Unveiling Dark Matter in Neutron Stars: A Bayesian Study of Fermionic and Bosonic Models ID 20

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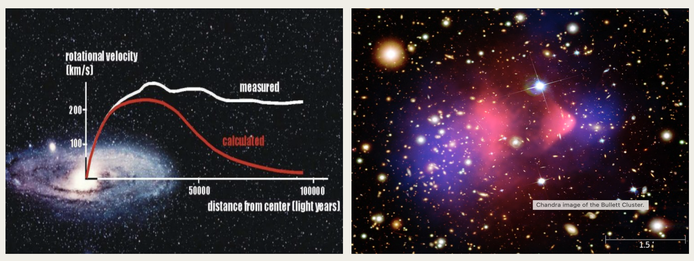
Abstract

Neutron stars offer a unique cosmic laboratory to probe the nature of dark matter (DM), one of the biggest open questions in physics. We study neutron stars carrying a small admixture of dark matter, modeling both ordinary (hadronic) matter and dark matter using nuclear physics-based equations of state, and comparing two possibilities: DM made of fermions versus DM made of bosons (via two different self-interaction models). Using Bayesian inference, we combine current astrophysical data - pulsar mass-radius measurements from the NICER mission and gravitational-wave data from the neutron star merger GW170817 - to constrain DM properties such as DM particle mass, coupling strength, and fraction inside the star. We address two questions: (1) the way these observations are incorporated, does it change the inferred DM parameters, and (2) can current data distinguish fermionic from bosonic dark matter? We find the DM fraction (below 10%) is the best-constrained parameter regardless of method, while DM mass and coupling remain weakly constrained. Crucially, present observations show no statistical preference between fermionic and bosonic DM, meaning both remain equally viable - motivating future, more precise measurements to resolve this question.

Dark Matter imprints



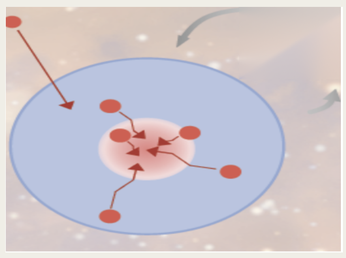
- **Rotational Curve of Spiral Galaxy**
- **Expected (visible matter only)**: Star's velocity rises then falls off beyond the visible disk
- **Observed**: velocity stays flat: extra unseen mass sustains the pull

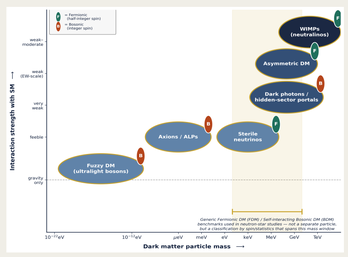
- **Bullet Cluster: collision of two galaxy clusters**
- RED: X-ray data(Chandra telescope): Visible matter
- BLUE: mass map(Gravitational lensing): Invisible matter

https://www.anl.gov/science

Neutron Stars as Probe of Dark Matter

- **Extreme densities**: efficient neutron capture.
- **Captured DM can**
  (a) self-annihilate: Heat up a NS (Thermal signature)
  (b) accumulate: alter NS structure/trigger collapse (Gravitational signature)

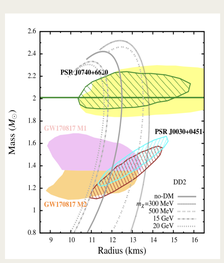


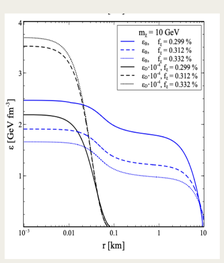


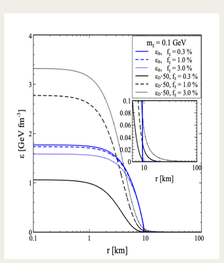
- **Promising DM candidates:** WIMPs, Axions/ALPs, Sterile neutrinos (some self Interacting) etc.
- **Why NS specifically**: Small DM admixtures leave measurable imprints on NS mass, radius, and tidal deformability.
- **Interaction of NS matter with DM**: a) through potential fields: *Single fluid* or b) through Gravity only: *Two fluid*

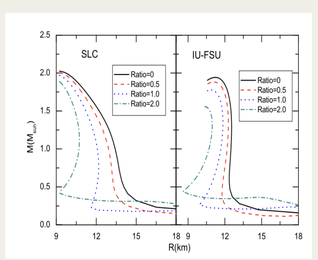
Bertone and Hooper, Rev. Mod. Phys. 90, 045002 (2018);https://ekamperi.github.io

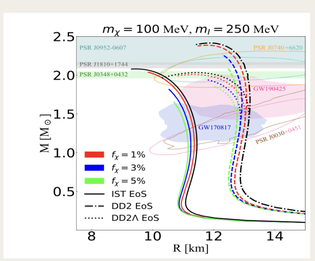
Mystery: unresolved nature of Dark Matter











- DM leaves structural imprints on NS; reduces the maximum mass
- Heavy DM → core, light DM → halo (qualitatively known); **transition mass unknown**
- Repulsive Self-interaction is expected to stiffen the DM sector
- **Fermionic vs. Bosonic DM**: distinguishing signatures on NS properties are still uknown

A. Guha and D. Sen, Phys. Rev. D 109, 043038 (2024);Ivanytskyi et al., Phys. Rev. D 102, 063028, 2020; Xiang et al., Phys. Rev. C 89, 025803 (2014); Giangrandi et al., Astr. J 953, 115 (2023)

APPROACH: Relativistic Mean Field Model

- Interaction between nucleons is mediated by mesons
- Scalar & Vector mesons: Medium-range attractive and Short-range repulsive interactions
- Hadronic (Visible) Matter Equation of State: Two Hadronic EoSs (BITSH-E & BITSH-I)

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

$$\mathcal{E}_{HM} = \frac{1}{\pi^2}\int_0^{k_n} dk k^2\sqrt{k^2+(M^*)^2} + \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{2}m_\omega^2\omega^2 - \frac{1}{2}m_\rho^2\rho^2 + \frac{A}{3}\sigma^3 + \frac{B}{4}\sigma^4 - \frac{C}{4}g_\omega^4\omega^4 + g_\omega\omega(\rho_p+\rho_n) - \frac{\Lambda_v}{2}(g_\rho g_\omega\rho\omega)^2 + \frac{g_\rho}{2}\rho(\rho_p-\rho_n),$$

$$P_{HM} = \frac{1}{3\pi^2}\int_0^{k_n} dk\frac{k^4}{\sqrt{k^2+(M^*)^2}} - \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}m_\omega^2\omega^2 + \frac{1}{2}m_\rho^2\rho^2 - \frac{A}{3}\sigma^3 - \frac{B}{4}\sigma^4 + \frac{C}{4}g_\omega^4\omega^4 + \frac{\Lambda_v}{2}(g_\rho g_\omega\rho\omega)^2.$$

Venneti and Gautam et al., Phys. Lett. B 854, 138756 (2024)

Dark Sector: Gravity-only interaction with hadronic sector

Lagrangian for Dark Matter

- **Fermionic DM (FDM)**: DM particles χ_D (mass M_D) couple via a dark vector meson V_D^μ (coupling g_{vd})

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

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

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

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

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

Arvikar and Gautam et al., 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

- Properties of NS are calculated by solving General relativity equations
- General Relativity: Tolman–Oppenheimer–Volkoff equations
- Gravitational Interaction between HM and DM: two-fluid TOV
- DM mass fraction is defined as: $f_{DM} = M_{DM}/M_{Total}$

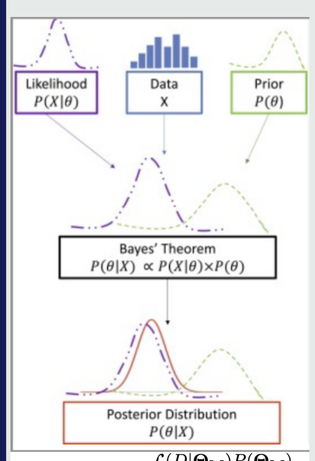
$$\frac{dP_{HM}}{dr} = -(P_{HM}+\mathcal{E}_{HM})\frac{4\pi r^3(P_{HM}+P_{DM})+m(r)}{r(r-2m(r))},$$

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

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

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

Bayesian Inference



$$P(\mathbf{\Theta_M}|D) = \frac{\mathcal{L}(D|\mathbf{\Theta_M})P(\mathbf{\Theta_M})}{\mathcal{Z}},$$

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

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

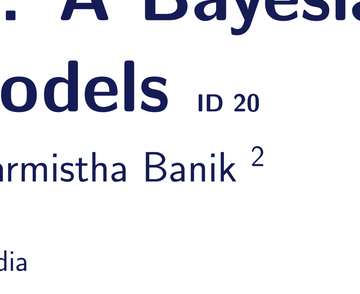
J. Keller et al, Phys. Rev. Lett. 130, 072701 (2023); Tsang et al., Phys. Rev C 102, 045808 (2020); Riley et al., Astrophys. J. Lett. 887, L21 (2019); 918, L27 (2021); Miller et al., 887, L24 (2019); 918, L28 (2021).

Constraint hierarchy across density scales:

- **Low density:** χEFT 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 J0437-4715 J0614-3329 + GW170817 tidal constraint
- **Uniform priors**
  ρ_0 = 0.14-0.17 E_0 = -16.5 -(-15.5)
  K_0 =150-300 M^*/M = 0.5-0.8
  J_0 = 20-40 L_0 = 20-100
  C_{vd} = 0.0005-0.040 M_D = 500-10000 [FDM]
  λ = 0.3-30 M_D = 50-1000 [BDM1]
  log l_D = log(1.1)-log(10^6) [BDM2]
  M_D = 500-10000 [BDM2]

Kendall's A

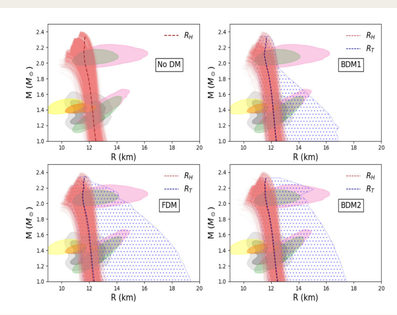
FINDINGS:Q1. How we impose Astrophysical Constraints- Does it matter?



- **Question**: 3 ways–*Case I*: max-mass + low-mass radius only
  Case II: full NICER KDE
  Case III: mock high-precision data
- **Takeaway**: f_{DM} comes out well constrained (∼4-8%). C_{vd} and M_D remain poorly constrained.
  What matters is the **stiffness of the hadronic EoS**

Arvikar and Gautam et al., Phys. Rev. D 112, 023021 (2025)

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



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)	$-16.03^{+0.33}_{-0.31}$	$-16.05^{+0.33}_{-0.29}$	$-16.01^{+0.31}_{-0.31}$	$-16.03^{+0.33}_{-0.30}$
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)	$31.68^{+1.16}_{-1.35}$	$31.60^{+1.21}_{-1.32}$	$31.74^{+1.30}_{-1.33}$	$31.85^{+1.19}_{-1.34}$
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	$M_{max}(M_\odot)$	$R_{M1.4}$ (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

- M-R posteriors remain consistent with NICER and GW170817; DM Halo forms, but rare and mostly sub-dominant ($R_H \approx R_T$)
- 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 → 305–329).

Arvikar and Gautam et al., JCAP 03, 012 (2026)

An independent check: Pulsar-pair Correlations

- DM flips the pulsar-pulsar log-likelihood correlations from anti-correlated (No DM) to strongly positive (FDM/BDM1/BDM2).
- This flip is a clear 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 and Gautam et al., JCAP 03, 012 (2026)

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