Neutron stars with fermionic dark matter: a two fluid approach

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Introduction

Recent observation of gravitational waves from compact star mergers such as GW170817 has opened a new window to the universe which may provide crucial inputs to probe and understand not only the dark sector but in the nuclear domain as well such as on the underlying nuclear equation of state of neutron stars as well. The cold dark matter (CDM) candidates such as WIMPs are perceived to be one of the ideal candidates and lately, is also being looked upon as one of the possible constituent in neutron stars and may influence the properties as well. Our incomprehensible understanding of the in-medium properties of dark matter e.g mass, self interaction etc, one can take alternative approach by ignoring the non-gravitational interaction between NM and DM treating both intrinsically as a two fluid system. The Λ-C which is refered to as universal relations of first kind can be extremely useful to extract information on the NS EOS from GW signal. Motivated by the same, we plan to study the quasi-universal relations in dark matter admixed NSs.

Model & Parameters

To account for the nuclear matter EoS, we employ the DDH model, the details of which can be found in [1]. In the mean-field approach the Lagrangian density for the dark sector is expressed by the following:

$$
\begin{aligned}
\mathcal{L}_{DM} &= \bar{\psi}_D \left[\gamma_\mu(i\partial^\mu - g_{\nu d}V^\mu) - (M_D - g_{sd}\phi_D)\right]\psi_D \\
&+ \frac{1}{2}\left(\partial_\mu\phi_D\partial^\mu\phi_D - m_{sd}^2\phi_D^2\right) \\
&- \frac{1}{4}V_{\mu\nu,D}V_D^{\mu\nu} + \frac{1}{2}m_{\nu d}^2 V_{\mu,D}V_D^\mu \qquad (1)
\end{aligned}
$$

Here M_D is the bare mass of fermionic dark matter, m_{sd} and m_{vd} are the corresponding masses of the scalar and vector dark mesons respectively and ψ_D, ϕ_D and V_D^μ represent 'fermionic dark matter', 'dark scalar meson' and 'dark vector meson' respectively.

Once we have the EOS of the NM as well as DM, we adopt two fluid formalism to study the properties of Dark matter Admixtured Neutron Stars (DANS). The detailed formalism and derivation of the two fluid approach can be found in [2]

Results

TABLE I: DANS properties with two fluid approach where the mass of the dark matter M_D ranges from (0.5 - 2) Gev for different dark matter proportions

M_D	f_d	M_{max}	R_{max}	$R_{1.4}$	$\Lambda_{1.4}$	$C_{1.4}$
0.5	0.01	2.352	11.52	12.529	423.63	0.165
	0.30	2.816	29.26	−−−	−−−	−−−
1	0.01	2.353	11.29	12.083	318.209	0.171
	0.30	2.275	11.12	11.938	285.868	0.173
1.5	0.01	2.353	11.08	11.693	246.047	0.176
	0.30	2.339	11.06	11.681	243.823	0.176
2.0	0.01	2.355	10.88	11.334	193.172	0.182
	0.30	2.353	10.86	11.333	192.972	0.182

Shown in fig.1 is the comparison of the mass radius relations with two fluid approach. With the inclusion of DM, the maximum mass and its corresponding radius decreases. The amount of reduction depends on the proportion of the DM with NM as well as the mass

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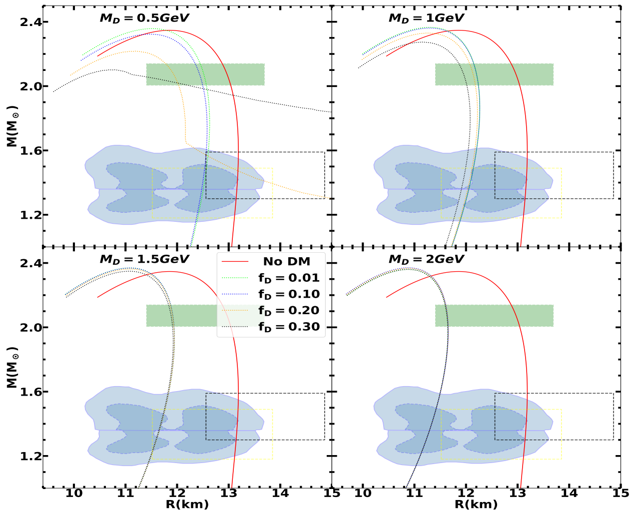

FIG. 1: Mass radius relations of DANS with mass of the dark matter candidate M_D ranging from (0.5 - 2) Gev and for various DM proportions. The outer and inner gray shaded regions indicate the 90% (solid) and 50% (dashed) confidence interval of the LIGO-Virgo analysis for BNS component from the GW170817 event. The rectangular regions enclosed by dotted lines indicates the constraints from the millisecond pulsar PSR J0030+0451 (black & lime) NICER x-ray data and PSR J0740+6620 (green).

of DM candidate. One can clearly see that DM has little impact on the mass radius values with $M_D \geq 2$ GeV. On the contrary, if the mass of DM is small (say 0.5 Gev) the influence seems to be significant. As for light DM particles i.e $M_D \leq 0.5$ Gev we see that small NM core (R=10.52 Km) surrounded by a DM halo as we increase DM fraction ≥ 0.30 with $R_D = 29.26$ km and $M_{max} = 2.816$ as given in Table I.

We also calculate the dimensionless tidal deformability Λ and compactness C which is enlisted in Table 1. Our results agree well with the bounds placed on a 1.4 $M_\odot$ NS with the Λ measurement from GW170817 by LIGO/Virgo ($\Lambda_{1.4} = 190^{+390}_{-120}$) and the compactness one from NICER ($C_{1.4} = 0.159^{+0.025}_{-0.022}$).

Conclusions

In this work, we have studied the effect of fermionic dark matter on NSs . We found that the mass and the radius of the DANS decreases with increase in the mass of the dark matter and also depends on the fraction of dark matter taken. It is also interesting to conclude that with addition of DM, Λ and $\Lambda_{1.4}$ decreases. Moreover, the values of Λ and C agrees to observations by LIGO/VIRGO and NICER.

References

[1] Tuhin Malik et al ApJ **930** 17 (2022).

[2] Qian-Fei Xiang, Wei-Zhou Jiang, Dong-Rui Zhang, and Rong-Yao Yang Phys. Rev. C **89**, 025803 (2014).