Co-Decaying Dark Matter: Formation of Sub-Structure and Primordial Black Holes

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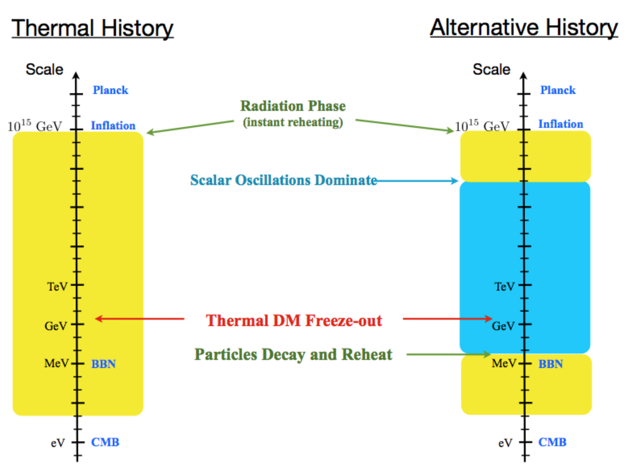
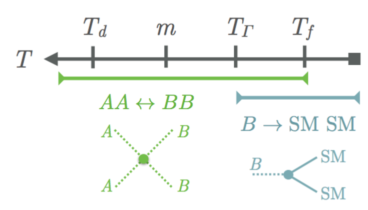
Introduction

- Dark Matter has continued to elude experiments attempting to directly and indirectly its particulate nature
- Co-Decaying Dark Matter explains the lack of signal in a novel way while also accounting for the observed Dark Matter abundance
- One consequence of this freeze-out scenario is the existence of an Early Matter Dominated Era, which can lead to the production of sub-structure and enhanced production Primordial Black Holes



Co-Decaying DM

- There is a dark sector that decoupled from the visible sector prior to becoming non-relativistic
- The LDSP decays to the SM out of equilibrium
- There is at least one additional particle in the dark sector that is degenerate and in thermal and chemical equilibrium with the LDSP
- The additional particles will play the role of dark matter



- $AA \leftrightarrow BB$ annihilations are suppressed by their velocity, $x^{-1} = T/m$:
$$\langle \sigma v \rangle = \frac{4}{\sqrt{\pi}} \frac{\sigma}{\sqrt{x'}}$$
- At freeze-out, $n_f \langle \sigma v \rangle \cong H_f$. The predicted relic density is then:
$$\frac{\Omega_A}{\Omega_{DM}} = \left(\frac{10^{-36}}{\sigma/\mathrm{cm}^2}\right)\left(\frac{m}{\mathrm{GeV}}\right)\left(\frac{10^{-18}}{\Gamma/m}\right)$$

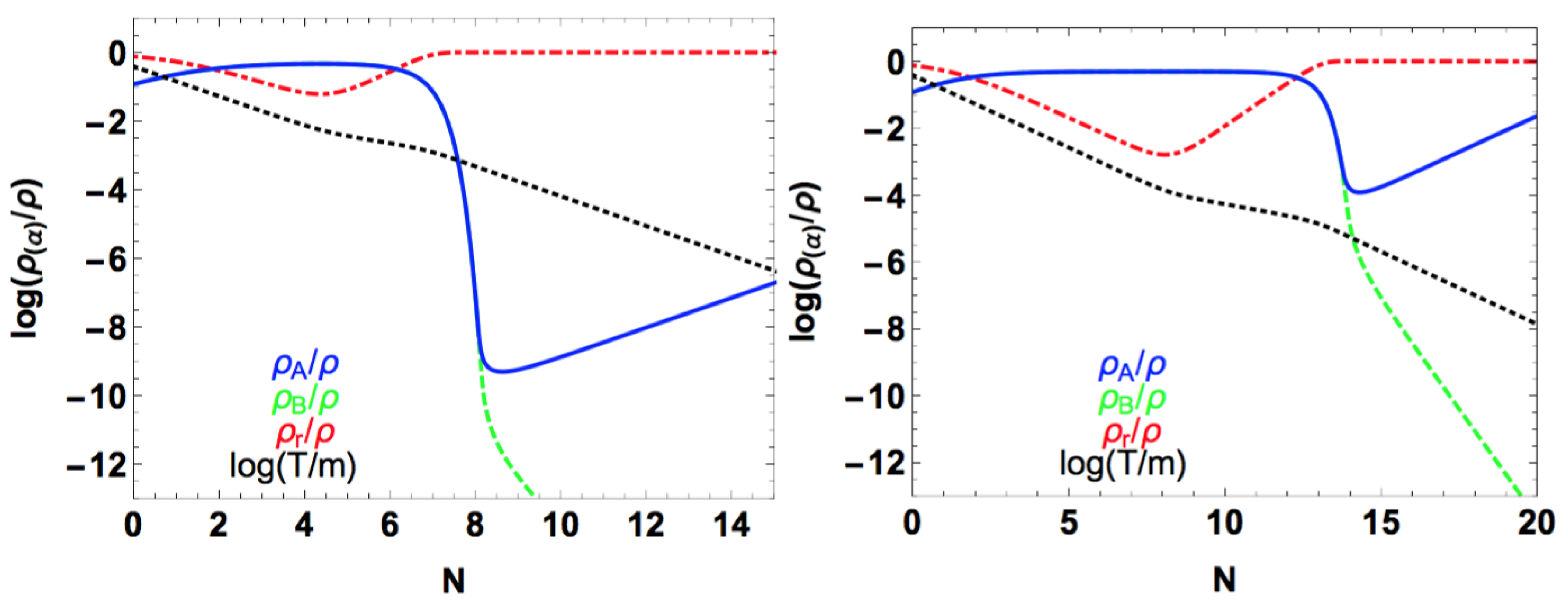


Figure 1: Examples of the background evolution of a universe with CDDM dynamics. Both have $m = 10.5$TeV and $\sigma = 10^{-30}\mathrm{cm}^2$. Left: $\Gamma/H_0 \cong 9 \times 10^{-5}$ Right: $\Gamma/H_0 \cong 9 \times 10^{-9}$

Cosmological Perturbations

We model the DS and SM as three, interacting perfect fluids.
Longitudinal Gauge and e-folds are easiest to work with (in Fourier space).
We numerically solved the following equations:

$$\delta_A' + \frac{\theta_A}{aH} - 3\Phi' = -\frac{\langle\sigma v\rangle}{mH\rho_A}\left[\rho_A^2(\Phi+\delta_A) - \rho_B^2(\Phi + 2\delta_B - \delta_A)\right]$$
$$\delta_B' + \frac{\theta_B}{aH} - 3\Phi' = -\frac{\Gamma}{H}\Phi + \frac{\langle\sigma v\rangle}{mH\rho_B}\left[\rho_A^2(\Phi+2\delta_A-\delta_B) - \rho_B^2(\Phi+\delta_B)\right]$$
$$\delta_r' + \frac{4}{3}\frac{\theta_r}{aH} - 4\Phi' = \frac{\Gamma}{H}\frac{\rho_B}{\rho_r}\left[\Phi + \delta_B - \delta_r\right]$$
$$\theta_A' + \theta_A - \frac{k^2}{aH}\Phi = \frac{\langle\sigma v\rangle}{mH\rho_A}\left[\rho_B^2(\theta_B - \theta_A)\right]$$
$$\theta_B' + \theta_B - \frac{k^2}{aH}\Phi = \frac{\langle\sigma v\rangle}{mH\rho_B}\left[\rho_A^2(\theta_A - \theta_B)\right]$$
$$\theta_r' - \frac{k^2}{aH}\left(\frac{\delta_r}{4} + \Phi\right) = \frac{\Gamma}{H}\frac{\rho_B}{\rho_r}\left[\frac{3}{4}\theta_B - \theta_r\right]$$

The novel feature of CDDM concerns the effects of free-streaming and wash-out due to decoupling. The ratios of the relevant scales

$$\frac{k_{kd}}{k_{RH}} \sim \left(\frac{T_{kd}}{T_{RH}}\right)^{8/3} \gg \mathcal{O}(10) \quad \frac{k_{fs}}{k_{RH}} \sim \left(\frac{m\xi}{T_{RH}}\right)^{2/3} > \mathcal{O}(1)$$

allows for the survival of the structures formed in the EMDE.

Results: Perturbation Growth

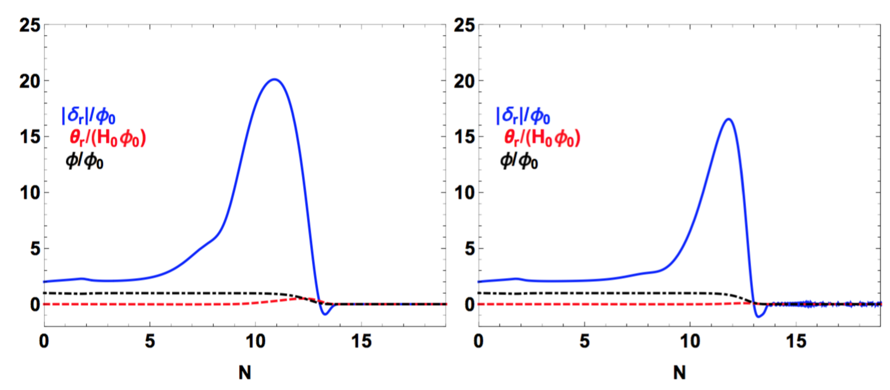


Figure 2: Numerical results of evolution of radiation perturbation fluid

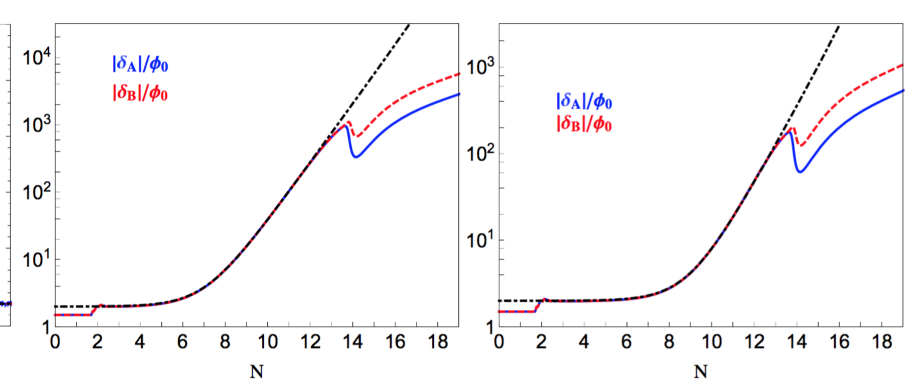


Figure 3: Numerical results of evolution of DM perturbation fluid

Primordial Black Holes (PBHs)

- PBHs form in the early universe from the collapse of overdense regions beyond their Schwarzschild radius.
- In a matter dominated phase, where pressure is absent, it is easier to form PBHs because perturbations can grow on all scales within the horizon. Mass fraction of the universe in form of PBHs
$$\beta \sim \left(\frac{\delta M}{M}\right)^{13/2}$$
- We can use the model dependent predictions for PBH formation to constrain the model parameters, i.e. spectral index, DM mass, etc.

Results: PBH Mass Fraction

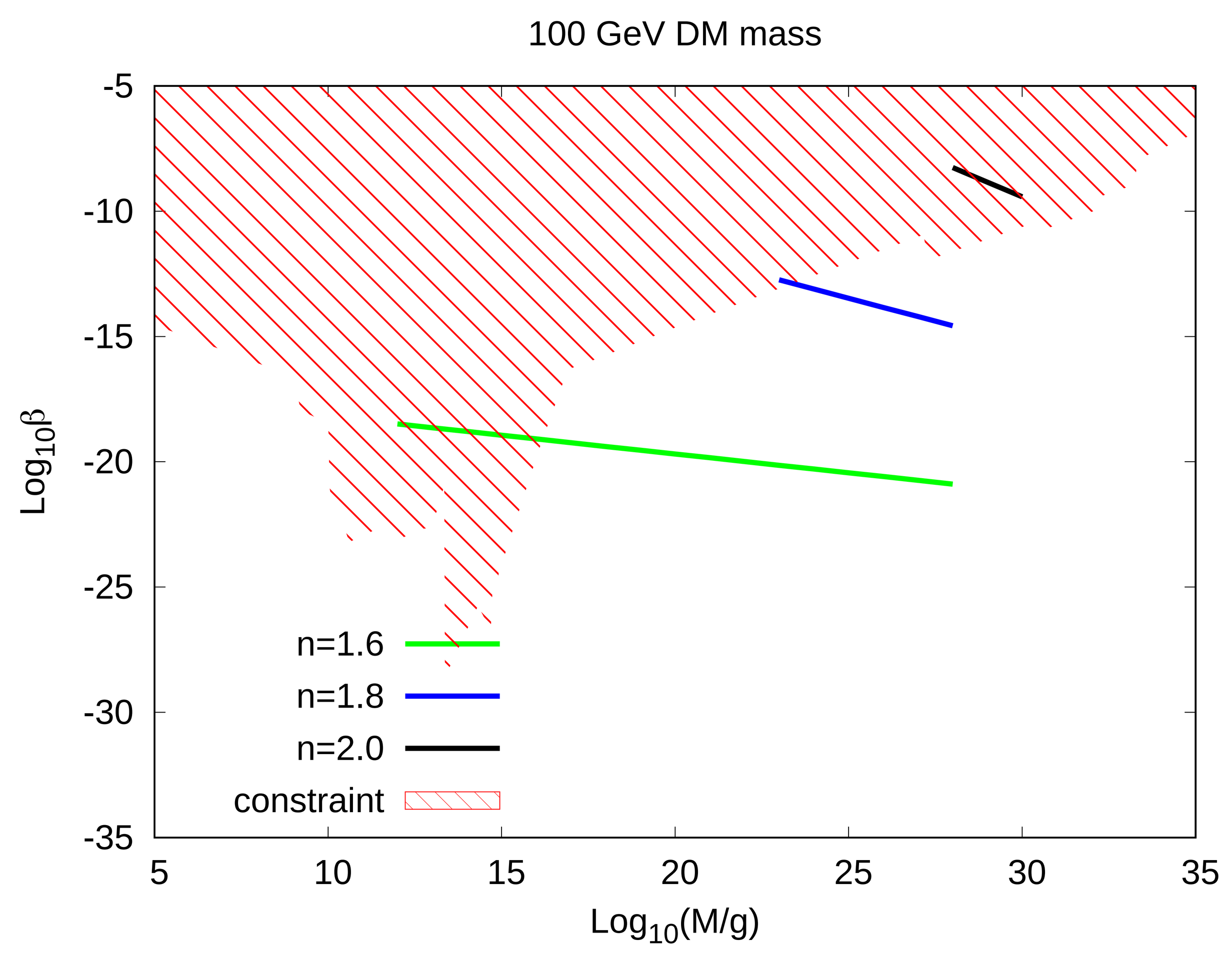


Figure 4: Mass fraction of PBHs

Conclusion

- CDDM provides a novel explanation for the observed DM relic abundance and the lack of an experimental signal
- Due to the details, this scenario offers a compelling environment for the growth of structure and PBHs
- We plan to continue work to characterize the signals from DM micro-halos that could be seen by FERMI and its like in the coming years

References

[1] J. A. Dror, E. Kuflik, B. Melcher, and S. Watson. Concentrated Dark Matter: Enhanced Small-scale Structure from Co-Decaying Dark Matter. 2017.

[2] J. A. Dror, E. Kuflik, and W. H. Ng. Codecaying Dark Matter. *Phys. Rev. Lett.*, 117(21):211801, 2016.

[3] J. Fan, O. Ozsoy, and S. Watson. Nonthermal histories and implications for structure formation. *Phys. Rev.*, D90(4):043536, 2014.

[4] J. Georg, G. Sengor, and S. Watson. Nonthermal WIMPs and primordial black holes. *Phys. Rev.*, D93(12):123523, 2016.

[5] J. Georg and S. Watson. A Preferred Mass Range for Primordial Black Hole Formation and Black Holes as Dark Matter Revisited. *JHEP*, 09:138, 2017. [JHEP09,138(2017)].

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