A New Window into Multi-component Dark Matter

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Introduction

1. **Evidences for existence of Dark Matter**
   - Rotation curves of spiral galaxies
   - Gravitional lensing effects
   - Cosmic Microwave Background (CMB) anisotropy, PLANCK/WMAP
2. **Types of Dark Matter**
   - **WIMPs** : Based on thermal freeze-out of DM candidate upon annihilation into visible sector.
   - **FIMPs** : Based on non thermal freeze-in production from decay or annihilation of unstable or metastable particles.
   - **SIMPs** : Based on number changing self annihilation (4$\rightarrow$ 2 or 3 $\rightarrow$2 processes).
   - **Other candidates** : Sterile neutrinos, ALPs etc.

Why not multi-component?

3. **Characteristics of multi-component Dark Matter (MCDM)**
   - **Relic density :** $\Omega_{\rm DM}{\rm h}^2 = \sum_i \Omega_i {\rm h}^2$

Assumption: The contribution of each DM component to the local density is same as their contribution to the relic density.

   - **Coupled Boltzmann equations** : Annihilations into visible and dark sector. Boltzmann equations changes depending on the nature of dark matter (WIMP, FIMP, SIMP etc.).

Symmetric versus Asymmetric

- **Symmetric: Particle and anti-particle abundance are equal.**
- **Asymmetric: Finite difference between co-moving number density of particle and anti-particle;** $\dfrac{d(Y_A - Y_{\bar{A}})}{dx} = 0$**, and** $Y_A - Y_{\bar{A}} = C(\neq 0)$**.**

$$\frac{Hx}{s}\frac{dY_S}{dx} = -\langle\sigma v\rangle_{SS\to XX}\left(Y_S^2 - Y_{S,\mathrm{eq}}^2\right)$$

$$\frac{Hx}{s}\frac{dY_A}{dx} = -\langle\sigma v\rangle_{A\bar{A}\to XX}\left(Y_A Y_{\bar{A}} - Y_{A,\mathrm{eq}} Y_{\bar{A},\mathrm{eq}}\right)$$

$$\frac{Hx}{s}\frac{dY_{\bar{A}}}{dx} = -\langle\sigma v\rangle_{A\bar{A}\to XX}\left(Y_A Y_{\bar{A}} - Y_{A,\mathrm{eq}} Y_{\bar{A},\mathrm{eq}}\right)$$

- Assumption: Self annihilation of particle or anti-particle is prohibited; $AA(\bar{A}\bar{A}) \not\to XX$.
- First proposed by Gelmini et. al.; JCAP 08, 003 (2013)

$$e^{\mu_A/T} = \frac{1}{2}\left(\frac{Cs}{n_{A,\mathrm{eq}}(\mu=0)} + \sqrt{4 + \left(\frac{Cs}{n_{A,\mathrm{eq}}(\mu=0)}\right)^2}\right)$$

Assisted freeze-out in multi-component dark matter

- Multi-component DM: Kathryn M. Zurek; Phys.Rev.D 79 (2009) 115002
- Assisted freeze-out: Genevieve Belanger and Jong-Chul Park; JCAP 03 (2012) 038 (Symmetric DM components)

$$\frac{dn_2}{dt} + 3Hn_2 = -\langle\sigma v\rangle_{22\to 11}\left[(n_2)^2 - \frac{(n_2^{\rm eq})^2}{(n_1^{\rm eq})^2}(n_1)^2\right]$$

$$\begin{aligned}\frac{dn_1}{dt} + 3Hn_1 &= -\langle\sigma v\rangle_{11\to XX}\left[(n_1)^2 - (n_1^{\rm eq})^2\right] - \langle\sigma v\rangle_{11\to 22}\left[(n_1)^2 - \frac{(n_1^{\rm eq})^2}{(n_2^{\rm eq})^2}(n_2)^2\right]\\ &= -\langle\sigma v\rangle_{11\to XX}\left[(n_1)^2 - (n_1^{\rm eq})^2\right] + \langle\sigma v\rangle_{22\to 11}\left[(n_2)^2 - \frac{(n_2^{\rm eq})^2}{(n_1^{\rm eq})^2}(n_1)^2\right]\end{aligned}$$

- Introducing a case of multi-component symmetric (S) and asymmetric (A, $\bar{A}$) DM:

$$n_{A(\bar{A}),\rm eq} = g_{A,\bar{A}}\left(\frac{m_A T}{2\pi}\right)^{3/2} e^{(-m_A \pm \mu_A)/T}; \; n_{S,\rm eq} = g_S\left(\frac{m_S T}{2\pi}\right)^{3/2} e^{-m_S/T}.$$

Boltzmann equations

A) $m_A > m_S$

$$\frac{Hx}{s}\frac{dY_A}{dx} = -\langle\sigma v\rangle_{A\bar{A}\to SS}\left(Y_A^2 - CY_A - \frac{Y_{A,\mathrm{eq}}Y_{\bar{A},\mathrm{eq}}}{Y_{S,\mathrm{eq}}^2}Y_S^2\right),$$

$$\frac{Hx}{s}\frac{dY_{\bar{A}}}{dx} = -\langle\sigma v\rangle_{A\bar{A}\to SS}\left(Y_{\bar{A}}^2 + CY_{\bar{A}} - \frac{Y_{A,\mathrm{eq}}Y_{\bar{A},\mathrm{eq}}}{Y_{S,\mathrm{eq}}^2}Y_S^2\right),$$

$$\frac{Hx}{s}\frac{dY_S}{dx} = -\langle\sigma v\rangle_{SS\to XX}\left(Y_S^2 - Y_{S,\mathrm{eq}}^2\right) + \langle\sigma v\rangle_{A\bar{A}\to SS}\left(Y_A^2 - CY_A - \frac{Y_{A,\mathrm{eq}}Y_{\bar{A},\mathrm{eq}}}{Y_{S,\mathrm{eq}}^2}Y_S^2\right)$$
$$+ \langle\sigma v\rangle_{A\bar{A}\to SS}\left(Y_{\bar{A}}^2 + CY_{\bar{A}} - \frac{Y_{A,\mathrm{eq}}Y_{\bar{A},\mathrm{eq}}}{Y_{S,\mathrm{eq}}^2}Y_S^2\right).$$

B) $m_A < m_S$

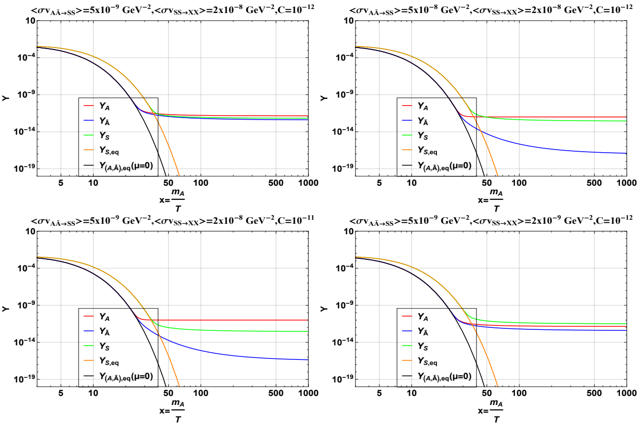
$$\frac{Hx}{s}\frac{dY_A}{dx} = -\langle\sigma v\rangle_{A\bar{A}\to XX}\left(Y_A^2 - CY_A - Y_{A,\mathrm{eq}}Y_{\bar{A},\mathrm{eq}}\right) + \langle\sigma v\rangle_{SS\to A\bar{A}}\left(Y_S^2 - \frac{Y_A^2 - CY_A}{Y_{A,\mathrm{eq}}Y_{\bar{A},\mathrm{eq}}}Y_{S,\mathrm{eq}}^2\right),$$

$$\frac{Hx}{s}\frac{dY_{\bar{A}}}{dx} = -\langle\sigma v\rangle_{A\bar{A}\to XX}\left(Y_{\bar{A}}^2 + CY_{\bar{A}} - Y_{A,\mathrm{eq}}Y_{\bar{A},\mathrm{eq}}\right) + \langle\sigma v\rangle_{SS\to A\bar{A}}\left(Y_S^2 - \frac{Y_{\bar{A}}^2 + CY_{\bar{A}}}{Y_{A,\mathrm{eq}}Y_{\bar{A},\mathrm{eq}}}Y_{S,\mathrm{eq}}^2\right),$$

$$\frac{Hx}{s}\frac{dY_S}{dx} = -\langle\sigma v\rangle_{SS\to A\bar{A}}\left(Y_S^2 - \frac{Y_{\bar{A}}^2 + CY_{\bar{A}}}{Y_{A,\mathrm{eq}}Y_{\bar{A},\mathrm{eq}}}Y_{S,\mathrm{eq}}^2\right) - \langle\sigma v\rangle_{SS\to A\bar{A}}\left(Y_S^2 - \frac{Y_A^2 - CY_A}{Y_{A,\mathrm{eq}}Y_{\bar{A},\mathrm{eq}}}Y_{S,\mathrm{eq}}^2\right).$$

Solution to BEs and results

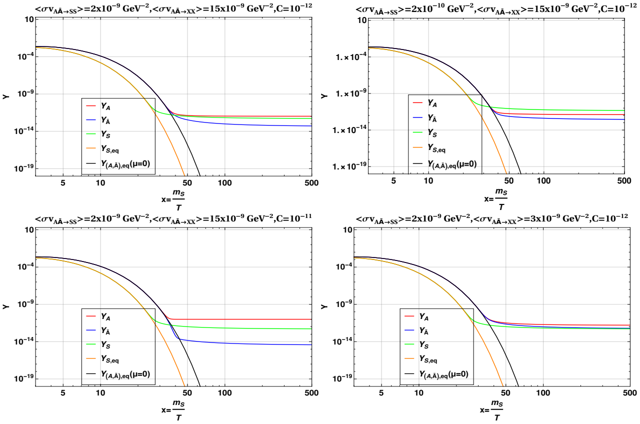
$m_A > m_S$



BP	$m_{A,\bar{A}}$ GeV	m_S GeV	$\langle\sigma v\rangle_{A\bar{A}\to SS}$ GeV^{-2}	$\langle\sigma v\rangle_{SS\to XX}$ GeV^{-2}	C	$\Omega_A h^2$	$\Omega_{\bar{A}} h^2$	$\Omega_S h^2$
I	200	150	5×10^{-9}	2×10^{-8}	10^{-12}	0.036	0.0110	0.013
II	200	150	5×10^{-8}	2×10^{-8}	10^{-12}	0.025	4.3×10^{-7}	0.005
III	200	150	5×10^{-9}	2×10^{-8}	10^{-11}	0.248	1.5×10^{-6}	0.006
IV	200	150	5×10^{-9}	2×10^{-9}	10^{-12}	0.036	0.011	0.062

Solution to BEs and results

$m_A < m_S$



BP	$m_{A,\bar{A}}$ GeV	m_S GeV	$\langle\sigma v\rangle_{SS\to A\bar{A}}$ GeV^{-2}	$\langle\sigma v\rangle_{A\bar{A}\to XX}$ GeV^{-2}	C	$\Omega_A h^2$	$\Omega_{\bar{A}} h^2$	$\Omega_S h^2$
I	300	400	2×10^{-9}	15×10^{-9}	10^{-12}	0.039	0.002	0.026
II	300	400	2×10^{-10}	15×10^{-9}	10^{-12}	0.048	0.011	0.238
III	300	400	2×10^{-9}	15×10^{-9}	10^{-11}	0.373	0.001	0.026
IV	300	400	2×10^{-9}	3×10^{-9}	10^{-12}	0.061	0.023	0.026

Fast expansion of Univesre and non-standard cosmology

- Influence of a scalar field φ, F. D'Eramo . *et. al* : JCAP 1705, no. 05, 012 (2017).

$$\rho_{rad} = \frac{\pi^2}{30} g_* T^4 \qquad\qquad s = \frac{2\pi^2}{45} g_{*s} T^3$$

$$H = \sqrt{\frac{8\pi G \rho_{rad}}{3}} = 1.66\sqrt{g_*}\frac{T^2}{M_P} .$$

Consider that a scalar field φ is also present at the early Universe and its energy density depends on the scale factor a

$$\rho_\varphi \sim a^{-(4+n)}, \qquad n > 0 .$$

- Total entropy $S = sa^3$ is conserved, $g_{*s} T^3 a^3 = \mathrm{Constant}$.
- Temperature T_R when energy density of φ becomes equal to energy density of radiation, i.e., at $T = T_R$, $\rho_\varphi = \rho_{rad}$.

Total energy density is expressed as

$$\rho_{Tot} = \rho_{rad} + \rho_{\varphi} = \rho_{rad}\left[1 + \frac{g_*(T_R)}{g_*(T)}\left(\frac{g_{*s}(T)}{g_{*s}(T_R)}\right)^{(4+n)/3}\left(\frac{T}{T_R}\right)^n\right].$$

At large T, $g_* \simeq g_{*s}$ are constant.

$$\rho_{Tot} = \rho_{rad}\left[1 + \left(\frac{T}{T_R}\right)^n\right].$$

The Hubble parameter can be redefined as

$$H' = 1.66\sqrt{g_*}\frac{T^2}{M_P}\left[1 + \left(\frac{T}{T_R}\right)^n\right]^{1/2} = H\left[1 + \left(\frac{T}{T_R}\right)^n\right]^{1/2}.$$

Results under modified expansion of Universe

	$m_{A,\bar{A}}$ GeV	m_S GeV	$\langle\sigma v\rangle_{A\bar{A}\to SS}$ GeV^{-2}	$\langle\sigma v\rangle_{SS\to XX}$ GeV^{-2}	C	$\Omega_A h^2$	$\Omega_{\bar{A}} h^2$	$\Omega_S h^2$
RD	200	150	5×10^{-9}	2×10^{-8}	10^{-12}	0.036	0.011	0.013
$n=1,\ T_R=1$ GeV	200	150	5×10^{-9}	2×10^{-8}	10^{-12}	0.056	0.031	0.026
$n=2,\ T_R=1$ GeV	200	150	5×10^{-9}	2×10^{-8}	10^{-12}	0.076	0.051	0.040

	$m_{A,\bar{A}}$ GeV	m_S GeV	$\langle\sigma v\rangle_{SS\to A\bar{A}}$ GeV^{-2}	$\langle\sigma v\rangle_{A\bar{A}\to XX}$ GeV^{-2}	C	$\Omega_A h^2$	$\Omega_{\bar{A}} h^2$	$\Omega_S h^2$
RD	300	400	2×10^{-9}	15×10^{-9}	10^{-12}	0.039	0.002	0.026
$n=1,\ T_R=1$ GeV	300	400	2×10^{-9}	15×10^{-9}	10^{-12}	0.051	0.013	0.069
$n=2,\ T_R=1$ GeV	300	400	2×10^{-9}	15×10^{-9}	10^{-12}	0.075	0.038	0.138

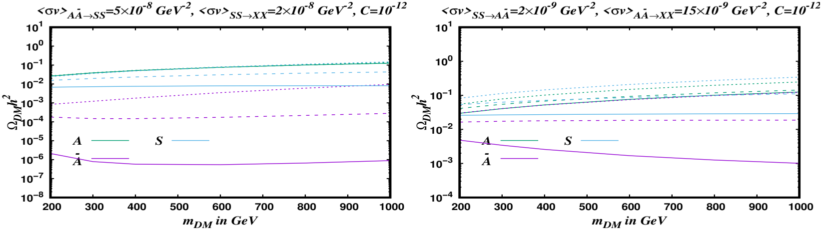


Figure: Comparison of DM relic density against DM mass with the variation of n for $T_R = 1$ GeV. Left panel $m_A - m_S = 10$ GeV, right panel $m_S - m_A = 10$ GeV.

Results under modified expansion of Universe

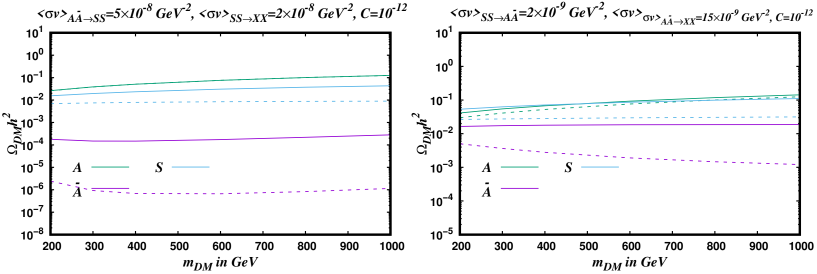


Figure: Comparison of DM relic density against DM mass with the variation of T_R for $n = 1$. Left panel $m_A - m_S = 10$ GeV, right panel $m_S - m_A = 10$ GeV.

Concluding Remarks

- For $m_A > m_S$, we observe that enhancement dark sector annihilation ($A\bar{A} \to SS$) results in a reduction in the abundance of all DM components. The visible sector annihilation $SS \to XX$ only affects the abundance of the S component.
- An increase in asymmetry parameter increases abundance of A but $\bar{A}$ component suffers significant loss in abundance. The effect in the abundance of S occurs due to the changes in abundances of A and $\bar{A}$, and due to change in annihilation cross-section $A\bar{A} \to SS$.
- For $m_A < m_S$, dark annihilation $SS \to A\bar{A}$ and visible annihilation $A\bar{A} \to XX$ has similar effects on DM relic abundance as in the case of $m_A > m_S$.
- With non-standard cosmology in effect, a large value of n, results in early freeze-out, and overall relic density of both symmetric and asymmetric DM tends to get boosted.
- In the presence of NS cosmology, large T_R has a complementary effect on DM relic density, reducing the abundance for a chosen n.

Thank you for your attention.