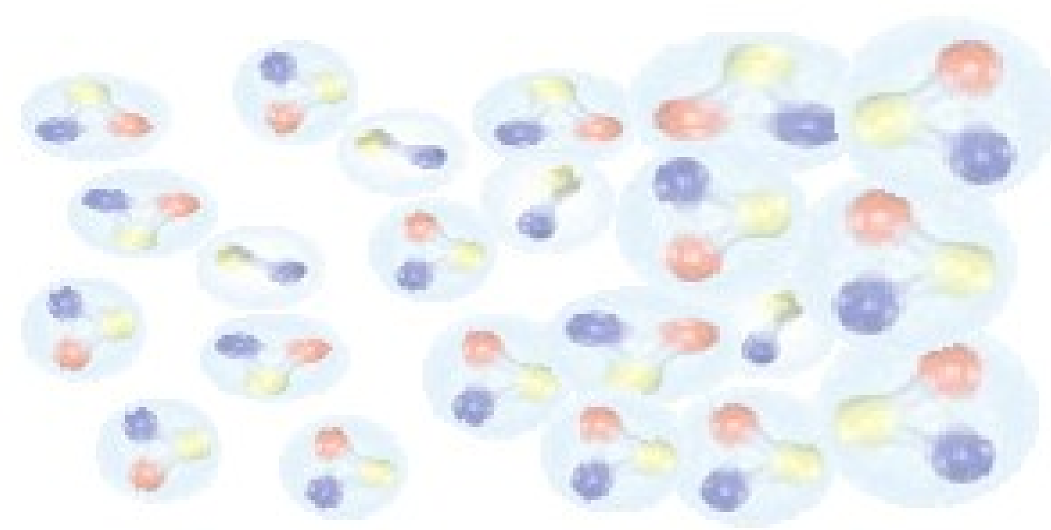
From hadron resonance gas to quark matter

David Blaschke
University of Wroclaw, Poland & JINR Dubna, Russia



Nuclear Physics Colloquium, Goethe-Universitaet Frankfurt, May 21, 2015

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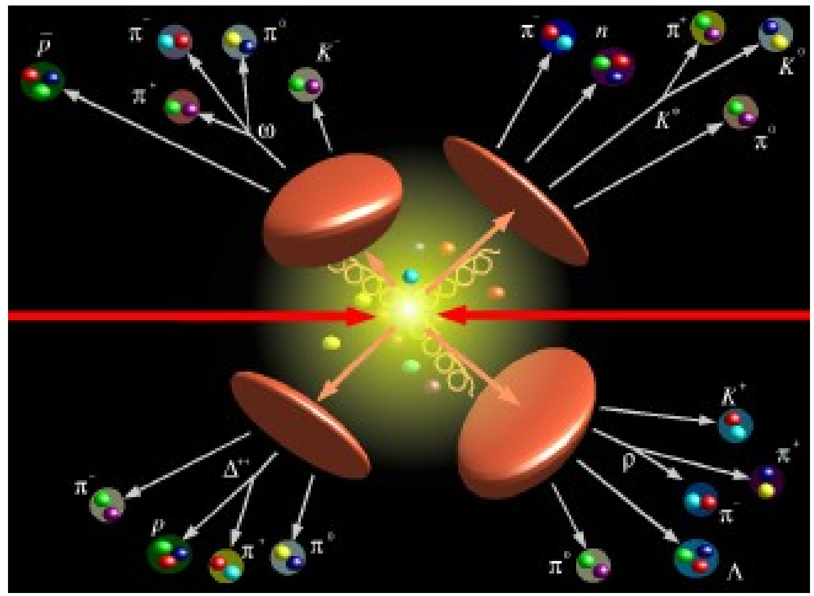

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1. **Introduction:**
   Mott-Anderson localization model for chemical freeze-out

2. **Mott dissociation of pions in a PNJL model**

3. **Thermodynamics of Mott-HRG and lattice QCD data**

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Mott-Anderson localization model for chemical freeze-out

DB, J. Berdermann, J. Cleymans, K. Redlich, Phys. Part. Nucl. Lett. 8 (2011) 811

The basic idea: Localization of (certain) multiquark states (“cluster”) = hadronization;
Reverse process = delocalization by quark exchange between hadrons

Freeze-out criterion:

$$\tau_{exp}(T,\mu) = \tau_{coll}(T,\mu)$$

$$\tau^{-1}_{coll}(T,\mu) = \sum_{i,j}\sigma_{ij} n_j$$

Povh-Huefner law,
PRC 46 (1992) 990

$$\sigma_{ij} = \lambda \langle r_i^2\rangle\langle r_j^2\rangle$$

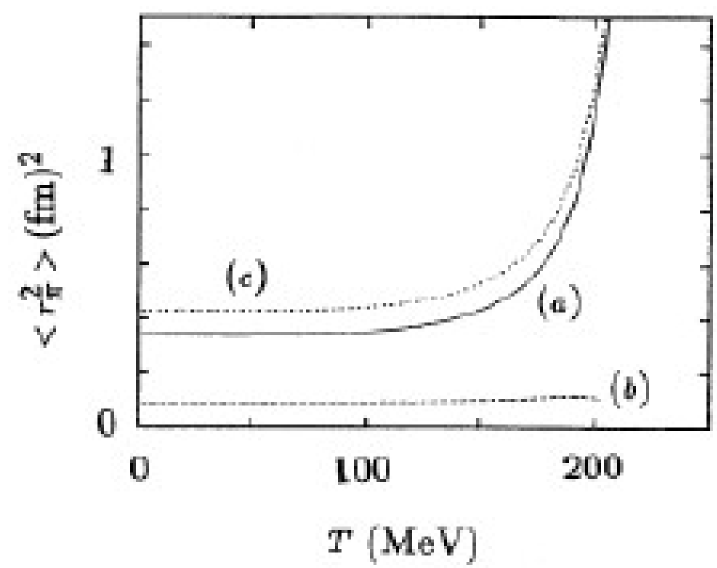
$$r_\pi^2(T,\mu) = \frac{3}{4\pi^2} f_\pi^{-2}(T,\mu)$$

$$f_\pi^2(T,\mu) = -m_0\langle\bar{q}q\rangle_{T,\mu}/M_\pi^2$$

$$r_\pi^2(T,\mu) = \frac{3M_\pi^2}{4\pi^2 m_q}\left|\langle\bar{q}q\rangle_{T,\mu}\right|^{-1}$$

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

Hippe & Klevansky, PRC 52 (1995) 2172



Mott-Anderson localization model for chemical freeze-out

DB, J. Berdermann, J. Cleymans, K. Redlich, Phys. Part. Nucl. Lett. 8 (2011) 811

Povh-Huefner law behaviour for quark exchange between hadrons

PHYSICAL REVIEW C VOLUME 51, NUMBER 5 MAY 1995

Quark exchange model for charmonium dissociation in hot hadronic matter

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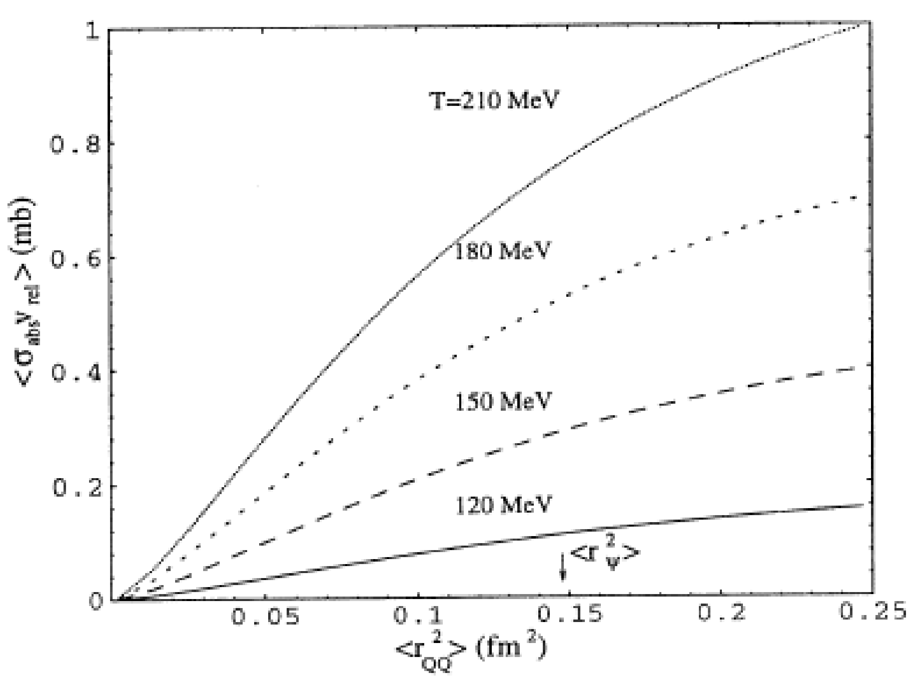
(Received 15 November 1994)



$$\langle \sigma_{\rm abs} v_{\rm rel} \rangle \propto \langle r^2 \rangle_{Q\bar{Q}} \langle r^2 \rangle_{q\bar{q}}$$

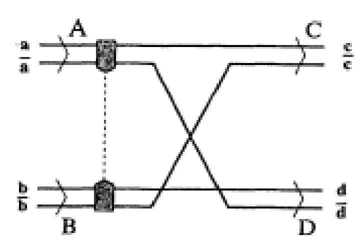
Flavor exchange processes

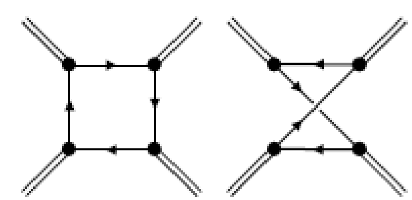
$$\phi + \pi \to K + \bar{K},$$

$$K^- + p \to \Lambda + X,$$
$$K^+ + p \to \Lambda + X,$$

Nonrelativistic → rel. quark loop integrals

M_{fi} =





Mott-Anderson localization model for chemical freeze-out

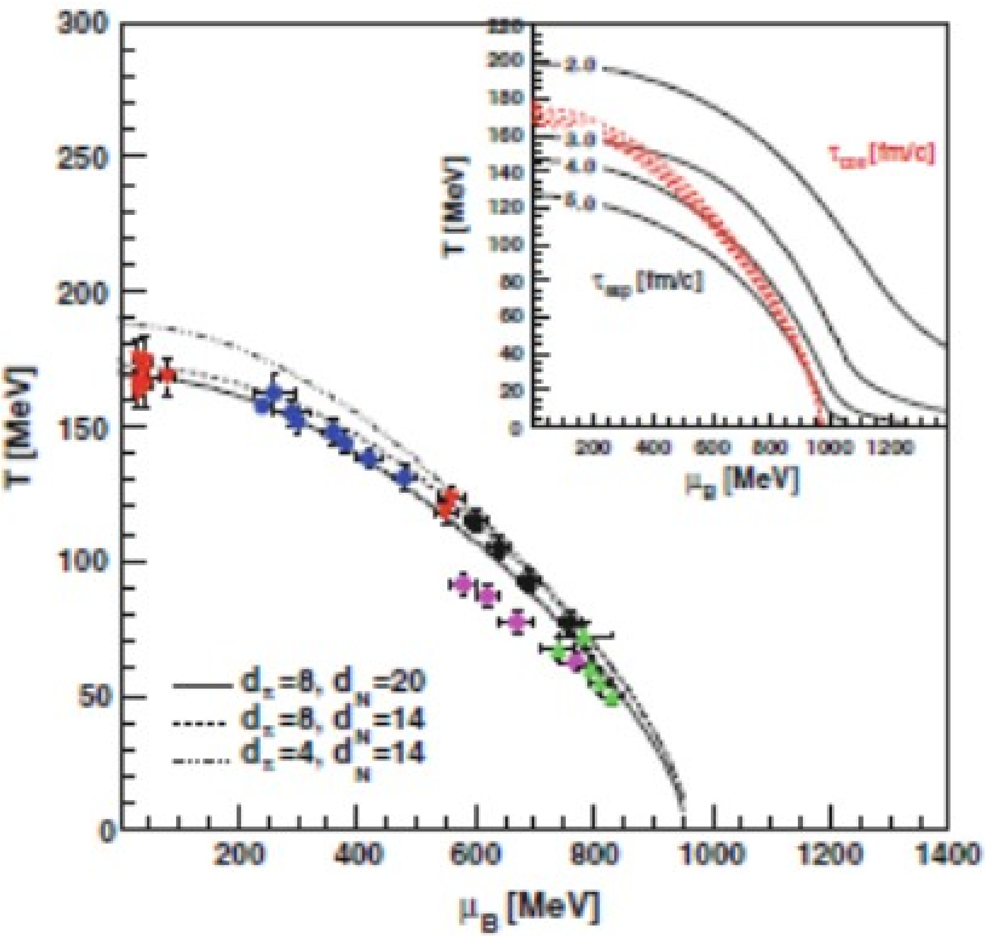
DB, J. Berdermann, J. Cleymans, K. Redlich, Phys. Part. Nucl. Lett. 8 (2011) 811

<u>Model results:</u>

$$\tau_{\rm exp}(T, \mu) = \tau_{\rm coll}(T, \mu)$$

Collision time strongly T, mu dependent !

Schematic resonance gas: dp pions, dN nucleons

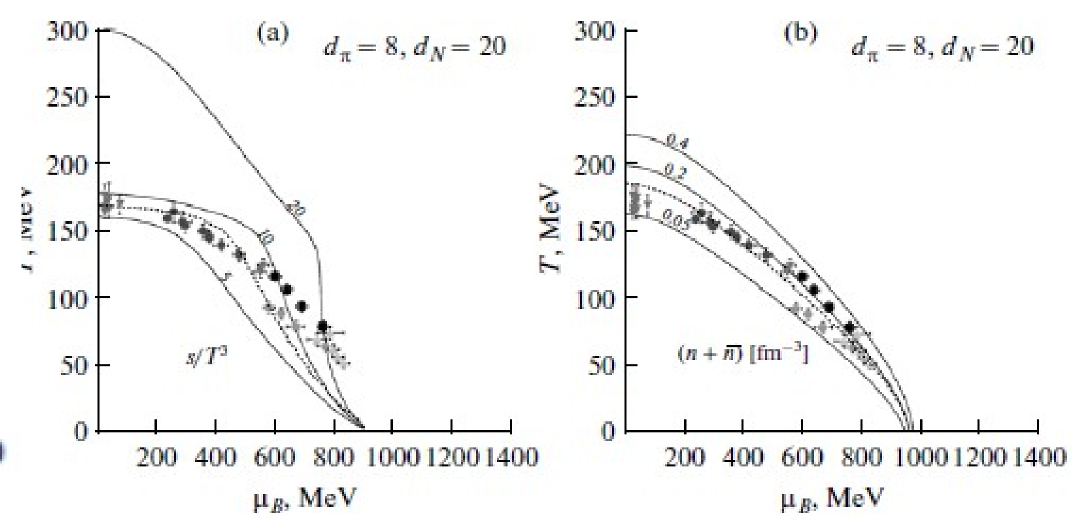


Expansion time scale from entropy conservation:

$$s(T, \mu)\, V(\tau_{\rm exp}) = {\rm const}$$

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

Thermodynamics consistent with phenomenological Freeze-out rules:



Mott-Anderson localization model for chemical freeze-out

DB, J. Berdermann, J. Cleymans, K. Redlich, Few Body Syst. 53 (2012) 99

<u>Model results:</u>

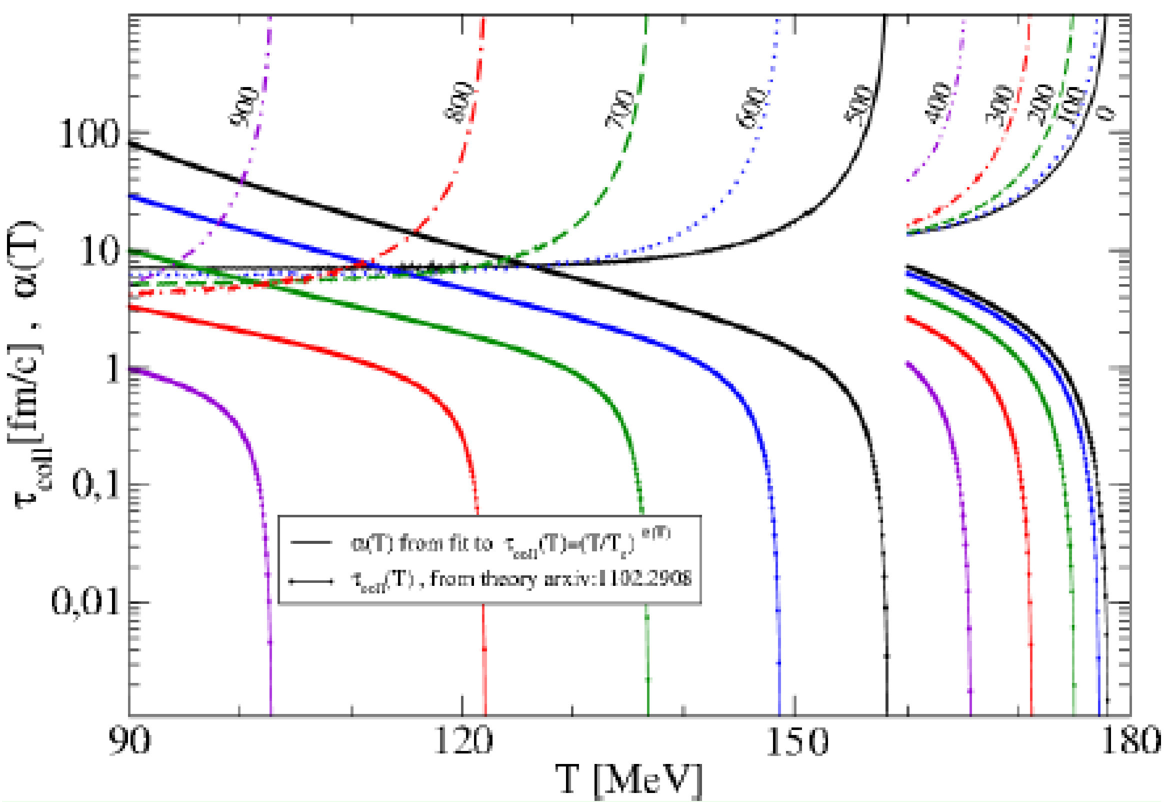
Full hadron resonance gas model

$$\sigma_{ij} = \lambda \langle r_i^2 \rangle \langle r_j^2 \rangle \;;$$

$$r_\pi^2(T,\mu) = \frac{3 M_\pi^2}{4\pi^2 m_q} \left| \langle \bar{q} q \rangle_{T,\mu} \right|^{-1}$$

$$r_N^2(T,\mu) = r_0^2 + r_\pi^2(T,\mu)$$

$$\frac{\langle \bar{q}q \rangle}{\langle \bar{q}q \rangle_{vac}} = 1 - \frac{m_0}{F_\pi^2 m_\pi^2} \Bigg\{ 4N_c \int \frac{dp\, p^2}{2\pi^2} \frac{m}{\varepsilon_p} [f_\Phi^+ + f_\Phi^-] + \sum_{M=f_0,\omega,\ldots} d_M (2-N_s) \int \frac{dp\, p^2}{2\pi^2} \frac{m_M}{E_M(p)} f_M(E_M(p)) + \sum_{B=N,\Lambda,\ldots} d_B (3-N_s) \int \frac{dp\, p^2}{2\pi^2} \frac{m_B}{E_B(p)} [f_B^+(E_B(p)) + f_B^-(E_B(p))] \Bigg\} - \sum_{G=\pi,K,\eta,\eta'} \frac{d_G r_G}{4\pi^2 F_G^2} \int dp \frac{p^2}{E_G(p)} f_G(E_G(p)).$$



Collision time follows a power law
t_coll ~ (T/Tc)^a
with a large exponent a ~ 20

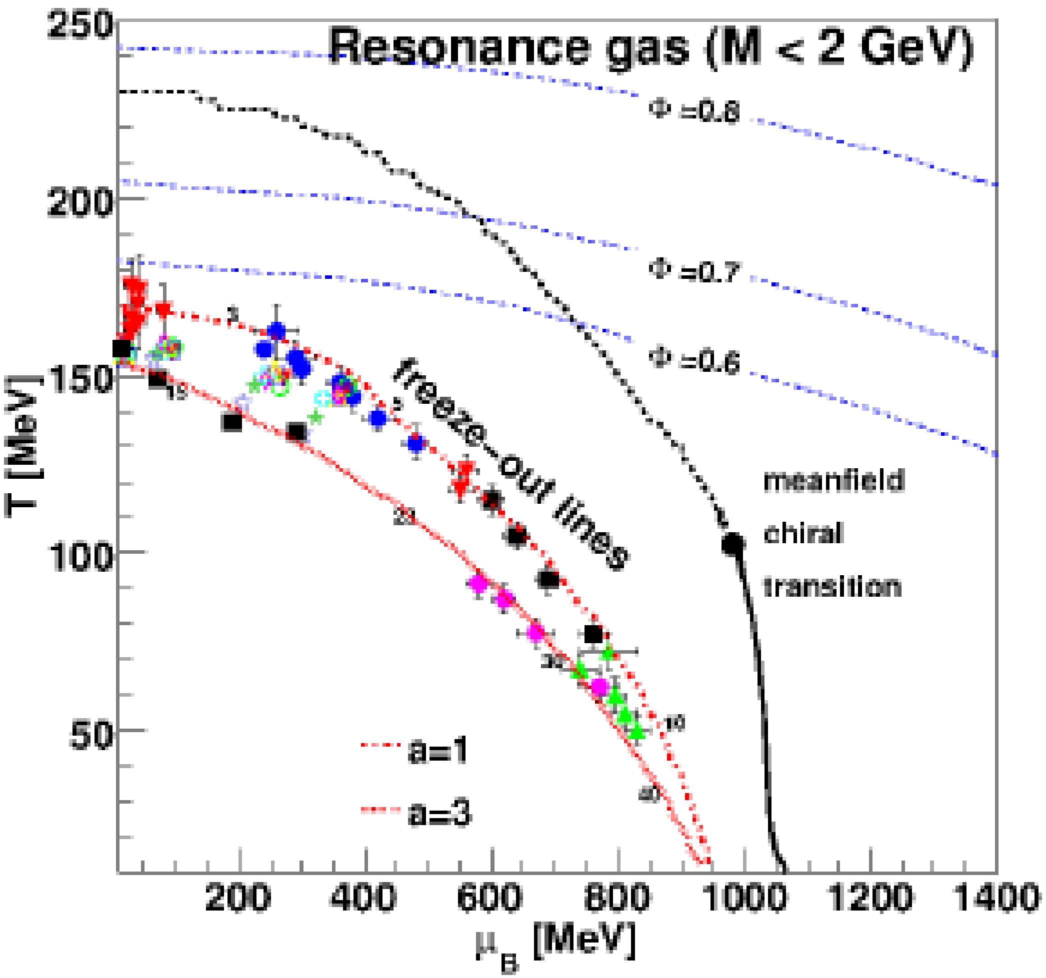
See also: P. Braun-Munzinger, J. Stachel, C. Wetterich, PLB (2004)

Mott-Anderson localization model for chemical freeze-out

DB, J. Berdermann, J. Cleymans, K. Redlich, Few Body Syst. 53 (2012) 99

Model results:
Full hadron resonance gas model

See also: S. Leupold, J. Phys. G (2006)



$$\frac{\langle\bar{q}q\rangle}{\langle\bar{q}q\rangle_{\rm vac}} = 1 - \frac{m_0}{F_\pi^2 m_\pi^2}\Bigg[4N_c \int \frac{dp\, p^2}{2\pi^2}\frac{m}{\varepsilon_p}[f_\Phi^+ + f_\Phi^-]$$

$$+ \sum_{M=f_0,\omega,\dots} d_M(2-N_s)\int \frac{dp\, p^2}{2\pi^2}\frac{m_M}{E_M(p)} f_M(E_M(p))$$

$$+ \sum_{B=N,\Lambda,\dots} d_B(3-N_s)\int \frac{dp\, p^2}{2\pi^2}\frac{m_B}{E_B(p)}[f_B^+(E_B(p)) + f_B^-(E_B(p))]\Bigg]$$

$$- \sum_{G=\pi,K,\eta,\eta'} \frac{d_G r_G}{4\pi^2 F_G^2}\int dp\, \frac{p^2}{E_G(p)} f_G(E_G(p)).$$

$$\sigma_{ij} = \lambda \langle r_i^2\rangle\langle r_j^2\rangle \quad ; \quad r_N^2(T,\mu) = r_0^2 + r_\pi^2(T,\mu)$$

$$r_\pi^2(T,\mu) = \frac{3M_\pi^2}{4\pi^2 m_q}\left|\langle\bar{q}q\rangle_{T,\mu}\right|^{-1}$$

The coefficient a stands for the inverse system size in the formula

$$\tau_{\rm exp}(T,\mu) = \tau_{\rm coll}(T,\mu)$$

for the 3D expansion time scale assuming entropy conservation

Mott Dissociation of Hadrons in Hadron Matter

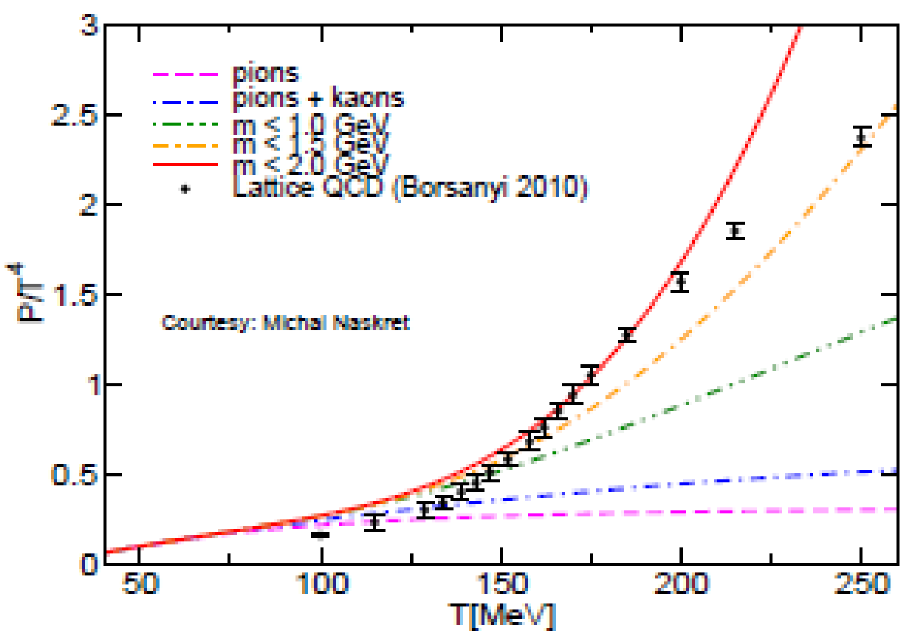
- Partition function as a Path Integral (imaginary time $\tau = i\,t$, $0 \leq \tau \leq \beta = 1/T$)

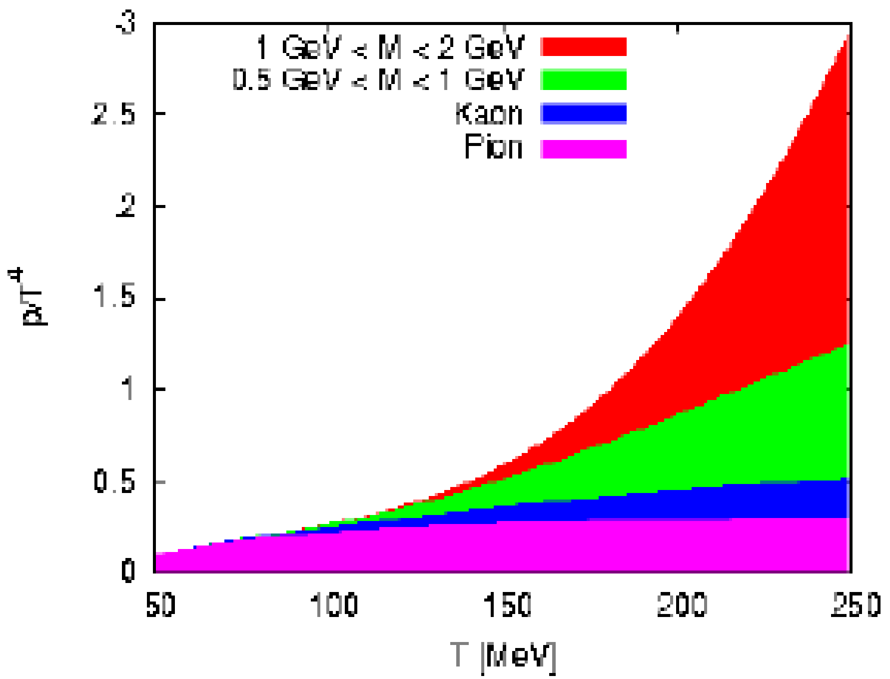
$$Z[T,V,\mu] = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}A \exp\left\{-\int_0^\beta d\tau \int_V d^3x\, \mathcal{L}_{QCD}(\psi,\bar{\psi},A)\right\}$$

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

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

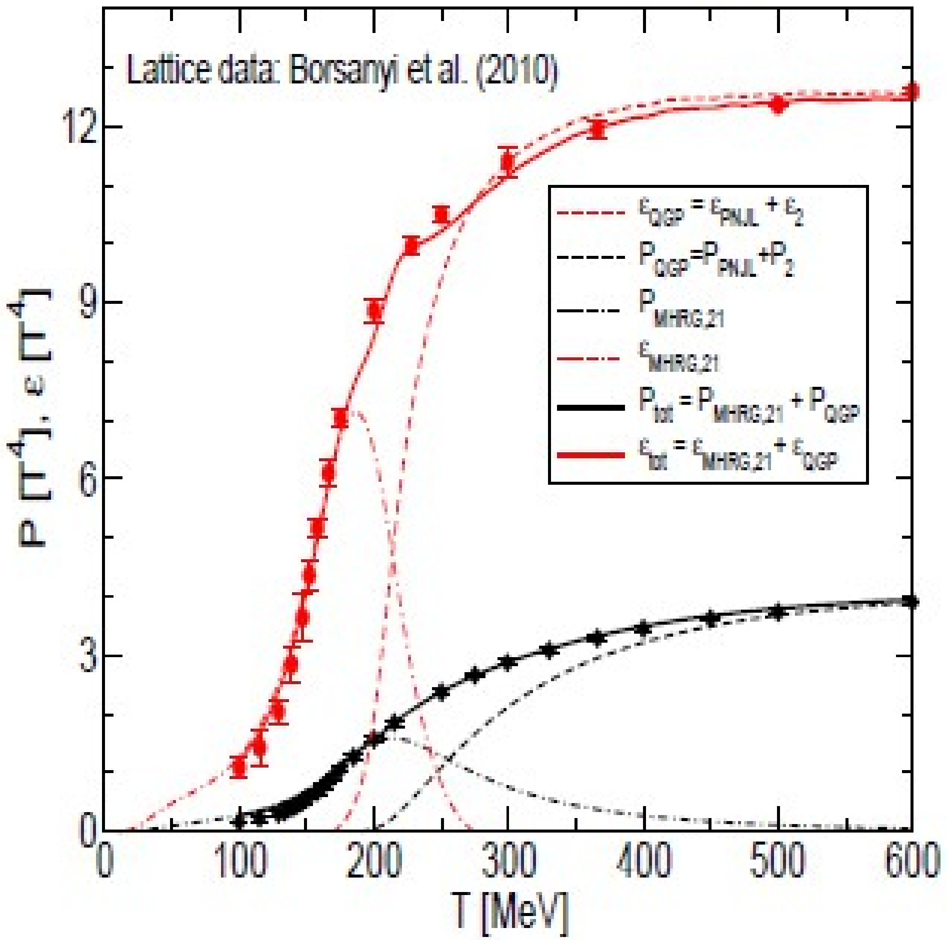
- Numerical evaluation: Lattice gauge theory simulations (hotQCD, Wuppertal-Budapest)





Mott Dissociation of Hadrons in Hadron Matter

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



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

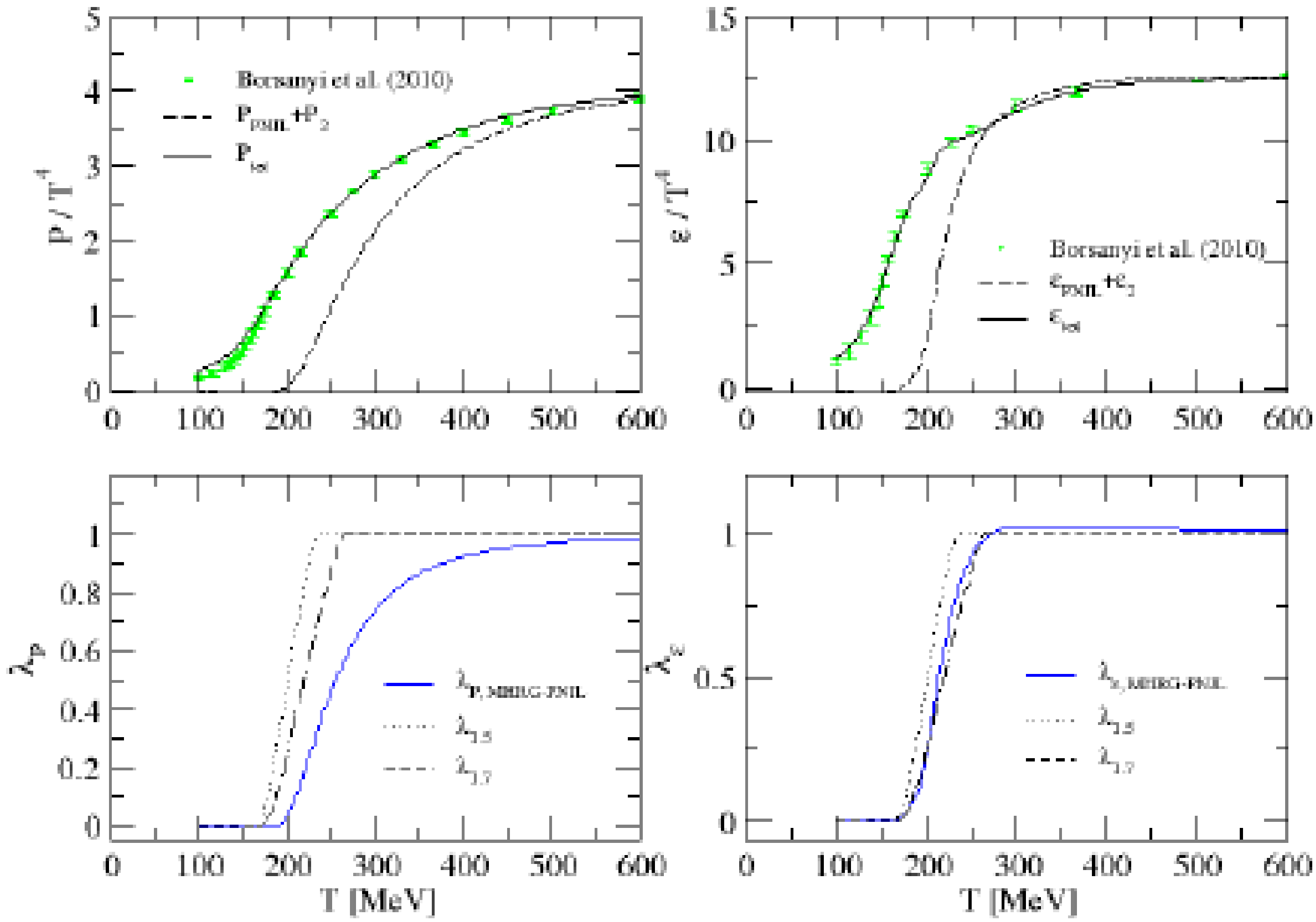
Hadron resonances present up to $T_{\rm max} \sim 250$ MeV

Blaschke & Bugaev, Fizika B13, 491 (2004)
Prog. Part. Nucl. Phys. 53, 197 (2004)
Turko, Blaschke, Prorok & Berdermann,
APPS 5, 485 (2012); J. Phys. Conf. Ser. 455, 012056 (2013)

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

Mott Dissociation of Hadrons in Hadron Matter

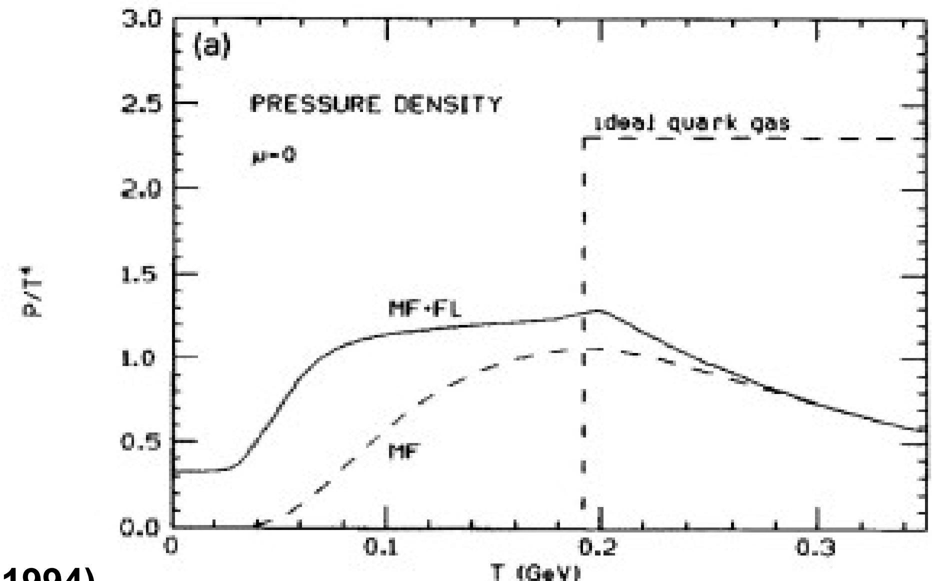
Possible application: parton fraction in the EoS at the hadronization transition



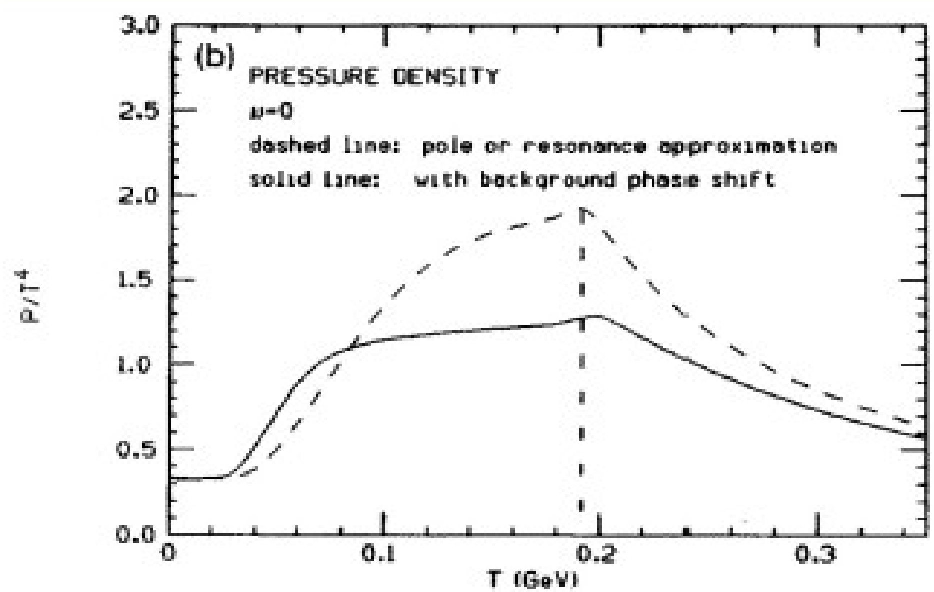
L. Turko et al. "Effective degrees of freedom in QCD …", EPJ Web Conf. 71 (2014) 00134
Compare:
M. Nahrgang et al. "Influence of hadronicbound states above Tc …", PRC 89 (2014) 014004

Mott Dissociation of Mesons in Quark Matter

J. Huefner, S.P. Klevansky, P. Zhuang, H. Voss, Ann. Phys. 234, 225 (1994)



P. Zhuang, J. Huefner, S.P. Klevansky, NPA 576, 525 (1994)



Mott Dissociation of Mesons in Quark Matter

D. Blaschke, M. Buballa, A. Dubinin, G. Roepke, D. Zablocki, Ann. Phys. 348, 228 (2014)

- 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 $\longrightarrow$ 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)

Mott Dissociation of Mesons in Quark Matter

- Separate the mean-field part of the quark determinant

$$\mathrm{Tr}\,\ln S^{-1}[\sigma,\pi] = \mathrm{Tr}\,\ln S_{\mathrm{MF}}^{-1}[m] + \mathrm{Tr}\,\ln[1 + (\sigma + i\gamma_5\vec{\tau}\vec{\pi})S_{\mathrm{MF}}[m]]$$

- Mean-field quark propagator

$$S_{\mathrm{MF}}(\vec{p}, i\omega_n; m) = \frac{\gamma_0(i\omega_n + \mu) - \vec{\gamma}\cdot\vec{p} + m}{(i\omega_n + \mu)^2 - E_p^2}$$

- Expand the logarithm: $\ln(1+x) = -\sum_{n=1}^{\infty}(-1)^n x^n/n = x - x^2/2 + \ldots$
- Thermodynamic potential in Gaussian approximation

$$\Omega(T,\mu) \;=\; -T\ln Z(T,\mu) = \Omega_{\mathrm{MF}}(T,\mu) + \sum_M \Omega_{\mathrm{M}}^{(2)}(T,\mu) + \mathcal{O}[\phi_M^3]$$

$$\Omega_{\mathrm{M}}^{(2)}(T,\mu) \;=\; \frac{N_M}{2}\int\frac{d^2p}{(2\pi)^3}\frac{1}{\beta}\sum_n \mathrm{e}^{i\nu_n\eta}\ln S_M^{-1}(\vec{p}, i\nu_n)\;,\quad N_\sigma = 1,\; N_\pi = 3$$

- Meson propagator $S_M(\vec{p}, i\nu_n) = 1/\left[1/(2G_S) - \Pi_M(\vec{p}, i\nu_n)\right]$
- Mesonic polarization loop

$$\Pi_M(\vec{p}, i\nu_n) = -\frac{1}{\beta}\sum_{n'}\mathrm{e}^{i\omega_{n'}\eta}\int\frac{d^2k}{(2\pi)^3}\mathrm{Tr}\left[\Gamma_M S_{\mathrm{MF}}(-\vec{k}, -i\omega_{n'})\Gamma_M S_{\mathrm{MF}}(\vec{k}+\vec{p}, i\omega_{n'} + i\nu_n)\right]$$

Mott Dissociation of Mesons in Quark Matter

- Polar representation of the analytically continued quark propagator

$$S_{\rm M} = |S_{\rm M}| e^{i\delta_{\rm M}} = S_R + iS_I ,$$

- Phase shift $\delta_{\rm M}(\omega, \mathbf{q}) = -{\rm Im} \ln S_{\rm M}^{-1}(\omega - \mu_M + i\eta, \mathbf{q})$
- Thermodynamic potential for mesonic modes

$$\begin{aligned} \Omega_{\rm M}(T,\mu) &= {\rm Tr} \ln S_{\rm M}^{-1}(iz_n, \mathbf{q}) = d_{\rm M} T \sum_n \int \frac{{\rm d}^3 q}{(2\pi)^3} \ln S_{\rm M}^{-1}(iz_n, \mathbf{q}) , \\ &= -d_{\rm M} T \sum_n \int \frac{{\rm d}^3 q}{(2\pi)^3} \int_{-\infty}^{\infty} \frac{{\rm d}\omega}{2\pi} \frac{1}{iz_n - \omega} {\rm Im} \ln S_{\rm M}^{-1}(\omega + i\eta, \mathbf{q}) \end{aligned}$$

- Perform Matsubara summation $\Omega_{\rm M}(T,\mu) = d_{\rm M} \int \frac{{\rm d}^3 q}{(2\pi)^3} \int_{-\infty}^{\infty} \frac{{\rm d}\omega}{2\pi} n_M^-(\omega) \delta_M(\omega, \mathbf{q})$
- Using symmetries of Bose function $n_M^-(-\omega) = -[1 + n_M^+(\omega)]$ and polarization loop

$$\Omega_{\rm M}(T,\mu) = d_{\rm M} \int \frac{{\rm d}^3 q}{(2\pi)^3} \int_0^{\infty} \frac{{\rm d}\omega}{2\pi} [1 + n_M^-(\omega) + n_M^+(\omega)] \delta_{\rm M}(\omega, \mathbf{q})$$

- Partial integration gives field theoretic Beth-Uhlenbeck formula

$$\Omega_{\rm M} = -d_{\rm M} \int \frac{{\rm d}^3 q}{(2\pi)^3} \int_0^{\infty} \frac{{\rm d}\omega}{2\pi} \left[\omega + T \ln\left(1 - {\rm e}^{-(\omega - \mu_{\rm M})/T}\right) + T \ln\left(1 - {\rm e}^{-(\omega + \mu_{\rm M})/T}\right) \right] \frac{d\delta_{\rm M}(\omega, \mathbf{q})}{d\omega}$$

Mott Dissociation of Mesons in Quark Matter

- When polarization loop integral can be expressed in the form

$$\Pi_{\rm M}(z,\mathbf{q}) = \Pi_{M,0} + \Pi_{M,2}(z,\mathbf{q})$$

- Factorization of two-particle propagator possible with $R_M(z,\mathbf{q}) = \frac{1-G_{\rm M}\Pi_{M,0}}{G_{\rm M}\Pi_{M,2}(z,\mathbf{q})}$

$$S_{\rm M}(z,\mathbf{q}) = \frac{1}{G_{\rm M}^{-1} - \Pi_{M,0} - \Pi_{M,2}(z,\mathbf{q})} = \frac{1}{\Pi_{M,2}(z,\mathbf{q})}\frac{1}{R_M(z,\mathbf{q}) - 1}$$

- This entails $\ln S_{\rm M}(z,\mathbf{q})^{-1} = \ln \Pi_{M,2}(z,\mathbf{q}) + \ln[R_M(z,\mathbf{q}) - 1]$
  and thus a separation of the phase shift in two contributions

$$\delta_{\rm M}(\omega,\mathbf{q}) = \delta_{X,c}(\omega,\mathbf{q}) + \delta_{X,R}(\omega,\mathbf{q})$$

- They correspond to continuum (state independent) and resonant phases

$$\delta_{M,c}(\omega,\mathbf{q}) = -\arctan\left(\frac{{\rm Im}\Pi_{M,2}(\omega-\mu_M+i\eta,\mathbf{q})}{{\rm Re}\Pi_{M,2}(\omega-\mu_M+i\eta,\mathbf{q})}\right)$$

$$\delta_{M,R}(\omega,\mathbf{q}) = \arctan\left(\frac{{\rm Im}R_M(\omega-\mu_M+i\eta,\mathbf{q})}{1-{\rm Re}R_M(\omega-\mu_M+i\eta,\mathbf{q})}\right)$$

Mott Dissociation of Mesons in Quark Matter

- Suppose $\delta_{X,R}(\omega,\mathbf{q})$ corresponds to a resonance at $\omega = \omega_M = \sqrt{\mathbf{q}^2 + M_{\rm M}^2}$, then the propagator shall have the representation with a complex pole at $z = z_M = \omega_M + i\Gamma_M/2$, where $\Gamma_{\rm M}$ is the width of the resonance.
- The position of the pole is found from the condition ${\rm Re}R_M(z_M,\mathbf{q}) = 1$, where $\delta_{M,R}(\omega \to \omega_M) \to \pi/2$ since $\tan\delta_{M,R}(\omega \to \omega_M) \to \infty$
- Expanding $R_M(z,\mathbf{q})$ at the complex pole z_M for small width, one obtains

$$1 - {\rm Re}R_M(z_M,\mathbf{q}) = -(\omega^2 - \omega_M^2)\frac{dR_M(z,\mathbf{q})}{d\omega^2}\Big|_{z=z_M} \quad , \quad {\rm Im}R_M(z_M,\mathbf{q}) = \omega_M\Gamma_M\frac{dR_M(z,\mathbf{q})}{d\omega^2}\Big|_{z=z_M} \quad (1)$$

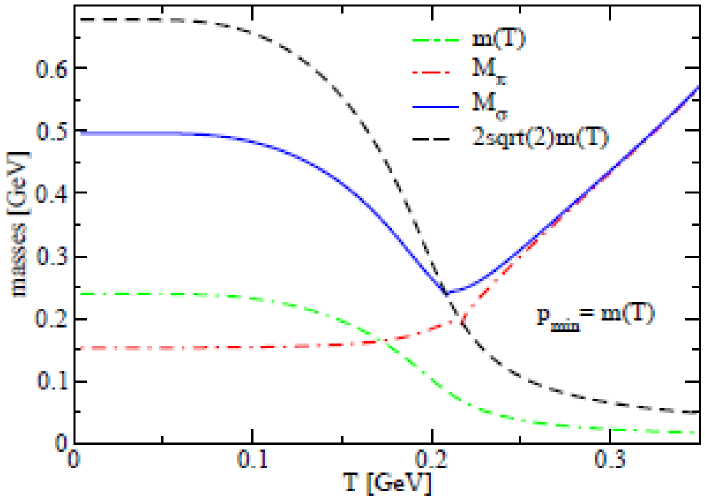
- The resonant shift becomes $\delta_{M,R}(\omega,\mathbf{q}) = -\arctan\left(\frac{\omega_{\rm M}\Gamma_{\rm M}}{\omega^2-\omega_M^2}\right)$ corresponding to a Breit-Wigner form of the spectral density in the Beth-Uhlenbeck EoS

$$\frac{{\rm d}\delta_{M,R}}{{\rm d}\omega} = \frac{2\omega\omega_{\rm M}\Gamma_{\rm M}}{(\omega^2-\omega_M^2)^2 + \omega_{\rm M}^2\Gamma_{\rm M}^2} \; .$$

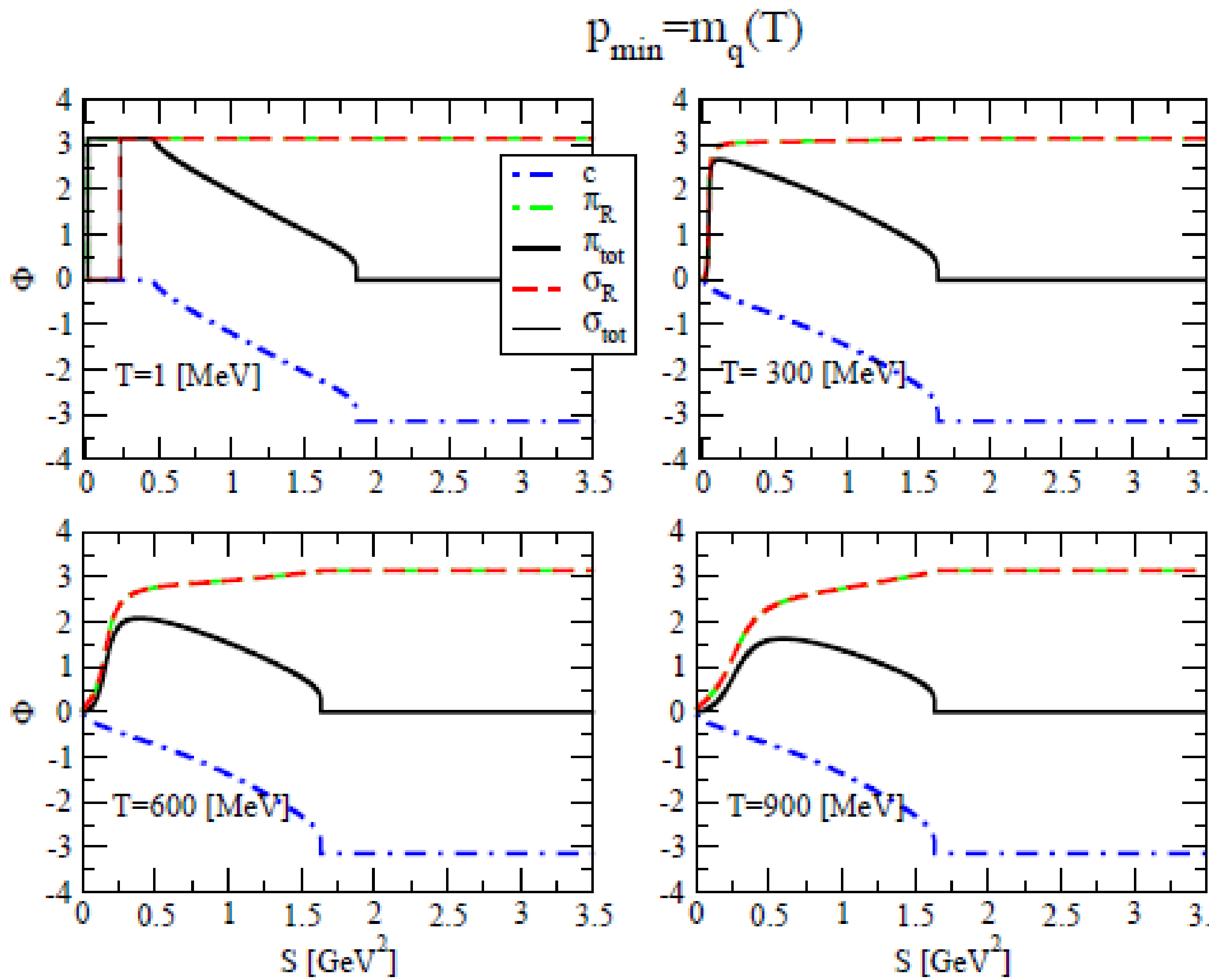
- This takes the form of a bound state spectral density for $\Gamma_M \to 0$

$$\lim_{\Gamma_{\rm M}\to 0} \delta'_{M,R}(\omega) = \pi\left[\delta(\omega-\omega_M) + \delta(\omega+\omega_M)\right]$$

Mott Dissociation of Mesons in Quark Matter



D. Blaschke, A. Dubinin, Yu. Kalinovsky,
Acta Phys. Pol. Suppl. 7 (2014)



**XXXI. Max Born Symposium,
Wroclaw (2013)**

Hadron Resonance Gas with Mott Dissociation

$$P(T) = \sum_{i=M,B} P_i(T) + P_{\rm PNJL}(T) + P_{\rm pert}(T) \ ,$$

$$\begin{aligned} P_i(T) &= d_i \int \frac{d^3p}{(2\pi)^3} \int_0^\infty \frac{d\omega}{\pi} f_i(\omega)\delta_i(\omega;T) \\ &= d_i \int_0^\infty \frac{dpp^2}{2\pi^2} \int_0^\infty \frac{ds}{2\pi} \frac{1}{\sqrt{p^2+s}} f_i(\sqrt{p^2+s})\delta_i(s;T), \end{aligned}$$

$$P_i(T) = d_i \int_0^\infty \frac{dpp^2}{2\pi^2} \int_0^\infty \frac{dM}{\pi} \frac{M}{\sqrt{p^2+M^2}} f_i(\sqrt{p^2+M^2})\delta_i(M^2;T).$$

By partial integration over M we obtain

$$P_i(T) = \mp d_i \int_0^\infty \frac{dpp^2}{2\pi^2} \int_0^\infty dM\, T \ln(1 \mp e^{-\sqrt{p^2+M^2}/T}) \frac{1}{\pi} \frac{d\delta_i(M^2;T)}{dM} \ ,$$

when $m(T) \to \infty$, $\Gamma_i(T) \to 0$, so that $\delta_i(M^2;T) = \pi\theta(M - M_i)$,

$$\frac{1}{\pi}\frac{d\delta_i(M^2;T)}{dM} = \delta(M - M_i),$$

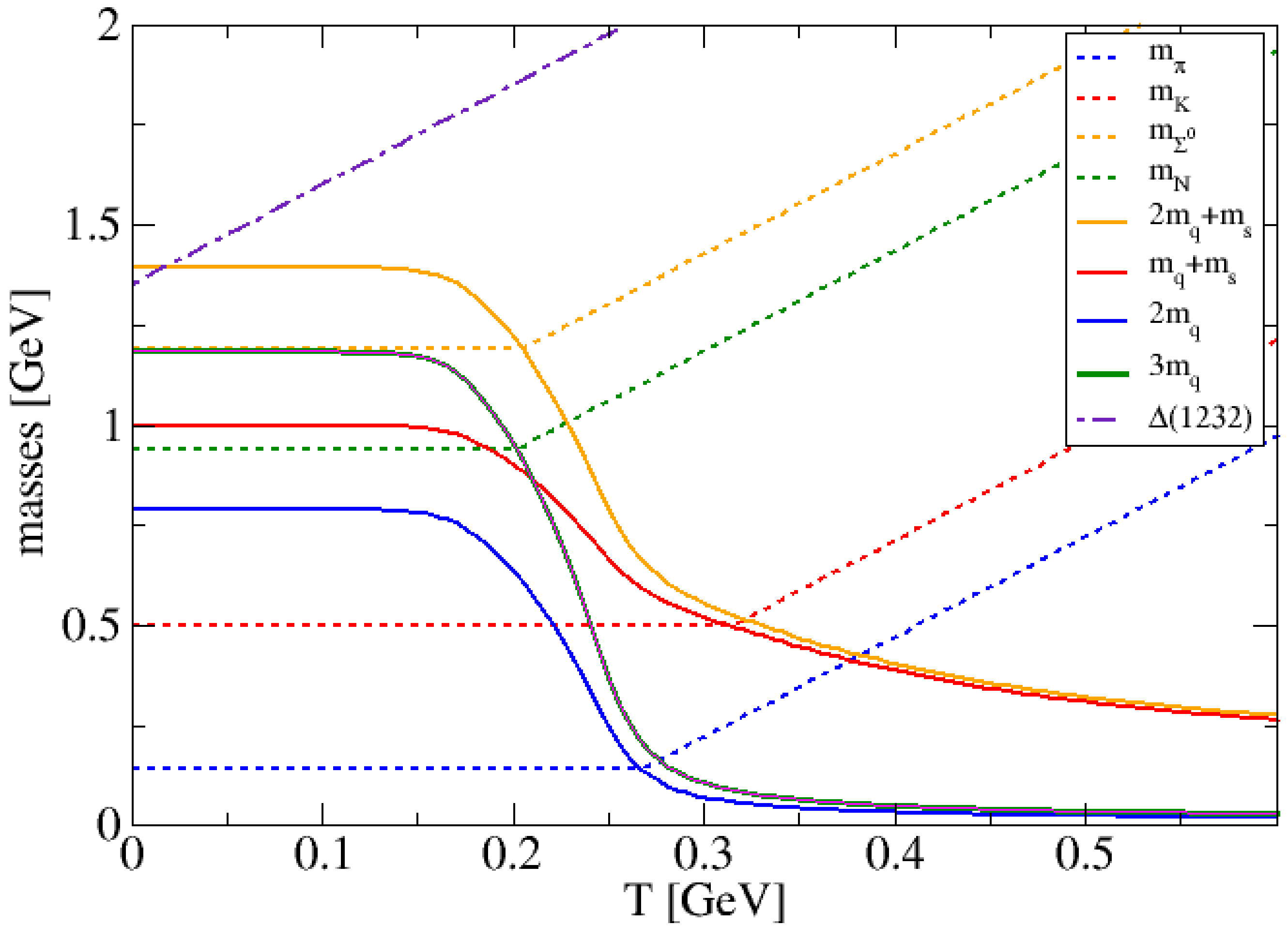
so that the M-integration becomes trivial and gives

$$P_i(T) = \mp d_i \int_0^\infty \frac{dp\, p^2}{2\pi^2} T \ln\left(1 \mp e^{-\sqrt{p^2+M_i^2}/T}\right),$$

D. Blaschke, A. Dubinin, L. Turko,
Phys. Part. Nucl. 46 (2015); arxiv:1501.00485

Hadron Resonance Gas with Mott Dissociation

D. Blaschke, A. Dubinin, L. Turko, Phys. Part. Nucl. 46 (2015); arxiv:1501.00485



$$M_i(T) = M_i(0) + \Gamma_i(T) \quad ,$$
$$\Gamma_i(T) = a\,(T - T_{\rm Mott,i})\Theta(T - T_{\rm Mott,i})$$

$$M_i(T_{\rm Mott,i}) = m_{\rm thr,i}(T_{\rm Mott,i}) \, ,$$
$$m_{\rm thr,M}(T) = (2 - N_s)m(T) + N_s m_s(T)$$
$$m_{\rm thr,B}(T) = (3 - N_s)m(T) + N_s m_s(T)$$

Hadron Resonance Gas with Mott Dissociation

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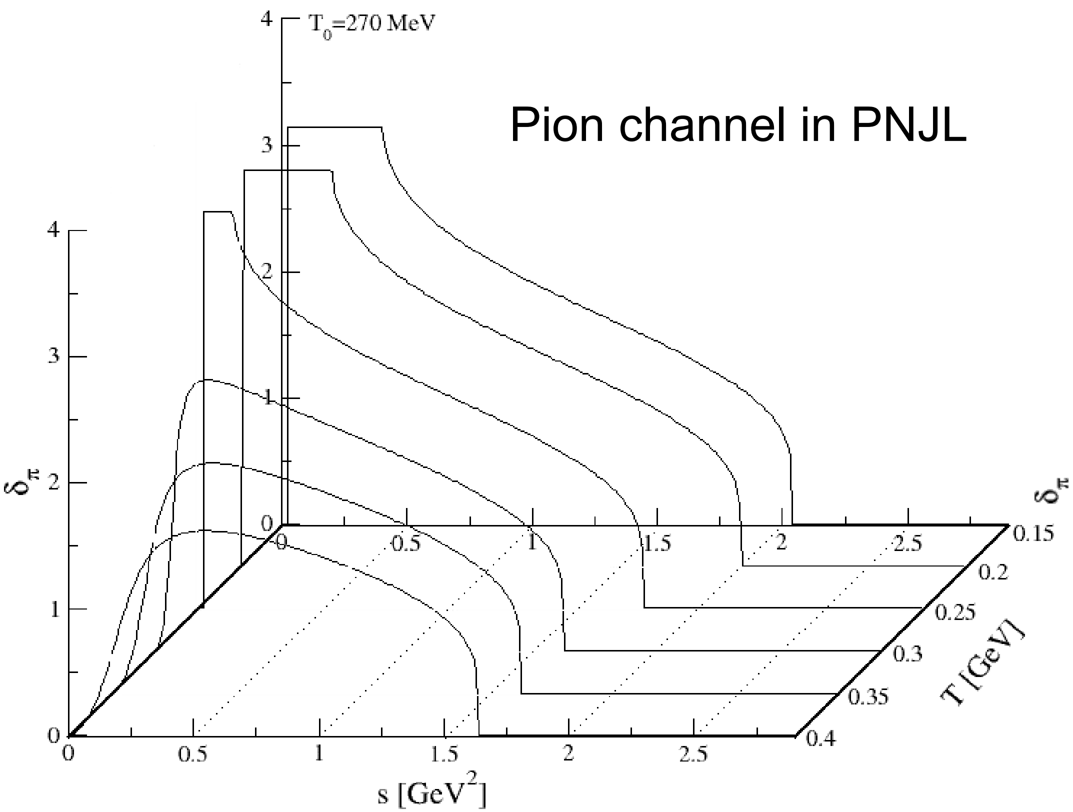
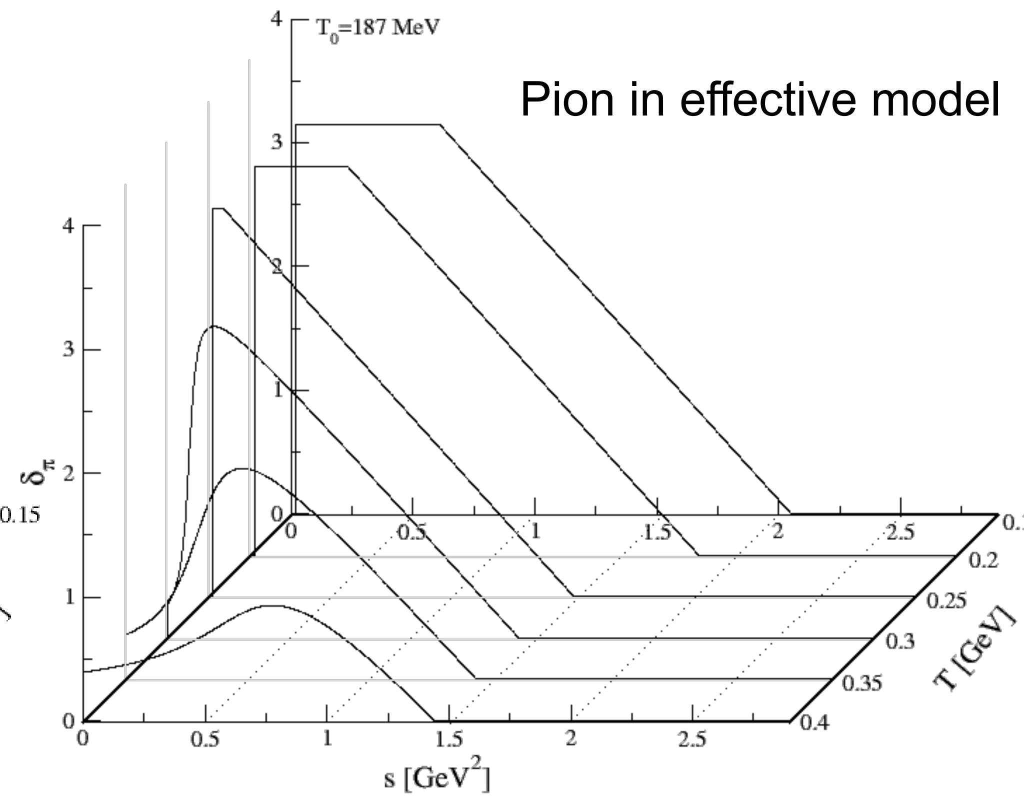


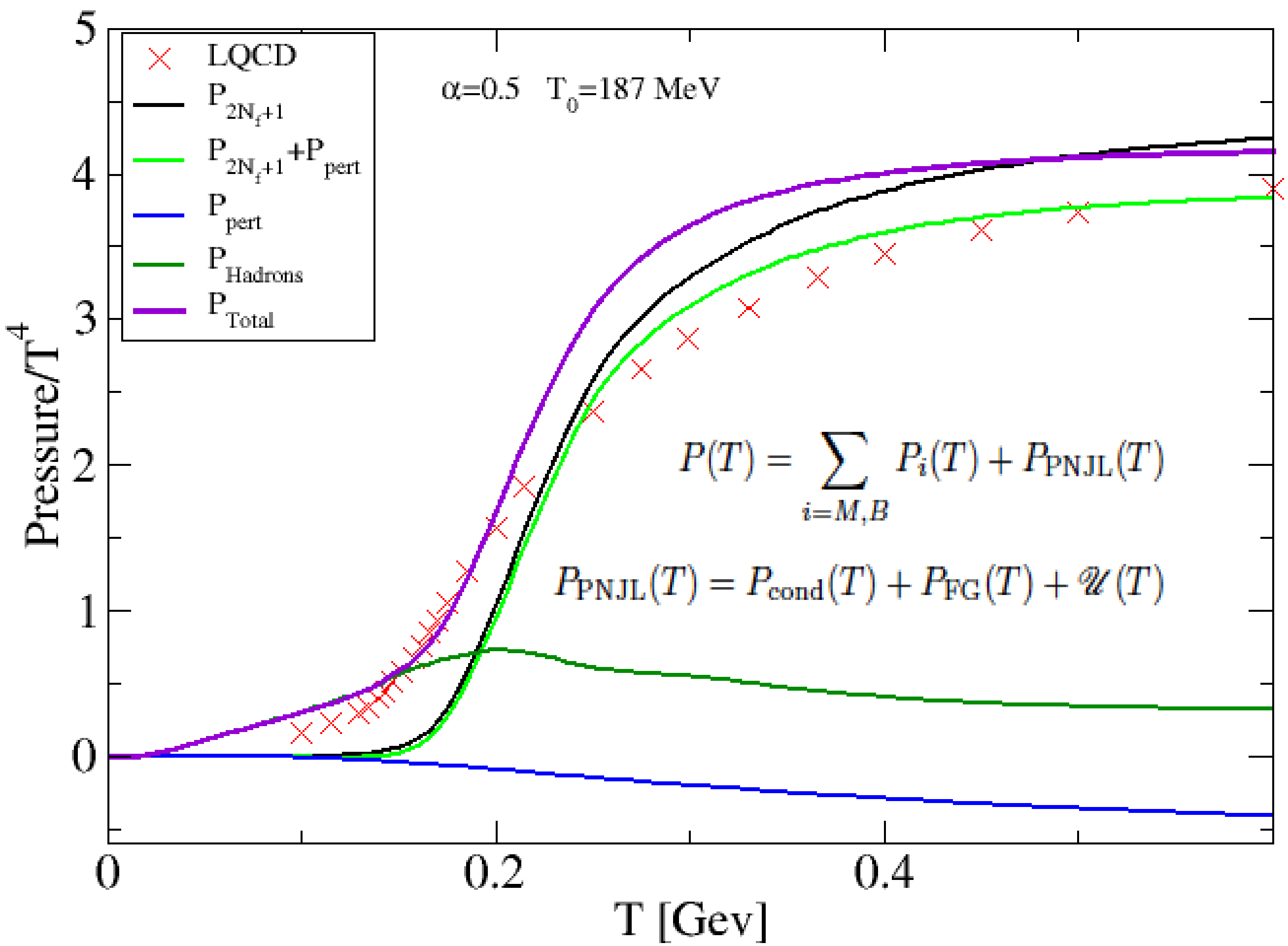


Effective model for in-medium hadron phase shifts

$$\delta_i(s;T) \;=\; \left[\frac{\pi}{2} + \arctan\left(\frac{s - M_i^2(T)}{M_i(T)\Gamma_i(T)}\right)\right] \left\{\Theta[m^2_{\rm thr,i} - s] + \Theta[s - m^2_{\rm thr,i}]\Theta[m^2_{\rm thr,i} + N_i^2\Lambda^2 - s]\left[\frac{m^2_{\rm thr,i} + N_i^2\Lambda^2 - s}{N_i^2\Lambda^2}\right]\right\} \quad (7)$$

Hadron Resonance Gas with Mott Dissociation

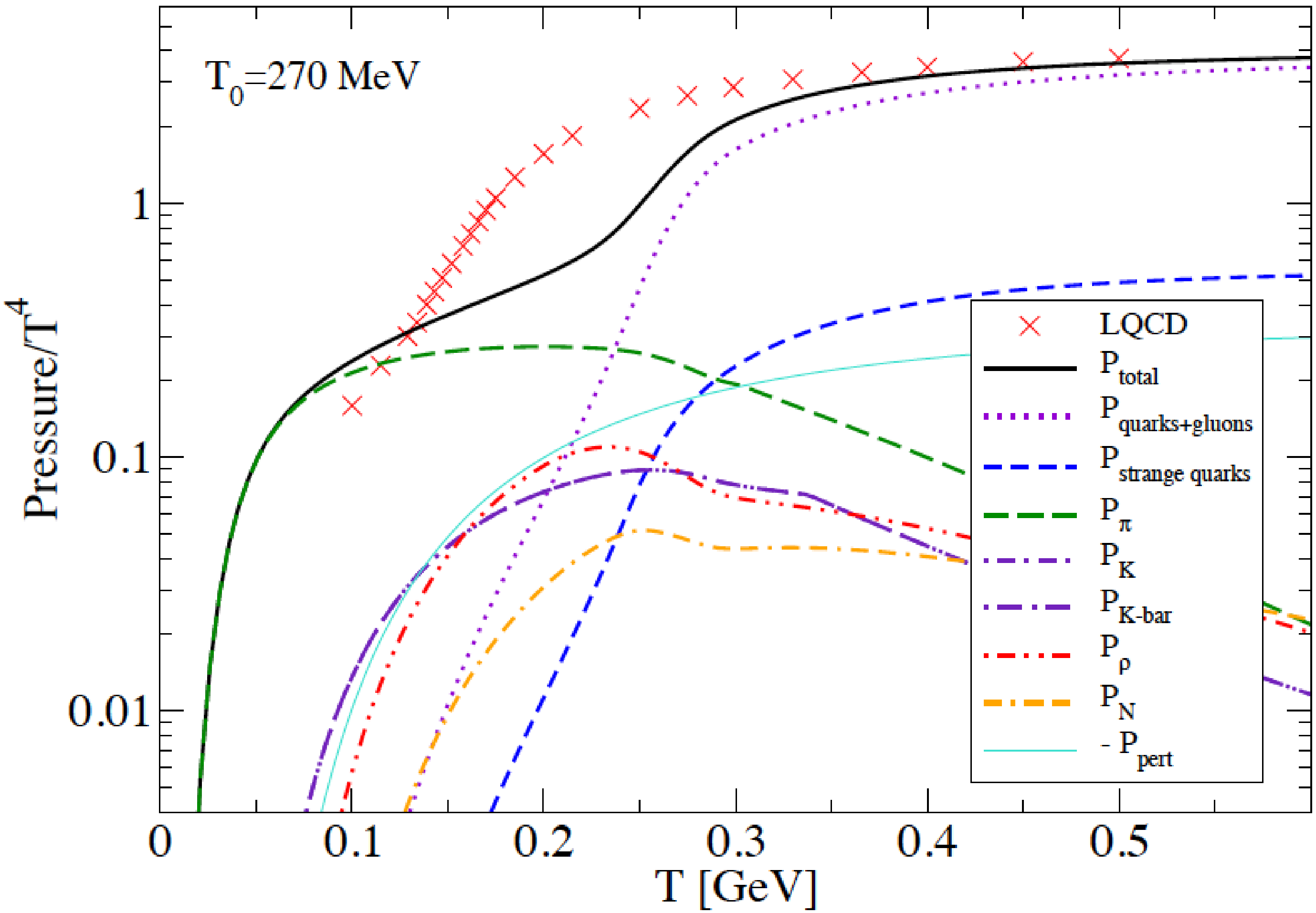
D. Blaschke, A. Dubinin, L. Turko, Phys. Part. Nucl. 46 (2015); arxiv:1501.00485



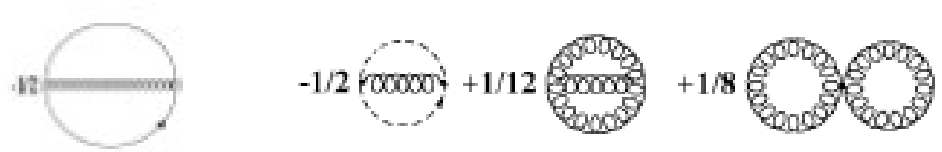
$$P_i(T) \;=\; d_i \int \frac{d^3p}{(2\pi)^3} \int_0^\infty \frac{d\omega}{\pi} f_i(\omega)\delta_i(\omega;T) \;=\; d_i \int_0^\infty \frac{dp\; p^2}{2\pi^2} \int_0^\infty \frac{ds}{2\pi} \frac{1}{\sqrt{p^2+s}} \; f_i(\sqrt{p^2+s})\delta_i(s;T)$$

Hadron Resonance Gas with Mott Dissociation

D. Blaschke, A. Dubinin, L. Turko, Phys. Part. Nucl. 46 (2015); arxiv:1501.00485



$$P_2(T) = P_2^{\mathrm{quark}}(T) + P_2^{\mathrm{gluon}}(T) =$$



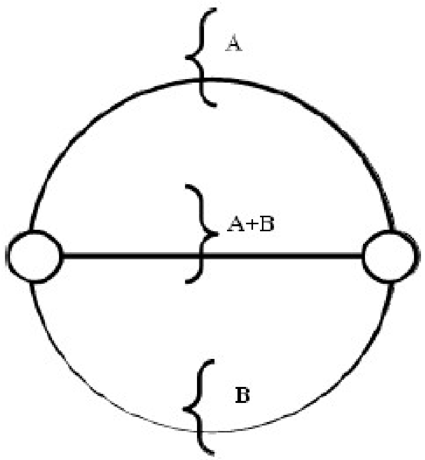
Towards Selfconsistence: Cluster Virial Expansion

D. Blaschke, PoS Baldin XXII (2014); arxiv: 1502.06279

Clusters in nuclear matter: Roepke et al., Nucl. Phys. A (2013)

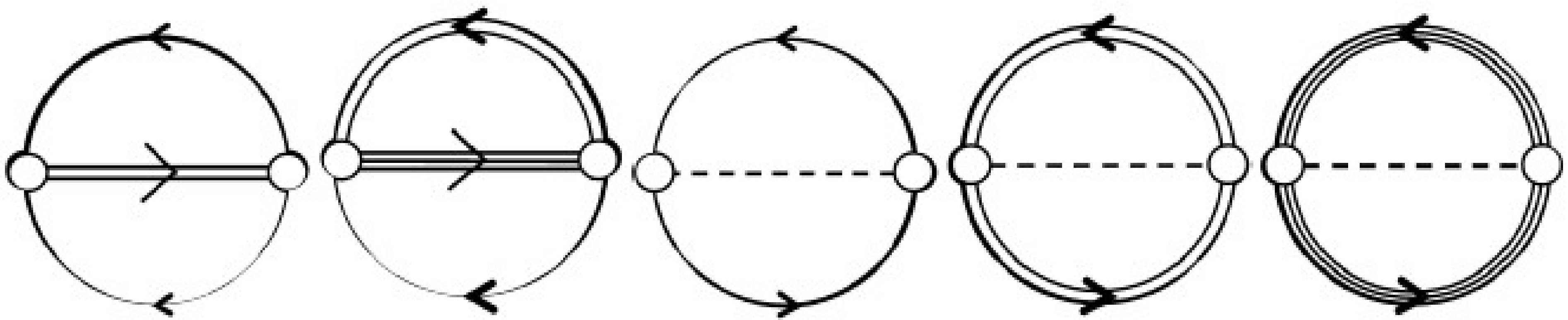
$$\Omega = \sum_A (-1)^A \left[\mathrm{Tr}\ln\left(-G_A^{-1}\right) + \mathrm{Tr}\left(\Sigma_A\, G_A\right)\right] + \sum_{A,B} \Phi[G_A, G_B, G_{A+B}] \ ,$$

$$G_A^{-1} = G_A^{(0)^{-1}} - \Sigma_A \ , \ \ \Sigma_A(1\ldots A, 1'\ldots A', z_A) = \frac{\delta\Phi}{\delta G_A(1\ldots A, 1'\ldots A', z_A)} \ .$$



Conserving approximation (Phi-derivable approach) for
Hadrons in Quark Matter

$$\Omega = \sum_{i=Q,M,D,B} (-1)^{c_i} \left[\mathrm{Tr}\ln\left(-G_i^{-1}\right) + \mathrm{Tr}\left(\Sigma_i\, G_i\right)\right] + \Phi[G_Q, G_M, G_D, G_B] \ , \quad \Sigma_i = \frac{\delta\, \Phi[G_Q, G_M, G_D, G_B]}{\delta\, G_i} \ .$$



Towards Selfconsistence: Cluster Virial Expansion

D. Blaschke, PoS Baldin XXII (2014); arxiv: 1502.06279

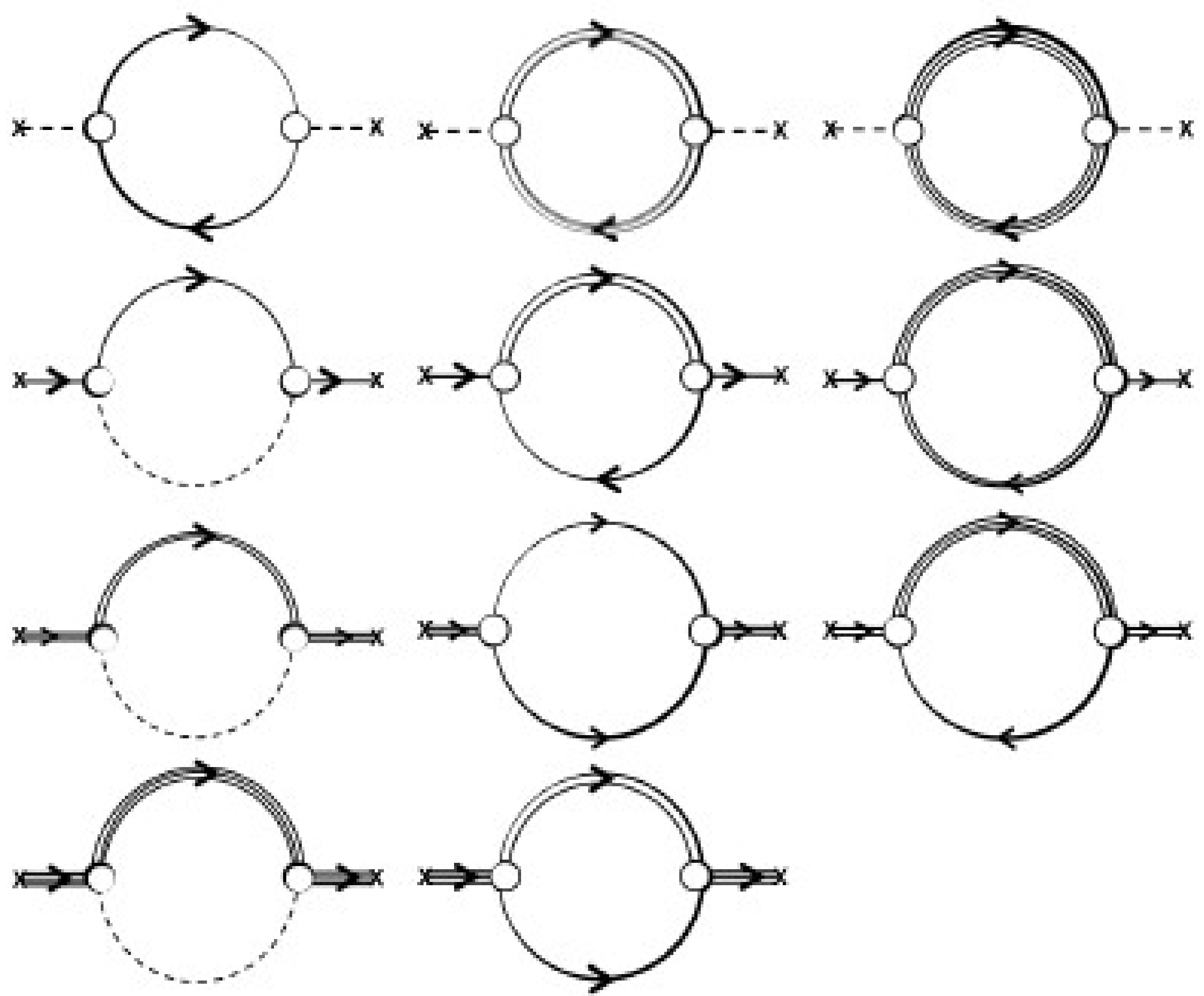
$$\Sigma_i = \frac{\delta\, \Phi[G_Q, G_M, G_D, G_B]}{\delta\, G_i}$$

Mesons =

Quarks =

Diquarks =

Nucleons =

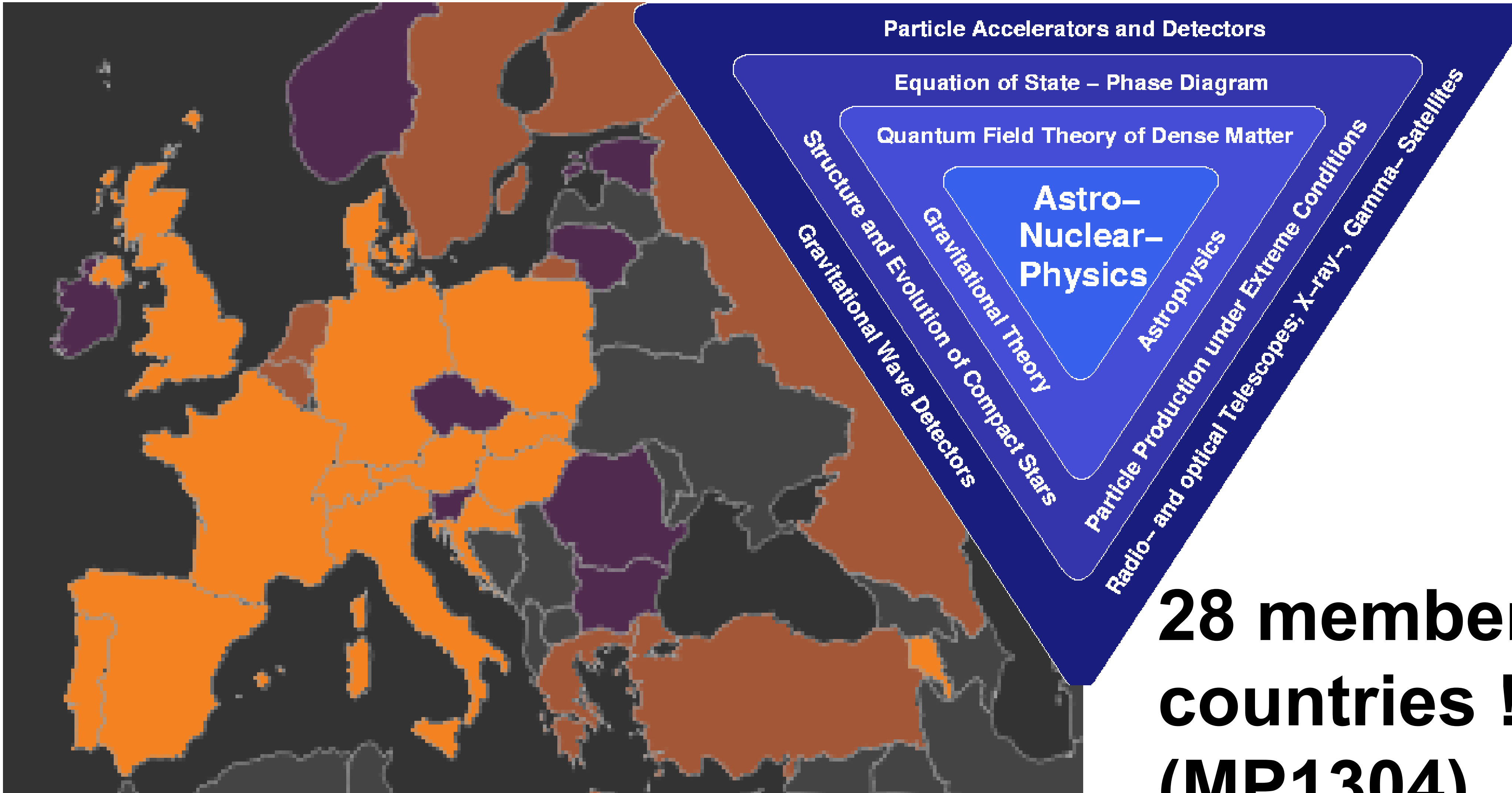


Summary

- 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 μ, 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

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



28 member countries !! (MP1304)

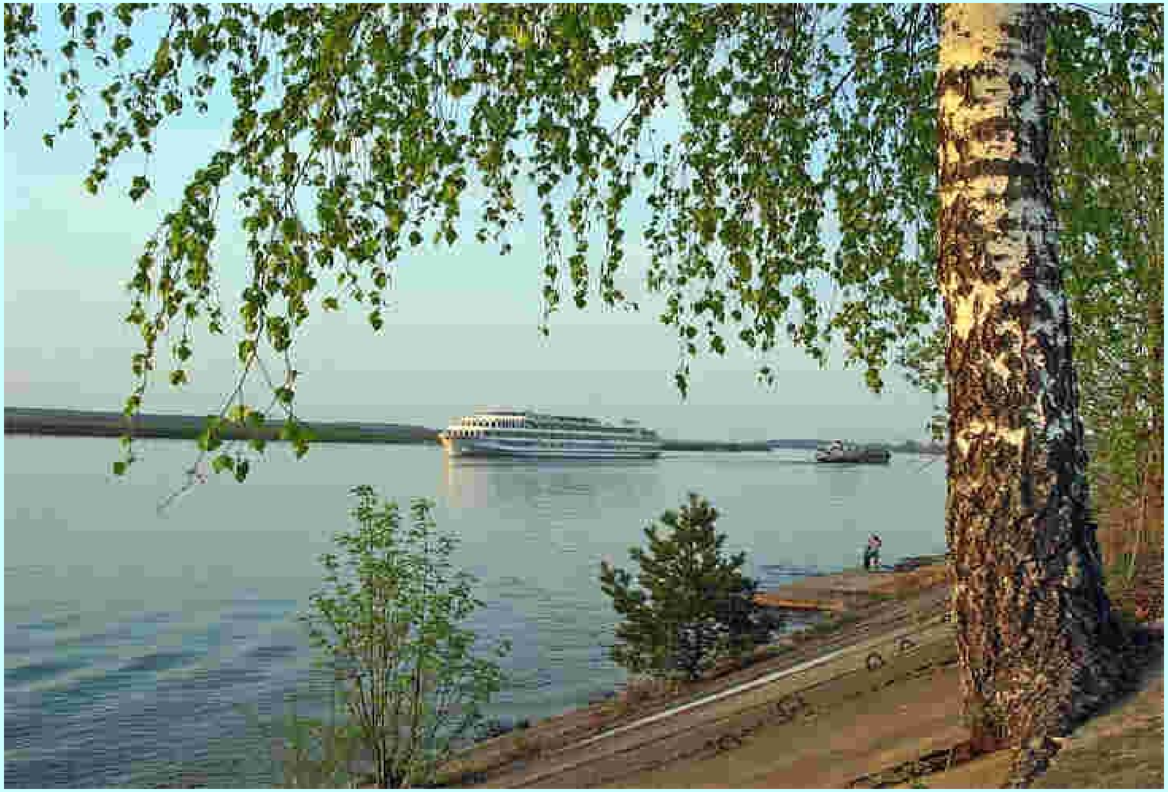
New comp star !

COST
EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

Kick-off: Brussels, November 25, 2013

Strangeness in Quark Matter 2015

Dubna, 6.-11. July 2015



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SQM DUBNA 2015

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Satellite Meetings:

Summer School “Dense Matter”, Dubna, June 29 – July 11, 2015

Roundtable “Physics at NICA”, Dubna, 5. July 2015