

Exploring Composition of Neutron Star Matter with Astrophysical Observations

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Phys. Rev. D **108**, 103045 (2023), arXiv:2307.12364 [nucl-th]

1st TEONGRAV international workshop on theory of gravitational waves,
September 16-20, 2024, Sapienza University of Rome



Outline

- A very brief introduction to neutron stars (NSs)
- Description of nuclear matter
- Models specific to this work and the constraints used
- Results
- Summary

Structure of a Neutron Star

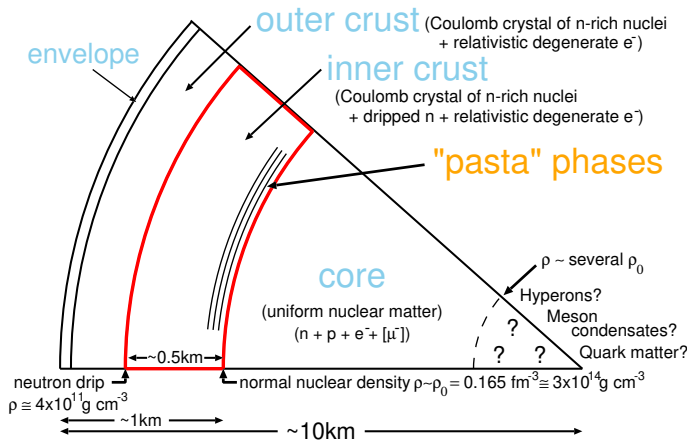
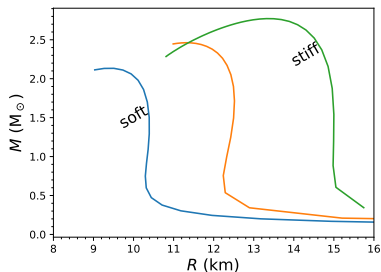
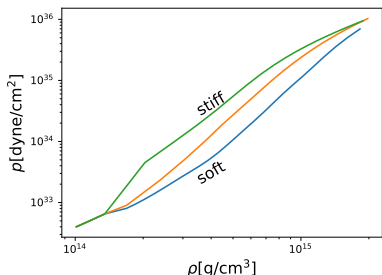


Figure: Schematic picture of a NS Interior

Equation of State and Mass-Radius

$$P = P(\rho)$$

$$M = M(R)$$



One to one correspondence between Equation of State (EOS) and mass-radius

NS Observations that an EOS must satisfy

- Precise mass-measurement of massive NSs:
 - (1.908 ± 0.016) M_{\odot} Arzoumanian et al, ApJS 235, 37 (2018).
 - (2.01 ± 0.04) M_{\odot} Antoniadis et al, Science 340, 448 (2013).
 - (2.08 ± 0.07) M_{\odot} E. Fonseca et al, ApJL 915 L12 (2021).
- BNS merger event GW170817 provides bounds on tidal deformability (Λ), and pressure at $2\rho_0$; Abbott et al, PRL 121, 161101 (2018):
 - $\Lambda_{1.4} = 190_{-120}^{+390} \Rightarrow \Lambda_{1.4} \leq 580, P(2\rho_0) = 3.5_{-1.7}^{+2.7} \times 10^{34} \text{ dyn/cm}^2$
- NICER collaboration provided:
 - 1) Simultaneous mass-radius measurements of PSR J0030+0451
 - $M = 1.34_{-0.16}^{+0.15} M_{\odot}, R = 12.71_{-1.19}^{+1.14} \text{ km}$ Riley et al, ApJL, 887, L21 (2019).
 - $M = 1.44_{-0.14}^{+0.15} M_{\odot}, R = 13.02_{-1.06}^{+1.24} \text{ km}$ Miller et al, ApJL, 887, L24 (2019).
 - 2) Radius measurements of J0740+6620
 - $R = 12.39_{-0.98}^{+1.30} \text{ km}$ Riley et al, ApJL, 918, L27 (2021).
 - $R = 13.7_{-1.5}^{+2.6} \text{ km}$ Miller et al, ApJL, 918, L28 (2021).
 - 3) Radius measurement of PSR J0437-4715
 - $R = 11.36_{-0.63}^{+0.95} \text{ km}$ Choudhury et al, ApJL, 971, L20 (2024).

Description of Nuclear Matter:

pressure as a function of energy

energy per particle of nuclear matter

$$P(\rho, \delta) = \rho^2 \frac{d}{d\rho} (E(\rho, \delta))$$

symmetric nuclear matter

symmetry energy

$$E(\rho, \delta) \approx E_0(\rho) + E_{\text{sym}}\delta^2$$

$$E_0(\rho) = E_0(\rho_0) + \frac{K_0}{2}\chi^2 + \frac{Q_0}{6}\chi^3$$

$$E_{\text{sym}}(\rho) = E_{\text{sym}}(\rho_0) + L_{\text{sym}}\chi + \frac{K_{\text{sym}}}{2}\chi^2 + \frac{Q_{\text{sym}}}{6}\chi^3$$

$$\delta = \text{“Isospin asymmetry”} = (\rho_n - \rho_p)/\rho, \quad \chi = (\rho - \rho_0)/3\rho_0$$

EOS of Dense Matter from Nuclear Physics

Difficulties

- Constituents are not known.
- Interaction between constituents are not fully known.
- Uncertainties in the many-body description.

⇒ EOS is model dependent.

Phenomenological approaches are most widely used.

- Based on effective Interaction.
 1. Non-relativistic Skyrme-Interaction (~ 255)
 2. Relativistic Mean Field (RMF) models (~ 270)

Dutra et al. PRC 85, 035201 (2012); Dutra et al. PRC 90, 055203 (2014);

Oertel et al. RMP 89, 015007 (2017); Sun et al. Phys.Rev.C 109, 055801 (2024)

Our main objective: Exploring the parameter space to understand the uncertainties.

RMF model

- Interaction between baryons is described via exchange of mesons.
- The most general form of the interaction Lagrangian density:

$$\begin{aligned}\mathcal{L}_{\text{DD}} = & \bar{\psi}(i\gamma^\mu\partial_\mu - M)\psi + \Gamma_\sigma(\rho)\sigma\bar{\psi}\psi - \Gamma_\omega(\rho)\bar{\psi}\gamma^\mu\omega_\mu\psi - \frac{\Gamma_\rho(\rho)}{2}\bar{\psi}\gamma^\mu\boldsymbol{\rho}_\mu\cdot\boldsymbol{\tau}\psi \\ & + \frac{1}{2}(\partial^\mu\sigma\partial_\mu\sigma - m_\sigma^2\sigma^2) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}\vec{B}^{\mu\nu}\vec{B}_{\mu\nu} + \frac{1}{2}m_\rho^2\rho_\mu\cdot\rho^\mu,\end{aligned}$$

σ , ω_μ , and $\boldsymbol{\rho}_\mu$ are meson fields.

- For the density dependent (DD) models, the coupling parameters Γ_σ , Γ_ω , and Γ_ρ are density dependent and do not have nonlinear terms.

$$\Gamma_i(\rho) = a_i + (b_i + d_i x^3)e^{-c_i x},$$

for $i = \sigma, \omega, \rho$, and $x = n/n_0$.

P. Gogelein, E. N. E. van Dalen, C. Fuchs, and H. Muther, Phys. Rev. C 77, 025802 (2008)

Saturation properties of nuclear matter:

Parameter sets are obtained by exploring the uncertainties of the saturation properties of nuclear matter:

- Saturation density: $\rho_{sat} = (0.135, 0.195) \text{ fm}^{-3}$
- Binding energy per nucleon: $E_{sat} = (-14, -17) \text{ MeV}$.
- Incompressibility: $K_{sat} = (150, 350) \text{ MeV}$.
- Symmetry energy: $E_{sym} = (20, 45) \text{ MeV}$.
- Symmetry energy slope : $L_{sym} = (20, 180) \text{ MeV}$.

Additionally, we use the constraints coming from chiral EFT calculations from [Drischler et al., Phys. Rev. C 93, 054314 \(2016\)](#)

Results: Unified EOS

- High density EOS is constructed for a set of model parameters corresponding to a unique set of nuclear matter parameters
- Low density EOS is calculated within the compressible liquid drop model (CLDM) model for the aforementioned set of nuclear matter parameters.
- β -equilibrium is applied over the whole range.
- The crust and the core are matched with the continuity of pressure and chemical potential.

Results:

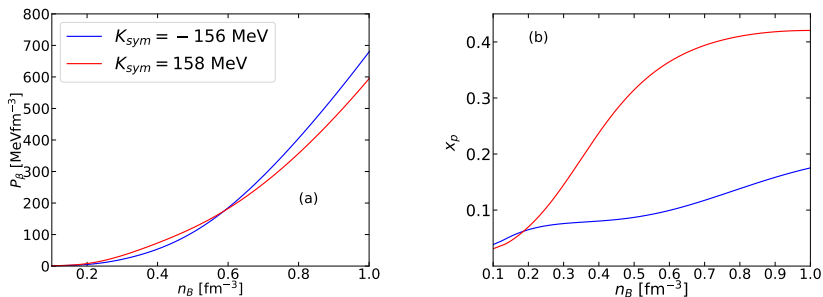
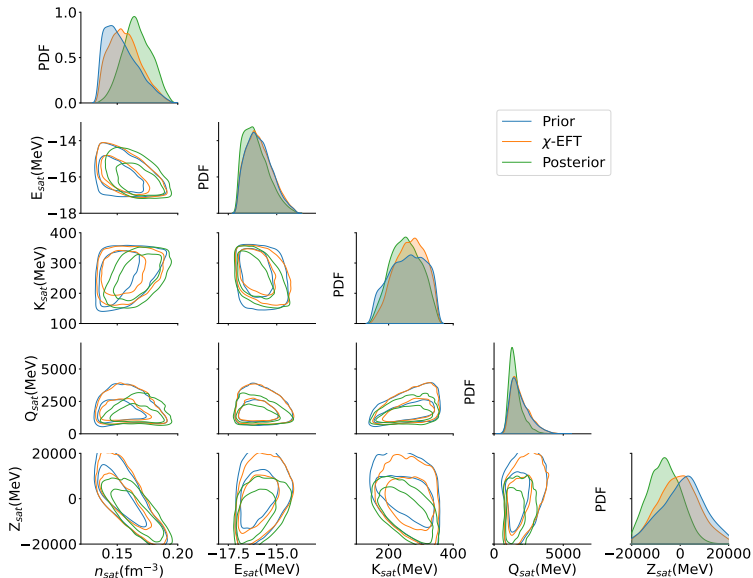
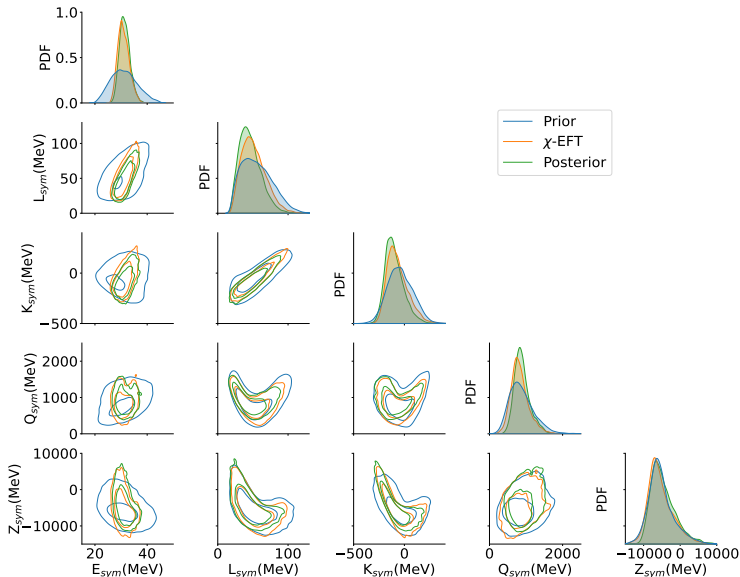


Figure: Pressure (panel a) and proton fraction (panel b) as a function of baryon density n_B for two example EOS models with negative and positive K_{sym} , respectively.

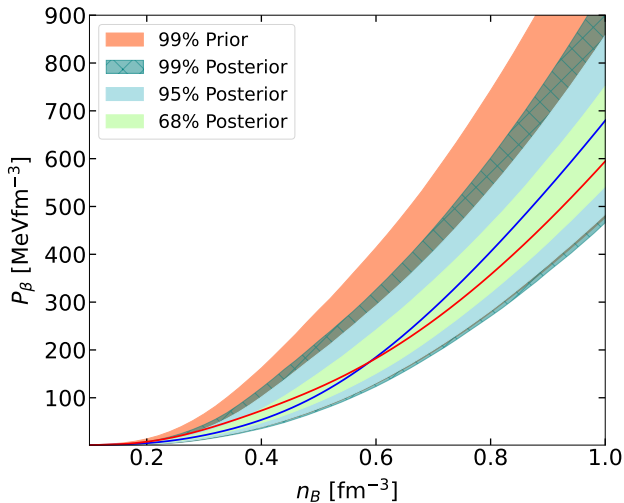
Results: Isoscalar Parameters



Results: Isovector Parameters



Results: EOS at β -equilibrium



Results: Mass - Radius - Tidal deformability

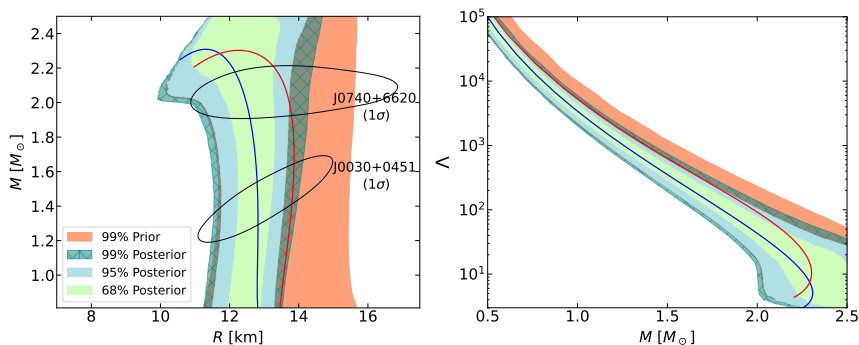
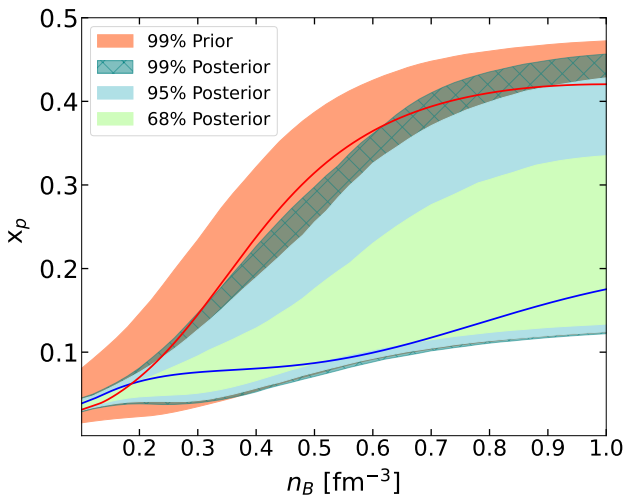
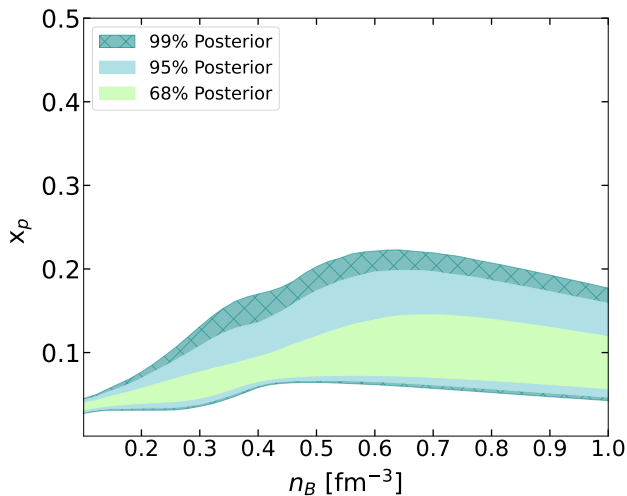


Figure: Mass-radius (left) and mass-tidal deformability (right) relations along with the Model I and II obtained in the present study. 1σ constraints from the NICER observations are also indicated in the mass-radius panel.

Results: Proton fraction

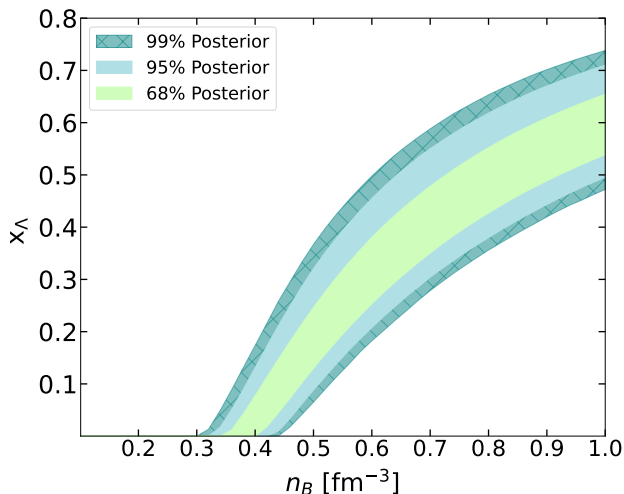


Results: Including Λ hyperons



(Char, Mondal, Oertel, Manuscript in preparation)

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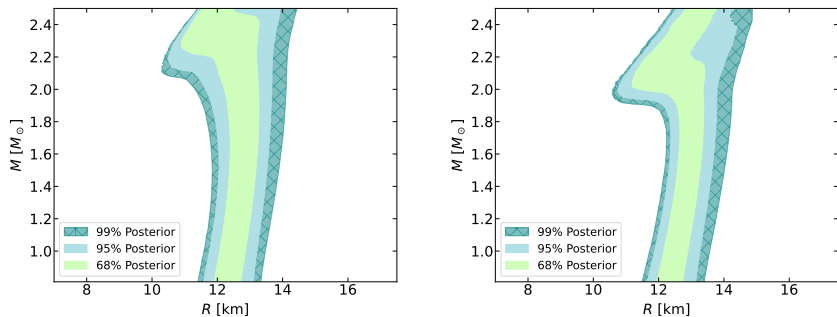


Figure: Mass-radius diagram for Nucleon-only (left) and Hyperon (right) matter, respectively.

(Char, Mondal, Oertel, Manuscript in preparation)

Summary:

- Any study of dense matter EOS is heavily model dependent. Therefore, a metamodelling approach to dense matter is very helpful to refine our knowledge.
- Within the GDFM type density-dependent RMF model, a wide range of EOSs can be generated with diverse nuclear matter properties that will be able to satisfy present observational constraints.
- One key finding is the large variation of proton fraction within this model.
- Ongoing project: Inclusion of hyperons
- Our future objective is to apply this model to study finite nuclei properties

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Thank You