The s-process in massive stars: the shell C-burning contribution

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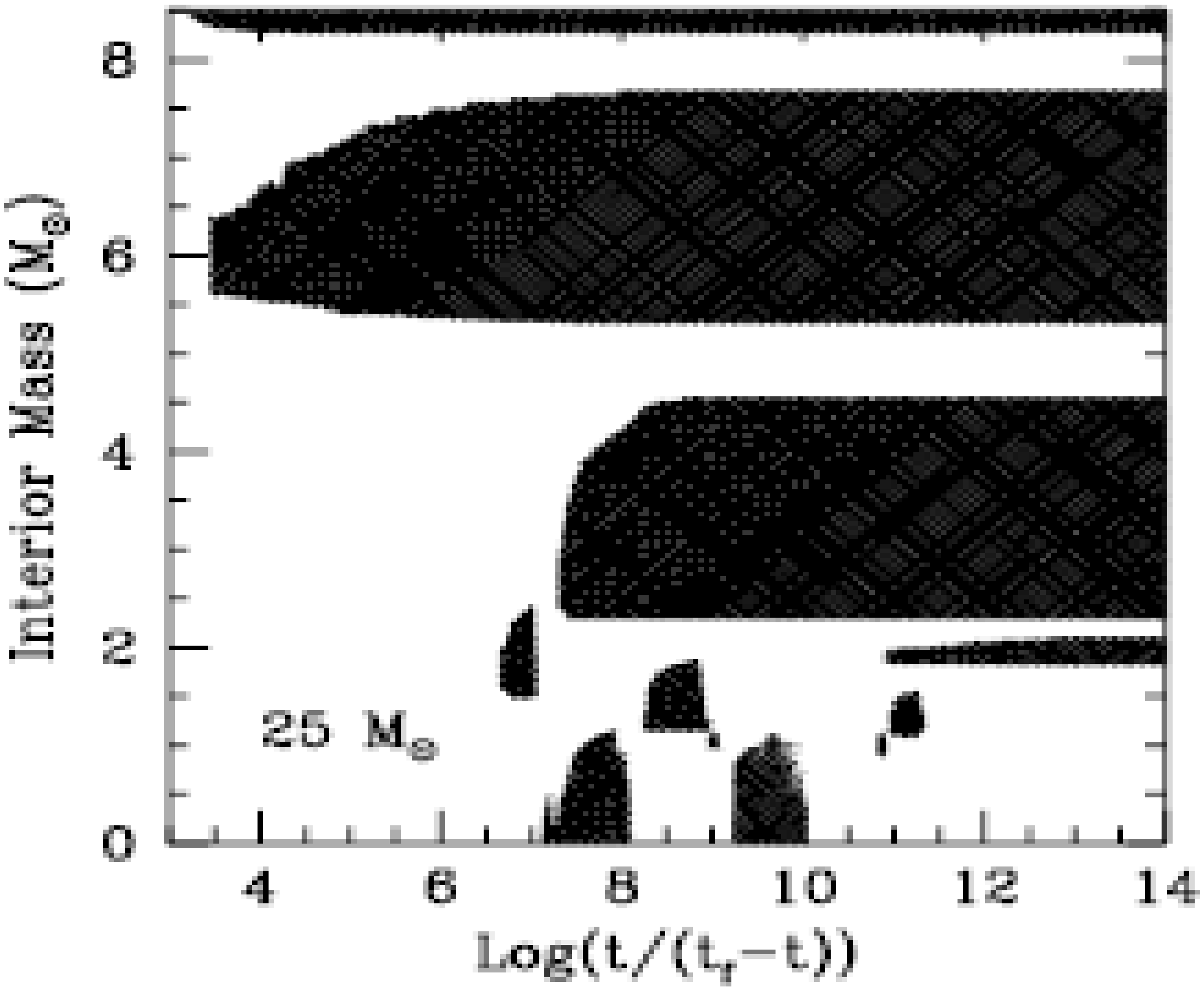
Kippenhahn's Diagram for a star with M= 25 M(sun) and solar metallicity (Limongi & Chieffi 2000, ApJ)

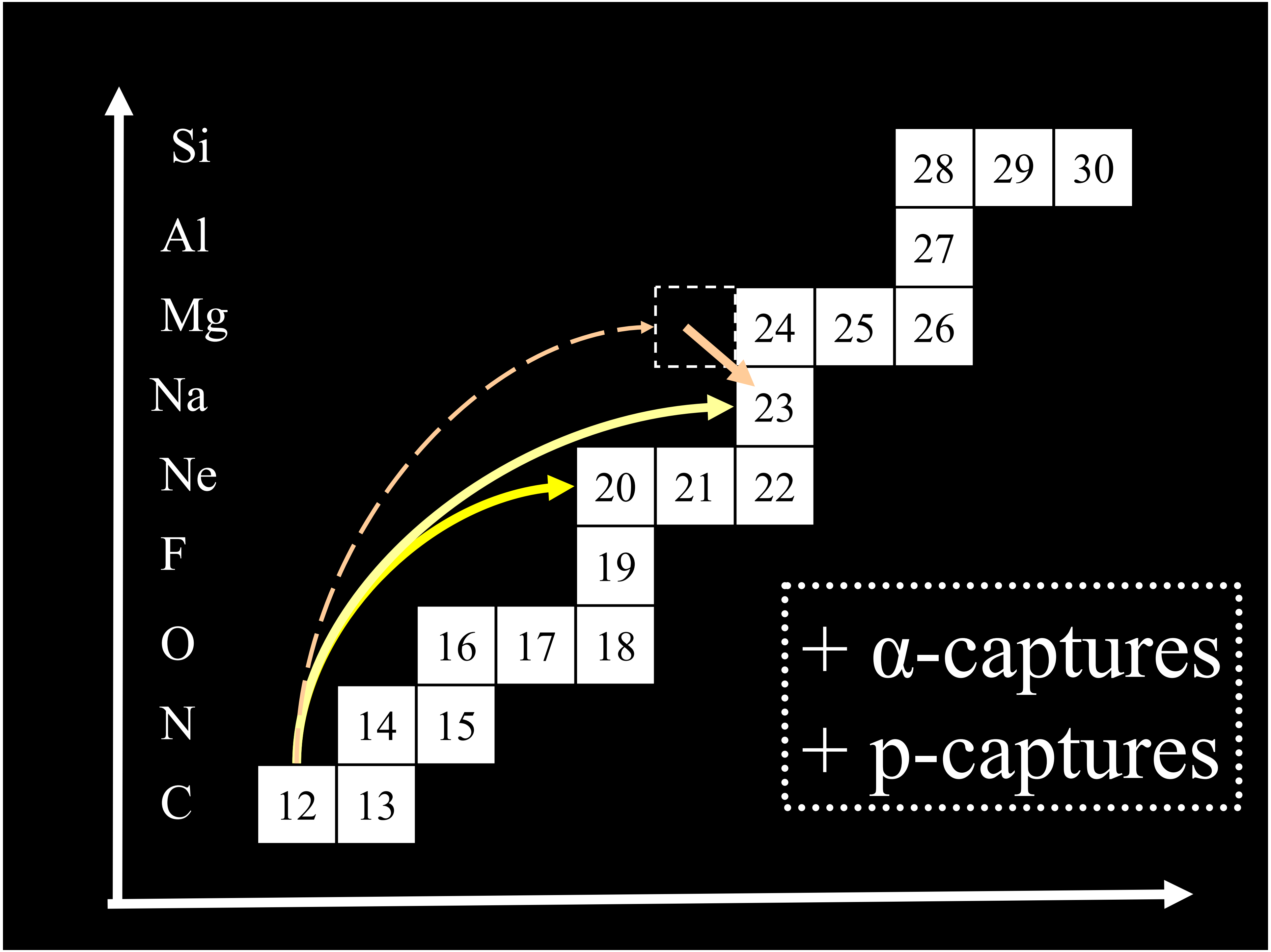


In the C shell:

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)


Si
Al
Mg
Na
Ne
F
O
N
C
28
29
30
27
24
25
26
23
20
21
22
19
16
17
18
14
15
12
13
+ α-captures
+ p-captures

Photodisintegrations to consider during shell C-burning:

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

* = photodisintegrations dominant on the direct reaction at 1 GK

For T9 > 1.2

$^{29}P(\gamma,p)^{28}Si$, …

In the C Shell:

Possible neutron sources:

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

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

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

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

$^{22}Ne(\alpha,n)^{25}Mg$ ←

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

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

The weak s-component: summary

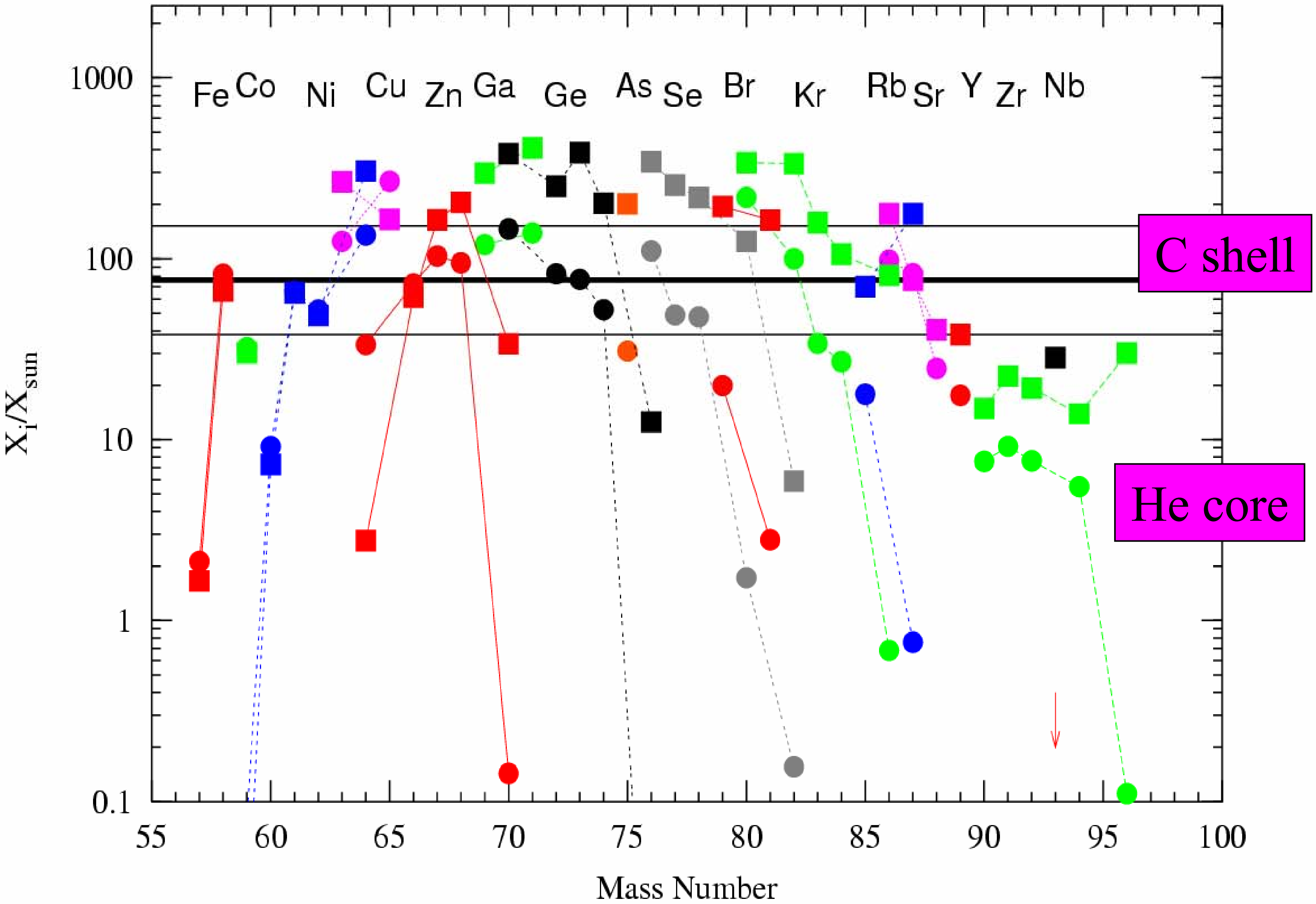
Convective Core He-burning	Convective Shell C-burning
Low neutron density (~10^6 n/cm^3) T~3-3.5 10^8 K Classical s-process See Lamb et al. 1977, Couch et al. 1974, Prantzos et al. 1987, Raiteri et al. 1991	Peak neutron density (10^{11}- 10^{12} n/cm^3) T~ 1 10^9 K The convective shell works over the ashes of the core He-burning (Raiteri et al. 1991)

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

Models:
Hydrostatic nucleosynthesis in massive stars

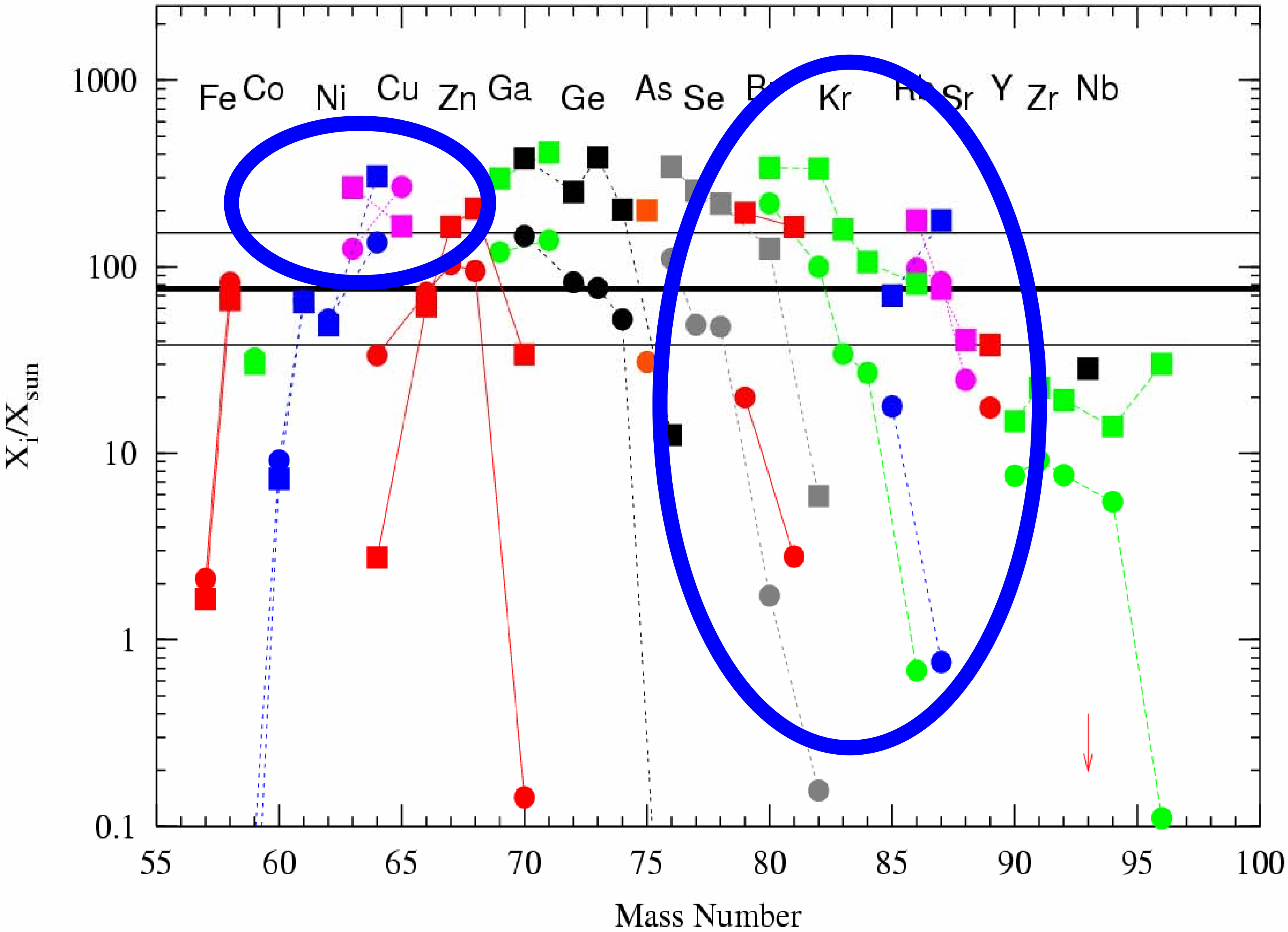
- Post-processing models follow:
  Convective core He-burning and
  Convective shell C-burning
  (Raiteri et al. 1991, 1993)
- Updated network
  Bao et al. 2000 for (n,γ) + more recent measures (**KADoNiS** , I. Dillmann poster),
  β decay rates from various sources,
  (n,p) and (n,α) channels....

25 M_{sun} [Fe/H] = 0

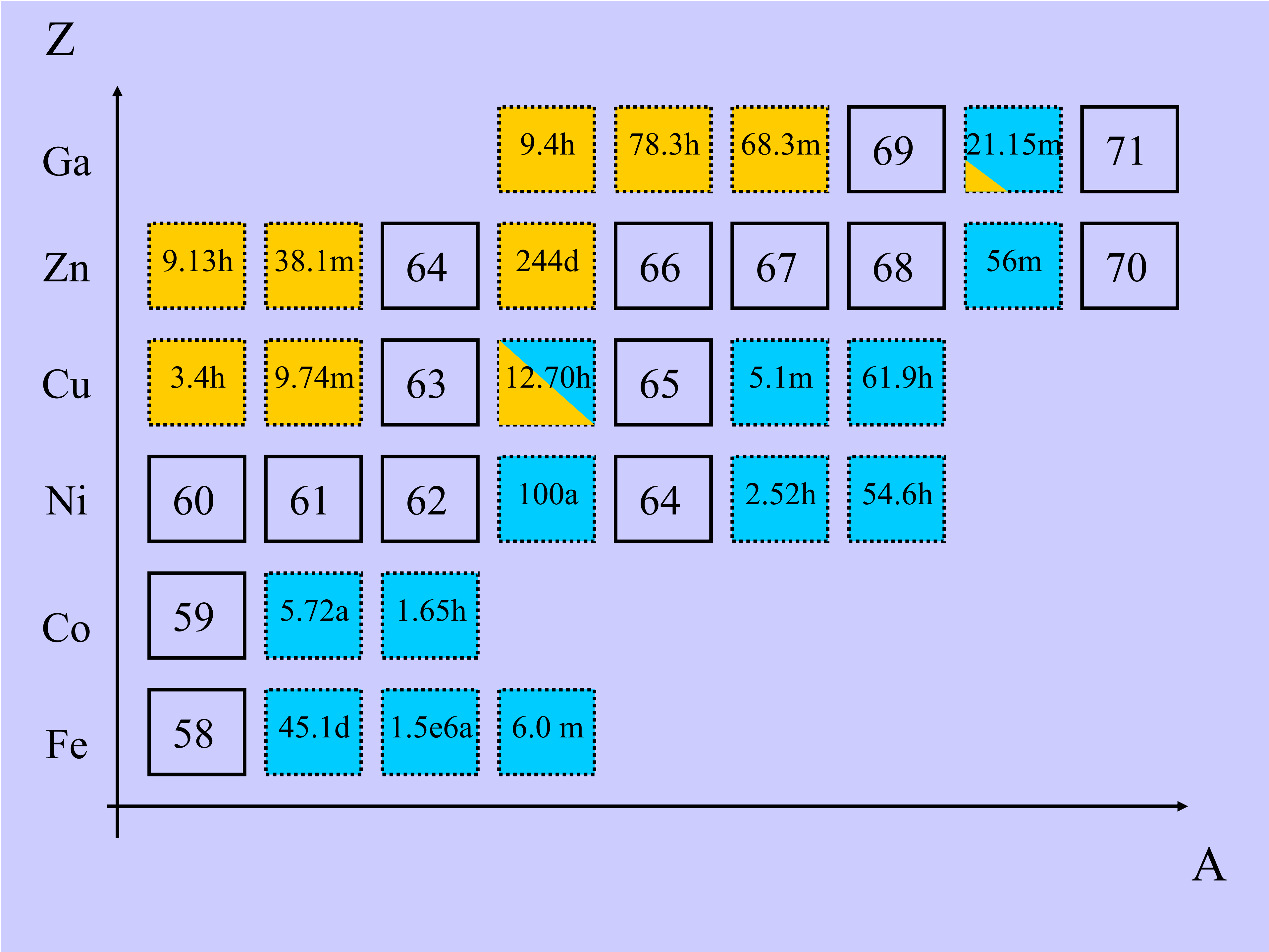


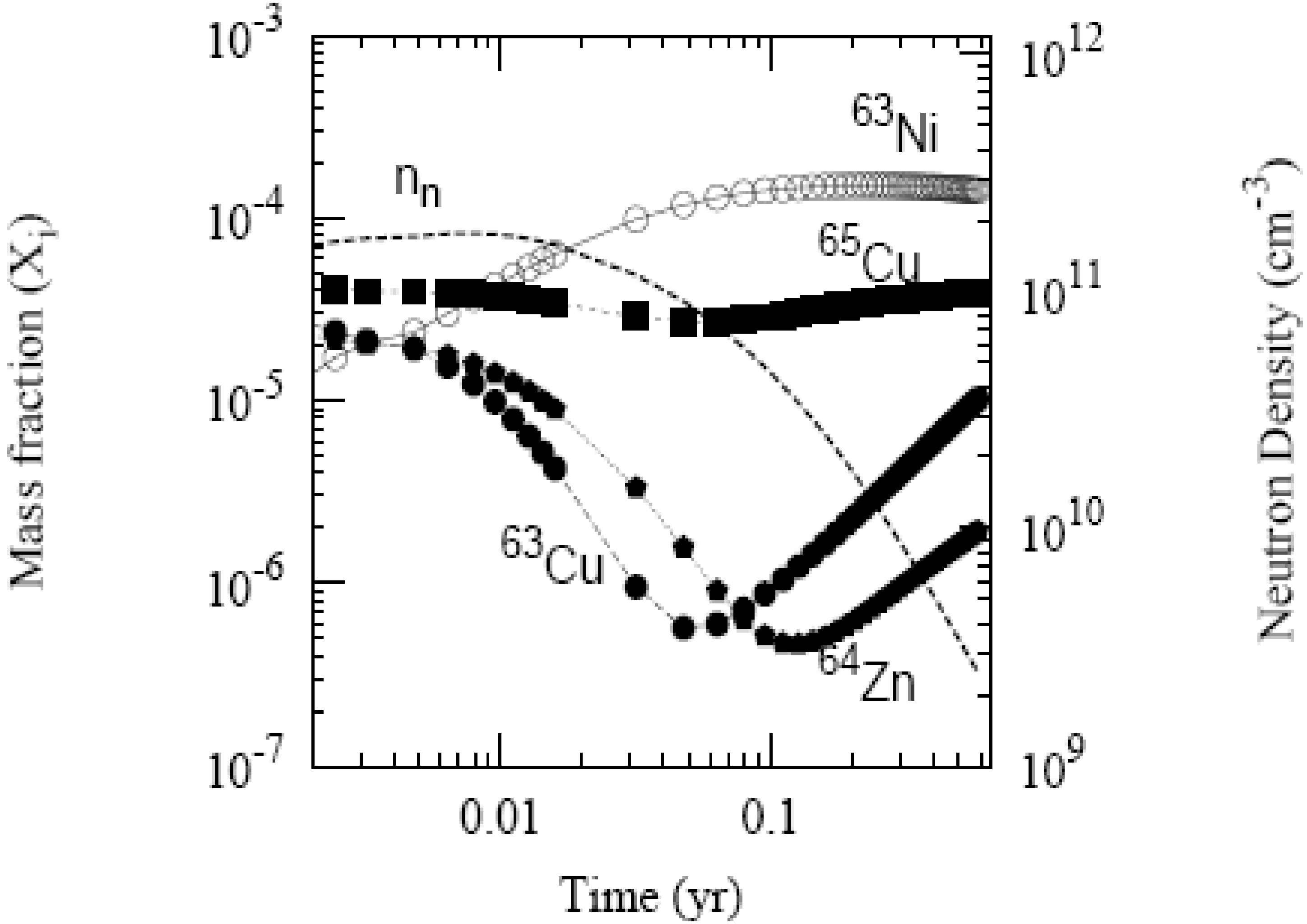
Fe Co Ni Cu Zn Ga Ge As Se Br Kr Rb Sr Y Zr Nb
1000
100
10
1
0.1
55 60 65 70 75 80 85 90 95 100
Mass Number
X_i/X_{sun}
C shell
He core

25 M_{sun} [Fe/H] = 0

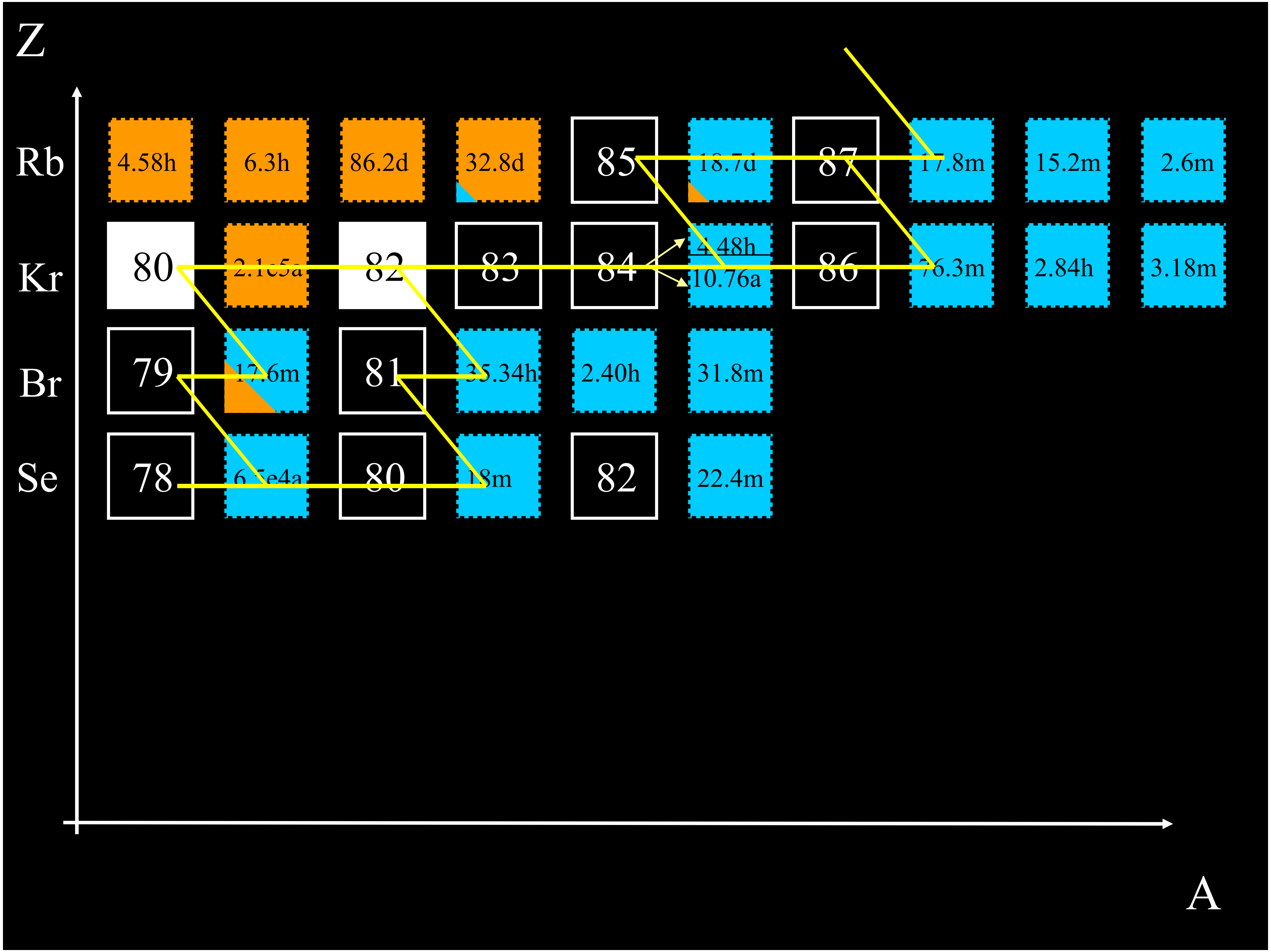


Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Kr
Sr
Y
Zr
Nb
1000
100
10
1
0.1
X_i/X_{sun}
55
60
65
70
75
80
85
90
95
100
Mass Number


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

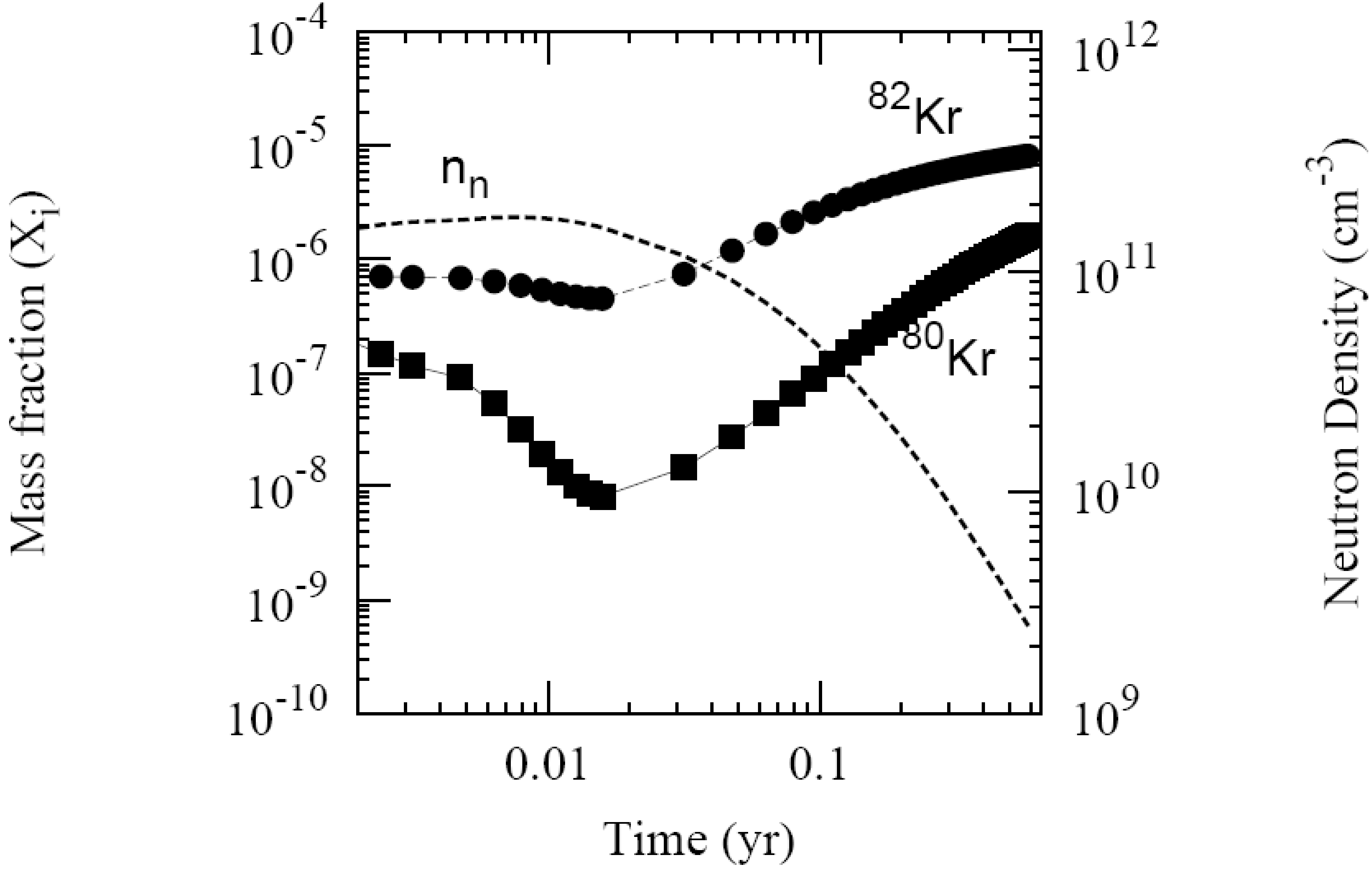


10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Mass fraction (X_i)
10^{12}
10^{11}
10^{10}
10^{9}
Neutron Density (cm^{-3})
0.01
0.1
Time (yr)
n_n
^{63}Ni
^{65}Cu
^{63}Cu
^{64}Zn



Z
Rb
Kr
Br
Se
4.58h
6.3h
86.2d
32.8d
85
87
15.2m
2.6m
80
82
83
84
4.48h
10.76a
86
2.84h
3.18m
79
81
2.40h
31.8m
78
80
82
22.4m
A

This is not a classic s-process!



Metallicity dependence of the Weak s-process

Weaver & Woosley 1995 ApJ

Chieffi & Limongi 2004 ApJ

He core:

^{22}Ne (secondary-like) is the neutron source
^{25}Mg (secondary-like) is the main neutron poison

→ constant neutron exposure at different metallicities
constant number of neutrons captured per iron seed

$$n_c = \Sigma_{56}^{209}(A-56)[N_{fin}(A)-N_{in}(A)]/^{56}Fe_{ini}$$

→ S-PROCESS YIELDS BEYOND IRON SCALES WITH THE METALLICITY

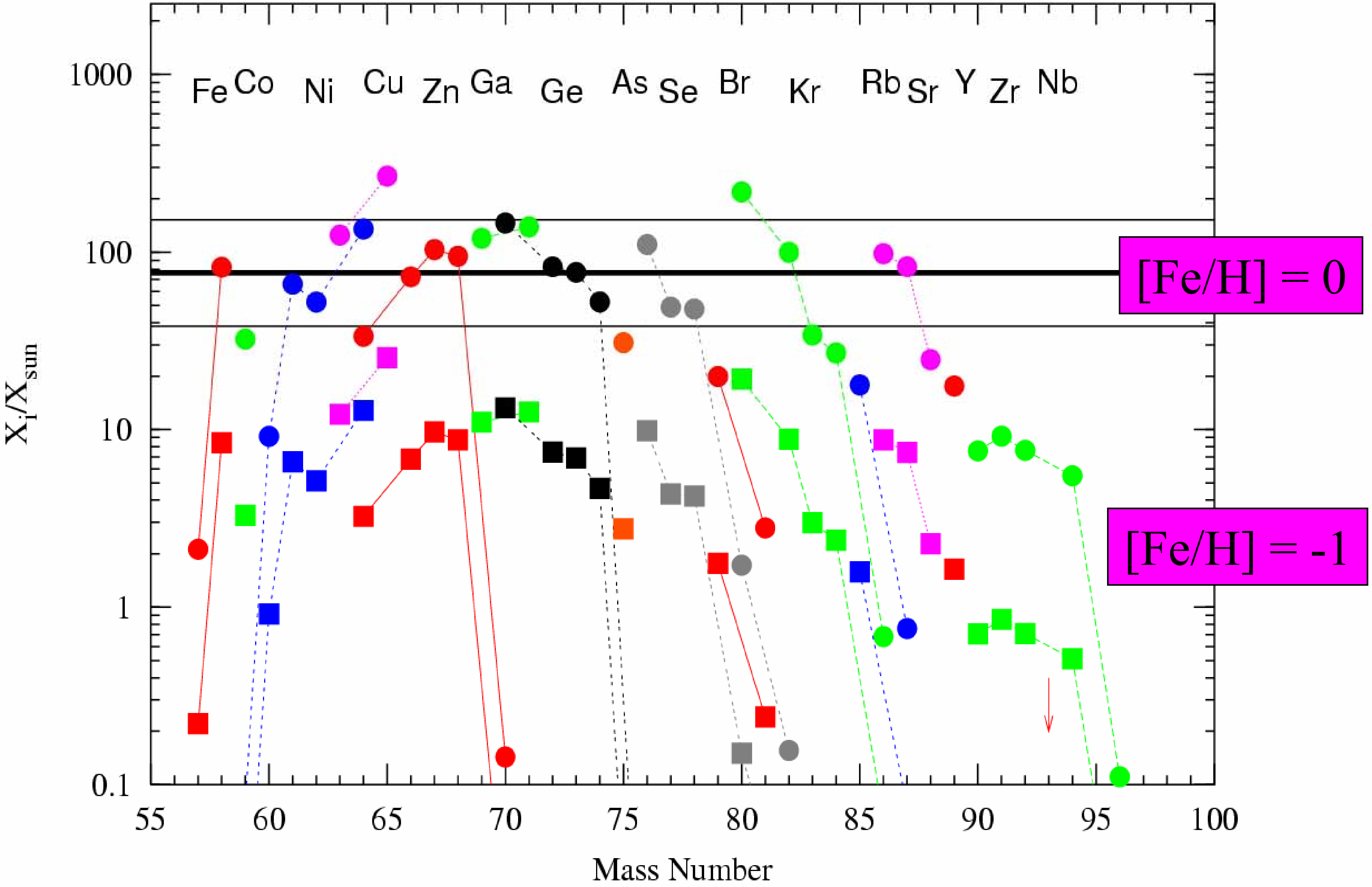
C shell:

^{22}Ne (secondary-like) is the main neutron source
^{25}Mg (secondary-like) and ^{16}O, ^{23}Na, ^{24}Mg, ^{28}Si….
(primary-like) are the main neutron poisons!

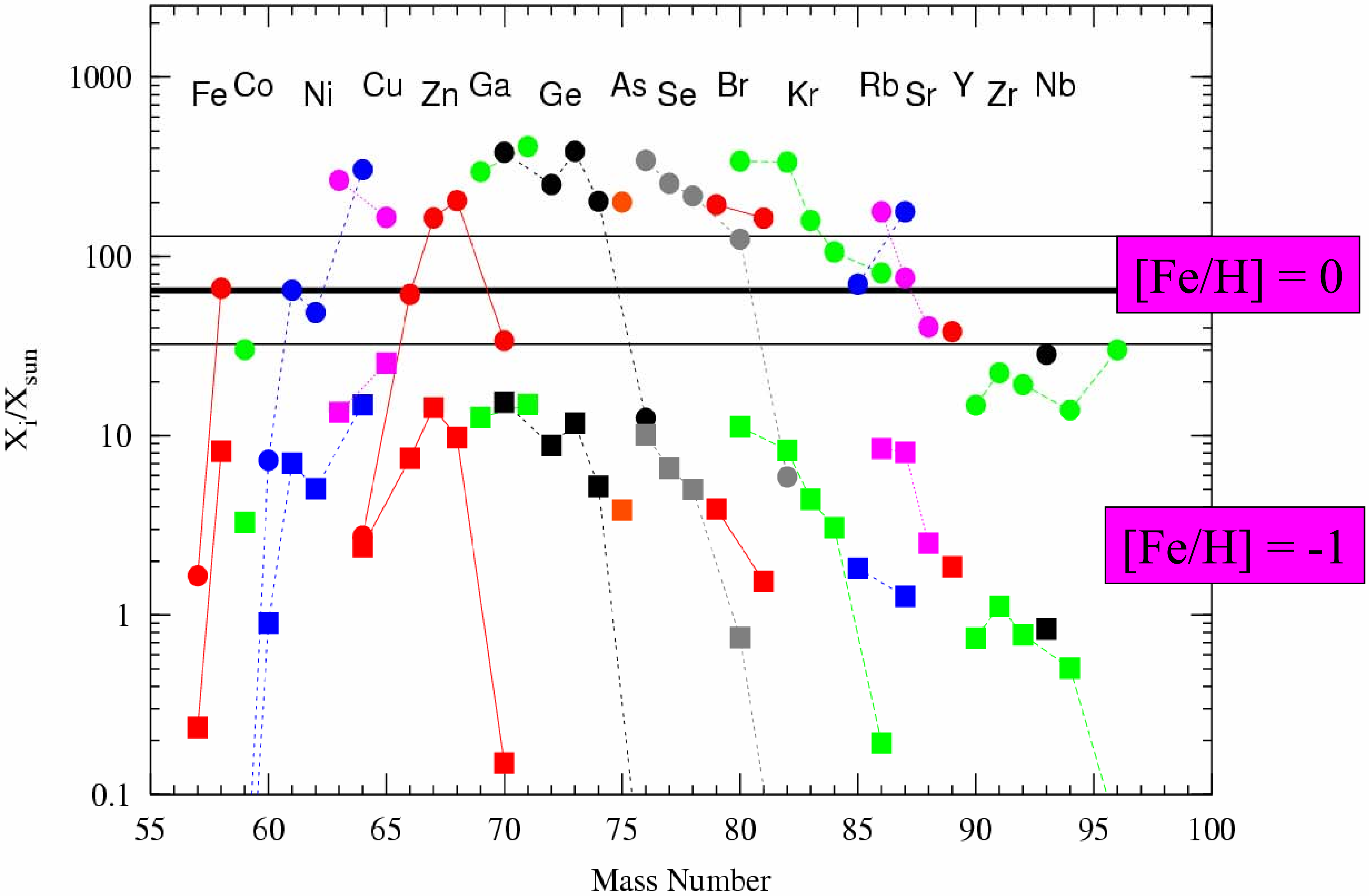
→ constant neutron exposure at different metallicities
constant neutrons captured per Iron seed **NO**

→ S-PROCESS YIELDS BEYOND IRON SCALES
WITH THE METALLICITY **NO**

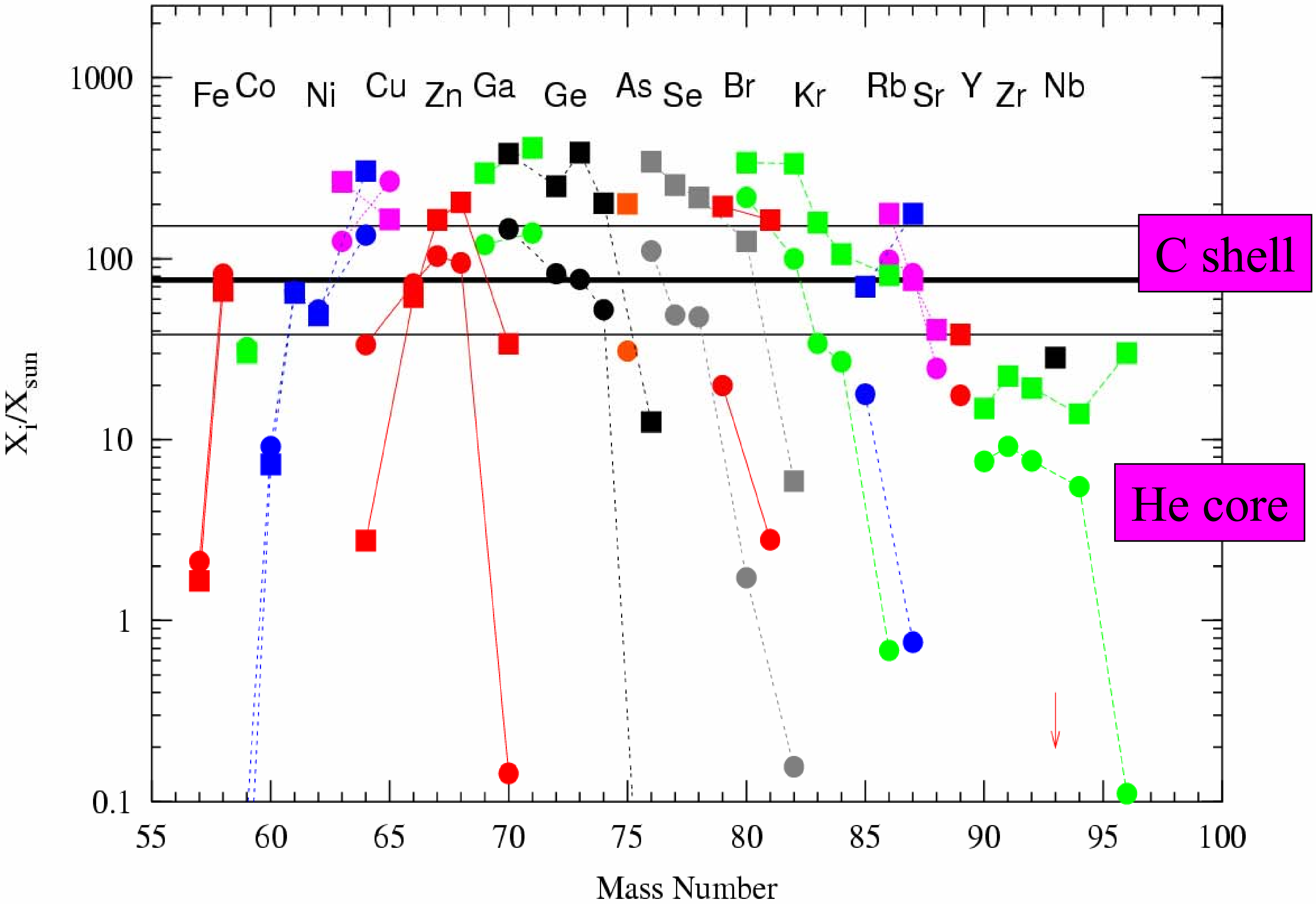
25 M_{sun} [Fe/H] = 0, -1 (He core)



25 M_{sun} [Fe/H] = 0, -1 (C shell)

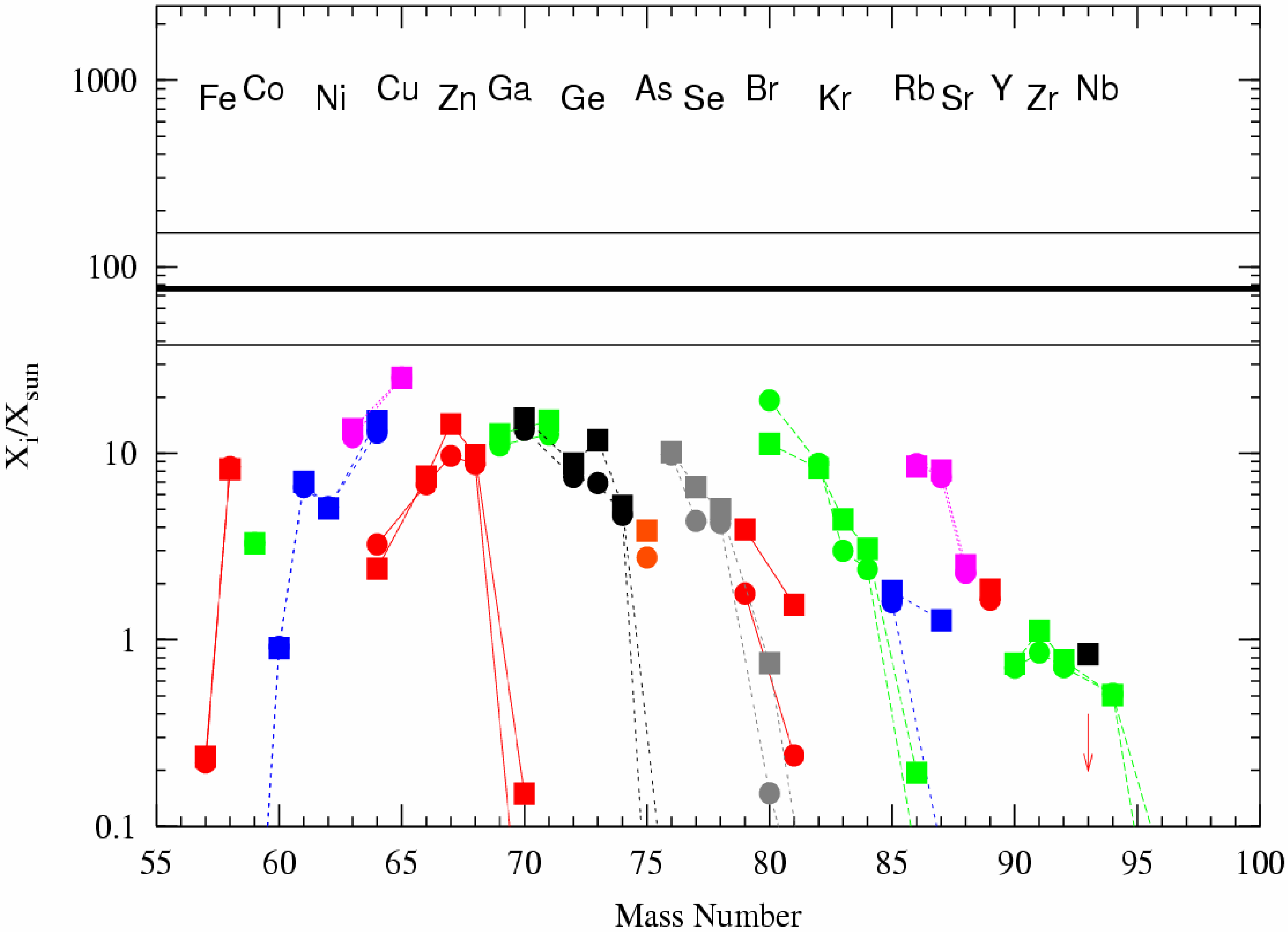


25 M_{sun} [Fe/H] = 0



Fe Co Ni Cu Zn Ga Ge As Se Br Kr Rb Sr Y Zr Nb
C shell
He core
1000
100
10
1
0.1
55 60 65 70 75 80 85 90 95 100
Mass Number
X_i/X_{sun}

25 M_{sun} [Fe/H] = -1

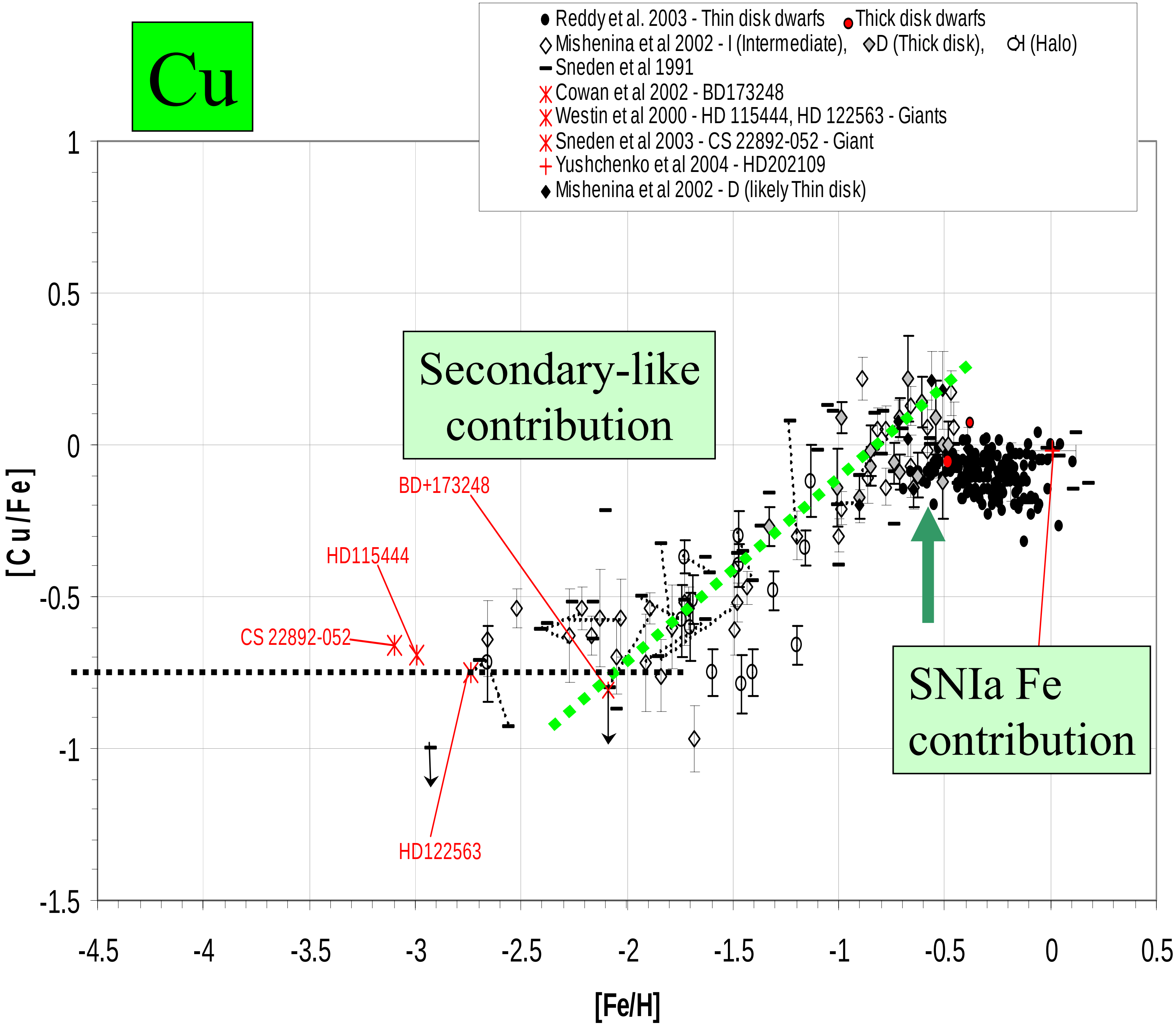


Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
1000
100
10
1
0.1
X_i/X_{sun}
55
60
65
70
75
80
85
90
95
100
Mass Number

Any confirmation
from
spectroscopic observations?

YES….copper!

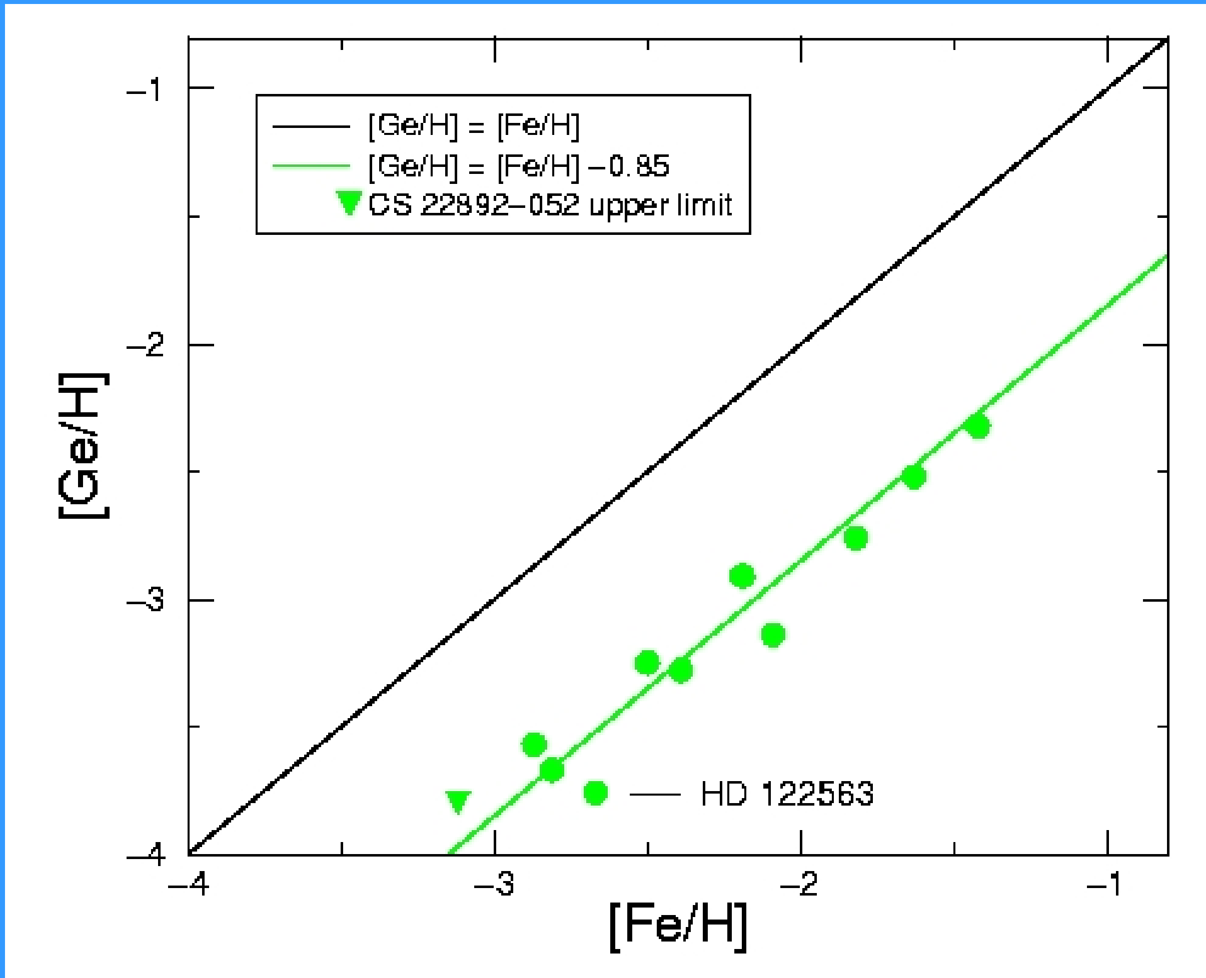
-Bisterzo et al. 2004, NPhA



Cu
Reddy et al. 2003 - Thin disk dwarfs
Thick disk dwarfs
Mishenina et al 2002 - I (Intermediate),
D (Thick disk),
H (Halo)
Sneden et al 1991
Cowan et al 2002 - BD173248
Westin et al 2000 - HD 115444, HD 122563 - Giants
Sneden et al 2003 - CS 22892-052 - Giant
Yushchenko et al 2004 - HD202109
Mishenina et al 2002 - D (likely Thin disk)
Secondary-like contribution
SNIa Fe contribution
BD+173248
HD115444
CS 22892-052
HD122563
[Cu/Fe]
[Fe/H]
1
0.5
0
-0.5
-1
-1.5
-4.5
-4
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5

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-process is not ... weak
- Convective C shell contribution is important for the Weak s-process
- The s-process in the He core is secondary-like. This is not true any more in the C shell.
- There are spectroscopic observations confirming that the Weak s-process is secondary-like at metallicities lower than solar

…..and

- R. Gallino and C. Baldovin (Universita’ di Torino)
- M. Wiescher (University of Notre Dame)
- F. Herwig and A. Heger (LANL)
- M. Heil and F. Käppeler (FZK Karlsruhe)