MULTI-COMPONENT MULTISCATTER CAPTURE OF DARK MATTER

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A LITTLE BIT ABOUT ME

I grew up in Kingston, Jamaica

I LOVE Music, and I’m learning Jazz Piano

I miss my dog (his name is Mr. Baggins, I also like LOTR)
WHO I WORK WITH

Cosmin Ilie, Colgate University (Advisor)

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WHAT IS DARK MATTER?

- We don’t know... but we know it exists.
- How do we know it exists?
  - Galaxy rotation curves are flat
  - Gravitational lensing of distant galaxies
  - Speed of galaxies in clusters
  - Cosmic Microwave Background
  - Etc.
WHAT DO WE KNOW ABOUT IT?

We can say a little more on this:

- ~85% of the mass budget of the universe
- ~27% of the energy budget of the universe
- Interacts extremely weakly **if at all** with “regular” matter
- Responsible for the structure of the universe \( \rightarrow \) It collapsed first into Halo structures
DM MINI-HALOS: HOME TO THE FIRST STARS 🌙

DARK MATTER COLLAPSED FIRST; BARYONS FOLLOWED

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DETECTING DARK MATTER

- Direct detection
  - Approaching Neutrino Floor
- Indirect detection
- Particle creation
- Astrophysical bodies

Click Dutta, Bhaskar, and Louis E. Strigari. “Neutrino Physics with Dark Matter Detectors.” Annual Review of Nuclear and Particle Science 69.1 (2019): 137–161.
OUTLINE

Introduction

Dark Matter Capture

DM Bounds with Pop. III Stars

Conclusion
CAPTURE FORMALISM
SINGLE-COMPONENT MULTI-SCATTER CAPTURE

- Capture Rate = DM Flux * Probability of N Scatters with 1 component * Probability of Capture after N Scatters
SINGLE-COMPONENT MULTI-SCATTER CAPTURE

J. Bramante, A. Delgado, and A. Martin, Phys. Rev. D 96, 063002 (2017), arXiv:1703.04043 [hep-ph].
\[ p_N(\tau) = 2 \int_0^1 \text{Poisson}(y\tau, N) \, y \, dy \]

\[ p_N(\tau) = \frac{2}{\tau^2} \left( N + 1 - \frac{\Gamma(N + 2, \tau)}{N!} \right) \]
\( \tau \approx 3 \)
Incidence Angle = 0°
\( \tau_{\text{effective}} = \cos(0) \times 3 = 3 \)
Prob. of N Collisions = Poisson(3, N)

- Particle comes straight in
- Longer path, “full” \( \tau \)
$\tau \approx 3$

Incidence Angle = 60°

$\tau_{\text{effective}} = \cos(60°) \times 3 = 1.5 \approx 2$

Prob. of N Collisions = Poisson(1.5, N)

- Particle at an angle
- Shorter path, “reduced” $\tau$
\[ p_N(\tau) = 2 \int_0^1 \text{Poisson}(y\tau, N) \, y \, dy \]

\[ p_N(\tau) = \frac{2}{\tau^2} \left( N + 1 - \frac{\Gamma(N + 2, \tau)}{N!} \right) \]
\[ g_N(w) = \int_0^1 dz_1 \int_0^1 dz_2 \cdots \int_0^1 dz_N \Theta \left( v_{esc} \prod_{i=1}^N (1 - z_i \beta_+)^{-1/2} - w \right), \]

\[ g_N(w) = \Theta \left( v_{esc} \left( 1 - \langle z_i \rangle \beta_+ \right)^{-N/2} - w \right) \]

**PROBABILITY OF CAPTURE FROM N SCATTERS**
SINGLE TO 2-COMPONENT

Single-Component

\[ C_{tot} = \sum_{N=1}^{\infty} C_N = \sum_{N=1}^{\infty} \pi R_x^2 \times n_X \int_{0}^{\infty} \frac{f(u)du}{u} \left( u^2 + v_{esc}^2 \right) \times p_N(\tau) \times g_N(u) \]

Two-Component

\[ C_{tot} = \sum_{N=1}^{\infty} C_N = \sum_{N=1}^{\infty} \sum_{i=0}^{N} \pi R_x^2 \times n_X \int_{0}^{\infty} \frac{f(u)du}{u} \left( u^2 + v_{esc}^2 \right) \times p_i(\tau_A)p_j(\tau_B) \times g_{ij}(u) \]

i = scatters with A
j = scatters with B

N = i + j
\[ p_i(\tau_A) = \begin{cases} \frac{2}{\tau_A^2} \left( i + 1 - \frac{\Gamma(i+2,\tau_A)}{i!} \right), & \text{if } \tau_A > 0 \\ \Theta(-i), & \text{if } \tau_A = 0 \end{cases} \]

\[ p_j(\tau_B) = \begin{cases} \frac{2}{\tau_B^2} \left( j + 1 - \frac{\Gamma(j+2,\tau_B)}{j!} \right), & \text{if } \tau_B > 0 \\ \Theta(-j), & \text{if } \tau_B = 0 \end{cases} \]
\[ g_{ij}(w) = \int_0^1 dz_1 \int_0^1 dz_2 \cdots \int_0^1 dz_i \int_0^1 dz_{i+1} \cdots \int_0^1 dz_{i+j} \Theta (v_{esc} - v_{ij}) \]

\[ g_{ij}(w) = \Theta \left( v_{esc} \prod_{k=1}^{i} (1 - \langle z_A \rangle \beta^A_+)^{-\frac{1}{2}} \prod_{n=1}^{j} (1 - \langle z_B \rangle \beta^B_+)^{-\frac{1}{2}} - w \right) \]
\[ C_{ij} = \pi R^2 p_i(\tau_H)p_j(\tau_{He}) \int_{v_{esc}}^{\infty} dw \frac{f(u)}{u^2} w^3 g_{ij}(w) \]

\[ C_{tot} = \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} C_{ij} \]

TOTAL CAPTURE RATE: ALTERNATE FORM
TWO TECHNIQUES FOR TOTAL CAPTURE ESTIMATIONS
GENERALIZED MULTI-COMPONENT CAPTURE

\[ C(\alpha, \beta, \gamma, ..., \omega) = \pi R^2 p_\alpha(\tau_I)p_\beta(\tau_{II}) \times ... \times p_\omega(\tau_n) \int_{v_{esc}}^{\infty} dw \frac{f(u)}{u^2} w^3 g(w, \alpha, \beta, \gamma, ..., \omega). \]

\[ C_{tot} = \sum_{\alpha=0}^{\infty} \sum_{\beta=0}^{\infty} ... \sum_{\omega=0}^{\infty} C(\alpha, \beta, ..., \omega) \]
\[ \sigma \equiv \sigma_H = \sigma_0^{SI-p}, \]
\[ \sigma_{He} = 4^4 \sigma_0^{SI-p} \langle F^2(E_R) \rangle, \]
\[ \tau_H = 10^{-5} \left( \frac{\sigma_H}{1.26 \times 10^{-40}} \right) \left( \frac{M_*}{M_\odot} \right) \left( \frac{R_\odot}{R_*} \right)^2 \left( \frac{f_H}{0.75} \right), \]
\[ \tau_{He} = 10^{-3} \left( \frac{\sigma_H}{1.26 \times 10^{-40}} \right) \left( \frac{M_*}{M_\odot} \right) \left( \frac{R_\odot}{R_*} \right)^2 \left( \frac{f_{He}}{0.25} \right) \left( \frac{\langle F^2(E_R) \rangle}{0.99} \right). \]
\[ \sigma = 10^{-40} \text{ cm}^2 \]

\[ \sigma = 10^{-35} \text{ cm}^2 \]

- \[ M_* = 100 M_\odot \]
- \[ M_* = 300 M_\odot \]
- \[ M_* = 1000 M_\odot \]

\[ \rho_x = 10^{14} \text{ GeV cm}^{-3} \]

- Solid: \( f_{\text{He}} = 0.25 \)
- Dashed: \( f_{\text{He}} = 0 \)
ANNIHILATION

- Provides an additional source of energy to the star
- Various Particle Models
  - WIMPs ~ MeV – 120 TeV
  - (S)HDM ~ > 120 TeV
EVAPORATION

RELEVANT IN SUB-GEV REGION

\[ E = \int n_x dV \int_0^\infty f(w) dw \int_0^{\infty} R^+(w \rightarrow \nu) dv \]

Rate/particle/shell/velocity
COMPETING EFFECTS: EQUILIBRATION

- Number of DM particles governed by differential equation
- Equilibrium occurs within lifetime of star for models considered
- Two distinct scenarios:
  - Capture-dominated (High Mass) → DM luminosity depends on Capture
  - Evaporation-dominated (Low Mass) → DM luminosity depends on Capture and Evaporation

\[
\frac{dN_x}{dt} = C - \Gamma_A - E
\]
EQUILIBRIUM AND DARK MATTER LUMINOSITY

- Equilibrium means we can calculate DM luminosity in terms of **Capture** and **Evaporation**
- This leads to the possibility of constraining DM scattering cross-section

\[ \Gamma_A = C - E \]

\[ L_{DM} = \Gamma_A m_\chi = m_\chi [C(\sigma) - E(\sigma)] \]
This limit on luminosity provides a means to bound DM properties through the DM luminosity.

\[ L_{nuc}(M_\star) + L_{cap}(M_\star; \text{DM params}) \leq L_{Edd}(M_\star) \]

\[ L_{Edd} = 3.5 \times 10^4 \left( \frac{M_\star}{M_\odot} \right) L_\odot \]
HIGH-MASS BOUNDS
Upper Bounds on $\sigma^{SI} - m_x, \rho_x = 10^{13} - 10^{16}$ GeV cm$^{-3}$, $M_* = 1000M_\odot$
MAIN TAKEAWAYS

New formalism for multi-component DM capture

Enhanced DM capture and luminosity in Pop. III stars

Ability to constrain DM cross section below the neutrino floor
FUTURE WORK

01 Apply formalism to other multi-component objects, such as white dwarves, exoplanets

02 Relax assumptions of even distributions of nuclei

03 Utilize stellar evolution code to directly implement multi-component capture
QUESTIONS?
$C_{ij}$, Partial Capture Rates

$m_\chi = 10^{14}$ GeV
$\rho_\chi = 10^9$ GeV cm$^{-3}$
$\sigma = 10^{-34}$ cm$^2$
$M = 100M_\odot$, $\rho_X = 10^{14}$ GeV cm$^{-3}$, $\sigma = \sigma^{X\gamma}$

![Graph showing the total capture rate vs. DM mass with lines for $f_{He} = 0.25$ and $0 \leq f_{He} \leq 1$.](image)