

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)



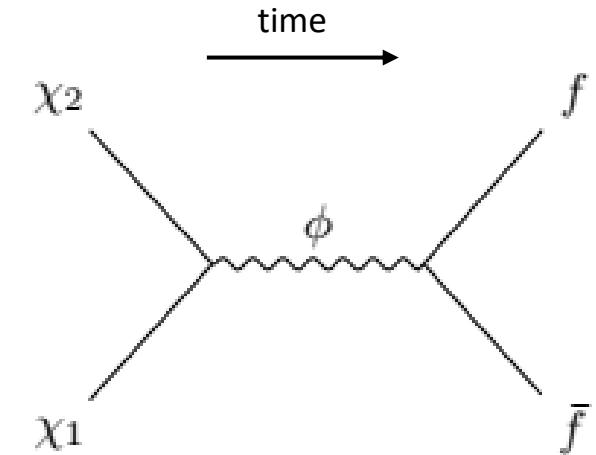
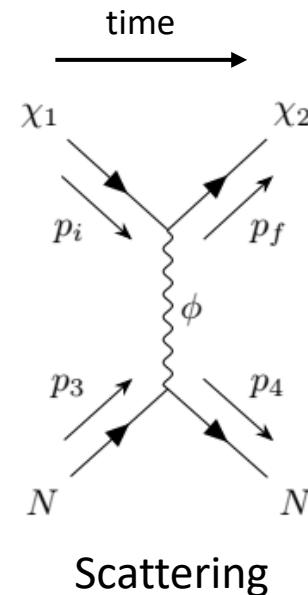
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Outline

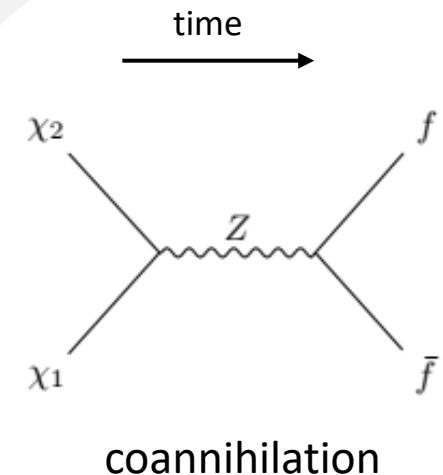
- Introduction
- Dark Matter Capture in Neutron Stars
- Results

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

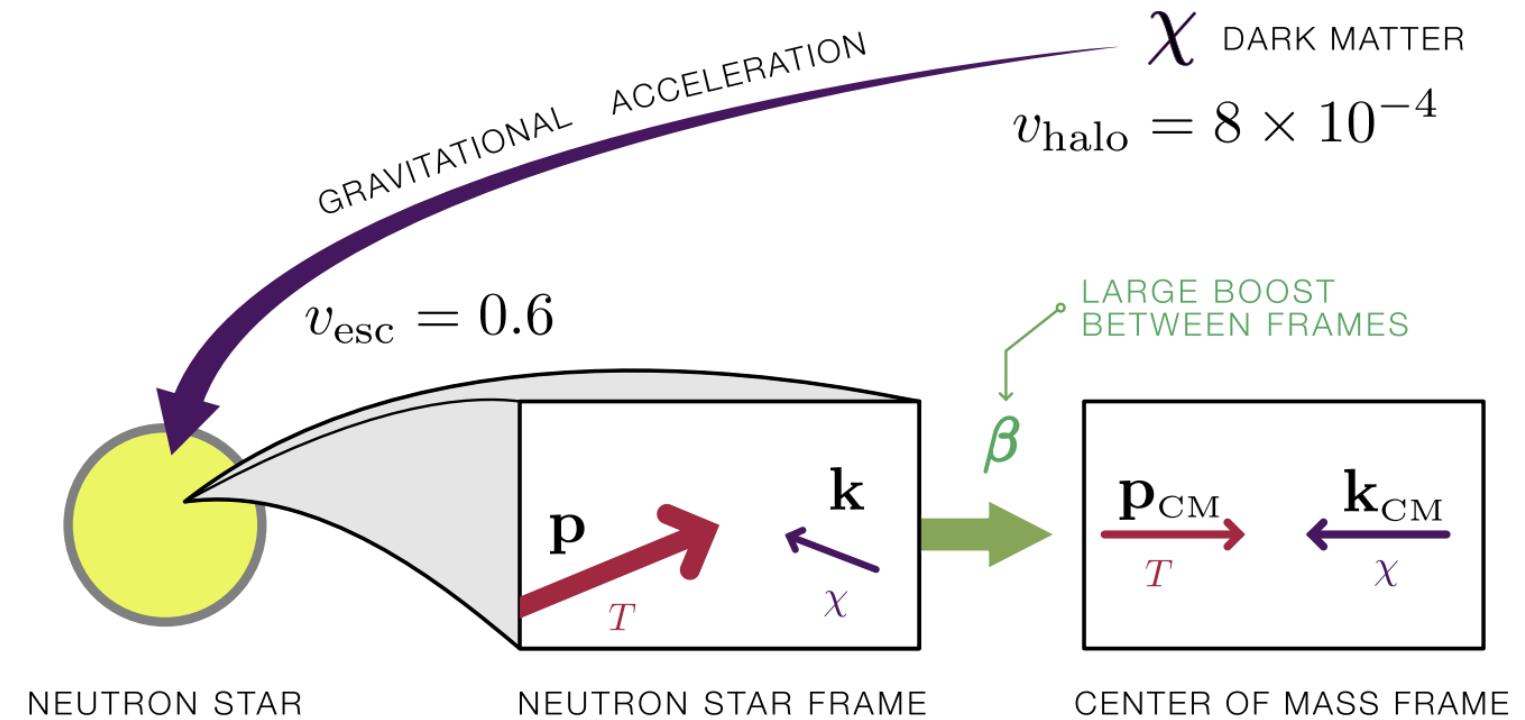


coannihilation

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

$$\left[\begin{array}{l} M_\star = 1.5 \text{ } M_\odot \\ R_\star = 12.6 \text{ km} \\ \gamma_{\text{esc}} \sim 1.25 \end{array} \right] \xrightarrow{\chi_1 \xi \rightarrow \chi_2 \xi} T = 1600 f^{1/4} \text{ K}$$

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.

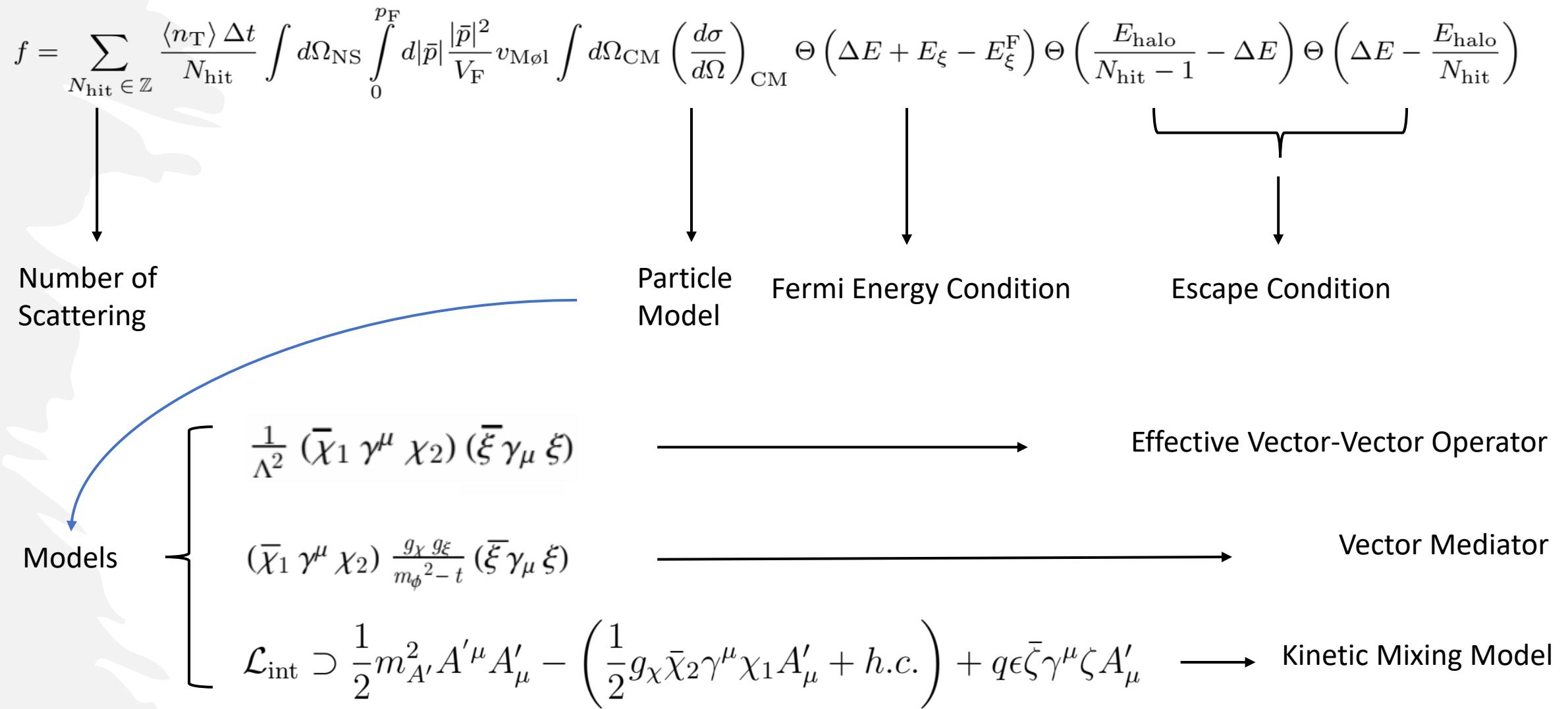
Mas Gap

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

Nonrelativistic m_ξ $\left\{ \begin{array}{lll} \text{Heavy } m_1 & \xrightarrow{\hspace{2cm}} & \delta m_{\text{max}} = (\gamma_{\text{esc}} - 1)m_\xi \\ \text{Light } m_1 & \xrightarrow{\hspace{2cm}} & \delta m_{\text{max}} = (\gamma_{\text{esc}} - 1)m_1 \end{array} \right.$

Relativistic m_ξ $\left\{ \begin{array}{lll} \text{Heavy } m_1 & \xrightarrow{\hspace{2cm}} & \delta m_{\text{max}} = 2\gamma_{\text{esc}}\beta_{\text{esc}}p_\xi^{\text{F}} \\ \text{Light } m_1 & \xrightarrow{\hspace{2cm}} & \delta m_{\text{max}} = \frac{(\gamma_{\text{esc}}^2 - 1)}{2}m_1 \end{array} \right.$

Capture Probability

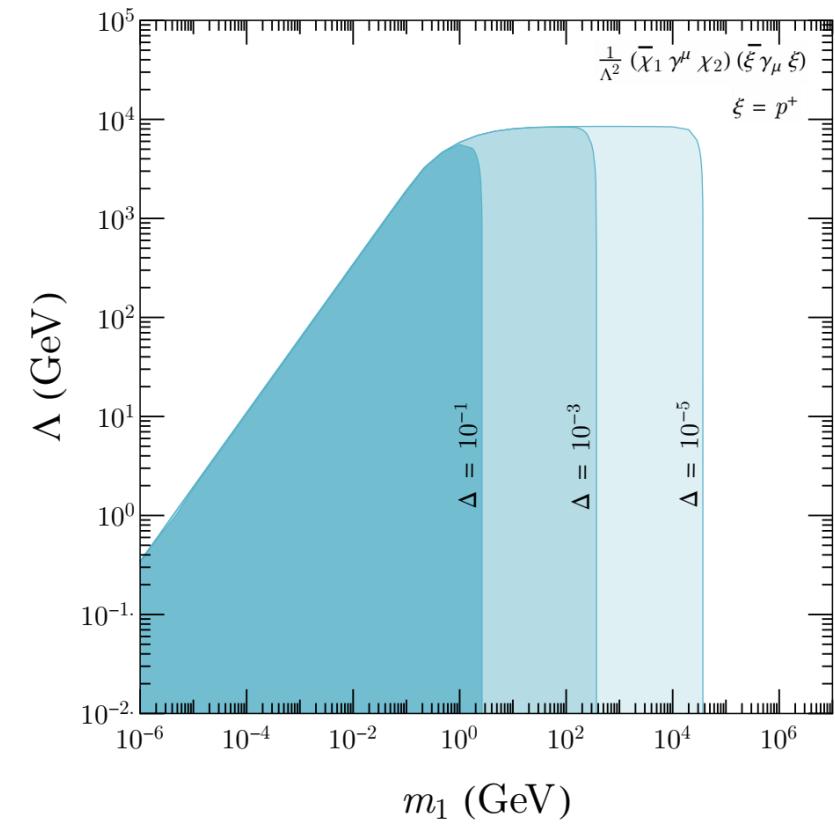
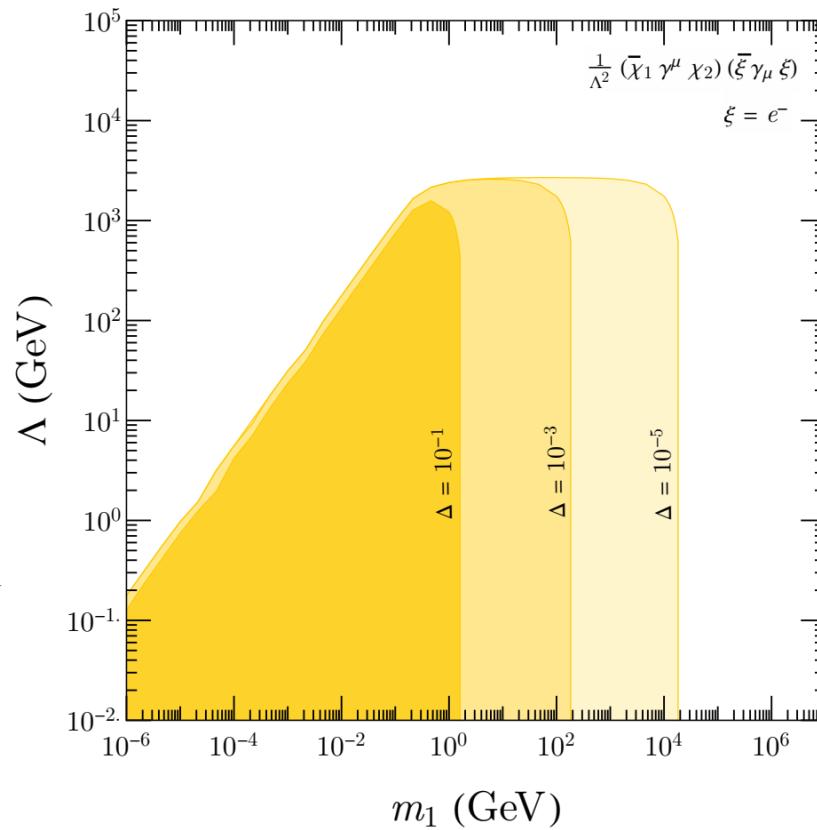


Effective Vector-Vector Operator

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

$$f = 1$$

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



Vector Mediator

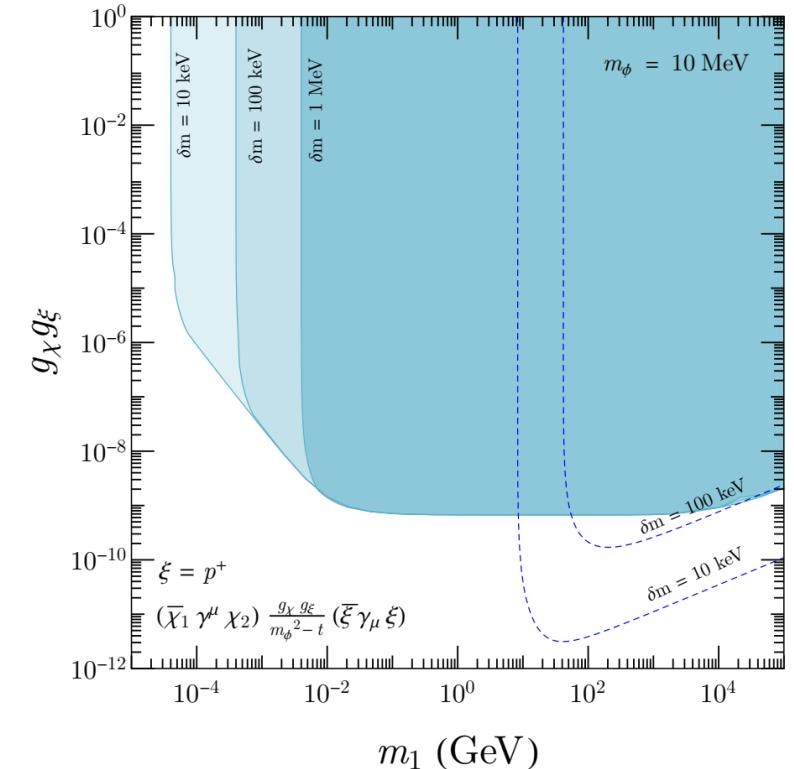
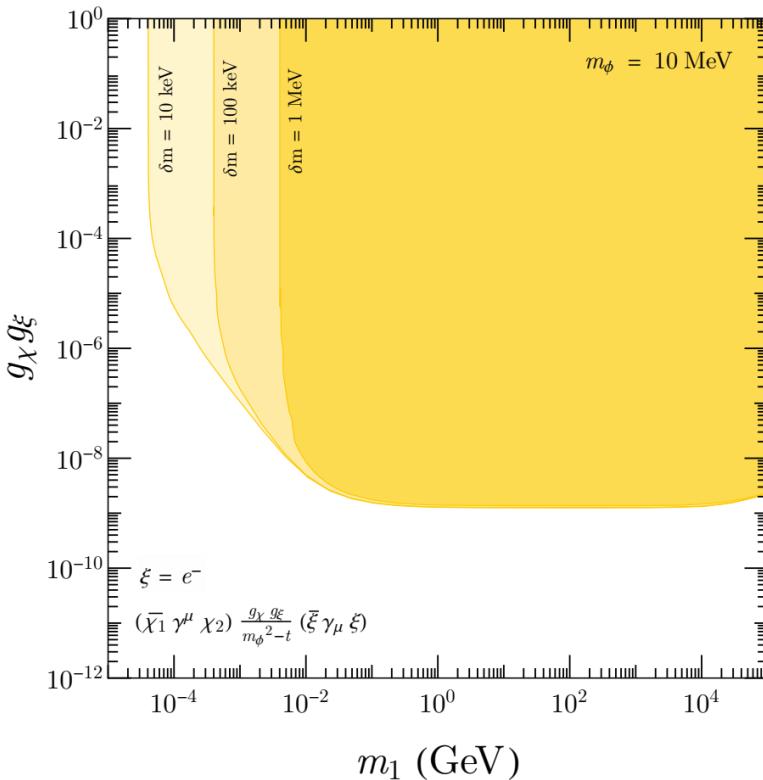
$$(\bar{\chi}_1 \gamma^\mu \chi_2) \frac{g_\chi g_\xi}{m_\phi^2 - t} (\bar{\xi} \gamma_\mu \xi)$$

$$f = 1$$

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

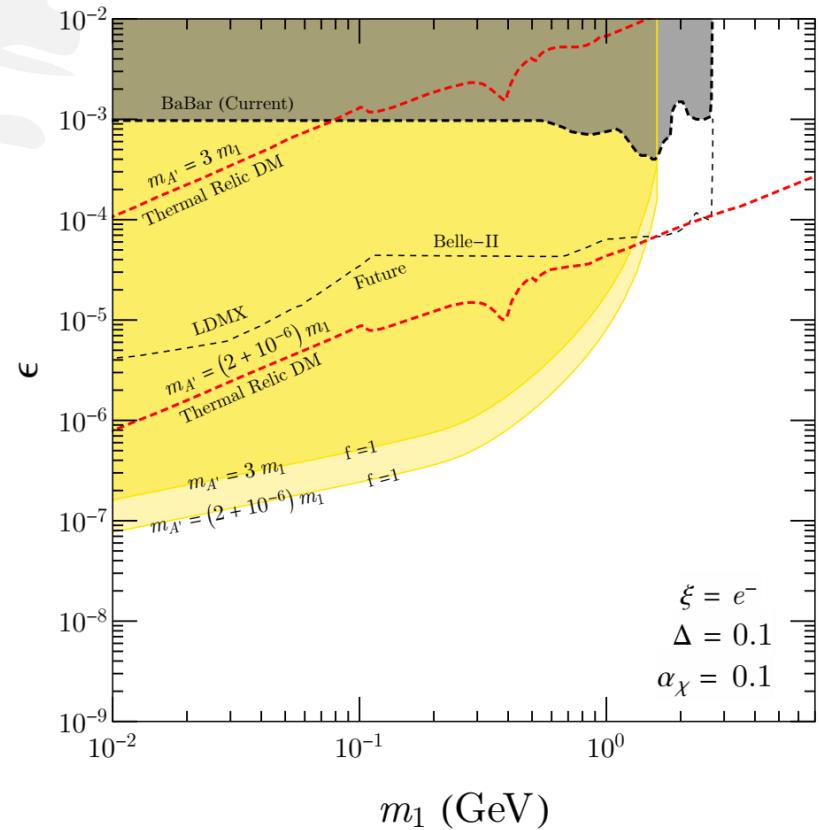
$$\frac{d\sigma}{dE_R} \approx \frac{m_N}{2\pi v^2} \frac{g_\chi^2 g_\xi^2 Z^2}{(m_\phi^2 - \delta m^2 + 2m_N E_R)^2} F^2(E_R)$$

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

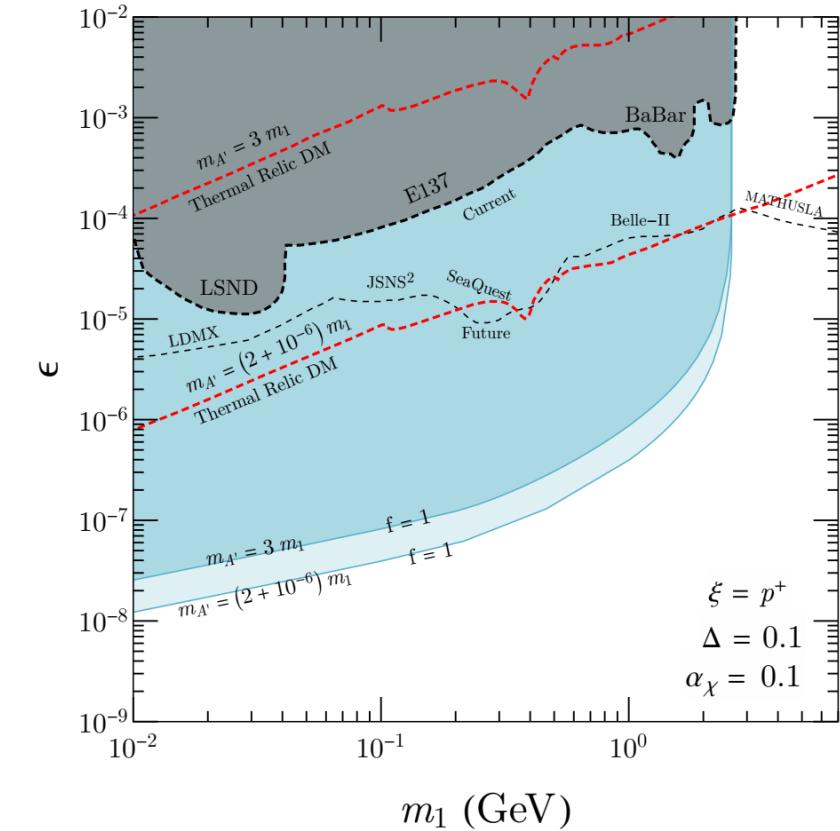


Kinetic Mixing Model

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



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



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

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.



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Thank You