2nd Workshop on modern equations of state and spectroscopy in neutron-star matter

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

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Outline

1. Introduction
2. Equation of state
3. The calculations

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The problem

- Terrestrial experiments on nuclear matter provide knowledge at density near $n_{\text{sat}} = 0.15\text{fm}^{-3}$
  - Rough shape of energy density, pressure etc is known
  - Certain intuition around n_{sat} is formulated
  - In particular, we suspect that quarks only emerge at much higher density
- It is tempting to apply the same intuition to neutron stars (unearthly conditions)
  - But the intuition might be severely misleading

Aim of the talk :

1. to demonstrate that the quark onset density within neutron stars may strongly deviate from earthly expectations
2. to connect matter's isospin asymmetry with the quark onset density.

Symmetric and asymmetric matter

The deviation between neutron stars (NSs) and nuclei (beside typical densities) lies in their isospin asymmetry.

Hadronic matter (npe)

$$I = \frac{n_n - n_p}{n_B}$$

Quark matter (ude)

$$I = \frac{n_d - n_u}{n_B}$$

- 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 between n, p and $u, d \Rightarrow$
  - quark onset is easier to reach?

Phase diagram of cold matter

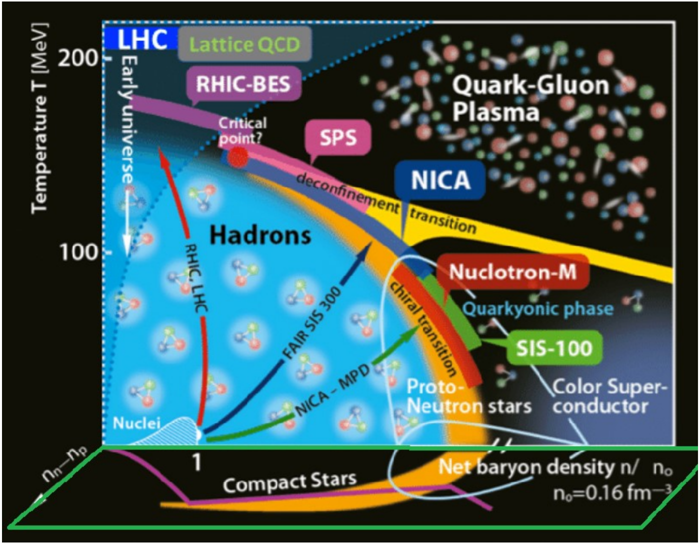

Figure: A schematic of QCD phase diagram.

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Equation of state in use

To describe onset properties we need hybrid EoS.

Hadronic EoS: MetaModel
[Margueron, Hoffmanm et al. 2017]

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.

Quark EoS: Relativistic Density Functional
[Ivanytskyi, Blaschke 2022]

Chiral quark model of the NJL-type $(ud + e)$ with vector repulsion and diquark attraction, 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 are supplied with demand for beta equilibrium and charge neutrality.

Matching scheme

Maxwell construction (bridge between hadronic (HP) and quark phases (QP)) ensures mechanical and baryon chemical equilibrium on the phase boundary

$$P_H(\mu_{HP}^{ons}) = P_Q(\mu_{QP}^{ons})$$
$$\mu_{HP}^{ons} = \mu_{QP}^{ons}$$

This type of matching ensures nonzero density jump $n_{QP}^{ons} - n_{HP}^{ons}$, which corresponds to slope difference in P/μ plane.

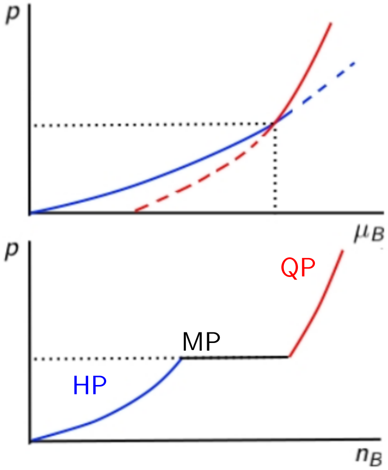

Figure: Sample Maxwell construction in P/μ and P/n planes

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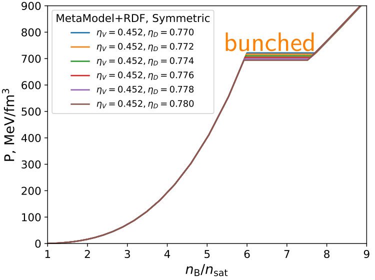
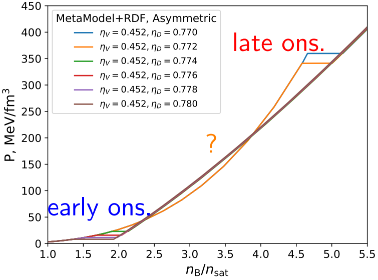
Matched MetaModel-RDF

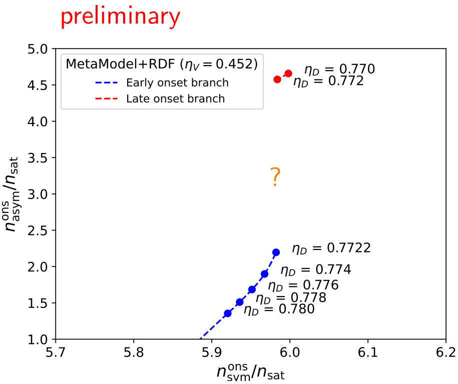
- Metamodel is fixed at slope $L = 70$ MeV, $K_0 = 240$ MeV
- (η_V, η_D) range selected to cover multiple opportunities for quark onset in NS
- Beta equilibrium, charge neutrality are enforced





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

Symmetric vs Asymmetric onsets



Density onsets in symmetric vs asymmetric MetaModel and RDF with fixed parametrization.

- Early onset branch : $n^{ons}_{sym} \gg n^{ons}_{asym}$
  - Extrapolating symmetric estimates to asymmetric realm may be misleading.
- Late onset branch : onsets are comparably close, opposite to the point made!
  - How are these branches different?
  - η_D population fails between branches, leaves gap in n^{ons}_{asym} $\Rightarrow$ PT-like structure emergent?

Panasiuk et al. 2025 (in prep)

Phase diagram of cold quark-hadron matter

To uncover more detail about asymmetric branches

- Fix specific η_D
- Fix a selection of asymmetries (instead of charge neutrality)
- Construct phase diagram in $I - n_B$

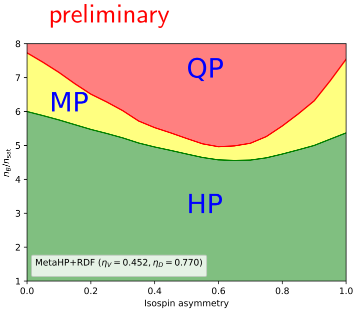


Figure: PD for EoS with $\eta_D = 0.770$ (late onset branch).

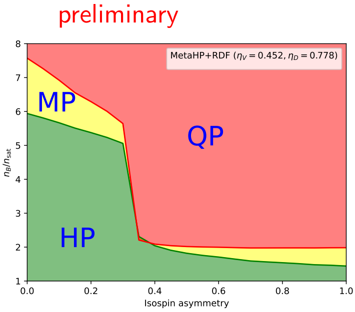


Figure: PD for EoS with $\eta_D = 0.778$ (early onset branch).

Panasiuk et al. 2025 (in prep)

Astrophysics constraints applied

preliminary

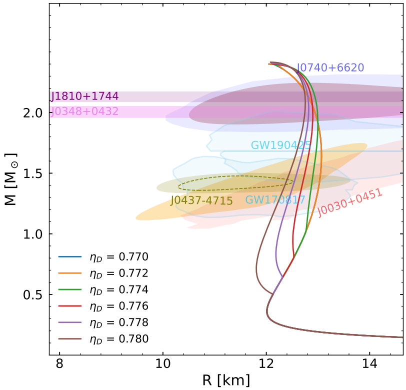


Figure: Asymmetric neutral MetaHP-RDF ($\eta_V = 0.452$, η_D) against astrophysics constraints.

An interesting question is if both low and late onset branches are compatible with known constraints.

- All the late onset models have their deconfinement emergence in the instable TOV region (see Fig.) $\Rightarrow$ they can be excluded
  - The considered EoSs only support early onset branch
  - However, is this a generic feature of late onset models? I.e. do they (not) exist in nature?

Panasiuk et al. 2025 (in prep)

Conclusions

- 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

Backup : Stability of RDF

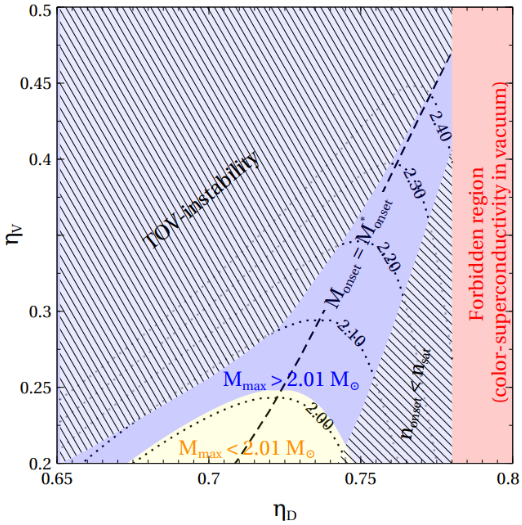


Figure: Credits: Gartlein et al 2023

Backup: RDF phases

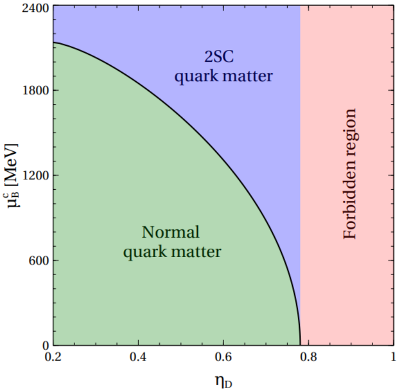


FIG. 5: Baryonic chemical potential of the 2SC phase onset μ_B^c as a function of the scaled diquark coupling η_D. The calculations are performed for symmetric quark matter and $\eta_V = 0$.

Figure: Credits: Ivanitskyi, Blaschke 2022