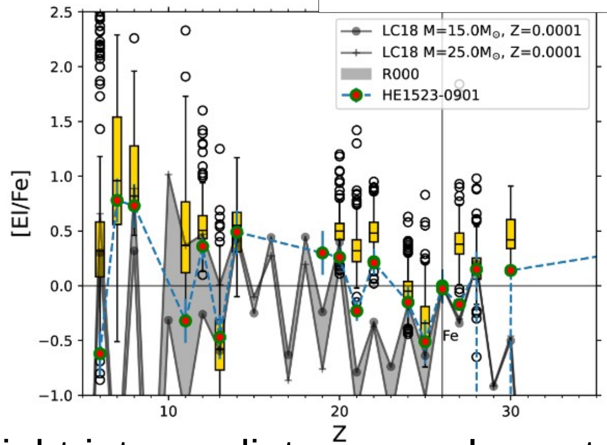
Impact of 12C+12C on massive stars nucleosynthesis of the elements heavier than iron

Marco Pignatari

- @Konkoly Observatory, CSFK HUN-REN & MTA Centre of Excellence, Budapest, Hungary
- @BGI, Bayreuth University, Bayreuth, Germany

Carbon Burning: Theory, Astrophysics and Experiments, Padova, June 30 - July 2 2026

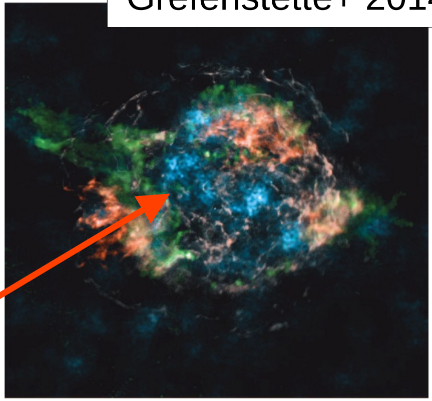
Mischenina+ 2024



Light-intermediate mass elements in metal-poor stars and GCE

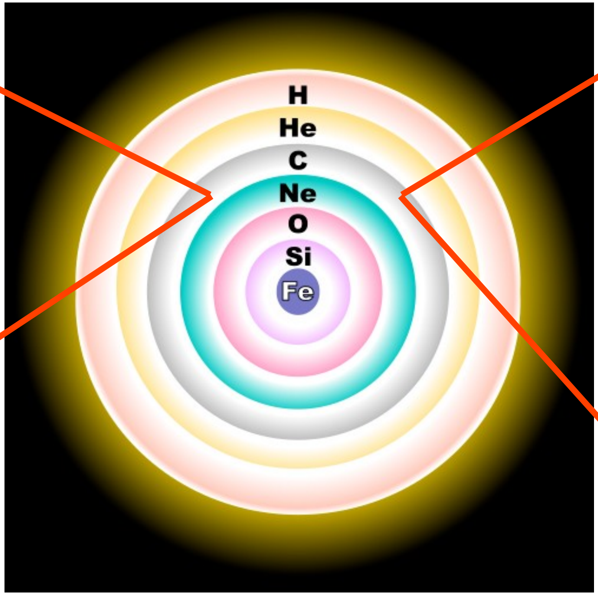
Lorenzo's talk

Grefenstette+ 2014



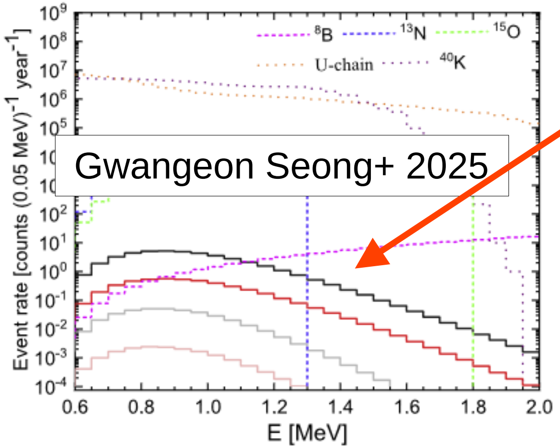
CCSN: Cas A
~ 11000 lyr
~ 300 years ago

Light-intermediate mass elements in SN remnants



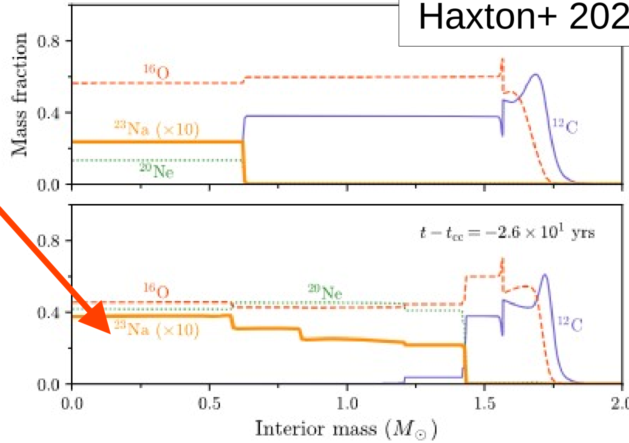
See Alessandro's and Thibaut's talks

Gwangeon Seong+ 2025



Neutrinos from Carbon-burning
(Future detectability?)

Haxton+ 2025

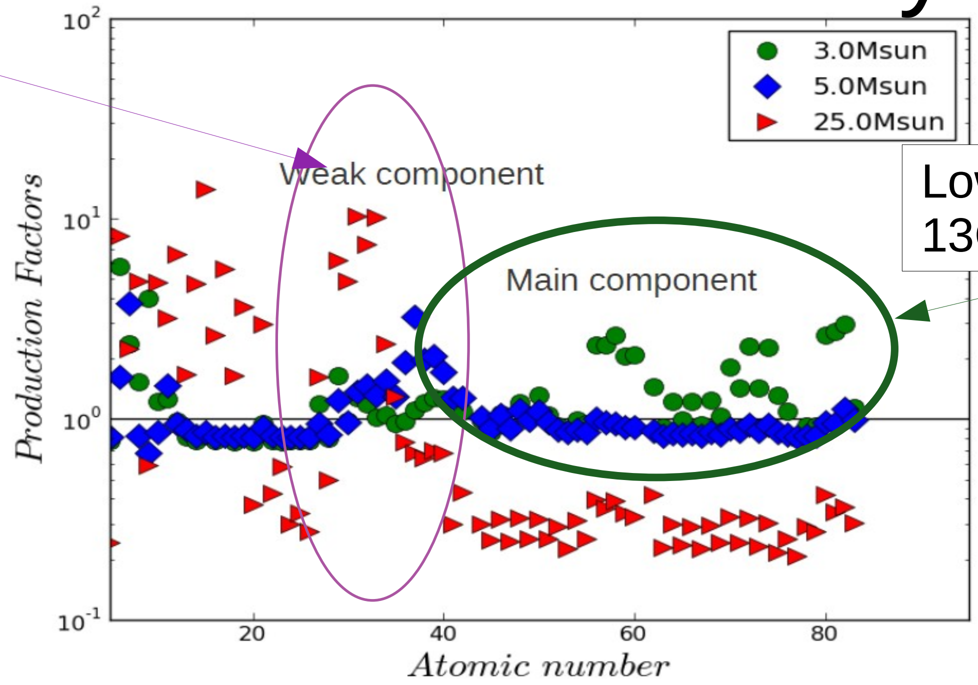


Axion emission from ^{23}Na → γ-ray ≈ 440 keV
(COSI detectability?)

Production of isotopes beyond iron?

massive stars… or
22Ne(α,n)25Mg

Stellar yields:

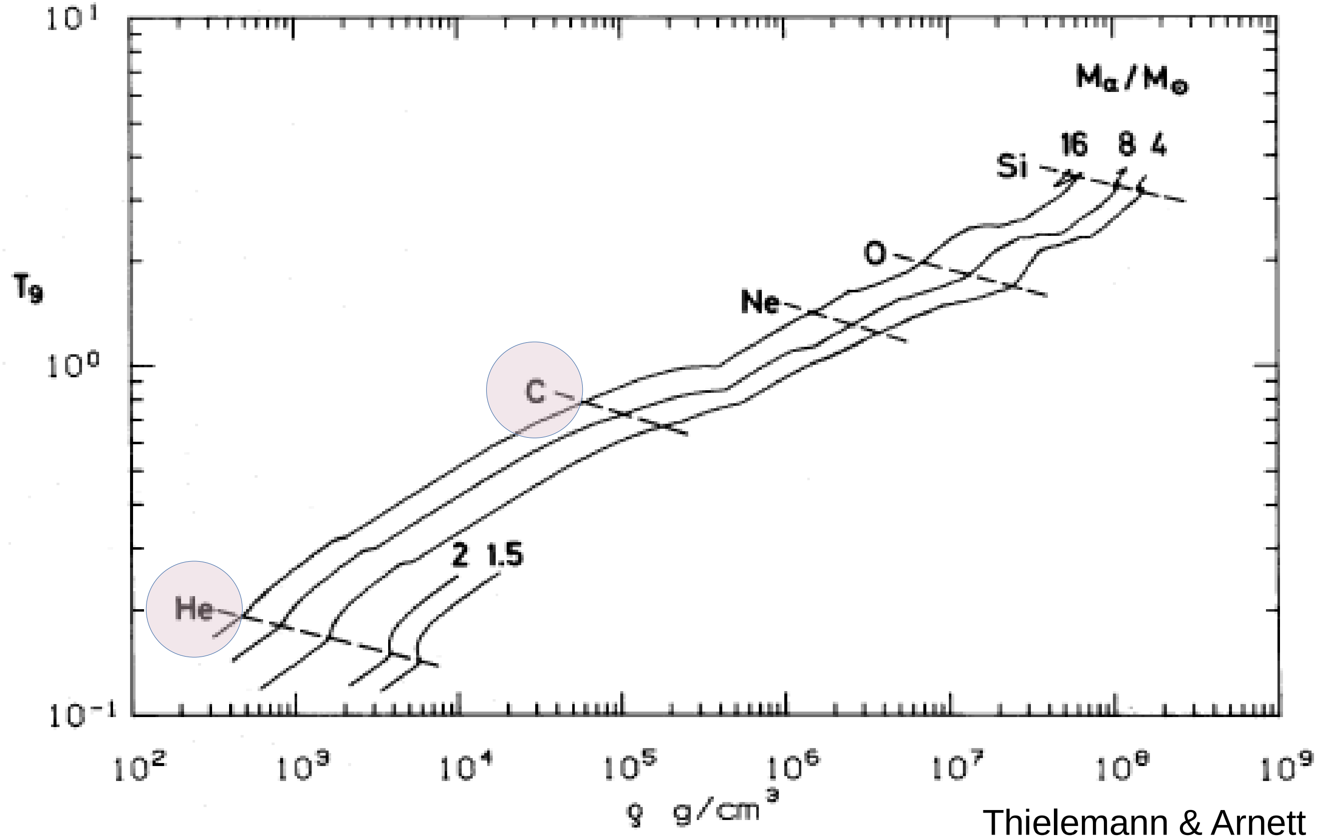


Low-mass AGB stars… or
13C(α,n)16O & 22Ne(α,n)25Mg

MP+2016, ApJS

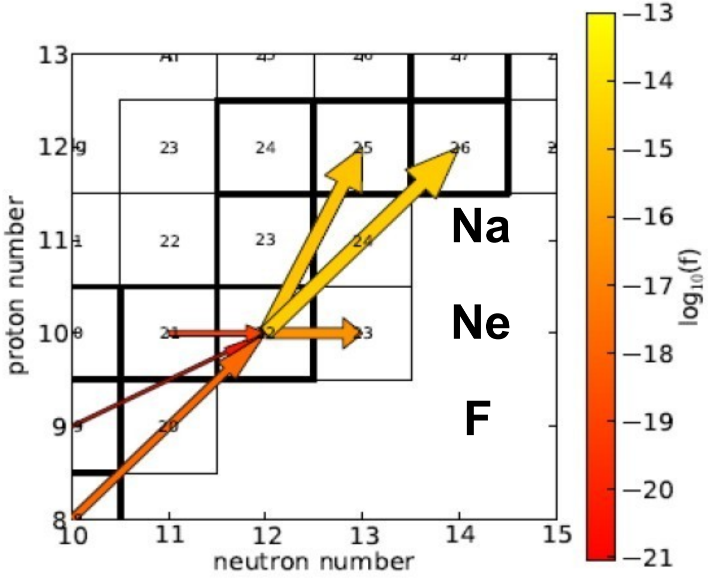
Elemental production factors for a low mass AGB star, a massive AGB stars, and a massive star (Z=0.01).

Conditions for the s-process



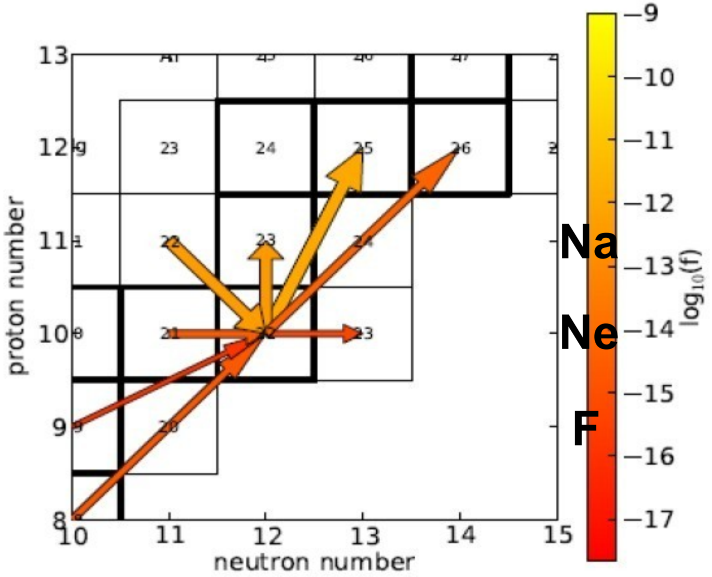
Thielemann & Arnett 1985 ApJ

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



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

N_n ~ few 10^7 cm^{-3}
≈ 70+% of neutrons



$N_n \lesssim 10^{12}$ cm^{-3}
$\lesssim$ 30% of neutrons

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

Why not the $^{13}C(\alpha,n)^{16}O$?

of 10 of the actual value.

Arguments of nucleosynthesis and, to some extent, energy generation during carbon burning depend upon the fate of the liberated protons and alpha particles, which will certainly be consumed quickly at the temperatures of carbon burning. There are many possible alternatives,[1] solution of which requires numerical analysis of the rates in a reaction network. Most of the protons seem to be captured by C^{12}, thereby forming N^{13}, which usually beta-decays to C^{13}. The C^{13} reacts with liberated alpha particles by the reaction $C^{13}(\alpha,n)O^{16}$. The net effect of this important sequence is the conversion of the free proton into a free neutron while converting C^{12} and He^4 into O^{16}. The C^{13} builds up a rather high abundance, roughly 1 percent of the initial C^{12} concentration, shortly after the carbon reactions begin. The free neutrons are available for capture by all the species in the gas, a very important circumstance for the synthesis of heavy elements by neutron-capture chains (see Chap. 7). The alpha particles are also captured by

From Clayton’s book (1968), Section 5.6 Advanced Burning Stages

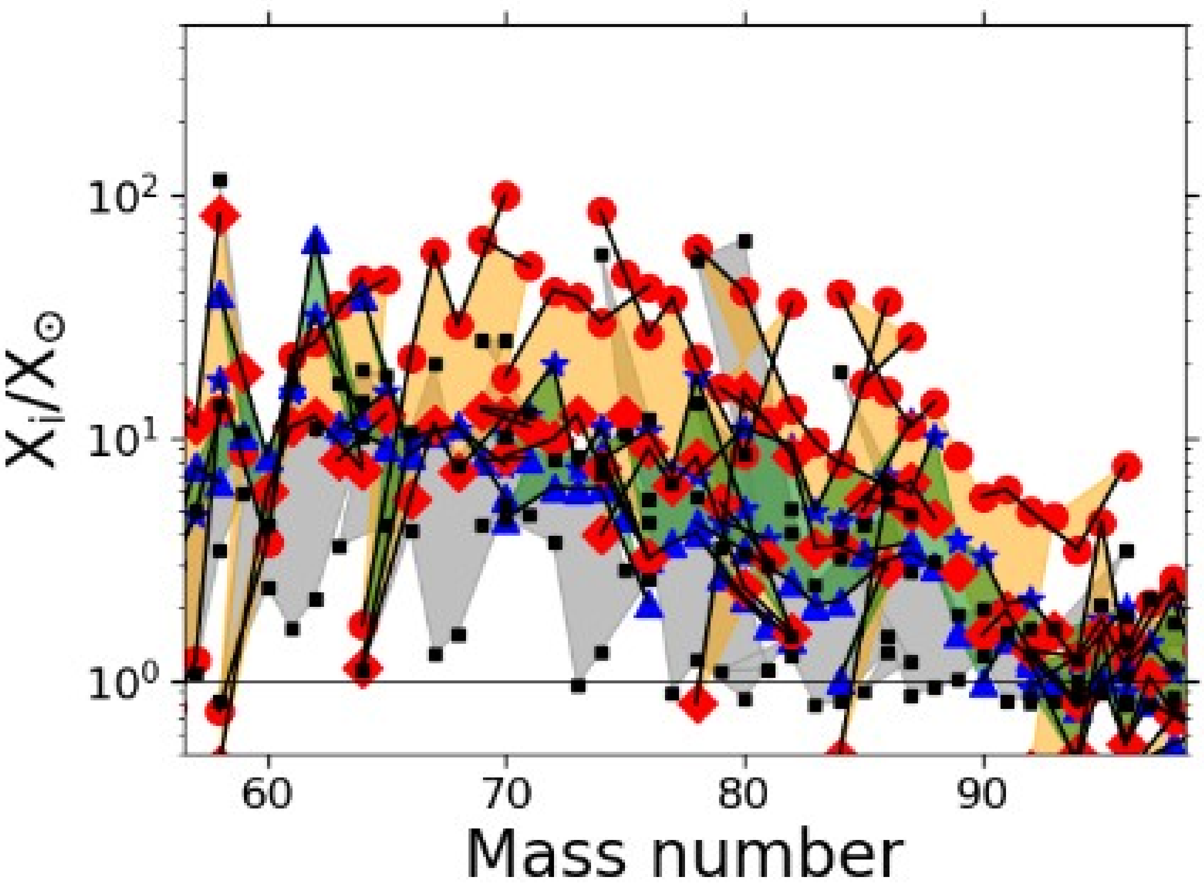
Probably the first photodisintegration of importance is that of N^{13}, formed when C^{12} captures a proton liberated in carbon burning. If $T_9 > 0.75$, it turns out that the photodisintegration of N^{13} is faster than its beta decay, with the result that the C^{13} concentration is sharply reduced, as is its effectiveness as a source of free neutrons. It turns out that most carbon-burning stages are at $T_9 > 0.75$, moreover.

From Clayton's book (1968), Section 5.7 Photodisintegration

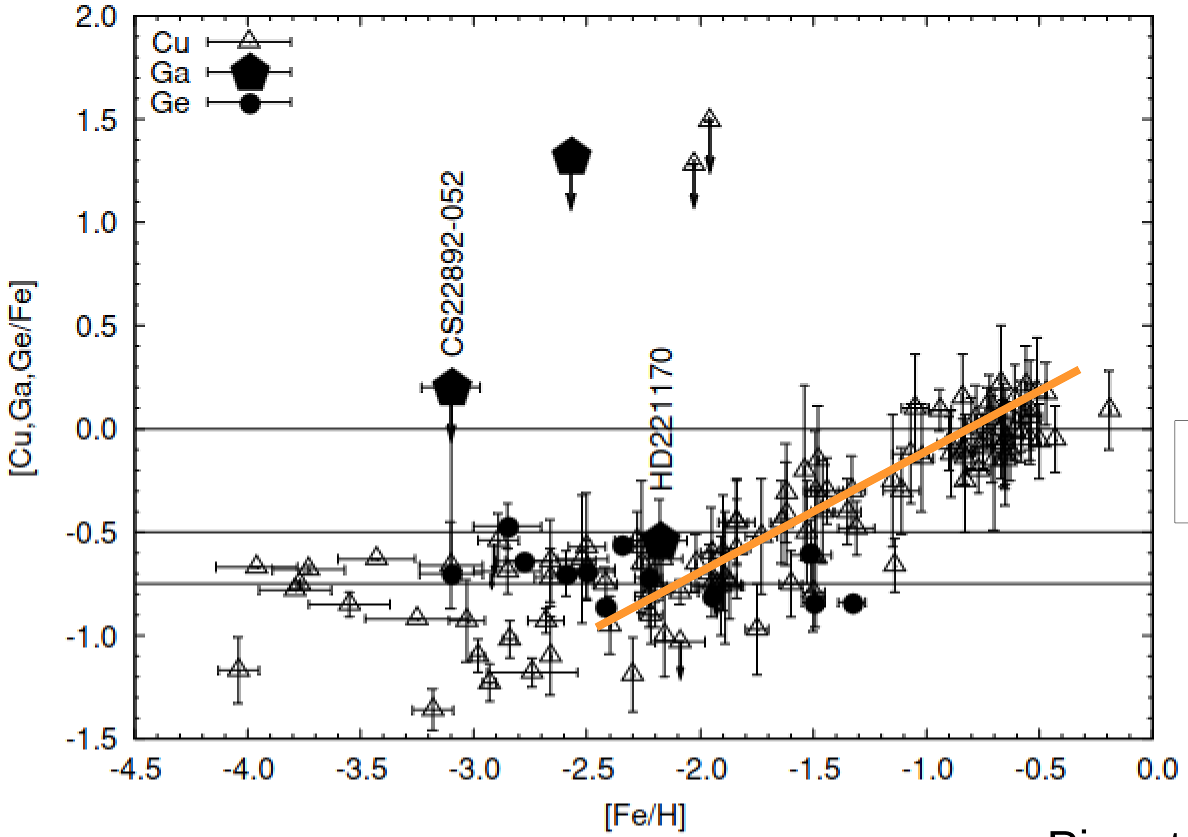
See also Chieffi+ 1998 ApJ (reaction list in Figure 6)

➡ **22Ne(α,n)25Mg is the main neutron source in massive stars**

He-burning component + **C-burning component** + SN explosion component



Pignatari+ 2026 EPJA
in honour of R. Gallino



GCE

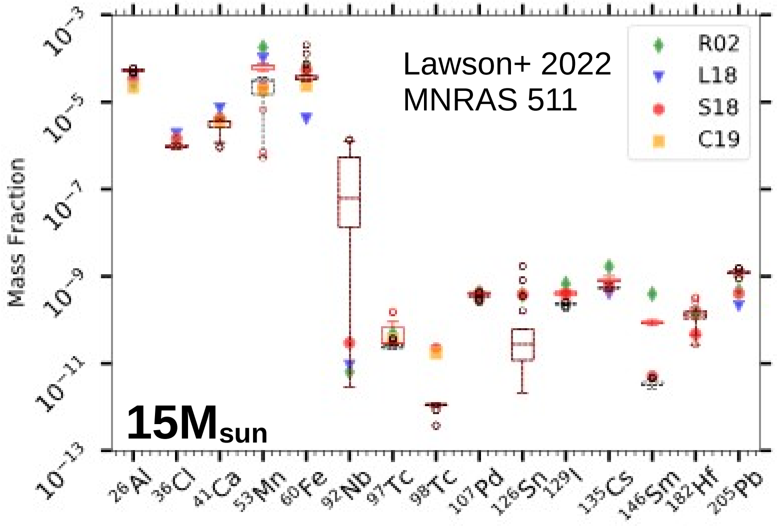
Pignatari+ 2010 ApJ

Short-lived-radioactive isotopes ($T_{1/2}$ ~ 0.1-100 million years) observed in the Early Solar System (Lugaro+ 2018 PrPNP 102)

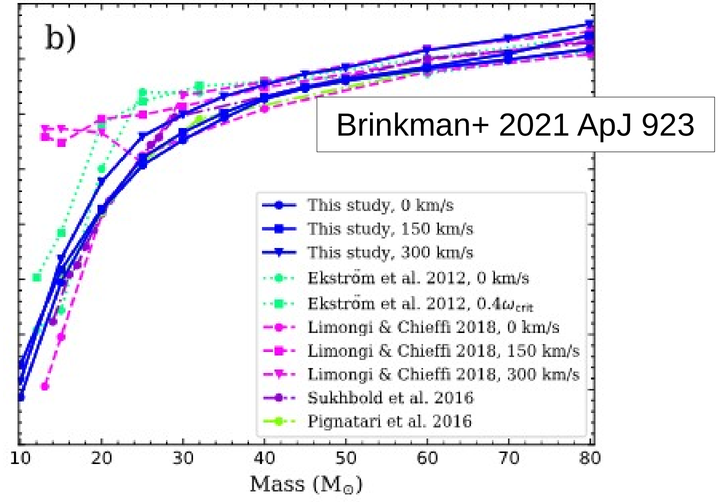
GCE contribution may be relevant for species with $T_{1/2} \geq 2$ Myr

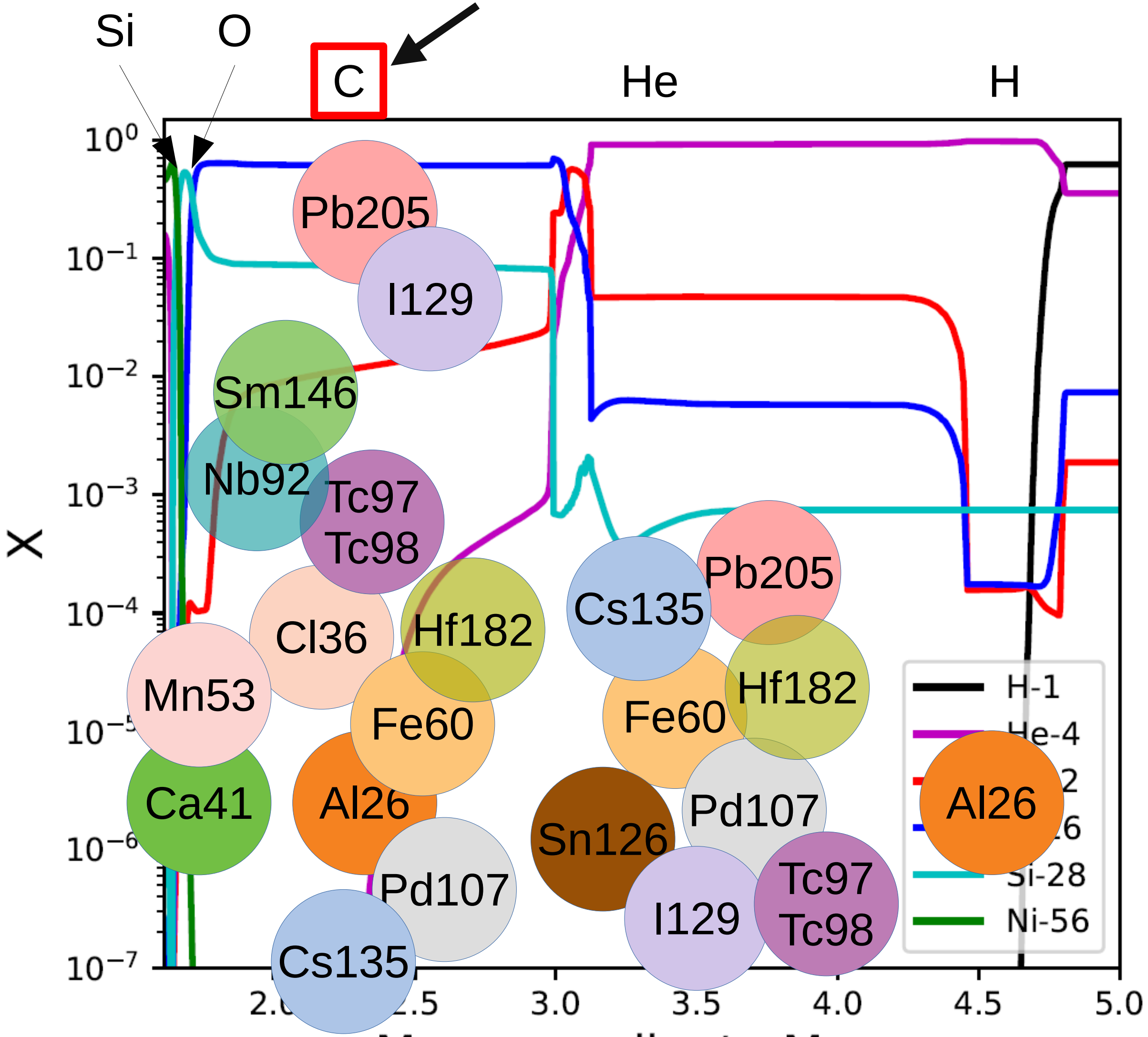
SLR	Daughter	Reference	$T_{1/2}$ (Myr)
^{26}Al	^{26}Mg	^{27}Al	0.72
^{36}Cl	^{36}S	^{35}Cl	0.30
^{41}Ca	^{41}K	^{40}Ca	0.099
^{53}Mn	^{53}Cr	^{55}Mn	3.7
^{60}Fe	^{60}Ni	^{56}Fe	2.6
^{92}Nb	^{92}Zr	^{92}Mo	34
^{97}Tc	^{97}Mo	^{98}Ru	4.2
^{98}Tc	^{98}Ru	^{98}Ru	4.2
^{107}Pd	^{107}Ag	^{108}Pd	6.5
^{126}Sn	^{126}Te	^{124}Sn	0.23
^{129}I	^{129}Xe	^{127}I	15
^{135}Cs	^{135}Ba	^{133}Cs	2.3
^{146}Sm	^{142}Nd	^{144}Sm	68
^{182}Hf	^{182}W	^{180}Hf	8.9
^{205}Pb	^{205}Tl	^{204}Pb	17

SLRs yields variation from CCSNe

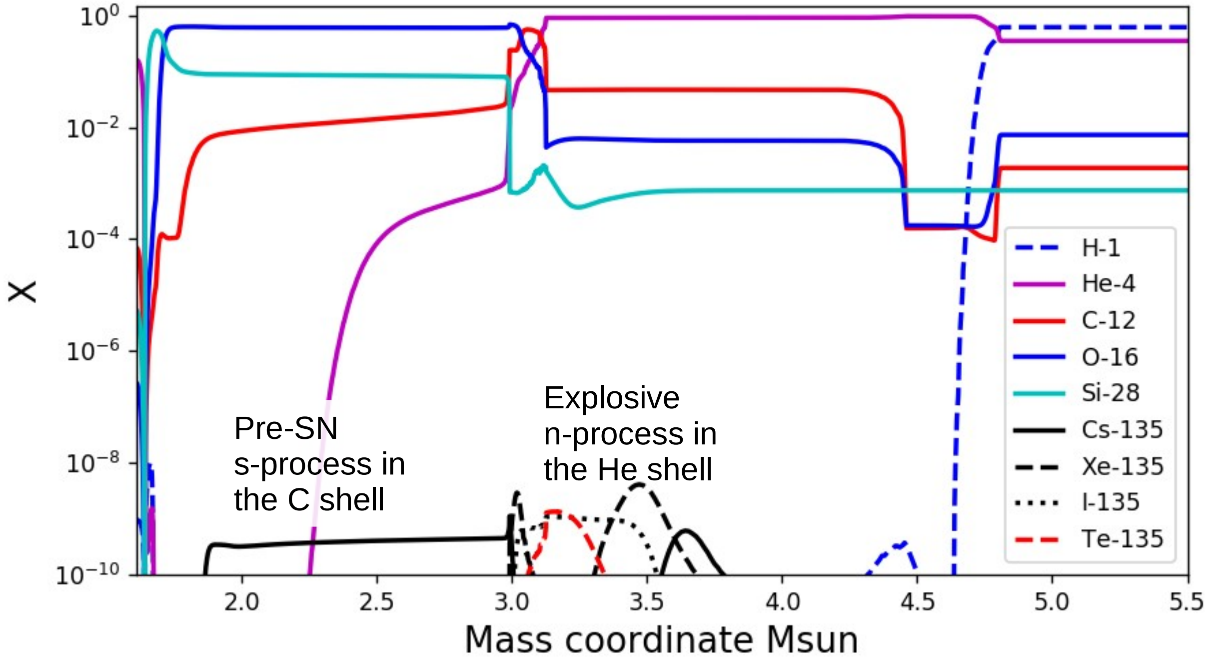


SLR Al26 yields from massive star winds




Si
O
C
He
H
X
Mass coordinate Msun
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
2.0
2.5
3.0
3.5
4.0
4.5
5.0
H-1
He-4
Si-28
Ni-56
Pb205
I129
Sm146
Nb92
Tc97
Tc98
Cl36
Hf182
Mn53
Fe60
Ca41
Al26
Pd107
Cs135
Sn126

Neutron burst driven by the ^{22}Ne(α,n) in explosive He-burning: ^{135}Cs (r-process SLR?!)



The n-process in CCSNe:
- Blake & Schramm 1976 ApJ
- Meyer+ 2000 ApJ
- Pignatari+ 2018 GeCoA

^{134}La 6.45 m β+	^{135}La 19.50 h β+	^{136}La 9.87 m β+	^{137}La 59.99 ka β+	^{138}La 102.01x10^{9} y 419 mb, β+
^{133}Ba 10.52 a β+	^{134}Ba 2.417% 176 mb	^{135}Ba 6.592% 455 mb	^{136}Ba 7.854% 61.2 mb	^{137}Ba 11.232% 76.3 mb
^{132}Cs 6.48 d β+	^{133}Cs 100% 509 mb	^{134}Cs 2.07 a 664 mb, β-	^{135}Cs 2.30 Ma 198 mb, β-	^{136}Cs 13.04 d β-
^{131}Xe 21.232% 340 mb	^{132}Xe 26.909% 64.6 mb	^{133}Xe 5.24 d 127 mb, β-	^{134}Xe 10.436% 20.2 mb	^{135}Xe 9.14 h β-
^{130}I 12.36 h β-	^{131}I 8.02 d β-	^{132}I 2.29 h β-	^{133}I 20.80 h β-	^{134}I 52.50 m β-

M=15Msun, Z=0.02
Ritter+2018 MNRAS
MESA progenitor
Fryer+12 explosion

The Astrophysical Journal, 762:31 (23pp), 2013 January 1 doi:10.1088/0004-637X/762/1/31
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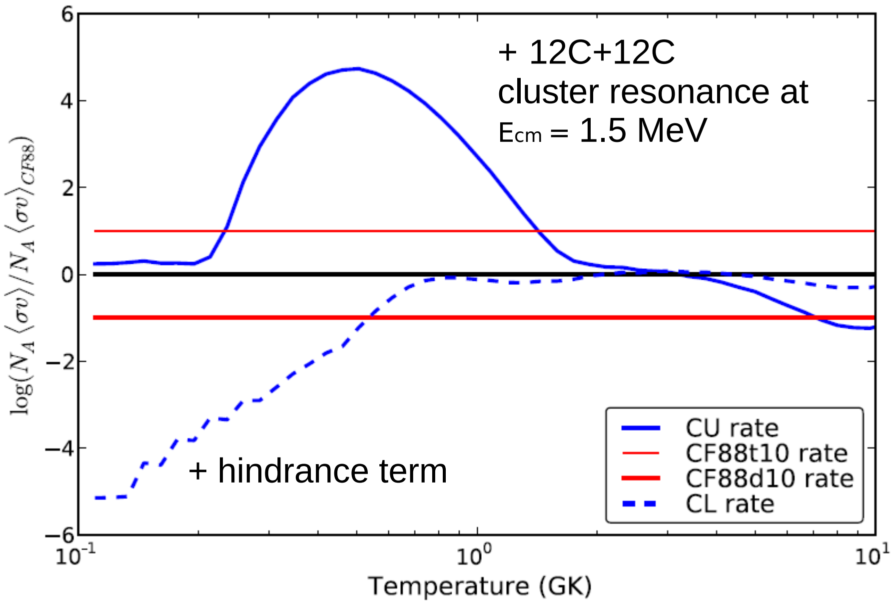
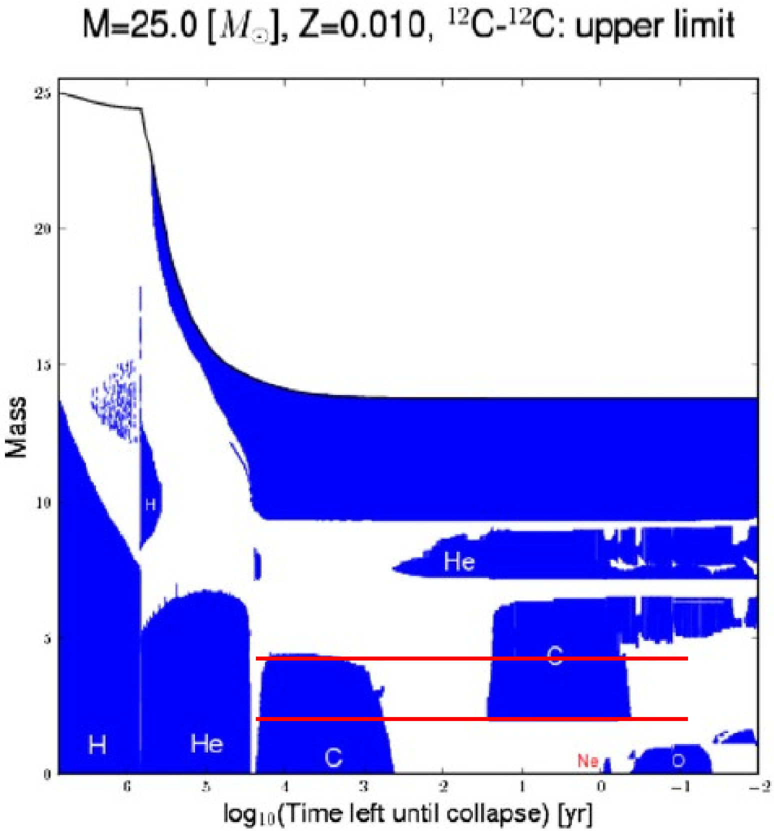
THE $^{12}C + ^{12}C$ REACTION AND THE IMPACT ON NUCLEOSYNTHESIS IN MASSIVE STARS

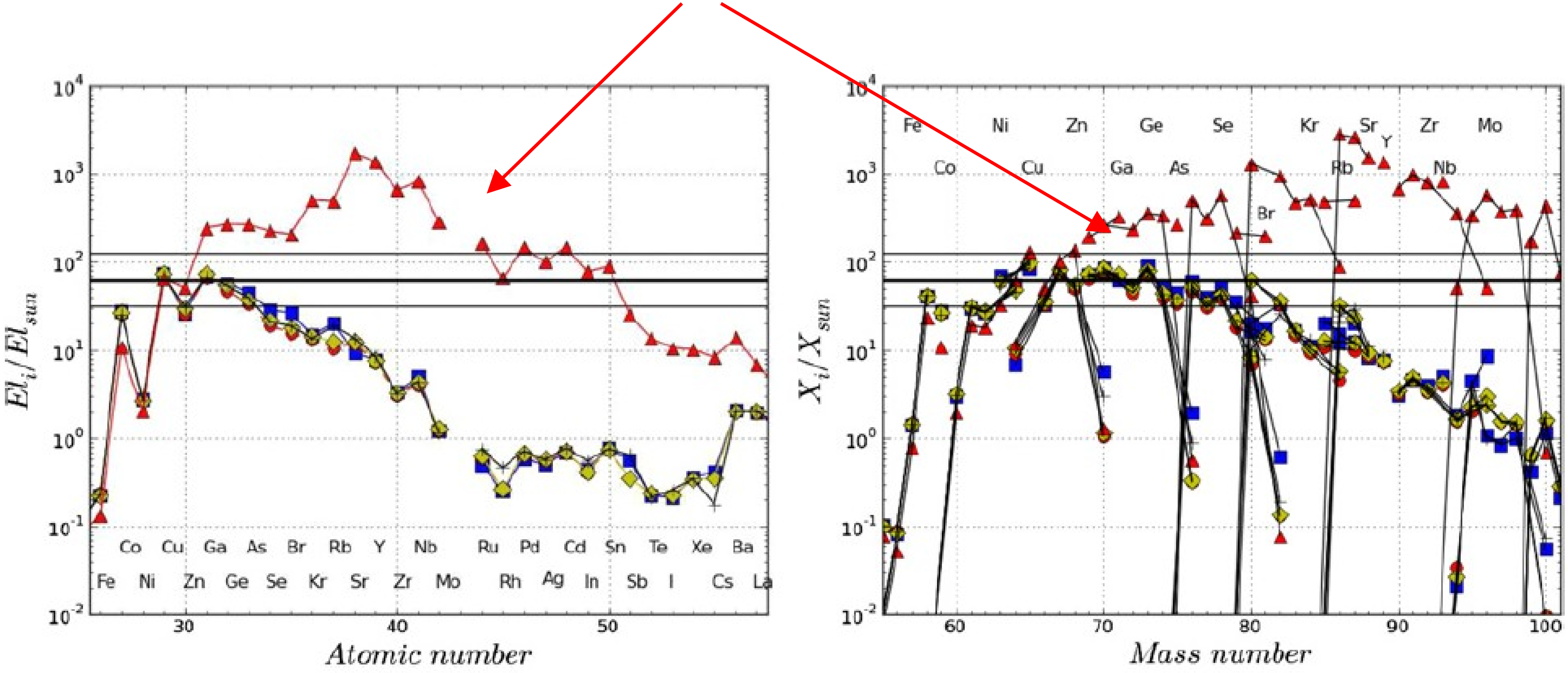
M. Pignatari[1,10], R. Hirschi[2,3,10], M. Wiescher[4,5], R. Gallino[6], M. Bennett[2,10], M. Beard[4,5,10],
C. Fryer[7,10], F. Herwig[5,8,10], G. Rockefeller[7,10], and F. X. Timmes[5,9,10]

...see also Bennett+ 2012 MNRAS





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



This does not look like the weak s-process component!

Is this a hidden LEPP component in the Solar System?

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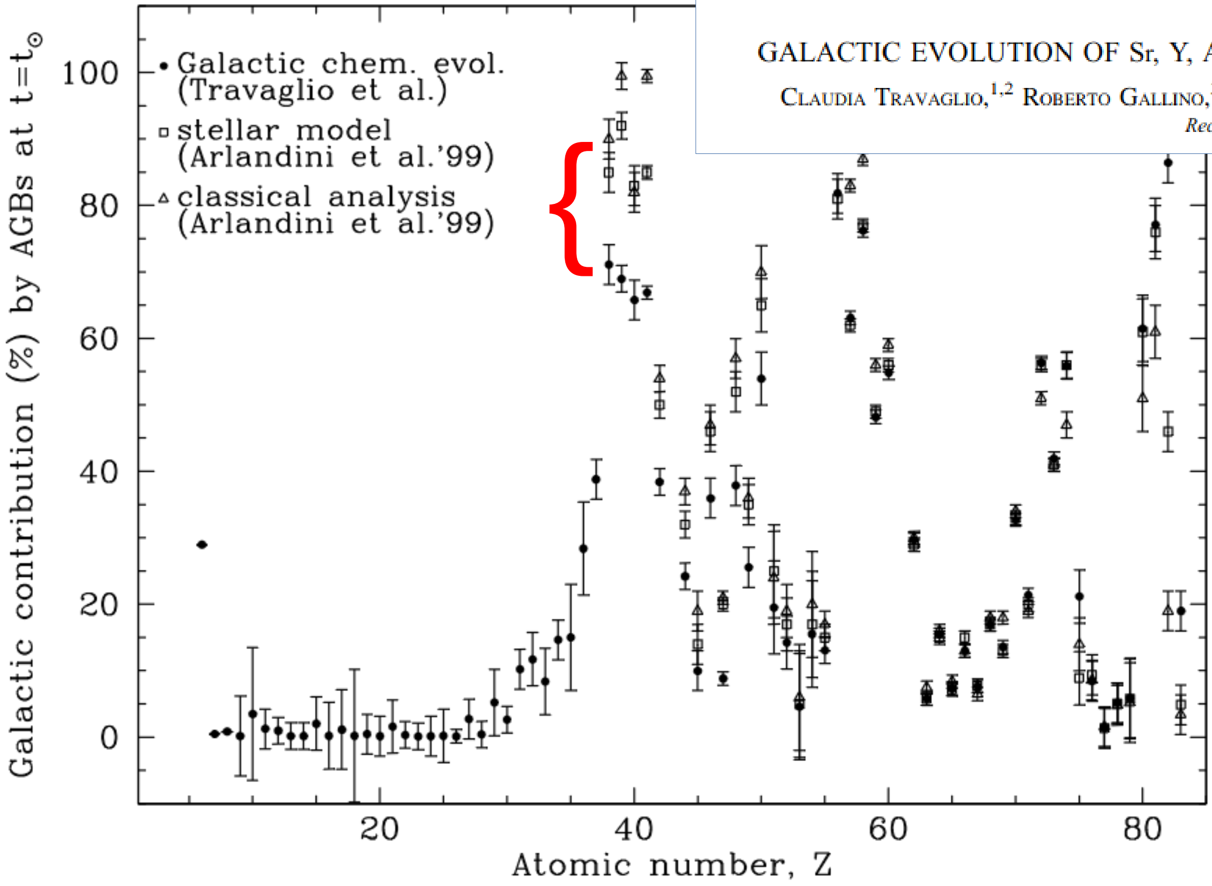
GALACTIC EVOLUTION OF Sr, Y, AND Zr: A MULTIPLICITY OF NUCLEOSYNTHETIC PROCESSES

Claudia Travaglio,[1,2] Roberto Gallino,[3] Enrico Arnone,[3,4] John Cowan,[5] Faith Jordan,[5] and Christopher Sneden[6]
Received 2003 June 27; accepted 2003 October 3



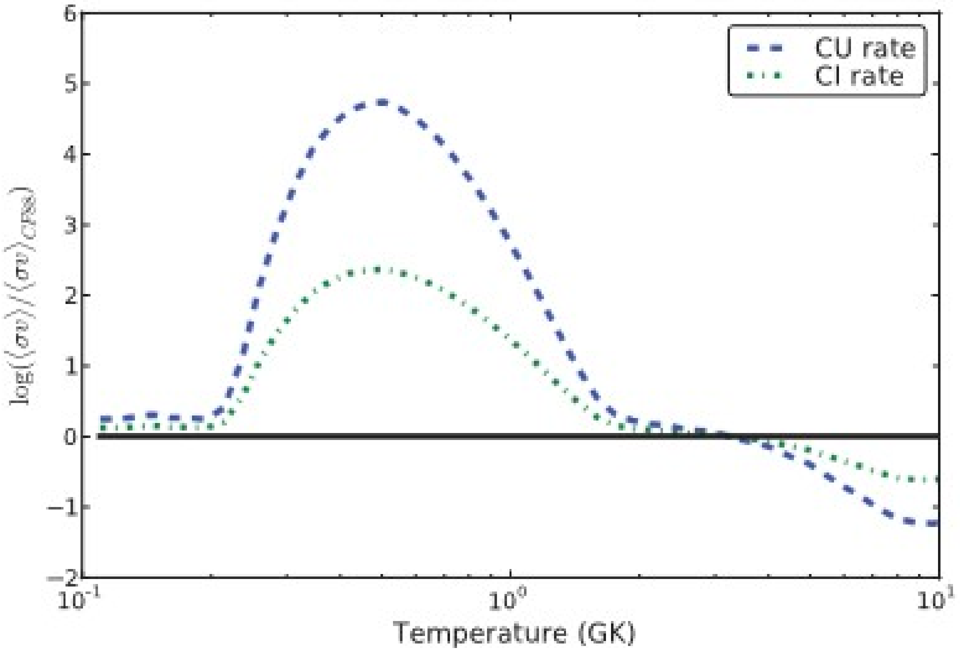
LEPP=
Lighter Element Primary Process

Is the LEPP controversial?
See e.g., Cristallo+ 2015 ApJ,
Involved with AGB s-process uncertainties, e.g., the role of rotation….Piersanti+ 2013 ApJ
Den Hartogh+ 2019 A&A...

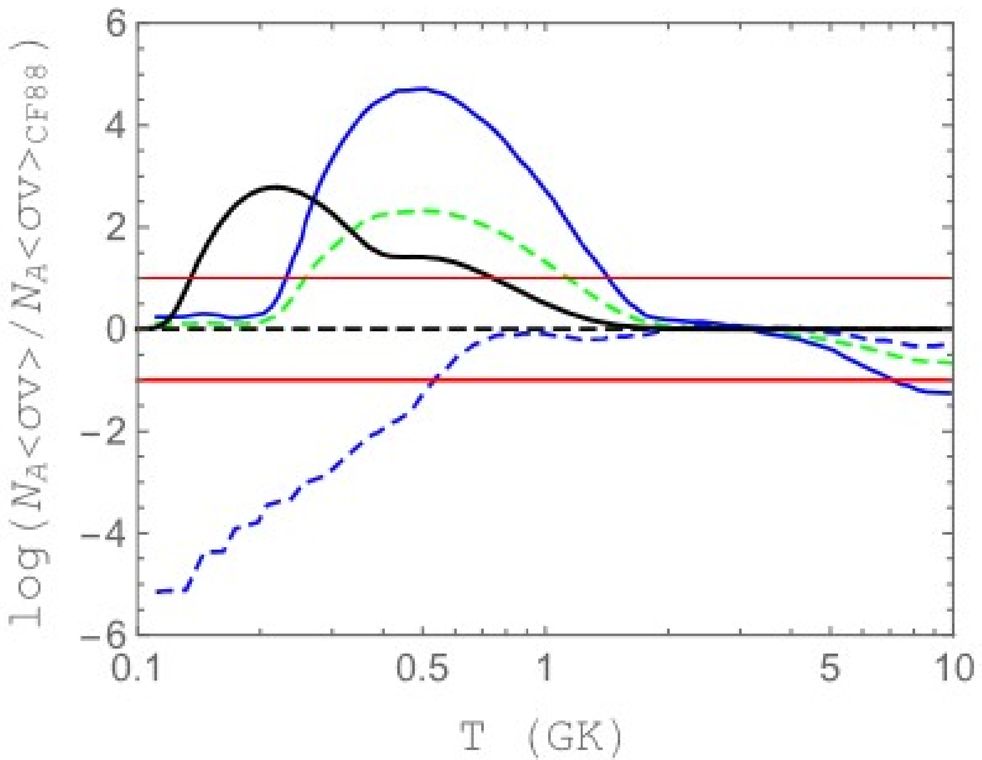
MP+ 2013

Such considerations provide a warning to bear in mind in our discussion and more generally for the present understanding of the *s*-process in massive stars. If the $^{12}C+^{12}C$ rate is higher than presently used, and the *cs*-process does exist, only 1%–2% of the *s*-process-rich material ejected from massive stars carrying such a component would be enough to explain the LEPP signature at the Sr peak. Therefore, it is extremely important to measure the $^{12}C+^{12}C$ rate down to stellar energies, to constrain C-burning conditions and *s*-process yields from massive stars.

If **≲20%** of the C-shell overlaps with C-core ashes, the 13C(α,n)16O exposure will dominate over the later 22Ne(α,n)25Mg contribution.

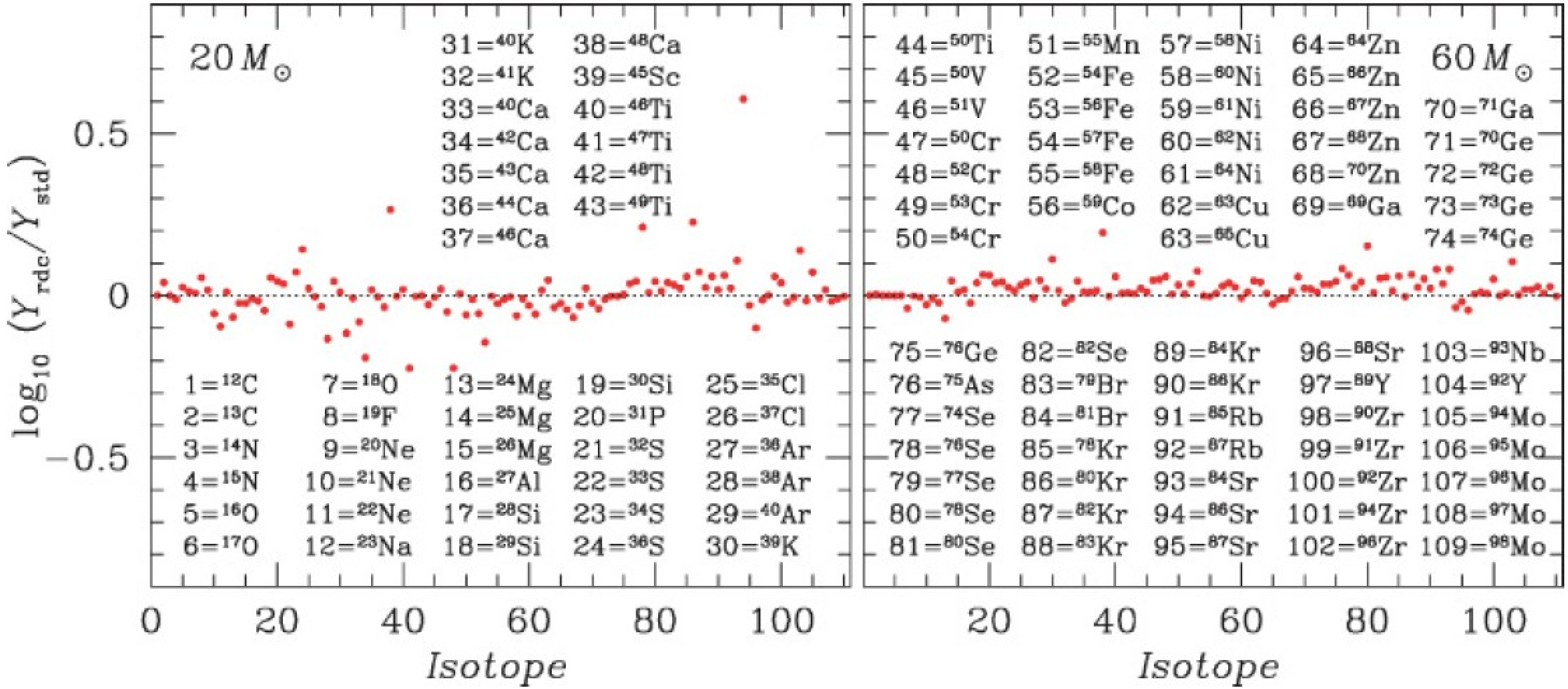


Bennett+ 2012 MNRAS



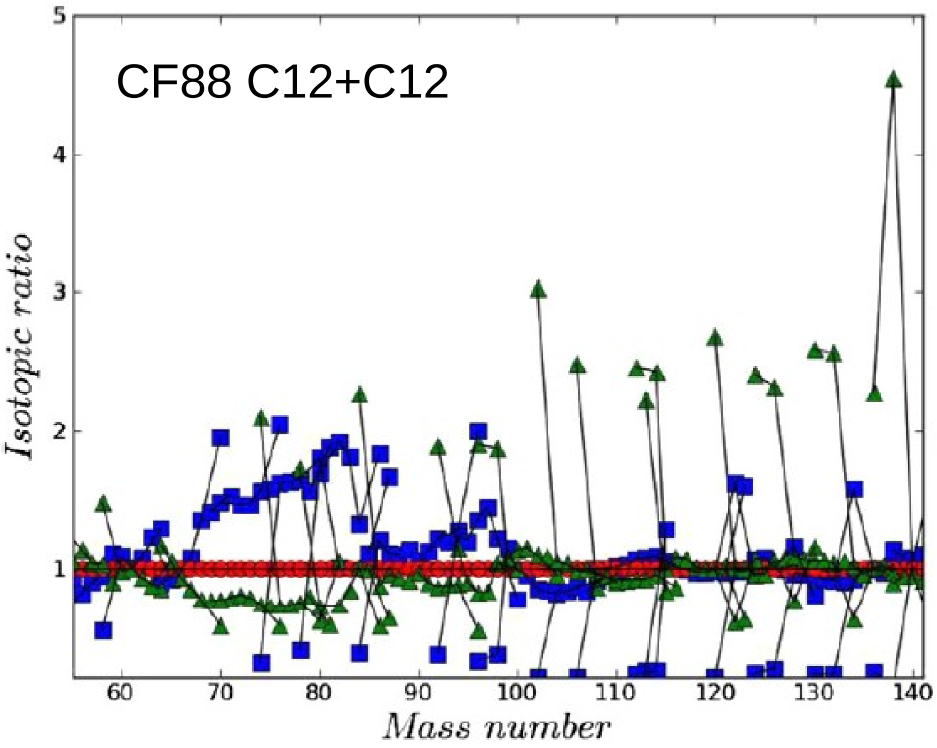
Chieffi+ 2021 ApJ

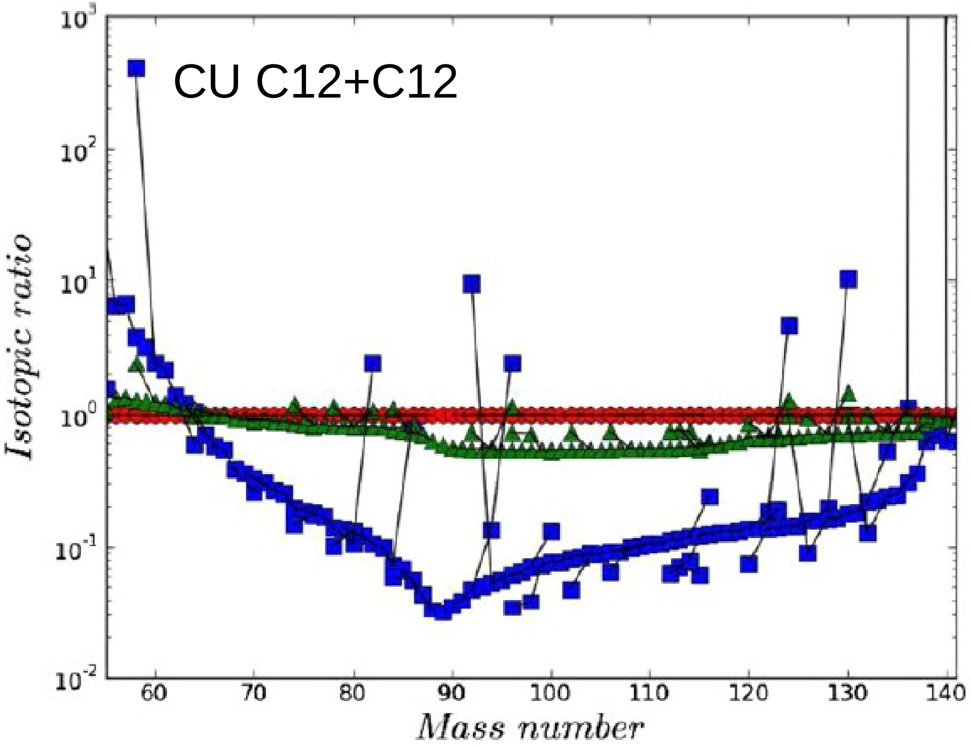
What about with low C12+C12 rates?



Gasques+ 2007 Phys Rev C (confirmed by MP+ 2013).

Impact of the α-/p- channel relative strength in the C12+C12

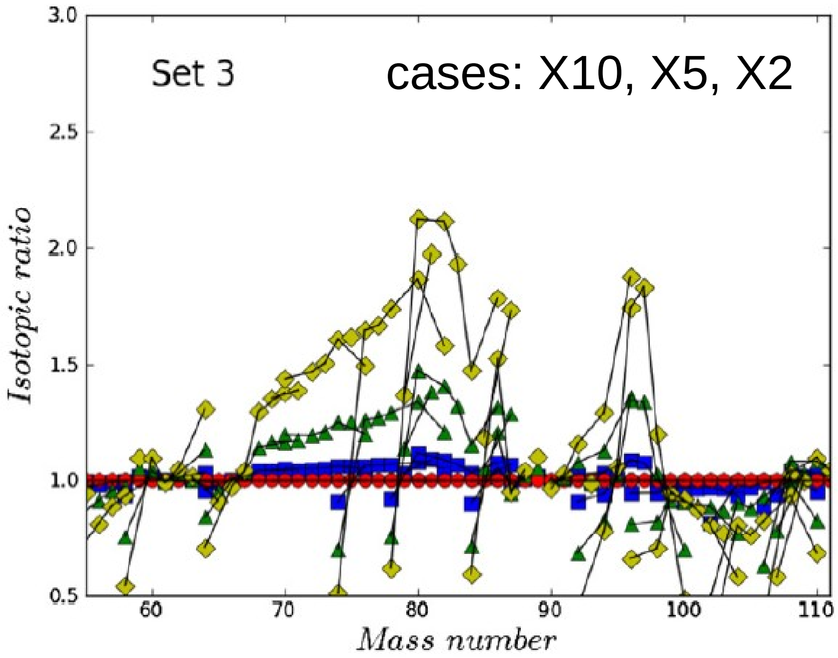


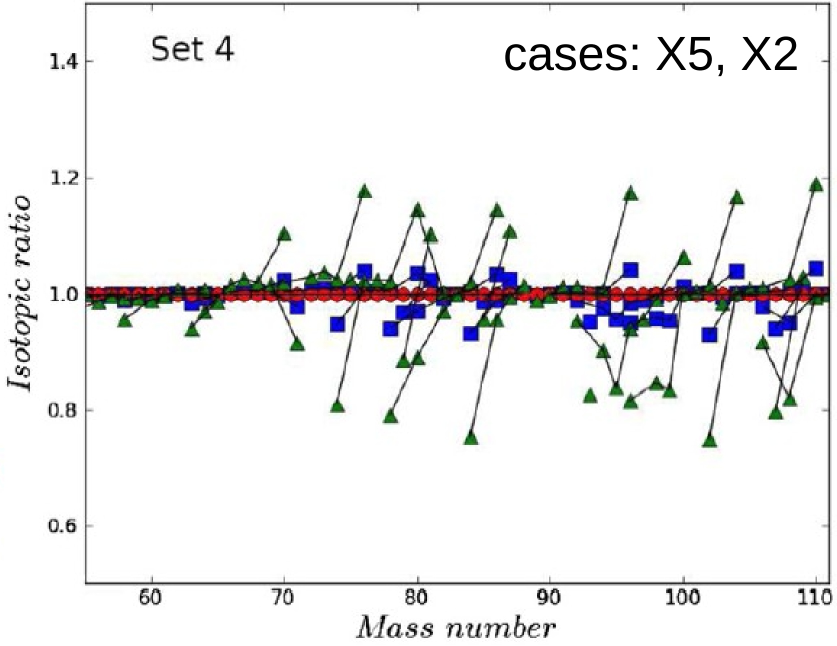


■ $R_\alpha/R_p = 0.95/0.05$

▲ $R_\alpha/R_p = 0.05/0.95$

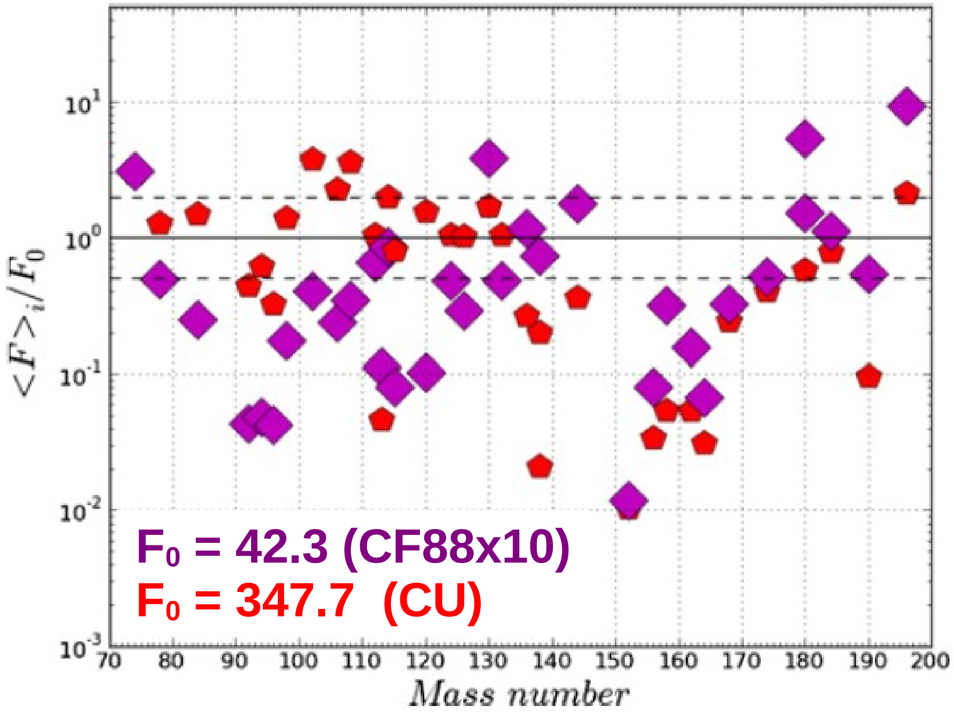
Impact of the n-channel C12(C12,n)Mg23





However, see Bucher+ 2015, PRL

Impact of the explosive γ-process production?



Uao! Could this solve the underproduction of the p-nuclei in the solar system and the missing production of Mo-Ru p-nuclei ?!

No, it does not work... :(
Remember, it must be a rare source

We have seen that the *cs*-component is difficult to reconcile with the *s*-process abundances observed in the solar system, unless only a few per cent of the total *s*-process-rich mass ejected by massive stars can carry it. By extension, the *p*-process-rich distribution obtained from CU (*cp*-component, hereafter) has to follow the same restrictions as discussed in Section 5. Indeed, we have shown that if about 2% of the

Summary

- High C12+C12 rates may strongly affect the s-process production, if C fusion yields at T9 < 0.75 made its way to the SN ejecta (and the $^{13}C(\alpha,n)^{16}O$ signature dominates over the $^{22}Ne(\alpha,n)^{25}Mg$).
- This should be a rare event in massive stars, in order to not break the weak s-process component from GCE (1-10% of all CCSN).
- The relative strength of the C-fusion α- and p-channels affect the s-process production
- The C-fusion n-channel is also relevant for the total neutron-budget, but currently covered by the 22Ne+α uncertainty (based on Bucher+ uncertainties). To be verified in CO shell mergers (Lorenzo’s talk).
- The γ-process signature resulting from the s-process boosted seeds from the C-core component is more compatible with the solar system abundance distribution of p nuclei than the standard γ-process from CCSN (or SNIa). However, even if it exists this should be a rare component, not relevant for GCE.