Exploring Composition of Neutron Star Matter with Astrophysical Observations

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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

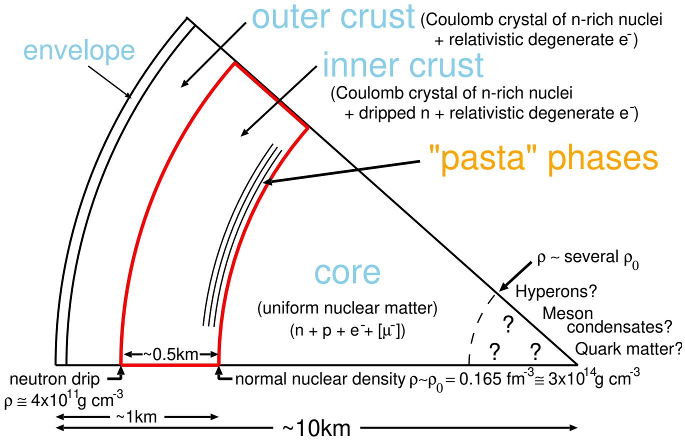


Figure: **Schematic picture of a NS Interior**

NS Observations that an EOS must satisfy

- Precise mass-measurement of massive NSs:

  $(1.908 \pm 0.016)M_\odot$ Arzoumanian et al, ApJS 235, 37 (2018).

  $(2.01 \pm 0.04)M_\odot$ Antoniadis et al, Science 340, 448 (2013).

  $(2.08 \pm 0.07)M_\odot$ 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):

  $\Lambda_{1.4} = 190^{+390}_{-120} \Rightarrow \Lambda_{1.4} \leq 580,\ P(2\rho_0) = 3.5^{+2.7}_{-1.7} \times 10^{34}$ dyn/cm^2

- NICER collaboration provided:

  1) Simultaneous mass-radius measurements of PSR J0030+0451

  $M = 1.34^{+0.15}_{-0.16} M_\odot,\ R = 12.71^{+1.14}_{-1.19}$km Riley et al, ApJL, 887, L21 (2019).

  $M = 1.44^{+0.15}_{-0.14} M_\odot,\ R = 13.02^{+1.24}_{-1.06}$km Miller et al, ApJL, 887, L24 (2019).

  2) Radius measurements of J0740+6620

  $R = 12.39^{+1.30}_{-0.98}$km Riley et al, ApJL, 918, L27 (2021).

  $R = 13.7^{+2.6}_{-1.5}$km Miller et al, ApJL, 918, L28 (2021).

  3) Radius measurement of PSR J0437–4715

  $R = 11.36^{+0.95}_{-0.63}$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

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

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

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

$\delta = \text{“Isospin asymmetry”} = (\rho_{\rm n} - \rho_{\rm p})/\rho, \qquad \chi = (\rho - \rho_0)/3\rho_0$

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.

$\Rightarrow$ EOS is model dependent.

Phenomenological approaches are most widely used.

- Based on effective Interaction.
  1. Non-relativistic Skyrme-Interaction ($\sim$ 255)
  2. Relativistic Mean Field (RMF) models ($\sim$ 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.

Nucleonic metamodelling

- Foundational aspects (Based on J. Margueron *et. al.*, PRC 97, 025805 (2018))
- Flexible functional $e(\rho_n, \rho_p)$ able to reproduce existing effective nucleonic models and interpolate between them.
- Expansion in powers of the Fermi momentum or of the density.
- Expansion around saturation: Parameter space = emp. par. $\overrightarrow{X}$
- Beta-equilibrium!!!

$$e_{Elf}(\rho_n, \rho_p) = KE(\rho_n, \rho_p) + \sum_{\alpha \geq 0} \frac{1}{\alpha!} \left(v_\alpha^{is} + v_\alpha^{iv} \delta^2 \right) x^\alpha$$

RMF model

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

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

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:

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

- Saturation density: $\rho_{sat} = (0.135, 0.195)$ fm^{-3}
- Binding energy per nucleon: $E_{sat} = (-14, -17)$ MeV.
- Incompressibility: $K_{sat} = (150, 350)$ MeV.
- Symmetry energy: $E_{sym} = (20, 45)$ MeV.
- Symmetry energy slope : $L_{sym} = (20, 180)$ 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 correspondening to a unique set of nuclear matter parameters
- Low density EOS is calculated within the compressible liquid drop model (CLDM) model for the aformentioned set of nuclear matter parameters.
- β-equlibrium is applied over the whole range.
- The crust and the core are matched with the continuity of pressure and chemical potential.

Results:

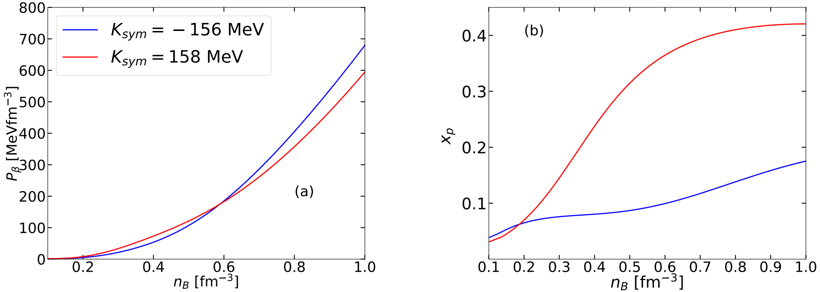
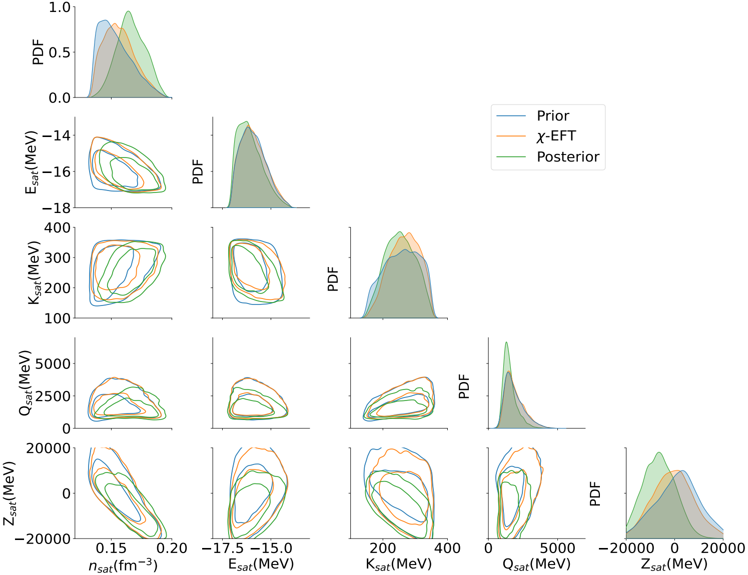
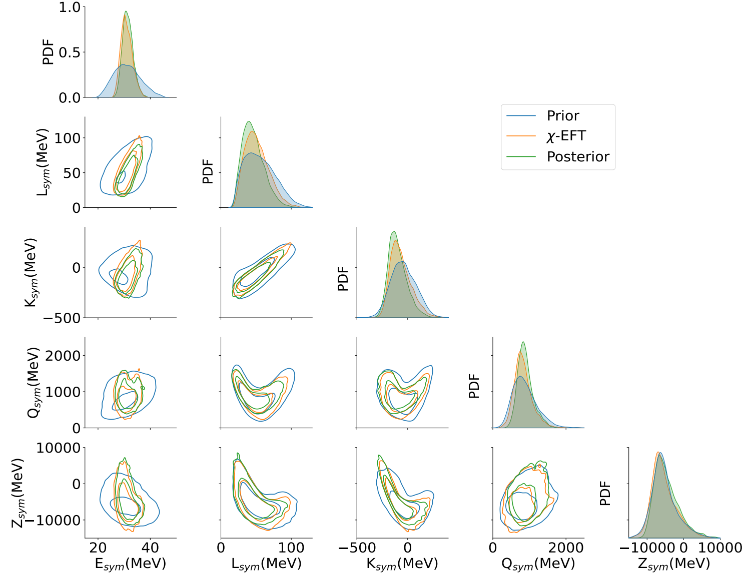


Figure: Pressure (panel a) and proton fraction (panel b) as a function of baryon density n_B for two example EOS models with negative and positive K_{sym}, respectively.

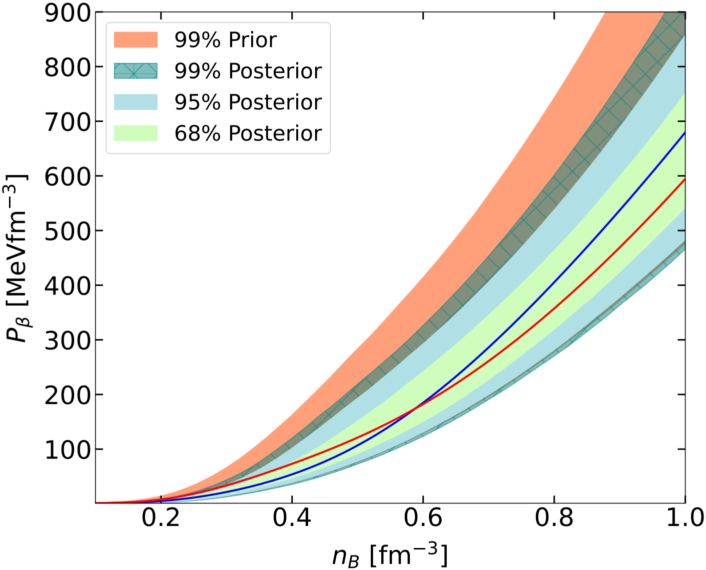
Results: SNM Parameters



Results: Isospin Parameters



Results: EOS at β-equlibrium



Results: Mass - Radius - Tidal deformability

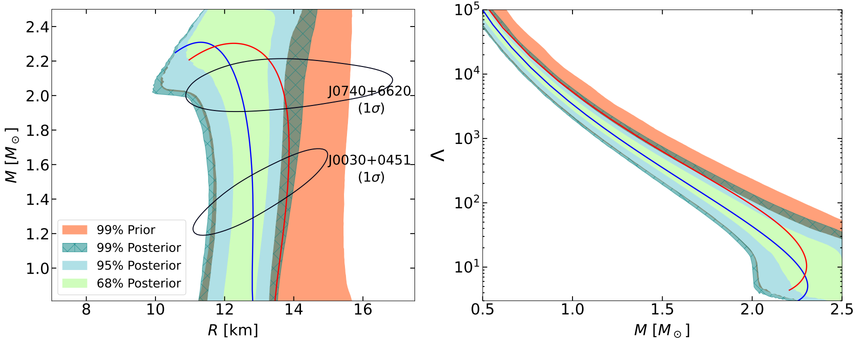
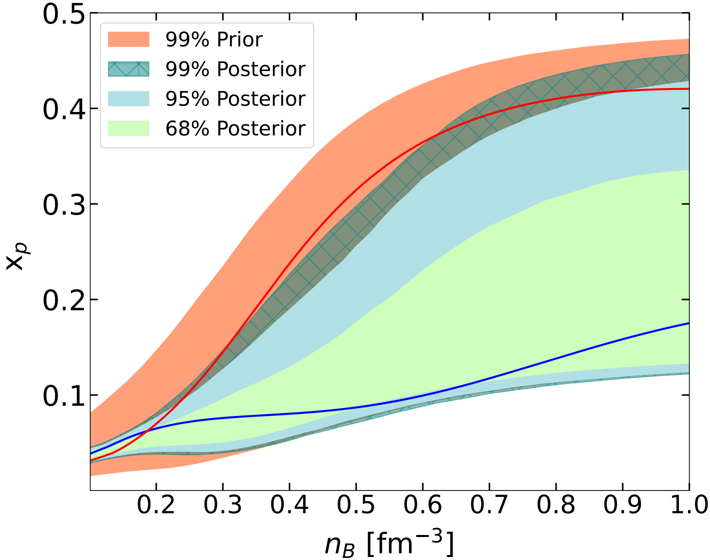
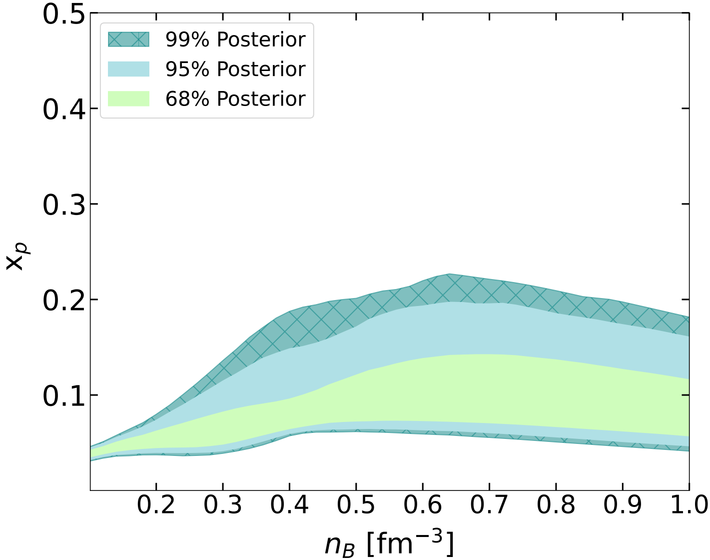


Figure: Mass-radius (left) and mass-tidal deformability (right) relations along with the Model I and II obtained in the present study. 1σ constraints from the NICER observations are also indicated in the mass-radius panel.

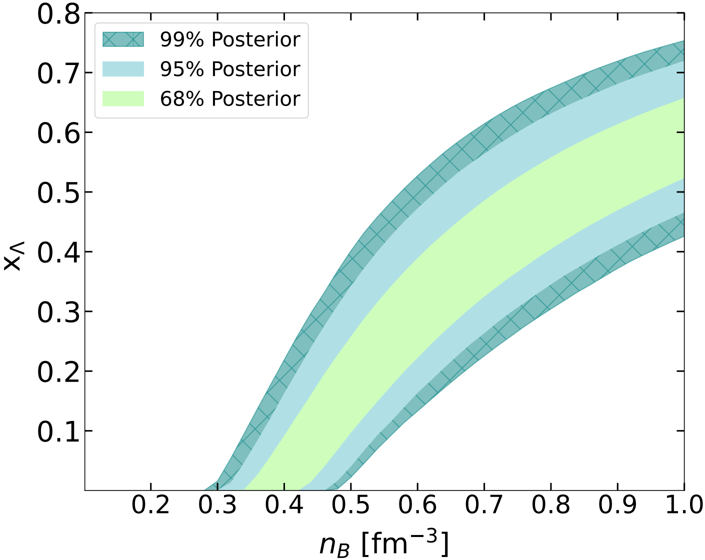
Results: Proton fraction



Results: Including Λ hyperons



Results: Including Λ hyperons



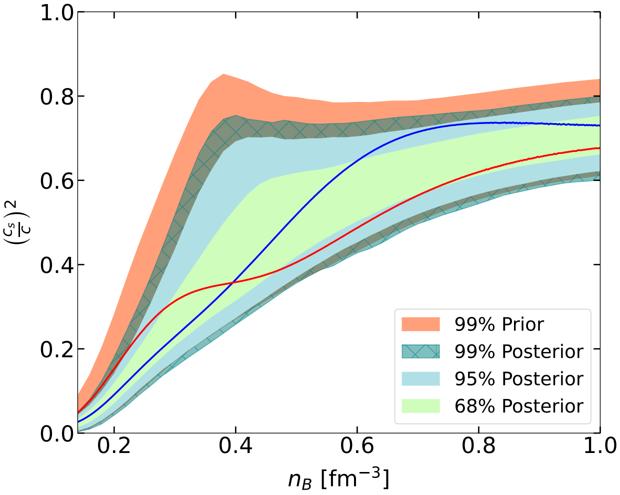
Summary:

- 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

Thank You

Backup

Backup: Speed of Sound



Backup: Correlations among NMPs

	E_{sat}	n_{sat}	K_{sat}	Q_{sat}	Z_{sat}	E_{sym}	L_{sym}	K_{sym}	Q_{sym}	Z_{sym}
E_{sat}		-0.36	-0.21	-0.03	0.25	-0.45	-0.19	-0.02	-0.24	0.12
n_{sat}	-0.46		0.34	0.05	-0.77	0.08	0.01	0.15	0.30	-0.04
K_{sat}	-0.44	0.48		0.45	-0.40	0.05	0.08	0.10	-0.03	-0.17
Q_{sat}	-0.09	0.05	0.32		0.28	0.03	0.07	0.05	-0.15	-0.32
Z_{sat}	0.38	-0.78	-0.60	0.15		-0.01	0.03	-0.11	-0.28	-0.12
E_{sym}	-0.58	0.59	0.28	-0.01	-0.45		0.56	0.07	0.37	-0.29
L_{sym}	-0.23	0.38	0.18	-0.04	-0.32	0.73		0.82	0.13	-0.50
K_{sym}	-0.12	0.40	0.14	-0.05	-0.35	0.51	0.88		0.15	-0.47
Q_{sym}	-0.09	0.15	-0.03	-0.09	-0.07	-0.06	-0.31	-0.07		0.31
Z_{sym}	0.17	-0.35	-0.13	-0.08	0.27	-0.41	-0.61	-0.77	0.27	

Posterior

Prior

Backup: Correlations among NMPs and selected Observables

	E_{sat}	n_{sat}	K_{sat}	Q_{sat}	Z_{sat}	E_{sym}	L_{sym}	K_{sym}	Q_{sym}	Z_{sym}
$R_{1.4}$	0.14	-0.53	0.05	0.32	0.45	0.04	0.41	0.35	-0.24	-0.19
$\Lambda_{1.4}$	0.15	-0.57	0.11	0.40	0.52	-0.13	0.21	0.20	-0.12	-0.05
$x_p^{1.4}$	-0.24	0.49	0.10	-0.22	-0.43	0.75	0.93	0.91	-0.04	-0.61
$R_{2.0}$	0.18	-0.68	0.05	0.41	0.62	-0.27	-0.02	-0.06	-0.05	0.18
$\Lambda_{2.0}$	0.19	-0.67	0.07	0.44	0.65	-0.36	-0.16	-0.17	0.01	0.27
$x_p^{2.0}$	-0.20	0.54	0.06	-0.27	-0.48	0.66	0.81	0.83	0.19	-0.43
M_{max}	0.20	-0.72	0.03	0.35	0.68	-0.49	-0.42	-0.47	0.05	0.52
$n_{B,c}^{M_{max}}$	-0.19	0.66	-0.03	-0.40	-0.64	0.42	0.31	0.34	-0.14	-0.48

Backup: With HESS J1731-347