The Effect of Stellar Velocity on Dark Matter Capture Rates of Pop III Stars

Jillian Paulin, Cosmin Ilie
Colgate University Department of Physics & Astronomy
Summer Research 2020

Background

- Population III stars were the first stars to form in the universe.
- They likely formed near dense regions of dark matter, called dark matter halos, out of hydrogen and helium. Pop III stars have low metallicity and are large in size.
- If Population III stars capture dark matter, it has been previously shown that this may increase their luminosity closer to the Eddington limit
- Pop III stars capture dark matter when the velocity of a dark matter particle falls below the escape velocity of the star.

Capture Rates: Single- and Multi-scatter Formalisms

- When dark matter is light in mass, it only needs to collide with a nucleon once (single scatter). The rate is found using the equation below ([1]):

$$\frac{dC}{dV} = \left(\frac{6}{\pi}\right)^{\frac{1}{2}} \sigma n n_w \bar{v} \frac{v_{esc}^2}{\bar{v}^2}\left[1 - \frac{1-\exp(-A^2)}{A^2}\right]$$

- In this regime, the total capture rate is found by integrating over the volume of the star.
- When dark matter is heavier, it loses less energy per collision, needing multiple scatters to be successfully captured by the star. The rate after N collisions is ([2, 3]):

$$C_N = \pi R^2 p_N(\tau) \int_0^\infty f(u) \frac{du}{u} w^2 g_N(w)$$

- For a star at rest with respect to the dark matter halo, we assume a Maxwell-Boltzmann distribution, and the multi-scatter capture rate equation is as follows, where v_N is the velocity after N scatters ([2, 4]):

$$C_N = \frac{1}{3}\pi R^2 p_N(\tau) \frac{\sqrt{6} n_\chi}{\sqrt{\pi}\bar{v}}\left((2\bar{v}^2 + 3v_{esc}^2) - (2\bar{v}^2 + 3v_N^2)\exp\left(-\frac{3(v_N^2 - v_{esc}^2)}{2\bar{v}^2}\right)\right)$$

- The total capture rate in this regime is obtained by adding the capture rates after N scatters.

Velocity Distributions

- The dark matter capture rate of Pop III stars typically assumes a Maxwell-Boltzmann distribution of the particles in the star and halo ([1, 5]):

$$f_0(u) = n_w \frac{4}{\pi^{1/2}} x^2 \exp(-x^2)$$

- If a star is moving relative to the dark matter halo, this distribution must be modified, or boosted ([1, 2]):

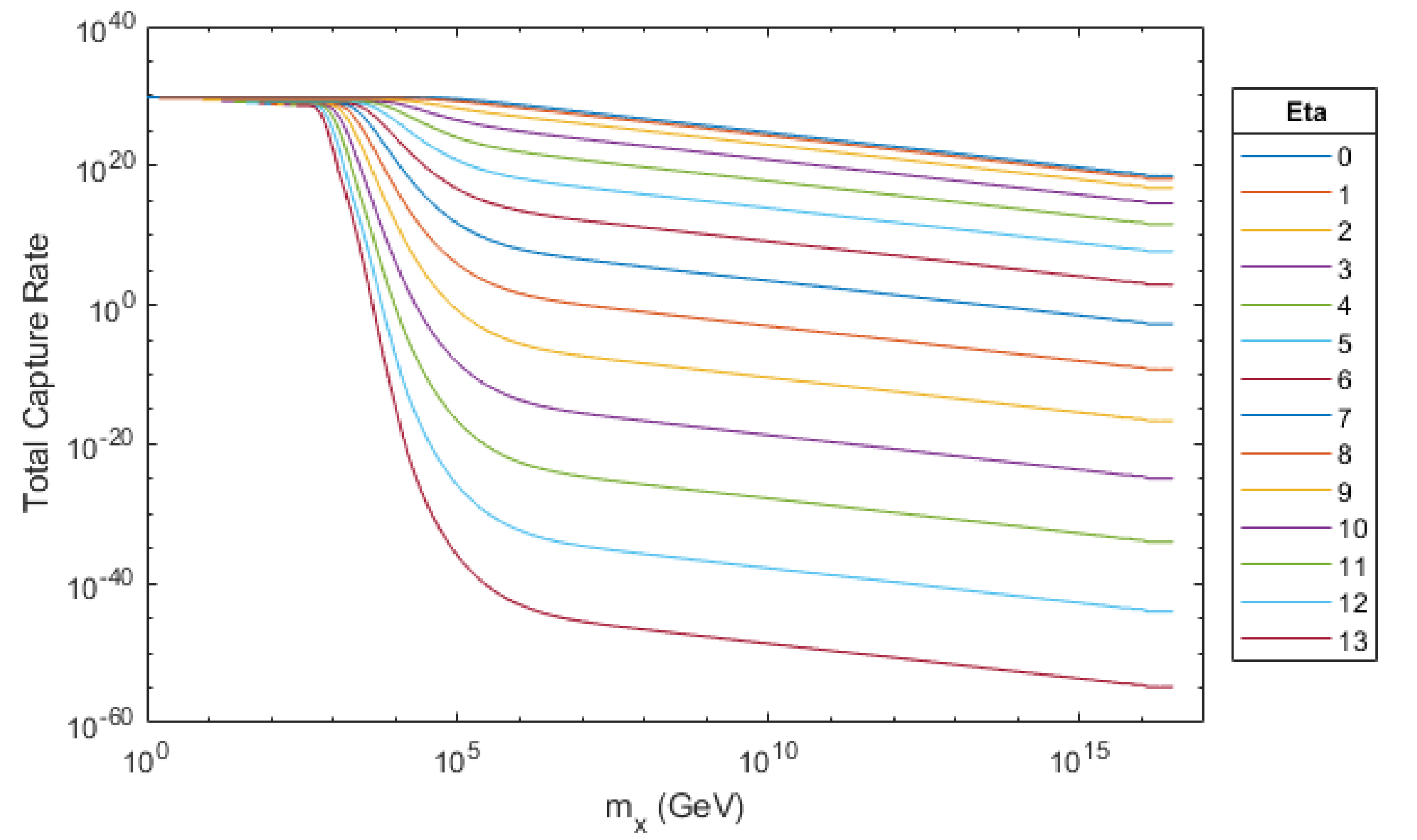
$$f_\eta(u) = f_0(u)\exp(-\eta^2)\frac{\sinh 2x\eta}{2x\eta}$$

- η is related to the velocity of the star relative to the dark matter halo by $\eta^2 = \frac{3\tilde{v}^2}{2\bar{v}^2}$, and $\tilde{v}$ is the velocity of the star relative to the dark matter halo [5].
- To account for this relative motion while using the previously-discussed formalism, one must integrate over this boosted distribution instead of the Maxwell-Boltzmann distribution.

Results

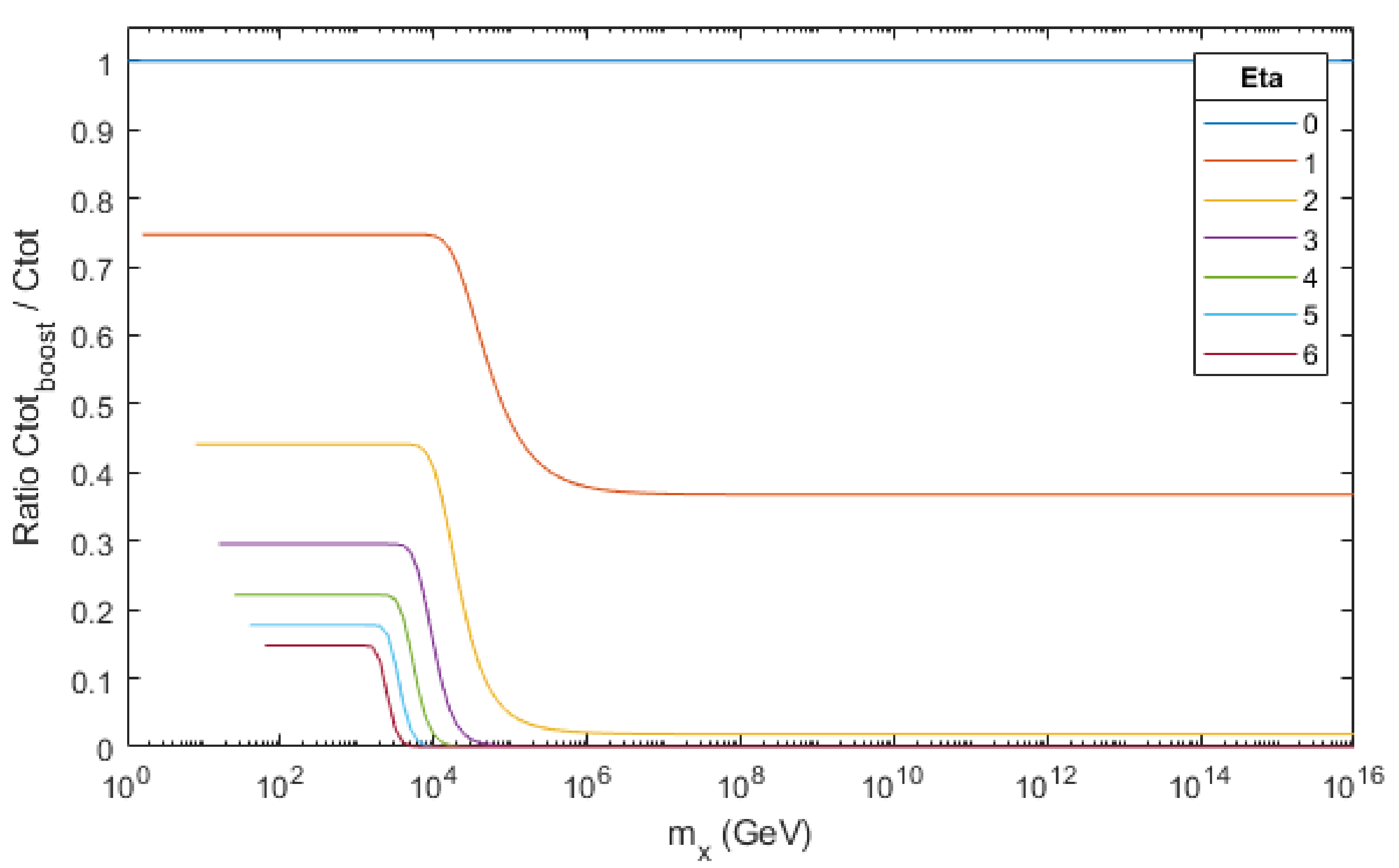
- Stellar motion has an extreme effect on the total dark matter capture rate. See Figure 1.
- Increasing the value of η by ~1 order of magnitude produces a reduction in the total capture rate of a Population III star by over 40 orders of magnitude when the mass of dark matter is high
- Parameters used: 12 solar mass, 1.43 solar radius Population III star with a dark matter density of 10^9 GeV/cm^3 and $\bar{v}$ = 10 km/s.

Figure 1



- Figure 2 represents the ratio of the capture rate obtained using a boosted distribution and a non-boosted Maxwell-Boltzmann distribution (η=0).
- The boosted result produces an almost constant multiple of the Maxwell-Boltzmann result in both the single- and multi-scatter regimes.
- By η=6, the ratio is already repressed almost to 0 for high dark matter masses.

Figure 2



Conclusion

- Stellar velocity significantly decreases the capture rate of dark matter in Pop III stars for high dark matter masses(~10^6 GeV).
- This suppression in capture rate tends to be of a constant value in both low and high mass regimes of dark matter.
- This study may be extended by considering how the suppression is dependent on the value of η.

References

[1] A. Gould, *Resonant enhancements in weakly interacting massive particle capture by the Earth*, ApJ 321 (1987) 571
[2] J. Bramante, A. Delgado and A. Martin, *Multiscatter stellar capture of dark matter*, Phys. Rev. D 96, 063002 (2017), arXiv:1703.04043 [hep-ph]
[3] C. Ilie and S. Zhang, *Multiscatter capture of superheavy dark matter by Pop III stars*, JCAP 12, 051 (2019), arXiv:1908.02700 [astro-ph.CO]
[4] C. Ilie, J. Pilawa and S. Zhang, *Comment on "Multiscatter stellar capture of dark matter"*, arXiv:2005.05946 [astro-ph.CO] (2020)
[5] B. Dasgupta, A. Gupta and A. Ray, *Dark matter capture in celestial objects: improved treatment of multiple scattering and updated constraints from white dwarfs*, JCAP 08 (2019) 018

Acknowledgements

I would like to thank Professor Cosmin Ilie for all of his guidance and support throughout this project. I would also like to thank the other members of our research group for their thoughtful discussions and advice: Caleb Levy, Federico Aguilera, Saiyang Zhang, and Jacob Pilawa.