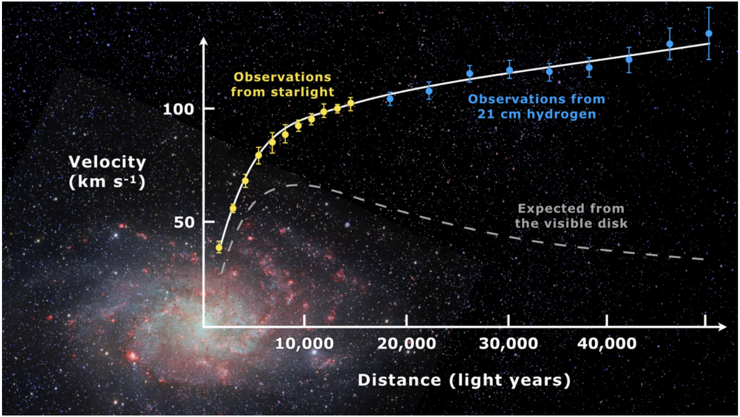
Probing the Microphysics of Neutron Stars: Impact of Dark Matter and Modified Nuclear Interactions on Global and Oscillation Properties

Prashant Thakur

Yonsei University
Bits Pilani, K.K. Birla Goa Campus

July 2, 2025

Galaxy Roation Curve



Rotation curve of spiral galaxy Messier 33. Image sourced from Bergstrom [2000]

Dark matter (DM) admixed neutron star (NS)

Accumulation of DM by a star or a NS during its life time

A) Progenitor B) Main sequence (MS) star, C) Supernova explosion & formation of a proto-NS D) Equilibrated NS

NS exists in a dense halo or region of DM or passes through it (Near the center of galaxy)

Dark star as an accretion center of baryonic matter

DM production in the NS matter or supernova explosions

Neutron decay anomaly

Accretion of DM into a NS

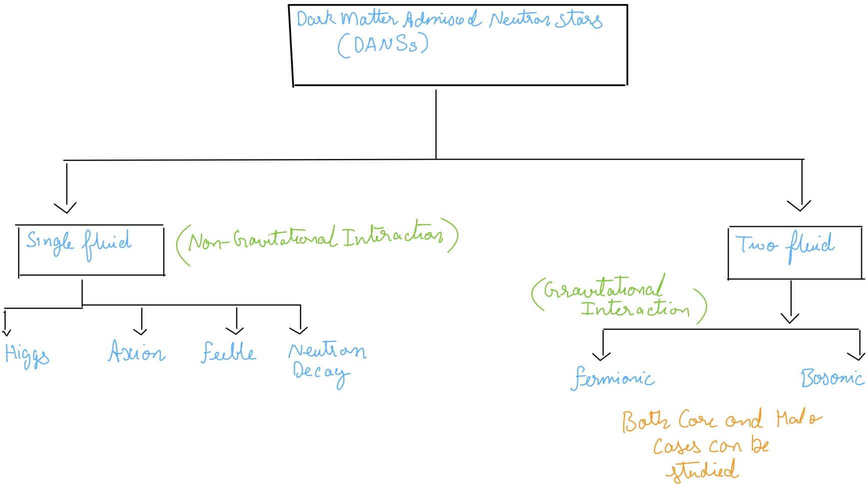
DM capture by NS in a binary system including Dark star or Dark star – NS merger

A. Nelson, S. Reddy, D. Zhou, **JCAP07(2019)012**
John Ellis, et al. **PRD 97, 123007 (2018)**
A. Del Popolo, et al. **Universe 6 (2020) 12, 222**

D.R. Karkevandi, *S. Shakeri, V. Sagun, O. Ivanytskyi,* **PRD 105, 023001 (2022)**
O. Ivanytskyi, V. Sagun, I. Lopes. **PRD 102, 063028 (2020)**
Raul Ciancarella, et al. **Phys.Dark Univ. 32 (2021) 100796**

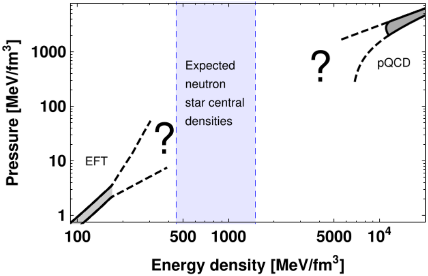
Ang Li, et al. **astropartphys.2012.07.006**
S. Shirke, S. Ghosh, D. Chatterjee, L. Sagunski, J. Schaffner-Bielich, **arXiv:2305.05664**
W. Husain, T. F. Motta, A.W. Thomas, **JCAP 10 (2022) 028**

Current Status of Dark Matter Admixed Neutron Stars



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.

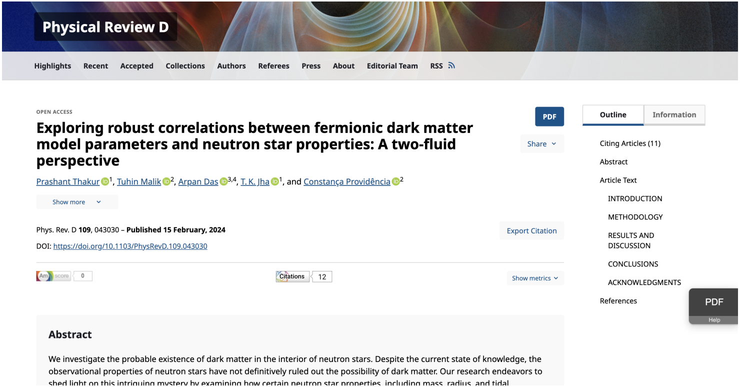


Reference: M Järvinen (2022). Holographic modeling of nuclear matter and neutron stars *The European Physical Journal C*, 282, 82.

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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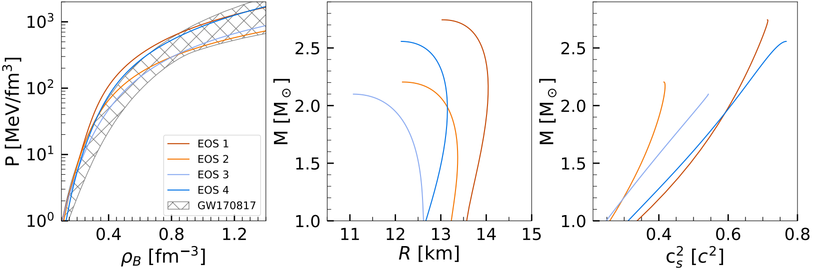
Abstract

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	ε_0	K_0	Q_0	$J_{\mathrm{sym},0}$	$L_{\mathrm{sym},0}$	$M_{\max}$	$R_{\max}$	$R_{1.4}$	$R_{2.08}$	$\Lambda_{1.4}$	c_s^2	M_{dUrca}	ρ_{dUrca}	$\rho_{\mathrm{B},1.4}$	$\rho_{\mathrm{B},1.6}$	$\rho_{\mathrm{B},1.8}$
	[fm^{-3}]			[MeV]			[M$_\odot$]		[km]		[...]	[c^2]	[M$_\odot$]		[fm^{-3}]		
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

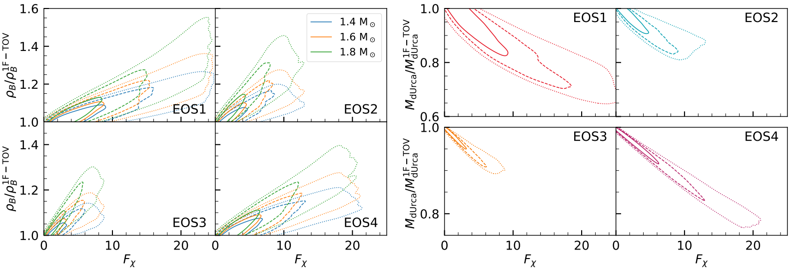
Dark Matter EOS

- 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).

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

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

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.

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:

	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	-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

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	-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

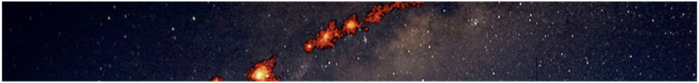
** Determining the parameters of a DM model is challenging, even when using a very simple model with constraints on only NS mass-radius and tidal deformability. **

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)

Astronomy & Astrophysics   All volumes   For authors



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A&A, 697, A220 (2025)

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

P. Thakur[1,2], T. Malik[2*], A. Das[3], T. K. Jha[1], B. K. Sharma[4] and C. Providência[2]

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Nuclear & Astrophysical Constraints Imposed

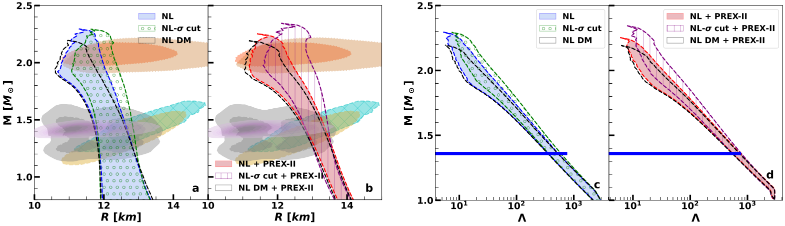
(See C. Y. Tsang et al., Nature Astronomy 8, 328 (2024) for details)

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)

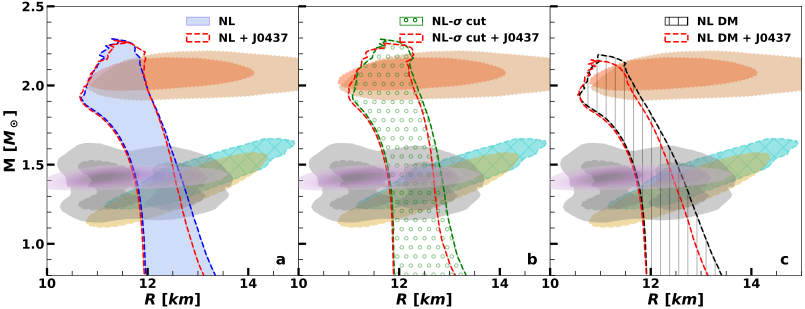
NS mass-radius-tidal deformability



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.

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

- Can We Differentiate Dark Matter in Neutron Stars?
    - 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?

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]

[1] Department of Physics, BITS-Pilani, K. K. Birla Goa Campus, Sancoale 403726, Goa, India

[2] CFisUC, Department of Physics, University of Coimbra, P-3004-516 Coimbra, Portugal

[*] Author to whom correspondence should be addressed.

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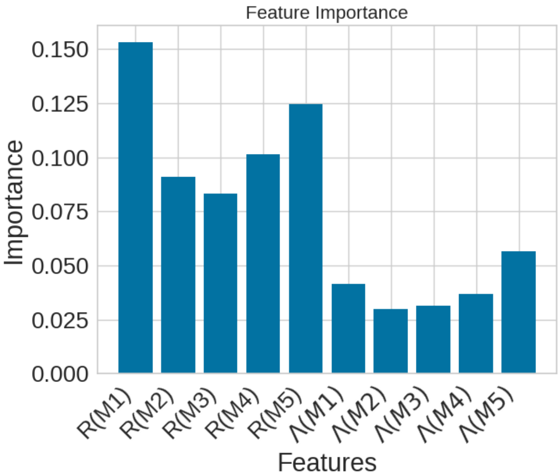
Sampling

- **Dataset Details:**
  - 32,000 Equation of States
  - **16,000** with **Dark Matter**
  - **16,000** with **Nuclear Matter Only**
- **Feature Creation:**
  - **X1:** Mass & Radius
  - **X2:** Mass, Radius & Tidal Deformability
- **Target Vector (Y):**
  - $\mathbf{Y = 0}$**:** Nuclear Matter
  - $\mathbf{Y = 1}$**:** Dark Matter
- **Data Preparation:**
  - Combined and shuffled 32,000 entries
  - Split into:
    - **60%** Training
    - **20%** Validation
    - **20%** Testing

Feature Importance Plot



Feature importance for Random Forest classification from $X2$.

Relationship between the radii of neutron stars

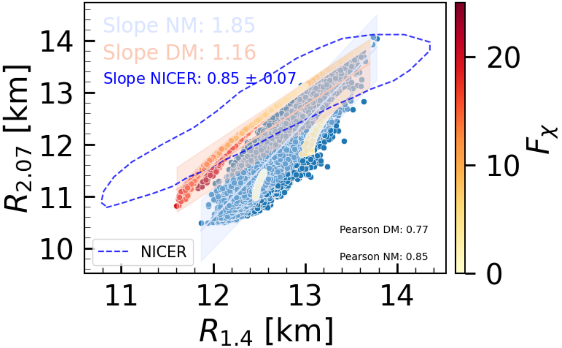


Figure displays the relationship between the radii of neutron stars with masses of 1.4 and 2.07 solar masses ($M_\odot$).

Objectives

- Effect of Dark Matter on the Macroscopic and Microscopic Properties of Protoneutron Stars.

Supernova remnants with mirror dark matter and hyperons

Physical Review D

Supernova remnants with mirror dark matter and hyperons

Adamu Issifu[1,*], Prashant Thakur[2], Franciele M. da Silva[3], Kau D. Marquez[1,†], Débora P. Menezes[3], M. Dutra[1], O. Lourenço[1], and Tobias Frederico[1]

Phys. Rev. D **111**, 083026 – **Published 17 April, 2025**

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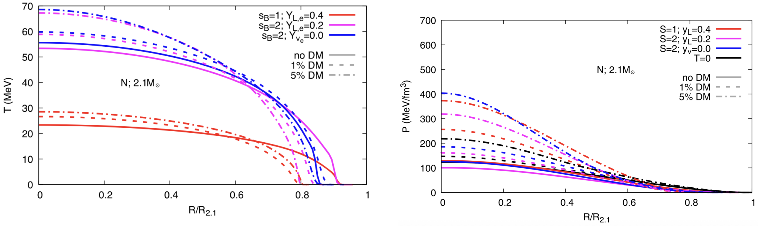
Results



Temperature & pressure profile of a 2.1 $M_\odot$ star

Oscillations in Neutron stars

- **Radial Oscillations:**
  - Involve spherically symmetric pulsations.
  - No angular dependence ($\ell = 0$).
  - Restore force: pressure gradient and gravity.
  - Used to probe stability
  - Do **not** emit GWs directly, but can couple to non-radial modes and modulate SGRBs in mergers.
- **Non-Radial Oscillations:**
  - Involve deformation with angular dependence ($\ell \geq 2$).
  - Classified as:
    - **Polar perturbations** (even parity: $(-1)^{\ell}$)
    - *f*-mode: Fundamental mode with no nodes; surface-peaked; $\sim$1.5–3 kHz; damping time $\sim$0.1–0.5 s.
    - *p*-modes: Pressure-driven modes with interior nodes; high frequency ($\sim$4–7 kHz); damping time few s–100 s
    - *g*-modes: buoyancy-driven, $<$100 Hz, require thermal/composition gradients.
    - **Axial perturbations** (odd parity: $(-1)^{\ell+1}$)
  - Can emit **gravitational waves**.
  - Sensitive to internal structure and EoS.

Objectives

- To investigate how oscillation modes of neutron stars can be used to constrain the nuclear equation of state

Effect of Dark matter and σ-cut potential on radial and non-radial oscillation modes in neutron stars

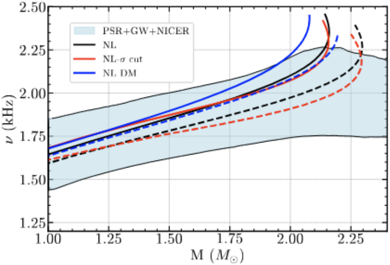
Effect of Dark matter and σ-cut potential on radial and non-radial oscillation modes in neutron stars

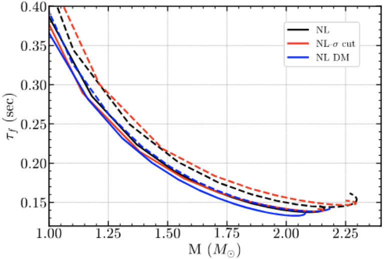
Prashant Thakur [1,2,*] Ishfaq Ahmad Rather [3,†] and Y. Lim [2,‡]

[1] *Department of Physics, BITS-Pilani, K. K. Birla Goa Campus, Goa 403726, India*
[2] *Department of Physics, Yonsei University, Seoul, 03722, South Korea*
[3] *Institut für Theoretische Physik, Goethe Universität, Max-von-Laue-Str. 1, D-60438 Frankfurt am Main, Germany*

In communication to PRD

f mode and Damping time





f mode frequency and damping time as a function of gravitational mass of neutron star. The solid (dashed) lines correspond to the soft (stiff) EoSs

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.
- Dark matter can facilitate processes such as hyperon onset, nucleonic URCA, and quark-hadron phase transitions.
- Models that include dark matter are the least supported; accurate and high-precision observations from multiple measurements will be required to provide more insights.
- Radius measurements, particularly at extreme mass values, emerge as promising features.
- Dark matter contributes to an increase in the thermal profile of protoneutron stars.
- Dark matter softens the EoS, producing more compact stars with higher frequencies and shorter damping times, while the σ-cut potential increases stiffness, leading to lower frequencies and longer damping times.

Future Scope

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**
  P. Thakur, T. Malik, A. Das, B.K. Sharma, T.K. Jha, C. Providência
  arXiv: arXiv:2408.03780v1
  Submitted to: Astron. & Astrophys.
- **Towards uncovering dark matter effects on neutron star properties: A machine learning approach**
  P. Thakur, T. Malik, T.K. Jha
  DOI: 10.3390/particles7010008
  Particles, Vol. 7, 80-95 (2024) • e-Print: arXiv:2401.07773 [hep-ph]
- **Supernova Remnants with Mirror Dark Matter and Hyperons**
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  Phys. Rev. D, Vol. 111, 083026 (2025)
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  In communication to Phys. Rev. D

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Dr. Tuhin Malik
CFisUC, Department of Physics, University of Coimbra, Portugal

Dr. Ishfaq Rather
Institut für Theoretische Physik, Goethe Universität,
Max-von-Laue-Str. 1, D-60438 Frankfurt am Main, Germany

Prof. Yeunhwan Lim
Department of Physics, Yonsei University, Seoul, 03722, South Korea

Prof. Constança Providência
CFisUC, Department of Physics, University of Coimbra, Portugal

Dr. Adamu
Federal university of Espirito Santo, department of physics

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