Model-independent constraints on dense matter EOS in a Bayesian approach

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Introduction

Neutron stars (NSs) are the densest objects in the observable universe. The study of the equation of state (EOS) of NS matter has become a primary goal in Nuclear physics, high energy physics, and cosmology over the decades. The behavior of the EOS at suprasaturation densities is studied using the observed maximum neutron star mass along with radius (R) and dimensionless tidal deformability (Λ)for canonical NSs ($1.4 M_\odot$).

The NS properties over a wide range of masses probe the EOS at different densities. The values of R and Λ at masses around 1.2 - 2.0 $M_\odot$ are found to be strongly correlated with the density content of symmetry energy as well as with the pressure of β-equilibrium matter ($P_{\text{BEM}}(\rho)$) at densities nearly twice the saturation density ($2\rho_0$). We study the extent to which the values of R and Λ obtained with different models may be correlated with the pressure of NS matter at $\sim 2\rho_0$. We construct a large set of EOSs within a Bayesian approach with minimal constraints those are (i) EOS of pure neutron matter (PNM) at low densities ($\rho = 0.5\rho_0 - 1\rho_0 \text{fm}^{-3}$) obtained from a precise next-to-next-to-next-to-leading order (N^{3}LO) calculation in chiral effective field theory (ii) some basic properties of saturated nuclear matter. We express our EOSs in terms of nuclear matter parameters (NMPs) using Taylor and $\frac{n}{3}$ expansions. Using these EOSs, the correlations of $\Lambda_{1.4}$, $R_{1.4}$ with $P_{\text{BEM}}(\rho)$ at different densities are studied.

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Taylor and $\frac{n}{3}$ expansions

The energy per nucleon $E(\rho, \delta)$ at given density and asymmetry(δ) can be decomposed as,

$$E(\rho, \delta) = E(\rho, 0) + E_{\text{sym}}(\rho)\delta^2 + ..., \quad (1)$$

where, $E(\rho, 0)$ is energy per nucleon for symmetric nuclear matter and $E_{\text{sym}}(\rho)$ is the density-dependent symmetry energy which can be expressed in terms of nuclear matter parameters using Taylor expansions as,

$$E(\rho, 0) = \epsilon_0 + \frac{1}{2}K_0\alpha^2 + \frac{1}{6}Q_0\alpha^3 + ...,$$

$$E_{\text{sym}}(\rho) = J_0 + L_0\alpha + \frac{1}{2}K_{sym,0}\alpha^2 + \frac{1}{6}Q_{sym,0}\alpha^3 + ...,$$

where, the α stands for $\frac{\rho-\rho_0}{3\rho_0}$ and the NMPs such as binding energy per nucleon (ϵ_0), incompressibility (K_0), skewness(Q_0), symmetry energy coefficient (J_0), it's slope (L_0) and others are evaluated at ρ_0. Likewise, $E(\rho, 0)$ and $E_{\text{sym}}(\rho)$ can also be expanded in powers of $\rho^{\frac{n}{3}}$ as,

$$E(\rho,0) = \sum_{n=2}^{6}(a_{n-2})\left(\frac{\rho}{\rho_0}\right)^{\frac{n}{3}}, E_{\text{sym}}(\rho) = \sum_{n=2}^{6}(b_{n-2})\left(\frac{\rho}{\rho_0}\right)^{\frac{n}{3}},$$

where, a_n and b_n can be expressed as linear combinations of NMPs[1].

Results

We obtained the EOSs for β-equilibrated matter using Taylor and $\frac{n}{3}$ expansions, Eq.1. The contributions of electrons and muons which satisfy charge neutrality and β-equilibrium conditions are obtained within the relativistic fermi gas approximation. We have constructed marginalized posterior distributions for the NMPs by applying a Bayesian approach to both the expansions considered.

The NMPs or the corresponding EOSs are consistent with a set of minimal constraints.

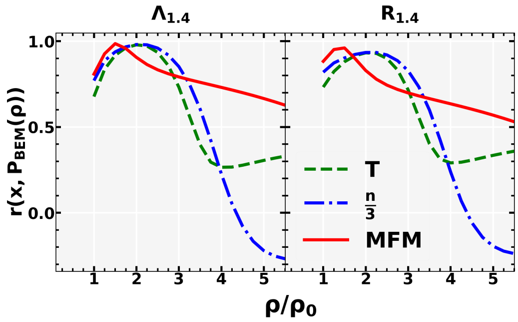

FIG. 1: The correlation coefficients r(x,$P_{\rm BEM}(\rho)$), for both Taylor (T) and $\frac{n}{3}$ expansions with x represents $\Lambda_{1.4}$, $R_{1.4}$ for the NS. For the comparison, results are also displayed for a diverse set of non-relativistic and relativistic microscopic mean-field models (MFMs).

The values of correlation coefficients are plotted as a function of density in Fig.1. For comparison, we also display the values of correlation coefficients for $\Lambda_{1.4}$ and $R_{1.4}$ with the pressure of β-equilibrated matter calculated using unified EOSs for a diverse set of 41 non-relativistic and relativistic microscopic mean-field models (MFMs). The values of $\Lambda_{1.4}$ and $R_{1.4}$ are strongly correlated with $P_{\rm BEM}(\rho)$ at density $\sim 1.5 - 2.5\rho_0$. This results indicates that the correlations of $\Lambda_{1.4}$ and $R_{1.4}$ with $P_{\rm BEM}(\rho)$ at density $\sim 2\rho_0$ are nearly model-independent.

Using the correlations displayed in Fig. 1, we have obtained a parametrized form for $P_{\rm BEM}(\rho)$ at a fixed ρ as,

$$\frac{P_{\rm BEM}(\rho)}{\rm MeVfm^{-3}} = a(M) + b(M)\Lambda_M, \qquad (2)$$

with mass-dependent coefficients $a(M)$ and $b(M)$ expanded as,

$$\begin{aligned} a(M) &= a_0 + a_1(M - M_0) + a_2(M - M_0)^2, \\ b(M) &= b_0 + b_1(M - M_0) + b_2(M - M_0)^2, \end{aligned}$$

where, the values of a_i and b_i are obtained at the densities $1.5\rho_0$, $2\rho_0$ and $2.5\rho_0$ in Ref.[1].

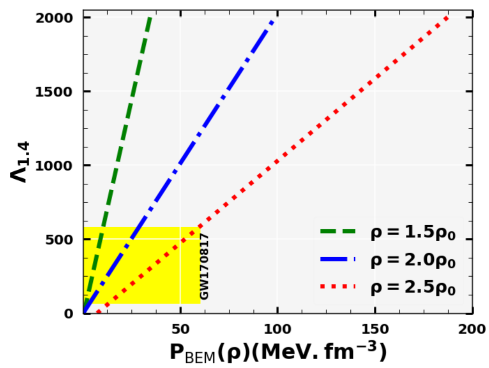

FIG. 2: The median values of $P_{\rm BEM}(\rho)$ as a function $\Lambda_{1.4}$ at densities $1.5\rho_0$, $2.0\rho_0$ and $2.5\rho_0$. The yellow color band correspond to the observational constraints of $\Lambda_{1.4}$ from GW170817.

In Fig.2 we show the pressure of β-equilibrium matter at ρ= $1.5\rho_0$, $2\rho_0$ and $2.5\rho_0$ as a function of $\Lambda_{1.4M_\odot}$. We have confronted our parametrized form of $P_{\rm BEM}(\rho)$, for $M = 1.4M_\odot$ with the MFM results displayed Fig.1. We find the average deviation of $P_{\rm BEM}(2\rho_0)$ is about 10% from actual values. The marginal improvement is found in the quadratic term in Λ is included in Eq. (2).

Conclusions

We have constructed large sets of EOSs for β-equilibrated matter using Taylor and $\frac{n}{3}$ expansions within a Bayesian approach with minimal constraints. The correlations of neutron star properties such as $\Lambda_{1.4}$ and $R_{1.4}$ with $P_{\rm BEM}(\rho)$ at different densities are investigated. These correlation systematics are in harmony with those obtained for unified EOSs for the β-equilibrated matter available for a diverse set of MFMs. The parametric form for $P_{\rm BEM}(\rho)$ in Eq. (2) may facilitate one to constrain the EOS at suprasaturation densities once the tidal deformability for the NS masses 1.2-2 $M_\odot$ are accurately known.

References

[1] N.K.Patra *et al.*, Phys. Rev. D **106** (2022), 043024