WE Heraeus Physics School and 62 Karpacz Winter School in Theoretical Physics

Role of isospin asymmetry in the onset of quark matter

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Outline

1. Introduction

2. Equation of state

3. Outcomes

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The problem

- ⇒ Terrestrial experiments with finite-size, almost isospin-symmetric nuclear matter (atomic nuclei) provide knowledge at densities near $n_{\mathrm{sat}} = 0.15\mathrm{fm}^{-3}$
  - → 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 onset density of quark deconfinement 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 $I = \dfrac{n_I}{n_B}$.

$\Rightarrow$ Nuclei : symmetric matter $n_n \approx n_p \Rightarrow I \approx 0$

$\Rightarrow$ NSs : highly asymmetric matter $n_n \gg n_p \Rightarrow I > 0$

Isospin asymmetry increases the energy cost of n and p

$\Rightarrow$ quark onset is easier to reach?

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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], maximum mass of NSs barely reaches $2M_{\odot}$.

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

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

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

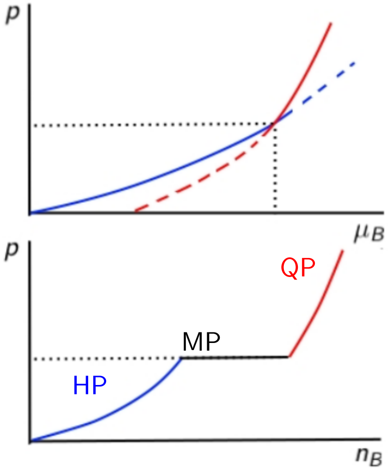

Figure: Sample Maxwell construction in P vs μ and P vs n planes

Matching scheme 2

Procedure:

- $\Rightarrow$ EoS matching for a uniform grid of couplings

  $$(\eta_V, \eta_D) \in [0.10, 1.00] \times [0.12, 0.50];$$

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

Limitations:

- $\Rightarrow$ Only 1st order PT is considered;
- $\Rightarrow$ Only consider crossings that exist in symmetric or neutron star EoS simultaneously.

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

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Coupling space

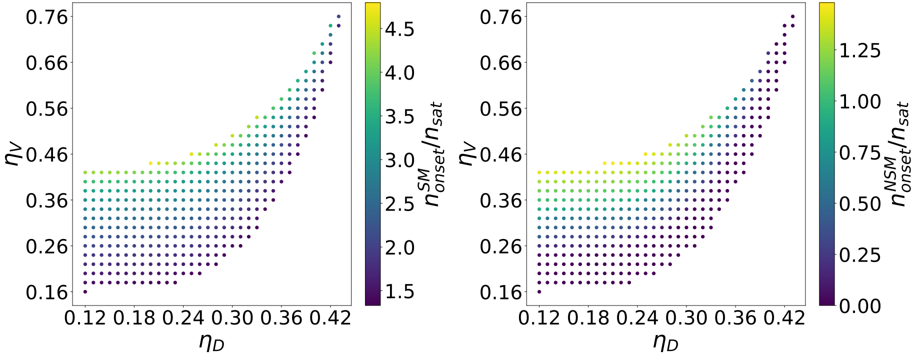


Figure: (η_V, η_D) space vs quark onset density in symmetric (left) and NS (right) matter.

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

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

Astrophysical sector

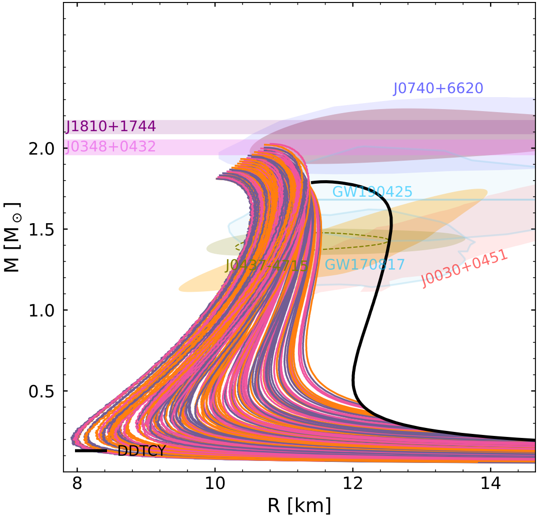


Figure: TOV solutions for DDTCY-NJL3f.

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.

Onset space

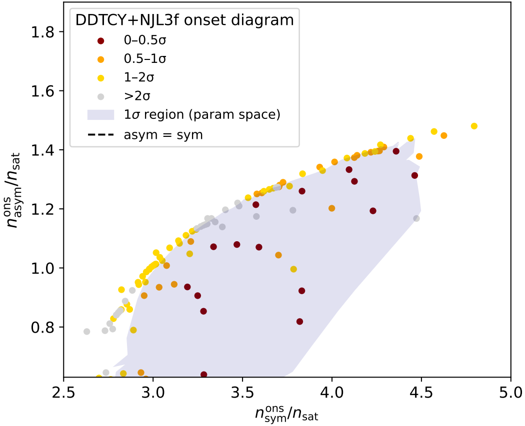
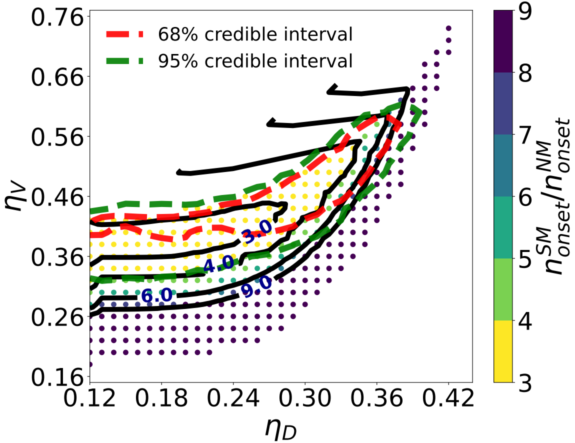


Figure: (η_V, η_D) EoS ensemble mapped onto $(n_{asym}^{ons}, n_{sym}^{ons})$ variables.

- $\Rightarrow$ $n_{asym} - n_{sym}$ relation is evidently strongly capped
  - $\rightarrow$ Support for "early" deconfinement in neutron stars.
- $\Rightarrow$ Below $1 n_{sat}$ is reachable in neutron stars, while maintaining $\sim 4 n_{sat}$ in symmetric matter
  - $\rightarrow$ n_{sat} does not carry the same intuition in neutron stars
- $\Rightarrow$ $(\eta_V, \eta_D) \rightarrow (n_{asym}^{ons}, n_{sym}^{ons})$ map is practically degenerate for low η_V

Credible couplings



$\Rightarrow$ Significant elimination achieved

$\Rightarrow$ Bayesian analysis supports $\frac{n_{sym}}{n_{asym}} \simeq (3, 6)$

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

But why? in words

- Significant onset ratio may seem counterintuitive..
  - We developed a toy model to show its origins
  - For simplicity, compare pure neutron matter with symmetric matter
- Model : Fermi gas with linear repulsion, nucleon mass running and symmetry energy
- Onset criterion : $\mu_N = 3m_q$ (kinematic requirement)

- Ideal Fermi gas $\dfrac{n_{\mathrm{SM}}}{n_{\mathrm{PNM}}} = \dfrac{d_{\mathrm{SM}}}{d_{\mathrm{PNM}}} = \dfrac{4}{2}$
  - Reason : SM has twice as many Fermi spheres to fill!
- Ratio above 2?
  - Symmetry energy relaxes kinematic requirement
  - Drop in nucleon mass increases spacing between solutions

$$n_{\mathrm{onset}} = \frac{d}{6\pi^2}\left[\left(3m_q - (\mu_0 - E_0)\frac{n_N}{n_0} - I^2\frac{\partial\varepsilon_{\mathrm{sym}}}{\partial n_N}\right)^2 - M_N^2\right]^{\frac{3}{2}}_{n_{\mathrm{onset}}}$$

d – degeneracy factor; m_q – quark constituent mass; $\mu_0 = 923$ MeV

But why? in plots

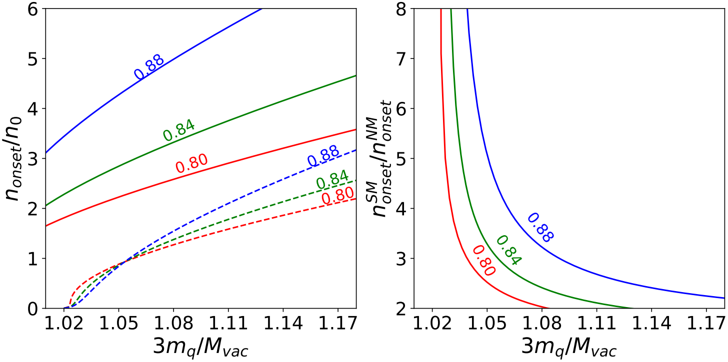


Figure: Left panel : toy model onset values for SM (solid) and PNM (dashed). Right panel : SM/PNM onset ratio.

Both are plotted against rescaled quark mass, $M_{\rm vac} \equiv M_N(0) = 939$ MeV.

Number above lines indicates $\dfrac{M_N(n_0)}{M_{\rm vac}}$.

Conclusions

- ⇒ The quark onset density of electrically neutral matter at β-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

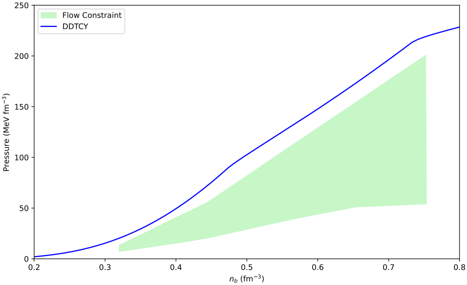


Figure: Symmetric DDTCY vs flow constraint band.

Backup : Onset space const lines

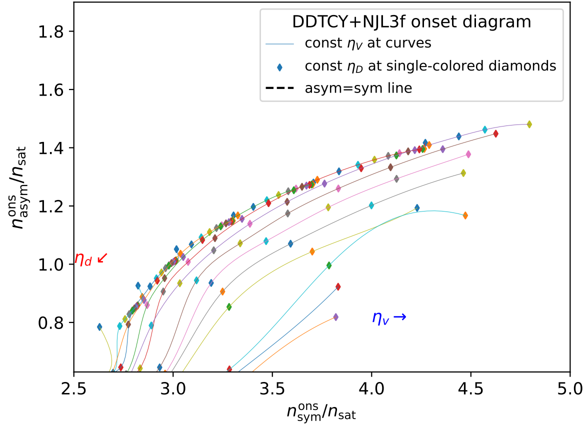


Figure: Onset space with level lines.