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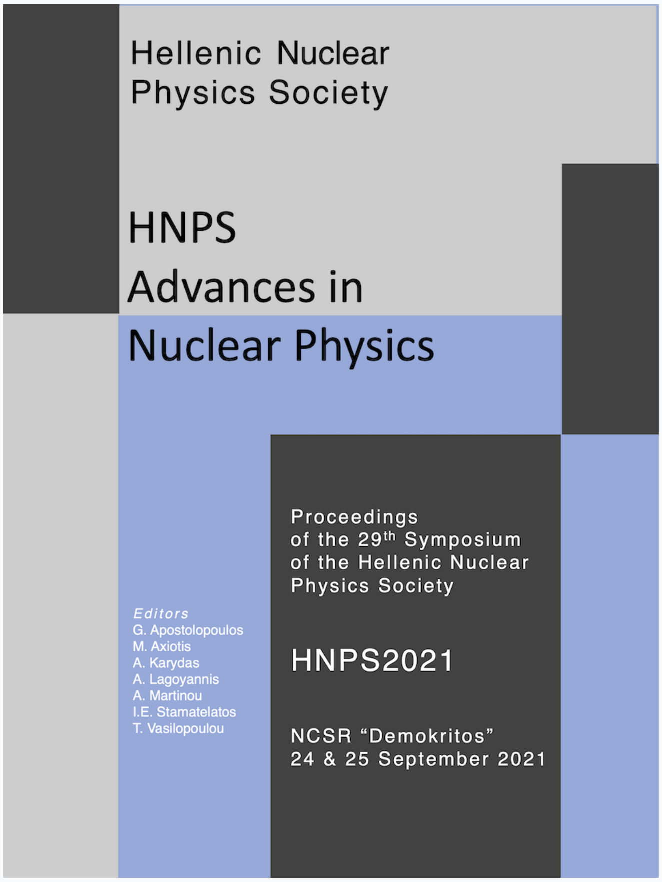

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Studying the speed of sound of dense nuclear matter via the tidal deformability of neutron stars

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Abstract Neutron stars are a natural laboratory for studying dense nuclear matter in its extreme condition. The speed of sound is a microscopic parameter of great interest for studying the equation of state. In this work, we examine possible constraints on the upper bound of the speed of sound. In our study, we use the measured effective tidal deformability from the two recently detected binary neutron star mergers to impose constraints on the equation of state by using the upper bound on the speed of sound. In our approach the stiffness of the equation of state is parametrized via two parameters: the speed of sound and the transition density. Moreover, our study is extended in the case of a very massive neutron star, using the recent detection of the GW190814 system. The tidal deformability and the upper bound on the speed of sound for such a massive neutron star are studied. According to our study, such a massive non-rotating neutron star may be existing. Finally, we postulate the kind of future detections that could be useful to impose further constraints and broaden our knowledge on these open problems.

Keywords equation of state, gravitational waves, neutron stars, speed of sound, tidal deformability

INTRODUCTION

A very interesting unsolved problem in Nuclear Physics is the properties of dense nuclear matter. Neutron stars are a unique tool for studying the dense nuclear matter [1]. Especially, the upper limit of the speed of sound is of great interest because this microscopic quantity affects the equation of state (EoS).

The main assumption for the upper bound of the speed of sound is that it is in agreement with the causality, i.e. the speed of sound cannot be higher than the speed of light [2]. In addition, in Ref. [3] the authors noticed that the observation of neutron stars with two solar masses, in combination with the EoS of hadronic matter at low densities, is not consistent with the conformal limit $c/\sqrt{3}$ of the speed of sound. Also, various studies have been made regarding the effects of the speed of sound on the tidal deformability [4-7].

In general, there are two main considerations regarding the possible upper limit of the speed of sound of dense nuclear matter; (a) the causality which means that the upper bound must be $v_s = c$, and (b) the conformal limit $v_s = c/\sqrt{3}$. Especially, the conformal limit is related to the existence of quark matter in the interior of neutron stars. Hence, the study of the upper bound of the speed of sound is very important (see also Refs. [8-9]).

The main idea that motivated our work is the extraction of possible constraints on the speed of sound and its upper bound by studying the tidal deformability of neutron stars. At this point we notice the presence of a contradiction which is related to the stiffness of the EoS; The observation of neutron stars with high masses favors stiff EoS, while the measured upper limit on the effective tidal deformability from gravitational-wave detectors favors softer EoS. In our study, we parametrized the stiffness of the EoS by using the upper bound of the speed of sound and the transition density, aiming to gain more information on this problem. For this reason we used the recent detections of two binary neutron stars mergers, the GW170817 and GW190425 events [10-12].

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The need of a) a soft EoS at low densities (to be in agreement with the upper limit of the effective tidal deformability) and b) a stiff enough EoS at high densities (to predict the high masses of neutron stars) leads to robust constraints on the EoS. Also, we postulate what kind of future binary neutron stars mergers detections can be suitable (for further details see Ref. [13]).

Furthermore, the detection of the GW190814 event [14], in which the lighter component compact object might be a neutron star, started a lot of discussion regarding the nature of this compact object. Following the hypothesis of the existence of such a massive non-rotating neutron star, we extended our study on the role of the speed of sound in that specific hypothetical scenario [15].

THEORETICAL FRAMEWORK

In our approach we used the following maximum mass configuration, by parametrizing the EoS [16]

$$P(\mathcal{E}) = \begin{cases} P_{crust}(\mathcal{E}), & \mathcal{E} \leq \mathcal{E}_{c-edge} \\ P_{NM}(\mathcal{E}), & \mathcal{E}_{c-edge} \leq \mathcal{E} \leq \mathcal{E}_{tr} \\ \left(\frac{v_s}{c}\right)^2 (\mathcal{E} - \mathcal{E}_{tr}) + P_{NM}(\mathcal{E}_{tr}), & \mathcal{E}_{tr} \leq \mathcal{E}. \end{cases}$$

where P is the pressure, $\mathcal{E}$ is the energy density, and $\mathcal{E}_{tr}$ is the transition energy density. In the region $\mathcal{E} \leq \mathcal{E}_{c-edge}$ we used the equation of Feynman *et al.* [17] and Baym *et al.* [18] for the crust and low densities of neutron star. In the intermediate region $\mathcal{E}_{c-edge} \leq \mathcal{E} \leq \mathcal{E}_{tr}$ we employed an EoS based on the MDI model and data taken from Akmal *et al.* [19], while for $\mathcal{E}_{tr} \leq \mathcal{E}$ the EoS is maximally stiff, with the speed of sound defined as $v_s = c\sqrt{(\partial P/\partial \mathcal{E})_S}$, where S is the entropy. Regarding the two events, GW170817 and GW190425, the speed of sound is fixed on the two values $c/\sqrt{3}$ and c. In addition, we chose various values for transition density which is taken to be $n_{tr} = pn_0$, where n_0 is the saturation density of symmetric nuclear matter ($n_0 = 0.16\, fm^{-3}$) and $p = \{1,1.5,2,3\}$. Therefore, the EoSs are functional of n_{tr} and v_s. For the GW190814 we used eight values for the speed of sound and two values for the transition density.

In order to ensure the continuity in the speed of sound at the transition density, we used the following parametrization

$$\frac{v_s}{c} = \left(\alpha - c_1 \exp\left[-\frac{(n - c_2)^2}{w^2}\right]\right)^{1/2}, \alpha = 1, 1/3$$

where c_1, c_2 and w are fit to the speed of sound and its derivative at n_{tr}, with the demands $v_s(n_{tr}) = [c, c/\sqrt{3}]$ [16] where the speed of sound is treated as a constant. Using the previous equation, the EoS for $n \geq n_{tr}$ can be constructed by combining the recipe of Ref. [20].

Moving on to the tidal effects that are present during the last orbits of the evolution of a binary neutron stars system before the merger, Flanagan and Hinderer [21] noticed that these effects of the inspiral phase are measurable. To be more specific, the reaction of a component neutron star in a binary neutron stars system to the tidal filed is described by the tidal Love number k_2

$$Q_{ij} = -\frac{2}{3} k_2 \frac{R^5}{G} E_{ij} \equiv -\lambda E_{ij},$$

where Q_{ij} is the quadrupole moment, E_{ij} is the tidal field, R is the neutron star radius, G is the gravitational constant, and λ is the tidal deformability. The exact formula for the tidal Love number k_2 is given in Ref. [21,22].

A quantity that is well measured by the gravitational wavews detectors, regarding the binary neutron stars systems, is the chirp mass of the system $\mathcal{M}_c$, which is given below [11]

$$\mathcal{M}_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = m_1 \frac{q^{3/5}}{(1+q)^{1/5}},$$

where m_1 is the heavier component neutron star and m_2 is the lighter one. Therefore, the binary mass ratio $q = m_2/m_1$ lies within $0 \leq q \leq 1$.

The information from the tidal deformation during the inspiral phase of the binary system is imprinted in the gravitational wave signal through the effective tidal deformability [11]

$$\tilde{\Lambda} = \frac{16}{13} \frac{(12q+1)\Lambda_1 + (12+q)q^4\Lambda_2}{(1+q)^5},$$

where Λ_i is the dimensionless tidal deformability, given below [11]

$$\Lambda_i = \frac{2}{3} k_2 \left(\frac{R_i c^2}{M_i G}\right)^5 \equiv \frac{2}{3} k_2 \beta_i^{-5}, \qquad i = 1, 2.$$

RESULTS AND DISCUSSION

In the first place, we studied the upper bound on the speed of sound. Especially, we focused on two cases; the lower limit $(v_s/c)^2 = 1/3$ and the upper one $(v_s/c)^2 = 1$. Additionally, we used four values for the transition density, $n_{tr} = \{1,1.5,2,3\}\, n_0$ [13]. In Fig. 1 we show the mass-radius (M-R) diagram. The brown EoSs correspond to the $(v_s/c)^2 = 1/3$ limit, while the green ones correspond to the $(v_s/c)^2 = 1$. For each value of n_{tr} there are two branches, with the lower (higher) limit for the speed of sound corresponding to lower (higher) mass. As the transition density increases, the EoS becomes softer. In general, the lower limit $(v_s/c)^2 = 1/3$ leads to softer EoS, compared to the upper limit $(v_s/c)^2 = 1$. The shaded regions indicate the GW170817 event (blue and orange shaded regions [10]) and the NICER's observation (black shaded region [23]). By using the observational data, the EoSs with $n_{tr} = n_0$ should be excluded, for bouth values of speed of sound.

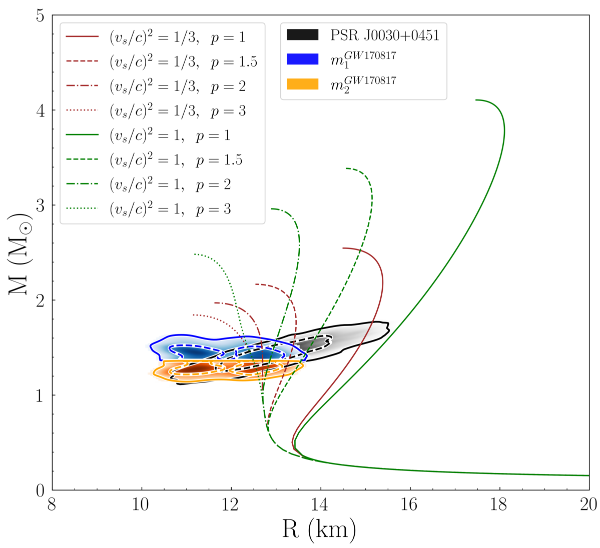

Fig. 1. *Mass-radius diagram for an isolated and non-rotating neutron star, for both speed of sound bounds. The solid (dashed) contour boundaries describe the 90% (50%) confidence interval.*

Furthermore, we used the measured upper limit on $\tilde{\Lambda}$ from the two events, GW170817 and GW190425[11-12]. We chose the component masses to bary within $m_1 \in (1.36, 1.60) M_\odot$, $m_2 \in (1.16, 1.36) M_\odot$ for the GW170817 event and $m_1 \in (1.654, 1.894) M_\odot$, $m_2 \in (1.45, 1.654) M_\odot$ for the GW190425 event. The chirp mass for the GW170817 (GW190425) event is $\mathcal{M}_c = 1.186 M_\odot$ ($\mathcal{M}_c = 1.44 M_\odot$) [11-12]. By using these ranges, we ensure that $q \leq 1$.

In Fig. 2 we display $\tilde{\Lambda}$ as a function of n_{tr} for both bounds of the speed of sound and the two events, GW170817 (left panel of Fig. 2) and GW190425 (right panel of Fig. 2). By using the measured upper limits on $\tilde{\Lambda}$, we found that for the GW170817 event the lower value of the transition density is $1.626 n_0$ for $v_s = c/\sqrt{3}$ and $1.805 n_0$ for $v_s = c$. For the second event (GW190425), the corresponding lower value is $1.015 n_0$ for $v_s = c/\sqrt{3}$ and $1.216 n_0$ for $v_s = c$. Therefore, the GW170817 event leads to more stringent constraints on the EoS, compared to the GW190425 event. Especially, our finding for the $v_s = c/\sqrt{3}$ bound is in agreement with outher studies (see Ref. [24]).

Beyond the so far observed binary neutron stars mergers, the detection of the GW190814 event started a wide discussion about the nature of the lighter component compact object with mass $\sim 2.6 M_\odot$. Moving a step forward from our previous work, we wanted to examine what would mean the existence of such a massive non-rotating neutron star. In our hypothesis, we concentrated on two transition densities $n_{tr} = [1.5, 2] n_0$ and eight values for the speed of sound [15]:

$$(v_s/c)^2 = [1/3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1]$$

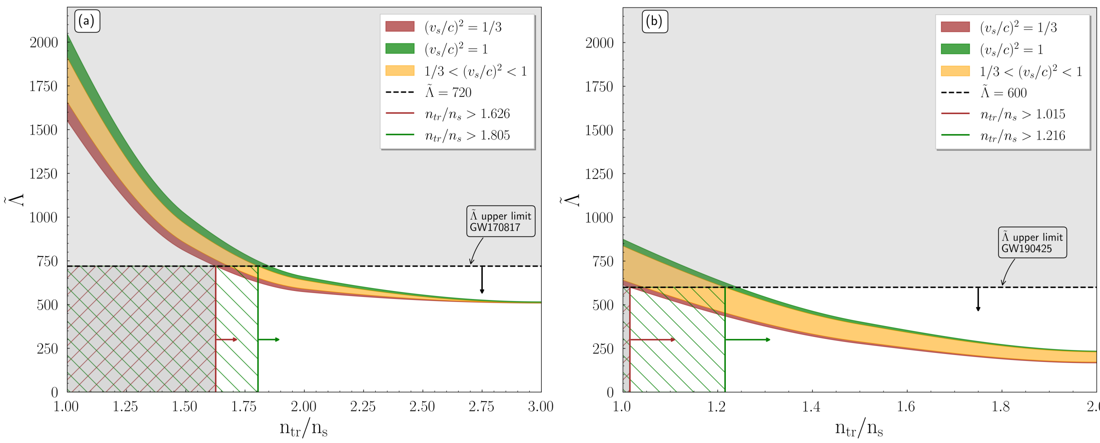

Fig. 2. *$\tilde{\Lambda}$ as a function of n_{tr} for the event (a) GW170817 (left panel) and (b) GW190425 (right panel). The brown (green) shaded region corresponds to the $v_s = c/\sqrt{3}$ ($v_s = c$) bound, while the yellow color indicates the intermediate values.*

Fig. 3(a) displays the corresponding M-R diagram. In general, there are two main branches of EoSs, according to the values of transition density. The purple horizontal line shows the mass of the $\sim 2.6 M_\odot$ compact object of Ref. [14]. In general, the EoSs with lower transition density are stiffer compared to the EoSs with higher n_{tr}. Also, the EoSs with higher value of speed of sound lead to higher masses. Therefore, a high enough speed of sound value is needed for the existence of such a massive non-rotating neutron star.

Fig. 3(b) shows the trend of the maximum mass values. By applying a fitting formula, we found that the speed of sound must be (a) $(v_s/c)^2 = 0.485$ ($n_{tr} = 1.5 n_0$), and (b) $(v_s/c)^2 = 0.659$ ($n_{tr} = 2 n_0$). Hence, a high enough value for the speed of sound, even above the conformal limit $v_s = c/\sqrt{3}$, is needed.

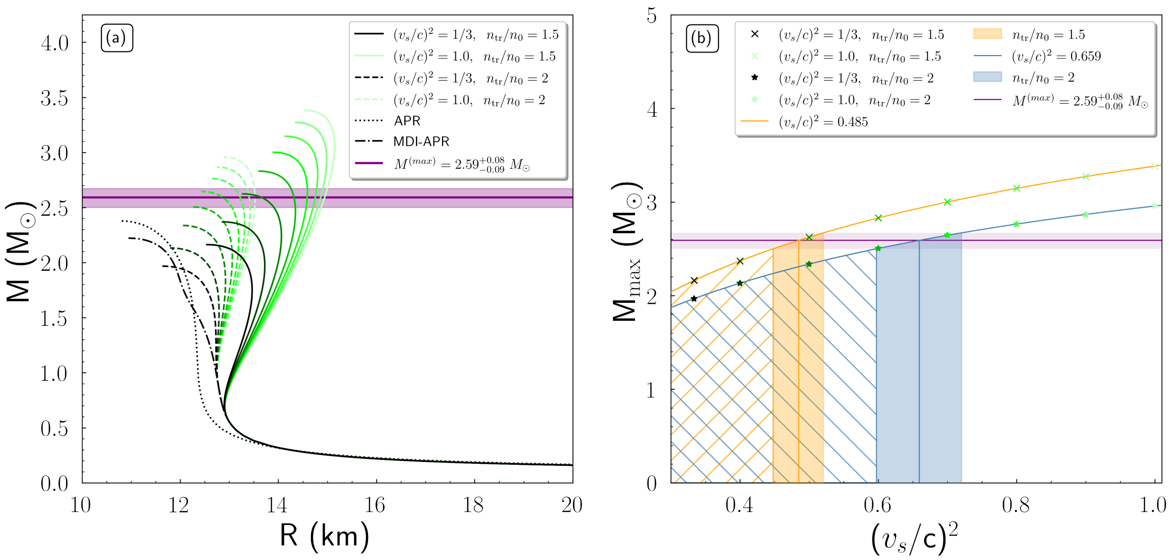

Fig. 3. *(a) M-R diagram for an isolated non-rotating neutron star. (b) M_{max} of a non-rotating neutron star as a relation to the speed of sound bounds $(v_s/c)^2$.*

CONCLUSIONS

The study of the EoS by using the two binary neutron stars mergers events (GW170817 and GW190425) allowed us to impose constraints on the speed of sound and the transition density. Our method was based on the usage of the measured upper limit on $\tilde{\Lambda}$. We employed the APR1-MDI EoS for two bounds of the speed of sound; the causal bound $v_s = c$ and the conformal one $v_s = c/\sqrt{3}$.

We found that for the GW170817 event v_s must be lower than the conformal limit $v_s = c/\sqrt{3}$ at least up to density $n_{tr} \approx 1.6n_0$, and lower than the causality $v_s = c$ at least up to $n_{tr} \approx 1.8n_0$. For the GW190425 event, the corresponding values are $n_{tr} \approx n_0$ for the lower bound and $n_{tr} \approx 1.2n_0$ for the upper one. Hence, the GW170817 provides more stringent constraints, leading us to postulate that these kind of events would be more informative.

For the GW190814 event, we examined the hypothesis of a non-rotating neutron star with $M \approx 2.6M_\odot$. The study of the maximum mass of eash EoS as a function of v_s allowed us to extract a specific value for each n_{tr}. To be more specific, for the $n_{tr} = 1.5n_0$ the speed of sound lies within $(v_s/c)^2 \in [0.448, 0.52]$, while for $n_{tr} = 2n_0$ the corresponding region is $(v_s/c)^2 \in [0.597, 0.72]$. Hence, if such a massive non-rotating neutron star exists, it would requires the violation of the conformal limit $v_s = c/\sqrt{3}$. This hypothesis shows the important role of the speed of sound and how it affects the EoS, in combination with n_{tr} .

References

[1] S. L. Shapiro, S. A. Teukolsky, “Black Holes, White Dwarfs, and Neutron Stars”, John Wiley and Sons, New York (1983)
[2] Ya. B. Zel’dovich,vSov. Phys. JETP 14, p. 1143 (1962)
[3] P. Bedaque et al., Phys. Rev. Lett. 114, p. 031103 (2015)
[4] C. C. Moustakidis et al., Phys. Rev. C 95, p. 045801 (2017)
[5] B. Reed et al., Phys. Rev. C 101, p. 045803 (2020)
[6] E. D. Van Oeveren et al., Phys. Rev. D 95, p. 083014 (2017)
[7] Y.-L. Ma et al., Phys. Rev. D 100, p. 114003 (2019)
[8] G. Baym et al., Rept. Prog. Phys. 81, p. 056902 (2018)
[9] E. Annala t al., Nat. Phys. 16, p. 907 (2020)

[10] B. P. Abbott et al., Phys. Rev. Lett. 121, p. 161101 (2018)
[11] B. P. Abbott et al., Phys. Rev. X 9, p. 011001 (2019)
[12] B. P. Abbott et al., Astrophys. J. Lett. 892, p. L3 (2020)
[13] A. Kanakis-Pegios et al., Phys. Rev. C 102, p. 0558013 (2020)
[14] R. Abbott et al., Astrophys. J. 896, p. L44 (2020)
[15] A. Kanakis-Pegios et al., Symmetry 14, p. 183 (2021)
[16] Ch. Margaritis et al., Phys. Rev. D 101, p. 043023 (2020)
[17] R. Feynman et al., Phys. Rev. 75, p. 1561 (1949)
[18] G. Baym et al., Astrophys. J. 170, p. 299 (1971)
[19] A. Akmal et al., Phys. Rev. C 58, p. 1804 (1998)
[20] I. Tews et al., Astrophys. J. 860, p. 149 (2018)
[21] E. E. Flanagan et al., Phys. Rev. D 77, p. 021502(R) (2008)
[22] T. Hinderer, Astrophys. J. 677, p. 1216 (2008)
[23] M. C. Miller et al., Astrophys. J. Lett. 887, p. L24 (2019)
[24] S. K. Greif et al., Mon. Not. Roy. Astron. Soc. 485, p. 5363 (2019)