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# Investigating the effects of the vacuum energy on compact objects

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**Abstract.** In this work, we explore some effects of the total equation of state of neutron stars based on a variable vacuum energy density, which is described here as a perfect fluid interacting with baryonic matter. To accomplish this, a fraction relating the vacuum energy densities of ordinary matter is phenomenologically defined by using ten different equations of state. It is shown how the variable vacuum affects the basic neutron star parameters. In particular, we found that its stability is maintained (for all cases studied) only when the maximum vacuum fraction is smaller than 30% of the total composition of neutron stars. Moreover, this amount of available vacuum was limited by mass and radius constraints already confirmed by observations.

**Resumo.** Neste trabalho, exploramos alguns efeitos da equação total de estado de estrelas de nêutrons com base em uma densidade de energia de vácuo variável, que é descrita aqui como um fluido perfeito interagindo com matéria bariônica. Para tal, uma fração que relaciona as densidades de energia do vácuo da matéria comum é definida fenomenologicamente utilizando dez equações de estado diferentes. É mostrado como o vácuo variável afeta os parâmetros básicos da estrela de nêutrons. Em particular, encontramos que sua estabilidade é mantida (para todos os casos estudados) apenas quando a fração máxima de vácuo é menor do que 30% da composição total das estrelas de nêutrons. Ademais, esta quantidade de vácuo disponível foi limitada pelas restrições de massa e raio já confirmadas pelas observações.

**Keywords.** neutron stars – dark energy

## 1. Introduction

The effects of vacuum energy on compact objects have been extensively examined (e.g. Campos & Lima 2012; Coleman & De Luccia 1980). Furthermore, among notable multi-messenger astrophysical objects, neutron stars stand out due to the high densities in their cores, making them useful tools for studying extreme, not yet completely understood, quantum chromodynamics diagram (QCD) phases. However, the composition of these stars is still uncertain, which means their equation of state is not well established.

To explore the configuration of these compact objects based on the cosmological effects of vacuum energy, with the assumption of negative pressure ($p_V = -\epsilon_v$) (Gron 1986) and based on the vacuum decay theory (Carvalho et al. 1992), we investigated the inclusion of this component as a perfect fluid that almost does not interact with baryonic matter in the stellar structure. On the other hand, the vacuum state nowadays is the best candidate to explain the present accelerated stage of the Universe (Lima 2004; Beltracchi & Gondolo 2019). In this way, we want to make a parallel with the known investigation of admixed-neutron stars characterized by the presence of dark matter (Li et al. 2012; Mukhopadhyay & Schaffner-Bielich 2016).

Considering the spherical symmetry and the static distribution of matter, we analyzed the contribution of the vacuum with a constant and a variable percentage in the composition, having a density dependent on the stellar radius and being associated with a negative pressure (Gliner 1966). The main objective was to investigate the possible implications on stellar properties, especially the mass-radius relationships. To this end, we consider the baryonic matter fluid characterized by ten different equations of state. In what follows, for the sake of definiteness, we consider that the compact object is a neutron star.

## 2. Modified structure equations

The structure equations of a neutron star can be obtained by the Einstein field equation. The metric for an isolated, spherically symmetric neutron star, is given by ($c = G = 1$):

$$ds^2 = e^{2\nu(r)}dt^2 - e^{2\mu(r)}dr^2 - r^2(d\theta^2 + \sin^2\theta d\phi^2). \quad (1)$$

In this background, the total energy-momentum for separated perfect fluids (matter + vacuum) is:

$$T_{\mu\nu} = T^m_{\mu\nu} + T^v_{\mu\nu}, \quad (2)$$

with:

$$T^i_{\mu\nu} = (p_i + \epsilon_i)u_\mu u_\nu - p_i g_{\mu\nu}, \quad (3)$$

being $i = m, v$, and $p$ and $\epsilon$ the pressure and the energy density, respectively. In this context, the conservation of mass, hydrostatic equilibrium, and the gravitational potential of the star are defined by:

$$\frac{dm}{dr} = 4\pi\epsilon r^2, \quad (4)$$

$$\frac{dp}{dr} = -\frac{(p+\epsilon)\left[m + 4\pi r^3 p\right]}{r^2 - 2mr}, \quad (5)$$

$$\frac{d\nu}{dr} = \frac{m + 4\pi r^3 p}{r^2 - 2mr} \quad (6)$$

where $m = m_m + m_v$, $p = p_m + p_v$, and $\epsilon = \epsilon_m + \epsilon_v$.

In this way, representing the energy density relation between baryonic matter and vacuum components, we define the fraction:

$$y = \frac{\epsilon_m}{\epsilon_v + \epsilon_m}, \quad (7)$$

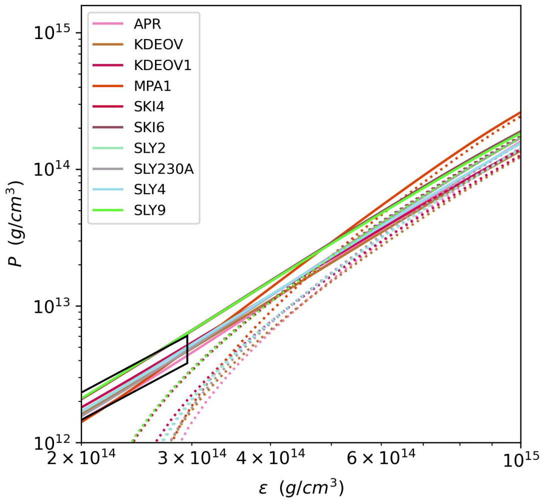


**Figure 1.** From Araújo et al. (2024): The EOSs for ordinary matter used in this work are constrained by chiral effective field theory up to 1.1 $n_0$ (Hebeler et al. 2013), represented by the black polygon. The dashed curves incorporate the effect of dark energy with an example constant value of $y = 0.99$.

being $y = 0$ for a star full of vacuum and $y = 1$ for baryonic matter only.

Therefore, using this modification on the structure equations, we obtain:

$$\frac{dp_m}{dr} = -\frac{(p_m+\epsilon_m)\left[m+4\pi r^3\left(p_m-\frac{1-y}{y}\epsilon_m\right)\right]}{r^2-2mr} \times \frac{1}{\left(1-\frac{1-y}{y}\frac{d\epsilon_m}{dp_m}\right)}. \tag{8}$$

for a constant distribution $y$ and

$$\frac{dp_m}{dr}\left[1+\frac{d\epsilon_m}{dp_m}\left(-\frac{1-y}{y}+\frac{\epsilon_m}{y^2}\frac{dy}{d\epsilon_m}\right)\right] = = -\frac{(p_m+\epsilon_m)\left[m+4\pi r^3\left(p_m-\frac{1-y}{y}\epsilon_m\right)\right]}{r^2-2mr}. \tag{9}$$

taking into account a larger fraction of vacuum in the core and a decrease to the surface (variable $y$). It is necessary to define the relation of $y$ through the star, which was made with the ansatz:

$$y(\epsilon_m) = 1 + \frac{\beta-1}{1+\left(\frac{\epsilon_\star}{\epsilon_m}\right)}, \tag{10}$$

where $\beta$ and $\epsilon_\star$ are free parameters.

So, having all the equations necessary to characterize the structure, including the equation of state of baryonic matter, it is possible to verify the effect of vacuum and how the mass and the radius answer to this presence.

## 3. Results and discussions

Taking the modified equations obtained above, and using the ten equations of state satisfying the chiral effective field theory (see Fig. 1), the behavior of mass-radius relation is obtained. In this work, we took 2 representing equations of state, the APR (more stiff) and the MPA1 (more soft).

As can be seen in Fig. 2, the vacuum tends to decrease the mass and the radius in all cases, being representative of $y \approx 0.7$, when a smaller radius is attached for smaller masses. On the other hand, the restrictions put on the observable selected data are respected for some values of $\beta$ (or $y$). Taking into account the entire sample, only $y > 0.99$ agrees in the constant case $y$ and $y > 0.70$ for the variable case, except for $\epsilon_\star = 8\epsilon_0$, which guarantees all the values $\beta$ due to the proximate behavior with the ordinary case.

To implement complementary observational restrictions, we also consider the analysis of tidal deformability visualized in mergers of neutron stars. It is defined by:

$$\Lambda = \frac{\lambda}{M^5} = \frac{2k_2}{3}\frac{R^5}{M^5}, \tag{11}$$

being $k_2$ the tidal Love number, dependent on the compactness of the star ($C = M/R$) by:

$$k_2 = \frac{8C^2}{5}(1-2C)^2[2+2C(y_R-1)-y_R]\{2C[6-3y_R + 3C(5y_R-8)] + 4C^3[13-11y_R+C(3y_R-2)+2C^2 (1+y_R)+3(1-2C)^2[2-y_R+2C(y_R-1)]]\ln(1-2C)\}^{-1}. \tag{12}$$

with the perturbed metric variable ($y_R$) defined by the first-order differential equation ($y_R(0) = 2$) (Postnikov et al. 2010):

$$r y_R'(r) + y_R(r)^2 + y_R(r)e^{\lambda(r)}1 + 4\pi r^2[p(r)-\epsilon(r)] + r^2 Q(r) = 0, \tag{13}$$

where:

$$Q(r) = 4\pi e^{\lambda(r)}\left[5\epsilon(r)+9p(r)+\frac{\epsilon(r)+p(r)}{dp/d\epsilon}\right] - 6\frac{e^\lambda}{r^2} - \frac{dv}{dr}^2. \tag{14}$$

Just like before, $m = m_m + m_v$, $p = p_m + p_v$, and $\epsilon = \epsilon_m + \epsilon_v$. The results are shown in Fig. 3

## 4. Conclusions

Regarding the effect that the energy of vacuum could have on the structure of compact objects, neutron stars appear to be an interesting target because of the very density of their cores. Therefore, we could analyze, using a straightforward method of a variable and constant fraction of energy densities relation between ordinary matter and the own vacuum defined by a total energy-momentum tensor of perfect fluids.

As shown, the presence of a negative pressure component decreases the mass and the radius of the neutron star, having a bounder limit in addition to the amount of vacuum. In this way, we show that until 30% of the vacuum could be present for all the investigated cases, about only 1 to 5% respect the observational constraints. Also, a more complete investigation was made considering the tidal deformabilities related to mergers.

A detailed discussion of such effects will be published as (Araújo et al. 2024) elsewhere.

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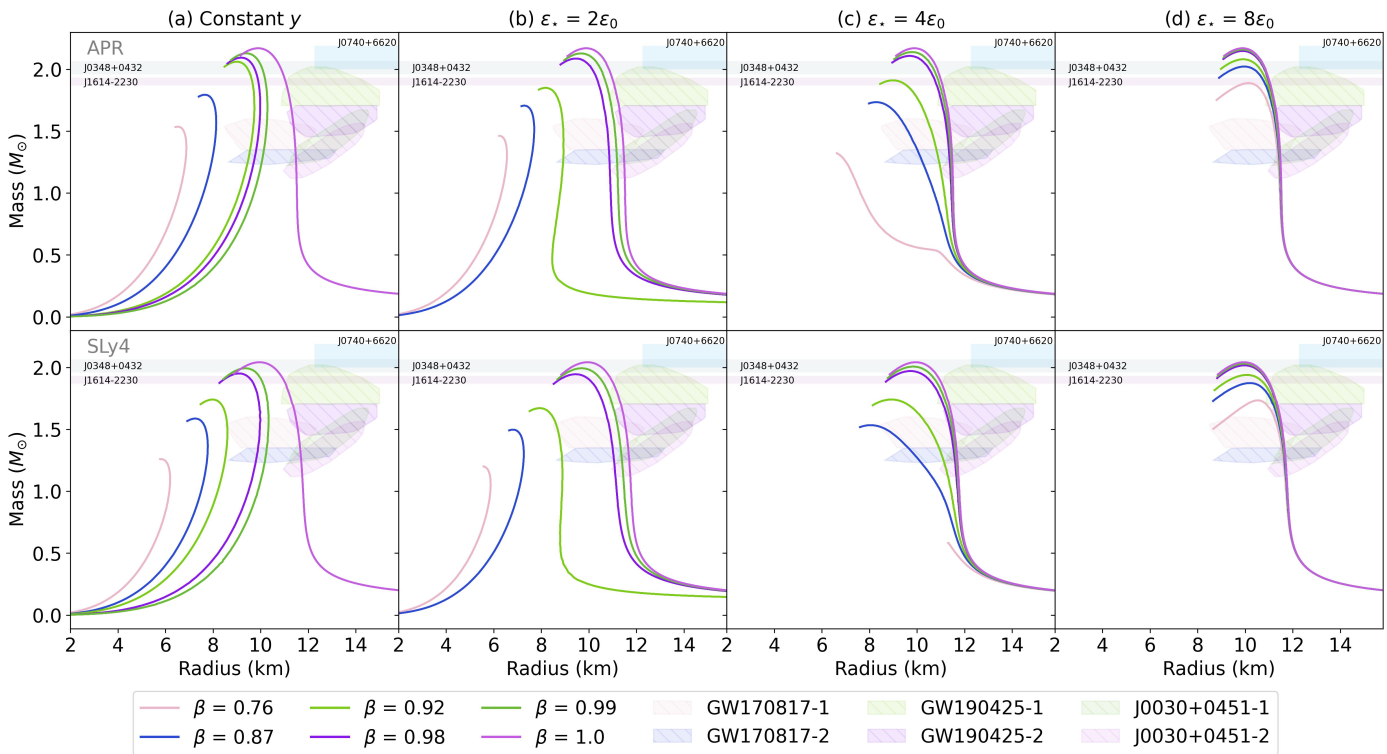


**FIGURE 2.** From Araújo et al. (2024): APR and SLy4 Mass-Radius relation and the inclusion of vacuum energy constrained by observational constraints (GW170817 from (Raithel et al. 2018), GW190425 from (Abbott et al. 2020), PSR J0030+0451 from (Miller et al. 2019), PSR J0348+0432 from (Antoniadis et al. 2013), PSR J1614+2230 from (Demorest et al. 2010) and PSR J0740+6620 from (Cromartie et al. 2020)).

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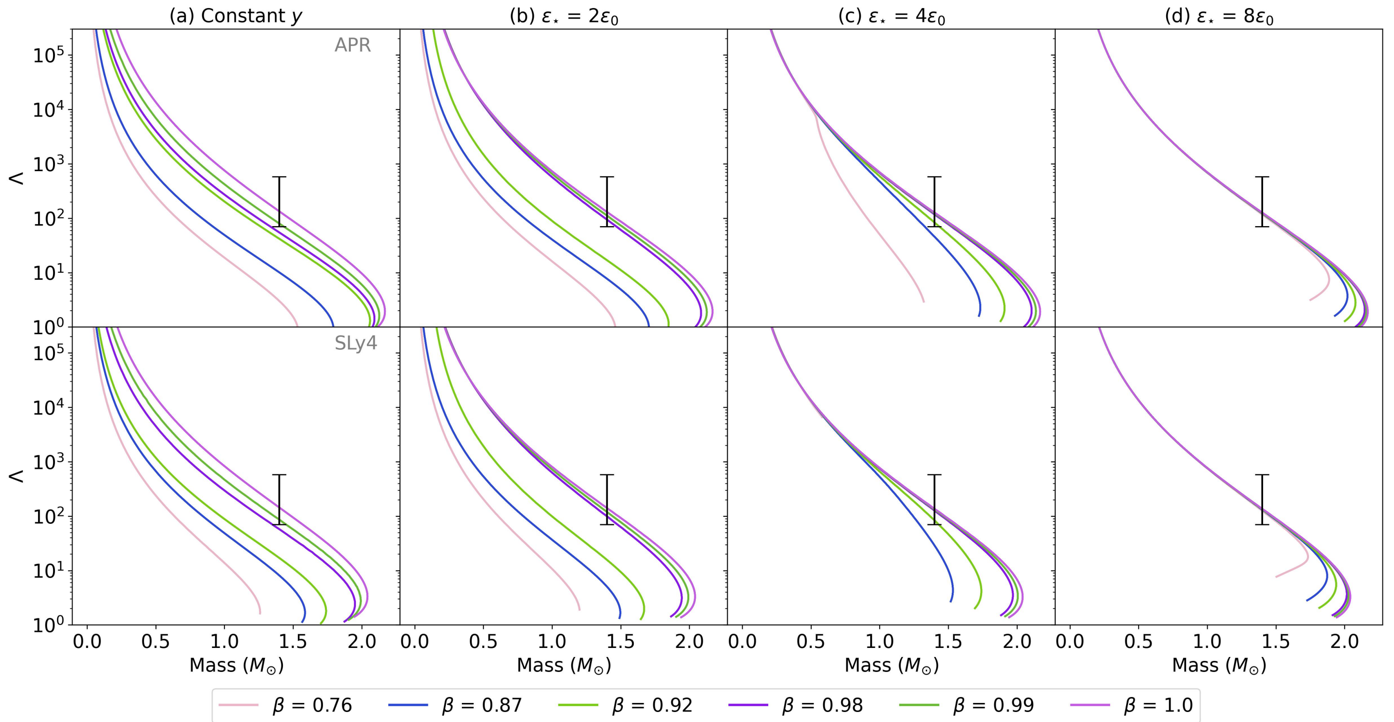


**FIGURE 3.** From Araújo et al. (2024): APR and SLy4 tidal deformability and the inclusion of vacuum energy restricted by the observational constraint (error bar) for the event GW170817 (Abbott et al. 2018).