General-purpose EoS with hadron-quark crossover for simulations of heavy-ion collisions and neutron stars

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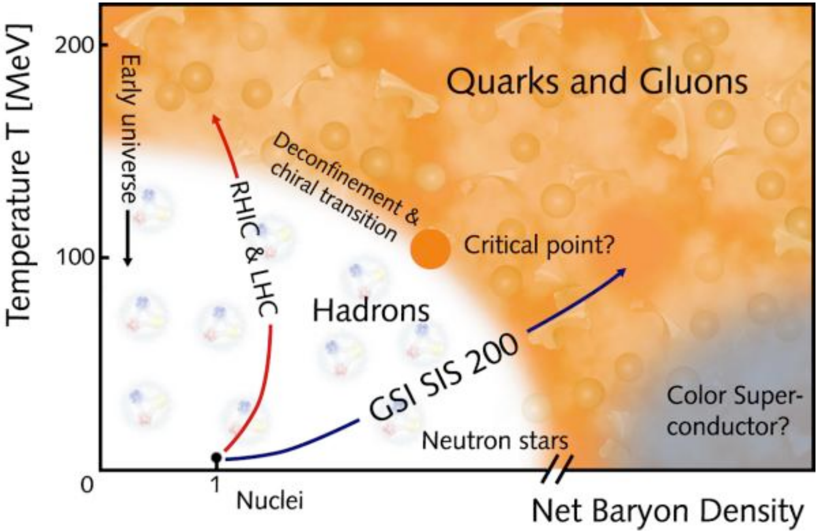
Temperature T [MeV]
200
100
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Nuclei
Net Baryon Density
Early universe
RHIC & LHC
Deconfinement &
chiral transition
Quarks and Gluons
Critical point?
Hadrons
GSI SIS 200
Neutron stars
Color Super-
conductor?

Albright 2014

Matching excluded-volume hadron-resonance gas models and perturbative QCD to lattice calculations

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We match three hadronic equations of state at low energy densities to a perturbatively computed equation of state of quarks and gluons at high energy densities. One of them includes all known hadrons treated as point particles, which approximates attractive interactions among hadrons. The other two include, in addition, repulsive interactions in the form of excluded volumes occupied by the hadrons. A switching function is employed to make the crossover transition from one phase to another without introducing a thermodynamic phase transition. A χ^2 fit to accurate lattice calculations with temperature $100 < T < 1000$ MeV determines the parameters. These parameters quantify the behavior of the QCD running gauge coupling and the hard core radius of protons and neutrons, which turns out to be 0.62 ± 0.04 fm. The most physically reasonable models include the excluded-volume effect. Not only do they include the effects of attractive and repulsive interactions among hadrons, but they also achieve better agreement with lattice QCD calculations of the equation of state. The equations of state constructed in this paper do not result in a phase transition, at least not for the temperatures and baryon chemical potentials investigated. It remains to be seen how well these equations of state will represent experimental data on high-energy heavy-ion collisions when implemented in hydrodynamic simulations.

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Switch function

$$P(T,\mu) = S(T,\mu)P_{qg}(T,\mu) + [1 - S(T,\mu)]P_h(T,\mu) \quad (1)$$

$$S(T,\mu) = exp[-\Theta(T,\mu)] \quad (2)$$

$$\Theta(T,\mu) = \left[\left(\frac{T}{T_0}\right)^r + \left(\frac{\mu}{\mu_0}\right)^r\right]^{-1} \quad (3)$$

This switching function contains two 3 parameters: r, T_0 and μ_0.

$$\mu_0 = 3\pi T_0 \quad (4)$$

That means in the end 2 free parameters.

Hadronic part

- mainly based on PDB 2014

$$P_\alpha(T,\mu) = (2s_\alpha + 1)\int \frac{d^3p}{(2\pi)^3}\frac{1}{e^{\beta(E_\alpha(p)-n_b\mu_\alpha)} \pm 1} \qquad (5)$$

excluded Volume

$$P_{ex}(T,\mu) = \frac{P_{PT}(T_*,\mu_*)}{1 - P_{PT}(T_*,\mu_*)/\epsilon_0} \tag{6}$$

Thereby T_* and μ_* are not independent but related by

$$\frac{T}{T_*} = \frac{\mu}{\mu_*}\,. \tag{7}$$

Using the equations 6 and 7 it remains one equation with one variable to determine the T_* and μ_* for a given pair of T and μ.

$$T = \frac{T_*}{1 - P_{PT}(T_*,\mu_*)/\epsilon_0} \tag{8}$$

Perturbative QCD

The pressure of QCD at finite temperatures and chemical potentials

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We compute the perturbative expansion of the pressure of hot QCD to order $g^6 \ln g$ in the presence of finite quark chemical potentials. In this process we evaluate all two- and three-loop vacuum diagrams of the theory at arbitrary T and μ and then use these results to analytically verify the outcome of an old order g^4 calculation of Freedman and McLerran for the zero-temperature pressure. The results for the pressure and the different quark number susceptibilities at high T are compared with recent lattice simulations showing excellent agreement especially for the chemical potential dependent part of the pressure.

Perturbative QCD

$$P = \frac{8\pi^2}{45} T^4 \left[f_0 + f_2 \left(\frac{\alpha_s}{\pi}\right) + f_3 \left(\frac{\alpha_s}{\pi}\right)^{\frac{3}{2}} + f_4 \left(\frac{\alpha_s}{\pi}\right)^2 + f_5 \left(\frac{\alpha_s}{\pi}\right)^{\frac{5}{2}} + f_6 \left(\frac{\alpha_s}{\pi}\right)^3 \right] \quad (9)$$

Perturbative QCD

$$P_q(\mu) = \frac{3}{4\pi^2} a_4 \left(\frac{\mu}{3}\right)^4 + \frac{3}{\pi^2} \Delta^2 \left(\frac{\mu}{3}\right)^2 - B_{\text{eff}} \qquad (10)$$

(nonlinear) Walecka model

At low temperatures describes protons and neutrons better than the hadron resonance gas.

Was presented in the talk by Elena Hanu on Tuesday.

PHYSICAL REVIEW C **105**, 035804 (2022)

Neutron stars with crossover to color superconducting quark matter

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We follow the idea that the QCD phase diagram may be described by a crossover from a hadron resonance gas to perturbative QCD using the switch function ansatz of Albright, Kapusta, and Young [Phys. Rev. C **90**, 024915 (2014)]. While the switch function could be calibrated at vanishing baryon chemical potential with data from lattice QCD simulations, it has been suggested recently by Kapusta and Welle [Phys. Rev. C **104**, L012801 (2021)] that in the zero temperature limit, the switch function parameter μ_0 could be constrained by neutron star phenomenology, in particular by massive pulsars such as PSR J0740+6620 with a mass exceeding $2\,M_{\mathrm{sun}}$. In this work we demonstrate that this procedure to constrain the QCD phase diagram does crucially depend on the fact that cold dense quark matter is very likely in a color superconducting state.

DOI: 10.1103/PhysRevC.105.035804

Nambu-Jona-Lasino model

- Calculation of NJL model
- Fitting of μ dependtdent gap
- Inclusion in the pertubative QCD

Was shown by Udita Shukla on Tuesday.
Publication in preparation.

Maxwell construction

- hadronic part from DD2 + excluded Volume
- quark part nonlocal NJL model with form factor
- interpolation by Maxwell construction

Quark-nuclear hybrid equation of state for neutron stars under modern observational constraints

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We study a family of equations of state (EOS) for hybrid neutron star matter. The hybrid EOS are obtained by a Maxwell construction of the first-order phase transition between a hadronic phase described by the relativistic density-functional EOS of the "DD2" class with excluded volume effects and a deconfined quark matter phase modeled by an instantaneous nonlocal version of the Nambu–Jona-Lasinio model in $SU(2)_f$ with vector interactions and color superconductivity. The form factor in the nonlocal quark matter model is fitted to lattice QCD results in the Coulomb gauge. Owing to strong coupling in the vector meson and diquark channels, a coexistence phase of color superconductivity and chiral symmetry breaking occurs. Our results show an approximately constant behavior for the squared speed of sound with values of 0.4–0.6 in the density region relevant for neutron star interiors. To simultaneously fulfill the constraints from the Neutron Star Interior Composition Explorer radius measurement for PSR J0740 + 6620 and tidal deformability from GW170817 it is necessary to consider a μ-dependent bag pressure that mimics confinement.

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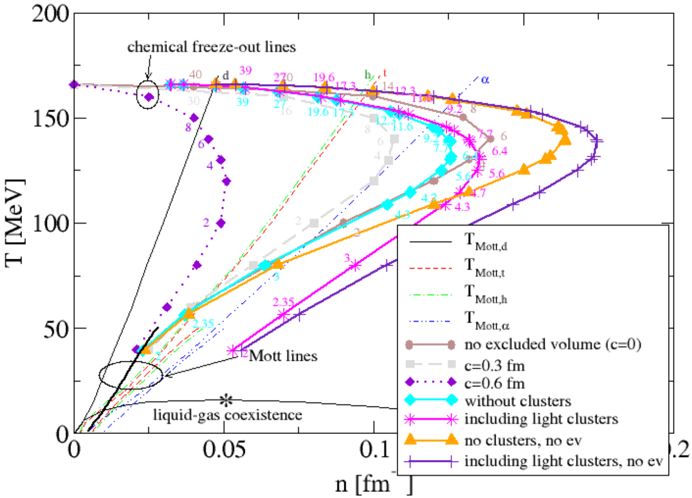
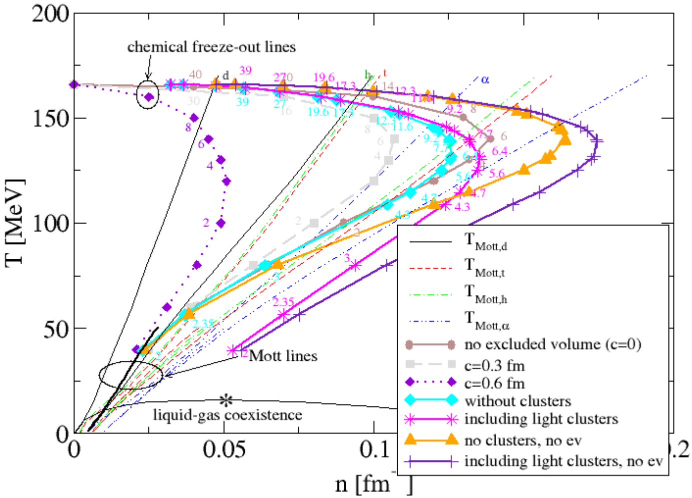
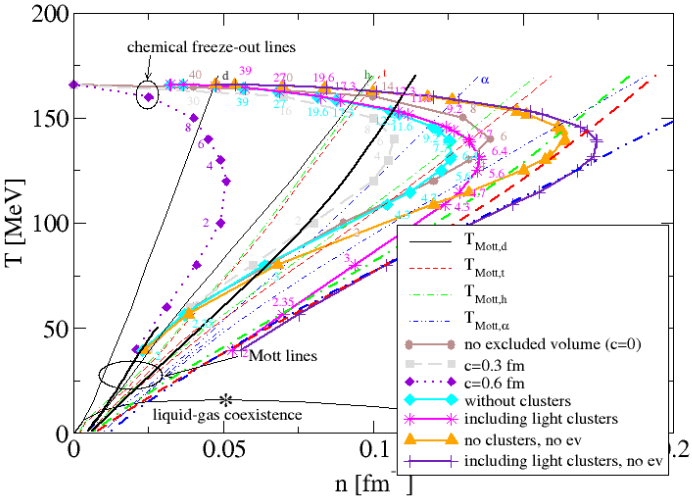
Chemical freezeout



Chemical freezeout



Chemical freezeout



Conclusions

- improving the physics of a simple EOS leads to better description of neutron star properties
- low density part of the freezeout can be unterstood as the direct crossover from QGP to hadron gas
- at higher densities the lines follow quit close the mott lines of light clusters

Thank you for attention