Co-scattering in the Extended Singlet-Scalar Higgs Portal

Jayita Lahiri
II. Institut für Theoretische Physik, Universität Hamburg

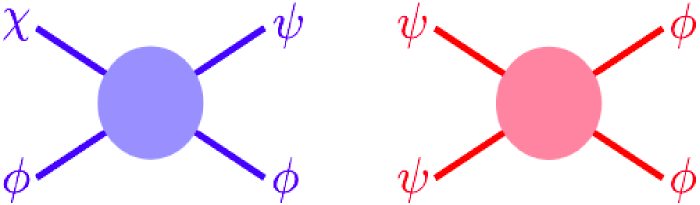
Based on Arxiv : 2404.19057 in collaboration with Bastián Díaz Sáez and Kilian Möhling

The origin of dark matter relic

- The origin of DM is not known.
- Thermal production of DM is one of the most popular hypotheses → WIMP mechanism.
- Freeze-out occurs when annihilation rate $\lesssim$ expansion rate of the universe.
- WIMP regime directs towards weak scale masses as well as interaction strengths, likely to be detected at collider experiments.
- Co-annihilation : Mutual annihilation of different species, $1, 2$ charged under same symmetry, into SM bath particles. Effective when $m_2 - m_1 \approx 5/10\%$ of DM mass. *Griest and Seckel, PRD 43, 3191 (1991)*

Conversion driven freezeout or co-scattering

- This is a thermal DM framework where inelastic conversion within the dark sector drives the relic abundance *Phys.Rev.Lett. 119 (2017) 6, 061102 D'Agnolo et al.* and *Phys.Rev.D 96 (2017) 10, 103521 Garny et al*.



Taken from *D'Agnolo et al.*

- Annihilation of DM into SM bath particles needs to be suppressed.
- CE within the dark sector is lost, conversion plays important role in DM freezeout.

Co-scattering in Higgs-portal scenario with additional scalar singlet

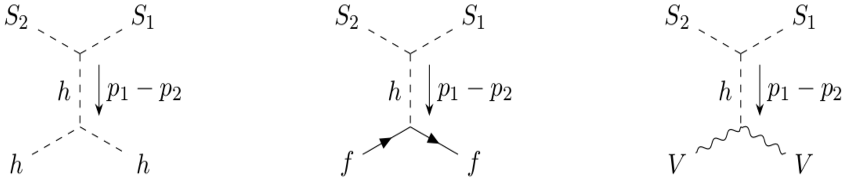
JHEP 05, (2017) 036 Casas et al

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{i=1,2} \left(\frac{1}{2}(\partial_\mu S_i)^2 - \frac{m_i^2}{2} S_i^2 - \lambda_{i4} S_i^4 \right)$$
$$-\lambda_{22} S_1^2 S_2^2 - \lambda_{13} S_1 S_2^3 - \lambda_{31} S_1^3 S_2$$
$$- \left(\lambda_{H1} S_1^2 + \lambda_{H2} S_2^2 + \lambda_{12} S_1 S_2\right) \left(|H|^2 - \frac{v_h^2}{2} \right),$$

- $\lambda_{H1} \approx 0$,
- $\lambda_{H2} \sim 1$,
- $\lambda_{12} << 1$,
- $\lambda_{13,31,22} \lesssim 0.1$ will be discussed soon.
- Onshell two-body decays of $S_2 \to S_1 + X$ should be suppressed(?)

  D'Agnolo et al.

Conversion/Co-scattering processes in Higgsportal scenario with additional scalar singlet



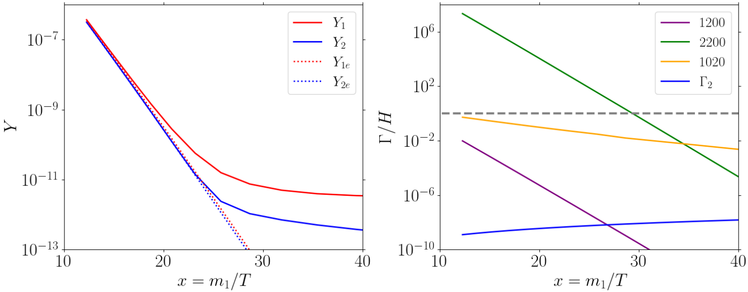
The Boltzmann Equations

$$\begin{aligned}
\frac{dY_1}{dx} = \frac{1}{3H}\frac{ds}{dx}\bigg[& \langle\sigma_{1100}v\rangle\left(Y_1^2 - Y_{1e}^2\right) + \langle\sigma_{1200}v\rangle\left(Y_1Y_2 - Y_{1e}Y_{2e}\right) \\
& + \langle\sigma_{1112}v\rangle\left(Y_1^2 - Y_1Y_2\frac{Y_{1e}}{Y_{2e}}\right) + \langle\sigma_{1222}v\rangle\left(Y_1Y_2 - Y_2^2\frac{Y_{1e}}{Y_{2e}}\right) \\
& + \langle\sigma_{1122}v\rangle\left(Y_1^2 - Y_2^2\frac{Y_{1e}^2}{Y_{2e}^2}\right) + \frac{\Gamma_{1\to 2}}{s}\left(Y_1 - Y_2\frac{Y_{1e}}{Y_{2e}}\right) - \frac{\Gamma_2}{s}\left(Y_2 - Y_1\frac{Y_{2e}}{Y_{1e}}\right)\bigg], \\
\frac{dY_2}{dx} = \frac{1}{3H}\frac{ds}{dx}\bigg[& \langle\sigma_{2200}v\rangle\left(Y_2^2 - Y_{2e}^2\right) + \langle\sigma_{1200}v\rangle\left(Y_1Y_2 - Y_{1e}Y_{2e}\right) \\
& - \langle\sigma_{1112}v\rangle\left(Y_1^2 - Y_1Y_2\frac{Y_{1e}}{Y_{2e}}\right) - \langle\sigma_{1222}v\rangle\left(Y_1Y_2 - Y_2^2\frac{Y_{1e}}{Y_{2e}}\right) \\
& - \langle\sigma_{1122}v\rangle\left(Y_1^2 - Y_2^2\frac{Y_{1e}^2}{Y_{2e}^2}\right) - \frac{\Gamma_{1\to 2}}{s}\left(Y_1 - Y_2\frac{Y_{1e}}{Y_{2e}}\right) + \frac{\Gamma_2}{s}\left(Y_2 - Y_1\frac{Y_{2e}}{Y_{1e}}\right)\bigg],
\end{aligned}$$

We need to use the `darkOmegaN` function, instead of `darkOmega` of `MicrOMEGAs`. *Alguero et al, SciPost Phys. 13 (2022) 124*

Evolution of DM and mediator in simplest benchmark scenario

simplest benchmark scenario : $\lambda_{13,31,22} = 0$, $\lambda_{H1} = 0$



$(m_1, m_2) = (500, 505)$ GeV, $(\lambda_{12}, \lambda_{H2}) = (2.6 \times 10^{-5}, 1)$

Various regimes

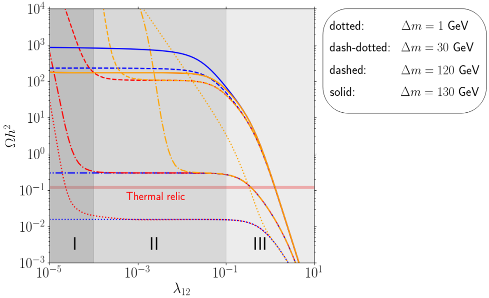


Figure: $m_1 = 500$ GeV, $\lambda_{H2} = 1$

blue:`darkOmega`,
red:`darkOmegaN`,
orange:`darkOmegaN` without coscattering.

Various regimes

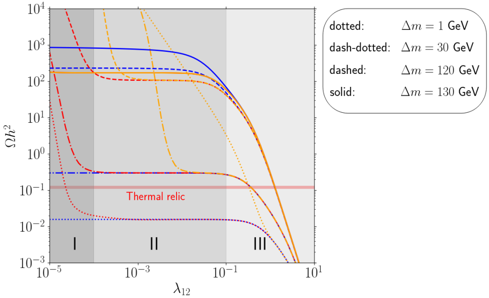


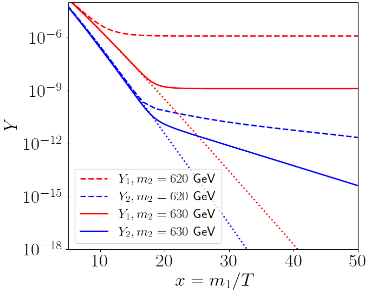
Figure: $m_1 = 500$ GeV, $\lambda_{H2} = 1$

- Region I : Coscattering regime : strong dependence on λ_{12}.
- Region II : Mediator freezeout regime: almost no dependence on λ_{12}, CE established.
- Region III : Co-annihilation regime : again dependence on λ_{12}.

blue:`darkOmega`,
red:`darkOmegaN`,
orange:`darkOmegaN` without coscattering.

Re-examining on-shell $S_2 \to S_1$+Higgs decays

On-shell decays being rapid processes, can equilibiriate S_2 and S_1, rendering co-scattering ineffective. However we decided to reinvestigate.



$m_1 = 500$ GeV, $\lambda_{12} = 10^{-5}$, $\lambda_{H2} = 1$

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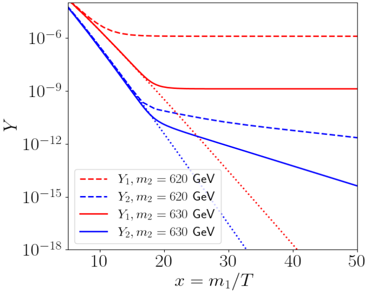

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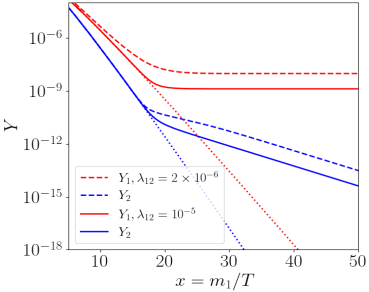

$(m_1, m_2) = (500, 630)$ GeV, with $\lambda_{12} = 2 \times 10^{-6}$ (dashed) and $\lambda_{12} = 10^{-5}$ (solid).

Co-scattering can determine relic density when, λ_{12} is even smaller.

Effect of contact terms

Contact terms in principle can help maintain chemical equilibrium within the dark sector.

$\Delta^{\Omega}_{1s} \equiv 1 - \frac{\Omega h^2(1\text{ sector})}{\Omega h^2(2\text{ sectors})}$ *Alguero et al SciPost Phys. 13 (2022) 124*

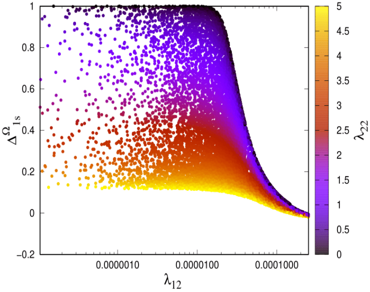

Figure: $(m_1, m_2) = (500, 505)$ GeV and $(\lambda_{H1}, \lambda_{12}, \lambda_{H2}) = (0, 2.6 \times 10^{-5}, 1)$

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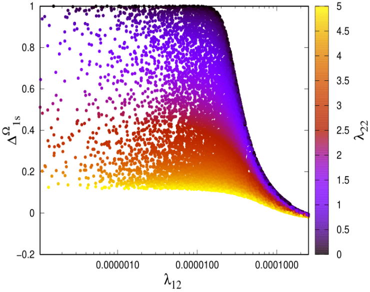


Figure: $(m_1, m_2) = (500, 505)$ GeV and $(\lambda_{H1}, \lambda_{12}, \lambda_{H2}) = (0, 2.6 \times 10^{-5}, 1)$

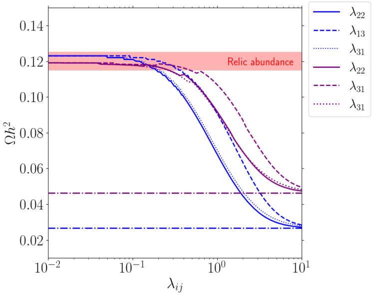
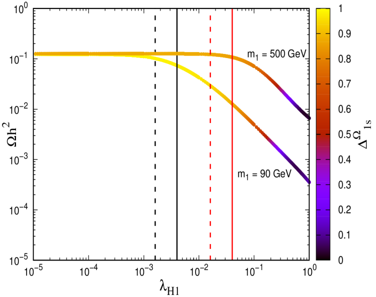


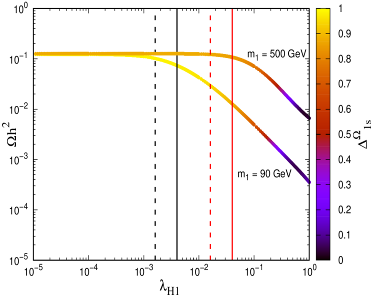
Figure: $(m_1, m_2) = (500, 505)$ GeV and $(\lambda_{H1}, \lambda_{12}, \lambda_{H2}) = (0, 2.6 \times 10^{-5}, 1)$(blue), $(m_1, m_2) = (500, 510)$ GeV and $(\lambda_{H1}, \lambda_{12}, \lambda_{H2}) = (0, 3.2 \times 10^{-5}, 1)$(purple)

Direct detection

- The stable DM S_1 can be found in direct detection experiments.
- The limit on the λ_{H1} coupling from LZ experiment is $\lambda_{H1} \lesssim \sqrt{\frac{4\pi m_h^4 m_1^2 \sigma_{LZ}}{f_N^2 m_n^4}}$
- In the co-scattering regime, naturally direct detection bound is easily satisfied, since $\lambda_{H1} \approx 0$.
- One can ask, what is the upper limit on λ_{H1}, for being in co-scattering regime which can also account for the observed relic?
- Whether an interaction strength of such order can be detected in future DD experiments?



$\Delta m = 1$ GeV, $\lambda_{H2} = 1$, $\lambda_{12} = \{3.86 \times 10^{-4}, 2.3 \times 10^{-5}\}$ for $m_1 = \{90, 500\}$ GeV



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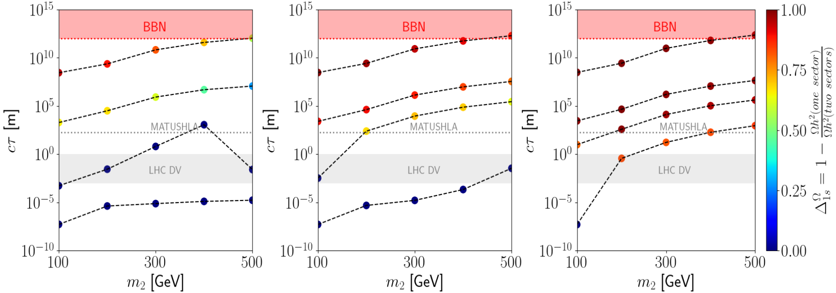
- For 500 GeV $\lambda_{H1} \lesssim 10^{-2}$, accounts for substantial co-scattering, as well as observed relic and close to the current LZ bound, although currently allowed by it.
- Future DARWIN experiment is expected to provide further sensitivity.

Long-lived particles (LLP) signature

- The co-scattering regime corresponds to $\lambda_{12} << 1$, $\Delta m << m_1, m_2$, making S_2 essentially long-lived.

- $pp \to h^* + X \to S_2 + S_2 + X$, S_2 decaying further.

- Estimating the life-time of S_2 in our model, and within the reach of current/future experiments.



$\Delta m = 1, 5, 10, 20$ GeV, $\lambda_{H2} = 0.5, 1, \pi$

- Small Δm is favored by co-scattering, but leads to extremely large decay length, beyond reach of LHC displaced vertices search.

- Large λ_{H2}, enables significant co-scattering even with comparatively larger Δm, making it possible to probe at MATUSHLA experiment, or even LHC displaced vertices search.

Summary

- Co-scattering is an important ‘alternate’ mechanism for the production of thermal DM relic.
- In co-scattering regime, the chemical equilibrium within the dark sector is lost and independent solution of Boltzman Equations for all dark sector particles are necessary.
- The on-shell decay as well as self-interaction between dark sector particles can restore the CE, altering the co-scattering regime.
- Long-lived particles are a direct manifestation of co-scattering regime. Future experiments in this direction can probe such scenarios effectively.