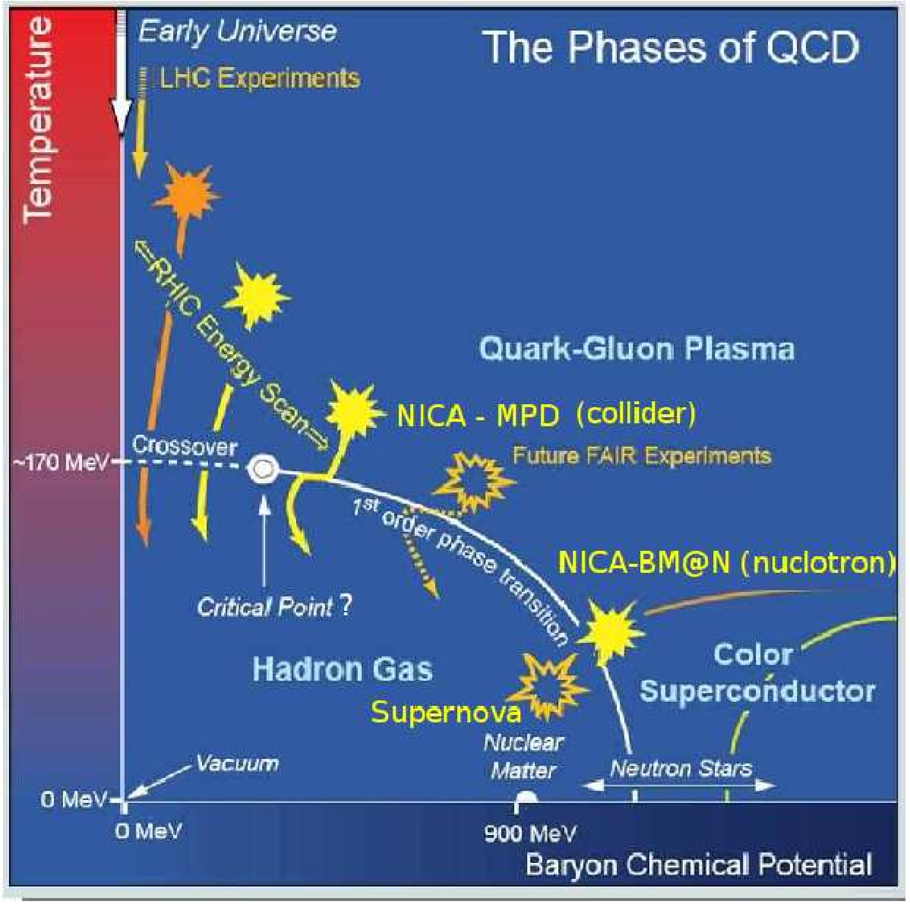
Exploring the QCD phase transition at highest baryon densities with NICA-MPD and FAIR-CBM

David Blaschke

Institute for Theoretical Physics, University of Wroclaw, Poland

Bogoliubov Laboratory for Theoretical Physics, JINR Dubna, Russia



- QCD Phase Transition:
  - QCD - Lattice vs. Models
  - χSR, hadron dissociation
- Observable effects in HIC:
  - Hadron yields, flow
  - Moments of fluctuations
- Experiments at NICA & FAIR
  - NICA - site and parameters
  - Mini-CBM @ Nuclotron, Collider

Partition function for Quantum Chromodynamics (QCD)

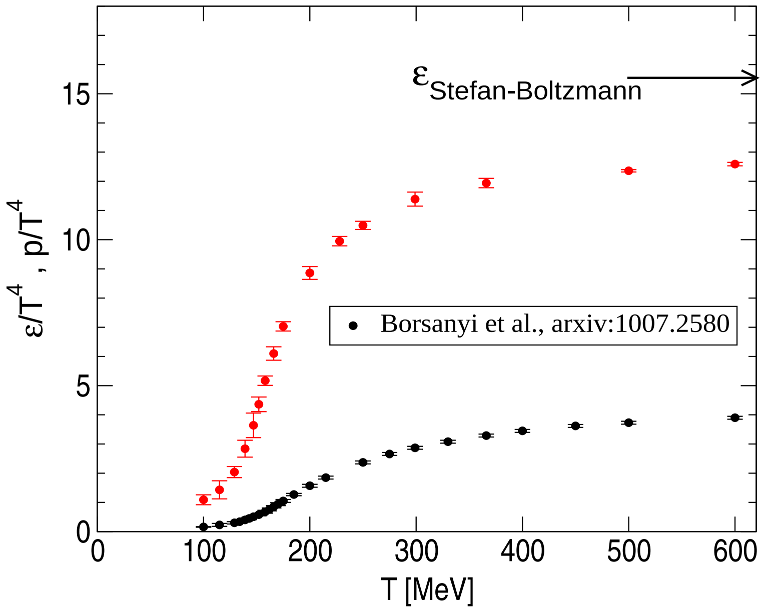
- Partition function as a Path Integral (imaginary time $\tau = i\,t$, $0 \le \tau \le \beta = 1/T$) $\Rightarrow$ PS I

$$Z[T,V,\mu] = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}A \exp\left\{-\int_0^\beta d\tau \int_V d^3x\ \mathcal{L}_{QCD}(\psi,\bar{\psi},A)\right\}$$

- QCD Lagrangian, non-Abelian gluon field strength: $F^a_{\mu\nu}(A) = \partial_\mu A^a\nu - \partial_\nu A^a_\mu + g\ f^{abc}[A^b_\mu, A^c_\nu]$

$$\mathcal{L}_{QCD}(\psi,\bar{\psi},A) = \bar{\psi}[i\gamma^\mu(\partial_\mu - igA_\mu) - m - \gamma^0\mu]\psi - \frac{1}{4}F^a_{\mu\nu}(A)F^{a,\mu\nu}(A)$$

- Numerical evaluation: Lattice gauge theory simulations (hotQCD, Wuppertal-Budapest)



- Equation of state: $\varepsilon(T) = -\partial \ln Z[T,V,\mu]/\partial\beta$
- Phase transition at $T_c = 155$ MeV
- Problem: Interpretation ?

$\varepsilon/T^4 = \frac{\pi^2}{30}N_\pi \sim 1$ (ideal pion gas)

$\varepsilon/T^4 = \frac{\pi^2}{30}(N_G + \frac{7}{8}N_Q) \sim 15.6$ (quarks and gluons)

- Hadron resonance gas

CHIRAL MODEL FIELD THEORY FOR QUARK MATTER

- Partition function as a Path Integral (imaginary time $\tau = i\ t$)

$$Z[T,V,\mu] = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi \exp\left\{ -\int^{\beta} d\tau \int_V d^3x [\bar{\psi}[i\gamma^\mu\partial_\mu - m - \gamma^0(\mu + \lambda_8\mu_8 + i\lambda_3\phi_3]\psi - \mathcal{L}_{\text{int}} + U(\Phi)] \right\}$$

Polyakov loop: $\Phi = N_c^{-1}\mathrm{Tr}_c[\exp(i\beta\lambda_3\phi_3)]$ Order parameter for deconfinement

- Current-current interaction (4-Fermion coupling) and KMT determinant interaction

$$\mathcal{L}_{\text{int}} = \sum_{M=\pi,\sigma,\dots} G_M(\bar{\psi}\Gamma_M\psi)^2 + \sum_D G_D(\bar{\psi}^C\Gamma_D\psi)^2 - K[\det{}_f(\bar{q}(1+\gamma_5)q) + \det{}_f(\bar{q}(1-\gamma_5)q)]$$

- Bosonization (Hubbard-Stratonovich Transformation)

$$Z[T,V,\mu] = \int \mathcal{D}M_M\mathcal{D}\Delta_D^\dagger\mathcal{D}\Delta_D\ \mathrm{e}^{-\sum_{M,D}\frac{M_M^2}{4G_M} - \frac{|\Delta_D|^2}{4G_D} + \frac{1}{2}\mathrm{Tr}\ \ln S^{-1}[\{M_M\},\{\Delta_D\},\Phi] + U(\Phi) + V_{\text{KMT}}}$$

- Collective quark fields: Mesons (M_M) and Diquarks (Δ_D); Gluon mean field: Φ
- Systematic evaluation: Mean fields + Fluctuations
  - Mean-field approximation: order parameters for phase transitions (gap equations)
  - Lowest order fluctuations: hadronic correlations (bound & scattering states)
  - Higher order fluctuations: hadron-hadron interactions

CHIRAL MODEL FIELD THEORY FOR QUARK MATTER

- Partition function as a Path Integral (imaginary time $\tau = i\ t$)

$$Z[T,V,\mu] = \int \mathcal{D}\bar{q}\mathcal{D}q \exp\left\{ -\int^{\beta} d\tau \int_V d^3x [\bar{q}(i\gamma^\mu\partial_\mu - m_0 - \gamma^0\mu)q + \sum_{M=\pi,\sigma} G_M(\bar{q}\Gamma_M q)^2] \right\}$$

- Couplings: $G_\pi = G_\sigma = G_S$ (chiral symmetry)
- Vertices: $\Gamma_\sigma = \mathbf{1}_D \otimes \mathbf{1}_f \otimes \mathbf{1}_c$; $\Gamma_\pi = i\gamma_5 \otimes \vec{\tau} \otimes \mathbf{1}_c$
- Bosonization (Hubbard-Stratonovich Transformation)

$$\exp\left[G_S(\bar{q}\Gamma_\sigma q)^2\right] = \text{const.} \int \mathcal{D}\sigma \exp\left[\frac{\sigma^2}{4G_S} + \bar{q}\Gamma_\sigma q \sigma\right]$$

- Integrate out quark fields ⟶ bosonized partition function

$$Z[T,V,\mu] = \int \mathcal{D}\sigma\mathcal{D}\pi \exp\left\{ -\frac{\sigma^2+\pi^2}{4G_S} + \frac{1}{2}\mathrm{Tr}\ \ln S^{-1}[\sigma,\pi] \right\}$$

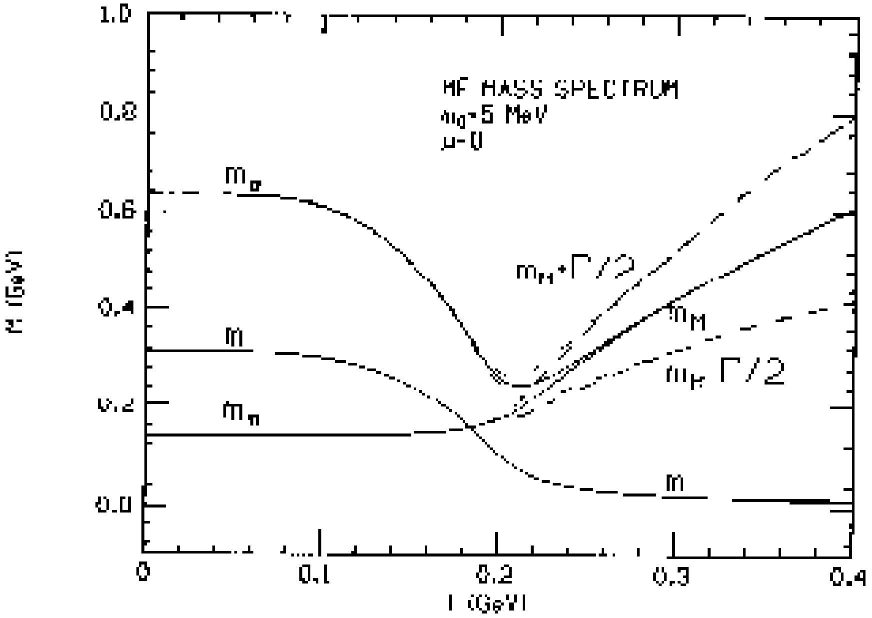
- Systematic evaluation: Mean fields + Fluctuations
  - Mean-field approximation: order parameters for phase transitions (gap equations)
  - Lowest order fluctuations: hadronic correlations (bound & scattering states)

Generalized Beth-Uhlenbeck EoS: NJL model results

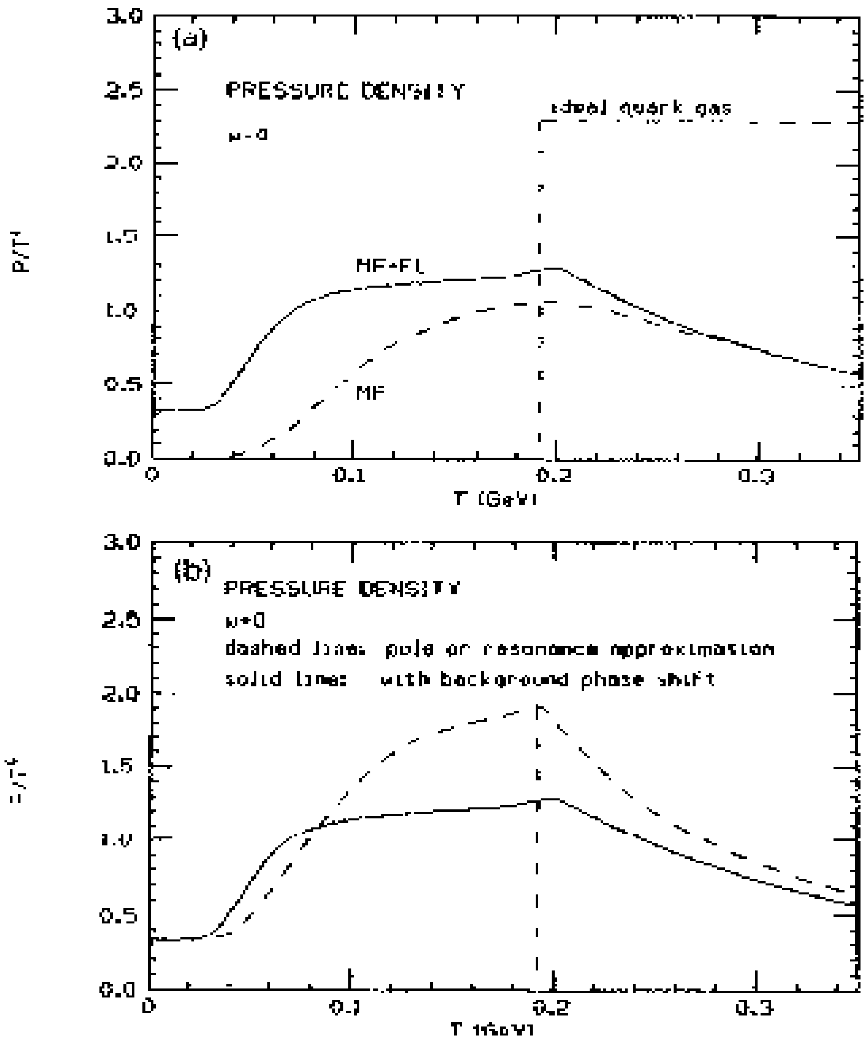
Generalized Beth-Uhlenbeck approach:

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

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



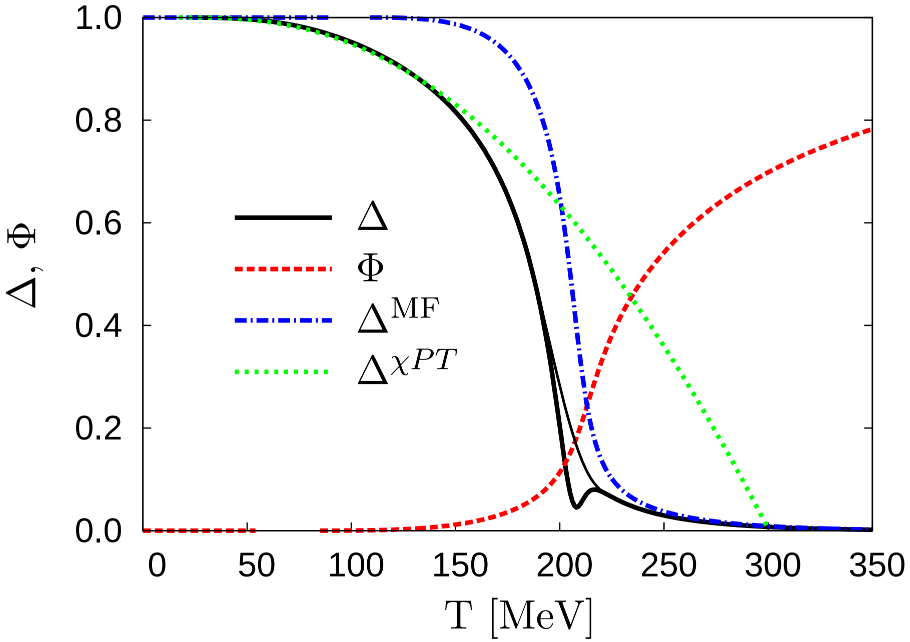
P. Zhuang et al. / Nuclear Physics A 576 (1994) 525–552

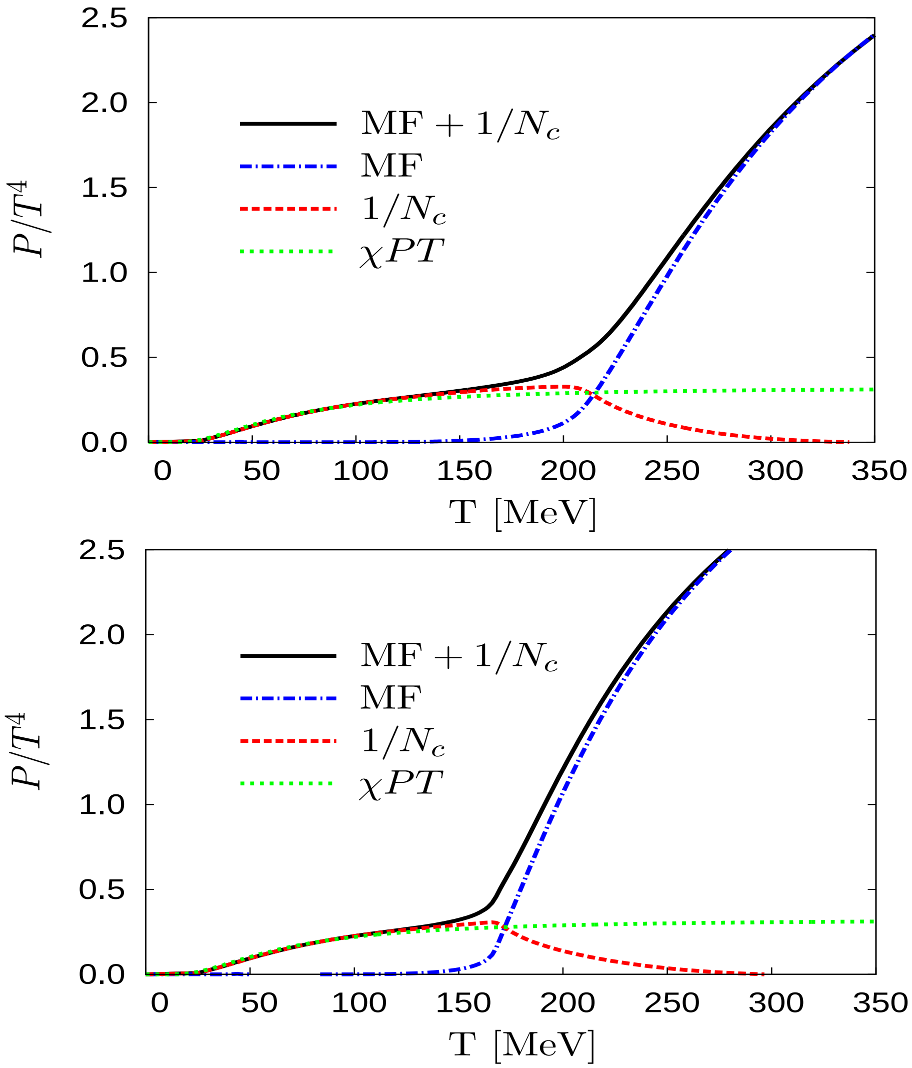


GEN. BETH-UHLENBECK EOS: NONLOCAL PNJL RESULTS

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) $\Longrightarrow$

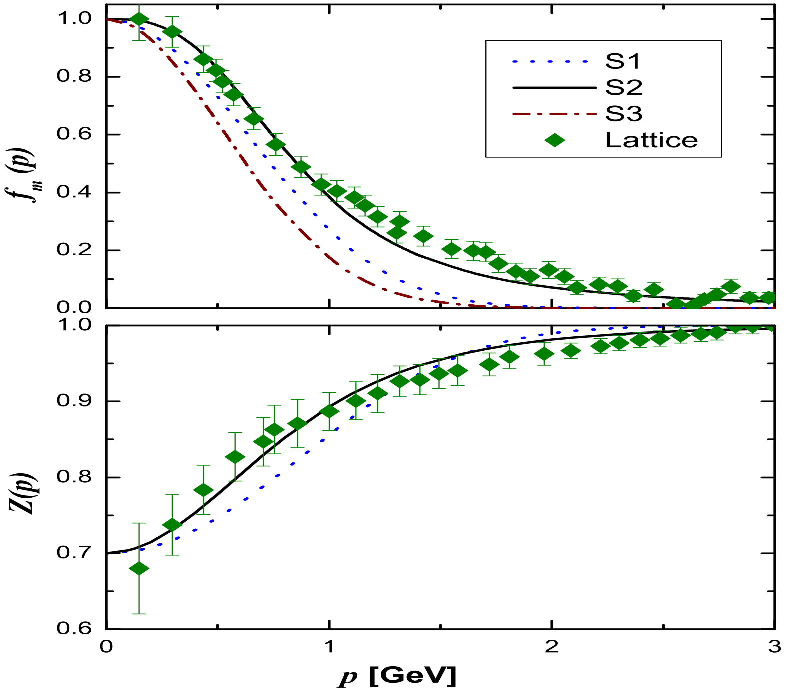
NONLOCAL PNJL MODEL VS. LATTICE QCD

$$S_E = \int d^4x \left\{ \bar{\psi}(x)\left(-i\gamma_\mu D_\mu + \hat{m}\right)\psi(x) - \frac{G_S}{2}[j_a(x)j_a(x) - j_P(x)j_P(x)] + \mathcal{U}\left(\Phi[A(x)]\right) \right\} \ ,$$

Nonlocal currents

$$j_a(x) = \int d^4z \ g(z) \ \bar{\psi}\left(x + \frac{z}{2}\right) \ \Gamma_a \ \psi\left(x - \frac{z}{2}\right)$$

$$j_P(x) = \int d^4z \ f(z) \ \bar{\psi}\left(x + \frac{z}{2}\right) \ \frac{i\overleftrightarrow{\not{\partial}}}{2\ \kappa_p} \ \psi\left(x - \frac{z}{2}\right)$$



Formfactors fitted to Lattice results

$$g(q) = \frac{1+\alpha_z}{1+\alpha_z \ f_z(q)} \frac{\alpha_m \ f_m(q) - m \ \alpha_z f_z(q)}{\alpha_m - m \ \alpha_z}$$

$$f(q) = \frac{1+\alpha_z}{1+\alpha_z \ f_z(q)} f_z(q)$$

$$f_m(q) = \left[1 + \left(q^2/\Lambda_0^2\right)^{3/2}\right]^{-1}$$

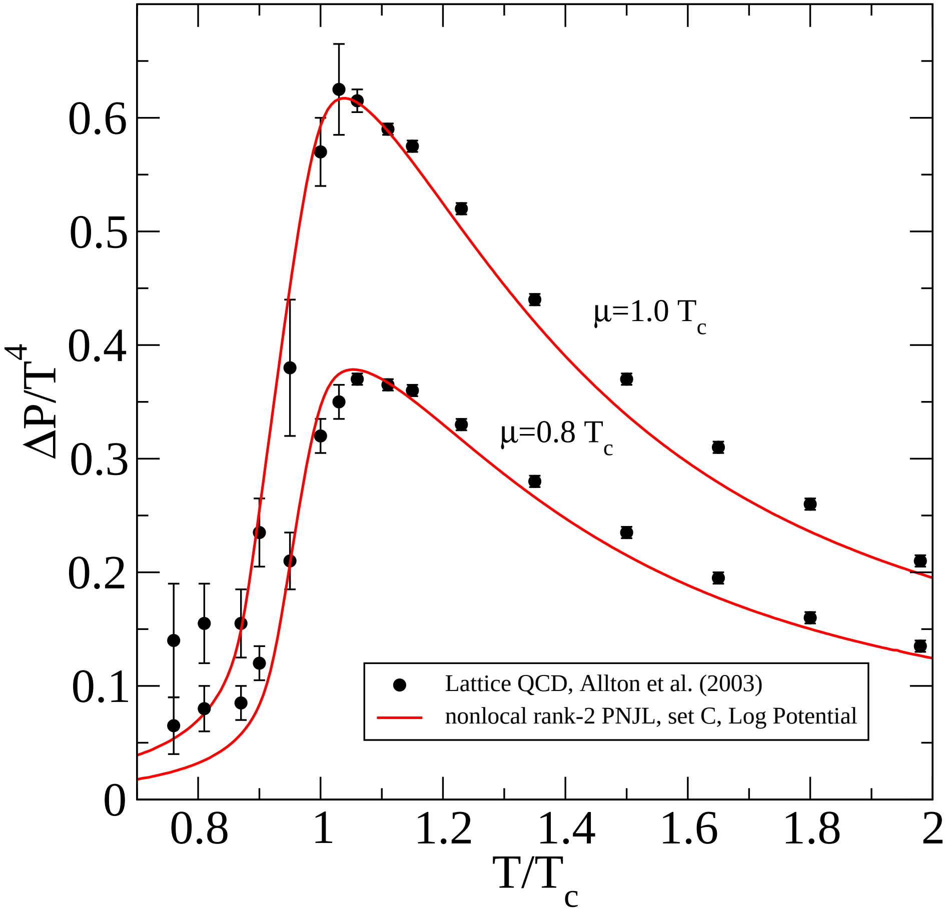
$$f_z(q) = \left[1 + \left(q^2/\Lambda_1^2\right)\right]^{-5/2} .$$

4 Parappilly et al., Phys. Rev. D

Noguera, Scoccola, PRD 78, 114002 (2008)

Nonlocal PNJL model vs. Lattice QCD (II)

$$\Omega^{\rm MFA} = -\frac{4T}{\pi^2}\sum_c \int_{p,n} \ln\left[\frac{(\rho^c_{n,\vec{p}})^2 + M^2(\rho^c_{n,\vec{p}})}{Z^2(\rho^c_{n,\vec{p}})}\right] + \frac{\sigma_1^2 + \kappa_p^2\ \sigma_2^2}{2G_S} + \mathcal{U}(\Phi, T)$$



Mass function and WF renormalization

$$M(p) = Z(p)\,[m + \sigma_1\ g(p)]$$

$$Z(p) = [1 - \sigma_2\ f(p)]^{-1}\,.$$

Finite T, μ formalism: Matsubara

$$(\rho^c_{n,\vec{p}})^2 = [(2n+1)\pi T - i\mu + \phi_c]^2 + \vec{p}^{\,2}\ ,$$

Polyakov-loop potential:

Dexheimer-Schramm, arXiv:0910.1312

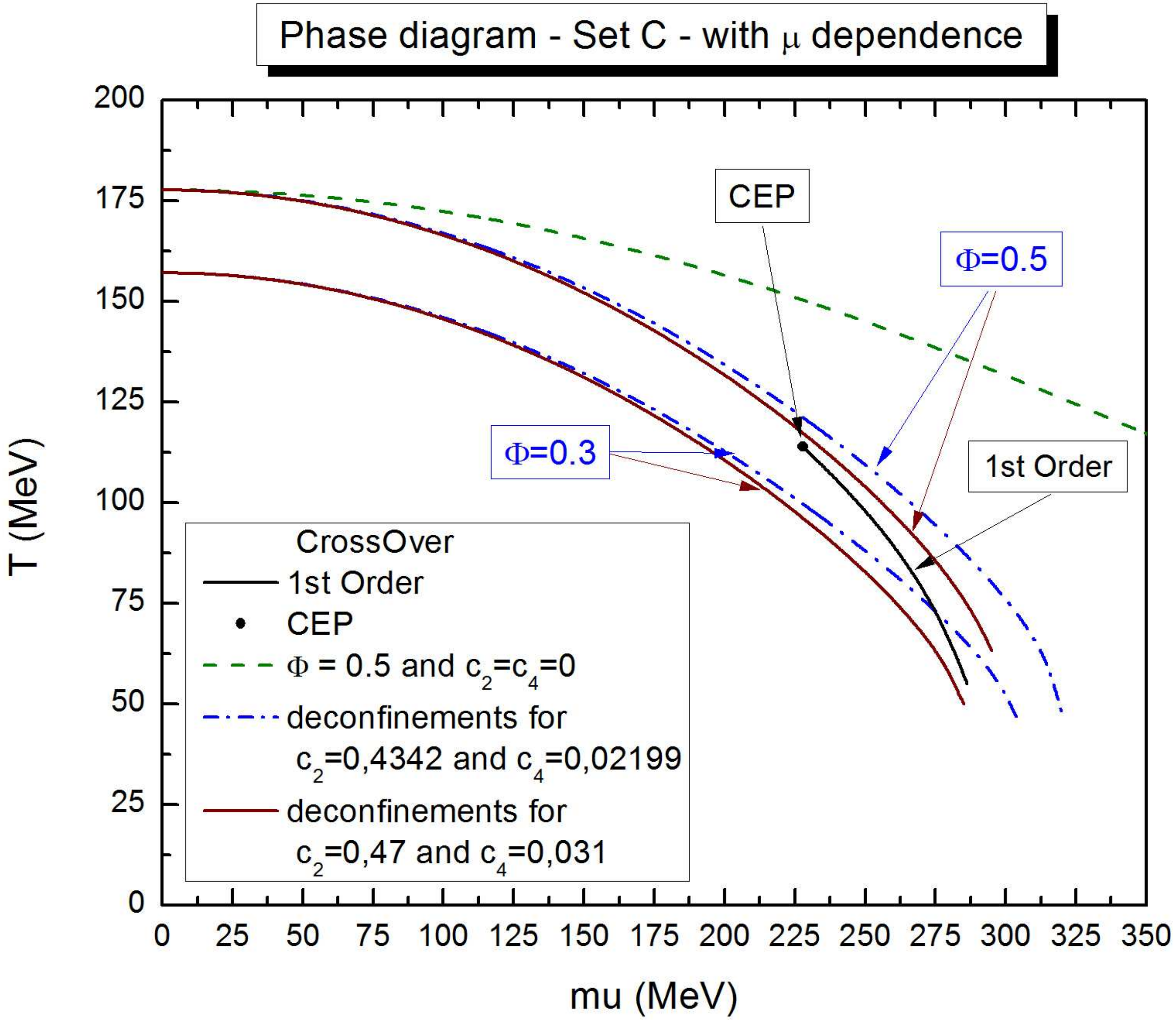
$$\begin{aligned}\mathcal{U}_3(\Phi, T, \mu) &= (a_0 T^4 + a_1\mu^4 + a_2 T^2\mu^2)\Phi^2 \\ &\quad + a_3 T_0^4 \ln\left(1 - 6\Phi^2 + 8\Phi^3 - 3\Phi^4\right)\end{aligned}$$

Parameters:

$a_0 = 1.85$, $a_1 = 1.44$x10^{-3}, $a_2 = 0.08$, $a_3 = 0.40$

Contrera, D.B., in preparation

NONLOCAL PNJL MODEL: PHASE DIAGRAM AND CP



CEP Parameters:

$T_{\mathrm{CP}} = 128.6$ MeV
$\mu_{\mathrm{CP}} = 223.3$ MeV
$\mu/T\big|_{CEP} = 1.74$

Gustavo Contrera, D.B., in preparation (2011)

From Diquarks to Baryons (I)

The inverse diquark propagator is then obtained from

$$(S_D^A)^{-1}(k_0,k) = \frac{1}{4G_D} - \Pi_D^A(k_0,k) \quad , \quad \Pi_D^A(k_0,k) = \int \frac{d^4q}{(2\pi)^4} S_Q(q)\Sigma^A(k)S_Q(q-k)\Sigma^A(k)$$

Propagator can be expressed via the spectral density after analytic continuation

$$S_D^A(z,k) = \int_{-\infty}^{\infty}\frac{\mathrm{d}\omega}{2\pi}\frac{\varrho_D^A(\omega,k)}{z-\omega} \quad , \quad \varrho_D^A(\omega,k) = \lim_{\varepsilon\to 0}\frac{8G_D^2\,\mathrm{Im}\Pi_D^A(\omega+i\varepsilon,k)}{[1-2G_D\mathrm{Re}\Pi_D^A(\omega+i\varepsilon,k)]^2+[2G_D\mathrm{Im}\Pi_D^A(\omega+i\varepsilon,k)]^2}$$

Similar, baryon propagator and spectral density

$$S_B^{-1}(P_0,P) = \frac{1}{G_B} - \Pi_B(P_0,P) \quad , \quad \Pi_B(P_0,P) = \sum_{A=2,5,7}\int\frac{\mathrm{d}k^4}{(2\pi)^4}\, S_Q^{11,A}(P-k)S_D^A(k)$$

Further details:

Wang, Wang, Rischke, PLB (2011); arXiv:1008.4029 [nucl-th]

Zablocki, Blaschke, Buballa, in preparation (2011)

THERMODYNAMIC POTENTIAL IN TERMS OF PHASE SHIFT

Integrating the spectral density over the coupling constant leads to

$$\int_0^G \frac{dg}{g^2}\rho^g_{\mu,T}(\omega,\mathbf{P}) = \frac{i}{2}\log\left(\frac{\frac{1}{G}-\chi_{\mu,T}(\omega+i\delta,\mathbf{P})}{\frac{1}{G}-\chi_{\mu,T}(\omega-i\delta,\mathbf{P})}\right) \equiv \delta_{\mu,T}(\omega,\mathbf{P}).$$

The in-medium phase shift $\delta_{\mu,T}(\omega,\mathbf{P})$ is the argument of the dynamic pair susceptibility

$$\frac{\frac{1}{G}-\chi_{\mu,T}(\omega\pm i\delta,\mathbf{P})}{|\frac{1}{G}-\chi_{\mu,T}(\omega,\mathbf{P})|} = e^{\mp i\delta_{\mu,T}(\omega,\mathbf{P})}.$$

Thermodynamical potential in Beth-Uhlenbeck type form

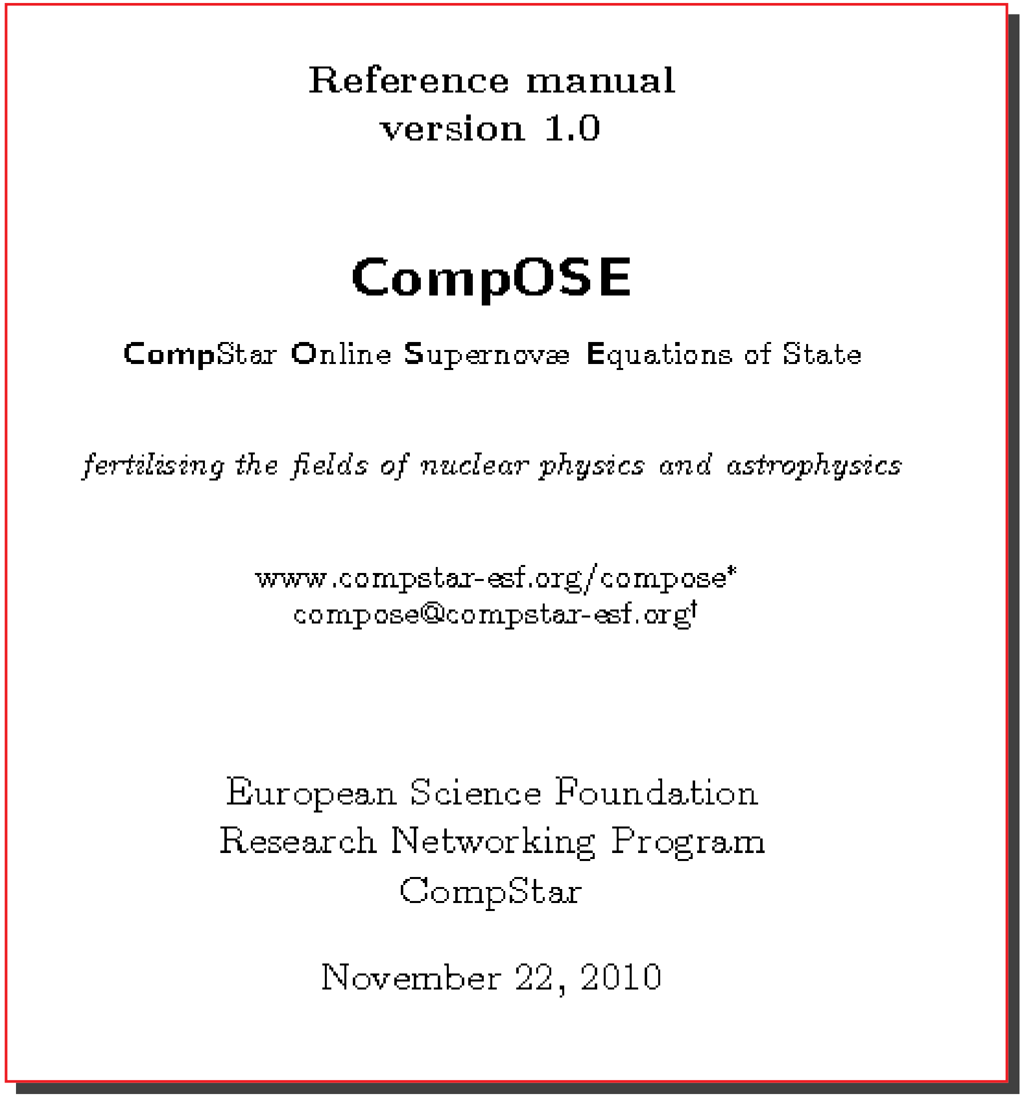
$$\Omega_{\rm NSR} = -d_B\int_{-\infty}^{\infty}\frac{d\omega}{\pi}\frac{d\mathbf{P}}{(2\pi)^3}\tilde{f}_B(\omega)\delta_{\mu,T}(\omega,\mathbf{P}),$$

$$\Omega_{\rm qfl} = -d_B\int_{-\infty}^{\infty}\frac{d\omega}{\pi}\frac{d\mathbf{P}}{(2\pi)^3}\frac{\epsilon(\omega)}{2}\left[\delta_{\mu,T}(\omega,\mathbf{P})-\delta_{0,0}(\omega,\mathbf{P})\right],$$

where $\Omega_{\rm NSR}$ is exactly the Nozieres–Schmitt-Rink result in J. Low Temp. Phys. **59** (1985) 195

See also Abuki, NPA **791** (2007) 117 and Zablocki, D.B., Buballa, in prep.

COMPOSE - COMPSTAR ONLINE SUPERNOVA EOS



Reference manual
version 1.0

CompOSE

CompStar **O**nline **S**upernovæ **E**quations of State

fertilising the fields of nuclear physics and astrophysics

www.compstar-esf.org/compose[*]
compose@compstar-esf.org[†]

European Science Foundation
Research Networking Program
CompStar

November 22, 2010

General Requirements:

- Densities: $10^{-8} \leq n/n_0 \leq 10$
- Temperatures: $0 \leq T \leq 200$ MeV
- Proton fractions: $0 \leq Y_p \leq 0.6$; $\beta = 1 - 2Y_p$

New Developments:

- Dissolution of clusters due to Pauli blocking
- Realistic high-density modeling: DD-RMF/3FSC PNJL
- Thermodynamics of 1^{st} order PT; pasta phases

I. For Contributors:

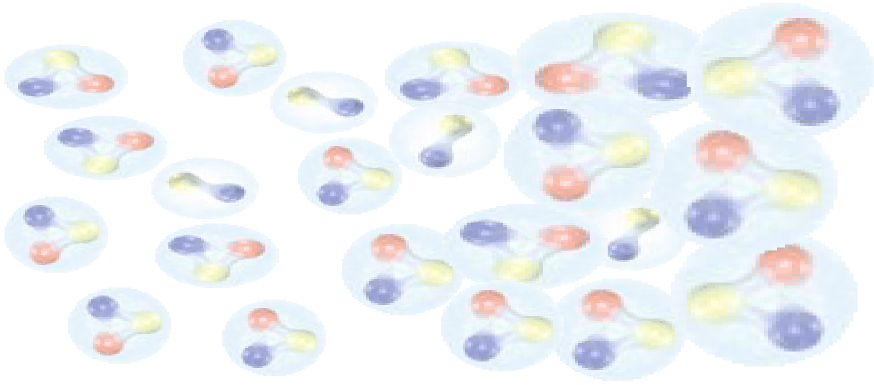
- How to prepare EoS tables
- How to submit EoS tables
- Extending CompOSE

II. For Users:

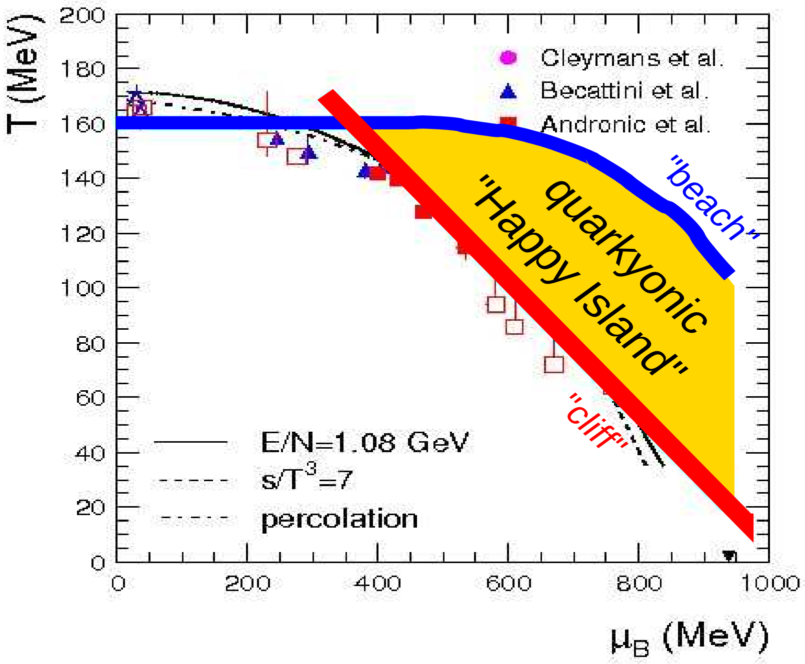
- Hadronic EoS: Statistical, Skyrme, DBHF, ...
- Quark Matter EoS: Bag, PNJL, ...
- Phase transition: Maxwell, Gibbs, Pasta, ...

QUARKYONIC PHASE = CHIRAL SYMMETRY + CONFINEMENT

APPLICATION OF GBU APPOACH: MOTT-ANDERSON FREEZEOUT



Andronic et al., arxiv:0911.4806



“beach”: hadron resonances ⟶ 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)
  → geometrical overlap (percolation)

D.B., Berdermann, Cleymans, Redlich,
Part. Nucl. Phys. Lett. (2011), arxiv:1102.2908;
Few Body Syst. (2011) arxiv:1109.5391

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!

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

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)

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

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

$$\begin{aligned}
\Omega_{\rm meson}(T,\mu) &= \sum_{M=\pi,\dots} d_M \int\frac{d\omega}{\pi}\int\frac{d^3k}{(2\pi)^3}\left\{\frac{\omega}{2} + T\ \ln\left[1-e^{-\beta\omega}\right]\right\} A_M(\omega,k)\ , \\
\Omega_{\rm baryon}(T,\mu) &= -\sum_{B=N,\dots} d_B \int\frac{d\omega}{\pi}\int\frac{d^3k}{(2\pi)^3}\left\{\frac{\omega}{2} + T\ \ln\left[1+e^{-\beta(\omega-\mu_B)}\right] + (\mu_B \leftrightarrow -\mu_B)\right\} A_B(\omega,k)\ , \\
A_M(\omega,k) &= \pi\delta(\omega - E_M(k)) + \text{continuum}\ , \quad A_B(\omega,k)\dots\text{analoguous}
\end{aligned}$$

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)

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

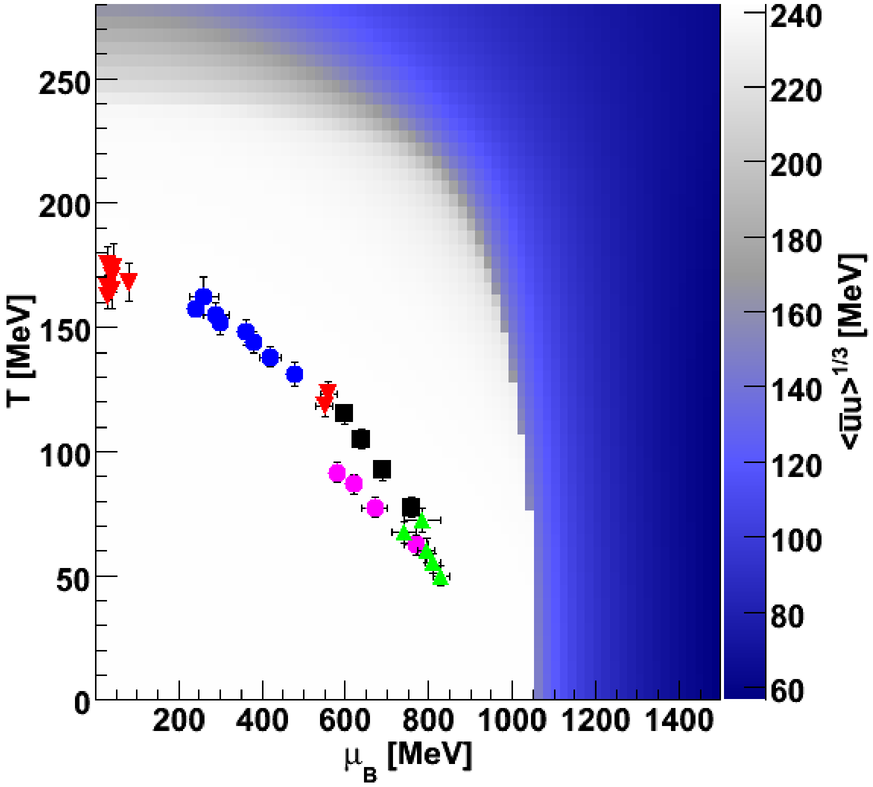
with the scalar nucleon density $n_{s,N}(T,\mu) = \frac{2}{\pi^2}\int_0^\infty dp\,p^2\frac{m_N}{E_N(p)}\left\{f_N(T,\mu) + f_N(T,-\mu)\right\}$

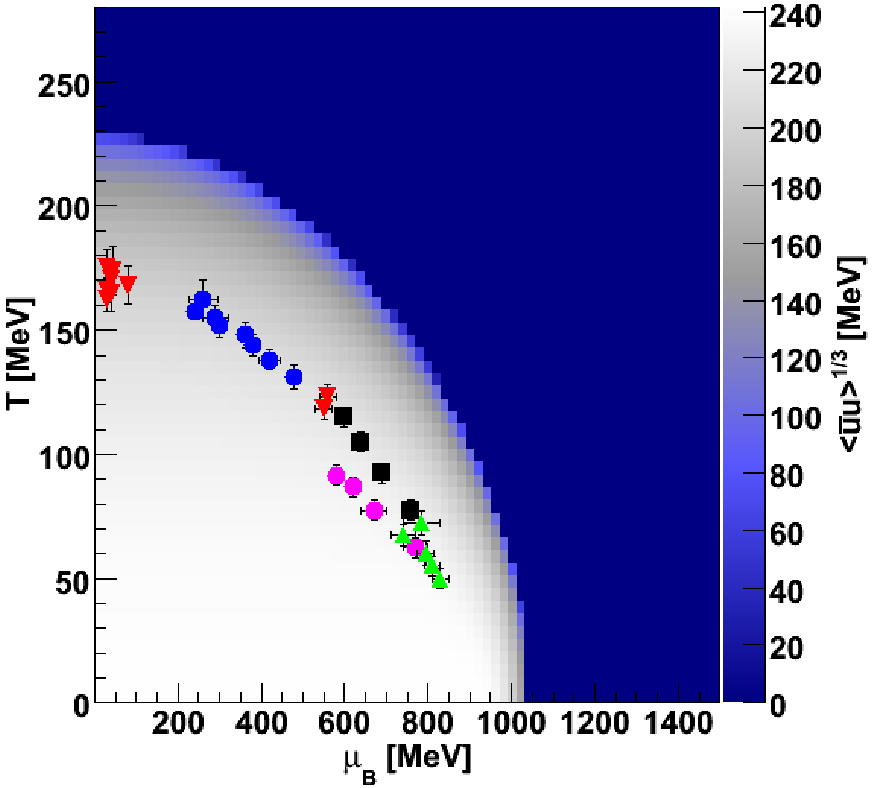
D.B., J. Berdermann, J. Cleymans, K. Redlich, arxiv:1102.2908 (2011)

PNJL MODEL BEYOND MF - RESULTS

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

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



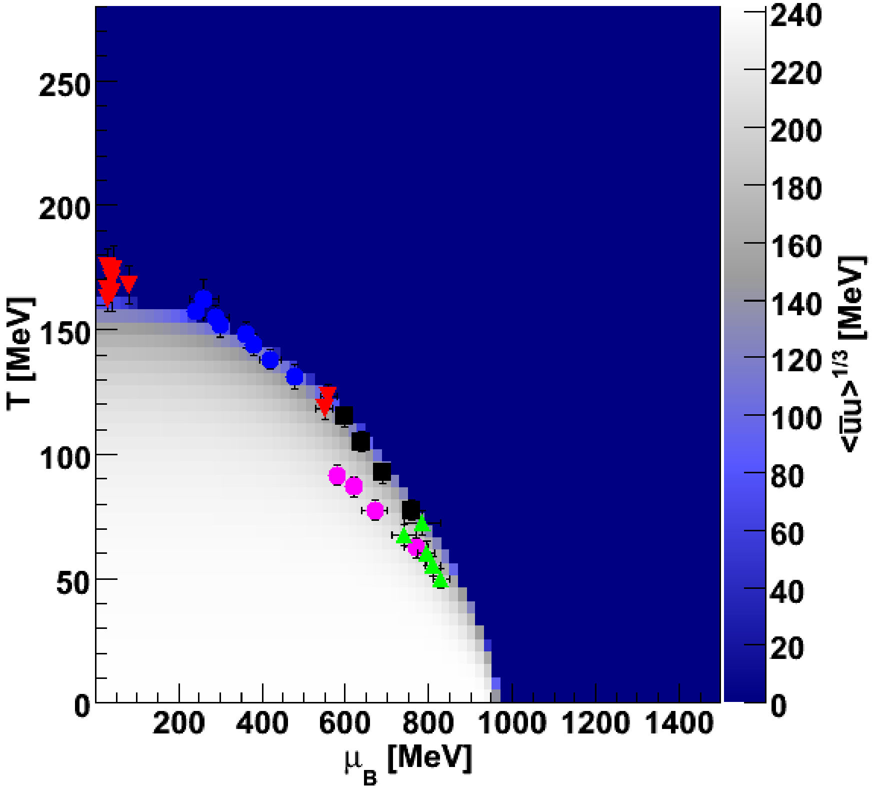


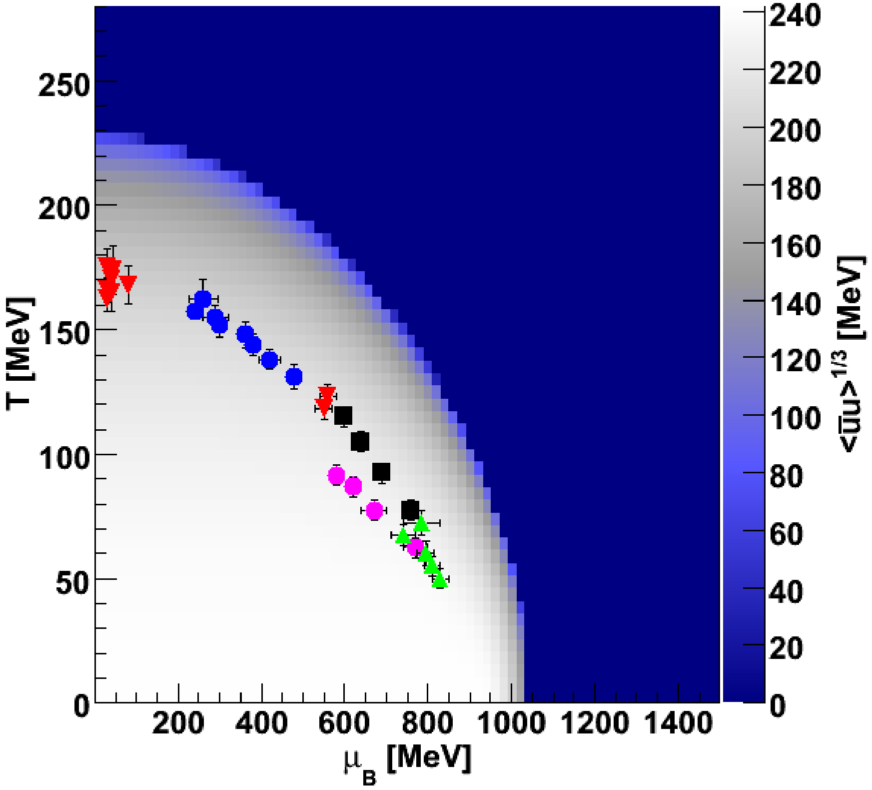
D.B., J. Berdermann, J. Cleymans, K. Redlich, arxiv:1102.2908 (2011)

PNJL MODEL BEYOND MF - RESULTS

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

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

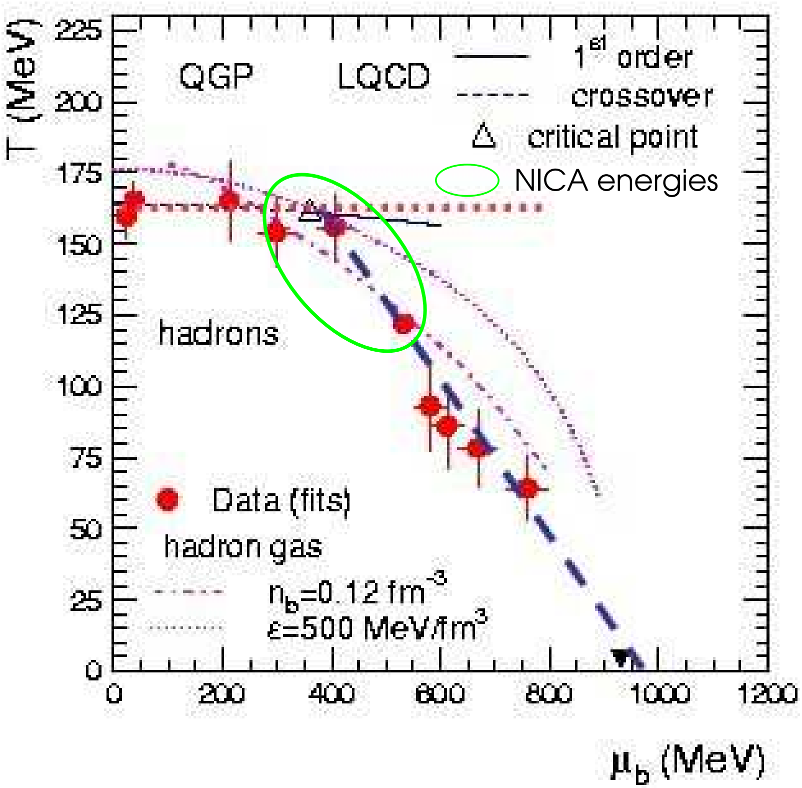


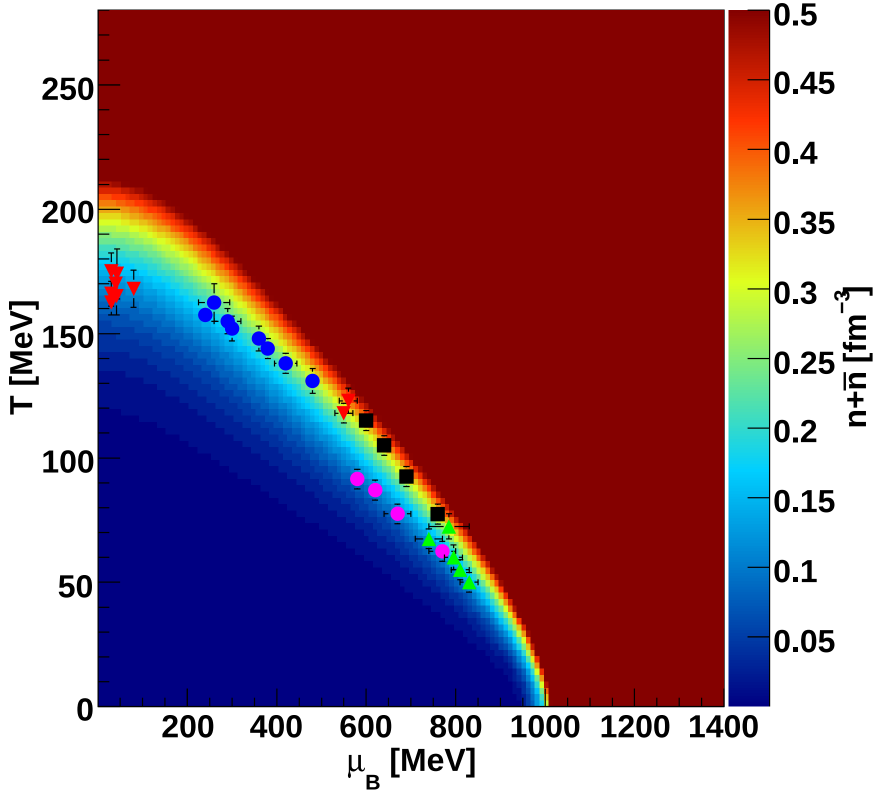


D.B., J. Berdermann, J. Cleymans, K. Redlich, arxiv:1102.2908 (2011)

PNJL Model beyond MF vs. Phenomenological Fit

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

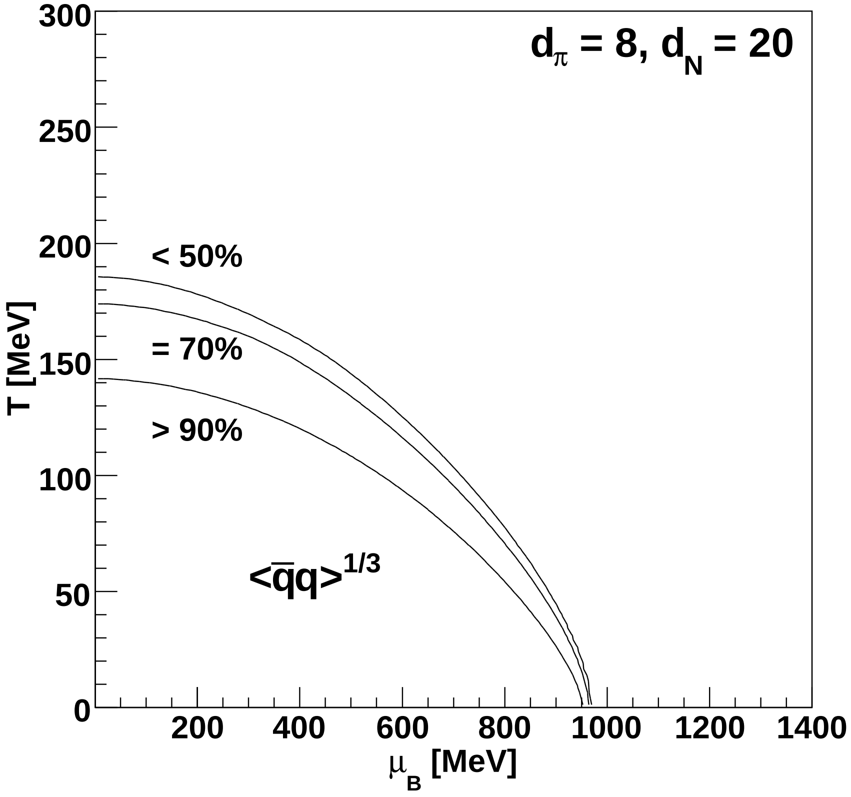


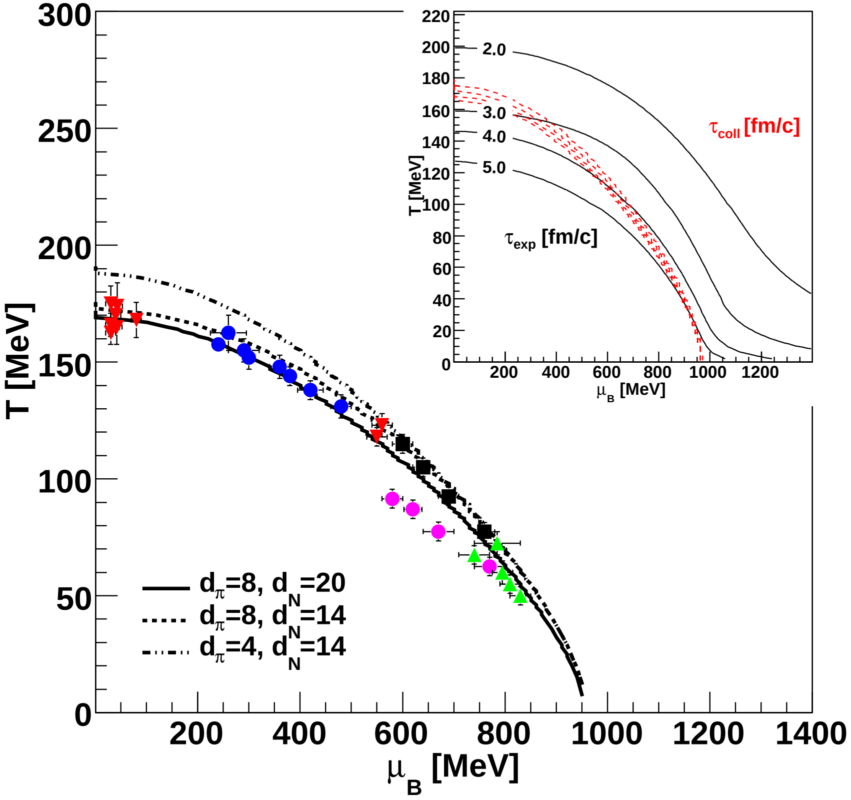


D.B., J. Berdermann, J. Cleymans, K. Redlich, arxiv:1102.2908 (2011)

PNJL MODEL BEYOND MF CONDENSATE VS. FREEZE-OUT COND.

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

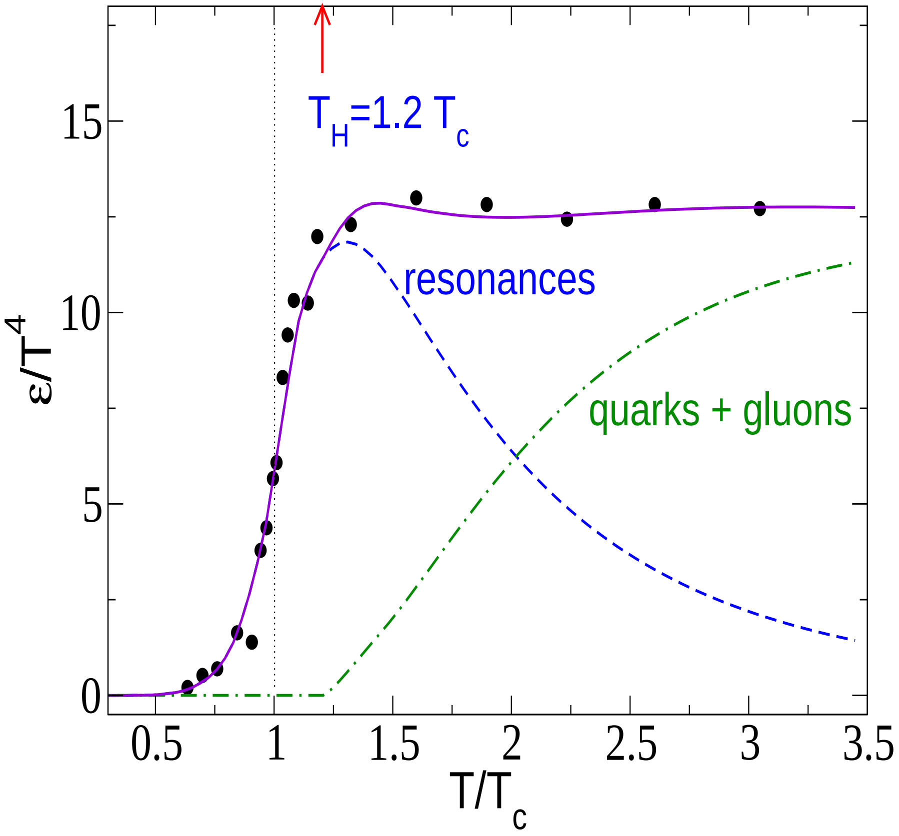




D.B., J. Berdermann, J. Cleymans, K. Redlich, arxiv:1102.2908 (2011);
Few Body Systems (2011); DOI: 10.1007/s00601-011-0261-6

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

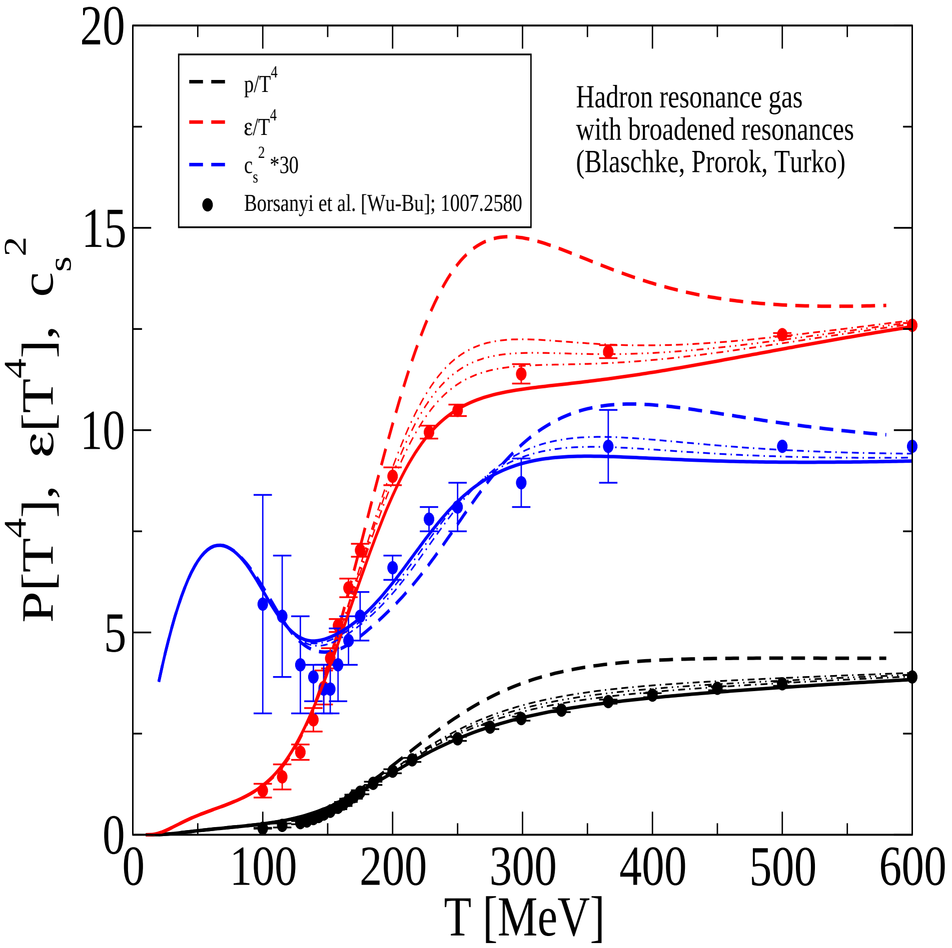
Blaschke & Bugaev, Fizika B13, 491 (2004)

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

Blaschke & Yudichev (2006)

Hybrid appoach: PNJL & Mott-Hagedorn Resonance Gas

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



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

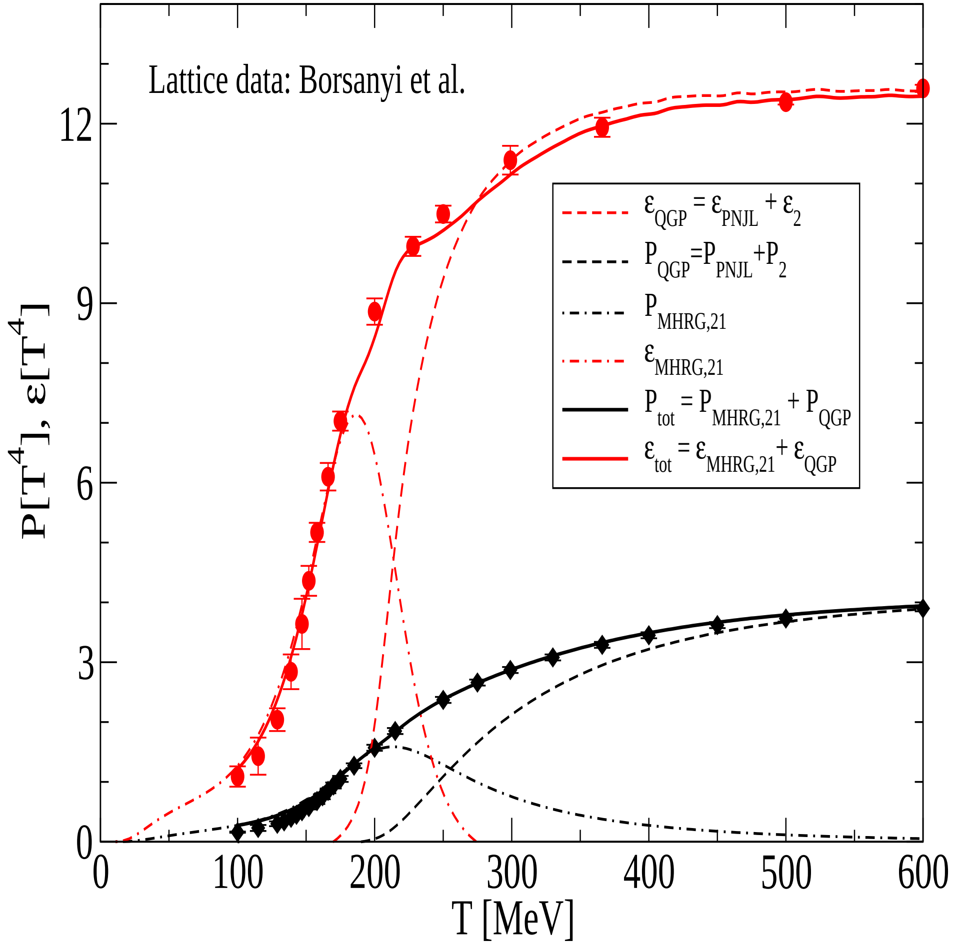
Blaschke & Bugaev, Fizika B13, 491 (2004)

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

Blaschke, Prorok & Turko, in preparation

Hybrid appoach: PNJL & Mott-Hagedorn Resonance Gas

$$P_{\rm tot}(T,\{\mu_j\}) = P_{\rm PNJL}(T,\{\mu_i\}) + \sum_{r=M,B} \delta_r g_r \int ds\, A_r(s,m_r;T) \int \frac{d^3p}{(2\pi)^3} T \ln\left\{1+\delta_r \exp\left(\frac{\sqrt{p^2+s}-\mu_r}{T}\right)\right\}$$



Spectral function for hadronic 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

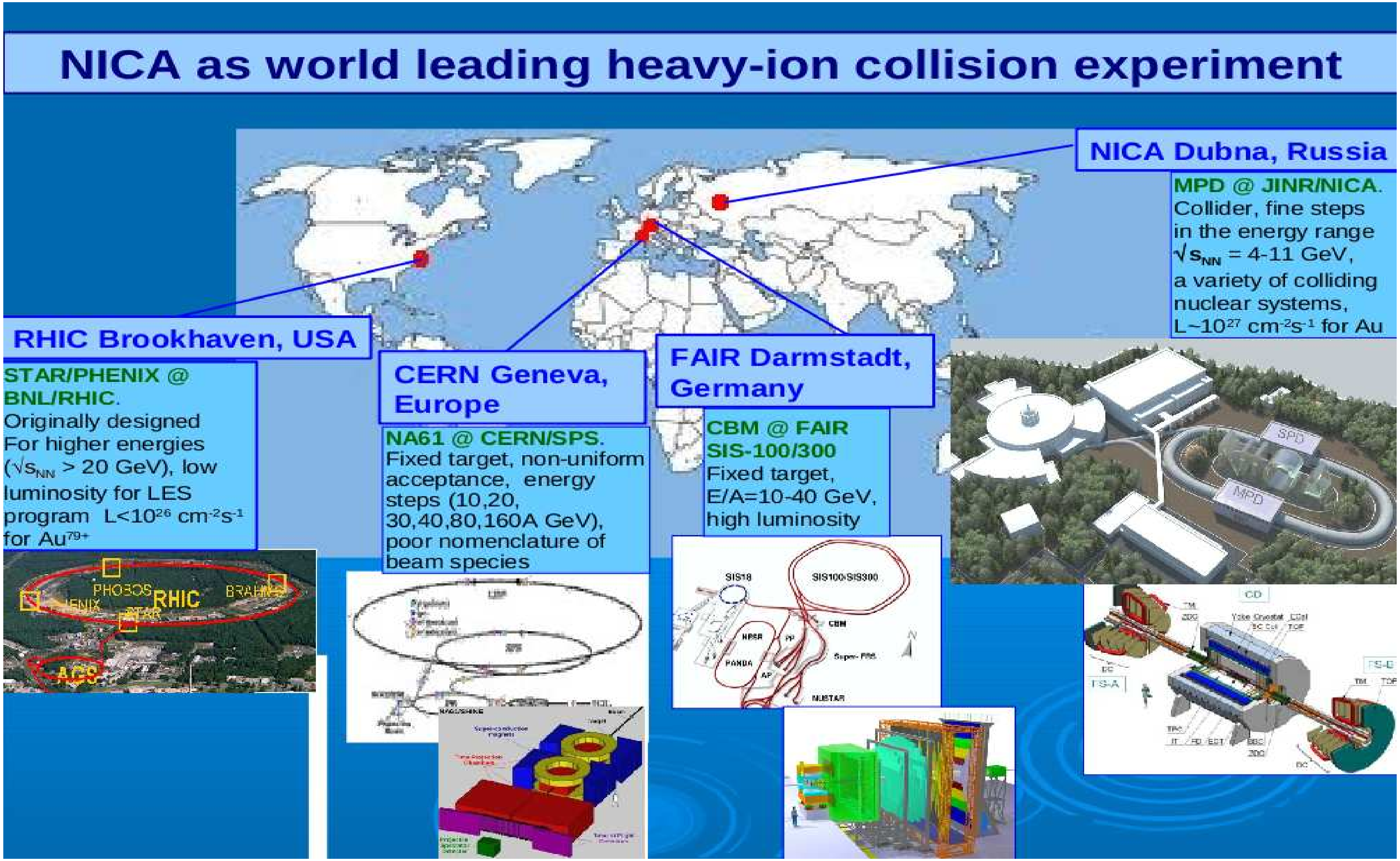
Hadron resonances present up to $T_{\rm max} \sim 250$ MeV

Blaschke & Bugaev, Fizika B13, 491 (2004)

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

Blaschke, Prorok & Turko, in preparation

Hadronic states above T_c ! See also: Ratti, Bellwied et al., arXiv:1109.6243 [hep-ph]



NICA as world leading heavy-ion collision experiment

NICA Dubna, Russia

MPD @ JINR/NICA.
Collider, fine steps
in the energy range
$\sqrt{s_{NN}}$ = 4-11 GeV,
a variety of colliding
nuclear systems,
L~10^{27} $cm^{-2}s^{-1}$ for Au

RHIC Brookhaven, USA

STAR/PHENIX @ BNL/RHIC.
Originally designed
For higher energies
($\sqrt{s_{NN}}$ > 20 GeV), low
luminosity for LES
program L<10^{26} $cm^{-2}s^{-1}$
for Au^{79+}

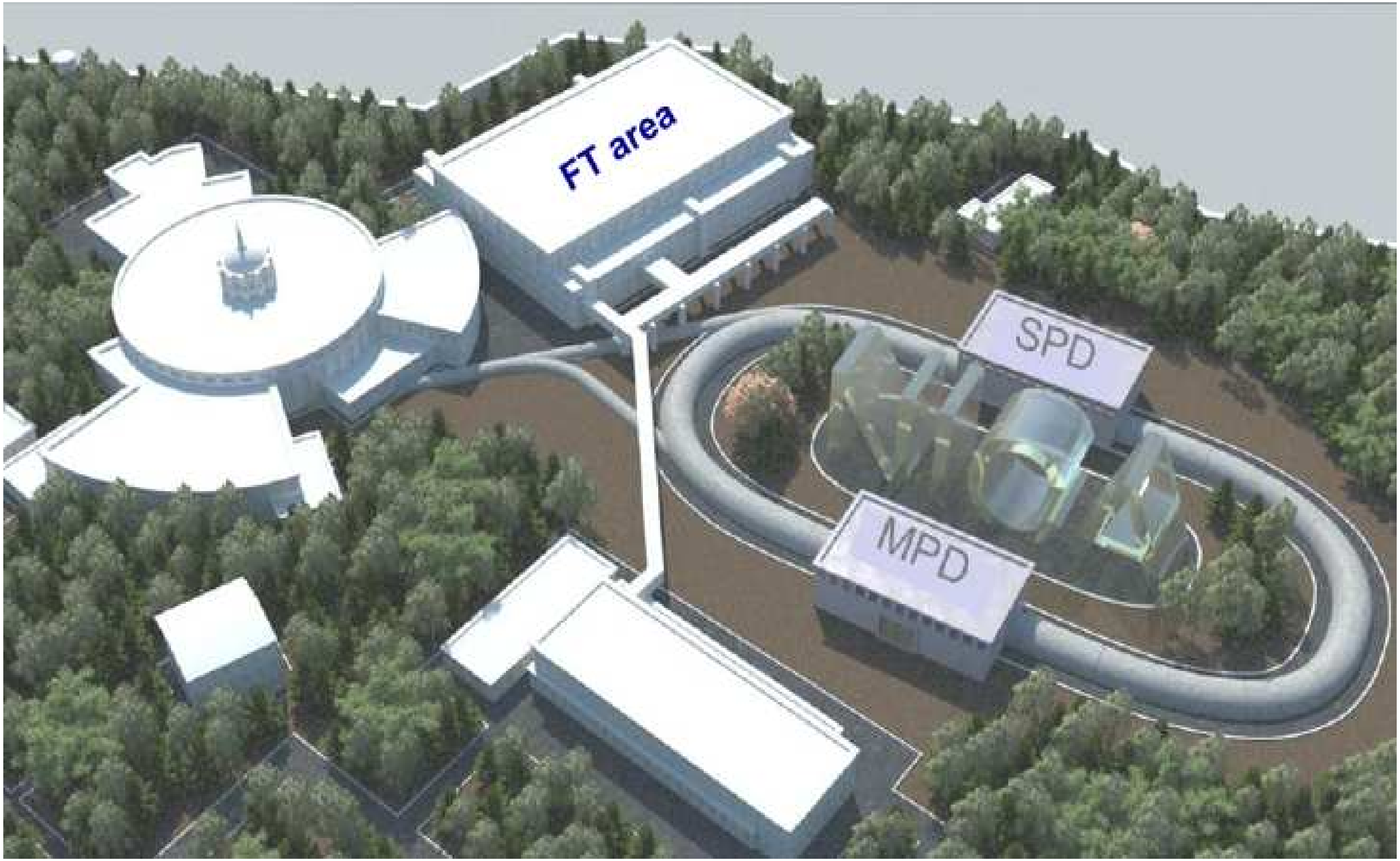
CERN Geneva, Europe

NA61 @ CERN/SPS.
Fixed target, non-uniform
acceptance, energy
steps (10,20,
30,40,80,160A GeV),
poor nomenclature of
beam species

FAIR Darmstadt, Germany

CBM @ FAIR SIS-100/300
Fixed target,
E/A=10-40 GeV,
high luminosity


FT experiment area
bld. 205 (10^4 m^2)
Collider
New Linac
Booster
Nuclotron
Lu 20


FT area
SPD
MPD

Комплекс NICA

Гелиевый комплекс

Линак-1

Линак-2

Зона пучков бустера

Нуклотрон

Детектор MPD

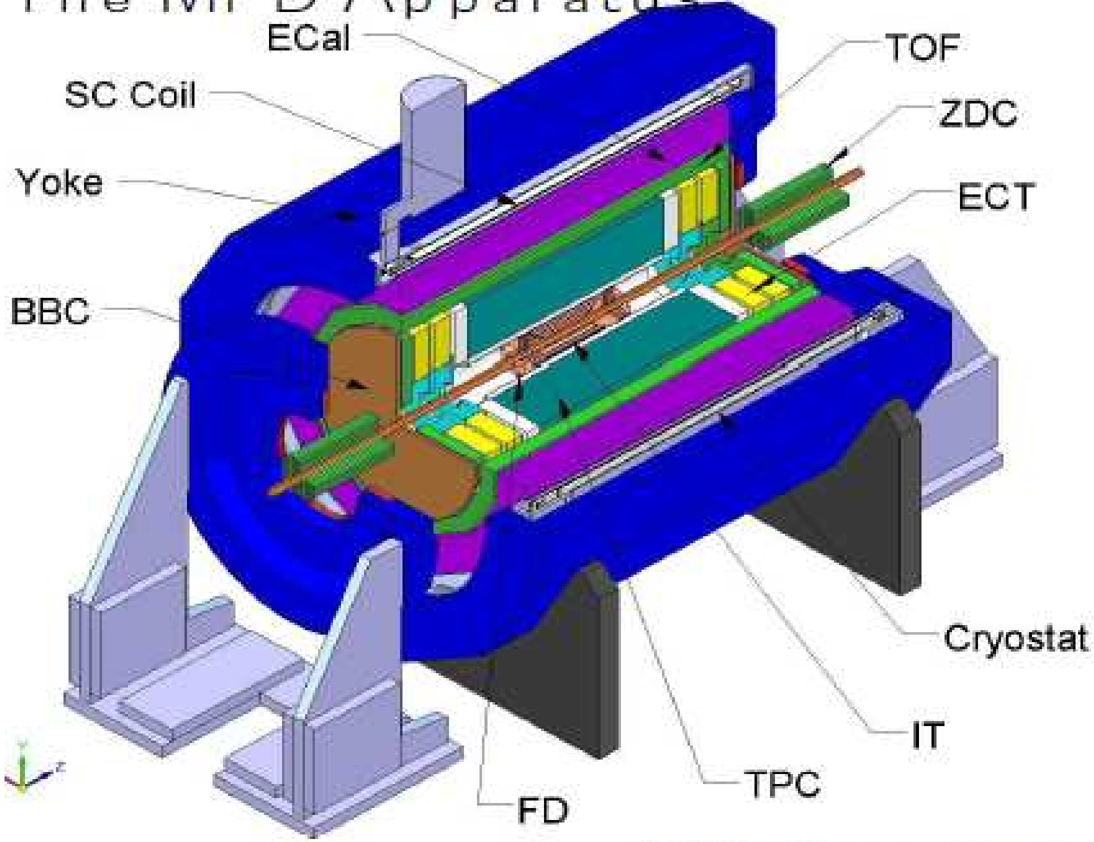
Бустер

Зона неподвижных мишеней

Детектор SPD

Коллайдер NICA

The MPD Apparatus

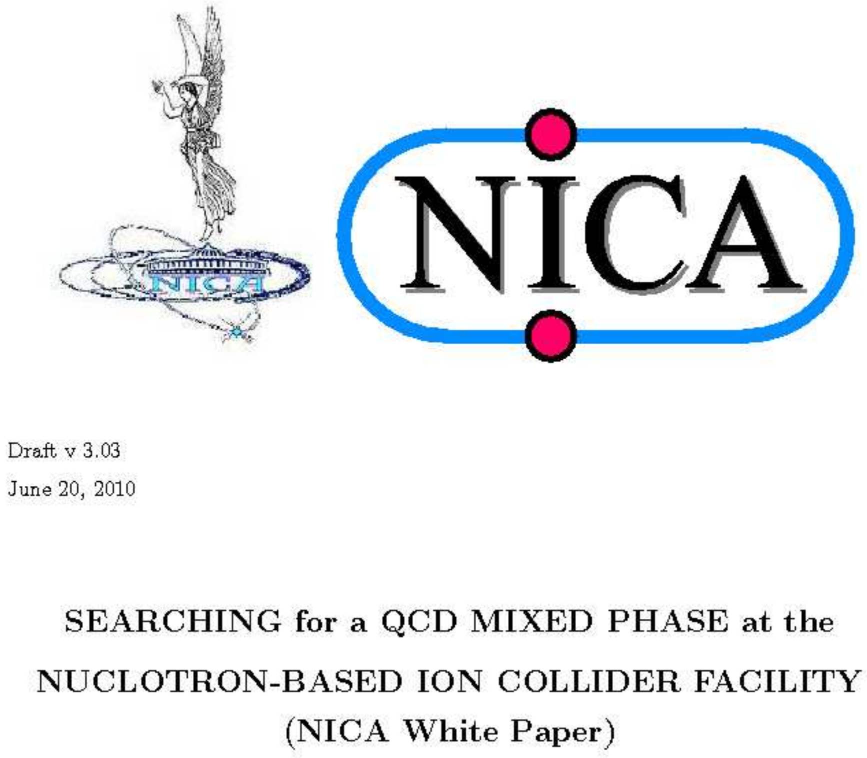


- **Active volume**
  5 m (length) x 4 m (diameter)
- **Magnet**
  0.5 T superconductor
- **Tracking**
  TPC & straw EndCapTracker & silicon pixels (IT) for vertexing
- **ParticleID**
  hadrons(TPC+TOF), π^0,γ (ECAL), e^+e^-(TPC+TOF+ECAL)
- **Centrality & T0 timing**
  ZDC FD

MPD Advantages:

- ❑ Hermeticity, homogenous acceptance (2π in azimuth), low material budget
- ❑ Excellent tracking performance and powerful PID
- ❑ High event rate capability and careful event characterization

Invitation: Contribute to the NICA White Paper



Draft v 3.03

June 20, 2010

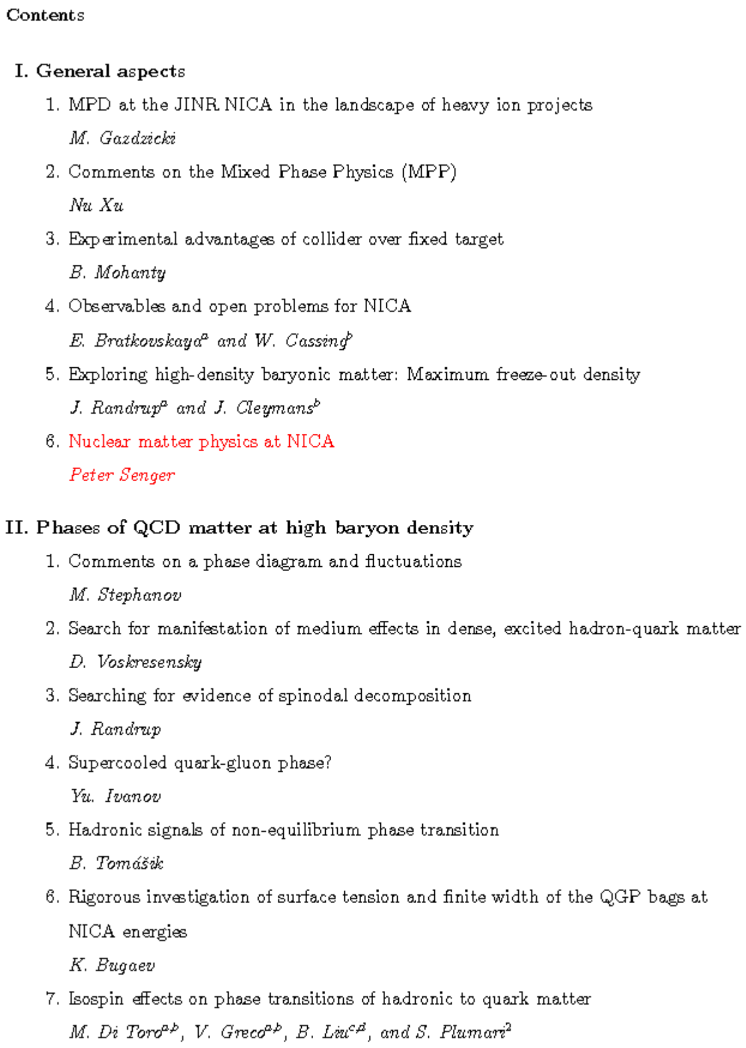
SEARCHING for a QCD MIXED PHASE at the

NUCLOTRON-BASED ION COLLIDER FACILITY

(NICA White Paper)

http://theor.jinr.ru/twiki-cgi/view/NICA/WebHome

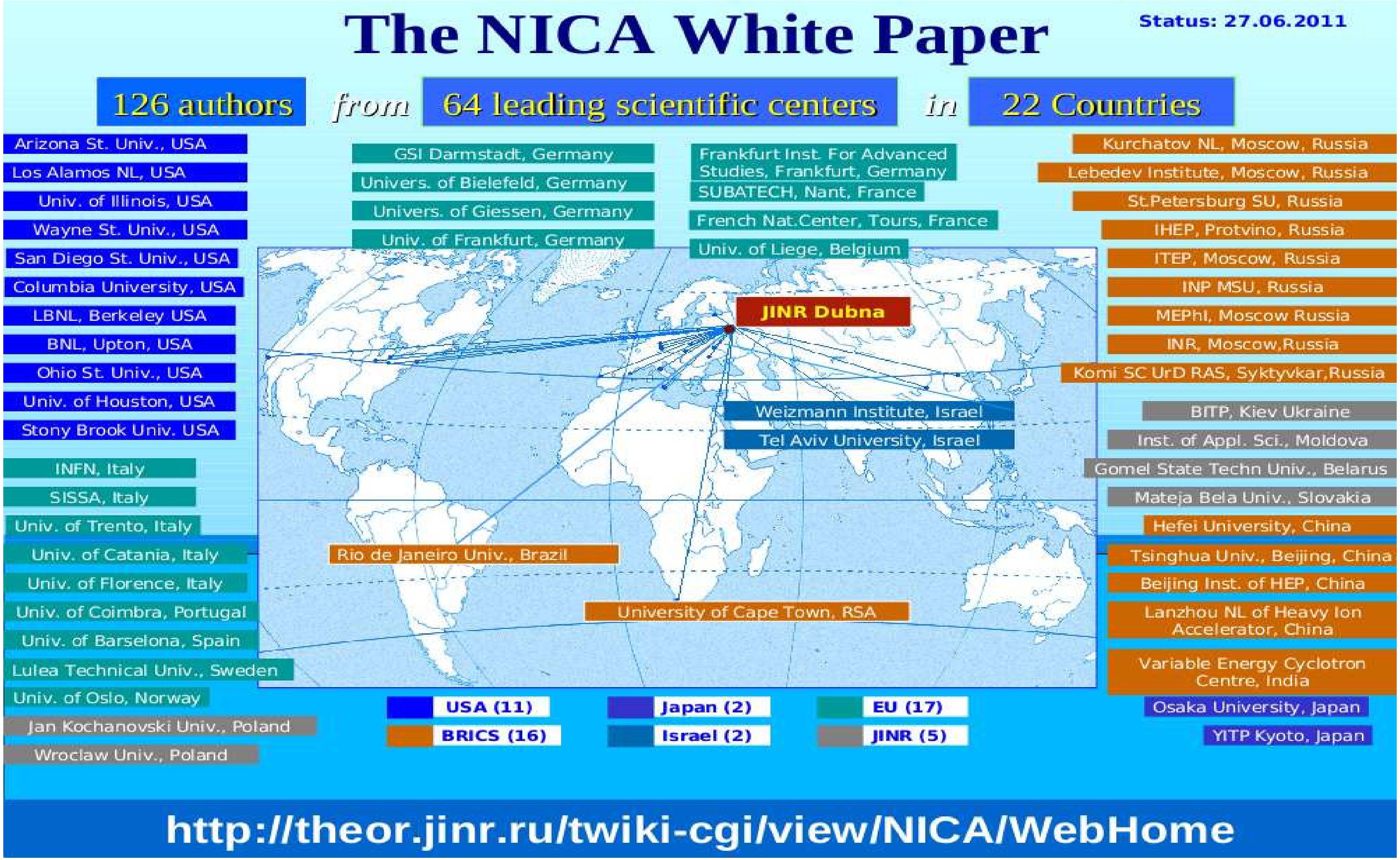
http://theor.jinr.ru



Contents

I. General aspects 11

II. Phases of QCD matter at high baryon density 36



The NICA White Paper

Status: 27.06.2011

126 authors *from* 64 leading scientific centers *in* 22 Countries

- Arizona St. Univ., USA
- Los Alamos NL, USA
- Univ. of Illinois, USA
- Wayne St. Univ., USA
- San Diego St. Univ., USA
- Columbia University, USA
- LBNL, Berkeley USA
- BNL, Upton, USA
- Ohio St. Univ., USA
- Univ. of Houston, USA
- Stony Brook Univ. USA
- INFN, Italy
- SISSA, Italy
- Univ. of Trento, Italy
- Univ. of Catania, Italy
- Univ. of Florence, Italy
- Univ. of Coimbra, Portugal
- Univ. of Barselona, Spain
- Lulea Technical Univ., Sweden
- Univ. of Oslo, Norway
- Jan Kochanovski Univ., Poland
- Wroclaw Univ., Poland
- GSI Darmstadt, Germany
- Univers. of Bielefeld, Germany
- Univers. of Giessen, Germany
- Univ. of Frankfurt, Germany
- Frankfurt Inst. For Advanced Studies, Frankfurt, Germany
- SUBATECH, Nant, France
- French Nat.Center, Tours, France
- Univ. of Liege, Belgium
- **JINR Dubna**
- Weizmann Institute, Israel
- Tel Aviv University, Israel
- Rio de Janeiro Univ., Brazil
- University of Cape Town, RSA
- Kurchatov NL, Moscow, Russia
- Lebedev Institute, Moscow, Russia
- St.Petersburg SU, Russia
- IHEP, Protvino, Russia
- ITEP, Moscow, Russia
- INP MSU, Russia
- MEPhI, Moscow Russia
- INR, Moscow,Russia
- Komi SC UrD RAS, Syktyvkar,Russia
- BITP, Kiev Ukraine
- Inst. of Appl. Sci., Moldova
- Gomel State Techn Univ., Belarus
- Mateja Bela Univ., Slovakia
- Hefei University, China
- Tsinghua Univ., Beijing, China
- Beijing Inst. of HEP, China
- Lanzhou NL of Heavy Ion Accelerator, China
- Variable Energy Cyclotron Centre, India
- Osaka University, Japan
- YITP Kyoto, Japan

USA (11) **Japan (2)** **EU (17)**

BRICS (16) **Israel (2)** **JINR (5)**

http://theor.jinr.ru/twiki-cgi/view/NICA/WebHome

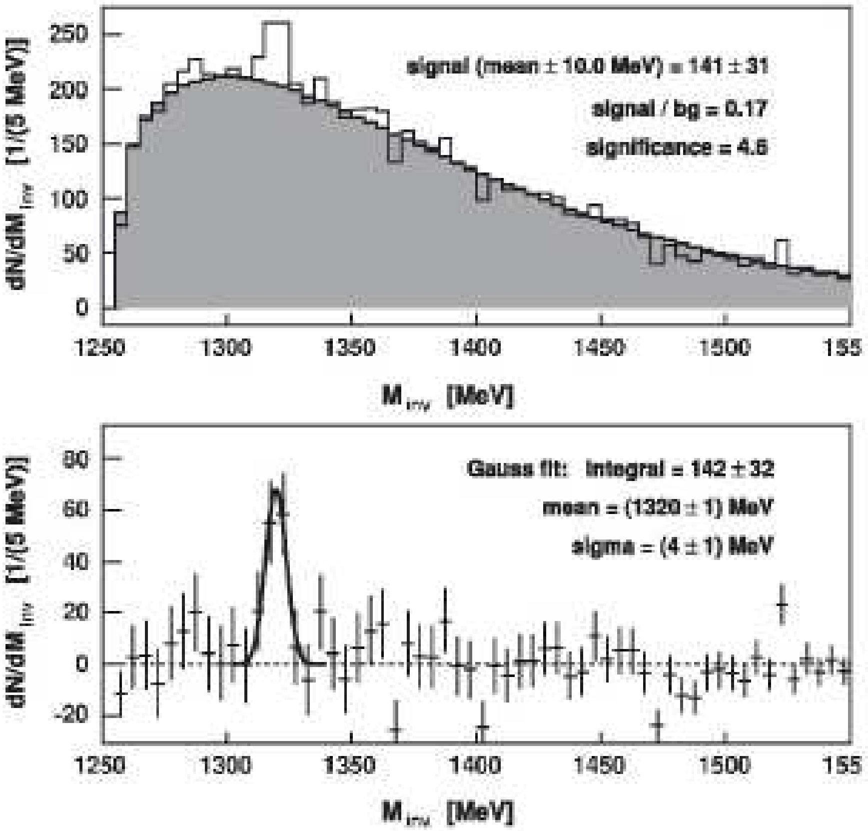
VISIT OF RF PRESIDENT V. PUTIN AT NICA SITE, 5.7.2011

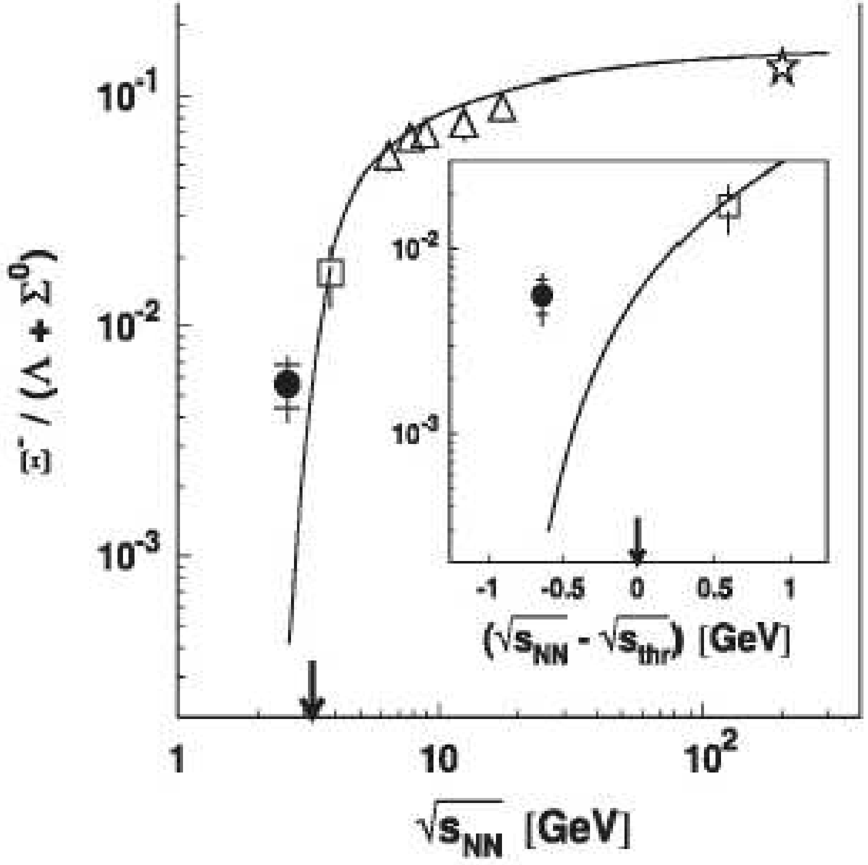
Strange matter production in heavy ion collisions at the Nuclotron extracted beam

- Collaboration **GSI-JINR**

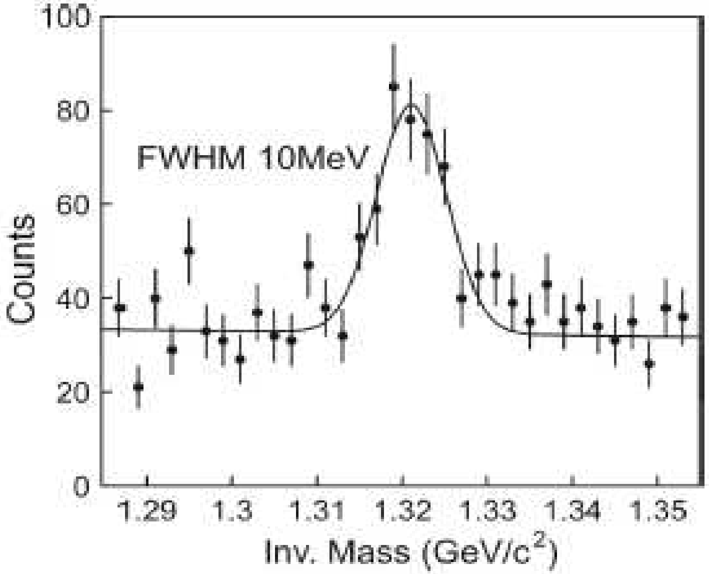
- The ultimative goal of the experiment is the systematic measurements of the observables for multistrange objects (Ξ^-, Ω^-, $\Lambda\Lambda$ etc.) in Au-Au collisions in the energy domain of the Nuclotron extracted beam (up to 5 A GeV)

Deep sub-threshold Ξ^- production Ar+KCl at 1.76 GeV at HADES



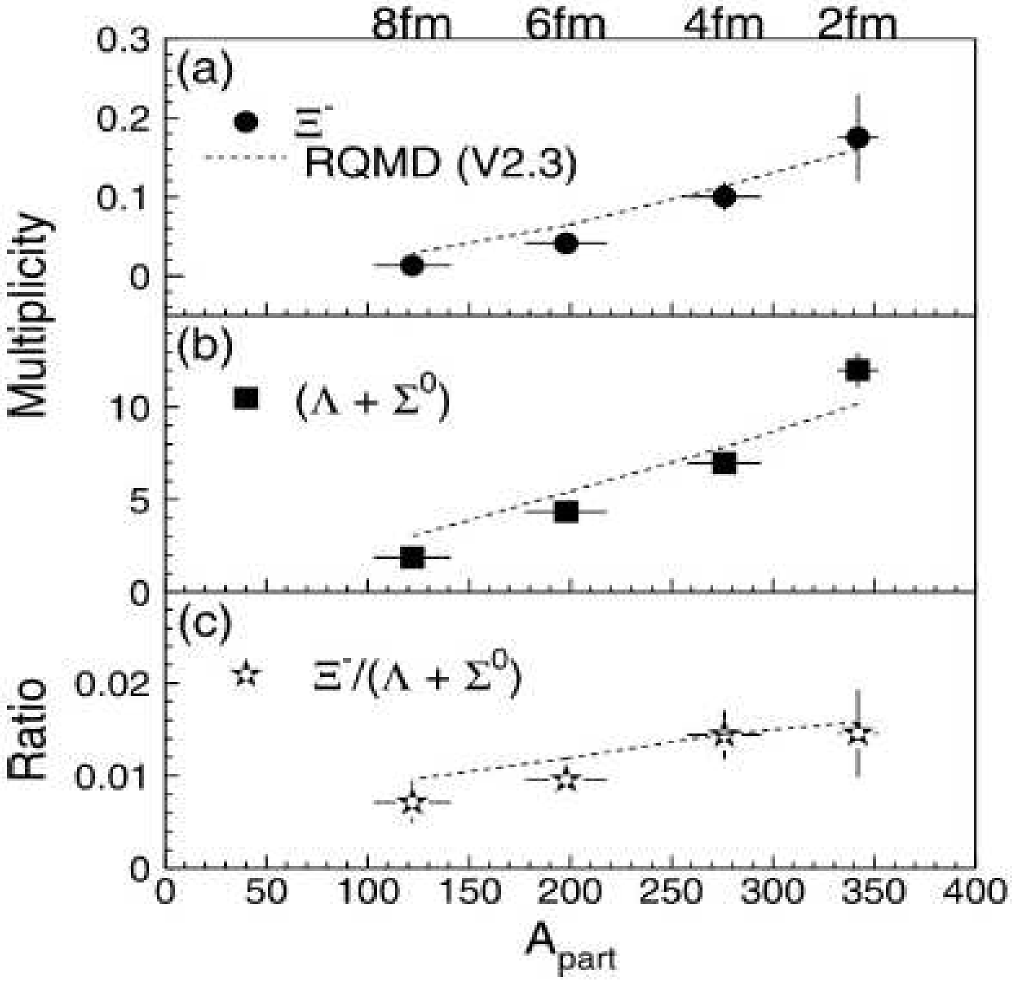


Ξ^- Hyperons at AGS: Au+Au 6 AGeV

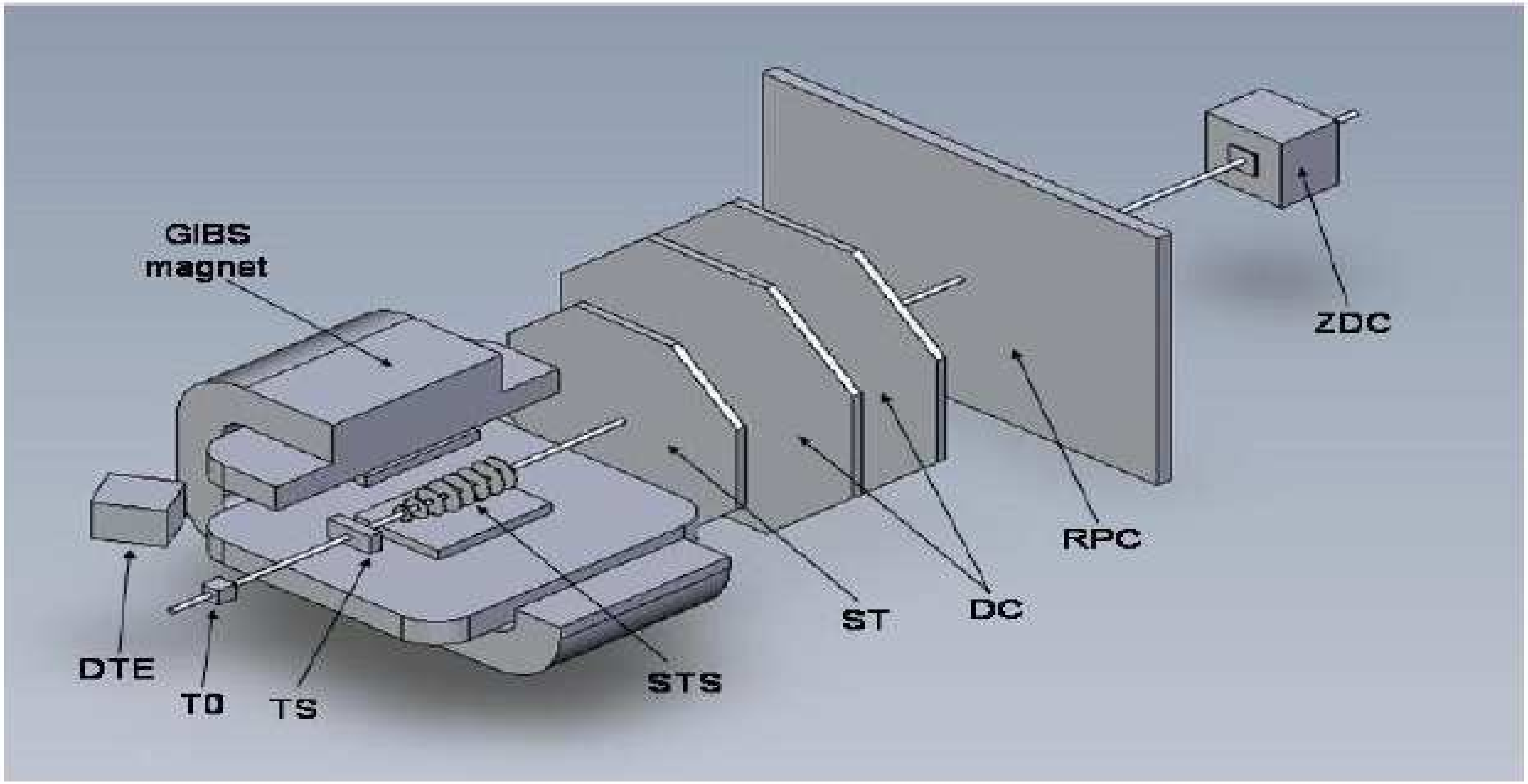


- E895 Collaboration
- P. Chung et al.,
- Phys. Rev. Lett. **91**, 202301 (2003).

- ~ 250 Xi measured



Large Acceptance Magnetic Spectrometer for Heavy Ions Collisions at Nuclotron



Main subdetectors for the fixed target experiment at Nuclotron beam

Silicon Tracker System (CBM-GSI)

Outer Tracker (NA48-CERN/JINR)

TOF-MRPCs (MPD-JINR)

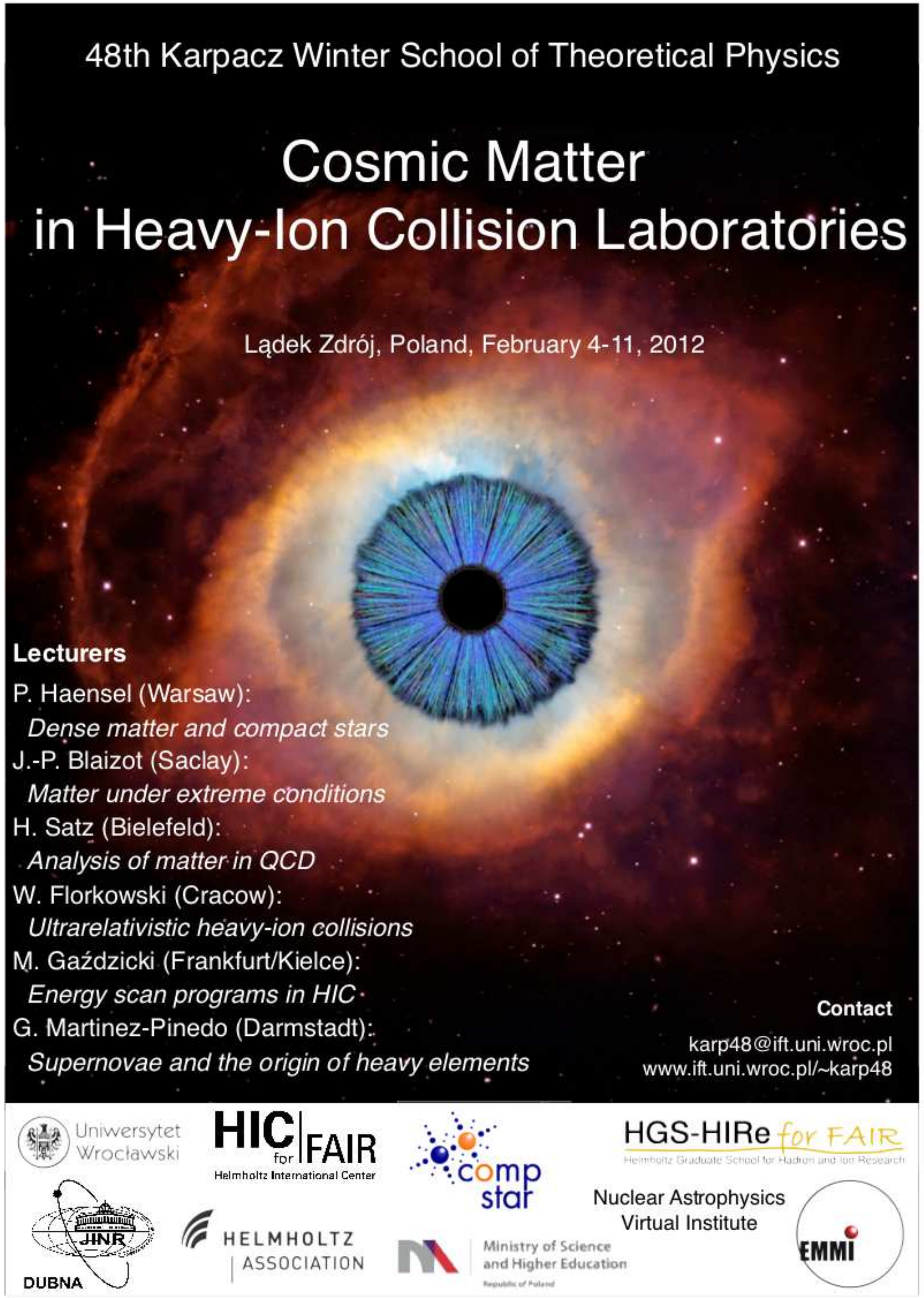
ZDC (INR-JINR)

SUMMARY

- Generalized Beth-Uhlenbeck approach as microphysical basis to account for hadron dissociation (Mott effect) at extreme temperatures and densities
- Benchmark: pion and sigma Mott effect within NJL model, revised within nonlocal PNJL model
- Nonlocal PNJL model calibrated with lattice quark propagator data, EoS at finite $T and \mu$, Phase diagram with critical point
- Application of GBU to interprete chemical freeze-out as Mott-Anderson localization
- Effective GBU model description: Mott-Hagedorn resonance gas + PNJL model describes LAttice QCD thermodynamics

OUTLOOK: NEXT STEPS ...

- Walecka model as limit of PNJL model: chiral transition effects in nuclear EoS
- Prospects for HIC (CBM & NICA) and Supernovae: color superconducting (quarkyonic) phases accessible!



48th Karpacz Winter School of Theoretical Physics

Cosmic Matter in Heavy-Ion Collision Laboratories

Lądek Zdrój, Poland, February 4-11, 2012

Lecturers

P. Haensel (Warsaw):
Dense matter and compact stars
J.-P. Blaizot (Saclay):
Matter under extreme conditions
H. Satz (Bielefeld):
Analysis of matter in QCD
W. Florkowski (Cracow):
Ultrarelativistic heavy-ion collisions
M. Gaździcki (Frankfurt/Kielce):
Energy scan programs in HIC
G. Martinez-Pinedo (Darmstadt):
Supernovae and the origin of heavy elements

Contact

karp48@ift.uni.wroc.pl
www.ift.uni.wroc.pl/~karp48

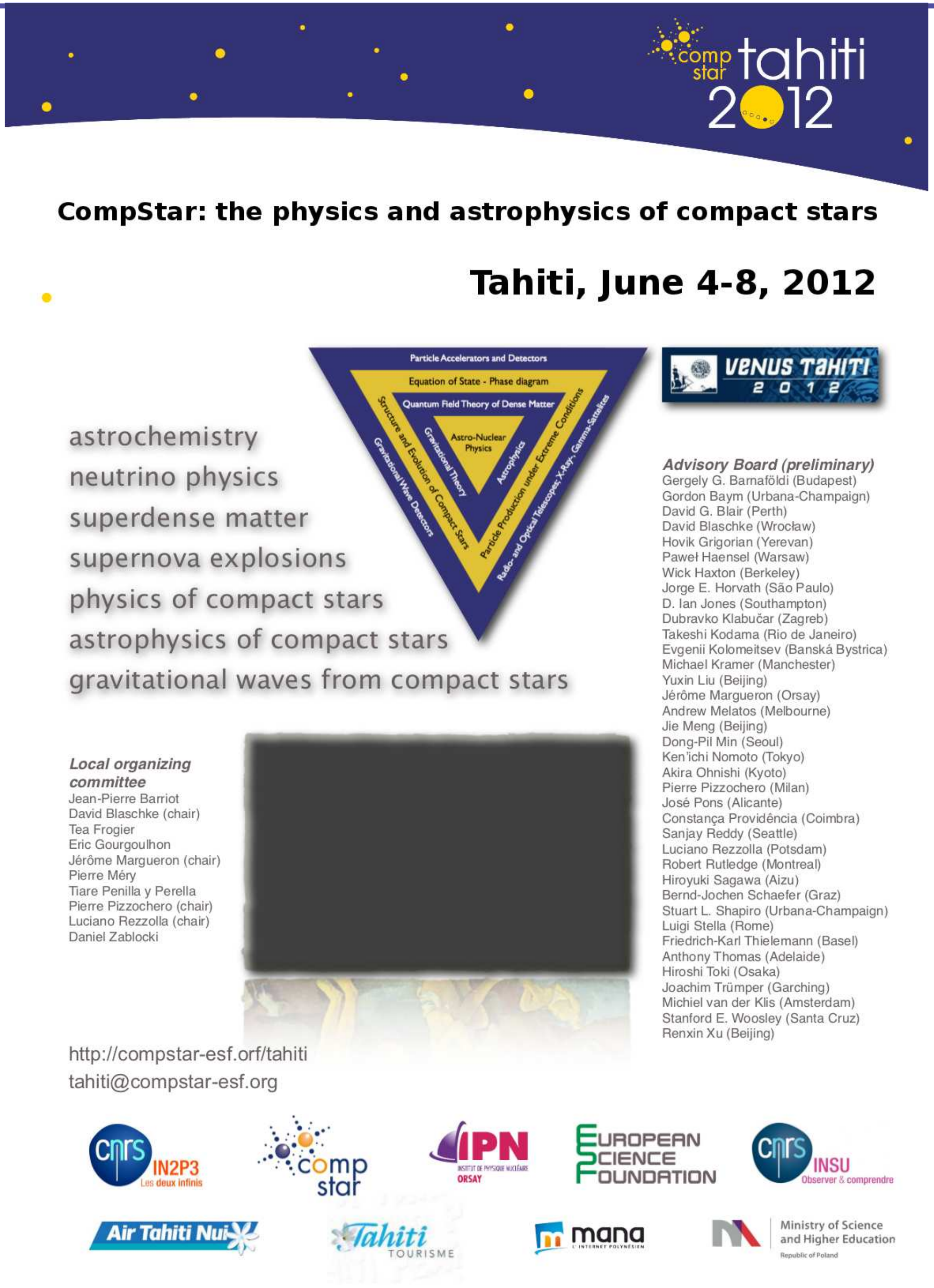
Invitations:

Karpacz Winter School on Theoretical Physics
"Cosmic Matter in Heavy-Ion Collision Laboratories"
Lądek Zdròj, Poland, February 4-11, 2012
http://www.ift.uni.wroc.pl/∼karp48

International Conference
"CompStar:
the physics and astrophysics of compact stars"
Tahiti, June 4-8, 2012
http://compstar-esf.org

Helmholtz International Summer School
"Dense Matter in HIC & Astrophysics"
Dubna, Russia, 2012
http://theor.jinr.ru/meetings

CompStar School & Workshop
"EoS in Compact Star Astrophysics & HIC"
Zadar, Croatia, September 2012
http://compstar-esf.org



CompStar: the physics and astrophysics of compact stars

Tahiti, June 4-8, 2012

astrochemistry
neutrino physics
superdense matter
supernova explosions
physics of compact stars
astrophysics of compact stars
gravitational waves from compact stars

Advisory Board (preliminary)
Gergely G. Barnaföldi (Budapest)
Gordon Baym (Urbana-Champaign)
David G. Blair (Perth)
David Blaschke (Wrocław)
Hovik Grigorian (Yerevan)
Paweł Haensel (Warsaw)
Wick Haxton (Berkeley)
Jorge E. Horvath (São Paulo)
D. Ian Jones (Southampton)
Dubravko Klabučar (Zagreb)
Takeshi Kodama (Rio de Janeiro)
Evgenii Kolomeitsev (Banská Bystrica)
Michael Kramer (Manchester)
Yuxin Liu (Beijing)
Jérôme Margueron (Orsay)
Andrew Melatos (Melbourne)
Jie Meng (Beijing)
Dong-Pil Min (Seoul)
Ken'ichi Nomoto (Tokyo)
Akira Ohnishi (Kyoto)
Pierre Pizzochero (Milan)
José Pons (Alicante)
Constança Providência (Coimbra)
Sanjay Reddy (Seattle)
Luciano Rezzolla (Potsdam)
Robert Rutledge (Montreal)
Hiroyuki Sagawa (Aizu)
Bernd-Jochen Schaefer (Graz)
Stuart L. Shapiro (Urbana-Champaign)
Luigi Stella (Rome)
Friedrich-Karl Thielemann (Basel)
Anthony Thomas (Adelaide)
Hiroshi Toki (Osaka)
Joachim Trümper (Garching)
Michiel van der Klis (Amsterdam)
Stanford E. Woosley (Santa Cruz)
Renxin Xu (Beijing)

Local organizing committee
Jean-Pierre Barriot
David Blaschke (chair)
Tea Frogier
Eric Gourgoulhon
Jérôme Margueron (chair)
Pierre Méry
Tiare Penilla y Perella
Pierre Pizzochero (chair)
Luciano Rezzolla (chair)
Daniel Zablocki

http://compstar-esf.orf/tahiti
tahiti@compstar-esf.org

Invitations:

Karpacz Winter School on Theoretical Physics
"Cosmic Matter in Heavy-Ion Collision Laboratories"
Lądek Zdròj, Poland, February 4-11, 2012
http://www.ift.uni.wroc.pl/∼karp48

International Conference
"CompStar:
the physics and astrophysics of compact stars"
Tahiti, June 4-8, 2012
http://compstar-esf.org

Helmholtz International Summer School
"Dense Matter in HIC & Astrophysics"
Dubna, Russia, 2012
http://theor.jinr.ru/meetings

CompStar School & Workshop
"EoS in Compact Star Astrophysics & HIC"
Zadar, Croatia, September 2012
http://compstar-esf.org