Electroweak Vector Dark Matter

Motoko Fujiwara

University of Tokyo → **Technische Universität München** (Oct. 2022-)

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, JHEP 10 (2021) 163 [arXiv:2107.10029]
T. Abe, MF, J. Hisano (work in progress)

東京大学 THE UNIVERSITY OF TOKYO → TUM

Direct & Indirect Detection of DM
@MPI für Kernphysik Heidelberg
Sep. 14, 2022

Today's Talk

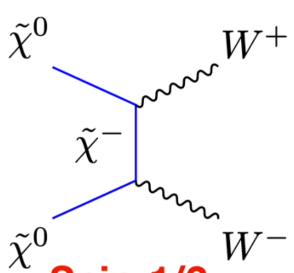
We study annihilation processes of Electroweakly interacting Spin-1 Dark Matter (DM)

(1) Construct renormalizable model of EW int. spin-1 DM

(2) Derive a non-relativistic effective theory for spin-1 DM

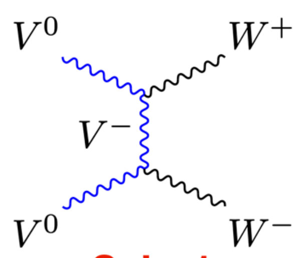
(3) Apply the effective theory to obtain predictions

- Evaluate thermal relic density of DM (Ωh^2)
- Reveal detectability of Monochromatic γ-ray signatures



Spin-1/2

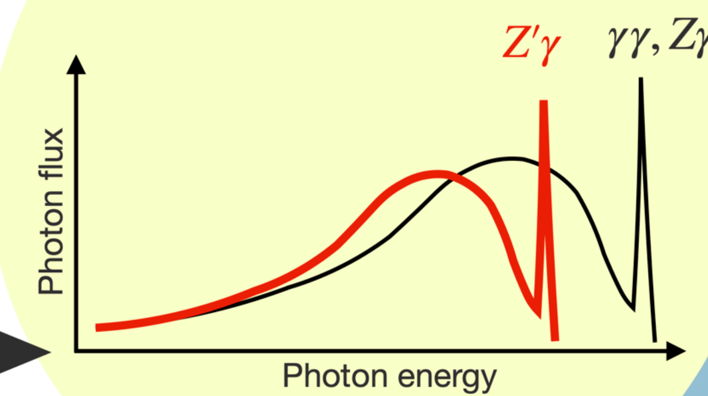
VS



Spin-1

- Quantitative: **Annihilation cross section & DM mass may be separable within experimental sensitivity**
- Qualitative: **Double peak spectrum is predicted**

We can reconstruct Mass spectrum!

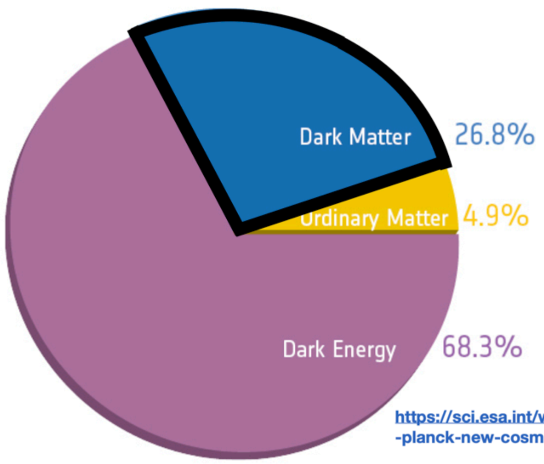


Dark matter

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



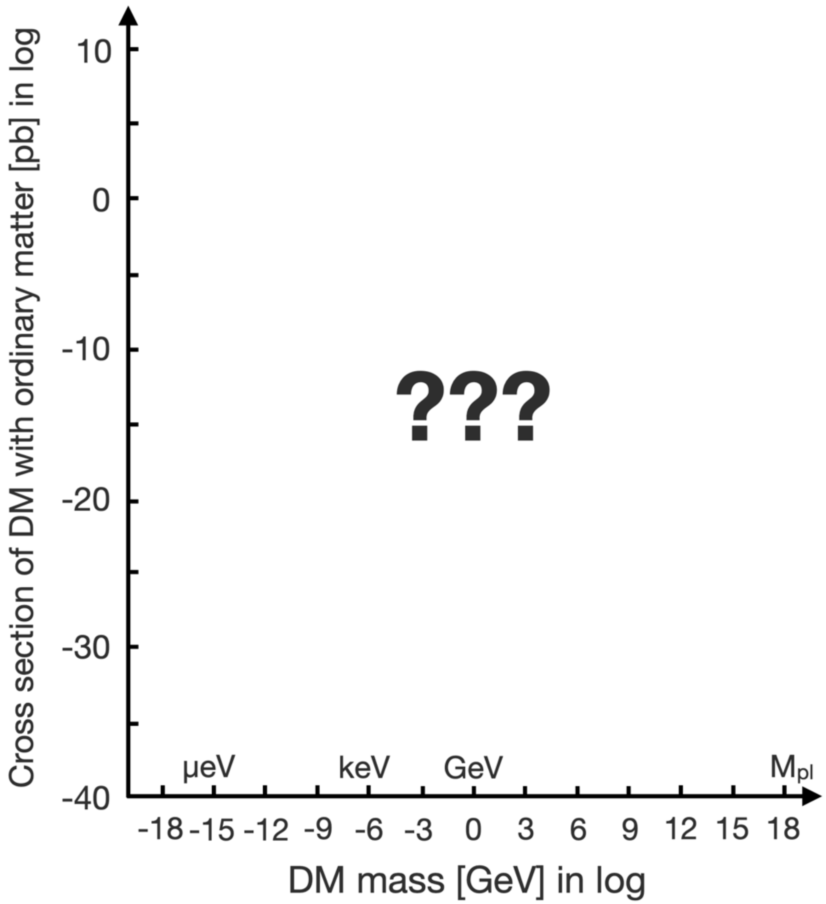
https://sci.esa.int/web/planck/-/51557-planck-new-cosmic-recipe

DM candidate?

Many possibilities for DM mass/interaction

Goal: **Identification of DM**

→ a window to probe new physics!



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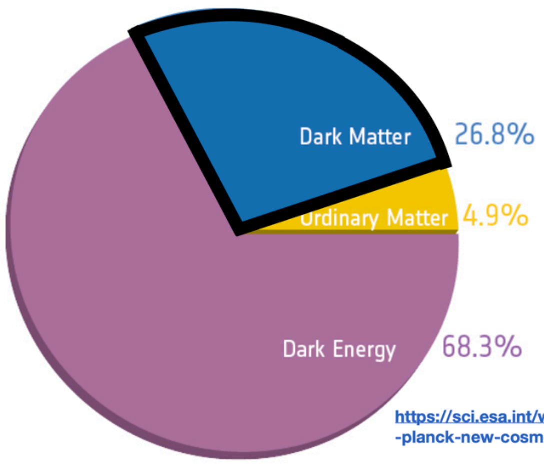

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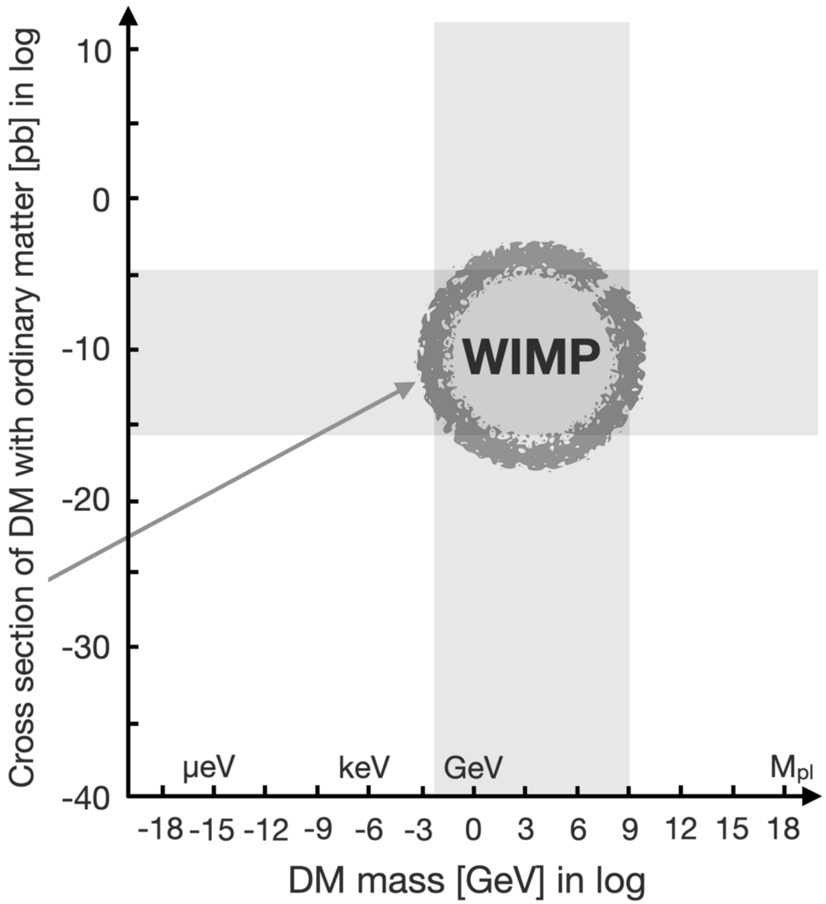
Weakly Interacting Massive Particle

- 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

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

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

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Today's topic: **EW interacting Spin-1** DM

Motivation: To construct a benchmark model of **EW int. Spin-1** DM for DM spin discrimination (eg. vs Wino DM candidate = **$SU(2)_L$ triplet**, **Spin-1/2** DM)

Hint: DM 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 = **$SU(2)_L$ triplet**, **Spin-1** DM

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$$\left[\begin{aligned}\langle\sigma_{\mathrm{ann}}v\rangle &\sim 3\times10^{-26}\ \mathrm{cm}^3/\mathrm{s}\\ &\simeq \frac{\alpha_{\mathrm{DM}}^2}{m_{\mathrm{DM}}^2}\ \begin{cases}\alpha_{\mathrm{DM}}\sim\alpha_2\\ m_{\mathrm{DM}}\sim\mathcal{O}(1)\ \mathrm{TeV}\end{cases}\end{aligned}\right]$$

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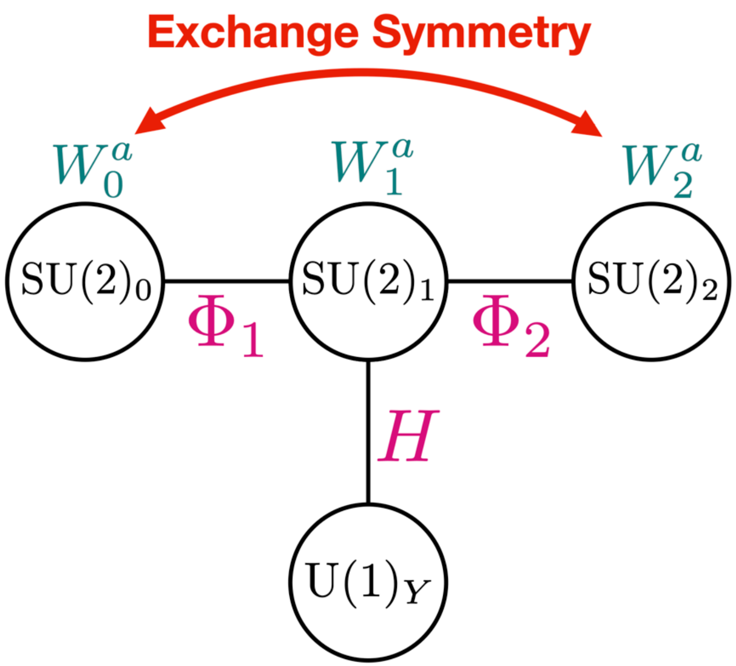
Our work: **Spontaneously broken gauge symmetry w/ exchange symmetry**

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

→ **Stable Spin-1 spectrum in renormalizable setup** (next page)

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)]

Scalar field definition

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

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

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

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.

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

※ $g_0 = g_2$ ($\neq g_1$)

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

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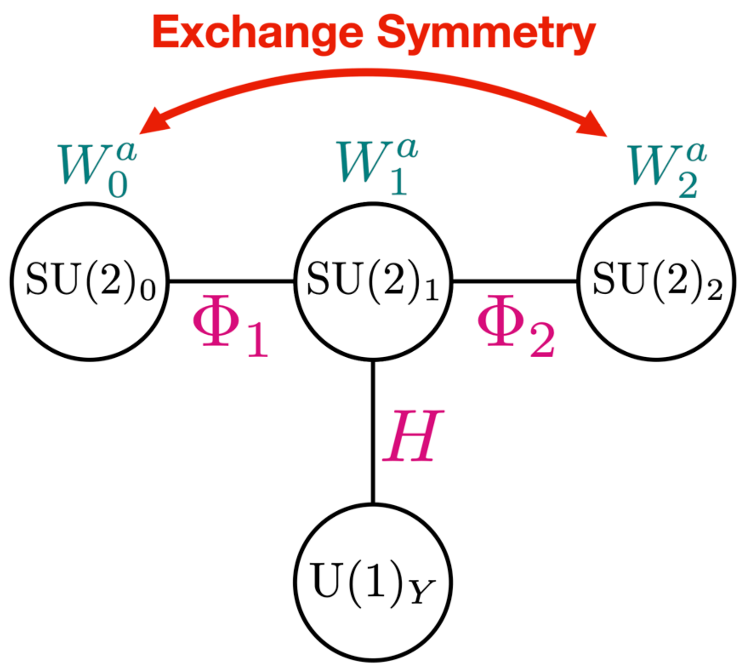

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- VEVs of Scalar fields break symm. into $\mathrm{U}(1)_{em}$

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

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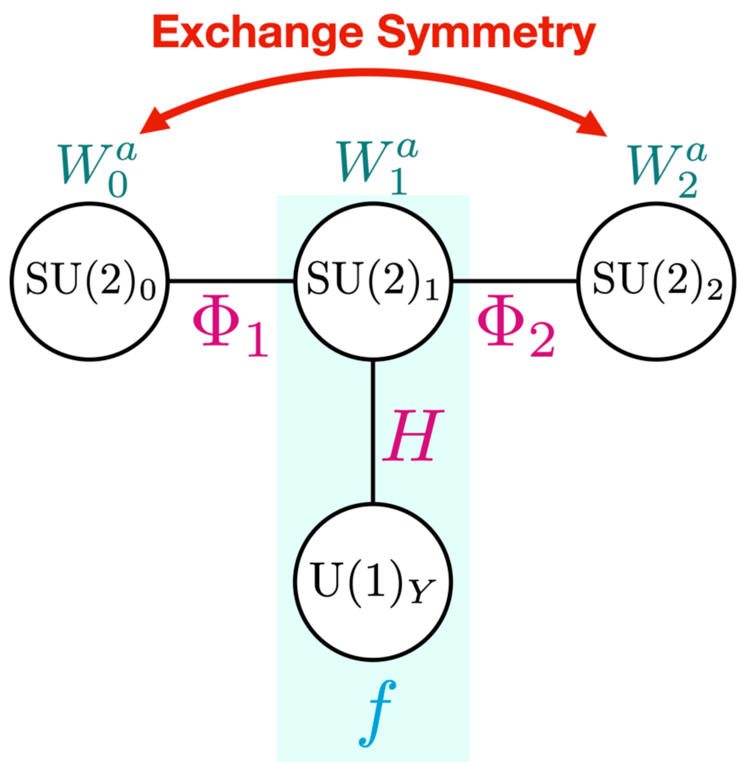

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- Fermion fields are only charged for $\mathrm{SU}(2)_1 \times \mathrm{U}(1)_Y$
  - Each field corresponds to the SM fermions
  - Nothing to do w/ exchange symmetry

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Spectrum

Z_2 **parity for physical spectrum** ↔ **exchange symmetry**

Energy	Vector	Scalar	Z_2 parity	Mass
2-mode	Z' $W'^{\pm}$	h'	**even**	$\sim v_\Phi$ $\mathcal{O}(1)$ TeV
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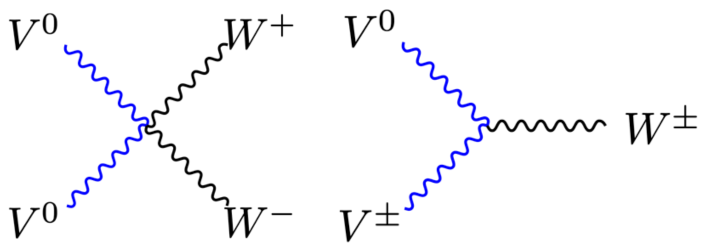
- Z_2-odd vectors ($V^0, V^\pm$) → **"V-particle"** $\simeq$ **SU(2)$_L$ triplet**
  - Non-abelian vector couplings
    → EW int. dominates phenomenology
  - Mass spectrum
    → V^0 is slightly lighter than $V^\pm$ due to the electroweak radiative corrections
    If we assume $m_V < m_{h_D}$, V^0 is the lightest Z_2-odd particle (= **EW interacting Spin-1 DM**)



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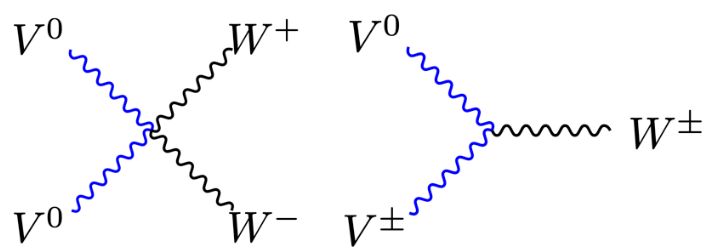

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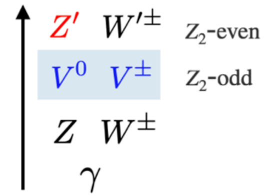
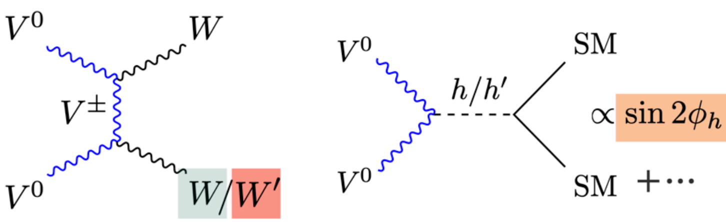
- Z_2**-even additional vectors (Z', W') also exist → Significant roles in DM phenomenology**

Directions for DM Search

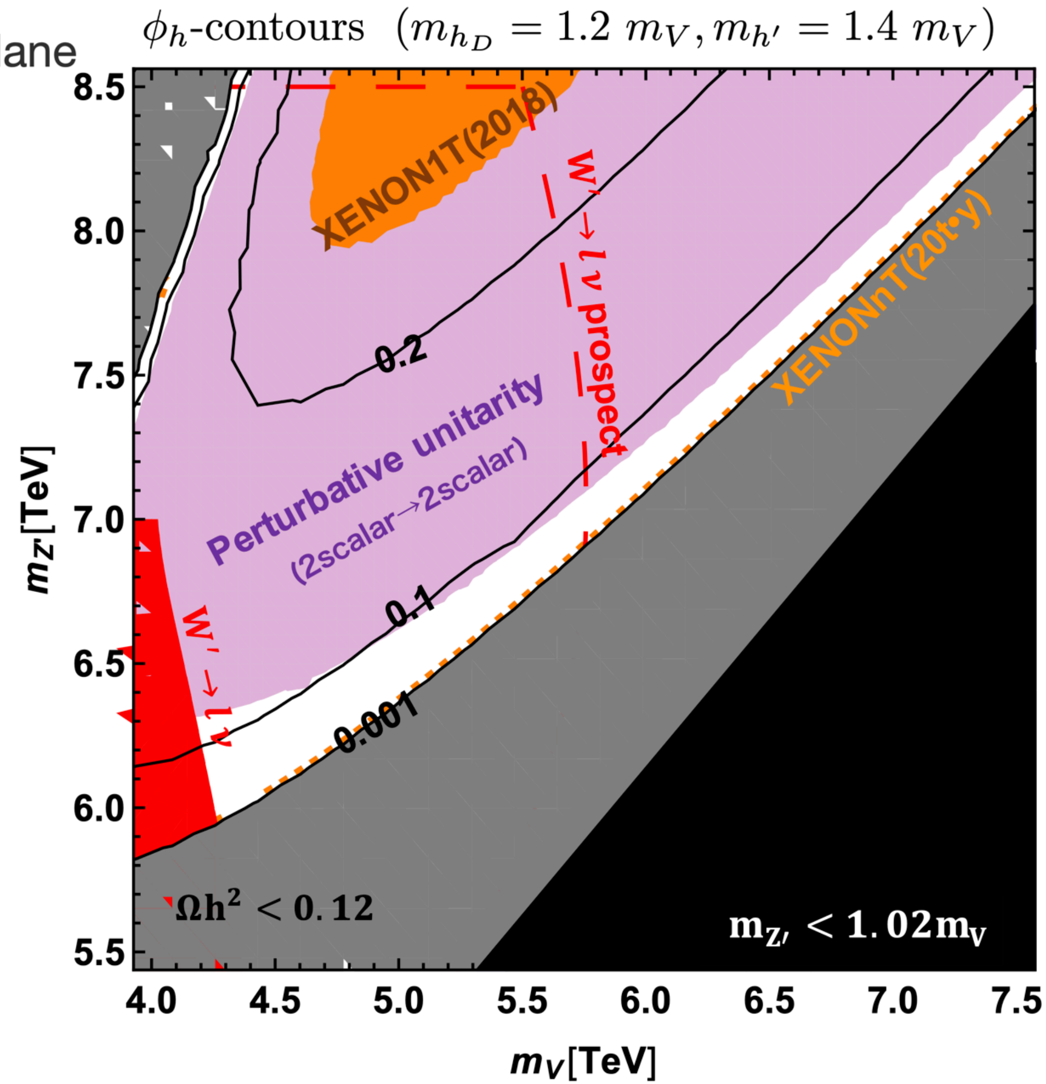


- Higgs mixing (ϕ_h) contours in m_V-$m_{Z'}$ plane

  (ϕ_h : fixed to realize $\Omega h^2 = 0.12$ (@tree-level))



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



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

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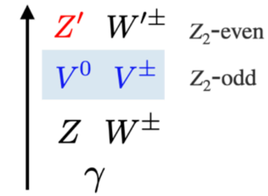

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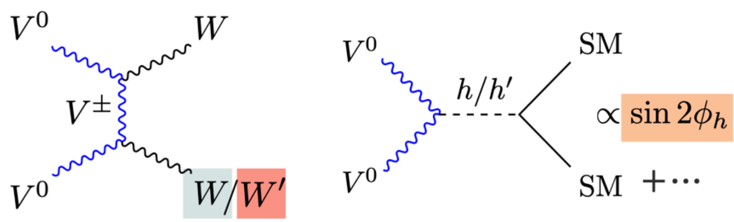
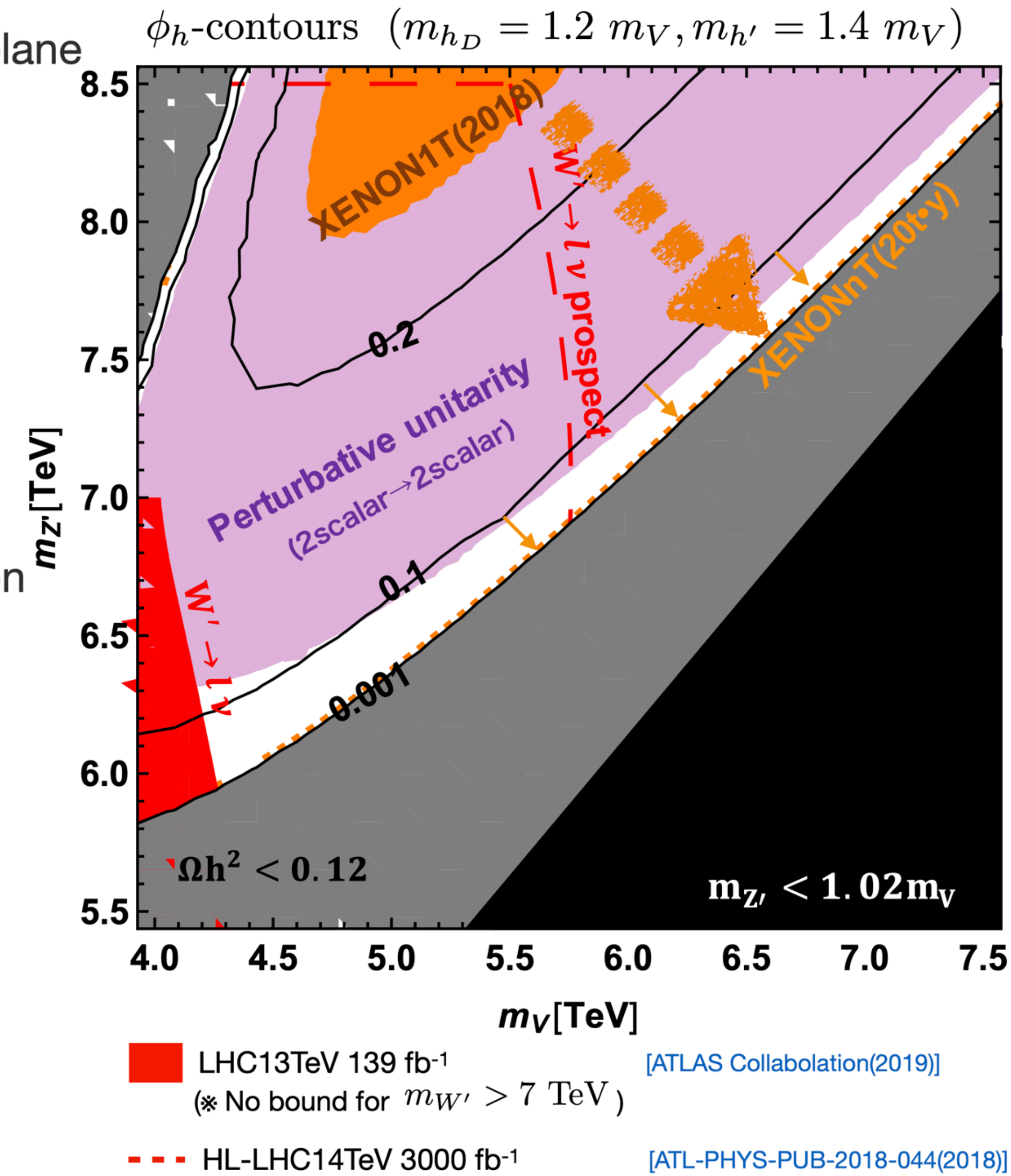


EW int. + Z'/W' + **Higgs sector**

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



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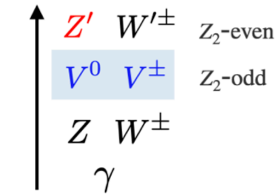

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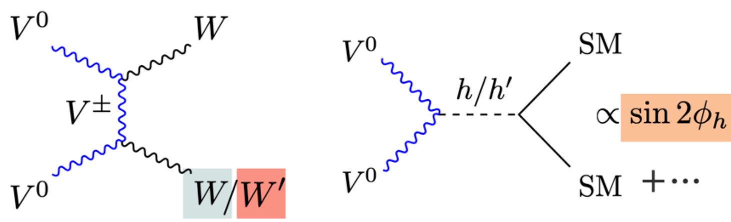

EW int. + Z'/W' + **Higgs sector**

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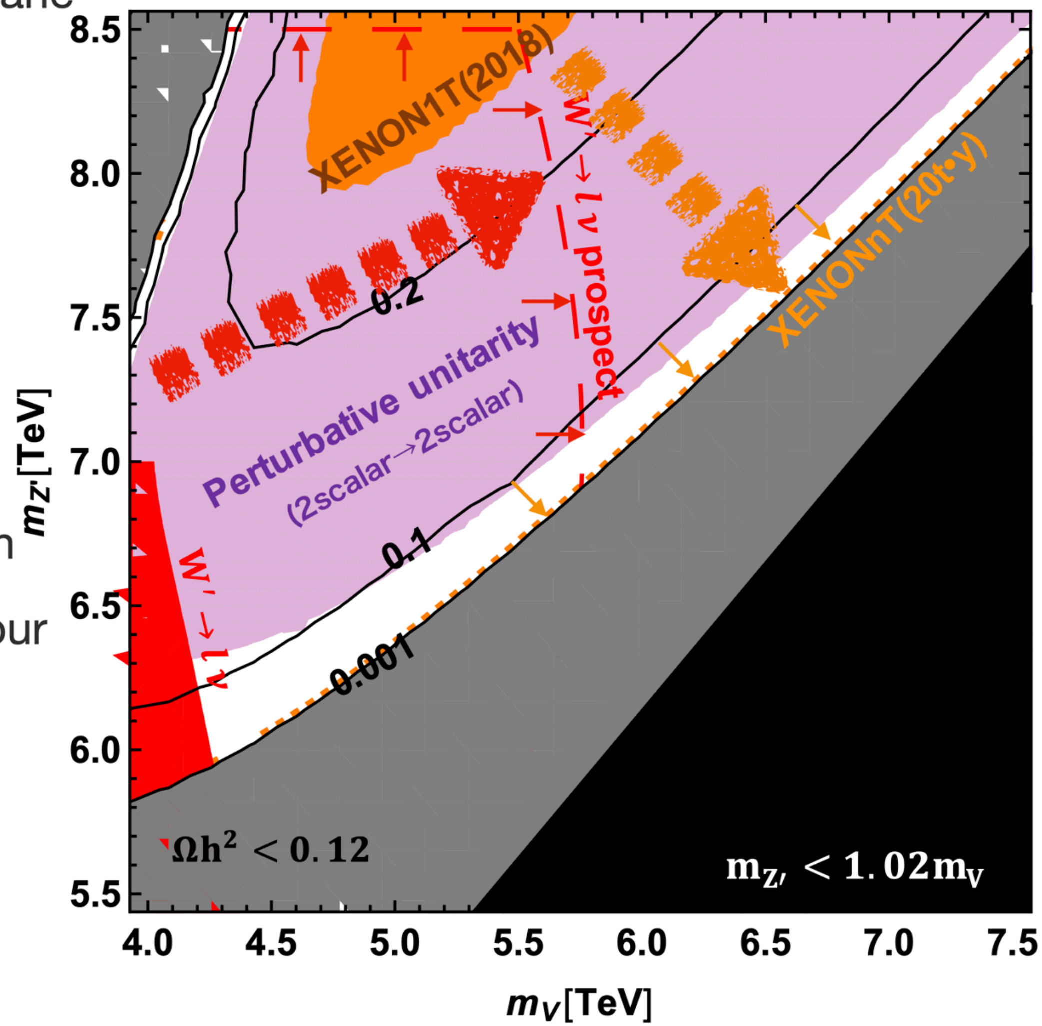
→ **HL-LHC** further probe thermal contour

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



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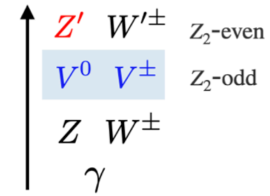

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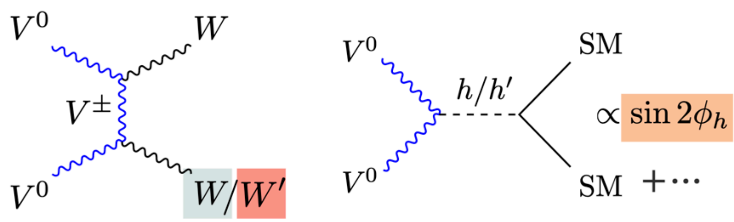

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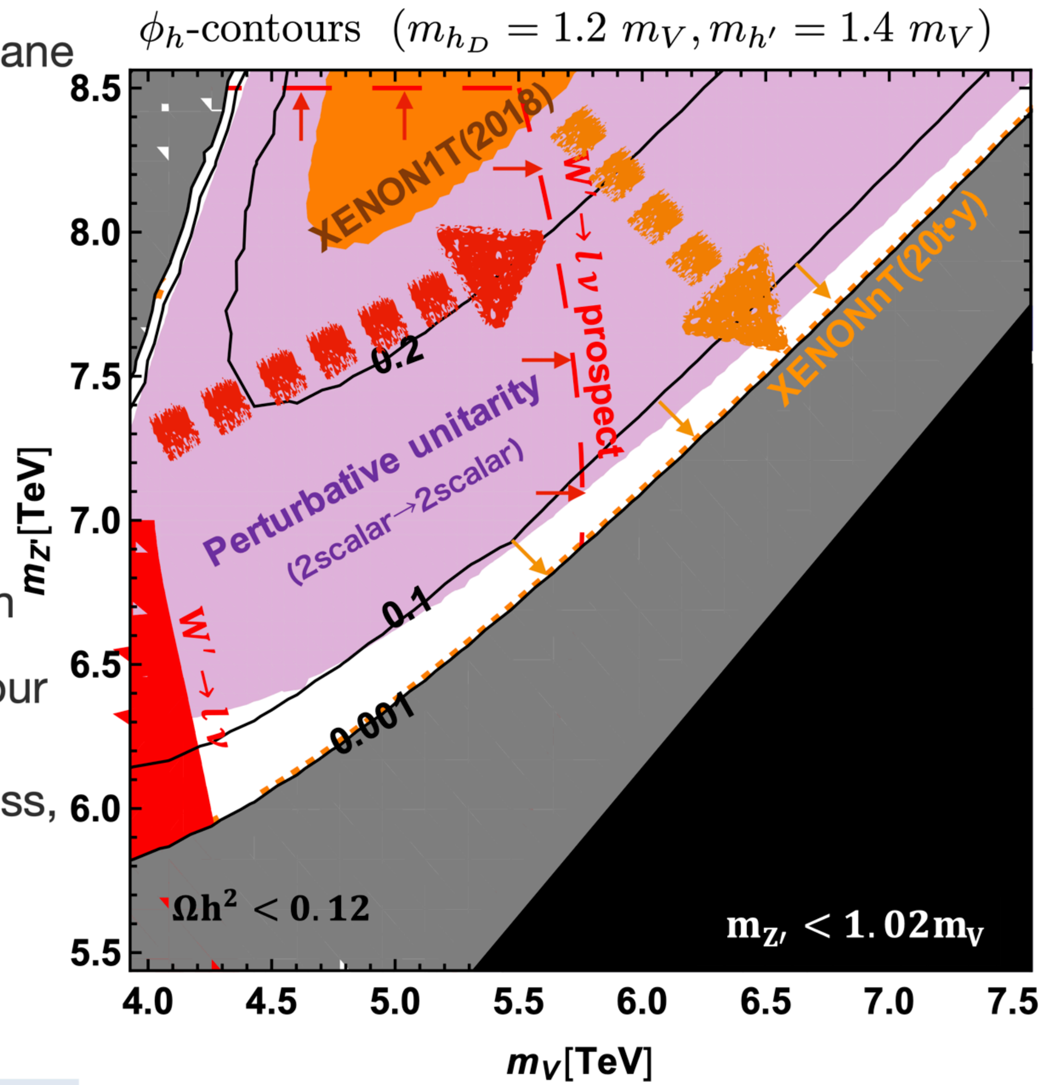
- For $m_V \simeq \mathcal{O}(1)$ TeV annihilation process,
  Sommerfeld effects should be viable

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



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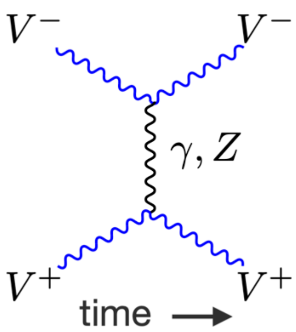
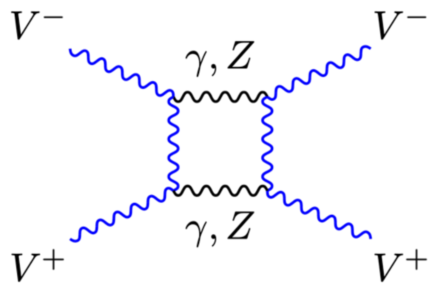
EFT of Spin-1 DM w/ EW int.





Full theory

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

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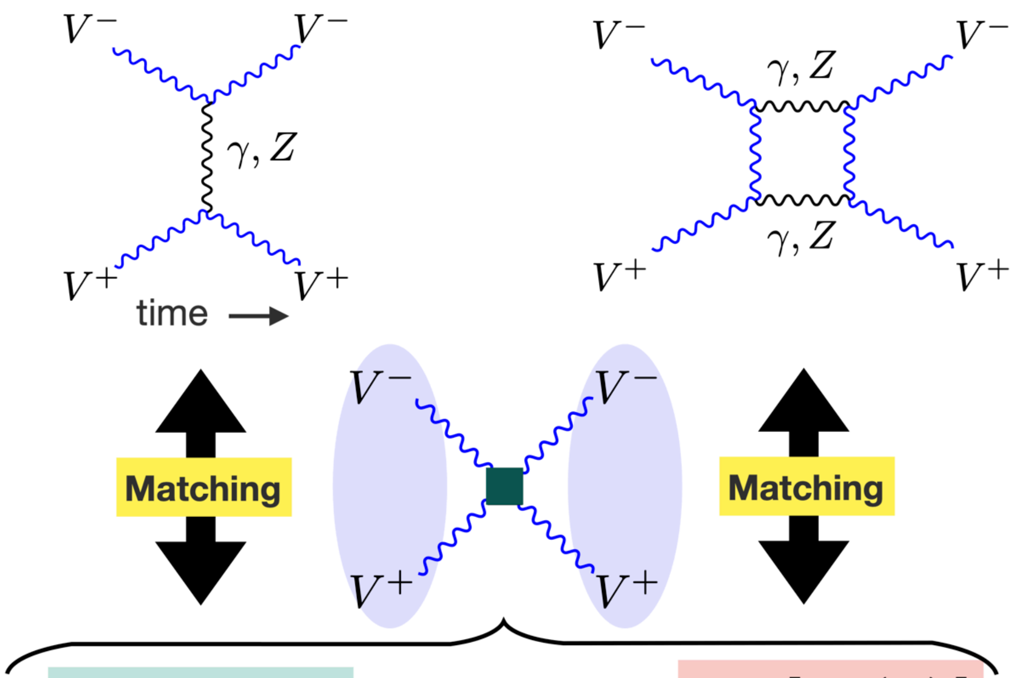


$$\mathrm{Re}[V(r)] \quad + \quad i\,\mathrm{Im}[V(r)]$$

Full theory

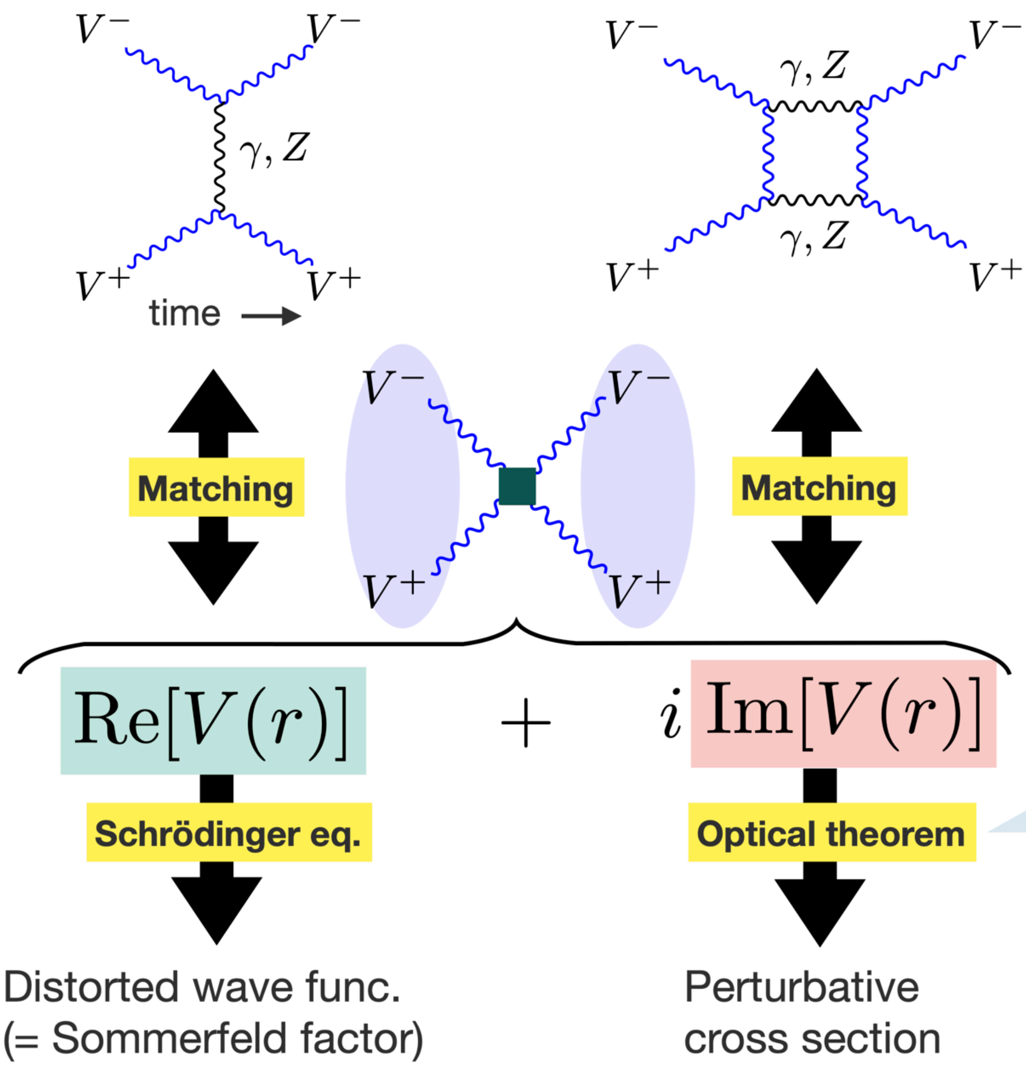
Dynamical fields = { $V^0, V^\pm, W^\pm, Z, \gamma$ }

Effective Theory

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

w/ Coulomb or Yukawa potential

EFT of Spin-1 DM w/ EW int.



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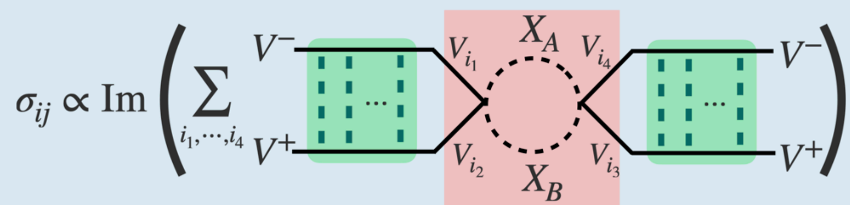
cf. Diagrammatic formula for annihilation cross section



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

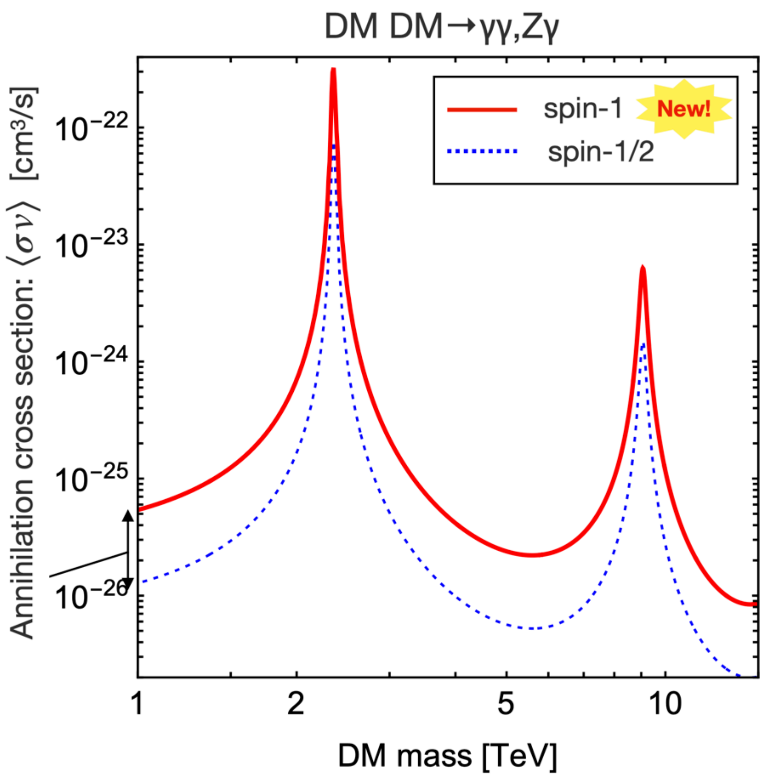
Thermal Relic Evaluation

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

Cross section

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

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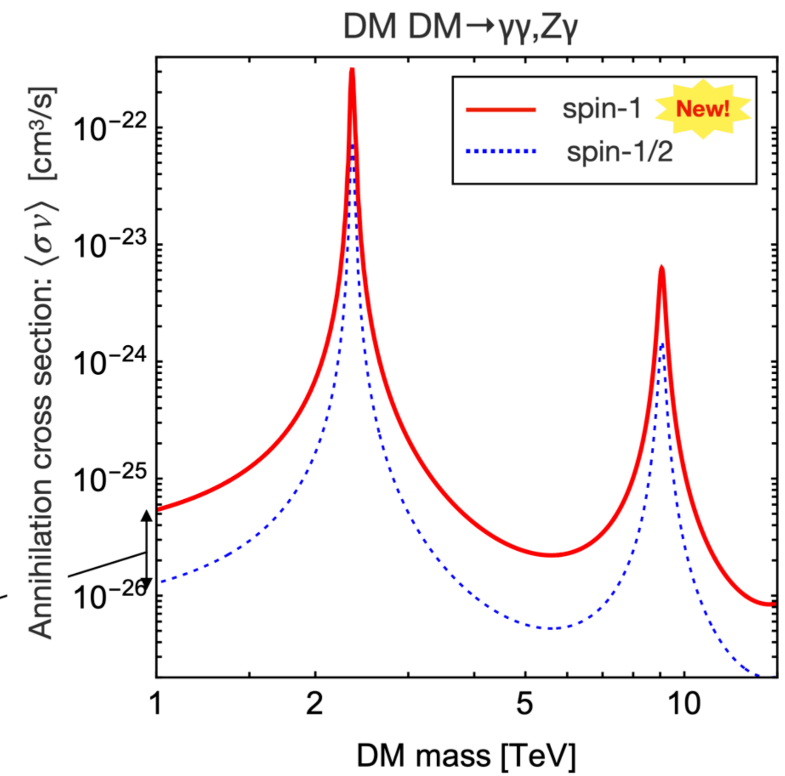

Thermal relic evaluation (leading order)

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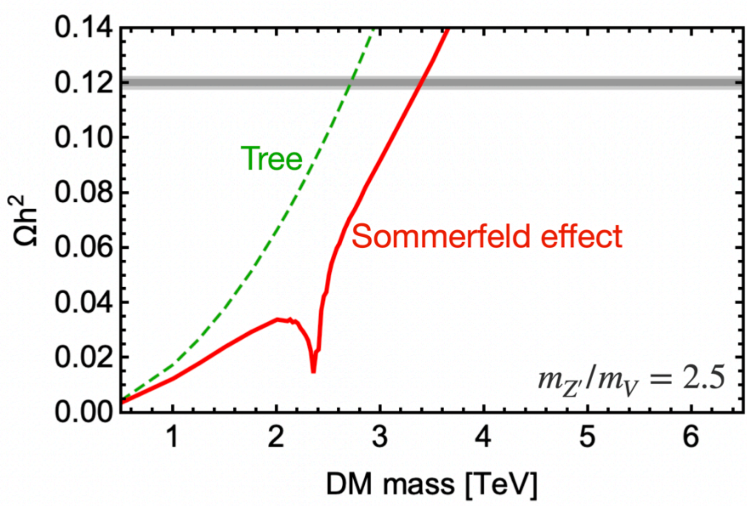

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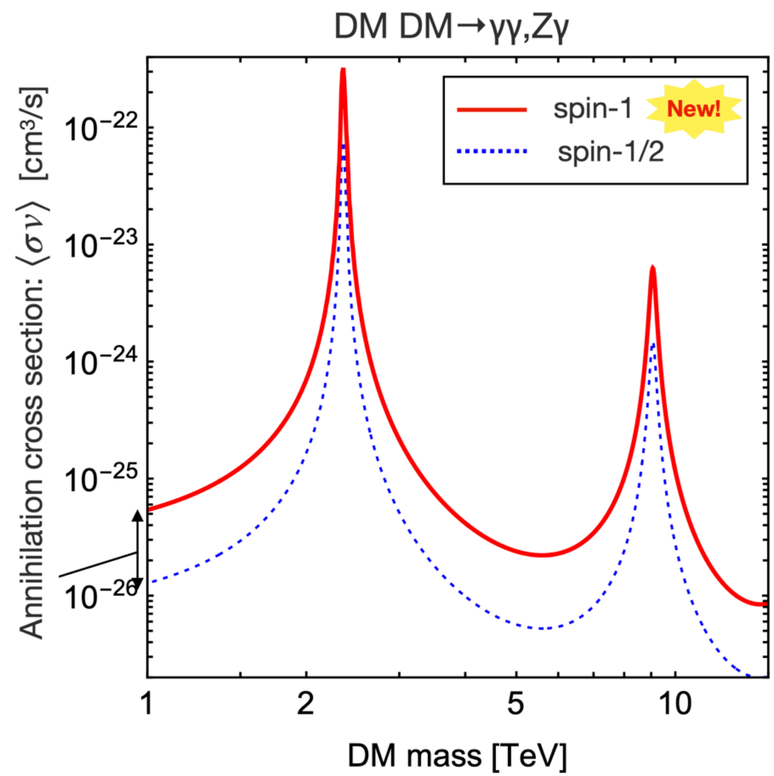
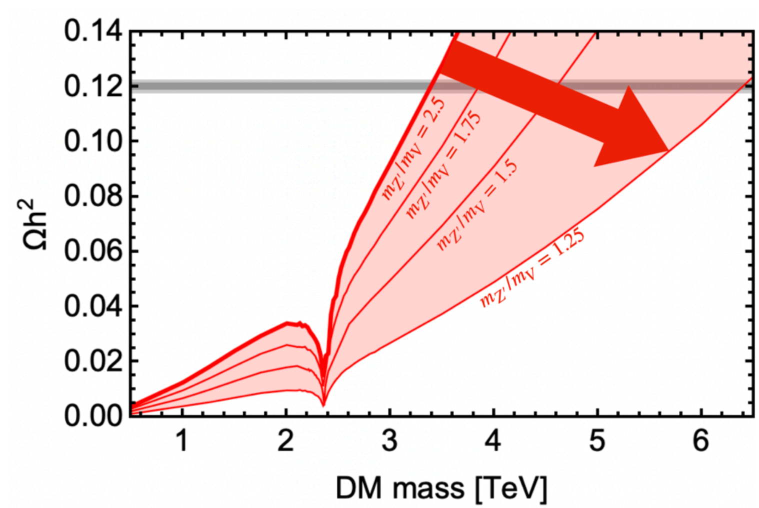


Thermal relic evaluation (leading order)

- 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

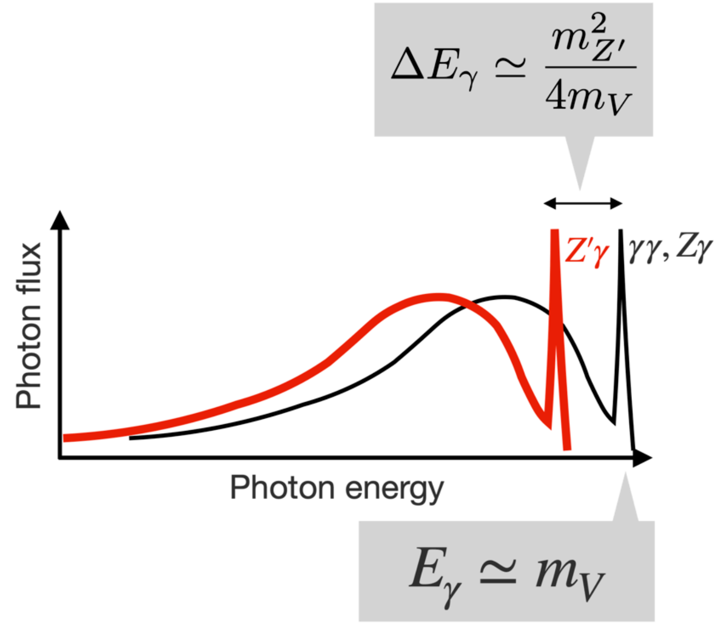


Monochromatic γ-ray Search

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



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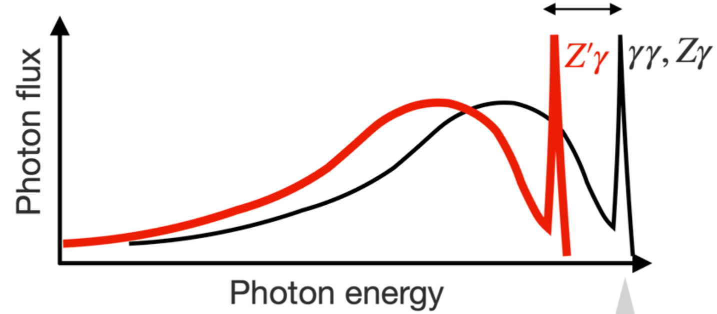
  - $\gamma\gamma, Z\gamma$ modes
  - $Z'\gamma$ mode

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

- 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)]

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



$$E_\gamma \simeq m_V$$

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

- 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, $\times 10$)]
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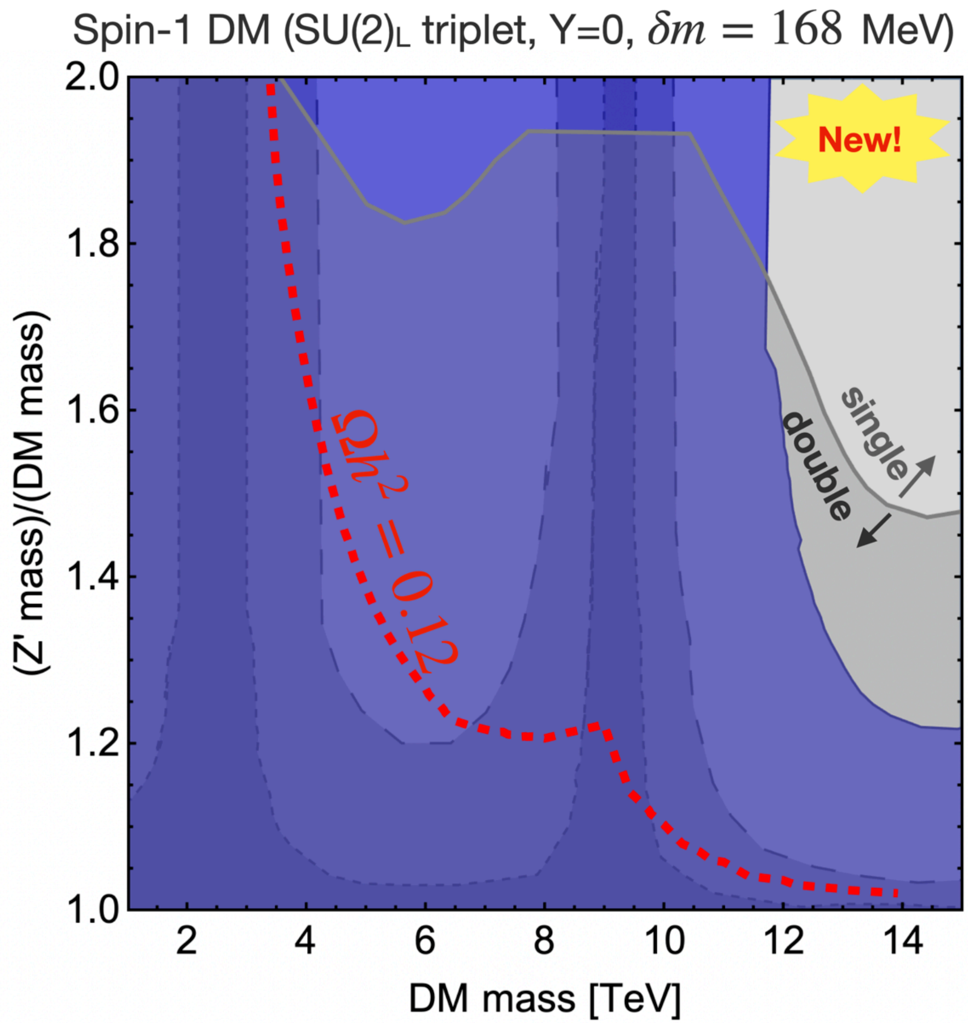
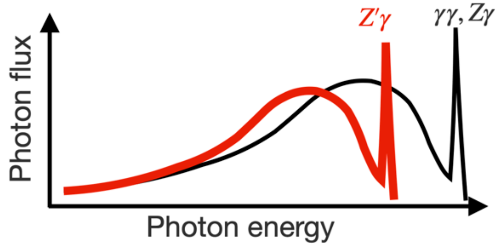
- Prospect [A. Acharyya, et al (2021)]
  Cherenkov Telescope Array (CTA)
  - Single peak, Einasto [cored, $r_c = 5$ kpc]
  - Double peak, Einasto [cored, $r_c = 5$ kpc]

[Preliminary]





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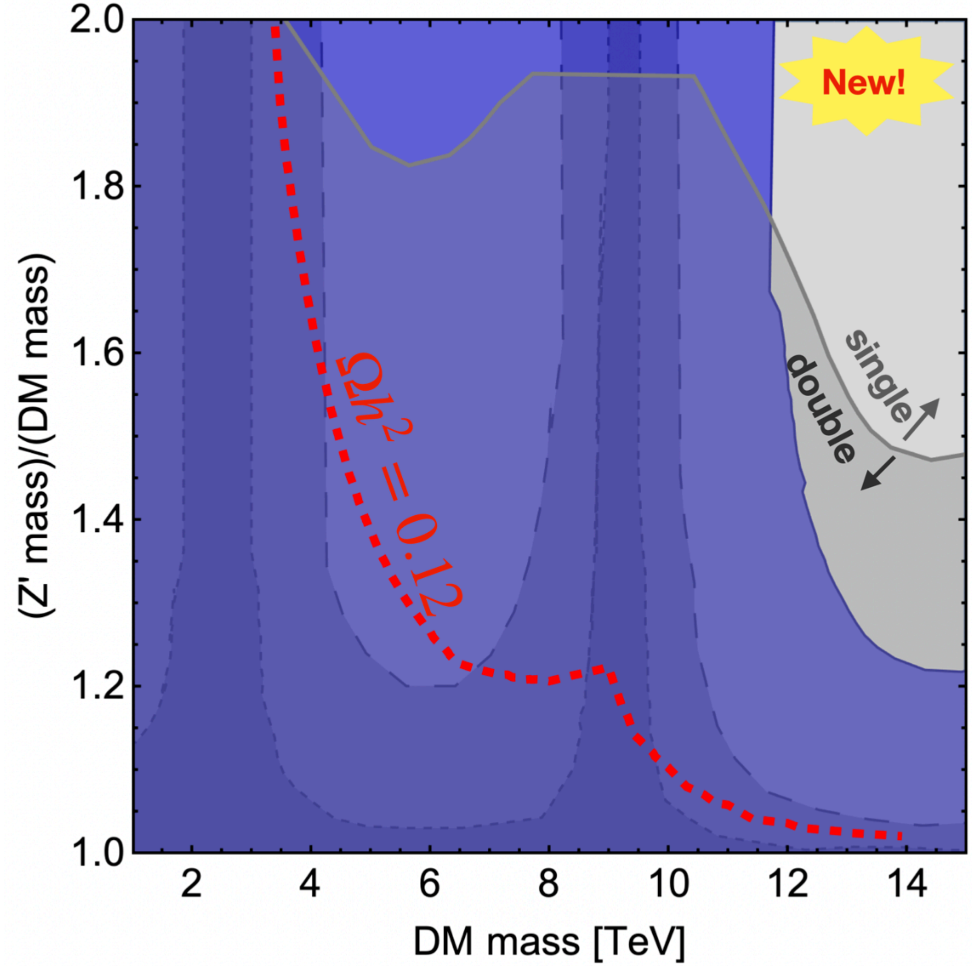
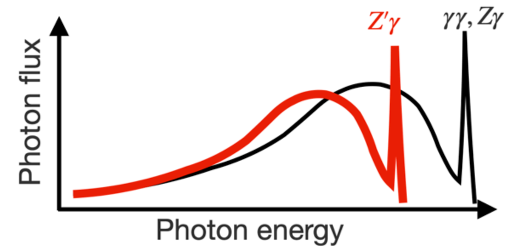
Spin-1 DM ($SU(2)_L$ triplet, Y=0, $\delta m = 168$ MeV)



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)**

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

(2) EFT construction:

- Annihilation process including Sommerfeld effects

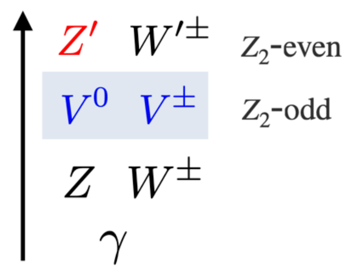
(3) Application of EFT:

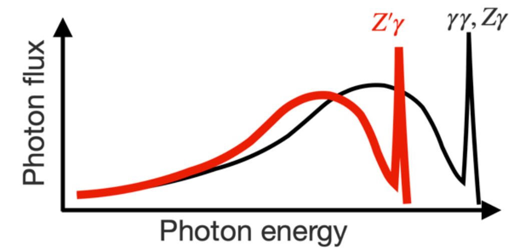
-Ωh^2=0.12 → **Relation btw DM mass & Z' mass**

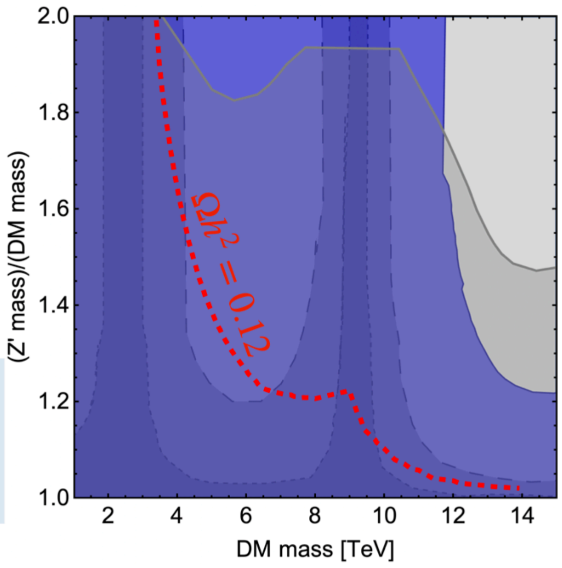
-Line γ-ray → **Double peak from γX ($X = \gamma, Z, Z'$) in CTA**

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

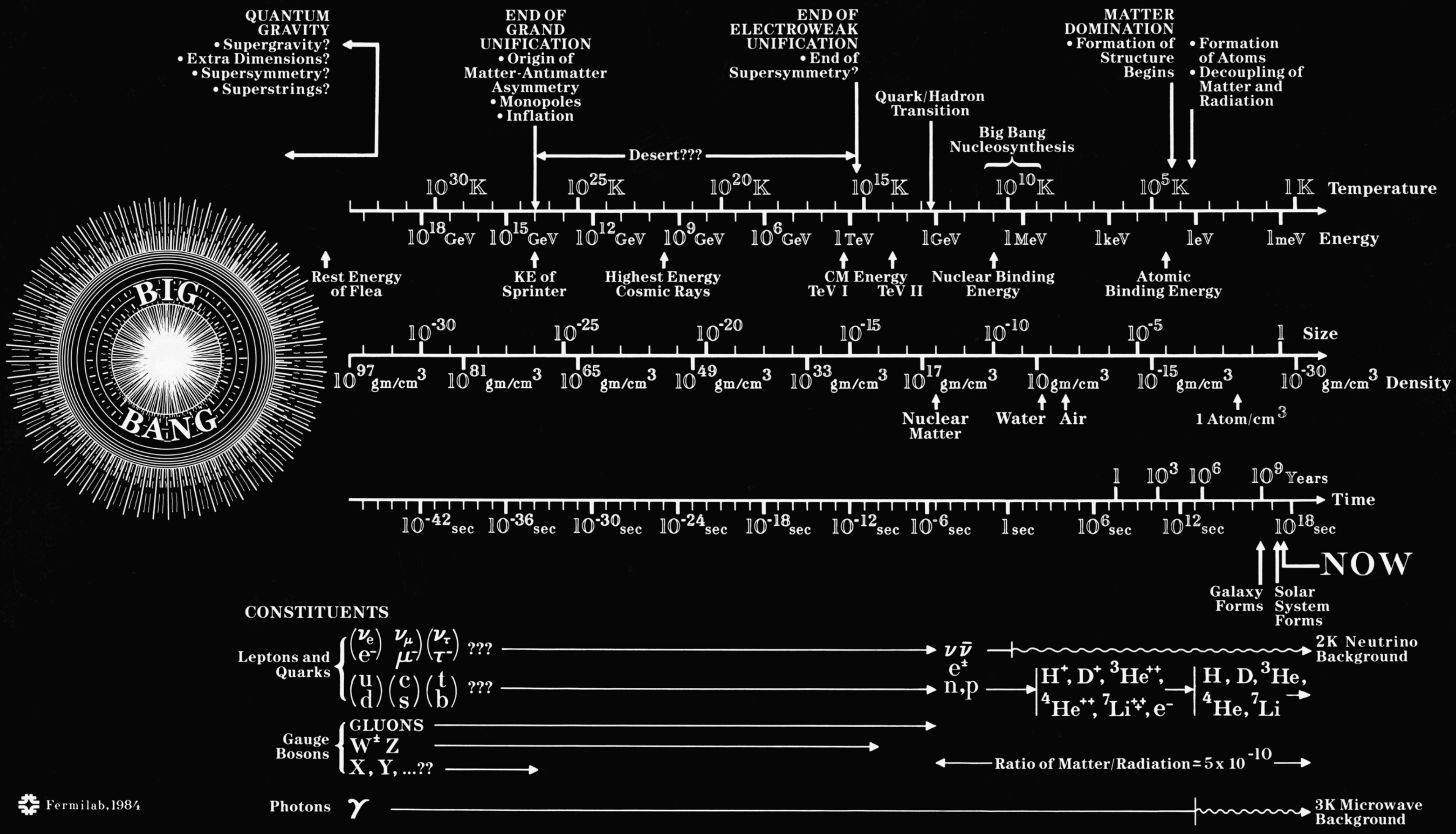
Spin-1 Spectrum







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 10 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
$\begin{pmatrix}\nu_e\\e^-\end{pmatrix}\begin{pmatrix}\nu_\mu\\\mu^-\end{pmatrix}\begin{pmatrix}\nu_\tau\\\tau^-\end{pmatrix}$???
$\begin{pmatrix}u\\d\end{pmatrix}\begin{pmatrix}c\\s\end{pmatrix}\begin{pmatrix}t\\b\end{pmatrix}$???
$\nu\bar{\nu}$
$e^\pm$
n,p
2K Neutrino Background
$H^+, D^+, {}^3He^{++}, {}^4He^{++}, {}^7Li^{+++}, e^-$
$H, D, {}^3He, {}^4He, {}^7Li$
Gauge Bosons
GLUONS
$W^\pm$ Z
X, Y, ...??
Ratio of Matter/Radiation ≈ 5 x 10^{-10}
Photons γ
3K Microwave Background
Fermilab, 1984

Result

- Theoretical prediction vs exp. upper bound on cross section for photon

  → Constraint on theoretical parameters $\{ m_V, m_{Z'} \}$

  [Uncertainty from DM profiles is shown by taking various choices of profile]

  - **Current bound**

    High Energy Stereoscopic System (H.E.S.S.) [H. Abdallah et al. (2018)]

    Einasto2 [Cusped]

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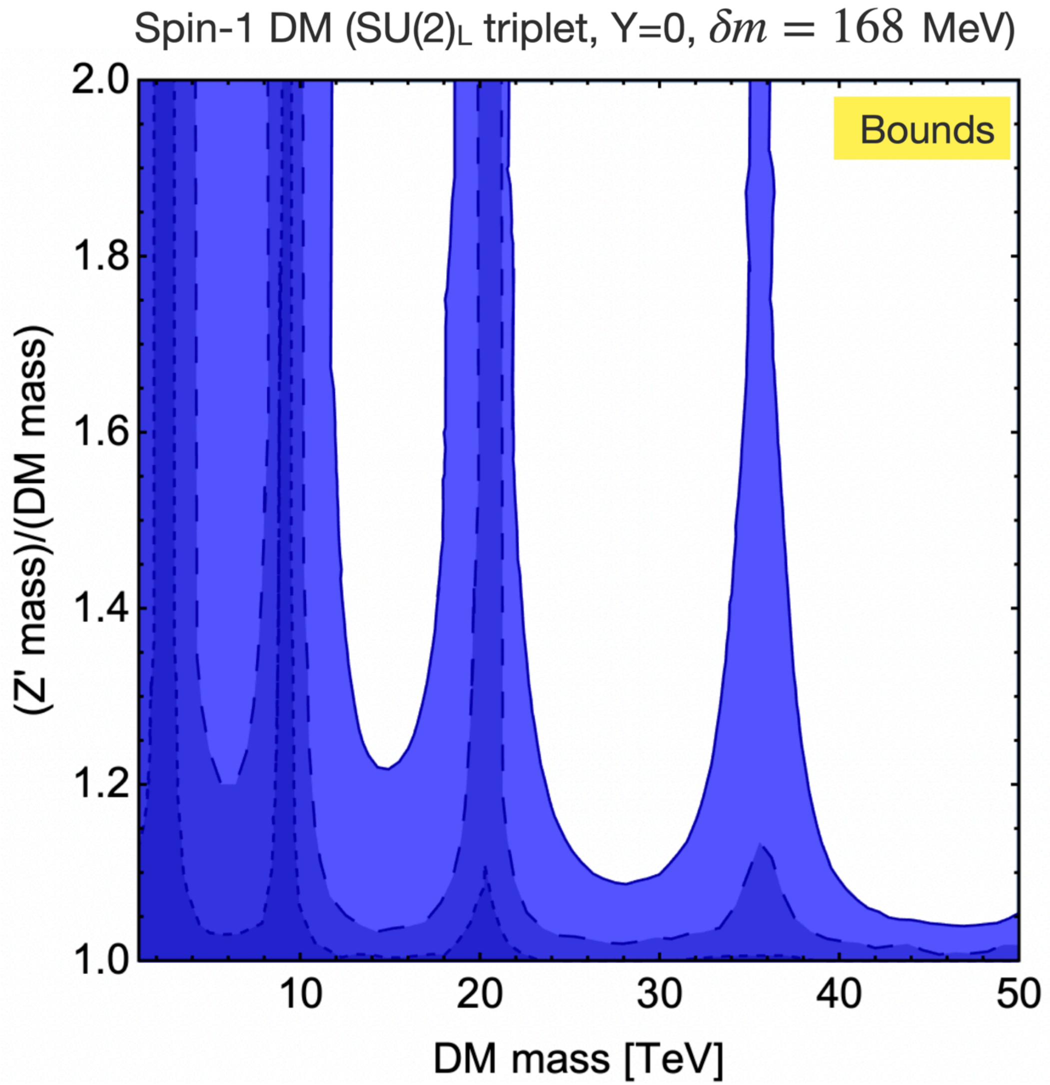

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- **Prospect**

  Cherenkov Telescope Array (CTA) [A. Acharyya, et al (2021)]

  Single peak, Einasto [cored, $r_c = 5$ kpc]

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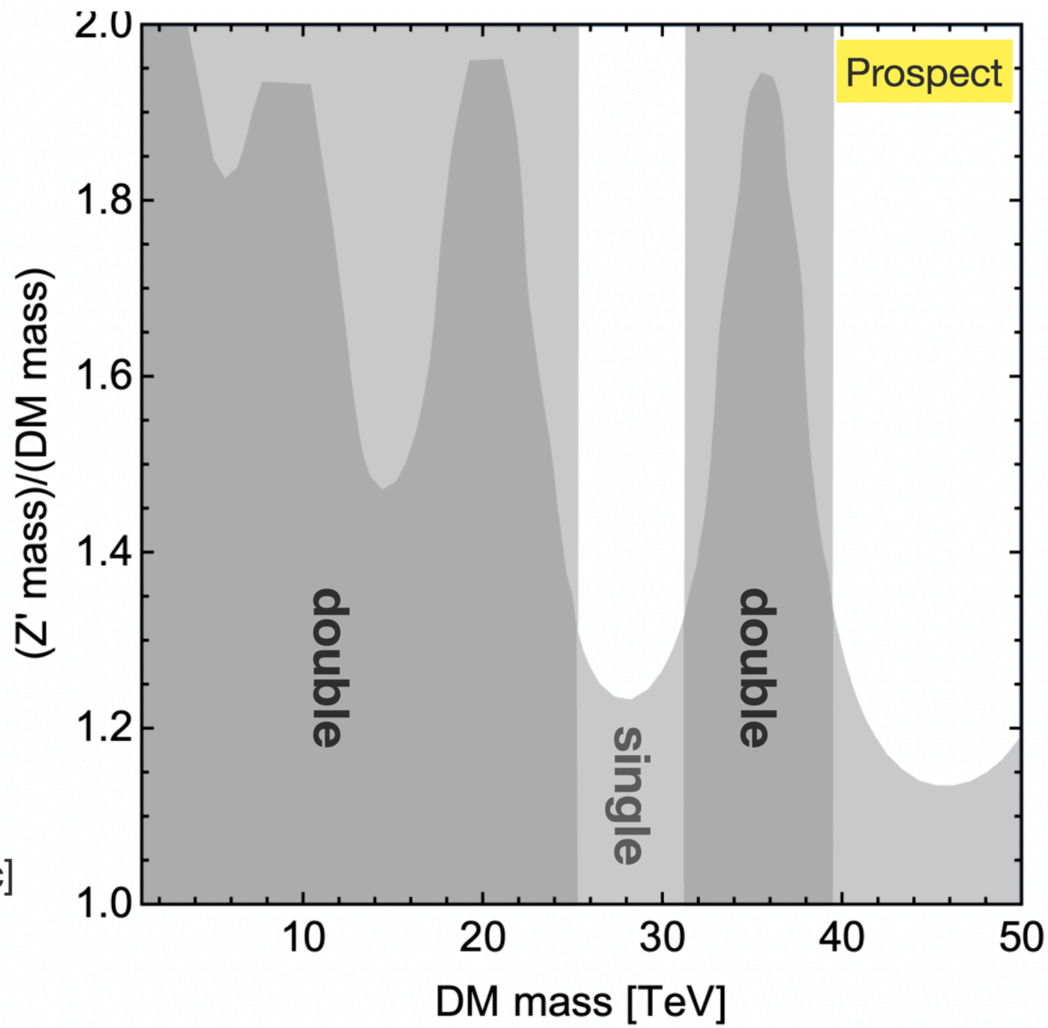
Spin-1 DM ($SU(2)_L$ triplet, Y=0, $\delta m = 168$ MeV)



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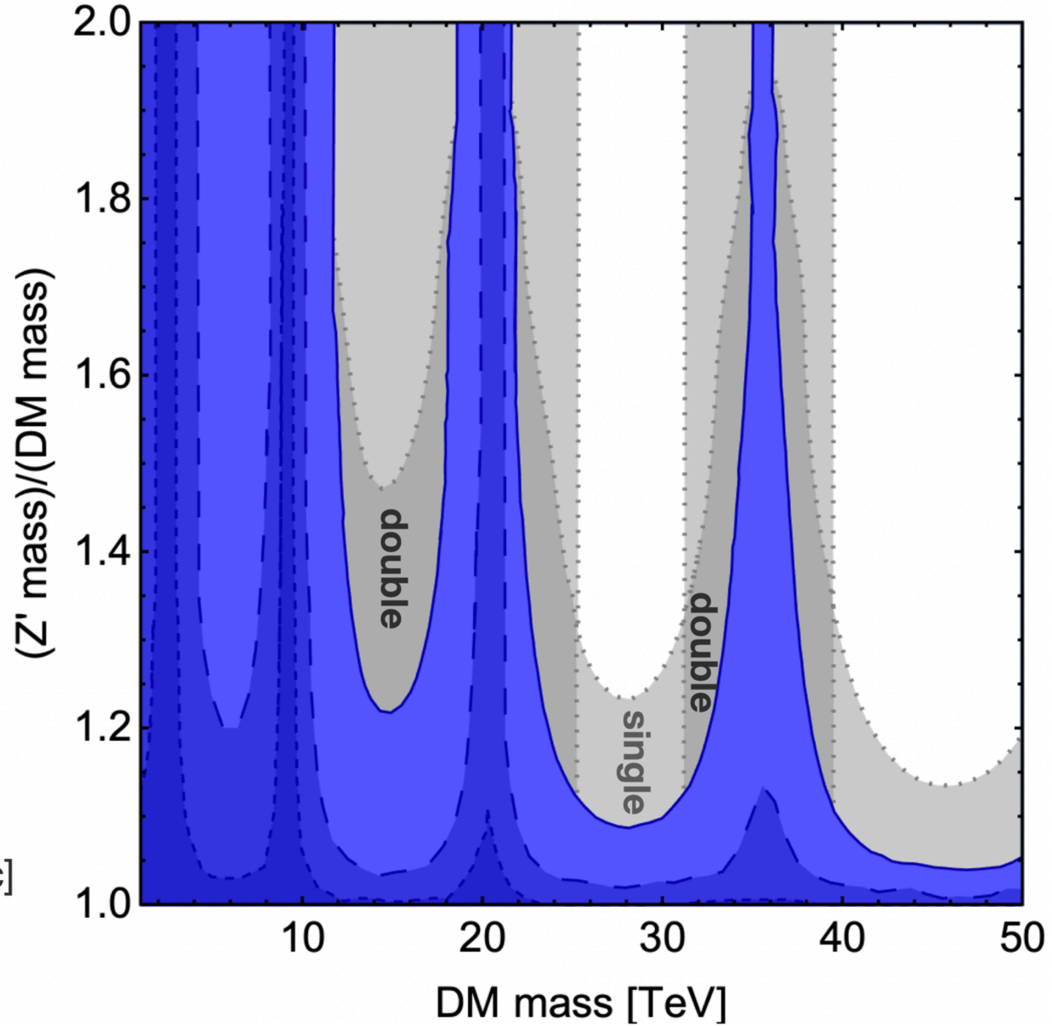


Effective Action (eg. $Q=0$ states)

$$S_{\text{eff}} = \sum_{J,J_z} \int d^4R d^3r\ \Phi^{J,J_z\dagger}(R,\boldsymbol{r}) \cdot \left[\left(i\partial_{R^0} + \frac{\nabla_R^2}{4m_V} + \frac{\nabla_r^2}{m_V} \right) - \hat{V}(r) + i\frac{9}{2}\hat{\Gamma}^J \delta^3(\boldsymbol{r}) \right] \cdot \Phi^{J,J_z}(R,\boldsymbol{r})$$

- $Q=0$ two-body states: $\Phi^{J,J_z}(R,\boldsymbol{r}) = \begin{pmatrix} \phi_C^{J,J_z}(R,\boldsymbol{r}) \\ \phi_N^{J,J_z}(R,\boldsymbol{r}) \end{pmatrix} \begin{array}{l} \leftarrow V^-V^+ \\ \leftarrow V^0V^0 \end{array}$
- Potential terms:

$$\hat{V}(r) = \begin{pmatrix} 2\delta m_V - \frac{\alpha_2 s_W^2}{r} - \frac{\alpha_2 c_W^2 e^{-m_Z r}}{r} & -\frac{\sqrt{2}\alpha_2 e^{-m_W r}}{r} \\ -\frac{\sqrt{2}\alpha_2 e^{-m_W r}}{r} & 0 \end{pmatrix}$$

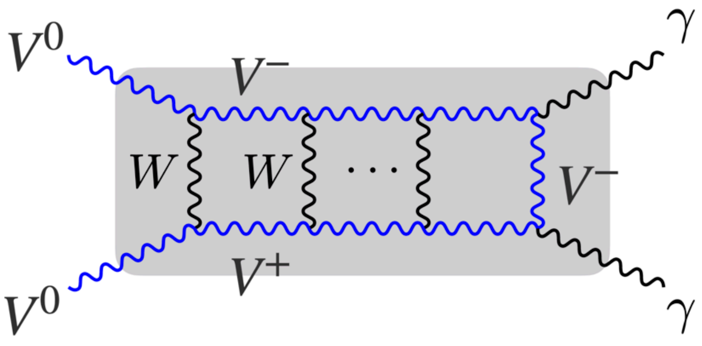
$$\hat{\Gamma}_{\gamma\gamma}^{J=0} = \frac{2}{3}\frac{\pi\alpha_2^2}{m_V^2} \begin{pmatrix} s_W^4 & 0 \\ 0 & 0 \end{pmatrix}$$

$$\hat{\Gamma}_{\gamma\gamma}^{J=2} = \frac{32}{45}\frac{\pi\alpha_2^2}{m_V^2} \begin{pmatrix} s_W^4 & 0 \\ 0 & 0 \end{pmatrix}$$

α_2: SU(2)$_L$ fine structure constant

- $Q=0$ two-body states are relevant in γ-ray search
- EW int. are imprinted in the potential btw V-particles
- Off-diagonal elements (induced by W) mix V^0V^0 & V^-V^+

  → DM can annihilate into γ with large cross section
- $Q=\pm 1, \pm 2$ two-body actions are also derived

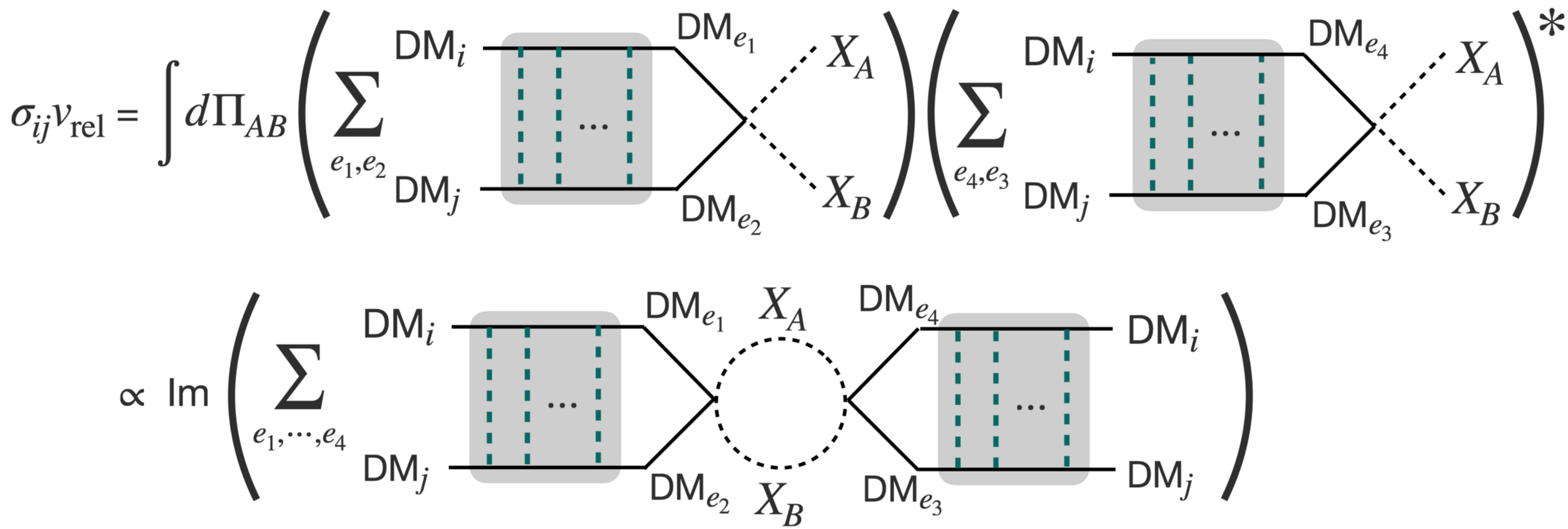


Sommerfeld Enhancement

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

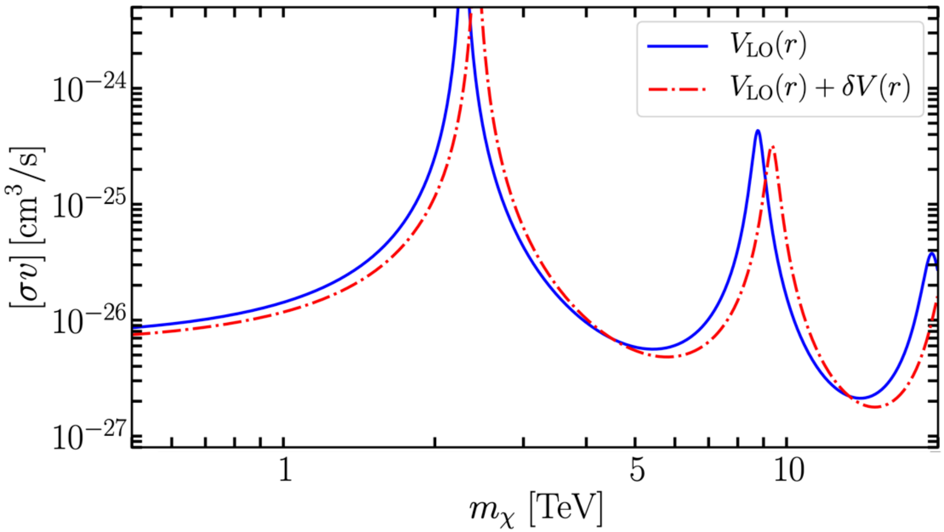
- Studied in pure Wino DM system

  [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 (≃ Schrödinger eq for two-body states)
- Solve equations numerically w/ appropriate boundary condition

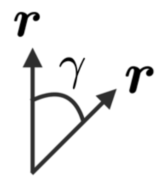
  $G(r) \propto e^{ikr}$ (outgoing wave @$r \to \infty$)

- Cross section is given by ≃ (tree-level cross section) × (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

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

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

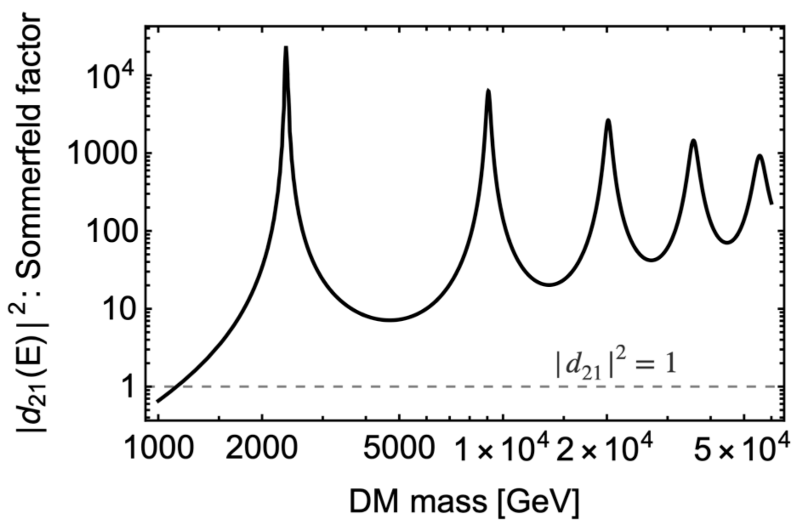
DM mass dependence

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

Sommerfeld effect for V−particle (δm_V=168 MeV)



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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 $\Gamma_{XX'}$ $(XX' = \gamma\gamma, Z\gamma, Z'\gamma)$

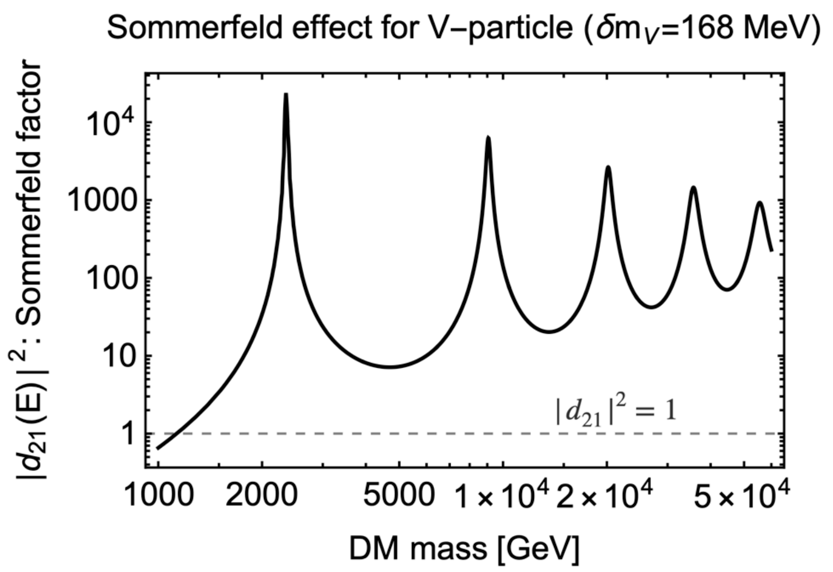
$$\hat\Gamma^{J=0}_{\gamma\gamma} = \frac{2}{3}\frac{\pi\alpha_2^2}{m_V^2}\begin{pmatrix} s_W^4 & 0 \\ 0 & 0 \end{pmatrix}, \quad \hat\Gamma^{J=0}_{Z\gamma} = \frac{2}{3}\frac{\pi\alpha_2^2}{m_V^2}\begin{pmatrix} 2c_W^2 s_W^2 & 0 \\ 0 & 0 \end{pmatrix}, \quad \hat\Gamma^{J=0}_{Z'\gamma} = \frac{1}{27}\frac{\alpha_2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

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

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)



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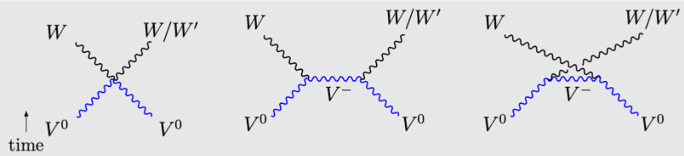
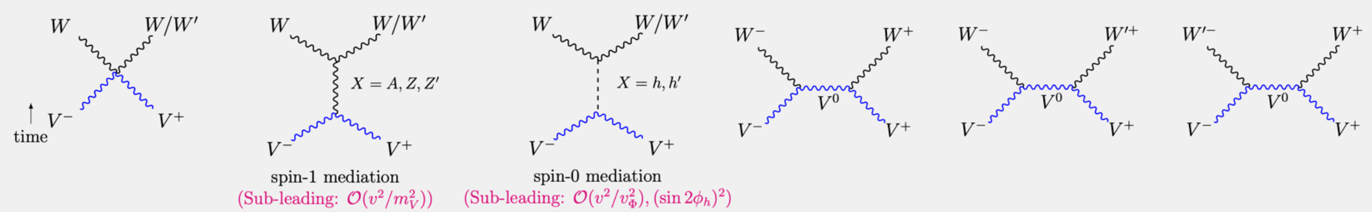
Annihilation Channels

$Q = 0$ state

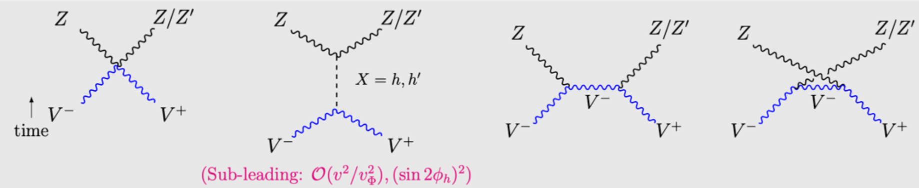
- $V^0 V^0 \to WW, WW'$



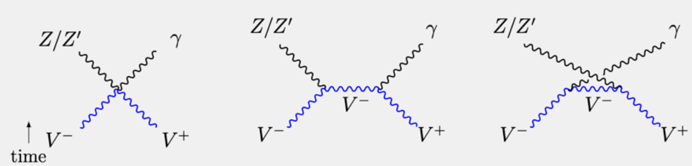
- $V^- V^+ \to WW, WW'$



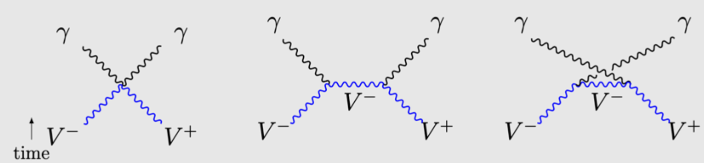
- $V^- V^+ \to ZZ, ZZ'$



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

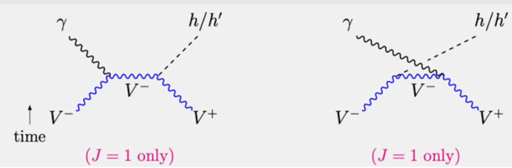


- $V^- V^+ \to \gamma\gamma$



Monochromatic γ-ray channel

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



$J = 0$ only
→ irrelevant to discuss indirect detection

BU

Our Model (more details)

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	$\frac{1}{2}$

Symmetry Breaking

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

$SU(2) \simeq$ **$SU(2)_L$**

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

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

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

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.

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

※ $g_0 = g_2$ ($\neq g_1$)

- Vacuum expectation values

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

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

$(v_\Phi \gg v)$

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

Model

BSM Lagrangian

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

Scalar potential

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

Mass Matrix (Gauge sector)

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

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

$$\lambda = \frac{m_h^2 \cos^2 \phi_h + m_{h'}^2 \sin^2 \phi_h}{2v^2},$$

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

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

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

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

Z2 parity from Exchange symme.

Exchange trans. (after SSB)

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

$$\left[\ \Phi_j = \begin{pmatrix} \frac{v_\Phi + \sigma_j + i\pi^0_j}{\sqrt{2}} & i\pi^+_j \\ i\pi^-_j & \frac{v_\Phi + \sigma_j - i\pi^0_j}{\sqrt{2}} \end{pmatrix} \ (\text{j=1, 2}) \qquad H = \begin{pmatrix} i\pi^+_3 \\ \frac{v + \sigma_3 - i\pi^0_3}{\sqrt{2}} \end{pmatrix}\ \right]$$

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

Physical states

$$\begin{cases} \frac{\sigma_1 - \sigma_2}{\sqrt{2}} \mapsto -\frac{\sigma_1 - \sigma_2}{\sqrt{2}} & \textbf{Z}_2\textbf{-odd} \\ \frac{\sigma_1 + \sigma_2}{\sqrt{2}} \mapsto +\frac{\sigma_1 + \sigma_2}{\sqrt{2}} & \textbf{Z}_2\textbf{-even} \\ \sigma_3 \mapsto +\sigma_3 & \textbf{Z}_2\textbf{-even} \end{cases}$$

No mixing → $h_D = \frac{\sigma_1 - \sigma_2}{\sqrt{2}}$

mixed by ϕ_h → h (125 GeV Higgs), h'

States are classified by **Z2 Parity**!

Exchange symmetry $\mathrm{SU}(2)_0 \leftrightarrow \mathrm{SU}(2)_2$ → **Z2 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)$_1$]

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

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

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

ϕ_h : mixing angle of Z_2-even scalars

$\sim v_\Phi$ (TeV scale)

Free parameters

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

Scattering Process

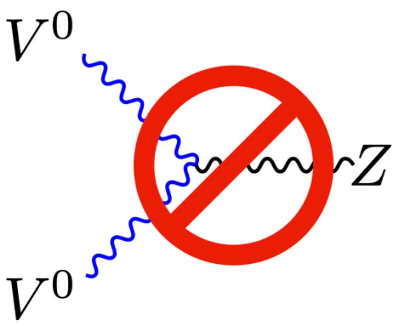
DM direct detection

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)

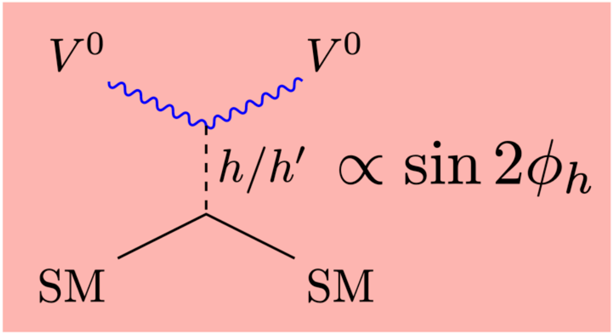
→ No Z-exchange in scattering process!



(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



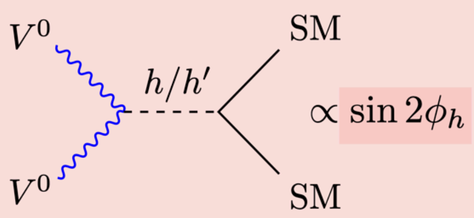
Thermal relic region [Without Sommerfeld effects]

ϕ_h : mixing angle btw h and h'

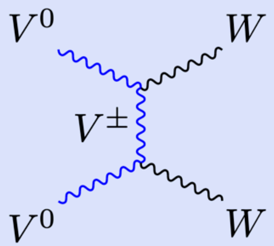
White region:
$\Omega h^2 \sim 0.12$ is achieved by adjusting ϕ_h

<u>Annihilation Channel</u>

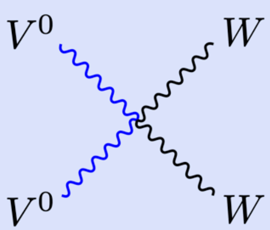
- Higgs channels



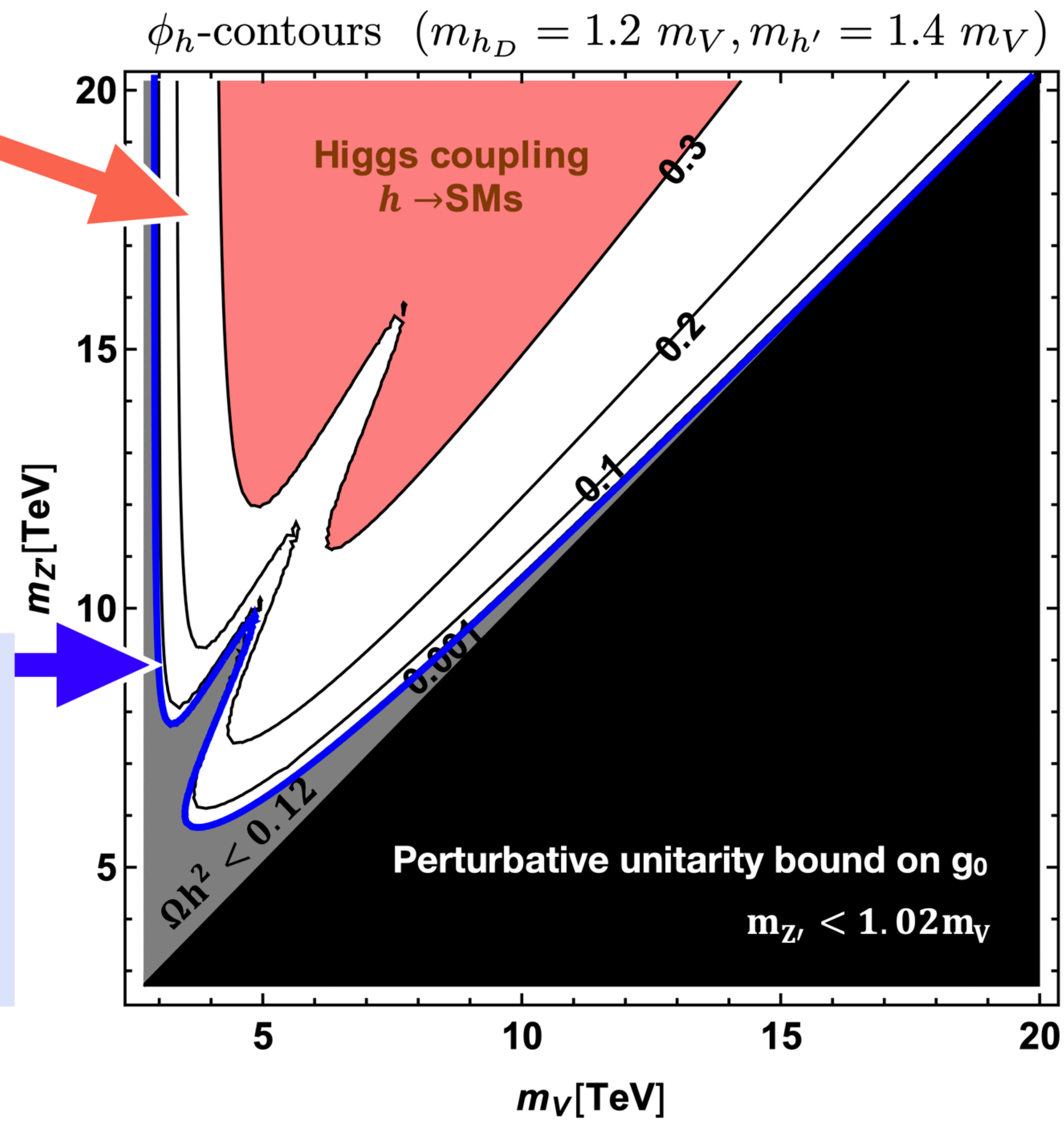
- EW channels



EW channel only



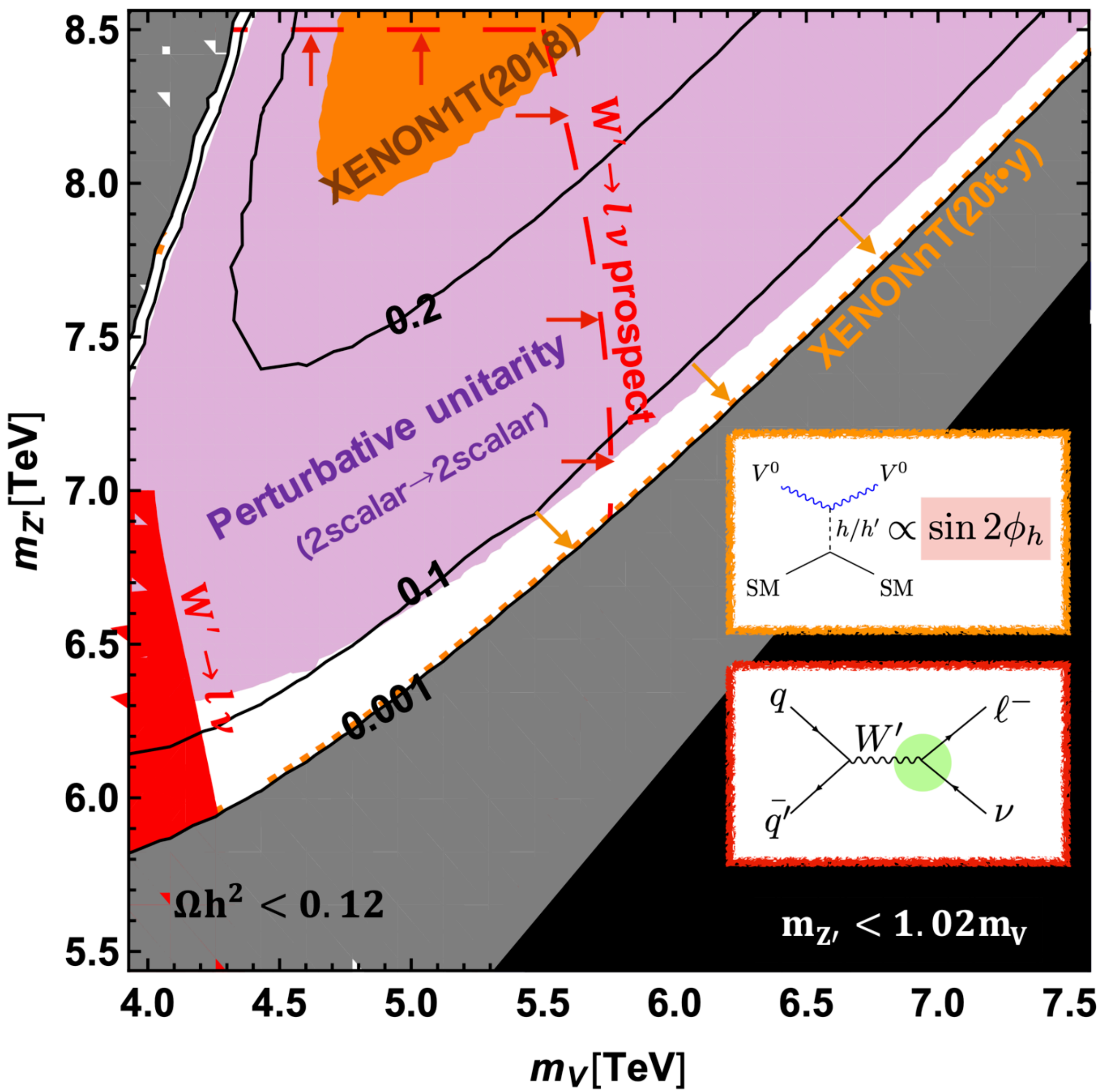
(+ many other channels…)

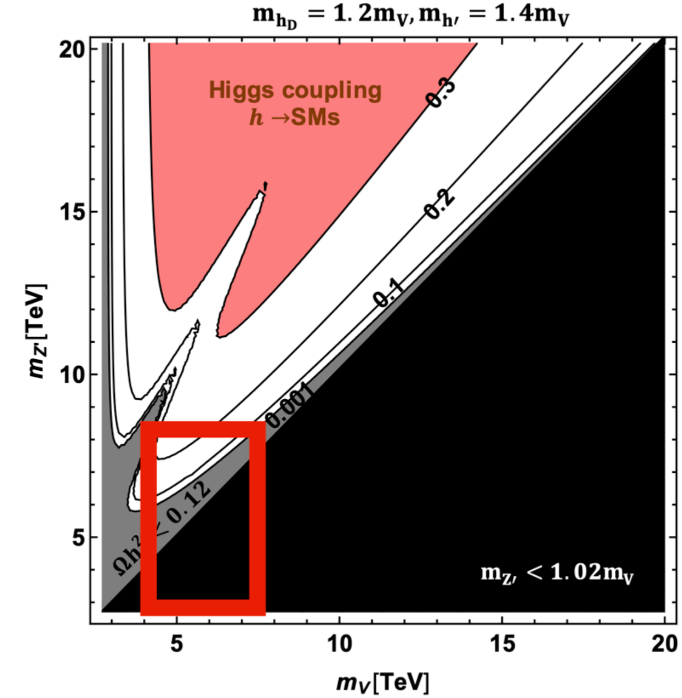


※ **We need to include Sommerfeld effect in evaluation of Ωh^2** [Future work is ongoing]

Constraints

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





- Perturbative unitarity bounds
  (2scalar→2scalar scattering)
  → $\phi_h \lesssim 0.1$

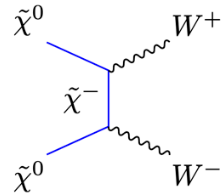
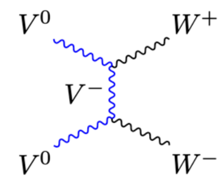
- Direct detection(XENON1T/nT)
  → probe Higgs contribution to DM annihilation process

- 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)]

Spin-1/2 vs Spin-1 $SU(2)_L$ triplet DM

Candidate	 cf. Wino DM ($\tilde{\chi}^0$) in supersymmetric scenario	 cf. KK EW boson DM (V^0) in extra-dimensional scenario
Spin	1/2 (Majorana fermion)	1 (Vector)
Mass difference	$\sim 166\ \mathrm{MeV}$	$\sim 168\ \mathrm{MeV}$
Annihilation	EW	EW + Higgs exchange
Scattering	tree-level: No loop-level: EW	tree-level: **Higgs exchange** loop-level: EW
Z_2-even vectors	—	Z', W'

????

EW process may dominate DM annihilation processes

$\Omega h^2 \simeq 0.12$ is expected for $m_V \gtrsim \mathcal{O}(1)\mathrm{TeV}$

Direct detection through Higgs coupling

W' search @LHC

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

Question: Can we distinguish two DM candidates w/ the same EW int. but different spin?

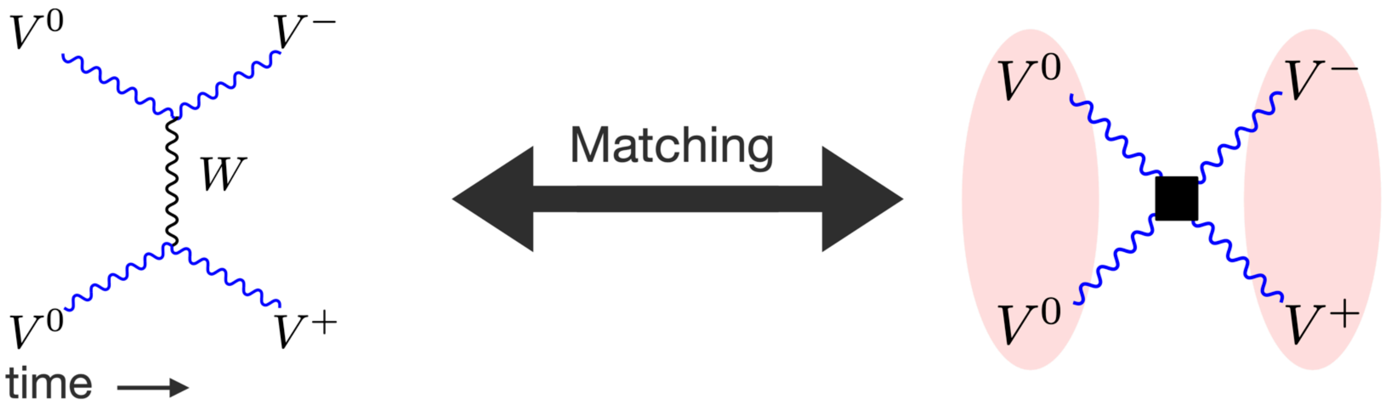
→ Sophisticated treatment of DM annihilation is key for discrimination

We explored physics by using simplified model of EW interacting spin-1 DM

Construct NR EFT for Spin-1 DM

We want to describe the non-relativistic process of **EW interacting spin-1** DM

Regime: $E \simeq m + \mathcal{O}(mv^2), \quad |\vec{p}| \simeq \mathcal{O}(mv), \quad |\vec{v}| \ll 1$



Full theory: $\mathcal{L} \supset i g_W \left[\left(V^-_\nu \overleftrightarrow{\partial}^\mu V^{0\nu} \right) W^+_\mu + (\text{cyclic}) \right] + h.c.$

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

Integrating out/matching

EFT: 4-vector effective coupling $\simeq$ two-body states w/ potential

Dynamical DoF = { V^0V^0, V^-V^+ } w/ Coulomb/Yukawa potential

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

Annihilation Cross Section

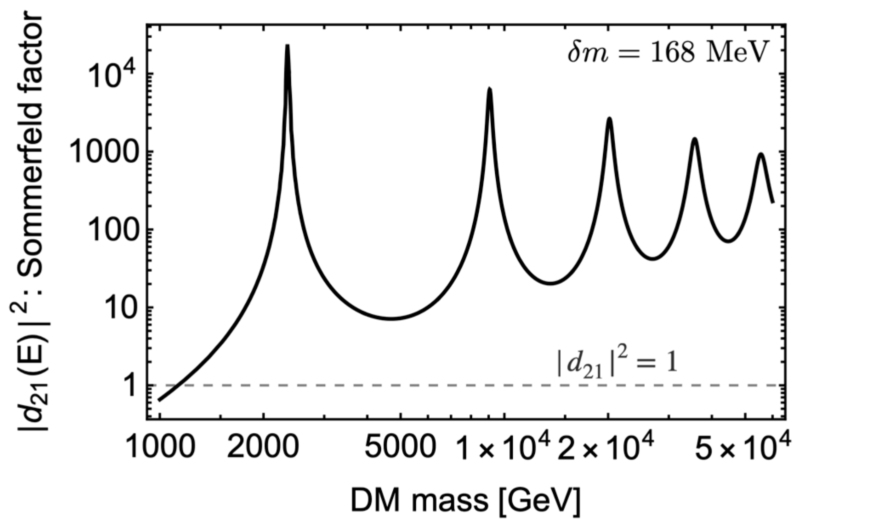
DM annihilation cross section

$$\langle \sigma v_{\mathrm{rel}} \rangle_{XX'} = 2 \sum_{\alpha,\beta} \sum_{J,J_z} (\Gamma^{J}_{XX'})_{\alpha\beta} \boxed{d_{2\alpha}(E) d^{\star}_{2\beta}(E)} \qquad (\alpha,\beta = 1,2) \qquad E \simeq \frac{m v_{\mathrm{rel}}^2}{4}$$: NR kinetic energy

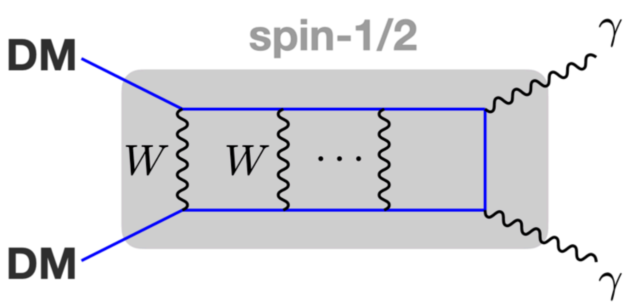
Sommerfeld factor

$m_W \ll m_{\mathrm{DM}}$

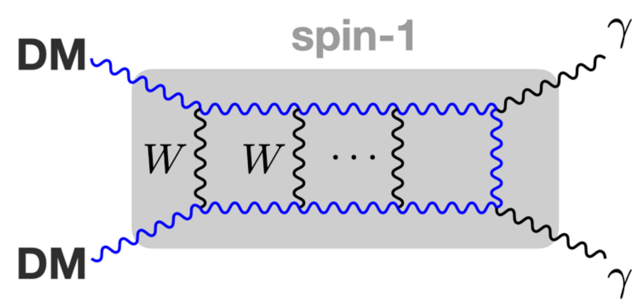
- Wave function profile is distorted from the plane wave due to (effectively) long-range EW forces
- Numerical evaluation of Schrödinger eq. for two-body states of DM multiplet
- Cross section has resonance structures
  → Enhancement even for photon channels
- Resonance due to $\begin{cases} \text{Real part of the potential} \\ \text{Mass splitting } \delta m \end{cases}$



No differences in resonance structure



SU(2)$_L$ triplet



Spin-1/2 vs Spin-1 (1/2)

S: symmetric under exchange of w.f.

A: Anti-symme. under exchange of w.f.

Classification of DM two-body state

Spin-1 DM can form $J=2$ partial wave states → Effectively lager cross section

Component: $\chi^0\chi^0$ (spin-1/2, identical particles) V^0V^0 (spin-1, identical particles)

Statistics: Fermi statistics Bose statistics

States:

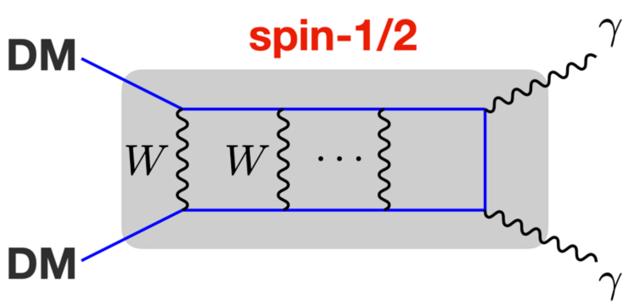
J: Total spin

Spin-1/2 ($\chi^0\chi^0$):

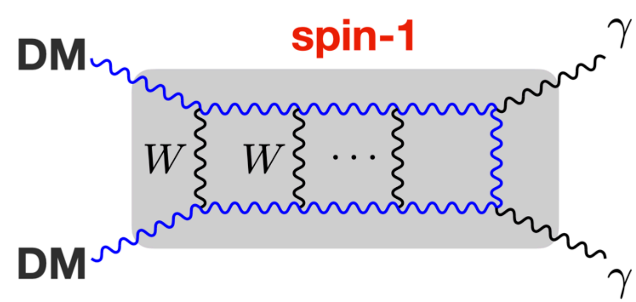
- $J=1$, S
- $J=0$, A

Spin-1 (V^0V^0):

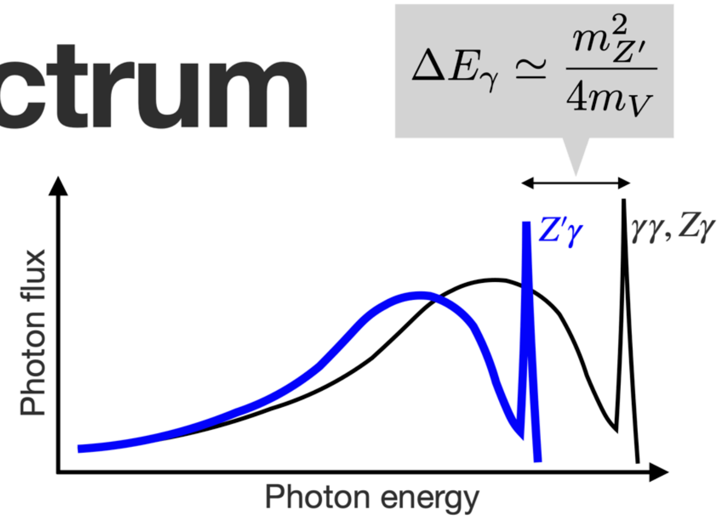
- New! $J=2$, S
- $J=1$, A
- $J=0$, S



SU(2)$_L$ triplet



Z’ search in γ-ray spectrum



- Our spectrum also has Z' (Z_2-even neutral vector)
- New annihilation channel $Z'\gamma$ is opened if kinematically allowed
- 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: $m_V \lesssim m_{Z'} \lesssim 2m_V$

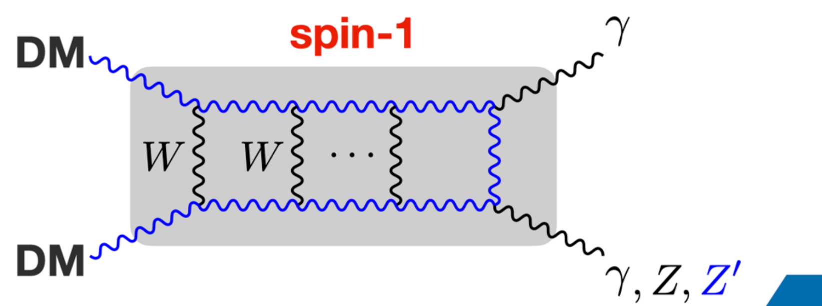
To separate peaks: $\frac{\Delta E_\gamma}{m_V} \simeq \left(\frac{m_{Z'}}{2m_V}\right)^2 \gtrsim 0.1$

Double peak spectrum is predicted
→ We can reconstruct DM, Z’ mass

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

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



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: $m_N > \cdots > m_1 \equiv m,$ $\rightarrow \chi_1$ is DM

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

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

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

Relevant process: $\chi^i\chi^j \to XX'$, $\leftarrow$ 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

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

Boltzmann eq.:

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

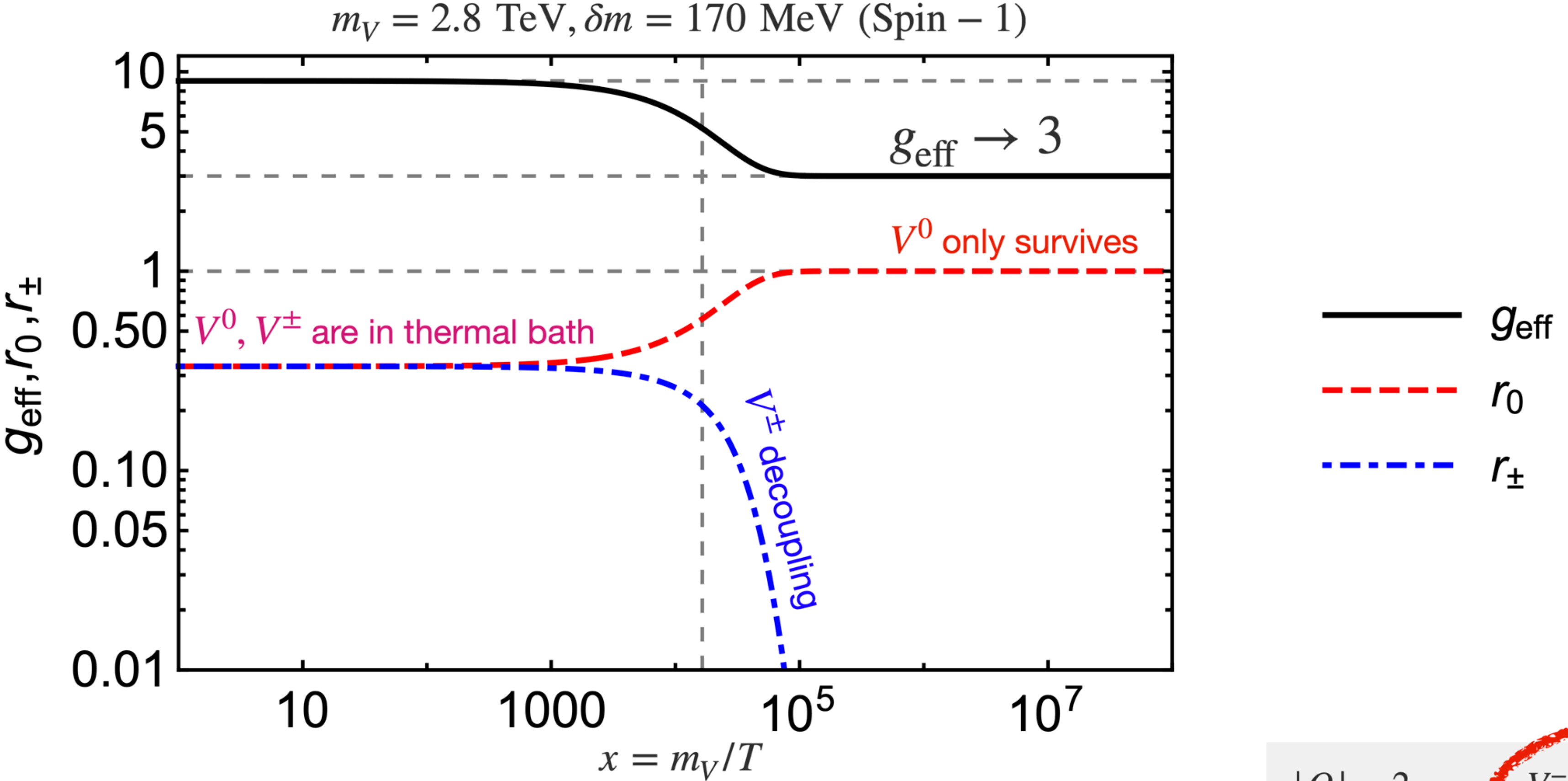
$$\langle\sigma_{\rm eff}v\rangle \equiv \sum_{i=1}^{n}\sum_{j=1}^{n}\langle\sigma_{ij}v\rangle\, r_i r_j$$

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

$\uparrow$

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

Coannihilation for V-particles



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

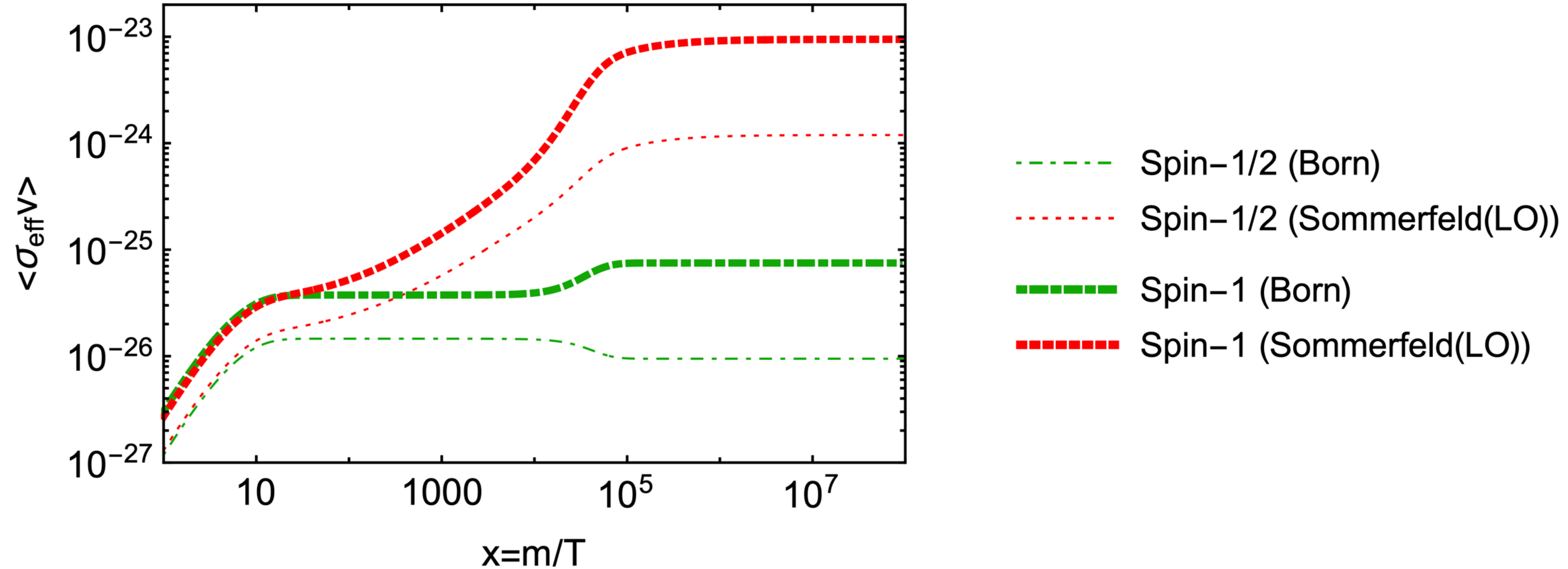
Eff. dof in thermal bath: $g_{\rm eff}(x) = 3 + 6\left(1+\frac{\delta m_V}{m_V}\right)^{\frac{3}{2}} \exp\left[-x\frac{\delta m_V}{m_V}\right]$,

$\lvert Q\rvert = 2$	$\cdots$	V^-V^-	V^+V^+
$\lvert Q\rvert = 1$	$\cdots$	V^0V^-	V^0V^+
$\lvert Q\rvert = 0$	$\cdots$	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, $m_{Z'} = 1.5\ m_V$



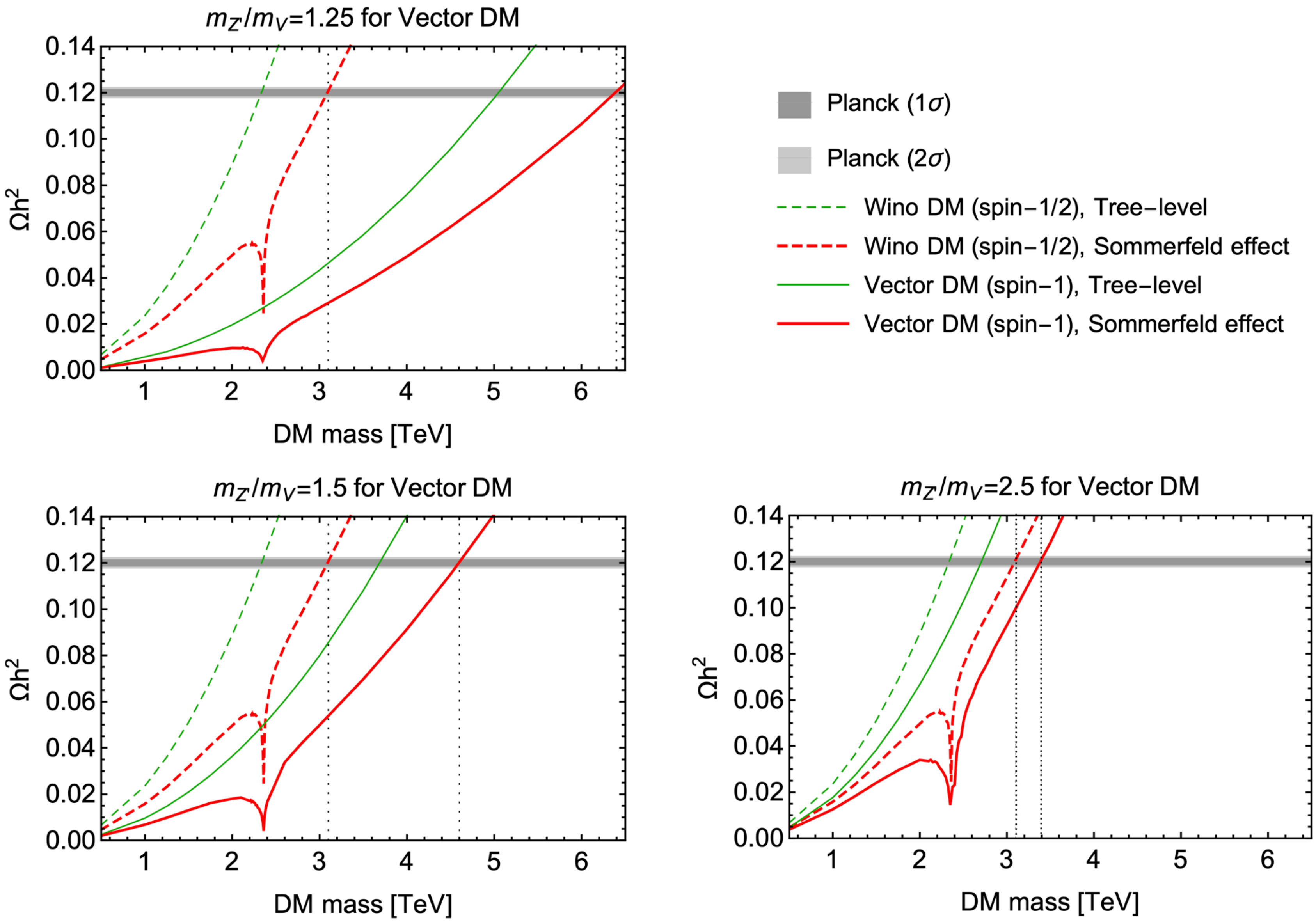
Behavior of Plot

- 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

DM candidate from Extra-dimensional theory

KK-parity in extra-dim. Theory

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

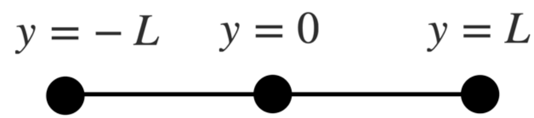
Typical Mass Spectrum

- 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: $\begin{cases} \boxed{r_L} \text{ ... on two boundary} \\ \boxed{r_0} \text{ ... on the middle point} \end{cases}$ ➡ $\dfrac{m_{(2\mathrm{nd})}}{m_{(1\mathrm{st})}} \simeq \sqrt{1 + \dfrac{r_L}{r_0 + L}}$

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

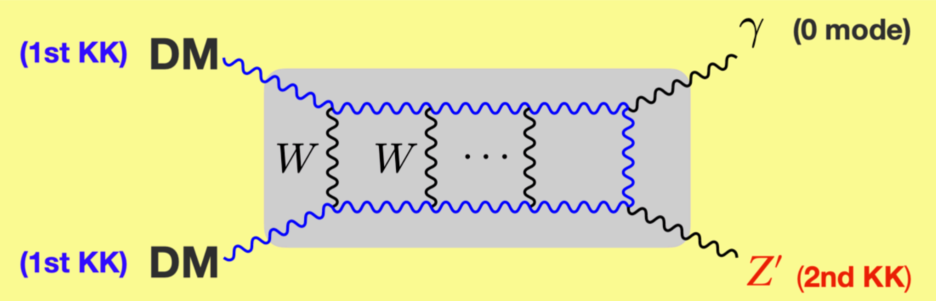
→ Directly affects mass spectrum

→ 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: $d^2 s = d^2 y + e^{-2k|y|}\ d^2 x$ (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

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

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

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

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

1st KK W^3_μ may be LKP

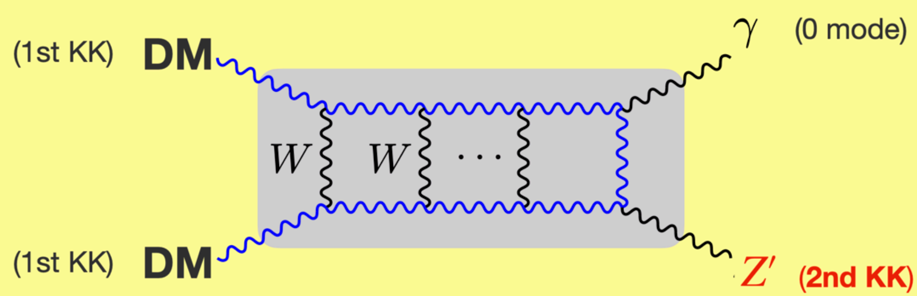
= **SU(2)$_L$ triplet spin-1 DM** (w/ **EW int.**)

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

Mass spectrum/Wave func. differ for each setup

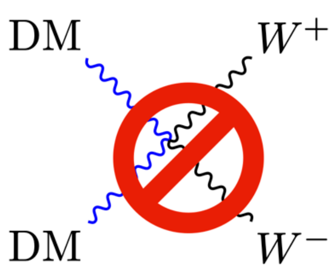
→ DM phenomenology drastically changes

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



Abelian Extension with Exchange Symmetry

CAUTION!

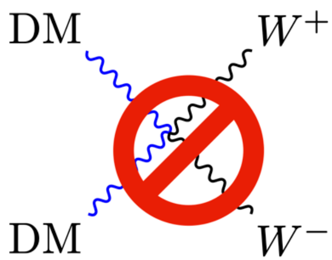


Stable neutral vector CANNOT have Non-Abelian EW couplings

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

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

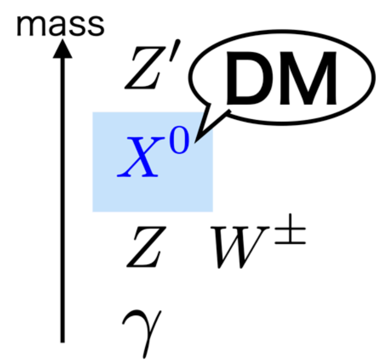
※ We have kinetic mixing terms(2nd line) in this Abelian extension model

field	spin	$\mathrm{SU}(3)_\mathrm{C}$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_0$	$\mathrm{U}(1)_1$	$\mathrm{U}(1)_2$
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**

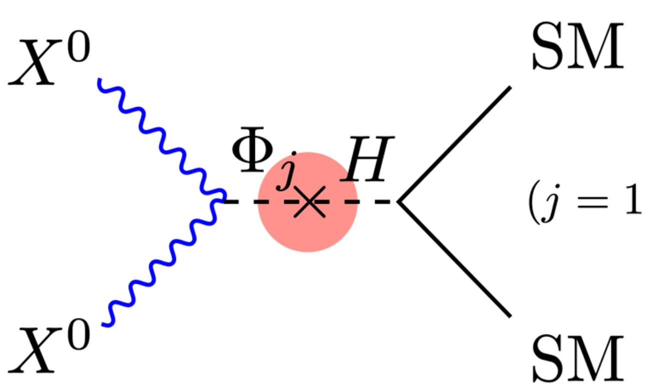
- X^0 do not appear in the $SU(2)_L$ neutral vector state

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

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

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

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



$(j = 1, 2)$

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!)