Hidden $SU(3)$ 対称性に基づく多成分暗黒物質

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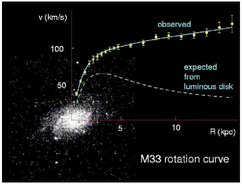
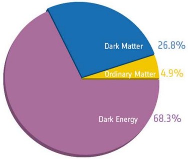
Work in Progress

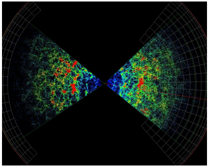
Evidences of dark matter

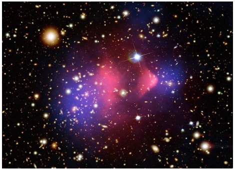
There are many evidences of dark matter.

- Rotation curves of spiral galaxies
- Observation of CMB ($\Omega h^2 = 0.12$)
- Gravitational lensing effect
- Large scale structure of the universe
- Collision of the bullet cluster









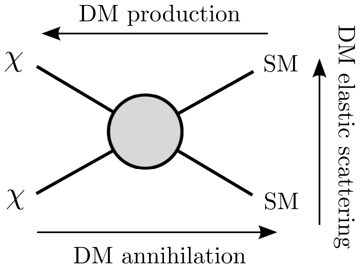
- Existence of dark matter is crucial.
- But its mass and interactions are not known yet.

Introduction

- Basic strategies to detect DM (WIMP)

  Indirect detection
  Direct detection
  Collider search

  → Strongly corrlated with each other for single-component DM

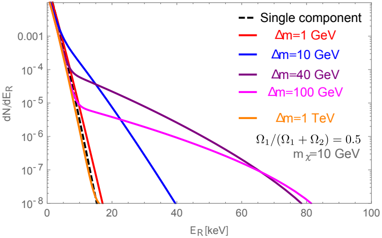


- Multi-component (WIMP) DM → Interesting phenomenology
  → Different observation prospects from single-component DM
  Ex. Disk formation made of sub-dominant DM
  → Double Disk Dark Matter

  J. Fan et al. arXiv:1303.1521, 1303.3271

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 arXiv:1505.07480:
  $SU(3)$ hidden gauge symmetry + minimal fields
  $\rightarrow$ naturally multi-component DM is realized ($\mathbb{Z}_2 \times \mathbb{Z}_2'$).

$$A_\mu^a \quad \mathbb{Z}_2 : \begin{cases} -1 \text{ for } a = 1,2,4,5 \\ +1 \text{ for } a = 3,6,7,8 \end{cases} \qquad \mathbb{Z}_2' : \begin{cases} -1 \text{ for } a = 1,3,4,6,8 \\ +1 \text{ for } a = 2,5,7 \end{cases}$$

The Hidden $SU(3)$ Model

The Model

- $SU(3)$ hidden symmetry is imposed.
- 8 hidden gauge bosons A_μ^a $(a = 1 - 8)$ exist.
  In order to minimally break the $SU(3)$ symmetry, 2 kinds of triplet scalars ϕ_1 and ϕ_2 are needed.

The Lagrangian:

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

After the $SU(3)$ symmetry breaking

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

The Full Scalar Potential

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

- The full model is hard to analyze due to complexity.
- Hidden particles interact with the SM via the Higgs boson.
  $\rightarrow$ Higgs portal
- Assuming CP symmetry, some components of vector bosons A_μ^a and CP-odd scalar χ can be stable because of the structure of $SU(3)$.
  $\rightarrow$ 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.

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

- $v_3,\ \lambda_{H11},\ \lambda_3,\ \lambda_{H12},\ \lambda_6,\ \lambda_7 \approx 0.$
  (not exactly zero to allow decay of extra Higgs bosons)
- $v_1/v_2 \gg 1$ to decouple some particles from dark sector.
- (Latest ver.) 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^7_μ	$(+,+)$
A^1_μ, A^4_μ	$(-,-)$
A^2_μ, A^5_μ	$(-,+)$
$\chi, A^3_\mu, A^6_\mu, A^8_\mu$	$(+,-)$

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

$$\to A_\mu \equiv \frac{A^1_\mu + iA^2_\mu}{\sqrt{2}}, \quad A'_\mu \equiv \frac{A^4_\mu + iA^5_\mu}{\sqrt{2}}$$

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

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

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) $\to$ possible combination $(A_\mu, \tilde{\chi})$
- 8 Independent parameters: m_A, $m_{\tilde{\chi}}$, $\tilde{g}$, $\sin\theta$, $m_{h_{2,3,4}}$, $r \equiv v_1/v_2$.

Numerical Computations

Relic Density of DM

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

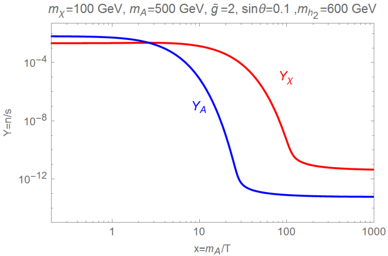
$$
\begin{aligned}
\frac{dn_A}{dt} + 3Hn_A &= -\langle\sigma v\rangle_{AA\to\mathrm{SM}}\left(n_A^2 - n_A^{\mathrm{eq}2}\right) - \langle\sigma v\rangle_{AA\to\tilde{\chi}\tilde{\chi}}\left(n_A^2 - n_A^{\mathrm{eq}2}\frac{n_{\tilde{\chi}}^2}{n_{\tilde{\chi}}^{\mathrm{eq}2}}\right) \\
&\quad -\langle\sigma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

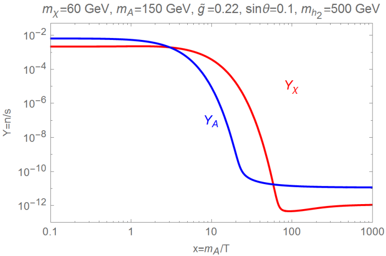
Red: normal annihilations, Blue: conversions,
Green: Semi-conversions, Magenta: Semi-coannihilations

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

Boltzmann equation

Example of solutions



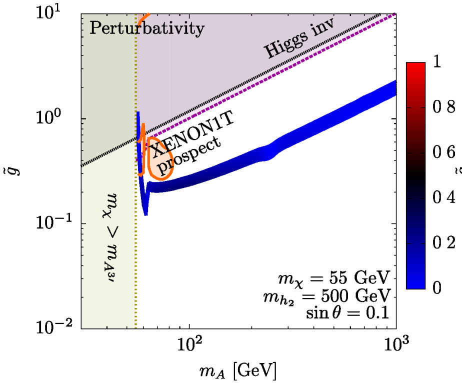


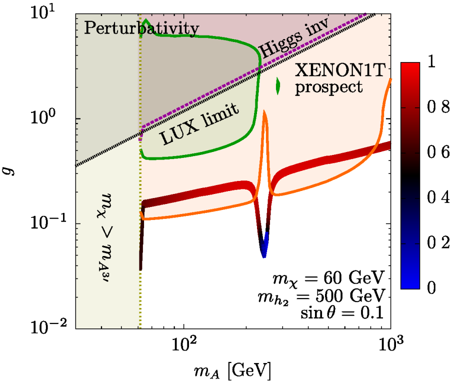
- DM relic density is basically dominated by scalar DM. Conversion process $AA \to \tilde{\chi}\tilde{\chi}$
- Annihilations to the SM particles are controlled by $\sin\theta$. $\sin\theta \lesssim 0.3$ by EWPD, collider experiments.

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

Example of plots 1

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





Left: slightly far from the resonance.

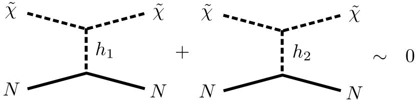
Right: close to the resonance $2m_{\tilde{\chi}} \approx m_{h_1}$

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)

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

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



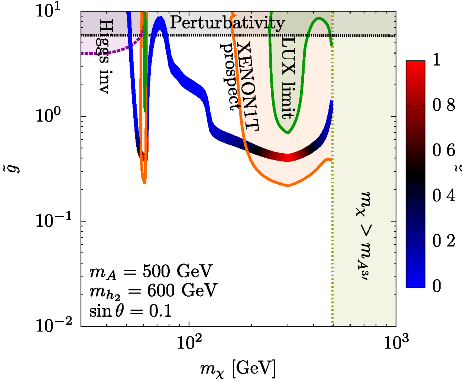
- Perturbativity

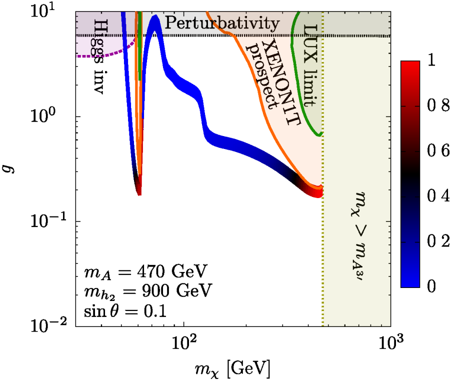
$$\lambda_2 = \tilde{g}^2 \frac{\sin^2\theta m_{h_1}^2 + \cos^2\theta m_{h_2^2}}{4m_A^2} < 4\pi, \quad \lambda_4 = \tilde{g}^2 \frac{m_{\tilde{\chi}}^2 + m_{h_4}^2}{4m_{A'}^2} < 4\pi$$

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





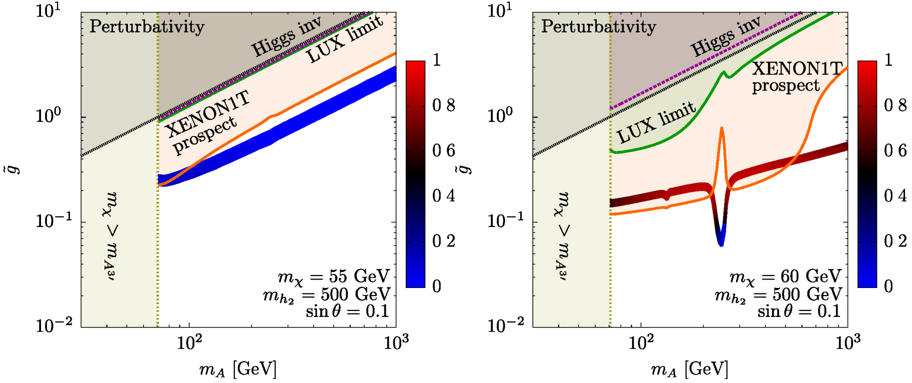
Left: slightly far from the resonance.

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, non-simplified case)

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

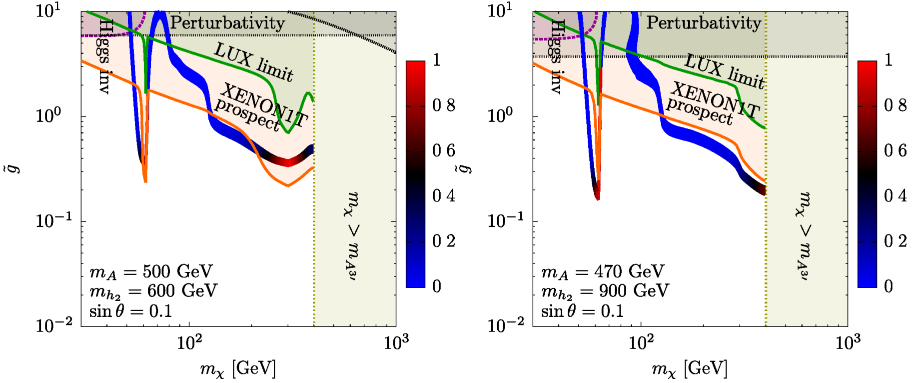


Direct detection rate for scalar DM increases.

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

Example of plots 4 (small r, non-simplified case)

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

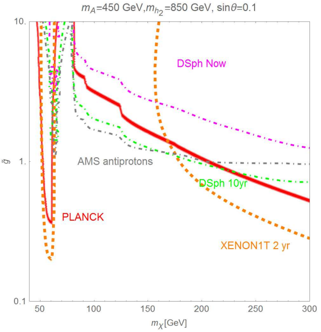


Direct detection rate for scalar DM increases.

Discriminative features of two-component DM

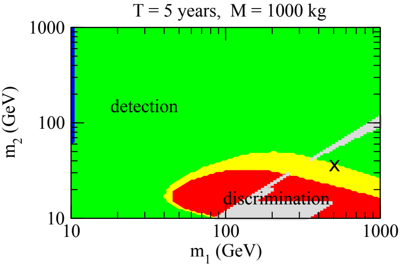
- For large $r = v_1/v_2$ regime (simplified case)
  Scalar DM tends to be dominant.
  Scalar DM is invisible by direct detection, but visible by indirect detection gamma-ray emission via $(\tilde{\chi}\tilde{\chi} \to b\bar{b}, t\bar{t}, WW, ZZ, hh)$
  $\to$ broad gamma-ray spectrum.

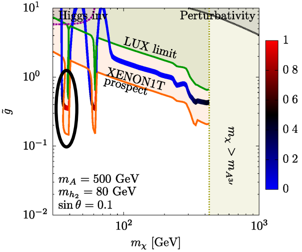
  Since the main channel for vector DM is $AA \to \tilde{\chi}\tilde{\chi}$,
  $\to$ no indirect signal. But vector DM can be detected by direct detection.
  Both DM can be tested by only one detection strategy.



Discriminative features of two-component DM

- For small r regime (non-simplified case)
  A kink may be viable in recoil energy distribution.
  S. Profumo et al arXiv:0907.4374, K. R. Dienes et al arXiv:1208.0336
  - Suppose ideal experimental data (recoil energy distribution)
  - Try to fit to the data with single-component DM and two-component DM in a parameter set.
  - If two-component fitting gives better fit $\rightarrow$ discriminable.





S. Profumo et al arXiv:0907.4374

Summary

1. The model with $SU(3)$ hidden symmetry naturally includes multi-component DM (A_μ, $\tilde{\chi}$).
2. The abundance of scalar DM dominates the total DM density in most of the parameter space. (exception: resonance at $2m_{\tilde{\chi}} \approx m_{h_i}$)
3. For large r regime, the model is simplified.
   Direct detection rate for scalar DM $\tilde{\chi}$ is small.
   $\rightarrow$ Descriminative feature of two-component DM:
   vector DM A_μ: DD signal,   scalar $\tilde{\chi}$: ID signal
4. For small r regime, the model is not simplified.
   Suppression of direct detection probability for scalar DM $\tilde{\chi}$ is relaxed.
   $\rightarrow$ possible to discriminate by direct detection experiments.