Asymmetric Dark Matter from Semi-annihilation

Deep Ghosh

IACS, Kolkata, India

*Email: matrideb1@gmail.com

1. Asymmetric Dark Matter (ADM)

The present-day DM density is made of either only DM particle or antiparticle or a mixture of both.

The relic density of DM : $\Omega_\chi = \frac{m_\chi}{\rho_c}(n^0_\chi + n^0_{\chi^\dagger}) = \frac{m_\chi}{\rho_c}\,\eta\, n^0_{\chi^\dagger}$

The relative abundance parameter : $\eta = \frac{n^0_\chi + n^0_{\chi^\dagger}}{n^0_{\chi^\dagger}}$

- Completely Asymmetric : No particle, $\eta = 1$
- Partially Asymmetric : The number density of particle and anti-particle are unequal, but both non-zero. $1 < \eta < 2$
- Symmetric : The number density of particle and anti-particle are equal. $\eta = 2$

2. Intitial Condition

Question : What type of processes can produce (partially or completely) ADM from a symmetric intial condition in the early universe ?

$$n_\chi(T) = n_{\chi^\dagger}(T) \underset{T_0<T}{\Longrightarrow} n_\chi(T_0) \neq n_{\chi^\dagger}(T_0)$$

- We shall assume that the DM and SM sectors reach a common temperature ($T_\chi = T_{SM}$) through elastic/inelastic scatterings.
- The thermal densities of DM may be too high even after dilution due to the expansion of the universe.
- Therefore, some number-changing reactions become necessary to achieve a relic density of DM consistent with observations.

3. Guideline of producing ADM

We need

- Number changing process : $\Delta(n_\chi + n_{\chi^\dagger}) \neq 0$
- DM number violating process : $\Delta(n_\chi - n_{\chi^\dagger}) \neq 0$

Possible Mechanisms

1. Set the required DM density by eliminating the symmetric part ($n_\chi + n_{\chi^\dagger}$), then convert particle to anti-particle or vice-versa, e.g.
$\chi + \chi^\dagger \to SM$; $\chi \underset{\text{process}}{\overset{\text{conversion}}{\Longrightarrow}} \chi^\dagger$, WIMP annihilation + Conversion
2. First produce the difference between particle-antiparticle yields, then eliminate the symmetric part, e.g.
$\phi \to \chi + \chi$, $\chi^\dagger + \chi^\dagger$; $\chi + \chi^\dagger \to SM$, Decay + WIMP annihilation

Observation : Two distinct processes required.

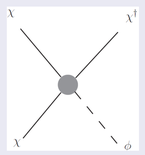
Q. Can we achieve it with just one process ?

A : Yes, we can, with Semi-annihilation!!

4. Semi-annihilation

- $\Delta(n_\chi + n_{\chi^\dagger}) = -1$
- $\Delta(n_\chi - n_{\chi^\dagger}) = -3$

Both conditions achieved in one process !!



For $m_\chi > m_\phi$, at $T < m_\chi$ $\chi\chi \to \chi^\dagger\phi$ happens

χ : DM candidate, complex scalar singlet with $\mathcal{Z}_3$ charge.

ϕ : Real scalar singlet, mixes with or decays to SM states

Sakharov Conditions

- Dark Number Violation : satisfied
- C and CP violation : depends on the specific model
- Out-of-equilibrium : Freeze-out of Semi-annihihilation

Asymmetry parameter

$$\epsilon = \frac{|M|^2_{\chi\chi\to\chi^\dagger\phi} - |M|^2_{\chi^\dagger\chi^\dagger\to\chi\phi}}{|M|^2_{\chi\chi\to\chi^\dagger\phi} + |M|^2_{\chi^\dagger\chi^\dagger\to\chi\phi}} \propto \mathcal{M}^*_{tree}\,\mathcal{M}_{loop}$$

$$\Omega_\chi = \mathcal{F}(m_\chi, \langle\sigma v\rangle_S, \epsilon)$$

$\langle\sigma v\rangle_S$: Semi-annihilation cross-section

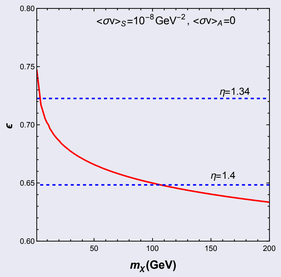
5. Model-Independent Analysis

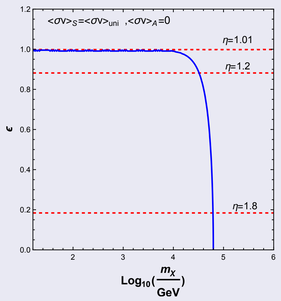
For constant semi-annihilation cross-section ($\langle\sigma v\rangle_S$)

- Higher is the CP-violation (ϵ), higher the difference between DM and anti-DM, $\eta \to 1$.
- Additionally, larger is the ϵ, the frozen number-density of DM is larger; hence the DM mass is smaller to achieve the observed relic.

Upper bound on DM mass

- $\langle\sigma v\rangle_S$ is bounded from S-matrix Unitarity, translated into the bound on mass
$\langle\sigma v\rangle_{\text{uni}} = (4\pi/m^2_\chi)(x_F/\pi)^{1/2}$
- For $\epsilon = 0$, m_χ is 80 TeV. (Symmetric relic)
- $\epsilon \to 1$, m_χ is 15 GeV. (Asymmetric relic)
very strong bound!!



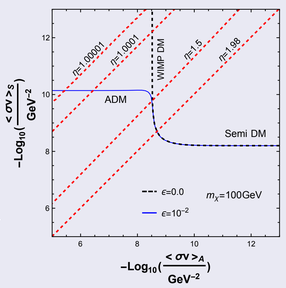


The solid contour in both the figures represents $\Omega_\chi h^2 = 0.12$

6. Semi ($\langle\sigma v\rangle_S$) + WIMP ($\langle\sigma v\rangle_A$)

Scenario with $\chi\chi \to \chi^\dagger\phi$ and $\chi\chi^\dagger \to \phi\phi$

- $\langle\sigma v\rangle_S > \langle\sigma v\rangle_A$, $\epsilon = 0$: Symmetric DM from Semi-annihilation only (Semi DM)
- $\langle\sigma v\rangle_S < \langle\sigma v\rangle_A$, $\epsilon = 0$: Symmetric DM from WIMP-annihilation only (WIMP DM)
- $\langle\sigma v\rangle_S < \langle\sigma v\rangle_A$, $\epsilon \neq 0$: Asymmetric DM from the interplay of Semi-WIMP annihilation (ADM)

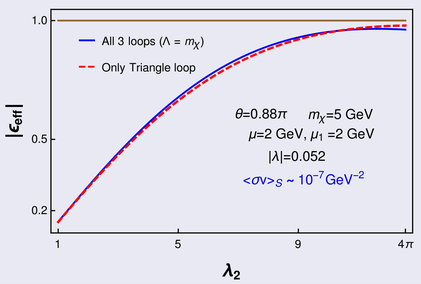


Takeaways : Two ways of producing ADM

Possibility I: With large CP-violation (ϵ), Semi-annihilation at one-loop is sufficient to create a complete DM asymmetry, and no subsequent number changing process is necessary.

Possibility II: Small asymmetry is generated via Semi-annihilation, and then a sufficiently large WIMP-annihilation removes the symmetric component.

7. Model Realizaton



- $\epsilon_{eff} = \dfrac{\langle\epsilon\sigma v\rangle_s}{\langle\sigma v\rangle_s} \sim \epsilon$
- $\mathcal{O}(1)$ CP violation can be realized through the Semi-annihilation process with dimensionless couplings taking perturbative values.
- Pair annihilation process is largely insignificant, as at the freeze out of Semi-annihilation symmetric part of DM becomes negligible for $\epsilon \sim \mathcal{O}(1)$

Low-energy effective Lagrangian (with $\mathbb{Z}_3$ symmetry)

$$-\mathcal{L} \supset \frac{1}{3!}\left(\mu\chi^3 + h.c\right) + \frac{1}{3!}\left(\lambda\chi^3\phi + h.c\right) + \frac{\lambda_1}{4}(\chi^\dagger\chi)^2 + \frac{\lambda_2}{2}\phi^2\left(\chi^\dagger\chi\right)$$
$$+\mu_1\phi\left(\chi^\dagger\chi\right) + \lambda_{H\chi}\left(\chi^\dagger\chi|H|^2\right) + \lambda_{H\phi}\left(\phi^2|H|^2\right) + \mu_{H\phi}\left(\phi|H|^2\right)$$

8. Conclusion

- Semi-annihilation with large CP-violation alone can make completely asymmetric DM.
- Large CP-violation can be realized within pertubative limits of relevant couplings in our model.

Reference : JHEP 08 (2020), 149, e-Print: 2004.07705 [hep-ph]

Co-authors : Avirup Ghosh, Satyanarayan Mukhopadhyay