Asymmetric Dark Matter From Semi-annihilation

Deep Ghosh

In collaboration with

Avirup Ghosh, S. Mukhopadhyay

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Thermal (particle) Dark matter

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1. $T_{DM} = T_{SM}, \mu_{DM} = 0$: WIMP, symmetric Lee, Weinberg, 1977
2. $T_{DM} = T_{SM}, \mu_{DM} \neq 0$: Thermal asymmetric DM Nussinov, 1985
3. $T_{DM} \neq T_{SM}, \mu_{DM} = 0$: HS DM, symmetric *Cheung et al. JHEP(2011)*
4. $T_{DM} \neq T_{SM}, \mu_{DM} \neq 0$: HS DM, asymmetric

The role of chemical potential

Consider a complex scalar DM, χ with mass m_χ whose relic density is set by freeze-out of $\chi + \chi^\dagger \to SM + SM$

$$\frac{dY_\chi}{dx} = -\frac{\lambda \langle \sigma v \rangle_{ann}}{x^2} \left(Y_\chi Y_{\chi^\dagger} - Y_\chi^{eq^2} \right), \;\; \lambda = 1.32\, M_{\rm P}\, m_\chi\, g_*^{1/2}$$

$$Y_\chi - Y_{\chi^\dagger} = C \quad \text{(related to } \mu_\chi\text{)}$$

Relic density in presence of chemical potential

$$\Omega_{\rm DM} = \frac{s_0}{\rho_c} m_\chi C \coth\left(\frac{C \lambda \langle \sigma v \rangle_{ann}}{2 x_d} \right)$$

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Symmetric limit : $C \to 0$, $\Omega_{\rm DM} = \frac{s_0}{\rho_c} m_\chi \frac{2 x_d}{\lambda \langle \sigma v \rangle_{ann}}$ (WIMP scenario)

Asymmetric limit : For sufficiently large pair annihilation only particles (antiparticles) survive.

$$\Omega_{\rm DM} = \frac{s_0}{\rho_c} m_\chi C \quad (Relic \equiv asymmetry)$$

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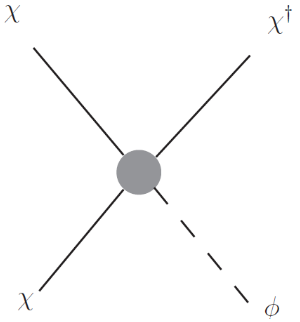
Can we do it by just one kind of process ?

- $\Delta(n_\chi + n_{\chi^\dagger}) = -1$
  $\Delta(n_\chi - n_{\chi^\dagger}) = -3$
- ϕ is a neutral unstable state, decays or mixes with SM states.
- For on-shell production of ϕ, $m_\chi > m_\phi$



Key Point : Thermal decoupling of semi-annihilation produces ADM

Semi-annihilation Continued...

Initial conditions

$$Y_\chi(x_i) = Y_{\chi^\dagger}(x_i) \overset{semi-annihilation}{\Longrightarrow} \quad Y_\chi(x_d) \neq Y_{\chi^\dagger}(x_d)$$

$$\frac{dY_\chi}{dx} = -\frac{s}{Hx}\left[A_s(Y_\chi^2 + \frac{Y_0 Y_\chi}{2}) - B_s(\frac{Y_{\chi^\dagger}^2}{2} + Y_0 Y_{\chi^\dagger})\right]$$

$$\frac{dY_{\chi^\dagger}}{dx} = -\frac{s}{Hx}\left[B_s(Y_{\chi^\dagger}^2 + \frac{Y_0 Y_{\chi^\dagger}}{2}) - A_s(\frac{Y_\chi^2}{2} + Y_0 Y_\chi)\right]$$

$$A_s = \langle\sigma v\rangle_s + \langle\epsilon\sigma v\rangle_s \,, \qquad B_s = \langle\sigma v\rangle_s - \langle\epsilon\sigma v\rangle_s$$

The relic density is a function of semi-annihilation cross-section ($\langle\sigma v\rangle_S$), *CP*-violation parameter ($\epsilon_{eff} = \frac{\langle\epsilon\sigma v\rangle_s}{\langle\sigma v\rangle_s}$) and the DM mass ($m_\chi$).

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Q1. How large the semi-annihilation cross-section can be ?

Q2. How large the mass of a semi-annihilating DM can be ?

S-matrix Unitarity

$\langle\sigma v\rangle_s$ is bounded from S-matrix unitarity, which in turn gives the upper bound on the DM mass

$$\langle\sigma v\rangle_{\rm uni} = (4\pi/m_\chi^2)(x_d/\pi)^{1/2} \quad \text{(for s-wave annihilation)}$$

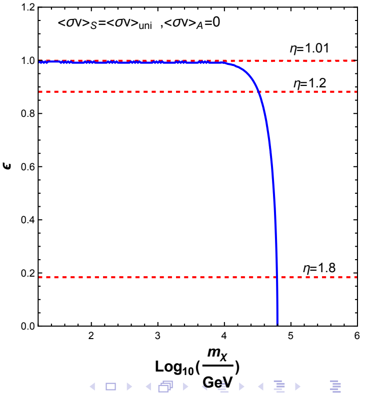
Griest et al. 1990

$$\eta = \frac{Y_\chi(x_d) + Y_{\chi^\dagger}(x_d)}{Y_\chi(x_d)}$$

$\eta \to 1$: only particle (or antiparticle) survives.

$\eta \to 2$: Both particle and antiparticle exist in equal abundance.

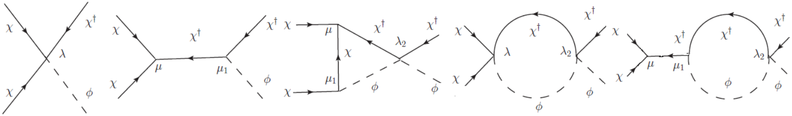
- $\eta \to 1$ for $\epsilon_{eff} \to 1$, then the DM mass, $m_\chi \leq 15$ GeV.
- For purely symmetric semi-annihilation ($\epsilon_{eff} = 0$), the DM mass, $m_\chi \leq 80$ TeV
  WIMP Bound : $m_\chi \lesssim 100$TeV

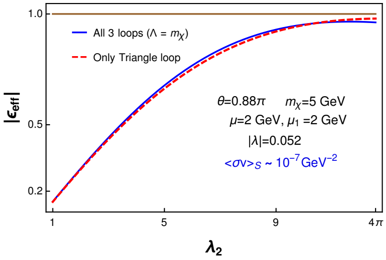


Model realization of Semi-annihilation

Z_3 symmetric Lagrangian

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





$$\epsilon_{eff} \propto Im\left(\mathcal{M}^*_{tree}\,\mathcal{M}_{loop}\right)$$

$\epsilon_{eff} \sim \mathcal{O}(1)$ CP violation can be realized with dimensionless couplings taking their perturbative values.

Takeaways

- The semi-annihilation process can simultaneously reduce the total number density of the DM sector as well as create a particle-antiparticle asymmetry.
- Maximal CP-violation can be achieved in a realistic model.

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