Manifesting hidden dynamics of a sub-component dark matter

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Introduction

In multi-component dark matter (DM) scenarios, less attention has been given to sub-dominant components of DM and the corresponding impact on their detectability. They are often thought to be hidden from observations in direct and indirect detections of DM due to its small fraction.

However, a sub-dominant DM component can play a dominant role in the dynamics of and detection of dark sector. The strategy to probe a sub-dominant DM component relies on its cosmological evolution which is sensitive to the interaction within a dark sector. Here, we show a case when the dynamics within a dark sector affect the detectability of a sub-component DM.

Reference model

For concreteness, we take a multi-component boosted DM scenario:

1. Minimally two DM components: χ_0 (heavy) and χ_1 (light)
2. The dominant component is the heavy DM χ_0 which does not have direct interactions with the SM particles. Its relic abundance is determined by the freeze-out of $\chi_0\chi_0 \leftrightarrow \chi_1\chi_1$ process, called assisted freeze-out mechanism.
3. The process $\chi_1\chi_1 \leftrightarrow$ SM freezes out later lowering the abundance of χ_1 compared to χ_0.
4. The light boosted DM χ_1 can be produced via $\chi_0\chi_0 \to \chi_1\chi_1$ with large kinetic energy about $m_{\chi 0}$.

Results

After the freeze-out of χ_0, the Boltzmann equation is

$$\frac{dY_{\chi_1}}{dx} \simeq -\frac{\lambda_{\chi_1}(x)}{x}\left[Y_{\chi_1}^2 - \left(Y_{\chi_1}^{\rm eq}(x)\right)^2 - Y_{\rm ast.}^2(x)\right]$$

$\chi_0\chi_0 \to \chi_1\chi_1$

$$\lambda_{\chi_i} = s\langle\sigma_i v_{\rm rel}\rangle/H$$

$$\langle\sigma_0 v_{\rm rel}\rangle = \langle\sigma v\rangle_{\chi_0\chi_0\to\chi_1\chi_1}$$
$$\langle\sigma_1 v_{\rm rel}\rangle = \langle\sigma v\rangle_{\chi_1\chi_1\to \rm SM}$$

$$Y_{\rm ast.}(x) = \sqrt{\frac{\langle\sigma_0 v_{\rm rel}\rangle}{\langle\sigma_1 v_{\rm rel}\rangle}}\,Y_{\chi_0}(x)$$

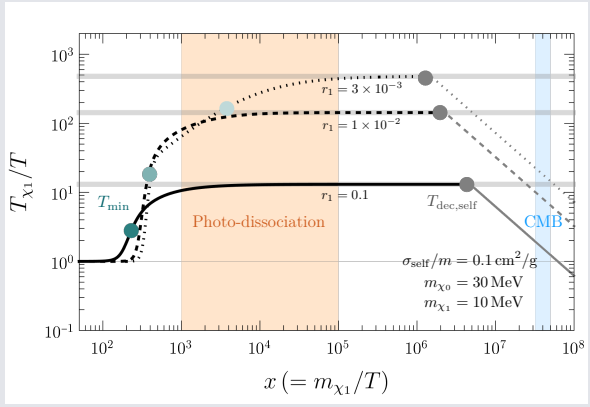
- If the ratio $r_1 \equiv \Omega_{\chi 1}/\Omega_{\rm DM,\,tot} \ll 1$, the light DM χ_1 is in thermal equilibrium with SM longer than the conventional WIMP case, i.e, $x_{\rm f.o.,\chi 1} > 20$ and hence $Y_{\chi_1}^{\rm eq} \ll Y_{\rm ast.}$ at the freeze-out of χ_1.

- Then the production rate of χ_1 from $\chi_0\chi_0 \to \chi_1\chi_1$ is non-negligible compared to the depletion by $\chi_1\chi_1 \to$ SM, increasing $Y_{\chi 1}$ compared to the standard WIMP freeze-out case.

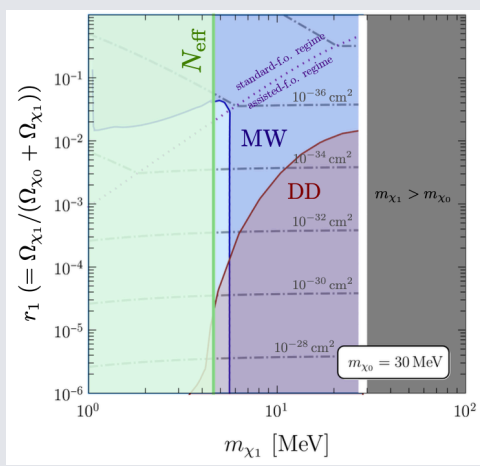
- So, for a fixed $r_1 \ll 1$, the depletion $\chi_1\chi_1 \to$ SM should be effective: $\langle\sigma_1 v_{\rm rel}\rangle$ is proportional to $1/r_1^2$, $1/r_1^3$ for the s-wave and p-wave dominant annihilation process, respectively.

- Then, the cosmo/astro observables of χ_1 proportional to $n_{\chi_1}^2\langle\sigma_1 v\rangle$ become not suppressed by r_1.

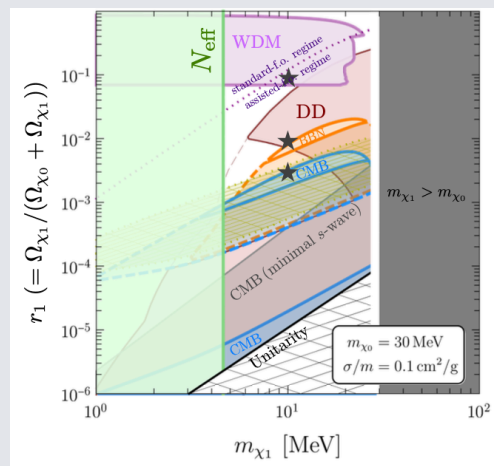
- Long after the freeze-out of $\chi_1\chi_1 \leftrightarrow$ SM, the energetically produced χ_1 from $\chi_0\chi_0 \to \chi_1\chi_1$ can transfer its energy to the relic χ_1 via self-interactions, increasing its kinetic energy. This is called the *self-heating mechanism*, which is important for the p-wave dominant $\chi_1\chi_1 \to$ SM annihilation case.



- The bounds from the observations of BBN, CMB, diffuse X-rays or γ-rays in our galaxy, DM direct detection experiments, and those constraining the warm dark matter (for $r_1 \gtrsim 7\%$) apply very strongly to the sub-component DM χ_1.



$\langle\sigma_1 v_{\rm rel}\rangle$: s-wave dominant



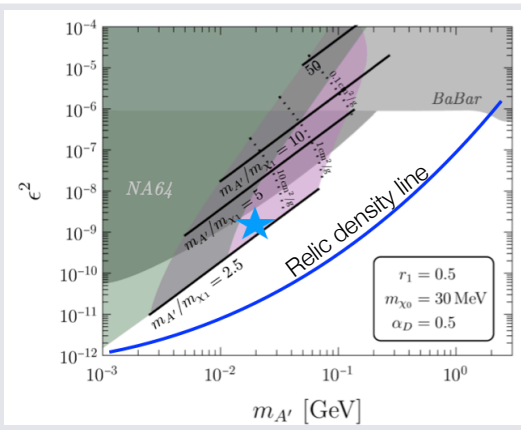
$\langle\sigma_1 v_{\rm rel}\rangle$: p-wave dominant

Discussion

- In multi-component DM scenarios, a sub-component DM (χ_1) can severely affect the cosmo/astro observables unlike conventional expectation; due to the strong current bounds the p-wave dominant $\chi_1\chi_1 \to$ SM annihilation case is preferred.

- Self-heating from $\chi_0\chi_0 \to \chi_1\chi_1$ followed by the self-interactions among χ_1 arises and changes the evolution of $T_{\chi 1}$ even after its freeze-out. Then, the constraints for warm dark matter can be applied to the p-wave dominant $\chi_1\chi_1 \to$ SM process for $r_1 \gtrsim 7\%$.

- Direct detection constraints may change and complementary searches in accelerators can interplay with cosmo/astro observations to probe the detailed structure of dark sector.



- Reference model: singlet scalar χ_1 interacting with SM with a dark photon (A')

- Green: $N_{\rm eff}$, Pink: Warm DM

- A future discovery of χ_1 (blue star) can be inconsistent with the cosmo/astro bounds.

References

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