The weak s-process production in massive stars: theory, uncertainties and comparison with observations

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KONKOLY
CSFK
ChETEC INFRA
NUGRID
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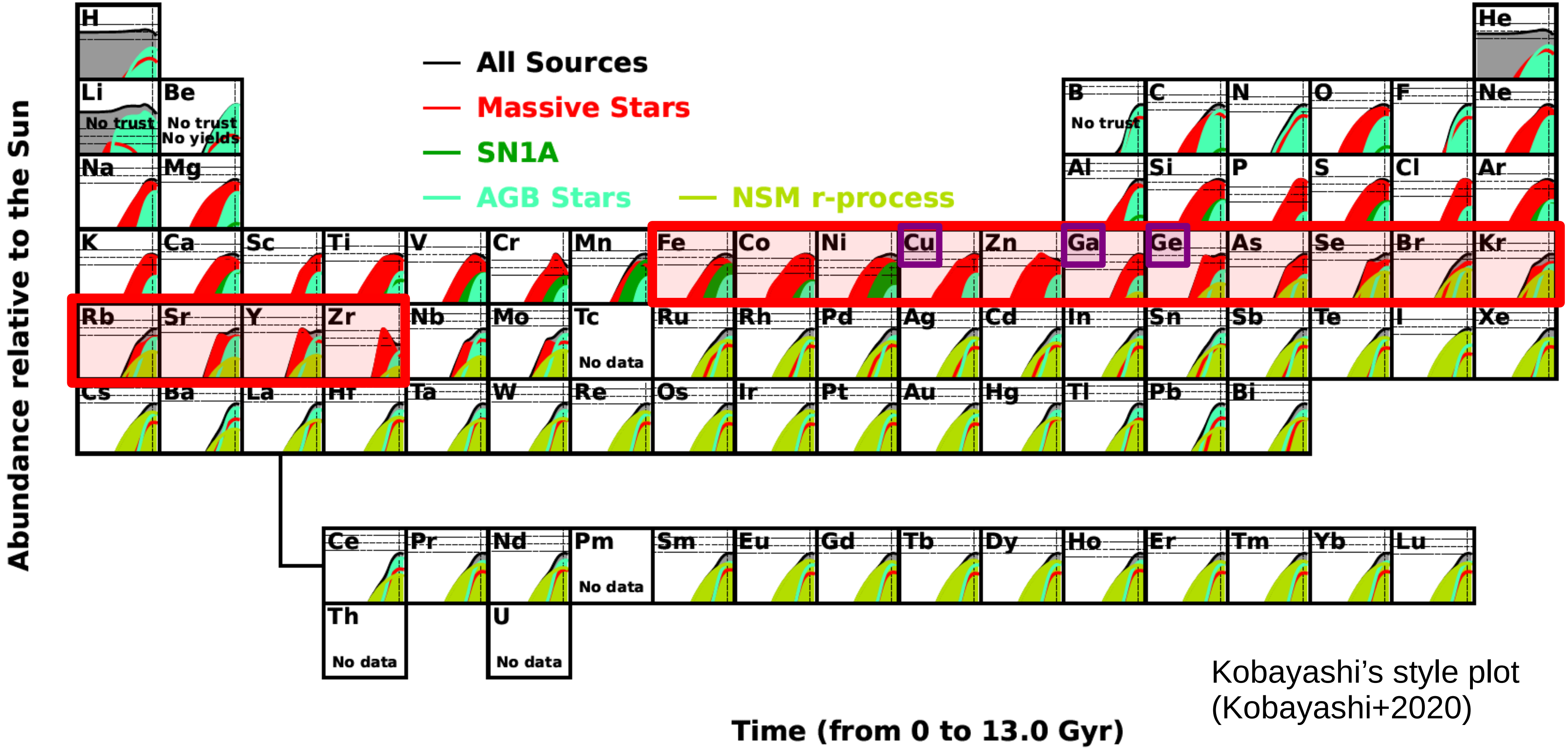
JINA-CEE

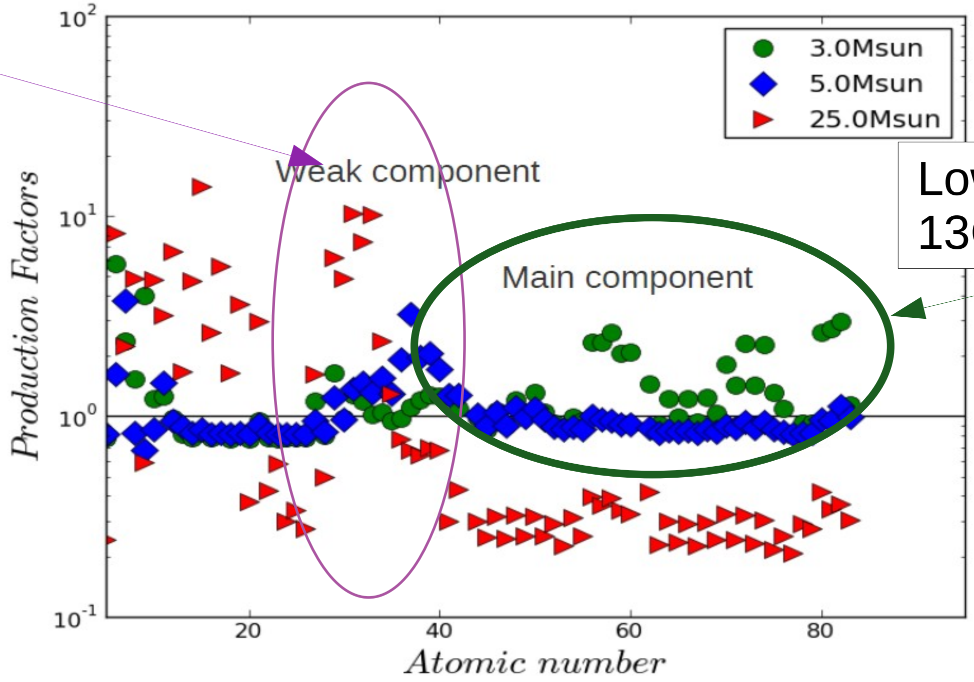
Open-source GCE codes
http://nugrid.github.io/NuPyCEE
https://github.com/becot85/JINAPyCEE



Kobayashi's style plot (Kobayashi+2020)

Stellar yields:

massive stars… or 22Ne(α,n)25Mg

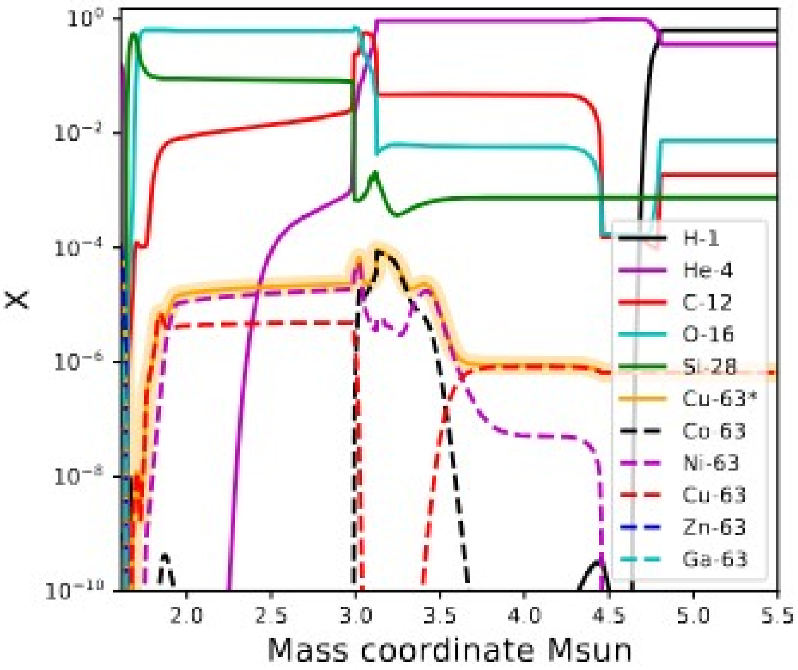


Low-mass AGB stars… or 13C(α,n)16O & 22Ne(α,n)25Mg

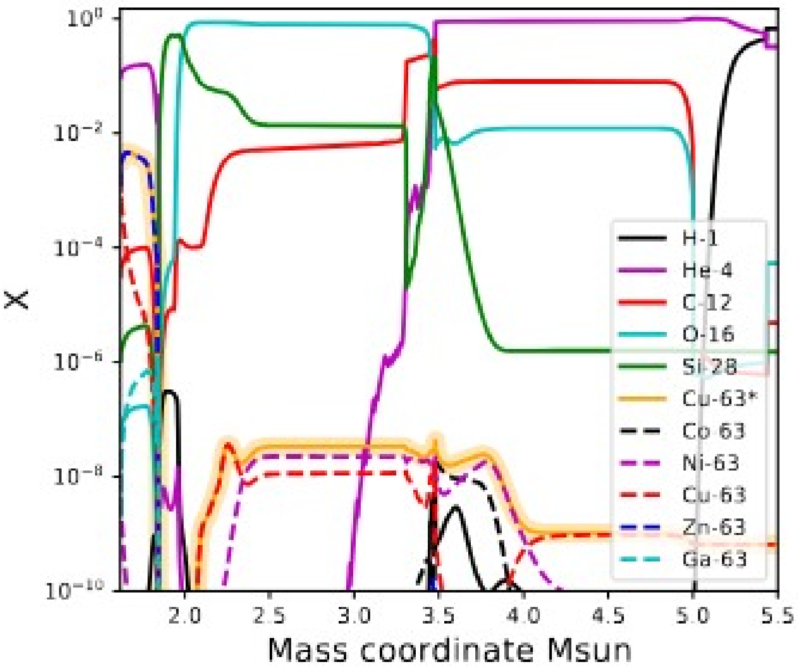
MP+2016, ApJS

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

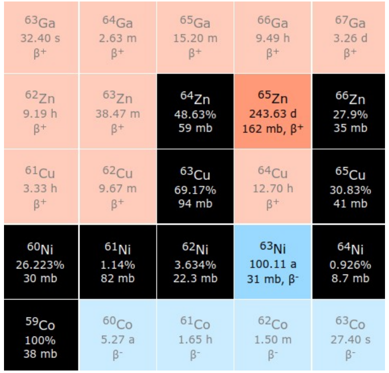
M=15Msun, Z=0.02



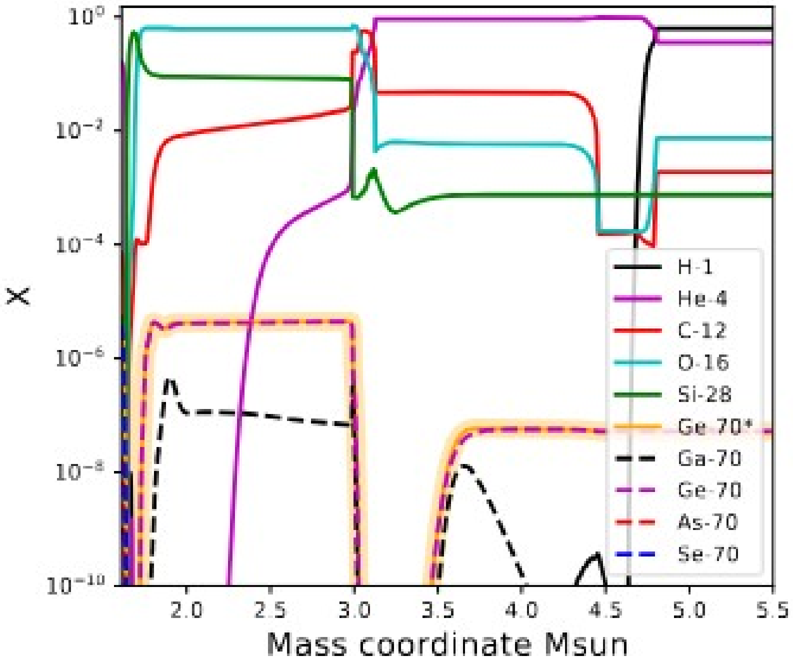
M=15Msun, Z=0.0001



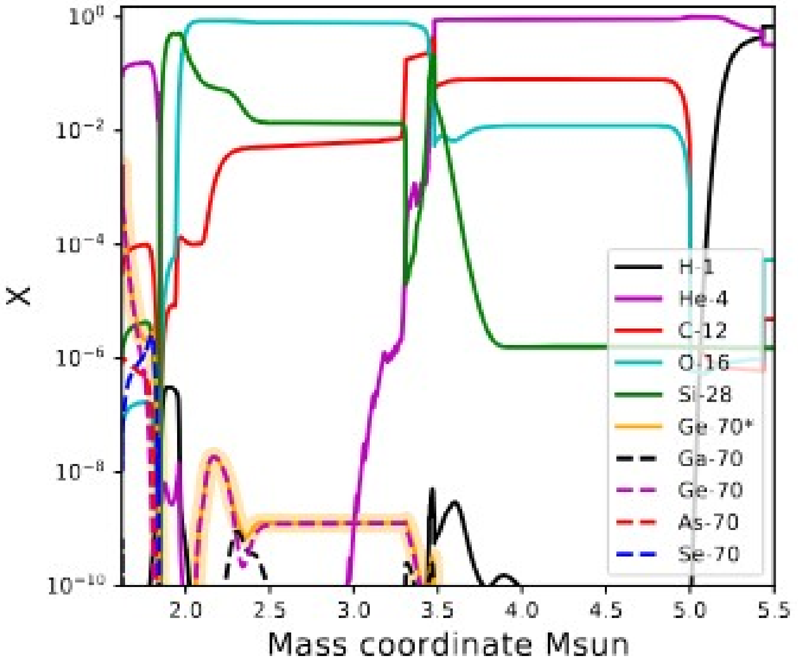
Models by
Ritter+ 2018 MNRAS



M=15Msun, Z=0.02



M=15Msun, Z=0.0001

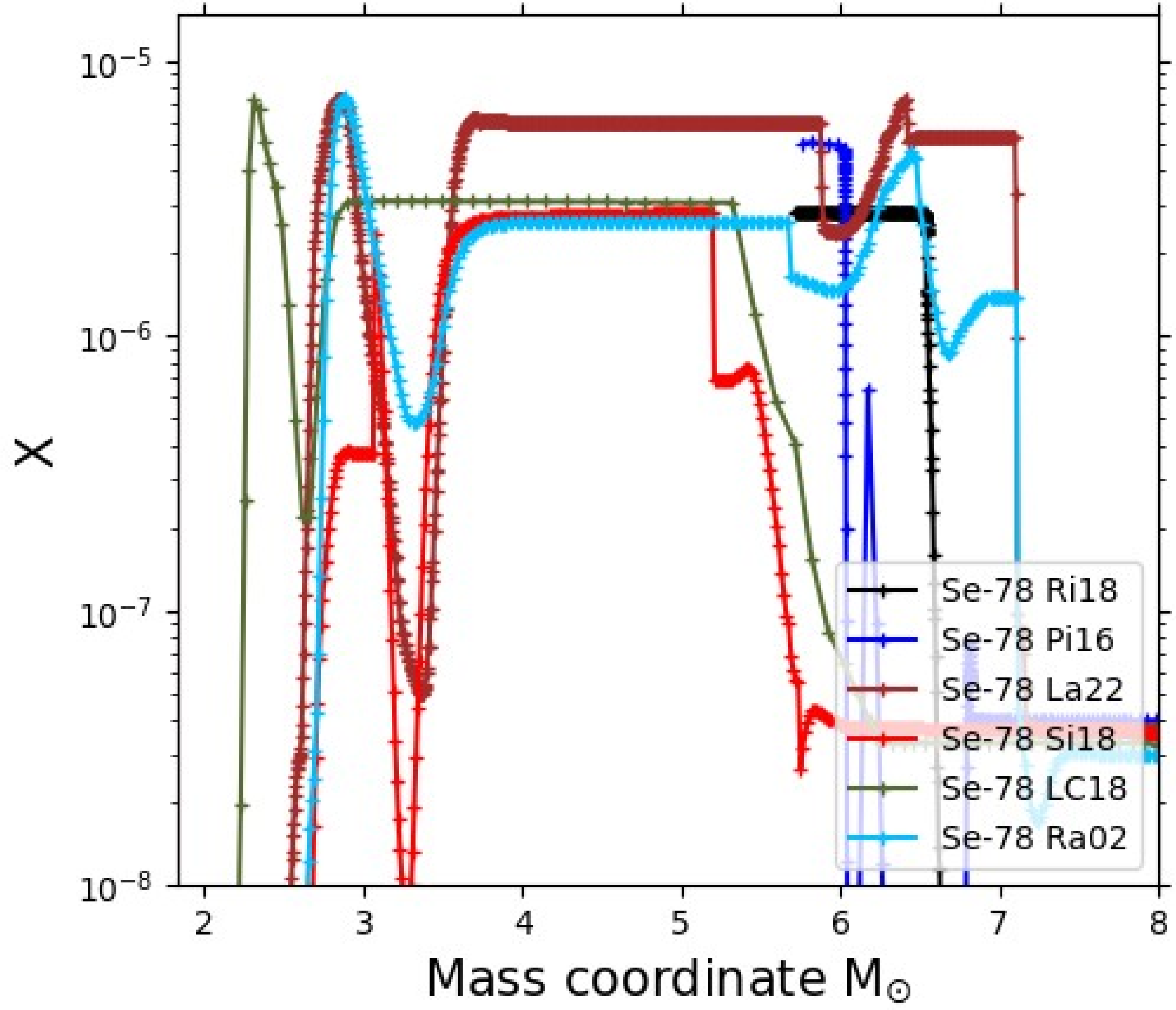


Models by
Ritter+ 2018 MNRAS

^{70}Se 41.10 m β+	^{71}Se 4.74 m β+	^{72}Se 8.40 d β+	^{73}Se 7.15 h β+	^{74}Se 0.89% 267 mb
^{69}As 15.20 m β+	^{70}As 52.60 m β+	^{71}As 2.72 d β+	^{72}As 1.08 d β+	^{73}As 80.30 d β+
^{68}Ge 270.95 d β+	^{69}Ge 1.63 d β+	^{70}Ge 20.37% 88 mb	^{71}Ge 11.43 d β+	^{72}Ge 27.31% 73 mb
^{67}Ga 3.26 d β+	^{68}Ga 1.13 h β+	^{69}Ga 60.108% 139 mb	^{70}Ga 21.14 m β-	^{71}Ga 39.892% 123 mb
^{66}Zn 27.9% 35 mb	^{67}Zn 4.1% 153 mb	^{68}Zn 18.75% 19.2 mb	^{69}Zn 56.40 m β-	^{70}Zn 0.62% 21.5 mb

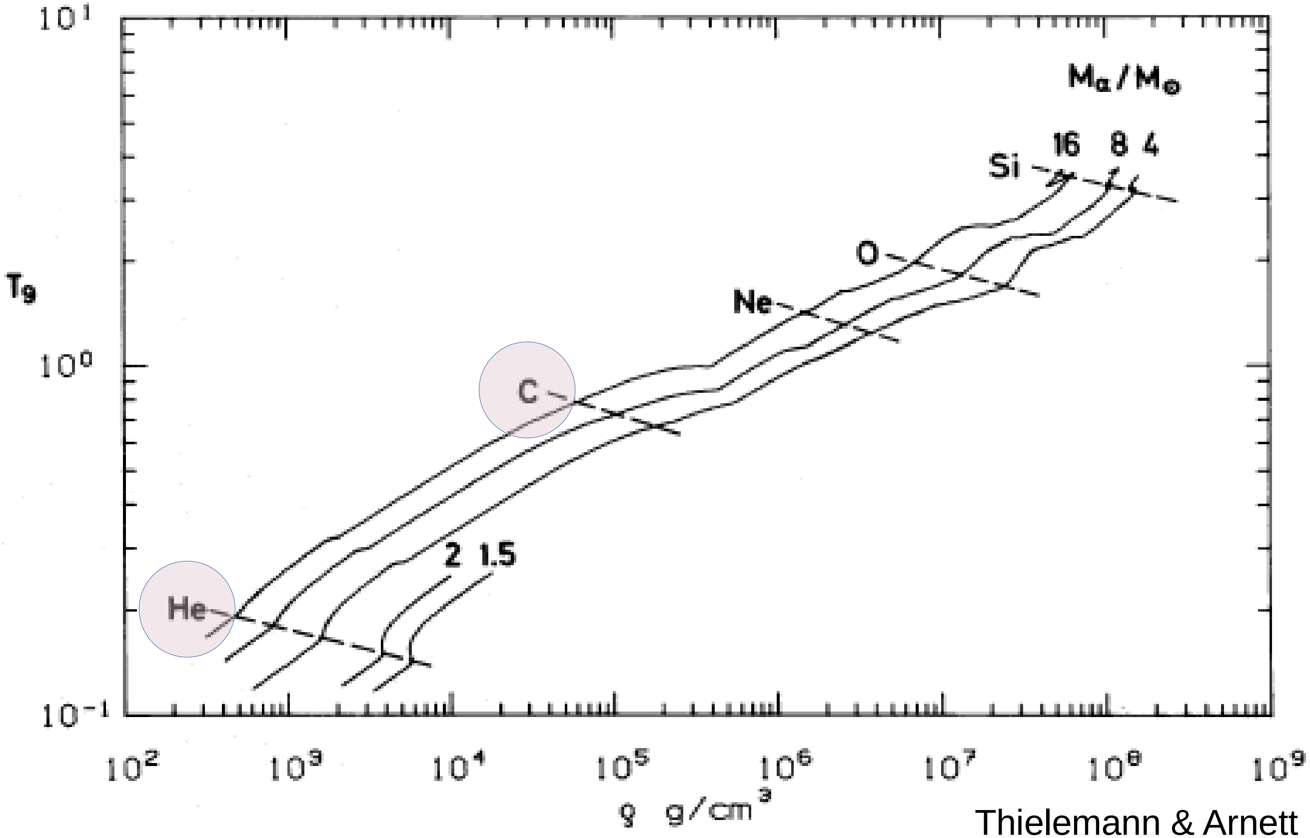
25Msun models, Z = solar

SIMPLE (Pignatari+2025, in prep)



Ritter+ 2018 MESA+Fryer
Pignatari+ 2016 GENEC+Fryer
Lawson+ 2022 KEPLER+Fryer
Sieverding+ 2018 KEPLER+piston
Limongi+ 2018 FRANEC+Hyperion*
Rauscher+ 2002 KEPLER+piston

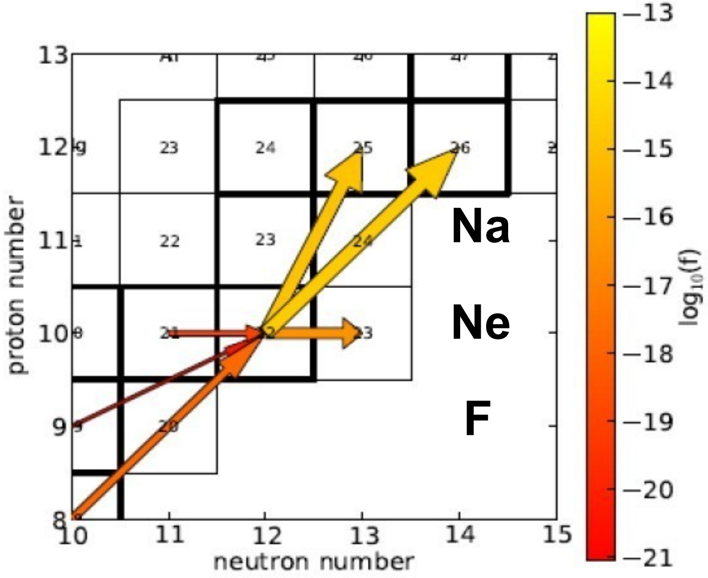
Conditions for the s-process



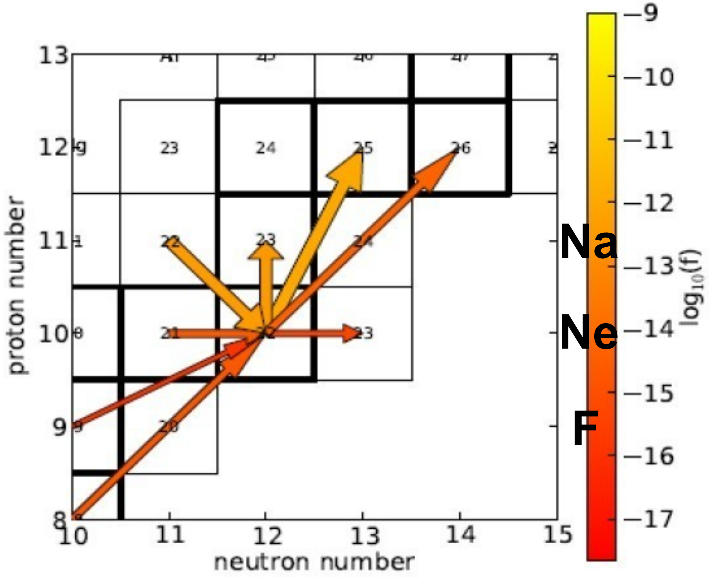
Thielemann & Arnett 1985 ApJ

12

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



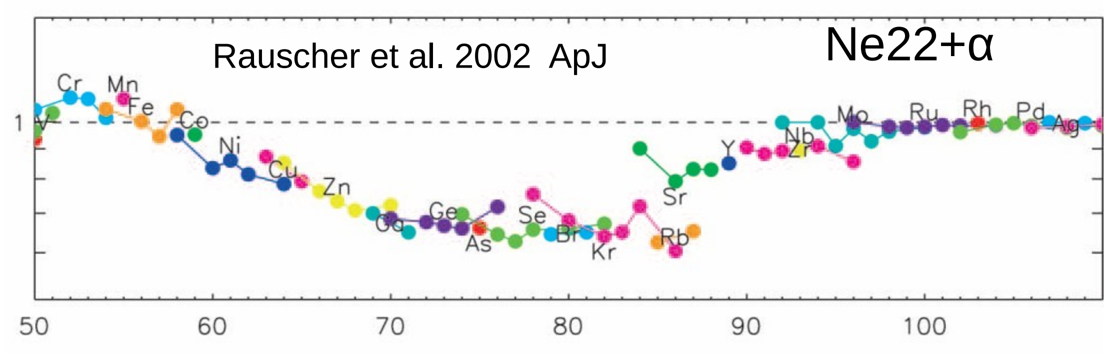
Ne22 nucleosynthesis in He-burning conditions (T9 ~ 0.3)

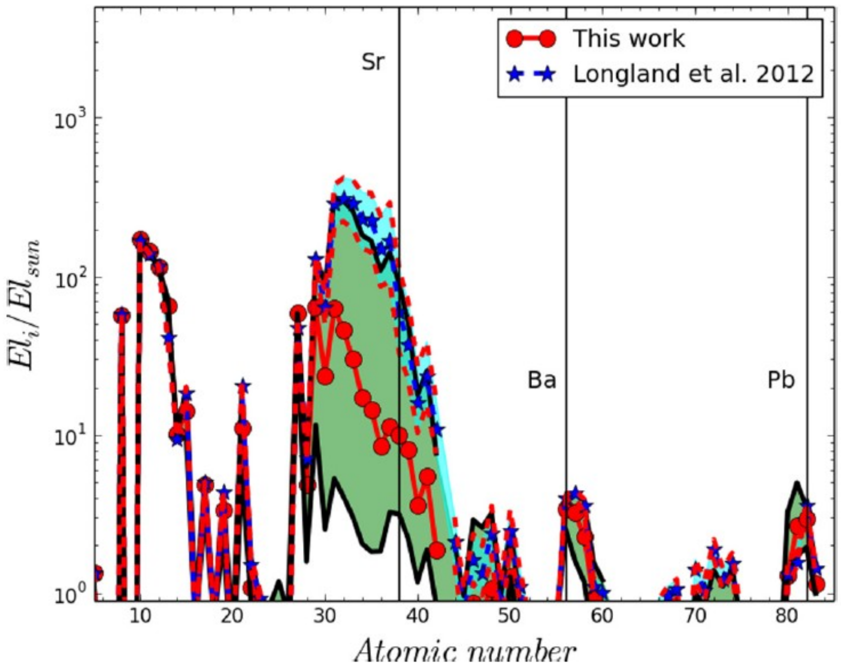


Ne22 nucleosynthesis in C-burning conditions (T9 ~ 1)

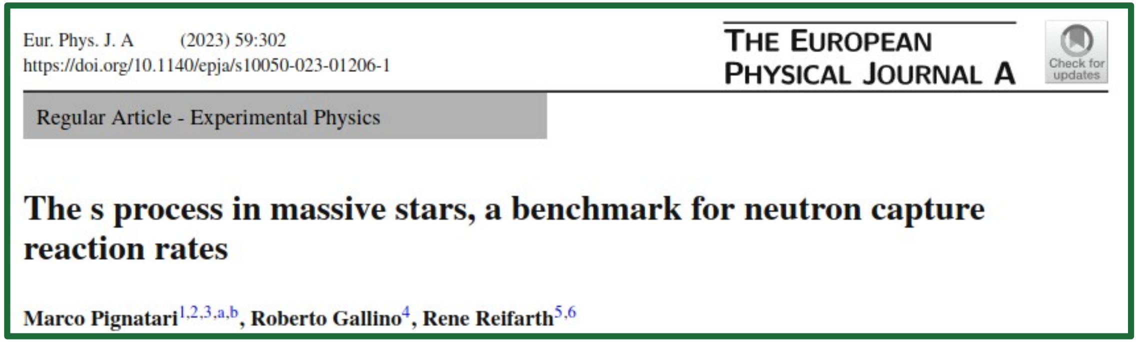
Nuclear uncertainties have large impact on the s-process products of massive stars

Talwar+ 2016 PRC





See also: Busso & Gallino 1985 A&A, Kaeppeler+ 1994 ApJ, Ota+ 2021 PRC, Adsley+ 2021 PRC, Wiescher+ 2023 EPJA, ...


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

THE EUROPEAN PHYSICAL JOURNAL A

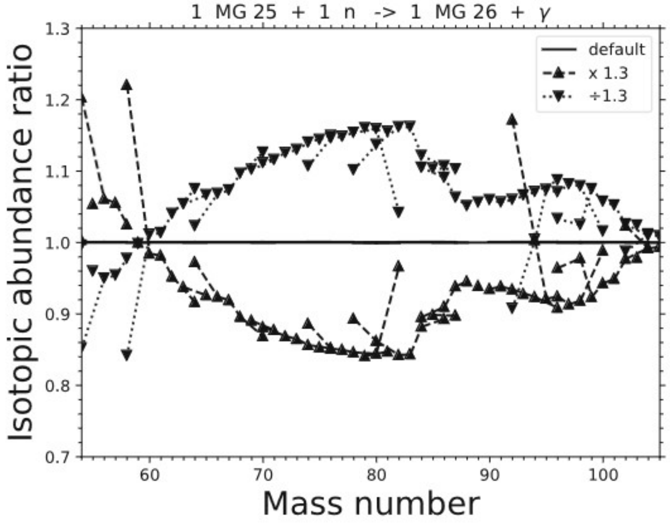
Regular Article - Experimental Physics

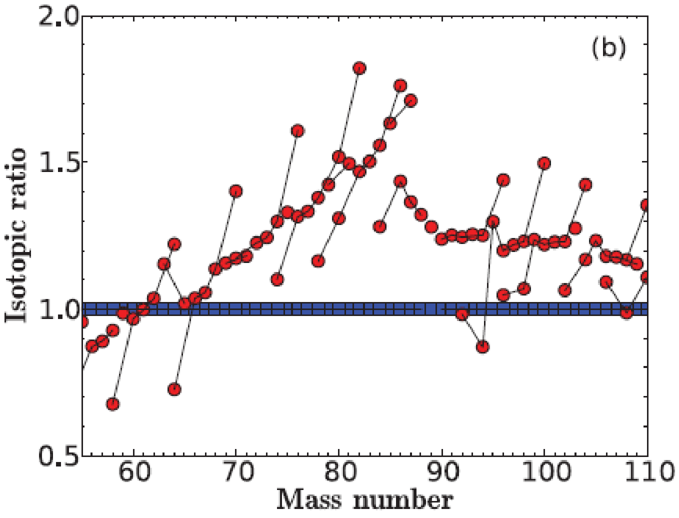
The s process in massive stars, a benchmark for neutron capture reaction rates

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

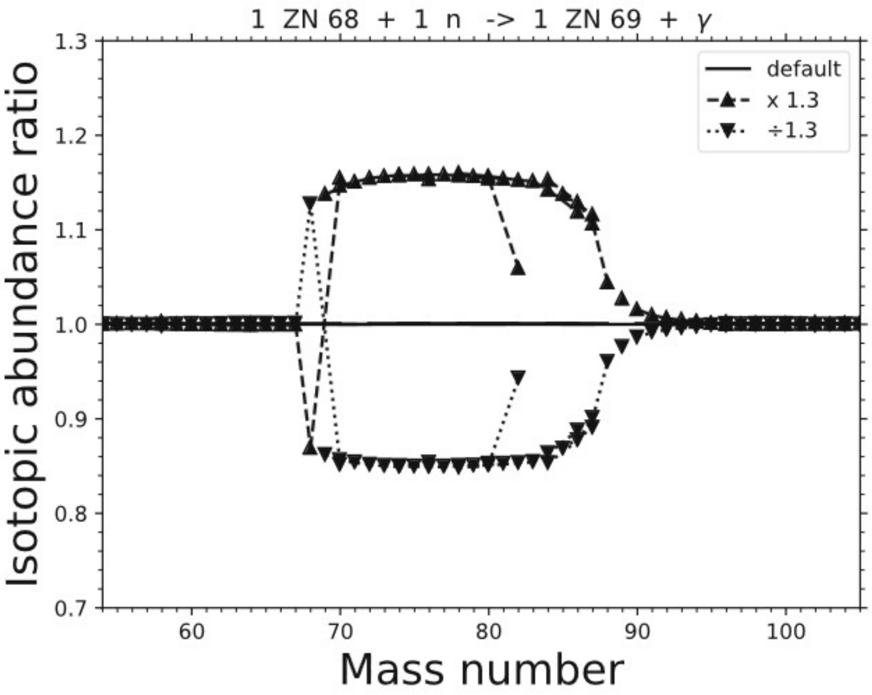
EPJA volume
in honour of
Franz Käppeler

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

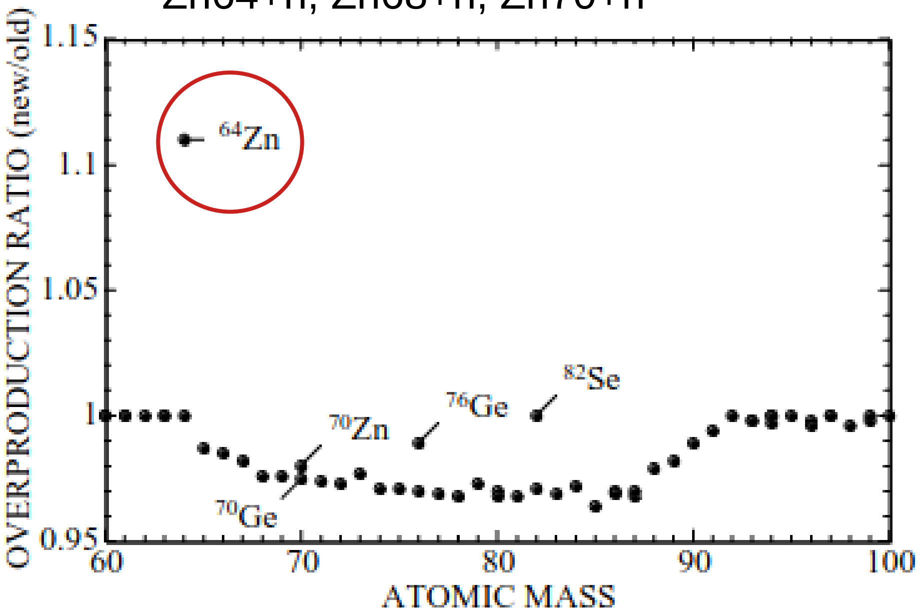


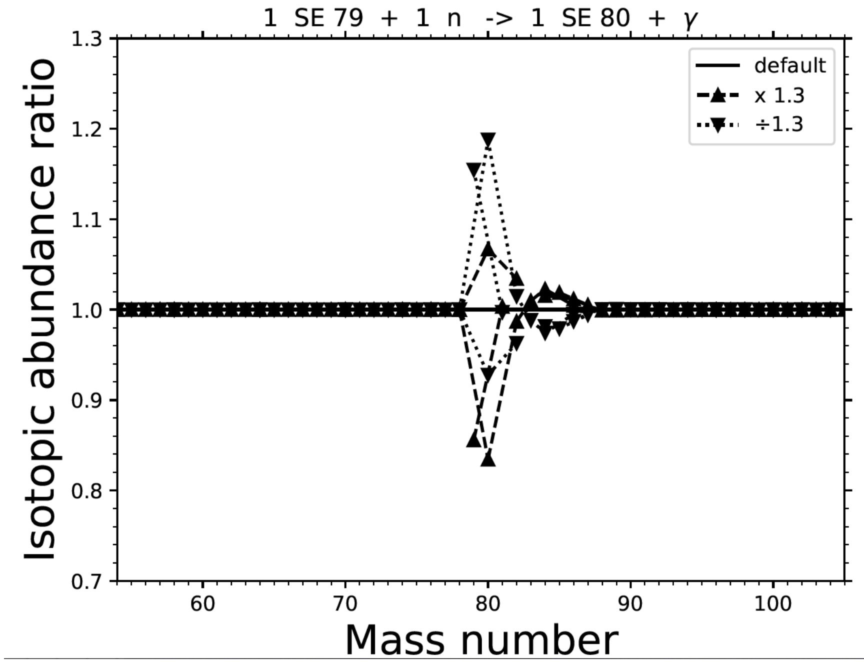


Massimi+2012 n_TOF:
24Mg+n, 25Mg+n, 26Mg+n



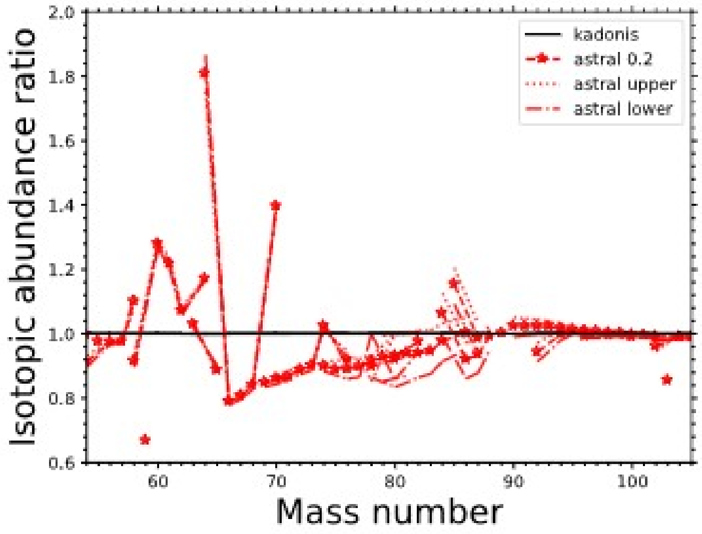
Reifarth+2012 Act. (NETZ calculations)
Zn64+n, Zn68+n, Zn70+n

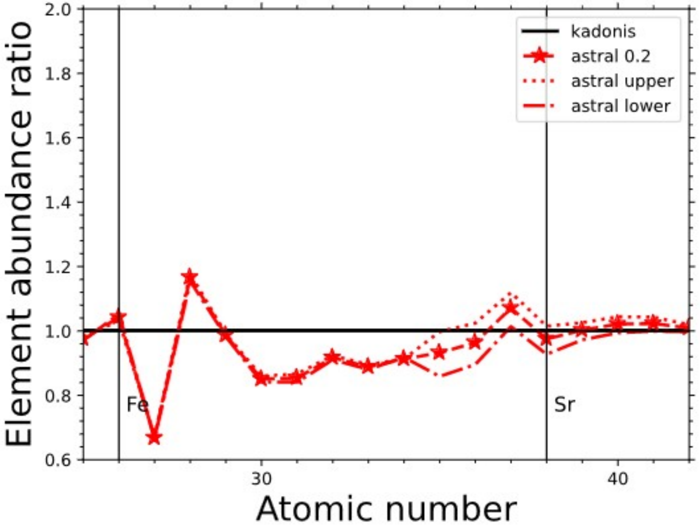


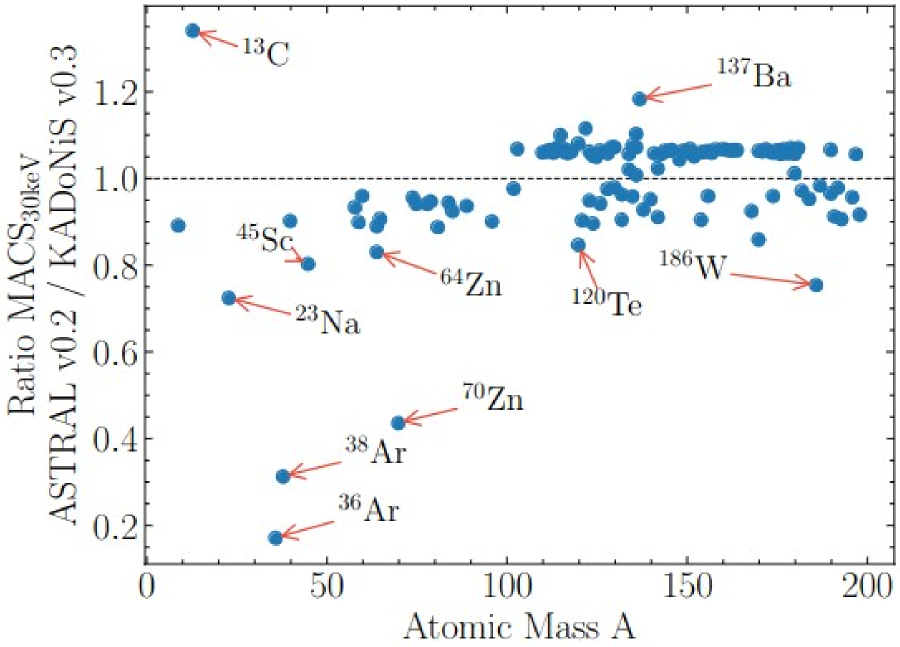


^{80}Rb 33.40 s β+	^{81}Rb 4.57 h β+	^{82}Rb 1.27 m β+	^{83}Rb 86.20 d β+	^{84}Rb 33.10 d β+
^{79}Kr 1.46 d 959 mb, β+	^{80}Kr 2.28 267 mb	^{81}Kr 229.02 ka 607 mb, β+	^{82}Kr 11.58 90 mb	^{83}Kr 11.49 243 mb
^{78}Br 6.46 m β+	^{79}Br 50.69 622 mb	^{80}Br 17.68 m β-	^{81}Br 49.31 239 mb	^{82}Br 1.47 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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impact_cross_sections_weaks.tar.gz md5:e62303d4589229b0f7ad1220fe8c4715	16.0 MB	Download

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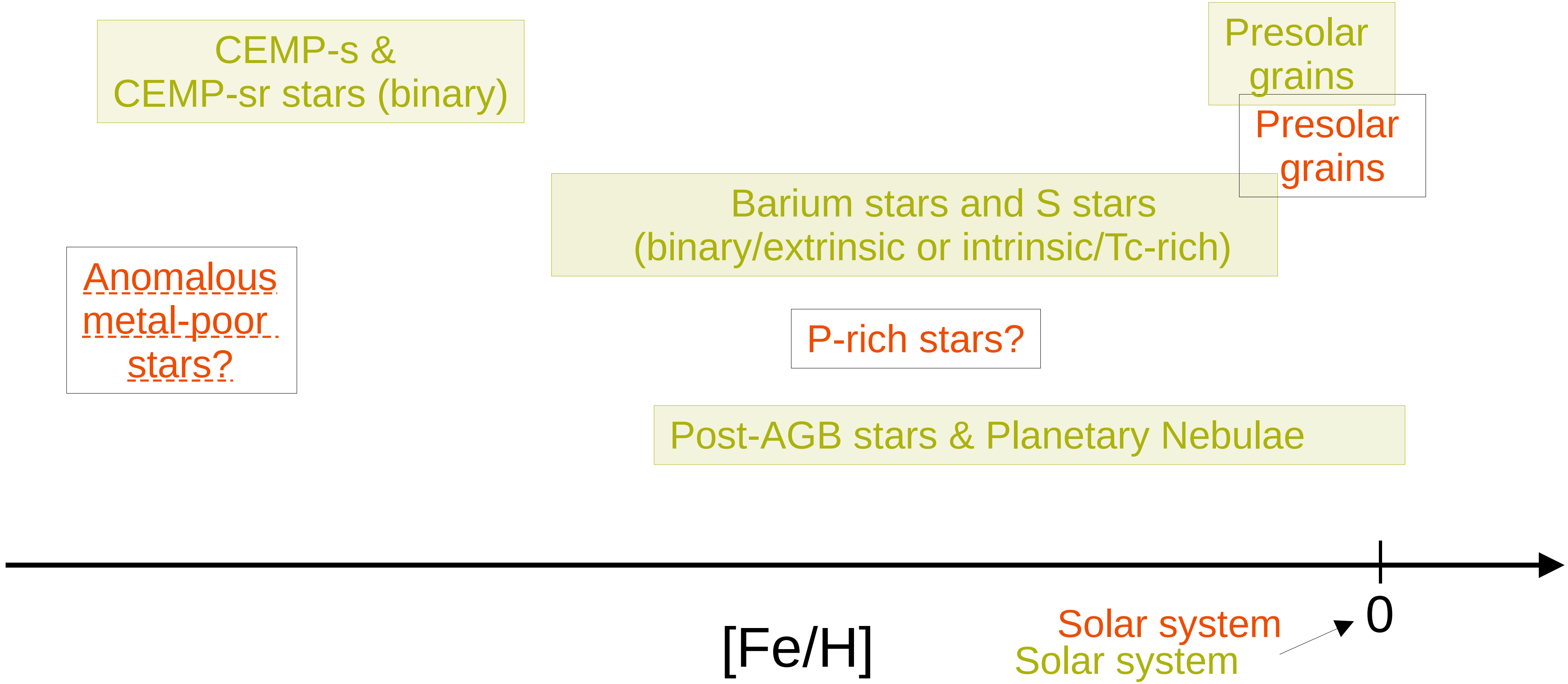
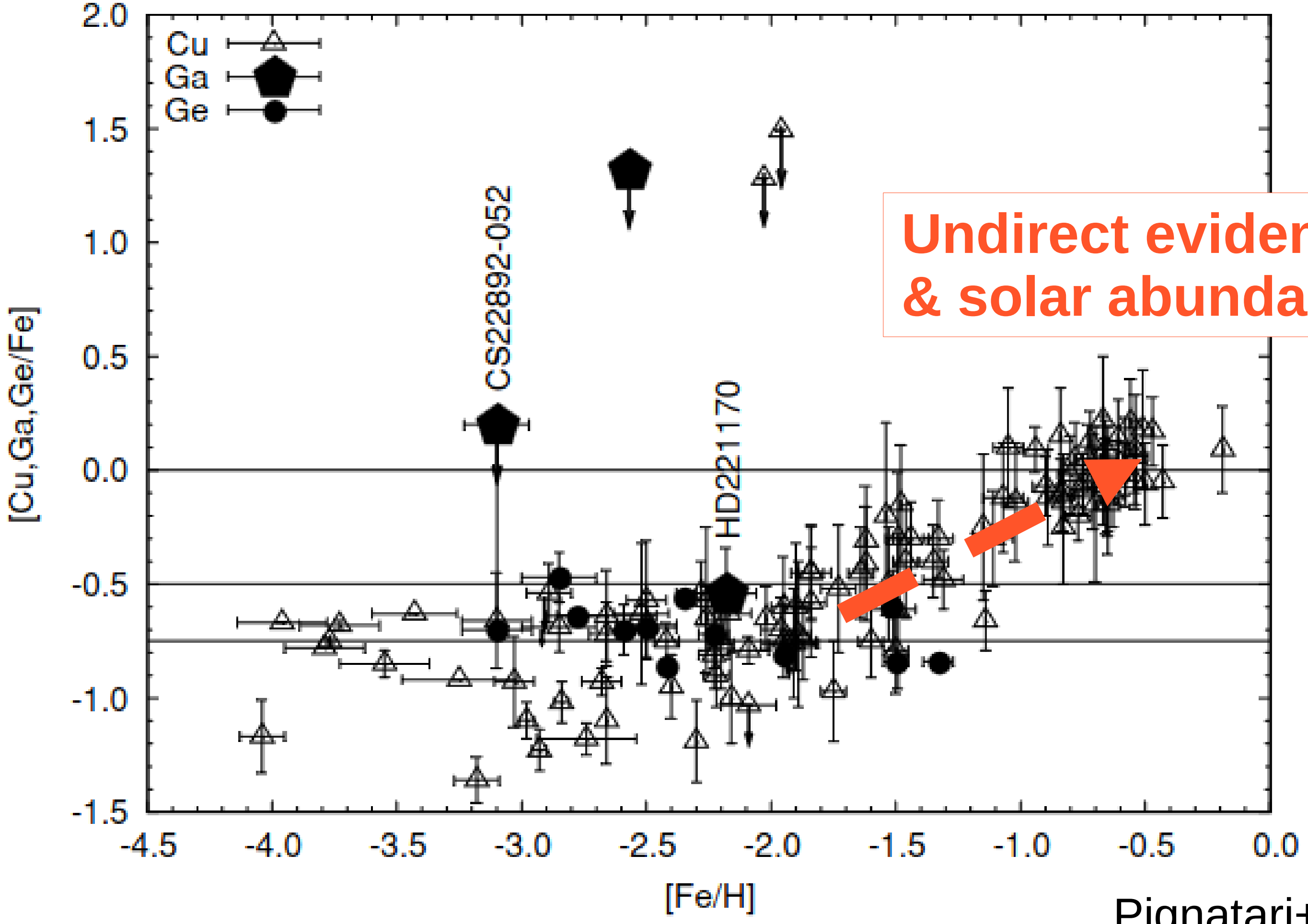
Observation of s-process signatures in AGB stars and in massive stars

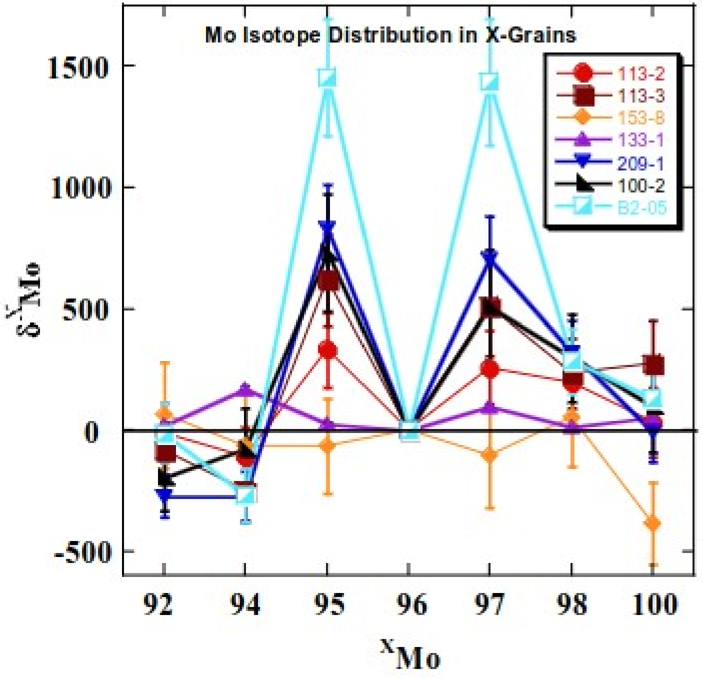


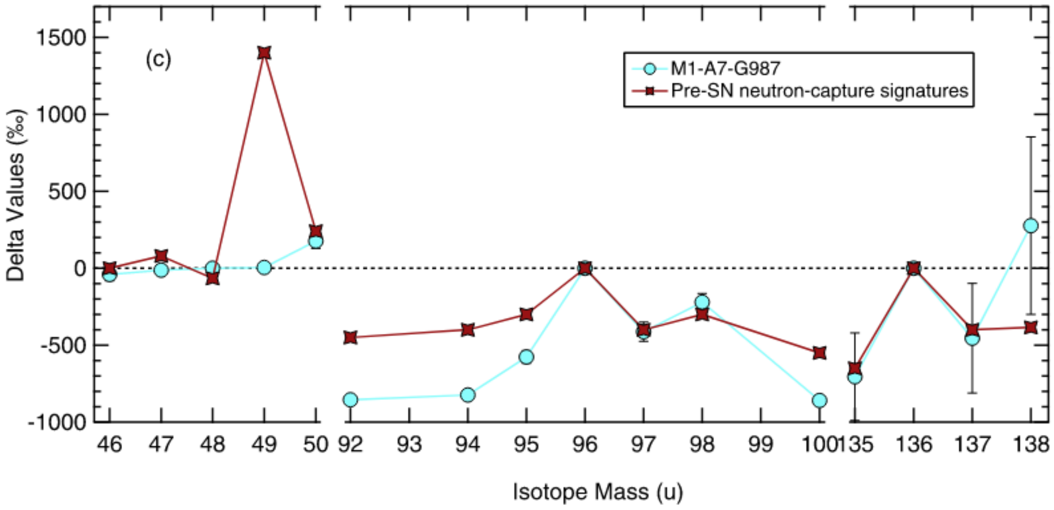


Undirect evidence: GCE & solar abundances

Pignatari+ 2010 ApJ

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

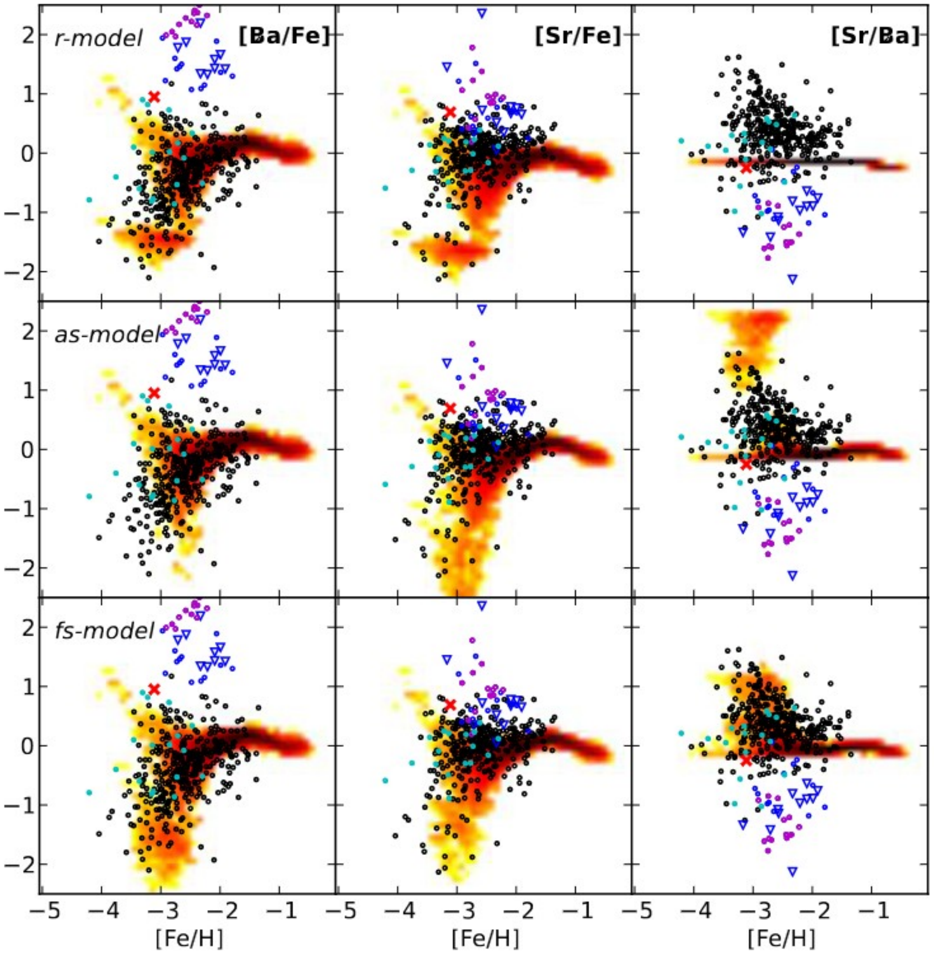




SiC-X grains (Pellin+ 2006)
Maybe also the SiC-X grain 153-8?

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?

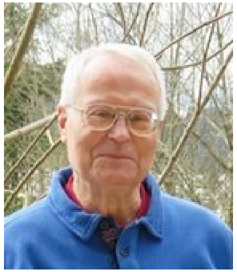


Cescutti+ 2013 A&A

See also e.g., Cescutti+ 2014 A&A,
Rizzuti+ 2019 MNRAS, Prantzos+ 2020 MNRAS,
Molero+ 2023, MNRAS ...

See the talks of Rizzuti and Molero this morning

The Honda star (HD 122563): weak-r or s-process?

Since the astrophysical conditions that would create the LEPP abundance pattern are not known, full reaction network calculations were performed in a heuristic way assuming different neutron capture process conditions. A variety of different neutron densities from s-process to r-process like were found to reproduce the abundance pattern between Sr and Ag within the observational uncertainties. However, intermediate neutron densities in between typical s- or r-process conditions seem to be excluded. Using a single component to reproduce

The Honda star could be s or r, we could not tell (!)

The i-process before rediscovering the i-process...

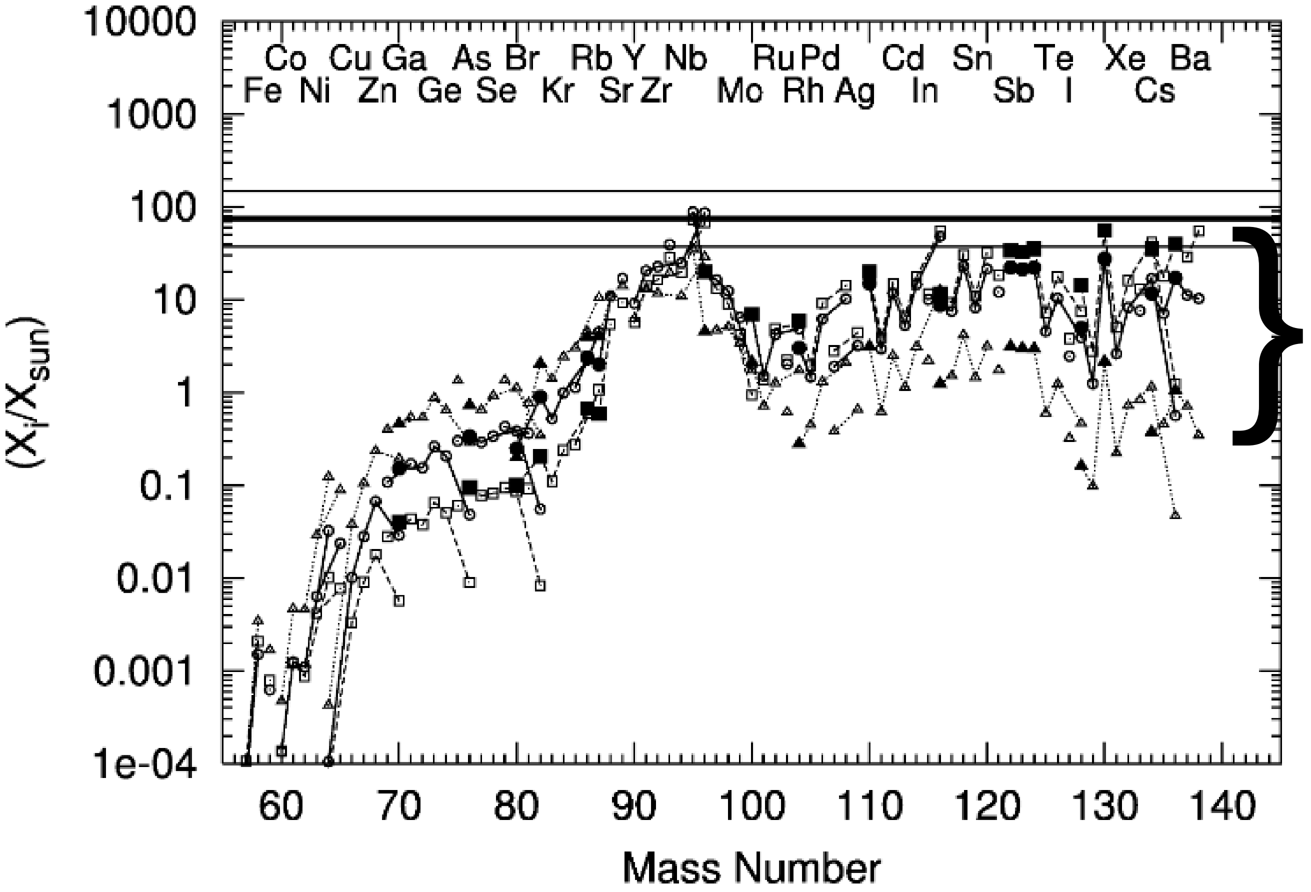
An s-process with some production up to Ba-Sm...

typical s- or r-process conditions seem to be excluded. Using a single component to reproduce the LEPP pattern only neutron densities $n_n \leq 10^{13}$ cm^{-3} seem to create enough Ba to Sm material (which actually consist of quite small contributions to solar) that is consistent within an order of magnitude with the abundances inferred for HD 122563. These low neutron densities correspond to densities found in the s-process, or not so far from it. A

The astrophysical scenarios involving neutron densities $n_n \leq 10^{13}$ cm^{-3} do not correspond to the traditional weak or main s-process because the nucleosynthesis occurs in very low metallicity stars and the required neutron flux duration is too long compared to what is expected in those scenarios. A particular challenge is to find a stellar scenario with low neutron densities during a long period of time occurring in low metallicity stars strong enough to produce elements up to Eu. Since it is hard to envision such a scenario, possibilities other

The s-process in fast-rotating massive stars before its time….

Montes+ 2007 ApJ

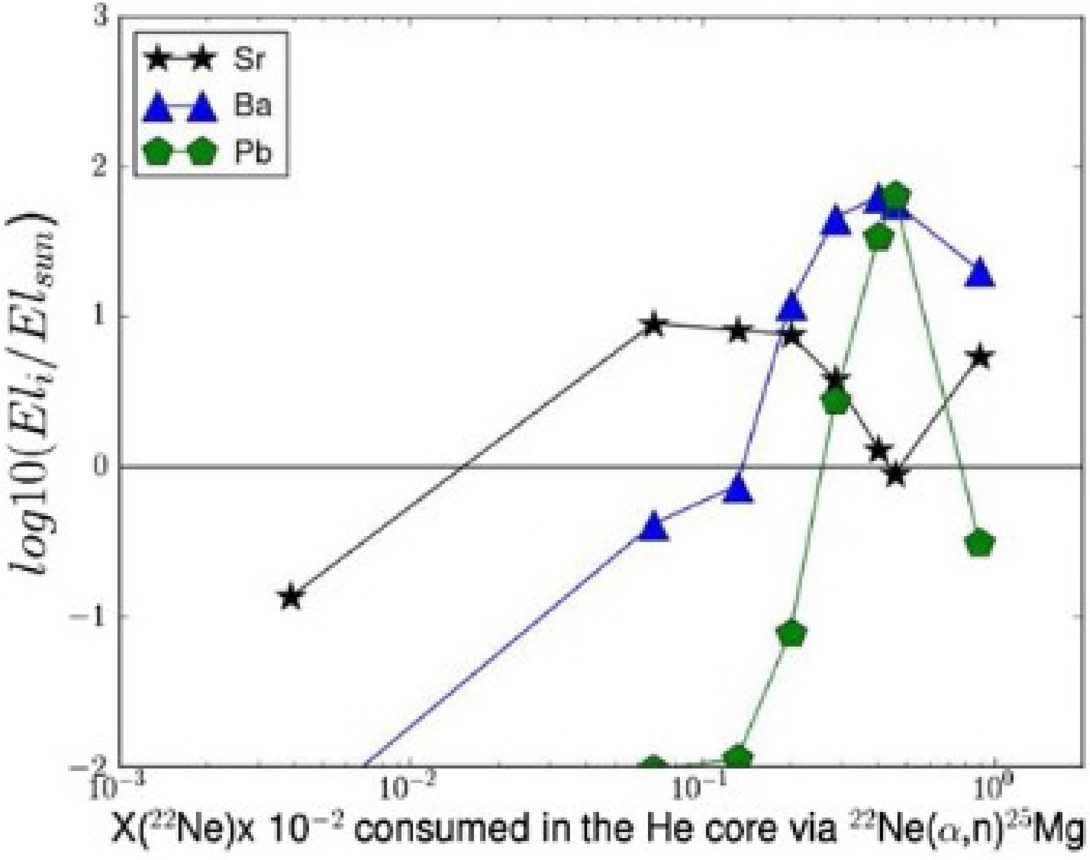


Ne22(α,n) multiplied and divided by 2

Pignatari+ 2008 ApJL

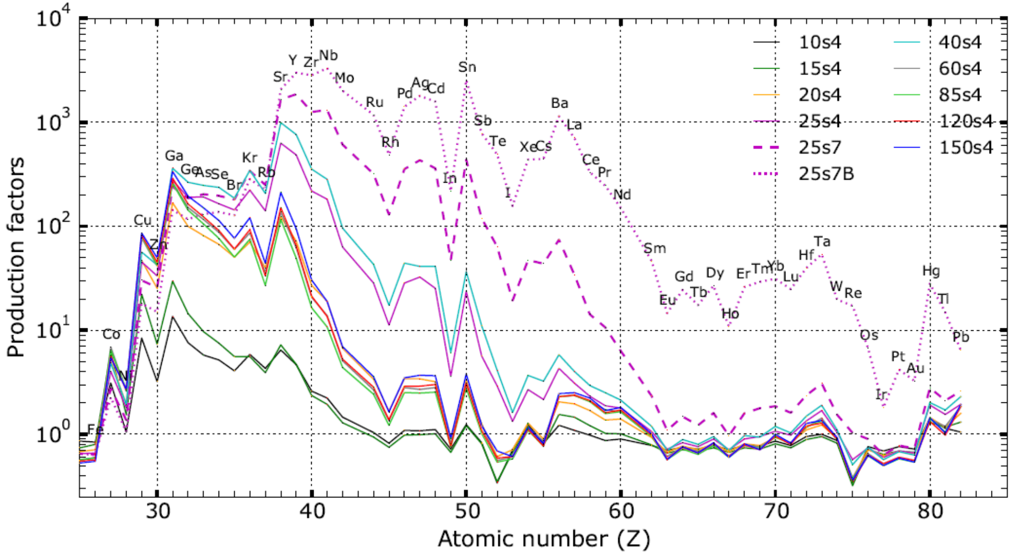
Other examples:
17O+α rates
e.g., Frost-Schenk+ 2022 MNRAS

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

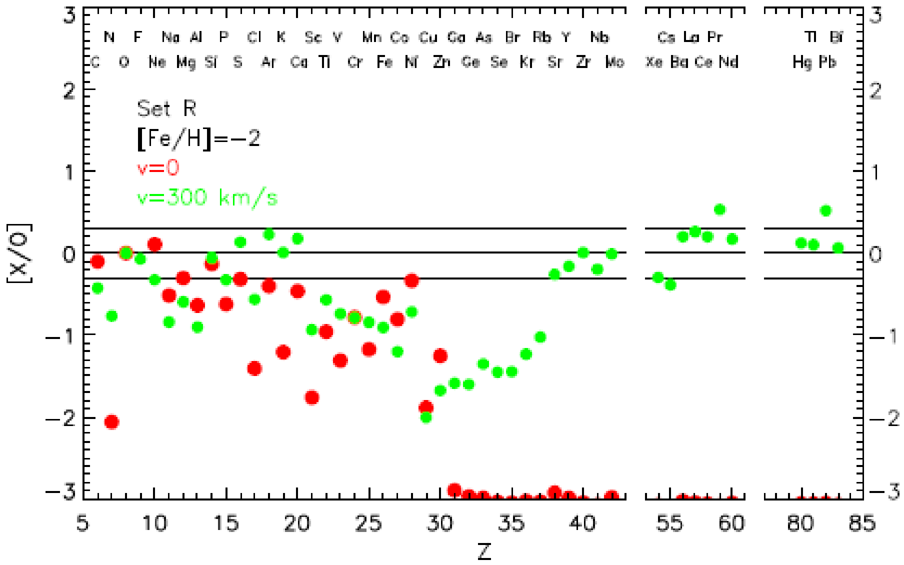


Pignatari+2013 ApJ

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



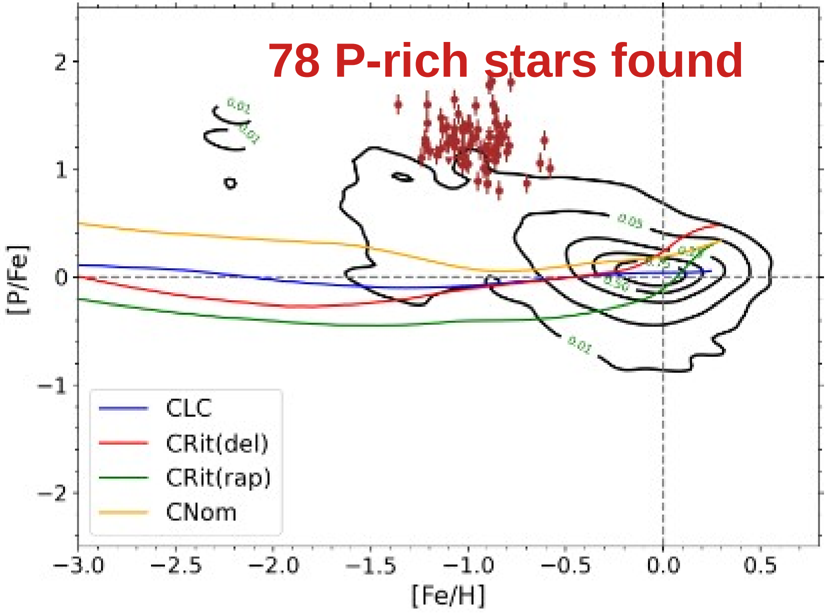
Choplin+ 2018 A&A



Limongi & Chieffi 2018 ApJ

See also Pignatari+ 2008 ApJL, Frischknecht+ 2016 MNRAS, Roberti+ 2024 ApJS

P-rich stars: s-process (and i-process) signatures

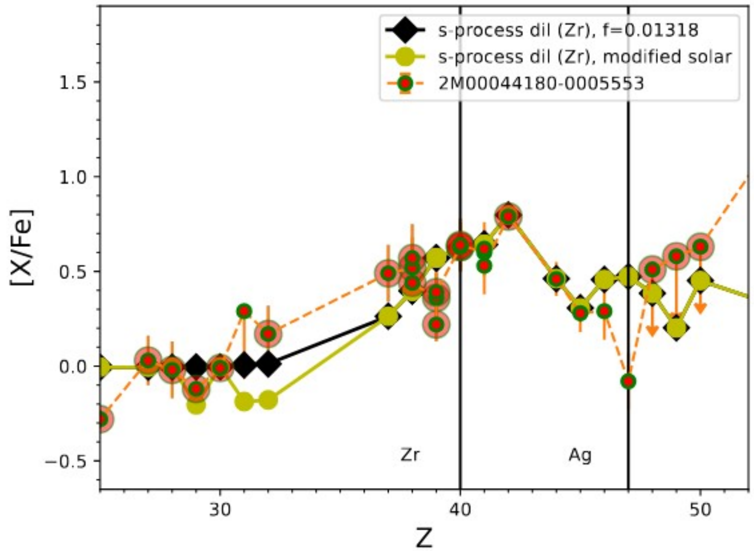


Brauner+ 2023 A&A: 78 P-rich stars (0.24 % of all APOGEE-2 DR17 giants)

Brauner, M., et al.: A&A, 690, A262 (2024)

Table 5. Observed elements that depart by 0.3 dex or more from the comparison with theoretical simulations.

	Scenario 1			Scenario 2		Scenario 3
	1a	1b	1c	2a	2b	
2M22480199	**Rb**, Ag, Ba, **La**	**first peak**	Ge, **Sn**, Ba	Ga, **Rb**, Ag, **La**	Ga, **Rb**, Ag, Ba	**Sn**
2M18453994	**Rb**, Y, Nb, Ag, Ba, **La–Eu**, Dy	**first peak** **Pr**, **Sm**, Hf, **Pb**	**Sr**, Y, Mo, Ru, Ba, **La–Eu**, Dy	**Rb**, **Y**, Nb–Ag, **Pr**, **Sm**, Hf, **Pb**	**Rb**, **Y**, Nb–Ag **Cs**	**Sr**, **Y**, Rh–0Cs, Hf
2M13472354	Ga, **Sr**, Mo, Ru, Ba, **La**, Hf	**first peak** Pr	Ba, **La**, Hf	Ga, Nb, Mo–Ag Pr	Ga, Mo, Ru, Ag, Ba, Pr, **Sm**	Pr, **Sm**
2M00044180	**Rb**, **Y**, Nb, Ag, Ba, **La**	**Rb–Ru**	Ag, Ba	**Rb**, Nb, Ag	**Rb**, Nb, Ag, Ba	Ag, Ba, **Pb**

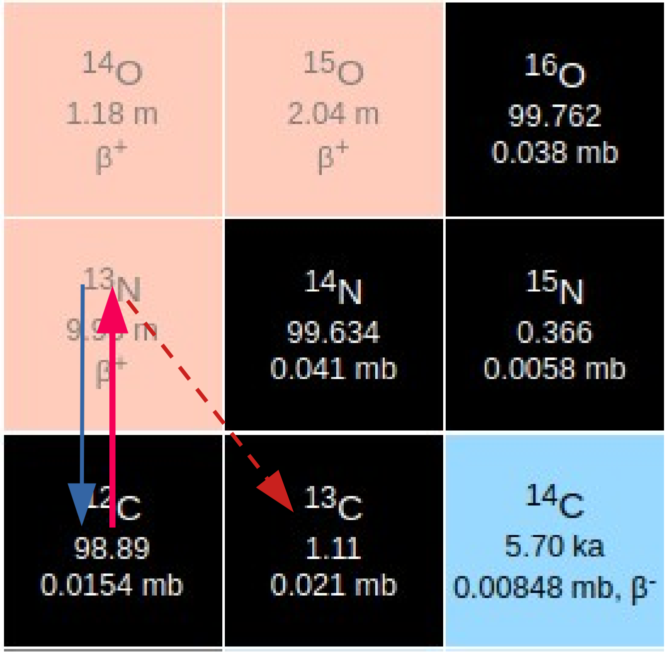


Most likely condition: s+i-process

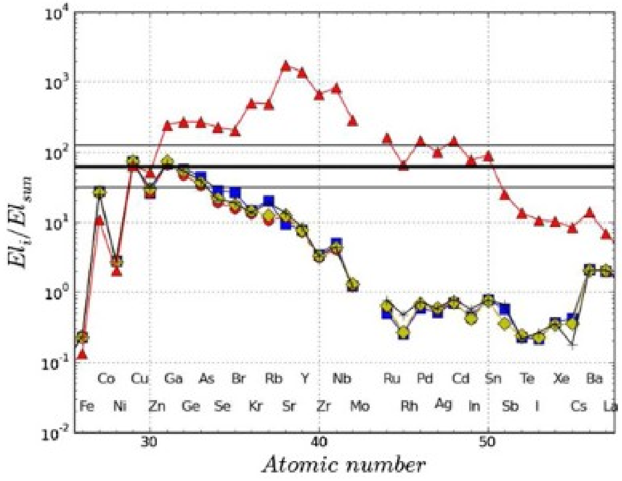
Brauner+ 2024 A&A

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.

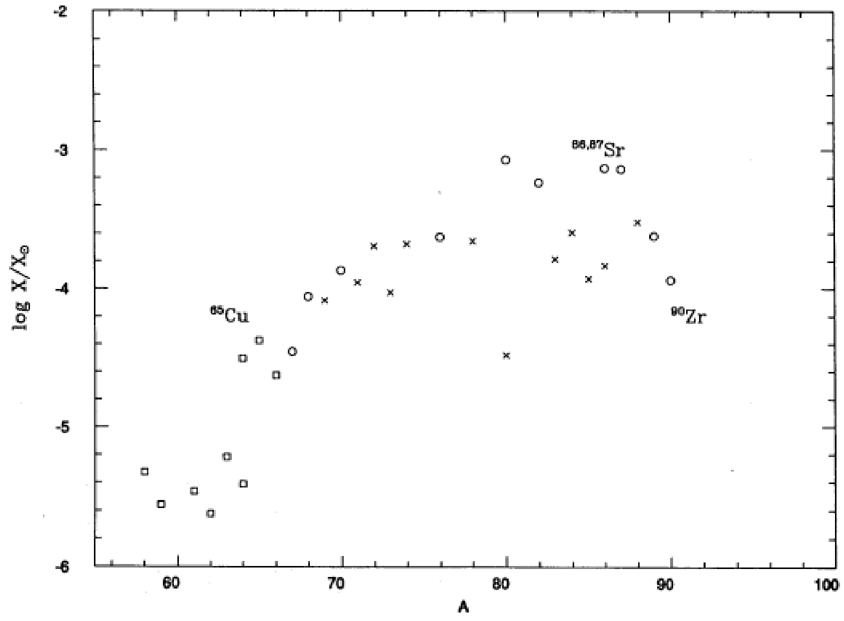


Pignatari+ 2013 ApJ

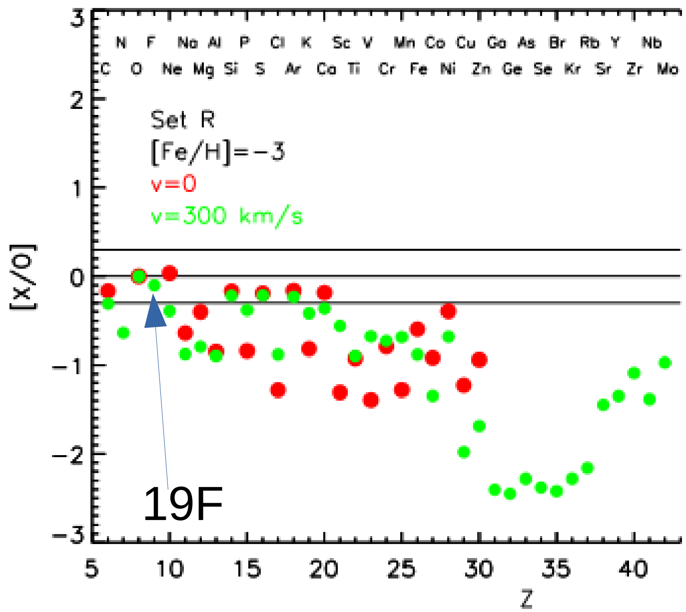
13C(α,n)16O and s-process in massive stars?

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)



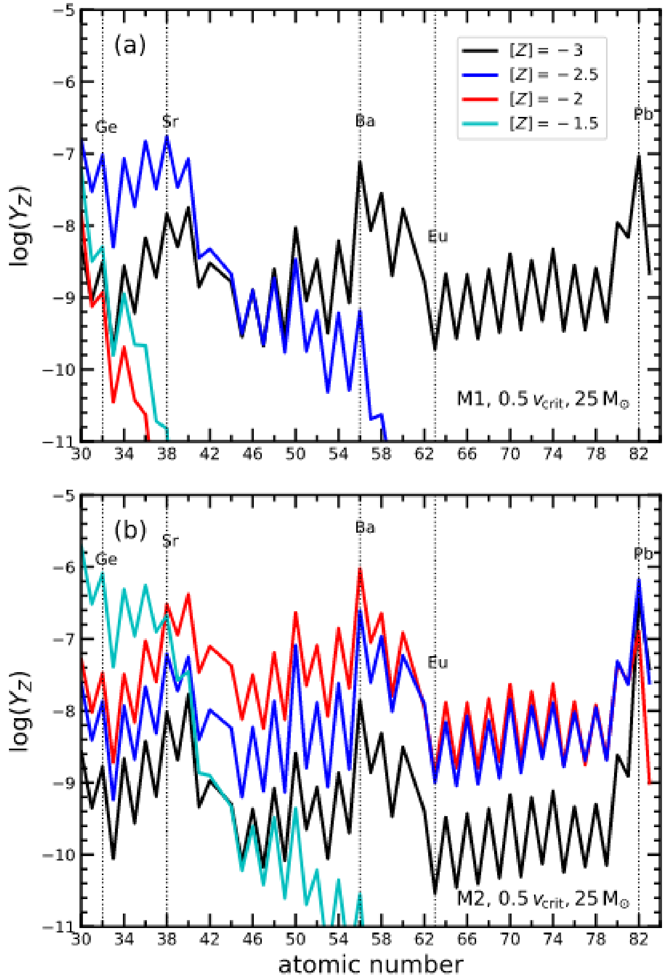
Baraffe+ 1992 A&A



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!



Summary and Conclusions

- Introduction to the s-process in massive stars: main properties
- Impact of nuclear uncertainties on the s-process in massive stars: examples with neutron capture rates and the 22Ne+ α rates (but there are more!).
- Observations: Solar System (as GCE product), presolar grains, metal-poor stars and P-rich stars;
- The 13C(α ,n)16O in massive stars: are there “s-process”-like conditions where it could become relevant? Maybe in rare events at different metallicities. It is most likely active at the end of central H burning/beginning of central He burning in popIII massive stars. First nuclear neutron source active?