The weak s-process dependence on initial star mass and metallicity

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…..and

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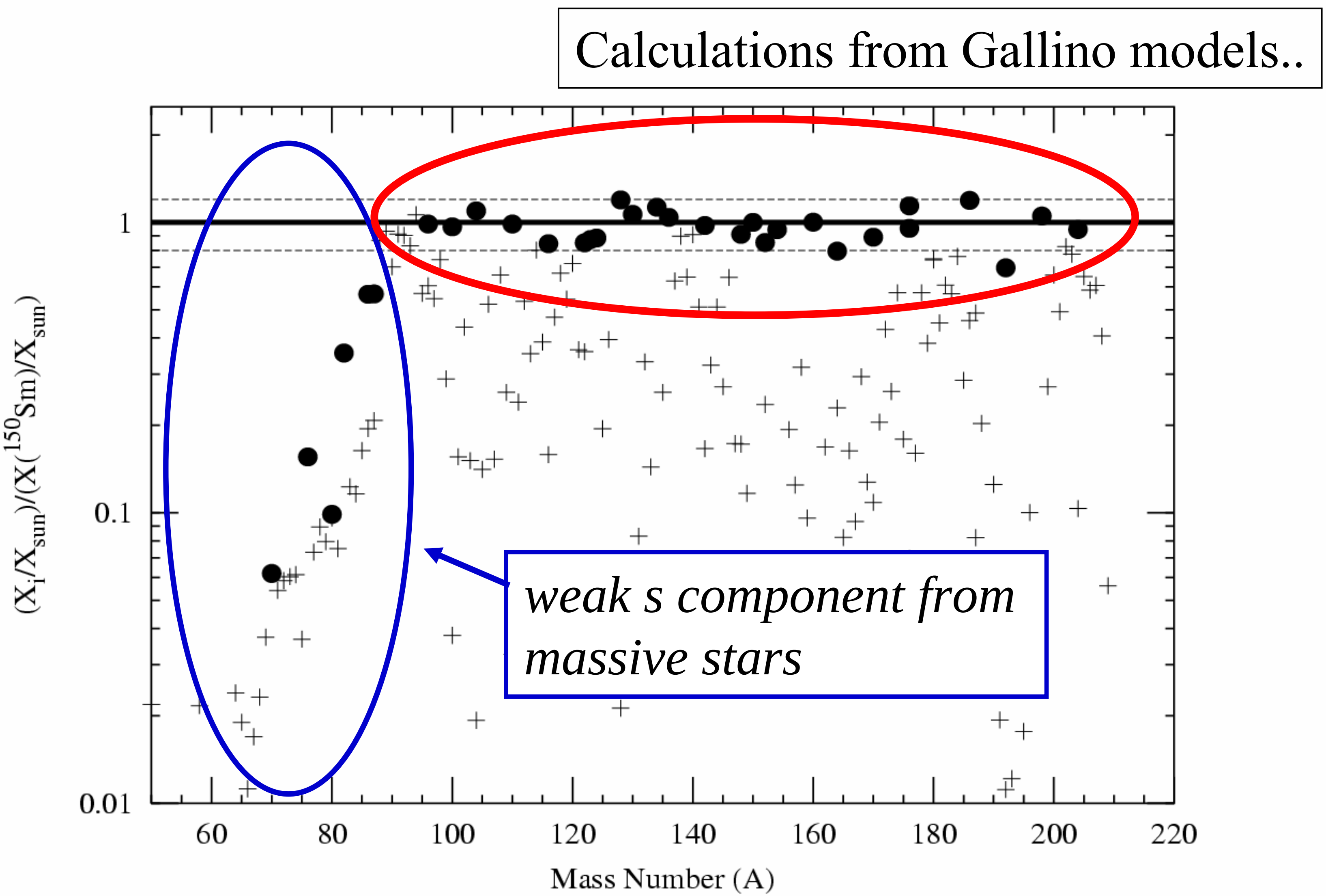
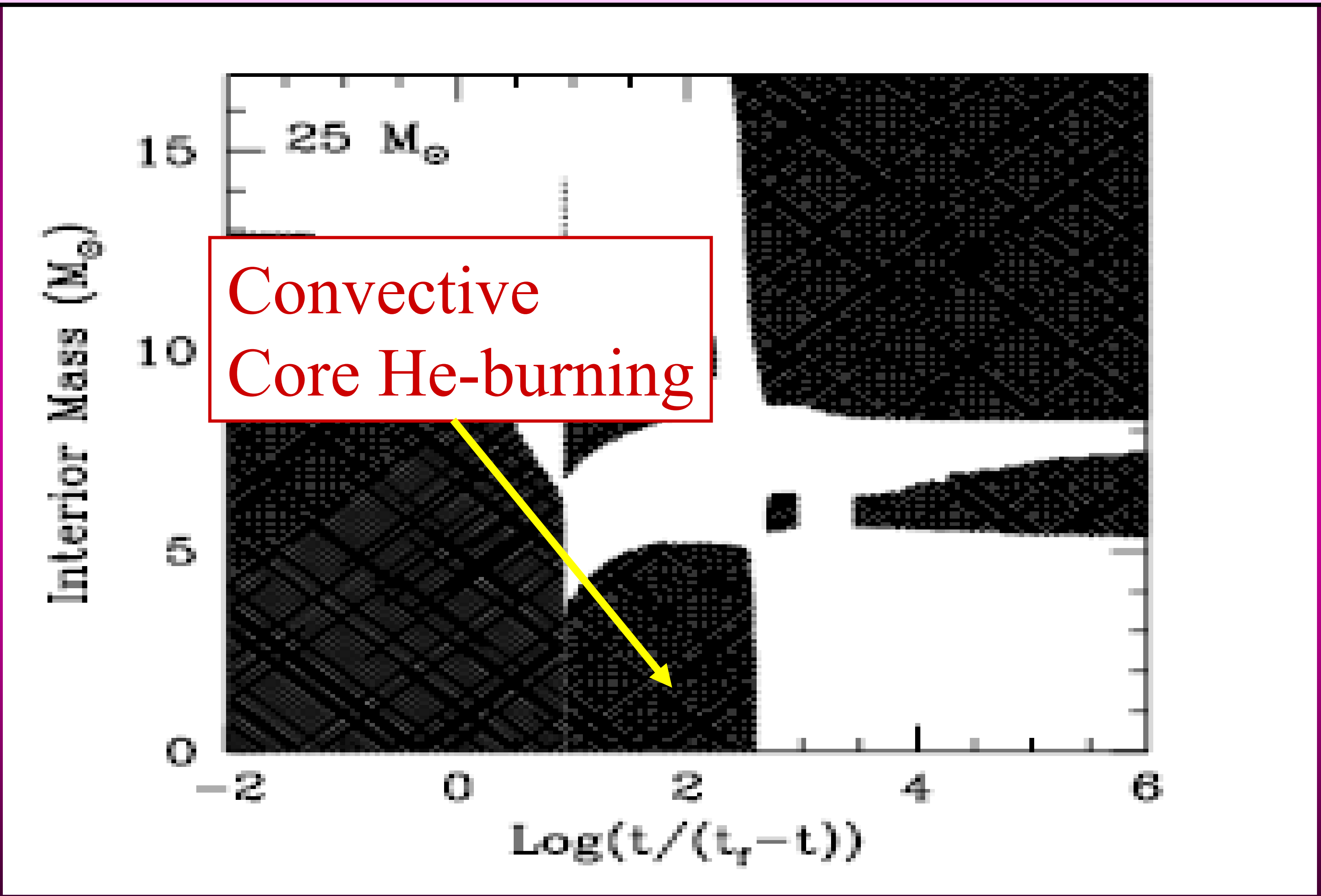
The main s component from AGB stars gives a marginal contribution in the region between Fe and Sr



Kippenhahn's Diagram for a star with M= 25 M(sun) and solar metallicity (Limongi, Straniero & Chieffi 2000)



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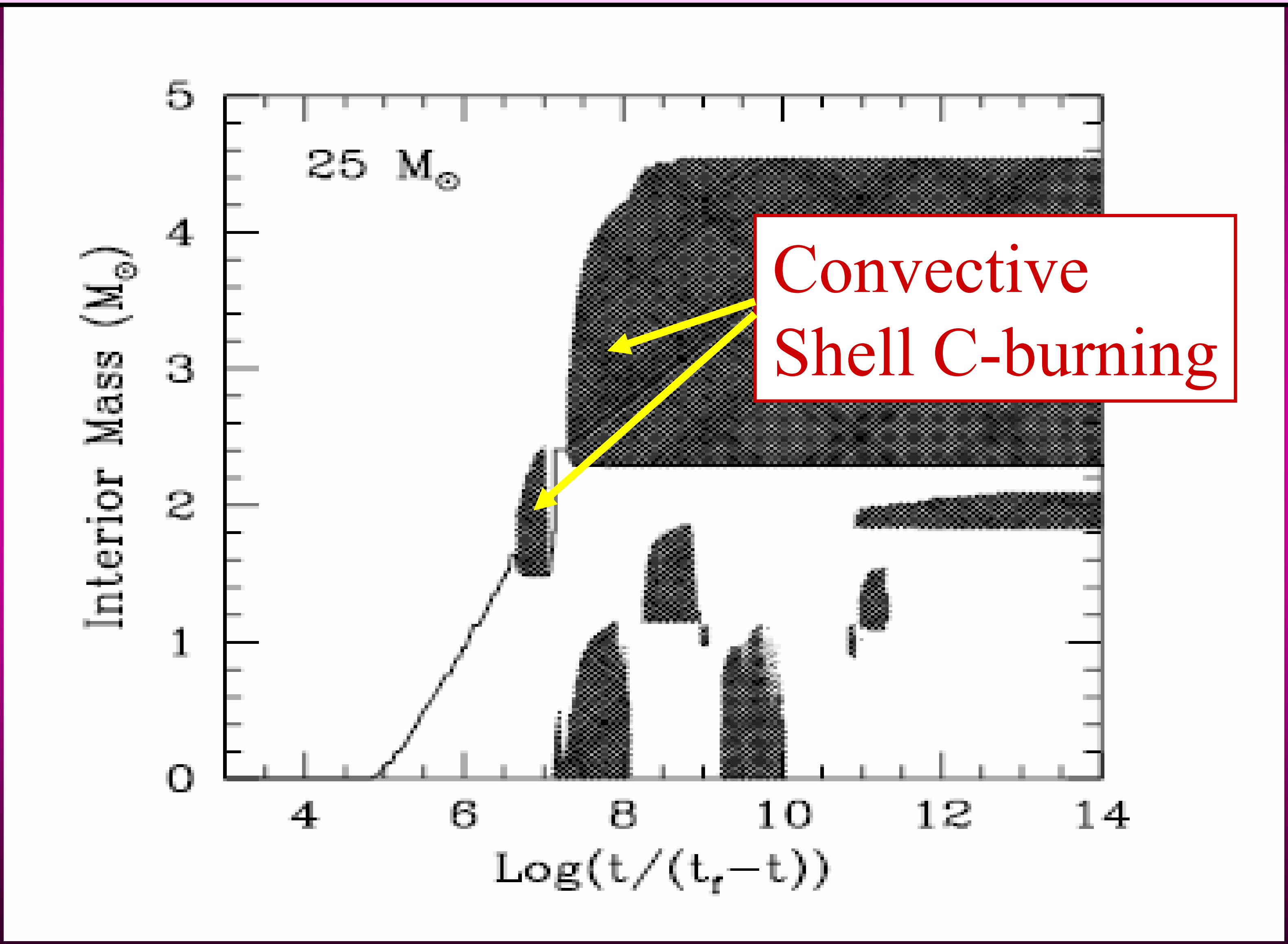


The weak s-component

Convective Core He-burning | **Convective Shell C-burning**

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

CNO cycle → ^{14}N

$^{14}N(\alpha,\gamma)^{18}F(\beta+)^{18}O$ in the initial phase of the He-burning

$^{18}O(\alpha,\gamma)^{22}Ne$ when $T_{eff} > 2.5\times10^{8}$ K

Residual ^{22}Ne in the He core ashes provides neutrons in the next convective C shell episodes.

^{22}Ne is secondary

In the C shell:

C-burning:

$^{12}C(^{12}C,\alpha)^{20}Ne$, α-source ((α,n) channels are activated!)
$^{12}C(^{12}C,p)^{23}Na$, p-source
$^{12}C(^{12}C,n)^{23}Mg^*$, negligible

^{16}O is the most abundant isotope (~ 0.7)

The weak s-component

Convective Core He-burning | **Convective Shell C-burning**

Other neutron sources:

$^{13}C(\alpha,n)^{16}O$ recycles neutrons captured by ^{12}C
In the C shell ^{13}C cannot be produced by $^{12}C(p,\gamma)^{13}N(\beta+)^{13}C$….

$^{17}O(\alpha,n)^{20}Ne$ recycles neutrons captured by ^{16}O
In the C shell…

Moreover, in the C shell there are also:
- $^{21}Ne(\alpha,n)^{24}Mg$ that recycles neutrons captured by ^{20}Ne.
- Marginal contribution from the primary $^{12}C(^{12}C,n)^{23}Mg$

The weak s-component

Convective Core He-burning

Low neutron density (~10^6 n/cm^3)
T~3-3.5×10^8 K
Classical s-process

Lamb et al. 1977,
Couch et al. 1974,
Prantzos et al. 1987,
Raiteri et al. 1991 ......

Convective Shell C-burning

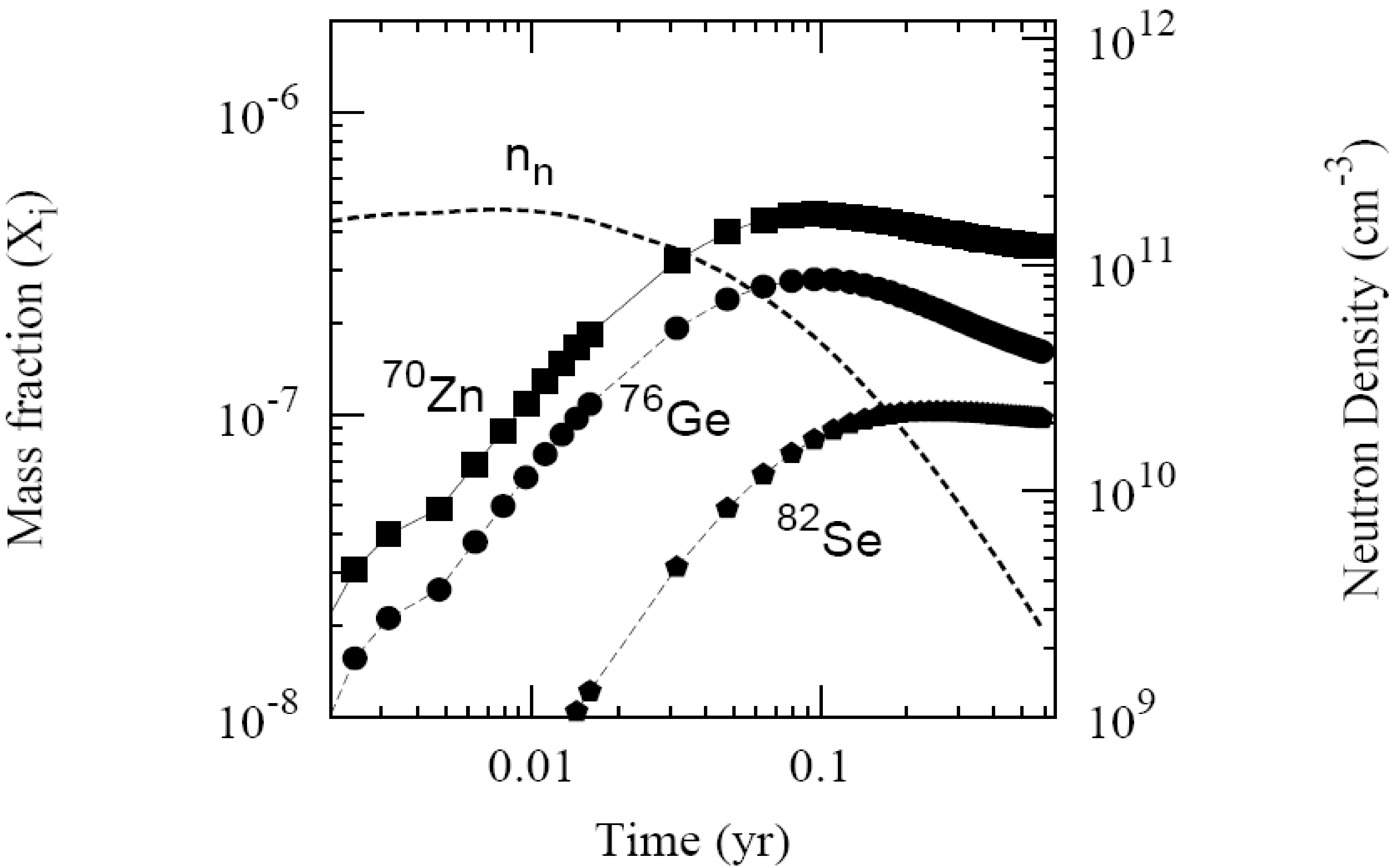
Peak neutron density
(10^{11}- 10^{12} n/cm^3)

T~ 1×10^9 K

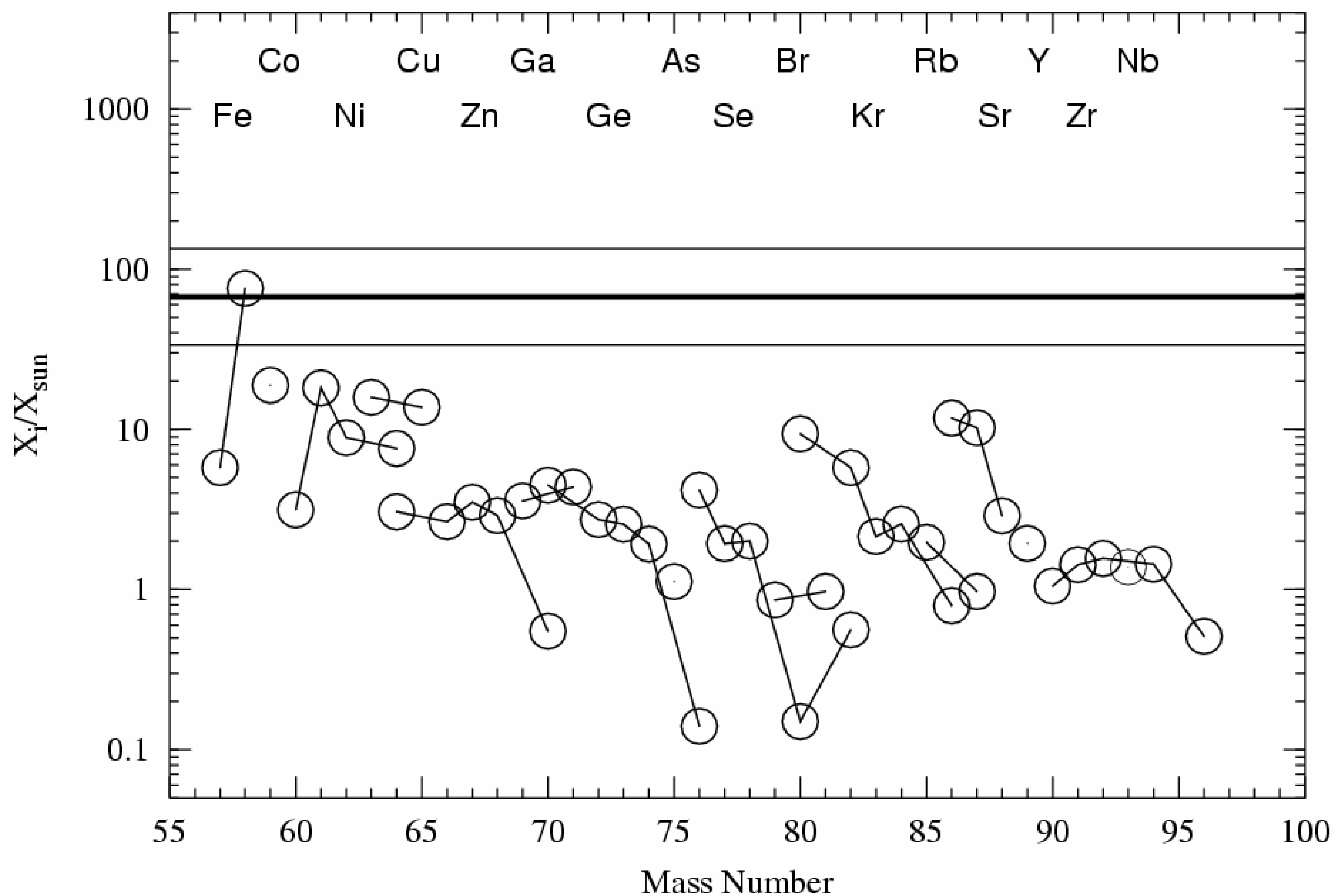
The convective shell works over the ashes of the previous core He-burning
(Raiteri et al. 1991)

The final weak s component is an overposition of two different s(s+) components

This is not a classic s-process,
the neutron density peak is 10^{11}-10^{12} cm^{-3}



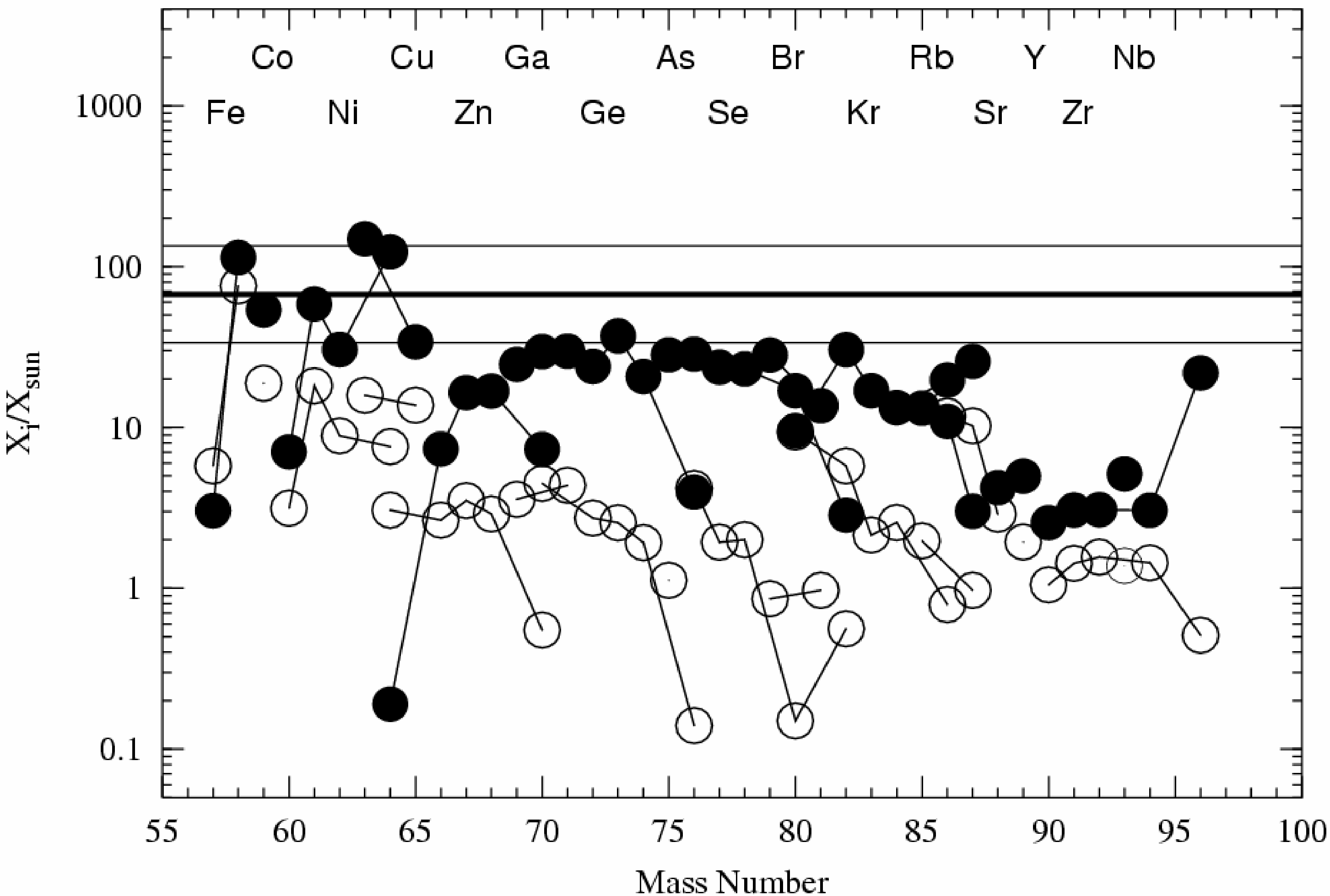
15 Msun [Fe/H] = 0
He core



$\tau = 0.059\ \mathrm{mb}^{-1}$

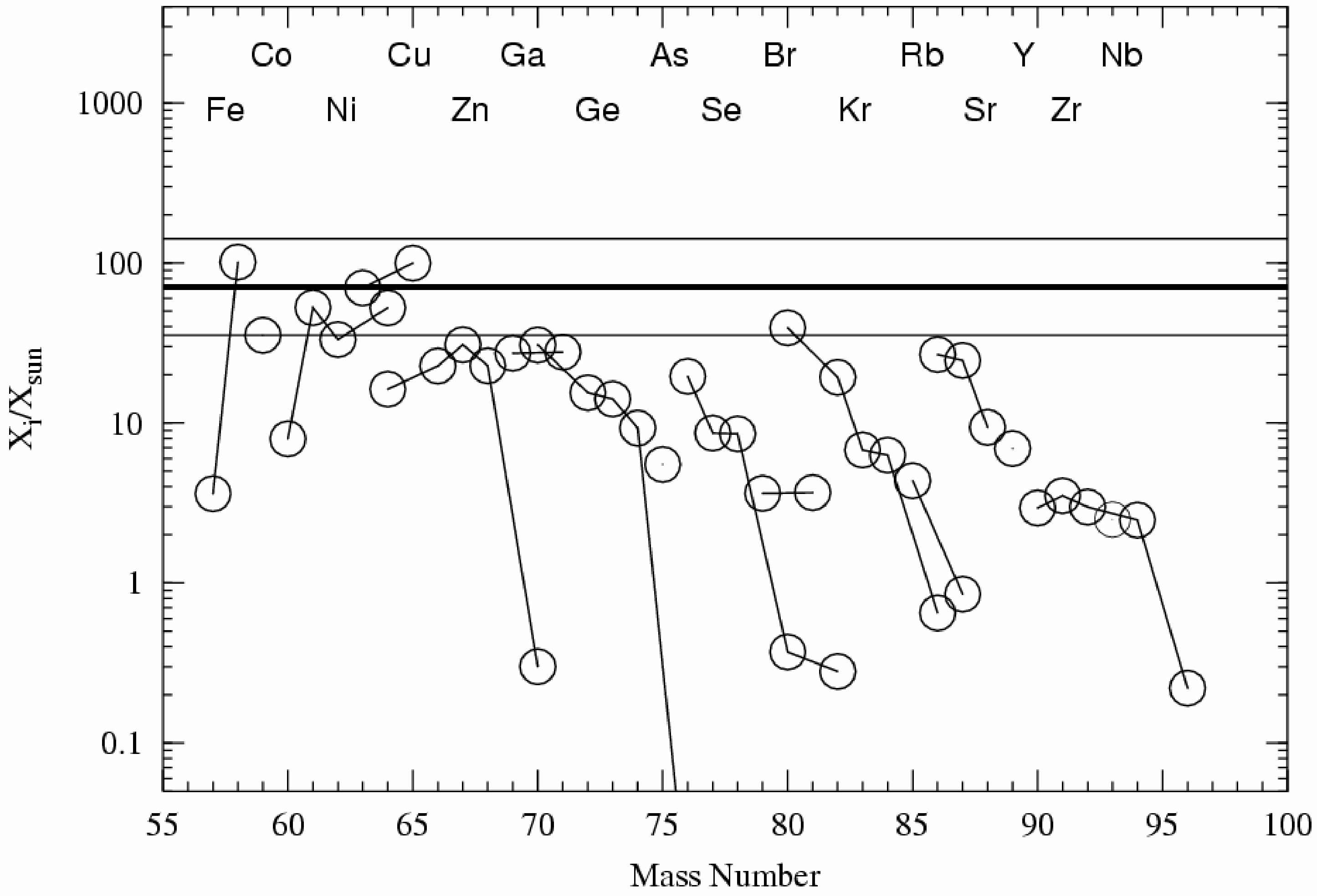
$d\tau = n_n \cdot v_T \cdot dt$

15 Msun [Fe/H] = 0
He core + C shell



$\tau = 0.059 + 0.149\ mb^{-1}$

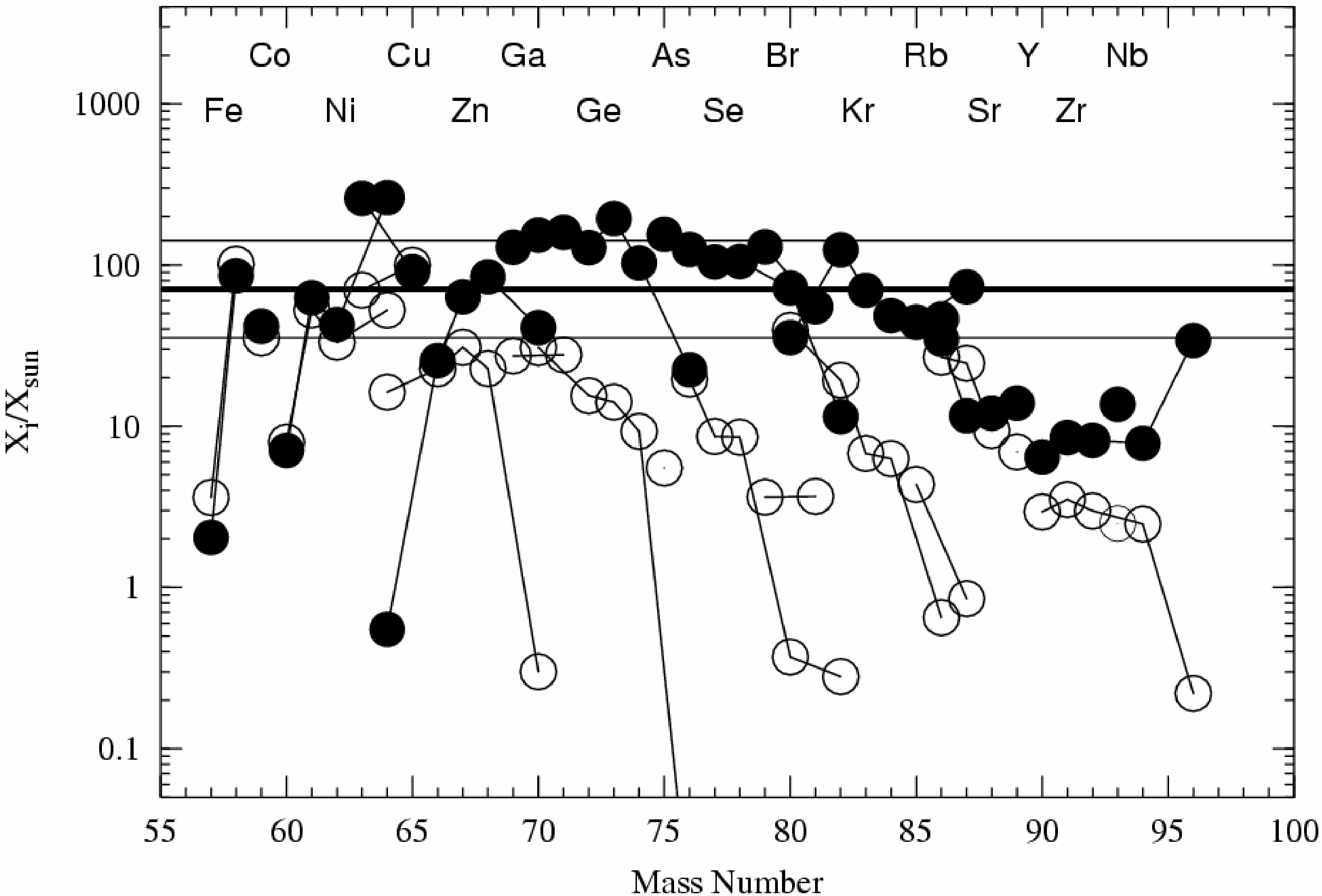
20 Msun [Fe/H] = 0
He core



$\tau = 0.130\ mb^{-1}$

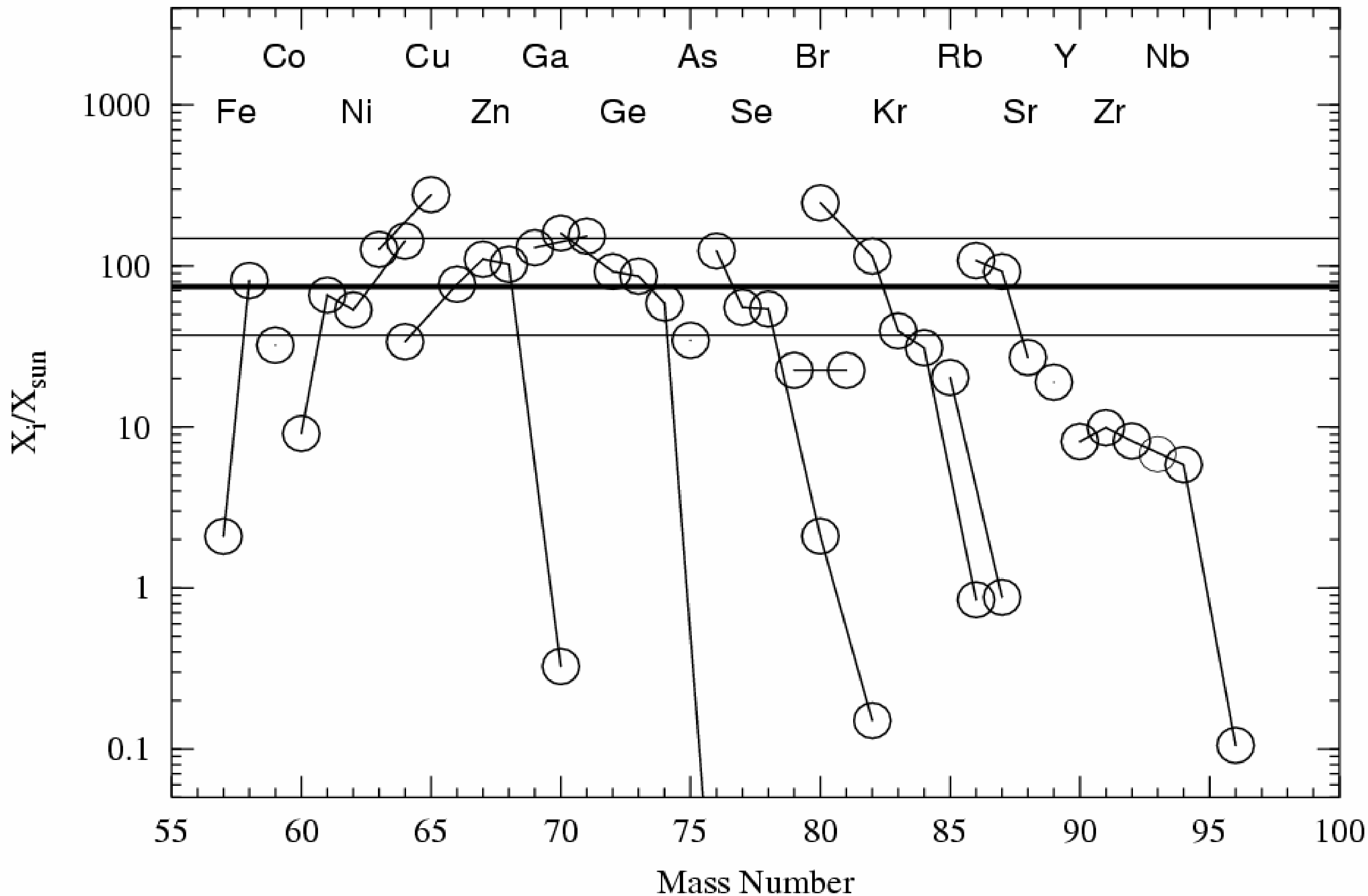
20 Msun [Fe/H] = 0

He core + C shell



$\tau = 0.130 + 0.122\ mb^{-1}$

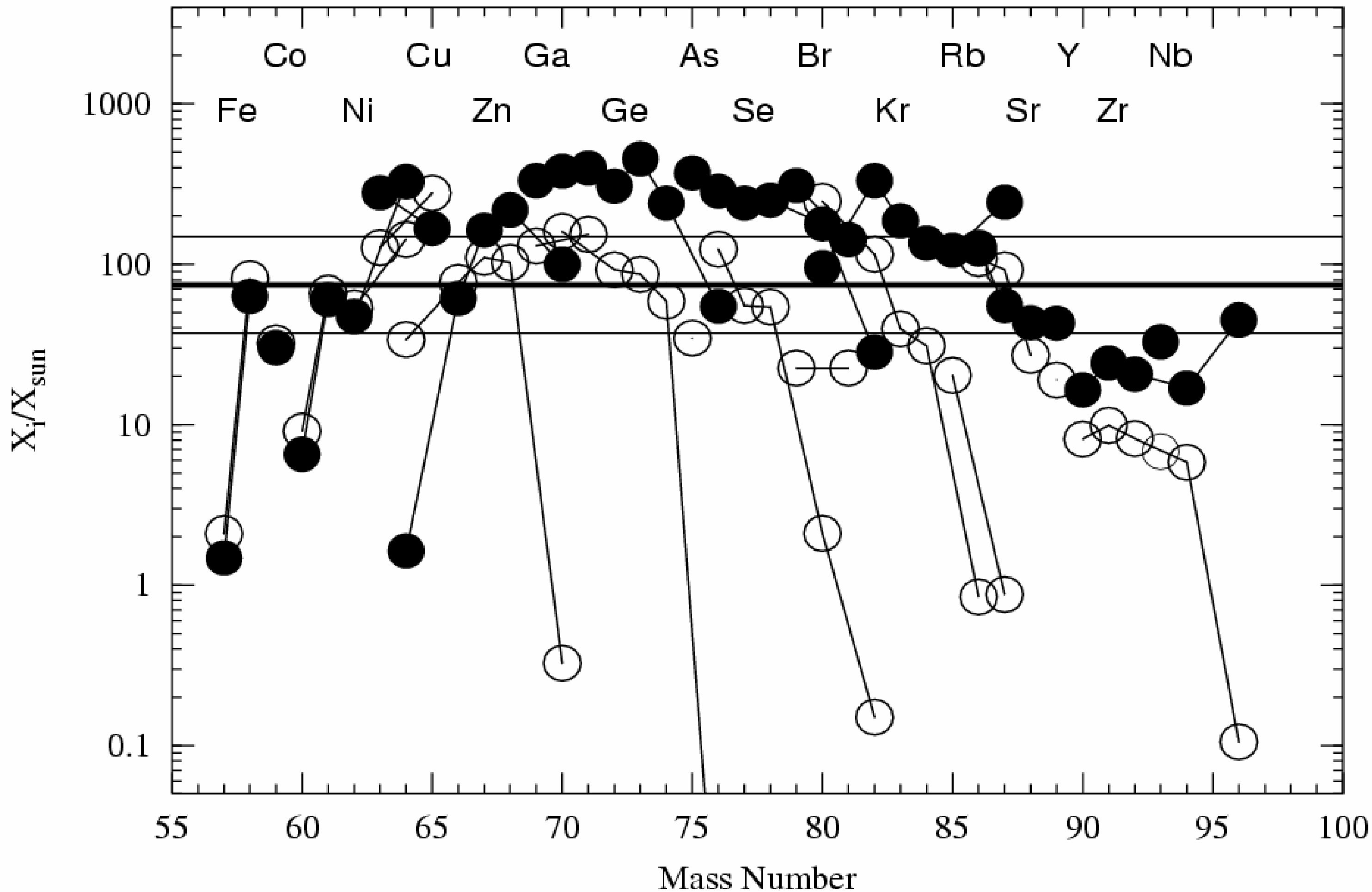
25 Msun [Fe/H] = 0
He core



$\tau = 0.196\ mb^{-1}$

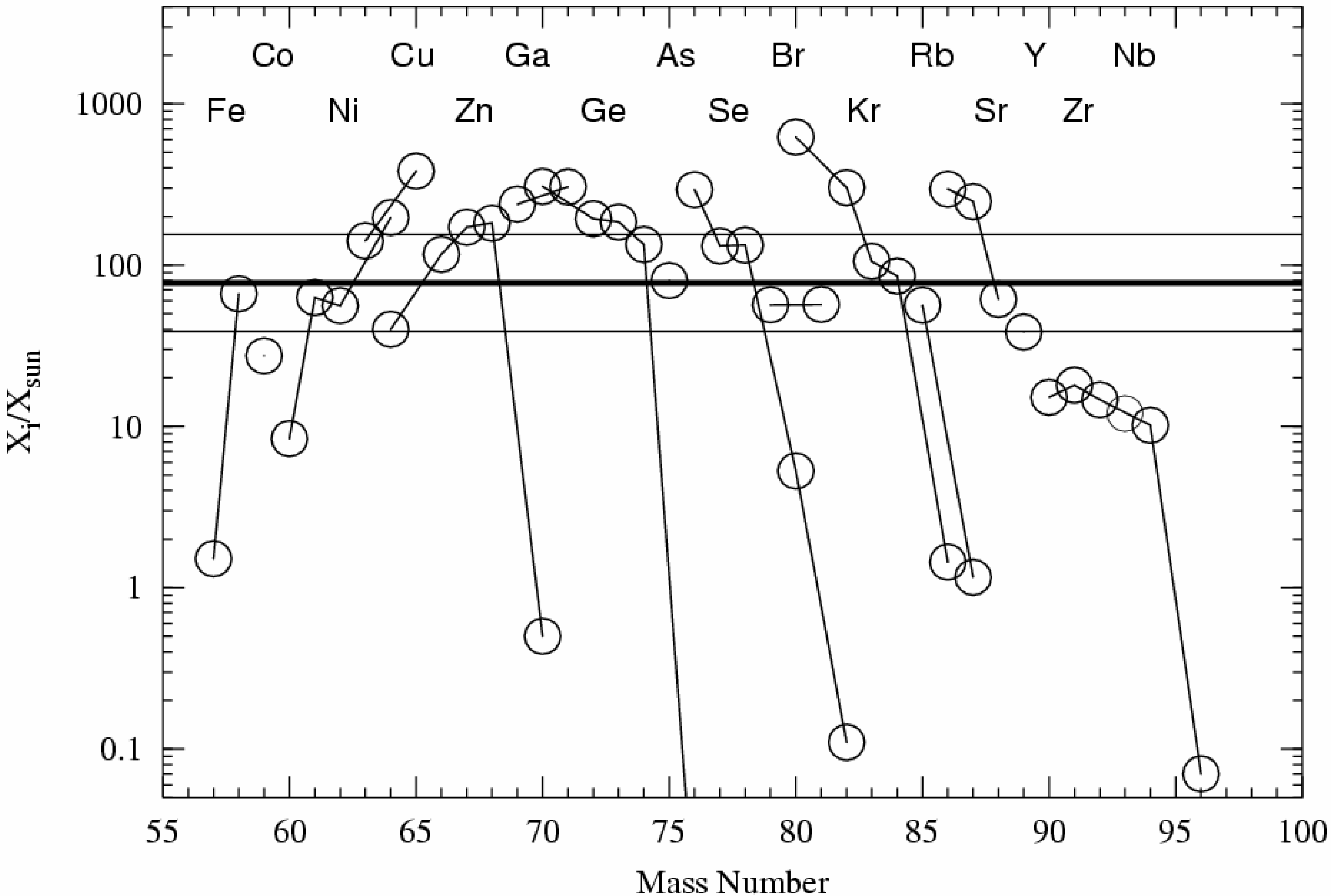
25 Msun [Fe/H] = 0

He core + C shell



$\tau = 0.196 + 0.091\ \mathrm{mb}^{-1}$

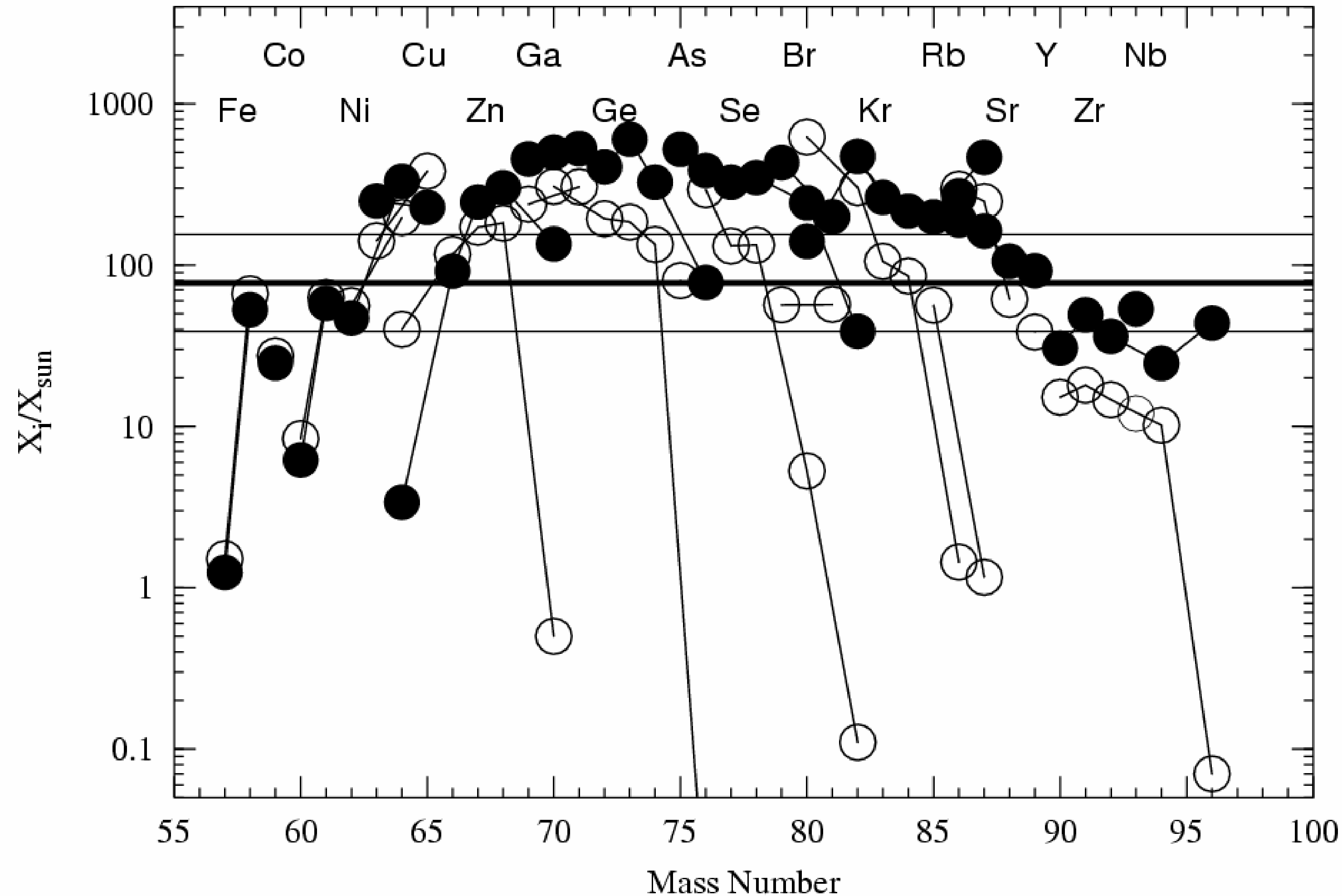
30 Msun [Fe/H] = 0
He core



$\tau = 0.233\ mb^{-1}$

30 Msun [Fe/H] = 0

He core + C shell



$\tau = 0.233 + 0.070\ mb^{-1}$

The weak s-process
vs
mass

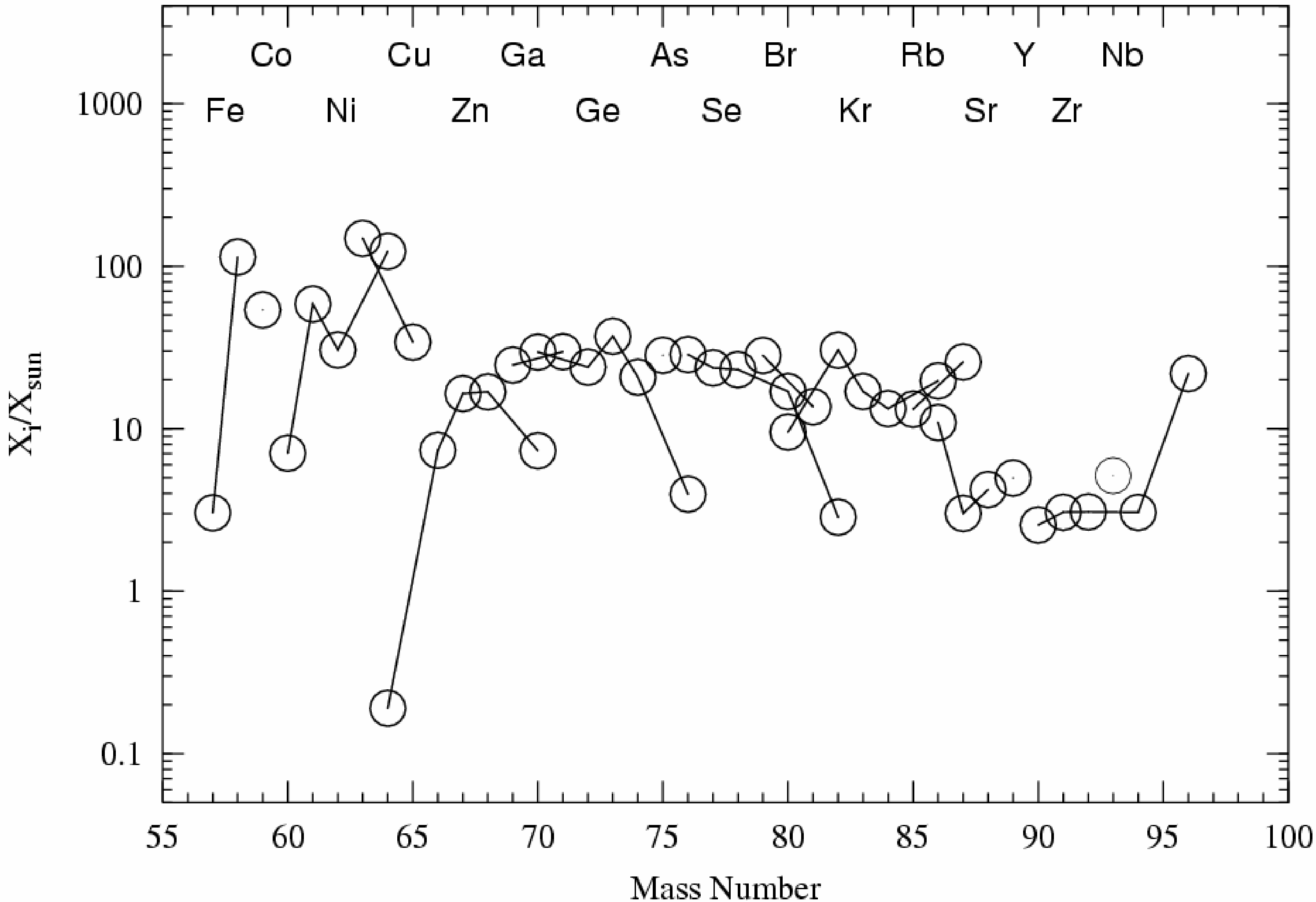
Models: 15,20,25,30 Msun [Fe/H] = 0

The s-process efficiency increases
with increasing the initial mass of the star.
Why?

Please remember that:
The initial CNO nuclei (→ ^{22}Ne) are the same
for different models;
In the ashes of the C shell ^{22}Ne is depleted
(X ~ few 10^{-4}) in all these models.

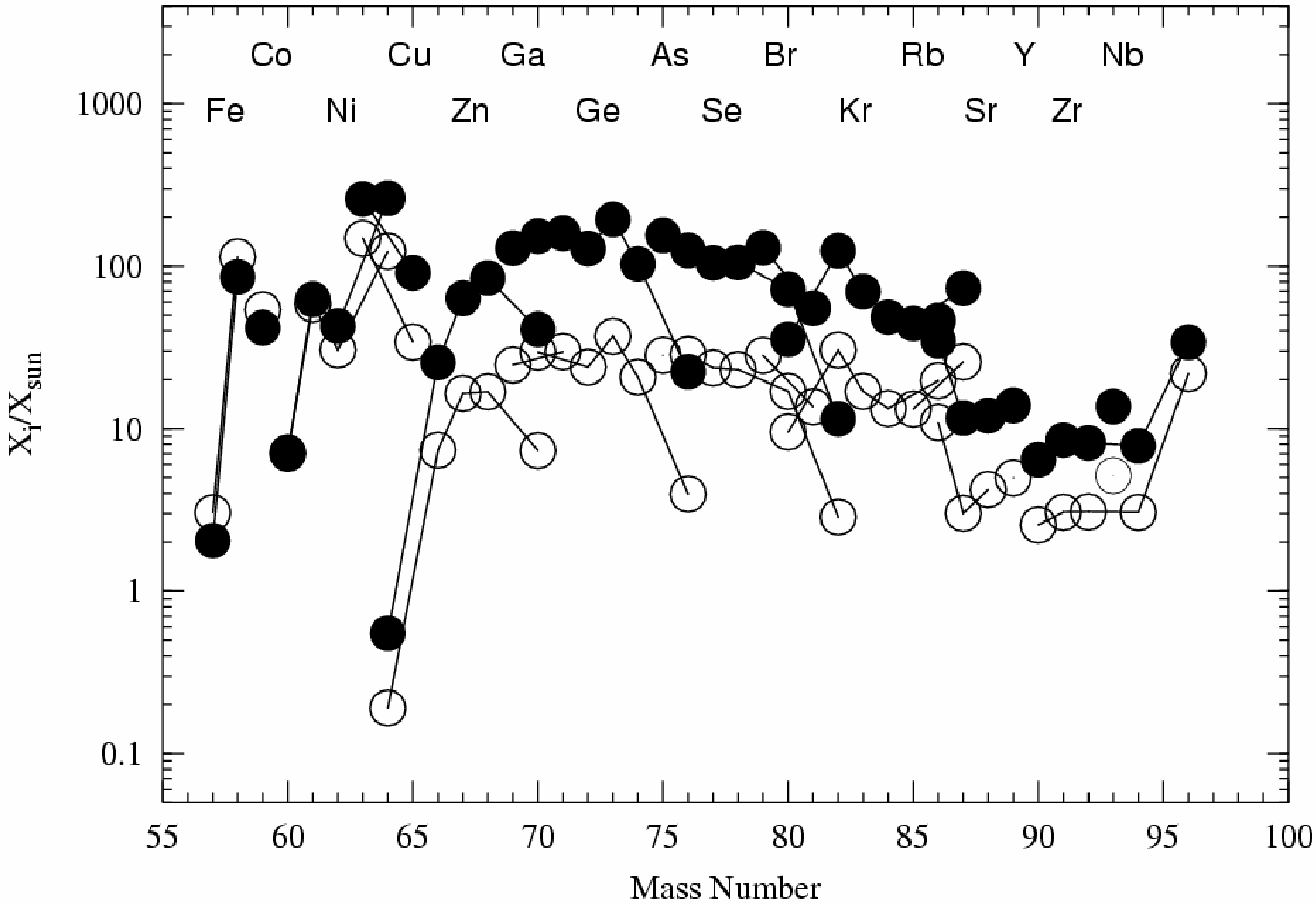
At the end of the C shell…..

15 Msun



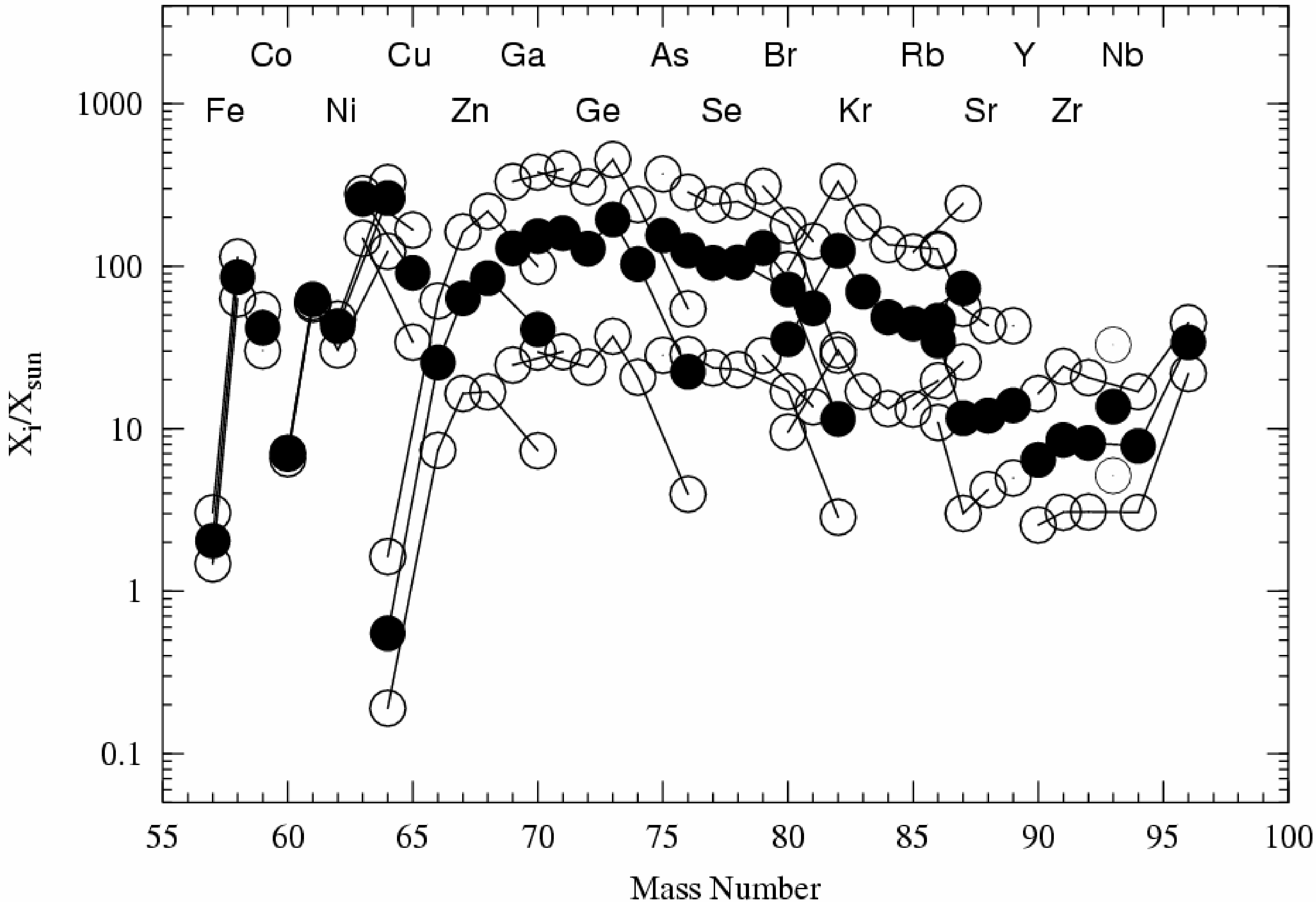
At the end of the C shell…..

15 - 20 Msun



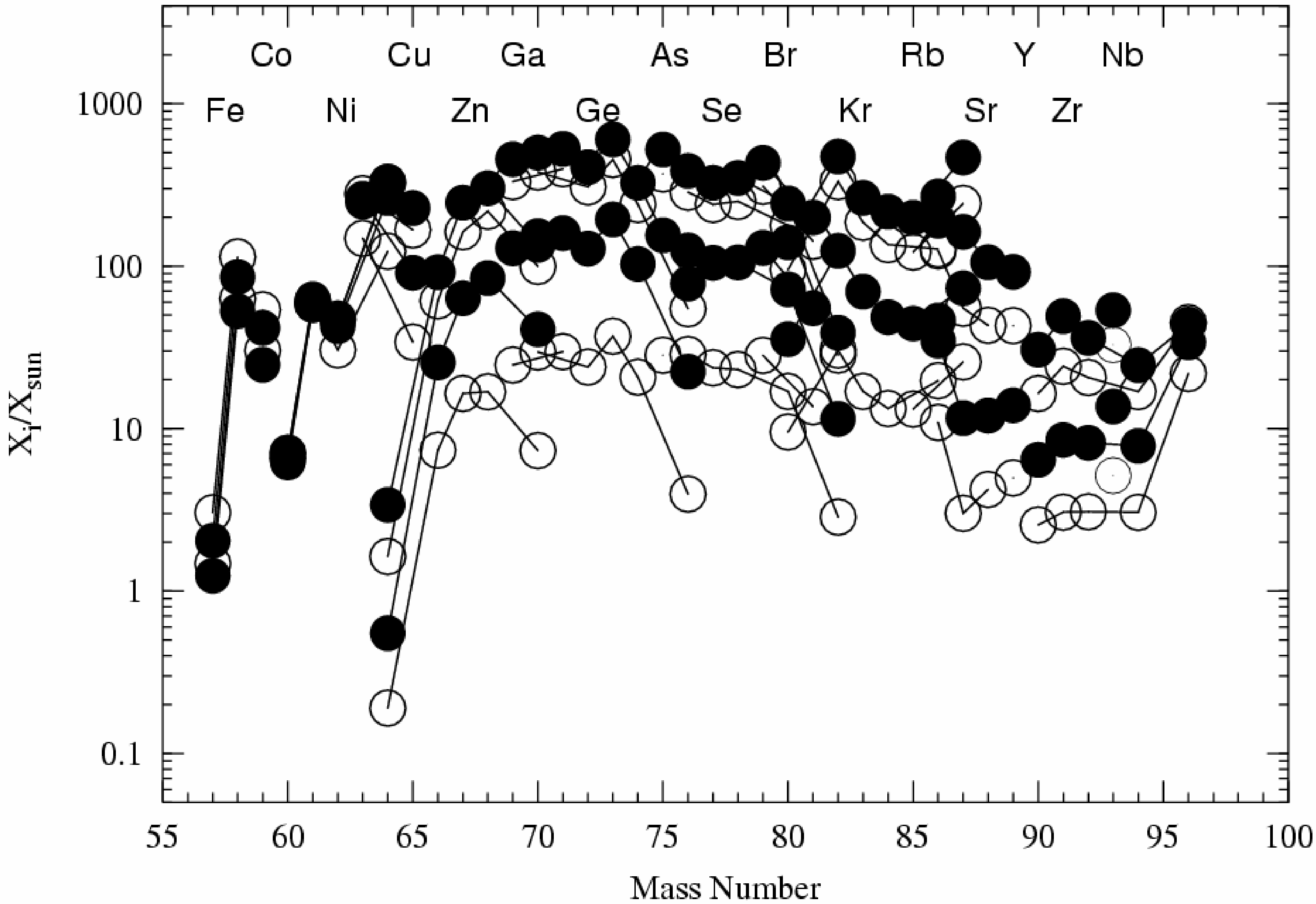
At the end of the C shell…..

15 – 20 – 25 Msun



At the end of the C shell…..

15 – 20 – 25 - 30 Msun



The s-process efficiency increases
with increasing the initial mass of the star.
Why?

Reason:

the neutron poisons are less efficient
in the He core than in the C shell

⇓

If more ^{22}Ne is depleted in the He core, beyond iron
the total s-process efficiency (He core + C shell)
increases.

The weak s-process
vs
metallicity

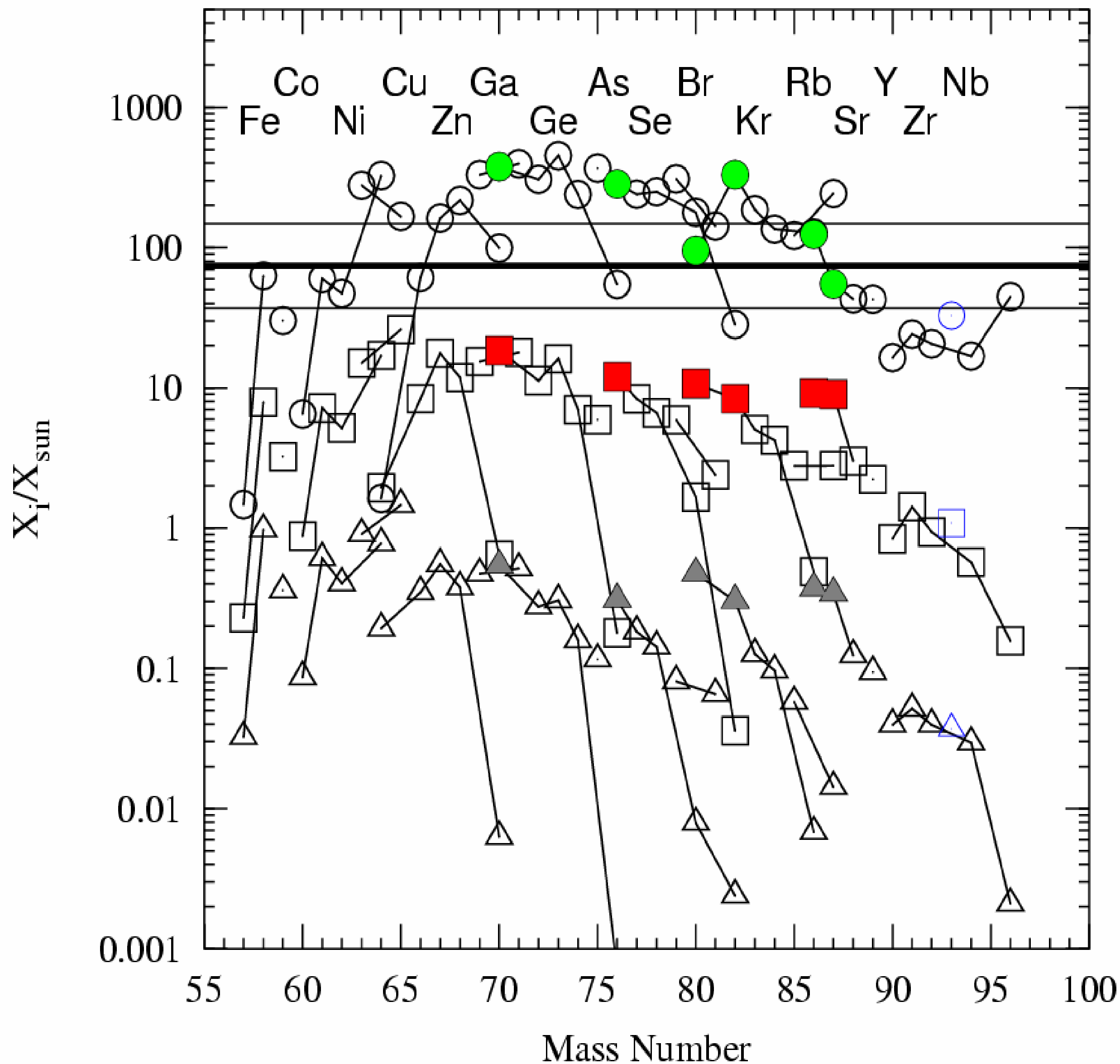
First point:

the initial composition of the star.

-The α-enhancements should be included for light isotopes;

-Solar scaled composition beyond Fe.

Weak s distribution at the end of the C shell – solar scaled composition

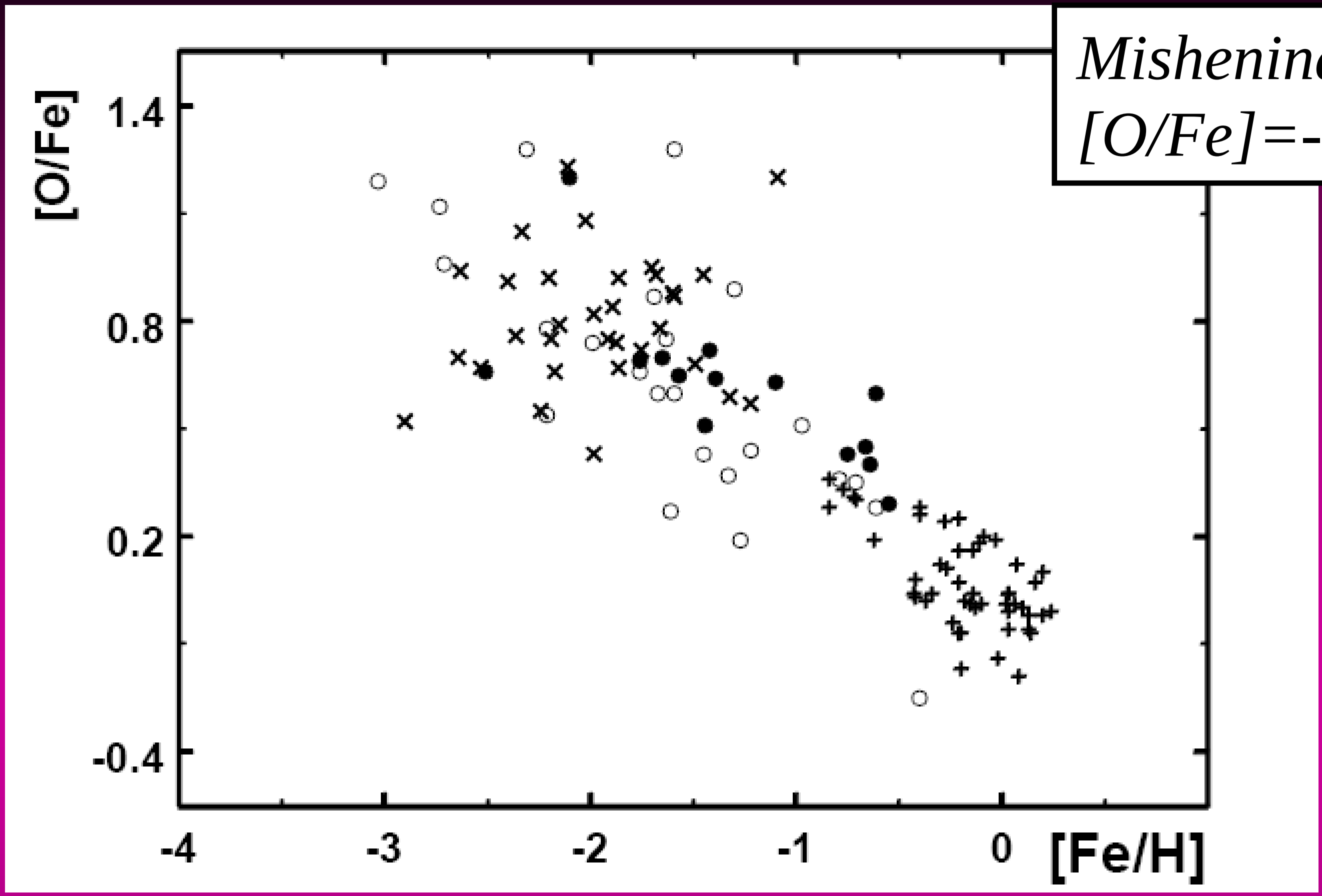


[Fe/H]=0

[Fe/H]=-1

[Fe/H]=-2

25 Msun



Mishenina et al.2000 A&A

[O/Fe]=-0.370[Fe/H]+0.047

OI triplet near-IR 7774 Å

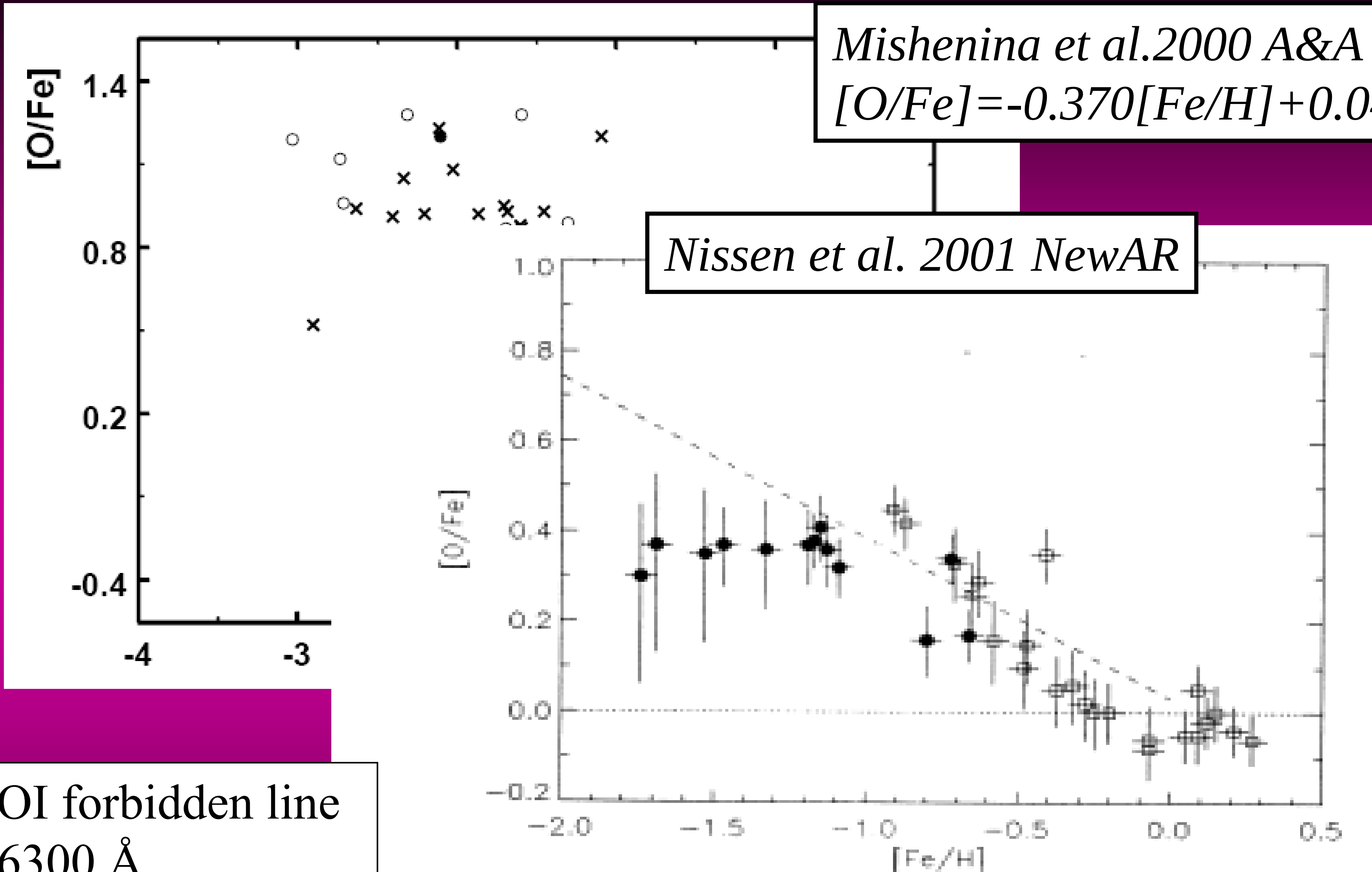
OH UV lines

Israelian et al. 1998

Boesgaard et al. 1999

Mishenina et al.2000 A&A
[O/Fe]=-0.370[Fe/H]+0.047

Nissen et al. 2001 NewAR



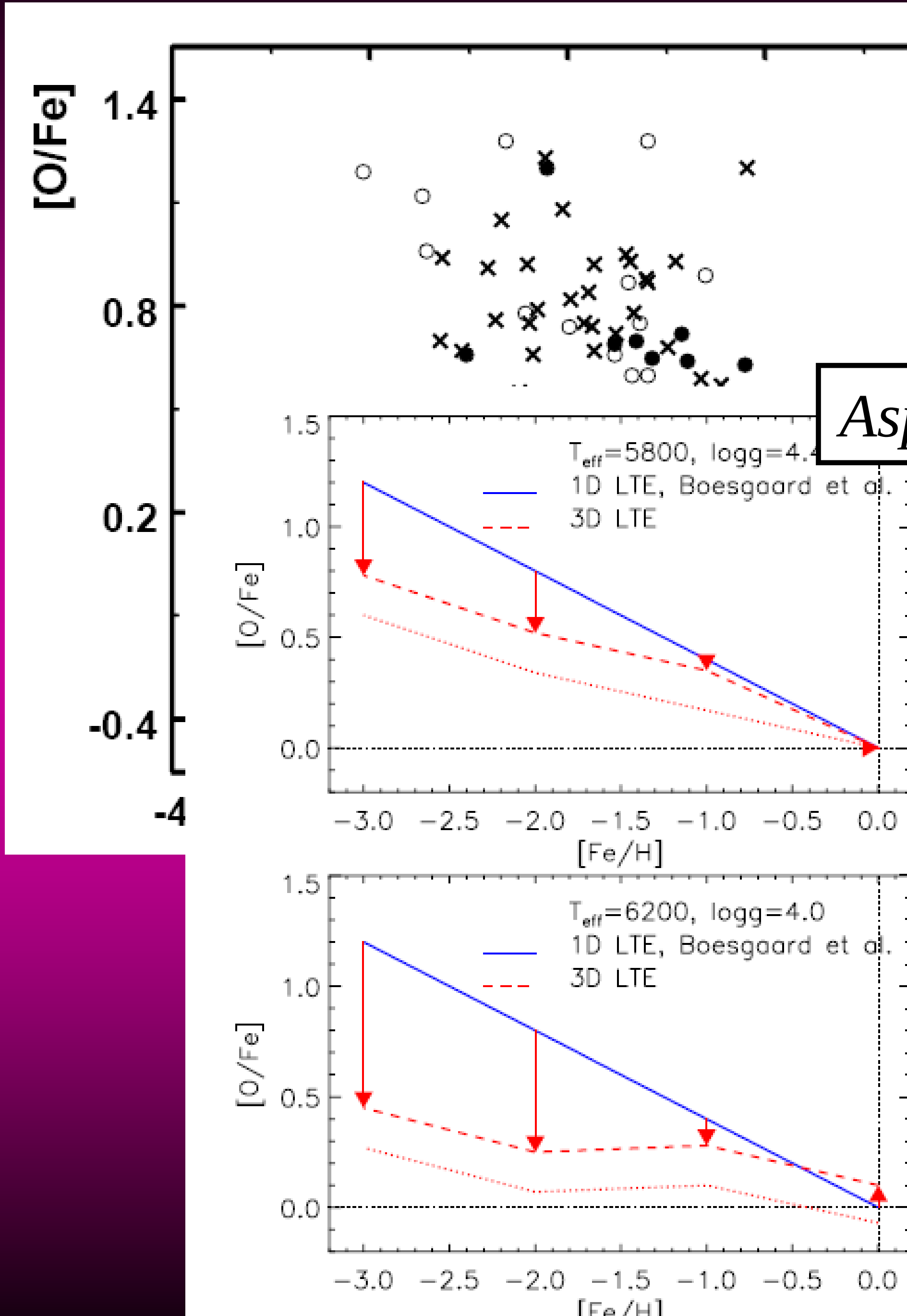
OI forbidden line
6300 Å
Sneden et al. 1991

Fig. 2. [O/Fe] vs. [Fe/H] with 1σ error bars. (●) Stars observed with UVES; (□) disk stars from Nissen and Edvardsson (1992). The dashed line is the relation derived by Israelian et al. (1998) and Boesgaard et al. (1999) from near-UV OH lines.

Mishenina et al.2000 A&A

[O/Fe]=-0.370[Fe/H]+0.047

Asplund & Garcìa Pèrez 2001 A&A



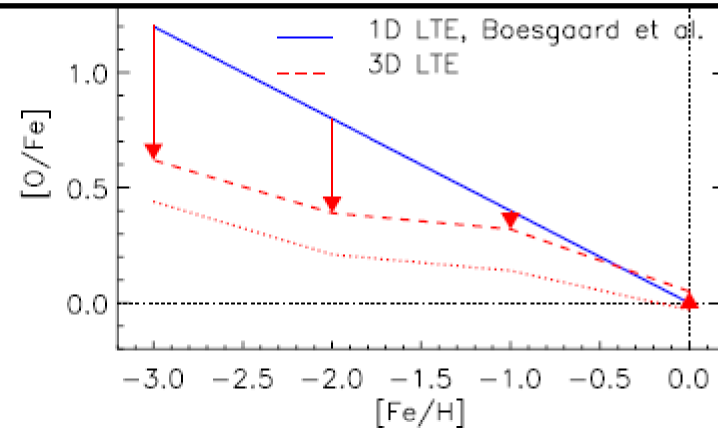
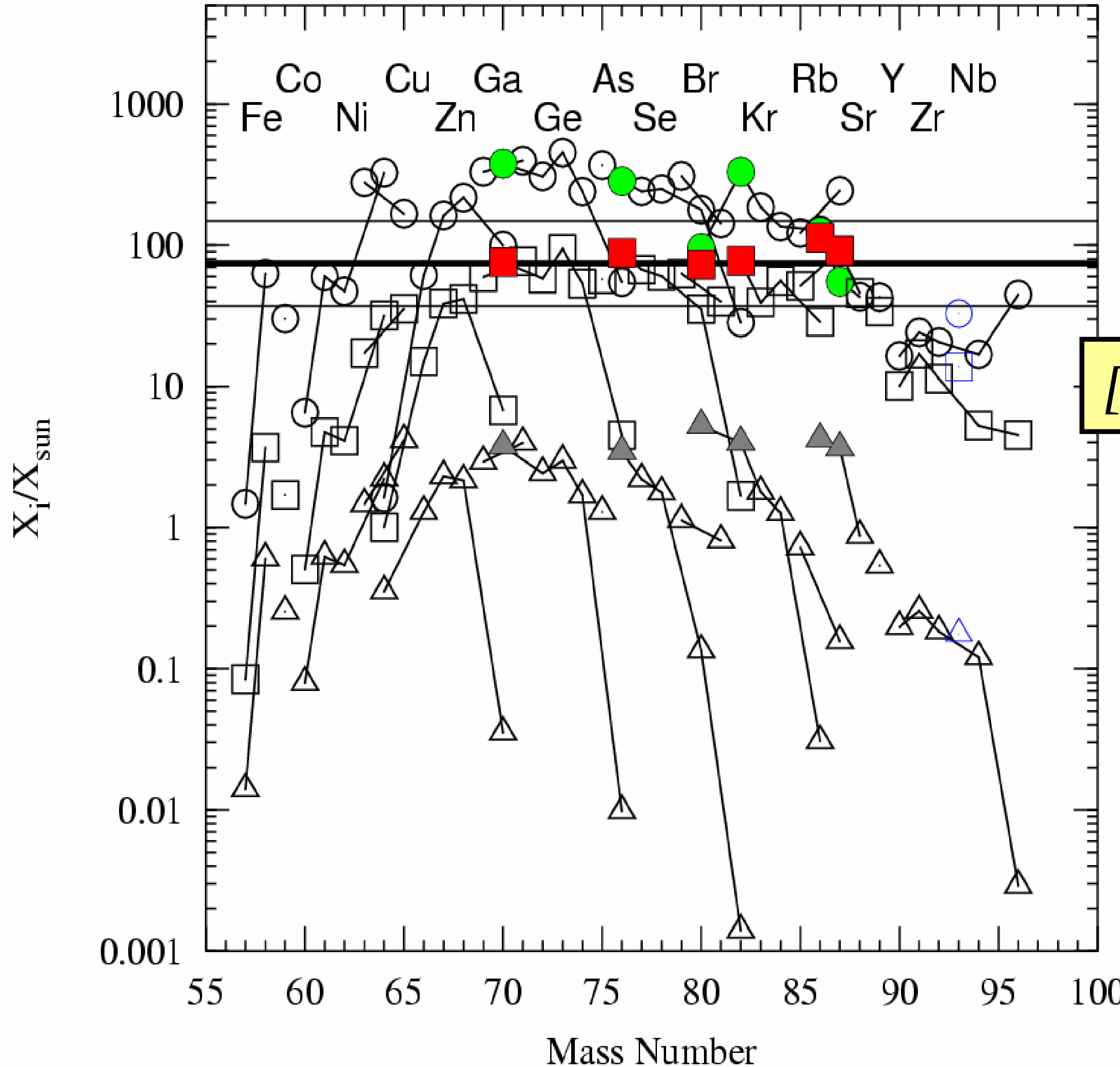


Fig. 4. The impact of the 3D LTE analysis of the OH lines on the [O/Fe] trend in metal-poor stars when averaging the granulation corrections for the solar and turn-off sequences for the two OH lines 313.9 and 316.7 nm. As in Fig. 3, both the cases when using the Holweger-Müller (1974) model atmosphere (dashed line) and the MARCS model atmosphere (dotted line) for the solar calibration are shown. It should be emphasized that the assumption of LTE in the molecule formation and radiative transfer may skew the results according to the discussion in Sect. 5.

Naively, one could expect that all OH molecular lines

Weak s distribution at the end of the C shell – enhanced distribution



[Fe/H]=0

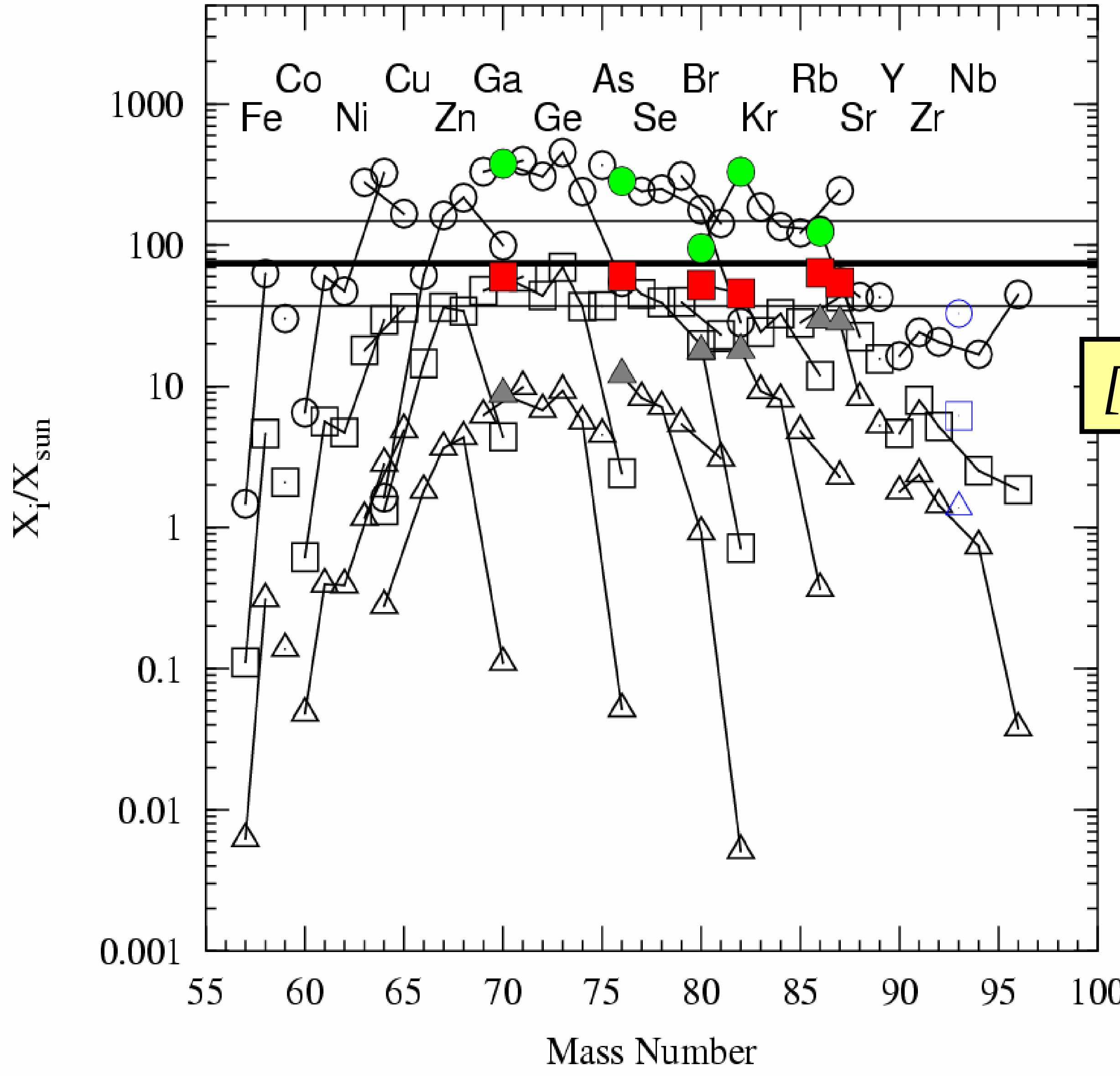
[O/Fe]=[Fe/H]+0.5

[Fe/H]=-1

[Fe/H]=-2

25 Msun

Weak s distribution at the end of the C shell – enhanced distribution



[Fe/H]=0

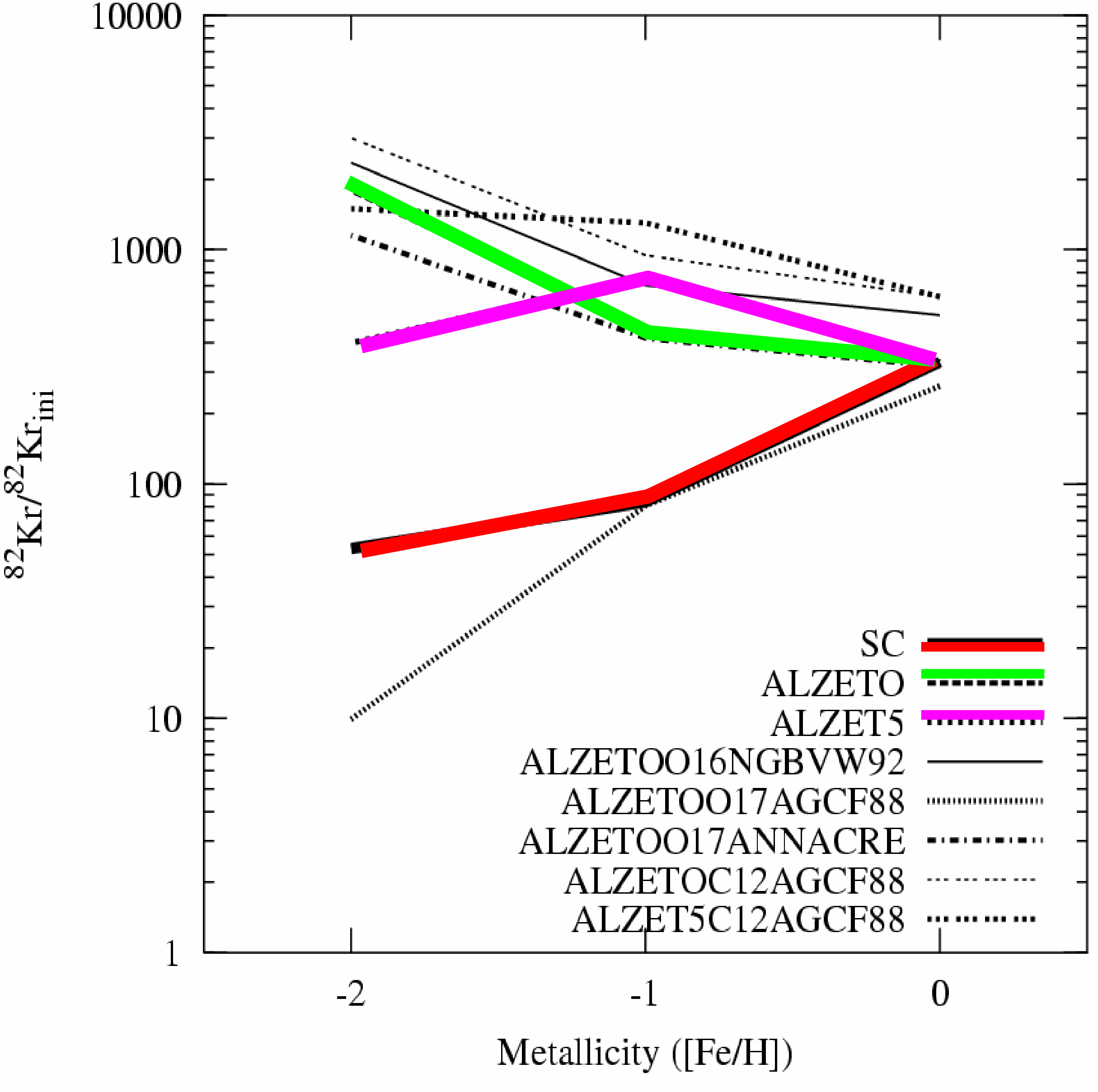
[O/Fe]=+0.4[Fe/H]

[Fe/H]=-1

[Fe/H]=-2

25 Msun

Weak s distribution at the end of the C shell

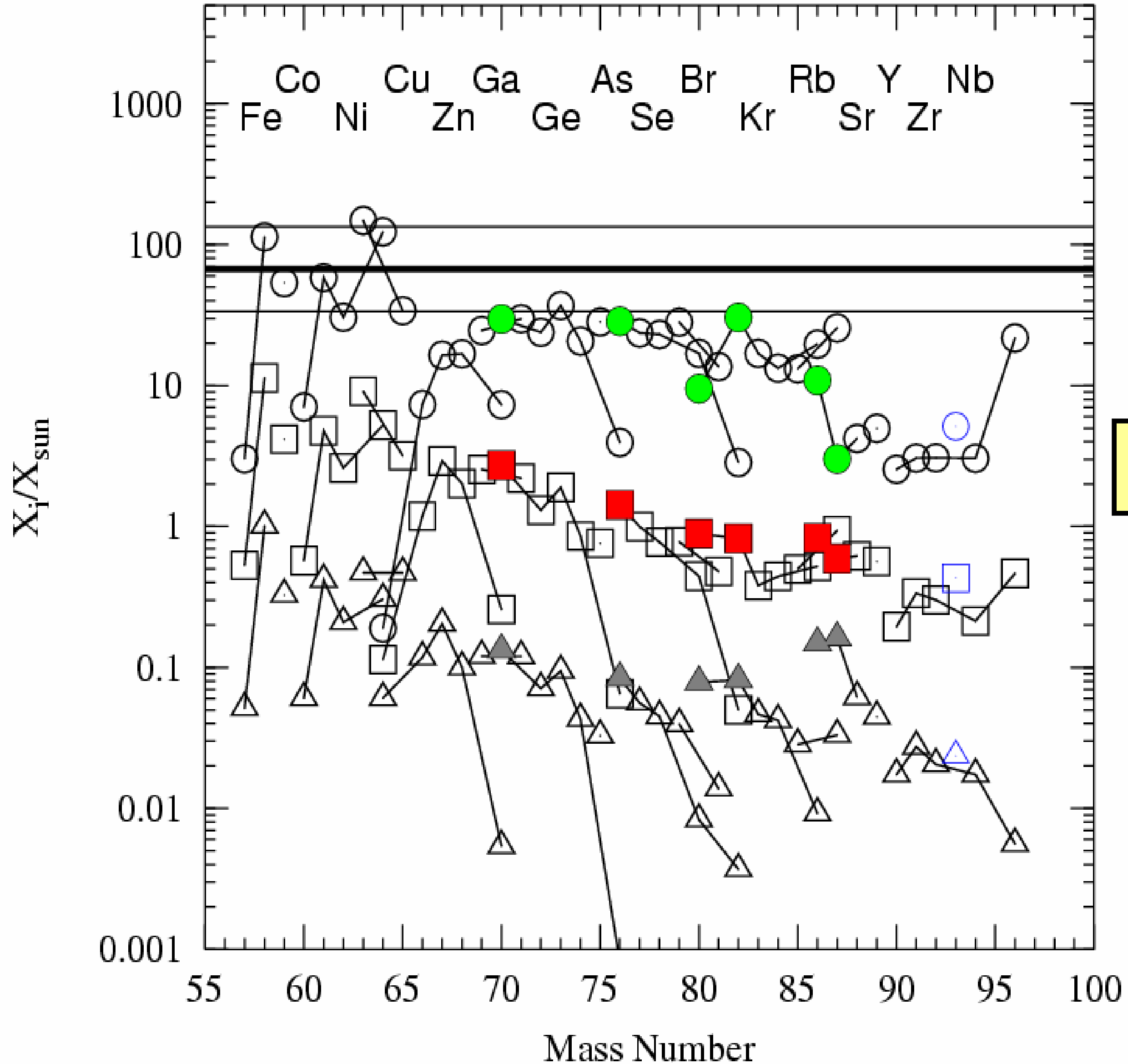


SC =
solar scaled

ALZETO =
[O/Fe]=+0.4[Fe/H]

ALZET5 =
[O/Fe]=[Fe/H]+0.5

Weak s distribution at the end of the C shell – enhanced distribution



[Fe/H]=0

[O/Fe]=+0.4[Fe/H]

[Fe/H]=-1

[Fe/H]=-2

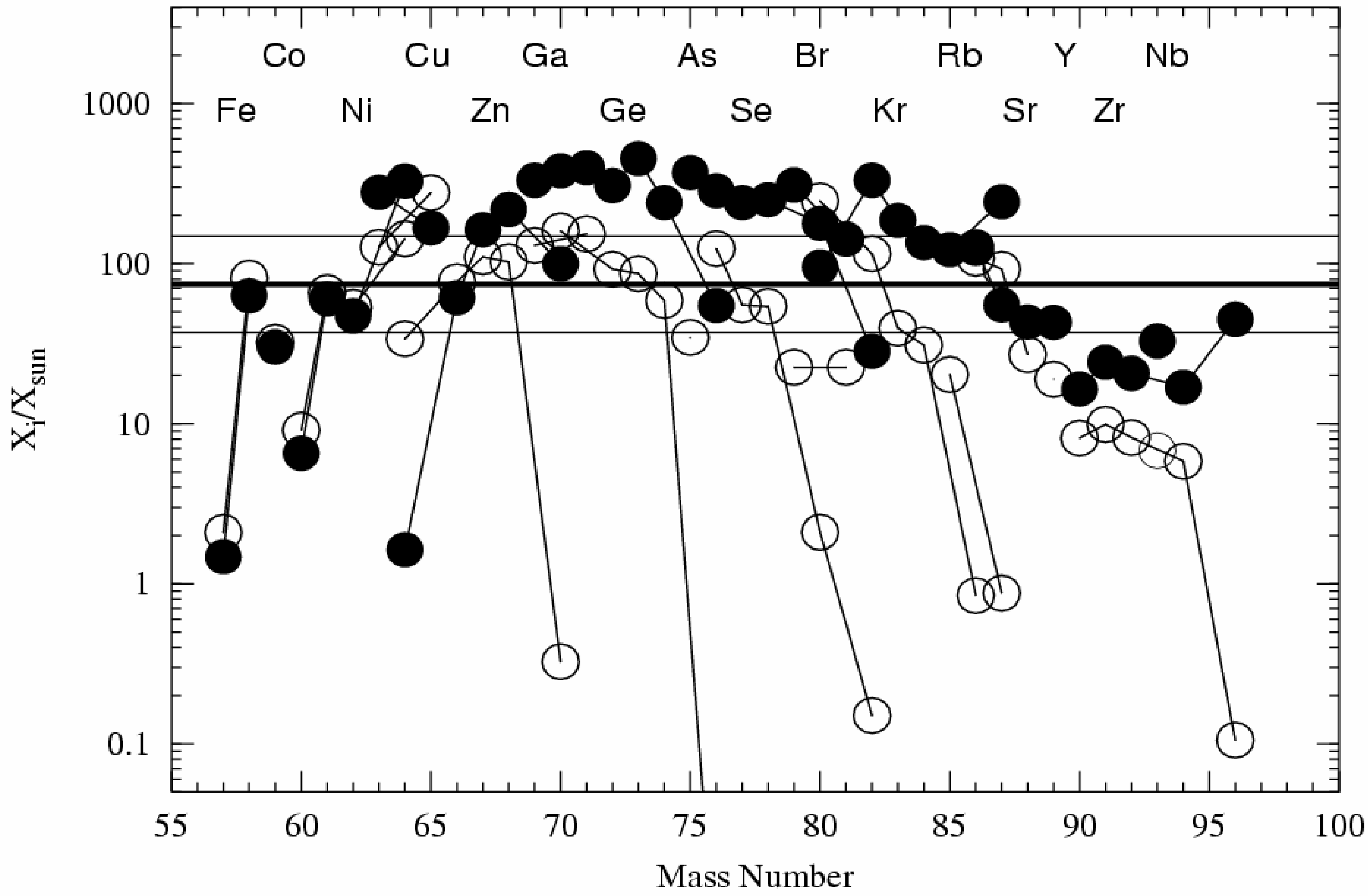
15 Msun

Second point:

For metallicities lower than solar in the C shell the s-process efficiency decreases faster than in the He core. Why?

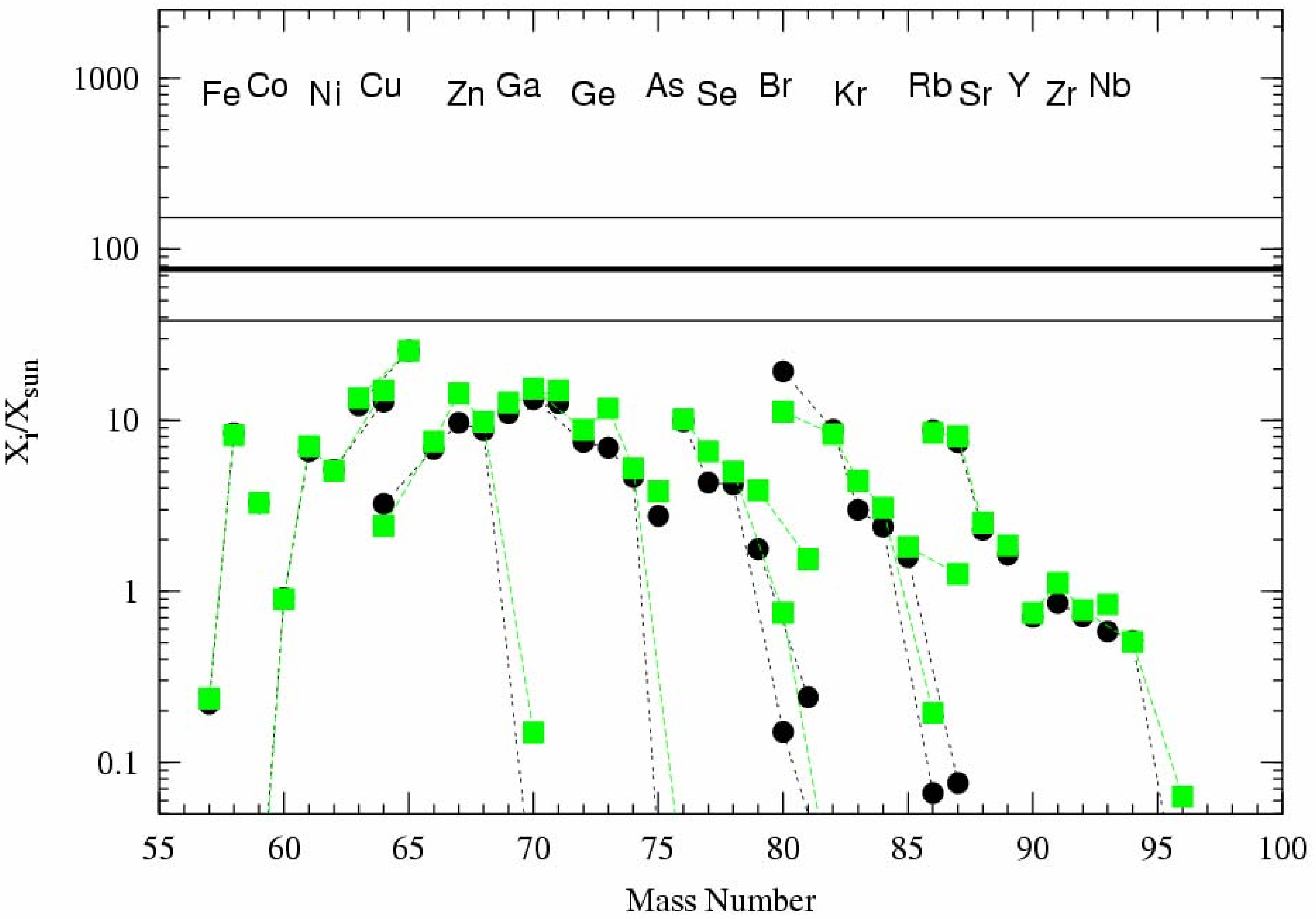
Primary neutron poisons effect.

25 Msun [Fe/H] = 0
He core + C shell



25 Msun [Fe/H] = -1

He core + C shell



Third point:

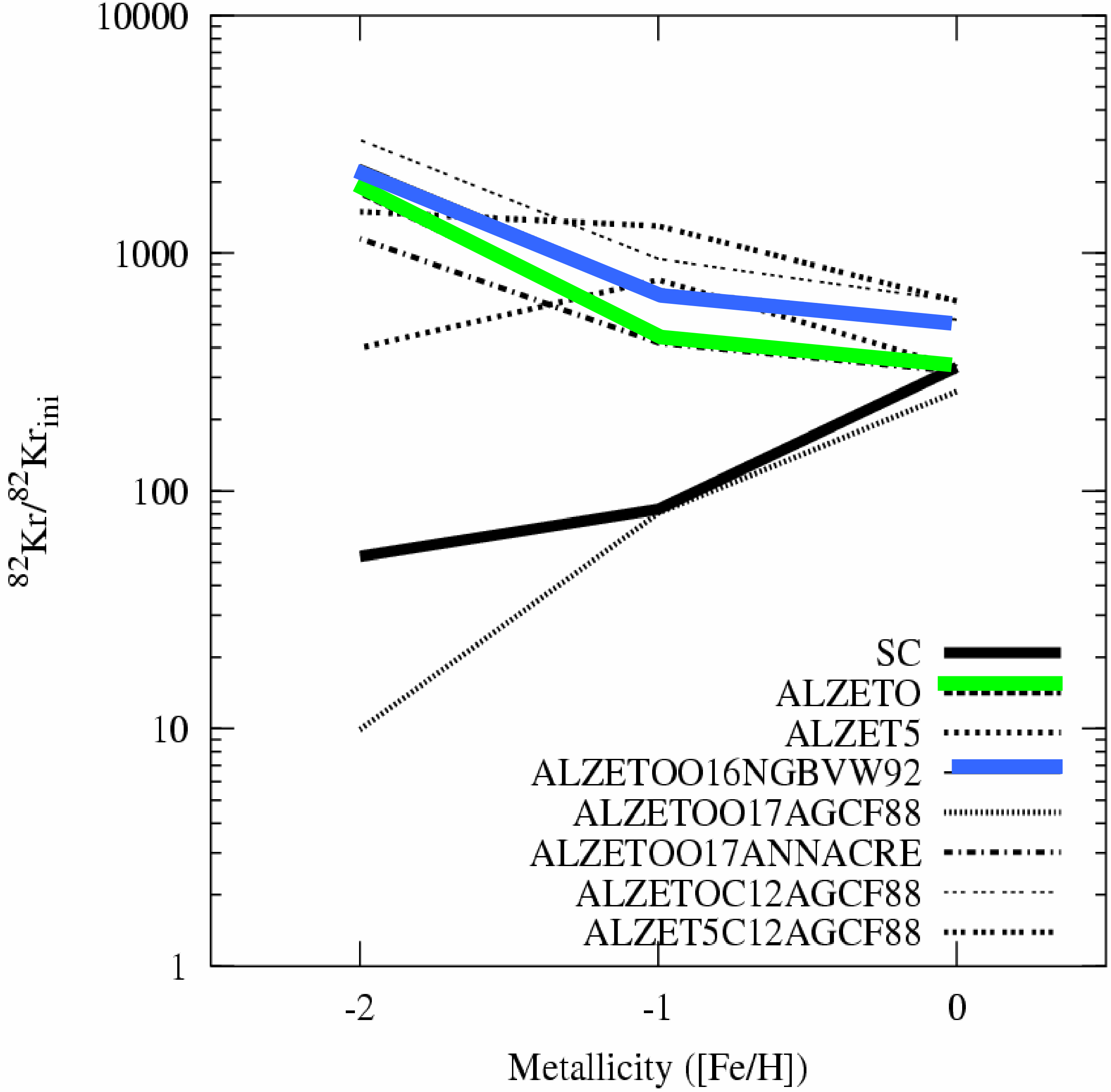
the nuclear network.

- ^{17}O neutron recycling point

$$^{16}O(n,\gamma)^{17}O(\alpha,n)^{20}Ne$$

$$^{17}O(\alpha,\gamma)^{21}Ne$$

Weak s distribution at the end of the C shell

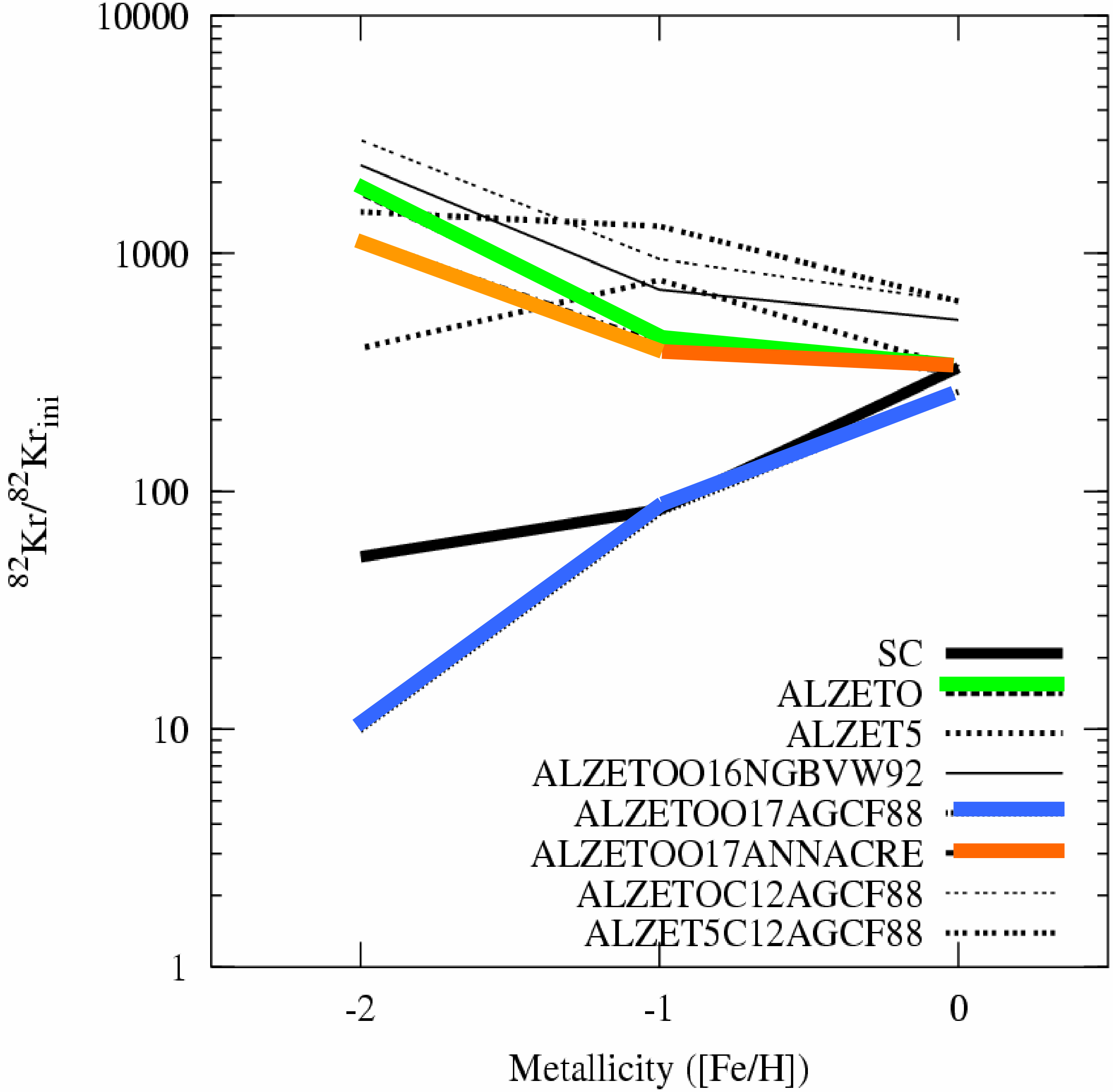


ALZETO =
[O/Fe]=+0.4[Fe/H]

O16ngbvw92 =
O16ng from bvw92

KeV	Bao 2000	Bvw 1992
30	3.8d-2	8.6d-4
90	0.114	2.0d-2

Weak s distribution at the end of the C shell



ALZETO = *[O/Fe]=+0.4[Fe/H]*

O17AGCF88 = O17ag from CF88

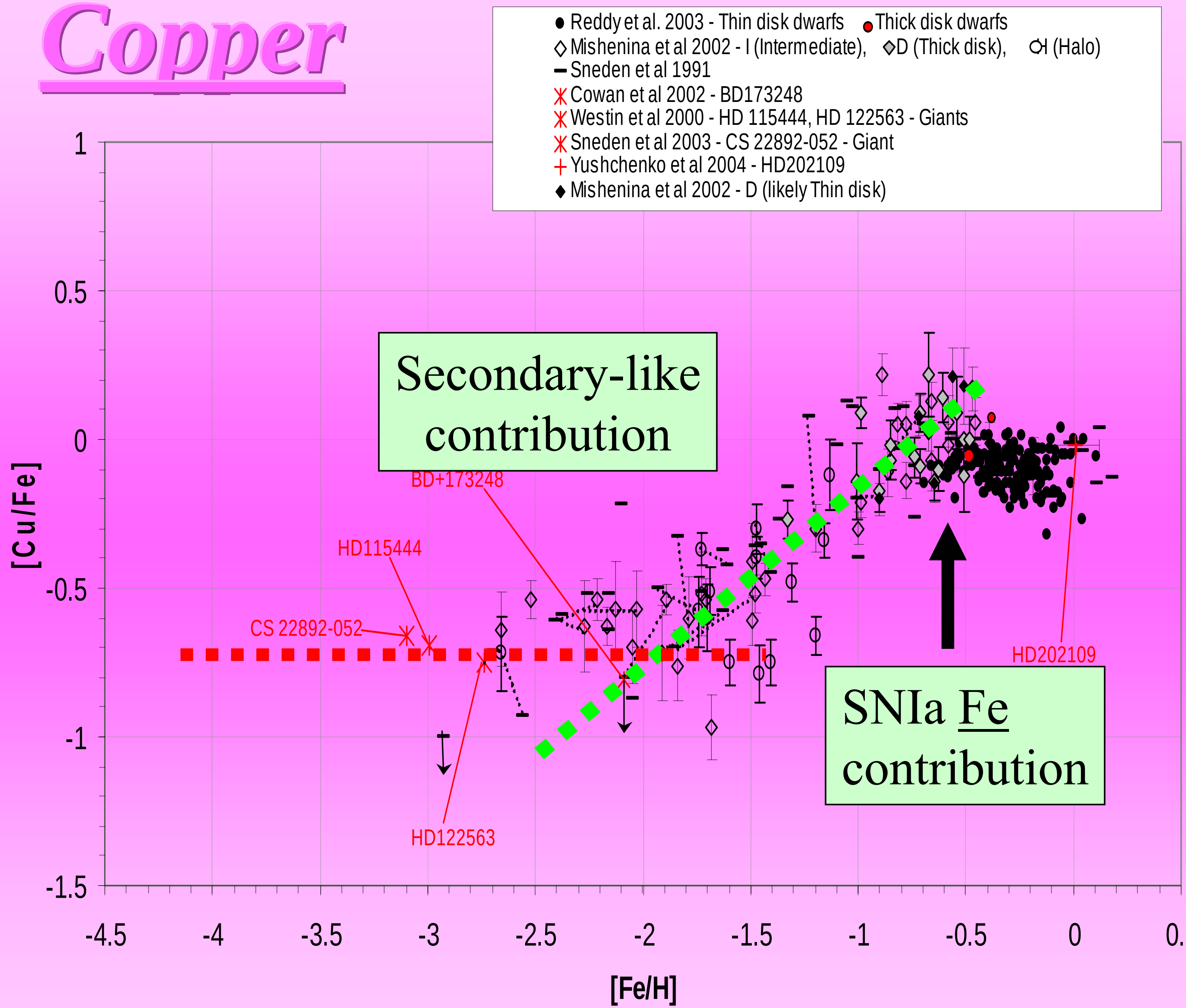
O17ANNACRE = O17an from NACRE

At 30 Kev:

30 KeV	O17ag/O17an
0.1	CF88
0.0001	Descouvemont 1993

Observations

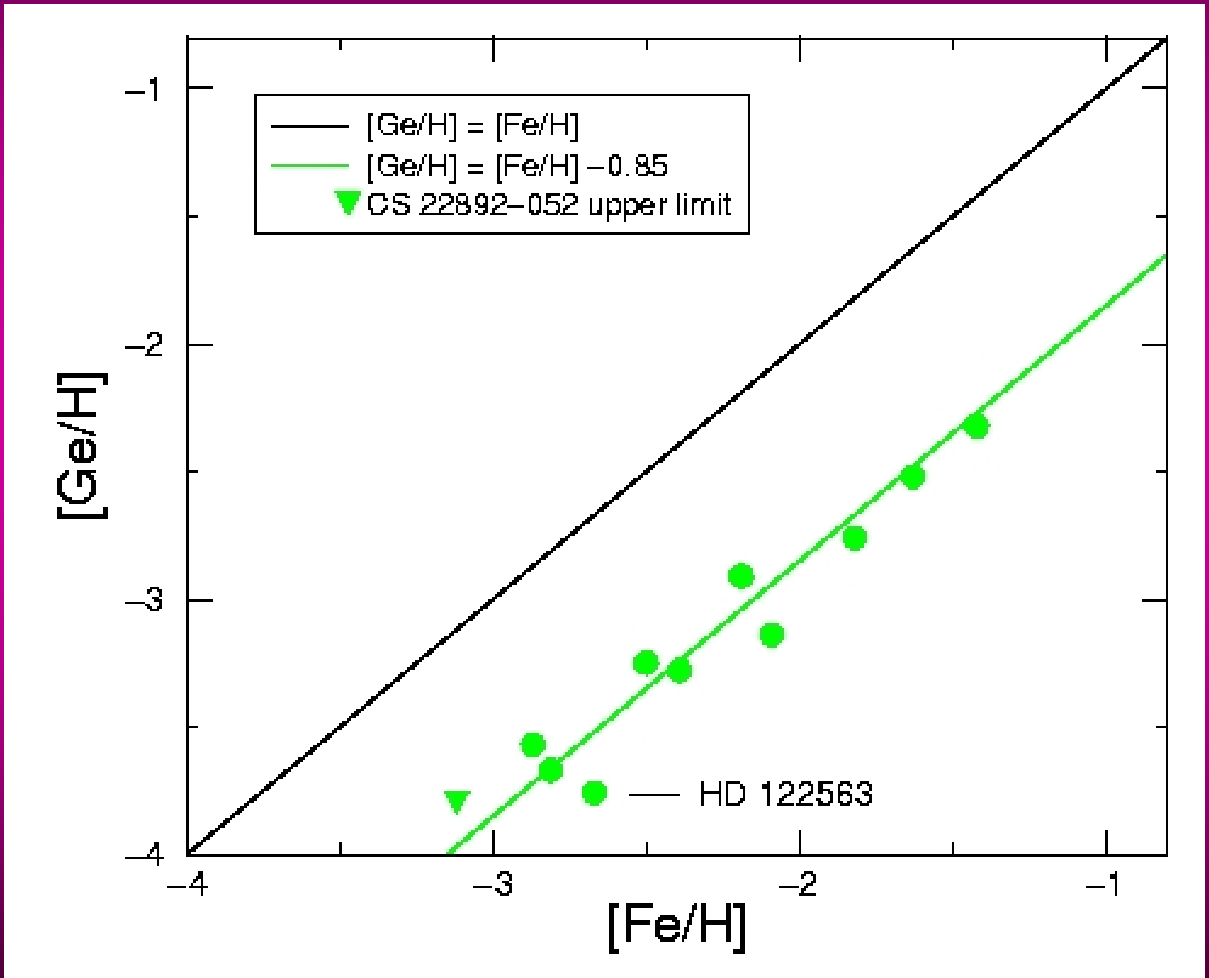
Copper



Bisterzo et al. 2006

Ge Abundances in Halo Stars

(slide courtesy of John Cowan)



Ge ∝ Fe

Challenge to theorists.

What happens at higher [Fe/H] with the s-process?

JC et al. (2005)

$[A/B] = \log_{10}(A/B)_{star} - \log_{10}(A/B)_{sun}$

Summary

- The weak s component is an overposition of two s components with different neutron exposures and different neutron densities: one from convective core He-burning and the other one from convective shell C-burning.
- The s-process efficiency increases with the initial mass of the star;
- The s-process contribution from convective

C-Shell is important at solar like-metallicity, but at low metallicity its contribution rapidly decreases;

Summary

- The weak s-process is a secondary process. However, the metallicity dependence of the s path beyond iron is affected by the initial distribution and by the nuclear uncertainties;
- There are spectroscopic observations confirming that the Weak s-process is secondary-like at metallicities lower than solar.