The Scoto-seesaw model: Dark matter and Stability

Sanjoy Mandal

IFIC, Valencia

Universitat de Valencia

Email: smandal@ific.uv.es

https://www.astroparticles.es/members/sanjoy-mandal/

Talk is based on PLB 819(2021) 136458

In collaboration with Jose W. F. Valle and R. Srivastava

TAUP 2021, Valencia, Spain

26 August - 3 September, 2021

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)

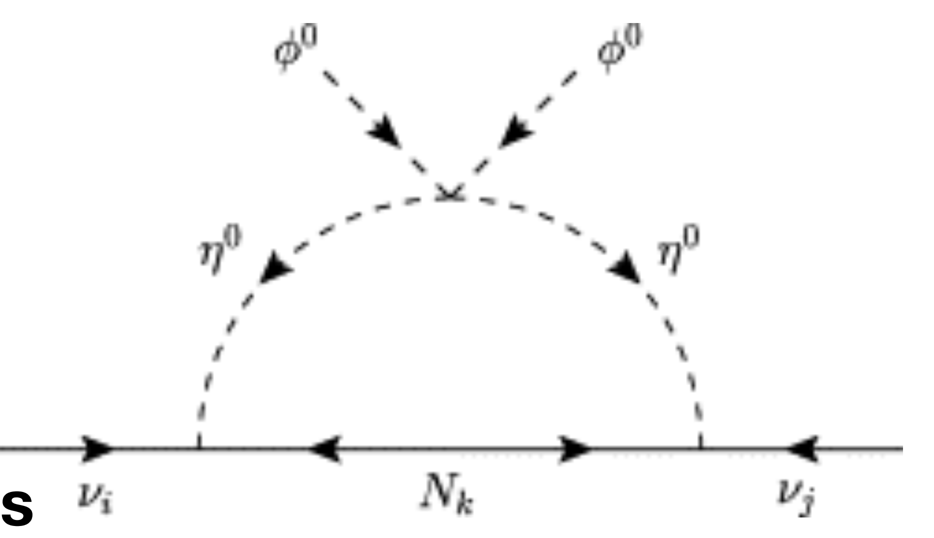
Is there any connection between dark matter and neutrino masses?

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

Add: $\mathbb{Z}_2 -$ odd fields: N_i (singlet) and η (doublet)

DM: either lightest of N_i or Re(η^0)/Im(η^0)

Dark particles plays vital role to generate neutrino masses



Simplest scot-seesaw mechanism

The ratio of squared solar-to-atmospheric mass splitting is:

arXiv:2006.11237, P.F. De Salas et al.

$$\text{NO: } \frac{\Delta m^2_{\text{SOL}}}{\Delta m^2_{\text{ATM}}} = 0.0294^{+0.0027}_{-0.0023}, \quad \text{IO: } \frac{\Delta m^2_{\text{SOL}}}{\Delta m^2_{\text{ATM}}} = 0.0306^{+0.0028}_{-0.0025}.$$

⇒ two mass scale arise from two very different mechanisms?

Solution: generate Δm^2_{ATM} at Tree level and Δm^2_{SOL} at one loop

Scoto-seesaw: Scotogenic extension of (3,1) seesaw, arXiv: 1807.11447, Valle et al.

Additional Fields: two singlet fermions $N(\mathbb{Z}_2 = +1)$, $f(\mathbb{Z}_2 = -1)$ and one bidoublet $\eta(\mathbb{Z}_2 = -1)$

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

Full Yukawa: $\mathscr{L}_{\text{Yuk}} = \mathscr{L}_{\text{SM}} + \mathscr{L}_{\text{ATM}} + \mathscr{L}_{\text{DM,SOL}}$

$$\mathscr{L}_{\text{ATM}} = -Y^a_N \bar{L}^a \tilde{H} N + \frac{1}{2} M_N \overline{N^c} N + h.c,$$

$$\mathscr{M}^{ab}_\nu = \begin{pmatrix} 0 & 0 & 0 & \frac{Y^1_N v}{\sqrt{2}} \\ 0 & 0 & 0 & \frac{Y^2_N v}{\sqrt{2}} \\ 0 & 0 & 0 & \frac{Y^3_N v}{\sqrt{2}} \\ \frac{Y^1_N v}{\sqrt{2}} & \frac{Y^2_N v}{\sqrt{2}} & \frac{Y^3_N v}{\sqrt{2}} & M_N \end{pmatrix}$$

⇒ **gives type-I seesaw neutrino mass** (Δm^2_{ATM})

$$\mathscr{M}_{\nu\text{TREE}} = -\frac{v^2}{2M_N} Y^a_N Y^b_N$$

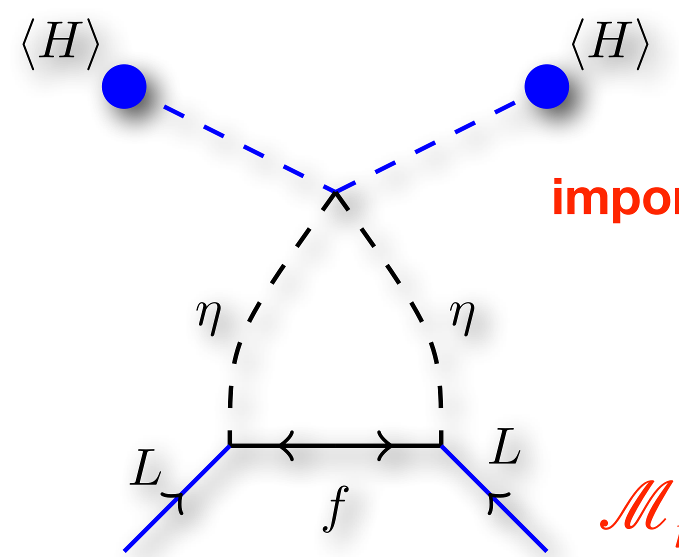
$\mathbb{Z}_2$ symmetry: f or η could be DM

DM+Solar Sector: $\mathscr{L}_{\text{DM,SOL}} = Y_f^a \bar{L}^a \tilde{\eta}\, f + \frac{1}{2} M_f \overline{f^c} f + h.c.$

Due to $\mathbb{Z}_2$ symmetry $<\eta> = 0 \Rightarrow$ **no solar mass at tree-level**

Scalar sector:

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



important terms: $Y_f^a \bar{L}^a \tilde{\eta} f,\ \frac{\lambda_5}{2}\left((H^\dagger \eta)^2 + h.c.\right)$

$$m_{\eta^R}^2 = m_\eta^2 + \frac{1}{2}\left(\lambda_3 + \lambda_4 + \lambda_5\right) v^2$$

$$m_{\eta^I}^2 = m_\eta^2 + \frac{1}{2}\left(\lambda_3 + \lambda_4 - \lambda_5\right) v^2$$

$$m_{\eta^+}^2 = m_\eta^2 + \frac{1}{2}\lambda_3 v^2 .$$

$$\mathscr{M}_\nu \sim \mathscr{F}(m_{\eta^R}, m_{\eta^I}, M_f) M_f Y_f^a Y_f^b$$

$m_{\eta^R}^2 - m_{\eta^I}^2$ **depends only on the parameter** λ_5

$$\mathscr{F}(m_{\eta^R}, m_{\eta^I}, M_f) = \frac{1}{32\pi^2}\left(\frac{m_{\eta^R}^2 \log\left(M_f^2/m_{\eta^R}^2\right)}{M_f^2 - m_{\eta^R}^2} - \frac{m_{\eta^I}^2 \log\left(M_f^2/m_{\eta^I}^2\right)}{M_f^2 - m_{\eta^I}^2}\right)$$

$\Rightarrow$ **This depends on** $\delta = m_{\eta^R}^2 - m_{\eta^I}^2 \propto \lambda_5$

$$\mathscr{M}_{\nu\text{TOT}}^{ab} = -\frac{v^2}{2M_N} Y_N^a Y_N^b + \mathscr{F}(m_{\eta^R}, m_{\eta^I}, M_f) M_f Y_f^a Y_f^b$$

$\lambda_5 = 0 \Rightarrow \#L$ **is restored in dark sector**

With the approximation $M_f^2, m_{\eta^R}^2, M_f^2 - m_{\eta^R}^2 \gg \lambda_5 v^2$

$$\Delta m^2_{\textsf{ATM}} = \left(\frac{v^2}{2M_N}\mathbb{Y}_N^2\right)^2, \quad \Delta m^2_{\textsf{SOL}} \approx \left(\frac{1}{32\pi^2}\right)^2 \left(\frac{\lambda_5 v^2}{M_f^2 - m_{\eta^R}^2} M_f \mathbb{Y}_f^2\right)^2$$

$\mathbb{Y}_\ell^2 = (Y_\ell^e)^2 + (Y_\ell^\mu)^2 + (Y_\ell^\tau)^2$ **for** $\ell = N, f$.

$$\frac{\Delta m^2_{\textsf{SOL}}}{\Delta m^2_{\textsf{ATM}}} \approx \left(\frac{1}{16\pi^2}\right)^2 \left(\lambda_5 \frac{M_N M_f}{M_f^2 - m_{\eta^R}^2}\right)^2 \left(\frac{\mathbb{Y}_f^2}{\mathbb{Y}_N^2}\right)^2$$

easily fit solar and atmospheric scale with adequate small value of λ_5

BP1: $M_N \sim 10^{14}$ **GeV**, $M_f \sim 10^{12}$ **GeV**, $m_{\eta^R} \sim 10^3$ **GeV**, $\mathbb{Y}_N \sim 0.4$, $\mathbb{Y}_f \sim 0.4$

BP2: $M_N \sim 10^{12}$ **GeV**, $M_f \sim 10^4$ **GeV**, $m_{\eta^R} \sim 10^3$ **GeV**, $\mathbb{Y}_N \sim 0.1$, $\mathbb{Y}_f \sim 10^{-4}$.

BP3: $M_N \sim 10^{14}$**GeV**, $M_f \sim 10^5$ **GeV**, $m_{\eta^R} \sim 10^3$ **GeV**, $\mathbb{Y}_N \sim 0.4$, $\mathbb{Y}_f \sim 10^{-4}$

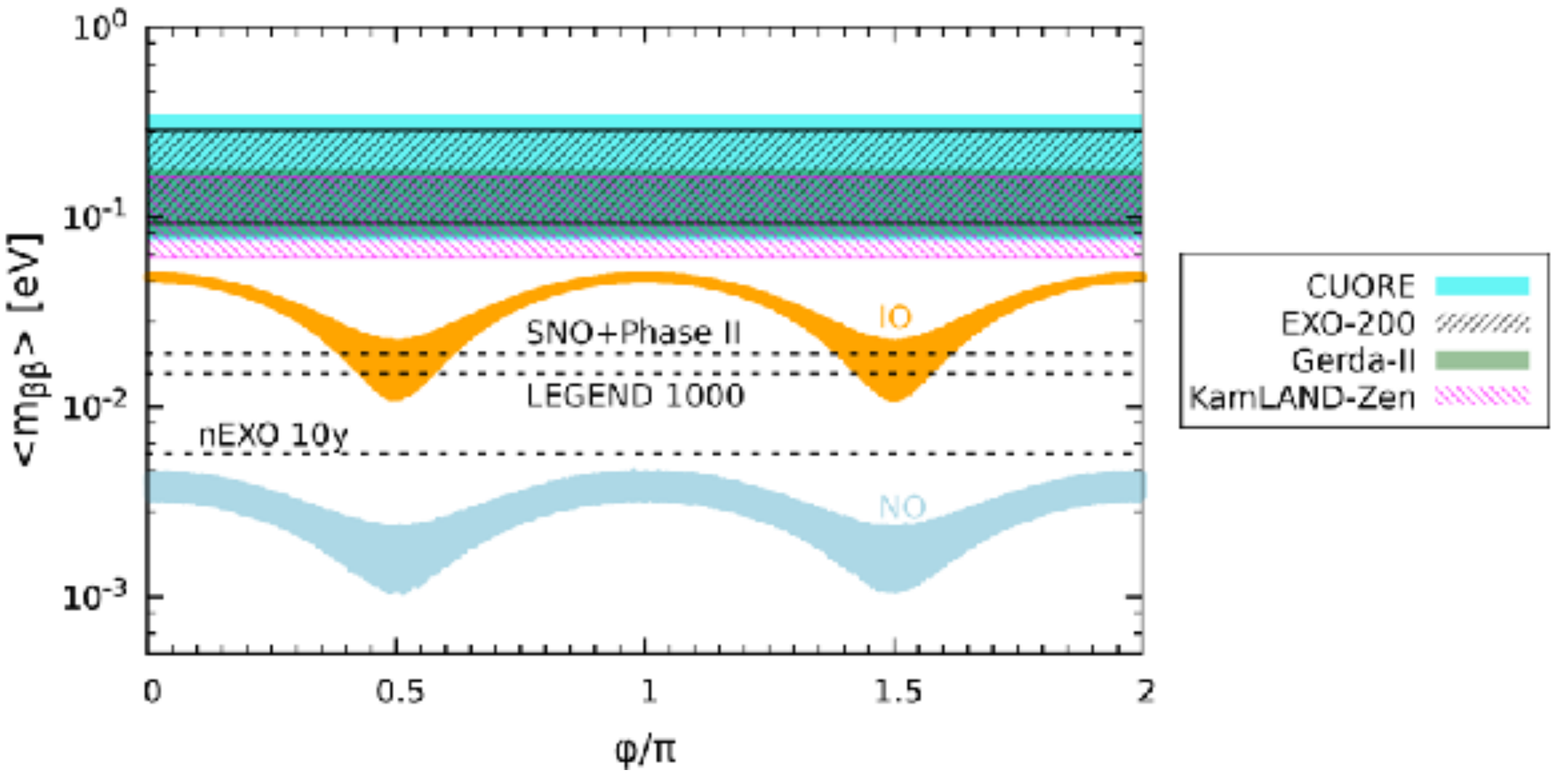
BP4: $M_N \sim 10^6$ **GeV**, $M_f \sim 10^6$ **GeV**, $m_{\eta^R} \sim 10^3$ **GeV**, $\mathbb{Y}_N \sim 10^{-5}$, $\mathbb{Y}_f \sim 10^{-4}$

Many more possibilities………….

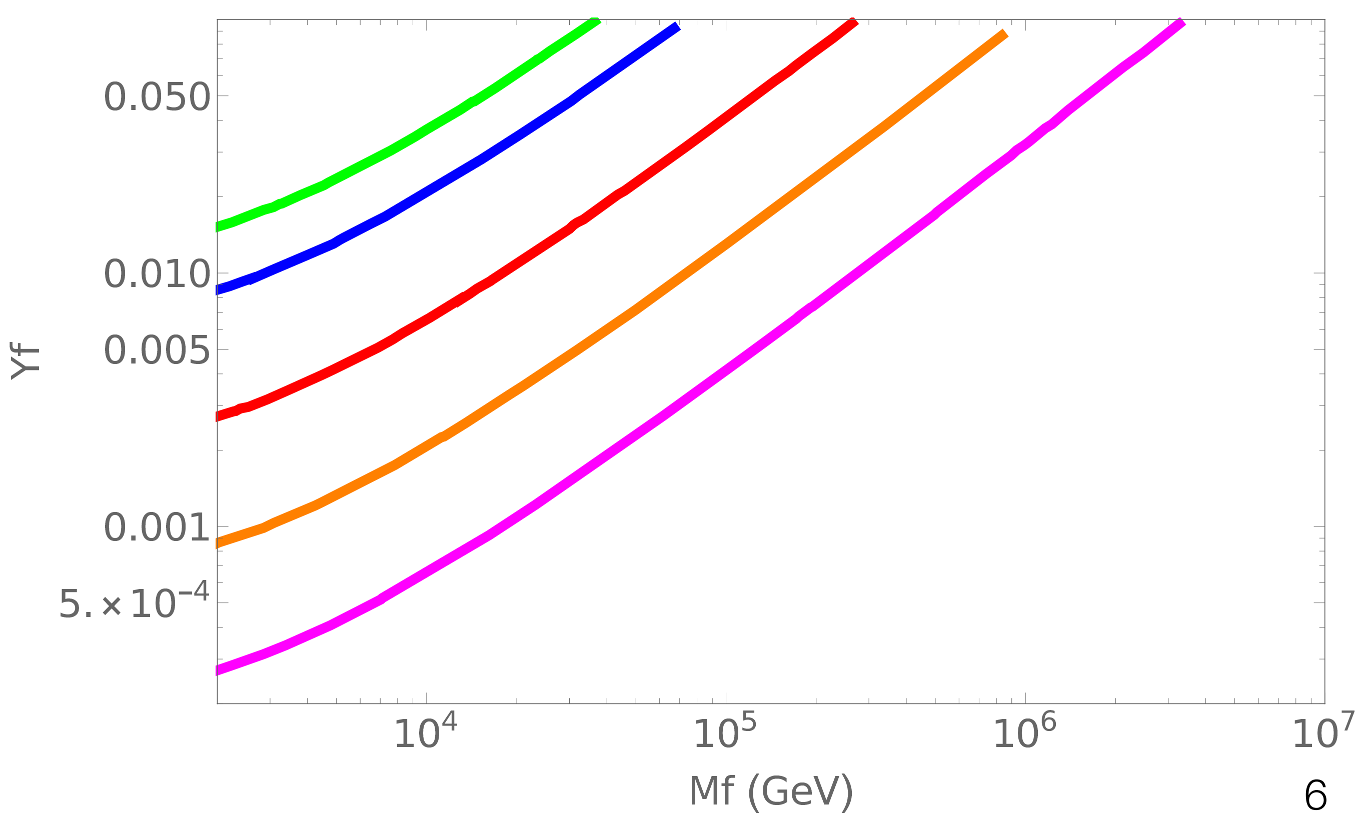
$m_{\eta^R} \sim 10^3$ **GeV: consistent WIMP dark matter, can be produced in collider**

$0\nu\beta\beta$ and LFV

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



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



Source of LFV: arises from Y_f (scotogenic contribution) and Y_N (seesaw contribution)

Dominant contribution: Scotogenic

- BR(μ→eγ) ~ 1.0×10^−15
- BR(μ→eγ) ~ 1.0×10^−16
- BR(μ→eγ) ~ 1.0×10^−18
- BR(μ→eγ) ~ 1.0×10^−20
- BR(μ→eγ) ~ 1.0×10^−22

DARK MATTER

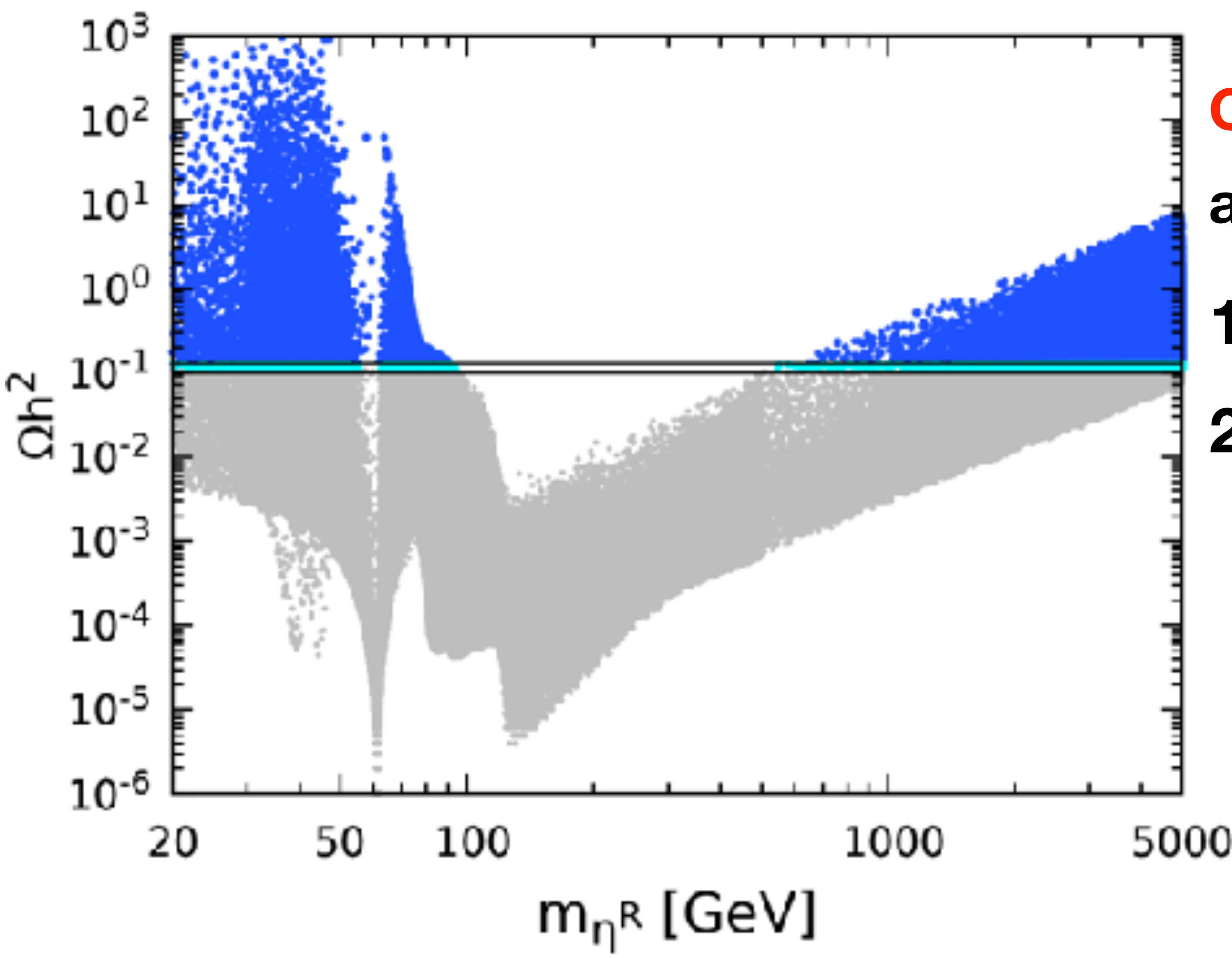
$\mathbb{Z}_2$ **symmetry: fermionic DM** (f) **or scalar DM** $(\eta^{R/I})$

In case of fermionic DM f, Y_f **plays the role in both LFV and DM annihiliation**

Scalar DM: η^R **if** $\lambda_5 < 0$ **or** η^I **if** $\lambda_5 > 0$ $(m^2_{\eta^R} - m^2_{\eta^I} = \lambda_5 v^2)$

Parameters	Range
m^2_η	$[100^2, 5000^2]$ (GeV^2)
λ_3	$[10^{-5}, 1]$
λ_4	$[10^{-5}, 1]$
$\|\lambda_5\|$	$[10^{-5}, 10^{-3}]$

Advantage: DM and LFV source is different



Correct Relic: $m_{\eta^R} < 50$ **GeV**, 70 **GeV** $< m_{\eta^R} < 100$ **GeV and** $m_{\eta^R} > 550$ **GeV**.

1st dip at $m^R_\eta \sim M_Z/2$: **s-channel** Z **exchange**

2nd dip at $m^R_\eta \sim m_h/2$: **s-channel** h **exchange**

2nd dip is more efficient as Z-mediation is momentum suppressed

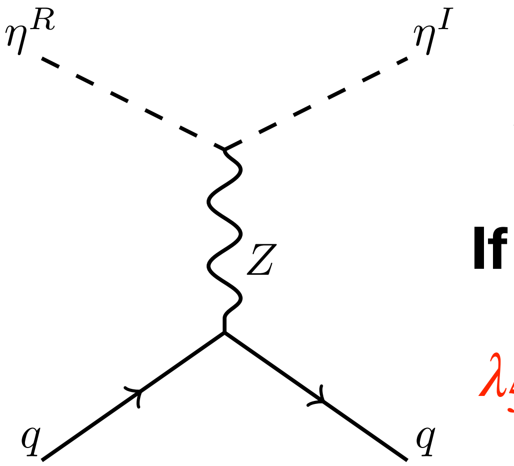
3rd dip: for $m_{\eta^R} > 80$ **GeV**, $\eta^R\eta^R \to WW, ZZ$ **via quartic couplings**

For $m^R_\eta > m_h, \eta^R\eta^R \to hh$ **and for** $m^R_\eta > m_t, \eta^R\eta^R \to t\bar{t}$ **opens up**

For large m^R_η, $< \sigma v > \propto \dfrac{1}{m^2_{\eta^R}} \Rightarrow \Omega h^2$ **increases**

coannihiliation with η^I **and** $\eta^\pm$ **if mass splitting is small**

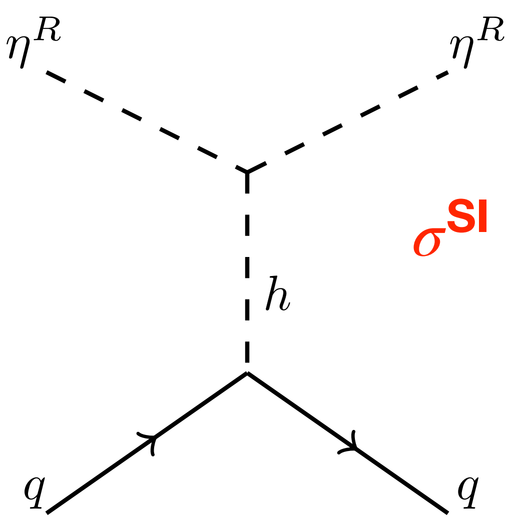
Direct detection



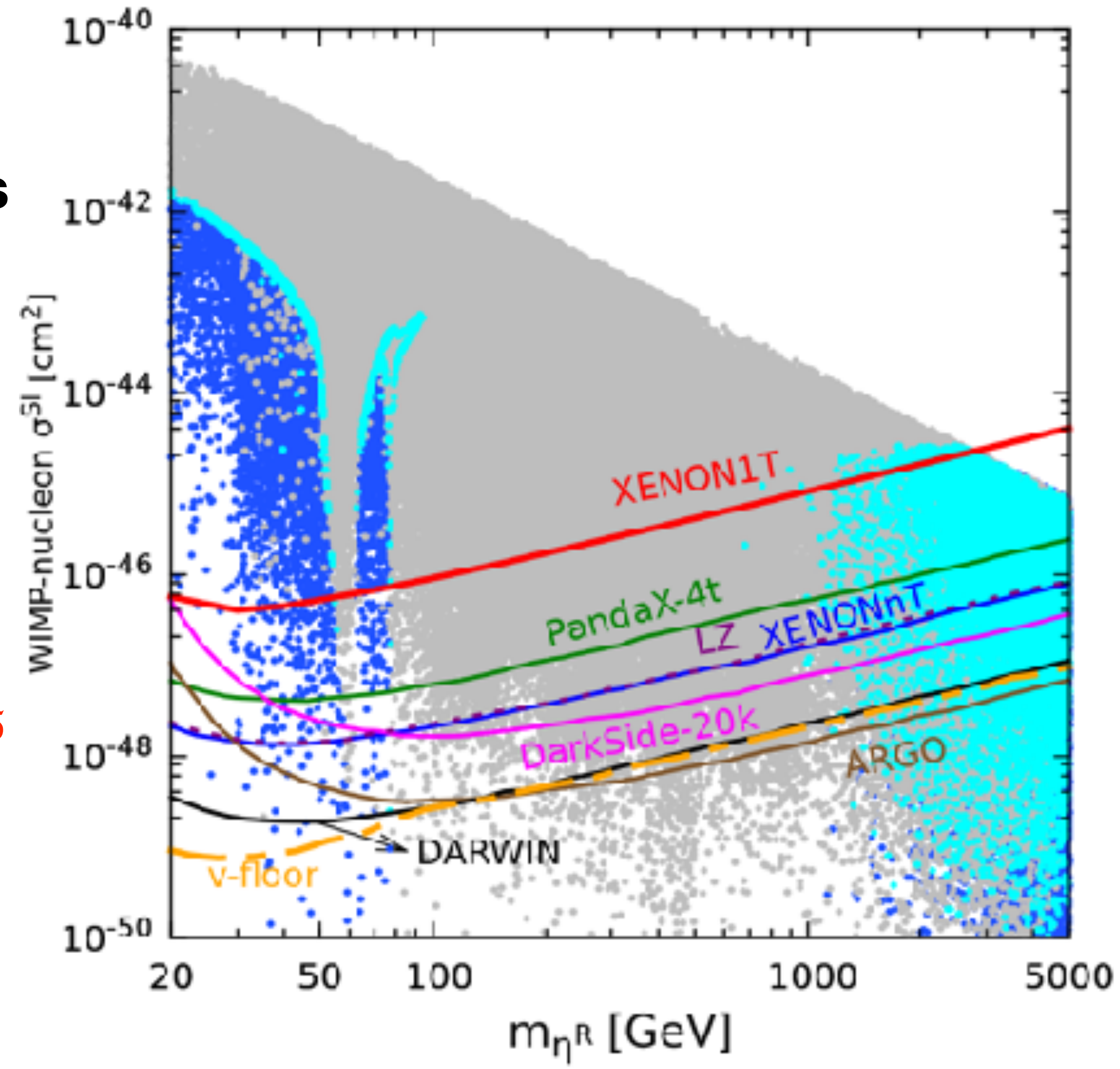
η **has non-zero hypercharge**

If $m_{\eta^R} = m_{\eta^I}$ **exceeds XENON1T DD limits**

$\lambda_5 \neq 0 \Rightarrow$ **inelastic cross section**



$$\sigma^{\text{SI}} = \frac{\lambda_{345}^2}{4\pi m_h^4}\frac{m_N^4 f_N^2}{(m_{\eta^R} + m_N)^2}, \; \lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$$



Collider Constraints:

LEP-I measurements of W, Z **decay widths:** $m_{\eta^R} + m_{\eta^I}, \, 2m_{\eta^\pm} > m_Z$ **and** $m_{\eta^R/\eta^I} + m_{\eta^\pm} > m_W$

Phys. Rev. D 76 (2007) 095011

Direct limit from LEP-II: $m_{\eta^R} > 80$ **GeV and** $m_\eta^\pm > m_W$.   **arXiv: 0810.3924**

Hence lower DM mass region is in conflict with XENON1T (arXiv: 2007.08796) and LEP data

Constraint from LHC

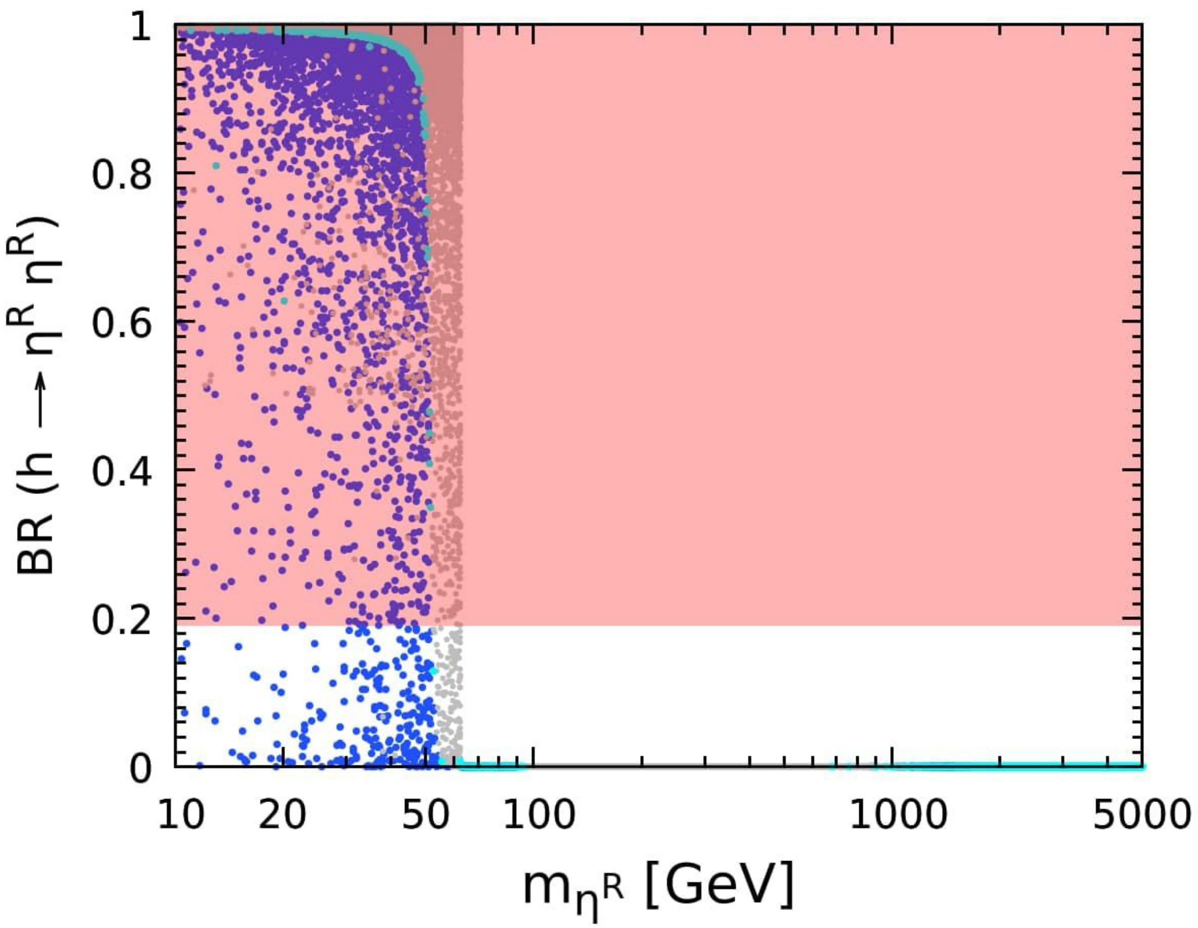
Invisible decay mode: $\Gamma(h \to \eta^R \eta^R) = \frac{v^2 \lambda_{345}^2}{32\pi m_h} \sqrt{1 - \frac{4m_{\eta^R}^2}{m_h^2}}$

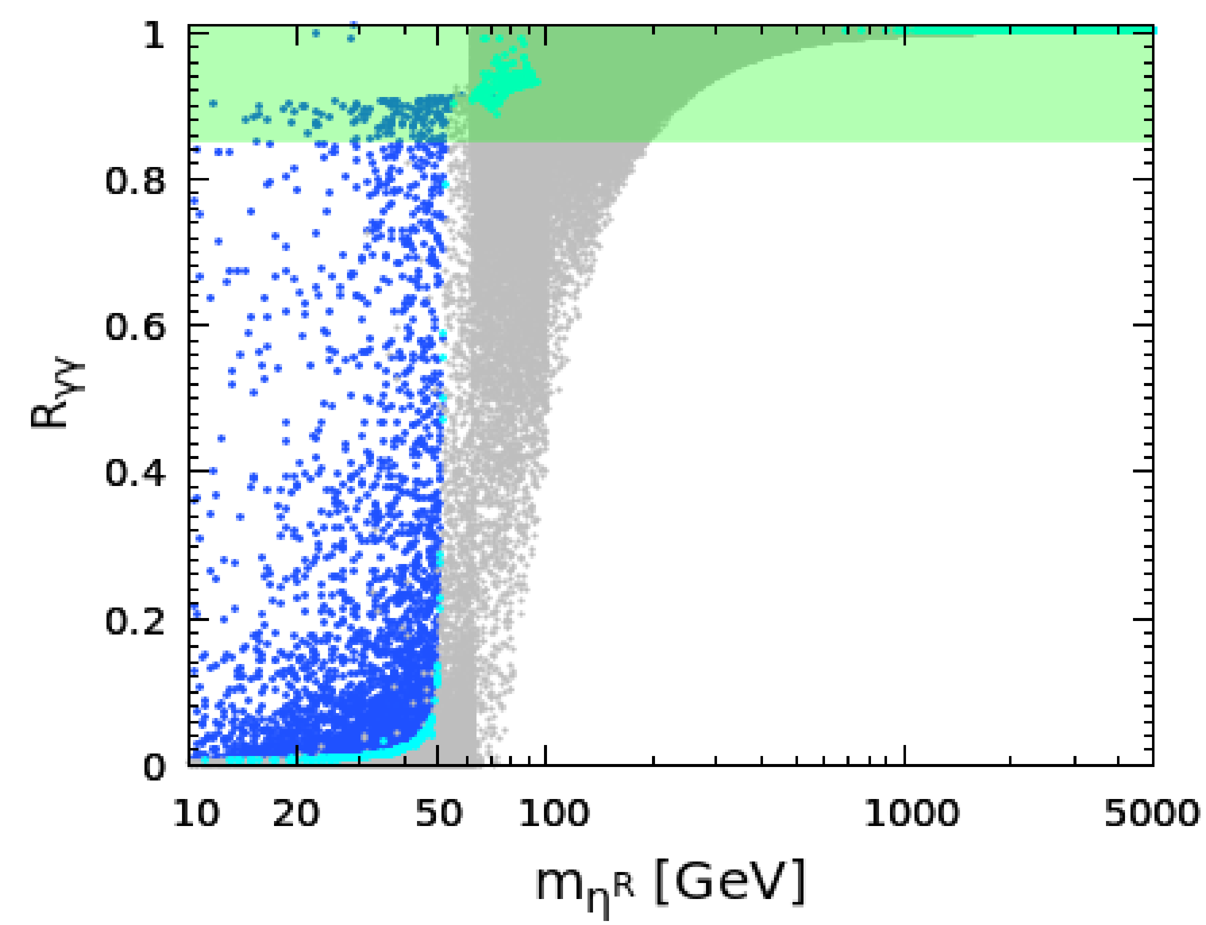
CMS Experiment: $\textbf{BR}(h \to \textbf{Inv}) \leq 0.19$ arXiv: 1809.05937

h **couples to charged** $\eta^\pm$: $h \to \gamma\gamma$ $\textbf{BR}(h \to \gamma\gamma)^{\textbf{SM}} \approx 2.27 \times 10^{-3}$

Deviation from SM: $R_{\gamma\gamma} = \frac{\textbf{BR}(h \to \gamma\gamma)}{\textbf{BR}(h \to \gamma\gamma)^{\textbf{SM}}}$. **13 TeV ATLAS data:** $R_{\gamma\gamma}^{\textbf{exp}} = 0.99^{+0.15}_{-0.14}$

arXiv: 1802.04146





Intermediate mass region is allowed from LHC data

Electroweak vacuum stability

quartic form: $V^{(4)} = \lambda(H^\dagger H)^2 + \lambda_\eta(\eta^\dagger\eta)^2 + \lambda_3(H^\dagger H)(\eta^\dagger\eta) + \lambda_4(H^\dagger\eta)(\eta^\dagger H) + \frac{\lambda_5}{2}\left((H^\dagger\eta)^2 + h.c.\right)$

BFB: $\lambda(\mu) > 0,\ \lambda_\eta(\mu) > 0, \lambda_A \equiv \lambda_3(\mu) + \sqrt{4\lambda(\mu)\lambda_\eta(\mu)} > 0, \lambda_B \equiv \lambda_3(\mu) + \lambda_4(\mu) + \sqrt{4\lambda(\mu)\lambda_\eta(\mu)} - |\lambda_5(\mu)| > 0.$

$\Rightarrow$ **this should be valid at each and every energy scale** μ .

Perturbativity: $\lambda_i(\mu) \leq 4\pi$

$$\beta^{(1)}_\lambda = +\frac{27}{200}g_1^4 + \frac{9}{20}g_1^2 g_2^2 + \frac{9}{8}g_2^4 + 2\lambda_3^2 + 2\lambda_3\lambda_4 + \lambda_4^2 + \lambda_5^2 - \frac{9}{5}g_1^2\lambda - 9g_2^2\lambda + 24\lambda^2$$
$$+12\lambda y_t^2 + 4\lambda \mathbf{Tr}\left(Y_N Y_N^\dagger\right) - 6y_t^4 - 2\mathbf{Tr}\left(Y_N Y_N^\dagger Y_N Y_N^\dagger\right)$$

$$\beta^{(1)}_{\lambda_\eta} = +\frac{27}{200}g_1^4 + \frac{9}{8}g_2^4 + 2\lambda_3^2 + 2\lambda_3\lambda_4 + \lambda_4^2 + \lambda_5^2 + \frac{9}{20}g_1^2\left(-4\lambda_\eta + g_2^2\right) - 9g_2^2\lambda_\eta + 24\lambda_\eta^2$$
$$+4\lambda_\eta \mathbf{Tr}(Y_f Y_f^\dagger) - 2\mathbf{Tr}(\left(Y_f Y_f^\dagger Y_f Y_f^\dagger\right))$$

Negative contribution from Yukawa couplings $Y_N,\ Y_f$

positive contribution from mixed quartic couplings

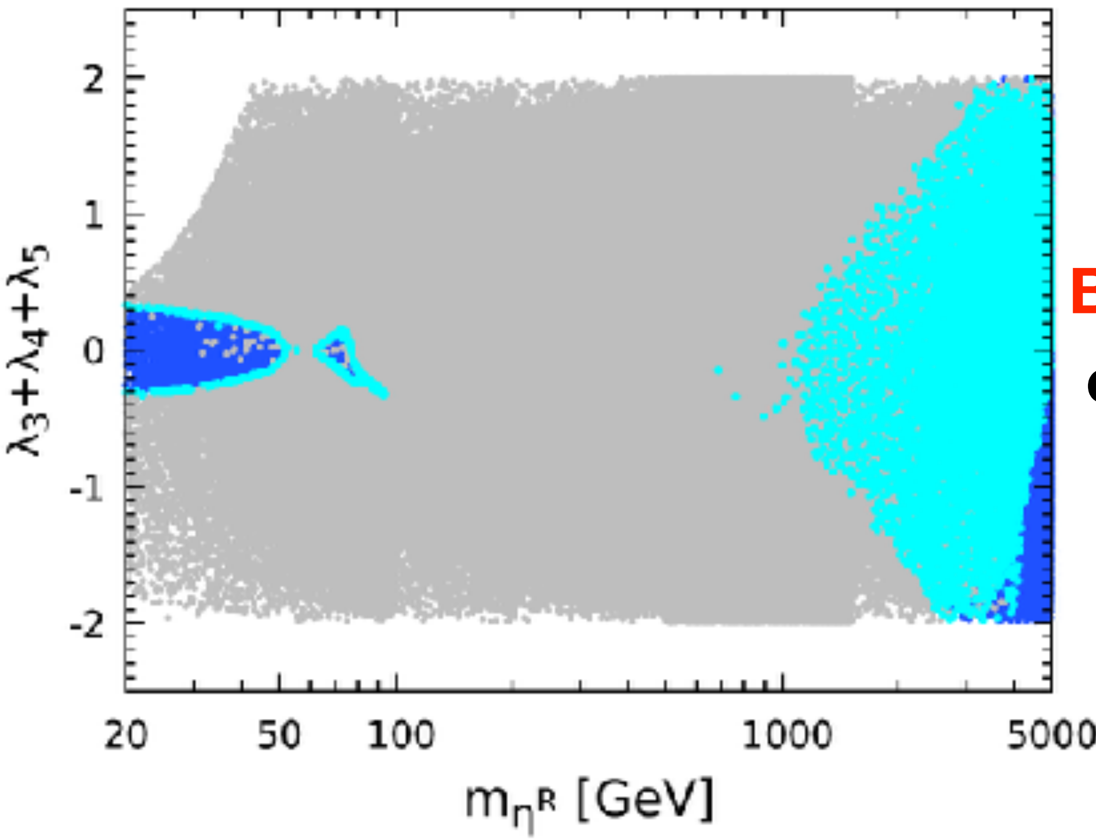
$$\beta^{(1)}_{\lambda_4} = +\frac{9}{5}g_1^2 g_2^2 - \frac{9}{5}g_1^2\lambda_4 - 9g_2^2\lambda_4 + 8\lambda_3\lambda_4 + 4\lambda_4^2 + 8\lambda_5^2 + 4\lambda_4\lambda_\eta + 4\lambda_4\lambda + 2\lambda_4\mathbf{Tr}\left(Y_f Y_f^\dagger\right)$$
$$-4\mathbf{Tr}\left(Y_f Y_N^\dagger Y_N Y_f^\dagger\right) + 2\lambda_4\mathbf{Tr}\left(Y_N Y_N^\dagger\right) + 6\lambda_4 y_t^2$$

$$\beta^{(1)}_{\lambda_3} = +\frac{27}{100}g_1^4 - \frac{9}{10}g_1^2 g_2^2 + \frac{9}{4}g_2^4 - \frac{9}{5}g_1^2\lambda_3 - 9g_2^2\lambda_3 + 4\lambda_3^2 + 2\lambda_4^2 + 2\lambda_5^2 + 12\lambda_3\lambda_\eta$$
$$+4\lambda_4\lambda_\eta + 12\lambda_3\lambda + 4\lambda_4\lambda + 2\lambda_3\mathbf{Tr}\left(Y_f Y_f^\dagger\right) + 2\lambda_3\mathbf{Tr}\left(Y_N Y_N^\dagger\right) + 6\lambda_3 y_t^2$$

$$\beta^{(1)}_{\lambda_5} = -\frac{9}{5}g_1^2\lambda_5 - 9g_2^2\lambda_5 + 8\lambda_3\lambda_5 + 12\lambda_4\lambda_5 + 4\lambda_5\lambda_\eta + 4\lambda_5\lambda + 2\lambda_5\mathbf{Tr}\left(Y_f Y_f^\dagger\right) + 2\lambda_5\mathbf{Tr}\left(Y_N Y_N^\dagger\right) + 6\lambda_5 y_t^2$$

$$\beta^{(1)}_{Y_f} = \frac{1}{20}\Big(10\left(3Y_fY_f^\dagger Y_f + Y_NY_N^\dagger Y_f\right) + Y_f\Big(20\mathbf{Tr}\left(Y_fY_f^\dagger\right) - 9\left(5g_2^2 + g_1^2\right)\Big)\Big)$$

$$\beta^{(1)}_{Y_N} = +\frac{1}{2}\left(3Y_NY_N^\dagger Y_N + Y_fY_f^\dagger Y_N\right) + Y_N\Big(3y_t^2 - \frac{9}{20}g_1^2 - \frac{9}{4}g_2^2 + \mathbf{Tr}\left(Y_NY_N^\dagger\right)\Big)$$



Above $m_{\eta^R} > 550$ GeV: λ_{345} covers wide range and stilll satisfies relic

Bad points: RGE for large values of quartic couplings exceed the perturbativity limit even before the Planck s

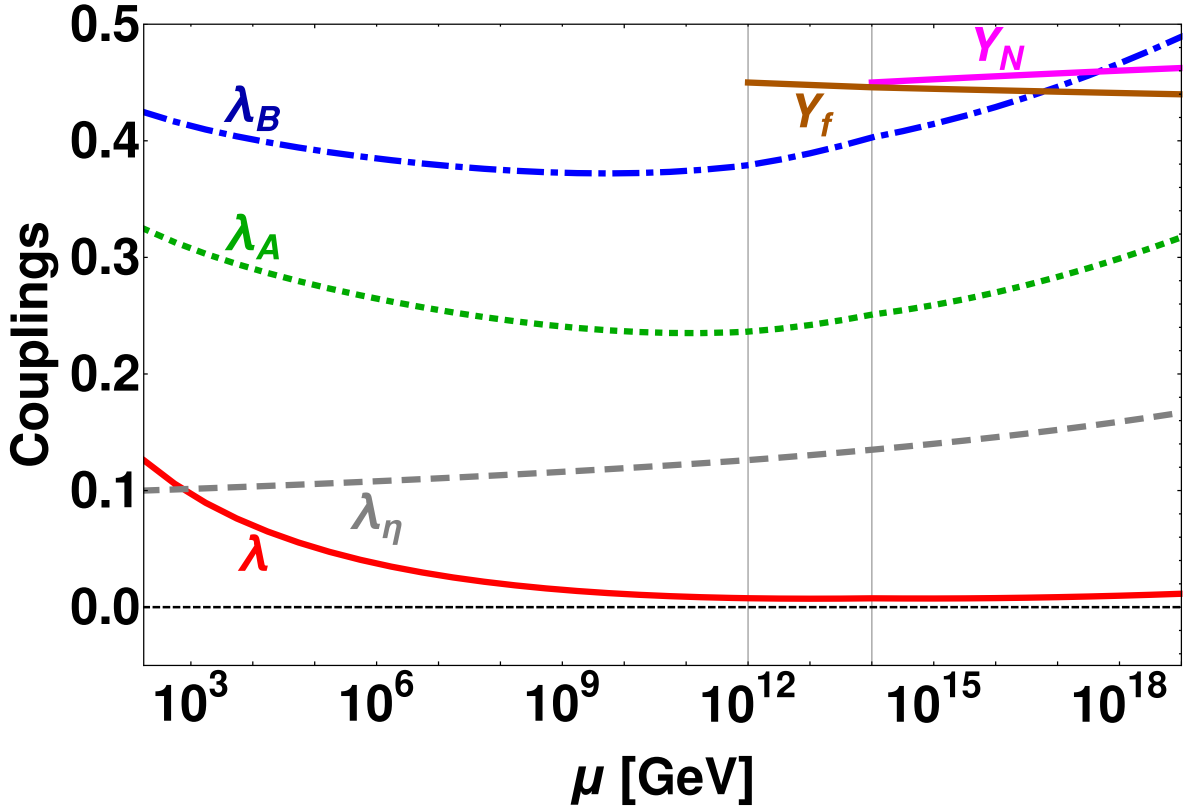
Good points: Moderate values of $\lambda_{3,4,5}$

BP1: $M_N \sim 10^{14}$ **GeV**, $M_f \sim 10^{12}$ **GeV**, $m_{\eta^R} \sim 10^3$ **GeV**, $\mathbb{Y}_N \sim 0.45, \mathbb{Y}_f \sim 0.45$, $\lambda_3 = \lambda_4 = 0.1$

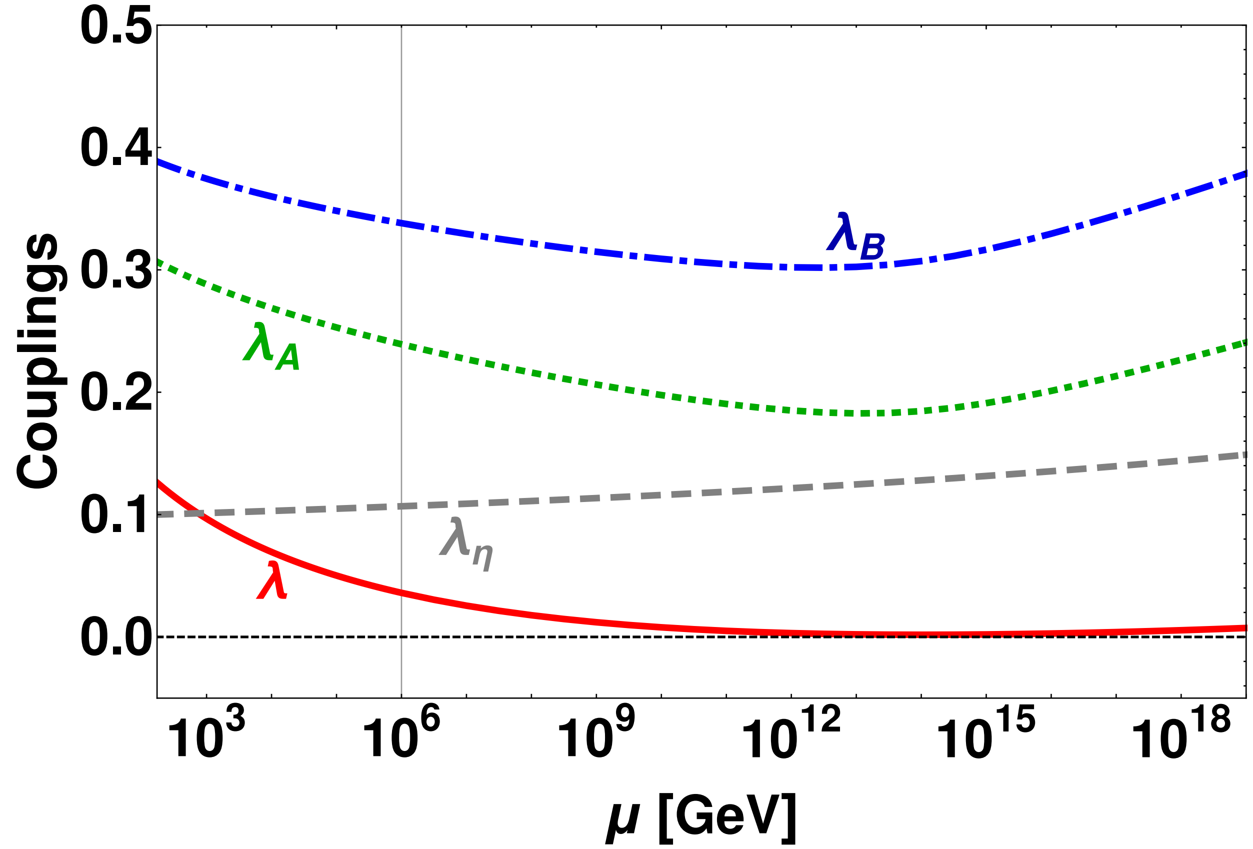
BP2: $M_N \sim 10^{14}$ **GeV**, $M_f \sim 10^{5}$ **GeV**, $m_{\eta^R} \sim 10^3$ **GeV**, $\mathbb{Y}_N \sim 0.45, \mathbb{Y}_f \sim 10^{-4}$, $\lambda_3 = \lambda_4 = 0.09$

BP3: $M_N \sim 10^{6}$ **GeV**, $M_f \sim 10^{6}$ **GeV**, $m_{\eta^R} \sim 10^3$ **GeV**, $\mathbb{Y}_N \sim 10^{-5}, \mathbb{Y}_f \sim 10^{-4}$, $\lambda_3 = \lambda_4 = 0.08$

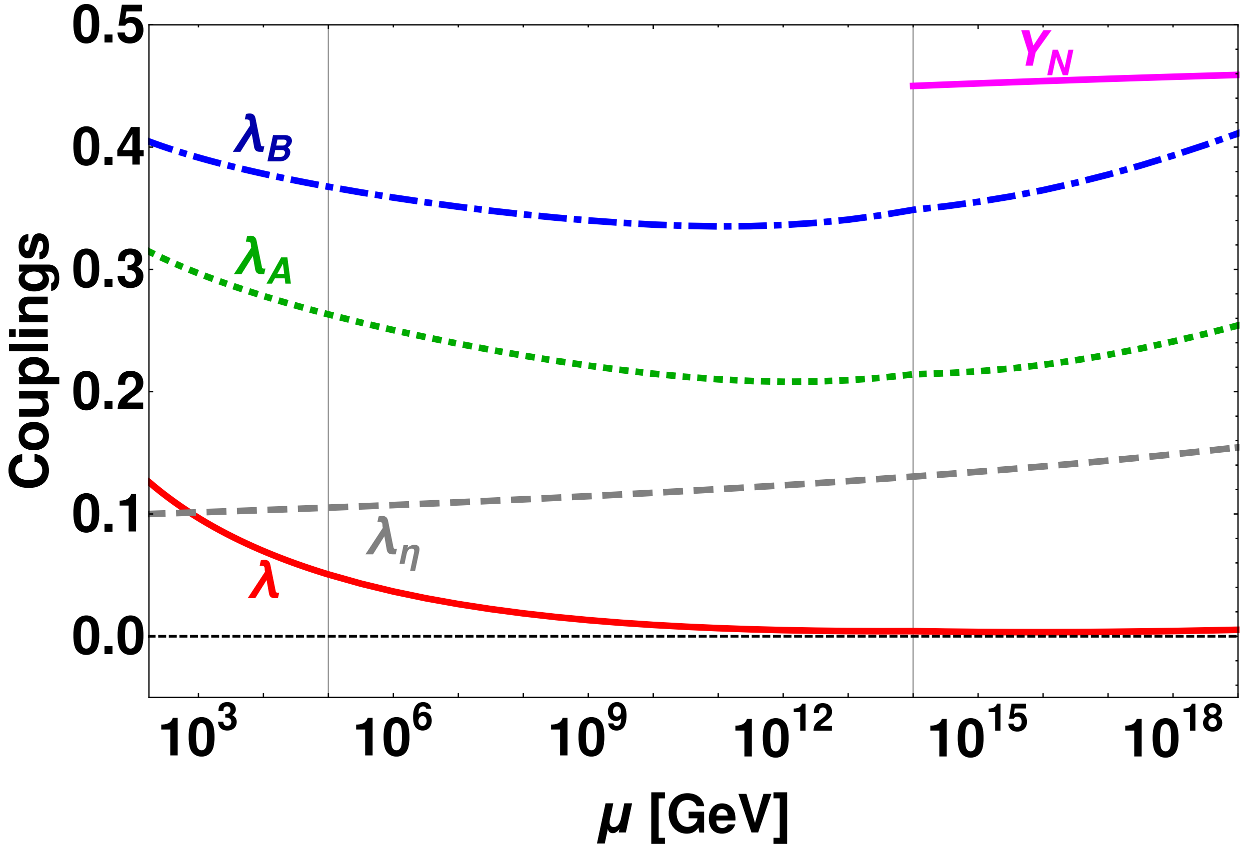
BP1 $Y_N(\Lambda_N)=0.45,\ Y_f(\Lambda_f)=0.45,\ \lambda_3=\lambda_4=0.1$



BP2 $Y_N(\Lambda_N)\approx10^{-5},\ Y_f(\Lambda_f)\approx10^{-4},\ \lambda_3=\lambda_4=0.08$



BP3 $Y_N(\Lambda_N)=0.45,\ Y_f(\Lambda_f)\approx10^{-4},\ \lambda_3=\lambda_4=0.09$



with reasonable initial choices, all of the stability condition can remain positive and quartic couplings can remain perturbative all the way up to the Planck scale.

For large Yukawa coupling $Y_{N,f}$ need large mixed quartic coupling

Improved stability properties due to extra scalars

HIGH ENERGY BEHAVIOR OF THE DARK PARITY $\mathbb{Z}_2$

Protection of $\mathbb{Z}_2$ symmetry at every energy scale is crucial to stabilise the DM

If RGE evolution drags m_η^2 negative at some energy scale then $<\eta> \neq 0$

$\Rightarrow$ **breaks $\mathbb{Z}_2$ symmetry**

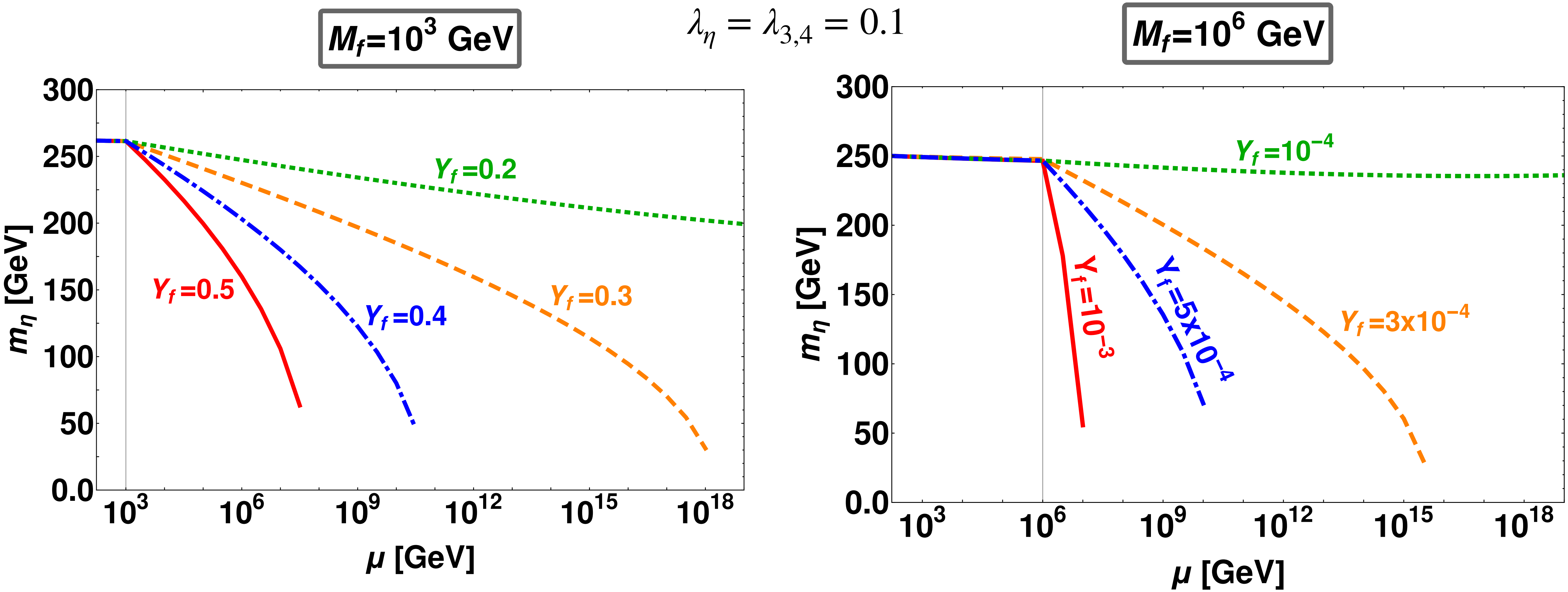
arXiv: 1608.00577, Lindner et al.

$$\beta^{(1)}_{m_\eta^2} = 12\lambda_\eta m_\eta^2 + 2\left(-2|M_f|^2 + m_\eta^2\right) \mathrm{Tr}\left(Y_f^\dagger Y_f\right) - 2(\lambda_4 + 2\lambda_3)\mu_H^2 - \left(\frac{9}{10}g_1^2 + \frac{9}{2}g_2^2\right) m_\eta^2$$

Dominating negative contribution: $-|M_f|^2 |Y_f|^2$

Positive contribution: $\lambda_\eta > 0,\ \lambda_{3,4} < 0$

$\lambda_\eta = \lambda_{3,4} = 0.1$



Larger the M_f, the smaller the allowed value of the Yukawa coupling Y_f in order to have the $\mathbb{Z}_2$ symmetry protection up to the Planck scale.

Summary

SM lacks neutrino mass and DM. New physics is required.

Scoto-seesaw: can explain neutrino masses as well as the hierarchy in "atmospheric" and "solar" mass scale

Additional features:

1. DM candidate (fermionic or scalar)

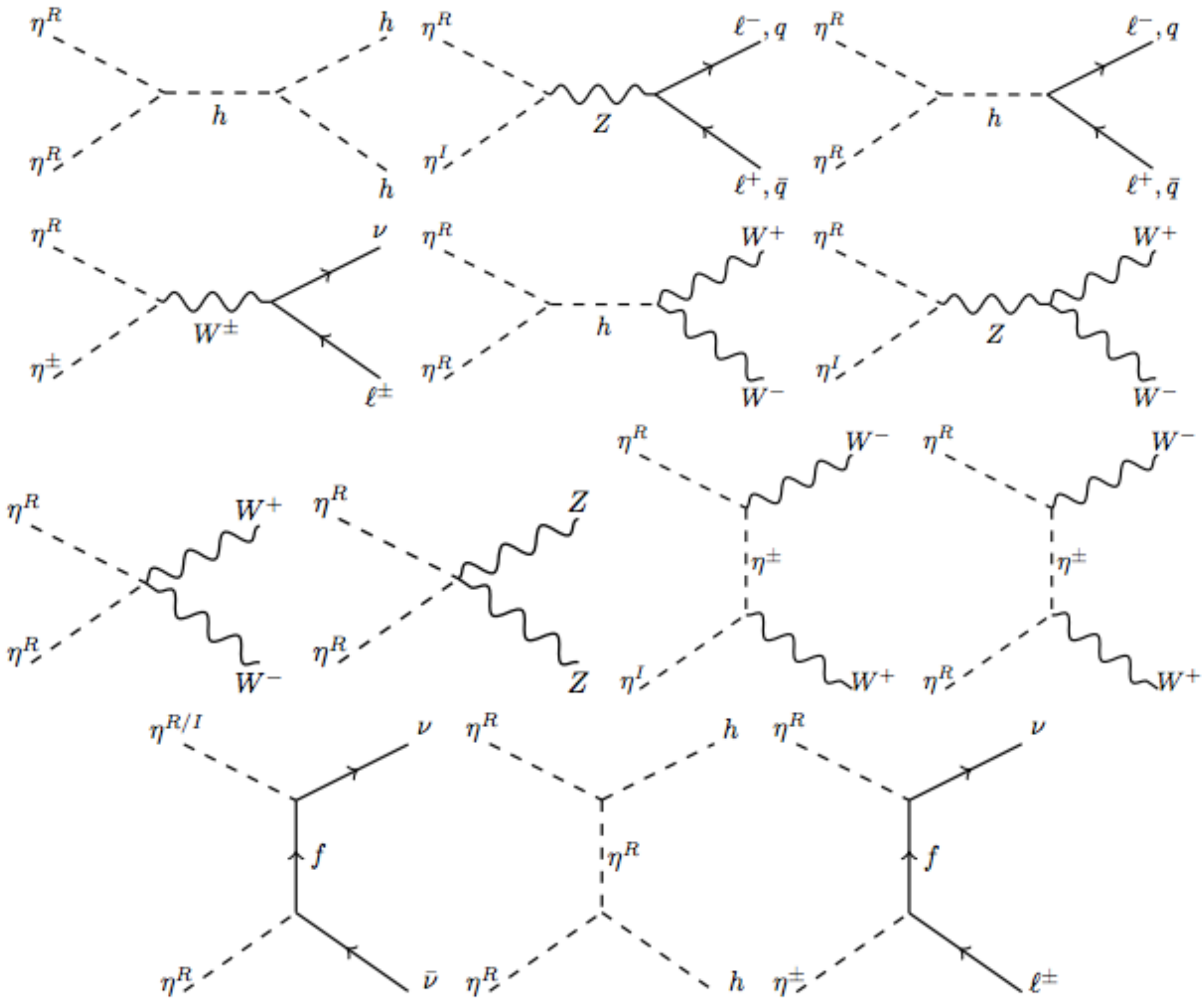
2. solar neutrino mass is seeded by drak particle exchange

3. large LFV, stable vacuum up to Planck scale

$4.\ \mathbb{Z}_2$ **symmetry conservation up to Planck scale**

Thank You for your attention

Back Up


η^R η^R h h h
η^R η^I Z ℓ^-, q $\ell^+, \bar{q}$
η^R η^R h ℓ^-, q $\ell^+, \bar{q}$
η^R $\eta^\pm$ $W^\pm$ ν $\ell^\pm$
η^R η^R h W^+ W^-
η^R η^I Z W^+ W^-
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