Distinct observational signatures of dark matter in evolving neutron stars

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Outline

1. Introduction
2. Methodology
3. Results: Structural Effects
4. Results: Thermal Evolution
5. DM-Specific Signatures
6. Conclusions

Introduction

- In the ΛCDM model, dark components (DM + dark energy) constitute $\sim 95\%$ of the Universe, leaving only $\sim 5\%$ visible matter.
- Strong evidence for DM comes from galactic rotation curves, large-scale structure, and gravitational lensing.
- Null results from leading detectors (XENONnT, PandaX, LUX-ZEPLIN, etc.) motivate indirect searches.
- Neutron-star densities enable efficient DM capture and accumulation.
- Two main modeling approaches in compact stars:
  - **Single-fluid:** includes particle-level interactions[1]
  - **Two-fluid:** purely gravitational coupling[2]

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Motivation

How does non-annihilating DM affect PNS thermal evolution and structure?

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[1] I. Goldman and S. Nussinov, Phys. Rev. D **40** (1989) 3221-3230

[2] F. Sandin and P. Ciarcelluti, Astropart. Phys. **32** (2009) 278-284

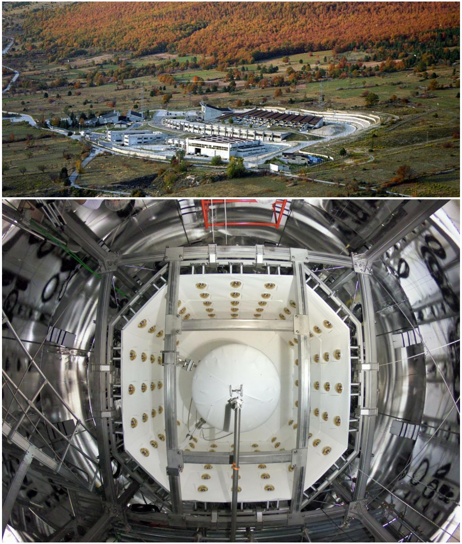


Figure: XENON Collaboration

XENON Collaboration, Phys.Rev.Lett. 135 (2025) 22, 221003

Figure: LUX-ZEPLIN collaboration

LZ Collaboration, Phys.Rev.Lett. 135 (2025) 1, 011802

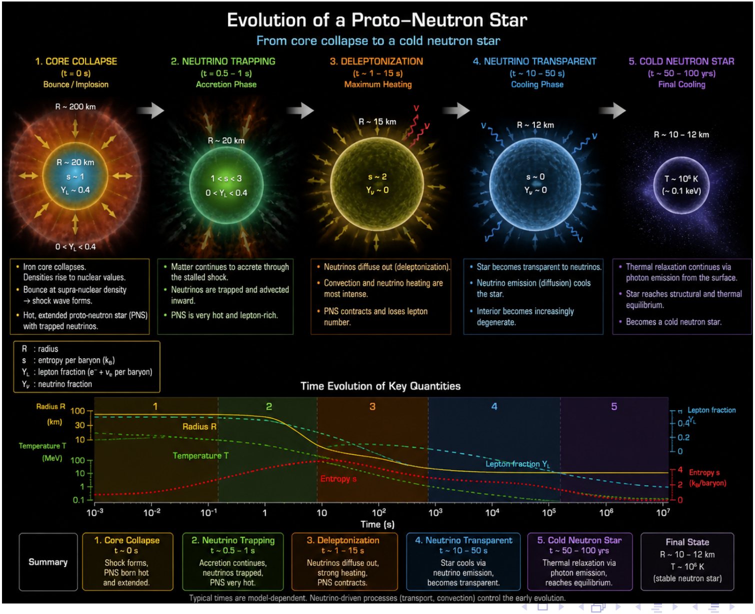
III stages for PANDAX

Stage I: 125 kg xenon target, 400 kg total mass
Stage II: 500 kg xenon target, 1.3T total mass
Stage III: 1.5 ton target, 3T total mass

Figure: PandaX collaboration

PandaX Collaboration, Phys.Rev.Lett. 134 (2025) 1, 011805

PNS Evolutionary Stages



Evolution of a Proto–Neutron Star

From core collapse to a cold neutron star

1. CORE COLLAPSE

(t = 0 s)
Bounce / Implosion

- Iron core collapses. Densities rise to nuclear values.
- Bounce at supra-nuclear density → shock wave forms.
- Hot, extended proto-neutron star (PNS) with trapped neutrinos.

2. NEUTRINO TRAPPING

(t = 0.5 – 1 s)
Accretion Phase

- Matter continues to accrete through the stalled shock.
- Neutrinos are trapped and advected inward.
- PNS is very hot and lepton-rich.

3. DELEPTONIZATION

(t ~ 1 – 15 s)
Maximum Heating

- Neutrinos diffuse out (deleptonization).
- Convection and neutrino heating are most intense.
- PNS contracts and loses lepton number.

4. NEUTRINO TRANSPARENT

(t ~ 10 – 50 s)
Cooling Phase

- Star becomes transparent to neutrinos.
- Neutrino emission (diffusion) cools the star.
- Interior becomes increasingly degenerate.

5. COLD NEUTRON STAR

(t ~ 50 – 100 yrs)
Final Cooling

- Thermal relaxation continues via photon emission from the surface.
- Star reaches structural and thermal equilibrium.
- Becomes a cold neutron star.

R : radius
s : entropy per baryon (k_B)
Y_L : lepton fraction ($e^- + \nu_e$ per baryon)
Y_ν : neutrino fraction

Time Evolution of Key Quantities

Summary	1. Core Collapse	2. Neutrino Trapping	3. Deleptonization	4. Neutrino Transparent	5. Cold Neutron Star	Final State
	t ~ 0 s Shock forms, PNS born hot and extended.	t ~ 0.5 – 1 s Accretion continues, neutrinos trapped, PNS very hot.	t ~ 1 – 15 s Neutrinos diffuse out, strong heating, PNS contracts.	t ~ 10 – 50 s Star cools via neutrino emission, becomes transparent.	t ~ 50 – 100 yrs Thermal relaxation via photon emission, reaches equilibrium.	R ~ 10 – 12 km T ~ 10^6 K (stable neutron star)

Typical times are model-dependent. Neutrino-driven processes (transport, convection) control the early evolution.

Model Formalism

- **Ordinary Matter**: RMF model with DDME2 parameterization

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Main assumption

DM is already present at the onset of PNS formation and persists through to the stage of cold, catalyzed NS configuration.

Visible-Matter Sector: RMF Framework

- OM described using a Relativistic Mean-Field (RMF) model:

$$\mathcal{L}_{\rm RMF} = \mathcal{L}_H + \mathcal{L}_{\rm m} + \mathcal{L}_{\rm l},$$

- **Baryons (octet)**:

$$\mathcal{L}_H = \sum_{b\in H} \bar{\psi}_b \Big[i\gamma^\mu \partial_\mu - \gamma^0 (g_{\omega b}\omega_0 + g_{\phi b}\phi_0 + g_{\rho b} I_{3b}\rho_{03}) - (m_b - g_{\sigma b}\sigma_0) \Big] \psi_b,$$

- **Mesons (mean fields)**:

$$\mathcal{L}_{\rm m} = -\frac{1}{2} m_\sigma^2 \sigma_0^2 + \frac{1}{2} m_\omega^2 \omega_0^2 + \frac{1}{2} m_\phi^2 \phi_0^2 + \frac{1}{2} m_\rho^2 \rho_{03}^2.$$

- **Leptons:** free relativistic Fermi gas

$$\mathcal{L}_{\rm l} = \sum_{l} \bar{\psi}_l \left(i\gamma^\mu \partial_\mu - m_l \right) \psi_l. \qquad (1)$$

Dark sector

- **Mirror DM model:**

$$\mathcal{L}_{\mathrm{DM}} = \overline{\psi}_D\Big[i\gamma_\mu\partial^\mu - \gamma^0 g_v V_0 - (m_D - g_{\tilde{\sigma}}\tilde{\sigma}_0)\Big]\psi_D - \frac{1}{2}m_{\tilde{\sigma}}^2\tilde{\sigma}_0^2 + \frac{1}{2}m_v^2 V_0^2 + \tfrac{1}{2}m_{\tilde{\rho}}^2\tilde{\rho}_{03}^2 \tag{2}$$

- **Bosonic DM model:**

$$\mathcal{L}_{\mathrm{BDM}} = \frac{1}{2}\partial_\mu\phi^*\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^*\phi - \frac{\lambda}{4}(\phi^*\phi)^2 \tag{3}$$

- **Higgs portal model:**

$$\mathcal{L}_{\mathrm{DM}} = \bar{\chi}(i\gamma^\mu\partial_\mu - (m_\chi - g_h h))\chi + \frac{1}{2}(\partial^\mu h\partial_\mu h - m_h^2 h^2) + \sum_N \frac{f m_N}{v}\bar{\psi}_N h\psi_N. \tag{4}$$

The stellar structure is studied using the coupled two-fluid TOV equations in the case of purely gravitational interactions, whereas non-gravitational interactions are described within a single-fluid TOV framework.

The two-fluid TOV equations are given as follows:

$$\frac{dP_{\mathrm{OM}}}{dr} = -(\varepsilon_{\mathrm{OM}} + P_{\mathrm{OM}})\frac{4\pi r^3(P_{\mathrm{OM}} + P_{\mathrm{D}}) + M(r)}{r\,[r - 2M(r)]}, \tag{25}$$

$$\frac{dP_{\mathrm{D}}}{dr} = -(\varepsilon_{\mathrm{D}} + P_{\mathrm{D}})\frac{4\pi r^3(P_{\mathrm{OM}} + P_{\mathrm{D}}) + M(r)}{r\,[r - 2M(r)]}, \tag{26}$$

and

$$\frac{dM(r)}{dr} = 4\pi r^2\left(\varepsilon_{\mathrm{OM}} + \varepsilon_{\mathrm{D}}\right). \tag{27}$$

When investigating the influence of DM on NSs, it is useful to define the DM mass fraction as

$$F_D = \frac{M_D(R_D)}{M(R)}. \tag{5}$$

P. Thakur, *et al.*, Phys. Rev. D **109** (2024) 4, 043030;
A. Das, *et al.*, Phys. Rev. D **105** (2022) 12, 123034.

Mass-Radius Relations: Core DM configurations

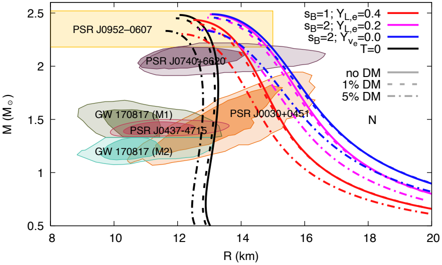
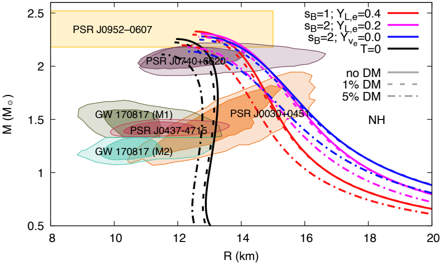


Figure: M–R diagram of nucleonic stars.



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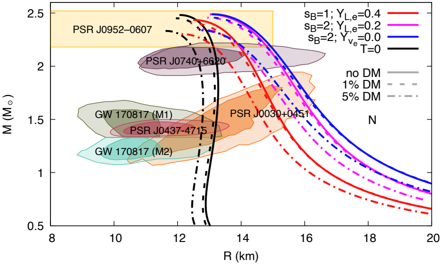

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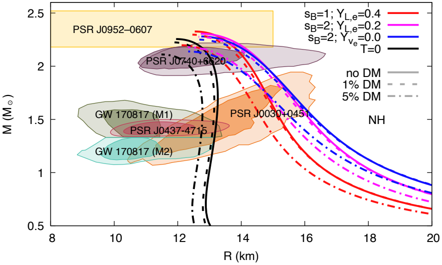
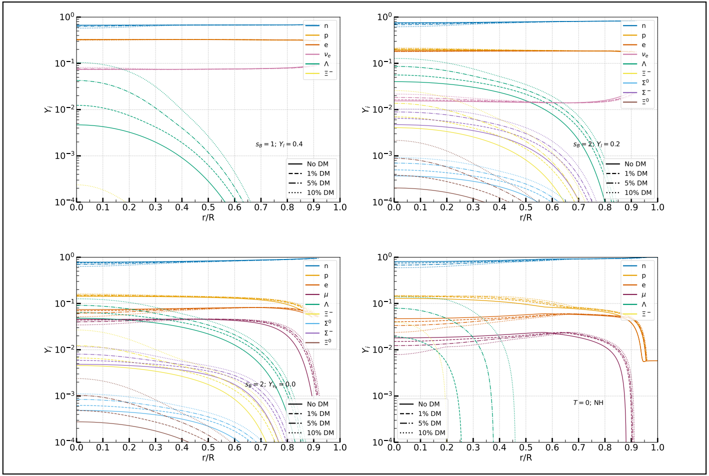


Figure: M–R diagram of hyperonic stars.

Key Finding

- **Core DM**: Systematically reduces $M_{\max}$ and R
- The presence of hyperons soften the EOS reduces $M_{\max}$ and R as well

Particle Distribution



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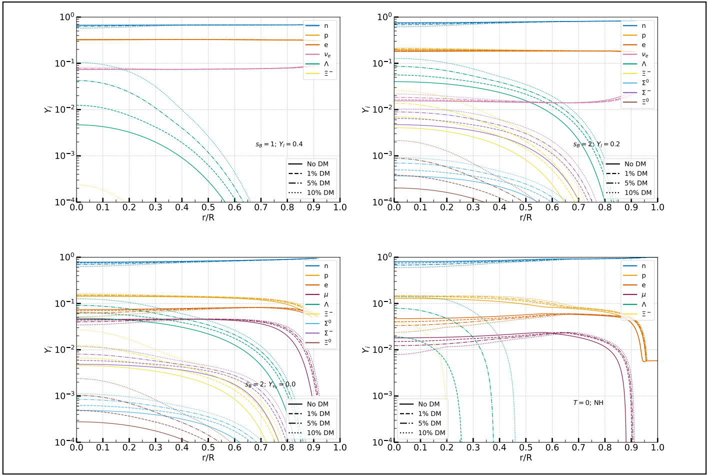

Key Findings

- DM accelerates the onset of hyperons and increases their abundances.
- Enhanced neutrino retention during early evolution stages.

DM-Induced Heating

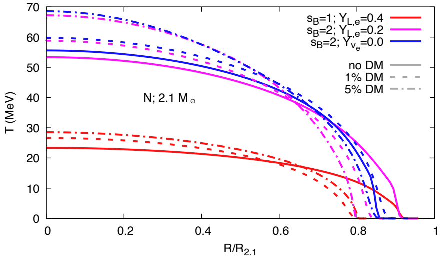

Figure: Temperature profile in nucleonic matter admixed with fermionic DM

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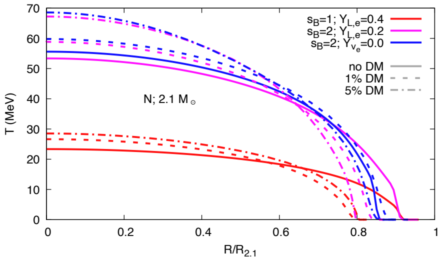

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- DM heats the stellar matter

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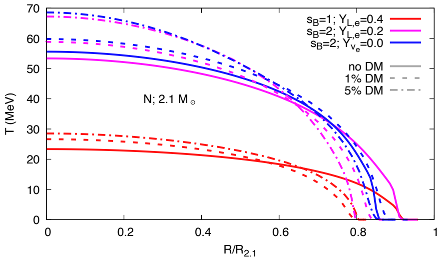

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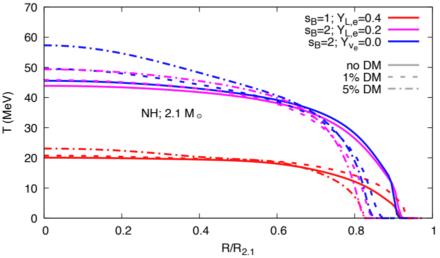

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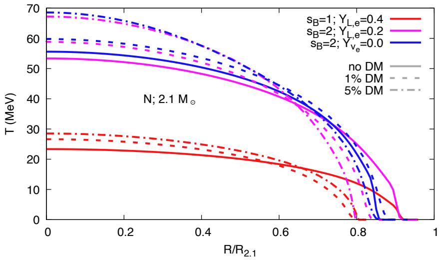

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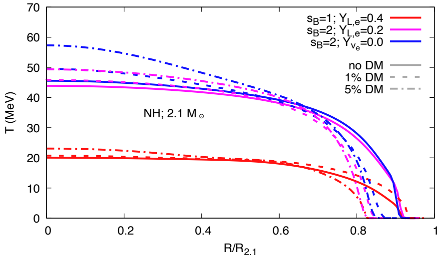

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Key Finding

- Hyperons reduce the thermal energy of the stellar matter
- DM heating contrasts hyperon cooling

A. Issifu, *et al.*, Phys. Rev. D **111** (2025) 8, 083026

Rotating PNSs

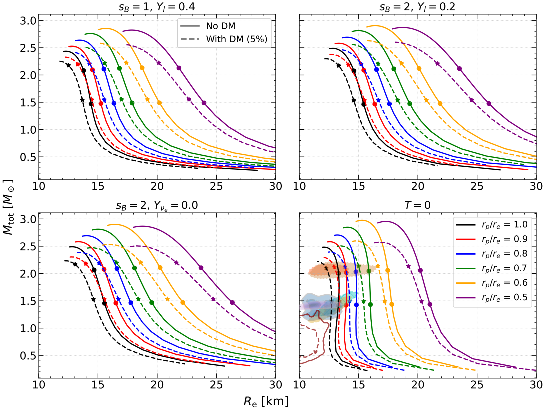

Figure: Gravitational mass vs. equatorial radius for rotating stars; stars: DM-admixed, bullets: no DM; $M_b = 1.55$ (lower) and $2.30\,M_\odot$ (upper).

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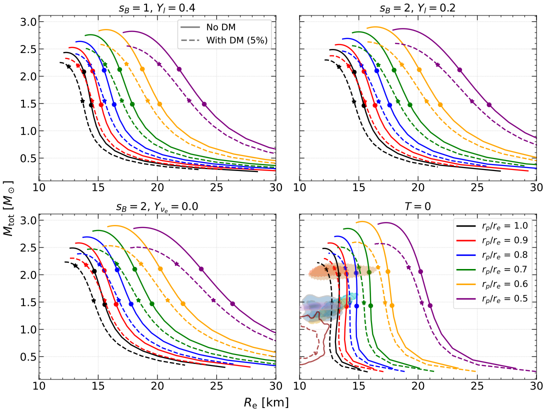

Key Findings

- Rotation increases mass and radius via centrifugal support.
- Higher F_D makes stars more compact, reducing both mass and radius.

Figure: Gravitational mass vs. equatorial radius for rotating stars; stars: DM-admixed, bullets: no DM; $M_b = 1.55$ (lower) and $2.30\ M_\odot$ (upper).

Competing effect of rotation and DM-induced heating

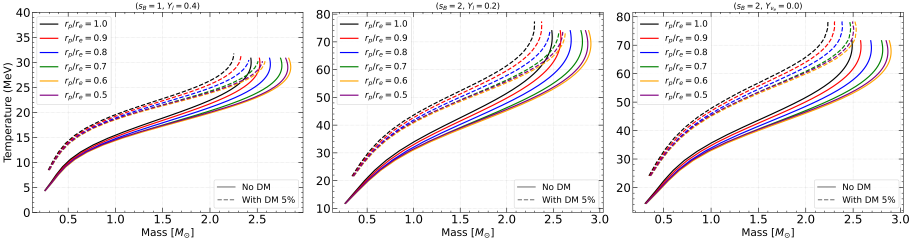

Figure: Central temperature vs. total mass for rotating PNSs with DM at different stages.

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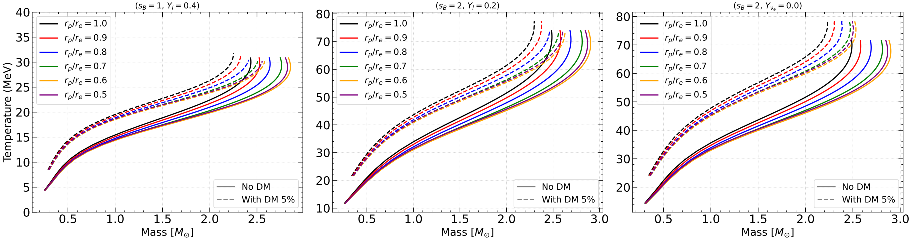


Figure: Central temperature vs. total mass for rotating PNSs with DM at different stages.

Key Finding

- Rotation expands the star, lowering its temperature
- DM heating warms it overall

A. Issifu, Phys. Rev. D **112** (2025) 10, 103026

Compare fermionic vs. bosonic DM-induced heating

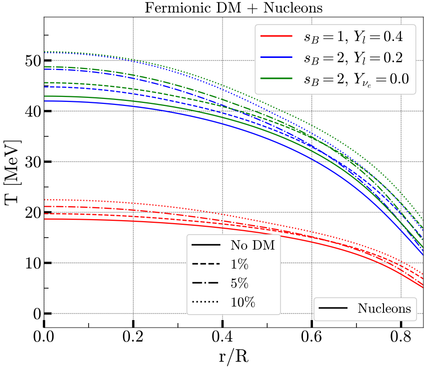
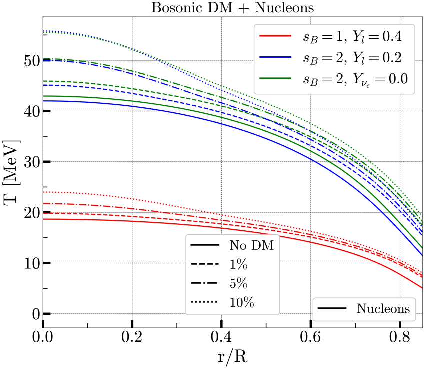


Figure: Temperature Profile of $M_b = 1.55\,\mathrm{M}_\odot$ star with mirror DM.



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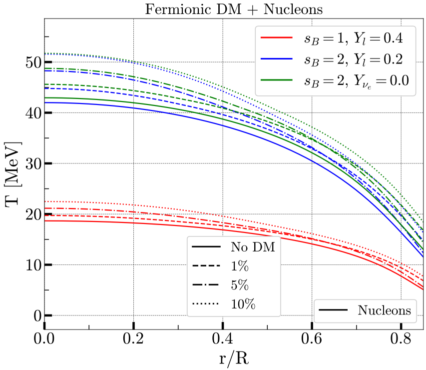

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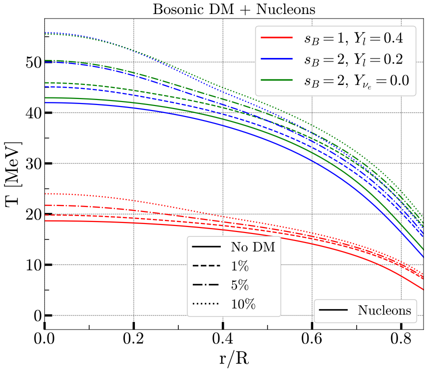


Figure: Temperature Profile of $M_b = 1.55\,\mathrm{M}_\odot$ star with bosonic DM.

Key Finding

- Bosonic DM produces stronger heating than fermionic DM
- Bosons, unconstrained by the Pauli exclusion principle, can condense into the same ground

DM-Halo: bosonic DM

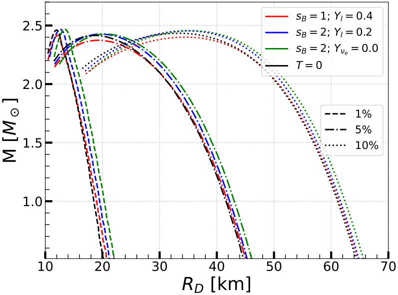


Figure: DM halo mass-radius curve.

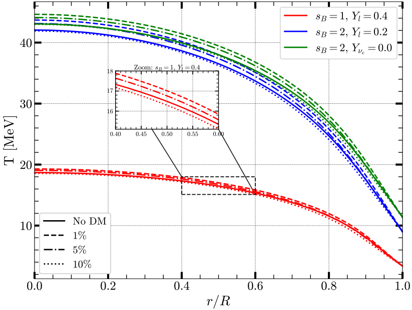
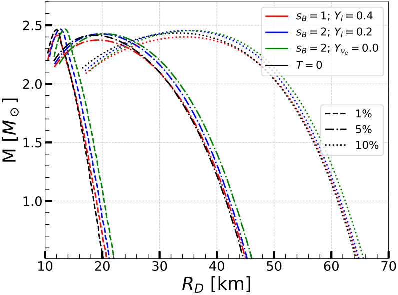


Figure: Temperature profile showing DM induced cooling.

DM-Halo: bosonic DM



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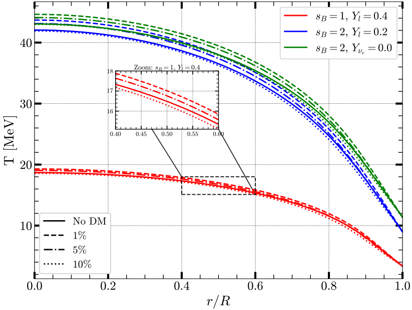

Figure: Temperature profile showing DM induced cooling.

Key Finding

- Halo growth correlates with a reduction in the stellar core temperature.
- The halo's gravitational support reduces the need for higher core pressure or temperature.

A. Issifu *et al.*, arXiv:2511.07567 [astro-ph.HE], accepted in *Phys. Rev. D*.

Summary

DM-Induced Heating

- **Core DM**: Deepens gravitational potential
- Increased gravitational compression
- Virial theorem: gravitational energy → kinetic energy
- Results in significant heating

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Halo DM

- External gravitational support
- Reduces core pressure requirement
- Cooling effect for $F_D \geq 5\%$
- Non-monotonic temperature response

Distinguishing DM from Exotic Baryons

Effect	DM	Hyperons
EoS stiffness	Softens	Softens
Compactness	Increases	Increases
Core temperature	**Increases**	**Decreases**
Hyperon onset	**Earlier**	Natural

Table: Comparison of effects

Distinguishing DM from Exotic Baryons

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Table: Comparison of effects

Unique DM Signature

- Gravitational heating vs. hyperonic cooling
- Observable in the early stages of the star's evolution
- Extended stellar radius due to DM halo

Comparing single and two-fluid approaches

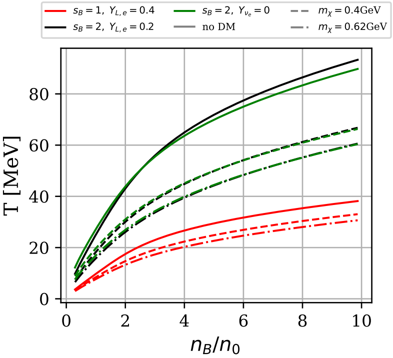

Figure: Temperature vs. baryon density.

Comparing single and two-fluid approaches

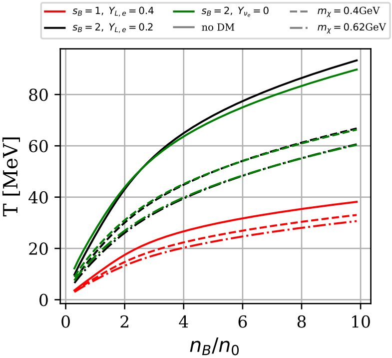

Figure: Temperature vs. baryon density.

Key points

- Upper limit set on m_χ accumulation in PNSs
- DM acts as a thermal reservoir

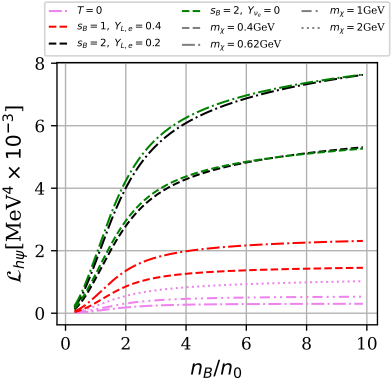

Figure: DM coupling vs. baryon density.

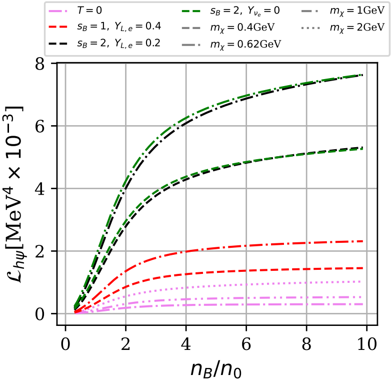

Figure: DM coupling vs. baryon density.

Key points

- DM–OM interaction grows with temperature
- PNSs capture DM more efficiently

A. Issifu, *et al.*, Phys. Dark Univ. **50** (2025) 102149

Observational Implications

Single vs. Two-Fluid Outcomes

- **Single-fluid:** DM and OM remain in thermal equilibrium, with DM acting as a heat reservoir
- **Two-fluid:** Weak coupling prevents equilibration, leading to distinct thermal evolution

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Testable Signatures

- Deviations in the PNS temperature during evolution, particularly during deleptonization
- Modified supernova neutrino light curves (energy + duration) (e.g., IceCube, Super-K / Hyper-K, JUNO)
- Anomalous cooling rates in young neutron stars (through analysis of cooling curves)
- Stage-dependent behavior tied to DM core/halo distribution

Key Conclusions

- **Gravitational heating** identified as unique DM signature:
    - Core DM: Heating through compression
    - Halo DM: Non-monotonic thermal effect due to external gravitational support
- **Clear discriminant** from hyperonic effects (which cause cooling)
- **Coupling Constraints** Gravitational coupling heats the core locally; non-gravitational interactions induce global cooling
- **Spatial distribution** crucial for thermal response
- **Observational signatures** in supernova neutrinos and young pulsar cooling

Main Message

DM produces distinctive thermal fingerprints in PNSs, offering new probes of DM through supernova remnants.

Acknowledgement

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FAPESP

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Thank You!

Questions?

Contact: ai@academico.ufpb.br

The presentation was based on:

- A. Issifu, *et al.*, Supernova remnants with mirror dark matter and hyperons, Phys. Rev. D **111** (2025) 8, 083026.
- A. Issifu, *et al.*, Rotating Proto-Neutron Stars Admixed with Mirror Dark Matter: A two fluid approach, Phys. Rev. D **112** (2025) 10, 103026.
- A. Issifu *et al.*, Dark Matter Heating in Evolving Proto-Neutron Stars: A Two-Fluid Approach, arXiv:2511.07567 [astro-ph.HE], accepted for publication in Phys. Rev. D.
- A. Issifu, *et al.*, Proto-neutron stars with dark matter admixture: A single-fluid approach, Phys.Dark Univ. **50** (2025) 102149.