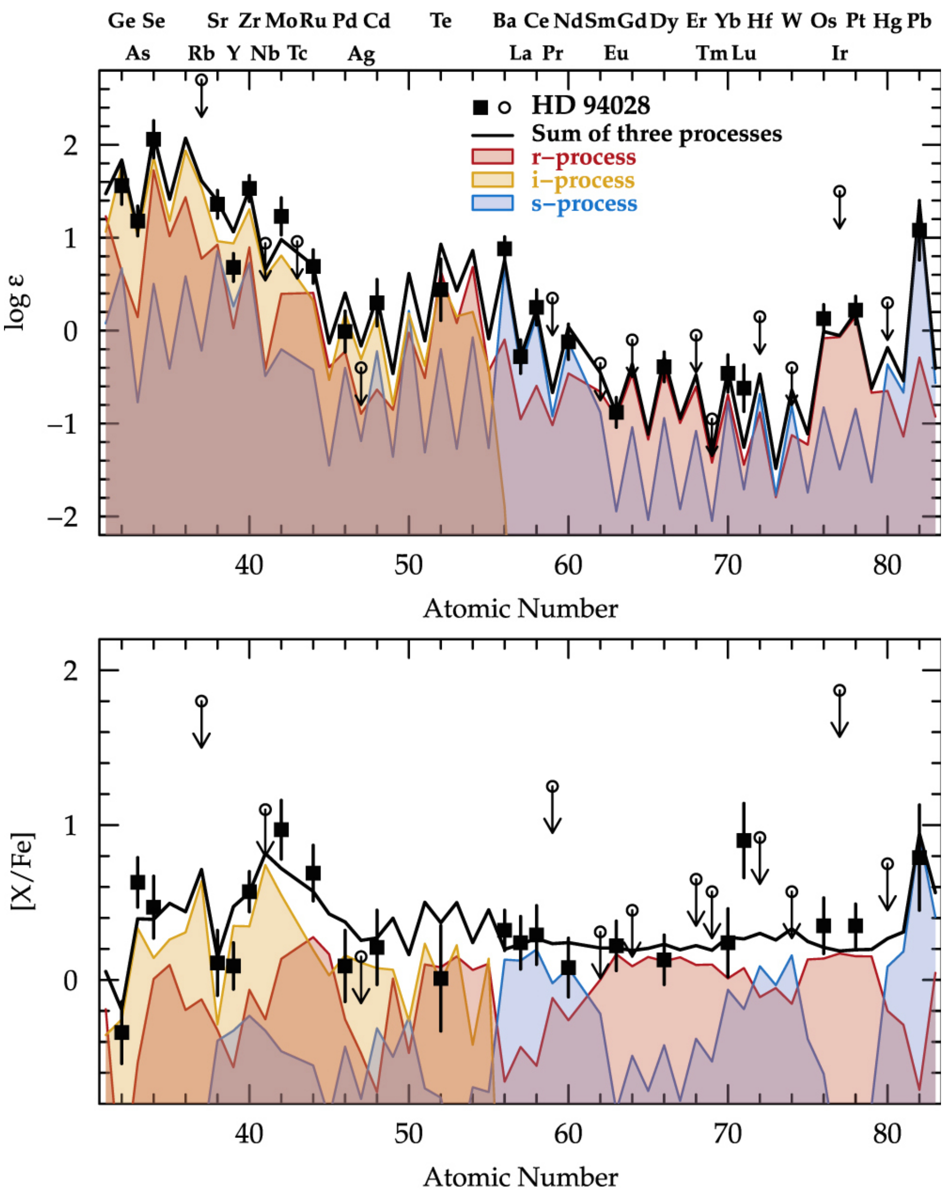
(Herwig et al. 2011; De Smedt et al. 2012, 2014; Lugaro et al. 2015)

- What about the origin of the carbon enhanced s/r stars?

(Dardelet et al. 2015; Jones et al. 2016; Stancliffe et al. 2016)

→ Ubiquitous in metal-poor stars throughout the Galaxy?

→ Roederer, Karakas et al. (2016)



Open questions

- Rotation completely inhibits the s-process (Herwig et al. 2003) or moderates its effects (Piersanti et al. 2013)
- However, there are very few AGB models with rotation that include the s-process
- The abundance distribution of low-metallicity post-AGB stars and the composition of CEMP s/r stars point toward another process that occurs in nature

→ intermediate-neutron capture process, or "i-process"

→ Low-mass (< 1.5Msun) and/or super-AGB stars are proposed sites…

→ How does the i-process contribute toward the enrichment of the Galaxy, if it does at all? Exciting times!