The s-process in massive stars: the Shell C-burning signature

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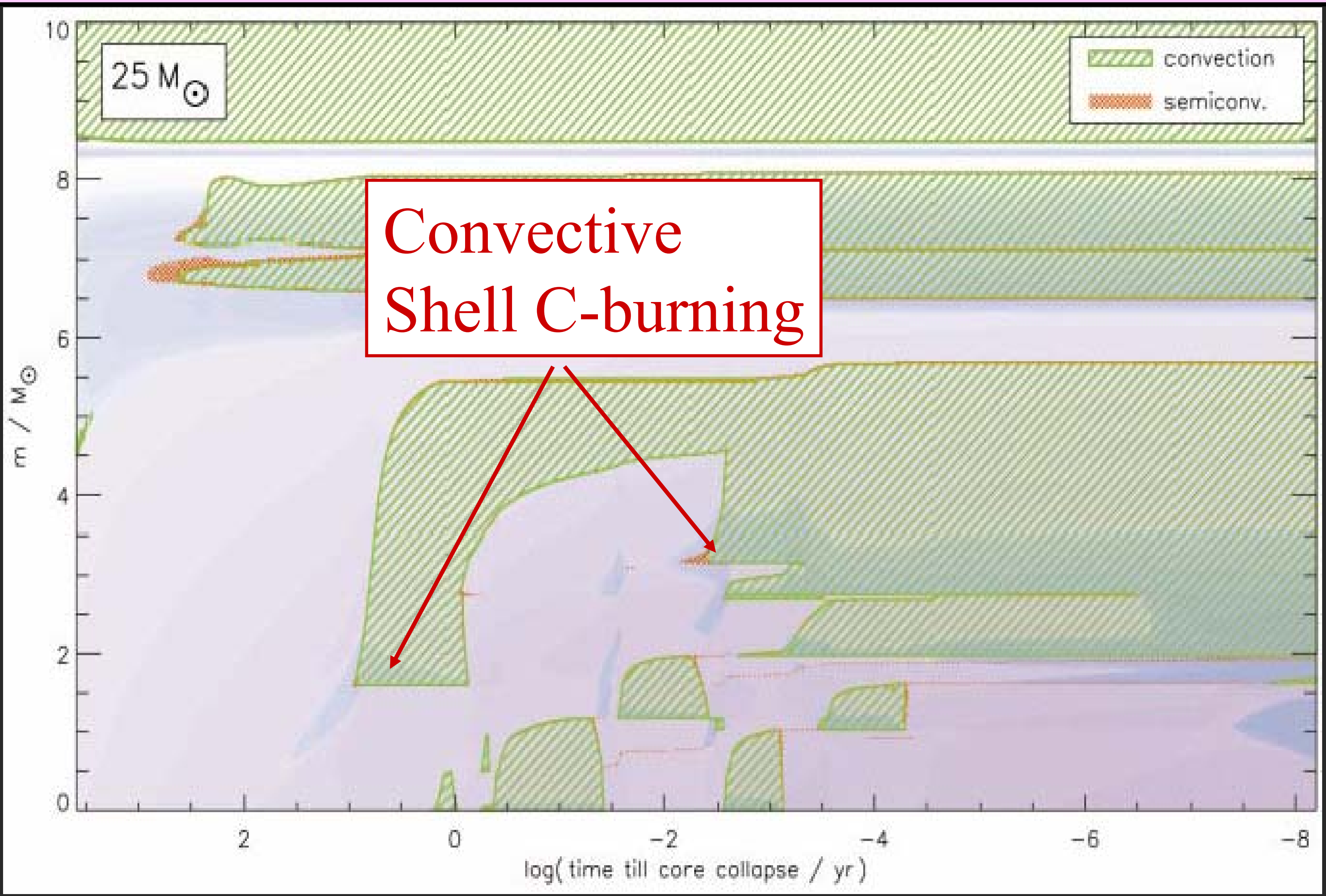
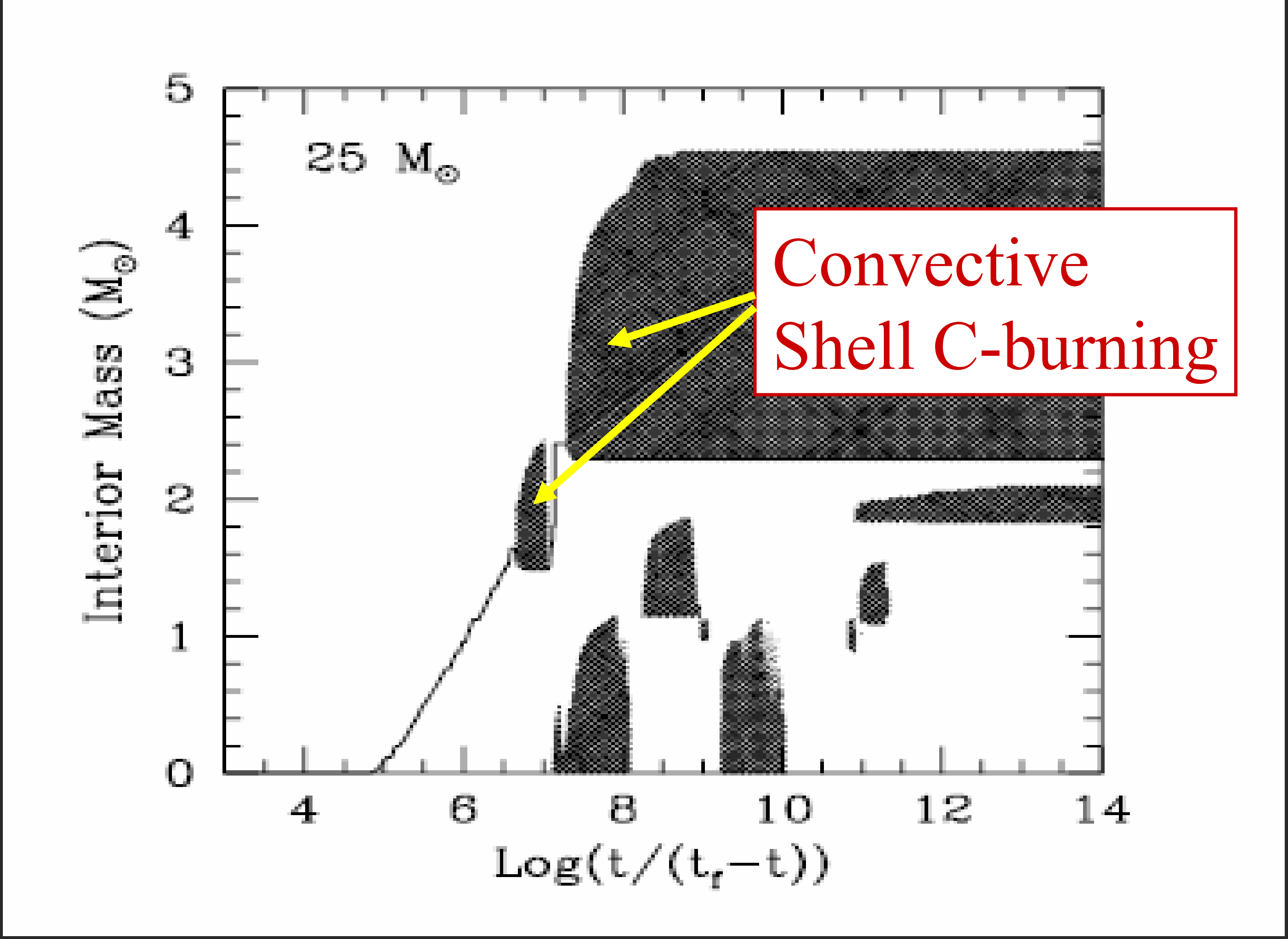
Models:
Hydrostatic nucleosynthesis in massive stars

- Post-processing models follow:
  Convective Core He-burning and
  Convective Shell C-burning
  (Raiteri et al. 1991, 1993)
- Updated network
  Bao et al. 2000 for (n,γ),
  β decay rates from various sources,
  (n,p) and (n,α) channels....

Kippenhahn's Diagram for a star with M= 25 M(sun) and solar metallicity (Woosley, Heger & Weaver 2002)



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



The weak s-process:

Convective Core He-burning

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

See Lamb et al., Couch et al., Raiteri et al., Prantzos et al. ......

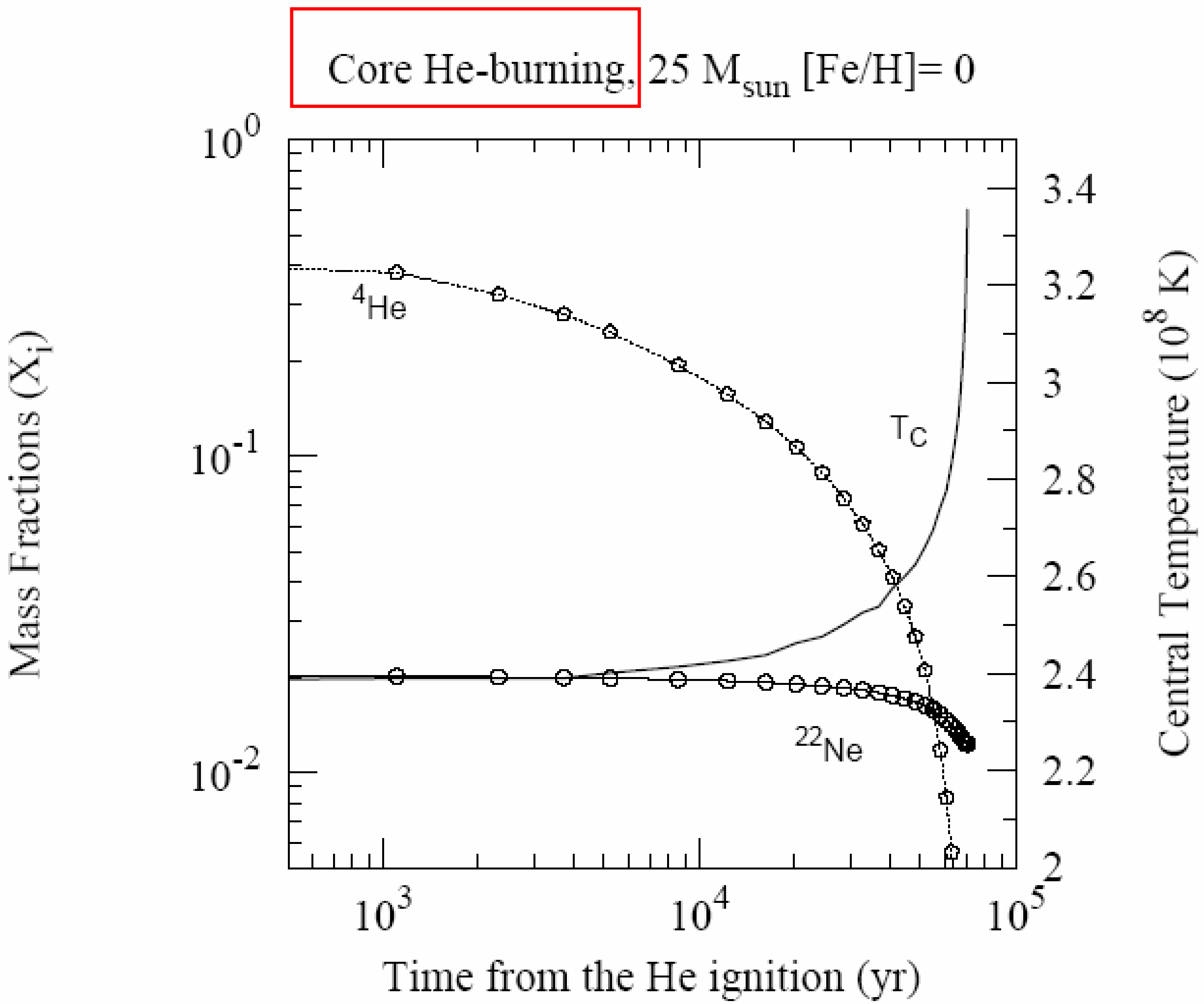
Convective Shell C-burning

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

T~ 10^9 K (?)

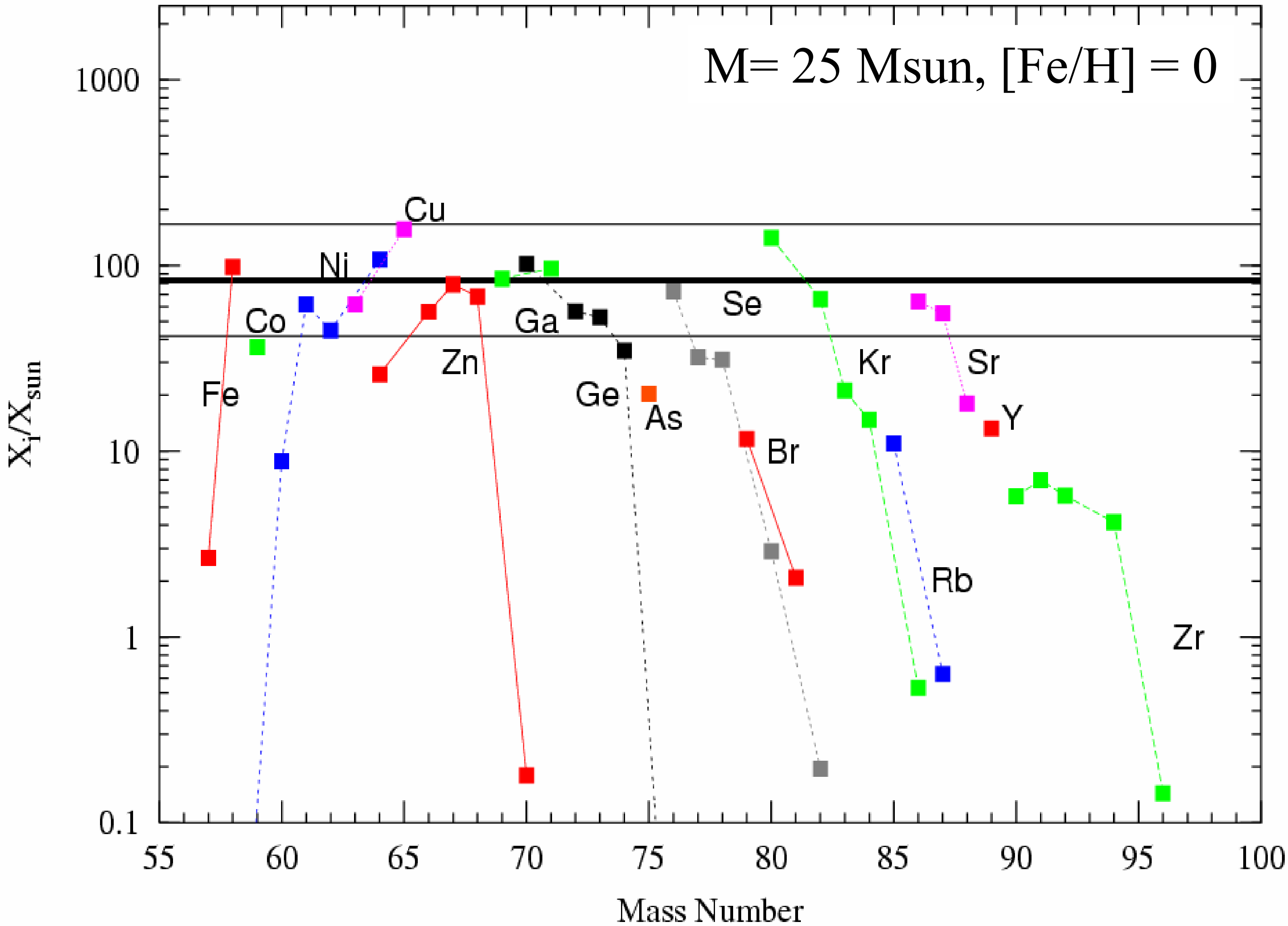
See Arnett & Truran 1969, Raiteri et al. 1991

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



Neutron source: $^{22}Ne(\alpha,n)^{25}Mg$ $T_{eff} > 2.5\text{-}3*10^8$ K!!!!

Neutron poisons: ^{25}Mg, ^{16}O



M= 25 Msun, [Fe/H] = 0
1000
100
10
1
0.1
55
60
65
70
75
80
85
90
95
100
Mass Number
X_i/X_{sun}
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr

In the following 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 (~ 1 ‰) ...

^{16}O is the most abundant isotope (and the most important neutron poison…)

Neutron exposure in the C Shell comparable with the Core He-burning neutron exposure!

In the convective C Shell:

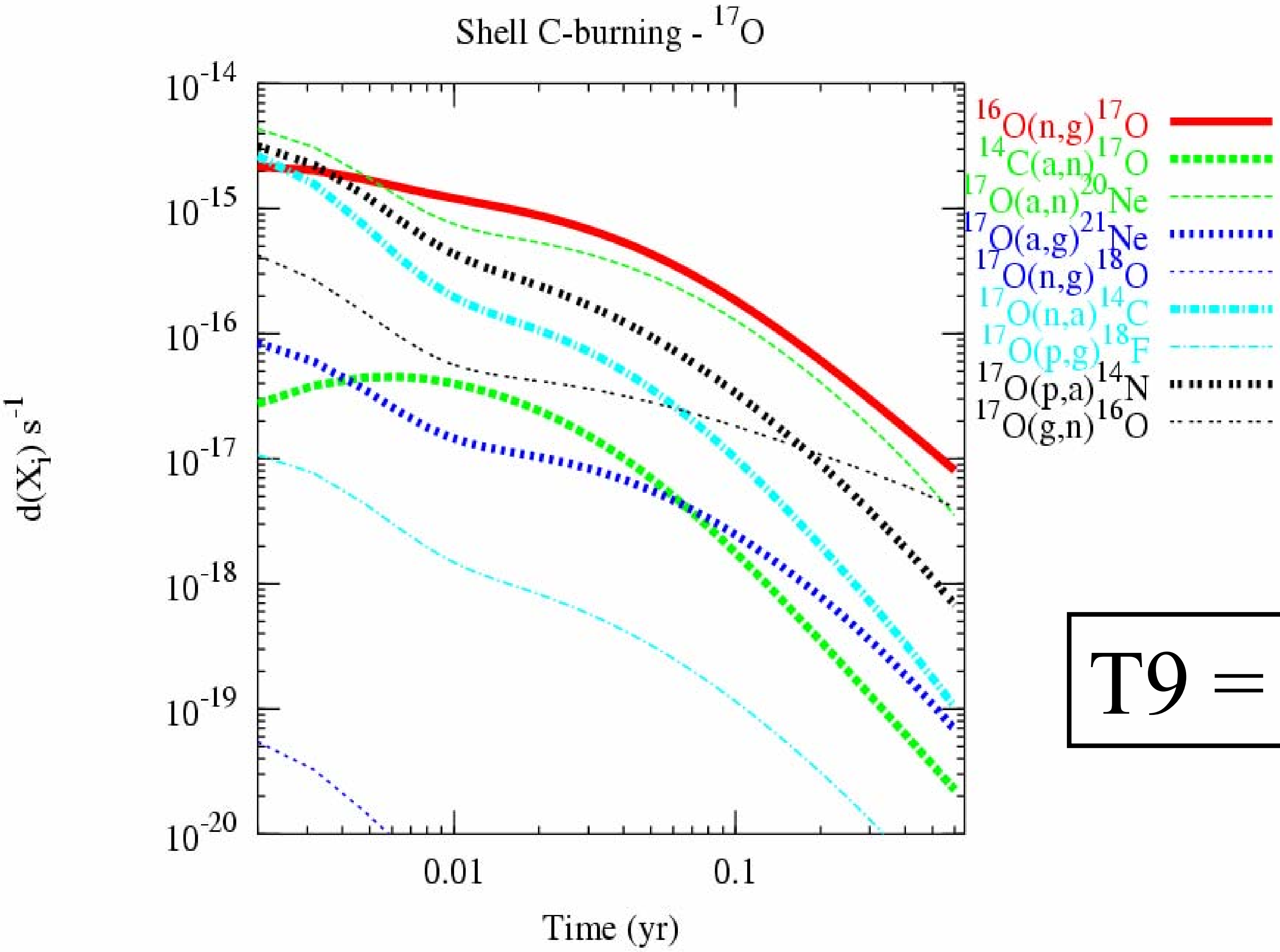
Neutron sources:

$^{13}C(\alpha,n)^{16}O$, (Clayton 1968, Arnett & Truran 1969);
^{13}C is produced by $^{12}C(p,\gamma)^{13}N(\beta+)^{13}C$.
Temperature dependence for this neutron source.

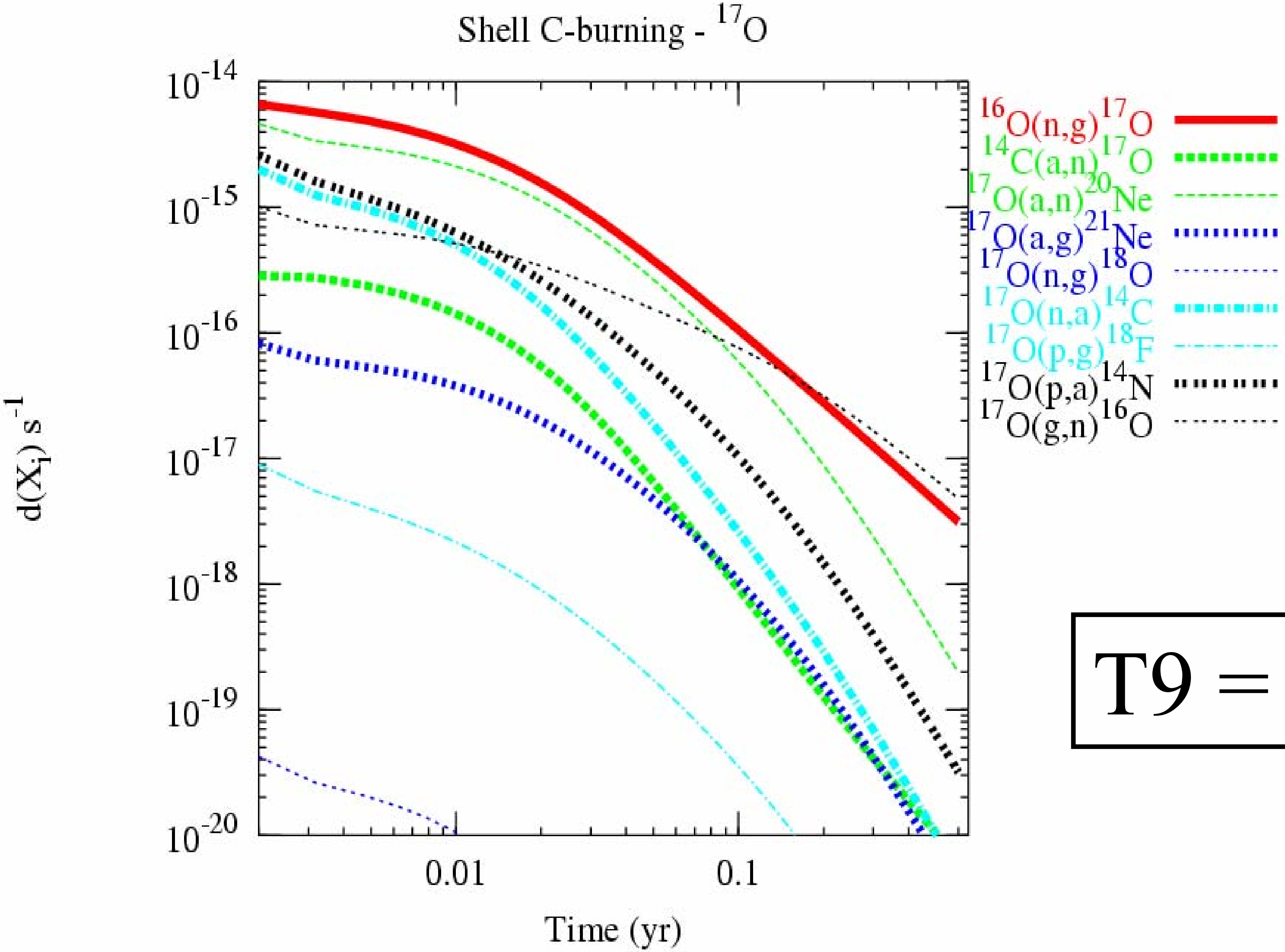
$^{22}Ne(\alpha,n)^{25}Mg$, (….);
^{22}Ne unburned in the Core He-burning ashes.

$^{17}O(\alpha,n)^{20}Ne$, is it inportant?
^{17}O strongly produced by $^{16}O(n,\gamma)^{17}O$

$$D(x(i)/A(i))/Dt = \rho*(x(j)/A(j))*(x(k)/A(k))*rate(jk)$$



T9 = 1.05



Shell C-burning - ^{17}O
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
$d(X_i)\ s^{-1}$
0.01
0.1
Time (yr)
$^{16}O(n,g)^{17}O$
$^{14}C(a,n)^{17}O$
$^{17}O(a,n)^{20}Ne$
$^{17}O(a,g)^{21}Ne$
$^{17}O(n,g)^{18}O$
$^{17}O(n,a)^{14}C$
$^{17}O(p,g)^{18}F$
$^{17}O(p,a)^{14}N$
$^{17}O(g,n)^{16}O$

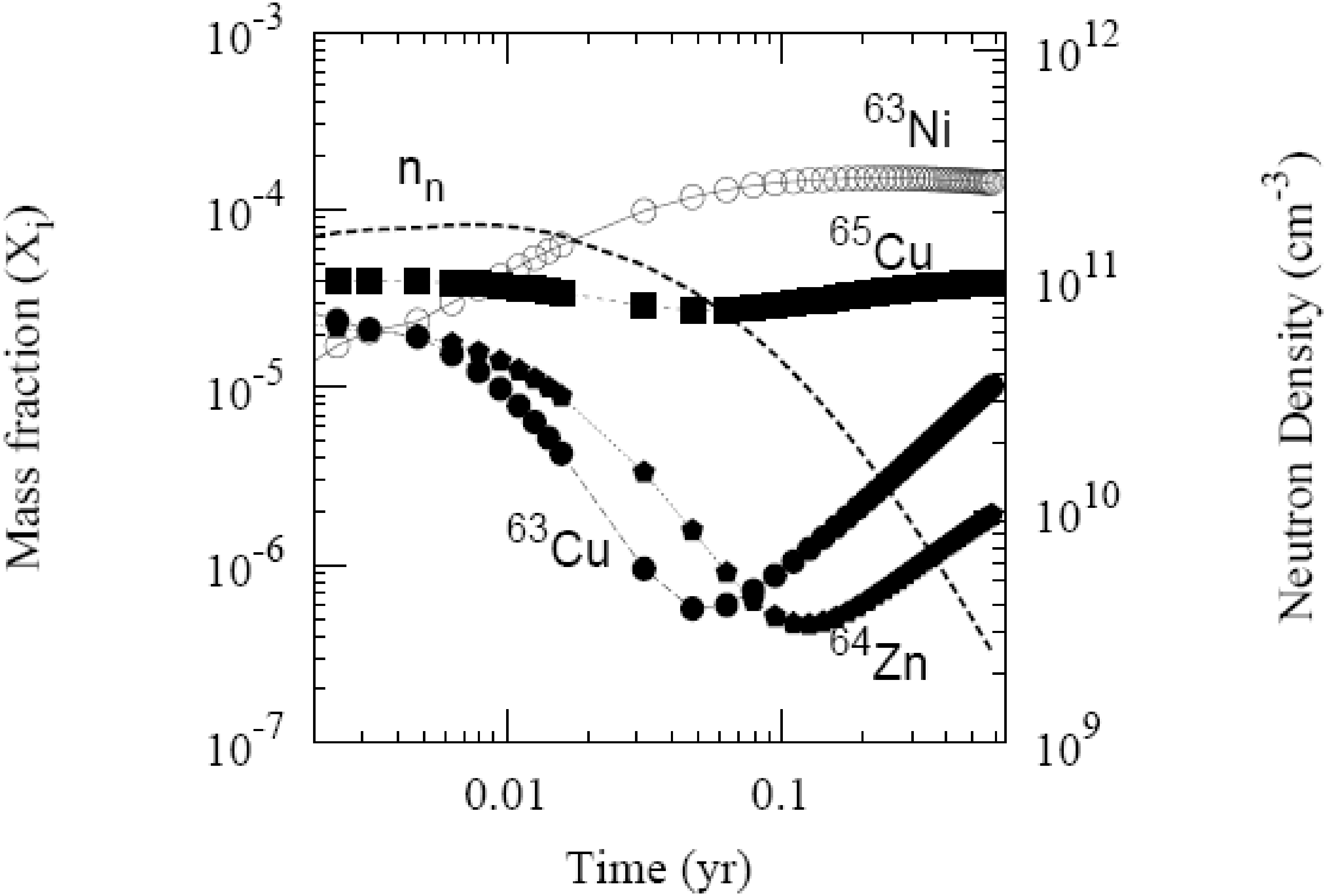
T9 = 1.10

Photodisintegrations to consider during Shell C-burning (up to T9 ~ 1.2):

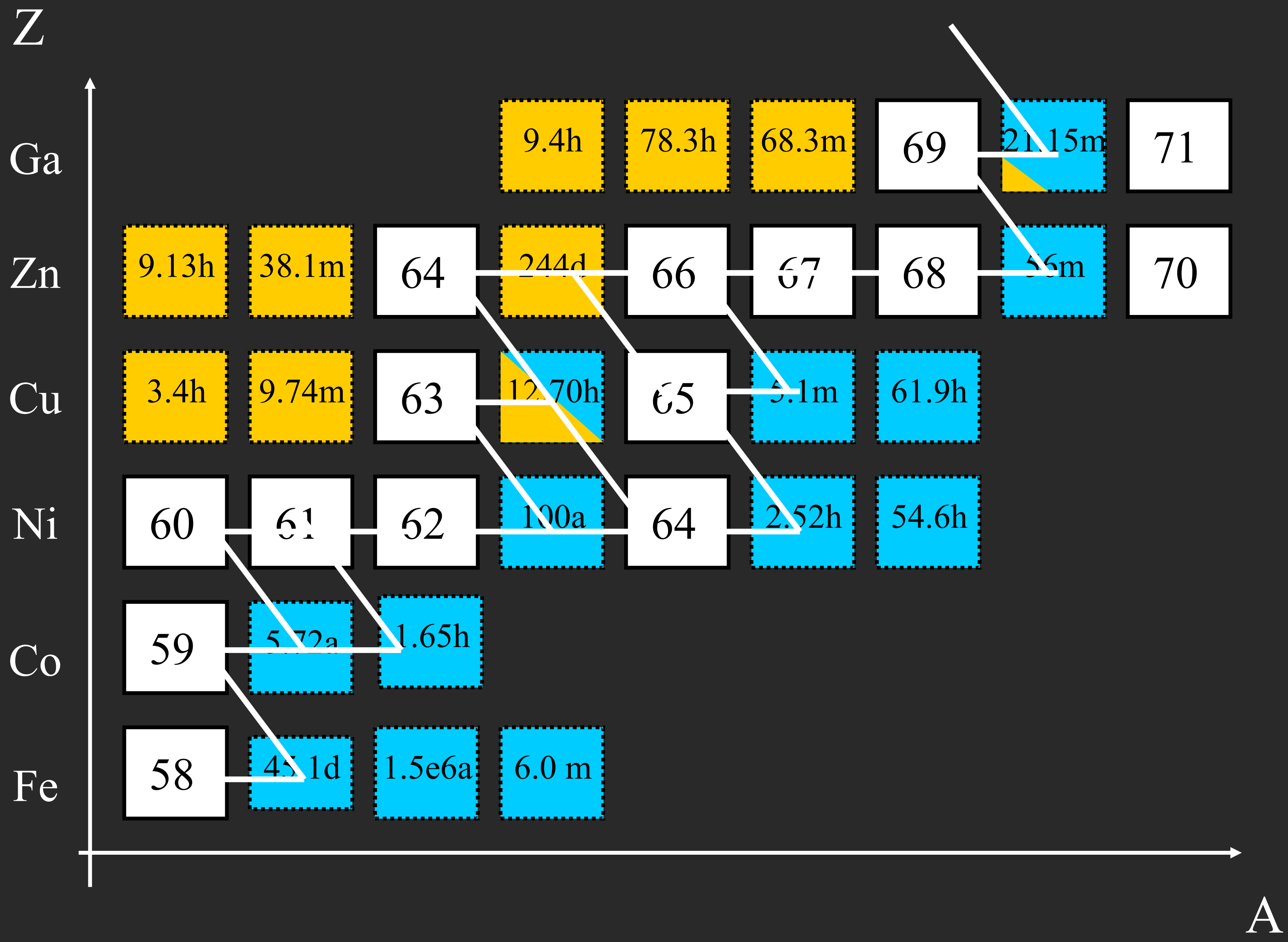
- $^{13}N(\gamma,p)^{12}C$
- $^{17}F(\gamma,p)^{16}O$
- $^{17}O(\gamma,n)^{16}O$
- $^{21}Na(\gamma,p)^{20}Ne$
- $^{25}Al(\gamma,p)^{24}Mg$

For T9 > 1.2

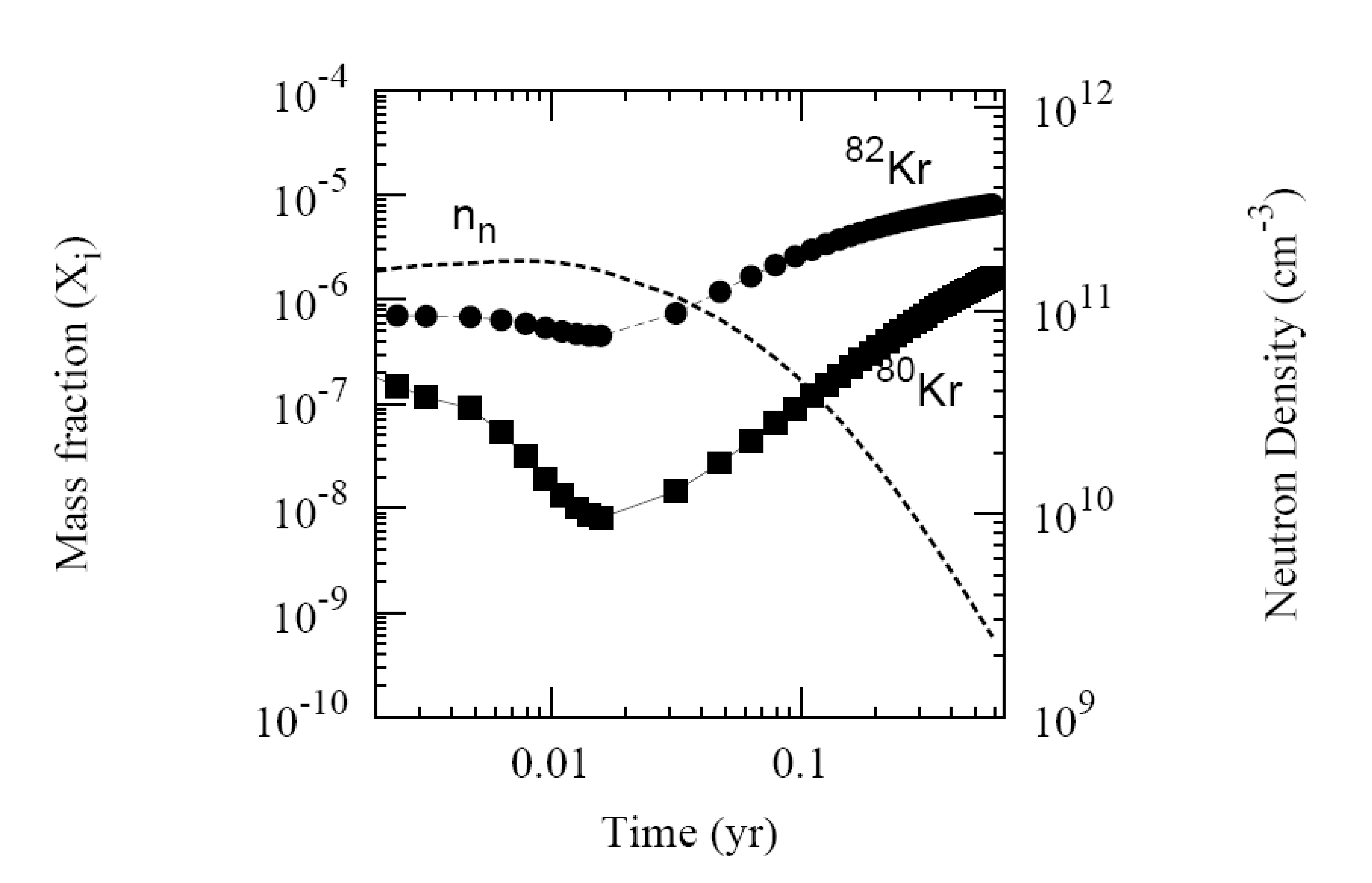
$^{29}P(\gamma,p)^{28}Si$, …

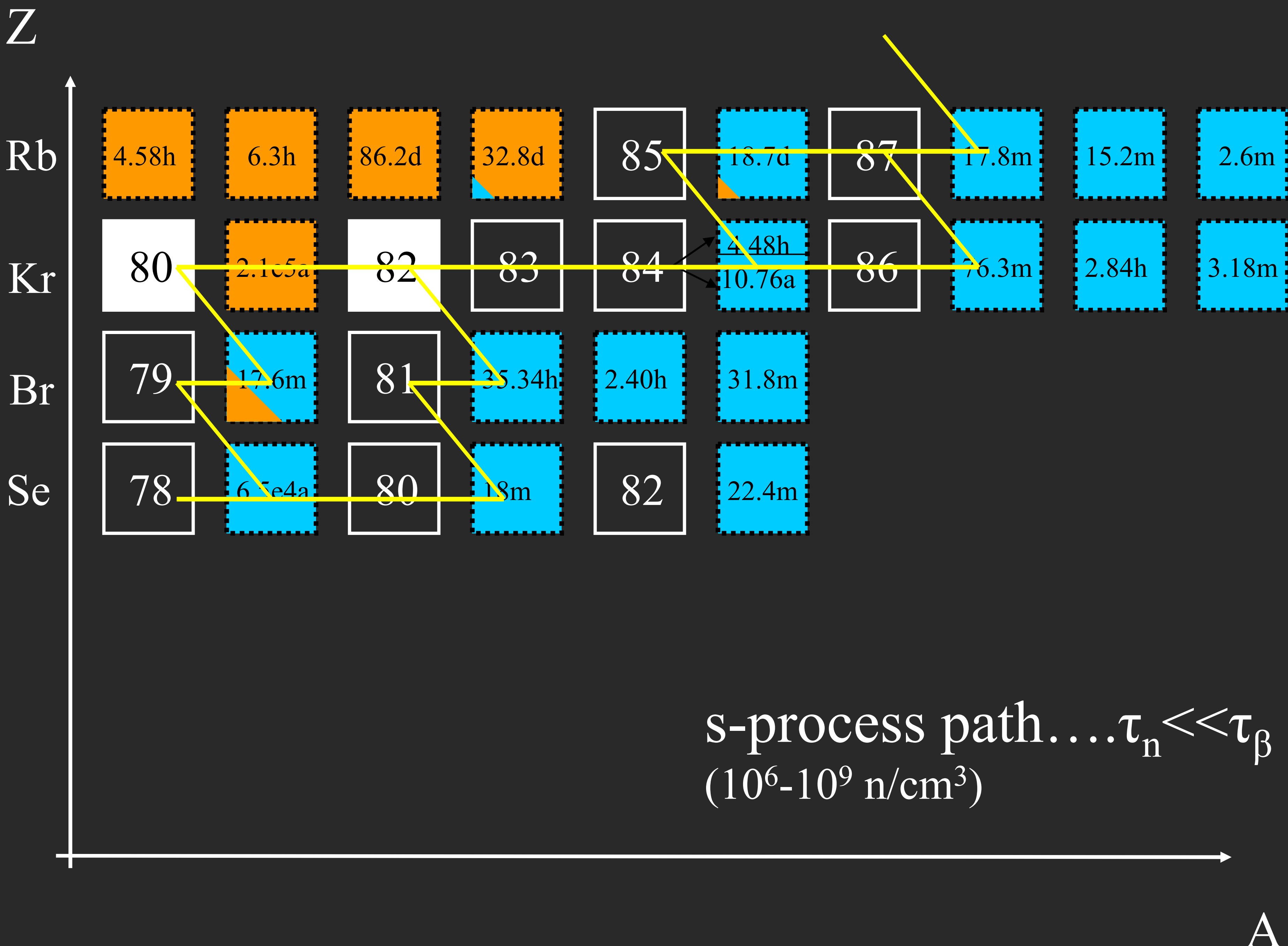


10-3
10-4
10-5
10-6
10-7
1012
1011
1010
109
0.01
0.1
Time (yr)
Mass fraction (Xi)
Neutron Density (cm-3)
63Ni
nn
65Cu
63Cu
64Zn


Z
Ga
Zn
Cu
Ni
Co
Fe
A
9.4h
78.3h
68.3m
69
21.15m
71
9.13h
38.1m
64
244d
66
67
68
56m
70
3.4h
9.74m
63
12.70h
65
5.1m
61.9h
60
61
62
100a
64
2.52h
54.6h
59
5.72a
1.65h
58
45.1d
1.5e6a
6.0 m

This is not a classic s-process!

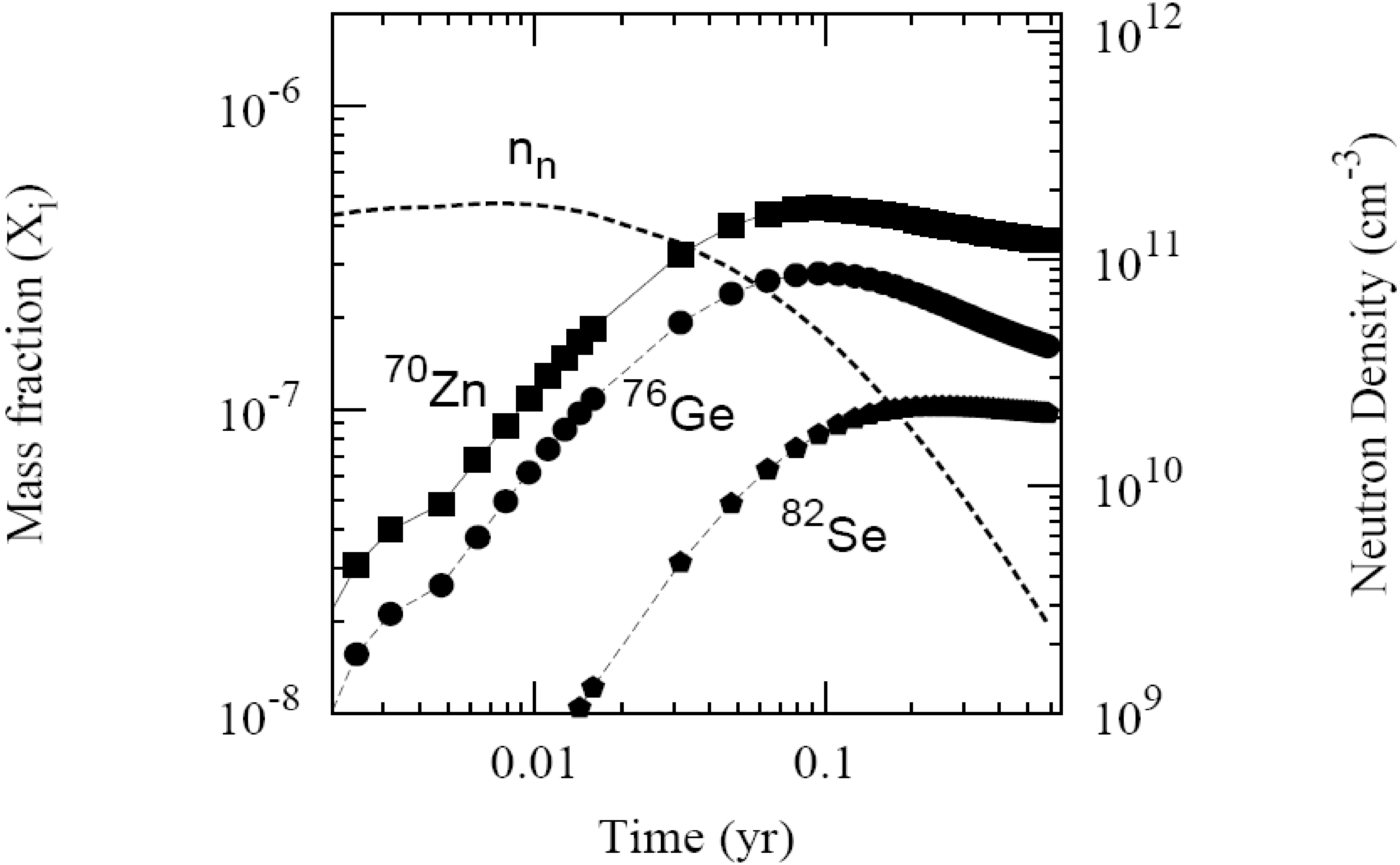




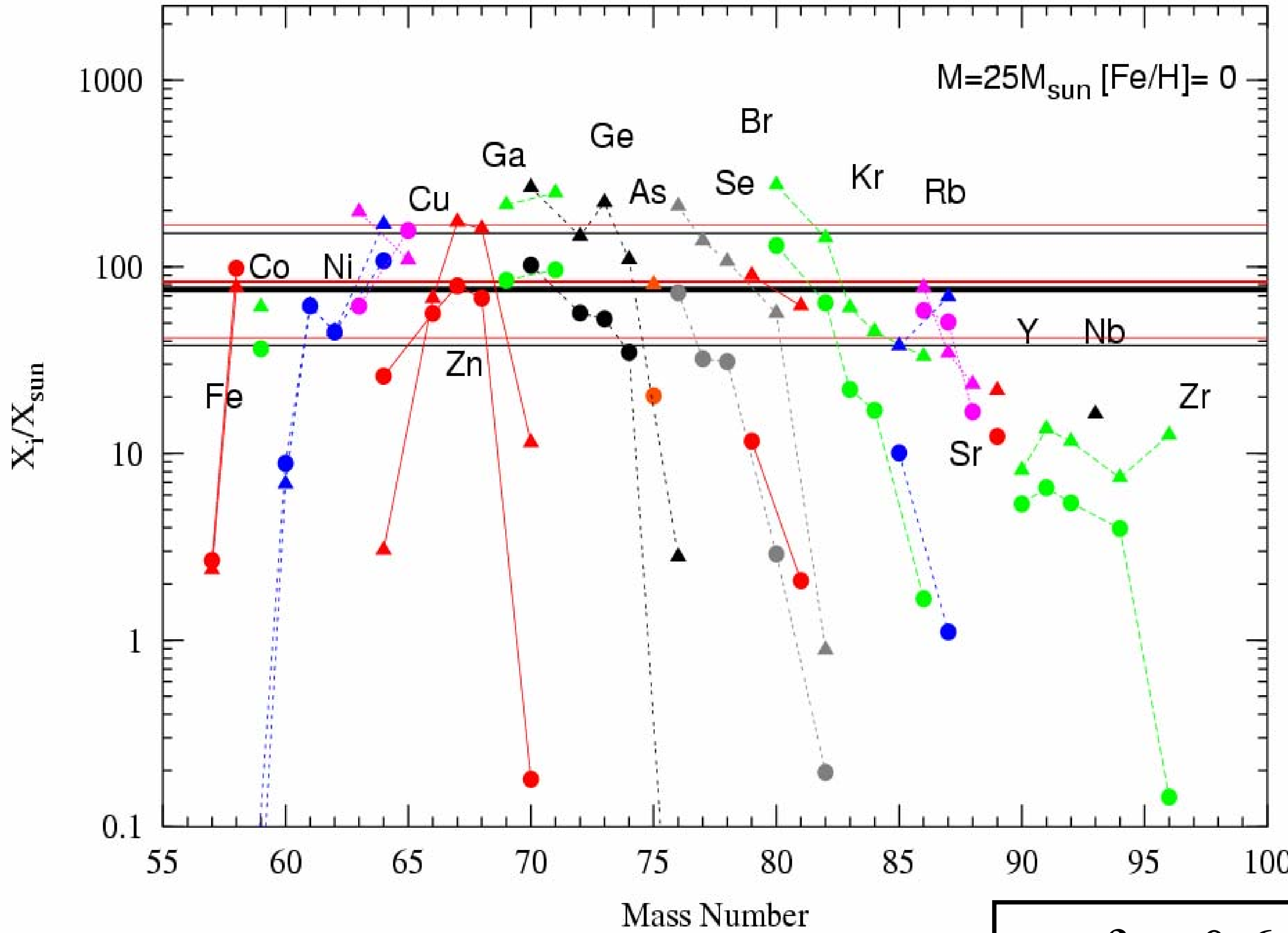
s-process path…. $\tau_n << \tau_\beta$

(10^6-10^9 n/cm^3)

This is not a classic s-process!

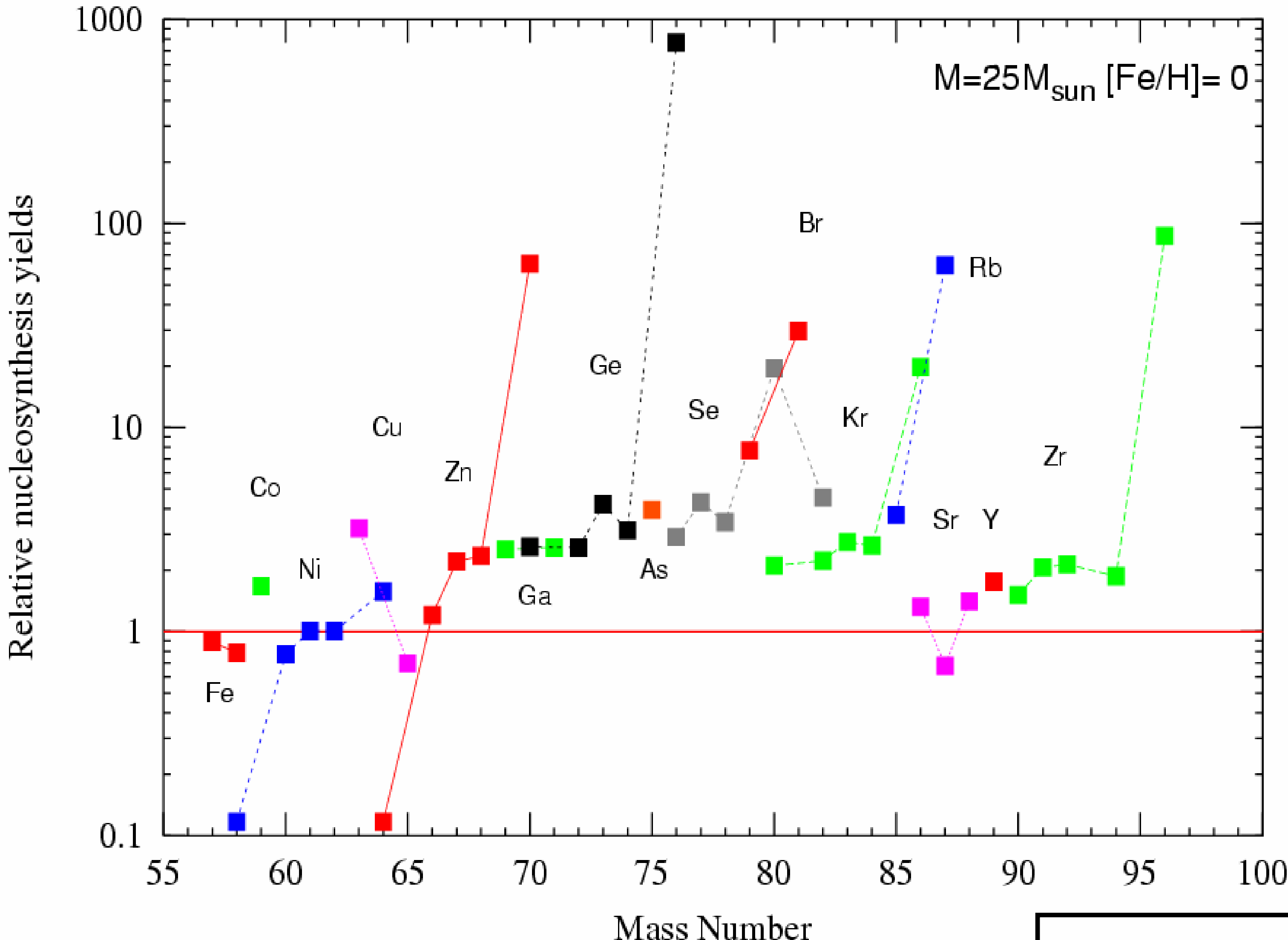


C-burning (T9 ~ 1.05) over the Core He-burning ashes...



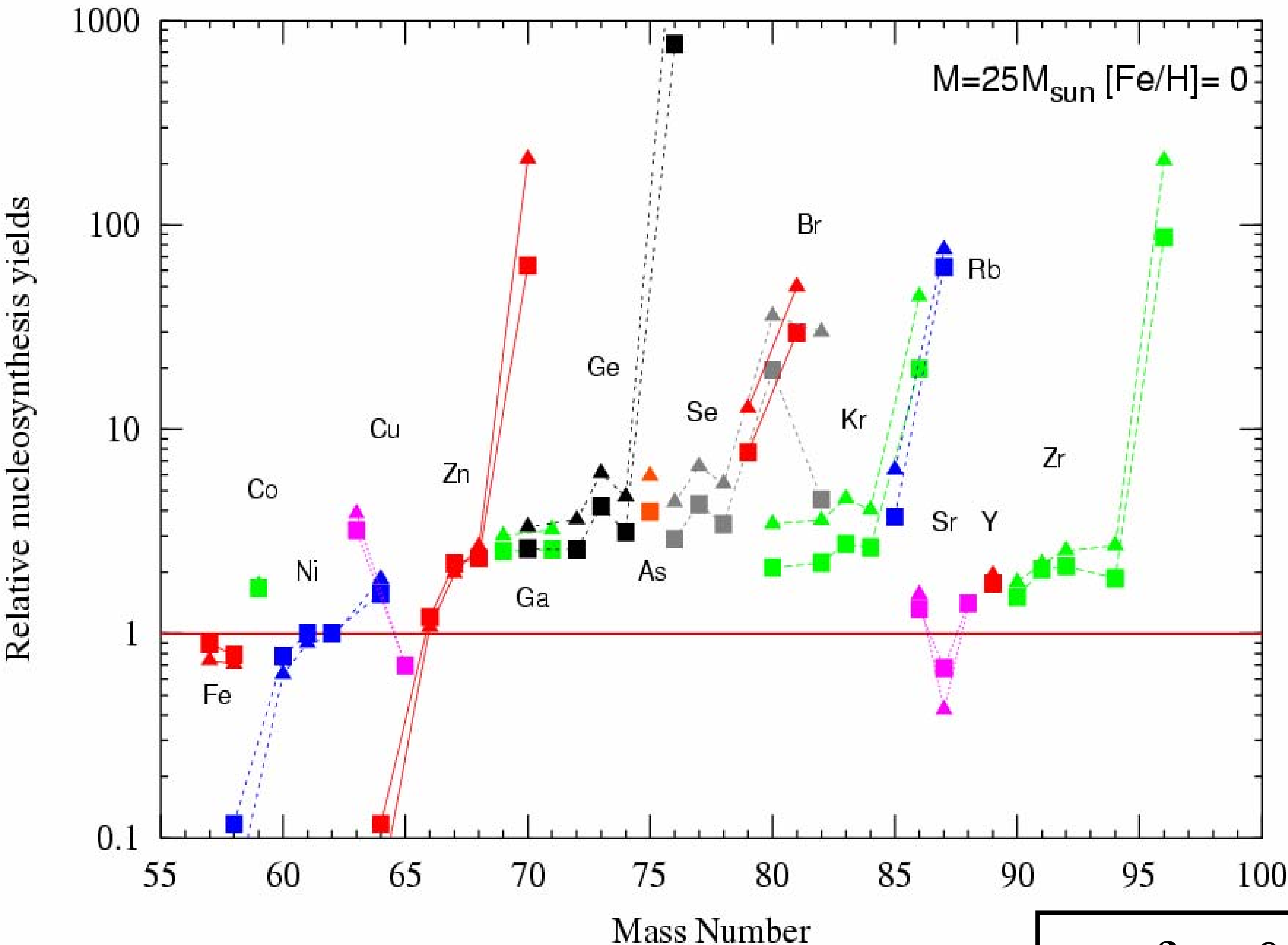
…after 0.6 yr

C-burning (T9 ~ 1.05) over the Core He-burning ashes...



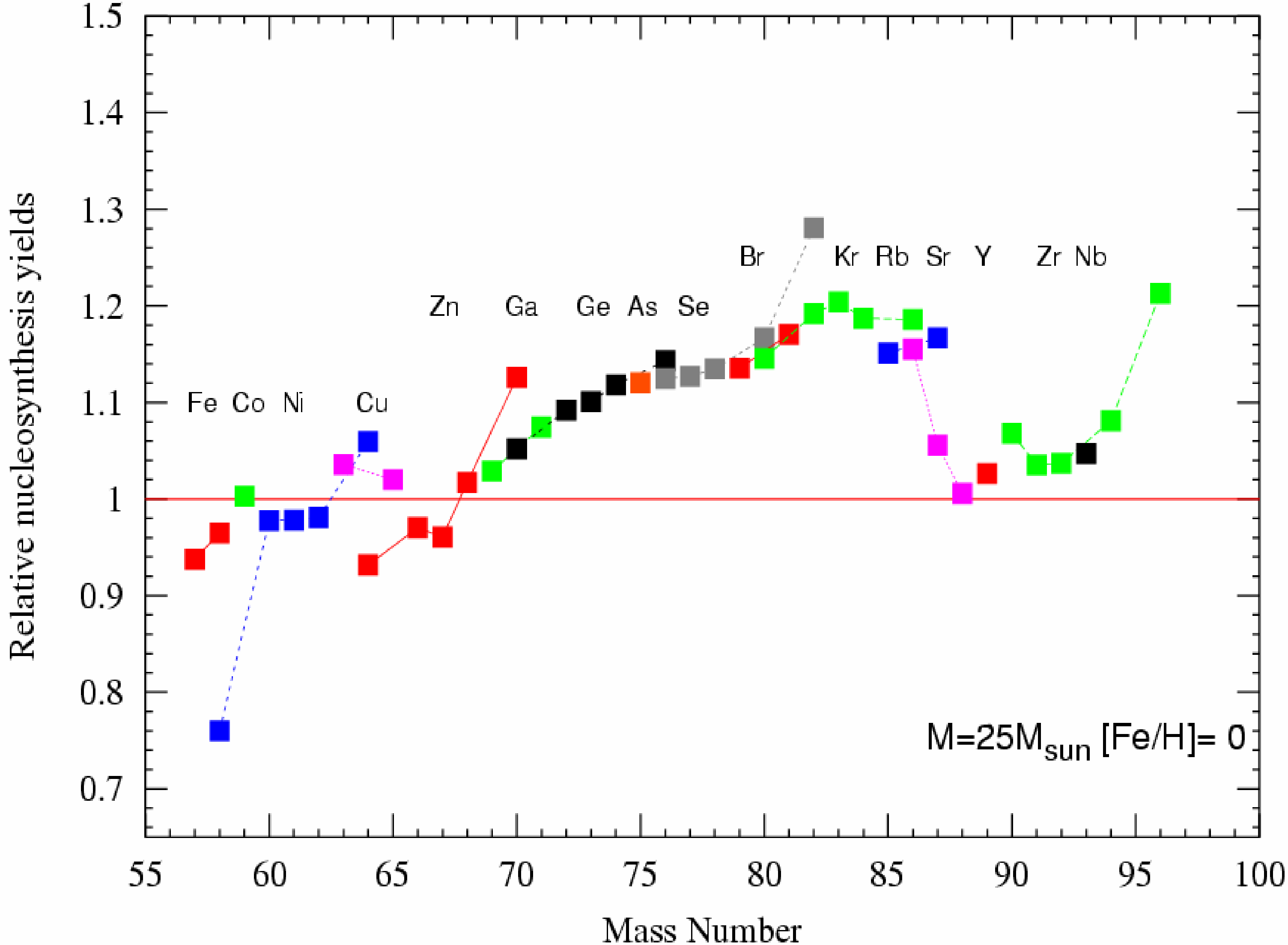
…after 0.6 yr

C-burning (T9 ~ 1.05, 1.10) over the Core He-burning ashes...



…after 0.6 yr

Test on the ^{12}C-burning channels, 65:35/50:50



Propagation effects of the neutron capture cross sections uncertainties on the weak s component

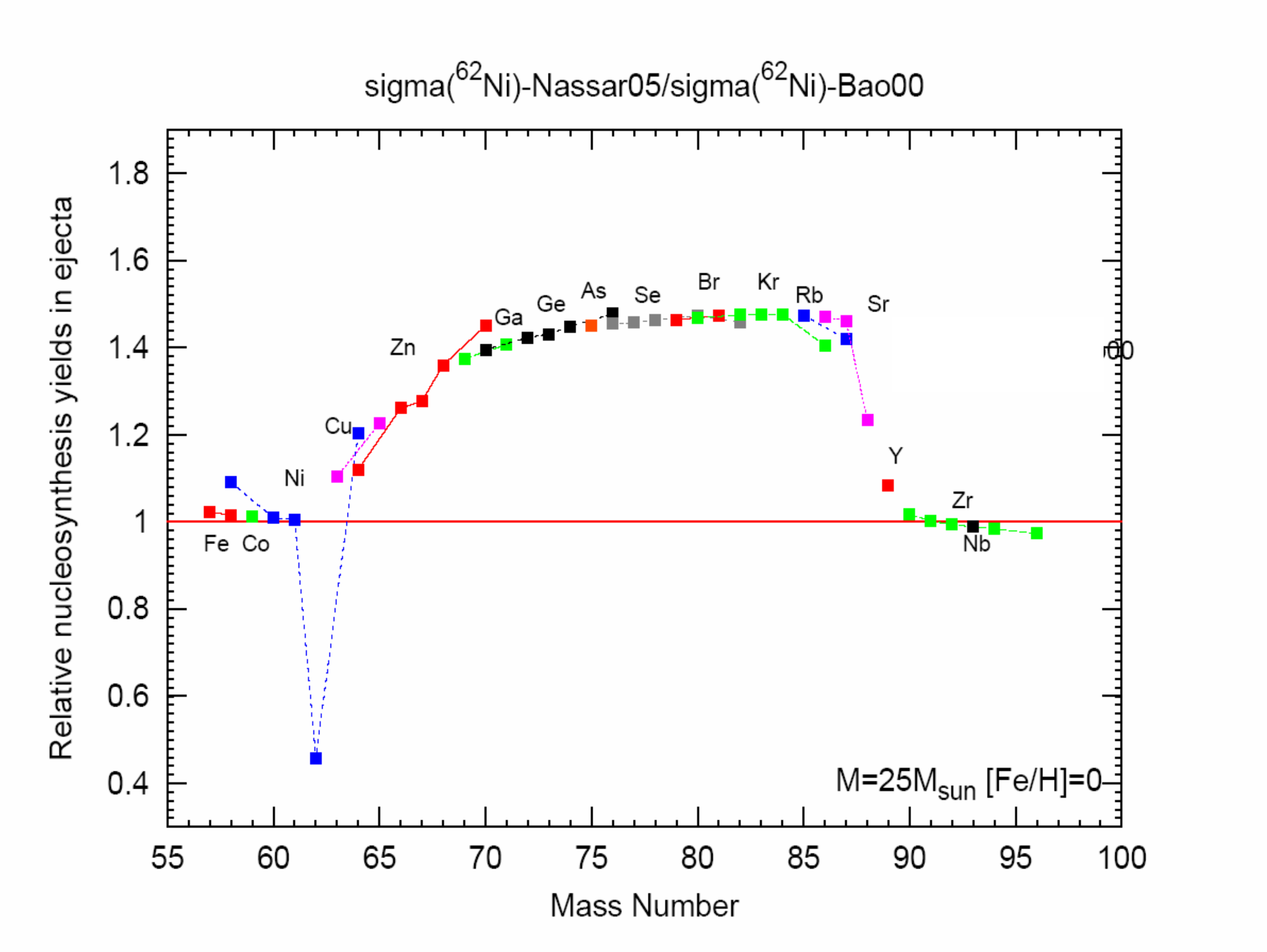
The case of the ^{62}Ni

Two discrepant estimates of the Maxwellian cross section at 30 KeV in the literature, based on the same experiment:

35.5 mb	Bao et al. 1987
13.5 mb	Bao et al. 2000

A new measurement provides:

30.5±2.8 mb	Nassar et al. 2005

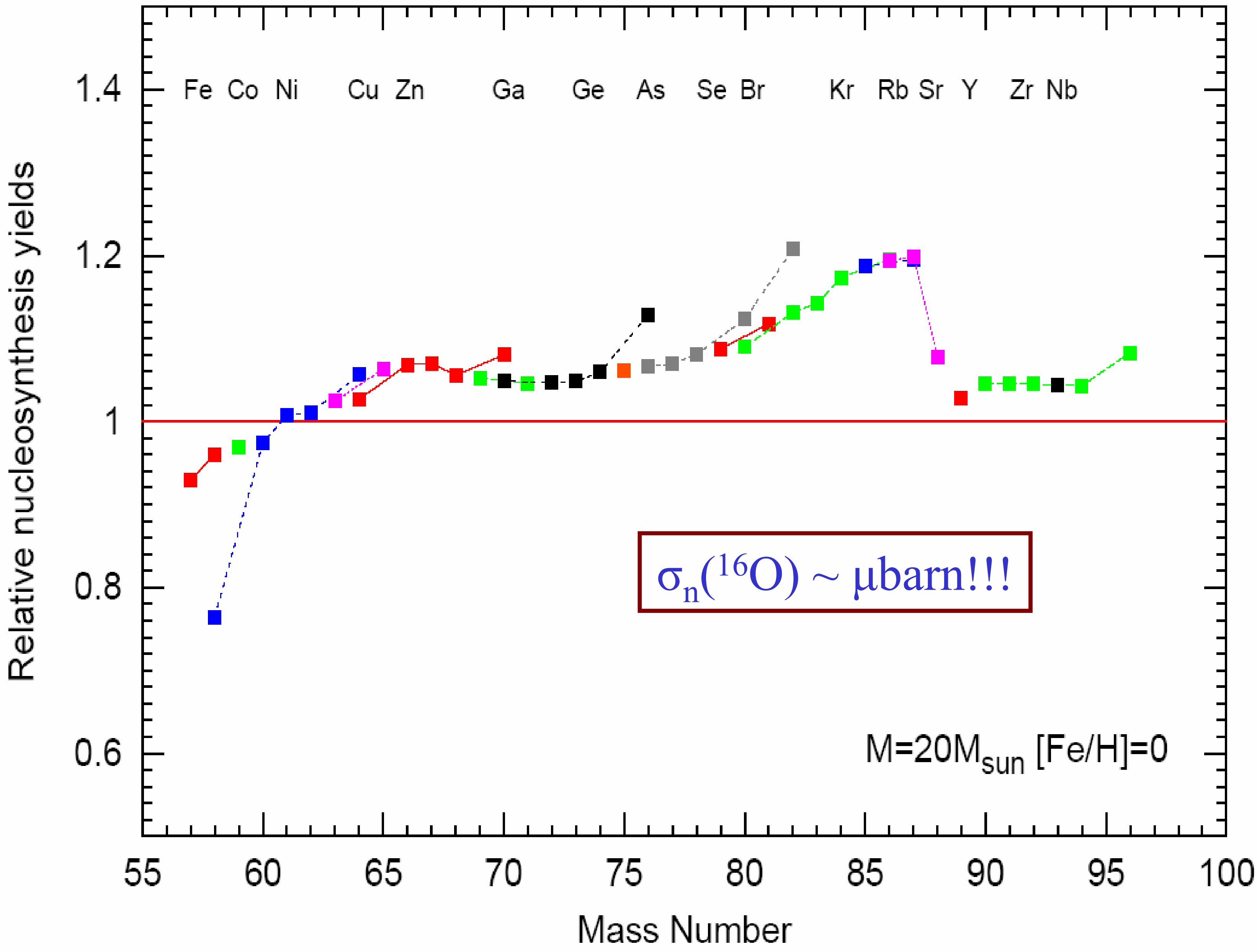


See also Nassar et al. 2005

Neutron poisons of the weak s-process: effect of cross section uncertainties

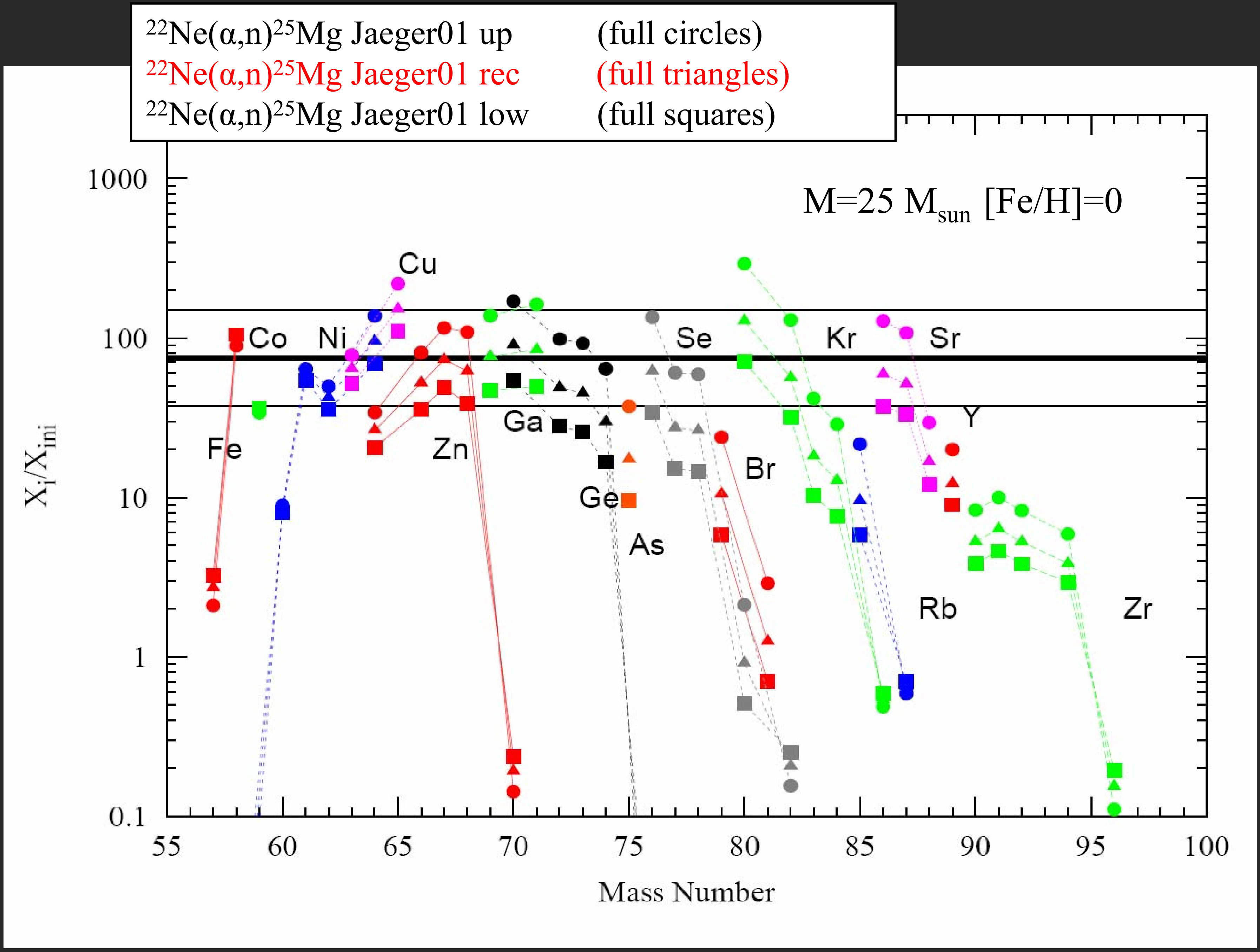
- The light isotopes capture the major fraction of the available neutrons, behaving as poisons for the weak s-process.
- The major poison is ^{16}O
- Other important poisons: ^{25}Mg, ^{23}Na, $^{17}O(n,\alpha)$….

Standard case/sigma(^{16}O)*1.1



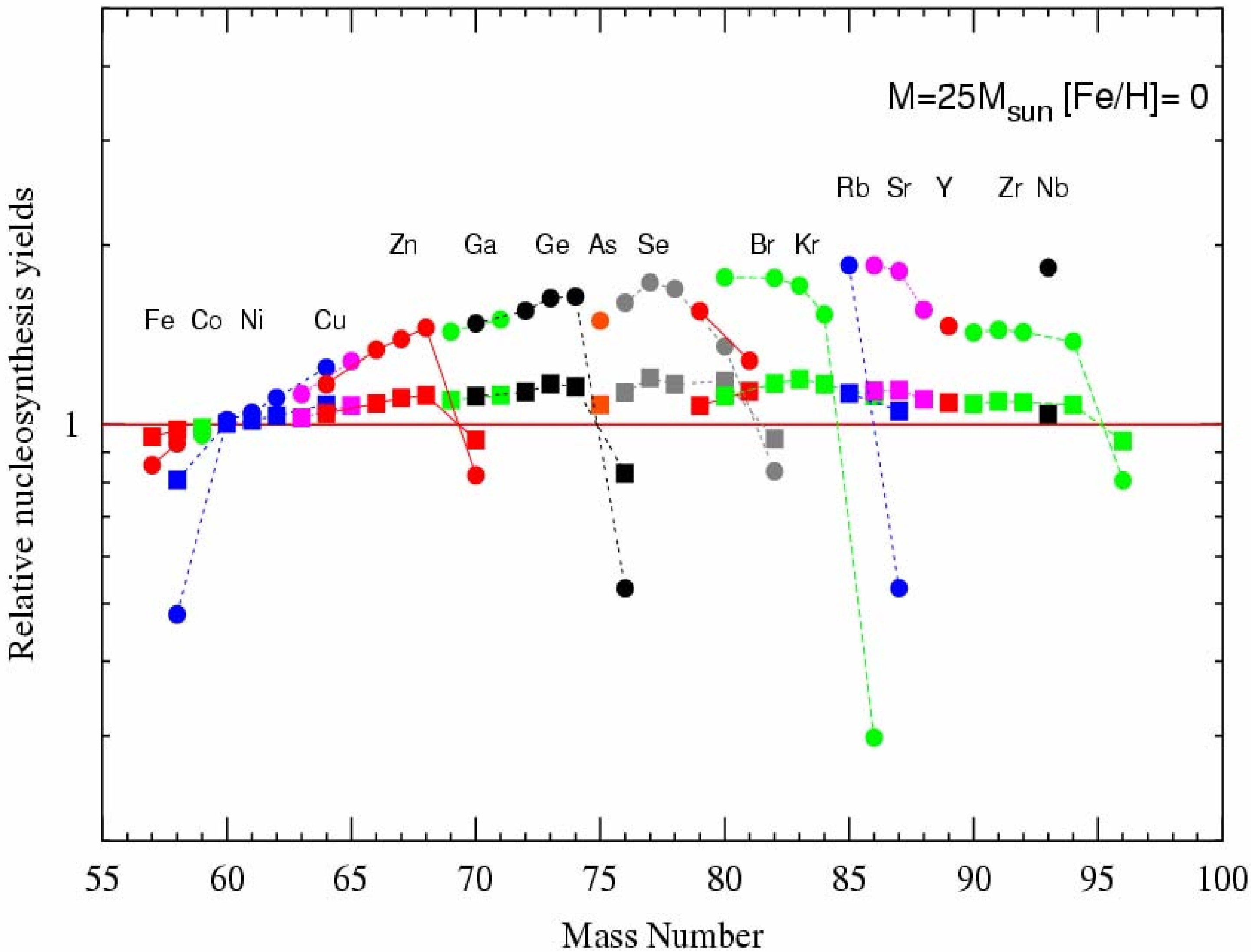
Conclusions

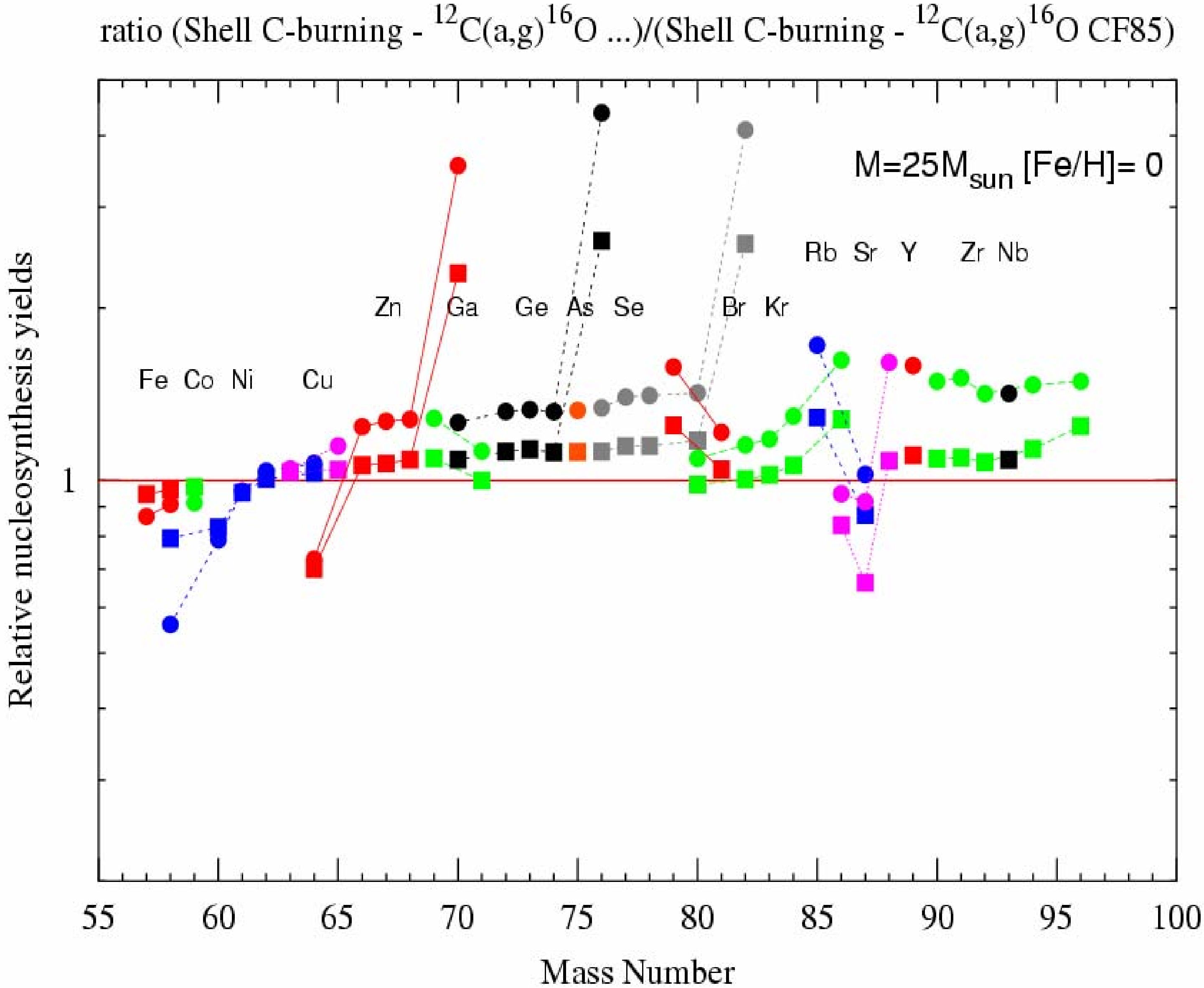
- The weak s component is an overposition of two weak s components with different neutron exposures and different neutron densities: the convective core He-burning and the convective shell C-burning.
- The s-process in the convective C-Shell is important for massive stars, but it is affected from several parameters and nuclear uncertainties.
- .....



^{22}Ne(α,n)^{25}Mg Jaeger01 up (full circles)
^{22}Ne(α,n)^{25}Mg Jaeger01 rec (full triangles)
^{22}Ne(α,n)^{25}Mg Jaeger01 low (full squares)
M=25 M_{sun} [Fe/H]=0
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
X_i/X_{ini}
Mass Number

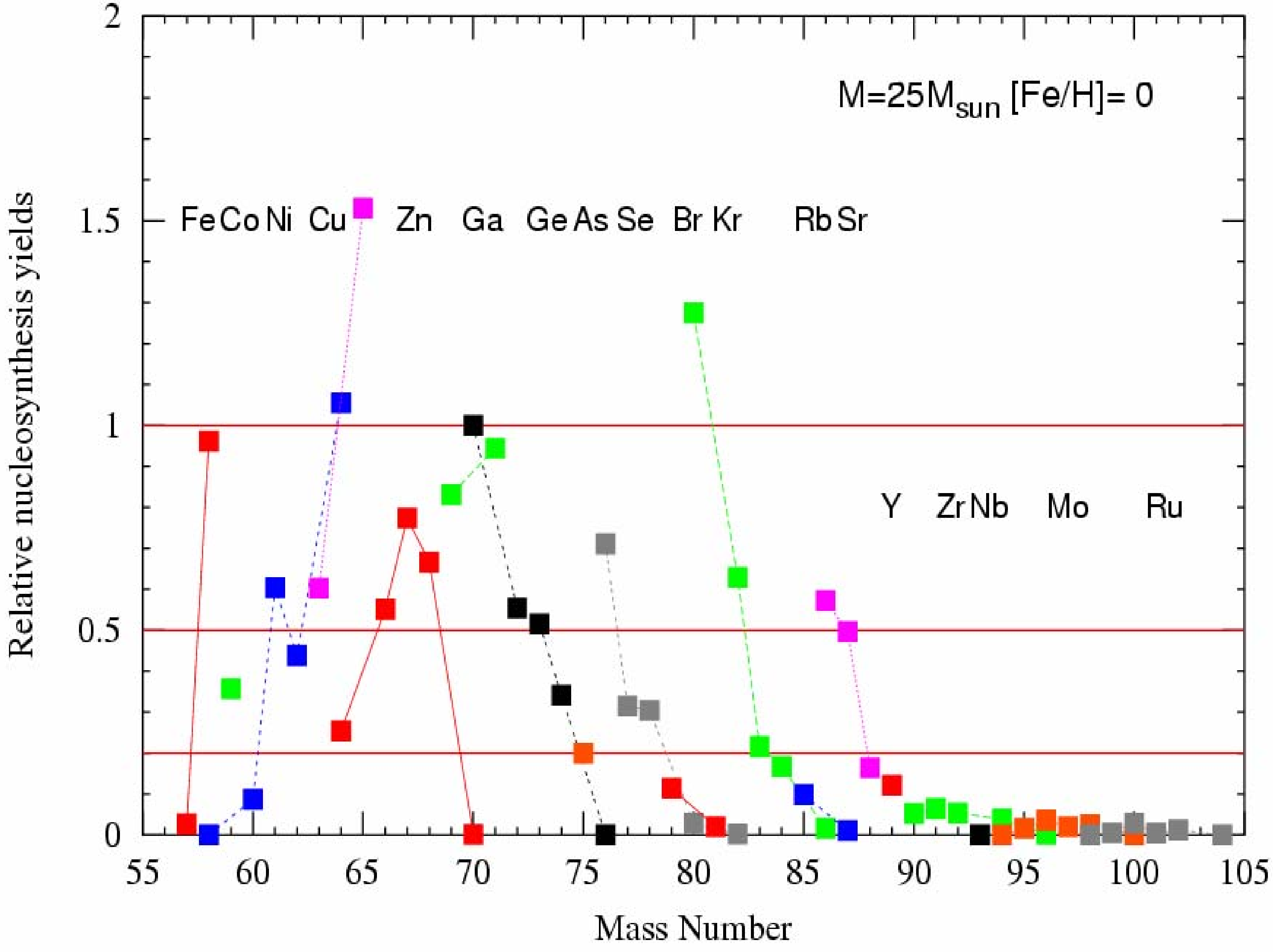
ratio (end Core He-burning - $^{12}C(a,g)^{16}O$ ...)/(end Core He-burning - $^{12}C(a,g)^{16}O$ CF85)





ratio (Shell C-burning - ^{12}C(a,g)^{16}O ...)/(Shell C-burning - ^{12}C(a,g)^{16}O CF85)
M=25M$_{sun}$ [Fe/H]= 0
Fe Co Ni Cu
Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb
Relative nucleosynthesis yields
1
55 60 65 70 75 80 85 90 95 100
Mass Number

Weak s-process contribution – Core He-burning



Weak s-process contribution – Shell C-burning