Feasibility of dark matter admixed neutron star based on recent observational constraints

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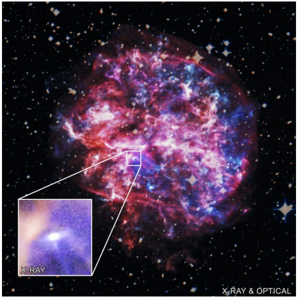
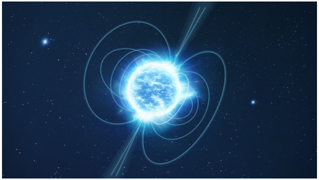
Formation

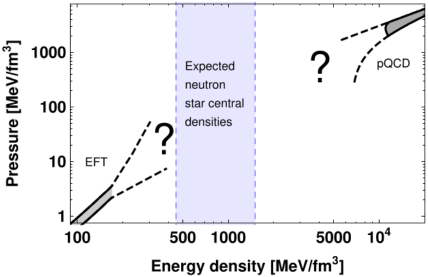
- A supernova explosion of star of mass 'M' $> 8\ M_\odot$ star blows away its outer layers leaving a remnant.
- The central core collapses into a compact object of $\approx$ a few $M_\odot$ and radius of ≈ 10 km.
- Compact objects more massive than the Chandrasekhar limit $(1.4 M_\odot$ collapse beyond the formation of a white dwarf).
- Pressure becomes so high that electrons and protons combine to form stable neutrons (Inverse $\beta-$ decay). $p + e^- \rightarrow n + \nu_e$





The Missing Link

- Chiral Effective Field Theory (ChEFT): robust in capturing the interactions at densities up to (1-2) times the nuclear saturation density (ρ_0).
- At densities exceeding (50-100) ρ_0, perturbative quantum chromodynamics (pQCD) provides a reliable framework.
- Still, there is no comprehensive theory that can fully explain the density regime from $(2-7)\rho_0$, relevant to neutron stars core density.

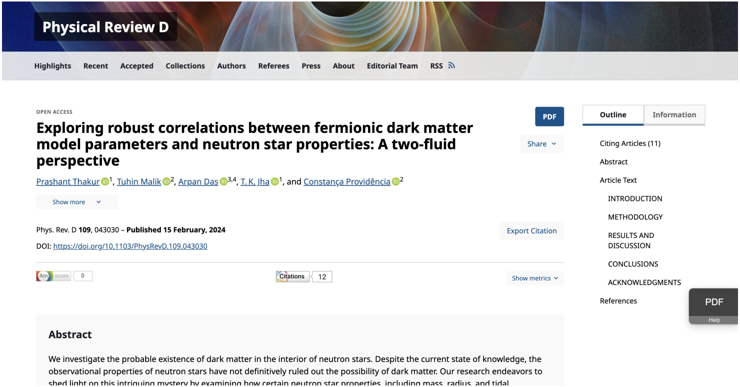


Reference: M Järvinen (2022). Holographic modeling of nuclear matter and neutron stars *The European Physical Journal C*, 282, 82.

Objectives

- Can we really constrain the Dark Matter EOS model for NS?
  - Explore correlations between dark matter model parameters and neutron star properties, with consideration of uncertainties in the nuclear sector.

Exploring robust correlations between fermionic dark matter model parameters and neutron star properties: A two-fluid perspective



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Exploring robust correlations between fermionic dark matter model parameters and neutron star properties: A two-fluid perspective

Prashant Thakur[1], Tuhin Malik[2], Arpan Das[3,4], T. K. Jha[1], and Constança Providência[2]

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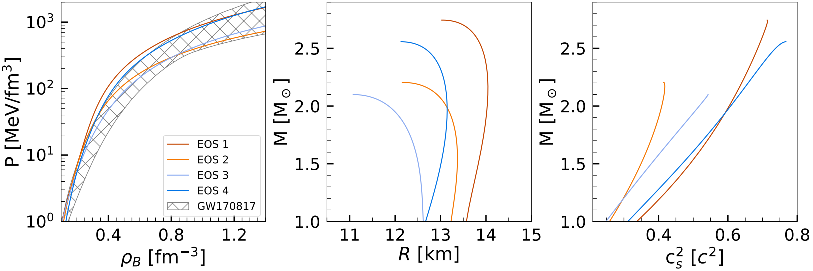
Abstract

We investigate the probable existence of dark matter in the interior of neutron stars. Despite the current state of knowledge, the observational properties of neutron stars have not definitively ruled out the possibility of dark matter. Our research endeavors to shed light on this intriguing mystery by examining how certain neutron star properties, including mass, radius, and tidal

Nuclear matter EOS

- We selected four random equations of state (EOS) for nuclear matter derived using the RMF method, which encompass the current uncertainties in the nuclear EOS sector and differ in their stiffness.



(left plot) Pressure P vs baryon density ρ_B, (middle plot) NS mass M vs radius R, and (right plot) NS mass M vs square of the speed of sound c_s^2 for nuclear matter EOS: EOS1, EOS2, EOS3, and EOS4, respectively.

EOS	NMP						NS										
	ρ_0 [fm^{-3}]	ε_0	K_0	Q_0 [MeV]	$J_{\mathrm{sym},0}$	$L_{\mathrm{sym},0}$	$M_{\max}$ [M$_\odot$]	$R_{\max}$	$R_{1.4}$ [km]	$R_{2.08}$	$\Lambda_{1.4}$ [...]	c_s^2 [c^2]	M_{dUrca} [M$_\odot$]	ρ_{dUrca}	$\rho_{\mathrm{B},1.4}$ [fm^{-3}]	$\rho_{\mathrm{B},1.6}$	$\rho_{\mathrm{B},1.8}$
EOS1	0.155	-16.08	177	-74	33	64	2.74	13.03	13.78	14.04	844	0.713	2.06	0.366	0.298	0.316	0.336
EOS2	0.154	-15.72	190	614	32	60	2.20	12.16	13.36	13.00	709	0.414	1.83	0.443	0.344	0.382	0.432
EOS3	0.157	-16.24	260	-400	32	57	2.10	11.08	12.55	11.53	462	0.543	2.07	0.829	0.432	0.491	0.570
EOS4	0.156	-16.12	216	-339	29	42	2.56	12.13	12.95	13.14	638	0.767	2.55	0.747	0.345	0.370	0.399

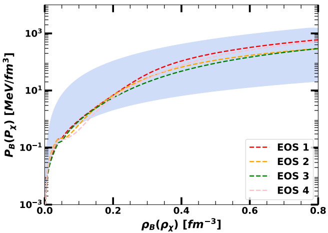
Dark Matter EOS

- Similar to the Lagrangian of the nuclear model, one can apply the knowledge from the nuclear mean field approach to describe the Lagrangian for the fermionic dark matter sector.
- We consider the simplest dark matter Lagrangian with a single fermionic component (χ_D).

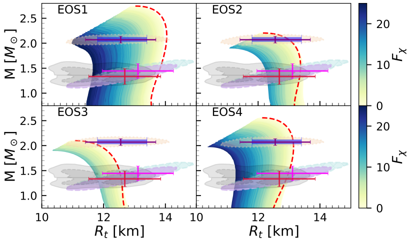
$$\begin{aligned}\mathcal{L}_\chi = \bar{\chi}_D \left[\gamma_\mu(i\partial^\mu - g_{vd} V_D^\mu) - m_\chi\right] \chi_D \\ - \frac{1}{4} V_{\mu\nu,D} V_D^{\mu\nu} + \frac{1}{2} m_{vd}^2 V_{\mu,D} V_D^\mu\end{aligned} \tag{1}$$

$$\varepsilon_\chi = \frac{1}{\pi^2} \int_0^{k_D} dk\ k^2 \sqrt{k^2 + m_\chi^2} + \frac{1}{2} c_\omega^2 \rho_D^2 \tag{2}$$

Sampling Dark Matter EOS & Mass-Radius



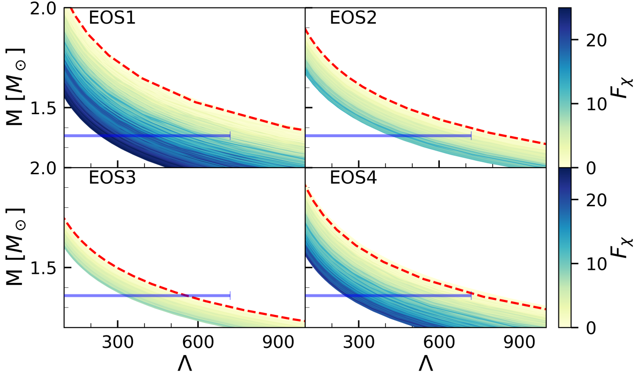
The shaded blue area illustrates the sampled dark matter EOS, depicting the relationship between pressure (P_χ) and density (ρ_χ).



The NS mass-radius relationships.

- 50K dark matter EOSs were solved per nucleonic EOS, totaling 200,000 M-R calculations.
- The recent mass and radius constraints from NICER or GW observations can't precisely determine the dark matter fraction F_χ.

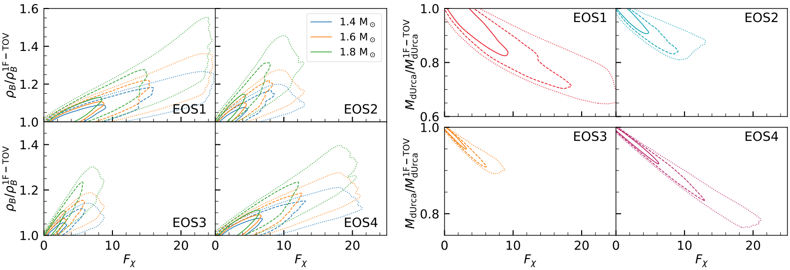
Tidal Deformability



The figure shows the tidal deformability (Λ) versus neutron star mass ($M_\odot$).

- Λ negatively correlated with DM fraction F_χ
- The inclusion of dark matter could potentially lead to a reduction in the higher tidal deformability attributed to the stiff nuclear EOS.
- The capability of the admixed neutron star to support varying mass fractions depends on the stiffness of the equation of state of nuclear matter F_χ

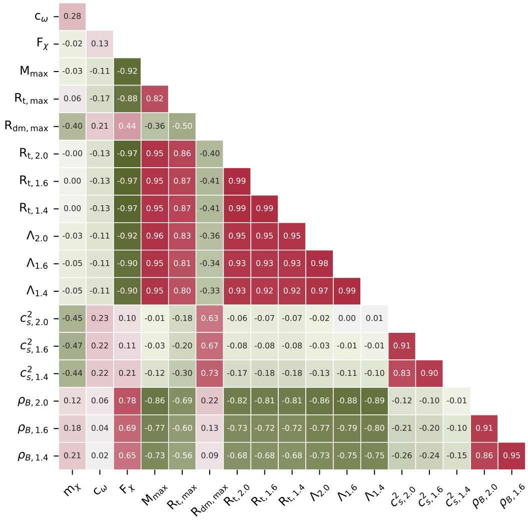
Neutron Star density profiles and dURCA Process



On the left is the ρ_B/ρ_B^{1F-TOV} as a function of F_χ with a fixed masses of 1.4, 1.6, 1.8 solar masses, while on the right is the neutron star mass threshold at which the dUrca process begins for various combinations of admixed dark matter neutron stars.

- The mass is pushed to the center, the central baryonic density increases, and the radius of the star decreases.
- A significant correlation is evident between the dark matter mass fraction and the NS mass at which Urca begins.

Correlations



Heat map illustrating the correlation between different properties of dark matter (DM) admixed neutron stars (NS) using the nuclear equation of state as EOS1.

- Strong correlation between F_χ and various properties of NS.
- Other DM model parameters, $m\chi$ and c_ω are weakly correlated with the NS properties.

Introducing Uncertainties in nuclear EOS

- When combining the admixed NS configuration with all four considered nuclear EOS configurations, the correlation among various properties vanishes.

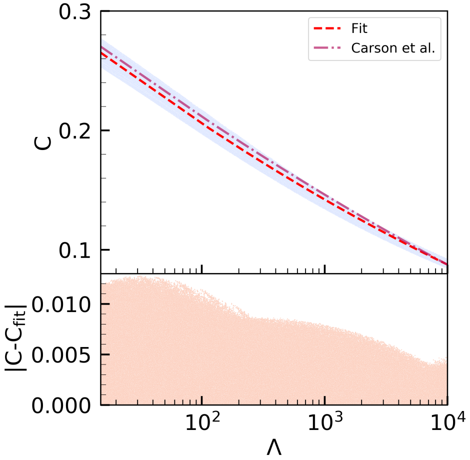
With EOS 1:

With all four nuclear EOS:

	m_χ	c_ω	M_{max}	$R_{t,max}$	$R_{dm,max}$	$R_{t,2.0}$	$R_{t,1.6}$	$R_{t,1.4}$	$\Lambda_{2.0}$	$\Lambda_{1.6}$	$\Lambda_{1.4}$	$C^2_{s,2.0}$	$C^2_{s,1.6}$	$C^2_{s,1.4}$	$\rho_{B,2.0}$	$\rho_{B,1.6}$	$\rho_{B,1.4}$
F_χ (EOS 1)	-0.02	0.19	-0.98	-0.97	0.53	-0.59	-1.00	-1.00	-0.98	-0.97	-0.97	-0.17	0.19	0.30	0.28	0.88	0.85
F_χ (all four nuclear EOS)	-0.06	0.17	-0.30	-0.32	0.56	-0.18	-0.59	-0.65	-0.43	-0.63	-0.70	0.03	0.38	0.46	-0.09	0.02	0.02

** Determining the parameters of a DM model is challenging, even when using a very simple model with constraints on only NS mass-radius and tidal deformability. **

Are the well-known universal relations distinguishable in neutron stars with admixed dark matter?



C-Love universal relationship within the context of 200,000 EOS configurations incorporating dark matter.

- C-Love relation stays intact, even with dark matter.

Objectives

- What is the possibility of Dark Matter existence inside NS core?
  - Assess the feasibility of Dark Matter in Neutron Stars using a Bayesian approach informed by current observational constraints.
- What is the impact of new PSR J0437-4715 measurements on neutron star mass-radius estimates?

Feasibility of dark matter admixed neutron star based on recent observational constraints
(A Bayesian Approach)

Feasibility of dark matter admixed neutron star based on recent observational constraints

Prashant Thakur [1,2,*] Tuhin Malik [2,†] Arpan Das [3,‡] T. K. Jha [1,§] B. K. Sharma [4,¶] and Constança Providência [2,**]

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(Dated: August 8, 2024)

arXiv:2408.03780

Nuclear & Astrophysical Constraints Imposed

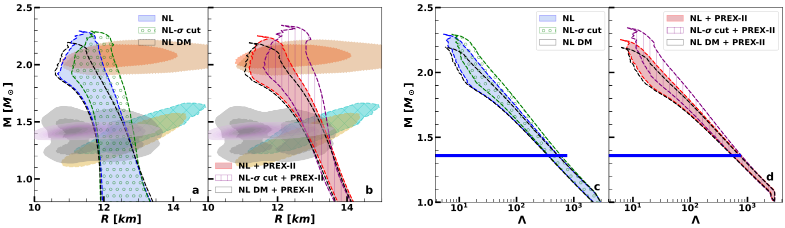
(See C. Y. Tsang et al., Nature Astronomy 8, 328 (2024) for details)

Symmetric matter Constraints	n (fm^{-3})	P_{SNM} (MeV/fm^3)	Ref.
HIC(DLL)	0.32	10.1 ± 3.0	Danielewicz et al. (2002)
HIC(FOPI)	0.32	10.3 ± 2.8	Le Fèvre et al. (2016)

Asymmetric matter Constraints	n (fm^{-3})	S(n) (MeV)	P_{sym} (MeV/fm^3)	Ref.
Nuclear structure				
α_D	0.05	15.9 ± 1.0		Zhang & Chen (2015)
PREX-II	0.11		2.38 ± 0.75	Adhikari et al. (2021); Reed et al. (2021); Lynch & Tsang (2022)
Nuclear masses				
Mass(Skyrme)	0.101	24.7 ± 0.8		Brown & Schwenk (2014); Lynch & Tsang (2022)
Mass(DFT)	0.115	25.4 ± 1.1		Kortelainen et al. (2012); Lynch & Tsang (2022)
IAS	0.106	25.5 ± 1.1		Danielewicz et al. (2017); Lynch & Tsang (2022)
Heavy-ion collisions				
HIC(Isodiff)	0.035	10.3 ± 1.0		Tsang et al. (2009); Lynch & Tsang (2022)
HIC(n/p ratio)	0.069	16.8 ± 1.2		Morfouace et al. (2019); Lynch & Tsang (2022)
HIC(π)	0.232	52 ± 13	10.9 ± 8.7	Estee et al. (2021); Lynch & Tsang (2022)
HIC(n/p flow)	0.240		12.1 ± 8.4	Cozma (2018); Russotto et al. (2011); Russotto & *et. al.* (2016); Lynch & Tsang (2022)

Astrophysical Constraints	$M_\odot$	R (km)	$\Lambda_{1.36}$	Ref.
LIGO [1]	1.36		300^{+420}_{-230}	Abbott *et al.* (2019)
*Riley PSR J0030+0451 [2]	1.34	$12.71^{+1.14}_{-1.19}$		Riley et al. (2019)
*Miller PSR J0030+0451 [3]	1.44	$13.02^{+1.24}_{-1.06}$		Miller et al. (2019)
*Riley PSR J0740+6620 [4]	2.07	$12.39^{+1.30}_{-0.98}$		Riley *et al.* (2021)
*Miller PSR J0740+6620 [5]	2.08	$13.7^{+2.6}_{-1.5}$		Miller et al. (2021)
*Choudhury PSR J0437-4715 [6]	1.418	$11.36^{+0.95}_{-0.63}$		Choudhury et al. (2024)

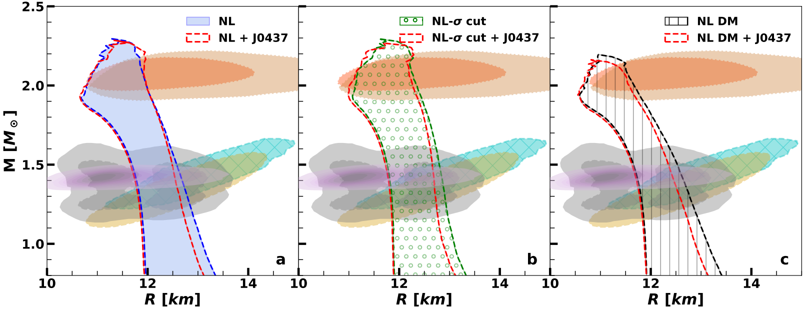
NS mass-radius-tidal deformability



Left the 90% credible interval (CI) region for the NS mass-radius posterior $P(R|M)$ is plotted, while right, the 90% CI region for the mass-tidal deformability posterior $P(\Lambda|M)$ is displayed for the NL, NL-σ cut, and NL-DM models.

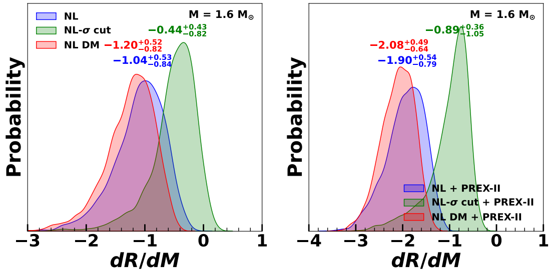
- The NL-σ cut shifts the M-R posterior right, increasing radius, while dark matter in NL-DM shifts it left.
- PREX-II data narrows the lower part of the M-R posterior.
- PREX-II also enhances both the radius and tidal deformability for a canonical neutron star mass.

Impact of PSR J0437-4715



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.

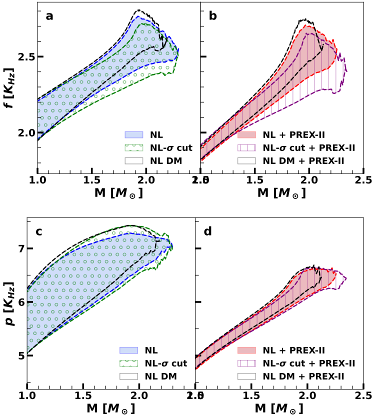
dR/dM



The dR/dM distribution at a neutron star mass of 1.6 $M_\odot$ for three scenarios: NL, NL-σ cut, and NL-DM, shown without PREX-II data on the left and with PREX-II data on the right.

- The dR/dM could be a good probe.
- PREX-II data make slopes more negative, with reduced Bayesian evidence for models.

f and p mode



The figure depicts the relationship between neutron star (NS) mass (M) and the frequencies of non-radial oscillation modes, with the fundamental mode (f) shown in the upper plots and the pressure mode (p) in the lower plots.

- For PREX-II, the distribution is narrower at lower neutron star masses.
- p-mode frequency is only marginally distinguishable

Bayes Evidence

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	...

Model1/Model2	$\Delta \ln(\mathcal{Z})$	Interpretation
NL-σc P2/NL-σc	-3.96	Decisive for NL-σc
NL-σc P2/NL P2	2.38	Substantial for NL-σc P2
NL-σc P2/NL	-2.01	Substantial for NL
NL-σc/NL P2	6.35	Decisive for NL-σc
NL-σc/NL	1.96	Substantial for NL-σc
NL P2/NL	-4.39	Decisive for NL

- NL-σ cut is the most preferred model.
- With the addition of PREX-II Bayes evidence decreases.
- Bayes evidence decrease of ~ 1 with incorporation of PSR J0437-4715

Objectives

- **Precision of Future Observatories:**
  Upcoming X-ray observatories (eXTP, STROBE-X) and third-generation gravitational-wave detectors (Einstein Telescope, Cosmic Explorer) aim to measure NS radii with remarkable precision (e.g., $\Delta R \leq 0.2$ km) at 90% credibility, enabling detailed analysis of NS properties.
- If we accurately know the sequence of NS properties, can we differentiate the admixed dark matter in the NS case from other scenarios?
  - So to answer this we have used the Machine learning classification technique (Random Forest Classifier)

Towards Uncovering Dark Matter Effects on Neutron Star Properties: A Machine Learning Approach

Open Access Article

Towards Uncovering Dark Matter Effects on Neutron Star Properties: A Machine Learning Approach

by Prashant Thakur [1], Tuhin Malik [2,*] and Tarun Kumar Jha [1]

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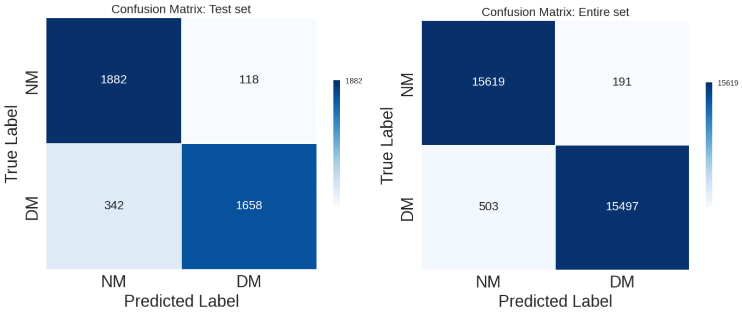
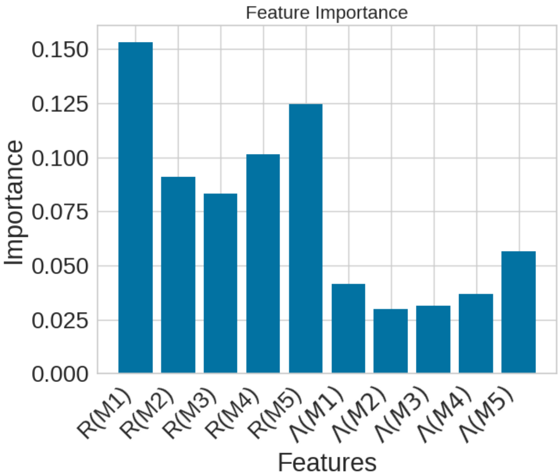
Confusion matrices



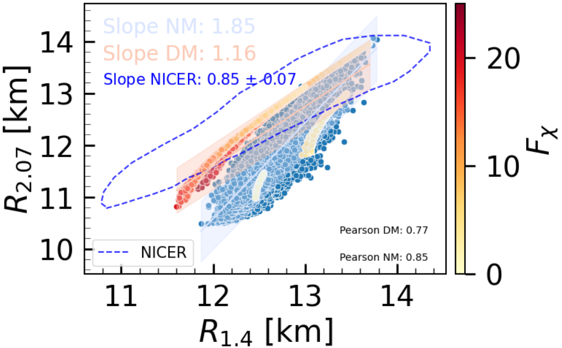
Contains a total of 15 features which includes mass, radius, and tidal deformability

Feature Importance Plot



Feature importance for Random Forest classification from $X2$.

Relationship between the radii of neutron stars



Relationship between radius at 1.4 $M_\odot$ and 2.07 $M_\odot$

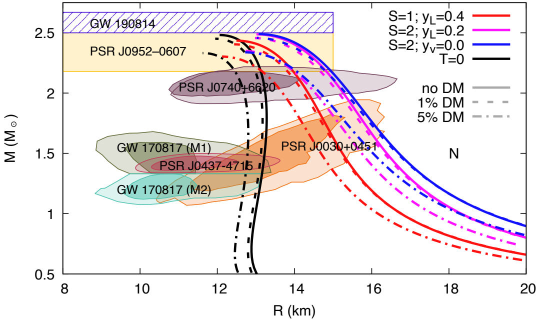
Conclusions

- Strong correlations between dark matter parameters and neutron star properties are evident, but these correlations weaken once uncertainties in the nuclear matter EOS are considered.
- Universal relations, like compactness versus Lambda, remain intact even with the presence of dark matter in neutron stars.
- Dark matter can facilitate processes such as hyperon onset, nucleonic URCA, and quark-hadron phase transitions.
- The NL-σ cut model, exhibiting behavior contrary to that of dark matter, is highly favored according to recent constraints, suggesting a preference for a stiffer equation of state at high densities.
- Models that include dark matter are the least supported; accurate and high-precision observations from multiple measurements will be required to provide more insights.

Conclusions

- Neutron stars with admixed dark matter have about a 17% chance of being misclassified as nuclear matter neutron stars.
- Additional tidal deformability parameter data do not significantly improve the precision of our predictions.
- Radius measurements, particularly at extreme mass values, emerge as promising features.

Future Plans



Total gravitational mass (M) of a PNS as a function of the total radius (R_t). The top panel illustrates the evolution of neutrino-trapped, β-equilibrated stellar matter at various stages of the star's evolution, characterized by different entropy per baryon (s_t) and lepton fraction ($Y_{L,e}$), compared to a neutrino-transparent star with $S_t = 2$; $Y_{\nu_e} = 0$ and $T = 0$ for nucleonic composition. The bottom panel shows the same scenario but with the inclusion of hyperonic degrees of freedom.

Paper in Preparation:

Effect of Dark Matter on Supernova Remnant: A Two-Fluid Model

Adamu Issifu, Prashant Thakur, Franciele M. da Silva

- Unveiling Dark Matter Effects on Neutron Stars via Multi-Messenger Astronomy

Future Plans

- Machine Learning-Driven Analysis of Neutron Star Composition and Dark Matter:
  - Develop a machine learning framework to deduce the equation of state (EoS) for neutron stars using mass-radius observational data.
  - Generate a diverse set of synthetic EoS models, partition the density range into segments, and assign sound velocities.
  - Solve the Tolman-Oppenheimer-Volkoff (TOV) equation to obtain mass-radius (M-R) relations.
  - Incorporate realistic observational errors for accurate model training.
  - Design and train a neural network with appropriate activation functions and optimize the loss function (e.g., mean square log of prediction errors).
  - Validate the model against independent data sets.
  - Compare machine learning results with Bayesian analysis for robustness and accuracy.

References

- **Exploring robust correlations between fermionic dark matter model parameters and neutron star properties: A two-fluid perspective**
  P. Thakur, T. Malik, A. Das, T.K. Jha, C. Providência
  DOI: 10.1103/PhysRevD.109.043030
  Phys. Rev. D, Vol. 109, 043030 (2024)
- **Feasibility of dark matter admixed neutron stars based on recent observational constraints**
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  arXiv: arXiv:2408.03780v1
  Submitted to: Astron. & Astrophys.
- **Towards uncovering dark matter effects on neutron star properties: A machine learning approach**
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Thank you