Exploring Composition of Neutron Star Matter with Astrophysical Observations

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arXiv: 2307.12364, 2502.04211

Recent Developments in Gravity (NEB-21), September 1-4, 2025, Corfu, Greece

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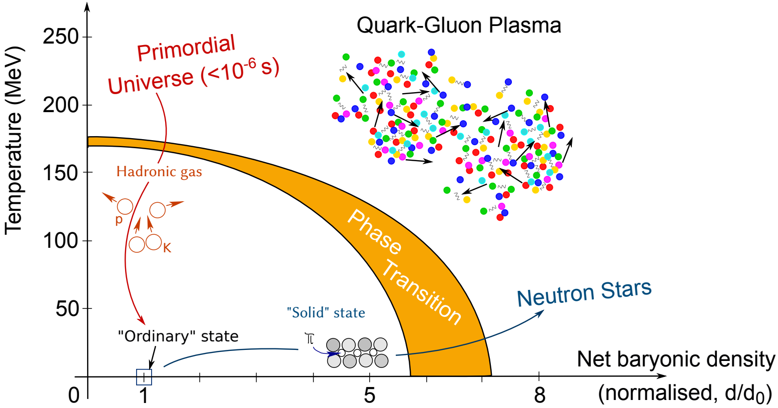
Outline

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

QCD Phase Diagram



Neutron stars

- Dead stars, produced from the gravitational collapse of a massive star after a supernova
- Mass $\sim 1 - 3M_{\odot}$
- $R \sim 10 - 15$ km
- Density $\sim 10^{15}$ g cm^{-3}
- Period ~ 1 ms -10 s
- Magnetic field $B_{\mathrm{surface}} \sim 10^{8} - 10^{15}$ G
- ~ 2500 NS discovered so far

Structure of a Neutron Star

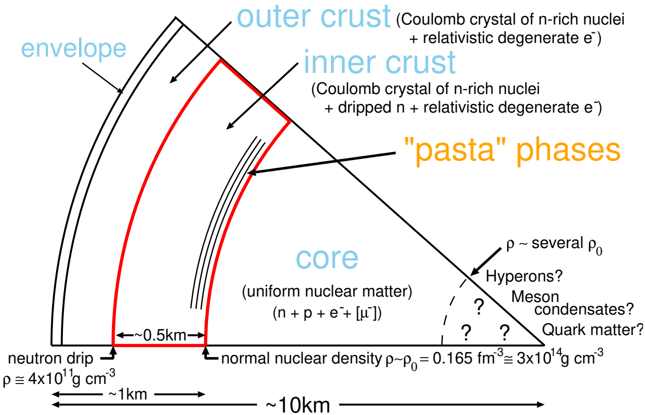
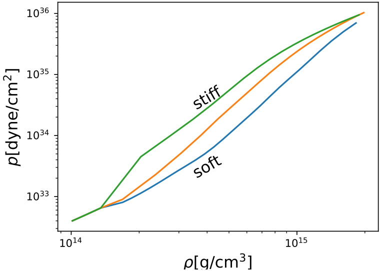


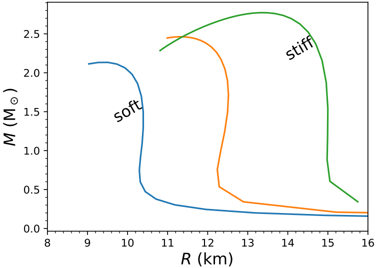
Figure: **Schematic picture of a NS Interior**

© Watanabe & Maruyama, arXiv:1109.3511

Equation of State and Mass-Radius

$\boxed{P = P(\rho)} \longleftrightarrow \boxed{M = M(R)}$





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

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Tidally Deformed Stars

- If a static spherically symmetric star of mass M and radius R is placed in a time-independent external tidal field $\mathcal{E}_{ij}$, a quadrupole moment Q_{ij} is induced onto the star and to linear order

$$Q_{ij} = -\lambda \mathcal{E}_{ij},$$

- Tidal deformation parameter λ related to the $l = 2$ dimensionless Love number k_2

$$\lambda = \frac{2}{3} k_2 R^5.$$

- Observational parameter in LIGO-Virgo, ET: $\Lambda = \lambda / M^5$

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

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

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

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

$\delta =$ "Isospin asymmetry" $= (\rho_{\rm n} - \rho_{\rm p})/\rho$, $\quad \chi = (\rho - \rho_0)/3\rho_0$

J. Margueron, R. Hoffmann Casali, and F. Gulminelli, Phys. Rev. C 97, 025805 (2018)

Approaches to EOS of Dense matter:

- Many-body description of matter
  - Ab-initio microscopic methods
    - Brueckner-Hartree-Fock
    - Self-consistent Green's function
    - Approaches based on the variational method
    - Chiral effective field theory
    - Quantum Monte Carlo methods
    - Perturbative QCD
  - Phenomenological approaches
    - Non-relativistic Skyrme-Interaction
    - Relativistic Mean Field (RMF) models
- Agnostic approaches
  - Piecewise polytropes
  - Spectral method
  - Nonparametric Gaussian processes

Chatziioannou et al. arXiv:2407.11153; Burgio et al. Prog. Part. Nucl. Phys. 120 (2021) 103879; Oertel et al. RMP 89, 015007 (2017); Sun et al. Phys. Rev. C 109, 055801 (2024)

RMF model:

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

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

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.

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

Choice of density dependence:

- TW:

$$\Gamma_i(\rho) = \Gamma_i(n_{sat}) f_i(x), \quad \text{with}$$
$$f_i(x) = a_i \frac{1 + b_i(x + d_i)^2}{1 + c_i(x + d_i)^2},$$

for $i = \sigma, \omega$, and

$$\Gamma_\rho(\rho) = \Gamma_\rho(n_{sat}) e^{-a(x-1)}, \quad \text{with} \quad x = n/n_{sat},$$

with conditions: $f_i(1) = 1, f_i''(0) = 0$ and $f_\sigma''(1) = f_\omega''(1)$.

S. Typel and H. H. Wolter, Nucl. Phys. A656, 331 (1999)

- GDFM:

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

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:

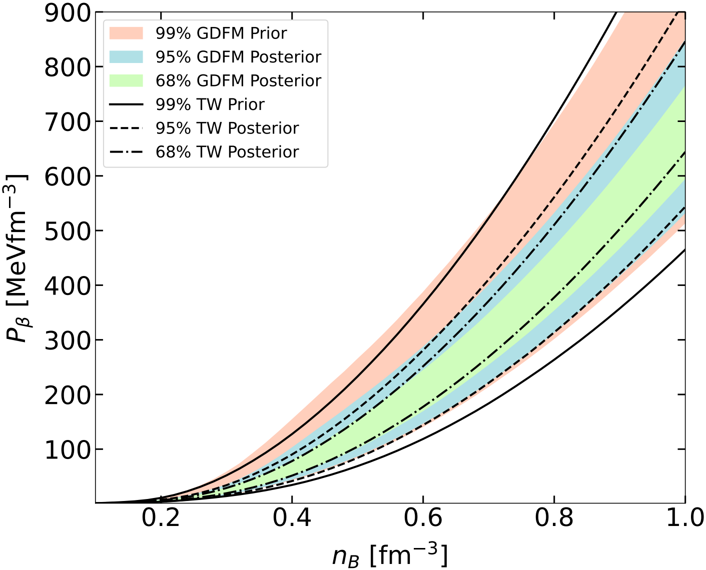
- Saturation density: $\rho_{sat} = (0.14, 0.17)$ fm^{-3}
- Binding energy per nucleon: $E_{sat} = (-17, -14)$ MeV.
- Incompressibility: $K_{sat} = (150, 350)$ MeV.
- Symmetry energy: $E_{sym} = (20, 45)$ MeV.
- Symmetry energy slope : $L_{sym} = (20, 180)$ MeV.

Additionally, we use the constraints coming from chiral EFT calculations from Huth et al, Phys Rev C 103, 025803 (2021)

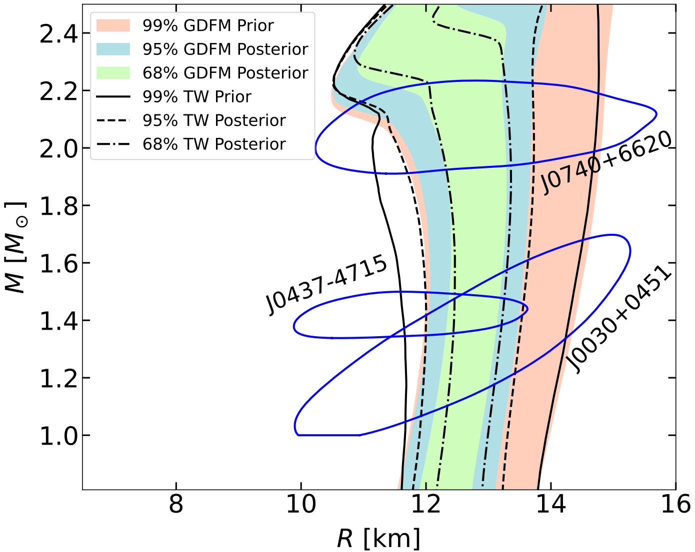
Results: Unified EOS

- 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.

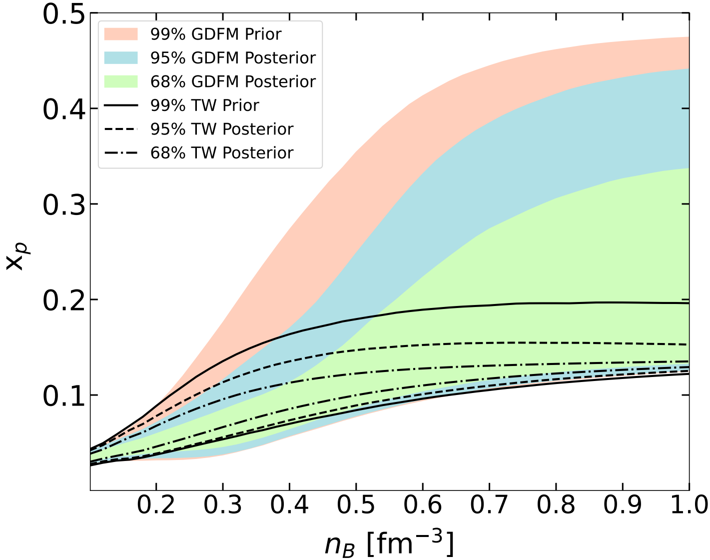
Results: EOS at β-equlibrium



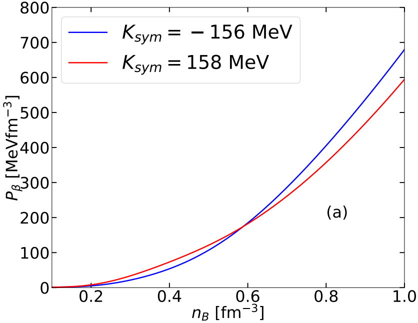
Results: Mass - Radius

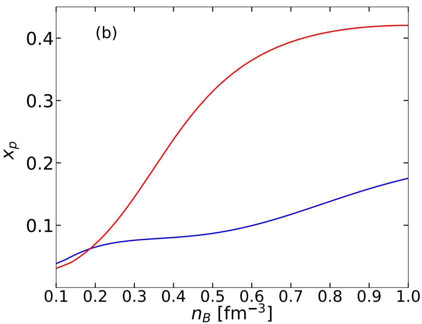


Results: Proton fraction



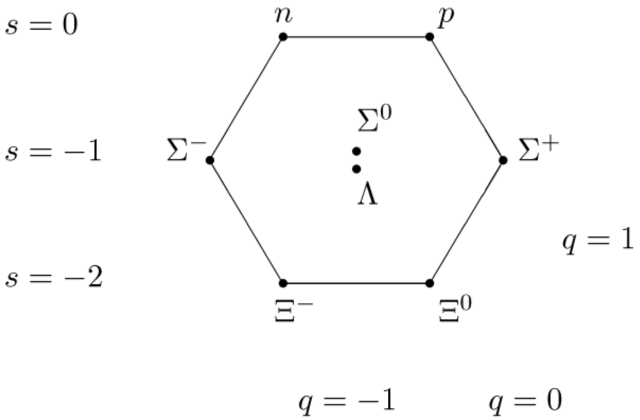
Results:



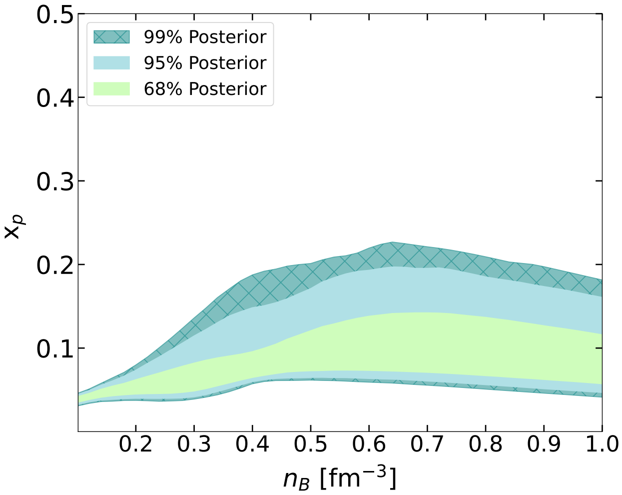


Pressure (panel a) and proton fraction (panel b) as a function of baryon density n_B for two example EOS models with negative and positive K_{sym}, respectively.

Hyperons

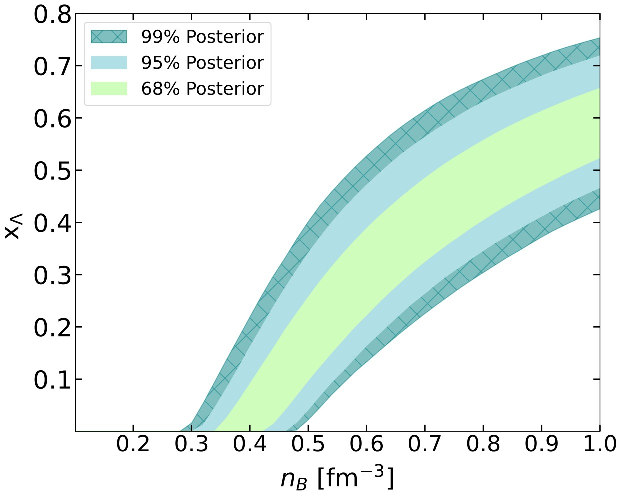


Results: Including Λ hyperons



(Char, Mondal, Oertel, Manuscript in preparation)

Results: Including Λ hyperons



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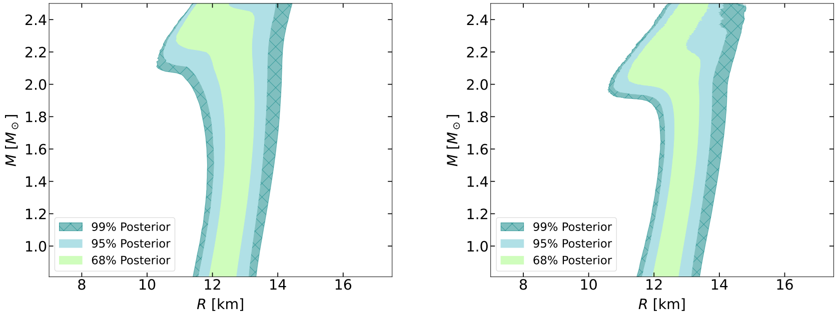

Figure: Mass-radius diagram for Nucleon-only (left) and Hyperon (right) matter, respectively.

(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