Thermodynamics of quark matter with multiquark clusters in an effective Beth-Uhlenbeck type approach

Mateusz Cierniak, David Blaschke

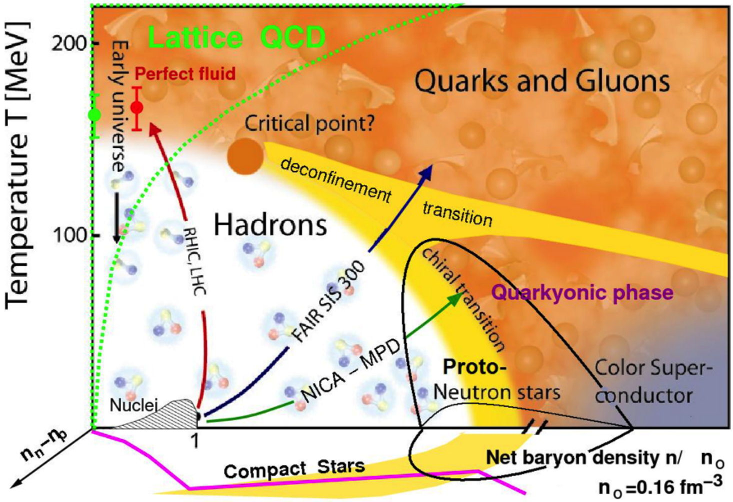
Division of Elementary Particle Theory,
Institute of Theoretical Physics,
University of Wroclaw.

Uniwersytet Wrocławski

National Science Centre Poland

Overview

QCD phase diagram[1]



[1] Image retrieved from http://theor0.jinr.ru/twiki-cgi/view/NICA.

The ansatz for the thermodynamic potential[2]

$$\Omega_{total}(T,\mu,\phi,\bar{\phi}) = \Omega_{QGP}(T,\mu,\phi,\bar{\phi}) + \Omega_{MHRG}(T,\mu,\phi,\bar{\phi})$$

The high–T,μ QGP part[3]

$$\Omega_{QGP}(T,\mu,\phi,\bar{\phi}) = \Omega_{PNJL}(T,\mu,\phi,\bar{\phi}) + \Omega_{pert}(T,\mu,\phi,\bar{\phi})$$

Mean–field PNJL potential

$$\Omega_{PNJL}(T,\mu,\phi,\bar{\phi}) = \mathcal{U}(T,\phi,\bar{\phi}) + \mathcal{V}(T,\mu) + \Omega_{Q}(T,\mu,\phi,\bar{\phi})$$

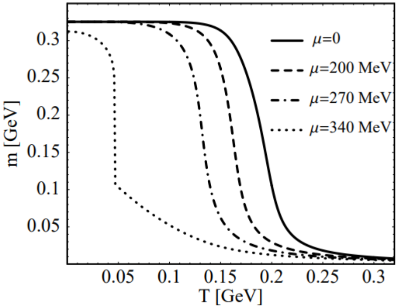
$$\Omega_{Q}(T,\mu,\phi,\bar{\phi}) = -\frac{2}{3}N_f N_c \int \frac{d^3p}{(2\pi)^3}\left\{3E_p + \frac{p}{E_p} f_\phi^{(1),+} + \frac{p}{E_p}\left[f_\phi^{(1),-}\right]^*\right\}$$

Polyakov–loop modified fermion distribution function

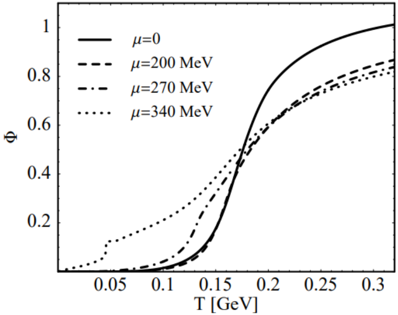
$$f_\phi^{(a),\pm} = \frac{(\bar{\phi} + 2\phi y_a^\pm)y_a^\pm + {y_a^\pm}^3}{1 + 3(\bar{\phi} + \phi y_a^\pm)y_a^\pm + {y_a^\pm}^3}\ ,\ y_a^\pm = e^{-(E_p \mp a\mu)/T}$$

[2]Blaschke et al., Symmetry 13 (2021)
[3]Turko et al., J.Phys.Conf.Ser. 455 (2013)

$$\mathcal{U}(T,\phi,\bar{\phi}) = T^4\left[-\frac{b_2(T)}{2}\bar{\phi}\phi - \frac{b_3}{6}(\phi^3+\bar{\phi}^3) + \frac{b_4}{4}(\bar{\phi}\phi)^2\right]$$

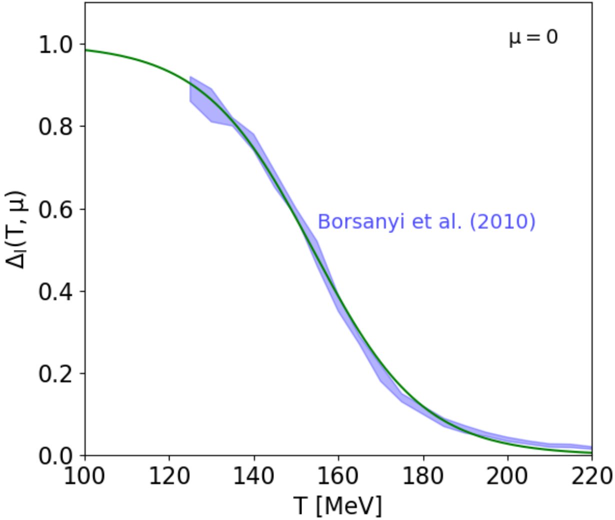


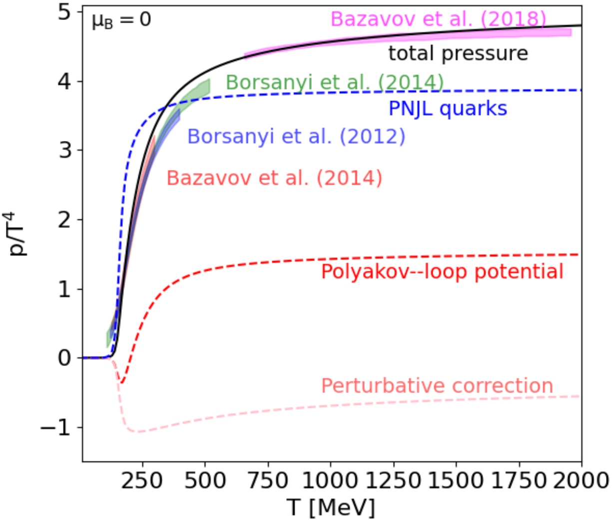
(a)

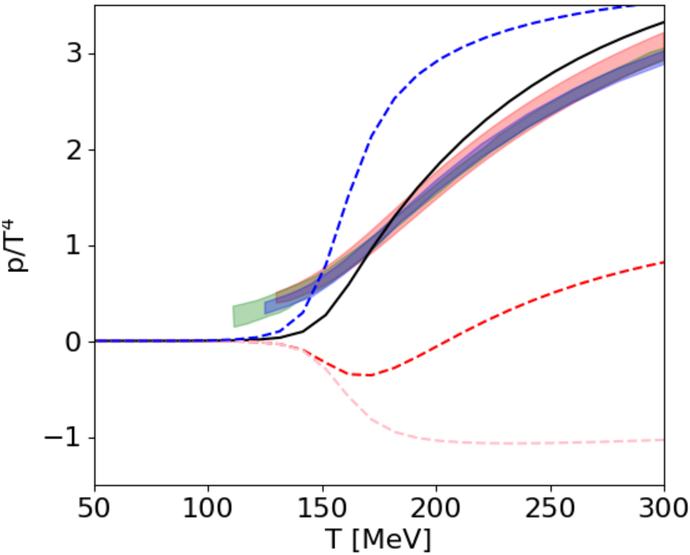


(b)

[4]Ratti et al., Phys.Rev.D 73, (2006)


μ = 0
Borsanyi et al. (2010)
1.0
0.8
0.6
0.4
0.2
0.0
Δl(T, μ)
100
120
140
160
180
200
220
T [MeV]


μB = 0
Bazavov et al. (2018)
total pressure
Borsanyi et al. (2014)
PNJL quarks
Borsanyi et al. (2012)
Bazavov et al. (2014)
Polyakov--loop potential
Perturbative correction
p/T4
T [MeV]
5
4
3
2
1
0
−1
250
500
750
1000
1250
1500
1750
2000


3
2
1
0
−1
p/T⁴
50
100
150
200
250
300
T [MeV]

The Mott–HRG potential

$$\Omega_{MHRG}(T,\mu,\phi,\bar{\phi}) = \sum_{i=M,B,\ldots} \Omega_i(T,\mu,\phi,\bar{\phi}),$$

Fermionic clusters (a - odd)

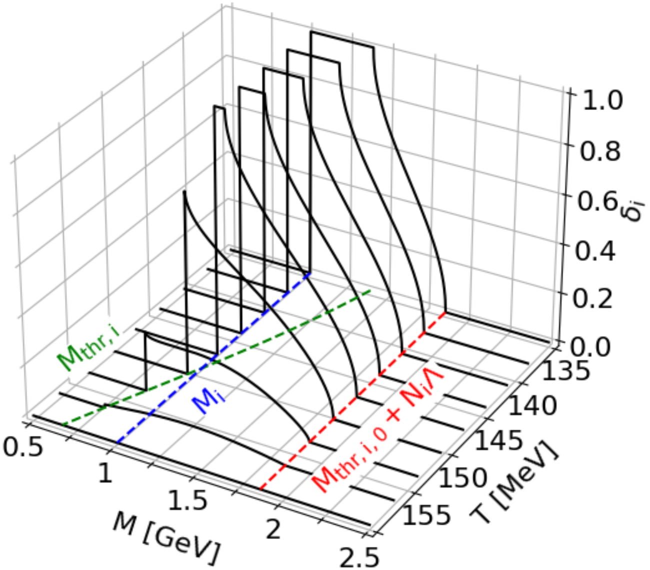
$$\Omega_i = -d_i \int_0^\infty \frac{dp\ p^2}{2\pi^2} \int_0^\infty \frac{dM}{\pi} \frac{M}{E_p} \left\{ f_\phi^{(a),+} + \left[f_\phi^{(a),-} \right]^* \right\} \delta_i(M,T,\mu),$$

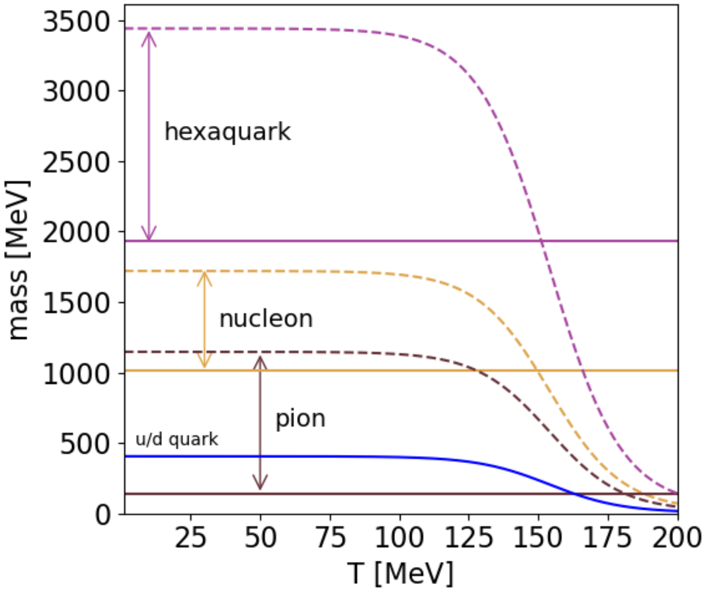
Bosonic clusters (a - even)

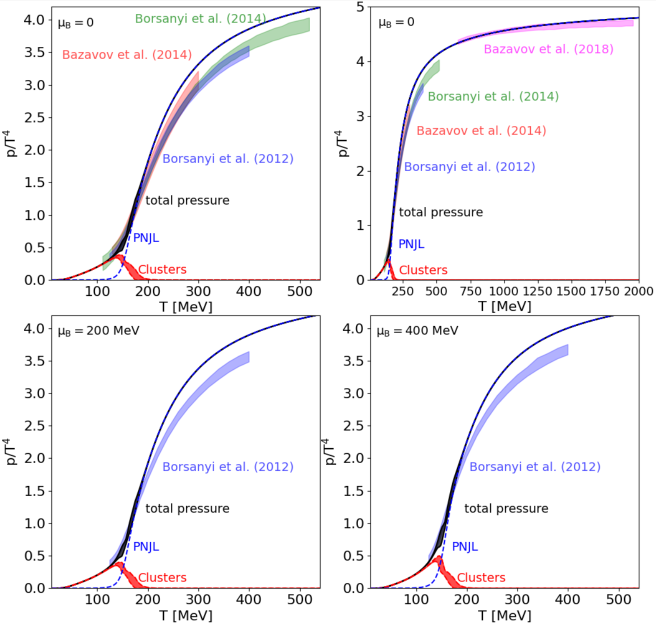
$$\Omega_i = d_i \int_0^\infty \frac{dp\ p^2}{2\pi^2} \int_0^\infty \frac{dM}{\pi} \frac{M}{E_p} \left\{ g_\phi^{(a),+} + \left[g_\phi^{(a),-} \right]^* \right\} \delta_i(M,T,\mu),$$

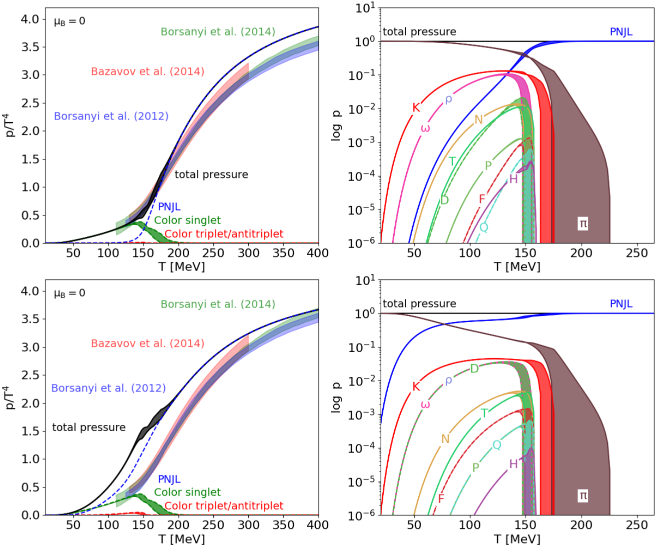
Polyakov–loop modified boson distribution function

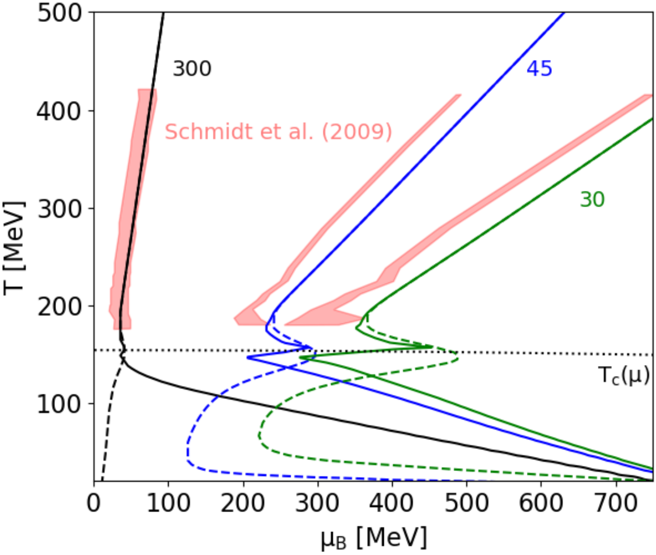
$$g_\phi^{(a),\pm} = \frac{(\bar{\phi} - 2\phi y_a^{\pm}) y_a^{\pm} + {y_a^{\pm}}^3}{1 - 3(\bar{\phi} - \phi y_a^{\pm}) y_a^{\pm} - {y_a^{\pm}}^3}$$


1.0
0.8
0.6
0.4
0.2
0.0
δ_i
$M_{thr,i}$
M_i
$M_{thr,i,0} + N_i\Lambda$
0.5
1
1.5
2
2.5
M [GeV]
135
140
145
150
155
T [MeV]


3500
3000
2500
2000
1500
1000
500
0
mass [MeV]
hexaquark
nucleon
pion
u/d quark
25
50
75
100
125
150
175
200
T [MeV]

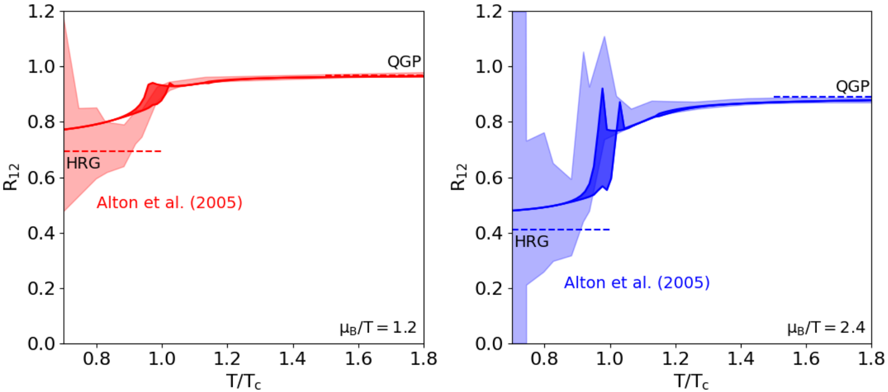

$\mu_B = 0$
Borsanyi et al. (2014)
Bazavov et al. (2014)
Borsanyi et al. (2012)
total pressure
PNJL
Clusters
p/T^4
T [MeV]
$\mu_B = 0$
Bazavov et al. (2018)
Borsanyi et al. (2014)
Bazavov et al. (2014)
Borsanyi et al. (2012)
total pressure
PNJL
Clusters
p/T^4
T [MeV]
$\mu_B = 200$ MeV
Borsanyi et al. (2012)
total pressure
PNJL
Clusters
p/T^4
T [MeV]
$\mu_B = 400$ MeV
Borsanyi et al. (2012)
total pressure
PNJL
Clusters
p/T^4
T [MeV]

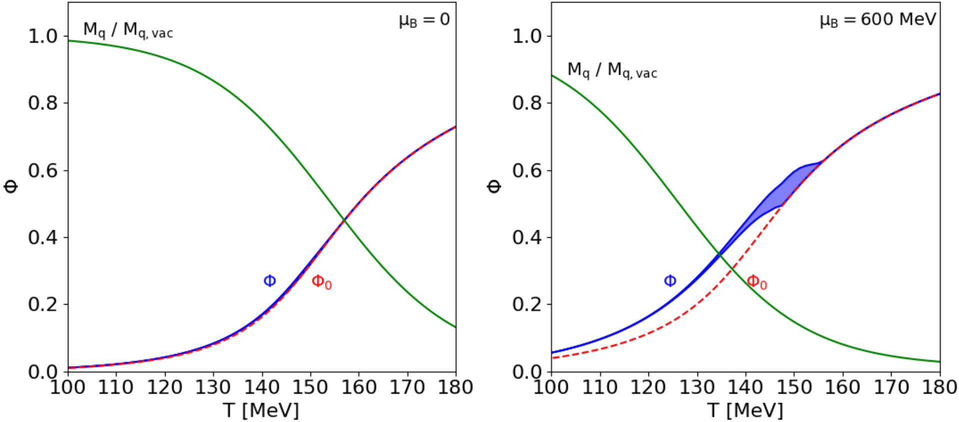

$\mu_B = 0$
Borsanyi et al. (2014)
Bazavov et al. (2014)
Borsanyi et al. (2012)
total pressure
PNJL
Color singlet
Color triplet/antitriplet
p/T^4
T [MeV]
log p
K
ρ
ω
N
T
D
P
F
H
Q
π


500
400
300
200
100
T [MeV]
0
100
200
300
400
500
600
700
μB [MeV]
300
45
30
Schmidt et al. (2009)
Tc(μ)

$$R_{12}(T,\mu_q) = \frac{n_q(T,\mu_q)}{\mu_q \chi_q(T,\mu_q)} \ , \ n_q(T,\mu_q) = -\frac{\partial \Omega(T,\mu_q)}{\partial \mu_q} \ ,$$

$$\chi_q(T,\mu_q) = \frac{\partial n_q(T,\mu_q)}{\partial \mu_q}$$




$\mu_B = 0$
$M_q / M_{q,vac}$
Φ
Φ_0
T [MeV]
$\mu_B = 600$ MeV
$M_q / M_{q,vac}$
Φ
Φ_0
T [MeV]

Conclusions:

- The MHRG model can be used to describe hadron thermodynamics within a unified quark–hadron approach.
- The model is able to reproduce existing lQCD thermodynamic data.
- Presence of quark clusters qualitatively changes the behavior of PNJL mean–fields at finite baryochemical potentials.

Literature:

- Blaschke et al., Symmetry 13 (2021); ArXiv: 2012.12894
- Blaschke, Cierniak, Röpke, Schuck, not yet published, soon available on ArXiv ;)