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Quark-Nuclear Hybrid EoS with Excluded-Volume Effects

Abstract

We outline a new 2-phase description of the quark-nuclear matter hybrid equation of state that takes into account effects of phase space occupation (excluded-volume) in both, the hadronic and the quark matter phases. For the nuclear matter phase, the reduction of the available volume at increasing density leads to a stiffening, while for the quark matter phase a reduction of the effective string tension in the confining density functional is obtained. The deconfinement phase transition in the resulting equation of state is sensitive to both excluded-volume effects. As an application, we consider matter under compact star constraints of electric neutrality and β-equilibrium. We obtain mass-radius relations for hybrid stars that fulfill the $2M_\odot$ constraint and exhibit the high-mass twin phenomenon.

Compact Stars

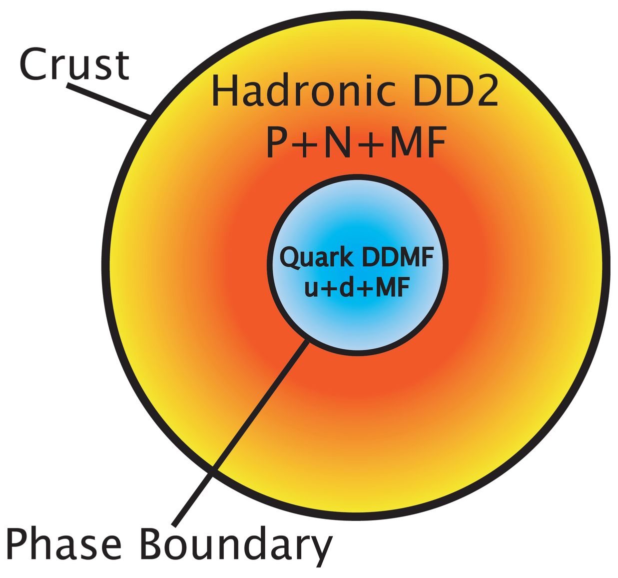

Figure 1: Two-phase model for compact stars in β-equilibrium at zero temperature. Hadronic model + Quark model.

Two-Phase Description:

Hadronic phase:

- Relativistic Mean-Field DD2 model [3].
- Protons and neutrons, dressed with three meson fields.

Quark phase:

- Relativistic Mean-Field, two-flavor (u, d) model [1].
- u and d quarks, dressed with a vector potential and a scalar potential.
- Equation of State:

$$P = -\frac{\Omega}{V} = \frac{T}{V}\ln\mathcal{Z}$$

$$P(T\to 0) = \sum_i \frac{g_i}{6\pi^2}\int_0^{p_F} \mathrm{d}p\,\frac{p^4}{E_i^*}\,.$$

p_F is the Fermi-momentum and g_i is the degeneracy for species i. E_i^* and μ_i^* are the quasi-particle energies and chemical potentials.

$$E_i^* = \sqrt{p^2 + M_i^{*2}};\quad M_i^* = m_i - U_S;\quad \mu_i^* = \mu_i - U_V\,.$$

$U_{S,V}$ are the scalar and vector mean-field potentials that dress the up and down quarks.

Mean-Field Modifications

Scalar MF: String-flip

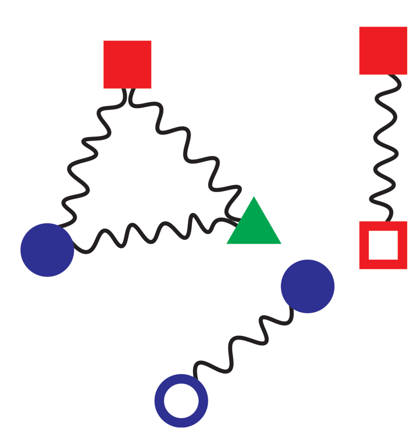

Figure 2: String configurations between quarks. Contributes to effective quark masses at deconfinement densities.

$$M_i^* = m_{i_0} - U_{Si} = m_{i_0} + \underbrace{D(n_S)\,n_S^{-\frac{1}{3}}}_{\text{confinement}} + \underbrace{C\,n_S^{\frac{1}{3}}}_{\text{Coulomb}}$$

The $D(n_S)$ term is the effective in-medium string tension resulting from multiplying the vacuum string tension [5, 6], D_0 between quarks with an available volume fraction, $\Phi(n_S)$:

$$D(n_S) = D_0\,\Phi(n_S) = D_0\,\exp\{-\alpha\,n_S^2\},\qquad (1)$$

where $\alpha = V_{ex}^2$ and V_{ex} is the excluded-volume parameter.

Vector MF: Multi-Quark collisions

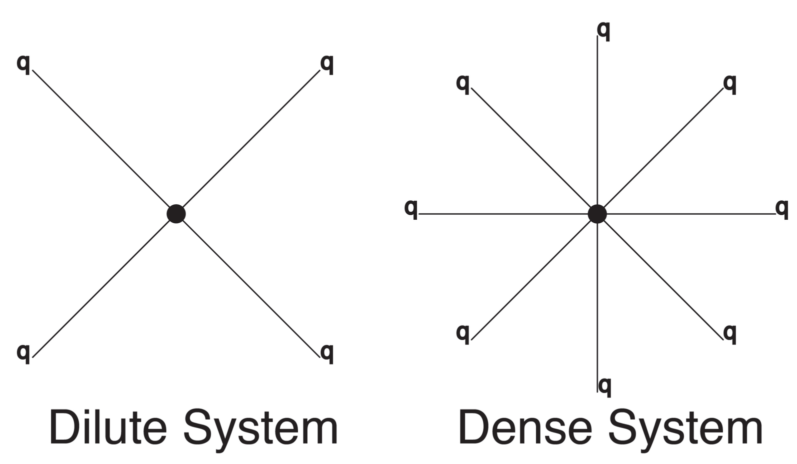

Figure 3: Multi-quark interactions (4-quark $\sim n_V$ and 8-quark $\sim n_V^3$) contribute strongly at densities larger than the onset of deconfinement, with the 4-quark contribution dominating first, followed by the domination of the 8-quark contribution at even larger densities.

The vector self-energy is taken from [2], giving us

$$\mu_i^* = \mu_{0,i} - U_{V,i} = \mu_{0,i} - a\,n_V - b\,n_V^3.$$

Excluded-Volume

For the hadronic EoS, it is implemented as a repulsive potential between nucleons increasing with density, effectively stiffening the hadronic matter.

The excluded-volume in the quark phase is taken into account as an effective reduction of the string tension in dense matter by the available volume fraction, $\Phi(n_S)$, resulting in a softening of quark matter at deconfinement densities.

High-Mass Twins

The large energy density jump $\Delta\varepsilon$ between phases from excluded-volume properties suggests there exists a hybrid star branch.

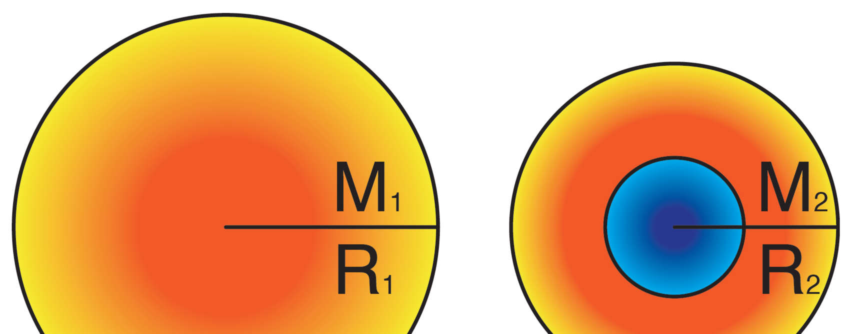

Figure 4: High-mass twin compact stars have identical masses, $M_1 = M_2$, but different radii, $R_1 \neq R_2$. If their radii could differ significantly, e.g., by 2 km, observable high-mass twin stars could be found, proving the existence of a strong first-order phase transition and thus the existence of a CEP.

Critical Endpoint

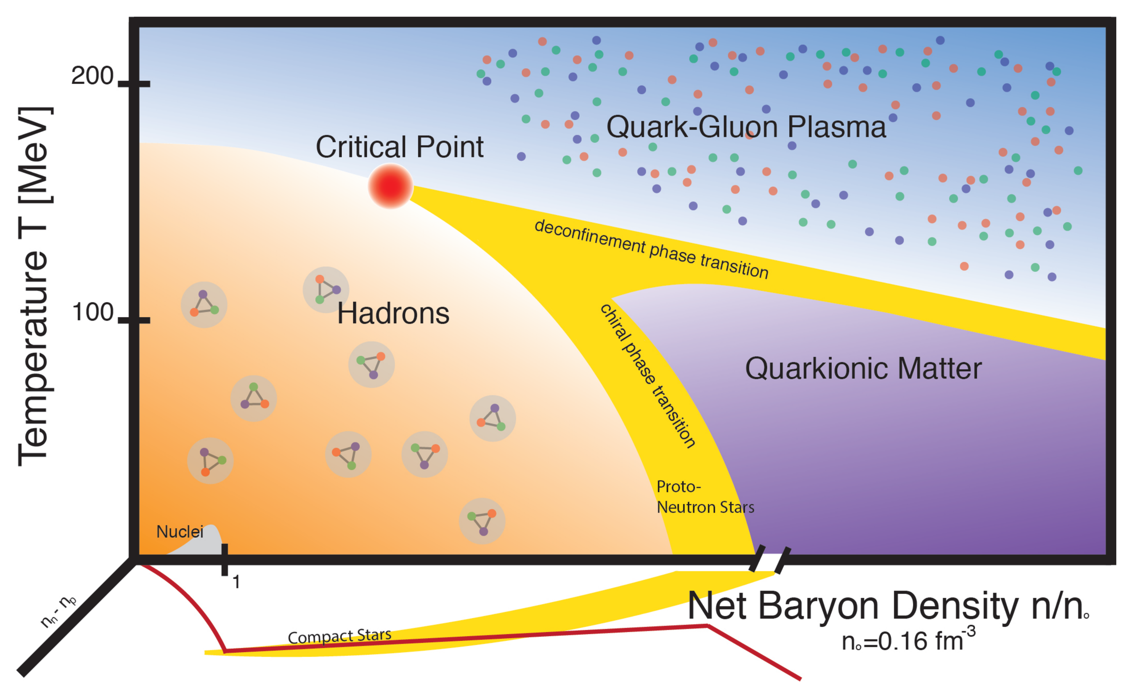

Figure 5: From lattice simulations, a cross-over phase transition exists at a high temperature. If a first order transition can be deduced from astrophysical observations of high-mass compact stars, the existence of the critical end-point will be confirmed. [4]

Results

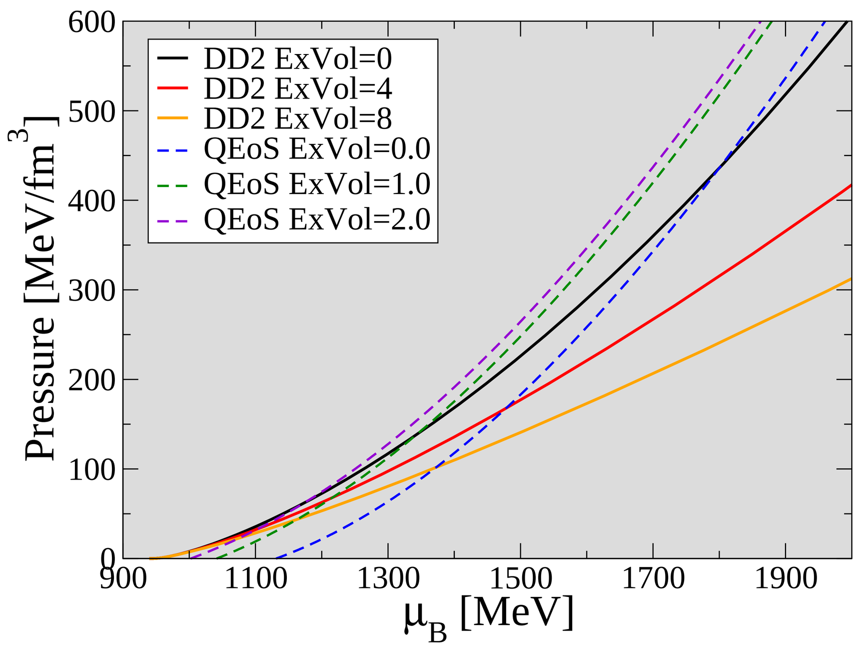

Figure 6: Hadronic phase with increasing excluded-volumes, pressure versus baryon chemical potential, crossed with quark-matter phase varying excluded-volume parameter. The crossing point represents the deconfinement phase transition from nuclear matter to quark matter.

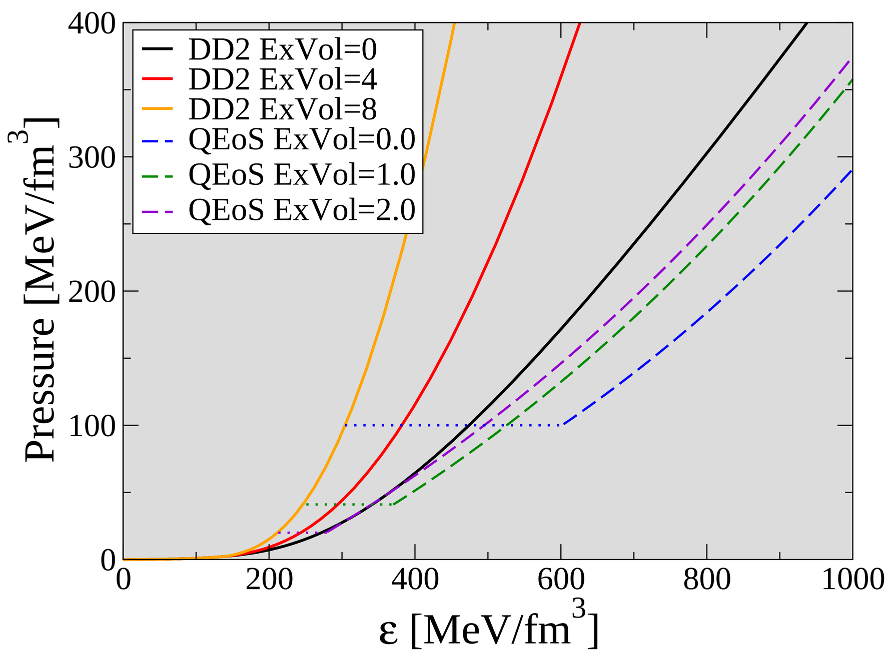

Figure 7: Hadronic phase with increasing excluded-volumes, pressure versus energy density, for the same parameters. The dashed lines connecting the DD2 ExVol=8 line with the quark lines represent the jump in energy density at the deconfinement phase transition from nuclear matter to quark matter.

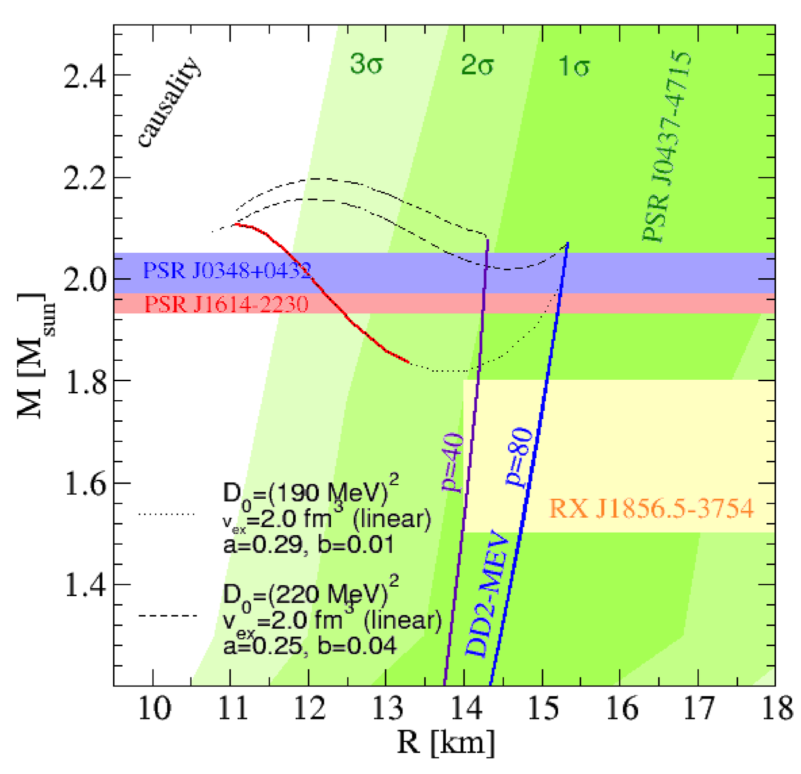

Figure 8: Mass-Radius plots for different parameterized equations of state, exhibiting a stable third family of compact stars with significant differences in radii in the high-mass region. If observable, the strong, first-order phase transition will prove the existence of the CEP.

References

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