Higgs 2021

HIGGS SECTOR IN LEFT-RIGHT SYMMETRIC MODEL

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CONTENT

LEFT-RIGHT MIRROR SYMMETRY

$$SU(3)_C \otimes S(2)_L \otimes U(1)_Y$$

$$\Updownarrow$$

$$S(2)_R$$

LEFT-RIGHT MIRROR SYMMETRY

$$SU(3)_C \otimes S(2)_L \otimes U(1)_Y$$

$$S(2)_R$$

$$SU(3)_C \otimes S(2)_R \otimes S(2)_L \otimes U(1)_{Y'}$$

LEFT-RIGHT MIRROR SYMMETRY

$$SU(3)_C \otimes S(2)_L \otimes U(1)_Y$$

$$S(2)_R$$

$$SU(3)_C \otimes S(2)_R \otimes S(2)_L \otimes U(1)_{Y'}$$

We also incluye a discrete symmetry → Z_2

Fields in the Model

The irreducible representations are presented for fermion and scalar fields. The bold numbers denote the dimensions of representations under the gauge group, meanwhile the last entry is for the new hypercharge.

Leptons

Field	$SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{Y'}$
ℓ^0_{iL}	$(\mathbf{1},\ \mathbf{2},\ \mathbf{1},\ -1)$
ν^0_{iR}	$(\mathbf{1},\ \mathbf{1},\ \mathbf{1},\ 0)$
e^0_{iR}	$(\mathbf{1},\ \mathbf{1},\ \mathbf{1},\ -2)$
$\hat{\nu}^0_{iL}$	$(\mathbf{1},\ \mathbf{1},\ \mathbf{1},\ 0)$
$\hat{e}^0_{iL}$	$(\mathbf{1},\ \mathbf{1},\ \mathbf{1},\ -2)$
$\hat{l}^0_{iR}$	$(\mathbf{1},\ \mathbf{1},\ \mathbf{2},\ -1)$

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Mirror

Gauge eigenstate

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u^0_{iR}	$(\mathbf{3},\ \mathbf{1},\ \mathbf{1},\ 4/3)$
d^0_{iR}	$(\mathbf{3},\ \mathbf{1},\ \mathbf{1},\ 2/3)$
q^0_{iL}	$(\mathbf{3},\ \mathbf{2},\ \mathbf{1},\ 1/3)$
$\hat{u}^0_{iL}$	$(\mathbf{3},\ \mathbf{1},\ \mathbf{1},\ 4/3)$
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Gauges

Field	$SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{Y'}$
W_L^μ	$(\mathbf{1},\ \mathbf{3},\ \mathbf{1},\ 0)$
B^μ	$(\mathbf{1},\ \mathbf{1},\ \mathbf{1},\ 0)$
W_R^μ	$(\mathbf{1},\ \mathbf{1},\ \mathbf{3},\ 0)$

SCALAR FIELDS AND SSB

Spontaneous Symmetry Breaking

SCALAR FIELDS AND SSB

The symmetry breaking pattern should be as follows

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{Y'} \xrightarrow{\langle\hat{\Phi}\rangle} SU(2)_L \otimes U(1)_Y \xrightarrow{\langle\Phi\rangle} U(1)_{qed}$$

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$$\langle \Phi \rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} v \end{pmatrix}$$

$$v = 246\, GeV$$

POTENTIAL FOR SCALAR FIELDS

The scalar potential is

$$V = -\left(\mu_1^2\Phi^\dagger\Phi + \mu_2^2\hat{\Phi}^\dagger\hat{\Phi}\right) + \frac{\lambda_1}{2}\left[\left(\Phi^\dagger\Phi\right)^2 + \left(\hat{\Phi}^\dagger\hat{\Phi}\right)^2\right] + \lambda_2\left(\Phi^\dagger\Phi\right)\left(\hat{\Phi}^\dagger\hat{\Phi}\right)$$

These terms can be included so that the parity symmetry is broken softly.

$$\hat{\Phi}^\dagger\Phi$$

Terms with mixing between ordinary and mirror doublet fields are excluded.

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After the symmetry breaking, the neutral Higgs boson squared mass matrix is

$$\mathrm{M}_{\mathrm{H}^0}^2 = \begin{pmatrix} 2\lambda_1 v^2 & 2\lambda_2 v\hat{v} \\ 2\lambda_2 v\hat{v} & 2\lambda_2\hat{v}^2 \end{pmatrix}$$

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Thus, the neutral physical states are

$$\begin{pmatrix} H \\ \hat{H} \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} \mathsf{Re}[\phi^0] \\ \mathsf{Re}[\hat{\phi}^0] \end{pmatrix}$$

In this case the mixing angle for neutral scalar is given by

$$\tan(2\alpha) = \frac{2\lambda_2 v \hat{v}}{\lambda_1 \left(v^2 - \hat{v}^2\right)}$$

and the neutral scalar masses are

$$m_H^2 = \lambda_1 \left(v^2 + \hat{v}^2\right) - \sqrt{\lambda_1^2 \left(v^2 - \hat{v}^2\right)^2 + 4\lambda_2 v^2 \hat{v}^2}$$

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$\hat{H}$ → Heavy neutral Higgs

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H → Higgs from SM

$\hat{H}$ → Heavy neutral Higgs ← New portal for DM

GAUGE AND SCALAR FIELDS

The kinetic terms for scalars are

$$\mathscr{L}_{scalar} = \left(\mathrm{D}^{\mu}\Phi\right)^{\dagger}\left(\mathrm{D}_{\mu}\Phi\right) + \left(\hat{\mathrm{D}}^{\mu}\hat{\Phi}\right)^{\dagger}\left(\hat{\mathrm{D}}_{\mu}\hat{\Phi}\right)$$

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For simplicity, we have written the covariant derivative as

$$D_{\mu} = \partial_{\mu} + ig_2\frac{\vec{\tau}}{2}\cdot\overrightarrow{W}_{L\mu} + ig_1Y'B_{\mu}$$

$$\hat{D}_{\mu} = \partial_{\mu} + i\hat{g}_2\frac{\vec{\tau}}{2}\cdot\overrightarrow{W}_{R\mu} + ig_1Y'B_{\mu}$$

the coupling constants associated $SU(2)_L$

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$$g_2 = \hat{g}_2$$

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$$\frac{1}{2}Y = T_{3R} + \frac{1}{2}Y'$$

FERMIONS AND SCALAR FIELDS

The renormalizable and gauge invariant interactions of the scalar doublets with the leptons are described by the Yukawa interactions, which takes the form for charged leptons

$$\mathscr{L}_Y^{\ell} = \sum_{i,j} \lambda_{ij} \overline{\ell}^o_{iL} \Phi e^o_{jR} + \sum_{i,j} \lambda'_{ij} \overline{\hat{\ell}}^o_{iR} \hat{\Phi} \hat{e}^o_{jL} + \sum_{i,j} \mu_{ij} \overline{\hat{e}}^o_{iL} e^o_{jR} + h.c.$$

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The VEV's of the neutral scalars produce the fermion mass terms, which in the gauge eigenstate basis read

$$\mathscr{L}_{\text{mass}} = \overline{\psi^{o}_{L}} \mathsf{M} \psi^{o}_{R} + h.c.$$

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$$\mathsf{M} = \begin{pmatrix} \mathsf{K} & 0 \\ \mu & \mathsf{K}' \end{pmatrix}$$

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$$\mathrm{K} = \frac{1}{2}\lambda \mathrm{v}$$

$$\mathrm{K}' = \frac{1}{2}\lambda' \hat{\mathrm{v}}$$

Thus, the mass matrices can be diagonalized through unitary matrices Ua, for a = L,R; as

$$M_D = U_L^\dagger M U_R \,.$$

We write Ua as

$$U_a = \begin{pmatrix} A_a & E_a \\ F_a & G_a \end{pmatrix}.$$

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In general, these matrices are not unitary

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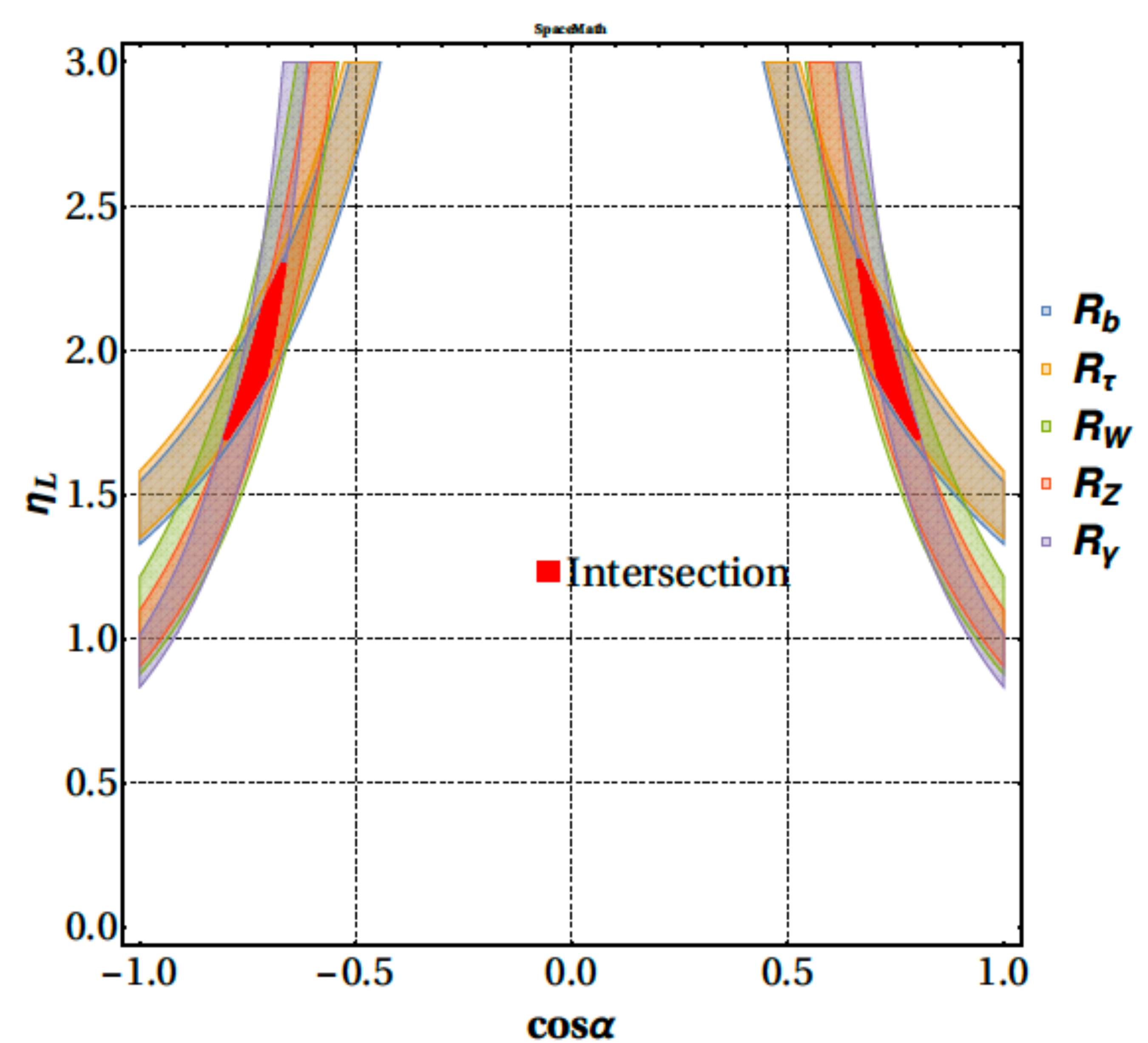
Thus, the tree-level interactions of the neutral Higgs bosons H and H^ with the light fermions are given by

$$\mathscr{L}_Y^l = \frac{g_2}{2\sqrt{2}} \bar{f}_L^i (\mathsf{A}_L^\dagger \mathsf{A}_L)_{ij} \frac{m_l}{M_W} f_R^j \left(H \cos\alpha - \hat{H} \sin\alpha \right) + \frac{g_2'}{\sqrt{2}} \bar{f}_L^i \frac{m_l}{M_{W'}} (\mathsf{F}_R^\dagger \mathsf{F}_R)_{ij} f_R^j \left(H \sin\alpha + \hat{H} \cos\alpha \right) + h.c.$$

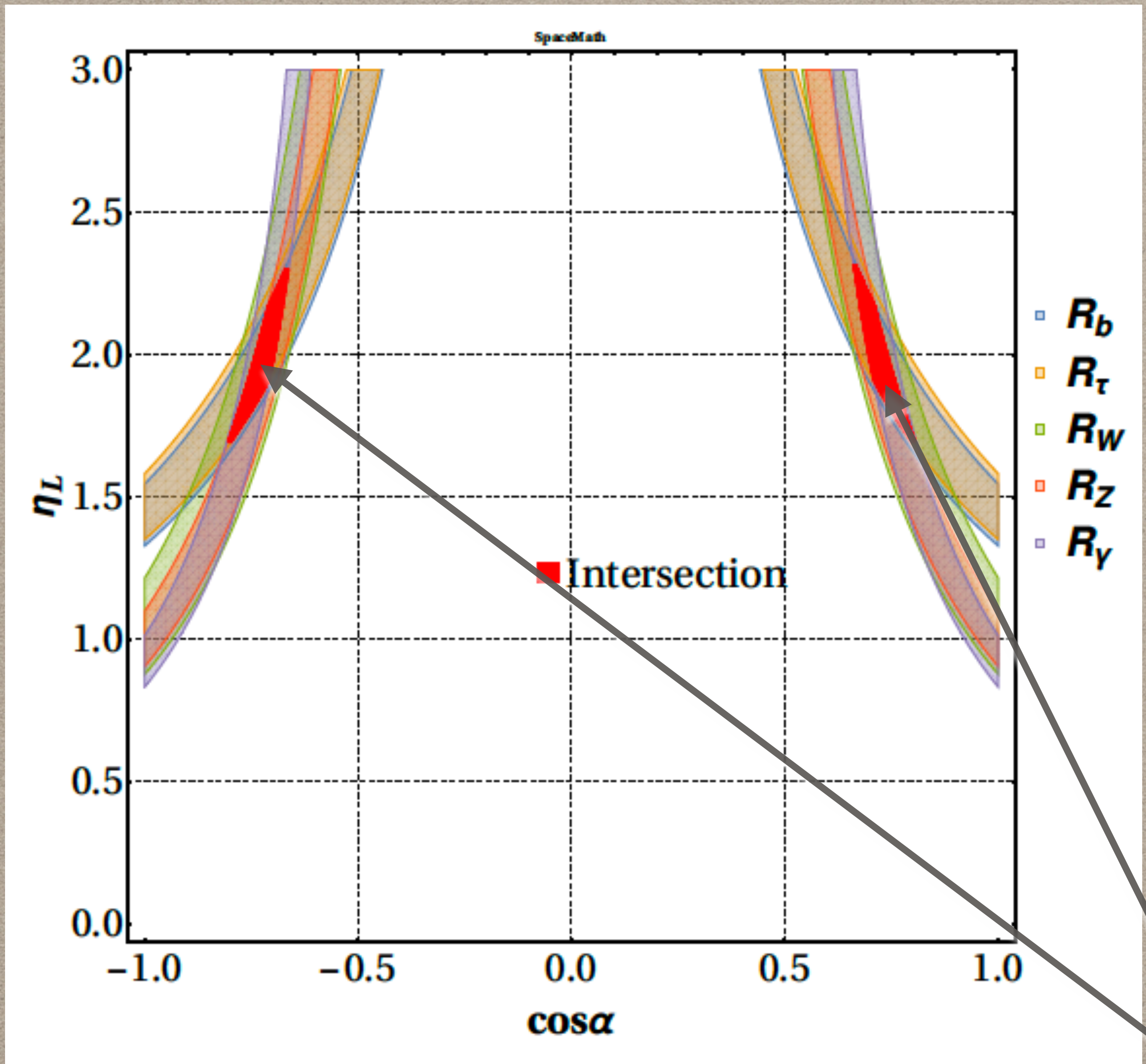


(a)

$$\left(A_L^\dagger A_L\right)_{f_i f_j} \equiv \left(\eta_L\right)_{f_i f_j}$$

$$\mathcal{R}_X = \frac{\sigma(pp \to H)\cdot \mathcal{BR}(H \to X)}{\sigma(pp \to H^{SM})\cdot \mathcal{BR}(H^{SM} \to X)}$$

$$X = b\bar{b},\, \tau^-\tau^+,\, \mu^-\mu^+,\, WW^*,\, ZZ^*,\, \gamma\gamma$$



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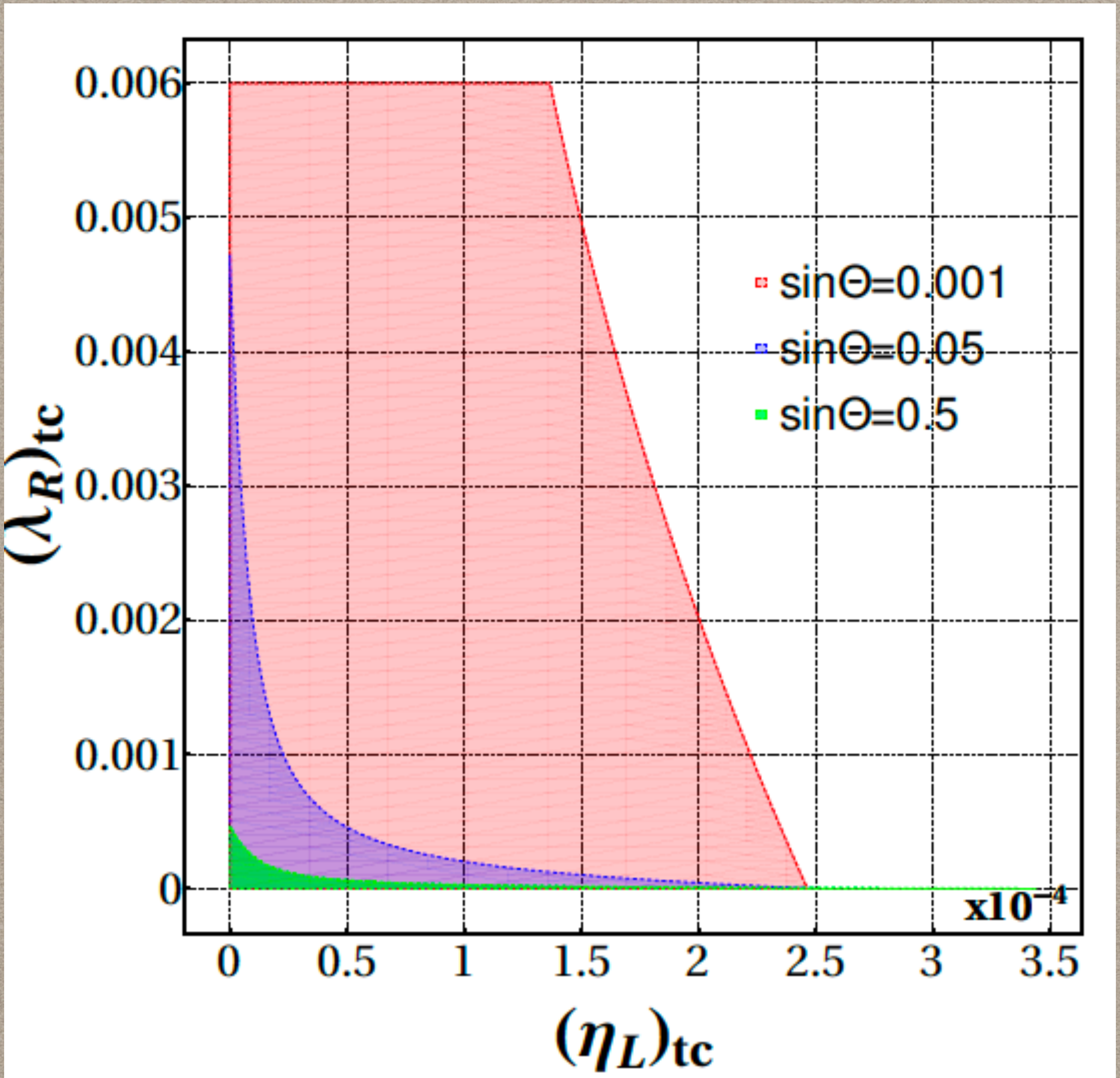
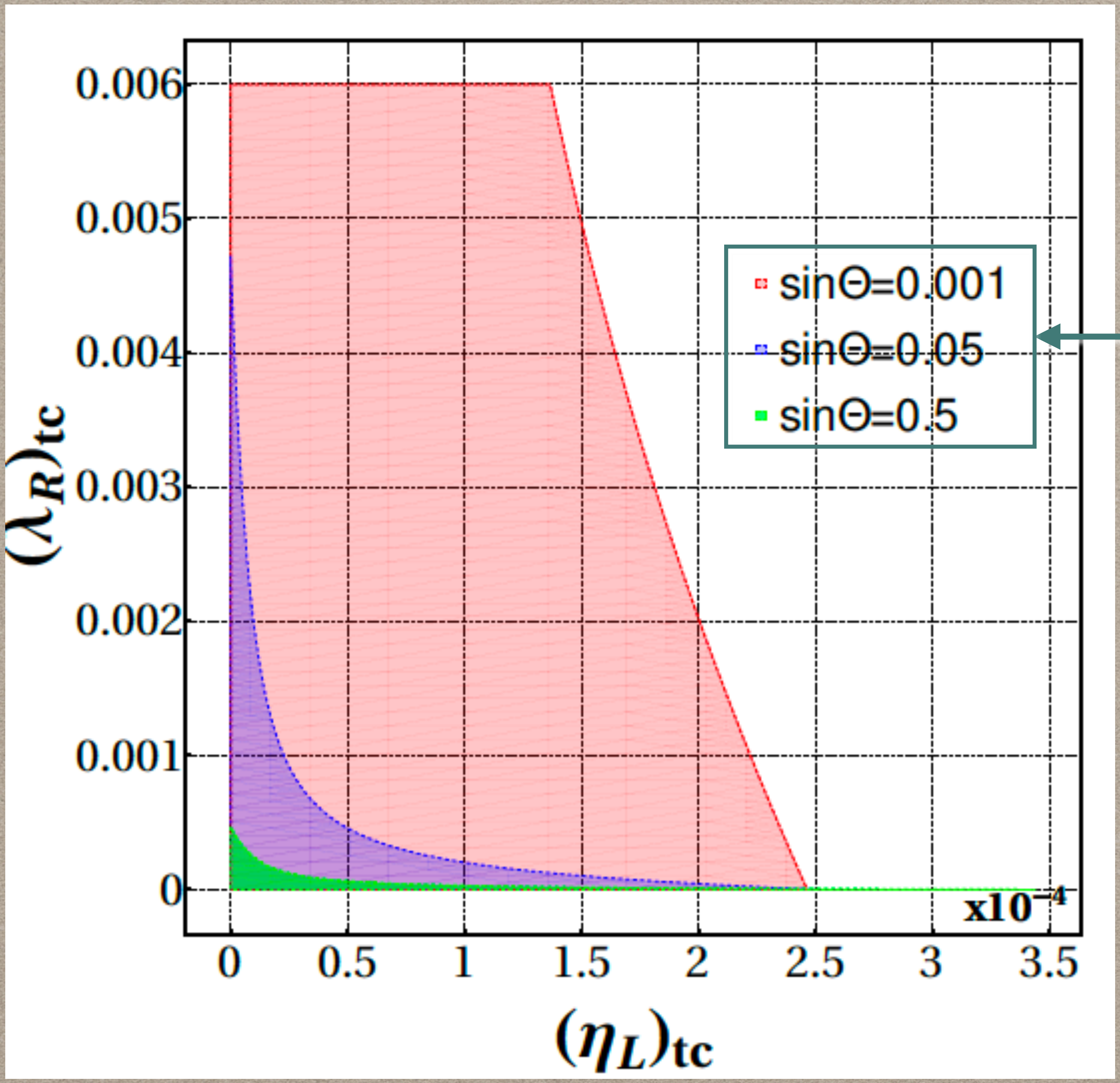
$\cos\alpha \approx \pm 0.7$

$1.9 \lesssim \eta_L \lesssim 2.2$



$\mathcal{BR}(t \to Zc) \lesssim 5 \times 10^{-6}$



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Mixing parameter for Z and Z′

NEUTRINO MASSES AND MIXING

With the fields of fermions introduced in the model, we may write the gauge invariant Yukawa couplings for the neutral sector:

$$\mathcal{L}_\nu = h_{ij}\bar{\hat{\nu}}_{iL}\nu_{jR} + \chi_{ij}\bar{\nu}_{iR}\left(\nu_{jR}\right)^c + \hat{\chi}_{ij}\bar{\hat{\nu}}_{iL}\left(\hat{\nu}_{jL}\right)^c + \sigma_{ij}\bar{l}_{iL}\tilde{\Phi}\left(\hat{\nu}_{jL}\right)^c$$

$$+\hat{\sigma}_{ij}\bar{\hat{l}}_{iR}\tilde{\hat{\Phi}}\left(\nu_{jR}\right)^c + \lambda_{ij}\bar{l}_{iL}\tilde{\Phi}\nu_{jR} + \hat{\lambda}_{ij}\bar{\hat{l}}_{iR}\tilde{\hat{\Phi}}\hat{\nu}_{jL} + \text{h.c.}$$

When doublet scalar fields acquire VEV's we get the neutrino mass terms

$$\mathcal{L}_{\nu-mass} = \left(\overline{\Psi}_{\nu L}, \quad \overline{\Psi^c}_{\nu L}\right)\begin{pmatrix} M_L & M_D \\ M_D & M_R \end{pmatrix}\begin{pmatrix} \Psi_{\nu R} \\ \Psi^c_{\nu R} \end{pmatrix}$$

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$$\Psi_{\nu(L,R)} = \begin{pmatrix} \nu_i \\ \hat{\nu}_i \end{pmatrix}_{(L,R)}$$

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$$M_L = \begin{pmatrix} 0 & \frac{v}{\sqrt{2}}\sigma_{ij} \\ \frac{v}{\sqrt{2}}\sigma^{T}_{ij} & \hat{\chi}_{ij} \end{pmatrix}$$

NEUTRINO MASSES AND MIXING

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$$\mathscr{L}_{\nu} = h_{ij}\bar{\hat{\nu}}_{iL}\nu_{jR} + \chi_{ij}\bar{\nu}_{iR}\left(\nu_{jR}\right)^{c} + \hat{\chi}_{ij}\bar{\hat{\nu}}_{iL}\left(\hat{\nu}_{jL}\right)^{c} + \sigma_{ij}\bar{l}_{iL}\tilde{\Phi}\left(\hat{\nu}_{jL}\right)^{c}$$

$$+\hat{\sigma}_{ij}\bar{\hat{l}}_{iR}\tilde{\hat{\Phi}}\left(\nu_{jR}\right)^{c} + \lambda_{ij}\bar{l}_{iL}\tilde{\Phi}\nu_{jR} + \hat{\lambda}_{ij}\bar{\hat{l}}_{iR}\tilde{\hat{\Phi}}\hat{\nu}_{jL} + h.c.$$

When doublet scalar fields acquire VEV's we get the neutrino mass terms

$$\mathscr{L}_{\nu-mass} = \left(\overline{\Psi}_{\nu L}, \quad \overline{\Psi^{c}}_{\nu L}\right)\begin{pmatrix} M_L & M_D \\ M_D & M_R \end{pmatrix}\begin{pmatrix} \Psi_{\nu R} \\ \Psi^{c}_{\nu R} \end{pmatrix}$$

$$M_R = \begin{pmatrix} \chi_{ij} & \frac{\hat{v}}{\sqrt{2}}\hat{\sigma}_{ij} \\ \frac{\hat{v}}{\sqrt{2}}\hat{\sigma}^{T}_{ij} & 0 \end{pmatrix}$$

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$$M_D = \begin{pmatrix} \frac{v}{\sqrt{2}}\lambda_{ij} & 0 \\ h_{ij} & \frac{\hat{v}}{\sqrt{2}}\hat{\lambda}_{ij} \end{pmatrix}$$

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In this case the ordinary neutrinos can be written separately from for mirror neutrinos in the matrix as follows

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Ordinary

$$\left(\overline{\hat{\nu}}_{iL}, \quad \overline{\hat{\nu}^c}_{\nu R}\right) \begin{pmatrix} \hat{\chi}_{ij} & \frac{\hat{v}}{\sqrt{2}}\hat{\lambda}_{ij} \\ \frac{\hat{v}}{\sqrt{2}}\hat{\lambda}^T_{ij} & 0 \end{pmatrix} \begin{pmatrix} \hat{\nu}^c_{iL} \\ \hat{\nu}_{jR} \end{pmatrix}$$

Mirror

By assuming the natural hierarchy $|\lambda_{ij}| \ll |\chi_{ij}|$ *among the mass terms, the mass matrix for ordinary neutrinos can approximately be diagonalized, yielding*

$$\begin{pmatrix} 0 & \frac{v}{\sqrt{2}}\lambda_{ij} \\ \frac{v}{\sqrt{2}}\lambda_{ij}^T & \chi_{ij} \end{pmatrix}$$

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Then, the inverse matrix for χ *is*

$$\chi^{-1} = \frac{1}{m} S^{-1} D$$

and the matrix for light neutrinos is

$$M_{\nu}^{light} = \frac{v^2 y^2}{2m} SD$$

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In order to diagonalize the matrix M we use the PNMS matrix

$$\text{Diagonal}\left[m_{\nu_1}, m_{\nu_2}, m_{\nu_3}\right] = \frac{v^2y^2}{2m} U_\nu^T S U_\nu^T D$$

PNMS transpose matrix

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DARK MATTER FROM MIRROR NEUTRINO

We consider the lightest mirror neutrino as Dark Matter candidate. The mass matrix for mirror neutrinos was introduced as

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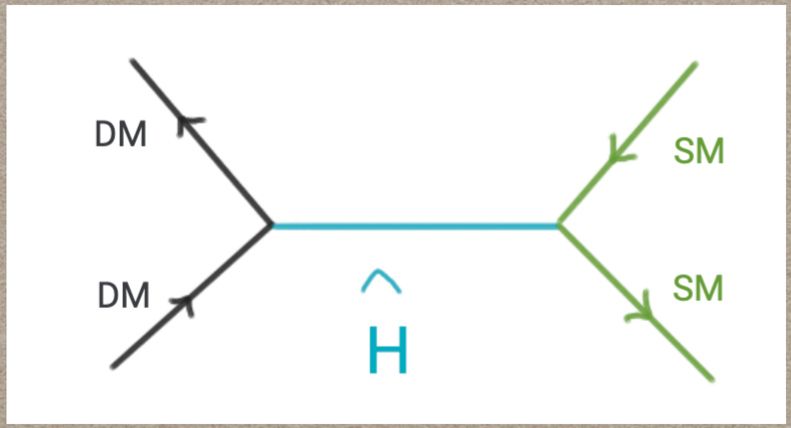
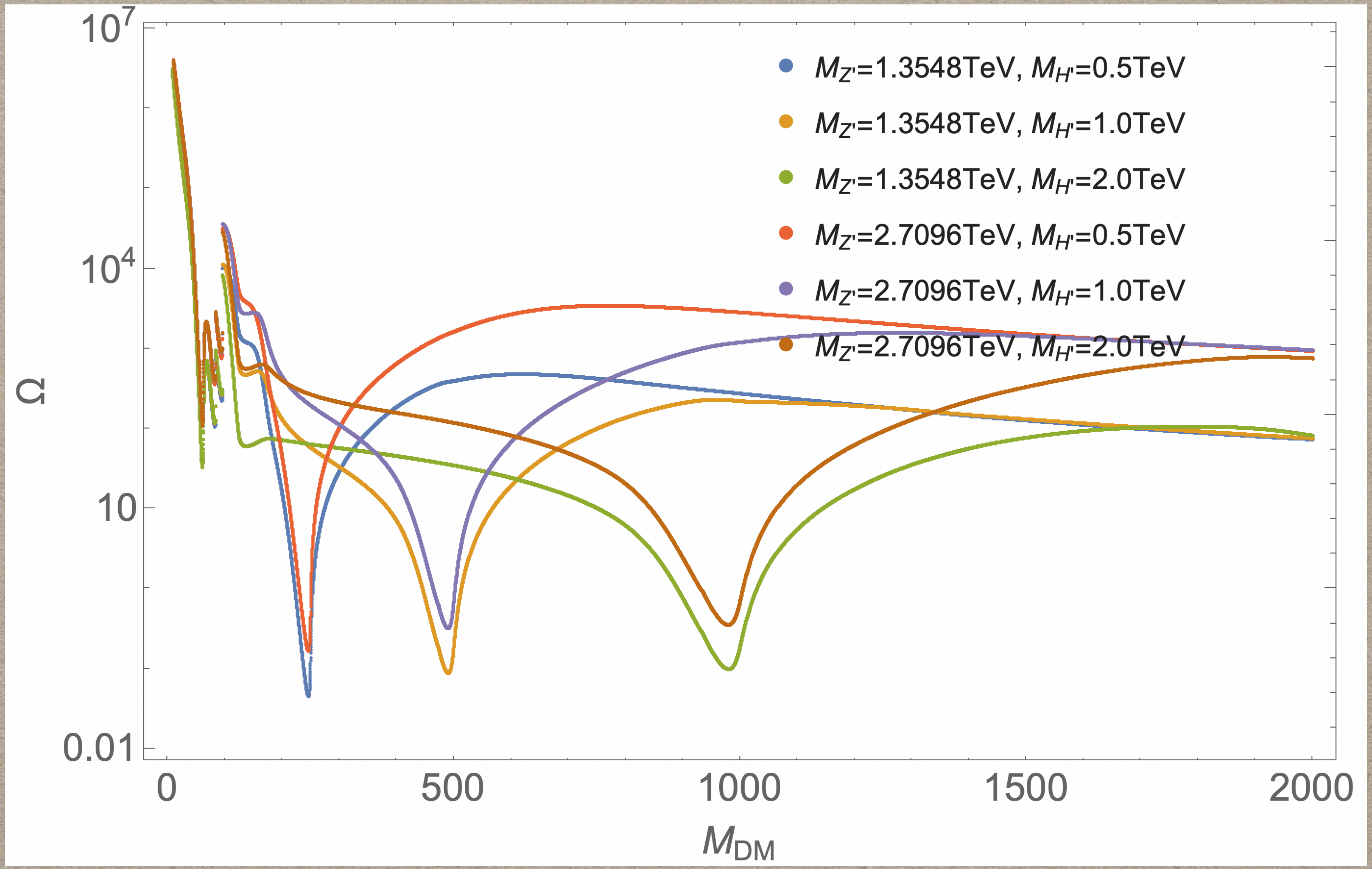
*the candidate is linked with particles through the mix of the H^*



RELIC DENSITY VS DM MASS [GEV]



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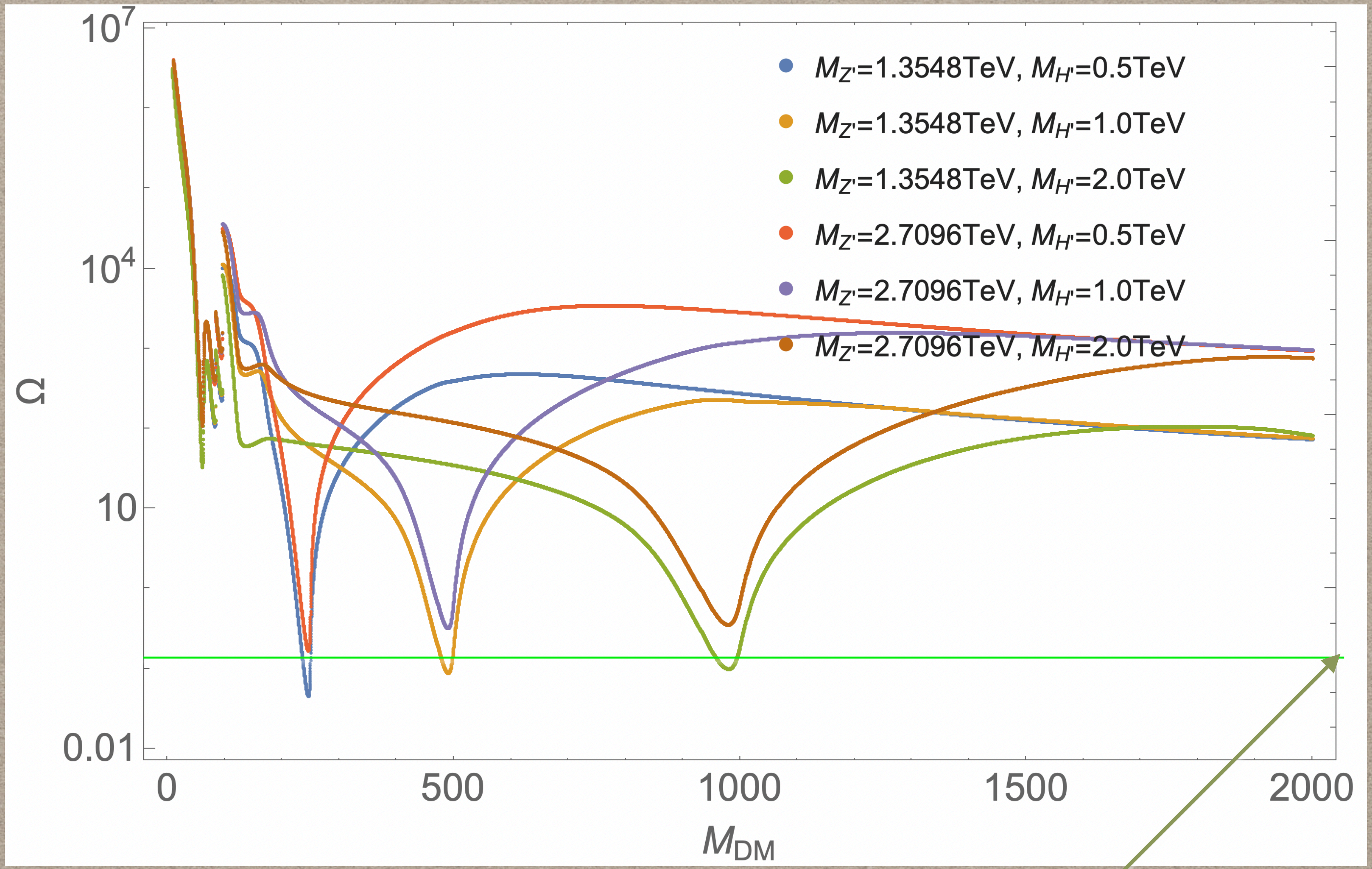
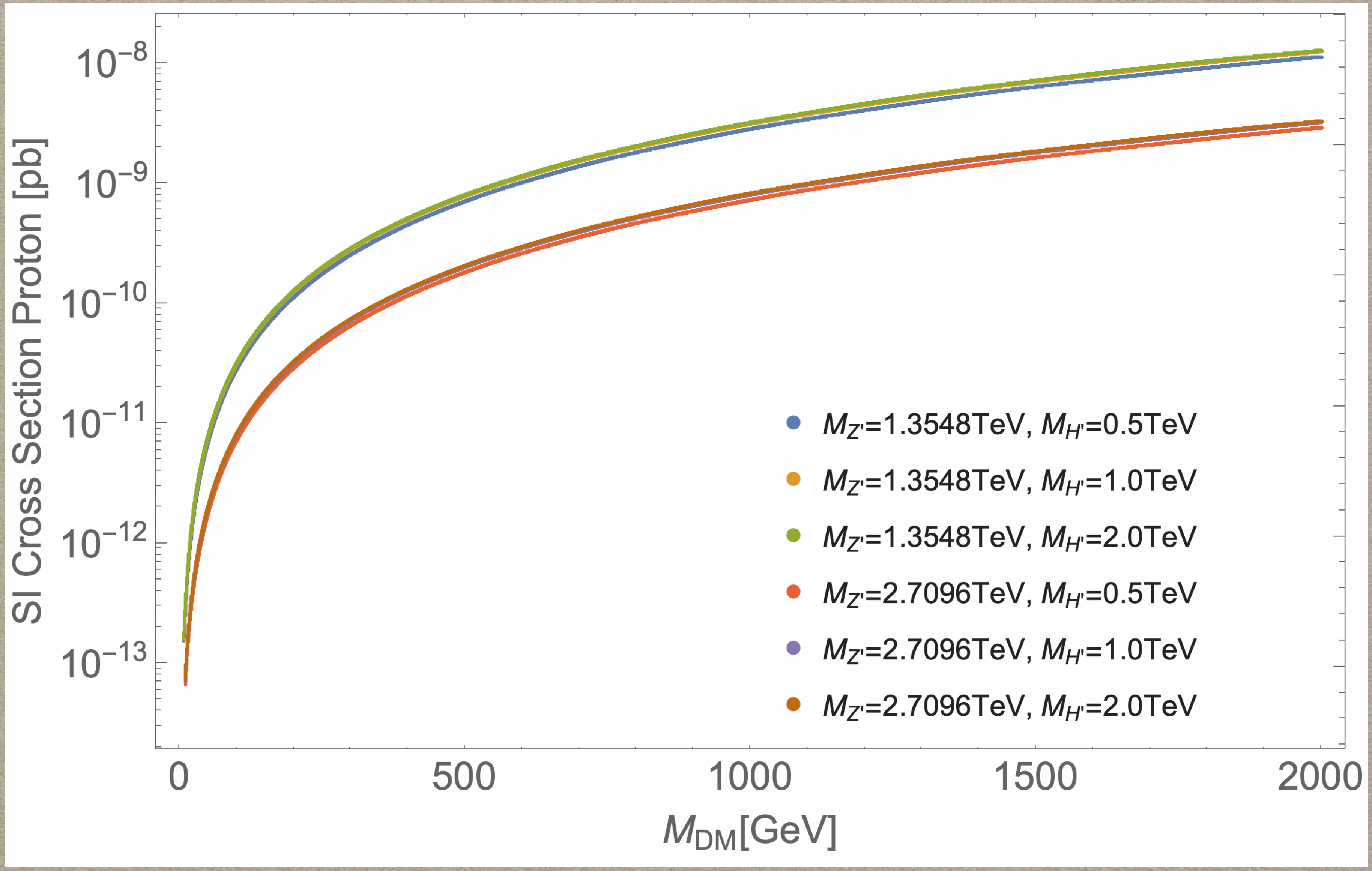


$$\Omega_{DM}h^2 = 0.12 \pm 0.001$$

Spin Independent Cross Section



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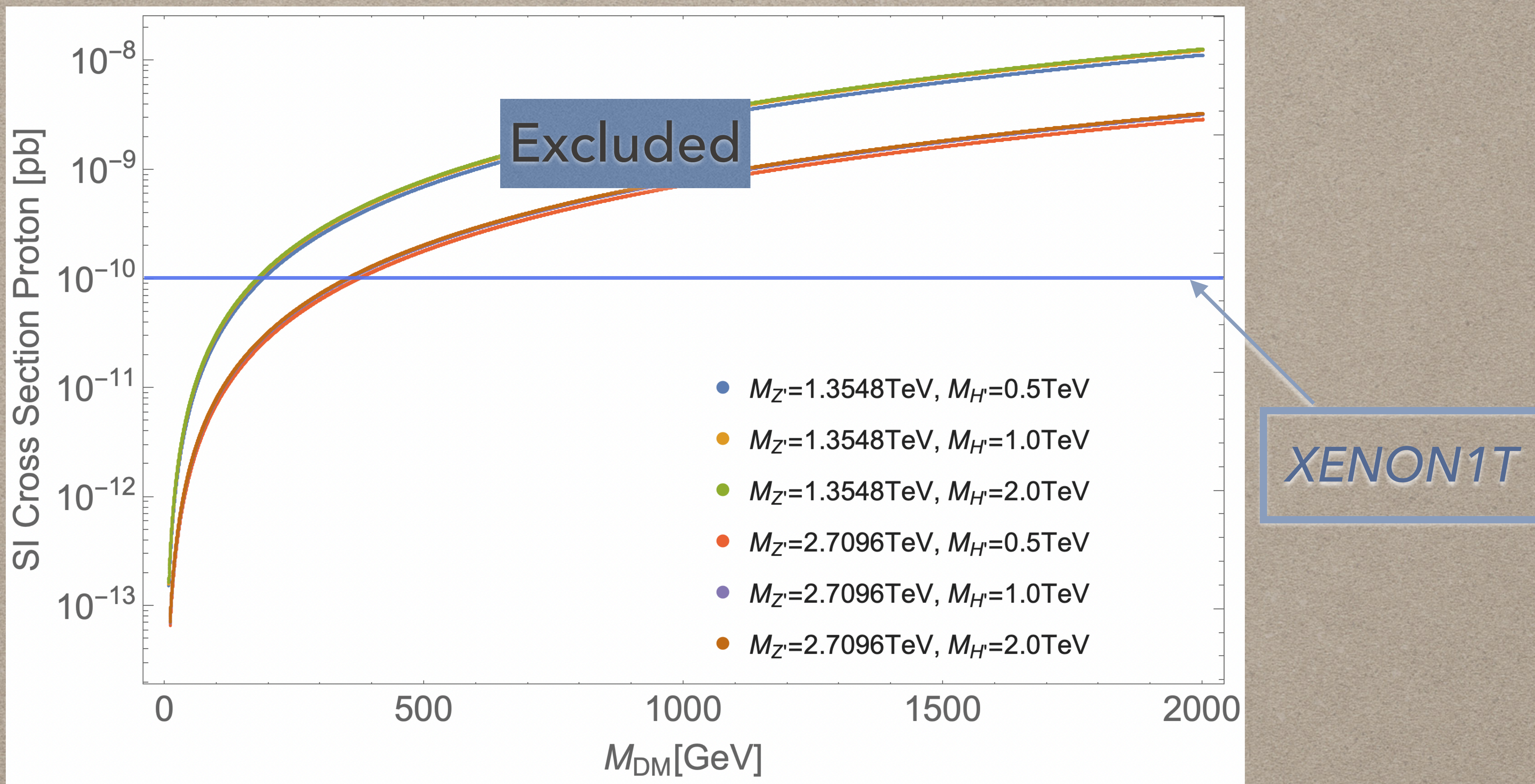

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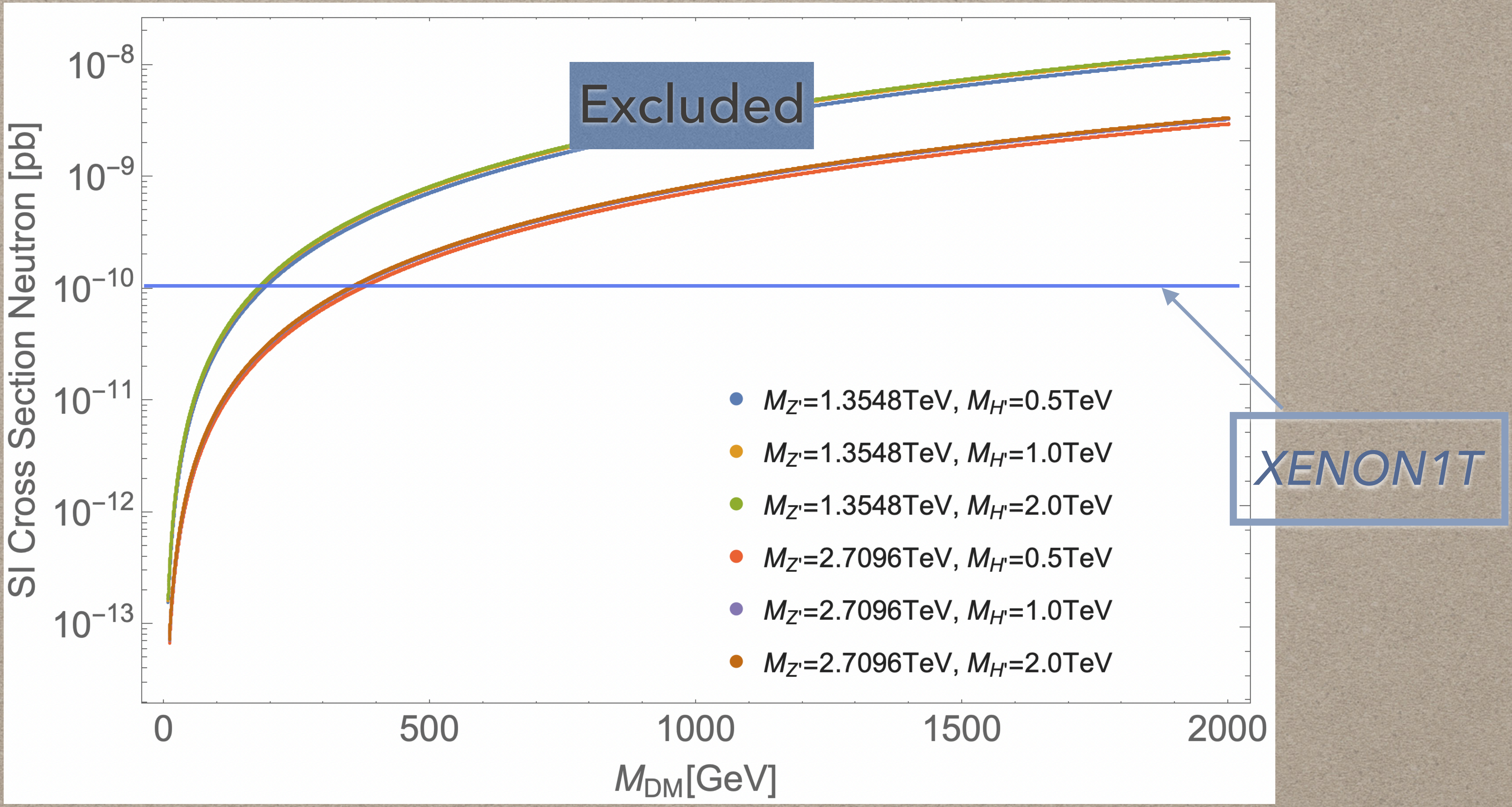

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- *Under lastest reported limit for SI cross section by XENON1T, we find that DM mass is viable for ~0.5TeV or less.*

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