

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

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Based on            T. Abe, **MF**, J. Hisano, K. Matsushita, [arXiv:2107.10029]

# 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?

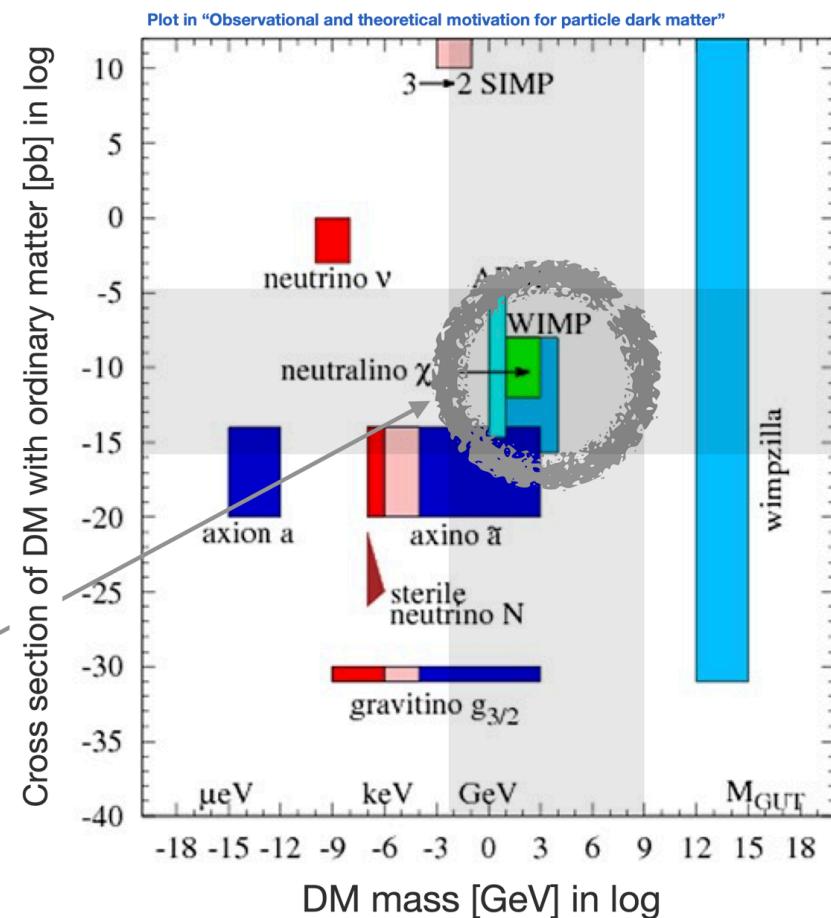
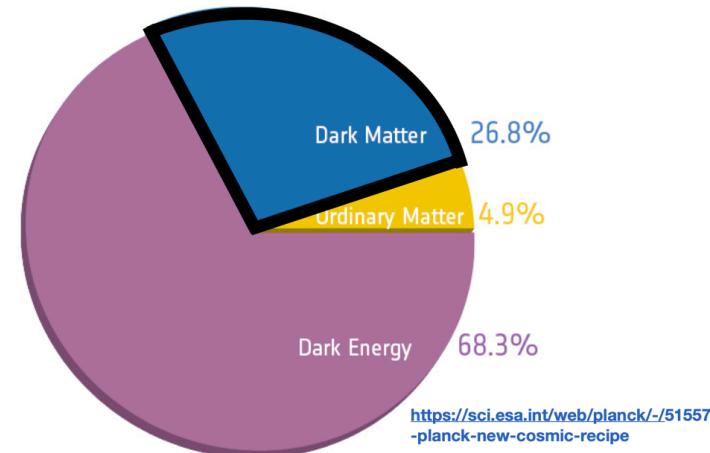
Many possibilities for DM mass/interaction

### 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!**

Table (Partially modified) from [M. Farina, D. Pappadopulo, A. Strumia (2013)]

	Quantum numbers		DM mass	$m_{\pm} - m_{DM}$	
	$SU(2)_L$	$U(1)_Y$	Spin	[TeV]	[MeV]
Higgsino	2	1/2	0	0.54	350
	2	1/2	1/2	1.1	341
Wino	3	0	0	2.5	166
	3	0	1/2	2.7	166
	:			:	:

$m_{DM}$  : DM mass

$m_{\pm}$  : mass of charged component

Model studies are focused on Spin-0, 1/2 DM scenarios

## [ Motivation ]

Study general features of EW interacting **spin-1** DM & possibility to probe in future experiment

→ How to know **DM spin** from experimental results?

Today's talk: indirect detection (**monochromatic gamma-ray**) → **EW int.** plays crucial roles

# Model

[T. Abe, MF, J. Hisano, K. Matsushita (2020)]

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

Exchange Symme.

Symmetry structure inspired from method of Deconstructing dimension

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

Matter Contents		$W_{0\mu}^a$	$W_{1\mu}^a$	$W_{2\mu}^a$		
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	$\frac{1}{2}$

## Symmetry Breaking

$$[SU(2)]^3 \otimes U(1)_Y \xrightarrow{\langle \Phi_j \rangle \neq 0} SU(2) \otimes U(1)_Y \xrightarrow{\langle H \rangle \neq 0} U(1)_{\text{em}}$$

$\underbrace{\quad}_{SU(2)_L}$

- Each fermion corresponds to SM fermion
- Scalar field to realize  $U(1)_{\text{em}}$  in low energy

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

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} i\pi^1 - \pi^2 \\ \sigma - i\pi^3 \end{pmatrix} \quad \text{4 real degrees of freedom for each}$$

- Symmetry transformation

- Gauge trans. (for scalars)
- Exchange trans.

$$\begin{cases} \Phi_1 \mapsto U_0 \Phi_1 U_1^\dagger \\ \Phi_2 \mapsto U_2 \Phi_2 U_1^\dagger \\ H \mapsto U_1 H \end{cases}$$

$$\Phi_1 \leftrightarrow \Phi_2, \quad W_{0\mu}^a \leftrightarrow W_{2\mu}^a$$

\*  $g_0 = g_2$  ( $\neq g_1$ )

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

- Vacuum expectation values

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

$$\langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

$$(v_\Phi \gg v)$$

$\uparrow$   
 $\mathcal{O}(1) \text{ TeV}$        $\uparrow$   
 $\mathcal{O}(100) \text{ GeV}$

# Spectrum

$Z_2$ -parity from exchange symmetry

Energy	Vector	Scalar	$Z_2$ parity	Mass
	$Z'$ $W'^\pm$	$h'$	<b>even</b>	$\sim v_\Phi \quad \mathcal{O}(1) \text{ TeV}$
	$V^0$ $V^\pm$	$h_D$	<b>odd</b>	
	$Z$ $W^\pm$	$h$	<b>even</b>	$\sim v \quad \mathcal{O}(100) \text{ GeV}$
	$\gamma$		<b>even</b>	massless

- $Z_2$ -odd vectors ( $V^0, V^\pm$ )  $\rightarrow$  “**V-particle**”  $\simeq \mathbf{SU(2)_L}$  triplet

- Non-abelian vector couplings  $\rightarrow$  EW int. dominates phenomenology

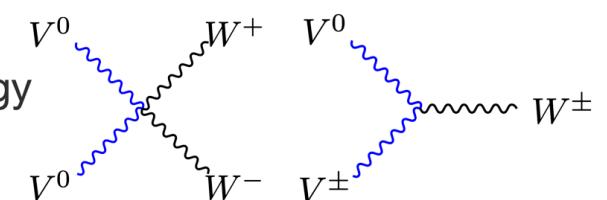
- Mass spectrum

- Tree-level:  $m_{V^0}^2 = m_{V^\pm}^2 = \frac{g_0^2 v_\Phi^2}{4} \ (\equiv m_V^2)$

- Loop-level:  $\delta m \equiv m_{V^\pm} - m_{V^0} \simeq 168 \text{ MeV}$  (Almost the same value as  $\mathbf{SU(2)_L}$  triplet,  $Y=0$  spin-1/2 DM)

If we assume  $m_V < m_{h_D}$ ,  $V^0$  is the lightest  **$Z_2$ -odd** particle (= **EW interacting Spin-1 DM**)

- $Z_2$ -even BSM vectors ( $Z', W'$ ) also exist



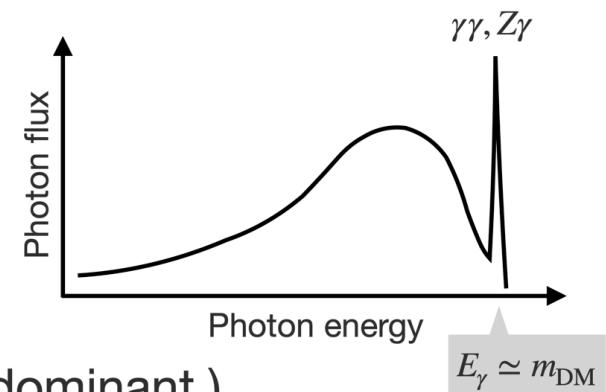
# ■ Monochromatic $\gamma$ -ray search

## Challenge to probe DM spin

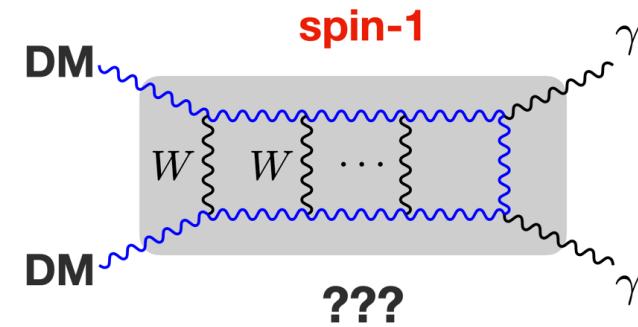
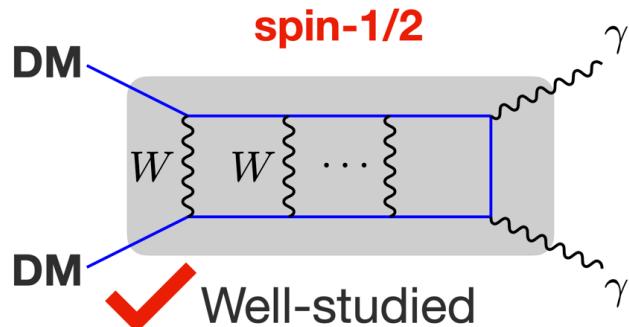
- Spin-dependent features decouple in non-relativistic processes due to momentum/velocity suppression (cf. averaged velocity of DM in current universe:  $v/c \simeq 10^{-3}$ )

## Monochromatic $\gamma$ -ray (DM DM $\rightarrow \gamma\gamma, Z\gamma$ )

- Line  $\gamma$ -ray signatures @  $E_\gamma \simeq m_{\text{DM}}$
- Sommerfeld enhancement by electroweak force  
[J.Hisano, S. Matsumoto, M. M. Nojiri, O. Saito (2005)]
- Total spin  $J$  is conserved in annihilation ( $\because$  S-wave is dominant)



→ Selection rules remember DM spin!



# Spin-1/2 vs Spin-1

## 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

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

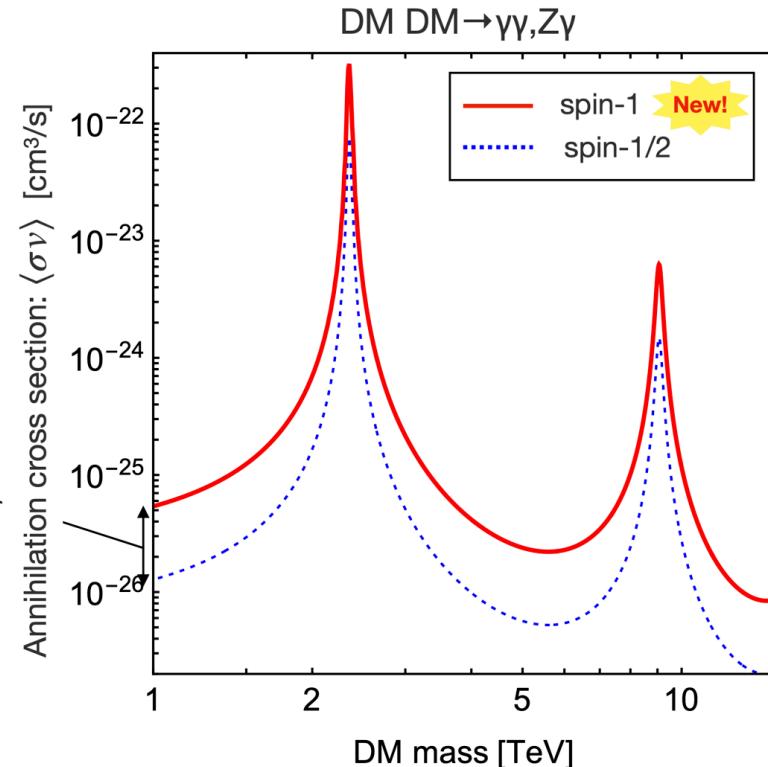
## Higher order correction

- 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

## DM mass (to obtain correct abundance)

- Pure Wino DM: 2.22 TeV  $\xrightarrow{\text{Sommerfeld}}$  2.88 TeV [M. Beneke, A. Bharucha, et. al (2016)]
- EW Spin-1 DM:  $\gtrsim 3$  TeV  $\xrightarrow{\text{Sommerfeld}}$  ??? (Ongoing)

↑Depends on Higgs sector



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 differences?

# Z' search in $\gamma$ -ray spectrum

$$\Delta E_\gamma \simeq \frac{m_{Z'}^2}{4m_V}$$

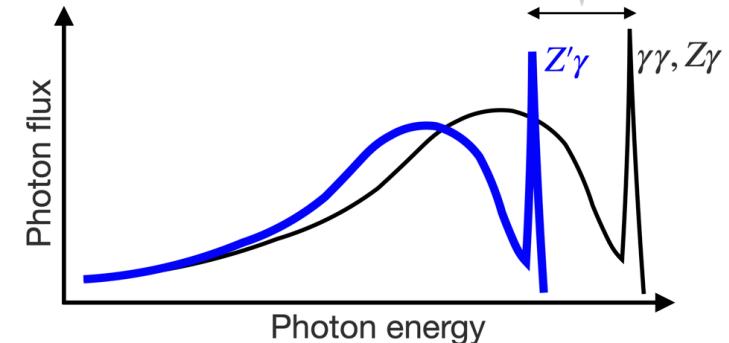
- Our spectrum also has  $Z'$  ( $Z_2$ -even neutral vector)
- New annihilation channel  $Z'\gamma$  may open

Unitarity if gauge couplings  $\downarrow$

$Z'\gamma$  mode is kinematically opened  $\downarrow$

Interesting region:  $m_V \lesssim m_{Z'} \lesssim 2m_V$

To separate peaks:  $\frac{\Delta E_\gamma}{m_V} \simeq \left( \frac{m_{Z'}}{2m_V} \right)^2 \gtrsim 0.1$



**Double peak  $\gamma$ -ray spectrum**  
→ We can reconstruct **DM, Z' mass**

## Future Detectability

Current bound from H.E.S.S experiment [H. Abdallah et al. (2018)]

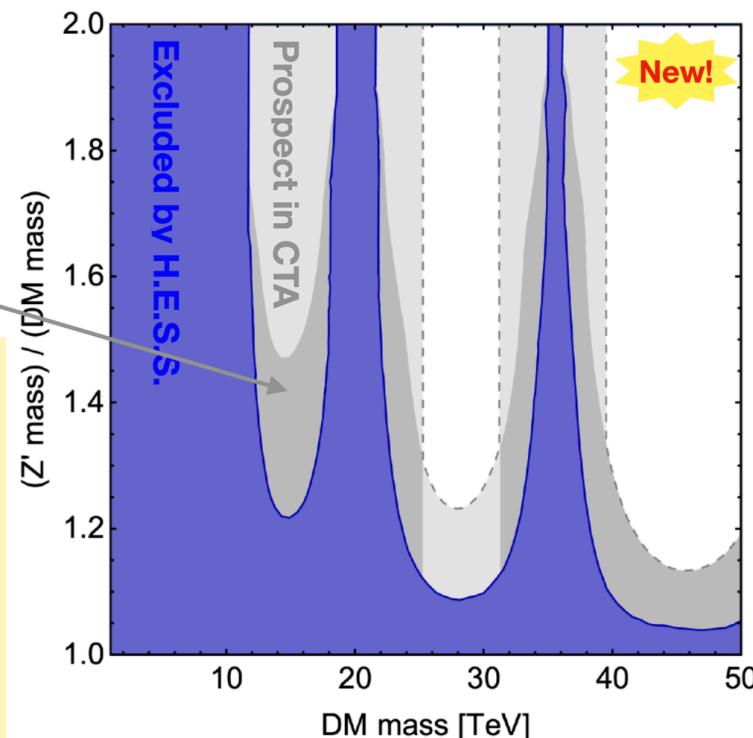
CTA experiment can probe double peak spectrum  
(Cored profile w/  $r_c \simeq 5$  kpc) [L. Rinchiuso, et al (2021)]

**Q. Is  $Z'\gamma$  mode not unique to EW spin-1 model?**

**NO.**  $Z'\gamma$  mode is predicted from DM model w/  $Z'$

But we have 3 enhancement effects in our model

$$\left\{ \begin{array}{l} (1) \text{ Enhancement of } Z' \text{ coupling } (m_V \simeq m_{Z'}) \\ (2) \text{ Sommerfeld effect due to EW int.} \\ (3) J = 2 \text{ contribution of spin-1 DM} \end{array} \right. \quad C_{V-V+Z'} \simeq \frac{g_2}{\sqrt{\frac{m_{Z'}^2}{m_V^2}} - 1}$$



# ■ Summary

We studied monochromatic  $\gamma$ -ray signatures  
from EW interacting Spin-1 DM

How to distinguish DM spin?

Comparison w/ other DM candidate

Different spin ( <b>spin-1/2</b> )	VS
Same EW int. (SU(2) <sub>L</sub> triplet, Y=0)	

**DM DM  $\rightarrow X\gamma$  ( $X = \gamma, Z, Z'$ )**

- Spin-1 DM has  $J = 2$  partial wave contribution  
 $\rightarrow \gamma\gamma, Z\gamma$  cross section of Spin-1 DM is enhanced by  $\frac{38}{9}$  ( $\simeq 4.22\dots$ )
- Spin-1 DM has new  $Z'\gamma$  annihilation mode  
 $\rightarrow$  Separable double peak spectrum may probed in CTA exp.  
 We can reconstruct masses of DM,  $Z'$

## Future work

- Specify DM mass range to explain correct DM abundance
- Study Extra-dimensional setup w/ similar phenomenology

