Dark Matter from Hidden Gauge Symmetry

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Open Questions in Particle Physics and Cosmology

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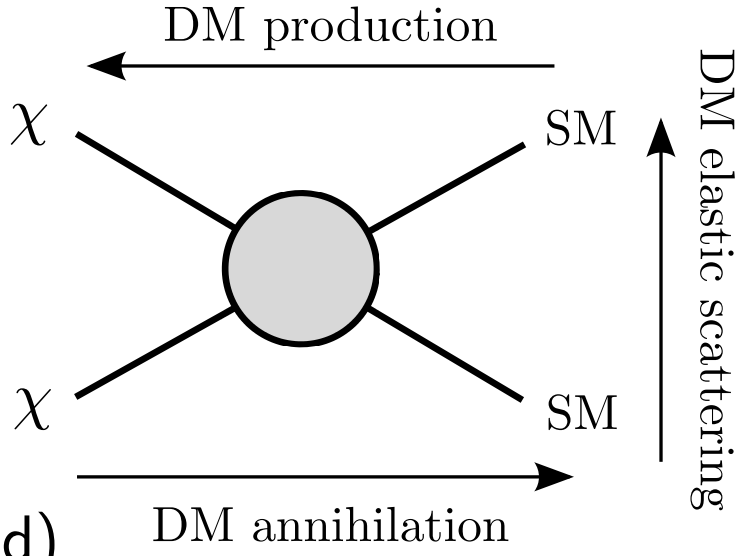
Introduction

- The existence of DM is crucial from many observations.
- Candidates: WIMP, axion, ADM, FIMP, SIMP etc
- Basic strategies to detect DM (WIMP)

  · Indirect detection
  · Direct detection
  · Collider search
  $\rightarrow$ Strongly correlated with each other



- Ex. singlet scalar DM (S, $\mathbb{Z}_2$ odd)

$$\mathcal{V} \supset \frac{\lambda_{HS}}{2}|H|^2 S^2 \quad \rightarrow \quad \sigma v \propto \lambda_{HS}^2, \quad \sigma_{\rm SI} \propto \lambda_{HS}^2$$

$\rightarrow$ tension between Ωh^2 and direct detection

Introduction

- Experimental results infer weak interactions between visible sector and DM.
  $\rightarrow$ DM is in hidden sector.
- Hidden gauge symmetry with minimal number of scalar fields
  $\rightarrow$ a vector boson is stabilized by unbroken symmetry.
  cf: T. Hambye arXiv:0811.0172, C. Gross et al arXiv:1505.07480
- Moreover, an additional paritcle can be stable depending on CP (conserved or not).
- We consider hidden $U(1)$ and $SU(3)$ symmetries.
  No kinetic mixing is assumed for $U(1)$ case.
  (motivatied by the $E_8 \times E_8$ gauge symmetry in string theory.)
  Note: Phenomenology of $SU(2)$ is similar with the $U(1)$ case, but no kinetic mixing automatically.

Outline

1. Introduction
2. Hidden $U(1)$ Model
3. Hidden $SU(3)$ Model (CP Violating case)
4. Hidden $SU(3)$ Model (CP Conserving case)
   $\rightarrow$ Multi-component DM
5. Summary

The $U(1)$ Model

The $U(1)$ Model

- The Lagrangian:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - \mathcal{V}, \quad \text{where} \quad D_\mu = \partial_\mu + \frac{i\tilde{g}}{2}A_\mu.$$

  The scalar potential includes $\mathcal{V} \supset \lambda_{H\phi}|H|^2|\phi|^2$.
- After the symmetry breaking

$$\phi = \frac{1}{\sqrt{2}}\left(\ \tilde{v} + \rho\ \right), \quad H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_H + h \end{pmatrix}$$

  $\rightarrow$ the gauge boson A_μ gets the mass $m_A = \tilde{g}\tilde{v}/2$.
- The new Higgs ρ mixes with h.

$$\begin{pmatrix} h \\ \rho \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} \quad h_1 \text{ is SM-like Higgs}$$

- No coupling A_μ-h_i-h_j. $\rightarrow$ the gauge boson A_μ is stabilized.

Relic density

- DM can interact with the SM particles through the Higgs boson (Higgs portal).
- Annihilation channels: $AA \to f\overline{f}, ZZ, WW, h_1h_1, h_1h_2$
  These channels are suppressed by the small mixing angle.

$$\sigma v \propto \sin^2\theta \cos^2\theta$$

  ($\sin\theta \lesssim 0.2$ by experiments) A. Falkowski et al arXiv:1502.01361
- But the channel $AA \to h_2h_2$ is not suppressed.
  In the limit of $\sin\theta \ll 1$ and $m_{h_1} \ll m_A, m_{h_2}$

$$\langle\sigma v\rangle = \frac{\tilde{g}^4}{576\pi m_A^2}\sqrt{1-\frac{m_{h_2}^2}{m_A^2}}\,\frac{11m_{h_2}^8 - 80m_{h_2}^6 m_A^2 + 240m_{h_2}^4 m_A^4 - 320m_{h_2}^2 m_A^6 + 176m_A^8}{(4m_A^2 - m_{h_2}^2)^2(2m_A^2 - m_{h_2}^2)^2}$$

- $\lambda_{H\phi}$ can be rewritten by the other parameters (not independent).

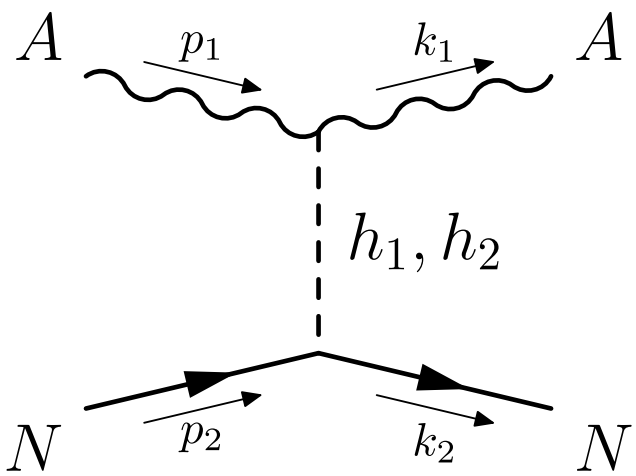
$$\lambda_{H\phi} = \tilde{g}\sin\theta\cos\theta\frac{m_{h_2}^2 - m_{h_1}^2}{2v_H m_A} \propto \sin\theta$$

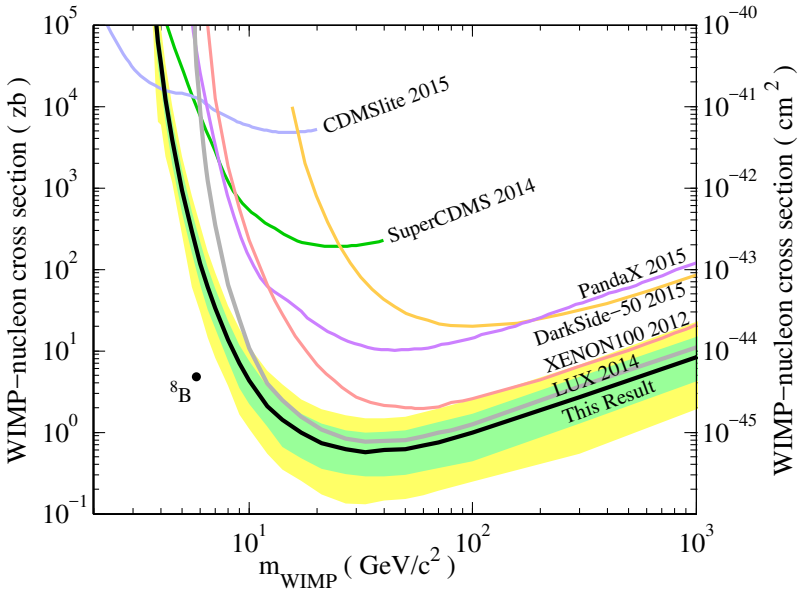
Direct Detection

- Spin-Independent cross section

$$\sigma_{\rm SI} = \frac{g_2^2 \tilde{g}^2}{16\pi} \frac{m_N^2 \mu_{AN}^2 f_N^2}{m_W^2} \left(\frac{1}{m_{h_1}^2} - \frac{1}{m_{h_2}^2} \right)^2 \sin^2\theta \cos^2\theta$$

$f_N \approx 0.3$ is the coupling between the SM Higgs and nucleon.

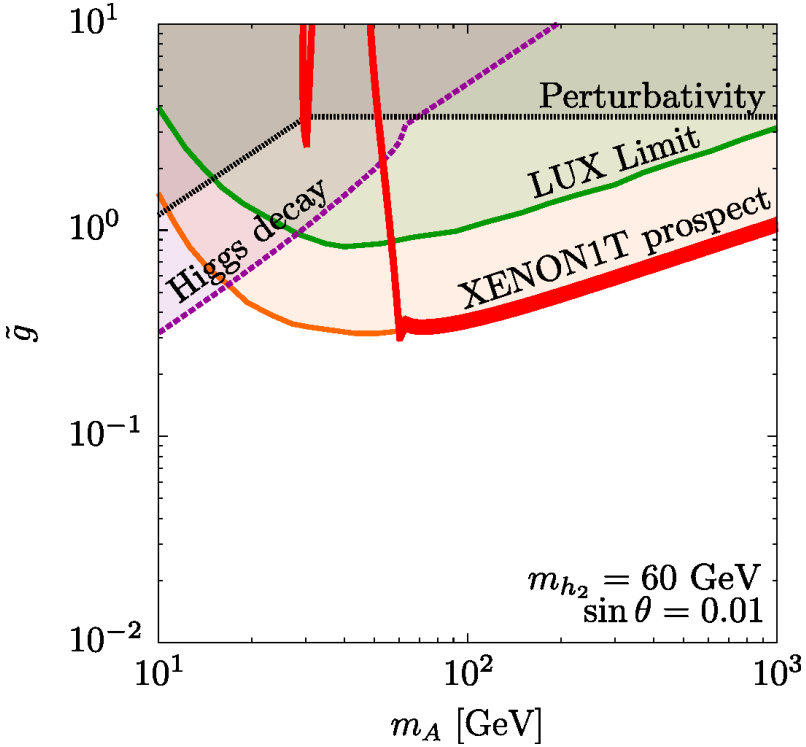


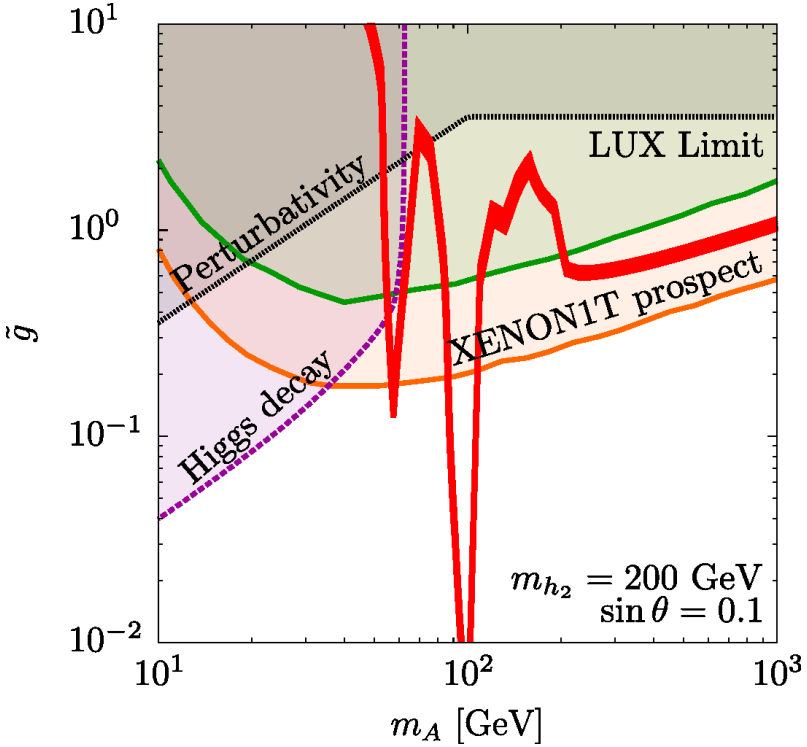


LUX Coll. arXiv:1512.03506

- 4 independent physical parameters: m_A, $\tilde{g}$, $\sin\theta$, m_{h_2}.

Numerical results





- Behaviour of the red band (PLANCK 3σ) drastically change at $m_A \sim m_{h_2}$. $\rightarrow$ channel $AA \rightarrow h_2 h_2$ kinematically open.
- Only $m_A \gtrsim m_{h_2}$ and resonance $m_A \sim m_{h_i}$ are allowed.
- We checked kinetic eq with the SM if $\sin\theta \gtrsim 0.01$.

The $SU(3)$ Model (CP Violating Case)

The $SU(3)$ Model

- 8 hidden gauge bosons A^a_μ $(a = 1 - 8)$ exist.
- 2 triplet scalars ϕ_1 and ϕ_2.
  (minimal field contents to break the $SU(3)$ symmetry)

The Lagrangian:

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

and $G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - \tilde{g} f^{abc} A^b_\mu A^c_\nu$.

Parametrization after the symmetry breaking

$$\phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ v_1 + \varphi_1 \end{pmatrix}, \quad \phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 + \varphi_2 \\ v_3 + \varphi_3 + i\varphi_4 \end{pmatrix}, \quad H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

The Full Scalar Potential

$$\mathcal{V} = \mu_H^2|H|^2 + \mu_1^2|\phi_1|^2 + \mu_2^2|\phi_2|^2 + \frac{\lambda_H}{2}|H|^4 + \frac{\lambda_1}{2}|\phi_1|^4 + \frac{\lambda_2}{2}|\phi_2|^4$$
$$+\lambda_{H11}|H|^2|\phi_1|^2 + \lambda_{H22}|H|^2|\phi_2|^2 + \lambda_3|\phi_1|^2|\phi_2|^2 + \lambda_4|\phi_1^\dagger\phi_2|^2$$
$$+\left[\mu_{12}^2\left(\phi_1^\dagger\phi_2\right) + \frac{\lambda_5}{2}\left(\phi_1^\dagger\phi_2\right)^2 + \lambda_6|\phi_1|^2\left(\phi_1^\dagger\phi_2\right)\right.$$
$$\left.\lambda_{H12}|H|^2\left(\phi_1^\dagger\phi_2\right) + \lambda_7|\phi_2|^2\left(\phi_1^\dagger\phi_2\right) + \text{H.c.}\right]$$

- The scalar potential is complicated. In addition, the model includes gauge self-interaction, mass mixing, kinetic mixing.
  $\rightarrow$ difficult to do numerical computations (even with micromegas)
- Simplify the model:
  [1] $v_3,\ \lambda_{H11},\ \lambda_3,\ \lambda_{H12},\ \lambda_6,\ \lambda_7,\ \mu_{12} \approx 0.$
  (not exactly zero to allow decay of extra Higgs bosons)
  [2] $v_1/v_2 \gg 1$ to decouple some particles from dark sector.

CP Violating Case

gauge eigenstates	$\mathbb{Z}_2$
$h, \varphi_i, A^3_\mu, A^6_\mu, A^7_\mu, A^8_\mu$	$+$
$A^1_\mu, A^2_\mu, A^4_\mu, A^5_\mu$	$-$

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

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

- Pair of (A^1_μ, A^2_μ) is DM.
- Mass mixing $(A^3, A^8) \to (A^{3\prime}, A^{8\prime})$ with mixing angle $\sin\alpha$
- Kinetic mixing: $(\varphi_4,\ \varphi_3) \to (\chi,\ \tilde{\varphi}_3)$ diagonalized

Light particles $\propto v_2$	Heavy particles $\propto v_1$
A, $A^{3\prime}$, h_1, h_2, χ	A', A^6, A^7, $A^{8\prime}$, h_3, h_4

$$v_1/v_2 \gg 1$$

- 5 Independent physical parameters: m_A, m_χ, $\tilde{g}$, $\sin\theta$, m_{h_2}.
- $m_A \gtrsim m_{A^{3\prime}}$ (mass difference $\propto v_2^2/v_1^2 \ll 1$)

Mass Specturm

- Gauge boson masses

$$m_{A^1}^2 = m_{A^2}^2 = \frac{\tilde{g}^2 v_2^2}{4}, \quad m_{A^4}^2 = m_{A^5}^2 = \frac{\tilde{g}^2 v_1^2}{4},$$

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

$$\frac{m_{A^{3\prime}}^2}{m_A^2} = 1 - \frac{\tan\alpha}{\sqrt{3}} < 1, \quad \frac{m_{A^{8\prime}}^2}{m_A^2} = \left(1 - \frac{\tan\alpha}{\sqrt{3}}\right)^{-1} > 1,$$

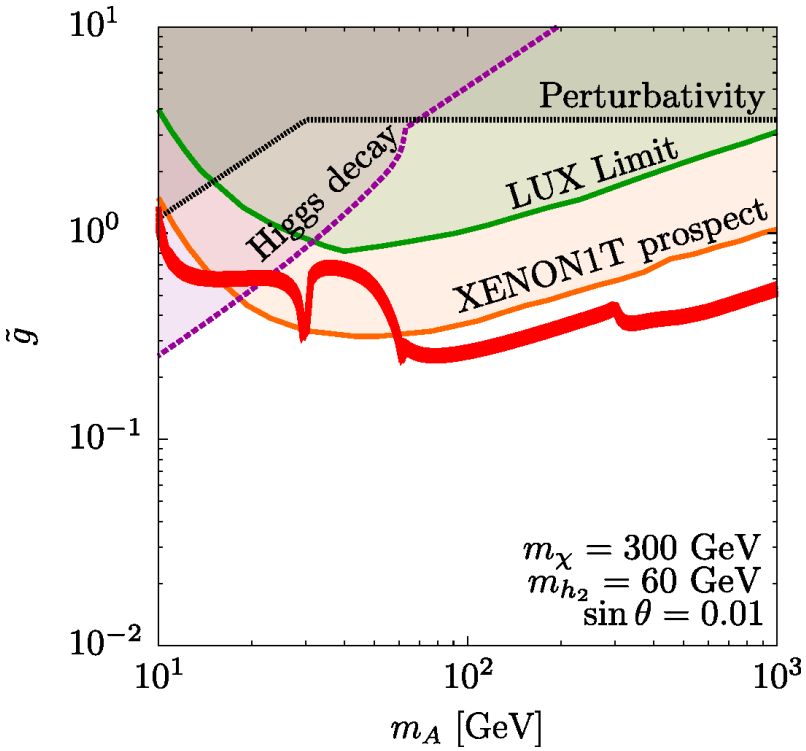
where $\tan 2\alpha = \dfrac{\sqrt{3} v_2^2}{2v_1^2 - v_2^2} \ll 1 \quad \left(\dfrac{v_2^2}{v_1^2} \ll 1\right)$

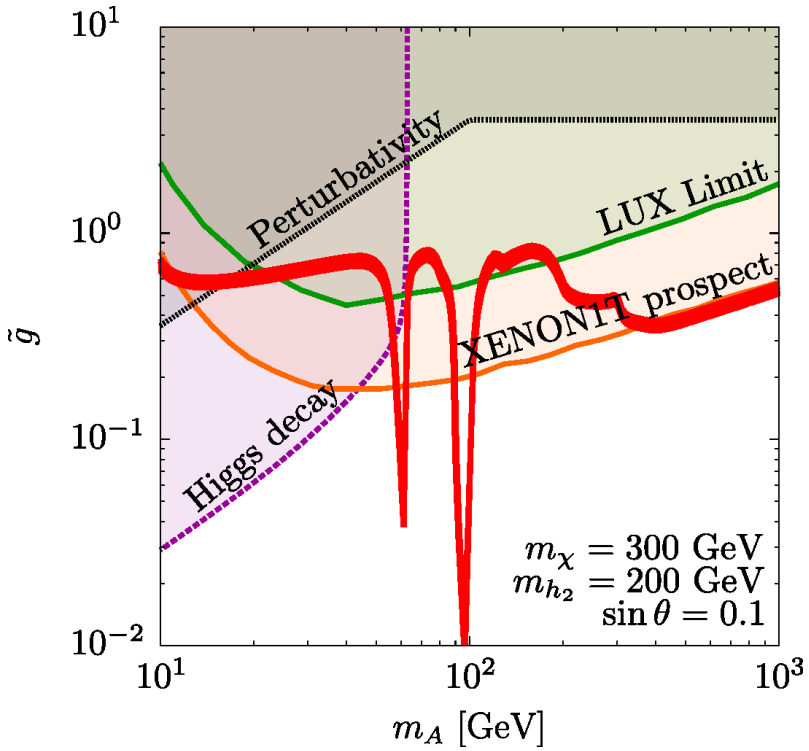
$\rightarrow$ $A^{3\prime}$ is always lighter than A (nealy degenerate).

- Pseudo-scalar mass

$$m_\chi^2 = \frac{\lambda_4 - \lambda_5}{2}(v_1^2 + v_2^2) = \frac{\lambda_4 - \lambda_5}{\tilde{g}^2} m_A^2 \left(\frac{v_1^2}{v_2^2} + 1\right)$$

Numerical results





- $AA \to A^{3\prime}A^{3\prime}$ is always possible even if $m_A < m_{h_2}$.
  $\to$ different from $U(1)$ case.
- This process is kinematically suppressed, but it is compensated by large gauge coupling $\tilde{g}$.

The $SU(3)$ Model (CP Conserving Case)

CP Conserving Case

CP violating case

gauge eigenstates	$\mathbb{Z}_2$
$h, \varphi_i, A^3_\mu, A^6_\mu, A^7_\mu, A^8_\mu$	$+$
$A^1_\mu, A^2_\mu, A^4_\mu, A^5_\mu$	$-$

$\Rightarrow$

CP conserving case

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	$(-,+)$
$\varphi_4, A^3_\mu, A^6_\mu, A^8_\mu$	$(+,-)$

- Mass and kinetic mixings are diagonalized.
  $(A^3, A^8) \to (A^{3\prime}, A^{8\prime})$, $\quad (\varphi_4,\, \varphi_3) \to (\chi,\, \tilde{\varphi}_3)$
- The lightest particle in φ_4, A^3_μ, A^6_μ, A^8_μ is also stable.
  $\to \chi$ is assumed to be the lightest (two-component DM).

Light particles $\propto v_2$	Heavy particles $\propto v_1$
A, $A^{3\prime}$, h_1, h_2, χ	A', A^6, A^7, $A^{8\prime}$, h_3, h_4

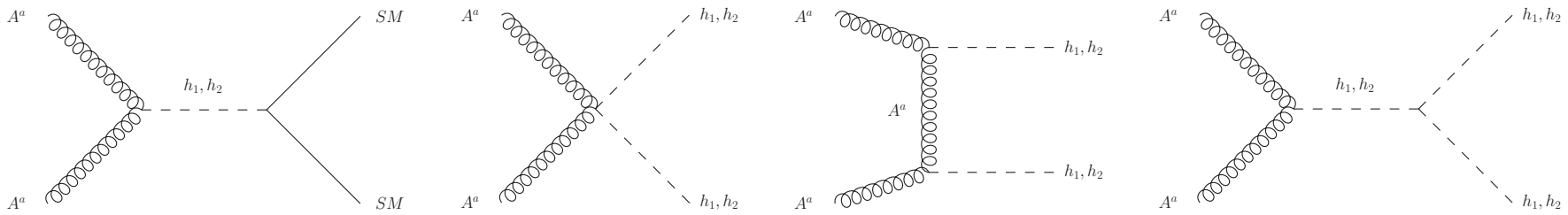
$v_1/v_2 \gg 1$

- 5 Independent parameters: m_A, m_χ, $\tilde{g}$, $\sin\theta$, m_{h_2}.

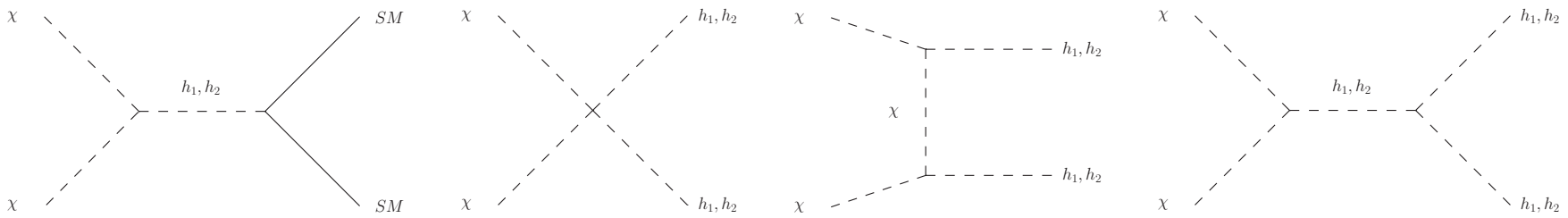
Relic Density of two-component DM (A and χ)

Possible processes ($m_A > m_\chi$)

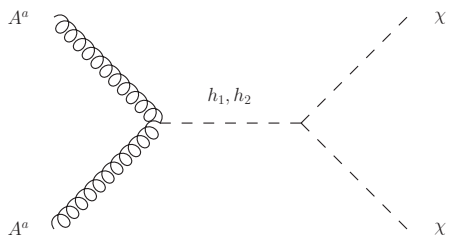
- $AA \to$SM, Higgs



- $\chi\chi \to$SM, Higgs



- $AA \to \chi\chi$



$+$ Other channels

Relic Density of two-component DM (A and χ)

Coupled Boltzmann equations ($m_A > m_\chi$)

$$\frac{dn_A}{dt} + 3Hn_A = -\langle\sigma v\rangle_{AA\to\mathrm{SM}}\left(n_A^2 - n_A^{\mathrm{eq}2}\right) - \langle\sigma v\rangle_{AA\to\chi\chi}\left(n_A^2 - n_A^{\mathrm{eq}2}\frac{n_\chi^2}{n_\chi^{\mathrm{eq}2}}\right)$$
$$-\langle\sigma v\rangle_{AA\to A^3 h_i}\left(n_A^2 - n_A^{\mathrm{eq}2}\frac{n_\chi^2}{n_\chi^{\mathrm{eq}2}}\right) + \cdots$$

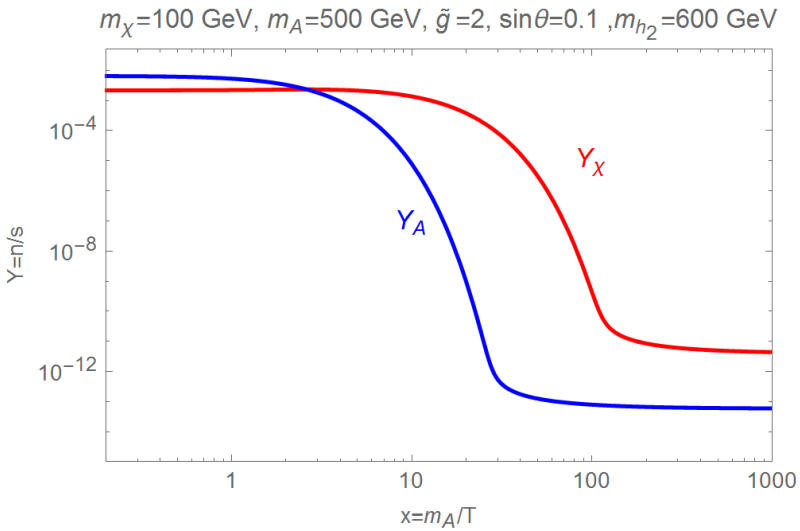
$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle_{\chi\chi\to\mathrm{SM}}\left(n_\chi^2 - n_\chi^{\mathrm{eq}2}\right) + \langle\sigma v\rangle_{AA\to\chi\chi}\left(n_A^2 - n_A^{\mathrm{eq}2}\frac{n_\chi^2}{n_\chi^{\mathrm{eq}2}}\right)$$
$$+\langle\sigma v\rangle_{AA\to A^3 h_i}\left(n_A^2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

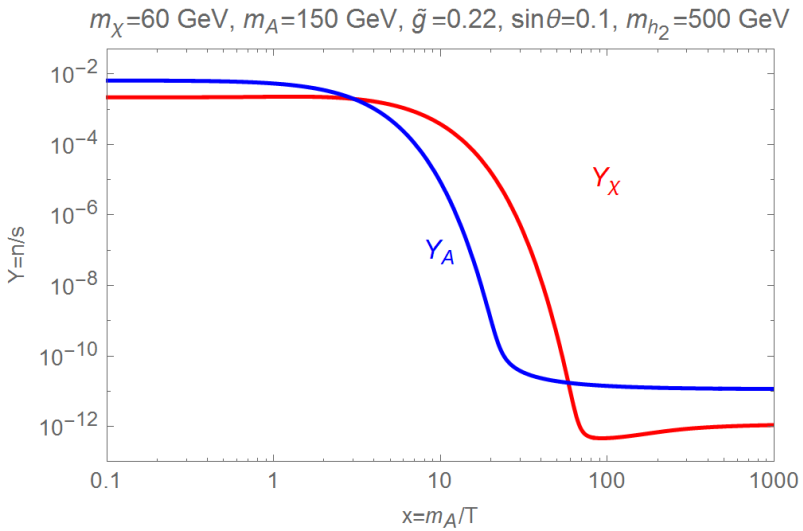
Red: normal annihilations, Blue: conversions,
Green: Semi-conversions, Magenta: Semi-coannihilations

- Semi-coannihilations are suppressed by the Boltzmann factor unless $m_A \approx m_\chi$.
- micromegas can deal with two-component DM.

Relic Density of two-component DM (A and χ)

Example of solutions



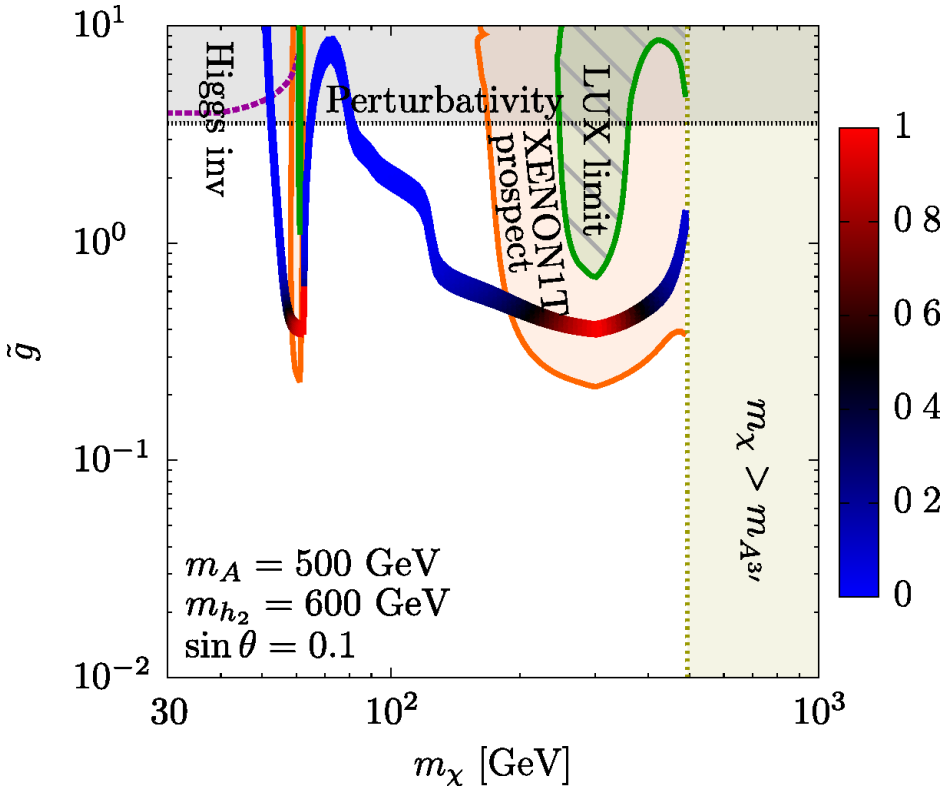


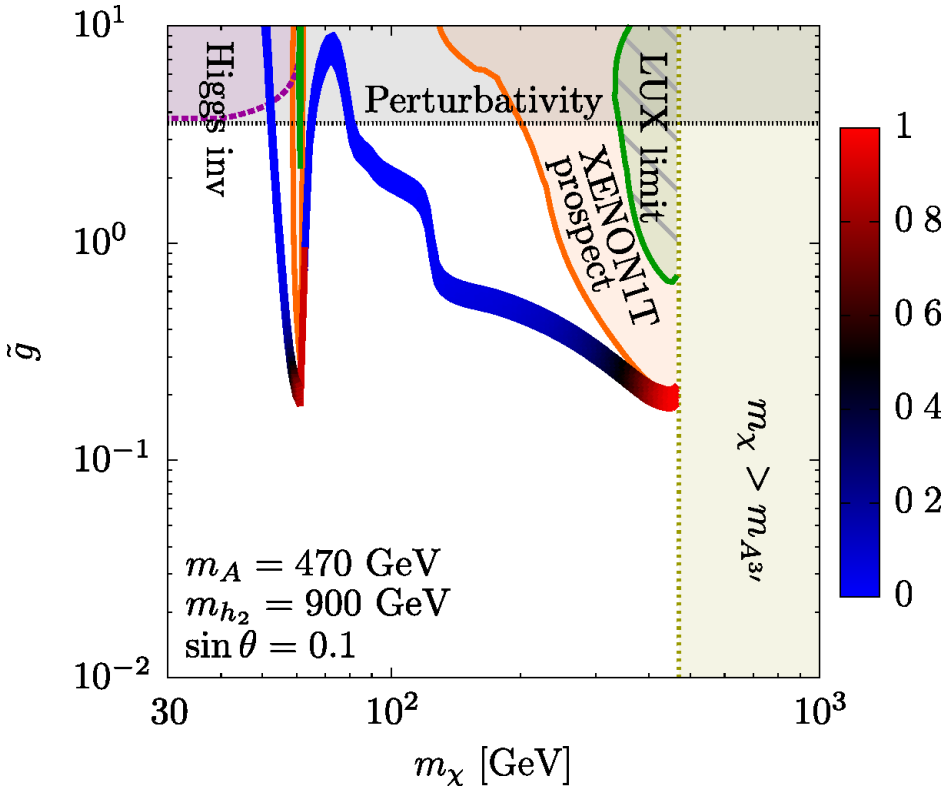
- DM relic density is basically dominated by scalar DM.
  $\leftarrow$ Due to conversion process $AA \to \chi\chi$ and small $\sigma_\chi v$.
- Annihilations to the SM particles are controlled by $\sin\theta$.
  $\sin\theta \lesssim 0.2$ by EWPD, collider experiments.
- Discriminative features may appear in indirect and direct detection searches.

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

Example of plots

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



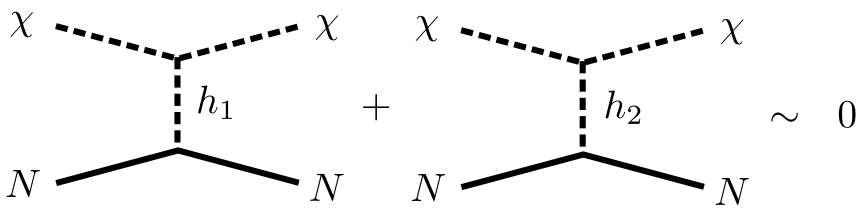


Left: slightly far from the resonance $2m_A \gtrsim m_{h_2}$.

Right: close to the resonance $2m_A \approx m_{h_2}$.

Implications of two-component DM

- A: detectable only by direct detection $AN \to AN$
  χ: detectable only by indirect detection $\chi\chi \to f\overline{f}, WW, ZZ, h_1 h_1$
  $\to$ Signals are differentiated from single WIMP.
  In fact, elastic cross section is cancelled between h_1 and h_2 mediated diagrams.



- Boosted DM χ
  $AA \to \chi\chi$ happens at Galactic Centre with energy spectrum
  $$\frac{dN}{dE_\chi} = \delta(E_\chi - m_A)$$
  · Boosted DM behaves similar to high energy neutrinos.
  · This could be detected by large experiments Super-K, Hyper-K, PINGU etc. K. Agashe et al. arXiv: 1405.7370

Summary

1. The models extended by hidden gauge symmetries with mimimal number of scalar fields naturally have DM candidates.
2. Annihilation channels into hidden sector particles relax the tension between DM relic abundance and strong experimental constraints.
3. For $SU(N)$ larger than $N \geq 3$, multi-particles can be stable. $\rightarrow$ multi-component DM inferring different signals from single WIMP.