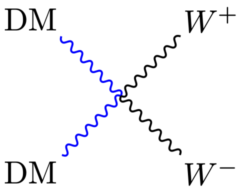
# A model of electroweakly interacting non-abelian vector dark matter

## Motivation & Summary

What is the nature of **electroweakly interacting spin-1 dark matter** (DM)?

- how to construct a spin-1 DM model w/ EW int.?
- What is a good probe for spin-1 DM?




**Exchange symme.** btw gauge groups → **$Z_2$-odd spin-1 DM w/ EW int.**
**Next-generation direct detection** can probe DM via **Higgs exchange**

## Model

**Exchange symmetry**

| field | spin | $SU(3)_c$ | $SU(2)_0$ | $SU(2)_1$ | $SU(2)_2$ | $U(1)_Y$ |
|---|---|---|---|---|---|---|
| $q_L$ | $\frac{1}{2}$ | 3 | 1 | 2 | 1 | $\frac{1}{6}$ |
| $u_R$ | $\frac{1}{2}$ | 3 | 1 | 1 | 1 | $\frac{2}{3}$ |
| $d_R$ | $\frac{1}{2}$ | 3 | 1 | 1 | 1 | $-\frac{1}{3}$ |
| $\ell_L$ | $\frac{1}{2}$ | 1 | 1 | 2 | 1 | $-\frac{1}{2}$ |
| $e_R$ | $\frac{1}{2}$ | 1 | 1 | 1 | 1 | -1 |
| $\Phi_1$ | 0 | 1 | 2 | 2 | 1 | 0 |
| $\Phi_2$ | 0 | 1 | 1 | 2 | 2 | 0 |
| $H$ | 0 | 1 | 1 | 2 | 1 | $\frac{1}{2}$ |
| | | | $W^a_{0\mu}$ | $W^a_{1\mu}$ | $W^a_{2\mu}$ | |

Symmetry trans. (after SSB)
$\sigma_1 \leftrightarrow \sigma_2, \quad W^a_{0\mu} \leftrightarrow W^a_{2\mu} \ (a=1,2,3)$

**Exchange symmetry**
**↔ $Z_2$-parity for physical states**

$Z_2$-odd particles

$$V^0 = \frac{W^3_{0\mu} - W^3_{2\mu}}{\sqrt{2}} \rightarrow$$ **Spin-1 DM w/ EW int.** $(m_V < m_{h_D})$

$$V^\pm = \frac{W^\pm_{0\mu} - W^\pm_{2\mu}}{\sqrt{2}}$$

$$h_D = \frac{\sigma_1 - \sigma_2}{\sqrt{2}}$$

$$\left( \frac{\sigma_1 + \sigma_2}{\sqrt{2}}, \ \sigma_3 \right) \xrightarrow{\text{mixing } \phi_h} h', \ h \text{ (SM Higgs)}$$

## Scalar sector

$$\Phi_j = \begin{pmatrix} \frac{v_\Phi + \sigma_j + i\pi^0_j}{\sqrt{2}} & i\pi^+_j \\ i\pi^-_j & \frac{v_\Phi + \sigma_j - i\pi^0_j}{\sqrt{2}} \end{pmatrix}, H = \begin{pmatrix} i\pi^+_3 \\ \frac{v + \sigma_3 - i\pi^0_3}{\sqrt{2}} \end{pmatrix}$$

$(j = 1, 2)$

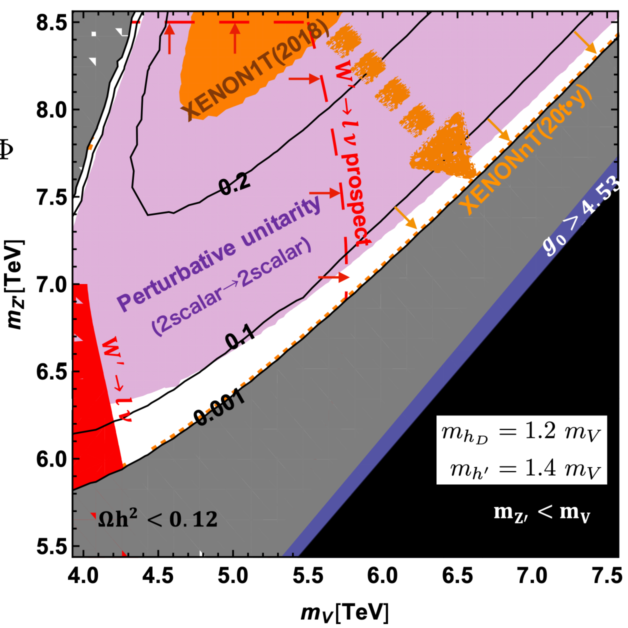
3 neutral scalars are physical after SSB

## BSM spectrum

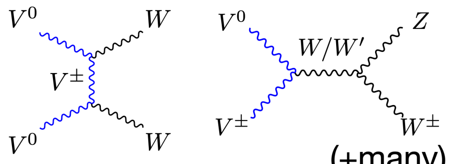
| vector | | scalar | $Z_2$ | mass |
|---|---|---|---|---|
| $Z'$ | $W'^\pm$ | $h'$ | even | $\sim v_\Phi$ |
| $V^0$ | $V^\pm$ | $h_D$ | odd | $\sim v_\Phi$ |

## Results

Contours of Higgs mixing angle (determined to reach $\Omega h^2$=0.12)

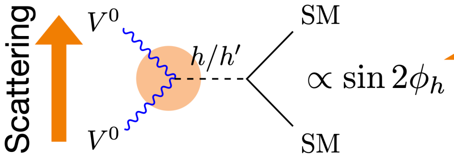



- EW channel



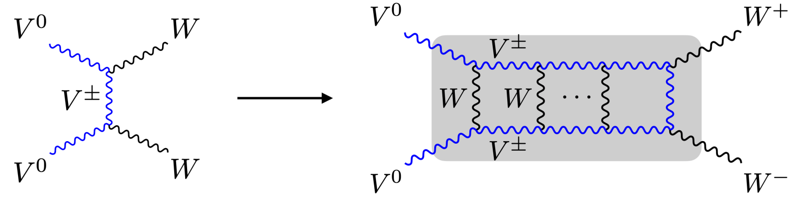

(+many)

- Higgs channel




**Next-generation direct detection can probe Higgs contributions in $\Omega h^2$ determination**

## Future Work




A chance to discriminate DM spins in indirect detection!
(Sommerfeld effect is relevant in annihilation processes)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work w/ Tomohiro Abe, Junji Hisano, Kohei Matsushita (Nagoya U.)

# Model & Symmetry breaking structure

$g_0$ : gauge coupling for SU(2)$_0$ & SU(2)$_2$
$g_1$ : gauge coupling for SU(2)$_1$

## BSM Lagrangian

$$\mathcal{L} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \sum_{j=0}^{2}\sum_{a=1}^{3}\frac{1}{4}W^a_{j\mu\nu}W^{a\mu\nu}_j + D_\mu H^\dagger D^\mu H + \frac{1}{2}\mathrm{tr}D_\mu\Phi_1^\dagger D^\mu\Phi_1 + \frac{1}{2}\mathrm{tr}D_\mu\Phi_2^\dagger D^\mu\Phi_2 - V_{\mathrm{scalar}},$$

$$\begin{aligned} V_{\mathrm{scalar}} =& m^2 H^\dagger H + m_\Phi^2 \mathrm{tr}\left(\Phi_1^\dagger\Phi_1\right) + m_\Phi^2\mathrm{tr}\left(\Phi_2^\dagger\Phi_2\right) \\ &+ \lambda(H^\dagger H)^2 + \lambda_\Phi\left(\mathrm{tr}\left(\Phi_1^\dagger\Phi_1\right)\right)^2 + \lambda_\Phi\left(\mathrm{tr}\left(\Phi_2^\dagger\Phi_2\right)\right)^2 \\ &+ \lambda_{h\Phi}H^\dagger H\mathrm{tr}\left(\Phi_1^\dagger\Phi_1\right) + \lambda_{h\Phi}H^\dagger H\mathrm{tr}\left(\Phi_2^\dagger\Phi_2\right) + \lambda_{12}\mathrm{tr}\left(\Phi_1^\dagger\Phi_1\right)\mathrm{tr}\left(\Phi_2^\dagger\Phi_2\right). \end{aligned}$$

## Parameters

$$\underbrace{g_0,\ g_1,\ g',\ v,\ v_\Phi,}\quad \underbrace{\lambda,\ \lambda_{h\Phi},\ \lambda_\Phi,\ \lambda_{12}}$$

$$\downarrow \qquad\qquad \downarrow$$

$$e,\ G_F,\ m_Z,\ m_V,\ m_{Z'},\ m_h,\ m_{h'},\ m_{h_D},\ \phi_h$$

Free parameters

TeV scale

$$\{\ m_V,\ m_{Z'},\ m_{h'},\ m_{h_D},\ \phi_h\ \}$$

## Gauge transformation

$U_n = \exp[i\theta_n(x)] \quad (n=0,1,2)$

$$\Phi_1 \mapsto U_0\Phi_1 U_1^\dagger \qquad \Phi_2 \mapsto U_2\Phi_2U_1^\dagger \qquad H \mapsto U_1 H$$

## Symmetry Breaking

$$\boxed{\mathrm{SU}(2)_0\otimes\mathrm{SU}(2)_1\otimes\mathrm{SU}(2)_2\otimes\mathrm{U}(1)_Y \xrightarrow{\langle\Phi_j\rangle\neq 0} \mathrm{SU}(2)\otimes\mathrm{U}(1)_Y \xrightarrow{\langle H\rangle\neq 0} \mathrm{U}(1)_{\mathrm{em}}}$$

$\cong$ SU(2)$_L$

$$\langle\Phi_1\rangle = \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} v_\Phi & 0 \\ 0 & v_\Phi\end{pmatrix} \qquad \langle H\rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}}\end{pmatrix}$$

$$(\underset{\mathcal{O}(1)\ \mathrm{TeV}}{v_\Phi} \gg \underset{\mathcal{O}(100)\ \mathrm{GeV}}{v})$$

$\langle\Phi_1\rangle, \langle\Phi_2\rangle$ are invariant under the following transformations

(1) Gauge trans. w/ $U_0 = U_1 = U_2$

$$U_0\langle\Phi_1\rangle U_1^\dagger = \langle\Phi_1\rangle$$
$$U_2\langle\Phi_2\rangle U_1^\dagger = \langle\Phi_2\rangle$$

Generators of SU(2)$_{0,1,2}$ are identified

→ SU(2)$_L$ gauge symmetry

(2) Exchange trans.

$$\langle\Phi_1\rangle \leftrightarrow \langle\Phi_2\rangle$$

Exchange symmetry still alive

→ $Z_2$ parity structure

# Features of EW spin-1 DM (Compared w/ Wino DM)

**$Z_2$-odd vectors**

DM

$$V^0 = \frac{W^3_{0\mu} - W^3_{2\mu}}{\sqrt{2}} \quad \text{(neutral)}$$

$$V^\pm = \frac{W^\pm_{0\mu} - W^\pm_{2\mu}}{\sqrt{2}} \quad \text{(charged)}$$

**"V-particles"**

**$SU(2)_L$ triplet-like features**

**Mass relations**

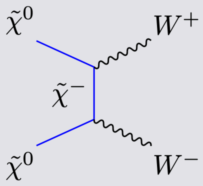
Mass degeneracy btw V-particles is broken by EW radiative corrections

tree: $m^2_{V^0} = m^2_{V^\pm} = \frac{g_0^2 v_\Phi^2}{4} \quad (\equiv m_V^2)$

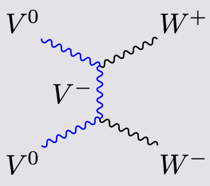
1-loop: $\delta_{m_V} \equiv m_{V^\pm} - m_{V^0} \simeq 168\ \mathrm{MeV}$ Almost same as Wino!

→ **Coannihilation is relevant** (efficient annihilation through EW int.)

**Wino(Spin-1/2) vs V-particles(Spin-1)**




vs




| | | |
|---|---|---|
| Spin | **1/2** (Majorana fermion) [$SU(2)_L$ triplet, Y=0] | **1** (vector) |
| Mass difference | $\sim 166\ \mathrm{MeV}$ | $\sim 168\ \mathrm{MeV}$ |
| Annihilation | EW | EW + **Higgs exchange** |
| Scattering | tree-level: None<br>loop-level: EW | tree-level: **Higgs exchange**<br>loop-level: EW |
| $Z_2$-even vectors | — | $Z', W'$ |

Features of electroweakly interacting DM?

(spin-1/2 vs spin-1)

Common properties

Coannihilation is efficient

→ **Thermal relic mass**

$\simeq \mathcal{O}(1)\mathrm{TeV}$

Different properties

good probes for spin-1 DM

→ **•Direct detection**

**•W' search @LHC**