

Gamma-ray line from electroweakly interacting non-abelian **spin-1** dark matter

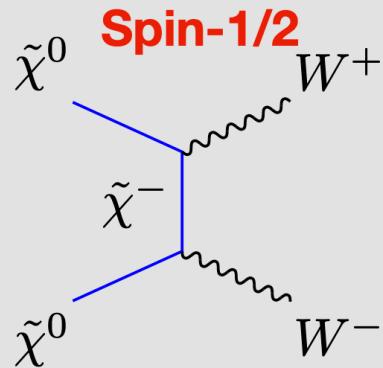
Motoko Fujiwara (Nagoya U.)

Collaboration w/ Tomohiro Abe (Tokyo U. of Science)
Junji Hisano (KMI, Nagoya U., Kavli iPMU)
Kohei Matsushita (Nagoya U.)

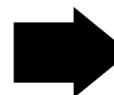
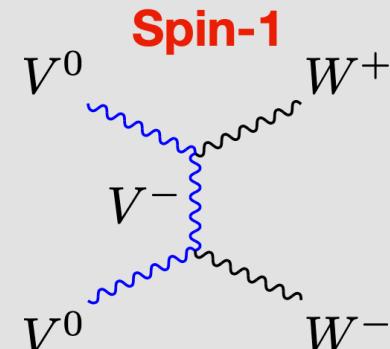
Based on T. Abe, **MF**, J. Hisano, K. Matsushita, JHEP 07 (2020) 136 [[arXiv:2004.00884](#)]
T. Abe, **MF**, J. Hisano, K. Matsushita, [[arXiv:2107.10029](#)]

1min. Summary

Spin identification of the electroweakly interacting Dark Matter (DM)
linking to the different New Physics scenarios



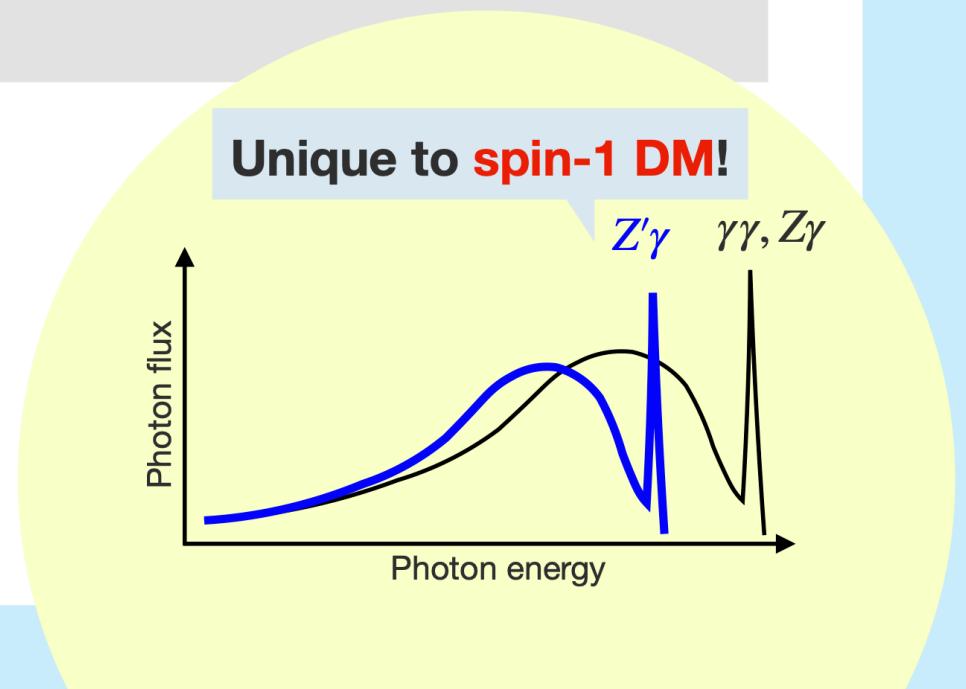
VS



Key: Gamma-ray signatures!

Spin-1 DM predicts

- larger annihilation cross section
- double-peak spectrum



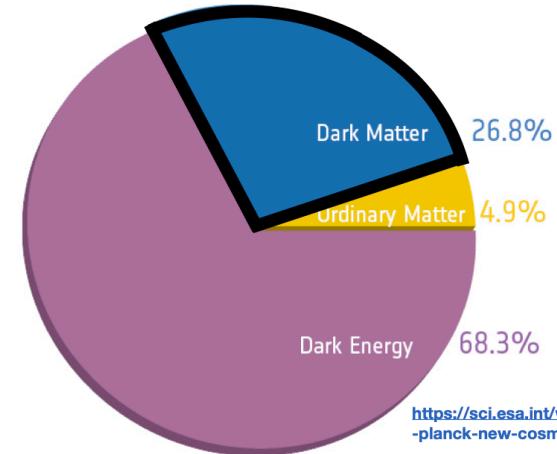


Dark matter

What is Dark Matter (DM)?

Invisible (=dark) unknown massive sources

- 1/4 of energy density in our universe
- Electrically neutral
- Massive
- Stable / Long-lived



DM candidate?

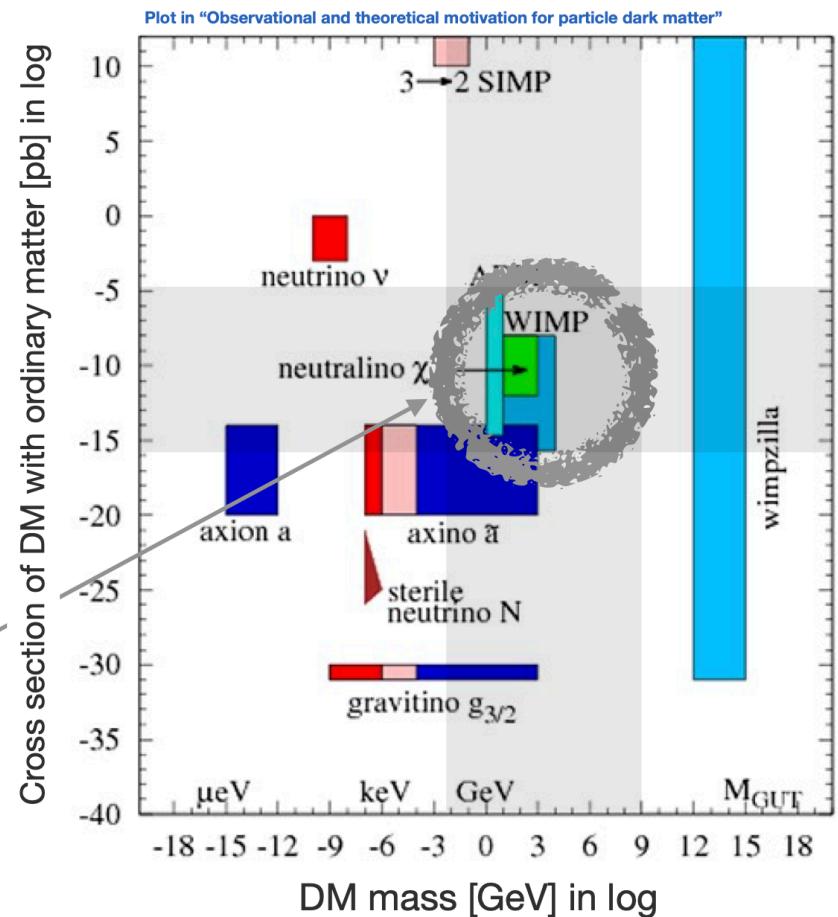
Many possibilities for DM mass/interaction

Goal: **Identification of DM**

→ a window to probe new physics!

Weakly Interacting Massive Particle

- DM abundance from thermal history
- Probed by various experiments

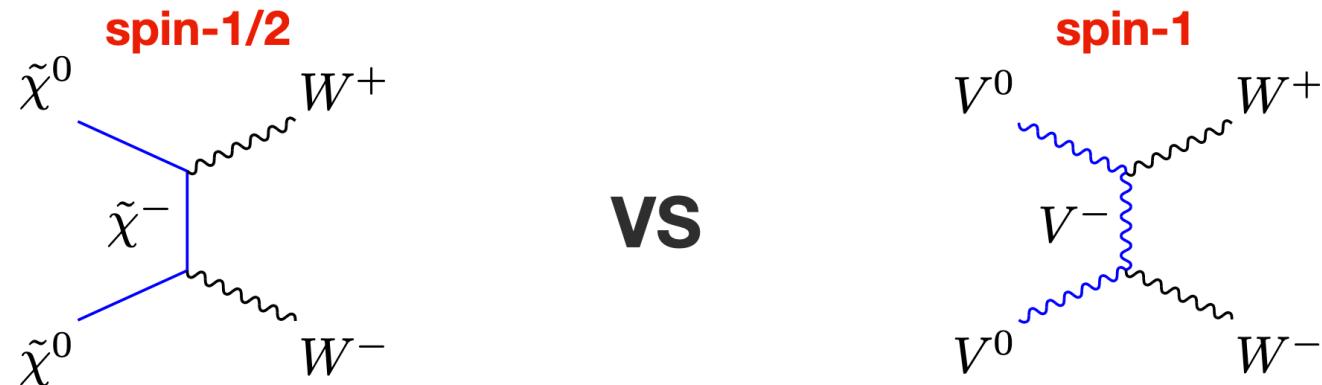


■ Electroweakly interacting DM

Assumption: DM = $SU(2)_L$ multiplet

- DM coupling: Electroweak coupling
 - DM mass: $\mathcal{O}(1)$ TeV to explain correct DM energy density
- **DM interaction theory is specified by determining DM spin!**

Spin identification of $SU(2)_L$ triplet DM



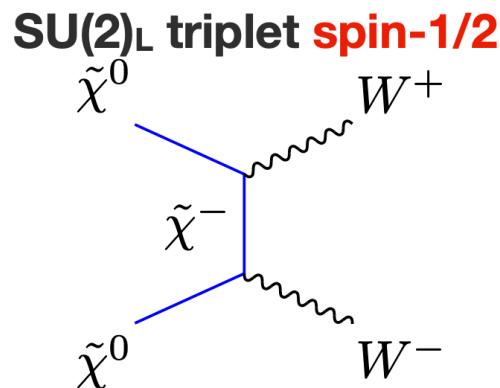
We can discriminate **two New Physics scenarios**
that provide **DM stabilization mechanism!**

Model of EW interacting DM

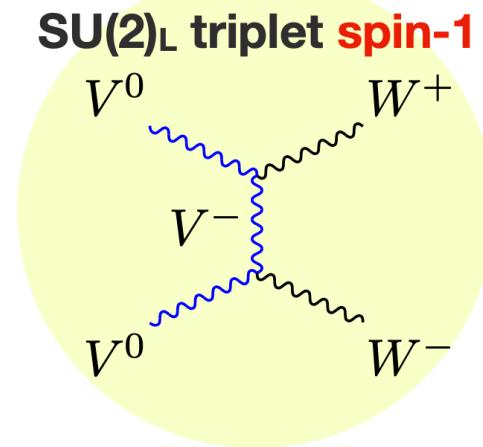
cf. Review talk by Prof. Kyu Jung Bae

Supersymmetric DM model	Model w/ Extra-dimension
<ul style="list-style-type: none">SM particles + SUSY partnersR-parity guarantees DM stabilityMany DM candidates<ul style="list-style-type: none">Wino DM	<ul style="list-style-type: none">SM particles + Kaluza-Klein (KK) towersKK-parity guarantees DM stabilityBulk action + Boundary Localized action → 1st KK W_μ^3 can be Lightest KK Particle

[T. Flacke, A. Menon, D. J. Phalen (2009)]
[T. Flacke, D. W. Kang, Kyoungchul Kong, Gopolang Mohlabeng, Seong Chan Park (2017)]



VS



Question: **What is the nature of SU(2)_L triplet spin-1 DM?**
How to identify DM spin?

■ Contents

- ✓ ● Introduction
- How to study Spin-1 DM
- Model of Spin-1 DM
- Gamma-ray line signals
- Summary



How to study Spin-1 DM



Extracting Spin-1 DM natures

How to study?

- We want to study DM phenomenology
- Focus on **KK particles of EW vectors** rather than treating infinite # of KK particles

		⋮		⋮	⋮	⋮	⋮	⋮
2-mode		$\gamma^{(2)}$	$Z^{(2)}$	$W^{\pm(2)}$	$h^{(2)}$	$f^{(2)}$		Z_2 -even
1-mode		$\gamma^{(1)}$	$Z^{(1)}$	$W^{\pm(1)}$	$h^{(1)}$	$f^{(1)}$		Z_2 -odd
0-mode	γ	Z	W^\pm	h	f			Z_2 -even

→ Construct a simplified model!

Deconstructing dimension

[N. Arkani-Hamed, A. G. Cohen, H. Georgi (2001)]

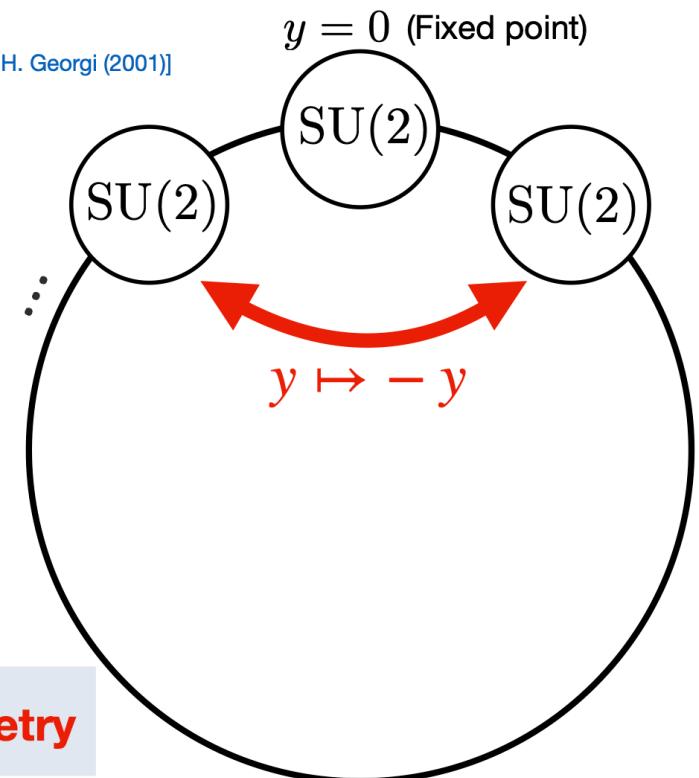
- Method to realize spectrum in extra-dim. theory from the renormalizable setup

We want $\begin{cases} \cdot \text{KK-tower} \\ \cdot Z_2\text{-parity} \end{cases}$ in $SU(2)_L$ vector sector

- Consider 5d $SU(2)$ gauge theory
- Orbifold compactification S_1/Z_2 ($y \mapsto -y$)
- Discretize the 5d axis



Direct products of $SU(2)$ w/ exchange symmetry





Model of Spin-1 DM



Non-Abelian extension of $SU(2)_L$

Symmetry

$$SU(3)_c \otimes SU(2)_0 \otimes SU(2)_1 \otimes SU(2)_2 \otimes U(1)_Y$$

Exchange Symmetry

Matter Contents

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	$-\frac{1}{3}$
ℓ_L	$\frac{1}{2}$	1	1	2	1	$-\frac{1}{2}$
e_R	$\frac{1}{2}$	1	1	1	1	-1
Φ_1	0	1	2	2	1	0
Φ_2	0	1	1	2	2	0
H	0	1	1	2	1	$\frac{1}{2}$

$W_{0\mu}^a$ $W_{1\mu}^a$ $W_{2\mu}^a$

- Each fermion corresponds to SM fermion
- Φ_1, Φ_2 : Bi-fundamental scalar
- Exchange symme. trans.

$$\begin{aligned} \Phi_1 &\mapsto \Phi_2, & W_{0\mu}^a &\mapsto W_{2\mu}^a \\ \Phi_2 &\mapsto \Phi_1, & W_{2\mu}^a &\mapsto W_{0\mu}^a \end{aligned}$$

* gauge coupling: $g_0 = g_2$ ($\neq g_1$)

Where are $SU(2)_L$ & Z_2 parity?

Scalar sector

Field definition

$$\Phi_j = \mathbf{1}\sigma_j + \tau^a\pi_j^a \quad \left[\text{that satisfy } \Phi_j = -\epsilon\Phi_j^*\epsilon \atop (j=1, 2) \right]$$

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} i\pi^1 - \pi^2 \\ \sigma - i\pi^3 \end{pmatrix}$$

Gauge trans.

$$\begin{cases} \Phi_1 \mapsto U_0 \Phi_1 U_1^\dagger \\ \Phi_2 \mapsto U_2 \Phi_2 U_1^\dagger \\ H \mapsto U_1 H \end{cases} \quad U_n = \exp[i\theta_n(x)] \quad (n = 0, 1, 2)$$

Symmetry Breaking

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

VEV of scalar:

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

SU(2)_L

$$\langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \quad \begin{matrix} (v_\Phi \gg v) \\ \uparrow \quad \uparrow \\ \mathcal{O}(1) \text{ TeV} \quad \mathcal{O}(100) \text{ GeV} \end{matrix}$$

$\langle \Phi_1 \rangle, \langle \Phi_2 \rangle$ are invariant under

- Gauge trans. w/ $U_0 = U_1 = U_2$
- Exchange trans. $\langle \Phi_1 \rangle \leftrightarrow \langle \Phi_2 \rangle$

→ **SU(2)_L gauge symmetry**

→ **Z₂ parity structure** (Next page)

Z₂ parity from Exchange symme.

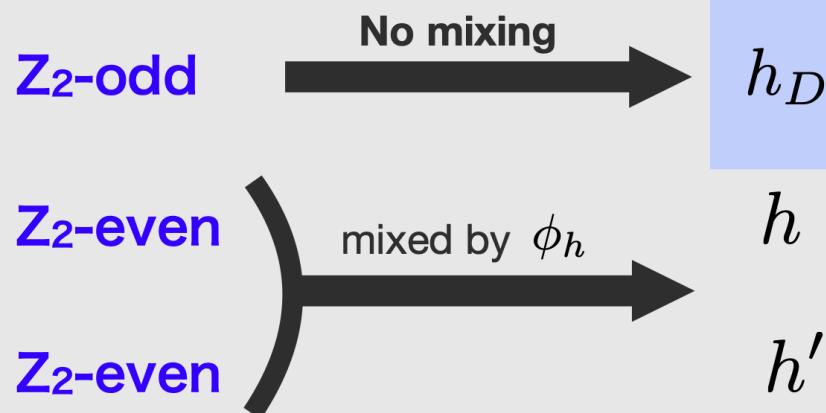
Exchange trans. (after SSB)

$$\sigma_1 \leftrightarrow \sigma_2, \quad W_{0\mu}^a \leftrightarrow W_{2\mu}^a$$

$$\left[\Phi_j = \begin{pmatrix} \frac{v_\Phi + \sigma_j + i\pi_j^0}{\sqrt{2}} & i\pi_j^+ \\ i\pi_j^- & \frac{v_\Phi + \sigma_j - i\pi_j^0}{\sqrt{2}} \end{pmatrix} \quad (j=1, 2) \quad H = \begin{pmatrix} i\pi_3^+ \\ \frac{v + \sigma_3 - i\pi_3^0}{\sqrt{2}} \end{pmatrix} \right]$$

eg. Trans. of neutral scalar: { $\sigma_1, \sigma_2, \sigma_3$ }

$$\left\{ \begin{array}{lcl} \frac{\sigma_1 - \sigma_2}{\sqrt{2}} & \mapsto & -\frac{\sigma_1 - \sigma_2}{\sqrt{2}} \\ \\ \frac{\sigma_1 + \sigma_2}{\sqrt{2}} & \mapsto & +\frac{\sigma_1 + \sigma_2}{\sqrt{2}} \\ \\ \sigma_3 & \mapsto & +\sigma_3 \end{array} \right.$$



States are classified by **Z₂ Parity!**

Exchange symmetry $SU(2)_0 \leftrightarrow SU(2)_2 \rightarrow$ **Z₂ Parity for physical states**

SU(2)_L vector triplet

Z_2 -odd vectors

DM

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

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

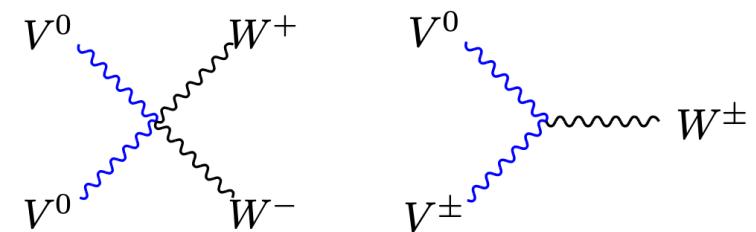
$$W_{n\mu}^\pm = \frac{W_{n\mu}^1 \mp iW_{n\mu}^2}{\sqrt{2}} \quad (n = 0, 2)$$

“V-particles”

Correspond to 1st KK mode of EW bosons
 → SU(2)_L triplet-like features

Features

- Non-Abelian EW couplings
 → EW properties dominate DM phenomenology
- Mass relation
 - Tree-level: $m_{V^0}^2 = m_{V^\pm}^2 = \frac{g_0^2 v_\Phi^2}{4} \quad (\equiv m_V^2)$
 - Loop-level: $\delta_{m_V} \equiv m_{V^\pm} - m_{V^0} \simeq 168 \text{ MeV}$



Almost same as
 SU(2)_L triplet spin-1/2 DM

V^0 is the lightest Z_2 -odd particle if we assume $m_V < m_{h_D}$
 = **Electroweakly interacting Spin-1 DM**

Spectrum

	Vector	Scalar	Z_2 parity	Mass
2nd KK	Z' W'^{\pm}	h'	even	$\sim v_\Phi$ $\mathcal{O}(1)$ TeV
1st KK	V^0 V^\pm	h_D	odd	
0-mode	Z W^\pm γ	h	even even	$\sim v$ $\mathcal{O}(100)$ GeV massless

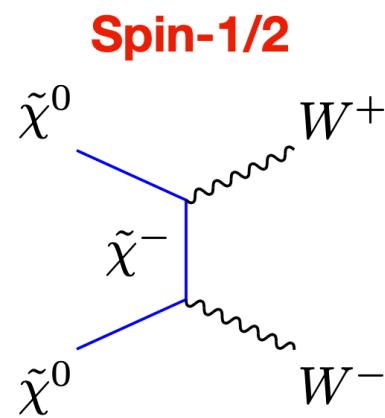
- Our model realize { **0-mode**, **1st-KK mode**, **2nd-KK mode** } in extra-dim. model
- SM limit: $v_\Phi \rightarrow \infty$
- No BSM fermions
(\because Fermion sector are separated from exchanged SU(2) symme.)

$SU(2)_0 \otimes SU(2)_1 \otimes SU(2)_2$

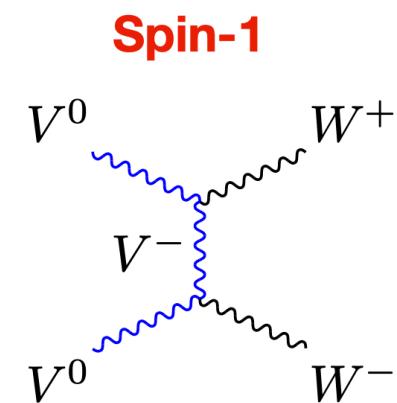
Exchanged

$$\mathcal{L} \supset -y_u \bar{q}_L \tilde{H} u_R - y_d \bar{q}_L H d_R - y_e \bar{\ell}_L H e_R + h.c. \quad \left[\tilde{H} = \epsilon H^* \quad \epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \right]$$

Gamma-ray line signals



VS





DM Spin in γ -ray search

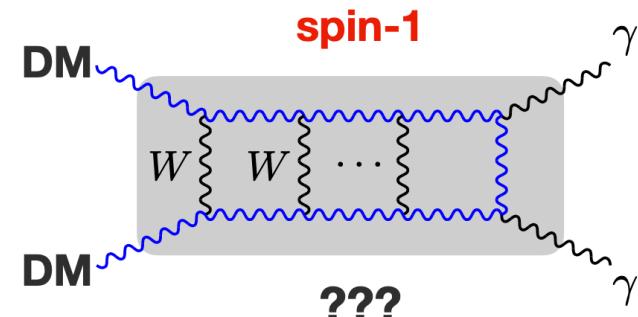
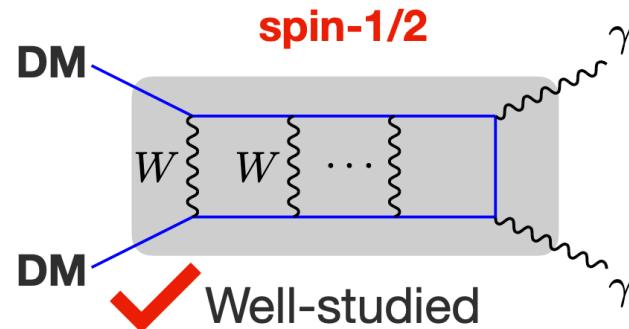
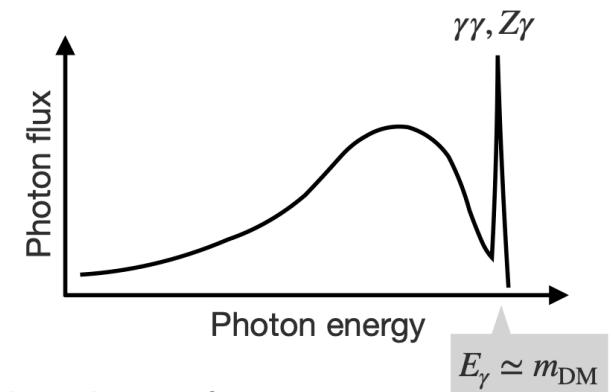
Challenge to probe DM spin

- Spin-dependent features decouple in non-relativistic processes due to momentum/velocity suppression (cf. DM speed in current universe: $v/c \simeq 10^{-3}$)

Gamma-ray line signals (DM DM $\rightarrow \gamma\gamma, Z\gamma$)

- Line γ -ray signatures @ $E_\gamma \simeq m_{\text{DM}}$
- Sommerfeld enhancement by electroweak force
- Total spin J is conserved in annihilation (\because S-wave is dominant)

→ Selection rules remember DM spin

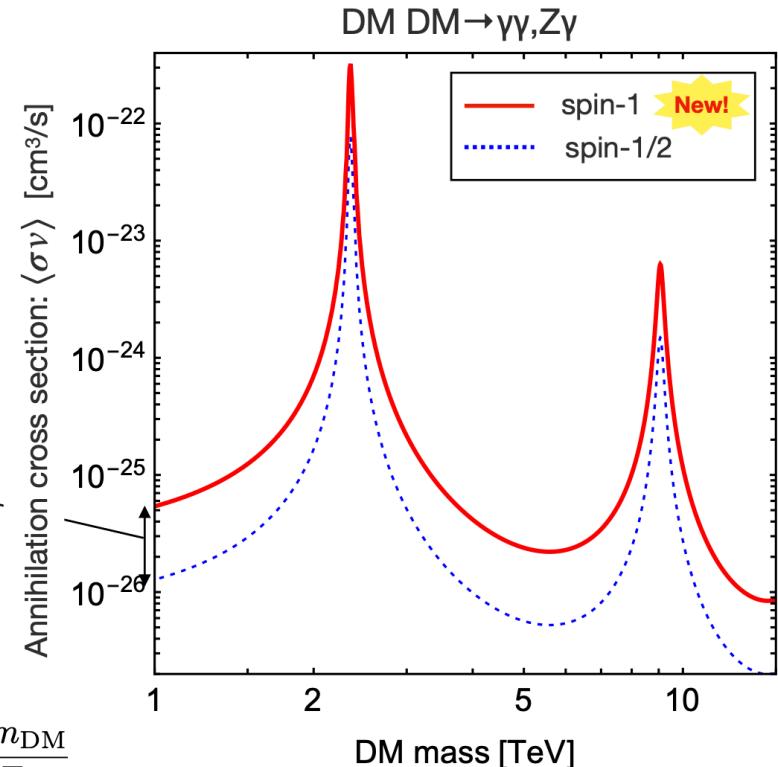


Spin identification in γ -ray search

Comparison of DM Spin

- Resonance structure is almost same
(\because determined by $SU(2)_L$ triplet-like features)
- Spin-1 DM pair forms $J = 2$ states

$$\times \frac{38}{9} (\approx 4.22...) \text{ for spin-1 DM!}$$



Higher order correction

- We need EW Sudakov resummation $\ln \frac{m_{\text{DM}}}{m_W} \times \ln \frac{m_{\text{DM}}}{E_\gamma^{\text{res}}}$
- NLO corrections of Potential shift resonance points
 - For Wino DM, we already have dedicated studies
 - We also need evaluation including higher order for spin-1 DM

Study of the Wino DM

Potential LO: [J. Hisano, S. Matsumoto, M. M. Nojiri, O. Saito (2005)]

Sudakov log: [T. Choen, M. Lisanti, A. Pierce, T. R. Slatyer (2013)]
[G. Ovanesyan, T. R. Slatyer, I. W. Stewart (2014)]
[G. Ovanesyan, N. L. Rodd, T. R. Slatyer, I. W. Stewart (2017)]
[M. Beneke, A. Broggio, C. Hasner, M. Vollmann (2018)]
[M. Beneke, A. Broggio, C. Hasner, K. Urban, M. Vollmann (2019)]

Potential NLO: [M. Beneke, R. Szafron, K. Urban (2020)]

Any other good ways to identify DM spin?

Spin-1 DM search

γ -ray line spectrum

- Spin-1 DM associates Z' (2nd KK neutral vector)
- New annihilation channel into $Z'\gamma$

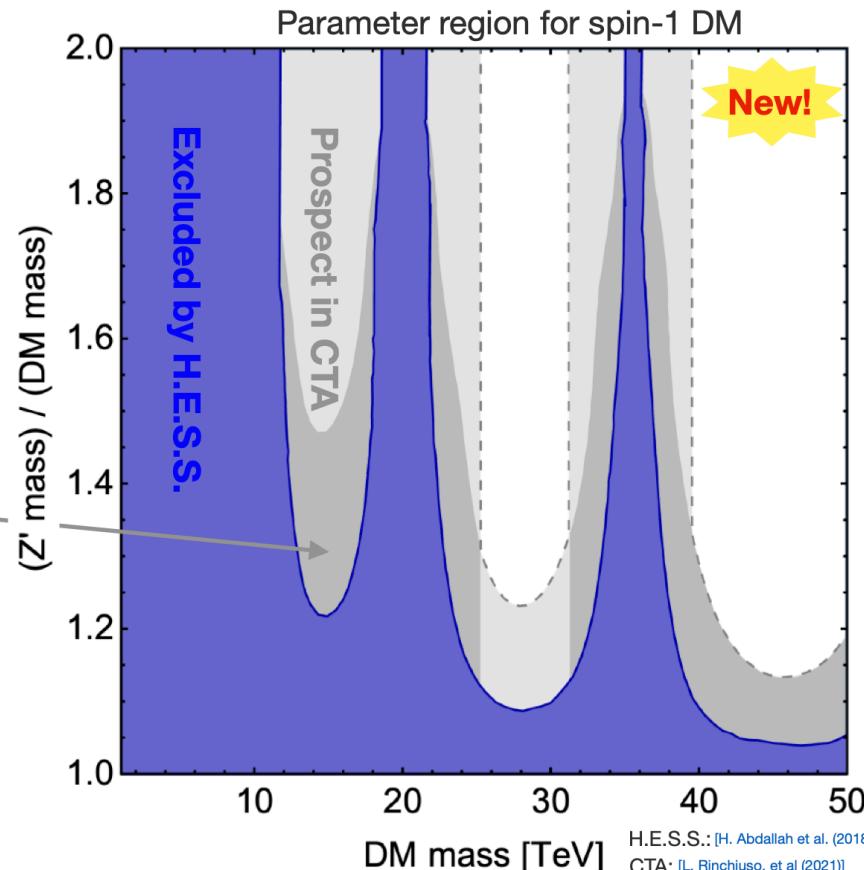
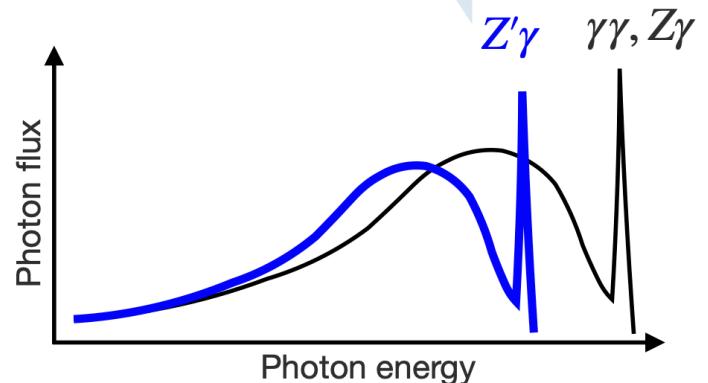
→ Reconstruct mass spectrum from double peak spectrum!

Future Detectability

- Wide region is covered in future γ -ray observation
- Chance to detect double peak signal from spin-1 DM in CTA

Unique prediction from spin-1 DM to test in future γ -ray observation!

Unique to spin-1 DM!



Summary

Spin identification of $SU(2)_L$ triplet DM

= identification of New Physics that include
DM stabilization mechanism!

Gamma-ray line signals

- Selection rules remember **DM spin**
→ Spin-1 DM annihilate efficiently by $\frac{38}{9}$ ($\simeq 4.22\dots$)
- Double peak signal that is **unique to spin-1 DM**
→ We can reconstruct masses of DM & Z'

Future work

- We specify the detectable parameter region
in simplified spin-1 model

→ Time to return extra-dim. setup!

