Neutron sources and the s-process nucleosynthesis

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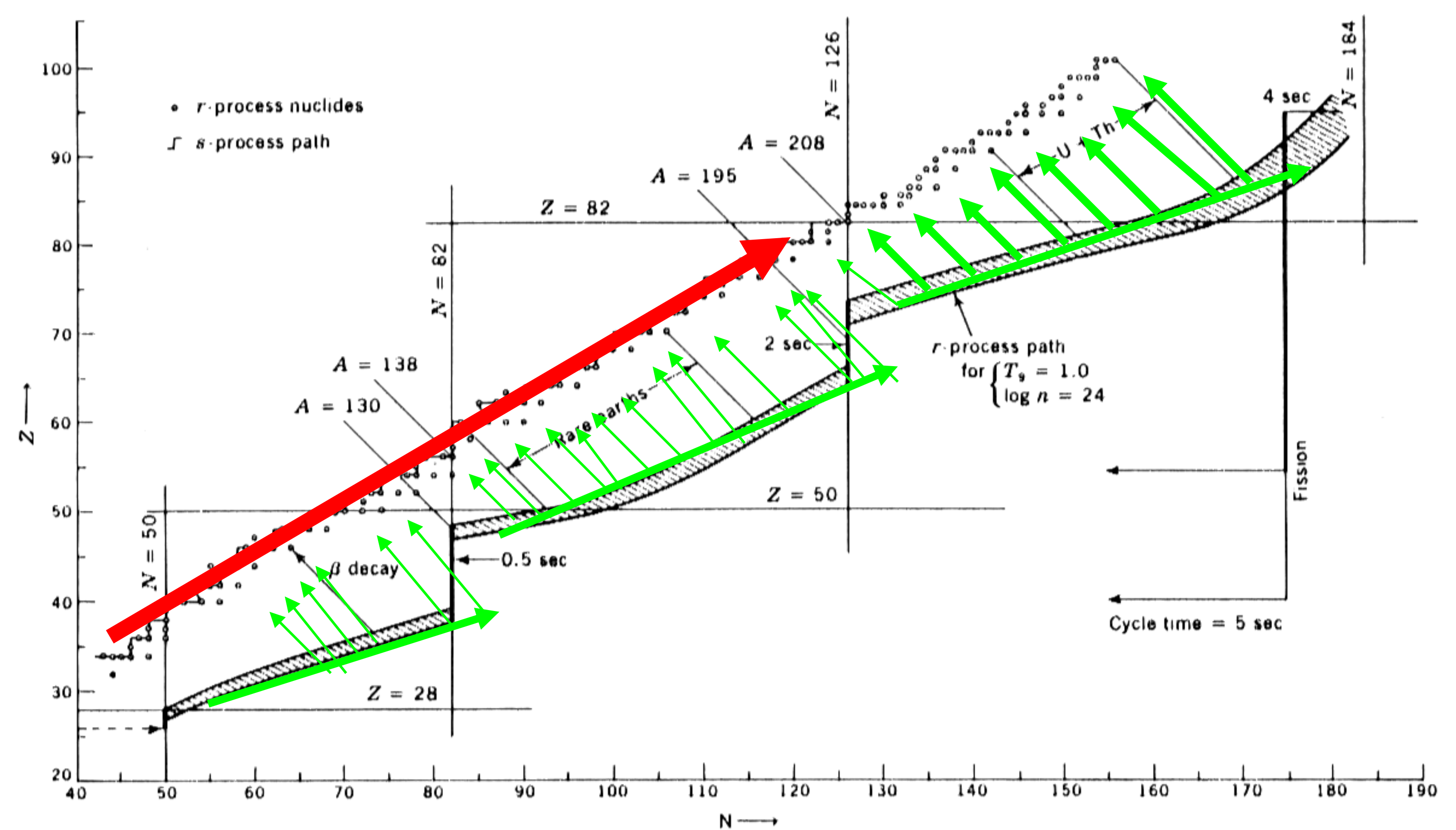


FROM CLAYTON 1968

***s*-process**

$\tau_\beta \ll \tau_n$

$N_n \sim 10^7$ n/cm^3

***r*-process**

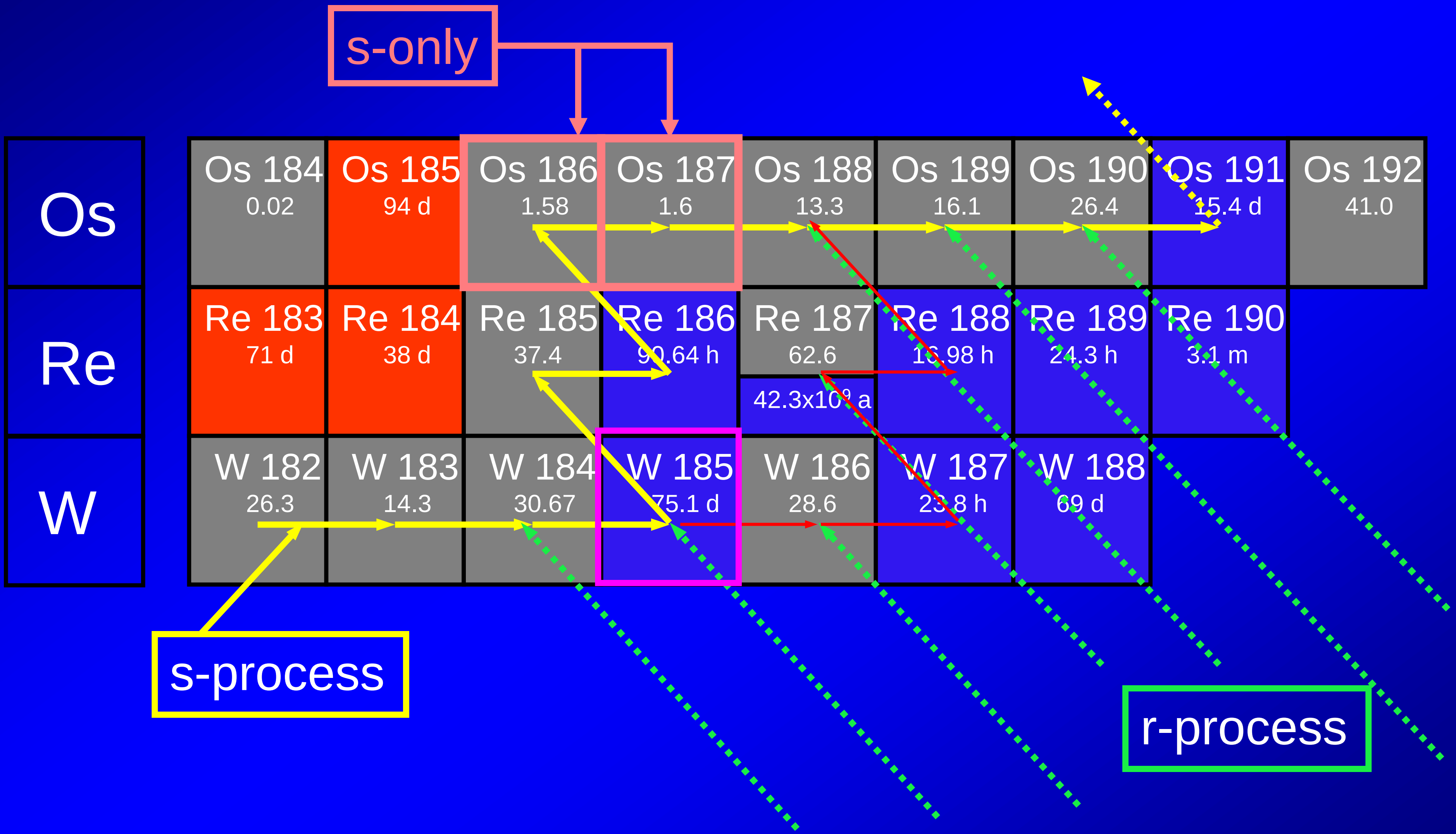
$\tau_\beta \gg \tau_n$

$N_n > 10^{20}$ n/cm^3

THE CLASSICAL COMPONENTS OF THE S PROCESS

Weak Component: $A<90$	Core-He and C-shell burning In Massive Stars
Main Component: $90<A<204$	AGB stars
Strong Component: $204<A<210$	Low Metallicity AGB stars

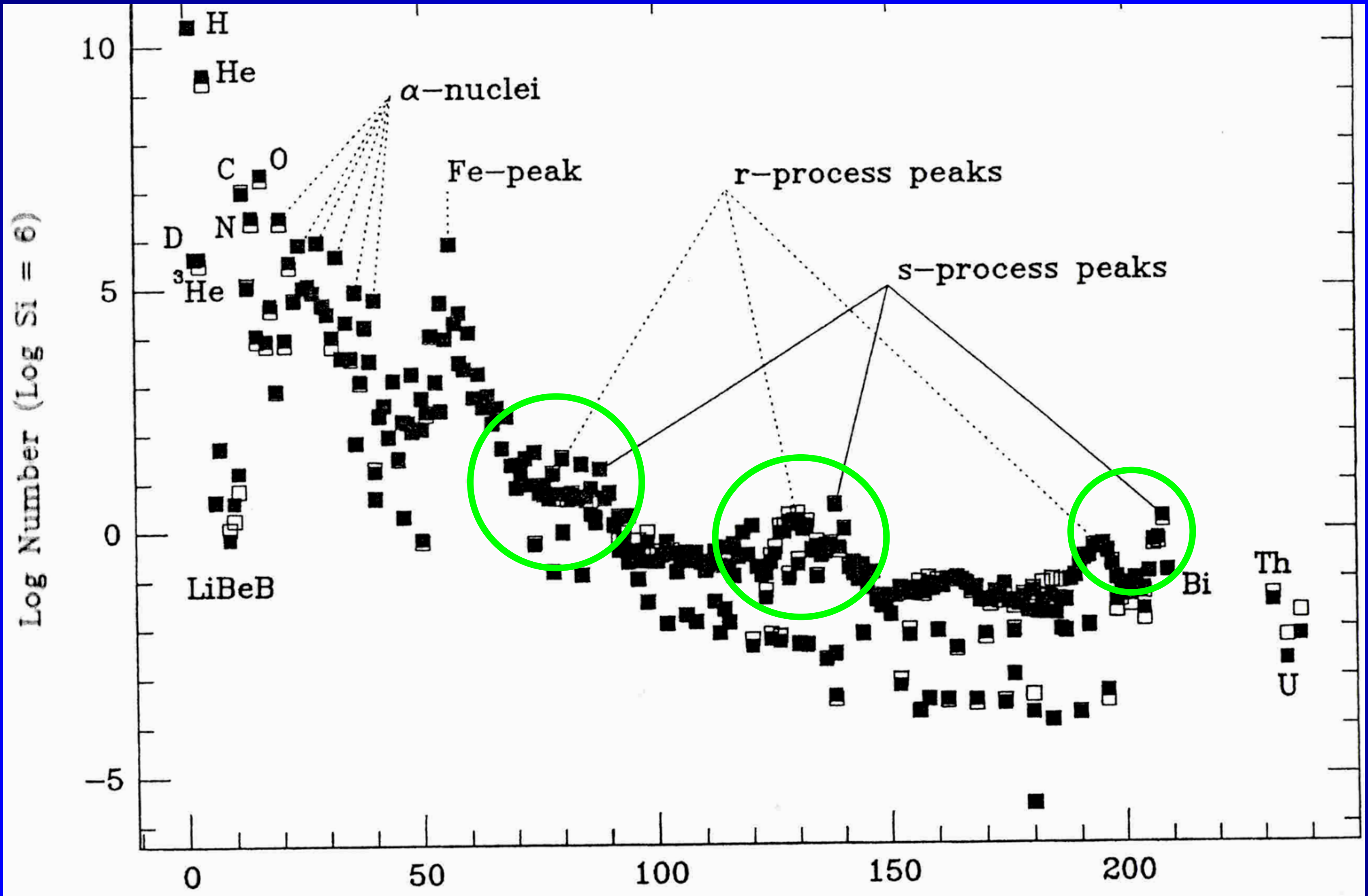
How do neutron captures work?



Os	Os 184 0.02	Os 185 94 d	Os 186 1.58	Os 187 1.6	Os 188 13.3	Os 189 16.1	Os 190 26.4	Os 191 15.4 d	Os 192 41.0
Re	Re 183 71 d	Re 184 38 d	Re 185 37.4	Re 186 90.64 h	Re 187 62.6 42.3x10^9 a	Re 188 16.98 h	Re 189 24.3 h	Re 190 3.1 m	
W	W 182 26.3	W 183 14.3	W 184 30.67	W 185 75.1 d	W 186 28.6	W 187 23.8 h	W 188 69 d		

Branching points:: if $\tau_\beta \sim \tau_n$ $\Rightarrow$ several paths are possible

Solar System Abundances

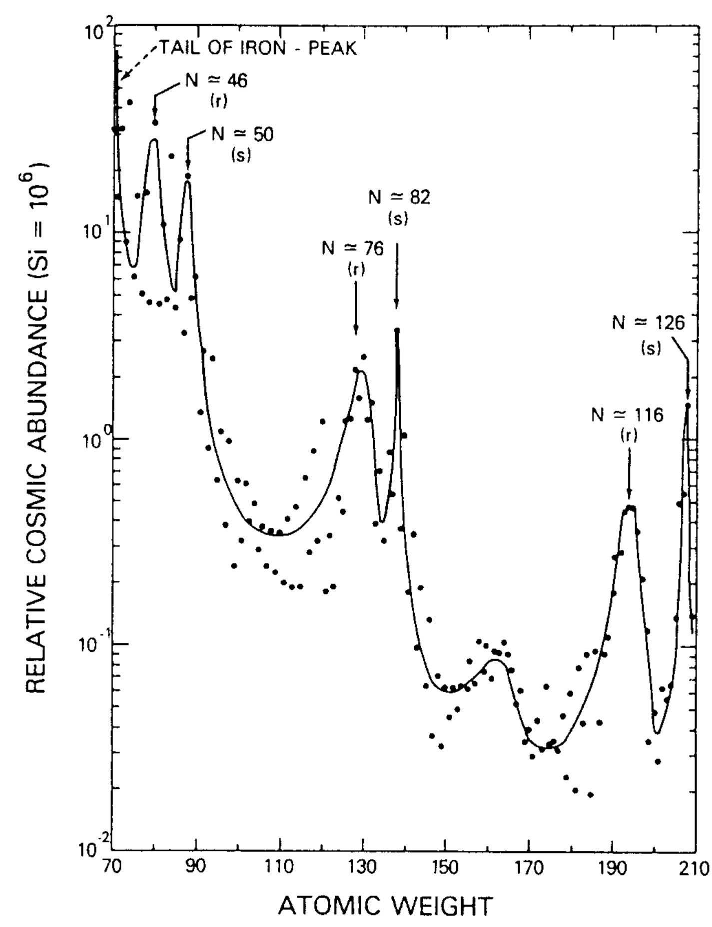


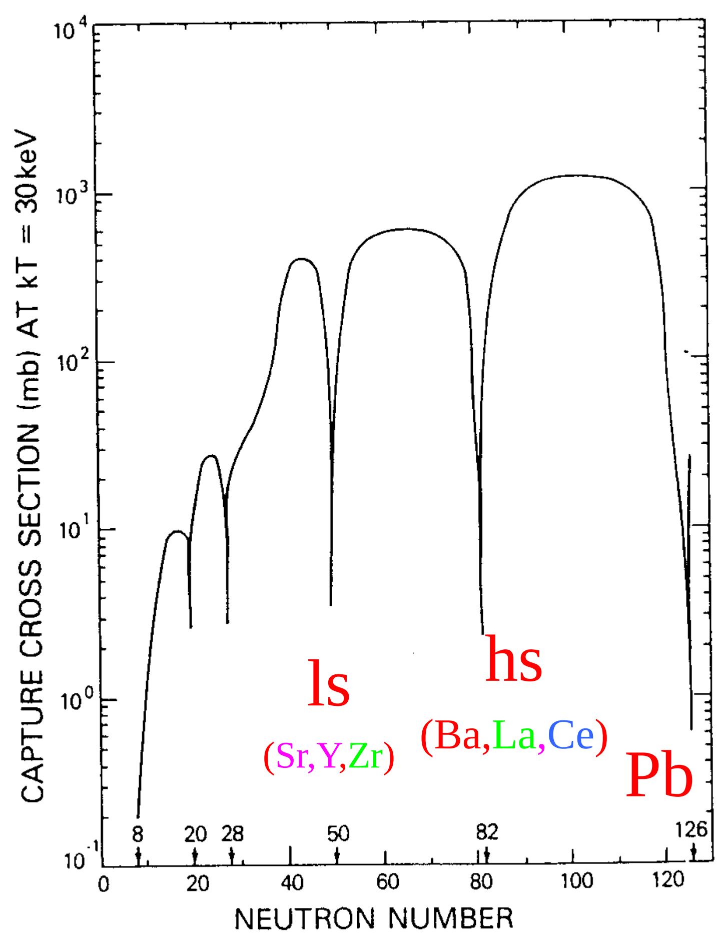
Anders & Grevesse 1989
Cameron 1982

MAGIC NUCLEI

abundance curve for elements beyond iron

very small σ(n,γ) at neutron <u>magic numbers</u>





Where do neutrons come from?

Free neutrons are NOT abundant in the major phases of nuclear burnings.

Neutrons are liberated to some extent by secondary reactions during helium burning in **Asymptotic Giant Branch (AGB) stars**.
Moreover they are produced during **core-He and shell-C burnings of massive stars**.

Major neutron sources

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

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

Radiative burning @ T>90 MK

Convective burning @ T>250 MK

The nuclear paths

^{13}C: major source for the Main component

Primary

$$^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(\beta^{+})^{13}\mathrm{C}$$

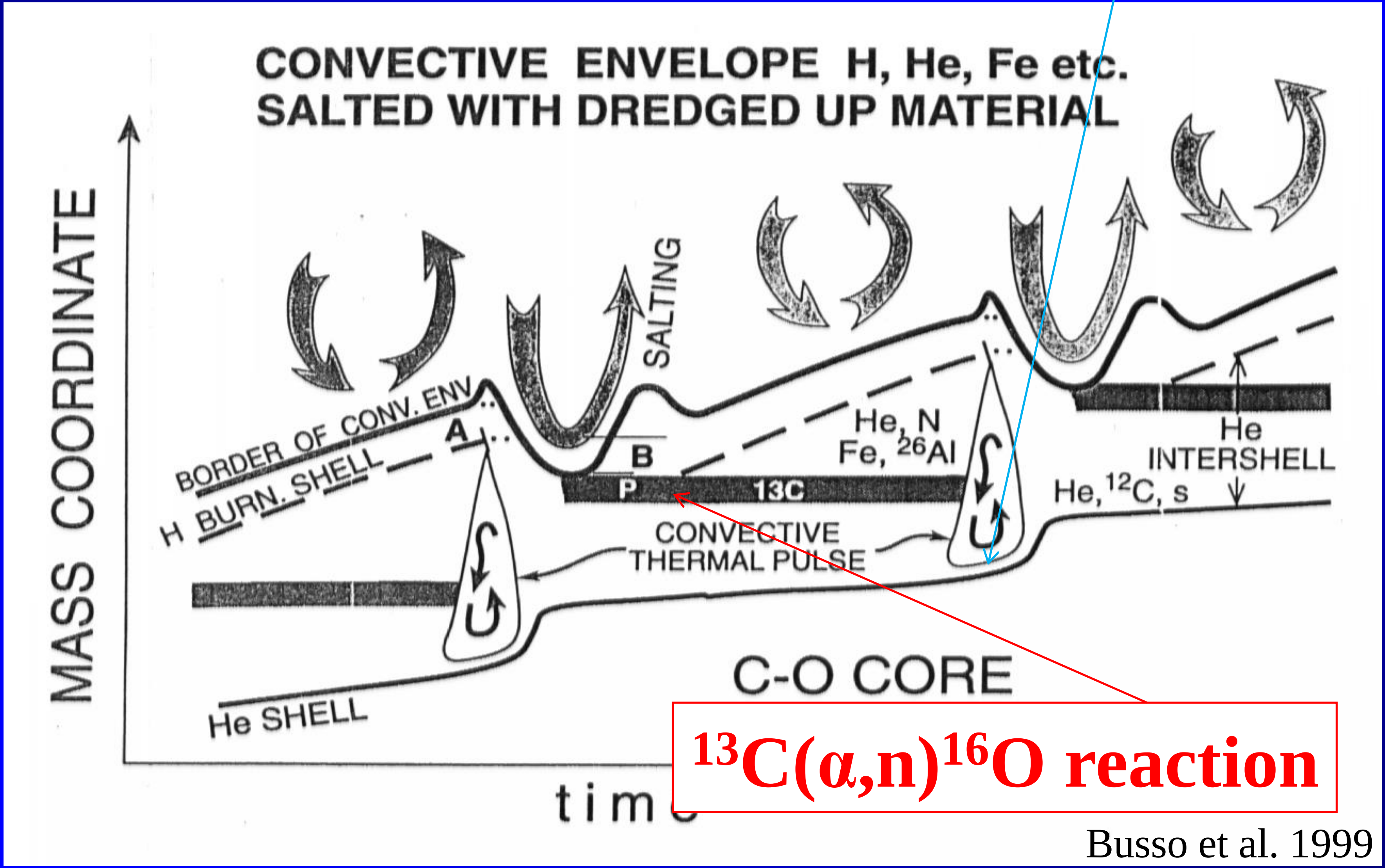
^{22}Ne: major source for the Weak component

Secondary

$$^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^{+})^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$$

The s-process in AGB stars

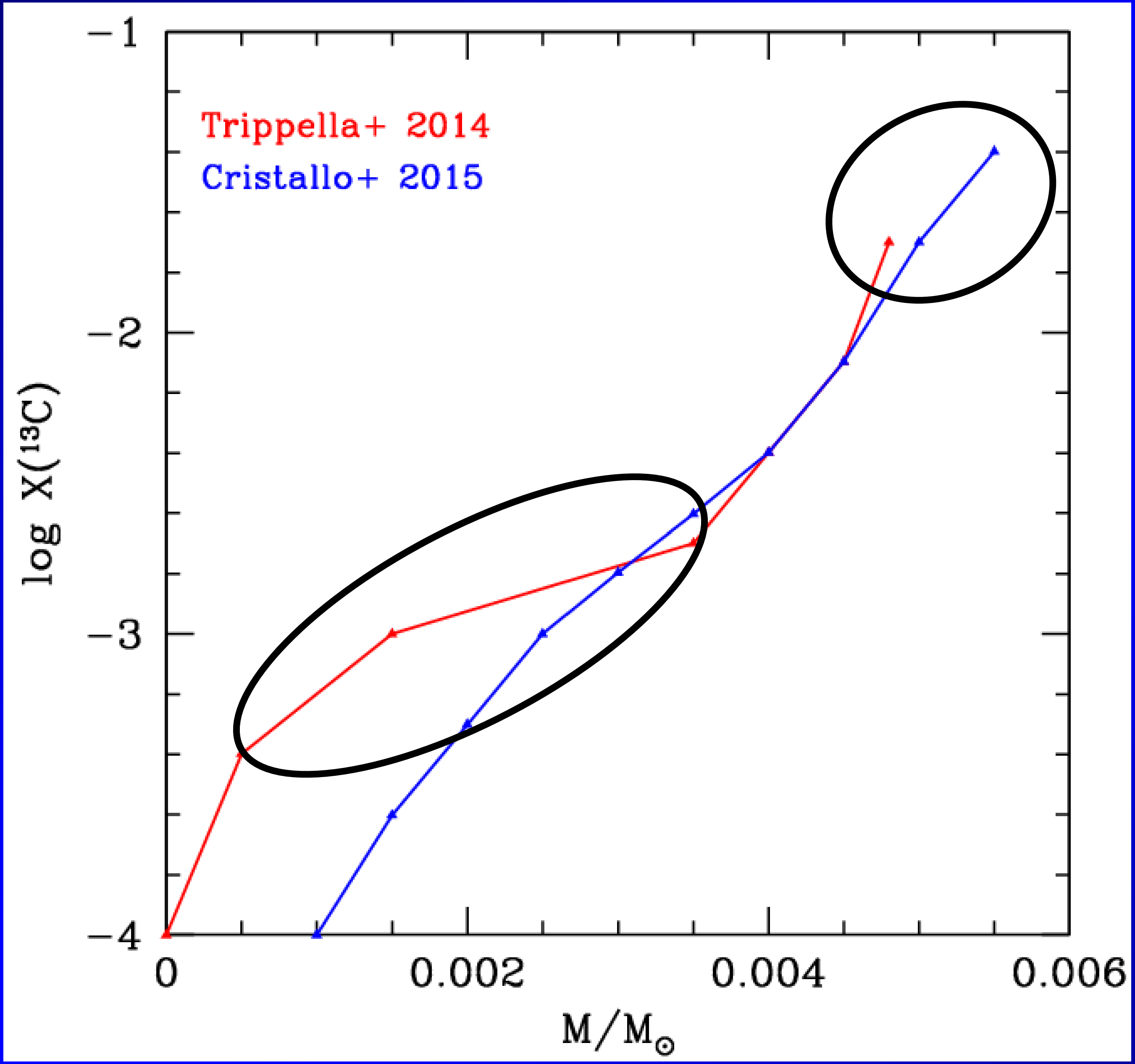
^{22}Ne(α,n)^{25}Mg reaction



^{13}C(α,n)^{16}O reaction

Busso et al. 1999

The ^{13}C pocket



^{14}N strong neutron poison via ^{14}N(n,p)^{14}C reaction

See also Gallino's models

Measurements of the $^{13}C(\alpha,n)^{16}O$ reaction

- Trippella+ 2017
- Avila+ 2015
- La Cognata+ 2013
- Xu+ 2013
- La Cognata+ 2012
- Guo+ 2012
- Heil+ 2008
- Kubono+ 2003
- Angulo+ 1999
- Drotleff+ 1993
- …

→ Asymptotic normalization coefficient (ANC) and the Trojan Horse Method (THM) ↓

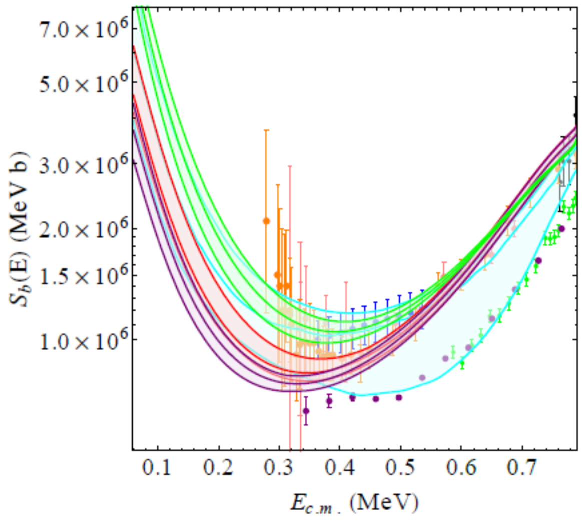


Fig. 4.— Comparison between $S(E)$-factor calculated in this paper (red band) with recent indirect determinations by La Cognata et al. (2013) and Avila et al. (2015) (green and purple band, respectively). The cyan band, instead, shows the astrophysical factor and the corresponding uncertainties suggested by NACRE II compilation (Xu et al. 2013). For ease of comparison, the same data set of Fig. 3 is shown in the low-energy region between 0.06 and 0.8 MeV where the contribution of the 1/2$^+$ state is more effective.

Explored models for the $^{13}C(\alpha,n)^{16}O$

• $M=1.5\ M_{SUN}\ Z=0.01$	Convective ^{13}C burning
• $M=3.0\ M_{SUN}\ Z=0.01$	s-process main component
• $M=4.0\ M_{SUN}\ Z=0.0001$	Intermediate AGBs in GCs
• $M=1.3\ M_{SUN}\ Z=0.00002$	Proton ingestions at low Z

Reference rate: Heil+ 2008

Upper case: *2

Lower case: *0.5

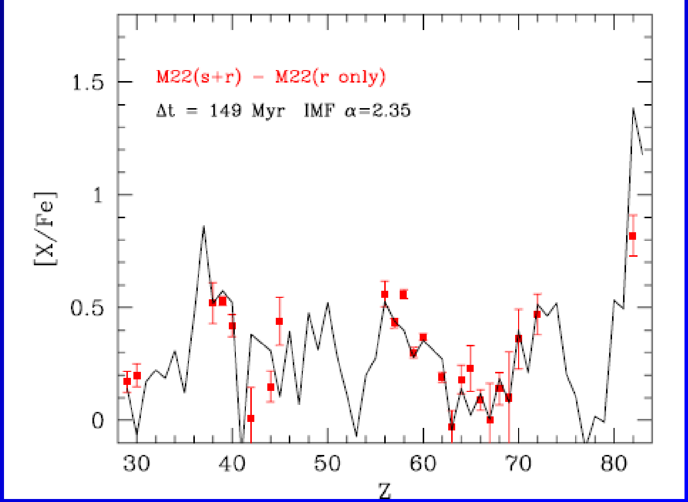
M=1.5 Msun Z=0.01

Part of the ^{13}C of the first pockets is engulfed in the following convective shells → CONVECTIVE ^{13}C BURNING

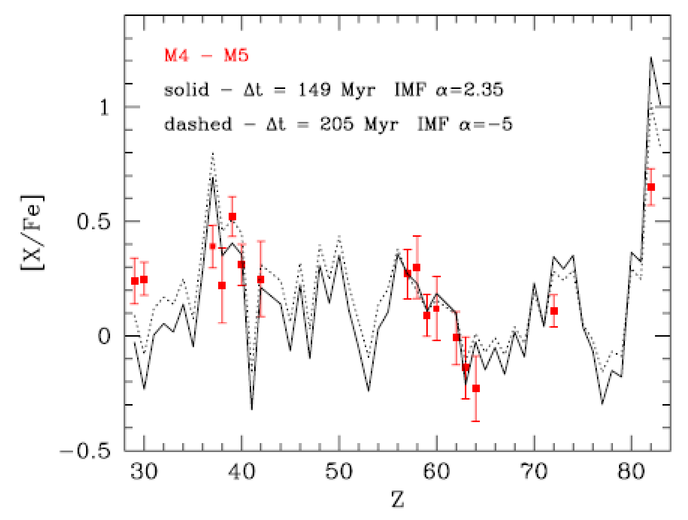
M=3.0 Msun Z=0.01

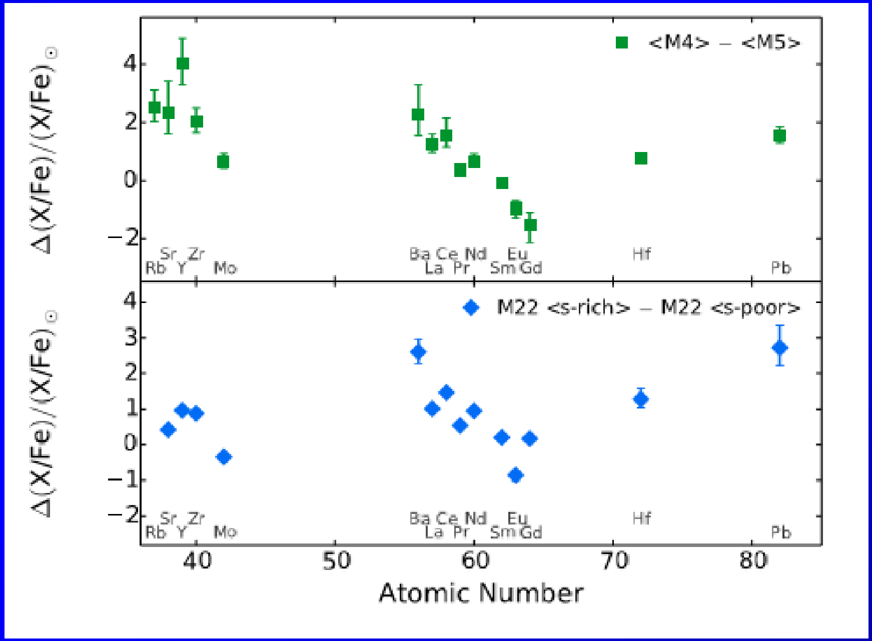
All ^{13}C in the pockets burns radiatively →
CLASSICAL S-PROCESS (MAIN COMPONENT)

s-rich Globular Clusters: the importance of massive AGBs



Straniero+ 2014

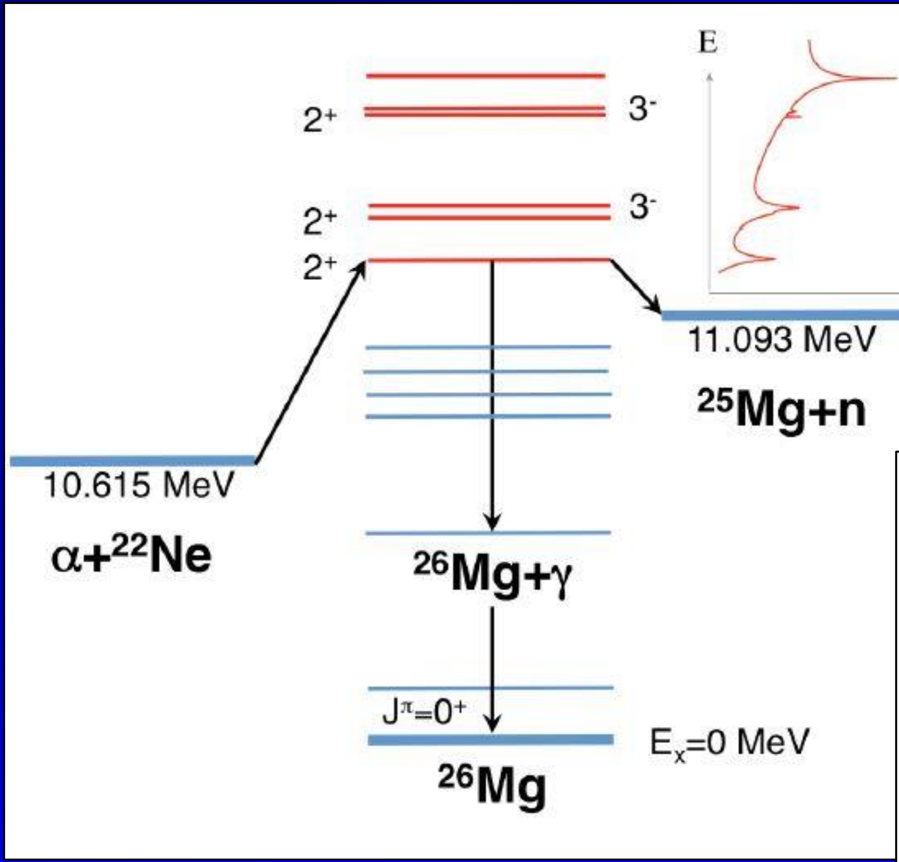


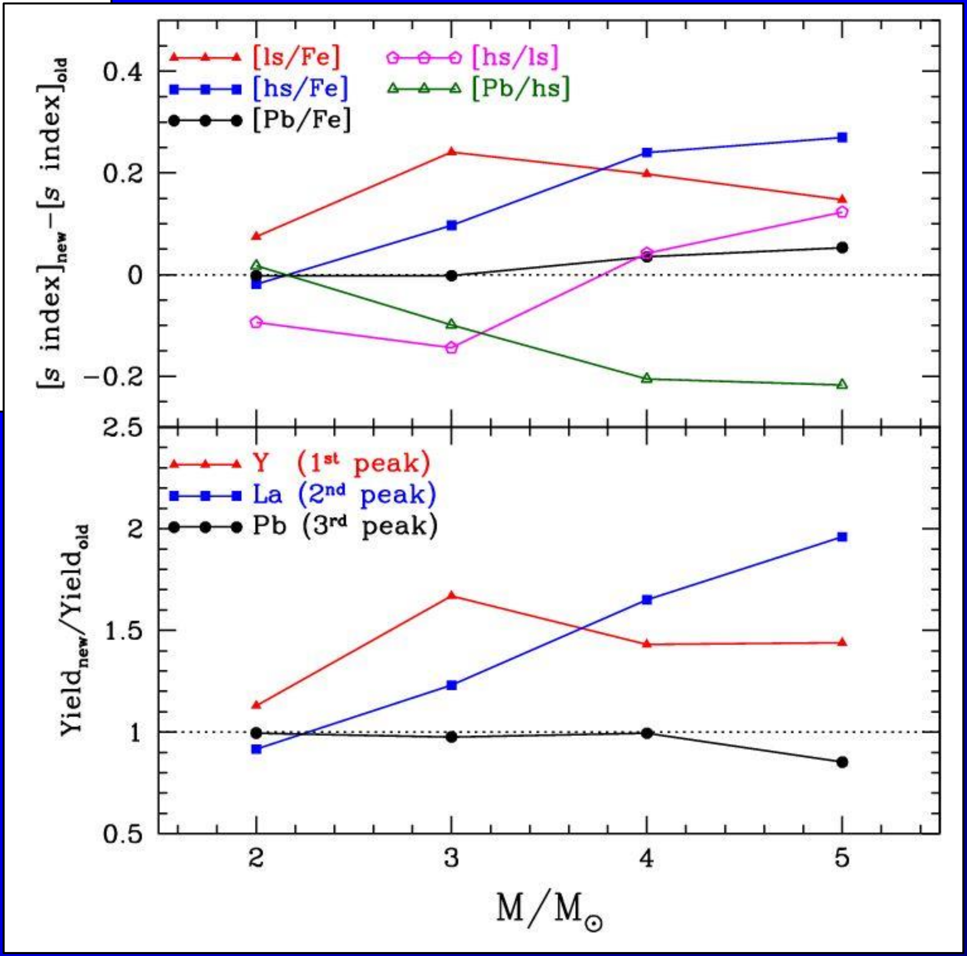


Shingles+ 2014

Massimi+ 2017 (n_TOF collaboration)

^{25}Mg(n,γ) and ^{25}Mg(n,tot)





An unambiguous spin/parity assignment of the corresponding excited states in ^{26}Mg

↓

Experimental upper limits of the reaction rates for ^{22}Ne(α,*n*)^{25}Mg and ^{22}Ne(α,γ)^{26}Mg, potentially leading to a significantly higher (α,*n*)/(α,γ) ratio than previously evaluated.

(SOME) CONCLUSIONS

- Neutron cross sections are particularly important for magic nuclei, neutron poisons and in correspondence of branching points (in particular those involving unstable isotopes)

- The $^{13}C(\alpha,n)^{16}O$ reaction rate is important for low mass AGBs ($M < 1.5\ M_{SUN}$) at solar metallicity, because it determines how much ^{13}C burns in a convective environment

- The $^{13}C(\alpha,n)^{16}O$ reaction rate does not modify the abundances in more massive AGBs ($M > 3\ M_{SUN}$) at low metallicities, where the $^{22}Ne(\alpha,n)^{25}Mg$ is more important;

- The $^{13}C(\alpha,n)^{16}O$ reaction could be important for low mass AGBs at very low metallicity, because in that case the convective ^{13}C burning (together with the subsequent neutron capture) affects the physical evolution of the model