Role of isospin asymmetry in the onset of quark matter in neutron stars

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Abstract:

While symmetric nuclear matter has been studied in laboratories, neutron star matter is characterized by high asymmetry. Therefore, by examining the strongly interacting matter properties in a wide range of densities and isospin asymmetries we confront two regimes to understand how the enforced electric neutrality and beta equilibrium alter the onset density of quark matter. Particularly, we demonstrate the dependence of the onset density of deconfined quarks in the electrically neutral beta-equilibrated matter on the onset density for symmetric matter. This allows us to map the phase diagram of cold strongly interacting matter in the plane of baryon density vs isospin asymmetry which is important in modeling hybrid stars based on the nuclear and low-energy heavy-ion collision experiments.

I. Introduction

- Terrestrial experiments on nuclear matter provide knowledge/intuition at density near n_{sat}
  - Shape of thermodynamic quantities is roughly known
  - Intuition about saturation density is formulated
    - In particular, quark onset is suspected at much higher density
- It is tempting to apply this intuition to neutron stars (unearthly conditions)
  - But intuition may be misleading..
- AIM OF THE RESEARCH:
  - *(A) to demonstrate that the quark onset density within neutron stars may be significantly smaller than expected earlier*
  - *(B) to connect matter's isospin asymmetry with the quark onset density*

Isospin asymmetry: disbalance between np/ud

Hadronic matter (npe) Quark matter (ude)

$$I = \frac{n_n - n_p}{n_B} \qquad I = \frac{n_d - n_u}{n_B}$$

- Nuclei : symmetric matter $n_n \approx n_p$, $I \approx 0$
- NSs : asymmetric matter $n_n > n_p$; $n_d > n_u \Rightarrow I > 0$

- Isospin asymmetry induces repulsion
  - Quark onset easier to reach?

II. Equation of state

For our purposes, we use a hybrid (hadron+quark) EoS:

Hadronic EoS: MetaModel [1]

Empirical, bases on Weizsacker formula

$$\varepsilon(n_p, n_n, n_e) = \left[\epsilon_0 + \frac{K_0}{2}x^2\right] n_B + I^2\left[J + Lx\right] n_B + \epsilon_{id}(n_e),$$

where $x = \frac{n_B - n_{sat}}{3n_{sat}}$, ϵ_0, K_0, J, L are nuclear properties at saturation.

L is fixed at 70 MeV

K_0 is fixed at 240 MeV

Quark EoS: Relativistic Density Functional (RDF) [2]

Chiral quark model of the NJL-type $(ud + e)$ with vector repulsion and diquark pairing, controlled by corresponding dimensionless couplings (η_V, η_D).

- Vector coupling $M_\omega = 782\text{MeV} \Rightarrow \eta_V = 0.452$
- Diquark coupling $\eta_D \leq 0.78$ to forbid color superconductivity in vacuum

These equations of state then get connected through Maxwell construction.

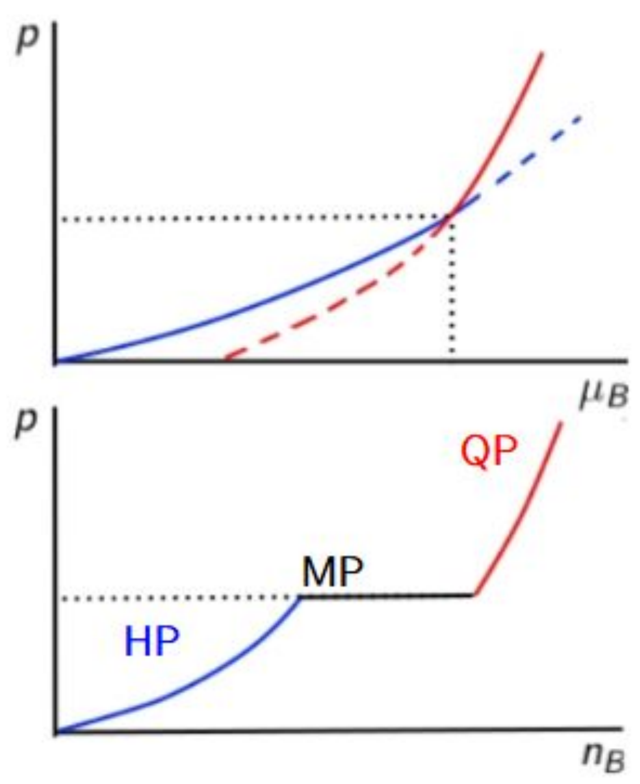
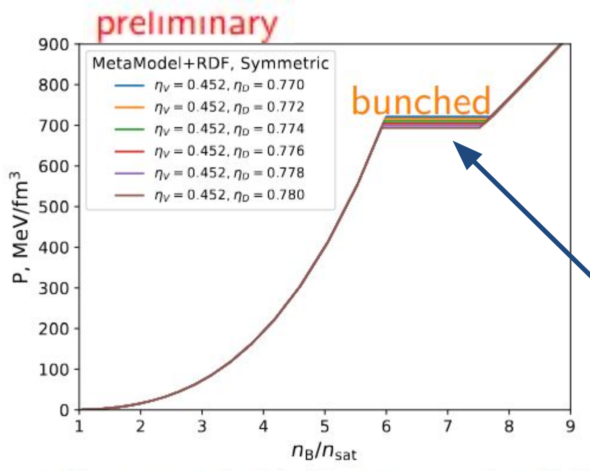


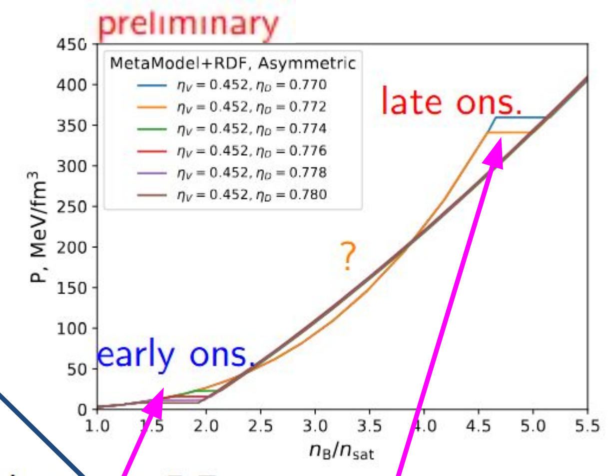
Figure: Sample Maxwell construction in P/μ and P/n planes

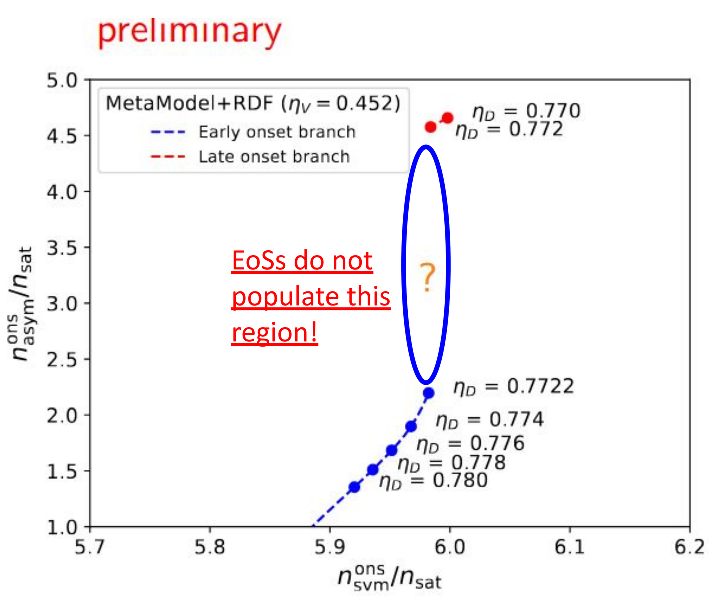
III. Results & Discussion

1. *(A)*

- We compose equations of state with Metamodel + RDF, described above
- Per each η_D from our selection, we construct symmetric and neutral β-equilibrated EoSs
- Hybrid EoSs are then built with Maxwell construction







- Symmetric EoSs vary only slightly, with $n_{ons} \approx 5.7 n_{sat}$
- Asymmetric $n_{QP}^{ons} - n_{HP}^{ons}$ are small $\Rightarrow$ 2nd order PT occurs at some $\eta_D \Rightarrow$ EoSs split into two categories, with early $\sim 2n_{sat}$ and late $\sim 4.5 n_{sat}$ onsets

- Early onset branch : supports $n_{sym}^{ons} \gg n_{asym}^{ons}$
  - Extrapolating symmetric properties into asymmetric realm may be misleading.
- **Speculation:** iscontinuity in onsets of asymmetric quark matter implies change in topology of the phase diagram w.r.t. diquark coupling?

2. *(B)*

- We construct phase diagrams for fixed η_D(from early/late onset branches)
  - Construct EoSs on isospin asymmetry grid + Maxwell construct them

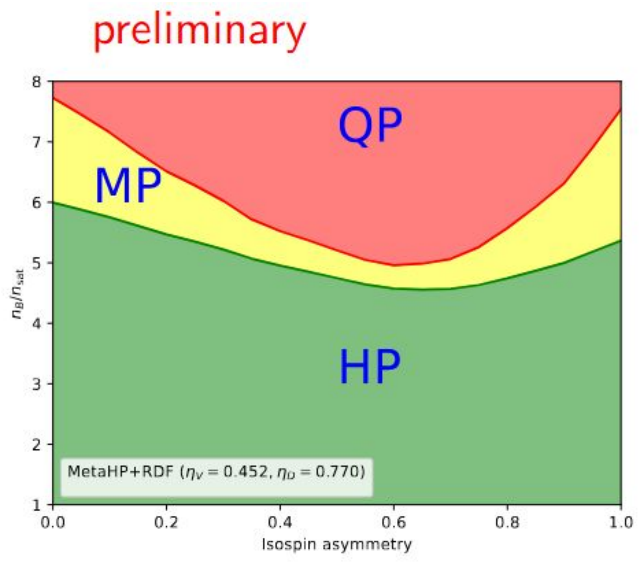


Figure: PD for EoS with $\eta_D = 0.770$ (late onset branch).

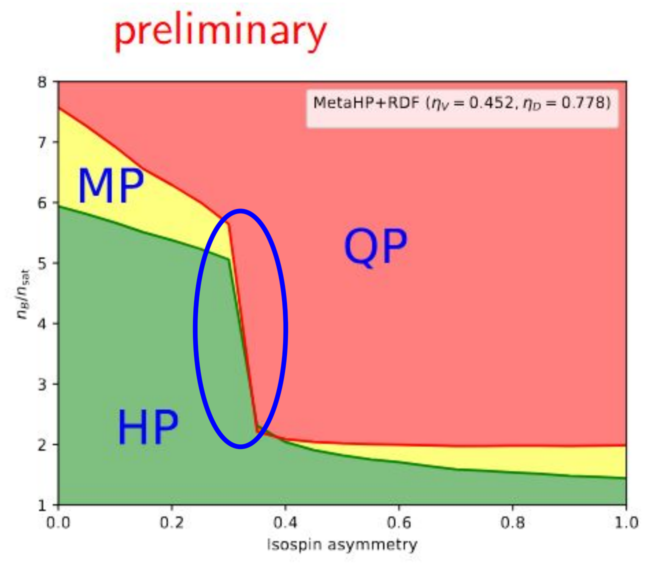


Figure: PD for EoS with $\eta_D = 0.778$ (early onset branch).

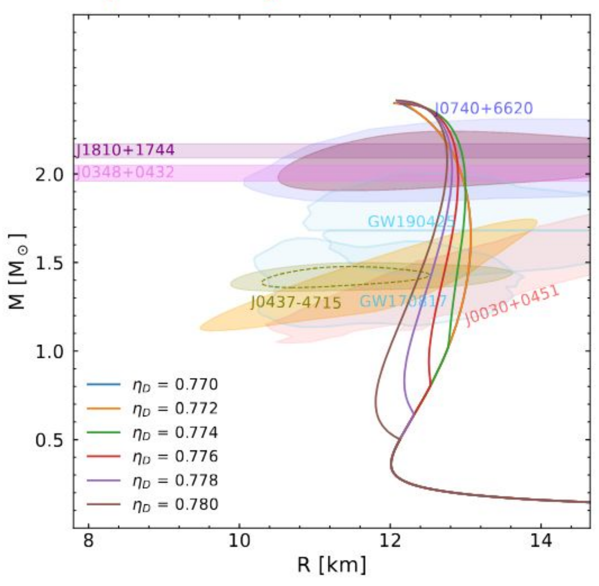


Figure: Asymmetric neutral MetaHP-RDF ($\eta_V = 0.452$, η_D) against astrophysics constraints.

- Two PD types emerge
  - Onset density at high asymmetry differs dramatically
  - Early-onset-type PD exhibits a jump in n-I plane
- Project EoSs of early/late type onto M-R diagram
  - Late onsets exceed TOV density!

IV. Summary

- The quark onset density of electrically neutral matter at beta equilibrium may exhibit significantly lower than in the symmetric case
- Phase diagram of cold quark-hadron matter strongly depends on isospin asymmetry
- The late onset branch model manifests incompatible with emergency of quark branch on mass-radius diagram of neutron stars

V. Future prospects

- Are the two types of PDs described exclusive?
- Can any of the two types be excluded from observations?

VI. References

1. J. Margueron, R. Hoffmann Casali, F. Gulminelli. The equation of state for dense nucleonic matter from a metamodeling. Phys. Rev. C 97, 025806 (2018).
2. Oleksii Ivanytskyi and David Blaschke. Density functional approach to quark matter with confinement and color superconductivity. Phys. Rev. D, 105(11):114042, 2022.
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