



Loop-level lepton flavor violation in the minimal left-right symmetric model

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based on

Shufang Qiang, Pei-Wen Wu & YCZ, 25xy.abcde

Motivation: lepton flavor violation (LFV) beyond SM

- Neutrino mass generation
(see the talks by Chengcheng Han, Yandong Liu, Zhaofeng Kang, Wei Chao, Chayan Majumdar)
- Charged LFV is always connected to beyond SM scalars.

LFV in LRSM

Parity violation



Figure: C. N. Yang, T. D. Lee & C. S. Wu

Left $\neq$ Right

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 talks by Frank Deppisch, Dongliang Fang

Minimal scalar sector

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

$$\begin{array}{c}
 SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\
 \Downarrow \Delta_R (1, 3, 2) \\
 SU(2)_L \times U(1)_Y \\
 \Downarrow \Phi (2, 2, 0) \\
 U(1)_{EM}
 \end{array}$$

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

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

Note: Left-handed triplet Δ_L decouples 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. $b \rightarrow s\gamma$, $b \rightarrow sg$, $b \rightarrow s\ell^+\ell^-$, $b \rightarrow s\nu\bar{\nu}$ [Cocolicchio et al, 1989].
- 1-loop level: light H_3 :

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

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

$$pp \rightarrow W_R \rightarrow \ell_\alpha^\pm N \rightarrow \ell_\alpha^\pm \ell_\beta^\mp(\pm) j\bar{j}$$

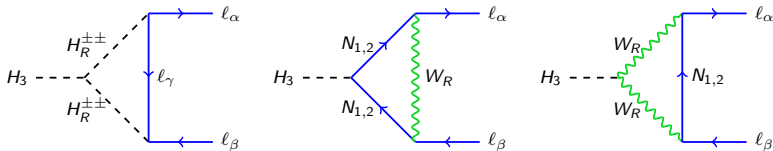
- 1-loop level: W_R and N_i in the LRSM contribute to lepton $g-2$, $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$ & $\mu - e$ conversion in nuclei [Cirigliano et al, hep-ph/0404233; Das, Deppisch et al, 1206.0256; Aguilar-Saavedra, Deppisch et al, 1203.5998], with

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

- 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:

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

- Relatively light H_3 such that the decays of H_3 into heavy particles are highly suppressed:

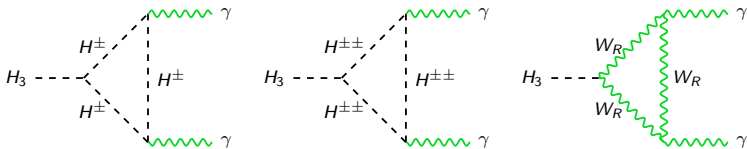
$$H_3 \rightarrow H_i H_j, N_i N_j, V_R V_R.$$

- $H_1 - H_3$ mixing $\implies$ tree-level LFV couplings of H_3 .

[Dev, Mohapatra & YCZ, 1602.05947]

$H_3 \rightarrow \gamma\gamma$ at 1-loop level

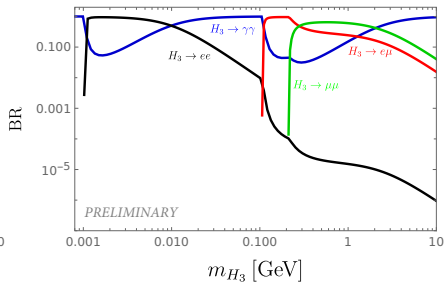
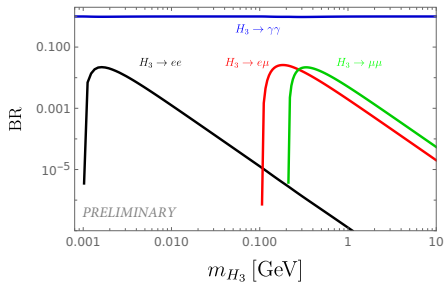
- Feynman diagrams for $H_3 \rightarrow \gamma\gamma$ in the LRSM:



- In the limit of light H_3 , all diagrams are suppressed by the v_R scale.
- Relatively light H_3 such that the decays of H_3 into heavy particles are highly suppressed:

$$H_3 \rightarrow H_i H_j, N_i N_j, V_R V_R.$$

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



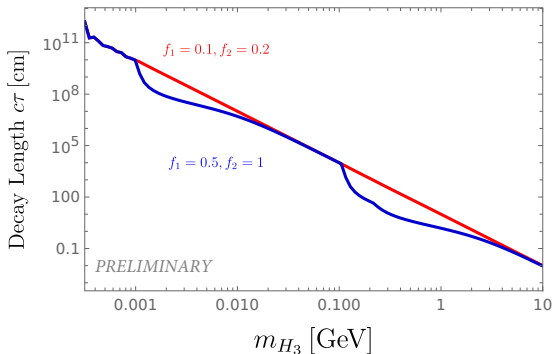
$$v_R = 10 \text{ TeV}, g_R = g_L,$$

Left: $f_1 = 0.1, f_2 = 0.2$.

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 $\mathcal{O}(\text{GeV})$.

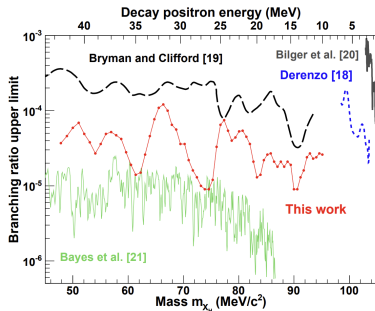
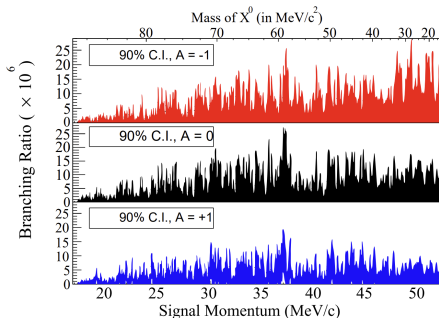
See the talk by Zeren Wang

Comparison of scalar & axion constraints

- We "borrow" the rich axion constraints in the literature to set limits on the CP-even scalar in LRSM.
- Production & decay.
 - Some are very close, e.g. $\ell_\beta \rightarrow \ell_\alpha + H_3/a$ and proton & electron beam dump experiments.
 - Some are significantly different, e.g. $H_3/a \rightarrow f\bar{f}$.
- We re-interpret the axion constraints, and set limits on H_3 .
- See the talks by Zuowei Liu, Kechen Wang, Chih-Ting Lu, Chayan Majumdar.

$$g_{e\mu, e\tau, \mu\tau}$$

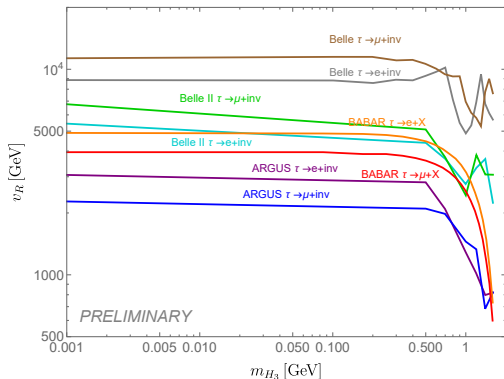
Laboratory LFV constraints: $\mu \rightarrow e + \text{inv}$



- Precision muon experiment TWIST (left) [1409.0638].
- Precision pion experiment PIENU (right) [2002.09170].
- H_3 very long-lived, decaying outside detectors.
- $\text{BR}(\mu \rightarrow e + \text{inv}) \lesssim 10^{-5} \implies \nu_R \gtrsim 10^6 \text{ GeV}$, up to $\mathcal{O}(100 \text{ MeV})$.
- Assuming maximal $N_{1,2}$ mixing: $\theta = 45^\circ$.

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

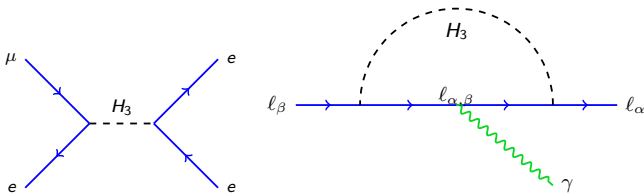
ZPC68(1995)25; 2106.02451; 2503.22195; 2212.03634



- With $m_{H_3} = 1$ GeV & $v_R = 10$ TeV, the lifetime of H_3 is at the meter order.
- $f_1 = 0.1$, $f_2 = 0.2$.
- Need to re-interpret the limits to constrain m_{H_3} & v_R .
- Assuming maximal $N_{1,2}$ mixing: $\theta = 45^\circ$.
- See the talk by Sen Jia.

LFV processes that are less constraining or not applicable

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



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

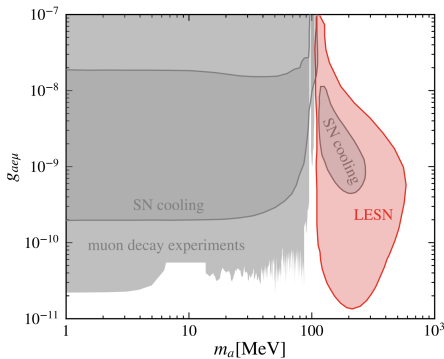
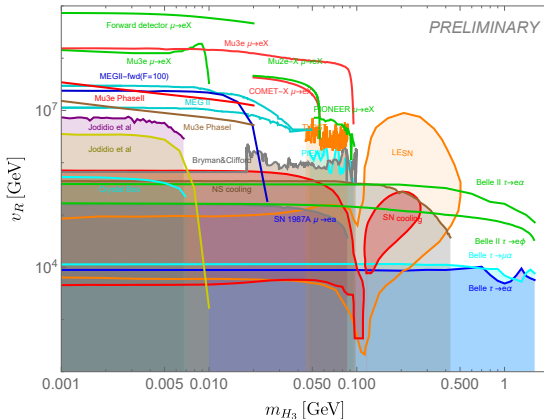


Figure: Figure from Zuowei Liu et al 2506.16922

- Low-energy supernova: explosion energies as low as $0.1 B = 10^{50}$ erg.
- dominant production channel: $e + \mu \rightarrow a$.
- The supernova limits on axion: $g_{ae\mu} \lesssim \times 10^{-11}$ [2506.16922]
(see the talk by Zuowei Liu).

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



$$g_R = g_L, f_1 = 0.1, f_2 = 0.2, \theta = 45^\circ$$

Shaded regions: current limits.

Lines: future prospects.

Only most constraining τ limits in the figure.

Direct LHC limits $m_{W_R} \gtrsim 6.4 \text{ TeV} \Rightarrow v_R \gtrsim 10 \text{ TeV}$ [2304.09553].

$$g_{ee,\mu\mu}$$

Weak meson limits

- PIENU [2407.12738]:
 $\pi \rightarrow \ell + \nu + X$, $\text{BR} \sim 10^{-6}$, limits rather weak.
- NA62 [2101.12304]:
 $K \rightarrow \ell + \nu + X$, $\text{BR} \sim 10^{-6}$, 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.

supernova constraints on g_{ee}

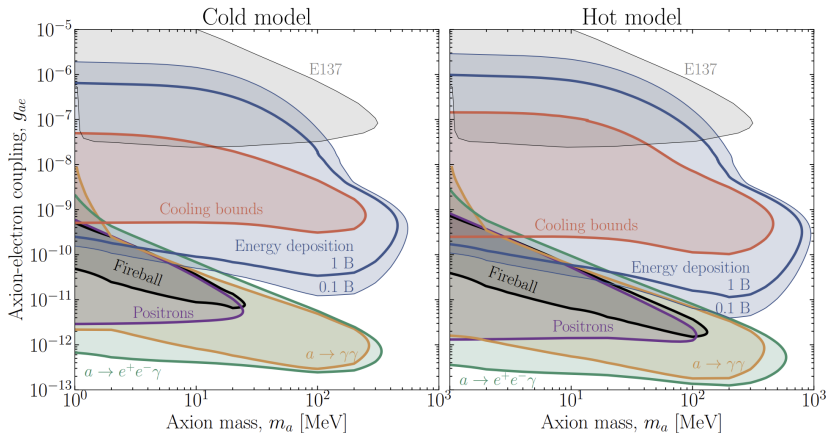


Figure: Figure from 2503.15630

- supernova limits on axion: $g_{aee} \lesssim 3 \times 10^{-12}$ [2503.15630].
- $\Rightarrow \nu_R \gtrsim 10^5$ GeV.

supernova constraints on $g_{\mu\mu}$

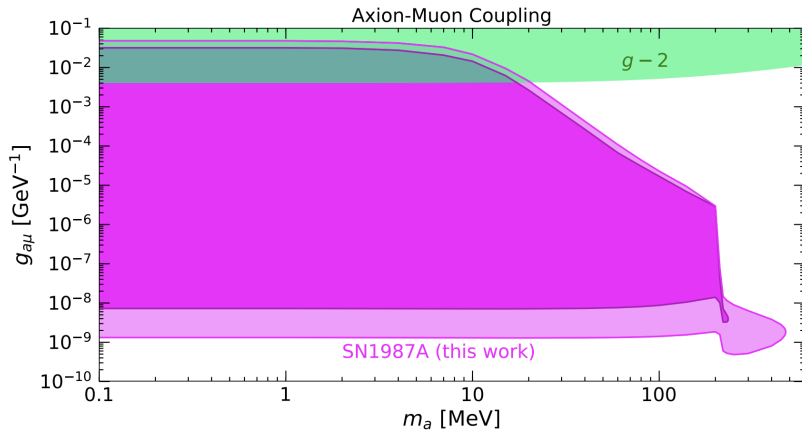
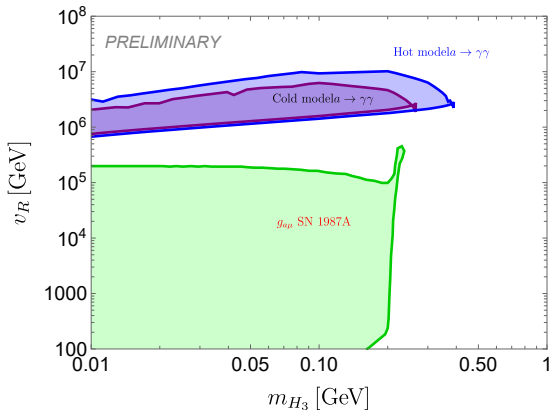


Figure: Figure from 2006.13942

- supernova limits on axion: $g_{a\mu\mu} \lesssim 10^{-9}$ [2006.13942].
- $\Rightarrow \nu_R \gtrsim 10^6$ GeV.

Limits on m_{H_3} & v_R : LFC case



$$f_1 = 0.1, f_2 = 0.2.$$

blue & purple: coupling g_{ee} .

green: coupling $g_{\mu\mu}$.

$$g_{\gamma\gamma} \text{ (\& } g_{\gamma Z})$$

Electron beam dump limits

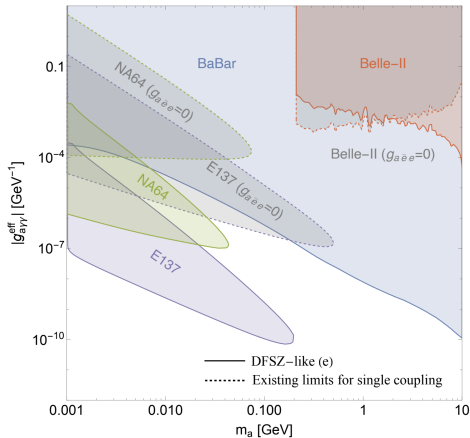


Figure: Figure from 2304.05435

- The E137 limit on $g_{a\gamma\gamma}$ can go down to $10^{-10} \text{ GeV}^{-1}$.
- $\implies \nu_R$ constrained up to 10^5 GeV .

Beam dump limits on LRSM

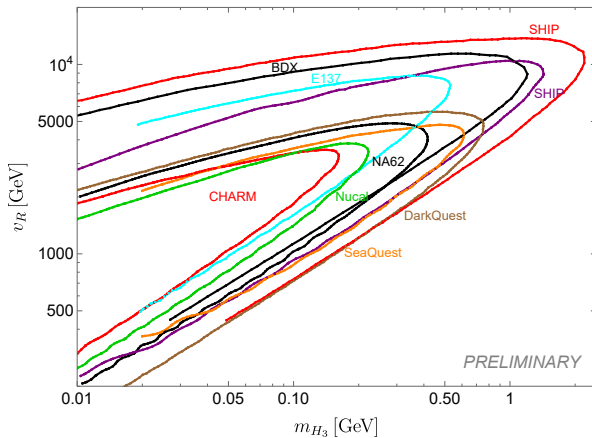


Figure: $f_1 = 0.1$, $f_2 = 0.2$

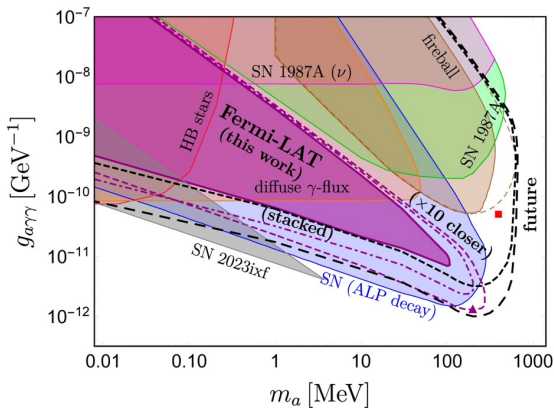
Weak limits on $g_{\gamma\gamma}$

- 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/ψ , $\Upsilon(1S)$, $\Upsilon(3S) \rightarrow \gamma + A^0$, $A^0 \rightarrow \text{inv}$, $g_{X\gamma\gamma} \lesssim 10^{-3} \text{ GeV}^{-1}$, 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 $g_{\gamma Z}$

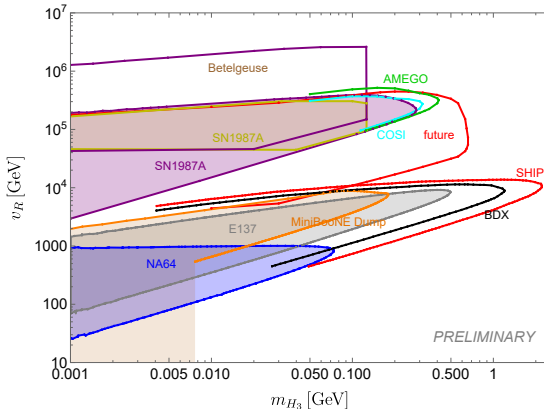
- L3 [PLB345(1995)609]:
 $Z \rightarrow \gamma + X, X \rightarrow \gamma\gamma, \text{BR}(Z \rightarrow \gamma X)\text{BR}(X \rightarrow \gamma\gamma) \lesssim 10^{-5}$,
applies to the case of relatively heavy H_3 with $m_{H_3} \gtrsim 10$ GeV, with lifetime shorter than $\mathcal{O}(0.1 \text{ cm})$, 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.

Astrophysical limits



- SN1987A limits [2212.09764, 2304.01060].
- NS merger limits [2305.01002]
- $\Rightarrow \nu_R$ up to 10^{5.5} GeV.

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



- $f_1 = 0.1$, $f_2 = 0.2$.
- shaded regions: excluded by current limits.
- lines: future prospects:
 - Betelgeuse: future supernova observations;
 - "future": future neutron star observations.

For larger Yukawa coupling case of $f_1 = 0.5$, $f_2 = 1.0$, the LFV & LFC prospects can be further improved by a factor of $\mathcal{O}(10)$.

more figures will be added...

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 ν_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 and neutron stars.
- ν_R is constrained up to the 10^7 GeV scale, well above the direct LHC constraints (direct W_R & Z_R searches).
- The right-handed scale ν_R can be probed up to $\sim 10^9$ GeV at the future high-intensity frontier experiments.

Thank you for your attention!