



BITS Pilani
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Unveiling Dark Matter in Neutron Stars: A Bayesian Study of Fermionic and Bosonic Models

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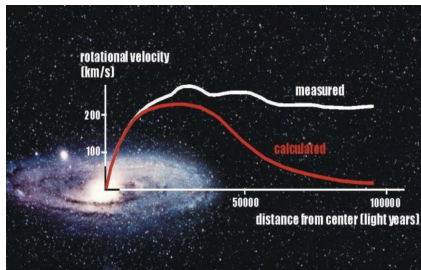
Symposium on Women in Physics: Networking, Innovation, Opportunity and Equity (SWPNIOE)

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September 12, 2026

- Neutron stars offer a unique cosmic laboratory to probe the nature of dark matter.
- **Aim:** Probe dark matter inside neutron stars using NICER and GW170817 data.
- We address two questions:
 - the way these observations are incorporated, does it change the inferred DM parameters?
 - can current data distinguish fermionic from bosonic dark matter?
- **Approach:** Bayesian inference with Fermionic and Bosonic DM models.

Dark Matter: Astrophysical Evidence



- ★ **Spiral galaxies**

Flat rotation curves $\Rightarrow$ unseen mass

- ★ **Bullet Cluster**

Gravitational lensing mass separated from visible matter

- ★ **Galaxy clusters**

X-ray emission + gravitational lensing $\Rightarrow$ missing mass

Neutron stars: another laboratory for DM

<https://www.anl.gov/science>



Crab Nebula — supernova remnant
observed in 1054

- ★ **Massive stars** ($M \gtrsim 8 M_{\odot}$) end their lives in core-collapse supernovae.
- ★ The remnant can be a **neutron star**:

$$M \sim 1.4 - 2 M_{\odot}, \quad R \sim 10 \text{ km}$$

- ★ Extreme conditions: $\rho \sim 10^{14-15} \text{ g cm}^{-3}$, $g_{\text{NS}} \sim 10^{11} g_{\oplus}$

Neutron Stars



Crab Nebula — supernova remnant

observed in 1054



Jocelyn Bell Burnell

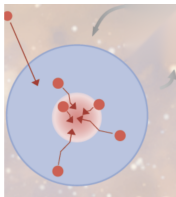
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- ★ **1967**: Jocelyn Bell Burnell discovered the first pulsar — a rapidly rotating neutron star.
- ★ Extreme conditions: $\rho \sim 10^{14-15} \text{ g cm}^{-3}$, $g_{\text{NS}} \sim 10^{11} g_{\oplus}$
- ★ A unique laboratory for **extreme physics** and the physics of ultra-dense matter.

What lies in the core? Neutrons + protons + electrons
→ possibly exotic matter

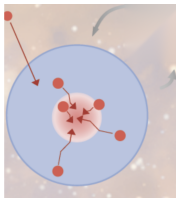
Neutron Stars as Probes of Dark Matter



- ★ **Extreme densities** → efficient DM capture
- ★ Captured DM **thermalises** and can
 - **self-annihilate** → thermal signatures
 - **accumulate** → modify NS structure

- ★ Even a **small DM admixture** can affect M , R , Λ : the observable signatures of NS.

Neutron Stars as Probes of Dark Matter

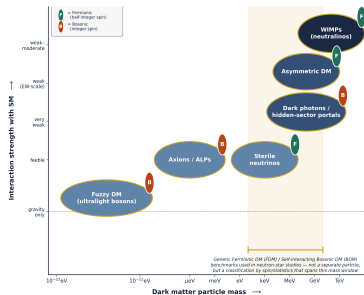


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★ Even a **small DM admixture** can affect M , R , Λ : the observable signatures of NS.

★ **DM–NS matter interaction:**

- **Single-fluid model:** DM and NS matter are coupled through interaction potentials
- **Two-fluid model:** DM and NS matter interact only through gravity

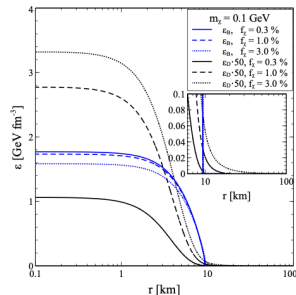
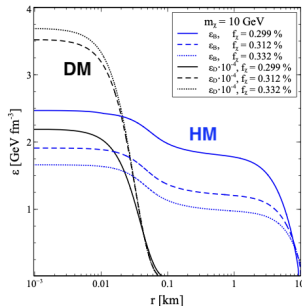
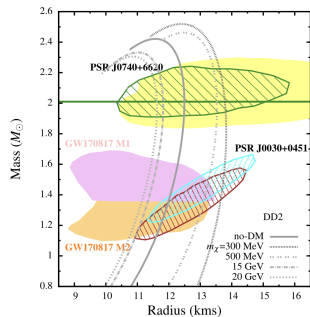


Mystery: Unresolved Nature of Dark Matter

* DM leaves structural imprints on NS; changes its maximum mass

* Heavy DM $\rightarrow$ core,

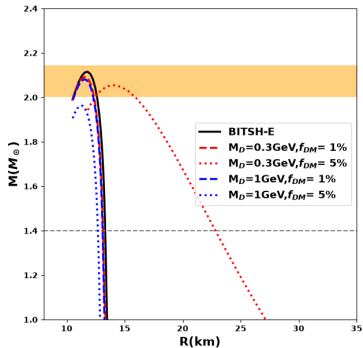
light DM $\rightarrow$ halo



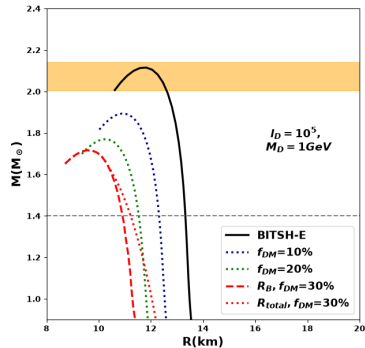
A. Guha and D. Sen, Phys. Rev. D 109, 043038, 2024;
Ivanytskyi et al., Phys. Rev. D 102, 063028, 2020

Mystery: Unresolved Nature of Dark Matter (*contd.*)

- * Repulsive Self-interaction is expected to stiffen the DM sector
- * **Fermionic vs. Bosonic DM**: distinguishing signatures on NS properties are still unknown



Fermionic DM model



Bosonic DM model

FORMALISM: Relativistic Mean Field Model

- * Baryon interactions mediated via mesons : Long-range attractive & Short-range repulsive

$$\begin{aligned}\mathcal{L}_{HM} = & \bar{\psi} (i\gamma^\mu \partial_\mu - M) \psi + g_\sigma \sigma \bar{\psi} \psi - g_\omega \bar{\psi} \gamma^\mu \omega_\mu \psi - \frac{g_\rho}{2} \bar{\psi} \gamma^\mu \vec{\rho}_\mu + \frac{1}{2} (\partial^\mu \sigma \partial_\mu \sigma - m_\sigma^2 \sigma^2) \\ & - \frac{A}{3} \sigma^3 - \frac{B}{4} \sigma^4 - \frac{1}{4} \Omega^{\mu\nu} \Omega_{\mu\nu} \\ & + \frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu + \frac{C}{4} (g_\omega^2 \omega_\mu \omega^\mu)^2 - \frac{1}{4} \vec{B}^{\mu\nu} \vec{B}_{\mu\nu} + \frac{1}{2} m_\rho^2 \vec{\rho}_\mu \vec{\rho}^\mu + \frac{1}{2} \Lambda_\nu g_\omega^2 g_\rho^2 \omega_\mu \omega^\mu \vec{\rho}_\mu \vec{\rho}^\mu.\end{aligned}$$

Here, $\Omega_{\mu\nu} = \partial_\nu \omega_\mu - \partial_\mu \omega_\nu$ and $\vec{B}_{\mu\nu} = \partial_\nu \vec{\rho}_\mu - \partial_\mu \vec{\rho}_\nu - g_\rho (\vec{\rho}_\mu \times \vec{\rho}_\nu)$.

FORMALISM: Relativistic Mean Field Model

- * Baryon interactions mediated via mesons : Long-range attractive & Short-range repulsive

$$\begin{aligned}\mathcal{L}_{HM} = & \bar{\psi} (i\gamma^\mu \partial_\mu - M) \psi + g_\sigma \sigma \bar{\psi} \psi - g_\omega \bar{\psi} \gamma^\mu \omega_\mu \psi - \frac{g_\rho}{2} \bar{\psi} \gamma^\mu \vec{\rho}_\mu + \frac{1}{2} (\partial^\mu \sigma \partial_\mu \sigma - m_\sigma^2 \sigma^2) - \frac{A}{3} \sigma^3 - \frac{B}{4} \sigma^4 \\ & - \frac{1}{4} \Omega^{\mu\nu} \Omega_{\mu\nu} + \frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu + \frac{C}{4} (g_\omega^2 \omega_\mu \omega^\mu)^2 - \frac{1}{4} \vec{B}^{\mu\nu} \vec{B}_{\mu\nu} + \frac{1}{2} m_\rho^2 \vec{\rho}_\mu \vec{\rho}^\mu + \frac{1}{2} \Lambda_v g_\omega^2 g_\rho^2 \omega_\mu \omega^\mu \vec{\rho}_\mu \vec{\rho}^\mu.\end{aligned}$$

- * Hadronic (Visible) Matter Equation of State: Two Hadronic EoSs (BITSH-E & BITSH-I)

$$\begin{aligned}\mathcal{E}_{HM} &= \frac{1}{\pi^2} \int_0^{k_p, k_n} dk k^2 \sqrt{k^2 + (M^*)^2} + \mathcal{E}_{mesons} + g_\omega \omega (\rho_p + \rho_n) + \frac{g_\rho}{2} \rho (\rho_p - \rho_n), \\ P_{HM} &= \frac{1}{3\pi^2} \int_0^{k_p, k_n} dk \frac{k^4}{\sqrt{k^2 + (M^*)^2}} - \mathcal{E}_{mesons} + \frac{\Lambda_v}{2} (g_\rho g_\omega \rho \omega)^2.\end{aligned}$$

where $\mathcal{E}_{meson} = +\frac{1}{2} m_\sigma^2 \sigma^2 - \frac{1}{2} m_\omega^2 \omega^2 - \frac{1}{2} m_\rho^2 \rho^2 + \frac{A}{3} \sigma^3 + \frac{B}{4} \sigma^4 - \frac{C}{4} g_\omega^4 \omega^4$

Lagrangian for Dark Matter

- * **Fermionic DM (FDM):** DM particle χ_D (of mass M_D) is considered to be Fermions & couples to a dark vector meson V_D^μ (with coupling g_{vd})

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

$$\mathcal{E}_D = \frac{1}{\pi^2} \int_0^k dk \, k^2 \sqrt{k^2 + M_D^2} + \frac{g_{vd}^2}{2m_{vd}^2} \rho_D^2, \quad P_D = \frac{1}{3\pi^2} \int_0^k dk \frac{k^4}{\sqrt{k^2 + M_D^2}} + \frac{g_{vd}^2}{2m_{vd}^2} \rho_D^2,$$

Lagrangian for Dark Matter

- * **Bosonic DM (BDM1, BDM2):** self-interacting complex scalar field ϕ

$$L = \frac{1}{2} \partial_\mu \phi^* \partial^\mu \phi - \frac{M_D^2}{2} \phi^* \phi + \frac{\lambda}{4} < \phi^* \phi >^2 .$$

$$P_D = \frac{M_D^4}{9\lambda} \left(\sqrt{1 + \frac{3\lambda \mathcal{E}_D}{M_D^4}} - 1 \right)^2 . \qquad P_D = \frac{2\pi l_D}{M_D^3} \mathcal{E}_D^2 ,$$

- * Boson Star

A hybrid NS within an anisotropic DM halo.

*Arvikar, Gautam, Venneti, **SB**, JCAP 03, 012 (2026);*
P. Thakur et al., Phys. Rev. D. 109, 043030 (2024);
D. R. Karkevandi et al., Phys. Rev. D 10, 023001 (2022);
Z. Stubbs et al., Phys. Rev. D 109, 043043 (2024).

Two-Fluid TOV formalism

- * M, R of NS-calculated by solving General relativistic Tolman–Oppenheimer–Volkoff eqns
- * Gravitational Interaction between HM and DM: two-fluid TOV
- * DM mass fraction is defined as: $f_{DM} = M_{DM}/M_{Total}$

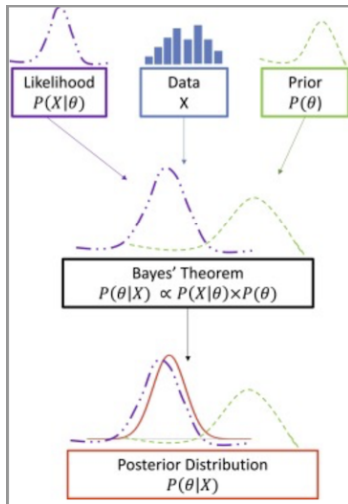
$$\frac{dP_{HM}}{dr} = -(P_{HM} + \mathcal{E}_{HM}) \frac{4\pi r^3(P_{HM} + P_{DM}) + m(r)}{r(r - 2m(r))},$$

$$\frac{dP_{DM}}{dr} = -(P_{DM} + \mathcal{E}_{DM}) \frac{4\pi r^3(P_{HM} + P_{DM}) + m(r)}{r(r - 2m(r))},$$

$$\frac{dm(r)}{dr} = 4\pi(\mathcal{E}_{HM}(r) + \mathcal{E}_{DM}(r))r^2.$$

Tolman, Phys. Rev. 55, 364 (1939); Oppenheimer & Volkoff, Phys. Rev. 55, 374 (1939)

Bayesian Inference

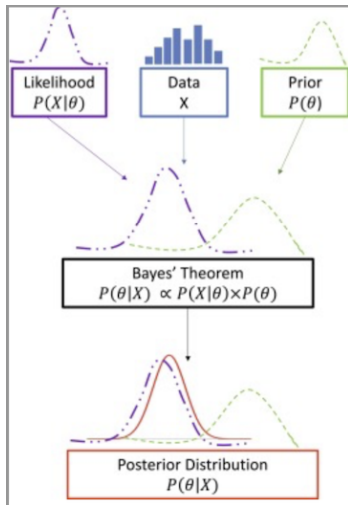


$$P(\Theta|X) = \frac{\mathcal{L}(X|\Theta)P(\Theta)}{\mathcal{Z}}$$

Θ model parameters, X observational data.

- Prior $P(\Theta)$: what parameter values we consider plausible before using the observations.
- Likelihood $\mathcal{L}(X|\Theta)$: how well a particular model reproduces the observations.
- Posterior $P(\Theta|X)$: our updated knowledge of the parameters after including the observations.
- $\mathcal{Z}$ is the normalization/evidence.

Bayesian Inference



Posterior

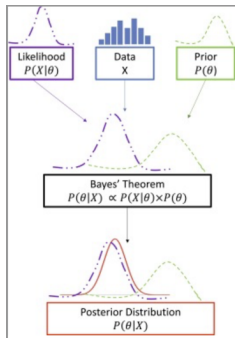
$$P(\Theta|X) = \frac{\mathcal{L}(X|\Theta)P(\Theta)}{\mathcal{Z}}$$

Gaussian likelihood

$$\mathcal{L}_\sigma(X|\Theta) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(X(\Theta) - X_{Obs})^2}{2\sigma^2}\right)$$

For a given set of model parameters, we calculate an observable $X(\Theta)$, and compare it with X_{Obs} .

Bayesian Inference



Posterior

$$P(\Theta|X) = \frac{\mathcal{L}(X|\Theta)P(\Theta)}{\mathcal{Z}}$$

Gaussian likelihood

$$\mathcal{L}_\sigma(X|\Theta) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(X(\Theta) - X_{Obs})^2}{2\sigma^2}\right)$$

Total Likelihood

$$\mathcal{L}_{Obs}(X|\Theta) = \mathcal{L}_{NICER}^{0740} \times \mathcal{L}_{NICER}^{0030} \times \mathcal{L}_{NICER}^{0437} \times \mathcal{L}_{NICER}^{0614} \times \mathcal{L}_{GW}$$

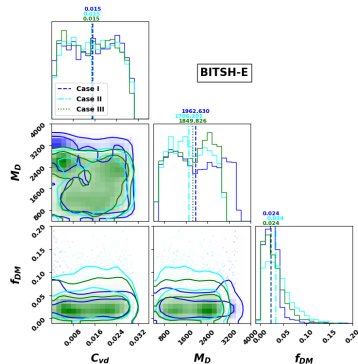
Given observational data, what range of DM parameters remains probable?

Constraint hierarchy across density scales:

- * **Low density:** χ EFT calculations (β -equilibrated EoS)
- * **Intermediate density:** finite-nuclei & heavy-ion collision data ($J(\rho)$, P_{SNM} , P_{sym})
- * **High density:** NICER mass-radius::
J0030+0451 J0740+6620 [Riley, ApJL.(2019), Miller, ApJL 887 (2019)]
J0437-4715 J0614-3329 [Riley, ApJL (2021), Miller APJL (2021)]
+ GW170817 tidal constraint, [Abbott, PRL (2018)]
- * **Uniform priors**
 $\rho_0 = 0.14\text{-}0.17$, $E_0 = -16.5 \text{ -} (-15.5)$, $K_0 = 150\text{-}300$, $M^*/M = 0.5\text{-}0.8$, $J_0 = 20\text{-}40$, $L_0 = 20\text{-}100$
 $C_{vd} = 0.0005\text{-}0.040$ $M_D = 500\text{-}10000$ [FDM]
 $\lambda = 0.3\text{-}30$ $M_D = 50\text{-}1000$ [BDM1]
 $\log l_D = \log(1.1)\text{-}\log(10^6)$ $M_D = 500\text{-}10000$ [BDM2]

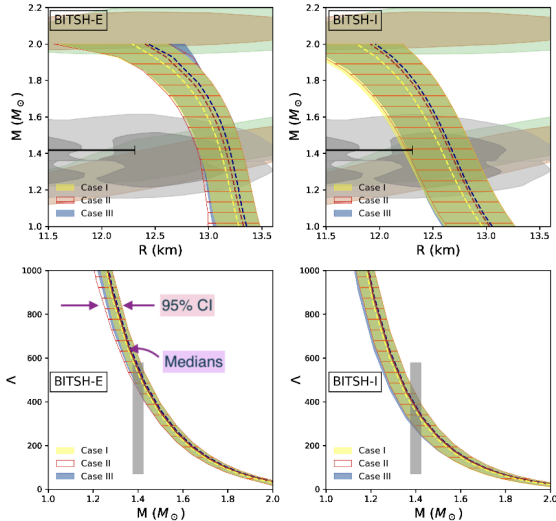
FINDINGS:Q1. How we impose Astrophysical Constraints- Does it matter?

- Case I: only constraints of M_{max} from PSR J0740+6620 and radii of PSR J0030+0451 at low M are implemented.
- Case II, the full NICER mass-radius datasets for these pulsars are used.
- Case III, a mock dataset generated with reduced uncertainty is imposed as constraints.
- **Takeaway:**
 - f_{DM} comes out well constrained ($\sim 4-8\%$).
 - C_{vd} and M_D remain poorly constrained.



Arvikaar, Gautam, Venneti, SB, PRD (2025)

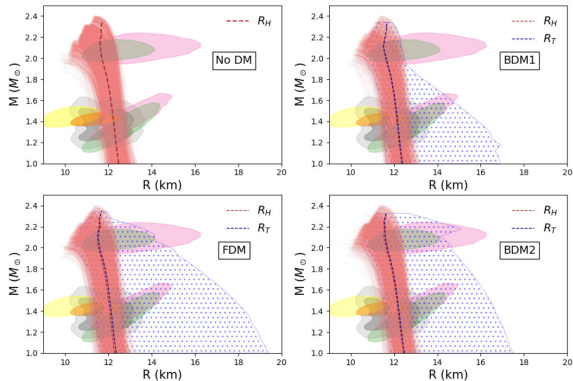
FINDINGS:Q1. How we impose Astrophysical Constraints- Does it matter?



Takeaway: What matters is the **stiffness of the hadronic EoS**

Arvikar, Gautam, Venneti, **SB**, PRD (2025)

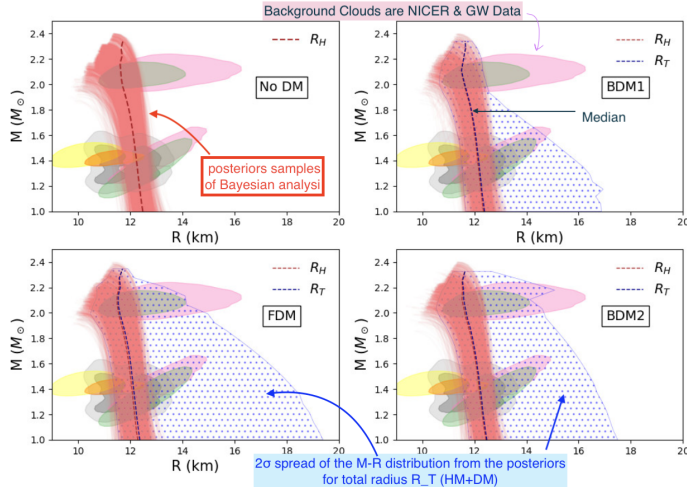
FINDINGS: Q2. Fermionic vs. Bosonic Dark Matter- can current NS observations distinguish them??



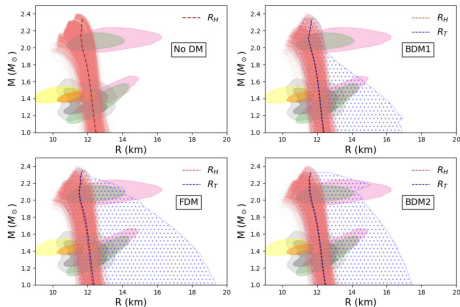
(Here HM parameters are also varied in the analysis)

Arvikar, Gautam, Venneti, **SB**, JCAP 03, 012 (2026);

FINDINGS: Q2. Fermionic vs. Bosonic Dark Matter- can current NS observations distinguish them??



FINDINGS: Q2. Fermionic vs. Bosonic Dark Matter- can current NS observations distinguish them??



- Median $M-R_T$ curves are consistent with astrophysical constraints, i.e. NICER X-ray data & GW170817 limits, $\rightarrow$ inclusion of DM remains compatible with observations.
- A DM halo forms in both fermionic and bosonic cases, as the DM distribution extends beyond R_H ($R_H < R_T$).
- Nevertheless, the median values of both R_H & R_T remain close, $\rightarrow$ DM is largely confined to the core, with only a small likelihood of forming a halo.

Arvikar, Gautam, Venneti, **SB**, JCAP 03, 012 (2026);

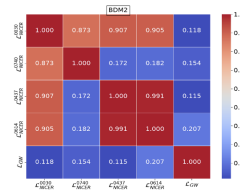
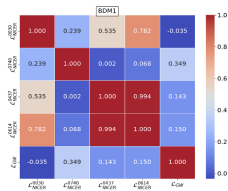
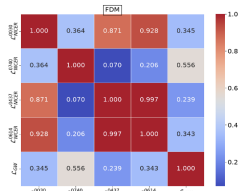
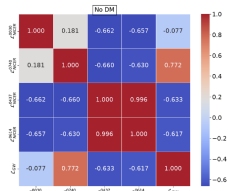
FINDINGS: Q2. Fermionic vs. Bosonic Dark Matter- continued

Parameters	No DM	FDM	BDM1	BDM2
ρ_0 (fm $^{-3}$)	$0.16^{+0.0045}_{-0.0080}$	$0.16^{+0.0046}_{-0.0083}$	$0.16^{+0.0045}_{-0.0077}$	$0.16^{+0.0026}_{-0.0027}$
E_0 (MeV)	$-16.03^{+0.33}_{-0.31}$	$-16.05^{+0.33}_{-0.29}$	$-16.01^{+0.31}_{-0.30}$	$-16.03^{+0.33}_{-0.30}$
K_0 (MeV)	$205.04^{+22.25}_{-18.25}$	$201.27^{+21.40}_{-17.52}$	$202.45^{+22.06}_{-17.86}$	$206.38^{+21.13}_{-18.76}$
M^*/M	$0.70^{+0.029}_{-0.028}$	$0.69^{+0.027}_{-0.027}$	$0.69^{+0.026}_{-0.025}$	$0.70^{+0.028}_{-0.028}$
J_0 (MeV)	$31.68^{+1.16}_{-1.33}$	$31.60^{+1.21}_{-1.32}$	$31.74^{+1.30}_{-1.33}$	$31.85^{+1.19}_{-1.34}$
L_0 (MeV)	$47.61^{+6.53}_{-5.68}$	$48.29^{+6.32}_{-5.53}$	$48.98^{+6.90}_{-5.70}$	$48.67^{+5.99}_{-5.77}$
Interaction parameter	—	$C_{vd} = 0.016^{+0.014}_{-0.010}$	$\lambda = 8.8^{+6.60}_{-5.66}$	$\log l_D = 4.032^{+1.38}_{-2.72}$
$\log M_D$ (MeV)	—	$3.4314^{+0.41}_{-0.48}$	$2.8401^{+0.41}_{-0.28}$	$3.2126^{+0.44}_{-0.34}$
M_D (MeV)	—	2700.2	691.99	1631.5
f_{DM} (%)	—	$6.44^{+6.41}_{-4.38}$	$6.72^{+8.86}_{-4.34}$	$8.9^{+8.7}_{-6.1}$

Model	$M_{\max}(M_{\odot})$	$R_{H1.4}$ (km)	$\Lambda_{1.4}$
No DM	2.20	12.23	337.40
FDM	2.15	12.06	304.60
BDM1	2.16	12.12	312.94
BDM2	2.18	12.18	329.29

- All models permit a DM fraction below 10%
FDM: 6.4%
BDM1: 6.7%
BDM2: 8.9%
- All models statistically indistinguishable. Log-evidence confirms this:
FDM = -58.19
BDM1 = -58.25
BDM2 = -57.97 .
- $\Lambda_{1.4}$ drops only slightly with DM ($337 \rightarrow 305\text{--}329$).

An independent check: correlations between log-likelihoods of different observational constraints.



- DM flips the pulsar-pulsar log-likelihood correlations from predominantly anti-correlated (No DM) to predominantly positive (FDM/BDM1/BDM2).
- This flip is a potential signature of DM presence, though the differences between models are not established as statistically discriminating.
- Breaking this degeneracy needs complementary probes (thermal signatures, GW post-merger, multi-messenger) + higher-precision M-R and tidal data.

Arvikar, Gautam, Venneti, SB, JCAP 03, 012 (2026);

- DM fraction is constrained to $\lesssim 10\%$.
- DM mass and coupling remain weakly constrained.
- Current observations show **no preference between fermionic and bosonic DM**.

Thank You!

Collaborators:

- Payaswinee Arvikar
- Anagh Venneti
- Sakshi Gautam