GW170817: constraining the nuclear matter equation of state from the neutron star tidal deformability

Tuhin Malik\textsuperscript{1,*}, N. Alam\textsuperscript{2,6}, M. Fortin\textsuperscript{3}, C. Providência\textsuperscript{4}, B. K. Agrawal\textsuperscript{2,6}, T. K. Jha\textsuperscript{1}, Bharat Kumar\textsuperscript{5,6}, and S. K. Patra\textsuperscript{5,6}

\textsuperscript{1}BITS-Pilani, Dept. of Physics, K.K. Birla Goa Campus, GOA - 403726, India
\textsuperscript{2}Saha Institute of Nuclear physics, Kolkata 700006, India
\textsuperscript{3}N. Copernicus Astronomical Center, Polish Academy of Science, Bartycka,18, 00-716 Warszawa, Poland
\textsuperscript{4}CFIsUC, Department of Physics, University of Coimbra, 3004-516 Coimbra, Portugal
\textsuperscript{5}Institute of Physics, Bhubaneswar - 751005, India.
\textsuperscript{6}Homi Bhabha National Institute, Anushakti Nagar, Mumbai - 400094, India.

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Constraints set on key parameters of the nuclear matter equation of state (EoS) by the values of the tidal deformability, inferred from GW170817, are examined by using a diverse set of relativistic and non-relativistic mean field models. These models are consistent with bulk properties of finite nuclei as well as with the observed lower bound on the maximum mass of neutron star \( \sim 2 \, M_\odot \). The tidal deformability shows a strong correlation with specific linear combinations of the isoscalar and isovector nuclear matter parameters associated with the EoS. Such correlations suggest that a precise value of the tidal deformability can put tight bounds on several EoS parameters, in particular, on the slope of the incompressibility and the curvature of the symmetry energy. The tidal deformability obtained from the GW170817 and its UV/optical/infrared counterpart sets the radius of a canonical 1.4 \( M_\odot \) neutron star to be \( 11.82 \leq R_{1.4} \leq 13.72 \) km.

I. INTRODUCTION

The physics of dense matter relevant to neutron stars (NSs) is poorly understood till date [1]. Neutron stars are made of incredibly dense matter reaching densities up to few times the nuclear saturation density \( (\rho_0 \sim 0.16 \, \text{fm}^{-3}) \) in the core region. The NS structure depends predominantly on the nuclear equation of state (EoS). Due to the lack of detailed knowledge of the nuclear interactions at densities typical of the NS interior, many theoretical models of nuclear EoS have been proposed. Matter at supra nuclear densities, as encountered in the NS interior, is difficult to access in terrestrial experiments. Inputs from astrophysical observations are, therefore, crucial in constraining the dense matter EoS. Currently, the most stringent constraint comes from the observation of NS with \( \sim 2 \, M_\odot \) [2, 3] which sets a lower limit for the maximum mass to be predicted by an EoS.

As NSs are massive and compact astrophysical objects, the coalescence of binary NS systems is one of the most promising sources of gravitational waves (GWs) observable by ground-based detectors [4–9]. The GW signals emitted during a NS merger depends on the behavior of neutron star matter at high densities [10, 11]. Therefore, its detection opens the possibility to constrain the nuclear matter parameters characterizing the EoS. A significant signature carried by GWs is the tidal deformability (polarizability) of the NS and it is well explored analytically [12–16]. In a coalescing binary NS system, during the last stage of inspiral, each NS develops a mass quadrupole due to the extremely strong tidal gravitational field induced by the other NS forming the binary. The dimensionless tidal deformability \( \Lambda \) describes the degree of deformation of a NS due to the tidal field of the companion NS and is sensitive to the nature of the EoS.

In August 2017 the Advanced LIGO and Advanced Virgo gravitational-wave observatories detected GWs emitted from a binary NS inspiral for the first time [17]. Remarkably, this discovery opened a new window in the field of multi-messenger astronomy and nuclear physics, which revealed the potential to directly probe the physics of NSs and of the synthesis of heavy elements in the rapid neutron-capture process (\( r \)-process) [18, 19]. The analysis of GW170817 data has allowed to put an upper bound on the NSs combined dimensionless tidal deformability with 90 \% confidence, using spin magnitudes consistent with the observed neutron star population. In the analysis, results for both a high-spin and a low-spin prior have been obtained to the same level of confidence. In our study we will consider the constraints set by the low-spin prior because they are consistent with the masses of all known binary neutron star systems. This prior predicts that the combined dimensionless tidal deformability of the NS merger is \( \Lambda \leq 800 \). In [20] a reanalysis of the gravitational-wave observations of the binary neutron star merger GW170817 has been done assuming the same EoS for both stars. For the low spin prior these authors have obtained the constraint \( \Lambda \leq 1000 \). On the other end, the investigation of the UV/optical/infrared counterpart of GW170817 with kilonova models in [21] has set a lower bound on \( \Lambda \), i.e. \( \Lambda > 400 \). We show that these bounds on \( \Lambda \) can be employed to deduce the respective bounds on the tidal deformability of a NS with mass 1.4 \( M_\odot \).

Studies of the correlations between nuclear matter parameters and the tidal deformability, based on a few se-
lected relativistic mean field models, have shown that measurements of the latter can constrain the high density behavior of the nuclear symmetry energy [22] as well as put bounds on the value of neutron skin thickness [23]. These preliminary studies need to be validated further using a more diverse set of models for the nuclear EoS. In earlier studies it was found that correlations between the various properties of NS and nuclear matter EoS parameters are significantly affected when a more diverse set of models are employed [24, 25]. Recently, astrophysical observations of NS, in particular, the maximum mass, the radius of a canonical 1.4 M⊙ NS, and the tidal deformability, have been used to constrain various parameters of the EoS [26]. However, within their assumptions, they found that the tidal deformability obtained from GW170817 is not very restrictive.

The present communication is an attempt, in view of the recent observation GW170817, to further explore the dependence of the tidal deformability on the various nuclear matter parameters describing the EoS. We study the correlations of the tidal deformability parameter with the different several nuclear matter parameters associated with a EoS by employing a representative set of relativistic mean field (RMF) models and of Skyrme Hartree-Fock (SHF) models. The EoS parameters considered are the nuclear matter incompressibility coefficient, the symmetry energy coefficient and their derivatives at the saturation density. We also study the model dependence of the Love number $k_2$ which plays a crucial role in determining the value of tidal deformability.

The paper is organized as follows. In Sec. II, we briefly outline the procedure for computing the tidal deformability and also define the various nuclear matter parameters that can be calculated for a given EoS. We also present the EoSs for our representative set of RMF and SHF models and use them to calculate the tidal deformability and the Love number over a wide range of NS masses. The main results for the correlations of the tidal deformability, Love number and NS radius with different nuclear matter parameters are discussed in Sec. IV. Finally the conclusions are drawn in Sec. V.

Conventions: We have taken the value of $G = c = 1$ throughout the manuscript.

II. FRAMEWORK

In this section, we outline the expressions required to compute the tidal deformability for a given EoS. We also define the various nuclear matter parameters that characterize the EoS.

A. Tidal deformability

The tidal deformability parameter $\lambda$ is defined as [12, 13, 16, 27],

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

where $Q_{ij}$ is the induced quadrupole moment of a star in a binary due to the static external tidal field $\mathcal{E}_{ij}$ of the companion star. The parameter $\lambda$ can be expressed in terms of the dimensionless quadrupole tidal Love number $k_2$ as

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

where $R$ is the radius of the NS. The value of $k_2$ is typically in the range $0.05 - 0.15$ [13, 16, 28] for NSs and depends on the stellar structure. This quantity can be calculated using the following expression [13]

$$k_2 = \frac{8C_5}{5} (1 - 2C)^2 \left[ 2 + 2C (y_R - 1) - y_R \right] \times \left\{ 2C(6 - 3y_R + 3C(5y_R - 8)) + 4C^3 [13 - 11y_R + C(3y_R - 2) + 2C^2(1 + y_R)] + 3(1 - 2C)^2 [2 - y_R + 2C(y_R - 1)] \log (1 - 2C) \right\}^{-1},$$

where $C (\equiv m/R)$ is the compactness parameter of the star of mass $m$. The quantity $y_R (\equiv y(R))$ can be obtained by solving the following differential equation

$$r \frac{dy(r)}{dr} + y(r)^2 + y(r) F(r) + r^2 Q(r) = 0,$$

with

$$F(r) = \frac{r - 4\pi r^3 (\epsilon(r) - p(r))}{r - 2m(r)},$$

$$Q(r) = \frac{4\pi r \left( 5\epsilon(r) + 9p(r) + \frac{\epsilon(r ) + p(r)}{\delta(1/r)} - \frac{6}{4\pi r^2} \right)}{r - 2m(r)} - 4 \left[ \frac{m(r) + 4\pi^3 p(r)}{r^2 (1 - 2m(r)/r)} \right]^2.$$

Where the $m(r)$ is mass enclosed within the radius $r$, and $\epsilon(r)$ and $p(r)$ are, respectively, the energy density and pressure in terms of radial coordinate $r$ of a star. These quantities are calculated within the nuclear matter model chosen to describe the stellar EoS. For a given EoS, Eq. (4) can be integrated together with the Tolman-Oppenheimer-Volkoff equations [29] with the boundary conditions $y(0) = 2$, $p(0) = p_c$, and $m(0) = 0$. Where $y(0)$, $p_c$ and $m(0)$ are the dimensionless quantity, pressure and mass at the center of the NS, respectively. One can then define the dimensionless tidal deformability: \( \Lambda = \frac{1}{3} k_2 C^{-5} \). The tidal deformabilities of the NSs present in the binary neutron star system can be combined to yield the weighted average as,

$$\tilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12m_2)m_1^4 \lambda_1 + (m_2 + 12m_1)m_2^4 \lambda_2}{(m_1 + m_2)^5},$$

where $\lambda_1$ and $\lambda_2$ are the individual tidal deformabilities corresponding to the two components in the NS binary with masses $m_1$ and $m_2$, respectively [12, 30].
B. The nuclear matter parameters

The energy per nucleon at a given density \( \rho = \rho_n + \rho_p \) with \( \rho_n \) and \( \rho_p \) the neutron and proton densities, respectively, and asymmetry \( \delta = (\rho_n - \rho_p)/\rho \), can be decomposed, to a good approximation, into the EoS for symmetric nuclear matter \( e(\rho, 0) \), and the density dependent symmetry energy coefficient \( S(\rho) \):

\[
e(\rho, 0) \approx e(\rho, 0) + S(\rho)\delta^2.
\]  

Expanding the isoscalar contribution until fourth order and the isovector until third order we obtain for the isoscalar part \( e(\rho, 0) \):

\[
e(\rho, 0) = e(\rho_0) + \frac{K_0}{2} x^2 + \frac{Q_0}{6} x^3 + O(x^4)
\]

and for the isovector part \( S(\rho) \):

\[
S(\rho) = J_0 + L_0 x + \frac{K_{\text{sym},0}}{2} x^2 + O(x^3).
\]

where \( x = \frac{\rho - \rho_0}{3\rho_0} \) and \( J_0 = S(\rho_0) \) is the symmetry energy at the saturation density. The incompressibility \( K_0 \), the skewness coefficient \( Q_0 \), the symmetry energy slope \( L_0 \), and its curvature \( K_{\text{sym},0} \) evaluated at saturation density are defined, e.g., Ref. [31]. The slope of the incompressibility, \( M_0 \), at saturation density is defined as [24],

\[
M_0 = 12K_0 + Q_0.
\]

In the section IV we shall consider the correlations of the tidal deformability of NS with the various nuclear matter parameters of the EoS: \( K_0, Q_0, M_0, J_0, L_0, K_{\text{sym},0} \).

III. EQUATION OF STATE AND TIDAL DEFORMABILITY

In the present section we introduce a set of relativistic and non-relativistic nuclear models that are constrained by the bulk properties of finite nuclei and the observed lower bound on the NS maximum mass. For these models we show how the tidal deformability and Love number behave over a wide range of NS masses.

A. Nuclear matter equation of state

The correlations of the properties of neutron stars with the various nuclear matter parameters of the EoS are studied using a set of eighteen relativistic and twenty-four non-relativistic nuclear models. These models have been employed for the study of finite nuclei and NS properties. Our set of models are based on RMF and SHF frameworks. The RMF models employed are BSR2, BSR3, BSR6, FSU2, GM1, NL3, NL3\(\sigma\rho\), NL3\(\rho\), NL3\(\rho\)2, NL3\(\rho\)3, TM1, TM1-2, DD2, DDH\(\delta\), DDH\(\delta\)Mod, DDME1, DDME2, and TW. The SHF models considered are the SKa, SKb, SkI [48], SkI2, SkI3, SkI4, SkI5, SkI6, SkI7, SkI9, SkI10, SkI20, SkI23, SkI24, SkI25, SK255, SK272, Sk20, Sk21, Sk22, Sk23, Sk24, Sk25, and Sk26 [60]. The values of the nuclear matter properties, such as, \( K_0, Q_0, M_0, J_0, L_0 \) and \( K_{\text{sym},0} \) vary over a wide range for our representative set of EoSs as can be seen from the supplementary material of Ref. [61]. As the mass of the stars in the GW170817 binary is 1.6 M\(\odot\) or smaller, we only consider nucleonic degrees of freedom. However, a NS with a mass of 1.6 M\(\odot\) could have non-nucleonic degrees of freedom [32, 62].

The EoSs for all the models considered are consistent with the observational constraint provided by the existence of 2 M\(\odot\) NS [25, 61]. Moreover, the SHF models considered do not become acausal for masses below 2 M\(\odot\). We have taken unified inner-crust core EoS for all the models [25] and the EoS of Baym-Pethick-Sutherland [63] is used for the outer crust.

In Fig. 1, we plot for NS matter the variation of pressure \( (p) \) with the energy density \( (\epsilon) \) in the left panel and the variation of \( dp/d\epsilon \) with the baryon number density in the right panel for our representative set of models. The black circles denote the central density corresponding to the NS maximum mass for each EoS. The dashed line indicates the causality limit (i.e. \( dp/d\epsilon = 1 \)). The values of \( dp/d\epsilon \) for SHF models are larger at higher densities \( (\rho > \rho_0) \) than those for the RMF models. The maximum mass NS configurations of all models studied are within the causality limit except for BSk20 and BSk26 EoSs, which are marginally acausal.

![FIG. 1. (Color online) Plots for the (a) pressure \( p \) as a function of the energy density \( \epsilon \), and (b) \( dp/d\epsilon \) as a function of the baryonic number density for beta equilibrated NS matter obtained using a representative set of RMF (black dashed lines) and SHF models (red lines). The circles in right panel correspond to the central densities and the slopes \( dp/d\epsilon \) at the maximum NS mass for each of the EoS. The BSk20 and BSk26 EoSs are marginally acausal at the NS maximum masses \( \sim 2.2 \ M_\odot \) [25, 61].](image-url)
B. Dependence of the tidal deformability on the equation of state

One of the main focus of the present work is to study the sensitivity of the tidal deformability to the properties of nuclear matter at saturation density. To facilitate our discussions in the next section, in Fig. 2 the dimensionless tidal deformability $\Lambda$ (left) and tidal Love number $k_2$ (right) obtained for our set of EoSs are plotted as a function of the NS mass. The values of $k_2$ show a noticeable spread across the various models. For instance, at $1.4 M_\odot$, the values of $k_2$ are in the range of 0.07 to 0.11. For the smaller masses the spread in $k_2$ is larger for the SHF models, but for the larger masses RMF models give on average larger values of $k_2$. One can also see from Fig. 1 of reference [61] that the RMF models predict larger radii, in particular, for large NS masses. Consequently, the parameter $\Lambda$ tends to be larger for the RMF models than for the SHF models. In the following, we will examine the dependence of $\Lambda$ on both $k_2$ and $R$ in detail.

In Fig. 3 we plot the tidal deformabilities in the phase space of $\Lambda_1$ and $\Lambda_2$ associated, respectively, with the high-mass $m_1$ and the low-mass $m_2$ components of the binary, for all the RMF and SHF models considered. The curves corresponding to every EoS are obtained by varying the high mass ($m_1$) independently in the range $1.365 < m/M_\odot < 1.60$ obtained for GW170817 whereas the low mass ($m_2$) is determined by keeping the chirp mass $M = (m_1m_2)^{1/2}/(m_1 + m_2)^{-1/2}$ fixed at the observed value 1.188 $M_\odot$ [17]. The dot-dot-dashed and the dot lines represent, respectively, the 90% and 50% confidence limits obtained from the GW170817 for the low spin priors. One can note that the 90% confidence limit suggests that SkI5 and the family of models NL3X and TM1X are ruled out except for NL3ωp03. For the SkI5 the values of $M_0$ and $L_0$ are 2745 MeV and 129 MeV, respectively. For NL3X family the value of $M_0$ is larger than 3400 MeV and $L_0$ is in the range of 55-70 MeV except for the base model NL3. Whereas, for TM1X family the value of $M_0 \sim 3100$ MeV and $L_0 \sim 110$ MeV. This indicates that very high value of $M_0$ and/or $L_0$ may not be favored by GW170817.

FIG. 2. (Color online) Tidal deformability $\Lambda$ and the Love number $k_2$ as a function of the NS mass ($m$) for a representative set of relativistic and non-relativistic models. The SHF model, SkI5, displays markedly different behavior for $\Lambda$ as well as for $k_2$.

FIG. 3. (Color online) Tidal deformability parameters for the case of high mass ($\Lambda_1$) and low mass ($\Lambda_2$) components of the observed GW170817. The 90% (dot-dot-dashed) and 50% (dot) confidence lines are taken from Ref. [17] corresponding to the low spin priors.

IV. RESULTS AND DISCUSSIONS

In the present section, we study the correlations of the tidal deformability $\Lambda$, the Love number $k_2$ and the radius of NSs $R$ with various nuclear matter parameters. As already mentioned in Sec. I, we consider the constraints from the properties of the binary neutron star that satisfy the low spin prior [17]. In our analysis, the correlation between a pair of quantities is quantified in terms of Pearson’s correlation coefficient, denoted as $R$ [64]. The magnitude of $R$ is at most unity indicating that the pair of quantities is completely correlated to each other. For $|R| < 0.5$, the correlations are usually said to be weak.

We calculate the values of the coefficients for the correlation of $\Lambda$, $k_2$ and $R$ with the nuclear matter saturation parameters $K_0$, $Q_0$, $M_0$, $J_0$, $L_0$, $K_{\text{sym},0}$ and with several linear combinations of two parameters, in particular with $K_0 + \alpha L_0$, $M_0 + \beta L_0$ and $M_0 + \eta K_{\text{sym},0}$. The values of $\alpha$, $\beta$ and $\eta$ are so obtained that, for each NS mass, they yield optimum correlations. Our correlation systematics is determined for NS masses in the range of $1.2 - 1.6 M_\odot$, since, for the low spin prior analysis, these masses are close to the ones involved in the GW170817 event. The results for the values of $R$ obtained for the correlation of $\Lambda$, $k_2$ and $R$ with individual nuclear matter parameters are presented in Table I. The Table
II contains the results obtained using the linear combinations of the nuclear matter parameters. The Fig. 4 is the pictorial representation of the results presented in Tables I and II. Only the cases with the correlation coefficients $R > 0.5$ are displayed. We see from Table I that for most of the cases, individual EoS parameters seem to be weakly or moderately correlated with the $\Lambda$, $k_2$ and $R$. Exceptionally, the $\Lambda$ and $R$ are strongly correlated with the individual nuclear matter parameters $L_0$ and $M_0$ for the NS masses 1.2 $M_\odot$ and 1.6 $M_\odot$, respectively. Let us point out that the correlation between the radius of low mass NSs and the neutron skin of $^{208}$Pb, which is itself correlated with $L_0$, was first discussed in [65]. It is seen from Table II, the $\Lambda$ and $R$ are strongly correlated with $M_0 + \beta L_0$ and $M_0 + \eta K_{sym,0}$ over a wide range of NS masses considered: the values of $R$ of the order of 0.9. The Love number $k_2$ is strongly correlated with $M_0 + \eta K_{sym,0}$. The values of $\alpha$, $\beta$ and $\eta$ decrease monotonically with the NS mass. This indicates that the density dependence of symmetry energy is less important in determining the values of $\Lambda$ and $R$ at higher NS masses. The mass dependence of $\alpha$, $\beta$ and $\eta$ is discussed in some detail in the Appendix A, where, in particular, an exponential dependence of these parameters on the NS mass is proposed.

As an example, in Fig. 5 we plot $M_0 + \beta L_0$ and $M_0 + \eta K_{sym,0}$ as a function of $k_2$ and $\Lambda$ for 1.4 $M_\odot$ NS. The strong correlations of $\Lambda, 1.4$ with the linear combinations of $M_0, L_0$ and $K_{sym,0}$ as considered are of particular importance. Since, $\Lambda, 1.4$ is not very well correlated with these nuclear matter parameters individually. The values of the correlation coefficients given in the figure are obtained with the entire set of RMF and SHF models as presented in section III.A. In order to check the model dependence of the correlations, we have determined the correlation coefficients for the sets of RMF and SHF models separately. The results are given in Table III which indicate that the model dependence is only marginal.

In Ref. [61], it was shown that the NS radius $R$ is strongly correlated with a linear combination of $M_0$ and $L_0$ over a wide range of NS masses. This was attributed to the dependence of the pressure on $M_0$ and $L_0$ and to the empirical relation of the star radius with the pressure at several reference densities, e.g. $R \times p(\rho)^{-1/4} = \text{constant for } \rho \sim 1.5 \rho_0$ and NS masses, $1 - 1.4 \, M_\odot$, irrespective of the model [66].

The solid lines in Fig. 5 are obtained using linear re-
We need to know the value of $\Lambda_{1.4}$ in order to exploit the correlations, as presented in Fig. 5, to estimate the values of nuclear matter properties at the saturation density. The GW170817 event provides the upper bound on $\Lambda$ as defined by Eq. (7). We calculate the $\Lambda$ using $m_1 = 1.40 M_\odot$ and $m_2 = 1.33 M_\odot$ such that the chirp mass $M$ is $1.188 M_\odot$ correspond to the GW170817. Fig. 6 shows the variation of $\Lambda_{1.4}$ as a function of $\tilde{\Lambda}$ for all the RMF and SHF models. The correlation between these two quantities is very strong which enables us to express $\Lambda_{1.4}$ in terms of $\Lambda$ as $\Lambda_{1.4} = 0.859 \times \tilde{\Lambda}$.

In order to constraint $\Lambda_{1.4}$ we impose the bounds determined in Refs. [17, 20, 21]. A lower bound of $\Lambda_{1.4} > 344$ is set by the UV/optical/infrared counterpart of GW170817 that imposes $\Lambda > 400$ [21]. Similarly, the gravitational-wave observations set an upper bound $\Lambda_{1.4} < 687$ or $\Lambda_{1.4} < 859$, respectively from the bounds $\tilde{\Lambda} < 800$ [17] and $\tilde{\Lambda} < 1000$ [20]. In the following, we will use these bounds on $\Lambda_{1.4}$ together with Eqs. (12 and 13) to constrain the nuclear matter properties.

In Fig. 7, the slope of the incompressibility coefficient at the saturation density $M_0$ is plotted as a function of $\Lambda_{1.4}$ for fixed values of $L_0$ using Eq. (12). The limiting values of $L_0$ employed in the plot correspond to $L_0 = 51 \pm 11$ MeV [67]. This limit on $L_0$ in conjunction with the bounds on $\Lambda_{1.4}$, as discussed above, constrain the $M_0$ as listed in Table IV. In the same table we also present the values of $M_0$ obtained for $L_0 = 58.7 \pm 28.1$.
The tidal Love number is displayed as a function of symmetry energy slope parameter \( L \). This value is obtained using a Skyrme-like energy density functional by imposing the constraint on the incompressibility slope parameter \( \Lambda \) for different limits on \( \Lambda_{1,4} \) and \( L_0 \). The bounds on \( \Lambda_{1,4} \) are derived from terrestrial, theoretical, and observational constraints. Our results are presented in Table IV, which gives the empirical values of \( M_0 \) and \( K_{\text{sym},0} \) derived for different limits on \( \Lambda_{1,4} \) and \( L_0 \). The bounds on \( \Lambda_{1,4} > 344 \) and \( < 687 \) (MeV) obtained from Fig. 6 are considered. The ranges of \( L_0 = 40 - 62 \) MeV and \( L_0 = 30 - 86 \) MeV are taken from Refs. [67, 68].

| \( L_0 \) (MeV) | \( \Lambda_{1,4} \) (MeV) | \( M_0 \) (MeV) | \( K_{\text{sym},0} \) (MeV) |
|------------------|------------------|-----------------|------------------|
| 40 - 62          | 344 - 687        | 2254 - 3272     | -113 - -52       |
| 30 - 86          | 344 - 687        | 1926 - 3409     | -141 - 16        |

 energies of the isoscalar giant monopole resonance in the \(^{132}\text{Sn}\) and \(^{208}\text{Pb}\) nuclei [70, 71].

We have next considered the range of acceptable values for \( M_0 \) just determined, together with the bounds on \( \Lambda_{1,4} \) and Eq. (13), to set also constraints on \( K_{\text{sym},0} \). The results are presented in Table IV: the ranges \( -113 < K_{\text{sym},0} < -52 \) MeV are obtained for the bounds for the symmetry energy slope from [67] and \( -141 < K_{\text{sym},0} < 16 \) MeV imposing the constraints from [68]. The symmetry energy curvature is a quantity that is still not constrained experimentally. In [72], the authors have obtained from the universality of the correlation structure between the different symmetry energy elements and from some well known nuclear matter properties the range \( K_{\text{sym},0} = -111.8 \pm 71.3 \) MeV. Our bounds discussed above are in a quite good agreement with these values.

Fig. 8 displays the tidal Love number \( k_{2,1,4} \) (top panel)
and the dimensionless tidal deformability $\Lambda_{1.4}$ (bottom panel) as a function of NS radius $R_{1.4}$. It is evident from the Eq. (2) that the tidal deformability depends mainly on the NS radius and the Love number $k_2$. The $\Lambda_{1.4}$ is expected to be strongly correlated with $R_{1.4}$ provided either $k_2$ is model independent or it is correlated with $R_{1.4}$. We observed from Fig. 2 that the value of $k_2$ is sensitive to the model used which might influence the correlation between $\Lambda_{1.4}$ and $R_{1.4}$. However, the $k_{2.1.4}$ is moderately correlated with $R_{1.4}$ (top panel) which ensures the persistence of the strong correlation ($R = 0.98$) between $\Lambda_{1.4}$ and $R_{1.4}$ (bottom panel). The solid line in the bottom panel represents the fitted curve with equation $\Lambda_{1.4} = 9.11 \times 10^{-5} \left(\frac{M}{M_\odot}\right)^{0.13}$. Using the derived bounds on $\Lambda_{1.4}$, the value of $R_{1.4}$ is found to be in the range $11.82 - 13.22$ (11.82 - 13.72) km for $\Lambda_{1.4}$ in the range of 344 - 687 (344 - 859).

V. CONCLUSIONS

The recent observation of GW170817 has provided an upper bound on tidal deformability parameter. Complementing the gravitation waves observation with the detection of the UV/optical/infrared counterpart of GW170817, a lower bound on tidal deformability parameter is suggested [21]. We have used a diverse set of relativistic and non relativistic mean field models to look for correlations of $\Lambda$ with several nuclear matter parameters characterizing the EoS such as the nuclear matter incompressibility and symmetry energy coefficients, and their density derivatives. All the models selected are consistent with the bulk properties of finite nuclei as well as with the observation of NS with mass of $\sim 2M_\odot$. Nevertheless, across these models, the values of $\Lambda$ and of the various nuclear matter parameters associated with different EoSs vary over a wide range.

The tidal deformability is found to be weakly or only moderately correlated with the individual nuclear matter parameters of the EoS. The stronger correlation of $\Lambda$ is found only for specific choices of the linear combinations of the isoscalar and isovector EoS parameters. The parameter $\Lambda$ is strongly correlated with the linear combination of the slopes of incompressibility and symmetry energy coefficients, i.e., $M_0 + \beta L_0$. Further, the parameter $\Lambda$ and the Love number $k_2$ both are strongly correlated with the linear combination of $M_0 + \eta K_{\text{sym},0}$.

We show that the bound on weighted average of tidal deformability for a system of binary neutron star, obtained from complementary analysis [17, 20, 21] of GW170817, yields the tidal deformability for NS with mass $1.4M_\odot$ in the range of $344 < \Lambda_{1.4} < 859$. With the aid of the correlations of $\Lambda_{1.4}$ with linear combinations of nuclear matter parameters as considered together with the bounds on $\Lambda_{1.4}$ and the empirical ranges of $L_0$ obtained in Ref. [67, 68], we have constrained the values of $M_0$ and $K_{\text{sym},0}$ to lie in the intervals $2254 < M_0 < 3631$ MeV and $-112 < K_{\text{sym},0} < -52$ MeV or $1926 < M_0 < 3768$ MeV and $-140 < K_{\text{sym},0} < 16$ MeV, depending on the constraints set on $L_0$. The strong correlation of tidal deformability with the NS radius for a 1.4 $M_\odot$ NS yields $R_{1.4}$ in the range 11.82 – 13.72 km. The precise measurement of tidal deformability will provide an alternative and accurate estimate for $M_0$, $K_{\text{sym},0}$ and $R_{1.4}$.

Appendix A: Mass dependence of $\alpha$, $\beta$ and $\eta$

The coefficients $\alpha$, $\beta$ and $\eta$ are obtained in such a way that they optimize the correlations of $\Lambda$ with the linear combinations $K_0 + \alpha L_0$, $M_0 + \beta L_0$ and $M_0 + \eta K_{\text{sym},0}$. The value of these coefficients are given in Table II for a few selected NS masses. In Figure 9, we plot the mass dependence of $\alpha$, $\beta$ and $\eta$. These coefficients can be easily fitted to the exponential decay like function which can be expressed as $\alpha = -0.13 + 14.87 \exp(-m/0.49)$, $\beta = -1.90 + 265.02 \exp(-m/0.49)$ and $\eta = -1.4 + 29.81 \exp(-m/0.89)$, where the NS mass $m$ is in the unit of solar mass.

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