



6th ComHEP: Colombian Meeting on
High Energy Physics

Left-Right Mirror Model with Dark Matter

JOSE HALIM
FESC-UNAM



In collaboration with: M.A. Arroyo, R. Gaitan, M. Lamprea, T. Valencia

This work was supported by: PAPIIT with registration codes IA106220 and IN115319 in DGAPA UNAM, PIAPI with registration code PIAPI2019 in FES-Cuautitlán UNAM, Sistema Nacional de Investigadores (SNI) CONACYT in México.

Left-Right Mirror Model

Gauge group

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

We also include a discrete symmetry $\rightarrow Z_2$

Leptons

Quarks

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

Field	$SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{Y'}$
u_{iR}^0	(3, 1, 1, 4/3)
d_{iR}^0	(3, 1, 1, 2/3)
q_{iL}^0	(3, 2, 1, 1/3)
\hat{u}_{iL}^0	(3, 1, 1, 4/3)
\hat{d}_{iL}^0	(3, 1, 1, 2/3)
\hat{q}_{iR}^0	(3, 1, 2, 1/3)

Mirror

Gauge eigenstate

Left-Right Mirror Model

Gauge group

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

We also include a discrete symmetry $\rightarrow Z_2$

Scalars

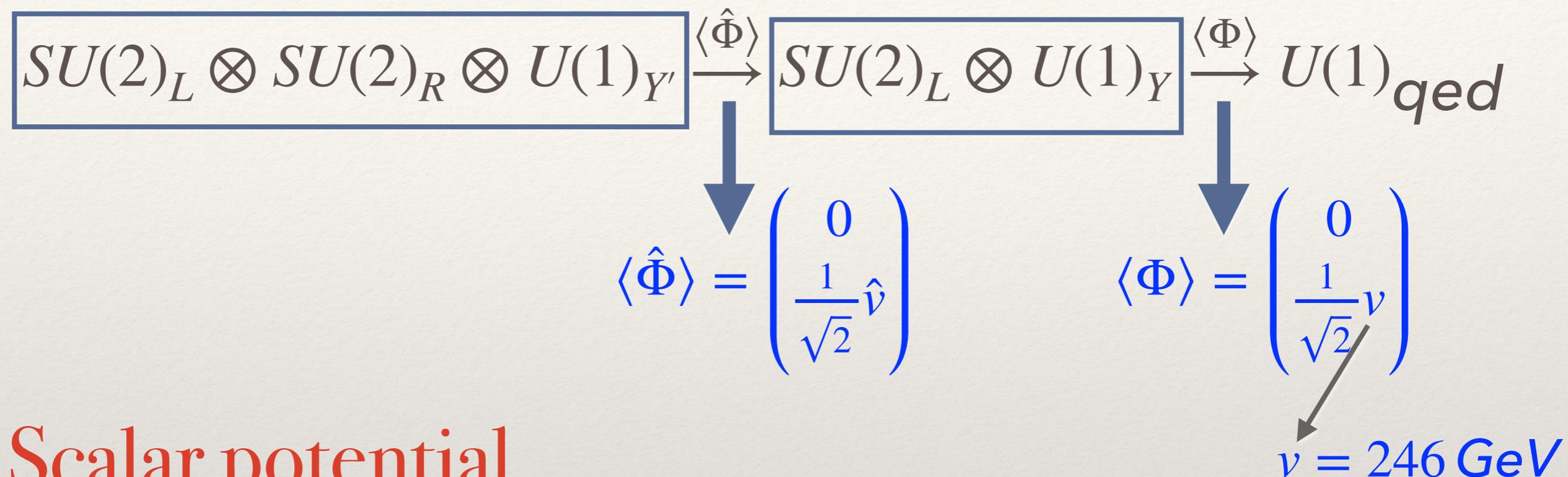
Field	$SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{Y'}$
Φ	(1, 2, 1, -1)
$\hat{\Phi}$	(1, 1, 2, -1)

Gauge fields

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

Spontaneous Symmetry Breaking

The symmetry breaking pattern should be as follows



Scalar potential

The scalar potential is

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

Scalar masses

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

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

Thus, the neutral physical states are

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

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

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

and the neutral scalar masses are

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

Higgs from SM

$$m_{\hat{H}}^2 = \lambda_1 (v^2 + \hat{v}^2) + \sqrt{\lambda_1^2 (v^2 - \hat{v}^2)^2 + 4\lambda_2 v^2 \hat{v}^2}$$

Heavy neutral Higgs

Scalar and fermion interactions

The Yukawa interactions are

$$\mathcal{L}_Y^\ell = \sum_{i,j} \lambda_{ij} \bar{\ell}_{iL}^o \phi e_{jR}^o + \sum_{i,j} \lambda'_{ij} \bar{\ell}_{iR}^o \phi' \hat{e}_{jL}^o + \sum_{i,j} \mu_{ij} \bar{\hat{e}}_{iL}^o e_{jR}^o + h.c.$$

After SSB,

$$\mathcal{L}_{\text{mass}} = \bar{\psi}_L^o M \psi_R^o + h.c.$$

For the lepton sector,

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

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

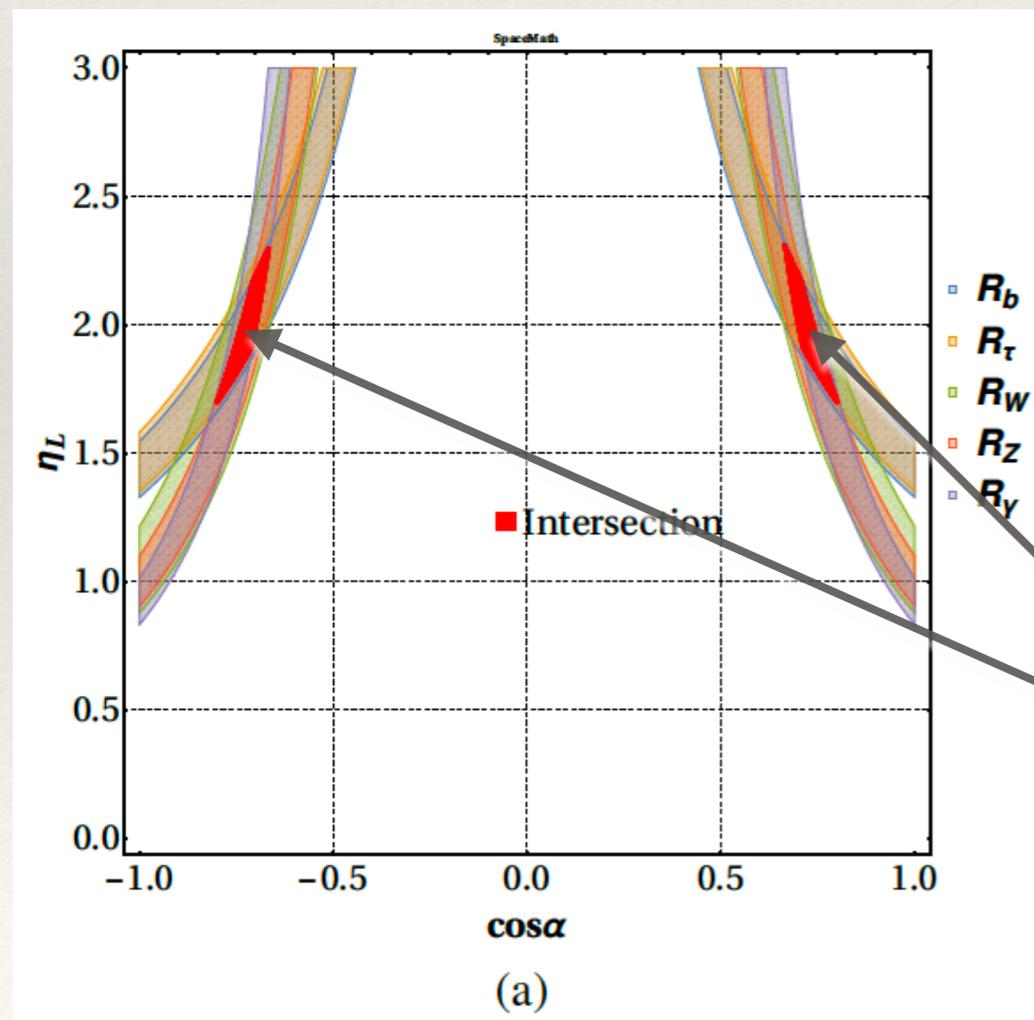
 $K' = \frac{1}{2} \lambda' \hat{v}$

Thus, the mass matrices can be diagonalized through unitary matrices U_a , for $a = L, R$; as $M_D = U_L^\dagger M U_R$.

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

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

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



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

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

$$\cos \alpha \approx \pm 0.7 \quad \left(A_L^\dagger A_L \right)_{fifj} \equiv (\eta_L)_{fifj}$$

$$1.9 \lesssim \eta_L \lesssim 2.2$$

Neutrinos masses and mixing

Yukawa couplings for the neutrino sector:

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

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

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

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

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

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

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

Dark matter and Neutrinos

The charge under Z_2 symmetry for the doublet scalar fields can generate two scenarios,

I) $\Phi, \hat{\Phi} \xrightarrow{Z_2} \Phi, \hat{\Phi} \Rightarrow h_{ij} = \sigma_{ij} = \hat{\sigma}_{ij} = 0$

$$\mathcal{L}_\nu = \cancel{h_{ij} \bar{\nu}_{iL} \nu_{jR}} + \chi_{ij} \bar{\nu}_{iR} (\nu_{jR})^c + \hat{\chi}_{ij} \bar{\nu}_{iL} (\hat{\nu}_{jL})^c + \cancel{\sigma_{ij} \bar{l}_{iL} \tilde{\Phi} (\hat{\nu}_{jL})^c} \\ + \hat{\sigma}_{ij} \bar{l}_{iR} \tilde{\Phi} (\nu_{jR})^c + \lambda_{ij} \bar{l}_{iL} \tilde{\Phi} \nu_{jR} + \hat{\lambda}_{ij} \bar{l}_{iR} \tilde{\Phi} \hat{\nu}_{jL} + h.c.$$

II) $\Phi, \hat{\Phi} \xrightarrow{Z_2} \Phi, -\hat{\Phi} \Rightarrow h_{ij} = \sigma_{ij} = \hat{\lambda}_{ij} = 0$

$$\mathcal{L}_\nu = \cancel{h_{ij} \bar{\nu}_{iL} \nu_{jR}} + \chi_{ij} \bar{\nu}_{iR} (\nu_{jR})^c + \hat{\chi}_{ij} \bar{\nu}_{iL} (\hat{\nu}_{jL})^c + \cancel{\sigma_{ij} \bar{l}_{iL} \tilde{\Phi} (\hat{\nu}_{jL})^c} \\ + \hat{\sigma}_{ij} \bar{l}_{iR} \tilde{\Phi} (\nu_{jR})^c + \lambda_{ij} \bar{l}_{iL} \tilde{\Phi} \nu_{jR} + \cancel{\hat{\lambda}_{ij} \bar{l}_{iR} \tilde{\Phi} \hat{\nu}_{jL}} + h.c.$$

$$1) \quad \Phi, \hat{\Phi} \xrightarrow{Z_2} \Phi, \hat{\Phi} \quad \Rightarrow \quad h_{ij} = \sigma_{ij} = \hat{\sigma}_{ij} = 0$$

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

$$\left(\bar{\nu}_{iL}, \quad \bar{\nu}_{\nu R}^c \right) \begin{pmatrix} 0 & \frac{v}{\sqrt{2}} \lambda_{ij} \\ \frac{v}{\sqrt{2}} \lambda_{ij}^T & \chi_{ij} \end{pmatrix} \begin{pmatrix} \nu_{iL}^c \\ \nu_{jR} \end{pmatrix} \quad \leftarrow \text{Ordinary}$$

$$\left(\hat{\bar{\nu}}_{iL}, \quad \hat{\bar{\nu}}_{\nu R}^c \right) \begin{pmatrix} \hat{\chi}_{ij} & \frac{\hat{v}}{\sqrt{2}} \hat{\lambda}_{ij} \\ \frac{\hat{v}}{\sqrt{2}} \hat{\lambda}_{ij}^T & 0 \end{pmatrix} \begin{pmatrix} \hat{\nu}_{iL}^c \\ \hat{\nu}_{jR} \end{pmatrix} \quad \leftarrow \text{Mirror}$$

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

$$\begin{pmatrix} 0 & \frac{v}{\sqrt{2}}\lambda_{ij} \\ \frac{v}{\sqrt{2}}\lambda_{ij}^T & \chi_{ij} \end{pmatrix} \sim \begin{pmatrix} M_\nu^{light} & 0 \\ 0 & M_\nu^{heavy} \end{pmatrix}$$

$M_\nu^{light} \approx -\frac{v^2}{2}\lambda\chi^{-1}\lambda^T$
 $M_\nu^{heavy} \approx \chi$

We parameterize λ and χ matrices as

$$\lambda = yS$$

$$S = S^T$$

$$\chi = mD^{-1}S$$

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

$$D = \text{Diagonal}(y_1, y_2, y_3)$$

So, the matrix for light neutrinos is

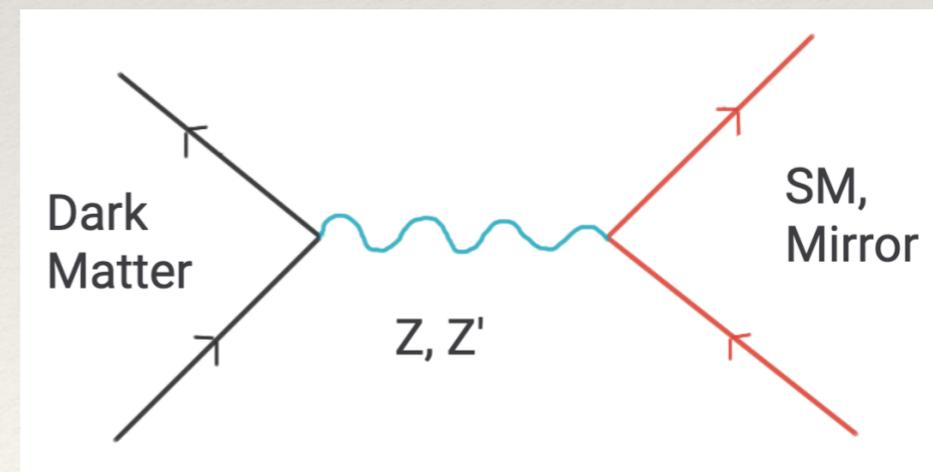
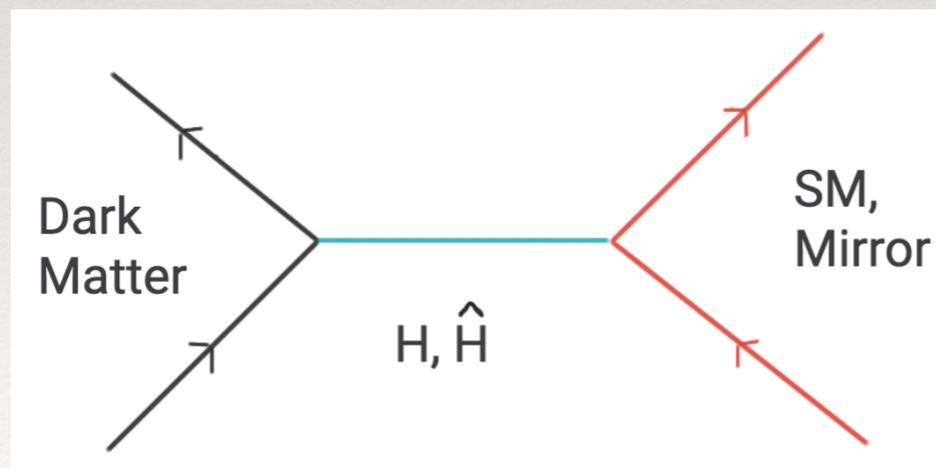
$$M_\nu^{light} = \frac{v^2 y^2}{2m} SD$$

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

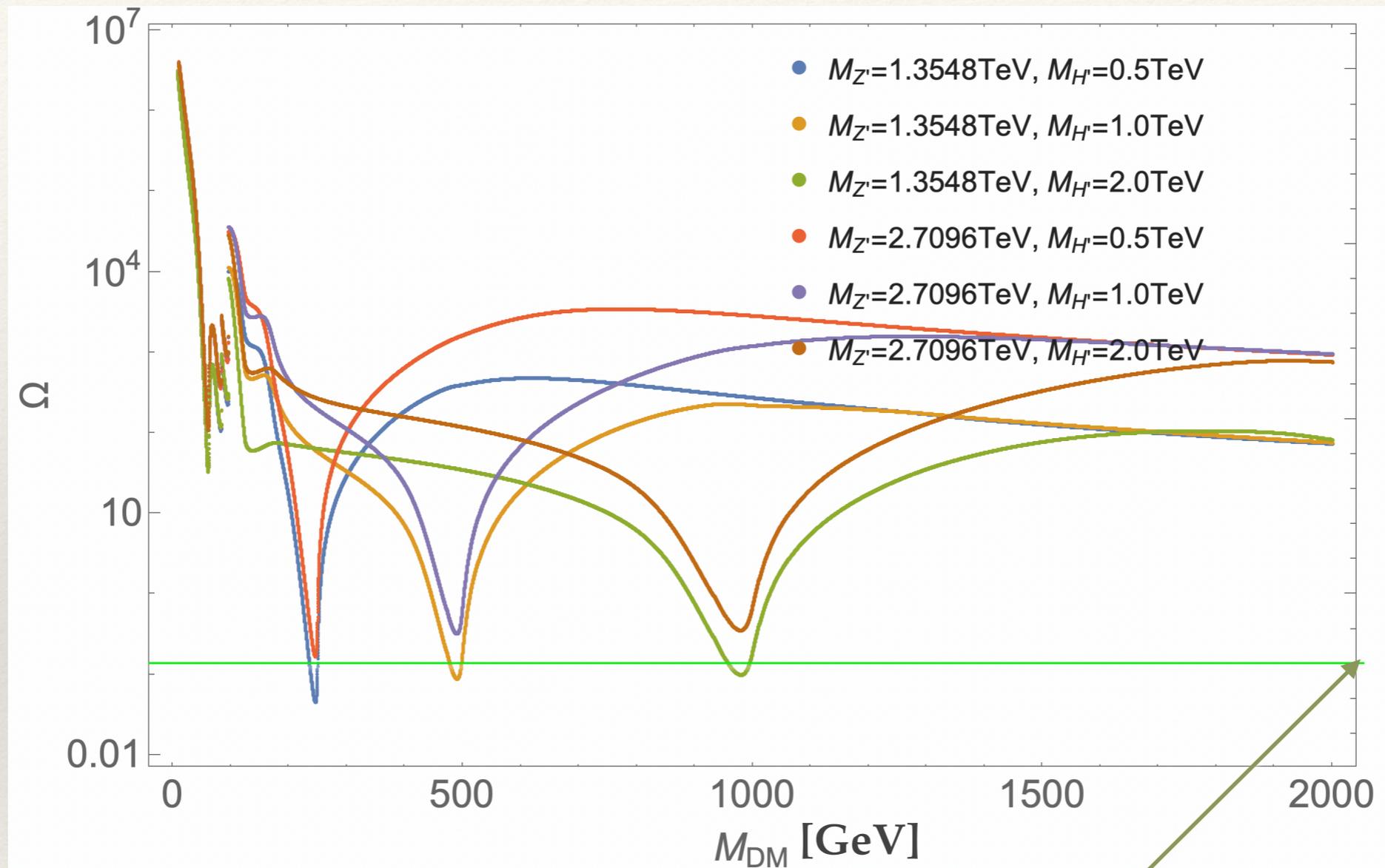
$$(\overline{\hat{\nu}}_{iL}, \overline{\hat{\nu}}^c_{\nu R}) \begin{pmatrix} \hat{\chi}_{ij} & \frac{\hat{\nu}}{\sqrt{2}} \hat{\lambda}_{ij} \\ \frac{\hat{\nu}}{\sqrt{2}} \hat{\lambda}_{ij}^T & 0 \end{pmatrix} \begin{pmatrix} \hat{\nu}^c_{iL} \\ \hat{\nu}_{jR} \end{pmatrix} \leftarrow \text{Mirror}$$

In the scenario $\Phi, \hat{\Phi} \xrightarrow{Z_2} \Phi, \hat{\Phi}$

the candidate is linked with particles through the mix of the H^\wedge

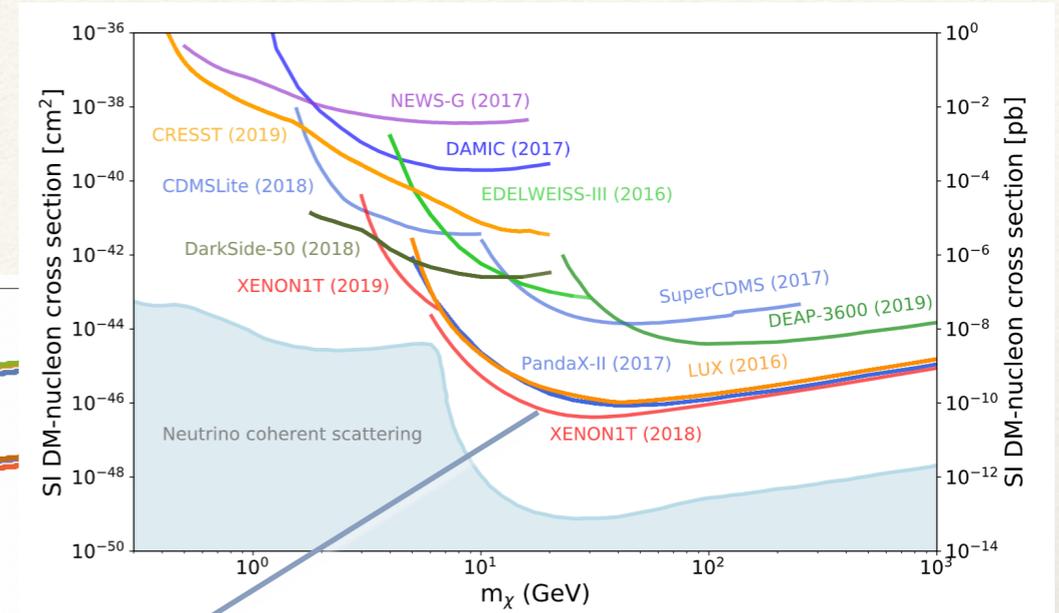
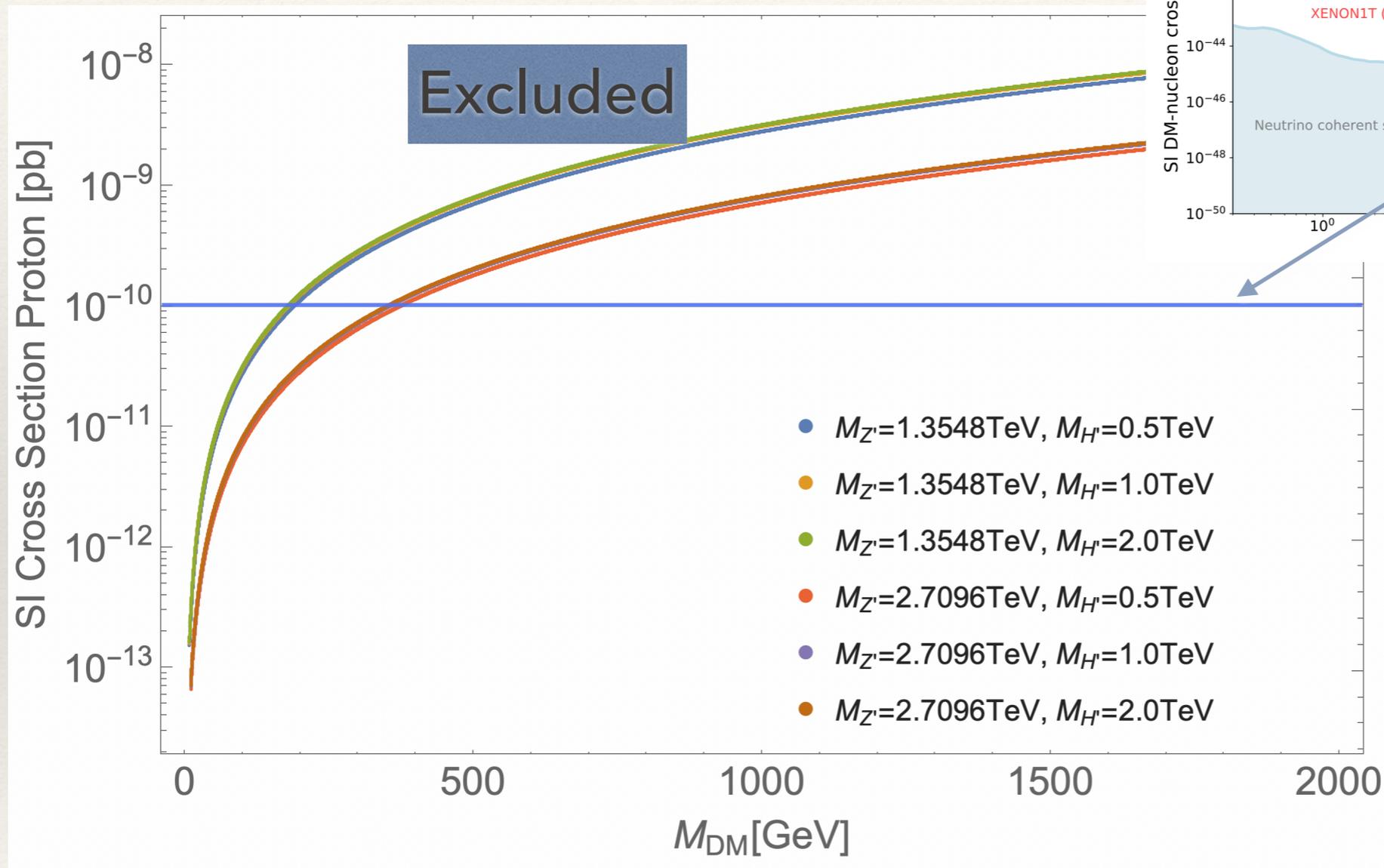


Relic density



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

SI scattering cross section



SUMMARY

- *We explore DM in LRMM, assuming the lightest mirror neutrino as DM.*
- *Masses for SM neutrinos are included by see-saw type I.*
- *Some model parameters are constrained to explore a benchmark for DM relic density and SI cross section*
- *Under the Plank collaboration reported value for non baryonic relic density, we find that the heavy neutral scalar is viable as portal with mass $\sim 1\text{TeV}$ for the reported limit for Z' mass in the LRM.*

REFERENCES

- *P.A. Zyla et al. (PDG), Prog. Theor. Exp. Phys. 2020, 083C01 (2020) and 2021 update.*
- *Planck 2018 results. VI. Cosmological parameters, Astron. Astrophys. 641, A6, (2018).*
- *M. A. Arroyo-Ureña, R. Gaitan, R. Martinez, J. H. Montes de Oca Yemha; Eur. Phys. J. C 80 (2020) 8, 788.*
- *Semenov. A., LanHEP, Nucl.Inst.&Meth. A393 (1997) p. 293 .*
- *G. Bélanger, F. Boudjema, A. Goudelis, A. Pukhov, B. Zaldivár, Comput.Phys.Commun.231 (2018) 173.*
- *K.S. Babu and Rabindra N. Mohapatra., Phys. Rev. D 41 (1990), p. 1286. DOI: 10.1103/PhysRevD.41.1286*
- *V E. Ceron et al., Phys. Rev. D 57 (1998), pp. 1934-1939. DOI: 10.1103/PhysRevD.57.1934. arXiv: hep-ph/9705478.*
- *U. Cotti et al., Phys. Rev. D 66 (2002), p. 015004. DOI: 10.1103/PhysRevD.66.015004. arXiv: hep-ph/0205170.*
- *Gaitan, et. al., Nucl.Part.Phys.Proc. 267-269 (2015) 101-107, Contribution to: SILAF AE 2014, 101-107.*
- *Gaitan, et. al., Eur.Phys.J.C 72 (2012) 1859 , e-Print: 1201.3155 [hep-ph]*
- *Gaitan, et. al., ,Int.J.Mod.Phys.A 22 (2007) 2935-2943 , e-Print: hep-ph/0605249 [hep-ph].*