Dark matter imposters with Higgs portal couplings in multicomponent dark sector

Takaaki Nomura (KIAS)

collaborated with

P. Ko (KIAS), Jinmian Li (KIAS→Sichuan U.)

(our paper is under preparation)

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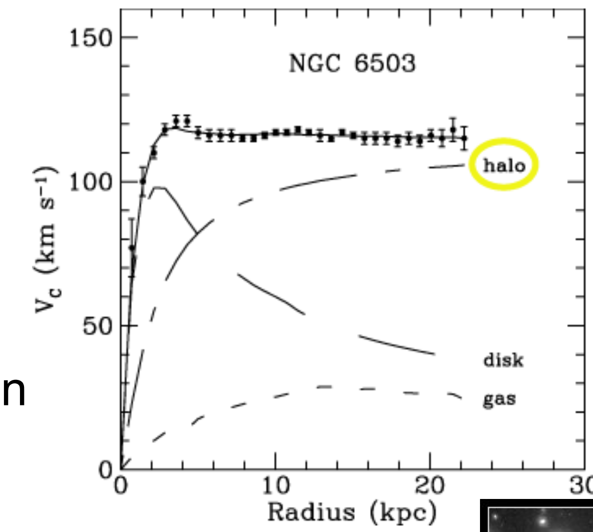
Introduction

Many observation indicate the existence of dark matter

❖**Rotation of spiral galaxies**

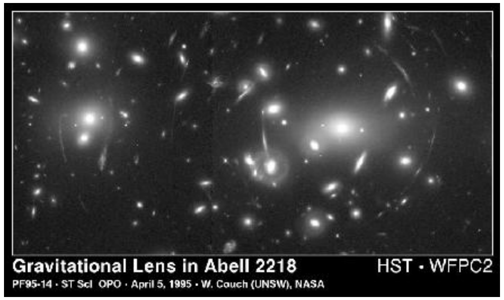
$$v(r) \propto \sqrt{M(r)/r}$$

M(r) ∝ r in outside of visible region



❖**Clusters of galaxies**

❖**Gravitational lensing**

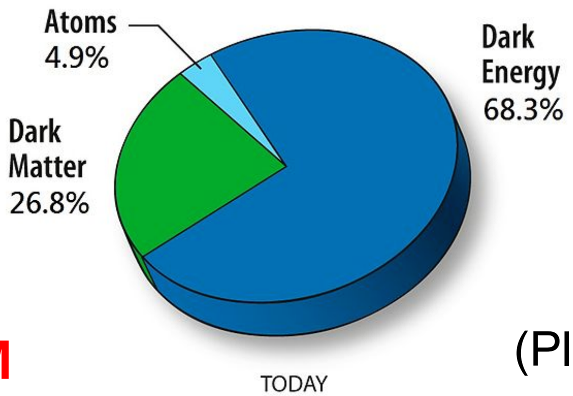


❖**Formation of Large scale structure**

❖**CMB anisotropy : WMAP, Planck**

$$\Rightarrow \quad \Omega_{DM} h^2 = 0.1188 \pm 0.0010$$

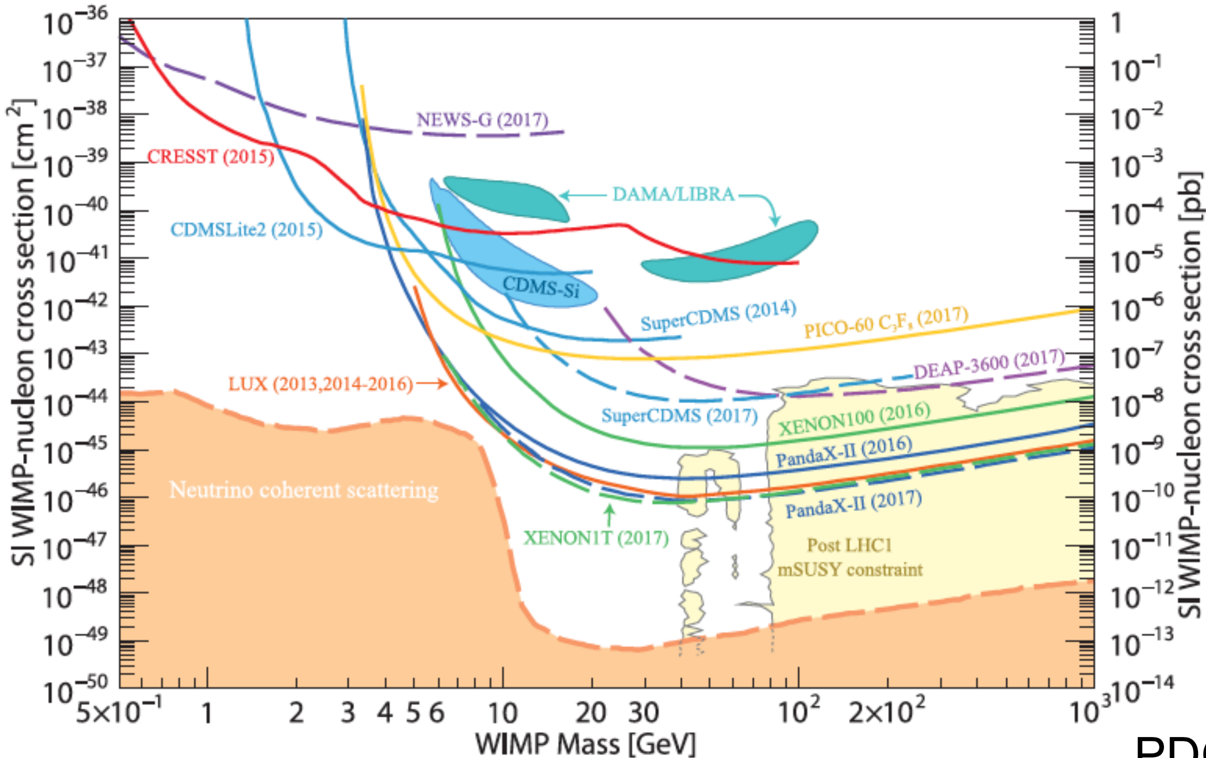
Planck (2015)



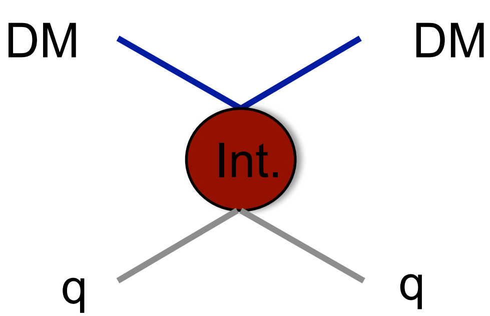
(Planck)

WIMP is attractive candidate as particle DM

Also we have constrains from direct detection experiments



PDG 2018



Constrained

Collider signal would be small in simple portal models

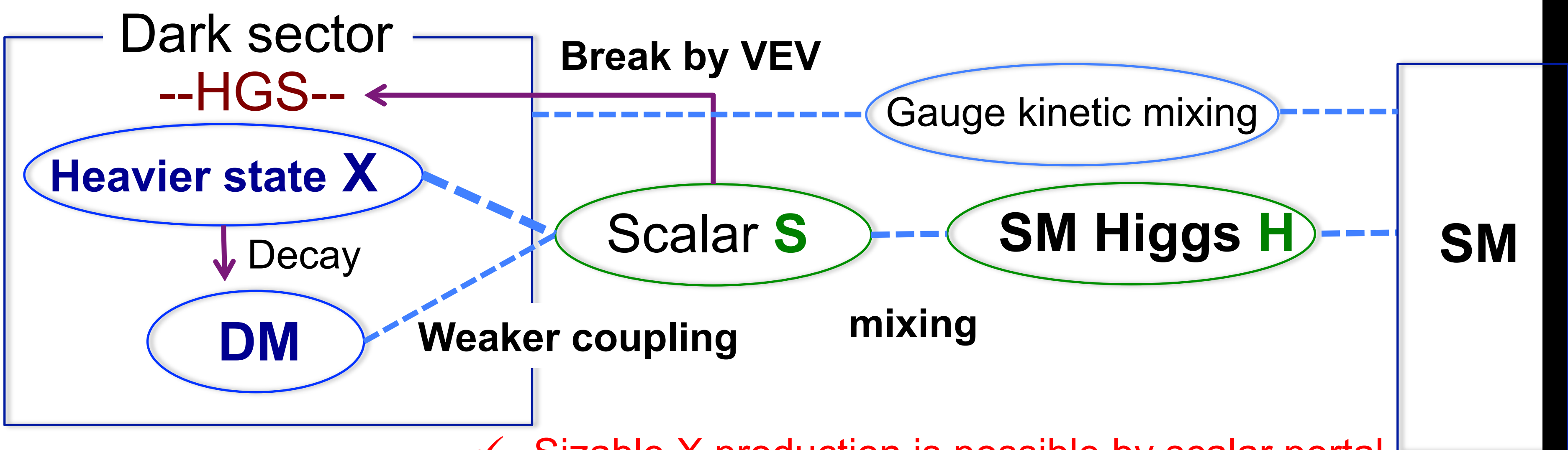
Higgs portal, Z' portal, etc.

Due to correlation between DD and DM production

Correlation between DD and DM production ratio is not necessary

➡ **It would be in the case of dark sector with richer structure**

- **In this talk we discuss models with hidden gauge symmetry (HGS)**



✓ Sizable X production is possible by scalar portal

Two models will be introduced

➡ { **Fermionic DM model with $U(1)_D$ gauge symmetry**
Vector DM model with $SU(2)_D \times U(1)_D$ gauge symmetry

Let us explore DM phenomenology of the models

Fermionic DM case

Fermionic DM model with hidden $U(1)_D$ symmetry

➢ **New field contetns**

	Dirac fermions		Scalar
Fields	χ_1	χ_2	S
$U(1)_D$	q_D	$-3q_D$	$4q_D$

✓ SM fields are not charged under $U(1)_D$

✓ These fields are SM singlet

❖ $U(1)_D$ gauge symmetry will be broken by VEV of S

❖ The lighter mass eigenstate from χ fields is stable due to remnant Z_2

❖ We have fermionic DM candidate

❖ Real component of S can mix with the SM Higgs

◆ New Lagrangian

$$\mathcal{L} = \sum_{i=1,2} \overline{\chi}_i (i\not{D} - m_i)\chi_i - [y_S \overline{\chi}_1 \chi_2 S + H.c.]$$
$$- \frac{1}{4} V_{\mu\nu} V^{\mu\nu} + D_\mu S^\dagger D^\mu S + (D_\mu \Phi)^\dagger D^\mu \Phi - V(\Phi, S),$$

$$V(\Phi, S) = m_\Phi^2 \Phi^\dagger \Phi + m_S^2 S^\dagger S + \frac{\lambda_\Phi}{2}(\Phi^\dagger \Phi)^2 + \frac{\lambda_S}{2}(S^\dagger S)^2 + \lambda_{\Phi S}(\Phi^\dagger \Phi)(S^\dagger S),$$

(Φ: SM-like Higgs doublet)

◆ Scalar field components

$$\Phi = \begin{pmatrix} G_W^+ \\ \frac{1}{\sqrt{2}}(v + \tilde{h} + iG_Z) \end{pmatrix}, \quad S = \frac{1}{\sqrt{2}}(v_S + s + iG_{Z'}),$$

NG bosons

Masses of new particles

Z' boson mass

$$D_\mu S (D^\mu S)^\dagger \supset 8 q_D^2 g_D^2 v_S^2 Z'_\mu Z'^\mu \equiv \frac{1}{2} m_{Z'}^2 Z'_\mu Z'^\mu \quad \Rightarrow \quad m_{Z'} = 4 q_D g_D v_S$$

Scalar boson masses

$$\mathcal{L} \supset \frac{1}{4} \begin{pmatrix} \tilde{h} \\ s \end{pmatrix}^T \begin{pmatrix} \lambda_\Phi v^2 & \lambda_{\Phi S} v v_S \\ \lambda_{HS} v v_S & \lambda_S v_S^2 \end{pmatrix} \begin{pmatrix} \tilde{h} \\ s \end{pmatrix} \Rightarrow \begin{cases} m_{h,H}^2 = \dfrac{\lambda_\Phi v^2 + \lambda_S v_S^2}{4} \pm \dfrac{1}{4} \sqrt{(\lambda_\Phi v^2 - \lambda_S v_S^2)^2 + 4 \lambda_{\Phi S}^2 v_S^2} \\ \begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \tilde{h} \\ s \end{pmatrix}, \sin 2\alpha = \dfrac{2 \lambda_{\Phi S} v_S}{m_h^2 - m_H^2} \end{cases}$$

Fermion masses

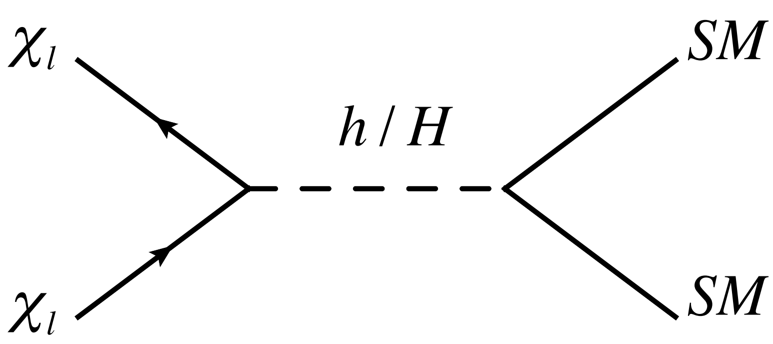
$$M_\chi = \begin{pmatrix} m_1 & \dfrac{y_S v_S}{\sqrt{2}} \\ \dfrac{y_S v_S}{\sqrt{2}} & m_2 \end{pmatrix} \Rightarrow \begin{cases} m_{\chi_l, \chi_h} = \dfrac{m_1 + m_2}{2} \pm \dfrac{1}{2} \sqrt{(m_1 - m_2)^2 + 2 y_S^2 v_S^2} \\ \begin{pmatrix} \chi_l \\ \chi_h \end{pmatrix} = \begin{pmatrix} \cos\theta_\chi & \sin\theta_\chi \\ -\sin\theta_\chi & \cos\theta_\chi \end{pmatrix} \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix}, \sin 2\theta_\chi = \dfrac{\sqrt{2} y_S v_S}{m_{\chi_l} - m_{\chi_h}} \end{cases}$$

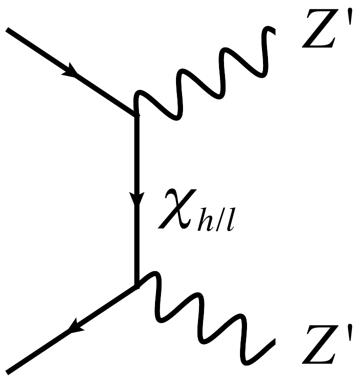
Relic density of Fermionic DM

❖ Interactions relevant to DM physics

$$\begin{aligned}\mathcal{L} \supset & \frac{y_S s_\alpha}{\sqrt{2}} h[2c_\chi s_\chi \bar{\chi}_l \chi_l + 2c_\chi s_\chi \bar{\chi}_h \chi_h + (c_\chi^2 - s_\chi^2)(\bar{\chi}_h \chi_l + h.c.)] \\ & + \frac{y_S c_\alpha}{\sqrt{2}} H[2c_\chi s_\chi \bar{\chi}_l \chi_l + 2c_\chi s_\chi \bar{\chi}_h \chi_h + (c_\chi^2 - s_\chi^2)(\bar{\chi}_h \chi_l + h.c.)] \\ & + g_D q_D Z'_\mu \left[(1 - 4s_\chi^2)\bar{\chi}_l \gamma^\mu \chi_l - 4c_\chi s_\chi (\bar{\chi}_l \gamma^\mu \chi_h + h.c.) + (1 - 4c_\chi^2)\bar{\chi}_h \gamma^\mu \chi_h\right] \\ & + \frac{c_\alpha m_{Z'}^2}{v_S} H Z'_\mu Z'^\mu + \sum_{f_{SM}} \frac{s_\alpha m_{f_{SM}}}{v} H \bar{f}_{SM} f_{SM} + \frac{2 s_\alpha m_W^2}{v} H W^{+\mu} W_\mu^- + \frac{s_\alpha m_Z^2}{v} H Z^\mu Z_\mu\end{aligned}$$

❖ Dominant DM annihilation processes





Relic density of Fermionic DM

Calculating relic density with micrOMEGAs

Relevant free parameters:

$$\{m_1, m_2, y_S, g_D, v_S, \lambda_\Phi, \lambda_S\}$$

($q_{D=}1$)

Scanning relevant parameters in the range of:

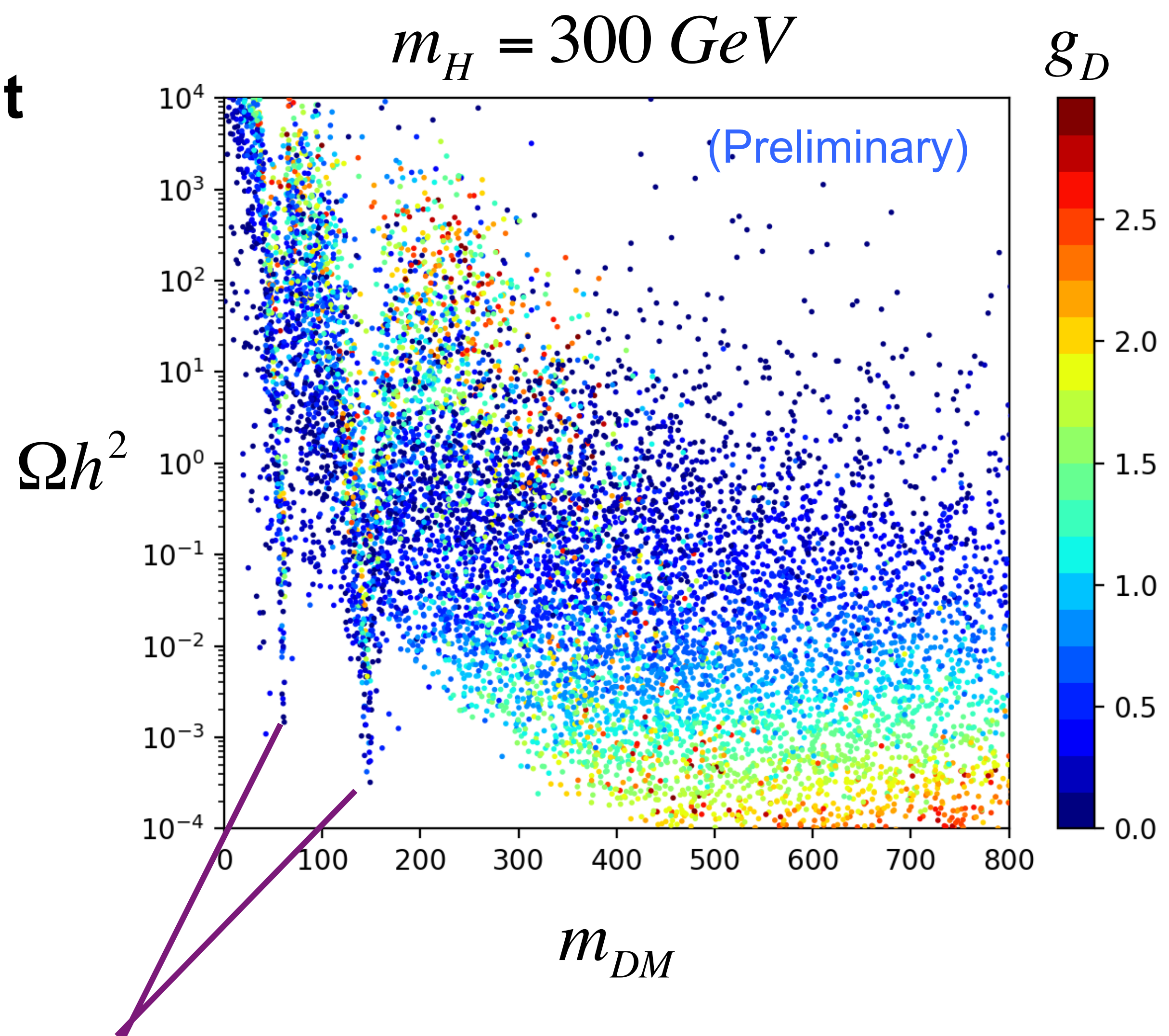
$$m_{1,2} \in [1.0, 1000]\ \text{GeV}, \quad v_S \in [1.0, 2000]\ \text{GeV}, \quad g_D \in [3.0 \times 10^{-5}, 3.0],$$

$$y_S \in [-1.0, 1.0], \quad \lambda_\Phi \in [10^{-4}, 10], \quad \lambda_S \in [10^{-4}, 10].$$

Values given by free parameters:

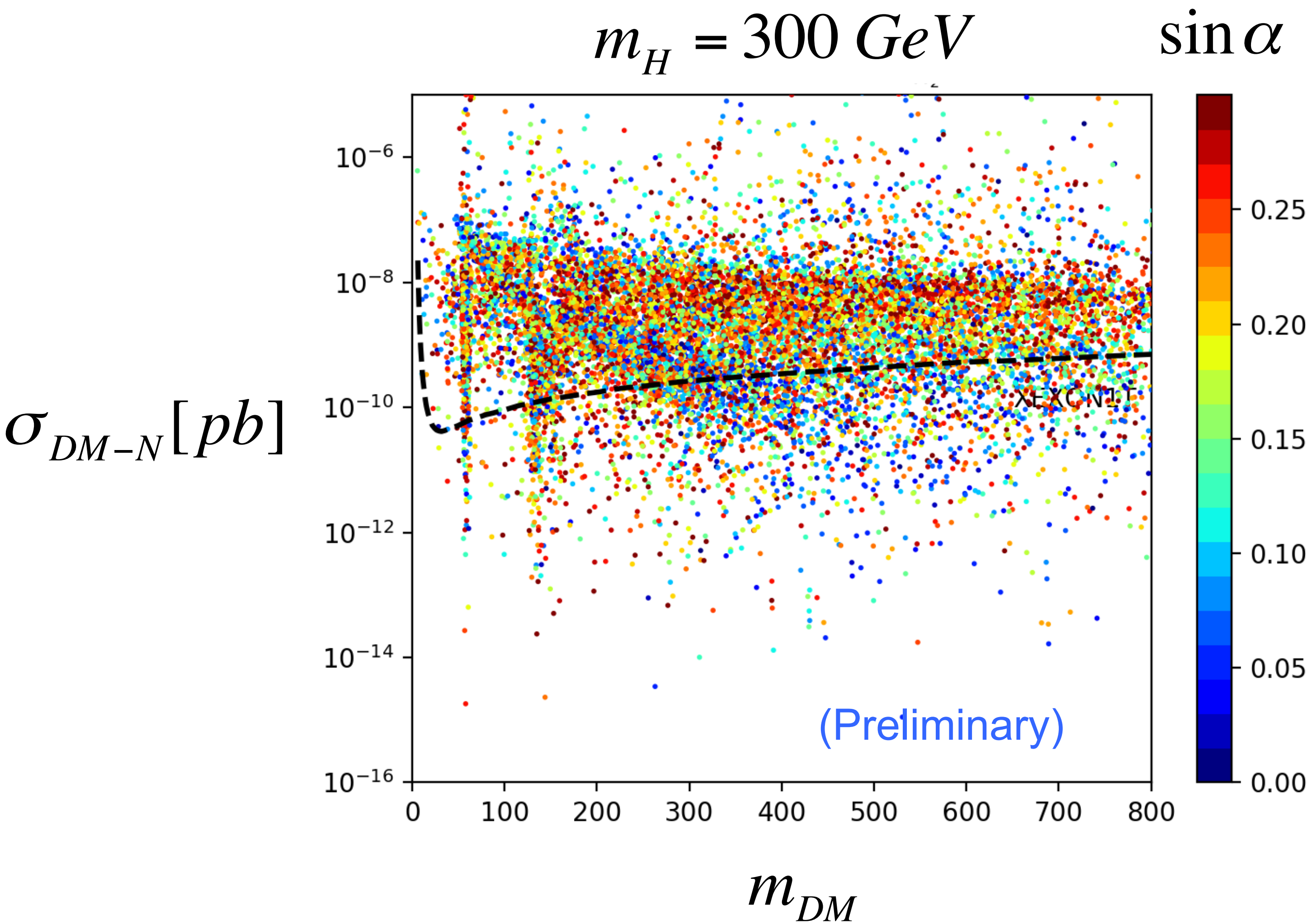
$$\{m_{\chi_l}, m_{\chi_h}, m_{Z'}, m_H, \sin\alpha, \sin\theta_\chi, \Omega h^2\}$$

❖ Result



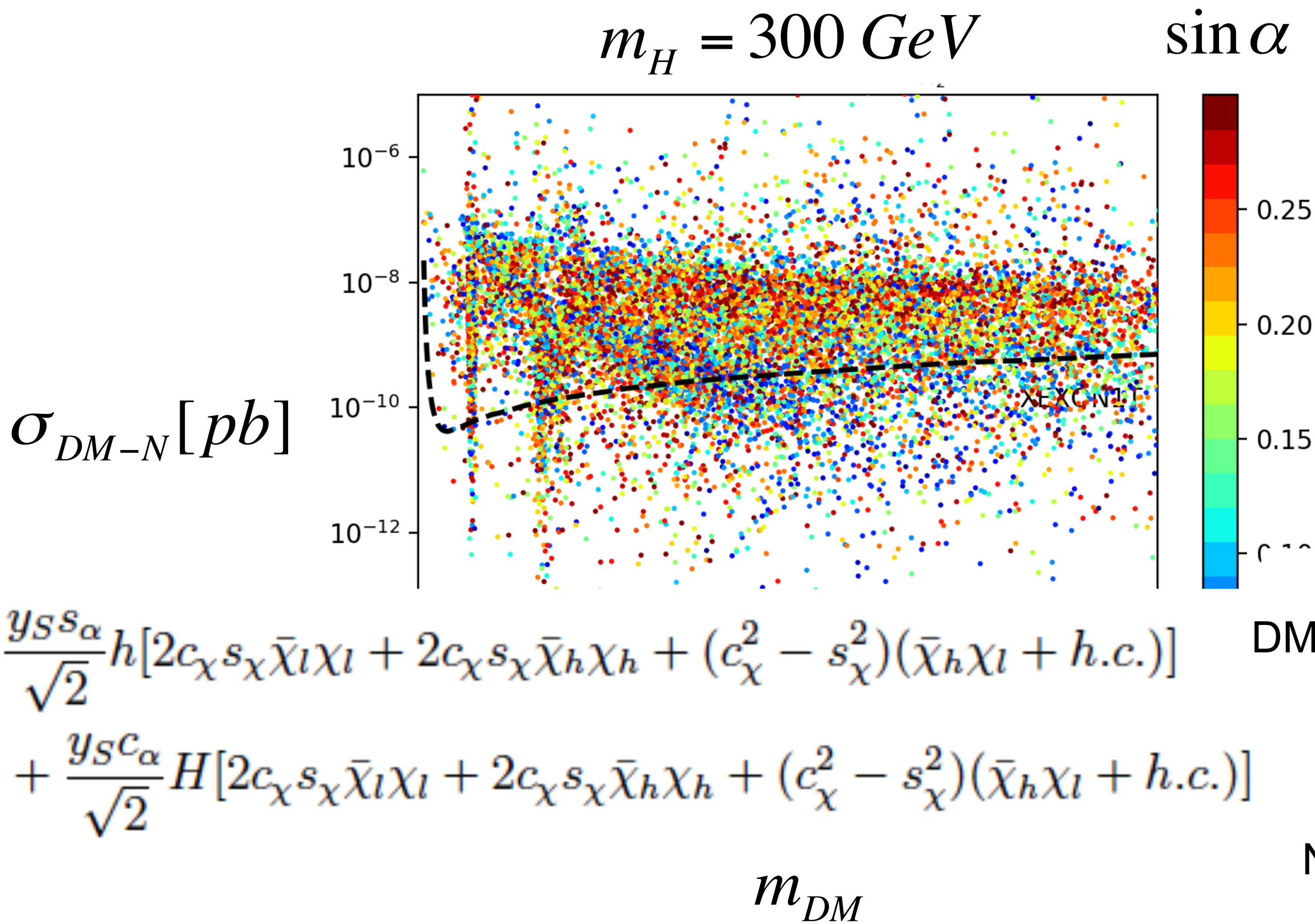
- ✓ **Resonance enhancement in Higgs portal process**
- ✓ **Z'Z' mode is dominant in Heavy DM mass region**

Direct detection in Fermionic DM

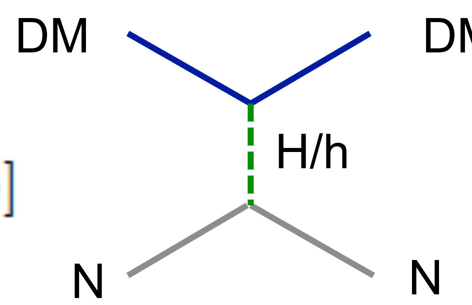


- ✓ **These point satisfy relic density**
- ✓ **Sizable scalar mixing is possible; $\sigma_{DM\text{-}N}$ is suppressed by small θ_X**

Direct detection in Fermionic DM



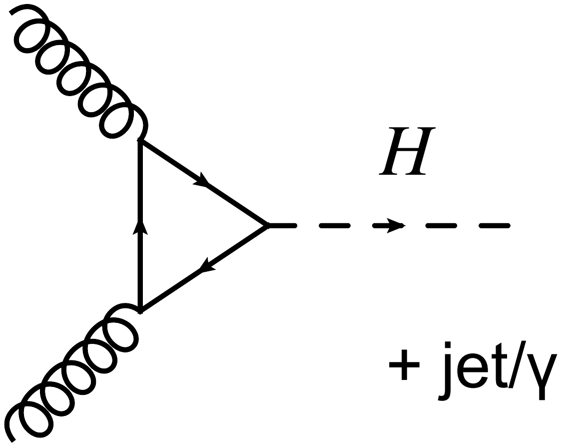
$$\frac{y_S s_\alpha}{\sqrt{2}} h[2c_\chi s_\chi \bar{\chi}_l \chi_l + 2c_\chi s_\chi \bar{\chi}_h \chi_h + (c_\chi^2 - s_\chi^2)(\bar{\chi}_h \chi_l + h.c.)]$$
$$+ \frac{y_S c_\alpha}{\sqrt{2}} H[2c_\chi s_\chi \bar{\chi}_l \chi_l + 2c_\chi s_\chi \bar{\chi}_h \chi_h + (c_\chi^2 - s_\chi^2)(\bar{\chi}_h \chi_l + h.c.)]$$



- ✓ **These point satisfy relic density**
- ✓ **Sizable scalar mixing is possible; $\sigma_{DM\text{-}N}$ is suppressed by small θ_χ**

Production of hidden Higgs boson and signal of DM

❖ Gluon fusion via scalar mixing



Cross section ∝ $(\sin\alpha)^2$

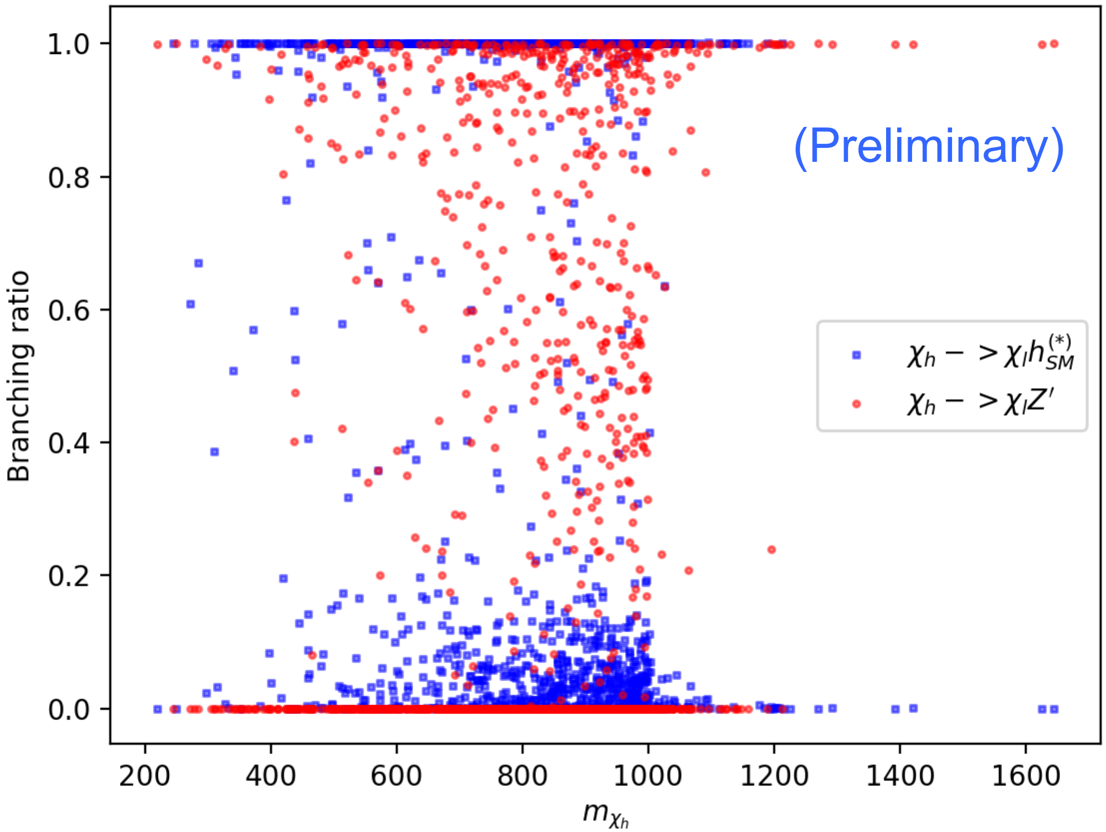
Detectable with sizable mixing α

H decay

$$gg \rightarrow H \rightarrow \chi_l \chi_h, \quad \chi_h \rightarrow \chi_l Z' \quad (Z' \rightarrow f_{SM} \bar{f}_{SM})$$

If kinematically allowed heavier χ state decays into DM + Z'

χ_h decay ratio



- ✓ Z' decay via Z-Z' mixing
- ✓ If Z' is long lived it passes detector
- ✓ Heavier state can be impostor of DM
- ✓ Sizable signal of missing E_T + j/γ

Vector DM case

Vector DM model with hidden $SU(2)_D \times U(1)_D$ symmetry

- **New field contetns**

Fields	H_D	S_D
$SU(2)_D$	**2**	**1**
$U(1)_D$	Y_D	Y_S

- ✓ SM fields are not charged under $SU(2)_D \times U(1)_D$
- ✓ These fields are SM singlet
- ✓ Only scalar fields are introduced
- ✓ These scalar VEVs break the symmetry

◆ New Lagrangian

$$\mathcal{L}_D = -\frac{1}{4} W_h^{a\mu\nu} W^a_{h\mu\nu} - \frac{1}{4} F_h^{\mu\nu} F_{h\mu\nu} + (D_\mu H_D)^\dagger (D^\mu H_D) + (D_\mu S_D)^\dagger (D^\mu S_D) - V, \quad (11)$$

$$\begin{aligned} V = & m_\Phi^2 \Phi^\dagger \Phi + m_{H_D}^2 H_D^\dagger H_D + m_{S_D}^2 S_D^\dagger S_D + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \lambda_{H_D} (H_D^\dagger H_D)^2 + \lambda_{S_D} (S_D^\dagger S_D)^2 \\ & + \lambda_{\Phi H_D} (\Phi^\dagger \Phi)(H_D^\dagger H_D) + \lambda_{\Phi S_D} (\Phi^\dagger \Phi)(S_D^\dagger S_D) + \lambda_{H_D S_D} (H_D^\dagger H_D)(S_D^\dagger S_D), \end{aligned} \quad (12)$$

◆ Scalar filed components

$$\Phi = \begin{pmatrix} G_W^+ \\ \frac{1}{\sqrt{2}}(v + \tilde{h} + iG_Z) \end{pmatrix}, \quad H_D = \begin{pmatrix} G_{W_D}^+ \\ \frac{1}{\sqrt{2}}(v_D + \tilde{h}_D + iG_{Z_{hA}}) \end{pmatrix}, \quad S_D = \frac{1}{\sqrt{2}}(v_S + \tilde{s}_D + iG_{Z_{hB}})$$

◆ Gauge boson mass

$$m_{W_h^\pm}^2 = \left(\frac{g_D v_D}{2}\right)^2 \qquad m^2(W_h^0, B_h) = \frac{1}{4}\begin{pmatrix} g_D^2 v_D^2 & -g_D g_S v_D^2 Y_D \\ -g_D g_S v_D^2 Y_D & g_S^2(v_D^2 Y_D^2 + v_S^2 Y_S^2) \end{pmatrix} \equiv \frac{1}{4}\begin{pmatrix} a & b \\ b & c \end{pmatrix}$$

$$\Rightarrow \begin{cases} m_{Z_{h1},Z_{h2}}^2 = \frac{1}{8}\left[(a+c) \mp \sqrt{(a-c)^2 + 4b^2}\right], \\ Z_{h1}^\mu = \cos\theta_X W_h^{0\mu} + \sin\theta_X B_h^\mu, \quad Z_{h2}^\mu = -\sin\theta_X W_h^{0\mu} + \cos\theta_X B_h^\mu, \\ \sin 2\theta_X = \frac{2b}{m_{Z_{h1}}^2 - m_{Z_{h2}}^2} \end{cases}$$

$W_h^\pm$ is the DM candidate in the model

◆ Mass matrix for scalar field

$$\mathcal{L} \supset \frac{1}{2}\begin{pmatrix}\tilde{h}\\ \tilde{h}_D\\ \tilde{s}_D\end{pmatrix}^T \begin{pmatrix}2\lambda_H v^2 & \lambda_{HH_D} v v_D & \lambda_{HS_D} v v_S\\ \lambda_{HH_D} v v_D & 2\lambda_{H_D} v_D^2 & \lambda_{H_D S_D} v_D v_S\\ \lambda_{HS_D} v v_S & \lambda_{H_D S_D} v_D v_S & 2\lambda_{S_D} v_S^2\end{pmatrix} \begin{pmatrix}\tilde{h}\\ \tilde{h}_D\\ \tilde{s}_D\end{pmatrix}$$

$$\equiv \frac{1}{2}\begin{pmatrix}\tilde{h}\\ \tilde{h}_D\\ \tilde{s}_D\end{pmatrix}^T \begin{pmatrix}M_{11}^2 & M_{12}^2 & M_{13}^2\\ M_{21}^2 & M_{22}^2 & M_{23}^2\\ M_{31}^2 & M_{32}^2 & M_{33}^2\end{pmatrix} \begin{pmatrix}\tilde{h}\\ \tilde{h}_D\\ \tilde{s}_D\end{pmatrix},$$

❖ **In general 3 scalars mix**

We take following assumption for scalar mass

$$\begin{pmatrix}\tilde{h}\\ \tilde{h}_D\\ \tilde{s}_D\end{pmatrix} \simeq \begin{pmatrix}\cos\beta & 0 & -\sin\beta\\ 0 & 1 & 0\\ \sin\beta & 0 & \cos\beta\end{pmatrix} \begin{pmatrix}h\\ H_1\\ H_2\end{pmatrix}$$

$$m_h^2 \simeq \frac{M_{11}^2 + M_{33}^2}{2} - \frac{1}{2}\sqrt{(M_{11}^2 - M_{22}^2)^2 + 4M_{13}^4},$$

$$m_{H_1}^2 \simeq M_{22}^2,$$

$$m_{H_2}^2 \simeq \frac{M_{11}^2 + M_{33}^2}{2} + \frac{1}{2}\sqrt{(M_{11}^2 - M_{33}^2)^2 + 4M_{13}^4},$$

$$\tan 2\beta = \frac{2M_{13}^2}{M_{11}^2 - M_{33}^2}.$$

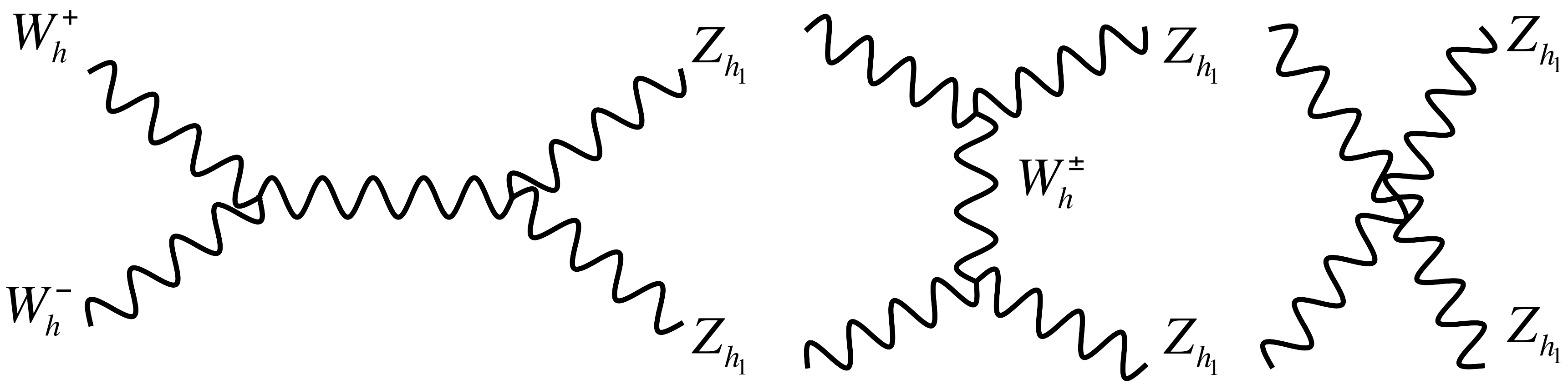
It is for avoiding DM direct detection constraints

Relic density of Vector DM

❖ Interactions relevant to DM physics

$$L \supset i g_D c_X (\partial_\mu W^+_{h\nu} - \partial_\nu W^+_{h\mu}) W_h^{-\mu} Z^\nu_{h_1} - i g_D c_X (\partial_\mu W^-_{h\nu} - \partial_\nu W^-_{h\mu}) W_h^{+\mu} Z^\nu_{h_1}$$
$$+ i g_D c_X (\partial_\mu Z_{h_1\nu} - \partial_\nu Z_{h_1\mu}) W_h^{+\mu} W_h^{-\nu} - g_D^2 \left[c_X^2 W^+_{h\mu} W_h^{-\mu} Z_{h_1\nu} Z^\nu_{h_1} - c_X^2 W^+_{h\mu} W^-_{h\nu} Z^\mu_{h_1} Z^\nu_{h_1} \right]$$

❖ Dominant DM annihilation processes

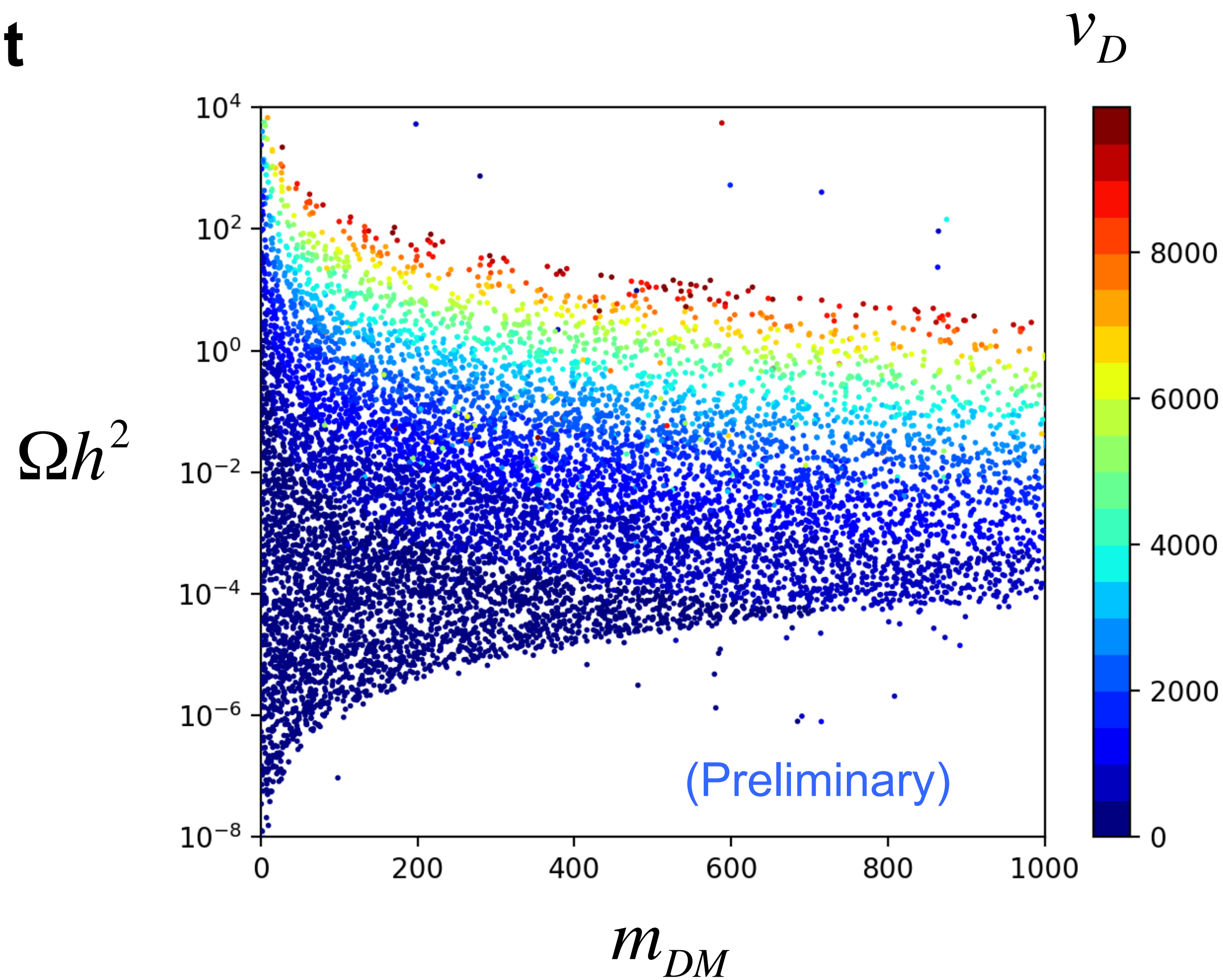


Relevant free parameters: $\{g_D, g_S, v_S, v_D, \lambda_H, \lambda_{S_D}, \lambda_{H_D}\}$ (Y_D=Y_S=1)

Scanning range: $v_{S,D} \in [1.0, 10000]$ GeV, $g_{D,S} \in [3.0 \times 10^{-5}, 3.0]$, $\lambda_{H,S_D,H_D} \in [10^{-4}, 10]$,

Relic density of Vector DM

❖ **Result**

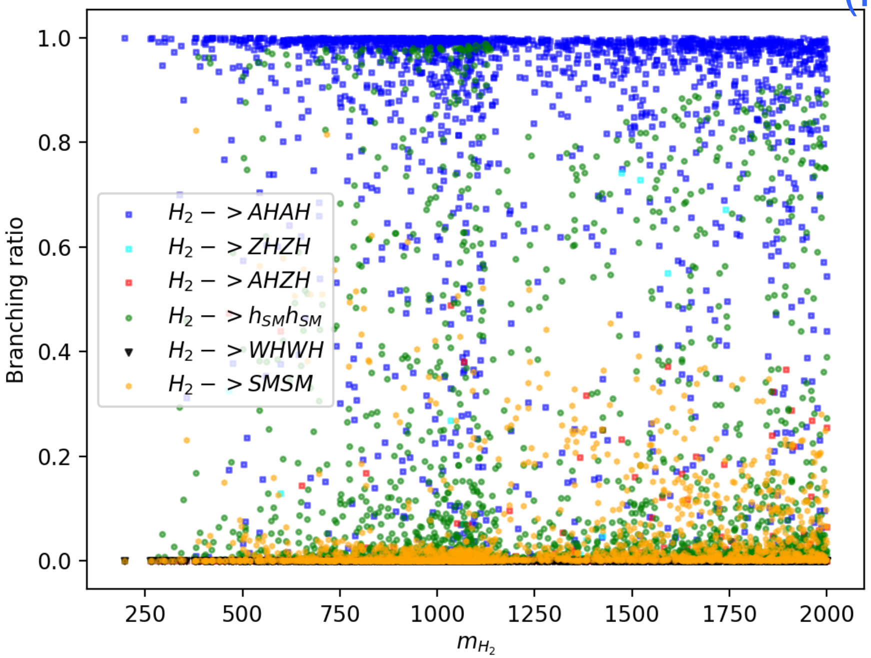


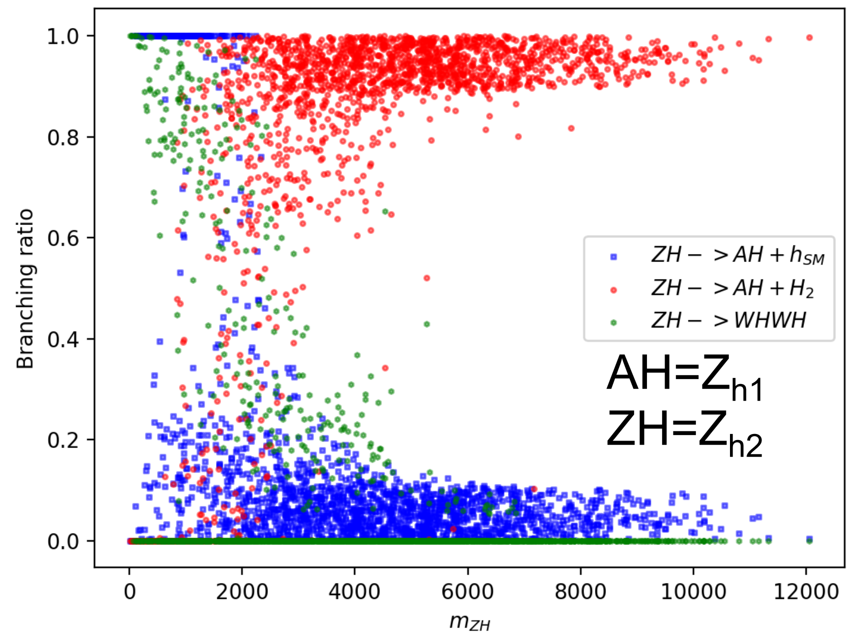
✓ **DM-nucleon scattering is suppressed**

H_2 decay ratio

Z_{h2} decay ratio

(Preliminary)





- ✓ H_2 mainly decay into Z_{h1} or Z_{h2}
- ✓ They decay via kinetic mixing with SM Z boson
- ✓ Heavier state can be impostor of DM if $Z_{h1/2}$ is long lived (small mixing)
- ✓ Sizable signal of missing E_T + j/γ

Summary and Discussions

- DM models with hidden gauge symmetry
  - ✓ Multiple components in hidden sector
  - ✓ DM stability from remnants of hidden gauge symmetry
  - ✓ Mixing in scalar sector giving Higgs portal interaction

- DM physics
  - ✓ Relic density can be explained by DM DM → Z' Z' mode
  - ✓ Direct detection constraints can be relaxed
  - ✓ Collider signal with sizable cross section of heavier state production
  - ✓ Heavier dark state is impostor of DM
  - ✓ This type of scenario can appear also in other model like NMSSM (fermionic DM case)

Appendix

❖ Full Lagrangian in gauge sector of vector DM model

$$
\begin{aligned}
L_G =& i g_D c_X (\partial_\mu W^+_{h\nu} - \partial_\nu W^+_{h\mu}) W_h^{-\mu} Z^\nu_{h_1} - i g_D s_X (\partial_\mu W^+_{h\nu} - \partial_\nu W^+_{h\mu}) W_h^{-\mu} Z^\nu_{h_2} \\
& - i g_D c_X (\partial_\mu W^-_{h\nu} - \partial_\nu W^-_{h\mu}) W_h^{+\mu} Z^\nu_{h_1} + i g_D s_X (\partial_\mu W^-_{h\nu} - \partial_\nu W^-_{h\mu}) W_h^{+\mu} Z^\nu_{h_2} \\
& + i g_D c_X (\partial_\mu Z_{h_1\nu} - \partial_\nu Z_{h_1\mu}) W_h^{+\mu} W_h^{-\nu} - i g_D s_X (\partial_\mu Z_{h_2\nu} - \partial_\nu Z_{h_2\mu}) W_h^{+\mu} W_h^{-\nu} \\
& - g_D^2 \Big[c_X^2 W^+_{h\mu} W_h^{-\mu} Z_{h_1\nu} Z^\nu_{h_1} - 2 c_X s_X W^+_{h\mu} W_h^{-\mu} Z_{h_1\nu} Z^\nu_{h_2} + s_X^2 W^+_{h\mu} W_h^{-\mu} Z_{h_2\nu} Z^\nu_{h_2} \\
& \quad - c_X^2 W^+_{h\mu} W^-_{h\nu} Z^\mu_{h_1} Z^\nu_{h_1} + c_X s_X W^+_{h\mu} W^-_{h\nu} Z^\mu_{h_1} Z^\nu_{h_2} + c_X s_X W^+_{h\mu} W^-_{h\nu} Z^\nu_{h_1} Z^\mu_{h_2} \\
& \quad - s_X^2 W^+_{h\mu} W^-_{h\nu} Z^\mu_{h_2} Z^\nu_{h_2} - \frac{1}{2} W^+_{h\mu} W_h^{+\mu} W^-_{h\nu} W_h^{-\nu} + \frac{1}{2} W^+_{h\mu} W_h^{-\mu} W^+_{h\nu} W_h^{-\nu} \Big],
\end{aligned}
$$

❖ Full Lagrangian in gauge sector of vector DM model

$$
\begin{aligned}
L \supset & \frac{2m^2_{W_h^\pm}}{v_D} W^+_{h\mu} W_h^{-\mu} \tilde{h}_D + \frac{m^2_{W_h^\pm}}{v_D^2} W^+_{h\mu} W_h^{-\mu} \tilde{h}_D \tilde{h}_D \\
& + \left(\frac{m^2_{Z_{h_1}}}{v_D} - \frac{g_S^2 Y_S^2 v_S^2}{v_D} s_X^2 \right) Z_{h_1\mu} Z^\mu_{h_1} \tilde{h}_D + \left(\frac{m^2_{Z_{h_2}}}{v_D} - \frac{g_S^2 Y_S^2 v_S^2}{v_D} c_X^2 \right) Z_{h_2\mu} Z^\mu_{h_2} \tilde{h}_D \\
& + \frac{1}{2} \left(\frac{m^2_{Z_{h_1}}}{v_D^2} - \frac{g_S^2 Y_S^2 v_S^2}{v_D^2} s_X^2 \right) Z_{h_1\mu} Z^\mu_{h_1} \tilde{h}_D \tilde{h}_D + \frac{1}{2} \left(\frac{m^2_{Z_{h_2}}}{v_D^2} - \frac{g_S^2 Y_S^2 v_S^2}{v_D^2} c_X^2 \right) Z_{h_2\mu} Z^\mu_{h_2} \tilde{h}_D \tilde{h}_D \\
& - \frac{g_S^2 Y_S^2 v_S^2}{2 v_D} c_X s_X Z_{h_1\mu} Z^\mu_{h_2} \tilde{h}_D - \frac{g_S^2 Y_S^2 v_S^2}{4 v_D^2} c_X s_X Z_{h_1\mu} Z^\mu_{h_2} \tilde{h}_D \tilde{h}_D \\
& + \frac{g_S^2 Y_S^2 v_S s_X^2}{4} Z_{h_1\mu} Z^\mu_{h_1} \tilde{s}_D + \frac{g_S^2 Y_S^2 v_S c_X^2}{4} Z_{h_2\mu} Z^\mu_{h_2} \tilde{s}_D + \frac{g_S^2 Y_S^2 v_S c_X s_X}{2} Z_{h_1\mu} Z^\mu_{h_2} \tilde{s}_D \\
& + \frac{g_S^2 Y_S^2 s_X^2}{8} Z_{h_1\mu} Z^\mu_{h_1} \tilde{s}_D \tilde{s}_D + \frac{g_S^2 Y_S^2 c_X^2}{8} Z_{h_2\mu} Z^\mu_{h_2} \tilde{s}_D \tilde{s}_D + \frac{g_S^2 Y_S^2 v_S c_X s_X}{4} Z_{h_1\mu} Z^\mu_{h_2} \tilde{s}_D \tilde{s}_D, \quad \text{(A2)}
\end{aligned}
$$