Dark Matter from Hidden Gauge Symmetry

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MIAPP Workshop 2017

Direct Dark Matter Detection: Experiment meets Theory

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Based on JHEP **1612**, 081 (2016) and arXiv:1611.09675

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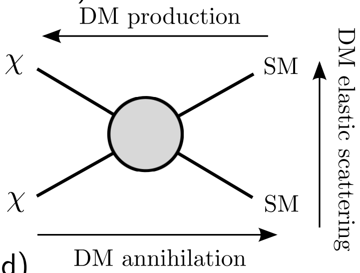
Introduction

- 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

- Experiments imply that interactions between visible sector and DM are weak.
  $\rightarrow$ DM is in hidden sector.
- Hidden gauge symmetry $\rightarrow$ a vector boson is stabilized by unbroken symmetry if the model is extended with minimal number of scalar fields. cf: C. Gross et al arXiv:1505.07480
- Moreover, an additional paritcle can be stable depending on situation (CP conserved or not).
- We consider hidden $U(1)$ and $SU(3)$ symmetries.
  No kinetic mixing is assumed.
  (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.

Outline

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.

$$\begin{pmatrix} h \\ \rho \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$ h_1 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 $m_{h_1} \ll m_A, m_{h_2}$

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

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

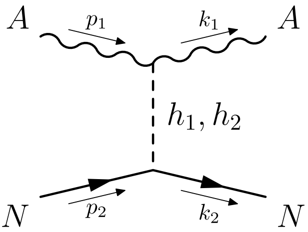
$$\lambda_{H\phi} = \tilde{g}\sin\theta\cos\theta\frac{m_{h_2}^2 - m_{h_1}^2}{2v_Hm_A} \propto \sin\theta$$

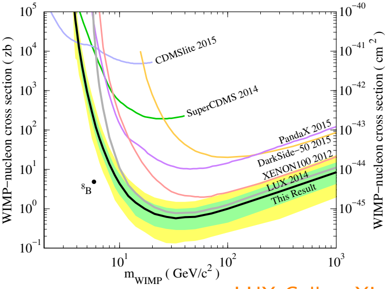
Direct Detection

- Spin-Independent cross section

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

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

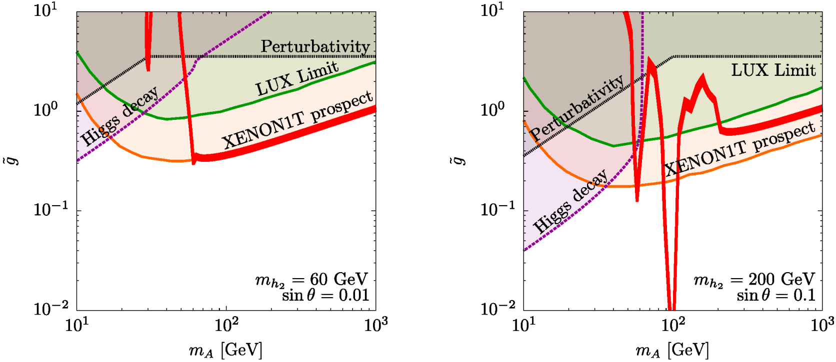




LUX Coll. arXiv:1512.03506

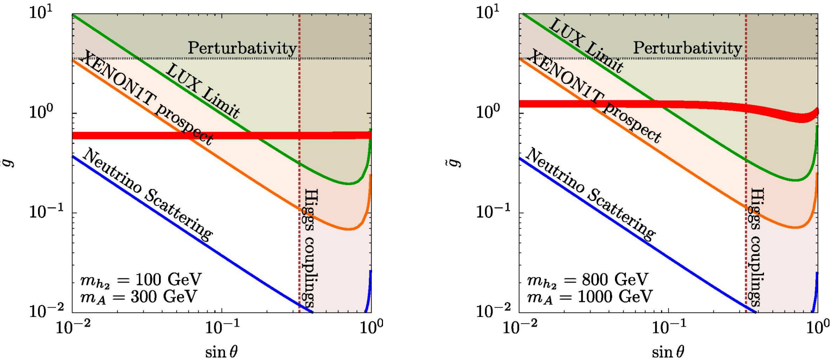
- 4 independent physical parameters: m_A, $\tilde{g}$, $\sin\theta$, m_{h_2}.

Numerical results



- Behaviour of the red band (PLANCK $\pm 3\sigma$) 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. (Resonance region may not be in kinetic eq with the SM.)

Numerical results 2



- One can see that $\sin\theta$ dependence is small if m_A is much heavier than the other particles.
  $\rightarrow \sigma v \sim \sum_{i,j=1,2} \sigma v(AA \rightarrow h_i h_j)$ is almost independent on $\sin\theta$.
- The region $\sin\theta \sim 0.1$ can be tested by XENON1T.

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

The $SU(3)$ Model

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

The Lagrangian:

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

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

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

- The full model is hard to analyze due to complexity.
  Including gauge self-interaction, mass mixing, kinetic mixing.
  $\rightarrow$ difficult to do numerical computations (even by micromegas)
- Simplify the potential: $v_3,\ \lambda_{H11},\ \lambda_3,\ \lambda_{H12},\ \lambda_6,\ \lambda_7,\ \mu_{12} \approx 0$.
  (not exactly zero to allow decay of extra Higgs bosons)
- $v_1/v_2 \gg 1$ 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.

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

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

Light particles	Heavy particles
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}.

Mass Specturm

- Gauge boson masses

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

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

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

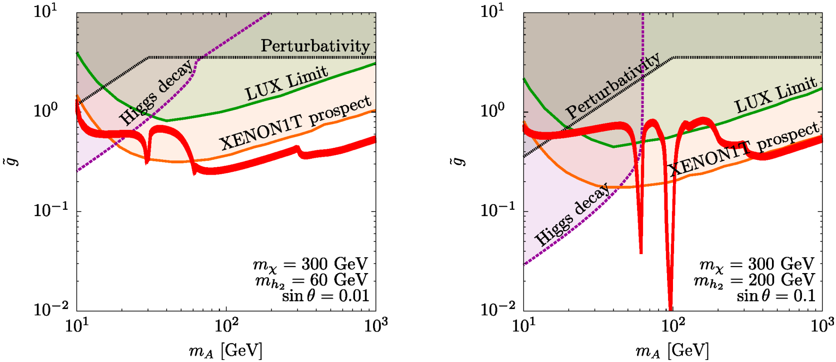
where $\tan 2\alpha = \dfrac{\sqrt{3}v_2^2}{2v_1^2 - v_2^2} \ll 1 \quad \left(\dfrac{v_2^2}{v_1^2} \ll 1\right)$

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

- Pseudo-scalar mass

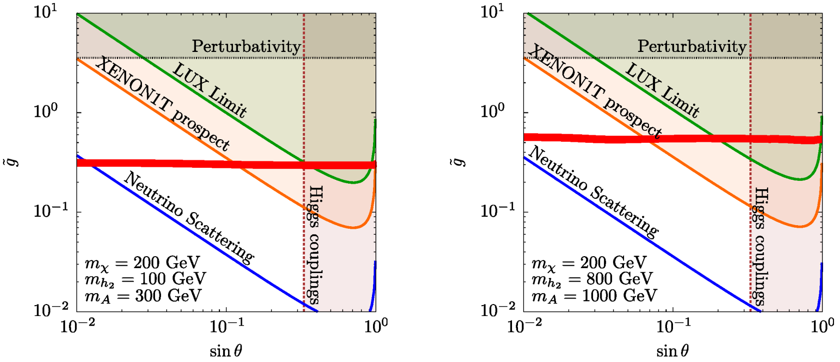
$$m_\chi^2 = \frac{\lambda_4 - \lambda_5}{2}(v_1^2 + v_2^2) = \frac{\lambda_4 - \lambda_5}{\tilde{g}^2} m_A^2 \left(\frac{v_1^2}{v_2^2} + 1\right)$$

Numerical results 1



- $AA \to A^{3\prime}A^{3\prime}$ 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 $\tilde{g}$.

Numerical results 2



- Behaviour is similar to the $U(1)$ case.
- Required $\tilde{g}$ is slightly smaller.
  $\leftarrow$ additional channels into hidden particles.

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

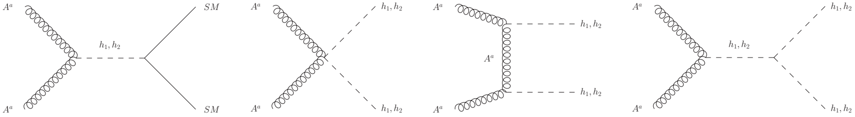
$v_1/v_2 \gg 1$

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

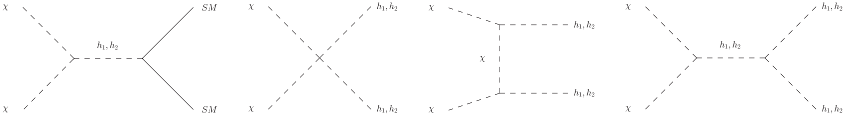
Relic Density of DM

Possible processes ($m_A > m_\chi$)

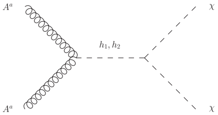
- $AA \to$SM, Higgs



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



- $AA \to \chi\chi$



$+$ Other channels

Relic Density of DM

Boltzmann equation $(m_A > m_\chi)$

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

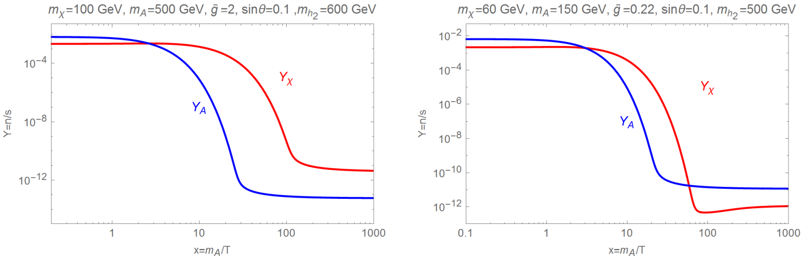
$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle_{\chi\chi\to\mathrm{SM}}\left(n_\chi^2 - n_\chi^{\mathrm{eq}2}\right) + \langle\sigma v\rangle_{AA\to\chi\chi}\left(n_A^2 - n_A^{\mathrm{eq}2}\frac{n_\chi^2}{n_\chi^{\mathrm{eq}2}}\right) + \langle\sigma v\rangle_{AA\to A^3 h_i}\left(n_A^2 - n_A^{\mathrm{eq}2}\frac{n_\chi^2}{n_\chi^{\mathrm{eq}2}}\right)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

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.

Boltzmann equation

Example of solutions

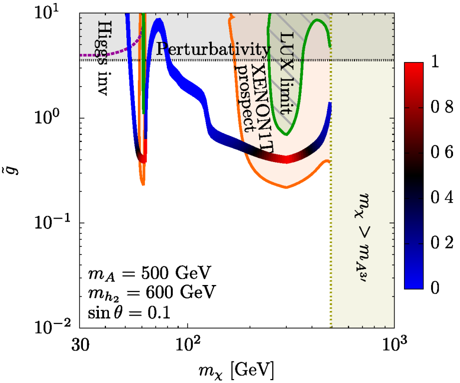


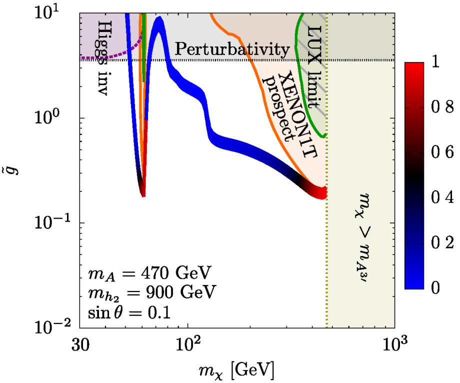
- DM relic density is basically dominated by scalar DM.
  $\leftarrow$ Conversion process $AA \to \chi\chi$
- Annihilations to the SM particles are controlled by $\sin\theta$.
  $\sin\theta \lesssim 0.2$ by EWPD, collider experiments.
- Discriminative features may appear in indirect and direct detection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

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

Example of plots

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





Left: slightly far from the resonance.

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

Summary

1. The models extended by hidden gauge symmetries 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.