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. Outcomes

Outline

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 establish a relation between symmetric and asymmetric onset densities, supported by constraints

Symmetric and asymmetric matter

The difference between neutron star matter and earthly nuclear matter lies in their typical isospin asymmetry $I = \frac{n_I}{n_B}$.

- $\Rightarrow$ Nuclei : symmetric matter $n_n \approx n_p \Rightarrow I \approx 0$
- $\Rightarrow$ NSs : highly asymmetric matter $n_n \gg n_p \Rightarrow I \gg 0$ (usually $I \approx 0.8$)

Isospin asymmetry induces repulsion between n, p

- $\Rightarrow$ quark onset is easier to reach?

Outline

Equation of state in use

To describe onset properties we need hybrid EoS.

Hadronic EoS: DDTCY
[Courtesy of S. Typel]

Relativistic mean-field description with nucleons and hyperons, with scalar attraction and vector repulsion employed. Marginally fits into flow constraint [Danielewicz et. al 2002], but does not describe $2M_\odot$ NSs.

Quark EoS: 3F nonlocal NJL
[O. Ivanytskyi, 2025]

Nambu-Jona-Lasinio model with nonlocal current-current interactions in scalar, vector and diquark channels, with latter controlled by corresponding dimensionless couplings (η_V, η_D).

- $\Rightarrow$ (η_V, η_D) priorly serve as free parameters
- $\Rightarrow$ *uds* particle content

For neutron star matter, charge neutrality and β-equilibrium is imposed.

Matching scheme 1

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

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

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

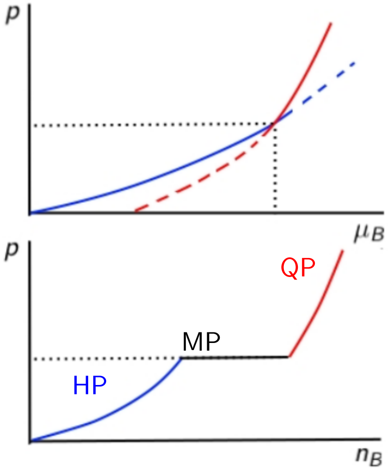

Figure: Sample Maxwell construction in P/μ and P/n planes

Matching scheme 2

Procedure:

- ⇒ EoS matching for a uniform grid of couplings

  $$(\eta_V, \eta_D) \in [0.00, 1.00] \times [0.12, 0.5];$$

- ⇒ Seek Maxwell crossings;
- ⇒ Only keep models which have Maxwell crossings in symmetric and neutron star EoS simultaneously.

Limitations:

- ⇒ Only 1st order PT is considered;
- ⇒ Cases, where crossings only exist in symmetric or neutron star EoS, are discarded.

This restriction defines the (η_V, η_D) sample space.

Outline

Coupling space

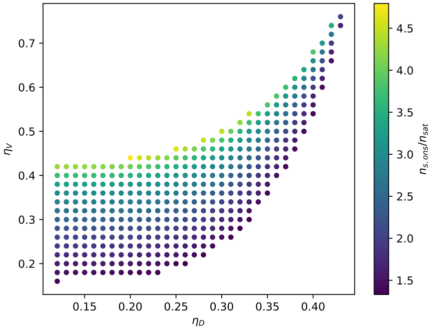

Figure: (η_V, η_D) space vs quark onset density in symmetric matter.

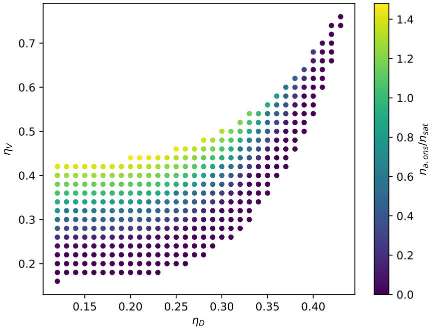

Figure: (η_V, η_D) space vs quark onset density in neutron star matter.

$\Rightarrow$ Asymmetric onset densities appear much lower (factor of 3?)

$\Rightarrow$ Symmetric onset densities reach $4.5 n_{sat} \rightarrow$ available experiments not violated

Onset space

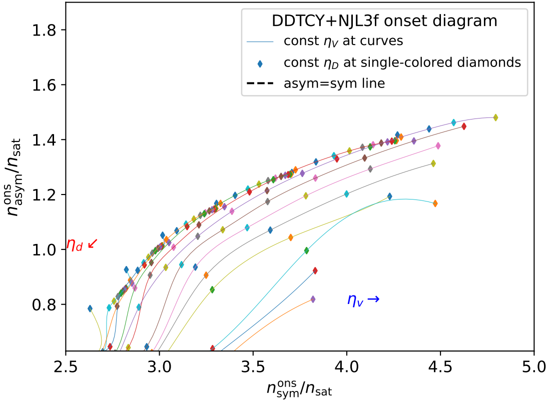

Figure: (η_V, η_D) mapping to $(n^{ons}_{asym}, n^{ons}_{sym})$ variables.

⇒ $n_{asym} - n_{sym}$ relation is evidently strongly capped

- → Support for "early" deconfinement in neutron stars.

⇒ Below $1n_{sat}$ is reachable in neutron stars, while maintaining $\sim 4n_{sat}$ in symmetric matter

- → n_{sat} does not carry the same intuition in neutron stars

Astrophysical sector

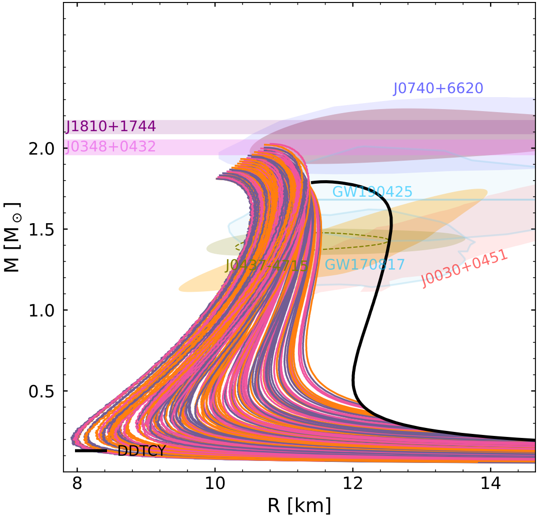

Figure: TOV solutions for DDTCY-NJL3f.

We run the EoS sample space through TOV equations to compare against astro constraints. Evidently, elimination with Bayesian analysis is possible. We apply

- ⇒ NICER constraints, J0740+6620 in particular;
- ⇒ GW170817 tidal deformability.

At the same time, flow constraint is marginally maintained for symmetric EoS.

Credible couplings

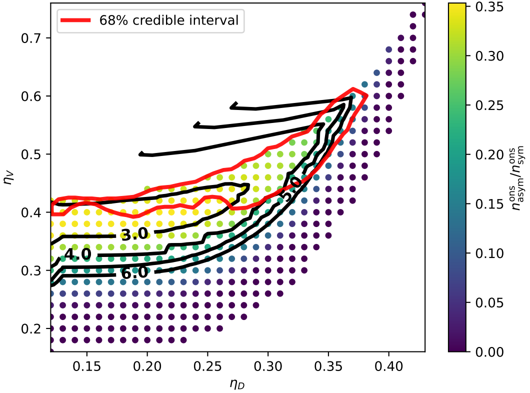

Figure: Coupling diagram with 1σ credible region (credits to A. Ayriyan). Levels indicate onset ratio.

- $\Rightarrow$ Significant elimination achieved
- $\Rightarrow$ Bayesian analysis supports $\frac{n_{sym}}{n_{asym}} \in (3, 6)$

Conclusions

- ⇒ The quark onset density of electrically neutral matter at beta equilibrium may exhibit significantly lower than in the symmetric case.
- ⇒ Bayesian analysis suggests relation between symmetric and asymmetric onset densities starting from 3, which elucidates the distinction between heavy ion and neutron star regimes.
- ⇒ Notably, the analysis does not disfavor asymmetric onset densities below 1 n_{sat}.

Backup : Flow constraint

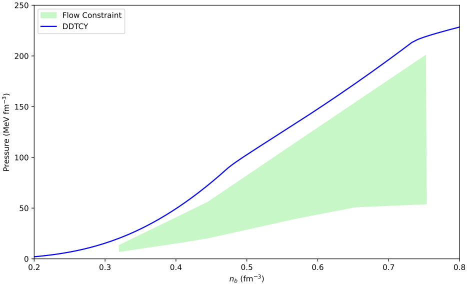

Figure: Symmetric DDTCY vs flow constraint band.

Backup : Onset constraint

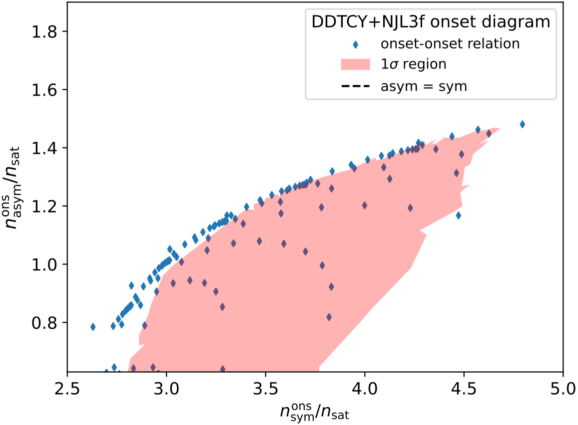

Figure: Onset space with 68% CL from BA.