The rates of neutron-realeasing reactions in He-burning phases and their astrophysical consequences

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1. Slow neutron captures in stars: a general reminder
2. The neutron sources and their activation
3. s-Processing from the $^{13}C(a,n)^{16}O$ reaction: status & needs for new measures
4. s-Processing from the $^{22}Ne(a,n)^{25}Mg$ reaction: status & needs for new measures

Round Table "LUNA-MV at LNGS“, Feb. 10-11, 2011

The distribution of s-elements: two components

Main component: TP-AGB Stars of Low & Intermediate Mass (Iben & Truran 1977; Gallino et al. 1998; Busso et al. 1999): repeated neutron fluences (originally imagined as exponentially distributed, they are actually more complex in nature).

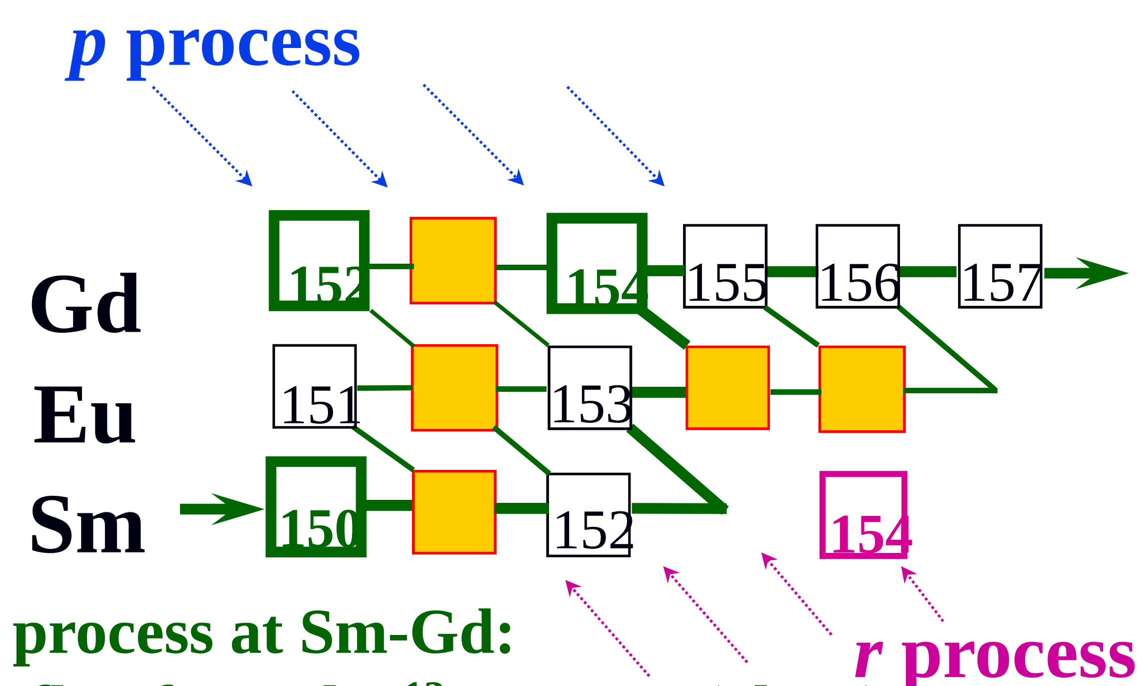
Weak component: Massive stars during He and C burning (Raiteri et al. 1991 a,b; Kaeppeler et al. 1994; Pignatari et al. 2010)

56 70 90 110 130 150 170 190 210

MASS NUMBER

FIG. 2.—The product of *s*-process abundance times cross section as a function of mass number. The symbols correspond to empirical values for *s*-only isotopes (*squares*) or to neutron magic isotopes which are predominantly produced by the *s*-process (*circles*). The respective abundances are taken from the solar abundance table of Cameron (1981). Error bars include the cross section uncertainties only. The calculated solid lines correspond to the strong and weak component in the exponential neutron fluence distribution.

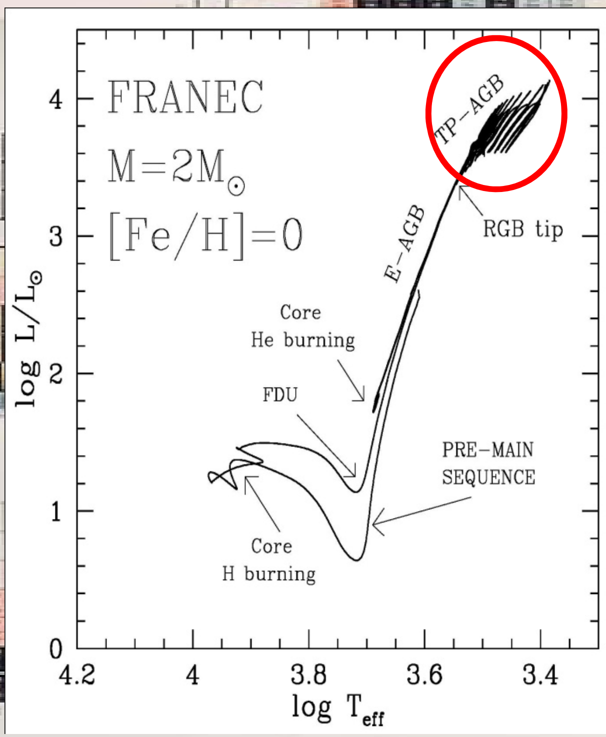
Neutron density and neutron source fro the main component

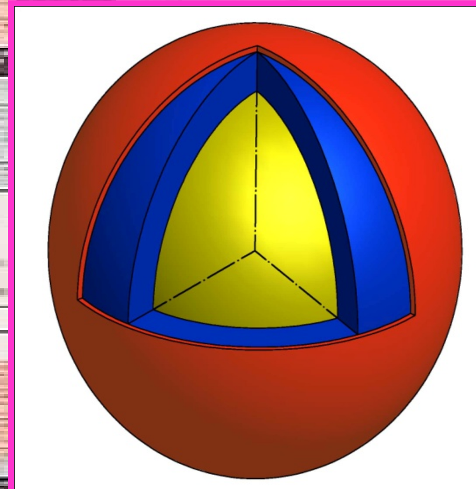


s process at Sm-Gd:
n-flux from the ^{13}C source (8keV)
branchings from the ^{22}Ne one (23 keV)

Precise cross sections, decay rate estimates near branching points and comparison with stellar models made clear that the main component is dominated by a regime with low n-density ($^{13}C(a,n)^{16}O$ reaction, at about 8 keV, $n_n = 10^7$ cm^{-3}), with small "corrections" from the marginal activation of the $^{22}Ne(a,n)^{25}Mg$ source at about 22-23 keV, with a higher neutron density, up to 10^{10} cm^{-3}.

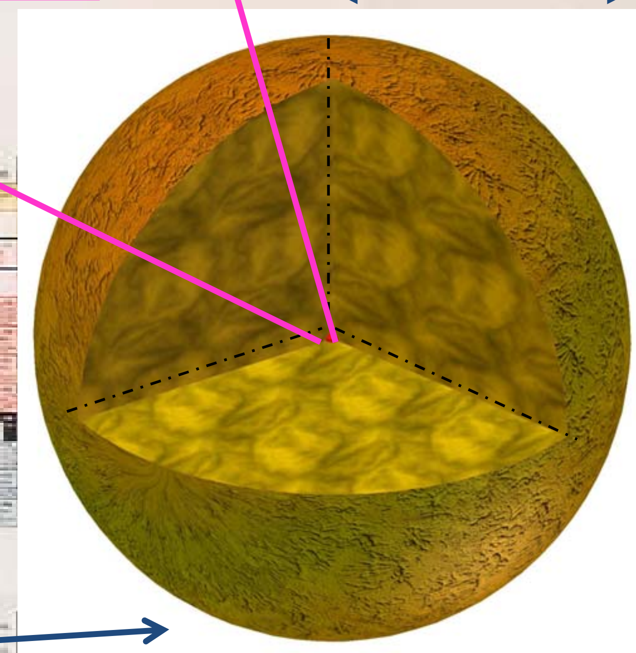
AGB stars





CORE

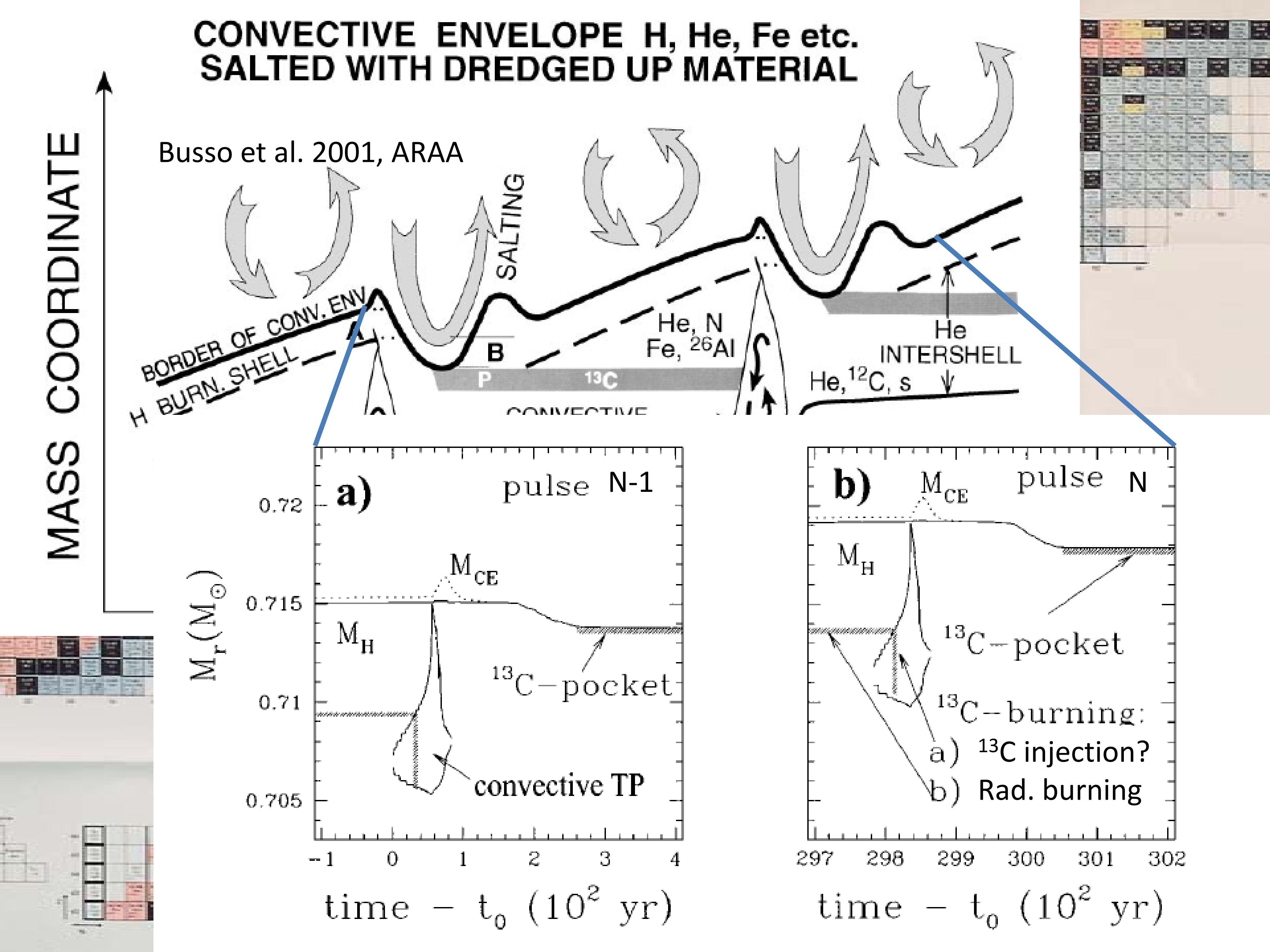
Earth-Sun
(~200 R_{SUN})



ENVELOPE

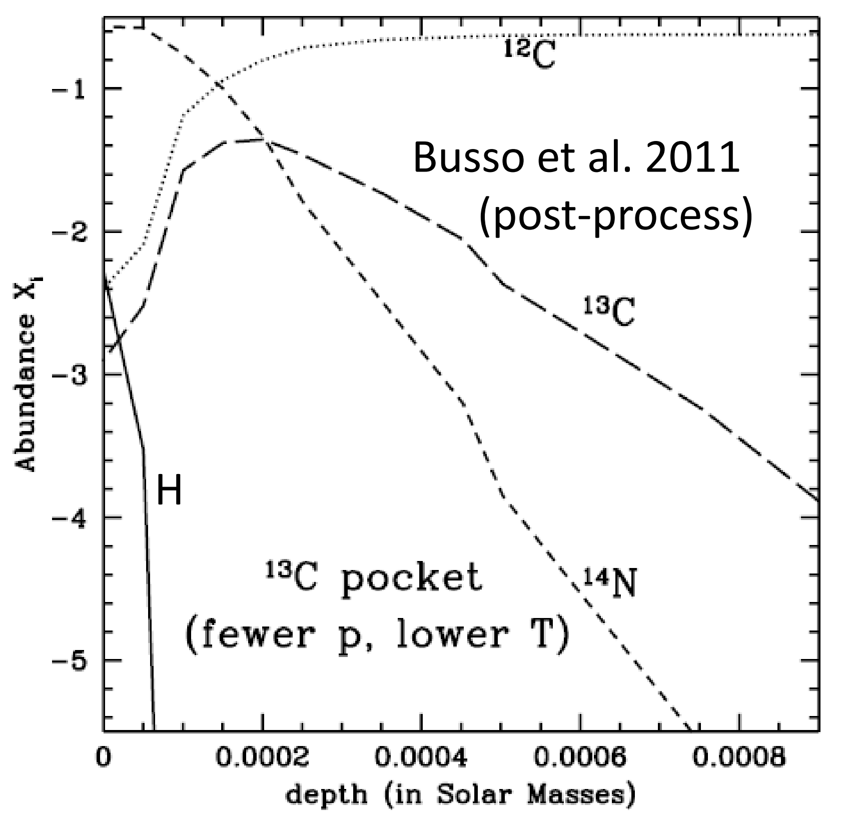
MAIN REFERENCES:

Chieffi et al. 1998
Straniero et al. 2005
Cristallo et al 2009

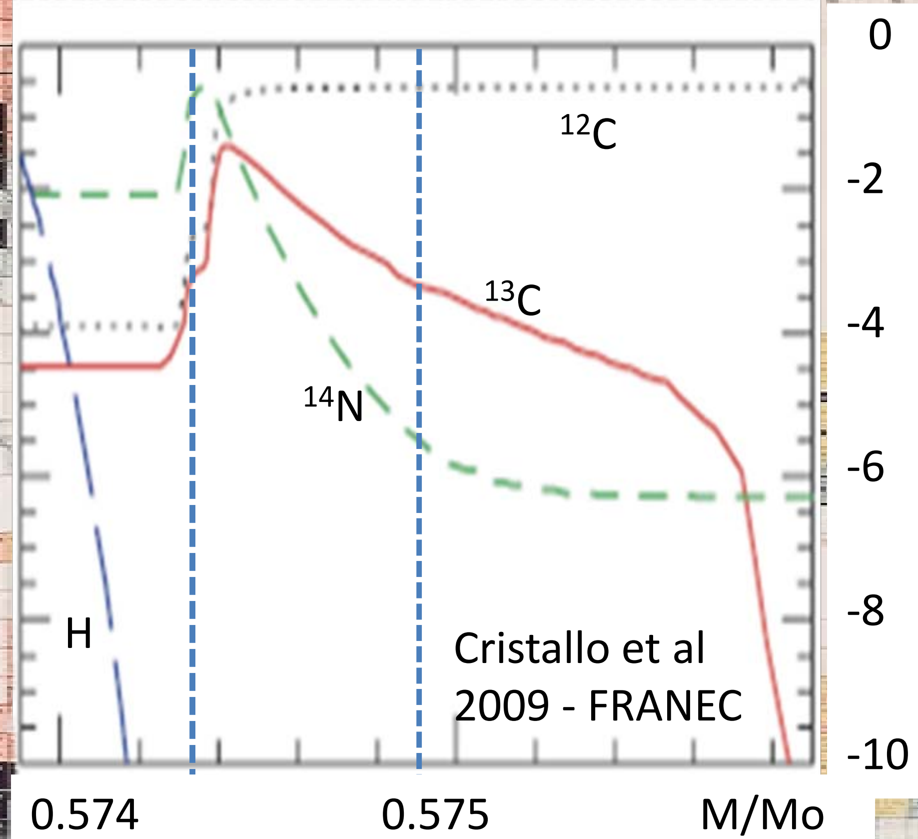


CONVECTIVE ENVELOPE H, He, Fe etc.
SALTED WITH DREDGED UP MATERIAL
Busso et al. 2001, ARAA
MASS COORDINATE
SALTING
BORDER OF CONV. ENV.
H BURN. SHELL
A
B
P
13C
He, N
Fe, 26Al
He
INTERSHELL
He, 12C, s
a) pulse N-1
b) pulse N
MCE
MH
13C−pocket
13C−burning:
a) 13C injection?
b) Rad. burning
convective TP
Mr(M☉)
0.72
0.715
0.71
0.705
time − t0 (10^2 yr)
−1
0
1
2
3
4
297
298
299
300
301
302

Current ways of modelling the ^{13}C neutron source formation



Obtained through $n(H) = n(H_{bce})\exp(-k\Delta M)$



(bc

In any case, the profile of protons is in general exponential-like, as expected (more or less) in a diffusive phenomenon

FIRST PROBLEM: if the subthreshold-resonance contribution to the rate of the $^{13}C+\alpha$ is much smaller than assumed (Kato et al. 2005; Kubono et al. 2003) then we might need more time to burn ^{13}C than available in the interpulse

→ ^{13}C would burn partly convectively, with all the inherent complicacies (extra energy, shell splitting, possibly higher neutron densities…..).

THIS POINT SHOULD BE VERIFIED CLEARLY (Heil et al. 2008 go toward opposite directions). REAL MEASURES, NOT EXTRAPOLATIONS, NEEDED

In the rare, but important cases in which Proton Ingestion Episodes (PIE: Critsallo et al. 2009b) occur, the structure is heavily affected, the convective shell is splitted, ^{13}C forms over a wide range of temperatures: better knowledge of the rate is needed from few keV up to about 30 keV.

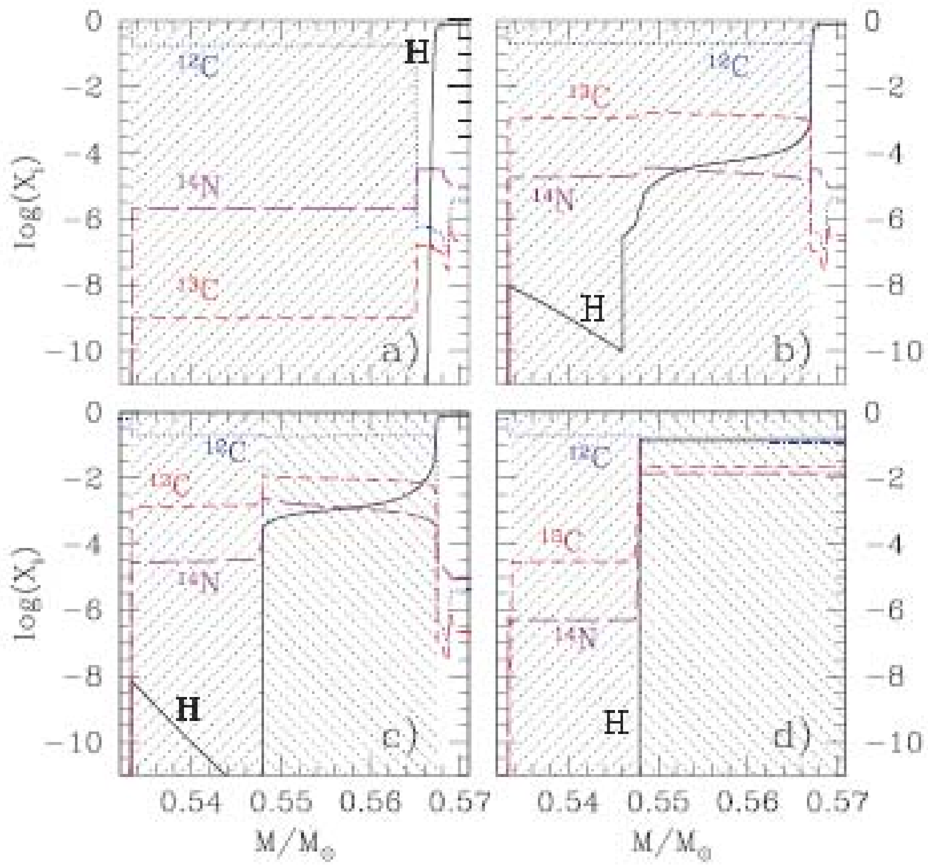
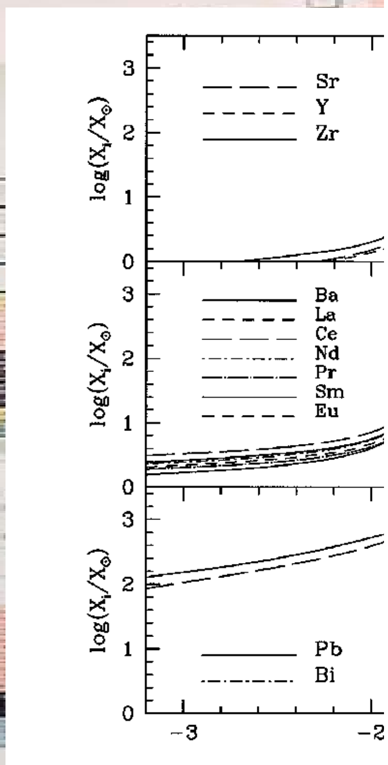
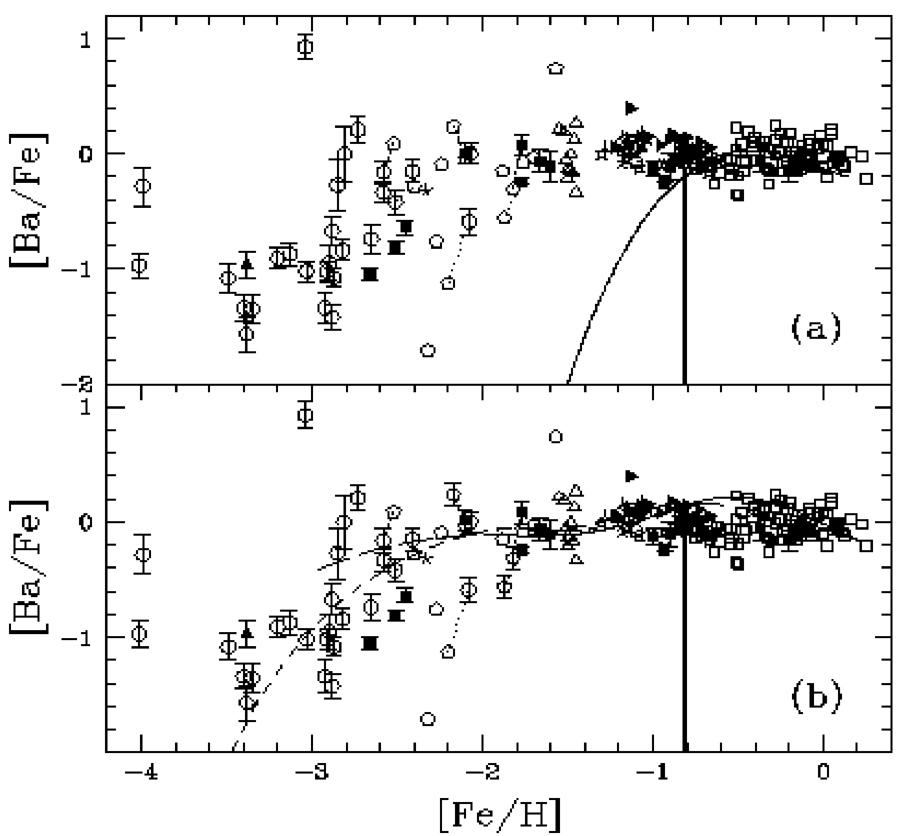
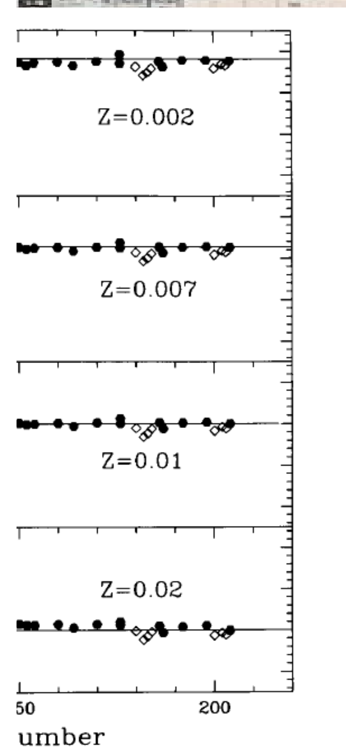


Figure 2: Evolution of selected key isotopes within the He-intershell during the PIE.

Average s-process increas in the Galaxy



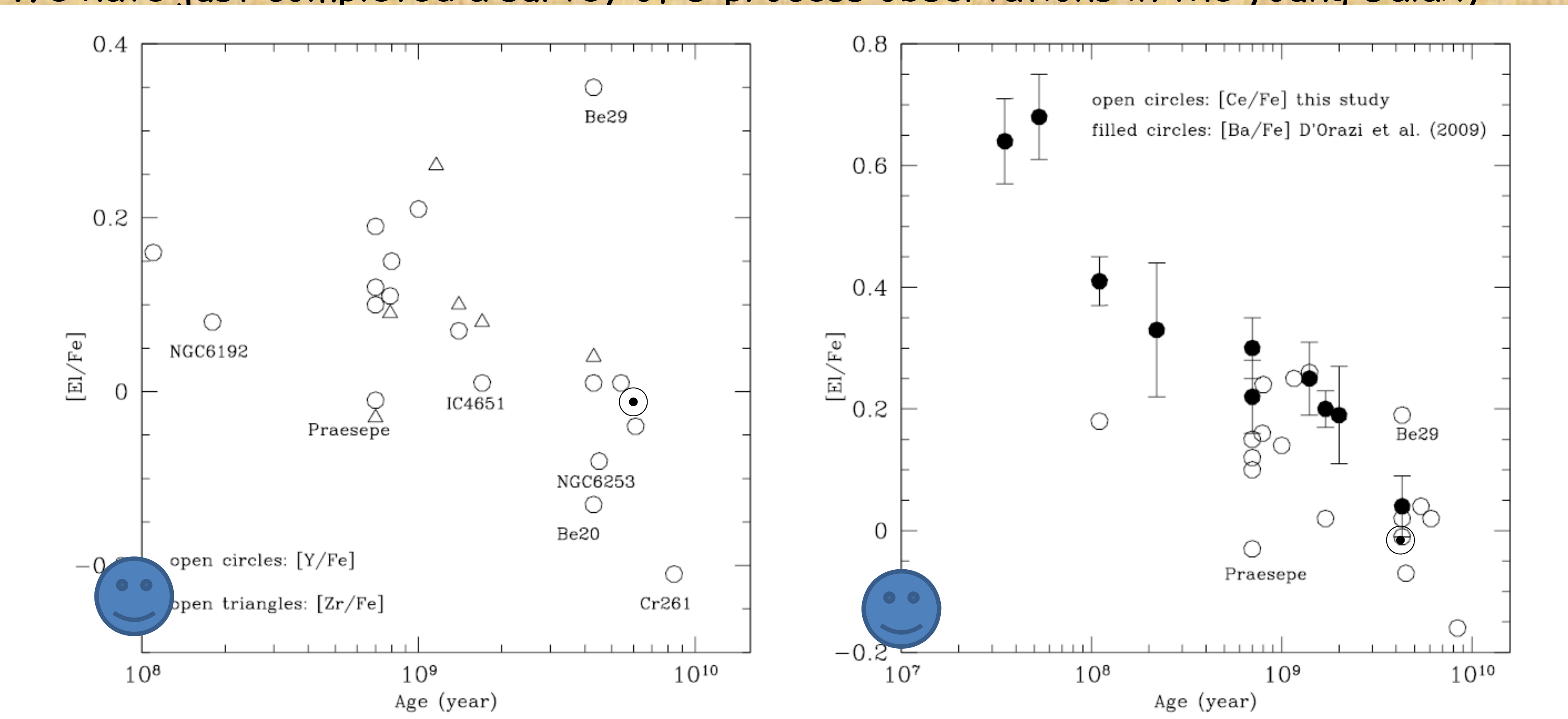




Travaglio et al. 1999

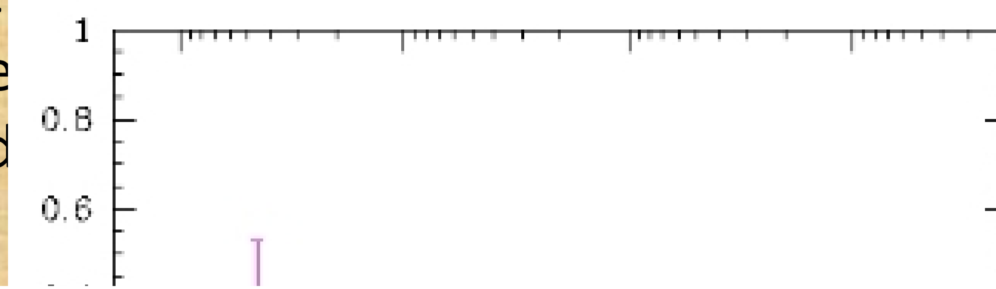
A new problem

We have just completed a survey of s-process observations in the young Galaxy



First hints in D'Orazi et al. 2009 from Ba. But now we have 5 elements at the two s-process abundance peaks, IN 23 CLUSTERS!!

For young clusters the traditional picture of s-processing fails

If we expand the  much s-processing in old … bundances

SECOND PROBLEM, FOR INTERPRETING THE YOUNG CLUSTERS:

If we need a more extended ^{13}C pocket in very low mass stars (1.2-1.4 $M_{\odot}$), with a relatively low ^{13}C abundance, but extending to higher T (10-11 keV) would this ^{13}C burn in the radiative region or remain partially unburnt up to the pulse?

Lower ^{13}C abundance at higher T (easily consumed): here we might have less problems if the rate is smaller. But what if it is larger? Then higher neutron density, change of the branching analysis!?

… where T is higher (more than the usual 8 KeV). A precise rate for $^{13}C+\alpha$ is crucial: we would burn it in the presence of a T gradient.

[Such pockets would need non-diffusive mixng, i.e. by wave instabilities]

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

Addressed theoretically and experimentally by numberless authors since the Caughlan and Fowler (1988) compilation

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inc
int
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But in ... ugh
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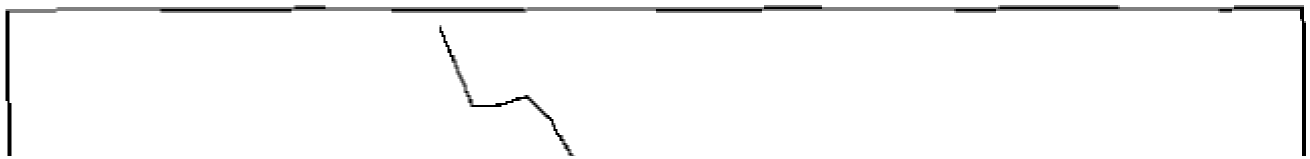
by Iliadis et al 2010)



Temperature (GK)

Fig. A.22. Previous reaction rates: Ref. [22]

FIRST MOTIVATION: verify that there are no increases w. respect to K94. This would put on solid grounds calculations that were so far based on speculations

On the contrary, a strong increase would need a revision of the s-process in AGB stars, mainly going toward lower masses, with lower T (< 23 keV) in the thermal pulses.

But for these stars, at solar metallicity, nobody can find dredge-up. How can we restitute the s-elements to the Galaxy??

Changes in the stellar models??

Production of ^{25}Mg in the envelope of a 5 Mo Star fo different rates

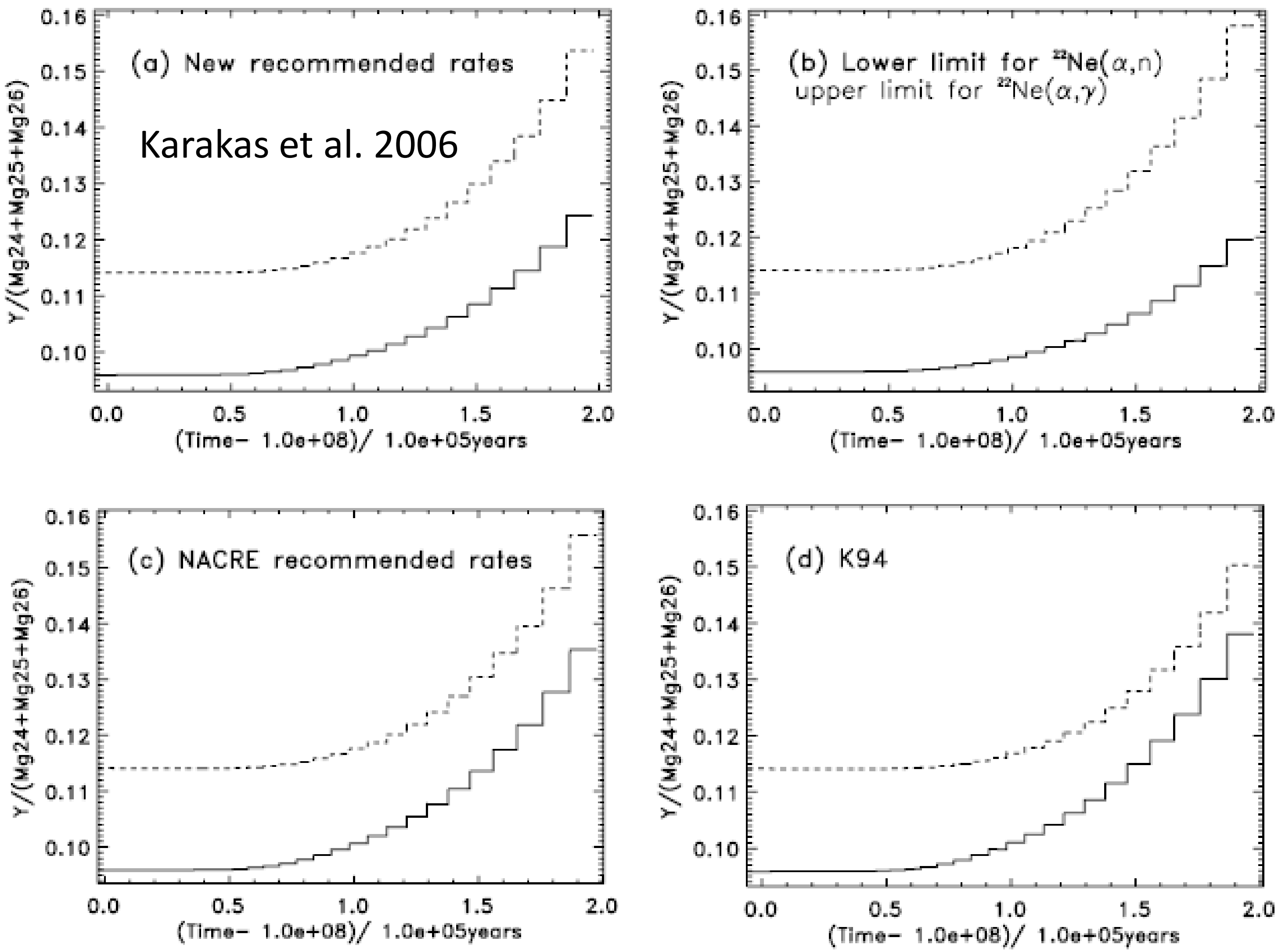


FIG. 5.—Evolution of the ^{25}Mg (*solid lines*) and ^{26}Mg (*dashed lines*) abundances at the surface of the $5 M_\odot$, $Z = 0.02$ VW93 model for four different choices of the ^{22}Ne+α reaction rates.

Another problem: O-Na anticorrelations in GC

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The ... he
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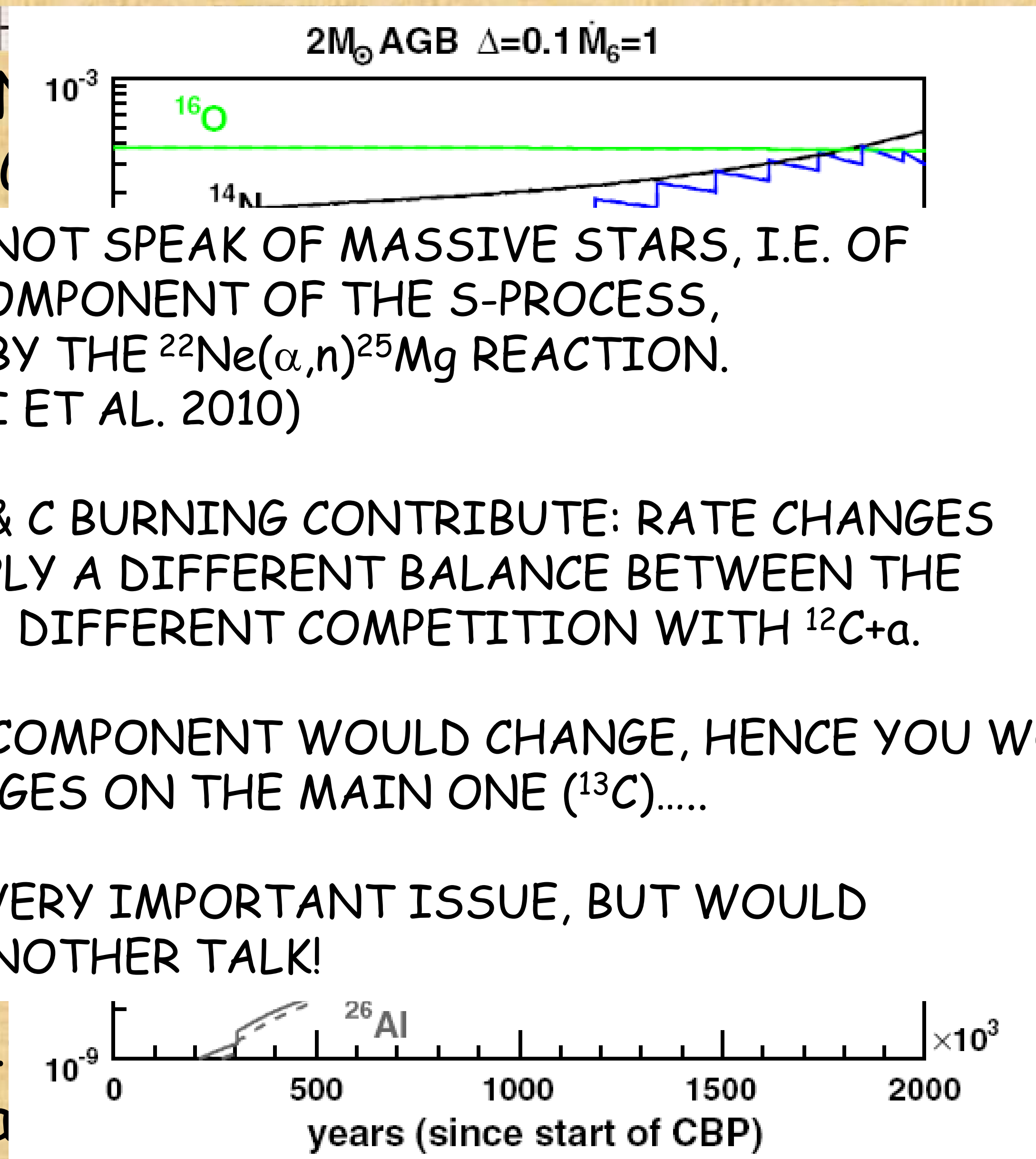
& Lagarde 201... Ne also in
second-genera... tures in
deep mixing phenomena.



AND I DID NOT SPEAK OF MASSIVE STARS, I.E. OF THE WEK COMPONENT OF THE S-PROCESS, PRODCUED BY THE $^{22}Ne(\alpha,n)^{25}Mg$ REACTION. (PIGNATARI ET AL. 2010)

THERE He- & C BURNING CONTRIBUTE: RATE CHANGES WOULD IMPLY A DIFFERENT BALANCE BETWEEN THE TWO AND A DIFFERENT COMPETITION WITH ^{12}C+a.

THE WEAK COMPONENT WOULD CHANGE, HENCE YOU WOULD NEED CHANGES ON THE MAIN ONE (^{13}C).....

THIS IS A VERY IMPORTANT ISSUE, BUT WOULD REQUIRE ANOTHER TALK!

Conclusions

$^{13}C+\alpha$

1. Changes in the rate might on one side specify whether the situations in which ^{13}C burns partly convectively are rare (as now believed) or more common. This risk would be real for a remarkable REDUCTION of the rate (by more than

HOW TO SAVE THE CONSERVATIVE SCENARIO:

1. NO CHANGE, OR MODERATE DECREASE, IN THE $^{22}Ne+\alpha$ W. RESPECT TO THE PRESENT RATE.

2. ONLY MODERATE CHANGES FOR $13C+\alpha$, NO REDUCTION BY MORE THAN A FACTOR OF THREE AS COMPARED TO NACRE.

GCs.

3. In Massive Stars, changes in the rate → change in the balance between He- and C-burning for the weak component, change in the competition with $^{12}C+a$.
4. More ^{22}Ne saved? Maybe explanation of the Ne excess of planetary nebulae!!