s-process in stellar sites

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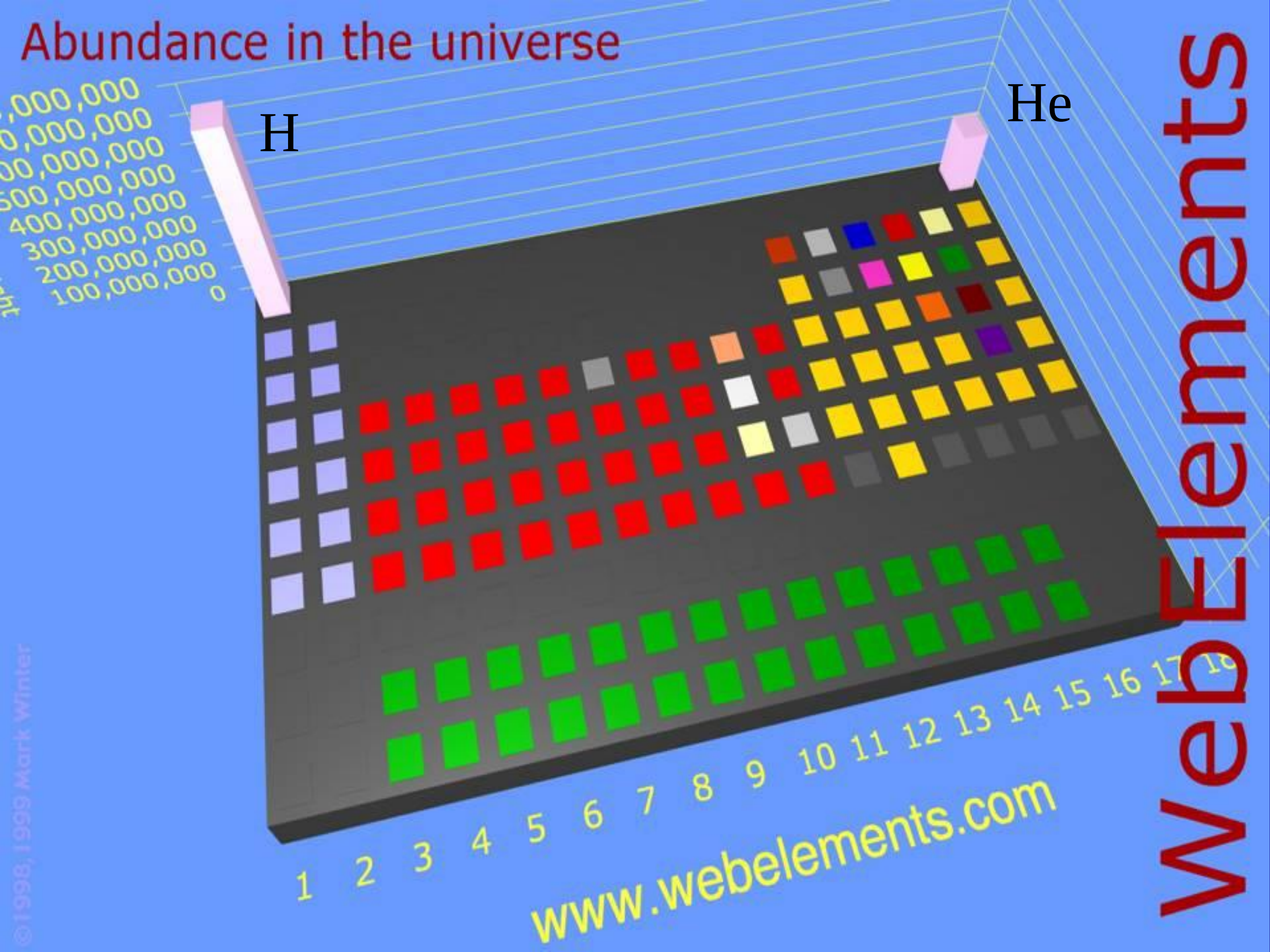
The elements Table

First version by Mendeleev in 1869 to illustrate recurrent (periodic) properties of the known elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII			IB	IB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110	111 111	112 112						

Naming conventions of new elements

* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr



Abundance in the universe
400,000,000
300,000,000
200,000,000
100,000,000
0
H
He
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
www.webelements.com
WebElements
©1998, 1999 Mark Winter

Some minutes after the Bib Bang there were basically only hydrogen (≈75%) and helium (≈25%).

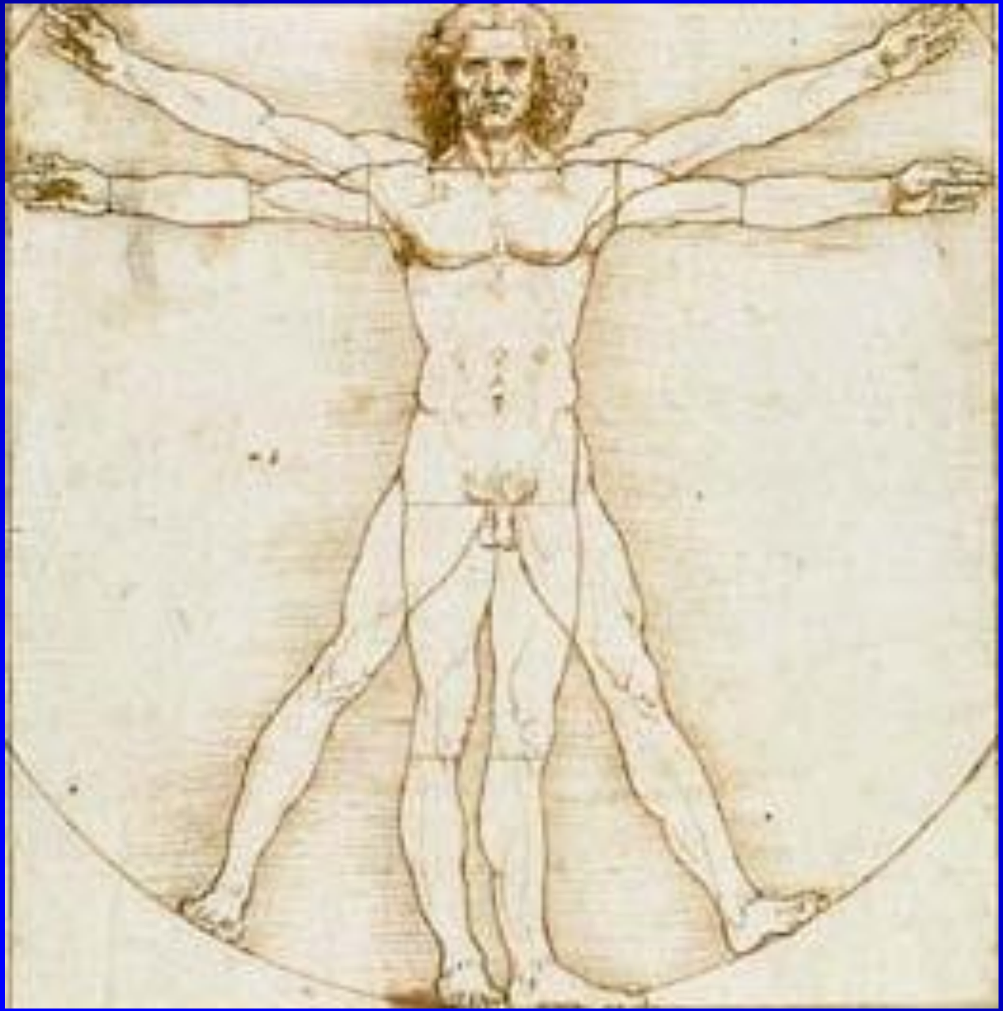
In the Sun there are 71% of hydrogen and 27% of helium. The remaining 2% are heavy elements (or metals).

In star forming regions hydrogen is about 65%, helium is about 31% and metal constitute the remaining 4%

H ↓ He ↑ Metals ↑

The human body

99% of our bodies consist of six elements:
oxygen, carbon, hydrogen, nitrogen, calcium and phosphorus.

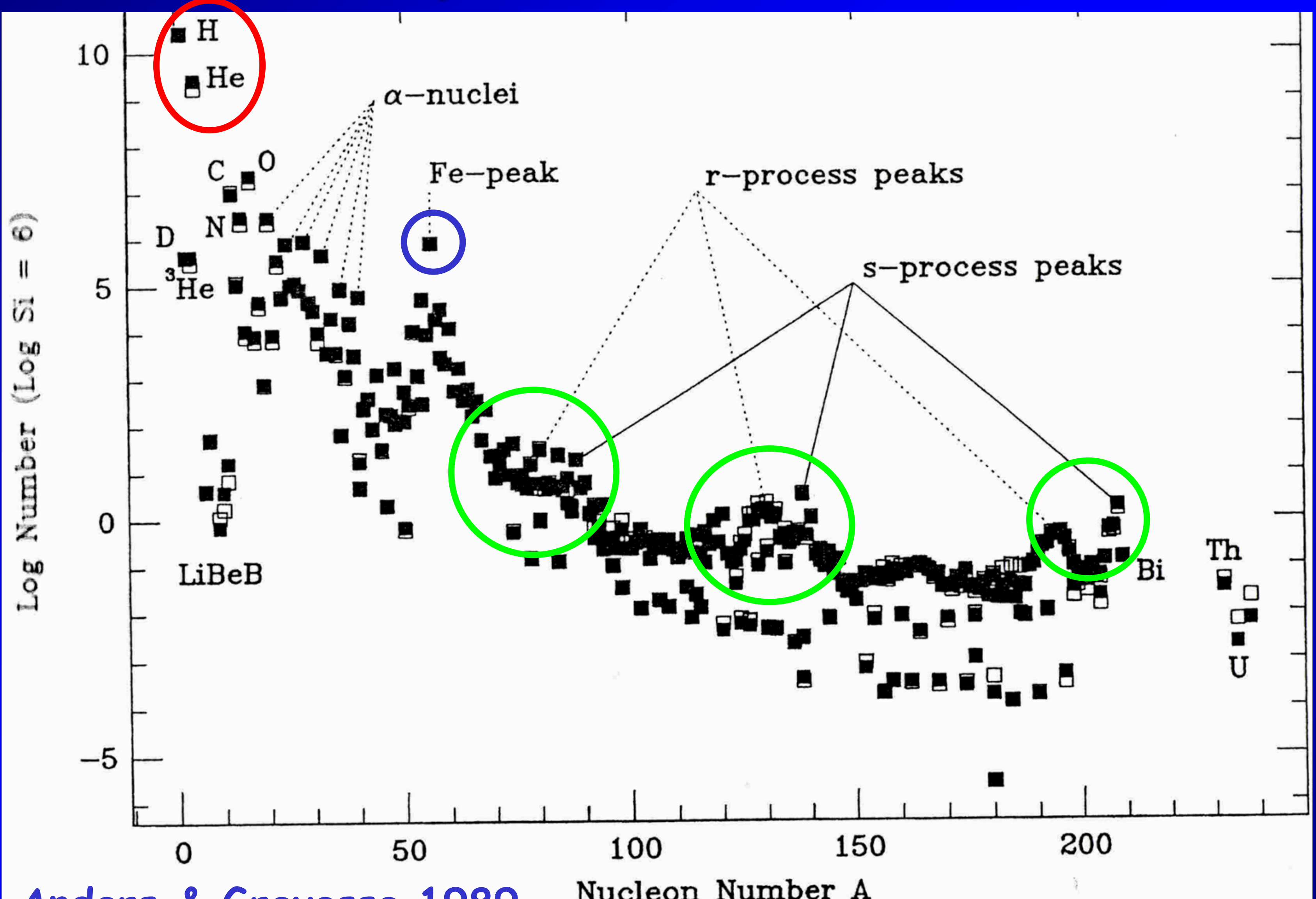


Element	Percentage in mass (%)
Oxygen	65
Carbon	18
Hydrogen	10
Nitrogen	3
Calcium	1.5
Phosphorus	1.2
Potassium	0.2
Sulfur	0.2
Chlorine	0.2
Sodium	0.1
Magnesium	0.05

Trivia questions (for students only)

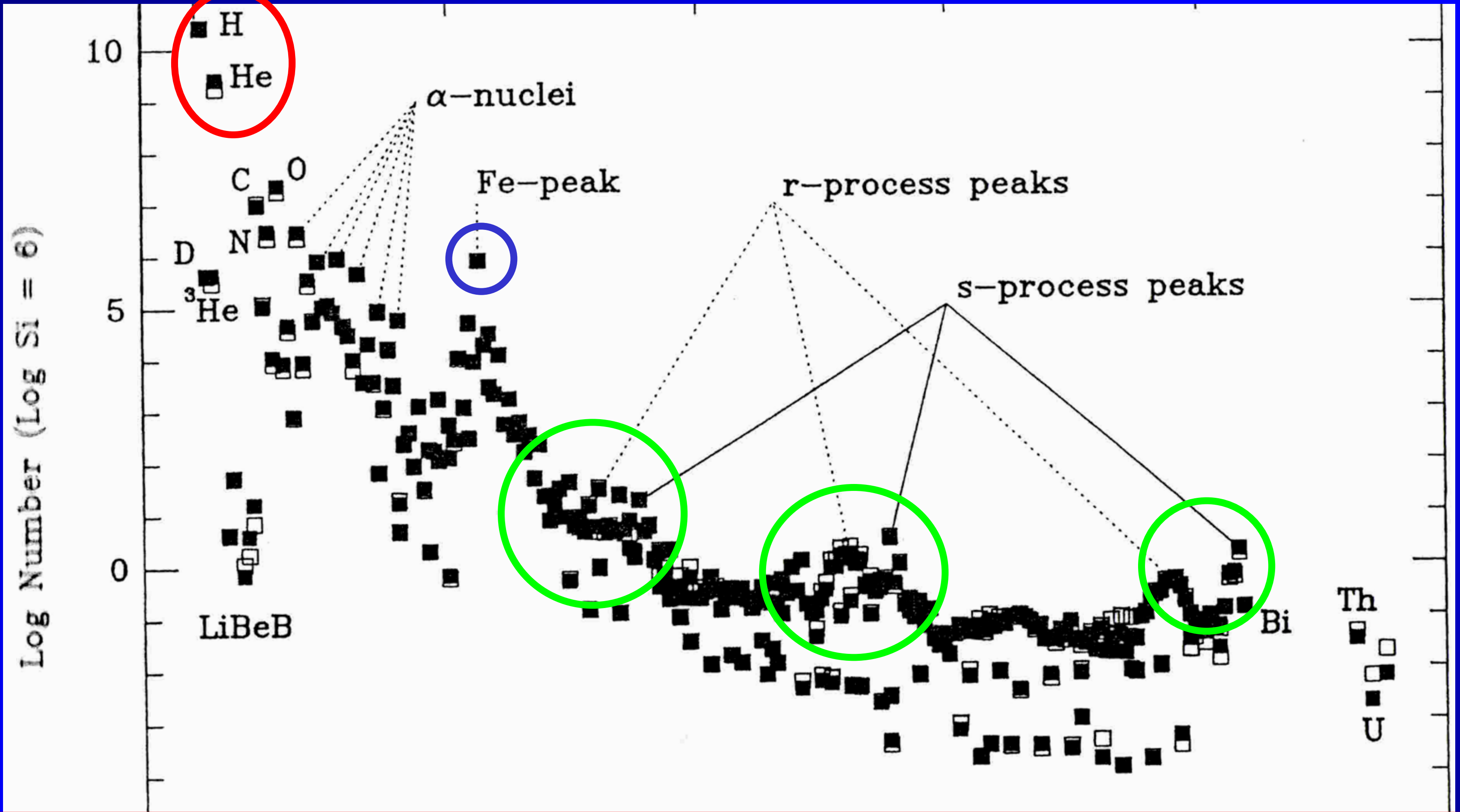
- Which element is labelled as Na?
- Which element is labelled as Au?
- Which element is labelled as Nb?
- Which element is labelled as Ce?
- Which element is labelled as Tm?

Solar System Abundances



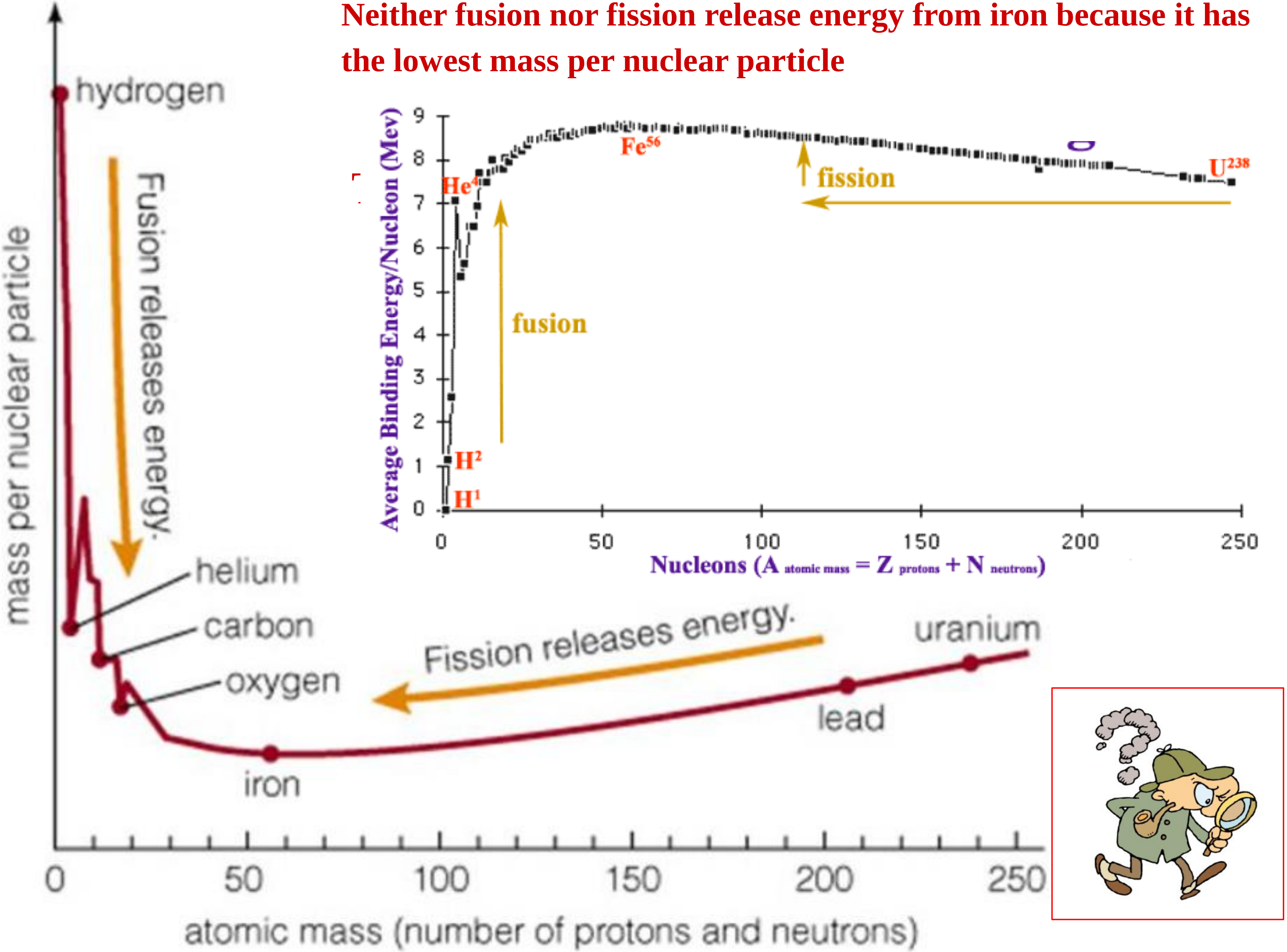
Anders & Grevesse 1989
Cameron 1982

Solar System Abundances



Their natural abundances are far greater that can be reproduced in nuclear statistical equilibrium, so that they seem to require a non-equilibrium mechanism.

Neither fusion nor fission release energy from iron because it has the lowest mass per nuclear particle



Neutron capture reactions

$$^{A}X_{Z}(n,\gamma)\,^{A+1}X_{Z}$$

With NO Coulomb barrier to overcome, heavy elements capture neutrons easily, even at extremely low energies.

Neutron cross section, in fact, generally INCREASES with decreasing energy

$(Z,A) + n \rightarrow (Z,A+1) + \gamma$

If the nucleus (Z,A+1) is stable, it waits until it captures another neutron, and so on.

If the nucleus (Z,A+1) is radioactive, the question whether it β-decays to (Z+1,A+1) or captures a second neutron depends upon the relative lifetimes of (Z,A+1) against β-decay and against capture of neutrons.

DEFINITION:

$$\tau_n(X) = \frac{1}{N_n < \sigma v >}$$

Mean lifetime of nucleus X against destruction by a neutron capture

(<σv> represents the destruction rate of the nucleus)

τ_β = beta-decay lifetime (seconds → years)

if $\tau_n > \tau_\beta \Rightarrow$ unstable nucleus decays
if $\tau_n < \tau_\beta \Rightarrow$ unstable reacts

The r-process

$\tau_\beta \gg \tau_n \quad \Leftrightarrow \quad N_n > 10^{20}$ n/cm^3

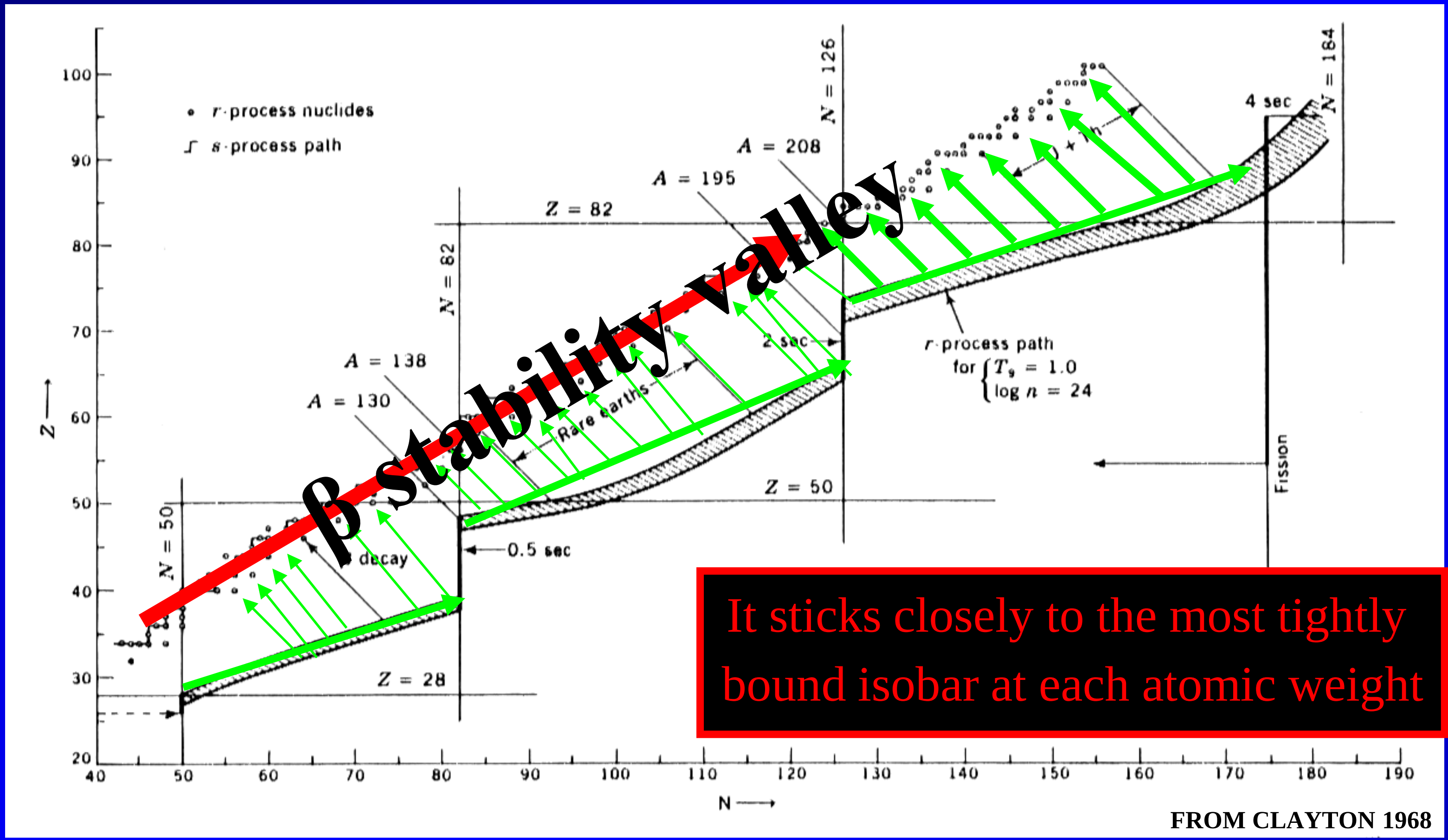
Unstable nucleus captures another neutron before decaying

The s-process

$\tau_\beta \ll \tau_n \quad \Leftrightarrow \quad N_n \sim 10^7$ n/cm^3

Unstable nucleus decays before capturing another neutron

In principle one might expect to encounter astrophysical neutron fluxes in the large region between these two densities and have thereby a process intermediate to the s and r processes. Such events are apparently not common, and it is one of the fortunate simplifications in the application theory of synthesis by neutron capture that the most common fluxes are either quite small or quite large... **if you ignore the i-process**.



s-process

r-process

Who is **Roberto Gallino** ?

"Chi non fa non falla…"

You do not make mistakes if you don't work…

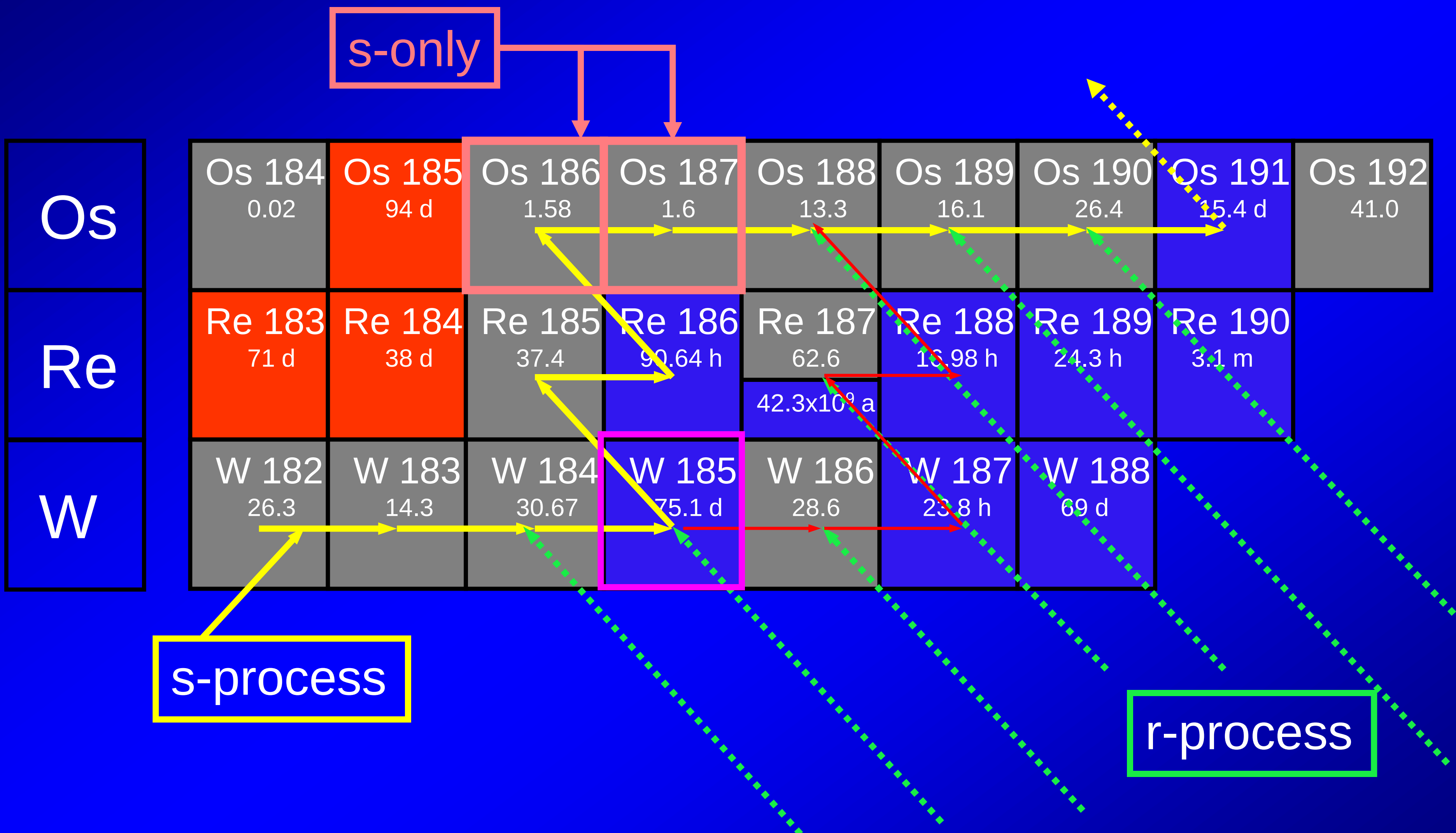
"Non credere mai a nessuno

- nemmeno a me"

Do not ever believe anyone

- not even me

How neutron captures work?



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

The s-only isotopes solar distribution

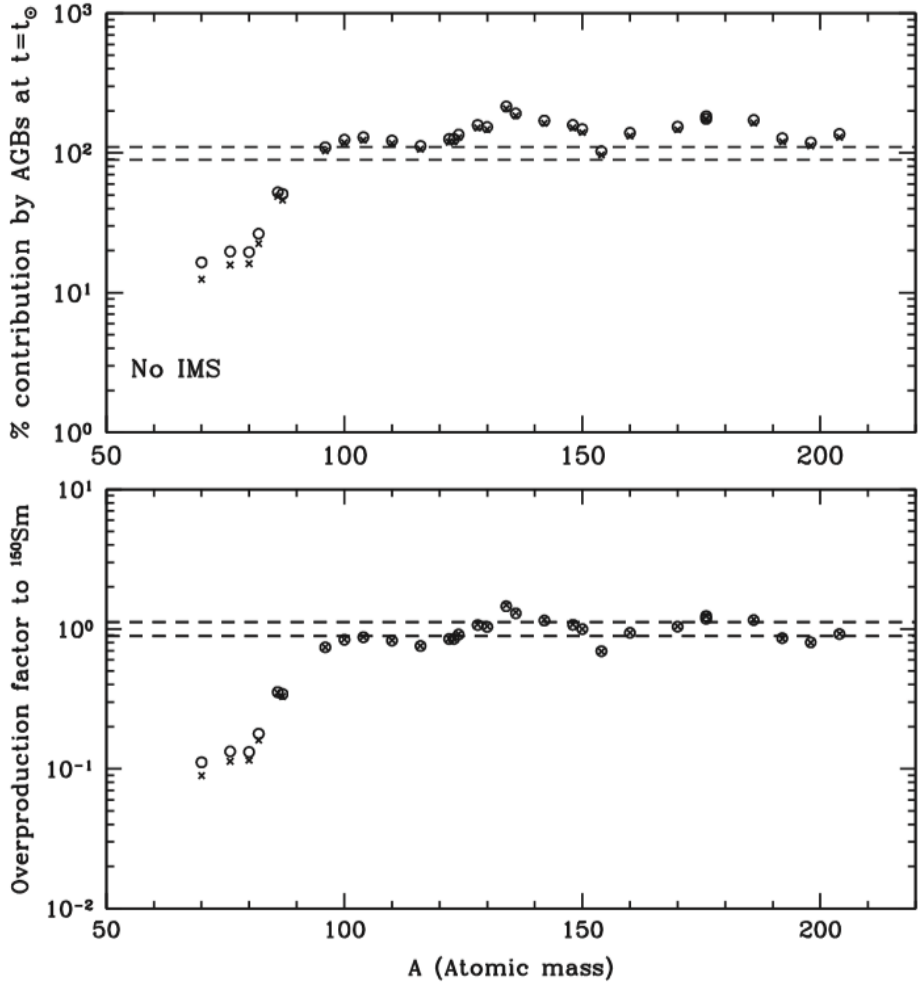


Figure 4. As in Figure 3, but including a GCE calculation without the contribution from IMS AGBs (crosses). The *Reference* case (open dots) is shown by comparison. We have omitted error bars for clarity.

Seeds for the s-process

Main seeds are ^{56}Fe nuclei…

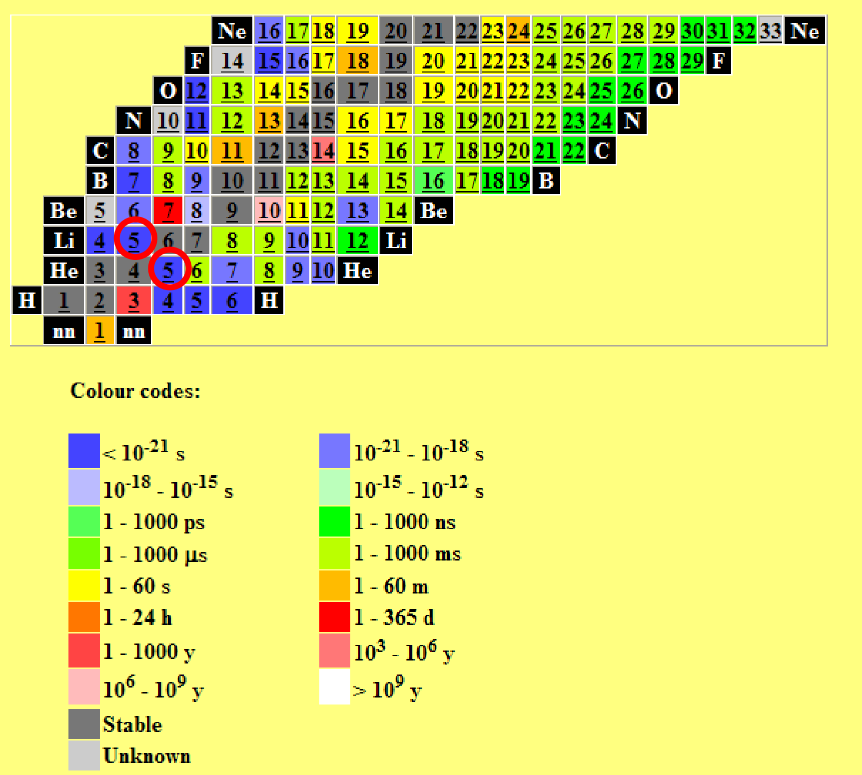
Why not the most abundant ^{1}H, ^{4}He or ^{12}C???

The reason lies in the nuclear structure of nuclei…and in the stars!!

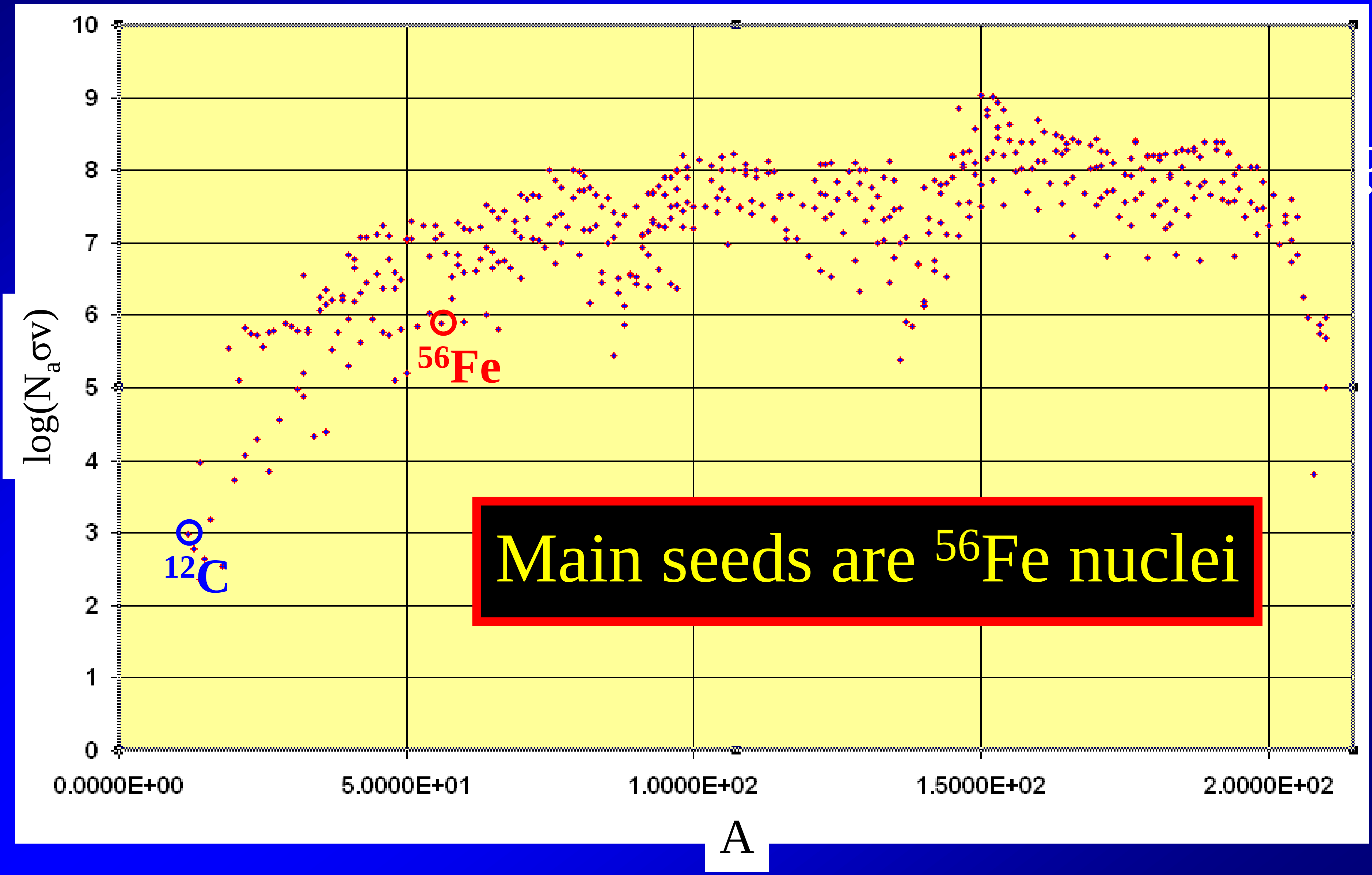
RATE[H(n,γ)^{2}H]∝N(H)

↓

10^{-12}



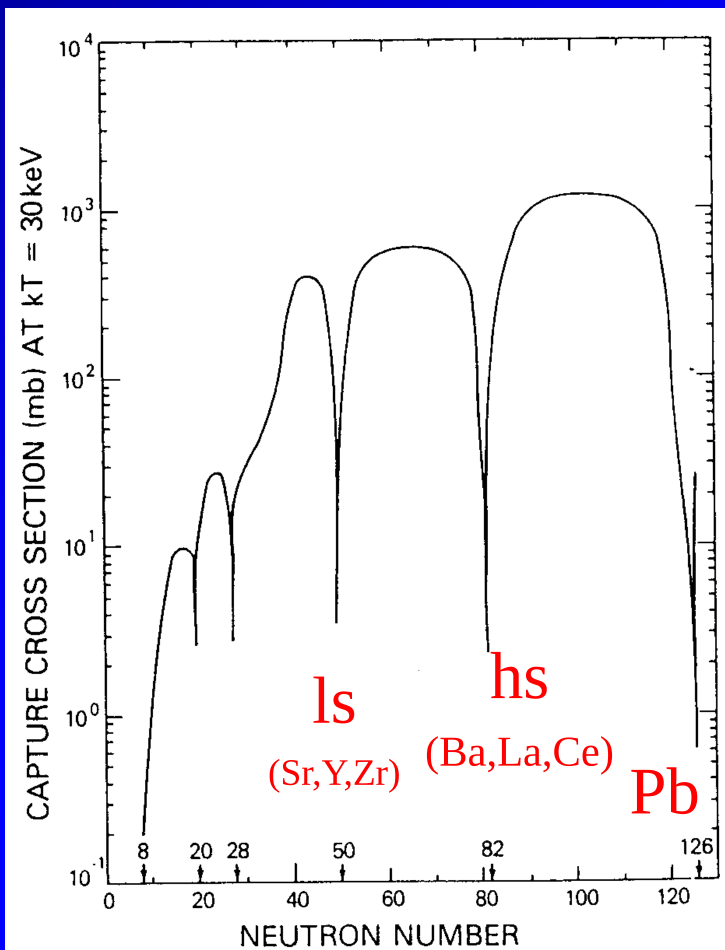
Seeds for the s-process



MAGIC NUCLEI

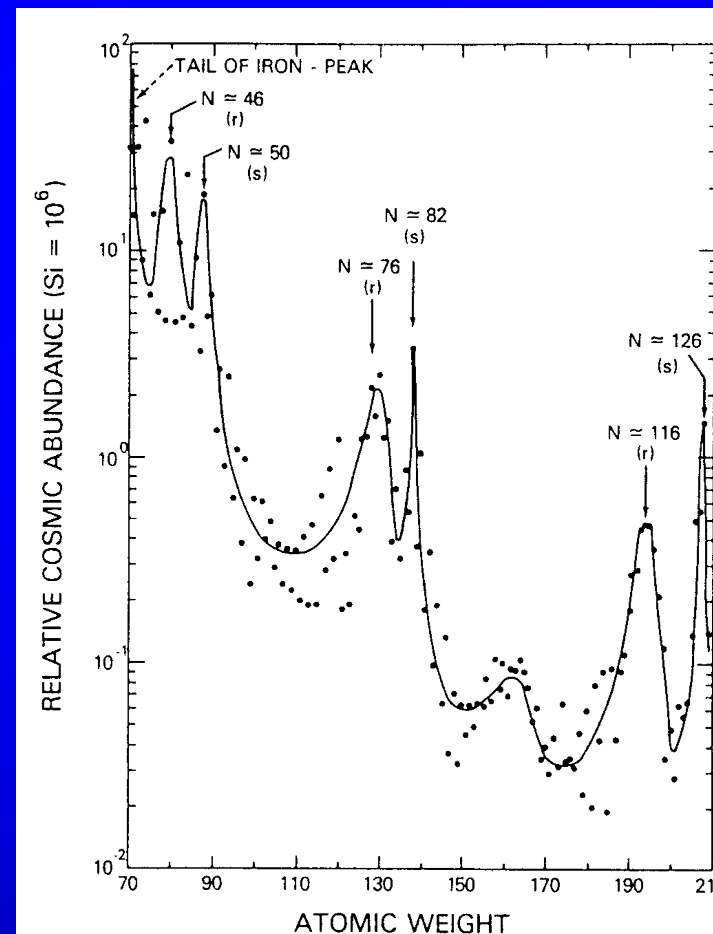
very small σ(n,γ)

at neutron magic numbers



abundance curve for

elements beyond iron



At atomic wieghts far from the closed shells, we find that the cross sections are so large that the differences between these two products is much smaller than the magnitude of either one of them, so that:

$$\sigma_A N_A \approx \sigma_{A-1} N_{A-1}$$

(local approximation)

In magic-numbered heavy nuclei the number of resonances is not so large and, therefore, the shell structure of the nucleus becomes an important feature in reducing the level density of resonances.

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 of the s-process

$^{13}C(\alpha,n)^{16}O$ $^{22}Ne(\alpha,n)^{25}Mg$

The nuclear paths

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

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

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

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

Primary and secondary elements (or isotopes)

* *Primary element*: produced from H & He directly: ^{12}C, ^{16}O…

* *Secondary element*: its production requires the presence of some metals: ^{14}N, ^{27}Al…

The ^{13}C is <u>primary</u> like

The ^{22}Ne is <u>secondary</u> like

Iron seeds (^{56}Fe) are <u>secondary</u> like

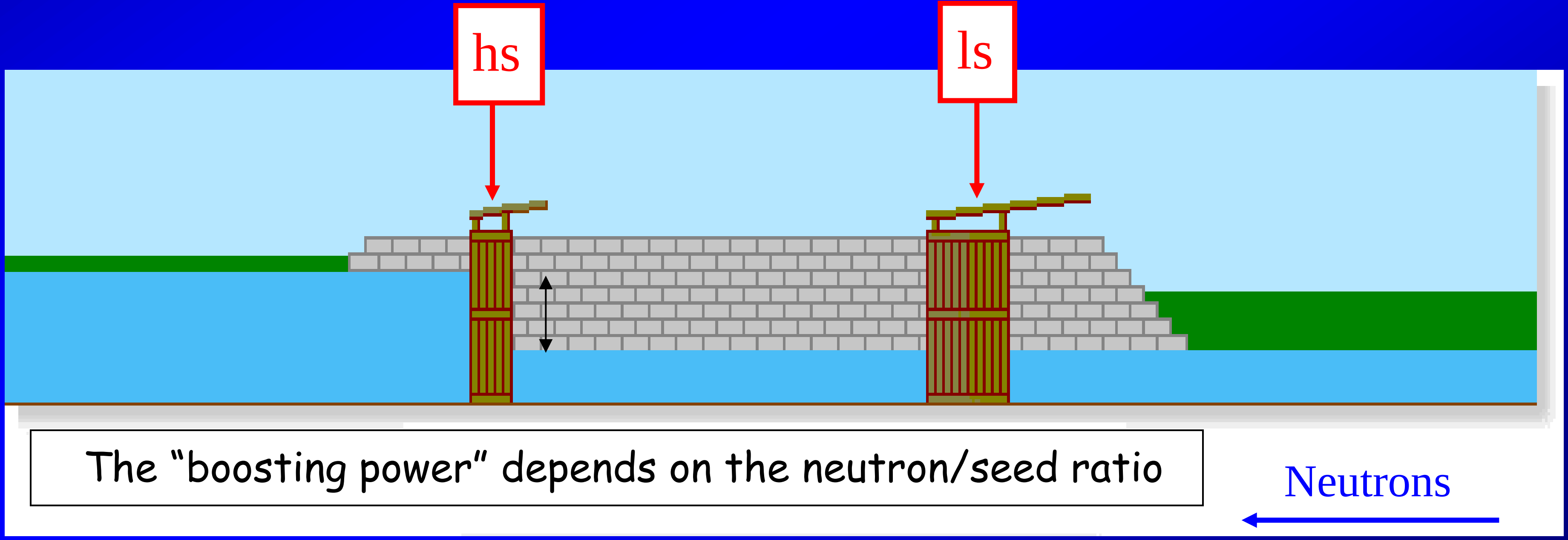
The key quantity is the neutron/seed ratio, for example: $N(^{13}C)/N(^{56}Fe)$

The three s-process peaks

1st peak → ls elements (Sr,Y,Zr) [N=50]

2nd peak → hs elements (Ba,La,Ce,Nd,Sm) [N=82]

3rd peak → lead (^{208}Pb) [N=126 & P=82]

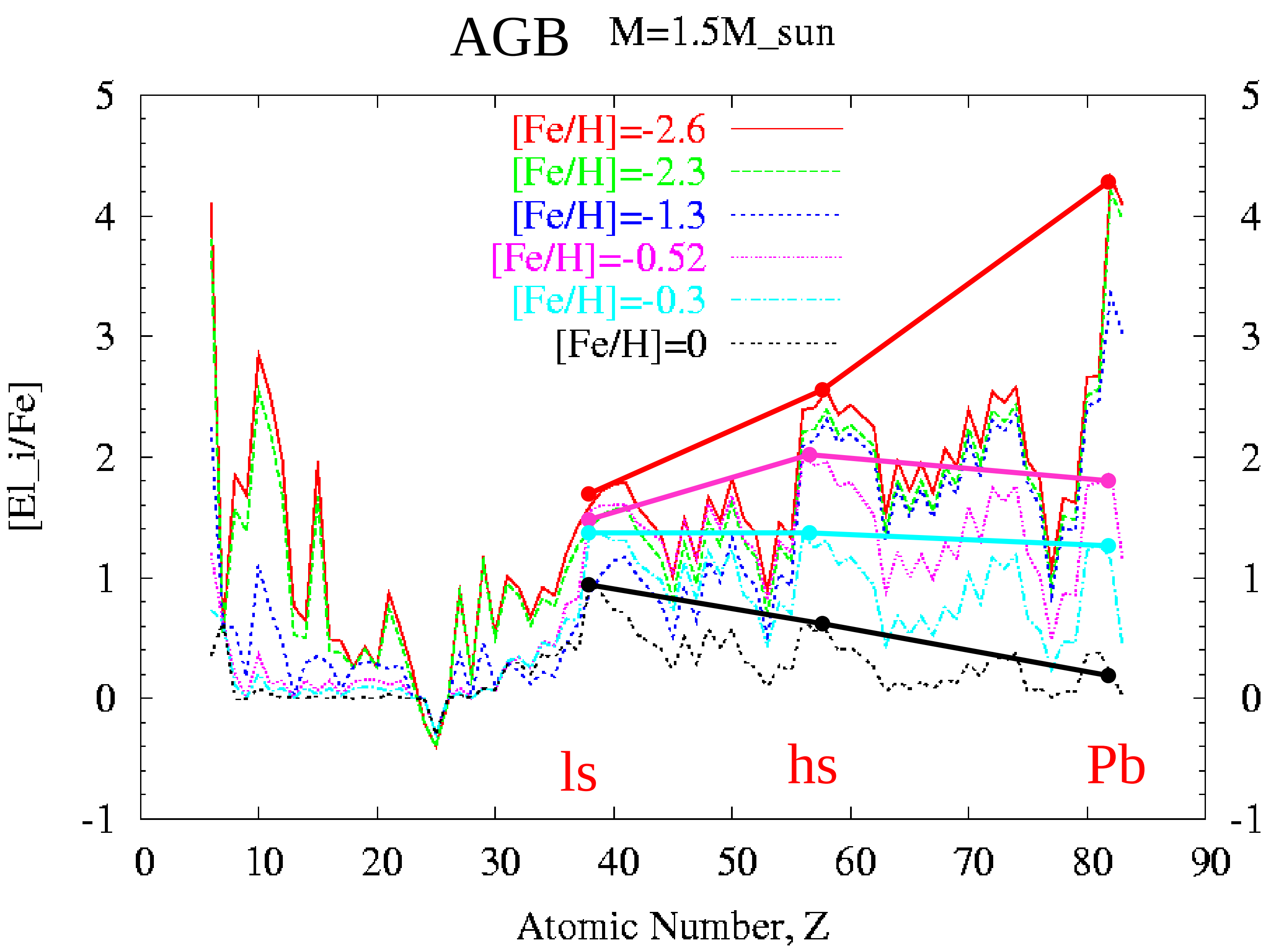


A sluice system with opening bulkheads

THE CLASSICAL COMPONENTS OF THE S PROCESS

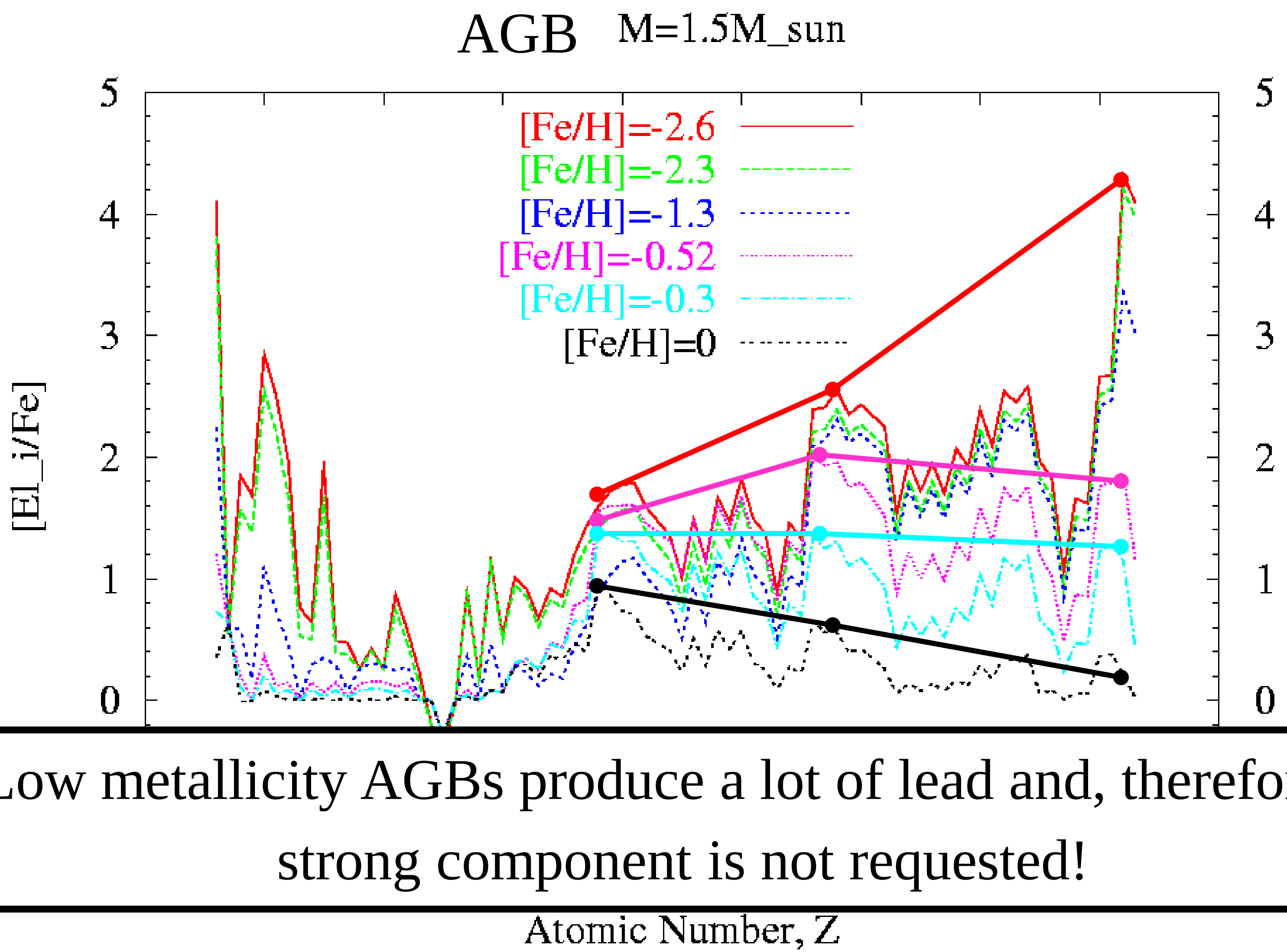
Weak Component: A<90	Core-He and C-shell burning In Massive Stars
Main Component: 90<A<204	AGB stars
Strong Component: 204<A<210	Low Metallicity AGB stars

SURFACE DISTRIBUTION



Gallino's models

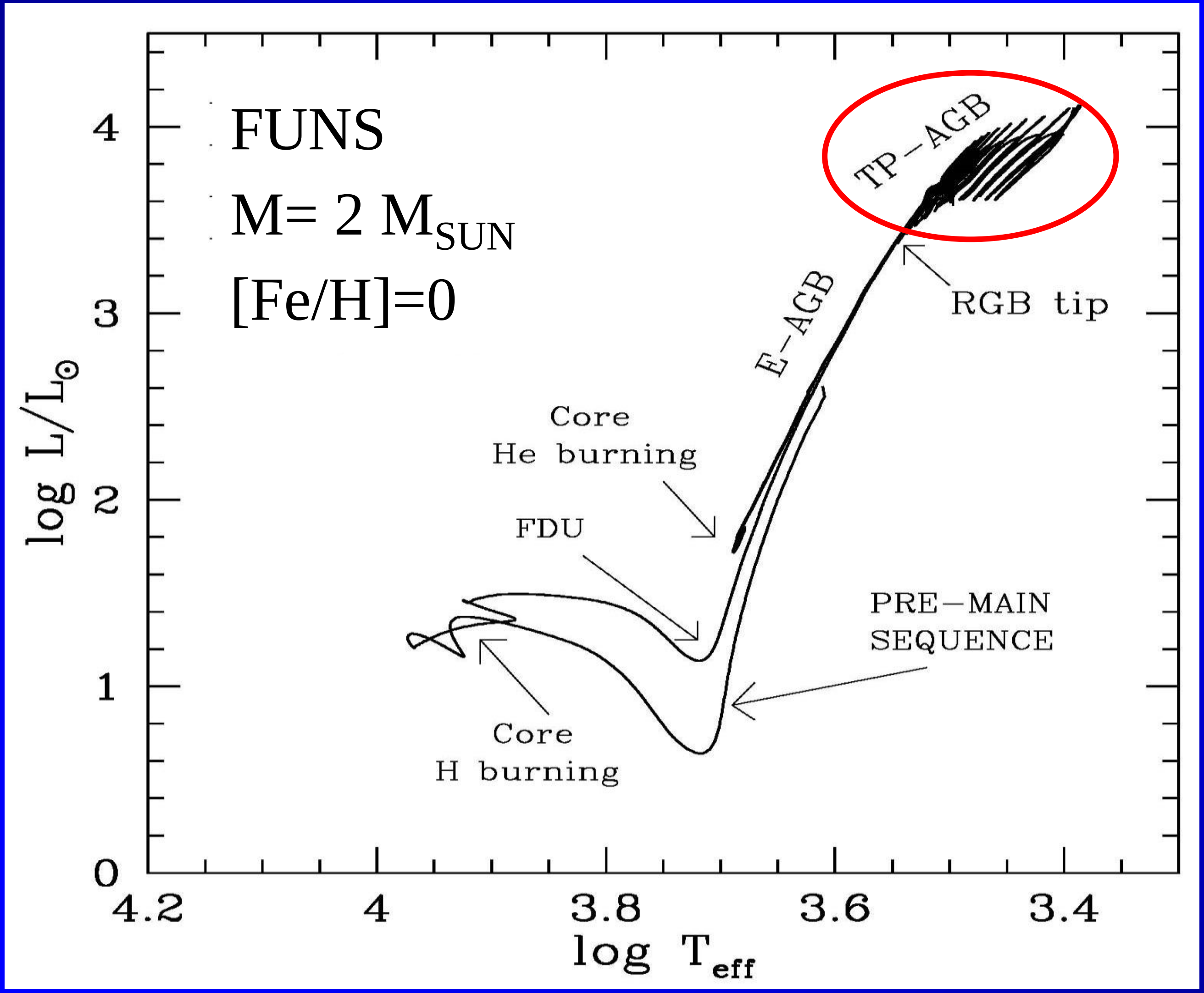
SURFACE DISTRIBUTION



Low metallicity AGBs produce a lot of lead and, therefore, a strong component is not requested!

Gallino's models

Asymptotic Giant Branch (AGB) stars



$\tau_{MS} \approx 1$ Gyr

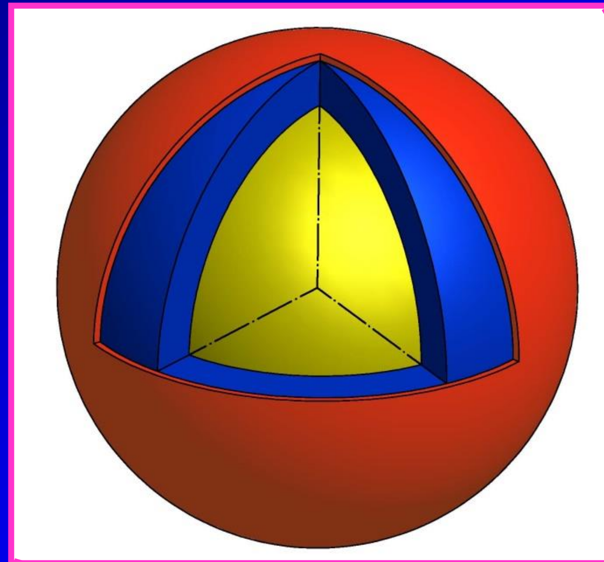
$\tau_{AGB} \approx 1$ Myr

AGBs: marvellous stellar cauldrons

- C (1.5-4.0 M_{SUN})
- N (4.0-7.0 M_{SUN})
- F (1.5-4.0 M_{SUN})
- Na (all)
- Mg&Al (5.0-7.0 M_{SUN})
- Half of the heavy elements is synthesized in AGBs

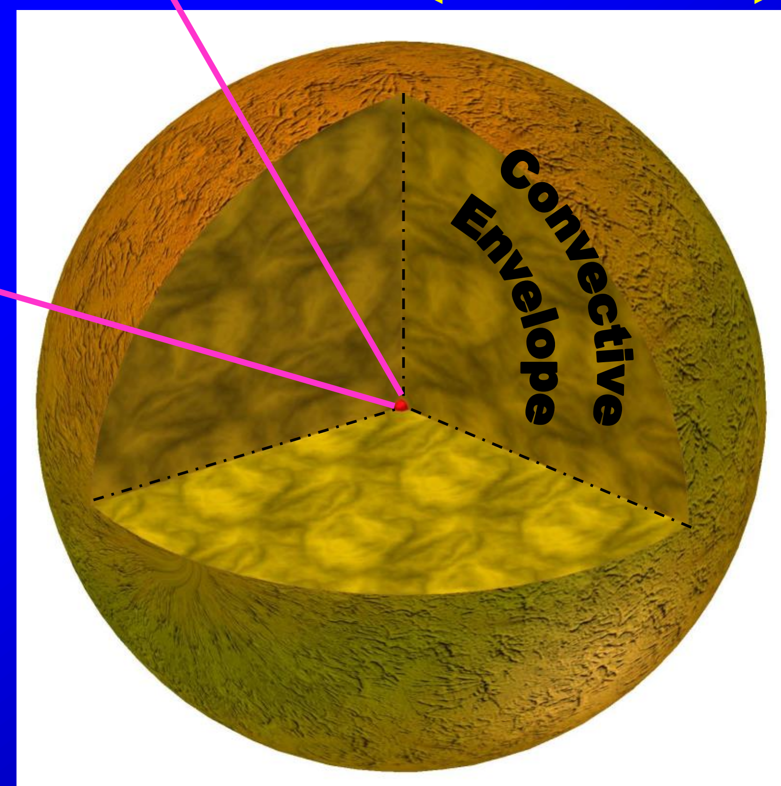
AGB structure

CO Core
He-shell
H-shell



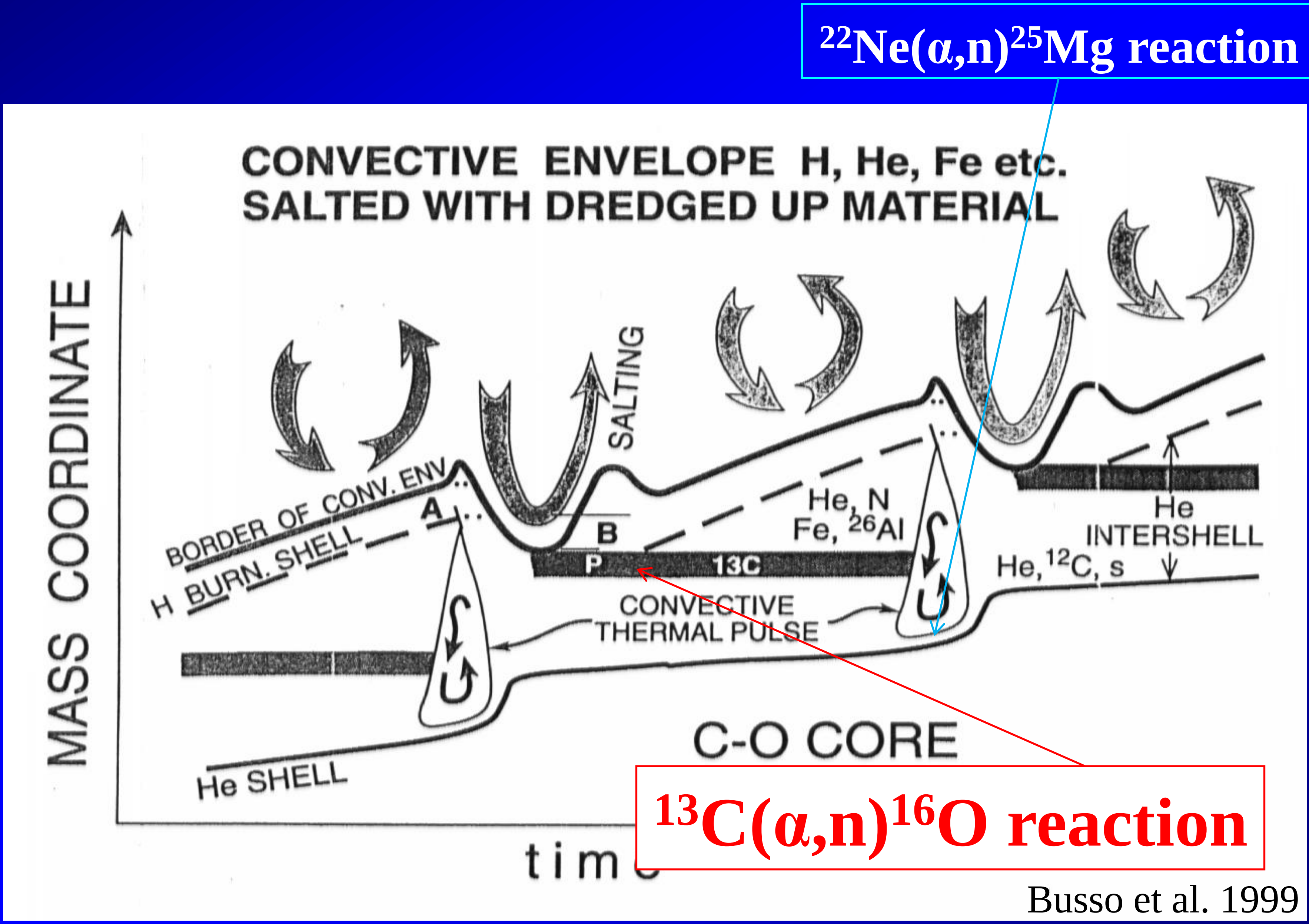
Earth radius
(~10^{-2} R_{SUN})

Earth-Sun
(~200 R_{SUN})



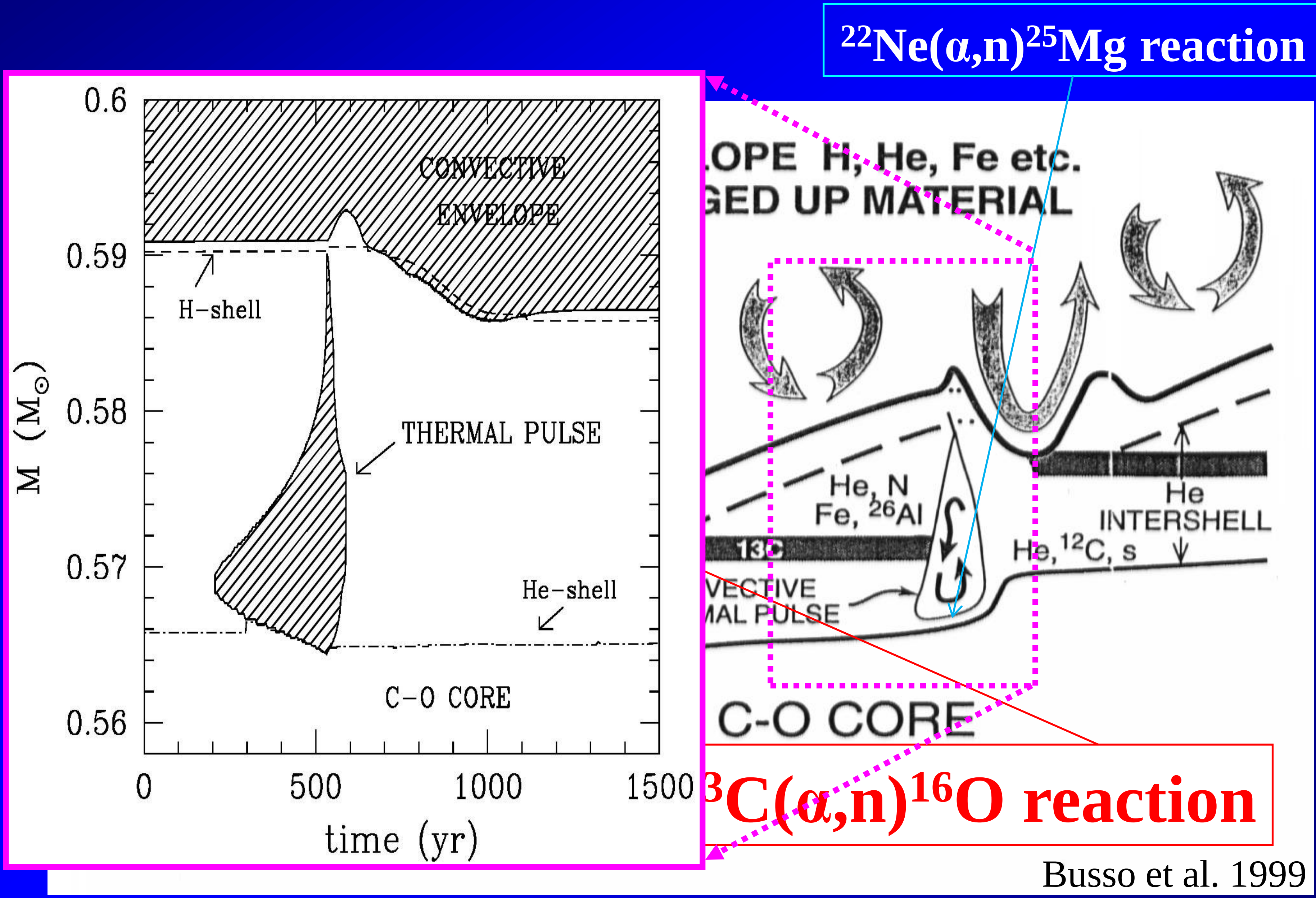
It's like you put a nut
in a 300 mts hot air balloon!!!

The s-process in AGB stars



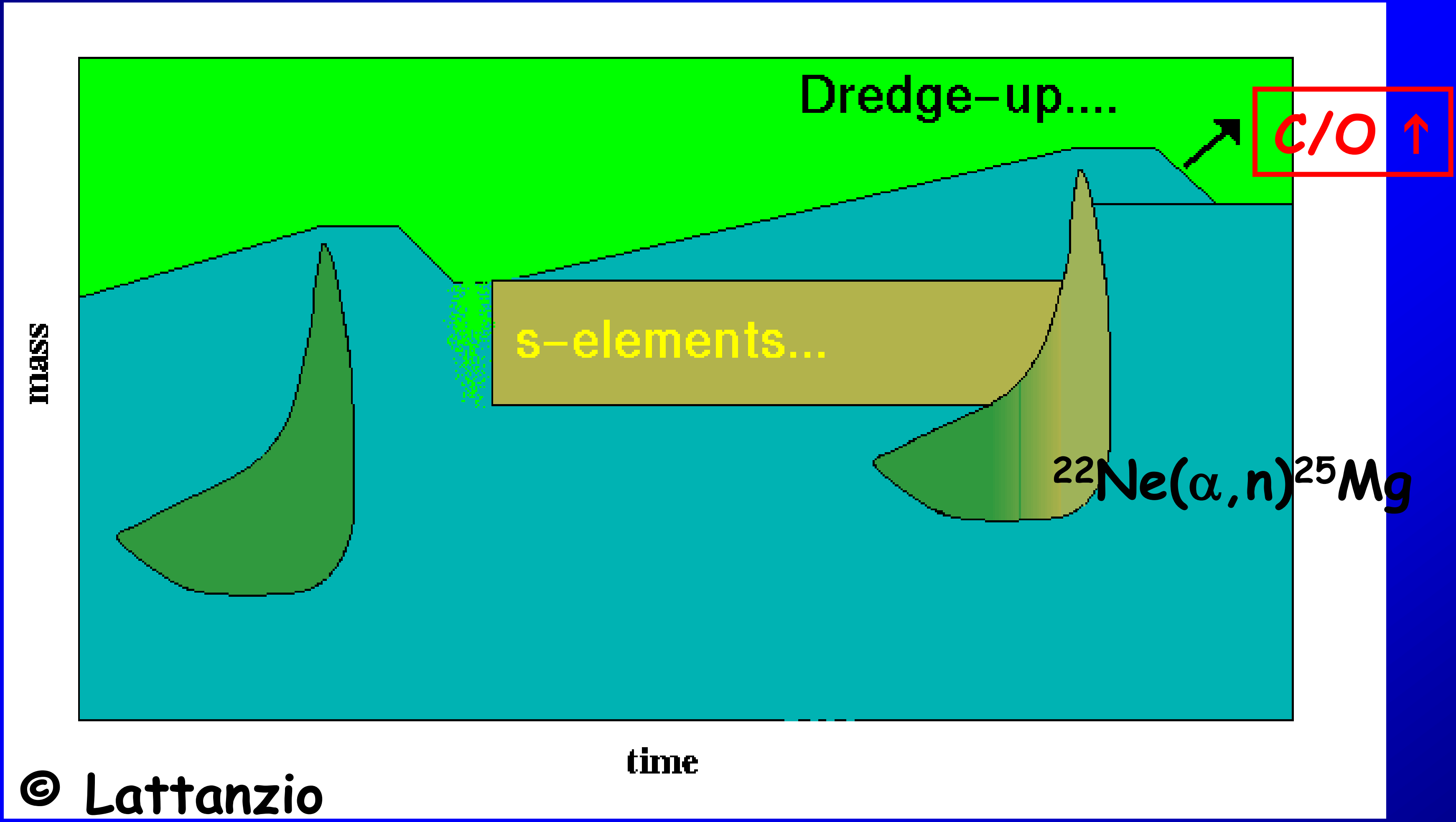
Busso et al. 1999

The s-process in AGB stars



Busso et al. 1999

Resuming...



SUN
↓
Oh, Be A Fine Girl Kiss Me Right Now!

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) ↓

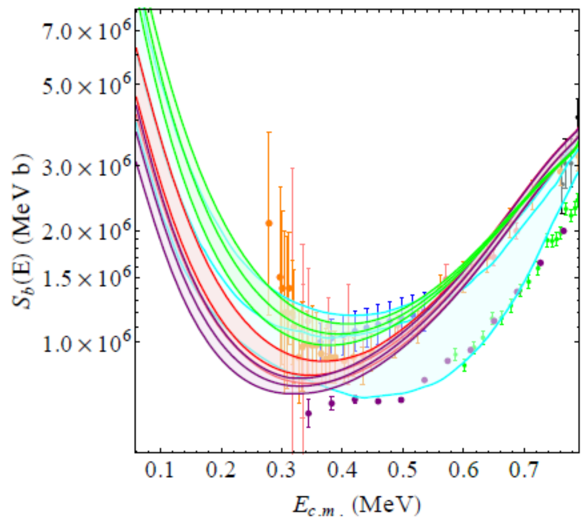


Fig. 4.— Comparison between $S(E)$-factor calculated in this paper (red band) with recent indirect determinations by La Cognata et al. (2013) and Avila et al. (2015) (green and purple band, respectively). The cyan band, instead, shows the astrophysical factor and the corresponding uncertainties suggested 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.

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

- Trippella+ 2017 → Asymptotic normalization coefficient (ANC) and the Trojan Horse Method (THM)
- Avila+ 2015
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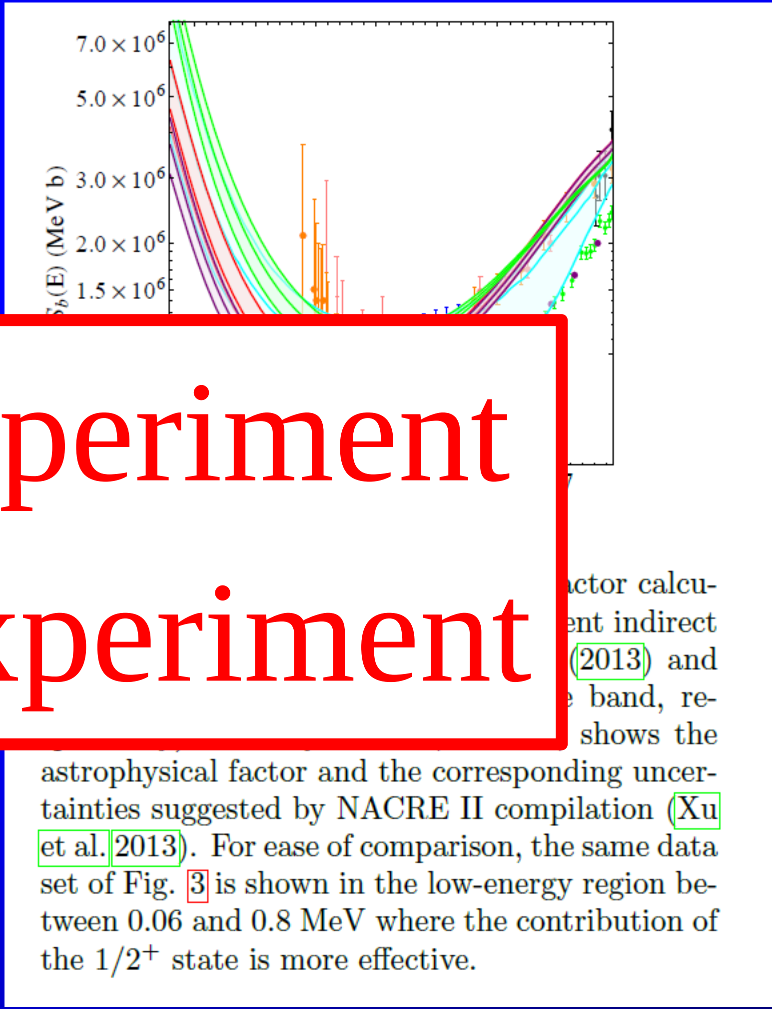
- Guo+ 201
- Heil+ 200
- Kubono+
- Angulo+ 1
- Drotleff+ 1993
- …



LUNA experiment

n_TOF experiment

How does the ^{13}C pocket form?

- ✓ Opacity induced overshoot
- ✓ Convective Boundary Mixing
- ✓ Magnetic fields

How does the ^{13}C pocket change?

- ✓ Rotation mixing
- ✓ Magnetic fields

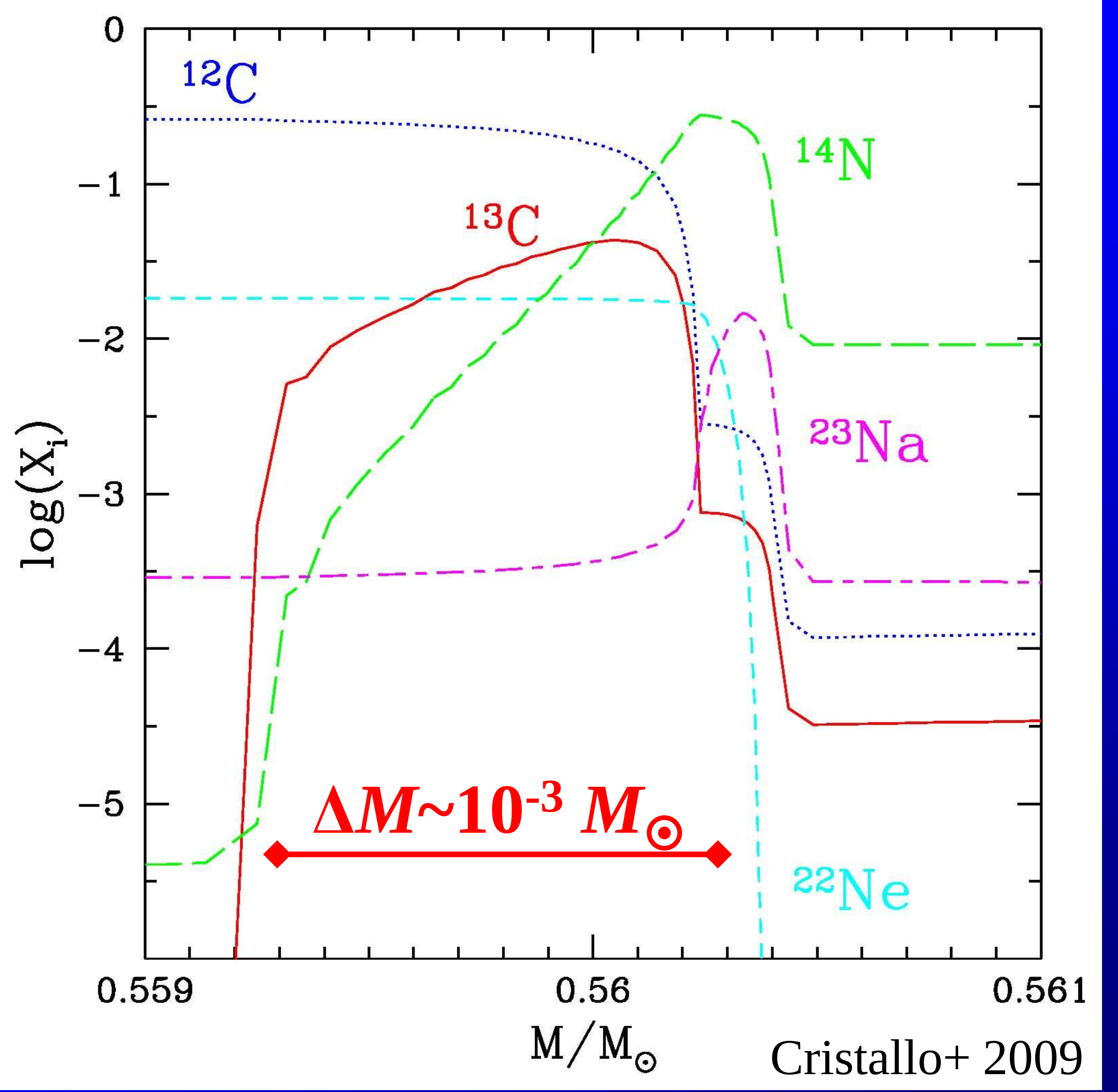
The formation of the ^{13}C pocket

^{13}C-pocket

^{14}N-pocket

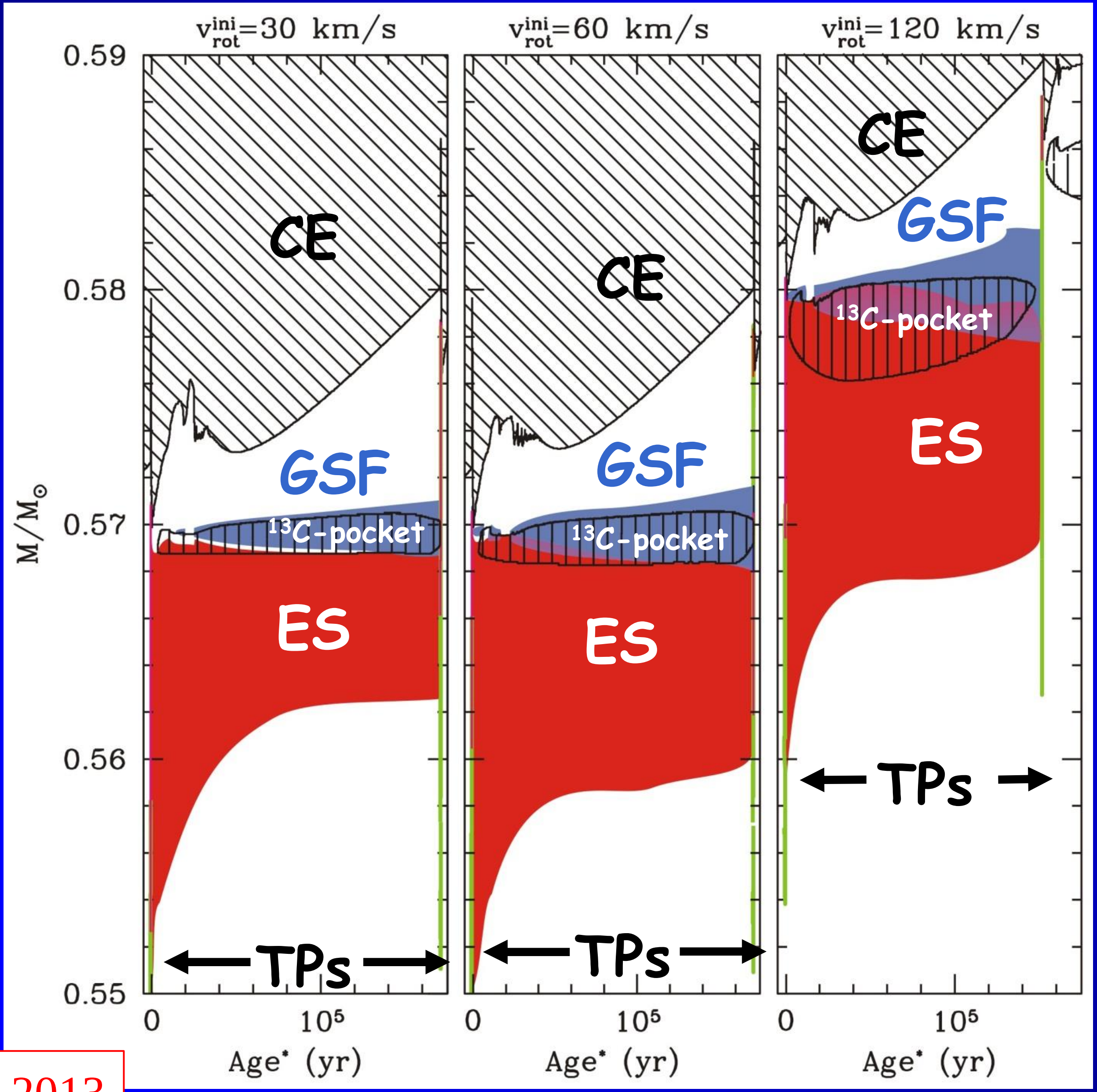
^{23}Na-pocket

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



Cristallo+ 2009

Rotation induced instabilities during the AGB phase

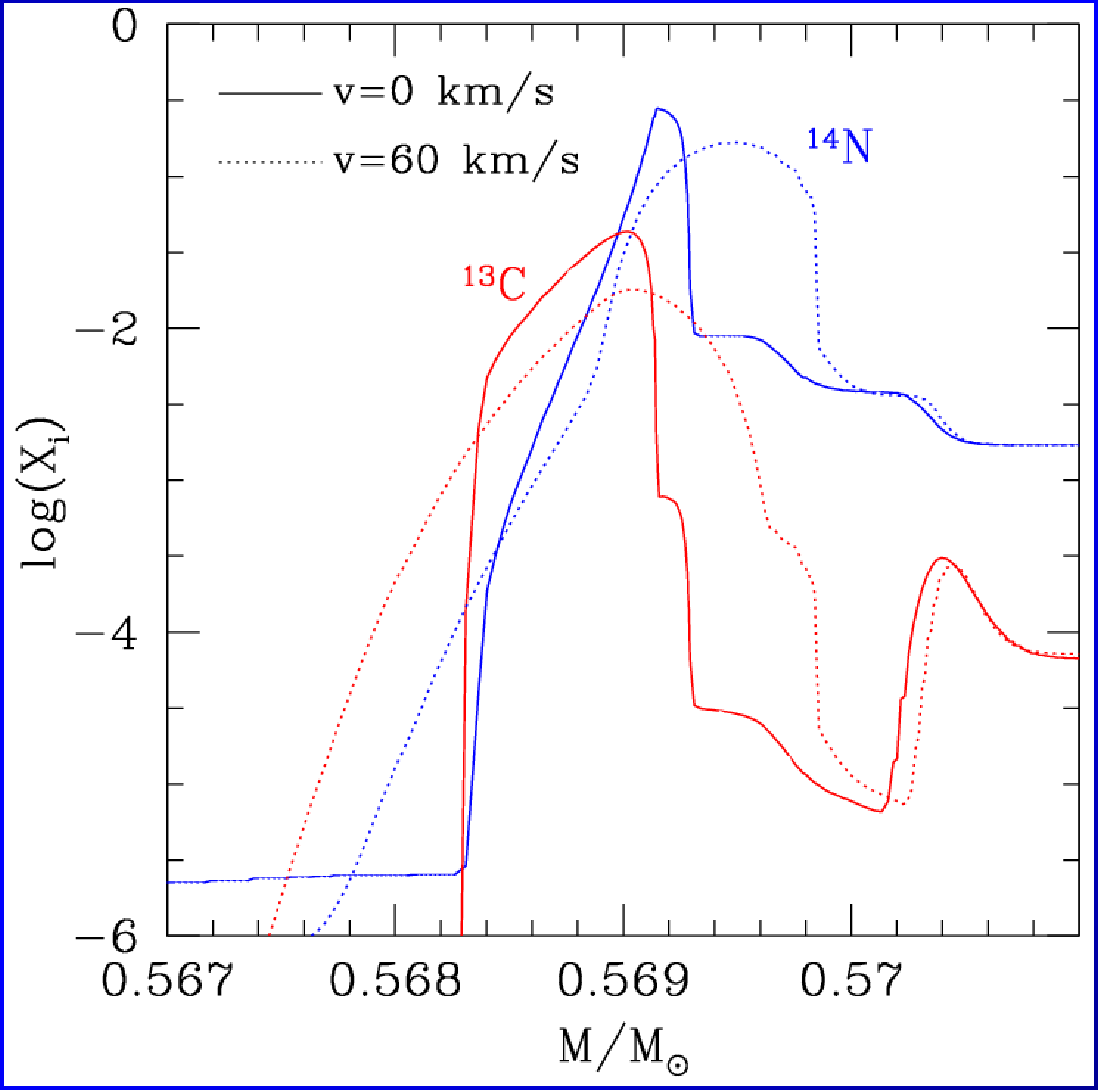


M=2.0 M_{SUN}
[Fe/H]=0

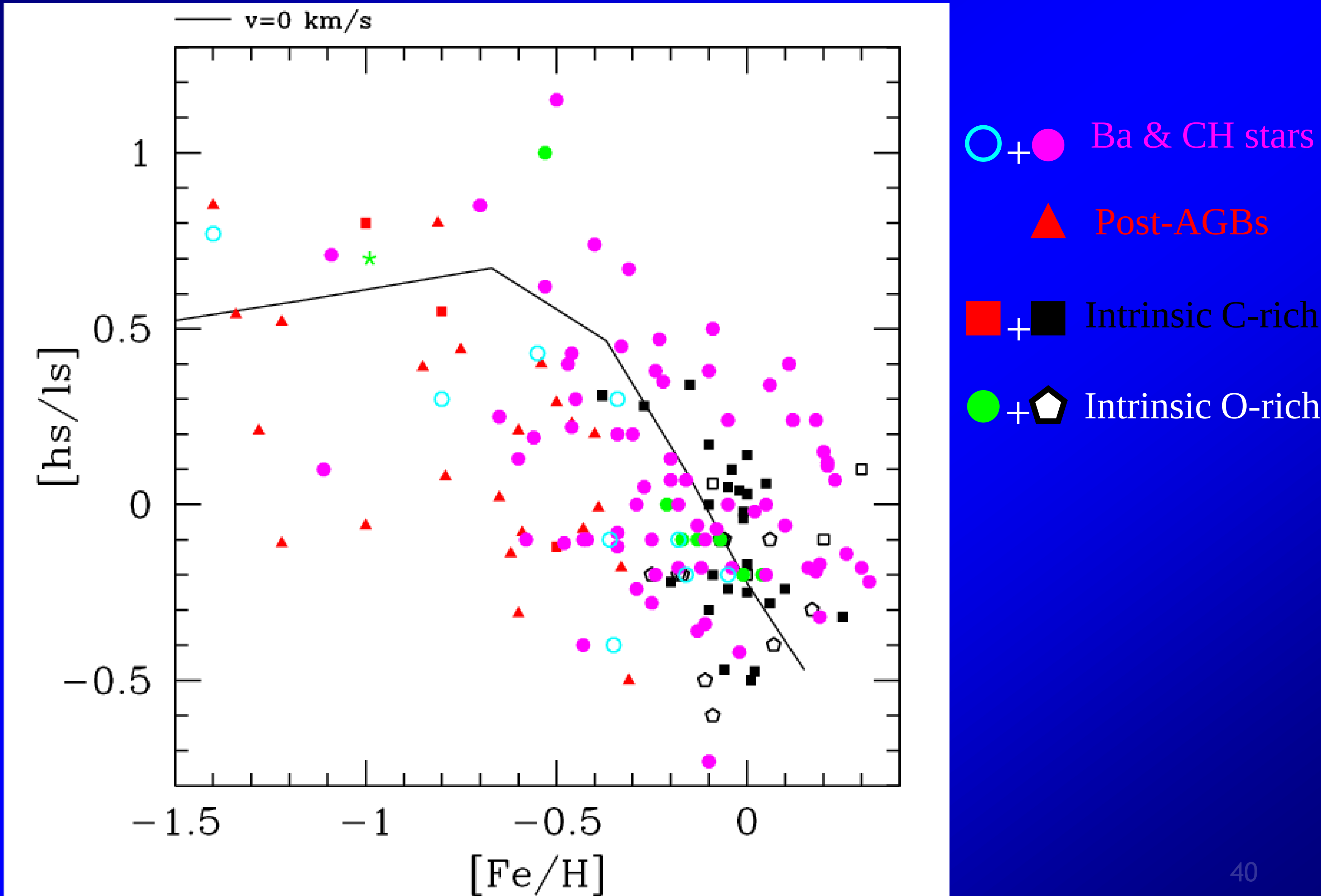
Piersanti+ 2013

NET EFFECT

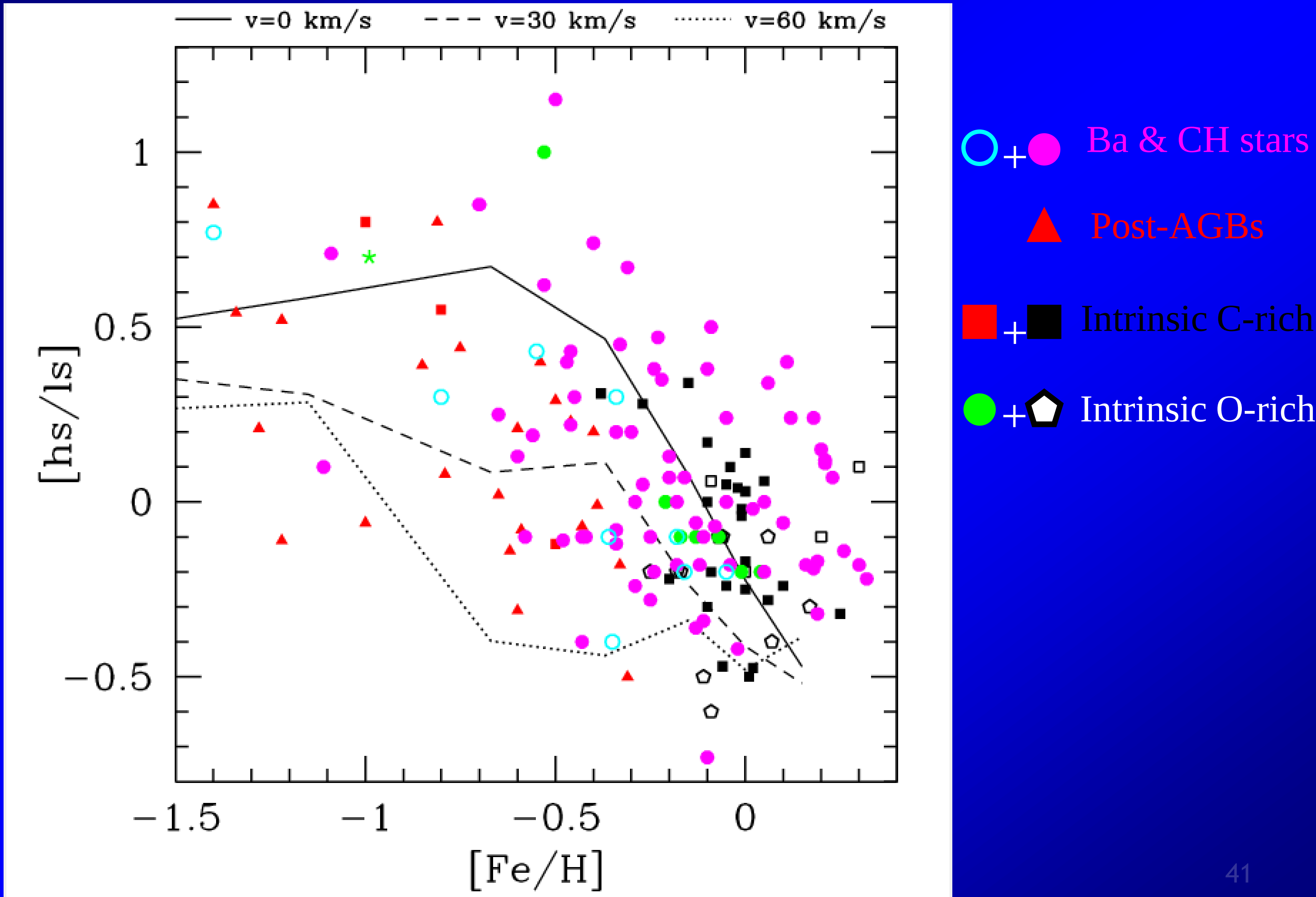
It mixes ^{14}N in ^{13}C-rich layers (and viceversa), thus implying a decrease of the local neutron density and an increase of the iron seeds. As a consequence, the surface s-process distributions change.



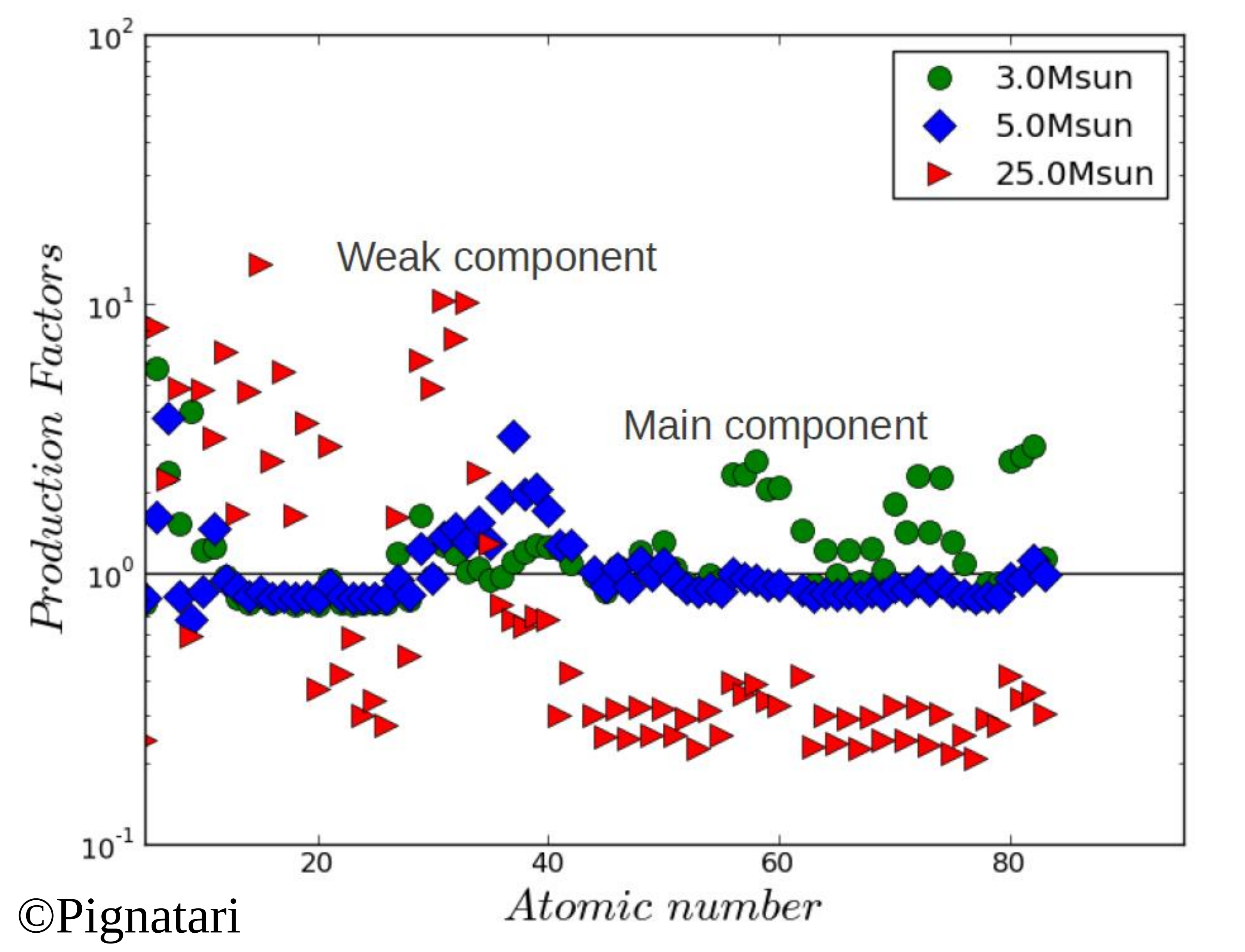
s-process indexes with rotation: [hs/ls]



s-process indexes with rotation: [hs/ls]



Different contributors



The contribution from intermediate mass AGBs

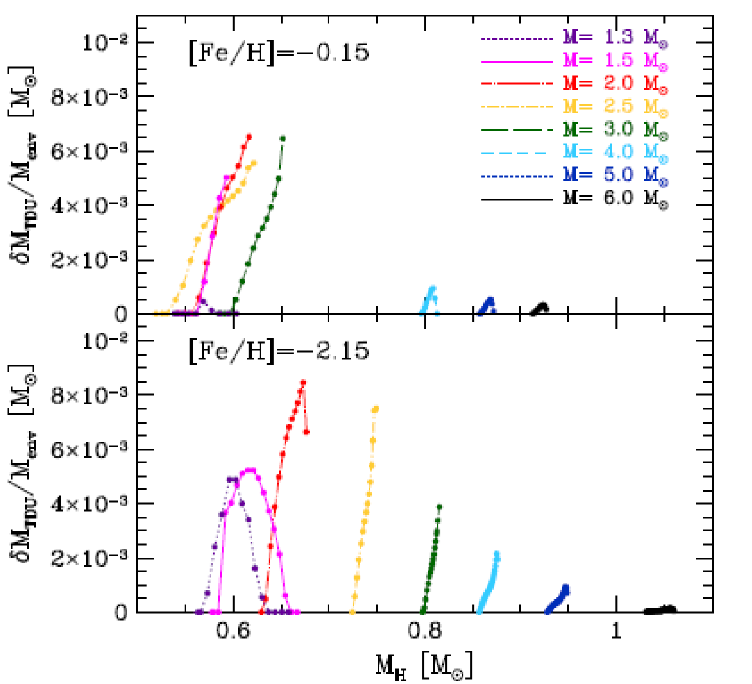


Figure 3. Ratio between the mass of H-depleted dredged-up material (δM_{TDU}) and the envelope mass (M_{env}) for different masses at $Z = 10^{-2}$ (upper panel) and $Z = 2.4 \times 10^{-4}$ (lower panel).

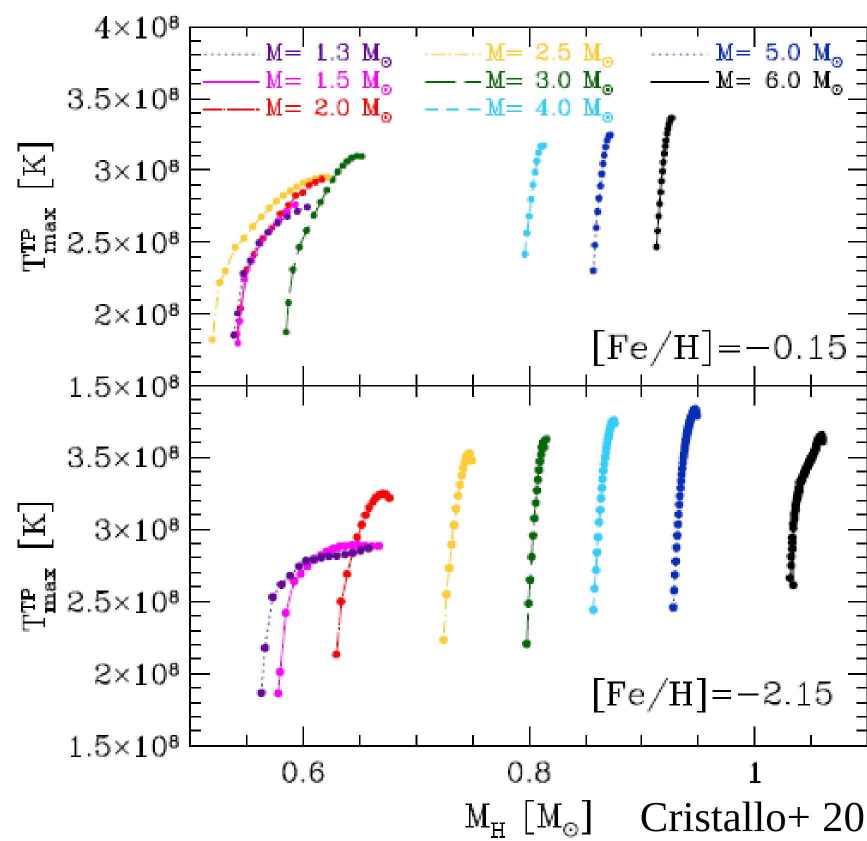
Cristallo+ 2015

The TDU efficiency decreases, but the number of thermal pulses is definitely larger. For instance, at low metallicities:

1.5 M_{SUN} ≈ 10 TDUs

2.5 M_{SUN} ≈ 20 TDUs

5.0 M_{SUN} ≈ 80 TDUs



Cristallo+ 2015

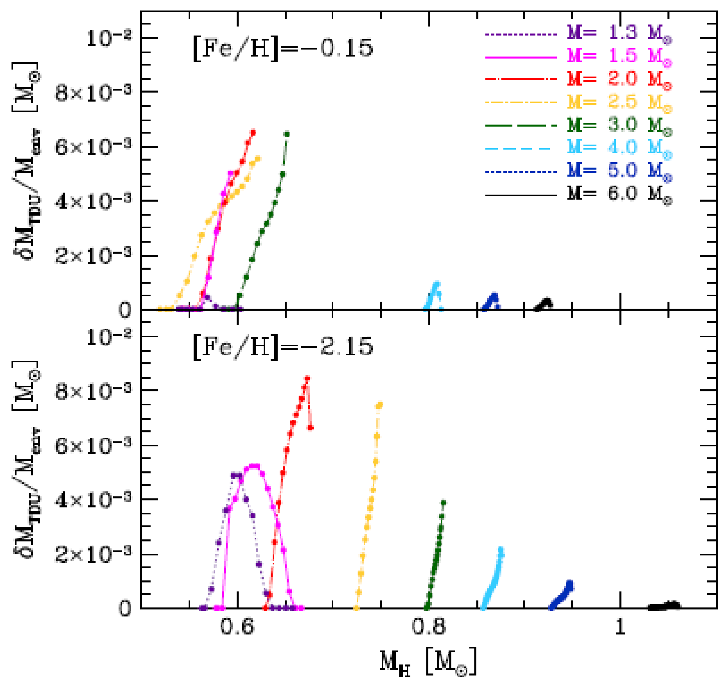
Moreover, the temperature attained at the base of the convective shell largely increases, For instance at low metallicities:

1.5 M_{SUN} ≈ 2.8x10^8 K

2.5 M_{SUN} ≈ 3.5x10^8 K

5.0 M_{SUN} ≈ 3.8x10^8 K

The contribution from intermediate mass AGBs



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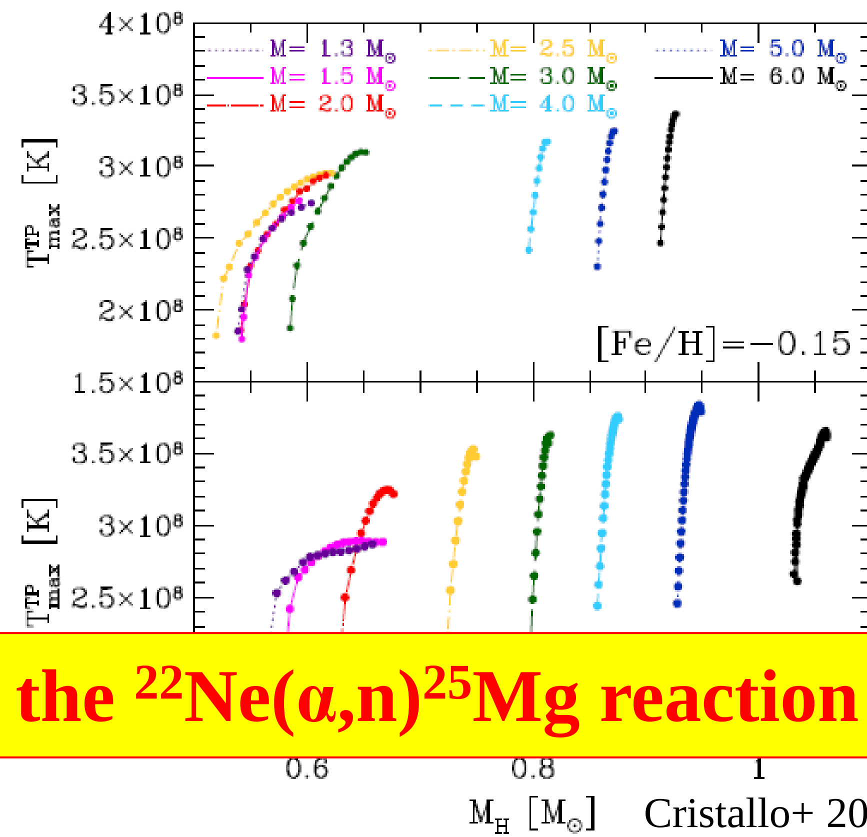
Cristallo+ 2015

The TDU efficiency decreases, but the number of thermal pulses is definitely larger. For instance, at low metallicities:

$1.5\ M_{SUN} \approx 10$ TDUs

$2.5\ M_{SUN} \approx 20$ TDUs

$5.0\ M_{SUN} \approx 80$ TDUs



Cristallo+ 2015

Moreover, the temperature attained at the base of the convective shell largely increases, For instance at low metallicities:

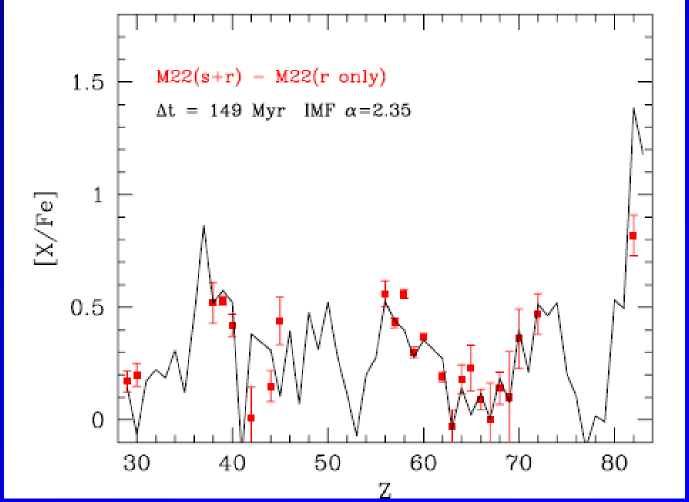
1.5 M

2.5 M

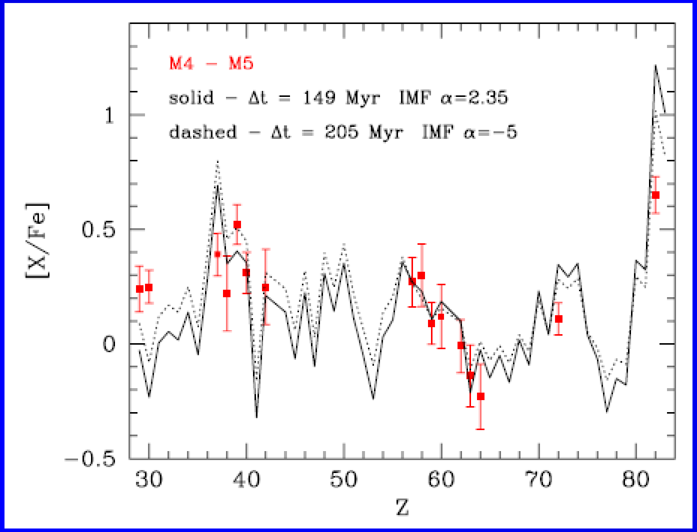
$5.0\ M_{SUN} \approx 3.8 \times 10^{8}$ K

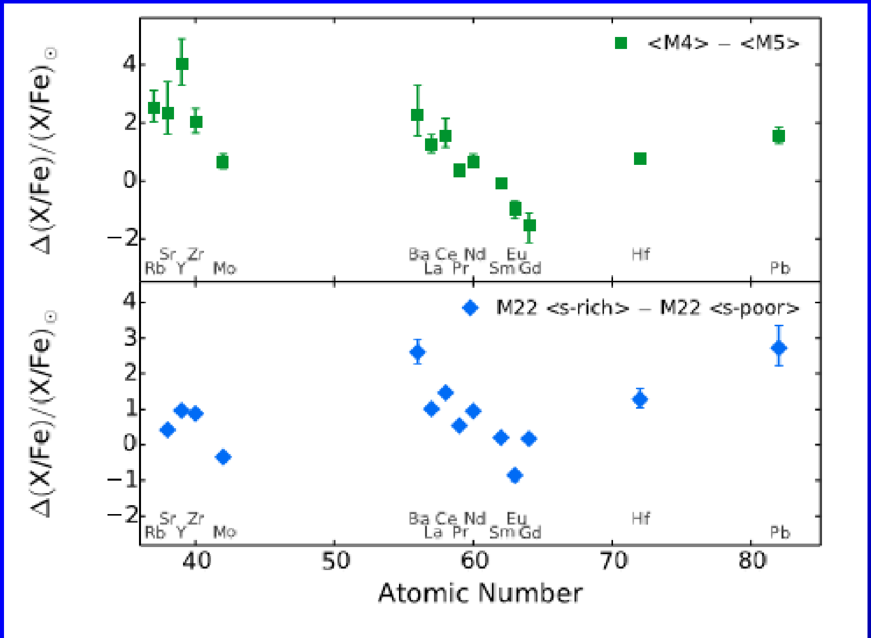
Larger contribution from the $^{22}Ne(\alpha,n)^{25}Mg$ reaction

s-rich Globular Clusters: the importance of massive AGBs



Straniero+ 2014

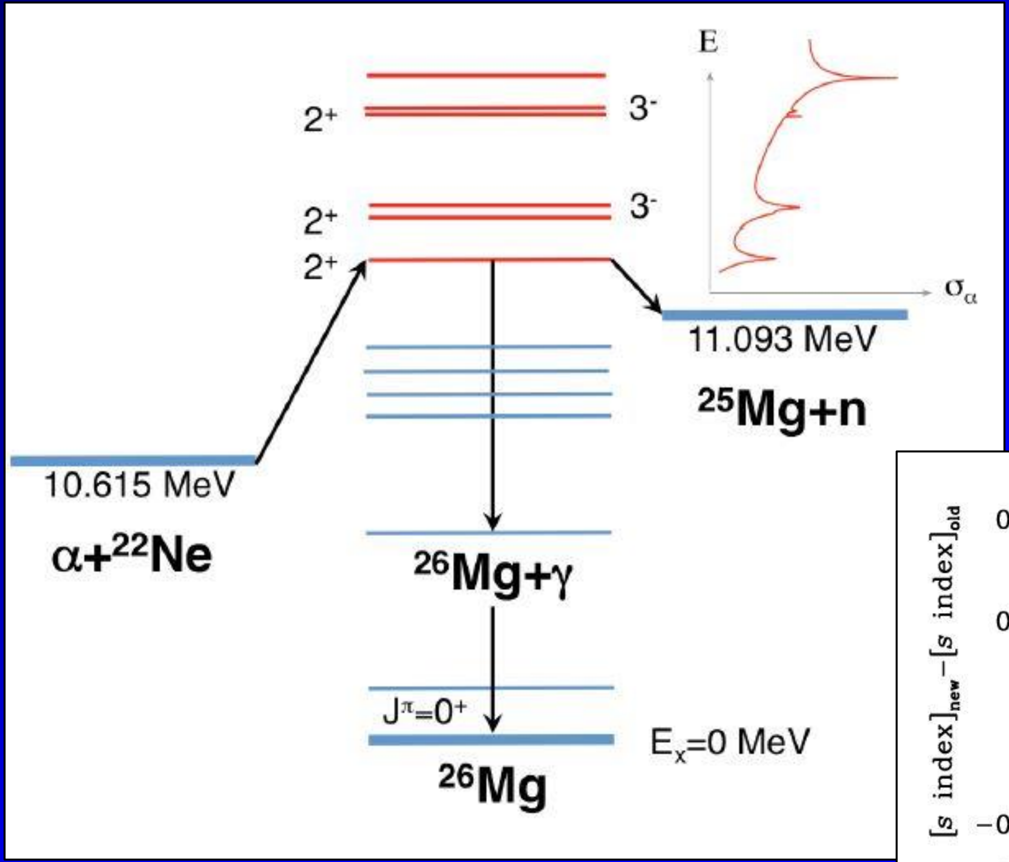


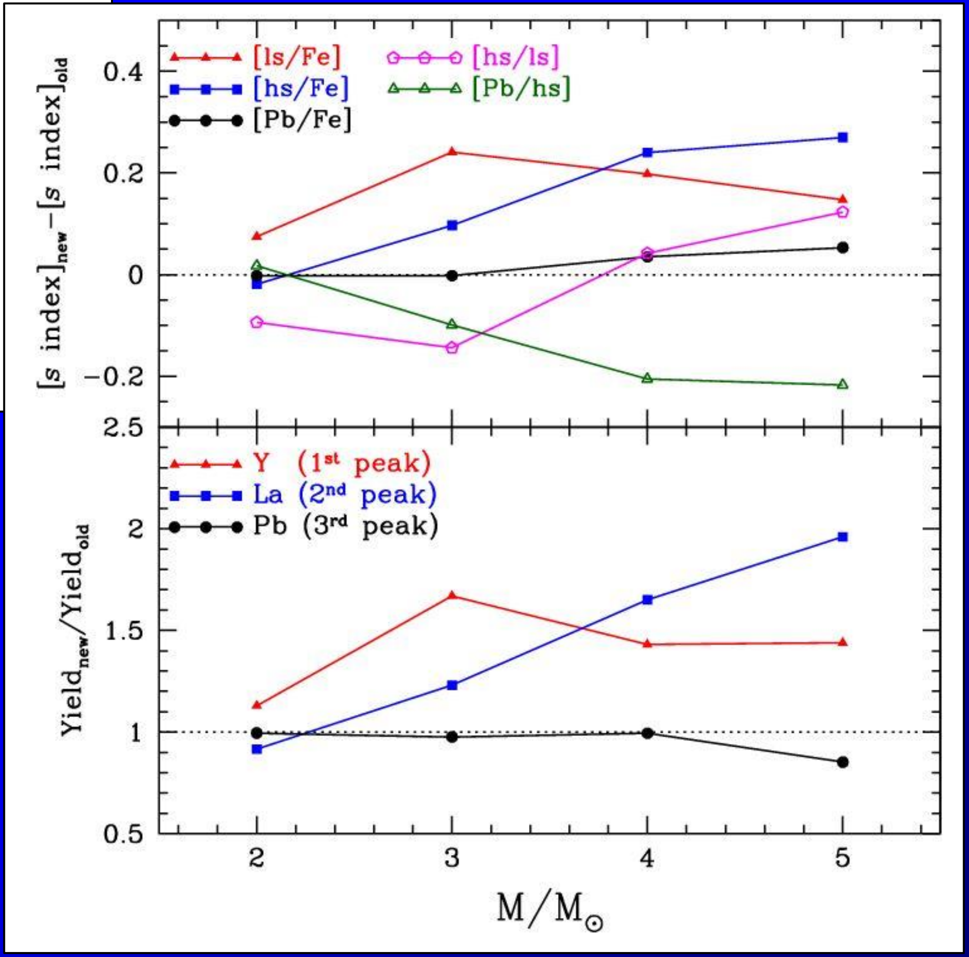


Shingles+ 2014

Massimi+ 2017 (n_TOF collaboration)

^{25}Mg(n,γ) and ^{25}Mg(n,tot)



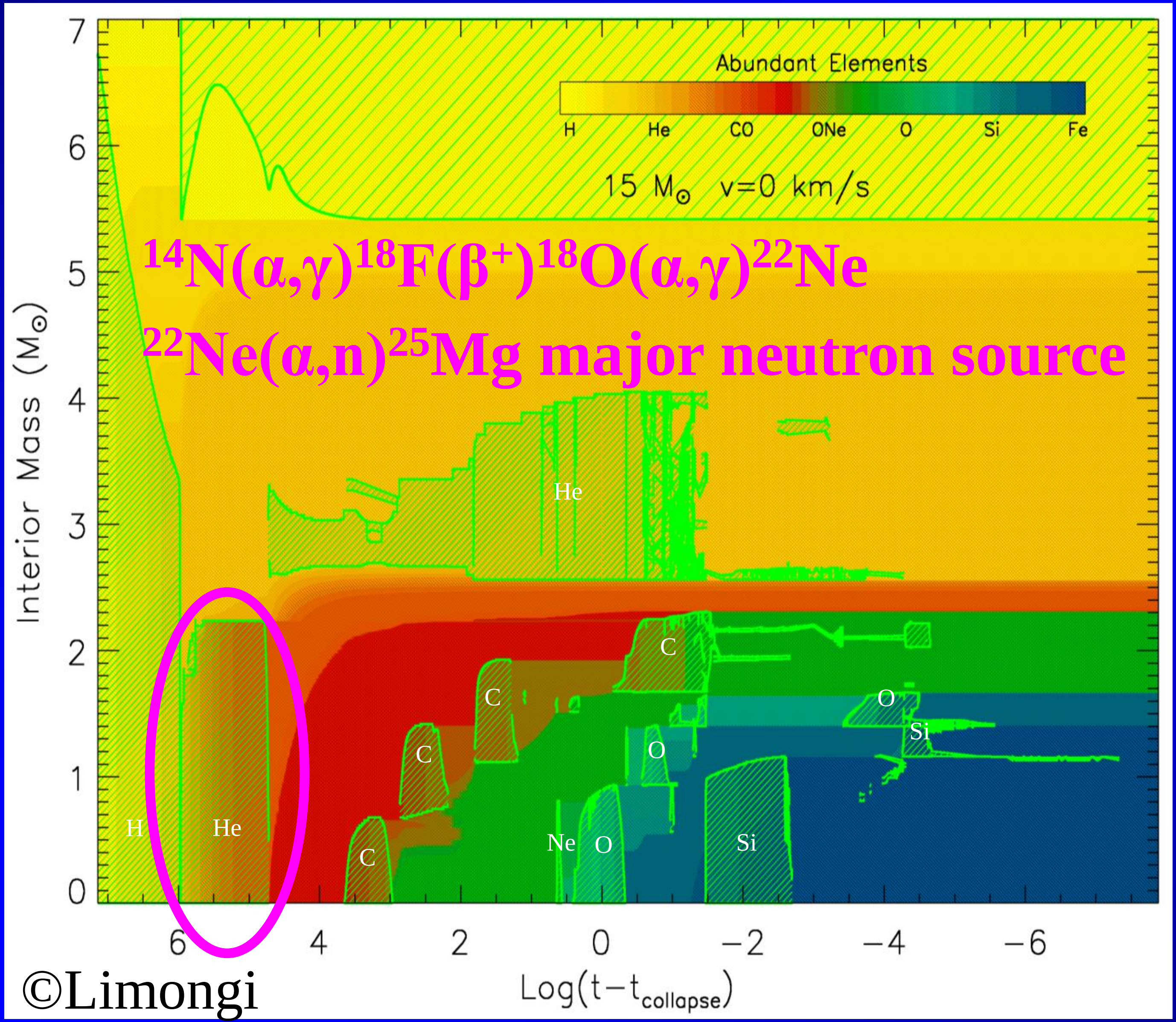


An unambiguous spin/parity assignment of the corresponding excited states in ^{26}Mg

↓

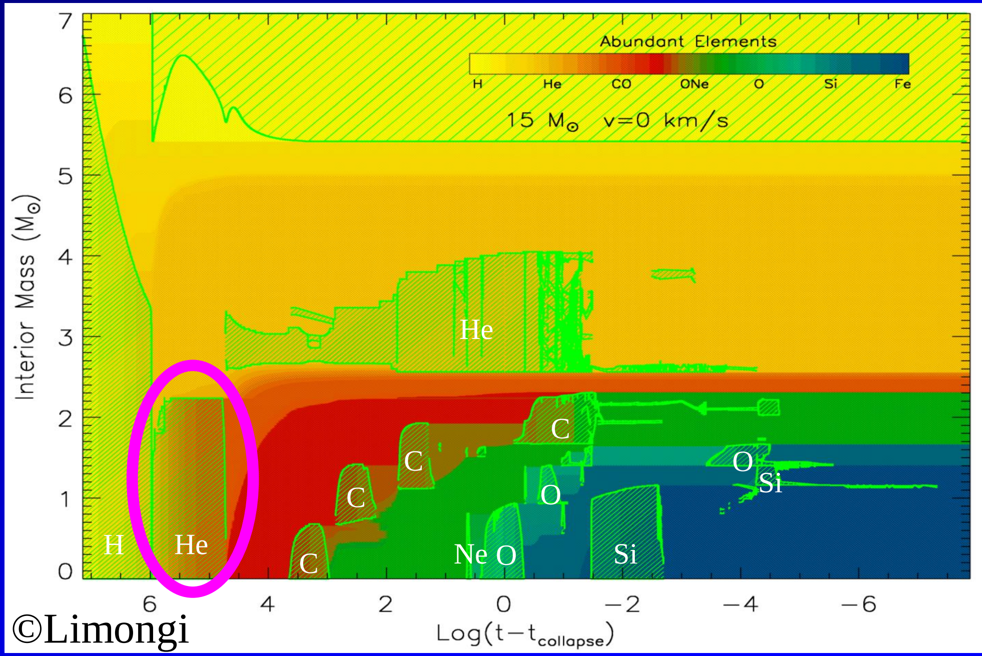
Experimental upper limits of the reaction rates for ^{22}Ne(α,*n*)^{25}Mg and ^{22}Ne(α,γ)^{26}Mg, potentially leading to a significantly higher (α,*n*)/(α,γ) ratio than previously evaluated.

The weak s-process and the evolution of massive stars



Oh, Be A Fine Girl Kiss Me Right Now!

Core He-burning phase



$3\alpha \rightarrow {}^{12}C$

${}^{12}C(\alpha,\gamma){}^{16}O$

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

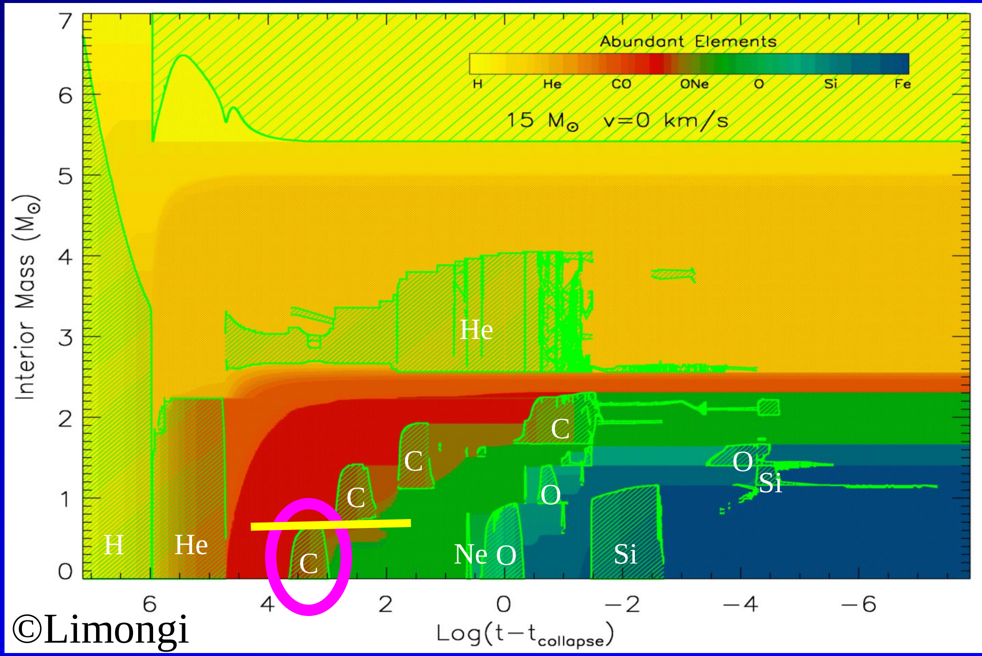
$\tau \approx 1$ Myr

When $T \sim 3 x 10^8$ K the **${}^{22}Ne(\alpha,n){}^{25}Mg$ is efficiently activated**

The resulting neutron density is low ($\sim 10^6$ n/cm^3)

Similar to the Classical s-process

Core C-burning phase



$^{12}C(^{12}C,\alpha)^{20}Ne$

$^{12}C(^{12}C,p)^{23}Na$

$^{12}C(^{12}C,n)^{23}Mg^*$

$\tau \approx 1$ Kyr

Some ^{22}Ne is left after He burning

All (α,n) channels are activated:

$^{13}C(\alpha,n)^{16}O$ - $^{17}O(\alpha,n)^{20}Ne$

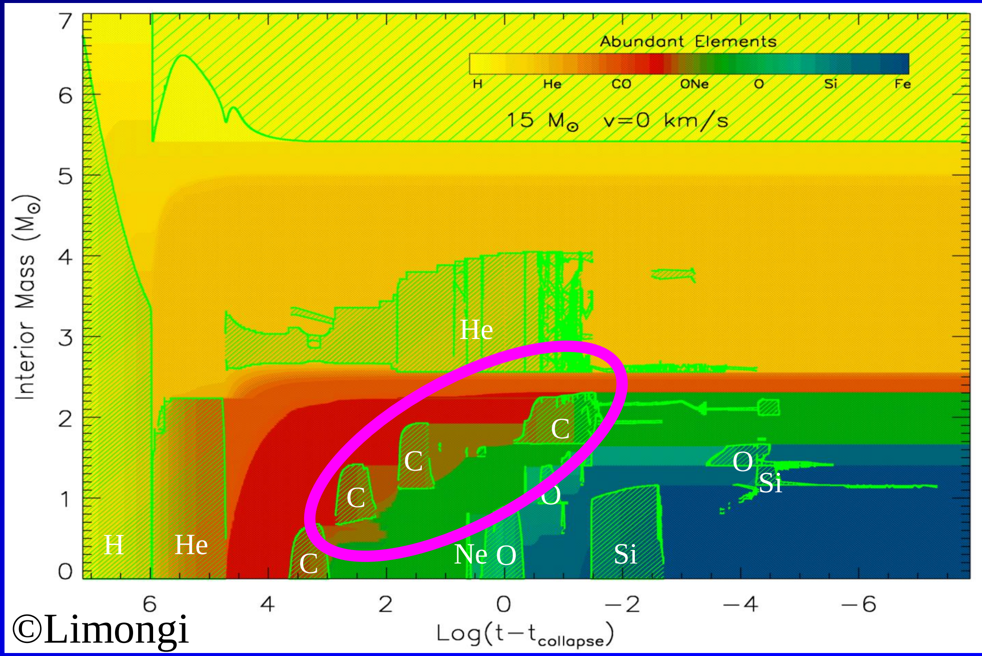
$^{18}O(\alpha,n)^{21}Ne$ - $^{21}Ne(\alpha,n)^{24}Mg$

$^{22}Ne(\alpha,n)^{25}Mg$ - $^{25}Mg(\alpha,n)^{28}Si$

$^{26}Mg(\alpha,n)^{29}Si$

The resulting neutron density is very high, BUT…

Shell C-burning phase



$^{12}C(^{12}C,\alpha)^{20}Ne$

$^{12}C(^{12}C,p)^{23}Na$

$^{12}C(^{12}C,n)^{23}Mg^*$

Why not the $^{13}C(\alpha,n)^{16}O$?
Because at $T\sim1\times10^9$ K
the $^{13}N(\gamma,p)^{12}C^*$ works!!

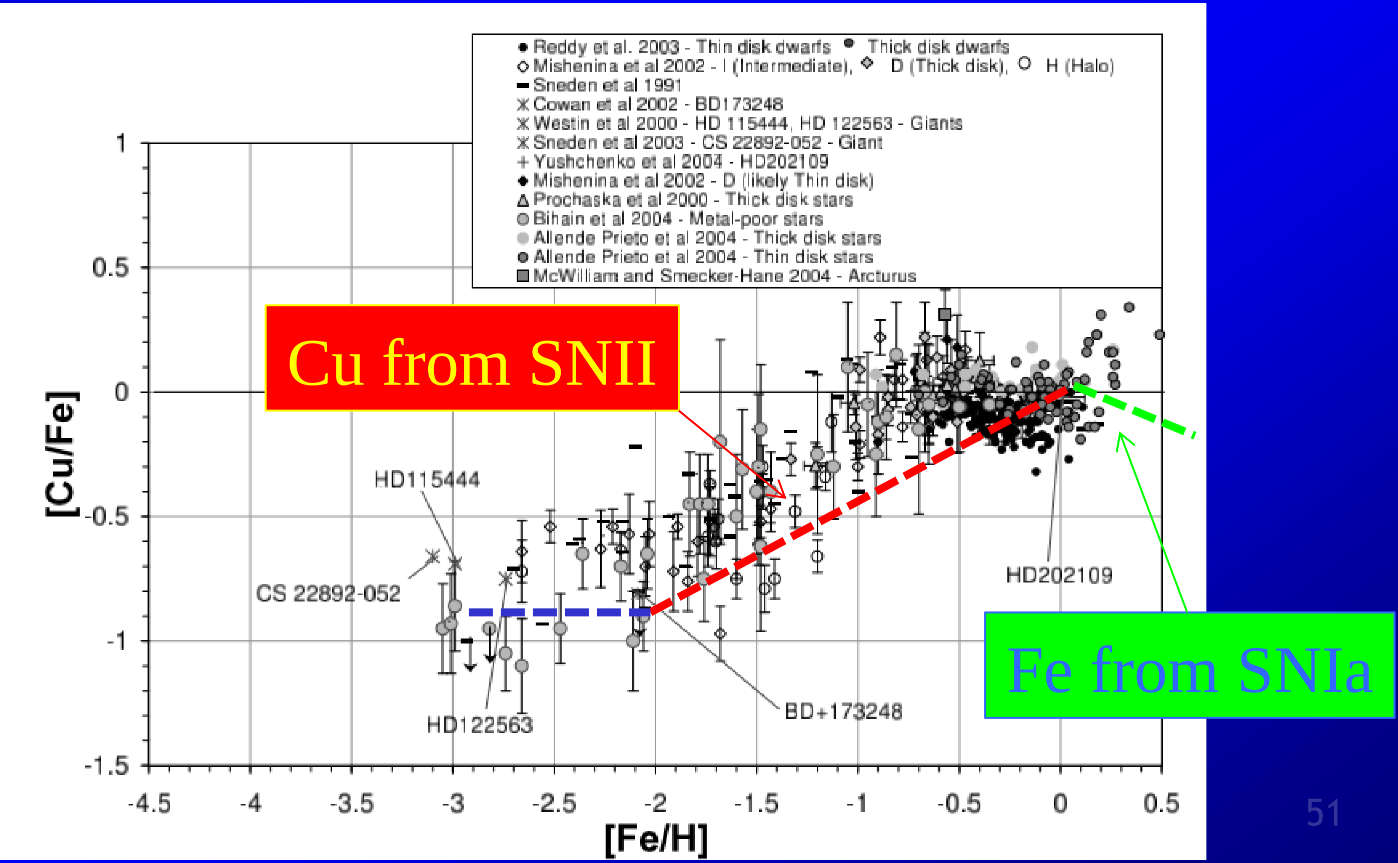
All (α,n) channels are activated:
$^{13}C(\alpha,n)^{16}O$ - $^{17}O(\alpha,n)^{20}Ne$
$^{18}O(\alpha,n)^{21}Ne$ - $^{21}Ne(\alpha,n)^{24}Mg$
$^{22}Ne(\alpha,n)^{25}Mg$ - $^{25}Mg(\alpha,n)^{28}Si$
$^{26}Mg(\alpha,n)^{29}Si$

The resulting neutron density is very high:
10^{11}-10^{12} n/cm^3

Secondary nature of the weak s-process

Both ^{22}Ne (neutron source) and ^{25}Mg (main neutron poison) scale with metallicity. Thus, weak s-process yields strongly depend on the initial metallicity.

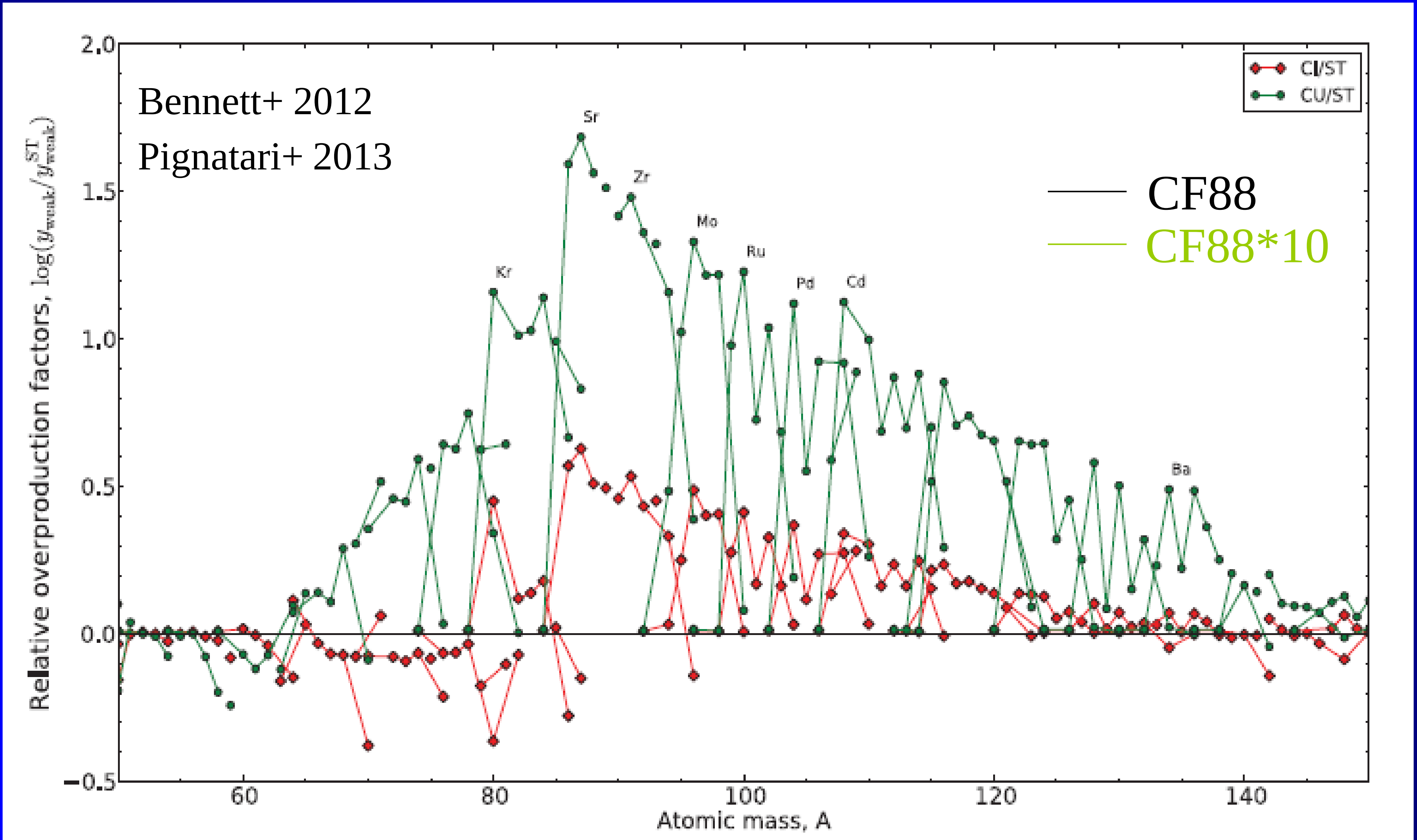
An example:
the Cu evolution



Bisterzo+ 2004

Uncertainties of the weak s-process: cross sections

$^{12}C(^{12}C,x)x$ - $^{22}Ne(\alpha,x)x$ - $^{12}C(\alpha,\gamma)^{16}O$



Uncertainties of the weak s-process: stellar modelling

Convection - Rotation

Strong production of primary ^{14}N at low metallicities

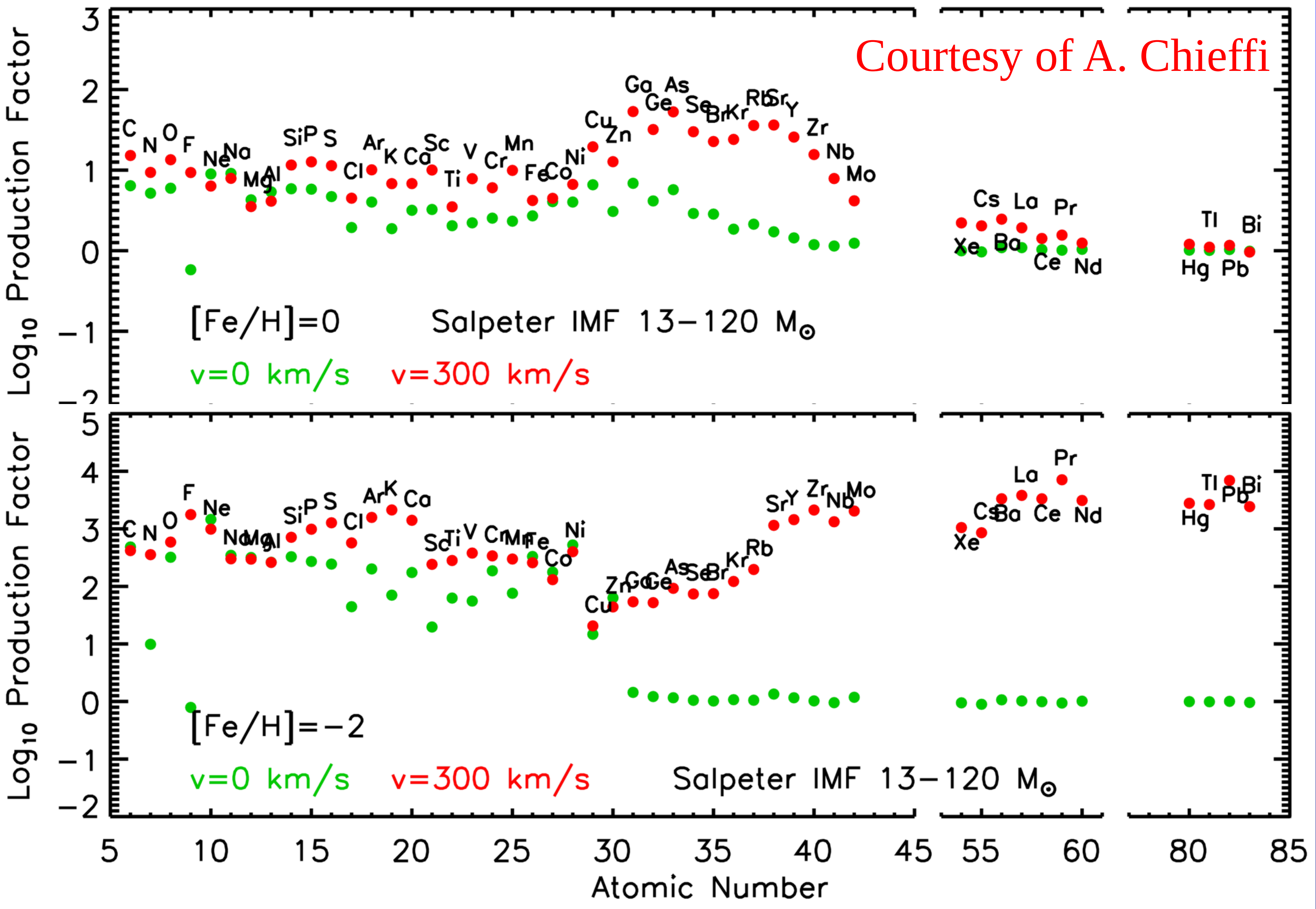
$$^{13}\mathrm{C}/^{14}\mathrm{N} \simeq 5.7 \cdot 10^{-3}$$

In any case the dominant source is the

^{22}Ne(α,n)^{25}Mg

Courtesy of A. Chieffi

The effect of rotation: differences in the stellar ejecta



“We are stardust”

Joni Mitchell, Woodstock

Thank you!