The Dark Matter Neutrino Portal and Implications for Stellar Collapse

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1. Introduction

There exists a class of models—christened the "neutrino portal" models—wherein the dark sector "sees" the standard model exclusively through its interactions with neutrinos. We investigate a particular example of such a model, wherein a fermionic light dark matter (DM) candidate, with an $\mathcal{O}(10\,\mathrm{MeV})$ rest mass, couples to the neutrinos via a heavy vector mediator ($m_V \gtrsim \mathcal{O}(\mathrm{GeV})$).

3. Dark matter annihilation and relic abundance

In this model, DM is produced in the early universe via neutrino pair annihilation: $\nu\bar{\nu} \to \chi\bar{\chi}$, and equilibrates via DM-ν or DM-DM scattering. The DM abundance is set when the rate of the pair-annihilation process, $\chi\bar{\chi} \to \nu\bar{\nu}$, drops below the expansion rate of the universe, resulting in a "freeze-out" of the DM distribution. The relic abundance is then set by the freeze-out temperature.

If DM particles are nonrelativistc at the time of freeze-out (relativistic freeze-out leads to overabundance unless there is prodigious entropy-dilution thereafter), the relic abundance is given by

$$\Omega_\chi h^2 \approx 4 \times 10^5\, g_\chi \frac{x_F^{3/2} e^{-x_F}}{g_{*s,F}} \left(\frac{m_\chi}{10\,\mathrm{MeV}}\right), \tag{2}$$

where $x_F = m_\chi/T_F$ is the ratio of DM mass to the freeze-out temperature, and g_χ and $g_{*s,F}$ are the DM spin degrees of freedom (including particle and antiparticle), and the effective entropic degrees of freedom at freeze-out, respectively. Setting $\Omega_\chi h^2 = 0.12$ (observed value) yields $x_F \approx 18.5$, which in turn constrains the velocity-averaged DM annihilation cross-section $\langle\sigma_{\mathrm{ann}} v\rangle$:

$$\langle\sigma_{\mathrm{ann}} v\rangle \approx 1.3 \times 10^{-14}\,\mathrm{MeV}^{-2} \left(\frac{g_{*,F}^{1/2}}{g_{*s,F}}\right) \left(\frac{x_F}{18.5}\right) \left(\frac{0.12}{\Omega_\chi h^2}\right), \tag{3}$$

where, $g_{*,F}$ is effective number of energetic degrees of freedom at freeze-out. In general, a larger $\langle\sigma_{\mathrm{ann}} v\rangle$ leads to a later DM freeze-out epoch, and consequently a lower relic abundance.

Using the Lagrangian from Eq. (1), the cross-section for $\chi\bar{\chi} \to \nu\bar{\nu}$ can be calculated:

$$\sigma_{\mathrm{ann}} = \frac{\varepsilon_\chi^2 \varepsilon_\nu^2}{12\pi s\,[(s - m_V^2)^2 + m_V^2 \Gamma^2]} \sqrt{\frac{s - 4m_\nu^2}{s - 4m_\chi^2}}\,(s + 2m_\chi^2)(s + 2m_\nu^2), \tag{4}$$

where m_V is the mediator mass, and s is the center-of-mass energy squared. Inserting the expression for the total mediator decay width, Γ, the velocity-averaged cross-section for non-relativistic DM is

$$\langle\sigma_{\mathrm{ann}} v\rangle \approx \frac{\varepsilon_\chi^2 \varepsilon_\nu^2}{\pi} \left[1 + \left(\frac{\varepsilon_\nu^2 + \varepsilon_\chi^2}{12\pi}\right)^2\right]^{-1} \left(\frac{m_\chi}{10\,\mathrm{MeV}}\right)^2 \left(\frac{10\,\mathrm{GeV}}{m_V}\right)^4 \times 10^{-14}\,\mathrm{MeV}^{-2}. \tag{5}$$

$\varepsilon_\nu, \varepsilon_\chi \sim 1$ leads to the correct DM relic abundance for $m_\chi \approx 10$ MeV and $m_V \approx 10$ GeV. Note that $\langle\sigma_{\mathrm{ann}} v\rangle$ cannot increase indefinitely with the coupling strengths because of the dependence on Γ. That is why, for very heavy mediators it becomes impossible to satisfy the relic density criterion, e.g., for $m_V = 100$ GeV, the maximum $\langle\sigma_{\mathrm{ann}} v\rangle$ is $\sim 10^{-16}$ MeV^{-2}, resulting in DM overabundance.

2. DM-ν vector portal

We consider a vector-mediated model of DM-neutrino interactions, with an effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \bar{\chi}\,(i\partial\!\!\!/ - m_\chi)\,\chi + \varepsilon_\nu\,(\bar{\nu}\gamma^\mu \nu)\,V_\mu + \varepsilon_\chi\,(\bar{\chi}\gamma^\mu \chi)\,V_\mu, \tag{1}$$

where χ is the DM fermion and V is a $U(1)'$ vector mediator. Models where the mediator couples to the full lepton doublet are more tightly constrainted. In order for the mediator to couple exclusively or almost exclusively to the neutrinos, interactions with charged leptons must be suppressed. This can be accomplished, e.g., by introducing a right-handed neutrino which couples to the mediator and mixes with the active neutrinos, or through higher dimensional operators.

4. Implictaions in a core-collapse supernova

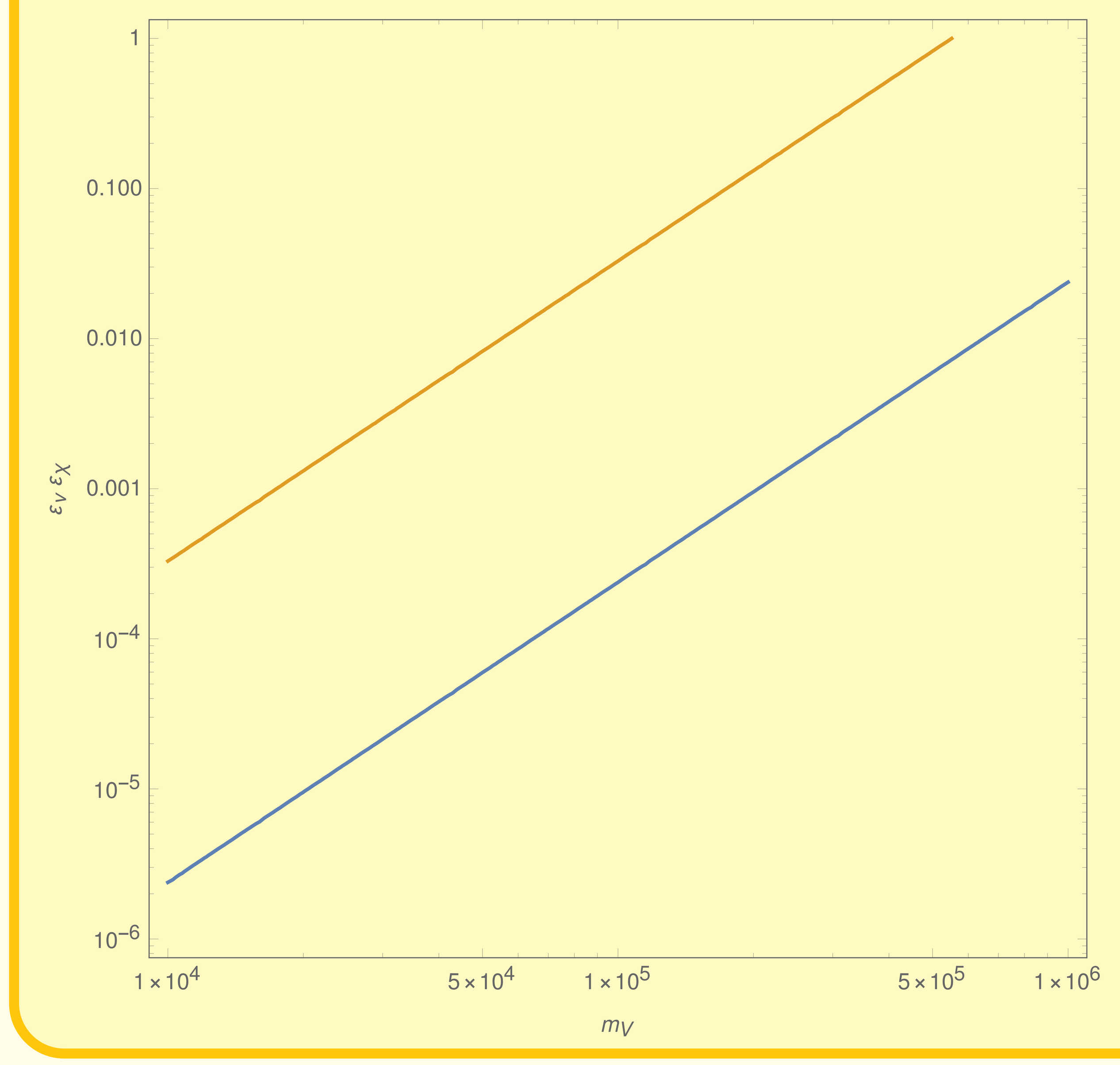
Light DM can be produced in core-collapse supernovae DM through $\nu\bar{\nu} \to \chi\bar{\chi}$ process. The cross-section for this process is given by the same expression as Eq. (4), except with labels ν and χ reversed. The emissivity [Energy/(time $\times$ volume)] is given by

$$\dot{\mathcal{E}}_V = \int \frac{d^3p_1\, d^3p_2}{(2\pi)^6} f_1 f_2 (E_1 + E_2)\, \sigma_{\nu\bar{\nu}\to\chi\bar{\chi}} v. \tag{6}$$

If the DM particles were to free-stream out of the protoneutron star, then the requirement that the luminosity in DM particles not exceed the neutrino luminosity leads to the Raffelt criterion:

$$\dot{\mathcal{E}}_M = \dot{\mathcal{E}}_V/\rho_B < 10^{19}\,\mathrm{erg\ g^{-1} s^{-1}}. \tag{7}$$

This results in an upper bound on the couplings as a function of the mediator mass. However, if the couplings are too large, then the DM becomes diffusively trapped and cannot free-stream—and then the energy-loss constraint does not apply. The two criteria taken together result in the exclusion of a band of coupling strengths as a function of mediator mass. The couplings that yield the correct relic abundance lie well above this exclusion region (between the blue and orange lines in the figure).



Outlook and Future work

Because of the large values of the coupling constants ε_ν and ε_χ required for satisfying the DM relic abundance criterion, the strength of the ν-ν and ν-DM interaction in this model can be considerably stronger than the standard weak interaction (for comparison, the weak-interaction cross-section between neutrinos is $\sigma_{\mathrm{weak}} \sim 10^{-20}\,\mathrm{MeV}^{-2}$ for typical energies of $\mathcal{O}(10)$ MeV). This can have potential implications for the physics of neutrino decoupling in a supernova environment, which we plan to investigate. A comparison with other terrestrial and astrophysical constraints on such secret interactions is also warranted.