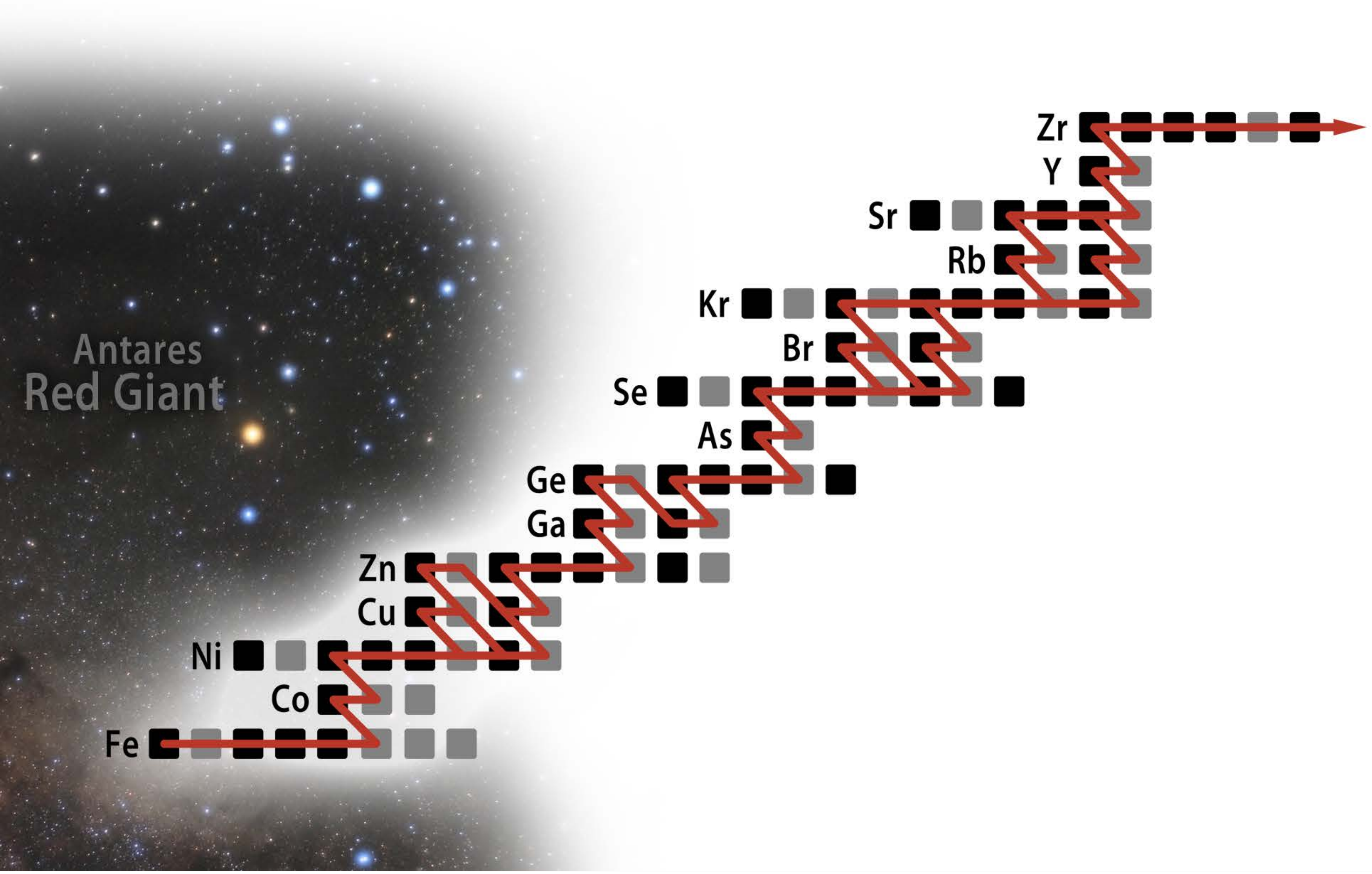
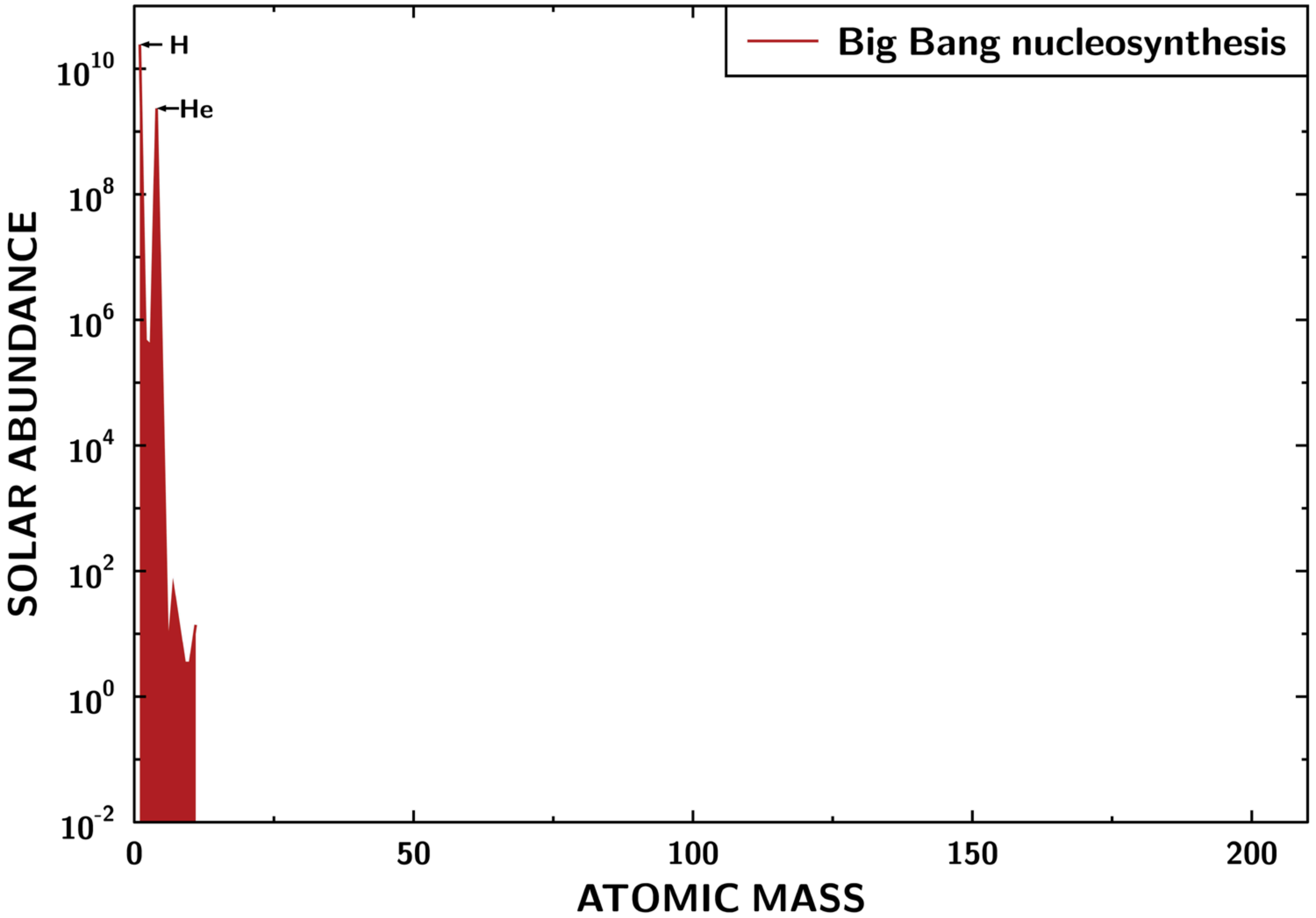
The s-process

René Reifarth & Kathrin Göbel

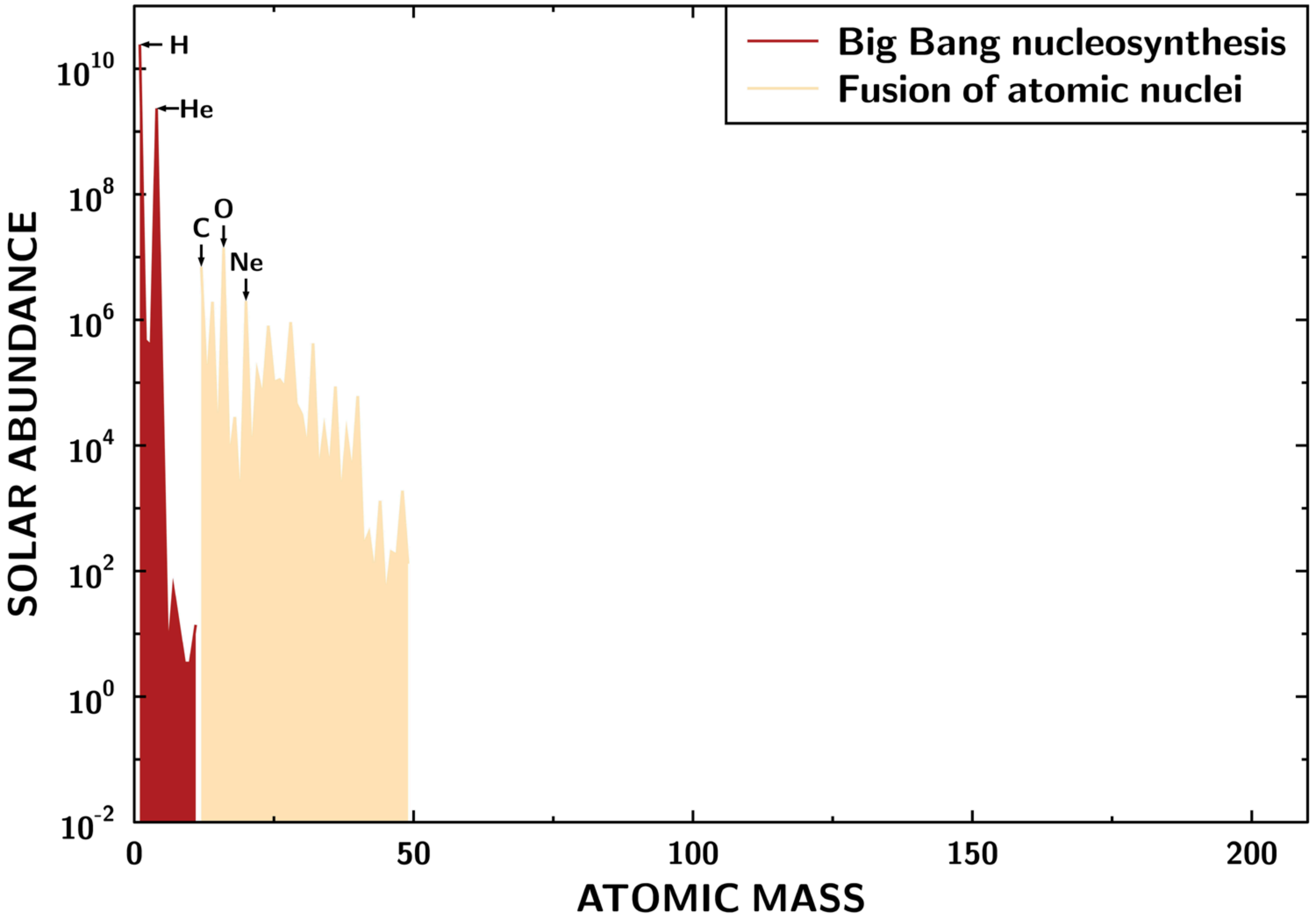
55th Karpacz Winter school on
Nuclear astrophysics in the multi-messenger era
February 25 – March 2, 2019, Karpacz, Poland

Nucleosynthesis – tales from the past

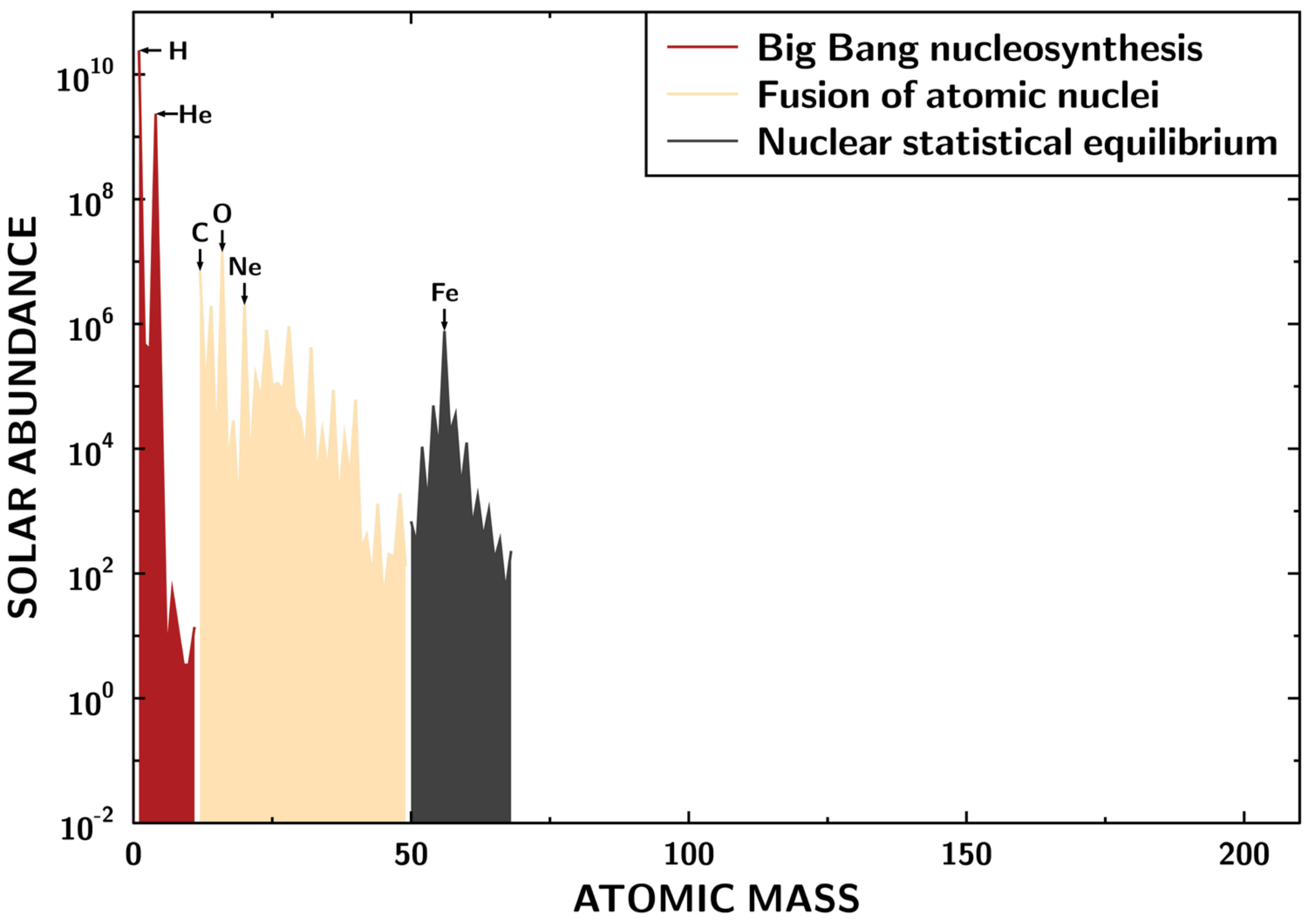




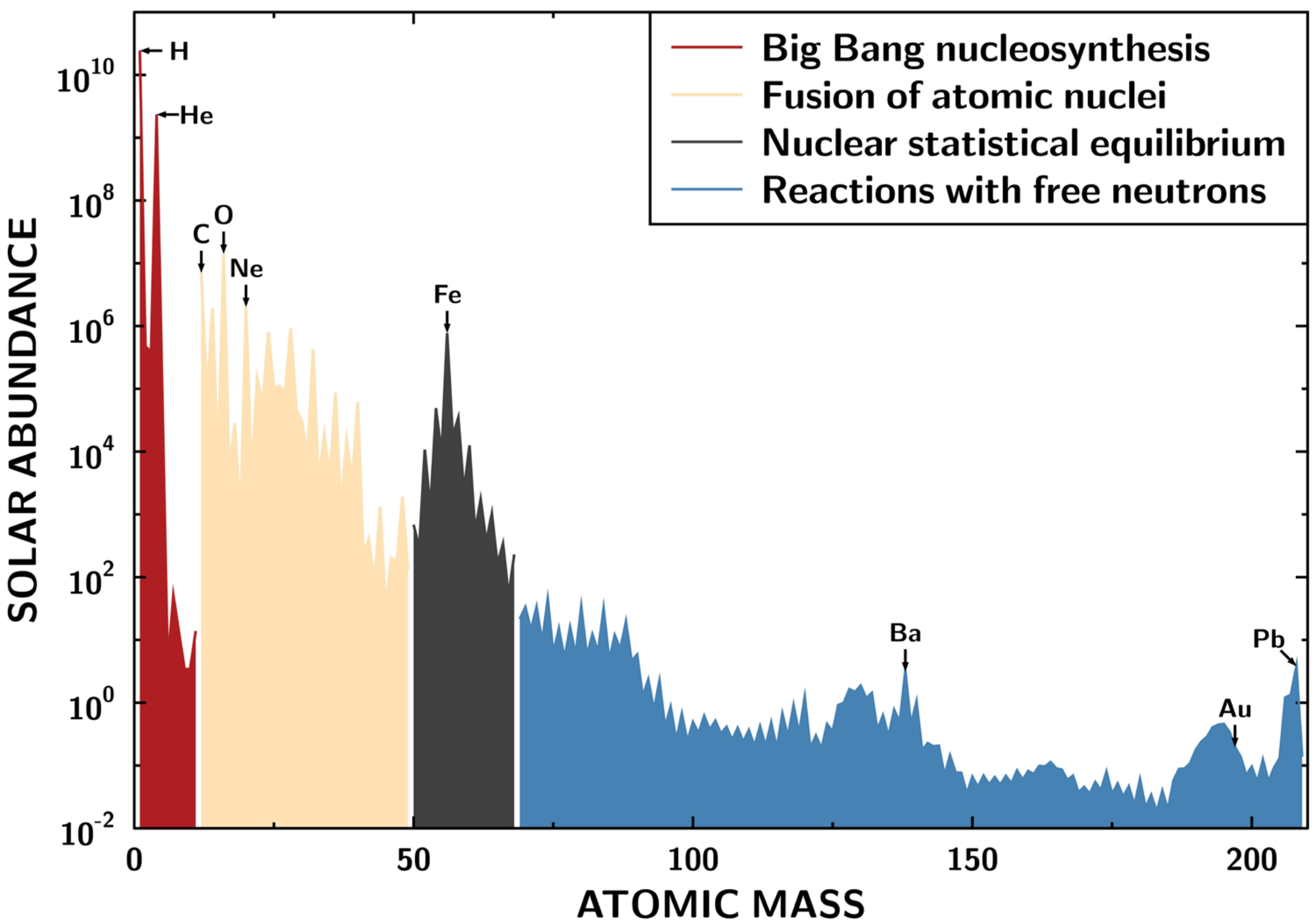
Big Bang nucleosynthesis
H
He
SOLAR ABUNDANCE
10^10
10^8
10^6
10^4
10^2
10^0
10^-2
0
50
100
150
200
ATOMIC MASS



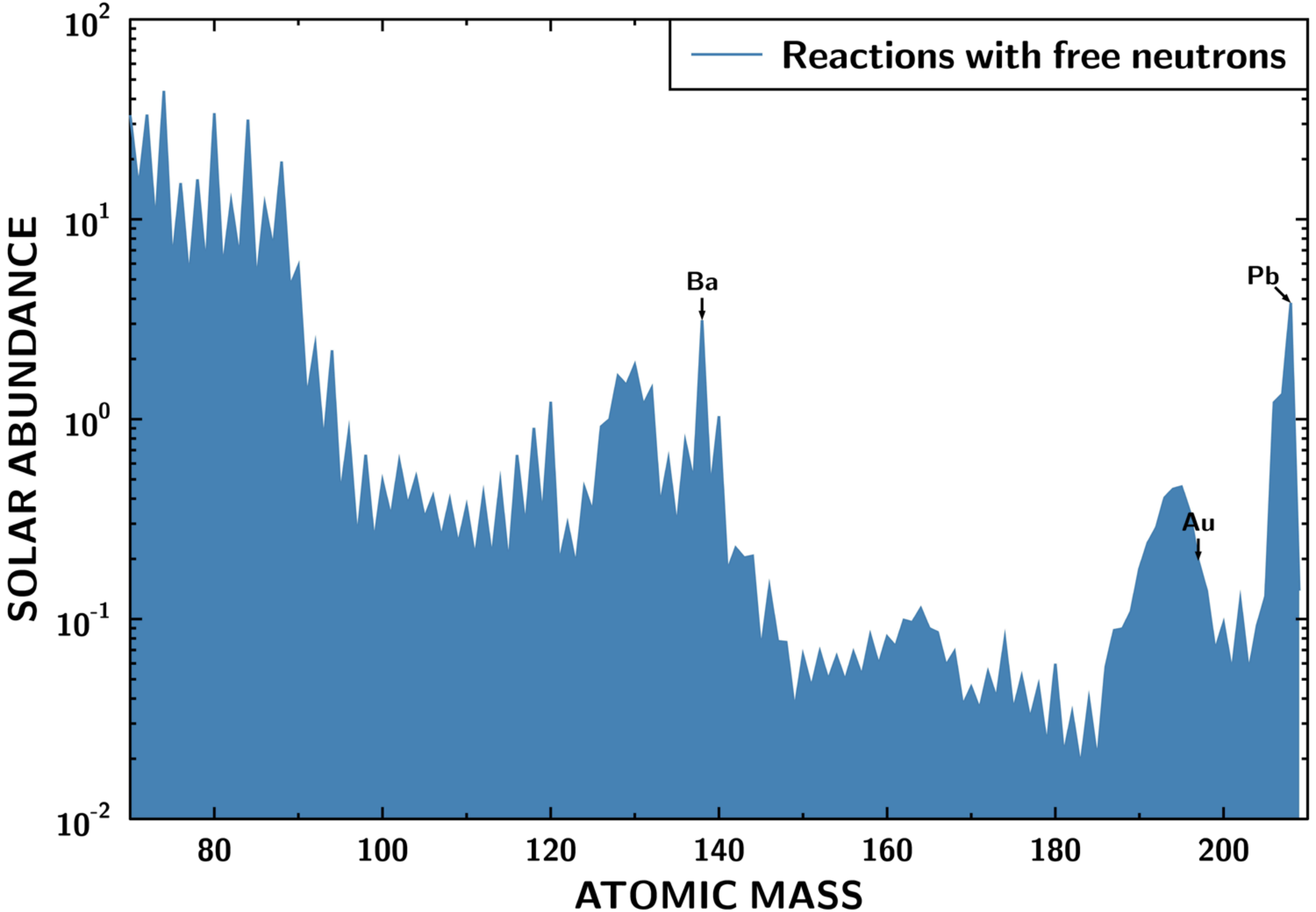
Big Bang nucleosynthesis
Fusion of atomic nuclei
H
He
C
O
Ne
SOLAR ABUNDANCE
ATOMIC MASS
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
0
50
100
150
200



Big Bang nucleosynthesis
Fusion of atomic nuclei
Nuclear statistical equilibrium
H
He
C
O
Ne
Fe
10^10
10^8
10^6
10^4
10^2
10^0
10^-2
0
50
100
150
200
SOLAR ABUNDANCE
ATOMIC MASS



Big Bang nucleosynthesis
Fusion of atomic nuclei
Nuclear statistical equilibrium
Reactions with free neutrons
H
He
C
O
Ne
Fe
Ba
Au
Pb
SOLAR ABUNDANCE
ATOMIC MASS
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
0
50
100
150
200

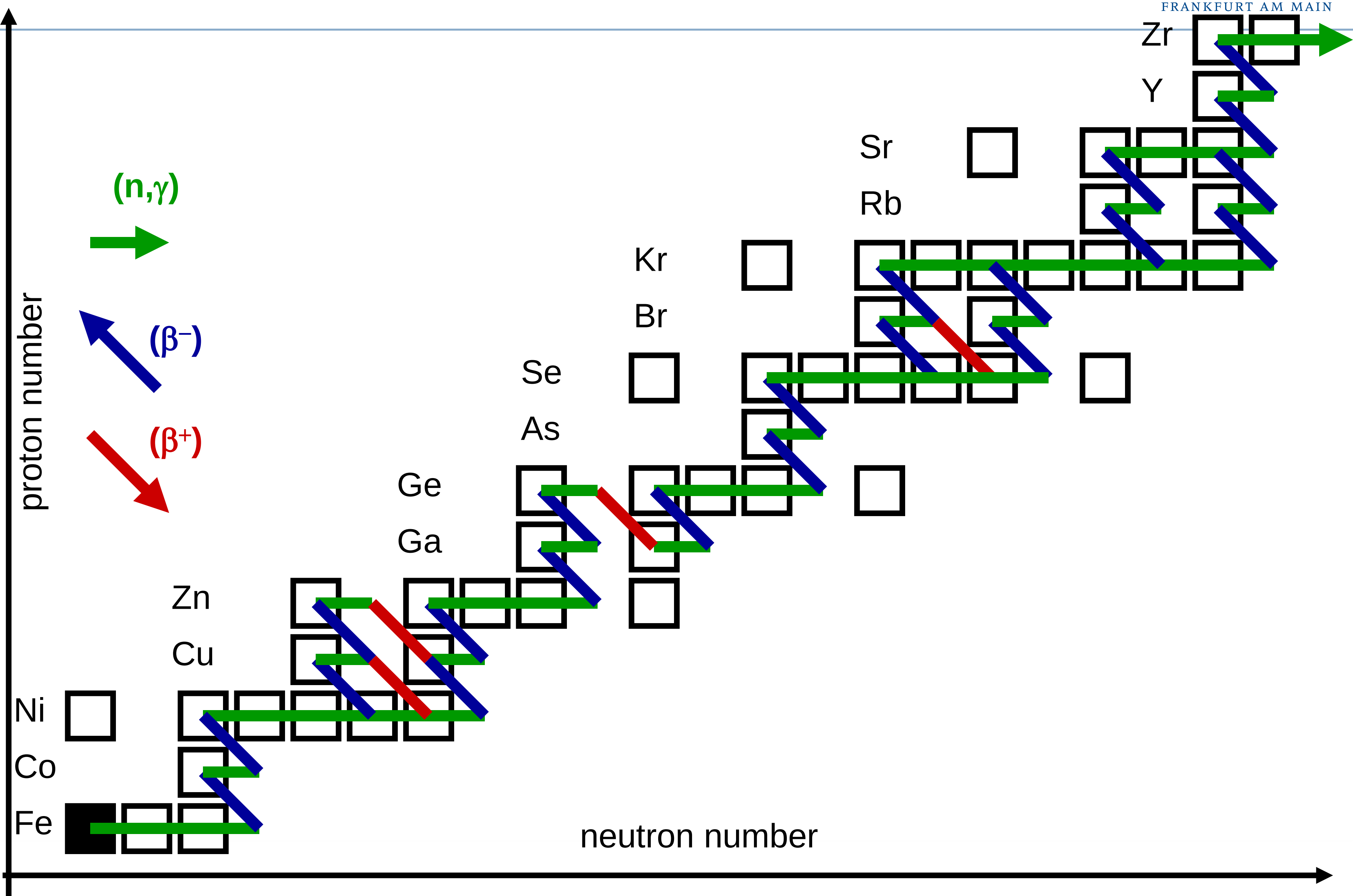


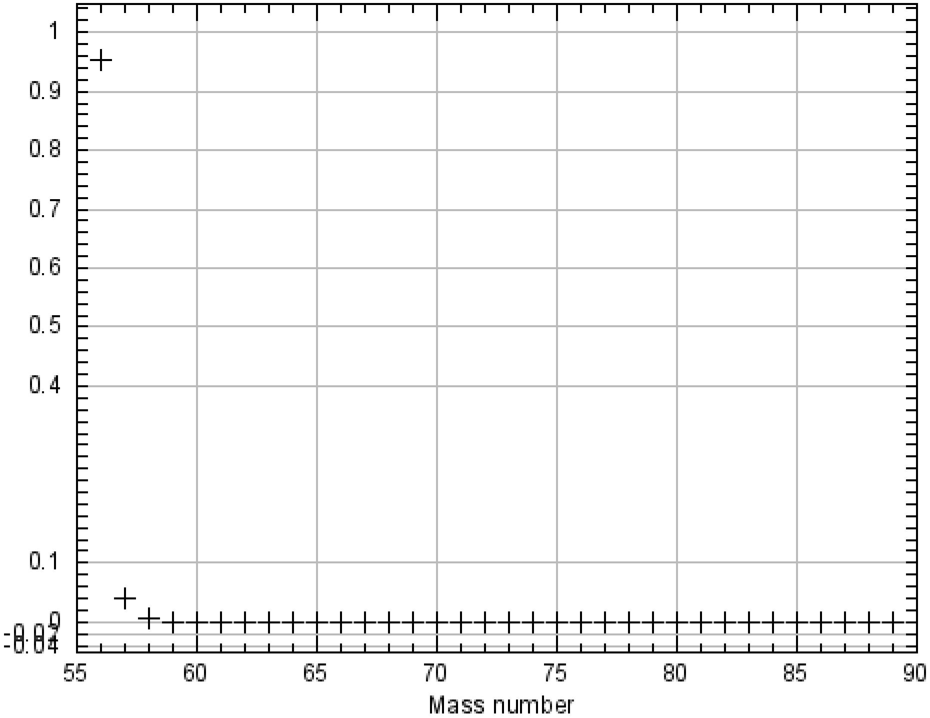
Reactions with free neutrons
SOLAR ABUNDANCE
ATOMIC MASS
10^2
10^1
10^0
10^{-1}
10^{-2}
80
100
120
140
160
180
200
Ba
Pb
Au

Let‘s irradiate matter with neutrons!

Seed: 100% ^{56}Fe

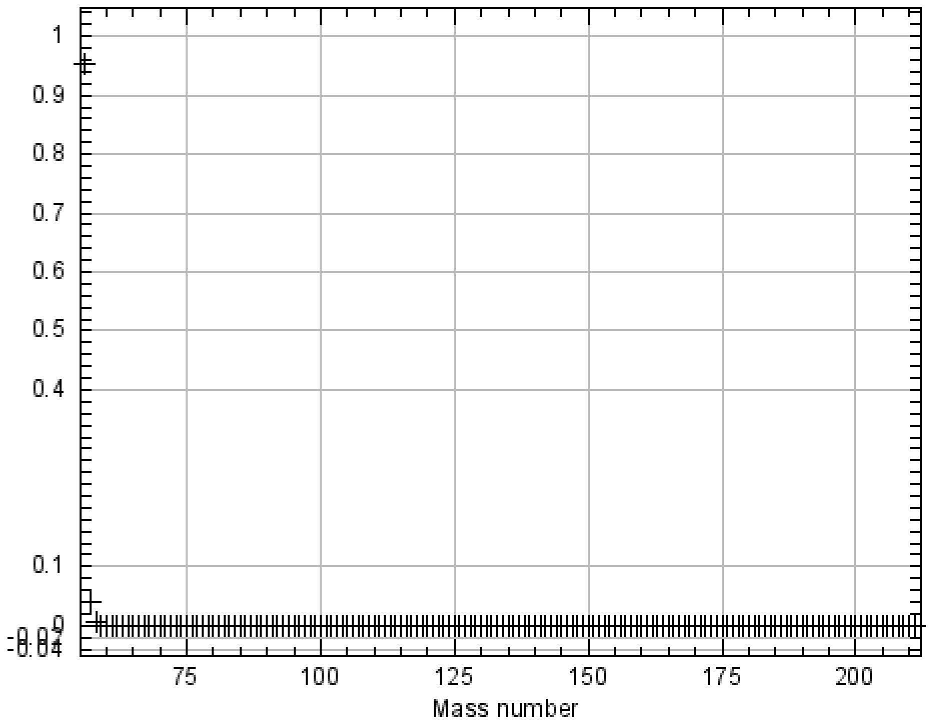
the s-process



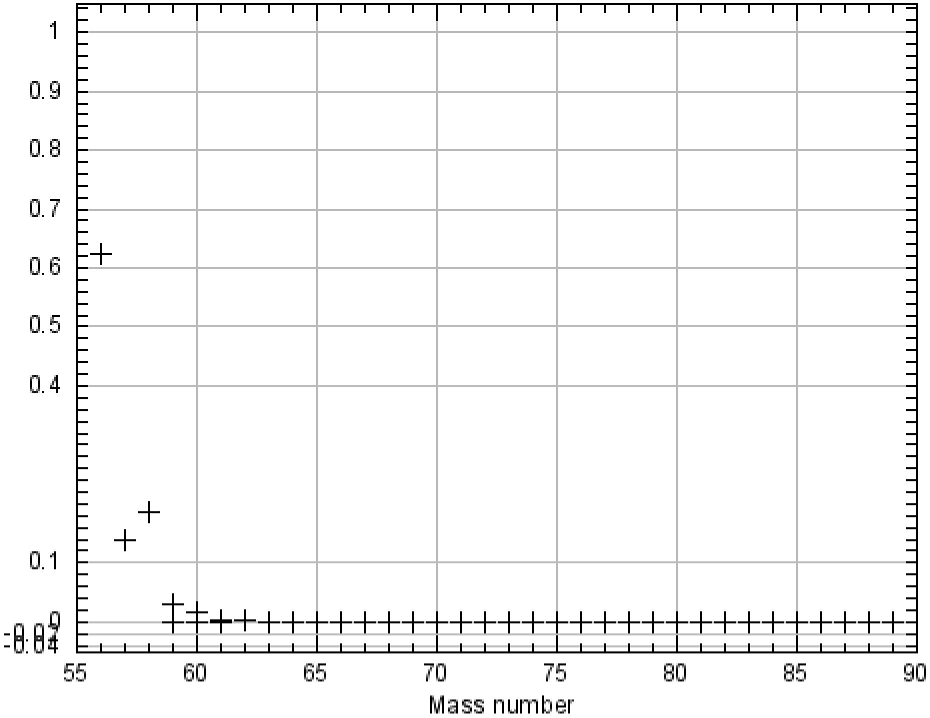


Neutron exposure time: 1 10^{11} s ~ 10^{4} yrs

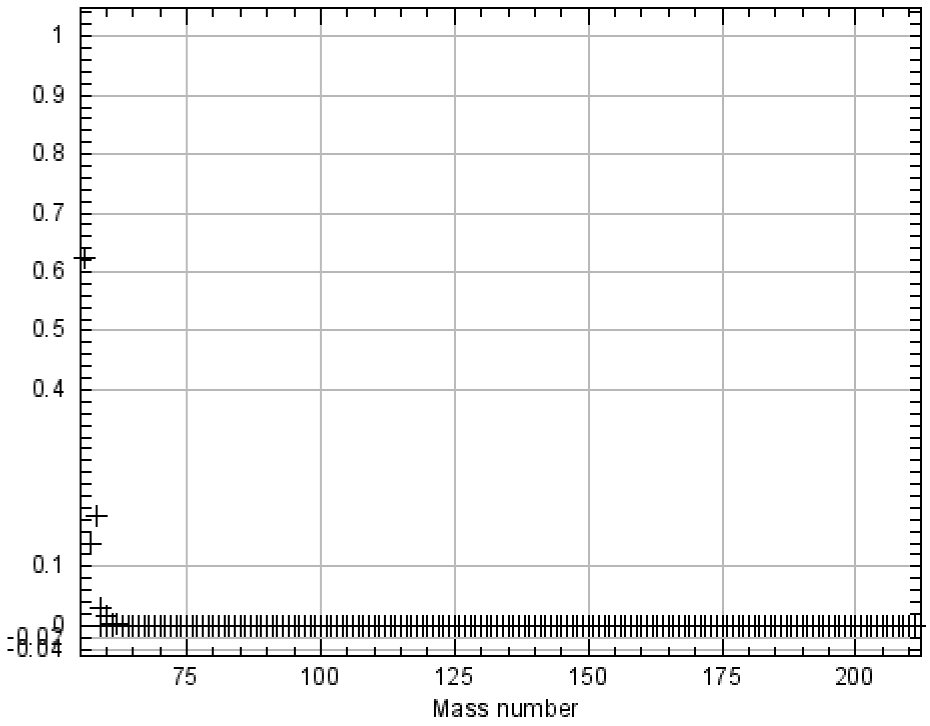
Neutron density: 2 10^{5} n/cm^{3}

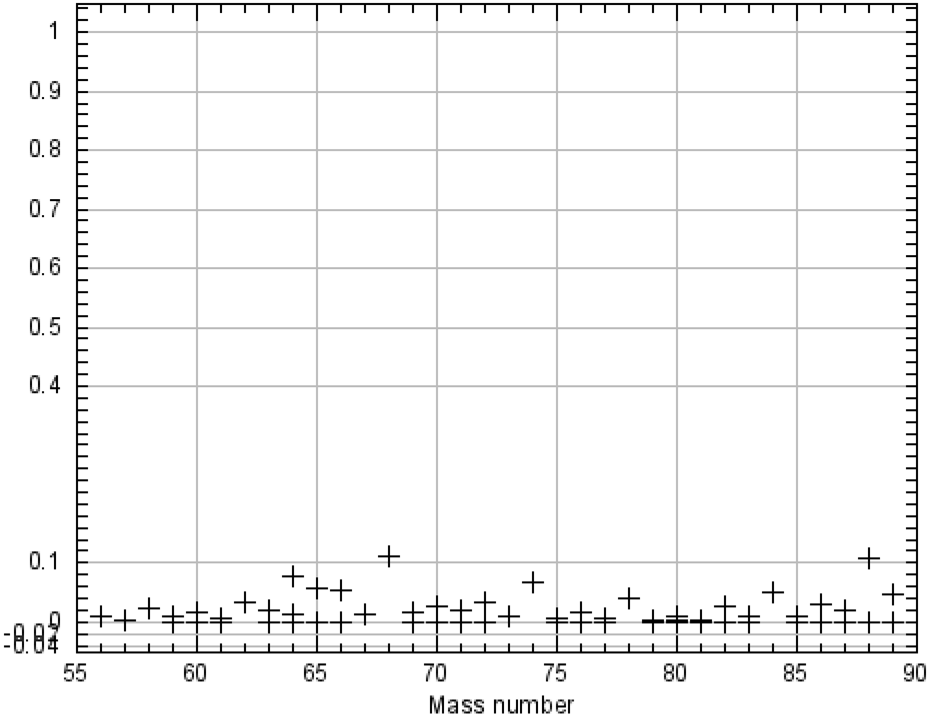


1
0.9
0.8
0.7
0.6
0.5
0.4
0.1
0
-0.02
-0.04
75
100
125
150
175
200
Mass number

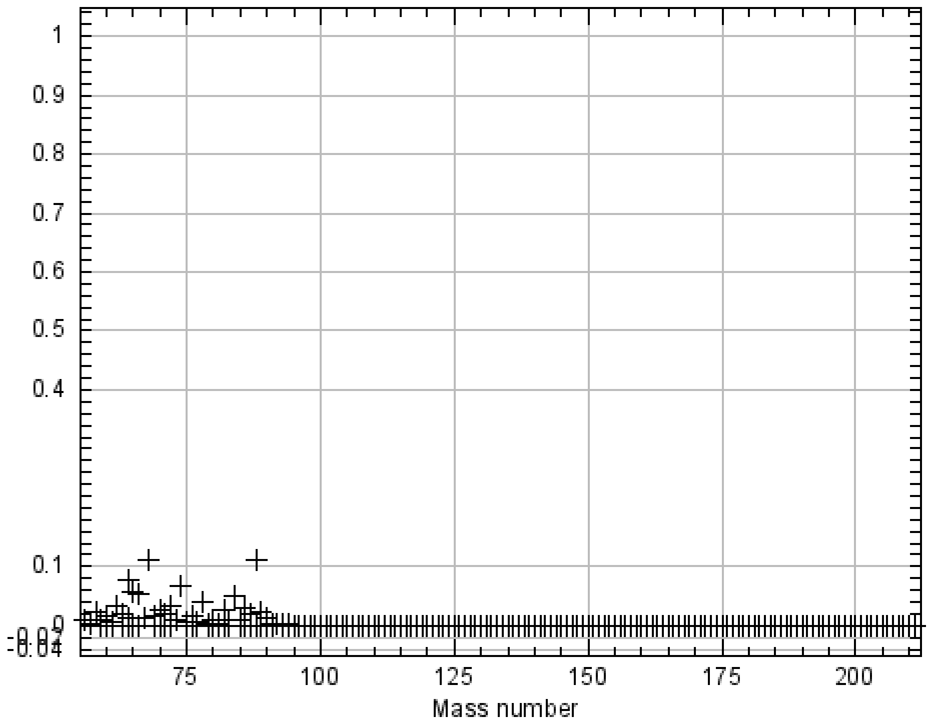


Neutron exposure time : 1 10^{12} s ~ 10^{5} yrs
Neutron density: 2 10^{5} n/cm^{3}

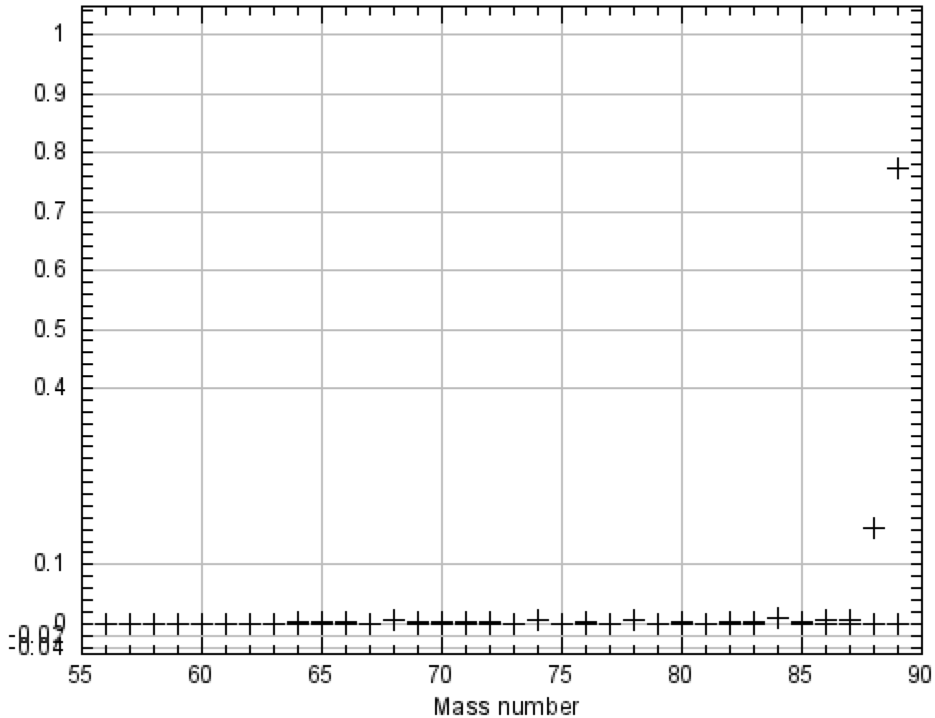

1
0.9
0.8
0.7
0.6
0.5
0.4
0.1
0
-0.02
-0.04
75
100
125
150
175
200
Mass number



Neutron exposure time: 1 10^{13} s ~ 10^{6} yrs
Neutron density: 2 10^{5} n/cm^{3}

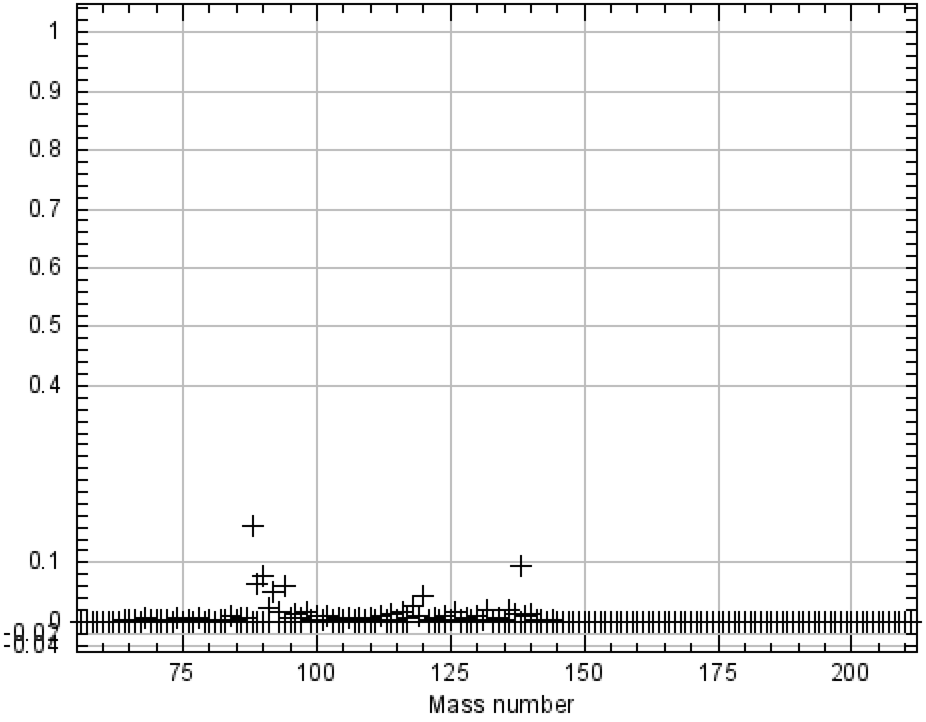


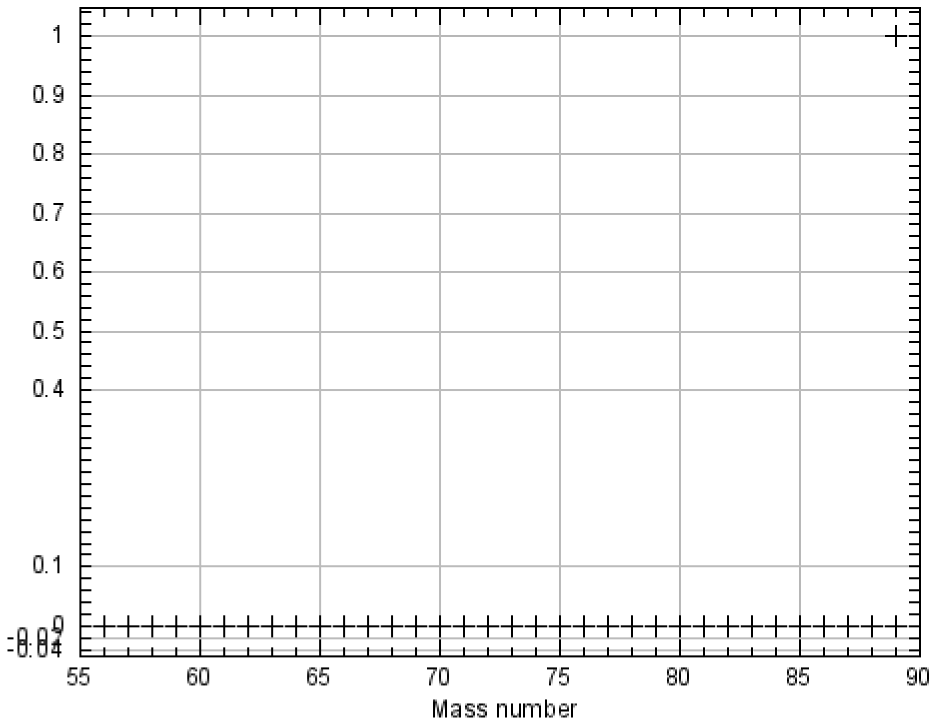
1
0.9
0.8
0.7
0.6
0.5
0.4
0.1
0
-0.02
-0.04
75
100
125
150
175
200
Mass number



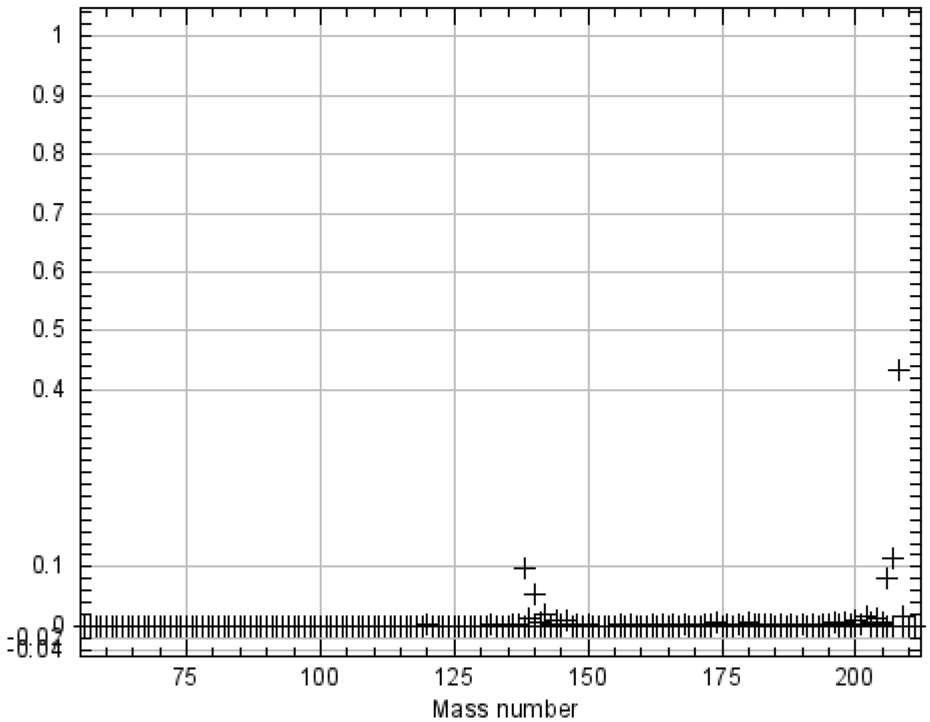
Neutron exposure time: $2\ 10^{13}$ s ~ 10^{6} yrs

Neutron density: $2\ 10^{5}$ n/cm^{3}

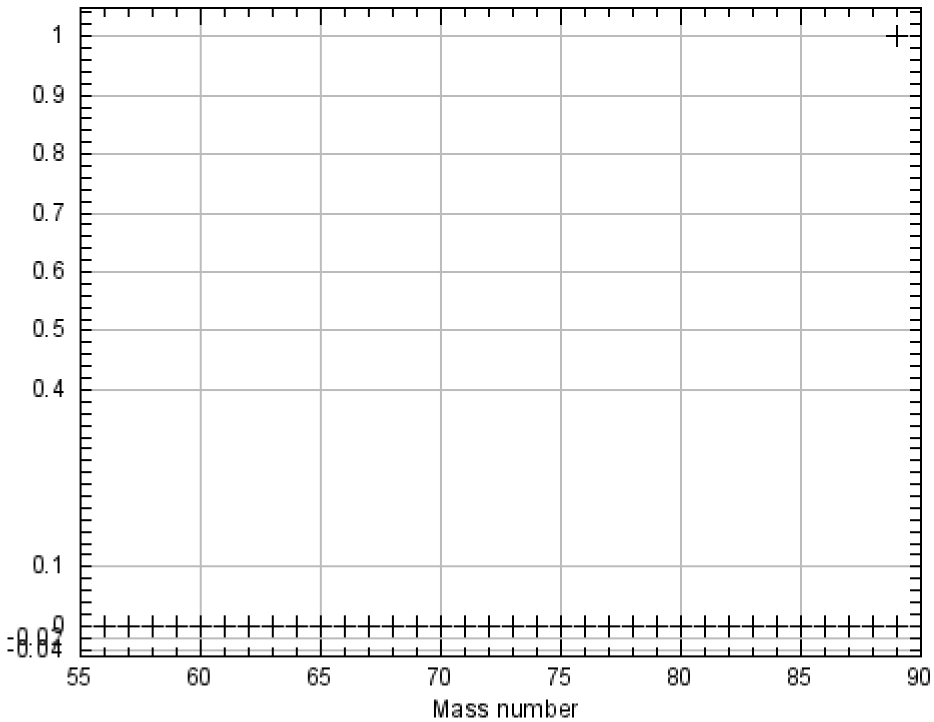

1
0.9
0.8
0.7
0.6
0.5
0.4
0.1
0
-0.02
-0.04
75
100
125
150
175
200
Mass number



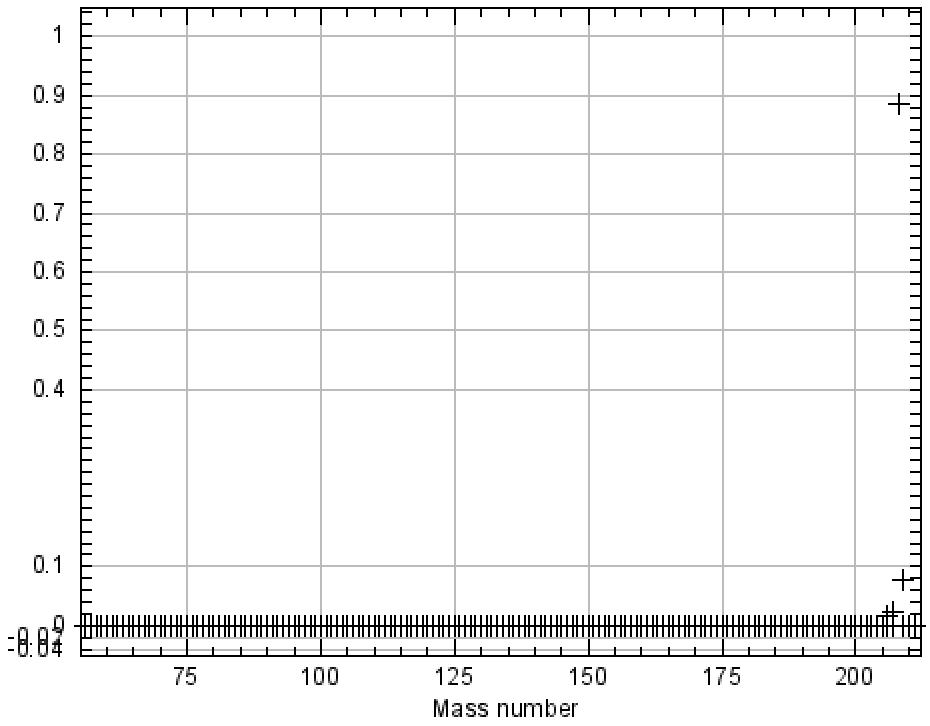
Neutron exposure time: 4 10^{13} s ~ 10^{6} yrs
Neutron density: 2 10^{5} n/cm^{3}



1
0.9
0.8
0.7
0.6
0.5
0.4
0.1
0
-0.02
-0.04
75
100
125
150
175
200
Mass number



Neutron exposure time: 2 10^{14} s ~ 10^{7} yrs
Neutron density: 2 10^{5} n/cm^{3}


1
0.9
0.8
0.7
0.6
0.5
0.4
0.1
0
-0.02
-0.04
75
100
125
150
175
200
Mass number

Equilibrium in the s-process

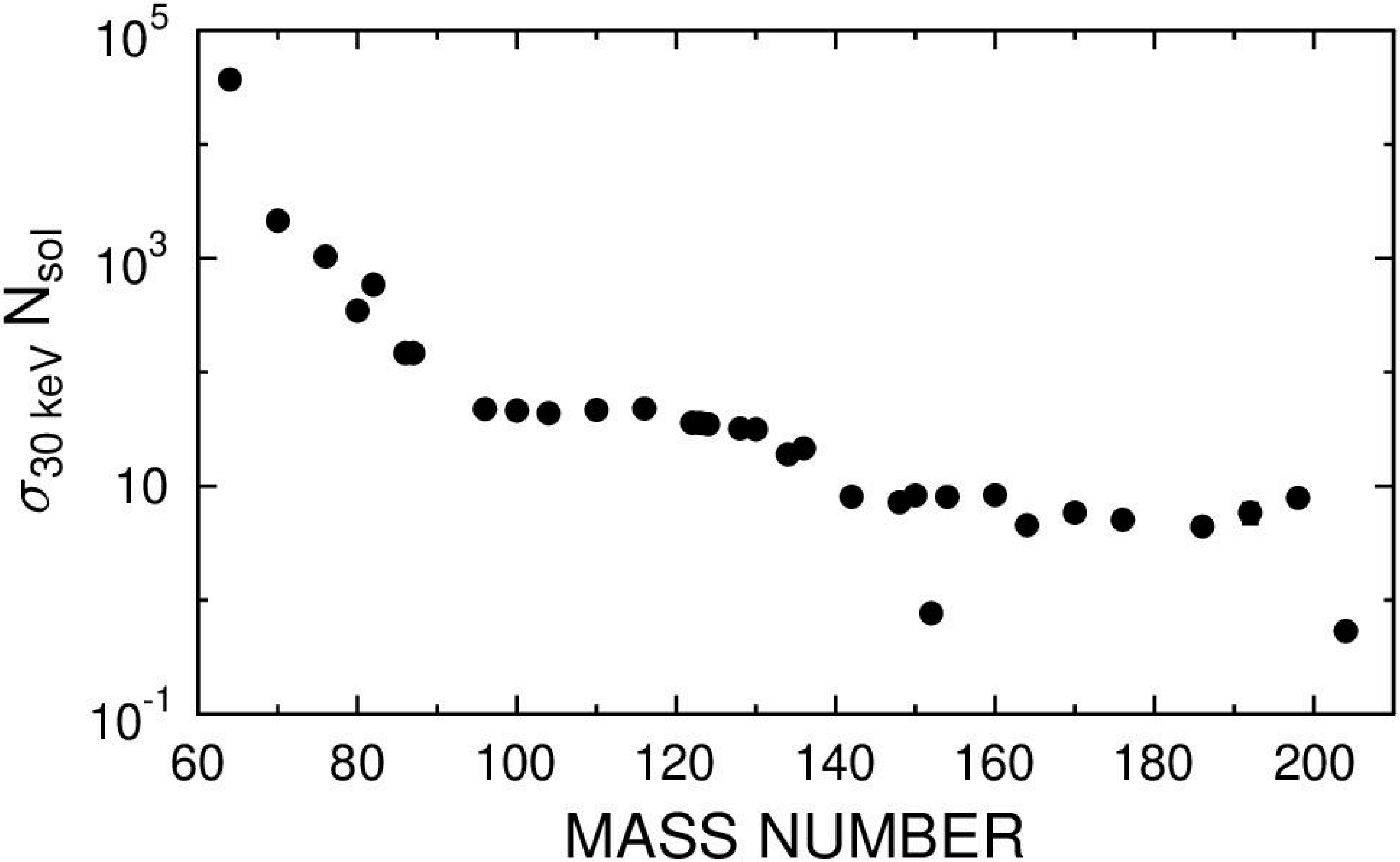
$$\left(\frac{\mathrm{d}N_A}{\mathrm{d}t}\right)^{\text{destruction}} = \left(\frac{\mathrm{d}N_{A+1}}{\mathrm{d}t}\right)^{\text{production}}$$

$$\left(\frac{\mathrm{d}N_A}{\mathrm{d}t}\right)^{\text{destruction}} = \lambda_{neutron} N_A = n_n v_{thermal} \langle \sigma_A \rangle N_A$$

Local Equilibrium:

$$\left(\frac{\mathrm{d}N_{A+1}}{\mathrm{d}t}\right)^{\text{production}} = \left(\frac{\mathrm{d}N_{A+1}}{\mathrm{d}t}\right)^{\text{destruction}}$$

$$\langle \sigma_A \rangle N_A \approx \langle \sigma_{A+1} \rangle N_{A+1}$$



10^5
10^3
10
10^{-1}
$\sigma_{30\ keV}\ N_{sol}$
60
80
100
120
140
160
180
200
MASS NUMBER

Exponential irradiation

Ansatz: $$N(\tau) = \frac{GN_{seed}}{\tau_0} \mathrm{e}^{-\tau/\tau_0}$$

with: $$\tau = \int_0^{t_{pulse}} n_n v_{thermal} \mathrm{d}t$$

Solution: $$\sigma(A)N(A) = \frac{GN_{seed}}{\tau_0} \prod_{\mathrm{i}=56}^{A} \left(1 + \frac{1}{\sigma(i)\tau_0}\right)^{-1}$$

A tool …

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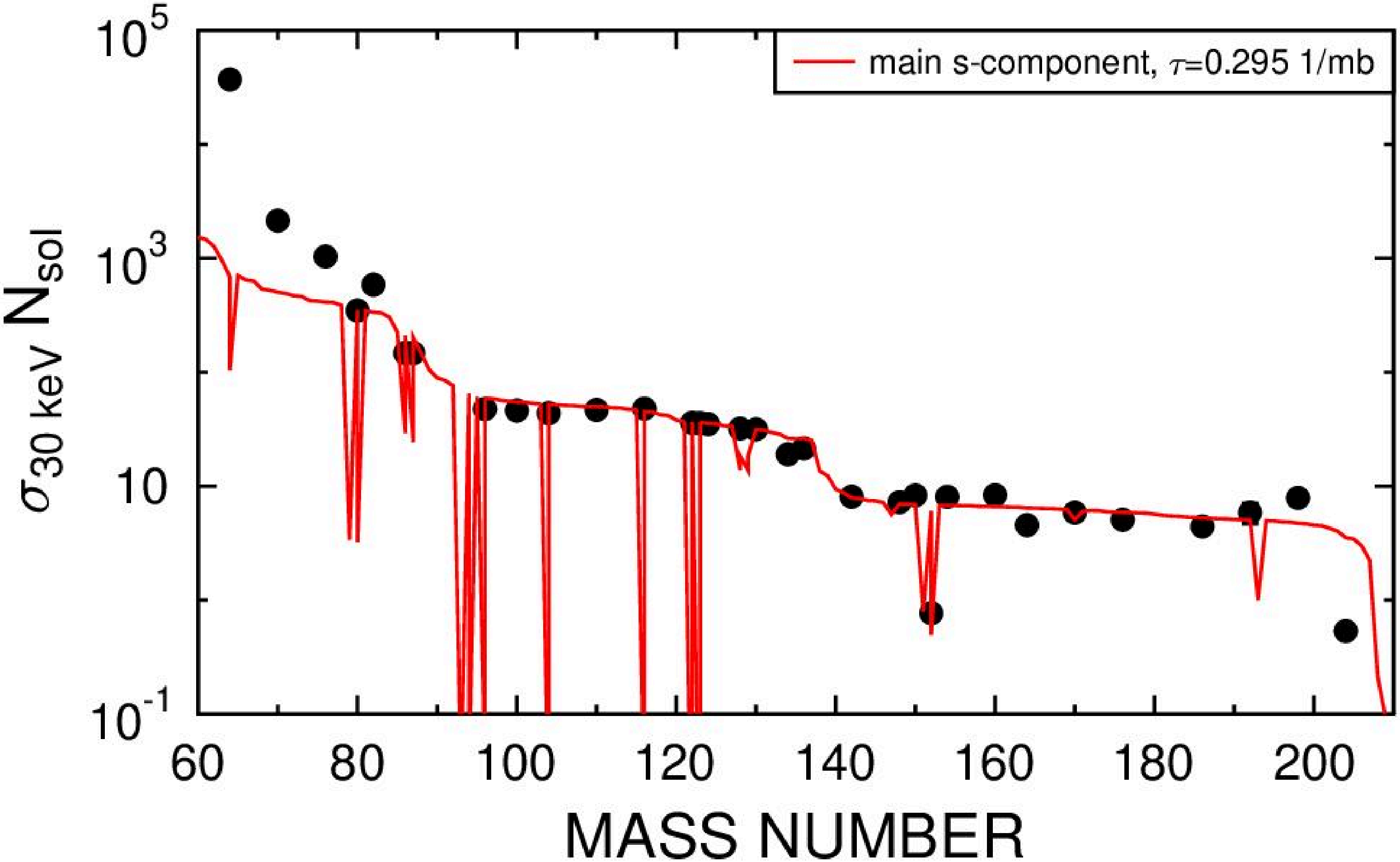
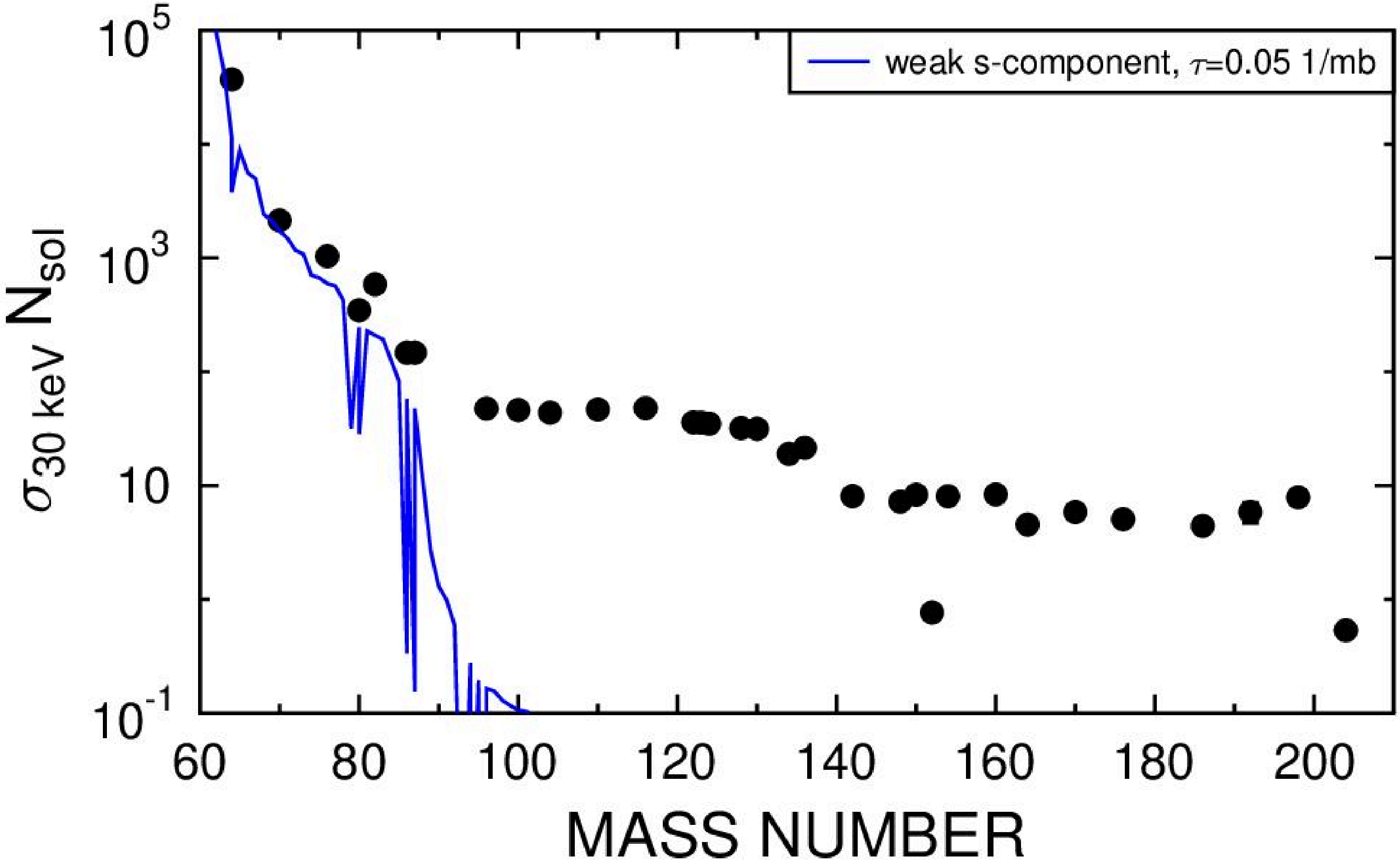
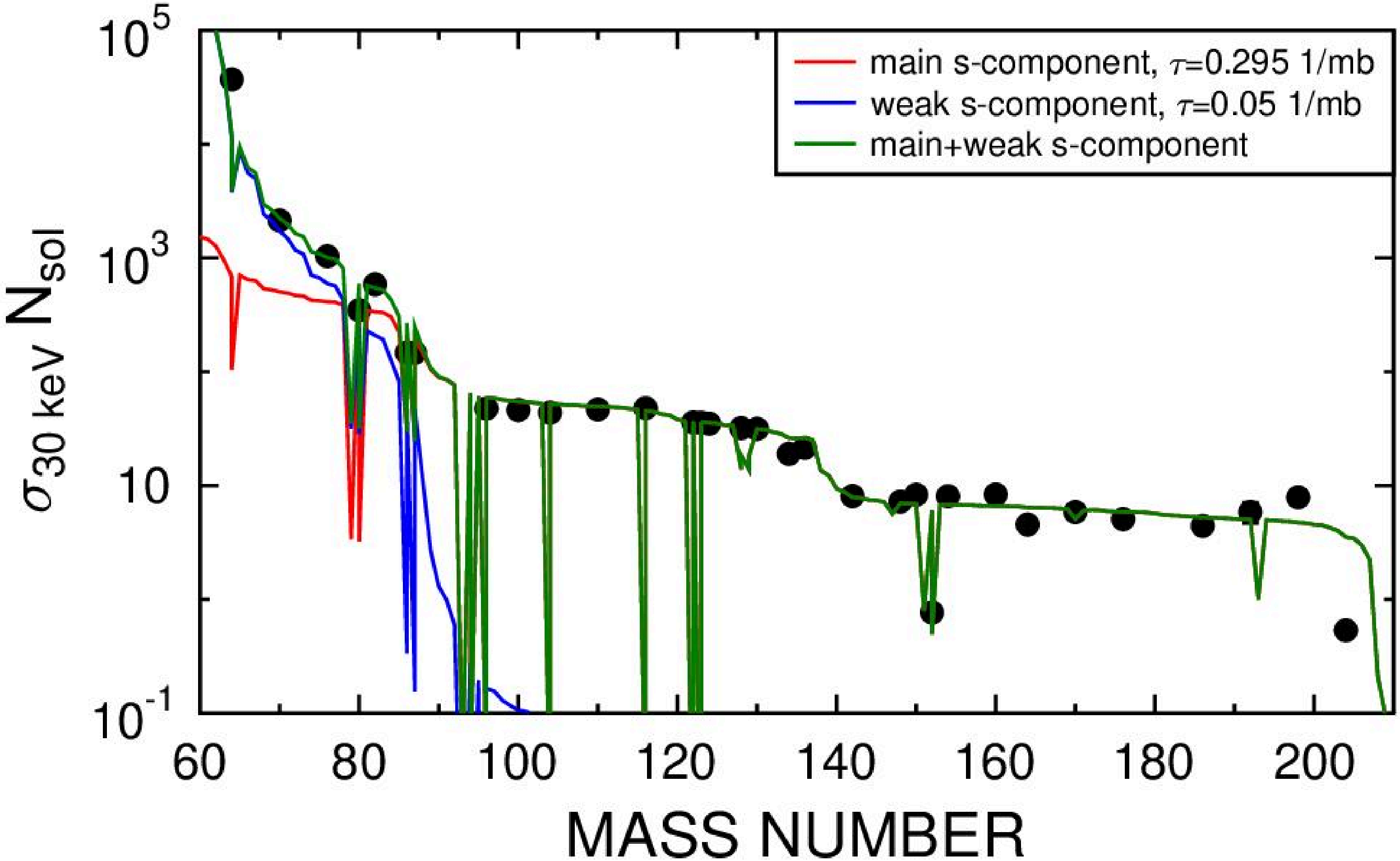
exp-astro.de/classical-s-process

Reifarth et al, Journal of Physics G 41 (2014) 53101

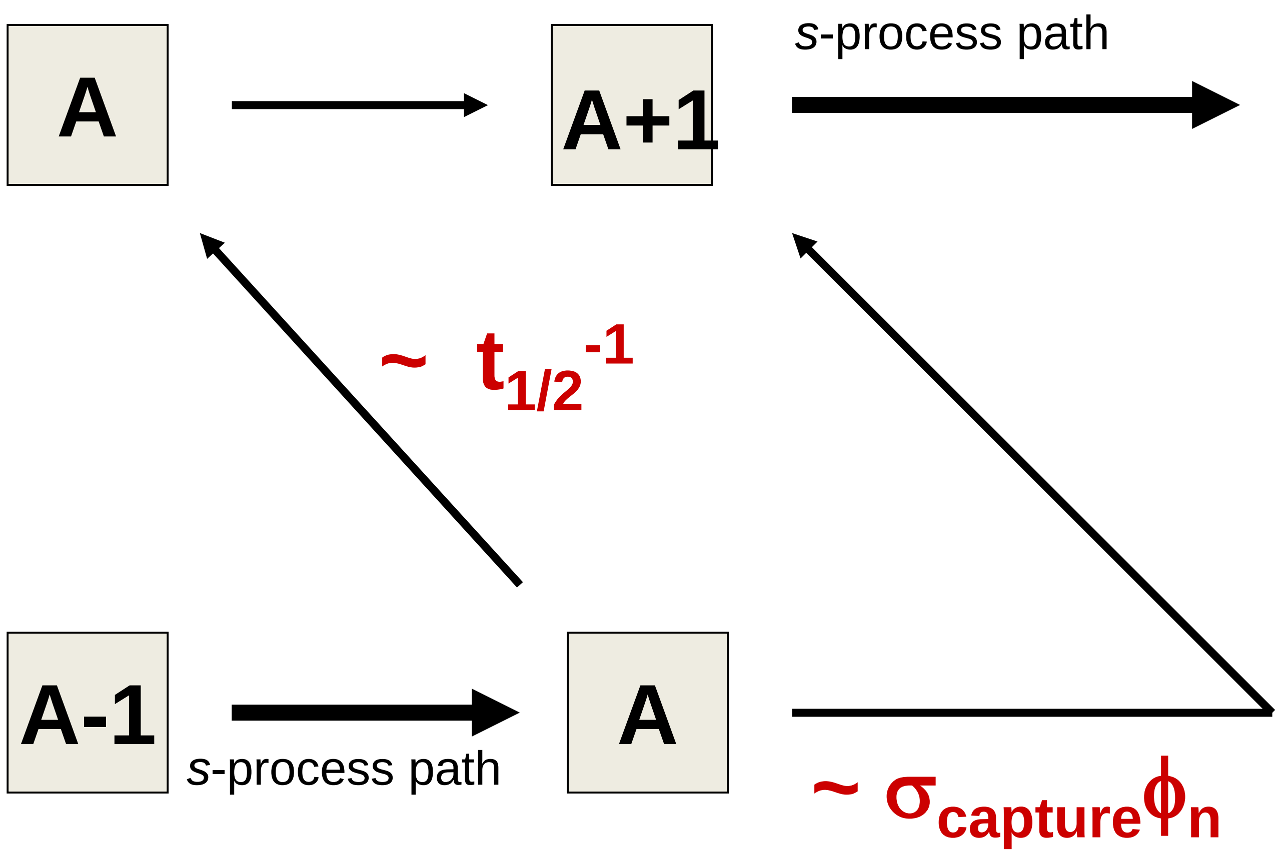


main s-component, τ=0.295 1/mb
$\sigma_{30\ keV}\ N_{sol}$
10^5
10^3
10
10^{-1}
60
80
100
120
140
160
180
200
MASS NUMBER

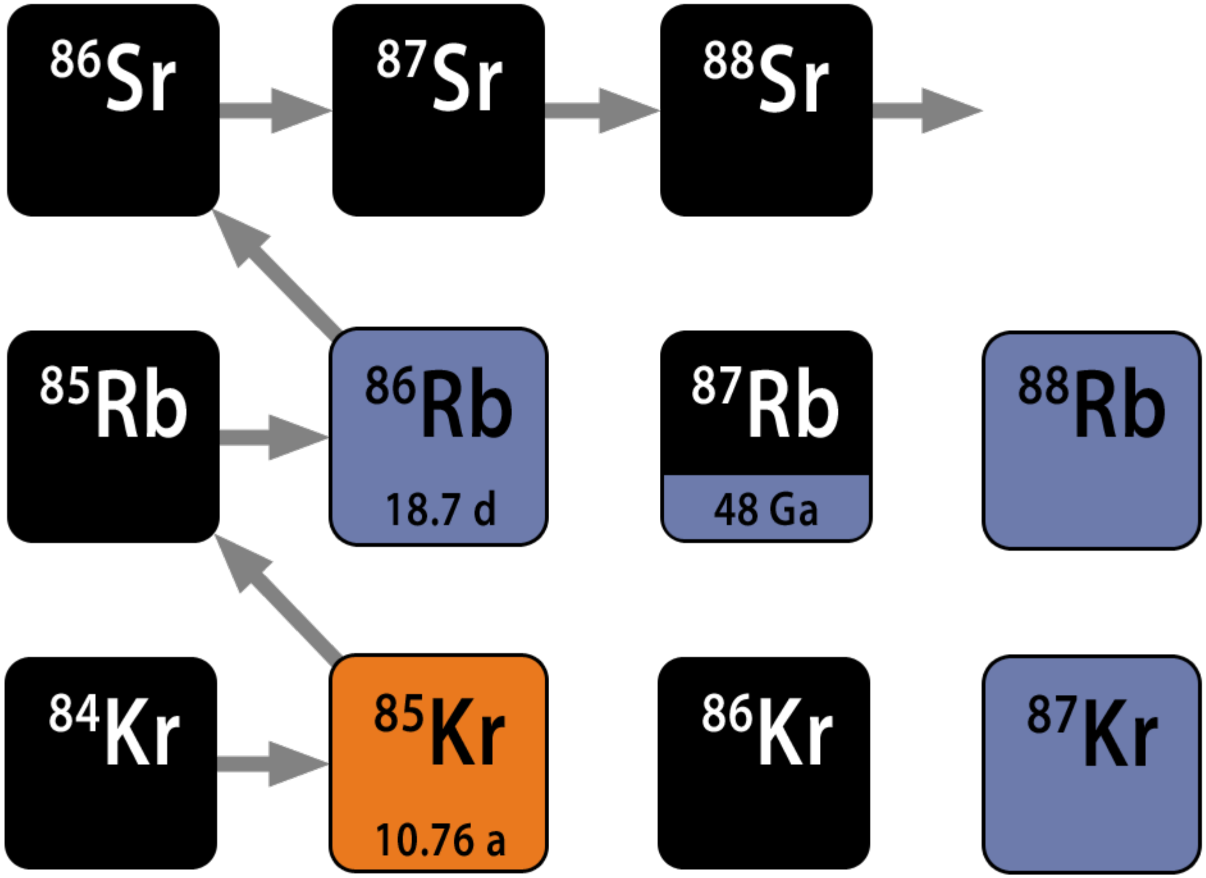

weak s-component, τ=0.05 1/mb
$\sigma_{30\,keV}\,N_{sol}$
10^5
10^3
10
10^-1
60
80
100
120
140
160
180
200
MASS NUMBER


main s-component, τ=0.295 1/mb
weak s-component, τ=0.05 1/mb
main+weak s-component
$\sigma_{30\ keV}\ N_{sol}$
10^5
10^3
10
10^{-1}
60
80
100
120
140
160
180
200
MASS NUMBER

branch point in the s-process path



Radioactive isotopes in the s-process



Radioactive isotopes in the s-process

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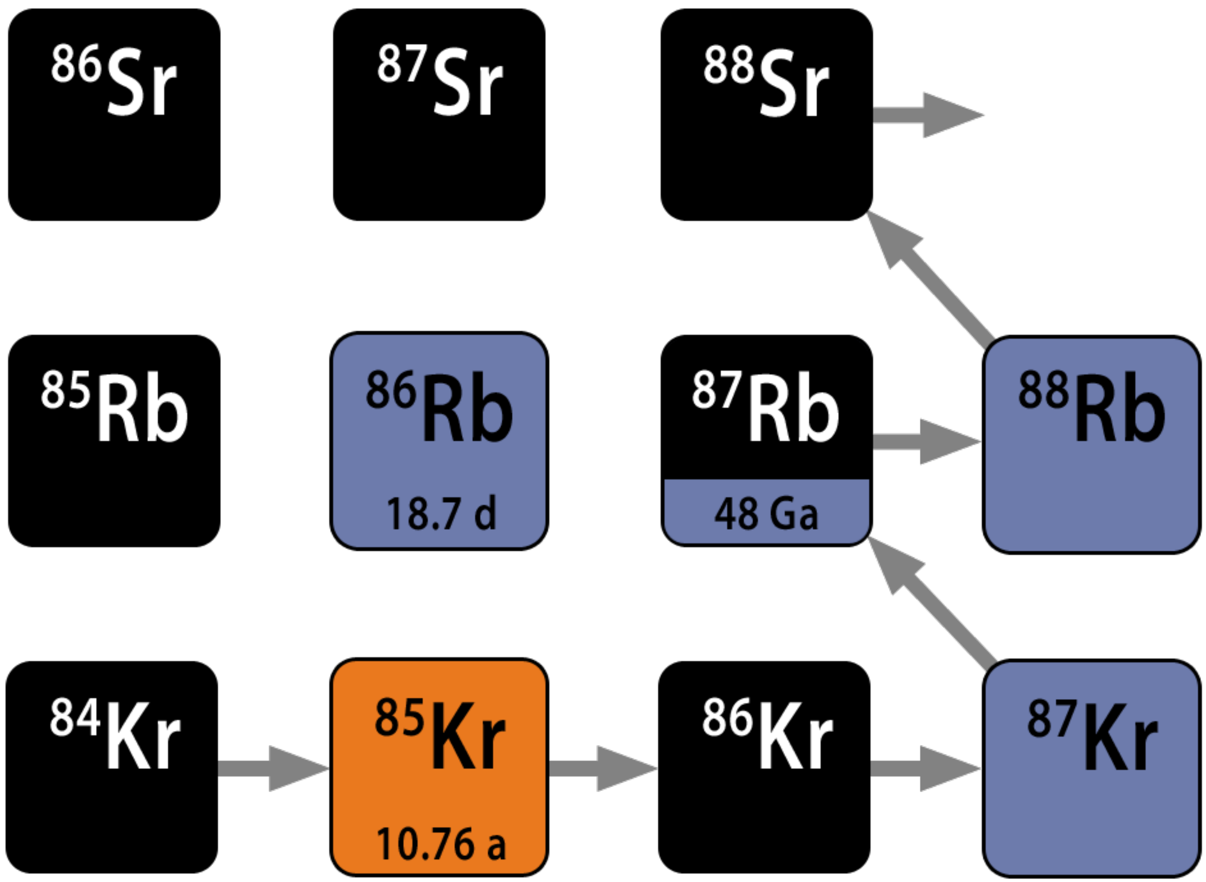
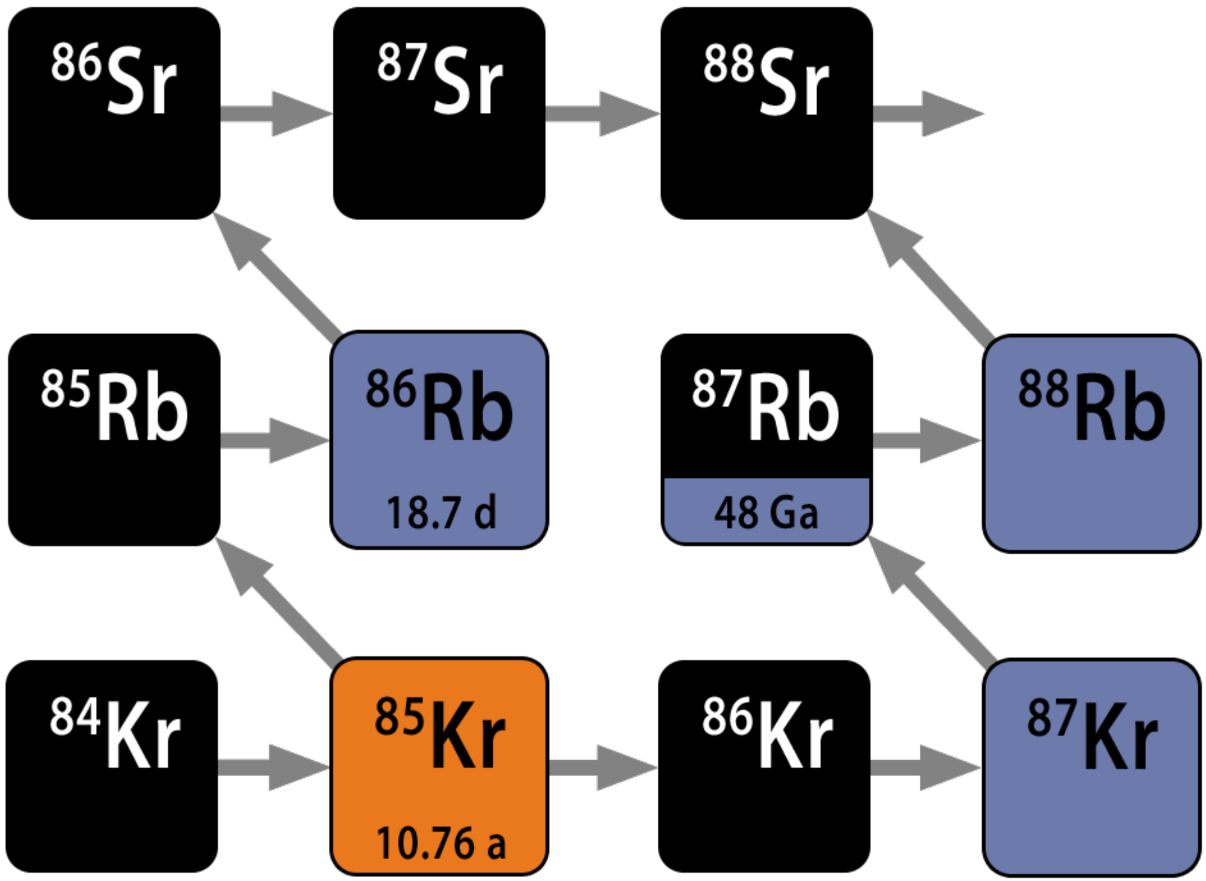


Radioactive isotopes in the s-process



Reifarth et al, Journal of Physics: Conf. Series 940 (2018) 012024

Meteorites and presolar grains

Meteorites and presolar grains

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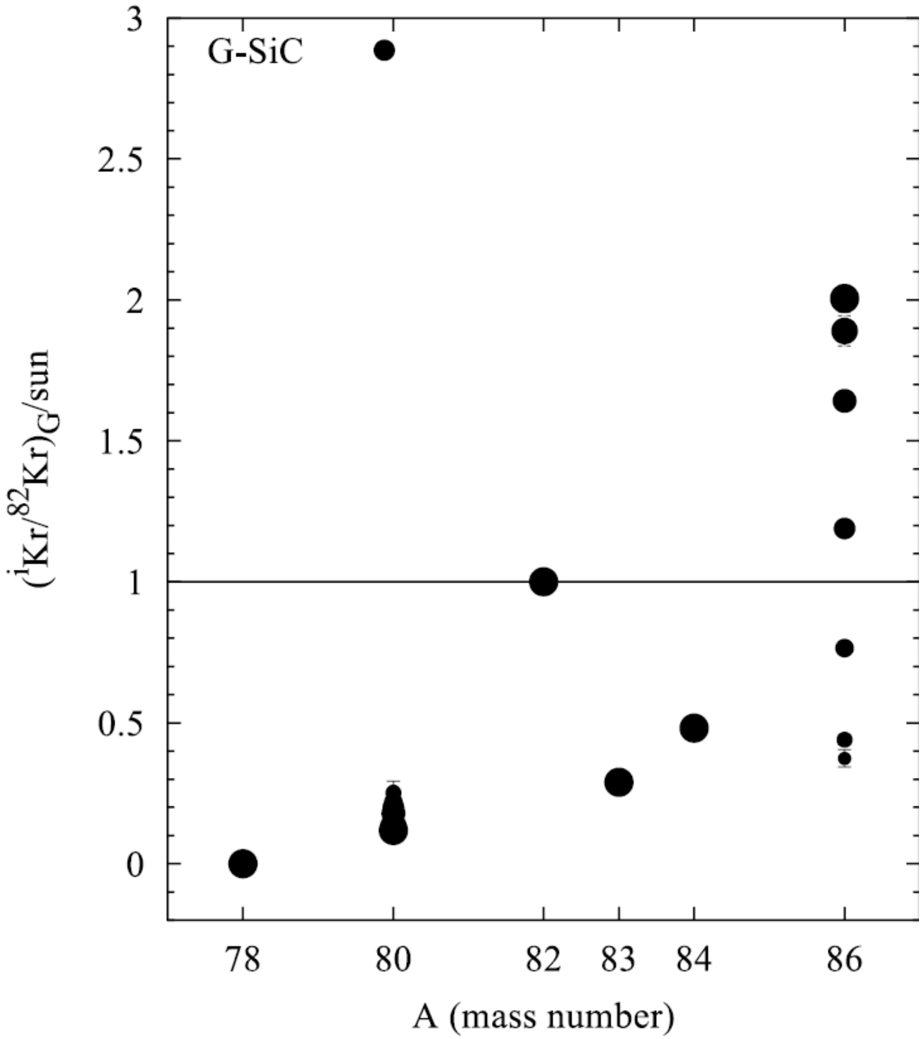
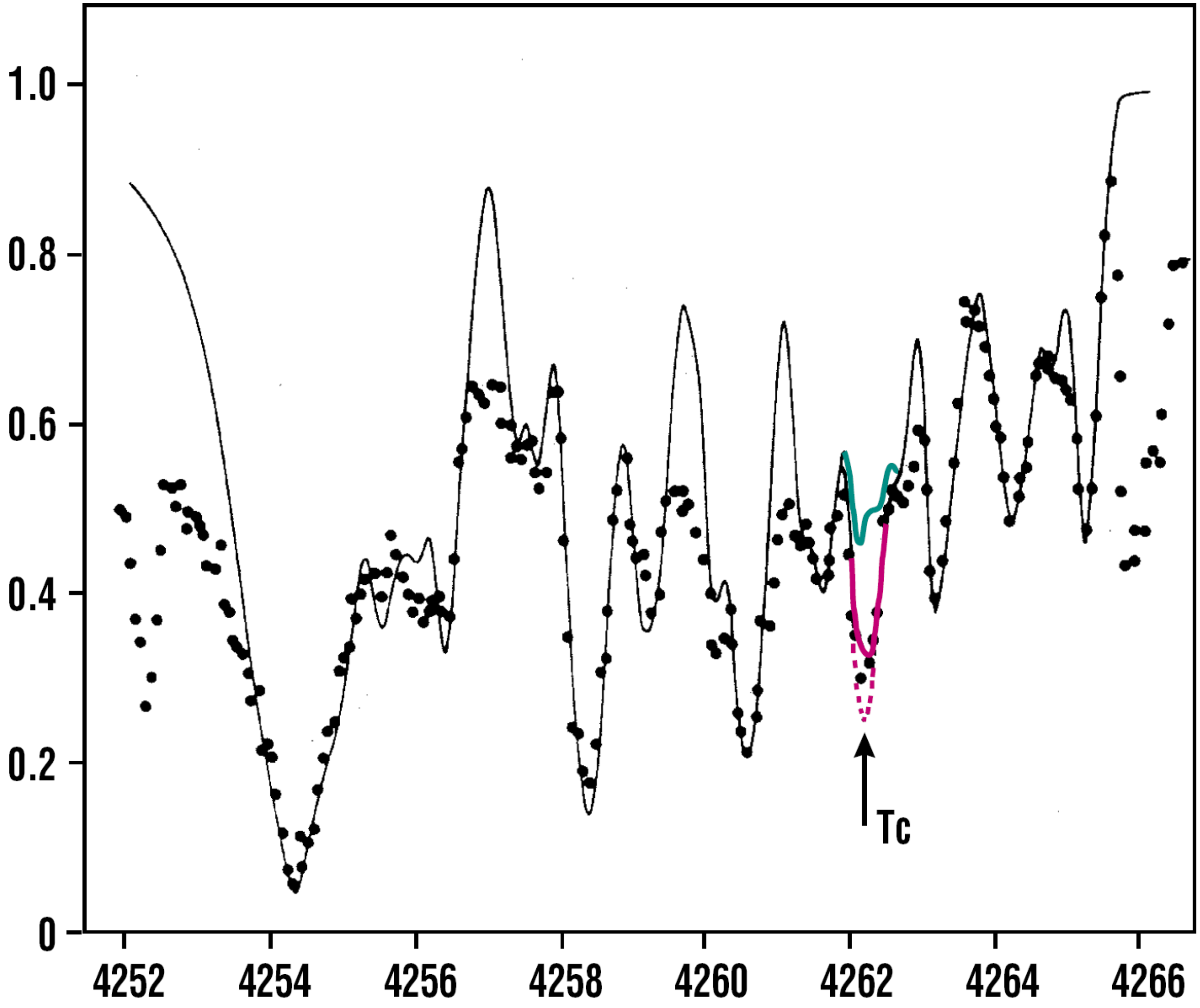
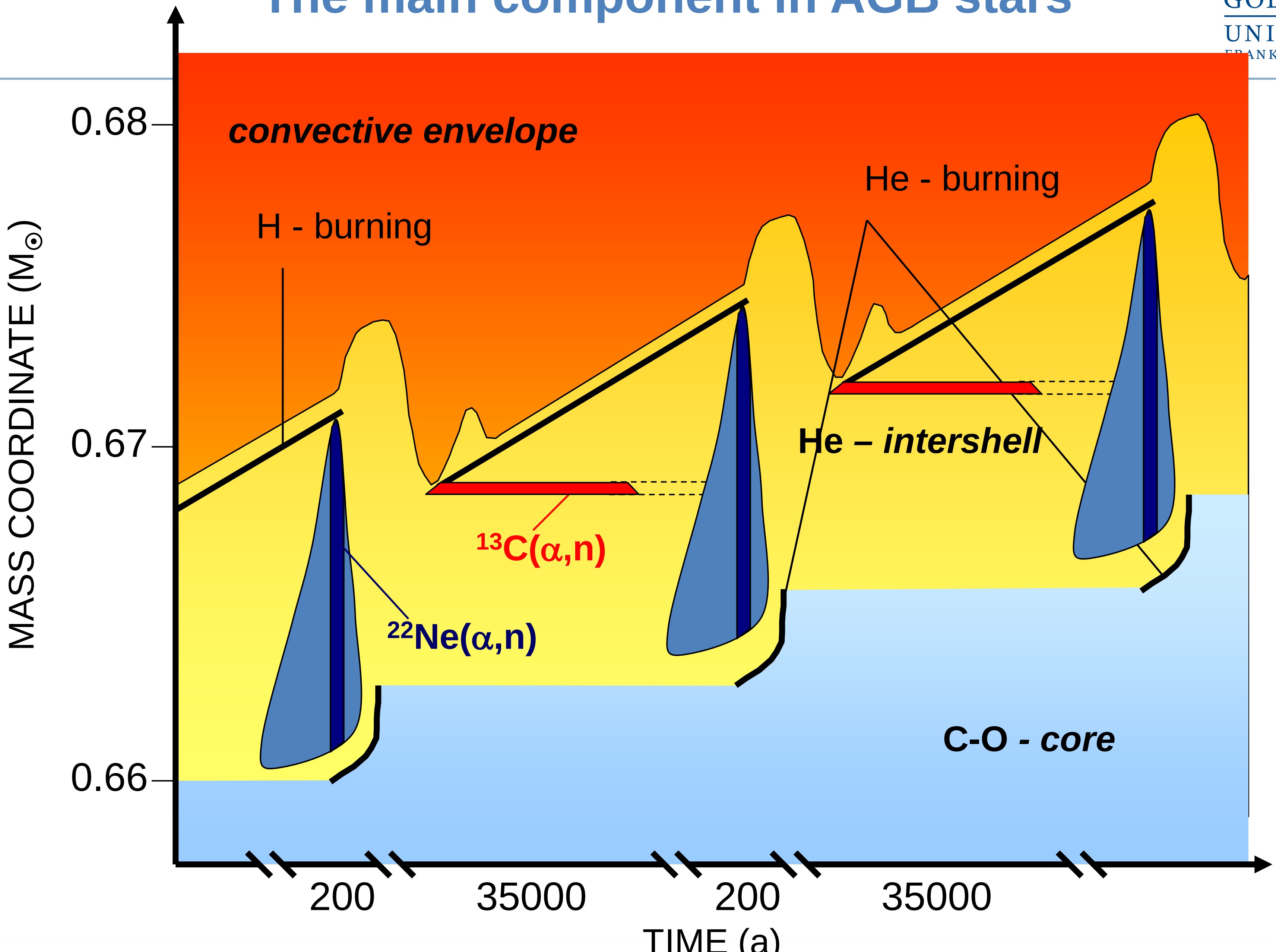


The stellar site of the s-process



P. Merrill, Science 115, 484 (1952)

The main component in AGB stars



Reifarth et al, The Astrophysical Journal, 614:363–370, 2004

Red Giants become White Dwarfs

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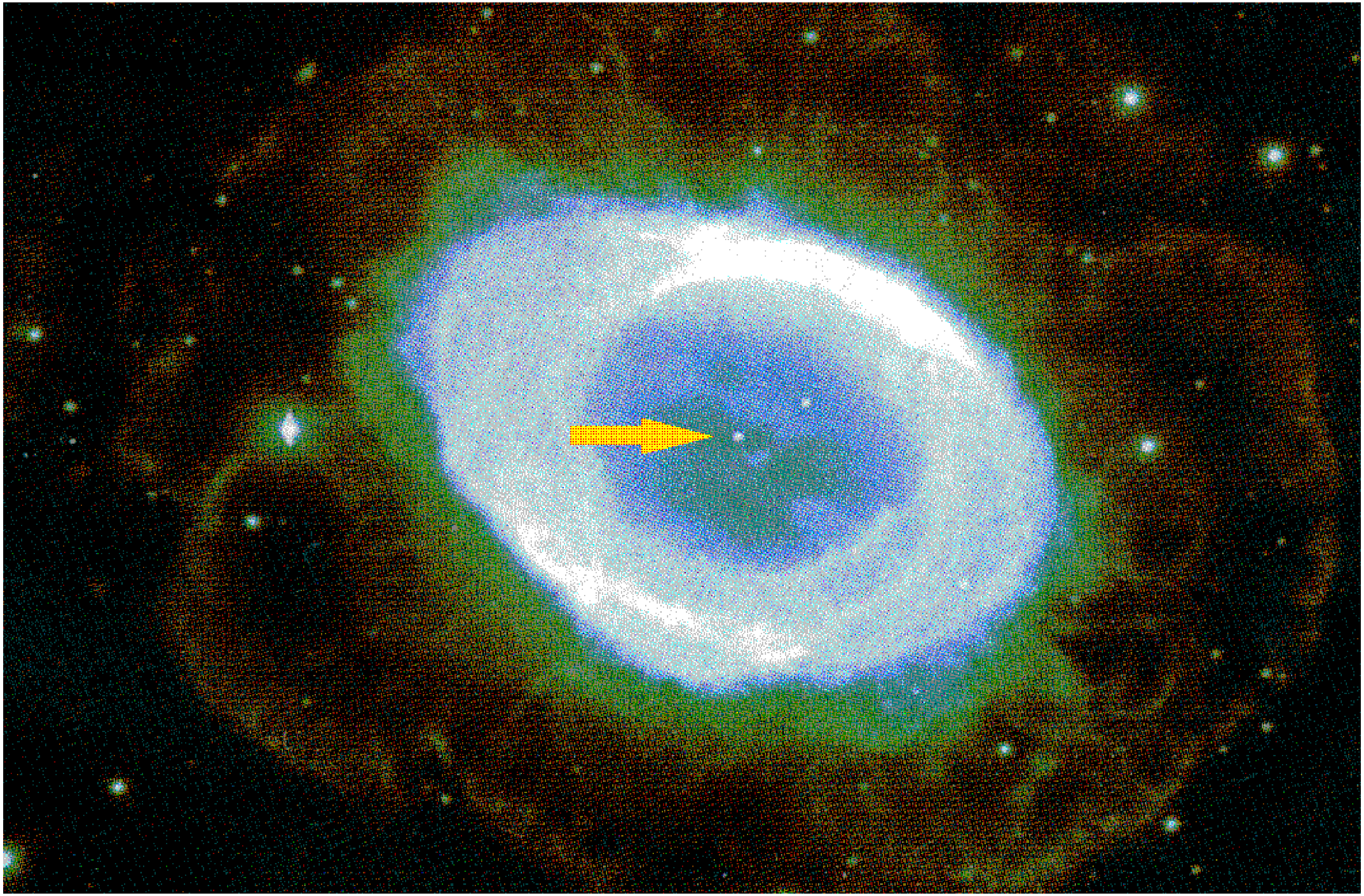

Ring nebula illuminated by the White Dwarf in the center.

s-process nucleosynthesis

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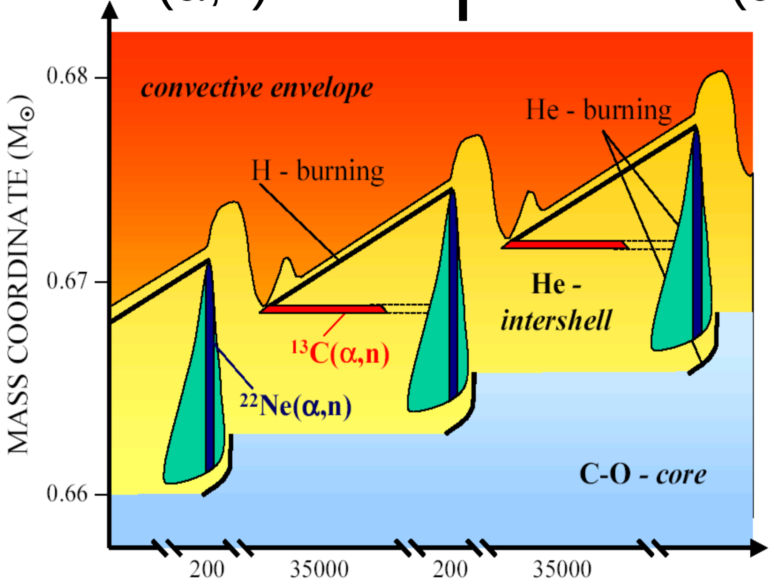
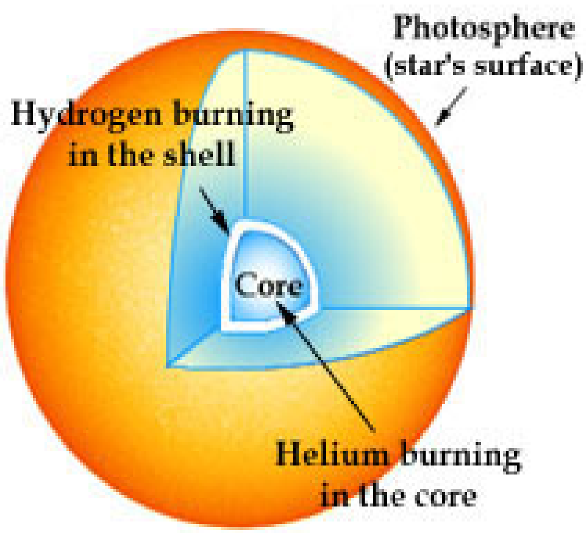
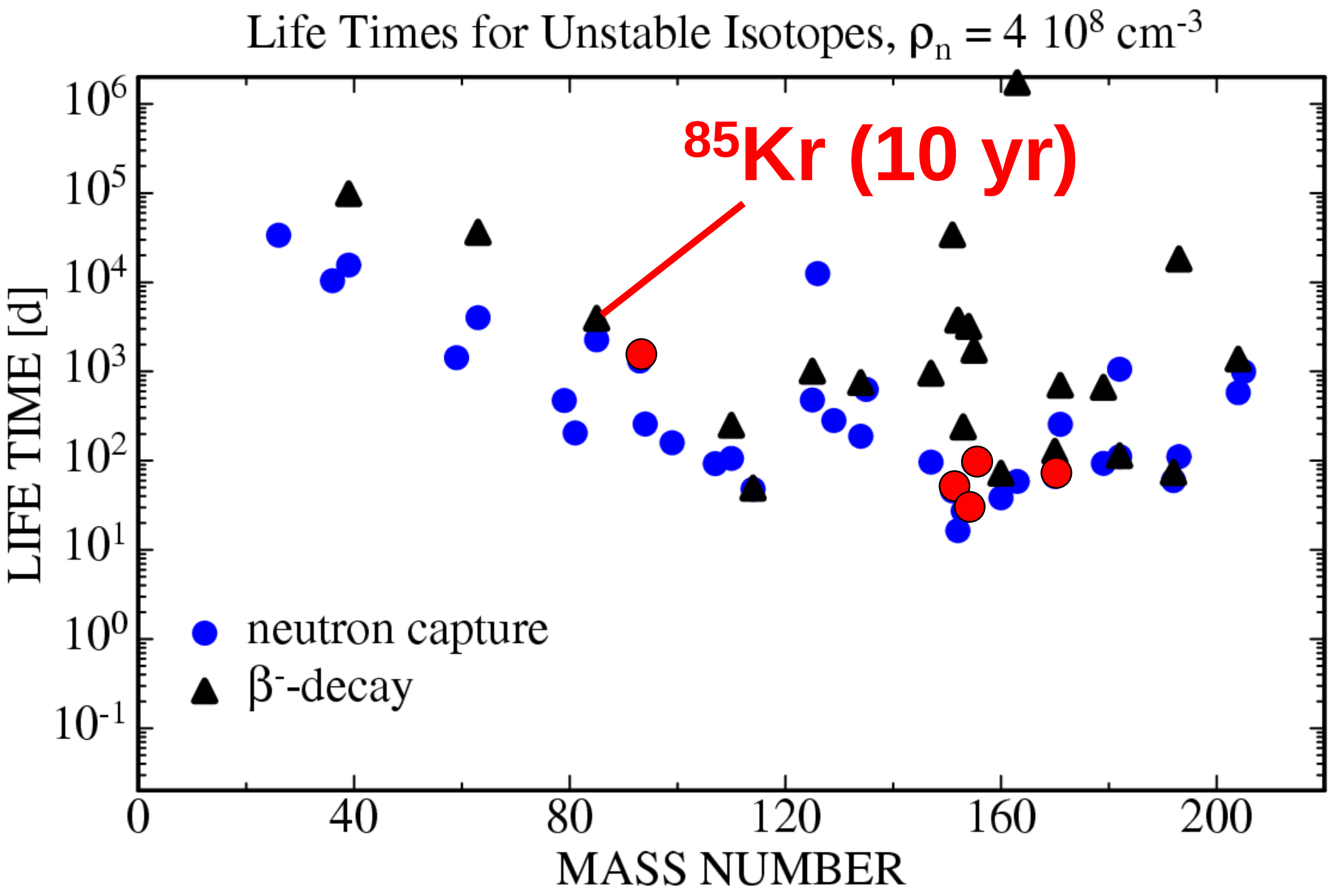
Two components were identified and connected to stellar sites:

Main s-process 90<A<210		Weak s-process A<90	
TP-AGB stars 1-3 $M_\odot$		massive stars > 8 $M_\odot$	
shell H-burning $0.9 \cdot 10^8$ K	He-flash $3\text{-}3.5 \cdot 10^8$ K	core He-burning $3\text{-}3.5 \cdot 10^8$ K	shell C-burning $\sim 1 \cdot 10^9$ K
kT=8 keV $10^7\text{-}10^8$ cm^{-3}	kT=25 keV $10^{10}\text{-}10^{11}$ cm^{-3}	kT=25 keV 10^6 cm^{-3}	kT=90 keV $10^{11}\text{-}10^{12}$ cm^{-3}
$^{13}C(\alpha,n)$	$^{22}Ne(\alpha,n)$	$^{22}Ne(\alpha,n)$	



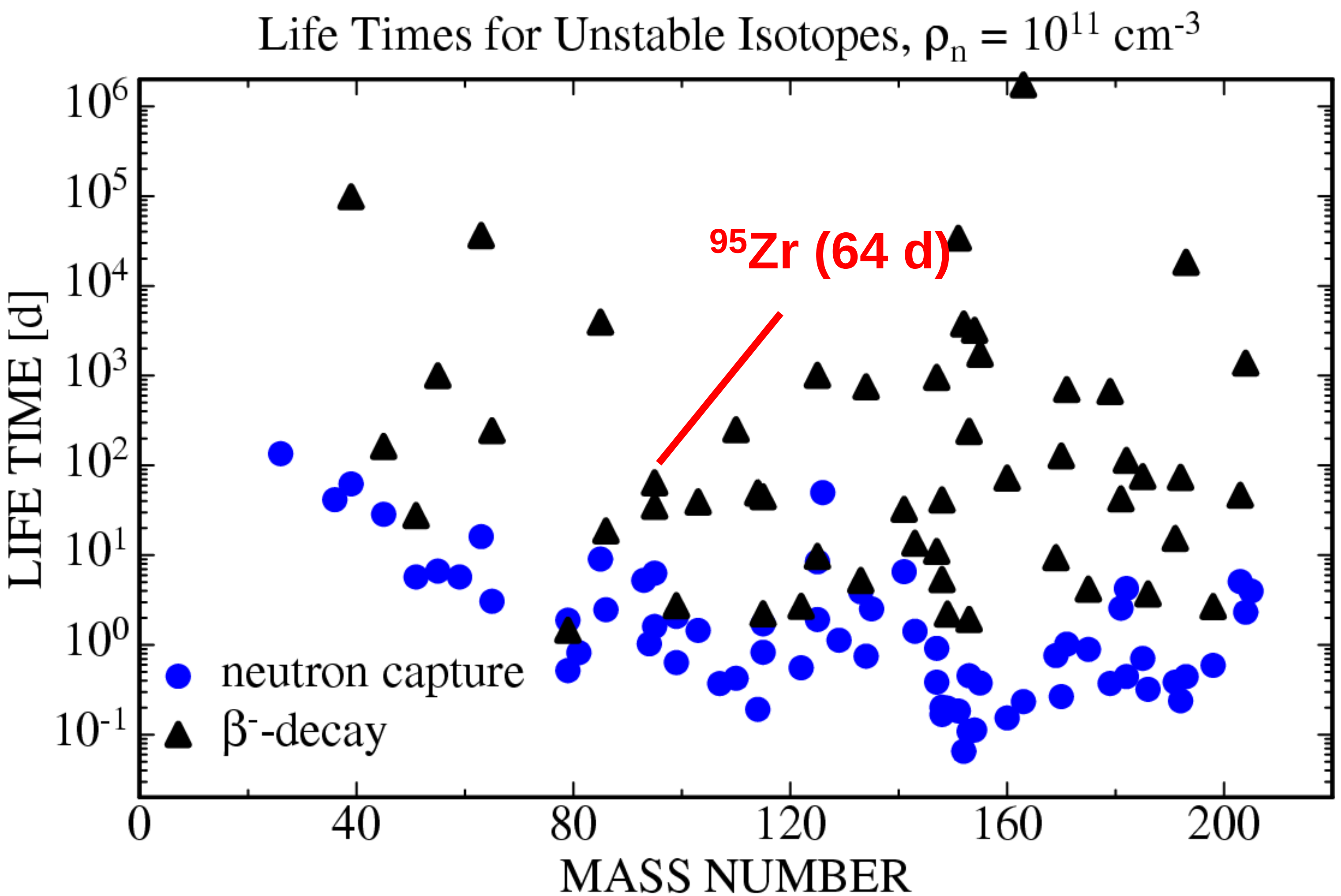


s-process models - classical s-process



$$\lambda_n > \lambda_\beta$$

s-process models – T-AGB stars, ^{22}Ne phase



$$\lambda_n > \lambda_\beta$$

Couture & Reifarth, ADNDT, 93 (2007) 807

Yet another tool …

exp-astro.de/sensitivities

Koloczek et al, ADNDT 108 (2016)

Another one???

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exp-astro.de/netz

Weigand et al, Physical Review C 94 (2015) 045810

OK, ok...

exp-astro.de/tools

- **More tomorrow …. ☺**