Towards a unified EoS for quark-nuclear matter.

Abstract

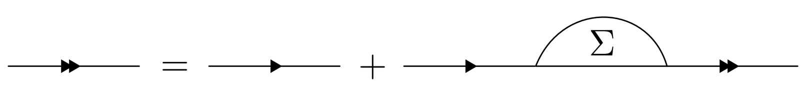
The aim of our work is to develop a unified equation of state (EoS) for nuclear and quark matter for a wide range in temperature, density and isospin so that it becomes applicable for heavy-ion collisions as well as for the astrophysics of neutron stars, their mergers and supernova explosions [1]. As a first step, we use improved EoS for the hadronic and quark matter phases and join them via Maxwell construction. For this we work with a generalized density functional approach for the self energies in a quasi particle picture, which gives us the possibility to start with a reasonable physical basis and apply improvements to fit certain constraints from lattice QCD and neutron star measurements.

Towards CVE

- Cluster Virial Expansion with quarks as fundamental degrees of freedom and hadrons as bound states
- formulation for nuclear matter already done [2]

quasiparticles

- replacing interacting particles by system of free quasi particles



- selfenergies shift energy dispertion relation

$$E_i^{\rm qu} = \sqrt{p^2 + (m-S)^2} + V \qquad (1)$$

virial expansion

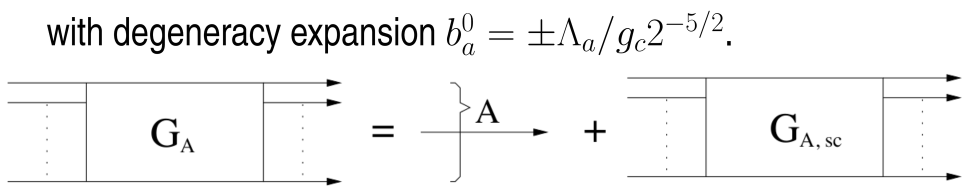
$$\beta p = \sum_a z_a + \sum_{ab} z_a z_b b_{ab} + \mathcal{O}(z^3) \qquad (2)$$

with fugacity $z_a = (2s+1)\Lambda_a^{-3} e^{\beta\mu_a}$; $\Lambda_a^2 = 2\pi\beta/m_c$;

- The second b_{ab} virial coefficient by Beth-Uhlenbeck formula

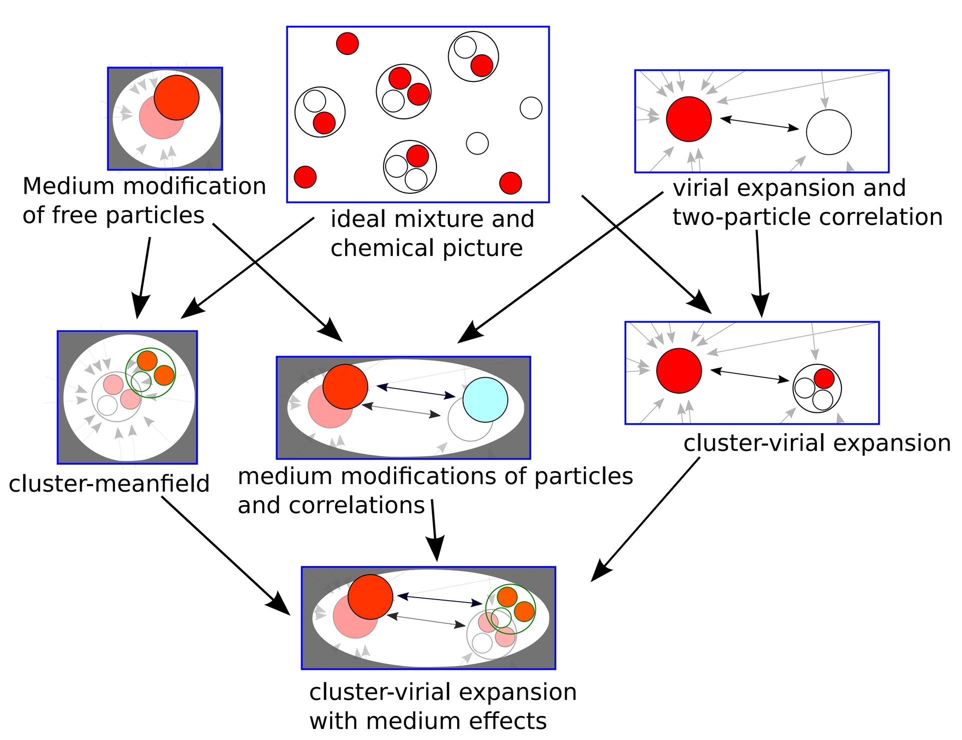
$$\begin{aligned} b_{ab} &= 8\pi^{3/2}\lambda_{ab}^3 \sum_l (2l+1) Z_{ab,l} + \delta_{ab} b_a^0 \\ Z_{ab,l} &= \sum_n e^{-\beta E_{ab}^{nl}} + \frac{1}{\pi}\int_0^\infty dE\, e^{-\beta E} \frac{d}{dE}\eta_{ab,l}(E) \ , \end{aligned} \qquad (3)$$

with degeneracy expansion $b_a^0 = \pm\Lambda_a / g_c 2^{-5/2}$.



- dividing into bound and scattering contribution
- replacing the particles by quasi-particles leads to absorbtion of scattering contribution in meanfield [3, 4]

$$Z_{ab,l}^{\rm scatt} = \frac{1}{\pi}\int_0^\infty dE\ e^{-\beta E}\ 2\sin^2(\delta_l(E)) \frac{d\delta_l(E)}{dE} \ . \qquad (4)$$



cluster expansion

- bound states are treated as new elementary particles
- virial expantion between quasi clusters up to 2nd order

CVE for quark matter

- hadrons (baryons, mesons) are bound states of quarks
- need proper inclusion of confinement → density functional

Density Functional Approach

- quasiparticle approach for grand potential

$$\omega = -g \int \frac{d^3p}{(2\pi)^3} \left\{ T \ln[1 + e^{-(E-\tilde{\mu})/T}] + \dots \right\} - U \qquad (5)$$

- effectiv mass $M = m - S$ and chemical potential $\tilde{\mu} = \mu - V$
- scalar $S = \Delta m + m^{\rm R}$ and vector $V = \Delta E + E^{\rm R}$ selfenergies
- mass and energy shifts can have arbitrary density dependence.
- rearrangement contributions $m^{\rm R}$, $E^{\rm R}$ and U garantee thermodynamical consistency by reproducing the usual quasi particle form for the densities

$$n^{\rm v} = g \int \frac{d^3p}{(2\pi)^3} \left\{ \frac{1}{e^{(E-\tilde{\mu})/T}} - \frac{1}{e^{(E+\tilde{\mu})/T}} \right\} \qquad (6)$$

$$n^{\rm s} = g \int \frac{d^3p}{(2\pi)^3} \frac{M}{E} \left\{ \frac{1}{e^{(E-\tilde{\mu})/T}} + \frac{1}{e^{(E+\tilde{\mu})/T}} \right\} \qquad (7)$$

Two phase construction

- constructing phasetransition of two seperate models

Hadron Phase

- Nucleons via DD2 model [5] → high density improvement via excluded volumen [6]
- Simplest ansatz of a hadron gas, including π, Λ and K, with $\mu_\pi = 0$; $\mu_\Lambda = \mu_{\rm B} - \mu_{\rm S}$; $\mu_{\rm K^0} = \mu_{\rm K^+} = \mu_{\rm S}$.
- determine $\mu_{\rm S}$ to ensure net strange neutrality

$$0 = n_{\rm S} = -n_\Lambda + n_{\bar{\Lambda}} + n_{K^+} - n_{K^-} + n_{K^0} - n_{\bar{K}^0} \qquad (8)$$

Quark Phase

- Quarks and Gluons with effective confinement mechanism [7]
- detailled information on poster of Mark Alexander Kaltenborn
- parameters are fit to satisfy lattice prediction for transition temperature for $\mu_{\rm B} = 0$ and maximal neutron star mass.

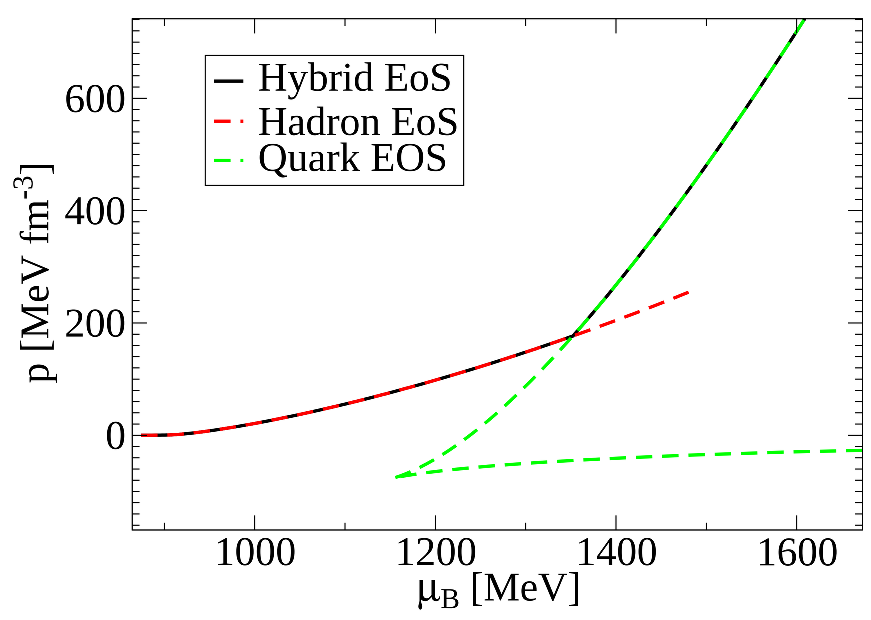


Figure 1: PT construction for $T = 21$ MeV. The crossing point represents equilibrium of both phases.

Phase transition

- first approach is Maxwell construction
- matching both EoS at point of chemical (μ) thermal (T) and mechanical (p) equilibrium.
- maxwell construction can't create a critical point!

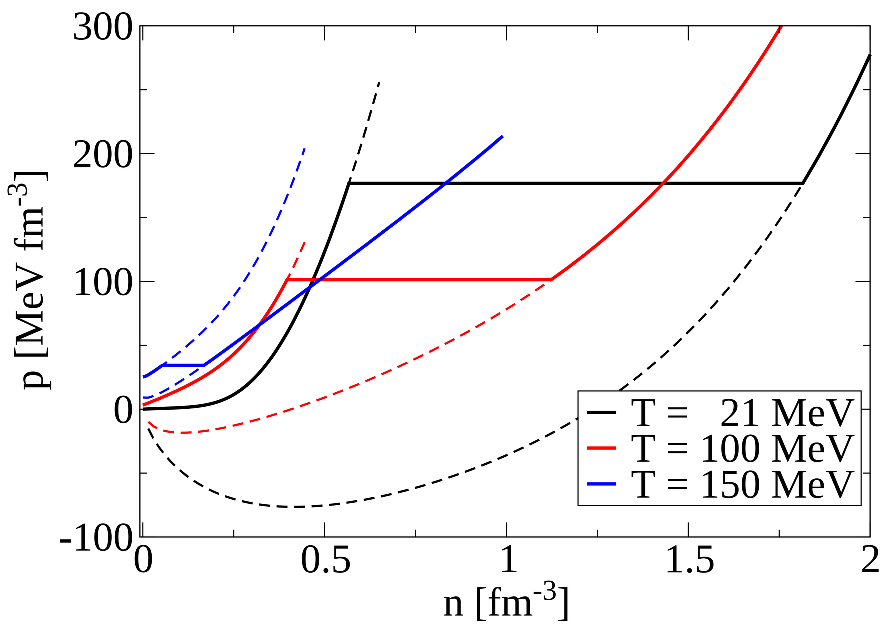


Figure 2: PT for several temperaturs with density jump.

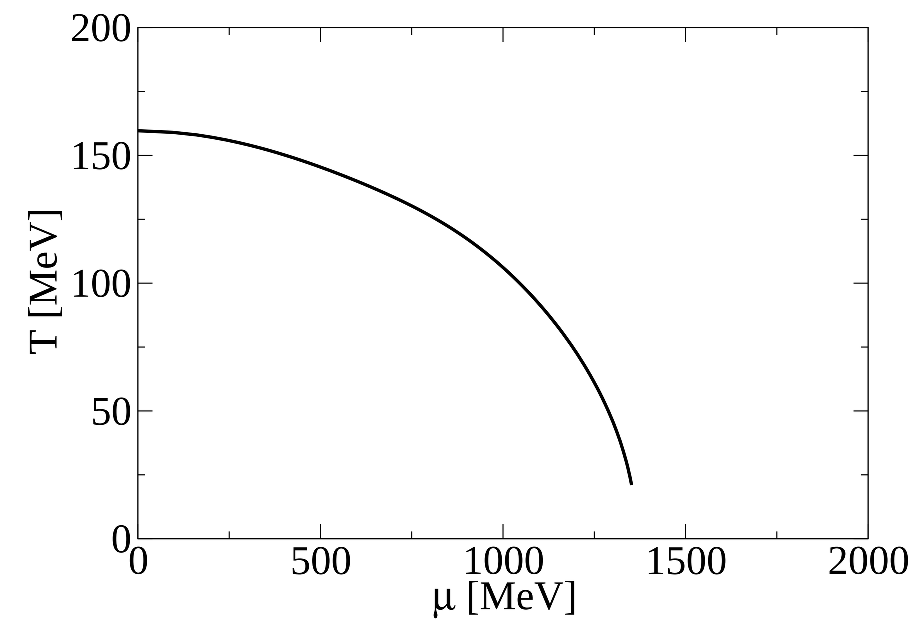


Figure 3: Resulting phasediagram with quark-hadron phasetransition for symmetric matter.

Outlook

- applying the results of the current EoS to simulations of heavy ion collisions and supernova explosions
- improving the PT construction by the approach of [8] to obtain critical point
- formulation and solution of the cluster virial expansion for quark-hadron matter

References

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