Dark matter physics In dark SU(2) gauge symmetry with non-Abelian kinetic mixing

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Based on work in progress
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1. Introduction
2. Model setup
3. Phenomenology
4. Summary and discussion

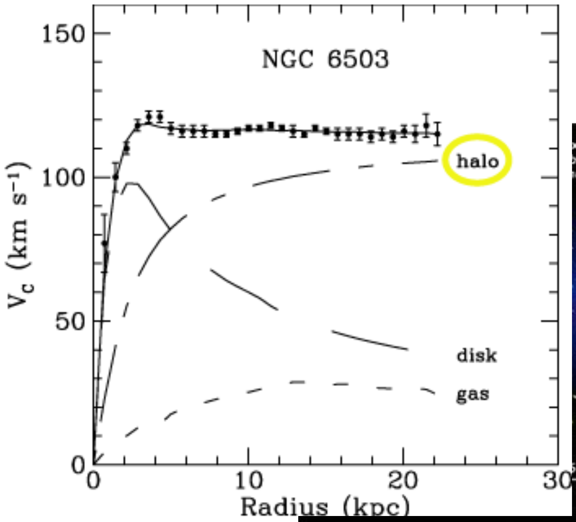
1. Introduction

Many observation indicate the existence of dark matter

❖**Rotation of spiral galaxies**

$$v(r) \propto \sqrt{M(r)/r}$$

M(r) ∝ r in outside of visible region



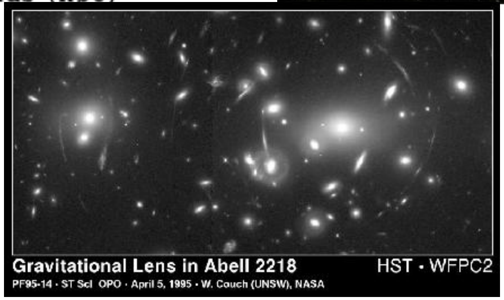
❖**Clusters of galaxies**

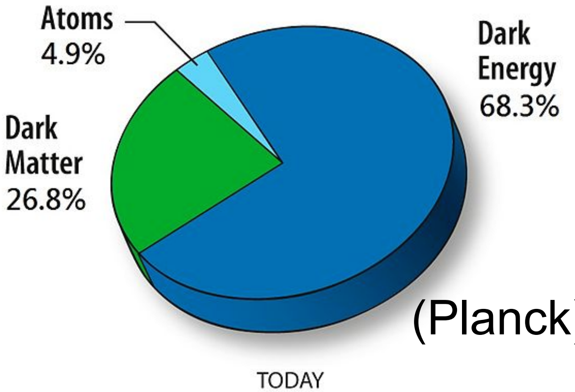
❖**Gravitational lensing**

❖**Formation of Large scale structure**

❖**Bullet Clusters**

❖**CMB anisotropy : WMAP, Planck**





(Planck)

Only through gravitational interaction

1. Introduction

Nature of typical particle DM candidate

DM
- ✧**No electric charge, no color, Non-baryonic**
- ✧**Weakly interacting**
- ✧**Stability**

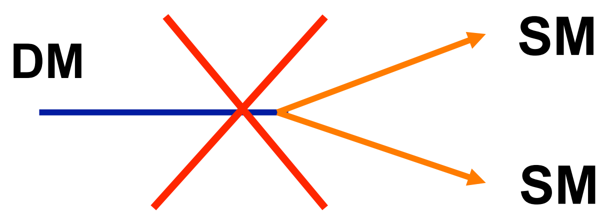
How DM can be stable? ⇒ **By some symmetry?**

Ex) Z_2 parity

Theory is symmetric under

$$\phi_{SM} \to \phi_{SM}$$
$$\phi_D \to -\phi_D$$

DM is lightest odd particle



$\phi_D \cancel{\phi_{SM}} \phi_{SM}$

DM cannot decay

Nature of typical particle DM candidate

DM

- ✧**No electric charge, no color, Non-baryonic**
- ✧**Weakly interacting**
- ✧**Stability**

How DM can be stable? → **By some symmetry?**

R-parity (SUSY), KK-parity (UED), Global Z_N symmetry, etc.

Usually Z_N symmetry is just assumed → there would be an origin

Stable DM form hidden gauge symmetry

- ❖ Abelian gauge symmetry
- ❖ Non-Abelian gauge symmetry

DM stability from Hidden gauge symmetry

- Abelian gauge symmetry case

Ex) Z_2 discrete symmetry from U(1) (Krauss and Wilczek PRL 62 (1989))

U(1) breaking by $<\Phi_2>\neq 0$ Φ_2 :Scalar field with U(1) charge 2

$$\exp\left[i\hat{Q}\pi\right]\left|Vacuum\right\rangle = \left|Vacuum\right\rangle$$:Vacuum has remaining symmetry

For any field ϕ_{2n+1} with U(1) charge 2n+1 (n: integer)

$$\phi_{2n+1} \to \exp\left[i\hat{Q}\pi\right]\phi_{2n+1} = \exp[i\pi(2n+1)]\phi_{2n+1} = -\phi_{2n+1}$$

$\Rightarrow$ Z_2 symmetry if U(1) charge of any field is integer

Stability of DM from the symmetry

There are models based on the idea

(B. Battel PRD 83 (2011); M. Ibe, S. Matsumoto, and T.T. Yanagida PLB 708 (2011); W.F.Chiang, C.F. Wong PRD 85 (2012); T.N., C.W.Chian, J.Tandean PRD 87 (2013); P.Ko, Y.Tang JCAP 1406 (2014); etc..)

DM stability from Hidden gauge symmetry

❖ Non-Abelian gauge symmetry scenarios

There are many scenarios

❖**Discrete symmetry from SU(2)**

(T.N., C.W.Chian, J.Tandean JHEP 1401 (2014); T.N., C.Chen PLB 746 (2015))

❖**Stable vector DM by unbroken U(1) from SU(2)**

(V.V.Khoze, G.Ro JHEP 1410 (2014); S.Beak, P.Ko, W.I.Park JCAP 1410 (2014))

❖**Stable vector DM by custodial symmetry from SU(N)**

(T.Hambye JHEP 0901 (2009); C.Gross, O.Lebedev, Y.Mambrini 1505.07480;
S.Di Chiara, K.Tuominen 1506.03285)

❖**Strongly interacting SU(N) hidden sector**

(T.Hur, P.Ko PRL 106 (2011); M.R.Buckley, E.T.Neil PRD 87 (2013);
J. Kubo, K.S.Lim, M.Lindner JHEP 1409 (2014) etc..)

1. Introduction

We consider simple case of $SU(2)_D$

Suppose SU(2) triplet scalars Φ,Φ' get VEVs as

$< \phi_0 > \neq 0, < \phi'_1 > \neq 0$ For components with eigenvalue of T_3 is 0 and 1

$$\exp\left[iT_3 2\pi\right]\left|Vacuum\right\rangle = \left|Vacuum\right\rangle$$ **Remaining discrete symmetry**

Then for any particle with odd T_3 value

$$\exp\left[iT_3 2\pi\right]X = \exp\left[i(2n+1)2\pi\right]X = -X$$

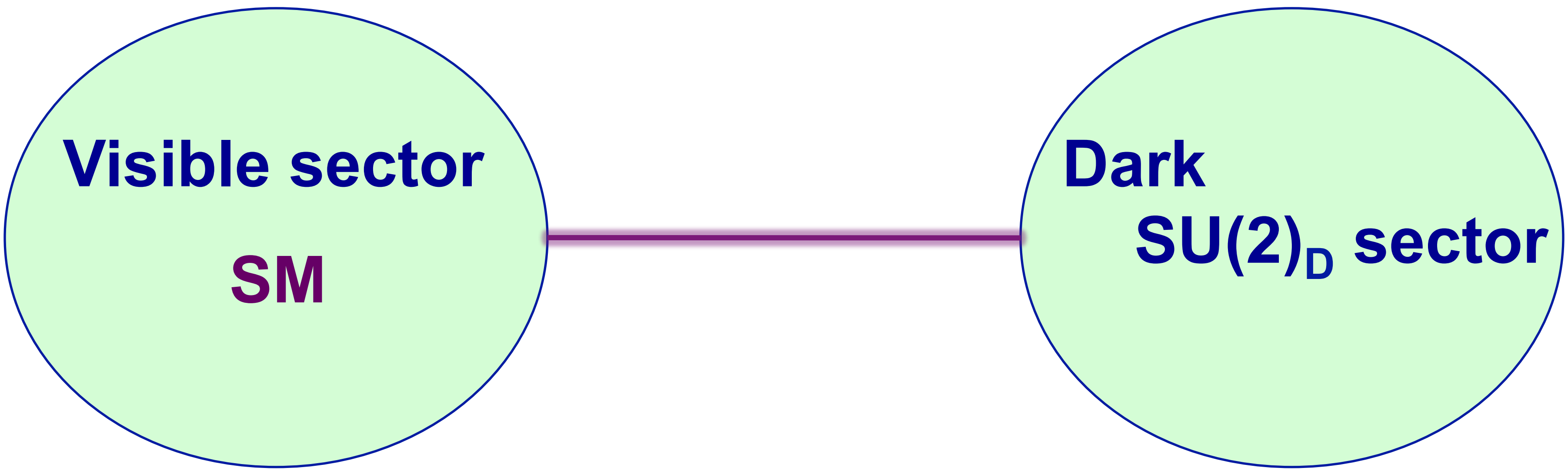
⇨ Z_2 symmetry: odd/even for field with odd/even T_3 value

The lightest Z_2 odd particle in dark sector is DM

Structure of the model

❖Singlet under $SU(2)_X$

❖Singlet under G_{SM}



Two sector can interact via scalar mixing and/or gauge boson mixing

⇨ We consider kinetic mixing associated with $SU(2)_D$

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We introduce $SU(2)_D$ dark sector

Fields	χ	$\vec{\phi}$	$\vec{\phi}'$
$SU(2)_D$	**2**	**3**	**3**

$$\vec{\phi} = (\phi_1, \phi_2, \phi_1)^T, \quad \vec{\phi}' = (\phi'_1, \phi'_2, \phi'_3)^T$$

$$\chi = (\chi_1, \chi_2)^T$$

Lagrangian

$$\mathcal{L}_D = -\frac{1}{4} X^a_{\mu\nu} X^{a\mu\nu} + D_\mu \vec{\phi} \cdot D^\mu \vec{\phi} + D_\mu \vec{\phi}' \cdot D^\mu \vec{\phi}' + \bar{\chi}(D_\mu \gamma^\mu - M_\chi)\chi$$

$$\begin{aligned} V =& \mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 \\ &+ \mu_1^2 \vec{\phi} \cdot \vec{\phi} + \mu_2^2 \vec{\phi}' \cdot \vec{\phi}' + \lambda_1 \left(\vec{\phi} \cdot \vec{\phi}\right)^2 + \lambda_2 \left(\vec{\phi}' \cdot \vec{\phi}'\right)^2 + \lambda_3 \left(\vec{\phi} \cdot \vec{\phi}'\right)^2 \\ &+ \lambda_4 \left(\vec{\phi} \cdot \vec{\phi}\right)\left(\vec{\phi} \cdot \vec{\phi}'\right) + \lambda_5 \left(\vec{\phi}' \cdot \vec{\phi}'\right)\left(\vec{\phi} \cdot \vec{\phi}'\right) + \lambda_6 \left(\vec{\phi} \cdot \vec{\phi}\right)\left(\vec{\phi}' \cdot \vec{\phi}'\right) \\ &+ \lambda_{H\phi} \left(\vec{\phi} \cdot \vec{\phi}\right)(H^\dagger H) + \lambda_{H\phi'} \left(\vec{\phi}' \cdot \vec{\phi}'\right)(H^\dagger H) \\ &+ \frac{y_{\chi\phi}}{2} \bar{\chi} \left(\vec{\phi} \cdot \vec{\sigma}\right) \chi + \frac{y_{\chi\phi'}}{2} \bar{\chi} \left(\vec{\phi}' \cdot \vec{\sigma}\right) \chi \end{aligned}$$

Spontaneous symmetry breaking in dark sector

We require VEV configuration

$$\langle\vec{\phi}\rangle = \left(0, 0, \frac{v_\phi}{\sqrt{2}}\right), \quad \langle\vec{\phi}'\rangle = \left(\frac{v_{\phi'}}{\sqrt{2}}, 0, 0\right)$$

$\Rightarrow$ **SU(2)$_D$ breaks into Z$_2$ symmetry**

$\chi = (\chi_1, \chi_2)^T$: Z$_2$ odd, Other particles: Z$_2$ even

Conditions to obtain the VEV configuration

$$\lambda_1 v_\phi^3 + \frac{1}{2}\lambda_6 v_\phi v_{\phi'}^2 + \frac{1}{2}\lambda_{H\phi} v_\phi v_H^2 - \mu_1^2 v_\phi = 0,$$

$$\lambda_2 v_{\phi'}^3 + \frac{1}{2}\lambda_6 v_\phi^2 v_{\phi'} + \frac{1}{2} v_\phi \lambda_{H\phi'} v_H^2 - \mu_2^2 v_{\phi'} = 0,$$

$$\lambda_H v_H^3 + \frac{1}{2}\lambda_{H\phi} v_\phi^2 v_H + \frac{1}{2}\lambda_{H\phi'} v_{\phi'}^2 v_H - \mu_H^2 v_H = 0,$$

$$\lambda_4 v_\phi^2 + \lambda_5 v_{\phi'}^2 = 0.$$

Scalar masses in dark sector

Scalar potential after SSB

$$\mathcal{L}_{M_S} \simeq \frac{1}{4}\lambda_3 v_{\phi'}^2 \phi_1^2 + \frac{1}{2}\lambda_3 v_\phi v_{\phi'} \phi_1 \phi_3' + \lambda_1 v_\phi^2 \phi_3^2 + \lambda_6 v_\phi v_{\phi'} \phi_3 \phi_1' + \lambda_2 v_{\phi'}^2 \phi_1'^2 + \frac{1}{4}\lambda_3 v_\phi^2 \phi_3'^2$$
$$+ \lambda_H v_H^2 \tilde{h}^2 + \lambda_{H\phi} v_\phi v_H \phi_3 h + \lambda_{H\phi'} v_{\phi'} v_H \phi_1' h,$$

(we took $\lambda_4 \to 0$ for simplicity)

NG bosons: $\phi_2, \phi'_2, -\sin\alpha\,\phi_1 + \cos\alpha\,\phi'_3$ $\left(\sin\alpha[\cos\alpha] = \frac{v_{\phi'}[v_\phi]}{\sqrt{v_\phi^2 + v_{\phi'}^2}}\right)$

Scalar mass terms

$\frac{1}{4}\lambda_3(v_\phi^2 + v_{\phi'}^2)\left(\cos\alpha\phi_1 + \sin\alpha\phi_3'\right)^2$: corresponding state does not mix

$$\mathcal{L}_{M_S} \supset \frac{1}{2}\begin{pmatrix} h \\ \phi_3 \\ \phi_1' \end{pmatrix}^T \begin{pmatrix} 2\lambda_H v_H^2 & \lambda_{H\phi} v_\phi v_H & \lambda_{H\phi'} v_{\phi'} v_H \\ \lambda_{H\phi} v_\phi v_H & 2\lambda_1 v_\phi^2 & \lambda_6 v_\phi v_{\phi'} \\ \lambda_{H\phi'} v_{\phi'} v_H & \lambda_6 v_\phi v_{\phi'} & 2\lambda_2 v_{\phi'}^2 \end{pmatrix} \begin{pmatrix} h \\ \phi_3 \\ \phi_1' \end{pmatrix}$$

Scalar masses in dark sector

We consider simplified scenario $\lambda_{H\phi'}, \lambda_6 \to 0$

Mass matrix becomes

$$\mathcal{L} \supset \frac{1}{2} \begin{pmatrix} \tilde{h} \\ \phi_3 \end{pmatrix}^T \begin{pmatrix} 2\lambda_H v_H^2 & \lambda_{H\phi} v_\phi v_H \\ \lambda_{H\phi} v_\phi v_H & 2\lambda_1 v_\phi^2 \end{pmatrix} \begin{pmatrix} \tilde{h} \\ \phi_3 \end{pmatrix}$$

Mass eigenvalues

$$m^2_{h,\Phi_1} = \lambda_H v_H^2 + \lambda_1 v_\phi^2 \pm \sqrt{\left(\lambda_H v_H^2 - \lambda_1 v_\phi^2\right)^2 + \lambda_{H\phi}^2 v_\phi^2 v_H^2}$$

Mass eigenstate

$$\begin{pmatrix} h \\ \Phi_1 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \tilde{h} \\ \phi_3 \end{pmatrix}, \quad \tan 2\alpha = \frac{\lambda_{H\varphi} v_\phi v_H}{\lambda_H v_H^2 - \lambda_1 v_\phi^2}$$

$$\Phi_2 \simeq \phi_1', \quad m^2_{\Phi_2} \simeq 2\lambda_2 v^2_{\phi'}$$

SM(-like) Higgs : h

Gauge sector with non-Abelian kinetic mixing

We introduce higher dimensional operator generating kinetic mixing

$$\mathcal{L}_{XB} = \frac{C_\phi}{\Lambda} X^a_{\mu\nu} B^{\mu\nu} \phi^a + \frac{C_{\phi'}}{\Lambda} X^a_{\mu\nu} B^{\mu\nu} \phi'^a$$

$$\Rightarrow \quad \mathcal{L}_{\rm KM} = -\frac{1}{2} \sin\chi_1 X^1_{\mu\nu} B^{\mu\nu} - \frac{1}{2} \sin\chi_3 X^3_{\mu\nu} B^{\mu\nu}$$

$$\left(\sin\chi_1 \equiv \sqrt{2} C_{\phi'} v_\phi / \Lambda \text{ and } \sin\chi_2 \equiv \sqrt{2} C_\phi v_{\phi'} / \Lambda \right)$$

For small mixing we approximate

$$B \simeq \tilde{B} - \chi_1 X^1_\mu - \chi_3 X^3_\mu, \quad X^1_\mu \simeq \tilde{X}^1_\mu, \quad X^3_\mu \simeq \tilde{X}^3_\mu.$$

Mass term

$$\mathcal{L}_M = g_D^2 v_\phi^2 X^1_\mu X^{1\mu} + g_D^2 (v_\phi^2 + v_{\phi'}^2) X^2_\mu X^{2\mu} + g_D^2 v_{\phi'}^2 X^3_\mu X^{3\mu}$$

Fermions in dark sector

Mass term after SSB

$$\mathcal{L} \supset M_\chi(\bar{\chi}_1\chi_1 + \bar{\chi}_2\chi_2) + \frac{y_{\chi\phi}v_\phi}{2}(\bar{\chi}_1\chi_1 - \bar{\chi}_2\chi_2) + \frac{y_{\chi\phi'}v_{\phi'}}{2}(\bar{\chi}_1\chi_2 + \bar{\chi}_2\chi_1)$$

$$\equiv M_{11}\bar{\chi}_1\bar{\chi}_1 + M_{12}(\bar{\chi}_1\chi_2 + \bar{\chi}_2\chi_1) + M_{22}\bar{\chi}_2\chi_2,$$

Mass eigenvalues and eigenstate

$$m_{\chi_l,\chi_h} = \frac{1}{2}(M_{11} + M_{22}) \pm \frac{1}{2}\sqrt{(M_{11} - M_{22})^2 + 4M_{12}^2},$$

$$\begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_\chi & -\sin\theta_\chi \\ \sin\theta_\chi & \cos\theta_\chi \end{pmatrix} \begin{pmatrix} \chi_l \\ \chi_h \end{pmatrix}, \qquad \tan 2\theta_\chi = \frac{2M_{12}}{M_{11} - M_{22}} = \frac{y_{\chi\phi'}v_{\phi'}}{y_{\chi\phi}v_\phi}$$

The lighter state is the DM candidate

Interactions associated with DM

Scalar portal interactions

$$\mathcal{L} \supset \frac{y_{\chi\phi}}{2}\Big[\phi_3(\cos 2\theta_\chi \bar{\chi}_l\chi_l - \cos 2\theta_\chi \bar{\chi}_h\chi_h - \sin 2\theta_\chi(\bar{\chi}_l\chi_h + \bar{\chi}_h\chi_l))$$
$$+ \phi_1(\sin 2\theta_\chi \bar{\chi}_l\chi_l - \sin 2\theta_\chi \bar{\chi}_h\chi_h + \cos 2\theta_\chi(\bar{\chi}_l\chi_h + \bar{\chi}_h\chi_l))\Big]$$
$$+ \frac{y_{\chi\phi'}}{2}\Big[\phi'_3(\cos 2\theta_\chi \bar{\chi}_l\chi_h - \cos 2\theta_\chi \bar{\chi}_h\chi_h - \sin 2\theta_\chi(\bar{\chi}_l\chi_h + \bar{\chi}_h\chi_l))$$
$$+ \phi'_1(\sin 2\theta_\chi \bar{\chi}_l\chi_l - \sin 2\theta_\chi \bar{\chi}_h\chi_h + \cos 2\theta_\chi(\bar{\chi}_l\chi_h + \bar{\chi}_h\chi_l))\Big]$$

Gauge interactions

$$\mathcal{L} \supset \frac{g_D}{2}\left(\cos 2\theta_\chi \bar{\chi}_l\gamma^\mu\chi_l - \sin 2\theta_\chi \bar{\chi}_l\gamma^\mu\chi_h - \sin 2\theta_\chi \bar{\chi}_h\gamma^\mu\chi_l - \cos 2\theta_\chi \bar{\chi}_h\gamma^\mu\chi_h\right) X^3_\mu$$
$$+ \frac{g_D}{2}\left(\sin 2\theta_\chi \bar{\chi}_l\gamma^\mu\chi_l + \cos 2\theta_\chi \bar{\chi}_l\gamma^\mu\chi_h + \cos 2\theta_\chi \bar{\chi}_h\gamma^\mu\chi_l - \sin 2\theta_\chi \bar{\chi}_h\gamma^\mu\chi_h\right) X^1_\mu$$
$$+ i\frac{g_D}{2}\left(\bar{\chi}_h\gamma^\mu\chi_l - \bar{\chi}_l\gamma^\mu\chi_h\right) X^2_\mu + e c_W \chi_1 X^1_\mu J^\mu_{EM} + e c_W \chi_3 X^3_\mu J^\mu_{EM},$$
$$J^\mu_{EM} = \sum_{f_{SM}} Q_{f_{SM}} \bar{f}_{SM}\gamma^\mu f_{SM},$$

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$$+ \phi_1(\sin 2\theta_\chi \bar{\chi}_l\chi_l - \sin 2\theta_\chi \bar{\chi}_h\chi_h + \cos 2\theta_\chi(\bar{\chi}_l\chi_h + \bar{\chi}_h\chi_l))\Big]$$
$$+ \frac{y_{\chi\phi'}}{2}\Big[\phi'_3(\cos 2\theta_\chi \bar{\chi}_l\chi_h - \cos 2\theta_\chi \bar{\chi}_h\chi_h - \sin 2\theta_\chi(\bar{\chi}_l\chi_h + \bar{\chi}_h\chi_l))$$
$$+ \phi'_1(\sin 2\theta_\chi \bar{\chi}_l\chi_l - \sin 2\theta_\chi \bar{\chi}_h\chi_h + \cos 2\theta_\chi(\bar{\chi}_l\chi_h + \bar{\chi}_h\chi_l))\Big]$$

In our scenario Φ_3 mix with SM Higgs
To avoid direct detection constraint $\theta_\chi \sim \pi/4$

Gauge interactions

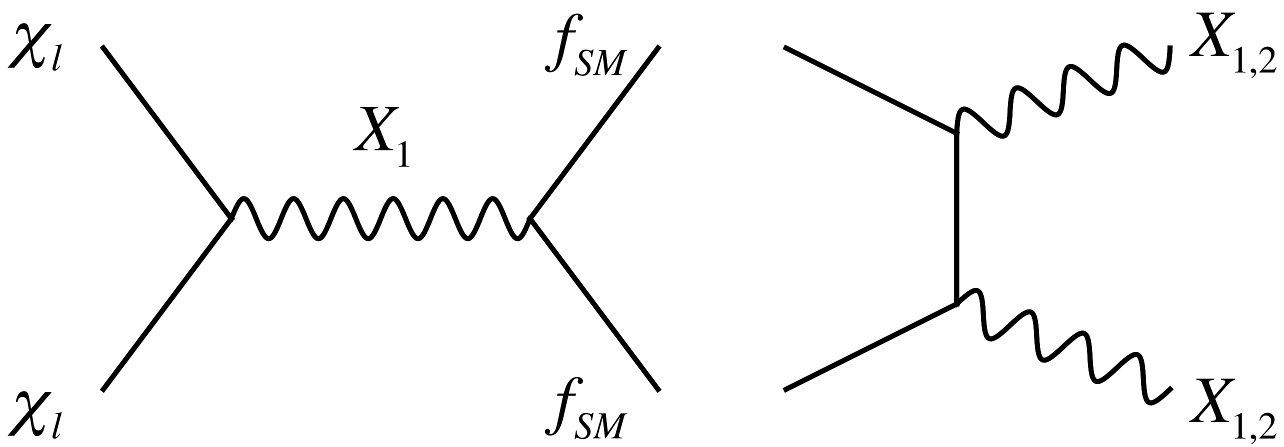
$$\mathcal{L} \supset \frac{g_D}{2}\left(\cos 2\theta_\chi \bar{\chi}_l\gamma^\mu\chi_l - \sin 2\theta_\chi \bar{\chi}_l\gamma^\mu\chi_h - \sin 2\theta_\chi \bar{\chi}_h\gamma^\mu\chi_l - \cos 2\theta_\chi \bar{\chi}_h\gamma^\mu\chi_h\right) X^3_\mu$$
$$+ \frac{g_D}{2}\left(\sin 2\theta_\chi \bar{\chi}_l\gamma^\mu\chi_l + \cos 2\theta_\chi \bar{\chi}_l\gamma^\mu\chi_h + \cos 2\theta_\chi \bar{\chi}_h\gamma^\mu\chi_l - \sin 2\theta_\chi \bar{\chi}_h\gamma^\mu\chi_h\right) X^1_\mu$$
$$+ i\frac{g_D}{2}\left(\bar{\chi}_h\gamma^\mu\chi_l - \bar{\chi}_l\gamma^\mu\chi_h\right) X^2_\mu + e c_W \chi_1 X^1_\mu J^\mu_{EM} + e c_W \chi_3 X^3_\mu J^\mu_{EM},$$

$$J^\mu_{EM} = \sum_{f_{SM}} Q_{f_{SM}} \bar{f}_{SM}\gamma^\mu f_{SM},$$

Relic density is determined by gauge interaction

Relic density of dark matter

DM relic density is explained by the processes:

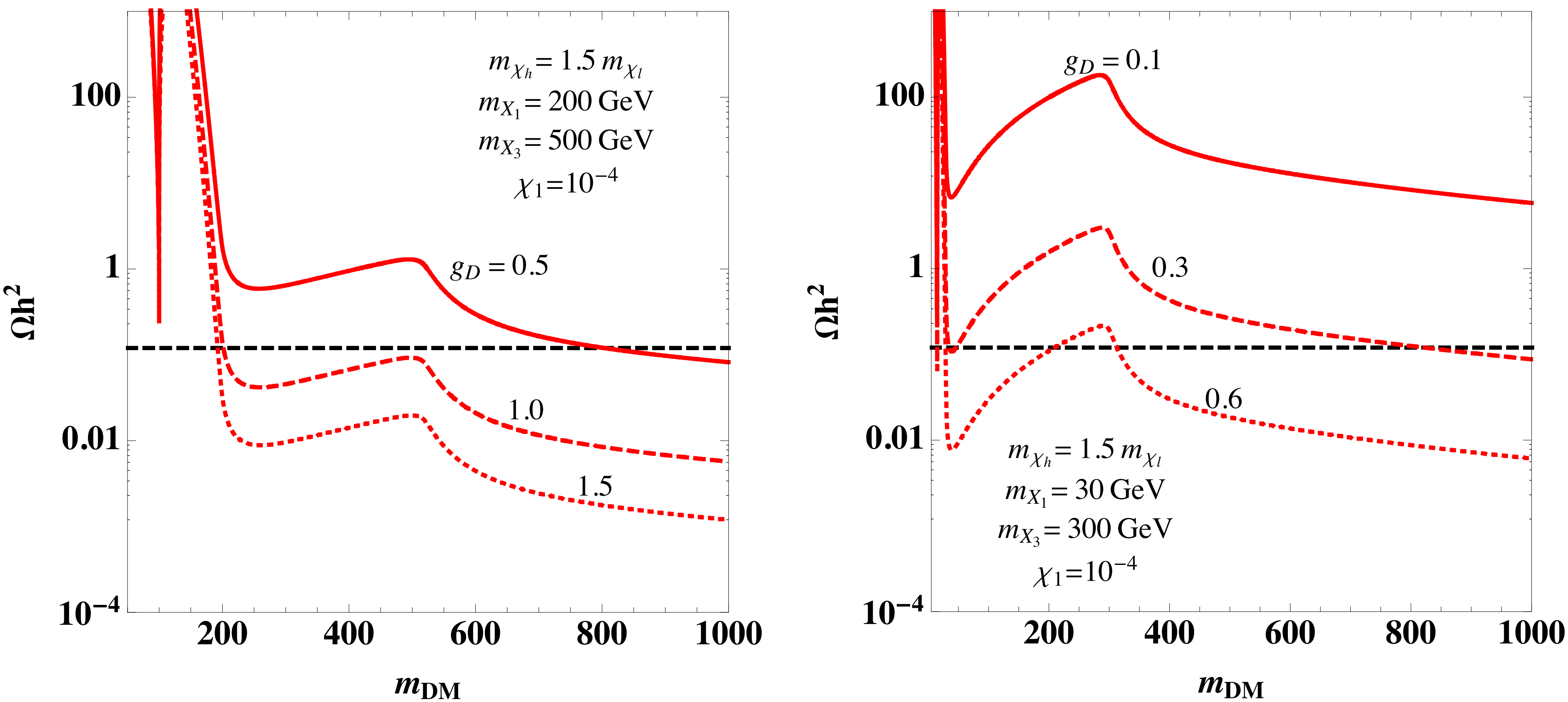


Relic density is determined by parameters:

$$\{m_{X_1}, m_{X_3}, g_D, m_{\chi_l}, m_{\chi_h}, \chi_1, \theta_\chi\}$$

- Here we chose $\theta_\chi = \pi/4$ to suppress DM-Nucleon scattering via scalar portal
- To suppress X_1 portal DM-Nucleon scattering $\chi_l \sim 10^{-4}$

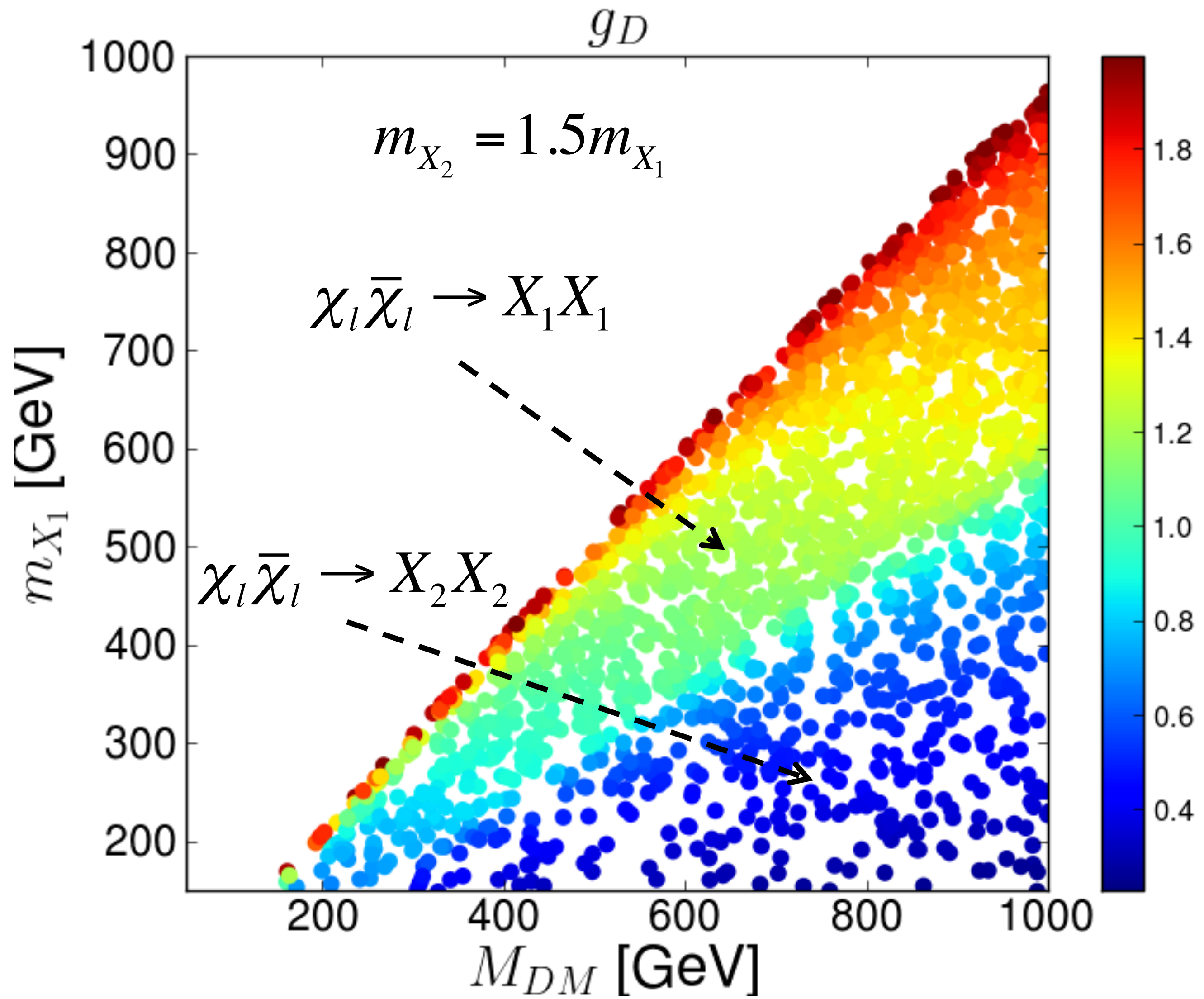
Relic density of dark matter



Computed by micrOMEGAs

- DM DM → X_1X_1, X_2X_2 can explain relic density
- S-channel process via X_1 exchange require fine tuning due to small χ_1

3. Phenomenology



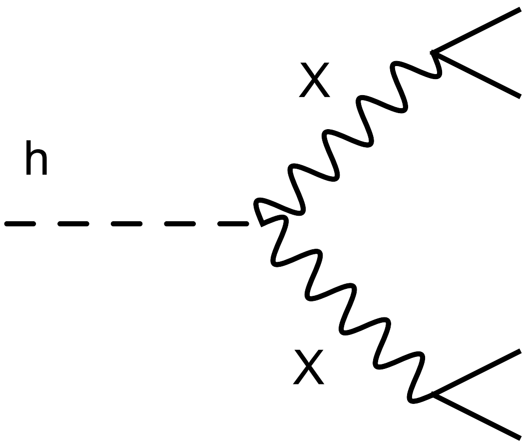
Parameter region satisfying: $0.11 < \Omega h^2 < 0.13$

Gauge coupling is smaller when DM DM$\to X_2X_2$ is open

Constraint from Higgs decay

SM Higgs can decay into dark gauge bosons via scalar mixing

⇨ Dark gauge boson can decay into SM leptons



$$\Gamma_{h\to X_1X_1} = \frac{{g_D}^4\cos^2\alpha}{8\pi}\frac{v_\phi^2}{m_h}\sqrt{1-\frac{4m_{X_1}^2}{m_h^2}}\left(2+\frac{m_h^4}{4m_{X_1}^4}\left(1-\frac{2m_{X_1}^2}{m_h^2}\right)^2\right)$$

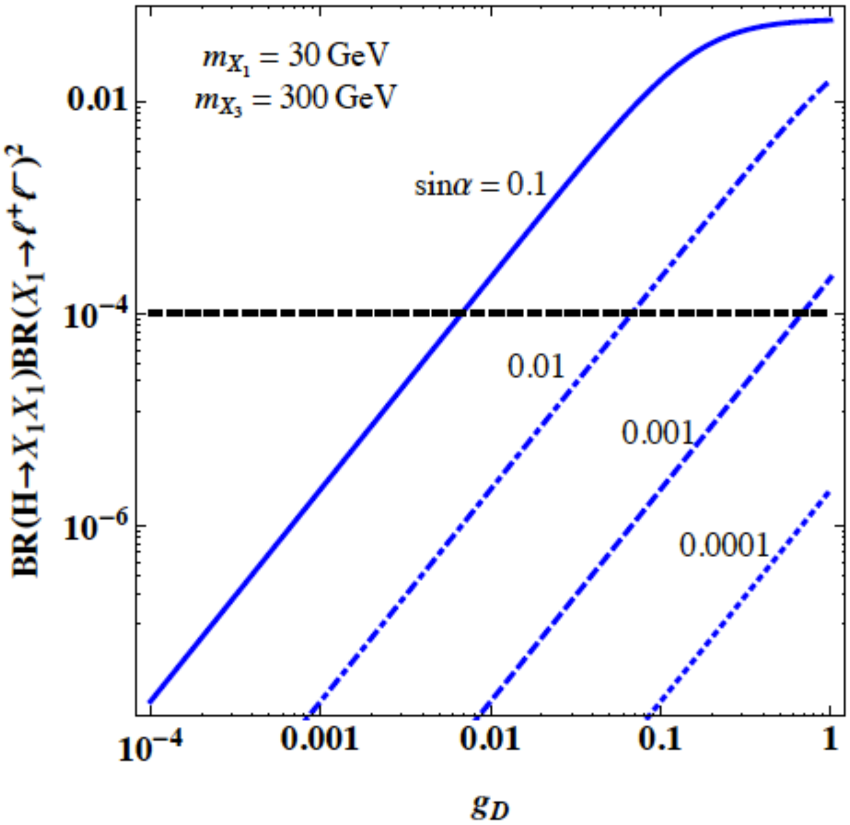
$$\Gamma_{h\to X_2X_2} = \frac{{g_D}^4\cos^2\alpha}{8\pi}\frac{v_\phi^2}{m_h}\sqrt{1-\frac{4m_{X_2}^2}{m_h^2}}\left(2+\frac{m_h^4}{4m_{X_2}^4}\left(1-\frac{2m_{X_2}^2}{m_h^2}\right)^2\right)$$

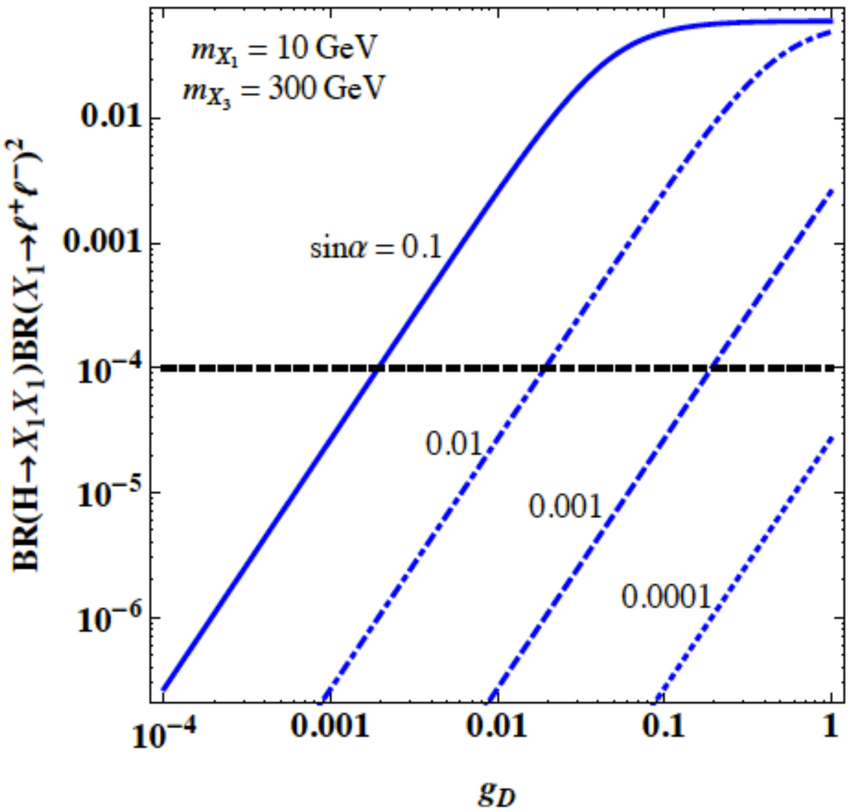
Constraint from $h \to X_1X_1 \to \ell^+\ell^-\ell^+\ell^-$ search at the LHC

⇨ $BR(h \to X_1X_1)BR(X_1 \to \ell^+\ell^-)^2 < 10^{-4}$

ATLAS, JHEP 1806 (2018) 166

Constraint from Higgs decay

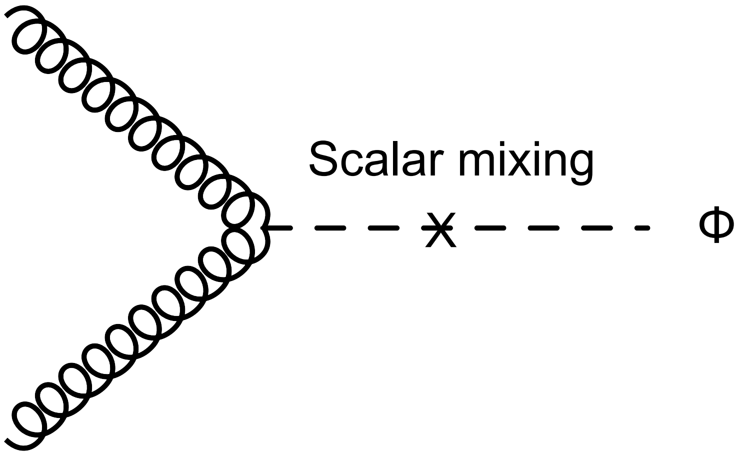


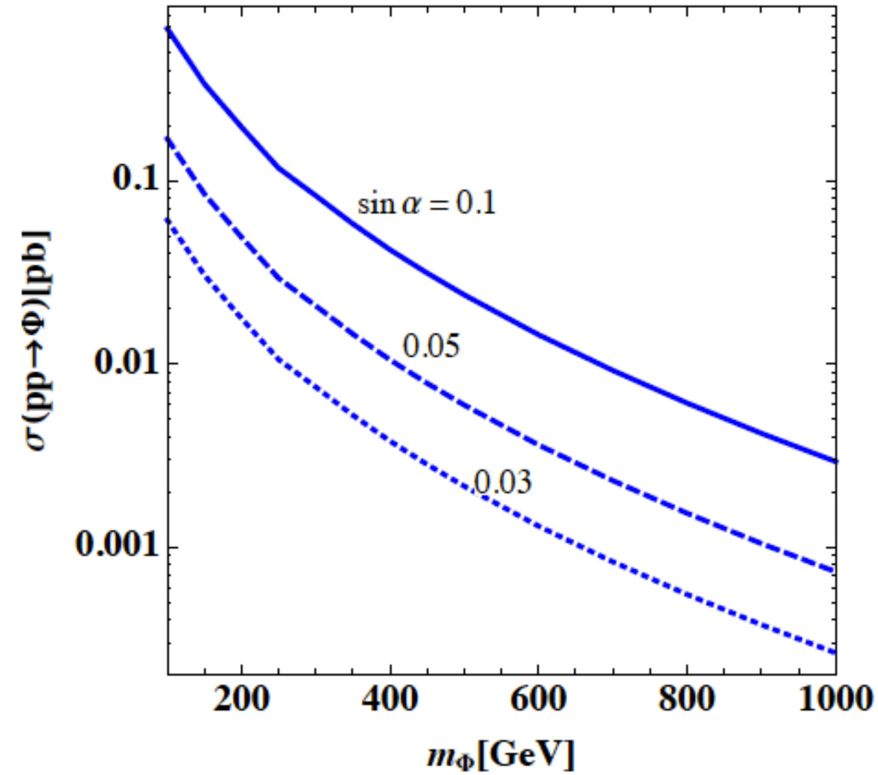


Gauge coupling and scalar mixing should be small when the decay mode is kinematically allowed

Extra scalar production via Higgs mixing

Extra scalar boson production by gluon fusion





Scalar Decay mode: $\Phi_1 \to X_1 X_1, X_2 X_2, \chi_h \chi_l$

Extra scalar production via Higgs mixing

Collider signature depending on mass relations

Ex)

$$m_\Phi > 2m_{X_1}, m_{X_h} + m_{X_l}$$

$$\Rightarrow \quad \Phi \to X_1 X_1 (X_1 \to f_{SM} \bar{f}_{SM}) \qquad \text{BR\sim0.99}$$

$$\Phi \to \chi_l \bar{\chi}_h \to \chi_l \bar{\chi}_l X_1 \to \chi_l \bar{\chi}_l f_{SM} \bar{f}_{SM} \qquad \text{BR\sim0.01}$$

$$m_\Phi < 2m_{X_1}, m_\Phi > m_{X_h} + m_{X_l}$$

$$\Rightarrow \quad \Phi \to \chi_l \bar{\chi}_h \to \chi_l \bar{\chi}_l X_1 \to \chi_l \bar{\chi}_l f_{SM} \bar{f}_{SM} \qquad \text{BR\sim1.0}$$

Summary and discussion

Construction of model with dark SU(2) model

- ✧Z_2 symmetry as a subgroup of SU(2)
- ✧DM candidate is Dirac fermion in dark sector
- ✧DM interaction with SM through kinetic mixing

Application to DM phenomenology

- ✧Relic density of DM
- ✧Constraints from direct detection
- ✧Collider signature; Higgs boson decay to dark sector
- ✧Collider signature via extra scalar production