



# Loop-level Lepton Flavor Violation & Diphoton Signals in the Minimal Left-Right Symmetric Model

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Jan 13, 2026

IAS Program on Fundamental Physics (FP 2026), HKUST

based on

Shufang Qiang, Peiwen Wu & YCZ, 2512.25019 & 260x.abcde

# Motivation: lepton flavor violation (LFV) beyond SM

- Neutrino masses and mixings.
- Charged LFV could be connected to beyond SM scalars.

# Minimal Left-Right Symmetric Model

Pati & Salam '74; Mohapatra & Pati '75; Senjanović & Mohapatra '75

- Minimal left-right symmetric extension:

$$SU(2)_L \times U(1)_Y \rightarrow SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

- Matter fields are left-right symmetric

left-handed	right-handed
$\begin{pmatrix} u_L \\ d_L \end{pmatrix} = Q_L$	$Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix}$
$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = \Psi_L$	$\Psi_R = \begin{pmatrix} N_R \\ e_R \end{pmatrix}$

(see the talk by Sida Lu)

# Minimal scalar sector

Pati & Salam '74; Mohapatra & Pati '75; Senjanović & Mohapatra '75

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$\Downarrow \Delta_R (\mathbf{1}, \mathbf{3}, 2)$$

$$SU(2)_L \times U(1)_Y$$

$$\Downarrow \Phi (\mathbf{2}, \mathbf{2}, 0)$$

$$U(1)_{EM}$$

$$\left( \begin{array}{cc} \frac{1}{\sqrt{2}} \Delta_R^+ & \Delta_R^{++} \\ \Delta_R^0 & -\frac{1}{\sqrt{2}} \Delta_R^+ \end{array} \right) \Rightarrow H_3 \text{ (CP-even)}$$

$$\left( \begin{array}{cc} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{array} \right) \Rightarrow h, \underbrace{H_1^0, A_1^0, H_1^\pm}_{\text{heavy doublet}}$$

Note: Left-handed triplet  $\Delta_L$  could decouple from the TeV scale physics.

[Chang, Mohapatra & Parida '84, Deshpande, Gunion, Kayser & Olness '91]

- Tree-level: heavy bidoublet scalars  $H_1^0$  and  $A_1^0$  contributing to neutral  $K$  &  $B_{d,s}$  meson mixing.
- 1-loop level: heavy  $W_R$  boson contributing to neutral  $K$  &  $B_{d,s}$  meson mixing.
- 1-loop level: heavy  $W_R$  boson contributing to FCNC decays, e.g.  $b \rightarrow s\gamma$ ,  $b \rightarrow sg$ ,  $b \rightarrow sl^+\ell^-$ ,  $b \rightarrow s\nu\bar{\nu}$  [Cocolicchio et al, 1989].
- 1-loop level: light  $H_3$ :

$$K \rightarrow \pi + H_3, B \rightarrow K/\pi + H_3 \implies v_R \gtrsim \text{TeV}.$$

- Tree-level: LFV induced by  $H_{L,R}^{\pm\pm}$ .
- Tree-level: Keung-Senjanović process [Das, Deppisch et al,1206.0256; Das et al, 1709.06553]:

$$pp \rightarrow W_R \rightarrow \ell_\alpha^\pm N \rightarrow \ell_\alpha^\pm \ell_\beta^\mp(\pm) jj$$

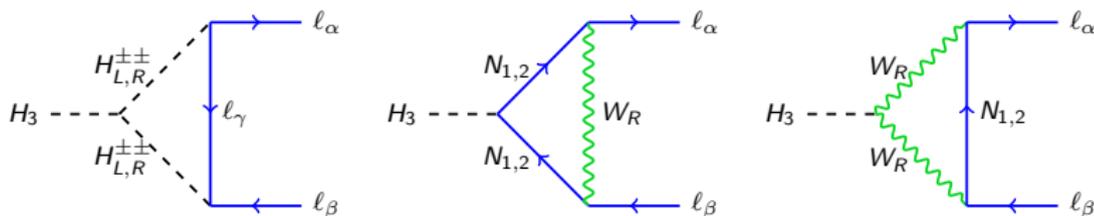
- 1-loop level:  $W_R$  and  $N_i$  in the LRSM contribute to lepton  $g-2$ ,  $\mu \rightarrow e\gamma$ ,  $\mu \rightarrow 3e$  &  $\mu - e$  conversion in nuclei [Cirigliano, Kurylov, Ramsey-Musolf, Vogel, hep-ph/0404233; Das, Deppisch et al, 1206.0256; Aguilar-Saavedra, Deppisch et al, 1203.5998], with

$$v_R \gtrsim \mathcal{O}(10 \text{ TeV}).$$

- 1-loop level:  $Z, Z_R \rightarrow q_\alpha \bar{q}_\beta, \ell_\alpha^+ \ell_\beta^-$  ( $\alpha \neq \beta$ ) [Perez & Soriano '92; Pilaftsis, hep-ph/9502330].

# Loop-level LFV couplings of $H_3$

- Loop-level LFV couplings of  $H_3$  in the LRSM:



- The LFV couplings  $\alpha \neq \beta$  originate from heavy neutrino mixing:

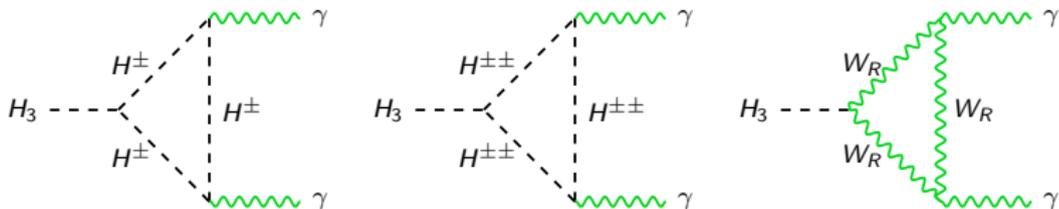
$$N_i = U_{i\alpha} N_\alpha$$

- The LFV (& LFC) couplings are effectively suppressed by the  $\nu_R$  scale.
- Neglecting the contribution from  $H_L^{\pm\pm}$ , which is directly relevant to active neutrino mass and mixing data via type-II seesaw.
- $H_1 - H_3$  mixing  $\implies$  tree-level LFV couplings of  $H_3$ .

[Dev, Mohapatra & YCZ, 1602.05947]

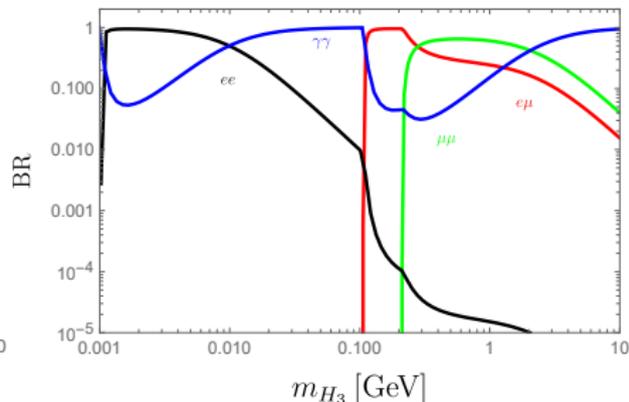
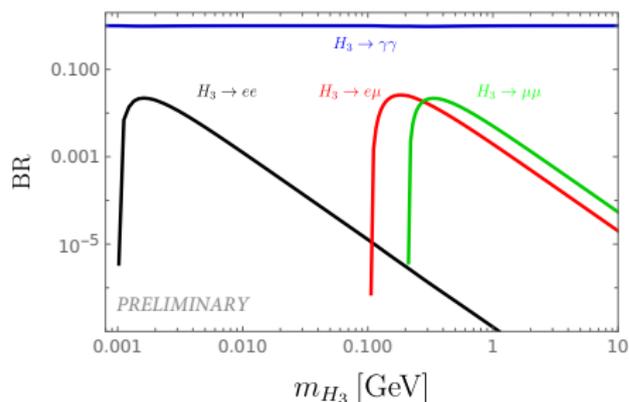
# $H_3\gamma\gamma$ (& $H_3\gamma Z$ ) couplings at 1-loop level

- Feynman diagrams for  $H_3 \rightarrow \gamma\gamma$  in the LRSM:



- In the limit of light  $H_3$ , all diagrams are suppressed by the  $v_R$  scale.
- There are similar diagrams for the effective 1-loop  $H_3\gamma Z$  coupling.

# BR: $N_{e,\mu}$ mixing



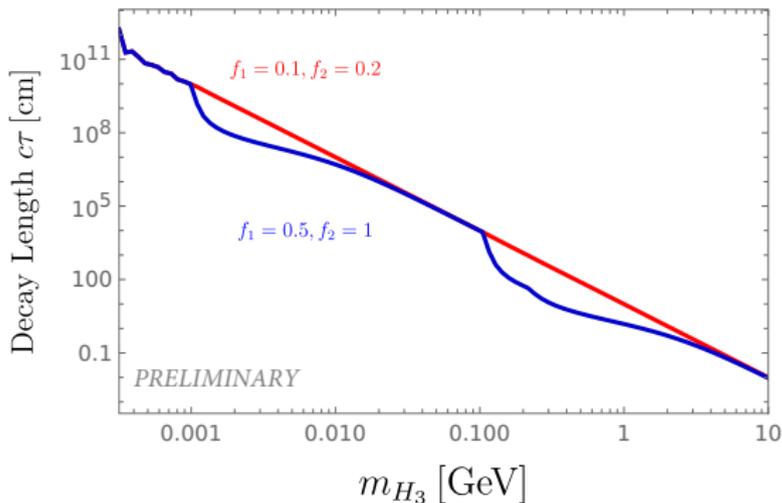
$$v_R = 10 \text{ TeV}, g_R = g_L,$$

$$\text{Left: } f_1 = 0.1, f_2 = 0.2.$$

$$\text{Right: } f_1 = 0.5, f_2 = 1.0.$$

Different dependence of dilepton and diphoton channels on  $m_{H_3}$ .

# The lifetime of $H_3$



$$v_R = 10 \text{ TeV}, g_R = g_L.$$

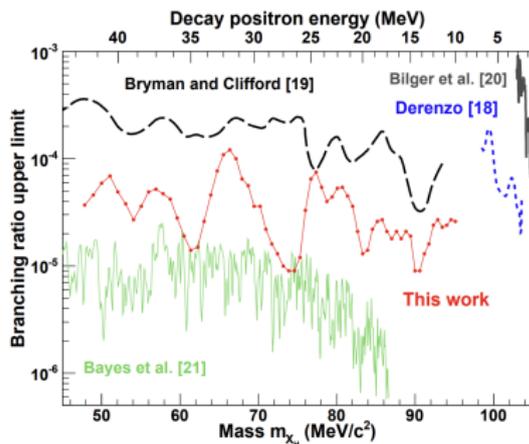
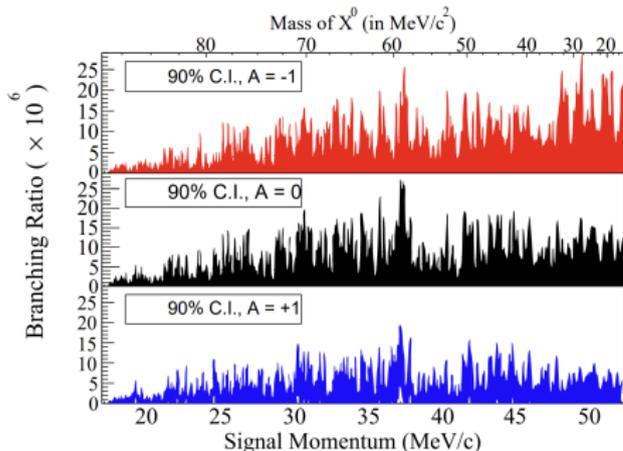
$H_3$  is very long-lived, in particular for mass below  $\mathcal{O}(\text{GeV})$ .

Axion limits  $\implies$  constraints on  $H_3$

(see other axion talks)

*ξεμ, ετ, μτ*

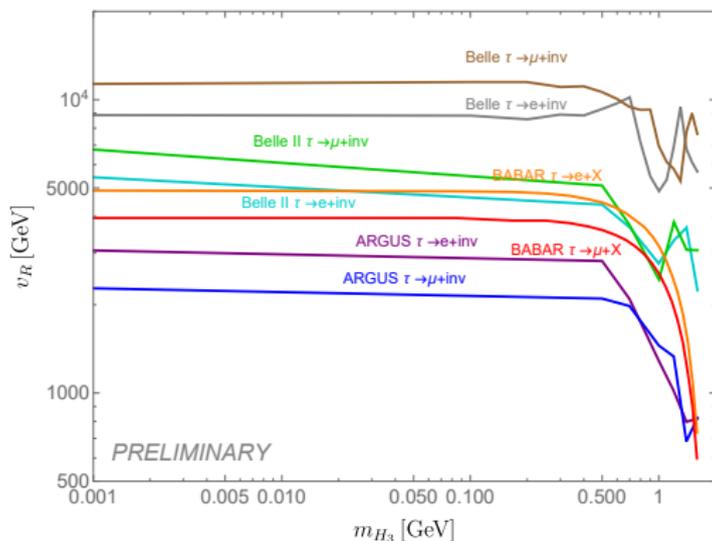
# Laboratory LFV constraints: $\mu \rightarrow e + \text{inv}$



- Precision muon experiment TWIST (left) [1409.0638].
- Precision pion experiment PIENU (right) [2002.09170].
- $H_3$  very long-lived, decaying outside detectors.
- $\text{BR}(\mu \rightarrow e + \text{inv}) \lesssim 10^{-5} \implies v_R \gtrsim 10^8 \text{ GeV}$ .

# Laboratory LFV constraints: $\tau \rightarrow e/\mu + \text{inv}$

ZPC68(1995)25; 2106.02451; 2503.22195; 2212.03634



- With  $m_{H_3} = 1$  GeV &  $v_R = 10$  TeV, the lifetime of  $H_3$  is at the meter order.
- $f_1 = 0.1$ ,  $f_2 = 0.2$ .
- For  $f_1 = 0.5$ ,  $f_2 = 1.0$ ,  $v_R \gtrsim 10^5$  GeV.

# Low-energy supernova constraints on $g_{e\mu}$

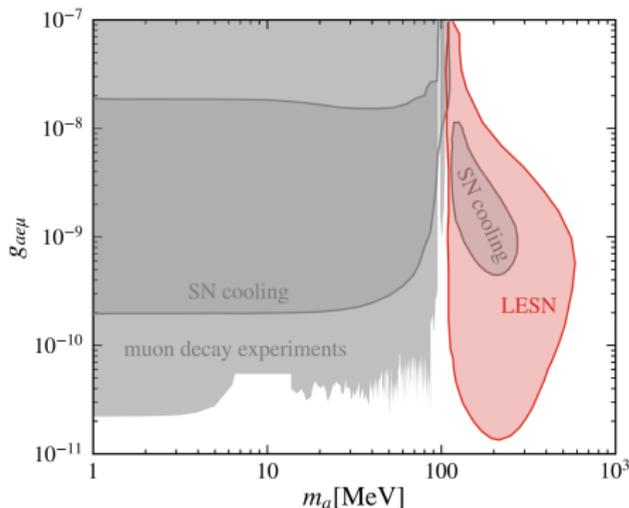
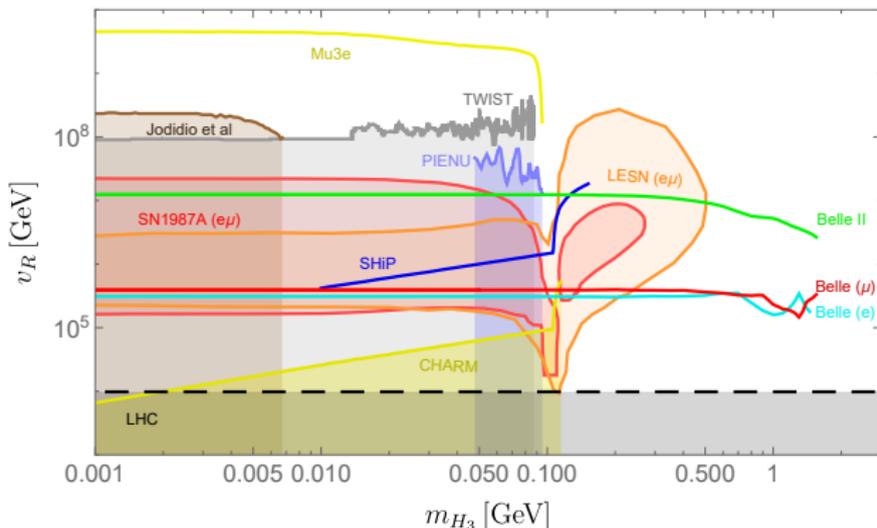


Figure: Figure from Zuwei Liu et al 2506.16922

- Low-energy supernova: explosion energies as low as  $0.1 B = 10^{50}$  erg.
- Dominant production channel:  $\mu \rightarrow e + a$ ,  $\ell + \gamma \rightarrow \ell' + a$ ,  $e + \mu \rightarrow a$ .
- The supernova limits on axion:  $g_{ae\mu} \lesssim \times 10^{-11} \Rightarrow v_R \gtrsim 10^8$  GeV.

# Limits & prospects of $m_{H_3}$ & $v_R$ : LFV case



$$g_R = g_L, f_1 = 0.5, f_2 = 1.0, \theta = 45^\circ$$

Shaded regions: current limits.

Lines: future prospects.

Direct LHC limits  $m_{W_R} \gtrsim 6.4 \text{ TeV} \implies v_R \gtrsim 9.8 \text{ TeV}$  [2304.09553].

$g_{ee}$

# supernova constraints on $g_{ee}$

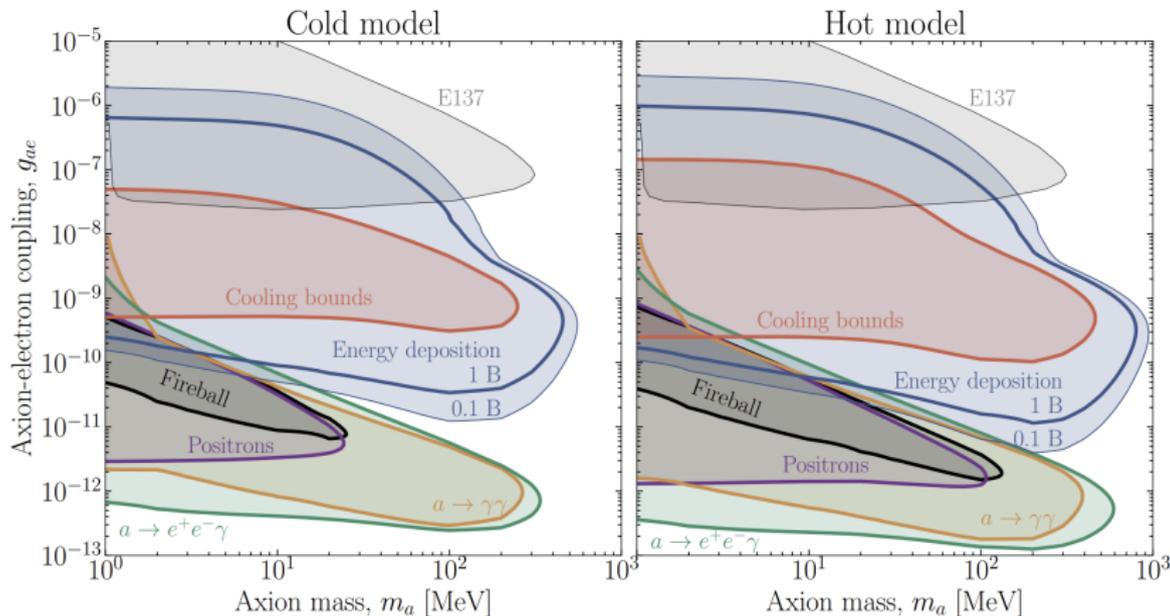
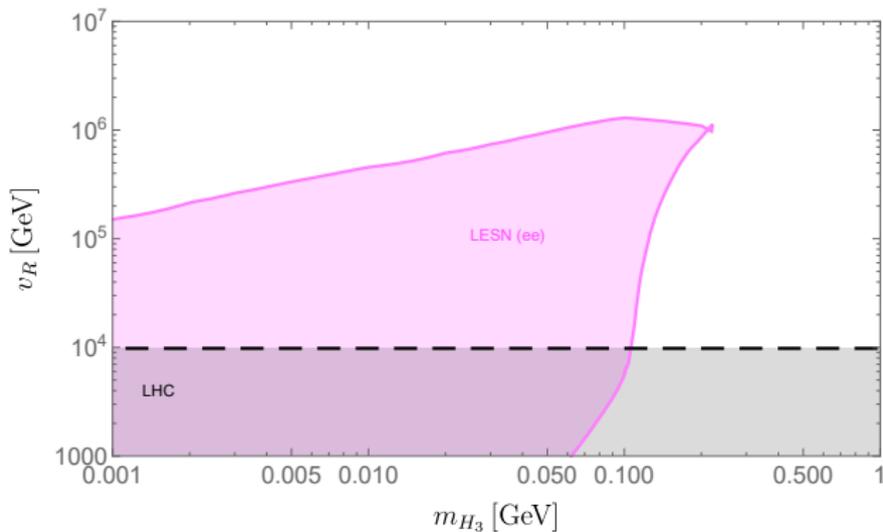


Figure: Figure from 2503.15630

- supernova limits on axion:  $g_{aee} \lesssim 3 \times 10^{-12}$  [2503.15630].
- $\Rightarrow v_R \gtrsim 10^6$  GeV.

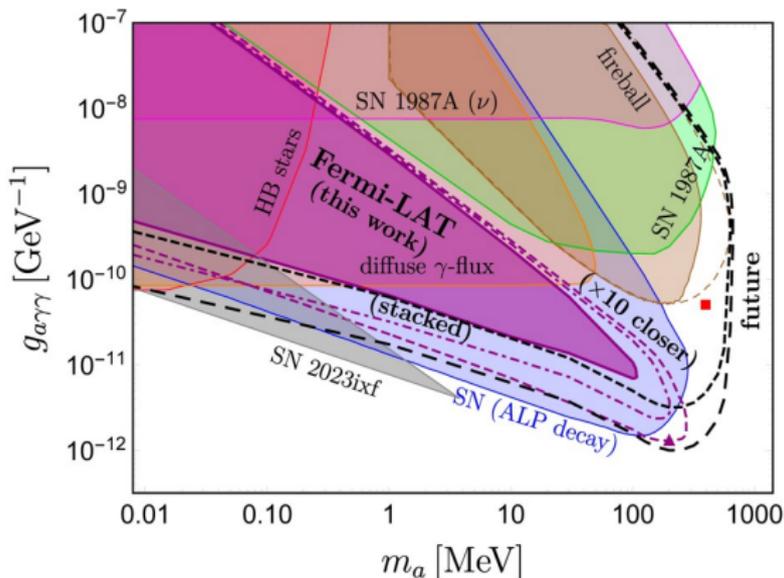
# Limits on $m_{H_3}$ & $v_R$ : LFC case



$$f_1 = 0.5, f_2 = 1.0.$$

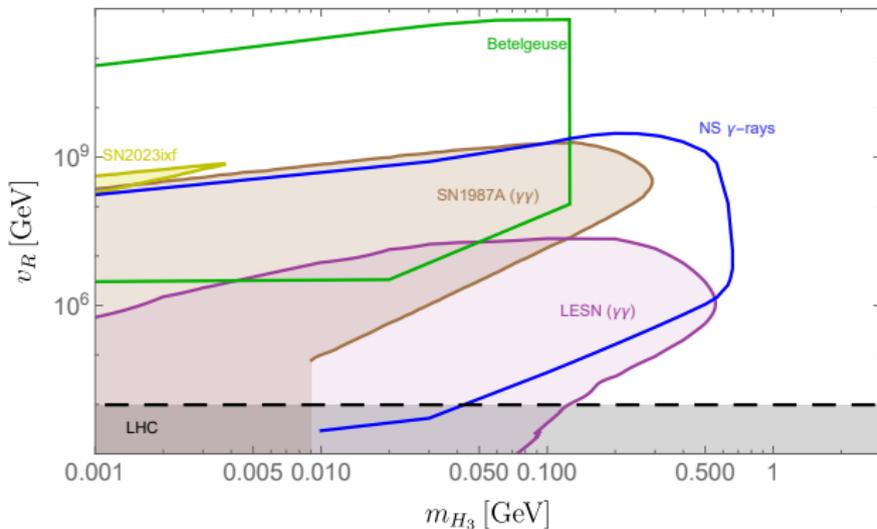
$g_{\gamma\gamma}$

# Astrophysical limits



- SN1987A limits [2212.09764, 2304.01060].
- Some supernova limits invalidated by fireball formation [2303.11395].
- More limits from type Ic supernovae [2509.18253].
- NS merger limits [2305.01002].
- $\implies v_R$  up to  $10^9$  GeV.

# Limits & prospects of $m_{H_3}$ & $v_R$ : diphoton case



$$f_1 = 0.5, f_2 = 1.0.$$

Shaded regions: excluded by current limits.

Lines: future prospects.

# Combining all the main limits & prospects

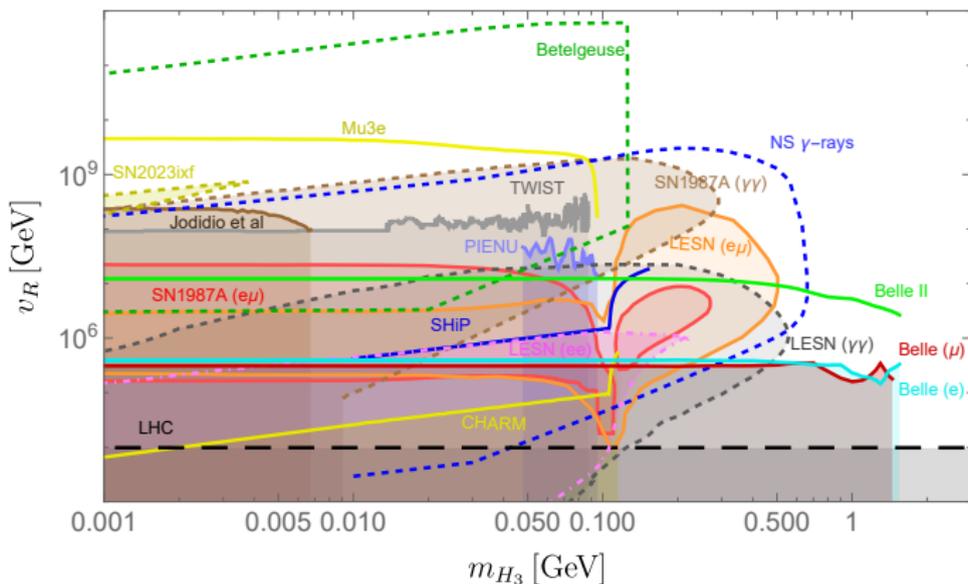


Figure:  $f_1 = 0.5$ ,  $f_2 = 1.0$

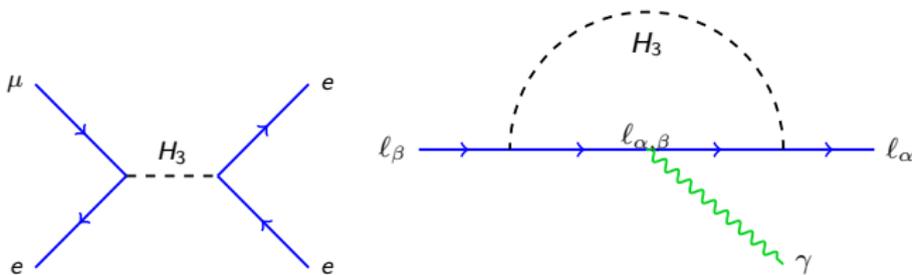
# Conclusion

- The phenomenologies of FCNC & LFV are very rich in the minimal LRSM, at the tree & 1-loop level.
- The light  $H_3$  induced LFV, LFC and diphoton signals are very rich, depending on its mass and the  $\nu_R$  scale.
- The most stringent limits are from the high-precision measurements, e.g. muon and tauon decays, and astrophysical limits, e.g. those from supernovae.
- $\nu_R$  is constrained up to the  $2 \times 10^9$  GeV scale, well above the direct LHC constraints (direct  $W_R$  &  $Z_R$  searches).
- The right-handed scale  $\nu_R$  can be probed up to  $\sim 5 \times 10^9$  GeV at the future muon experiments, and up to  $\sim 6 \times 10^{11}$  GeV by astrophysical observations.

Thank you for your attention!

# LFV processes that are less constraining or not applicable

- Some LFV processes involving two 1-loop effective couplings of  $H_3$ :  
 $l_\beta \rightarrow l_\alpha \gamma$ ,  $l_\beta \rightarrow l_\alpha \gamma \gamma$ ,  $l_\beta \rightarrow l_\alpha l_\gamma l_\delta$ ,  $(g - 2)_{e, \mu}$ .



# Weak meson limits on LFC couplings

- PIENU [2407.12738]:  
 $\pi \rightarrow \ell + \nu + X$ , BR  $\sim 10^{-6}$ , limits rather weak.
- NA62 [2101.12304]:  
 $K \rightarrow \ell + \nu + X$ , BR  $\sim 10^{-6}$ , limits rather weak.
- BaBar, Belle & LHCb [2211.08343]:  
 $K, D, B \rightarrow \mu + \nu + a$ ,  $f_a \gtrsim \text{GeV}$ , limits rather weak.
  
- SINDRUM [PLB175(1986)101]:  
 $\pi \rightarrow e + \nu + a$ ,  $a \rightarrow e^+ e^-$ , not applicable.
- E865 [hep-ex/0204006]:  
 $K \rightarrow e + \nu + a$ ,  $a \rightarrow e^+ e^-$ , not applicable.
- BaBar [1406.2980]:  
 $e^+ e^- \rightarrow \gamma A'$ ,  $A' \rightarrow e^+ e^-$ ,  $\mu^+ \mu^-$ , not applicable.
- BaBar [1606.03501]:  
 $e^+ e^- \rightarrow \mu^+ \mu^- Z'$ ,  $Z' \rightarrow \mu^+ \mu^-$ , not applicable.

# Electron beam dump limits

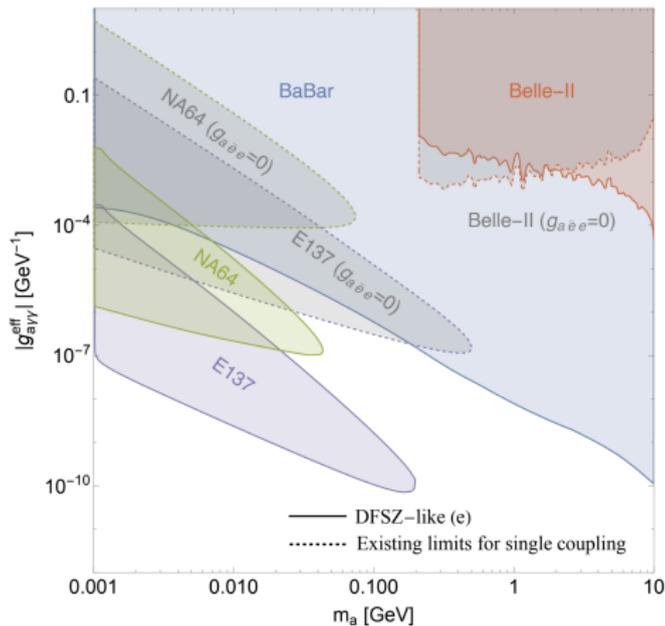


Figure: Figure from 2304.05435

# Beam dump limits on LRSM

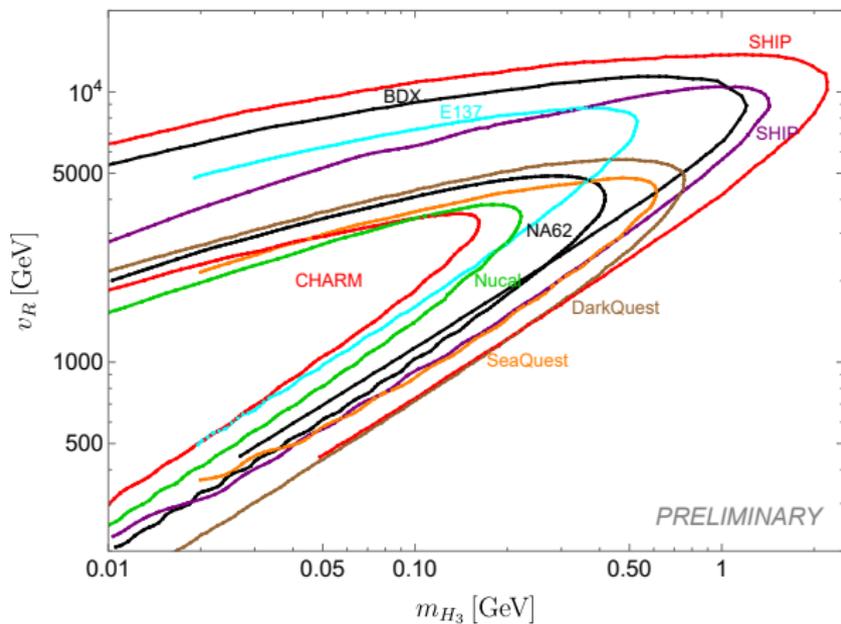


Figure:  $f_1 = 0.1$ ,  $f_2 = 0.2$

# Weak limits on $g_{\gamma\gamma}$

- BESIII [2211.12699]:  
 $J/\psi \rightarrow a + \gamma$ ,  $a \rightarrow \gamma\gamma$ , not applicable or weak limit.
- Belle II [2007.13071]:  
The searches of  $\Upsilon(4S) \rightarrow a + \gamma$ ,  $a \rightarrow \gamma\gamma$ , not applicable or weak limit.
- BESIII, Belle, BaBar [2003.05594, 1809.05222, 1007.4646, 0808.0017]:  
 $J/\psi$ ,  $\Upsilon(1S)$ ,  $\Upsilon(3S) \rightarrow \gamma + A^0$ ,  $A^0 \rightarrow \text{inv}$ ,  $g_{X\gamma\gamma} \lesssim 10^{-3} \text{ GeV}^{-1}$ , weak limits.
- GlueX [2308.06339]:  
 $\gamma + N \rightarrow N + a$ ,  $a \rightarrow \gamma\gamma$ ,  $f_a \gtrsim \text{TeV}$ , not applicable or weak limit.
- CMS [2202.03450]:  
vector boson scattering  
 $\gamma\gamma \rightarrow a^* \rightarrow \gamma\gamma$ ,  $g_{a\gamma\gamma} < 4.99 \text{ TeV}^{-1}$ , weak limit.
- ATLAS and CMS [2008.05355, 1810.04602]:  
ultra-peripheral heavy-ion collisions  
 $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ ,  $f_a \gtrsim 10 \text{ TeV}$ , weak limit.

# Weak limits on $g_{\gamma Z}$

- L3 [PLB345(1995)609]:  
 $Z \rightarrow \gamma + X, X \rightarrow \gamma\gamma, \text{BR}(Z \rightarrow \gamma X)\text{BR}(X \rightarrow \gamma\gamma) \lesssim 10^{-5}$ ,  
applies to the case of relatively heavy  $H_3$  with  $m_{H_3} \gtrsim 10$  GeV, with lifetime shorter than  $\mathcal{O}(0.1 \text{ cm})$ , weak limit.
- CDF [1311.3282]:  
 $Z \rightarrow \pi^0\gamma, \text{BR} < 2.01 \times 10^{-5}$ , weak limit.
- ATLAS [1509.05051]:  
 $Z \rightarrow 3\gamma, \text{BR} < 2.2 \times 10^{-6}$ , weak limit.