On the dynamics of proto-neutron star winds and the r-process nucleosynthesis

I.V. Panov and H.-Th. Janka

short introduction – neutrino-wind models and r-process
dependence Y_A on s, Y_e, τ_{dyn} - the model
deceleration of expansion – different modes
r-process $\rightarrow$ rβ-process
Discussion and Conclusions

The neutrino-driven wind from a hot neutron star

The neutrino-driven wind from a hot neutron star produced in a supernova explosion has been considered by Meyer et al. 1992; Woosley et al. 1994 (s~400); Witti et al. 1993 (s~100); Otsuki et al. 2000; Sumiyoshi et al. 2000; Terasawa et al. 2001; Wanajo et al. 2001

Otsuki et al. 2000; Sumiyoshi et al. 2000, 2001; Thompson et al. 2001, Wanajo et al. 2001, 2002 confirmed the need of fairly extreme conditions concerning expansion timescale or entropy for strong r-processing up to $A \sim 200$.

The most likely site for r-process element formation up to the platinum peak - winds from compact neutron stars: **R<10, M>2M**$_{\odot}$ (Thompson et al. 2001)

The importance of dymamical timescale:

(τ_{dyn} was defined as duration of α-process over which a temperature of an expanding wind decreases from T = 0.5 to ~0.2 MeV)

200 ms (Meyer etal. 1992)

300ms, s=400 (Woosley et al. 1994; tr.40)

23-33ms (Terasawa et al. 2001)

Thompson et al. (2001):

s~300, τ>500ms OR:

s≤150, τ ~ 1-5 ms

(Otsuki et al. 2000; τ ~ 6-10 ms; M=2; s=140)

the parameters of the dynamical model

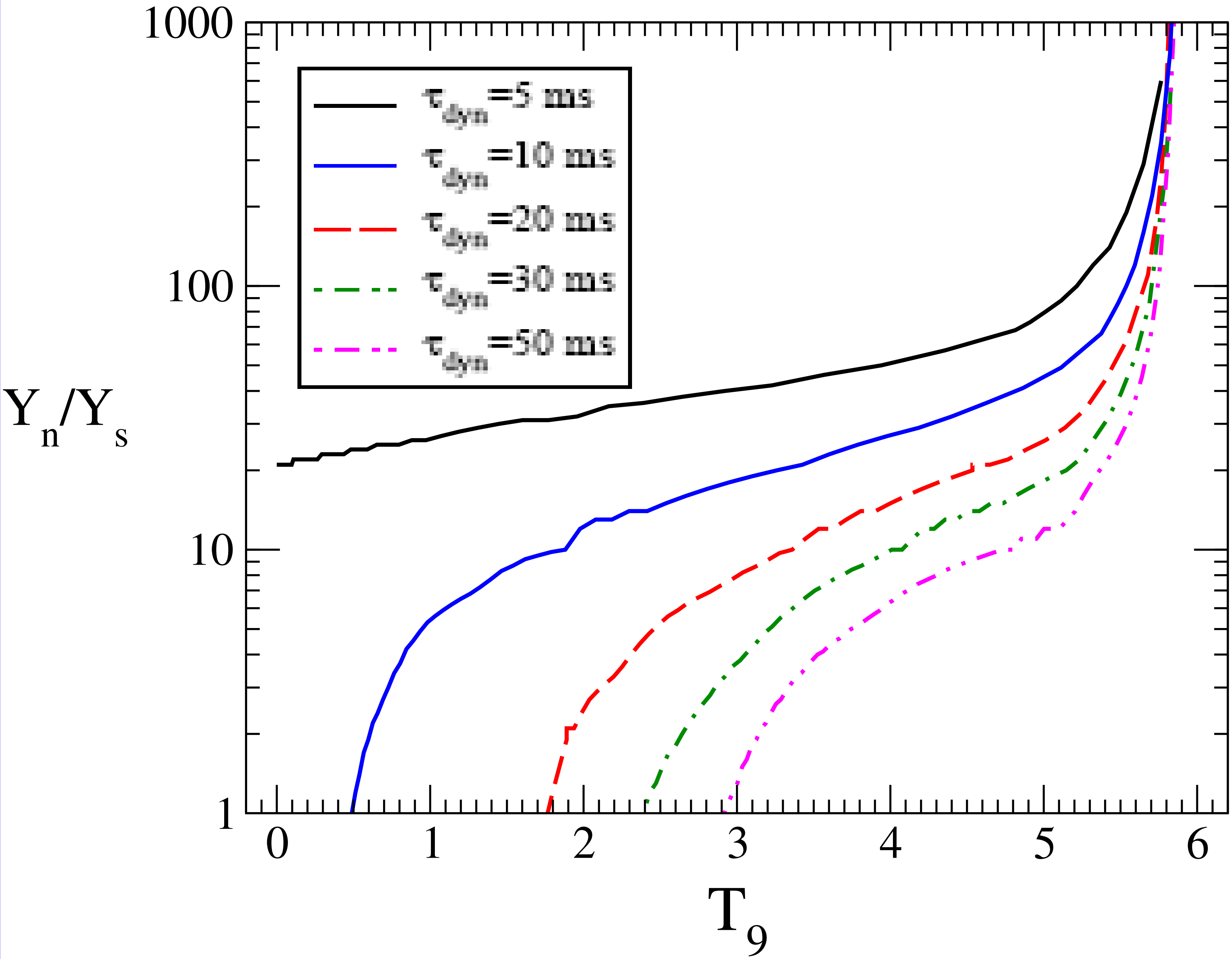
- $T_9^{ini}(0)$=5-6 $\rho_{ini}(0)$ =(2-6) 10^5 г/см$^{-3}$
- начальный состав: n, p, α, seeds
- S/k_B~105 – 200,   s≈ 3.34 T_9^3/ρ_5
- Y_e= 0.42 – 0.46   ($\eta = 1 - 2\,Y_e$)
- τ_{dyn}=1-25ms
- $T_9^f(t_0)$=0.1 – 1.4, $\rho_0^f(t_0)$ = 1 – 3000 г/см$^{-3}$

The outflow behavior during the early and late expansion phases was defined by different analytic functions, which qualitatively describe the wind acceleration through the sonic point on the one hand, and the evolution of the outflow after its deceleration by a reverse shock on the other hand.

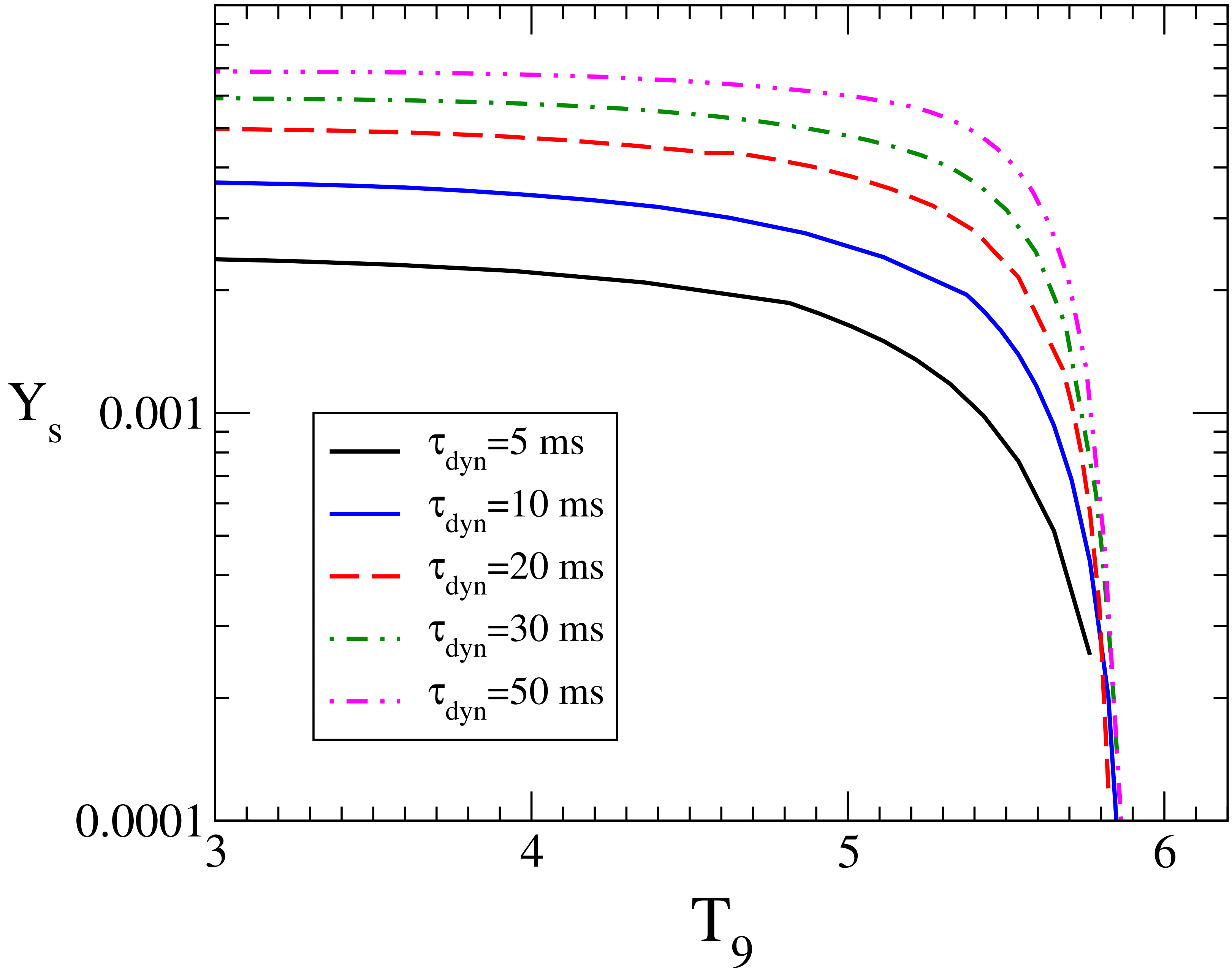
In the first stage of the expansion v~ r and

$\rho(t) = \rho_{ini} \exp(-3t_{dyn})$; $T_9(t) = T_9^{ini} \exp(-t_{dyn})$

For reasons of simplicity, we always assume $T^3/\rho = const$

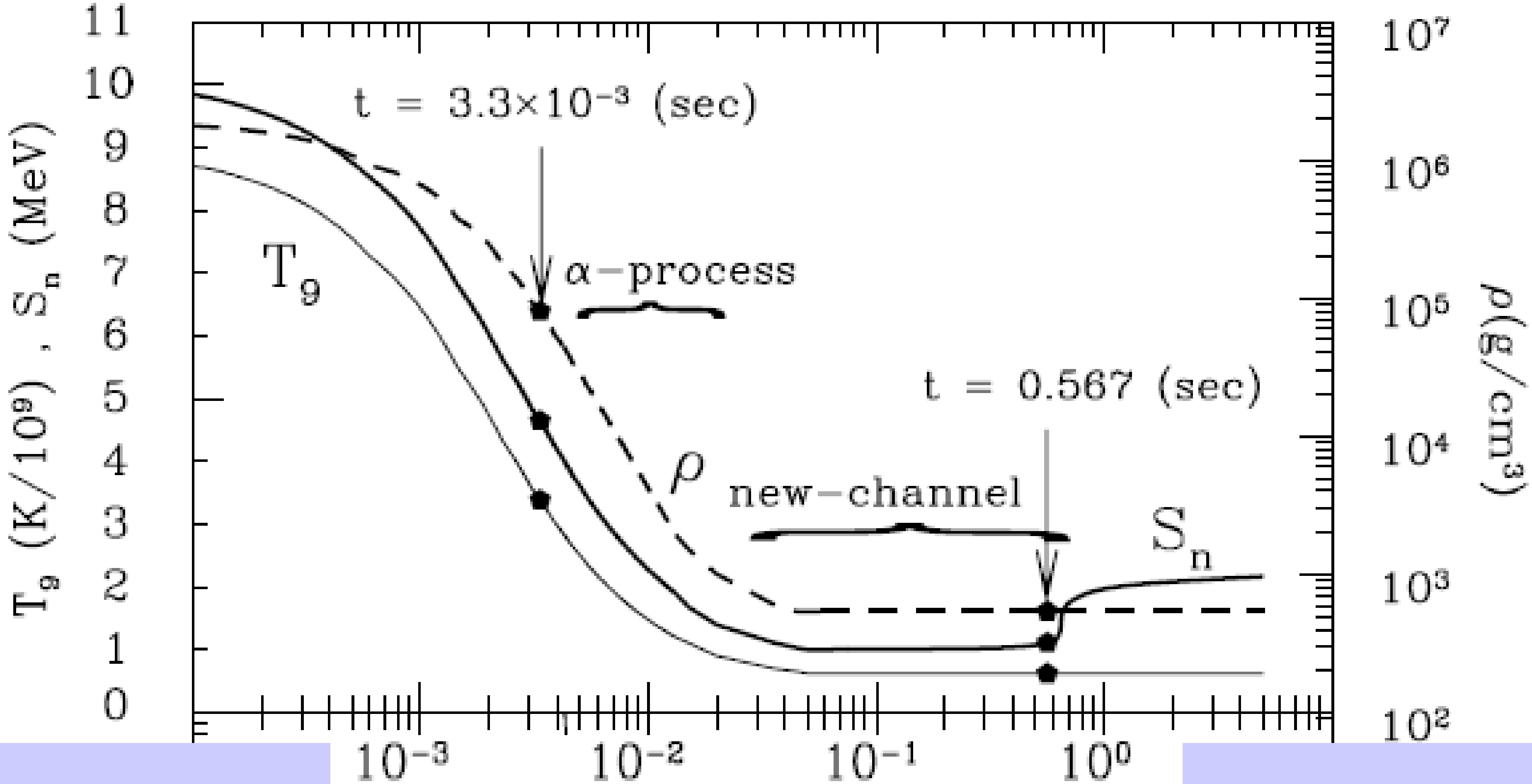


1000
100
10
1
0
1
2
3
4
5
6
T_9
Y_n/Y_s
τ_{dyn}=5 ms
τ_{dyn}=10 ms
τ_{dyn}=20 ms
τ_{dyn}=30 ms
τ_{dyn}=50 ms



Y_s
0.001
0.0001
3
4
5
6
T_9
τ_dyn=5 ms
τ_dyn=10 ms
τ_dyn=20 ms
τ_dyn=30 ms
τ_dyn=50 ms

Terasawa et al. 2001 AJ 562 ; 2002 AJ 578



t, ms

$$
\begin{aligned}
dY_{A,Z}/dt = & -\lambda_\beta(A,Z)\cdot Y_{A,Z} - \lambda_{n\gamma}(A,Z)\cdot Y_{A,Z} + \lambda_{n\gamma}(A-1,Z)\cdot Y_{A-1,Z} - \\
& \lambda_{\gamma n}(A,Z)\cdot Y_{A,Z} + \lambda_{\gamma n}(A+1,Z)\cdot Y_{A+1,Z} - \\
& \lambda_{p\gamma}(A,Z)\cdot Y_{A,Z} + \lambda_{\gamma p}(A+1,Z+1)\cdot Y_{A+1,Z+1} - \\
& \lambda_{\gamma p}(A,Z)\cdot Y_{A,Z} + \lambda_{p\gamma}(A-1,Z-1)\cdot Y_{A-1,Z-1} - \\
& \lambda_{\alpha\gamma}(A,Z)\cdot Y_{A,Z} + \lambda_{\gamma\alpha}(A+4,Z+2)\cdot Y_{A+4,Z+2} - \\
& \lambda_{\gamma\alpha}(A,Z)\cdot Y_{A,Z} + \lambda_{\alpha\gamma}(A-4,Z-2)\cdot Y_{A-4,Z-2} - \\
& \lambda_{np}(A,Z)\cdot Y_{A,Z} + \lambda_{np}(A,Z+1)\cdot Y_{A,Z+1} - \\
& \lambda_{pn}(A,Z)\cdot Y_{A,Z} + \lambda_{pn}(A,Z-1)\cdot Y_{A,Z-1} - \\
& \lambda_{p\alpha}(A,Z)\cdot Y_{A,Z} + \lambda_{\alpha p}(A-3,Z-1)\cdot Y_{A-3,Z-1} - \\
& \lambda_{\alpha p}(A,Z)\cdot Y_{A,Z} + \lambda_{p\alpha}(A+3,Z+1)\cdot Y_{A+3,Z+1} + \\
& \lambda_{\alpha n}(A-3,Z-2)\cdot Y_{A-3,Z-2} - \lambda_{\alpha n}(A,Z)\cdot Y_{A,Z} - \\
& \lambda_{n\alpha}(A,Z)\cdot Y_{A,Z} + \lambda_{n\alpha}(A+3,Z+2)\cdot Y_{A+3,Z+2} + \\
& \lambda_{\nu e}(A,Z-1)\cdot Y_{A,Z-1} - \lambda_{\nu e}(A,Z)\cdot Y_{A,Z} + \\
& \sum_{k=0,1,2,3} \lambda_\beta(A+k,Z-1)\cdot P_k(A+k,Z-1)\cdot Y_{A+k,Z-1}\ , \\
& + \sum_{A_f,Z_f} \cdot W_\beta(A_f,Z_f,A,Z)\lambda_\beta(A_f,Z_f)P_{\beta df}(A_f,Z_f)Y_{A_f,Z_f} \\
& + \sum_{A_f,Z_f} \cdot W_{nf}(A_f,Z_f,A,Z)\lambda_{nf}(A_f,Z_f)Y_{A_f,Z_f} \\
& + \sum_{A_f} W_{sf}(A_f,99,A,Z)\lambda_{sf}(A_f,Z_{99})Y_{A_f,Z_{99}}
\end{aligned}
$$

- In the nucleosynthesis studies presented here, the triple and n reactions of helium burning, $3a \rightarrow 12C$ and $\alpha+\alpha+n \rightarrow {}^{9}Be$, respectively, along with their inverse reactions, were included. The rates for both processes, as well as for other reactions with charged particles, were taken from Cowan et al. (1991).
- Nuclear mass values as predicted by FRDM (Kratz et al. 1993) were used, the beta-decay rates were calculated in the framework of the QRPA-model (Kratz et al. 1993), and the reaction rates with neutrons were described according to the calculations of Cowan et al. (1991) and of Rauscher & Thielemann (2000).

- For the second stage we consider two cases with different limiting behavior for $t >> t_0$.
- In the 1-st case we assume that the density and temperature asymptote to constant values,

$$\rho(t) = \rho(0) \quad \text{and} \quad T(t) = T(0) \quad \text{for } t \geq t_0$$

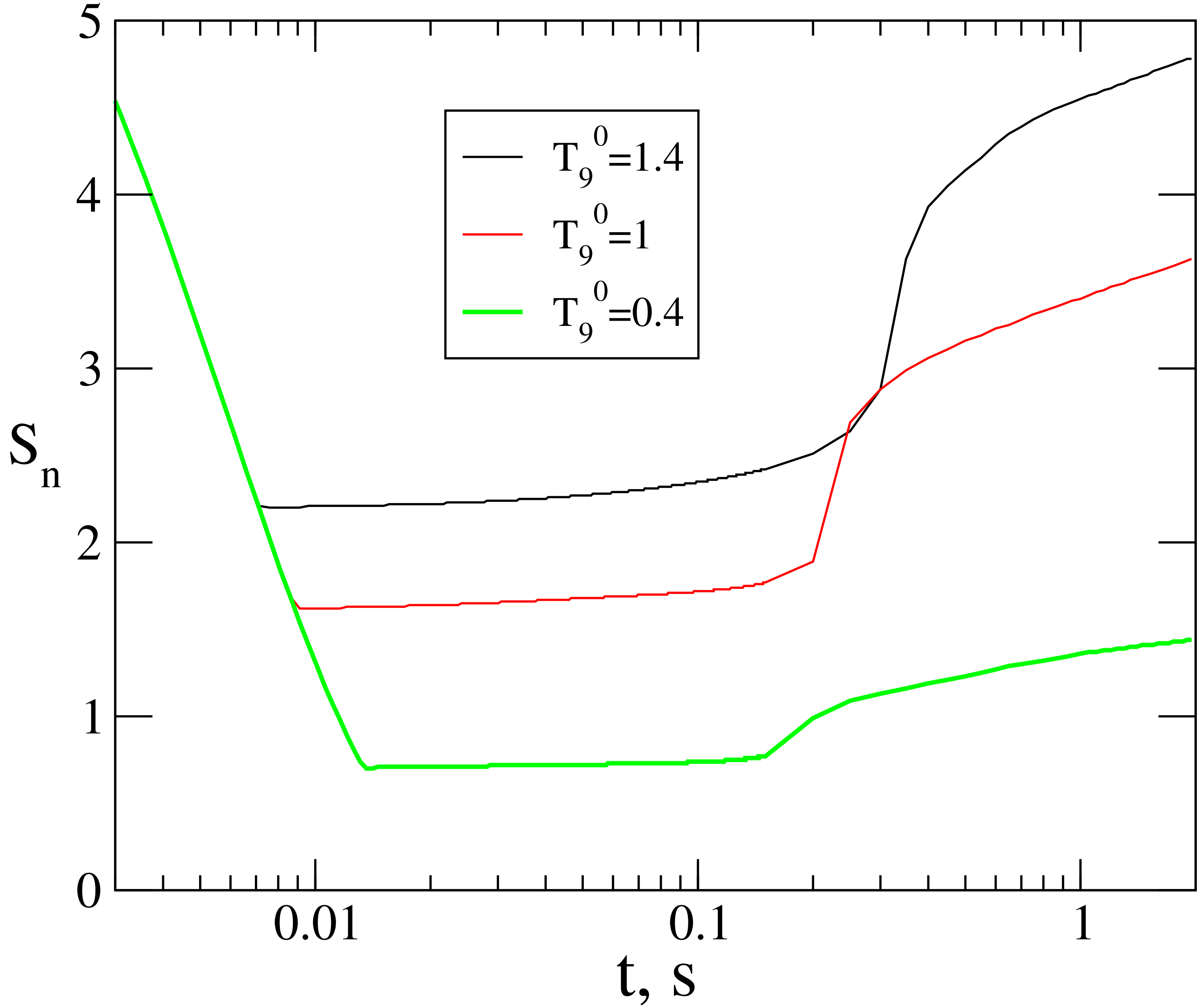
- For steady-state conditions this implies that the radius and the velocity of a Lagrangian mass shell evolve at $t \geq t_0$ according to:

$$\mathrm{r}(t) = \mathrm{r}_0[1 + 3\,\mathrm{v}_0/r_0(t \geq t_0)]^{1/3}$$

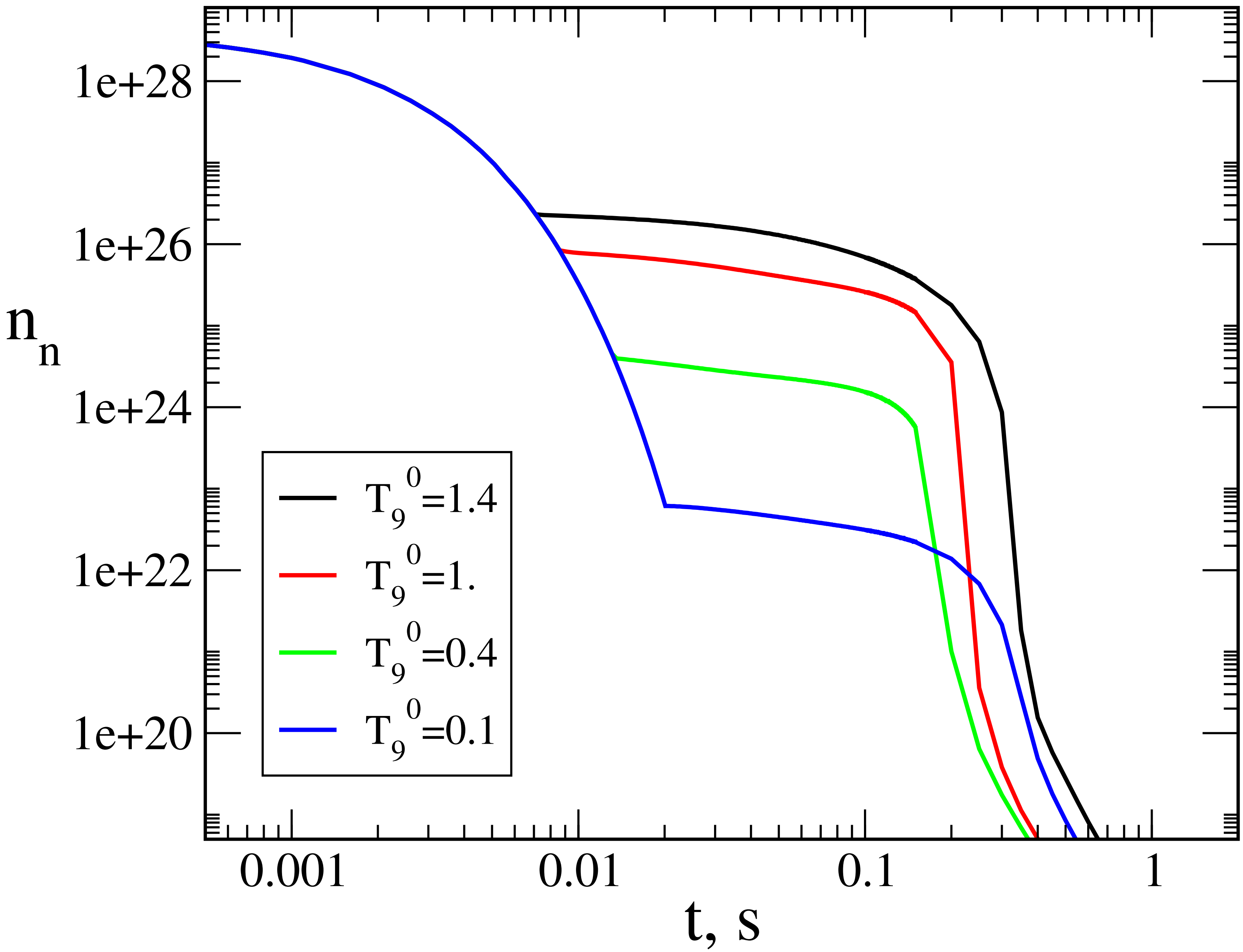
$$\mathrm{v}(t) = \mathrm{v}_0[1 + 3\,\mathrm{v}_0/r_0(t \geq t_0)]^{1/3}$$

and therefore $r(t) \sim t^{\,1/3}$

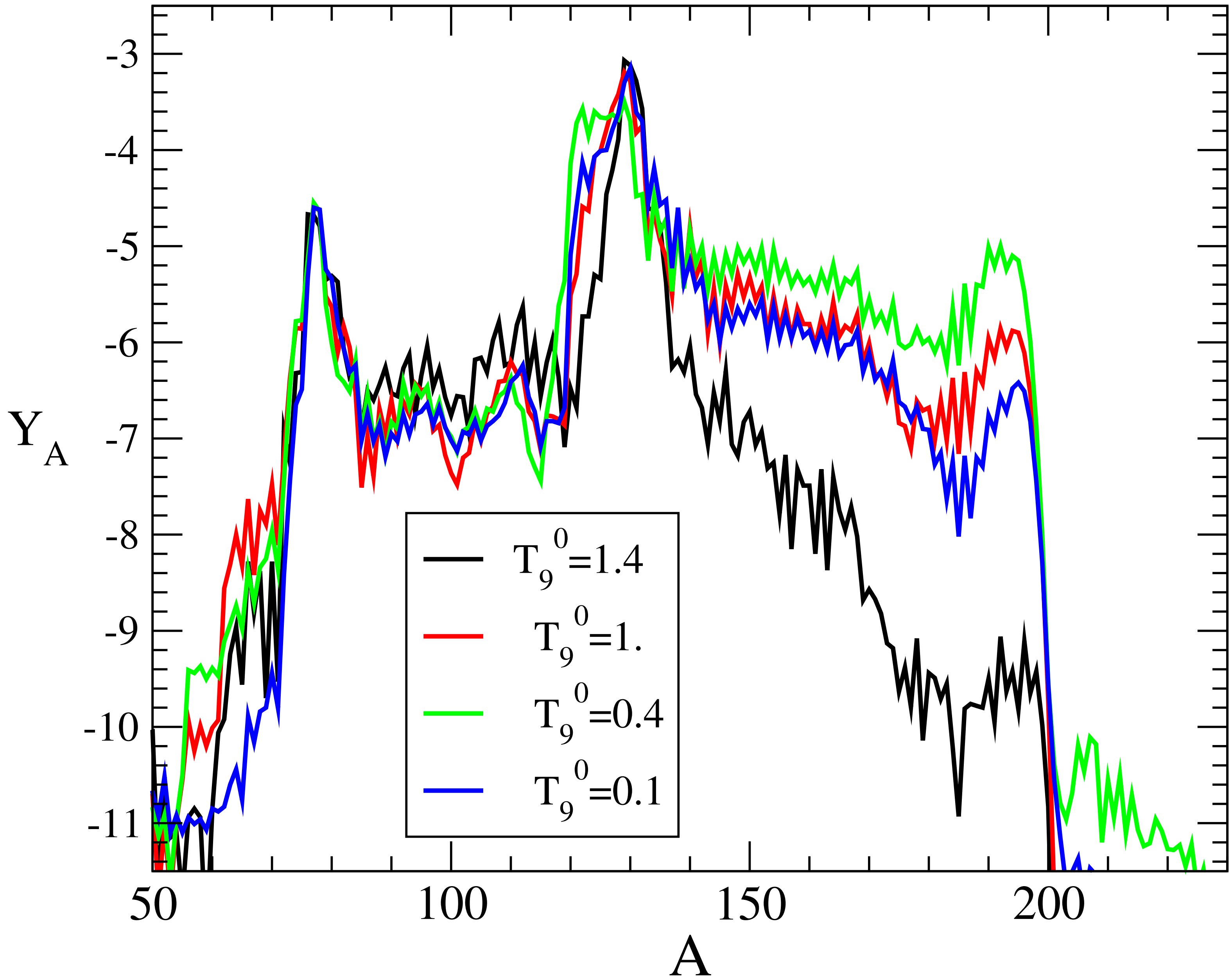
=> $\mathrm{v}(t) \sim t^{\,-2/3} \rightarrow 0$ for $t >> t_0$.



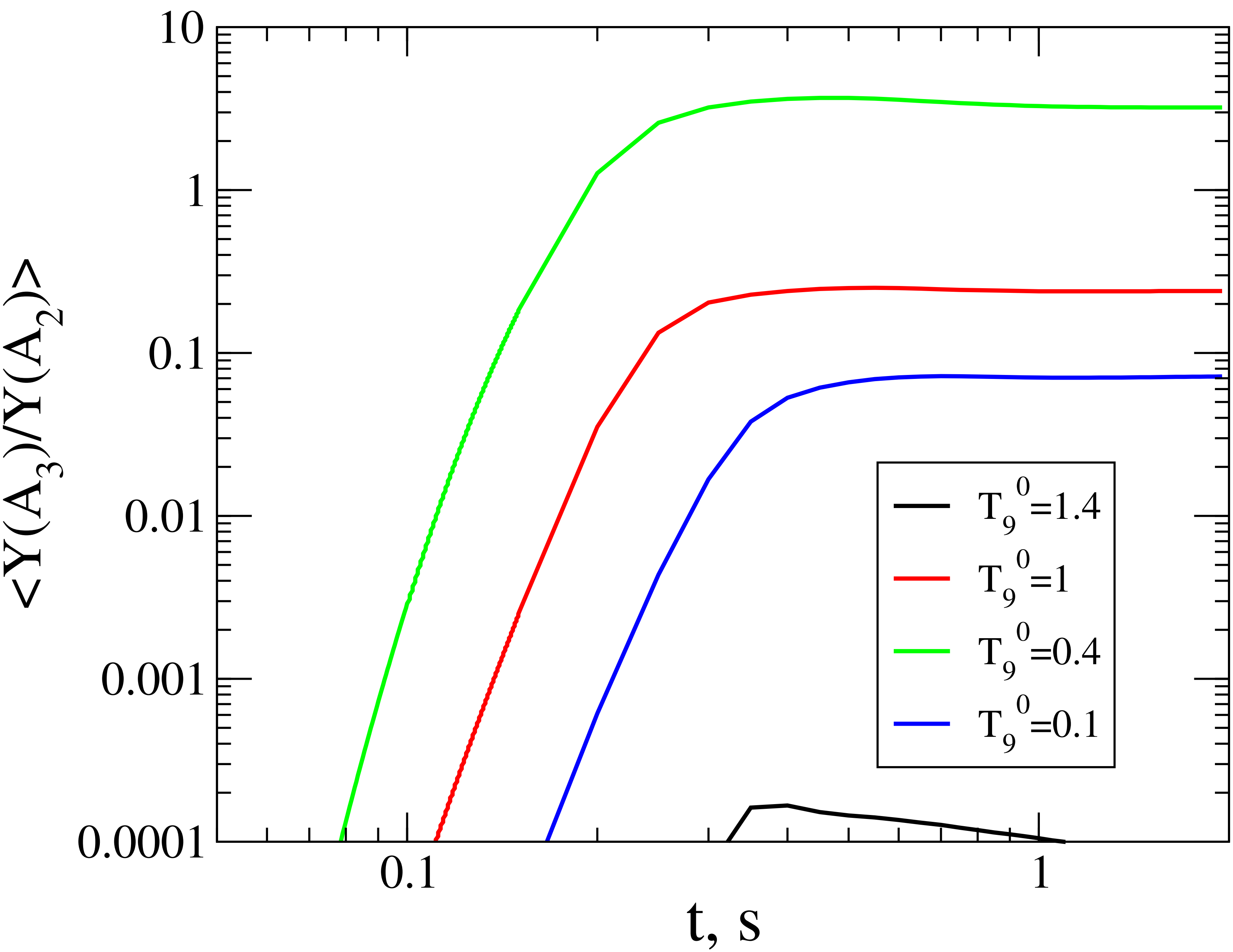
5
4
3
2
1
0
S_n
0.01
0.1
1
t, s
T_9^0=1.4
T_9^0=1
T_9^0=0.4

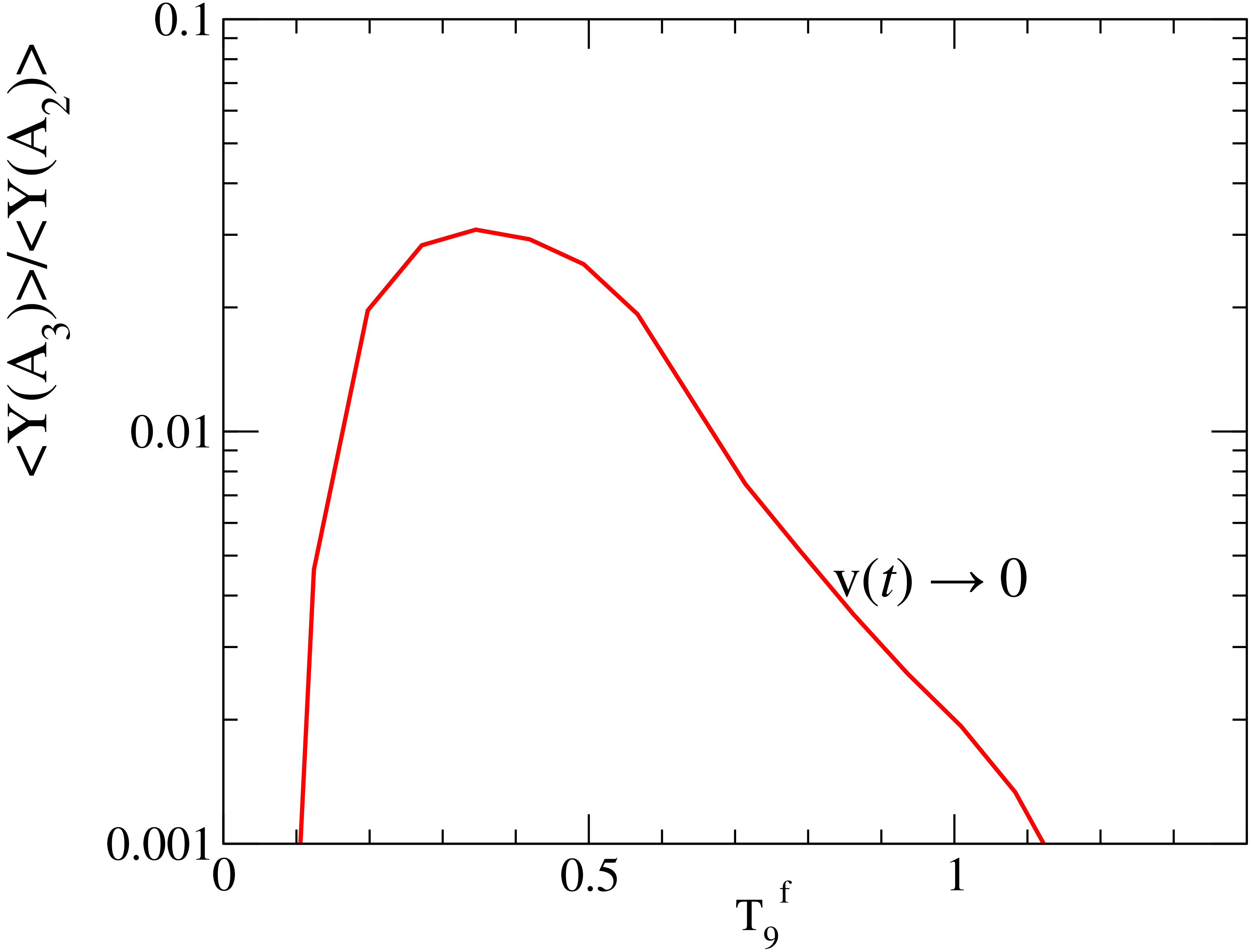


1e+28
1e+26
1e+24
1e+22
1e+20
n_n
0.001
0.01
0.1
1
t, s
T_9^0=1.4
T_9^0=1.
T_9^0=0.4
T_9^0=0.1

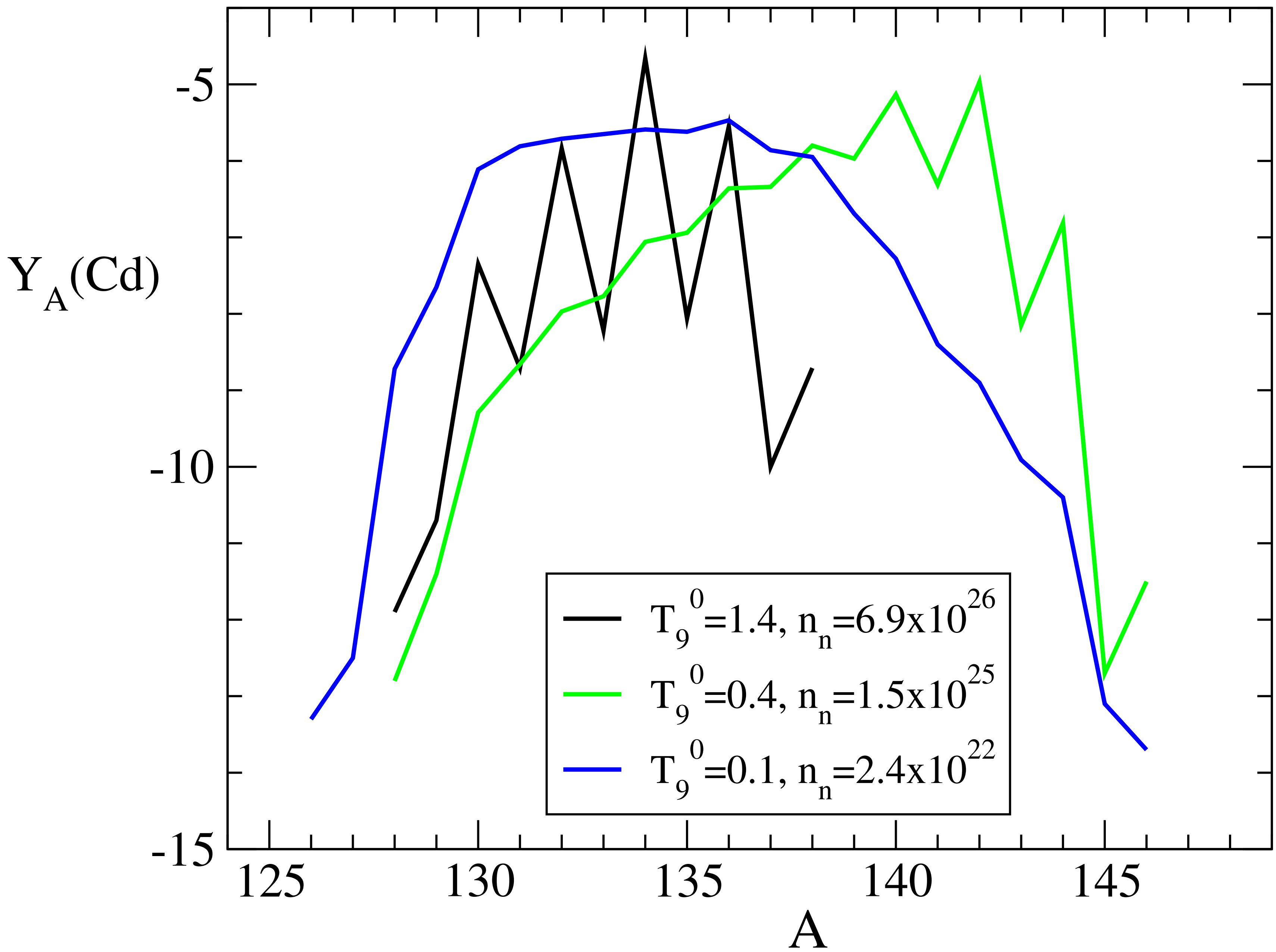


-3
-4
-5
-6
-7
-8
-9
-10
-11
Y_A
50
100
150
200
A
T_9^0=1.4
T_9^0=1.
T_9^0=0.4
T_9^0=0.1


10
1
0.1
0.01
0.001
0.0001
0.1
1
t, s
<Y(A$_3$)/Y(A$_2$)>
T_9^0=1.4
T_9^0=1
T_9^0=0.4
T_9^0=0.1



<Y(A3)>/<Y(A2)>
0.1
0.01
0.001
0
0.5
1
T9 f
v(t) → 0



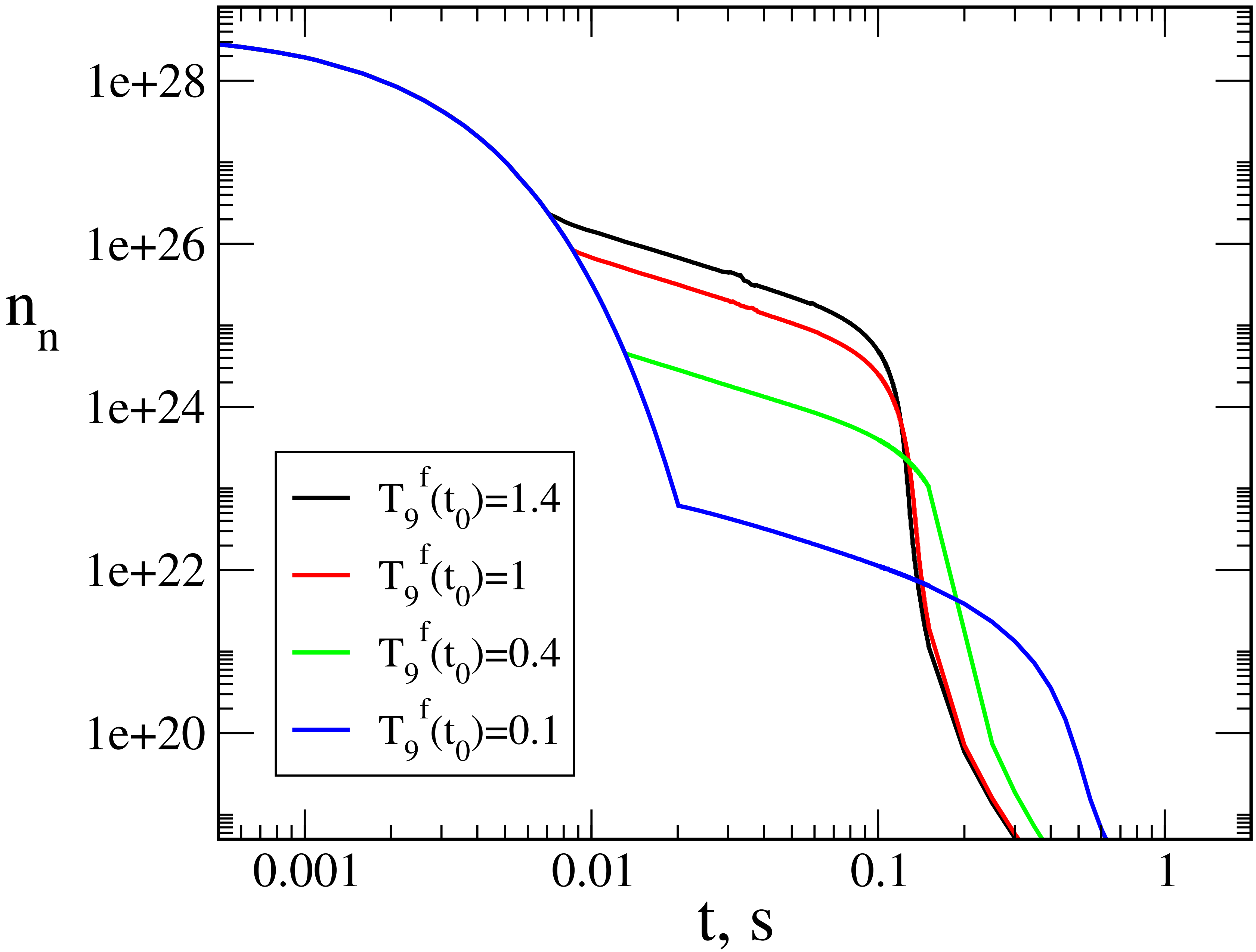
$Y_A(Cd)$
-5
-10
-15
125
130
135
140
145
A
T_9^0=1.4, n_n=6.9x10^{26}
T_9^0=0.4, n_n=1.5x10^{25}
T_9^0=0.1, n_n=2.4x10^{22}

- In the second investigated case the density and temperature are still assumed to decline at late times, but much less steeply than during the exponential rst expansion phase:
- $T(t) = T_0\,(t/t_0)^{-2/3}$ $\rho(t) = \rho_0\,(t/t_0)^{-2}$ $t > t_0$
- For steady-state conditions this corresponds for

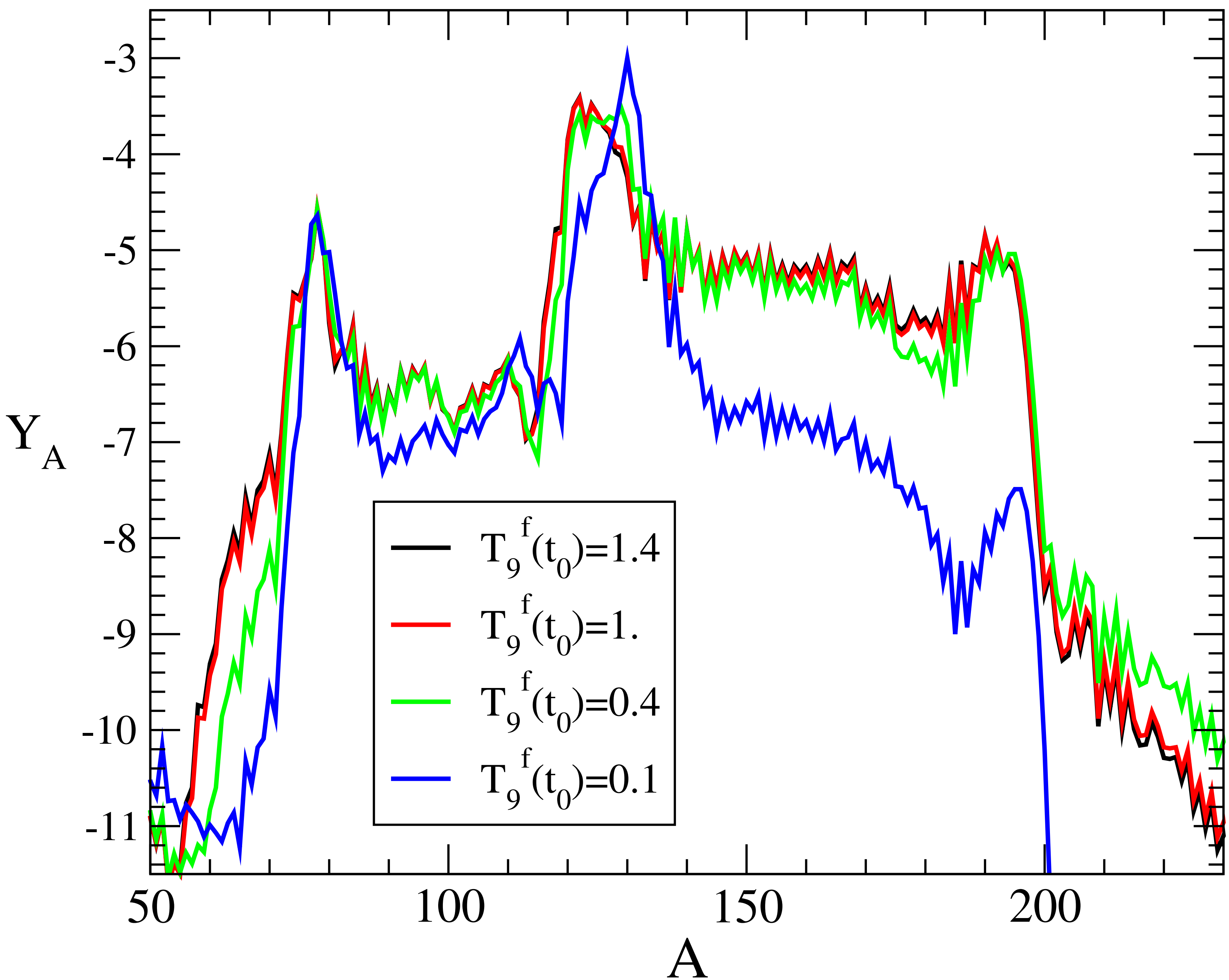
  $r(t) \sim t$ and $v(t) = v_0^{1/3}(r_0/t_0)^{2/3}$ =const > 0

  in case $t \gg t_0$
- $v(t \rightarrow \mathrm{INF}) < v_0$, i.e. deceleration

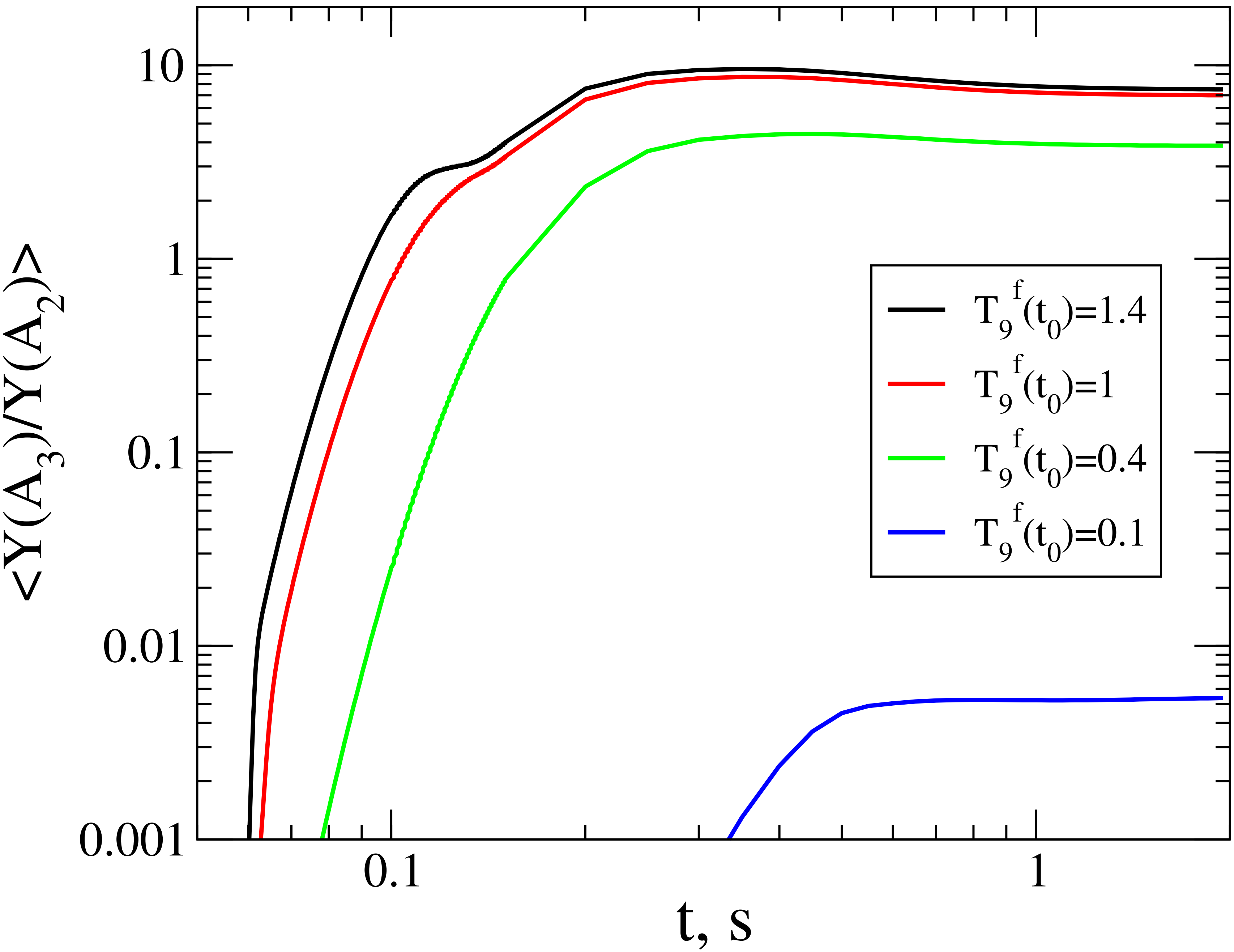
  (and not only a slow-down of the expansion) happens, if $t_0 > \tau_{dyn}$.



1e+28
1e+26
1e+24
1e+22
1e+20
n_n
0.001
0.01
0.1
1
t, s
$T_9^f(t_0)$=1.4
$T_9^f(t_0)$=1
$T_9^f(t_0)$=0.4
$T_9^f(t_0)$=0.1

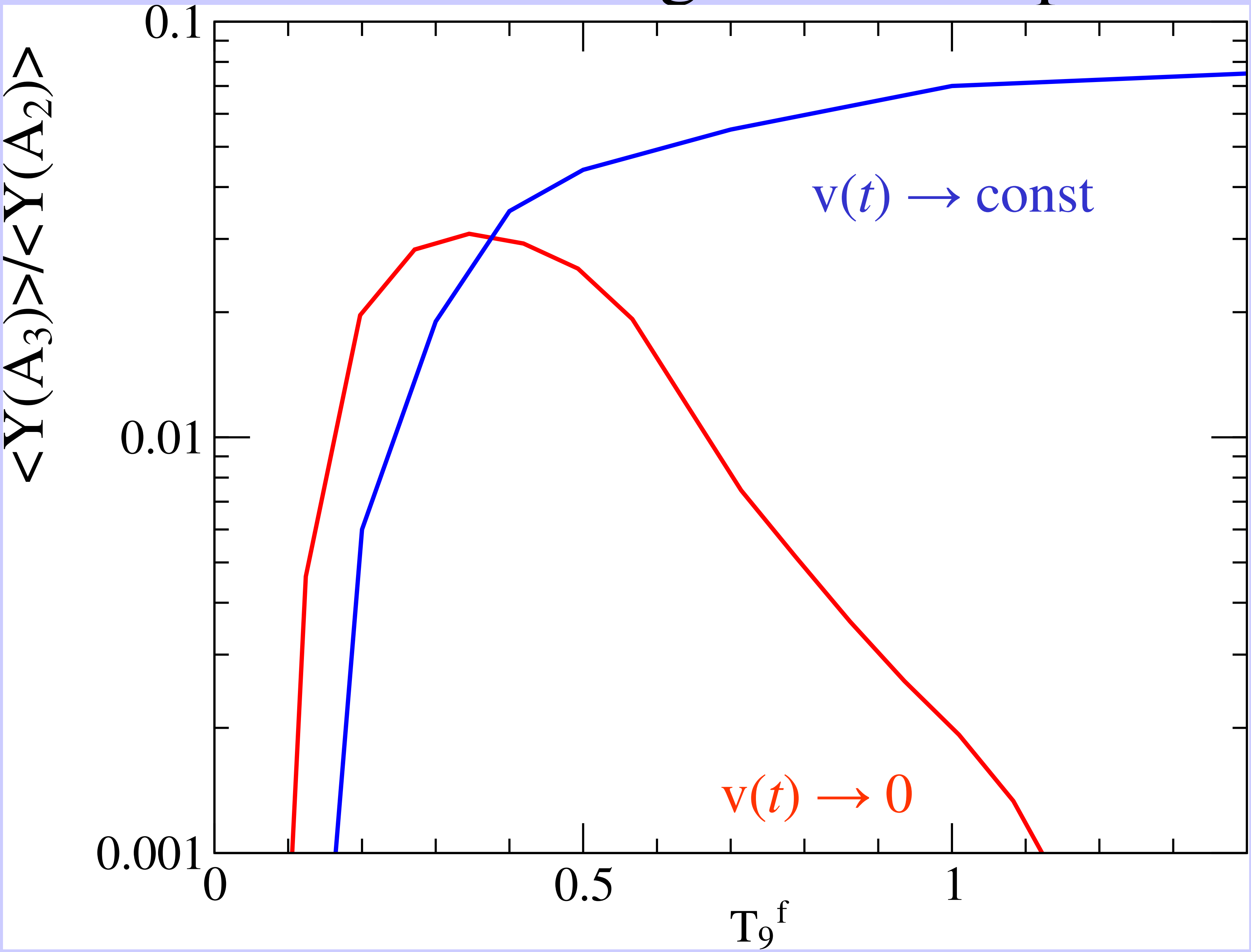


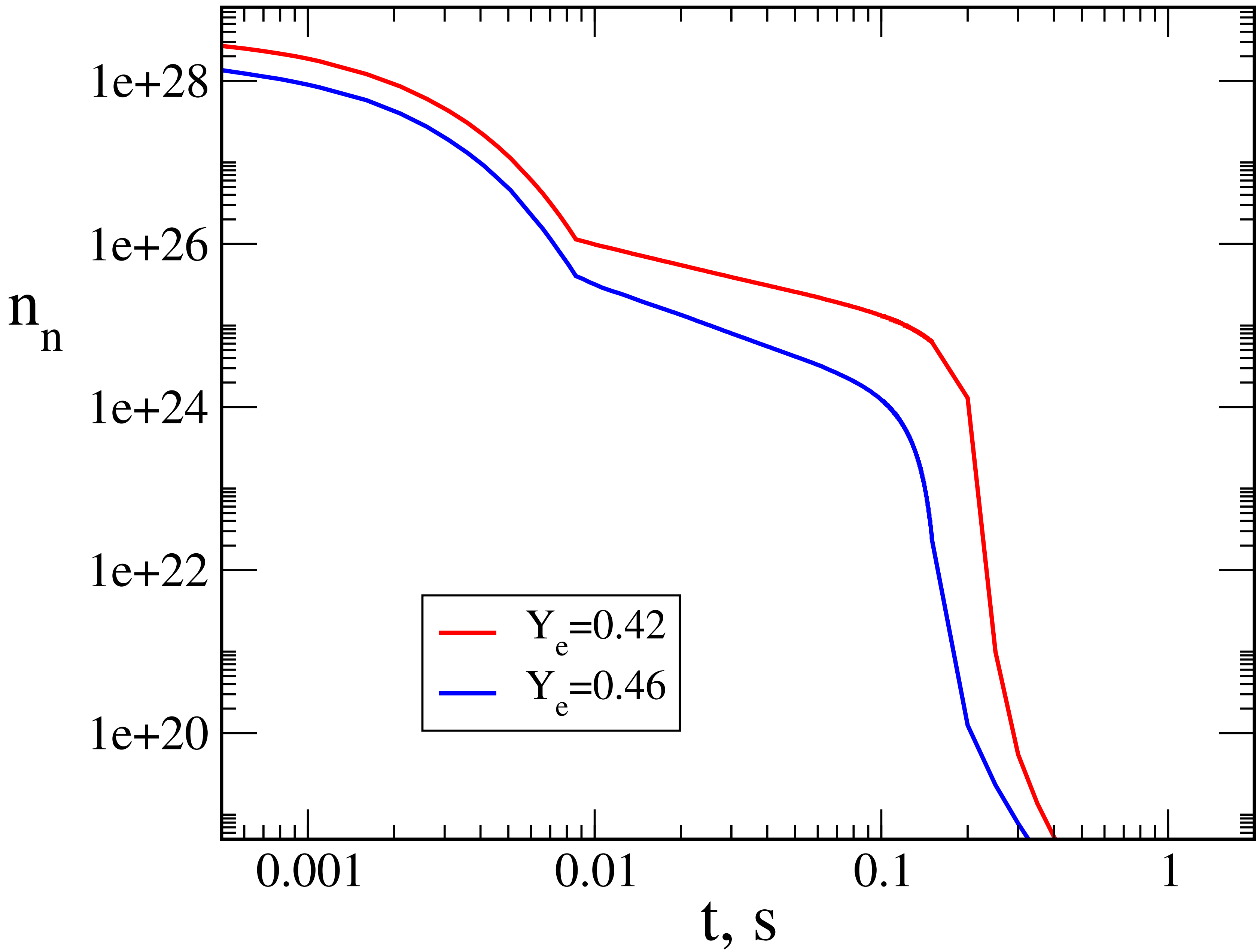
Y_A
A
-3
-4
-5
-6
-7
-8
-9
-10
-11
50
100
150
200
$T_9^f(t_0)$=1.4
$T_9^f(t_0)$=1.
$T_9^f(t_0)$=0.4
$T_9^f(t_0)$=0.1



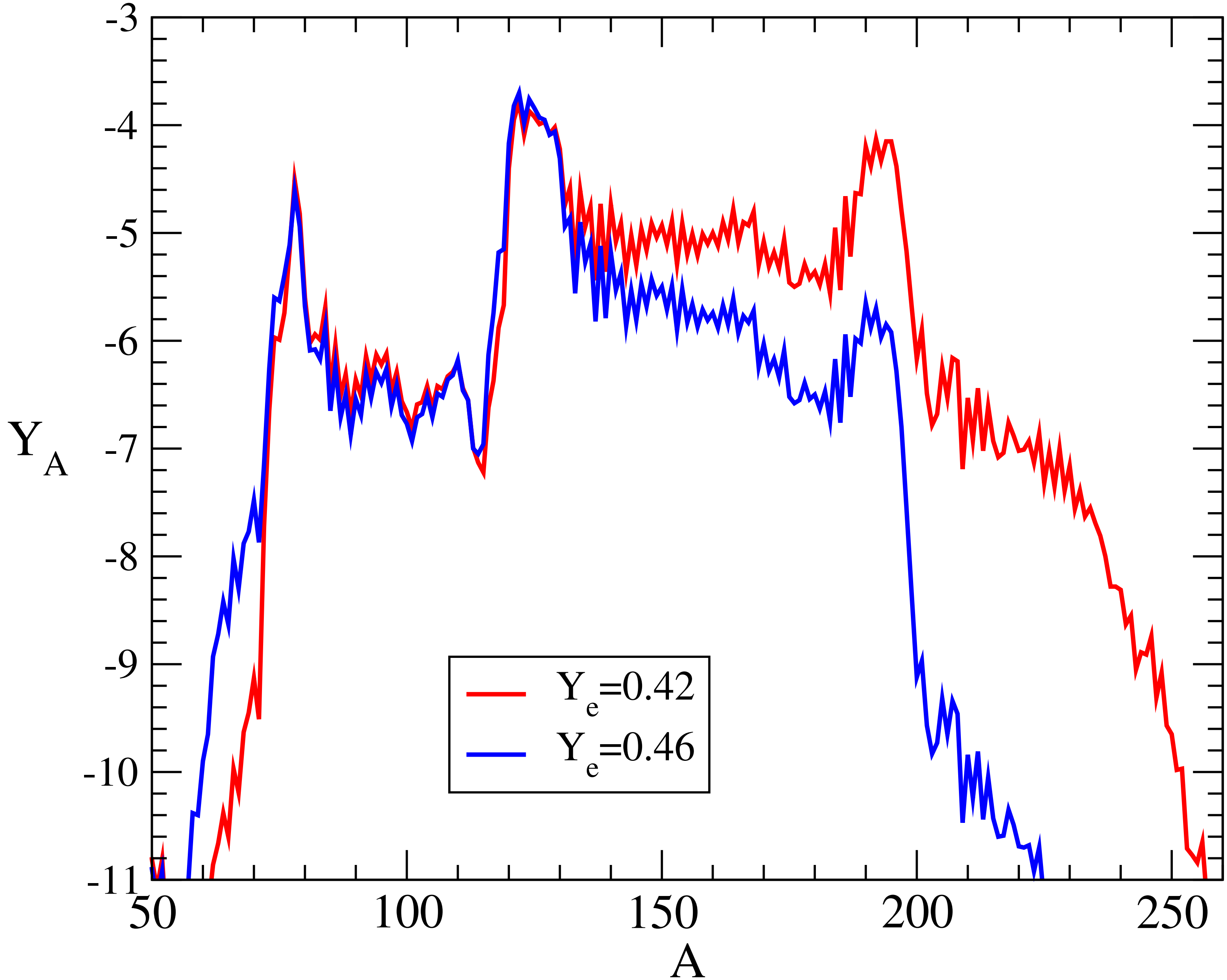
10
1
0.1
0.01
0.001
0.1
1
t, s
<Y(A3)/Y(A2)>
T9f(t0)=1.4
T9f(t0)=1
T9f(t0)=0.4
T9f(t0)=0.1

models of second stage of the expansion

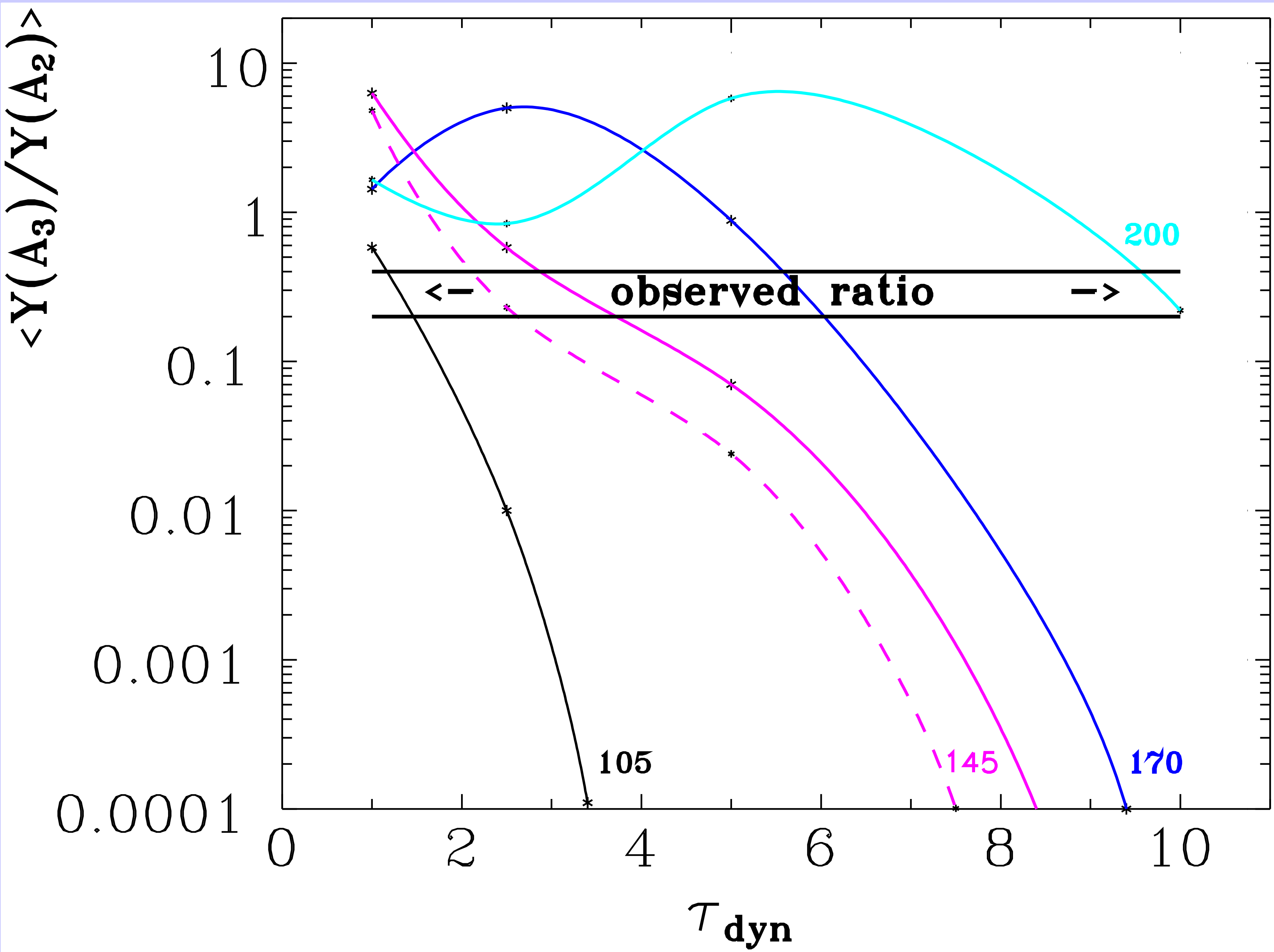




1e+28
1e+26
1e+24
1e+22
1e+20
n_n
0.001
0.01
0.1
1
t, s
Y_e=0.42
Y_e=0.46



-3
-4
-5
-6
-7
-8
-9
-10
-11
50
100
150
200
250
A
Y_A
Y_e=0.42
Y_e=0.46



<Y(A3)/Y(A2)>
10
1
0.1
0.01
0.001
0.0001
0
2
4
6
8
10
τ dyn
<– observed ratio –>
200
105
145
170

$$v = const * r = r/\tau \quad => \quad r = r_0 \times \exp(t/\tau),$$
$$v \equiv dr/dt = v_{ini} \times \exp(t/\tau);$$
$$r_i = 10^6 \text{ см}, \quad \text{for } \tau = 5\text{мс} \quad v_{ini} = 2000 \text{ км/с}$$

τ_{dyn} [ms]	entropy [k_B/N]	$T_9^f(t_0)$	t_0 [ms]	v_{ini} [km/s]	v_0 [km/s]	$\langle A \rangle$	$\langle Y(A_3)/Y(A_2) \rangle$
5	105	1	9	2000	12000	118	10^{-10}
2.5	105	1	4.5	4000	24000	127	0.01
5	145	1.4	8	2000	10000	128	0.075
5	145	0.4	14	2000	33000	128	0.04
2.5	145	1	4	4000	20000	144	0.45
10	170	1	16	1000	5000	119	10^{-5}
5	170	1	8	2000	10000	145	0.75

Conclusions

- short or very short exponential timescale (τ_{dyn}~10 ms for s = 200 and τ_{dyn} ~1 ms for s = 100) is needed for A3 peak formation during the homologous expansion
- Elements in the vicinity of A_3 can be formed under the next values of parameters:

  s~150 $\tau_{dyn} \leq$5ms Y_e=0.42

  s>170 $\tau_{dyn} \leq$5ms Y_e=0.46
- Changes of the asymptotic of ρ, T_9 from v~0 till v≈const leads to weak dependences of Y(A3) on initial values of $\rho^f(t_0)$, $T_9^f(t_0)$