Chiral quark models of hadronic matter (IV)

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Contents:

- Particle production in HIC: statistical model and freeze-out in the PhD
- The idea: self-induced hadron delocalization! Mott-Anderson freeze-out!
- Chiral condensate beyond meanfield and freeze-out curve
- Mott-Hagedorn resonance gas: Beth-Uhlenbeck EoS and phase diagram

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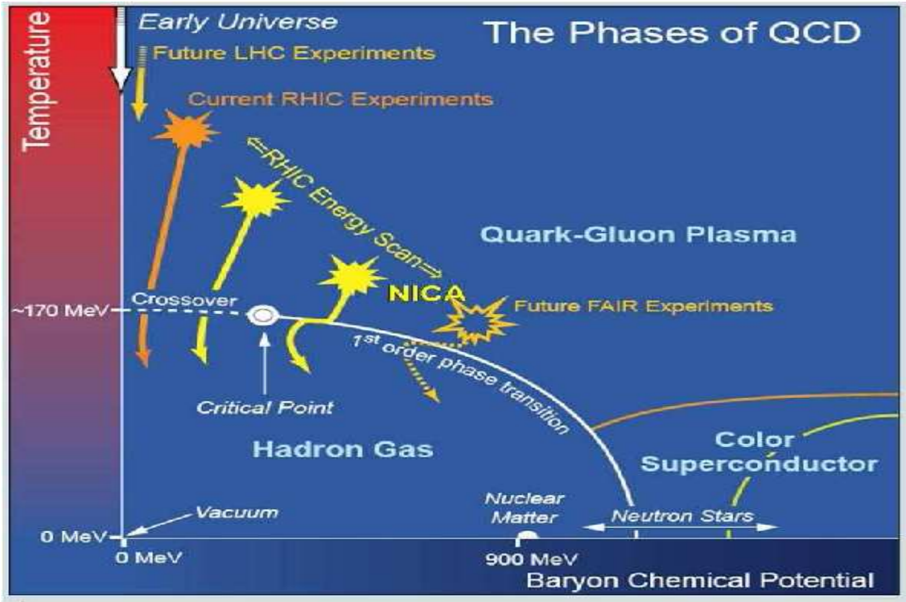
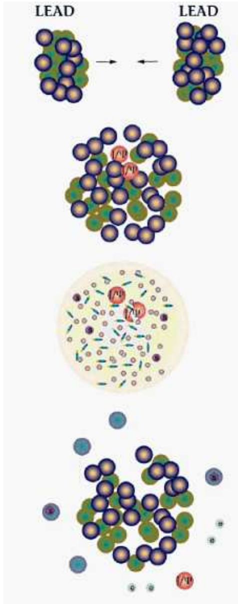
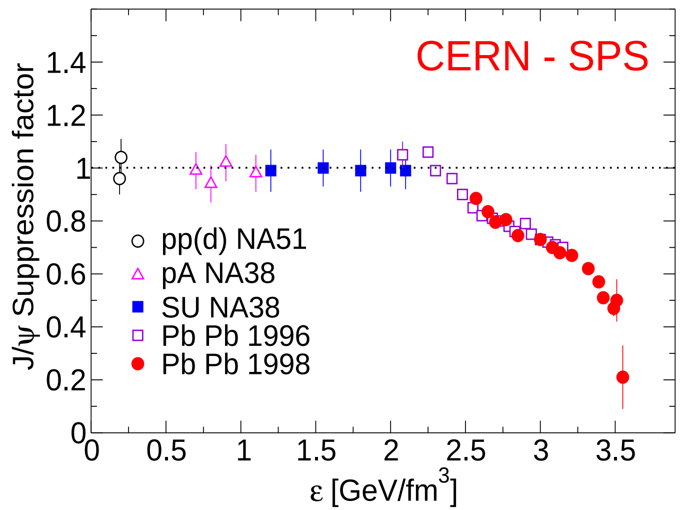
Lattice QCD, Hadron Structure and Hadronic Matter, Dubna, 05.-16.09.2011

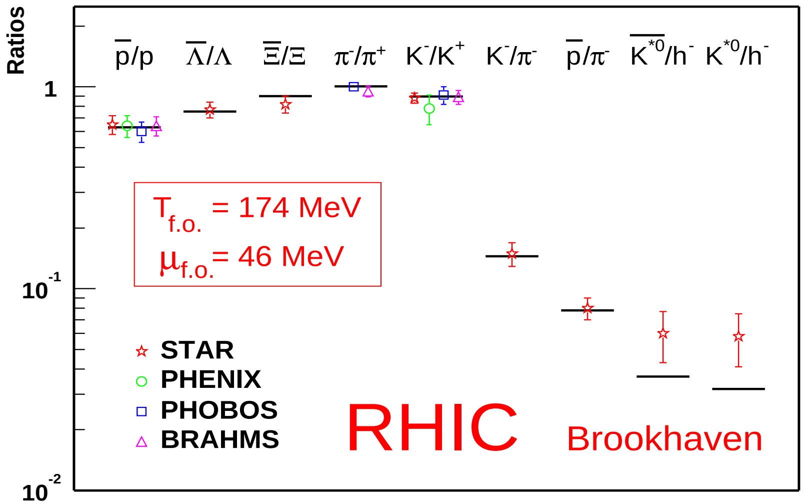
PHASEDIAGRAM: FREEZE-OUT IN HEAVY-ION COLLISIONS





QGP Signal: Anomalous J/ψ suppression





Statistical model describes composition of hadron yields in Heavy-Ion Collisions with few freeze-out parameters.

$$\ln Z[T,V,\{\mu\}] = \pm V \sum_i \frac{g_i}{2\pi^2}\int_0^\infty dp\, p^2 \ln[1 \pm \lambda_i \exp(-\beta\varepsilon_i(p))]$$

$$\lambda_i(T,\{\mu\}) = \exp[\beta(\mu_B B_i + \mu_S S_i + \mu_Q Q_i)]$$

Braun-Munzinger, Redlich, Stachel, in *QGP III* (2003)

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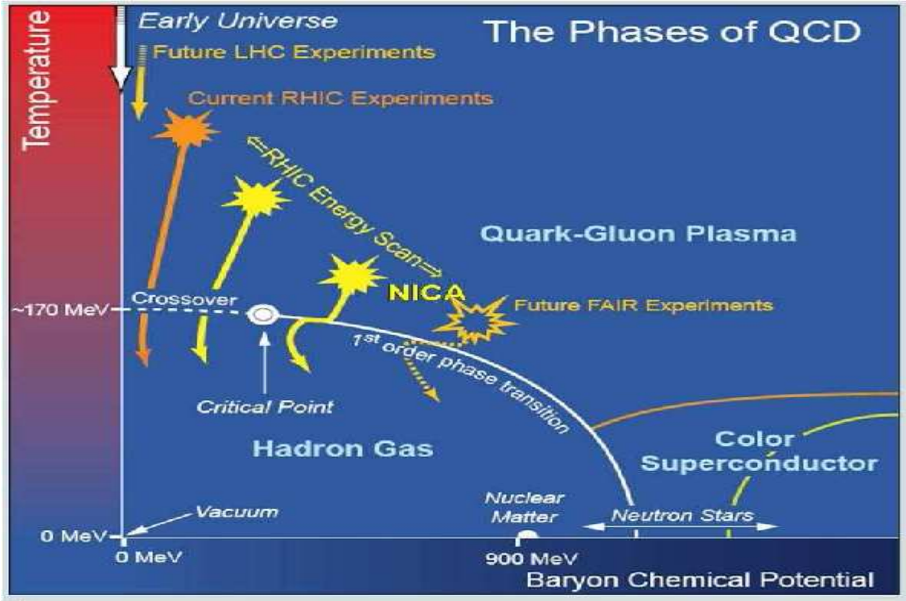

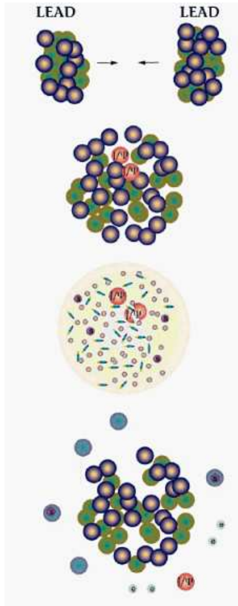

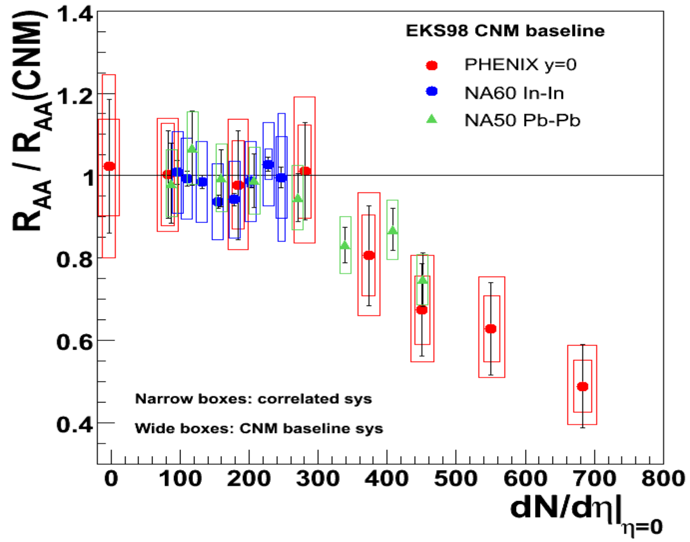

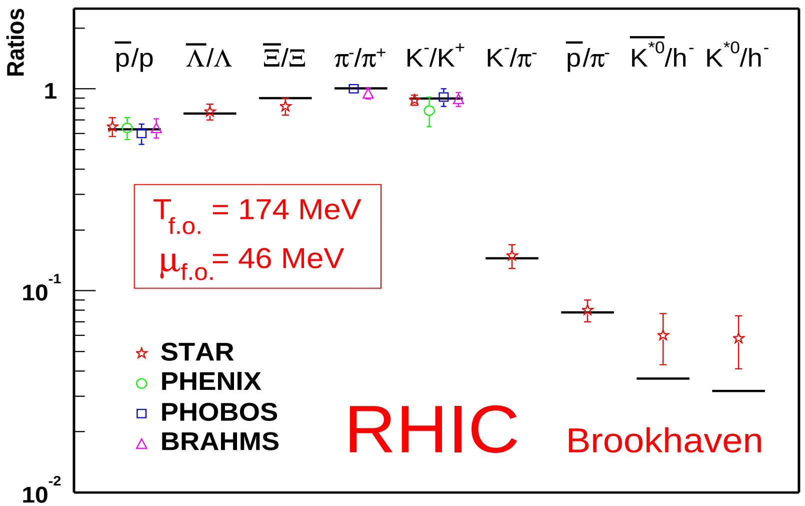

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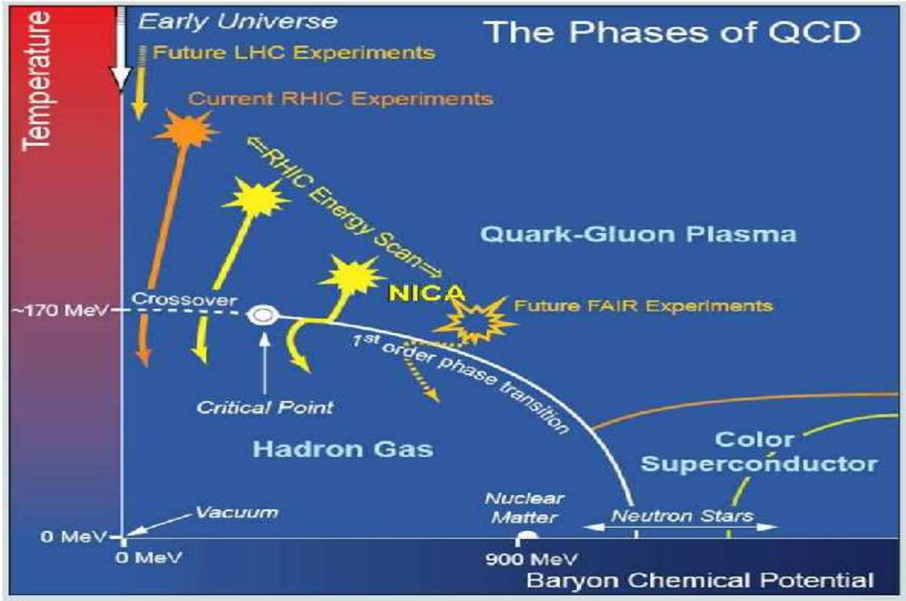
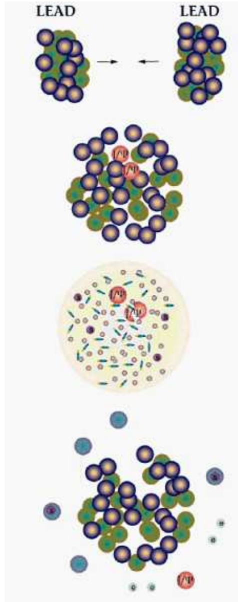
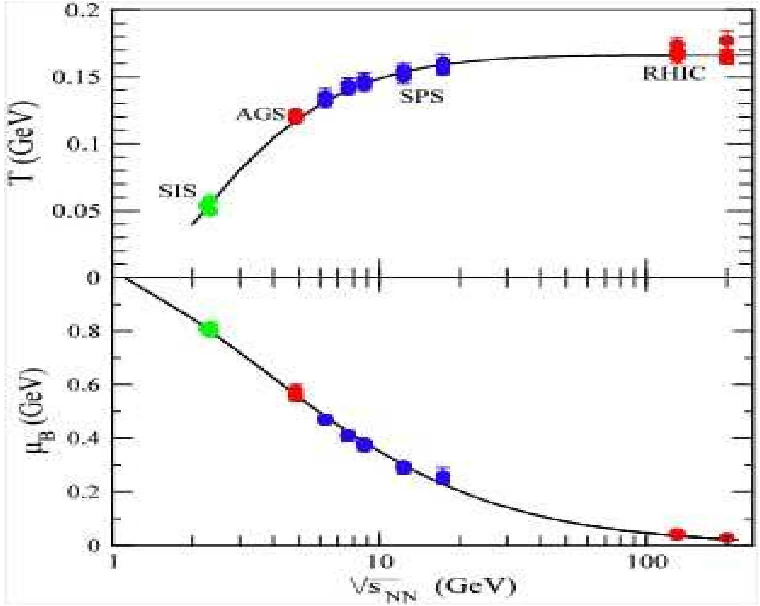
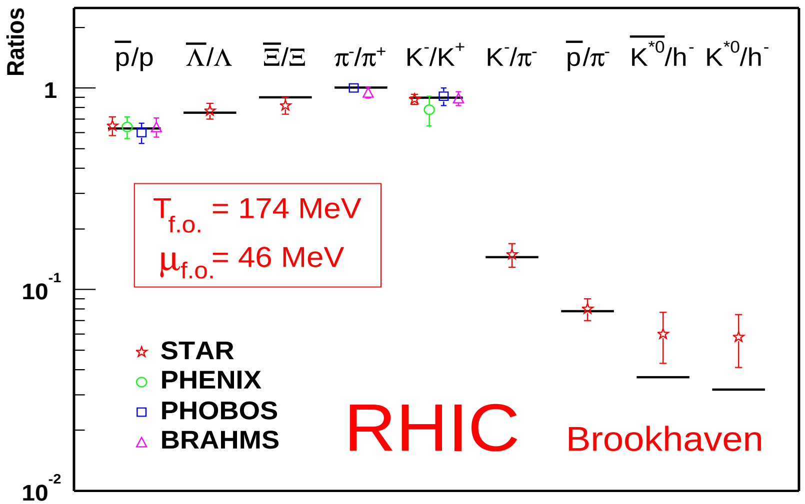
Braun-Munzinger, Redlich, Stachel, in *QGP III* (2003)

Phasediagram: Freeze-out in Heavy-Ion Collisions (II)









Statistical model describes composition of hadron yields in Heavy-Ion Collisions with few freeze-out parameters.

$$\ln Z[T, V, \{\mu\}] = \pm V \sum_i \frac{g_i}{2\pi^2} \int_0^\infty dp\, p^2 \ln[1 \pm \lambda_i \exp(-\beta\varepsilon_i(p))]$$

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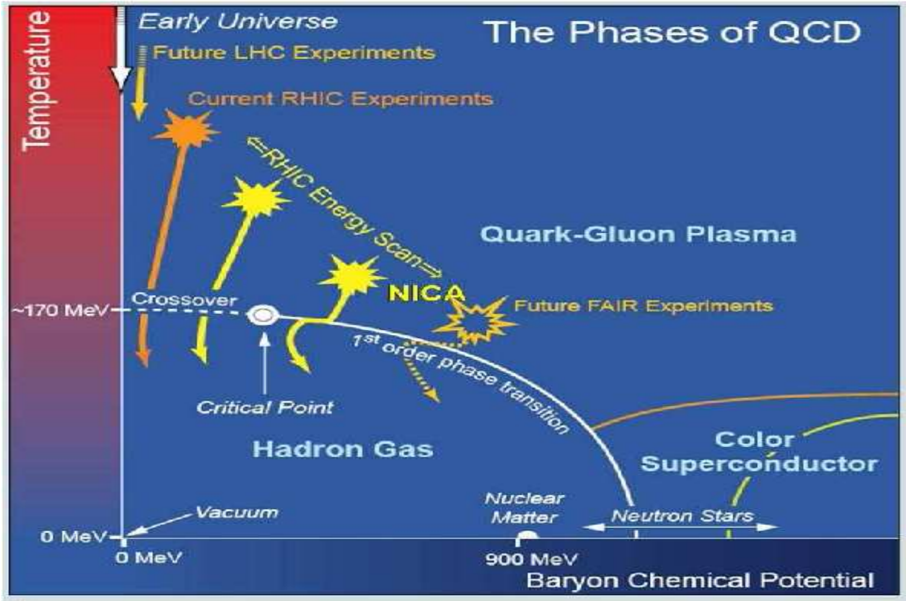
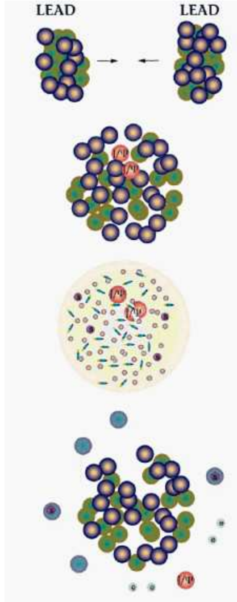
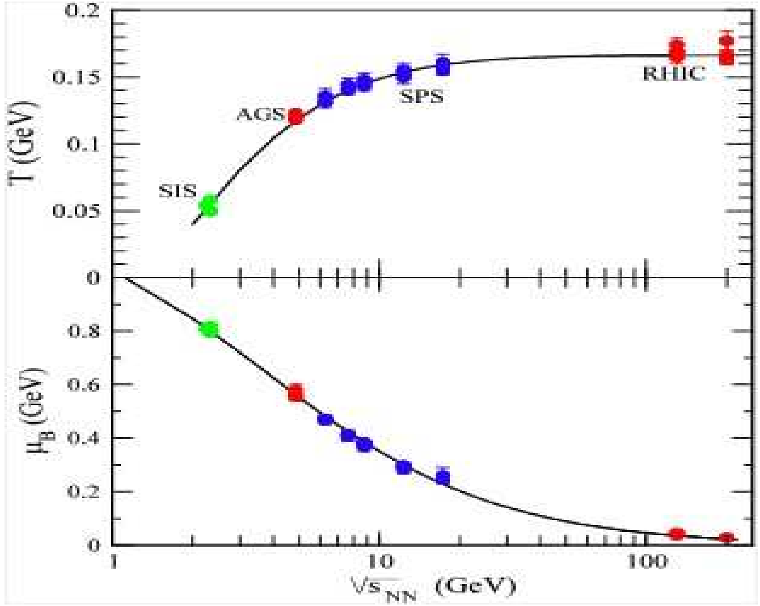
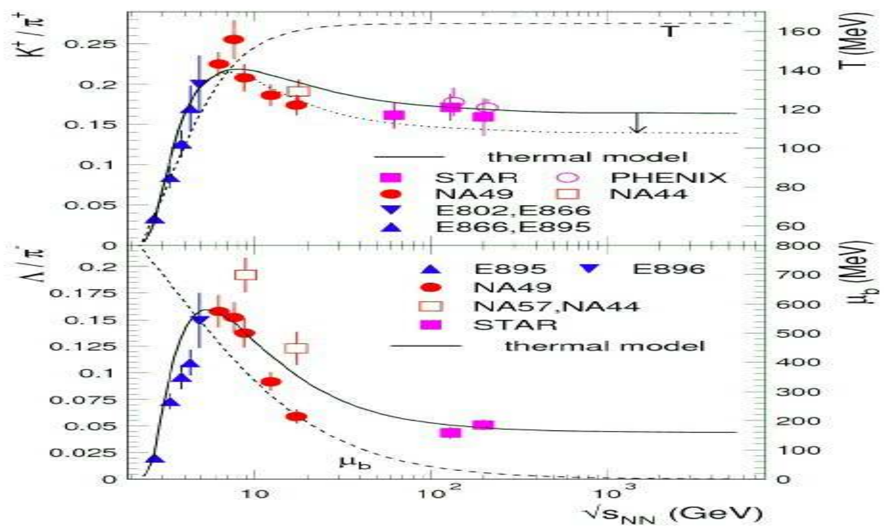
Braun-Munzinger, Redlich, Stachel, in *QGP III* (2003)

PHASEDIAGRAM: FREEZE-OUT IN HEAVY-ION COLLISIONS (III)



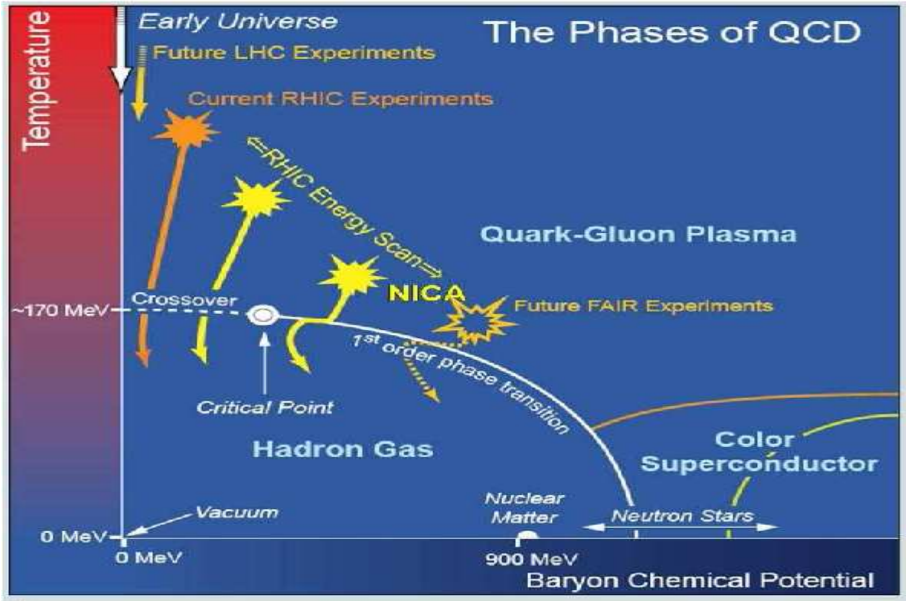


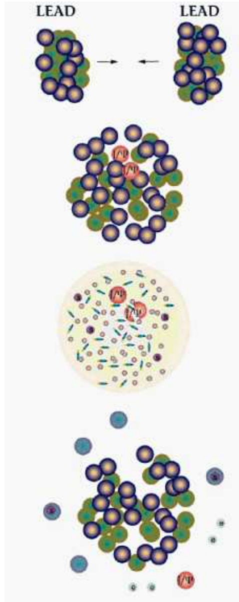


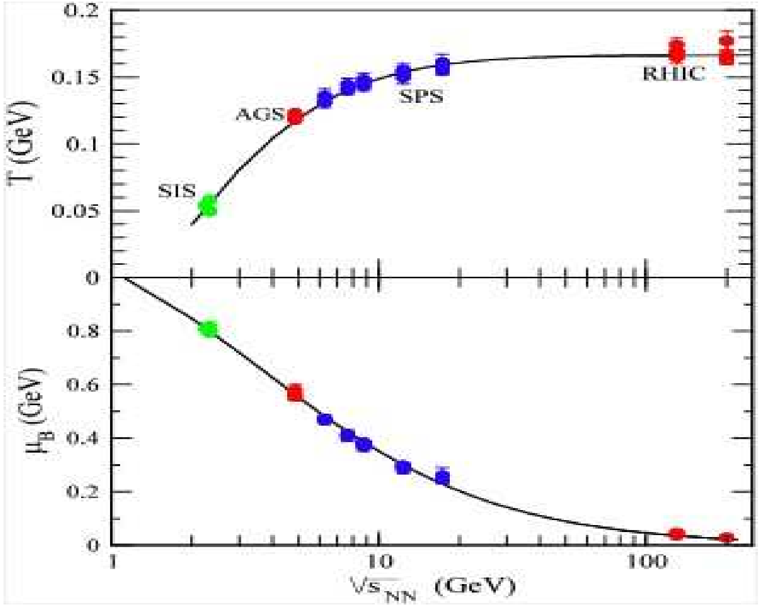


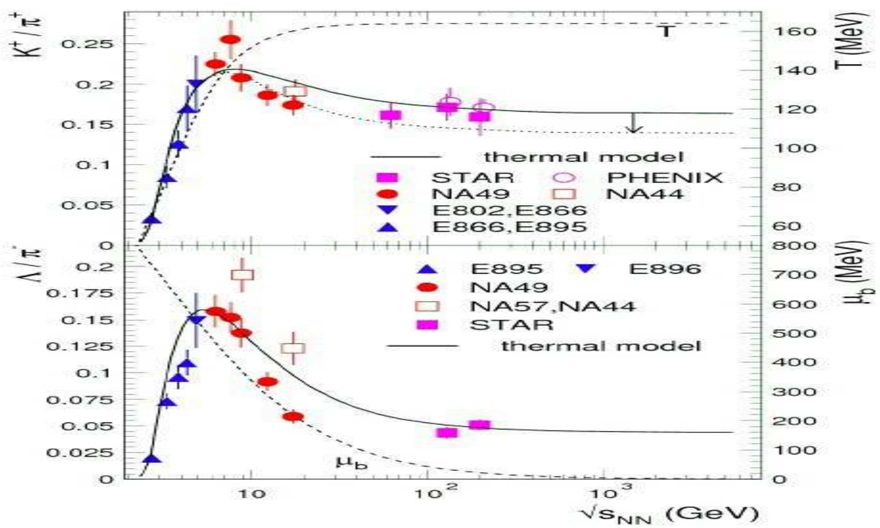
Strange MatterHorn (Pisarski)

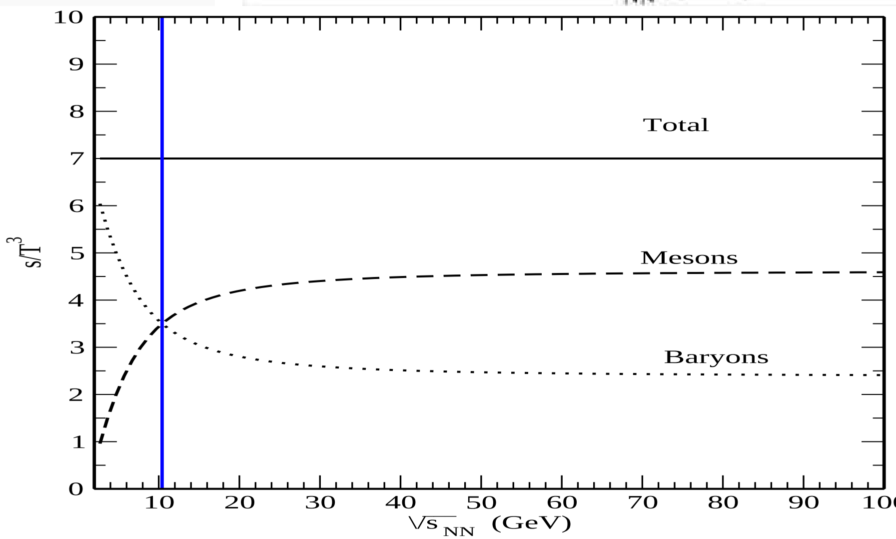
PHASEDIAGRAM: FREEZE-OUT IN HEAVY-ION COLLISIONS (III)





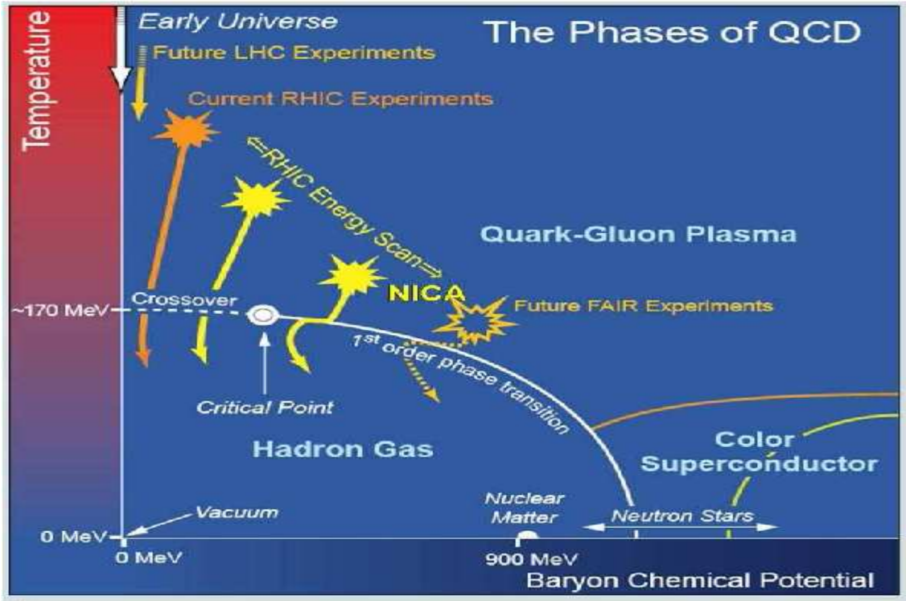


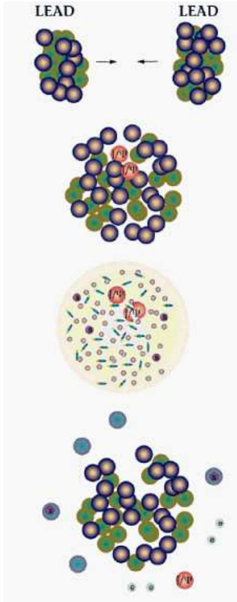




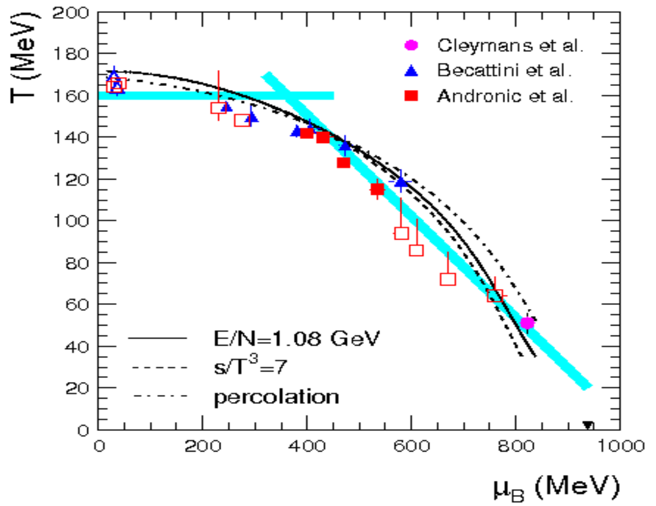
Baryon → Meson Dominance

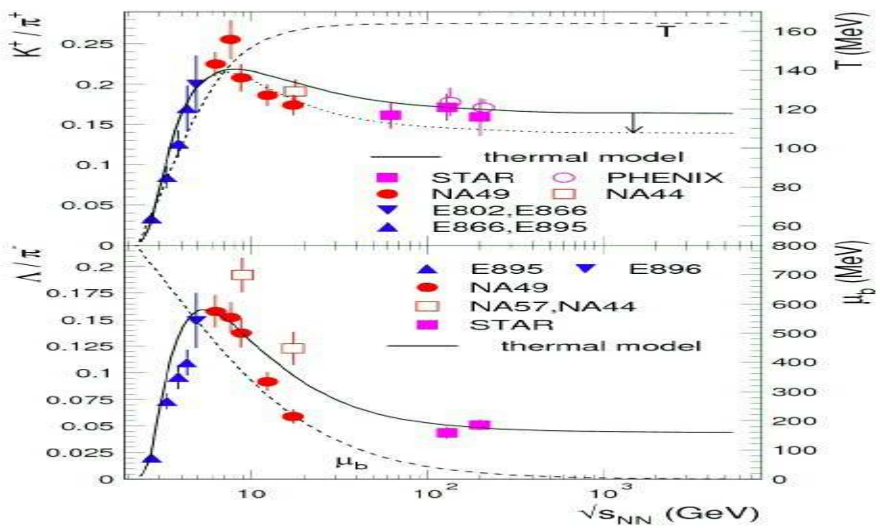
PHASEDIAGRAM: FREEZE-OUT IN HEAVY-ION COLLISIONS (IV)

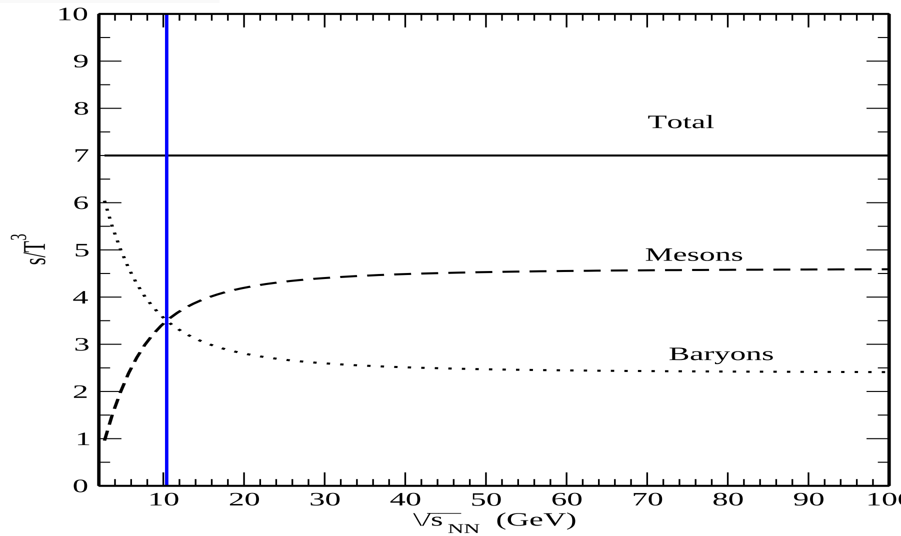




Andronic et al., arxiv:0911.4806

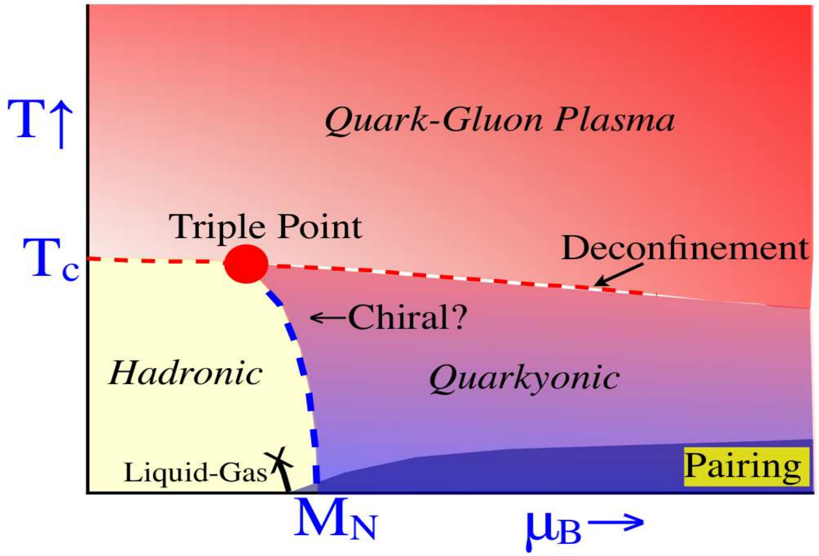


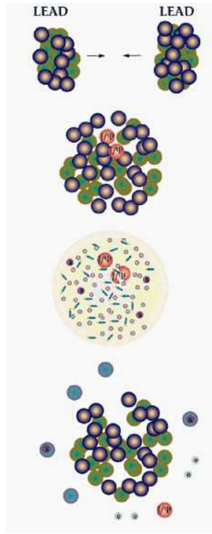


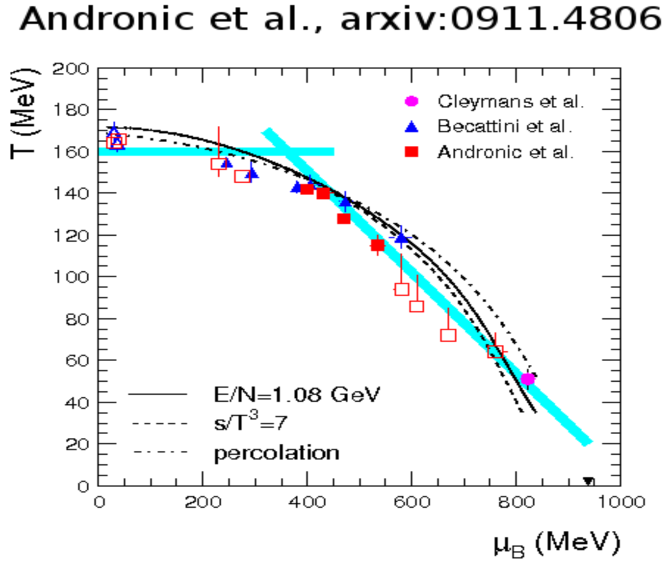


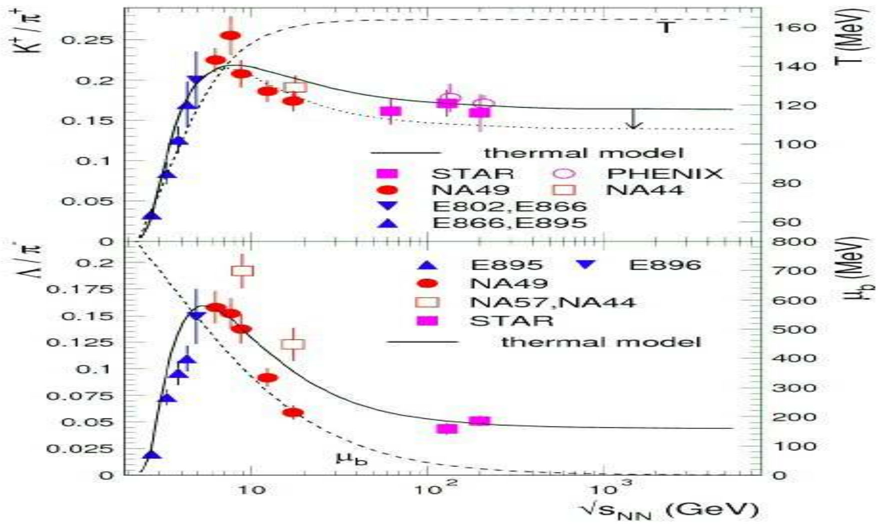
Baryon → Meson Dominance

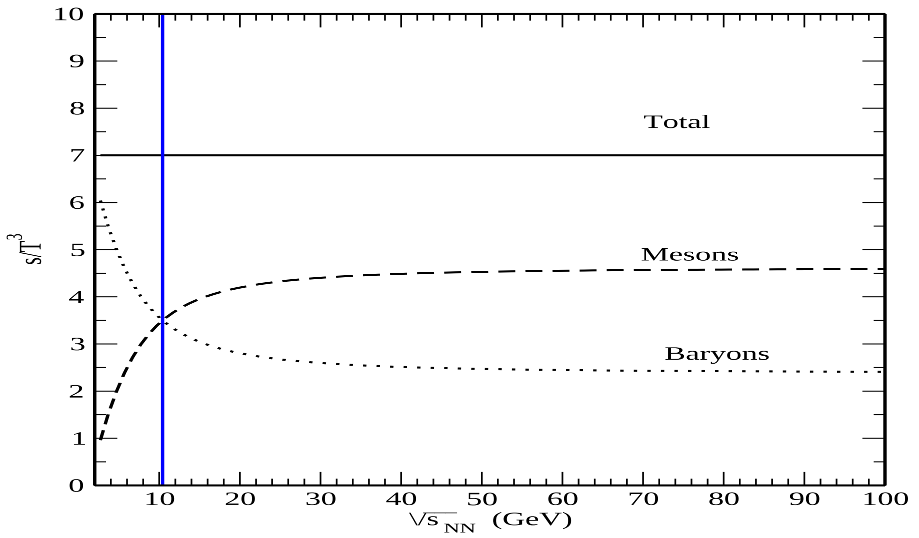
PHASEDIAGRAM: FREEZE-OUT IN HEAVY-ION COLLISIONS (V)







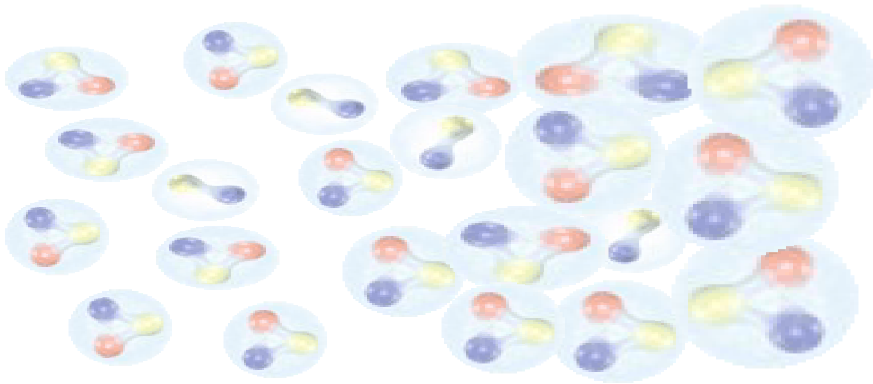




Andronic et al., arxiv:0911.4806; NPA (2010)

QUARKYONIC PHASE = CHIRAL SYMMETRY + CONFINEMENT

What happens on "Happy Island"?



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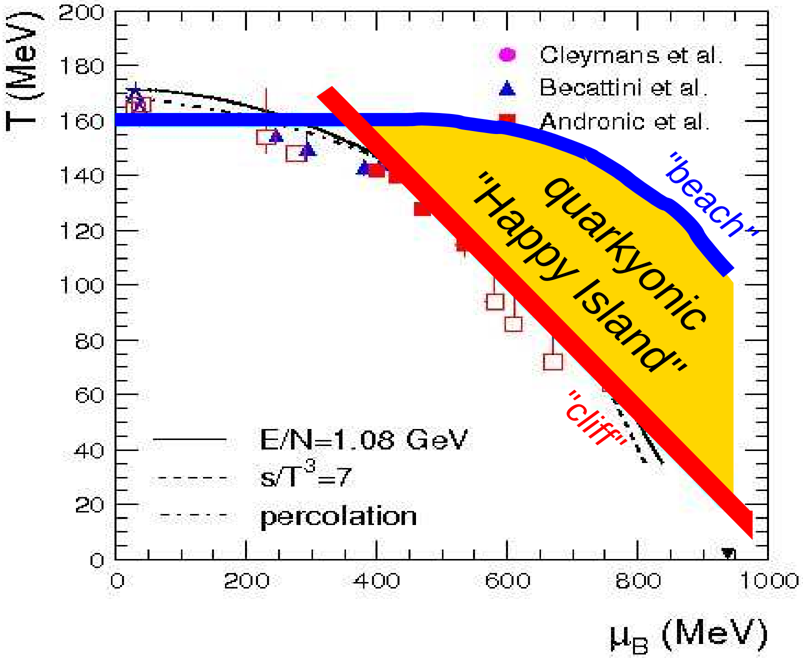


"beach": hadron resonances $\longrightarrow$ QGP

"cliff":

- (unmodified) vacuum bound state energies
- fast chemical equilibration

Explanation:

Strong medium dependence of rates for flavor (quark) exchange processes

Reason:

- lowering of thresholds
- increase of hadron size (Pauli principle) $\to$ geometrical overlap (percolation)

IDEA: FREEZE-OUT BY HADRON LOCALIZATION (INVERSE MOTT-ANDERSON MECHANISM)

Kinetic freeze-out: $\tau_{\rm exp}(T,\mu) = \tau_{\rm coll}(T,\mu)$

Reactive collisions: $\tau_{\rm coll}^{-1}(T,\mu) = \sum_{i,j} \sigma_{ij} n_j$

Povh-Hüfner law: $\sigma_{ij} = \lambda \langle r_i^2 \rangle \langle r_j^2 \rangle \ , \quad \lambda \sim 1~{\rm GeV/fm} = 5~{\rm fm}^{-2}$

Also for quark-exchange in hadron-hadron scatt. [Martins et al., PRC 51, 2723 (1995)]

Pion swelling at χSR: $r_\pi^2(T,\mu) = \frac{3}{4\pi^2} f_\pi^{-2}(T,\mu)$,   [Hippe & Klevansky, PRC 52, 2173 (1995)]

Use GMOR relation $f_\pi^2(T,\mu) = -m_0 \langle \bar{q} q \rangle_{T,\mu} / M_\pi^2$ to connect hadron radii and chiral restoration!

$$r_\pi^2(T,\mu) = \frac{3M_\pi^2}{4\pi^2 m_q} |\langle \bar{q} q \rangle_{T,\mu}|^{-1} \ , \quad r_N^2(T,\mu) = r_0^2 + r_\pi^2(T,\mu) \ ; \quad r_\pi = 0.59~{\rm fm}, \ r_N = 0.74~{\rm fm}, \ r_0 = 0.45~{\rm fm}$$

Expansion time scale: $\tau_{\rm exp}(T,\mu) = a \ s^{-1/3}(T,\mu)$,

follows from $S = s(T,\mu)\, V(\tau_{\rm exp}) = {\rm const}$ and $\tau_{\rm exp}(T,\mu) = a \ s^{-1/3}(T,\mu)$.

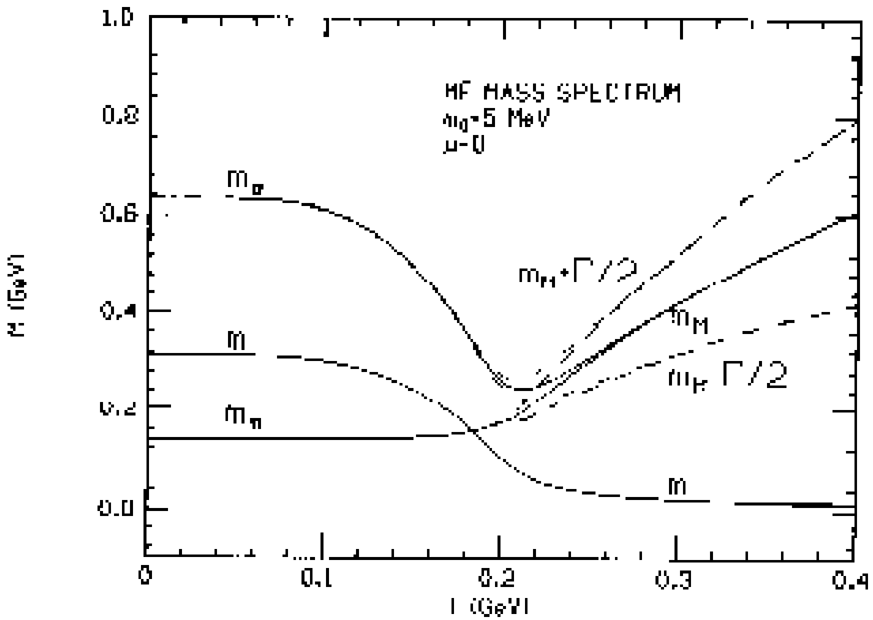
D.B., J. Berdermann, J. Cleymans, K. Redlich, arxiv:1102.2908 (2011)

GENERALIZED BETH-UHLENBECK EOS: NJL MODEL RESULTS

Generalized Beth-Uhlenbeck approach:

Schmidt, Röpke, Schulz, Ann. Phys. 202 (1990) 57
Hüfner, Klevansky et al., Ann. Phys. 234 (1994) 225

P. Zhuang et al. / Nuclear Physics A 576 (1994) 525–552



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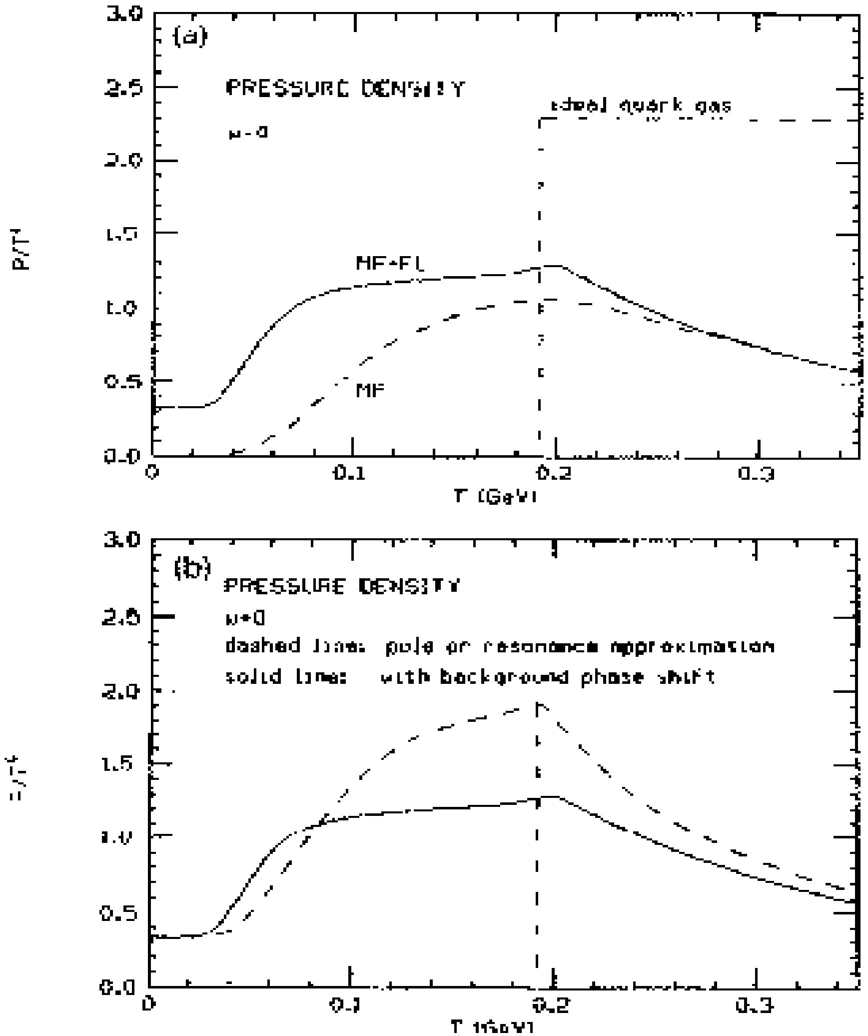
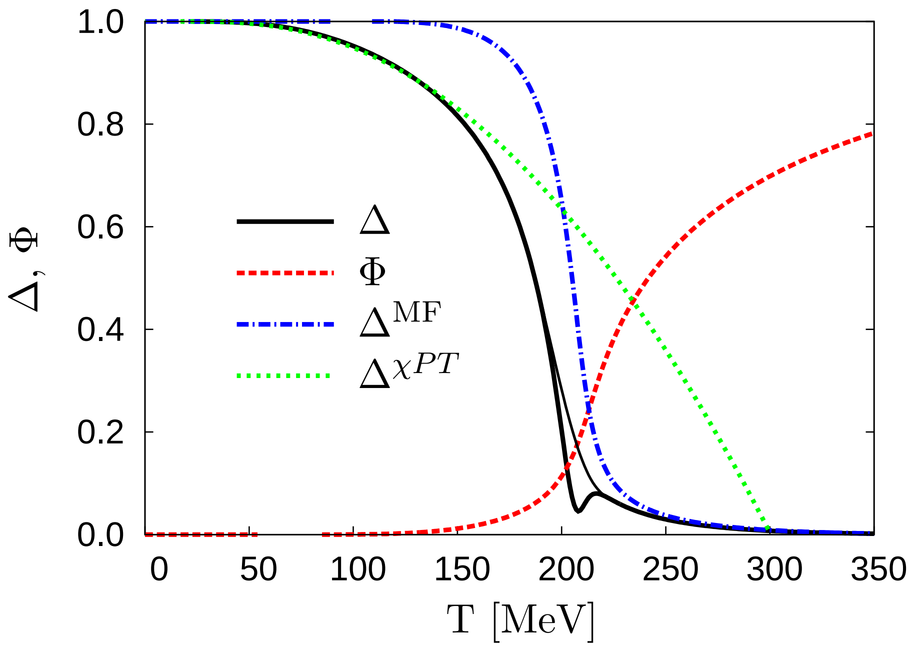
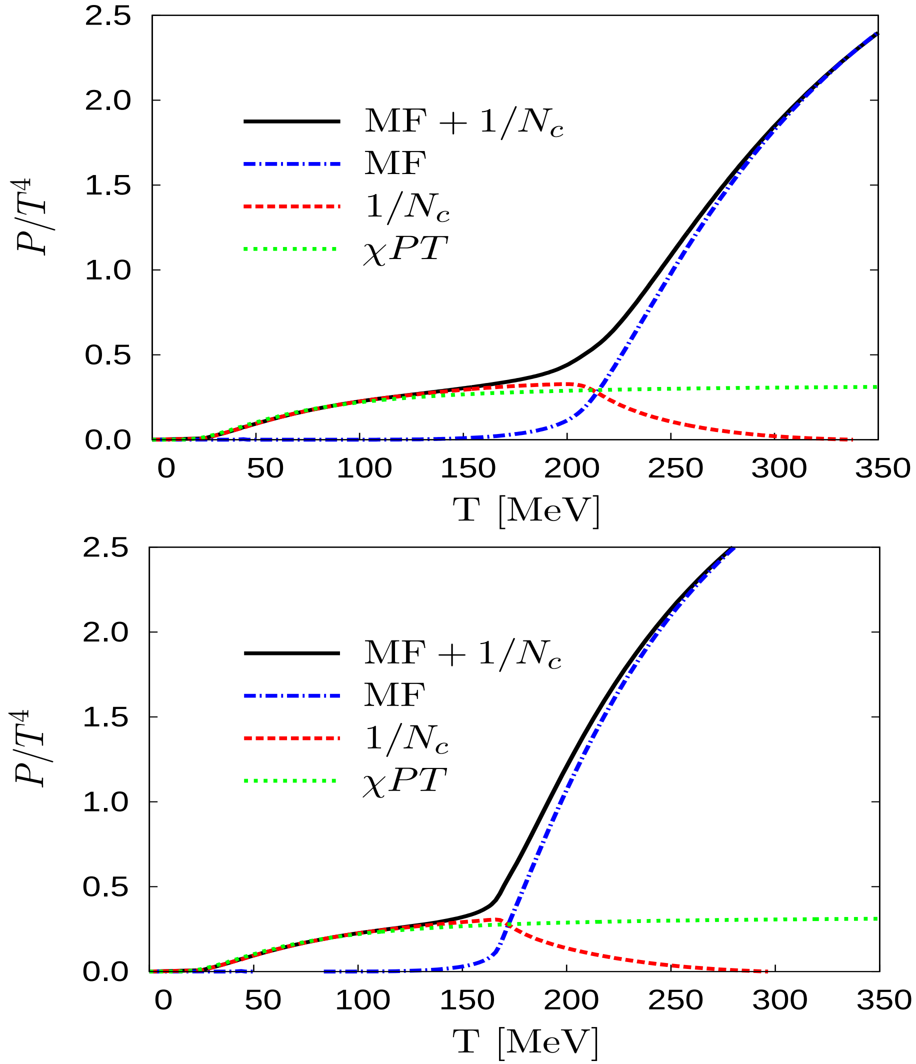


Gen. Beth-Uhlenbeck EoS: nonlocal PNJL results

Nonlocal PNJL model beyond meanfield:

Blaschke et al., Yad. Fiz. 71 (2008)
Radzhabov et al., PRD 83 (2011) 116004





PL-Potential with $T_0 = 270$ MeV (upper panel), and $T_0 = 208$ MeV (lower panel) $\Longrightarrow$

PNJL BEYOND MF: PION $(q\bar{q})$ AND NUCLEON (qqq) MEDIUM

Idea: melting $\langle\bar{q}q\rangle \to$ swelling hadrons $\to$ flavor kinetics = quark percolation $\to$ freeze-out

$$\langle\bar{q}q\rangle(T,\mu) = \frac{\partial}{\partial m_0}\Omega(T,\mu)\ , \quad \Omega(T,\mu) = \Omega_{\rm PNJL,MF}(T,\mu) + \Omega_{\rm meson}(T,\mu) + \Omega_{\rm baryon}(T,\mu)$$

$$\Omega_{\rm meson}(T,\mu) = \sum_{M=\pi,\dots} d_M \int \frac{d\omega}{\pi} \int \frac{d^3k}{(2\pi)^3} \left\{\frac{\omega}{2} + T\ \ln\left[1 - e^{-\beta\omega}\right]\right\} A_M(\omega,k)\ ,$$

$$\Omega_{\rm baryon}(T,\mu) = -\sum_{B=N,\dots} d_B \int \frac{d\omega}{\pi} \int \frac{d^3k}{(2\pi)^3} \left\{\frac{\omega}{2} + T\ \ln\left[1 + e^{-\beta(\omega-\mu_B)}\right] + (\mu_B \leftrightarrow -\mu_B)\right\} A_B(\omega,k)\ ,$$

$$A_M(\omega,k) = \pi\delta(\omega - E_M(k)) + \text{continuum}\ ,\quad A_B(\omega,k)\ldots\text{analoguous}$$

Remove vacuum terms; neglect continuum (for the freeze-out);
use GMOR: $M_\pi^2\, f_\pi^2 = -m_0\langle\bar{q}q\rangle$ and $\sigma_N = m_0(\partial m_N/\partial m_0) = 45$ MeV,
Enforce $M_\pi(T,\mu) = \text{const}$ by setting $f_\pi^2(T,\mu) = -m_0\langle\bar{q}q\rangle(T,\mu)/M_\pi^2$, (“BRST”, arxiv:1005.4610)

$$-\langle\bar{q}q\rangle(T,\mu) = -\langle\bar{q}q\rangle_{\rm PNJL,MF}(T,\mu) + \frac{M_\pi^2 T^2}{8m_0} + \frac{\sigma_N}{m_0} n_{s,N}(T,\mu)$$

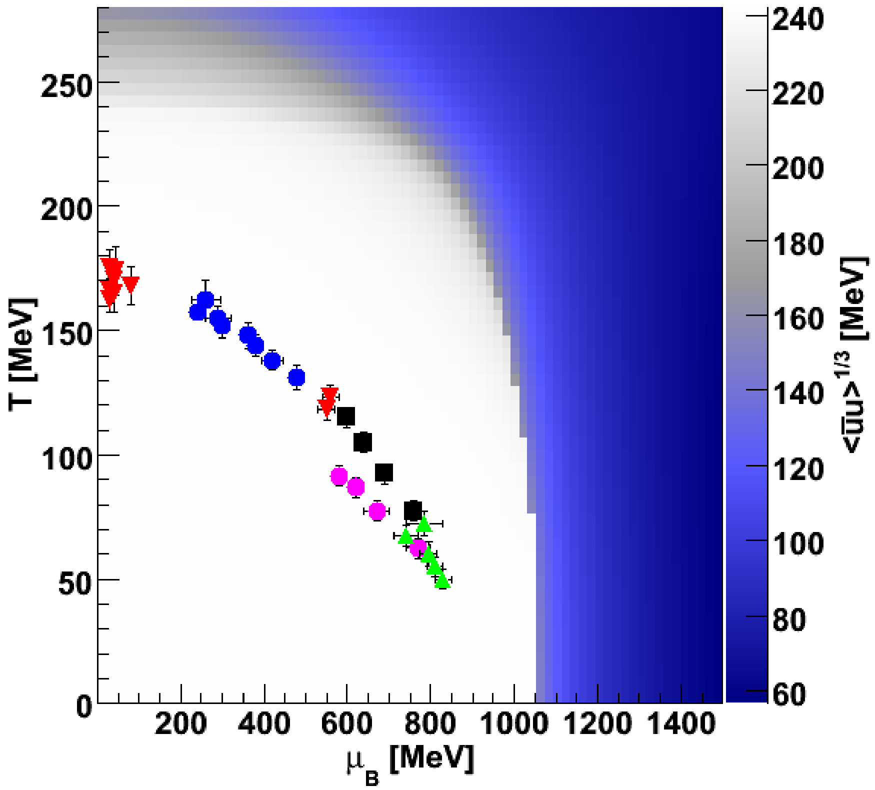
with the scalar nucleon density $n_{s,N}(T,\mu) = \frac{2}{\pi^2}\int_0^\infty dp\, p^2 \frac{m_N}{E_N(p)}\left\{f_N(T,\mu) + f_N(T,-\mu)\right\}$

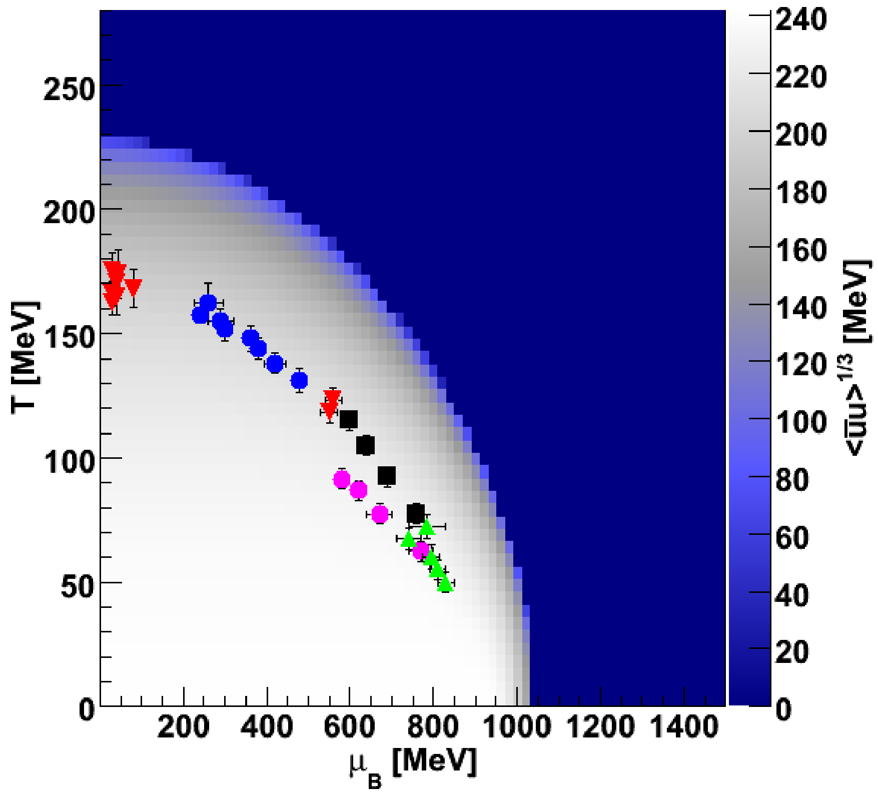
D.B., J. Berdermann, J. Cleymans, K. Redlich, arxiv:1102.2908 (2011)

PNJL Model beyond MF - results

$$-\langle \bar{q}q \rangle = -\langle \bar{q}q \rangle_{\mathrm{PNJL,MF}}$$

$$-\langle \bar{q}q \rangle = -\langle \bar{q}q \rangle_{\mathrm{PNJL,MF}} + \frac{M_\pi^2 T^2}{8 m_0} + \frac{\sigma_N}{m_0} n_{s,N}(T,\mu) + \ldots$$



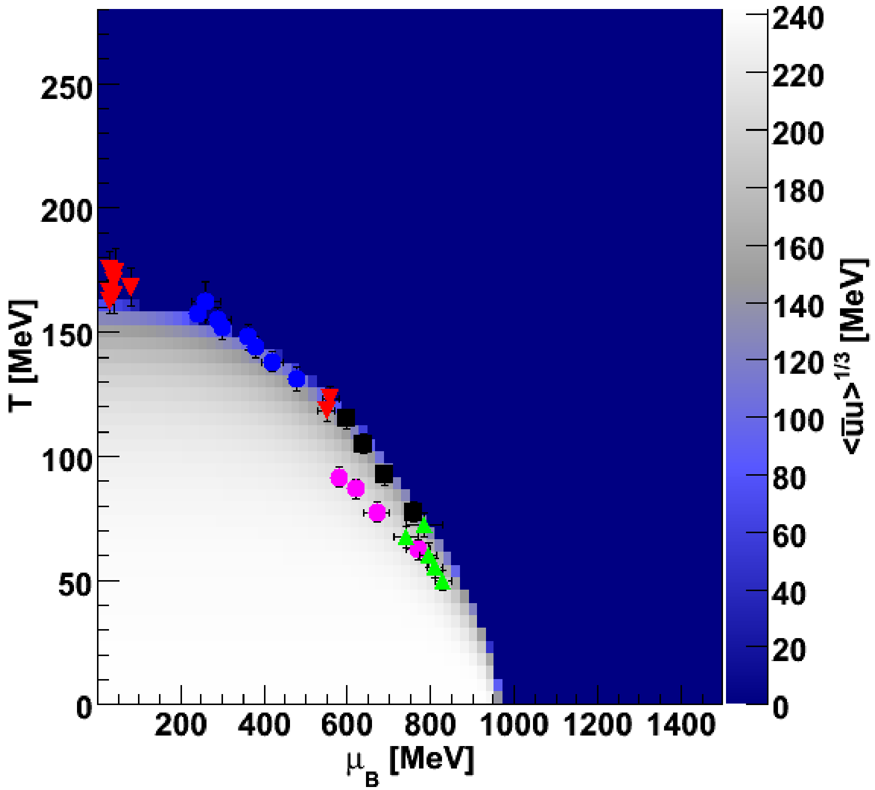


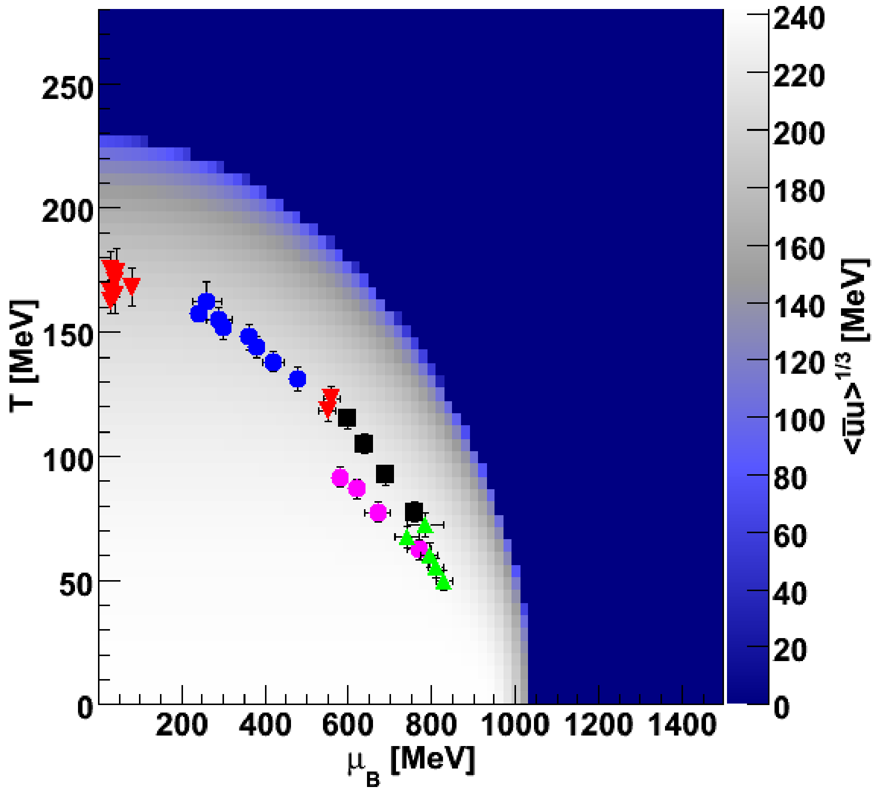
D.B., J. Berdermann, J. Cleymans, K. Redlich, arxiv:1102.2908 (2011)

PNJL Model beyond MF - results

$$-\langle\bar{q}q\rangle = -\langle\bar{q}q\rangle_{\mathrm{PNJL,MF}} + \kappa_M \frac{M_\pi^2 T^2}{8m_0} + \kappa_B \frac{\sigma_N}{m_0} n_{s,N}(T,\mu)$$

$$-\langle\bar{q}q\rangle = -\langle\bar{q}q\rangle_{\mathrm{PNJL,MF}} + \frac{M_\pi^2 T^2}{8m_0} + \frac{\sigma_N}{m_0} n_{s,N}(T,\mu) + \ldots$$

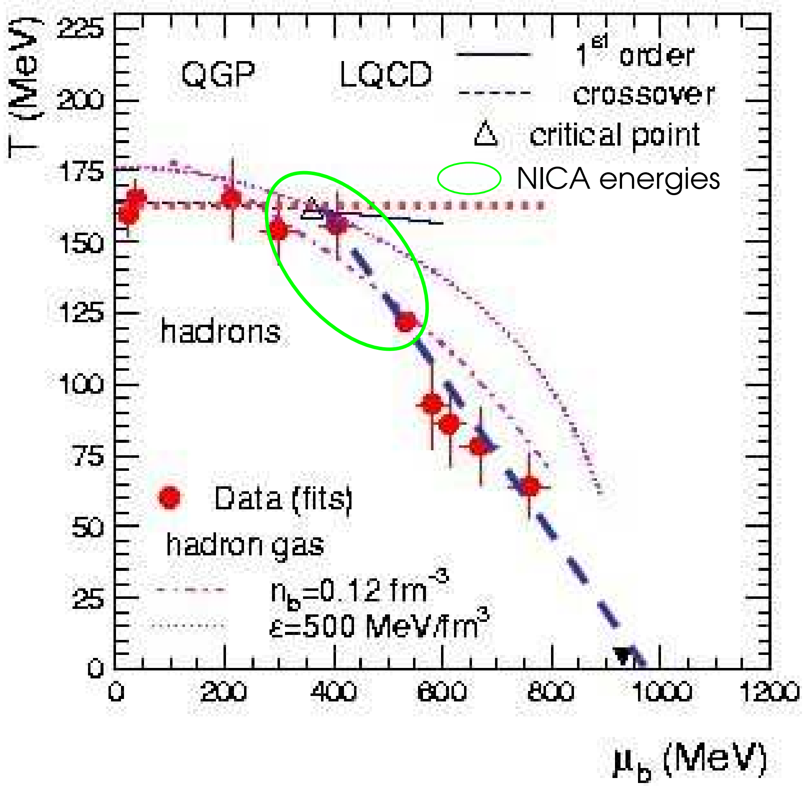


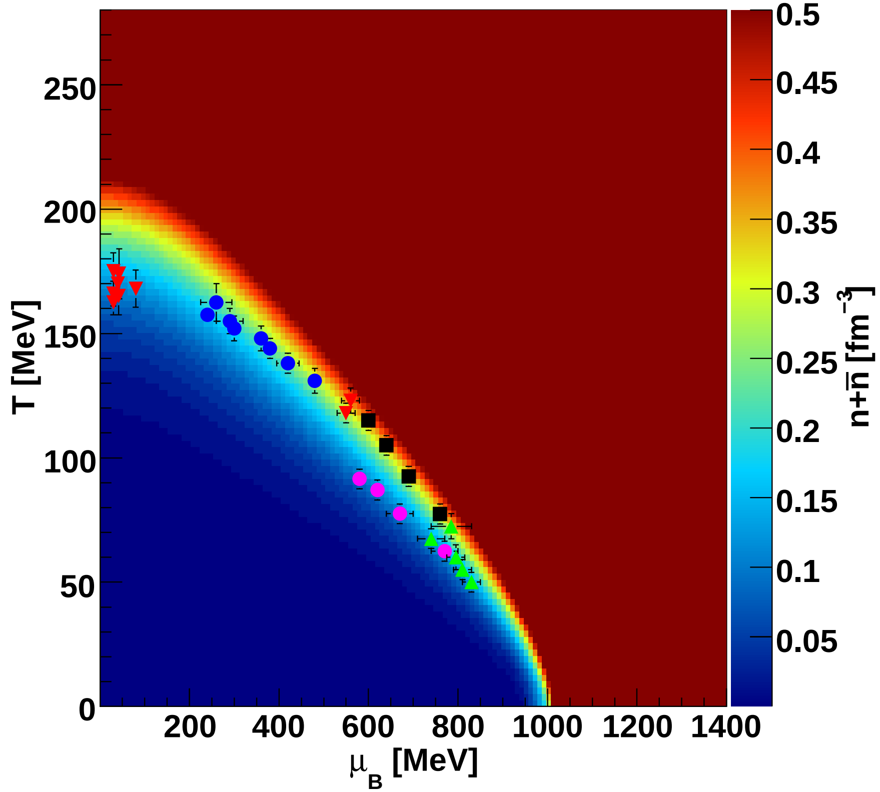


D.B., J. Berdermann, J. Cleymans, K. Redlich, arxiv:1102.2908 (2011)

PNJL Model beyond MF vs. Phenomenological Fit

$$n_b = n(T,\mu) + \bar{n}(T,\mu) = \sum_{i=N,\Delta,xB} d_i \int \frac{dp\, p^2}{2\pi^2} \left[\frac{1}{\exp(\beta[E_i(p) - \mu]) + 1} + (\mu \leftrightarrow -\mu) \right]$$

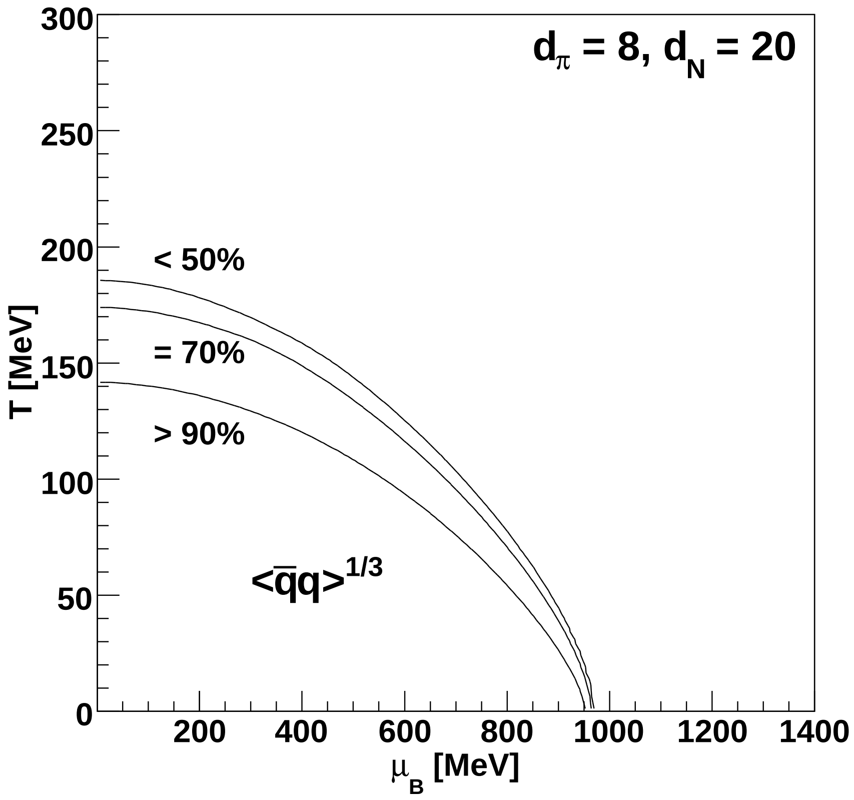


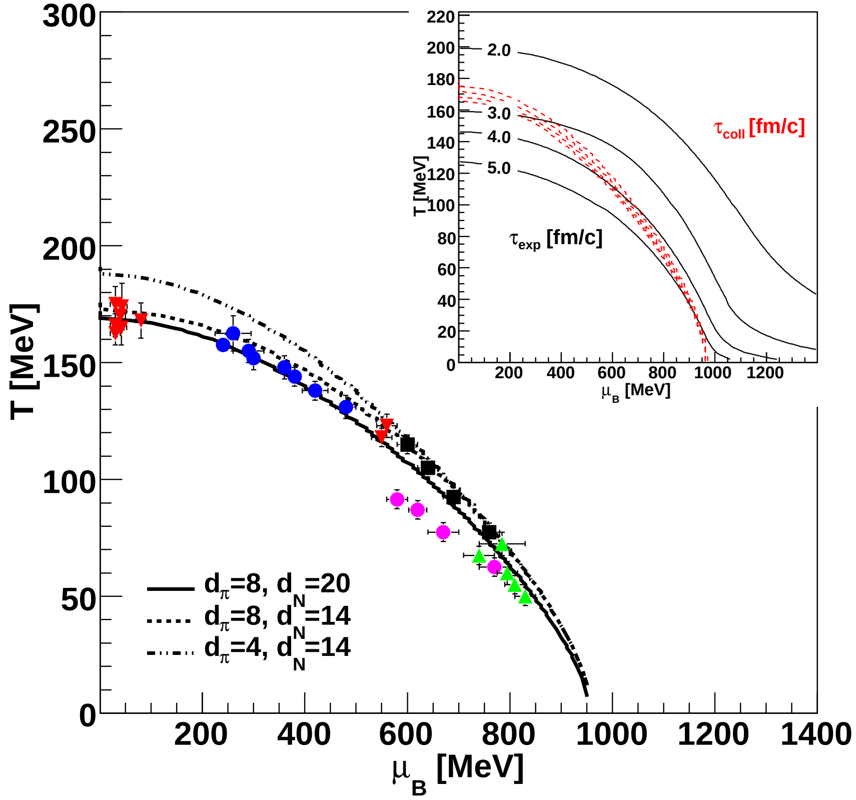


D.B., J. Berdermann, J. Cleymans, K. Redlich, arxiv:1102.2908 (2011)

PNJL Model beyond MF condensate vs. freeze-out cond.

$$\langle \bar{q}q \rangle = \langle \bar{q}q \rangle_{\rm MF} \left[1 - \frac{T^2}{8 f_\pi^2(T,\mu)} - \frac{\sigma_N n_{s,N}(T,\mu)}{M_\pi^2 f_\pi^2(T,\mu)} \right] \;, \quad n_{s,\pi} = d_\pi M_\pi T^2/12$$

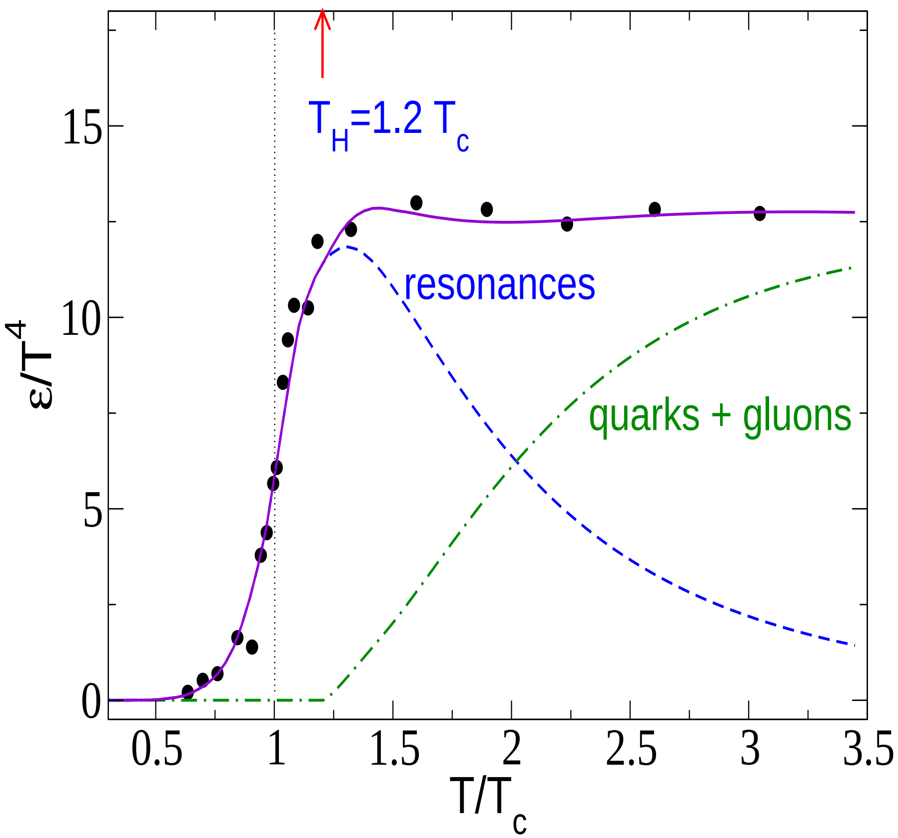




D.B., J. Berdermann, J. Cleymans, K. Redlich, arxiv:1102.2908 (2011);
Few Body Systems (2011) in press.

Lattice QCD EoS and Mott-Hagedorn Gas

$$\varepsilon_{\rm R}(T,\{\mu_j\}) = \sum_{i=\pi,K,\ldots} \varepsilon_i(T,\{\mu_i\}) + \sum_{r=M,B} g_r \int_{m_r} dm \int ds\, \rho(m) A(s,m;T) \int \frac{d^3p}{(2\pi)^3} \frac{\sqrt{p^2+s}}{\exp\left(\frac{\sqrt{p^2+s}-\mu_r}{T}\right)+\delta_r}$$



Hagedorn mass spectrum: $\rho(m)$

Spectral function for heavy resonances:

$$A(s,m;T) = N_s \frac{m\Gamma(T)}{(s-m^2)^2 + m^2\Gamma^2(T)}$$

Ansatz with Mott effect at $T = T_H = 192$ MeV:

$$\Gamma(T) = B\Theta(T-T_H)\left(\frac{m}{T_H}\right)^{2.5}\left(\frac{T}{T_H}\right)^{6}\exp\left(\frac{m}{T_H}\right)$$

No width below T_H: Hagedorn resonance gas

Apparent phase transition at $T_c \sim 160$ MeV

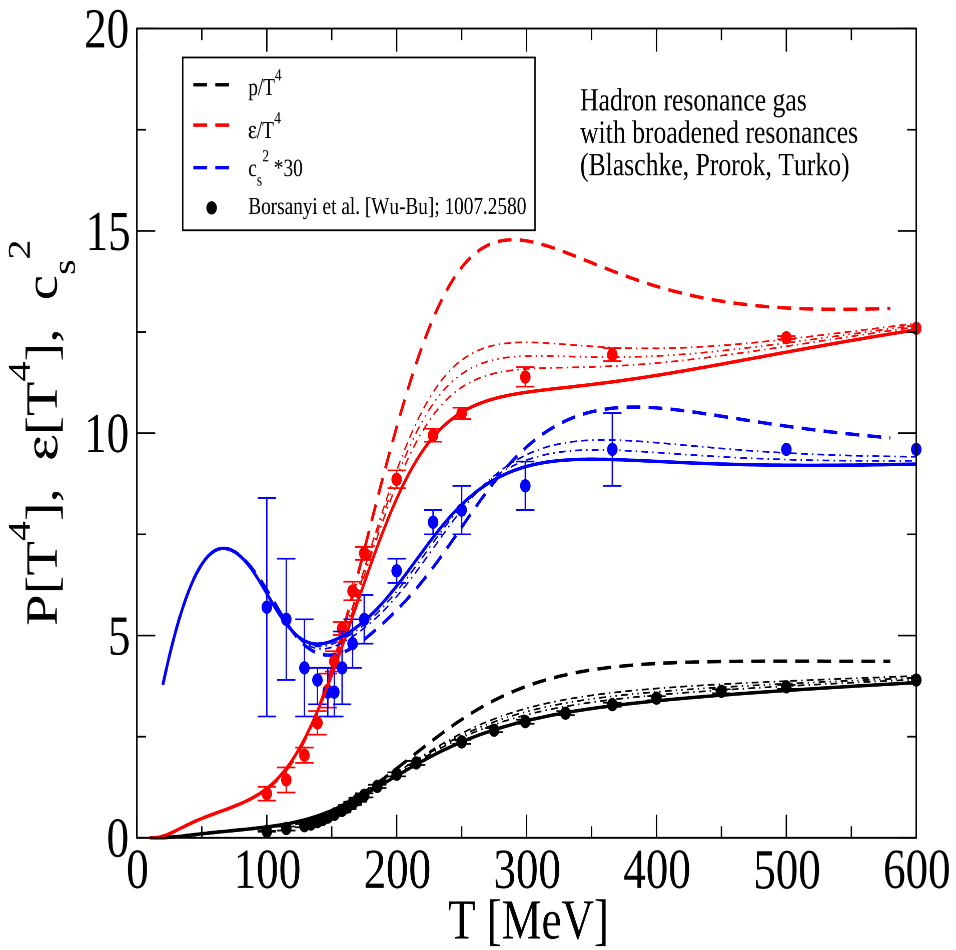
Blaschke & Bugaev, Fizika B13, 491 (2004)

Prog. Part. Nucl. Phys. 53, 197 (2004)

Blaschke & Yudichev (2006)

Hybrid appoach: PNJL & Mott-Hagedorn Resonance Gas

$$\varepsilon_{\rm hybrid}(T,\{\mu_j\}) = \varepsilon_{\rm PNJL}(T,\{\mu_i\}) + \sum_{r=M,B} g_r \int ds\, A(s,m_r;T) \int \frac{d^3p}{(2\pi)^3} \frac{\sqrt{p^2+s}}{\exp\left(\frac{\sqrt{p^2+s}-\mu_r}{T}\right)+\delta_r}$$



Spectral function for heavy resonances:

$$A(s,m;T) = N_s \frac{m\Gamma(T)}{(s-m^2)^2 + m^2\Gamma^2(T)}$$

Ansatz with Mott effect at $T = T_H = 198$ MeV:

$$\Gamma(T) = B\Theta(T-T_H)\left(\frac{m}{T_H}\right)^{2.5}\left(\frac{T}{T_H}\right)^{6}\exp\left(\frac{m}{T_H}\right)$$

Apparent phase transition at $T_c \sim 165$ MeV

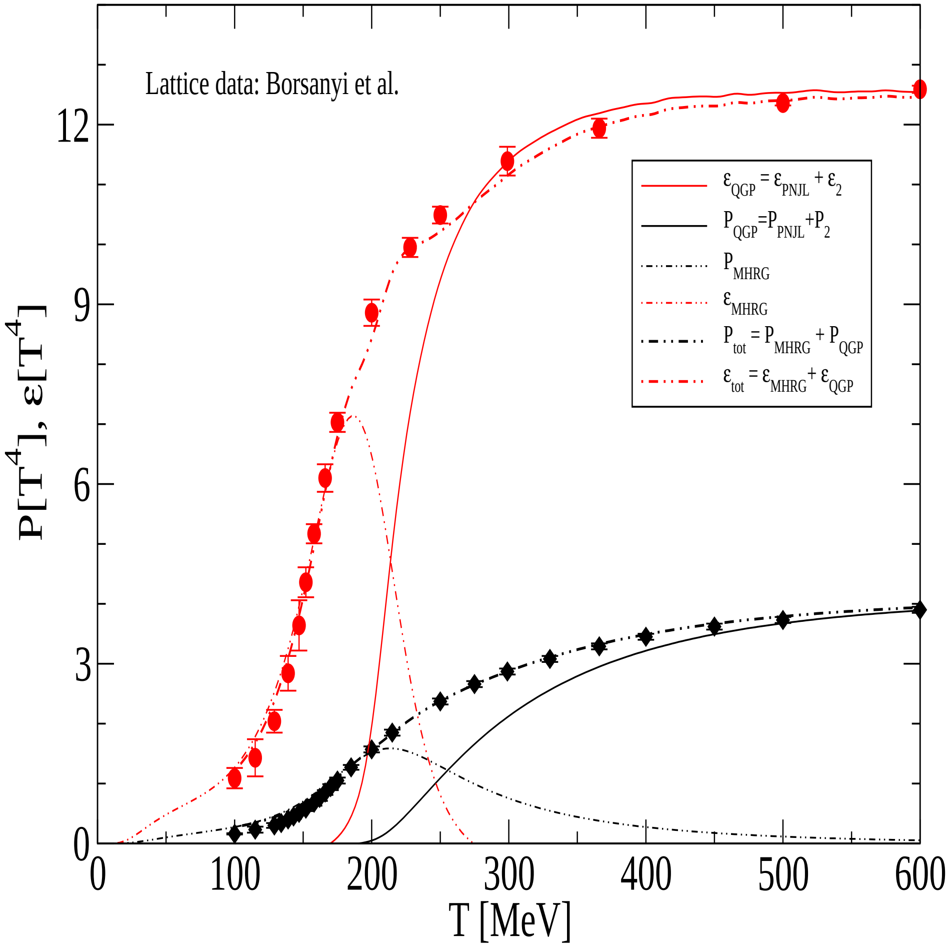
Blaschke & Bugaev, Fizika B13, 491 (2004)

Prog. Part. Nucl. Phys. 53, 197 (2004)

Blaschke, Prorok & Turko, in preparation

Hybrid appoach: PNJL & Mott-Hagedorn Resonance Gas

$$\varepsilon_{\text{hybrid}}(T,\{\mu_j\}) = \varepsilon_{\text{PNJL}}(T,\{\mu_i\}) + \sum_{r=M,B} g_r \int ds\, A_r(s,m_r;T) \int \frac{d^3p}{(2\pi)^3} \frac{\sqrt{p^2+s}}{\exp\left(\frac{\sqrt{p^2+s}-\mu_r}{T}\right)+\delta_r}$$



Spectral function for heavy resonances:

$$A_r(s,m;T) = N_s \frac{m\Gamma_r(T)}{(s-m^2)^2 + m^2\Gamma_r^2(T)}$$

Ansatz motivated by chemical freeze-out model:

$$\Gamma_r(T) = \tau_r^{-1}(T) = \sum_h \lambda < r_r^2 >_T < r_h^2 >_T n_h(T)$$

Apparent phase transition at $T_c \sim 165$ MeV

Blaschke & Bugaev, Fizika B13, 491 (2004)

Prog. Part. Nucl. Phys. 53, 197 (2004)

Blaschke, Prorok & Turko, in preparation

ROADMAP FOR PHASE DIAGRAM AND EOS RESEARCH