The Strongly Interacting Massive Particle Paradigm

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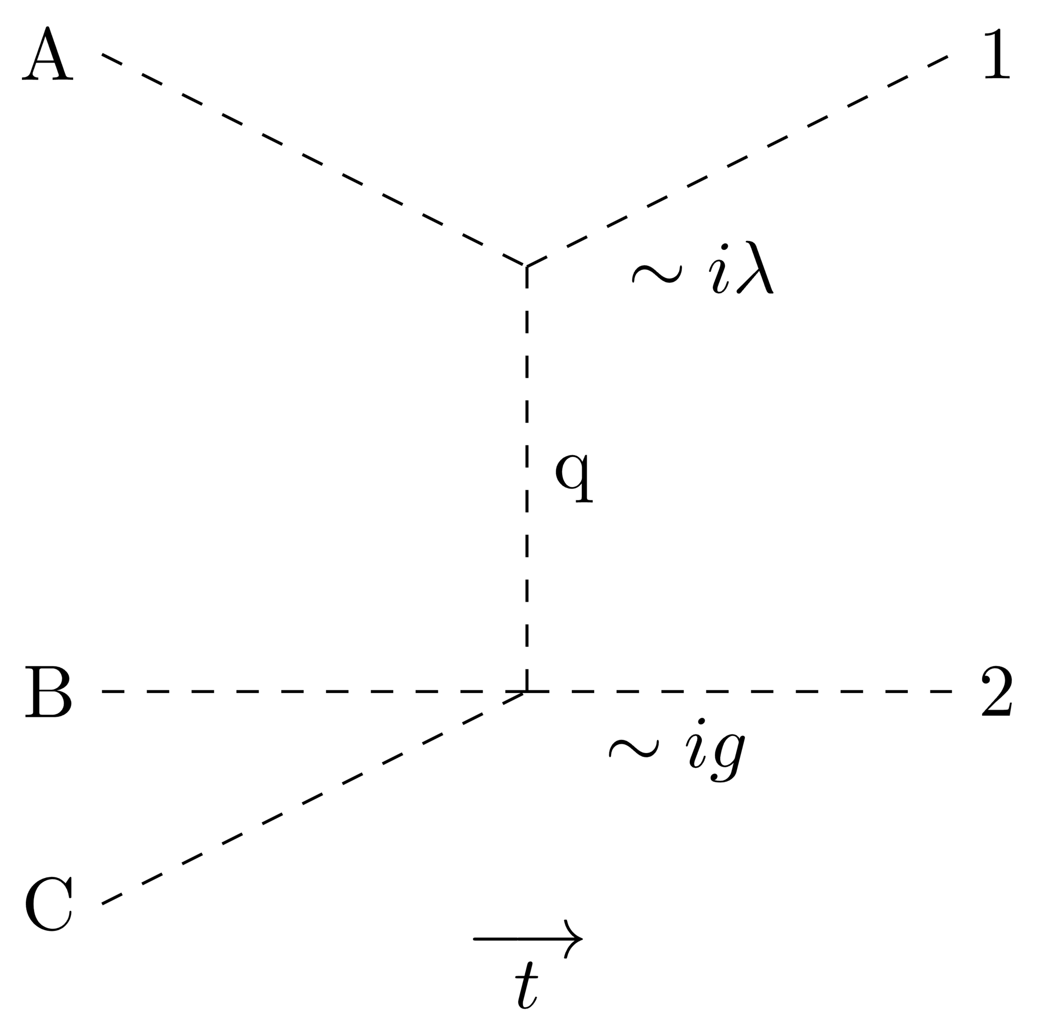
Introduction

One hypothesis for dark matter's identity is that it is a cold thermal relic from the early universe. The Strongly Interacting Massive Particle (SIMP) paradigm fits this hypothesis. It is characterized by strong self interactions and weak interactions with standard model particles. The model incorporates various self-interaction, scattering and annihilation processes, but this project focuses on a specific case of the 3-to-2 annihilation process. In this process three scalar dark matter (DM) particles collide and produce two scalar DM particles. This annihilation is essential for freeze out and thus the behavior of SIMPs can be accurately modeled using only this process. The following image is the corresponding Feynman diagram.



Boltzmann Equation

The Boltzmann Equation is an important tool for modeling a population of particles. For the SIMP under a 3-to-2 annihilation process, the Boltzmann Equation is:

$$\partial_t n + 3Hn = -(n^3 - n^2 n_{eq})\langle\sigma v^2\rangle_{3\to 2} \qquad (1)$$

Collisional Term

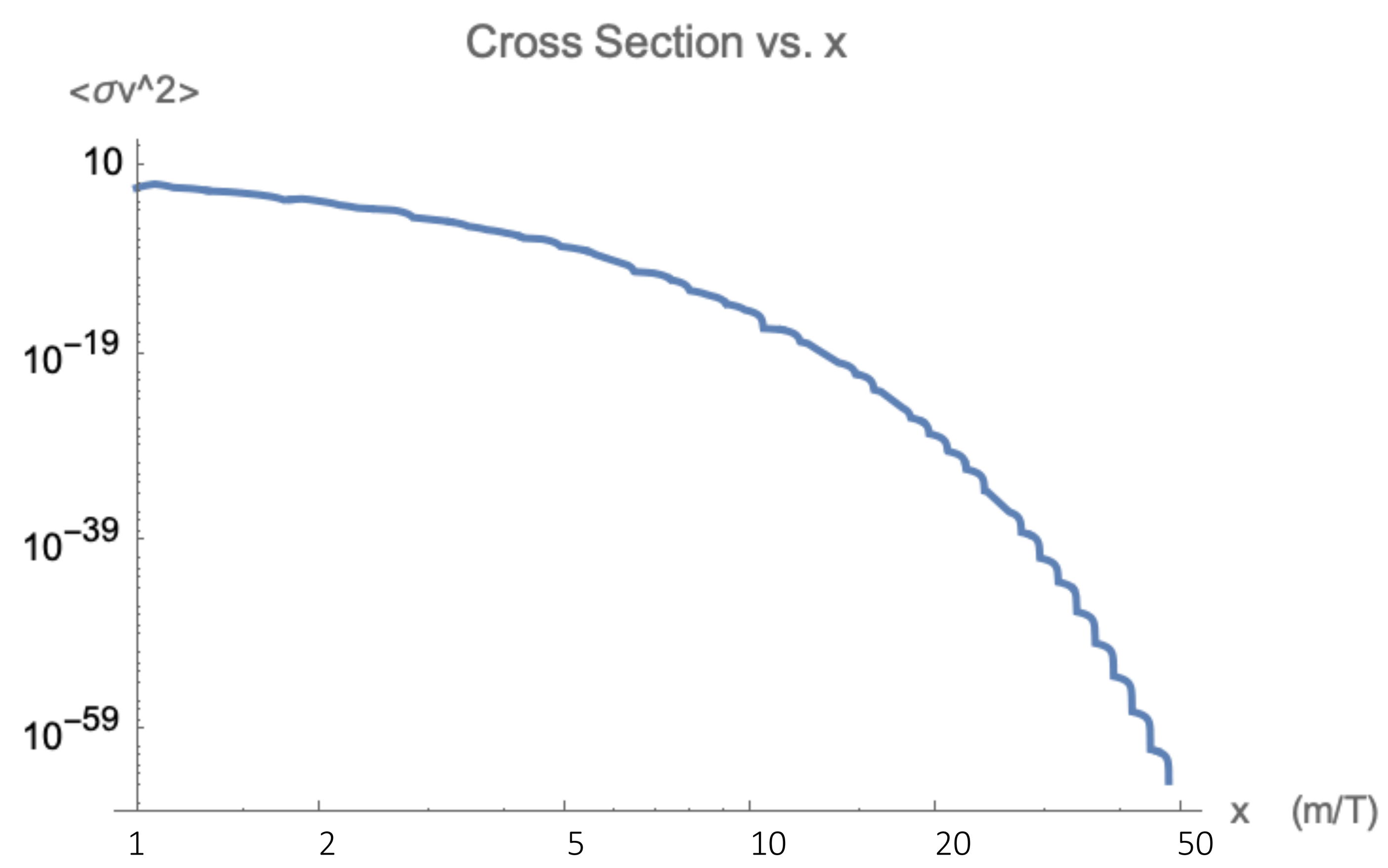
An important piece of the Boltzmann equation is the collisional term, which accounts for the righthand side of (1). The integral for the collisional term is:

$$\int \frac{\mathrm{d}^3p_A}{(2\pi)^3}\frac{\mathrm{d}^3p_B}{(2\pi)^3}\frac{\mathrm{d}^3p_C}{(2\pi)^3}\frac{\mathrm{d}^3p_1}{(2\pi)^3}\frac{\mathrm{d}^3p_2}{(2\pi)^3}\frac{1}{2^5E_AE_BE_CE_1E_2}(2\pi)^4\delta^4(p_A+p_B+p_C-p_1-p_2) \cdot \frac{\lambda^2g^2}{(q^2-m_\chi^2)^2}e^{-(E_A+E_B+E_C)/T}\cdot\frac{1}{n_{eq}^3} \qquad (2)$$

Evaluating the delta functions, applying normal integration techniques, and the using following parameterizations: $x \equiv \frac{m_\chi}{T}$ $\quad y_i \equiv \frac{E_i}{T}$ results in the following expression for the cross section $(\langle\sigma v^2\rangle_{3\to 2})$

$$\langle\sigma v^2\rangle = -\frac{\lambda^2g^2}{128\pi^3}T^3\frac{1}{n_{eq}^3}\int\frac{\mathrm{d}\theta_A\,\mathrm{d}y_A\,\mathrm{d}y_B\,\mathrm{d}y_C\,\mathrm{d}y_1\,(y_A^2-x^2)(y_1^2-x^2)}{(y_A^2y_1+y_Ay_By_1+y_Ay_Cy_1-y_Ay_1^2)} \cdot \frac{\sqrt{y_B^2-x^2}\sqrt{y_C^2-x^2}e^{-y_A-y_B-y_C}}{(x^2-2y_1y_A+2\sqrt{y_1^2-x^2}\sqrt{y_A^2-x^2}\cos\theta_A)^2} \qquad (3)$$

By numerically integrating (3) we obtained a table of cross sections and their corresponding value of x.



Using numerical integration, we can use this result in a modified form of the Boltzmann equation as follows. First, we apply the following parameterizations (seen at the top of the next column):

$$H(m) = 1.67\sqrt{g_\star}\frac{m_\chi^2}{m_{pl}} \qquad s = \frac{2\pi^2}{45}g_\star\frac{m^3}{x^3}$$

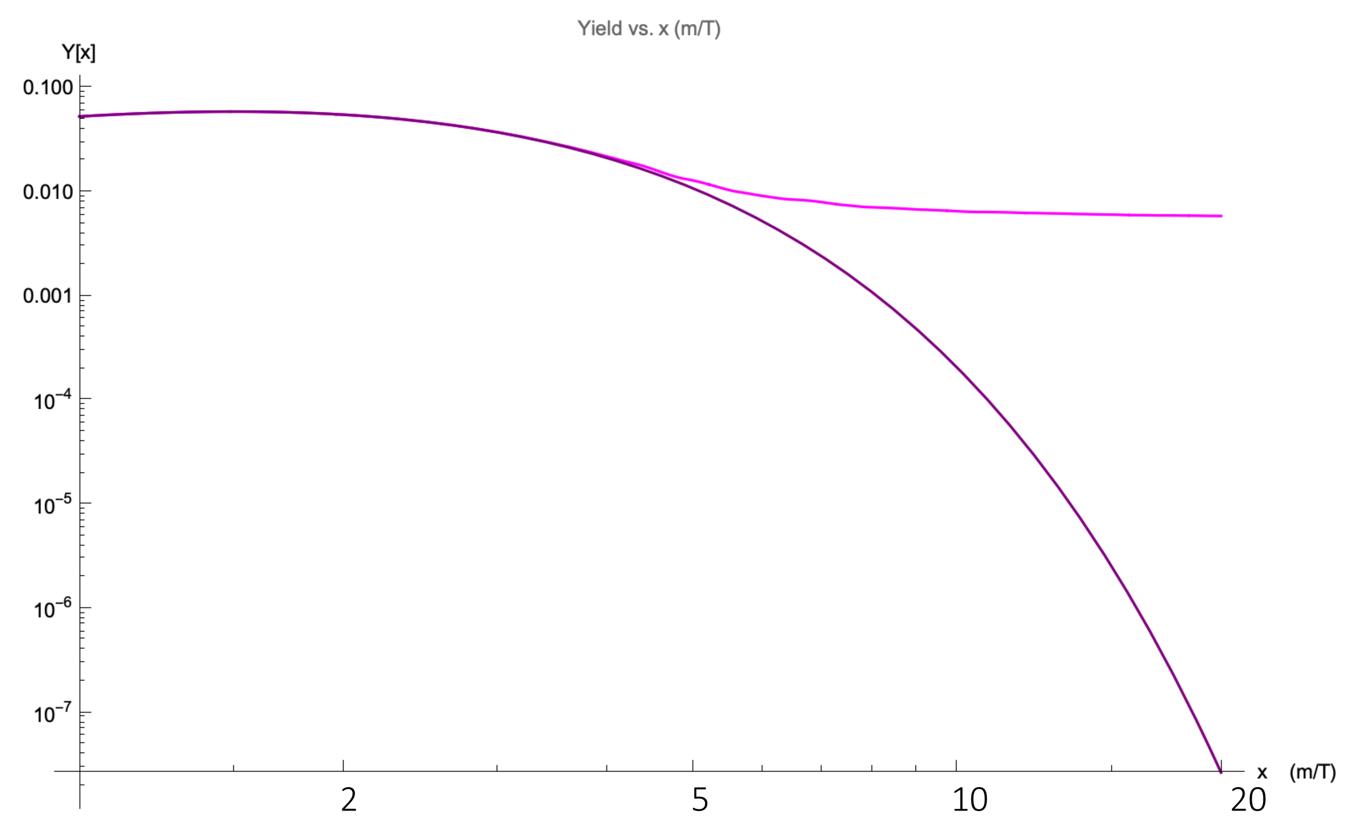
$$Y = \frac{n}{s} \qquad Y_{eq} = \frac{n_{eq}}{s}$$

Which then results in the following differential equation:

$$\frac{\mathrm{d}Y}{\mathrm{d}x} = \frac{-x}{H(m)s}(Y^3 - Y^2Y_{eq})\frac{1}{Y_{eq}^3}\langle\sigma v^2\rangle_{3\to 2} \qquad (4)$$

Results

Finally, combining our cross-section results from (3) and numerically solving (4) we obtain the following graph:



Where the magenta line represents the freeze out of dark matter, and the purple line displays the behavior of a particle that doesn't freeze out and instead continues to annihilate until it goes extinct.

References

Hochberg, Yonit, et al. "The Simp Miracle." The SIMP Miracle, 28 Oct. 2014, https://arxiv.org/pdf/1402.5143.pdf.

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