VIII Incontro dei Gruppi Italiani di Astrofisica Nucleare Teorica e Sperimentale
INFN Sezione di Padova e LNL - Dipartimento di Fisica e Astronomia - INAF

The nucleosynthesis of Ne, Na, Mg and Al in massive stars

Alessandro Chieffi
INAF – Istituto di Astrofisica e Planetologia Spaziale Italy
Centre for Stellar and Planetary Astrophysics
Monash University – Australia
Institut d'Astronomie et Astrophysique - ULB – Bruxelles

alessandro.chieffi@inaf.it

Marco Limongi
INAF – Osservatorio Astronomico di Roma, Italy
Institute for the Physics and Mathematics of the Universe, Japan
Centre for Stellar and Planetary Astrophysics
Monash University – Australia

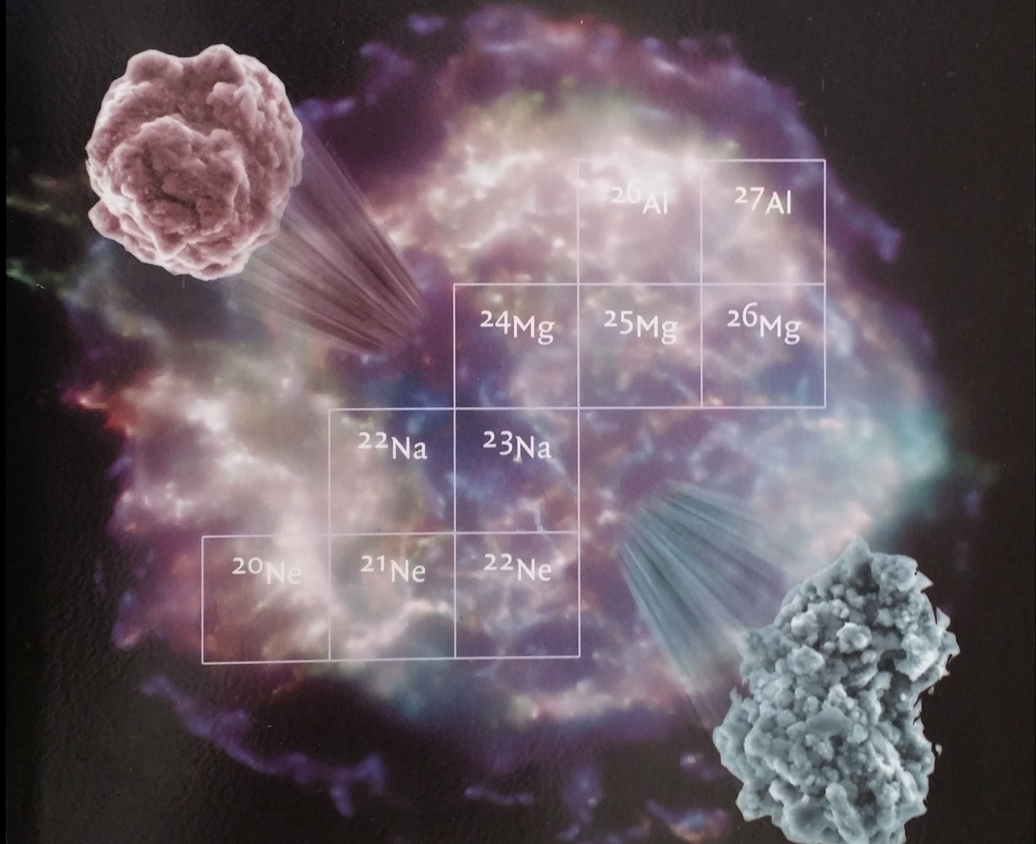
marco.limongi@inaf.it

Handbook of

Isotopes in the Cosmos

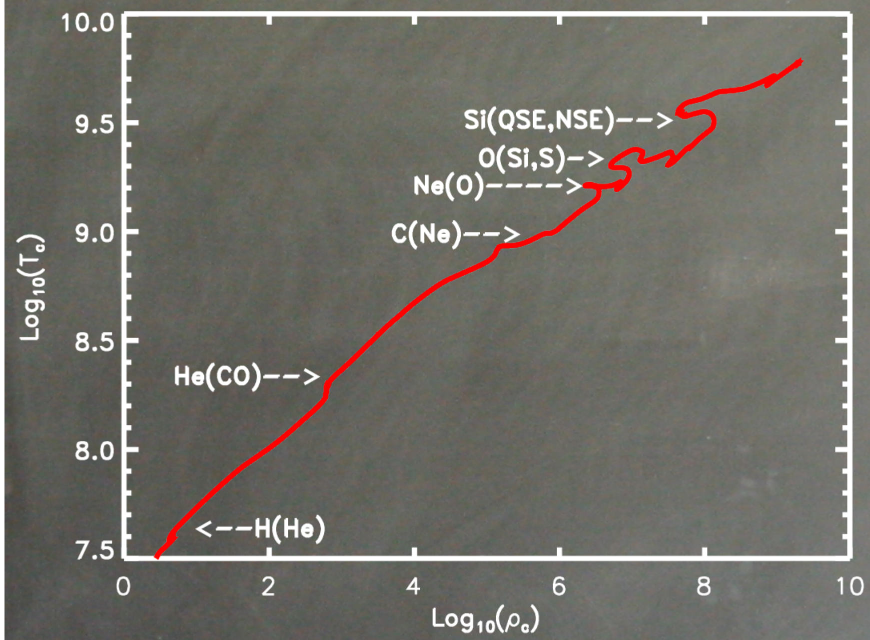
Hydrogen to Gallium

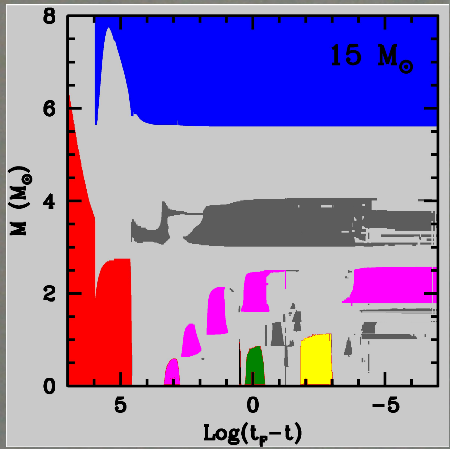
Donald Clayton

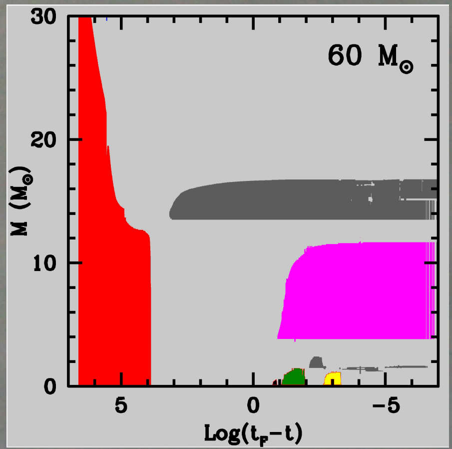


CAMBRIDGE

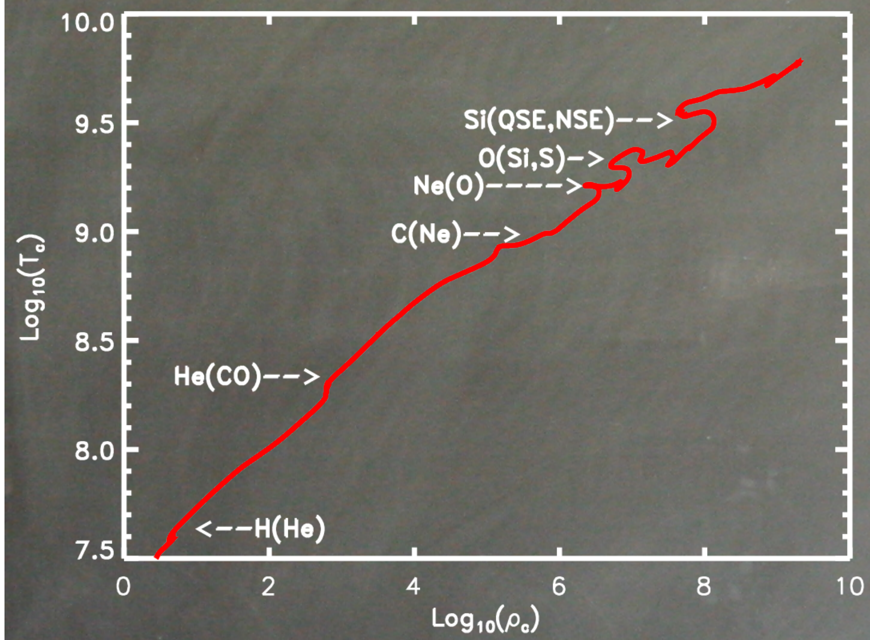
Massive stars

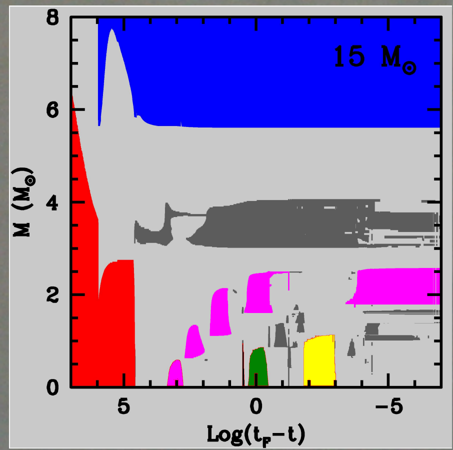


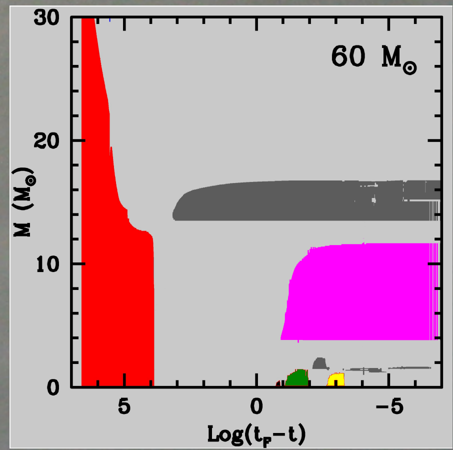


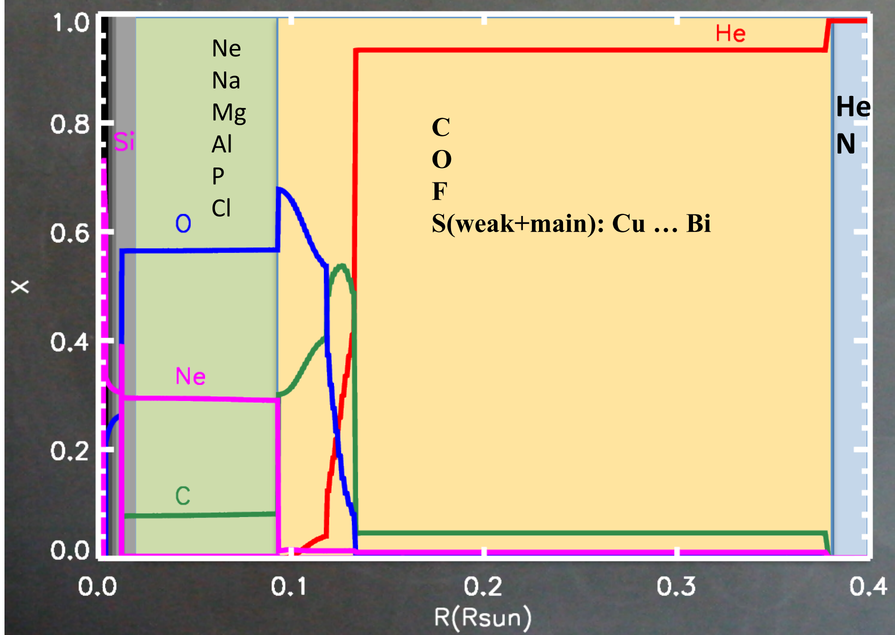


Massive stars

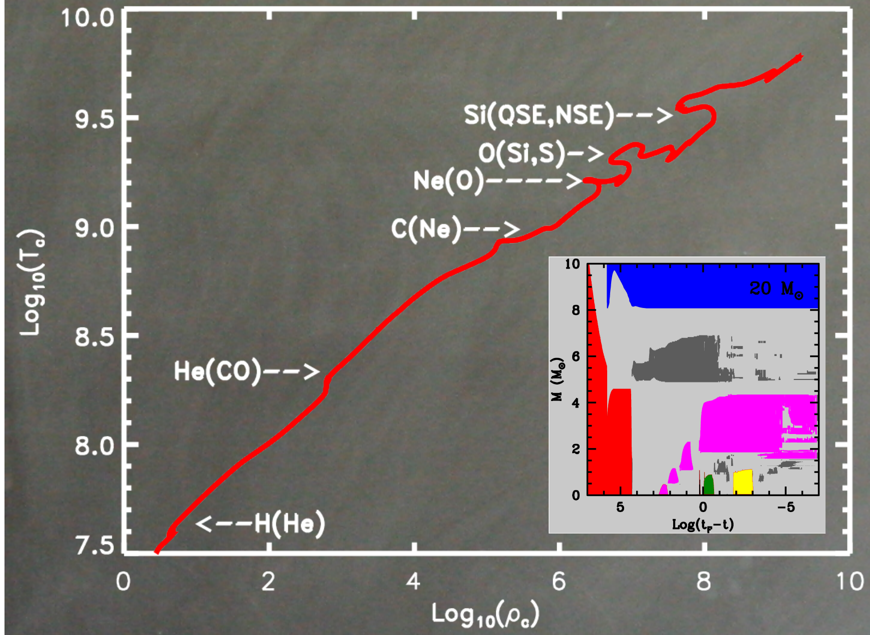


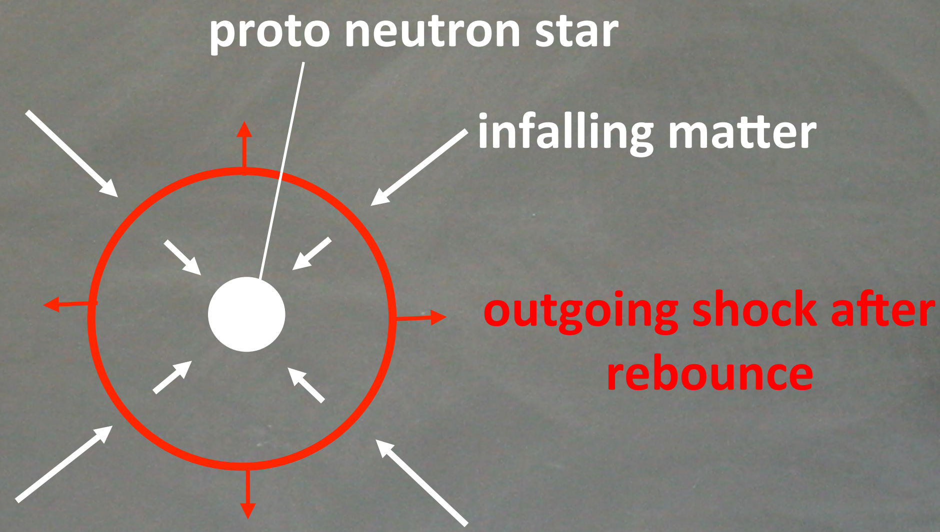


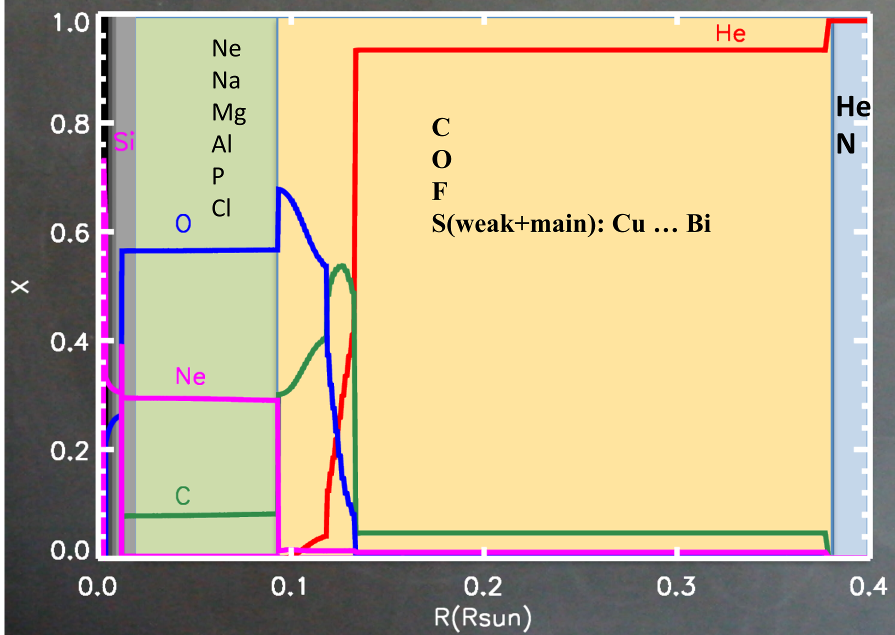


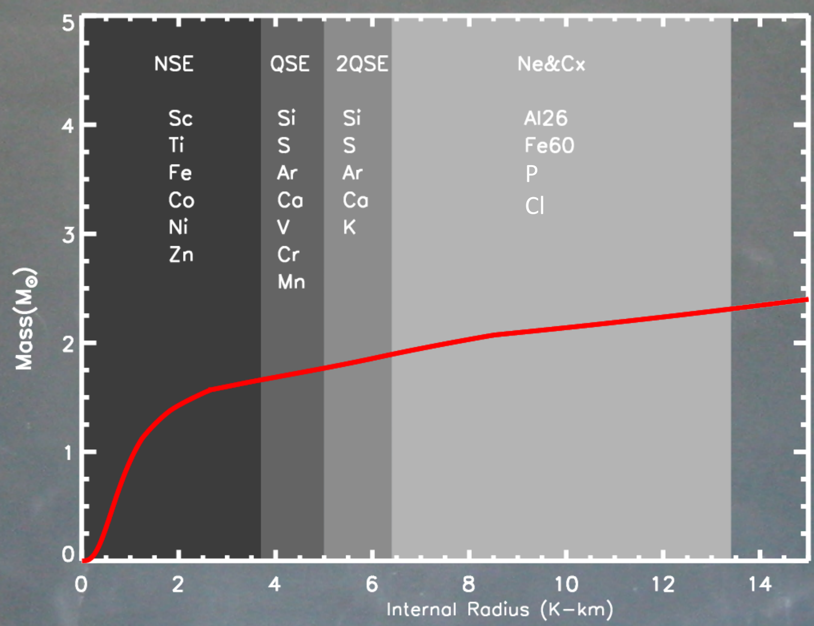


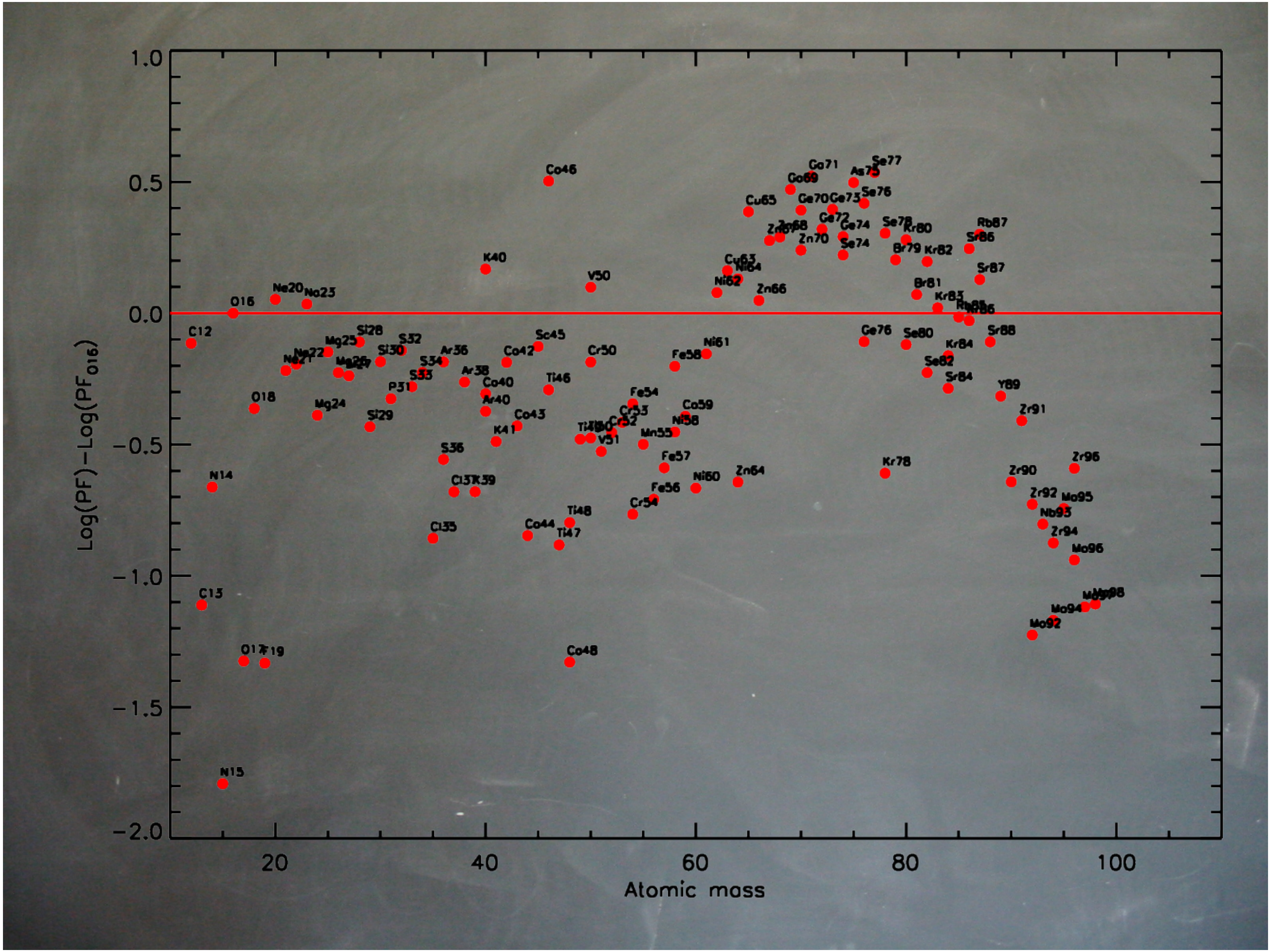
Massive stars



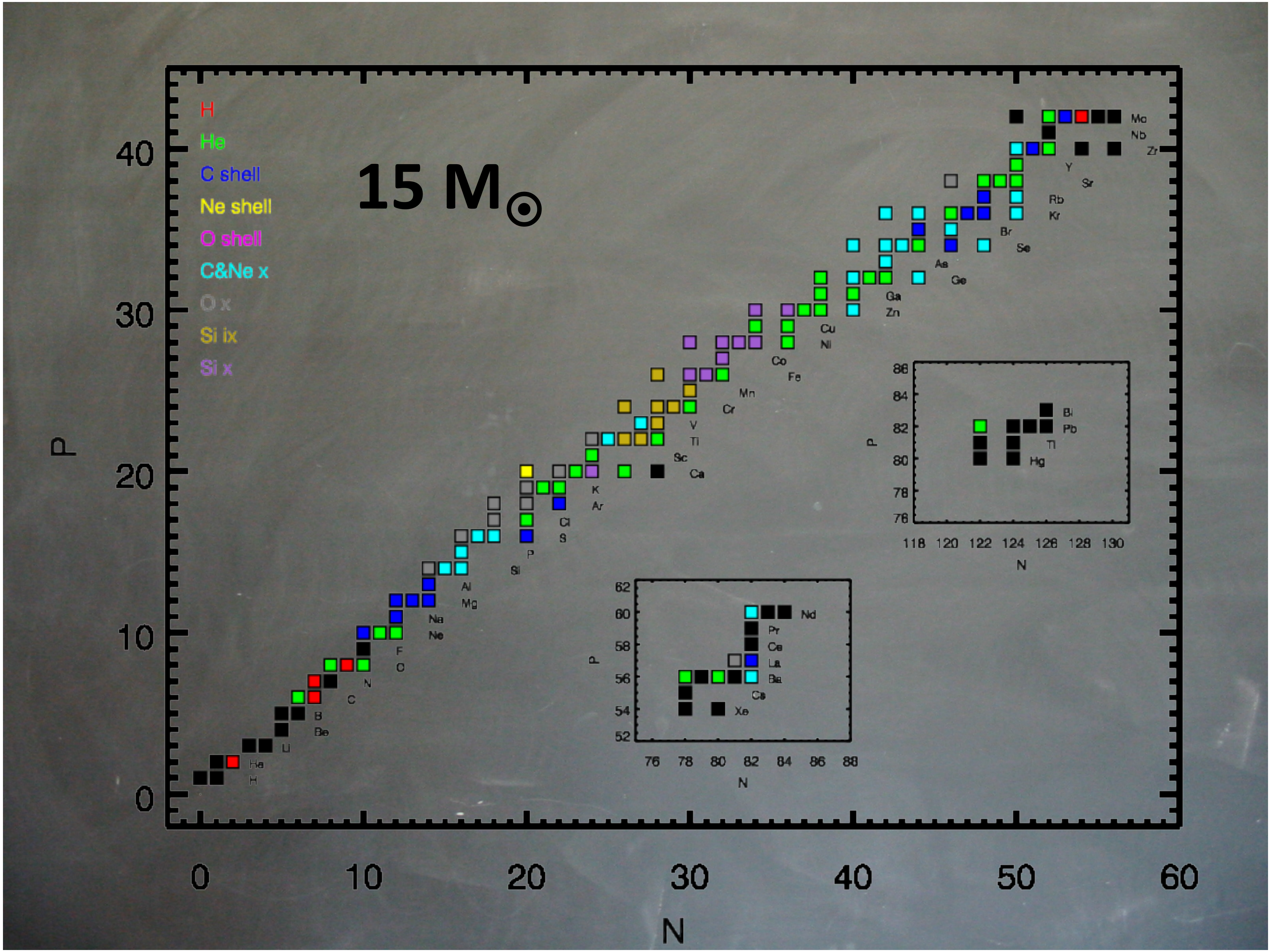




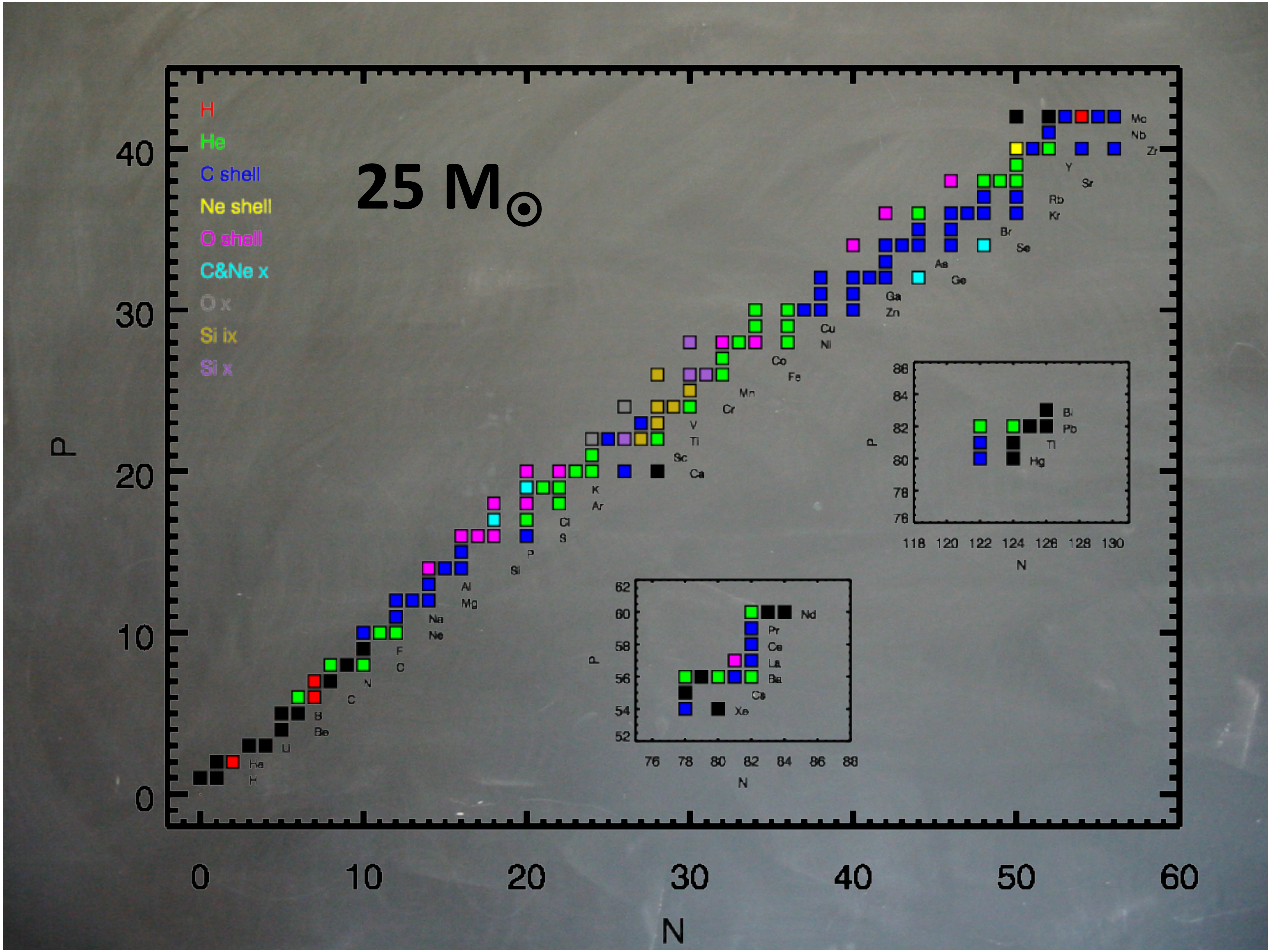


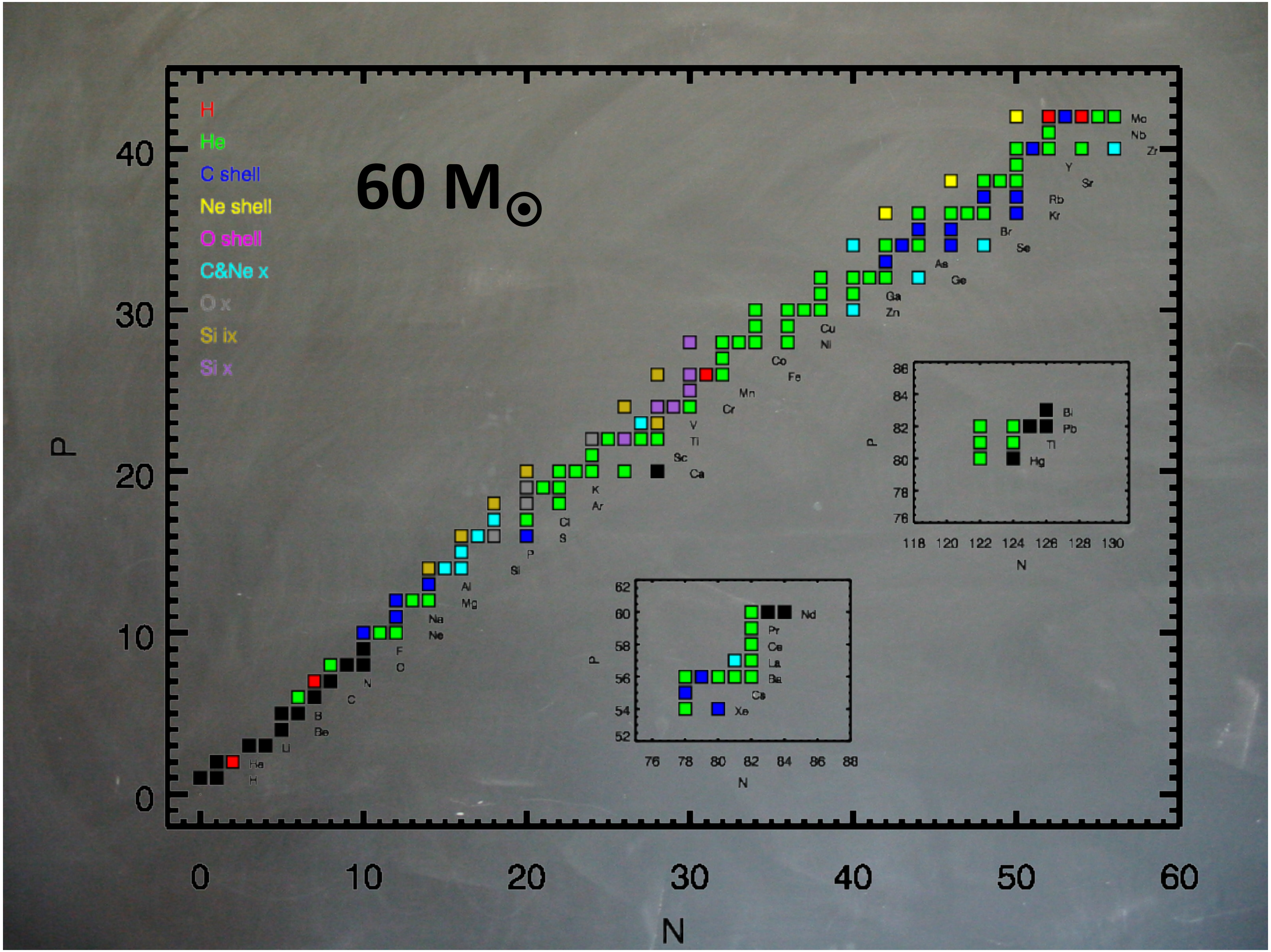


Log(PF)−Log(PF$_{O16}$)
Atomic mass
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
20
40
60
80
100

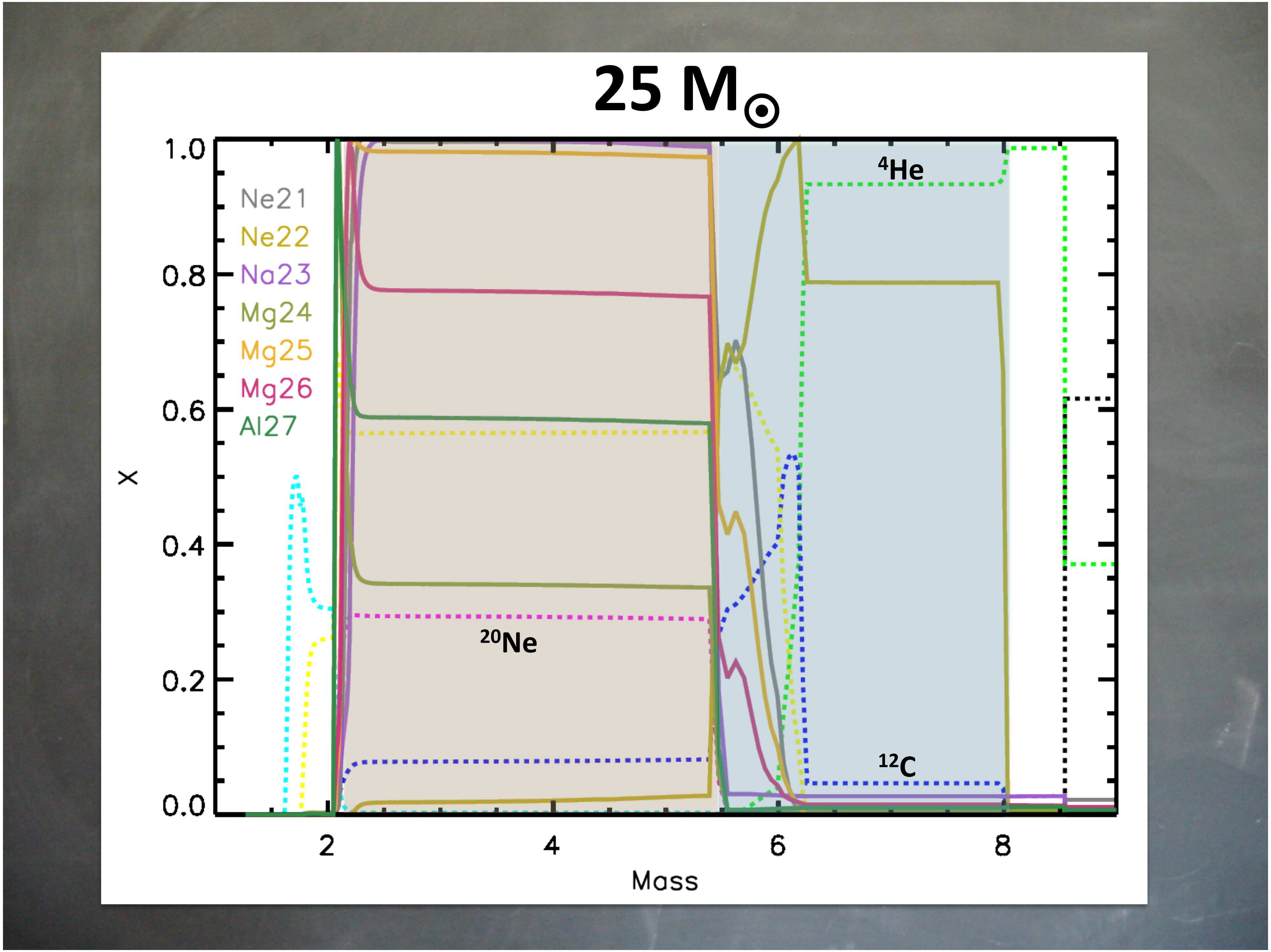


15 M⊙
H
He
C shell
Ne shell
O shell
C&Ne x
O x
Si ix
Si x
P
N


25 M⊙
H
He
C shell
Ne shell
O shell
C&Ne x
O x
Si ix
Si x
P
N
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
Mo
Xe
Cs
Ba
La
Ce
Pr
Nd
Hg
Tl
Pb
Bi



60 M☉
H
He
C shell
Ne shell
O shell
C&Ne x
O x
Si ix
Si x
P
N
0
10
20
30
40
50
60
H He Li Be B C N O F Ne Na Mg Al Si P S Cl Ar K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr Rb Sr Y Zr Nb Mo
Xe Cs Ba La Ce Pr Nd
Hg Tl Pb Bi



25 M☉
Ne21
Ne22
Na23
Mg24
Mg25
Mg26
Al27
4He
20Ne
12C
X
Mass
1.0
0.8
0.6
0.4
0.2
0.0
2
4
6
8

Basic Assumptions

A generation of solar metallicity stars must return to the interstellar gas yields that preserve a scaled solar distribution: i.e., the Production Factors of the various nuclear species should be the same.

Oxygen may be used as the reference nucleus because either it is the most abundant nucleus (after H and He) and because it is mainly produced by massive stars.

Elements Ne to Al are basically produced by massive stars (with the notable exception of ^{22}Ne)

LATEST GRID:

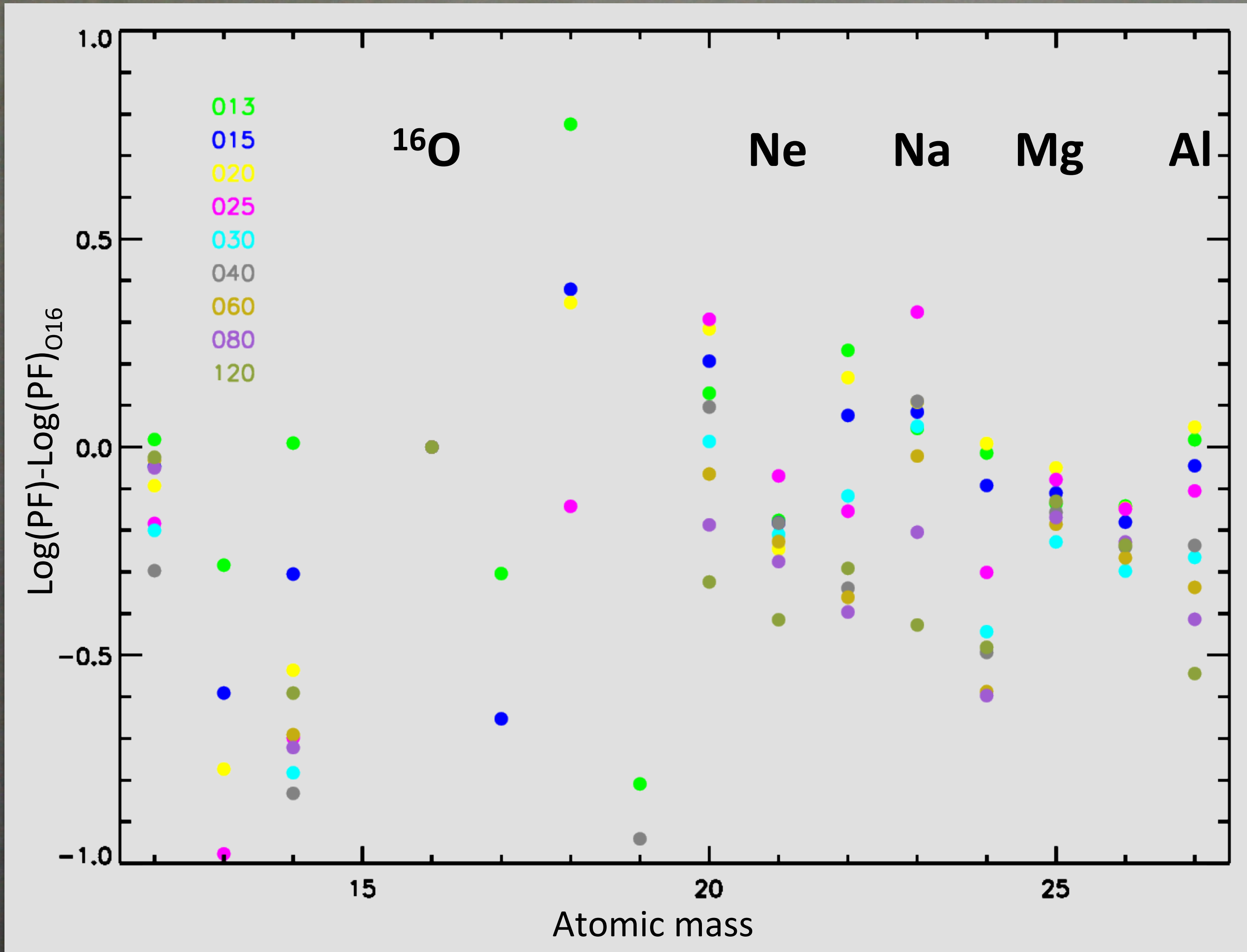
(Limongi & Chieffi, in peparation)

Initial masses: 13, 15, 20, 25, 30, 35, 40, 60, 80 and 120 $M_\odot$

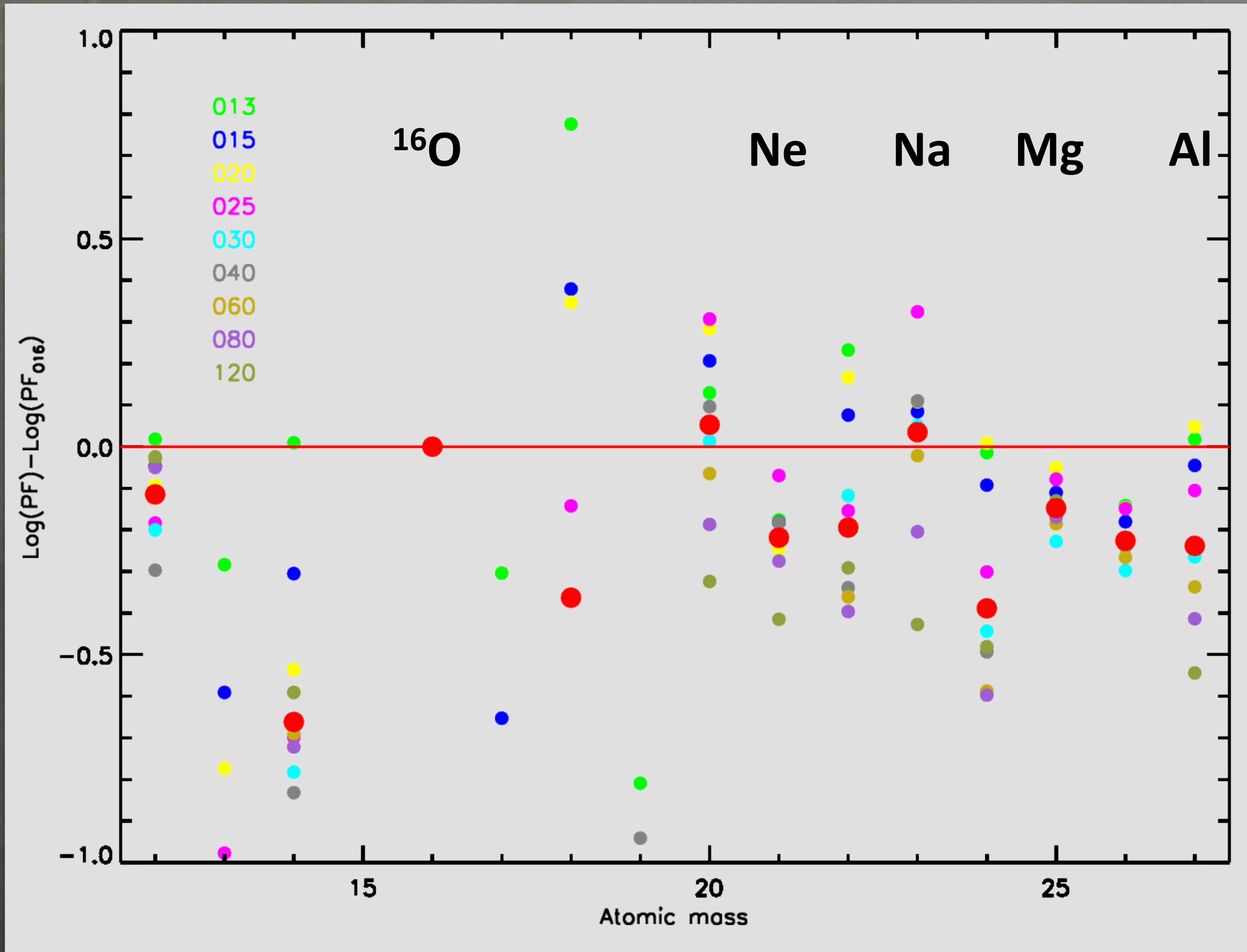
Initial equatorial rotational velocities: 0, 150, 300 km/s

Initial chemical composition:

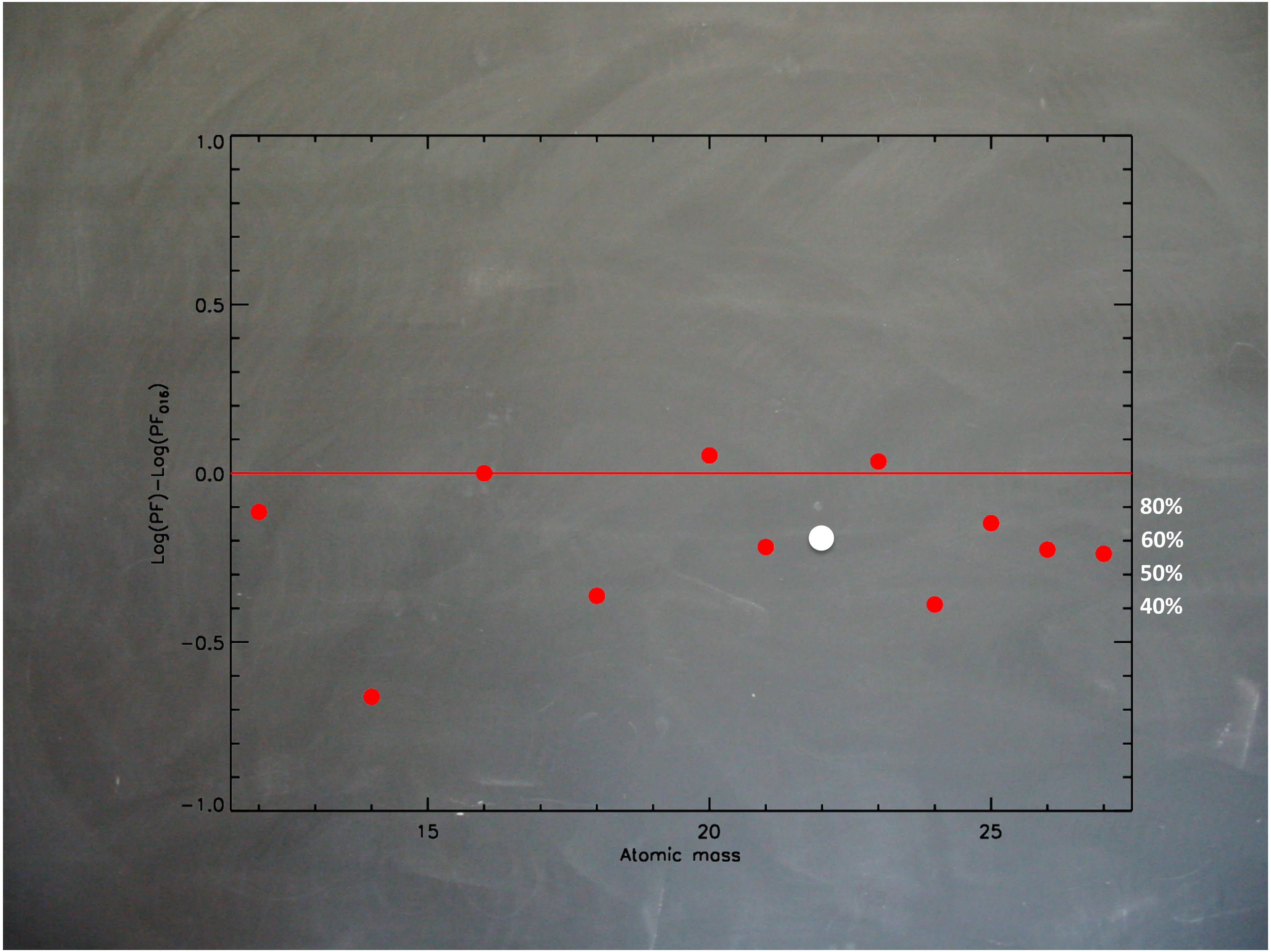
[Fe/H]=0, Z=1.345 10^{-2}	Asplund et al. 2009
[Fe/H]=-1, Z=3.236 10^{-3} [Fe/H]=-2, Z=3.236 10^{-4} [Fe/H]=-3, Z=3.236 10^{-5}	Scaled solar Fe/$Fe_\odot$=0.1,0.01,0001 except [C/Fe]=0.18 [O/Fe]=0.47 [Mg/Fe]=0.27 [Si/Fe]=0.37 [S/Fe]=0.35 [Ar/Fe]=0.35 [Ca/Fe]=0.33 [Ti/Fe]=0.23 (Cayrel+ 2004 and Spite+ 2005)



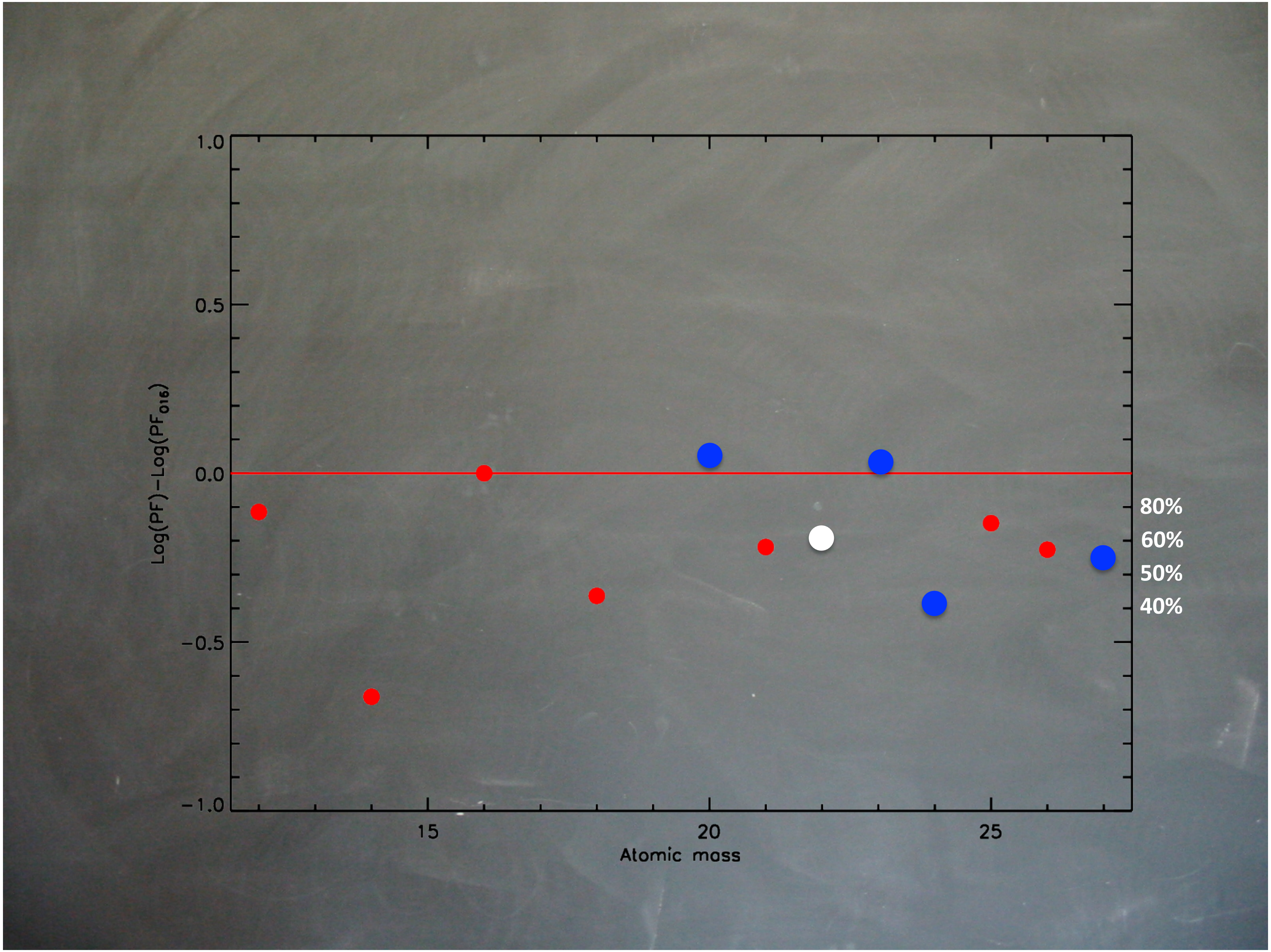
013
015
020
025
030
040
060
080
120
^{16}O
Ne
Na
Mg
Al
1.0
0.5
0.0
-0.5
-1.0
15
20
25
Log(PF)-Log(PF)$_{O16}$
Atomic mass



013
015
020
025
030
040
060
080
120
^{16}O
Ne
Na
Mg
Al
1.0
0.5
0.0
−0.5
−1.0
Log(PF)−Log(PF$_{016}$)
15
20
25
Atomic mass

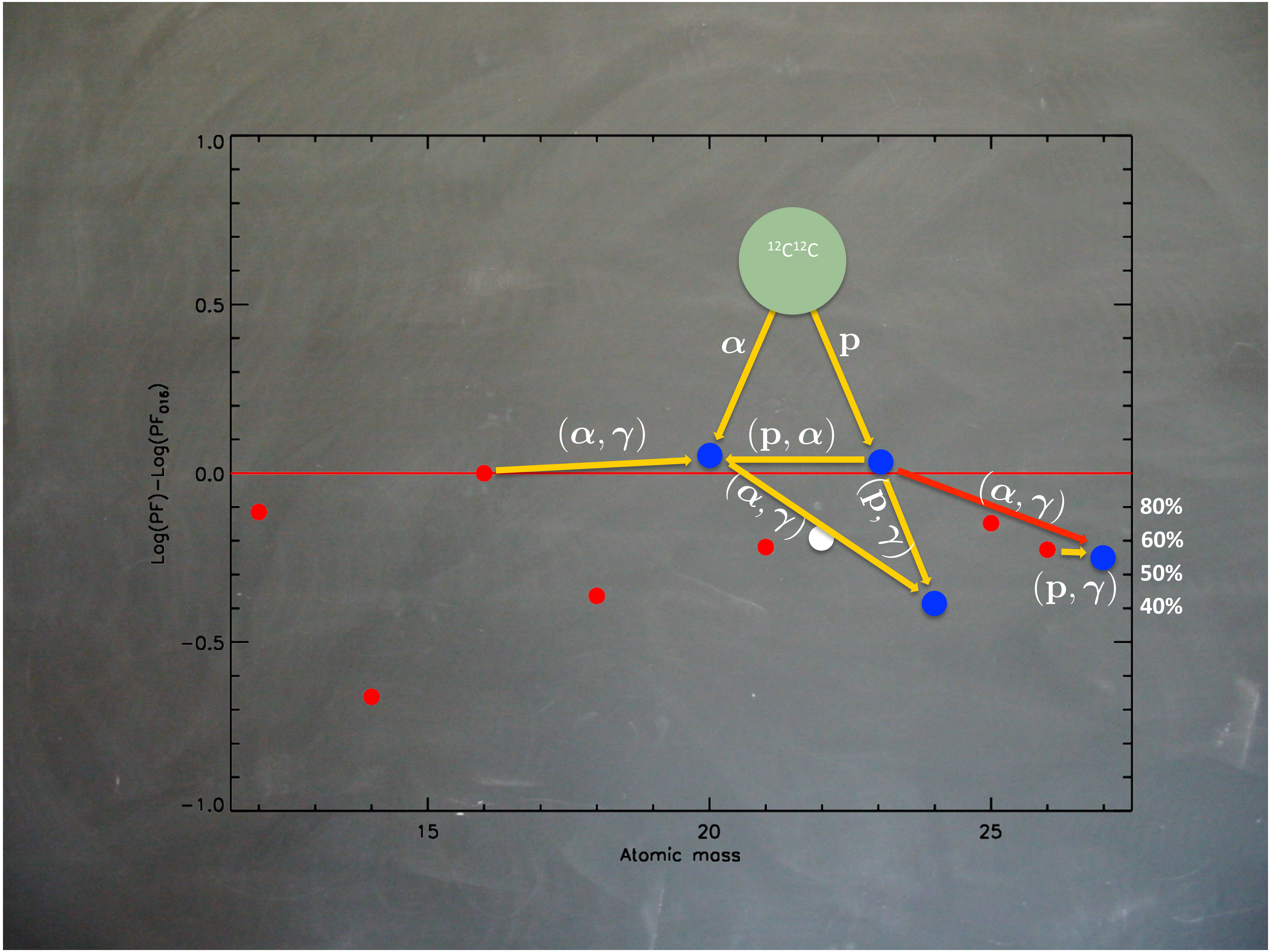


1.0
0.5
0.0
−0.5
−1.0
15
20
25
Atomic mass
Log(PF)−Log(PF016)
80%
60%
50%
40%

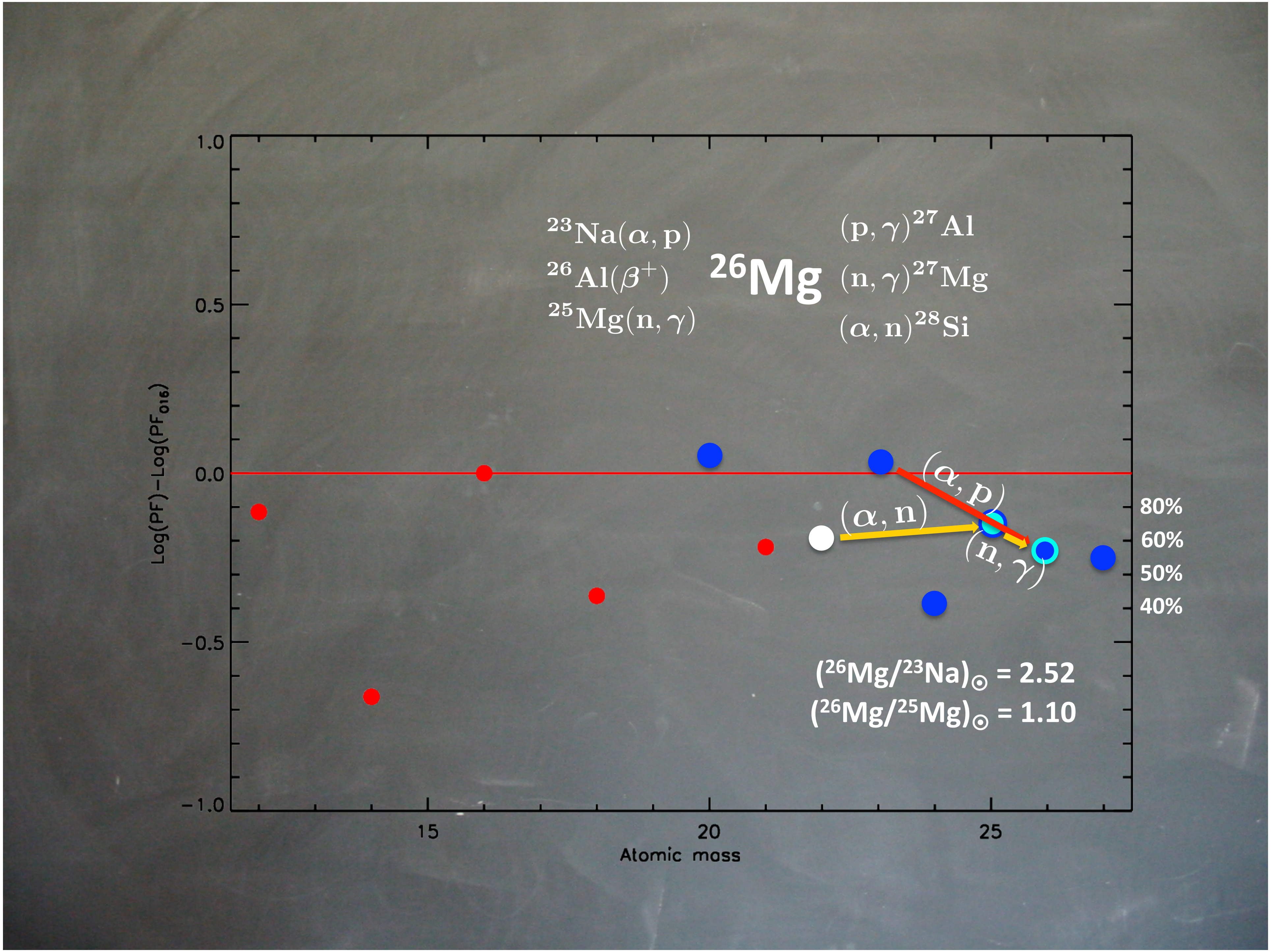


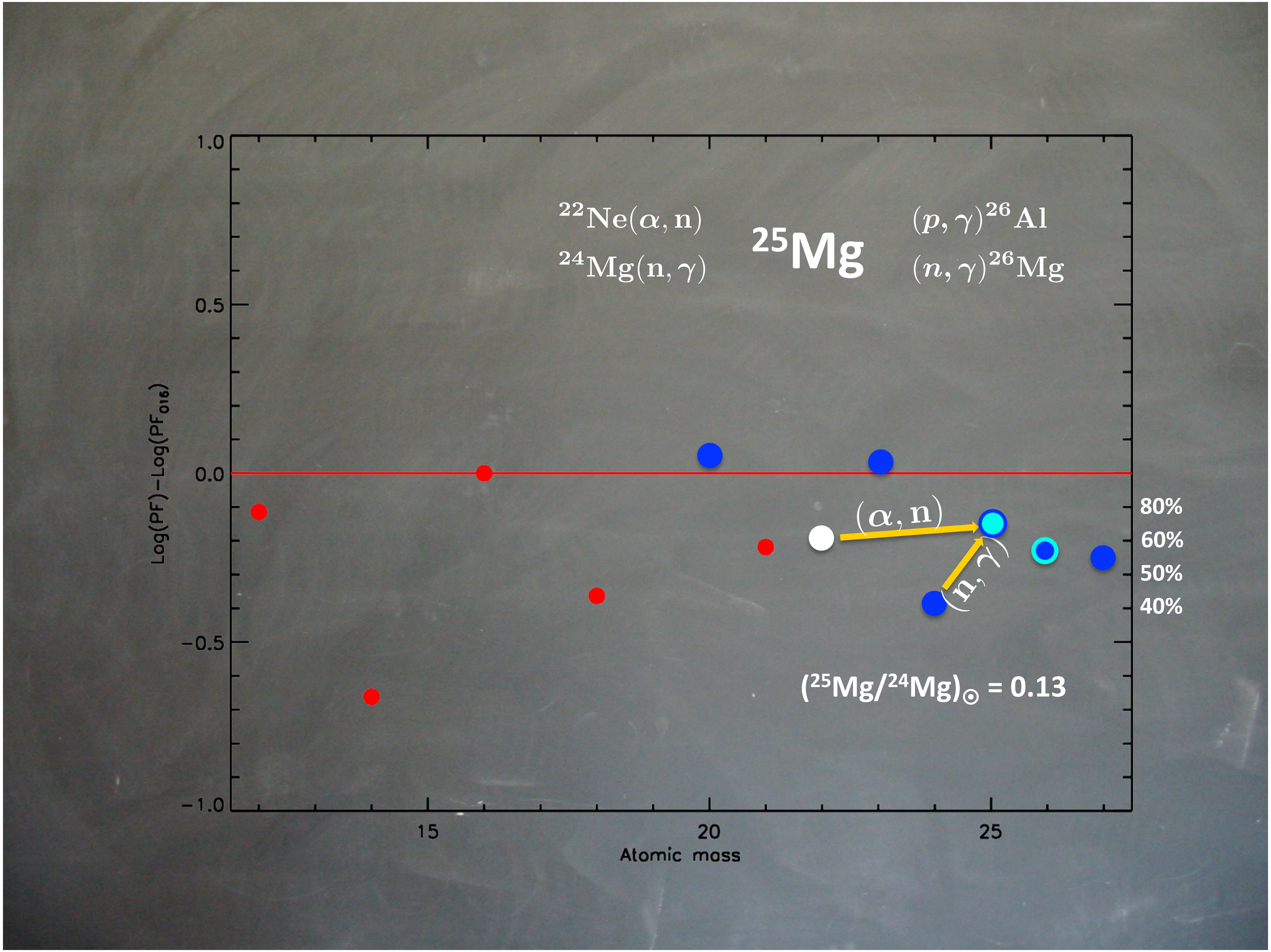
1.0
0.5
0.0
−0.5
−1.0
Log(PF)−Log(PF016)
15
20
25
Atomic mass
80%
60%
50%
40%

Solar ratio	Production	Nucleus	Destruction	
	$^{16}\mathrm{O}(\alpha,\gamma)$ $^{12}\mathrm{C}(^{12}\mathrm{C},\alpha)$ $^{23}\mathrm{Na}(\mathrm{p},\alpha)$	**^{20}Ne**	$(\alpha,\gamma)^{24}\mathrm{Mg}$ $(\mathrm{n},\gamma)^{21}\mathrm{Ne}$	
$(^{23}\mathrm{Na}/^{20}\mathrm{Ne})_{\odot} = 0.022$	$^{12}\mathrm{C}(^{12}\mathrm{C},\mathrm{p})$	**^{23}Na**	$(\mathrm{p},\alpha)^{20}\mathrm{Ne}$	**Equilibrium abundance**
$(^{24}\mathrm{Mg}/^{20}\mathrm{Ne})_{\odot} = 0.40$ **$(^{24}\mathrm{Mg}/^{23}\mathrm{Na})_{\odot} = 18.1$**	$^{20}\mathrm{Ne}(\alpha,\gamma)$ $^{23}\mathrm{Na}(\mathrm{p},\gamma)$	**^{24}Mg**	$(\mathrm{n},\gamma)^{25}\mathrm{Mg}$ $(\alpha,\gamma)^{28}\mathrm{Si}$	
$(^{27}\mathrm{Al}/^{26}\mathrm{Mg})_{\odot} = 0.64$ **$(^{27}\mathrm{Al}/^{23}\mathrm{Na})_{\odot} = 1.62$**	$^{26}\mathrm{Mg}(\mathrm{p},\gamma)$ $^{23}\mathrm{Na}(\alpha,\gamma)$	**^{27}Al**	$(\mathrm{p},\alpha)^{25}\mathrm{Mg}$ $(\mathrm{p},\gamma)^{28}\mathrm{Si}$ $(\mathrm{n},\gamma)^{28}\mathrm{Al}$	

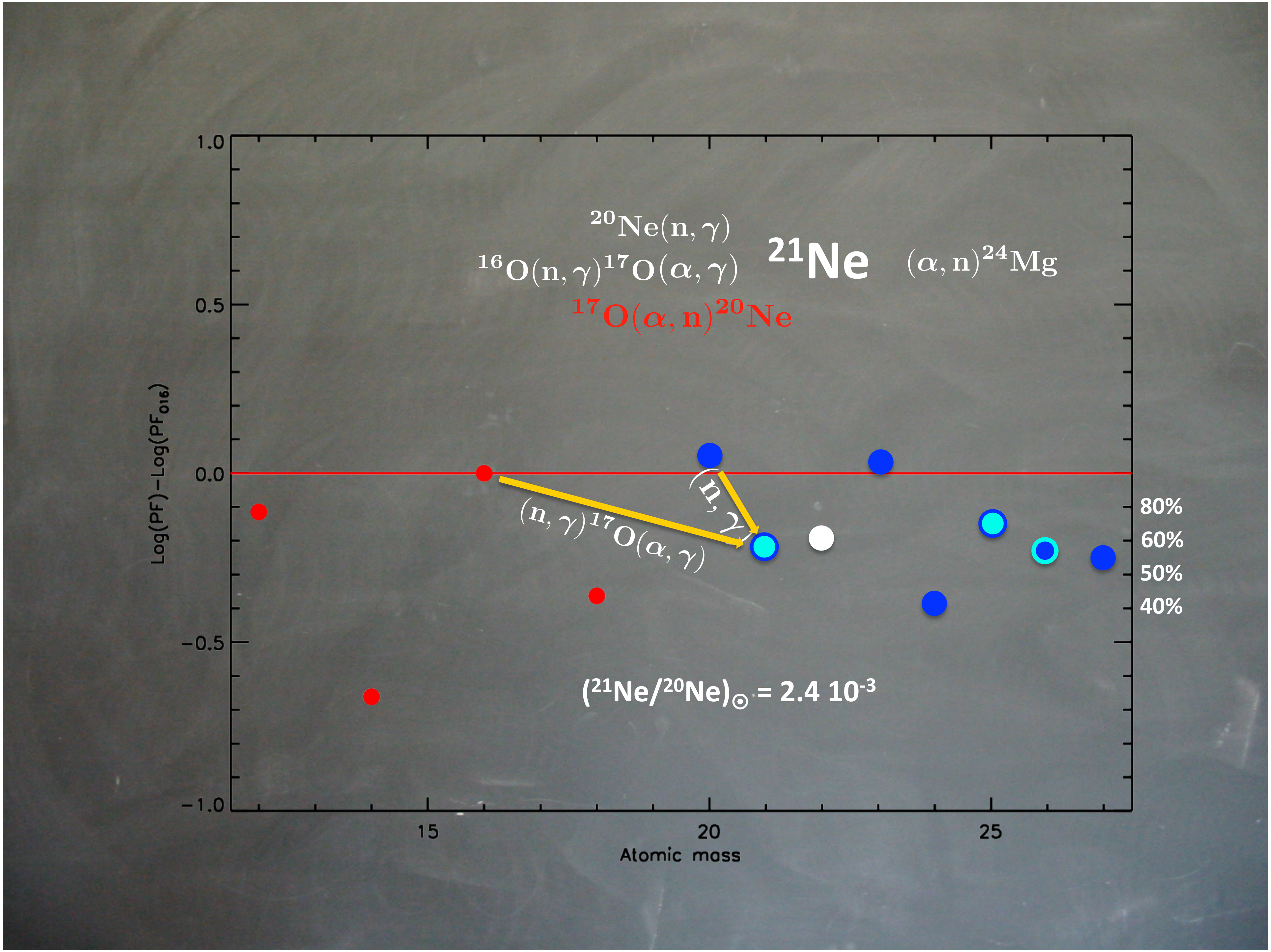


$^{12}C^{12}C$
α
p
(α,γ)
(p,α)
(α,γ)
(p,γ)
(α,γ)
(p,γ)
80%
60%
50%
40%
1.0
0.5
0.0
−0.5
−1.0
15
20
25
Atomic mass
Log(PF)−Log(PF_{O16})

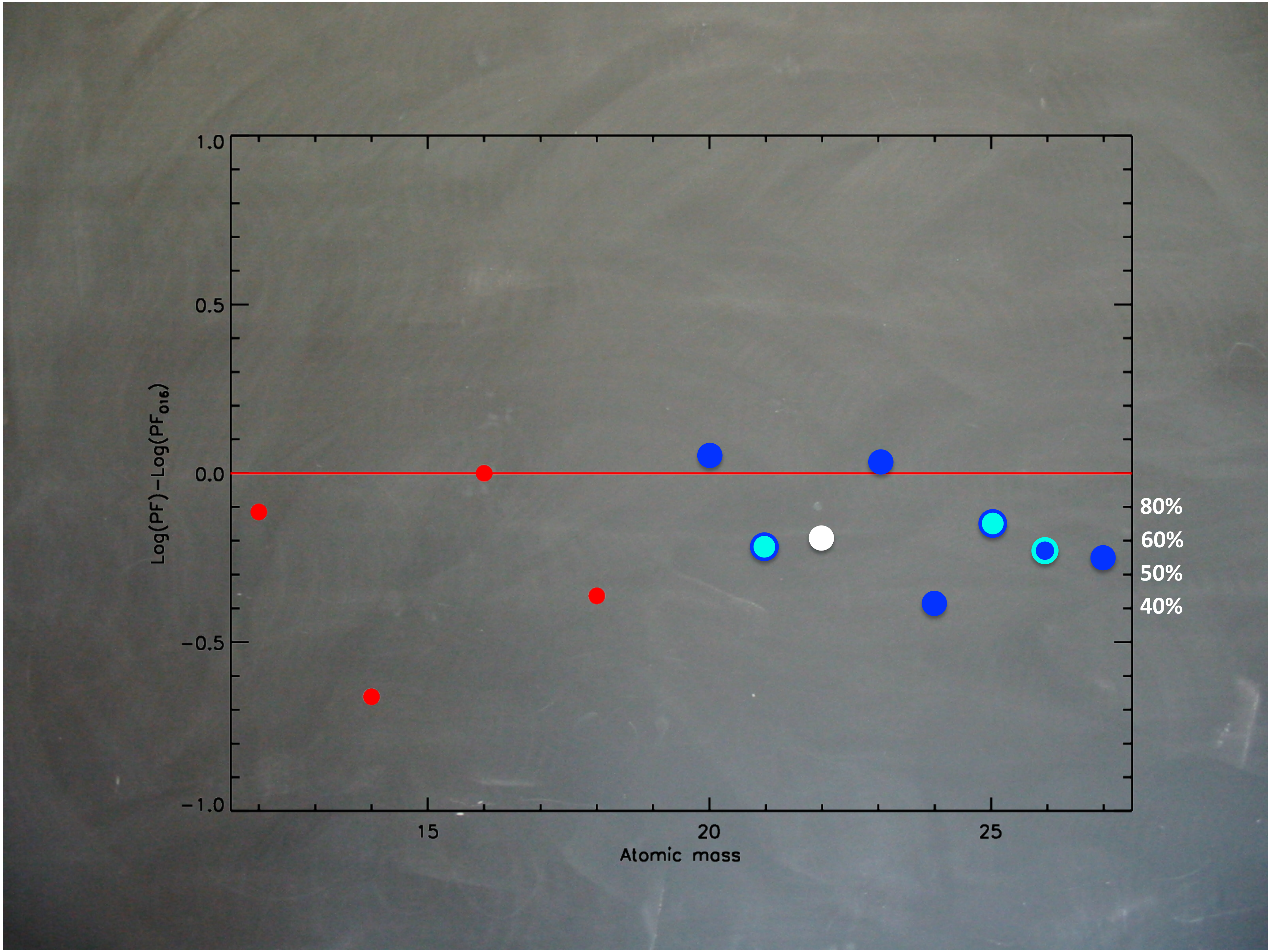

$^{23}Na(\alpha, p)$
$^{26}Al(\beta^+)$
$^{25}Mg(n, \gamma)$
^{26}Mg
$(p, \gamma)^{27}Al$
$(n, \gamma)^{27}Mg$
$(\alpha, n)^{28}Si$
(α, p)
(α, n)
(n, γ)
80%
60%
50%
40%
$(^{26}Mg/^{23}Na)_\odot = 2.52$
$(^{26}Mg/^{25}Mg)_\odot = 1.10$
1.0
0.5
0.0
−0.5
−1.0
15
20
25
Atomic mass
$Log(PF)-Log(PF_{O16})$

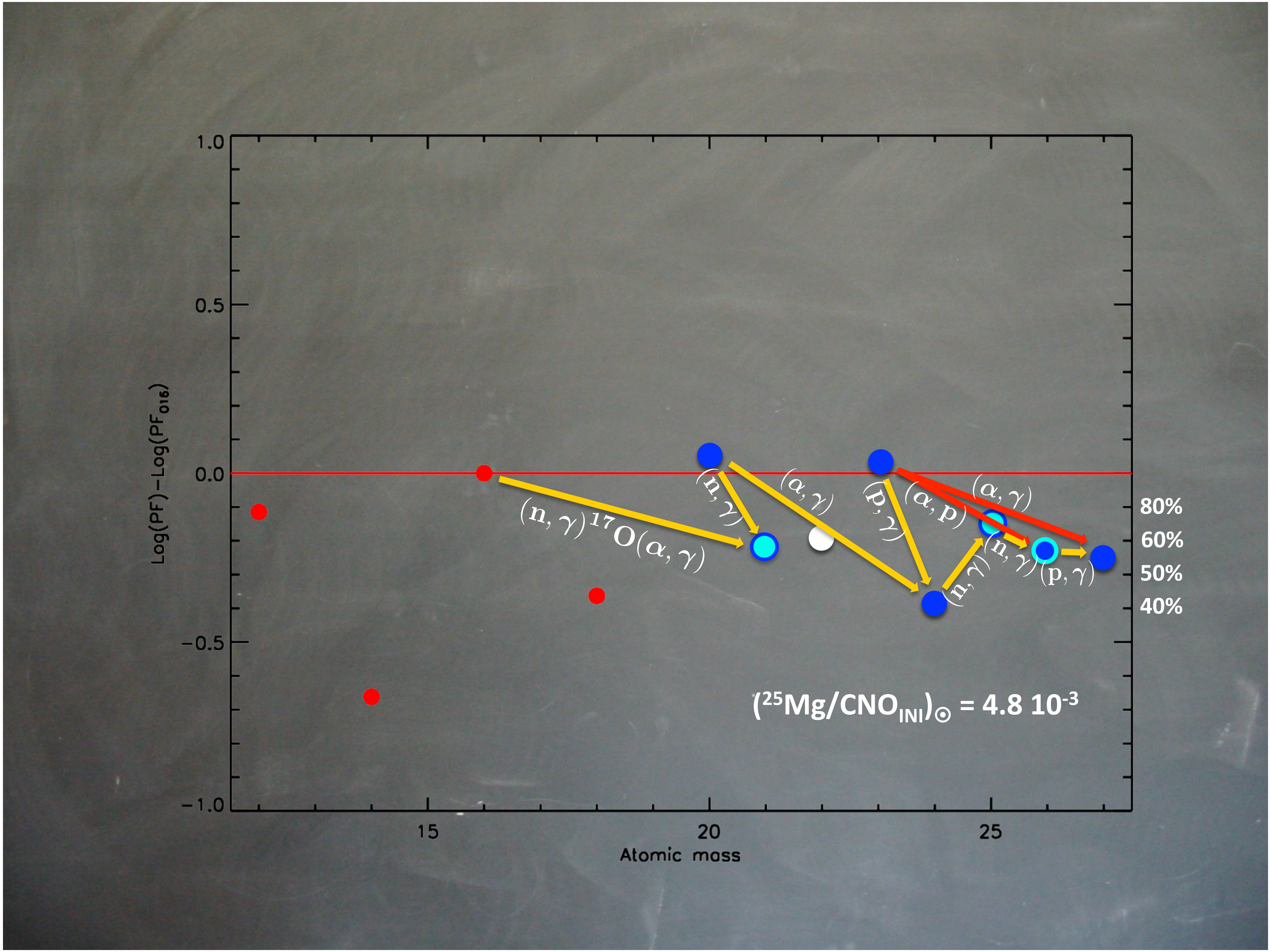


1.0
0.5
0.0
−0.5
−1.0
Log(PF)−Log(PF016)
15
20
25
Atomic mass
^{22}Ne(α, n)
^{24}Mg(n, γ)
^{25}Mg
(p, γ)^{26}Al
(n, γ)^{26}Mg
(α, n)
(n, γ)
80%
60%
50%
40%
(^{25}Mg/^{24}Mg)$_{\odot}$ = 0.13



$^{20}Ne(n,\gamma)$
$^{16}O(n,\gamma)^{17}O(\alpha,\gamma)$
^{21}Ne
$(\alpha,n)^{24}Mg$
$^{17}O(\alpha,n)^{20}Ne$
(n,γ)
$(n,\gamma)^{17}O(\alpha,\gamma)$
80%
60%
50%
40%
$(^{21}Ne/^{20}Ne)_{\odot} = 2.4\ 10^{-3}$
1.0
0.5
0.0
−0.5
−1.0
Log(PF)−Log(PF$_{O16}$)
15
20
25
Atomic mass


1.0
0.5
0.0
−0.5
−1.0
Log(PF)−Log(PF$_{O16}$)
15
20
25
Atomic mass
80%
60%
50%
40%



1.0
0.5
0.0
−0.5
−1.0
Log(PF)−Log(PF016)
15
20
25
Atomic mass
(n, γ)17O(α, γ)
(n, γ)
(α, γ)
(p, γ)
(α, p)
(α, γ)
(n, γ)
(n, γ)
(p, γ)
80%
60%
50%
40%
(25Mg/CNOINI)⊙ = 4.8 10-3

$(3\alpha)^{12}C$ NACRE compilation

$^{12}C(\alpha,\gamma)^{16}O$ Kunz + ApJ, 567, 643

$^{12}C(^{12}C, p\ /\ \alpha)$ Caughlan & Fowler 1988

$^{16}O(\alpha,\gamma)^{20}Ne$ Iliadis + Nucl.Phys.A, 841, 31

$^{17}O(\alpha,\gamma)^{21}Ne$ Caughlan & Fowler 1988

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

$^{20}Ne(\alpha,\gamma)^{24}Mg$ Iliadis + Nucl.Phys.A, 841, 31

$^{22}Ne(\alpha,\gamma)^{26}Mg$ Iliadis + Nucl.Phys.A, 841, 31

$^{22}Ne(\alpha,n)^{25}Mg$ Iliadis + Nucl.Phys.A, 841, 31

$^{23}Na(\alpha,p)^{26}Mg$ REACLIB Rauscher & Thielemann

$^{23}Na(\alpha,\gamma)^{27}Al$ REACLIB Rauscher & Thielemann

$^{23}Na(p,\alpha)^{20}Ne$ Iliadis + Nucl.Phys.A, 841, 31

$^{23}Na(p,\gamma)^{24}Mg$ Iliadis + Nucl.Phys.A, 841, 31

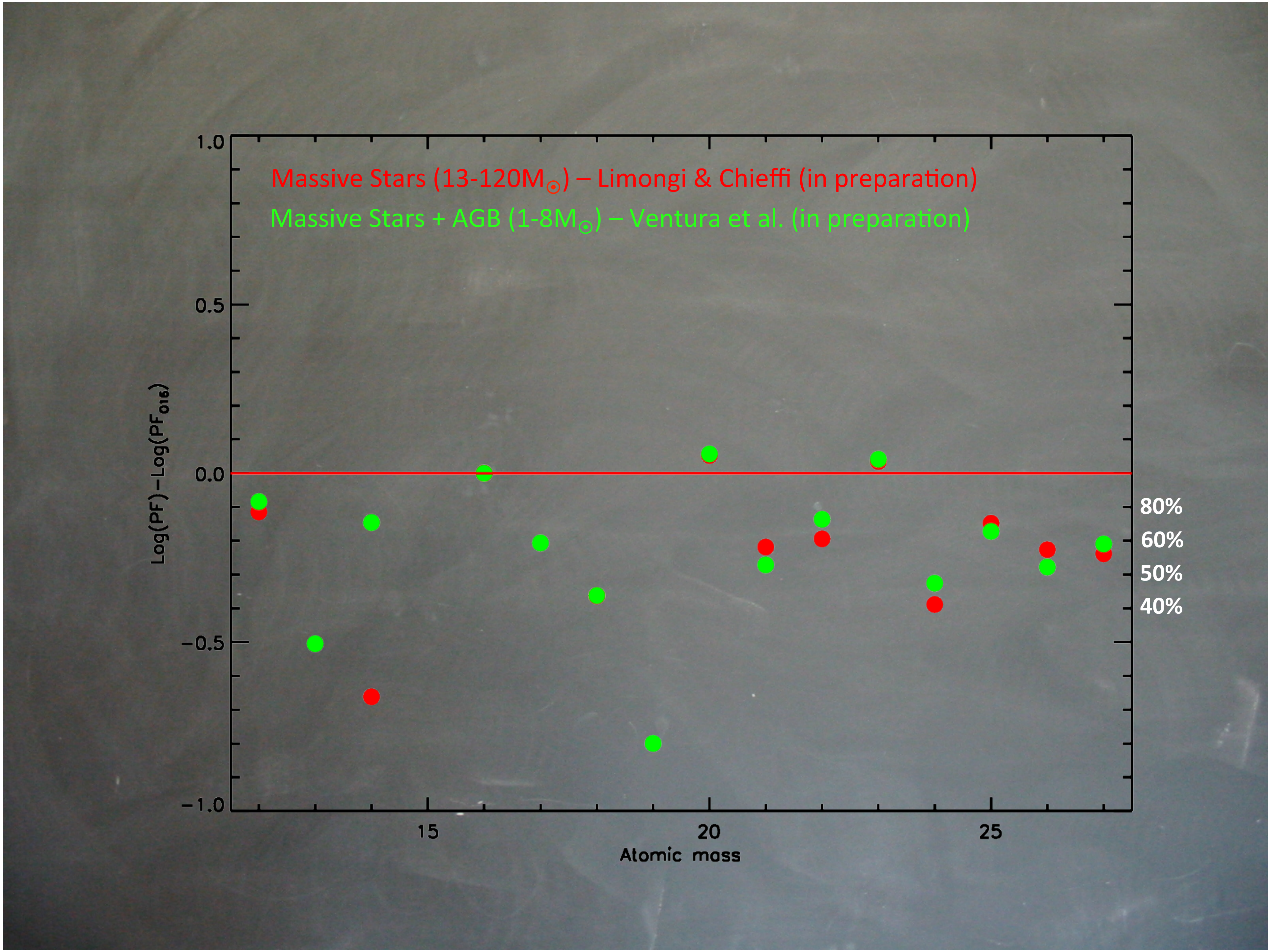
$^{26}Mg(p,\gamma)^{27}Al$ Iliadis + Nucl.Phys.A, 841, 31

$^{16}O(n,\gamma)^{17}O$ KADONIS03 (Karlsruhe Astrophysical Database Of Nucleosynthesis In Stars)

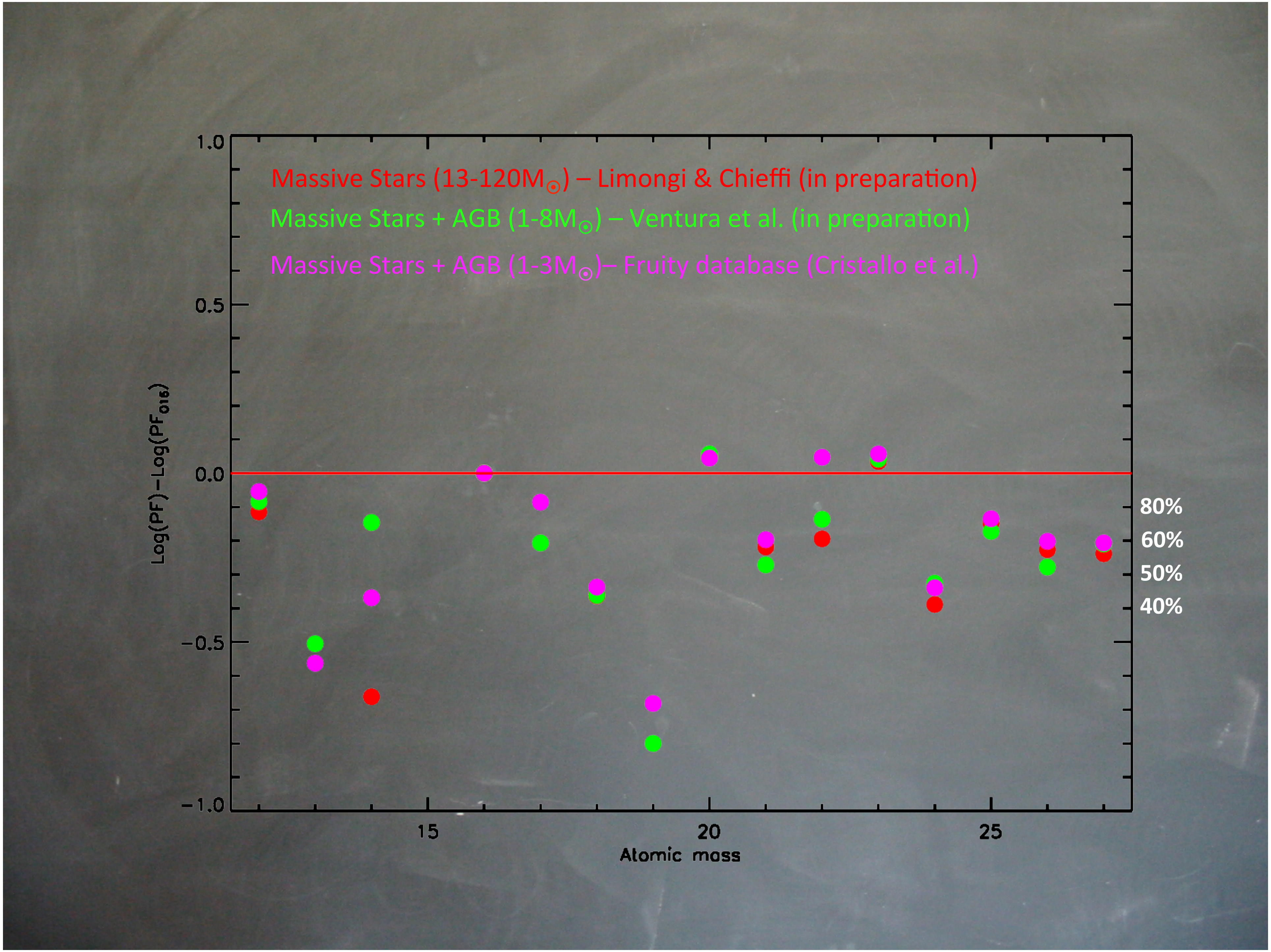
$^{20}Ne(n,\gamma)^{21}Ne$ KADONIS03

$^{24}Mg(n,\gamma)^{25}Mg$ KADONIS03

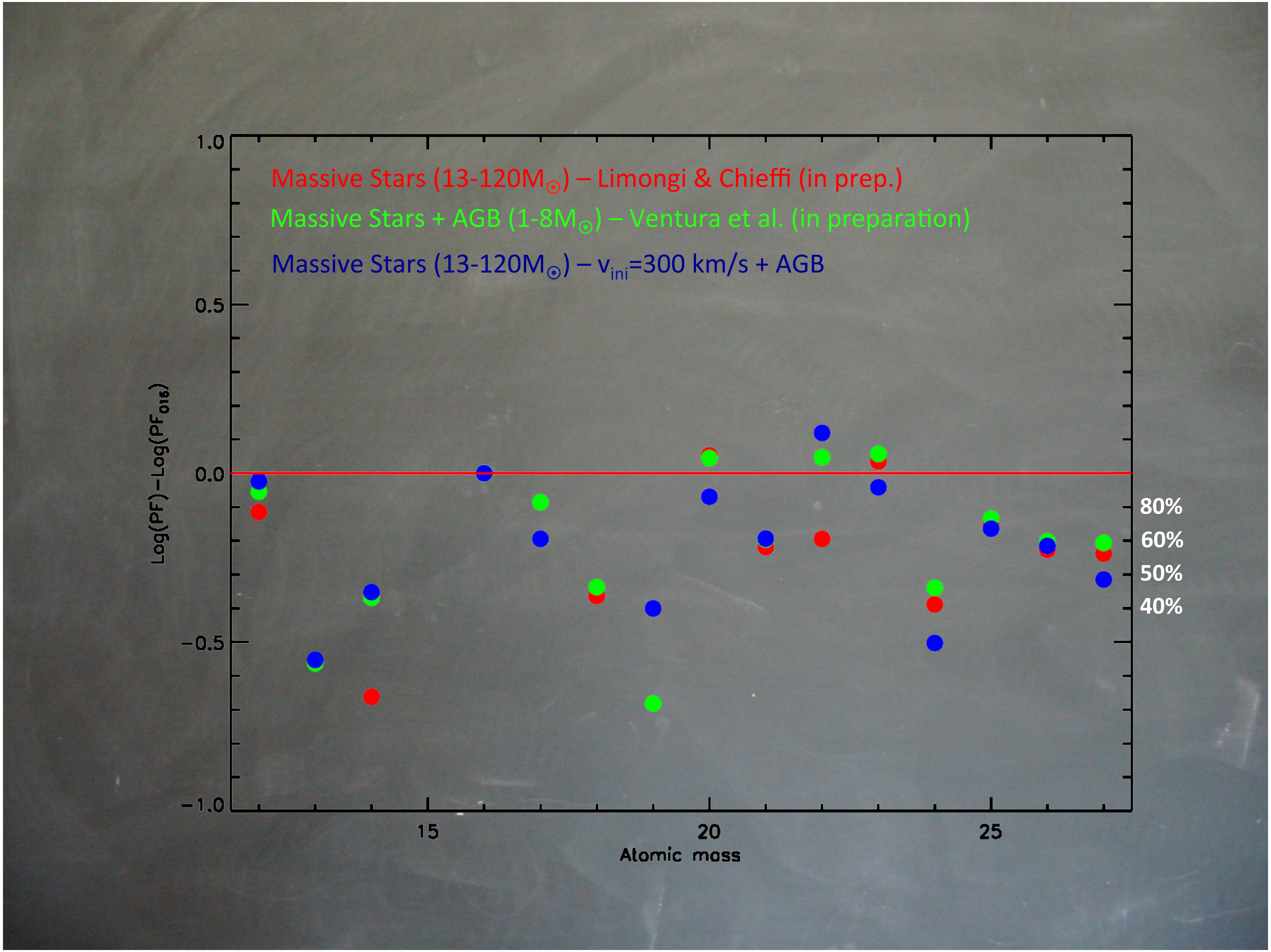
$^{25}Mg(n,\gamma)^{26}Mg$ KADONIS03



Massive Stars (13-120M☉) – Limongi & Chieffi (in preparation)
Massive Stars + AGB (1-8M☉) – Ventura et al. (in preparation)
1.0
0.5
0.0
−0.5
−1.0
Log(PF)−Log(PF016)
15
20
25
Atomic mass
80%
60%
50%
40%



Massive Stars (13-120M$_\odot$) – Limongi & Chieffi (in preparation)
Massive Stars + AGB (1-8M$_\odot$) – Ventura et al. (in preparation)
Massive Stars + AGB (1-3M$_\odot$)– Fruity database (Cristallo et al.)
1.0
0.5
0.0
−0.5
−1.0
Log(PF)−Log(PF$_{O16}$)
15
20
25
Atomic mass
80%
60%
50%
40%



Massive Stars (13-120M☉) – Limongi & Chieffi (in prep.)
Massive Stars + AGB (1-8M☉) – Ventura et al. (in preparation)
Massive Stars (13-120M☉) – v_ini=300 km/s + AGB
1.0
0.5
0.0
−0.5
−1.0
Log(PF)−Log(PF_O16)
15
20
25
Atomic mass
80%
60%
50%
40%

Conclusions

There is no single mass that mimicks the production factors (PFs) of a full IMF

^{20}Ne and ^{23}Na have integrated PFs in excellent agreement with that of O

^{21}Ne, ^{24}Mg, ^{25}Mg, ^{26}Mg and ^{27}Al are underproduced by a factor that varies between 40% to 60%

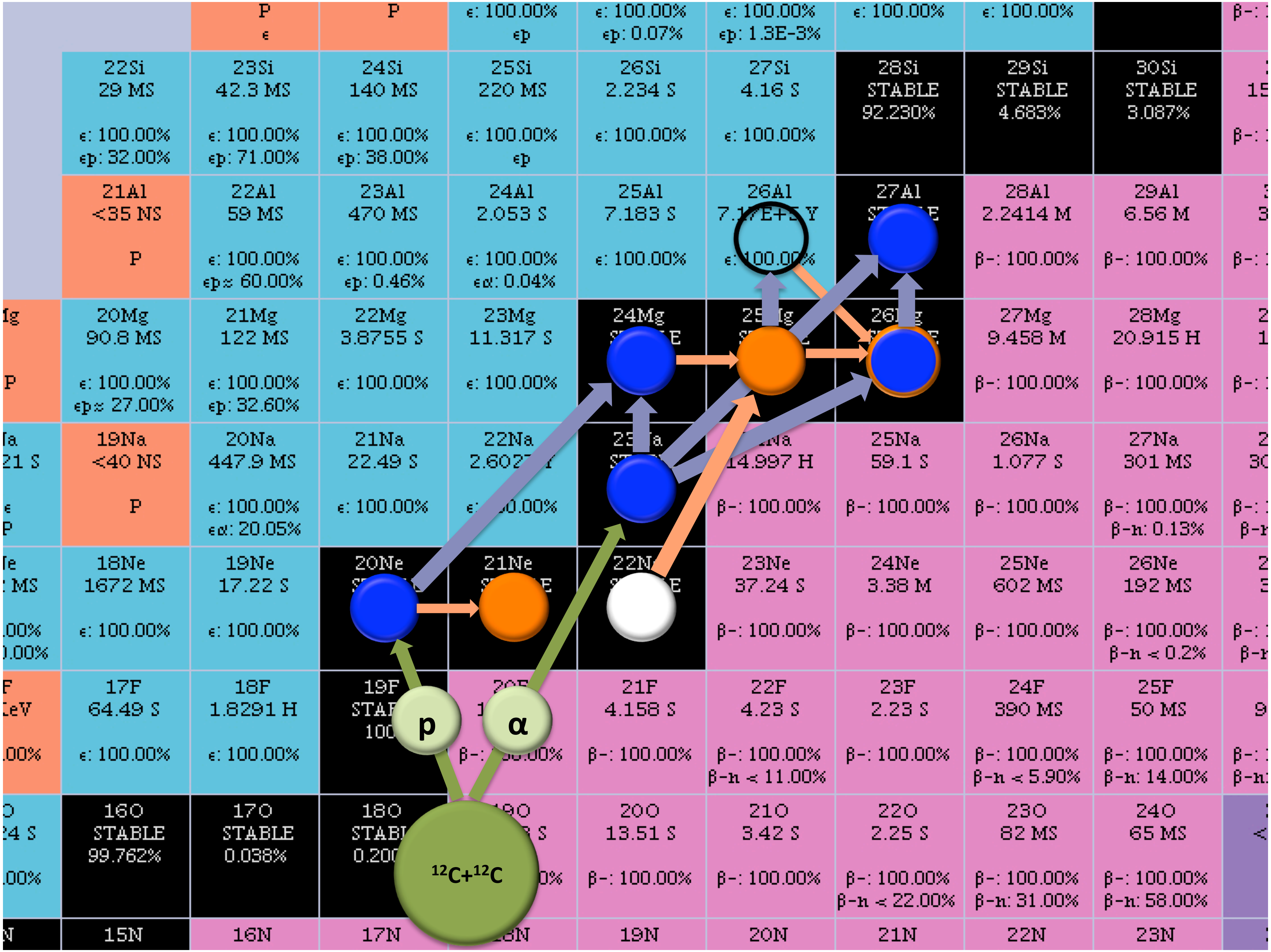
^{20}Ne, ^{23}Na, ^{24}Mg and ^{27}Al are pure products of the C burning

^{21}Ne, ^{25}Mg and ^{26}Mg are basically a product of C burning but their production is controlled by the $^{22}Ne(\alpha,n)$ nuclear reaction rate, process that may be efficient also in He burning (this actually occurs in the more massive stars ($M>60M_{\odot}$)

The production factors of ^{21}Ne, ^{25}Mg, ^{26}Mg (and maybe ^{27}Al) could be increased and brought to the level of O if the $^{22}Ne(\alpha,n)$ nuclear cross section were more effective

To reconcile the production factor of ^{24}Mg with that of O would require a reanalysis of the $^{20}Ne(\alpha,\gamma)$ that at present seems quite robust (Is it true?????)

The nuclear cross sections $^{23}Na(\alpha,\gamma)$ and $^{23}Na(\alpha,p)$ are still purely theoretical:
PLEASE MEASURE THEM!



22Si 29 MS ϵ: 100.00% ϵp: 32.00%
23Si 42.3 MS ϵ: 100.00% ϵp: 71.00%
24Si 140 MS ϵ: 100.00% ϵp: 38.00%
25Si 220 MS ϵ: 100.00% ϵp
26Si 2.234 S ϵ: 100.00%
27Si 4.16 S ϵ: 100.00%
28Si STABLE 92.230%
29Si STABLE 4.683%
30Si STABLE 3.087%
21Al <35 NS P
22Al 59 MS ϵ: 100.00% ϵp≈ 60.00%
23Al 470 MS ϵ: 100.00% ϵp: 0.46%
24Al 2.053 S ϵ: 100.00% ϵα: 0.04%
25Al 7.183 S ϵ: 100.00%
26Al
27Al
28Al 2.2414 M β-: 100.00%
29Al 6.56 M β-: 100.00%
20Mg 90.8 MS ϵ: 100.00% ϵp≈ 27.00%
21Mg 122 MS ϵ: 100.00% ϵp: 32.60%
22Mg 3.8755 S ϵ: 100.00%
23Mg 11.317 S ϵ: 100.00%
24Mg
25Mg
26Mg
27Mg 9.458 M β-: 100.00%
28Mg 20.915 H β-: 100.00%
19Na <40 NS P
20Na 447.9 MS ϵ: 100.00% ϵα: 20.05%
21Na 22.49 S ϵ: 100.00%
22Na
23Na
24Na 14.997 H β-: 100.00%
25Na 59.1 S β-: 100.00%
26Na 1.077 S β-: 100.00%
27Na 301 MS β-: 100.00% β-n: 0.13%
18Ne 1672 MS ϵ: 100.00%
19Ne 17.22 S ϵ: 100.00%
20Ne
21Ne
22Ne
23Ne 37.24 S β-: 100.00%
24Ne 3.38 M β-: 100.00%
25Ne 602 MS β-: 100.00%
26Ne 192 MS β-: 100.00% β-n < 0.2%
17F 64.49 S ϵ: 100.00%
18F 1.8291 H ϵ: 100.00%
19F
21F 4.158 S β-: 100.00%
22F 4.23 S β-: 100.00% β-n < 11.00%
23F 2.23 S β-: 100.00%
24F 390 MS β-: 100.00% β-n < 5.90%
25F 50 MS β-: 100.00% β-n: 14.00%
16O STABLE 99.762%
17O STABLE 0.038%
20O 13.51 S β-: 100.00%
21O 3.42 S β-: 100.00%
22O 2.25 S β-: 100.00% β-n < 22.00%
23O 82 MS β-: 100.00% β-n: 31.00%
24O 65 MS β-: 100.00% β-n: 58.00%
15N
16N
17N
19N
20N
21N
22N
23N
p
α
12C+12C