Electroweakly Interacting Spin-1 Dark Matter and Its Phenomenology

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Based on T. Abe, **MF**, J. Hisano, K. Matsushita, JHEP 07 (2020) 136 [arXiv:2004.00884]
T. Abe, **MF**, J. Hisano, K. Matsushita, JHEP 10 (2021) 163 [arXiv:2107.10029]
T. Abe, **MF**, J. Hisano (work in progress)

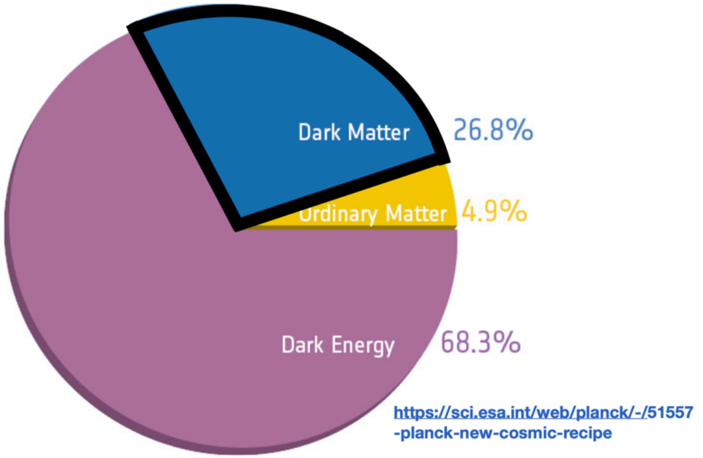
Physics in LHC and Beyond @Matsue/zoom May 12, 2022

Dark matter

What is Dark Matter (DM)?

Invisible (=dark) unknown massive sources

- 1/4 of energy density in our universe: $\Omega h^2 = 0.12$
- Electrically neutral
- Non-relativistic comp. in structure formation
- Stable / Long-lived



DM candidate?

Many possibilities for DM mass/interaction

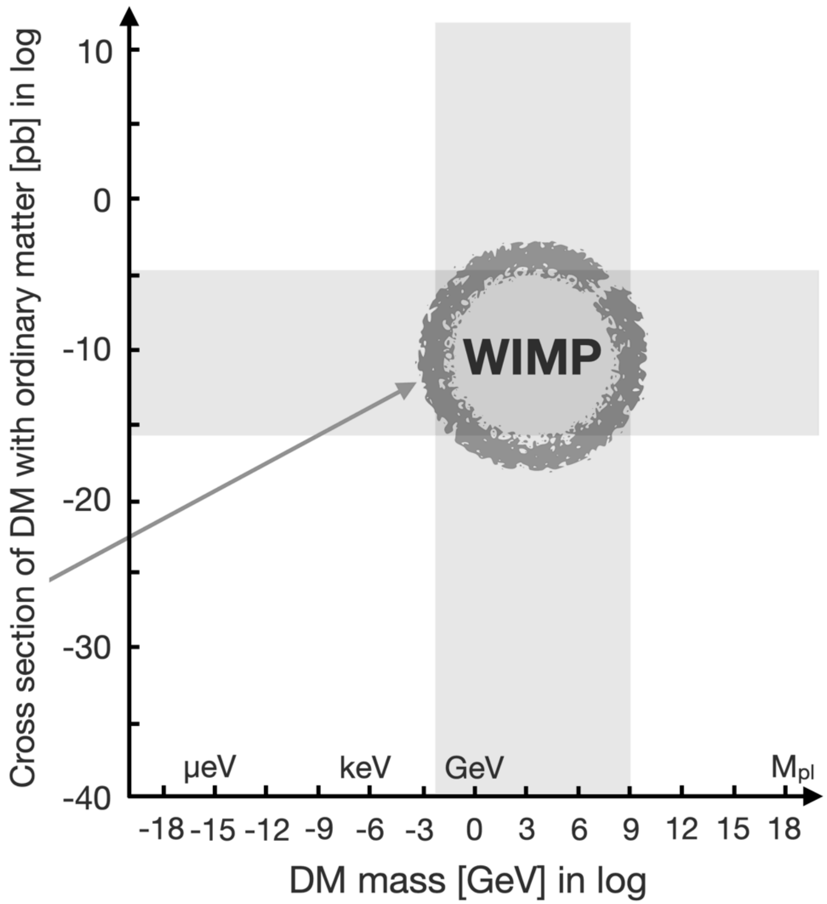
Goal: **Identification of DM**

→ a window to probe new physics!

Weakly Interacting Massive Particle

- Prediction on Ωh^2 from thermal history

  → Probed by various experiments



Electroweakly(EW) interacting DM

Assumption: DM interacts w/ the SM particles mainly through **EW interaction**

- DM coupling: EW coupling
- DM mass: Fixed to explain correct DM energy density

$$\left[\begin{array}{l} \langle \sigma_{\rm ann} v \rangle \sim 3 \times 10^{-26}\ {\rm cm}^3/{\rm s} \\ \qquad \simeq \dfrac{\alpha_{\rm DM}^2}{m_{\rm DM}^2} \begin{cases} \alpha_{\rm DM} \sim \alpha_2 \\ m_{\rm DM} \sim \mathcal{O}(1)\ {\rm TeV} \end{cases} \end{array}\right]$$

➡ **DM interaction theory is specified by determining DM spin!**

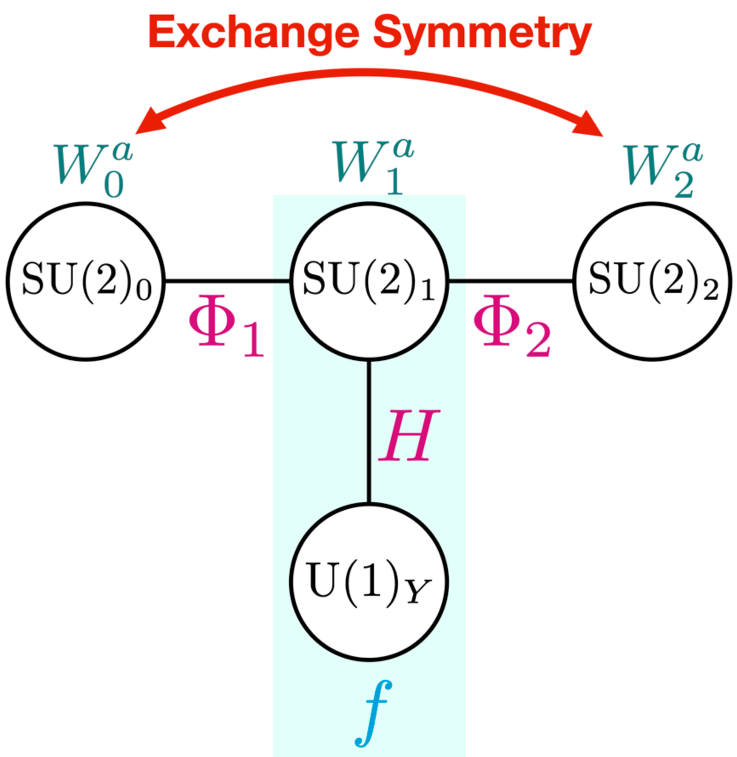
Questions: Possibility of **EW interacting Spin-1** DM?
How to realize **EW interaction** & **DM stability**?

1. Model w/ Extra-dimension [T. Flacke, A.Menon, D. J. Phalen (2009)] [T. Flacke, D. W. Kang, K. Kong, G. Mohlabeng, S. C. Park (2017)]
   → Neutral Kaluza-Klein boson DM (spin-1, $SU(2)_L$ triplet)

2. **Spontaneously broken gauge symmetry**
   → **Renormalizable model for EW spin-1 DM**

Our work: Construct a renormalizable model of EW interacting Spin-1 DM and reveal its phenomenology

Model



- Extend $\mathrm{SU}(2)_L \to [\mathrm{SU}(2)]^3$

  Impose **Exchange symmetry**: $\mathrm{SU}(2)_0 \leftrightarrow \mathrm{SU}(2)_2$

  → Gauge fields & Scalar fields are exchanged

  → Z_2-parity assignment for physical spectrum

  ※ Inspired from deconstructing dimension

  [N. Arkani-Hamed, A. G. Cohen, H. Georgi (2001)] [C. T. Hill, S. Pokorski and J. Wang (2001)]

- VEVs of Scalar fields break symm. into $\mathrm{U}(1)_{\mathrm{em}}$

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

- Fermion fields are only charged for $\mathrm{SU}(2)_1 \times \mathrm{U}(1)_Y$
  - Each field corresponds to the SM fermions
  - Nothing to do w/ exchange symmetry

Scalar field definition

$$\Phi_j = \begin{pmatrix} \frac{v_\Phi + \sigma_j + i\pi_j^0}{\sqrt{2}} & i\pi_j^+ \\ i\pi_j^- & \frac{v_\Phi + \sigma_j - i\pi_j^0}{\sqrt{2}} \end{pmatrix} \quad (\text{j=1, 2})$$

$$H = \begin{pmatrix} i\pi_3^+ \\ \frac{v + \sigma_3 - i\pi_3^0}{\sqrt{2}} \end{pmatrix}$$

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

Symmetry transformation

- Gauge trans. (for scalars)

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

- Exchange trans.

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

※ $g_0 = g_2$ ($\neq g_1$)

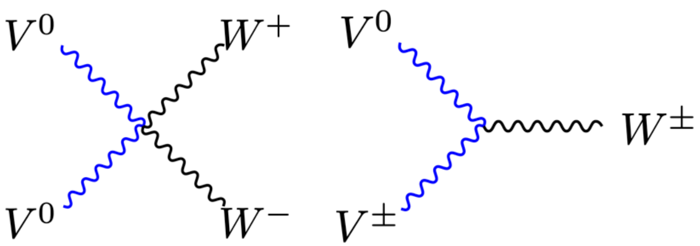
$$U_n = \exp[i\theta_n(x)] \quad (n = 0, 1, 2)$$

Spectrum

Z_2 **parity for physical spectrum** $\leftrightarrow$ **exchange symmetry**

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

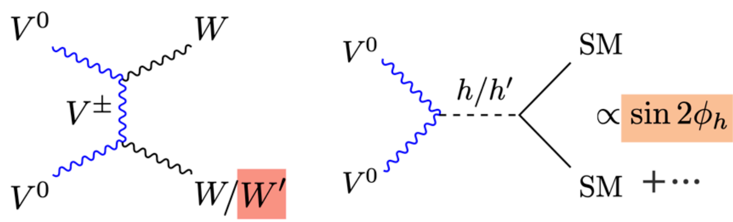
- Z_2-odd vectors ($V^0, V^{\pm}$) → **"V-particle"** $\simeq$ **SU(2)$_L$ triplet**
  - Non-abelian vector couplings
    → EW int. dominates phenomenology
  - Mass spectrum
    → V^0 is slightly lighter than $V^{\pm}$ due to the electroweak radiative corrections
    If we assume $m_V < m_{h_D}$, V^0 is the lightest Z_2-odd particle (= **EW interacting Spin-1 DM**)



- Z_2**-even additional vectors (** Z', W' **) also exist** → **Significant roles in DM phenomenology**

Directions for DM Search

- Higgs mixing (ϕ_h) contours in m_V-$m_{Z'}$ plane
  (ϕ_h : fixed to realize $\Omega h^2 = 0.12$ (@tree-level))



EW int. + Z'/W' + **Higgs sector**

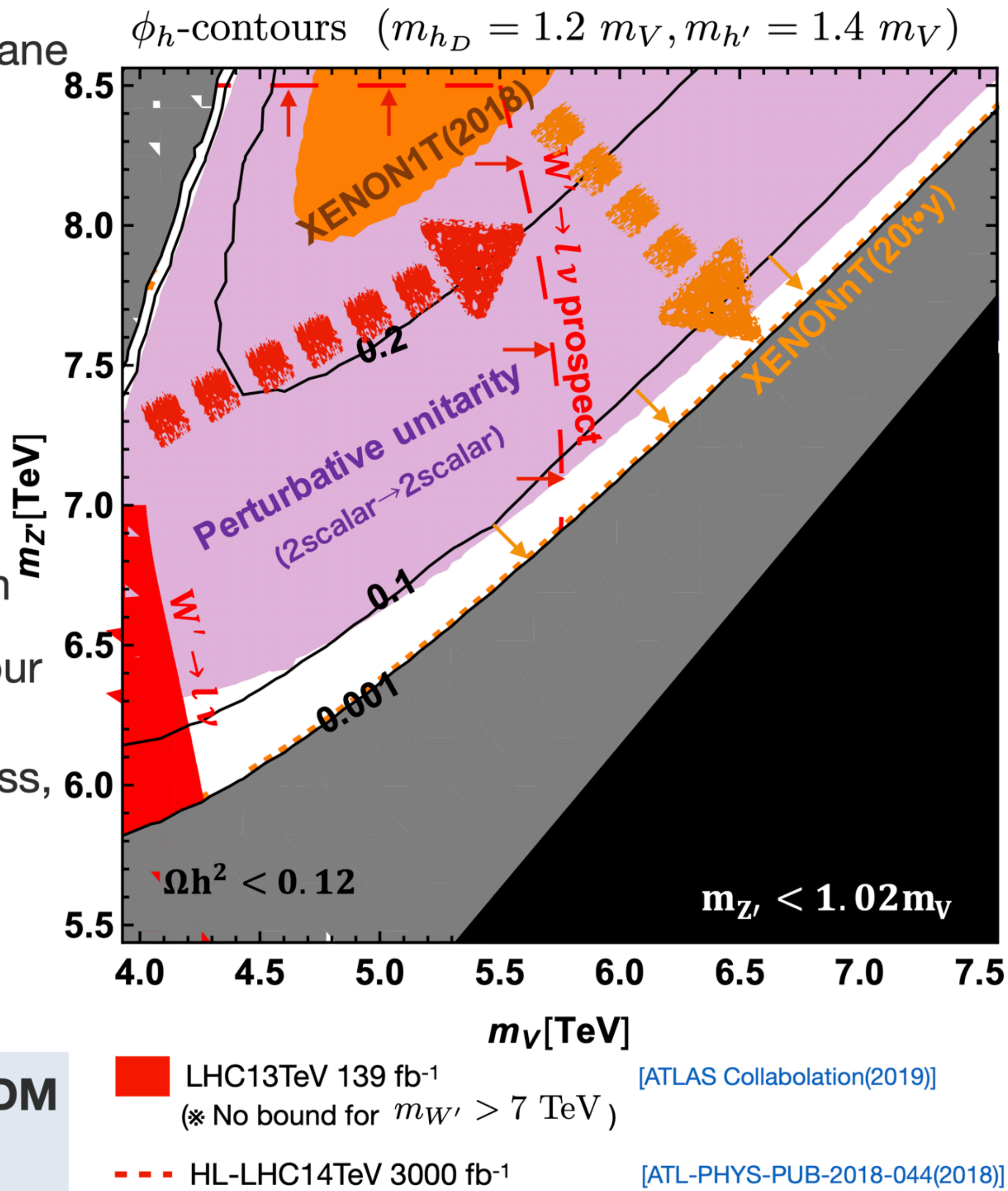
→ **Next-generation direct detection** may narrow down Higgs contribution

→ **HL-LHC** further probe thermal contour

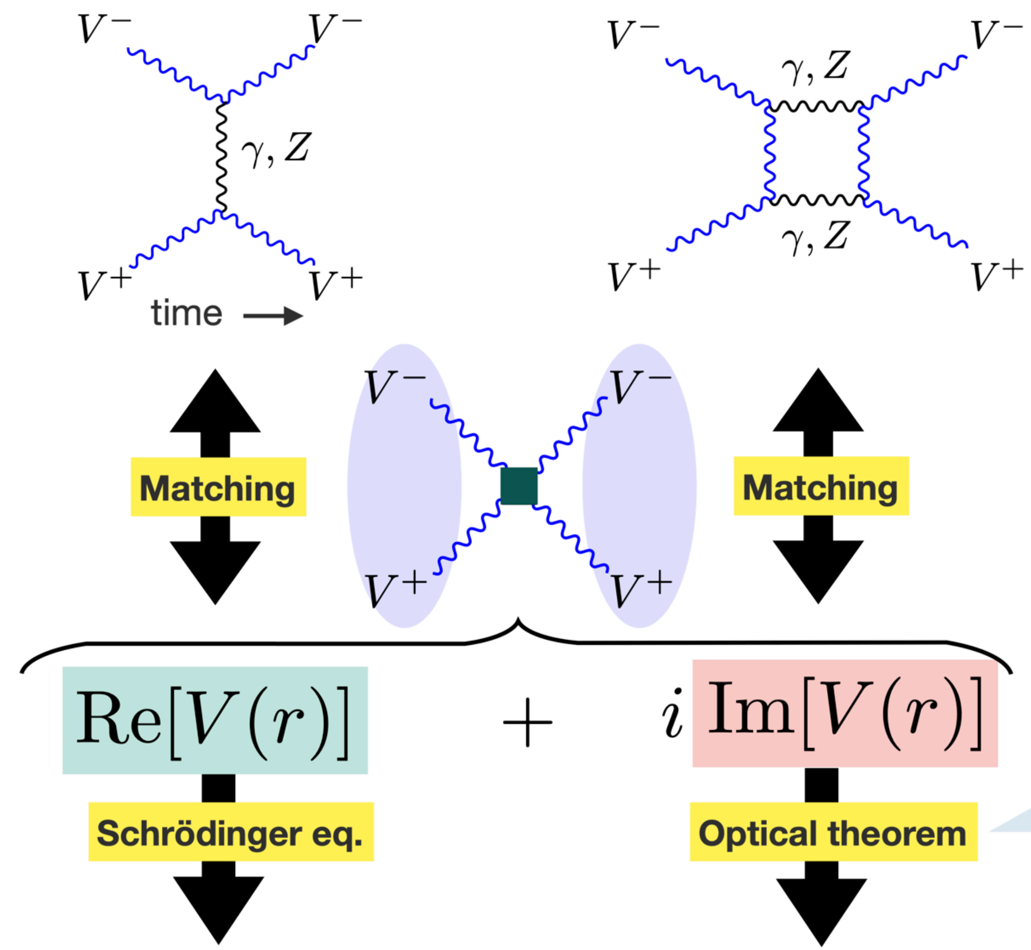
- For $m_V \simeq \mathcal{O}(1)$ TeV annihilation process, **Sommerfeld effects** should be viable

condition: $1/m_{\rm DM} \lesssim \alpha_2/m_W$
(DM wave func.) (EW potential)

We construct EFT for EW int. spin-1 DM for the systematical treatment



EFT of Spin-1 DM w/ EW int.



Distorted wave func.
(= Sommerfeld factor)

Perturbative
cross section

Full theory

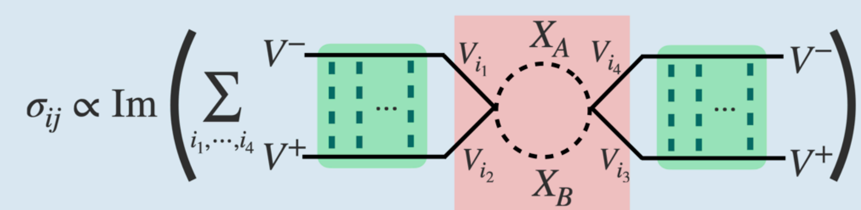
Dynamical fields = { $V^0, V^\pm, W^\pm, Z, \gamma$ }

Effective Theory

Dynamical fields = { $V^0V^0, V^-V^+, V^0V^\mp, V^\mp V^\mp$ }

w/ Coulomb or Yukawa potential

cf. Diagrammatic formula for annihilation cross section



EFT is described in terms of two-body states of NR Spin-1 DM multiplet

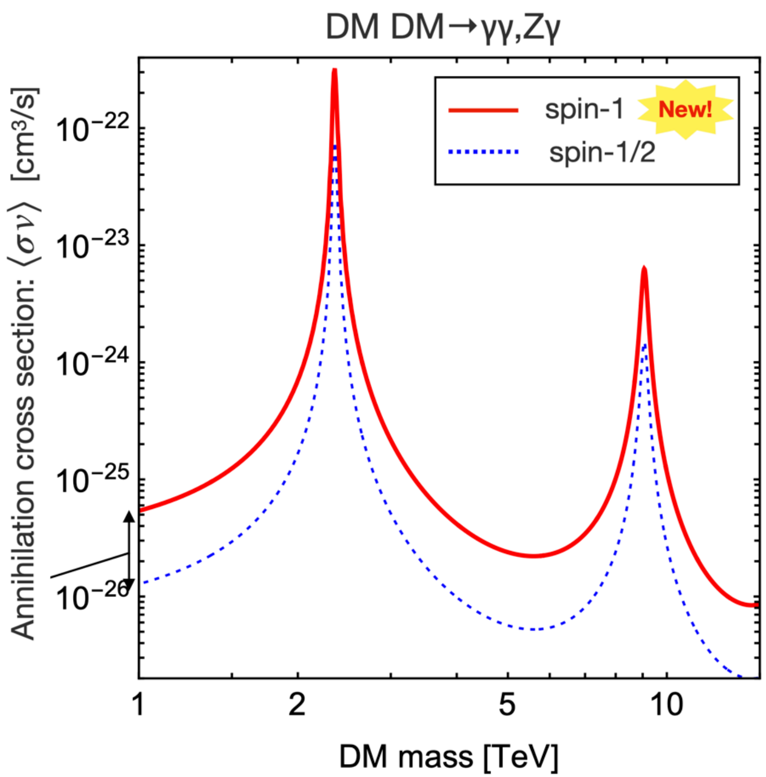
Thermal Relic Evaluation

Cross section

- Resonance structure appears
  (∵ determined by $SU(2)_L$ triplet-like features)
- Spin-1 DM pair forms $J = 2$ states New!

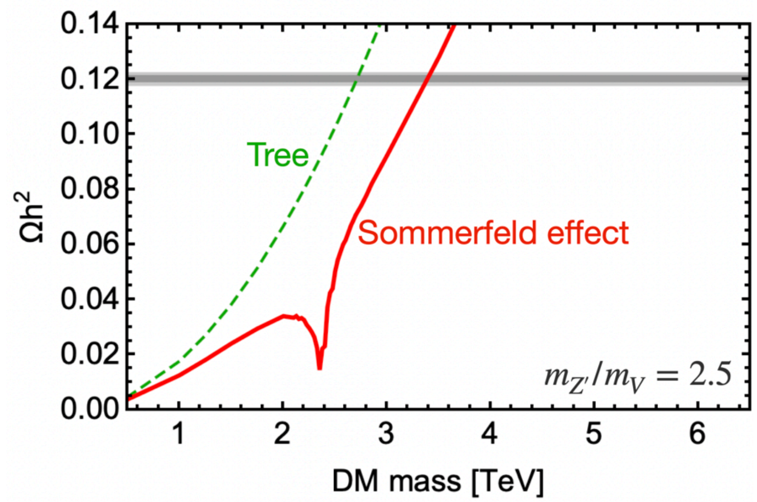
  → Predicted annihilation cross section is larger if compared w/ other spin cases

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



Thermal relic evaluation (leading order)

- Mass region is shifted to the heavier region due to the EW potential force



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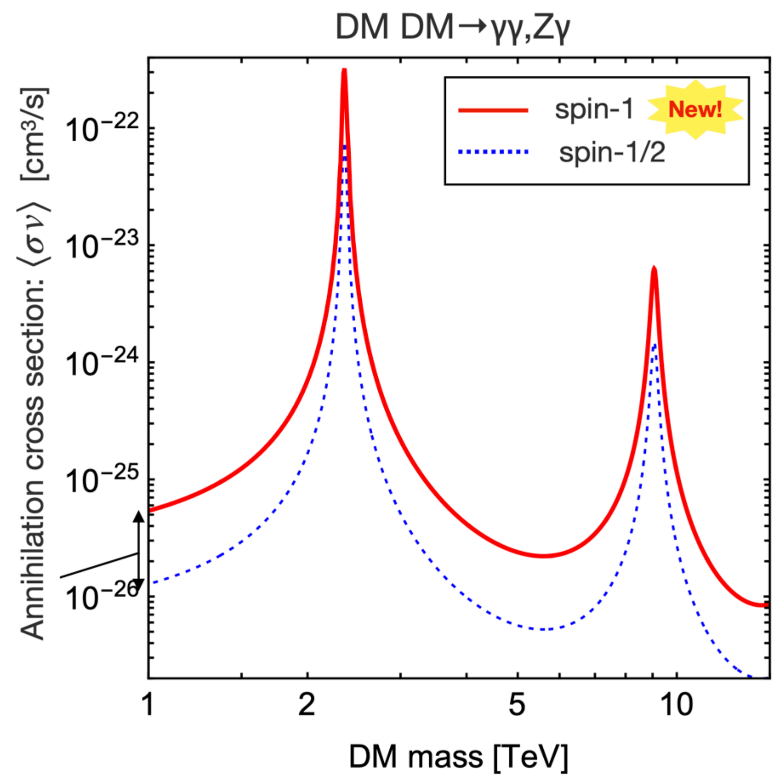
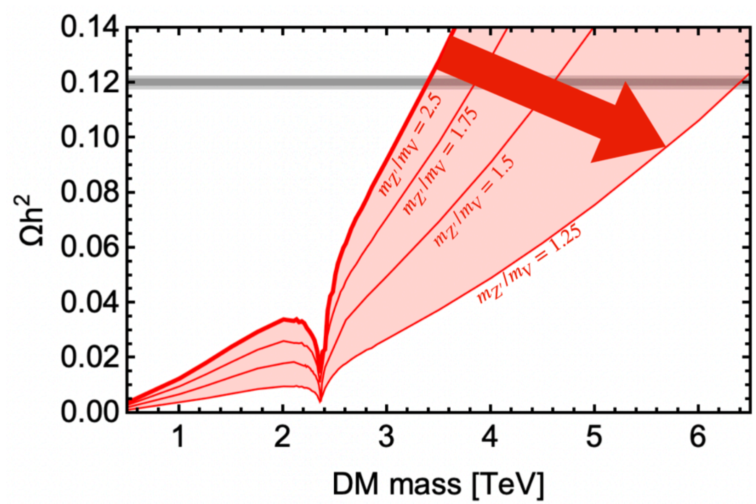


Thermal relic evaluation (leading order)

- Mass region is shifted to the heavier region due to the EW potential force
- Z' mass tunes thermal relic prediction
  → Requiring $\Omega h^2 = 0.12$, we obtain
  non-trivial prediction btw DM mass & Z' mass



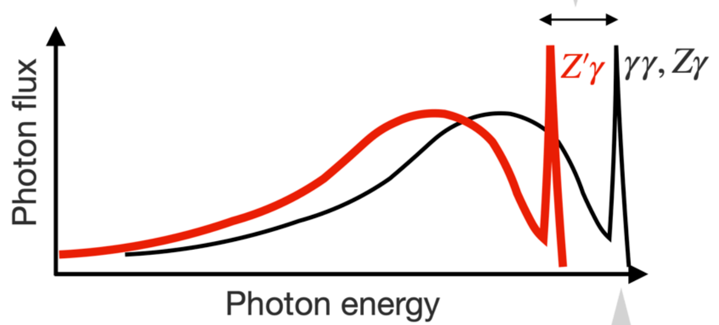
Monochromatic γ-ray Search

DM DM → $X\gamma$ $(X = \gamma, Z, Z')$

- Monochromatic peaks will be predicted from
  - $\gamma\gamma, Z\gamma$ modes
  - $Z'\gamma$ mode

  Peak energy is shifted due to non-negligible Z' mass

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



$$E_\gamma \simeq m_V$$

- Energy resolution is ~10 % for $\gtrsim 300$ GeV in current/future γ-ray observation [H. Abdallah et al. [HESS] (2018)] [A. Acharyya, et al [CTA] (2021)]

Unitarity of gauge couplings ↓ $Z'\gamma$ mode is kinematically opened ↓

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

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

→ **Double peaks are always separable!**

Double peak spectrum → We can reconstruct DM & Z' mass at the same time

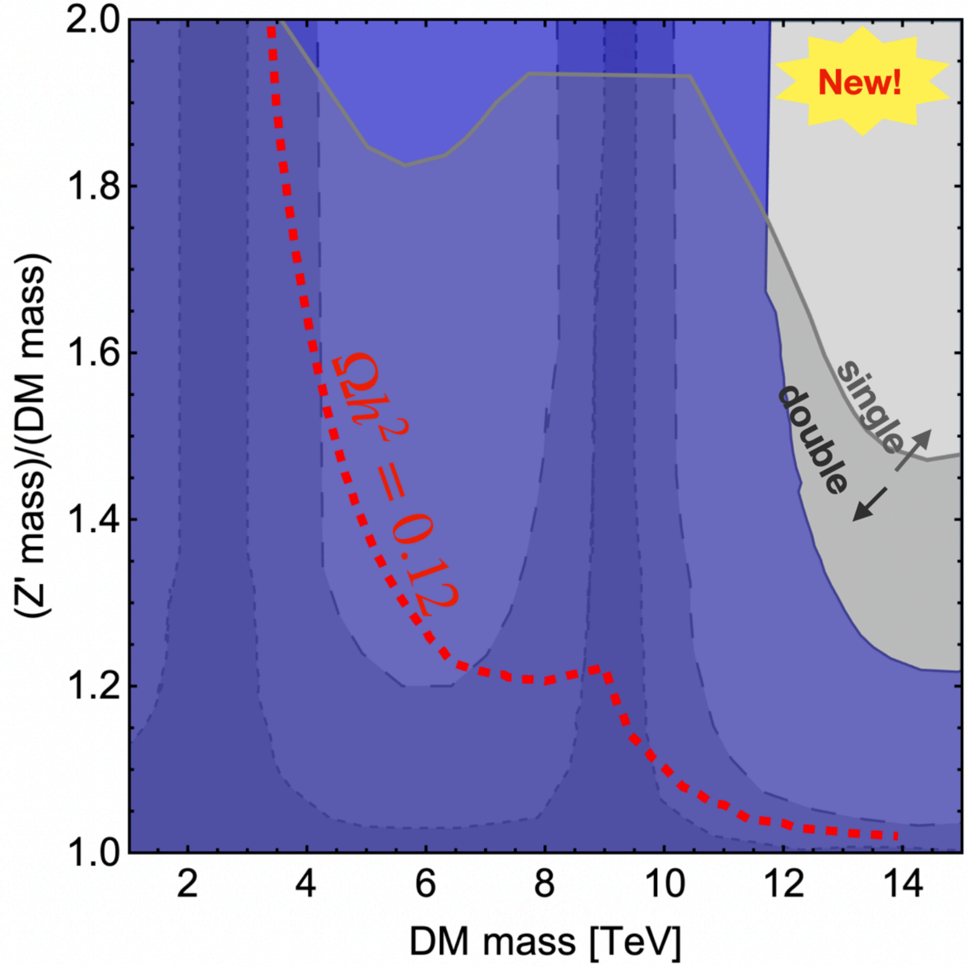
Result

[Preliminary]

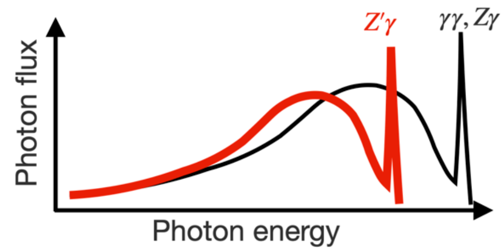
- Contour of $\Omega h^2 = 0.12$
  + Constraint from current γ-ray obs.
  + Prospect region in future γ-ray obs.

  - Current bound [H. Abdallah et al. (2018)]
    High Energy Stereoscopic System (H.E.S.S.)
    - Einasto2 [Cusped]
    - Einasto2 [Cored (estimated, $\times 10$)]
    - Einasto2 [Cored (estimated, $\times 100$)]
  - Prospect [A. Acharyya, et al (2021)]
    Cherenkov Telescope Array (CTA)
    - Single peak, Einasto [cored, $r_c = 5$ kpc]
    - Double peak, Einasto [cored, $r_c = 5$ kpc]

Spin-1 DM (SU(2)$_L$ triplet, Y=0, $\delta m = 168$ MeV)



Double peak signal may be probed in CTA
→ DM & Z' mass reconstruction tests this scenario



Summary

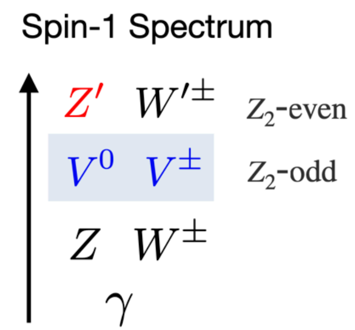
We studied Phenomenology of **Electroweakly interacting Spin-1** Dark Matter (DM)

(1) Model building

Exchange symmetry btw gauge groups

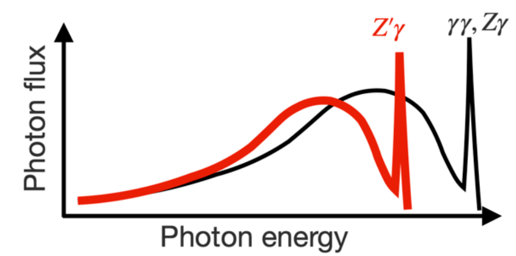
→ Electroweak interacting & Stable spin-1 DM candidate

→ Associating Z' **(neutral** Z_2-even **vector)**



(2) Signatures:

- Scattering → **Narrowing down Higgs contributions**
- Collider search → Z'/W' **search in LHC/HL-LHC**

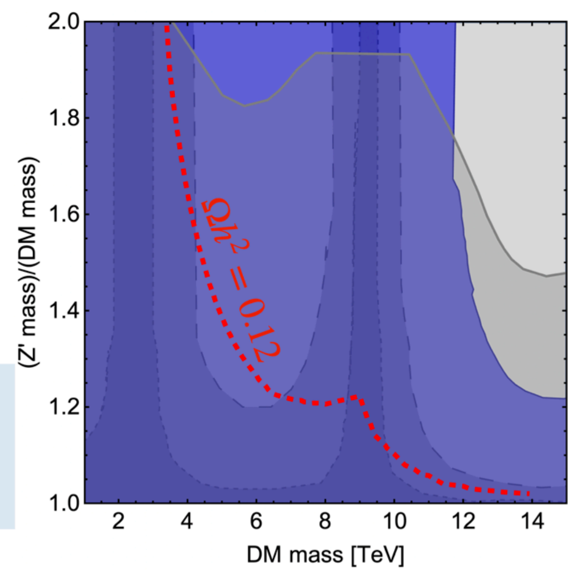


(3) EFT construction:

- Annihilation process including Sommerfeld effects

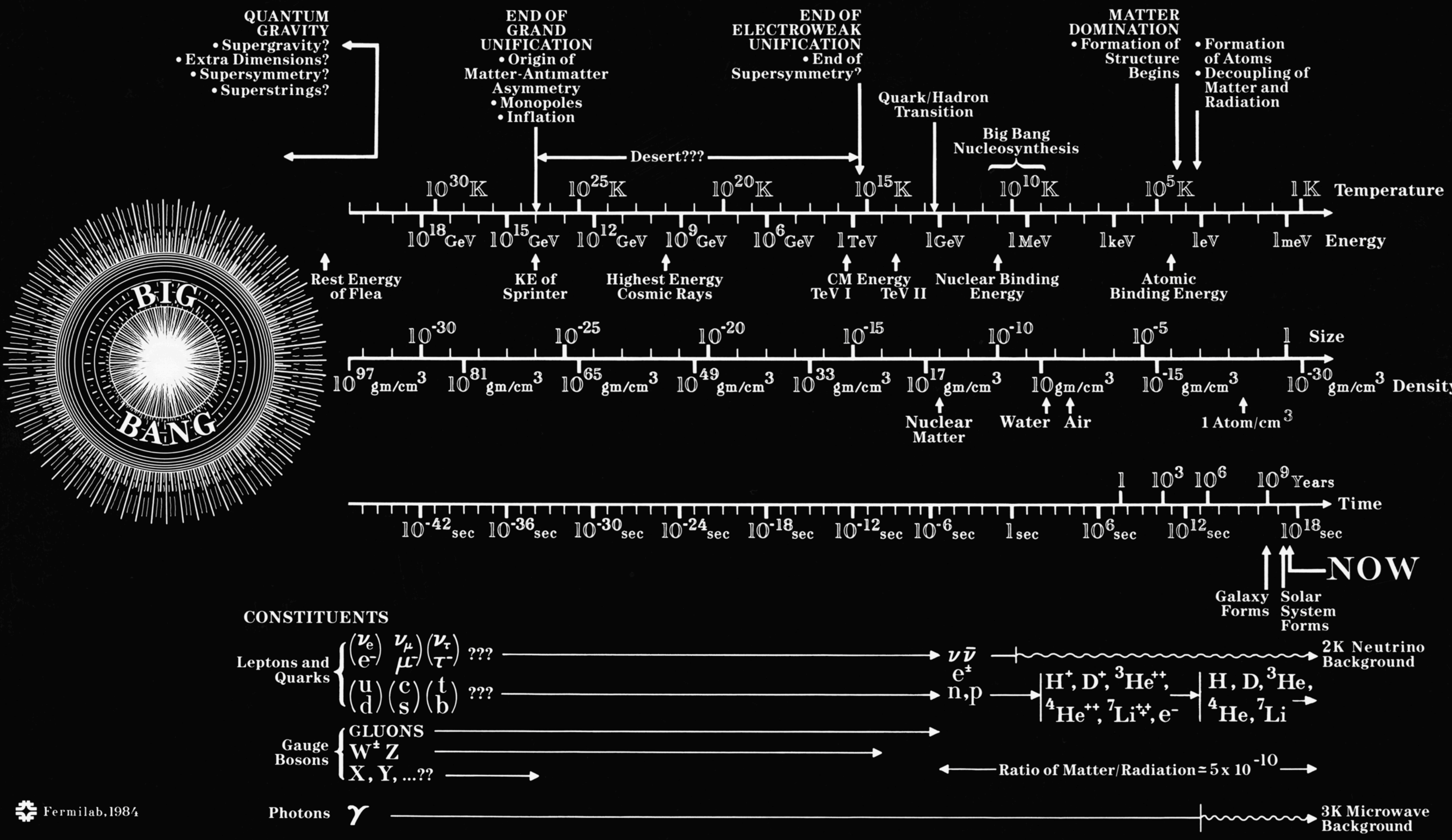
  -Ωh^2=0.12 → **Relation btw DM mass &** Z' **mass**

  -Line γ-ray → **Double peak from** γX $(X = \gamma, Z, Z')$ **in CTA**



Higgs sector will be covered by next-gene. Direct Detection
Prediction on DM and Z' **mass are testable in HL-LHC & CTA**

Backup



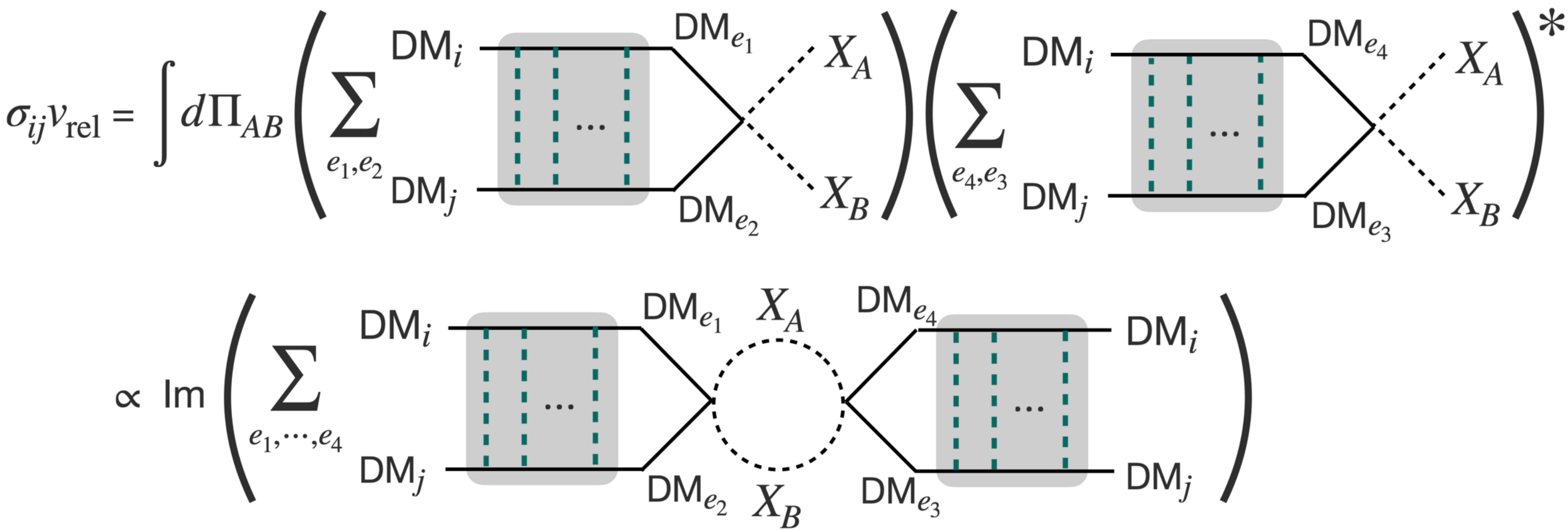
QUANTUM GRAVITY
• Supergravity?
• Extra Dimensions?
• Supersymmetry?
• Superstrings?
END OF GRAND UNIFICATION
• Origin of Matter-Antimatter Asymmetry
• Monopoles
• Inflation
END OF ELECTROWEAK UNIFICATION
• End of Supersymmetry?
Quark/Hadron Transition
Big Bang Nucleosynthesis
MATTER DOMINATION
• Formation of Structure Begins
• Formation of Atoms
• Decoupling of Matter and Radiation
Desert???
10^30 K
10^25 K
10^20 K
10^15 K
10^10 K
10^5 K
1 K
Temperature
10^18 GeV
10^15 GeV
10^12 GeV
10^9 GeV
10^6 GeV
1 TeV
1 GeV
1 MeV
1 keV
1 eV
1 meV
Energy
Rest Energy of Flea
KE of Sprinter
Highest Energy Cosmic Rays
CM Energy
TeV I
TeV II
Nuclear Binding Energy
Atomic Binding Energy
BIG BANG
10^-30
10^-25
10^-20
10^-15
10^-10
10^-5
1
Size
10^97 gm/cm^3
10^81 gm/cm^3
10^65 gm/cm^3
10^49 gm/cm^3
10^33 gm/cm^3
10^17 gm/cm^3
1 gm/cm^3
10^-15 gm/cm^3
10^-30 gm/cm^3
Density
Nuclear Matter
Water
Air
1 Atom/cm^3
1
10^3
10^6
10^9 Years
Time
10^-42 sec
10^-36 sec
10^-30 sec
10^-24 sec
10^-18 sec
10^-12 sec
10^-6 sec
1 sec
10^6 sec
10^12 sec
10^18 sec
NOW
Galaxy Forms
Solar System Forms
CONSTITUENTS
Leptons and Quarks
(ν_e e^-) (ν_μ μ^-) (ν_τ τ^-) ???
(u d) (c s) (t b) ???
ν ν̄
e^±
n,p
2K Neutrino Background
H^+, D^+, ^3He^++,
^4He^++, ^7Li^+++, e^-
H, D, ^3He,
^4He, ^7Li
Gauge Bosons
GLUONS
W^± Z
X, Y, ...??
Ratio of Matter/Radiation ≃ 5 x 10^-10
Photons γ
3K Microwave Background
Fermilab, 1984

Sommerfeld Enhancement

Sommerfeld Effect for EW int. DM

Cross section formula

[J.Hisano, S. Matsumoto, M. M. Nojiri, O. Saito (2005)]
[M. Beneke,C. Hellmann, P. Ruiz-Femenia (2013,2015)]
[C. Hellmann, P. Ruiz-Femenia (2013)]…



- Optical theorem → $\sigma_{ij} v_{\mathrm{rel}} \propto \mathrm{Im}\ (\mathrm{forwardscant\,.\,amp.})$
- Non-relativistic (NR) DM feels effectively long-range potential due to **EW interactions**
- Enhancement/Suppression effects (**Sommerfeld factor**) are obtained from **EFT of NR DM**
- EFT construction for Spin-0,1/2 DM is already studied in many contexts

We have to construct Effective Field Theory for NR Spin-1 DM multiplet

Corrections to Potential Real Part

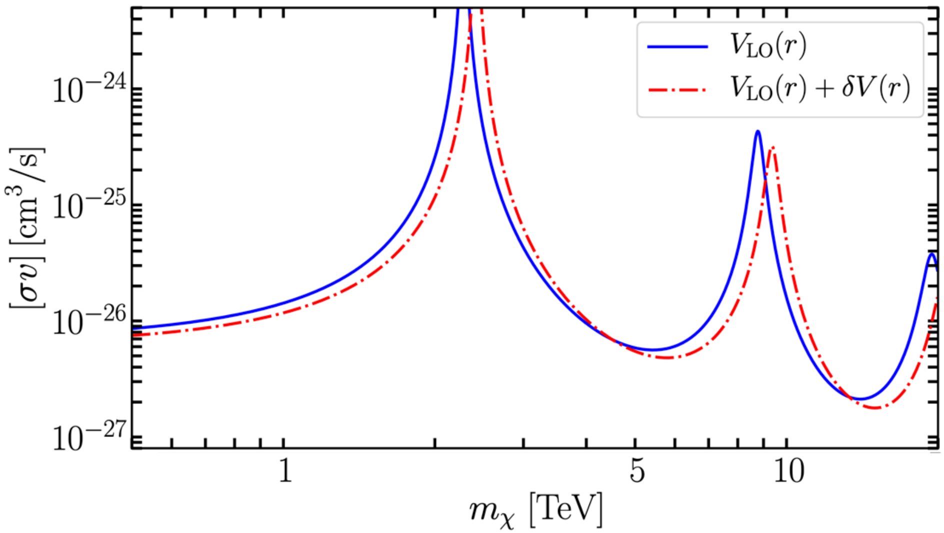
@Tree-level

- SM Higgs contribution → Suppressed by small mixing angle ϕ_h
- W', Z', h' contribution → Exponentially suppressed by heavy mass
  - $m_{W',Z'} \gtrsim m_V$ to satisfy the unitarity bound on gauge coupling
  - We assume $m_{h'} \simeq \mathcal{O}(1)$ TeV to focus on the EW aspects)
- Contributions from vector 4-couplings → Suppressed by $1/m_V^2$

Sub-leading

@Loop-level

- Studied in pure Wino DM system
  [M. Beneke, R. Szafron, K. Urban (2020)]
  - Comparison btw tree-level & 1-loop results
    → Resonance mass is shifted by 3 %
  - The same order correction is expected in our spin-1 DM system



Technical Procedures

Derivation of NR Effective Action

- Integrating out $W^{\pm}, Z, \gamma$
- Non-relativistic expansion of DM multiplet: $V^0, V^{\pm}$
- Integrating out the large momentum mode of DM multiplets
- Irreducible decomp. of 4-vector couplings into two-body states (using Fierz identity)

  → Obtain effective action: S_{eff} for NR two-body states of DM multiplets

Evaluation of Sommerfeld Enhancement Factors

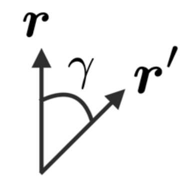
- Derive the Schwinger-Dyson equation ($\simeq$ Schrödinger eq for two-body states)
- Solve equations numerically w/ appropriate boundary condition

  $G(r) \propto e^{ikr}$ (outgoing wave @$r \to \infty$)
- Cross section is given by $\simeq$ (tree-level cross section) $\times$ (Sommerfeld factor)^2

Sommerfeld Enhancement Factor

Definition

$\Phi(R, r)$: two-body state



$$\langle 0 \,|\, \mathrm{T}\Phi(R, \boldsymbol{r})\Phi^\dagger(R', \boldsymbol{r}') \,|\, 0 \rangle = \int \frac{d^4P}{(2\pi)^4} e^{-iP\cdot(R-R')} \sum_\ell \frac{2\ell+1}{4\pi} P_\ell(\cos\gamma)(-i)G^{E,\ell}(r, r')$$

$$g(\boldsymbol{r}, \boldsymbol{r}') \equiv rr' G^{(E,\ell=0)}(\boldsymbol{r}, \boldsymbol{r}') \xrightarrow{\text{Im. part}} \frac{m^2}{2\pi}[g_>(r)\cdot\Gamma\cdot g_>^{\mathrm{T}}(r')]$$

Asymptotic behavior @$r \to \infty$ is important to evaluate annihilation cross section

$$g_>(r)\big|_{r\to\infty} = d(E) \times e^{i|\boldsymbol{k}|r}$$

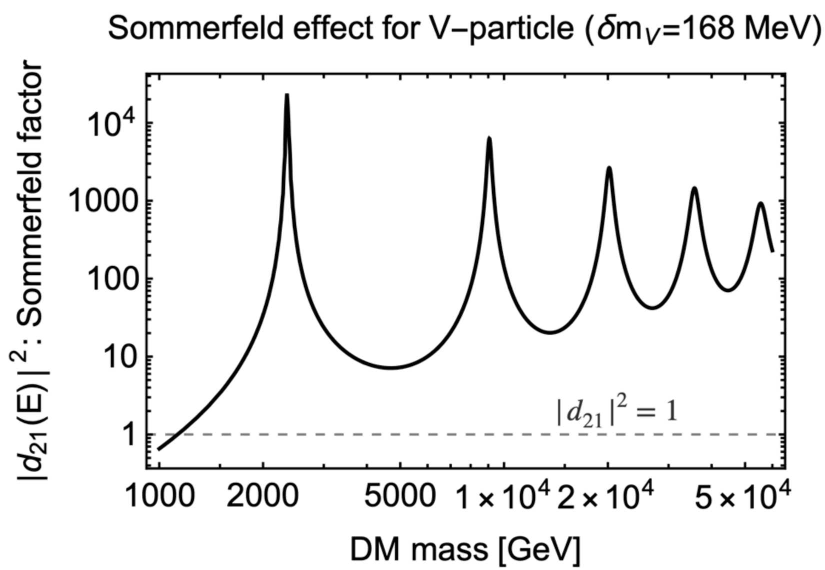
- Distortion from the plane wave
- Depend on $E \simeq mv^2/4$

DM mass dependence

Resonance condition for a well potential approx.

$$\sqrt{\frac{\alpha_2 m}{m_W}} \simeq \frac{(2n-1)\pi}{4} \quad (n = 1,2,\cdots)$$

Numerical evaluation is needed



Annihilation Cross Section

$$\langle \sigma v_{\rm rel} \rangle_{XX'} = 2 \sum_{\alpha,\beta} \sum_{J,J_z} \left(\Gamma^J_{XX'}\right)_{\alpha\beta} d_{2\alpha}(E) d^\star_{2\beta}(E)$$

$$\left(\begin{aligned} r_{Z'} &\equiv \frac{m_{Z'}^2}{4m_V^2} \\ g_{Z'} &\equiv \frac{g_W}{\sqrt{\frac{m_{Z'}^2}{m_V^2} - 1}} \end{aligned} \right)$$

- Annihilation cross sections are expressed in $\Gamma_{XX'}$ $(XX' = \gamma\gamma, Z\gamma, Z'\gamma)$

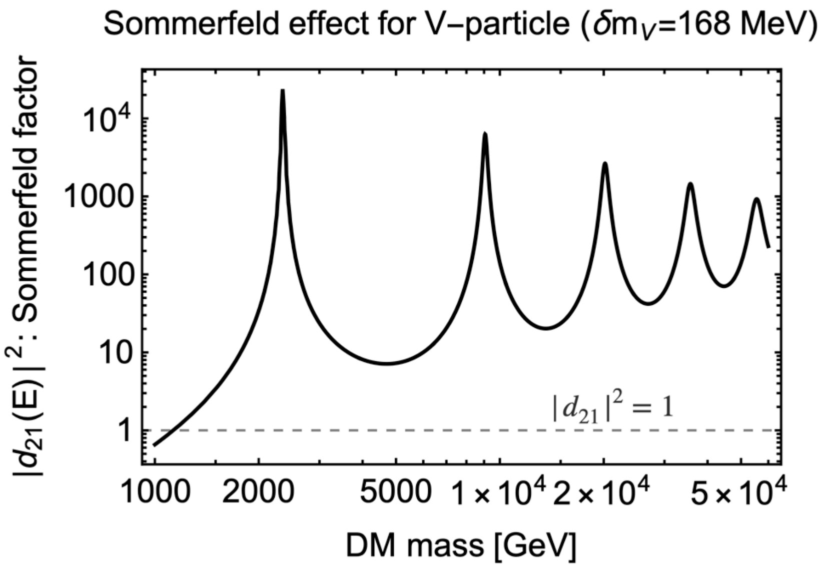
$$\hat{\Gamma}^{J=0}_{\gamma\gamma} = \frac{2}{3}\frac{\pi\alpha_2^2}{m_V^2}\begin{pmatrix} s_W^4 & 0 \\ 0 & 0 \end{pmatrix}, \quad \hat{\Gamma}^{J=0}_{Z\gamma} = \frac{2}{3}\frac{\pi\alpha_2^2}{m_V^2}\begin{pmatrix} 2c_W^2 s_W^2 & 0 \\ 0 & 0 \end{pmatrix}, \quad \hat{\Gamma}^{J=0}_{Z'\gamma} = \frac{1}{27}\frac{\alpha_2 g_{Z'}^2}{m_V^2}(1 - r_{Z'})(3 - 2r_{Z'})^2\begin{pmatrix} s_W^2 & 0 \\ 0 & 0 \end{pmatrix},$$

$$\hat{\Gamma}^{J=2}_{\gamma\gamma} = \frac{32}{45}\frac{\pi\alpha_2^2}{m_V^2}\begin{pmatrix} s_W^4 & 0 \\ 0 & 0 \end{pmatrix}, \quad \hat{\Gamma}^{J=2}_{Z\gamma} = \frac{32}{45}\frac{\pi\alpha_2^2}{m_V^2}\begin{pmatrix} 2c_W^2 s_W^2 & 0 \\ 0 & 0 \end{pmatrix}, \quad \hat{\Gamma}^{J=2}_{Z'\gamma} = \frac{8}{135}\frac{\alpha_2 g_{Z'}^2}{m_V^2}(1 - r_{Z'})(6 + 3r_{Z'} + r_{Z'}^2)\begin{pmatrix} s_W^2 & 0 \\ 0 & 0 \end{pmatrix},$$

Sommerfeld enhancement factor

$$d_{\alpha\beta}(E) \quad (\alpha, \beta = 1,2) \qquad E \simeq \frac{m v_{\rm rel}^2}{4}$$: NR kinetic energy

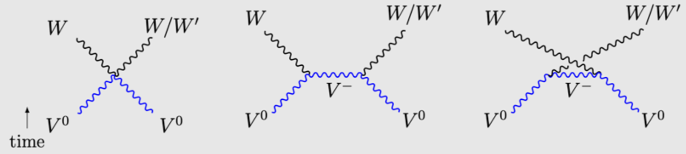
- Solving Schrödinger equation numerically
- $|d_{21}|^2$ is enhanced by several orders (especially around the resonance masses)



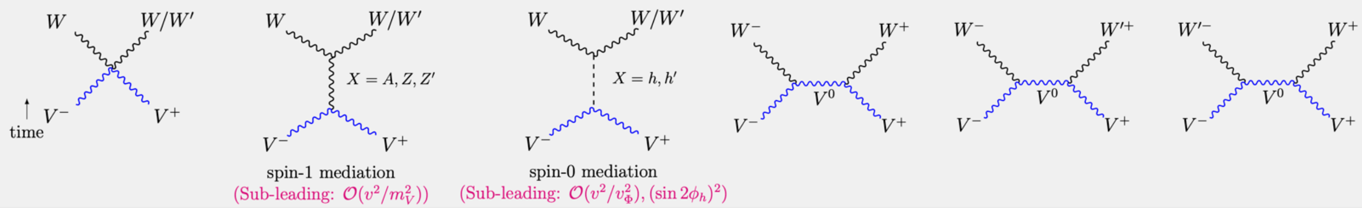
Annihilation Channels

$Q = 0$ state

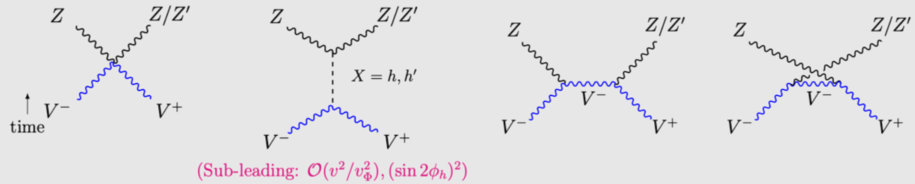
- $V^0 V^0 \to WW, WW'$



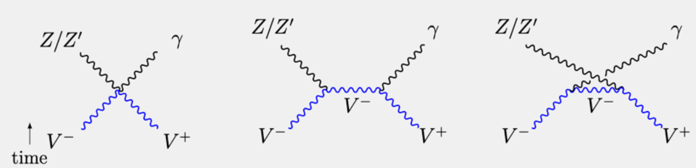
- $V^- V^+ \to WW, WW'$



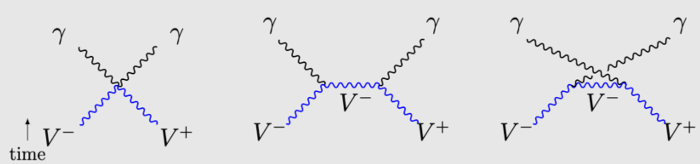
- $V^- V^+ \to ZZ, ZZ'$



- $V^- V^+ \to Z\gamma, Z'\gamma$

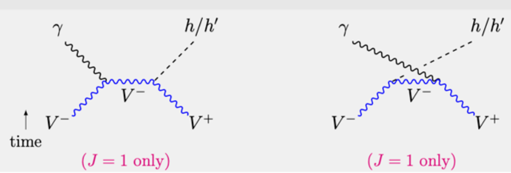


- $V^- V^+ \to \gamma\gamma$



Monochromatic γ-ray channel

- $V^- V^+ \to h\gamma, h'\gamma$



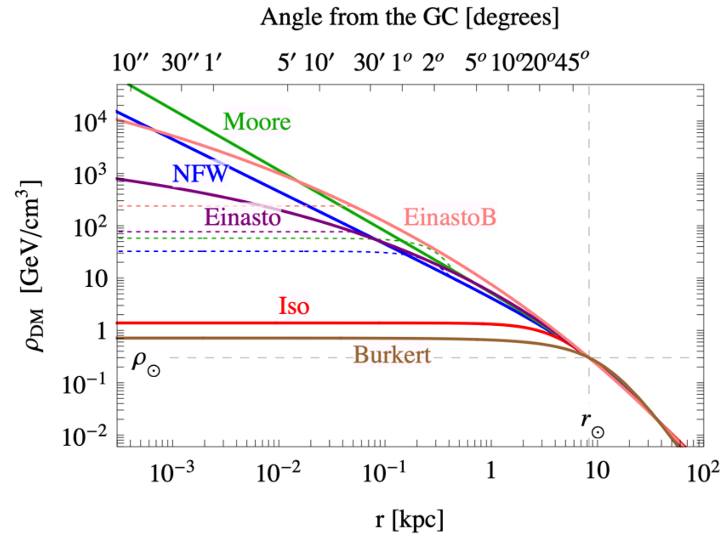
$J = 0$ only

→ irrelevant to discuss indirect detection

γ-ray search

ρ : DM energy density

[M. Cirelli, et al (2011)]



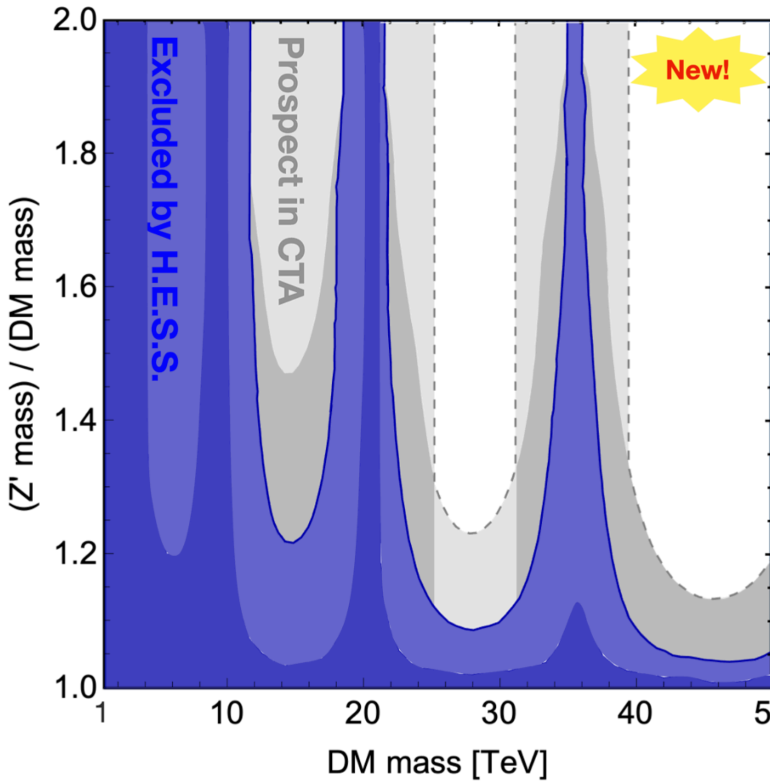
Energy spectrum of γ-ray flux

$$\frac{d\Phi}{dE_\gamma}(E_\gamma, \Delta\Omega) = \frac{\langle \sigma v \rangle}{8\pi m_{\rm DM}^2} \cdot \frac{dN}{dE_\gamma} \cdot J(\Delta\Omega)$$

$$J(\Delta\Omega) \equiv \int_{\Delta\Omega} \int_{\rm LOS} ds\ d\Omega\ \rho^2\left(r(s,\theta)\right)$$

- High DM density region is suitable to search signatures
  → **Galactic Center region**
- Uncertainty comes from choice of density profile

Spin-1 DM (SU(2)$_L$ triplet, Y=0, $\delta m = 168$ MeV)



- Bound: High Energy Stereoscopic System (H.E.S.S.)

  [H. Abdallah et al. (2018)]

  - Current bound, Einasto2 [cusped]
  - Current bound, Einasto2 [cored (estimated)]

- Prospect: Cherenkov Telescope Array (CTA) [A. Acharyya, et al (2021)]
  - Single peak, Einasto [cored, $r_c = 5$ kpc]
  - **Double peak**, Einasto [cored, $r_c = 5$ kpc]

Double peak signal may be probed in CTA experiment

Thermal Relic Evaluation

[T. Abe, MF, J. Hisano (Work in progress)]

Coannihilation (general discussion)

Z_2-odd particles w/ nearly degenerated spectrum $\{\chi_i\}$ $(i = 1, \cdots, N)$

Mass relation: $m_N > \cdots > m_1 \equiv m, \quad \to \chi_1$ is DM

$\delta m_i \equiv m_i - m$ (mass difference w/ DM)

Condition: $\delta m_i \lesssim T_{\rm fo} \quad \to$ **χ_i also contribute to DM annihilation**

($\because$ χ_i is kinematically archivable in thermal bath)

Relevant process: $\chi^i \chi^j \to X X'$, $\leftarrow$ Change # of χ_i w/ $\sigma_{ij} \equiv \sigma(\chi^i\chi^j \to XX')$

(Conserving Z_2) $\chi^i X \to \chi^j X'$, $\leftarrow$ Thermalize χ_i in the SM thermal bath

$\chi^j \to \chi^i X X'$, $\leftarrow$ The lightest particle survives in the end

Boltzmann eq.:

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

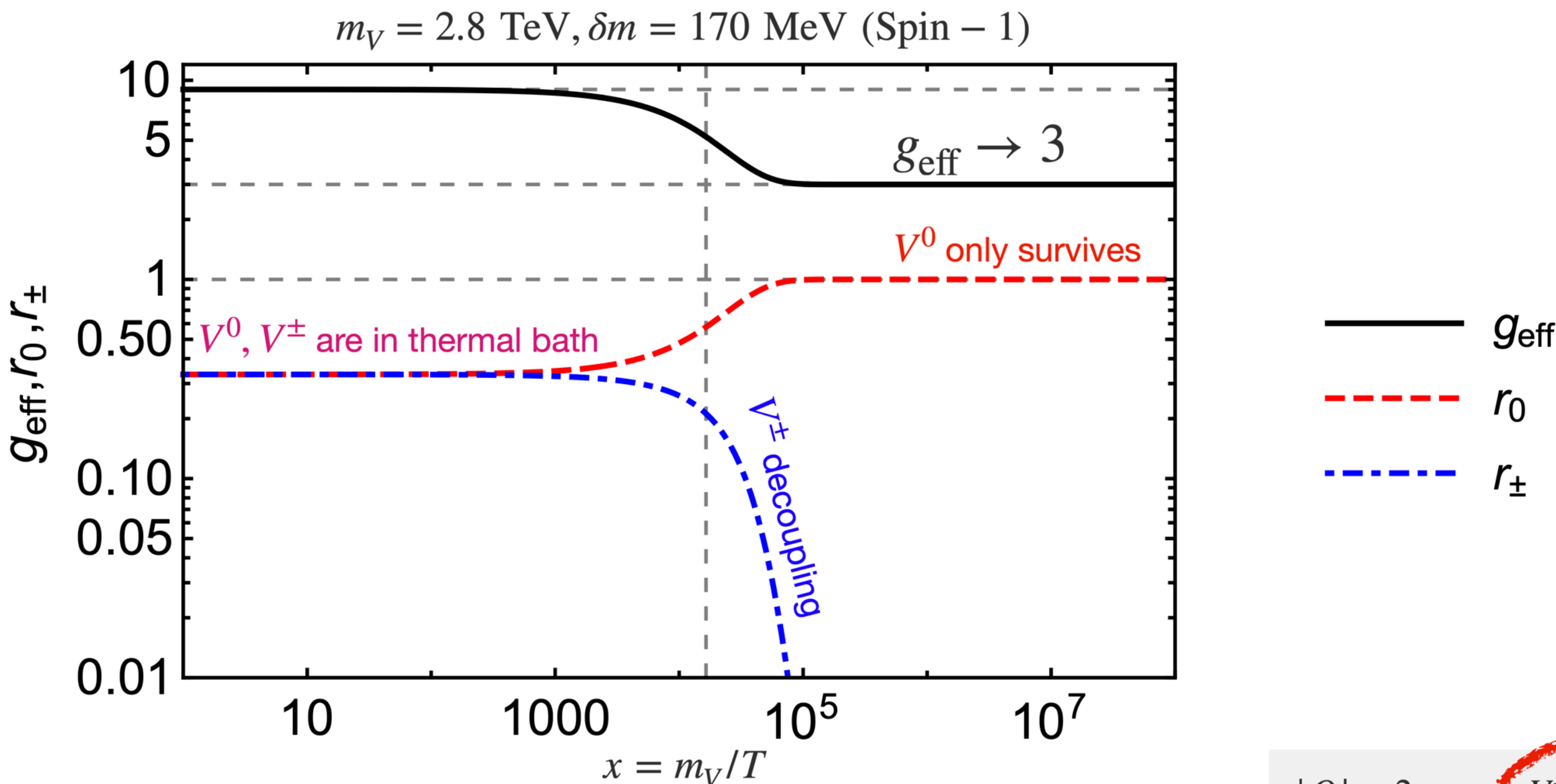
$$\langle\sigma_{\rm eff} v\rangle \equiv \sum_{i=1}^{n}\sum_{j=1}^{n} \langle\sigma_{ij} v\rangle\, r_i r_j$$

$$\left[\begin{array}{l} n \equiv \sum_i n_i \\ \langle\sigma_{ij} v\rangle \equiv \left(\frac{m}{4\pi T}\right)^{3/2} \int dv 4\pi v^2 (\sigma_{ij} v) \exp\left(-\frac{mv^2}{4T}\right) \\ r_i \equiv n_i^{\rm eq}/n^{\rm eq} \end{array}\right]$$

$\uparrow$

Difference from the case w/o degenerated spectrum (next page)

Coannihilation for V-particles



Ratio for total # of $\{\chi_i\}$: $r_i \equiv n_i^{\rm eq}/n^{\rm eq}$

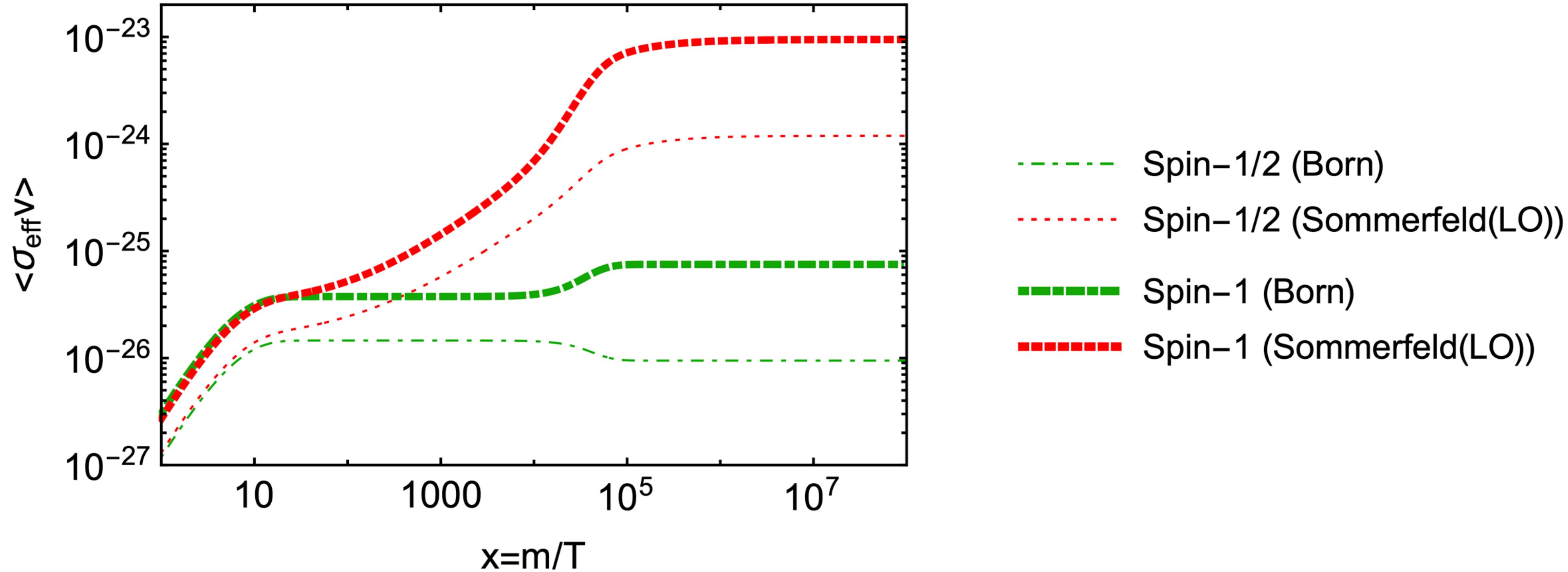
Eff. dof in thermal bath: $g_{\rm eff}(x) = 3 + 6\left(1+\frac{\delta m_V}{m_V}\right)^{\frac{3}{2}} \exp\left[-x\frac{\delta m_V}{m_V}\right]$,

$\lvert Q\rvert = 2$	⋯	V^-V^-	V^+V^+
$\lvert Q\rvert = 1$	⋯	V^0V^-	V^0V^+
$\lvert Q\rvert = 0$	⋯	V^0V^0	V^-V^+

We need to evaluate thermal relic including not only V^0 but also $V^\pm$

Result: Effective Cross Section

m=2.8 TeV, δm=170 MeV, $m_{Z'} = 1.5\ m_V$



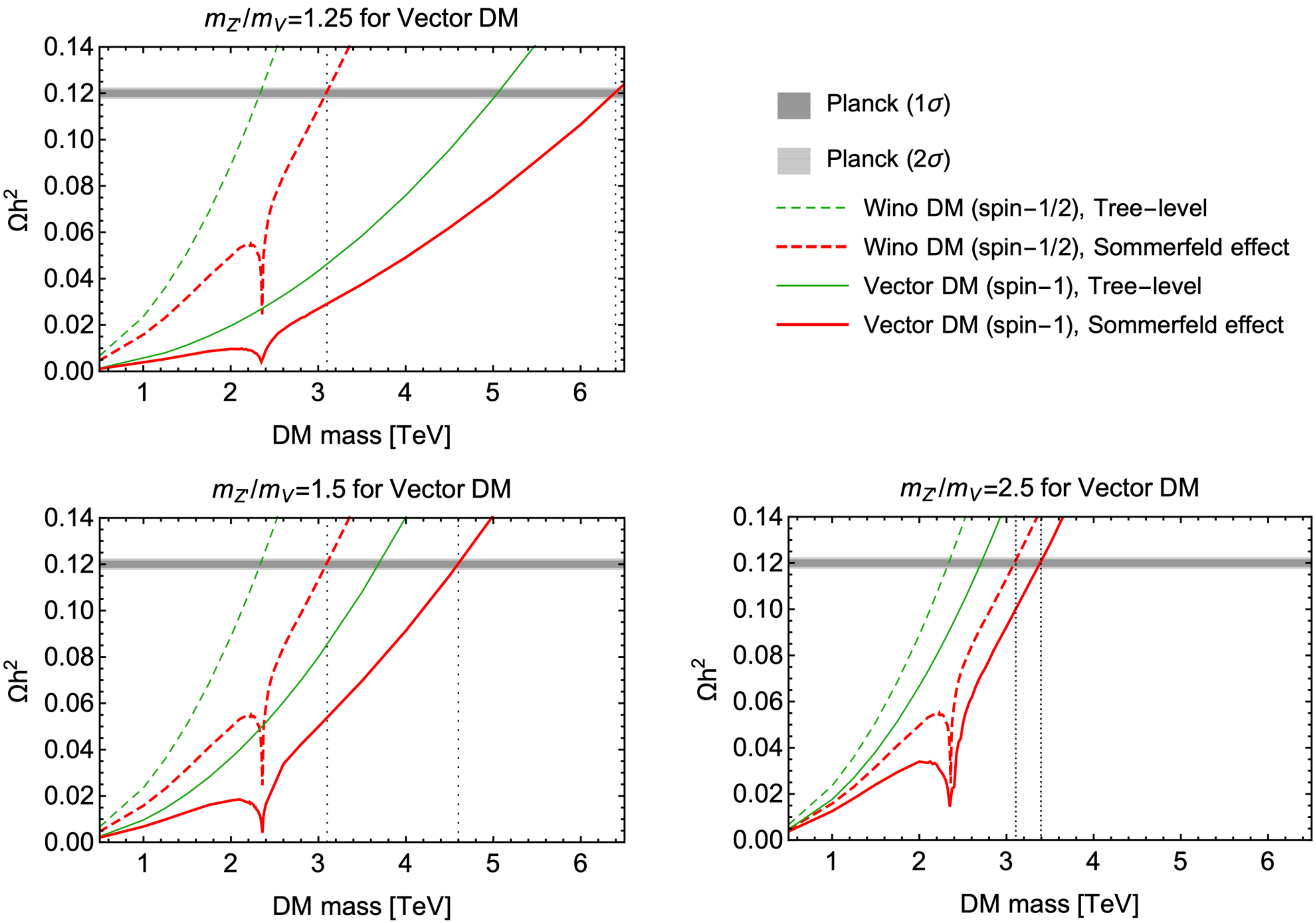
Behavior of Plot

- m/T→1: Consistent w/ Born approximation (w/o Sommerfeld effects)
- m/T>>1: Sommerfeld enhancement effects are viable

Spin-1/2 vs Spin-1

- |Q|=1 state potential are **Attractive for Spin-1/2** and **Repulsive for Spin-1**, respectively
  → Annihilation of |Q|=1 states are irrelevant for Spin-1 DM in the NR phase

Result: Evaluation of Ωh^2



EW Spin-1 DM: $\gtrsim$ 3 TeV $\xrightarrow{\text{Sommerfeld}}$ $\gtrsim$ 3.4 TeV

↑Depends on Higgs sector

Our Model (more details)

Electroweakly interacting DM

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

- DM coupling: Electroweak coupling
- DM mass: Fixed 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	$m_\pm - m_{\rm DM}$
	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	Spin	[TeV]	[MeV]
	2	1/2	0	0.54	350
Higgsino	**2**	1/2	1/2	1.1	341
	3	0	0	2.5	166
Wino	**3**	0	1/2	2.7	166
		⋮		⋮	⋮

$m_{\rm DM}$: DM mass

$m_\pm$: mass of charged component

Feature

•Ωh^2~0.12 → O(1) TeV DM

•mass splitting → O(100) MeV

(from EW radiative correction※)

General for Electroweakly interacting DM

※ We also have contribution from Higher Dimensional Operators

How about Spin-1 DM?

Can we construct a concrete model?

What is the origin of spin-1 particle?

How to realize **DM stability** & **EW interaction**?

cf. R-parity for Supersymmetric spin-1/2 DM candidate

Model

Symmetry $SU(3)_c \otimes SU(2)_0 \otimes SU(2)_1 \otimes SU(2)_2 \otimes U(1)_Y$ (4 dim. theory)

Exchange Symme.

Matter Contents

field	spin	$SU(3)_c$	$SU(2)_0$ ($W^a_{0\mu}$)	$SU(2)_1$ ($W^a_{1\mu}$)	$SU(2)_2$ ($W^a_{2\mu}$)	$U(1)_Y$
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	$\frac{1}{2}$

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

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

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

4 real degrees of freedom for each

- Symmetry transformation

• Gauge trans. (for scalars)

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

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

• Exchange trans.

$$\boxed{\Phi_1 \leftrightarrow \Phi_2, \qquad W^a_{0\mu} \leftrightarrow W^a_{2\mu}}$$

※ $g_0 = g_2$ ($\neq g_1$)

Symmetry Breaking

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

$SU(2) \cong SU(2)_L$

- Vacuum expectation values

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

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

$(v_\Phi \gg v)$

v_Φ: $\mathcal{O}(1)$ TeV, v: $\mathcal{O}(100)$ GeV

Spectrum

Z_2 parity from exchange symmetry: $W^a_{0\mu} \leftrightarrow W^a_{2\mu}, \quad \Phi_1 \leftrightarrow \Phi_2$

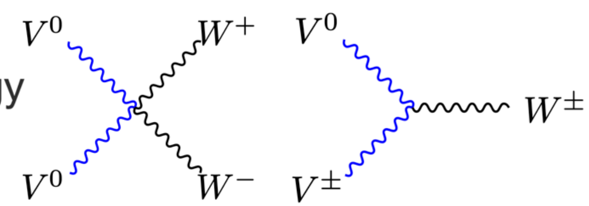
Energy	Vector	Scalar	Z_2 parity		Mass
2-mode	$Z' \quad W'^{\pm}$	h'	**even**	$\sim v_\Phi$	$\mathcal{O}(1)$ TeV
1-mode	$V^0 \quad V^{\pm}$	h_D	**odd**	$\sim v_\Phi$	$\mathcal{O}(1)$ TeV
0-mode	$Z \quad W^{\pm}$	h	**even**	$\sim v$	$\mathcal{O}(100)$ GeV
	γ		**even**		massless

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

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

$$\left[W^{\pm}_{n\mu} = \frac{W^1_{n\mu} \mp i W^2_{n\mu}}{\sqrt{2}} \quad (n = 0, 2) \right]$$

- Z_2-odd vectors ($V^0, V^{\pm}$) → **"V-particle"** $\simeq$ **SU(2)$_L$ triplet**
  - Non-abelian vector couplings → EW int. dominates phenomenology



  - Mass spectrum
    - Tree-level: $m^2_{V^0} = m^2_{V^\pm} = \dfrac{g_0^2 v_\Phi^2}{4} \quad (\equiv m_V^2)$
    - Loop-level: $\delta m \equiv m_{V^\pm} - m_{V^0} \simeq 168\ \mathrm{MeV}$ (Almost the same value as 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 (→ outstanding prediction in γ-ray spectrum)

Model

BSM Lagrangian

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

Scalar potential

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

Mass Matrix (Gauge sector)

$$\mathcal{L} \supset \begin{pmatrix} W_{0\mu}^{+} & W_{1\mu}^{+} & W_{2\mu}^{+} \end{pmatrix} \mathcal{M}_C^2 \begin{pmatrix} W_0^{-\mu} \\ W_1^{-\mu} \\ W_2^{-\mu} \end{pmatrix} + \frac{1}{2} \begin{pmatrix} W_{0\mu}^{3} & W_{1\mu}^{3} & W_{2\mu}^{3} & B_\mu \end{pmatrix} \mathcal{M}_N^2 \begin{pmatrix} W_0^{3\mu} \\ W_1^{3\mu} \\ W_2^{3\mu} \\ B^\mu \end{pmatrix}$$

Charged vector

$$\mathcal{M}_C^2 = \frac{1}{4} \begin{pmatrix} g_0^2 v_\Phi^2 & -g_0 g_1 v_\Phi^2 & 0 \\ -g_0 g_1 v_\Phi^2 & g_1^2 (v^2 + 2 v_\Phi^2) & -g_1 g_0 v_\Phi^2 \\ 0 & -g_1 g_0 v_\Phi^2 & g_0^2 v_\Phi^2 \end{pmatrix},$$

Neutral vector

$$\mathcal{M}_N^2 = \frac{1}{4} \begin{pmatrix} g_0^2 v_\Phi^2 & -g_0 g_1 v_\Phi^2 & 0 & 0 \\ -g_0 g_1 v_\Phi^2 & g_1^2 (v^2 + 2 v_\Phi^2) & -g_1 g_0 v_\Phi^2 & -g_1 g' v^2 \\ 0 & -g_1 g_0 v_\Phi^2 & g_0^2 v_\Phi^2 & 0 \\ 0 & -g_1 g' v^2 & 0 & g'^2 v^2 \end{pmatrix}.$$

Mass Matrix (Scalar sector)

$$\mathcal{L} \supset \frac{1}{2} \begin{pmatrix} \sigma_3 & \sigma_1 & \sigma_2 \end{pmatrix} \begin{pmatrix} 2\lambda v^2 & 2vv_\Phi\lambda_{h\Phi} & 2vv_\Phi\lambda_{h\Phi} \\ 2vv_\Phi\lambda_{h\Phi} & 8v_\Phi^2\lambda_\Phi & 4v_\Phi^2\lambda_{12} \\ 2vv_\Phi\lambda_{h\Phi} & 4v_\Phi^2\lambda_{12} & 8v_\Phi^2\lambda_\Phi \end{pmatrix} \begin{pmatrix} \sigma_3 \\ \sigma_1 \\ \sigma_2 \end{pmatrix} .$$

Dimensionless couplings

$$\begin{aligned}
\lambda =& \frac{m_h^2 \cos^2\phi_h + m_{h'}^2 \sin^2\phi_h}{2v^2}, \\
\lambda_{h\Phi} =& -\frac{\sin\phi_h \cos\phi_h}{2\sqrt{2}vv_\Phi}(m_{h'}^2 - m_h^2), \\
\lambda_\Phi =& \frac{m_h^2 \sin^2\phi_h + m_{h'}^2 \cos^2\phi_h + m_{h_D}^2}{16v_\Phi^2}, \\
\lambda_{12} =& \frac{m_h^2 \sin^2\phi_h + m_{h'}^2 \cos^2\phi_h - m_{h_D}^2}{8v_\Phi^2}.
\end{aligned}$$

Bounded from Below(BFB) Condition

$$
\begin{aligned}
&\lambda > 0, \\
&\lambda_\Phi > 0, \\
&\lambda_\Phi + \frac{\lambda_{12}}{2} > 0, \\
&\frac{\lambda_{h\Phi}}{2} + \sqrt{\lambda\lambda_\Phi} > 0, \\
&\begin{cases} \lambda_{h\Phi} \geq 0, \\ \text{or} \\ \lambda_{h\Phi} < 0 \quad \text{and} \quad \lambda\left(\lambda_\Phi + \frac{\lambda_{12}}{2}\right) - \frac{\lambda_{h\Phi}^2}{2} > 0. \end{cases}
\end{aligned}
$$

※ We find **all the BFB conditions are automatically satisfied** by using the the expressions of scalar quartic couplings

$$
\lambda = \frac{m_h^2 \cos^2\phi_h + m_{h'}^2 \sin^2\phi_h}{2v^2}, \qquad \lambda_\Phi = \frac{m_h^2 \sin^2\phi_h + m_{h'}^2 \cos^2\phi_h + m_{h_D}^2}{16 v_\Phi^2},
$$

$$
\lambda_{h\Phi} = -\frac{\sin\phi_h \cos\phi_h}{2\sqrt{2} v v_\Phi}(m_{h'}^2 - m_h^2), \qquad \lambda_{12} = \frac{m_h^2 \sin^2\phi_h + m_{h'}^2 \cos^2\phi_h - m_{h_D}^2}{8 v_\Phi^2}.
$$

Unitarity Bound for Scalar Coupling

$$|\lambda| \leq 4\pi,$$

$$|\lambda_{h\Phi}| \leq 4\pi,$$

$$|\lambda_{\Phi}| \leq \pi,$$

$$|\lambda_{12}| \leq 2\pi,$$

$$|3\lambda_{\Phi} - \lambda_{12}| \leq \pi,$$

$$\left|3\lambda + 4(3\lambda_{\Phi} + \lambda_{12}) \pm \sqrt{(3\lambda - 4(3\lambda_{\Phi} + \lambda_{12}))^2 + 32\lambda_{h\Phi}^2}\right| \leq 8\pi.$$

$$|\lambda| = \left|\frac{m_h^2 \cos^2\phi_h + m_{h'}^2 \sin^2\phi_h}{2v^2}\right| \lesssim \frac{4}{3}\pi$$ in the limit of $\lambda \gg \lambda_{h\Phi}, \lambda_{\Phi}, \lambda_{12}$

For $m_{h'} \gg v$, we need small ϕ_h to realize $\lambda \simeq \mathcal{O}(1)$

→ **Perturbative unitarity bounds give a viable constraint on ϕ_h**

Z_2 parity from Exchange symme.

Exchange trans. **(after SSB)**

$$\sigma_1 \leftrightarrow \sigma_2, \qquad W^a_{0\mu} \leftrightarrow W^a_{2\mu}$$

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

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

$$\begin{cases} \frac{\sigma_1 - \sigma_2}{\sqrt{2}} \mapsto -\frac{\sigma_1 - \sigma_2}{\sqrt{2}} & Z_2\text{-odd} \\ \frac{\sigma_1 + \sigma_2}{\sqrt{2}} \mapsto +\frac{\sigma_1 + \sigma_2}{\sqrt{2}} & Z_2\text{-even} \\ \sigma_3 \mapsto +\sigma_3 & Z_2\text{-even} \end{cases}$$

Z_2-odd $\xrightarrow{\text{No mixing}}$ $h_D = \frac{\sigma_1 - \sigma_2}{\sqrt{2}}$

Z_2-even, Z_2-even $\xrightarrow{\text{mixed by } \phi_h}$ h (125 GeV Higgs), h'

Physical states

States are classified by **Z_2 Parity**!

Exchange symmetry $\mathrm{SU}(2)_0 \leftrightarrow \mathrm{SU}(2)_2$ ➡ **Z_2 Parity for physical states**

DM Phenomenology

Parameters

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

$$g_0,\quad g_1,\quad g',\quad v,\quad v_\Phi,\qquad \text{(scalar quartic couplings)} \times 4$$

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

ϕ_h : mixing angle of Z_2-even scalars

$\sim v_\Phi$ (TeV scale)

Free parameters

$$\{\ \underbrace{m_V,\quad m_{Z'}}_{\text{Characterize vector sector}},\quad \underbrace{m_{h'},\quad m_{h_D},\quad \phi_h}_{\text{Characterize scalar sector}}\ \}$$

Scattering Process

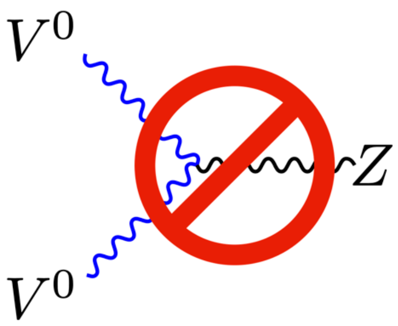
DM direct detection

DM-nucleus scattering is searched, but no significant excess now
→ Severe constraint on DM-Z coupling & DM-Higgs coupling

(1) Z-exchange process

Neutral boson triple coupling is forbidden
(∵ non-Abelian extension)

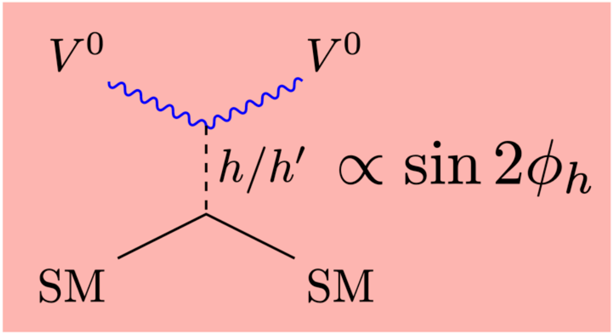
→ No Z-exchange in scattering process!



(2) Higgs-exchange process

Mixing angle ϕ_h tunes the scattering process
→ direct detection bounds give upper bound on ϕ_h

For sufficiently small ϕ_h,
$\sigma_{\rm scat}$ is dominated by 1-loop EW processes



Thermal relic region

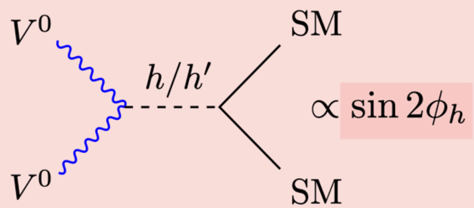
[Without Sommerfeld effects]

ϕ_h : mixing angle btw h and h'

White region:
$\Omega h^2 \sim 0.12$ is achieved by adjusting ϕ_h

Annihilation Channel

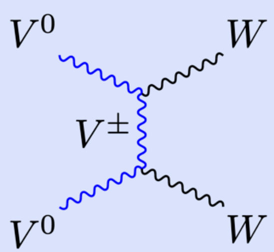
- Higgs channels

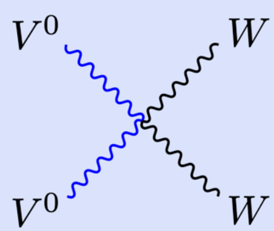


$\propto \sin 2\phi_h$

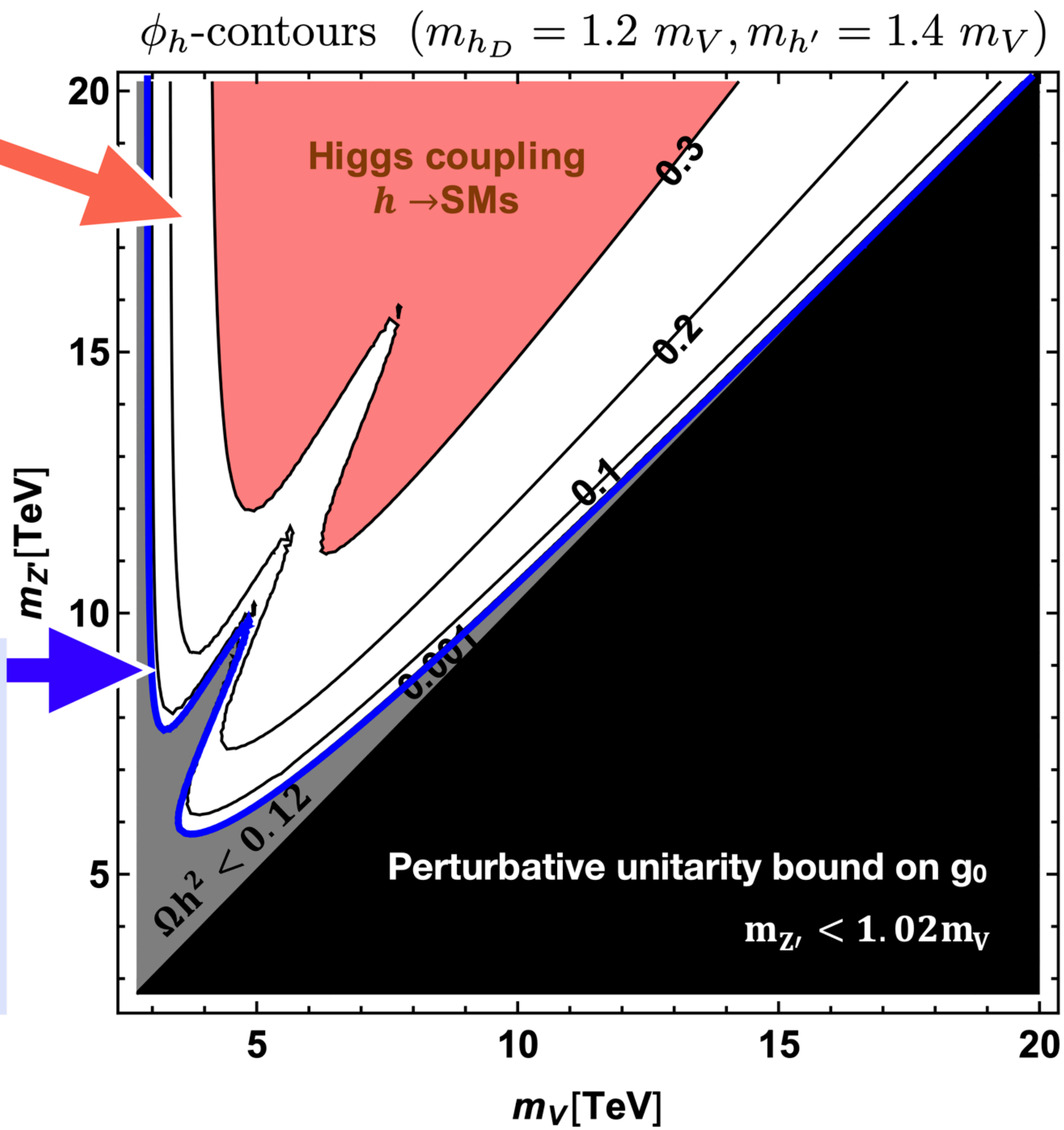
- EW channels

EW channel only





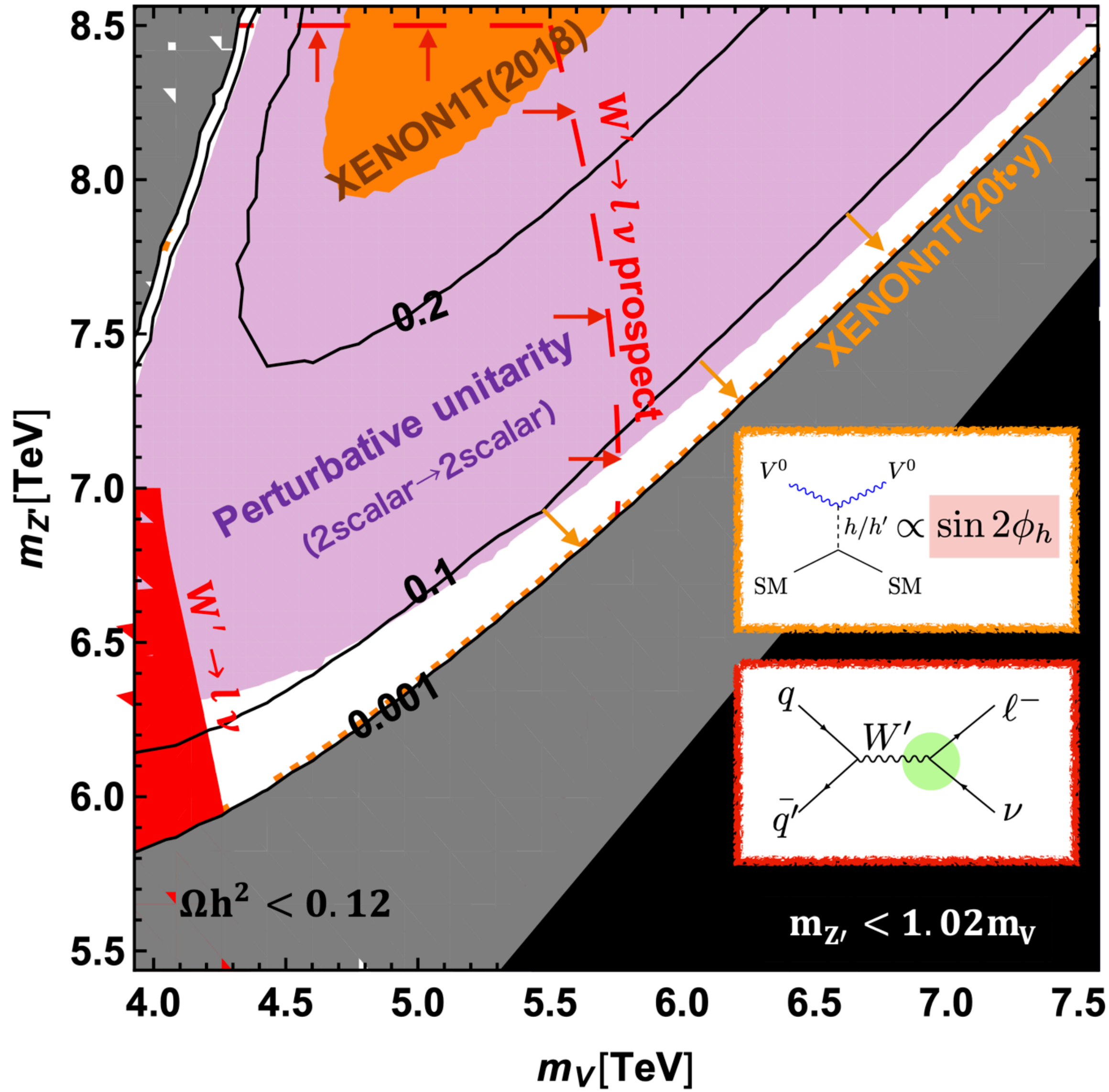
(+ many other channels…)

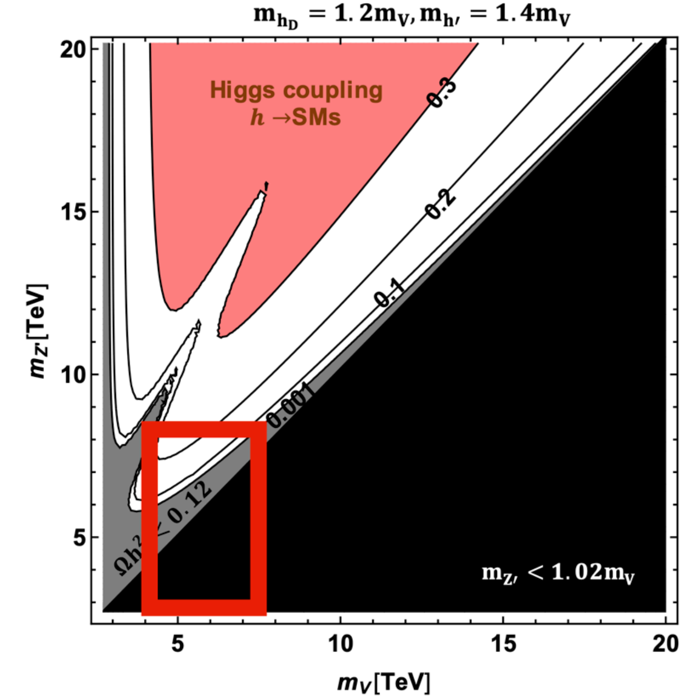


※ **We need to include Sommerfeld effect in evaluation of Ωh^2** [Future work is ongoing]

Constraints

ϕ_h-contours $(m_{h_D} = 1.2\, m_V, m_{h'} = 1.4\, m_V)$





- Perturbative unitarity bounds
  (2scalar→2scalar scattering)
  → $\phi_h \lesssim 0.1$
- Direct detection(XENON1T/nT)
  → probe Higgs contribution to DM annihilation process
- W' search by LHC/HL-LHC
  → probe thermal relic scenario **even if** $\phi_h \simeq 0$

LHC13TeV 139 fb^{-1} [ATLAS Collaboration(2019)] (※ No bound for $m_{W'} > 7$ TeV)

HL-LHC14TeV 3000 fb^{-1} [ATL-PHYS-PUB-2018-044(2018)]

DM candidate from Extra-dimensional theory

KK-parity in extra-dim. Theory

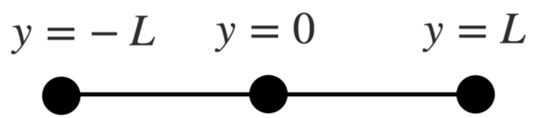
= "Reflection Symmetry about middle point of extra-coordinate"

Typical Mass Spectrum

- zeromode (= SM particles)
- (Nearly) equally separated masses for higher modes

	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	
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

DM model w/ warped extra-dim. (example)



- Gluing two AdS slice w/ respect to reflection about $y = 0$

Metric: $d^2s = d^2y + e^{-2k|y|}\, d^2x$ (k : warp factor)

Boundary localized term: $\begin{cases} r_L & \text{… on two boundary} \\ r_0 & \text{… on the middle point} \end{cases}$ $\Rightarrow$ $\dfrac{m_{(2\mathrm{nd})}}{m_{(1\mathrm{st})}} \simeq \sqrt{1 + \dfrac{r_L}{r_0 + L}}$

(for $r_{IR} \gg 1/k$)

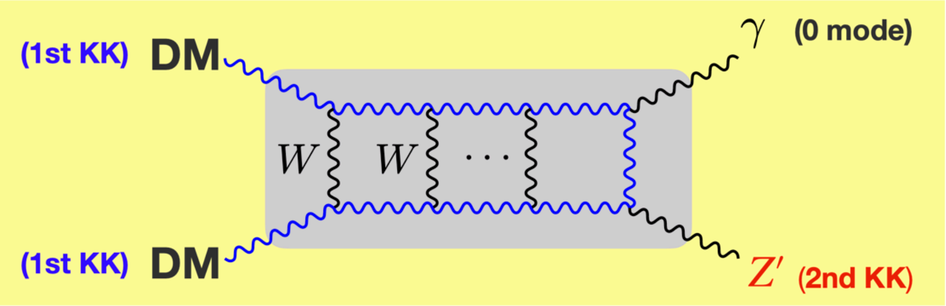
→ Directly affects mass spectrum

→ KK-mode-number is not conserved

1st KK W^3_μ may be lightest KK-odd particle

= **SU(2)$_L$ triplet spin-1 DM** (w/ **EW int.**)

What is distinctive features?



[K. Agashe, A. Falkowski I. Low, G. Servant (2008)]

KK-parity in warped extra-dim.

- Gluing two AdS slice w/ respect to **geometric reflection about middle point**

  Metric: $d^2s = d^2y + e^{-2k|y|}\ d^2x$ (k : warp factor)

Abelian theory (for demonstration)

r_{UV} : BL kinetic term @UV plane [mass]$^{-1}$

r_{IR} : BL kinetic term @IR plane [mass]$^{-1}$

$$S = -\int d^4x \int_{-L}^{L} dy \sqrt{-g}\ \frac{1}{4g_5^2}\left[F^{MN}F_{MN} + 2r_{UV}F^{\mu\nu}F_{\mu\nu}\delta(y) + 2r_{IR}F^{\mu\nu}F_{\mu\nu}\delta(y-L) + 2r_{IR}F^{\mu\nu}F_{\mu\nu}\delta(y+L)\right]$$

Boundary conditions

$$\begin{cases} e^{-2kL}\partial_y f_{n_\pm}(L) = m_{n_\pm}^2 r_{IR} f_{n_\pm}(L) \\ \partial_y f_{n_+}(0) = -m_{n_+}^2 r_{UV} f_{n_+}(0) \\ f_{n_-}(0) = 0 \end{cases}$$

$A_\mu(x,y) = \sum_{n_\pm} A_{\mu,n_\pm}(x)\, f_{n_\pm}(y)$: even(+)/odd(-) under $y \mapsto -y$

$m_{n_\pm}$: mass eigenvalue of each mode

$$\frac{m_{1_+}}{m_{1_-}} \approx \sqrt{1 + \frac{r_{IR}}{r_{UV} + L}} \quad (\text{for } r_{IR} \gg 1/k)$$

1st KK W_μ^3 may be LKP

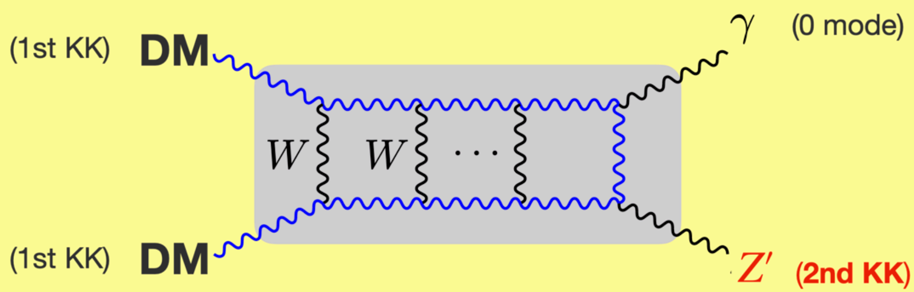
= **SU(2)$_L$ triplet spin-1 DM** (w/ **EW int.**)

$m_{(1st)} \simeq m_{(2nd)}$ **depending on BLTs**

Mass spectrum/Wave func. differ for each setup

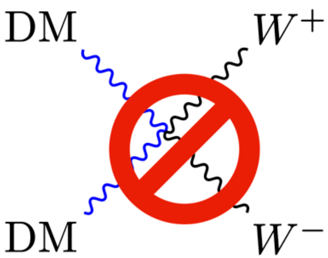
→ DM phenomenology drastically changes

eg. $2m_{(1st)} \gtrsim m_{(2nd)}$, w/o KK # cons.



Abelian Extension with Exchange Symmetry

CAUTION!

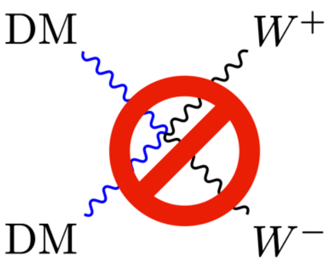


Stable neutral vector CANNOT have Non-Abelian EW couplings

Abelian Extension with Exchange Symmetry(1/2)

We can also construct the Abelian extension spin-1 DM model with exchange symmetry

$$\mathrm{SU}(2)_L \otimes \underbrace{\mathrm{U}(1)_0 \otimes \mathrm{U}(1)_1 \otimes \mathrm{U}(1)_2}_{\text{Exchange Symmetry}}$$



Stable neutral vector CANNOT have Non-Abelian EW couplings

Model

$$\mathcal{L} \supset -\frac{1}{4}(B^0)_{\mu\nu}(B^0)^{\mu\nu} - \frac{1}{4}(B^1)_{\mu\nu}(B^1)^{\mu\nu} - \frac{1}{4}(B^2)_{\mu\nu}(B^2)^{\mu\nu}$$
$$+ \frac{1}{2}\epsilon_{01}\left[(B^0)^{\mu\nu} + (B^2)^{\mu\nu}\right](B^1)^{\mu\nu} + \frac{1}{2}\epsilon_{02}(B^0)_{\mu\nu}(B^2)^{\mu\nu}$$
$$+ (D_\mu\Phi_1)^\dagger(D^\mu\Phi_1) + (D_\mu\Phi_2)^\dagger(D^\mu\Phi_2) + (D_\mu H)^\dagger(D^\mu H)$$
$$- (\text{Scalar Potential})$$

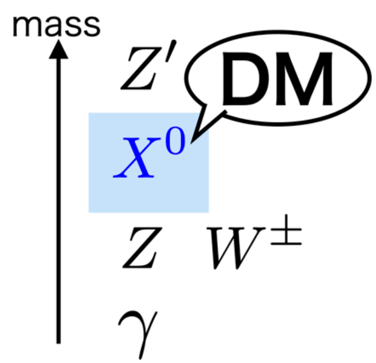
※ We have kinetic mixing terms(2nd line) in this Abelian extension model

field	spin	$\mathrm{SU}(3)_C$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_0$	$\mathrm{U}(1)_1$	$\mathrm{U}(1)_2$
q_L	$\frac{1}{2}$	3	2	0	$\frac{1}{6}$	0
u_R	$\frac{1}{2}$	3	1	0	$\frac{2}{3}$	0
d_R	$\frac{1}{2}$	3	1	0	$-\frac{1}{3}$	0
ℓ_L	$\frac{1}{2}$	1	2	0	$-\frac{1}{2}$	0
e_R	$\frac{1}{2}$	1	1	0	-1	0
H	0	1	2	0	$\frac{1}{2}$	0
Φ_1	0	1	1	y_1^0	y_1^1	0
Φ_2	0	1	1	0	y_1^1	y_1^0
			W_μ^a	B_μ^0	B_μ^1	B_μ^2

Spectrum

$$\boxed{X^0 = \frac{B_\mu^0 - B_\mu^2}{\sqrt{2}}}$$

(Z₂-odd neutral vector)



Abelian Extension with Exchange Symmetry(2/2)

NOTE: **Exchange symmetry forbids X^0 to have EW interactions**

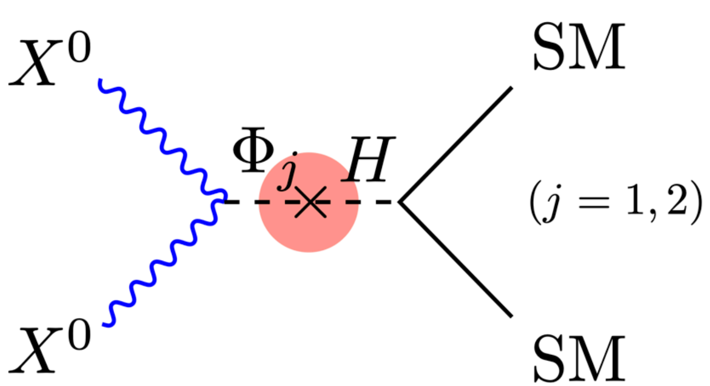
- X^0 do not appear in the $SU(2)_L$ neutral vector state

$$W^3_\mu = \# A_\mu + \# Z_\mu + \# Z'_\mu \longleftarrow \textbf{No } X^0 \textbf{ states}$$

- X^0 do not mix with the other neutral vectors(Z_2-even) even through the kinetic mixing terms

$$\mathcal{L}_{\text{kinetic}} = \frac{\epsilon_{02}}{4} X_{\mu\nu} X^{\mu\nu} + (\text{mixing btw } Z_2\text{-even vectors})$$

$$X_{\mu\nu} = \partial_\mu X^0_\nu - \partial_\nu X^0_\mu$$



DM relies on the Higgs mixing in the annihilation process

→ **Strict bound from direct detection**

(That is why we choose the non-Abelian extension approach!)