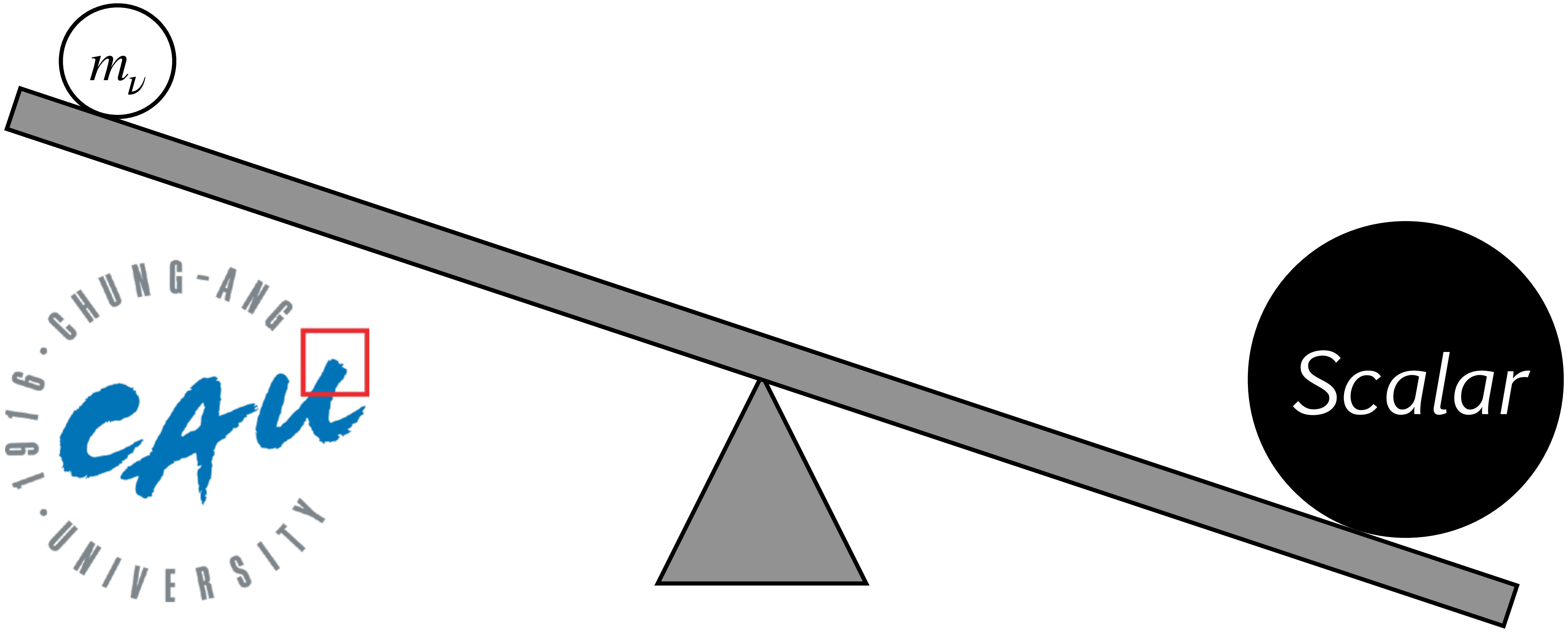

Small Neutrino Masses from a Decoupled Singlet Scalar Field

High1 Workshop on Particle, String, and Cosmology
2025 Jan 17
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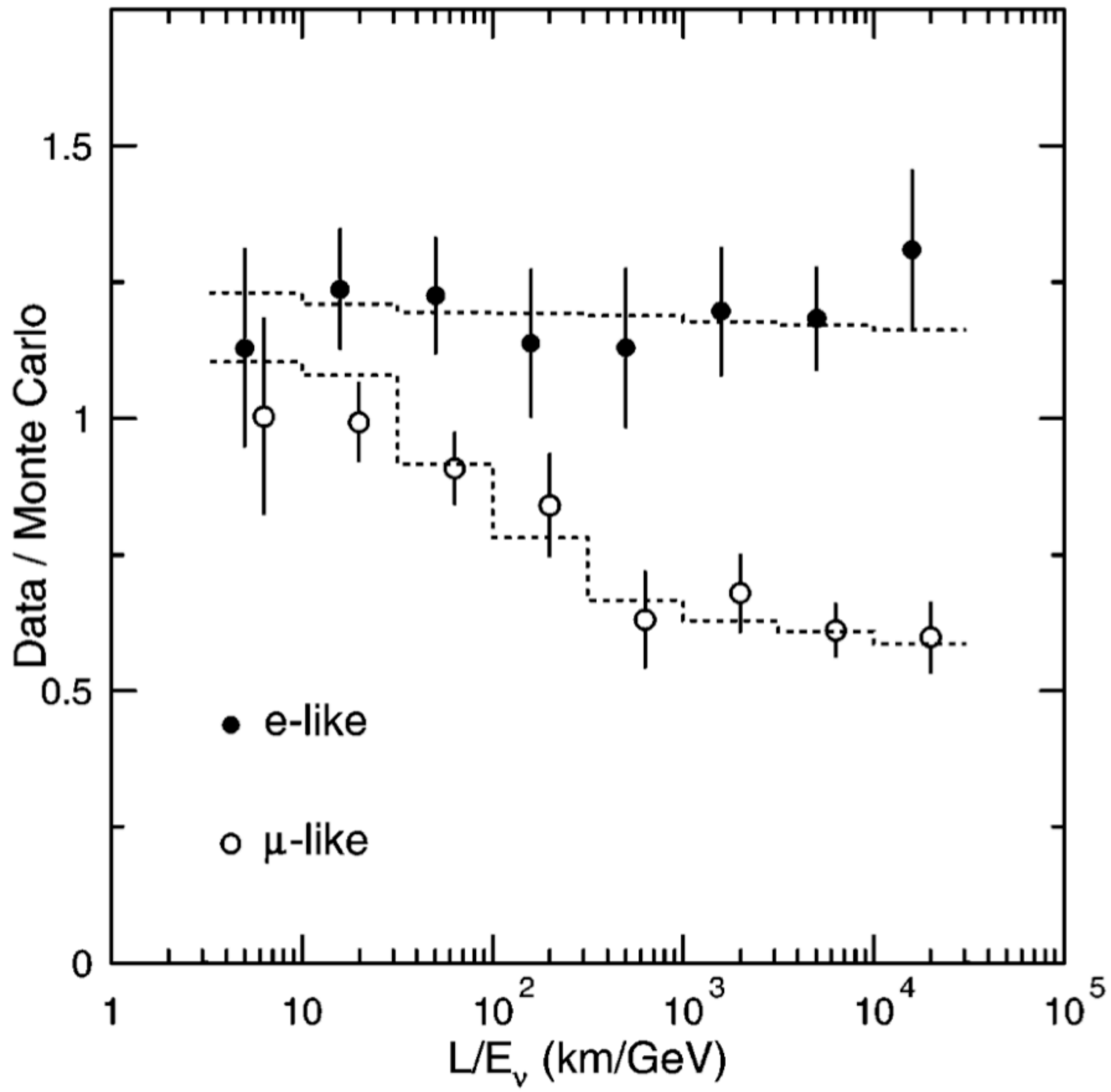
(Chung-Ang University)
arXiv:2407.13595 / Phys. Lett. B 861 (2025) 139243

Neutrino Mass

Zero in the Standard Model (due to lack of Right Handed partner)

Y. Fukuda et al.. Phys. Rev. Lett., 81:1562–1567, Aug 1998



Lack of Atmospheric neutrino observed in SuperKamiokande

The difference between the 'mass' eigenstate and the 'flavor' eigenstate of neutrinos explains the phenomena

At least two non-zero Neutrino mass states! The presence of Right-Handed Neutrinos, which is a BSM species, is required

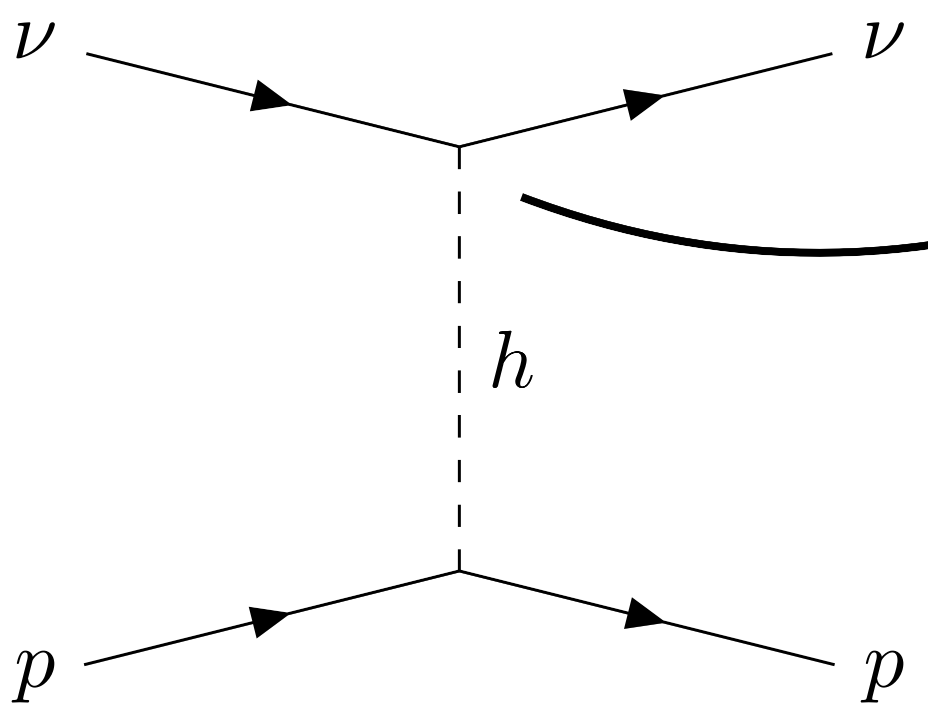
Neutrino Oscillation: Strong Reason for Seeking BSM

Possible Scenarios for Neutrino Mass

1. Dirac Mass: Simplest Solution

$$\mathscr{L} \supset -\frac{m_\nu}{v}\bar{\nu}_L H \nu_R + \mathrm{h.c.}$$

Right-handed neutrino does not hurt SM symmetry.
just isolated.



Too weak!

Strong Motivation for finding alternative scenarios!

Example for experimental confirmation:

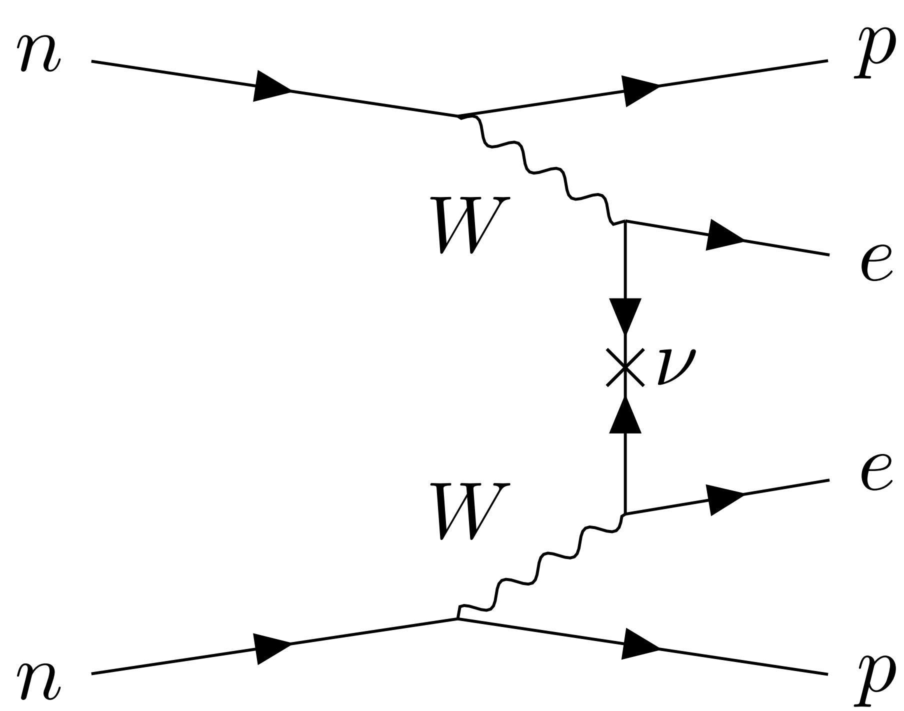
Practically Impossible

Possible Scenarios for Neutrino Mass

2. Majorana Hypothesis

$$\mathscr{L} \supset -\frac{1}{2}\bar{\nu}_R^C \, m \, \nu$$

Neutrino as Majorana Particle
Anti-neutrino as Right-handed partner



Not observed yet!

Example for experimental confirmation:
Neutrinoless Double beta decay

Possible Scenarios for Neutrino Mass

3. Seesaw Mechanism

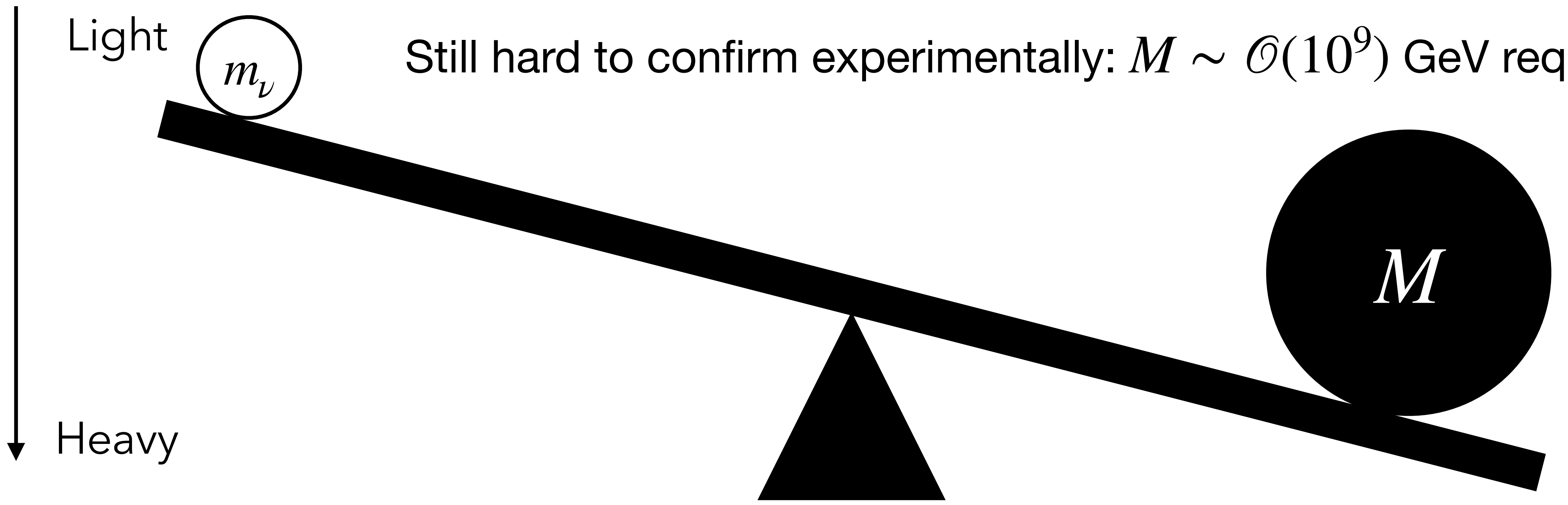
Mass mixing with Right-Handed Majorana Neutrino

$$\mathcal{L} \supset -\bar{N}_R m \nu_L - \frac{1}{2}\bar{N}^c_R M N_R + \text{h.c.}$$

Small m and Large Majorana Mass M leads physical neutrino mass $m_\nu \simeq \dfrac{m^2}{M}$:

The greater M, the smaller m_ν

Still hard to confirm experimentally: $M \sim \mathcal{O}(10^9)$ GeV required



(Example is Type-1 Seesaw)

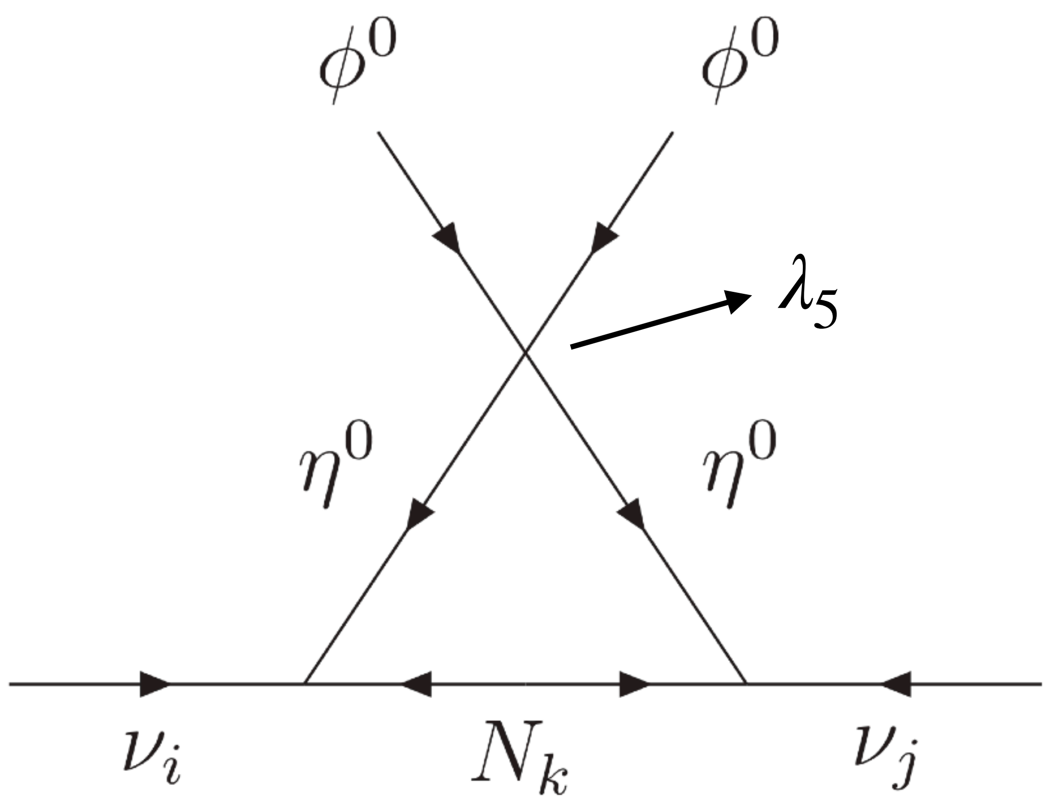
P. Minkowski, Phys. Lett. B 67 (1977)
T. Yanagida, Conf. Proc. C 7902131 (1979)

Possible Scenarios for Neutrino Mass

4. Scotogenic Model

Ernest Ma., Phys. Rev. D 73, 077301

Similar to Seesaw but experimentally reachable!



Loop-induced neutrino mass:

Requirement:
Non-zero VEV of SM Higgs ϕ,
Additional scalar doublet η that couples to Higgs and neutrinos,
and heavy Majorana neutrino

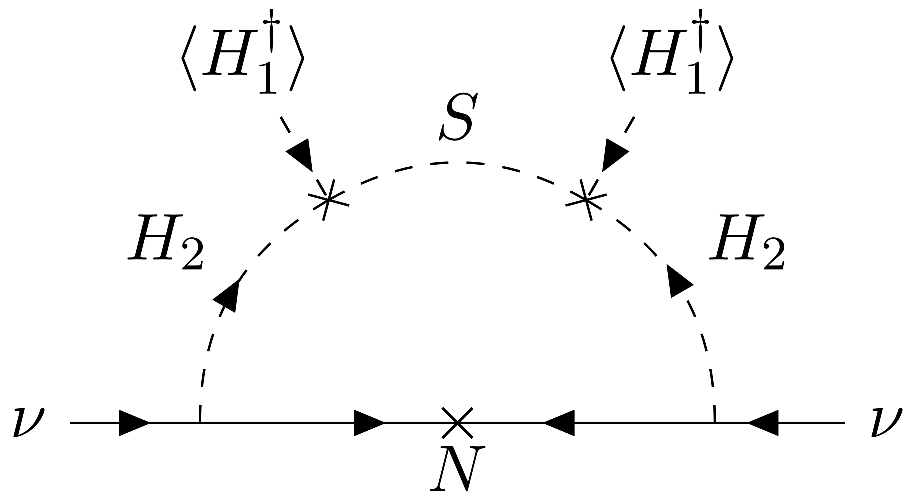
Seesaw scale reduced by a factor $\lambda_5/16\pi^2$:
$\lambda_5 \sim \mathcal{O}(10^{-4})$ gives *experimentally reachable* $M_N \sim \mathcal{O}(1)$ TeV!

$$(\mathcal{M}_\nu)_{ij} = \sum_k \frac{h_{ik}h_{jk}M_k}{16\pi^2}\left[\frac{m_R^2}{m_R^2 - M_k^2}\ln\frac{m_R^2}{M_k^2} - \frac{m_I^2}{m_I^2 - M_k^2}\ln\frac{m_I^2}{M_k^2}\right],$$

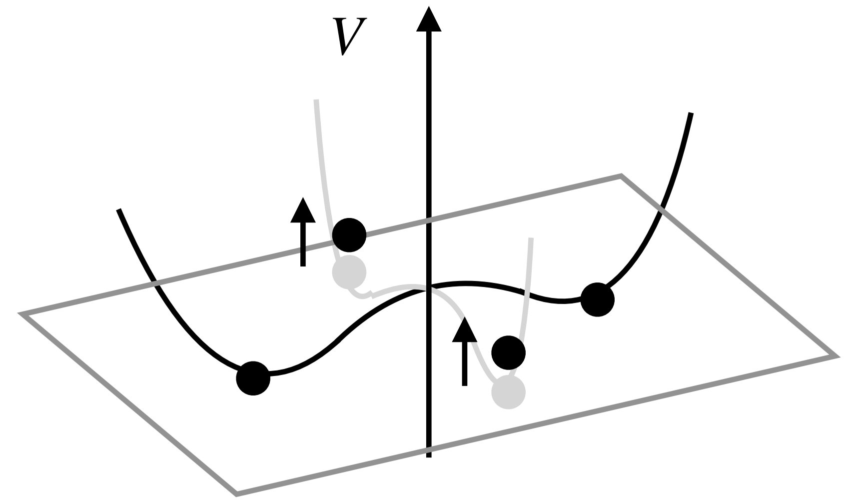
Additional features: $\mathrm{Re}\ \eta^0$ might be Dark Matter & Leptogenesis

Outline of Our Model

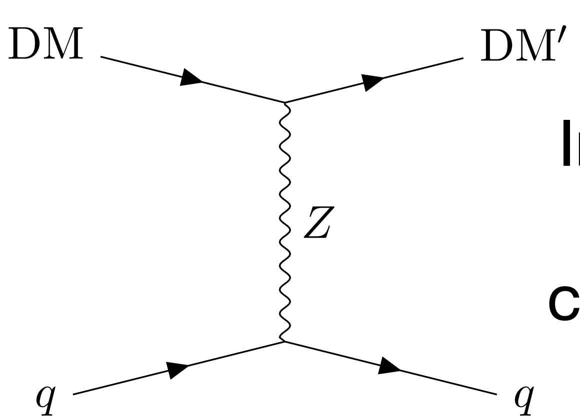
Scotogenic Model and Inert Higgs Doublet Model



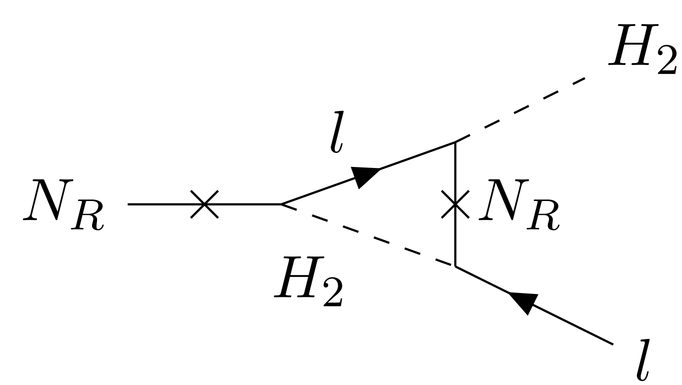
Small SM neutrino mass from Inert Higgs H_2, decoupled scalar S, and TeV Scale Right-handed neutrino (RHN) N



The imposed symmetry Z_4 is broken down to Z_2 by Spurion.
This breaking causes RHN mass, mass mixing between scalars



Inert Higgs might be DM and such possibility is constrained by mass gap



RHN could be origin of leptogenesis

Particle Contents

	SU(2)	Z_4
S	$\mathbf{1}$	$e^{i\pi/2}(=i)$
φ	$\mathbf{1}$	$e^{i\pi}(=-1)$
H_1	$\mathbf{2}$	$e^{0}(=1)$
H_2	$\mathbf{2}$	$e^{i\pi/2}(=i)$
N_R	$\mathbf{1}$	$e^{i\pi/2}(=i)$

$$S = \frac{1}{\sqrt{2}}(s + ia)$$

Heavy Scalar

$$\varphi = v_\varphi + \rho$$

Spoiler: we will give VEV for φ which breaks Z_4 symmetry

$$H_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_H + h \end{pmatrix}$$

Correspond to the SM Higgs

$$H_2 = \begin{pmatrix} H^+ \\ (H_0 + iA_0)/\sqrt{2} \end{pmatrix}$$

Inert Higgs

Note: In our model, the 125 GeV Higgs is different from h: h is not mass eigenstate
125GeV is the linear combination between h and ρ (after symmetry breaking)

Particle Interactions

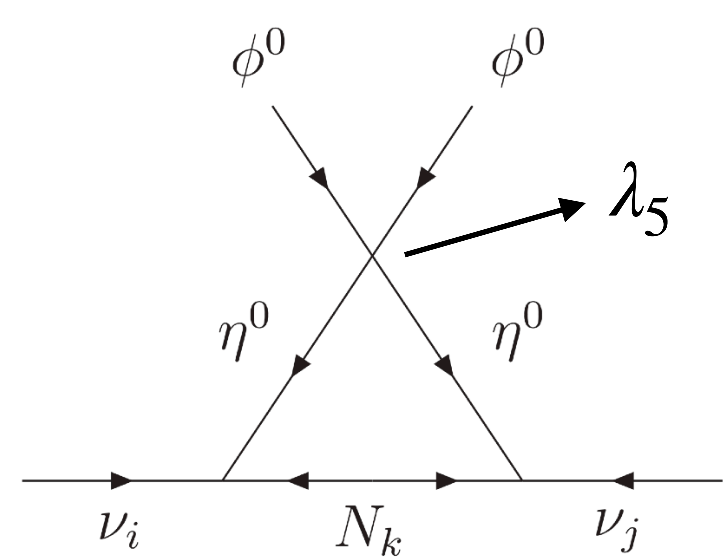
The General Z_4 Invariant Lagrangian for New species

$$\mathcal{L}_{\rm int} = -m_1^2|H_1|^2 - m_2^2|H_2|^2 - \lambda_1|H_1|^4 + \lambda_2|H_2|^4 - \lambda_3|H_1|^2|H_2|^2 - \lambda_4\left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right)$$
$$-m_S^2|S|^2 - \lambda_S|S|^4 - \frac{1}{2}m_\varphi^2\varphi^2 - \frac{1}{4}\lambda_\varphi\varphi^4 - \frac{1}{2}\lambda_{S\varphi}|S|^2\varphi^2$$
$$+\left(\sqrt{2}\kappa S^\dagger H_1^\dagger H_2 + \sqrt{2}\lambda'_{S\varphi}\varphi S H_1^\dagger H_2 + \mu\varphi S^2 + \text{h.c.}\right) - \sum_{i=1,2}\left[\lambda_{H_iS}\left(H_i^\dagger H_i\right)|S|^2 - \frac{1}{2}\lambda_{H_i\varphi}\left(H_i^\dagger H_i\right)\varphi^2\right]$$
$$-y_{N,ij}\bar{l}_i\widetilde{H}_2 N_{R,j} - \frac{1}{2}\lambda_{N,ij}\varphi\overline{N_{R,i}^c}N_{R,j} + \text{h.c.} \quad (\widetilde{H}_2 \equiv i\sigma_2 H_2^*)$$

Too many parameters

Too much dynamics

No λ_5 term: which is the part of the loop in the Scotogenic Model



Particle Interactions

Not every dynamics is in our concern!

$$\begin{aligned}\mathcal{L}_{\rm int} = &-m_1^2|H_1|^2 - m_2^2|H_2|^2 - \lambda_1|H_1|^4 + \lambda_2|H_2|^4 - \lambda_3|H_1|^2|H_2|^2 - \lambda_4\left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right) \\ &-m_S^2|S|^2 - \lambda_S|S|^4 - \frac{1}{2}m_\varphi^2\varphi^2 - \frac{1}{4}\lambda_\varphi\varphi^4 - \frac{1}{2}\lambda_{S\varphi}|S|^2\varphi^2 \\ &+\left(\sqrt{2}\kappa S^\dagger H_1^\dagger H_2 + \sqrt{2}\lambda'_{S\varphi}\varphi S H_1^\dagger H_2 + \mu\varphi S^2 + \text{h.c.}\right) - \sum_{i=1,2}\left[\lambda_{H_iS}\left(H_i^\dagger H_i\right)|S|^2 - \frac{1}{2}\lambda_{H_i\varphi}\left(H_i^\dagger H_i\right)\varphi^2\right] \\ &-y_{N,ij}\bar{l}_i\widetilde{H}_2 N_{R,j} - \frac{1}{2}\lambda_{N,ij}\varphi\overline{N_{R,i}^c}N_{R,j} + \text{h.c.} \quad (\widetilde{H}_2 \equiv i\sigma_2 H_2^*)\end{aligned}$$

Rather, the particle and their mass spectrum will be analyzed

The dynamics we have to consider are only those.

1. Interactions related to small neutrino mass
2. Interactions may be bounded from experiments

Symmetry Breaking

Z_4 symmetry to be broken to Z_2

	$\mathrm{SU}(2)$	Z_4		Z_2
S	$\mathbf{1}$	$e^{i\pi/2}(=i)$		$-$
φ	$\mathbf{1}$	$e^{i\pi}(=-1)$		$+$
H_1	$\mathbf{2}$	$e^{0}(=1)$	$\rightarrow$	$+$
H_2	$\mathbf{2}$	$e^{i\pi/2}(=i)$		$-$
N_R	$\mathbf{1}$	$e^{i\pi/2}(=i)$		$-$

As φ gets VEV, Z_4 symmetry is broken down to its subgroup Z_2

Consequences of Symmetry Breaking

1. RHN gets mass proportional to v_φ
2. Mass mixing between components of scalar: (h, ρ), (s, H_0), (a, A_0)
3. The Lightest particle with $(-)$ parity is stabilized: Dark matter candidates

$$S = \frac{1}{\sqrt{2}}(s + ia) \quad \varphi = v_\varphi + \rho \quad H_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_H + h \end{pmatrix} \quad H_2 = \begin{pmatrix} H^+ \\ (H_0 + iA_0)/\sqrt{2} \end{pmatrix}$$

Scalar Spectrum after SSB

Not only for determining DM candidate also for neutrino mass

(1) (2) (3) (5)

$$S = \frac{1}{\sqrt{2}}(s + ia) \quad \varphi = v_\varphi + \rho \quad H_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_H + h \end{pmatrix} \quad H_2 = \begin{pmatrix} H^+ \\ (H_0 + iA_0)/\sqrt{2} \end{pmatrix}$$

(4) (6) (7)

Mass Mixing after Symmetry Breaking

$$\mathcal{L} \supset -\frac{1}{2}(h \;\; \rho)\begin{pmatrix} \lambda_1 v_H^2 + \frac{\lambda_{H_1\varphi} v_\varphi^2}{2} & \lambda_{H_1\varphi} v_H v_\varphi \\ \lambda_{H_1\varphi} v_H v_\varphi & \lambda_\varphi v_\varphi^2 + \frac{\lambda_{H_1\varphi} v_H^2}{2} \end{pmatrix}\begin{pmatrix} h \\ \rho \end{pmatrix} \qquad \kappa' \equiv \lambda'_{S\varphi} v_\varphi \quad \hat{m}_S^2 = 2\mu v_\varphi$$

$$-\frac{1}{2}(H_0 \;\; s)\begin{pmatrix} m_2^2 + \frac{\lambda_3 v_H^2}{2} + \frac{\lambda_{H_2\varphi} v_\varphi^2}{2} & (\kappa + \kappa') v_H \\ (\kappa + \kappa') v_H & m_S^2 + \frac{\lambda_{H_1 S} v_H^2}{2} + \frac{\lambda_{S\varphi} v_\varphi^2}{2} + \hat{m_S}^2 \end{pmatrix}\begin{pmatrix} H_0 \\ s \end{pmatrix}$$

$$-\frac{1}{2}(A_0 \;\; a)\begin{pmatrix} m_2^2 + \frac{\lambda_3 v_H^2}{2} + \frac{\lambda_{H_2\varphi} v_\varphi^2}{2} & (\kappa - \kappa') v_H \\ (\kappa - \kappa') v_H & m_S^2 + \frac{\lambda_{H_1 S} v_H^2}{2} + \frac{\lambda_{S\varphi} v_\varphi^2}{2} - \hat{m_S}^2 \end{pmatrix}\begin{pmatrix} A_0 \\ a \end{pmatrix}$$

→ Mass Eigenstates:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix}\begin{pmatrix} h \\ \rho \end{pmatrix} \quad \begin{pmatrix} \mathcal{H}_1 \\ \mathcal{H}_2 \end{pmatrix} = \begin{pmatrix} c_s & s_s \\ -s_s & c_s \end{pmatrix}\begin{pmatrix} H_0 \\ s \end{pmatrix} \quad \begin{pmatrix} \mathcal{A}_1 \\ \mathcal{A}_2 \end{pmatrix} = \begin{pmatrix} c_a & s_a \\ -s_a & c_a \end{pmatrix}\begin{pmatrix} A_0 \\ a \end{pmatrix}$$

Scalar Mass Spectrum

General Formulae

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h \\ \rho \end{pmatrix} \quad \begin{pmatrix} \mathcal{H}_1 \\ \mathcal{H}_2 \end{pmatrix} = \begin{pmatrix} c_s & s_s \\ -s_s & c_s \end{pmatrix} \begin{pmatrix} H_0 \\ s \end{pmatrix} \quad \begin{pmatrix} \mathcal{A}_1 \\ \mathcal{A}_2 \end{pmatrix} = \begin{pmatrix} c_a & s_a \\ -s_a & c_a \end{pmatrix} \begin{pmatrix} A_0 \\ a \end{pmatrix}$$

$$m^2_{h_{1,2}} = \frac{1}{2}\left[m_h^2 + m_\rho^2 \pm (m_h^2 - m_\rho^2)\sqrt{1 + \frac{4v_H^2 v_\varphi^2 \lambda^2_{H_1\varphi}}{(m_h^2 - m_\rho^2)^2}}\right]$$

$$m^2_{\mathcal{H}_{1,2}} = \frac{1}{2}\left[m_{H_0}^2 + m_s^2 \pm (m_{H_0}^2 - m_s^2)\sqrt{1 + \frac{4(\kappa + \kappa')^2 v_H^2}{(m_{H_0}^2 - m_s^2)^2}}\right]$$

$$m^2_{\mathcal{A}_{1,2}} = \frac{1}{2}\left[m_{H_0}^2 + m_a^2 \pm (m_{H_0}^2 - m_a^2)\sqrt{1 + \frac{4(\kappa - \kappa')^2 v_H^2}{(m_{H_0}^2 - m_a^2)^2}}\right]$$

Lightest among these four is DM candidate!

We will use the phenomenological limit and simplified formula

Scalar Mass Spectrum

Comments on Scalar mass

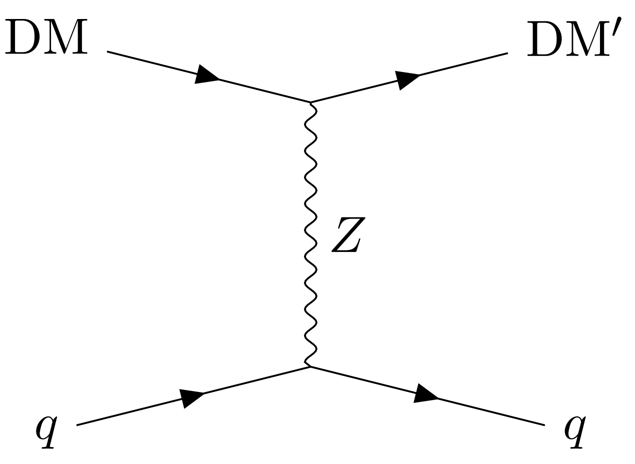
$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h \\ \rho \end{pmatrix} \quad \begin{pmatrix} \mathcal{H}_1 \\ \mathcal{H}_2 \end{pmatrix} = \begin{pmatrix} c_s & s_s \\ -s_s & c_s \end{pmatrix} \begin{pmatrix} H_0 \\ s \end{pmatrix} \quad \begin{pmatrix} \mathcal{A}_1 \\ \mathcal{A}_2 \end{pmatrix} = \begin{pmatrix} c_a & s_a \\ -s_a & c_a \end{pmatrix} \begin{pmatrix} A_0 \\ a \end{pmatrix}$$

Z_2 even $\qquad$ Z_2 odd $\qquad$ Z_2 odd

h_1, one of the Z_2 even scalar, corresponds to 125 GeV Higgs.
h_1 is different from the interaction eigenstate h.

Modification of Higgs quartic coupling is required, which is not tested well

Z_2 symmetry stabilizes the lightest odd particle (Including $R_{N,i}$).
There is a strong experimental bound from the inelastic scattering process $\mathrm{DM}\, q \to \mathrm{DM}' q$ for Z_2 odd DM.
(DM': the next-lightest Z_2 odd particle)



Scalar masses appear in the neutrino mass formula

Neutrino Mass

Lagrangian after Symmetry Breaking

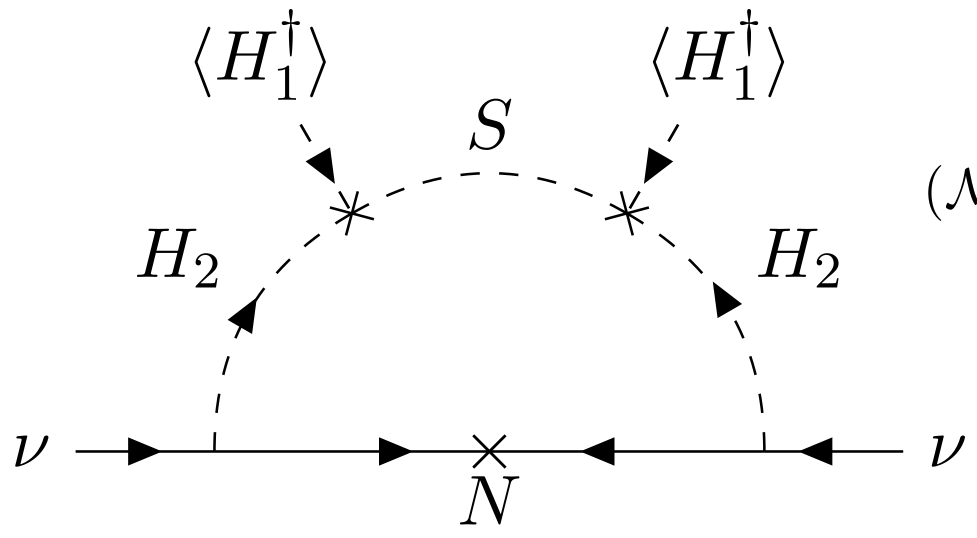
$$\mathcal{L}_{\rm int,eff} \supset -\sqrt{2}\kappa S^\dagger H_1^\dagger H_2 - \sqrt{2}\kappa' S H_1^\dagger H_2 - y_{N,ij}\bar{l}_i \widetilde{H}_2 N_{R,j} - \frac{1}{2} M_{N,i} \overline{N^c_{R,i}} N_{R,i} + \text{h.c.}$$

$$(\kappa' \equiv \lambda'_{S\varphi} v_\varphi)$$

Sterile Neutrino mass parameter $M_{N,i} = \lambda_{N,ii} v_\varphi$

(diagonal $\lambda_{N,ij}$ is assumed for simplicity)

Small Neutrino Mass



Relevant Diagram

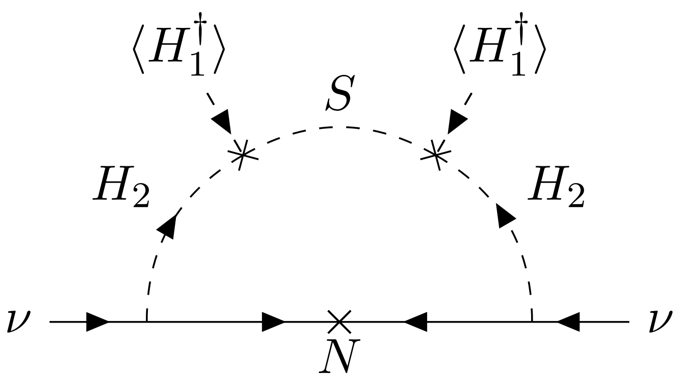
$$(\mathcal{M}_\nu)_{ij} = \frac{1}{16\pi^2} \sum_\alpha \sum_k y_{N,ik} y_{N,jk} M_{N,k} F_\alpha \left[\frac{m_\alpha^2}{m_\alpha^2 - M_{N,k}^2} \ln \frac{m_\alpha^2}{M_{N,k}^2} \right]$$

$$(F_\alpha, m_\alpha) = (c_s^2, m_{\mathcal{H}_1}), (s_s^2, m_{\mathcal{H}_2}), (c_a^2, m_{\mathcal{A}_1}), (c_a^2, m_{\mathcal{A}_2})$$

General formula for neutrino mass

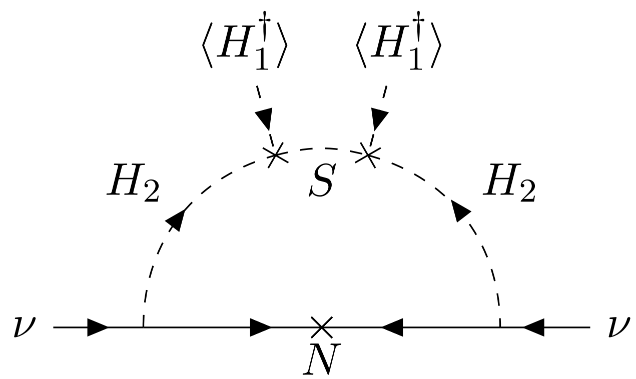
Neutrino Mass

In Scalar Decoupling Limit



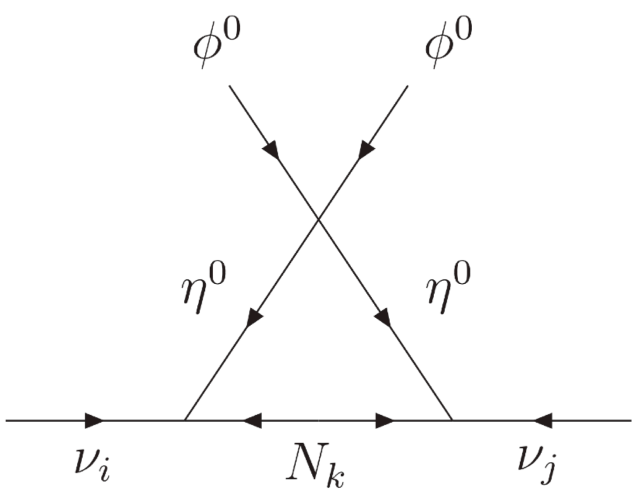
Our Model

→



Heavy Scalar Limit

→



Original Scotogenic

The decoupling scalar limit ($m_S \gg \kappa'$, $2\mu v_\varphi$)

corresponds to the original scotogenic case with $\lambda_{5,\mathrm{eff}} = -\dfrac{4\kappa\kappa'}{m_S^2}$

Scotogenic & Inert Higgs model unified!

Neutrino Mass in Decoupling Scalar Limit

$$(\mathcal{M}_\nu)_{ij} \simeq \frac{\lambda_{5,\mathrm{eff}} v_H^2}{16\pi^2} \sum_k \frac{y_{N,ik} y_{N,jk} M_{N,k}}{m_0^2 - M_{N,k}^2} \left[1 - \frac{M_{N,k}^2}{m_0^2 - M_{N,k}^2} \ln \frac{m_0^2}{M_{N,k}^2} \right]$$

$$m_0^2 \equiv \frac{m_{\mathcal{H}_1}^2 + m_{\mathcal{A}_1}^2}{2} \approx m_{H_0}^2$$

Mass Spectrum in Decoupling Limit

In the small $\lambda_{5,\text{eff}}$ limit

$$m_{H^\pm}^2 = m_2^2 + \frac{1}{2}\lambda_3 v_H^2,$$

$$\left.\begin{aligned} m_{H_0}^2 &= m_2^2 + \frac{1}{2}\left(\lambda_3 + \lambda_4 + \lambda_{5,\text{eff}}\right) v_H^2, \\ m_{A_0}^2 &= m_2^2 + \frac{1}{2}\left(\lambda_3 + \lambda_4 - \lambda_{5,\text{eff}}\right) v_H^2 \end{aligned}\right\}$$

Avoiding DD bound requires at least 100keV mass difference between H_0 and A_0

Mass Splitting in Decoupling Limit

$$m_{H_0} - m_{A_0} \approx \frac{\lambda_{5,\text{eff}} v_H^2}{m_{H_0}^2 + m_{A_0}^2}$$

Limit 1: $M_{N,k} \gg m_0$ (Scalar as DM Candidate)

$$(\mathcal{M})_{ij} \approx \frac{\lambda_{5,\text{eff}} v_H^2}{16\pi^2} \sum_k \frac{y_{N,ik} y_{N,jk}}{M_{N,k}} \left[\ln \frac{M_{N,k}}{m_0^2} - 1\right]$$

The case we focused on

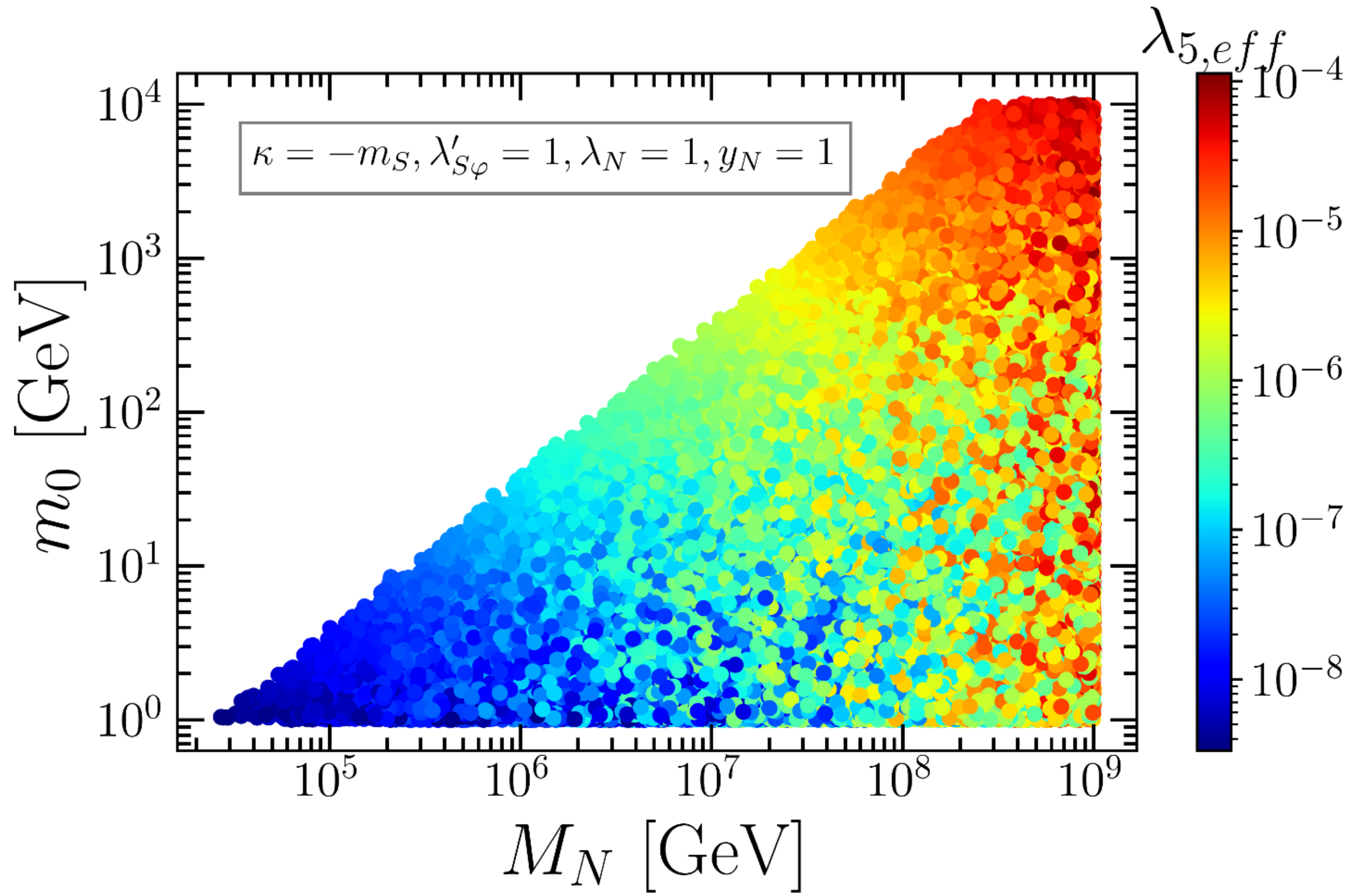
Limit 2: $m_0 \gg M_{N,k}$ (RHN as DM Candidate)

$$(\mathcal{M})_{ij} \approx \frac{\lambda_{5,\text{eff}} v_H^2}{16\pi^2 m_0^2} \sum_k y_{N,ik} y_{N,jk} M_{N,k}$$

$$m_0^2 \equiv \frac{m_{\mathcal{H}_1}^2 + m_{\mathcal{A}_1}^2}{2} \approx m_{H_0}^2$$

Analysis on Neutrino

Parameter Space for Inert Doublet mass vs. RHN mass in the $M_{N,k} \gg m_0$ limit



Assumptions

$m_\nu = 0.1$ eV

$|m_{H_0} - m_{A_0}| > 100$ keV

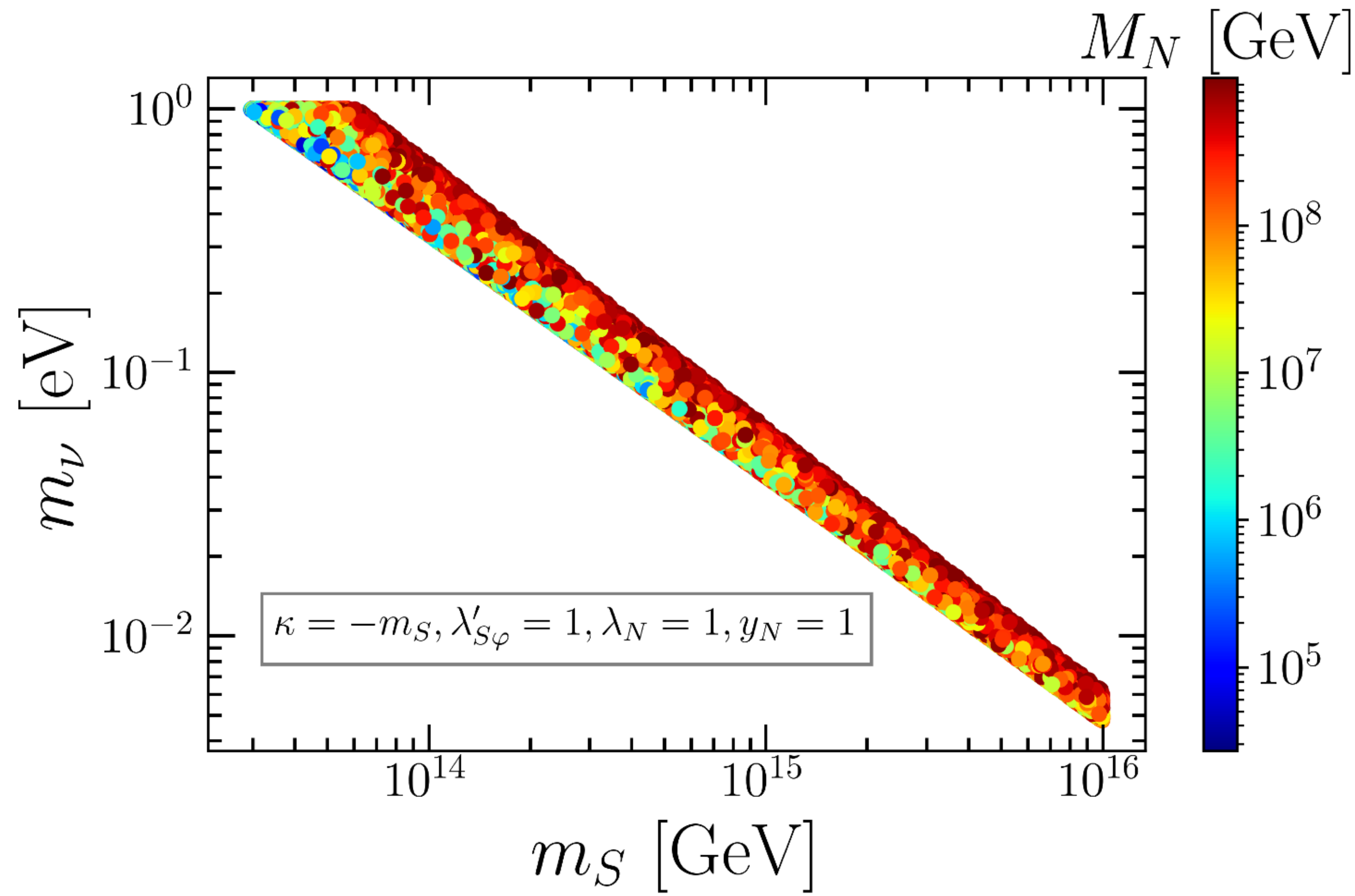
$|\lambda_{5,\mathrm{eff}}| < 1$

$$m_0^2 \equiv \frac{m_{\mathcal{H}_1}^2 + m_{\mathcal{A}_1}^2}{2} \approx m_{H_0}^2$$

Note: Smaller y_N ($\mathscr{L}_{\mathrm{int}} \supset -y_N \bar{l} \tilde{H}_2 N_R$) leads the diagonal bound shift to the left

Analysis on Neutrino

Correlation between m_ν and Heavy Scalar Mass in the $M_{N,k} \gg m_0$ limit



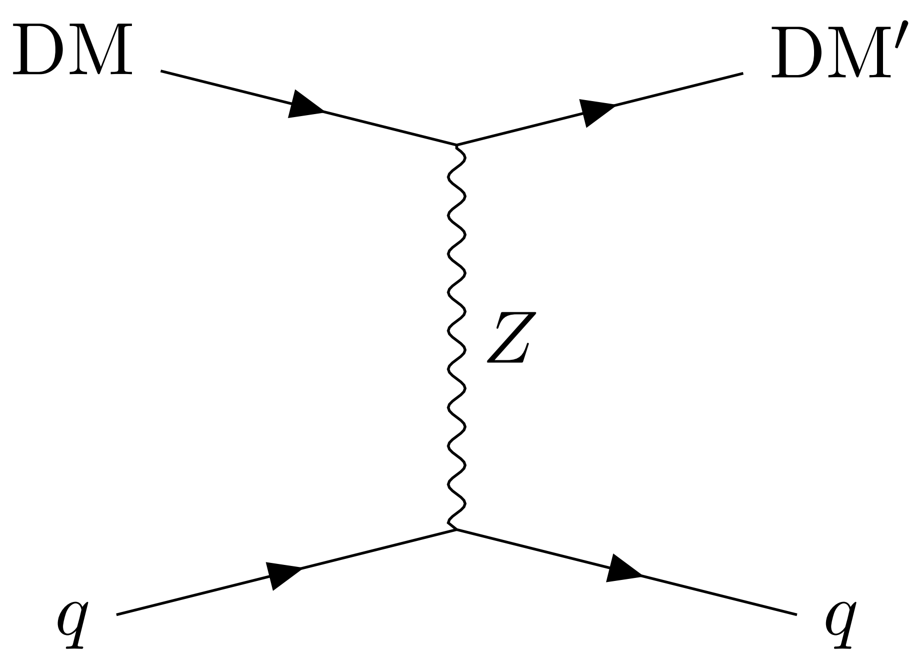
Assumptions

$|m_{H_0} - m_{A_0}| > 100$ keV

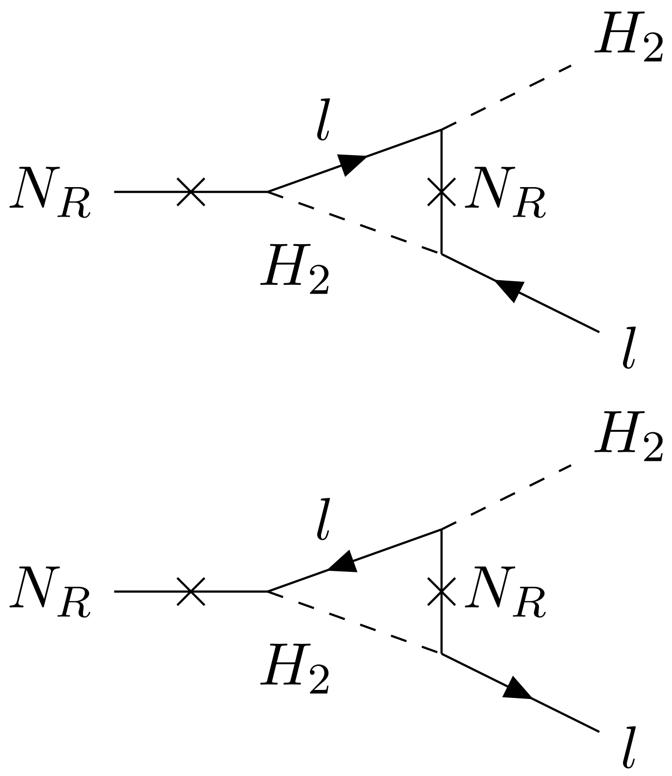
$|\lambda_{5,\text{eff}}| < 1$

Note: Smaller y_N leads the diagonal bound shift to the bottom

Remaining Discussions



Detectability of DM



Leptogenesis

The reason for at least 100 keV mass difference between H_0 and A_0

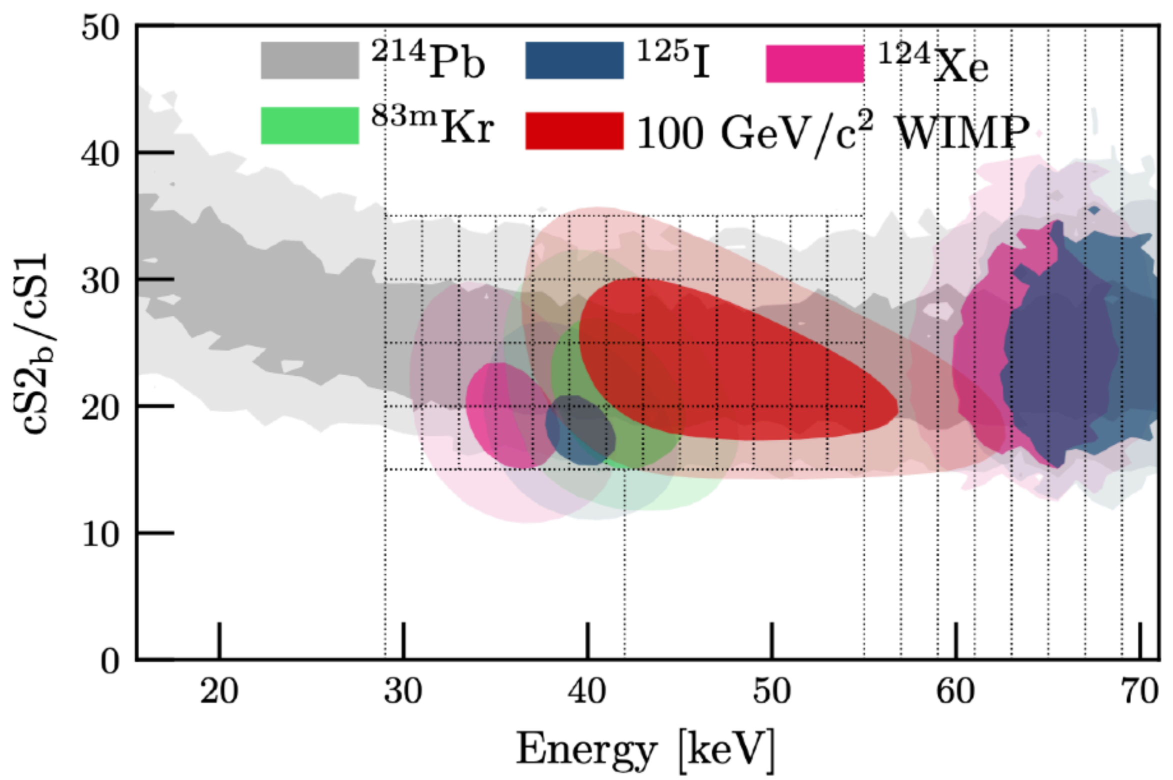
Baryon Asymmetry from RHN Decay

Note: The sign of $\lambda_{5,\mathrm{eff}}$ determines which particle is Dark matter among $\mathcal{H}_1, \mathcal{H}_2, \mathcal{A}_1, \mathcal{A}_2$. However, since all heavier species was annihilated into DM, this does not change phenomenology significantly. We assume $\lambda_{5,\mathrm{eff}}$ to be positive.

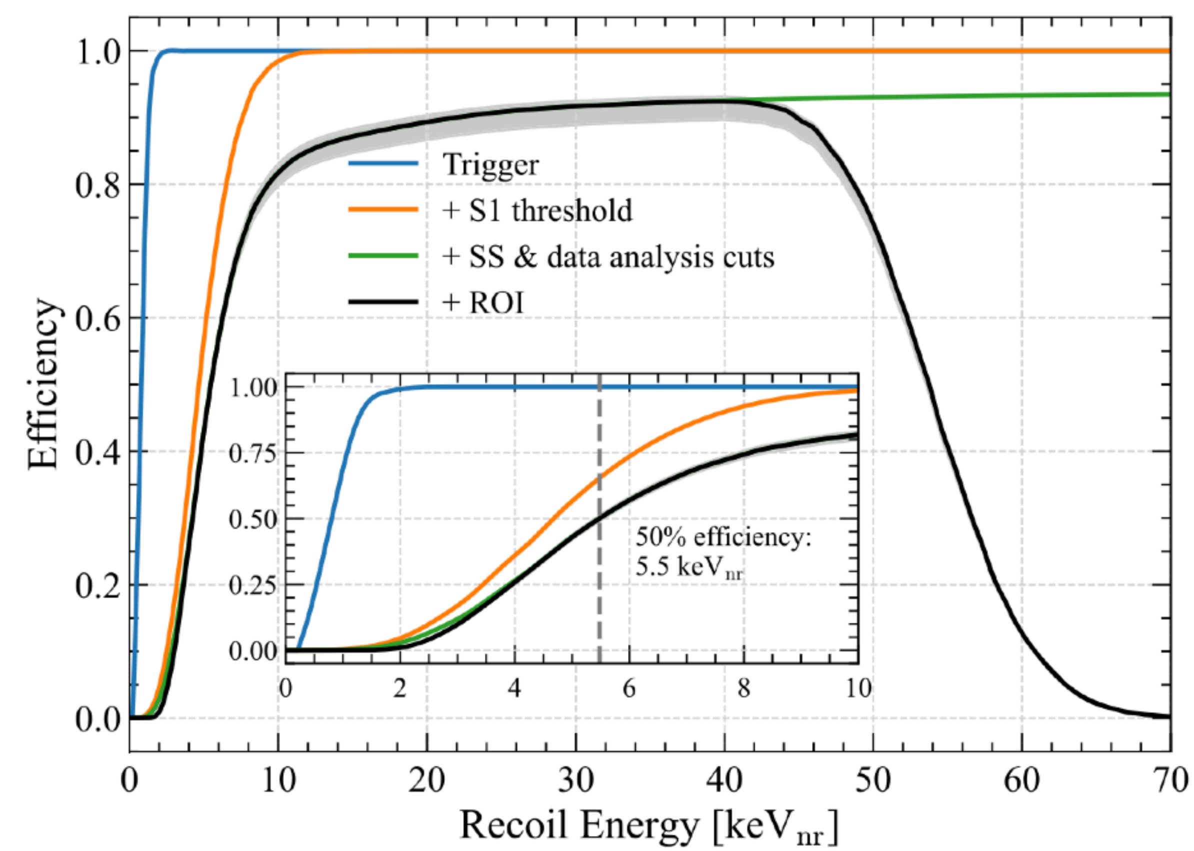
Detectability of the Inert Higgs DM

Strong Experimental Bound for mass gap less than 100 keV

XENON1T Collaboration., Phys. Rev. D 103, 063028 (2021)



LZ Collaboration., Phys. Rev. Lett. 131, 041002



The Region of interest in several DM DD is energy transfer less than $\mathcal{O}(100)$ keV: inelastic scattering with energy transfer (= mass gap between DM and next-lightest DS particle) greater than $\mathcal{O}(100)$ keV is not constrained well.

Mass Splitting in Decoupling Limit

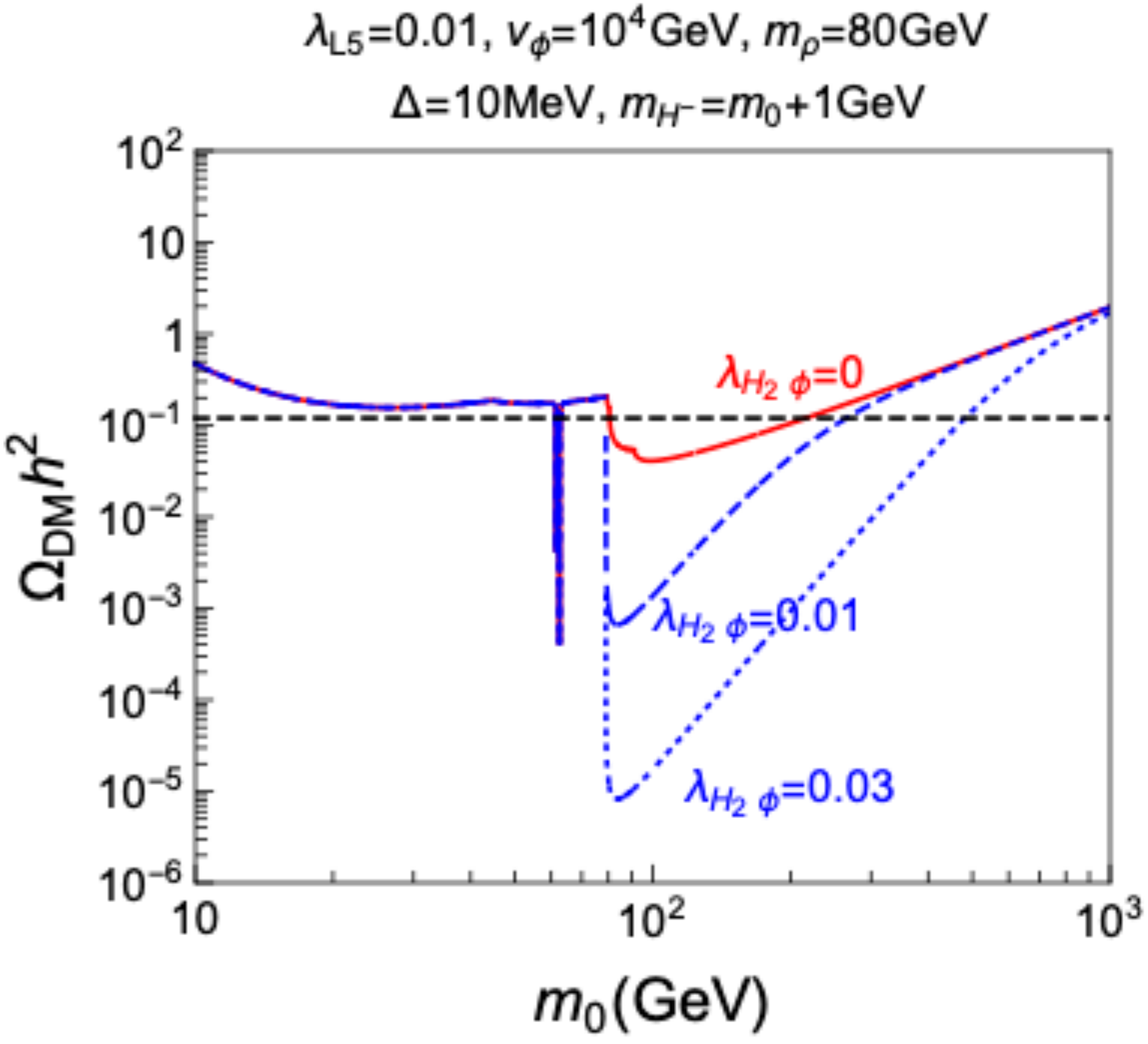
$$m_{H_0} - m_{A_0} \sim \frac{\lambda_{5,\mathrm{eff}} v_H^2}{\sqrt{2(m_{H_0}^2 + m_{A_0}^2)}}$$

Scattering Cross-section b/w DM and nucleus

$$\sigma_{A_0}^{\mathrm{SI}} = (\lambda_3 + \lambda_4 - \lambda_{5,\mathrm{eff}})^2 \frac{\mu_N^2 (Z f_p + (A-Z) f_n)^2}{4\pi m_{A_0}^2 A^2} \left(\frac{c_\alpha^2}{m_{h_1}^2} - \frac{s_\alpha^2}{m_{h_2}^2} \right)^2$$

Relic of the Inert Higgs DM

$$-\frac{1}{2}\lambda_{H_i\varphi}\left(H_i^\dagger H_i\right)\varphi^2$$



Dark Matter Relic for each DM mass with three $\lambda_{H_2\varphi}$ ($= 0, 0.01, 0.03$) values with

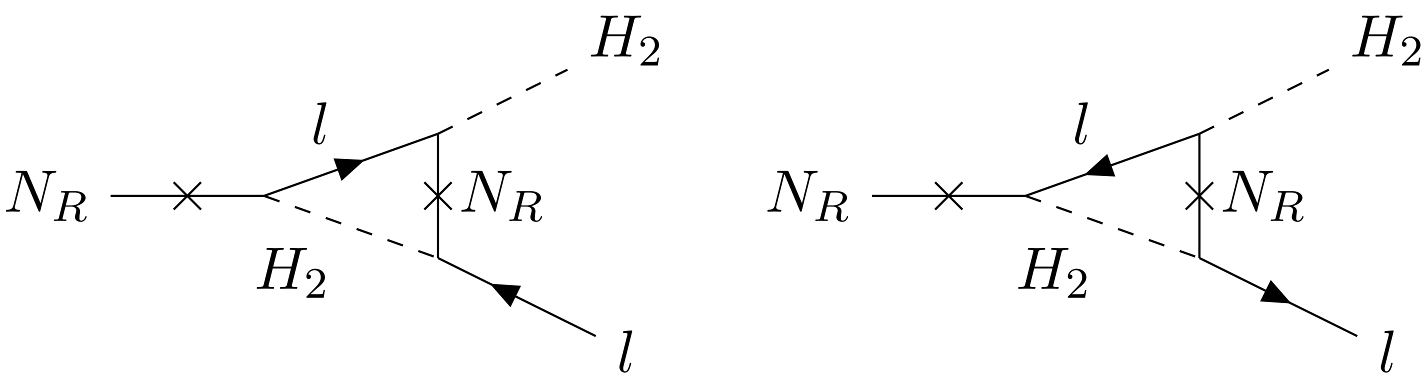
$$c_\alpha = 1 \ , s_\alpha = 0, \ \lambda_{H_1\varphi} = 0, \ v_\varphi = 10^4\text{GeV},$$

$$m_\pm = m_0 + 1\text{GeV}, \ |m_{H_0} - m_{A_0}| = 10\text{MeV}$$

$$m_{h_2} = 80\text{GeV}, \ (\lambda_3 + \lambda_4 - \lambda_{5,\text{eff}}) = 0.01$$

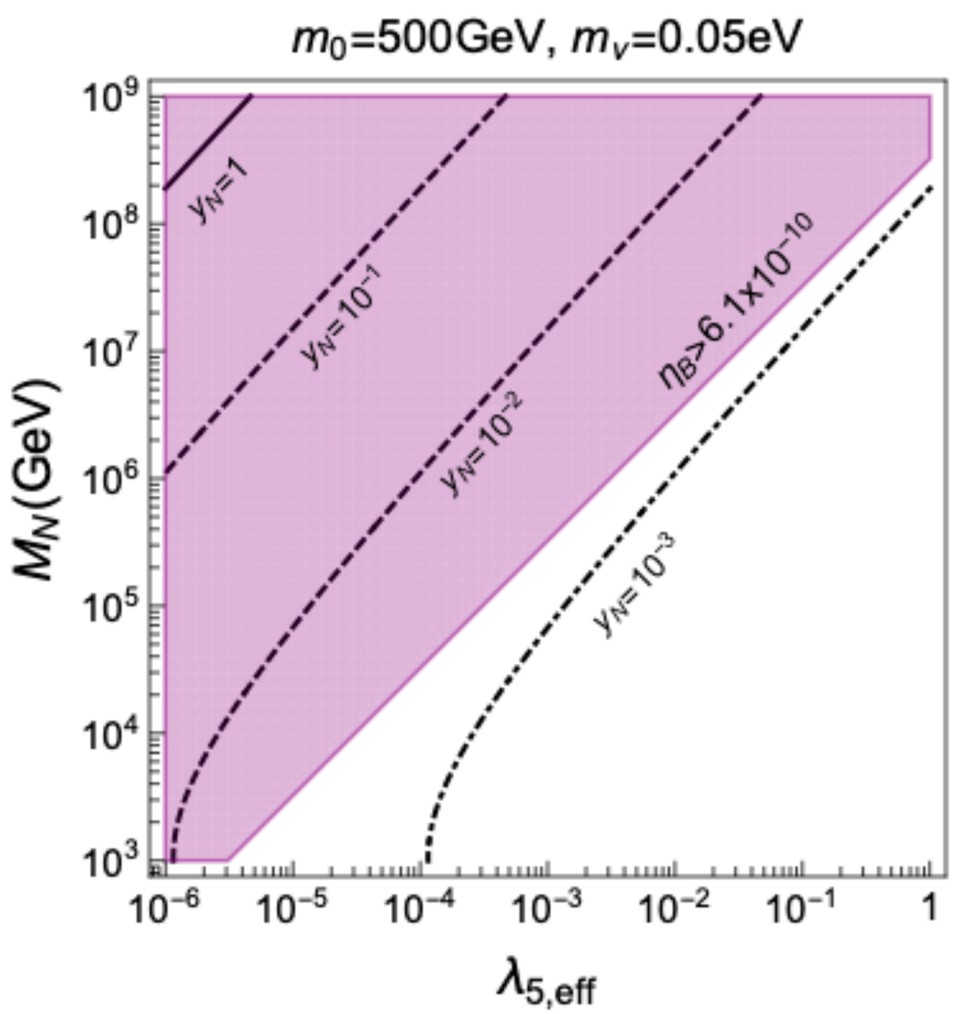
Thermal Leptogenesis

From Heavy RHN Decay



Assumption

The lightest RHN dominates whole leptogenesis process (Contribution from heavier RHN is ignored due to washout)



Baryon-to-photon ratio (From $B-L$ asymmetry)

$$\eta_B \simeq 3.8\times 10^{-10}\left(\frac{M_{N,1}}{10^4\,\mathrm{GeV}}\right)\left(\frac{10^{-4}}{\lambda_{5,\mathrm{eff}}}\right)\left(\frac{m_{\nu,h}}{0.1\,\mathrm{eV}}\right)$$

$\eta_B^{\mathrm{obs}} = 6.1\times 10^{-10}$ $m_{\nu,h}$: Heaviest SM Neutrino mass

Parameter Space for M_N vs $\lambda_{5,\mathrm{eff}}$ with $m_{\nu,h} = 0.05$eV

Purple Region: $\eta_B > \eta_B^{\mathrm{obs}}$

Conclusion

- The scotogenic model provides the possibility of heavy but experimentally viable Right-Handed neutrino

- We imposed Z_4 symmetry and its breaking to our model.
  Here, Inert Higgs and scalar S provides a small neutrino mass.

- In the decoupling scalar limit, our model goes to the scotogenic limit, and the λ_5 term: explaining small neutrino mass is effectively generated

- The lightest particle in Z_2 odd sector is a DM candidate.
  If the Inert Higgs is the lightest, evading strong direct detection bounds requires at least a 100keV mass gap (determined by λ_5)

- We commented on the possibility of RHN as the source of the leptogenesis in our model