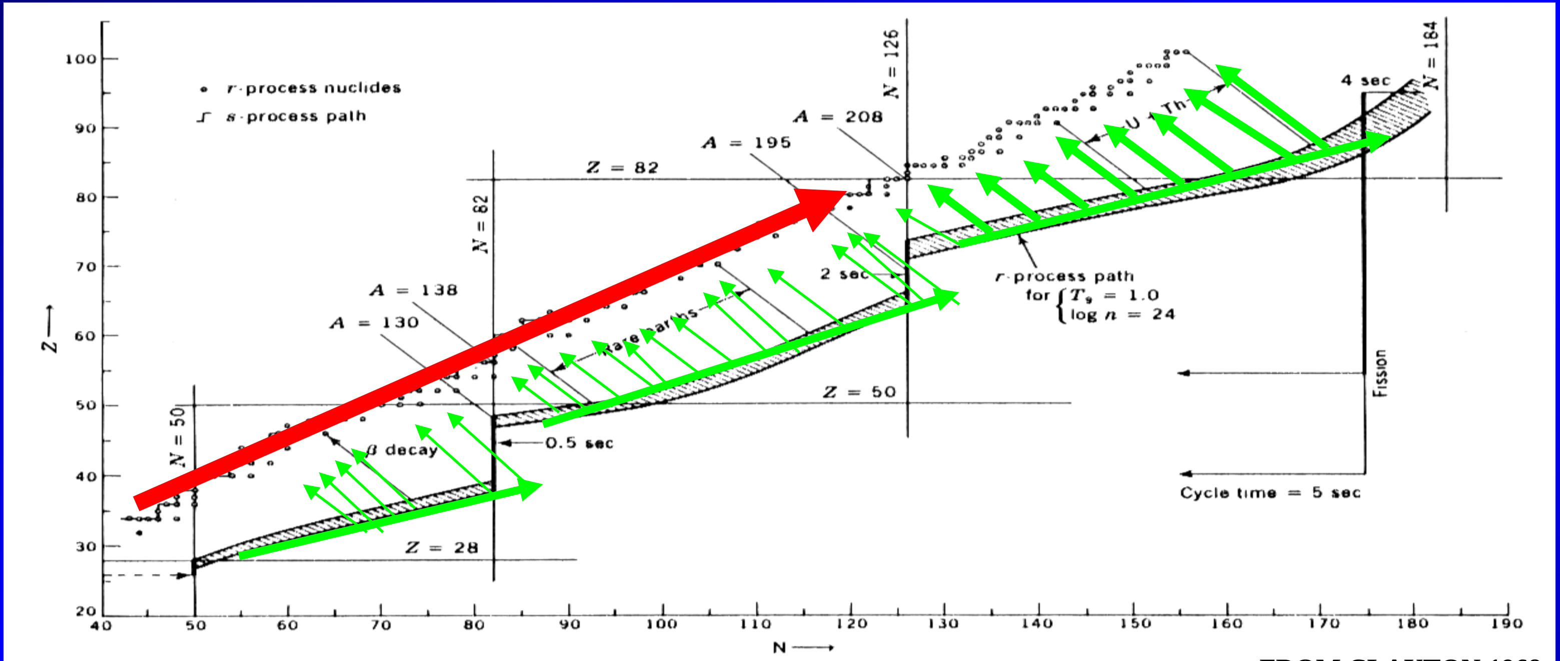
The importance of the $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$ reaction in Asymptotic Giant Branch stars

Sergio Cristallo

INAF – Osservatorio Astronomico d’Abruzzo

INFN – Sezione di Perugia



FROM CLAYTON 1968

***s*-process**

$\tau_\beta << \tau_n$

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

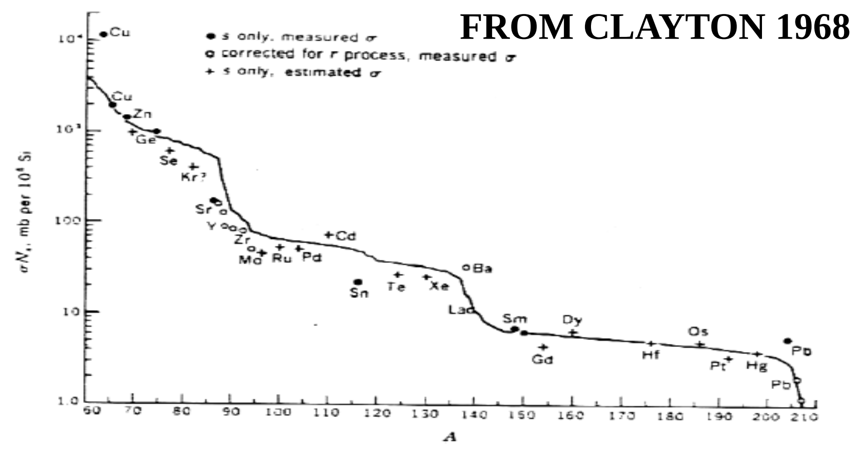
***r*-process**

$\tau_\beta >> \tau_n$

$N_n > 10^{22}$ n/cm^3

s-process

Easy to be reproduced with an exponential distribution of neutron exposures.

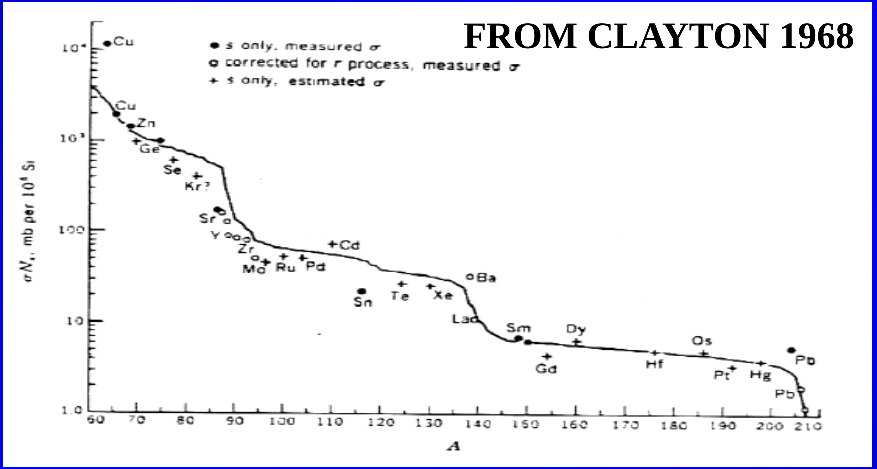

FROM CLAYTON 1968

Moreover, since neutron flow reaches equilibrium between nuclei with magic neutron numbers, the product of the Maxwellian averaged stellar (*n*,*γ*) cross section of a nuclide, $<\sigma>$, and its corresponding abundance, N_s, remains almost constant (the difference in the two product is much smaller than the magnitude of either one of them):

LOCAL APPROXIMATION

$$<\sigma>_A N_A \approx <\sigma>_{A+1} N_{A+1}$$

s-process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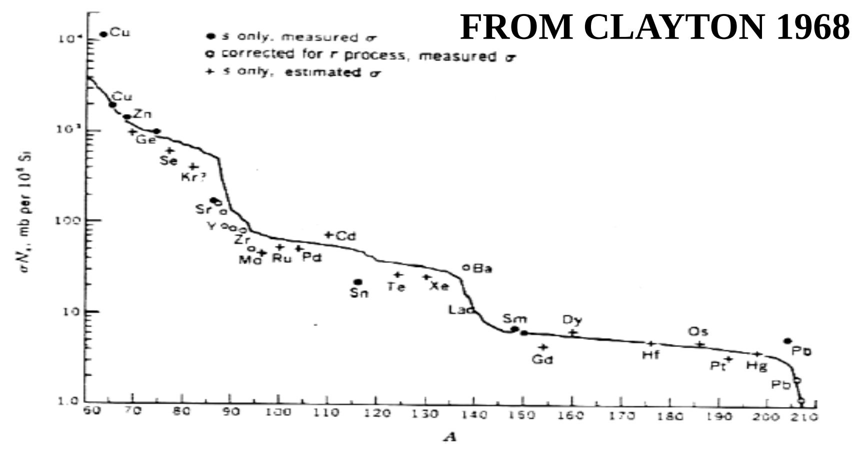
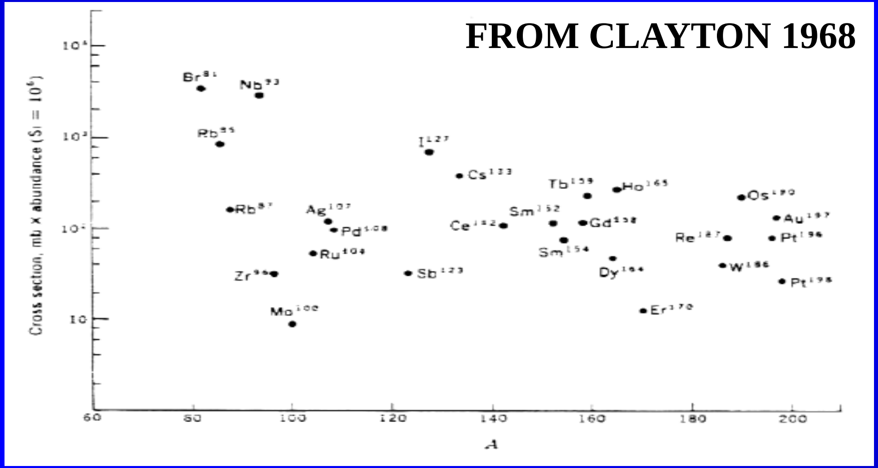
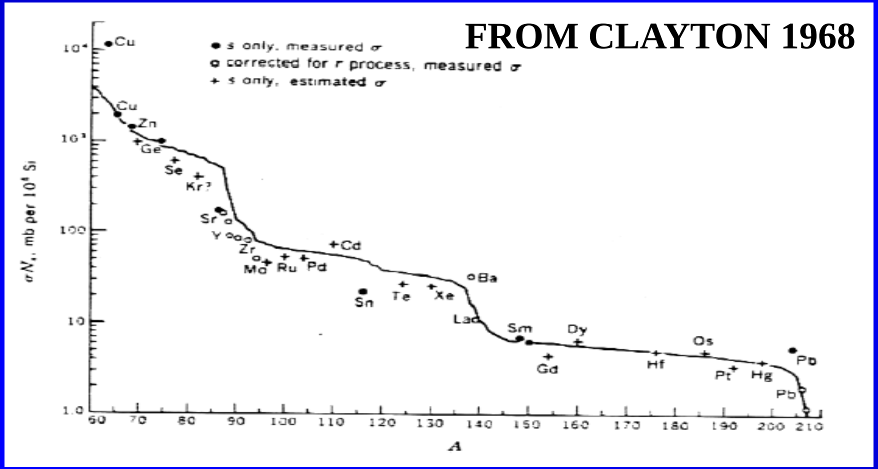

FROM CLAYTON 1968


FROM CLAYTON 1968

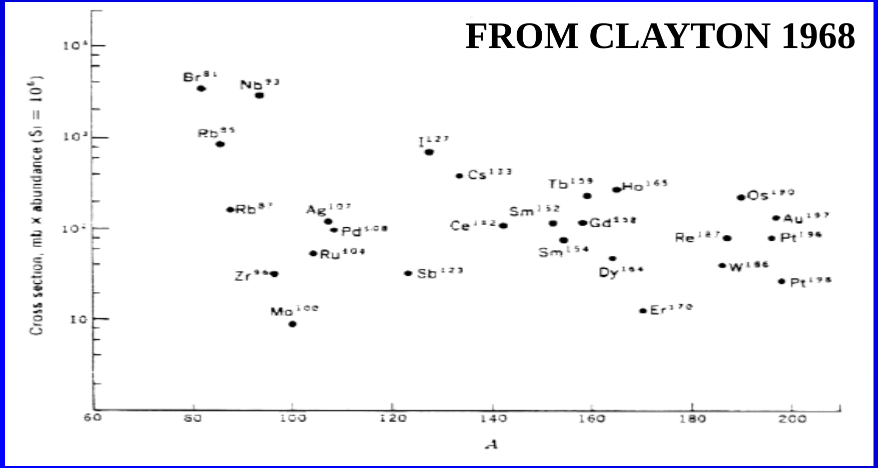
r-process

s-process

Easy to be reproduced with an exponential distribution of neutron exposures.



FROM CLAYTON 1968

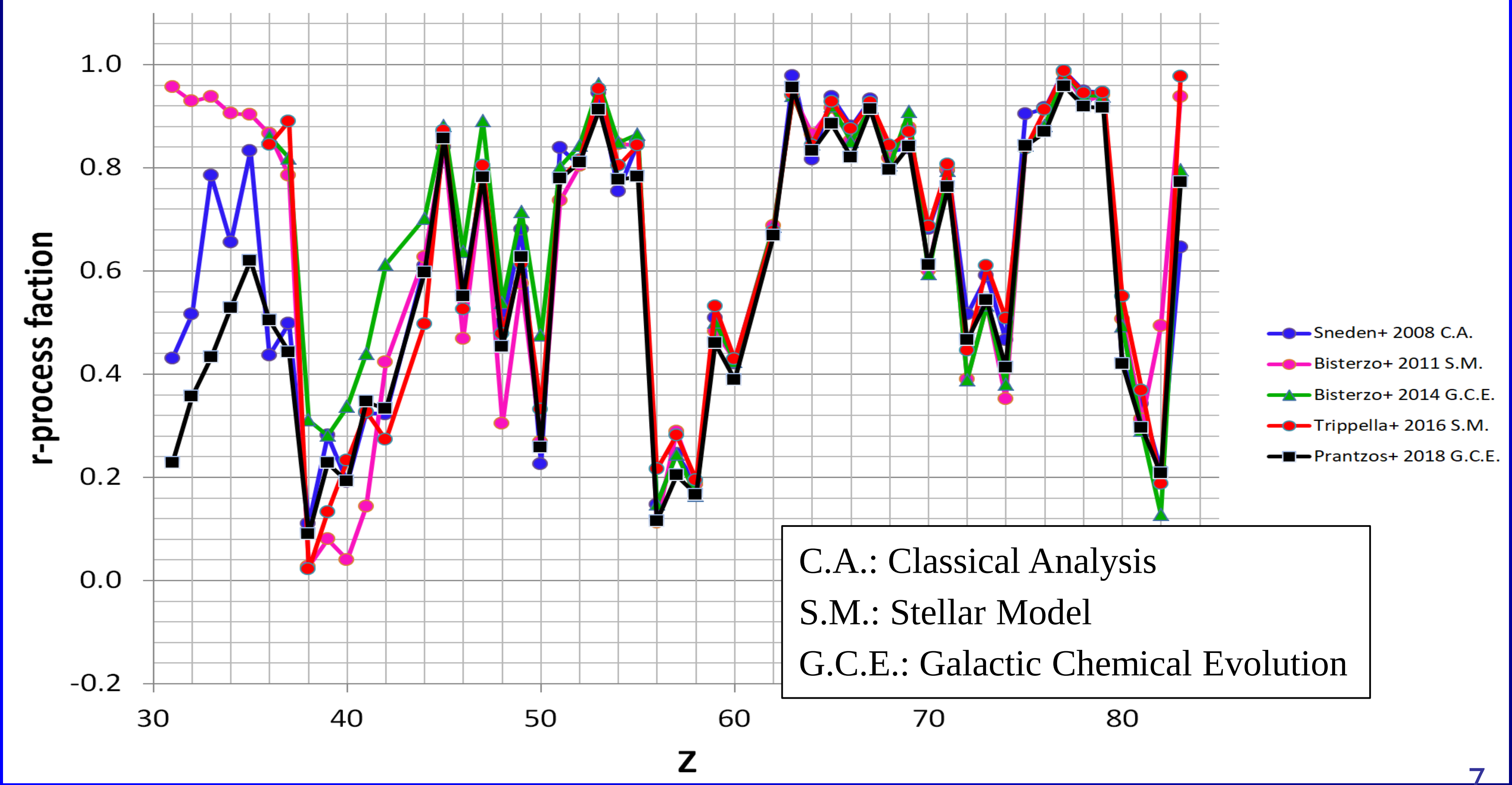


FROM CLAYTON 1968

r-process

$$r = 1 - s$$

r-process residuals from s-process studies



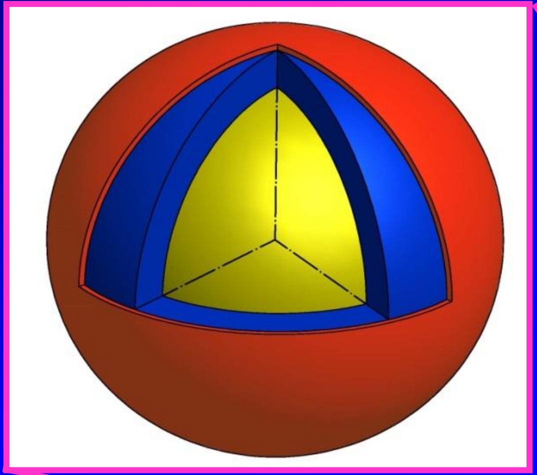
C.A.: Classical Analysis

S.M.: Stellar Model

G.C.E.: Galactic Chemical Evolution

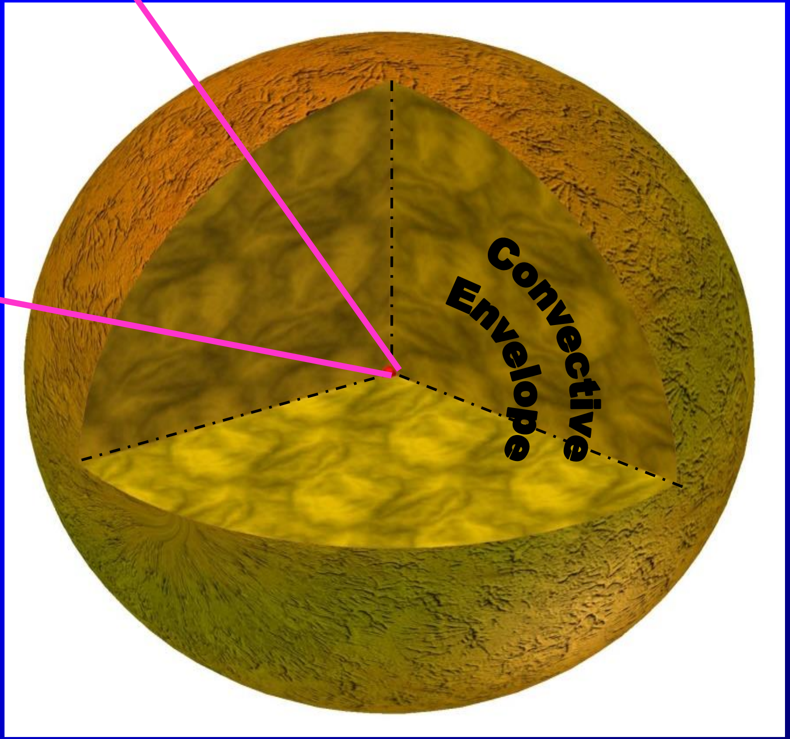
AGB structure

CO Core
He-shell
H-shell

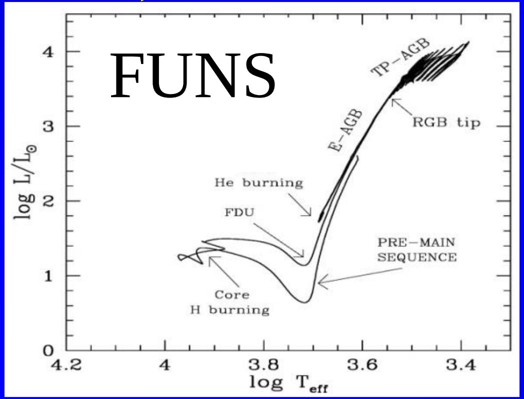


Earth radius (~10^{-2} R_{SUN})

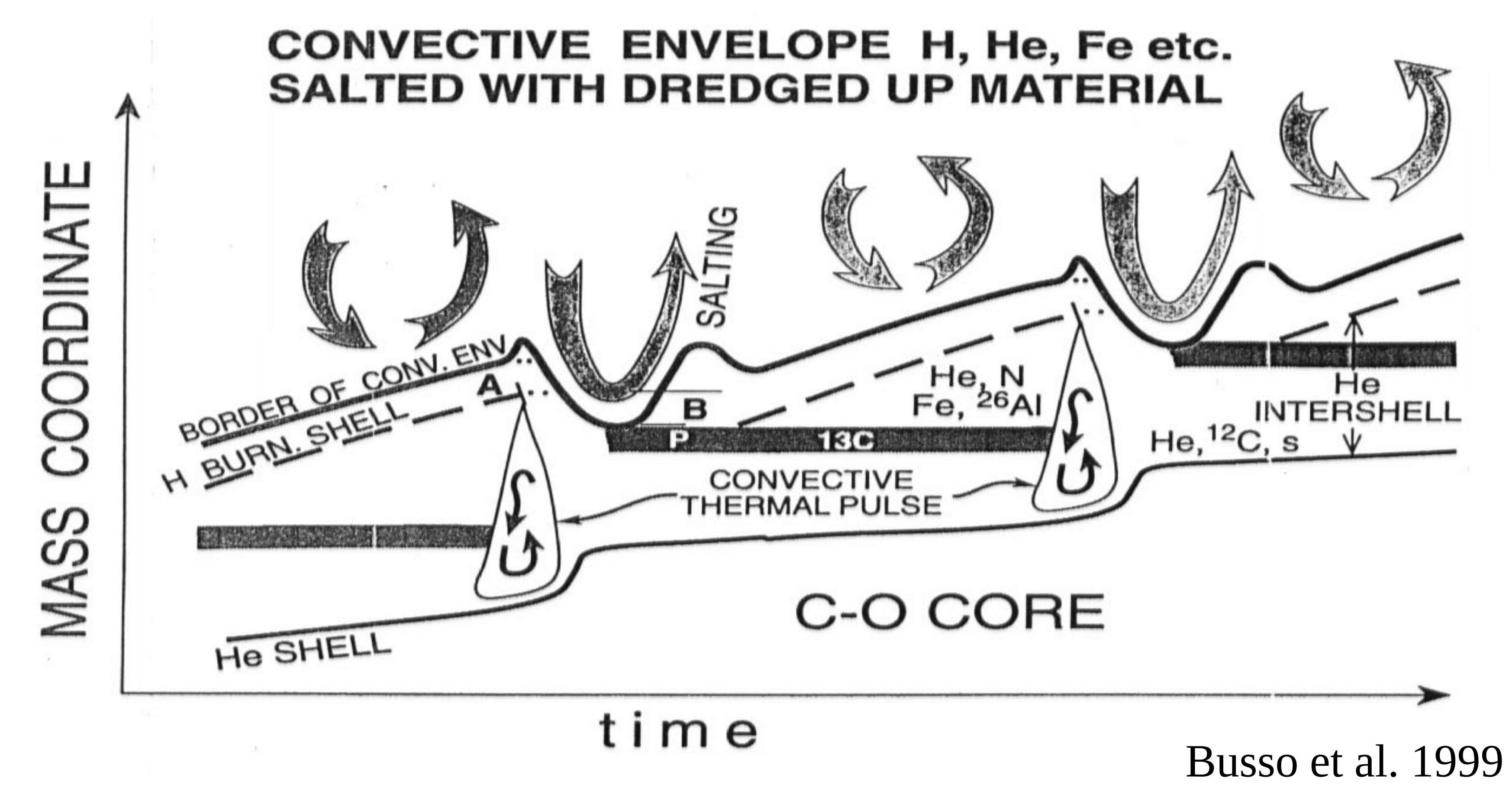
Earth-Sun
(~200 R_{SUN})



Straniero, Gallino & Cristallo 2006

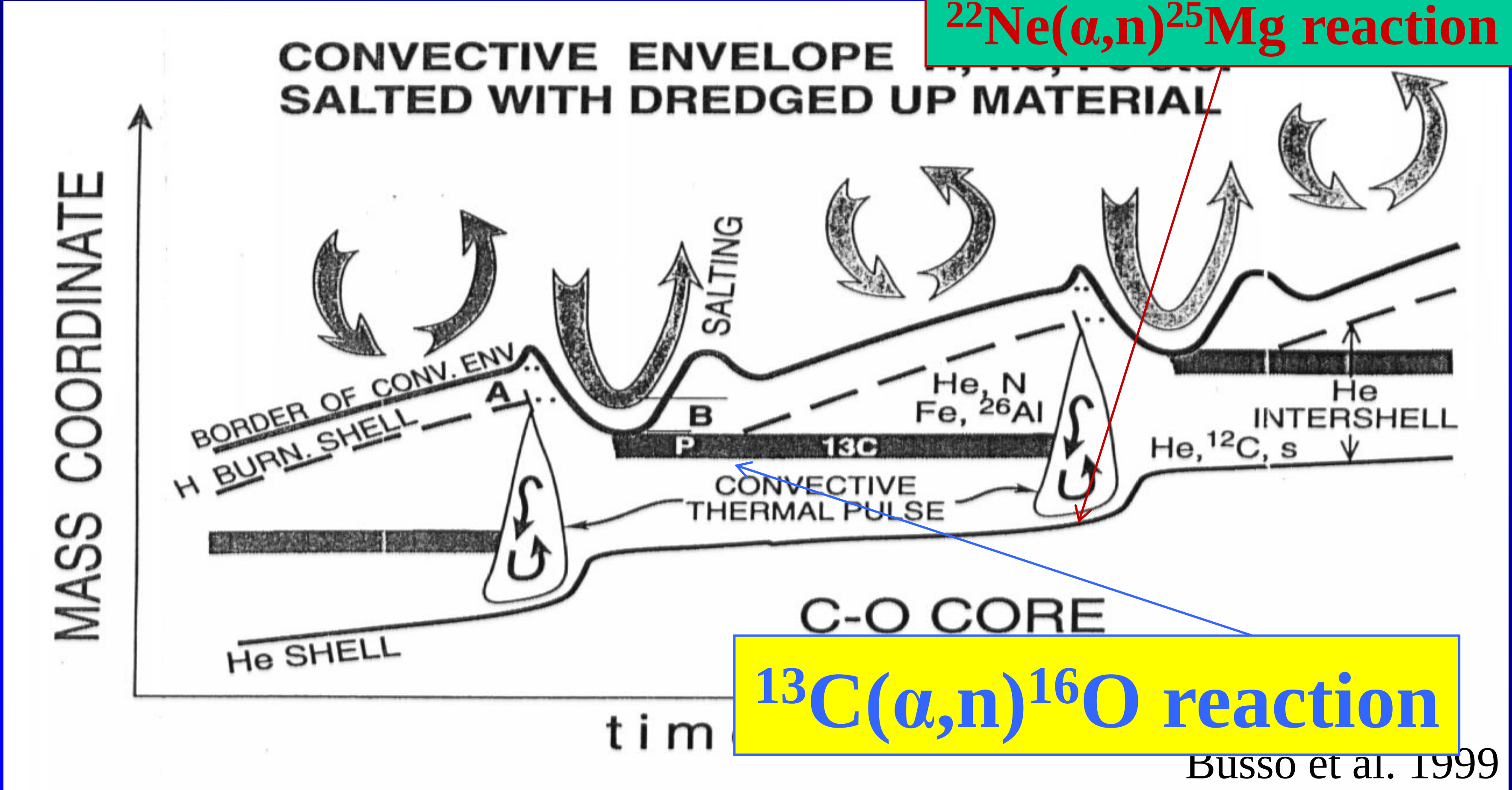


The s-process in AGB stars



Busso et al. 1999

The s-process in AGB stars



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

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

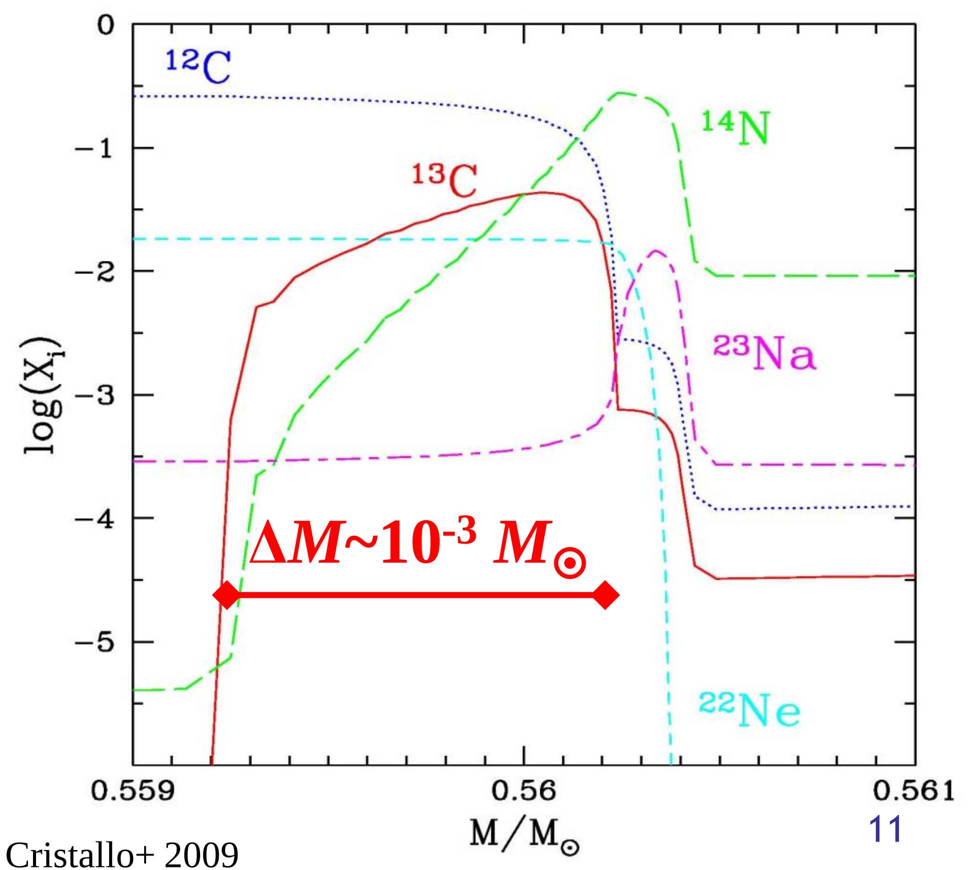
Busso et al. 1999

The formation of the ^{13}C pocket

^{13}C-pocket

^{14}N-pocket

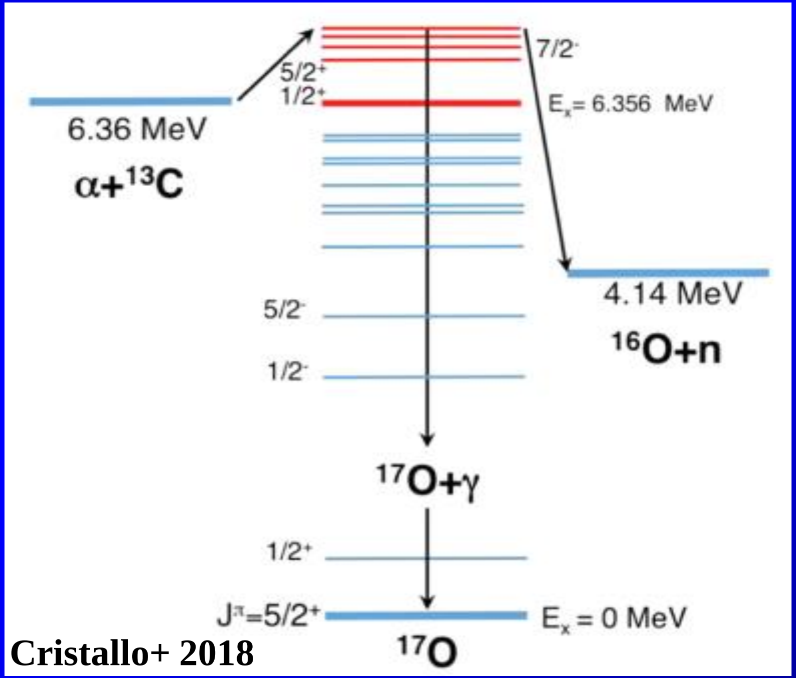
^{14}N strong neutron poison via $^{14}N(n,p)^{14}C$ reaction



Cristallo+ 2009

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
- …



Cristallo+ 2018

- S. Urlass: $^{16}O(n,\alpha)^{13}C$ (n_TOF)
- G.F. Ciani: $^{13}C(\alpha,n)^{16}O$ (LUNA)

Reference rate (most recent direct measure): Heil+ 2008

Upper case: *1.5 - *2

Lower case: *0.67 - *0.5

Substantial scatter of existing data, showing a broad (up to a factor of 2) range of absolute values for the astrophysical S-factor

$$\sigma(E) = \frac{1}{E} S(E) e^{-2\pi\eta}$$

Explored stellar models

M=1.5 M_{SUN} [Fe/H]=-0.15	Convective ^{13}C burning
M=3.0 M_{SUN} [Fe/H]=-0.15	s-process main component
M=4.0 M_{SUN} [Fe/H]=-2.15	Intermediate AGBs in GCs
M=1.3 M_{SUN} [Fe/H]=-2.85	Proton ingestions at low Z

$$[A/B]=\log(N_A/N_B)_{STAR}-\log(N_A/N_B)_{SUN}$$

Refere

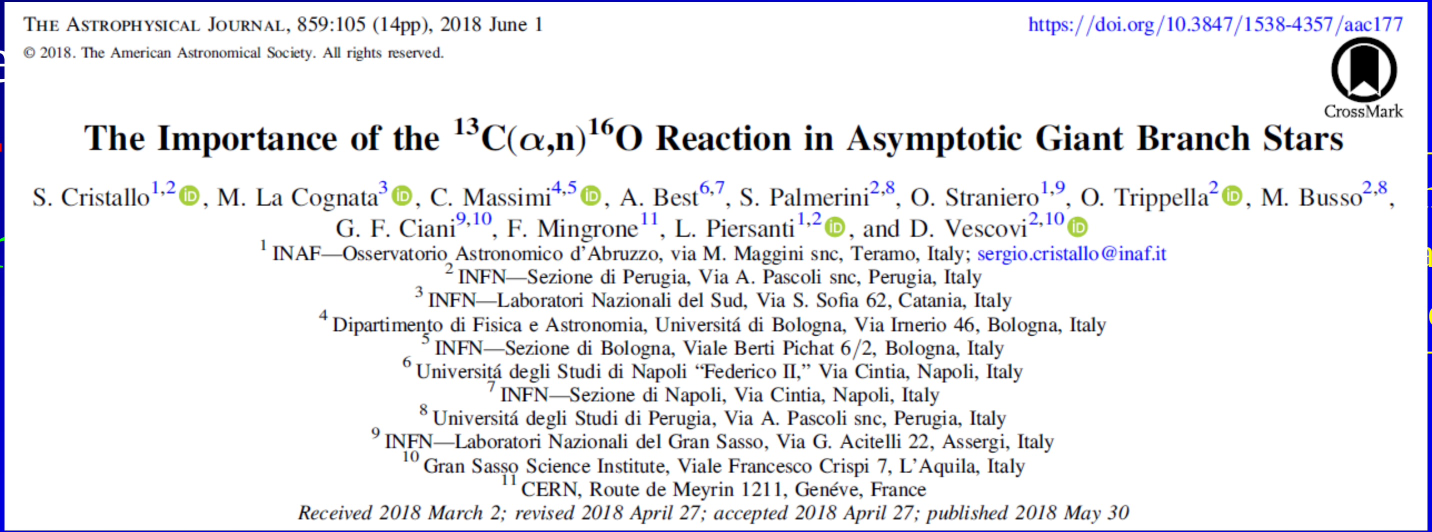
Upper

Lower

howing a

bsolute

ctor



The Astrophysical Journal, 859:105 (14pp), 2018 June 1
https://doi.org/10.3847/1538-4357/aac177

The Importance of the $^{13}C(\alpha,n)^{16}O$ Reaction in Asymptotic Giant Branch Stars

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Received 2018 March 2; revised 2018 April 27; accepted 2018 April 27; published 2018 May 30

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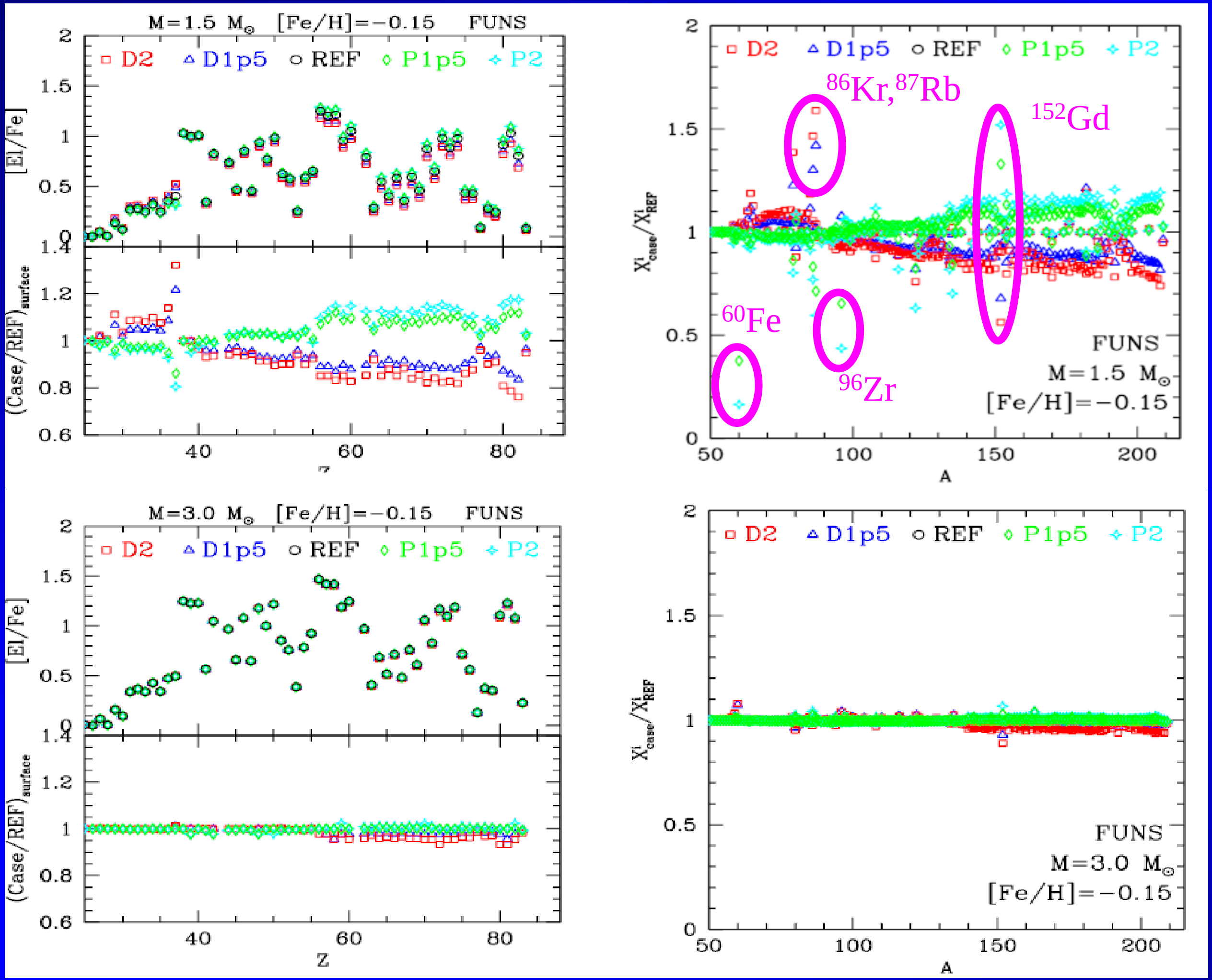
$$[A/B]=\log(N_A/N_B)_{STAR}-\log(N_A/N_B)_{SUN}$$

ELEMENTS ISOTOPES



M=1.5 M_{SUN}

[Fe/H]=-0.15

M=3.0 M_{SUN}

[Fe/H]=-0.15

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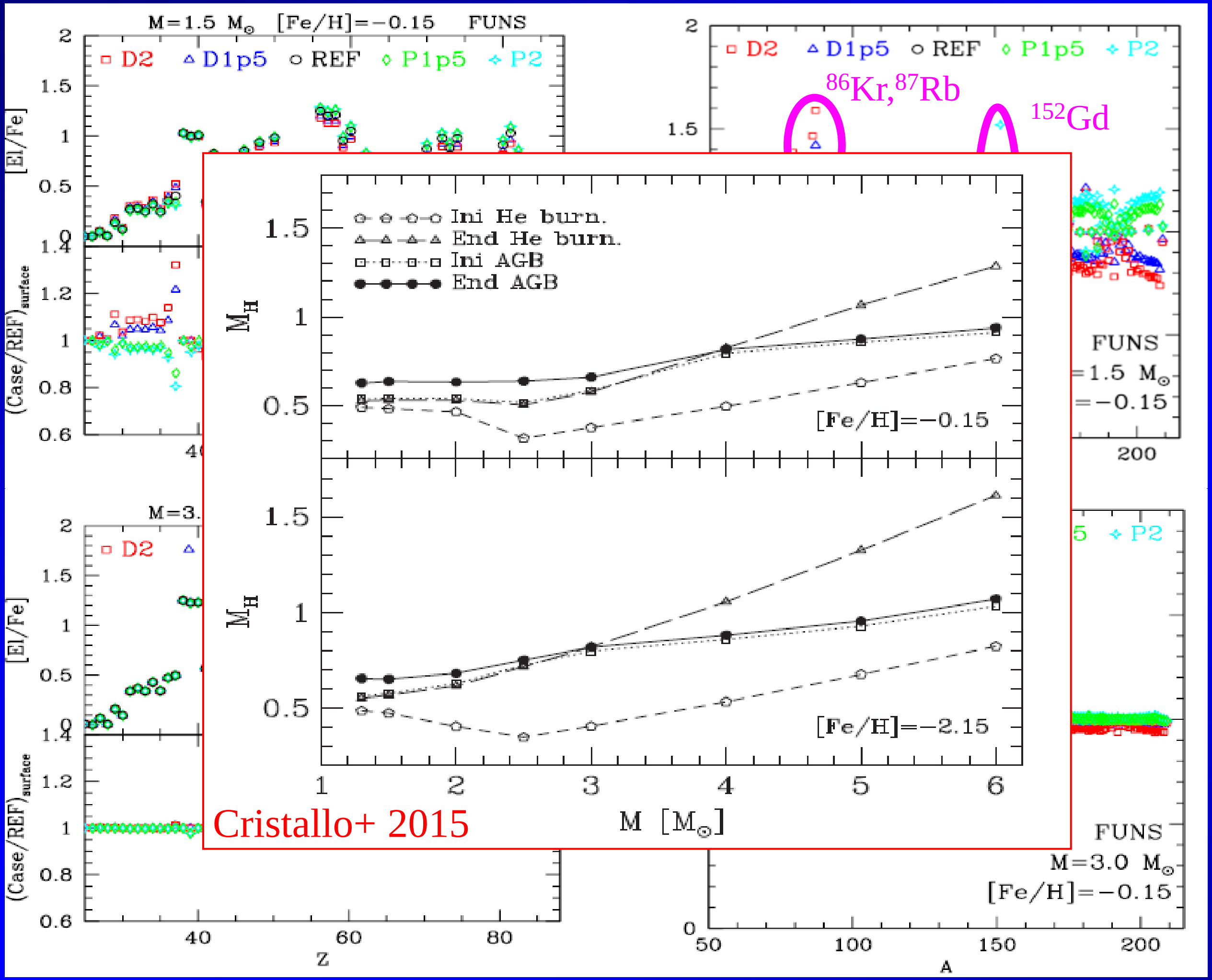


Cristallo+ 2015

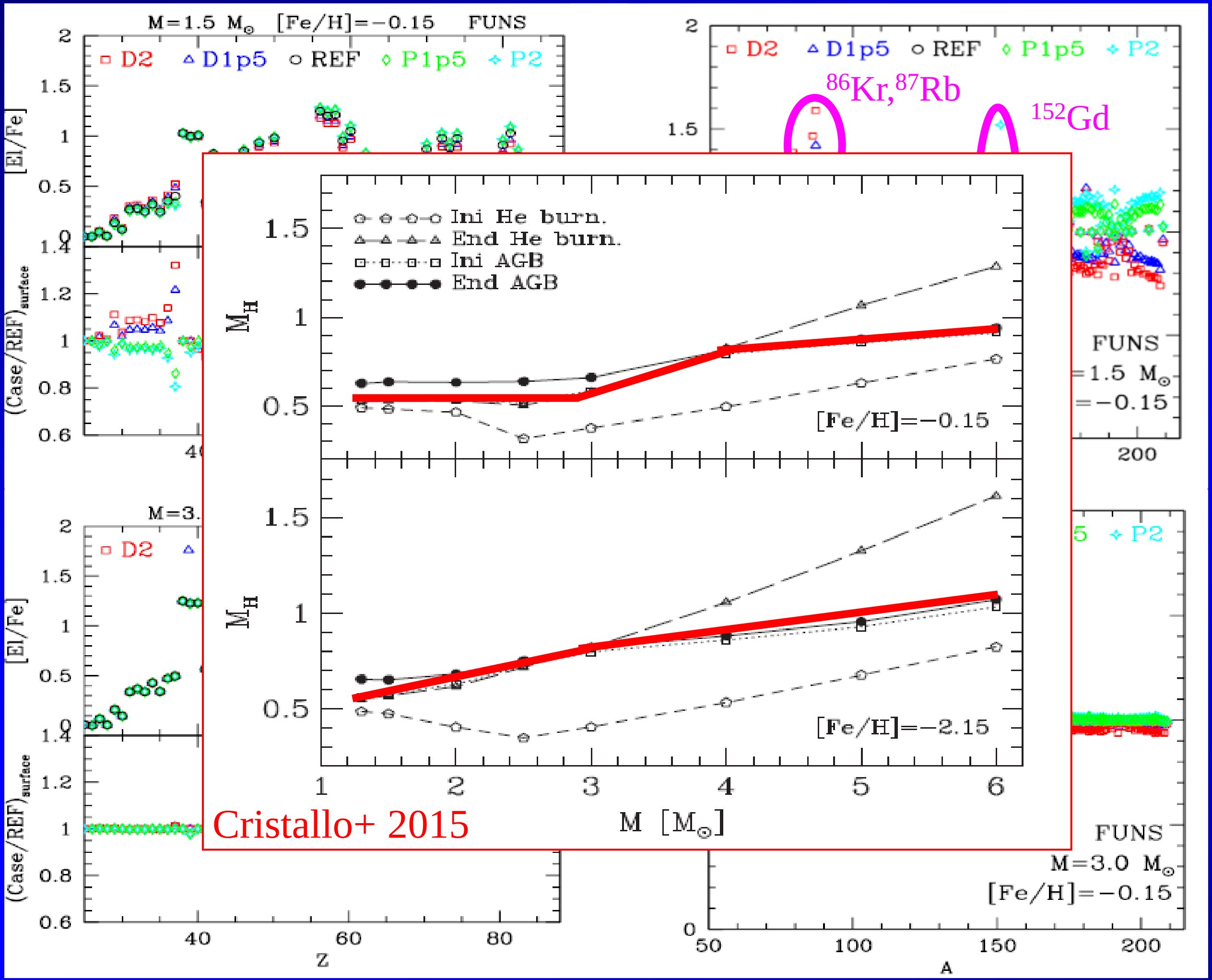
$M=1.5\ M_{SUN}$

$[Fe/H]=-0.15$

$M=3.0\ M_{SUN}$

$[Fe/H]=-0.15$

ELEMENTS ISOTOPES



^{86}Kr,^{87}Rb

^{152}Gd

Cristallo+ 2015

M=1.5 M_{SUN}

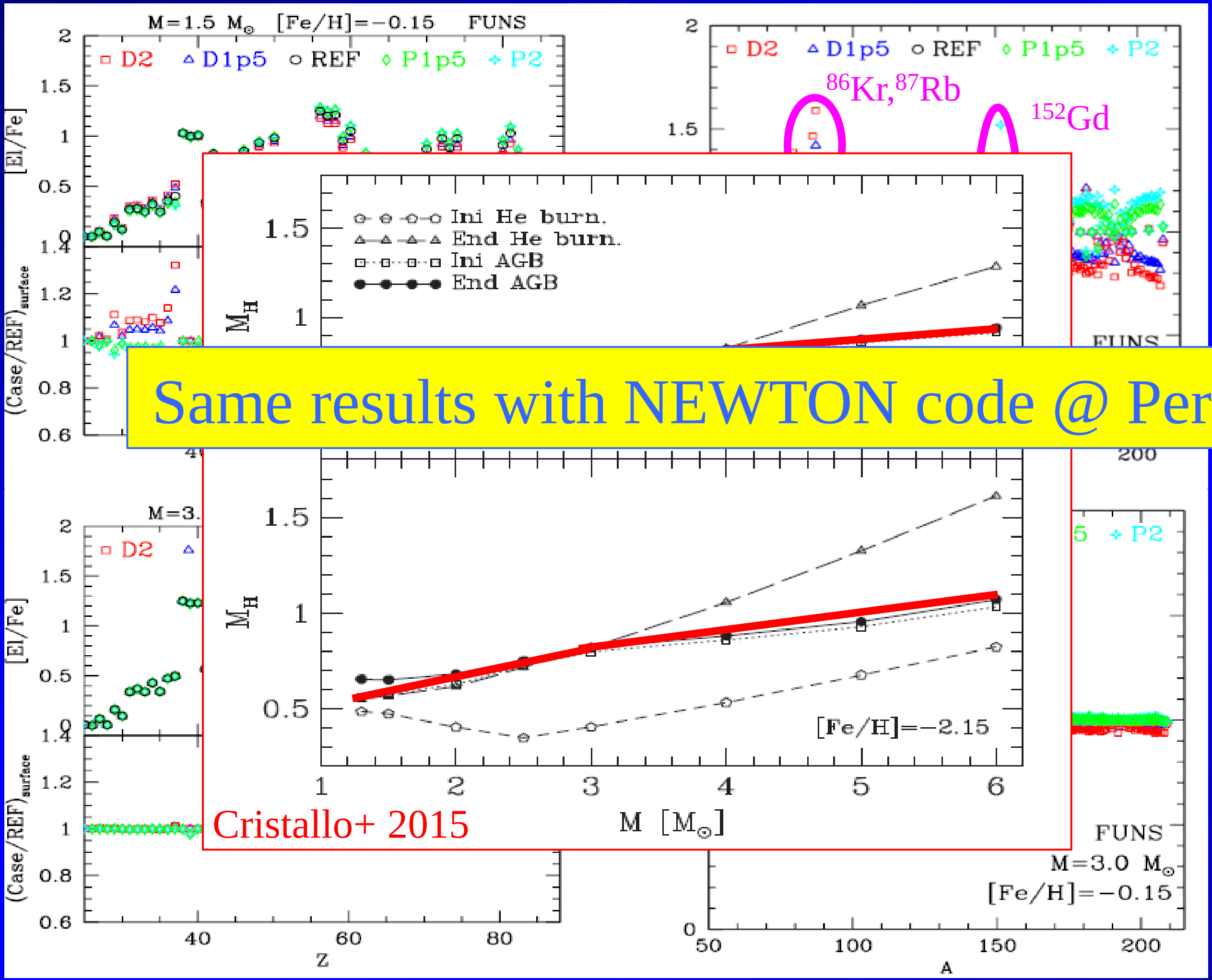
[Fe/H]=-0.15

M=3.0 M_{SUN}

[Fe/H]=-0.15

ELEMENTS

ISOTOPES



Same results with NEWTON code @ Perugia

Cristallo+ 2015

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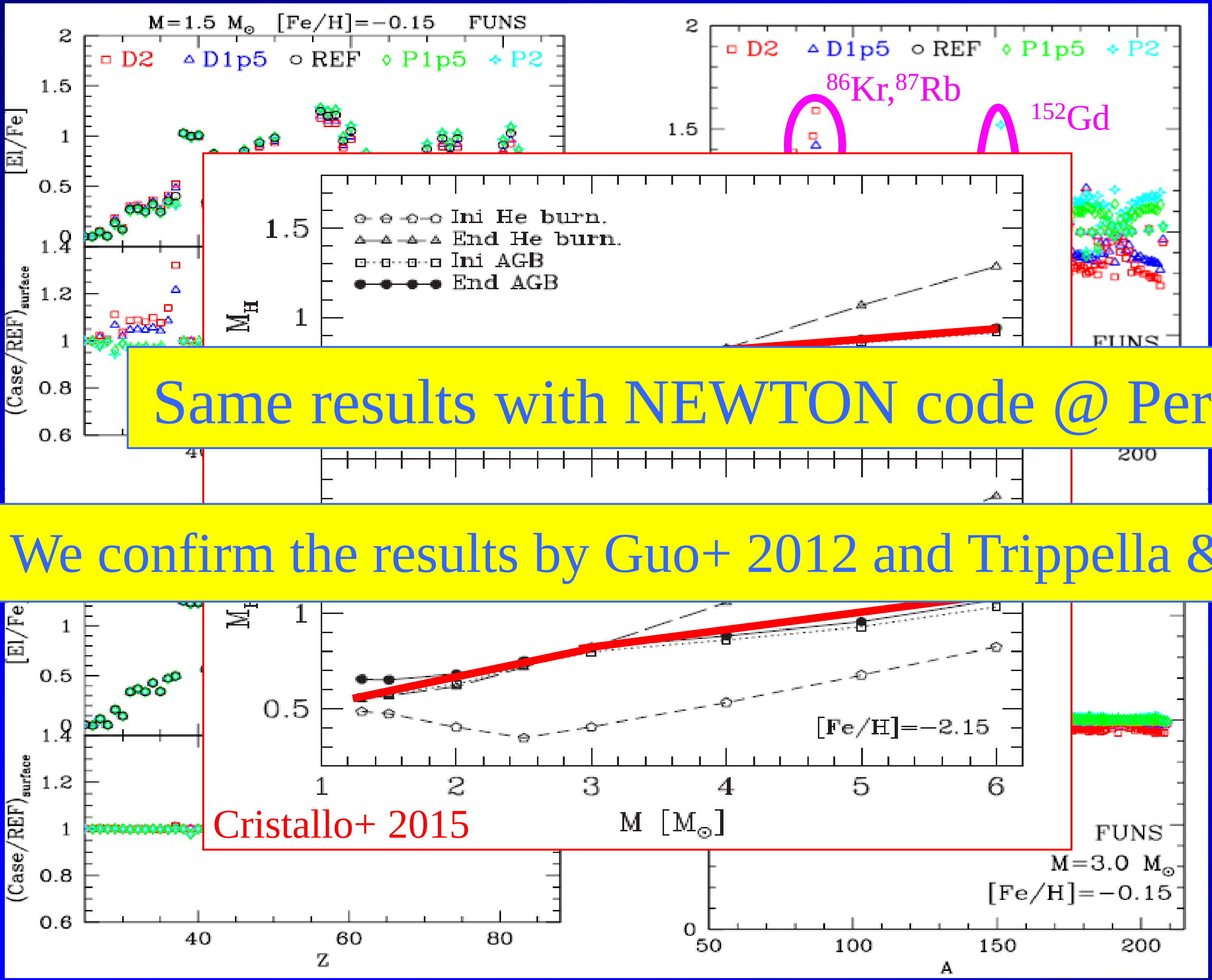
ELEMENTS ISOTOPES



Cristallo+ 2015

Same results with NEWTON code @ Perugia

We confirm the results by Guo+ 2012 and Trippella & La Cognata 2017

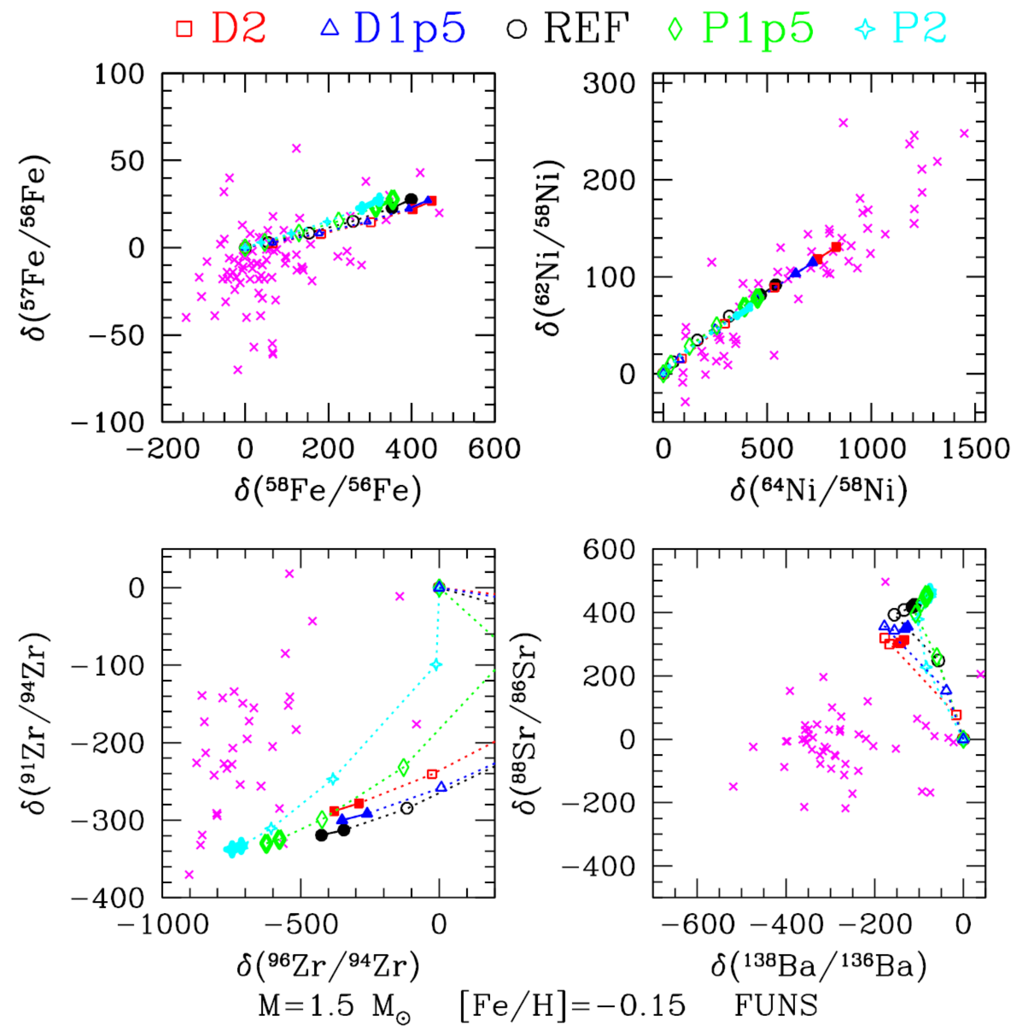
$M=1.5\ M_{SUN}$

$[Fe/H]=-0.15$

$M=3.0\ M_{SUN}$

$[Fe/H]=-0.15$

Isotopic anomalies in pre-solar SiC grains

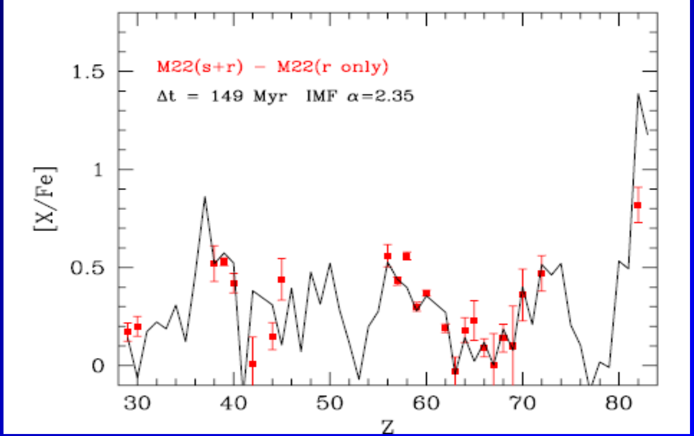


$\delta(X_i/X_j) \equiv [(X_i/X_j)_{MEASURED}/(X_i/X_j)_{SUN} - 1] \times 1000$

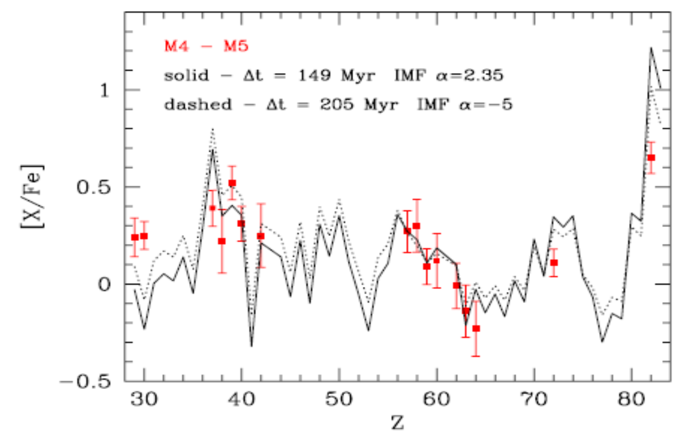
Schonbachler TALK

Davis TALK

s-rich Globular Clusters:
the importance of intermediate AGBs

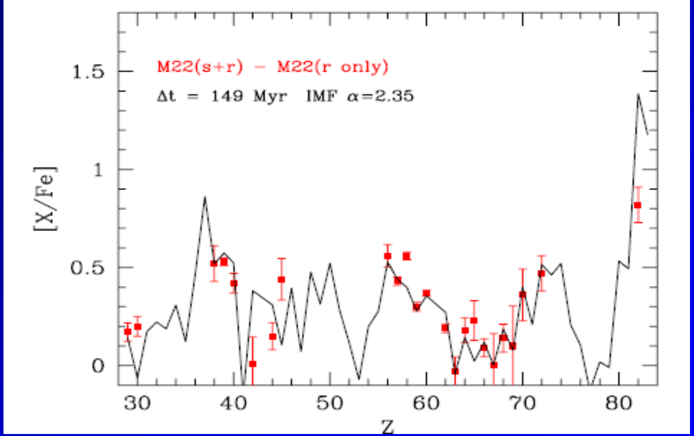


Straniero+ 2014 (Shingles+ 2014)



s-rich Globular Clusters:
the importance of intermediate AGBs

M=4.0 M_{SUN} [Fe/H]=-2.15



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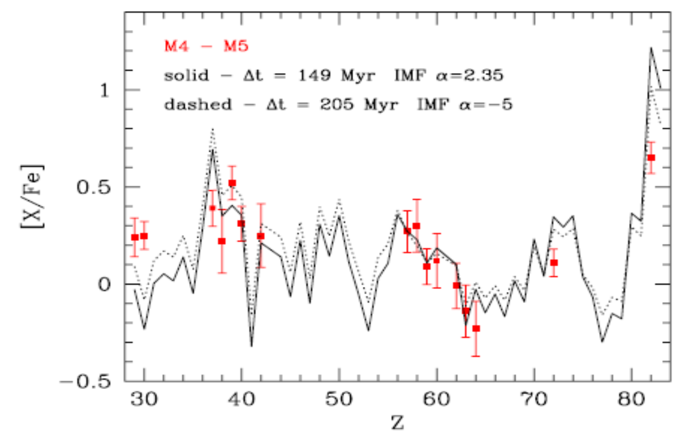
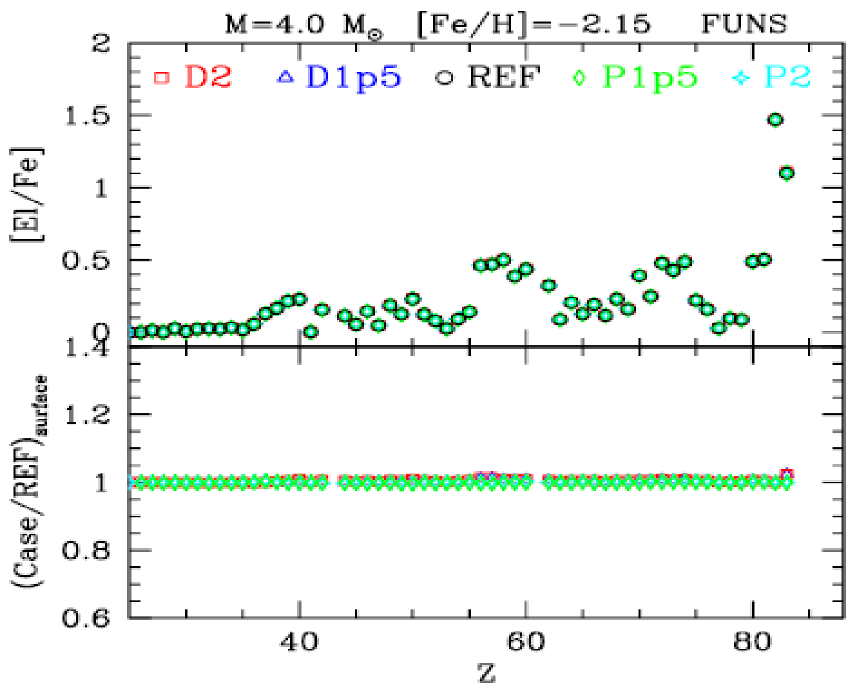
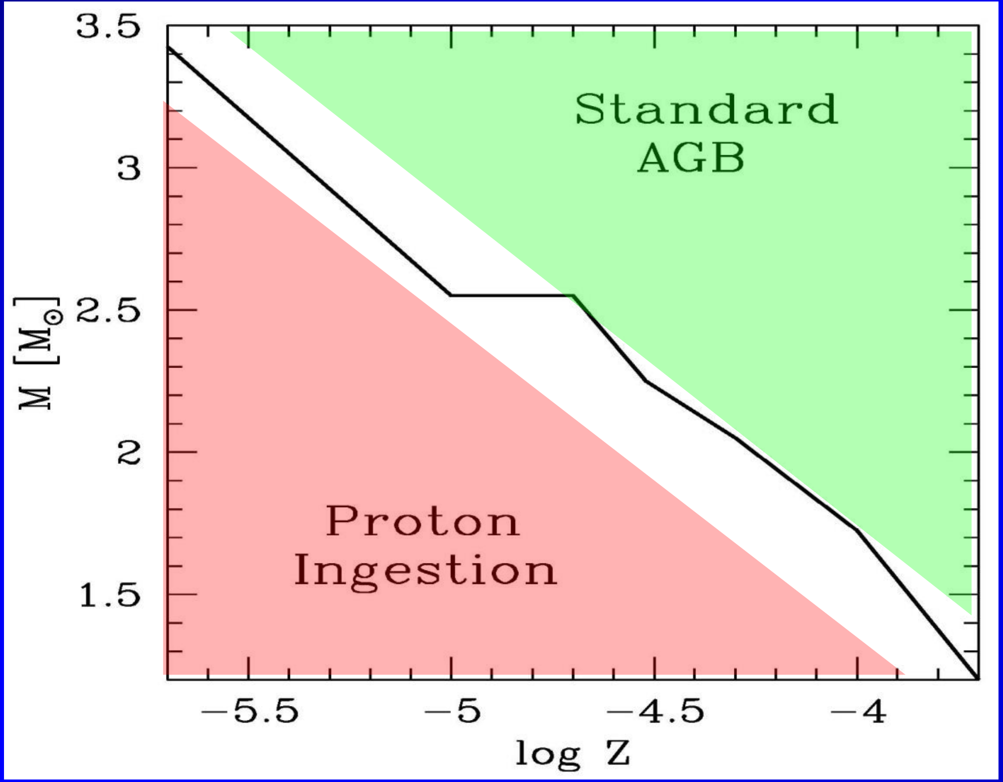




Low-metallicity low-mass AGB stars



Hollowell+ 1990

Fujimoto+ 2000

Iwamoto+ 2004

Suda+ 2004

Campbell+ 2007

Cristallo+ 2009

Herwig+ 2014

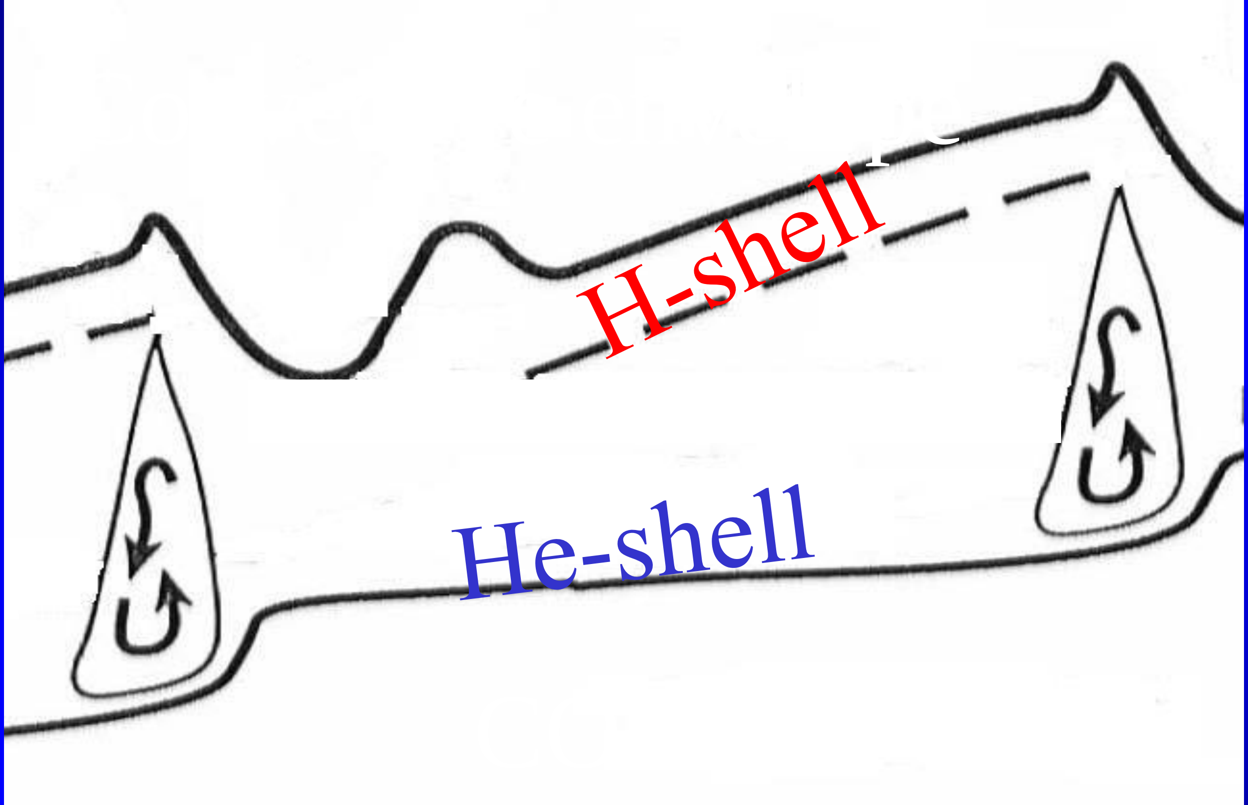
Dardelet+ 2015

Hampel+ 2016

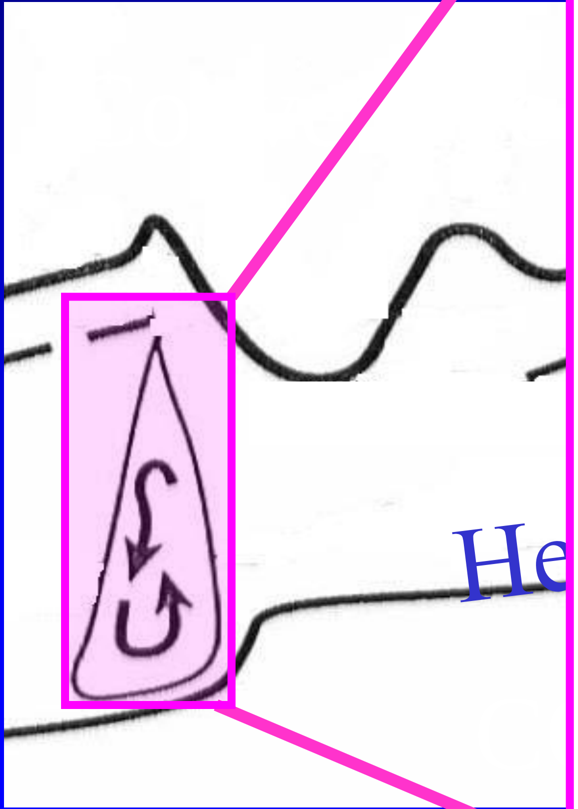
Cristallo+ 2016

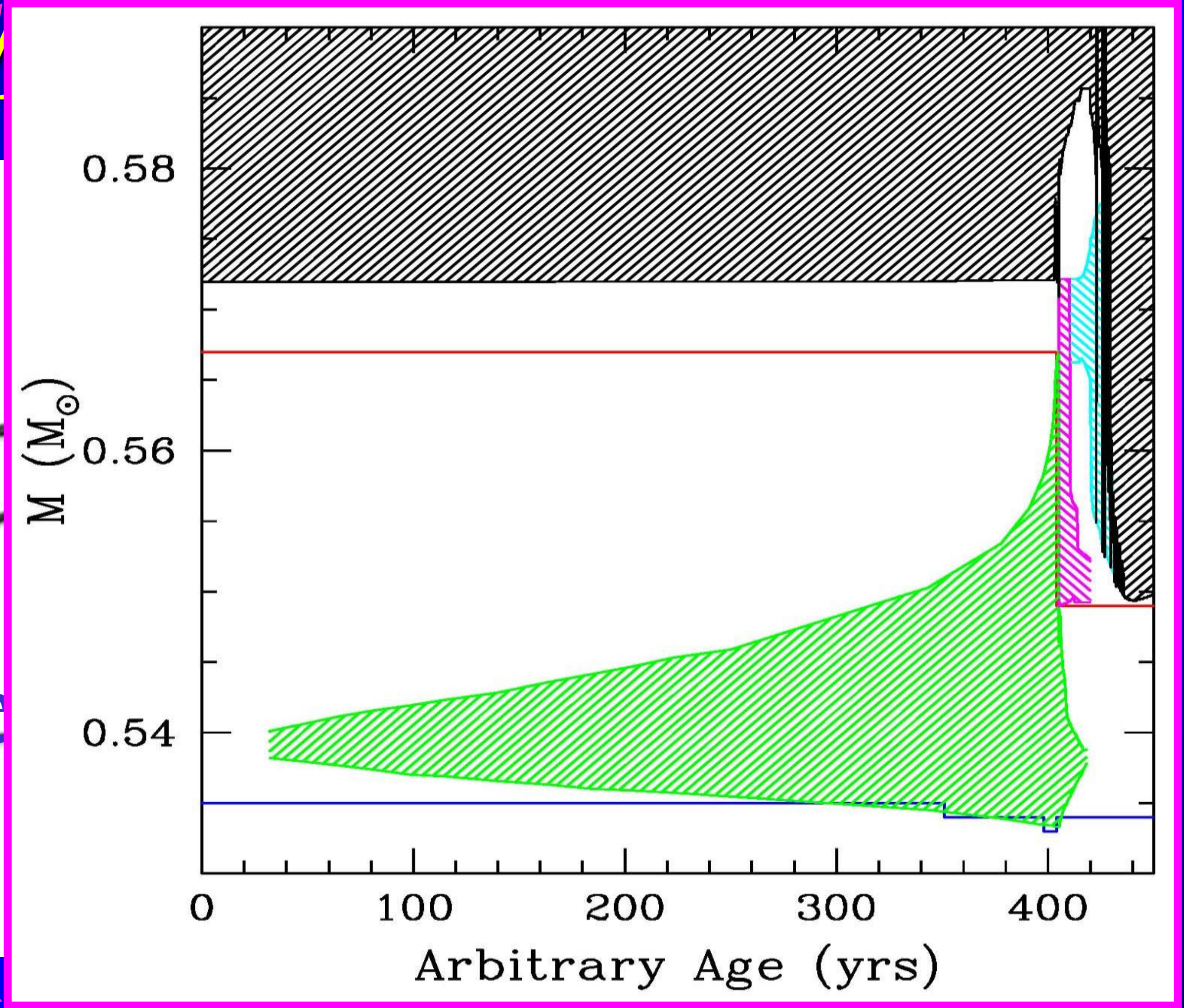
…

M=1.3 Msun [Fe/H]=-2.85

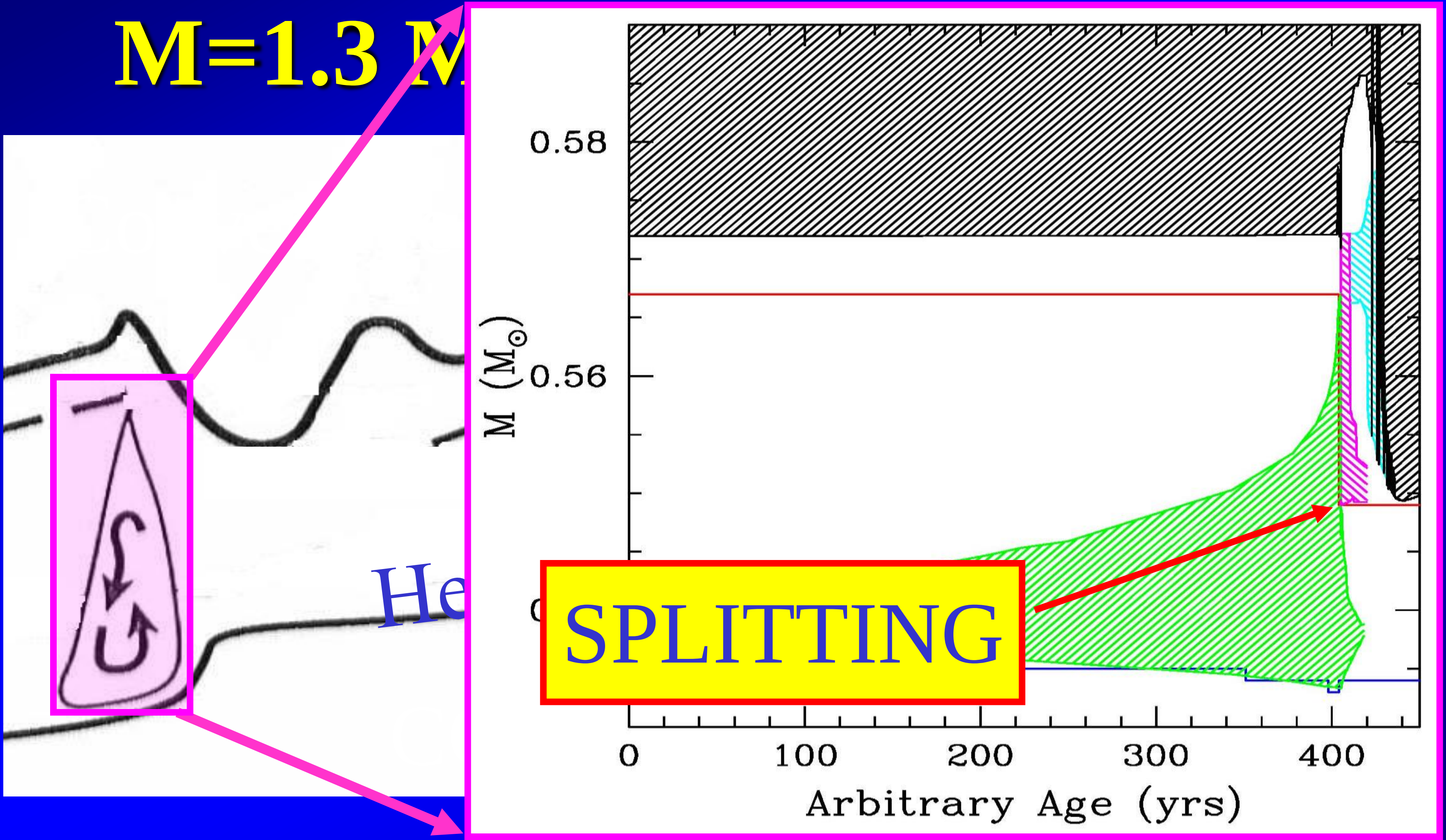


M=1.3 M

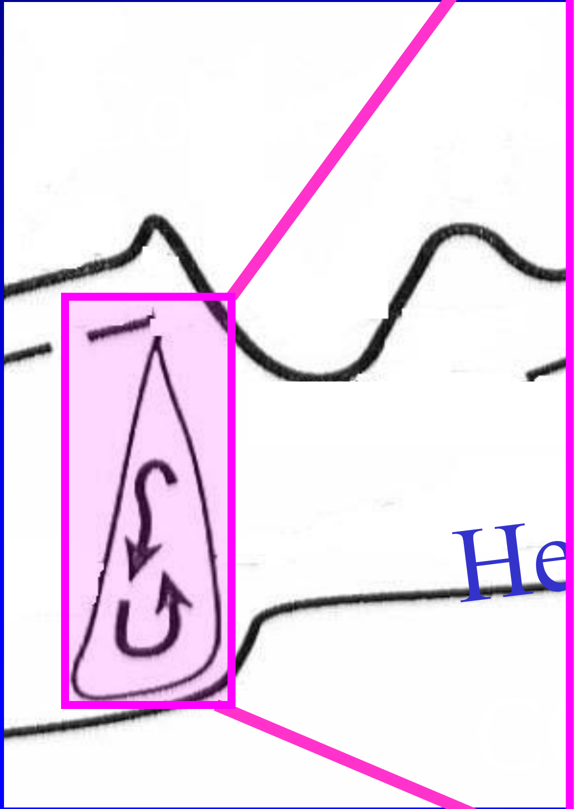


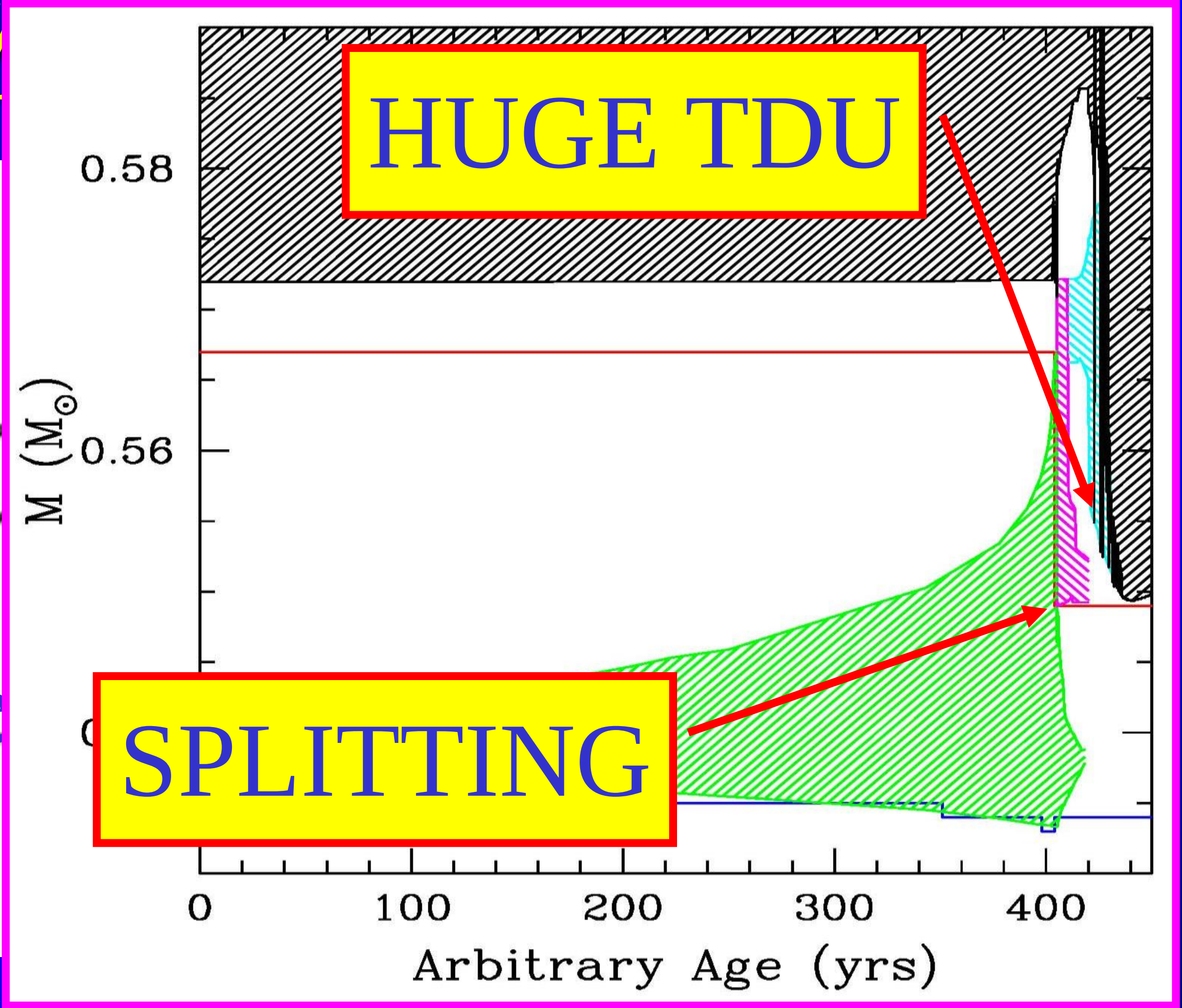


M=1.3 M


He
0.58
0.56
0
M (M$_\odot$)
SPLITTING
0
100
200
300
400
Arbitrary Age (yrs)

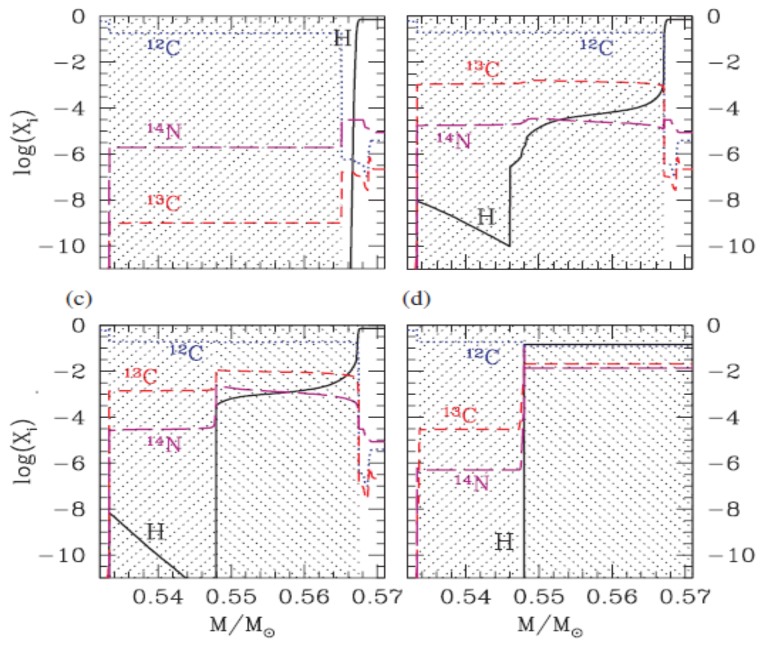
M=1.3 M

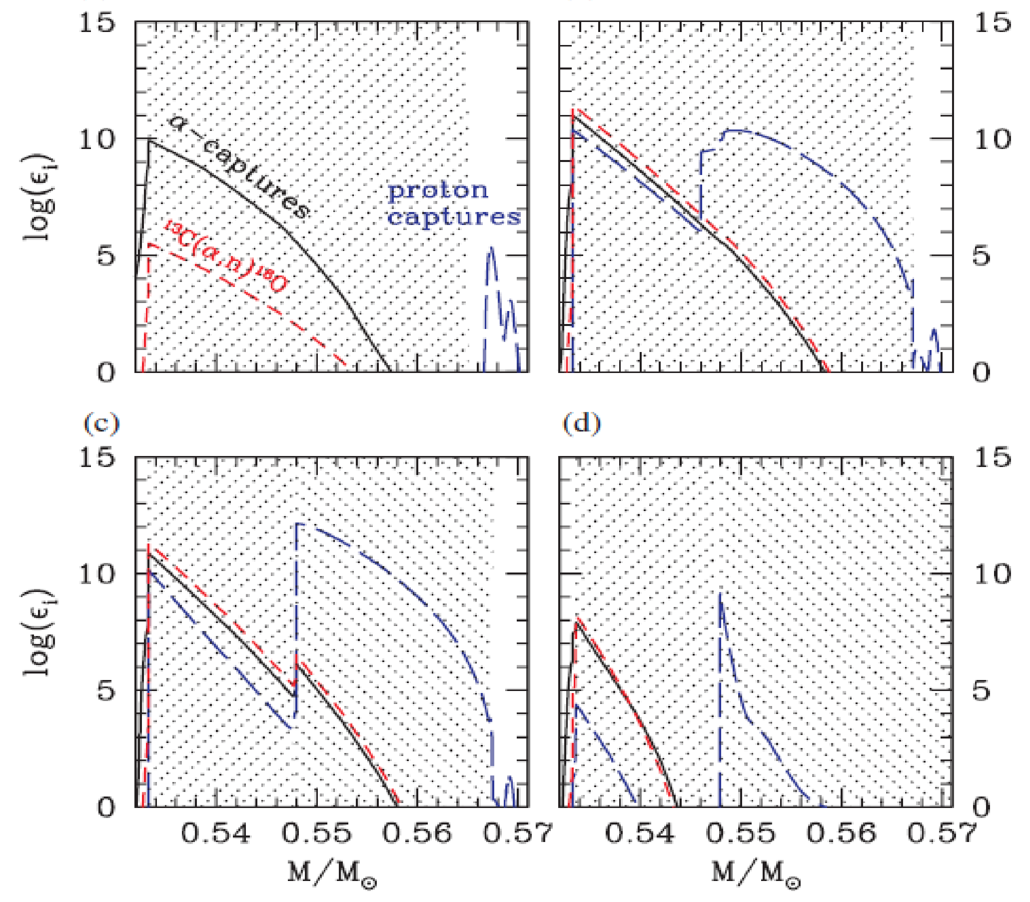



HUGE TDU

SPLITTING

The importance of the $^{13}C(\alpha,n)^{16}O$ reaction (energetic point of view)



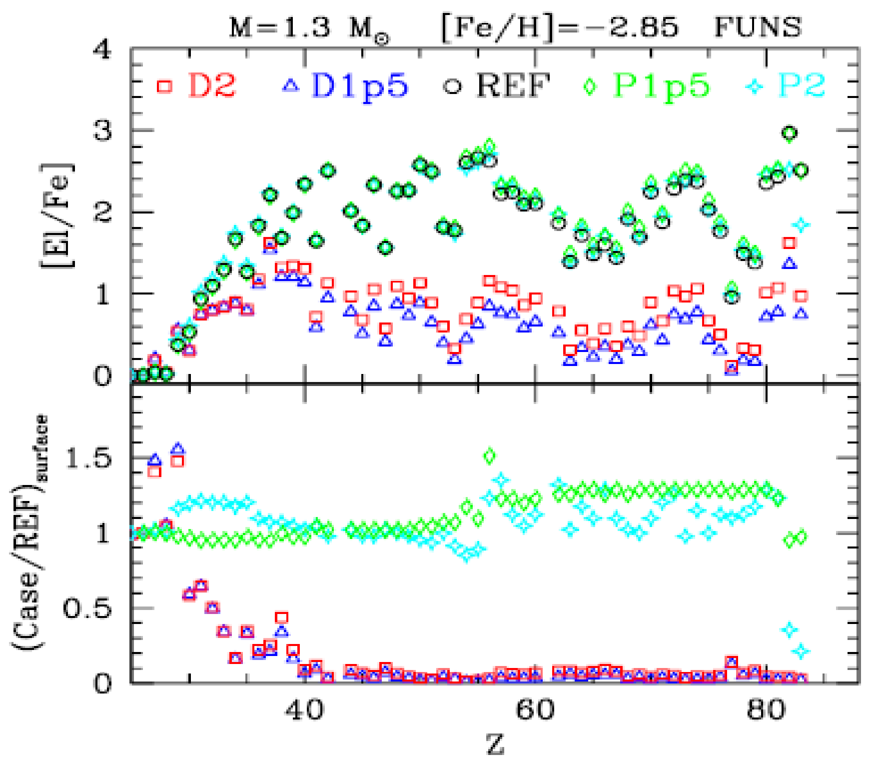


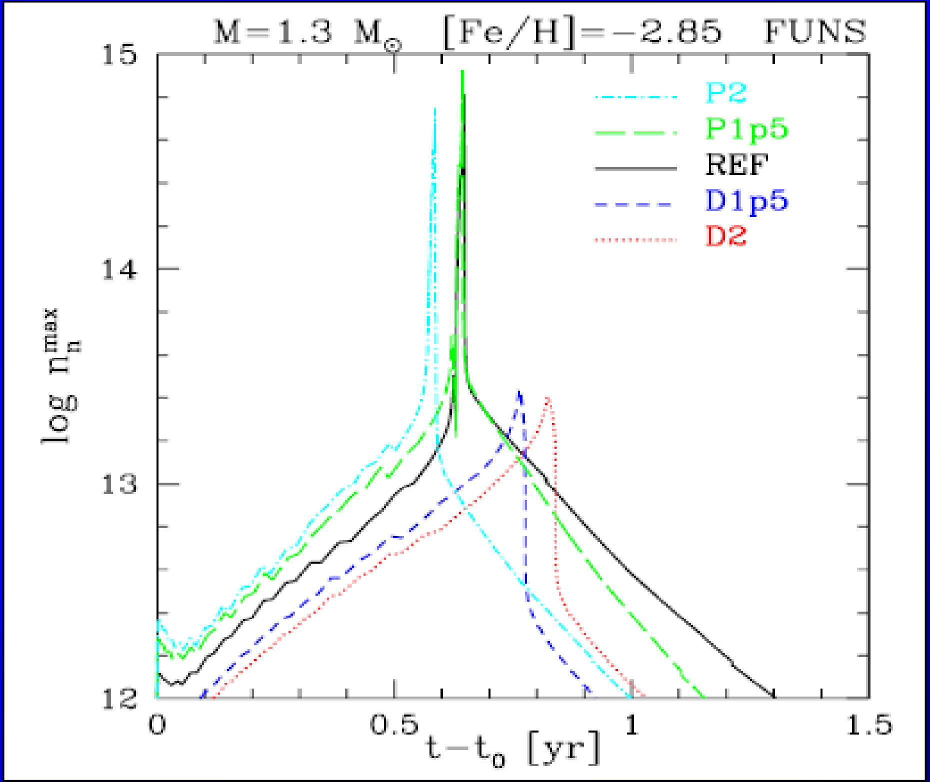
<u>NECESSARY CONDITION</u>:

Full network coupled to physical evolution, due to neutron captures energetics!!!

Cristallo+ 2009

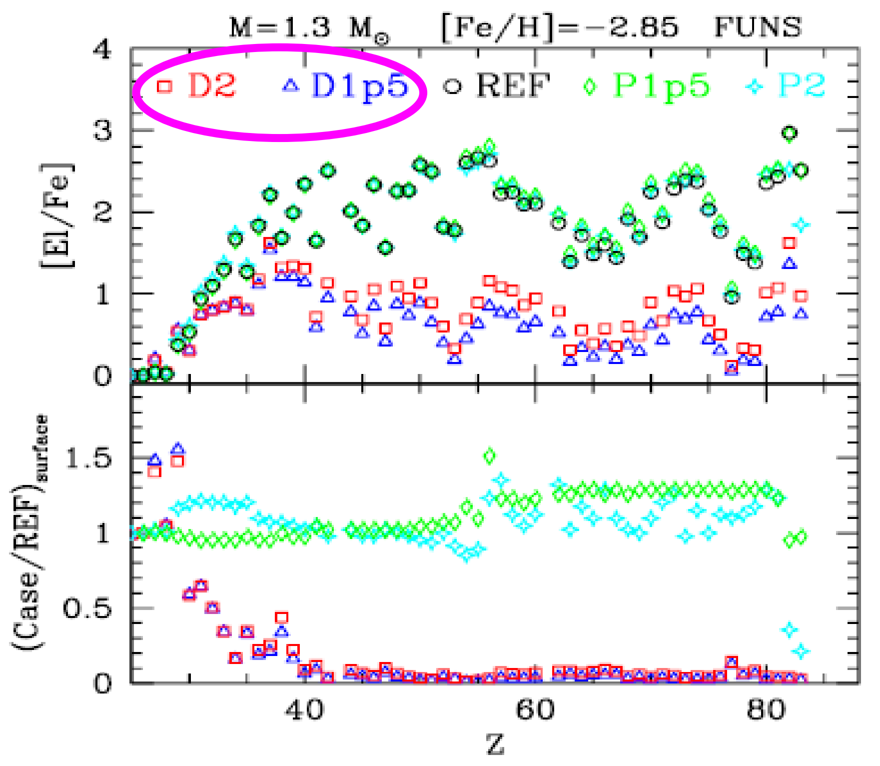
$M=1.3\ M_{SUN}$ [Fe/H]=-2.85

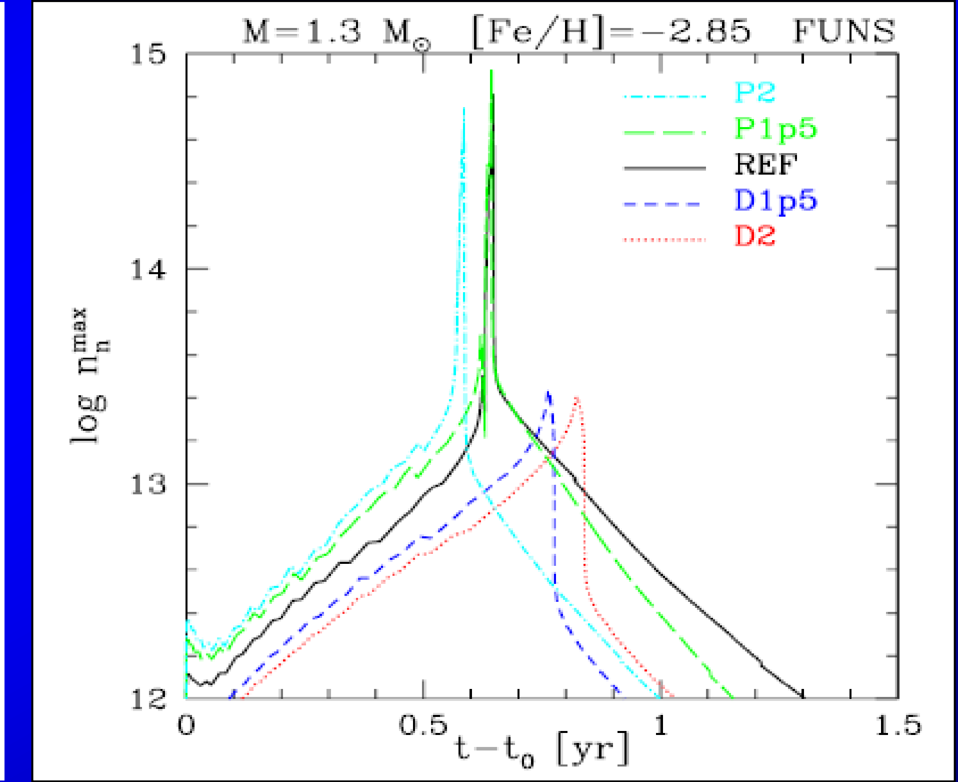




M=1.3 M_{SUN} [Fe/H]=-2.85

Thresold effect: not enough ^{13}C mixed before shell splitting





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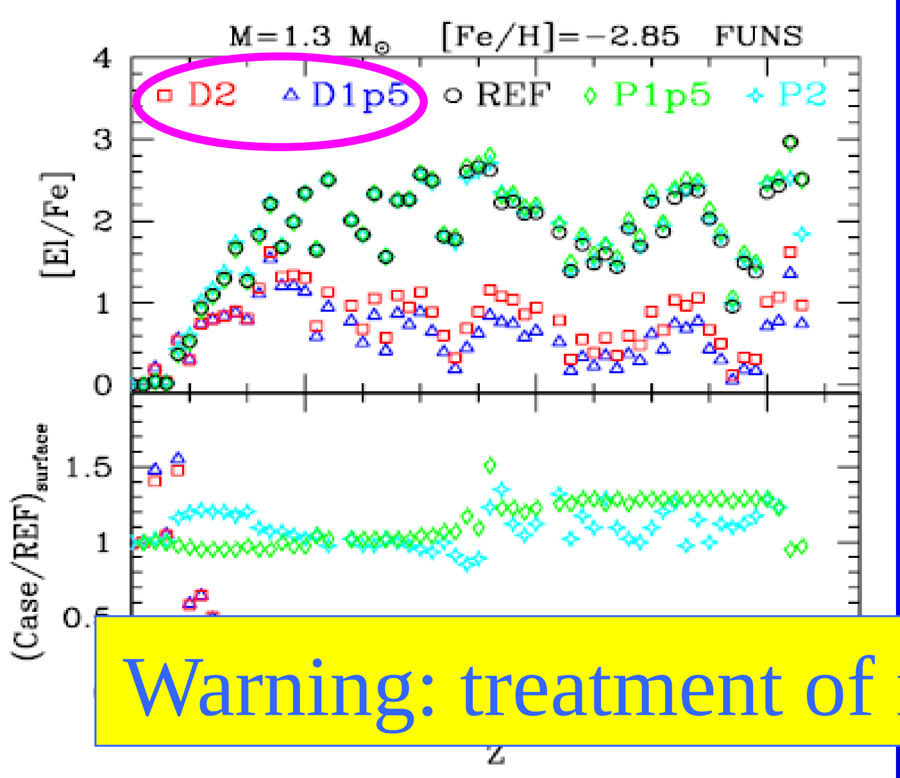

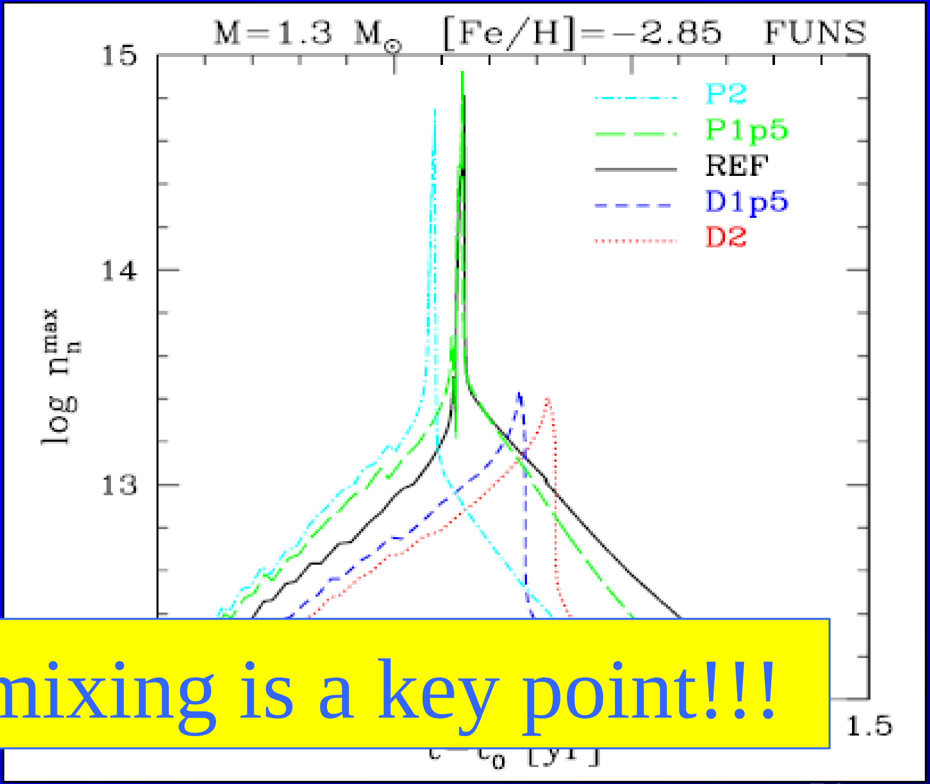

Warning: treatment of mixing is a key point!!!

CONCLUSIONS

- The $^{13}C(\alpha,n)^{16}O$ reaction rate is **important** in low mass AGBs ($M < 3.0\ M_{SUN}$) at close-to-solar metallicities, because it determines how much ^{13}C burns in a convective environment;

- A variation of the $^{13}C(\alpha,n)^{16}O$ reaction rate **does not change** s-process abundances in more massive AGBs ($M > 3\ M_{SUN}$), as well as in all masses at low metallicities;

- The $^{13}C(\alpha,n)^{16}O$ reaction **could be important** for low mass AGBs at very low metallicities, because in that case the convective ^{13}C burning (together with the subsequent neutron capture) affects the physical and chemical evolution of the model. However, the treatment of mixing is equally important.