Quantum van der Waals Quarkyonic Matter at Non-zero Isospin Asymmetry

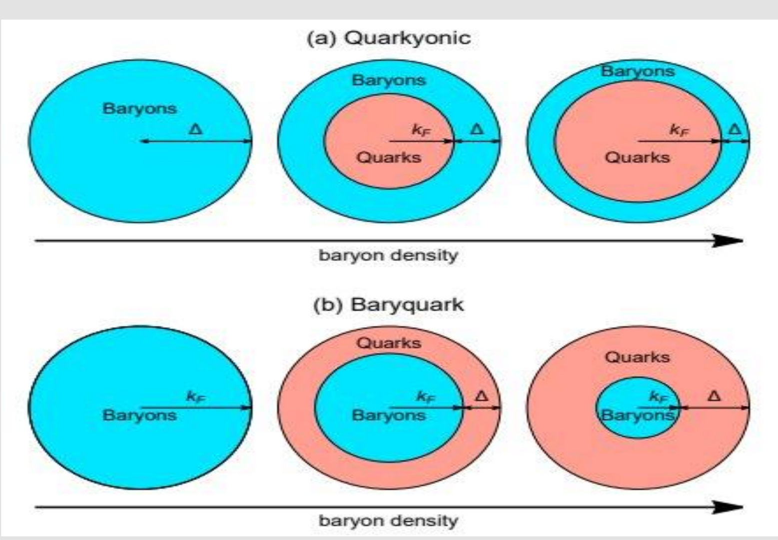
Max L. Moss, Volodymyr Vovchenko, and Roman Poberezhniuk
The University of Houston
mlmoss2@cougarnet.uh.edu

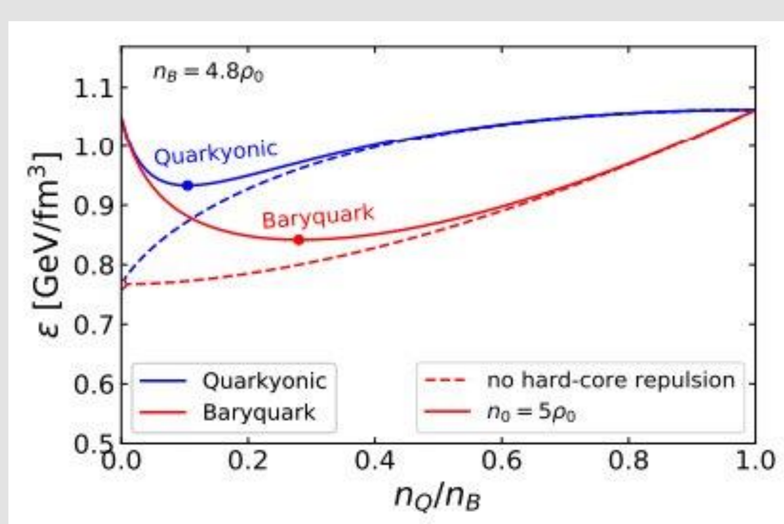
Abstract

Quarkyonic matter is a possible realization of dense QCD matter, corresponding to a mixture of hadrons and quarks with a mixed phase in momentum space. Recently, the quantum van der Waals theory of quarkyonic matter was developed [Phys. Rev. C 108 (2023) 045202], indicating that quarkyonic regime in symmetric nuclear matter may occur at densities as low as twice the saturation density, achievable in heavy-ion collisions. Here, we extend the framework to non-zero isospin asymmetries by utilizing the two-component van der Waals equation and separate Fermi surfaces for ***u*** and ***d*** quarks. We utilize constraints on the symmetry energy and its slope to fix the isospin dependence of the van der Waals interaction parameters. We also outline the extension to finite temperatures, which will allow direct applications of the proposed framework to heavy-ion collisions.

Motivation

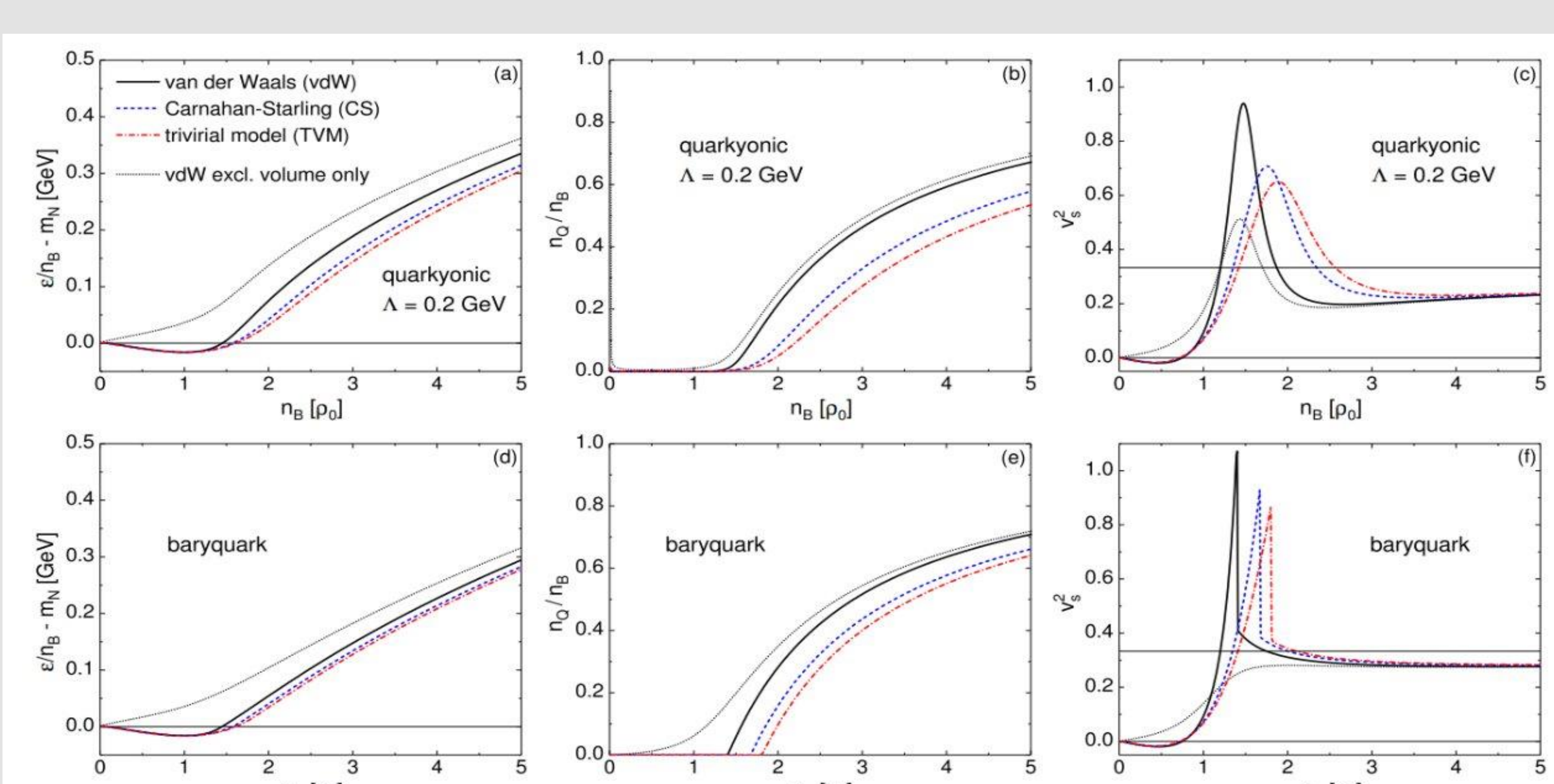
- Quarkyonic matter features a sea of noninteracting quarks occupying low-momentum states and a nucleonic shell of hadrons at high-momentum. Baryquark matter exhibits the opposite momentum-shell structure
- Deconfined quarks Pauli-block the corresponding hadronic states
- The proper configuration of the system is found by minimizing energy density
- Deconfined quark states emerge dynamically at high densities due to nucleon-nucleon interactions [1][2]





Applications to Isospin Symmetric Matter at Zero Temperature

- This framework has been applied to symmetric nuclear matter, and various thermodynamic quantities were calculated
- The system exhibits a rapidly stiffening EoS which is then softened by the onset of free quarks
- Quarkyonic matter features a sudden appearance of quarks, which causes a discontinuous speed of sound. This can be smoothed out by including an infrared regulator
- Nucleonic interactions are included via quantum van der Waals theory, utilizing excluded volume formalisms of van der Waals, Carnahan-Starling, and the Trivirial Model
- These interactions are parameterized by matching ground-state properties of symmetric nuclear matter [3][4]



$$n_p = (1 - b_n n_p - b_{pn} n_n) n_p^{\rm id}$$
$$n_n = (1 - b_{pn} n_p - b_n n_n) n_n^{\rm id}$$

$$\varepsilon_N = \sum_{i \in p,n} f_{\rm vdW}(x_i)\varepsilon_i^{\rm id} - a_n(n_p^2 + n_n^2) - 2a_{pn} n_p n_n$$

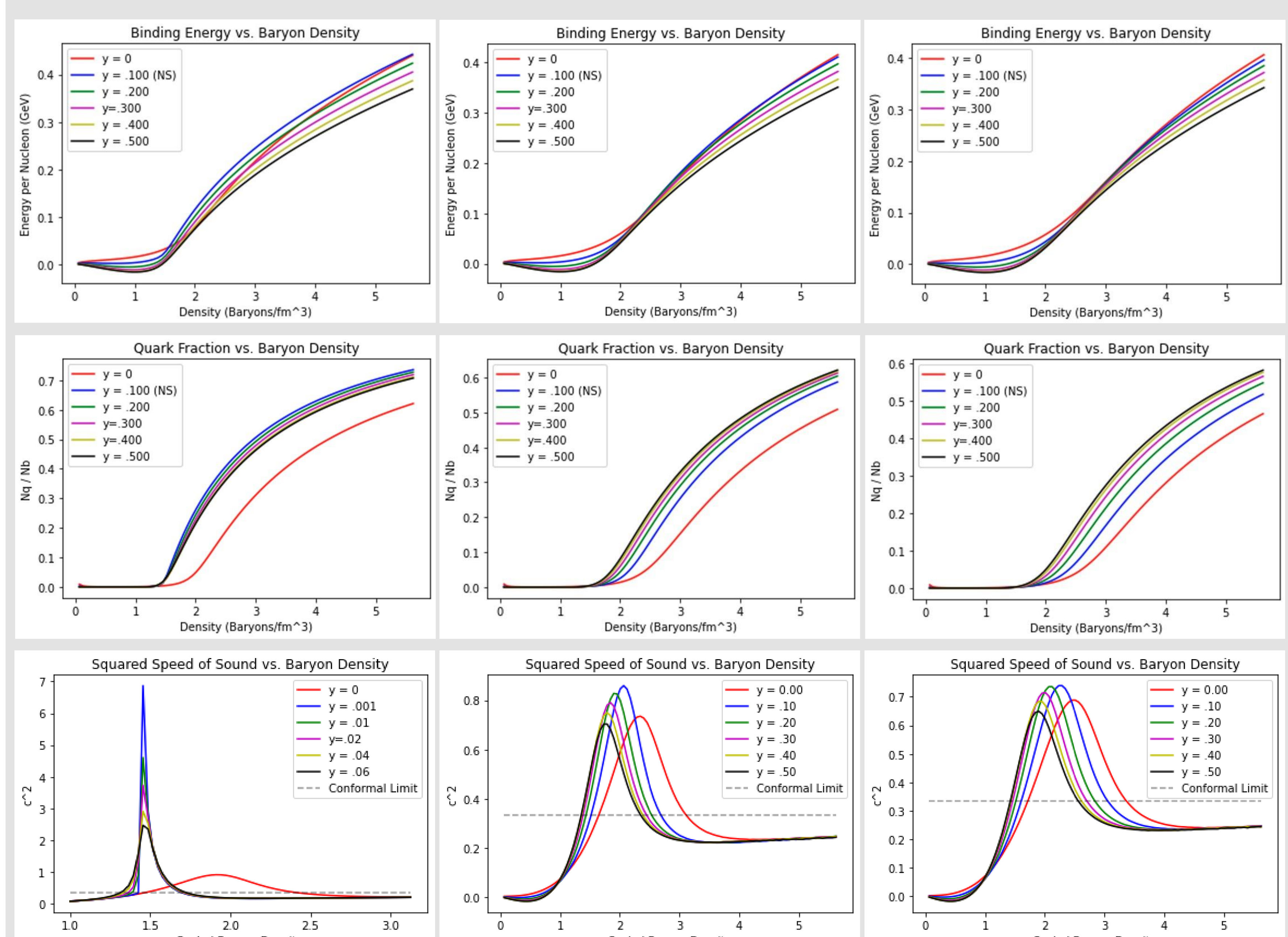
Extension to Isospin Asymmetric Nuclear Matter at Zero Temperature

- For symmetric matter, the van der Waals interaction terms reduce to a simple one-component model
- For asymmetric matter, we must consider both ***n-n*** and ***n-p*** interactions. We constrain these free parameters via nuclear ground state properties, symmetry energy, and slope of the symmetry energy
- Fermi surfaces for ***u*** and ***d*** quarks are chosen to match the charge fraction of the nucleonic sector and to produce uniform charge distribution in momentum-space
- vdW-EV features an acausal speed of sound at transition densities which is not present in other excluded-volume formulations. Model predictions are shown below for van der Waals (left), Carnahan-Starling (middle), and Trivirial Model (right) excluded-volume
- Current model predictions have been calculated only within the quarkyonic matter framework. Comparison to baryquark matter is reserved for future work

$$\frac{\frac{2}{3}n_u - \frac{1}{3}n_d}{\frac{1}{3}n_u + \frac{1}{3}n_d} = y,$$

$$n_u = \frac{1+y}{2-y}\frac{g}{2\pi^2}\int_0^{k_{\rm bu}/N_c} q\sqrt{q^2+\Lambda^2}\,dq$$
$$n_d = \frac{g}{2\pi^2}\int_0^{k_{\rm bu}/N_c} q\sqrt{q^2+\Lambda^2}\,dq.$$

Van der Waals ***Carnahan-Starling*** ***Trivirial Model***



Future Work

- Incorporate leptonic states, charge neutrality, and beta-decay equilibrium
- Use EoS as input to Tolman-Oppenheimer-Volkoff equation to calculate neutron star mass-to-radius ratios
- Extend to finite temperature with proper treatment of energy, entropy, and boundary conditions
- Include hypernuclei/strange quark states with appropriate interactions

References

[1] Y. Fujimoto, T. Kojo, L. McLerran: "Momentum Shell in Quarkyonic Matter from Explicit Duality: A Dual Model for Cold, Dense QCD" *Phys. Rev. Lett. 132 112701 (2024)*
[2] V. Koch, V. Vovchenko: "Quarkyonic or baryquark matter? On the dynamical generation of momentum space shell structure" *Phys. Lett. B, Vol. 841, 137942 (2023)*
[3] V. Vovchenko "Hadron resonance gas with van der Waals interactions" *International Journal of Modern Physics E, Vol. 29, No. 05, 2040002 (2020)*
[4] R. Poberezhniuk, H. Stoecker, V. Vovchenko "Quantum van der Waals theory meets quarkyonic matter" *Phys. Rev. C 108, 045202 (2023)*