The dark matter neutrino portal and implications for stellar collapse

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Today's talk

- Brief overview of stellar collapse and SN1987A
- The dark matter neutrino portal
- Light dark matter ($m_\chi \sim 10$ MeV), coupling to neutrinos via heavy vector mediator ($m_A \gg T_{\rm SN}$)
  - Obtaining the correct relic density
  - (Non-)constraints on model parameters from stellar cooling

Core-collapse supernovae and neutrinos

- Stars with $M_\star \gtrsim 8\,M_\odot$ undergo gravitational collapse when core mass exceeds $\sim 1.4\,M_\odot$, i.e., when gravity overcomes electron degeneracy pressure support
- Core bounce at nuclear density sends shockwave through infalling material $\rightarrow$ shock eventually loses energy and stalls before it can blow up the star
- Mechanism for stellar exploson (i.e., shock reheating) not fully known: neutrinos expected to play at least some part
- CCSNe are neutrino factories: $\sim 99\%$ of the gravitational binding energy of the star radiated away as neutrinos
    - $\sim 10^{53}$ ergs radiated as neutrinos $\implies$ $\sim 10^{58}$ neutrinos with average energy ~ 10 MeV

Core-collapse supernovae and neutrinos

- Neutrinos depositing $\sim 1\%$ of their energy behind the stalled shock front could revive the shock
- Charged-current weak processes governing energy deposition and n/p ratio are flavor asymmetric:

$$\nu_e + n \longleftrightarrow p + e^-$$
$$\bar{\nu}_e + p \longleftrightarrow n + e^+$$

- Thorough understanding of neutrino transport and flavor evolution is essential for understanding explosion mechanism as well as nucleosynthesis

SN1987A and neutrinos: what we know

- 24 events detected over ~ 12 s, in three different detectors: Kamiokande (11), IMB (8), and Baksan (5)
- Energy thresholds: $\sim$ 7.5 MeV, 19 MeV, 10 MeV respectively
- Broadly confirmed that our understanding of core-collapse physics was correct
- Recent: NS remnant may have been discovered (arXiv:1910.02960, arXiv:2004.06078)

The dark matter neutrino portal

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- One intriguing possibility is that the DM may “see” the SM via its couplings with neutrinos
  - Sterile neutrino that mixes with active flavors
  - Secret interactions between neutrinos and DM, mediated by new scalar/vector boson

- If DM allowed to interact with the full lepton doublet $\Rightarrow$ more tightly constrainted

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \overline{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \frac{c_\alpha}{\Lambda^2}\,\overline{\chi}\gamma_\mu\chi\,\overline{L_\alpha}\gamma^\mu L_\alpha\,,$$

(Blennow *et al.*, arxiv:1903.00006)

Neutrino dark matter portal: some examples

- Alternatively, DM may interact exclusively with neutrinos
- Two ways to suppress interactions with charged leptons
  - Couple the DM couple to a singlet of the SM gauge group, such as a right-handed neutrino (Cherry *et al.*, arXiv:1411.1071, Blennow *et al.*, arxiv:1903.00006)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \overline{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \overline{N}\left(i\partial\!\!\!/ - m_N\right)N - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu} + \frac{1}{2}m_{Z'}^2 Z'_\mu Z'^\mu$$
$$+g'\overline{\chi_R}\gamma^\mu\chi_R Z'_\mu + g'\overline{N_L}\gamma^\mu N_L Z'_\mu - \left[\lambda_\alpha\overline{L_\alpha}\tilde{H}N_R + \text{h.c.}\right]$$

  - Higher dimensional operators (Kelly *et al.*, arXiv:2005.03681)

$$\mathcal{L} = \mathcal{L}_{\rm SM+\nu_s} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu + \sum_{\alpha,\beta}\frac{(\overline{L}_\alpha i\sigma_2 H^*)\gamma_\mu(Hi\sigma_2 L_\beta)V^\mu}{\Lambda_{\alpha\beta}^2},$$

This work

- Effective low-energy Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \overline{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \varepsilon_\nu \left(\overline{\nu}\gamma^\mu \nu\right) V_\mu + \varepsilon_\chi \left(\overline{\chi}\gamma^\mu \chi\right) V_\mu$$

- Light, fermionic dark matter particle ($m_\chi \sim$ 10 MeV)
  - Light enough to perhaps make things interesting in core-collapse supernovae ($T_{\rm SN} \sim$ 30 MeV)
  - Heavy enough to not contribute to radiation energy density during big-bang nucleosynthesis (nevertheless, residual DM annihilation into neutrinos at $T \sim$ MeV could maybe have some effect on ν decoupling and/or BBN)

- Heavy vector mediator particle ($m_V \gg T_c$), cannot be produced on-shell in supernovae

Dark matter relic density

- DM produced in early universe through $\nu\bar{\nu} \to \chi\bar{\chi}$ and comes into equilibrium by DM-ν and DM-DM scattering

- Freeze-out: $\Gamma_{\chi\bar{\chi}\to\nu\bar{\nu}} = \langle\sigma_{\rm ann} v\rangle\, n_{\rm eq}(\chi) < H$

- DM annihilation must not freeze-out until DM becomes non-relativistic—otherwise it gets overproduced

$$\Omega_\chi h^2 \approx 5.8 \times 10^5 \left(\frac{m_\chi}{10\,\mathrm{MeV}}\right) \left(\frac{g_\chi\, g_{*s,F}}{g_{*s,0}^2} \cdot \frac{1}{F_D}\right)$$

$\implies \langle\sigma_{\rm ann} v\rangle$ has to be large enough to keep DM in equilibrium until $T < m_\chi$

Non-relativistic freeze-out

- If the DM particles are non-relativistic at the time of freeze-out

$$n_\chi(T_F) = g_\chi \left(\frac{m_\chi T_F}{2\pi}\right)^{3/2} e^{-m_\chi/T_F}$$

- With $x_F = m_\chi/T_F$, freeze-out condition becomes

$$x_F^{1/2} e^{-x_F} = \sqrt{\frac{4\pi^3}{45} g_{*,F}} \frac{2\pi}{m_{pl}\, m_\chi\, g_\chi \langle \sigma_{\rm ann} v\rangle},$$

- Relic density then given by

$$\left(\frac{\Omega_\chi h^2}{0.12}\right) \sim \sqrt{\frac{g_{*,F}}{g_{*S,F}^2}} x_F \left(\frac{8.5 \times 10^{-17}\,{\rm MeV}^{-2}}{\langle \sigma_{\rm ann} v\rangle}\right)$$

Annihilation cross-section

- Cross section for $\chi\bar{\chi} \to \nu\bar{\nu}$, mediated by a vector boson, is

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

Here, $\Gamma = \Gamma_\nu + \Gamma_\chi$ is the total decay width of the vector mediator, where

$$\Gamma_i = \frac{\varepsilon_i^2 m_V}{12\pi}\left(1+\frac{m_i^2}{m_V^2}\right)\sqrt{1-\frac{m_i^2}{4m_V^2}}$$

- For non-rel freeze-out, in the limit $m_V \gg m_\chi$, one obtains

$$\langle\sigma_{\rm ann} v\rangle \approx \frac{\varepsilon_\chi^2\varepsilon_\nu^2}{\pi}\left(\frac{m_\chi}{10\,{\rm MeV}}\right)^2\left(\frac{100\,{\rm GeV}}{m_V}\right)^4 \times 10^{-18}\,{\rm MeV}^{-2}$$

Obtaining the right relic density requires $\varepsilon_\nu^2\,\varepsilon_\chi^2 \sim 10^3$ for $m_V \sim 100$ GeV

Supernova cooling

- DM can also be produced in supernovae through $\nu\bar{\nu} \to \chi\bar{\chi}$ process, if kinematically allowed

- The emissivity [Energy/(time × volume)] is given by

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

  $\sigma_{\rm prod}$ has the same expression as $\sigma_{\rm ann}$, but with $\nu \leftrightarrow \chi$

- The requirement that the luminosity of DM particles not exceed that of neutrinos leads to the Raffelt criterion

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

Dark matter diffusive trapping

- If the DM particles produced in a SN cannot free-stream out, then the previous energy loss constraint does not apply
- Since there are no DM particles present in a SN at the onset, the DM diffusive trapping condition is set by DM-ν scattering
- We use the optical depth criterion: DM particles produced at a radius r_0 are diffusively trapped if

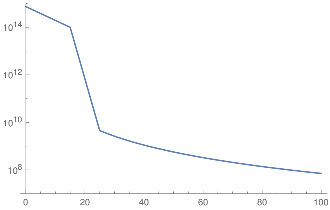
$$\int_{r_0}^{\infty} dr\, \lambda_{\chi\nu}^{-1} \geq \frac{2}{3},$$

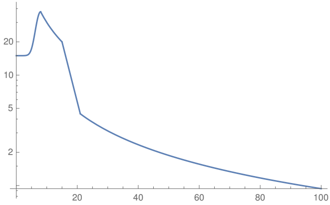
where $\lambda_{\chi\nu} = \dfrac{1}{n_\nu\, \sigma_{\chi\nu}}$ is the DM mean free path

Cooling and trapping criteria

- For simplicity, DM interactions with only ν_μ or ν_τ considered for the time being (the ν_es have high degeneracy in a SN, so results may be different)

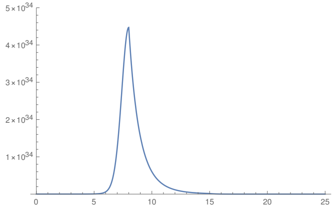
- SN density & temperature profiles: we used analytic fits described in DeRocco *et al.* (arXiv:1905.09284)





Cooling and trapping criteria

- The emissivity of DM particles depends strongly on temperature ($\sim T^9$ if DM particles relativistic)
- For the density profile taken here, emission strongly peaked around $r = 8$ km. Consequently, we chose $r_0 = 8$ km for the trapping calculations



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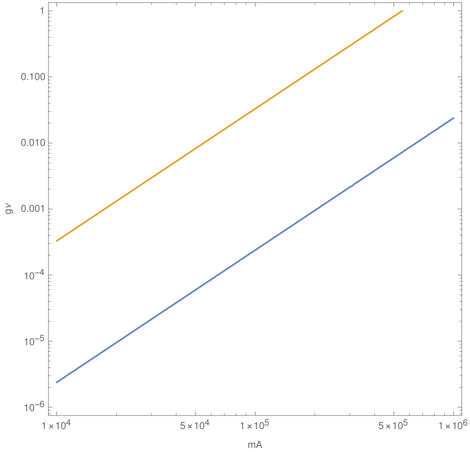

- Region between the lines is where cooling via DM free streaming exceeds cooling via ν diffusion, and is therefore ruled out
- The contour (not shown here) of coupling vs mediator mass that gives the correct DM relic density lies well outside this excluded region

Neutrino decoupling

- For ν_μ and ν_τ neutrinos, energy and number changing processes freeze-out deeper at some radius in the PNS, and subsequently the neutrinos diffuse via ν-N scattering until they get to the " free-streaming surface". However, energy exchange is not as significant in νN scattering

- If ν-ν or ν-DM secret interactions are stronger than ν-N, then the "energy-sphere" gets pushed out, and neutrinos will freeze-out at lower temperatures

- This could have implications for shock reheating, nucleosynthesis, and a future detection may allow us to put constraints on this

Other constraints

- Indirect detection from DM annihilations
- Constraints from cosmological structure formation (DM-ν interactions could lead to suppression of small-scale structure)
- Neutrino self-interactions
- Dark matter self-interactions

Conclusions and Future work

- Intriguing possibility that neutrinos could be the portal through which SM interacts with the dark sector
- For a light DM particle ($m_\chi \sim 10$ MeV) interacting via a heavy mediator, it is possible to obtain the correct relic density if ν-DM interactions are stronger than the weak interaction
- Interesting potential implications in environments with prodigious neutrino fluxes, such as core-collapse supernove
- Future work:
  - Detailed study of neutrino decoupling in supernovae DM/neutrino heat transport
  - Coupling to ν_e: neutrino degeneracy in a supernova environment could have an affect on the outcomes