TRIPLE POINT AND QUARKYONIC MATTER IN THE NICA SLICE OF THE PHASE DIAGRAM

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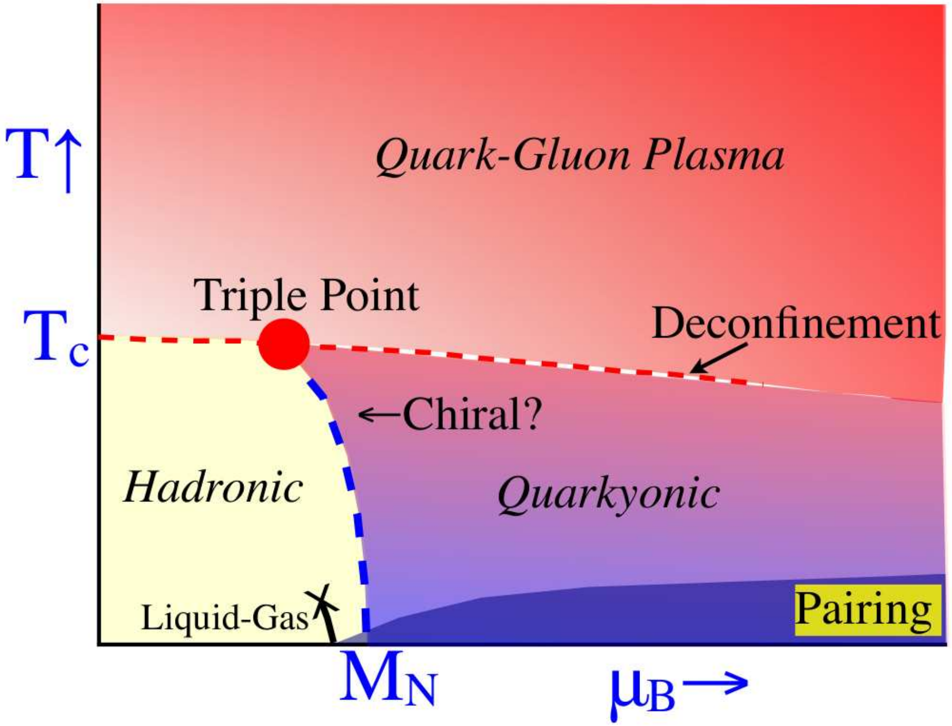
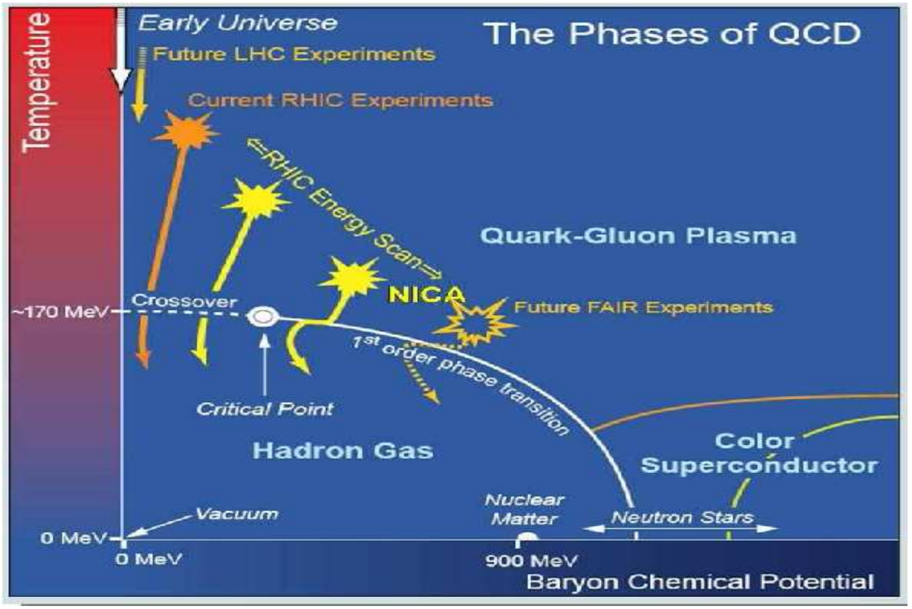
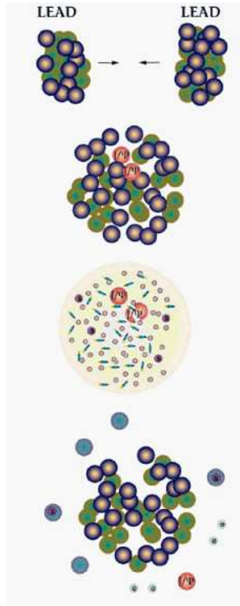


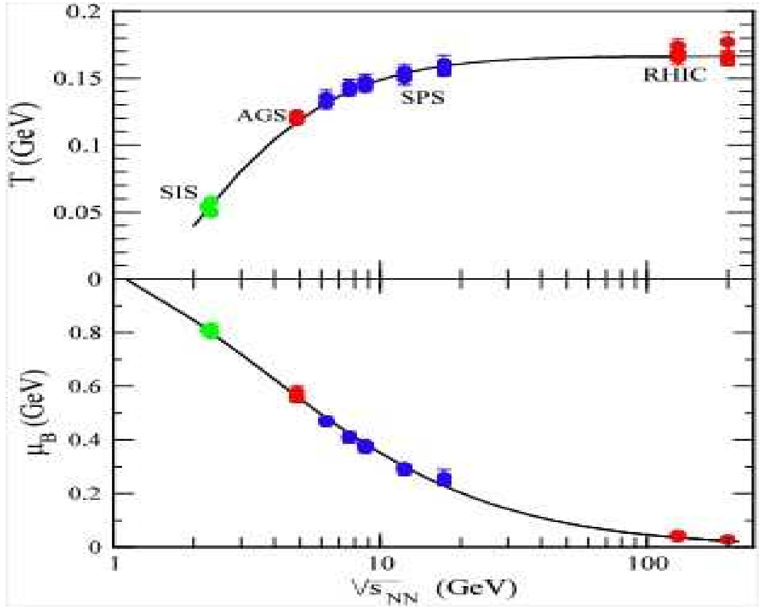
- Hadronic Freezeout
- Quarkyonic matter in phase diagram
- Chiral resonance model
- NICA / Nuclotron-N on “Happy Island”

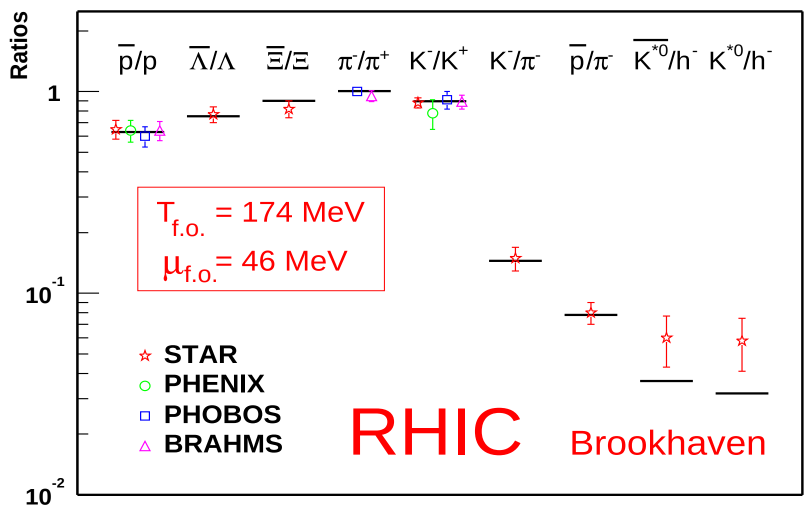
Andronic, D.B., Braun-Munzinger, Cleymans, Fukushima, Oeschler, Pisarski, McLerran, Redlich, Sasaki, Satz, Stachel, **arxiv:0911.4806 [hep-ph]**

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









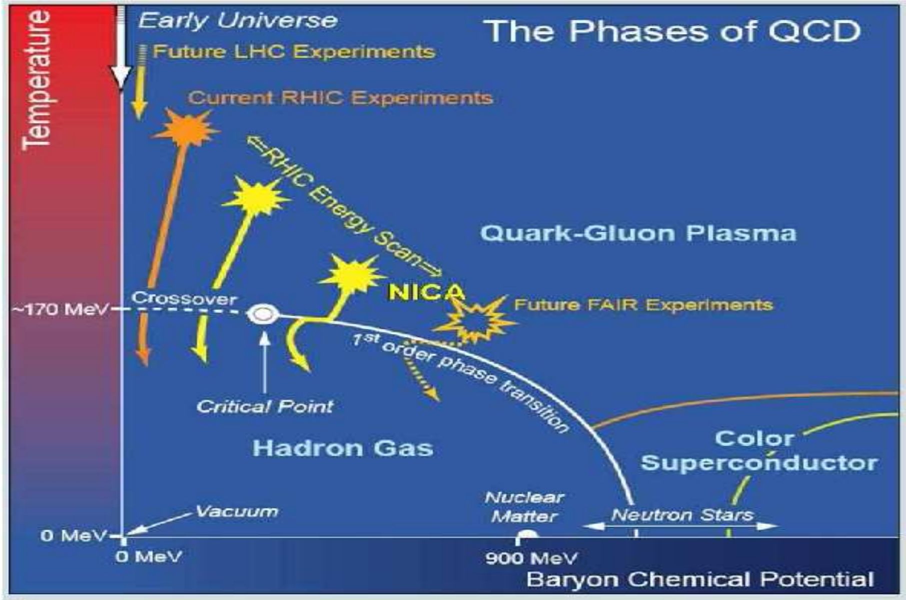
Statistical model describes composition of hadron yields in Heavy-Ion Collisions with few freeze-out parameters.

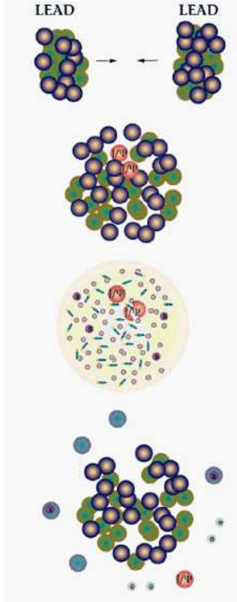
$$\ln Z[T,V,\{\mu\}] = \pm V \sum_i \frac{g_i}{2\pi^2} \int_0^\infty dp\, p^2 \ln[1 \pm \lambda_i \exp(-\beta\varepsilon_i(p))]$$

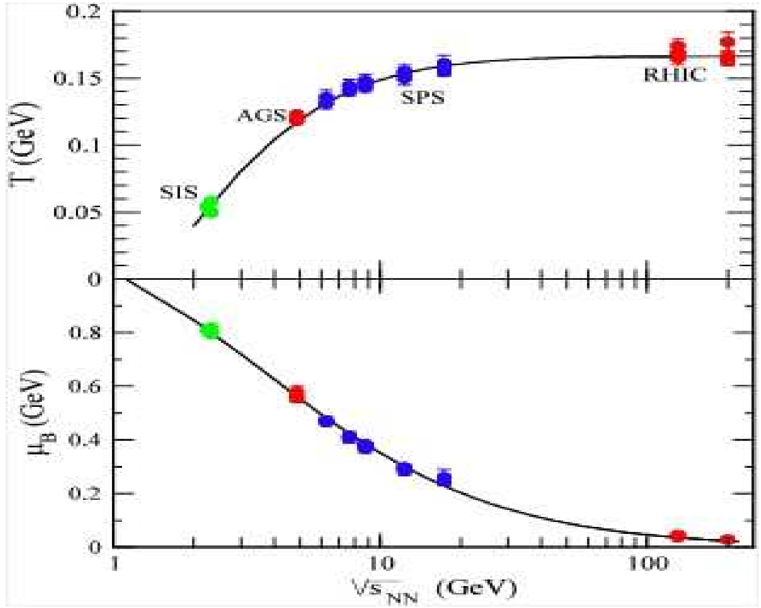
$$\lambda_i(T,\{\mu\}) = \exp[\beta(\mu_B B_i + \mu_S S_i + \mu_Q Q_i)]$$

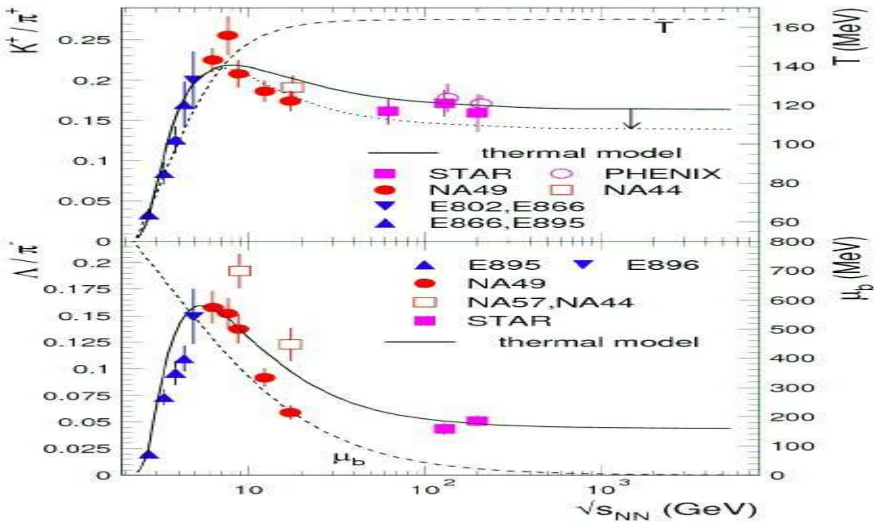
Braun-Munzinger, Redlich, Stachel, in *QGP III* (2003)

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



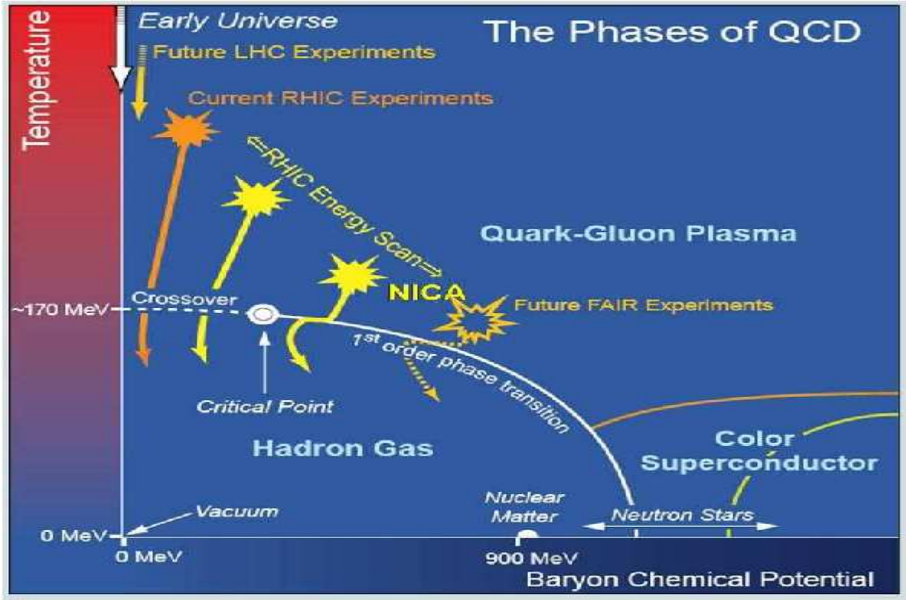


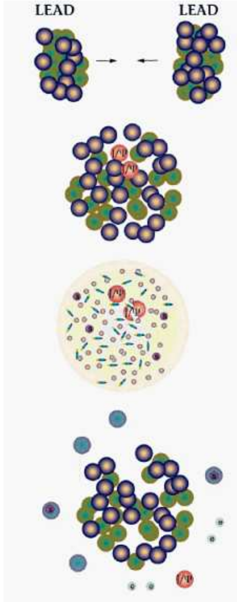


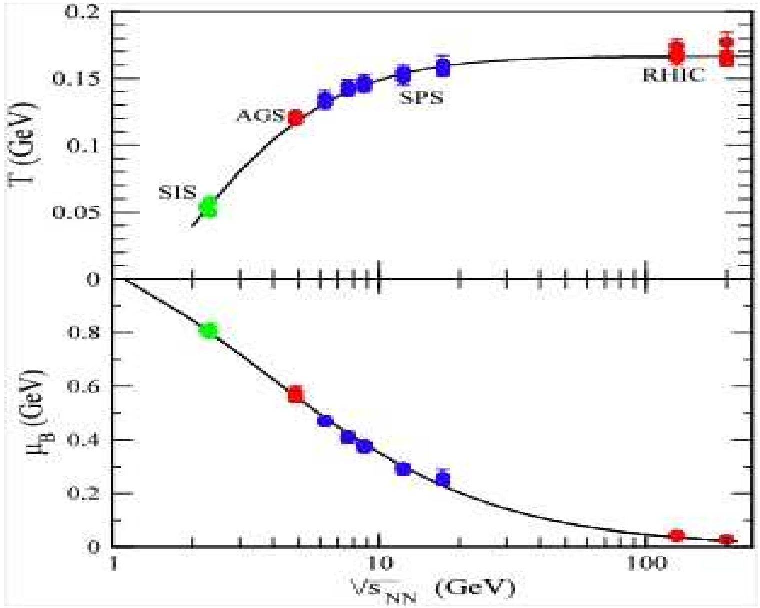


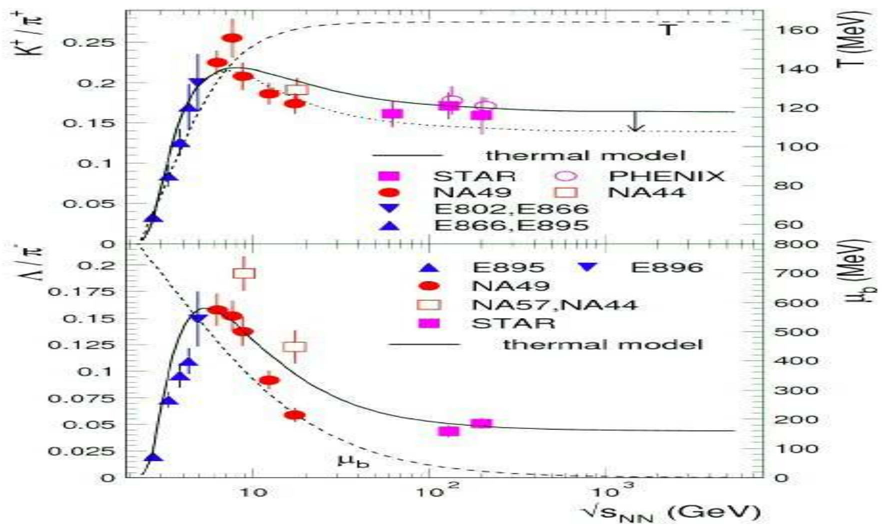
Strange MatterHorn (Pisarski)

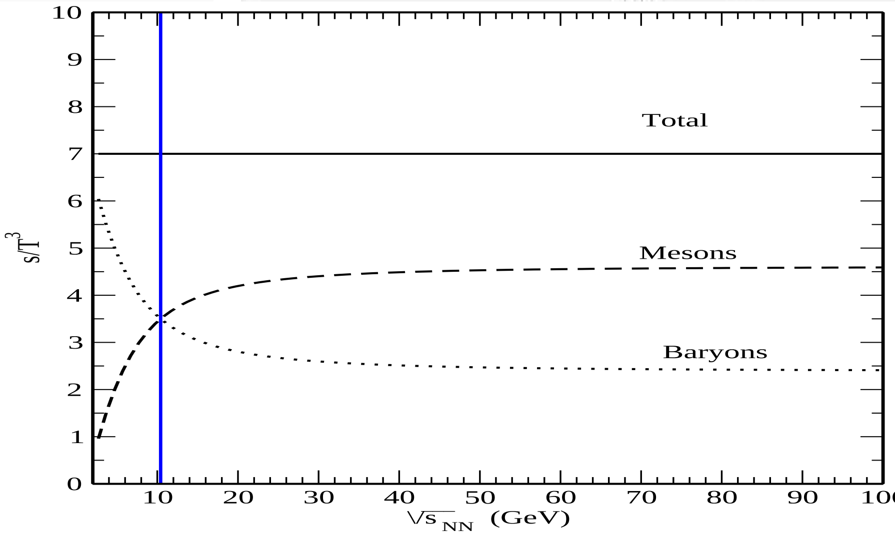
PHASEDIAGRAM: FREEZE-OUT IN HEAVY-ION COLLISIONS (III)





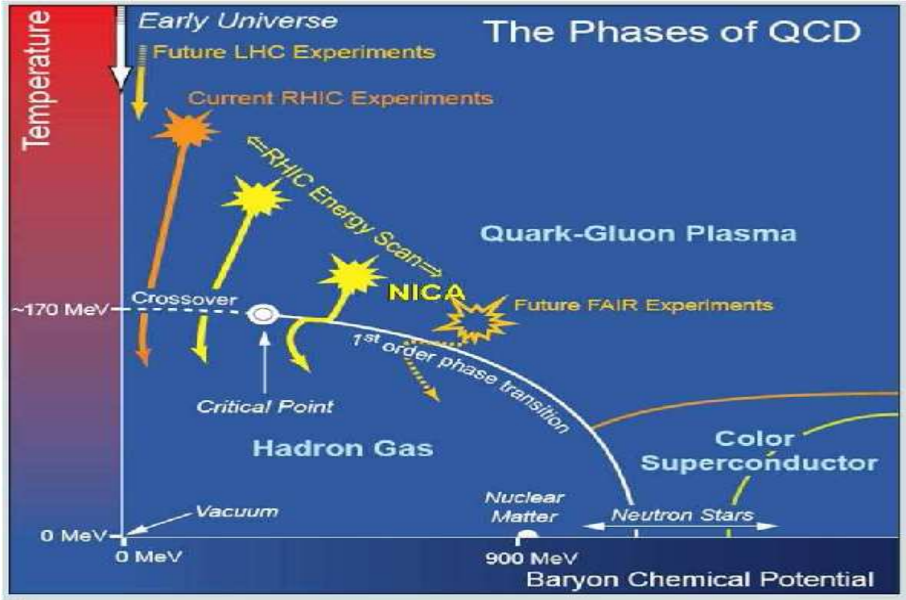


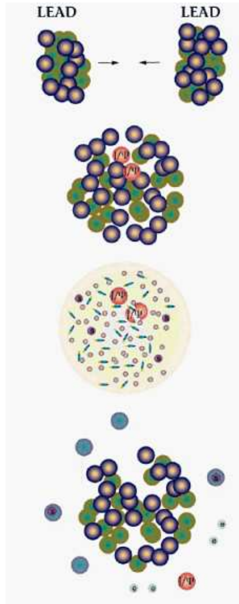


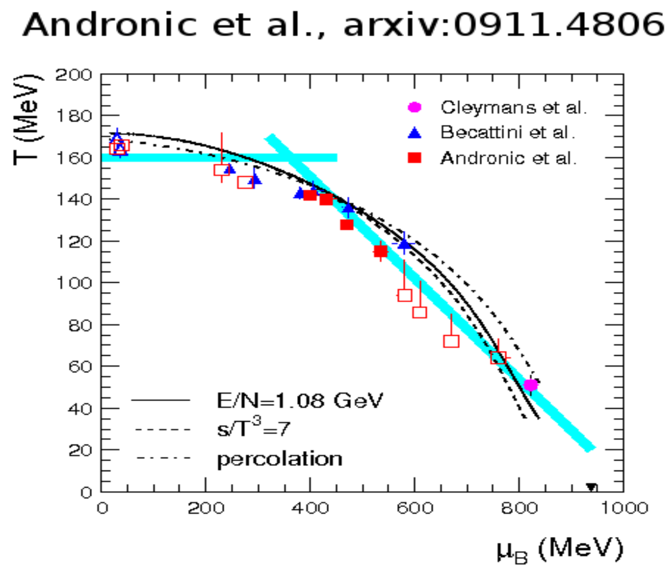


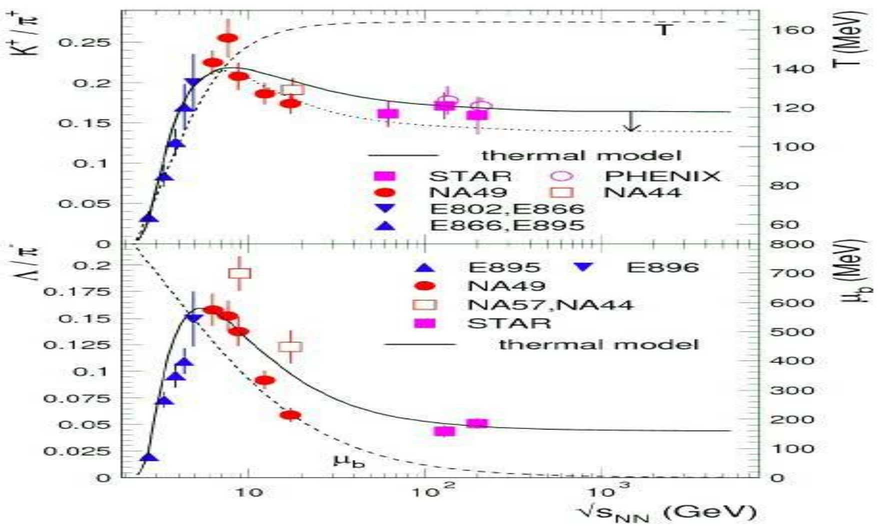
Baryon → Meson Dominance

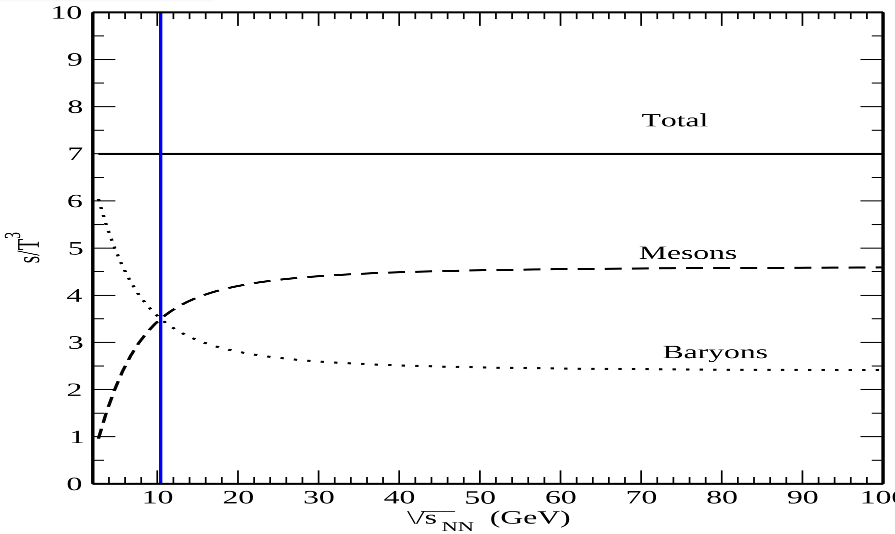
PHASEDIAGRAM: FREEZE-OUT IN HEAVY-ION COLLISIONS (IV)





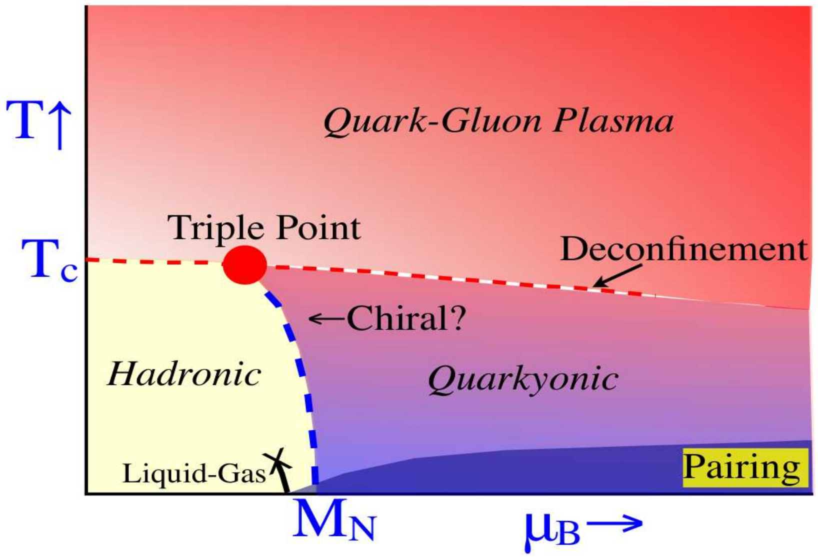


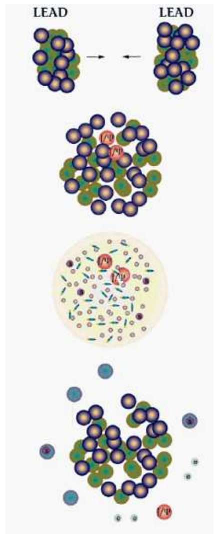


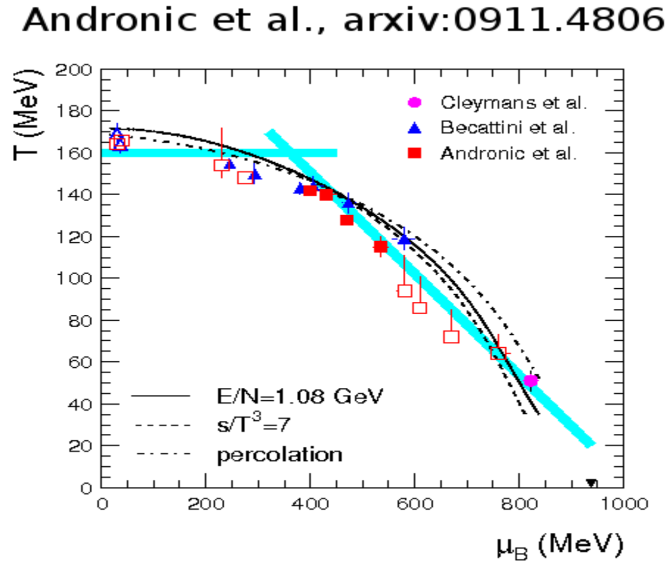


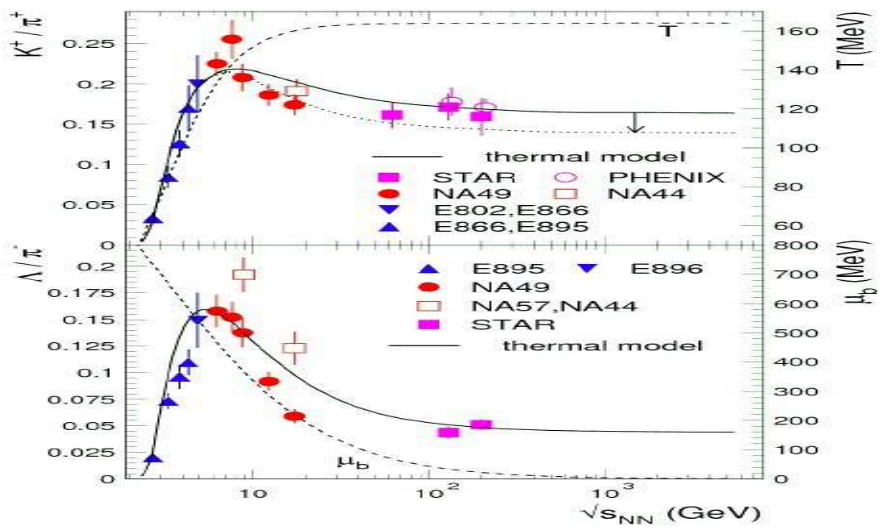
Baryon → Meson Dominance

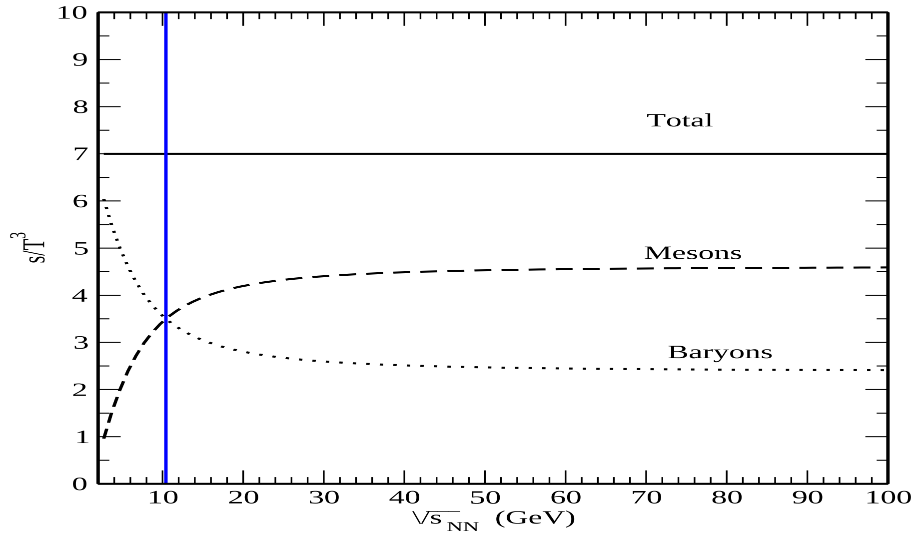
PHASEDIAGRAM: FREEZE-OUT IN HEAVY-ION COLLISIONS (V)





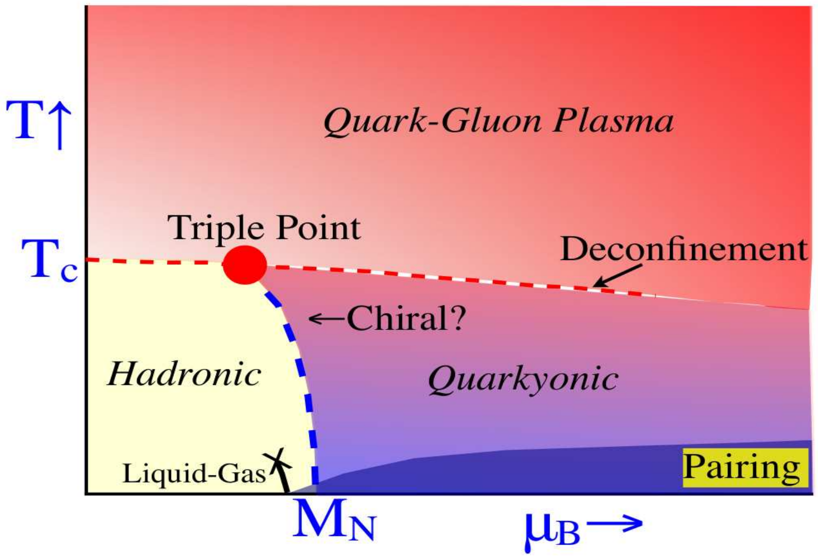


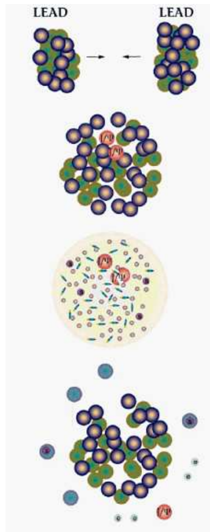


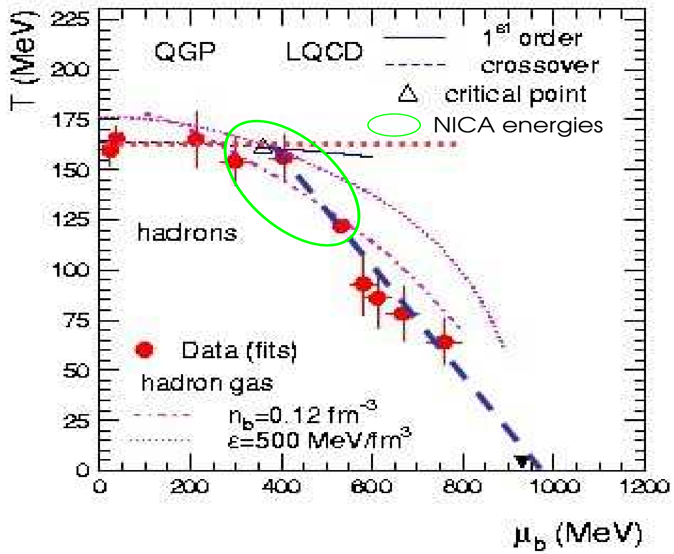


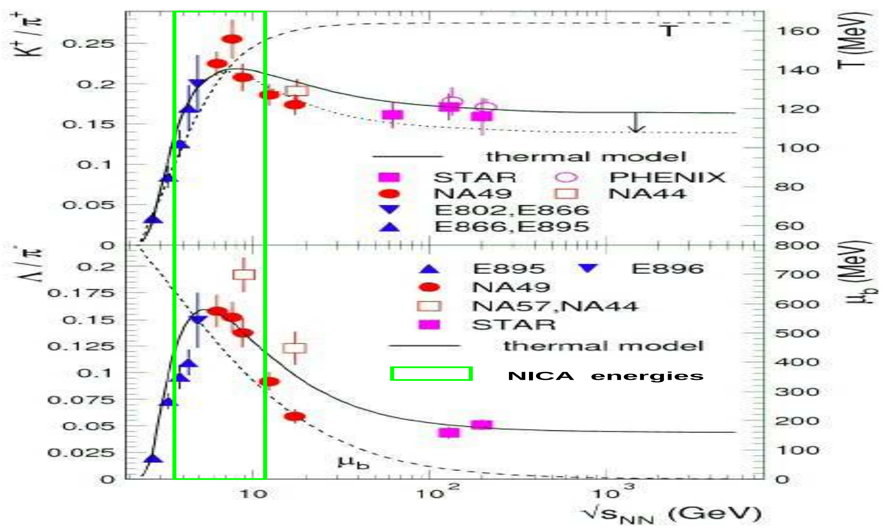
Andronic et al., arxiv:0911.4806; NPA (2010)

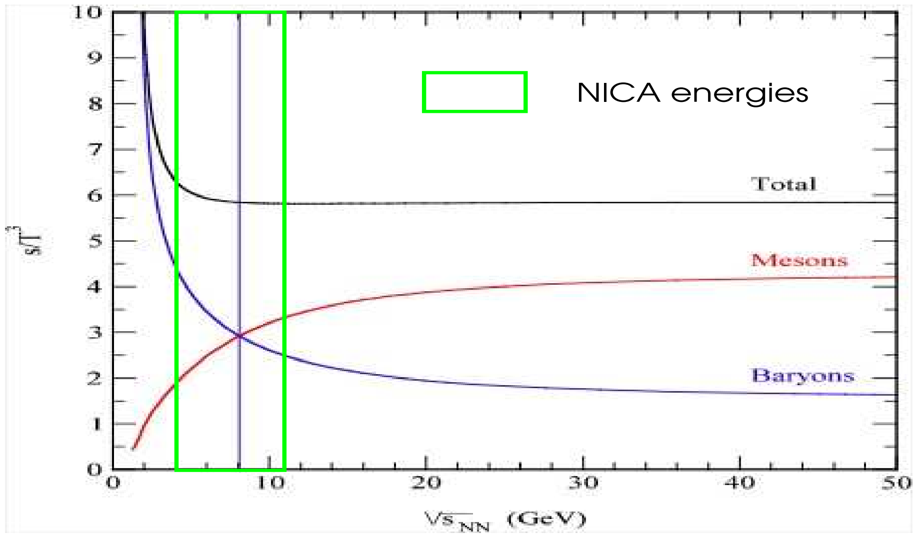
Phasediagram: Freeze-out in Heavy-Ion Collisions (V)





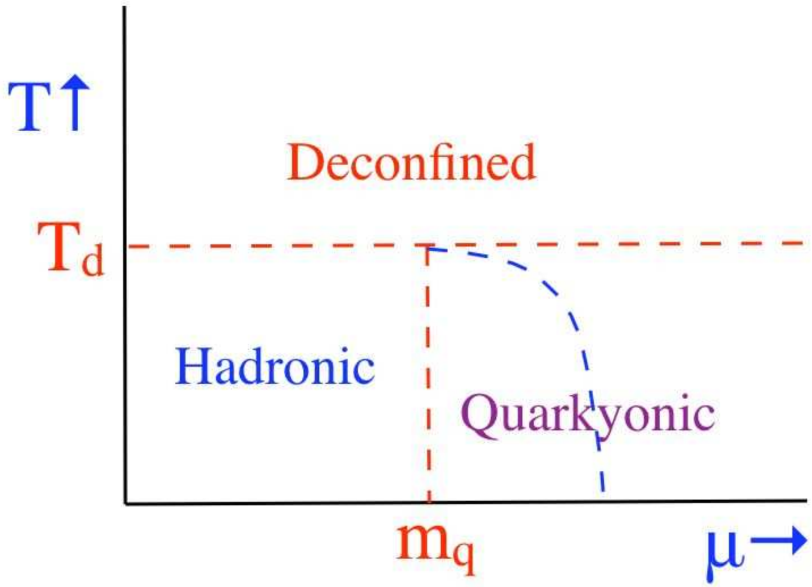


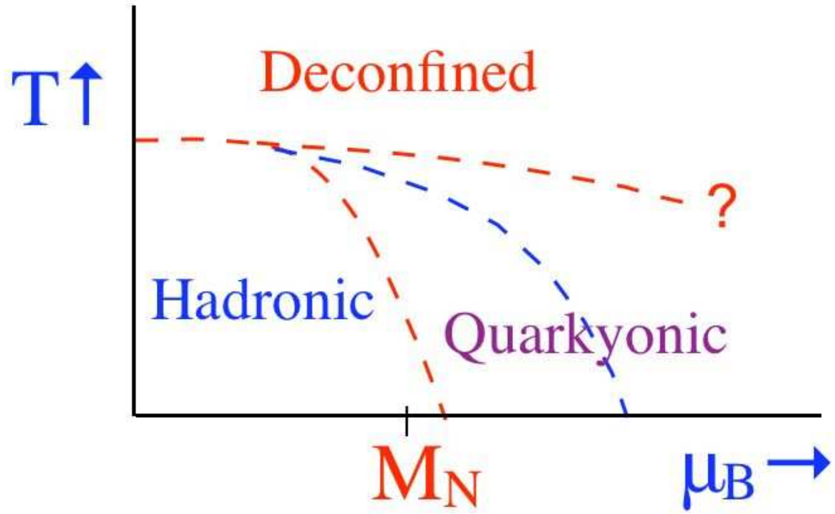




Andronic et al., arxiv:0911.4806; NPA (2010)

QUARKYONIC PHASE = CHIRAL SYMMETRY + CONFINEMENT





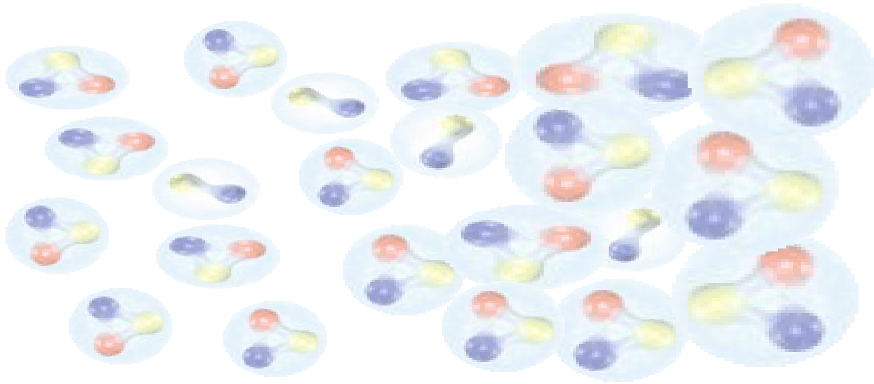
Phase diagram for $N_c \to \infty$ and finite N_f

Phase diagram for $N_c \to \infty$ and small N_f/N_c

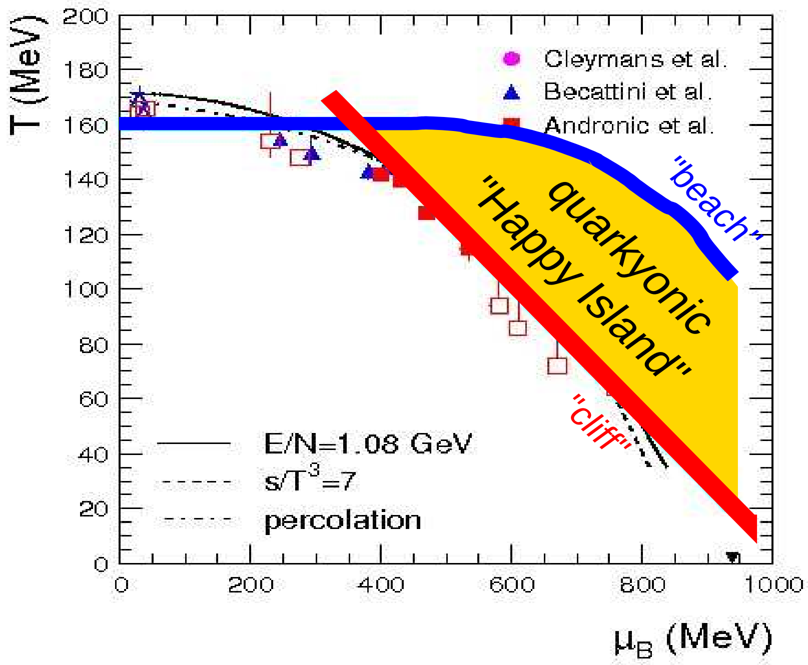
Hidaka, McLerran, Pisarski, Nucl. Phys. A 808 (2008) 117.
McLerran, Pisarski, Nucl. Phys. A 796 (2007) 83.

McLerran, Redlich, Sasaki, Nucl. Phys. A 824 (2009) 86; arXiv:0812.3585

What happens on "Happy Island"?



Andronic et al., arxiv:0911.4806



"beach": later

"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) $\rightarrow$ geometrical overlap (percolation)

PNJL beyond MF: pion $(q\bar{q})$ and nucleon (qqq) medium

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

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

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

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

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

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)

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

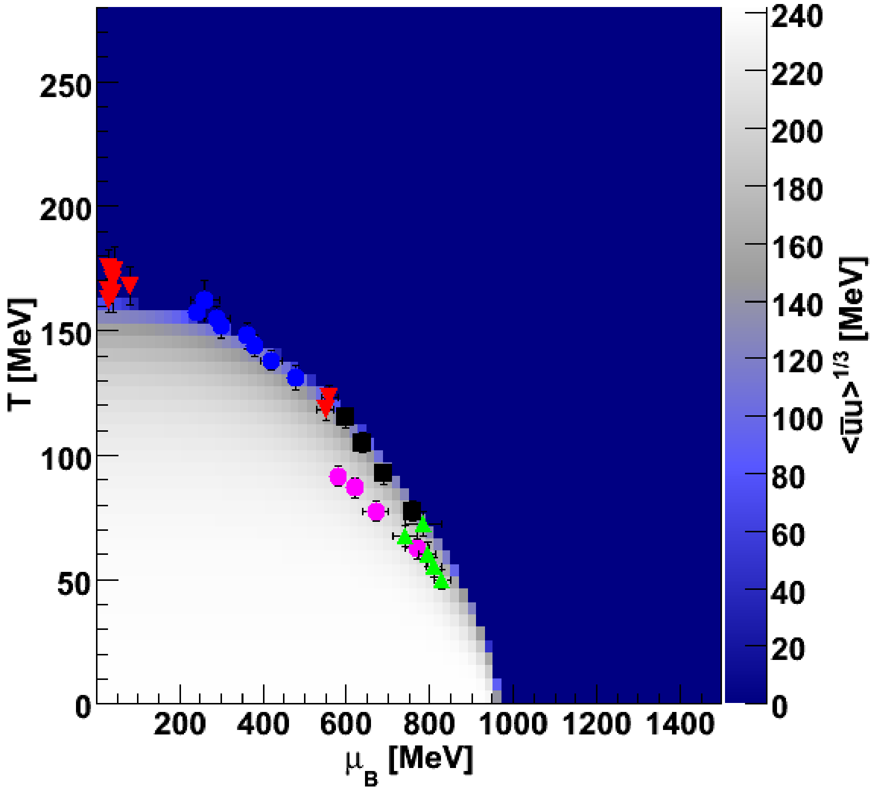
with the scalar nucleon density $n_{s,N}(T,\mu) = \frac{2}{\pi^2}\int_0^\infty dp\, p^2 \frac{m_N}{E_N(p)}\left\{f_N(T,\mu) + f_N(T,-\mu)\right\}$

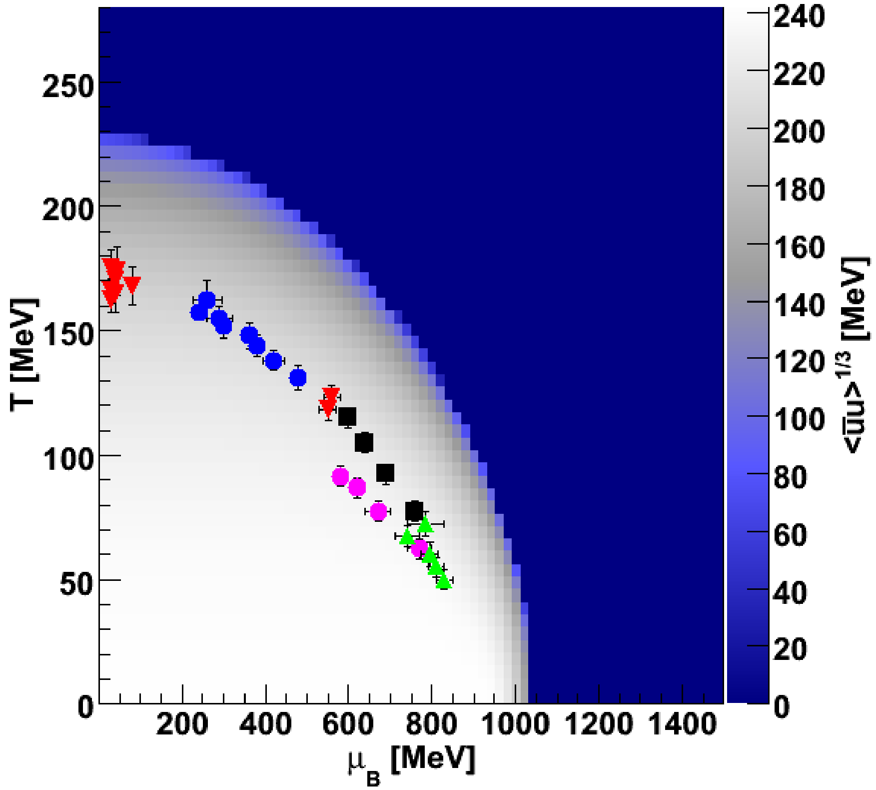
J. Berdermann, D.B., J. Cleymans, K. Redlich, in progress (2010)

PNJL Model beyond MF - results

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

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

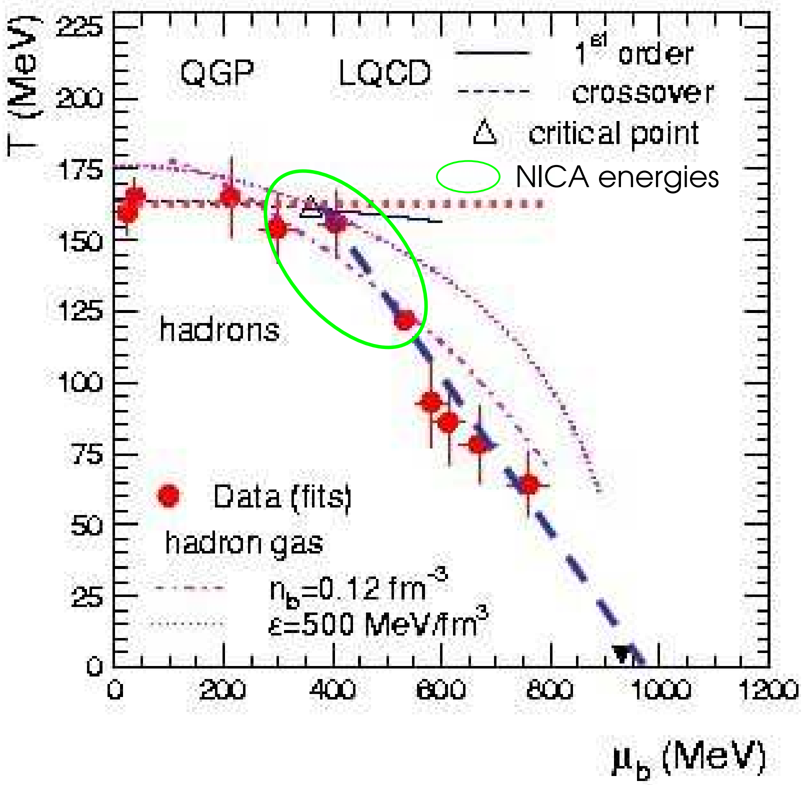


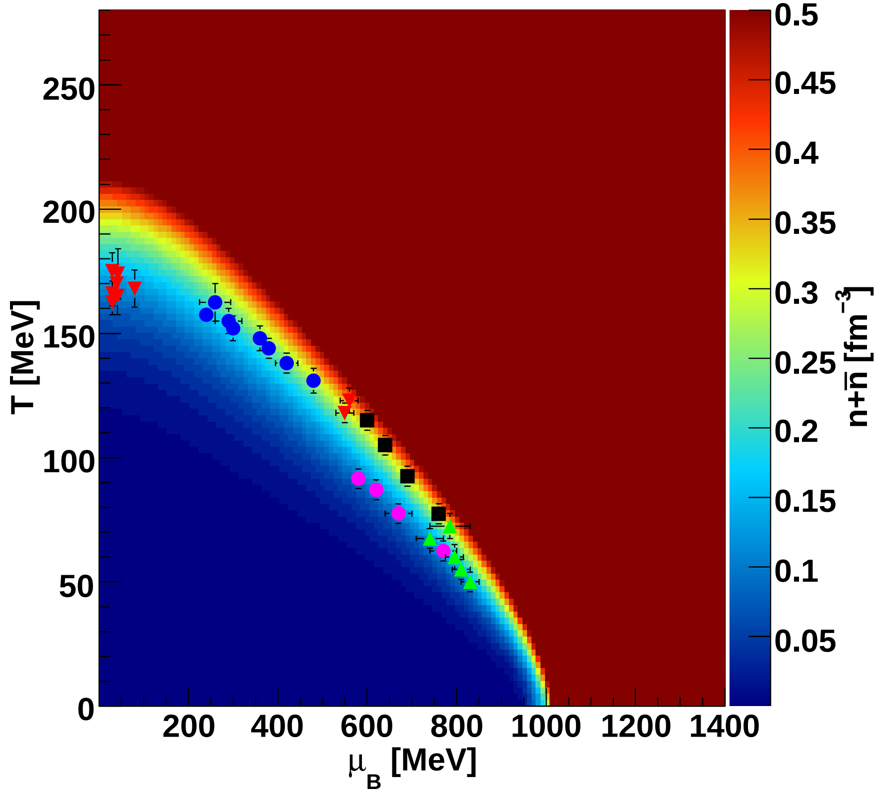


J. Berdermann, D.B., J. Cleymans, K. Redlich, in progress (2010)

PNJL Model beyond MF vs. Phenomenological Fit

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

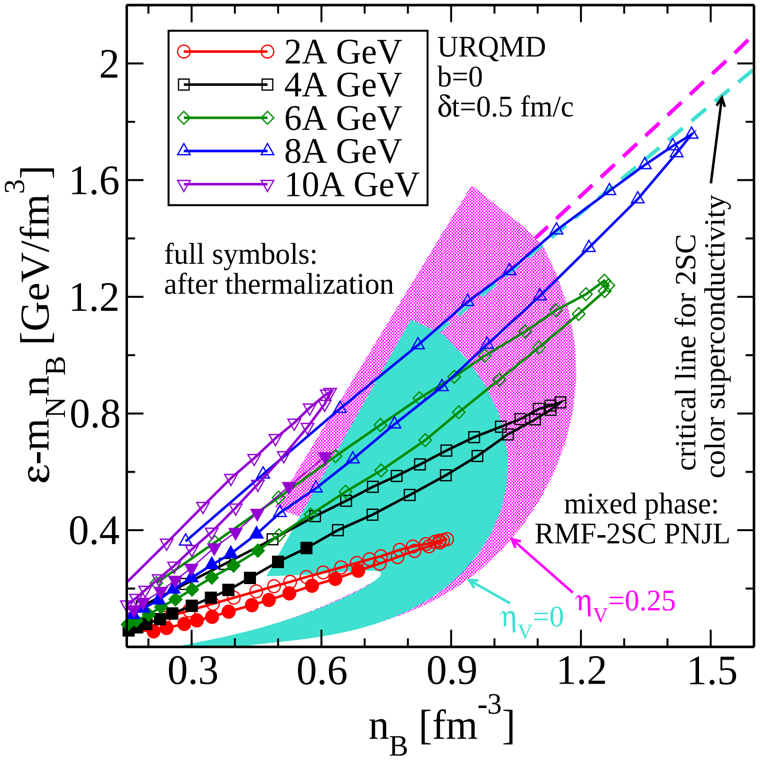




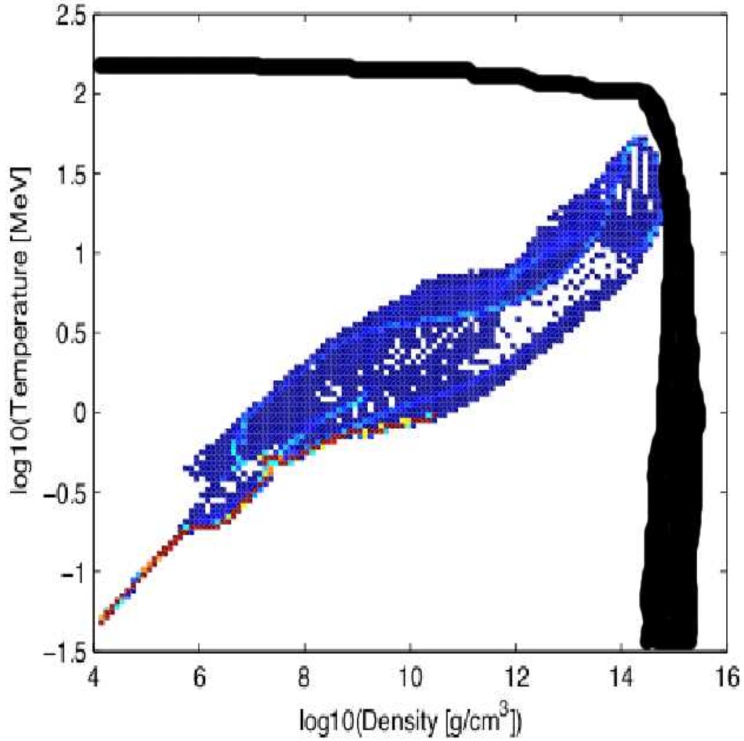
J. Berdermann, D.B., J. Cleymans, K. Redlich, in progress (2010)

EXPLORING THE QCD PHASE DIAGRAM: TRAJECTORIES

Heavy-Ion Collisions:



Supernova Explosions (15 $M_\odot$):



D.B.,Skokov, Sandin, NICA WhitePaper (2009)

Liebendoefer et al. (2005)
Sagert et al., PRL 102 (2009)

SUMMARY

- Hadron production data suggest the existence of three forms of matter:
  Hadronic Matter, Quarkyonic Matter and Quark-Gluon Plasma
- Mott-Hagedorn model as alternative interpretation of Lattice data
- Chiral condensate melting may be explained by hadron resonance excitation
- Phenomenological laws for freeze-out curve qualitatively reproduced
- Quarkyonic island can be accessed by NICA and Nuclotron-N
- More, better data have to be provided in the NICA/Nuclotron-M range
- Is the working hypothesis of hadron swelling (multiquark states) as an explanation
  for increase of flavor exchange reaction rates and fast chemical equilibration testable?

Invitations:

International Conference
"Critical Point and Onset of Deconfinement"
Dubna, Russia, August 23-29, 2010
http://theor.jinr.ru/cpod

HIC-for-FAIR Summer School
"Dense QCD Phases in HIC"
Dubna, Russia, August 21-September 4, 2010
http://theor.jinr.ru/∼dm10

XXVIII. Max-Born Symposium
"Three Days on H.I."
Wroclaw, Poland, May/June 2011
http://www.ift.uni.wroc.pl

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THANKS FOR YOUR ATTENTION!