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Feasibility of Dark Matter in Neutron Stars: A Quantitative Analysis

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Introduction

Dark matter makes up 26.5% of the universe's mass-energy, with 4.9% being baryonic matter and 68.6% dark energy, according to popular theories like the Λ-CDM model and observations alike. Though dark matter is invisible across the electromagnetic spectrum, its presence is inferred through gravitational interactions with visible matter, crucial to galaxy formation and dynamics. Despite its influence, the nature of dark matter remains unknown, and researchers across various fields are investigating its properties. Experimental efforts, like CDMS II and CRESST, aim to detect dark matter particles directly, alongside particle accelerator studies.

This thesis aims to address the existing gaps by exploring potential solutions within the framework of Dark Matter Admixed Neutron Stars (DANS).

Objectives

Following are the main objectives of the thesis:

1) Explore correlations between dark matter and neutron star properties, while carefully considering the uncertainties in the baryonic matter's equation of state.

2) To employ Machine learning techniques to explore the impact of dark matter on neutron star properties, that may provide insights and connect to the upcoming observational studies.

3) To statistically evaluate admixed dark matter scenarios in neutron stars, comparing different scenarios to determine which one aligns with recent observational data and sheds light on the star's interior structure.

Methodolgy

We employ a plethora of relativistic mean field model for baryonic matter and construct similar interaction to account for the dark matter sector as well. However, we consider both the approach, wherein dark matter self-interaction can be mapped with "single fluid formalism", where the lagrangian is described by:

$$\mathcal{L} \supset -g_V \bar{\chi}\gamma^{\mu}\chi V_{\mu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_{\mu}V^{\mu} \tag{1}$$

where g_V is the coupling strength and m_V is the mass of the vector boson. The energy density of DM is given by:

$$\epsilon_{DM} = \frac{1}{\pi^2}\int_0^{k_{F_\chi}} k^2\sqrt{k^2+m_\chi^2}\,dk + \frac{1}{2}G_\chi n_\chi^2, \tag{2}$$

where, $G_\chi$is the vector coupling constant.

In order to include dark matter only via gravitational interactions, we also employed the so called "Two Fluid Fromalism" and some of the important findings of the thesis are briefed below.

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Results & Discussion

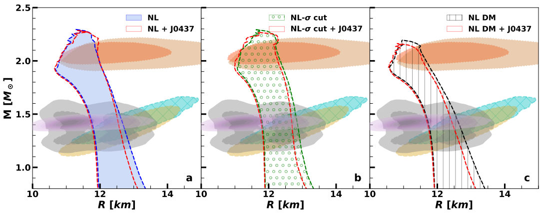

FIG. 1: The posterior distribution of the neutron star mass-radius $P(R|M)$ for the models (a) NL, (b) NL-σcut, and (c) NL-DM is compared with the distribution that includes the new PSR J0437-4715 NICER mass-radius measurements.

NICER's nearest and brightest target is the 174 Hz millisecond pulsar PSR J0437-4715. Using NICER data from July 2017 to July 2021, and incorporating NICER background estimates, the latest mass-radius measurements of PSR J0437-4715 are reported. We have investigated the effect of these measurements, together with the two old NICER measurements for pulsars PSR J0030+0451 and PSR J0740+6620, on NL, NL-σ cut, and NL-DM. All were compared without PREX-II. Fig. 1 shows the posterior distribution of neutron star mass-radius relations for the NL, NL-σ cut, and NL-DM models, incorporating the new data from PSR J0437-4715 by NICER. Panels (a), (b), and (c) represent NL, NL-σ cut [2], and NL-DM, respectively, and illustrate the effect of the new NICER measurements on the mass-radius posterior. The inclusion of data from PSR J0437-4715 particularly affects the estimated radius for neutron stars in the 1 to 1.5 $M_\odot$ mass range. This new data reduces the upper limit of the 90% confidence interval by about 200 m and the lower limit by less than $\sim$ 30 m [1], with a consistent effect across all models, We have computed the Bayes evidence for each model that incorporates PSR J0437-4715 data but excludes PREX-II and observed a decrease of $\sim$ 1 in the logarithm of the Bayes evidence in all instances. This suggests that the new NICER data conflicts with the old data or that the current EOS model lacks the flexibility to simultaneously accommodate all NICER data.

TABLE I: Log evidence $\ln(\mathcal{Z})$ Values for the different Models. The *Best Model* is NL-σ cut (without PREX-II) with the highest log evidence of -62.18.

Model	$\ln(\mathcal{Z})$	$\ln(\mathcal{Z})$ (With PSR J0437-471)
NL	-64.14 ± 0.16	-65.25 ± 0.15
NL + PREX-II	-68.53 ± 0.17	...
NL-σ cut	*-62.18 ± 0.15*	*-63.36 ± 0.15*
NL-σ cut + PREX-II	-66.15 ± 0.17	...
NL DM	-64.53 ± 0.15	-65.57 ± 0.15
NL DM + PREX-II	-69.12 ± 0.17	...

Conclusion

In conclusion, while strong correlations between dark matter parameters and neutron star properties exist, they weaken with the inclusion of nuclear matter EOS uncertainties. Despite this, universal relations like compactness versus Λ remain intact. Dark matter can also trigger processes like hyperon onset, nucleonic URCA, and quark-hadron transitions. However, the NL-σ cut model, favoring a stiffer EOS at high densities, is more consistent with recent constraints. Currently, models including dark matter are less supported, and high-precision observations are needed to clarify their role in neutron stars.

Acknowledgments

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References

[1] P. Thakur et al.,"Feasibility of dark matter admixed neutron star based on recent observational constraints," arXiv:2408.03780 [nucl-th].

[2] P. Thakur et. al., "Influence of the symmetry energy and σ-cut potential on the properties of pure nucleonic and hyperon-rich neutron star matter," Phys. Rev. C **109**, no.2, 025805 (2024), doi:10.1103/PhysRevC.109.025805.