Neutron Star Heating with Inelastic Dark Matter

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Based on:
Gerardo Alvarez, Aniket Joglekar, Mehrdad Phoroutan-Mehr, Hai-Bo Yu, arxiv: 2301.08767 (PRD)

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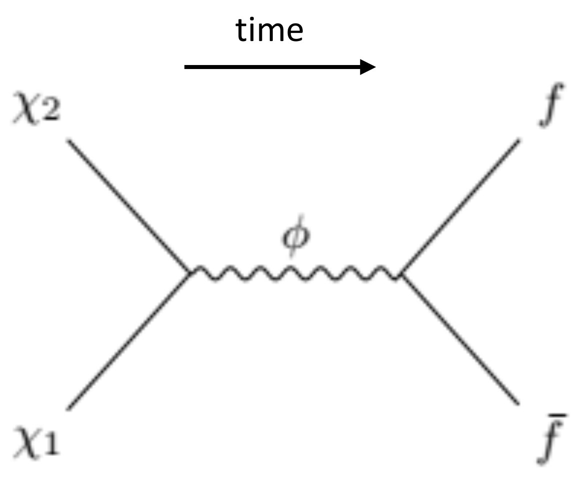
Outline

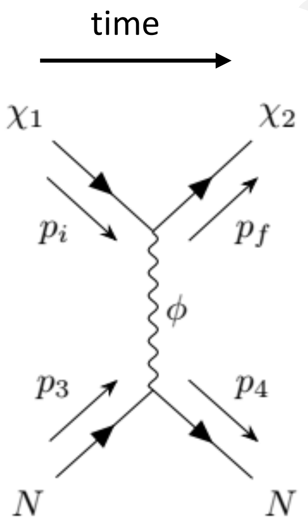
- Introduction
- Dark Matter Capture in Neutron Stars
- Results

Theory of Inelastic Dark Matter Physics

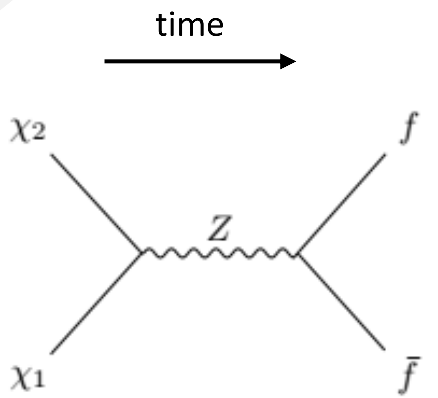
- Two species of dark matter particles with a mass gap.
- It carries its own force.
- Its mediator couples to the standard model particles.
- This model predicts novel phenomenology, coannihilation in the early universe, and unusual spectrum in dark matter direct detection.



coannihilation



Scattering

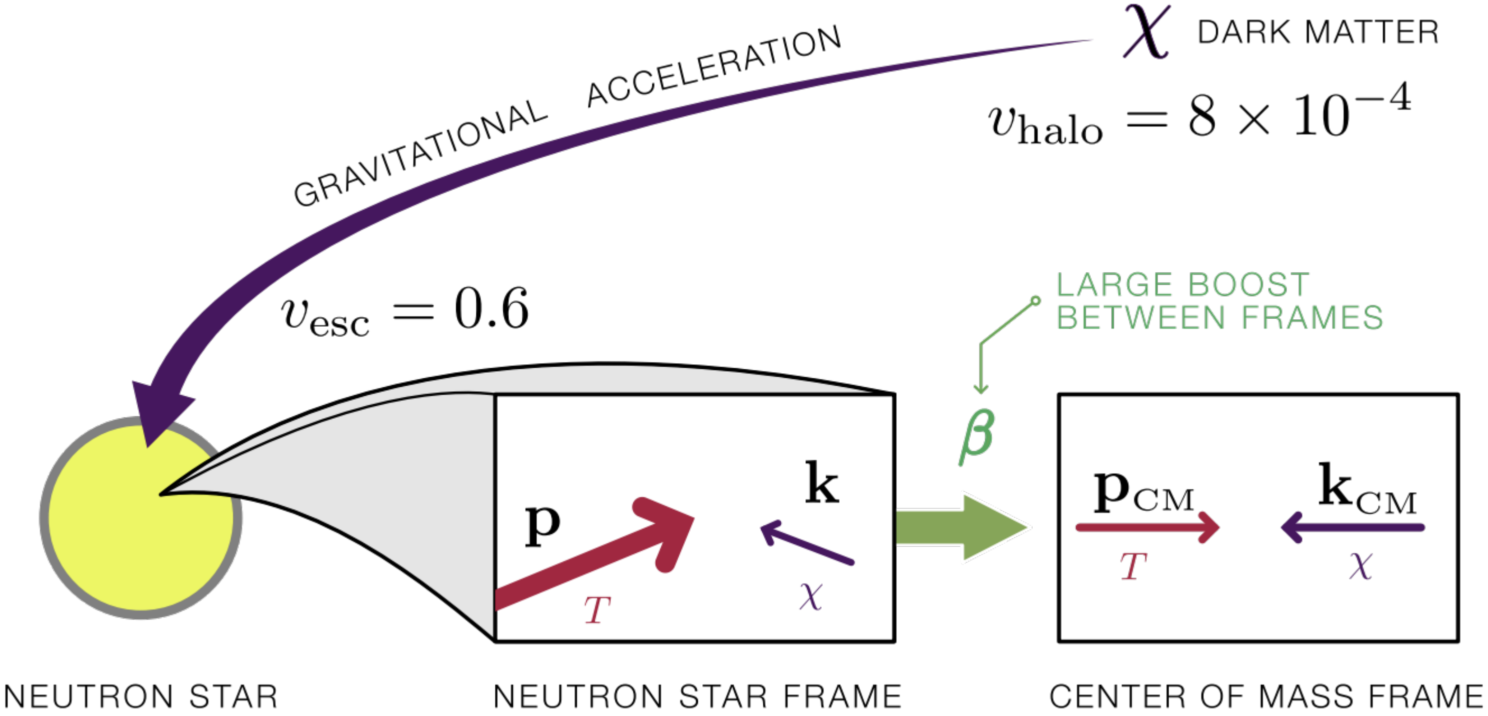


coannihilation

Astrophysical Objects Can Capture Dark Matter

- As astrophysical objects move within the DM halo, they sweep DM particles along their path.
- Gravitational forces accelerate DM particles toward these objects.
- If the particles lose enough kinetic energy, they become captured.
- The captured DM particles can contribute to neutrino emission, leading to the formation of black holes within the objects, and increasing their temperatures.
- The temperature increase occurs through the deposition of DM kinetic energy into the objects and via DM annihilation.
- Neutron stars could accelerate DM particles to relativistic velocities. They could deposit their kinetic energy into neutron stars and heat them up.
- Neutron stars are an ideal target for studying inelastic DM because they can accelerate infalling DM to relativistic velocities.

Temperature Estimation



Joglekar, Raj, Tanedo, Yu 2020

$$\left\{\begin{array}{l} M_\star = 1.5\ \mathrm{M}_\odot \\ R_\star = 12.6\ \mathrm{km} \\ \gamma_{\rm esc} \sim 1.25 \end{array}\right. \xrightarrow{\quad \chi_1 \xi \to \chi_2 \xi \quad} T = 1600\, f^{1/4}\, \mathrm{K}$$

The study of neutron star capture is complicated

- The scattering is inelastic.
- The electron targets are ultra-relativistic, while the infalling DM is relativistic.
- The target rest frame is different from the neutron star rest frame.
- The mass of the electron is less than the Fermi momentum.

Mas Gap

$$\left\{\begin{aligned} k'^2_{\rm CM} &= k^2_{\rm CM} - \frac{\left(m_2^2 - m_1^2\right)\left(2E^2_{\rm CM} + 2m_\xi^2 - m_1^2 - m_2^2\right)}{4E^2_{\rm CM}} \\ \Delta E_{\rm NS} &= \gamma\left(\sqrt{m_1^2 + k^2_{\rm CM}} - \sqrt{m_1^2 + k'^2_{\rm CM}}\right) + \gamma\left(\boldsymbol{\beta}\cdot\mathbf{k}_{\rm CM}\right)\left(1 - \frac{k'_{\rm CM}}{k_{\rm CM}}\cos\psi\right) \\ &\quad - \frac{k'_{\rm CM}}{k_{\rm CM}}\gamma\sqrt{\beta^2 k^2_{\rm CM} - \boldsymbol{\beta}\cdot\mathbf{k}_{\rm CM}}\,\sin\psi\cos\alpha, \end{aligned}\right.$$

$$\text{Nonrelativistic}\quad m_\xi \begin{cases} \text{Heavy} \quad m_1 \longrightarrow \delta m_{\max} = (\gamma_{\rm esc} - 1)m_\xi \\ \text{Light} \quad m_1 \longrightarrow \delta m_{\max} = (\gamma_{\rm esc} - 1)m_1 \end{cases}$$

$$\text{Relativistic}\quad m_\xi \begin{cases} \text{Heavy} \quad m_1 \longrightarrow \delta m_{\max} = 2\gamma_{\rm esc}\beta_{\rm esc}p_\xi^{\rm F} \\ \text{Light} \quad m_1 \longrightarrow \delta m_{\max} = \frac{(\gamma_{\rm esc}^2 - 1)}{2}m_1 \end{cases}$$

Capture Probability

$$f = \sum_{N_{\mathrm{hit}} \in \mathbb{Z}} \frac{\langle n_{\mathrm{T}} \rangle \, \Delta t}{N_{\mathrm{hit}}} \int d\Omega_{\mathrm{NS}} \int_0^{p_{\mathrm{F}}} d|\bar{p}| \, \frac{|\bar{p}|^2}{V_{\mathrm{F}}} v_{\mathrm{M\o l}} \int d\Omega_{\mathrm{CM}} \left(\frac{d\sigma}{d\Omega} \right)_{\mathrm{CM}} \Theta\left(\Delta E + E_{\xi} - E_{\xi}^{\mathrm{F}} \right) \Theta\left(\frac{E_{\mathrm{halo}}}{N_{\mathrm{hit}} - 1} - \Delta E \right) \Theta\left(\Delta E - \frac{E_{\mathrm{halo}}}{N_{\mathrm{hit}}} \right)$$

Number of Scattering

Particle Model

Fermi Energy Condition

Escape Condition

Models

$$\frac{1}{\Lambda^2} (\bar{\chi}_1 \, \gamma^{\mu} \, \chi_2) (\bar{\xi} \, \gamma_{\mu} \, \xi)$$

Effective Vector-Vector Operator

$$(\bar{\chi}_1 \, \gamma^{\mu} \, \chi_2) \, \frac{g_{\chi} \, g_{\xi}}{m_{\phi}{}^2 - t} \, (\bar{\xi} \, \gamma_{\mu} \, \xi)$$

Vector Mediator

$$\mathcal{L}_{\mathrm{int}} \supset \frac{1}{2} m_{A'}^2 A'^{\mu} A'_{\mu} - \left(\frac{1}{2} g_{\chi} \bar{\chi}_2 \gamma^{\mu} \chi_1 A'_{\mu} + h.c. \right) + q \epsilon \bar{\zeta} \gamma^{\mu} \zeta A'_{\mu}$$

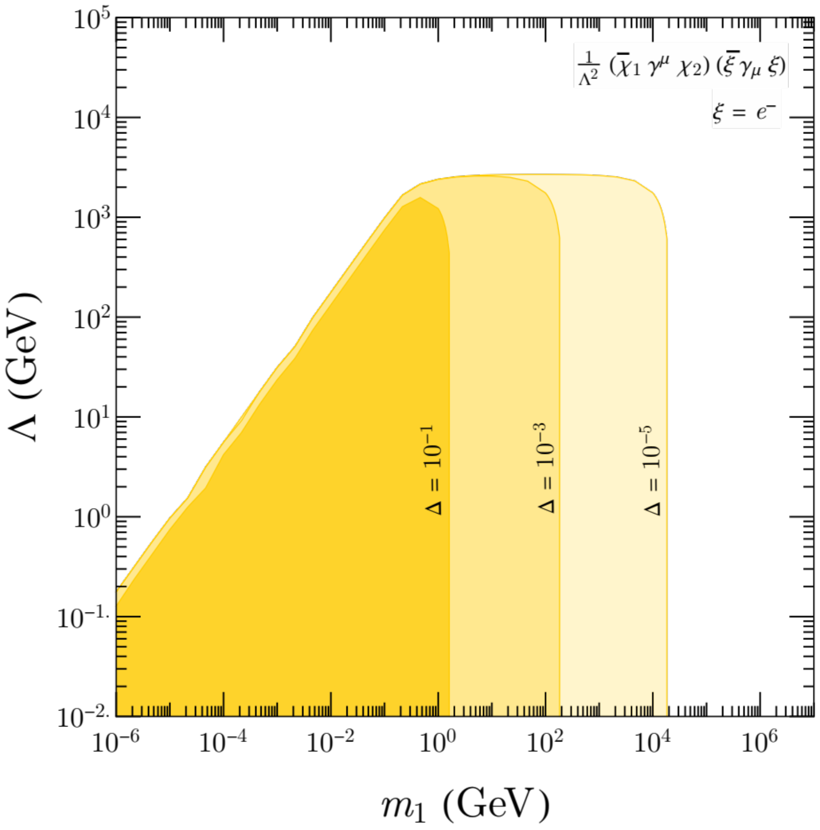
Kinetic Mixing Model

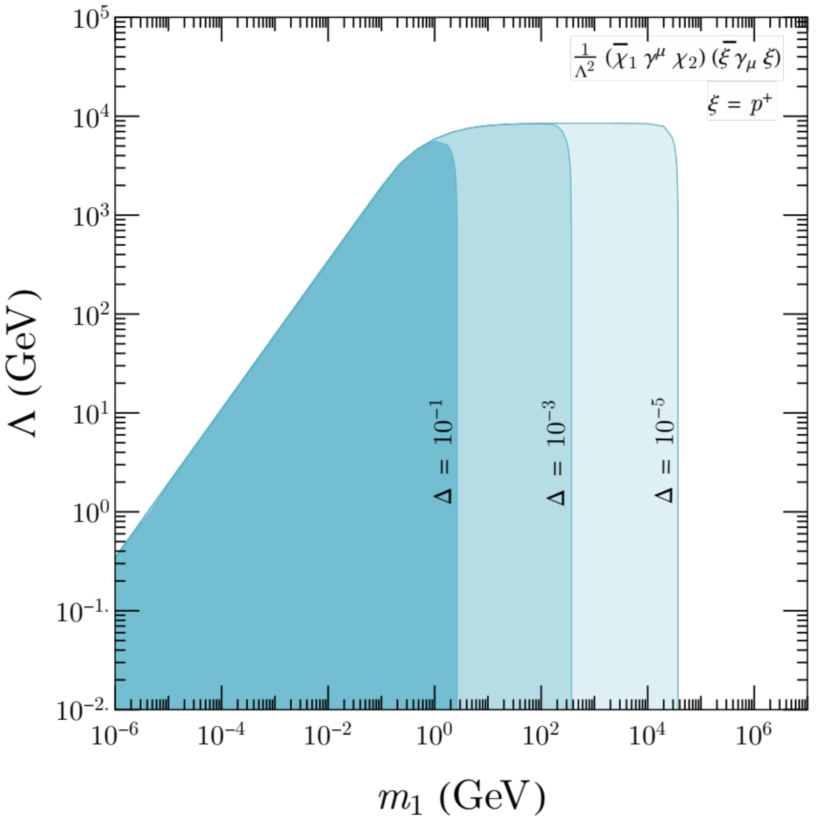
Effective Vector-Vector Operator

$$\frac{1}{\Lambda^2}\,(\overline{\chi}_1\,\gamma^\mu\,\chi_2)\,(\overline{\xi}\,\gamma_\mu\,\xi)$$

$$f = 1$$

$$\Delta \equiv (m_2 - m_1)/m_1 = \delta m/m_1$$



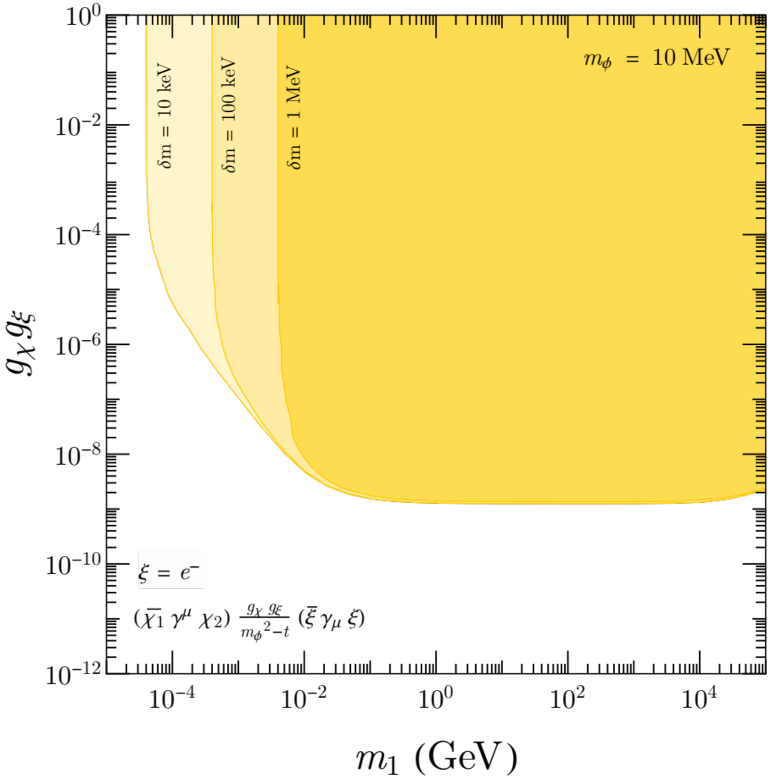


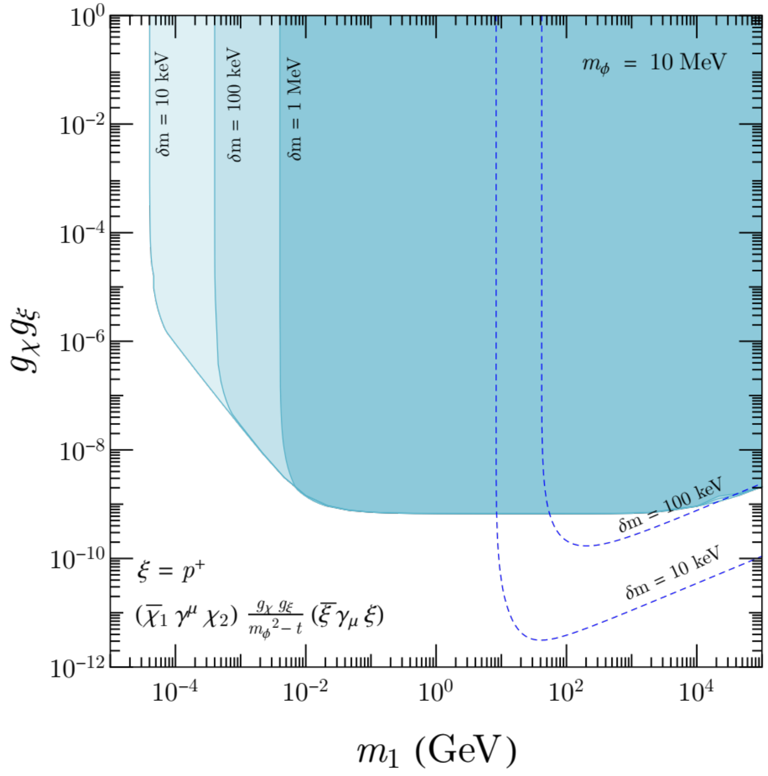
Vector Mediator

$$(\overline{\chi}_1\,\gamma^\mu\,\chi_2)\,\frac{g_\chi\,g_\xi}{{m_\phi}^2 - t}\,(\overline{\xi}\,\gamma_\mu\,\xi)$$

$$f\ = 1$$

$$\Delta \equiv (m_2 - m_1)/m_1\ = \delta m/m_1$$



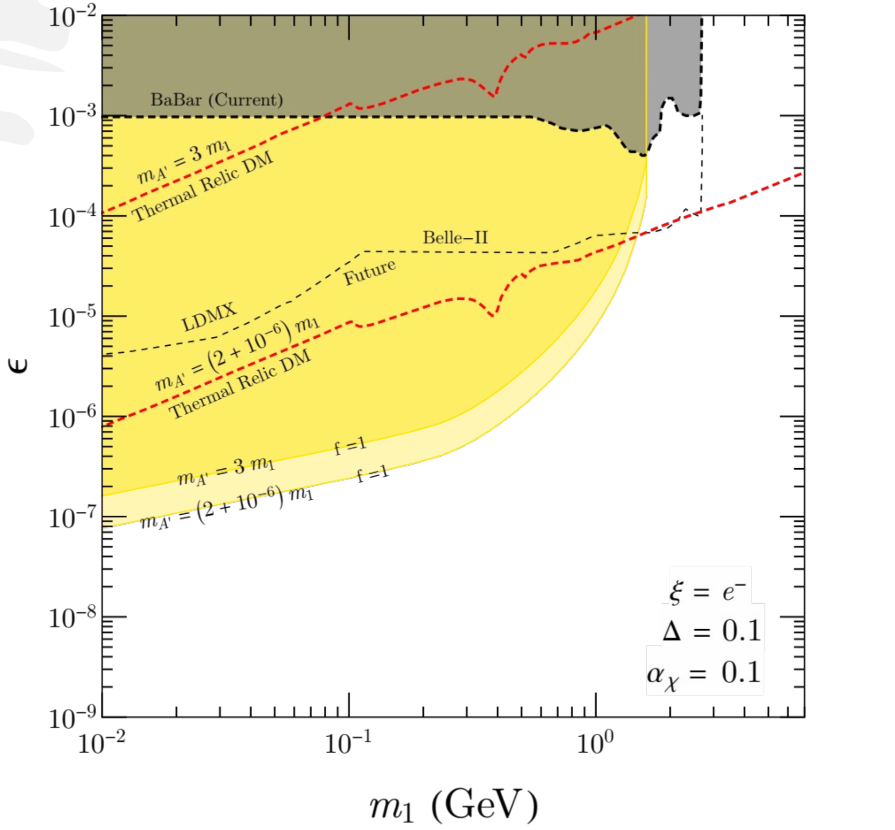


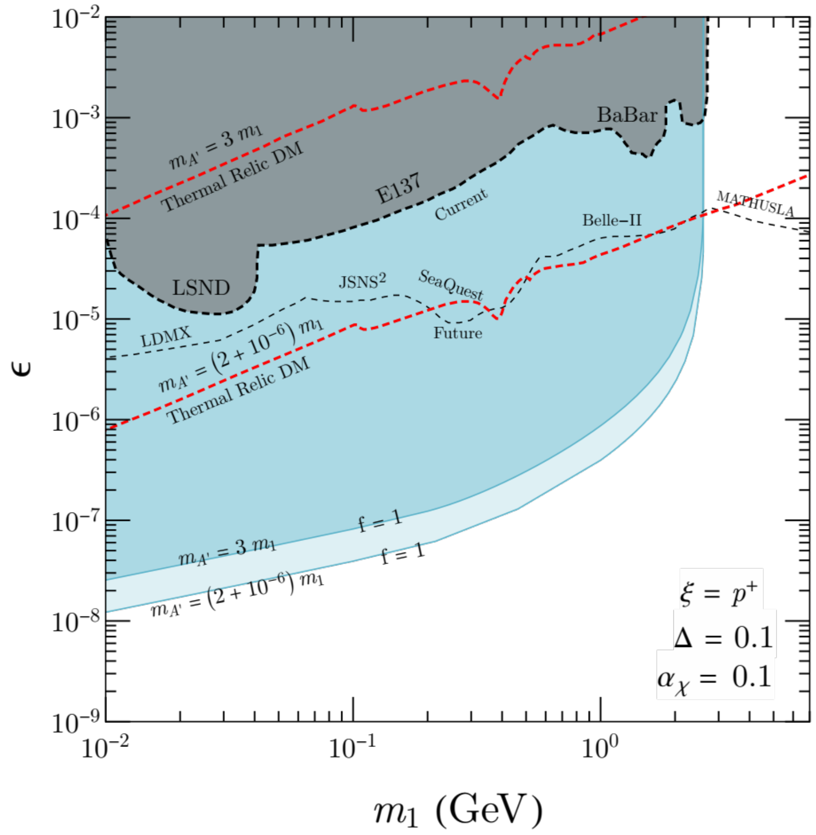
$$\frac{d\sigma}{dE_R} \approx \frac{m_N}{2\pi v^2}\frac{g_\chi^2 g_\xi^2 Z^2}{\left(m_\phi^2 - \delta m^2 + 2m_N E_R\right)^2} F^2\left(E_R\right)$$

$$v_{\min} \approx \frac{(E_R m_N/\mu + \delta m)}{\sqrt{2E_R m_N}}$$

Kinetic Mixing Model

$$\mathcal{L}_{\text{int}} \supset \frac{1}{2} m_{A'}^2 A'^{\mu} A'_{\mu} - \left(\frac{1}{2} g_\chi \bar{\chi}_2 \gamma^\mu \chi_1 A'_\mu + h.c. \right) + q\epsilon \bar{\zeta} \gamma^\mu \zeta A'_\mu$$





$$\Omega h^2 = 8.77 \times 10^{-11} GeV^{-2} \left(\int_{x_f}^{x_0} \frac{g_{energy}^{1/2} < \sigma v >_{eff}}{x^2} \right)^{-1}$$

$$< \sigma v >_{eff} = \frac{2(1 + \frac{\Delta m}{m_{\chi 1}})^{3/2} e^{-x \Delta m / m_{\chi 1}}}{(1 + (1 + \frac{\Delta m}{m_{\chi 1}})^{3/2} e^{-x \Delta m / m_{\chi 1}})^2} < \sigma v >_{NR}$$

Summary and Outlook

- The capture of relativistic Dark Matter by ultra-relativistic electrons in neutron stars requires a somewhat complicated formalism.
- Neutron stars are highly efficient targets for studying inelastic dark matter.
- The bounds on parameter space provided by neutron stars are stronger than those from direct detection, relic abundance, and accelerator experiments.

Thank You

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