The r-Process in the High-Entropy Wind of Type II SNe

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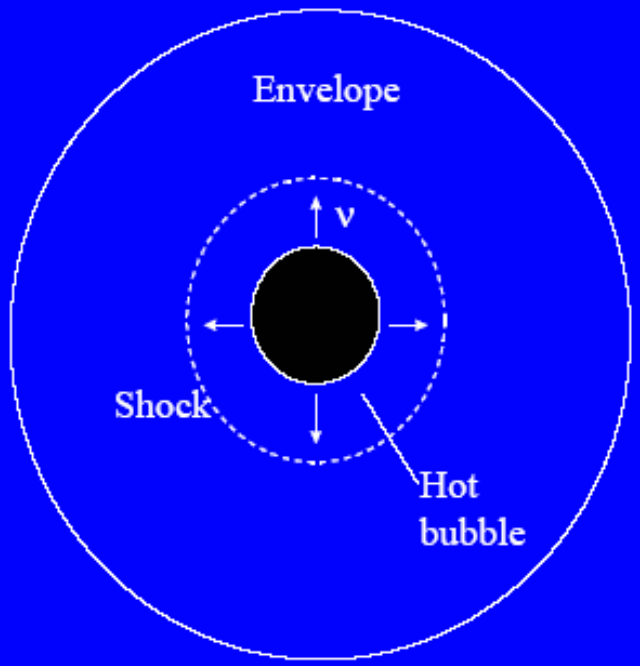
Core collapse Supernova

- Core of massive star collapses to from a hot proto-neutron star (black).
- This cools by ν emission.
- Intense ν flux creates low density hot bubble region behind shock.
- This may have relatively high entropy S but is it very neutron rich?
- r-process depends on S, expansion time scale t, and electron fraction Y_e.



For a given blob of matter behind the shock front above the protoneutron star :

define three parameters:

- **Electron abundance: $Y_e = Y_p = 1 - Y_n$ (p/n-ratio)**

  For example: Ye=0.45 -> 55% neutrons & 45% protons

- **Radiation entropy: $S_{rad} \sim T^3/\rho$**
- **Expansion speed V_{exp} wich determines the process durations τ_α and τ_{rp} :**

$$\tau_{\exp} = \frac{R_0}{V_{\exp}} \left(\frac{T_i}{T_f} - 1 \right)$$

Example: V_{exp}= 7500 km/s, R_0= 130 km → τ_α = 35, $\tau_{rp=}$ 450 ms

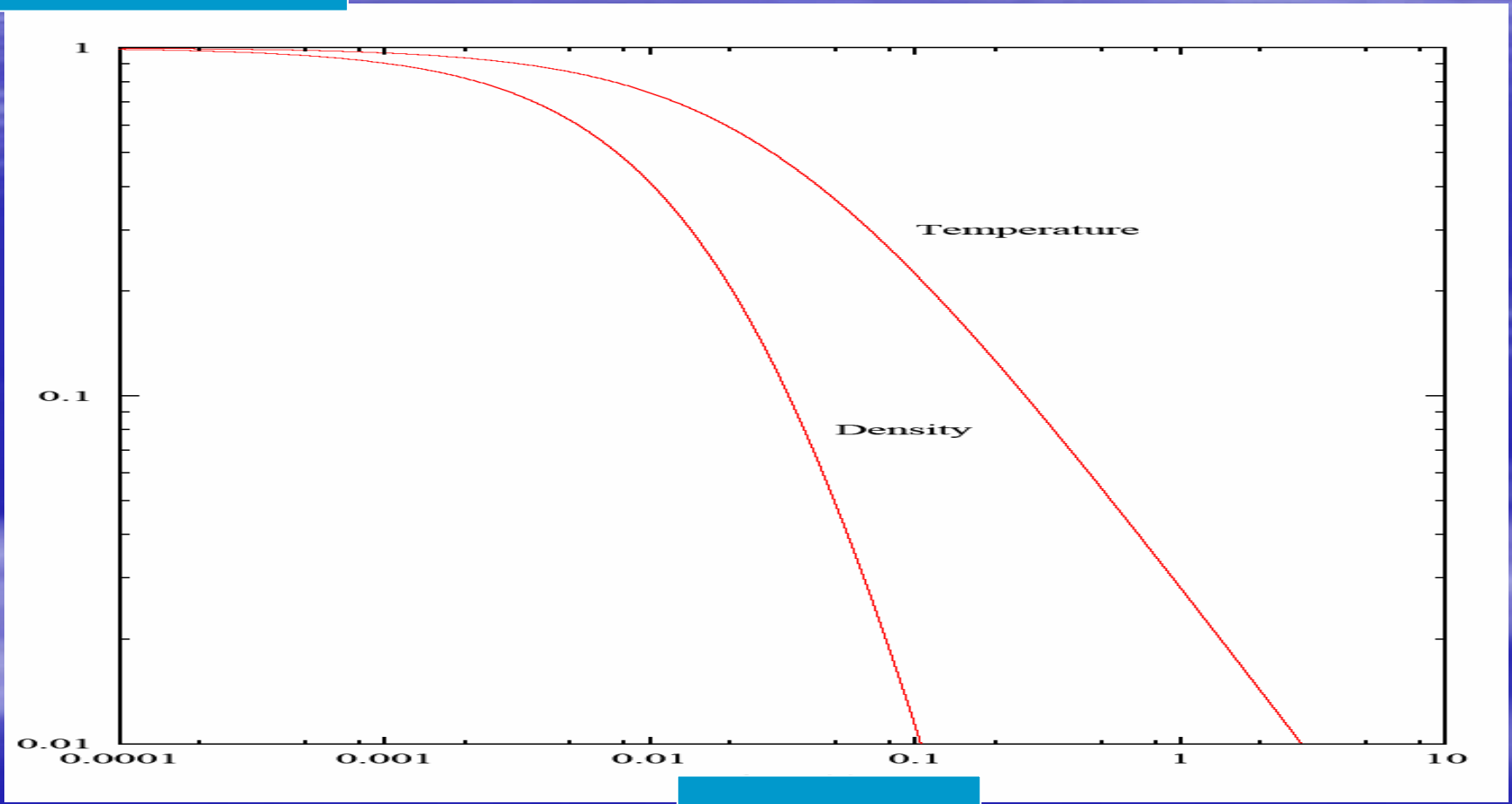
$$S = 1.21\frac{T_9^3}{\rho_5}[1+\frac{7}{4}f(T_9)], where$$

$$0 < f(T_9) = \frac{T_9^2}{T_9^2+5.3} < 1 \Leftrightarrow 1.21\frac{T_9^3}{\rho_5} < S < 3.33\frac{T_9^3}{\rho_5},$$

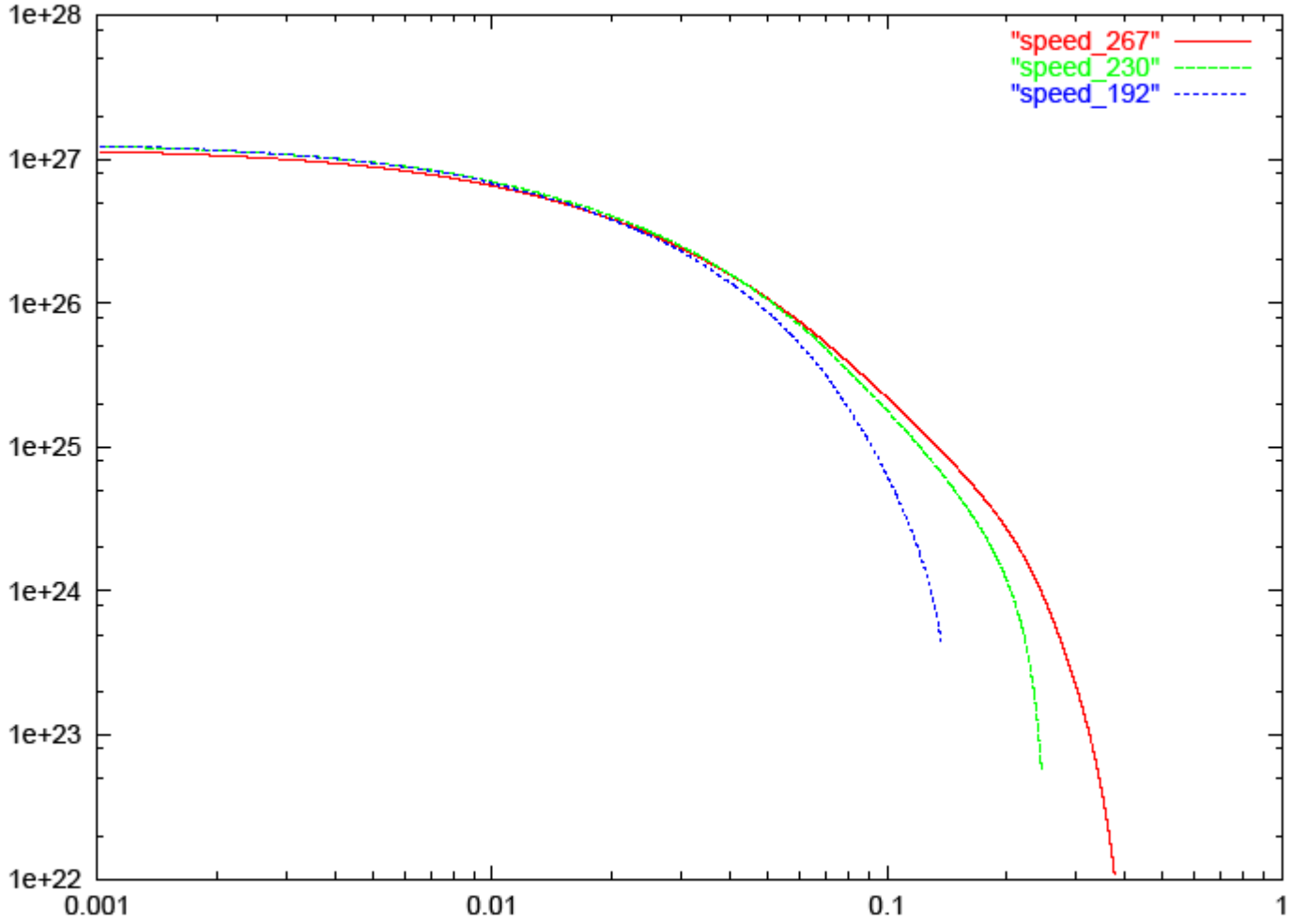
$$T(t) = T_0(\frac{R_0}{R_0+V_{\exp}t}), \rho_5(t) = 1.21\frac{T_9^3}{S}[1+\frac{7}{4}f(T_9)]$$

Time dependence of the density and temperature

Relative ρ and T



Time (s)


"speed_267"
"speed_230"
"speed_192"
1e+28
1e+27
1e+26
1e+25
1e+24
1e+23
1e+22
0.001
0.01
0.1
1

The α-process $3<T_9<6$

- **NSE**: All nuclear reactions via strong and electro-magnetic interactions are very fast when compared with dynamical timescales.

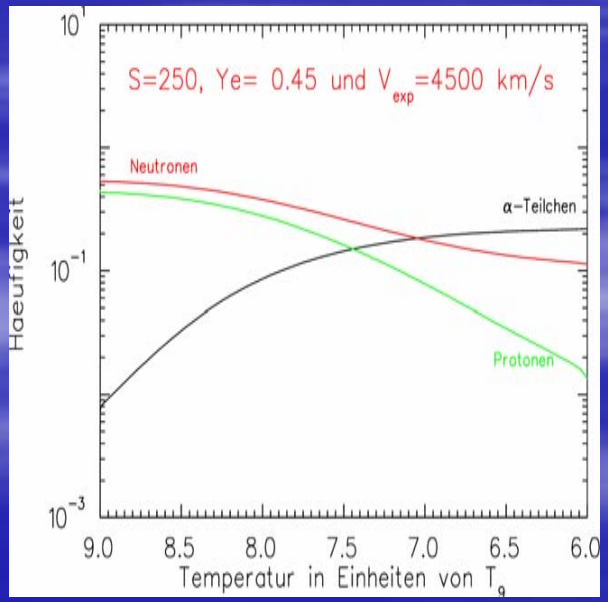
At T_9 ~6, α-particles become the dominant constituent of the hot bubble!

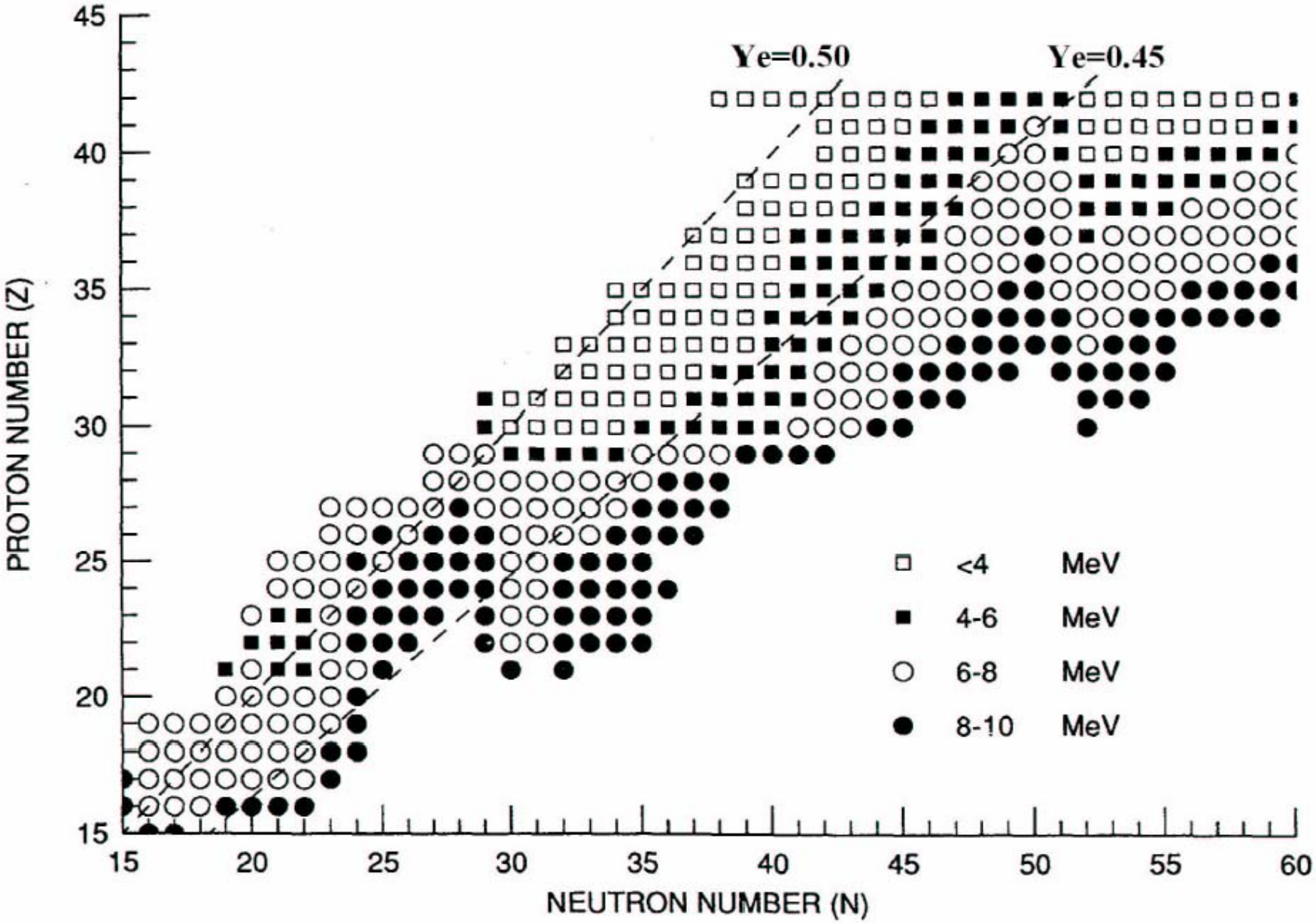
Recombination of the α-particles is possible via:

1. $3\alpha \rightarrow {}^{12}C$ and
2. $\alpha+\alpha+n \rightarrow {}^{9}Be$, followed by ${}^{9}Be(\alpha,n)\,{}^{12}C$

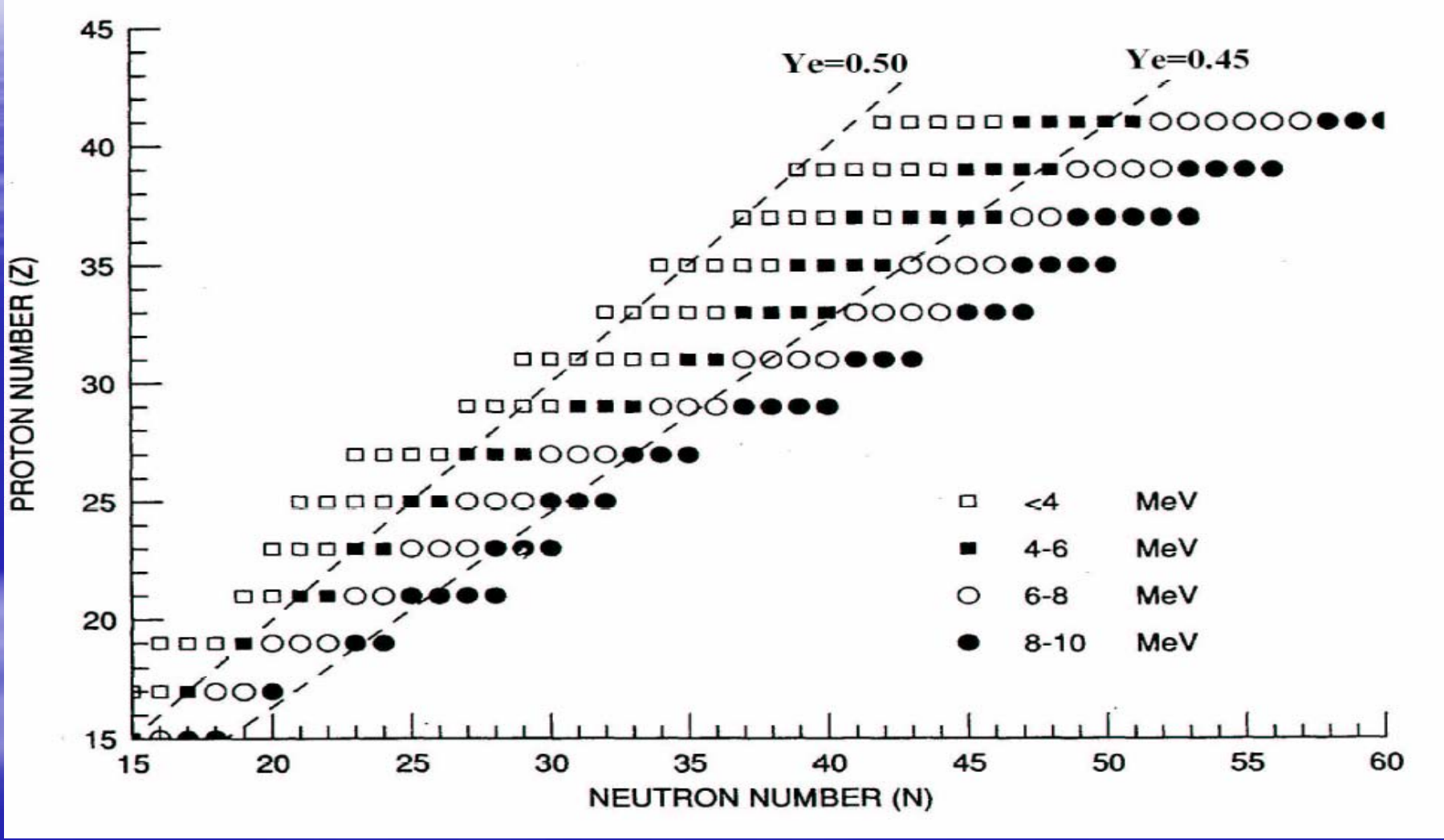
- **Charged-particle freeze-out at T_9 ~ 3 with:**
  - Dominant part of α-particles ~ 80%
  - Some heavy nuclei beyond iron (80 <A< 110)
  - Probably a little bit of free neutrons

↳ **Seed composition for a subsequent r-process.**





α-particle separation energies

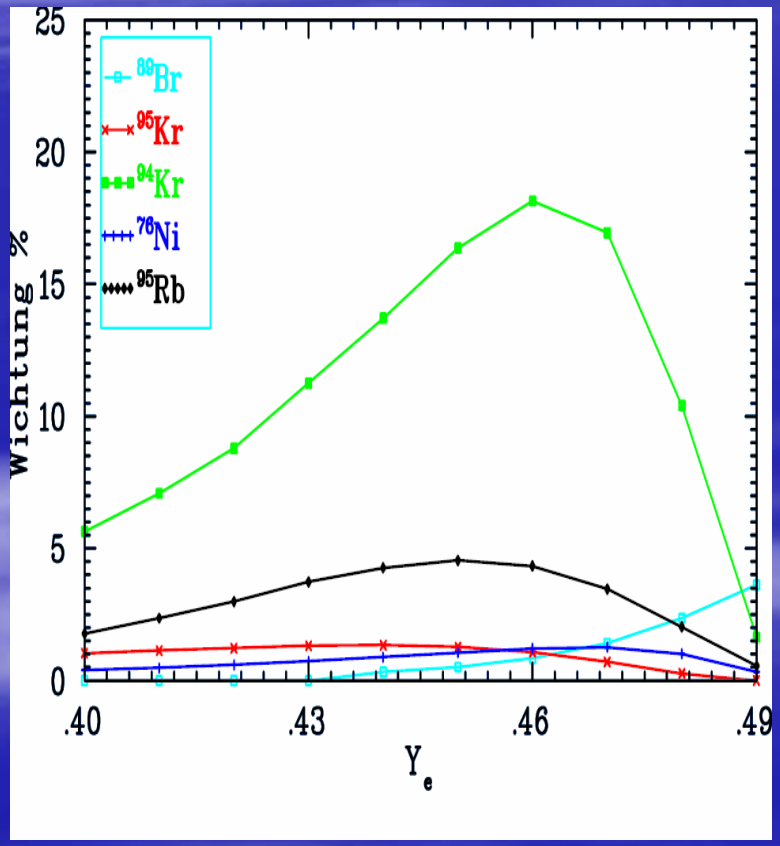


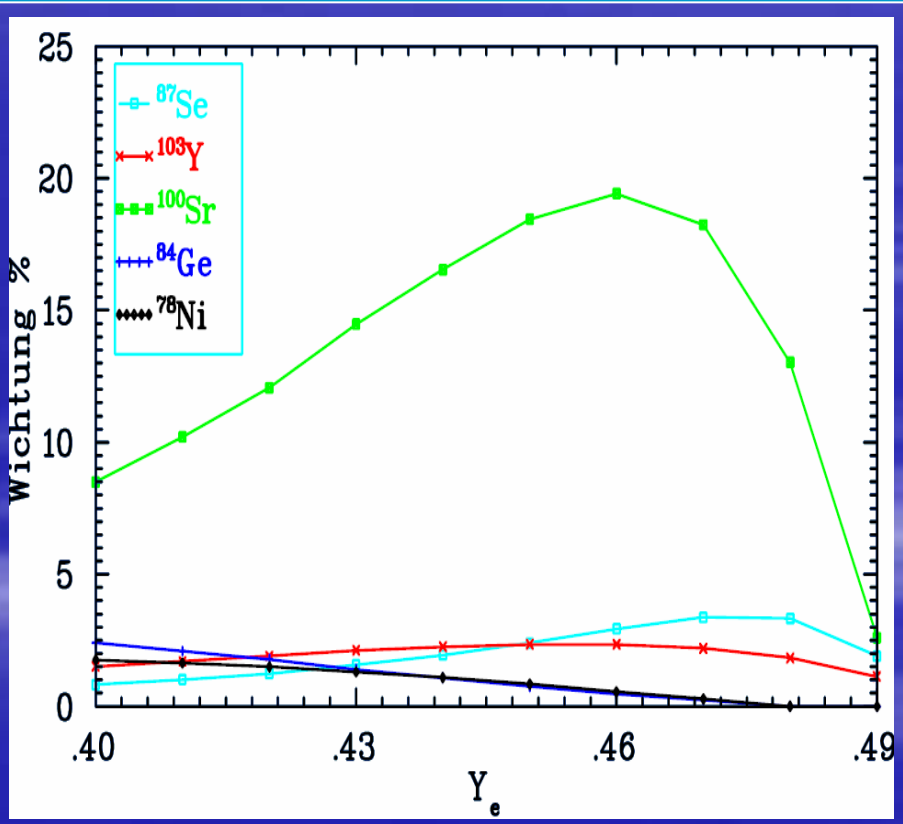
Proton separation energies

Seed nuclei after an α-rich freezeout

S=200, V_{exp}=7500 km/s

Neutron-rich seed beyond N=50
↳ difference to „classical“ r-process with ^{56}Fe seed
↳ avoid N=50 r-process bottle-neck
↳ seed nuclei: ^{94}Kr, ^{100}Sr (^{87}Se, ^{103}Y, ^{89}Br, ^{84}Ge, ^{95}Kr, ^{76}Ni, ^{95}Rb below 5%)





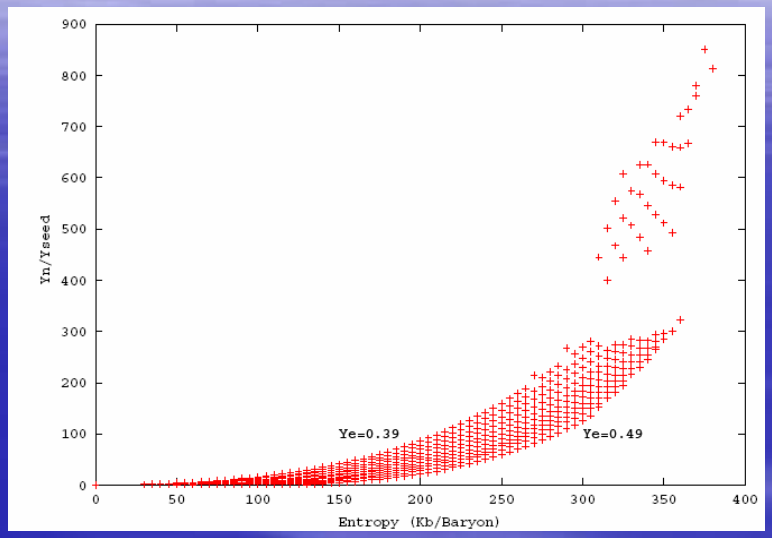
Y_e	Isotop	Häufigkeit in %
0.49	^{90}Kr	12.3
	^{92}Kr	10.8
	^{86}Se	8.3
	^{82}Ge	7.2
	^{91}Kr	7.1
	^{93}Rb	6.7
	^{98}Sr	5.9
	^{89}Br	5.1
	^{80}Zn	4.2
	^{87}Se	3.2
	^{96}Sr	3
	^{74}Ni	2.6
	^{68}Fe	2.6
	^{94}Kr	2.4
	^{100}Sr	2.3
	^{79}Zn	1.5
	^{88}Se	1.3
	^{83}As	1.1
	^{94}Sr	1

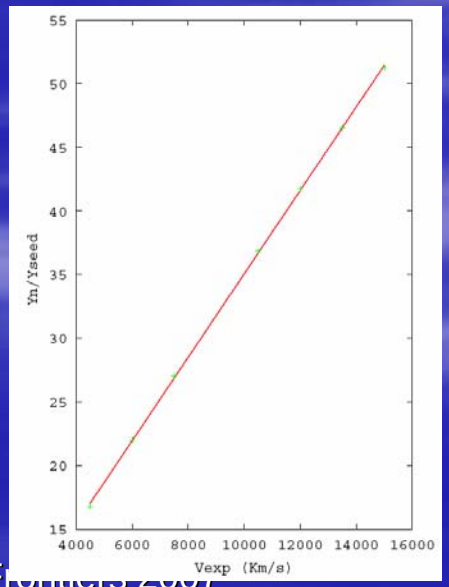
Y_e	Isotop	Häufigkeit in %
0.45	^{94}Kr	17.2
	^{100}Sr	12.4
	^{96}Kr	9.8
	^{88}Se	8.2
	^{82}Ge	5.6
	^{80}Zn	5.2
	^{95}Rb	4.2
	^{87}Se	3.9
	^{102}Sr	3.8
	^{92}Kr	2.9
	^{86}Se	2
	^{76}Ni	2
	^{93}Rb	1.7
	^{103}Y	1.5
	^{68}Fe	1.3
	^{91}Br	1.3
	^{78}Ni	1.3
	^{95}Kr	1.2
	^{98}Sr	1.1

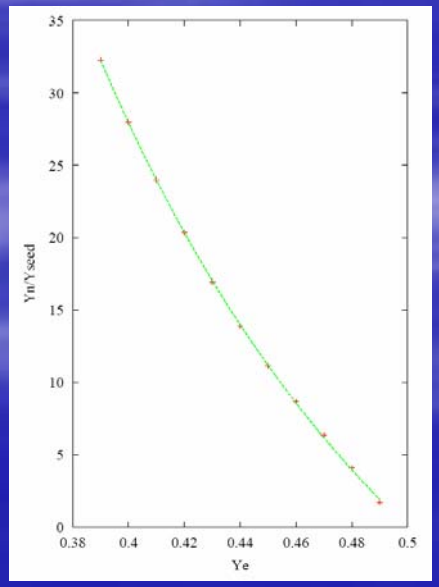
Parameter combinations allowing a subsequent r-process

(1<Yn/Yseed<150)

V_{exp} (km/s)	Y_e	S (K_B/Baryon)
4500	0.49	$155 \leq S \leq 375$
	0.45	$105 \leq S \leq 340$
	0.41	$60 \leq S \leq 305$
7500	0.49	$130 \leq S \leq 310$
	0.45	$90 \leq S \leq 290$
	0.41	$50 \leq S \leq 260$
9000	0.49	$125 \leq S \leq 300$
	0.45	$85 \leq S \leq 270$
	0.41	$50 \leq S \leq 245$
12000	0.49	$115 \leq S \leq 265$
	0.45	$80 \leq S \leq 245$
	0.41	$45 \leq S \leq 225$



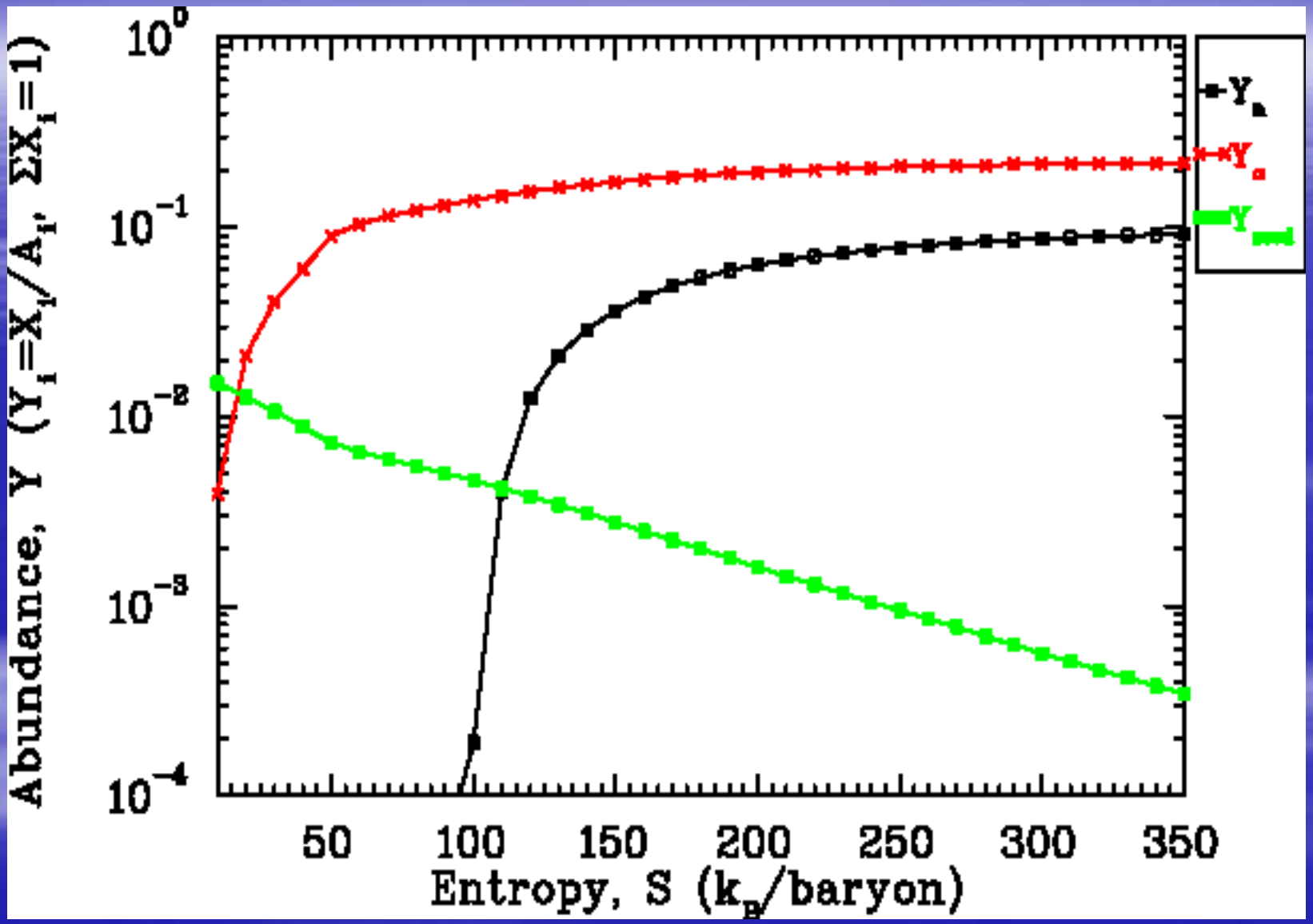




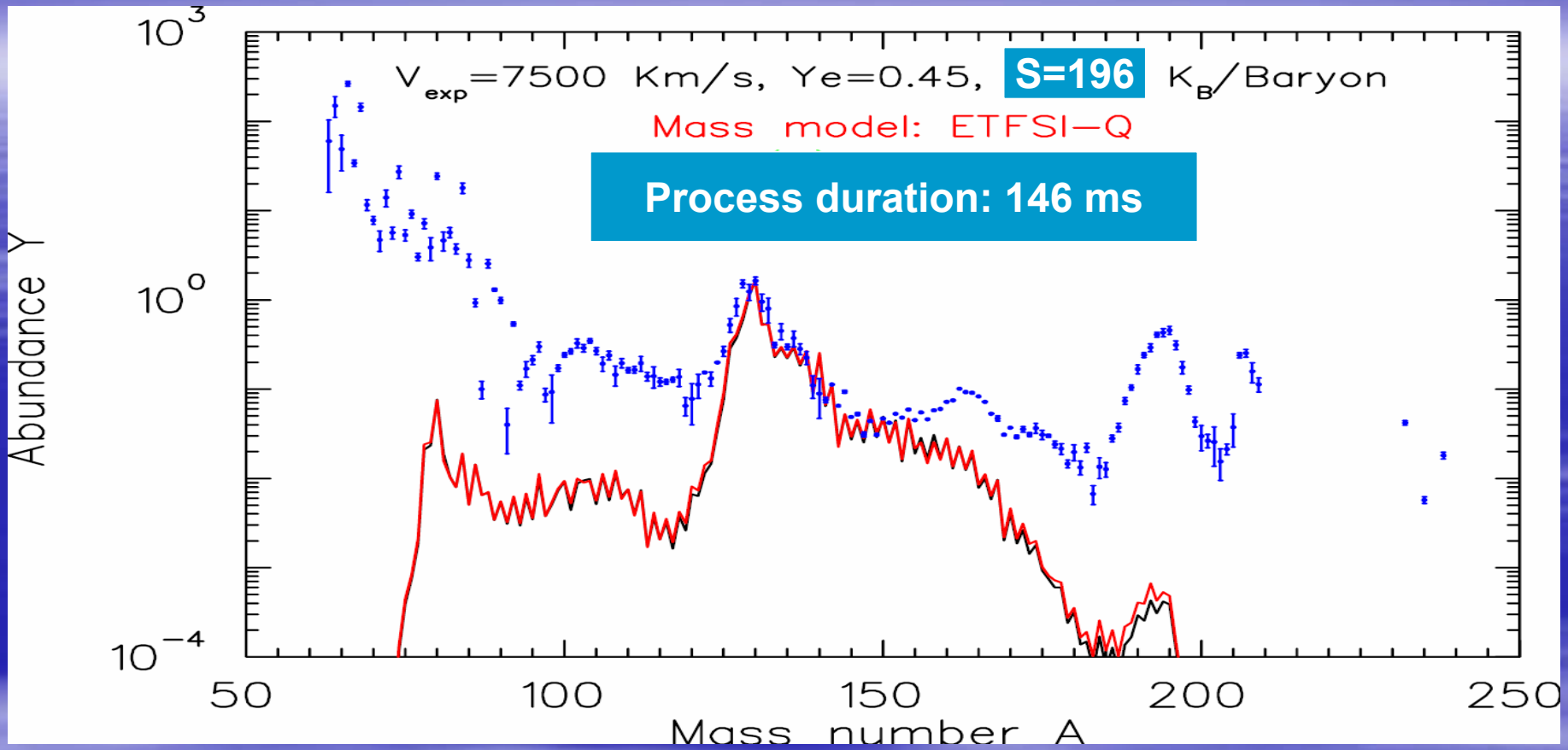
r-Process strength formula

$$\frac{Y_n}{Y_{Seed}} = k_{SN} V_{Exp} \left(\frac{S}{Y_e} \right)^3,$$

$$k_{SN} \approx 8 \cdot 10^{-11} \left(\frac{km}{Baryon} \right)^{-1} \left(\frac{k_B}{Baryon} \right)$$

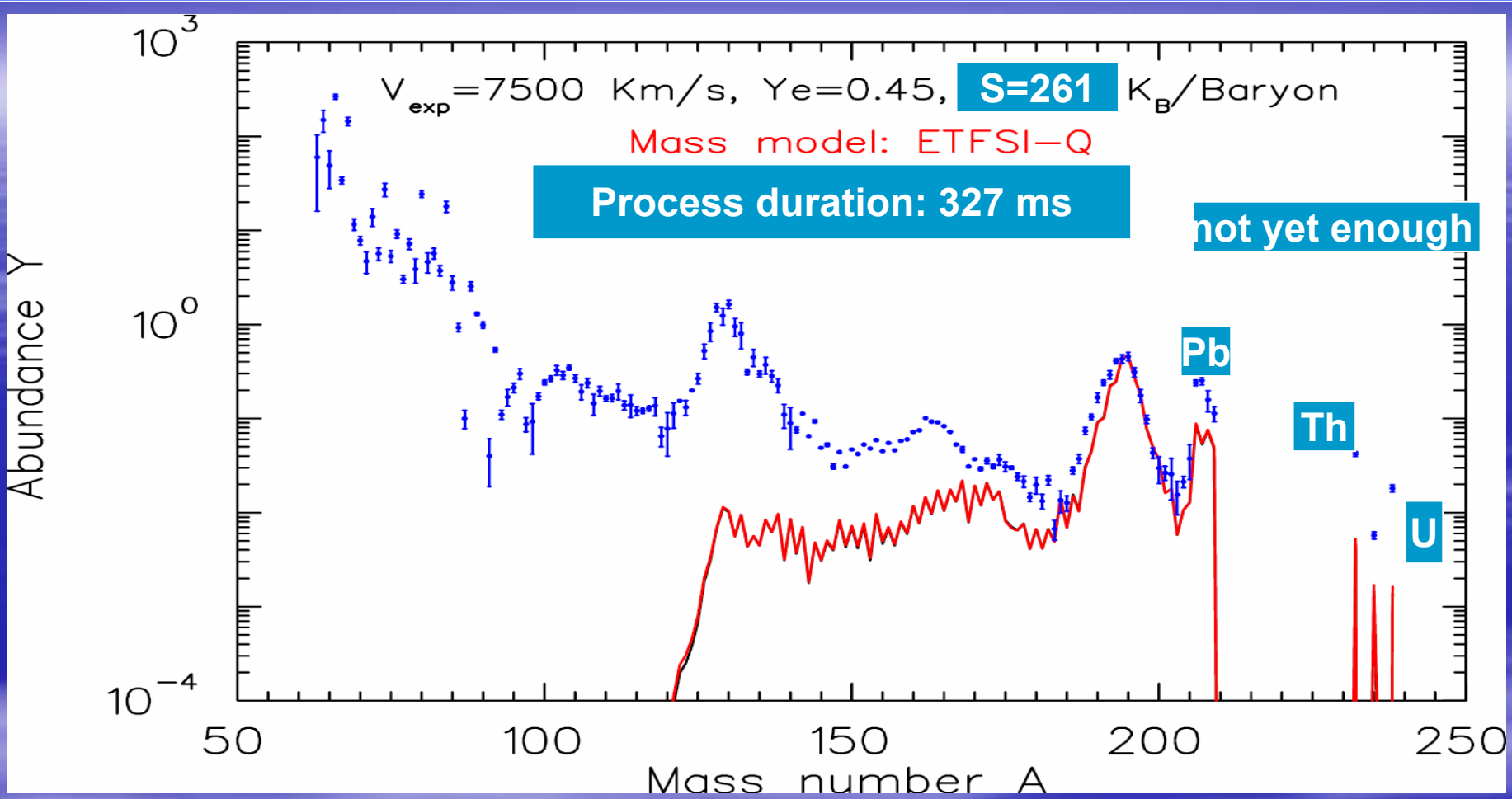

Abundance, Y (Y_i=X_i/A_i, ΣX_i=1)
10^0
10^-1
10^-2
10^-3
10^-4
50
100
150
200
250
300
350
Entropy, S (k_B/baryon)
Y_n
Y_α
Y_seed

Synthesizing the A=130 peak

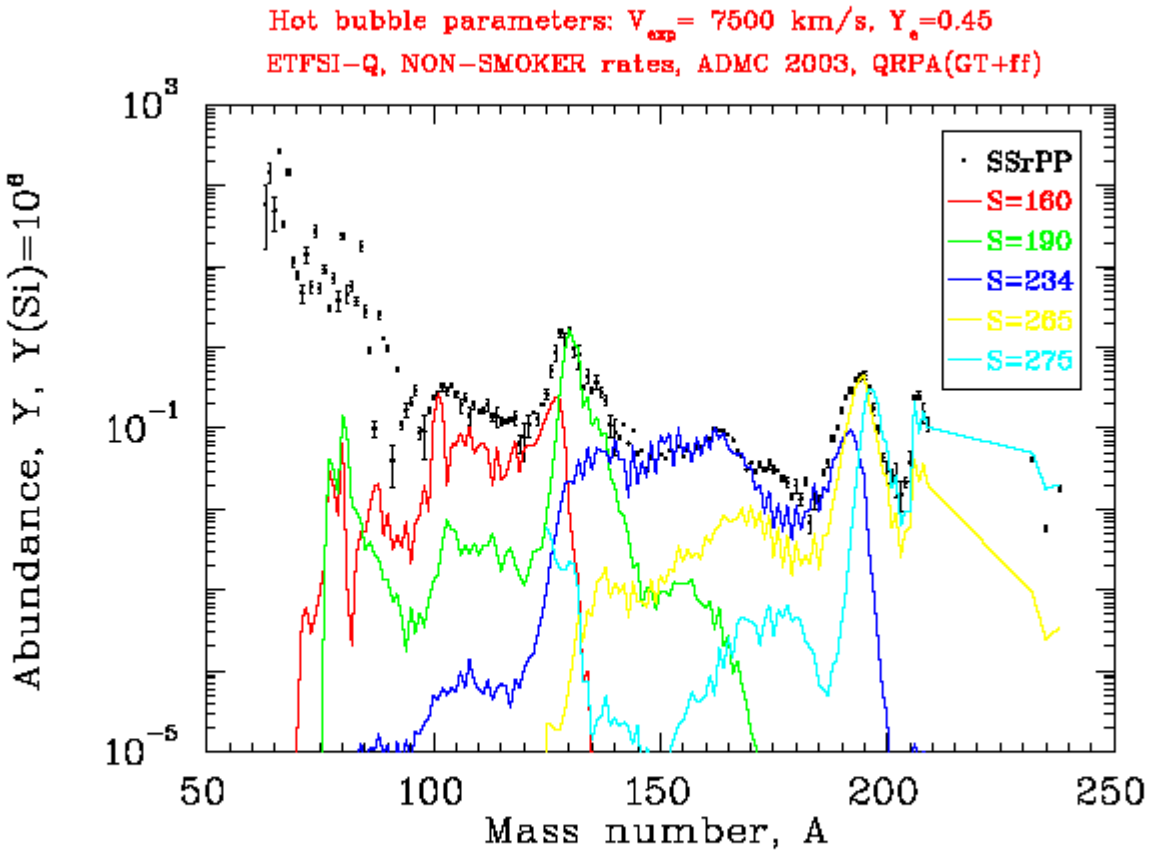


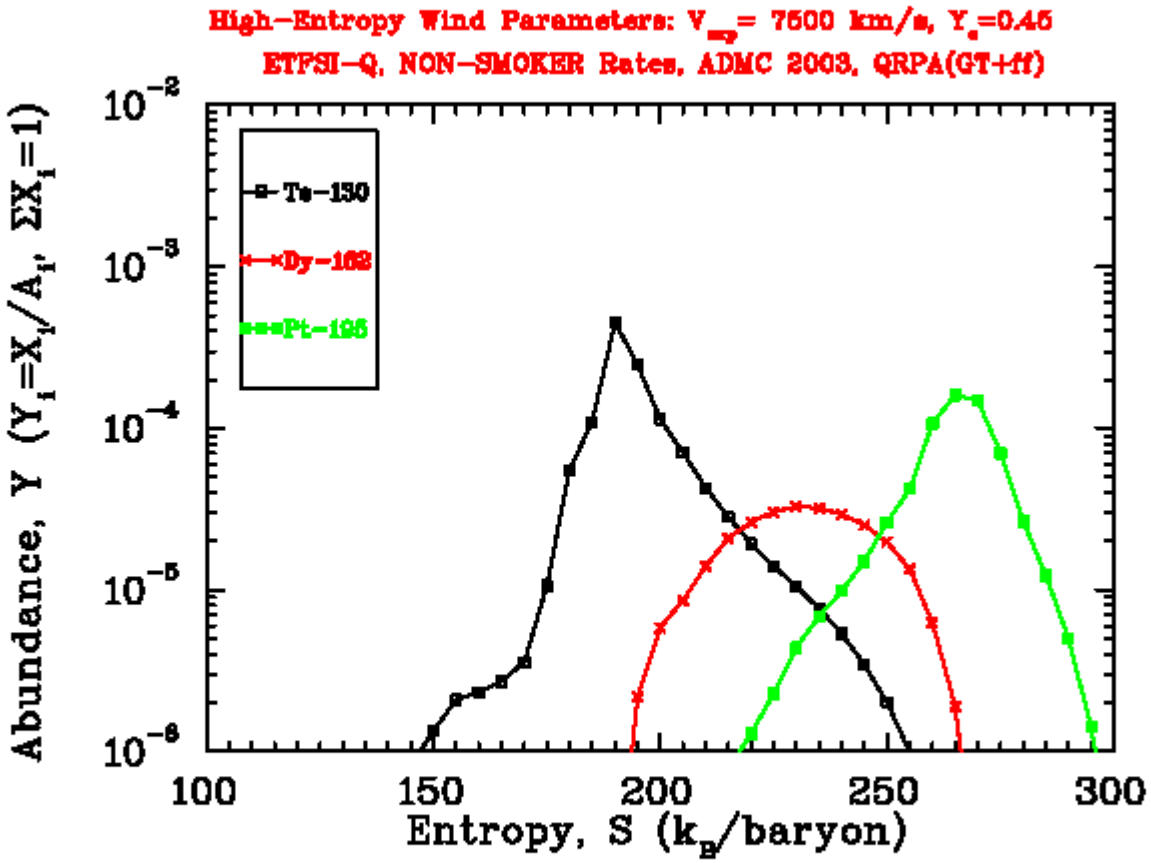
Y_e	Entropy S	r-process duration τ [ms]	n_n [cm^{-3}] at freeze out	T_9 [10^9 K] at freeze out
0.49	230	234	1.9 x10^{20}	0.53
0.45	190	146	8.1 x10^{21}	0.79
0.41	160	109	9.0 x10^{21}	0.77

Synthesizing the A=195 peak



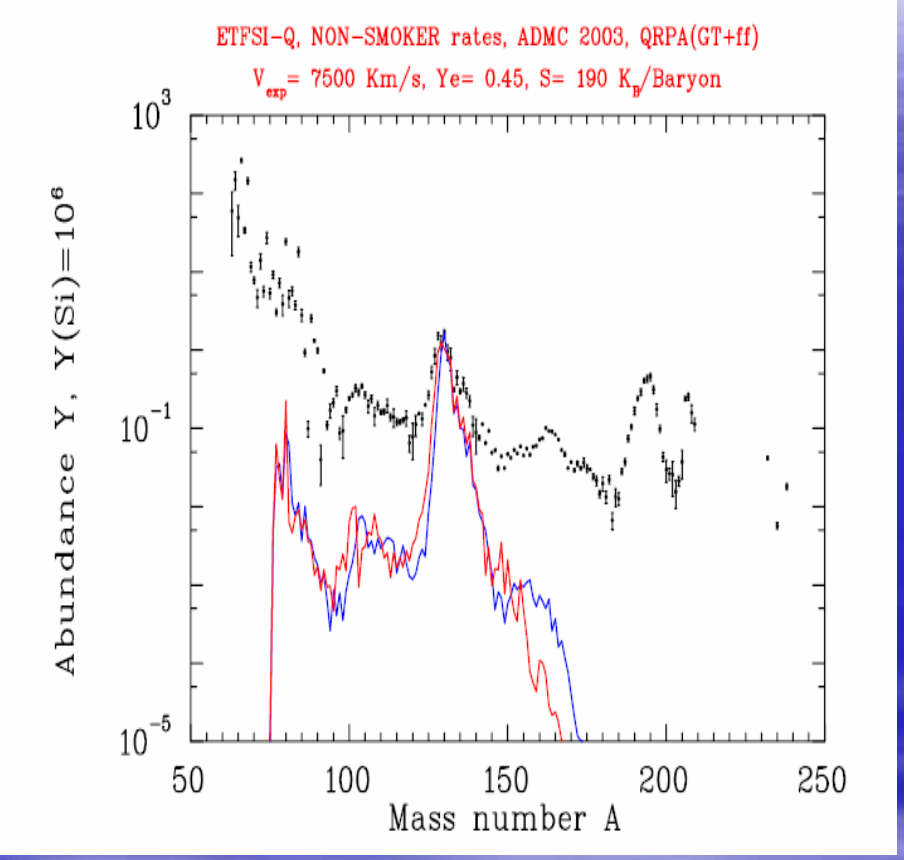
Y_e	Entropy S	r-process duration τ [ms]	n_n [cm^{-3}] at freeze out	T_9 [10^9 K] at freeze out
0.49	290	412	2.0 x10^{21}	0.33
0.45	260	327	1.5 x10^{22}	0.41
0.41	235	213	2.9 x10^{22}	0.42

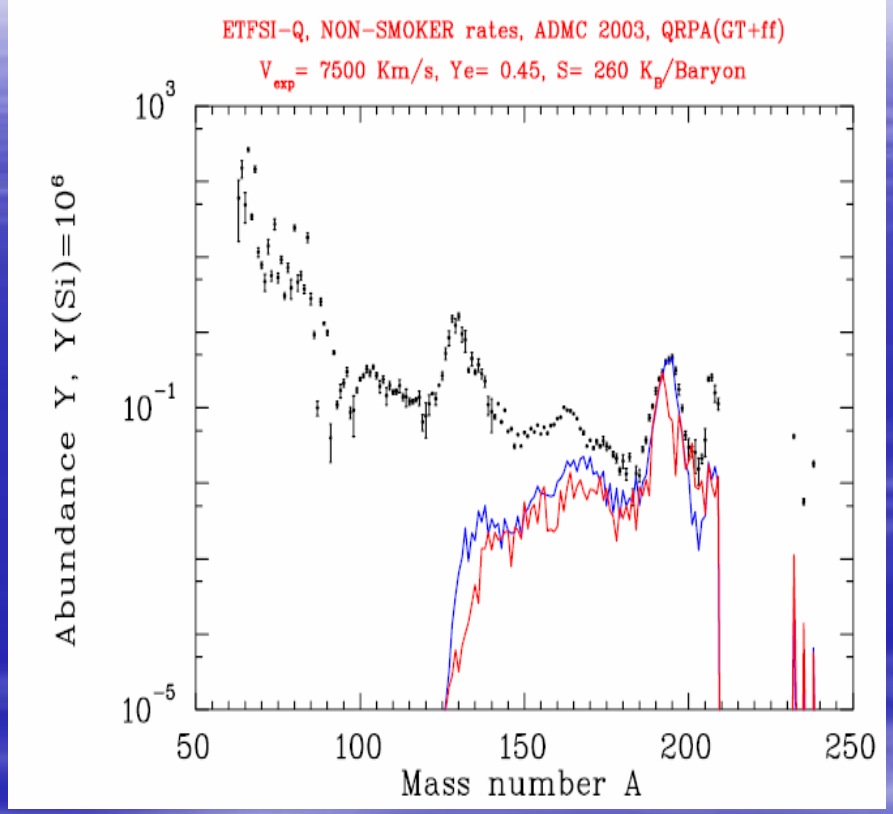

Hot bubble parameters: V_exp= 7500 km/s, Y_e=0.45
ETFSI-Q, NON-SMOKER rates, ADMC 2003, QRPA(GT+ff)
SSrPP
S=160
S=190
S=234
S=265
S=275
Abundance, Y, Y(Si)=10^6
Mass number, A
10^3
10^-1
10^-5
50
100
150
200
250


High-Entropy Wind Parameters: V = 7500 km/s, Y=0.45
ETFSI-Q, NON-SMOKER Rates, ADMC 2003, QRPA(GT+ff)
Te-130
Dy-162
Pt-195
Abundance, Y (Y_i=X_i/A_i, ΣX_i=1)
Entropy, S (k_B/baryon)
10^-2
10^-3
10^-4
10^-5
10^-6
100
150
200
250
300

Z	$1 \leq S \leq 50$	$50 \leq S \leq 110$	$110 \leq S \leq 150$	$150 \leq S \leq 200$	$200 \leq S \leq 250$	$250 \leq S \leq 300$
26	100.00	0.00	0.00	0.00	0.00	0.00
27	99.99	0.01	0.00	0.00	0.00	0.00
28	99.98	0.02	0.00	0.00	0.00	0.00
29	99.95	0.05	0.00	0.00	0.00	0.00
30	99.24	0.50	0.26	0.00	0.00	0.00
31	85.77	2.80	10.11	1.32	0.00	0.00
32	85.84	4.57	8.45	1.14	0.00	0.00
33	44.49	4.84	44.37	6.30	0.00	0.00
34	22.54	17.87	21.95	35.12	2.52	0.00
35	28.19	6.32	19.91	41.75	3.83	0.00
36	23.14	72.67	2.96	1.13	0.10	0.00
37	47.56	42.41	7.31	2.58	0.13	0.00
38	79.91	18.35	1.44	0.29	0.01	0.00
39	61.37	37.44	0.88	0.29	0.02	0.00
40	14.25	80.74	4.69	0.31	0.02	0.00
41	0.08	94.15	4.51	1.22	0.03	0.00
42	0.03	63.70	31.67	4.53	0.07	0.00
44	0.00	27.34	61.49	11.09	0.09	0.00
45	0.00	67.09	26.71	5.96	0.24	0.00
46	0.00	11.61	66.84	21.34	0.21	0.00
47	0.00	3.66	71.38	24.74	0.22	0.00
48	0.00	3.51	54.31	41.73	0.46	0.00
49	0.00	2.09	48.29	49.06	0.56	0.00
50	0.00	0.33	35.96	63.14	0.57	0.00
51	0.00	0.05	32.83	66.45	0.67	0.00
52	0.00	0.01	9.10	78.54	5.46	6.89
53	0.00	0.00	11.15	83.30	1.67	3.88

The role of β-delayed neutrons in the r-process at A=130 and 195





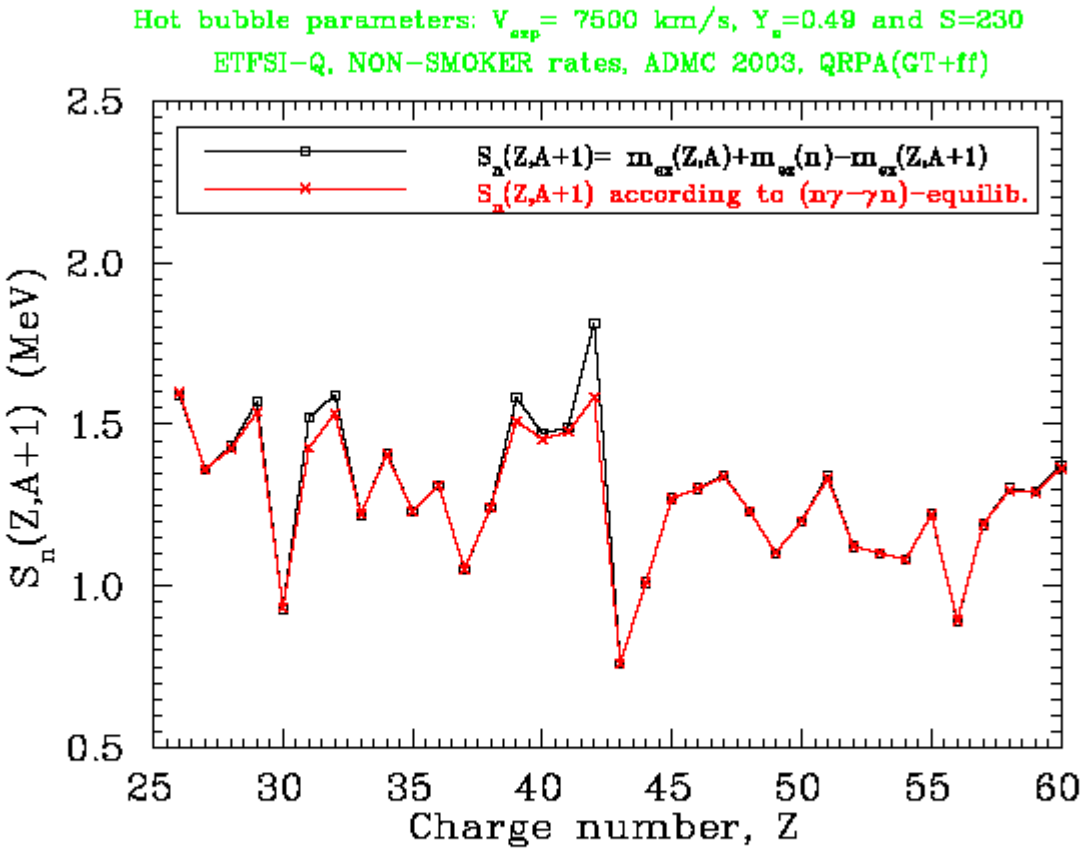
red: no re-captured β-delayed neutrons

blue: β-delayed neutrons re-captured

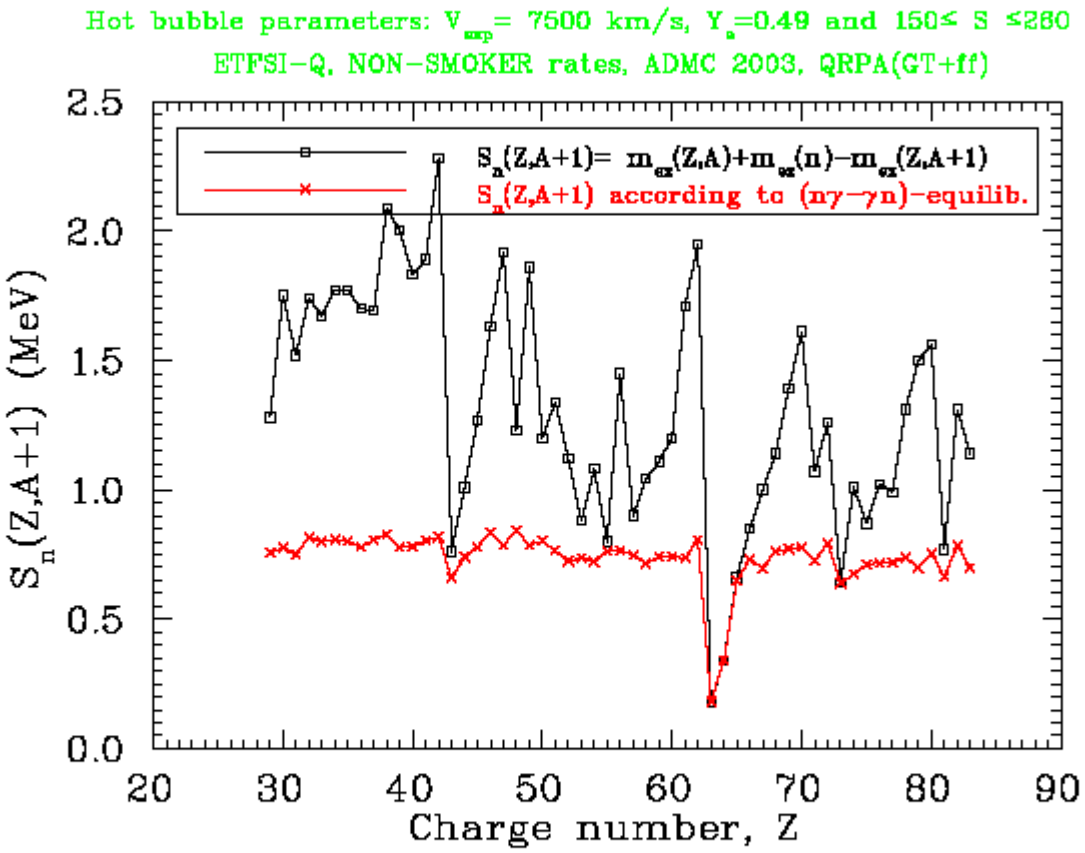
red: no β-delayed neutrons emitted

↪ „progenitor“ abundances

blue: β-delayed neutrons emitted and re-captured



$$\frac{Y_{(Z,A+1)}}{Y_{(Z,A)}} = n_n \frac{G_{(Z,A+1)}}{2G_{(Z,A)}} \left(\frac{A+1}{A}\right)^{3/2} \left(\frac{2\pi\hbar^2}{m_u k_B}\right)^{3/2} T^{-3/2} \exp\left(-\frac{{}^{Z,A+1}S_n}{k_B T}\right)$$


Hot bubble parameters: V_exp= 7500 km/s, Y_e=0.49 and 150≤ S ≤280
ETFSI-Q, NON-SMOKER rates, ADMC 2003, QRPA(GT+ff)
S_n(Z,A+1)= m_ex(Z,A)+m_ex(n)-m_ex(Z,A+1)
S_n(Z,A+1) according to (nγ-γn)-equilib.
S_n(Z,A+1) (MeV)
Charge number, Z
0.0
0.5
1.0
1.5
2.0
2.5
20
30
40
50
60
70
80
90

Summary

- The **waiting-point approximation**“ seems to hold for expansion velocities slower than 4500 km/s. However at higher velocities like 7500 km/s the mass region beyond A=140 only the peak regions are stil in chemical equilibrium.

  - The hydrodynamical simualtions of type II SNe predict entropies up to 80 and Ye-values between 0.52 and 0.49! Under those conditions it is impossible to make an r-process. However, wind termination shock (Munich group) could lead to a sudden increase of the entropy up to 280 kb/baryon!