Supernova Remnants with Mirror Dark Matter and Hyperons

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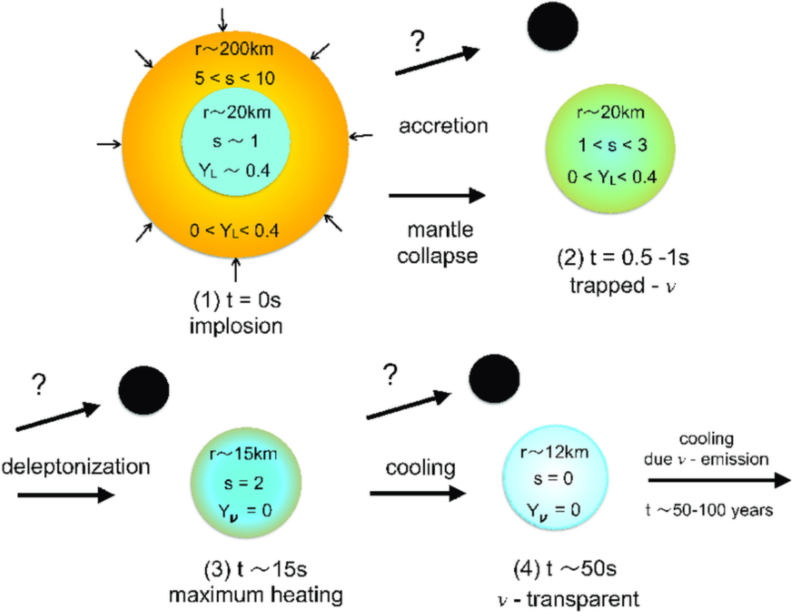
Outline

Why should we probe DM through astrophysical objects?

- The dominance of dark matter in the universe
- The weak interactions make it difficult to be detected in lab experiments
- The role of extreme astrophysical environments as natural laboratories
- The potential advantage of astrophysical observations over Earth-based particle experiments
- Complementary to Direct & Collider Searches

Main motivation: The ability of DM to mimic ordinary matter and form structures in isolation (Mirror DM model)


r~200km
5 < s < 10
r~20km
s ~ 1
Y_L ~ 0.4
0 < Y_L < 0.4
(1) t = 0s
implosion
?
accretion
mantle
collapse
r~20km
1 < s < 3
0 < Y_L < 0.4
(2) t = 0.5 -1s
trapped - ν
?
deleptonization
r~15km
s = 2
Y_ν = 0
(3) t ~15s
maximum heating
?
cooling
r~12km
s = 0
Y_ν = 0
(4) t ~50s
ν - transparent
cooling
due ν - emission
t ~50-100 years

Mathematical Model

Hadronic Model:

$$\mathcal{L}_{\rm OM} = \mathcal{L}_{\rm H} + \mathcal{L}_{\rm m} + \mathcal{L}_{\rm L}; \tag{1}$$

$$\begin{aligned}\mathcal{L}_{\rm H} = \sum_b \bar{\psi}_b \Big[i\gamma^\mu \partial_\mu - \gamma^0 \big(g_{\omega b}\omega_0 + g_{\phi b}\phi_0 + g_{\rho b} I_{3b}\rho_{03} \big) \\ - \Big(m_b - g_{\sigma b}\sigma_0 \Big) \Big] \psi_b, \end{aligned} \tag{2}$$

$$\mathcal{L}_{\rm m} = -\frac{1}{2} m_\sigma^2 \sigma_0^2 + \frac{1}{2} m_\omega^2 \omega_0^2 + \frac{1}{2} m_\phi^2 \phi_0^2 + \frac{1}{2} m_\rho^2 \rho_{03}^2, \tag{3}$$

$$\mathcal{L}_{\rm L} = \sum_L \bar{\psi}_L \left(i\gamma^\mu \partial_\mu - m_L \right) \psi_L. \tag{4}$$

The mirror DM model:

$$\begin{aligned}\mathcal{L}_{\rm DM} = \overline{\psi}_D [(i\gamma_\mu \partial^\mu - \gamma^0 g_v V_0) - (m_D - g_{\tilde{\sigma}} \tilde{\sigma}_0)] \psi_D \\ -\frac{1}{2} m_{\tilde{\sigma}}^2 \tilde{\sigma}_0^2 + \frac{1}{2} m_v^2 V_0^2. \end{aligned} \tag{5}$$

Coupling parameters

$$g_{ib}(n_B) = g_{ib}(n_0) a_i \frac{1 + b_i(\eta + d_i)^2}{1 + c_i(\eta + d_i)^2}, \tag{6}$$

$$g_{\rho b}(n_B) = g_{\rho b}(n_0) \exp\left[-a_\rho\left(\eta - 1\right)\right], \tag{7}$$

where $\eta = n_B/n_0$, with $n_0 = 0.152\,\mathrm{fm}^{-3}$ [Lalazissis G. A., et al., 2005, Phys. Rev. C, 71].

Table: DDME2 parameter set.

meson(i)	m_i(MeV)	a_i	b_i	c_i	d_i	$g_{iN}(n_0)$
σ	550.1238	1.3881	1.0943	1.7057	0.4421	10.5396
ω	783	1.3892	0.9240	1.4620	0.4775	13.0189
ρ	763	0.5647	—	—	—	7.3672

Table: Hyperon Couplings [L. L. Lopes, et al., Phys. Rev. D 107, 036011]

b	$\chi_{\omega b}$	$\chi_{\sigma b}$	$\chi_{\rho b}$	$\chi_{\phi b}$
Λ	0.714	0.650	0	-0.808
Σ^0	1	0.735	0	-0.404
Σ^-, Σ^+	1	0.735	0.5	-0.404
Ξ^-, Ξ^0	0.571	0.476	0	-0.606

The two-fluid TOV:

$$\frac{dP_{OM}}{dr} = -\left(P_{OM}+\varepsilon_{OM}\right)\frac{4\pi r^3(P_{OM}+P_D)+M(r)}{r(r-2M(r))}, \tag{8}$$

$$\frac{dP_D}{dr} = -\left(P_D+\varepsilon_D\right)\frac{4\pi r^3(P_{OM}+P_D)+M(r)}{r(r-2M(r))}, \tag{9}$$

and

$$\frac{dM(r)}{dr} = 4\pi(\varepsilon_{OM}+\varepsilon_D)r^2. \tag{10}$$

It is useful to define a DM mass fraction F_D, defined as

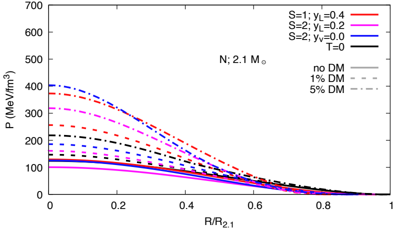
$$F_D = \frac{M_D(R_D)}{M(R)}. \tag{11}$$

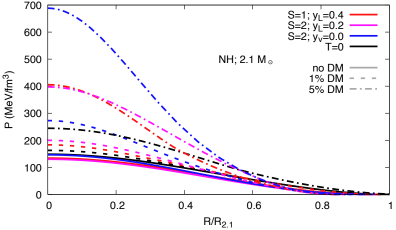
Here, $M_D(R_D) = 4\pi\int_0^{R_D} r^2\varepsilon_D(r)dr$ [N. Rutherford, et al., Phys. Rev. D 107, 103051].

Pressure profile

Boundary Conditions:

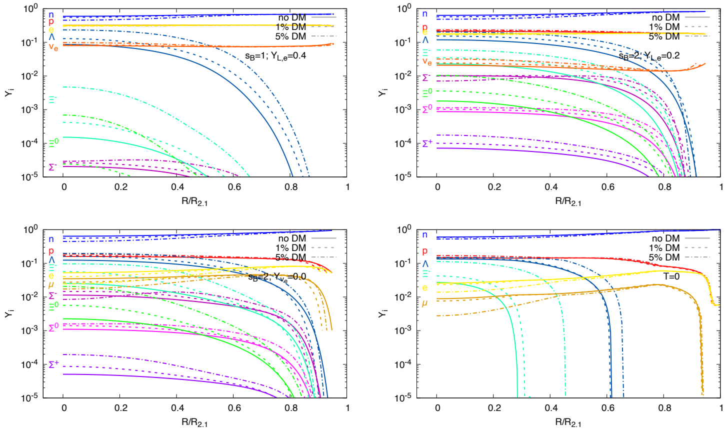
- $M(R) = 2.10 M_\odot$
- $M(r=0) = 0$
- $P(r=0) = P_{\text{center}}$
- $P(r=R) = 0$
- $P = P_{OM} + P_D$
- $\varepsilon = \varepsilon_{OM} + \varepsilon_D$





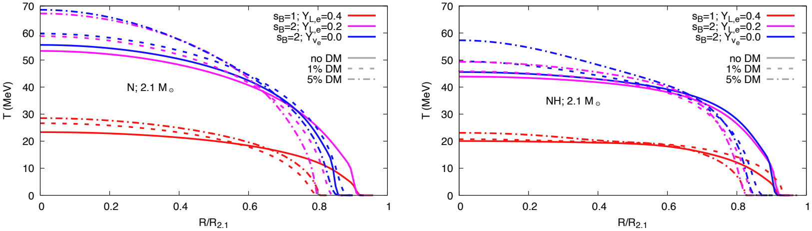
- Key observations: The presence of new degrees of freedom increases the pressure in the core.

Particle fraction



- Key observations: The presence of DM suppresses n, e, and μ productions and enhances p, ν_e, and hyperon productions.
- The effect of DM is more pronounced during deleptonization.

Temperature distribution



- Key observations: New degrees of freedom of the OM reduce T[1]
- In gravitational bound system $2T + U = 0$ (virial theorem) [V. Y. Terebizh, Astronomy & Astrophysics 686, A35]
- This means DM releases a thermal energy into the stellar matter
- This could alter the cooling curves, deviating them from conventional models

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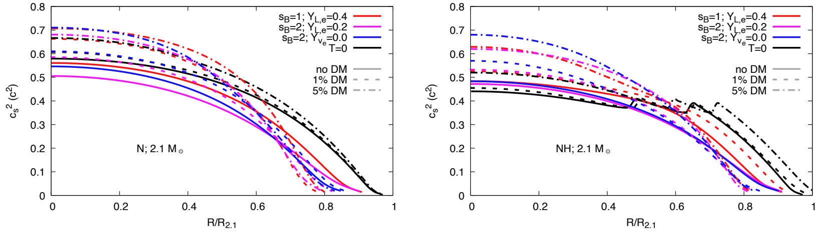
[1] A discussion on thermalization and interaction between DM and OM can be found in [G. Bertone, et al., Phys.Rept.405:279-390]

Speed of sound



- Key observations: An increase in degree of freedom decreases c_s^2 due to softening of the EoS [2]
- DM increases c_s^2 due to an increase in core density
- The bumps indicate the emergence of new particles

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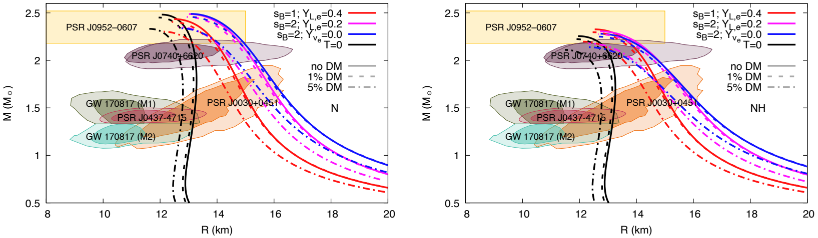
[2] E. Giangrandi, et al. ApJ 953 1, 115

Mass-Radius relation



- Key observations: An increase in F_D enhances gravitational attraction which compresses the star and reduces its mass and radius[3]
- Core clustering due to DM accumulation also displaces the OM which is meant to provide pressure support to the star
- The mirror DM does not provide sufficient pressure support due to the gravitational interaction

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[3] [A. de Lavallaz, et al., Phys. Rev. D 81, 123521; I. Goldman, et al., Phys. Rev. D 40, 3221]

Summary and Future Work

- The increase in gravitational attraction due to the introduction of F_D leads to:
  - Compression of the stellar matter
  - Compactification
    - Alteration of the β-equilibrim of the stellar matter
    - Increase in core temperature governed by the viral theorem
    - Increase in core pressure
    - Increase in c_s^2
- The impact of the DM is more pronounced during deleptonization and after all the neutrinos have escaped from the stellar core. This is due to the absence of neutrino pressure support to the star.

It would be appropriate to undertake similar studies using different DM models, such as bosonic DM, axion DM, FIMPs, WIMPs, etc.

Dedicated to the memory of Kau Dalfovo Marques

Aknowledgement

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arXiv:2412.17946 [hep-ph]

Thank You!