Role of Helium in Capture of Dark Matter by Population III Stars

Caleb Levy, Cosmin Ilie
Colgate University, Department of Physics and Astronomy
Summer Research 2020

Introduction

Dark matter (DM) is perhaps one of the most perplexing puzzles facing Physics today. Its existence is justified by a plethora of observational evidence from sub-galactic scales (rotation curves) to cosmological scales (cosmic microwave background, pictured below).

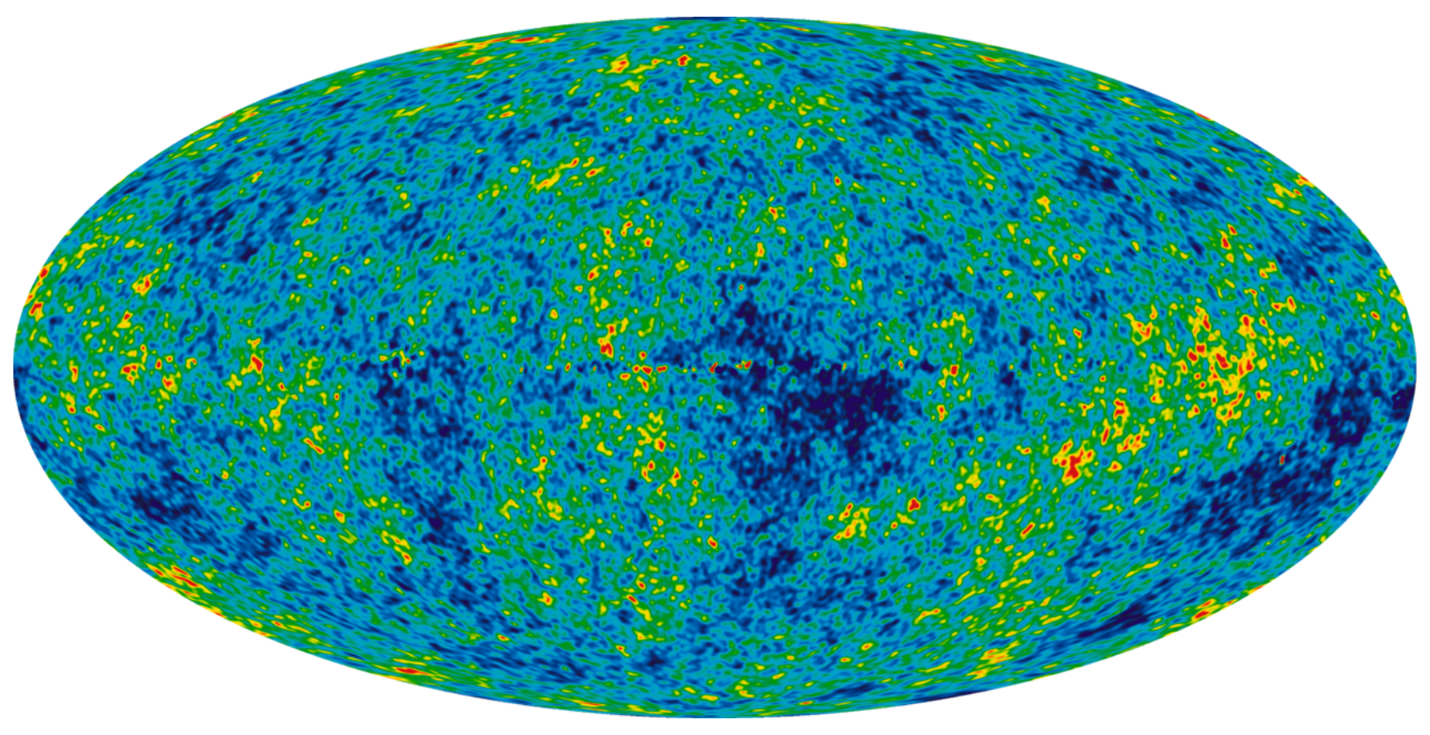


Image Displaying Cosmic Microwave Background (CMB)

Over the summer, I conducted research on the processes of dark matter capture and annihilation by stellar objects. **Capture** is the process of trapping DM particles in a star through collisions with stellar components. **Annihilation** is the process through which captured DM particles are converted into a useful source of energy for the star.

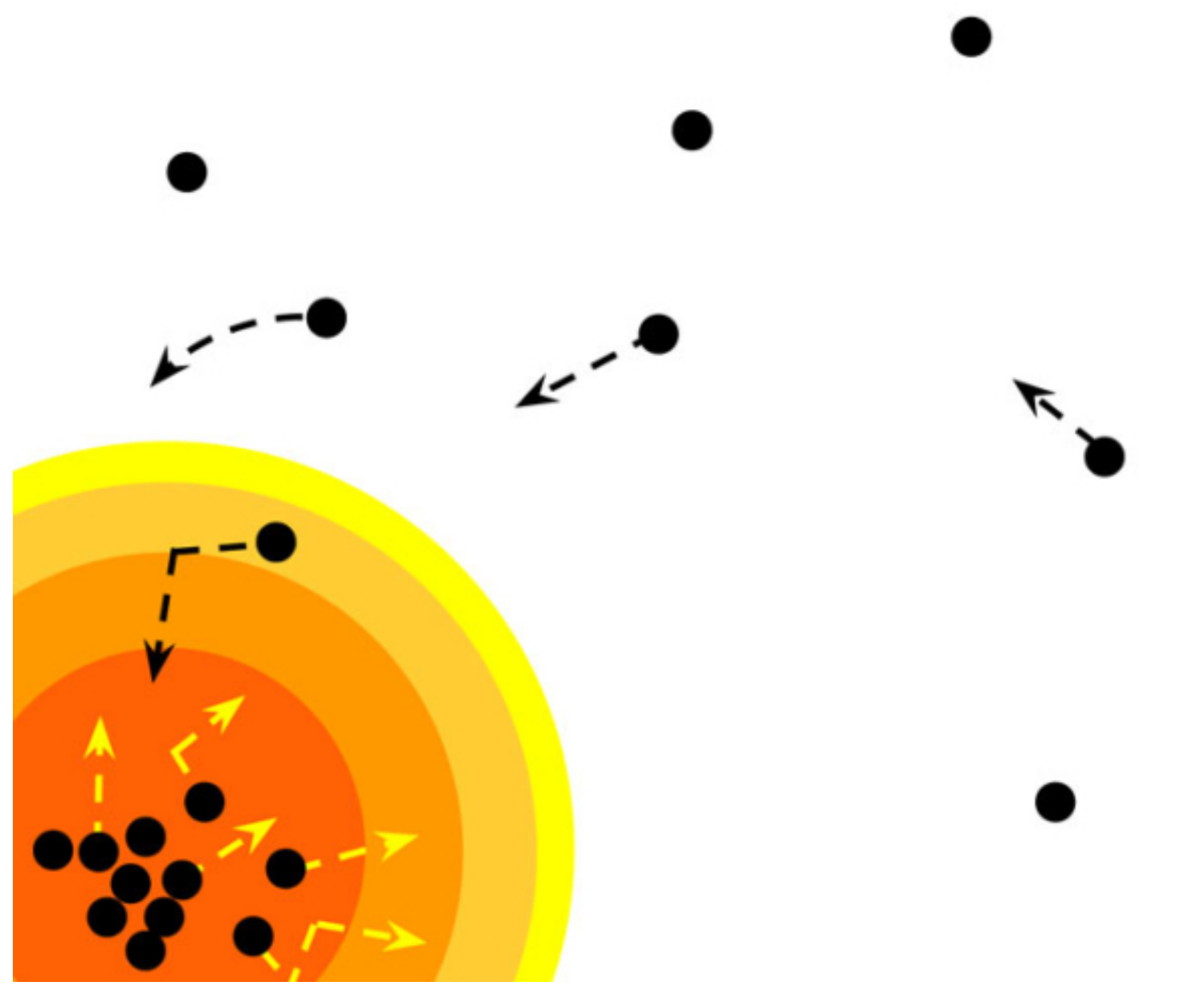


Image Illustrating the Idea of DM Capture

My focus was on extending the single-component, multi-scatter capture formalism to a multi-component, multi-scatter formalism in order to account for the effects of Helium on the capture process of population III stars.

Population III stars are the first stars to form in the universe and are yet to be observed. Our research seeks to place bounds on the maximum mass population III stars can have given an additional source of luminosity from DM annihilation. We also suggest a method for placing bounds on DM parameter space if these stars are to be observed.

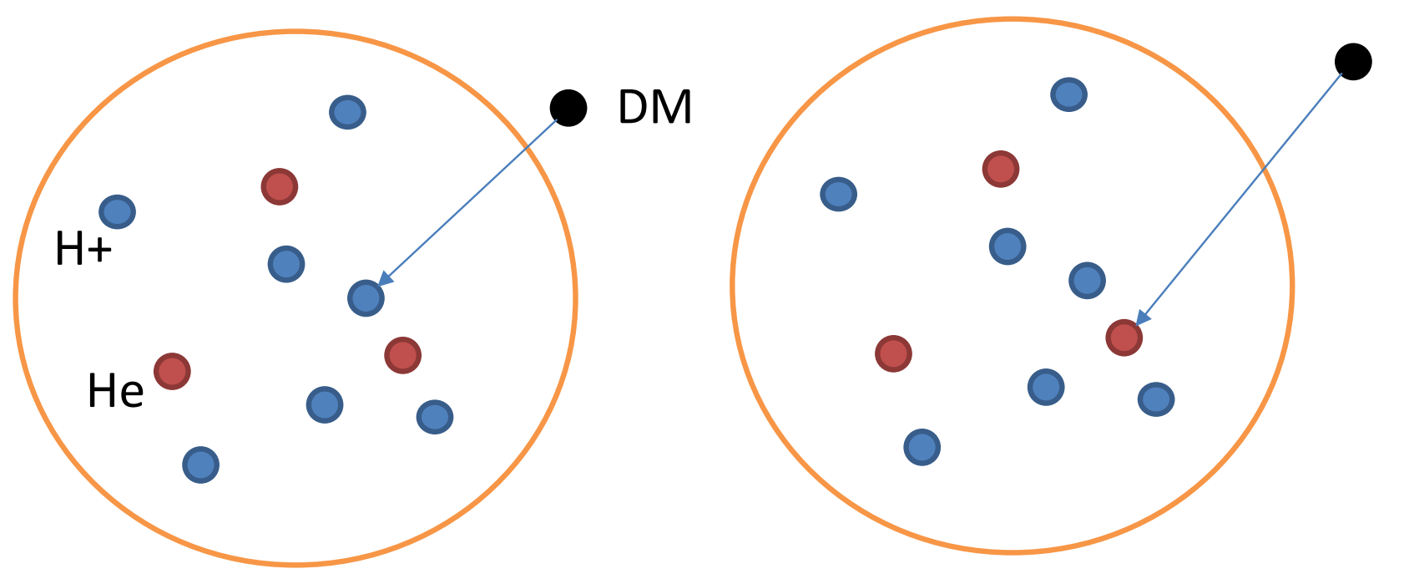
Multi-component, Multi-scattering Formalism

$$C_N = \sum_{k=0}^{N} \frac{\pi}{3} R^2 p_k(\tau_{He}) p_m(\tau_H) \frac{\sqrt{6} n_\chi}{\sqrt{\pi}\bar{v}} \left((2\bar{v}^2 + 3v_{esc}^2) - (2\bar{v}^2 + 3v_{N,k}^2) \exp\left(-\frac{3(v_{N,k}^2 - v_{esc}^2)}{2\bar{v}^2} \right) \right)$$

$$C_{tot}(m_\chi) = \sum_{N=1}^{\infty} C_N$$

The multi-component, multi-scattering formalism for DM capture by stellar objects allows use to calculate the number of particles that become trapped in the star every second. Some key features of this formalism are:

- ❑ The total capture rate is an infinite sum of '**partial**' capture rates, where the partial capture rate is the DM particles captured every second after exactly N scatters.
- ❑ The partial capture rates are a sum over all **N + 1** possible combinations of collisions that can occur in a two-component star, given a DM particle collides N times.



This example demonstrates a simple scenario where a DM particle collides N = 1 times and hence there are N + 1 = 2 possible collisions satisfying that condition, each with its own unique capture rate.

Enhanced Dark Matter Capture

We find that 25% helium pop. III stars have higher DM capture rates across all stellar and DM masses relative to pure-hydrogen stars. This can be attributed to a greater average number of scatters and a greater loss of energy per scatter due to the helium in the star.

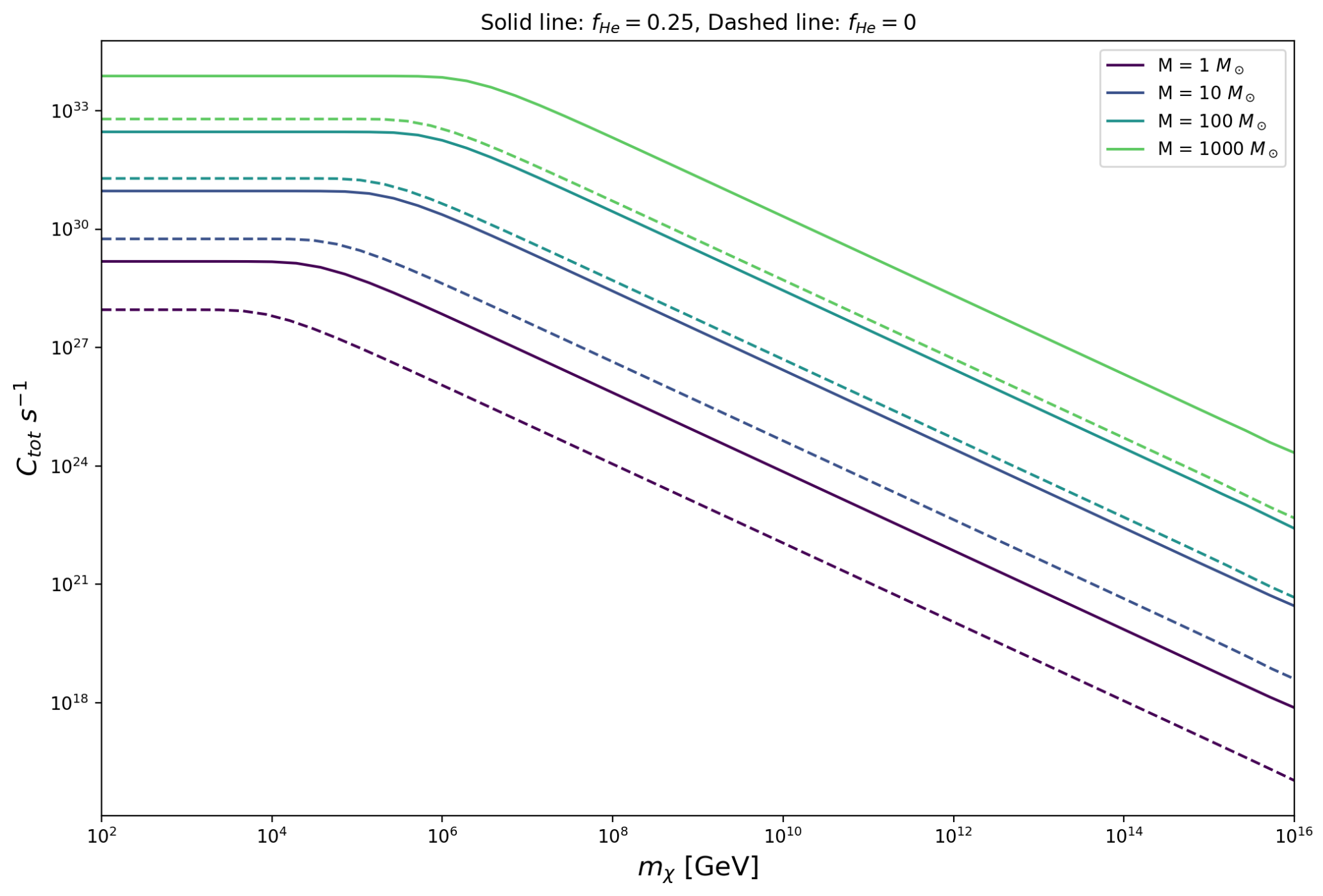
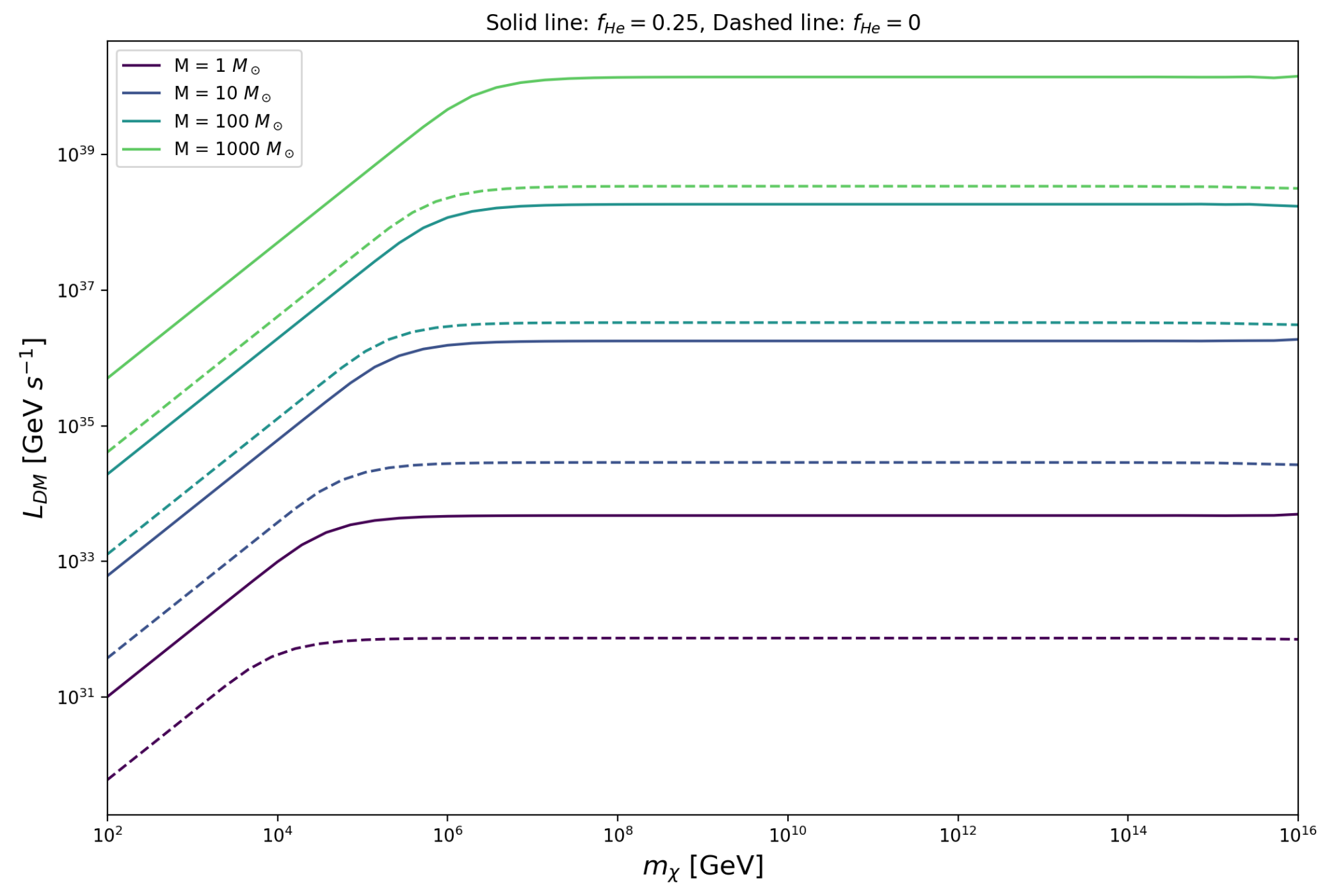


Figure Showing Enhanced Capture Rate, (f = mass fraction of helium)

Enhanced Dark Matter Luminosity

We can quantify the effect of capture and annihilation on pop. III stars by examining the additional luminosity provided by these processes. The following equation describes the DM luminosity as ultimately a function of the capture rate and mass of dark matter after the processes of annihilation and capture reach equilibrium.

$$L_{DM} = f\Gamma_A 2m_\chi = fCm_\chi$$



The enhancement of the capture rate ultimately leads to a stronger source of luminosity from DM for pop III stars made of ~25% Helium relative to pure-hydrogen stars. In either case, the effect of this additional source of luminosity is that pop III stars have a **maximum mass** beyond which they are unable to maintain hydrostatic equilibrium.

Helium makes this maximum mass **lower**.

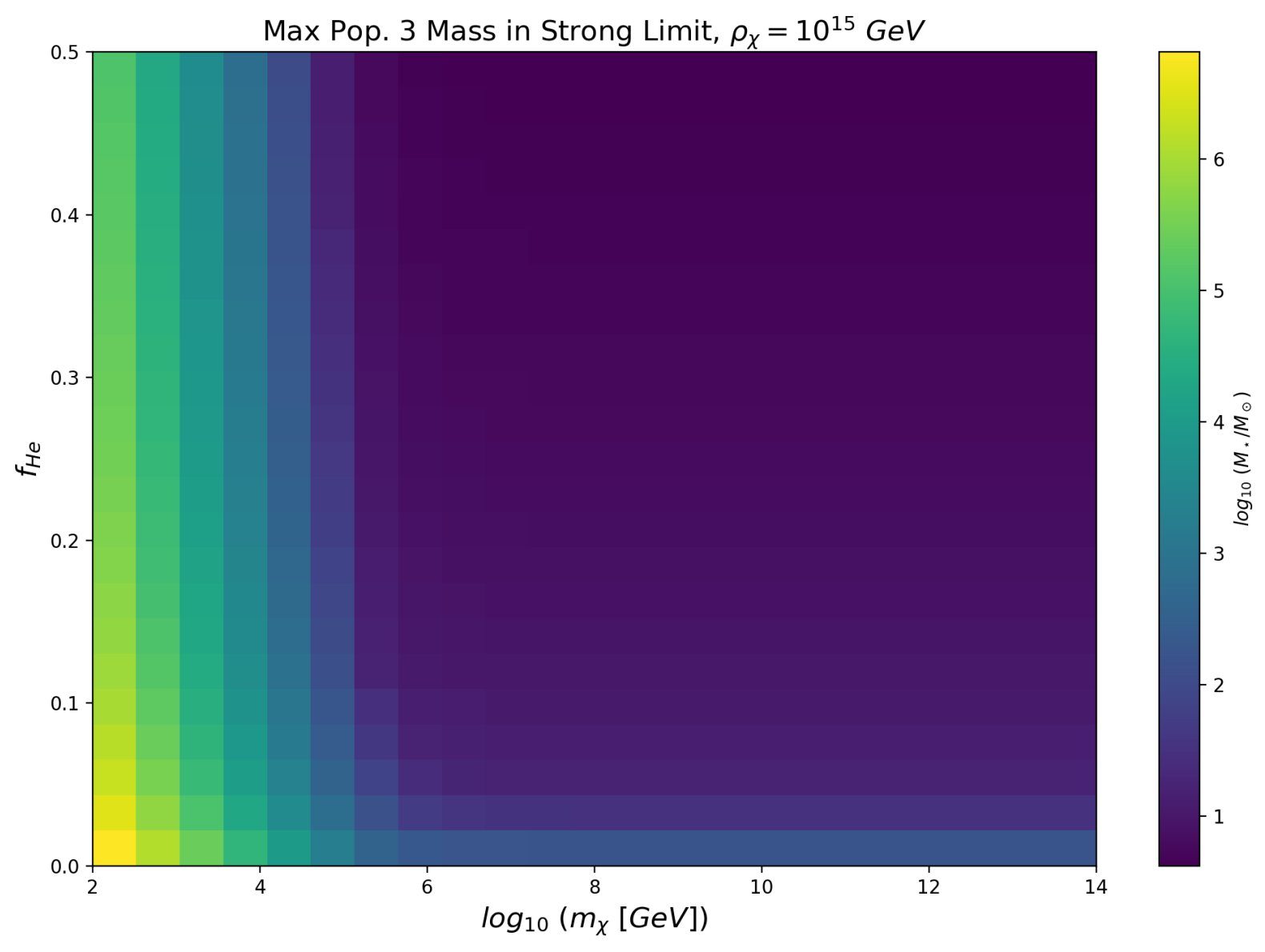
Figure Showing Enhanced Luminosity, (f = mass fraction of helium)

Tighter Pop III and DM Parameter Bounds

The maximum luminosity a star of a given mass can have is known as the **Eddington luminosity**. Stars are unable to shine above this luminosity and maintain hydrostatic equilibrium. Using this fact, we can find the maximum mass a pop III star can have assuming it is Eddington limited.

$$L_{Edd}(M_{max}) = L_{nuc}(M_{max}) + L_{DM}(M_{max})$$
$$L_{Edd}(M_{max}) = L_{DM}(M_{max})$$

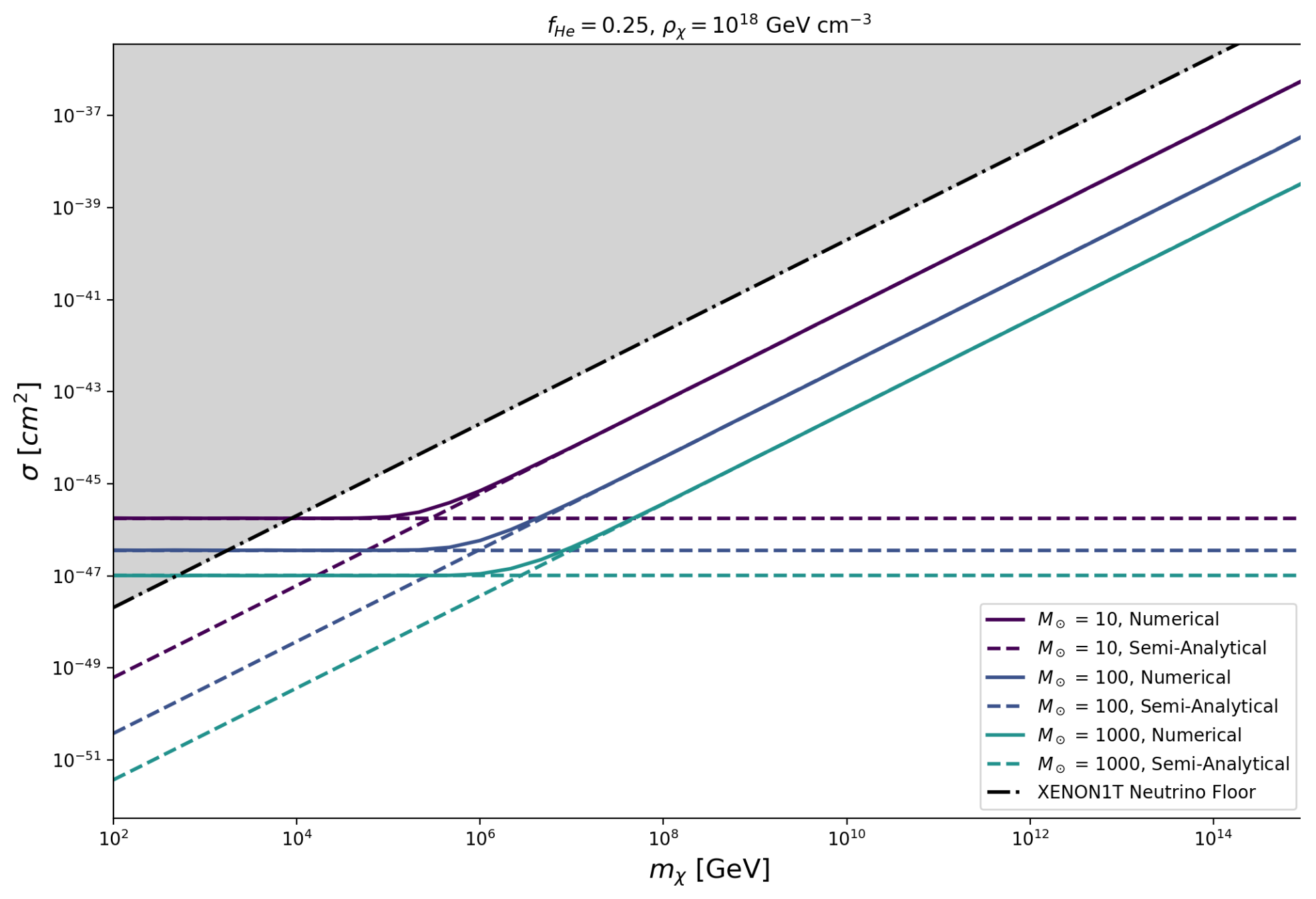
We call the maximum mass resulting from DM luminosity and the star's nuclear luminosity the **strong limit**. The maximum mass resulting from only DM luminosity is referred to as the **weak limit**. The true maximum mass is likely much closer to the strong limit because nuclear luminosity is not negligible



The following plot demonstrates the effects of increasing the helium in the star on the maximum mass in the strong limit. The colors at each point in parameter space represent the maximum Pop III mass given by those specific parameters. Notice the darkening of the plot as we tend towards higher DM masses and higher fractions of helium in the star. This results from an increase in the DM luminosity, pushing the star closer to the Eddington limit.

Figure Showing Max Pop III Masses

Just as we can infer bounds on pop III stellar properties under assumptions of DM properties, observing pop III stars shining at the Eddington limit can allow us to place bounds on DM properties, namely the DM-nucleon cross section and DM mass parameter space. The following plot demonstrates this idea



One of the major takeaways here is the ability to constrain DM properties below the **neutrino floor**. The neutrino floor is a background of neutrino noise that DM experiments on earth will soon become sensitive to. Beyond this sensitivity, these experiments will be unable to discern DM signals from the background and thus lose constraining power. We provide a way to probe **below this neutrino floor** by detecting Eddington-limited pop III stars.

Figure Showing DM-nucleon cross-section and DM mass Parameter Space

Acknowledgements

I would first like to thank Professor Cosmin Ilie for mentoring me over the summer and being there to field my many questions and concerns, physics-related or not. I would also like to thank everybody who worked on the DM research team this summer, namely Jillian, Federico, Jacob and Saiyang, for always being there to talk about and work through the issues inherent to research.

References

J. Bramante, A. Delgado and A. Martin, *Multiscatter stellar capture of dark matter*, Phys. Rev. D **96** (2017) 063002 [`1703.04043`].

C. Ilie and S. Zhang, *Multiscatter capture of superheavy dark matter by Pop. III stars*, *JCAP* **12** (2019) 051 [`1908.02700`].

K. Freese, D. Spolyar and A. Aguirre, *Dark Matter Capture in the first star: a Power source and a limit on Stellar Mass*, *JCAP* **0811** (2008) 014 [`0802.1724`].