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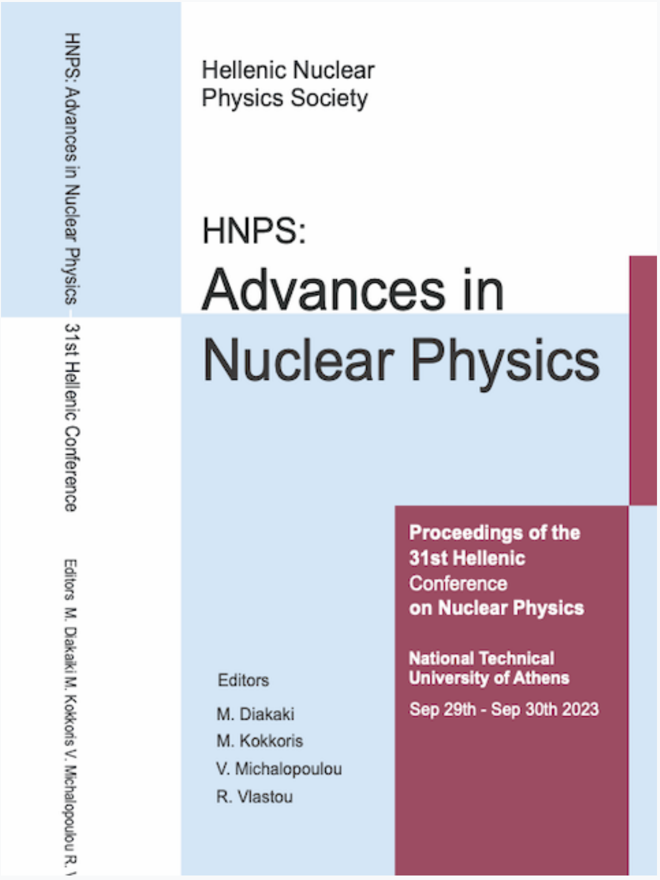

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Constraining the hypothetical X17 boson from compact objects observations

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Abstract We investigate the hypothetical X17 boson on neutron stars and Quark Stars (QSs) using various hadronic Equation of States (EoSs) with phenomenological or microscopic origin. Our aim is to set realistic constraints on its coupling constant and the mass scaling, with respect to causality and various possible upper mass limits and the dimensionless tidal deformability $\Lambda_{1.4}$. In particular, we pay special attention on two main phenomenological parameters of the X17, the one is related to the coupling constant g that it has with hadrons or quarks and the other with the in-medium effects through the regulator C. Both are very crucial concerning the contribution on the total energy density and pressure.In the case of considering the X17 as a carrier of nuclear force in Relativistic Mean Field (RMF) theory, an admixture into vector boson segment was constrained by 20% and 30%. In our investigation, we came to the general conclusion that the effect of the hypothetical X17 both on neutron and QSs constrained mainly by the causality limit, which is a specific property of each EoS, and it depends on the interplay between the two main parameters, the interaction coupling g and the in-medium effects regulator C. These effects are more pronounced in the case of QSs concerning all the bulk properties.

Keywords X17 Boson, Neutron star, Quark Stars, Equation of State

INTRODUCTION

In 2016 an article of Krasznahorkay *et al.* appeared [1], where an anomaly in angular correlation of the e^-e^+ decay of the 1^+ excited level of ^{8}Be nucleus at 18.15 MeV reported, and specifically observed enhancement at folding angles. Since first report till today, Krasznahorkay and his group, reported in addition the same anomaly –observed in the angular correlation of the e^-e^+ emission– in the excited states of ^{4}He and ^{12}C. The reported anomalies at a folding angles was interpreted as a signature of a new neutral boson with a mass of about m_X=17 MeV. These reported observations placed the hypothetical X17 boson as a dark matter candidate and in that spirit since then, several theoretical works pursued this claim. However, an explanation relating this particle to the QCD vacuum was also proposed, in the conjecture that the 17 MeV particle could mediate the nucleon-nucleon interactions at large distances in an unbound cluster configuration. Since the assumption that the 17 MeV boson is the only carrier of nuclear interactions is somewhat extreme, we investigated the possible influence of the hypothetical 17 MeV boson on nuclear matter and its influence on the structure of the compact astrophysical objects like neutron stars [2]. A further investigation [2], explores the hypothetical 17 MeV boson in the frame of the Relativistic Mean Field (RMF) theory, constructing a universal Equation of State (EoS) that satisfies all of the well known experimental constraints, from finite nuclei, heavy ion collisions all the way to the neutron stars, allowing a reproduction in masses from 1.4 up to 2.5 solar masses. In our present work, having as a candidate a 17 MeV boson (hereafter X17), we investigating the effects of the non–Newtonian gravity together with a series of different models - hadronic EoSs with phenomenological and realistic or microscopic origin, from the RMF to the Momentum Dependent Interaction (MDI) model and QSs. Our main motivation is to set realistic constraints on the X17

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coupling constant g and the scaling of its mass, which is affected by the changes in the baryon density well above its saturation value inside the neutron star and QS. All of our research is compared with astrophysical observations, reported from LIGO-VIRGO and pulsar observations.

THE NUCLEAR MODELS

We employ two different nuclear models: a) The Relativistic Mean Field (RMF) model [3] and the Momentum Dependent Interaction model (MDI) [4]. In the case of the RFM model we consider the possibility that the hypothetical 17 MeV boson could contribute as a second vector boson and we can write an effective mass term in the following form

$$\mathrm{m_v^*}^2 = \alpha_\chi^2 \mathrm{m}_\chi^2 + \left(1-\alpha_\chi\right)^2 \mathrm{m}_\omega^2$$

where a_X is the admixture coefficient of the m_X = 17 MeV boson to the total vector potential. Using two different values for the admixture coefficient (a_X: 0.2(20%, m^*_v = 626 MeV) and 0.3(30%, m^*_v = 547.8 MeV) and increasing the value on the standard ρ-coupling by 5% and 10% (effective ρ-coupling: g^*_ρ, respectively, we constructed a set of 13 EoSs, fulfilling experimental constraints, where properties of nuclear matter and finite nuclei were considered.

In the case of the MDI model, by suitable choice of the parameters we can regulate the stiffness of the corresponding EoS. This stiffness is well reflected by the values of the slope parameter L. The contribution of the X17 bosons on the total energy density reads

$$\mathcal{E}_{\mathcal{B}} = \pm \frac{(\hbar c)^3}{2} \left(\frac{\mathrm{g}}{\mathrm{m_B c^2}}\right)^2 \mathrm{n_b^2}$$

In previous work [5,6] the range of the ratio $(g/m_Bc^2)^2$ was varying between [0-200] GeV^{-2}. However, in the present study we consider that the coupling varies in the interval [0.001-0.022] which corresponds (m_Bc^2=17 MeV) the interval ratio $(g/m_Bc^2)^2$ for [0.00346,1.675] GeV^{-2}. Moreover, According to Brown and Rho [7], the in-medium modification of the mesons follows the linear scaling:

$$m_B^* \equiv m_B \left(1 - C\frac{n_b}{n_0}\right) \quad (MeV)$$

We consider, following the suggestion in Ref. [5] that, at least at low densities, in-medium modification of X17 mass takes a similar form to those proposed in Ref [7]. The parameter C is fixed in order the predicted EoS to be compatible with the bulk properties in symmetric nuclear matter (E_{bind}=-16 MeV and n_0 =0.16 fm^{-3}). A suitable parametrization is also the following:

$$m_B^* \equiv \frac{17}{1-C}\left(1 - C\frac{n_b}{n_0}\right) \quad (MeV)$$

which ensures that at the saturation density n_0, m_B^*=17 MeV. To good approximation the contribution of the WILB begins after the crust-core interface.

In the present work we use the Color-Flavor Locked (CFL) model for the Quark Stars (QSs), following the previous work of Lugones and Horvath [8]. In particular, we use the lowest order approximation, in which the EoSs are given in a simple and analytical form and in particular the contribution of the pairing correlations and the mass of the strange quark are provided explicitly. The contribution on the energy density of the bosons is given by

$$\mathcal{E}_{\mathcal{B}} = \pm \frac{9(\hbar c)^3}{2} \left(\frac{\mathrm{g}}{\mathrm{m_B c^2}}\right)^2 \mathrm{n_b^2}$$

Very important sources of gravitational waves are those produced during the phase of the inspiral on a binary system of neutron stars before they finally merge. The effective tidal deformability Λ plays important role on the neutron star merger process and is one of the main quantities that can be inferred by the detection of the corresponding gravitation waves.

RESULTS AND DISCUSSION

Starting with the RMF nuclear model of Pure Neutron Matter (PNM), we see that its parameterization makes the EoSs to present two different behaviors. The general tendency is, as we can see in the Fig. 1, that the increase of the admixture fraction coefficient a_X leads to stiffer EoS and on the other hand the increase of the ρ-coupling leads to a softer EoS. The combination between these two parameters can be optimized, resulting a reasonable EoS which fits inside the accepted limits with respect the observational data. In addition as we can see from Fig. 2, in the Λ-q diagram concerning the effective tidal deformability with respect to the binary mass ratio q, the aforementioned optimization can exist well below the specified upper limit of the first gravitational wave GW170817 observation given by LIGO.

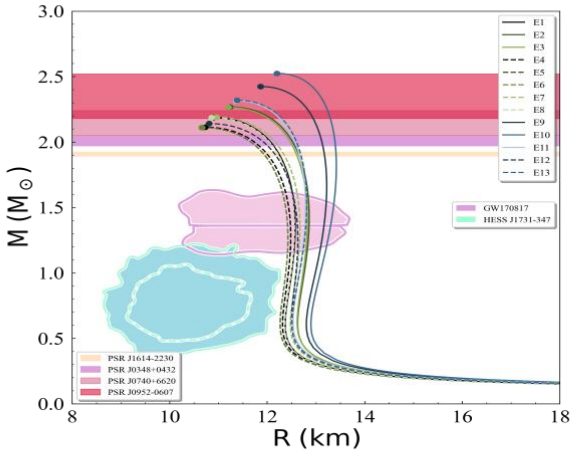


Figure 1. *The M-R diagram corresponds to the RMF model of PNM for various EoSs*

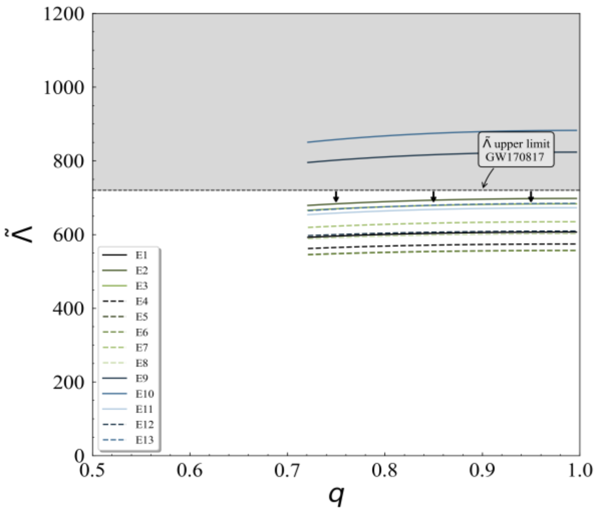


Figure 2. *The Λ−q dependence corresponds to the RMF model of PNM. The shaded region shows the excluded values derived.*

Furthermore, we studied the effect of the X17 boson using the MDI model. To be more specific, we used as a base three main MDI EoSs with different slope parameter =65, 72.5 and 80 MeV, with blue, green, and red color in the corresponding figures, respectively. The coupling constant g is allowed to take values up to g ~ 0.022 to fulfill the properties of symmetric nuclear matter at n_0, while the parameter C ranges in the interval $[0,C_{max}]$ where C_{max} is the higher allowed value, unique for each EoS, derived from the non-violation of causality. To be more specific, the value of g_{max} ~ 0.022 arises from the deviation of the binding energy of the symmetric nuclear matter at the saturation density. On the other hand, the lower limit g_{min} ~ 0.001 is defined as the value of the coupling constant in which the contribution of the X17 boson, on the bulk properties of the compact objects, starts to become appreciable. In Fig. 3 we display various regions in the parameter spaces ($g^2/4\pi$, μ) and ($|a_G|$,λ) in comparison with constraints from different experiments (for more details see Fig. 1 from Ref. [6]). The constrain g^2/m^2=200 GeV^{-2}, which suggested in Ref. [6] and defines an excluded region, has been also included for comparison. The constraints for the X17 boson in the current study, indicated with a short blue vertical line. The extrapolation of the constraints to other masses, indicated by the blue-shaded band which corresponds to: 0.00346 GeV^{-2} < g^2/μ^2 < 1.675 GeV^{-2}. One can see that the theoretical predictions are close to some experimental ones and in particular to the experiment of low-energy. In any case, future experimental studies may help to better define the range of parameters concerning the hypothetical X17 boson and in this way to improve our theoretical predictions regarding it's effect on the properties of dense nuclear matter.

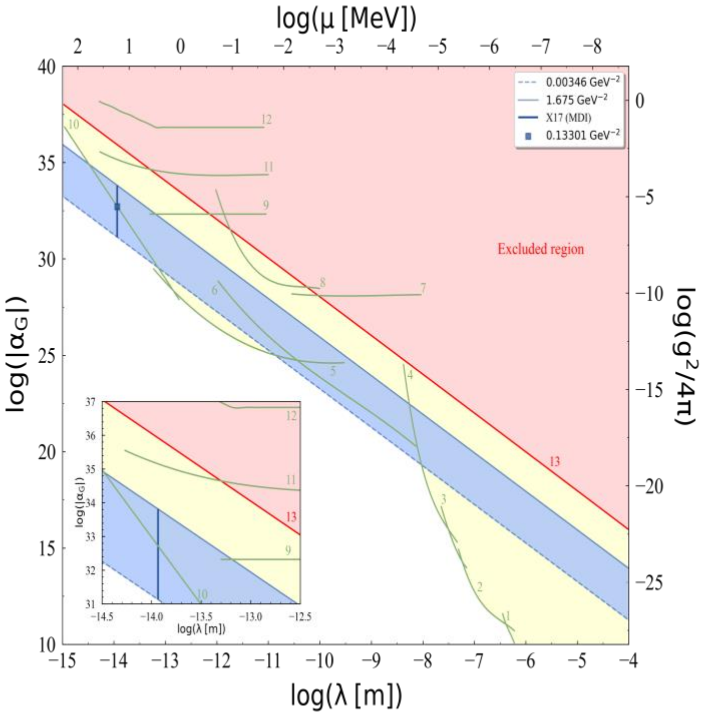


Figure 3. *Constraints on α_G-λ (equivalently $g^2/4\pi$-μ) derived. The specific range for the X17 boson in the MDI model is shown with blue vertical.*

In Fig. 4 the mass-radius dependence for all the cases of the MDI model is displayed. The solid curves correspond to the three initial EoSs without the contribution of the X17 boson, while the dashed and dash-dotted curves correspond to the EoSs within the presence of the X17 boson for g=0.011, and g=0.022, respectively. Among the same set of EoS and g, the darker colored curve corresponds to C=0, while the lighter one to $C=C_{max}$. At first sight, the higher value of L provides stiffer EoS, nevertheless the amount of contribution of X17. The EoSs with g=0.011 (dashed curves) lie closely to their corresponding initial EoS (solid curves) leading to a slight increment of M_{max} and radius R, while the bigger differentiation from the initial EoSs is for g=0.022. Also, the effect from the contribution of the X17 is stronger on the coupling constant g than the parameter C. We notice that all the EoSs lie outside the estimated region for the HESS J1731-347 remnant [9].

So far we studied the two main parameters, g and C, through their dependence on the macroscopic properties of neutron stars, derived from the EoS, and by exploiting the available observations. In general, only for higher coupling constant g the EoS becomes more sensitive to the C. In order to examine further how g and C affects the EoSs, we introduced a g-C parameter space, displayed in Fig. 4. This figure is suitable for an overall view on these parameters and the way that the constraints affect them. The green shaded region shows the allowed parameter space with respect to causality, for all three set of MDI EoSs. The green arrows show the direction of the accepted region.

The green solid curve indicates the limit for the L=80 MeV EoS, the dashed one indicates the limit for the L=72.5 MeV EoS, while the dash-dotted curve indicates the limit for the L=65 MeV EoS.

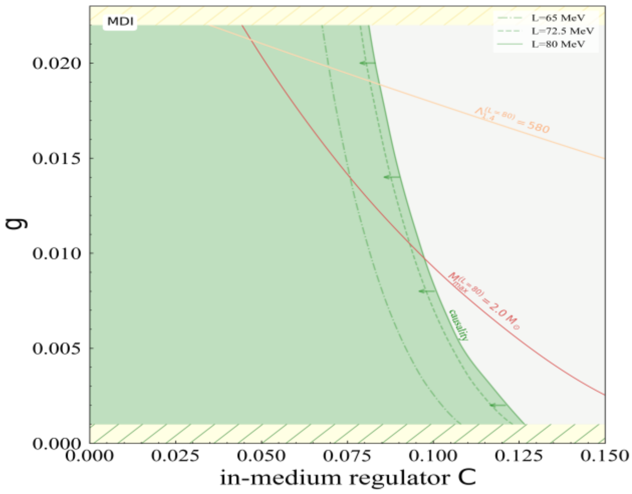


Figure 4. *Constraints for g and C for the three MDI EoSs with respect to causality, the possible upper mass limit $M_{max} = 2M_\odot$ and the dimensionless tidal $\Lambda_{1.4} = 580$ for the MDI (L=80 MeV) EoS*

Beyond the hadronic EoSs, we expanded our study of the contribution of the X17 boson to QSs. The effect of this contribution is depicted on the mass-radius dependence in Fig. 5. In particular, we used three different -concerning the parametrization- sets of EoSs running from soft (CFL13 EoS) and medium (CFL2 EoS) to stiff (CFL10 EoS) behavior, covering the most possible cases. We notice that in the case of QSs we chose the same upper value for g so that the comparison with the hadronic EoSs of the MDI model to be more clear (the quark EoSs does not have to respect the properties of symmetric nuclear matter at the saturation density). The dashed curves correspond to coupling constant g=0.011 while the dash-dotted ones correspond to g=0.022. For the same value of g the lighter colored curves correspond to higher C.

As we underlined in the hadronic EoSs, the contribution of X17 in general depends stronger on g than on C. It is worth noticing that in the case of a pure QS the effects of X17 are more pronounced compared to the neutron star case, beucase of the additional contribution of factor of 9 on energy density and pressure. Especially, the possible existence of X17 affects dramatically the provided maximum mass in each set of EoSs. The effect on the radius of a 1.4 solar masses star is moderate but enough to affect the tidal deformability. Also, it is interesting and noteworthy that the CFL10 (stiff) and CFL13 (medium) EoSs satisfy simultaneously both the observational data and the corresponding constraints. By applying the study of quark EoSs to the observational estimations of the properties of the GW170817 event, we examined further the behavior of X17 in the CFL EoSs. through the Λ-q dependence. The effect of the X17 depends on the parametrization of both the coupling constant g and the in-medium effects described by the parameter C, leading to an appreciably increase of Λ. As in the case of hadronic EoSs, the dependence on g is stronger than on C. In general, the stiffness on the EoS magnifies gradually this deviation on Λ from the initial (without X17) EoS.

For the purpose of the aforementioned examination, we constructed the g-C parameter space for each set of quark EoS, by applying various upper limits on M_{max} and $\Lambda_{1.4}$ and including the non-violation of causality. In Fig. 6 the three parameter spaces are demonstrated; the change on the stiffness (soft to stiff) of the EoS corresponds to the direction from the left to the right panel. This kind of diagrams clarify specifically the role of the two parameters.

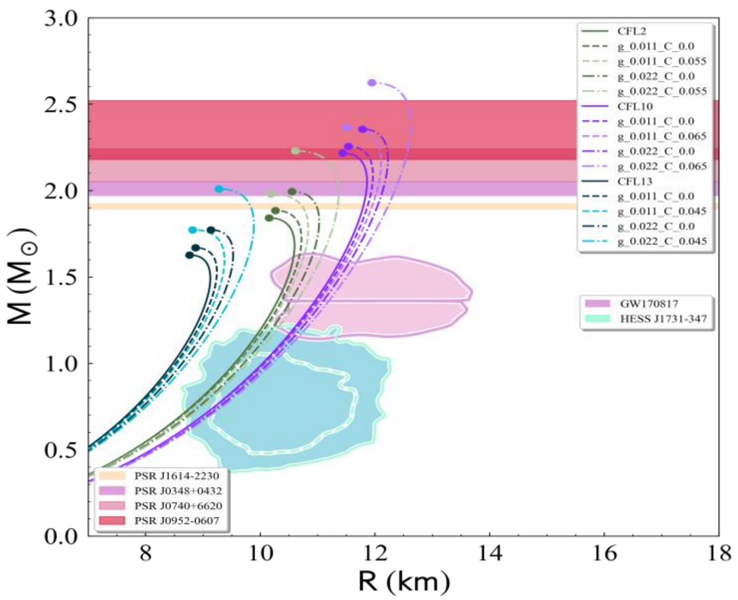


Figure 5. *Constraints for g and C for the three MDI EoSs with respect to causality, the possible upper mass limit* $M_{max} = 2M_{\odot}$ *and the dimensionless tidal* $\Lambda_{1.4} = 580$ *for the MDI (L=80 MeV) EoS.*

As we move from softer to stiffer EoS, the range of pair values (g,C) that satisfy the mentioned constraints increases. Therefore, since the range of values for the coupling constant g is common for all cases, the stiffer the EoS the higher the value of C_{max}, meaning higher contribution of X17. We underline at this point that across the same set of EoSs the contribution of X17 is characterized firstly by the value of g. The displayed points correspond to the crossed colored curves' values with the causality limit. The curves of $M_{max}(C)$ and $\Lambda_{1.4}(C)$ are unique for each set of CFL EoSs. The $M_{max}(C)$ curves define that the (g,C) pair of values on the left of each one of these curves do not provided the desired $M_{max}(C)$.

We observe that as we move to stiffer EoS only higher values on $M_{max}(C)$ can provide further constraints. Concerning the constraints imposed by the $\Lambda_{1.4}$, these can be useful in stiffer EoSs. Concluding, the more soft the equation of state the more limited is the range of parameters, for both hadronic and quark case. In this context, additional observational data concerning the maximum mass as well as more strict upper and even lower limits on $\Lambda_{1.4}$ may lead to much stringent constraints regarding the coupling constant g and the in-medium effect regulator C.

CONCLUSION

The main conclusions and comments of the present study can be summarized as follows:

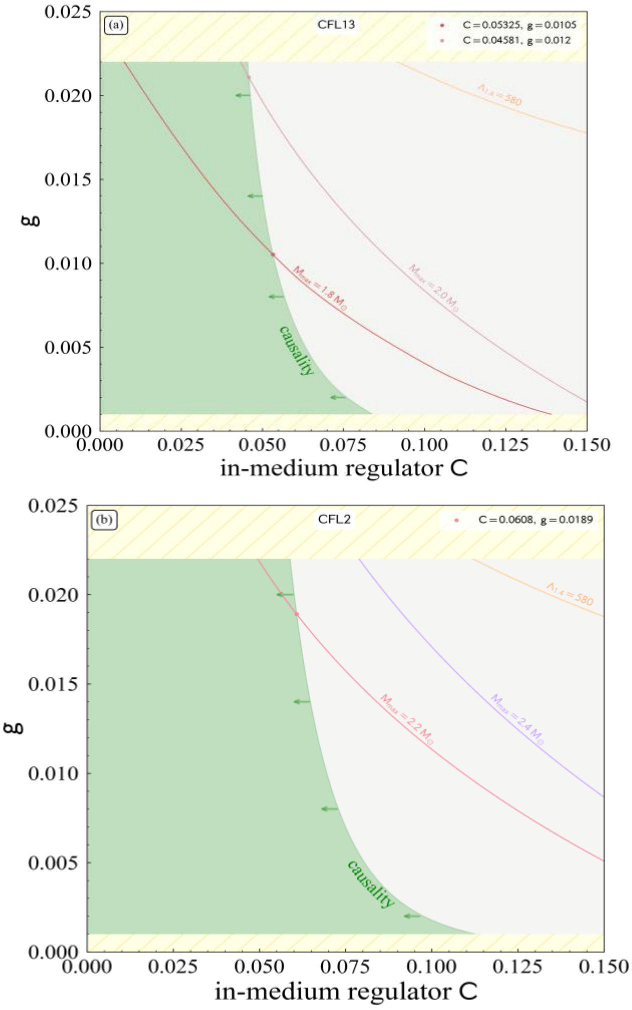
a) We use EoS's originated from two different nuclear models such as from RMF theory and from a MDI model. In the first case (RMF) the existence of the X17 affects mainly the nuclear symmetry energy resulting a stiffer EoS. In the second case the X17 directly contributes positively to the hadron pressure also leading to a stiffer EoS. Similar is the case concerning the contribution of the X17, to the total pressure of pure quark matter.

b) We payed attention on two main phenomenological parameters of the X17, the coupling constant g of its interaction with hadrons or quarks, and the in-medium effects through a regulator C. Both are very crucial concerning the contribution on the total energy density and pressure. We suggest that it is possible to provide constraints on these parameters with respect to causality and various possible upper mass limits and the dimensionless tidal deformability $\Lambda_{1.4}$.

c) We found that also the more stiff is the EoS (hadronic or quark), the more indiscernible are the effects on the properties of compact objects. In particular, we found that the effect of the existence of the hypothetical X17 boson, are more pronounced, in the case of QSs, concerning all the bulk properties. This is due mainly on the extra factor 9 both on the energy and pressure contribution to the total ones.

d) It must be emphasized that in the present study, special attention was paid to maintain the non violation of causality on the EoSs, while systematically taken into account the in-medium effects on the mass of the hypothetical boson (which usually had been omitted in similar works so far). Both of them impose important constraints on the effect of X17 on the properties of neutron stars (or quark stars). In this way they help to determine the extent of the effect of X17 on the properties of nuclear matter.

e) In addition, an attempt was made to find possible constraints on the hypothetical X17 boson with the help of observational data and mainly those derived from the detection of gravitational waves. To be more specific, the measurements of the tidal deformability of recent events impose constraints on the two key microscopic parameters that characterize X17. It is worth to notice that the present study can form the framework for similar studies concerning the possible existence of bosons in nuclear matter and their consequences on the structure and basic properties of compact objects. In this case it will be possible from both terrestrial and astrophysical observations to make the best possible estimate of the properties of these particles



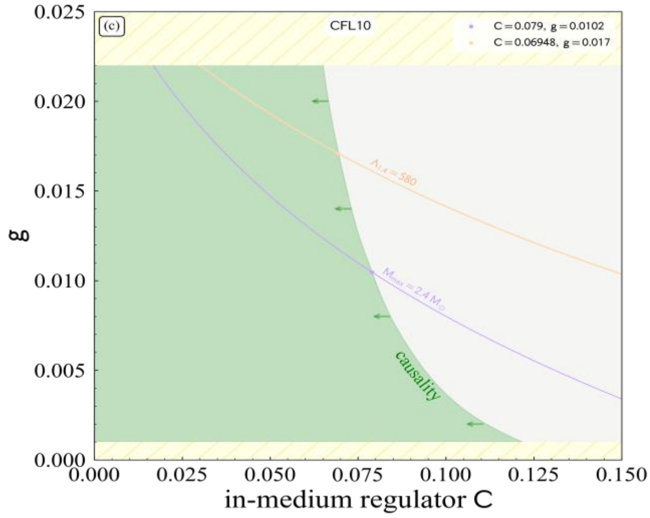


Figure 6. *Constraints for g and C for (a) the CFL13 quark EoS (soft), the possible upper mass limits 1.8*$M_\odot$ *and 2.0*$M_\odot$ *and the dimensionless tidal* $\Lambda_{1.4}$ *= 580, (b) the CFL2 quark EoS (intermediate), the possible upper mass limits 2.2*$M_\odot$ *and 2.4*$M_\odot$ *and the dimensionless tidal* $\Lambda_{1.4}$ *= 580, and (c) the CFL10 quark EoS (stiffer), the possible upper mass limit 2.4*$M_\odot$ *and the dimensionless tidal* $\Lambda_{1.4}$ *= 580. In all panels, the green shaded region indicates the allowed parameter space derived by thenon-violation of causality, while the yellow ones indicate the regions where we not include in our study.*

Acknowledgments

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