# Accidentally Stable Dark Matter in a Parity Solution to the Strong CP Problem

**Matthew J. Baldwin**

**University of Chicago**

**Collaborators: Keisuke Harigaya and Isaac R. Wang**

**PIKIMO at PITT PACC**
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# Overview

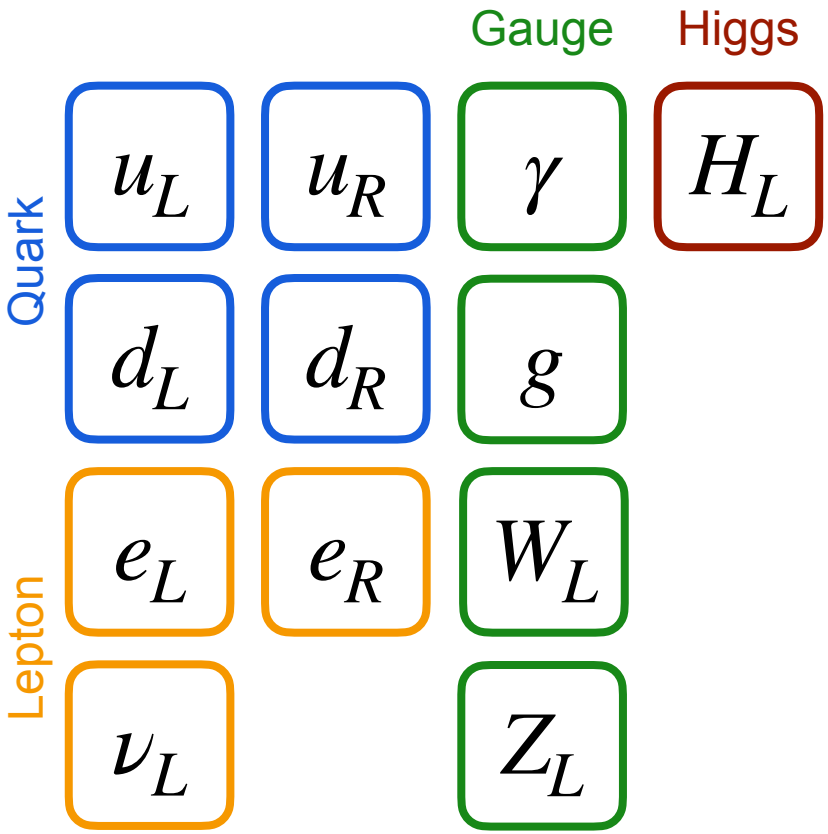
## Introduction

- Parity Symmetric Left-Right Models

## Outline

- WIMP Dark Matter Embeddings
- Upper Bound on Parity Breaking Scale
- Constraints on Parameter Space

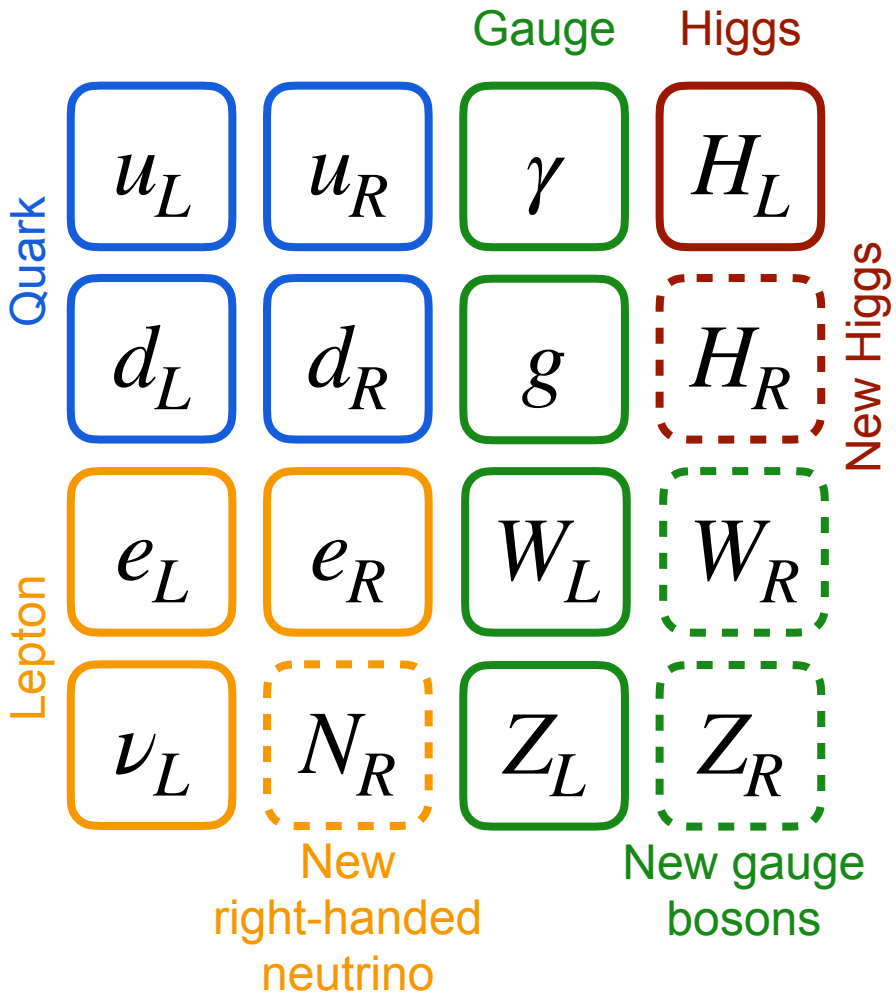
# Parity Symmetric Left-Right Models




**Left-right models** are extensions of the SM gauge group with an additional $SU(2)_R$

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X$$

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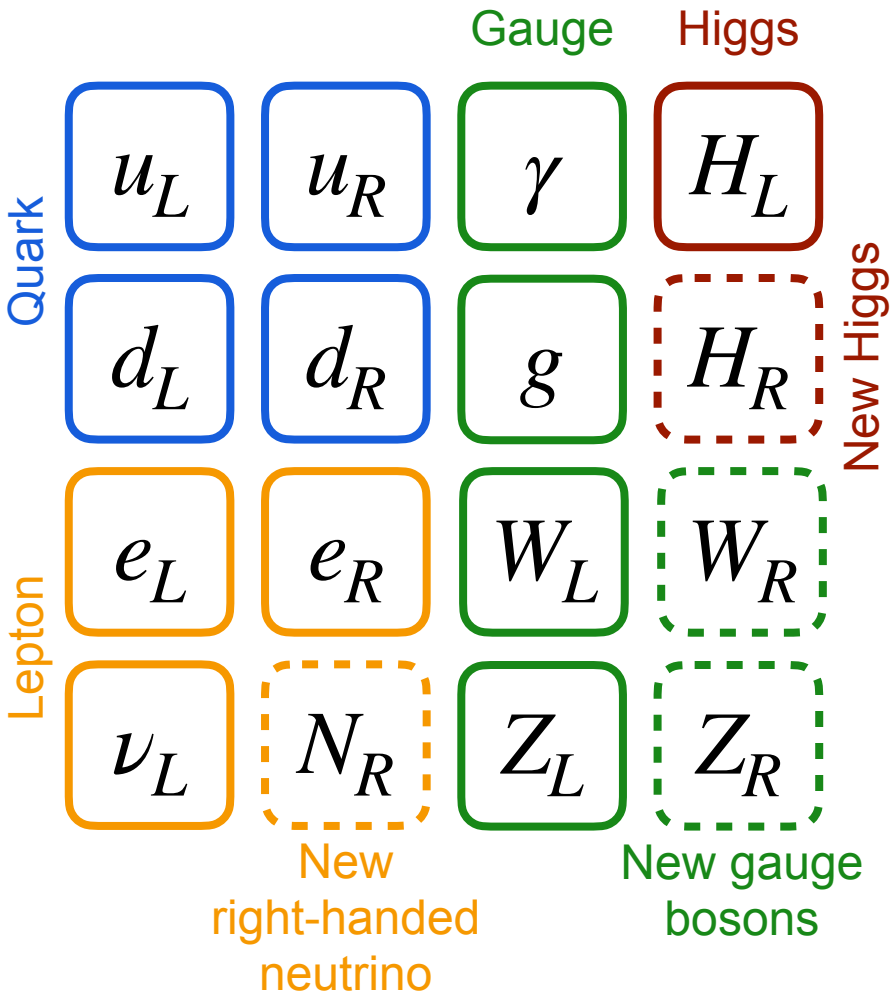



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**Parity ($P$) symmetry** exchanges $SU(2)_L$ and $SU(2)_R$ charged particles

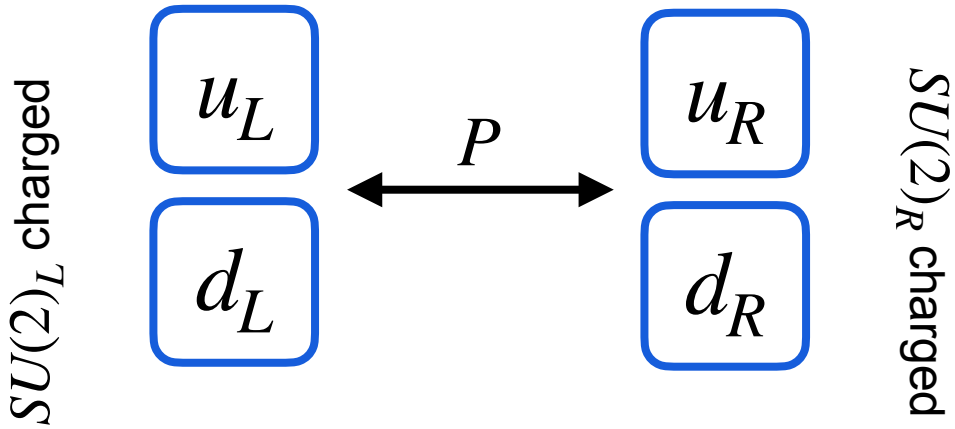
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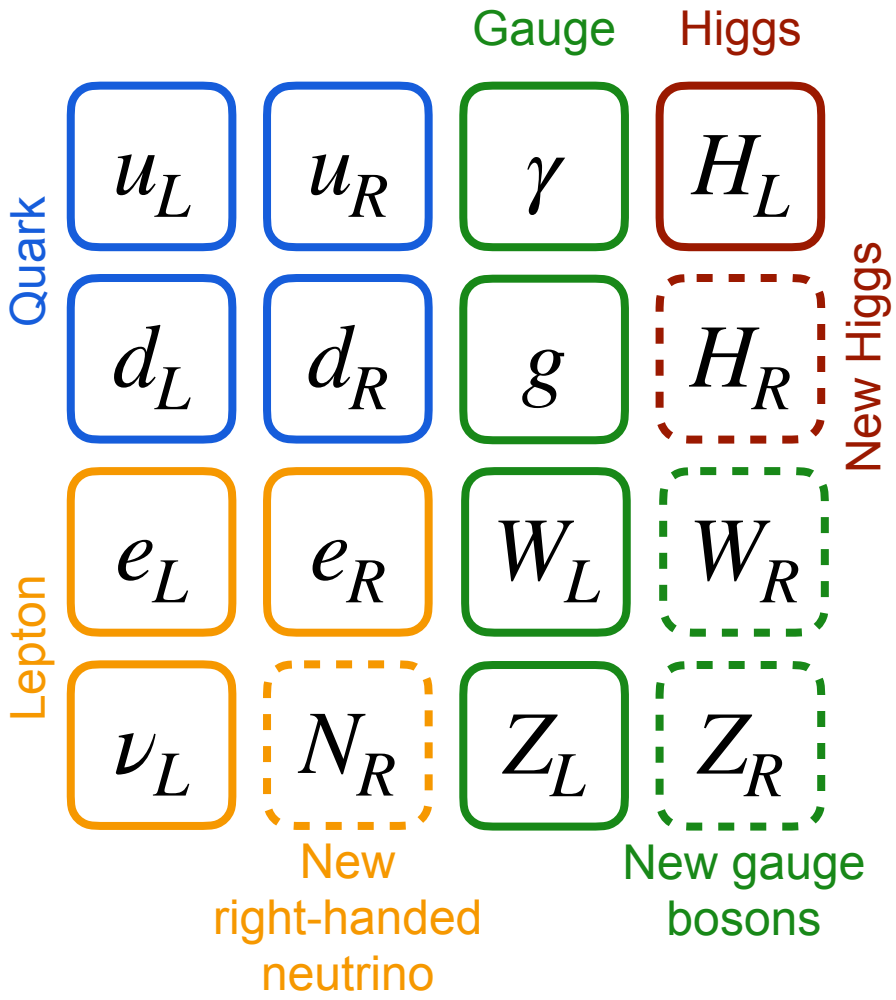
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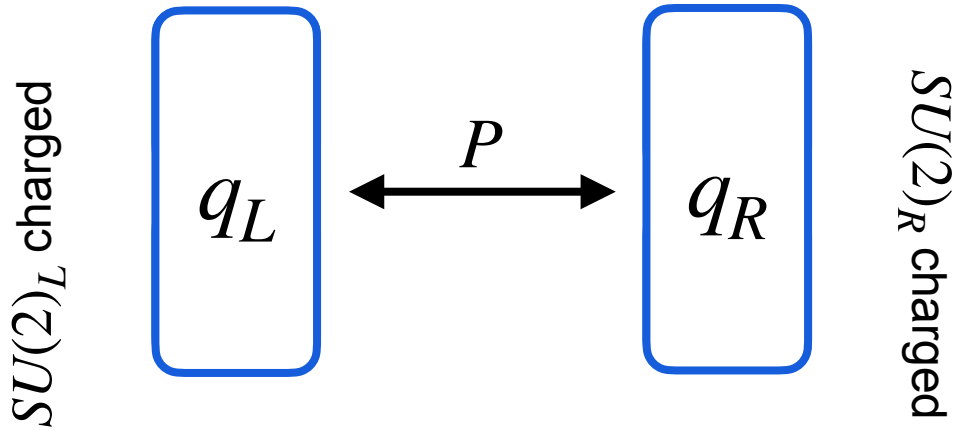
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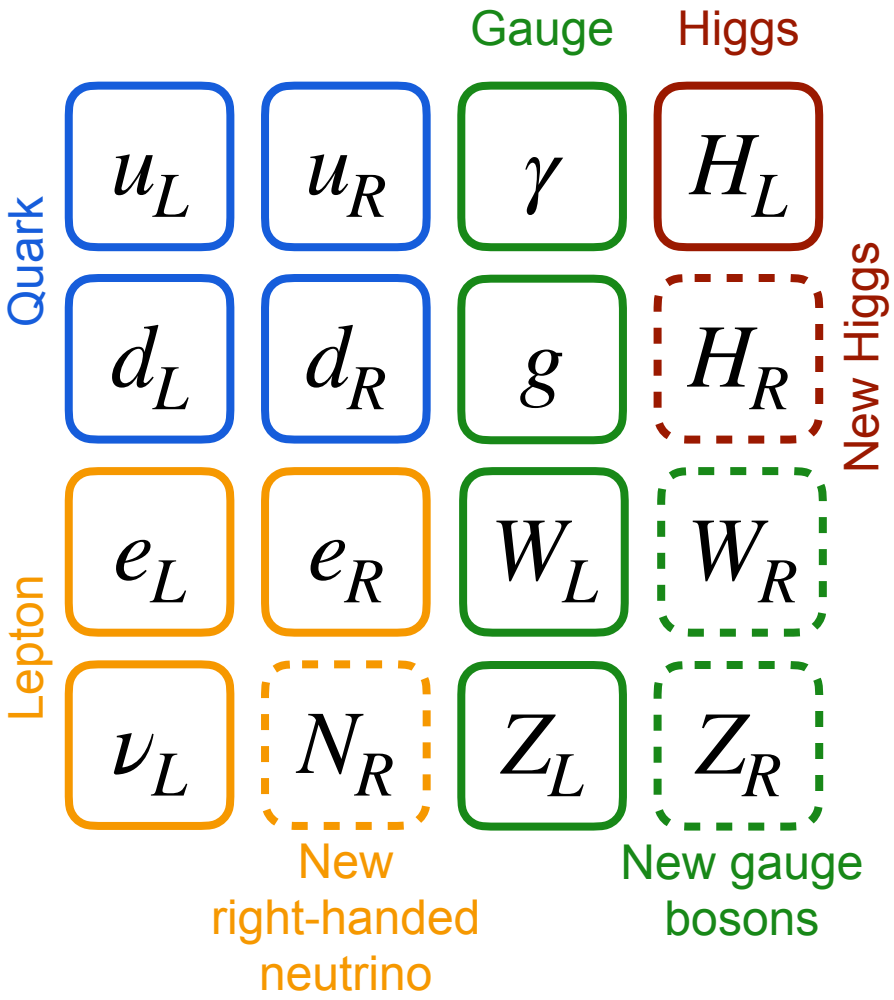
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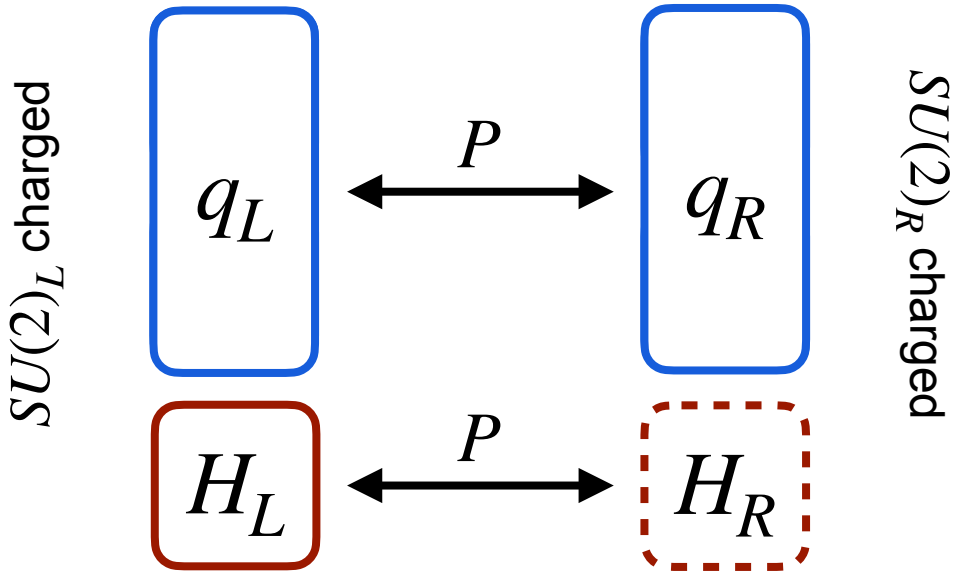
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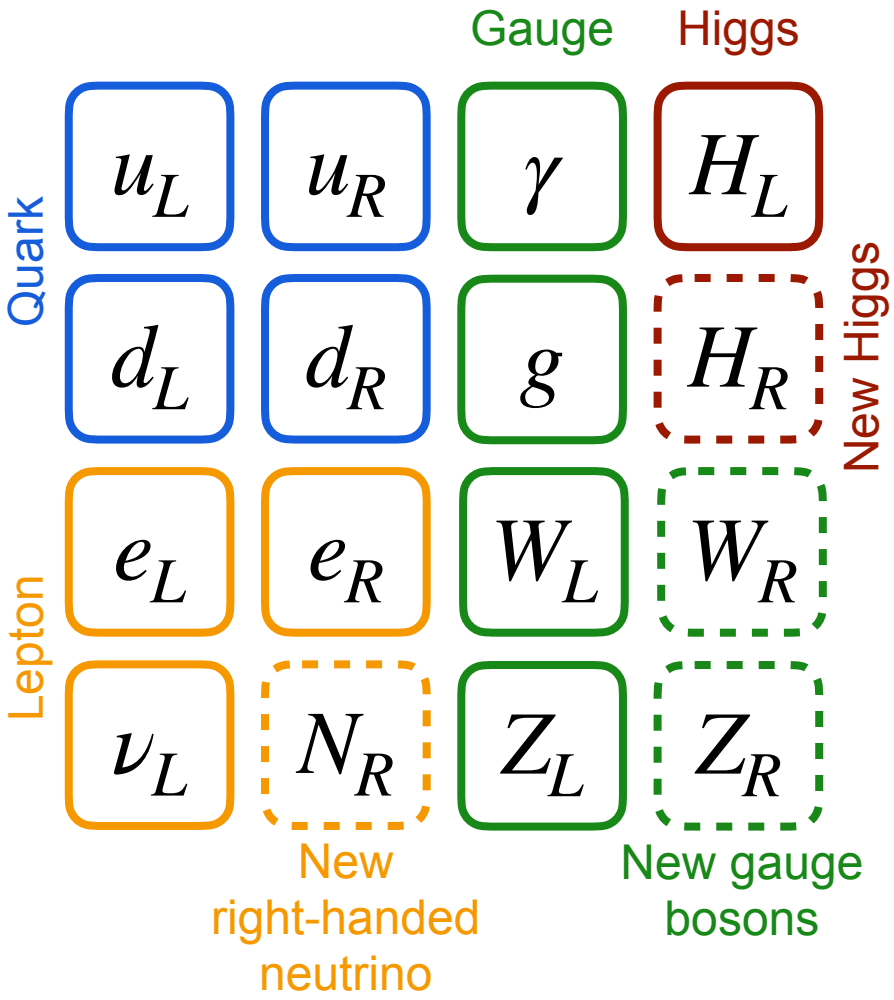

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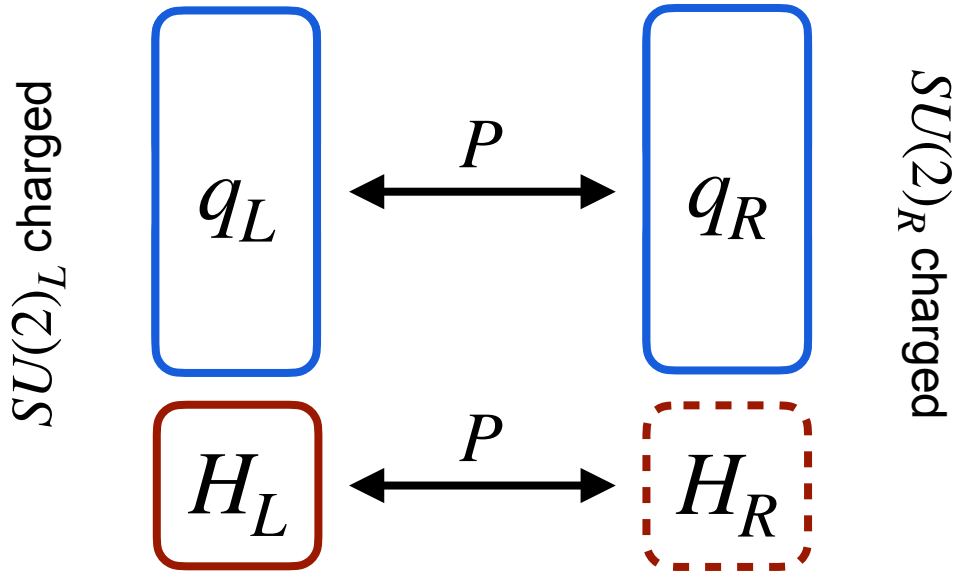
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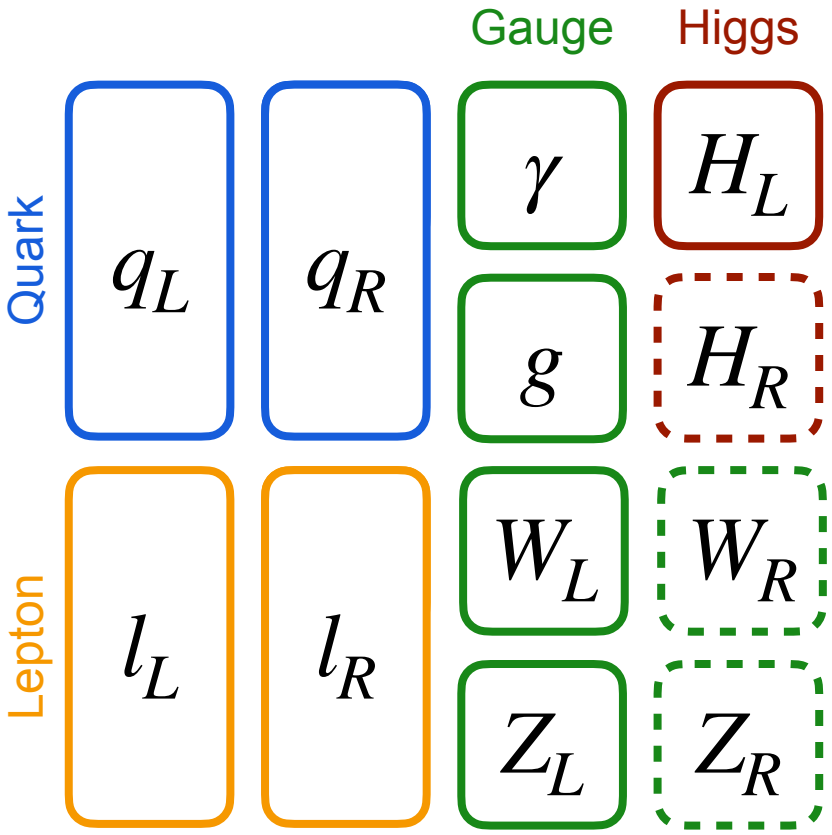
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Parity **forbids a $\theta$-term** and requires **Hermitian SM Yukawas**, thus **no strong CP phase**[1]

1 Loop corrections to $\bar{\theta}$ much below experimental bounds. Hall, Harigaya (2018); de Vries, Draper, Patel (2021); Hisano, Kitahara, Osamura, Yamada (2023)

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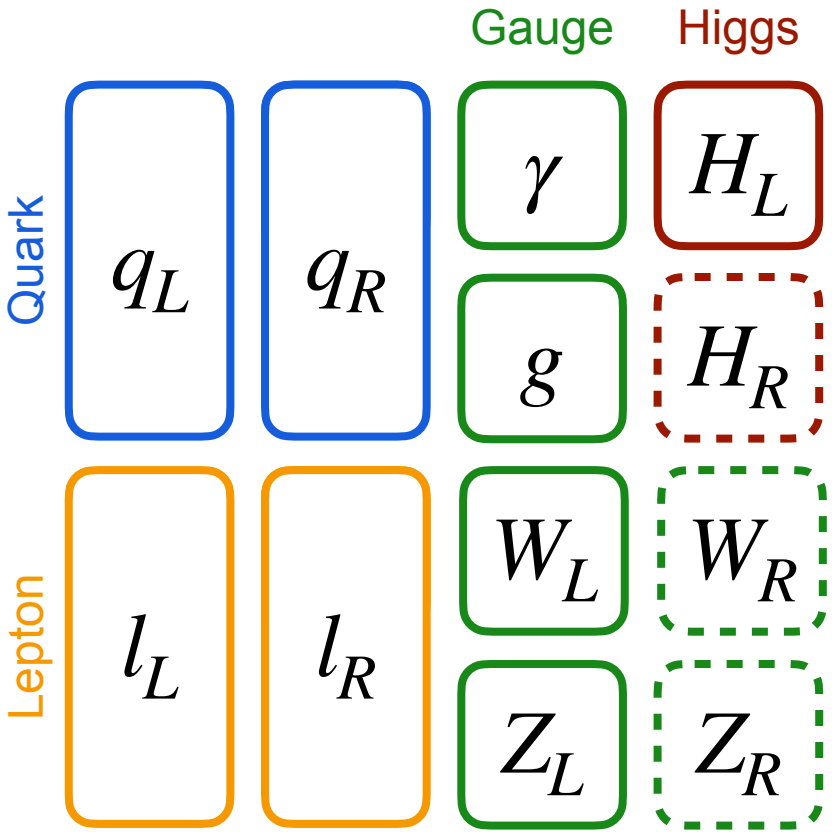



SM Higgs Parity partner breaks left-right model to SM[1]

$$H_L(1,2,1,1/2) \overset{P}{\longleftrightarrow} H_R(1,1,2,-1/2)$$

1 bi-fundamental and triplet Higgs embeddings are possible but do not minimally solve the strong CP problem

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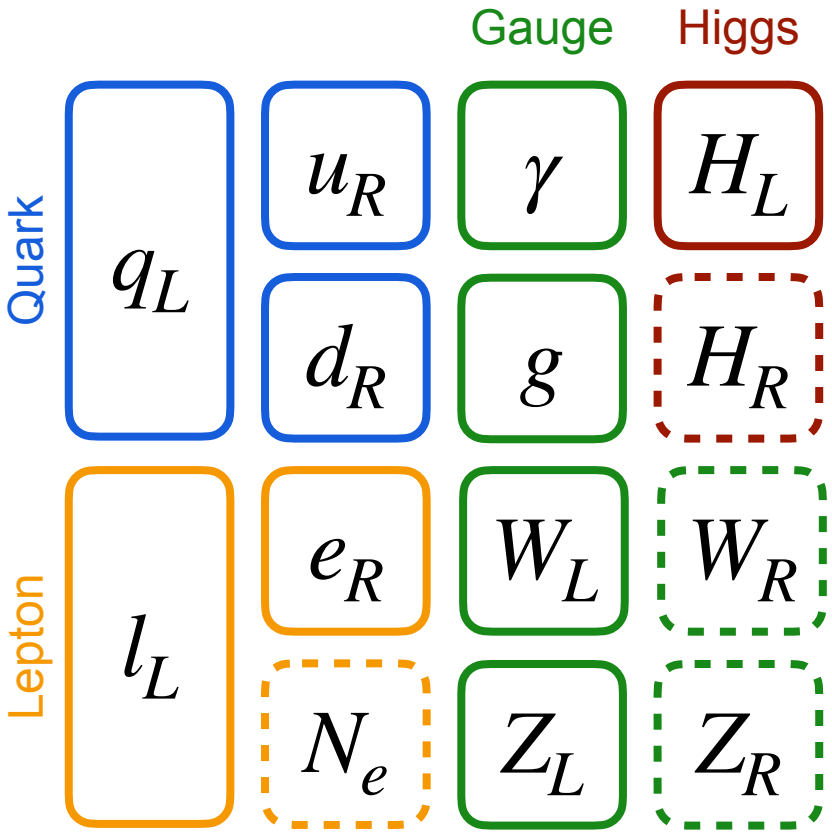

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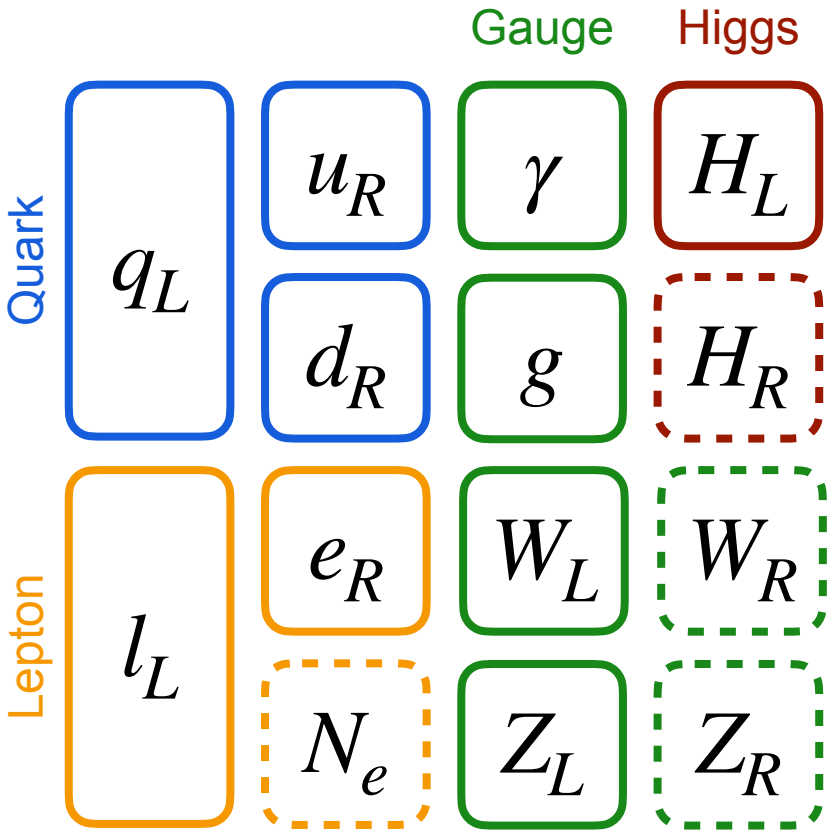
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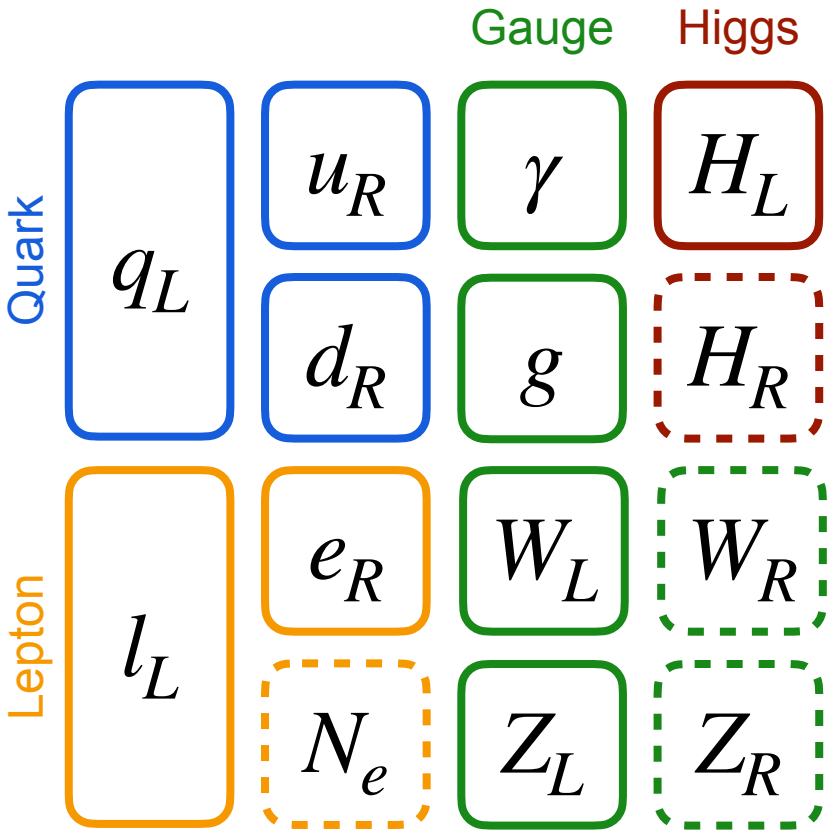
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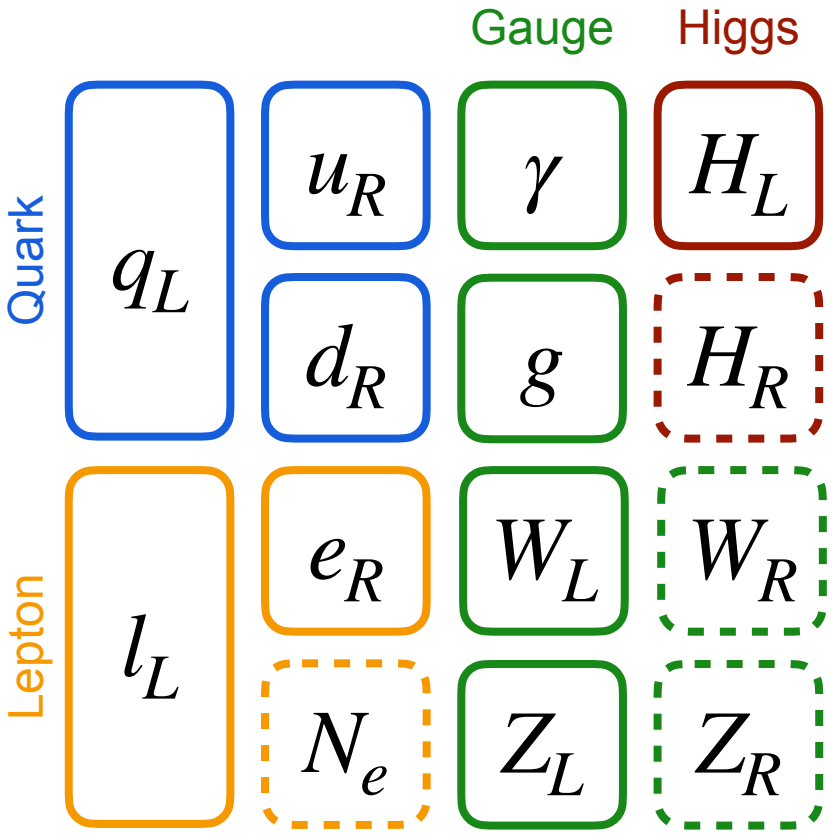
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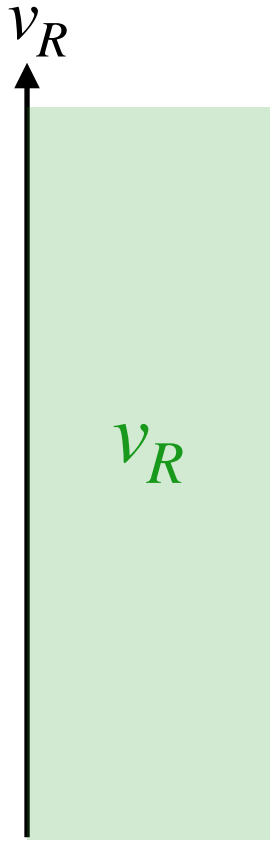
**How can we probe $v_R$?**



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# Parity Symmetric Left-Right Models



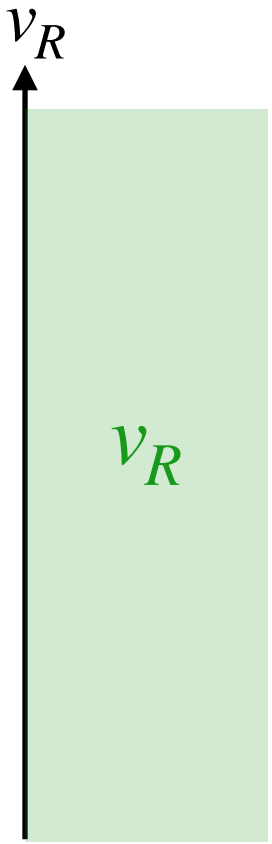




Parity breaking leads to **heavy gauge bosons**

$W_R$ $Z_R$

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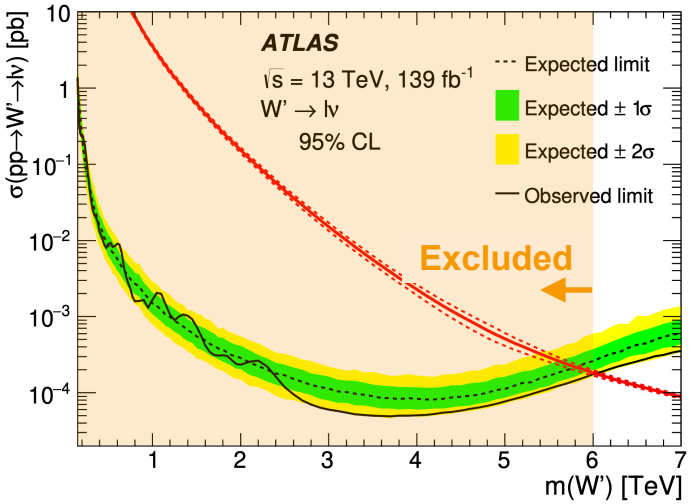
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| Lepton | $l_L$ | $e_R$ | $W_L$ | $W_R$ |
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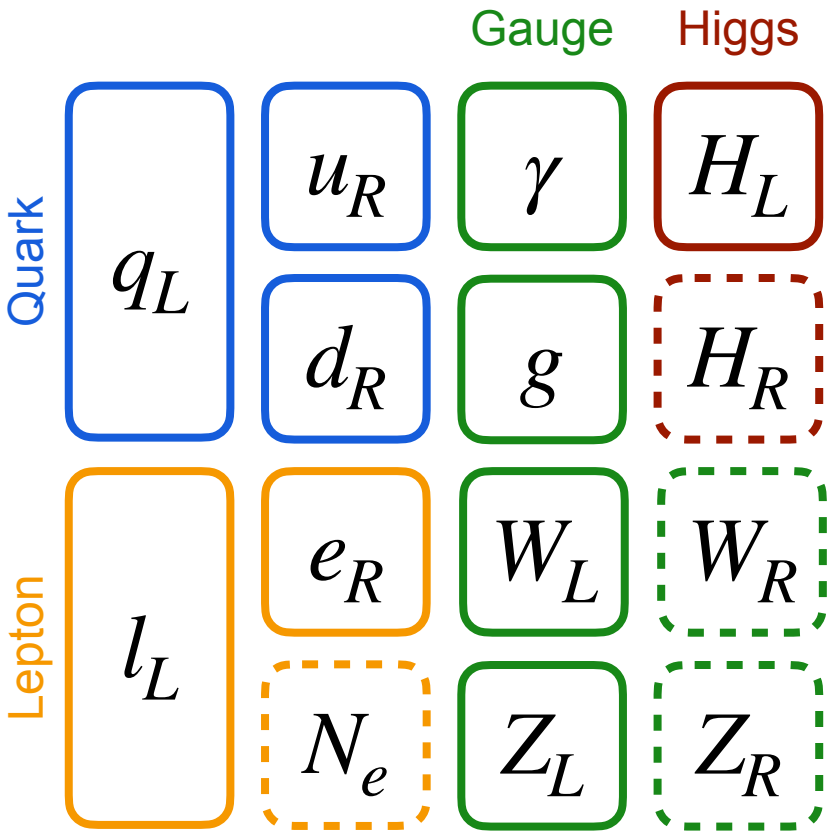
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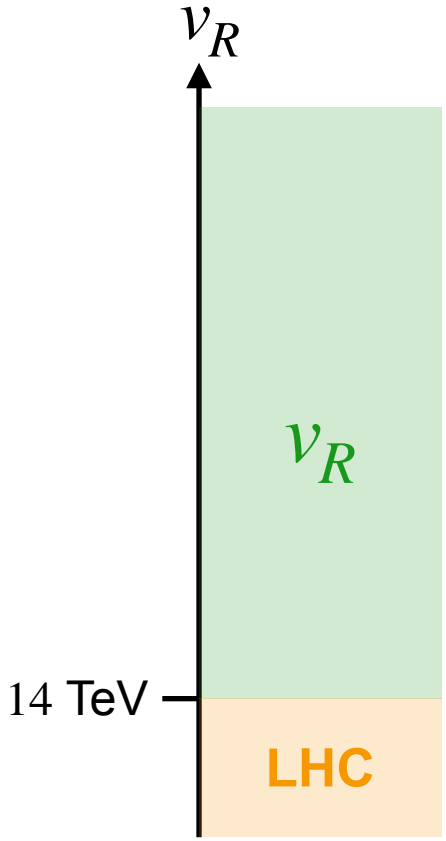
$W_R \to l\nu$ **LHC** search provides strongest constraint




*ATLAS Collaboration (2019)*

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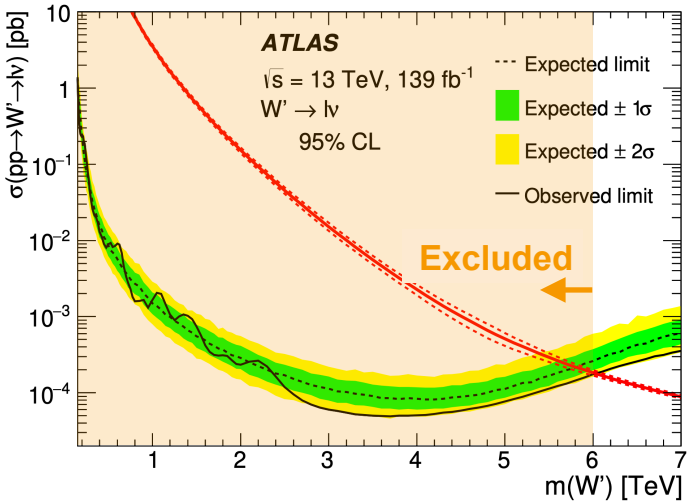



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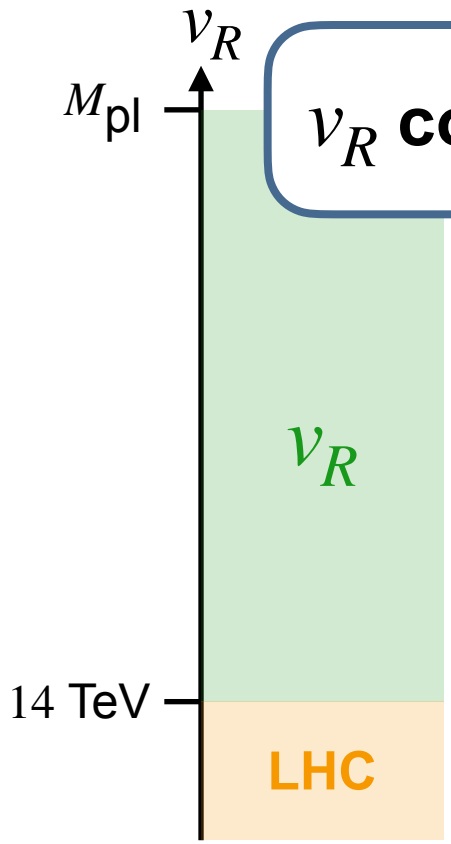



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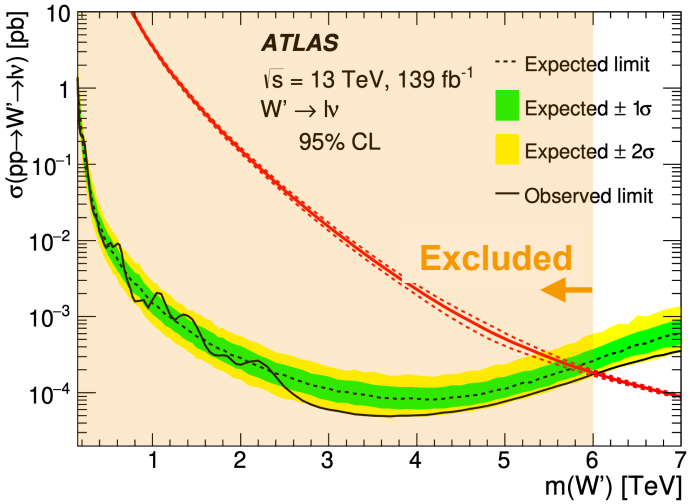
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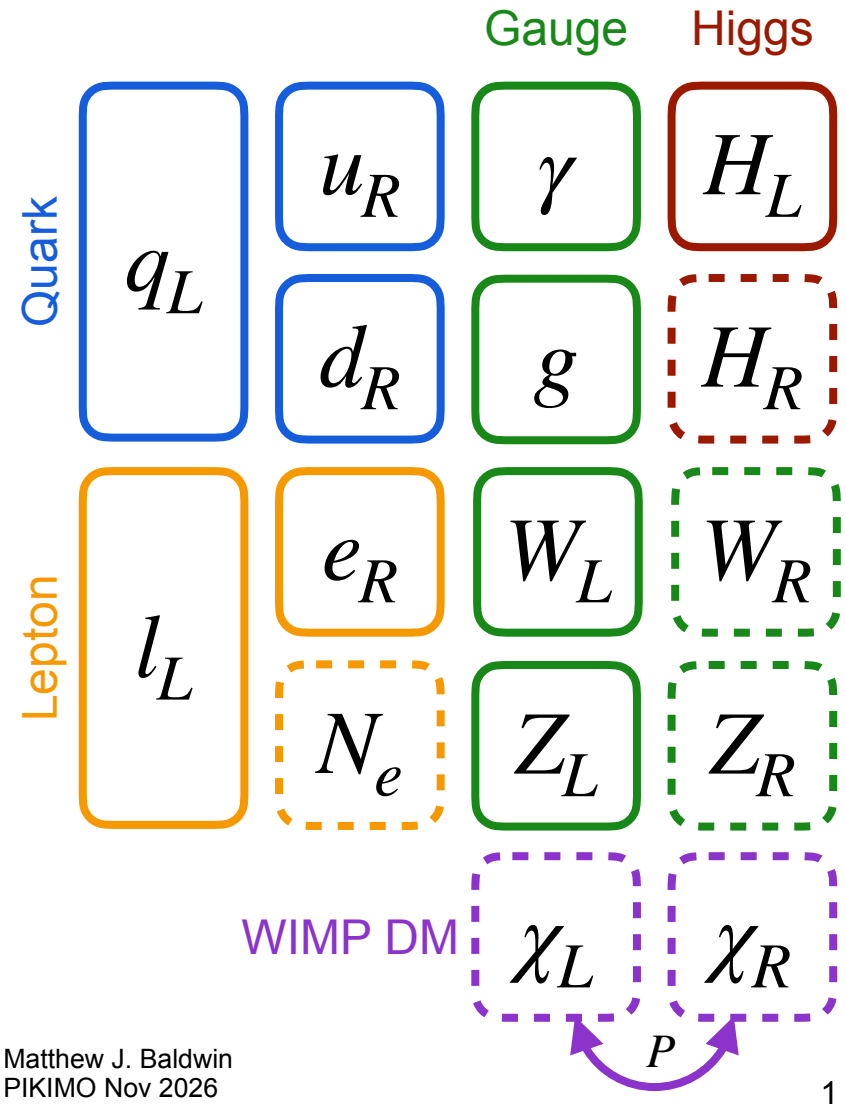

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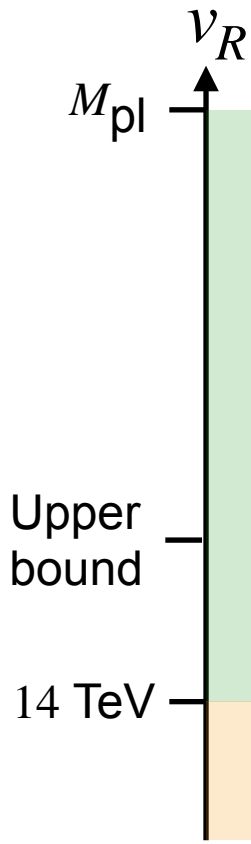


1 Bounds on higher dimensional operators contributing a $\theta$-term can lead to upper bound $v_R \lesssim 10^{13}$ GeV

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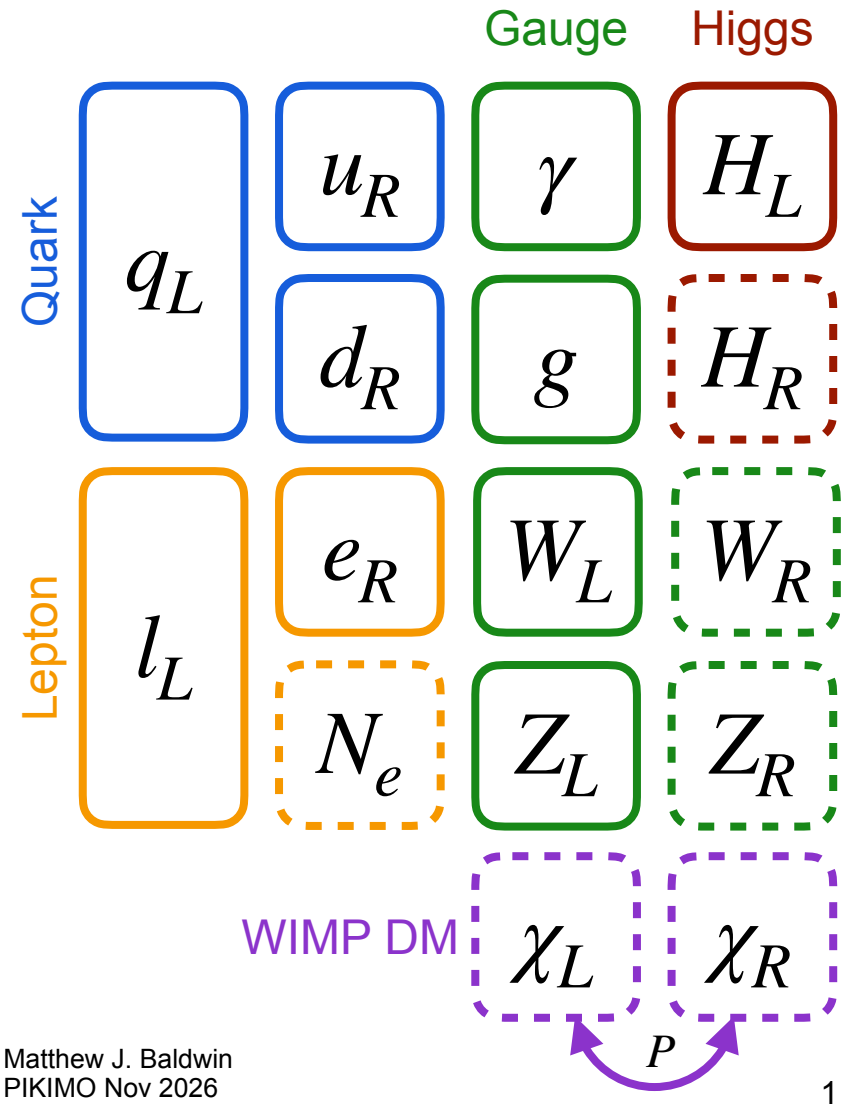
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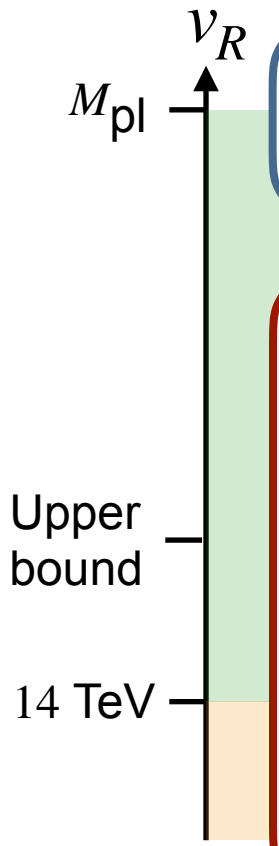

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**Goal: constrain the two free parameters $v_R$ and DM mass**

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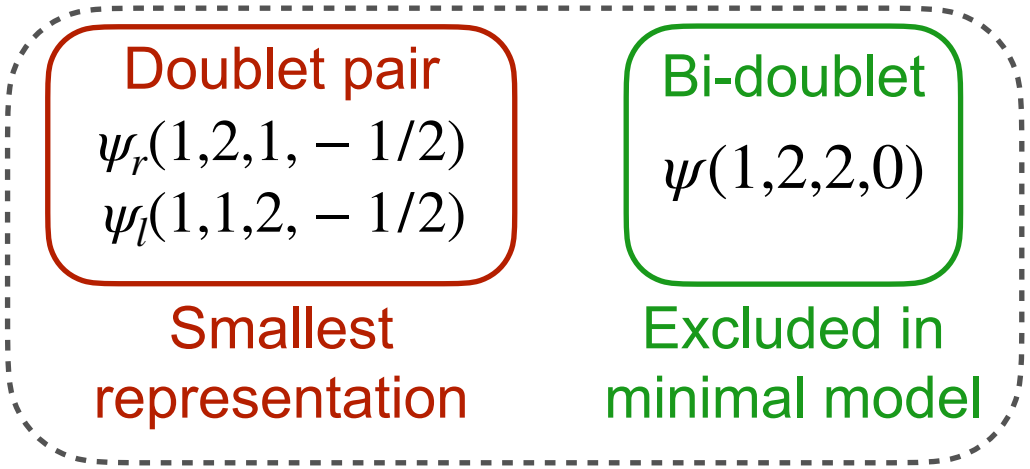
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Smallest representation

Bi-doublet

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Excluded in minimal model

**MB**, Harigaya, Wang (2025)

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$\chi(1,3,3,0)$

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Lifetime for UV scale $\Lambda$

$$\tau_\chi \sim 10^{31}\ \text{sec} \left(\frac{10\ \text{TeV}}{m_\chi}\right) \left(\frac{40\ \text{TeV}}{v_R}\right)^4 \left(\frac{\Lambda}{m_{Pl}}\right)^4$$

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Fermi-LAT constraint: $\tau_\chi \gtrsim 10^{28}$ sec

Cohen, Murase, Rodd, Safdi, Soreq (2019)

**MB**, Harigaya, Wang (2026)

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**This talk— focus on $\chi(1,3,3,\pm 1)$**

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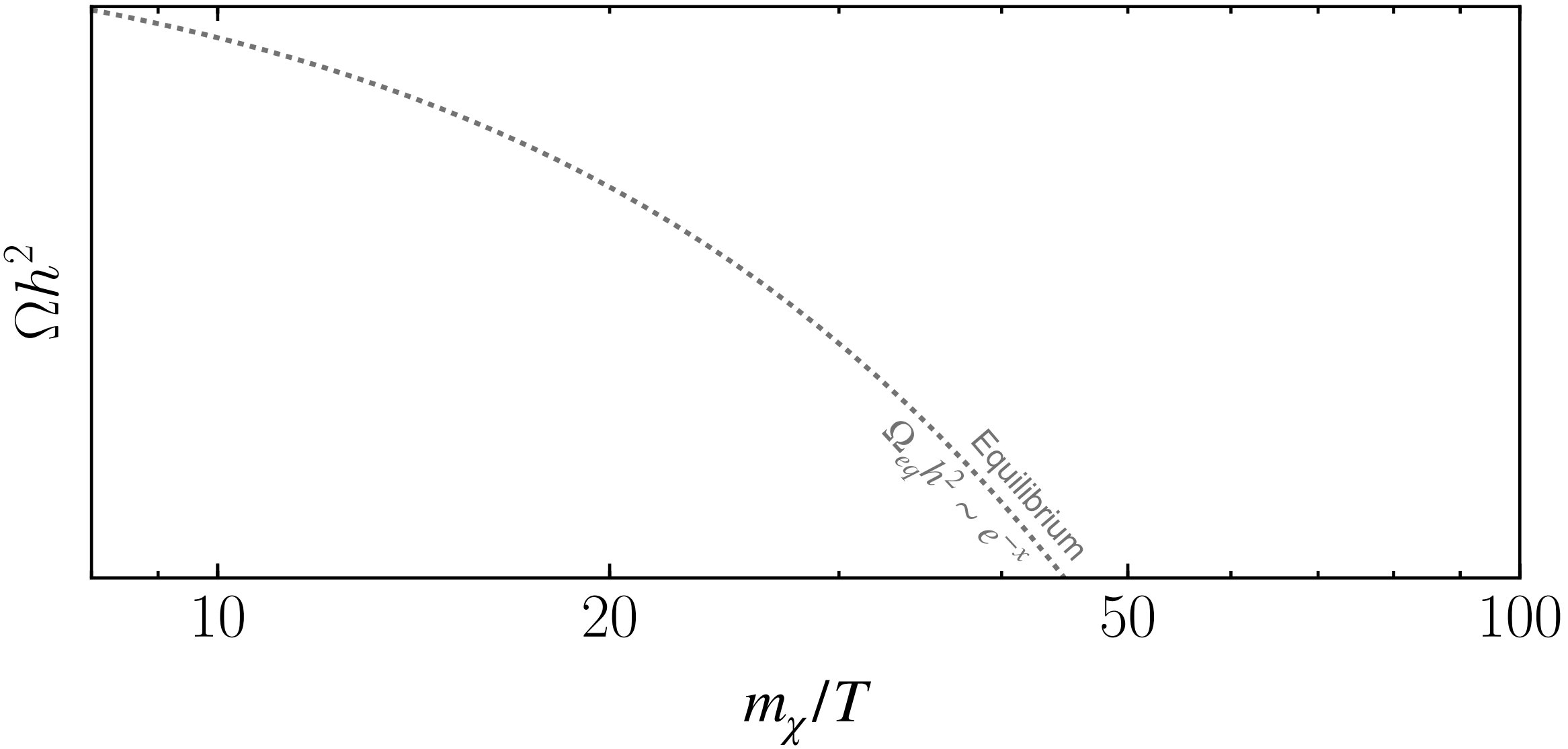
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- Parity Symmetric Left-Right Models

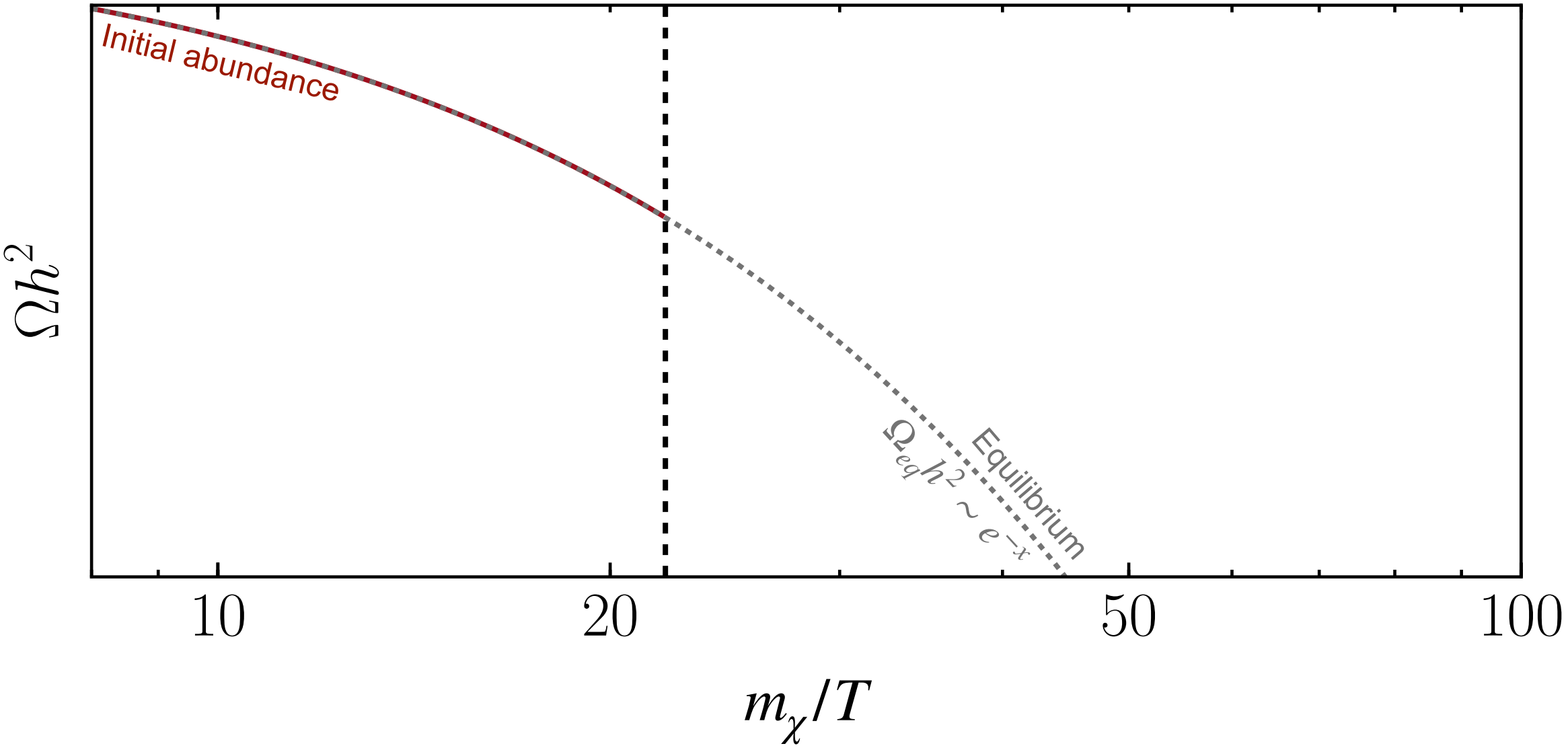
## Outline

- WIMP Dark Matter Embeddings
- Upper Bound on Parity Breaking Scale
- Constraints on Parameter Space

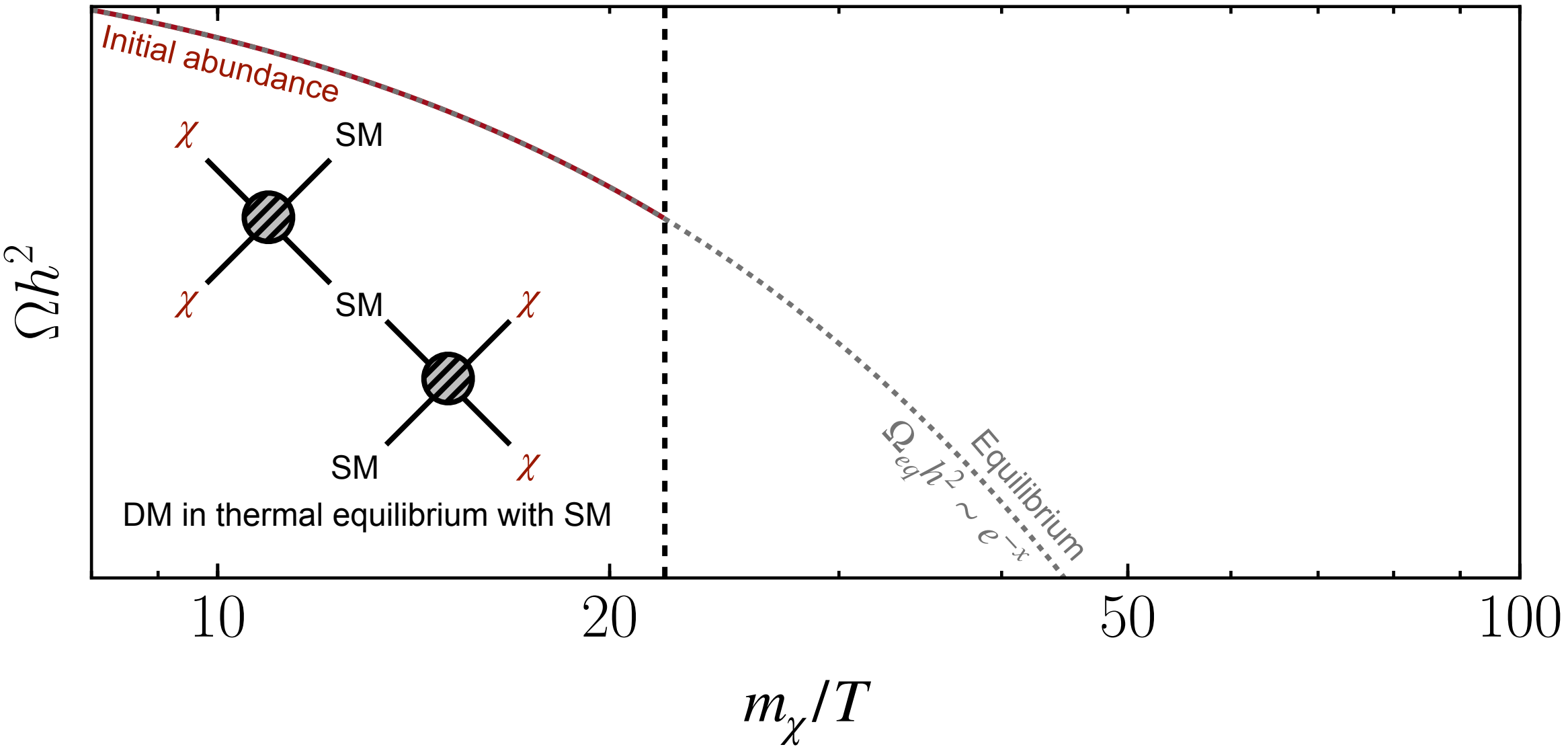
# Freeze-out in Parity Symmetric Left-Right Models



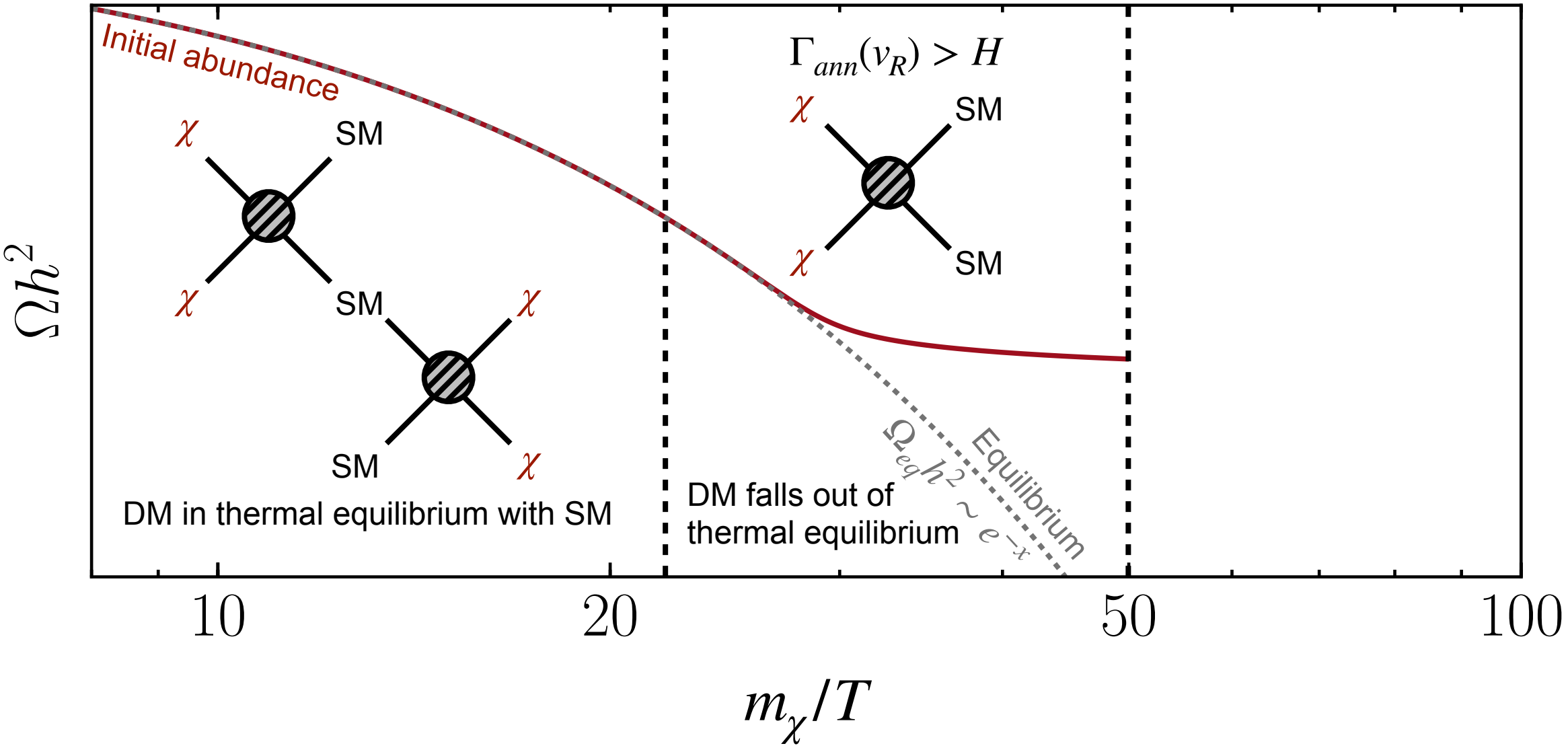
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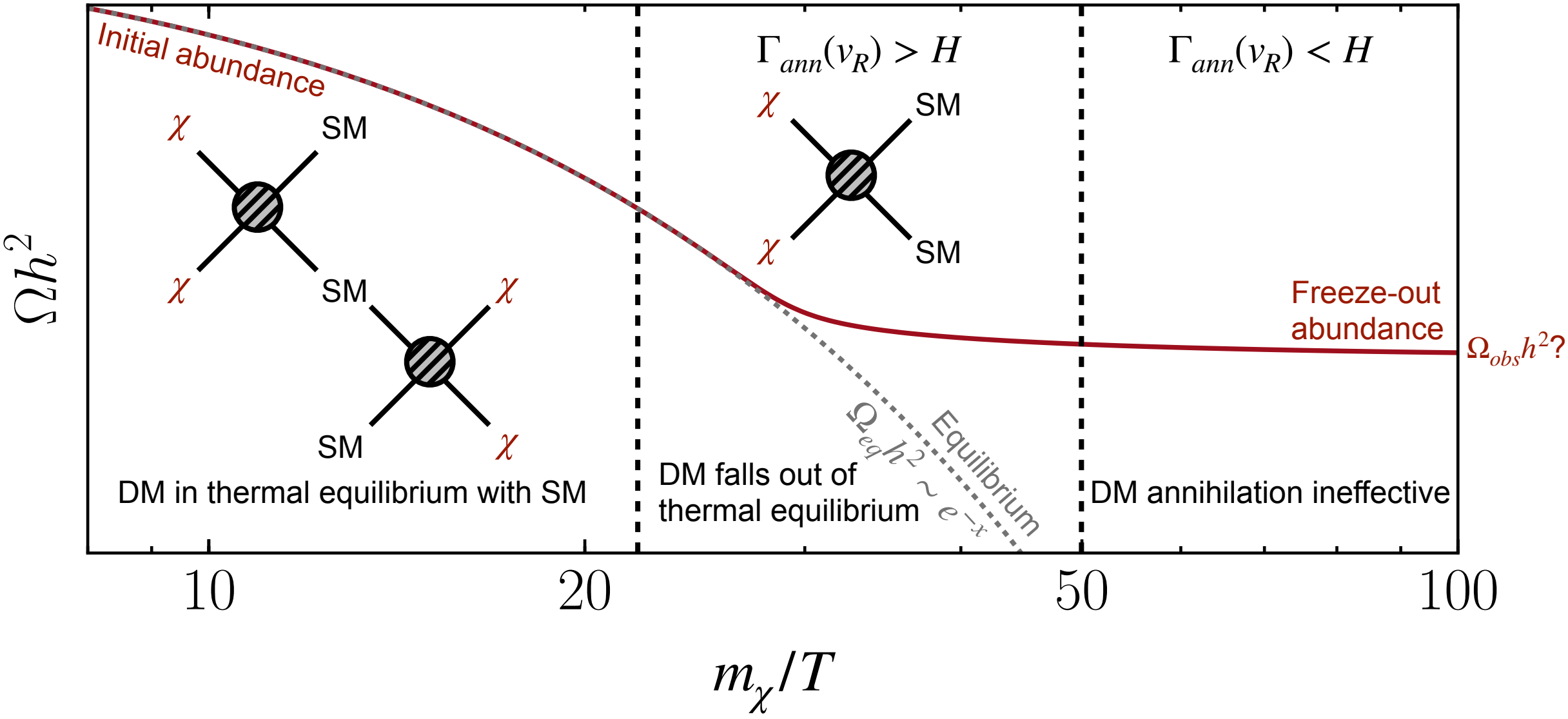
# Freeze-out in Parity Symmetric Left-Right Models



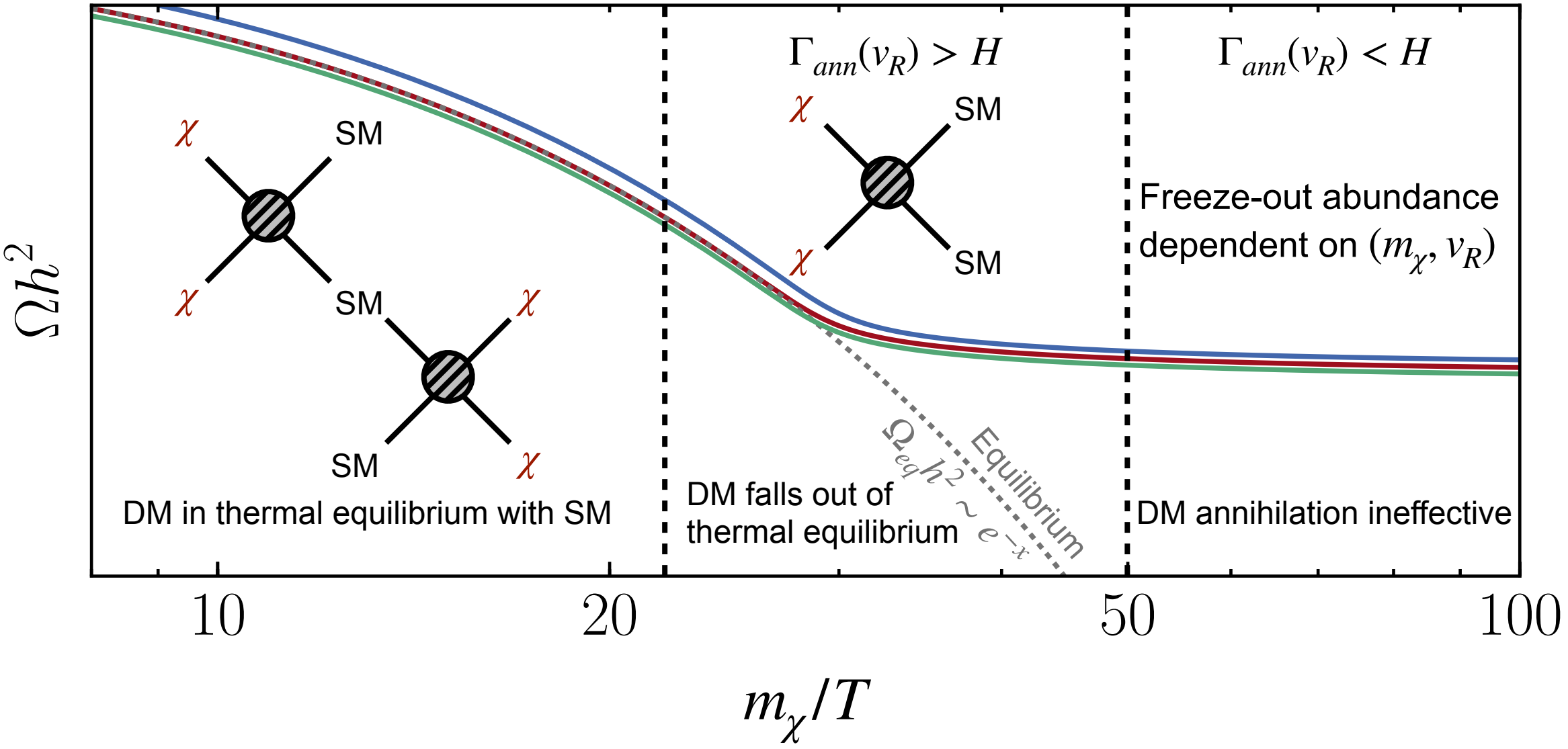
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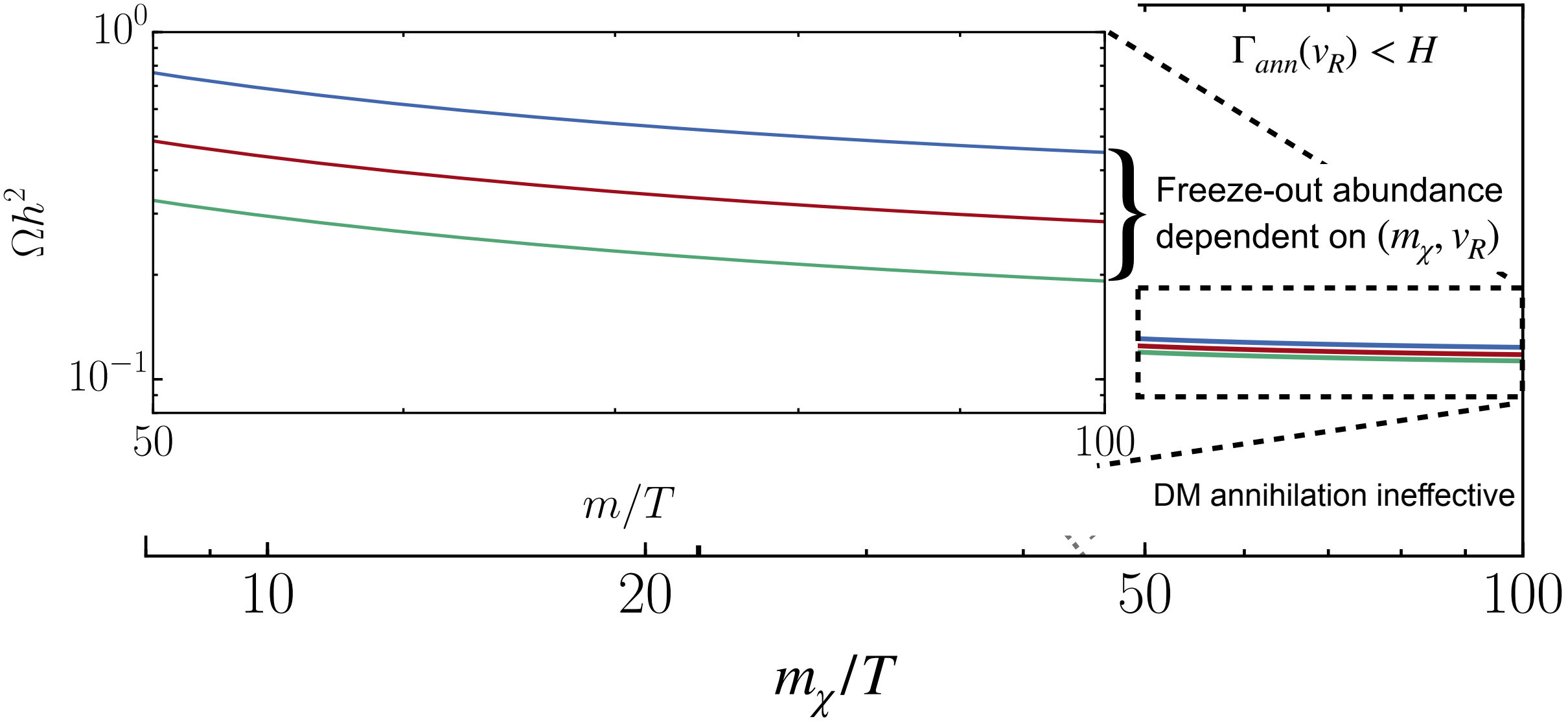
# Freeze-out in Parity Symmetric Left-Right Models



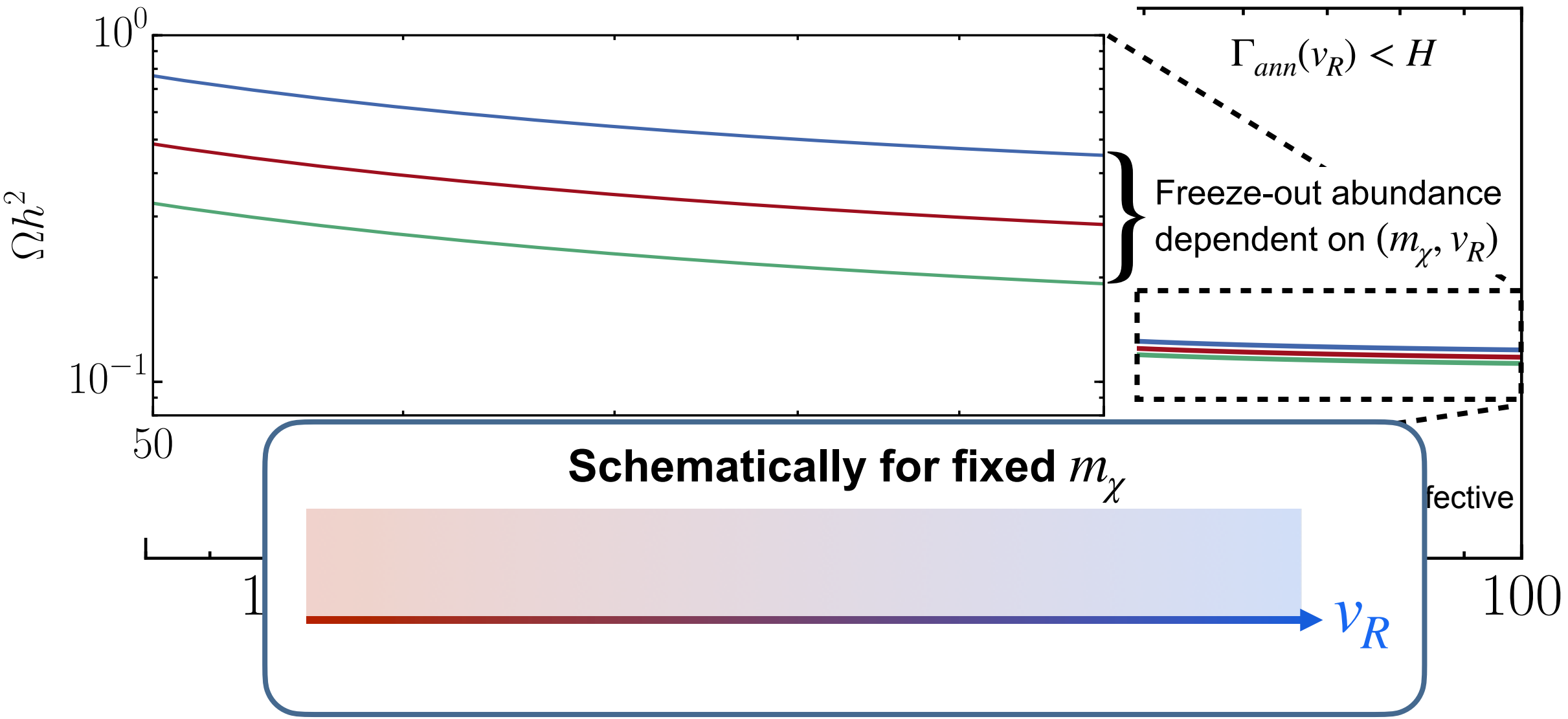
# Freeze-out in Parity Symmetric Left-Right Models



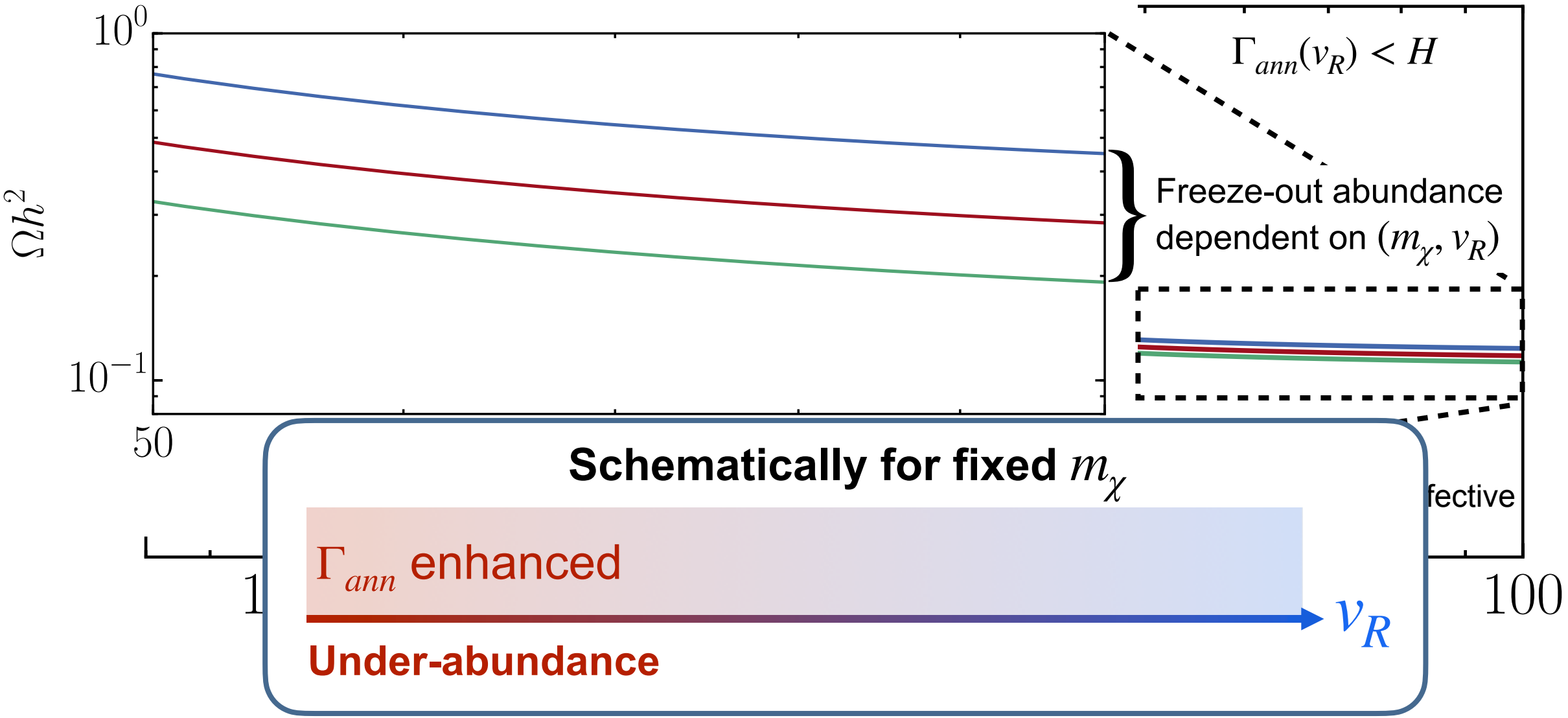
# Freeze-out in Parity Symmetric Left-Right Models



# Freeze-out in Parity Symmetric Left-Right Models



# Freeze-out in Parity Symmetric Left-Right Models



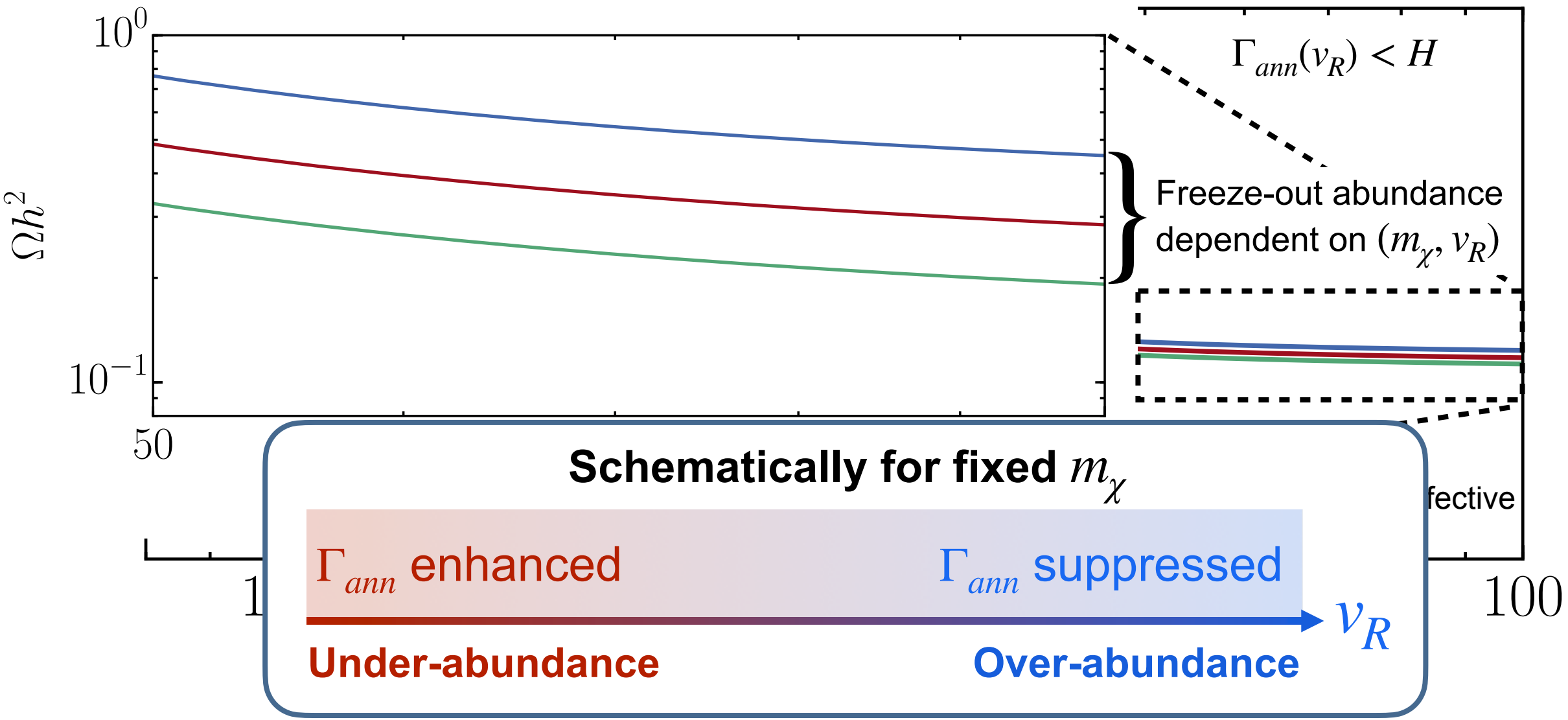

**Schematically for fixed $m_\chi$**

$\Gamma_{ann}$ enhanced

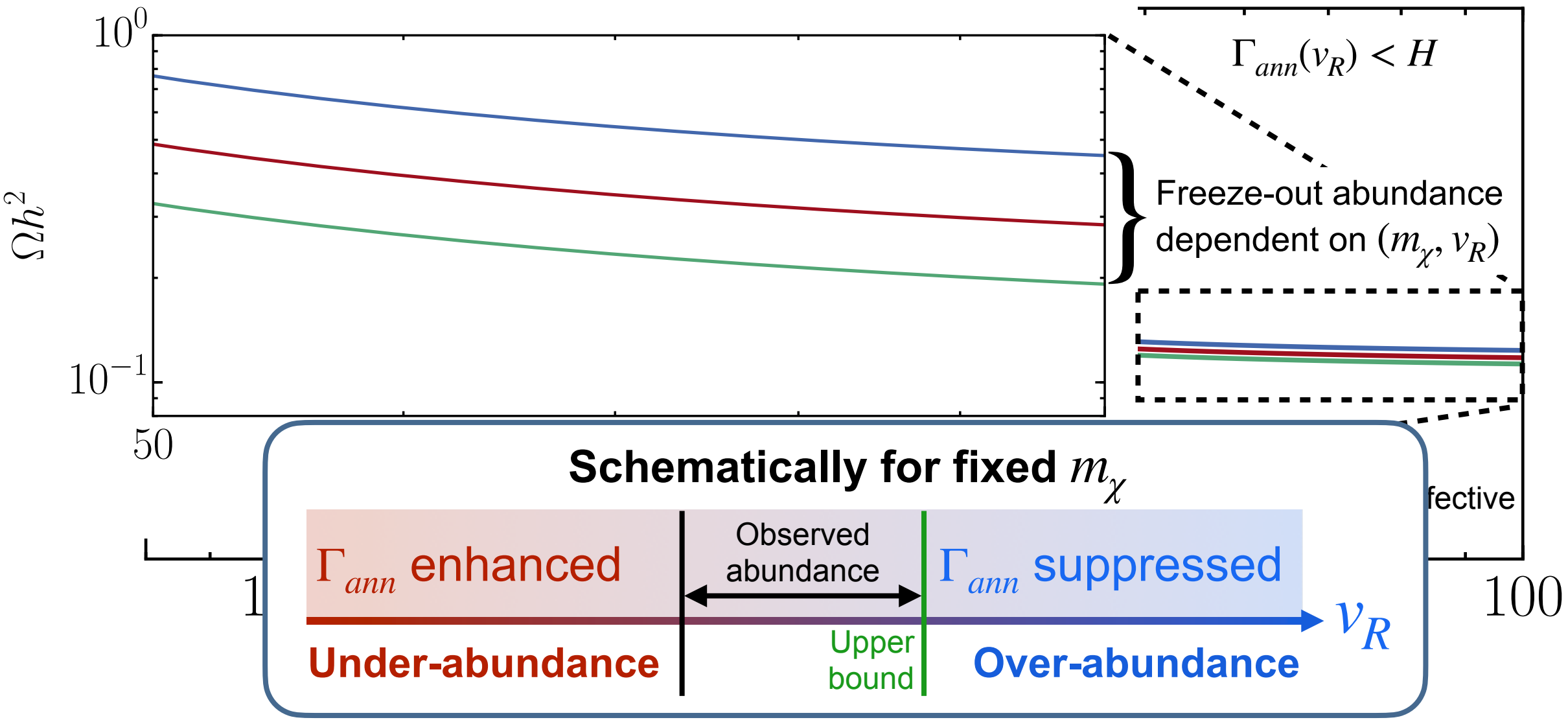
$v_R$

**Under-abundance**

# Freeze-out in Parity Symmetric Left-Right Models



# Freeze-out in Parity Symmetric Left-Right Models



# Thermal Relic Abundance

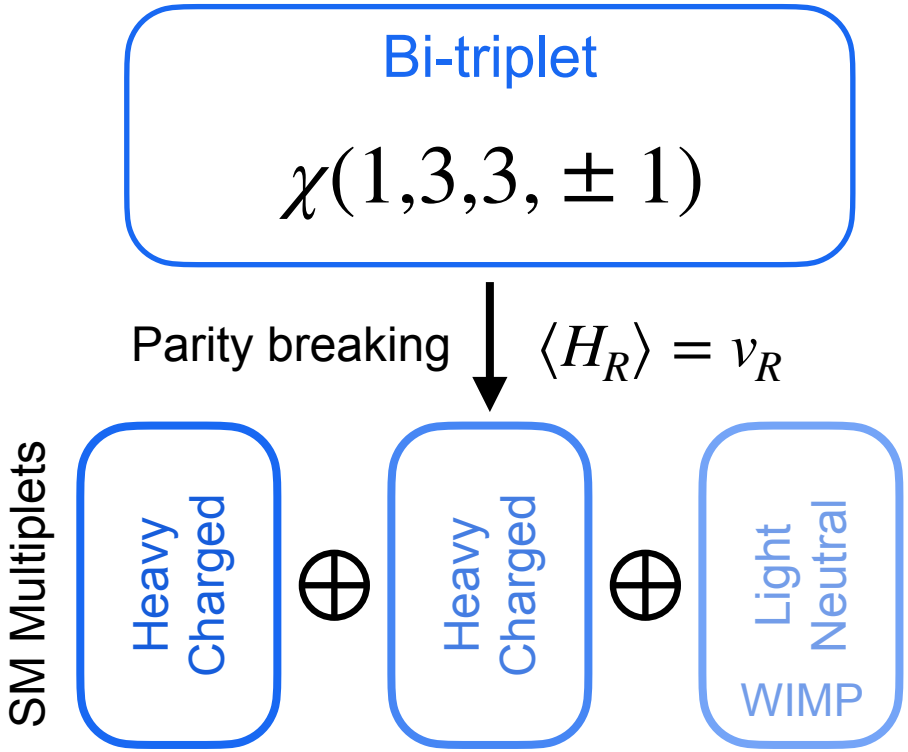
Example:$(1,3,3,\pm 1)$, $v_R = 40$ TeV

Bi-triplet

$\chi(1,3,3,\pm 1)$

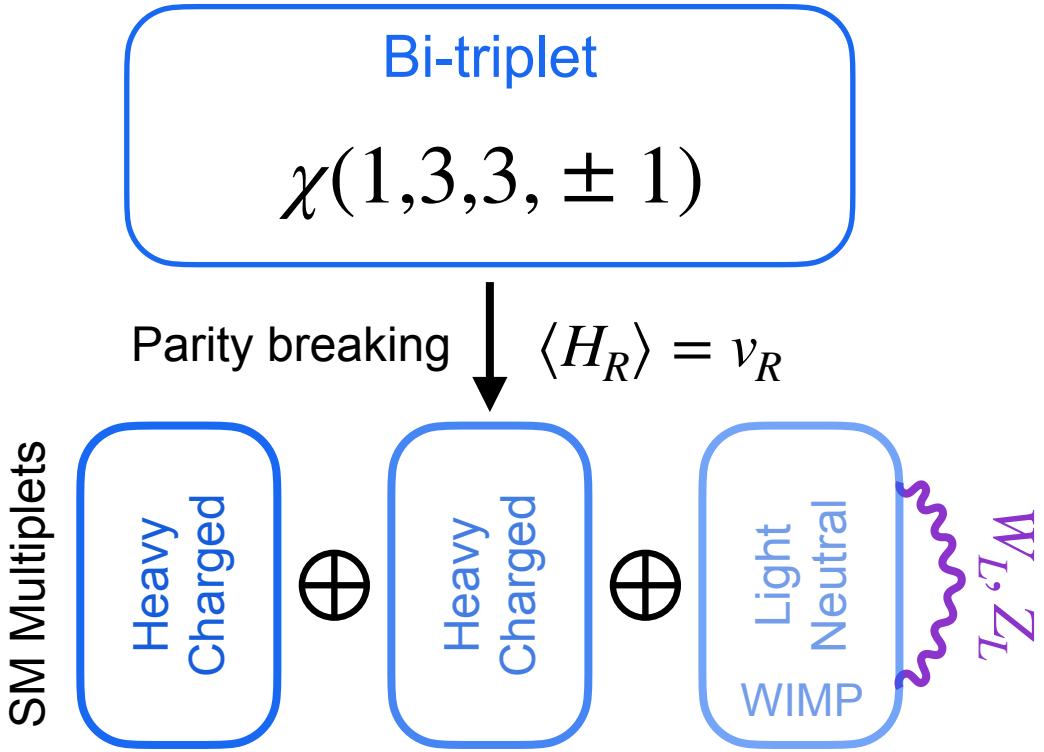
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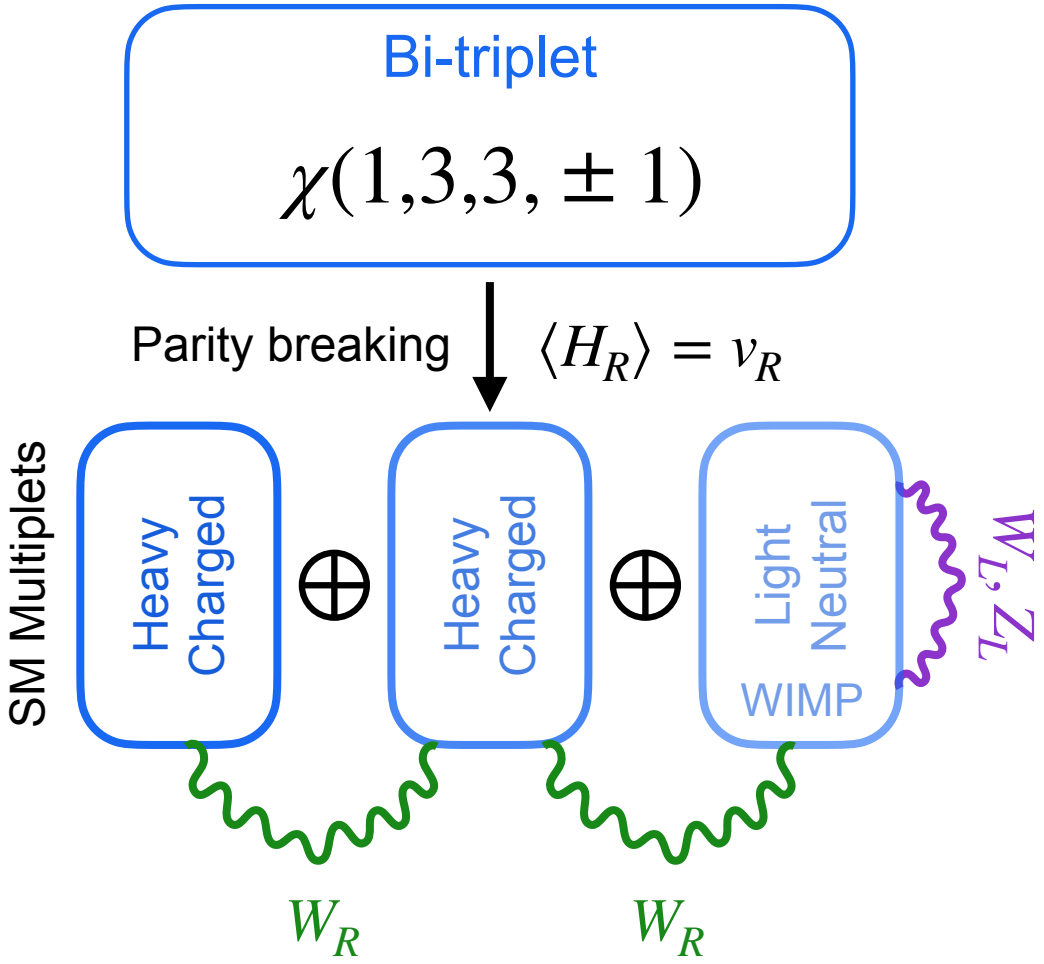
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Example:$(1,3,3,\pm 1)$, $v_R = 40$ TeV

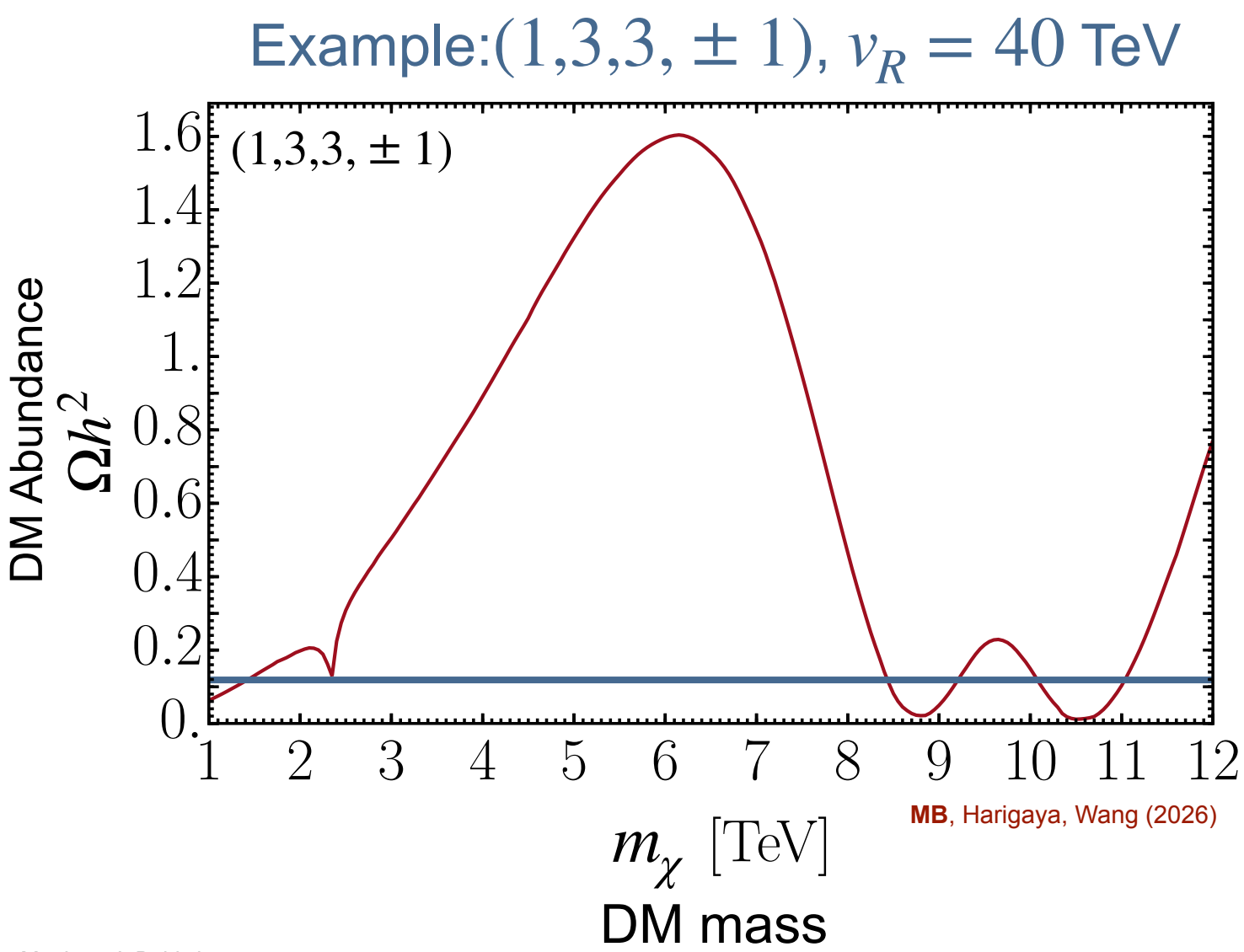


# Thermal Relic Abundance

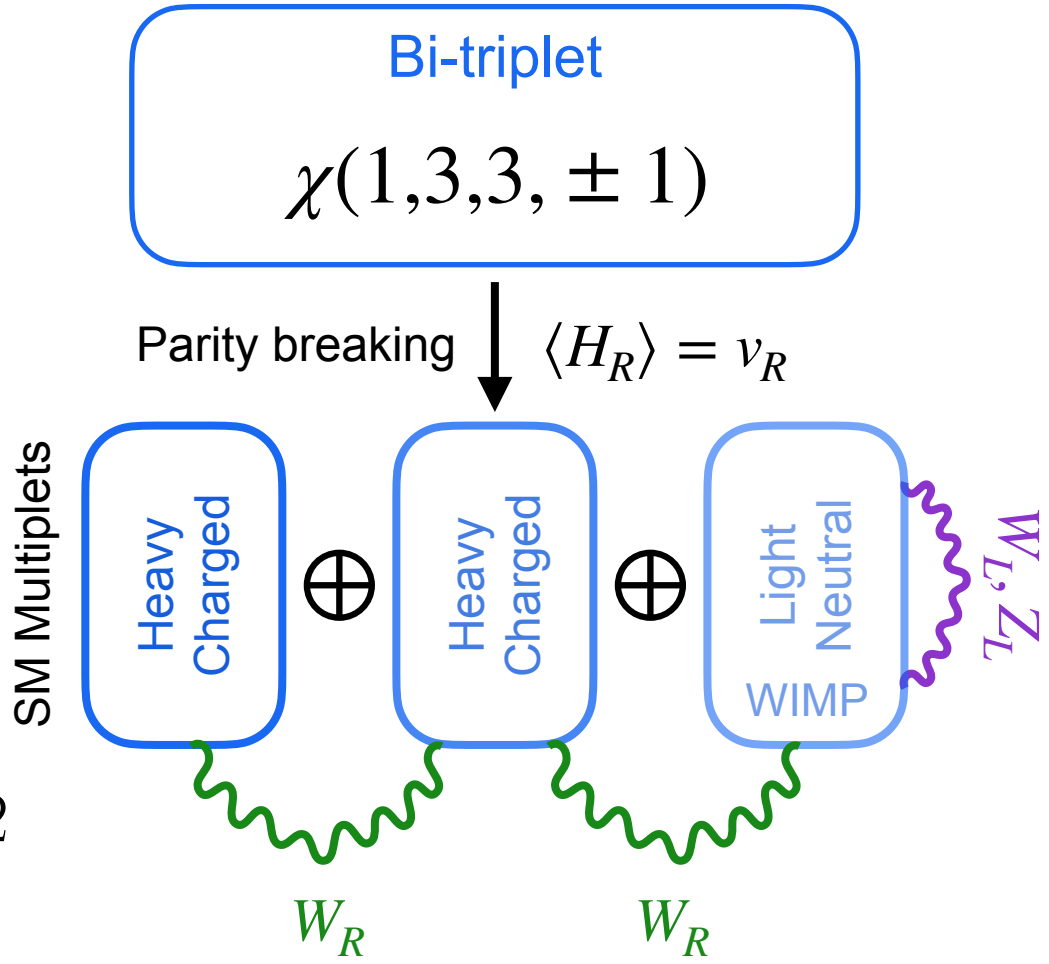
Example:$(1,3,3,\pm 1)$, $v_R = 40$ TeV



# Thermal Relic Abundance

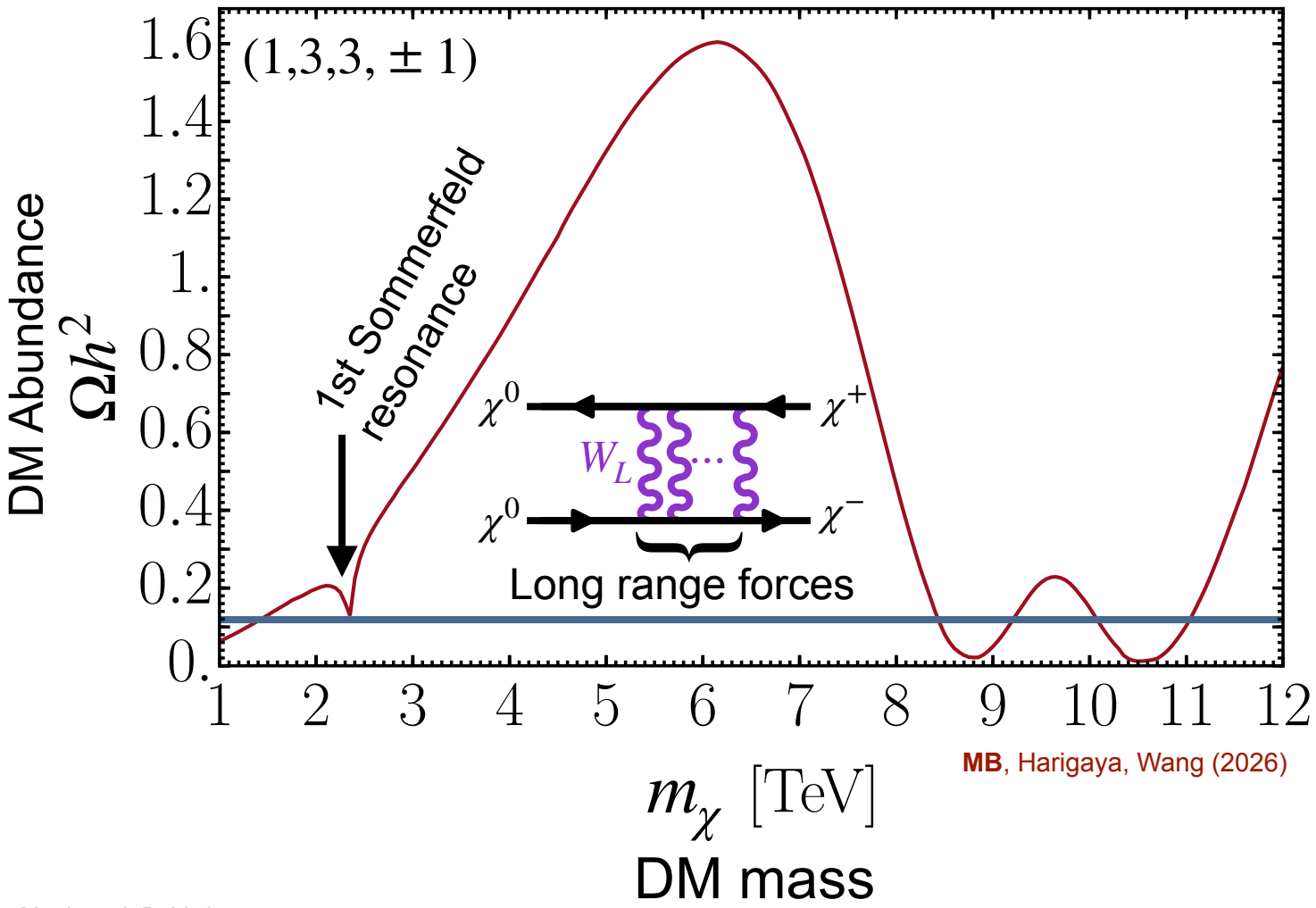



**MB**, Harigaya, Wang (2026)

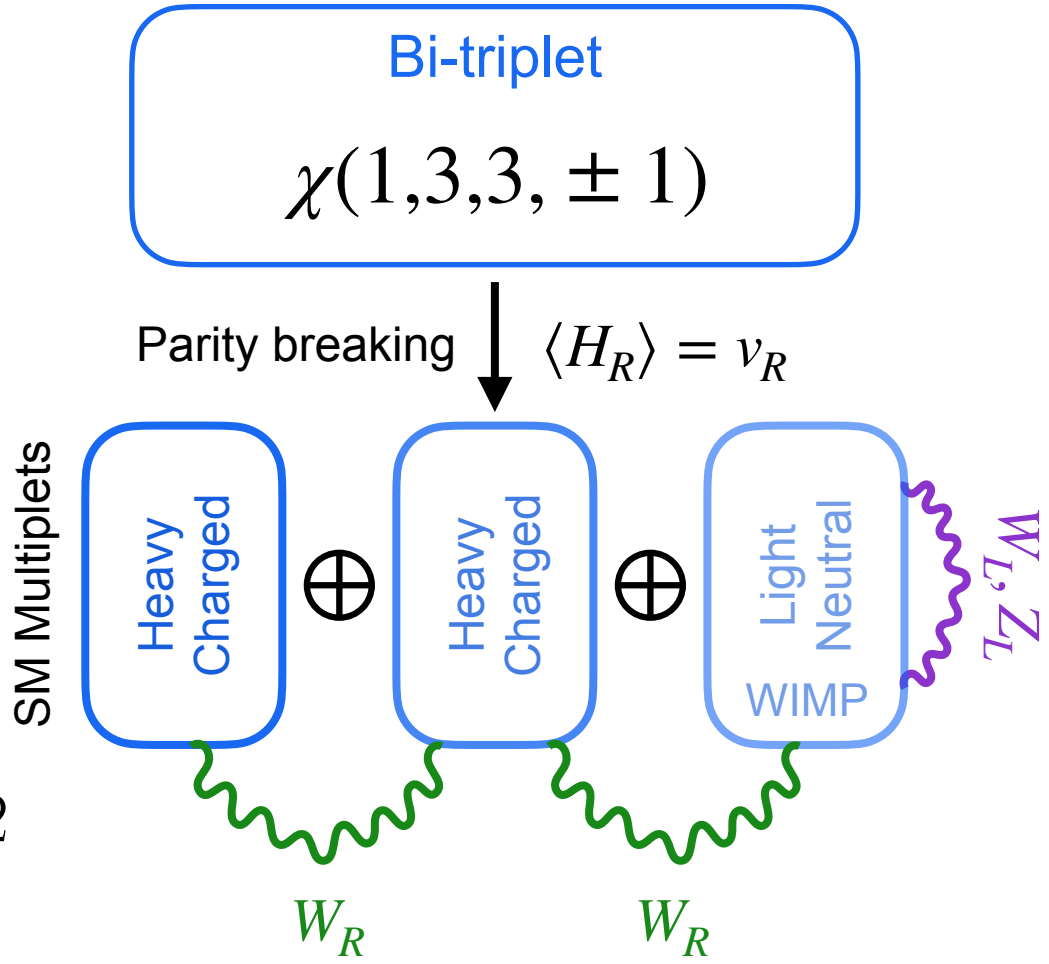


# Thermal Relic Abundance

## Example:$(1,3,3,\pm 1)$, $v_R = 40$ TeV

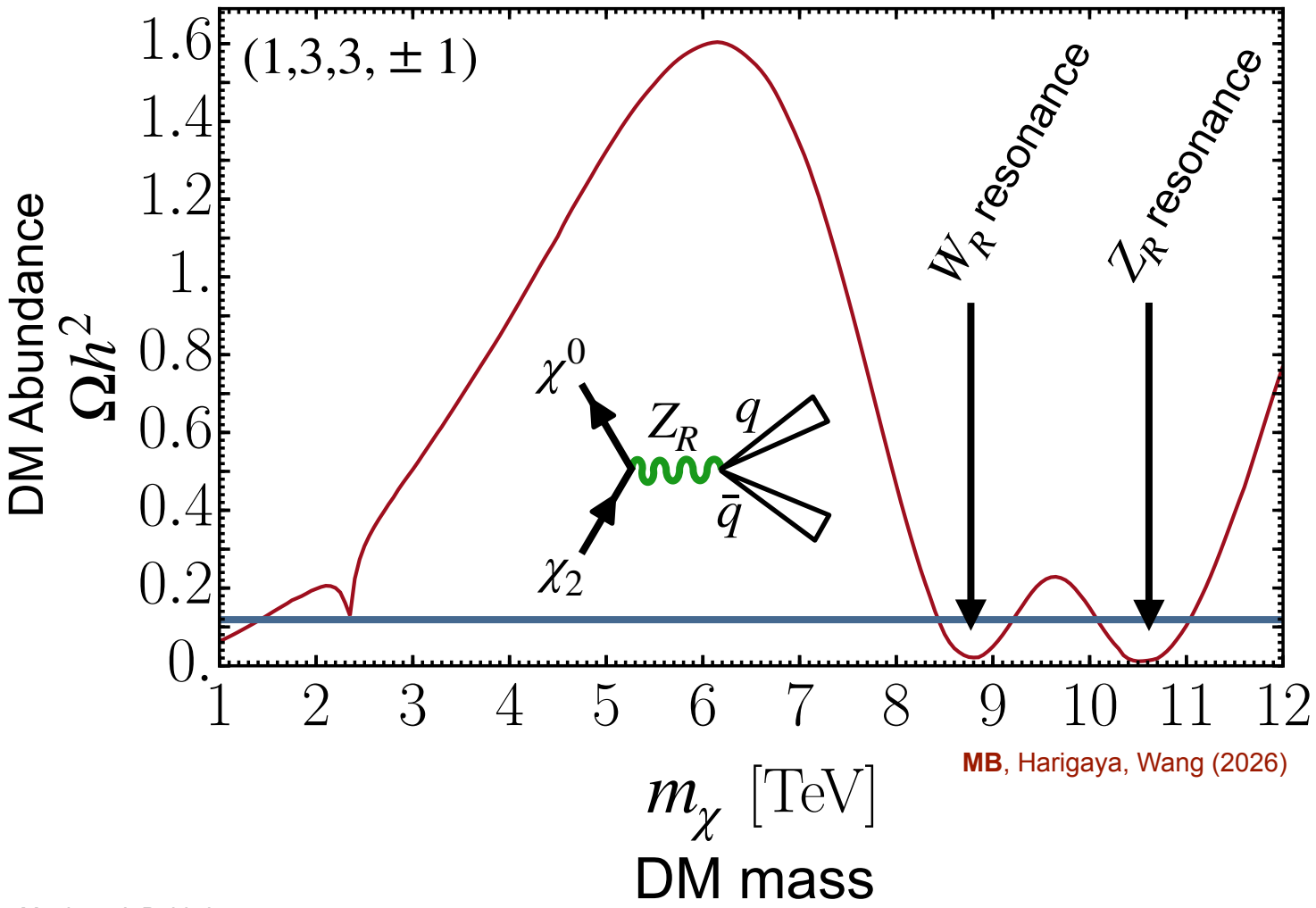



**MB**, Harigaya, Wang (2026)

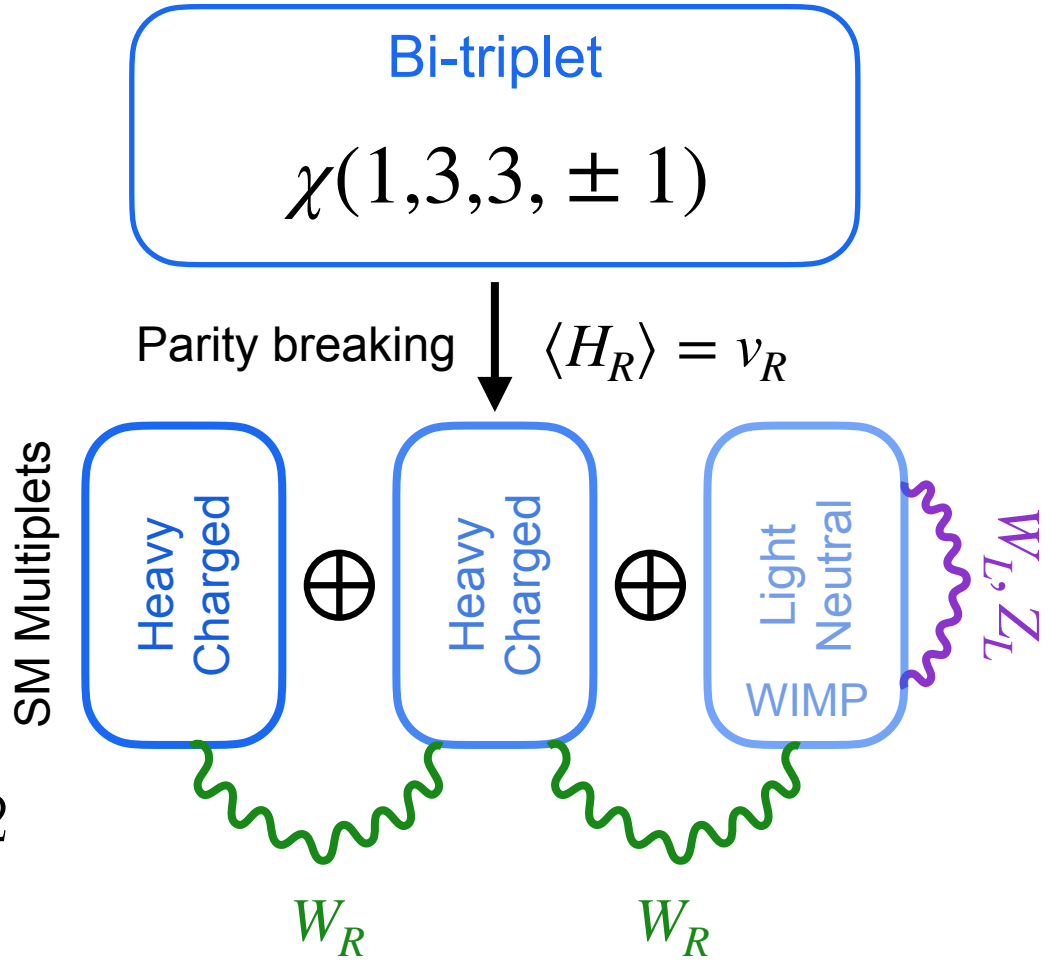


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Example:$(1,3,3,\pm 1)$, $v_R = 40$ TeV

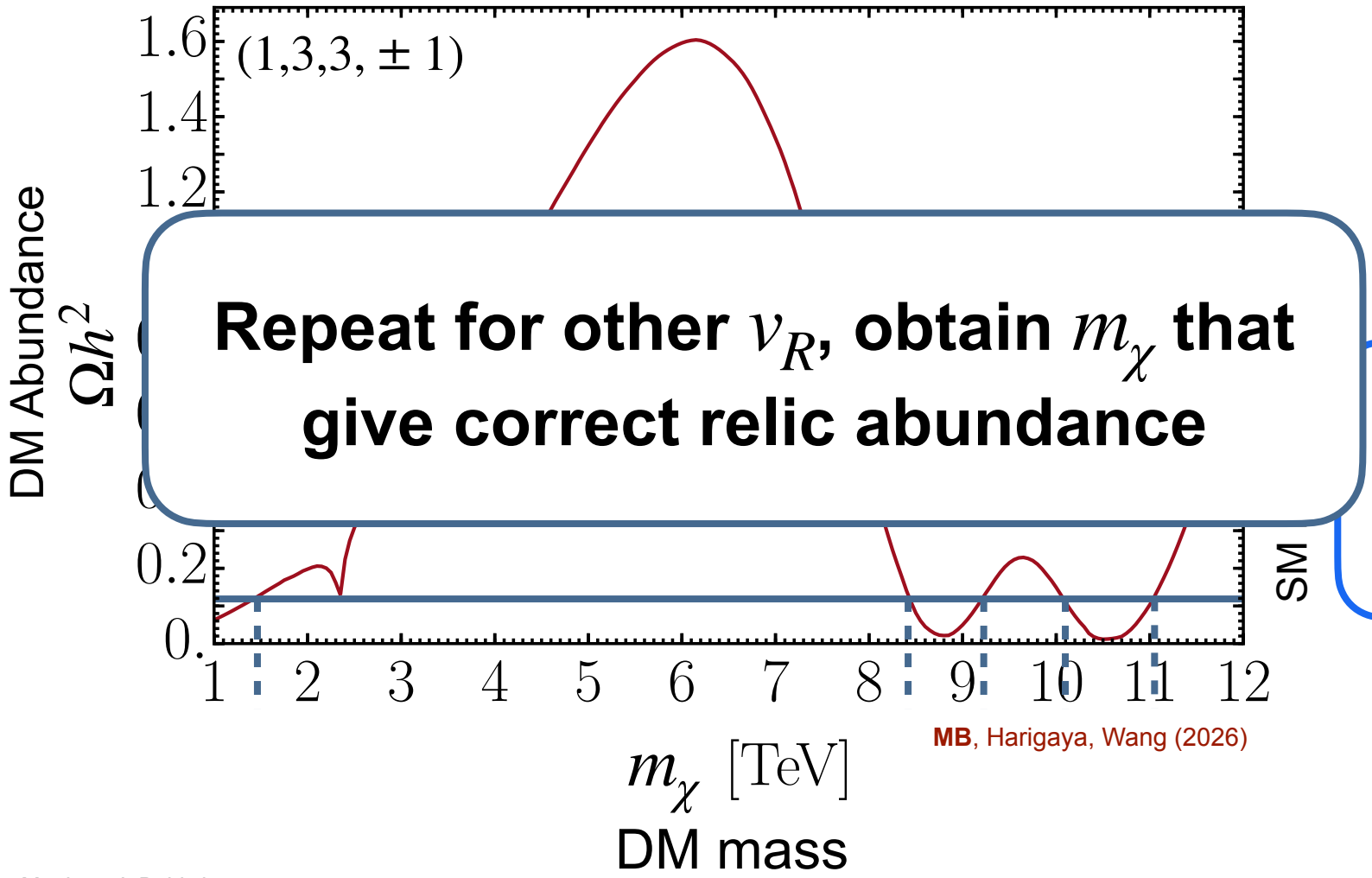



**MB**, Harigaya, Wang (2026)



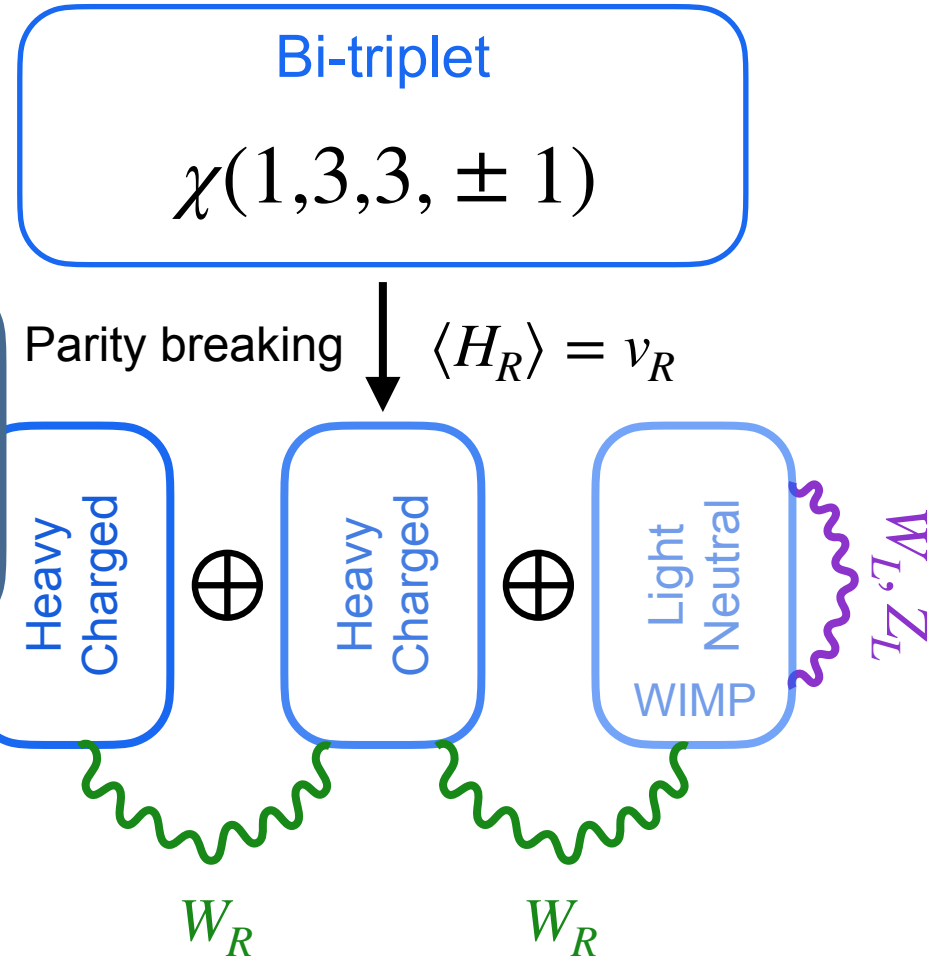
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Example:$(1,3,3,\pm 1)$, $v_R = 40$ TeV

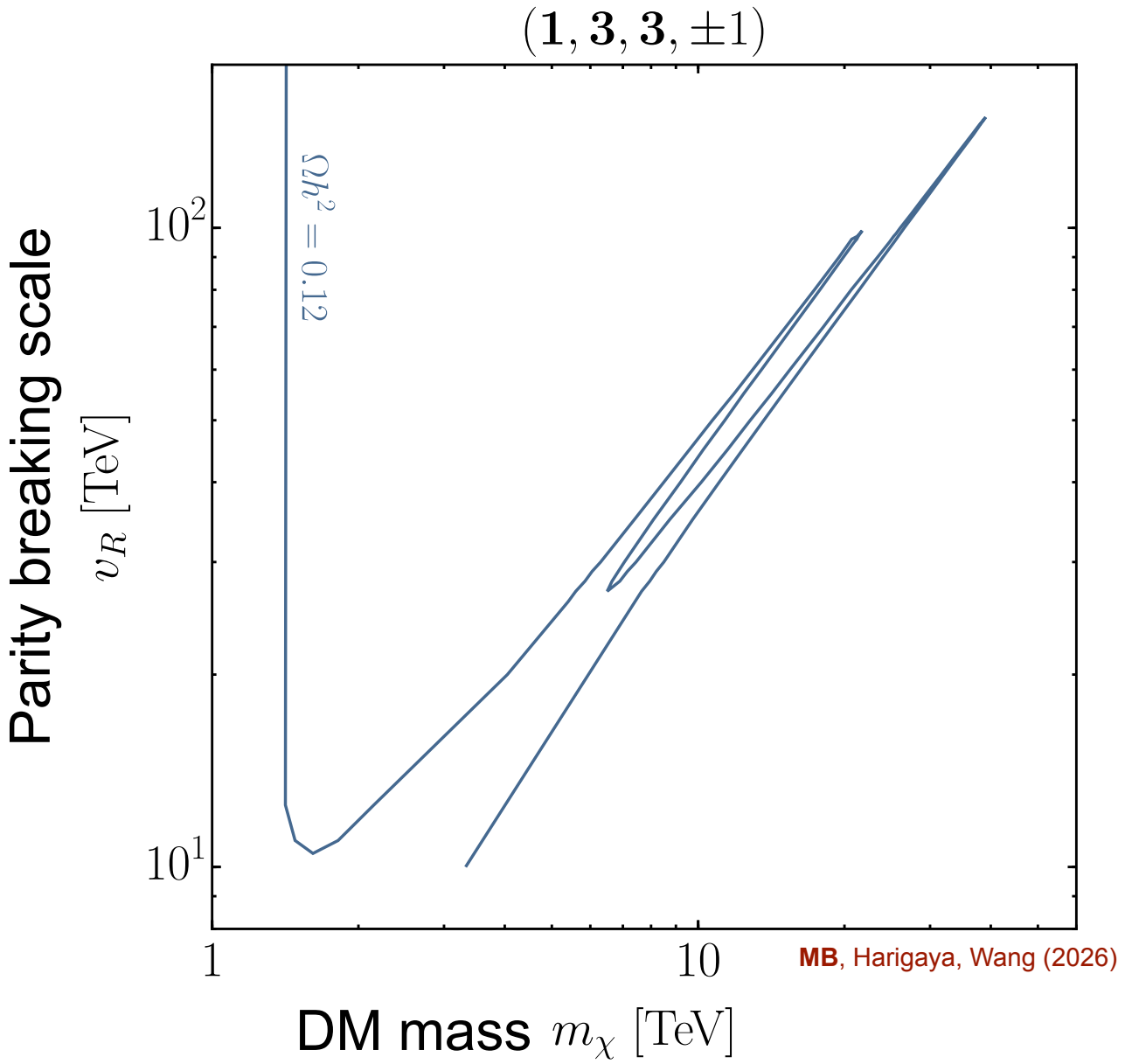



**Repeat for other $v_R$, obtain $m_\chi$ that give correct relic abundance**

**MB**, Harigaya, Wang (2026)

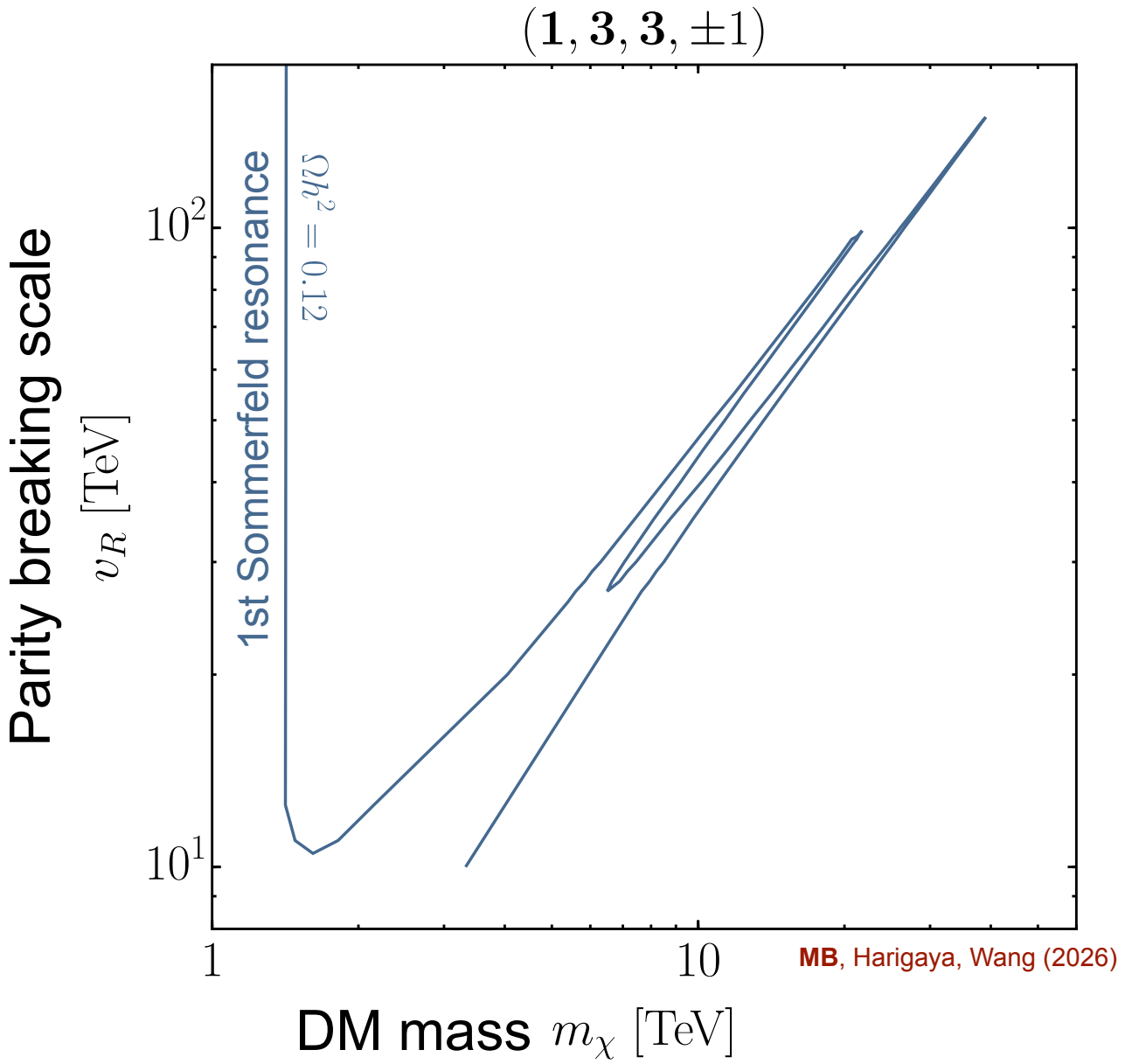


# Thermal Relic Abundance



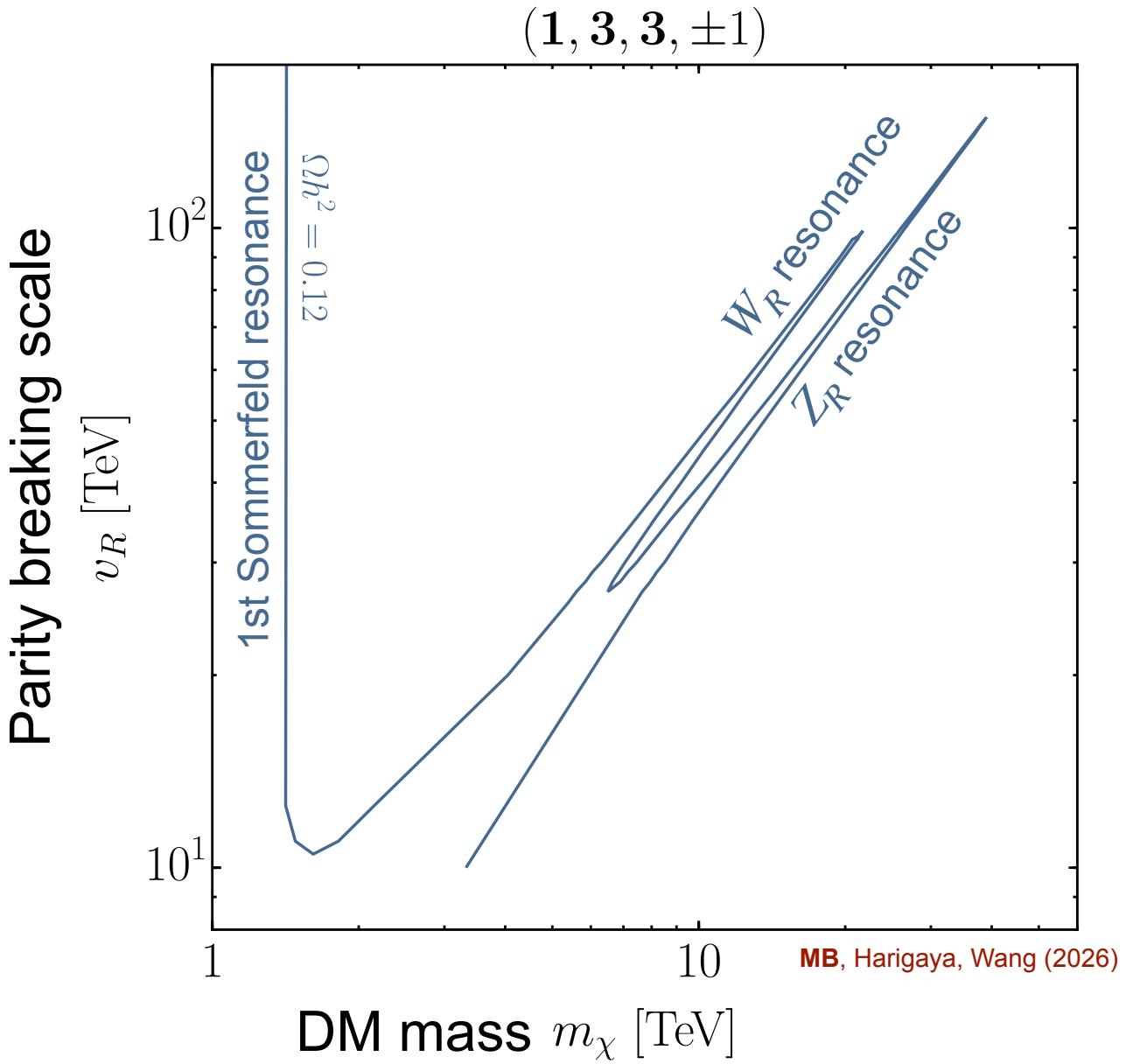

**MB**, Harigaya, Wang (2026)

# Thermal Relic Abundance



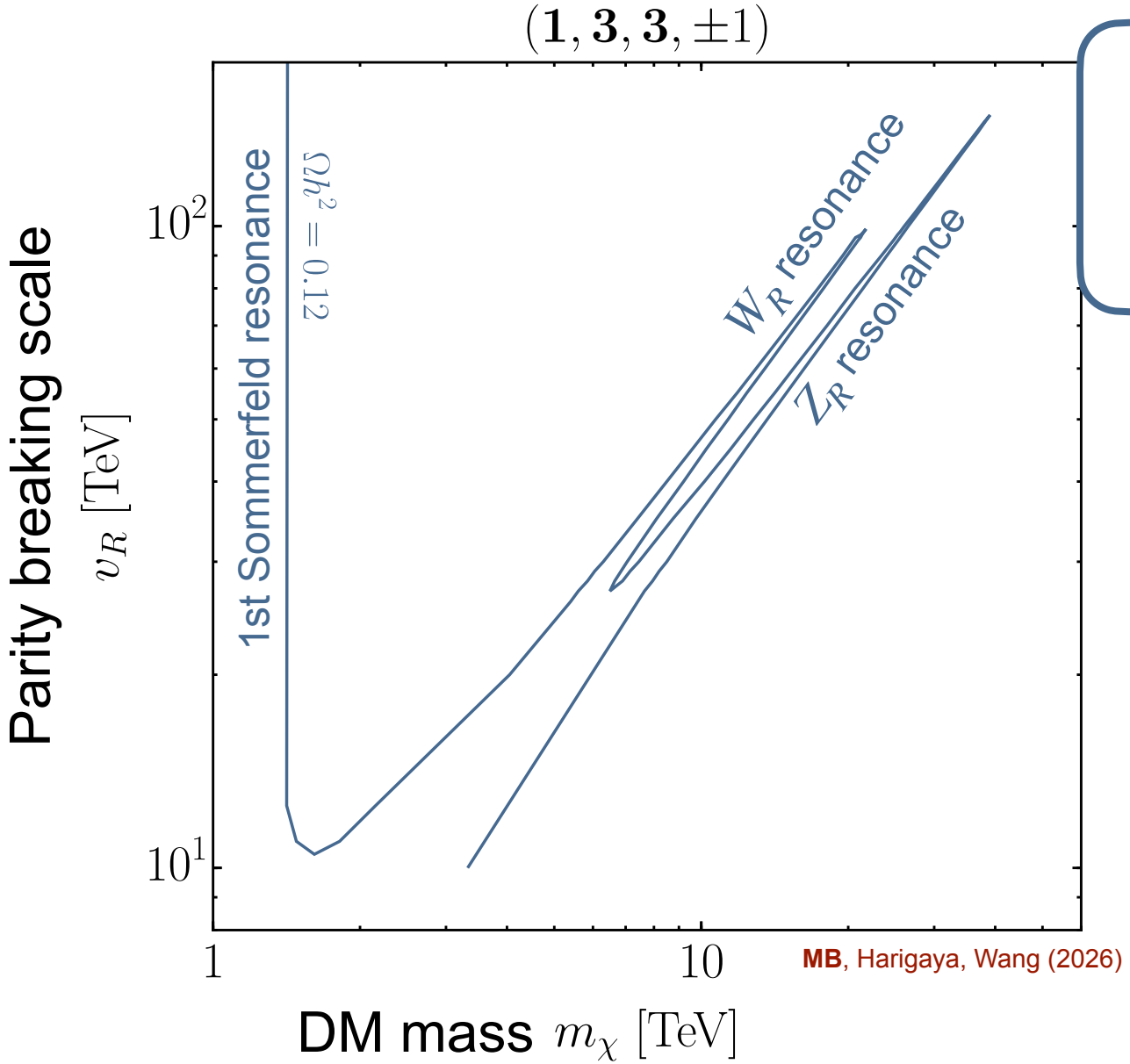

**MB**, Harigaya, Wang (2026)

# Thermal Relic Abundance




**MB**, Harigaya, Wang (2026)

# Thermal Relic Abundance

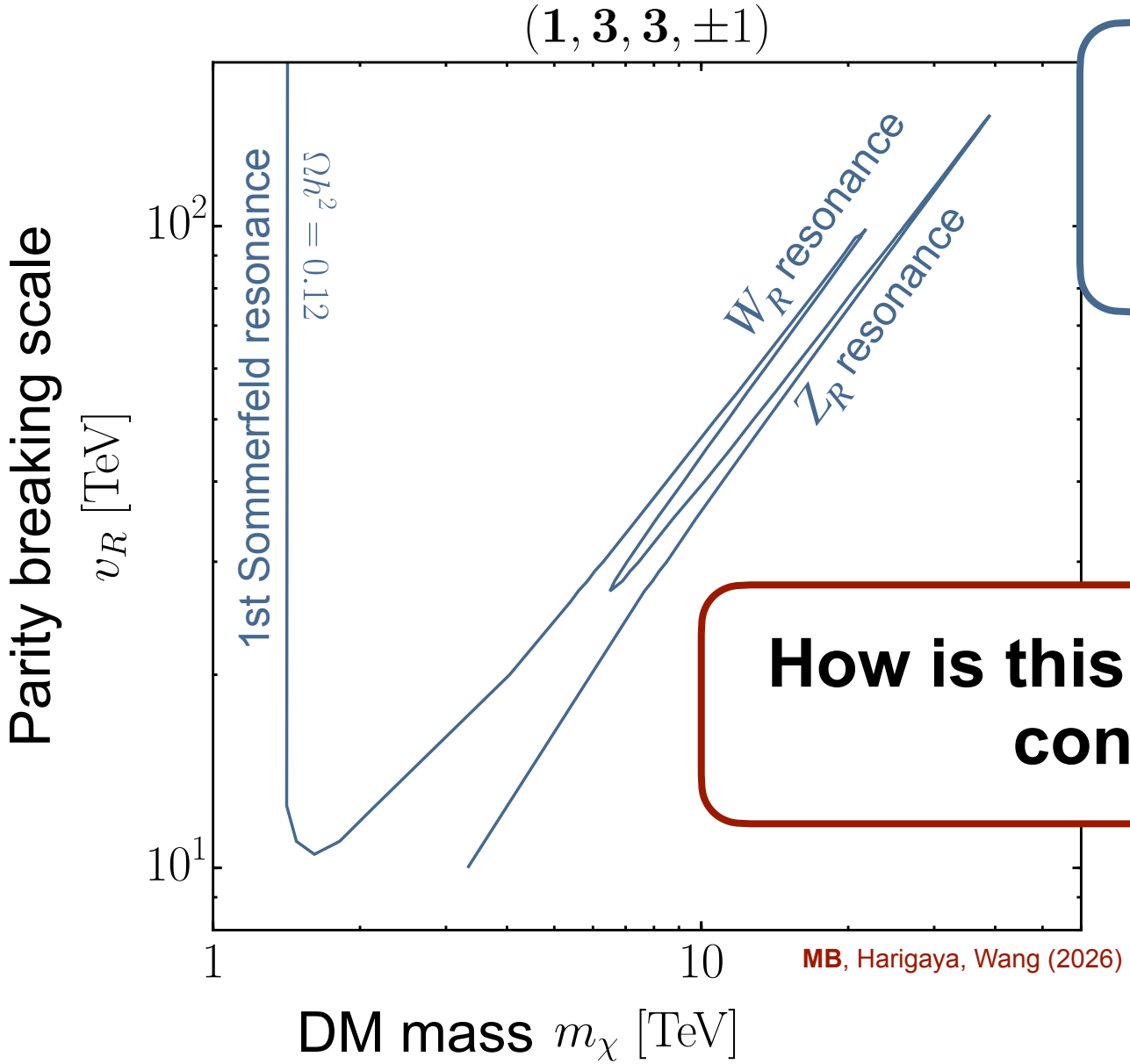



**Upper bound**

$v_R \lesssim 150$ **TeV**

**MB**, Harigaya, Wang (2026)

# Thermal Relic Abundance




**Upper bound**

$v_R \lesssim 150$ **TeV**

**How is this parameter space constrained?**

**MB**, Harigaya, Wang (2026)

# Overview

## Introduction

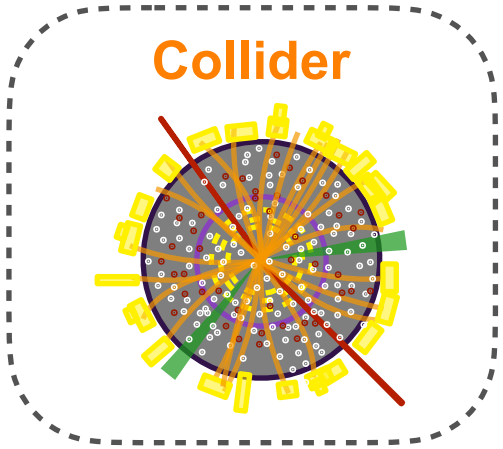
- Parity Symmetric Left-Right Models

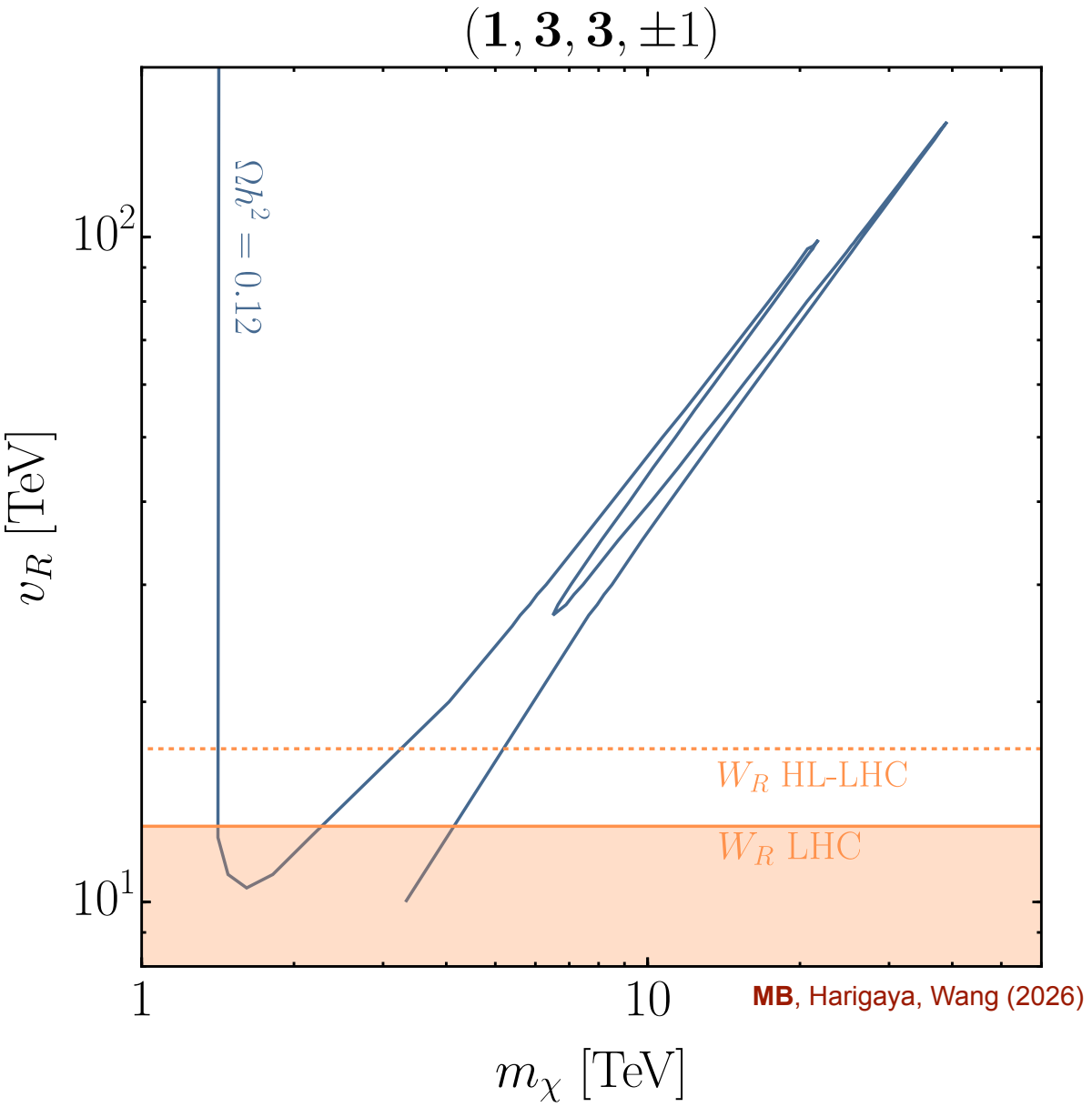
## Outline

- WIMP Dark Matter Embeddings
- Upper Bound on Parity Breaking Scale
- Constraints on Parameter Space

# Collider Constraints

**Constraints:**

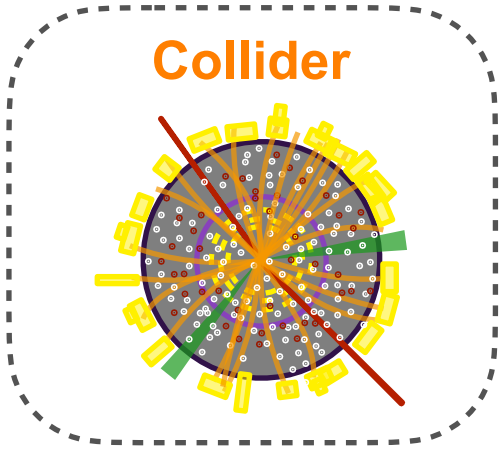


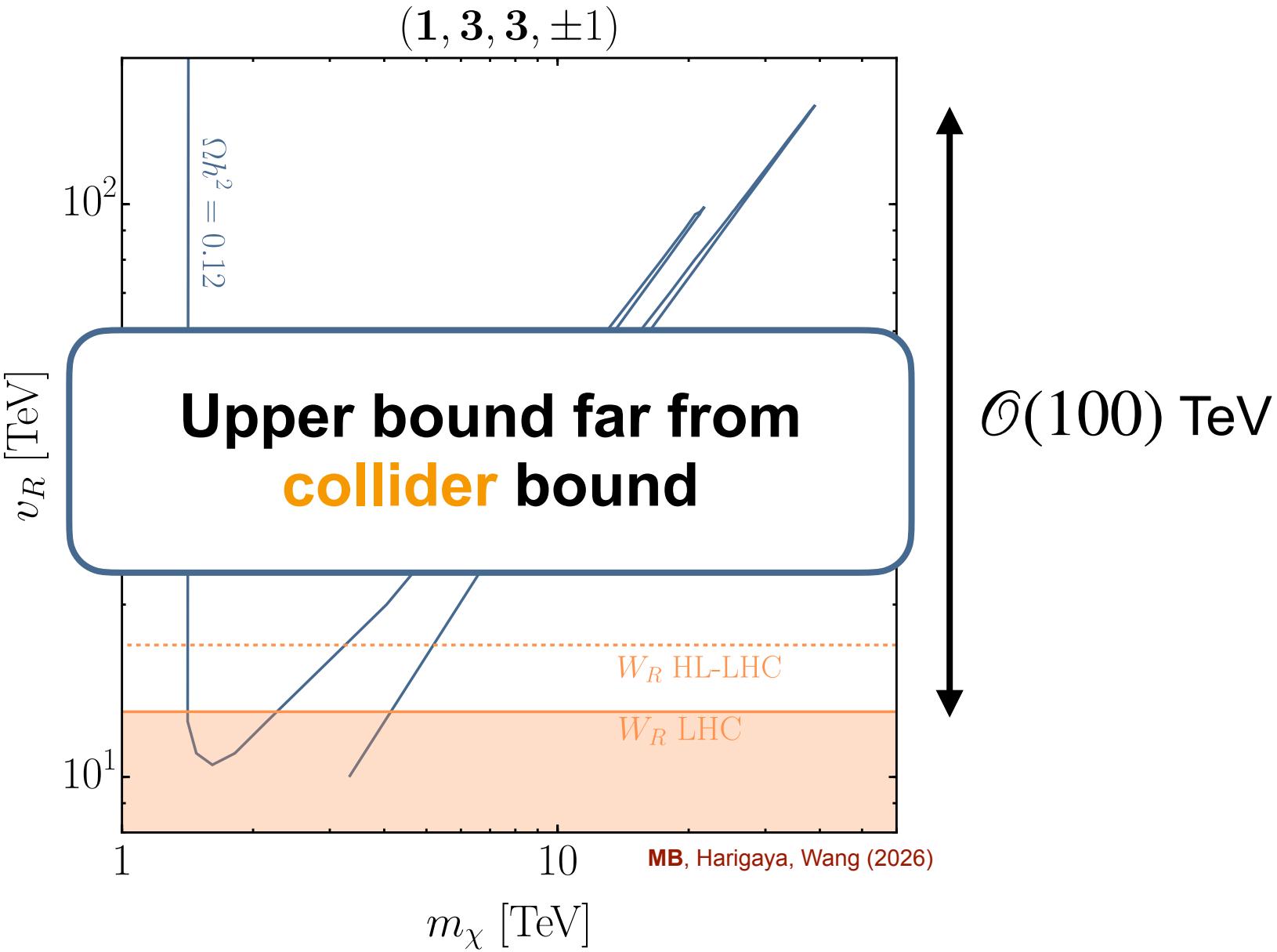




**MB**, Harigaya, Wang (2026)

# Collider Constraints

**Constraints:**



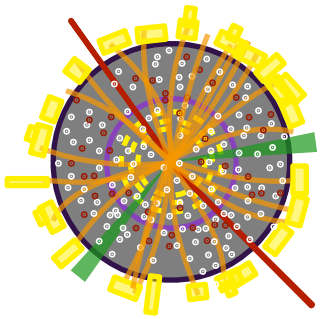




**MB**, Harigaya, Wang (2026)

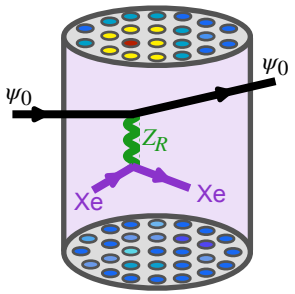
# Direct Detection

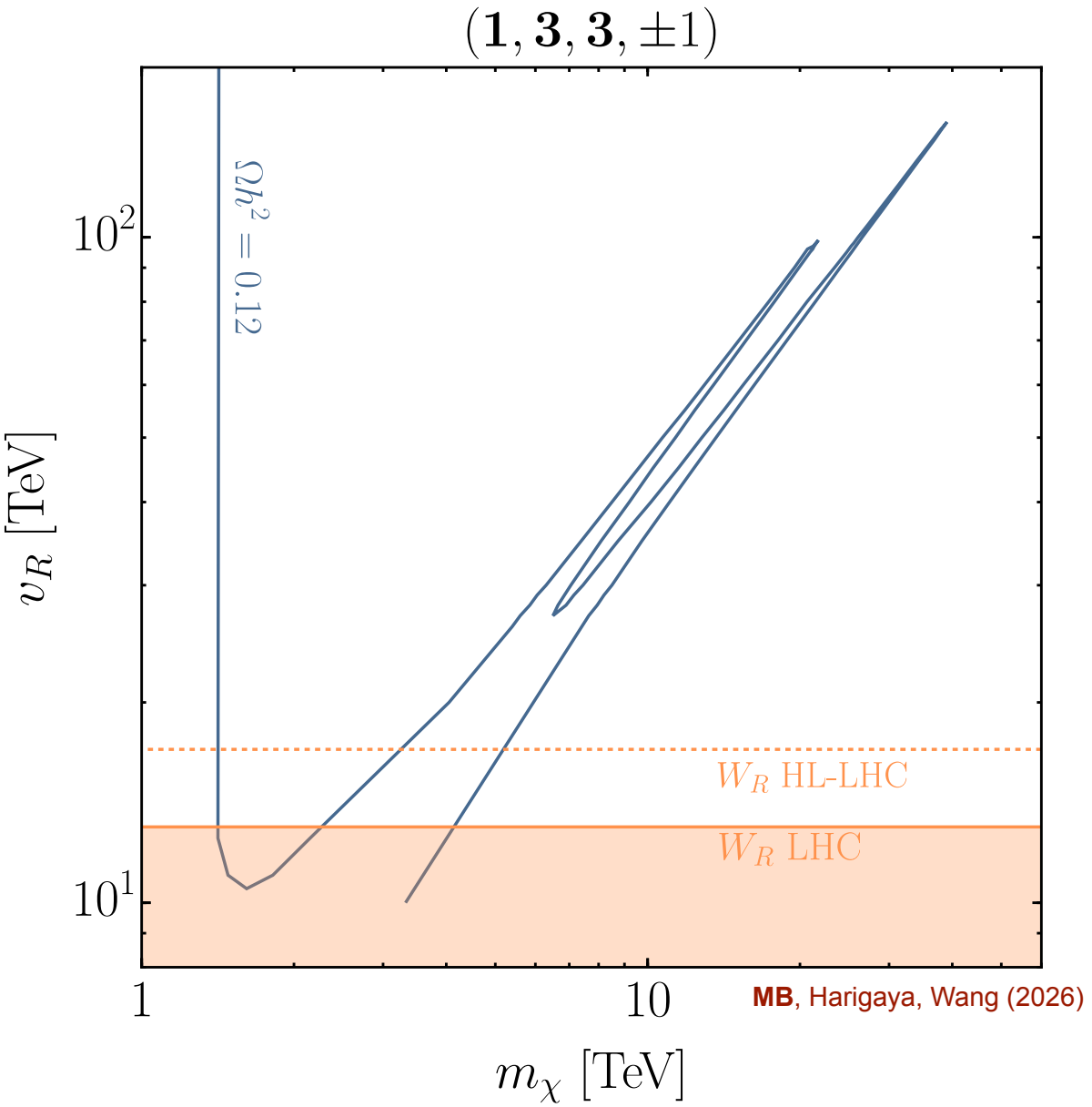
**Constraints:**

**Collider**



**Direct detection**



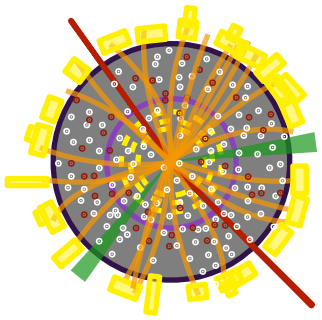




**MB**, Harigaya, Wang (2026)

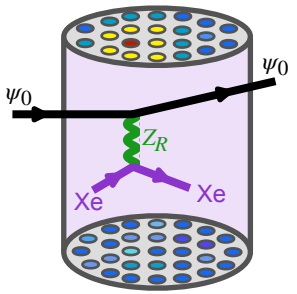
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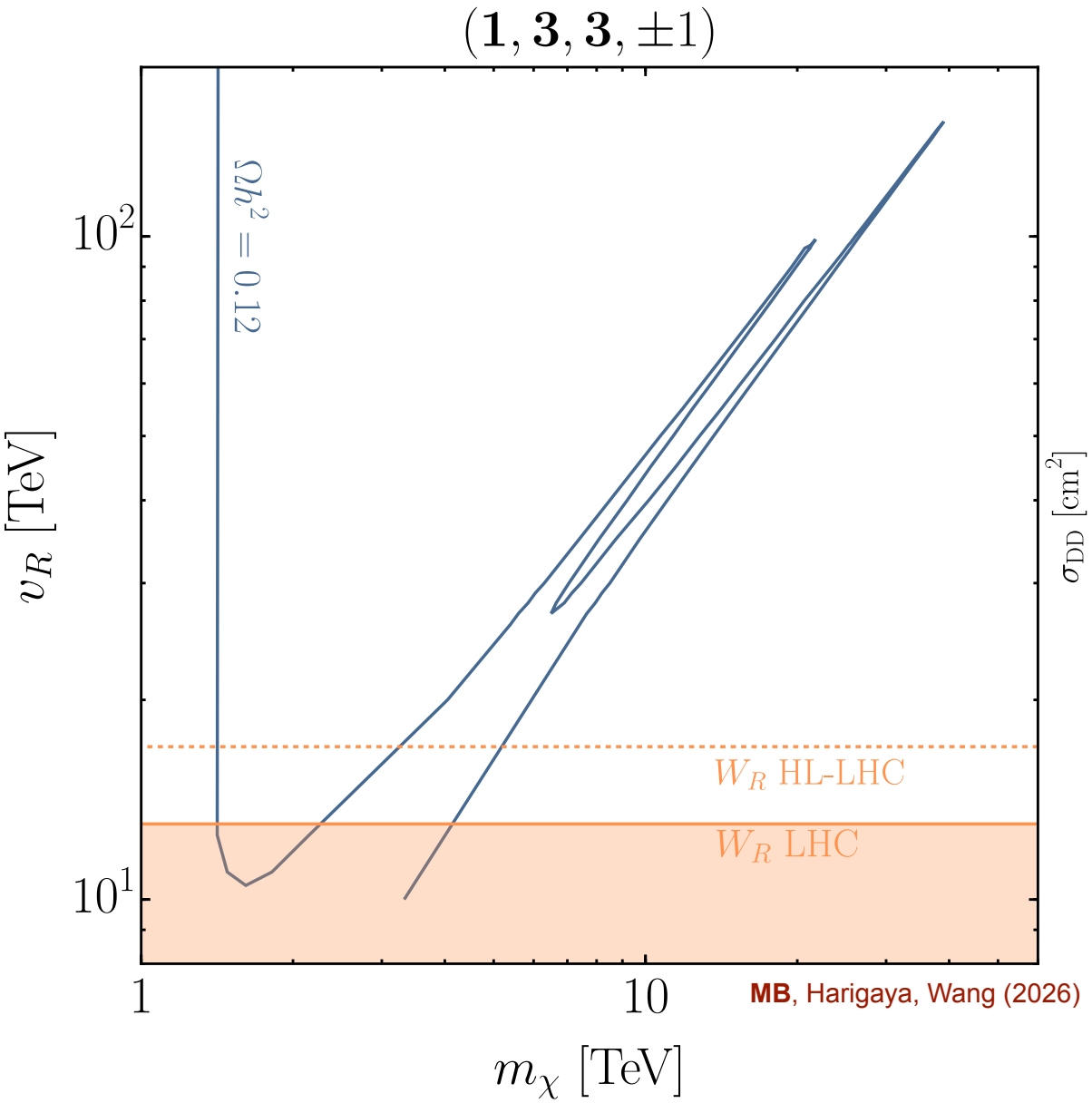
**Constraints:**

**Collider**



**Direct detection**

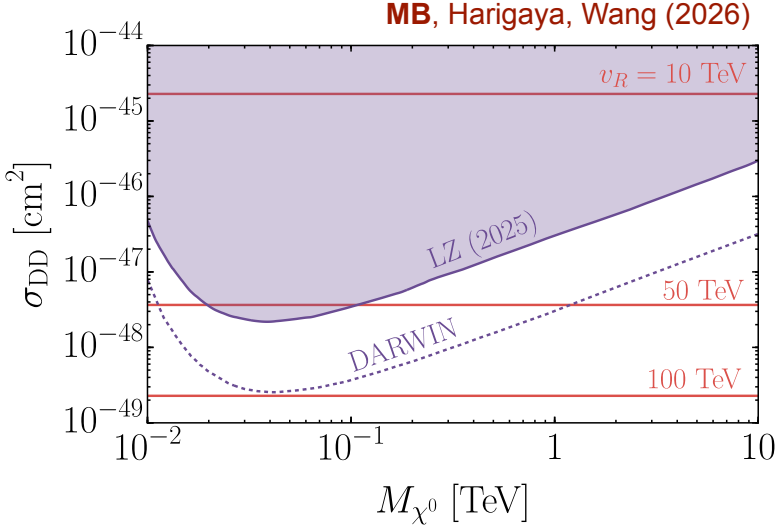



**MB**, Harigaya, Wang (2026)

**DM can scatter with nucleons via $Z_R$ exchange**

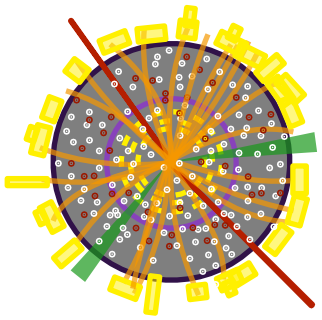
**MB**, Harigaya, Wang (2026)



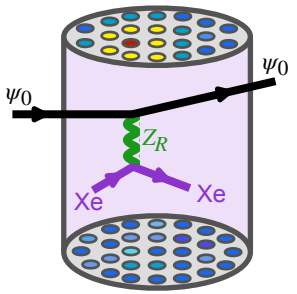
# Direct Detection

**Constraints:**

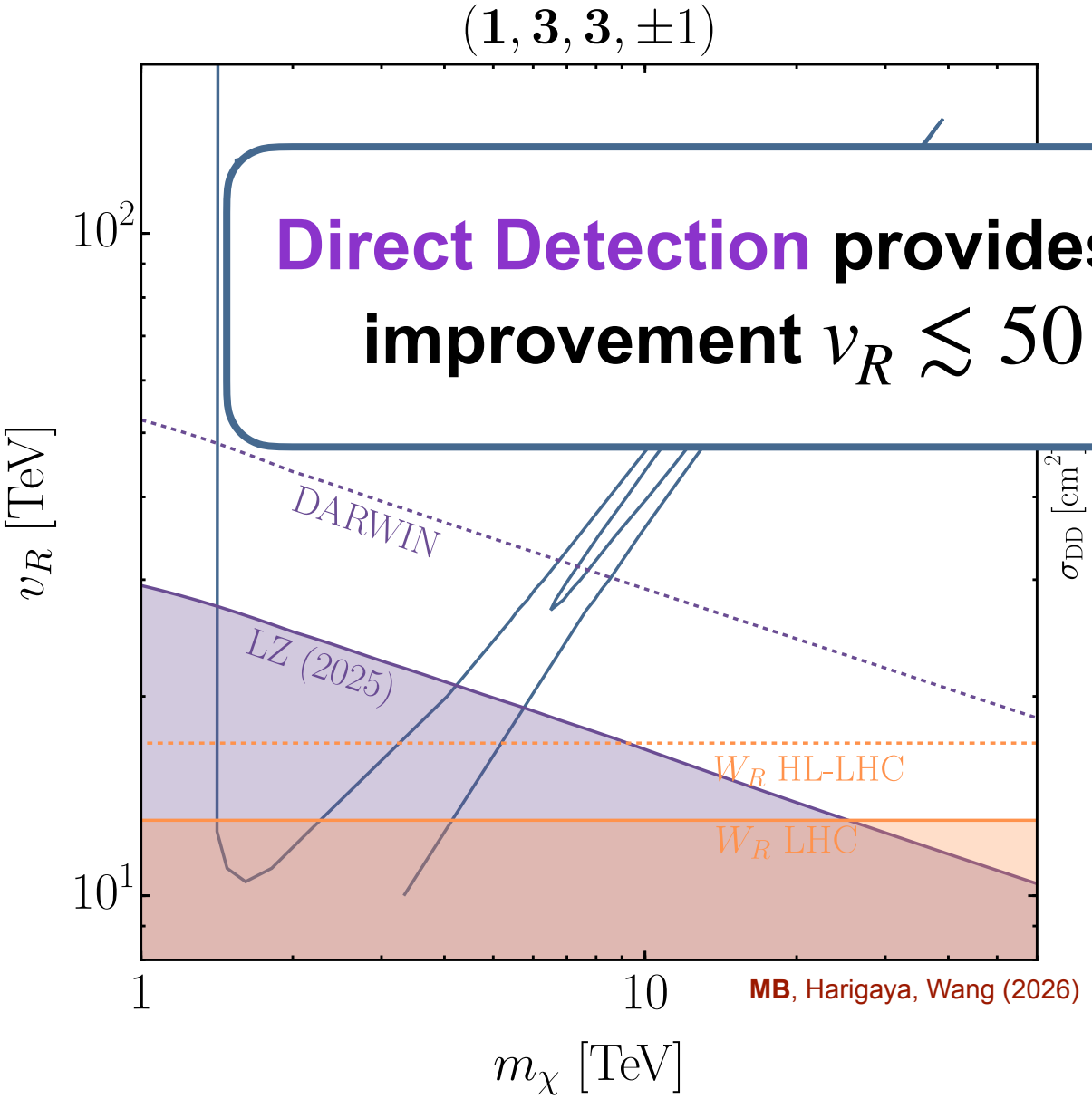
**Collider**



**Direct detection**



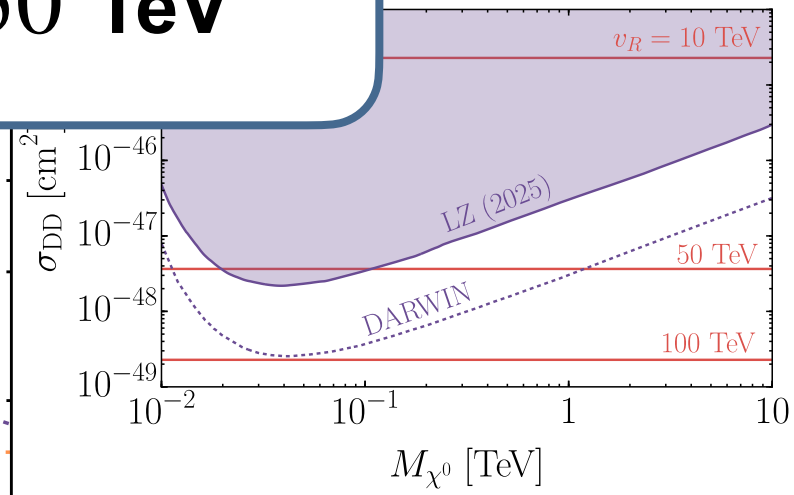

**Direct Detection provides small improvement $v_R \lesssim 50$ TeV**




**MB**, Harigaya, Wang (2026)

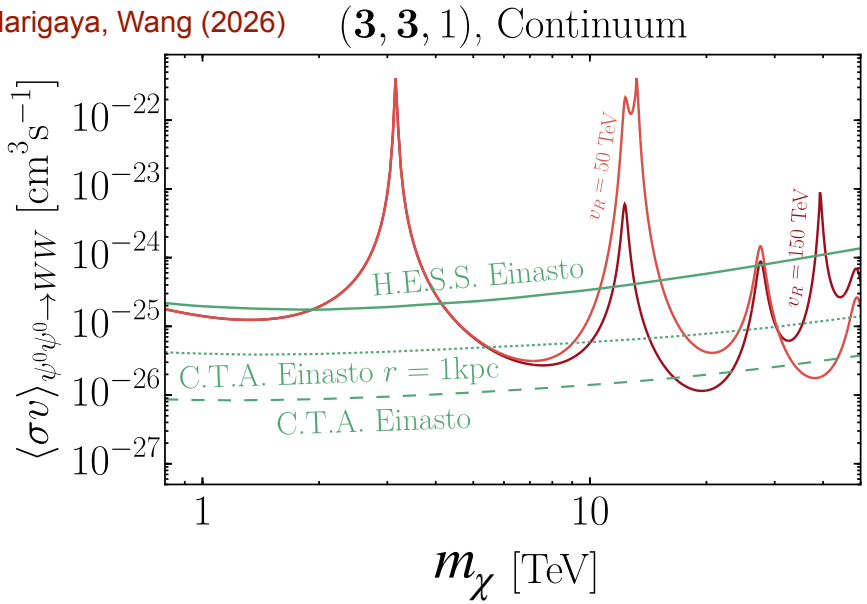
**ter with nucleons**
**nge**

**MB**, Harigaya, Wang (2026)



# Indirect Detection

**MB**, Harigaya, Wang (2026)

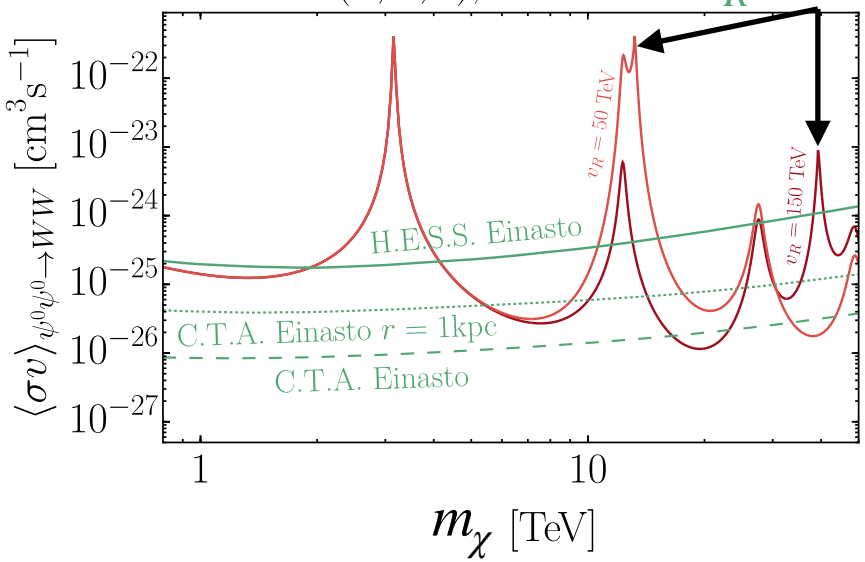



**Indirect detection** probes photons from DM annihilation at galactic center:

**1) Continuum signal**

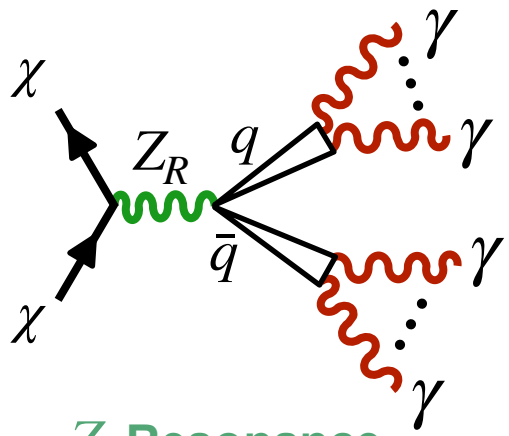
# Indirect Detection

**MB**, Harigaya, Wang (2026) $(\mathbf{3},\mathbf{3},1)$, Continuum $Z_R$ **resonances**




**Indirect detection** probes photons from DM annihilation at galactic center:

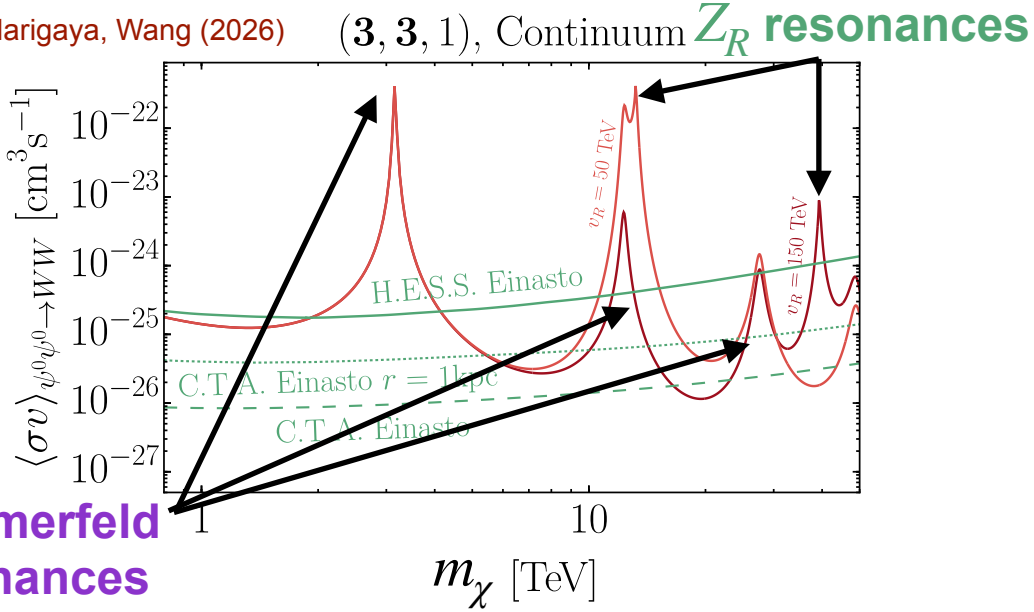
**1) Continuum signal**




$Z_R$**Resonance**

# Indirect Detection

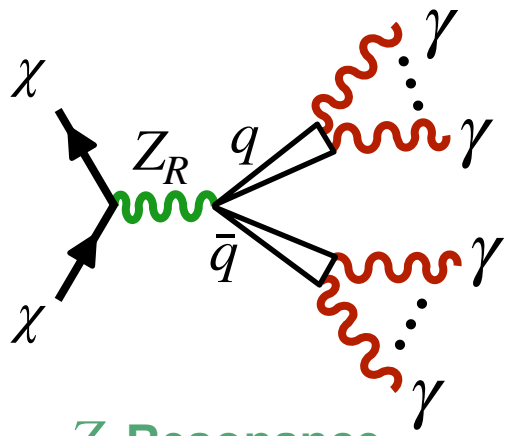
**MB**, Harigaya, Wang (2026)



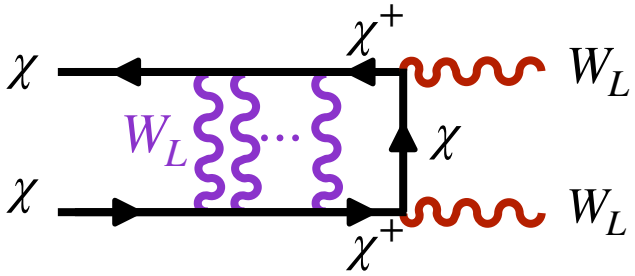

**Sommerfeld resonances**

**Indirect detection** probes photons from DM annihilation at galactic center:

**1) Continuum signal**



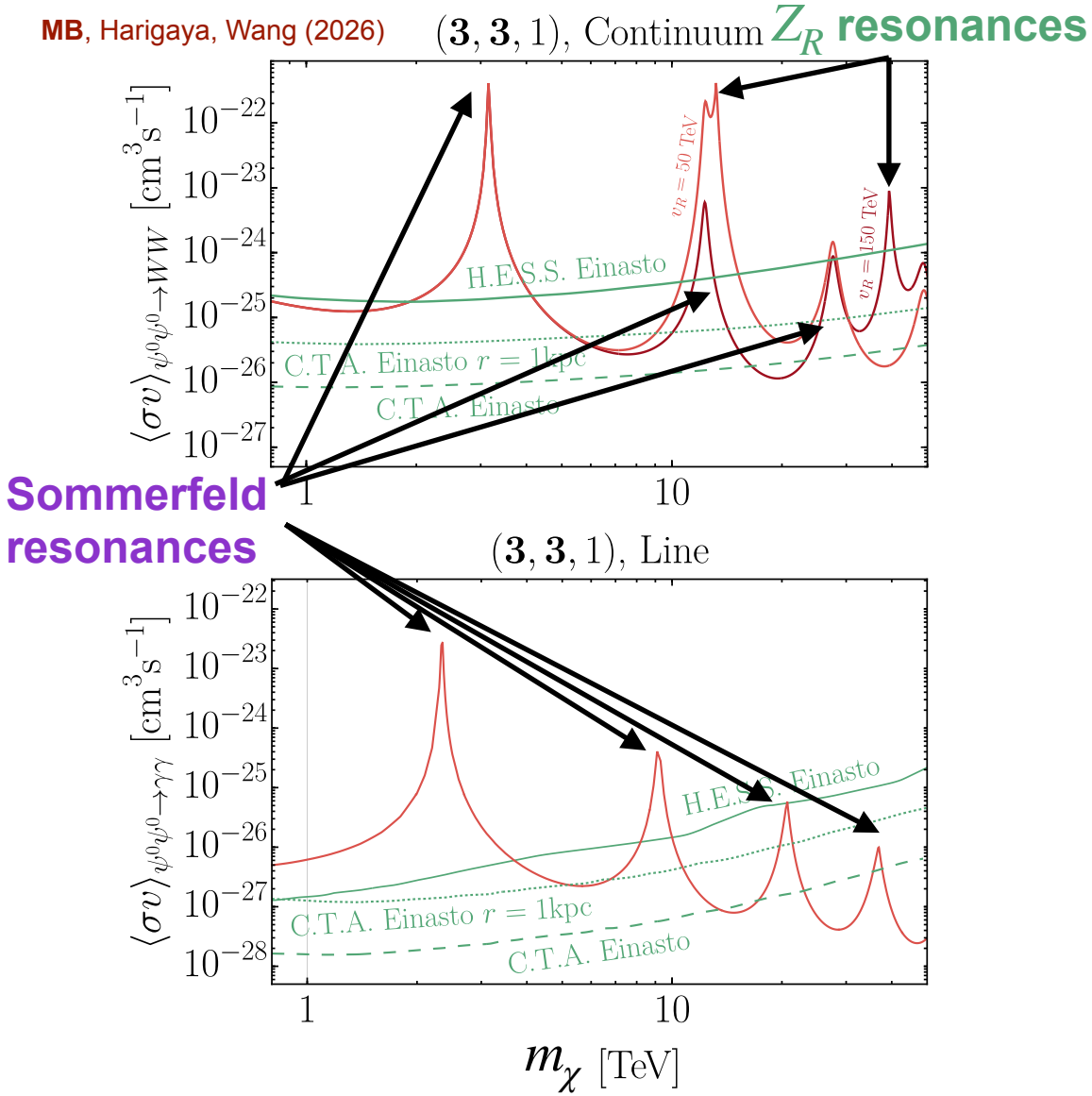

$Z_R$**Resonance**




**Sommerfeld Effect**

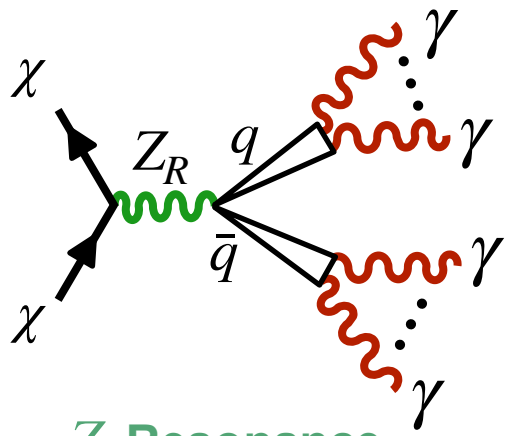
# Indirect Detection

**MB**, Harigaya, Wang (2026)

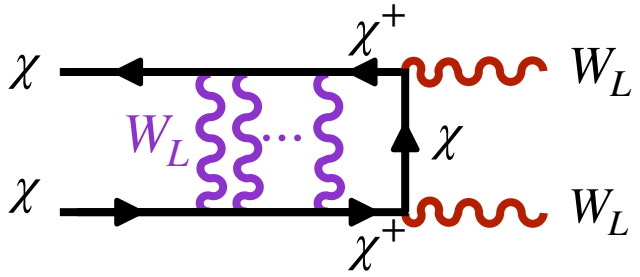



**Indirect detection** probes photons from DM annihilation at galactic center:

## 1) Continuum signal

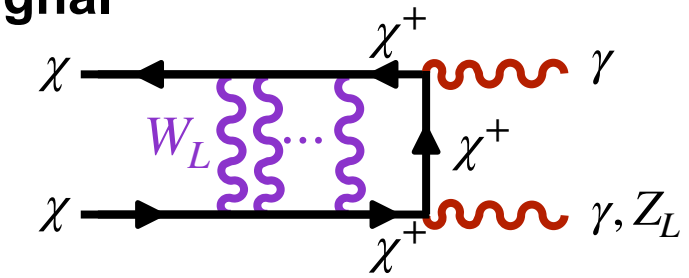



$Z_R$Resonance




Sommerfeld Effect

## 2) Line signal

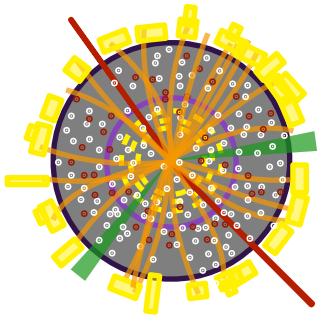



Sommerfeld Effect

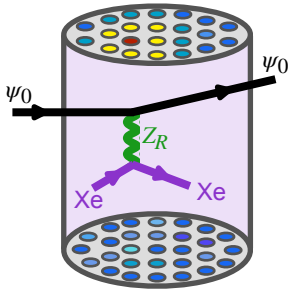
# Direct Detection

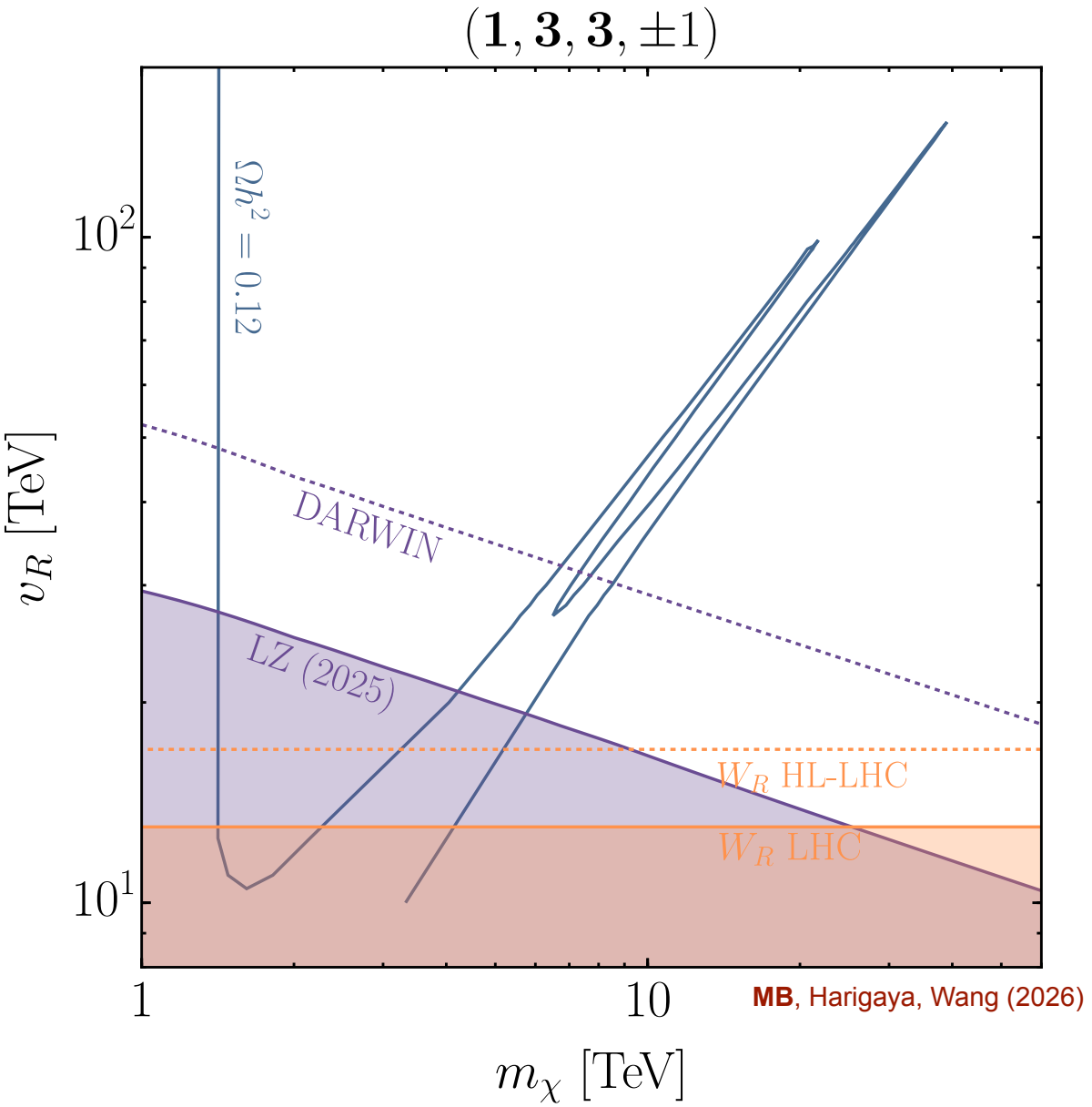
**Constraints:**

**Collider**



**Direct detection**



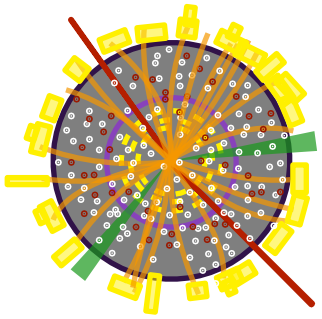




**MB**, Harigaya, Wang (2026)

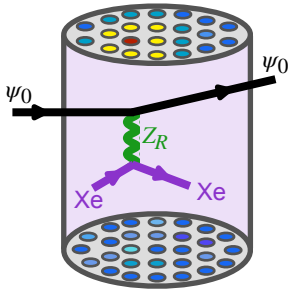
# Indirect Detection

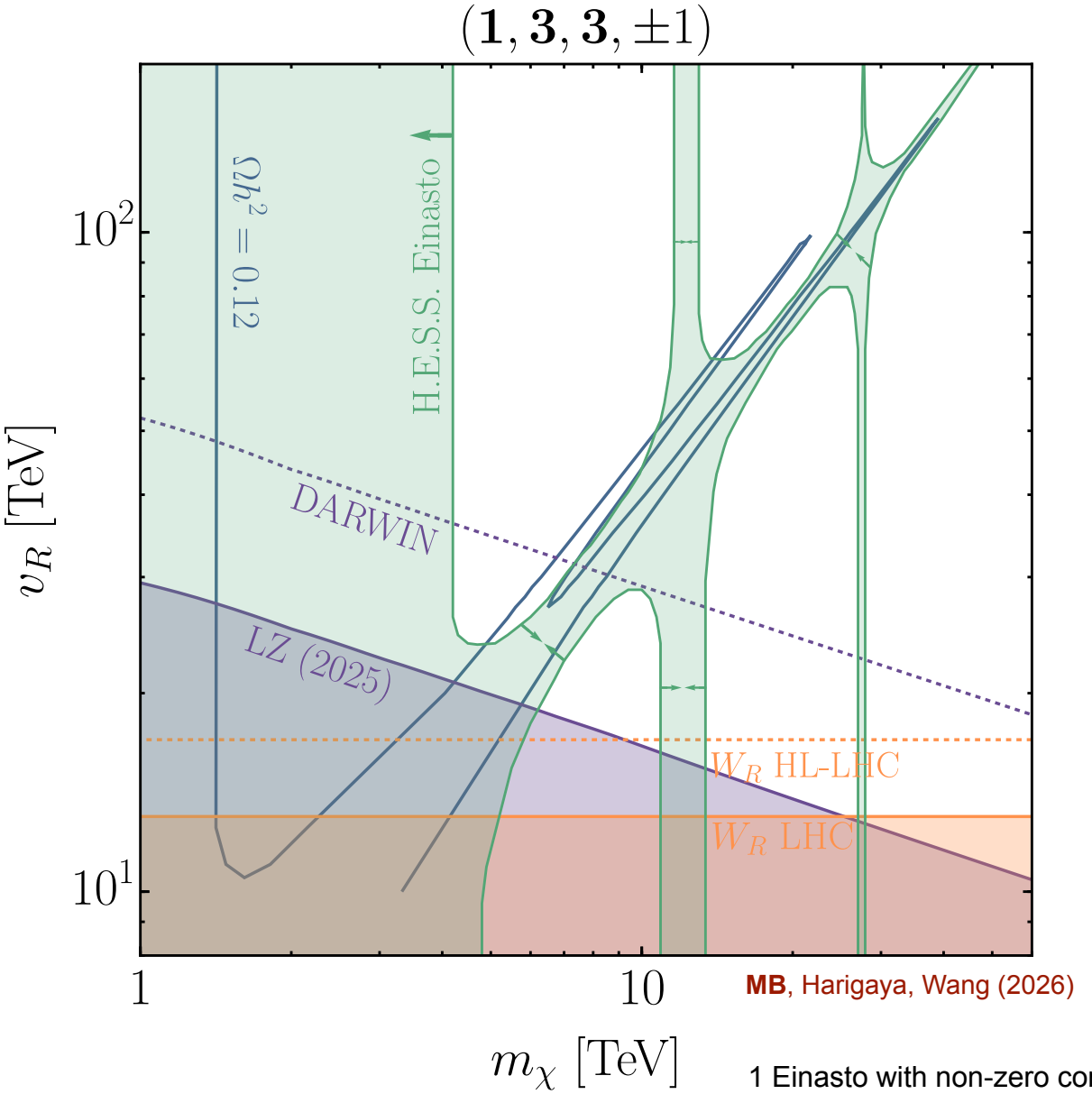
**Constraints:**

**Collider**



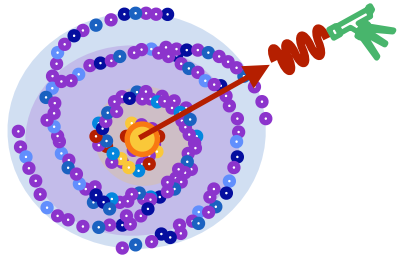
**Direct detection**




**MB**, Harigaya, Wang (2026)

**Indirect detection**



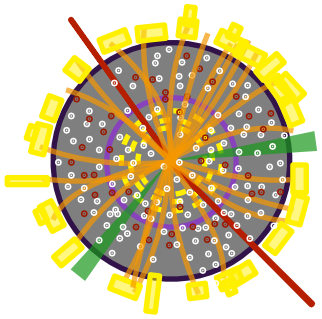
1

1 Einasto with non-zero core significantly weakens the H.E.S.S. bounds

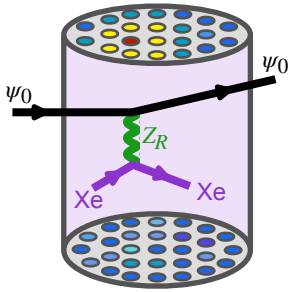
# Indirect Detection

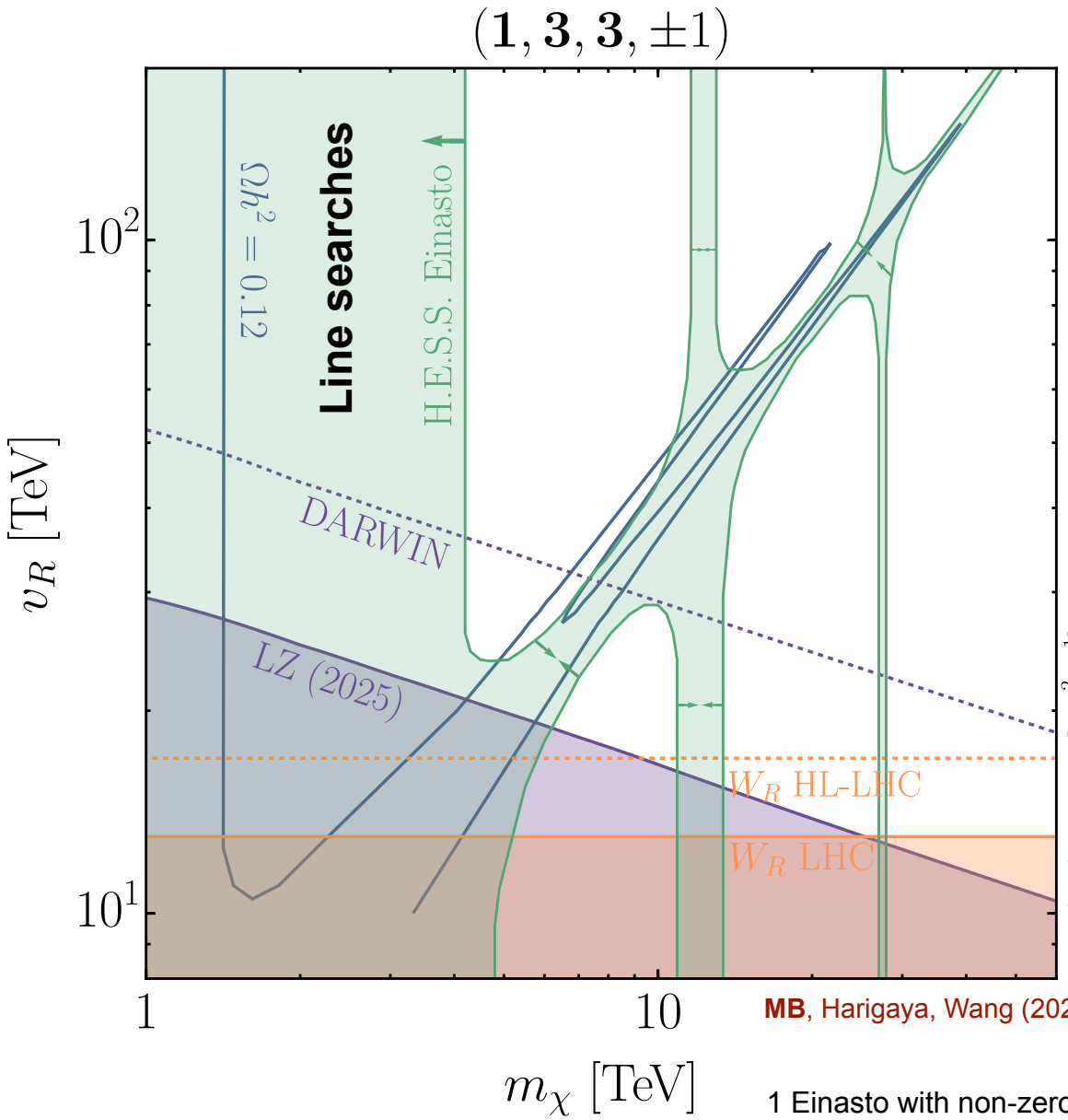
**Constraints:**

**Collider**



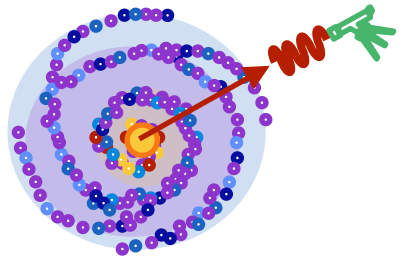
**Direct detection**



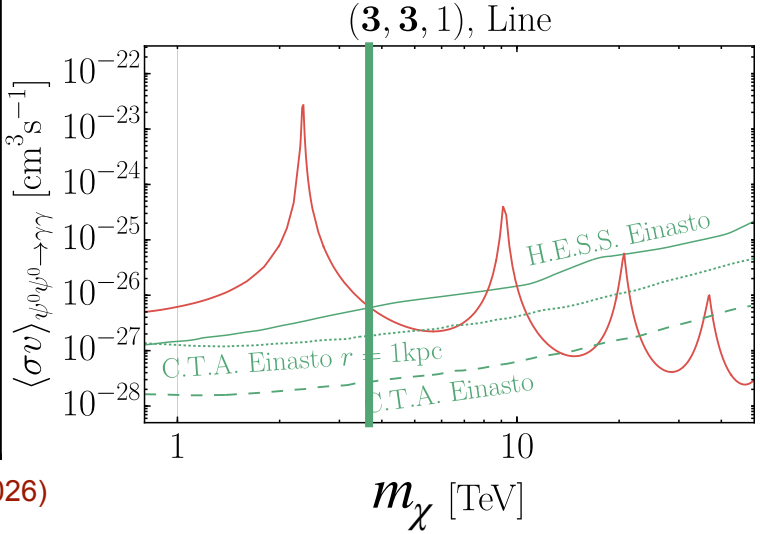




**MB**, Harigaya, Wang (2026)

**Indirect detection**



1

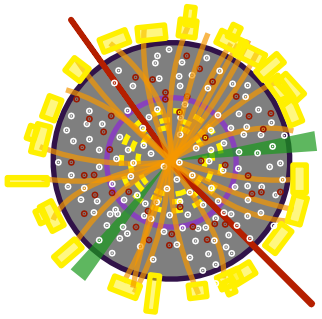



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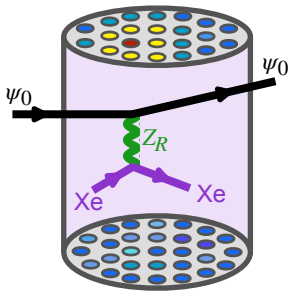
# Indirect Detection

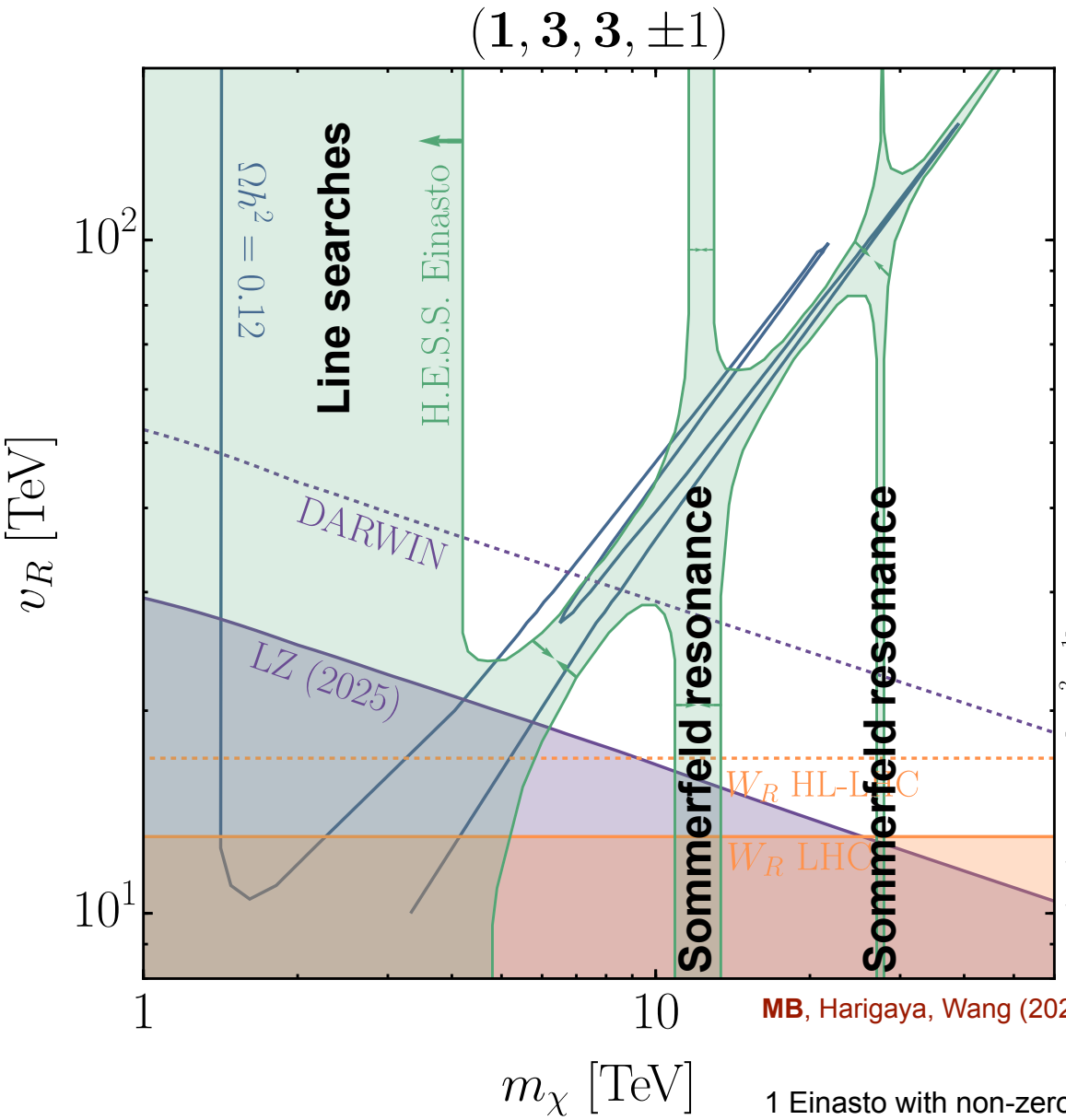
**Constraints:**

**Collider**



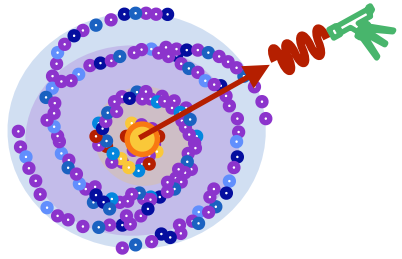
**Direct detection**



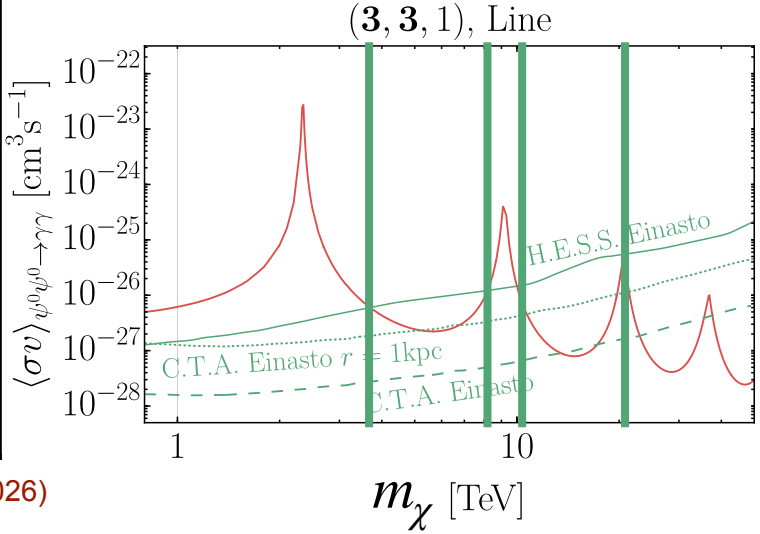




**MB**, Harigaya, Wang (2026)

**Indirect detection**



1

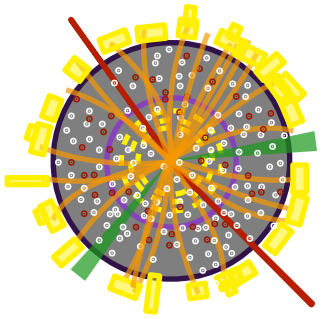



1 Einasto with non-zero core significantly weakens the H.E.S.S. bounds

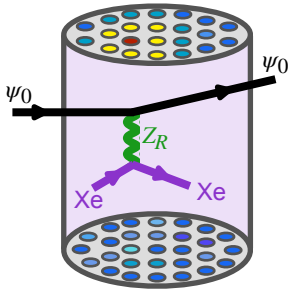
# Indirect Detection

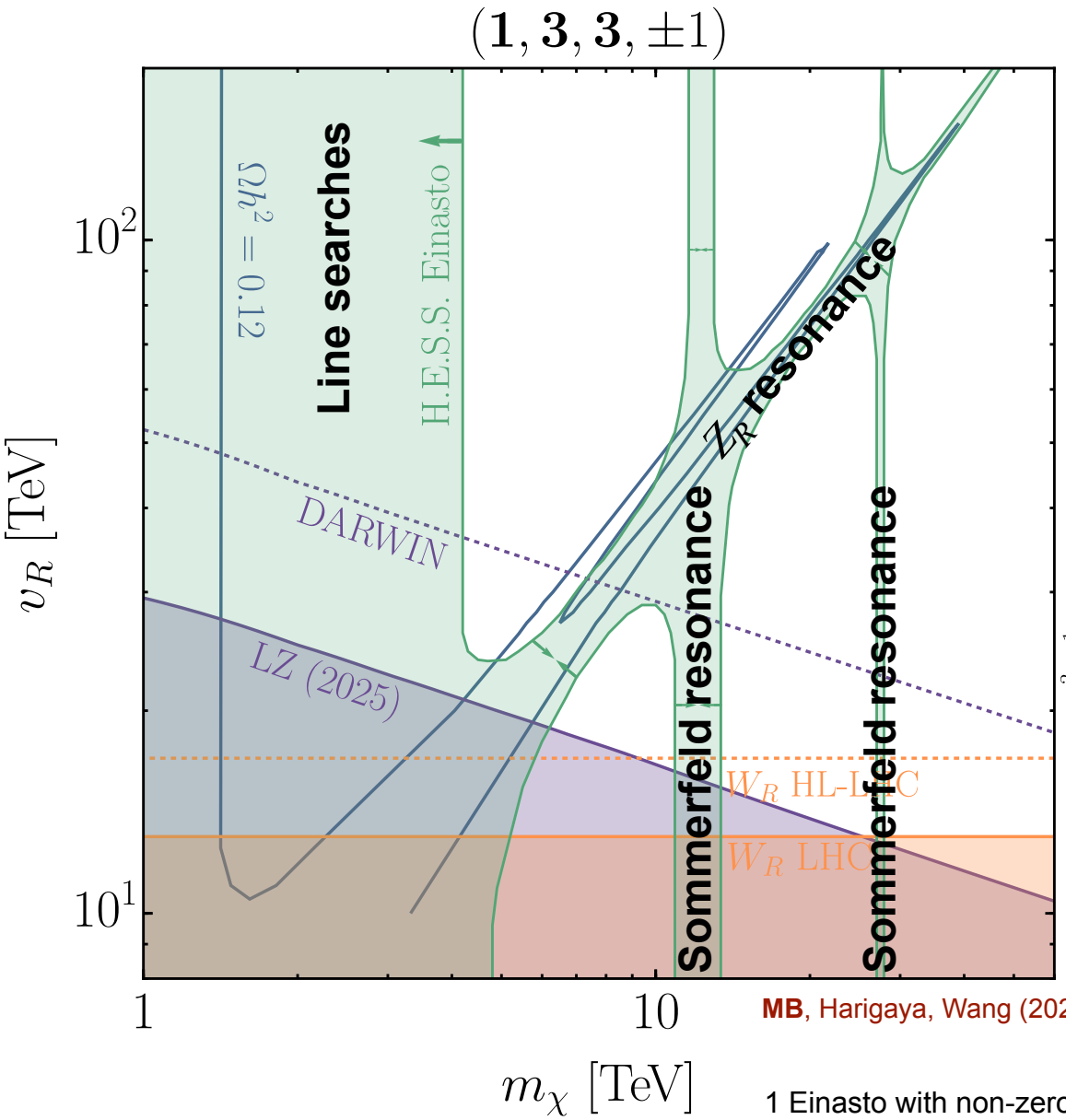
## Constraints:

### Collider



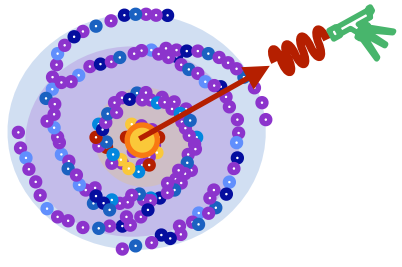
### Direct detection



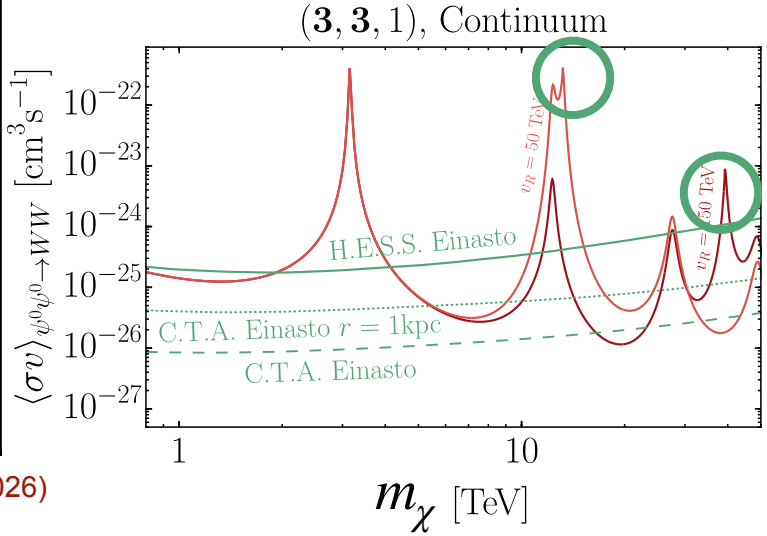




MB, Harigaya, Wang (2026)

### Indirect detection



1

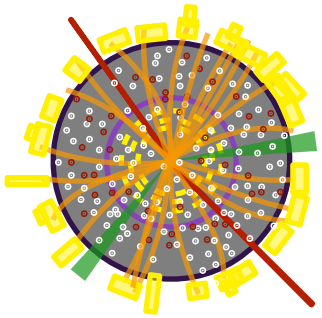



1 Einasto with non-zero core significantly weakens the H.E.S.S. bounds

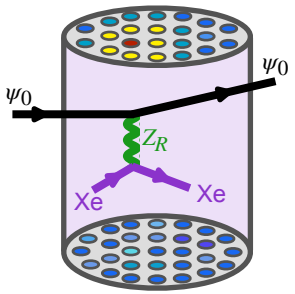
# Indirect Detection

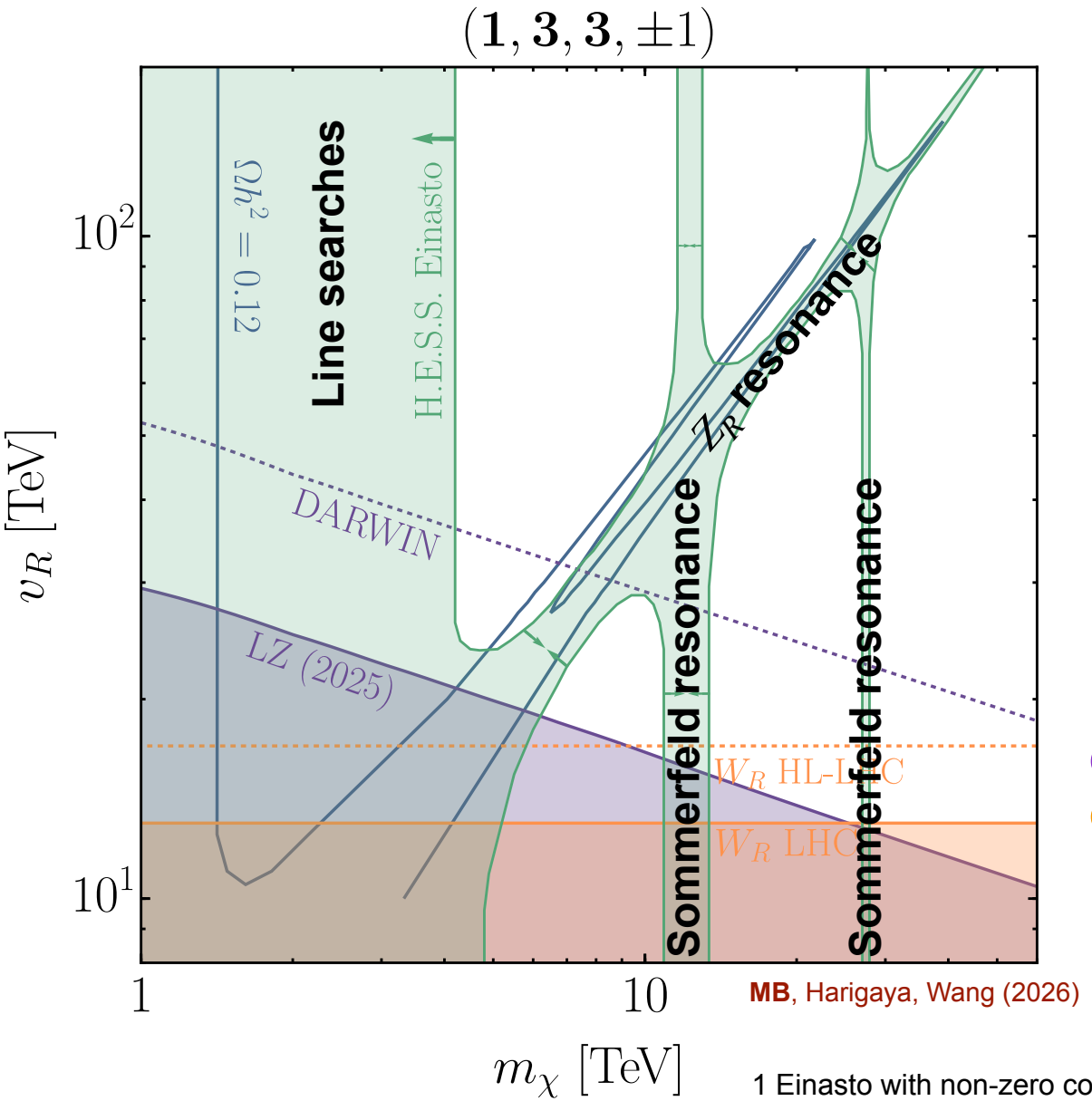
**Constraints:**

**Collider**



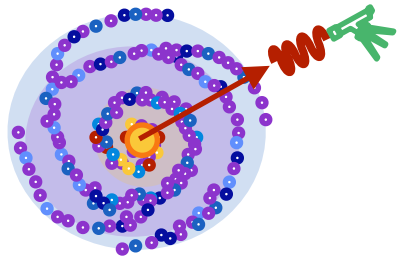
**Direct detection**




**MB**, Harigaya, Wang (2026)

**Indirect detection**



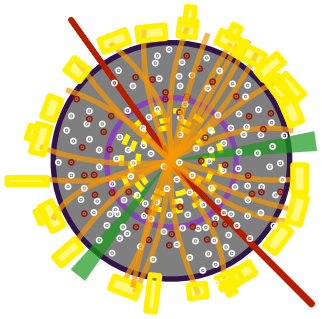
Upper bound out of reach of **direct detection** and **collider** searches: need **indirect detection**

1 Einasto with non-zero core significantly weakens the H.E.S.S. bounds

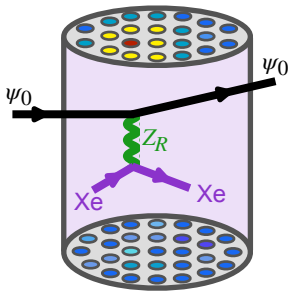
# Indirect Detection

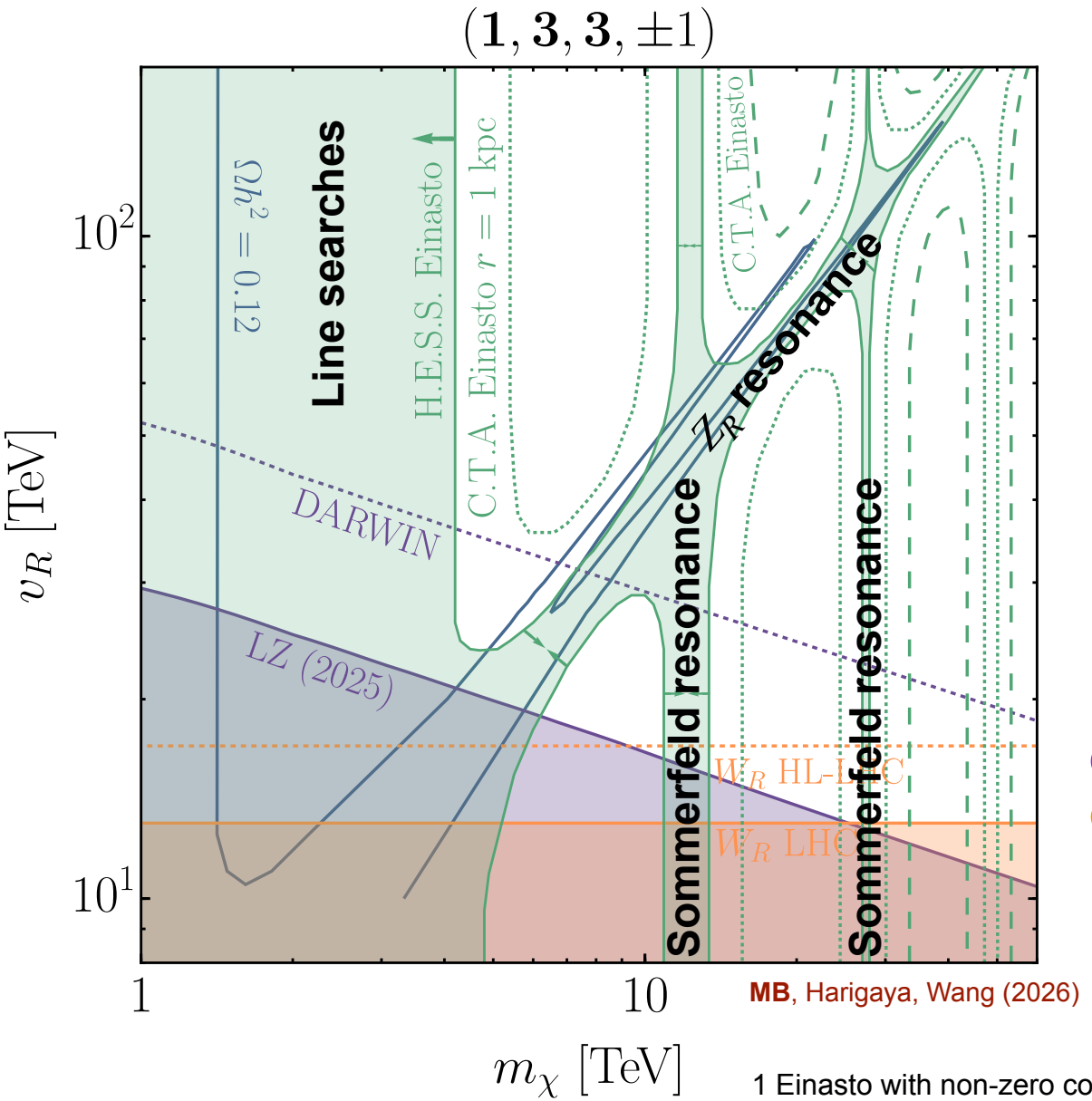
**Constraints:**

**Collider**



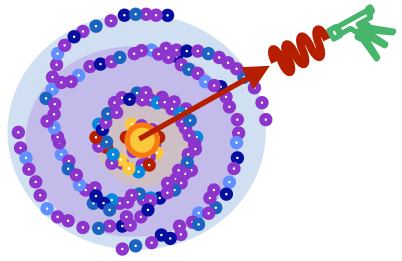
**Direct detection**




**MB**, Harigaya, Wang (2026)

**Indirect detection**



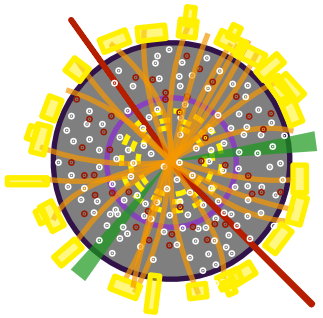
1

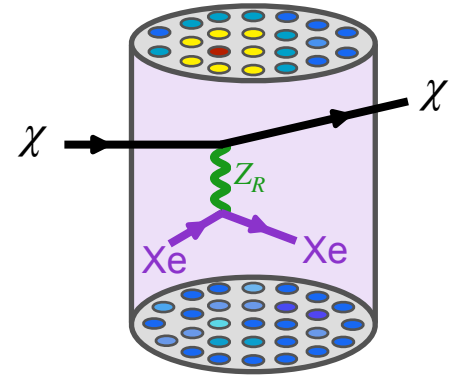
Upper bound out of reach of **direct detection** and **collider** searches: need **indirect detection**

1 Einasto with non-zero core significantly weakens the H.E.S.S. bounds

# Conclusion

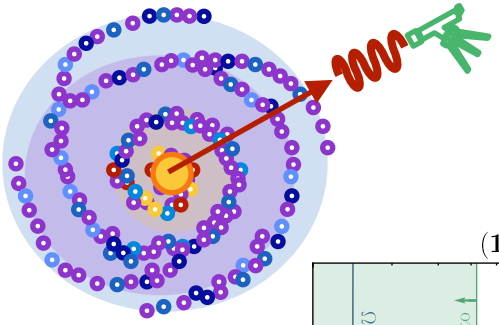
**Parity** symmetric Left-right models can solve many BSM problems



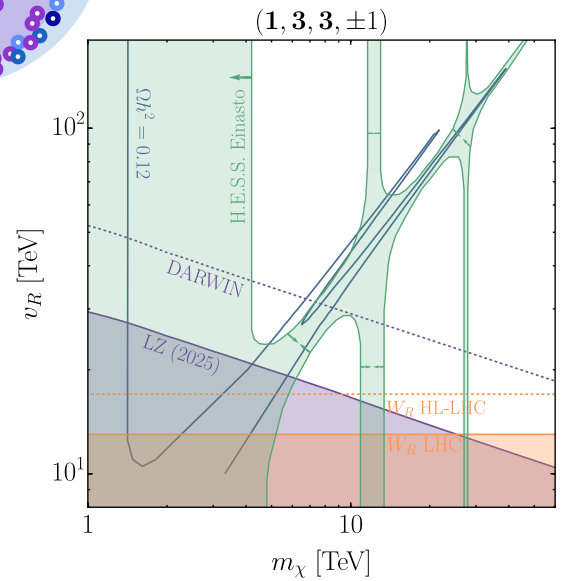



**WIMP candidate** embeds into Left-right models in various ways

**Thermal relic abundance** places **upper bound** on parity breaking scale for bi-triplet WIMP embedding



**Collider** and **direct detection** probe small parity breaking scale.
**Indirect detection** needed to probe full parameter space

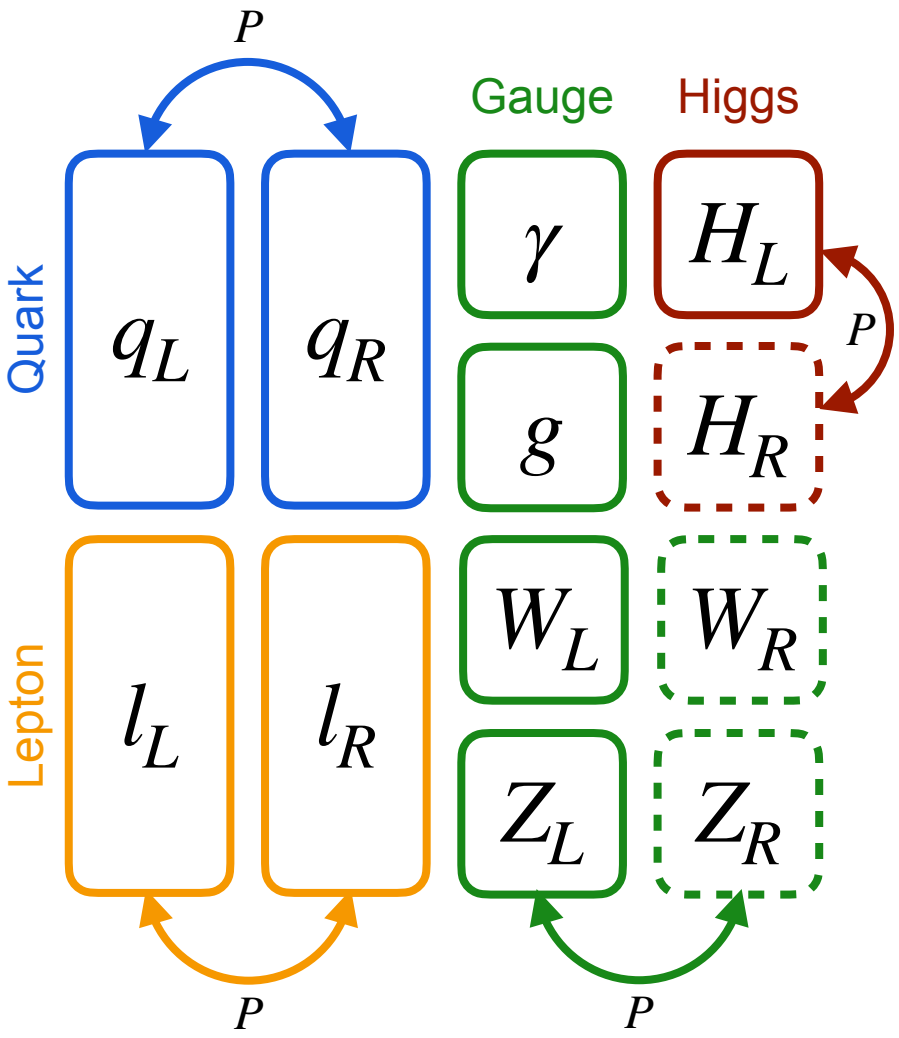



**Next**— rare processes e.g. $\mu \to e + \gamma$ probes of parity breaking scale

**Thank you**

# Backup Slides

# Parity Symmetric left-right models can solve BSM problems

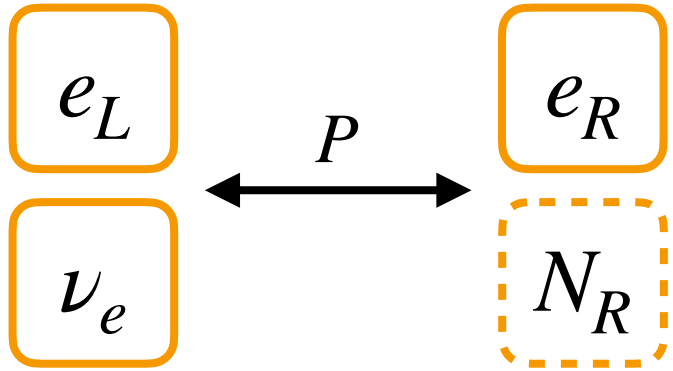



**Solution to the strong CP problem:** Parity forbids a $\theta$-term and requires Hermitian SM Yukawas, thus no strong CP phase[1]

Beg, Tsao (1978)
Mohapatra, Senjanovic (1978)

**Neutrino masses:** right-handed $N_e$ forms doublet under $SU(2)_R$ with $e_R$. Allows for neutrino Yukawas by introducing relevant Yukawa sector fermions

Hall, Harigaya, Shpilman (2023)




**Unification:** can be embedded into GUTs e.g. $SO(10)$ with WIMP dark matter candidates

**MB**, Harigaya (2024)



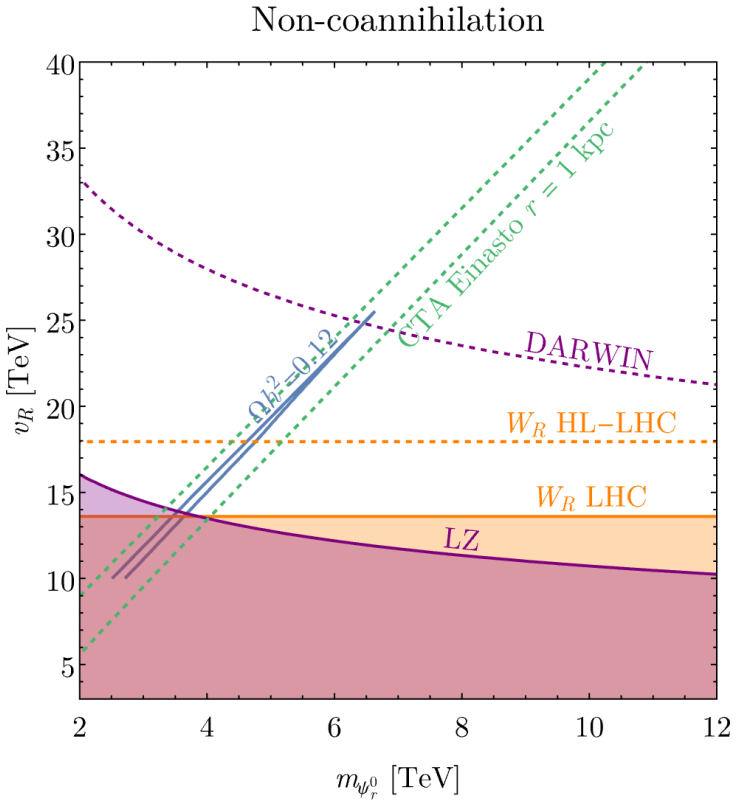
1 Loop corrections to $\bar{\theta}$ much below experimental bounds. Hall, Harigaya (2018) ; de Vries, Draper, Patel (2021); Hisano, Kitahara, Osamura, Yamada (2023)

# Constraints for other DM embeddings

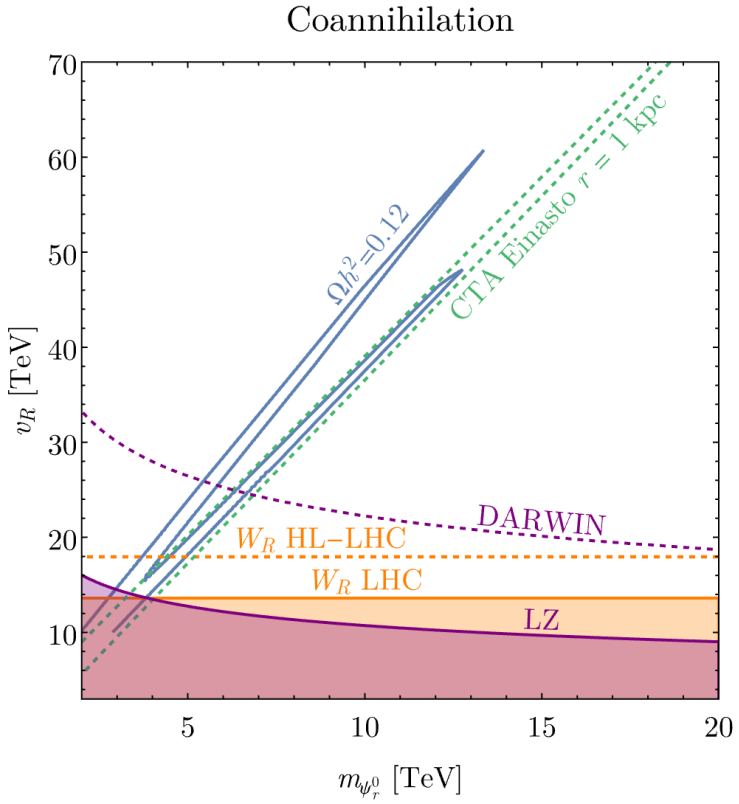
## Doublet pair

$$(1,2,1,1/2) \oplus (1,1,2,-1/2)$$

Parity breaking scale



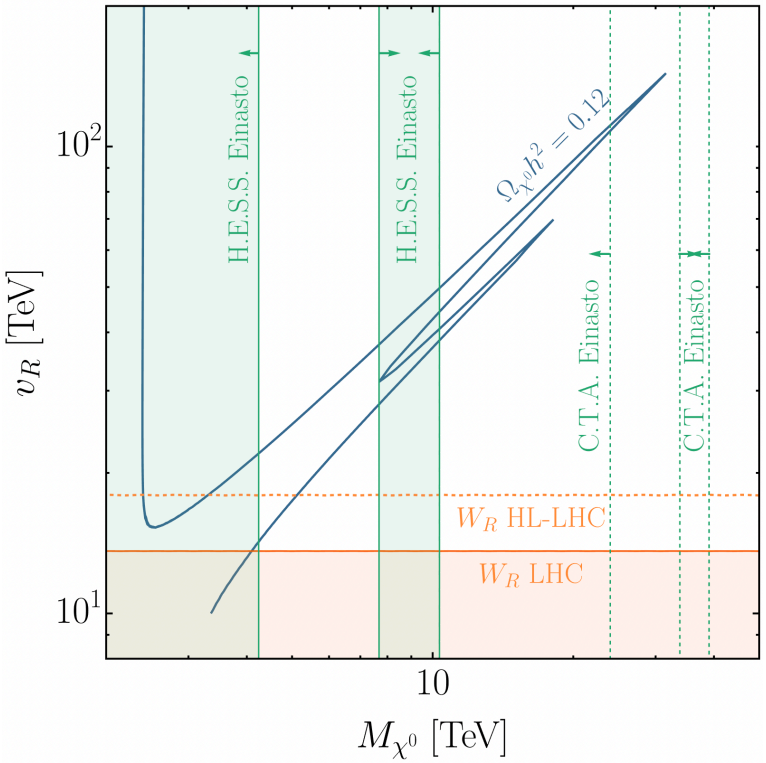

DM mass




DM mass

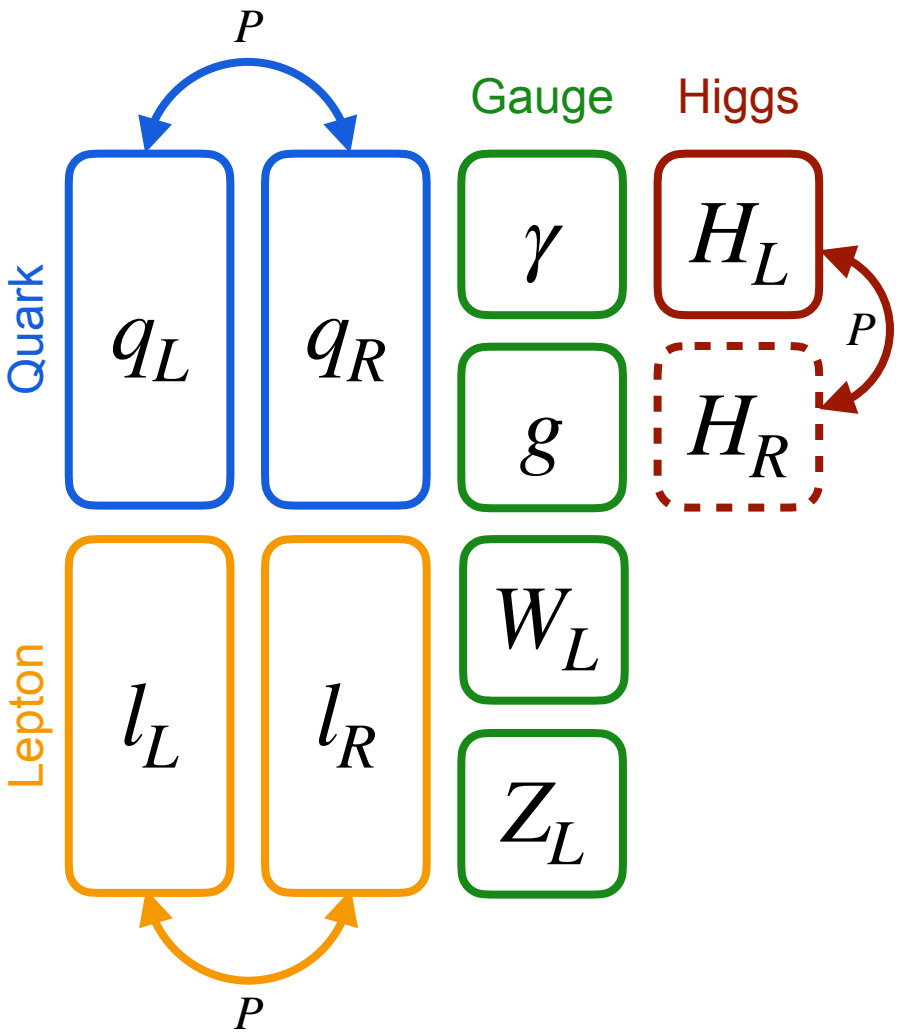
## Bi-triplet

$$(1,3,3,0)$$




DM mass

# Parity Symmetric Left-Right Models




**Solution to Strong CP Problem**

Under parity $\theta$-term transforms as

$$P : \theta F\tilde{F} \to -\theta F\tilde{F} \implies \boxed{\text{no } \theta\text{-term}}$$

Right-handed SM fermions now form doublets, requiring

$$P : Y_{u,d} = Y_{u,d}^{\dagger} \implies \boxed{\arg\det Y_{u,d} = 0}$$

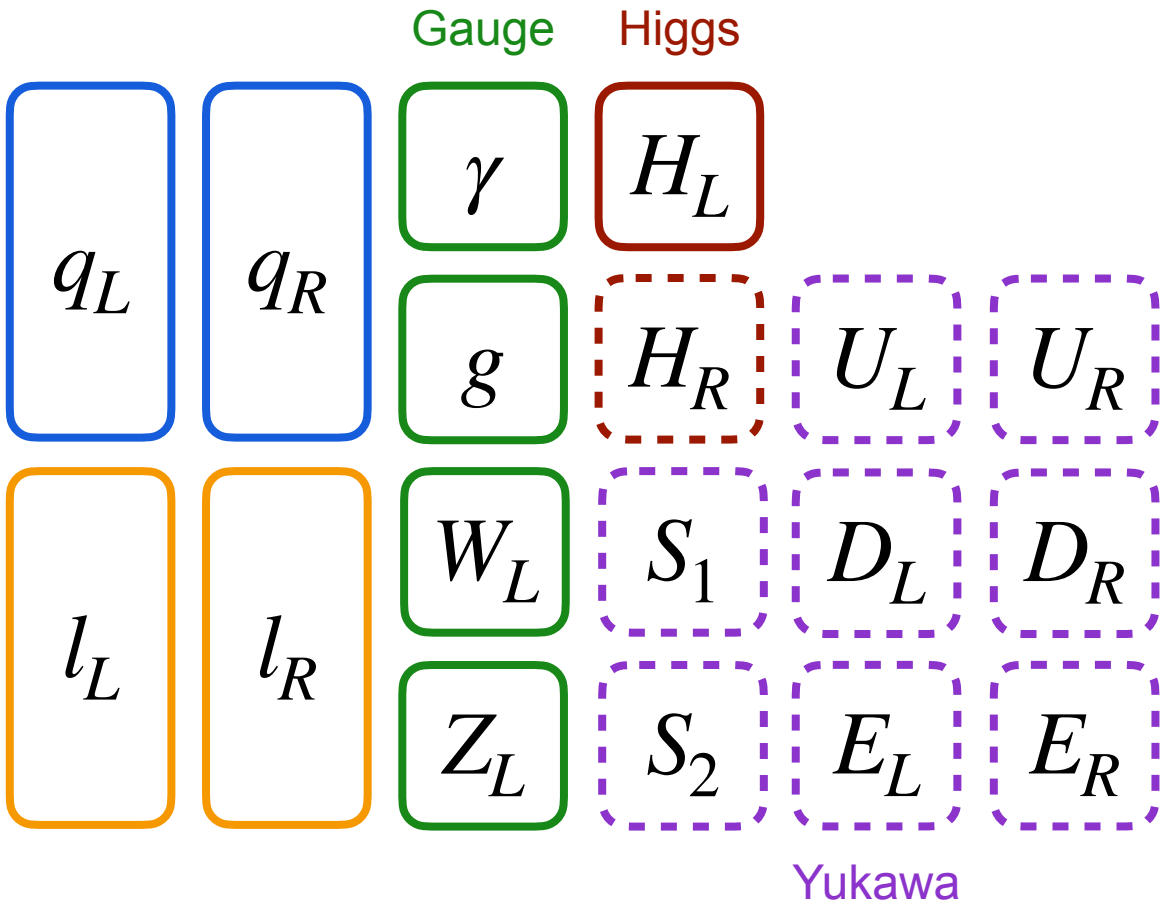
Therefore $\bar{\theta} = 0$ at tree level and **strong CP problem solved**

Beg, Tsao (1978)
Mohapatra, Senjanovic (1978)

Loop corrections to $\bar{\theta}$ much below experimental bounds

Hall, Harigaya (2018)
de Vries, Draper, Patel (2021)
Hisano, Kitahara, Osamura, Yamada (2023)

# Yukawa Sector of Parity Symmetric Left-Right Models




In SM Yukawas generated via, e.g.

$$\mathscr{L}_u \supset Y_u H_L q u_R \qquad q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

In left-right model, right-handed quarks form doublet

$$\mathscr{L}_u \not\supset Y_u H_L q \bar{q} \qquad \bar{q} = \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

No longer a gauge invariant Yukawas

Up: $\mathscr{L}_U \supset X_U H_R \bar{q} U_L + X_U H_L q U_R$

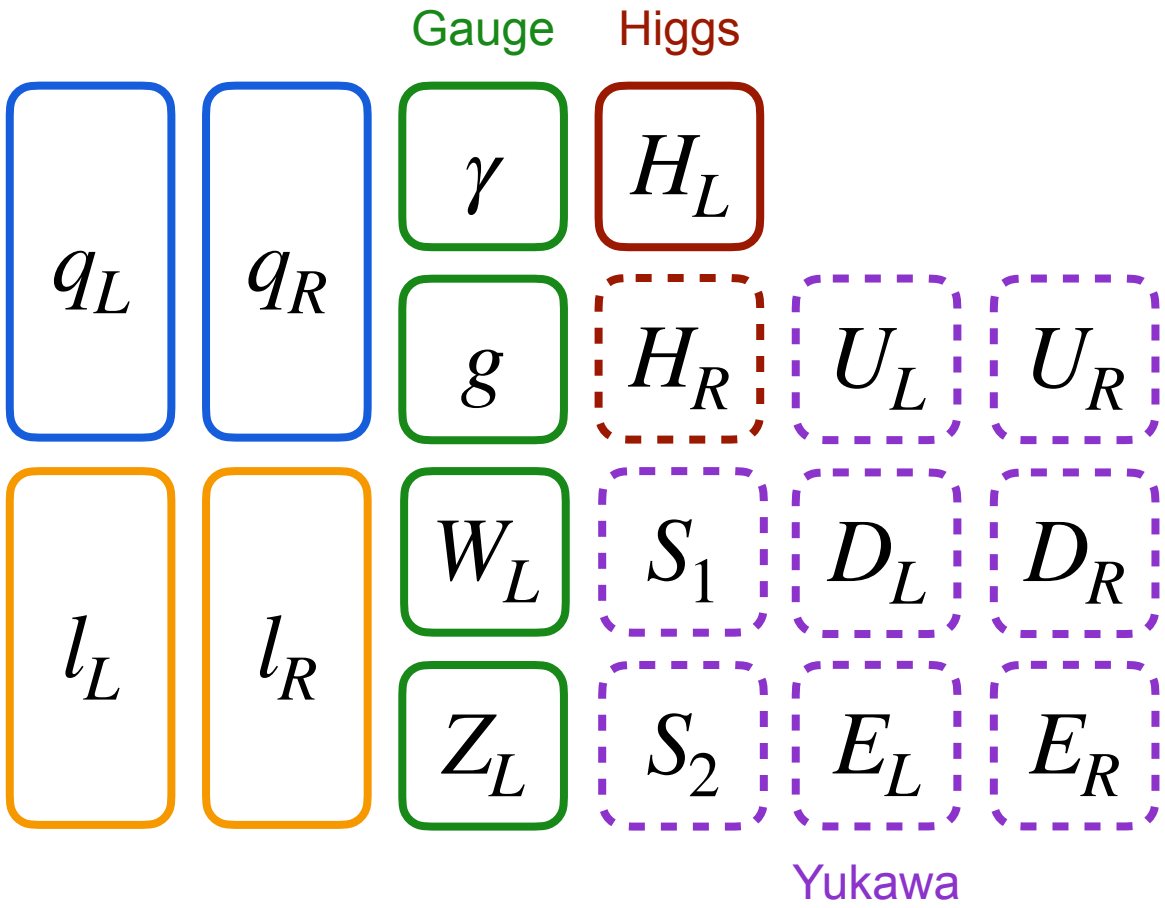
Down: $\mathscr{L}_D \supset X_D H_R^* \bar{q} D_L + X_D H_L^* q D_R$

Electron[1]: $\mathscr{L}_E \supset X_E H_R l E_R + X_E H_L \bar{l} E_L$

Matthew J. Baldwin
PIKIMO Nov 2026

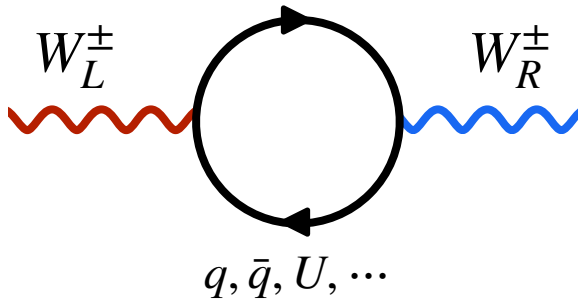
1 Charge lepton Yukawas can be generated by $\Delta(\mathbf{1},\mathbf{2},\mathbf{2},0)$, but this generates dim-6 bi-triplet decays with UV scale $\Lambda \ll M_{Pl}$. We assume $\Delta(\mathbf{1},\mathbf{2},\mathbf{2},0)$ doesn't generate charged lepton Yukawas

# Yukawa Sector Fermions Generate Gauge Boson Mixing




Left-right Yukawas generate mixing between $W_L$ and $W_R$

$$\mathscr{L}_U \supset X_U H_R \bar{q} U_L + X_U H_L q U_R$$




This mixing generates the Majorana mass for the bi-doublet to evade nucleon scattering

Colliders also probe exotic quarks $U$ and $D$

# Co-annihilation

Abundance can be expressed in terms of yield

$$Y = \frac{\rho_{crit}}{m_\chi s h^2}\,\Omega h^2$$

Yield satisfies Boltzmann equation

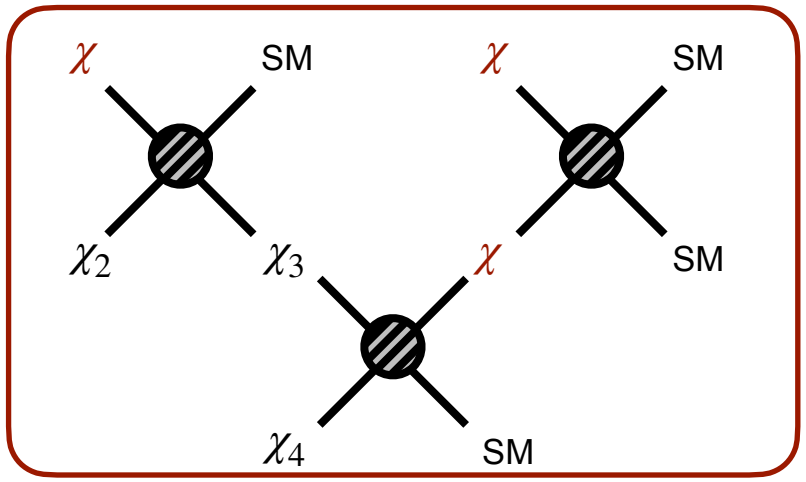
$$\frac{dY}{dx} = -\langle\sigma_{eff} v\rangle \frac{s}{H\,x}\left(1 - \frac{1}{3}\frac{d\ln g_{*s}}{d\ln x}\right)\left(Y^2 - Y_{eq}^2\right)$$

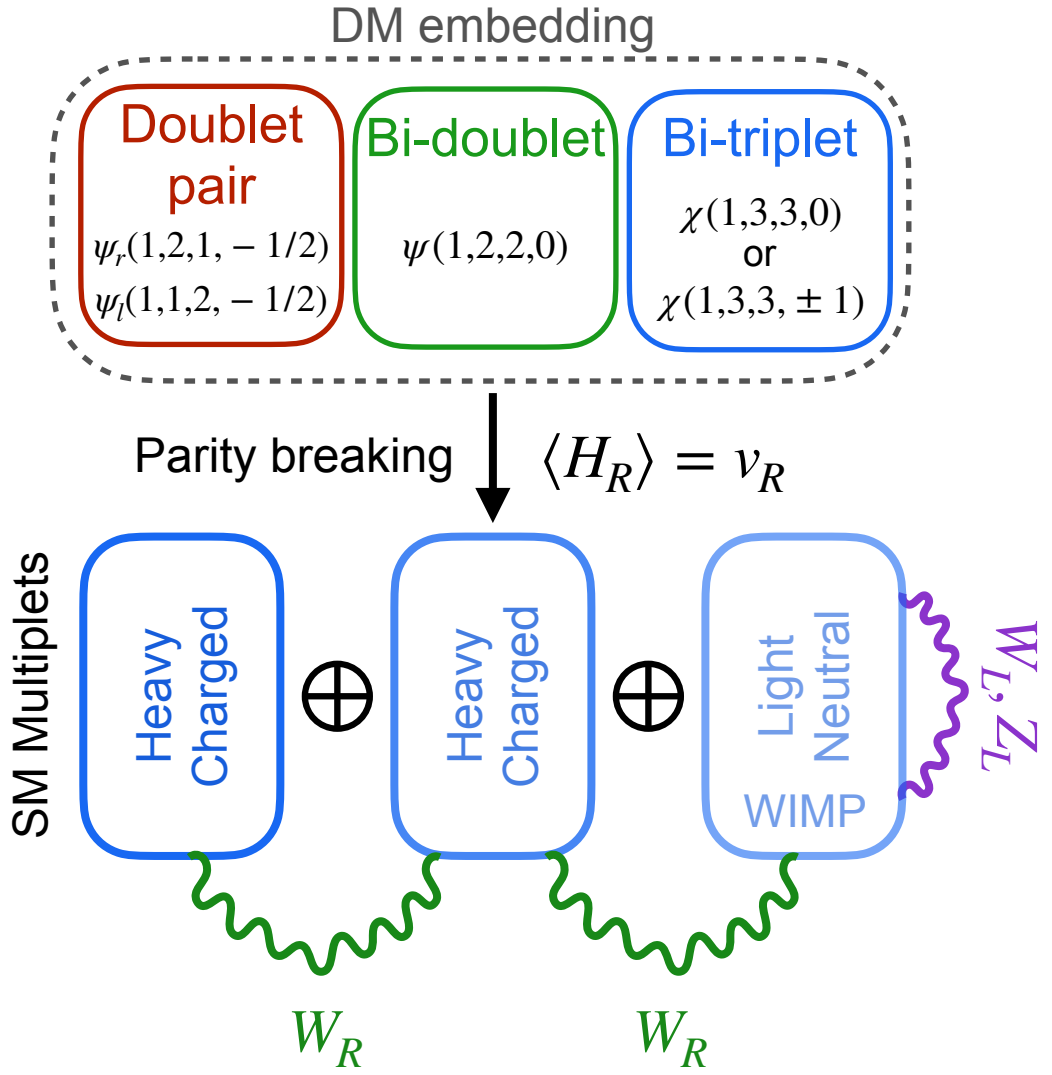
Thermal averaged annihilation cross section

Hubble expansion

Deviation from equilibrium

Griest, Seckel (1991)




Particles in different SM multiplets co-annihilate with DM

# Doublet pair co-annihilation

Doublet pair particles contained in separate multiplets

| Contains WIMP | |
|---|---|
| $\psi_r(1,2,1,-1/2)$ | $\psi_l(1,1,2,-1/2)$ |
| Annihilate via $W_R$, $Z_R$ | Annihilate via $W_L$, $Z_L$ |

$\psi_\ell \to \psi_r$ decays via dim-5 operator $\frac{1}{\Lambda}\psi_\ell \psi_r H_L H_R^*$

**Two scenarios during freeze-out**[1]

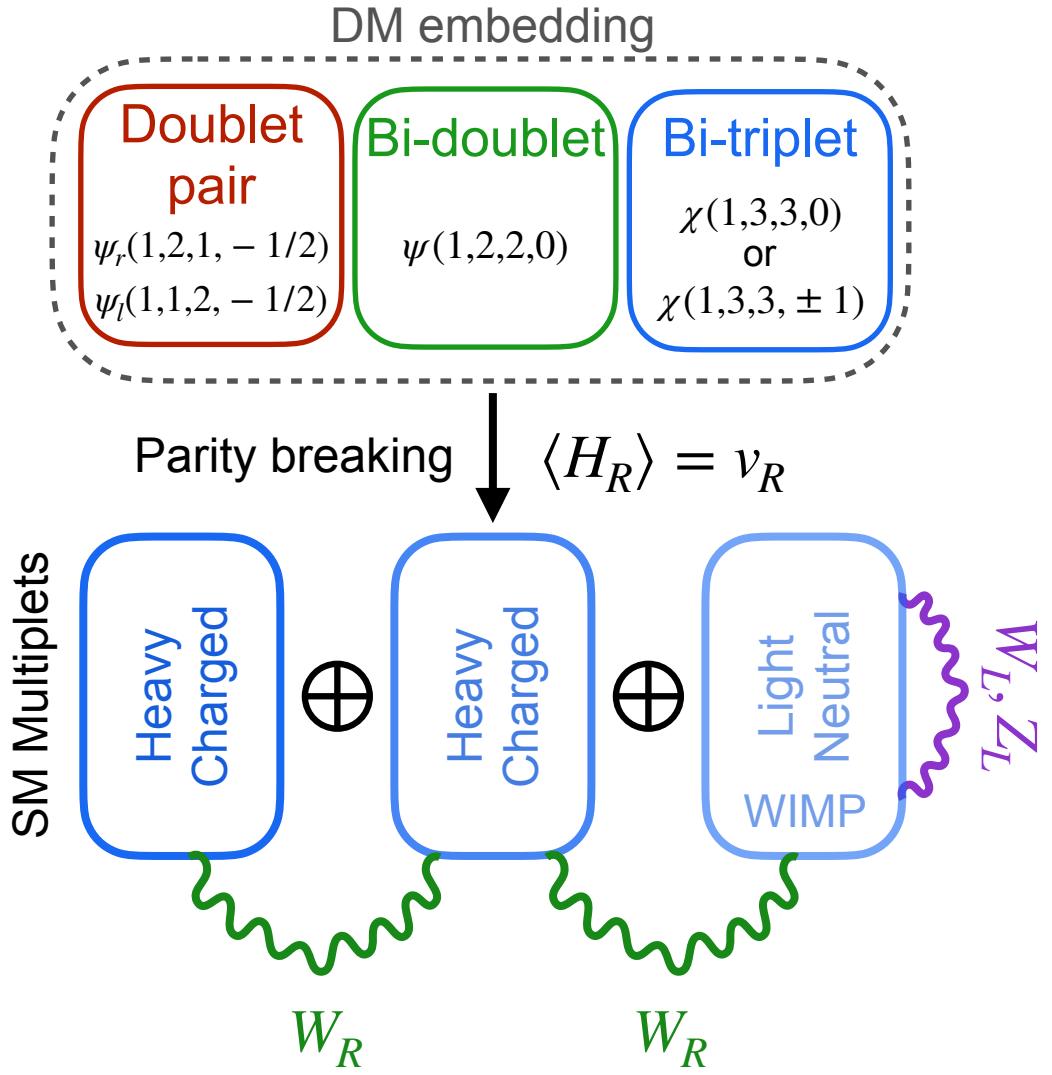
1) Co-annihilation ($\Lambda$ sufficiently small, decays effective)

$$\Omega h^2 = \Omega_{\psi_r} h^2$$

2) Non-co-annihilation ($\Lambda$ large, decays ineffective)

$$\Omega h^2 = \Omega_{\psi_r} h^2 + \frac{m_{\psi_r}}{m_{\psi_\ell}} \Omega_{\psi_\ell} h^2$$

$\psi_\ell \to \psi_r$ after freeze-out




1 Similar conclusions hold for other embeddings when co-annihilation between different SM multiplets mediated by $W_R$

# Doublet pair co-annihilation

$\psi_\ell \to \psi_r$ decays via dim-5 operator generated by $\frac{1}{\Lambda}\psi_\ell \psi_r H_L H_R^*$ have decay rate:

$$\Gamma \simeq \begin{cases} \frac{1}{4\pi}\frac{v_R^2}{\Lambda^2}\left(m_{\psi_\ell} - m_{\psi_r}\right) & \text{if } m_{\psi_\ell} - m_{\psi_r} > M_{Z_L} \\ \frac{1}{128\pi^3}\frac{v_R^2}{\Lambda^2}\frac{\left(m_{\psi_\ell} - m_{\psi_r}\right)^3}{v_L^2} & \text{if } m_{\psi_\ell} - m_{\psi_r} < M_{Z_L} \end{cases}$$

For the decays to be effective around the time of freeze-out, we require

$$\Lambda < \begin{cases} 10^{11}\ \text{GeV}\left(\frac{m_{\psi_\ell} - m_{\psi_r}}{200\ \text{GeV}}\right)^{1/2}\left(\frac{v_R}{20\ \text{TeV}}\right)\left(\frac{x}{20}\right)\left(\frac{6\ \text{TeV}}{m_{\psi_\ell}}\right) \\ 10^{9}\ \text{GeV}\left(\frac{m_{\psi_\ell} - m_{\psi_r}}{50\ \text{GeV}}\right)^{3/2}\left(\frac{v_R}{20\ \text{TeV}}\right)\left(\frac{x}{20}\right)\left(\frac{6\ \text{TeV}}{m_{\psi_\ell}}\right) \end{cases}$$

# Indirect Detection

**Indirect detection** probes photons produced from DM annihilation at galactic center

Indirect detection differential gamma flux

Energy spectrum

$$\frac{d\Phi}{d\Omega dE} = \frac{\sigma v}{8\pi m_{DM}^2} \times \frac{dN}{dE} \times \int ds\ \rho_{DM}^2$$

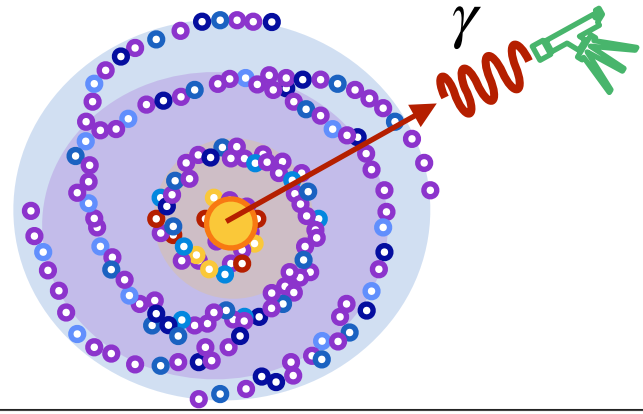
Annihilation cross section

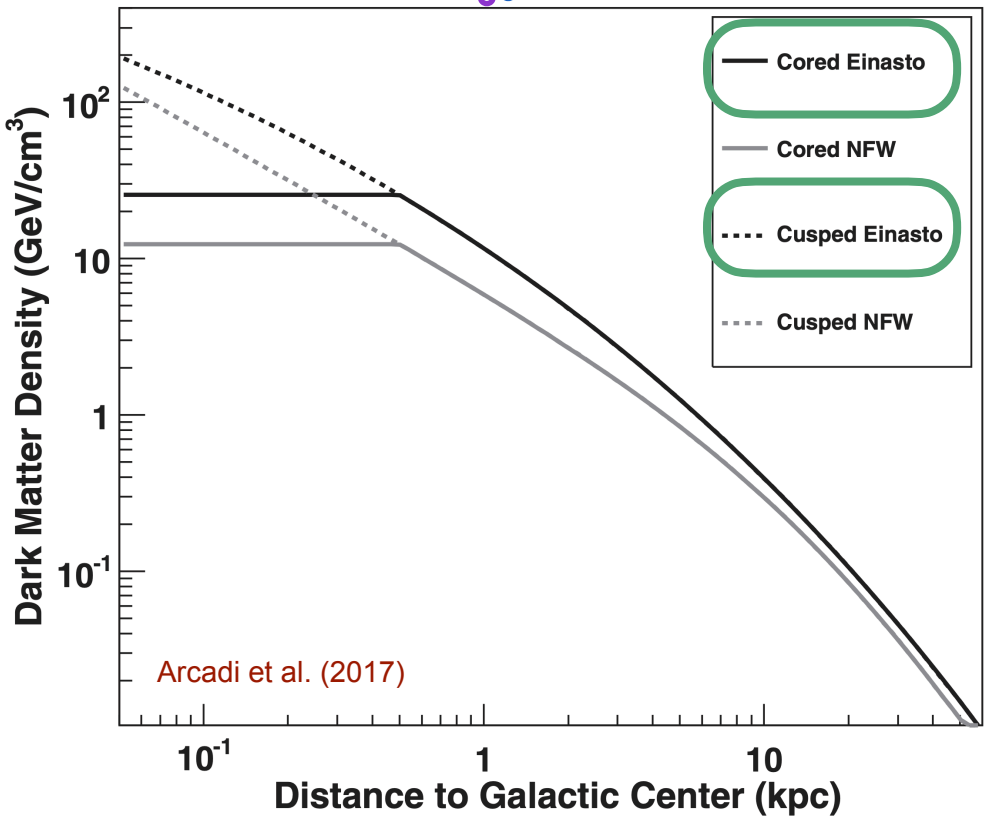
Integral over line of sight DM density "$J$-factor"

Uncertainty in DM profile near galactic centre makes $J$-factor uncertain

Cored profiles can predict smaller fluxes compared to cuspy profiles

H.E.S.S. Collaboration (2015)

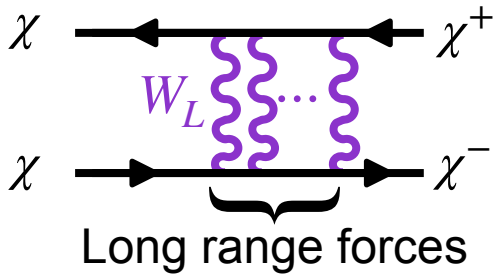


# Sommerfeld effect

Thermal averaged annihilation cross section modified by long range forces between initial states— Sommerfeld effect

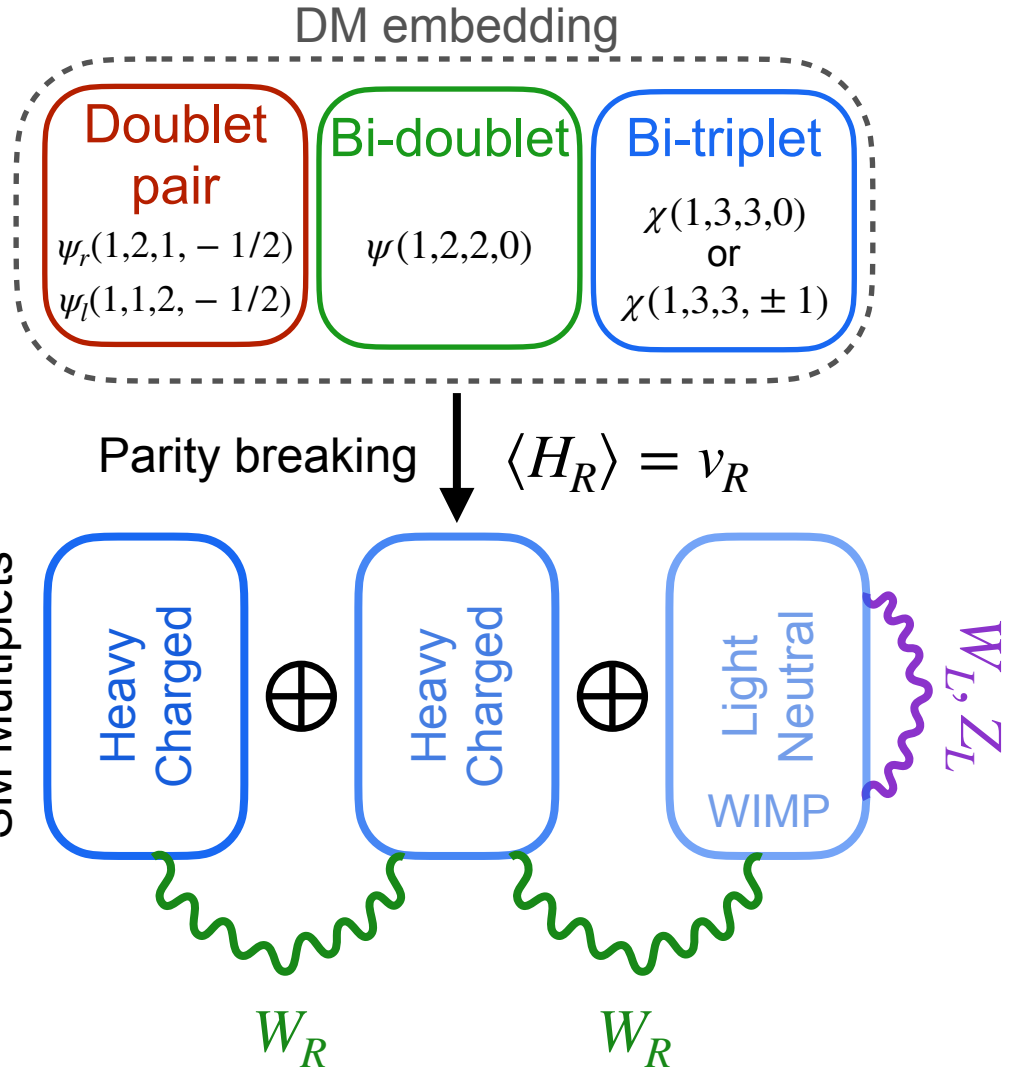
Sommerfeld (1931)
Hisano, Matsumoto, Nojiri, Saito (2005)
Hisano, Matsumoto, Nagai, Saito, Senami (2007)





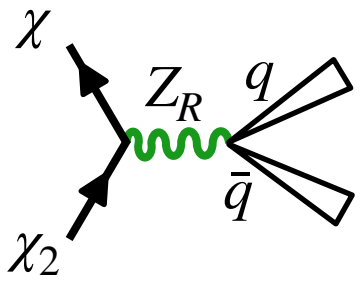


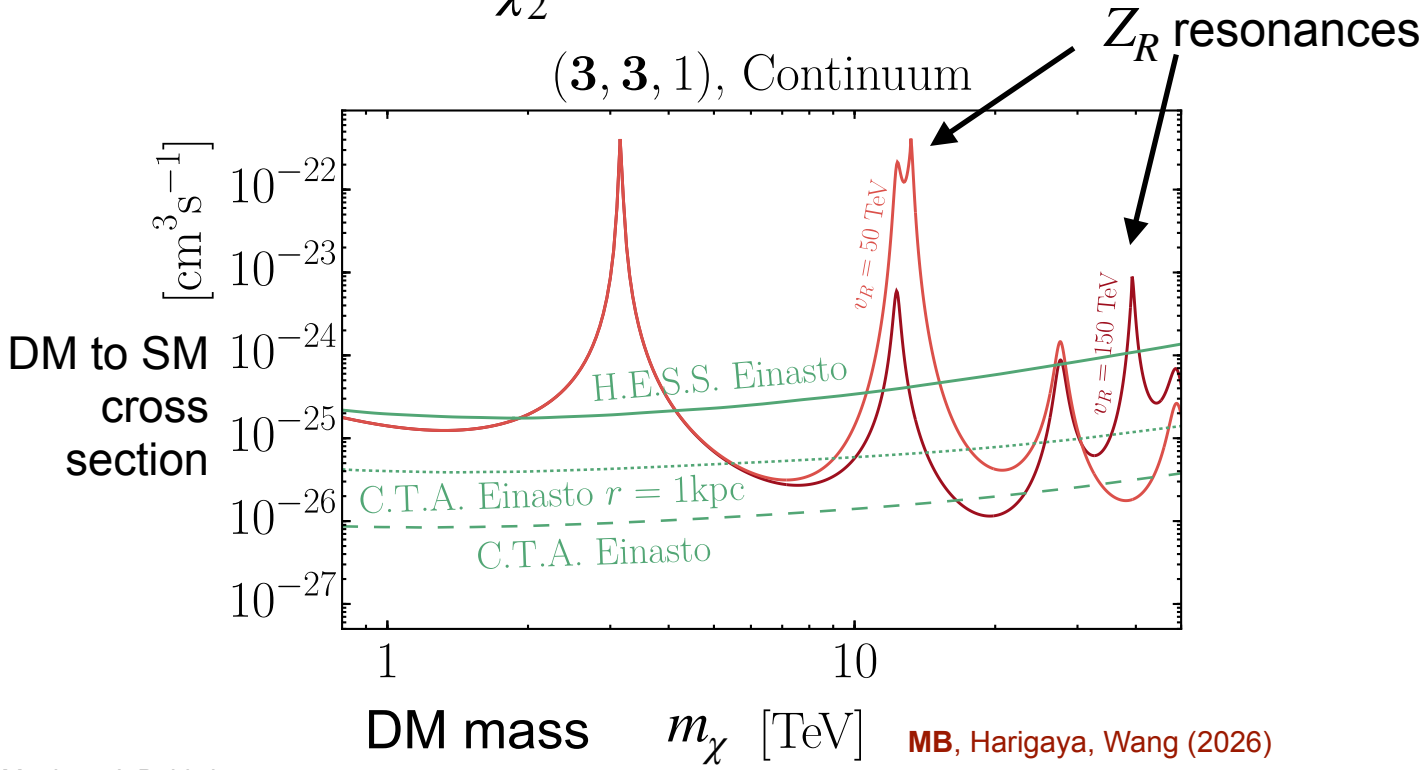
**MB**, Harigaya, Wang (2026)



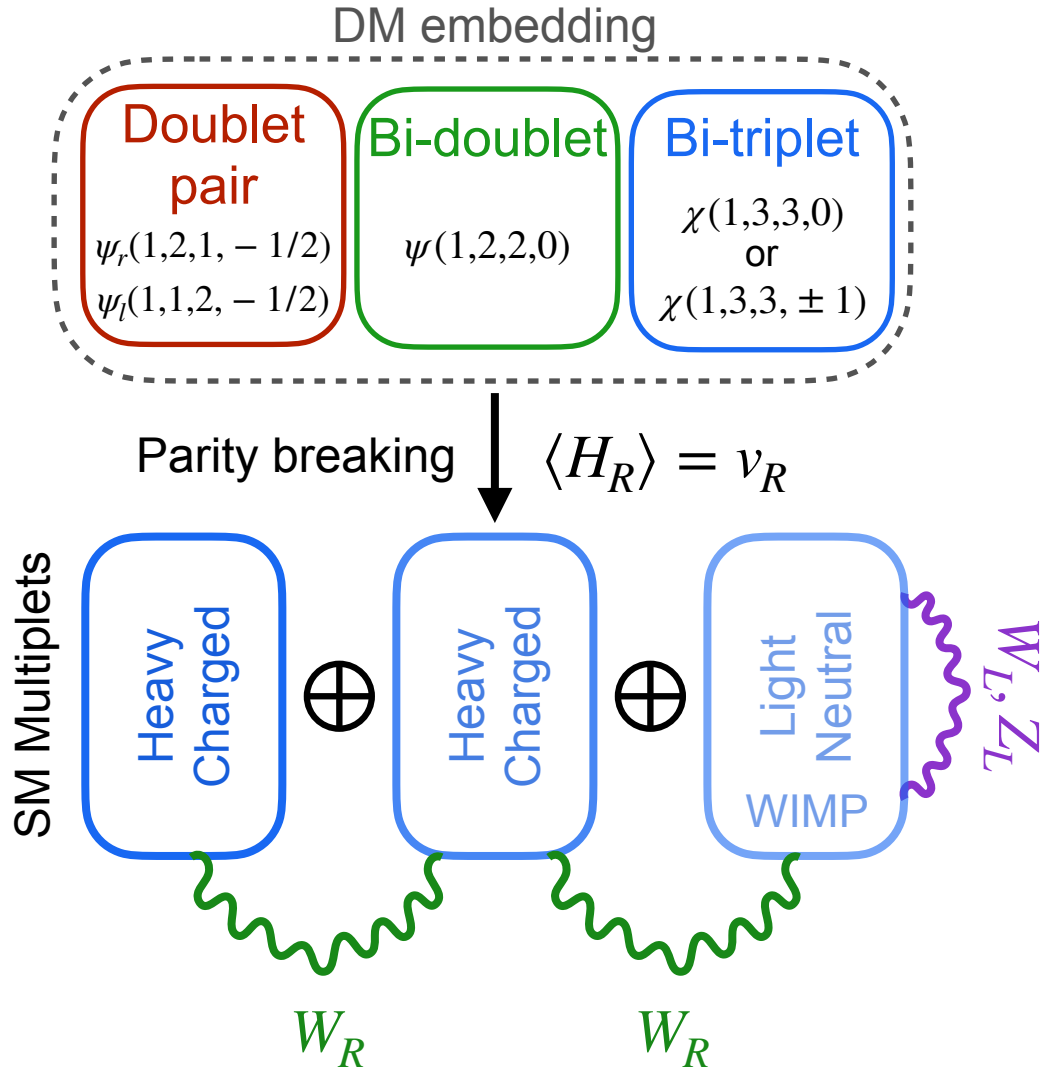
# Resonance

DM can co-annihilate via $Z_R$ and $W_R$ $s$-channel resonance[1]




**MB**, Harigaya, Wang (2026)



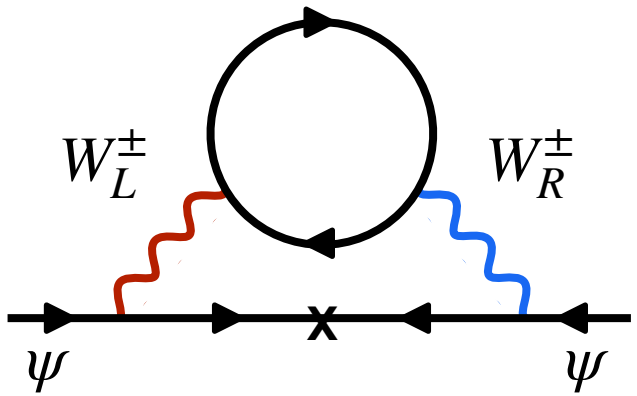



1 Resonance via $SU(2)_R$ Higgs suppressed by UV scale generating coupling e.g. $\chi\chi H_R H_R$

# Bi-doublet WIMP Dark Matter

Majorana mass $\gtrsim 200$ keV makes WIMP-nucleon scattering kinematically inaccessible

$W_L$—$W_R$ mixing via Yukawa sector fermion loop[1] can generate Majorana mass for WIMP, giving $v_R$ upper bound

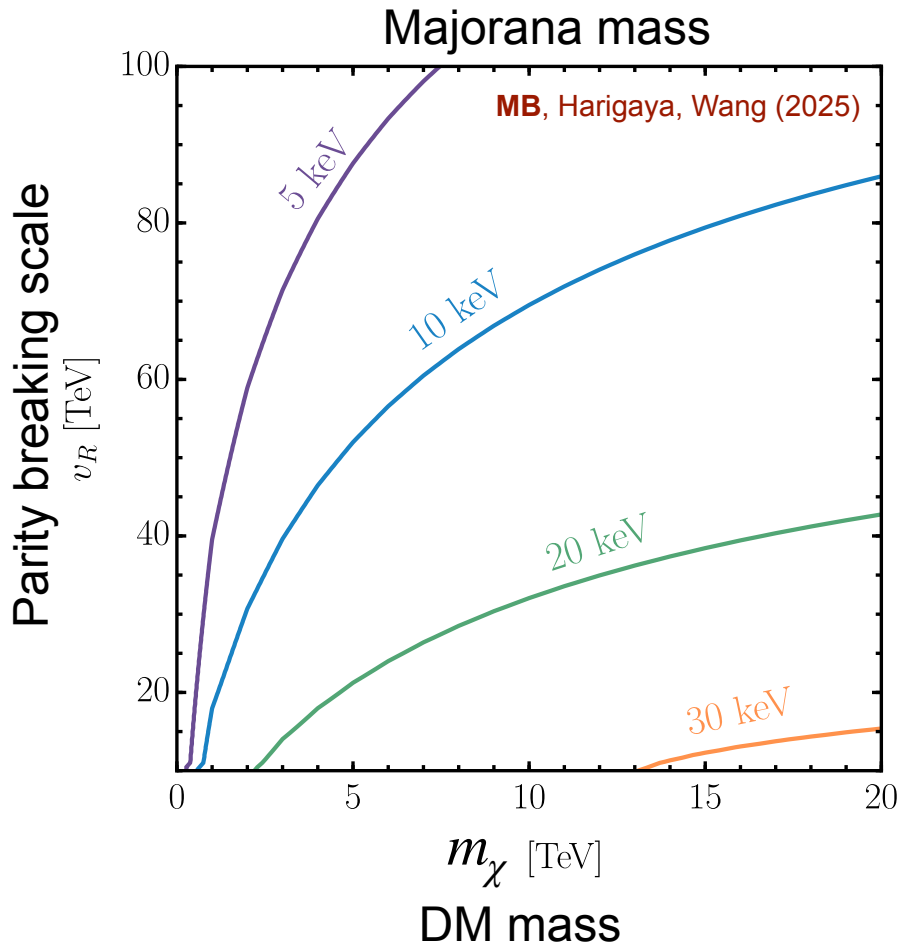



Only $O(10)$ keV possible in next-to-minimal model, which excludes the entire viable relic abundance parameter space

**MB**, Harigaya, Wang (2025)

Bi-doublet

$\psi(1,2,2,0)$



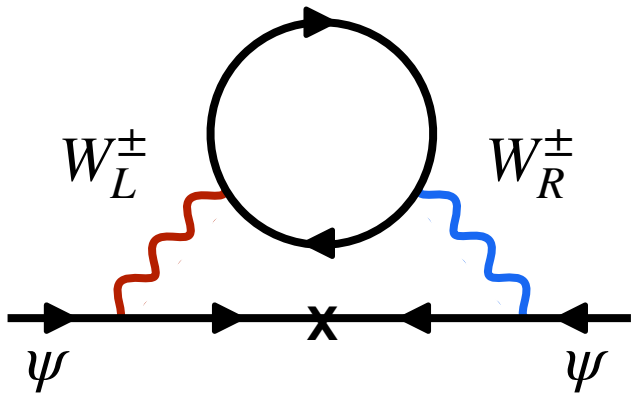



1 Previous work generates tree level $W_L$—$W_R$ mixing *Garcia-Cely, Heeck* (2016)

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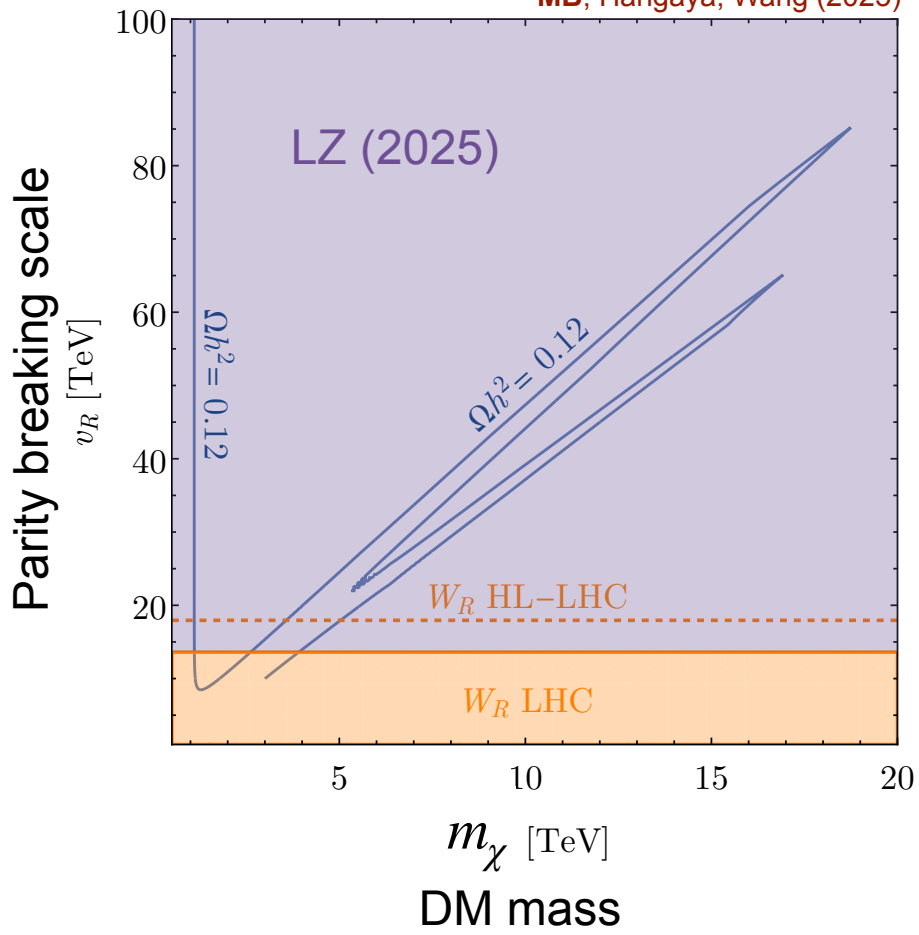

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**MB**, Harigaya, Wang (2025)

Bi-doublet

$\psi(1,2,2,0)$

**MB**, Harigaya, Wang (2025)

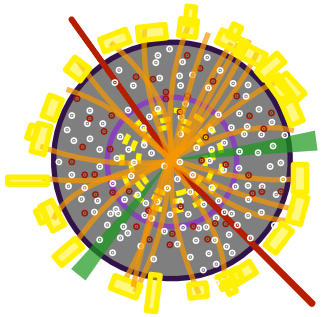
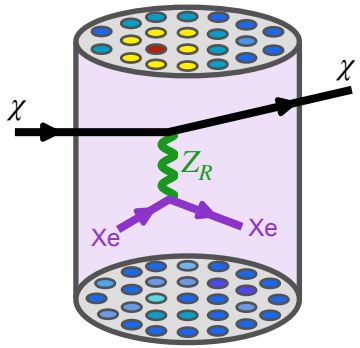
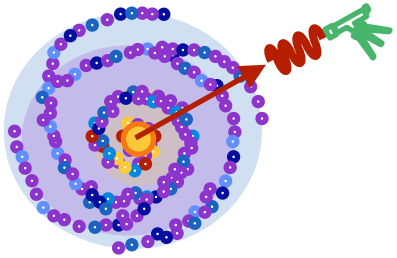




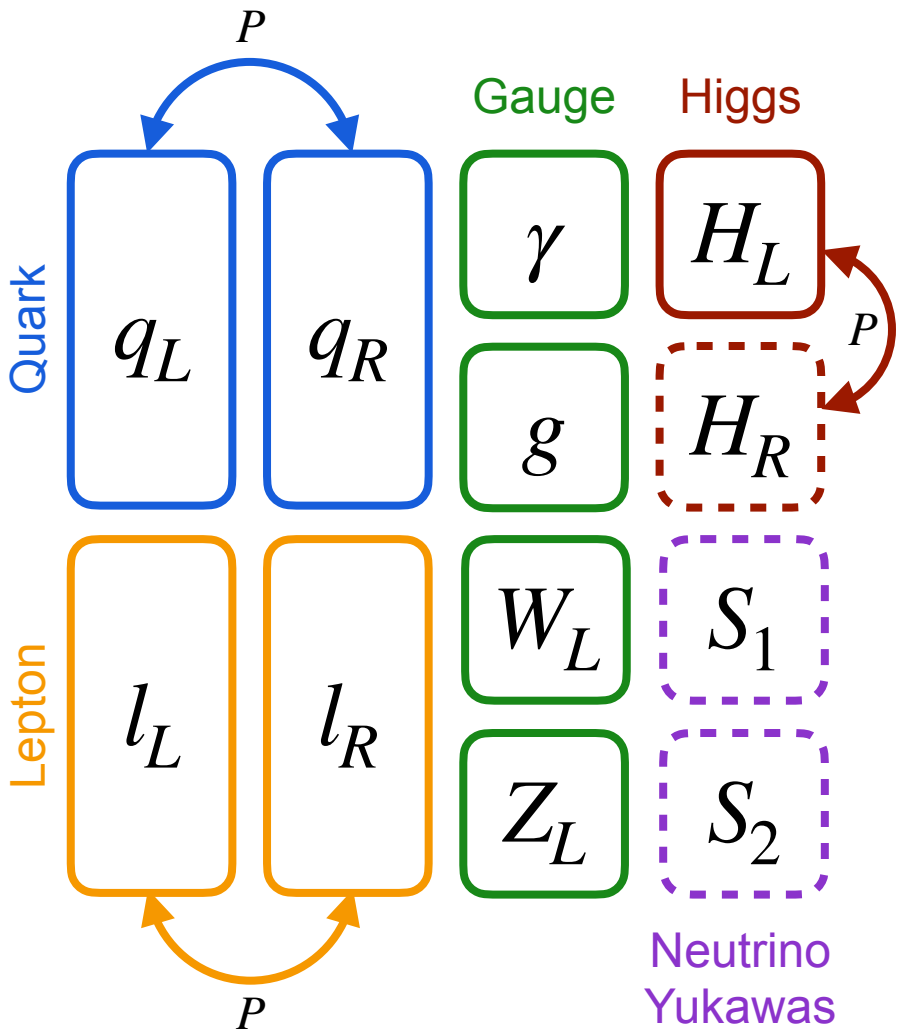

1 Previous work generates tree level $W_L$—$W_R$ mixing *Garcia-Cely, Heeck* (2016)

# Constraints on different DM embeddings

**Constraints:**

| | Collider | Direct detection | Indirect detection |
|---|---|---|---|
| |  |   |  |
| Doublet pair $\psi_r(1,2,1,-1/2)$ $\psi_l(1,1,2,-1/2)$ | ✓ lower bound | ✓ lower bound | ✓ |
| Bi-doublet $\psi(1,2,2,0)$ | ✓ lower bound | ✓ upper bound | ✓ |
| Bi-triplet $\chi(1,3,3,\pm 1)$ | ✓ lower bound | ✓ lower bound | ✓ |
| Bi-triplet $\chi(1,3,3,0)$ | ✓ lower bound | ✘ no $Z_R$ coupling | ✓ |

# LFV Processes can Probe the Parity Breaking Scale



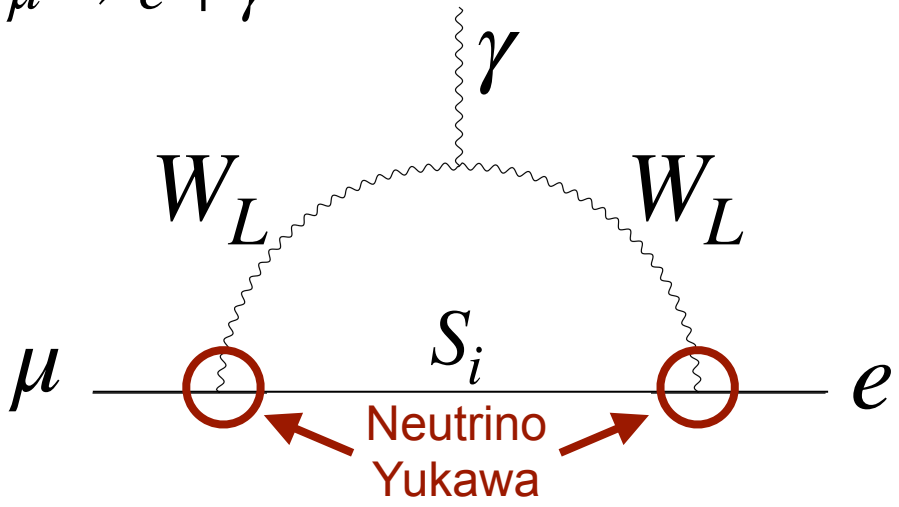

Neutrino masses can be generated via Radiative Singlet Model by introduction of singlets $S_{1,2}$

Hall, Harigaya, Shpilman (2023)

$$\mathscr{L} = x_{S_i} S_i \left( l H_L + \boxed{\bar{l} H_R} \right) + \frac{1}{2} m_{S_i} S_i^2 + \Delta m S_1 S_2$$

Neutrino Yukawas $v_R$ dependent

Generates $\mu \to e + \gamma$



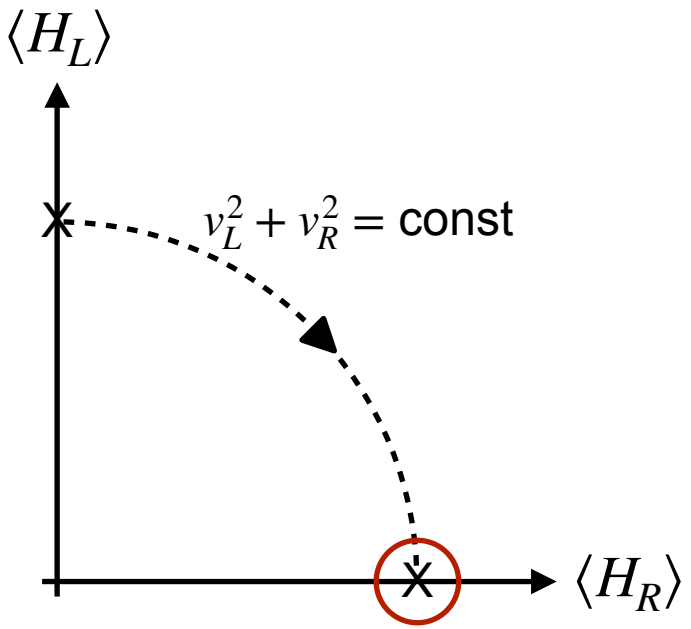

$\Longrightarrow$ $\boxed{\mu \to e + \gamma \text{ probes } v_R}$ **MB**, Harigaya, Shapir (in preparation)

# Domain Walls From Parity Breaking

To avoid a domain wall problem, Parity can be spontaneously broken via an additional $SU(N)$ pure Yang Mills sector with $\theta = \pi$.

$$\frac{F\tilde{F}}{M_{pl}^2}\left(|H_L|^2 - |H_R|^2\right)$$

$$\langle F\tilde{F}\rangle \sim \Lambda^4 \sim v_R^2 M_{pl}^2 \implies \Lambda \sim \sqrt{v_R M_{pl}} \approx 10^{11}\ \text{GeV}$$




If temperature does not return above $10^{11}$ GeV after reheating, domain walls from Parity breaking inflated away

# Other Higgs Embeddings

Higgs may also be embedded into bi-fundamentals or triplets in left-right models

$$H_P(1,2,2,0) \oplus H_L(1,3,1,2) \oplus H_R(1,1,3,-2)$$

However, these Higgs' VEVs can have physical phase degrees of freedom and contribute a strong CP phase

In this case, additional symmetry, e.g. SUSY, must be introduced to ensure the strong CP problem is solved.

# Upper Bound on $v_R$ From Higher Dimensional Operators

Higher dimensional Parity symmetric operators can contribute a tree-level $\theta$ term, for example

$$\frac{1}{\Lambda^2}\left(|H_L|^2 - |H_R|^2\right) F\tilde{F}$$

After Parity breaking, to ensure the $\theta$ term is sufficiently small, $v_R$ is bounded from above

$$v_R \lesssim 10^{13}\ \text{GeV}\left(\frac{\Lambda}{10^{18}\ \text{GeV}}\right)$$

This still leaves a large possible range for $v_R$ if no other upper bounds constrain $v_R$