Exploring robust correlations between fermionic dark matter model parameters and neutron star properties

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Prashant Thakur, Tuhin Malik, Arpan Das, T. K. Jha and Constança Providência

Tuhin Malik

CFisUC, University of Coimbra

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Universidade de Coimbra

CFisUC

FCT Fundação para a Ciência e a Tecnologia

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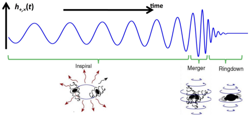
Neutron Stars

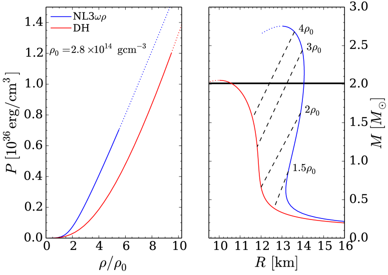
In 1967, Jocelyn Bell Burnell, then a graduate student in radio astronomy at the University of Cambridge, discovered the first radio pulsars.

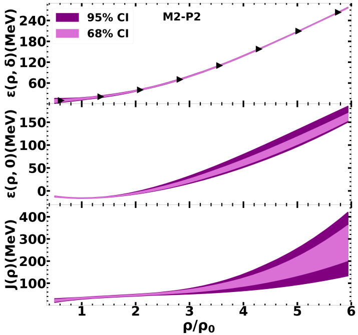
- The neutron stars (NS) laboratory for dense baryonic matter (the core density $\sim$ 4-5 times nuclear saturation density).
- Very asymmetric nuclear matter $I = \frac{\rho_n - \rho_p}{\rho_n + \rho_p} \sim 0.7$.
- The observational constraints
  - Radio Channel: J1614-2230 $1.97 \pm 0.04 M_\odot$, J0348+0432 $2.01 \pm 0.04 M_\odot$, J0740+6620 $2.14^{+0.10}_{-0.09} M_\odot$, PSR J0740+6620 $2.08^{+0.07}_{-0.07} M_\odot$.
  - X-Ray channel: NICER allowing a prediction of both the NS mass and radius.
  - GW channel: binary neutron star merger GW170817.



Probing the interior of Neutron Stars

- mass-radius → equation of state → composition?





- hyperons?
- deconfined quark matter?
- dark matter?
- ~~or modified gravity?~~

Sk Md Adil Imam et al. PRC 105, 015806 (2022)
See also:

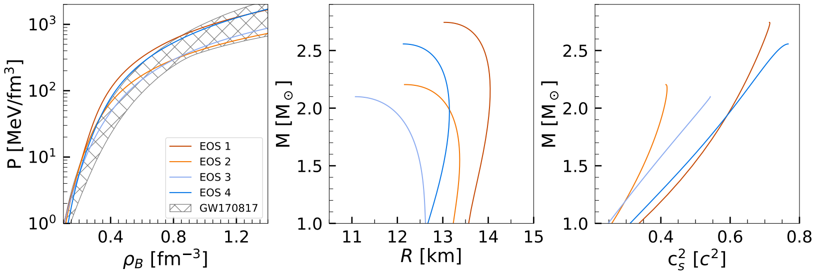
- Tovar et al., PRD 104 (2021)
- Mondal & Gulminelli, PRD 105 (2022)
- Essick, PRL 127, 192701 (2021)

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.
- 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?

Nuclear matter EOS

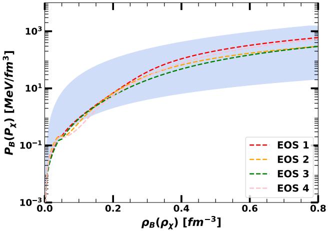
- We selected four random equations of state (EOS) for nuclear matter derived using the RMF method, which encompass the current uncertainties in the nuclear EOS sector and differ in their stiffness.



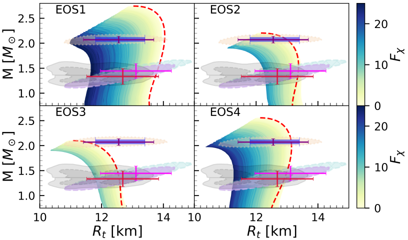
(left plot) Pressure P vs baryon density ρ_B, (middle plot) NS mass M vs radius R, and (right plot) NS mass M vs square of the speed of sound c_s^2 for nuclear matter EOS: EOS1, EOS2, EOS3, and EOS4, respectively.

EOS	NMP						NS										
	ρ_0	ε_0	K_0	Q_0	$J_{sym,0}$	$L_{sym,0}$	M_{max}	R_{max}	$R_{1.4}$	$R_{2.08}$	$\Lambda_{1.4}$	c_s^2	M_{dUrca}	ρ_{dUrca}	$\rho_{B,1.4}$	$\rho_{B,1.6}$	$\rho_{B,1.8}$
	[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

Sampling Dark Matter EOS & Mass-Radius



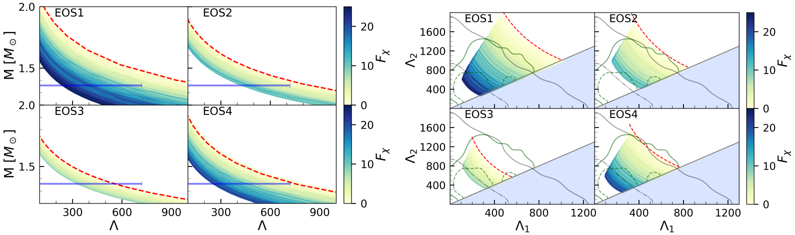
The shaded blue area illustrates the sampled dark matter EOS, depicting the relationship between pressure (P_χ) and density (ρ_χ).



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.

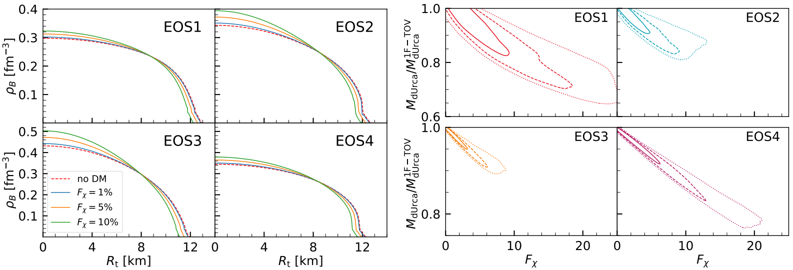
Tidal Deformability



The left figure shows the tidal deformability (Λ) versus neutron star mass ($M_\odot$). Right figure displays the Λ_1-Λ_2 relation with dark matter fraction (F_χ) from 0 to 25%, based on the GW170817 event with a chirp mass of M_{chirp} = 1.186 $M_\odot$.

- 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 baryon number density profile for a neutron star with a fixed mass of 1.4 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

	m_χ	c_ω	F_χ	M_{max}	$R_{t,max}$	$R_{dm,max}$	$R_{t,2.0}$	$R_{t,1.6}$	$R_{t,1.4}$	$\Lambda_{2.0}$	$\Lambda_{1.6}$	$\Lambda_{1.4}$	$c^2_{s,2.0}$	$c^2_{s,1.6}$	$c^2_{s,1.4}$	$\rho_{B,2.0}$	$\rho_{B,1.6}$
c_ω	0.28																
F_χ	-0.02	0.13															
M_{max}	-0.03	-0.11	-0.92														
$R_{t,max}$	0.06	-0.17	-0.88	0.82													
$R_{dm,max}$	-0.40	0.21	0.44	-0.36	-0.50												
$R_{t,2.0}$	-0.00	-0.13	-0.97	0.95	0.86	-0.40											
$R_{t,1.6}$	0.00	-0.13	-0.97	0.95	0.87	-0.41	0.99										
$R_{t,1.4}$	0.00	-0.13	-0.97	0.95	0.87	-0.41	0.99	0.99									
$\Lambda_{2.0}$	-0.03	-0.11	-0.92	0.96	0.83	-0.36	0.95	0.95	0.95								
$\Lambda_{1.6}$	-0.05	-0.11	-0.90	0.95	0.81	-0.34	0.93	0.93	0.93	0.98							
$\Lambda_{1.4}$	-0.05	-0.11	-0.90	0.95	0.80	-0.33	0.93	0.92	0.92	0.97	0.99						
$c^2_{s,2.0}$	-0.45	0.23	0.10	-0.01	-0.18	0.63	-0.06	-0.07	-0.07	-0.02	0.00	0.01					
$c^2_{s,1.6}$	-0.47	0.22	0.11	-0.03	-0.20	0.67	-0.08	-0.08	-0.08	-0.03	-0.01	-0.01	0.91				
$c^2_{s,1.4}$	-0.44	0.22	0.21	-0.12	-0.30	0.73	-0.17	-0.18	-0.18	-0.13	-0.11	-0.10	0.83	0.90			
$\rho_{B,2.0}$	0.12	0.06	0.78	-0.86	-0.69	0.22	-0.82	-0.81	-0.81	-0.86	-0.88	-0.89	-0.12	-0.10	-0.01		
$\rho_{B,1.6}$	0.18	0.04	0.69	-0.77	-0.60	0.13	-0.73	-0.72	-0.72	-0.77	-0.79	-0.80	-0.21	-0.20	-0.10	0.91	
$\rho_{B,1.4}$	0.21	0.02	0.65	-0.73	-0.56	0.09	-0.68	-0.68	-0.68	-0.73	-0.75	-0.75	-0.26	-0.24	-0.15	0.86	0.95

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

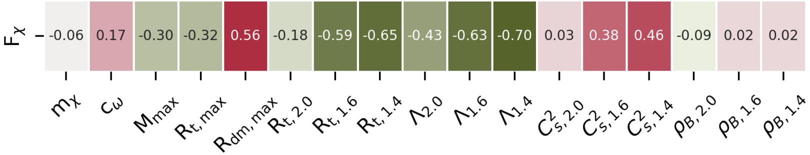
- Strong correlation between F_χ and various properties of NS.
- Other DM model parameters, $m\chi$ and c_ω are weakly correlated with the NS properties.

Introducing Uncertainties in nuclear EOS

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

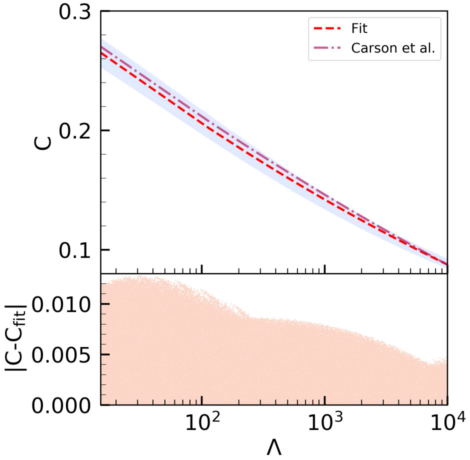
With EOS 1:

With all four nuclear EOS:



** 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.

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,**]

[1] *Department of Physics, BITS-Pilani, K. K. Birla Goa Campus, Goa 403726, India*
[2] *CFisUC, Department of Physics, University of Coimbra, P-3004 - 516 Coimbra, Portugal*
[3] *Department of Physics, Birla Institute of Technology and Science Pilani, Pilani Campus, Pilani, Rajasthan-333031, India*
[4] *Department of Sciences, Amrita School of Physical Sciences, Amrita Vishwa Vidyapeetham, Coimbatore 641112, India*

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Nuclear & Astrophysical Constraints Imposed

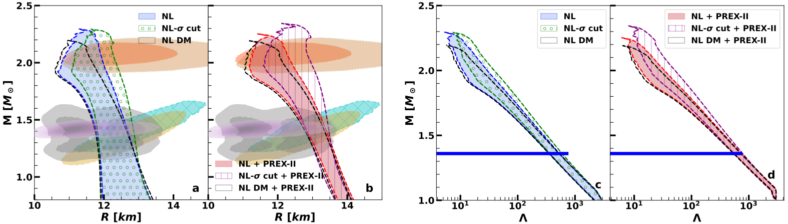
(See C. Y. Tsang et al., Nature Astronomy 8, 328 (2024) for details)

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)

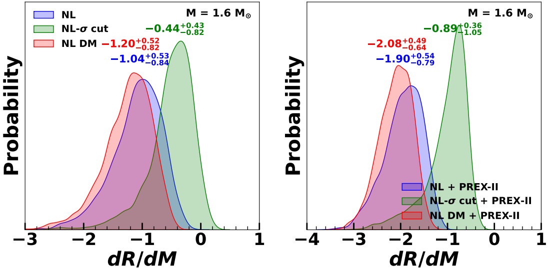
NS mass-radius-tidal deformability



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.

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.

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

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.

References

- **Exploring robust correlations between fermionic dark matter model parameters and neutron star properties: A two-fluid perspective**
  Prashant Thakur, Tuhin Malik, Arpan Das, T.K. Jha, Constança Providência
  DOI: 10.1103/PhysRevD.109.043030
  Journal: Physical Review D, Vol. 109, No. 4, 043030 (2024)
- **Feasibility of dark matter admixed neutron stars based on recent observational constraints**
  Prashant Thakur, Tuhin Malik, Arpan Das, B.K. Sharma, T.K. Jha, Constança Providência
  arXiv: arXiv:2408.03780v1
  Submitted to: Astronomy & Astrophysics


Thank you

Bayesian Setup

- NMP:

$$\mathcal{L}(\mathcal{D}_{\rm NMP}|\theta) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(\frac{-(D(\theta)-D_{\rm NMP})^2}{2\sigma^2}\right) = \mathcal{L}^{\rm NMP}$$

- GW:

$$P(d_{\rm GW}|{\rm EoS}) = \int_{M_{\rm min}}^{M_{\rm max}} dm_1 \int_{M_{\rm min}}^{m_1} dm_2 P(m_1, m_2|{\rm EoS}) \times P(d_{\rm GW}|m_1, m_2, \Lambda_1(m_1, {\rm EoS}), \Lambda_2(m_2, {\rm EoS})) = \mathcal{L}^{\rm GW}$$

where $P(m|{\rm EoS})$ can be written as:

$$P(m|{\rm EoS}) = \begin{cases} \frac{1}{M_{\rm max}-M_{\rm min}} & \text{if } M_{\rm min} \leq m \leq M_{\rm max}, \\ 0 & \text{otherwise.} \end{cases}$$

Here, $M_{\rm min}$ is 1 $M_\odot$, and $M_{\rm max}$ represents the maximum mass of a NS for the given equation of state (EOS).

- X-ray observation (NICER):

$$P(d_{\rm X-ray}|{\rm EoS}) = \int_{M_{\rm min}}^{M_{\rm max}} dm\, P(m|{\rm EoS}) \times P(d_{\rm X-ray}|m, R(m, {\rm EoS})) = \mathcal{L}^{\rm NICER}$$

The final likelihood for the calculation is then given by:

$$\mathcal{L} = \mathcal{L}^{\rm NMP}\mathcal{L}^{\rm GW}\mathcal{L}^{\rm NICERI}\mathcal{L}^{\rm NICERII}\mathcal{L}^{\rm NICERIII}$$