Hadronization and Freeze Out from Supercooled QGP

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Entropy condition

$$[S^\mu d\sigma_\mu] \geq 0$$

Long time hadronization

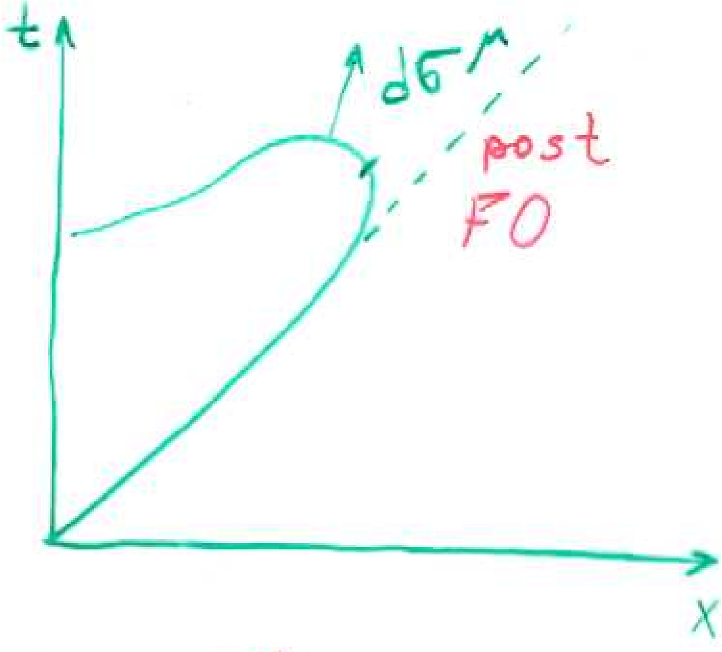
Long living QGP should be seen in HBT experiments as a peak in R_{out}/R_{side} ratio
D.H. Rischke, M. Gyulassy, Nucl. Phys. A608(1996) 479

Not seen in HBT at RHIC

Sharp hadronization from supercooled QGP

First suggested in T. Csörgő, L. Csernai, Phys. Lett. B 333 (1994) 494

Can be verified only in HYDRO models with corresponding EoS



$$T^{\mu\nu} d\sigma_\nu = T^{\mu\nu}_{FO} d\sigma_\nu$$

$$N_B^{\nu} d\sigma_\nu = N^{\nu}_{B,FO} d\sigma_\nu$$

$$N_S^{\nu} d\sigma_\nu = N^{\nu}_{S,FO} d\sigma_\nu$$

$$+ N^{\nu}_{s,\bar{s}} d\sigma_\nu = N^{\nu}_{s,\bar{s},FO} d\sigma_\nu$$

$$S^{\nu} d\sigma_\nu \leq S^{\nu}_{FO} d\sigma_\nu$$

For a time-like hypersurface $d\sigma_\nu = (1, 0, 0, 0)$

$$u(x) = \gamma(x)\,(1, 0, 0, v(x))$$

$$u_{FO}(x) = \gamma_{FO}(x)\,(1, 0, 0, v_{FO}(x))$$

Conservation laws

$$(e+P)\gamma^2 - P = (e_{FO}+P_{FO})\gamma_{FO}^2 - P_{FO}$$

$$(e+P)v\gamma^2 = (e_{FO}+P_{FO})v_{FO}\gamma_{FO}^2$$

$$n_B\gamma = n_{B,FO}\gamma_{FO}$$

$$n_s\gamma = n_{s,FO}\gamma_{FO} = 0$$

$$n_{s,\bar{s}}\gamma = n_{s,\bar{s},FO}\gamma_{FO}$$

$$\gamma_s = \frac{n_{s,\bar{s}}}{n_s^{eq}} \qquad \gamma_s = 1 \text{ in QGP}$$

A. Keranen, F. Becattini PRC 65 (2002) 044901

Post FO Matter

- Quantum ideal gas, composed of hadrons up to $M_h = 2.5$ GeV

- Additional fugacity γ_s is introduced for each strange particle i

$$\lambda_i \to \lambda_i \gamma_s^{|S_i|}$$

- Mesons carrying $s\bar{s}$ pairs are taken into account

$$\lambda_i = \gamma_s^{2c_s}$$

c_s – is a relative $s\bar{s}$ content

$c_s = 0.5$ 2 mesons

$c_s = 1$ ϕ, $f_0(980)$, $f_1(1510)$, $\phi(1680)$, $\phi_3(1850)$

QGP EoS

$m_u = m_d = 0 \quad m_s = 150, 250 \text{ MeV}$

$$\ln Z = \ln Z_q^0 + \ln Z_g + \ln Z_s + \ln Z_{vac}$$

$$\ln Z_q^0 = V\left(\frac{7}{30}\pi^2 T^3 + \mu_q^2 T + \frac{1}{2\pi^2}\mu_q^4 \frac{1}{T}\right)$$

$$\ln Z_g = \frac{8}{45}\pi V T^3$$

$$\ln Z_s = \frac{6V}{\pi^2}\int_0^\infty dp\, p^2 \ln\left(1 + e^{-\beta\sqrt{p^2+m_s^2}}\right)$$

$$\ln Z_{vac} = -\frac{BV}{T}$$

1) $B = 0 \Rightarrow P(T,\mu_q) = \frac{1}{3} e(T,\mu_q)$

$e(T,\mu_q) = e_{SB}$

2) $B \neq 0 \quad P(T,\mu_q) = \frac{1}{3} e_{SB} - B$

$e(T,\mu_q) = e_{SB} + B$

In lattice calculations (for example T. Blum, L. Kärkkäinen, D. Toussaint PRD51 (1995) 5153) show that after T_c energy density, e, rise sharp and soon saturates with $e = e_{SB}$, while P increases slowly and reach $p \to \frac{e_{SB}(T)}{3}$ only at very high T.

There are many recent models of QGP EoS:

- Quasiparticle description
  A. Peshier et al. PRC 61 (2000) 045203
- condensed Polyakov loops
  O. Scavenius et. al. hep-ph/0201079
- quark-gluon liquid model
  S. Hamieh et al. PRC 62 (2000) 064901

Only for $T \geq T_c$

We extrapolate EoS(3) for

$T_m \leq T \leq T_c$

G. Kallman, PL B134 (1984) 363
M. Gorenstein, O. A. Mogilevsky Z. Phys. C38 (1988) 161

$$P(T) = \frac{1}{3} e(T) - bT \quad (\mu = 0)$$

$$e(T) = e_{SB} = \sigma T^4$$

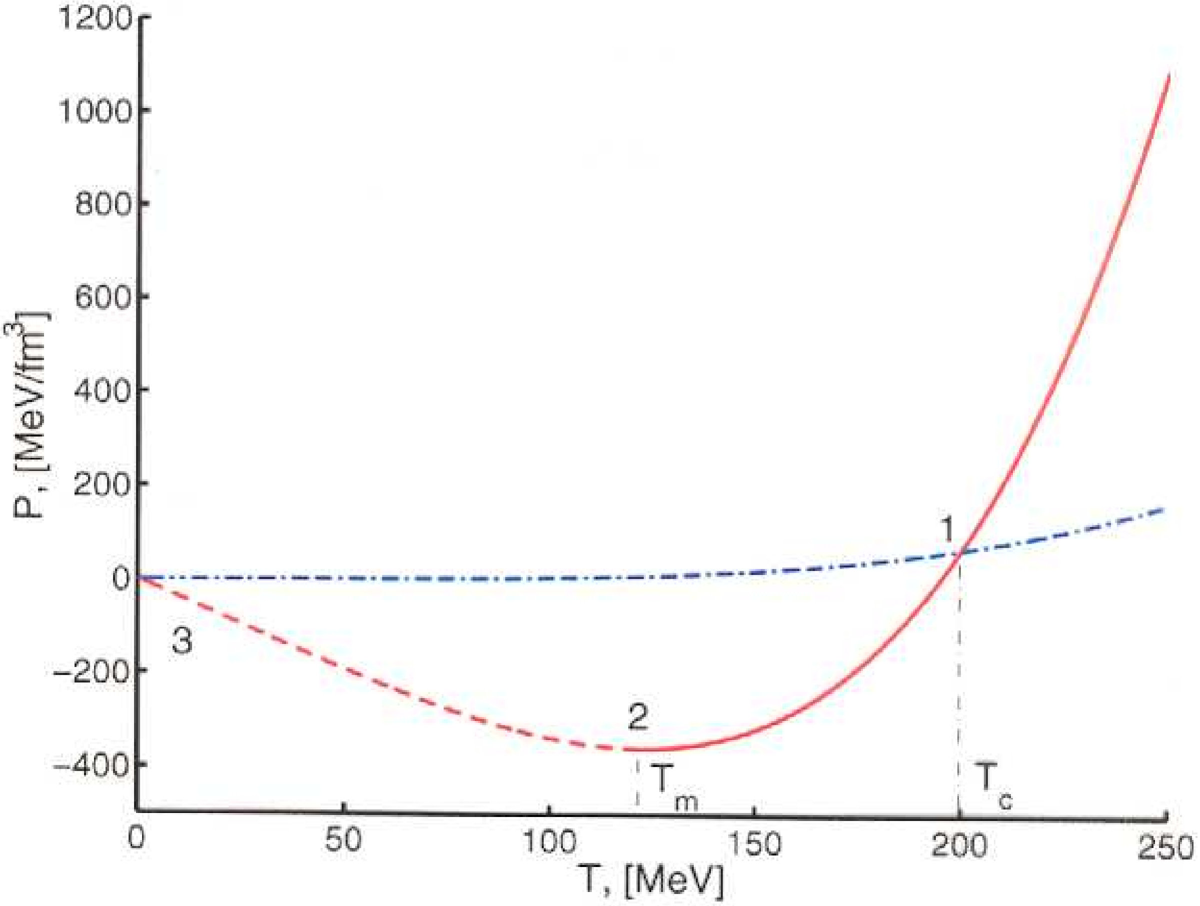
satisfies $e = T \frac{dP}{dT} - P$

Minimum at $T = T_m = \left(\frac{3b}{4\sigma}\right)^{1/3}$

$$P_{HG}(T_c, \underset{0}{\underset{\shortparallel}{\mu}}) = P_{QGP}(T_c, \underset{0}{\underset{\shortparallel}{\mu}})$$

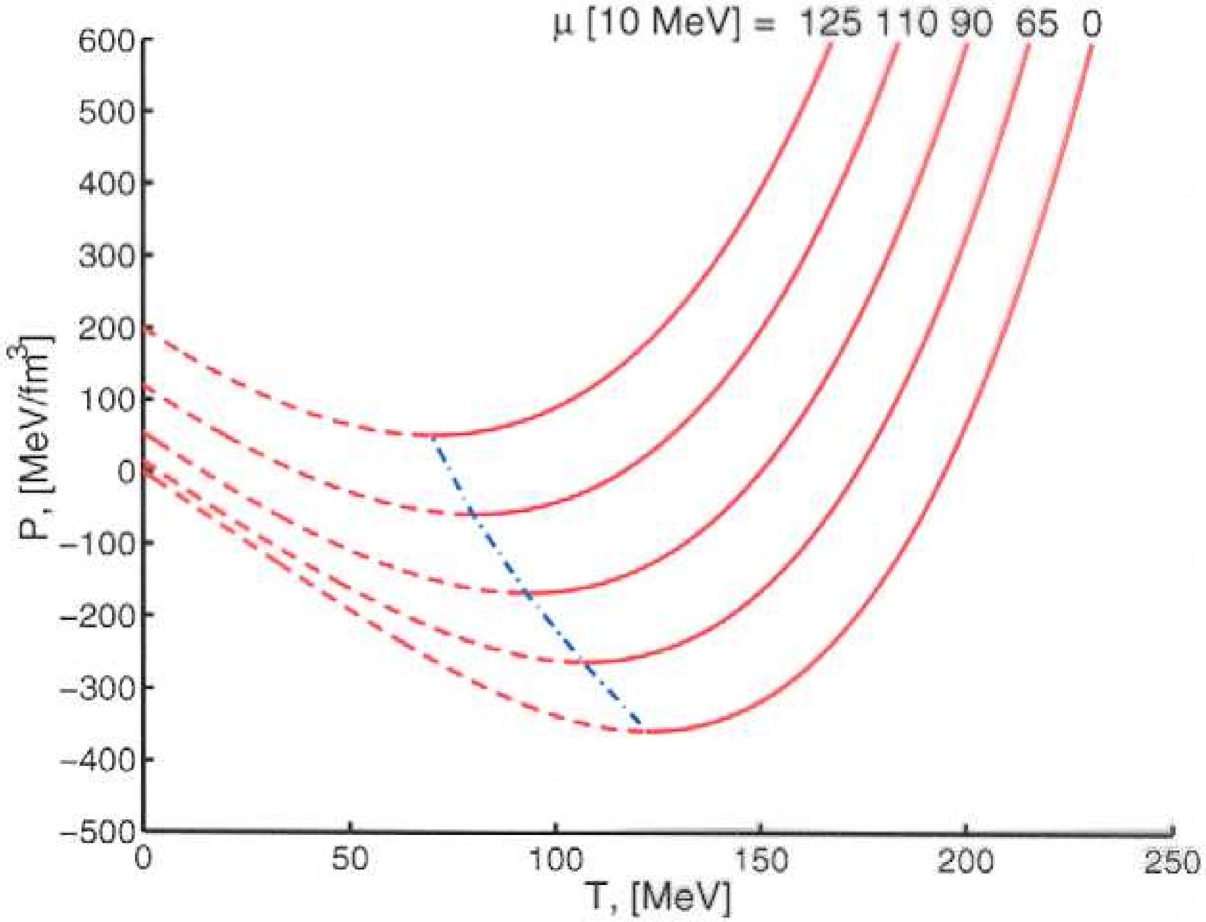
$$\Rightarrow b(T_c)$$

Perspectives for supercooled QGP

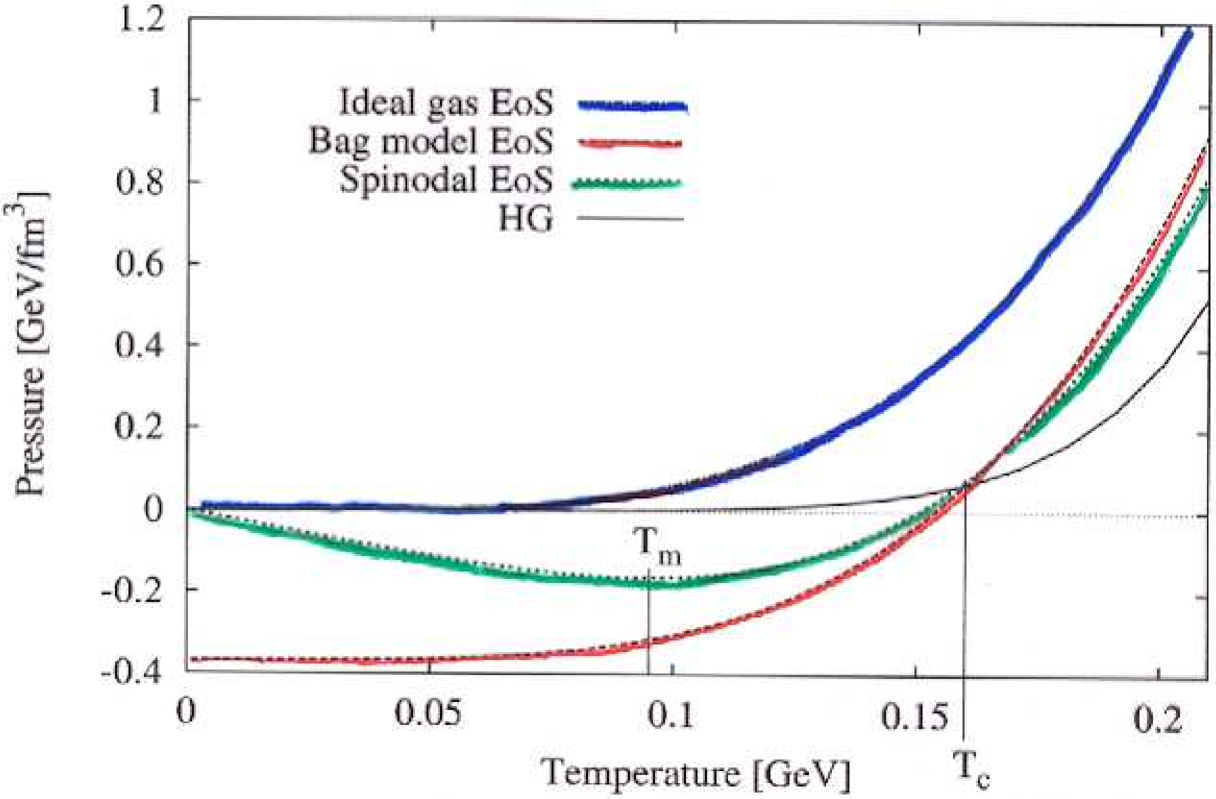


Generalized Bag-like EoS, - full + dashed line; hadronic EoS, - dot-dashed line. By supercooling one can penetrate into metastable states (branch 1-2) out of phase equilibrium and approach the spinodal point at $T = T_m$. Then, further cooling will result in a phase transition since interval 2-3 is thermodynamically forbidden ($\frac{\partial P}{\partial T} < 0$) even for a single phase

Perspectives for supercooled QGP



QGP EoS, with temperature dependent Bag constant, is shown for different value of μ - full + dashed line. The spinodal is shown by dot-dashed line



Hadron gas pressure and quark-gluon plasma pressures with ideal gas, bag model and spinodal model equations of state with parameters $\mu_B = 100$ MeV and $T_c = 160$ MeV.

Bjorken scenario

$$\begin{cases} \dfrac{\partial e}{\partial \tau} + \dfrac{e+P}{\tau} = 0 \\ \dfrac{\partial n_i}{\partial \tau} + \dfrac{n_i}{\tau} = 0 \end{cases}$$

$\tau = \sqrt{t^2 - z^2}$

Initial Conditions

$\tau = 1$ $\quad e_0 = 5\ GeV/fm^3$, $(n_B)_0 = 1\ fm^{-3}$

for ideal gas EoS (1)

$e_0 = 8\ GeV/fm^3$

FO hypersurface

$t = 10\ fm$

EoS (3)

$\mu = 0$

$$T(\tau) = \left[T_m^{\,3} + \left(T_0^{\,3} - T_m^{\,3} \right) \frac{\tau_0}{\tau} \right]^{1/3}$$

$$s(\tau) = \frac{4}{3} \sigma \left(T_0^{\,3} - T_m^{\,3} \right) \frac{\tau_0}{\tau}$$

$$e(\tau) = \sigma \left[T_m^{\,3} + \left(T_0^{\,3} - T_m^{\,3} \right) \frac{\tau_0}{\tau} \right]^{4/3}$$

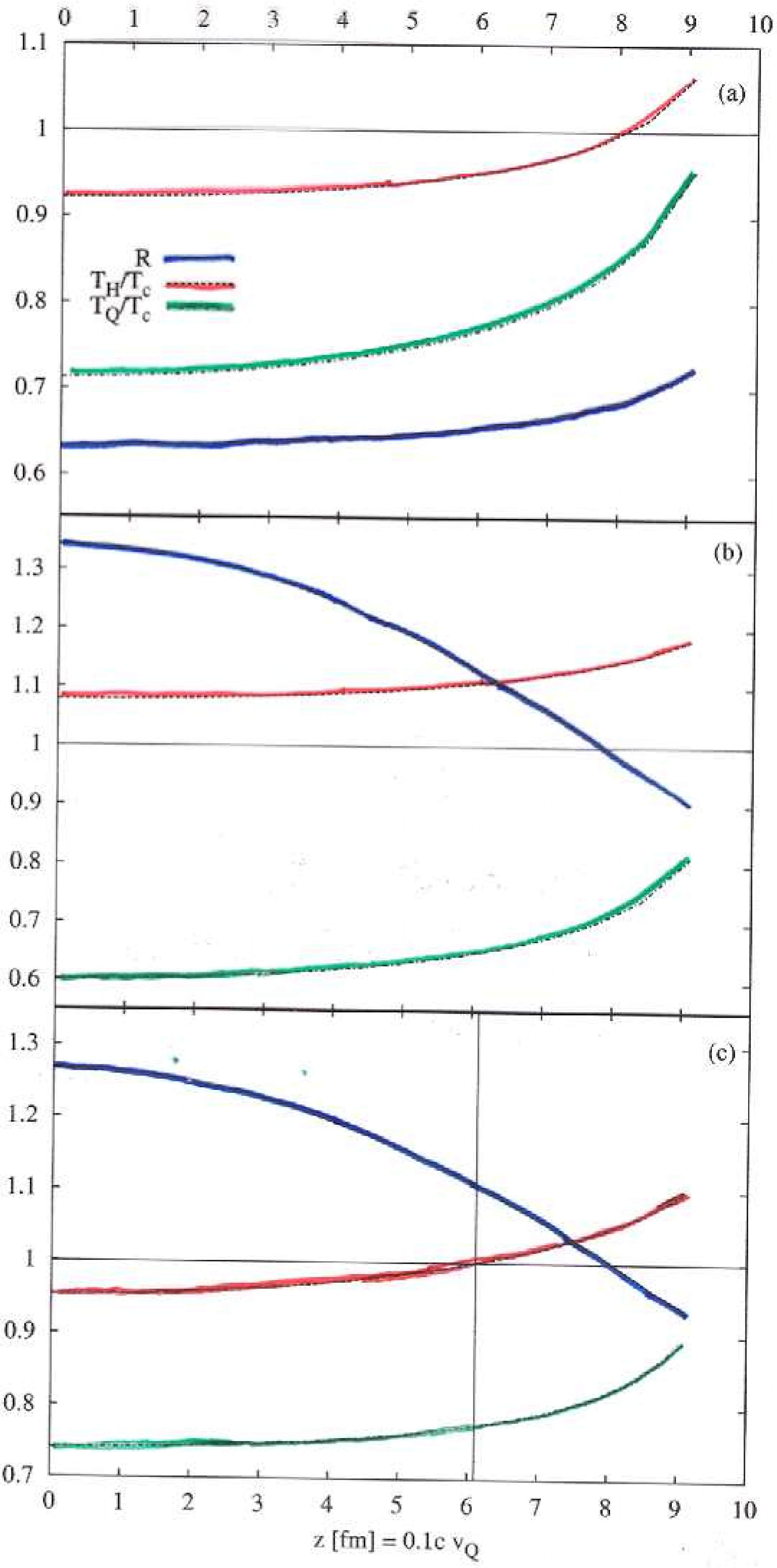
$$p(\tau) = \frac{\sigma}{3} T^4(\tau) - b\, T(\tau)$$

$\tau \to \infty \;,\quad T \to T_m$

$e \to e_m = \sigma T_m^{\,4}$

$$\text{EoS (1)} \Rightarrow \quad e = e_0 \left(\frac{\tau_0}{\tau} \right)^{4/3} \xrightarrow[\tau \to \infty]{} 0$$

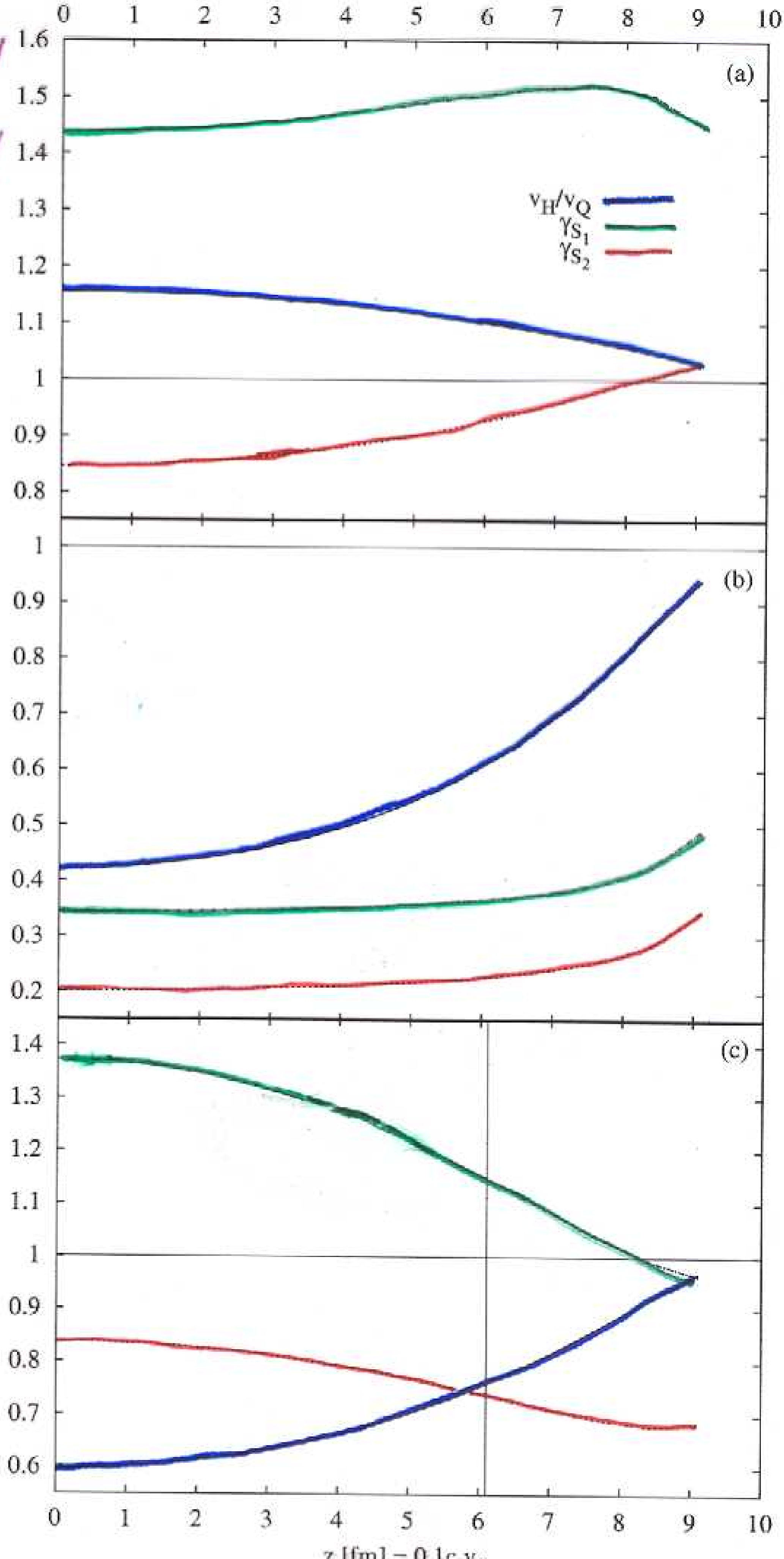
$$\text{EoS (2)} \Rightarrow \quad e = e_0 \left(\frac{\tau_0}{\tau} \right)^{4/3} + B \left(1 - \left(\frac{\tau_0}{\tau} \right)^{4/3} \right) \xrightarrow[\tau \to \infty]{} B$$



Quantities are
not sensative to m_s

γ_{S_1} : $m_s = 150$ MeV

γ_{S_2} : $m_s = 250$ MeV



$\frac{V_H}{V_Q}$ is not sensative to m_s.

Conclusions

- Realistic and accurate study of FO can not be neglected

- FO process is very sensative to the properties of EoS

- Strangeness production is very sensative to the correct FO treatment and pre FO EoS

- With an accurate FO description strangeness production could be a QGP signal and a tool to study properties of pre FO EoS

- More realistic model is needed to compare with experimental data