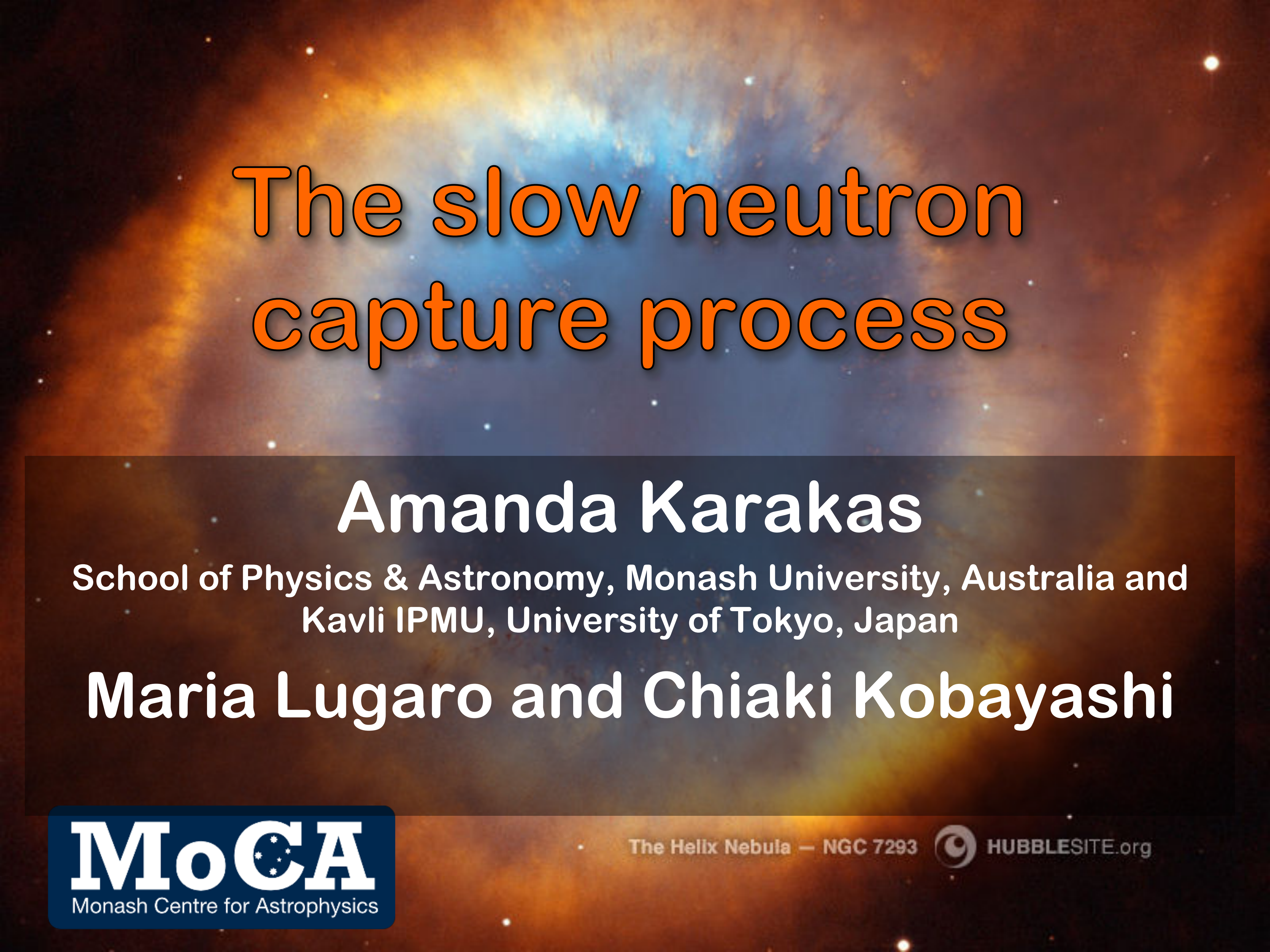

The slow neutron capture process

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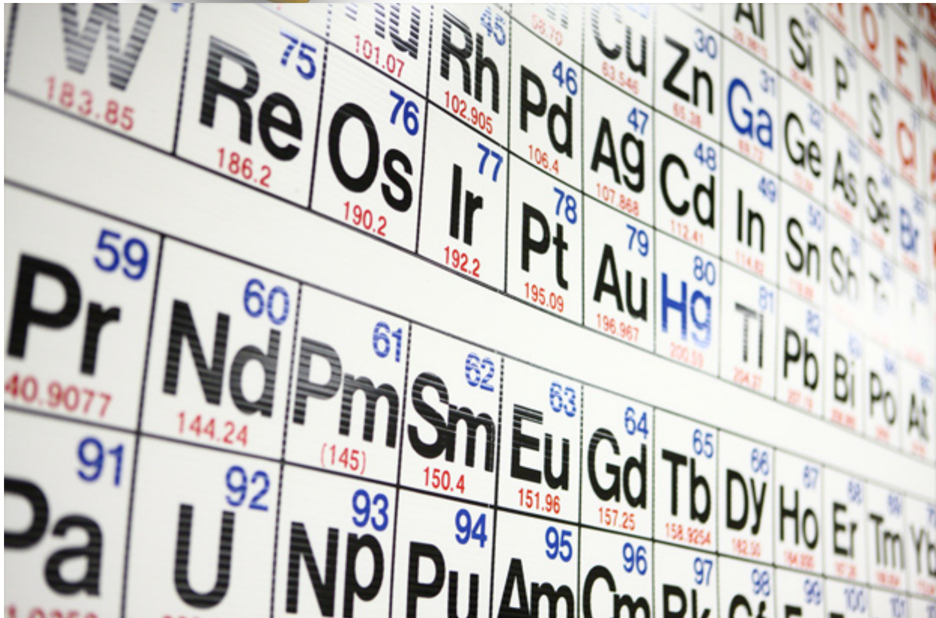
MoCA
Monash Centre for Astrophysics

The Helix Nebula — NGC 7293 HUBBLESITE.org

Origin of heavy elements

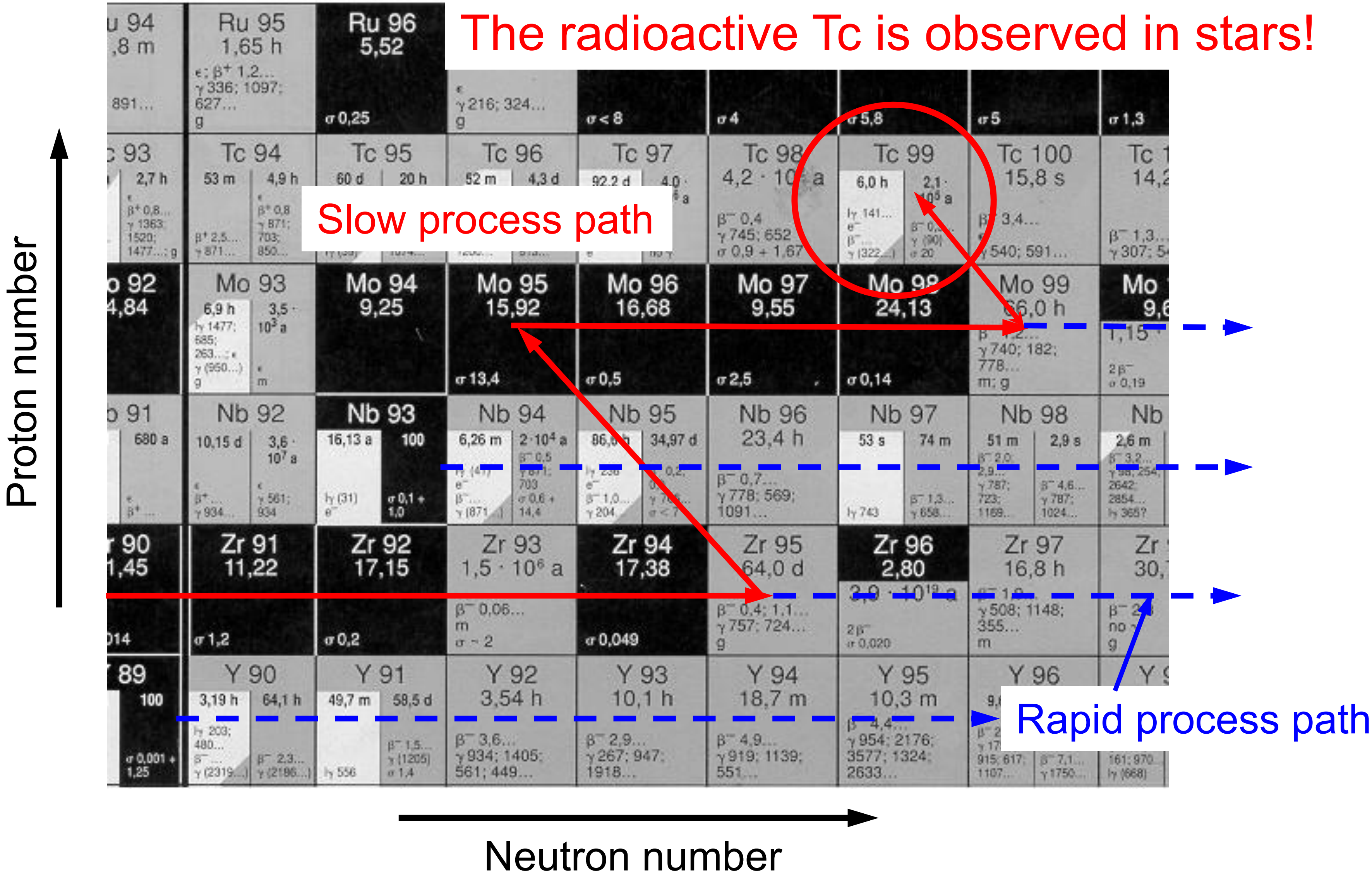
- Most heavy nuclei are formed by neutron addition onto Fe-peak elements
- Two processes:
  - *r-process* (rapid neutron capture)
  - *s-process* (slow neutron capture)



References:

- Meyer (1994), Gallino et al. (1998), Busso et al. (2001), Sneden et al. (2008), Käppeler et al. (2011)

Making heavy elements



The radioactive Tc is observed in stars!

Slow process path

Rapid process path

Proton number

Neutron number

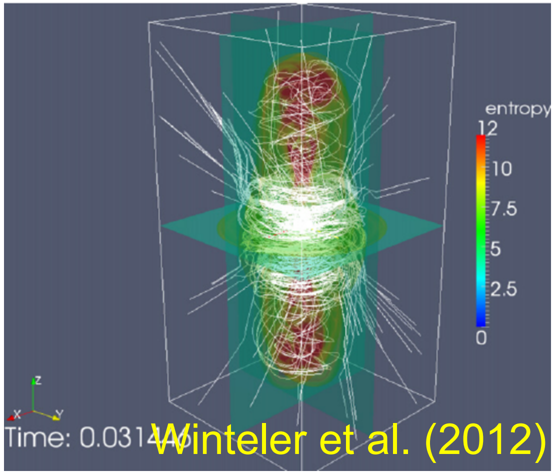
SITES OF HEAVY ELEMENT NUCLEOSYNTHESIS

Sites of heavy element nucleosynthesis

Neutron star mergers

Credit: NASA Goddard Space Flight Center

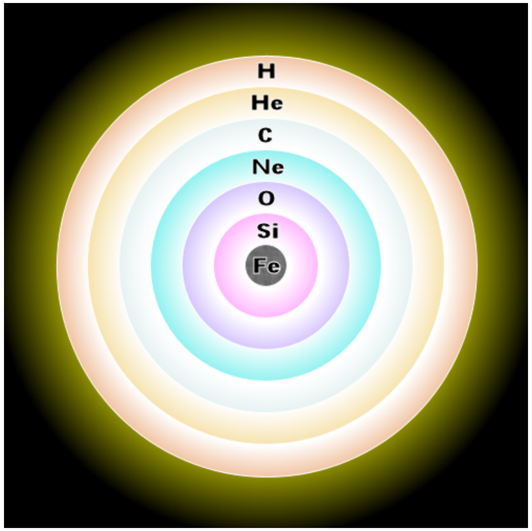
Magneto-hydrodynamically driven supernovae → unusual supernovae



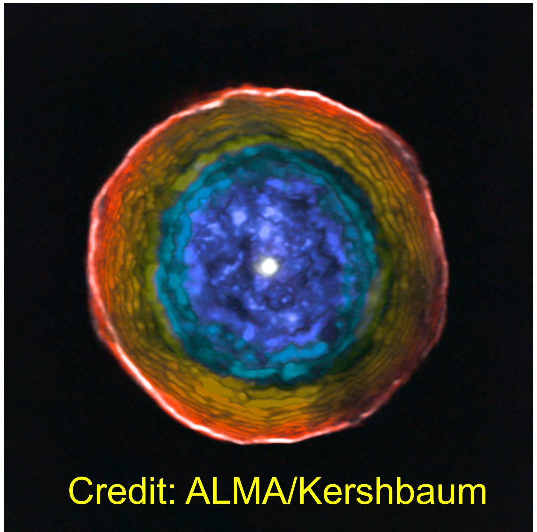
Winteler et al. (2012)

The r-process ~50%

Massive stars



Asymptotic giant branch stars

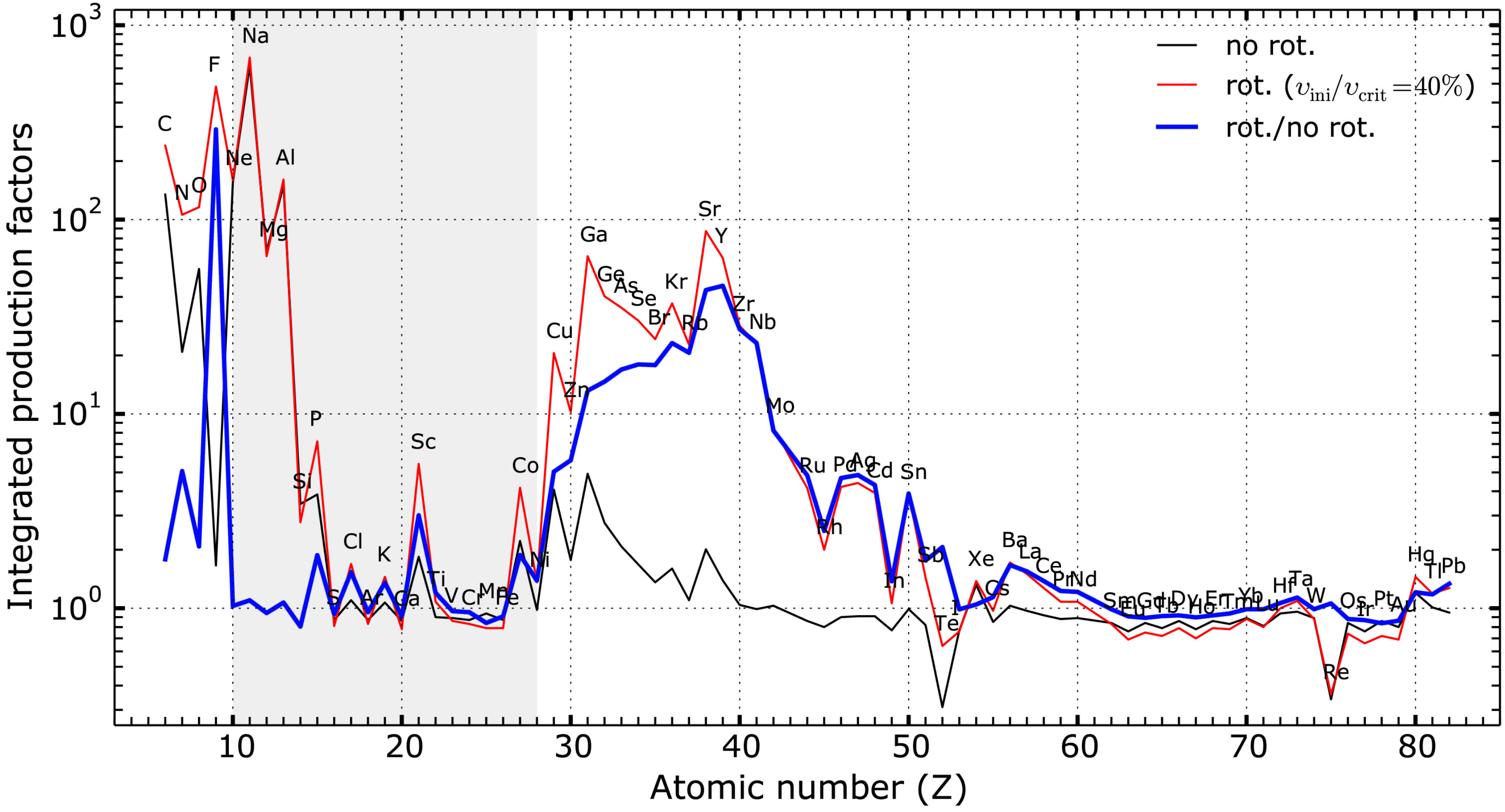


Credit: ALMA/Kershbaum

The s-process ~50%

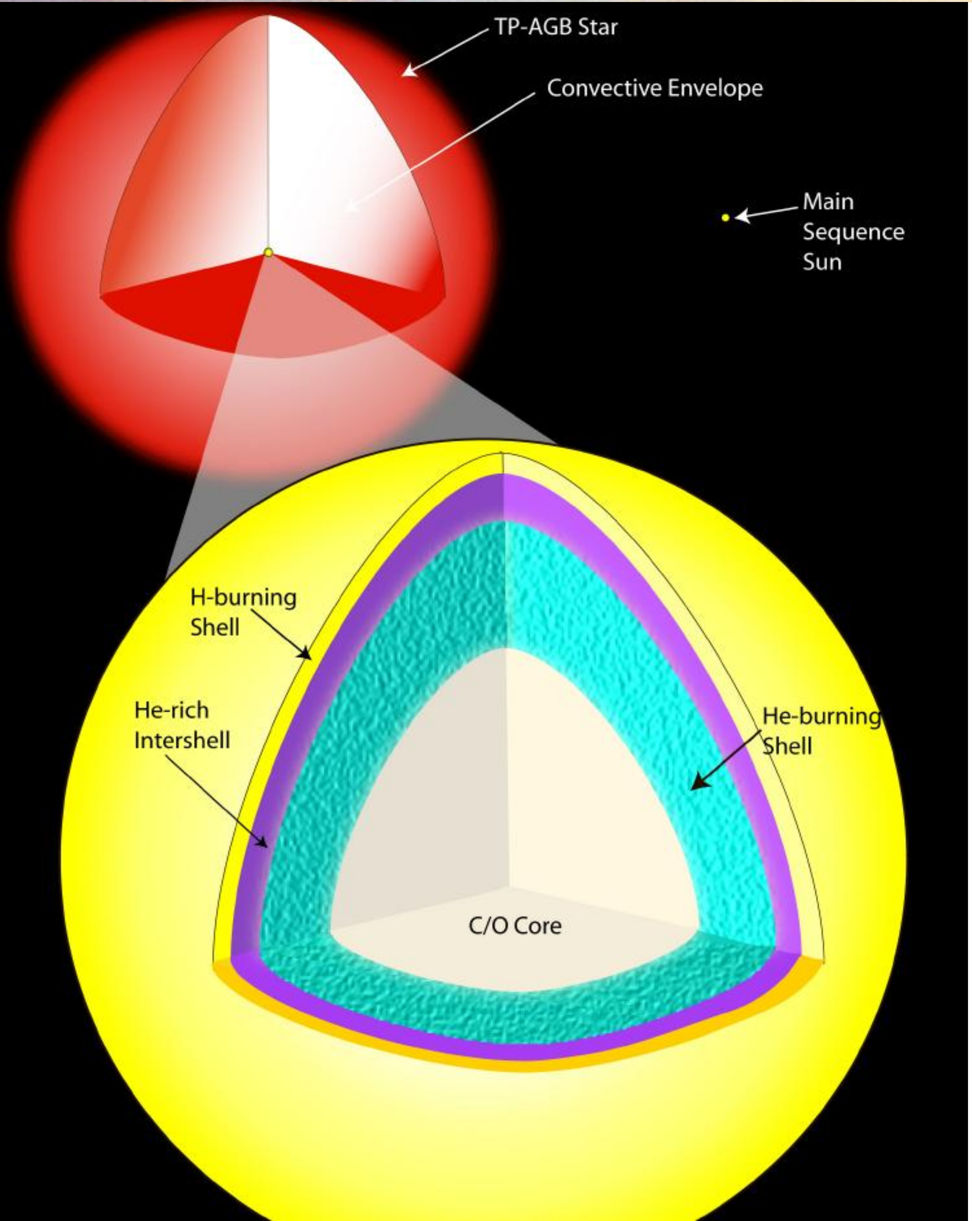
The s-process: massive stars

- Rotation can significantly affect s-process production inside massive stars, e.g., from Choplin et al. (2018) for models with metallicity = 10^{-3}



See also Limongi & Chieffi (2018), Frischknecht et al. (2016), Pignatari et al. (2008)

Asymptotic Giant Branch Stars

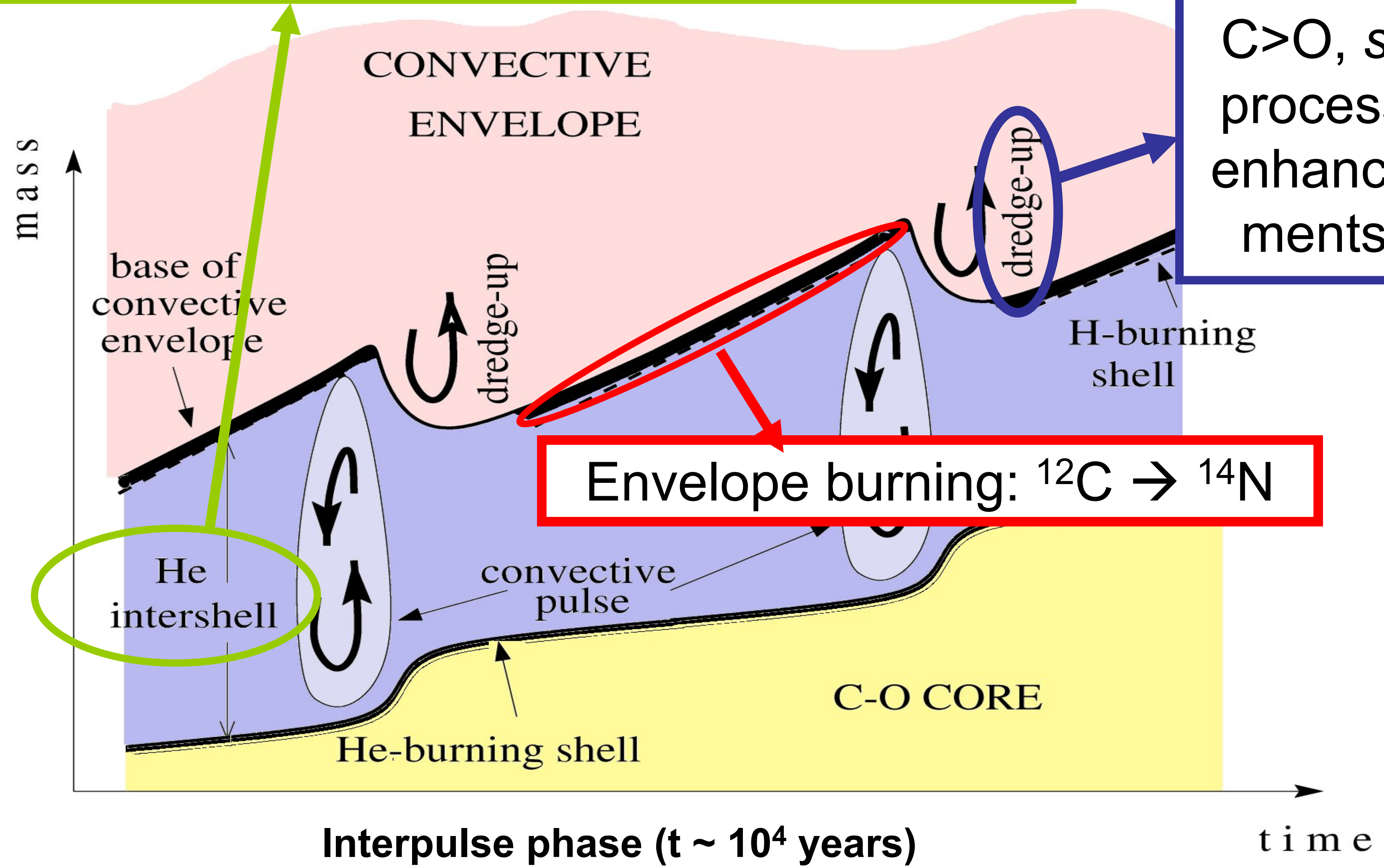


Asymptotic Giant Branch stars:
(upper mass limit ~6-8Msun)

- 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

Review by Karakas & Lattanzio (2014)

Schematic AGB evolution



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

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

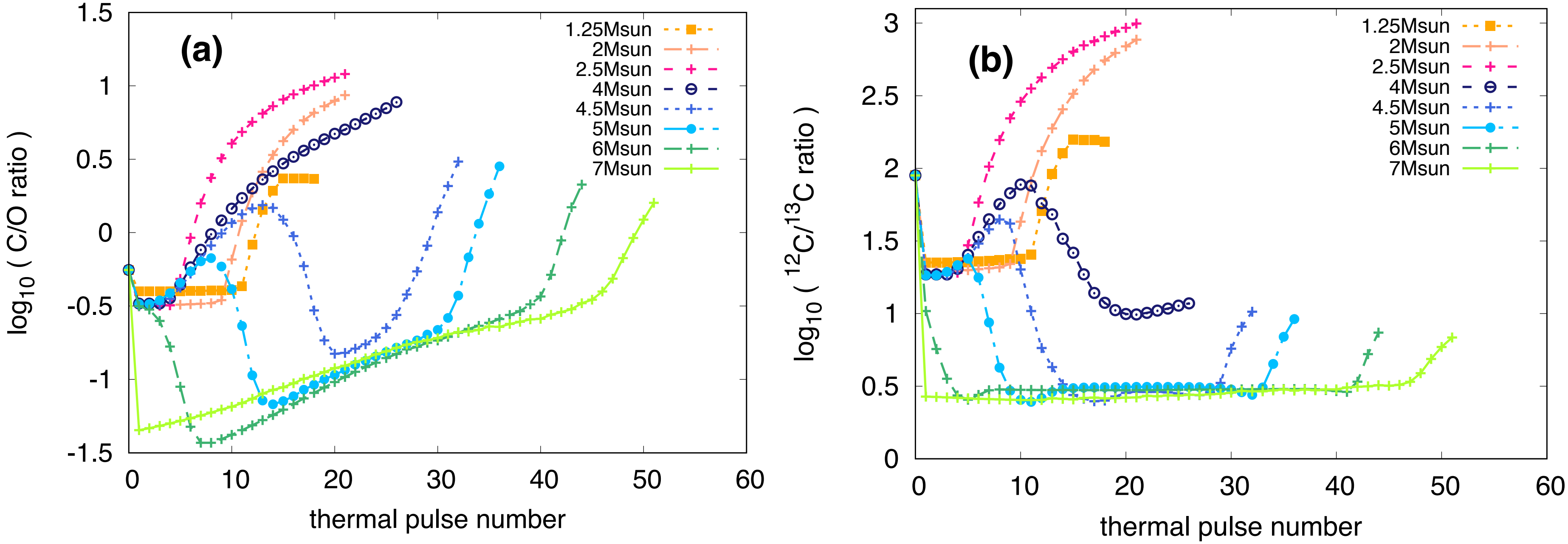
Envelope burning: $^{12}C \rightarrow {}^{14}N$

Interpulse phase (t ~ 10^4 years)

Nucleosynthesis in AGB stars

- **Low-mass:** ~0.9 to 3M$_{sun}$ for [Fe/H] ≤ -1 → Ba, CEMP
  - Third dredge-up: helium shell mixed into the envelope (e.g., ^{12}C, s-elements)
- **Intermediate-mass:** M ≳ 3 M$_{sun}$ for [Fe/H] ≤ -1 → N-rich
  - H-burning (e.g., ^{14}N) plus third dredge-up → primary C and N

Models of [Fe/H] = -0.7 from Karakas et al. (2018)



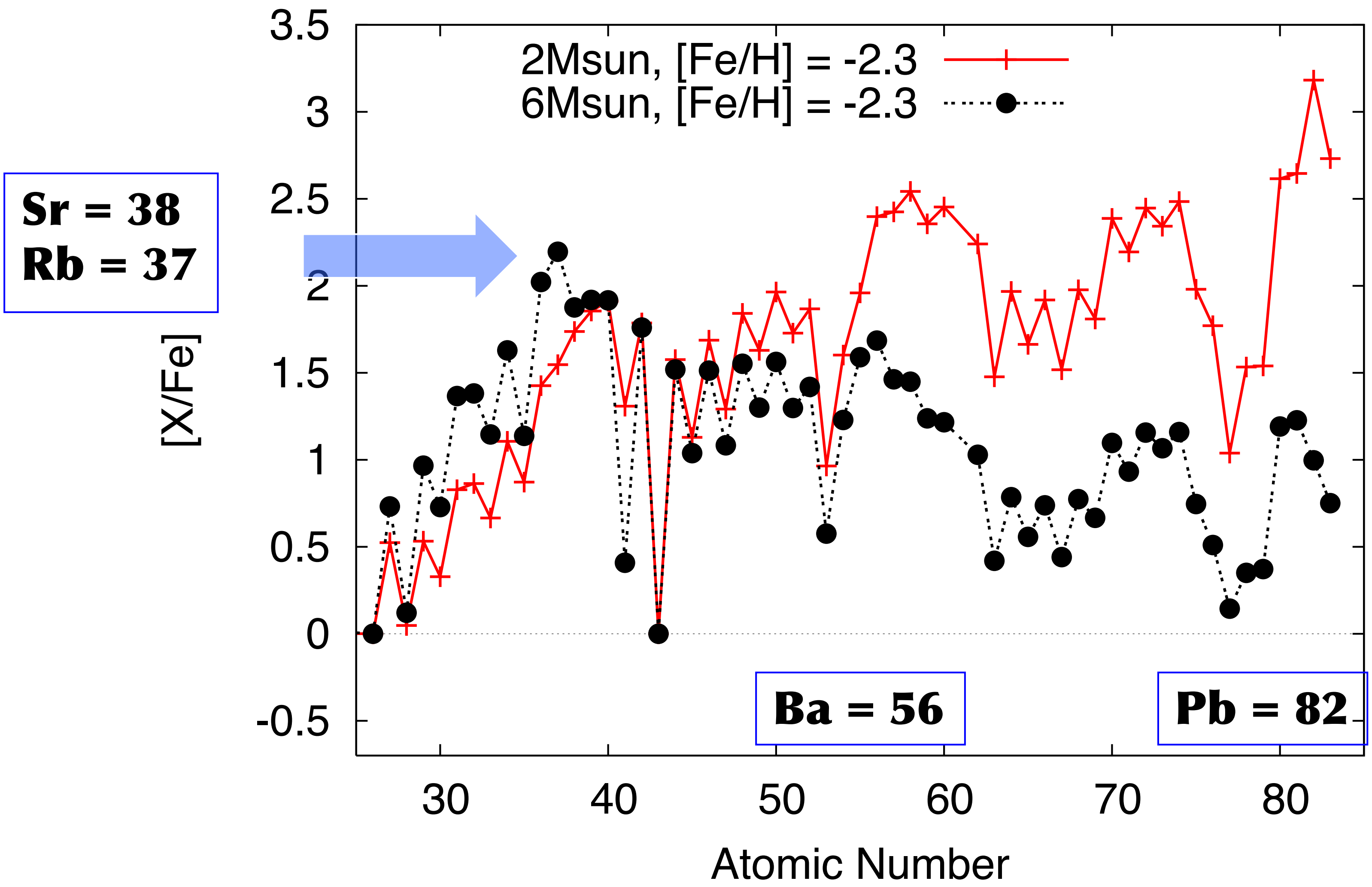
THE S-PROCESS IN AGB STARS

The s-process depends upon

1. Mass
2. Metallicity
3. Rotational velocity

The s-process: The effect of mass

- Models of [Fe/H] = −2.3 from Lugaro, Karakas, et al. (2012):



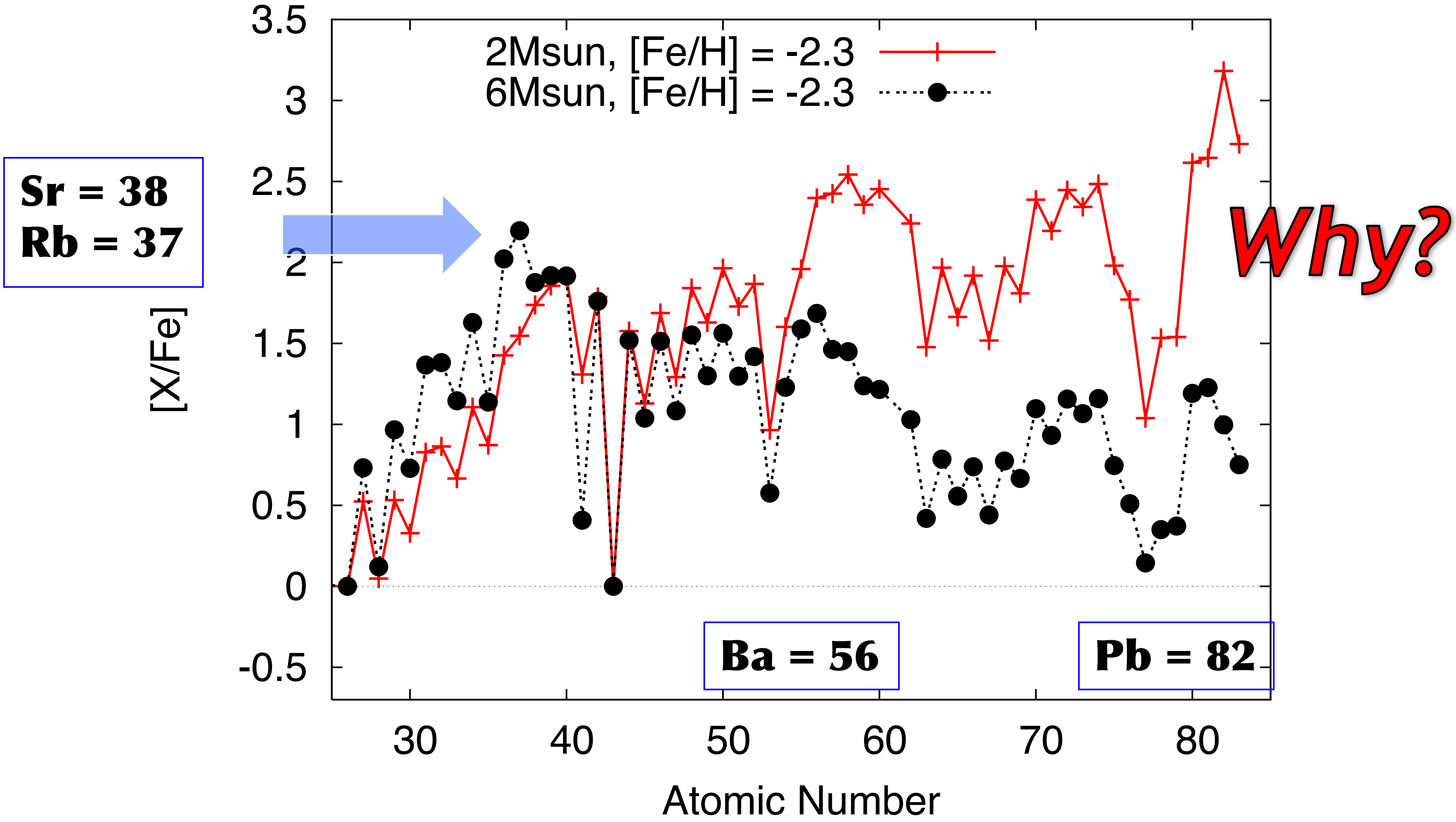
Sr = 38
Rb = 37

Ba = 56

Pb = 82

The s-process: The effect of mass

- Models of [Fe/H] = −2.3 from Lugaro, Karakas, et al. (2012):



Sr = 38
Rb = 37

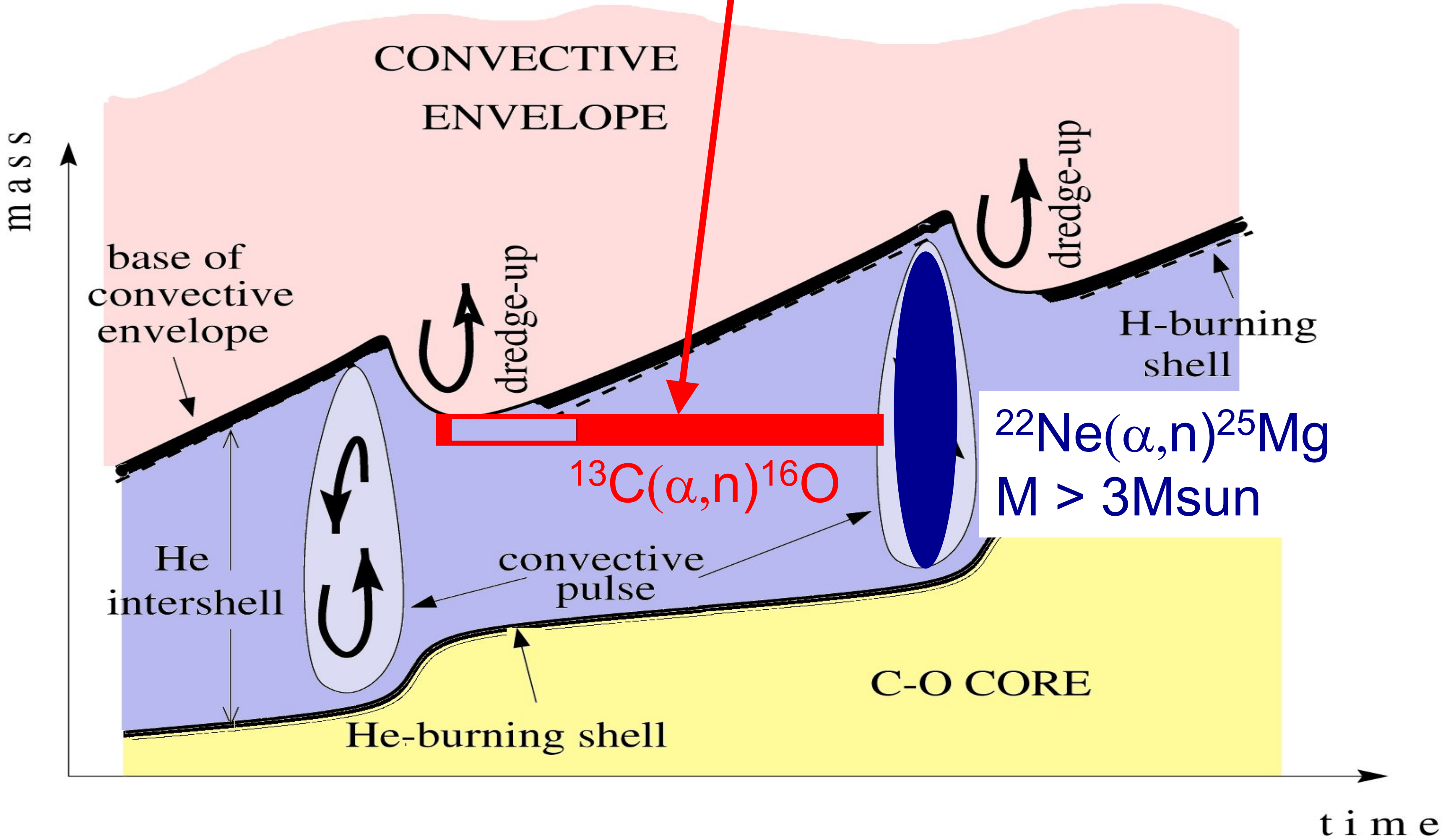
Ba = 56

Pb = 82

Why?

Neutron production: ^{13}C source

Mixing a few protons into the top of the He-shell produces a ^{13}C pocket → ^{13}C burns *radiatively*



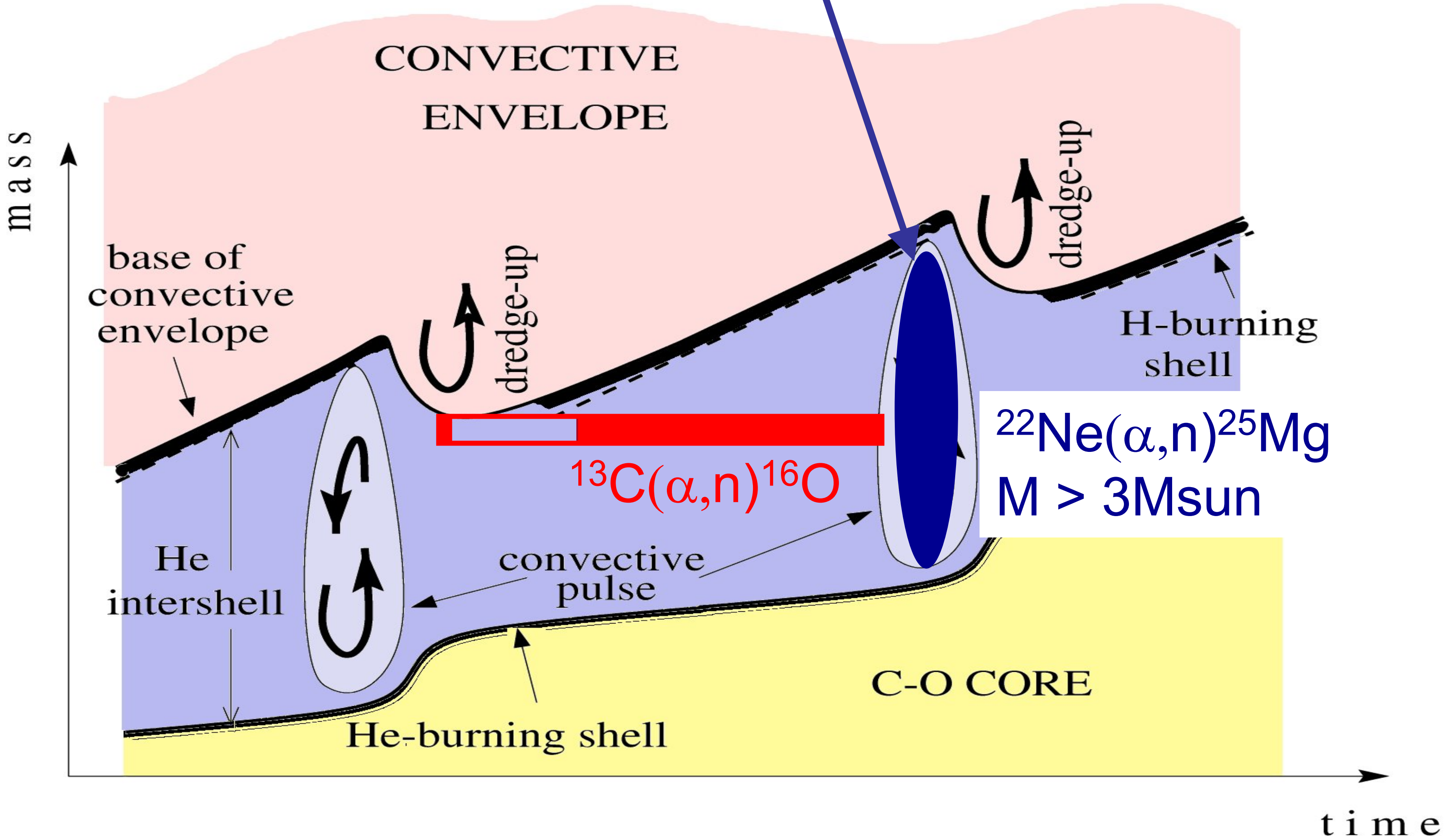
$^{13}C(\alpha,n)^{16}O$

$^{22}Ne(\alpha,n)^{25}Mg$

M > 3Msun

Neutron production: ^{22}Ne source

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

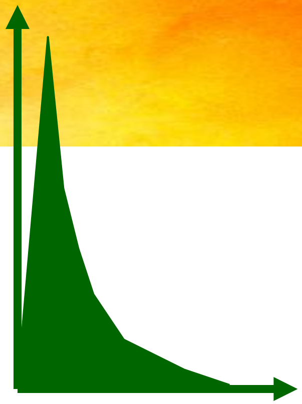


$^{13}C(\alpha,n)^{16}O$

$^{22}Ne(\alpha,n)^{25}Mg$

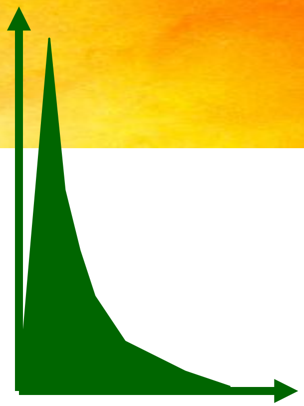
M > 3Msun

Theoretical models

Typical neutron density profile in time:	 Low mass	 Intermediate mass
Neutron source	$^{13}C(\alpha,n)^{16}O$	$^{22}Ne(\alpha,n)^{25}Mg$
Maximum neutron density	10^{8} n/cm^{3}	~10^{14} n/cm^{3}
Timescale	~10,000 yr	days – 10 yr
Neutron exposure	**0.3 mbarn^{-1}**	**0.02 mbarn^{-1}**

(at solar metallicity)

Theoretical models

Typical neutron density profile in time:	 Low mass	 Intermediate mass
Neutron source	$^{13}C(\alpha,n)^{16}O$	$^{22}Ne(\alpha,n)^{25}Mg$
Maximum neutron density	10^{8} n/cm^{3}	~10^{14} n/cm^{3}
Timescale	~10,000 yr	days – 10 yr
Neutron exposure	**1-2 mbarn^{-1}**	**~0.2 mbarn^{-1}**

(at low metallicities)

Effect of stellar metallicity?

1. All ^{13}C nuclei are converted into neutrons and the main neutron absorber is ^{56}Fe:

Neutron density ≈ ^{13}C / ^{56}Fe

2. ^{13}C in the pocket is produced by proton captures on primary ^{12}C, from triple-a in the He shell:

^{13}C is a primary neutron source!

Clayton (1988)

What are the implications?

3. The neutron density scales with the inverse of ^{56}Fe, i.e., with the metallicity.

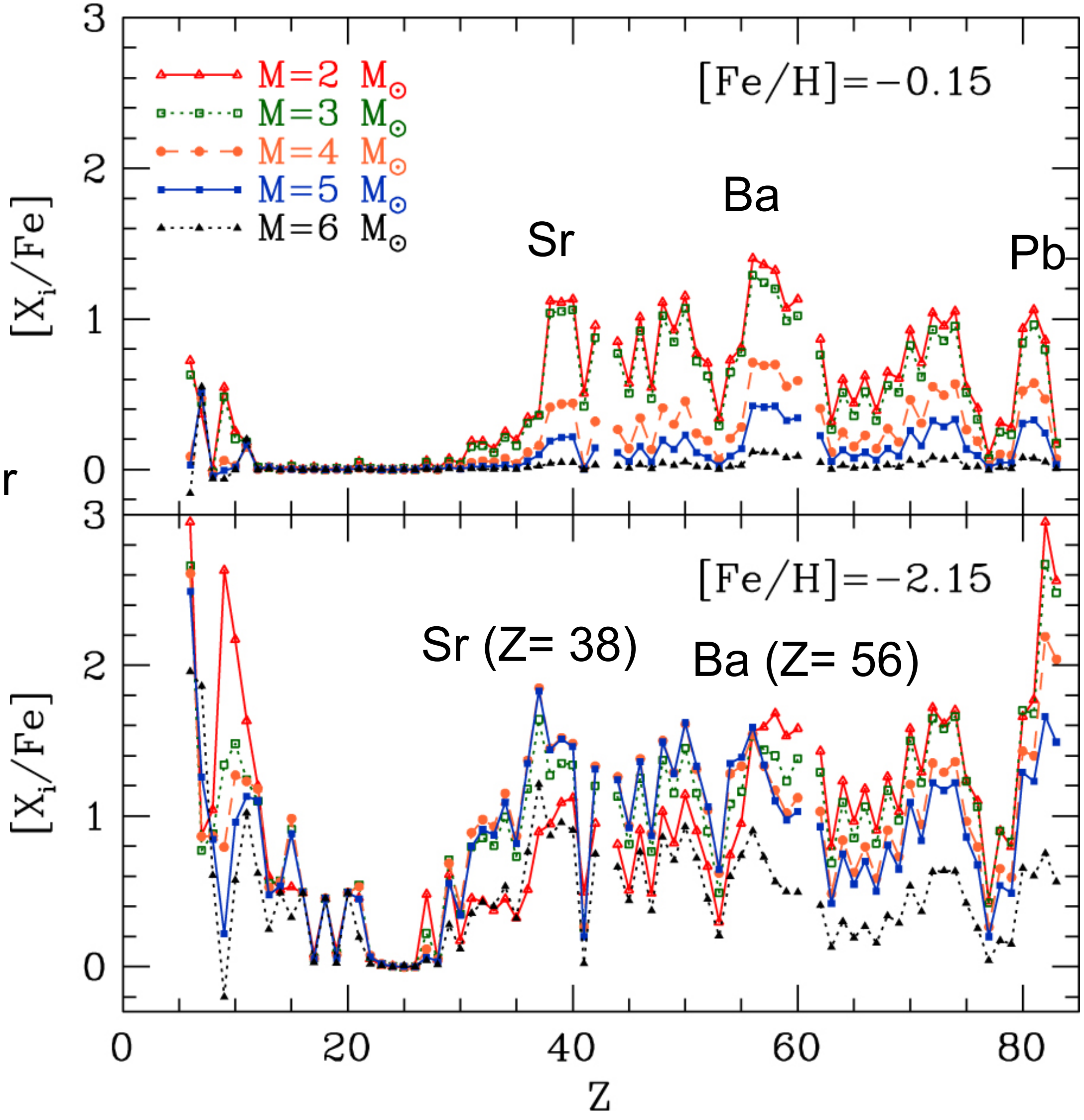
This means that lower metallicity stars produce more neutrons and more heavier elements.

[Ba/Sr] (or [Ce/Y]) should increase with decreasing metallicity

Is this true?

From theoretical models

From the FRUITY database: From Cristallo et al. (2015)

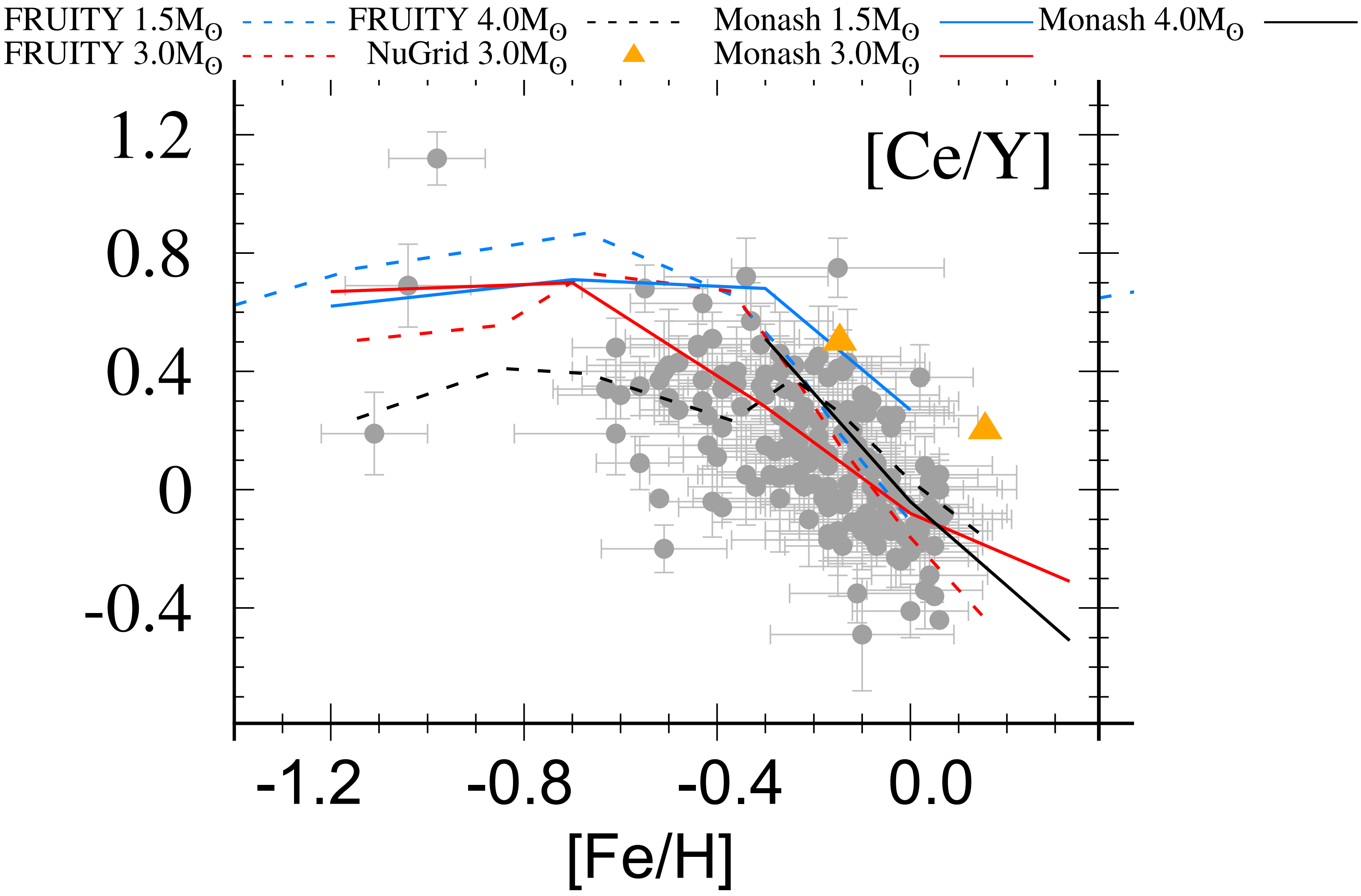


Pb (Z= 82)

Z = proton number

From observations of Barium stars

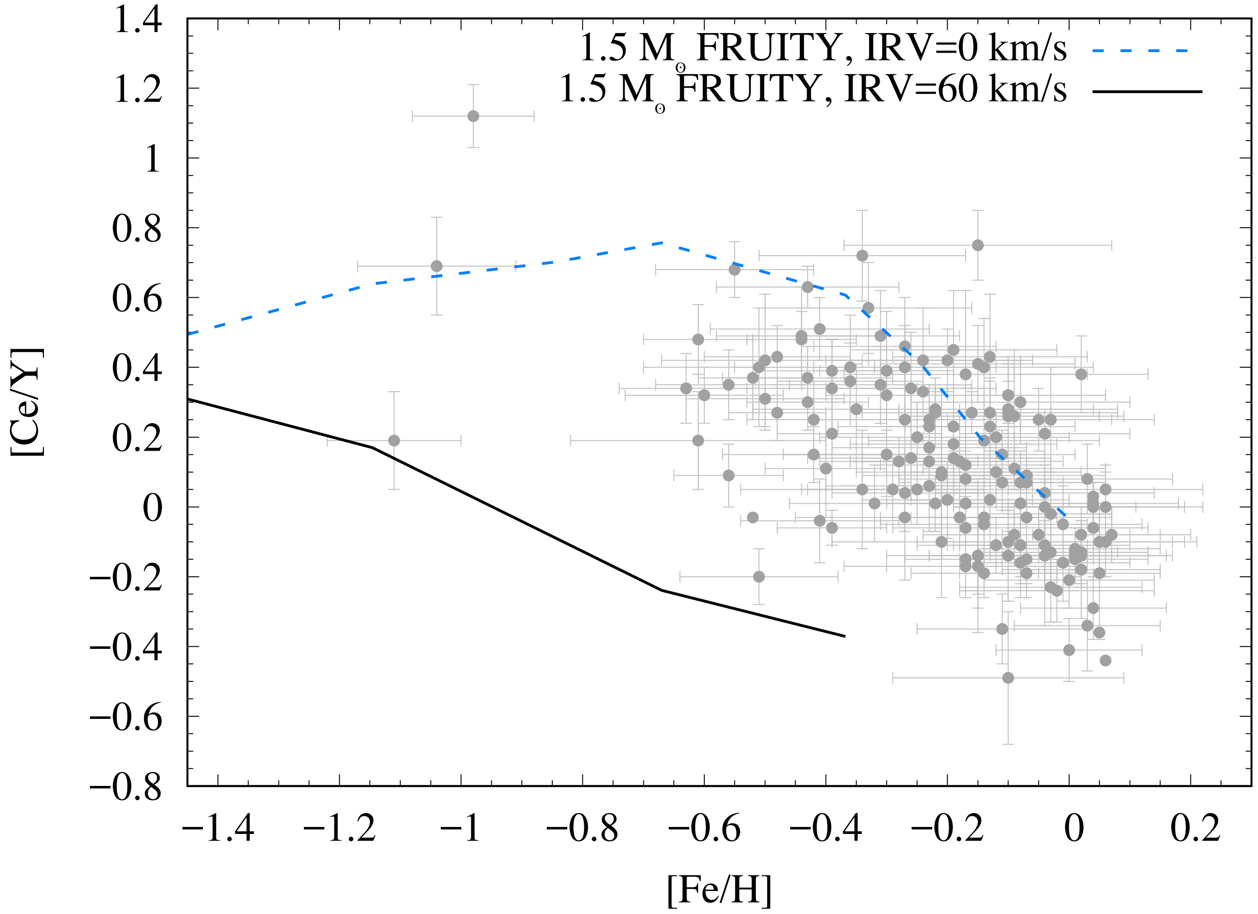
Cseh et al. (2018) compared the data with model predictions:



The effect of stellar rotation?

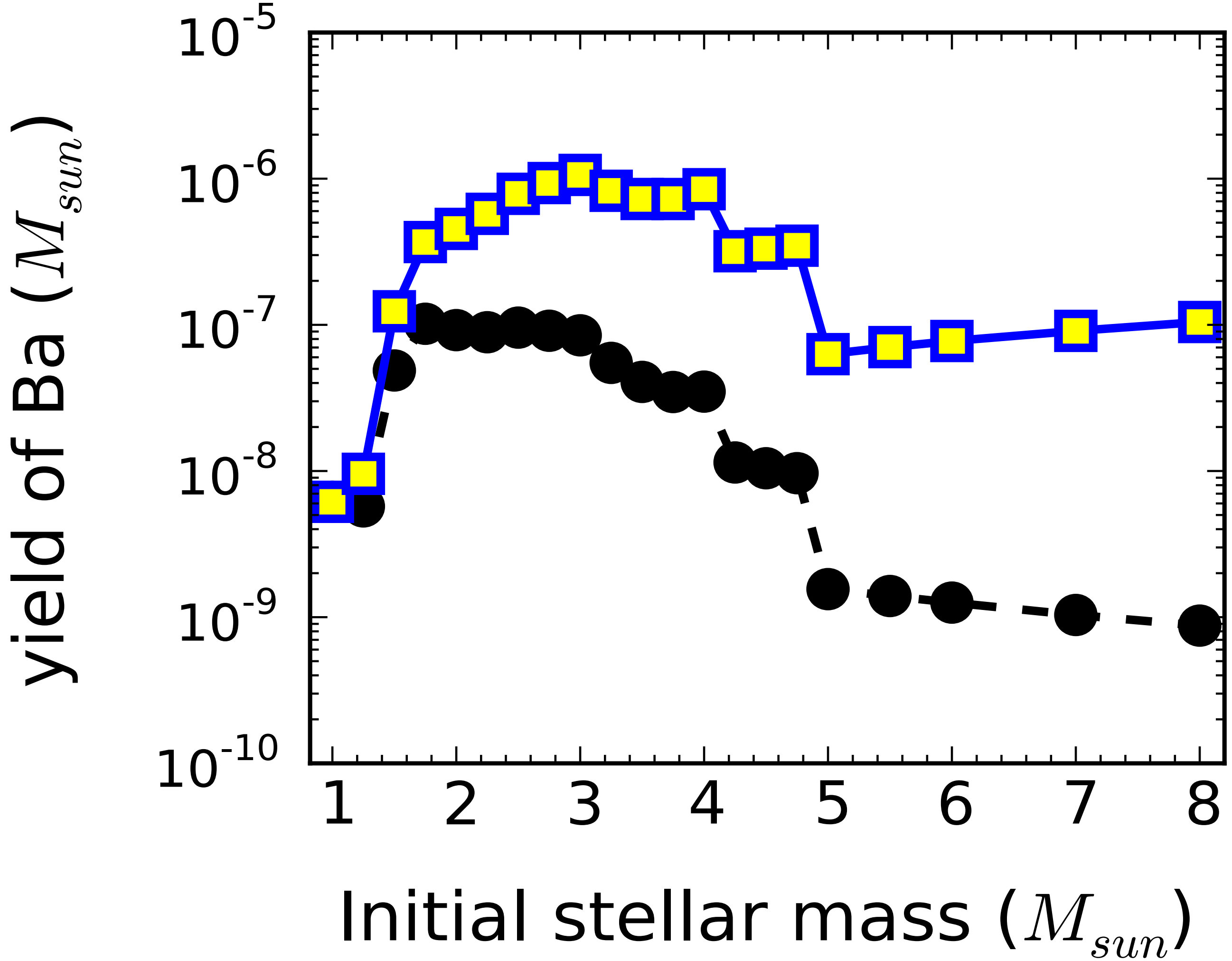
Cseh et al. (2018) compared the data with model predictions:

It suppresses the neutron flux (Herwig et al. 2003, Siess et al. 2004, Piersanti et al. 2013)



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

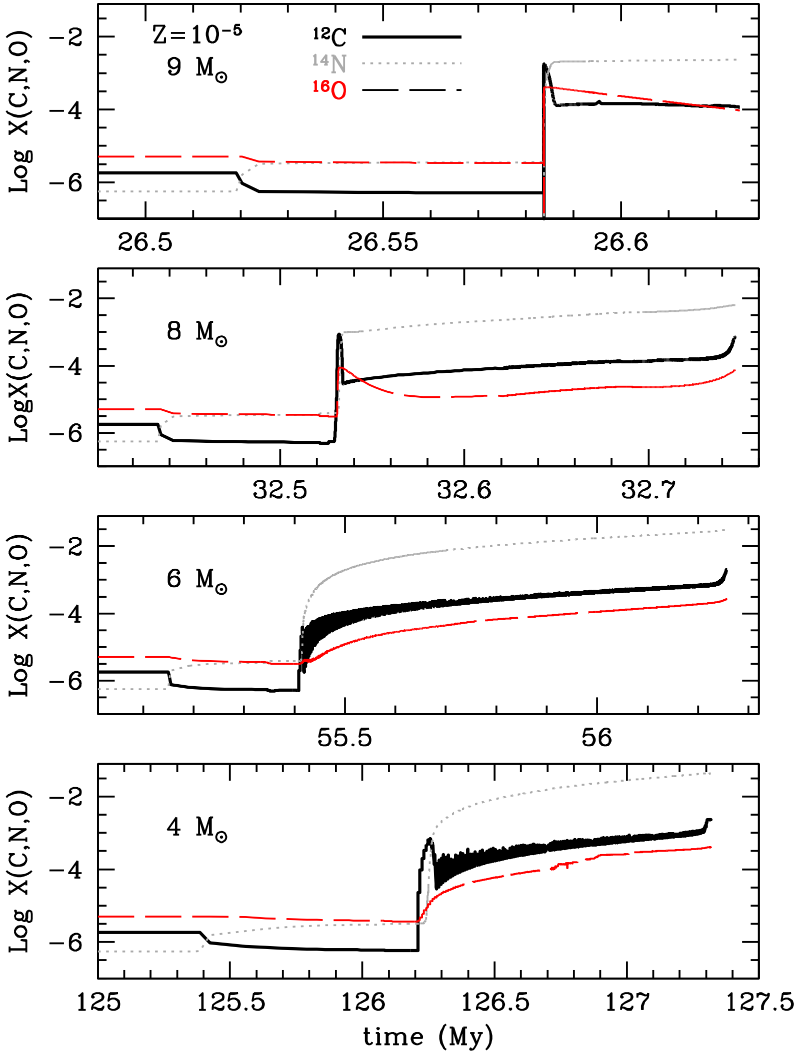
AGB yields with s-process elements

- **Our group:** Fishlock et al. (2014), Karakas & Lugaro (2016), Karakas et al. (2018); yields of 1 to ~8Msun (-2.3 ≤ [Fe/H] ≤ +0.3)
- **FRUITY database:** Cristallo et al. (2015); includes a few models with rotation (-2.15 ≤ [Fe/H] ≤ +0.15)
- **NuGrid/MESA:** Pignatari et al. (2016), Ritter et al. (2018); for Z = 0.001, 0.006, 0.01 and 0.02

What is lacking? Yields for low metallicity for all masses. Super-AGB yields (Q: are they even needed?)

Very low-metallicities

Here [Fe/H] < -2.5



Model mass ranges studied:

- M = 4 to 9Msun
- Metallicities: [Fe/H] = -3.2

What is lacking?

- **No s-process**
- No non-standard stellar physics (e.g., rotation)

From Gil-Pons et al. (2013) – tabulated yields

See also studies by Siess et al. (2002), Iwamoto et al. (2004), Iwamoto (2009), Campbell & Lattanzio (2008), Suda & Fujimoto (2010), Cruz et al. (2013)

PUZZLES

Challenges and puzzles

1. The Sr, Y, Zr abundances in metal-poor stars → points to another source of heavy elements (light *r*-process?)
2. The CEMP r/s stars → CEMP *i*? Site? (e.g., Hampel et al. 2016, Denissenkov et al. 2018)
3. Origin of neutron-capture elements in post-AGB stars. Also i-process?
4. Did pre-solar SiC grains originate in a *metal-rich* AGB population?

Puzzles: CEMP r/s stars

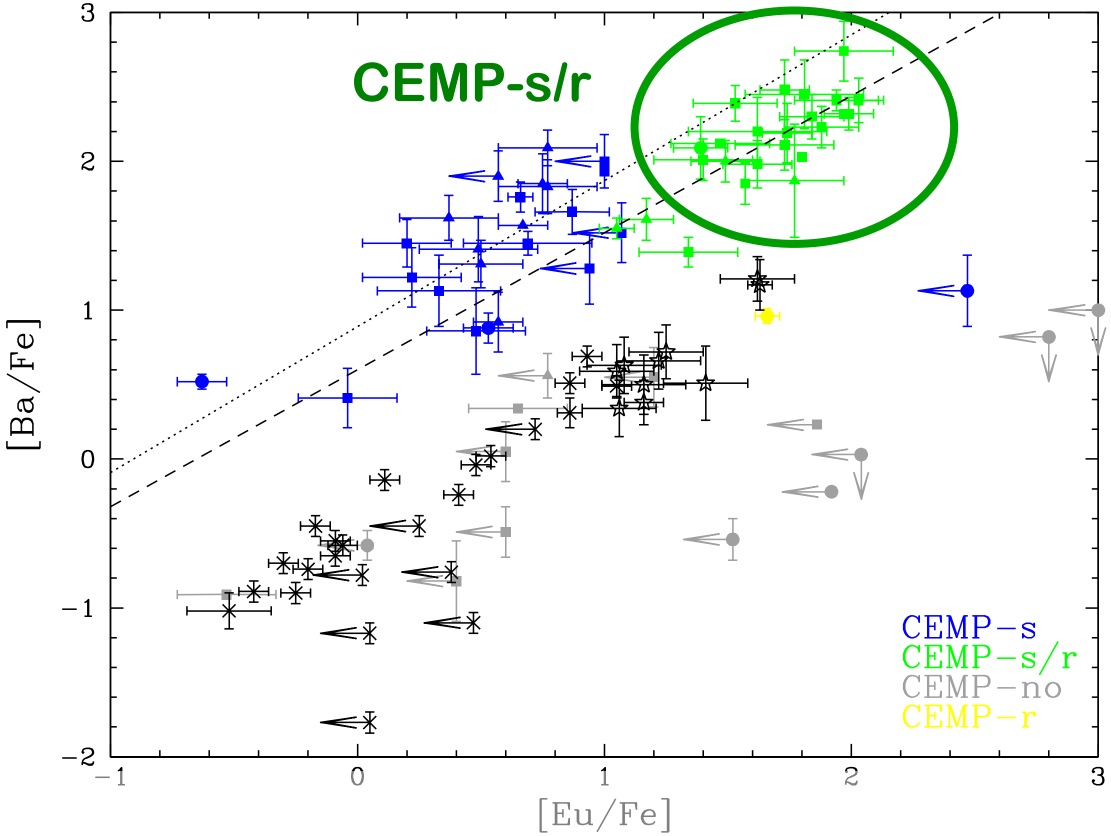
- About 50% of CEMP stars with an s-process signature also show an enrichment in r-process elements

→ *Is this the i-process? E.g.,*

→ Dardelet et al. (2015),

→ Hampel et al. (2016)

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

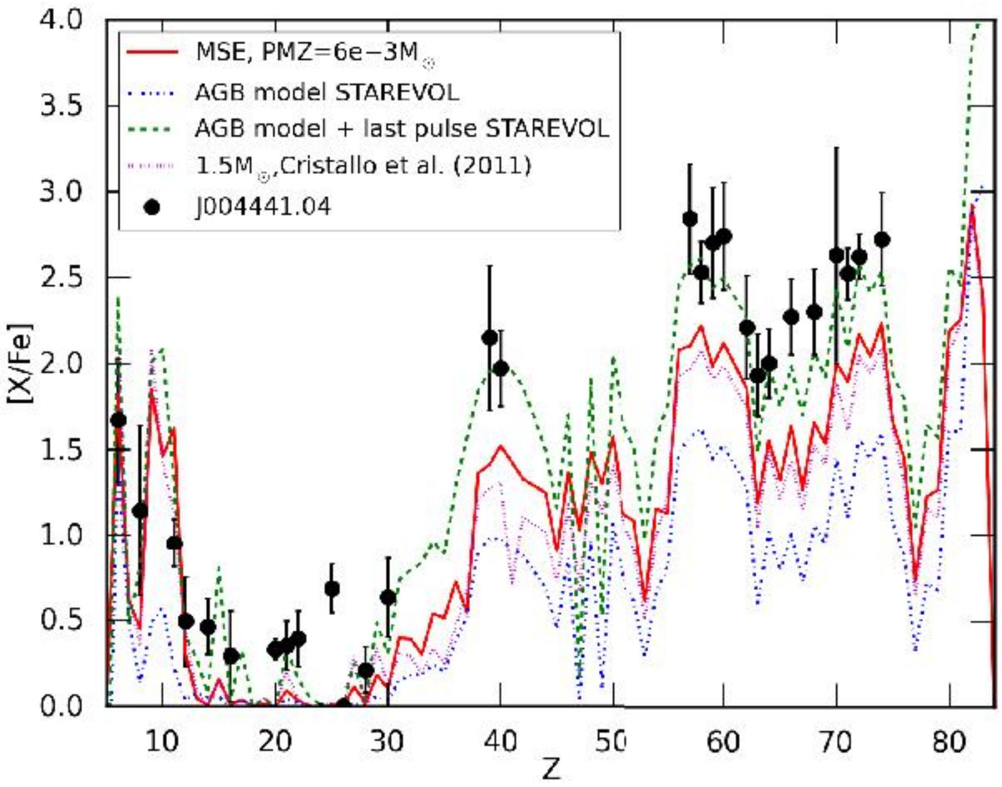


Definition of CEMP s/r:

- [Eu/Fe] > 1
- [Ba/Eu] > 0 but lower than for CEMP-s
- Appear distinct from CEMP-s (e.g., Lugaro et al. 2012; Cohen et al. 2005)

Puzzles: metal-poor post-AGB stars

- In the Small and Large Magellanic Cloud, a population of very s-process enriched post-AGB stars have been discovered
- The stars only have *upper limits* for Pb

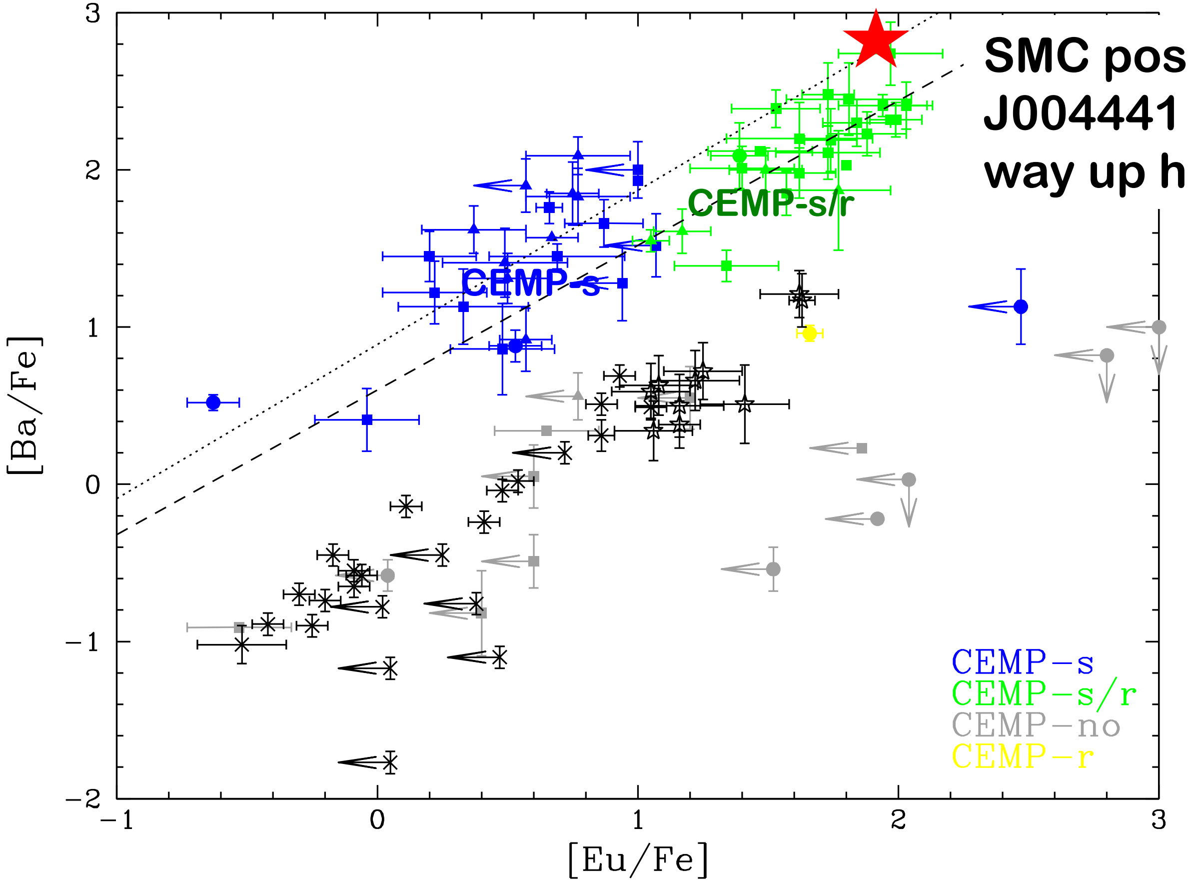


The abundance pattern of the post-AGB star J004441.04 ([Fe/H] = -1.4) in comparison with model predictions from various groups

From De Smedt et al. (2012)

Metal-poor post-AGB stars

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



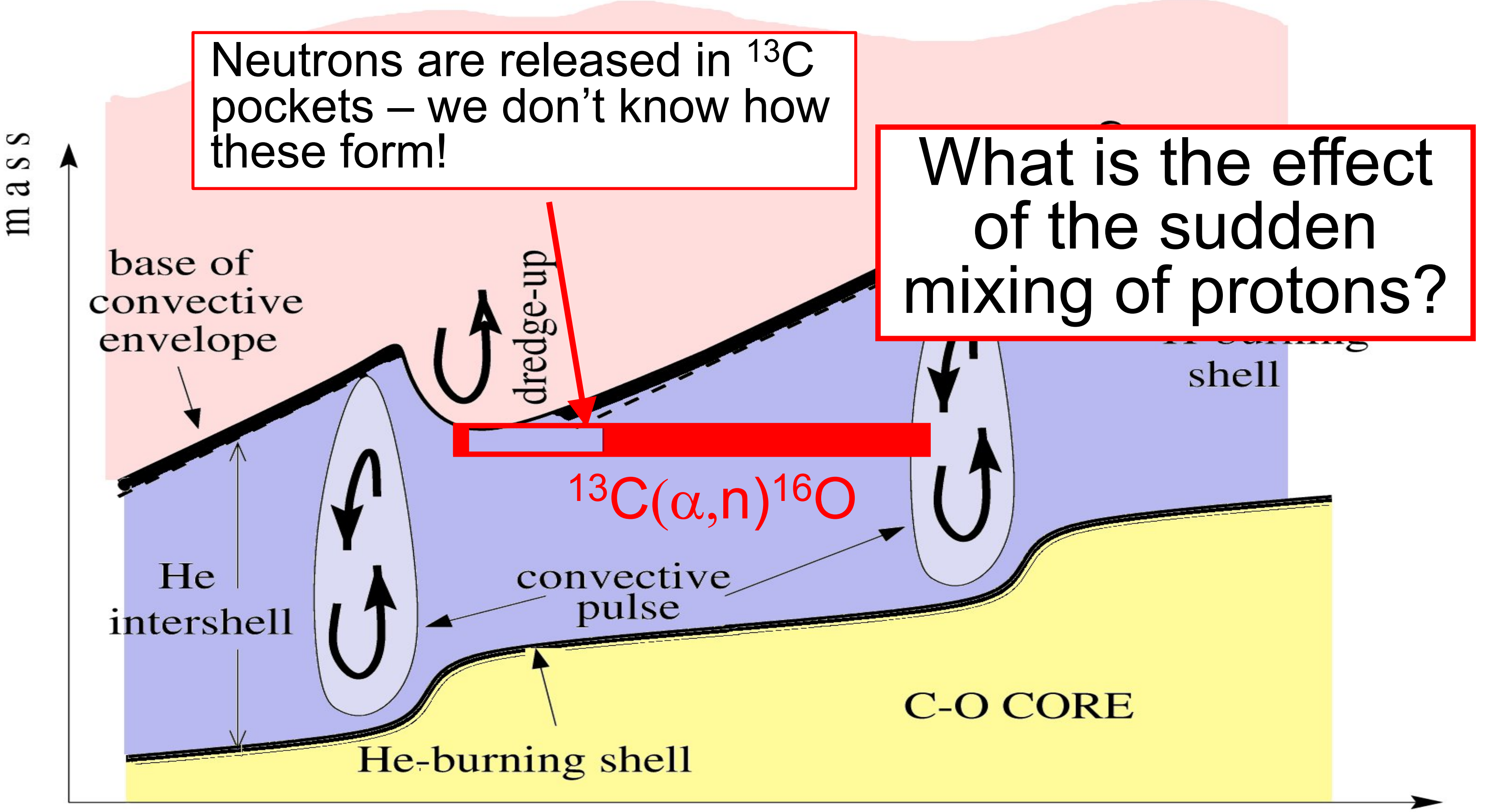
SMC post-AGB star J004441 sits all the way up here!!

[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…

Modelling heavy elements in AGB stars

We have made considerable progress in spite of severe modelling uncertainties (e.g., mass loss, convection…)



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

What is the effect of the sudden mixing of protons?

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

See Tripella et al. (2016), Buntain et al. (2017), Piersanti et al. (2013)

The intermediate-neutron capture process

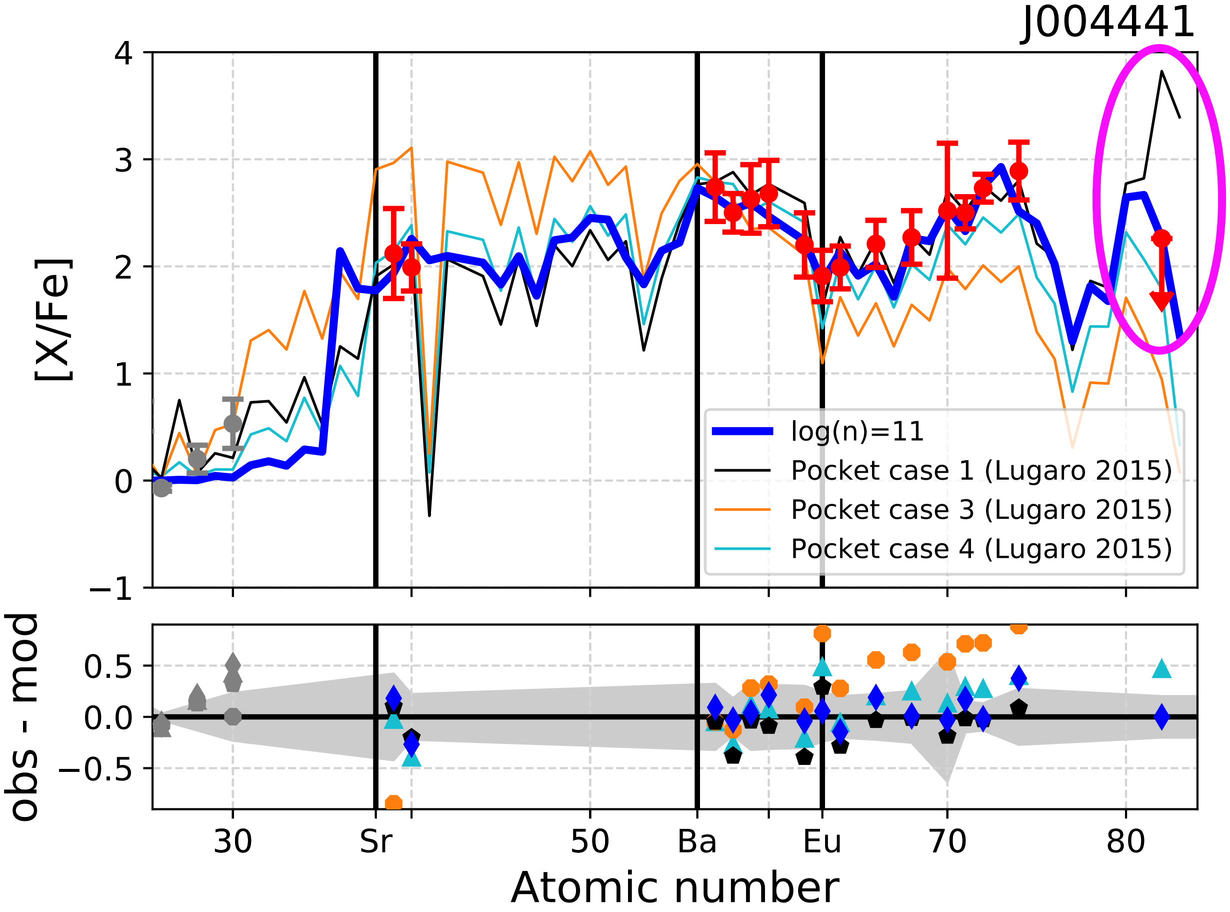
- Observations have presented us with abundances that are not easily explained with s-process models
- Could they be better fit by an “intermediate” process?

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

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

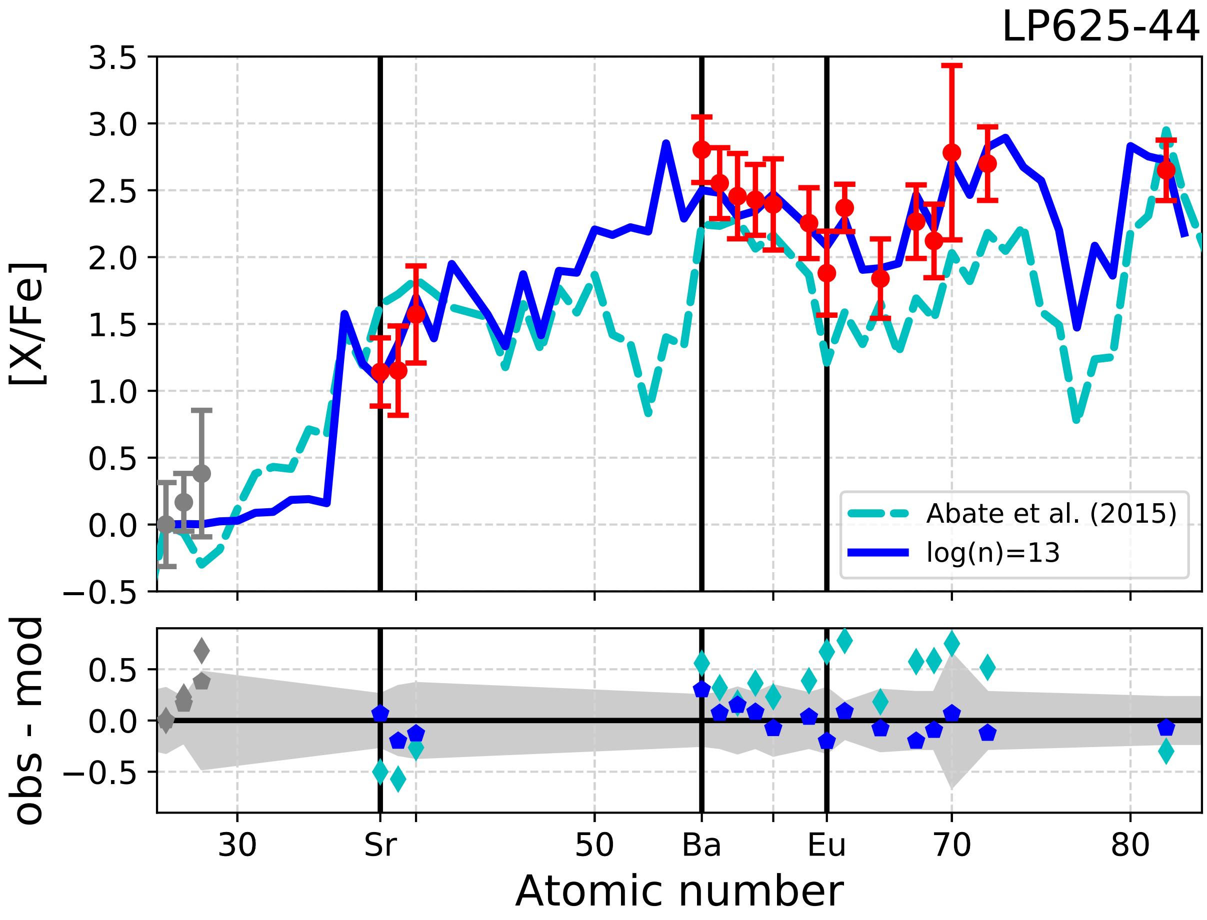
The i-process in post-AGB stars

- 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)



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

- Best-fitting model for CEMP-*s/r* star LP625-44
- Hampel et al. (2018, in prep) now including Pb

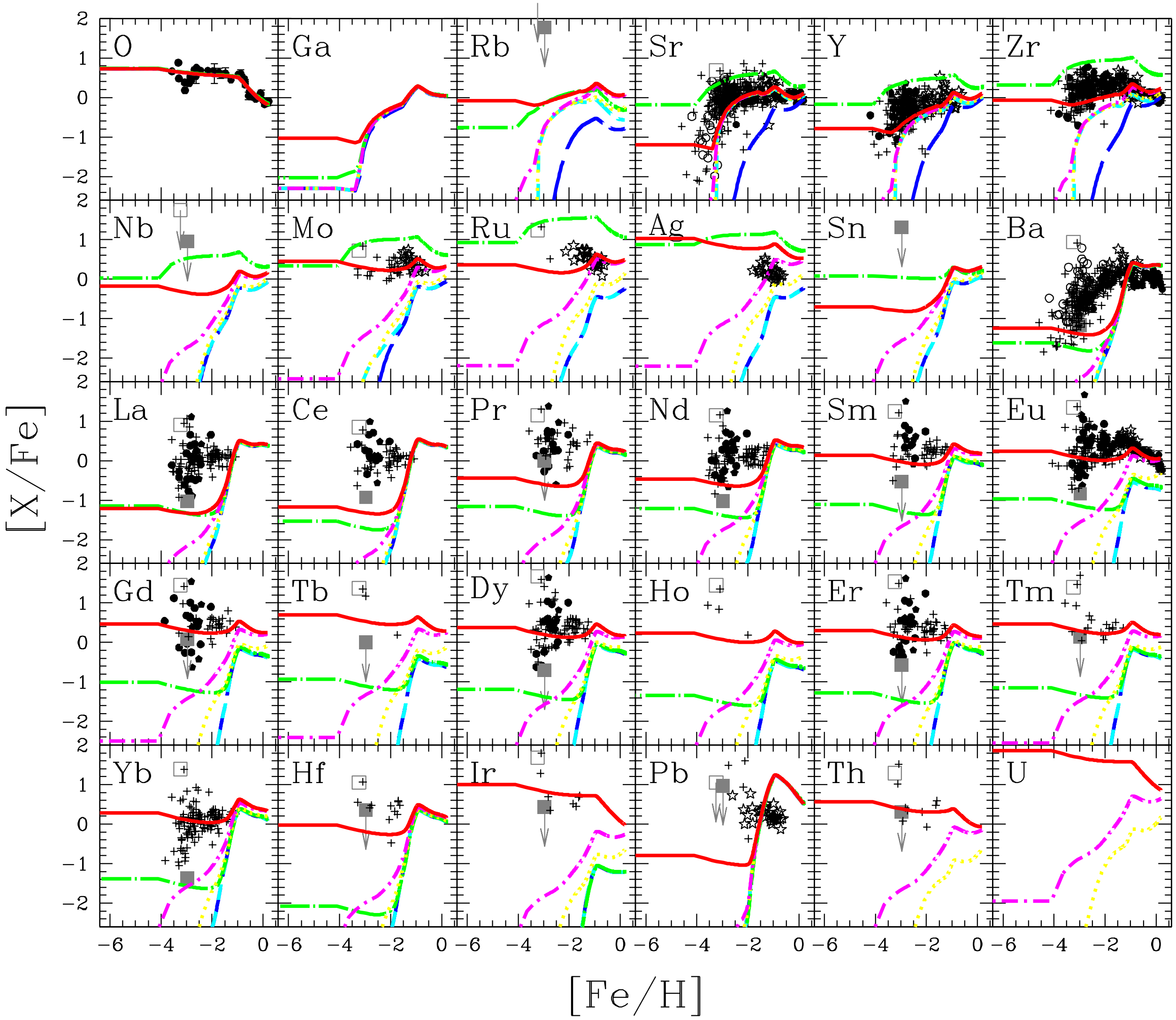


What are the site(s) of the *i*-process?

- Low-mass, low-metallicity post-AGB stars (Lugaro et al. 2015)?
- Low-metallicity intermediate-mass AGB stars (Jones et al. 2016)?
- Rapidly accreting white dwarfs (e.g., Hillebrandt et al. 1986, Denissenkov et al. 2017, 2018)
  - There are issues with the Denissenkov et al. models but the idea as a site for GCE is interesting

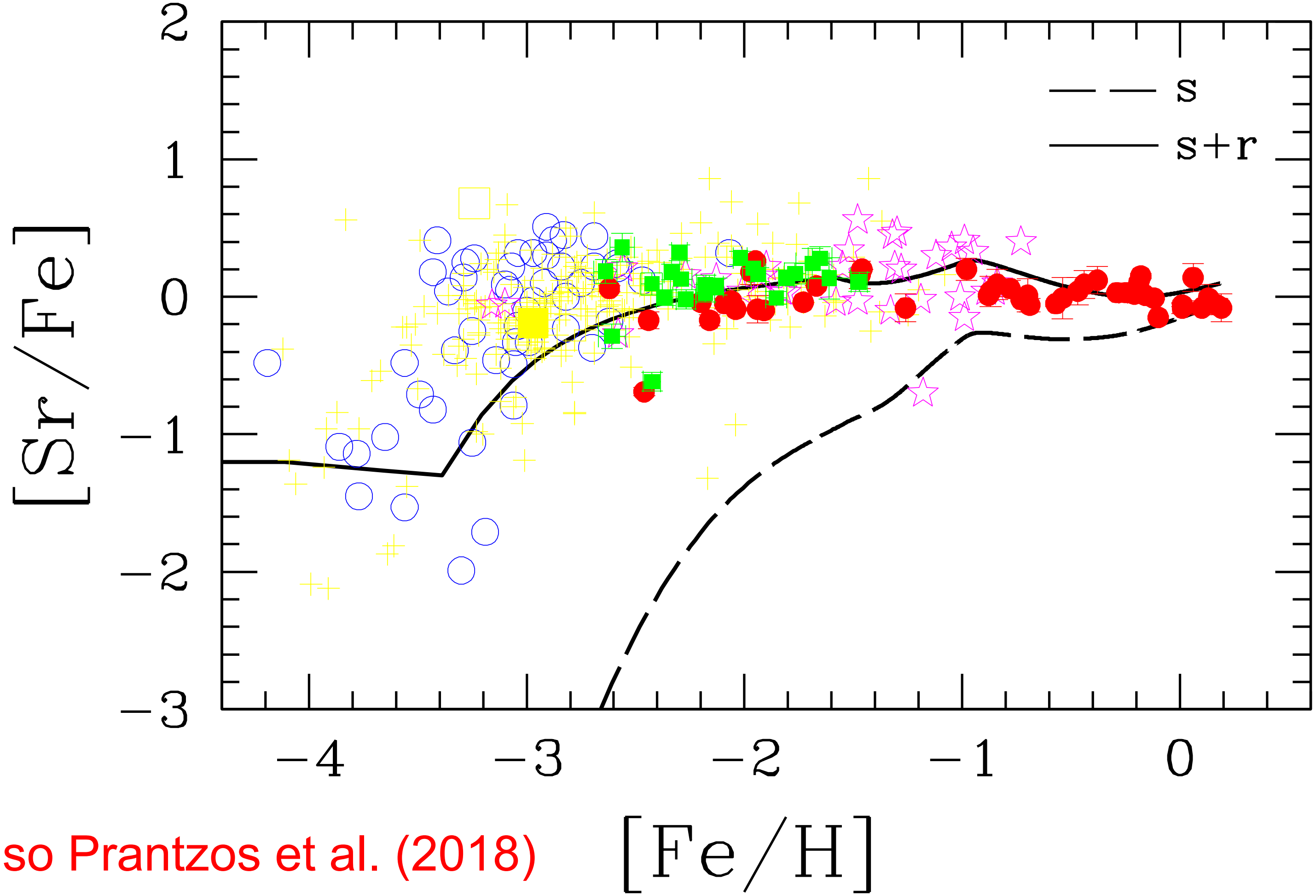
Chemical evolution with heavy elements

Kobayashi, Karakas & Lugaro (2018, in prep)



Chemical evolution with heavy elements

Kobayashi, Karakas & Lugaro (2018, in prep) – see her talk on Friday!



See also Prantzos et al. (2018)

Summary

- With available s-process yields, we can now make 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, Buder et al. 2018; K2 mission, e.g. Huber et al. 2016)
- We are still missing predictions for the lowest metallicities
- Puzzles related to post-AGB and CEMP r/s may be related to the i-process