Dark matter as the origin of neutrino mass in the inverse seesaw mechanism

Sanjoy Mandal

KIAS, Seoul

Email: smandal@kias.re.kr

Talk is based on *Phys.Lett.B* 821 (2021) 136609

In collaboration with Jose W. F. Valle, N. Rojas and R. Srivastava

The Future is Illuminating, 2022

NCTS, TAIWAN

Outline

Introduction

A quick review of Original Scotogenic Model

Brief overview of Scotogenic inverse seesaw mechanism

1. Explicit lepton number breaking
2. Dynamical lepton number breaking

Phenomenology of scalar dark matter

Relic density and direct detection

Neutrinoless double beta decay and LFV

Conclusion

Introduction

Neutrinos are massive: from oscillations

Dark matter: from cosmology

The SM is incomplete: New Physics is required to account for neutrino masses and dark matter

Neutrino masses are at least $\mathcal{O}(10^6)$ smaller than electron mass

Addition of RHN $\Rightarrow$ $Y_\nu \bar{L}\tilde{H}N_R$, mass generation through Higgs mechanism

$\Rightarrow$ Y_ν will be very small $\Rightarrow$ Neutrino mass origin is different?

Many ways to generate small neutrino mass: Tree-level(seesaw models), loop-level (radiative models)

Big question: Is there any connection between dark matter and neutrino masses?

May be yes: Scotogenic Model arXiv: hep-ph/0601225, Ernest Ma

Address both questions (neutrino mass and dark matter) in an “economical” way

Neutrino masses are “seeded” by dark sector

Original Scotogenic model

Scotogenic model = SM + 3 singlet fermions + 1 scalar doublet + a dark $\mathbb{Z}_2$ parity

	Standard Model			New Fermions	New Scalar
	L_a	e_a	H	N	η
$SU(2)_L$	2	1	2	1	2
$U(1)_Y$	-1/2	-1	1/2	0	1/2
$\mathbb{Z}_2$	+	+	+	−	−

$\mathbb{Z}_2$ parity: $< \eta > = 0$

No tree level neutrino mass

arXiv: hep-ph/0601225, Ernest Ma

$$\mathcal{L}_N = \overline{N}_i \partial\!\!\!/ N_i - \frac{M_{R_i}}{2} \overline{N_i^c} N_i + y_{i\alpha} \eta \overline{N}_i \ell_\alpha + \text{h.c.}$$

$$V = -\mu_H^2 H^\dagger H + m_\eta^2 \eta^\dagger \eta + \lambda (H^\dagger H)^2 + \lambda_\eta (\eta^\dagger \eta)^2 + \lambda_3 (H^\dagger H)(\eta^\dagger \eta)$$
$$+ \lambda_4 (H^\dagger \eta)(\eta^\dagger H) + \frac{\lambda_5}{2} \left((H^\dagger \eta)^2 + h.c.\right)$$

Inert scalar sector: $\eta^\pm \quad \eta^0 = (\eta_R + i\eta_I)/\sqrt{2}$

$$m_{\eta^+}^2 = m_\eta^2 + \frac{\lambda_3}{2} v^2$$

$$m_{\eta_R}^2 = m_\eta^2 + \frac{(\lambda_3 + \lambda_4 + \lambda_5)}{2} v^2$$

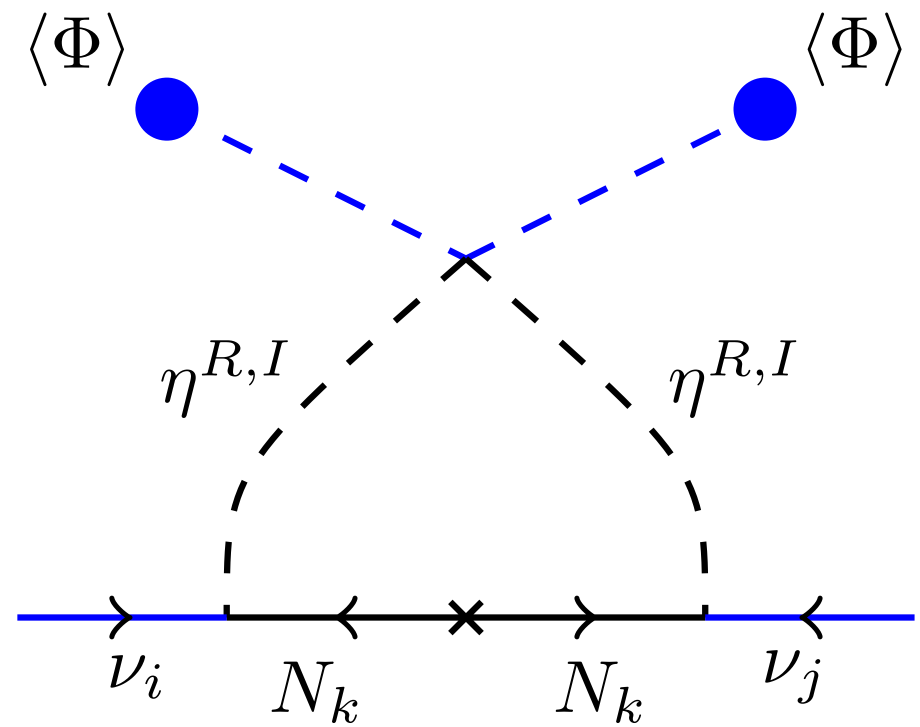
$$m_{\eta_I}^2 = m_\eta^2 + \frac{(\lambda_3 + \lambda_4 - \lambda_5)}{2} v^2$$

$\Rightarrow$

$$m_{\eta_R}^2 - m_{\eta_I}^2 = \lambda_5 v^2$$

Tree-level: **Forbiden by the $\mathbb{Z}_2$ symmetry**

1-loop neutrino masses



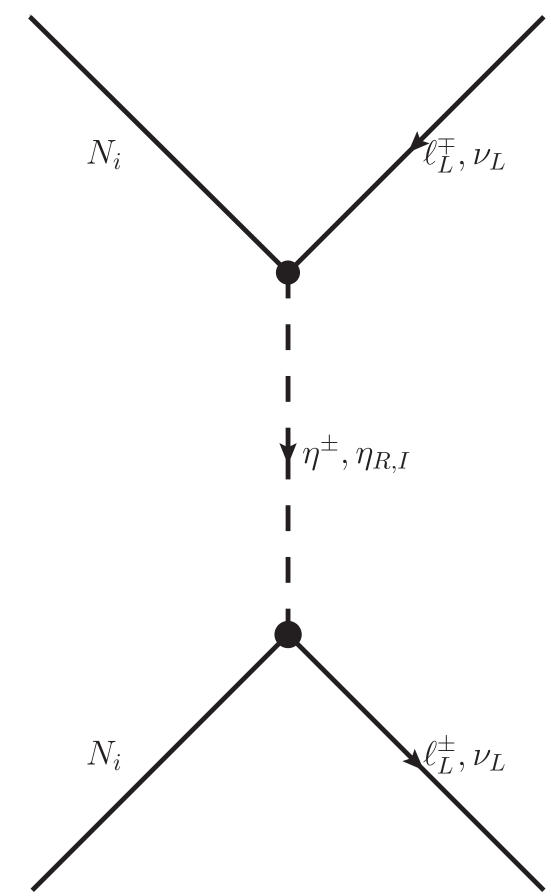
$$\mathscr{M}^{\nu}_{\alpha\beta} = \frac{Y^{\nu}_{\alpha i} Y^{\nu}_{\beta i}}{32\pi^2} M_{N_i} \left[\frac{m^2_{\eta_R}}{m^2_{\eta_R} - M^2_{N_i}} \log\left(\frac{m^2_{\eta_R}}{M^2_{N_i}}\right) - \frac{m^2_{\eta_I}}{m^2_{\eta_I} - M^2_{N_i}} \log\left(\frac{m^2_{\eta_I}}{M^2_{N_i}}\right) \right]$$

Approximation: $M_N^2,\ m^2_{\eta_{R,I}},\ M_N^2 - m^2_{\eta_{R,I}} \gg \lambda_5 v^2$

$$\mathscr{M}^{\nu}_{\alpha\beta} \approx \frac{Y^{\nu}_{\alpha i} Y^{\nu}_{\beta i}}{32\pi^2} \lambda_5 v^2 \frac{M_{N_i}}{m^2_{\eta} - M^2_{N_i}}$$

$\eta^{R,I}/N_k$: **Dark particles in the loop**

The lightest particle odd under $\mathbb{Z}_2$ is stable: dark matter candidate



Fermionic dark matter: lightest of N_i

- **can be produced only through Yukawa interaction**
- **Potential problems with LFV: is it compatible with the current bounds?**

Scalar dark matter: lightest of η_R/η_I

- **It also has gauge interactions**
- **Not correlated to LFV**

Low-scale-seesaw

Mohapatra, Valle, 1986

Valle et al, 1404.3752

SM et al., 2009.10116

Add pair of singlets ν^c and S with $L[\nu^c]=1,\ L[S]=1$

$$-\mathscr{L} = \sum_{ij} Y_\nu^{ij} L_i \tilde{\Phi} \nu_j^c + M^{ij} \nu_i^c S_j + \frac{1}{2}\mu_S^{ij} S_i S_j + \text{H.c.}$$

$\mu_s^{ij} S_i S_j$: **Explicit breaking of #L by two units**

Neutrino mass: $m_\nu \approx m_D M^{-1} \mu_S (M^T)^{-1} m_D^T = \frac{v^2}{2} Y_\nu M^{-1} \mu_S (M^T)^{-1} Y_\nu^T$

With very small μ_S, one can allow large $Y_\nu \sim \mathcal{O}(1)$, even for $M_N \sim \mathcal{O}(1)$ TeV

No explanation for smallness of μ_S!!

Let's try with Dynamical breaking:

$L[\nu^c]=1,\ L[S]=1,\ L[\sigma]=-2$

$$-\mathscr{L} = \sum_{i,j}^{3} Y_\nu^{ij} L_i \tilde{\Phi} \nu_j^c + M^{ij} \nu_i^c S_j + Y_S^{ij} \sigma S_i S_j + \text{H.c.}$$

SM et al., 2103.02670

$$m_\nu \simeq \frac{v_\Phi^2}{\sqrt{2}} Y_\nu M^{-1} Y_S v_\sigma M^{-1T} Y_\nu^T$$

$\mu_s = Y_S v_\sigma/\sqrt{2}$, hence can take Y_S very small and $v_\sigma \sim \mathcal{O}$(TeV)

CP-even scalars: h and H

Imaginary part of the σ corresponds to the physical majoron $J = \text{Im}\ \sigma$

KeV scale majoron can play the role of Warm dark matter candidate. It decays to neutrinos, with a tiny strength proportional to their mass

Scotogenic Inverse-seesaw: Explicit breaking

SM et al., 1907.07728

	L	e^c	ν^c	S	f	Φ	ξ
$SU(2)_L \times U(1)_Y$	$(2,-1)$	$(1,2)$	$(1,0)$	$(1,0)$	$(1,0)$	$(2,1)$	$(1,0)$
$U(1)_{B-L}$	-1	1	1	-1	0	0	1
$\mathcal{Z}_2$	$+$	$+$	$+$	$+$	$-$	$+$	$-$

$\mathbb{Z}_2$-odd extra particles: fermion f and scalar ξ

$$\mathcal{L}^{\text{Yukawa}} = -Y_{\nu^c}\overline{L}i\tau_2\Phi^*\nu^c - Y_\xi \xi f S - M\nu^c S - \frac{1}{2}\mathcal{M}_f f f + H.c.$$

Minimal case:
2-copies of ν^c, S and f

$$\mathcal{V}_{(s)} = -m^2\Phi^\dagger\Phi + \frac{\lambda_\Phi}{2}\left(\Phi^\dagger\Phi\right)^2 - m_\xi^2\xi^*\xi + \frac{\lambda_\xi}{2}\left(\xi^*\xi\right)^2 + \lambda_{\Phi\xi}\left(\Phi^\dagger\Phi\right)\left(\xi^*\xi\right) + \frac{\mu_\xi^2}{4}\left(\xi^2 + \text{h.c.}\right)$$

↓ Softly breaks $U(1)_{B-L}$

$$\Phi = \begin{pmatrix} \phi^+ \\ (v_\Phi + h + i\phi^0)/\sqrt{2} \end{pmatrix}, \quad \xi = (\xi_R + i\xi_I)/\sqrt{2}$$

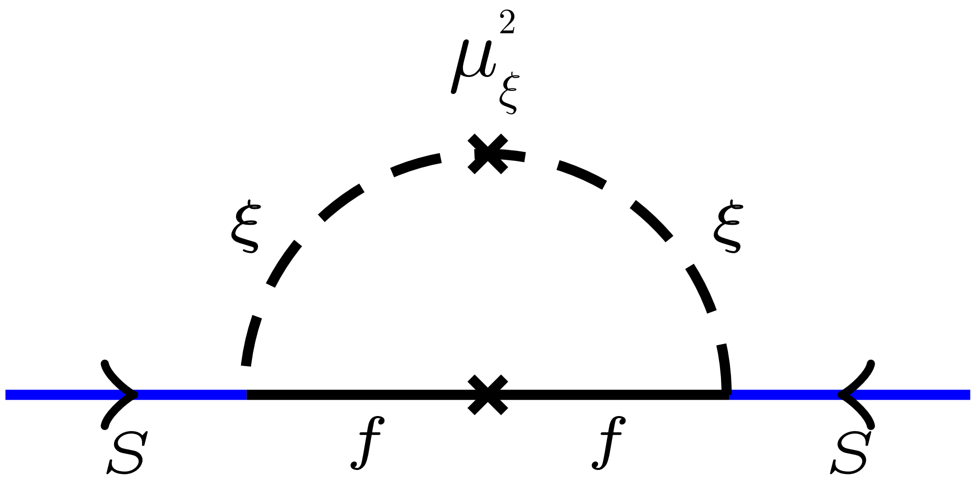
$$m_{\xi_R}^2 = m_\xi^2 + \frac{1}{2}\left(\lambda_{\Phi\xi}v_\Phi^2 + \mu_\xi^2\right)$$
$$m_{\xi_I}^2 = m_\xi^2 + \frac{1}{2}\left(\lambda_{\Phi\xi}v_\Phi^2 - \mu_\xi^2\right)$$

No neutrino mass at tree-level

$$\mathcal{M}_{F^0} = \begin{bmatrix} 0 & m_D & 0 \\ m_D & 0 & M \\ 0 & M & 0 \end{bmatrix} = \begin{bmatrix} 0 & Y^i_{\nu^c}\frac{v_\Phi}{\sqrt{2}} & 0 \\ Y^j_{\nu^c}\frac{v_\Phi}{\sqrt{2}} & 0 & M \\ 0 & M & 0 \end{bmatrix}.$$

$$m_{\xi_R}^2 - m_{\xi_I}^2 = \mu_\xi^2$$

Goal: generate the term: μSS at loop-level



comes from $Y_\xi \xi f S$ and $\frac{\mu_\xi^2}{4}(\xi^2 + h.c)$

Generates the term: μSS

$$\mu = \frac{Y_\xi Y_\xi}{16\pi^2}\mathcal{M}_f \left(B_0(0, \mathcal{M}_f^2, m_{\xi_R}^2) - B_0(0, \mathcal{M}_f^2, m_{\xi_I}^2)\right)$$

$$= \frac{Y_\xi Y_\xi}{16\pi^2}\mathcal{M}_f \left(\frac{m_{\xi_R}^2}{m_{\xi_R}^2 - \mathcal{M}_f^2}\log\left(\frac{m_{\xi_R}^2}{\mathcal{M}_f^2}\right) - \frac{m_{\xi_I}^2}{m_{\xi_I}^2 - \mathcal{M}_f^2}\log\left(\frac{m_{\xi_I}^2}{\mathcal{M}_f^2}\right)\right)$$

without μ_ξ, $m_{\xi_R} = m_{\xi_I}$ and hence $\mu = 0$

$$\mathscr{M}_{F^0} = \begin{bmatrix} 0 & m_D & 0 \\ m_D & 0 & M \\ 0 & M & \mu \end{bmatrix} \longrightarrow \mathcal{M}_\nu = m_D M^{-1} \mu M^{-1T} m_D^T.$$

Smallness of μ is related with smallness of μ_ξ^2 and loop suppression factors

Not a pleasant solution as potential is not B-L invaraint

Scotogenic Inverse-seesaw: Dynamical breaking

	L	e^c	ν^c	S	f	Φ	ξ	σ
$SU(2)_L \times U(1)_Y$	$(2,-1)$	$(1,2)$	$(1,0)$	$(1,0)$	$(1,0)$	$(2,1)$	$(1,0)$	$(1,0)$
$U(1)_{B-L}$	-1	1	1	-1	0	0	1	1
$\mathcal{Z}_2$	$+$	$+$	$+$	$+$	$-$	$+$	$-$	$+$

New complex scalar σ

$$\mathcal{L}^{\text{Yukawa}} = -Y_{\nu^c}\overline{L}i\tau_2\Phi^*\nu^c - Y_\xi \xi f S - M\nu^c S - \frac{1}{2}\mathcal{M}_f ff + H.c.$$

$$\mathscr{V}_{(s)} = -m^2\Phi^\dagger\Phi + \frac{\lambda_\Phi}{2}\left(\Phi^\dagger\Phi\right)^2 - m_\xi^2\xi^*\xi + \frac{\lambda_\xi}{2}\left(\xi^*\xi\right)^2 - m_\sigma^2\sigma^*\sigma + \frac{\lambda_\sigma}{2}(\sigma^*\sigma)^2$$

$$+\lambda_{\Phi\sigma}\left(\Phi^\dagger\Phi\right)(\sigma^*\sigma) + \lambda_{\xi\sigma}\left(\xi^*\xi\right)(\sigma^*\sigma) + \lambda_{\Phi\xi}\left(\Phi^\dagger\Phi\right)\left(\xi^*\xi\right) + \frac{\lambda_5}{2}\left(\xi^*\sigma\right)^2 + h.c.$$

$B-L$ invariant

$\#L$ is broken by the vev of the complex singlet σ

$$\phi^0 = \frac{1}{\sqrt{2}}(v_\Phi + R_1 + iI_1),$$

$$\sigma = \frac{1}{\sqrt{2}}(v_\sigma + R_2 + iI_2)$$

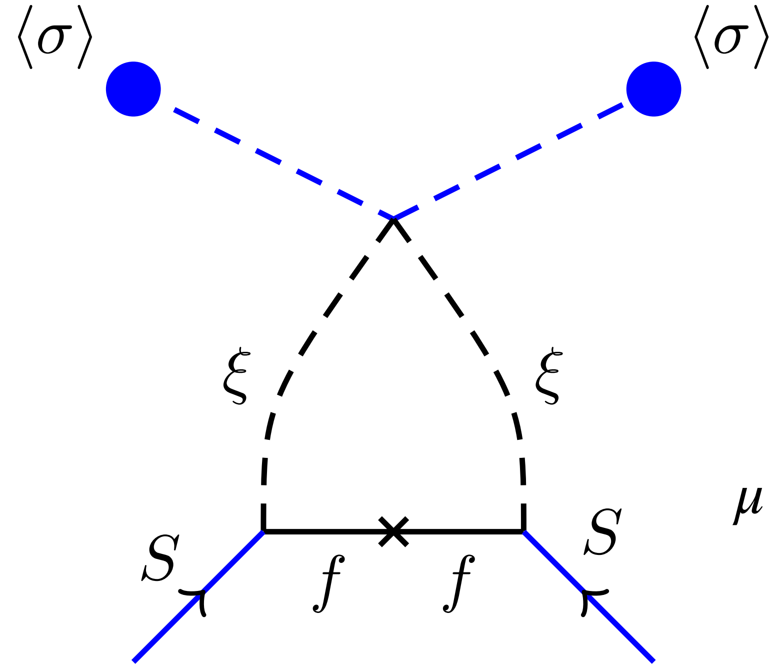
$$\xi = \frac{1}{\sqrt{2}}(\xi_R + i\xi_I)$$

$$m_{\xi_R}^2 = m_\xi^2 + \frac{\lambda_{\Phi\xi}}{2}v_\Phi^2 + \frac{\lambda_{\xi\sigma}+\lambda_5}{2}v_\sigma^2$$

$$m_{\xi_I}^2 = m_\xi^2 + \frac{\lambda_{\Phi\xi}}{2}v_\Phi^2 + \frac{\lambda_{\xi\sigma}-\lambda_5}{2}v_\sigma^2$$

$$\longrightarrow \quad m_{\xi_R}^2 - m_{\xi_I}^2 = \lambda_5 v_\sigma^2$$

Now $\lambda_5 v_\sigma^2$ plays the role of μ_ξ



comes from $Y_\xi \xi f S$, $\frac{\lambda_5}{2}((\xi^*\sigma)^2 + h.c)$ and $\mathcal{M}_f ff$

Again generates the term: μSS

$$\mu = \frac{1}{16\pi^2} Y_\xi \mathcal{M}_f \left(\frac{m^2_{\xi_R}}{m^2_{\xi_R} - \mathcal{M}^2_f} \log\left(\frac{m^2_{\xi_R}}{\mathcal{M}^2_f}\right) - \frac{m^2_{\xi_I}}{m^2_{\xi_I} - \mathcal{M}^2_f} \log\left(\frac{m^2_{\xi_I}}{\mathcal{M}^2_f}\right)\right) Y^T_\xi$$

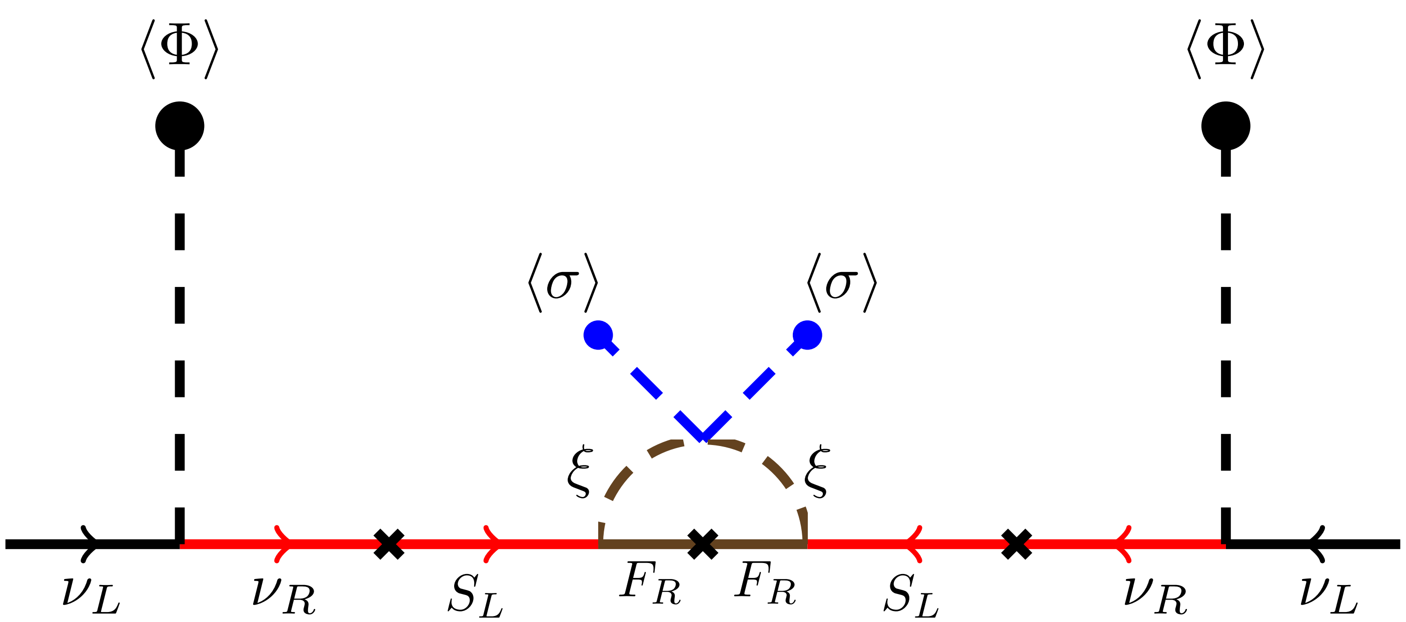
Assumption: Y_ξ and $\mathcal{M}_f$ diagonal → factorize the loop function

$$\mu_i = \frac{Y^{(i)2}_\xi M^{(i)}_f}{16\pi^2} \left(\frac{m^2_{\xi_R}}{m^2_{\xi_R} - M^{(i)2}_f} \log\left(\frac{m^2_{\xi_R}}{M^{(i)2}_f}\right) - \frac{m^2_{\xi_I}}{m^2_{\xi_I} - M^{(i)2}_f} \log\left(\frac{m^2_{\xi_I}}{M^{(i)2}_f}\right)\right)$$

$$\mu_i \approx \frac{1}{16\pi^2} \frac{\lambda_5 v^2_\sigma}{M^{(i)2}_f - m^2_{\xi_R}} M^{(i)}_f Y^{(i)2}_\xi$$

Neutrino mass:

$$\mathcal{M}_\nu = m_D M^{-1} \mu M^{-1T} m^T_D.$$



$\lambda_5 \to 0$: neutrinos are massless: restore $\#L$

Phenomenology

Scalar sector and constraints:

CP-even scalars: h and H

Imaginary part of the σ corresponds to the physical majoron $J = \text{Im}\ \sigma$

$$M_R^2 = \begin{bmatrix} \lambda_\Phi v_\Phi^2 & \lambda_{\Phi\sigma} v_\Phi v_\sigma \\ \lambda_{\Phi\sigma} v_\Phi v_\sigma & \lambda_\sigma v_\sigma^2 \end{bmatrix} \rightarrow \begin{bmatrix} h \\ H \end{bmatrix} = O_R \begin{bmatrix} R_1 \\ R_2 \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} R_1 \\ R_2 \end{bmatrix}$$

The coupling of SM Higgs boson to SM particles gets modified as:

$$h_{\textbf{SM}} \rightarrow \cos\theta\, h - \sin\theta\, H$$

Large invisible Higgs decay for $v_\sigma \sim \mathcal{O}(\text{TeV})$

$$\Gamma(h \rightarrow JJ) = \frac{1}{32\pi m_h} \frac{m_h^4 \sin^2\theta}{v_\sigma^2} \sqrt{1 - \frac{4m_J^2}{m_h^2}}$$

In case of $m_{\xi_{R/I}} < m_h/2$:

$$\Gamma(h \rightarrow \xi_R \xi_R) = \frac{1}{32\pi m_h} \left((\lambda_{\xi\sigma} + \lambda_5) v_\sigma \sin\theta + \lambda_{\Phi\xi} v_\Phi \cos\theta\right)^2 \sqrt{1 - \frac{4m_{\xi_R}^2}{m_h^2}}$$

$$\Gamma(h \rightarrow \xi_I \xi_I) = \frac{1}{32\pi m_h} \left((\lambda_{\xi\sigma} - \lambda_5) v_\sigma \sin\theta + \lambda_{\Phi\xi} v_\Phi \cos\theta\right)^2 \sqrt{1 - \frac{4m_{\xi_I}^2}{m_h^2}}$$

→ **contributes to invisible decay**

Note that, λ_5 is so small

Total invisible decay width:

$$\Gamma^{\textbf{inv}}(h) = \Gamma(h \rightarrow JJ) + \Gamma(h \rightarrow \xi_R \xi_R) + \Gamma(h \rightarrow \xi_I \xi_I)$$

Collider constraints: Signal strength parameter and Invisible Higgs decay

Invisible sector: $\mathbf{BR}^{\mathbf{inv}}(h) = \dfrac{\Gamma^{\mathbf{inv}}(h)}{\cos^2\theta\,\Gamma^{\mathbf{SM}}(h) + \Gamma^{\mathbf{inv}}(h)}$

Present bound on Invisible Higgs decay is:

$\mathrm{BR}(h \to \mathrm{Inv}) \leq 19\,\%$ CMS, 1809.05937

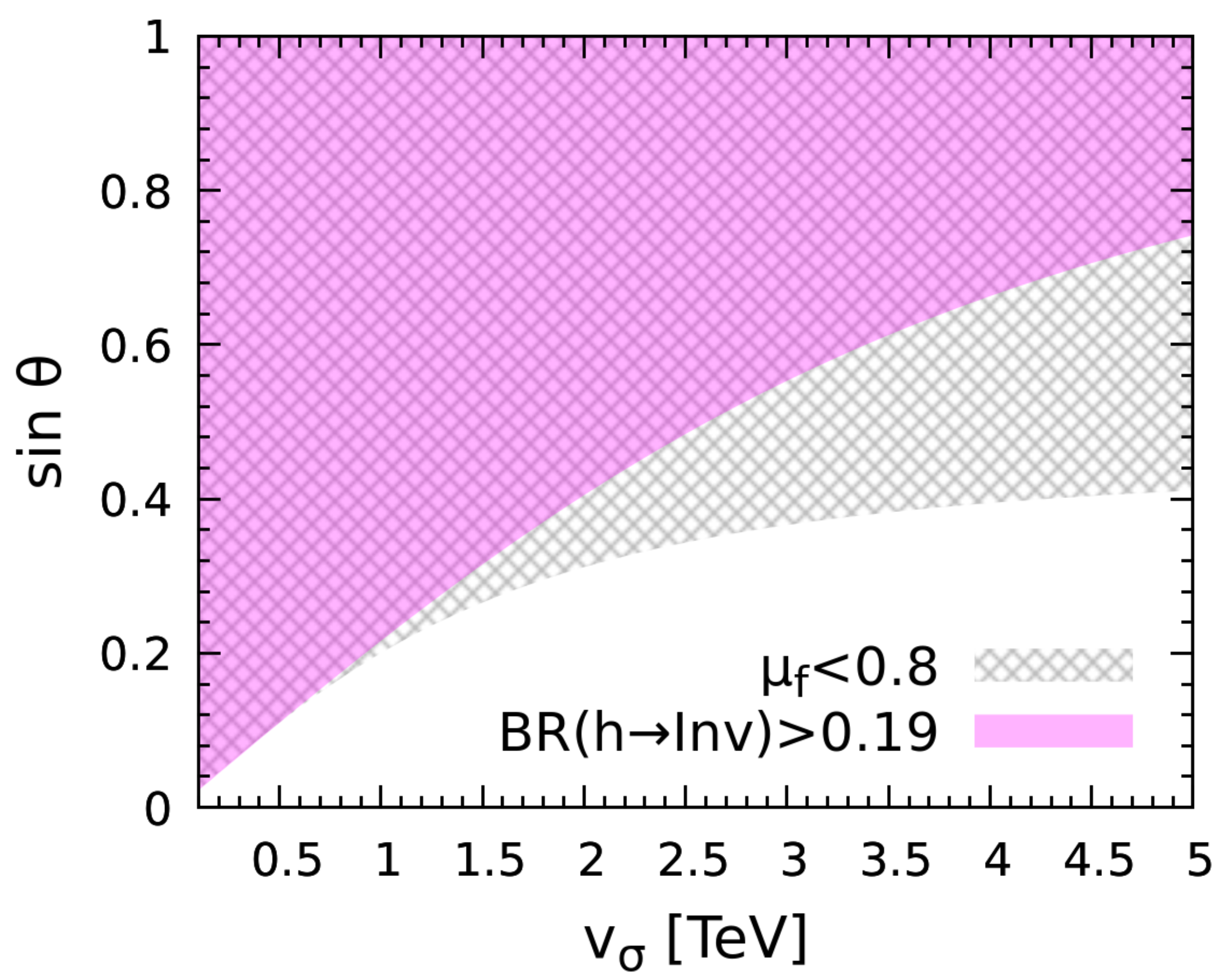
Visible sector: $\mathbf{BR}_f(h) = \dfrac{\cos^2\theta\,\Gamma_f^{\mathbf{SM}}(h)}{\cos^2\theta\,\Gamma^{\mathbf{SM}}(h) + \Gamma^{\mathbf{inv}}(h)}$

Modified Higgs production: $\sigma(pp \to h) = \cos^2\theta\,\sigma^{\mathbf{SM}}(pp \to h), \quad \sigma(pp \to H) = \sin^2\theta\,\sigma^{\mathbf{SM}}(pp \to H)$

Signal strength: $\mu_f = \dfrac{\sigma^{\mathbf{NP}}(pp \to h)}{\sigma^{\mathbf{SM}}(pp \to h)}\,\dfrac{\mathbf{BR}^{\mathbf{NP}}(h \to f)}{\mathbf{BR}^{\mathbf{SM}}(h \to f)}$

ATLAS, 1909.02845

Decay Mode	Production Processes			
	ggF	VBF	VH	ttH
$H \to \gamma\gamma$	$0.96^{+0.14}_{-0.14}$	$1.39^{+0.40}_{-0.35}$	$1.09^{+0.58}_{-0.54}$	$1.10^{+0.41}_{-0.35}$
$H \to ZZ$	$1.04^{+0.16}_{-0.15}$	$2.68^{+0.98}_{-0.83}$	$0.68^{+1.20}_{-0.78}$	$1.50^{+0.59}_{-0.57}$
$H \to WW$	$1.08^{+0.19}_{-0.19}$	$0.59^{+0.36}_{-0.35}$	–	$1.50^{+0.59}_{-0.57}$
$H \to \tau\tau$	$0.96^{+0.59}_{-0.52}$	$1.16^{+0.58}_{-0.53}$	–	$1.38^{+1.13}_{-0.96}$
$H \to bb$	–	$3.01^{+1.67}_{-1.61}$	$1.19^{+0.27}_{-0.25}$	$0.79^{+0.60}_{-0.59}$



Assuming only $h \to JJ$ is present $(m_{\xi_{R/I}} > m_h/2)$

For $m_{\xi_{R/I}} < m_h/2$, exclusion region depends on $\lambda_{\Phi\xi}$ and $\lambda_{\xi\sigma}$

For $\sin\theta = 0,\ h \to JJ$ is not present: constrain $\lambda_{\Phi\xi}$ from BR$(h \to$ Inv$) < 19\,\%$.

$$\lambda_{\Phi\xi}\left(1 - \frac{4m_\xi^2}{m_h^2}\right)^{\frac{1}{4}} \leq 9.8 \times 10^{-3}$$

Constraint from direct search: $pp \to H \to WW \to 2\ell 2\nu, \quad pp \to ZZ \to 4\ell$

If $m_H > 2m_h,\ \ pp \to H \to hh$

SM et al., arXiv: 2103.02670

But for $v_\sigma \gg v_H$, the constraint from the signal strength parameter is stronger.

Dark matter phenomenology

$\mathbb{Z}_2$ symmetry: fermionic DM (f) or scalar DM $(\xi_{R/I})$

In case of fermionic DM f, $Y_\xi \xi f S$ will determine the relic

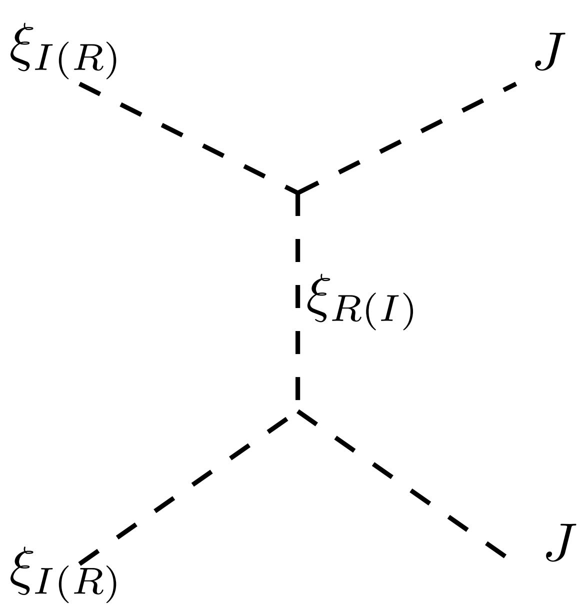
Scalar DM: ξ_R if $\lambda_5 < 0$ or ξ_I if $\lambda_5 > 0$ $(m_{\xi_R}^2 - m_{\xi_I}^2 = \lambda_5 v_\sigma^2)$

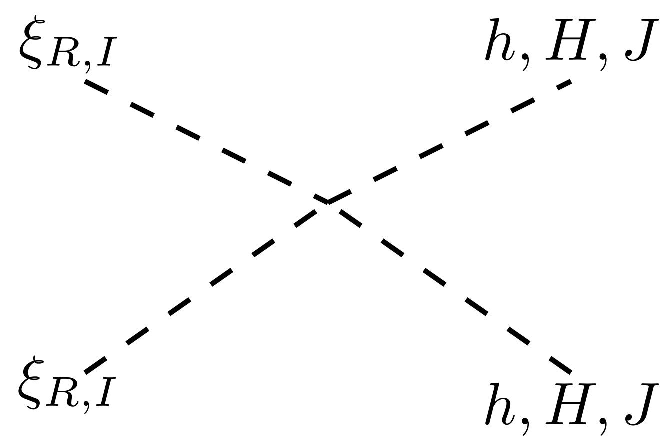
Advantage: DM and LFV source is different for both fermionic and scalar dark matter

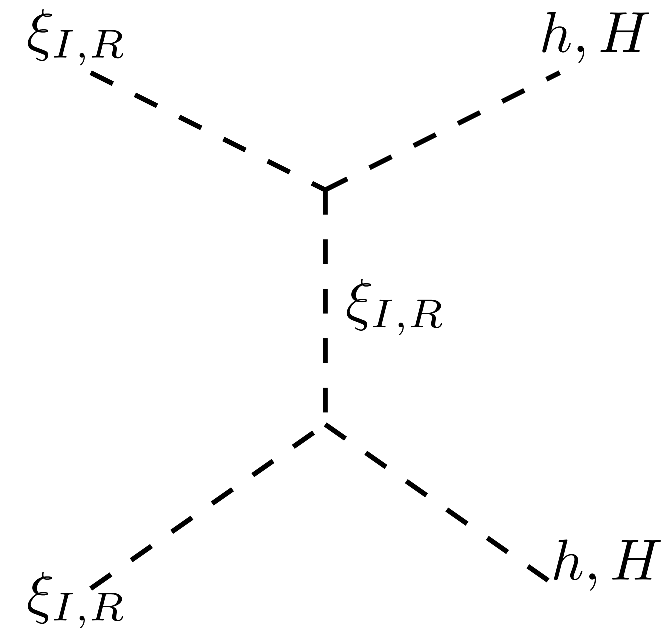
Source of LFV: $Y_{\nu^c} \bar{L} i\sigma_2 H^* \nu^c$

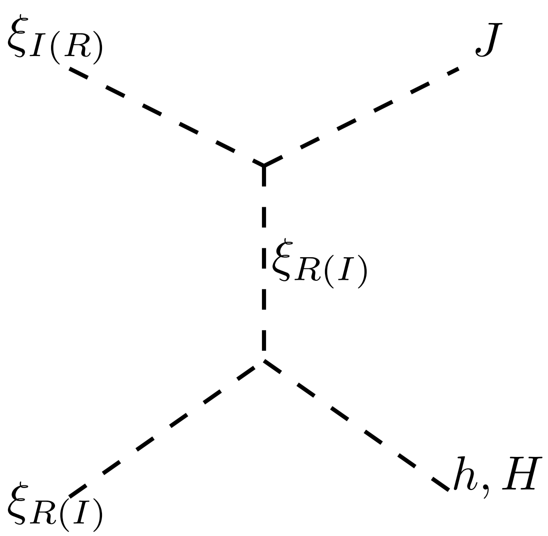
Annihilation channels

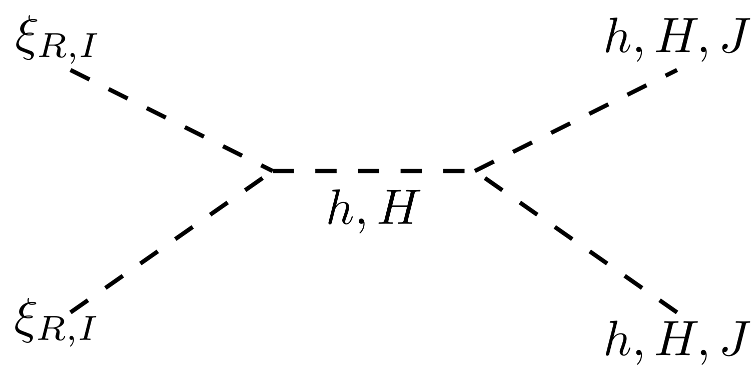
Close to complex scalar dark matter but not quite due to presence of majoron J

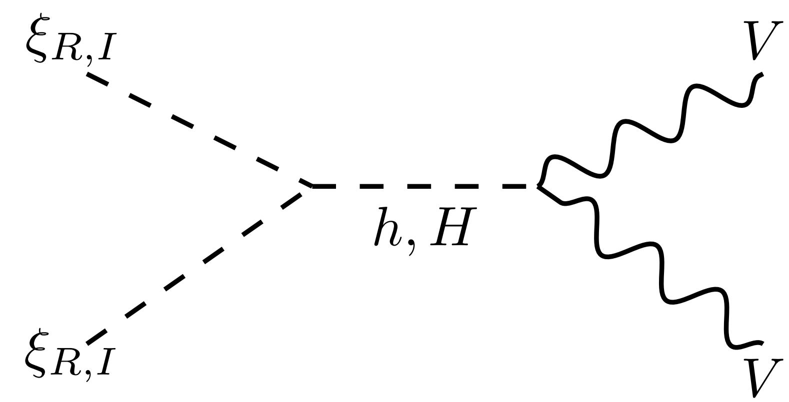


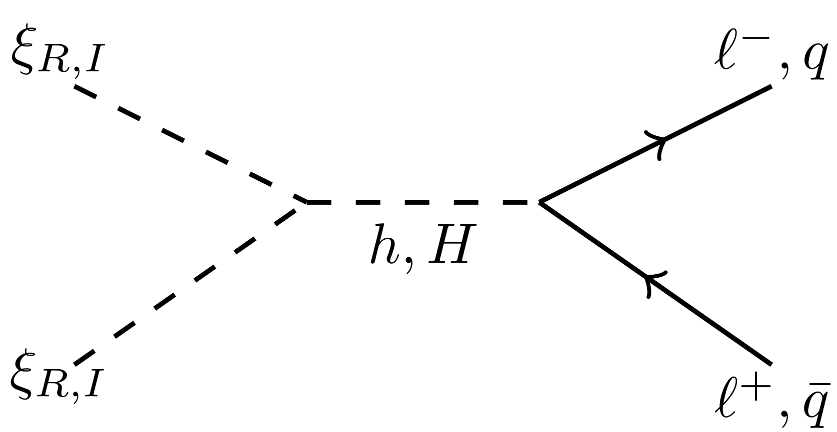












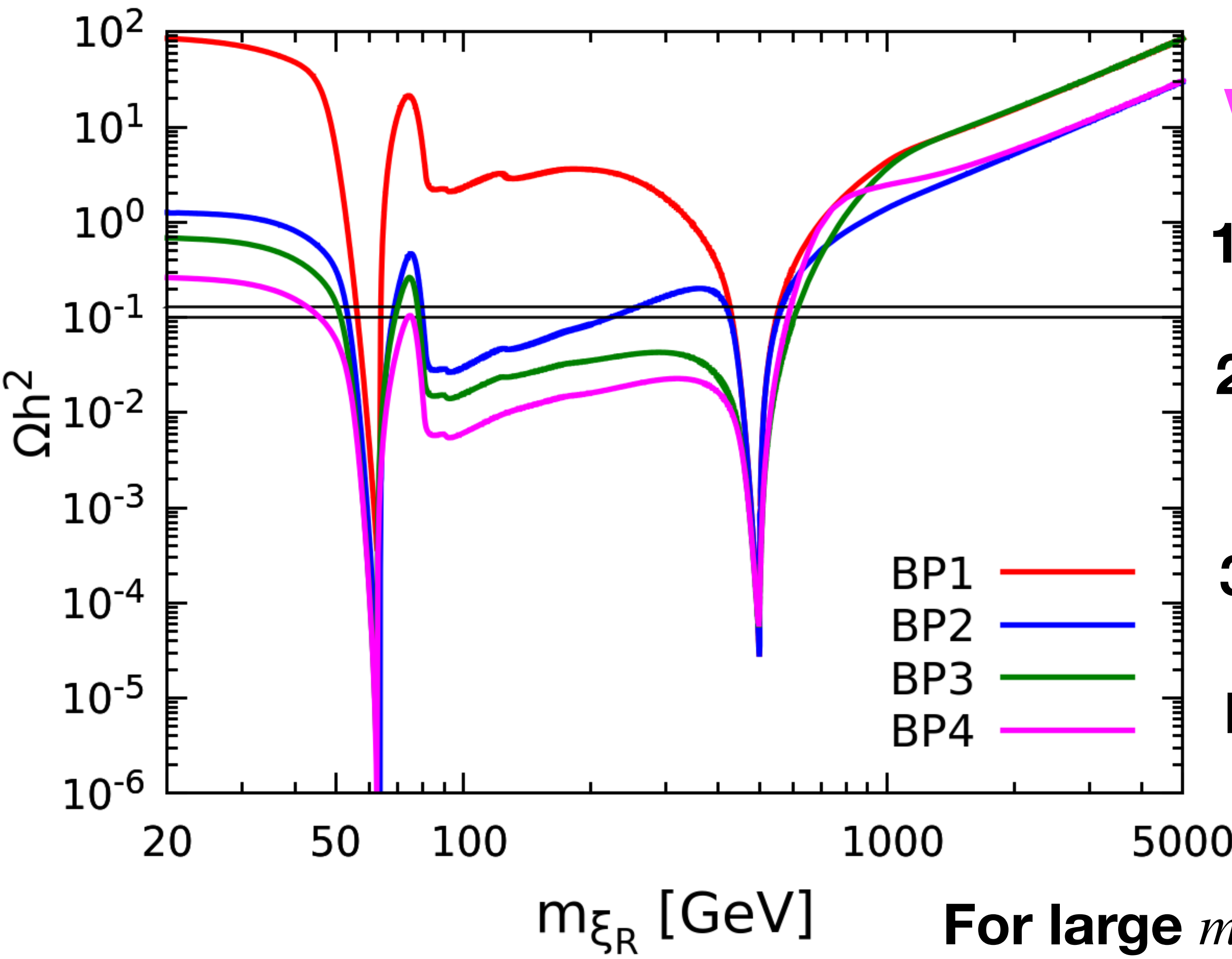
In case of small λ_5, annihilation to J depends on $\sin\theta$ and $\lambda_{\xi\sigma}$

Relic density and direct detection

BP1: $\sin\theta = 0,\ \lambda_{\Phi\xi} = 0.01,$ **BP2:** $\sin\theta = 0,\ \lambda_{\Phi\xi} = 0.1.$

BP3: $\sin\theta = 0.1,\ \lambda_{\Phi\xi} = 0.01,$ **BP4:** $\sin\theta = 0.1,\ \lambda_{\Phi\xi} = 0.1.$

Fix: $m_H = 1$ **TeV**, $v_\sigma = 3$ **TeV**, $\lambda_\xi = 0.1$ **and** $\lambda_{\xi\sigma} = 0.1$



Various features of relic density:

1st dip at $m_{\xi_R} \sim m_h/2$: **s-channel** h **exchange**

2nd dip: for $m_{\xi_R} > 80$ **GeV**, $\xi_R\xi_R \to WW, ZZ$ **are important**

3rd dip at $m_{\xi_R} \sim m_H/2$: **s-channel** H **exchange**

For large m_{ξ_R}, $<\sigma v> \propto \dfrac{1}{m_{\xi_R}^2} \Rightarrow \Omega h^2$ **increases**

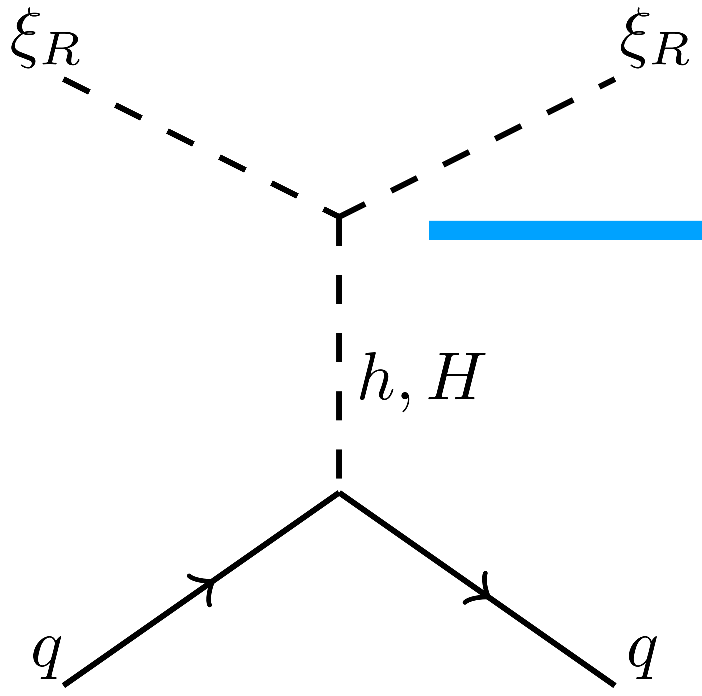
For large m_{ξ_R}, $\xi_R\xi_R \to WW, ZZ$ **through Higgs dominates, and depends on** $\lambda_{\Phi\xi}$ **(fixed** $\lambda_{\xi\sigma}, \sin\theta \sim 0$)

Hence, BP1,BP3 and BP2,BP4 coincides

coannihiliation with ξ_I **if mass splitting is small**

Sizeable annihilation to JJ **depending on the mixed quartic couplings**

Direct Detection



$$\lambda_{h\xi_R\xi_R} = \lambda_{\Phi\xi} v_\Phi \cos\theta + (\lambda_{\xi\sigma} + \lambda_5) v_\sigma \sin\theta$$

$$\lambda_{H\xi_R\xi_R} = -\lambda_{\Phi\xi} v_\Phi \sin\theta + (\lambda_{\xi\sigma} + \lambda_5) v_\sigma \cos\theta$$

$$\sigma^{\mathbf{SI}} = \frac{\mu_N^2 m_N^2 f_N^2}{4\pi m_{\xi_R}^2 v_\Phi^2} \left(\frac{\lambda_{h\xi_R\xi_R}}{m_h^2} \cos\theta - \frac{\lambda_{H\xi_R\xi_R}}{m_H^2} \sin\theta \right)^2$$

The relative sign between the h and H contributions as:

$$h_{\mathbf{SM}} \to \cos\theta\, h - \sin\theta\, H$$

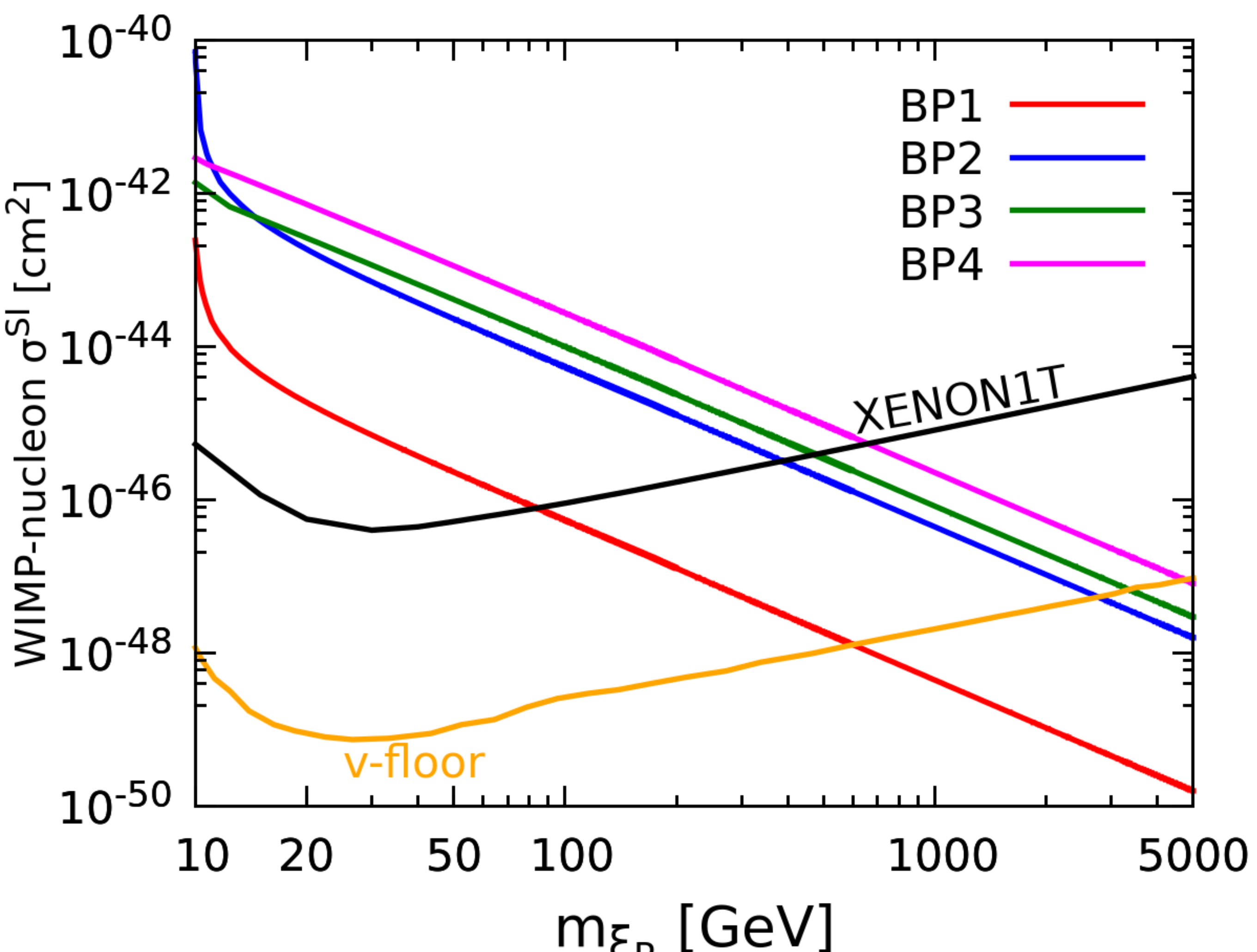
Possibility of destructive interference:

DD can be very small

BP1: $\sin\theta = 0,\ \lambda_{\Phi\xi} = 0.01,$ **BP2:** $\sin\theta = 0,\ \lambda_{\Phi\xi} = 0.1.$

BP3: $\sin\theta = 0.1,\ \lambda_{\Phi\xi} = 0.01,$ **BP4:** $\sin\theta = 0.1,\ \lambda_{\Phi\xi} = 0.1.$

Difficult to obtain low mass dark matter

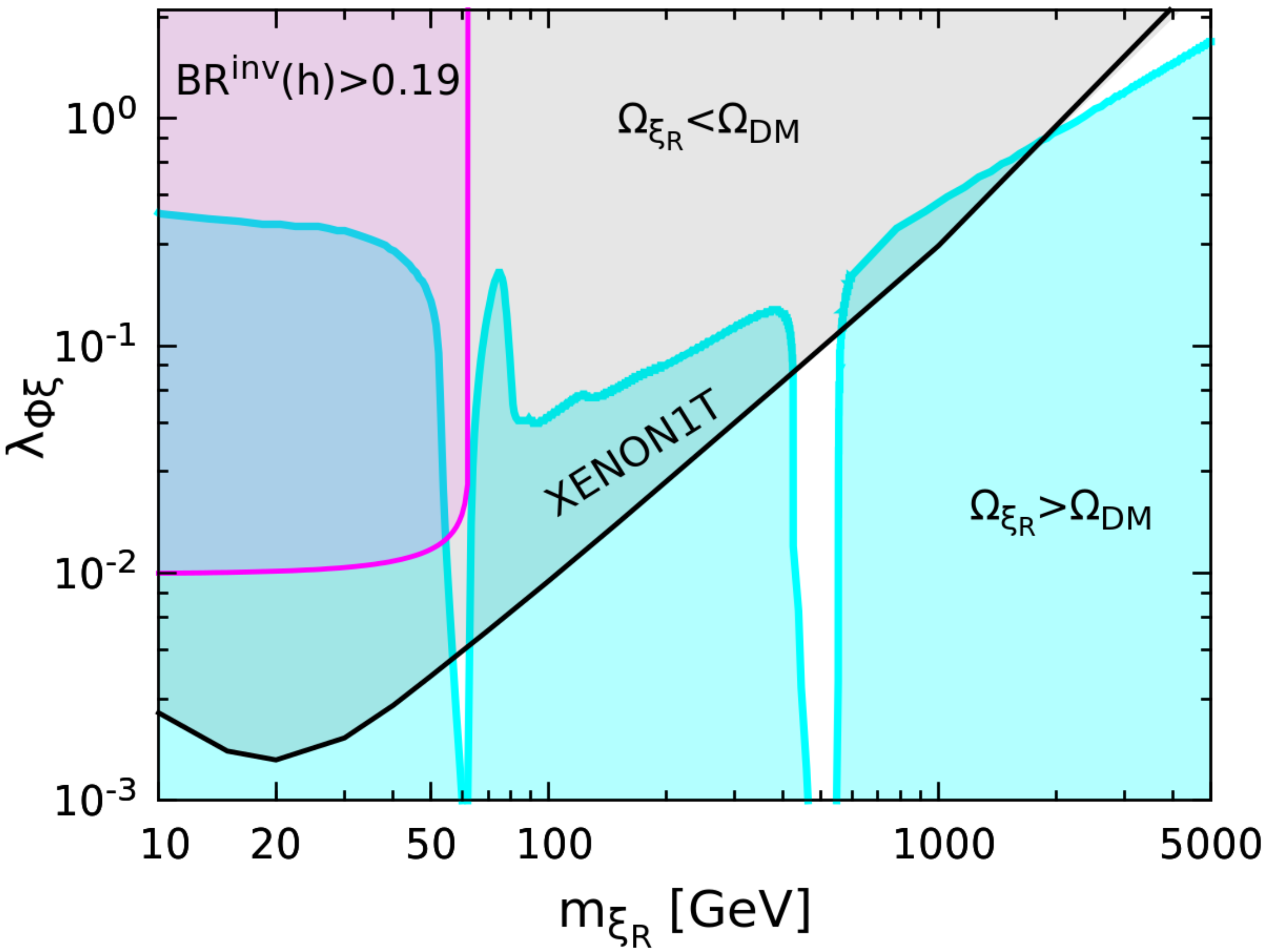


Compilation of relic density, DD and invisible Higgs decay

Fix: $m_H = 1$ **TeV**, $\sin\theta = 0,\ v_\sigma = 3$ **TeV**, $\lambda_\xi = 0.1,\ \lambda_{\xi\sigma} = 0.1$

Free parameter: $\lambda_{\Phi\xi}$

Correct relic: Along the cyan line



$0\nu\beta\beta$ and LFV

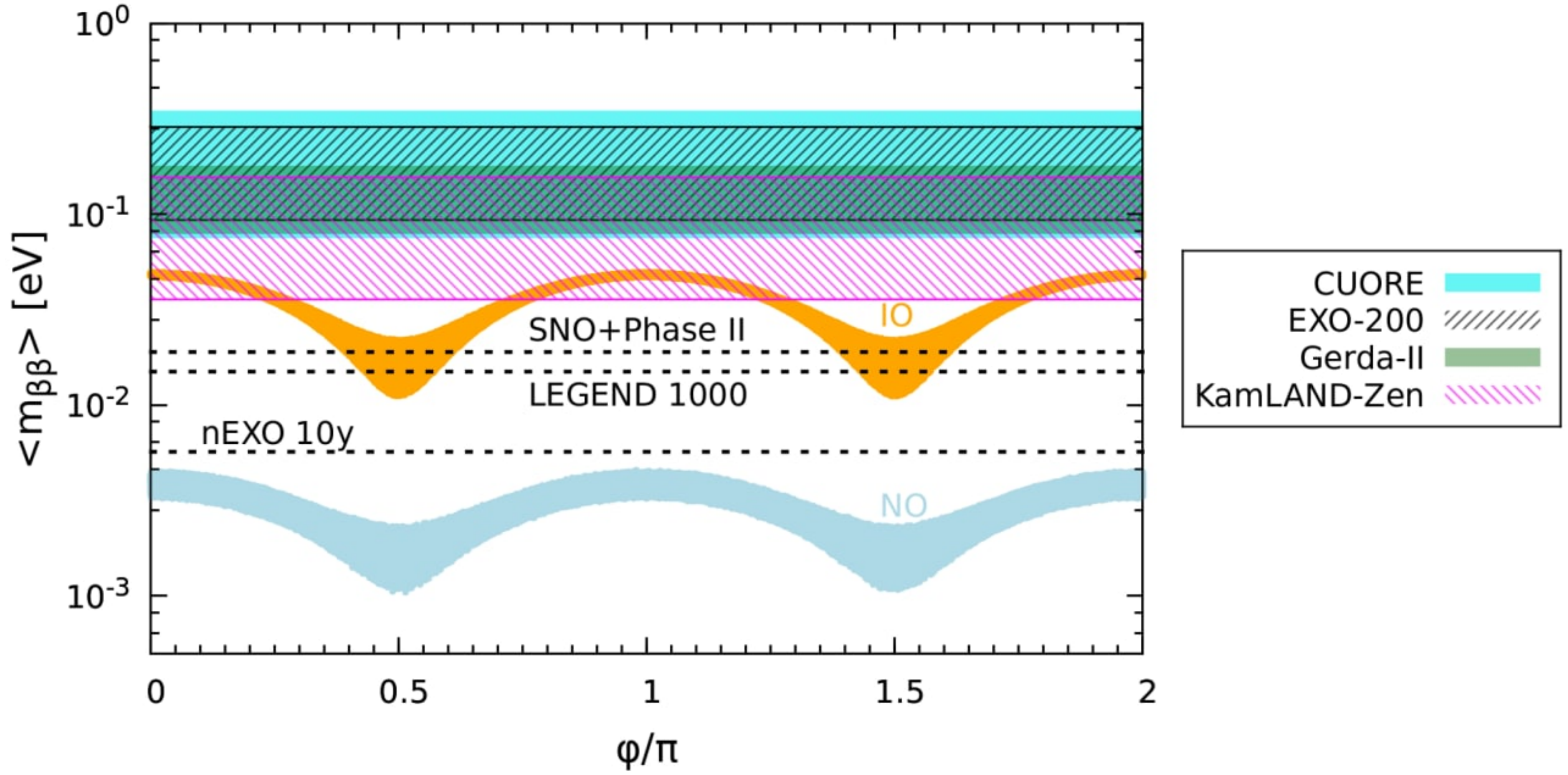
$$< m_{\beta\beta} > = \left| \sum_j U^2_{\nu,ej} m_j \right| = \left| \cos\theta_{12}^2 \cos\theta_{13}^2 m_1 + \sin\theta_{12}^2 \cos\theta_{13}^2 m_2 e^{2i\phi_{12}} + \sin\theta_{13}^2 m_3 e^{2i\phi_{13}} \right|$$

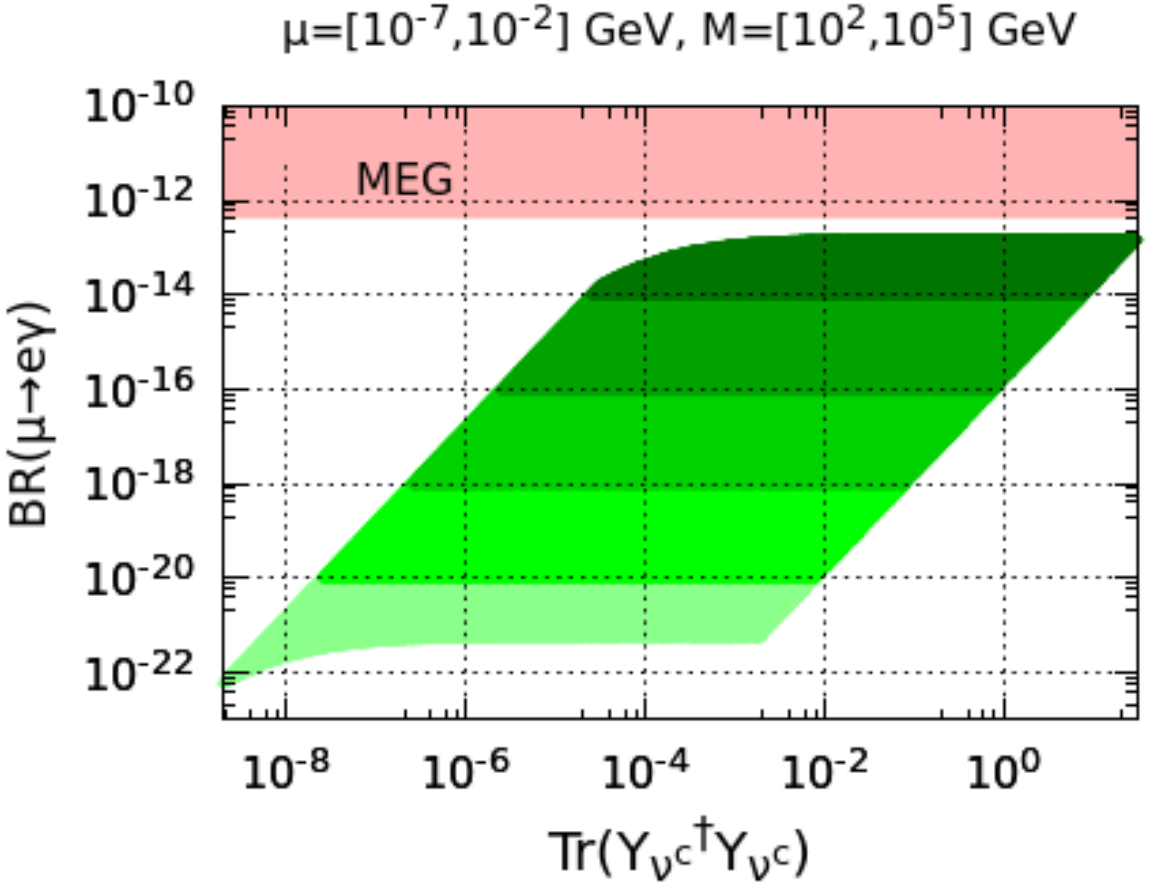
With two copies of ν^c, S and f

$m_{\text{lightest}} = 0$

As $m_1 = 0$, only one Majorana phase $\phi \equiv \phi_{12} - \phi_{13}$ $\Rightarrow$ $0\nu\beta\beta$ has lower limit

This is the consequence of incomplete seesaw





Source of LFV: $Y_{\nu^c} \bar{L} i \sigma_2 H^* \nu^c$

$$\textbf{BR}(\ell_i \to \ell_j \gamma) = \frac{\alpha_w^3 s_w^2}{256\pi^2} \left(\frac{m_{\ell_i}}{M_W}\right)^4 \left(\frac{m_{\ell_i}}{\Gamma_{\ell_i}}\right) \left| \frac{v_H^2}{2M^2} (Y_{\nu^c} Y_{\nu^c}^\dagger)_{ji} G_\gamma \left(\frac{M^2}{M_W^2}\right) \right|^2$$

$$Y_{\nu^c} = \frac{\sqrt{2}}{v_\Phi} U^\dagger_{\text{lep}} \sqrt{\widehat{\mathscr{M}}_\nu} R \sqrt{\mathscr{M}_R} \quad \textbf{with } \mathscr{M}_R^{-1} = M^{-1} \mu M^{-1T}$$

Summary

SM lacks neutrino mass and dark matter. New physics is required.

The scotogenic model is a very economical scenario for neutrino masses that includes a dark matter candidate

We have studied a variant of scotogenic model in the framework of low-scale seesaw

generation of μ parameter through scotogenic loop

We have studied the scalar dark matter. The nature of dark matter is different from doublet η of scotogenic model

Presence of majoron modifies the invisible Higgs decay

Nature of dark matter is not excatly same as complex scalar dark matter due to the presence of majoron J

Thank You for your attention

Cubic and quartic couplings

λ_{abc}	Couplings in terms of Lagrangian parameter
$h\xi_R\xi_R$	$(\lambda_{\xi\sigma}+\lambda_5)v_\sigma \sin\theta + \lambda_{\Phi\xi}v_\Phi \cos\theta$
$H\xi_R\xi_R$	$(\lambda_{\xi\sigma}+\lambda_5)v_\sigma \cos\theta - \lambda_{\Phi\xi}v_\Phi \sin\theta$
$h\xi_I\xi_I$	$(\lambda_{\xi\sigma}-\lambda_5)v_\sigma \sin\theta + \lambda_{\Phi\xi}v_\Phi \cos\theta$
$H\xi_I\xi_I$	$(\lambda_{\xi\sigma}-\lambda_5)v_\sigma \cos\theta - \lambda_{\Phi\xi}v_\Phi \sin\theta$
$\xi_I\xi_R J$	$\lambda_5 v_\sigma$
hJJ	$m_h^2 \sin\theta / v_\sigma$
HJJ	$m_H^2 \cos\theta / v_\sigma$

λ_{abcd}	Couplings in terms of Lagrangian parameter
$hh\xi_R\xi_R$	$\lambda_{\Phi\xi}\cos^2\theta + (\lambda_{\xi\sigma}+\lambda_5)\sin^2\theta$
$hh\xi_I\xi_I$	$\lambda_{\Phi\xi}\cos^2\theta + (\lambda_{\xi\sigma}-\lambda_5)\sin^2\theta$
$HH\xi_R\xi_R$	$\lambda_{\Phi\xi}\sin^2\theta + (\lambda_{\xi\sigma}+\lambda_5)\cos^2\theta$
$HH\xi_I\xi_I$	$\lambda_{\Phi\xi}\sin^2\theta + (\lambda_{\xi\sigma}-\lambda_5)\cos^2\theta$
$JJ\xi_R\xi_R$	$\lambda_{\xi\sigma}-\lambda_5$
$JJ\xi_I\xi_I$	$\lambda_{\xi\sigma}+\lambda_5$