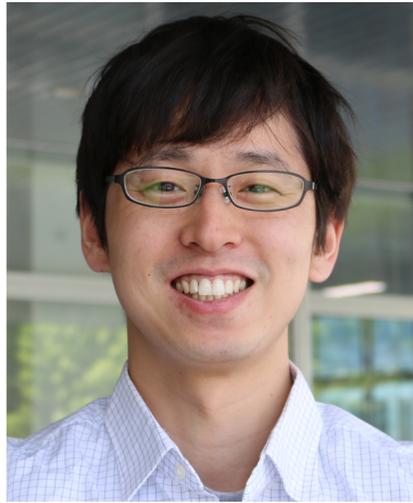# Phenomenology of electroweakly interacting spin-1 dark matter with Sommerfeld enhancement

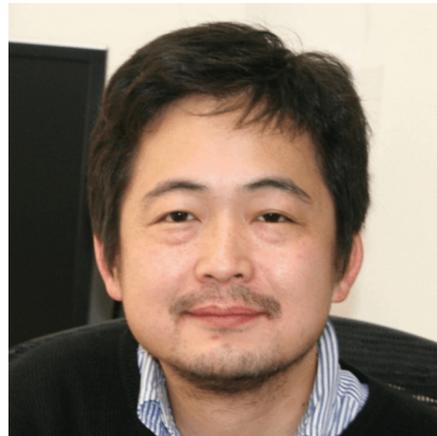**Tomohiro Abe**

Tokyo University of Science

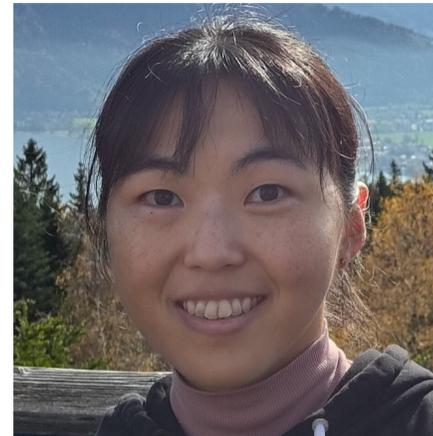in collaboration with

Junji Hisano

Nagoya U, KMI, Kavli IPMU

Motoko Fujiwara

U. Toyama

This talk is based on an ongoing project (arXiv:26mm.xxxxx)

WIMP

· DM was in thermal equilibrium in the early universe

· Evolution is determined by the Boltzmann equation

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left(n^2 - n_{\text{eq}}^2 \right)$$

annihilation

DM SM

?

DM SM

pair production

Measured value of the DM energy density is obtained

if $\langle \sigma v \rangle \simeq 2 \times 10^{-26}$ cm³ s⁻¹ $\simeq 1$ pb c

· typical value of the weak interaction!

· This implies DM is a neutral component
  of an SU(2)$_{\text{L}}$ multiplet

χ^0 —————— W

$\chi^{\pm}$

χ^0 —————— W
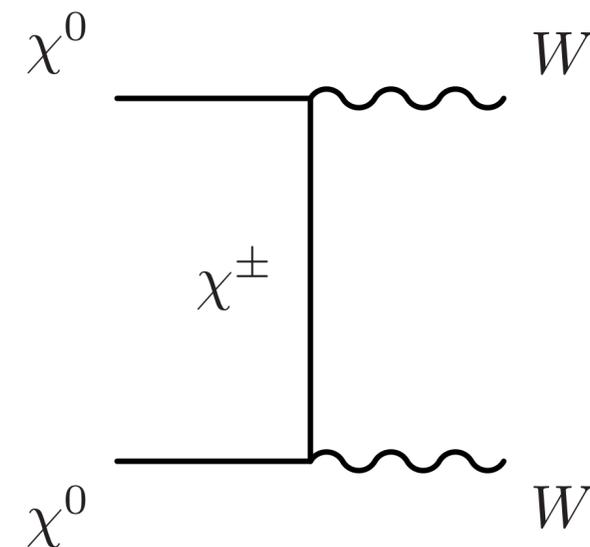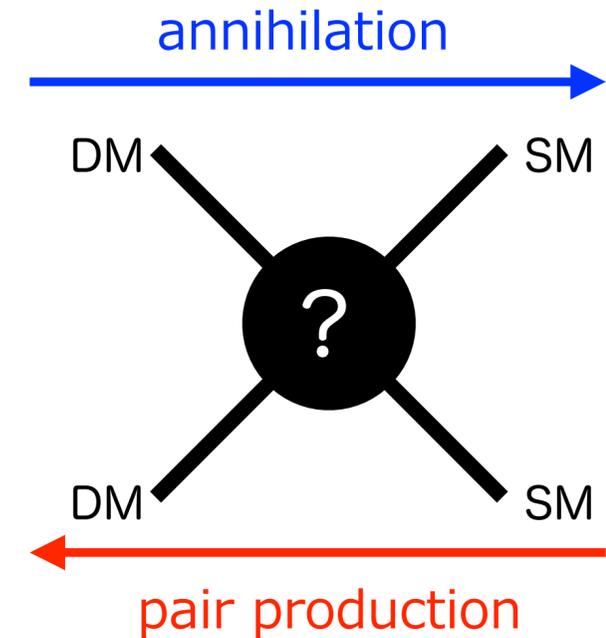
Many models

Quantum numbers				DM could decay into	$M_{\rm DM}$ in TeV		$M_{\rm DM^\pm} - M_{\rm DM}$ in MeV	$\sigma_{\rm SI}$ in $10^{-46}\,{\rm cm}^2$
$U(1)_Y$	$SU(2)_L$	$SU(3)_c$	Spin		tree	non-pert		
1/2	2	1	0	EL	0.54		350	$(0.4 \pm 0.6)\,10^{-3}$
1/2	2	1	1/2	EH	1.1		341	$(0.3 \pm 0.6)\,10^{-3}$
0	3	1	0	HH^*	2.0	2.5	166	0.23 ± 0.04
0	3	1	1/2	LH	2.4	2.6	166	0.23 ± 0.04
1	3	1	0	HH, LL	1.6	?	540	0.001 ± 0.001
1	3	1	1/2	LH	1.9	?	526	0.001 ± 0.001
1/2	4	1	0	HHH^*	2.4	?	353	0.27 ± 0.08
1/2	4	1	1/2	(LHH^*)	2.4	?	347	0.27 ± 0.08
3/2	4	1	0	HHH	2.9	?	729	0.15 ± 0.07
3/2	4	1	1/2	(LHH)	2.6	?	712	0.15 ± 0.07
0	5	1	0	(HHH^*H^*)	5.0	14	166	2.0 ± 0.5
0	5	1	1/2	none	4.4	14	166	2.0 ± 0.5

How about spin one?

spin-1 is not matter field but a gauge field

Q) how to obtain VVW interaction?

V^a

W^c

V^b
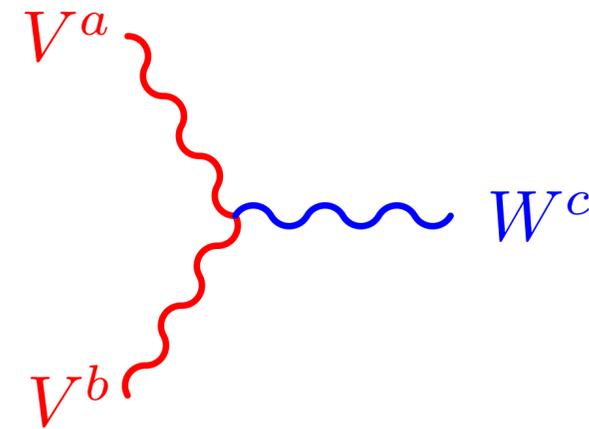
・V is DM

・W is the SU(2)$_L$ gauge field

A) extend the electroweak gauge symmetry [TA Fujiwara Hisano Matsushita ('20)]
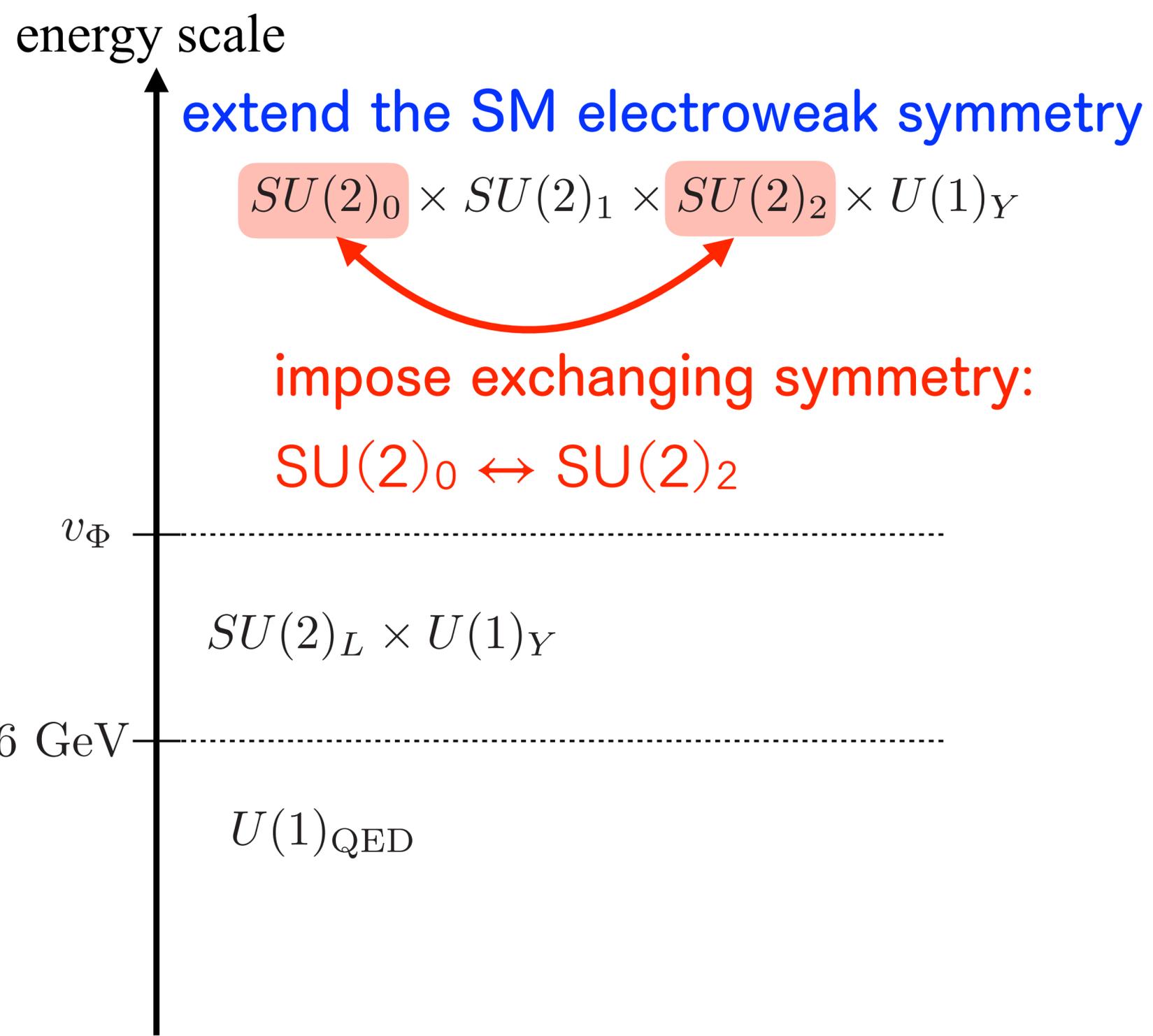
$$SU(2)_0 \times SU(2)_1 \times SU(2)_2 \times U(1)_Y$$

・V and W are the mixtures of SU(2)$_{0,1,2}$ gauge fields

・V behaves an SU(2)$_L$ triplet

・a renormalizable model

(c.f.) see also other works but they are non-renormalizable models

・ EFT framework [Díaz Sáez+ ('18), Belyaev+ ('20), Escalona+ ('24)]

・ Extra-dimension [Maru+ ('18), ⋯]

・ ⋯

Our models

energy scale

extend the SM electroweak symmetry

$$SU(2)_0 \times SU(2)_1 \times SU(2)_2 \times U(1)_Y$$

impose exchanging symmetry:

SU(2)$_0$ ↔ SU(2)$_2$

v_Φ ------

$SU(2)_L \times U(1)_Y$

$v \simeq 246$ GeV ------

$U(1)_{\rm QED}$

Matter fields

fields	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
H	0	**1**	**1**	**2**	**1**	$\frac{1}{2}$
Φ_1	0	**1**	**2**	**2**	**1**	0
Φ_2	0	**1**	**1**	**2**	**2**	0

·left-handed fermions are SU(2)$_1$ doublet

·$\langle \Phi_1 \rangle = \langle \Phi_2 \rangle = v_\Phi$

How does vector DM couple to the weak gauge boson?

vector DM is a linear combination of $SU(2)_0$ and $SU(2)_2$ gauge fields

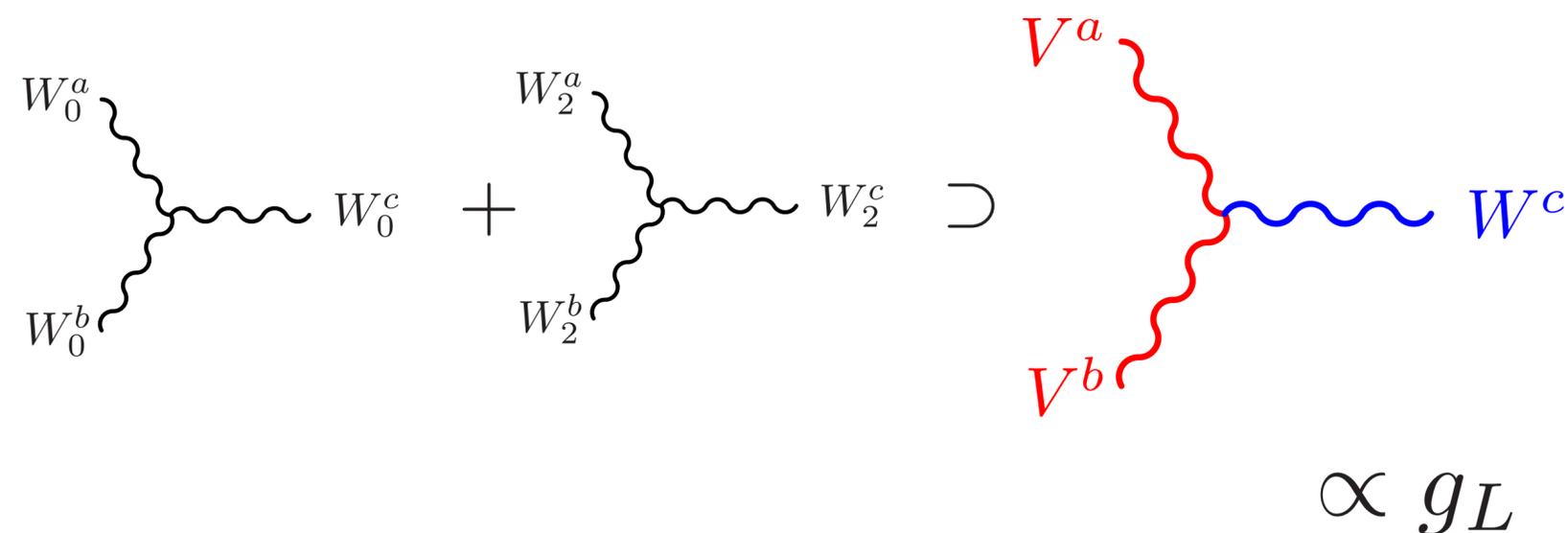$$V_\mu^a = \frac{W_{0\mu}^a - W_{2\mu}^a}{\sqrt{2}}$$

$$SU(2)_0 \times SU(2)_1 \times SU(2)_2 \times U(1)_Y$$

$$W_\mu^a \simeq \frac{g_L}{g_0} W_{0\mu}^a + \frac{g_L}{g_1} W_{1\mu}^a + \frac{g_L}{g_2} W_{2\mu}^a$$

SM $SU(2)_L$ is linear combinations of all the $SU(2)_{0,1,2}$ fields

$$g_L = \left(\frac{1}{g_0^2} + \frac{1}{g_1^2} + \frac{1}{g_2^2} \right)^{-1/2} \quad : \text{SU(2)}_L \text{ gauge coupling}$$

$SU(2)_{0,2}$ contain both vector DM and electroweak gauge bosons

$$\propto g_L$$

$\rightarrow$ vector DM has electroweak interaction!

Particle contents and model parameters

particle contents

Z₂-even	Z₂-odd
Heavy vector triplet $\left(W'^{+}, Z', W'^{-}\right)$	vector DM $\left(V^{+}, V^{0}, V^{-}\right)$
CP even scalar h'	CP even scalar h_D
SM particles $\left(W^{+}, Z, W^{-}\right), \gamma$ h (other SM particles)	

five parameters

m_V vector DM mass

$m_{Z'}$ heavy vector triplet mass

· $m_{W'} = m_{Z'}$ at LO due to SU(2)$_L$

· we can choose m$_{Z'}$ to obtain $\Omega h^2 = 0.12$

· always $m_{Z'} > m_V$

$m_{h'}$ = 1.4 m$_V$ for benchmark

m_{h_D} = 1.2 m$_V$ for benchmark

θ_h mixing angle for h and h'
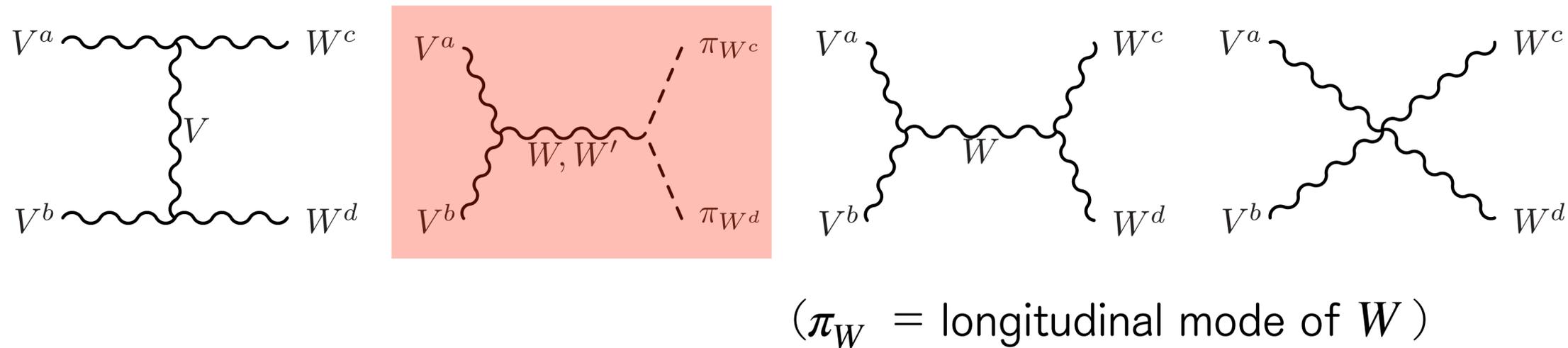
· should be small to suppress σ SI

· $|\theta_h| \lesssim 0.23$ from the SM Higgs coupling measurement

[ATLAS (2207.00092)] [CMS (2207.00043)]

· $\theta_h = 0.001$ for benchmark

relic abundance

Same as higgsino, wino, or minimal DM, there are VV → WW processes
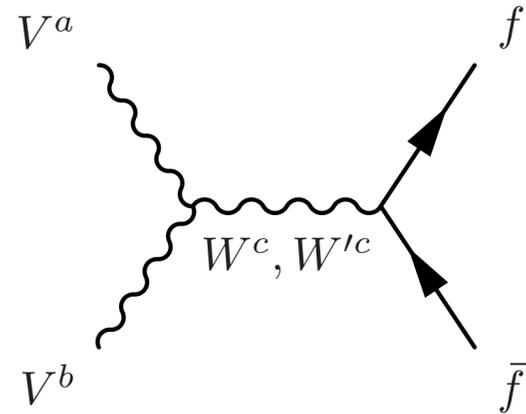

$(\pi_W = $ longitudinal mode of $W)$

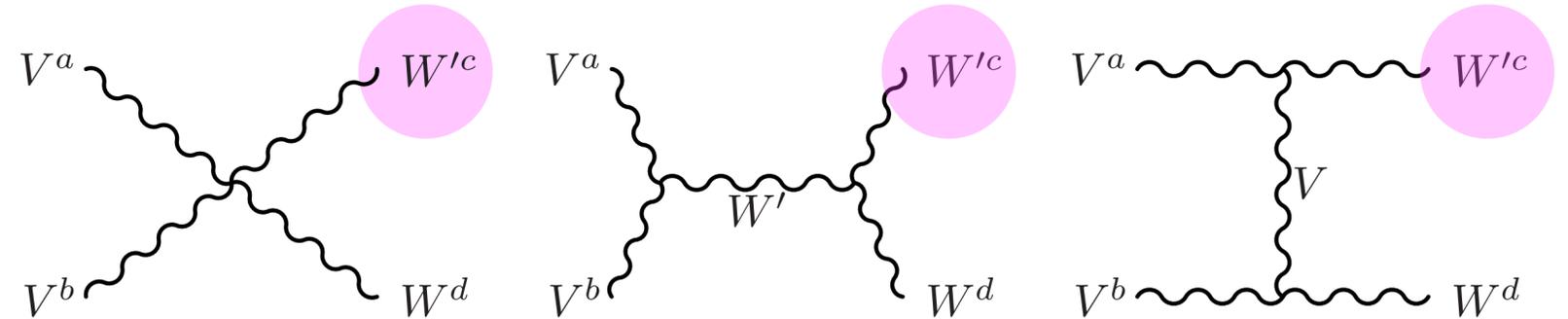## There are s-channel resonance due to W' and Z'

- annihilation cross section is resonantly enhanced for $2m_V \simeq m_{Z'}$

- different features from the spin-0, spin-1/2 electroweakly interacting models
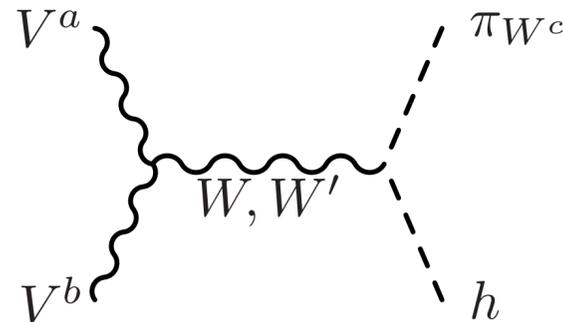
more annihilation channels

$VV \to f\bar{f}$

$VV \to Wh$

$(\pi_W = \text{longitudinal mode of } W)$

$VV \to WW'$

a heavy vector triplet ($W'^{\pm}$ or Z') can be an

annihilation product for $m_{Z'} \lesssim 2m_V$

couplings

$$g_{VVW'} \simeq \frac{g_L}{\sqrt{\frac{m_{Z'}^2}{m_V^2} - 1}}$$

larger for $\frac{m_{Z'}}{m_V} \to 1$ limit
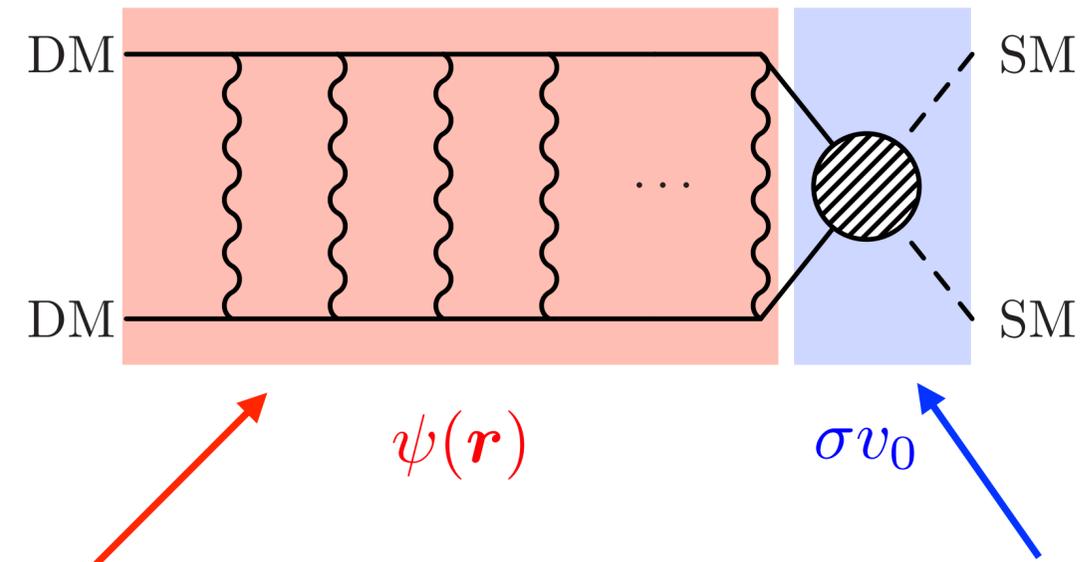
$$g_{WW'W'} \simeq g_L$$

Sommerfeld enhancement

DM particles exchange electroweak gauge bosons before annihilation

［Hisano, Matsumoto, Nojiri ('03, '04)］
［Hisano, Matsumoto, Nojiri, Saito ('05)］
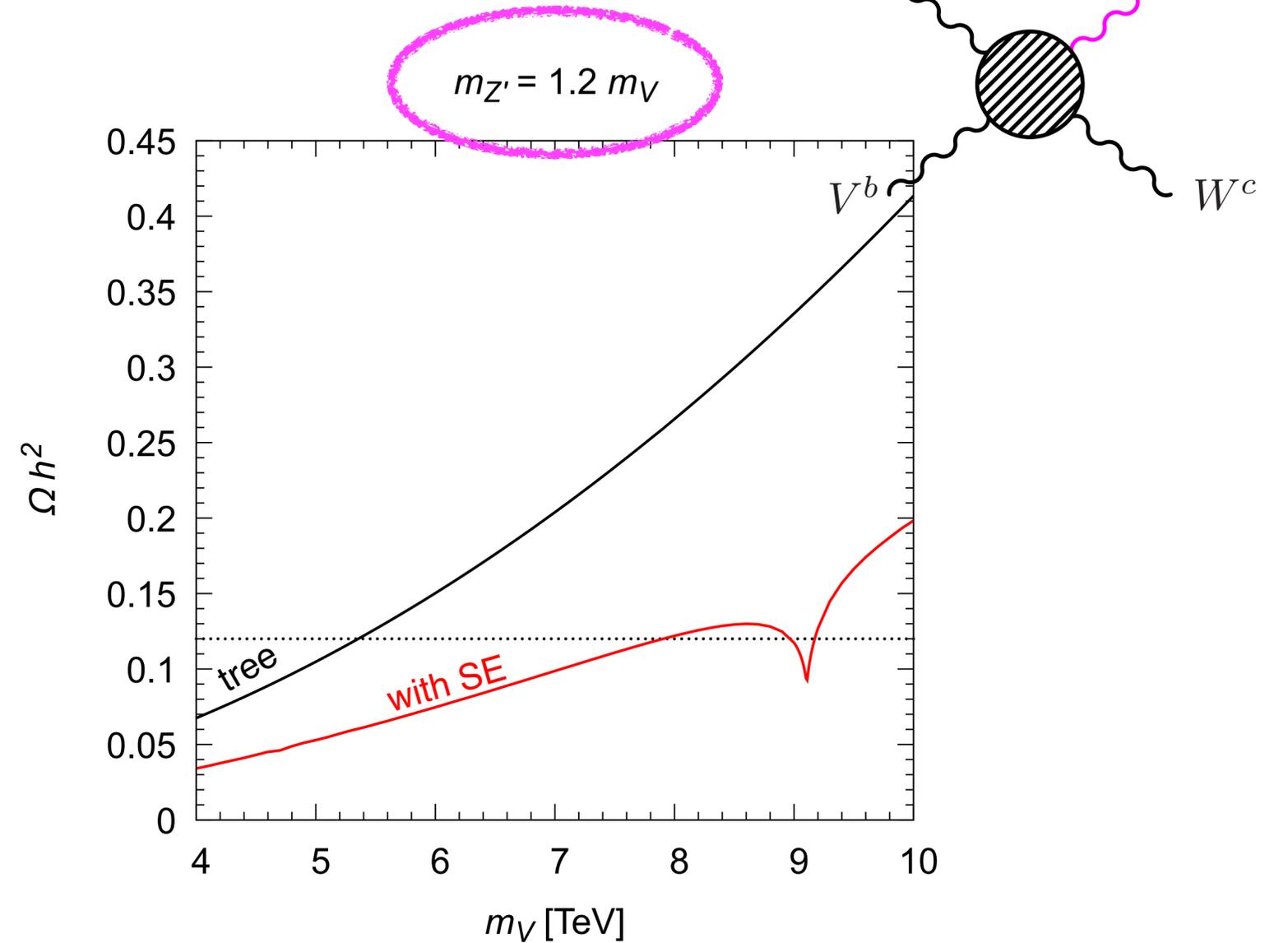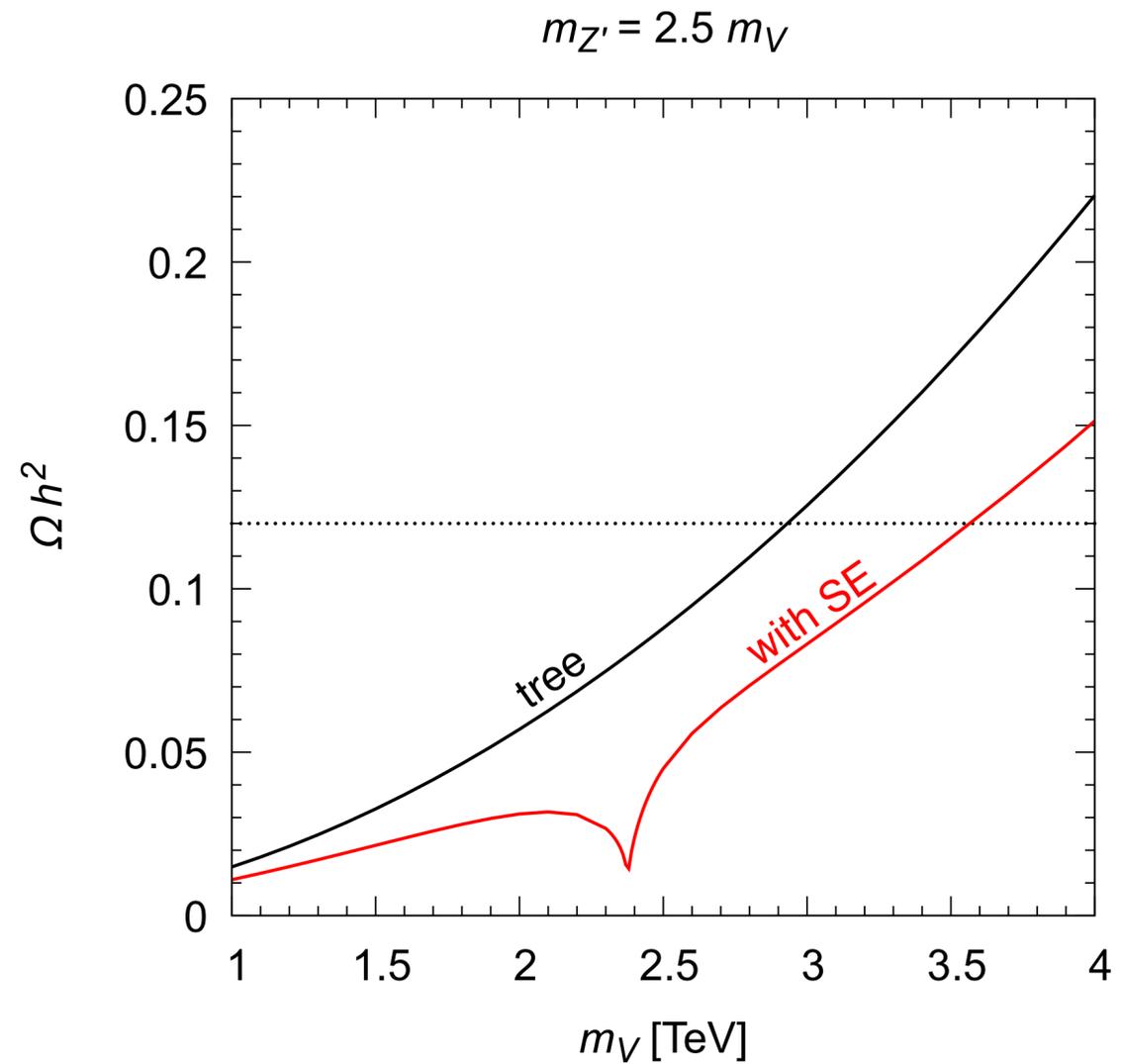［Arkani-Hamed, Finkbeiner, Slatyer Weiner ('09)

$\psi(\boldsymbol{r})$

σv_0

wavefunction is distorted from plain wave $\psi_0(\boldsymbol{r})$

LO calculation

$$\sigma v = \sigma v_0 \left| \frac{\psi(\boldsymbol{0})}{\psi_0(\boldsymbol{0})} \right|^2$$
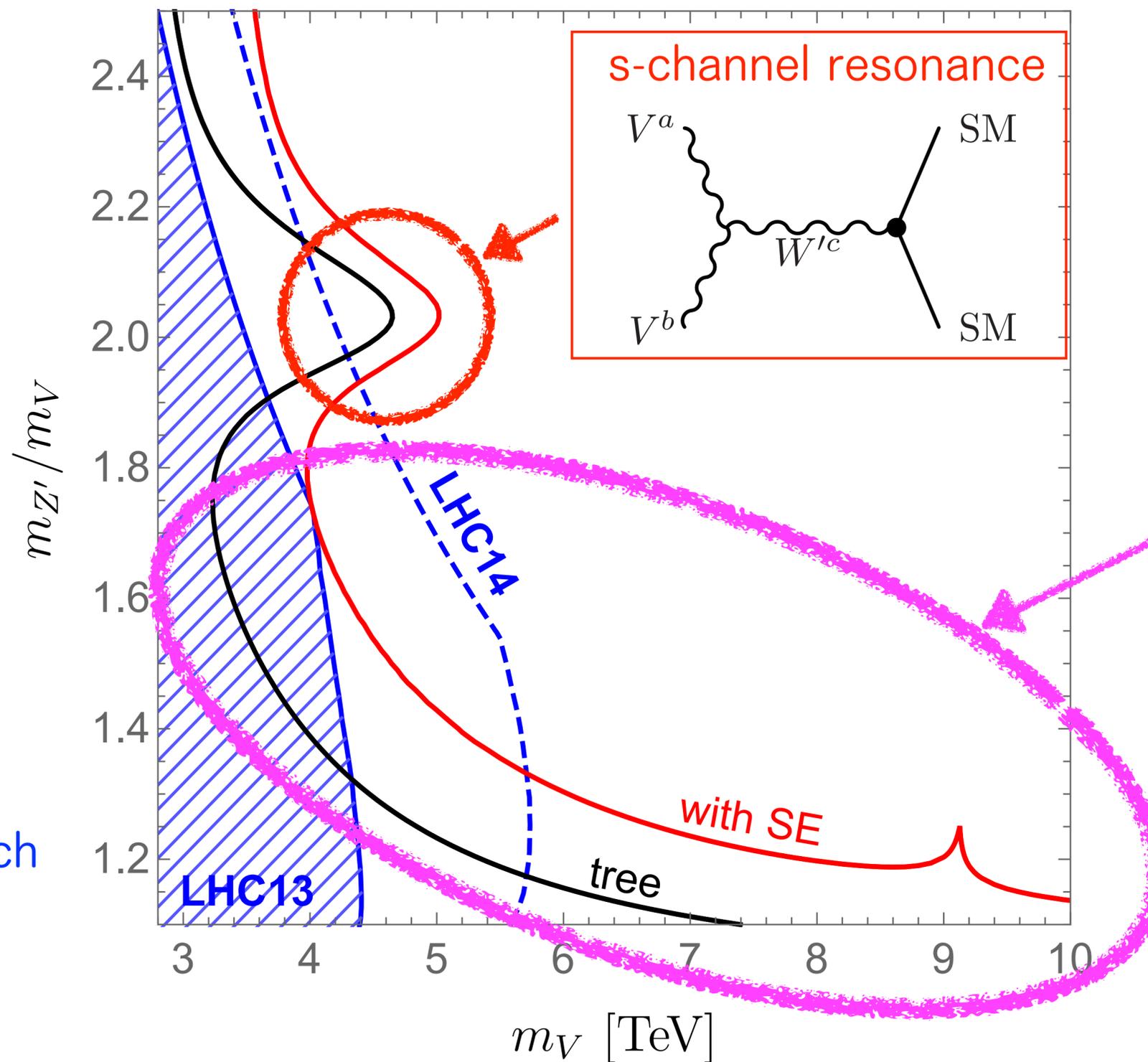
Sommerfeld Enhancement factor

vector DM and Sommerfeld enhancement

$m_{Z'} = 2.5\, m_V$

$m_{Z'} = 1.2\, m_V$

m$_V$ and m$_{Z'}$ for $\Omega h^2 = 0.12$

·relic abundance is
explained for $m_V > 3.6$ TeV

·this is heavier than other
SU(2)$_L$ triplet DM
(e.g. wino, 2.7 TeV)

constraints from W' search
$pp \to W' \to \ell\nu$

indirect detection
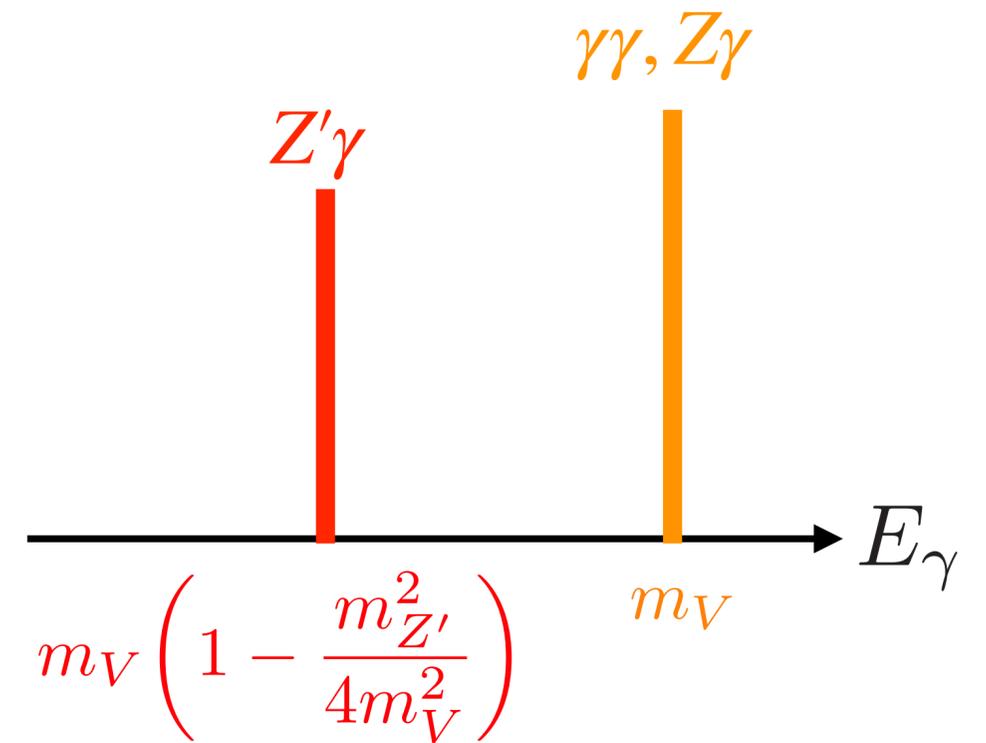
Channels for indirect detection

$$V^0 V^0 \to WW, ZZ$$

We focus on gamma-ray lines

$$V^0 V^0 \to \gamma\gamma, Z\gamma \qquad E_\gamma \simeq m_V$$

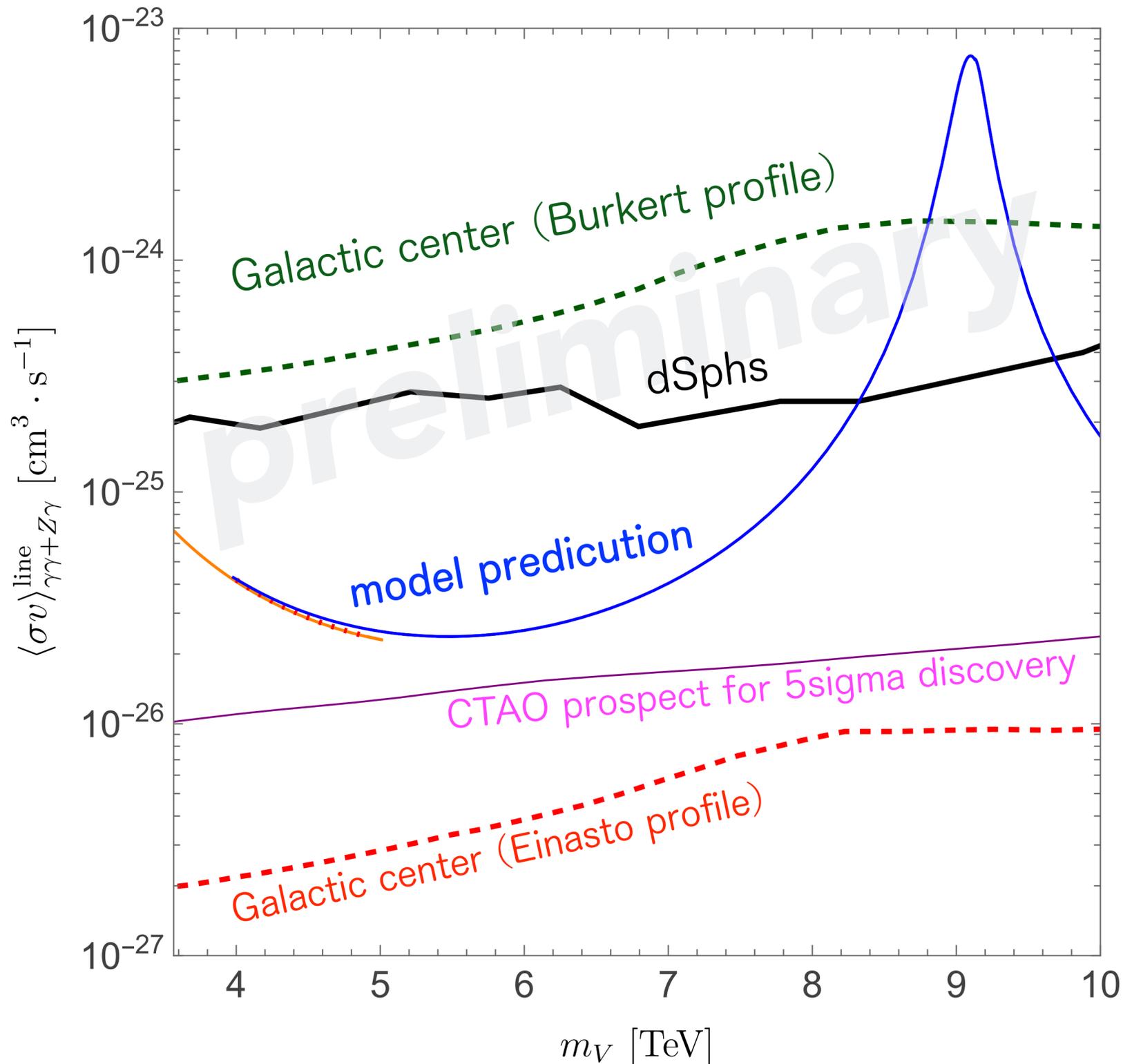$$V^0 V^0 \to Z'\gamma \qquad E_\gamma \simeq m_V \left(1 - \frac{m_{Z'}^2}{4m_V^2} \right)$$

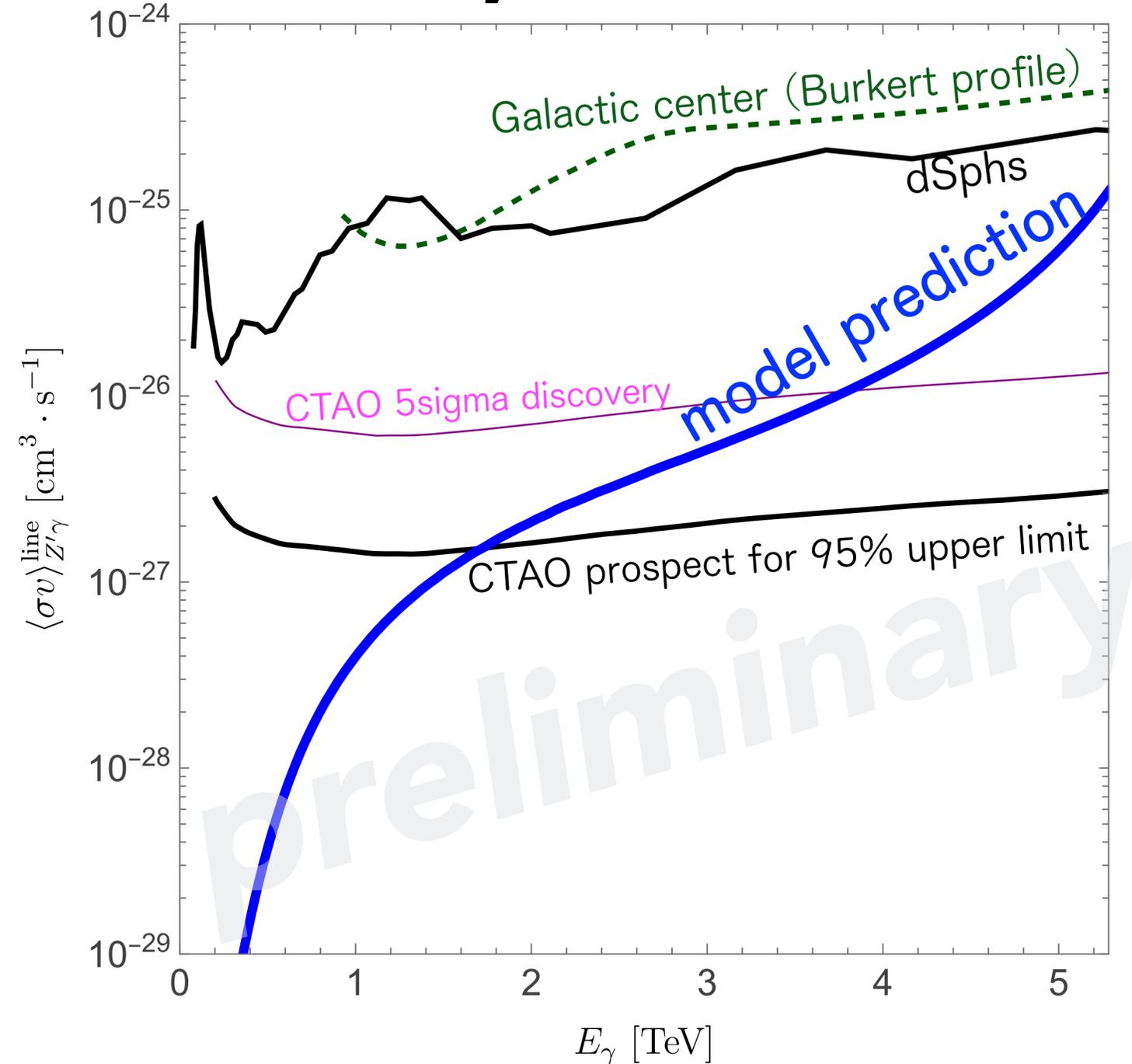

We have two γ-ray line peaks

γ-ray line from $\gamma\gamma + Z\gamma$

Galactic center (Burkert profile)

dSphs

model predicution

CTAO prospect for 5sigma discovery

Galactic center (Einasto profile)

preliminary

Constraints by MAGIC [2111.15009, 2212.10527]

- $m_{Z'}$ is fixed to obtain $\Omega h^2 = 0.12$ (see page 12)

- dSphs excludes for $8.3 < m_V/\text{TeV} < 9.7$

- Large uncertainty in the J-factor of GC
  - Einasto (cuspy profile) excludes the model
  - Burkert (cored profile) excludes for
    $$8.8 < m_V/\text{TeV} < 9.4$$

- the model is tested by CTAO [2403.04857] (cored Einasto profile)

γ-ray line from $Z'\gamma$

$$E_\gamma \simeq m_V\left(1 - \frac{m_{Z'}^2}{4m_V^2}\right)$$

($m_{Z'}$ is determined to obtain $\Omega h^2 = 0.12$)

GC $(\gamma\gamma + z\gamma)$

dSph (WW)

dSph $(\gamma\gamma + z\gamma)$

Galactic center (Burkert profile)

dSphs

CTAO 5sigma discovery

model prediction

CTAO prospect for 95% upper limit
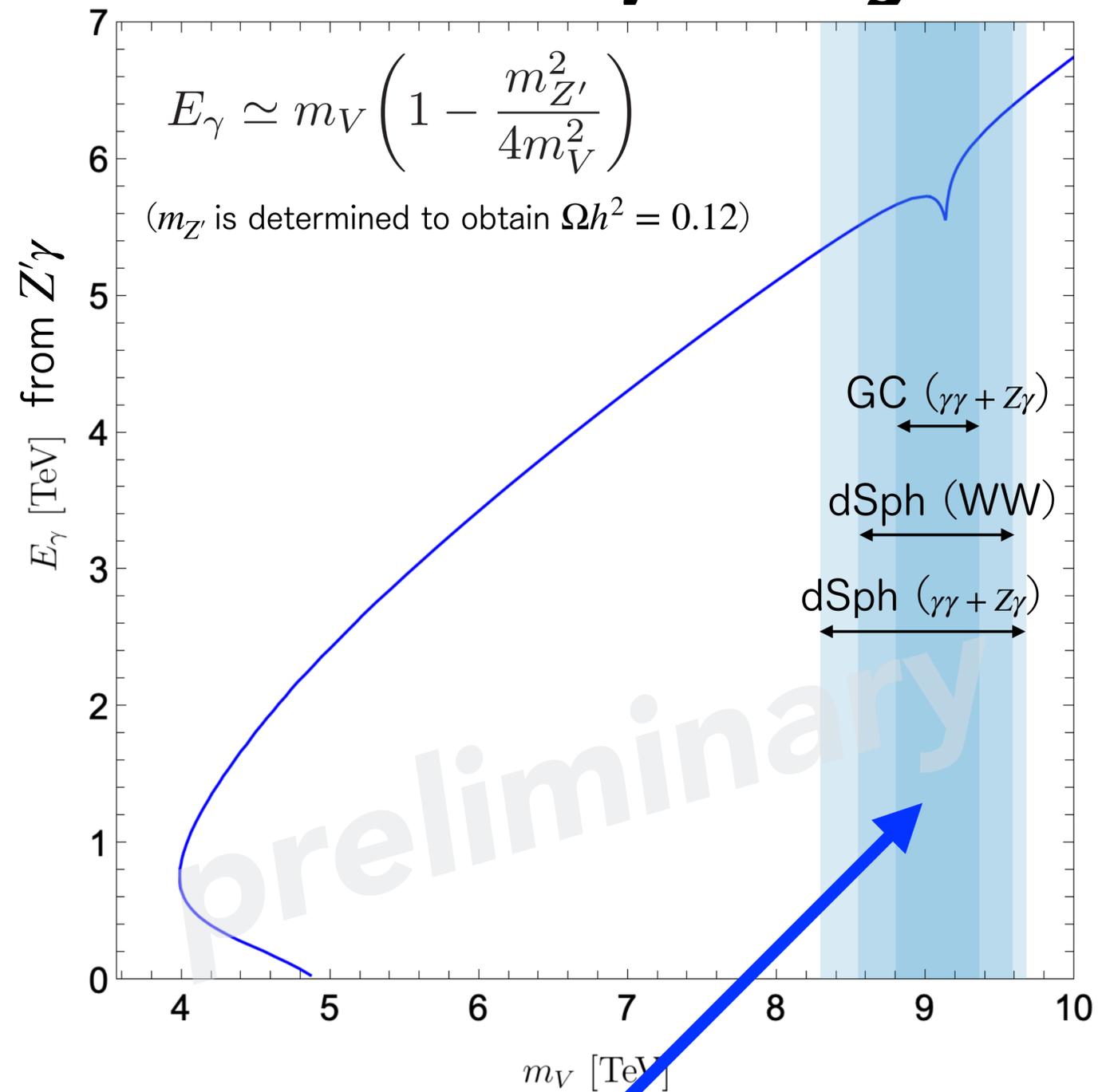
·excluded by $\gamma\gamma, Z\gamma,$ and WW

·Constraints from dSphs: 5.4 TeV $\lesssim E_\gamma \lesssim 6.5$ TeV

CTAO covers large region of the parameter space

Summary

electroweakly interacting vector DM

- $SU(2)_0$ x $SU(2)_1$ x $SU(2)_2$ x $U(1)_Y \to SU(2)_L$ x $U(1)_Y$

- spin-1 vector field behaves as an $SU(2)_L$ triplet

- also heavy vector triplet (W' and Z') arises

relic abundance with Sommerfeld enhancement

- relic abundance is explained for $m_V > 3.6$ TeV

- ($m_\chi \sim 2.5$ TeV for spin-0 triplet, $m_\chi \sim 2.6$ TeV for spin-1/2 triplet)

indirect detection

- excluded for 8.8 TeV $\lesssim m_V \lesssim 9.4$ TeV
- γ-ray spectral line has two E_γ
- CTAO can test the model

$\gamma\gamma, Z\gamma$

$Z'\gamma$

E_γ

$m_V \left(1 - \dfrac{m_{Z'}^2}{4m_V^2} \right)$

m_V