Radial oscillations of the dark matter admixed neutron star

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I. INTRODUCTION

Neutron Star (NS) is one of the most compact objects which provides a natural laboratory to explore cold, dense nuclear matter (NM) with a density $5-10$ times the nuclear saturation density. It is well known that NS pulsate with different quasi-normal modes, which are segmented into radial and non-radial oscillations and further classed according to various restoring forces. The oscillations of the compact stars emit the gravitational waves via different modes such as fundamental (f), pressure (p), gravity (g), etc., and these modes are classified according to the different mechanisms that happen inside the star. The detection of gravitational waves in the near future may provide a unique way to constrain some properties of the NS. Therefore, in this study, we calculate some properties of the radially oscillating dark matter admixed NS (DMANS) in the framework of the general theory of relativity.

Dark matter (DM) particles are accreted inside the NS due to its huge baryonic density and immense gravitational potential. After accretion, the macroscopic properties are affected due to its interactions with nucleons. In this present case, we mainly focus on the oscillations frequency emitted due to radially oscillating NS. Different DM models have been hypothesized in literature, such as fermionic and bosonic, based on the type of particles. But the exact nature of DM is still in debate due to the null results provided by the different dark matter detection experiments. Hence, we choose a simple DM model and explore the oscillating properties of the DMANS. We give a brief formalism on the aspects of DM interactions and their effects on the f and p modes frequencies in the following sections.

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II. FORMALISM

The governing equation for the radial oscillations is obtained by changing both fluid and space-time parameters while preserving the spherical symmetry of the background body. If we assume a harmonic time dependency and define $\delta r(r,t) = X(r)e^{iwt}$, as the time-dependent radial displacement of a fluid element at position (r) in the unperturbed model, we can obtain the following perturbed equation describing the radial oscillations [1]

$$c_s^2 X'' + \left[\left(c_s^2\right)' - Z + \frac{4\pi G}{c^4} r\gamma P e^{2\lambda} - \nu'\right] X' + \Big[2\left(\nu'\right)^2 + \frac{2Gm}{c^2 r^3} e^{2\lambda} - Z' - \frac{4\pi G}{c^4}(P+\mathcal{E}) \times Z r e^{2\lambda} + \frac{\omega^2}{c^2} e^{2\lambda - 2\nu}\Big] X = 0, \quad (1)$$

The eq. 1 can be solved numerically by breaking it into two first order differential equations with appropriate boundary conditions as given in Ref. [1]

We construct the DM model Lagrangian by assuming that the DM particles interact with nucleons by exchanging standard model Higgs. The Lagrangian density for

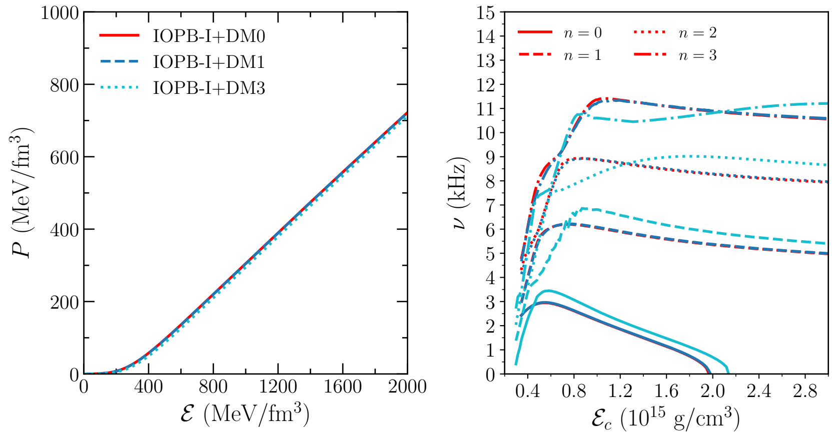

FIG. 1: *Left:* The EOSs for DMANS with percentages 0.00, 0.01, and 0.03 GeV are represented as DM0, DM1, and DM3, respectively. *Right:* The first four radial oscillation nodes as a function of central density for each EOSs.

the DMANS is in the following [2]

$$\begin{aligned}\mathcal{L}_{\rm NS} &= \mathcal{L}_{\rm NM} + \bar{\chi}\left[i\gamma^{\mu}\partial_{\mu} - M_{\chi} + yh\right]\chi \\ &+\frac{1}{2}\partial_{\mu}h\partial^{\mu}h - \frac{1}{2}M_h^2h^2 + f\frac{M_{\rm nucl.}}{v}\bar{\varphi}h\varphi \\ &+ \sum_{l=e^-,\mu}\bar{\psi}_l\Big(i\gamma^{\mu}\partial_{\mu} - m_l\Big)\psi_l, \qquad (2)\end{aligned}$$

For DMANS EoS, one has to solve the eq. 2 within mean-field approximations. Here, we use the unified IOPB-I EOS [3] with three different fractions to calculate the properties of the radial oscillations [2].

III. RESULTS

The first four radial modes as a function of central density are shown in Fig. 1 in the right panel for the EOSs with different fractions of DM. The drop at lower densities can be attributed to the star's homogeneous and non-relativistic behaviour, where ω is connected to the adiabatic index as $\omega^2 \propto \rho(4-3\gamma)$ since γ does not vary considerably at lower central densities. We can also observe evidence of avoided crossings between modes, where the frequencies of two nodes 'repel' each other before getting too close, because a certain frequency can only correspond to a single mode for a given EoS. At higher densities, the first radial mode, the f-mode, falls down and becomes unstable because ω_0^2 becomes negative.

IV. CONCLUSION

The frequency of the f-mode approaches zero near 1.96×10^{15}, 1.97×10^{15} and 2.17×10^{15} g/cm^3 for IOPB-I with DM fractions 0.00, 0.01 and 0.03 respectively, which corresponds to the stability point at which the EoSs reach their maximum mass. It is observed that the stability point increases with DM percentage since with the addition of DM, the EOSs become softer, reducing the star's mass and radius. Therefore, less massive NS with higher DM content will remain stable for a bigger range of densities as compared to the same NS without DM.

References

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