Multi-component Dark Matter with Hidden $SU(3)$ Symmetry

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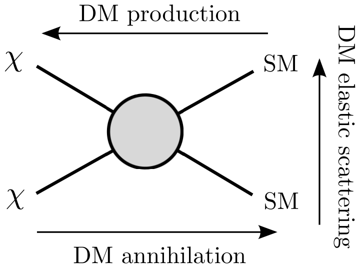
Work in Progress

Introduction

- The exsitence of DM is crucial from many observations.
- Basic strategies to detect DM

Indirect detection
Direct detection
Collider search

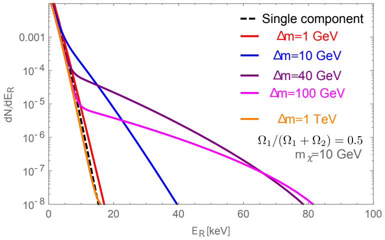
$\rightarrow$ Closely corrlated with each other for single-component DM



- Multi-component (WIMP) DM $\rightarrow$ Interesting phenomenology
  $\rightarrow$ Different observation prospects from single-component DM

Introduction

- For example, recoil energy distribution for direct detection may change.



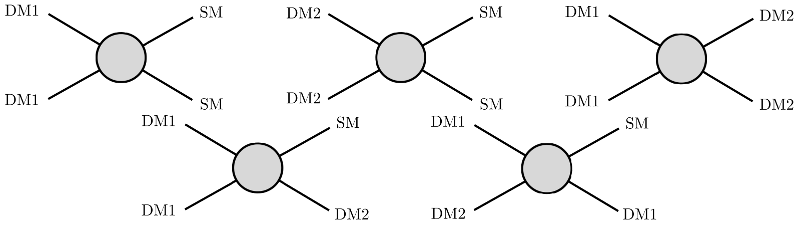
- A kink feature can be seen in recoil energy distribution.
  $\rightarrow$ descriminative feature of multi-component DM

  S. Profumo et al arXiv:0907.4374,
  K. R. Dienes et al arXiv:1208.0336

- A concrete model:
  $SU(3)$ hidden gauge symmetry
  $\rightarrow$ naturally multi-component DM is realized ($\mathbb{Z}_2 \times \mathbb{Z}_2'$).
  (Oleg's talk)

Introduction

Coupled Boltzmann equations for DM1 and DM2 ($m_1 > m_2$)



- Various processes are relevant to DM relic densities.

$$\frac{dn_1}{dt} + 3Hn_1 = -\langle\sigma v\rangle_{11\to 00}\left(n_1^2 - n_1^{\mathrm{eq}2}\right) - \langle\sigma v\rangle_{11\to 22}\left(n_1^2 - n_1^{\mathrm{eq}2}\frac{n_2^2}{n_2^{\mathrm{eq}2}}\right) + \cdots$$

$$\frac{dn_2}{dt} + 3Hn_2 = -\langle\sigma v\rangle_{22\to 00}\left(n_2^2 - n_2^{\mathrm{eq}2}\right) + \langle\sigma v\rangle_{11\to 22}\left(n_1^2 - n_1^{\mathrm{eq}2}\frac{n_2^2}{n_2^{\mathrm{eq}2}}\right) + \cdots$$

Red: normal annihilations, Blue: conversions, $\cdots$

The Model

- Hidden $SU(3)$ symmetry is implosed.
- 8 hidden gauge bosons exist.
  In order to minimally break the $SU(3)$ symmetry, 2 kinds of triplet scalars ϕ_1 and ϕ_2 are required. (Ref:Oleg's talk)

The Lagrangian:

$$\mathcal{L} = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + |D_\mu\phi_1|^2 + |D_\mu\phi_2|^2 - \mathcal{V}, \quad \text{where} \quad D_\mu = \partial_\mu + i\tilde{g}A^a_\mu T^a.$$

After the $SU(3)$ symmetry breaking

$$\phi_1 = \begin{pmatrix} 0 \\ 0 \\ v_1 + \varphi_1 \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} 0 \\ v_2 + \varphi_2 \\ v_3 + \varphi_3 + i\chi \end{pmatrix}, \quad H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

The Full Scalar Potential

$$\begin{aligned}\mathcal{V} = {} & \mu_H^2|H|^2 + \mu_1^2|\phi_1|^2 + \mu_2^2|\phi_2|^2 + \frac{\lambda_H}{2}|H|^4 + \frac{\lambda_1}{2}|\phi_1|^4 + \frac{\lambda_2}{2}|\phi_2|^4 \\ & + \lambda_{H11}|H|^2|\phi_1|^2 + \lambda_{H22}|H|^2|\phi_2|^2 + \lambda_3|\phi_1|^2|\phi_2|^2 + \lambda_4|\phi_1^\dagger\phi_2|^2 \\ & + \Big[\lambda_{H12}|H|^2\left(\phi_1^\dagger\phi_2\right) + \frac{\lambda_5}{2}\left(\phi_1^\dagger\phi_2\right)^2 + \lambda_6|\phi_1|^2\left(\phi_1^\dagger\phi_2\right) \\ & \qquad + \lambda_7|\phi_2|^2\left(\phi_1^\dagger\phi_2\right) + \mathrm{H.c.}\Big]\end{aligned}$$

- The full model is hard to analyze due to complexity.
- Hidden particles interact with the SM via the Higgs bosons.
  $\rightarrow$ Higgs portal
- Assuming CP symmetry, vector bosons and CP-odd scalar can be stable because of the structure of Lie Group.
  $\rightarrow$ multi-component DM

Simplifying the Model

The full model is hard to perform numerical computations (even using micromegas) due to non-abelian gauge symmetry.
We simplify the model.

$$\begin{aligned}\mathcal{V} = & \mu_H^2|H|^2 + \mu_1^2|\phi_1|^2 + \mu_2^2|\phi_2|^2 + \frac{\lambda_H}{2}|H|^4 + \frac{\lambda_1}{2}|\phi_1|^4 + \frac{\lambda_2}{2}|\phi_2|^4 \\ & + \lambda_{H11}|H|^2|\phi_1|^2 + \lambda_{H22}|H|^2|\phi_2|^2 + \lambda_3|\phi_1|^2|\phi_2|^2 + \lambda_4|\phi_1^\dagger\phi_2|^2 \\ & + \left[\lambda_{H12}|H|^2\left(\phi_1^\dagger\phi_2\right) + \frac{\lambda_5}{2}\left(\phi_1^\dagger\phi_2\right)^2 + \lambda_6|\phi_1|^2\left(\phi_1^\dagger\phi_2\right)\right. \\ & \left. \quad + \lambda_7|\phi_2|^2\left(\phi_1^\dagger\phi_2\right) + \mathrm{H.c.}\right]\end{aligned}$$

- $v_3 = \lambda_{H11} = \lambda_3 = \lambda_{H12} = \lambda_6 = \lambda_7 \approx 0.$
  (not exactly zero to allow decay of extra Higgs bosons)
- $v_1/v_2 \gg 1$ to decouple some particles from dark sector.
- (Latest) micromegas can deal with two-component DM.

DM candidates in the Simplified Model

gauge eigenstates	$\mathbb{Z}_2 \times \mathbb{Z}_2'$
h, φ_i, A_μ^7	$(+,+)$
A_μ^1, A_μ^4	$(-,-)$
A_μ^2, A_μ^5	$(-,+)$
$\chi, A_\mu^3, A_\mu^6, A_\mu^8$	$(+,-)$

- Pairs of (A_μ^1, A_μ^2) and (A_μ^4, A_μ^5) are completely degenerate.

$$\rightarrow A_\mu \equiv \frac{A_\mu^1 + iA_\mu^2}{\sqrt{2}}, \quad A_\mu' \equiv \frac{A_\mu^4 + iA_\mu^5}{\sqrt{2}}$$

- Kinetic mixing: $\mathcal{L} \supset \frac{\tilde{g}}{2} v_2 A_\mu^6 \partial^\mu \chi - \frac{\tilde{g}}{2} v_2 A_\mu^7 \partial^\mu \varphi_3$

  This can be diagonalized $(\chi, \varphi_3) \rightarrow (\tilde{\chi}, \tilde{\varphi}_3)$

Light particles	(decoupled) Heavy particles
A, $A^{3\prime}$, h_1, h_2, $\tilde{\chi}$	A', A^6, A^7, $A^{8\prime}$, h_3, h_4

$v_1/v_2 \gg 1$

- Possible combinations of two-component DM:
  $(A_\mu, \tilde{\chi})$, $(A_\mu', \tilde{\chi})$, (A_μ, A_μ') $\rightarrow$ possible combination $(A_\mu, \tilde{\chi})$
- 8 Independent parameters: m_A, $m_{\tilde{\chi}}$, $\tilde{g}$, $\sin\theta$, $m_{h_{2,3,4}}$, $r \equiv v_1/v_2$.

Mass spectra in the Simplified Model

- The masses of the hidden gauge bosons in the simplified model

$$m_A^2 = \frac{\tilde{g}^2}{4} v_2^2, \quad m_{A'}^2 = \frac{\tilde{g}^2}{4} v_1^2, \quad m_{A^6}^2 = m_{A^7}^2 = \frac{\tilde{g}^2}{4}\left(v_1^2 + v_2^2\right),$$

$$m_{A^{3\prime}/A^{8\prime}}^2 = \frac{2}{3} m_A^2 \left(1 + r^2\right) \left[1 \mp \sqrt{1 - \frac{3r^2}{(1+r^2)^2}}\right]$$

where $r = v_1/v_2 \gg 1$. $\rightarrow m_{A^{3\prime}} \lesssim m_A$ (degenerate).

- The masses of the scalar bosons in the simplified model

$$m_{h_3}^2 = \lambda_1 v_1^2, \quad m_{h_4}^2 = \frac{\lambda_4 + \lambda_5}{2} v_1^2, \quad m_{\tilde{\chi}}^2 = \frac{\lambda_4 - \lambda_5}{2} v_1^2,$$

φ_3 and h mix with $\sin\theta$ $\rightarrow$ the mass eigenstates h_1 and h_2

a little tuning between λ_4 and λ_5 may be needed so that $\tilde{\chi}$ is a light particle.

Numerical Computations

Relic Density of DM

Boltzmann equation $(m_A > m_{\tilde{\chi}})$

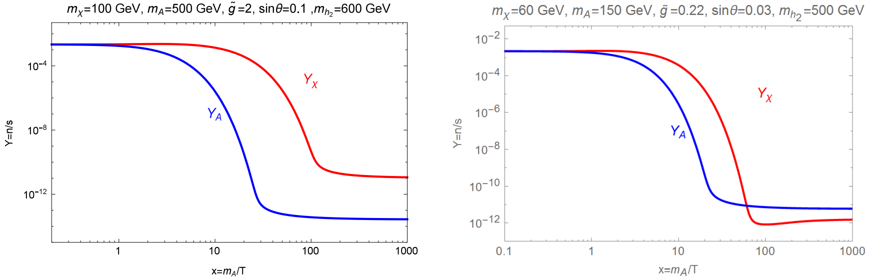
$$\begin{aligned}
\frac{dn_A}{dt} + 3Hn_A &= -\langle\sigma v\rangle_{AA\to \mathrm{SM}}\left(n_A^2 - n_A^{\mathrm{eq}2}\right) - \langle\sigma v\rangle_{AA\to\tilde{\chi}\tilde{\chi}}\left(n_A^2 - n_A^{\mathrm{eq}2}\frac{n_{\tilde{\chi}}^2}{n_{\tilde{\chi}}^{\mathrm{eq}2}}\right) \\
&\quad -\langle\sigma v\rangle_{AA\to A^3 h_i}\left(n_A^2 - n_A^{\mathrm{eq}2}\frac{n_{\tilde{\chi}}^2}{n_{\tilde{\chi}}^{\mathrm{eq}2}}\right) \\
\frac{dn_{\tilde{\chi}}}{dt} + 3Hn_{\tilde{\chi}} &= -\langle\sigma v\rangle_{\tilde{\chi}\tilde{\chi}\to \mathrm{SM}}\left(n_{\tilde{\chi}}^2 - n_{\tilde{\chi}}^{\mathrm{eq}2}\right) + \langle\sigma v\rangle_{AA\to\tilde{\chi}\tilde{\chi}}\left(n_A^2 - n_A^{\mathrm{eq}2}\frac{n_{\tilde{\chi}}^2}{n_{\tilde{\chi}}^{\mathrm{eq}2}}\right) \\
&\quad +\langle\sigma v\rangle_{AA\to A^3 h_i}\left(n_A^2 - n_A^{\mathrm{eq}2}\frac{n_{\tilde{\chi}}^2}{n_{\tilde{\chi}}^{\mathrm{eq}2}}\right) - \langle\sigma v\rangle_{AA^3\to Ah_i} n_A \frac{n_A^{\mathrm{eq}}}{n_{\tilde{\chi}}^{\mathrm{eq}}}\left(n_{\tilde{\chi}} - n_{\tilde{\chi}}^{\mathrm{eq}}\right)
\end{aligned}$$

Red: normal annihilations, Blue: conversions,
Green: Semi-conversions, Magenta: Semi-coannihilations

- Semi-coannihilations are suppressed by the Boltzmann factor unless $m_A \approx m_{\tilde{\chi}}$.

Boltzmann equation

Example of solutions

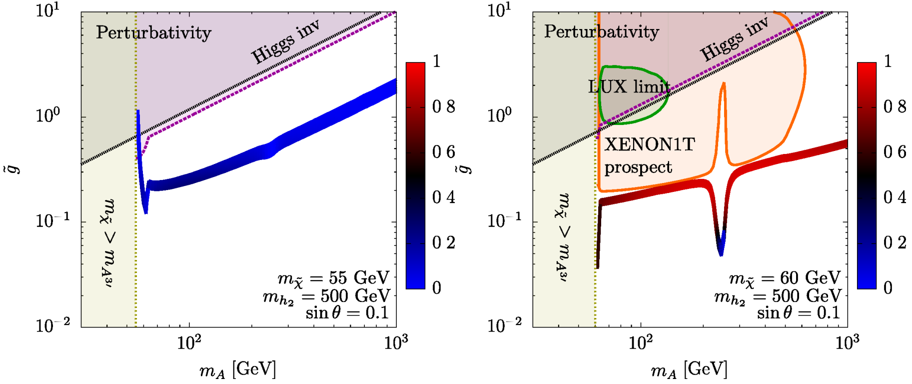


- DM relic density is basically dominated by scalar DM. Conversion process $AA \to \tilde{\chi}\tilde{\chi}$
- Annihilations to the SM particles are controlled by $\sin\theta$. $\sin\theta \lesssim 0.3$ by EWPD, collider experiments.

Example plots on $(\tilde{g}, m_A)$ plane

Example of plots 1

$r = 10$, $m_{h_3} = 5$ TeV, $m_{h_4} = 6$ TeV $\quad$ $\color{blue}{0} \leq \Omega_A/(\Omega_A + \Omega_{\tilde{\chi}}) \leq \color{red}{1}$



Left: slightly far from the resonance.

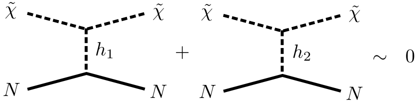
Right: close to the resonance $2m_{\tilde{\chi}} \approx m_{h_1}$

Direct Detection in The Simplified Model

- The scalar DM candidate does not scatter with nuclei in non-relativistic limit since the amplitude mediated by h_1 and h_2 cancels.
- This is actually not exactly zero, but scattering cross section is suppressed by the mass of A^6. (kinetic mixing)

$$\sigma_{\tilde{\chi}N} = \tilde{g}^2 \frac{\mu_{\tilde{\chi}N}^2}{16\pi} \frac{m_{\tilde{\chi}}^2 m_A^2}{m_{A^6}^4} \sin^2 2\theta \left(\frac{1}{m_{h_1}^2} - \frac{1}{m_{h_2}^2} \right)^2 \frac{(Zf_p + (A-Z)f_n)^2}{A^2}$$

$$\propto (\lambda_4 - \lambda_5) \frac{v_2^2}{v_1^2}$$



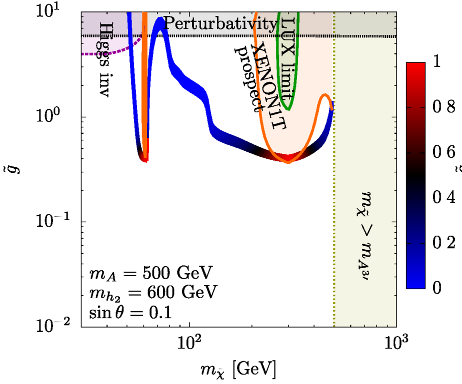
- Perturbativity

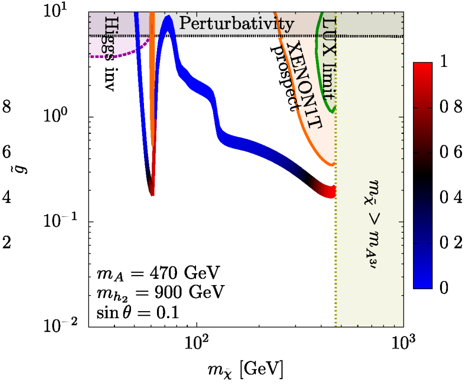
$$\lambda_2 = \tilde{g}^2 \frac{\sin^2\theta m_{h_1}^2 + \cos^2\theta m_{h_2^2}}{4m_A^2} < 4\pi, \quad \lambda_4 = \tilde{g}^2 \frac{m_{\tilde{\chi}}^2 + m_{h_4}^2}{4m_{A'}^2} < 4\pi$$

Example plots on $(\tilde{g}, m_{\tilde{\chi}})$ plane

Example of plots 2

$r = 10$, $m_{h_3} = 5$ TeV, $m_{h_4} = 6$ TeV





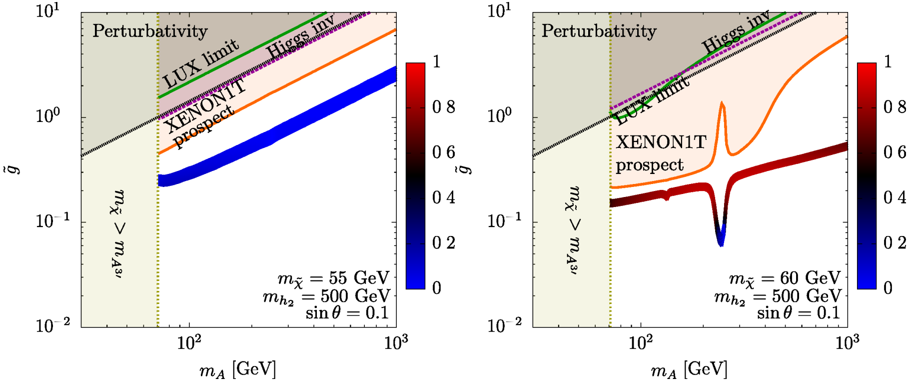
Left: slightly far from the resonance.

Right: close to the resonance $2m_A \approx m_{h_1}$

Example plots on $(\tilde{g}, m_A)$ plane

Example of plots 3 (small r)

$r = 1.2$, $m_{h_3} = 400$ GeV, $m_{h_4} = 300$ GeV

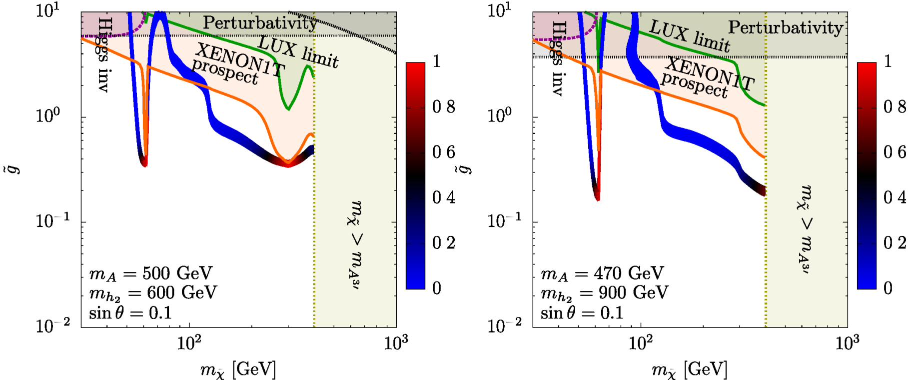


Direct detection rate for scalar DM increases.

Example plots on $(\tilde{g}, m_{\tilde{\chi}})$ plane

Example of plots 4 (small r)

$r = 1.2$, $m_{h_3} = 400$ GeV, $m_{h_4} = 300$ GeV



Direct detection rate for scalar DM increases.

How to discriminate two-component DM

- A kink may be viable in recoil energy distribution $\rightarrow$ since the pseudo-scalar DM does not scatter with nuclei in the simplified case.

  S. Profumo et al arXiv:0907.4374, K. R. Dienes et al arXiv:1208.0336

- However discriminative features would be obtained in combination of direct and indirect detection signals.
  - Scalar DM $\tilde{\chi}$: gamma-ray in indirect detection may be able to fit to the gamma-ray excess in the galactic centre.
  - Vector DM A_μ: responsible for direct detection.

Different signals of two-component DM in different mass range.

Work in progress

Summary

1. The model with $SU(3)$ hidden symmetry naturally includes multi-component DM.
2. In the simplified model, two-component DM composed of (A_μ, $\tilde{\chi}$) is the only possibility. $(m_{\tilde{\chi}} < m_A)$
3. To determine the relic density of vector DM, the conversion process $AA \to \tilde{\chi}\tilde{\chi}$ is dominant.
   $\to$ The abundance of scalar DM dominates the total DM density in the most of parameter space.
   (exception: resonance at $2m_{\tilde{\chi}} \approx m_{h_i}$)
4. Direct detection rate for scalar DM $\tilde{\chi}$ is small.
   $\to$ Descrimination from single-component DM:
   vector DM A_μ: direct detection
   scalar $\tilde{\chi}$: indirect detection