The weak component of the s-process

Marco Pignatari

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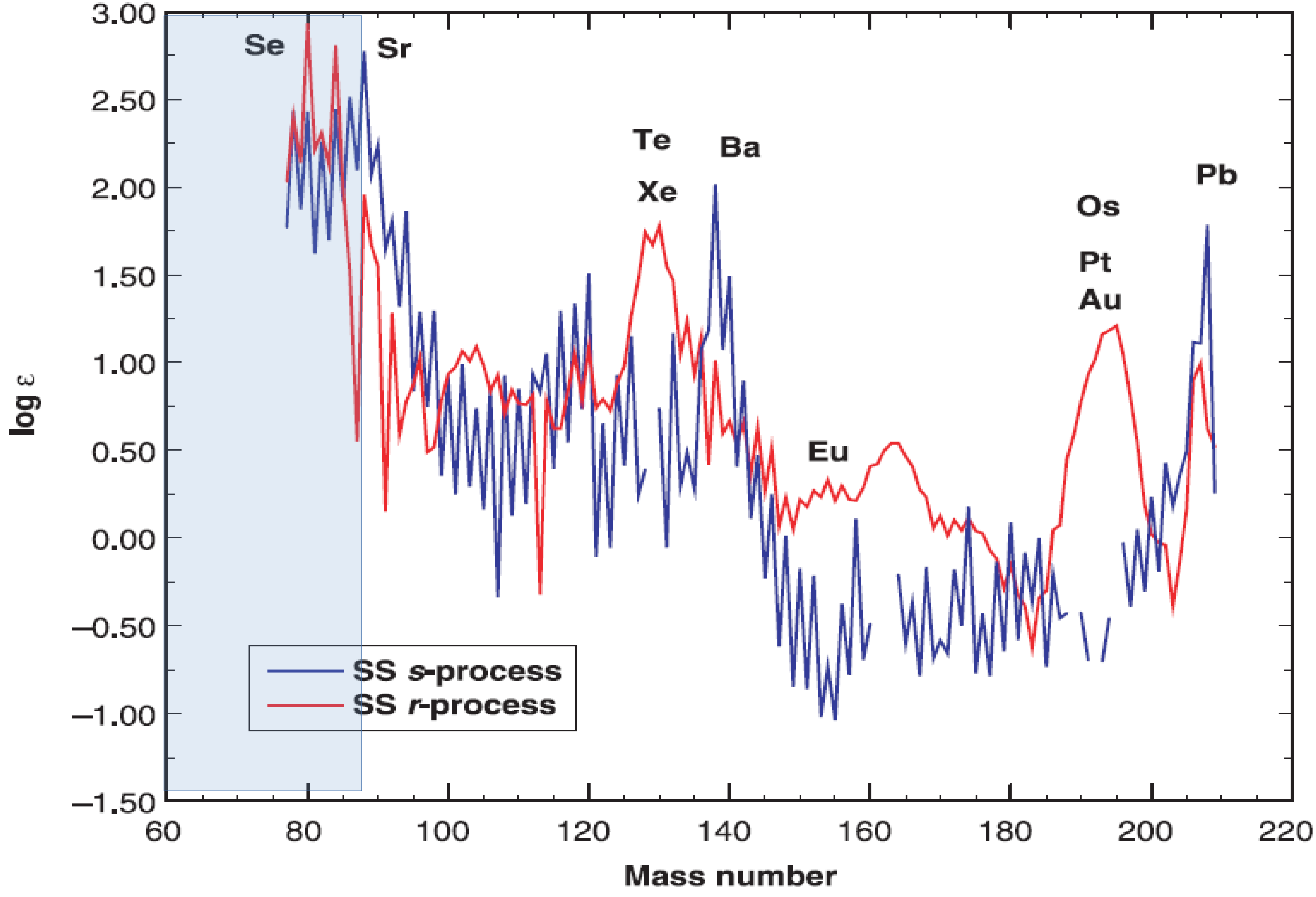
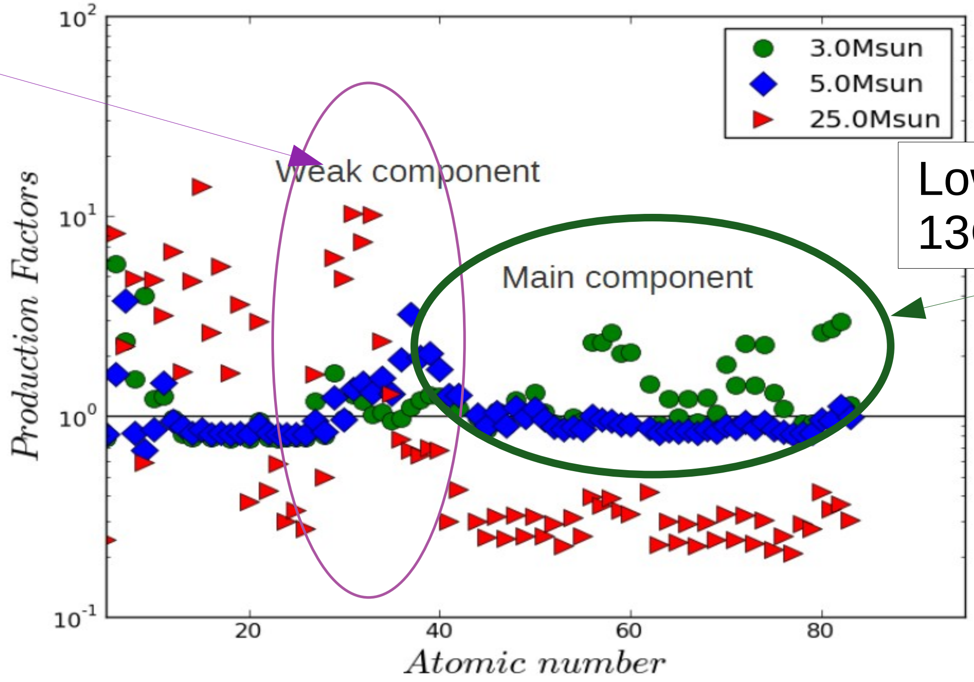
MTA Centre of Excellence, Budapest, Hungary

Sneden & Cowan 2003



Stellar yields:

massive stars… or
22Ne(α,n)25Mg

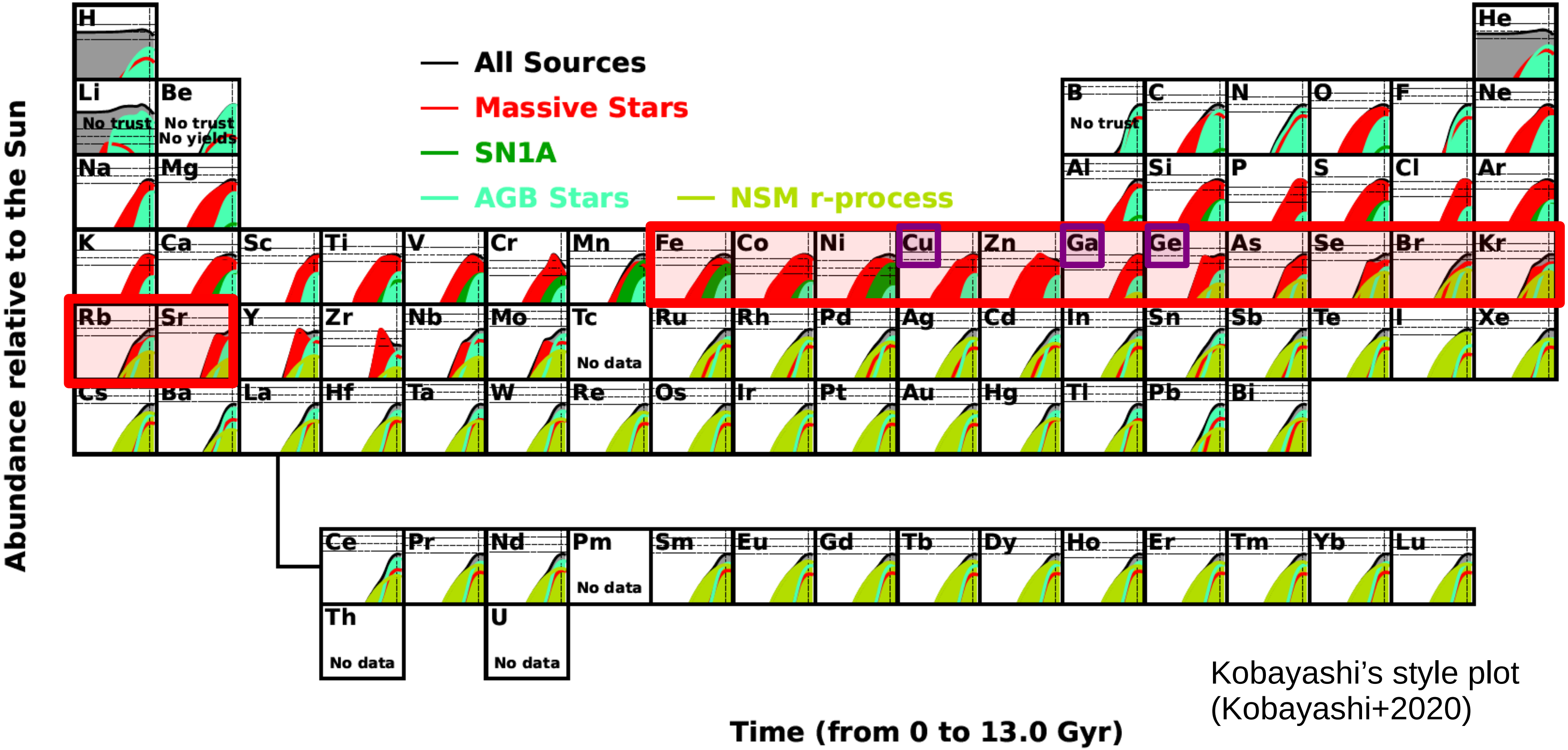


Low-mass AGB stars… or
13C(α,n)16O & 22Ne(α,n)25Mg

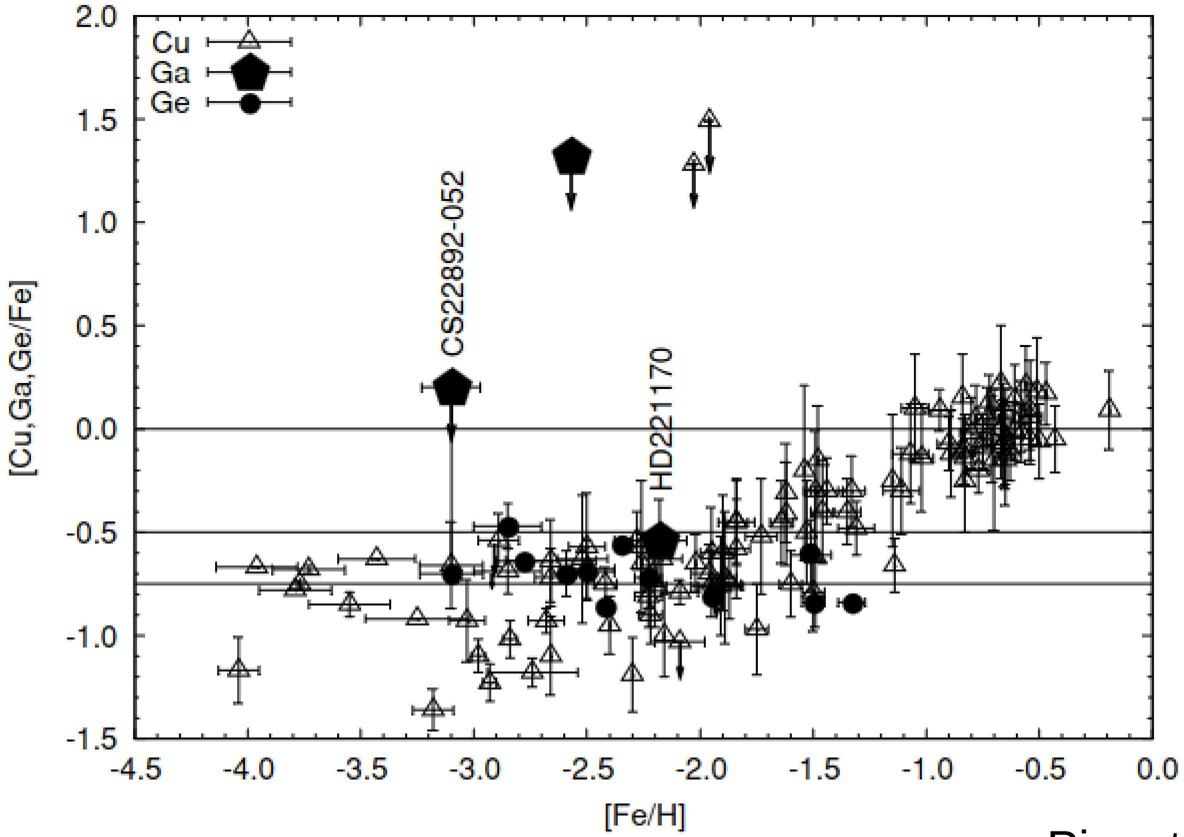
MP+2016, ApJS

Elemental production factors for a low mass AGB star, a massive AGB stars, and a massive star (Z=0.01).

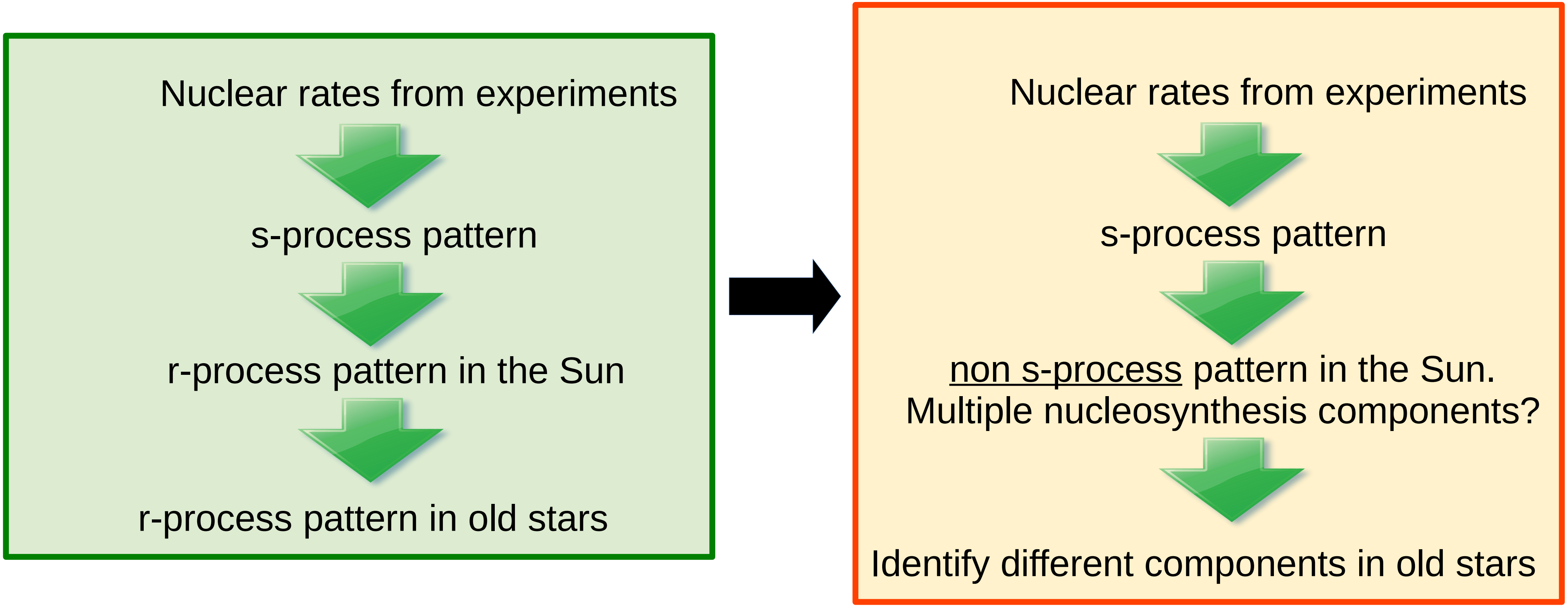
Open-source GCE codes
http://nugrid.github.io/NuPyCEE
https://github.com/becot85/JINAPyCEE



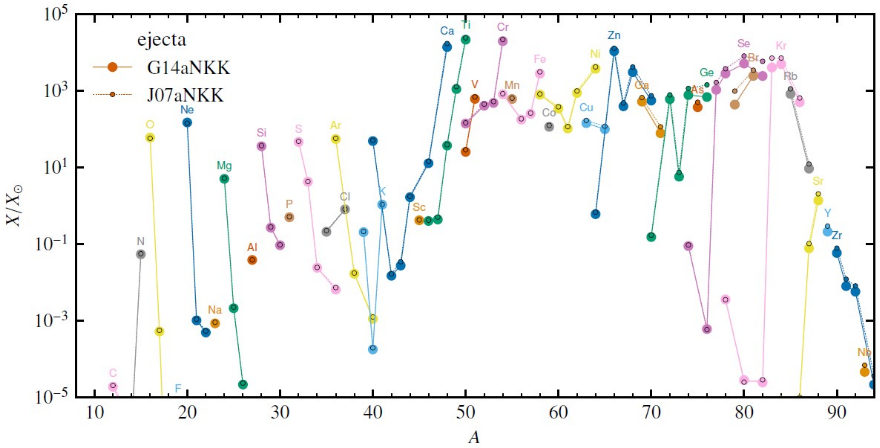
Kobayashi's style plot
(Kobayashi+2020)



Pignatari+ 2010 ApJ

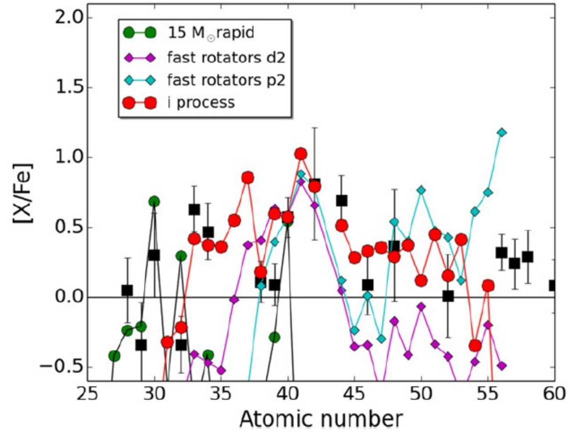

Nuclear rates from experiments
s-process pattern
r-process pattern in the Sun
r-process pattern in old stars
Nuclear rates from experiments
s-process pattern
non s-process pattern in the Sun.
Multiple nucleosynthesis components?
Identify different components in old stars

Jones+ 2019 ApJ

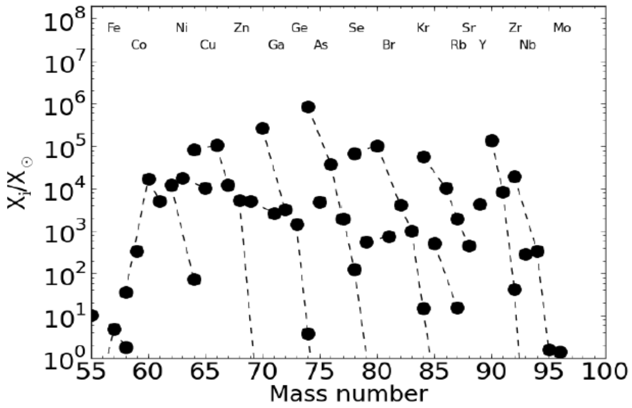


EC-SNe: e.g, Jones et al. 2019 ApJ , Wanajo et al. 2011 ApJL, etc

Roederer+ 2016 ApJ

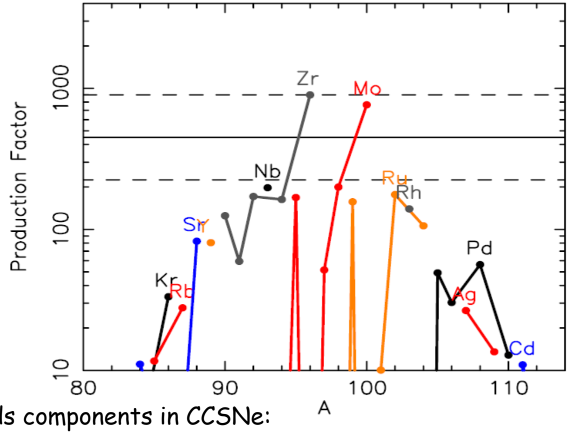


The i-process triggered by H-ingestion in He-burning regions:
(Roederer+ 2016 ApJ, Clarkson+ 2018 ApJ, Banerjee+ 2018 ApJ, etc)



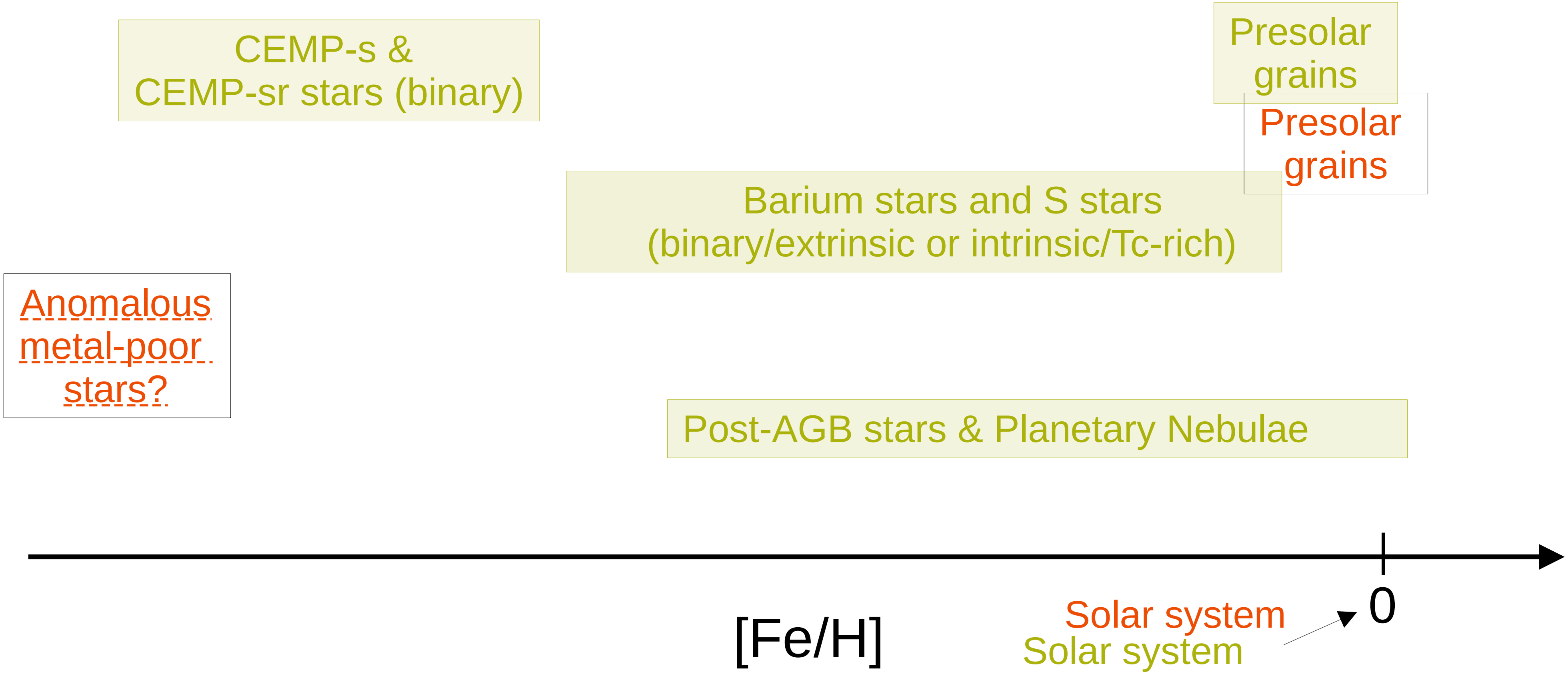
α-rich feezount in CCSNe:
e.g, Woosley & Hoffman 1992 ApJ, MP et al. 2016 ApJS

Roberts+ 2010 ApJ

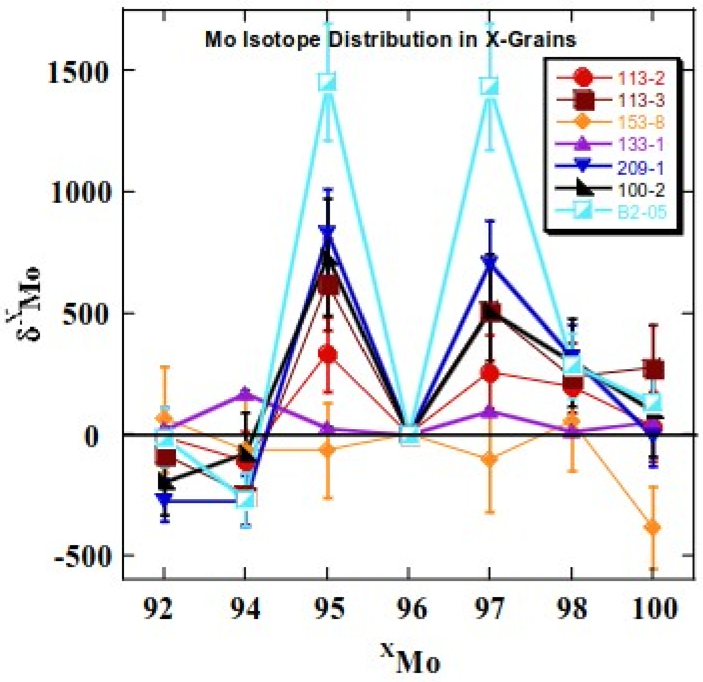


Neutrino-winds components in CCSNe:
e.g, Fröhlich et al. 2006 PhRvL and ApJ, Farouqi et al. 2009 ApJ,
Roberts et al. 2010 ApJ, Wanajo et al. 2011 ApJ, Wanajo et al. 2018 ApJ, etc

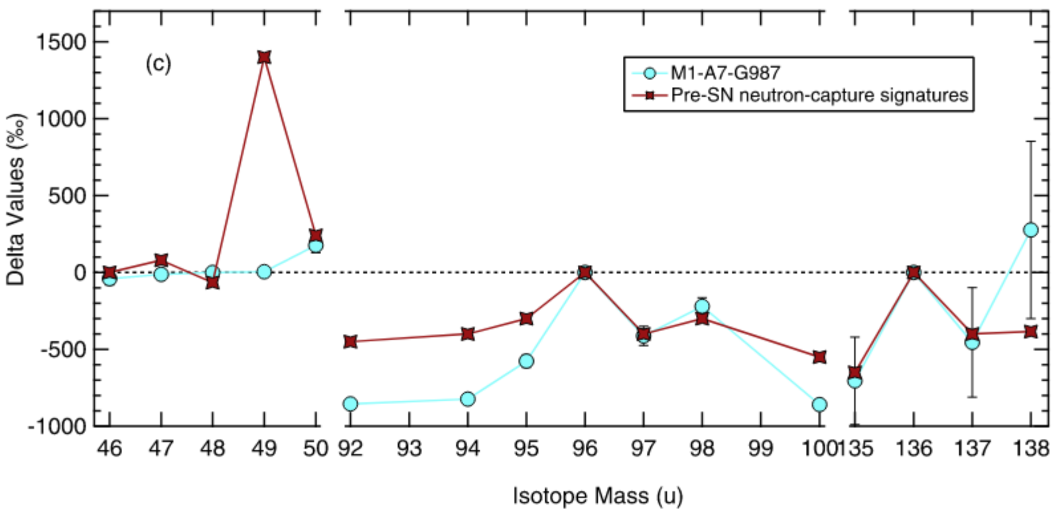
Observation of s-process signatures in AGB stars and in massive stars



Presolar grains: first observational evidence of the s-process at play in massive stars

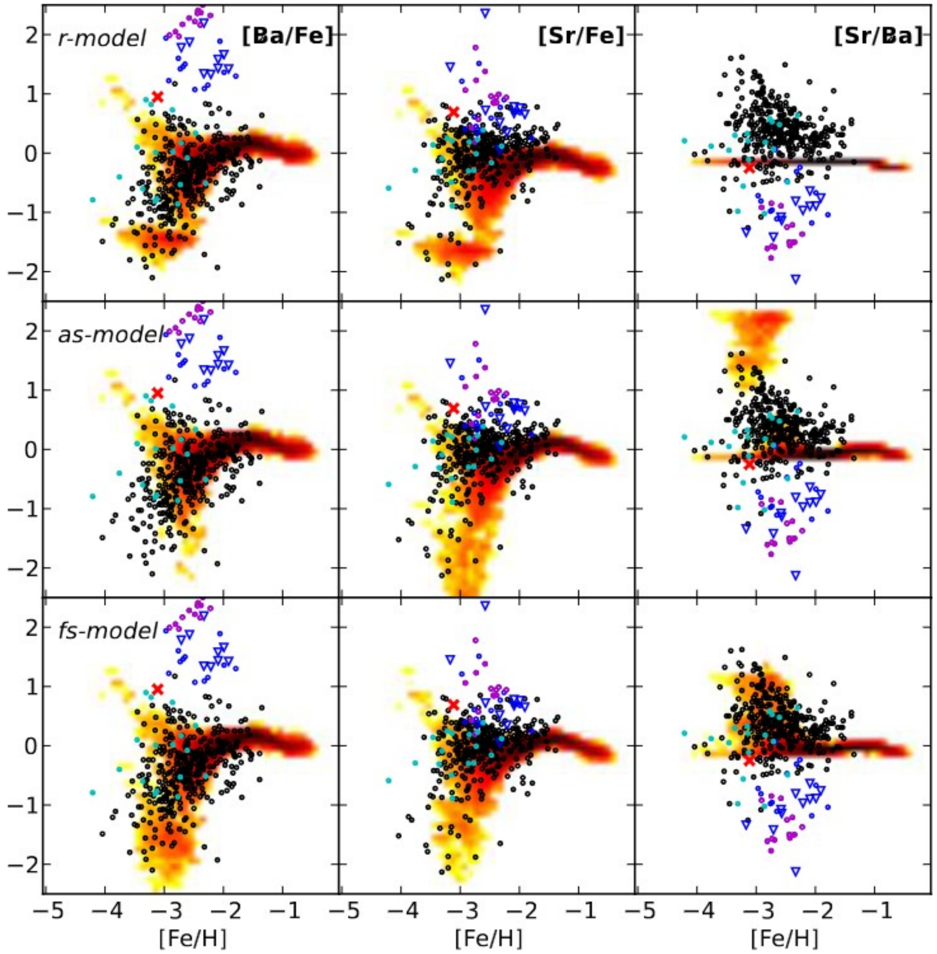


SiC-X grains (Pellin+ 2006)
Maybe grains 153-8?



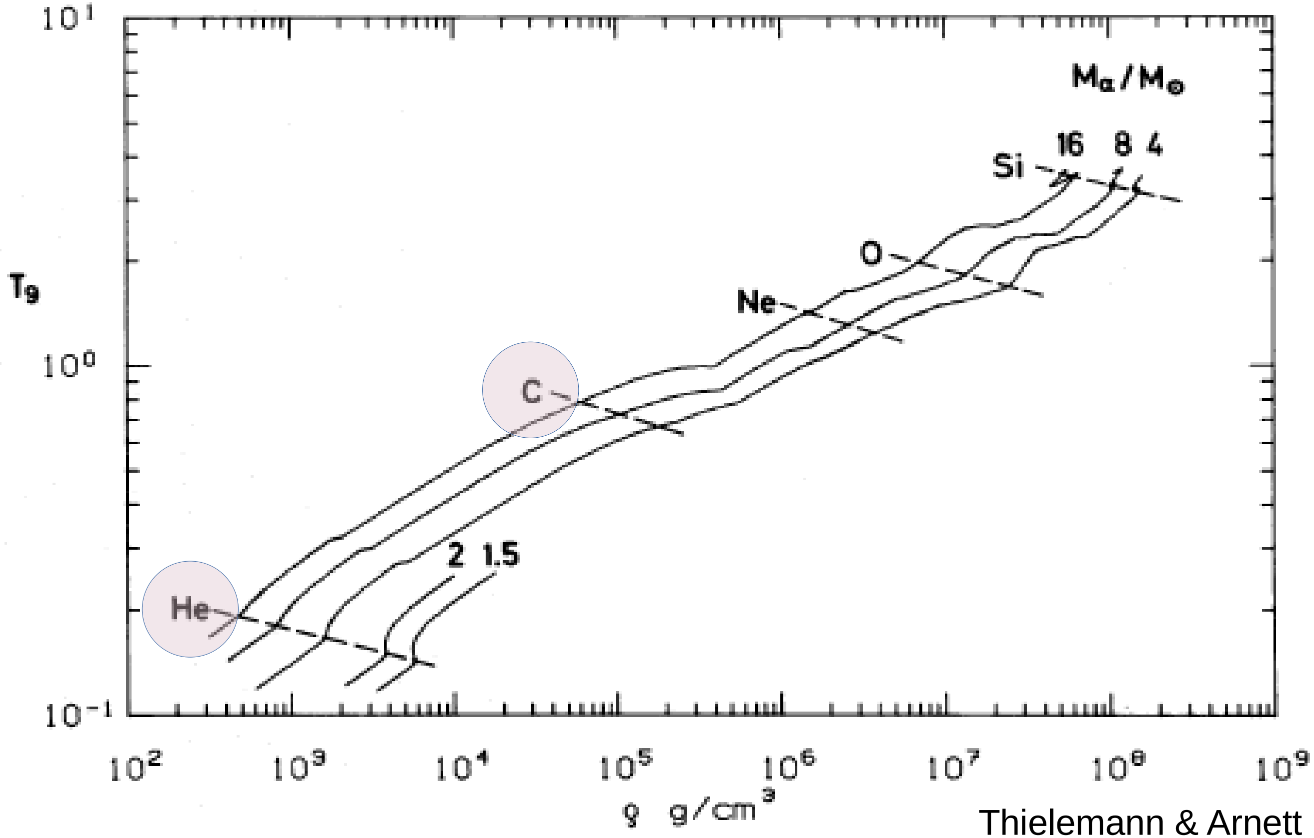
SiC-AB1 grains from massive stars show Mo and Ba with s-process signature of the preSN He shell. NO I-PROCESS and NO N-PROCESS!
Liu, N. et al. 2019 ApJ 2018

At low metallicity …
s-process in fast-rotating massive stars or something else?



Cescutti+ 2013 A&A

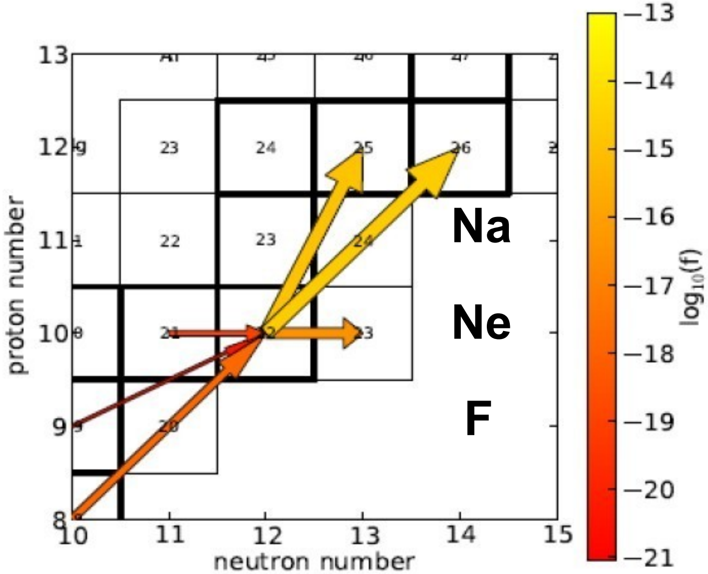
Conditions for the s-process



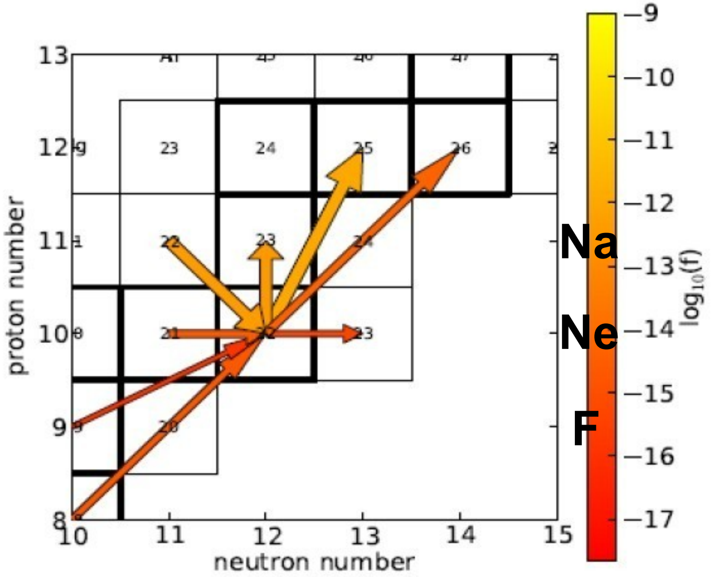
Thielemann & Arnett 1985 ApJ

12

Ne22(α,n)Mg25: main neutron source of the weak s-process in massive stars.

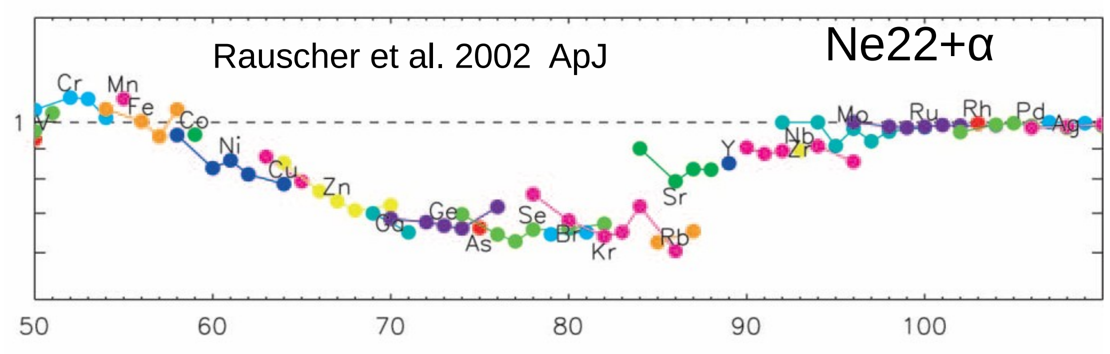


Ne22 nucleosynthesis in He-burning conditions (T9 ~ 0.3)

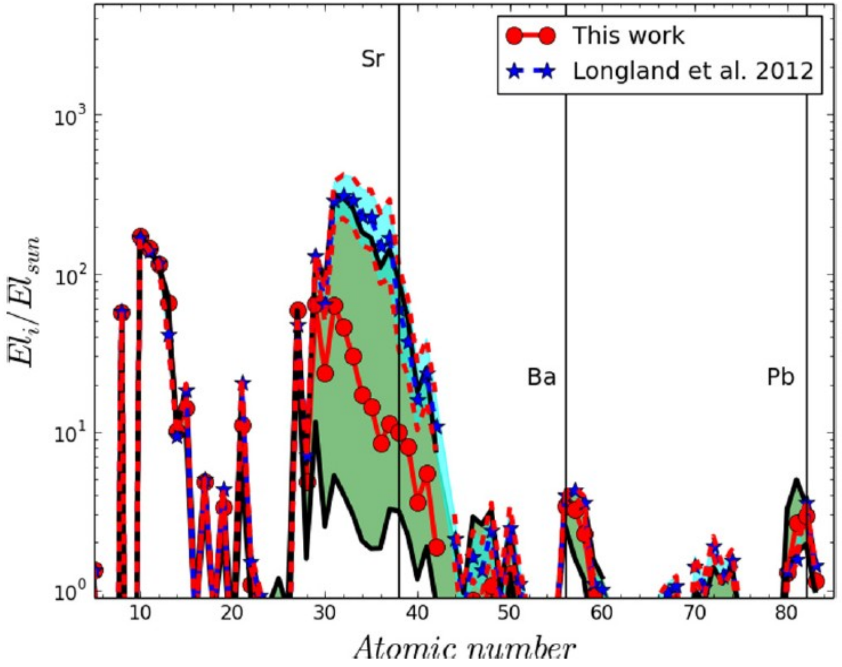


Ne22 nucleosynthesis in C-burning conditions (T9 ~ 1)

Nuclear uncertainties have large impact on the s-process products of massive stars



Talwar+ 2016 PRC



22Ne(α,n)25Mg rate ($cm^3\ mol^{-1}\ s^{-1}$) & 22Ne(α,γ)26Mg ($cm^3\ mol^{-1}\ s^{-1}$)

T9	Longland+2012		Talwar+2016		~ Ota+ 2020 Adsley+2021 (with TAMU)		Massimi+ 2017*	
0.3	3.36e-11	1.13e-11	3.10e-11	5.20e-11	1.05e-11	8.60e-12	4.52e-11	**5.82e-13**
1.0	6.64e-02	4.11e-04	8.68e-02	4.17e-04	1.33e-01	3.85e-04	8.45e-02	**1.43e-04**

(*) upper limit
0.06<T9<1

- **In low-mass AGB stars: only partial 22Ne(α,n)25Mg activation**
- **In massive stars:**
  - **At 0.3 GK both rates and their relative ratios are important**
  - **At 1.0 GK the 22Ne(α,γ)26Mg is not relevant**

22Ne(α,n)25Mg rate (cm^3 mol^{-1} s^{-1}) & 22Ne(α,γ)26Mg (cm^3 mol^{-1} s^{-1})

T9	Longland+2012		Talwar+2016		~ Ota+ 2020 Adsley+2021 (with TAMU)		Massimi+ 2017*	
0.3	3.36e-11	1.[illegible]-11	3.10e-11	5.[illegible]-11	1.05e-11	8.[illegible]-12	4.52e-11	5.82e-13
1.0	6.64e-02	4.[illegible]-04	8.68e-02	4.[illegible]-04	1.[illegible]-01	3.[illegible]-04	8.45e-02	1.43e-04

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Eur. Phys. J. A (2023) 59:302
https://doi.org/10.1140/epja/s10050-023-01206-1

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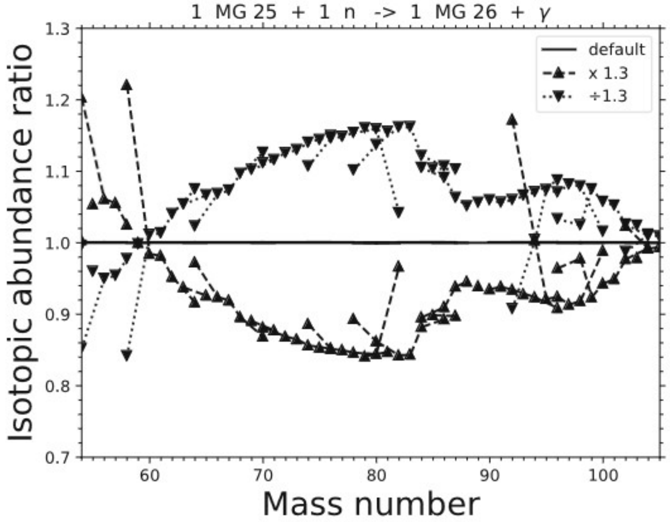
Regular Article - Experimental Physics

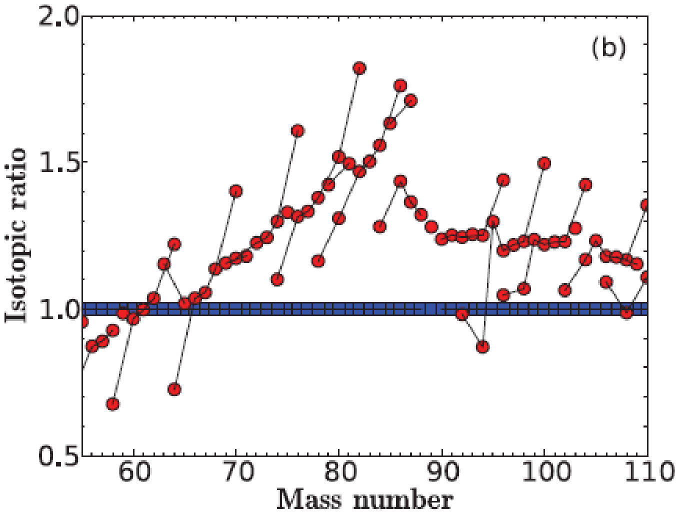
The s process in massive stars, a benchmark for neutron capture reaction rates

Marco Pignatari[1,2,3,a,b], Roberto Gallino[4], Rene Reifarth[5,6]

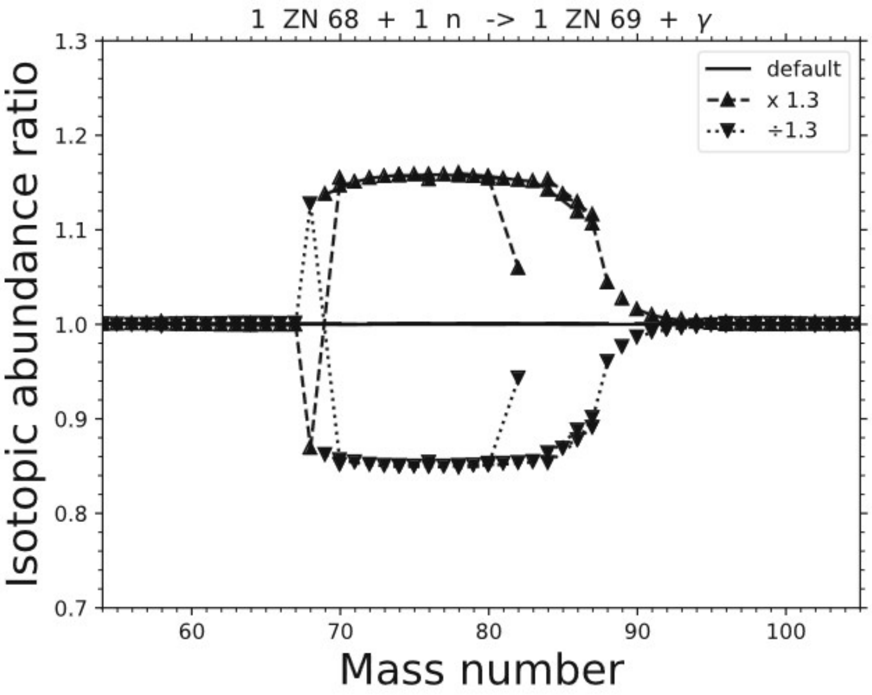
EPJA volume
in honour of
Franz Käppeler

Sensitivity study: 86 neutron-capture rates in the mass regions C-Si & Fe - Zr

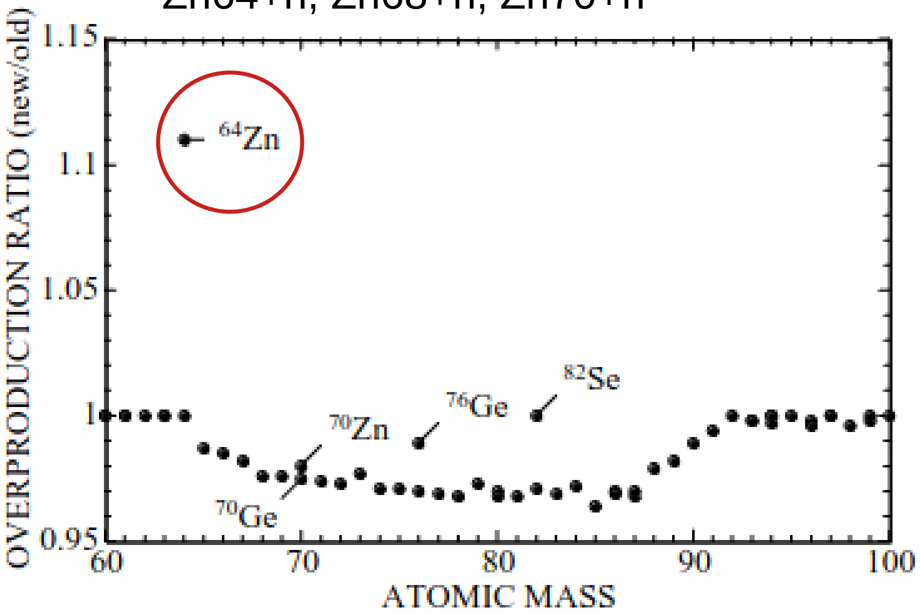


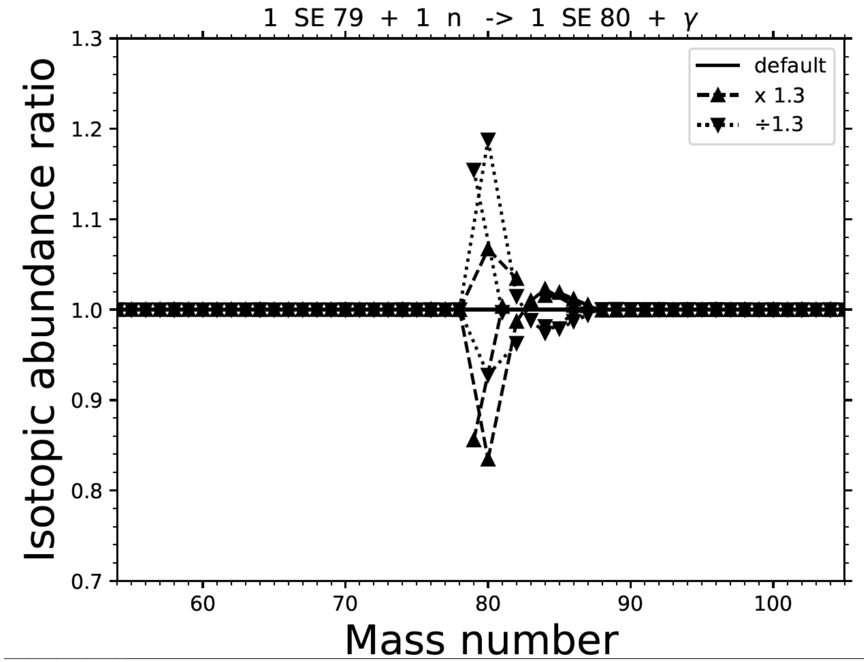


Massimi+2012 n_TOF:
24Mg+n, 25Mg+n, 26Mg+n



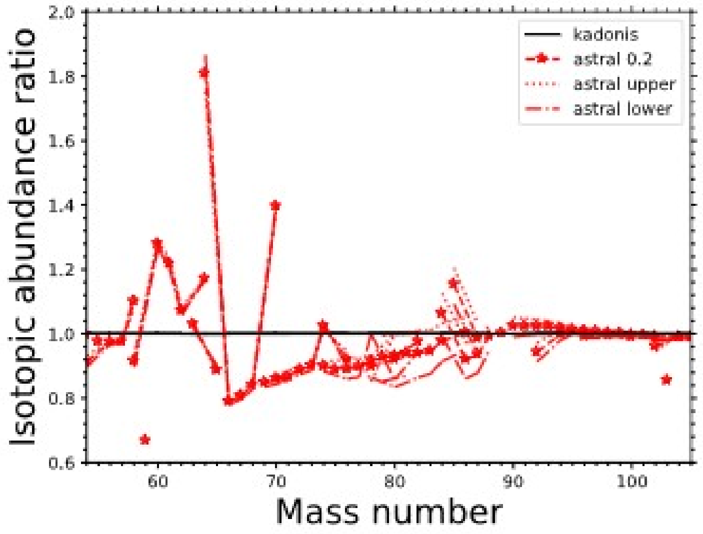
Reifarth+2012 Act. (NETZ calculations)
Zn64+n, Zn68+n, Zn70+n

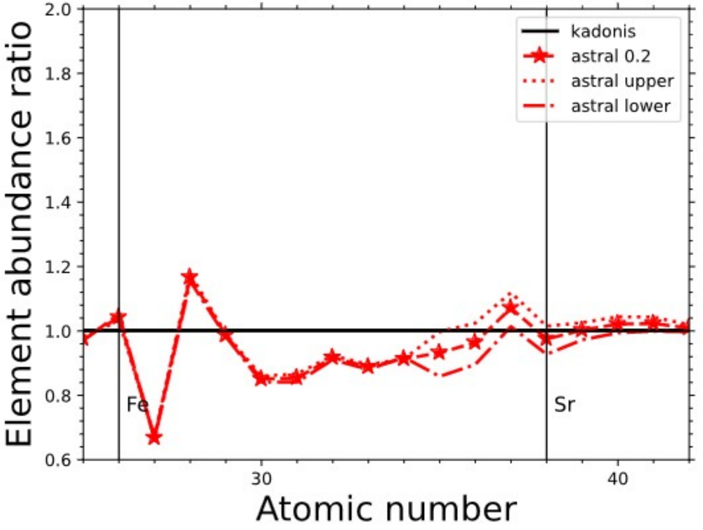


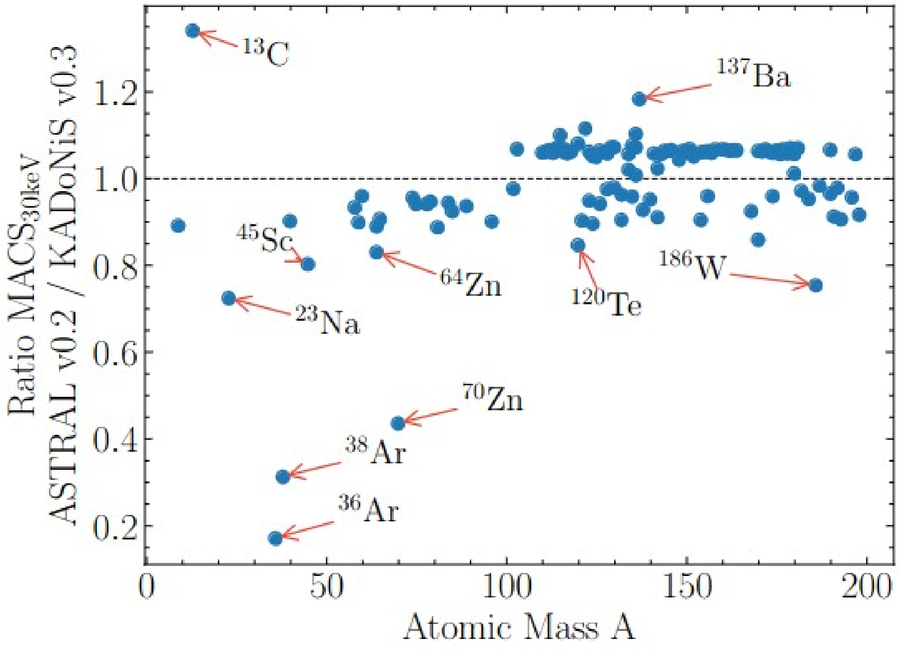


^{80}Rb 33.40 s β^{+}	^{81}Rb 4.57 h β^{+}	^{82}Rb 1.27 m β^{+}	^{83}Rb 86.20 d β^{+}	^{84}Rb 33.10 d β^{+}
^{79}Kr 1.46 d 959 mb, β^{+}	^{80}Kr 2.28 267 mb	^{81}Kr 229.02 ka 607 mb, β^{+}	^{82}Kr 11.58 90 mb	^{83}Kr 11.49 243 mb
^{78}Br 6.46 m β^{+}	^{79}Br 50.69 622 mb	^{80}Br 17.68 m β^{-}	^{81}Br 49.31 239 mb	^{82}Br 1.47 d β^{-}
^{77}Se 7.63 418 mb	^{78}Se 23.77 109 mb	^{79}Se 294.99 ka 263 mb, β^{-}	^{80}Se 49.61 42 mb	^{81}Se 18.45 m β^{-}
^{76}As 1.09 d β^{-}	^{77}As 1.62 d β^{-}	^{78}As 1.51 h β^{-}	^{79}As 9.01 m β^{-}	^{80}As 15.20 s β^{-}

n_TOF: status experiment
Lerendegui-Marco+ 2023







Vescovi+2023 EPJWC
ASTRAL library
(https://exp-astro.de/astral/)

… all data available in Zenodo: https://zenodo.org/records/10124711

NuGrid Nucleosynthesis Grid collaboration

Published November 14, 2023 | Version v1

Dataset | Open

Output from paper: The s process in massive stars, a benchmark for neutron capture reaction rates

Pignatari, Marco[1]; Gallino, Roberto[2]; Reifarth, Rene[3]

Show affiliations

Title: "The s process in massive stars, a benchmark for neutron capture reaction rates"; Authors: Marco Pignatari, Roberto Gallino, Rene Reifarth

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Content: tar.gz package including a README file and two folders. The folders contain all the abundance plots associated to the work Pignatari, Gallino & Reifarth, 2023 The European Physical Journal A, Special Issue on: 'From reactors to stars' in honor of Franz Kaeppeler.

Files

Files (16.0 MB)

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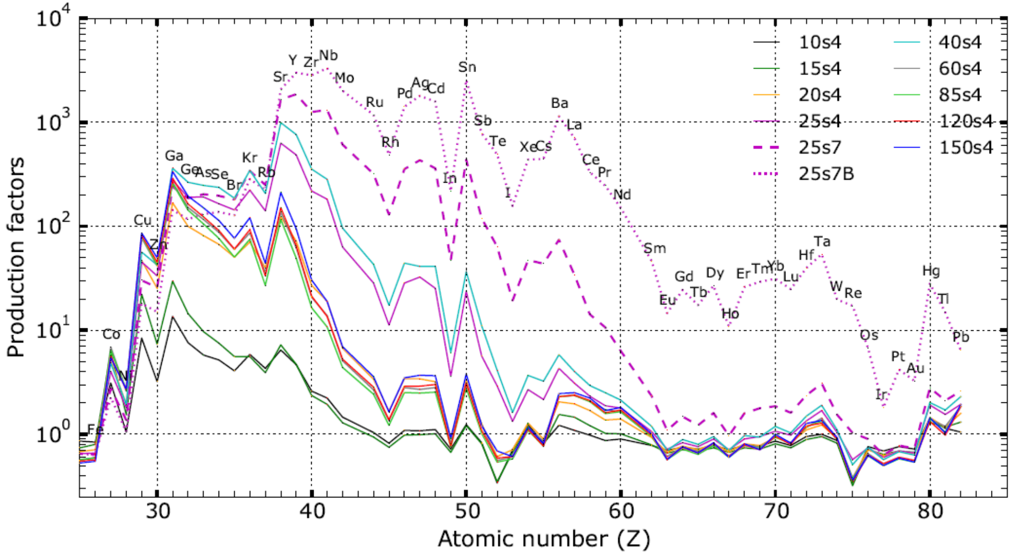
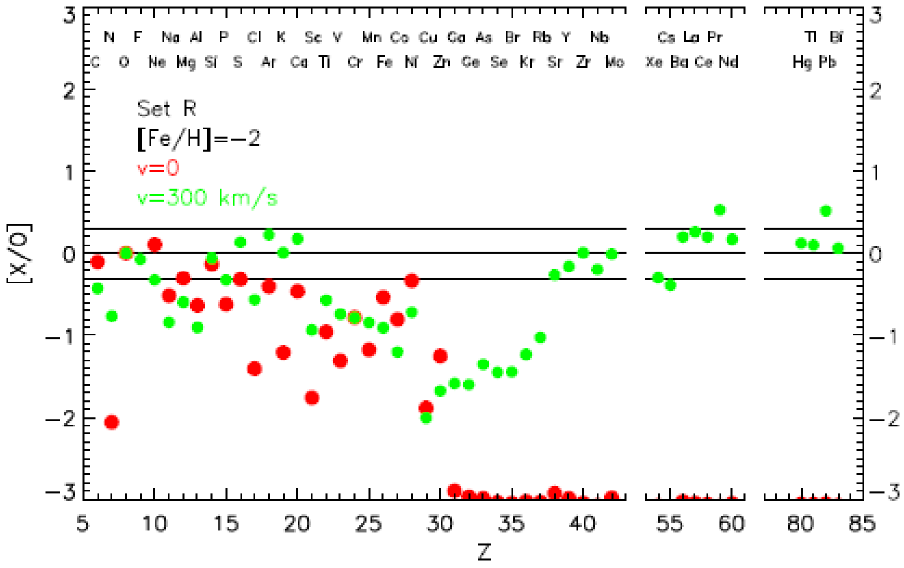
Enhanced s process due to rotation in massive stars at low metallicity



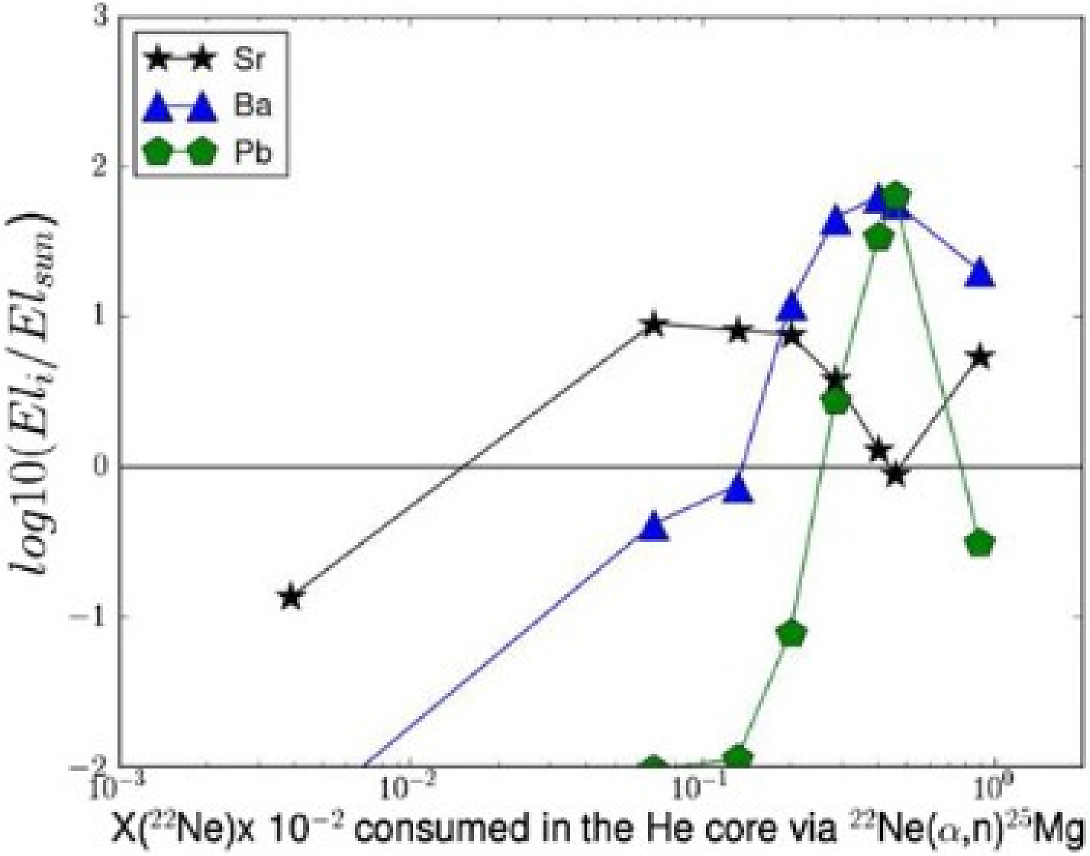
Choplin+ 2018 A&A



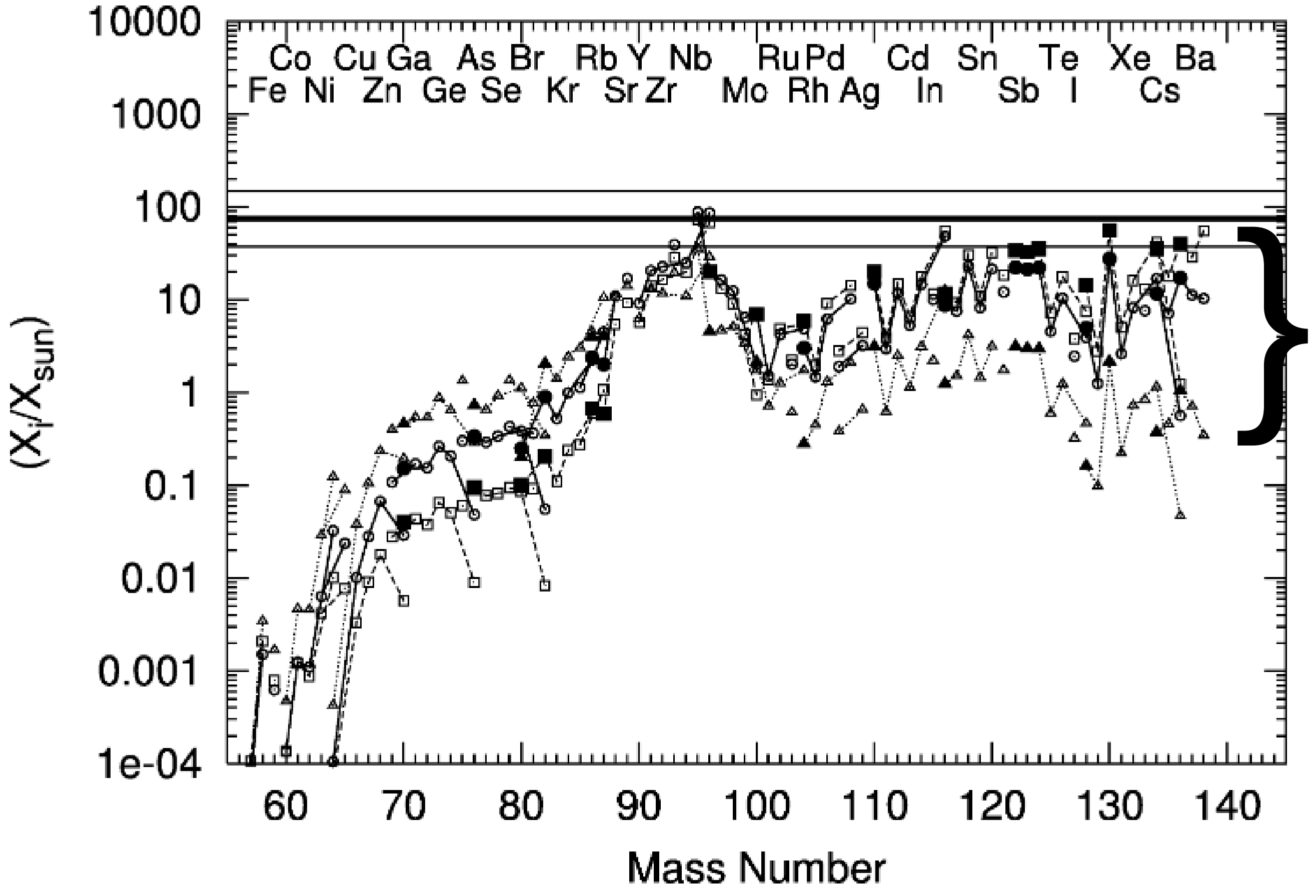
Limongi & Chieffi 2018 ApJ

See also Pignatari+ 2008 ApJL, Frischknecht+ 2016 MNRAS

22Ne+α:
impact on the s-process in fast-rotating massive stars



Pignatari+2013 ApJ



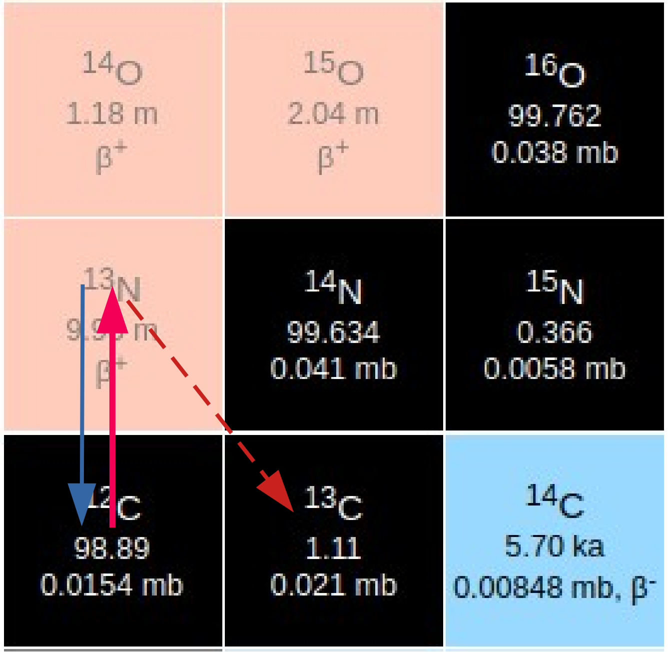
Ne22(α,n) multiplied and divided by 2

Pignatari+ 2008 ApJL

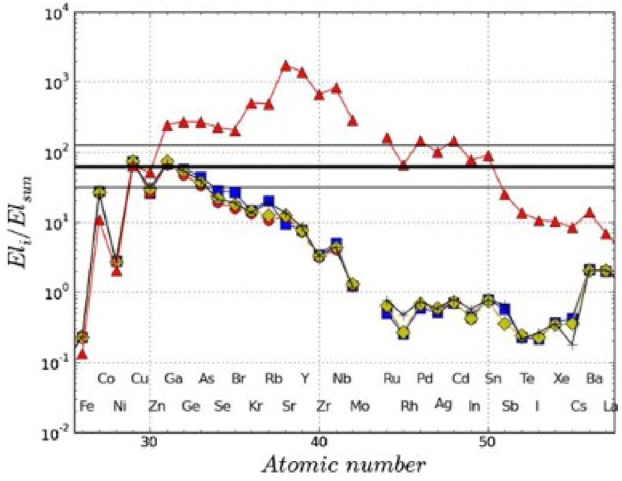
Other examples:
17O+α
e.g., Frost-Schenk+ 2022

13C(α,n)16O and s-process in massive stars?

Neutron source activated in the convective C core, but <u>not</u> in the C shell (Chieffi+ 1998 ApJ).



For high C12+C12 rates, the convective C core may overlap with the C shell boosting the s-process.

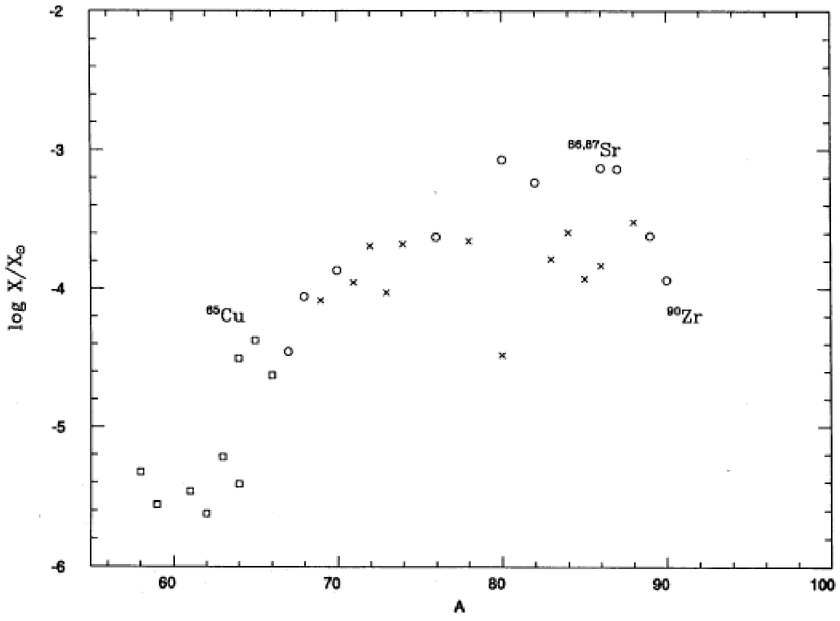


Pignatari+ 2013 ApJ

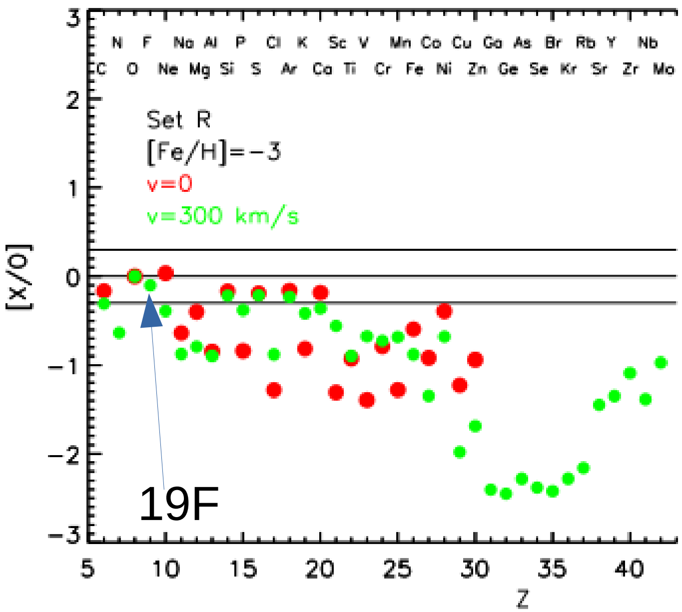
13C(α,n)16O and s-process in massive stars?

At the beginning of central He burning, for Z ≤ Zsun/1000 (Baraffe+ 1992 A&A) and in WR progenitor stars (Prantzos+1987 ApJ. Brinkman+2021 ApJ).

Convective He shell in low Z rotating massive stars (Limongi & Chieffi 2018 ApJS)

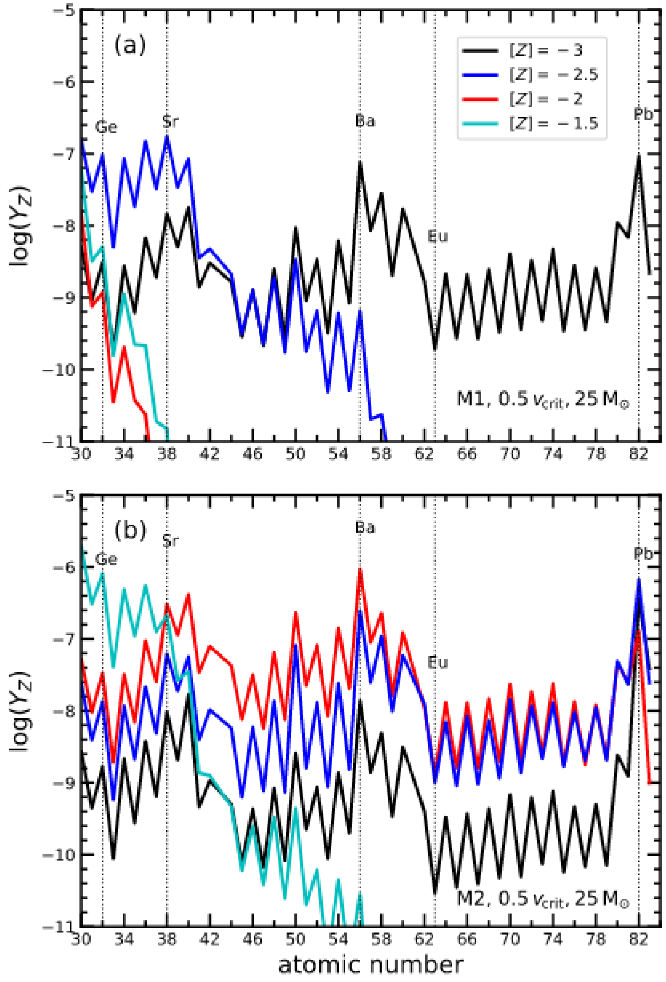


Baraffe+ 1992 A&A



13C(α,n)16O and s-process in massive stars?

Convective He core in low Z fast-rotating massive stars (quasi-chemical homogeneus, v = 0.3/0.7 v_{crit}), Banerjee+ 2019 ApJ.



The s-process production in rotating massive stars at low Z: really uncertain!

Conclusions

- More general definition of the classical residual method;
- First direct observation of the weak s-process in action confirmed;
- 22Ne(α , γ)26Mg: we need a rate + errors compatible with the upper limits Massimi+ 2017;
- For comprehensive implementation of the 22Ne(α , γ)26Mg upper limit in stellar yields calculations, we need it up to at least 2 GK;
- Sensitivity study for the weak s-process & propagation effect;
- The s-process in massive stars at low metallicity
- The 13C(α ,n)16O in massive stars