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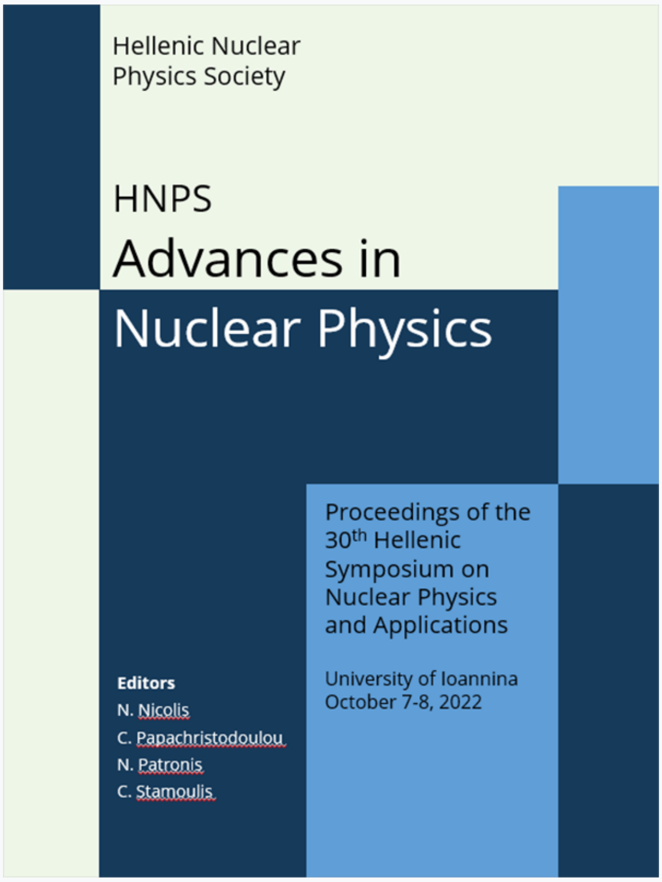

The role of temperature on the tidal deformability of an inspiraling binary neutron star system

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The role of temperature on the tidal deformability of an inspiraling binary neutron star system

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Abstract The detection of gravitational waves emitted by binary neutron star mergers constitutes a very promising tool for studying the properties of dense nuclear matter. The lack of exact evidence for a zero-temperature scenario regarding the inspiral phase of a coalescing binary neutron star system raises the question of the role of temperature. Based on some theoretical studies, the existence of temperature (about a few MeV) before the merger is possible. The main goal of our work is to study the thermal effects on the tidal deformability of neutron stars, by taking into consideration the observations of binary neutron star mergers. In our study, we used various hot equations of state, both isothermal and adiabatic, and for different nuclear models. The main finding is that, for temperature below 1 MeV, the tidal deformability as a function of the neutron star mass remains insensible. In the adiabatic case, this behavior is present up to entropy per baryon S=0.2 k_B.

Keywords equation of state, neutron stars, tidal deformability, temperature, binary neutron star system

INTRODUCTION

The detection of gravitational waves originated from binary black holes, binary neutron star and black hole-neutron star systems is a very informative source for physics [1,2]. The entire process of a binary neutron star system is of great interest because of its useful insights on the properties of both cold and hot nuclear matter. In our work (for more details see Ref. [3]), we combined theoretical predictions and observational constraints via the tidal deformability [4-11].

According to theoretical statements, the temperature of a neutron star in a binary system before the merger could be a few MeV [12-16]. Arras and Weinberg [17] suggested a main mechanism for the conversion of the mechanical energy into heat in the interior of a neutron star. Furthermore, Meszaros and Rees [12] noticed that in the late phase of the inspiral of a binary neutron star system, the tidal effects can lead to a heat. Similar results were found in various studies [13,14], while a relevant discussion has been unfolded recently [15,16].

Numerous studies suggested the presence of tidal heating effects, independently of the source that causes it [18-20]. Moreover, the meltdown of the crust during the inspiral phase has been studied in Ref. [21]. Additionally, the heat blanketing envelopes of neutron stars have been studied in Ref. [22]. As a general remark, the important role of the viscosity regarding neutron stars has risen, affecting the heating of a component neutron star in a binary system. The predictions for the amount of heating are focused in the following interval T=0.01-10 MeV. At this point, we notice that the tidal deformability is very sensitive to the applied equation of state (EoS). Especially, it depends on the tidal Love number k_2 and the star's radius R. Hence, the study of the temperature effect in the tidal deformability is of great interest, since the latter can be detected and constrained from the gravitational waves.

The main goal of our work was the study of how the temperature affects the tidal deformability of a neutron star, during the inspiral phase. In our study, we focused on the case of isothermal matter in the interior of neutron stars, by using various sets of EoSs, for temperatures in the range T=0.01-1 MeV [23-27]. More details about the construction of hot EoSs can be found in Refs. [16, 28-34].

The lack of theoretical studies about the thermal effects on tidal deformability, led us to this work.

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The important role of the tidal deformability, as it connects the EoS of dense nuclear matter to the macroscopic quantities of neutron stars, emphasizes this kind of study.

We underline that the study of the isothermal equilibrium of the star is not the most realistic. However, as a first order approach, it is more realistic than the cold star consideration. At the range of temperature of this study, the structure of the core of neutron stars is not affected too much. On the contrary, the crust is much more sensitive to the temperature effects. Nevertheless, in the mass range that is mainly measured from gravitational waves ($1.2 - 1.6\ M_\odot$), the radius and consequently the tidal deformability, are quite sensitive to the structure and size of the crust. Moreover, we extended our study to isentropic (adiabatic) EoSs for entropy S<1 (in k_B units), considering the neutron star to be in an adiabatic equilibrium.

WARM MATTER OF NEUTRON STARS

Regarding the EoSs in the interior of neutron stars at finite temperature, as well as entropy per baryon, we employed the work of Koliogiannis and Moustakidis [27]. To be more specific, we used the data for the energy per particle for the symmetric nuclear matter and pure neutron matter, regarding the APR-1 EoS [35], and the momentum-dependent interaction model. This parameterization is applied for the construction of three isothermal EoSs with T=[0.01,0.1,1] MeV in a beta equilibrium state, and three isentropic EoSs with S=[0.1,0.2,0.5] and proton fraction Y_p=0.2.

For the core of neutron stars we considered the absence of neutrinos in adiabatic EoSs (to simulate the increment of temperature due to merger), in both isothermal and adiabatic profiles. The exact relation for the chemical potentials $\mu_i, i = \{e, p, n\}$ is

$$\mu_e = \mu_n - \mu_p = 4I(n,T)[F(n,T,I=1) - F(n,T,I=0)],$$

where F(n,T,I) is the free energy per particle, and I=1-2Y_p is the asymmetry parameter. We assumed that the EoS contains only protons, neutrons, and electrons.

The density of electrons is given by

$$n_e = \frac{2}{(2\pi)^3} \int \frac{d^3k}{1 + \exp\left(\frac{\sqrt{\hbar^2 k^2 c^2 + m_e^2 c^4}}{T}\right)}$$

We notice that in the cace of adiabatic profile, the proton fraction is almost constant. The following expressions describe the energy density and pressure inside the core of neutron stars

$$E(n,T,I) = E_b(n,T,I) + E_e(n,T,I),$$
$$P(n,T,I) = P_b(n,T,I) + P_e(n,T,I).$$

In the case of the crust of neutron stars ($n_b < 0.08\ fm^{-3}$), for both profiles the EoSs are given by tabulated EoSs with finite temperature from StellarCollapse (for more details see Ref. [3]). For the crust region of the isothermal profile we used the EoSs of Ref. [23]. In all cases the proton fraction remains constant, Y_p=[0.1,0.2,0.3] leading to a total of nine EoSs. In adiabatic profile, for the crust we used the EoSs of Ref. [23] and Ref. [24]. In this case, the proton fraction matches the one of the cores, leading to a total of six EoSs.

In addition, we employed the EoSs of Lattimer and Swesty [23], Shen *et al.* [24], Banik *et al.* [25], and Steiner *et al.* [26] at full range, by considering the proton fraction to be constant, Y_p=0.1.

TIDAL DEFORMABILITY

One important source for the gravitational wave detectors is the emission of gravitational waves from the late phase of an inspiraling binary neutron star system, just before the merger [36-39]. During this phase, the tidal effects can be measured [37]. The exact relation which describes the tidal field is given below

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

where k_2 is the tidal Love number which describes the reaction of a neutron star to the tidal field and depends on the EoS, R is the neutron star's radius, and $\lambda = 2R^5 k_2/3G$ is the tidal deformability. The exact description about k_2 is given in Refs. [37, 38].

A well constrained quantity by the detectors is the so-called chirp mass of the system, which is given below [1]

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

where m_1 (m_2) is the mass of the heavier (lighter) component neutron star. Therefore, the binary mass ratio q lies inside the range $0 < q \leq 1$.

Another well measured quantity is the effective tidal deformability $\widetilde{\Lambda}$ [1],

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

where Λ_i is the dimensionless tidal deformability [1]

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

RESULTS AND DISCUSSION

In our study we used EoSs which are based on the work of Ref. [27]. Especially, we follow the procedure of Ref. [27] for the construction of the neutron star's core using the MDI+APR1 EoS, for both isothermal and adiabatic profiles. We note that in all profiles, the EoSs contain only protons, neutrons, and electrons. Regarding the crust region, we employed the EoSs of Lattimer and Swesty [23] for the isothermal profile, while for the adiabatic one, we used the EoSs of Lattimer and Swesty [23] and Shen *et al.* [24]. In more detail, in the isothermal case, the tabulated finite temperature EoSs contain entries up to $n_b = 10^{-13} fm^{-3}$, which in this case we consider to be the surface of the neutron star ($n_{surf}^{iso} = 10^{-13}\ fm^{-3}$). On the other hand, in the adiabatic EoSs, we chose a common value, $n_b = 10^{-15} fm^{-3}$, and extrapolate the EoSs for the crust until this value, i.e. $\log(n_b) - \log(E)$ and $\log(n_b) - \log(P)$. Hence, the surface of the adiabatic EoSs is at $n_{surf}^{ise} = 10^{-15} fm^{-3}$. To be more specific, we used the hot EoSs of Lattimer and Swesty [23], Shen *et al.*, [24], Banik *et al.* [25], and Steiner *et al.* [26]. In addition, we employed the MDI+APR1 EoS which is suitable for the description of both cold and hot neutron star matter [27, 40].

Figure 1 indicates the mass-radius relation for a) the four different nuclear models and various values of temperature (the different line styles and family colors indicate the different models, while the higher temperature corresponds to the lighter color in each case; the same holds for the isothermal profile's figures) and b) the MDI+APR1 EoS for different values of temperature and proton fraction. In all cases as the temperature increases, the radius also increases (for a fixed value of mass). This behavior is clearer for much higher values of temperature. Moreover, the increase of the proton fraction on the warm crust leads to the increase of the size of the neutron star, amplifying the effect of temperature.

In Figure 2, we represent the temperature and proton fraction effects on the tidal parameters k_2, y_R,, and λ for all nuclear models (top panel) and the MDI+APR1 EoS (bottom panel). As a general remark from the top panel of Figure 2, as the temperature increases the k_2 decreases, but simultaneously y_R increases for all EoSs. We notice that the latter parameter depends mainly on the neutron star structure. While the radius and k_2 are sensitive to the temperature, the tidal deformability is not, as it is shown on

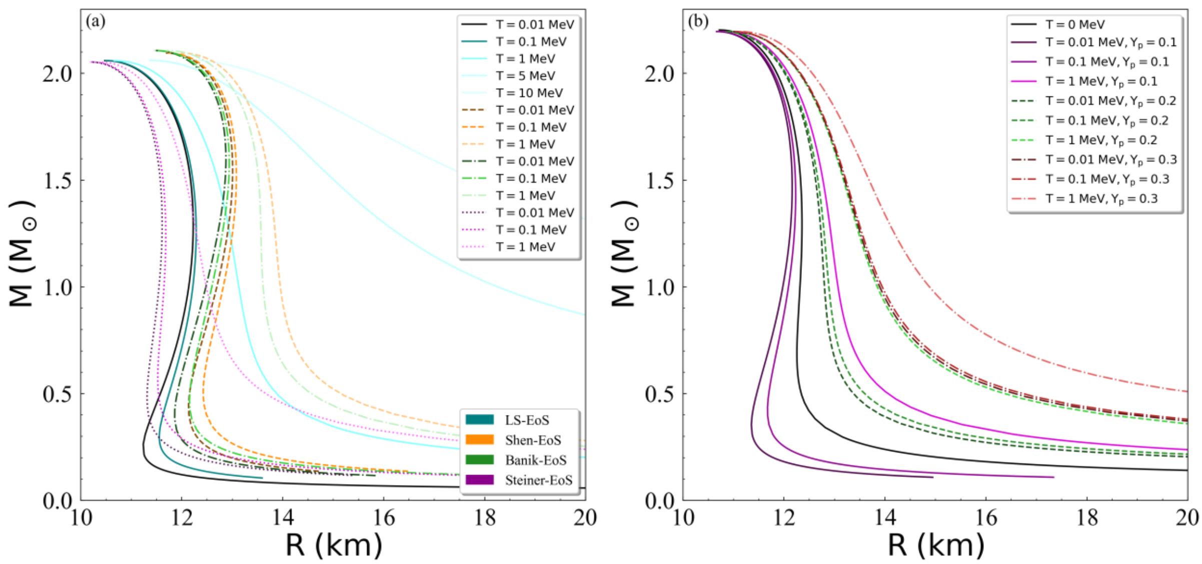

Figure 1. *Mass-radius diagram for (a) the four different nuclear models for various values of temperature and (b) various values of temperature and proton fraction for the MDI+APR1 EoS. In panel (a), the blue family of curves corresponds to the Lattimer and Swesty EoSs [23], the orange one to the Shen et al. [24], the green one to the Banik et al. [25], and the purple one to the Steiner et al. [26].*

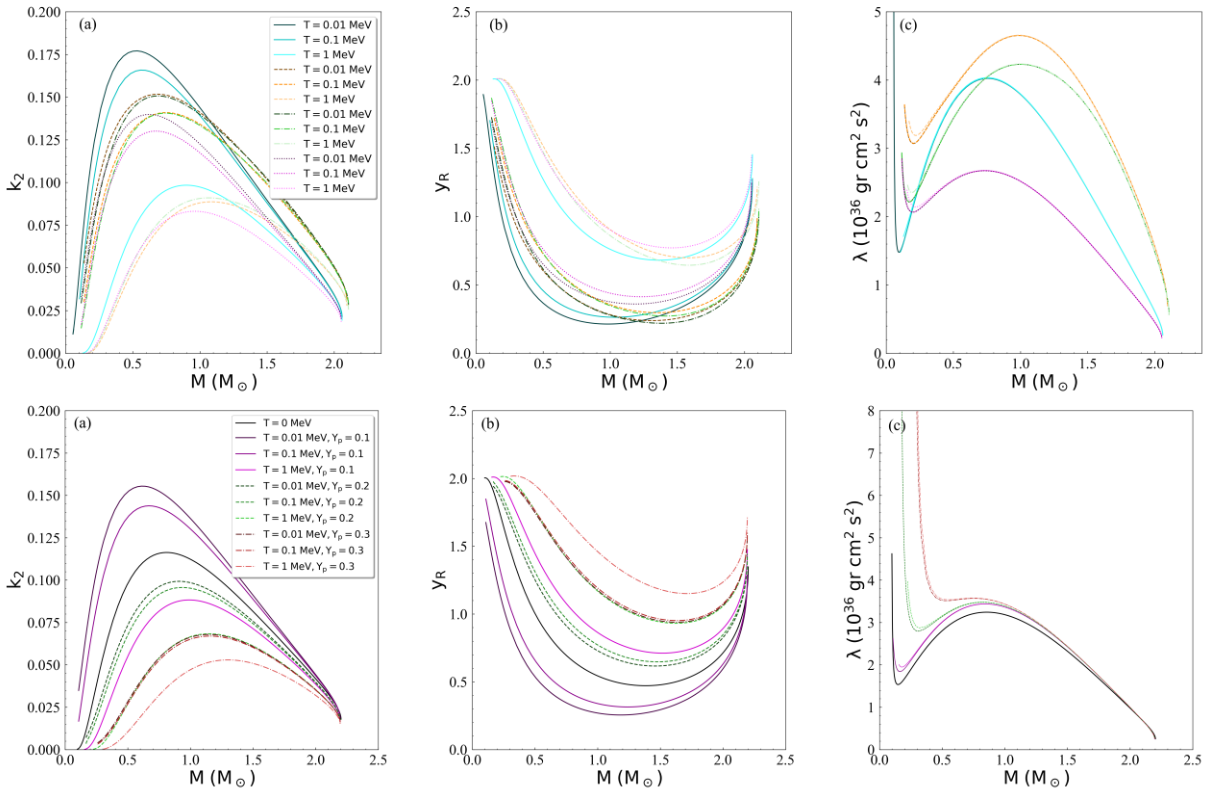

Figure 2. *Temperature effects on the tidal Love number k_2, parameter y_R, and tidal deformability λ for various values of temperature and for the four different nuclear models (top panel) and the MDI+APR1 EoS under different values of proton fraction [27] (bottom panel). The curves of diagrams (b) and (c) correspond to the legend of the diagram (a), for each panel (top and bottom) respectively. The color of the curves on the top panel corresponds to those of the left panel of Figure 1.*

the top panel in Figure 2(c). We underline there is not any clear theoretical explanation for this kind of behavior. Exploring further this aforementioned behavior, we found that for values of temperature up to T=1 MeV the product $\lambda \sim k_2 R^5$ holds. In the bottom panel of Figure 2 the effect of the proton fraction on λ is shown. This effect is too small, and it is present mainly on the very low mass region $(M \lesssim 1\ M_{\odot})$ which is out of interest in our study. Despite the differentiation of the EoSs in the panels (a) and (b) for the various values of proton fraction and temperature, this behavior evaporates in the $\lambda - M$ diagram, leading the EoSs to be identical for high neutron star masses.

Figure 3 shows the effect of the temperature and proton fraction on $\tilde{\Lambda}$ for the MDI+APR1 EoS, by using the binary neutron star mergers [1,2]. For the purpose of our study, we used the proposed values for the chirp mass and the component masses (under minor modification for the GW190425 event, so that $q \leq 1$) of both events.

Especially, Figure 3(a) corresponds to the GW170817 event, while Figure 3(b) corresponds to the GW190425 one. In similar way to the behavior of tidal deformability for a single neutron star, all the EoSs have an identical behavior regardless of the value of temperature, except from the cold case. Another remark is that the thermal effects are present mainly on the GW170817 event, which has lower chirp mass than the GW190425 one. Therefore, we expect that binary neutron star systems with lower component masses could be more suitable compared to those with higher ones.

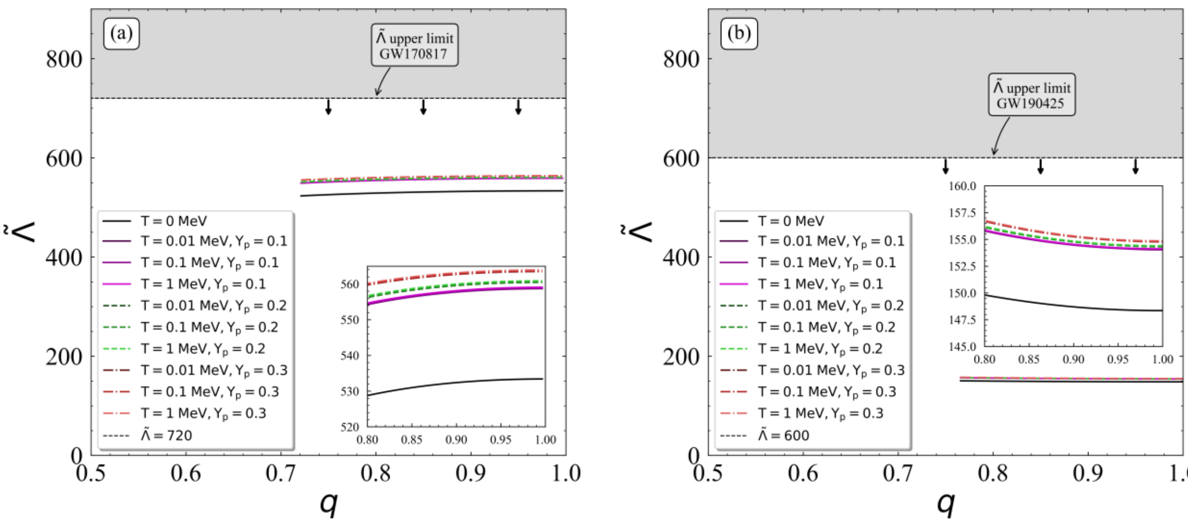

Figure 3. *Temperature effects on* $\tilde{\Lambda}$ *as a function of q for various values of temperature and proton fraction for the MDI+APR1 EoS and for the (a) GW170817 and (b) GW190425 event, respectively [1,2]. The black curve corresponds to the cold EoS. The gray shaded regions indicate the measured upper limit on* $\tilde{\Lambda}$ *for each event.*

Furthermore, we used a set of adiabatic EoSs under the consideration that the entropy per baryon is fixed. In this case, the gradient of the temperature is regulated to ensure constant entropy in the interior of the star. To be more specific, we employed two cases of adiabatic EoSs (according to the crust approach) with S=[0.1,0.2,0.5] (in k_B units).

Figure 4 shows the mass-radius diagram for the two EoSs and the three specific values of the entropy that we used in our study. The thermal effects are insignificant for high neutron star masses. On the other hand, for lower masses, especially in the range we are interested, around $M = 1.4M_{\odot}\$$, there is an increase in the radius of the star as the temperature increases.

Moreover, in Figure 5 one can observe the effects of entropy on $k_2, y_R,$ and λ. The thermal effects are negligible for $k_2, y_R,$ and consequently for λ. Especially, the two set of EoSs lead to similar predictions for each value of the entropy (regardless of the EoS) and depend mainly on the values of the entropy as displayed in Figure 5(b).

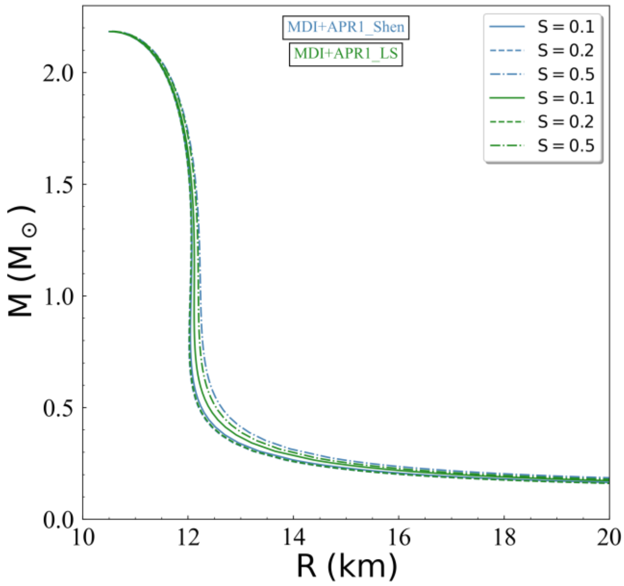

Figure 4. *Mass-radius diagram for different values of S (in units of k_B) and for both crust considerations. The blue (green) curves indicate the Shen et al. [24] (Lattimer and Swesty [23]) crust approach, respectively.*

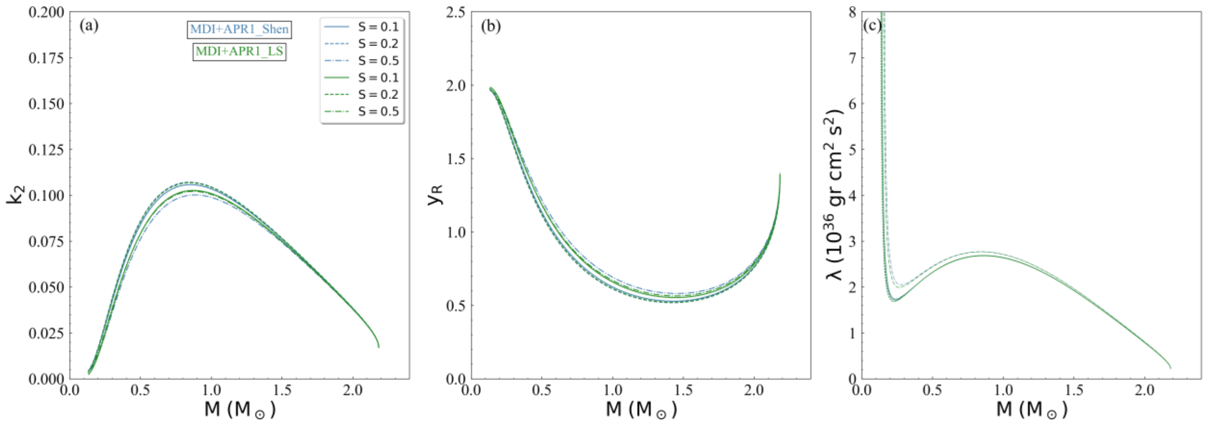

Figure 5. *Entropy effects on tidal parameters, for both crust approaches. The blue (green) curves indicate the Shen et al. [24] (Lattimer and Swesty [23]) crust consideration. The curves of panels (b) and (c) correspond to the legend of the panel (a).*

CONCLUSIONS

According to our knowledge, this is the first effort to study the effect of temperature on the tidal deformability during the inspiral phase of a binary neutron star system. According to numerous studies, the existence of temperature of about a few MeV before the merger, is possible. In our work, we studied how the temperature affects the tidal deformability, for both a single neutron star and a binary neutron star system, by using the detections of binary neutron star mergers from the gravitational-waves point of view. According to our study, the main finding is that even if the effect of temperature is important for k_2 and y_R parameters, this effect is negligible for the tidal deformability λ for temperature up to T<1 MeV, regardless of the EoS that we used. In addition, it is of great importance an accurate measure of neutron star's radius, so that we could obtain useful information regarding the temperature. To conclude, we expect that future detections of binary neutron star mergers could shed more light on the open question of the role of temperature.

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