Sterile Neutrinos as a Window to New Physics

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中山大学物理与天文学院

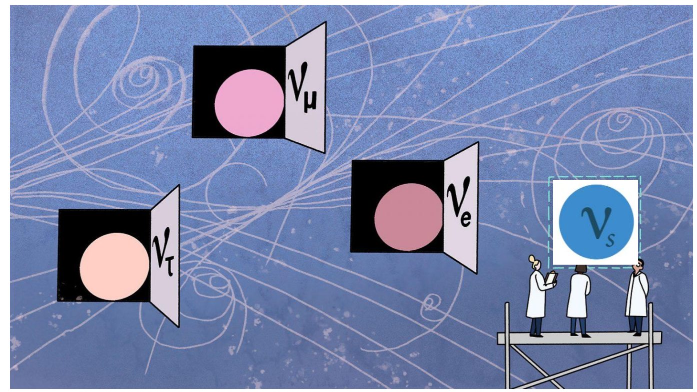
第二十一届全国重味物理和CP破坏研讨会

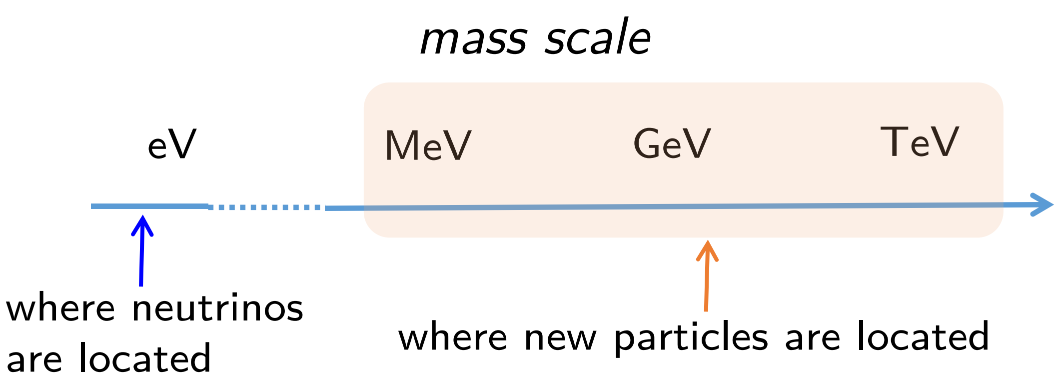
2024年10月26日，衡阳

New physics

The Standard Model is successful but incomplete:

- neutrino masses
- baryon asymmetry
- dark matter
- strong CP problem
- ....

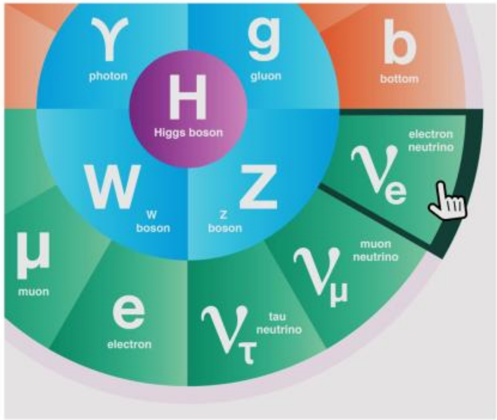




Neutrino physics

Open questions:

- **Normal or Inverted (sign of Δm^2_{31}?)**
- **Leptonic CP Violation (δ = ?)**
- **Octant of θ_{23} (> or < 45°?)**
- **Absolute Neutrino Masses ($m_{\rm lightest} = 0$?)**
- **Majorana or Dirac Nature ($\nu = \nu^c$?)**
- **Majorana CP-Violating Phases (how?)**



- **Extra Neutrino Species**
- **Exotic Neutrino Interactions**
- **Various LNV & LFV Processes**
- **Leptonic Unitarity Violation**

- **Origin of Neutrino Masses**
- **Flavor Structure (Symmetry?)**
- **Quark-Lepton Connection**
- **Relations to DM and/or BAU**

credit: Shun Zhou

Neutrino physics

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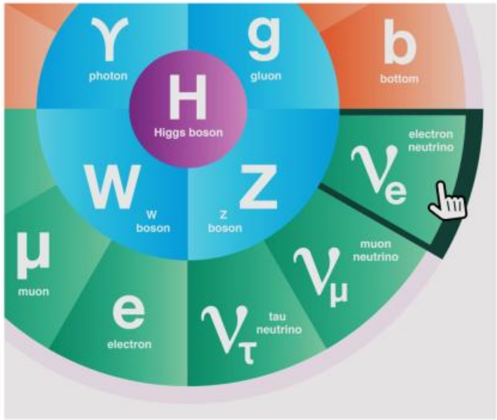

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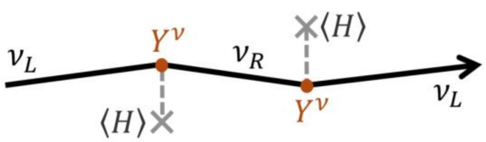
2407.06523
2410.12180

ν -New Physics connection

Neutrino masses

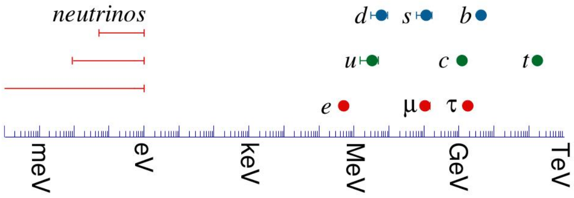
Two ways to generate netrino masses

Dirac mass:



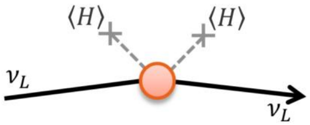
$$\mathcal{L}_D = -(Y^\nu \bar{L} H \nu_R + \text{h.c.})$$

Higgs mechanism



unnaturally small $Y_\nu < 10^{-13}$

Majorana mass:



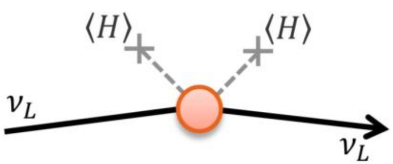
$$\mathcal{L}_M = \frac{C_5}{\Lambda}(\bar{L}^c \tilde{H}^*)(\tilde{H}^\dagger L) + \text{h.c.}$$

seesaw mechanism

heavy new physics

Majorana nature

Majorana mass and LNV interactions:

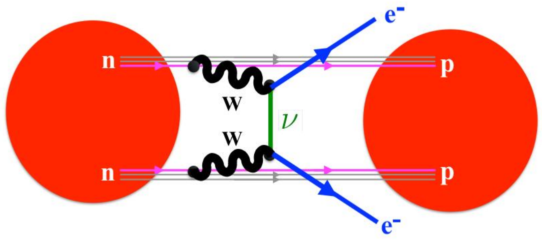


$$\mathcal{L}_M = \frac{C_5}{\Lambda}(\bar{L}^c \tilde{H}^*)(\tilde{H}^\dagger L) + \text{h.c.}$$

$\Delta L = 2$ **L**epton **N**umber **V**iolation

ingredient of leptogenesis to generate baryon asymmetry

The most sensitive probe for Majorana neutrinos is nuclear neutrinoless double beta ($0\nu\beta\beta$) decay:



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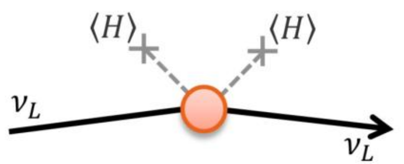

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regardless of LNV interactions in the "black box"

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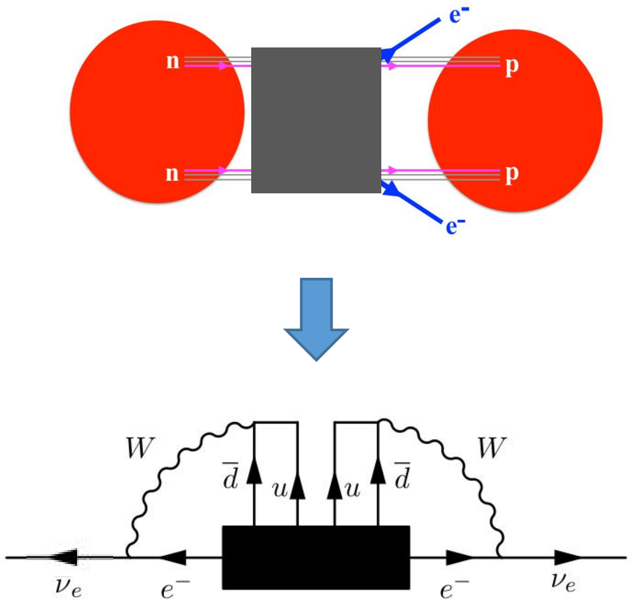
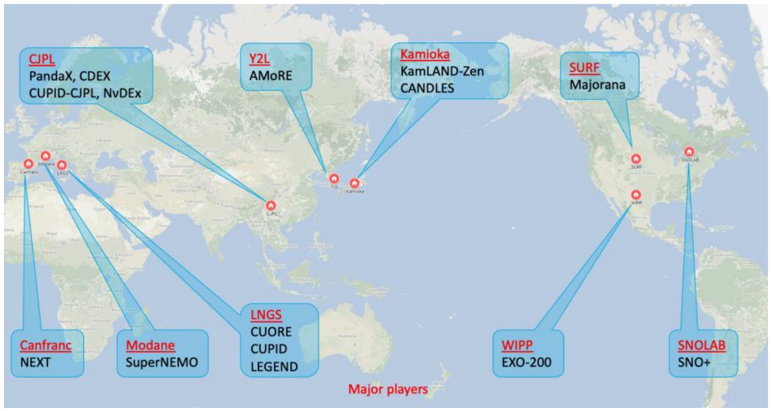
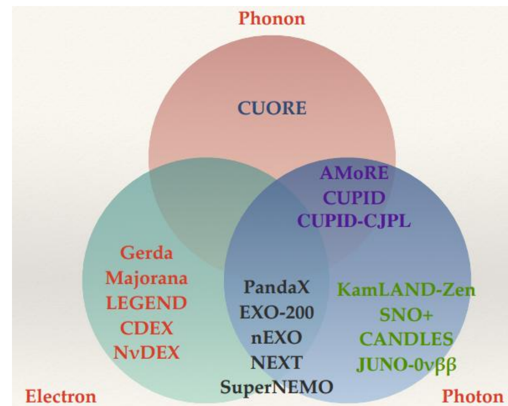


Neutrinoless double beta decay

Global experimental efforts





- Current limits:

$$^{136}\text{Xe} \to {}^{136}\text{Ba} + e^- + e^-: \quad T_{1/2}^{0\nu}(\text{Xe}) > 1.07 \times 10^{26}\ \text{year}\ \ (\text{KamLAND-Zen})$$

$$^{76}\text{Ge} \to {}^{76}\text{Se} + e^- + e^-: \quad T_{1/2}^{0\nu}(\text{Ge}) > 1.8 \times 10^{26}\ \text{year}\ \ (\text{GERDA})$$

- Future prospects:

$$T_{1/2}^{0\nu} \gtrsim 10^{28}\ \text{year} \qquad \text{CDEX, PandaX, JUNO-}0\nu\beta\beta\text{, etc}$$

Neutrinoless double beta decay

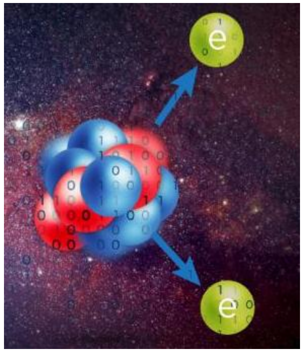
Theoretical interpretations:

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu} {M_{0\nu}}^2 \langle m_{\beta\beta} \rangle^2$$

$G_{0\nu}$: phase space factor (atomic physics)

$M_{0\nu}$: nuclear matrix element (nuclear physics)

$\langle m_{\beta\beta} \rangle$: effective Majorana mass (particle physics)



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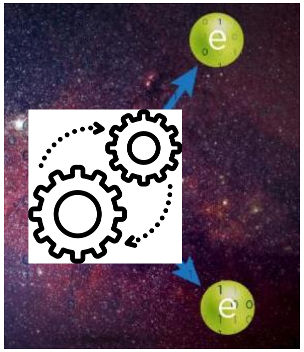
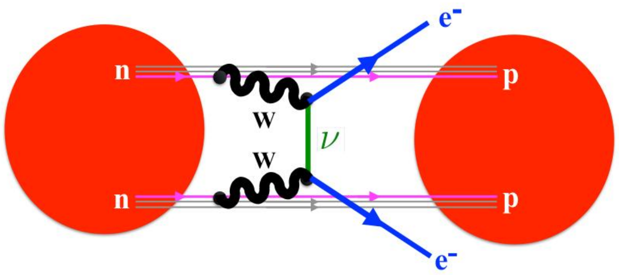
- ✔ $G_{0\nu}$: phase space factor (atomic physics)
- ✔ $M_{0\nu}$: nuclear matrix element (nuclear physics)
- ? $\langle m_{\beta\beta} \rangle$: effective Majorana mass (particle physics)

$\langle m_{\beta\beta} \rangle$ depends on the underlying *mechanism* for $0\nu\beta\beta$ decay

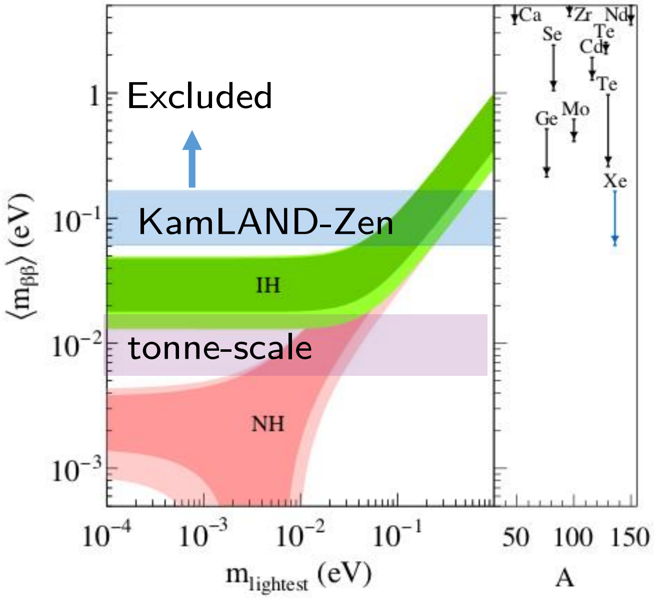


Neutrinoless double beta decay

- Standard mechanism



$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right|$$



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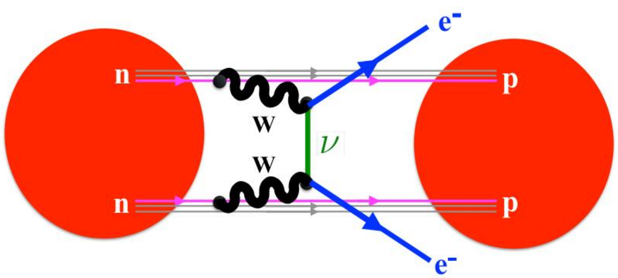

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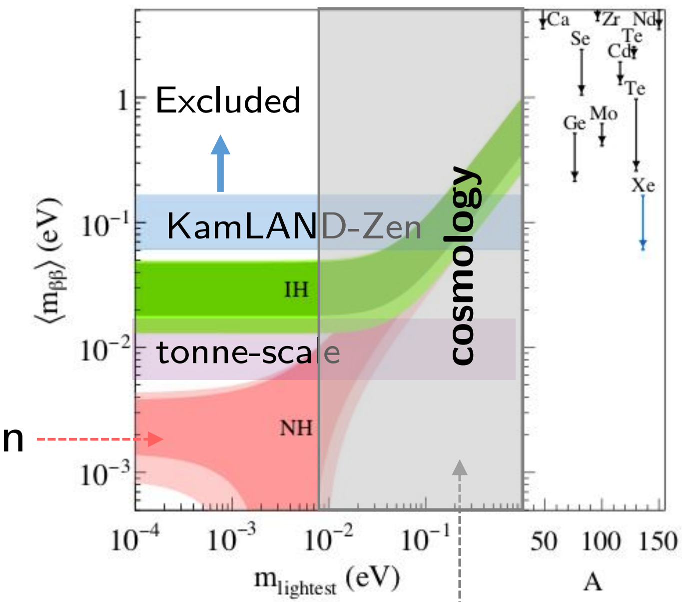
oscillation data



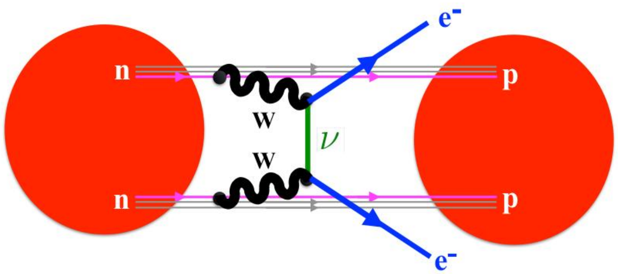
$$\sum m_\nu < 72 \text{ meV}$$ CMB + DESI BAO, ΛCDM

DESI, 2404.03002

$$\Rightarrow \quad \mathrm{m_{lightest}} < 8.7 \times 10^{-3} \text{ eV}$$

Neutrinoless double beta decay

- Standard mechanism



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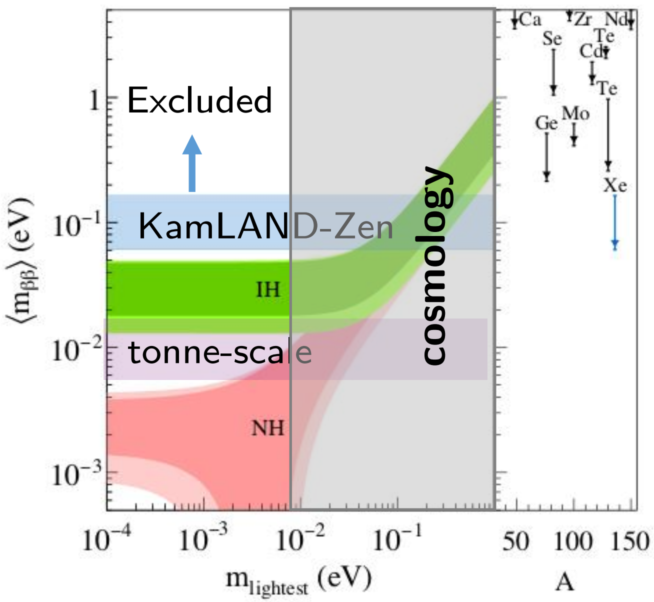
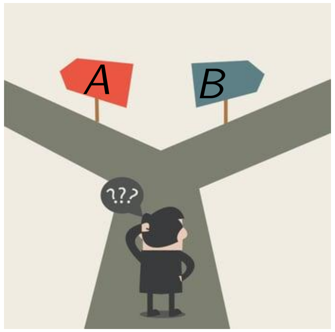


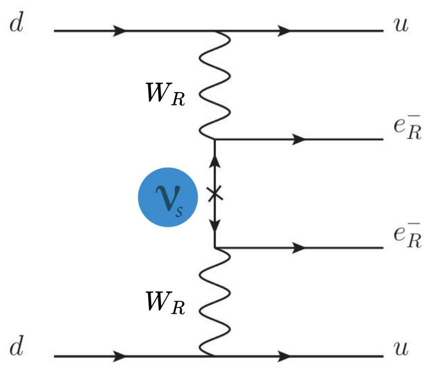
A: better sensitivity of $0\nu\beta\beta$ decay experiments

B: other theoretical scenarios



Neutrinoless double beta decay

- Non-standard mechanism



$q \sim 200$ MeV

right-handed current:

$$P_R \frac{\not{q} + m_i}{q^2 - m_i^2} P_R = P_R \frac{m_i}{q^2 - m_i^2} P_R \qquad i > 3$$

Neutrinoless double beta decay

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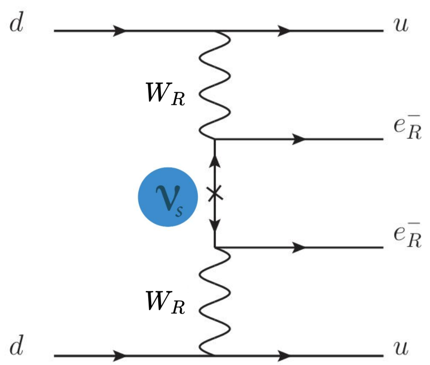

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$m_i^2 \ll -q^2$ → $P_R \frac{m_i}{q^2} P_R$ small mass region

$m_i^2 \gg -q^2$ → $-P_R \frac{1}{m_i} P_R$ large mass region

Comparison of the $0\nu\beta\beta$ decay amplitudes:

$$\frac{\text{sterile}}{\text{active}} \qquad \boxed{\frac{m_i}{m_\nu}\left(\frac{M_{W_L}}{M_{W_R}}\right)^4} \qquad \boxed{\frac{q^2}{m_i m_\nu}\left(\frac{M_{W_L}}{M_{W_R}}\right)^4}$$

Left-Right symmetric model

Gauge group: $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

Doublets:

$$q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \qquad q_R = \begin{pmatrix} u \\ d \end{pmatrix}_R$$

$$L_L = \begin{pmatrix} \nu \\ l \end{pmatrix}_L \qquad L_R = \begin{pmatrix} N \\ l \end{pmatrix}_R$$

Bidoublet:

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \Rightarrow \langle \Phi \rangle = \begin{pmatrix} v_1 & 0 \\ 0 & v_2 e^{i\alpha} \end{pmatrix} \qquad \boxed{\tan\beta \equiv \frac{v_2}{v_1}}$$

Triplets:

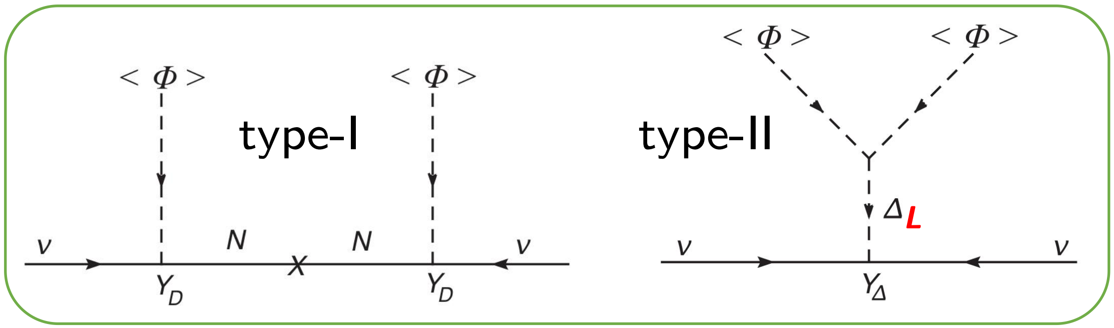
$$\Delta_{L,R} = \begin{pmatrix} \delta_{L,R}^+/\sqrt{2} & \delta_{L,R}^{++} \\ \delta_{L,R}^0 & -\delta_{L,R}^+/\sqrt{2} \end{pmatrix}$$

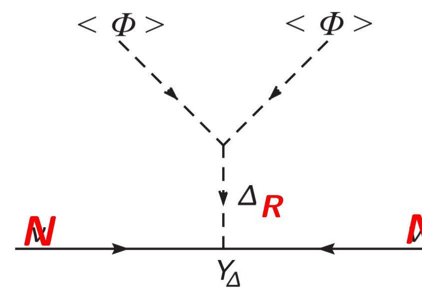
$$\Rightarrow \langle \Delta_R \rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}, \qquad \langle \Delta_L \rangle = \begin{pmatrix} 0 & 0 \\ v_L e^{i\theta_L} & 0 \end{pmatrix}$$

Mohapatra and Senjanovic, Phys.Rev.Lett. 44 (1980) 912, Phys.Rev.D 23 (1981) 165

Left-Right symmetric model

- Type I+II seesaw:





$$M_L = Y_{\Delta_L} v_L$$

$$M_N = Y_{\Delta_R} v_R$$

$$M_\nu = M_L - M_D^T \frac{1}{M_N} M_D$$

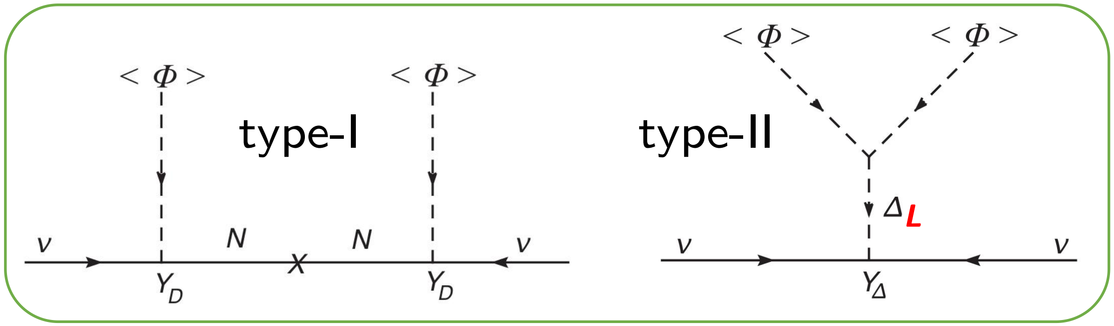
Dynamical origin of right-handed neutrino mass

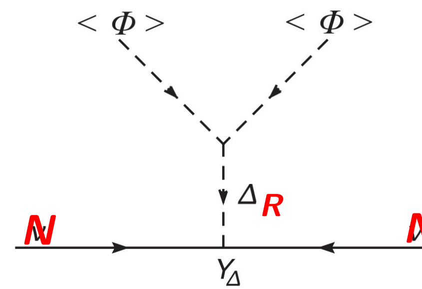
- Triplet vev: $v_L \propto v^2 / v_R$

flavor basis: RH neutrino
mass basis: sterile neutrino

Left-Right symmetric model

- Type I+II seesaw:





$$M_L = Y_{\Delta_L} v_L$$

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$$M_\nu = M_L - M_D^T \frac{1}{M_N} M_D$$

- Triplet vev: $v_L \propto v^2/v_R$

- Left-right symmetry:

$$\mathcal{P}: \; Y_{\Delta_L} = Y_{\Delta_R}$$

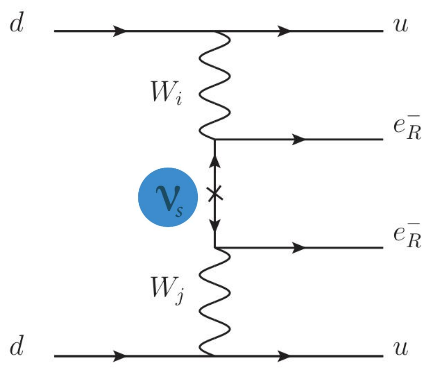
$$\mathcal{C}: \; Y_{\Delta_L} = Y_{\Delta_R}^*$$

(lepton sector)

flavor basis: RH neutrino
mass basis: sterile neutrino

Left-Right symmetric model

- Contributions to $0\nu\beta\beta$ decay



In the large mass region

$$\frac{q^2}{m_i m_\nu}\left(\frac{M_{W_L}}{M_{W_R}}\right)^4 \times \max\left\{\frac{\Lambda_\chi^2}{m_\pi^2}\ \tan\beta,\ 1\right\}$$

In the small mass region

$$\frac{m_i}{m_\nu}\left(\frac{M_{W_L}}{M_{W_R}}\right)^4 \times \max\left\{\frac{\Lambda_\chi^2}{m_\pi^2}\ \tan\beta,\ 1\right\}$$

Left-Right symmetric model

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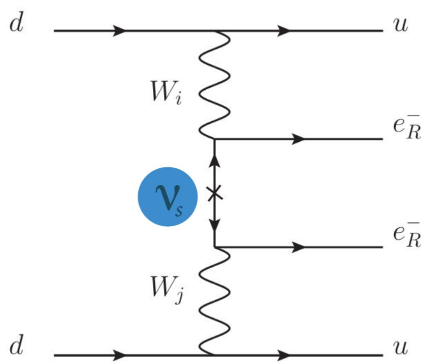

$$\begin{pmatrix} W_L \\ W_R \end{pmatrix} \longrightarrow \begin{pmatrix} W_1 \\ W_2 \end{pmatrix}$$

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$\tan\beta \in [0, 0.5]$ $\quad W_L - W_R$ mixing

Left-Right symmetric model

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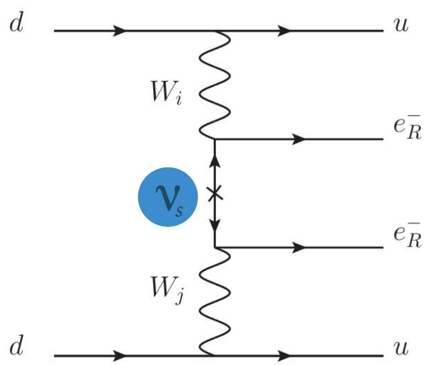

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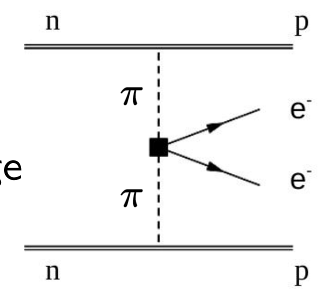
$$\frac{\Lambda_\chi^2}{m_\pi^2} \sim 25$$

In the small mass region

$$\frac{m_i}{m_\nu}\left(\frac{M_{W_L}}{M_{W_R}}\right)^4 \times \max\left\{\frac{\Lambda_\chi^2}{m_\pi^2}\tan\beta,\ 1\right\}$$

long-range
pion exchange



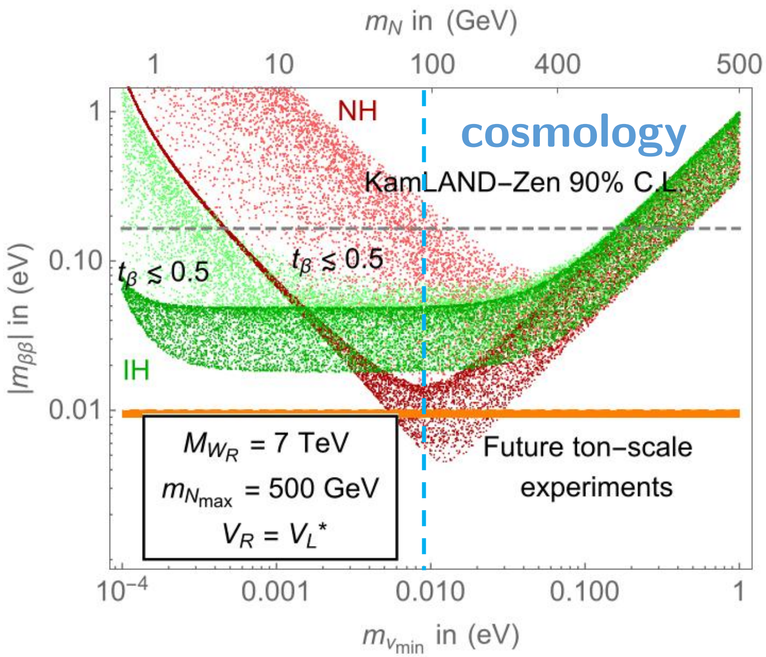
chiral enhancement

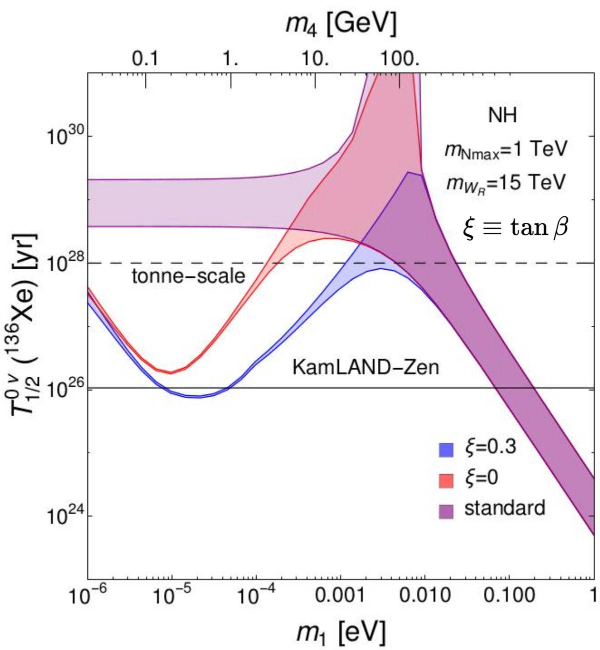
Prézeau, Ramsey-Musolf, Vogel,
Physical Review D 68, 034016 (2003)

Sterile neutrinos and Lepton Number Violation

- Type-II seesaw dominance

$$M_\nu = M_L = \frac{v_L}{v_R} M_N$$





GL, M. Ramsey-Musolf, J. C. Vasquez, 2009.01257 (PRL)

J. de Vries, GL, M. J. Ramsey-Musolf, J. C. Vasquez, 2209.03031 (JHEP)

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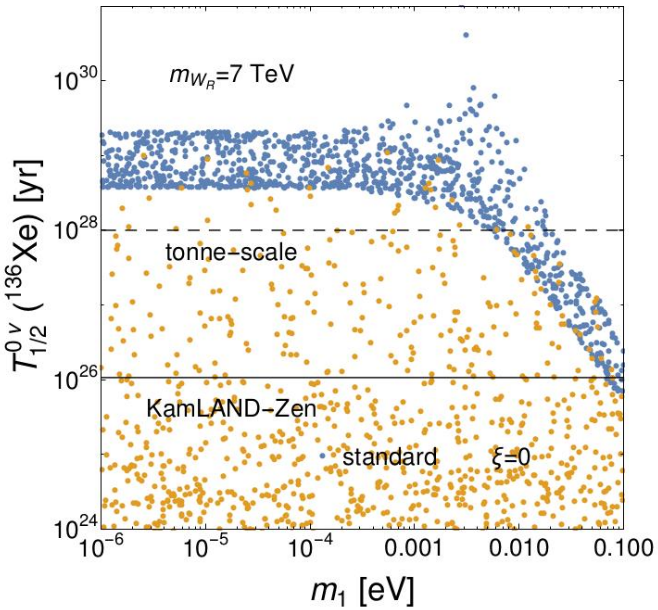
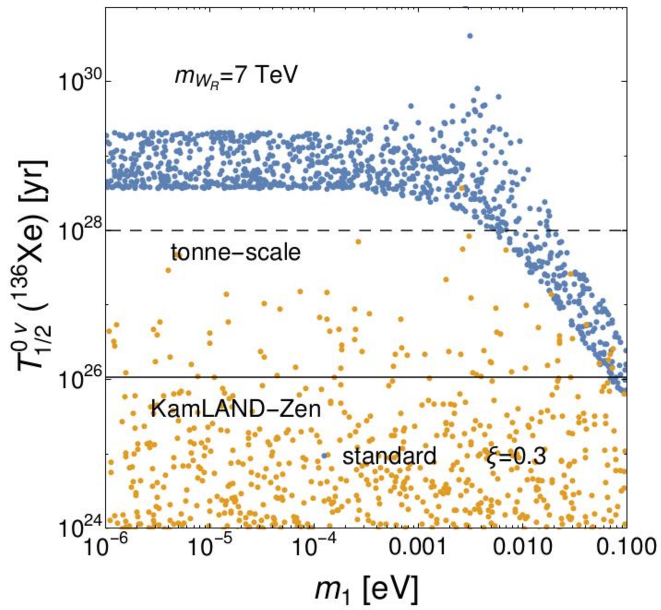
- Type-I seesaw dominance

$$M_\nu = -M_D^T \frac{1}{M_N} M_D$$





The sterile neutrino masses are randomly chosen in $[10\ \mathrm{MeV}, 1\ \mathrm{TeV}]$

J. de Vries, GL, M. J. Ramsey-Musolf, J. C. Vasquez, 2209.03031 (JHEP)

New physics

The Standard Model is successful but incomplete:

- neutrino masses
- baryon asymmetry
- dark matter
- strong CP problem ✔
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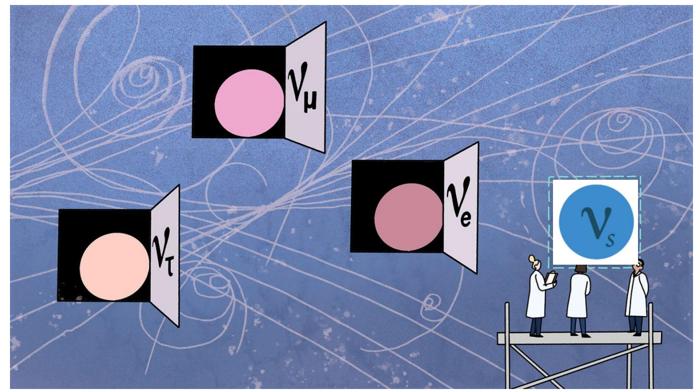

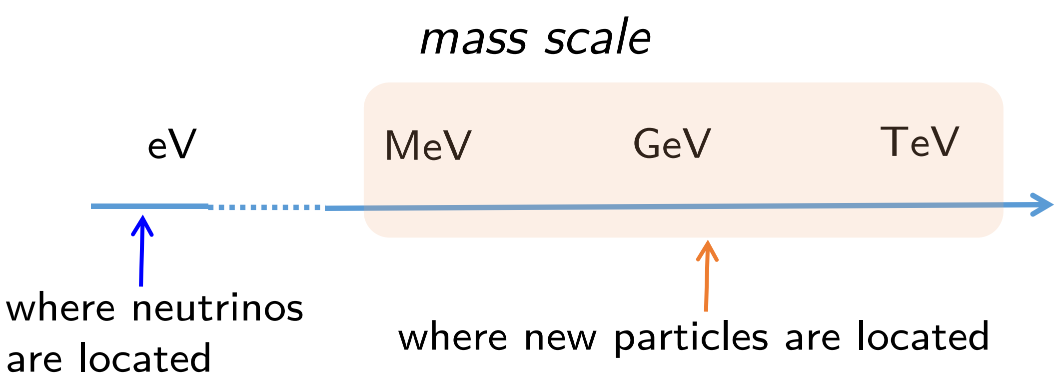

Solution of strong CP problem

In the SM,

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4}G_{\mu\nu}G^{\mu\nu} + \theta\frac{g_s^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu} + \bar{q}\left(i\gamma^\mu D_\mu - M_q\right)q$$

$\bar{\theta} = \theta + \arg\det\left(M_u M_d\right)$ $\quad$ $\bar{\theta}_{\rm exp} < 10^{-10}$ $\quad$ unnaturally small

Beyond the SM,

- Peccei-Quinn solution: promote $\bar{\theta}$ to be a dynamic field (axion)

  Peccei, Quinn, 1977; Weinberg 1978; Wilczek 1978

- Parity solution: forbid θ at tree and one-loop levels in the left-right symmetric model

  Mohapatra, Senjanovic, 1978
  Babu, Mohapatra, 1989-1990

$$\bar{\theta} = \arg\det(M_u M_d)$$

Solution of strong CP problem

In the left-right symmetric model,

Parity as the left-right symmetry: $Y_q = Y_q^\dagger$ (quark sector)

Quark mass matrix $M_q = Y_q \langle \Phi \rangle$ is generally complex

$$\langle \Phi \rangle = \begin{pmatrix} v_1 & 0 \\ 0 & v_2 e^{i\alpha} \end{pmatrix}$$ spotaneous CP phase

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$$\bar{\theta} = \arg\det(M_u M_d) \simeq s_\alpha t_{2\beta} m_t / (2 m_b)$$

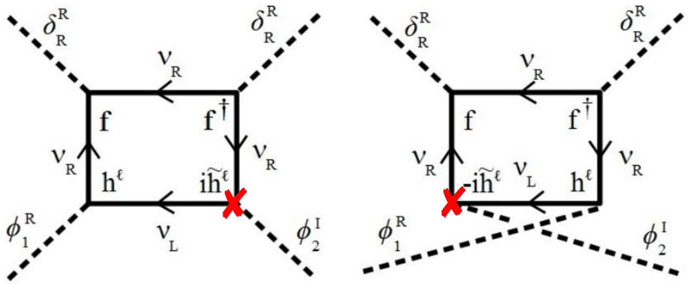
A. Maiezza and M. Nemevšek, 1407.3678 (PRD)

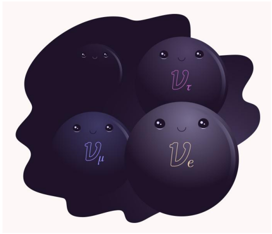
The stringent limit on $\bar{\theta}$ implies an extremely small CP phase α

Why is it so small?

Sterile neutrinos and strong CP problem

- Strong and leptonic CP violation





Necessary conditions:

- **sterile neutrinos** in the loop
- leptonic CP violation

R. Kuchimanchi, 1408.6382 (PRD)

$$V \supset \left[\alpha_2 \,\mathrm{Tr}\left(\tilde{\Phi}\Phi^\dagger\right) + \text{ h.c. } \right] \mathrm{Tr}\left(\Delta_R \Delta_R^\dagger\right)$$
$$+ \alpha_3 \,\mathrm{Tr}\left(\Phi^\dagger \Phi \Delta_R \Delta_R^\dagger\right).$$

complex scalar potential

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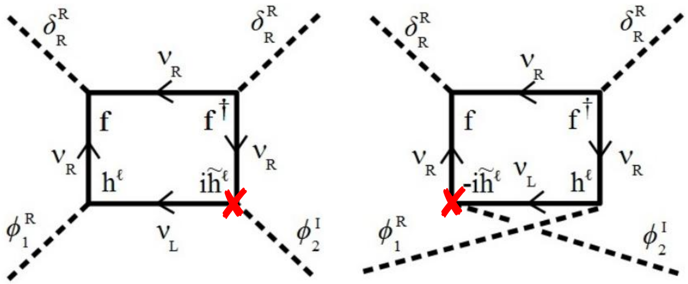
- Strong and leptonic CP violation



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$$s_\alpha t_{2\beta} = -4 \frac{\mathrm{Im}\, \alpha_2}{\alpha_3}$$

$$\bar{\theta} \simeq s_\alpha t_{2\beta} m_t / \left(2 m_b\right)$$

complex scalar potential

spotaneous symmetry breaking

complex vacuum

strong CP violation

Sterile neutrinos and strong CP problem

- In terms of mass parameters

One-loop strong CP parameter

$$\bar{\theta}_{\rm loop} \simeq \frac{1}{16\pi^2}\frac{m_t}{m_b}\frac{1}{v_R^2 v^2}{\rm Im\,Tr}\left(M_N^T M_N^* [M_D, M_\ell]\right)\ln\frac{M_{\rm Pl}}{v_R}$$

Earlier studies assuming the simplest case: $V_R = V_L$

$[M_D, M_\ell] = 0$ ⟹ $\bar{\theta}_{\rm loop} = 0$

- We propose a general parametrization

$$M_N = P M_\nu^{-1} P^T \qquad V_R = \hat{P} V_L$$

$$\hat{P} \equiv P V_L \sqrt{m_N m_\nu}^{-1} V_L^\dagger$$

$\hat{P}$ is an arbitrary unitary matrix, and P can be Hermitian or anti-Hermitian

GL, Ding-Yi Luo, Xiang Zhao, 2404.16740 (PRD)

Sterile neutrinos and strong CP problem

- In terms of mass parameters

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Non-trivial cases:

$$\hat{P}_1 = i\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \qquad \hat{P}_2 = i\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

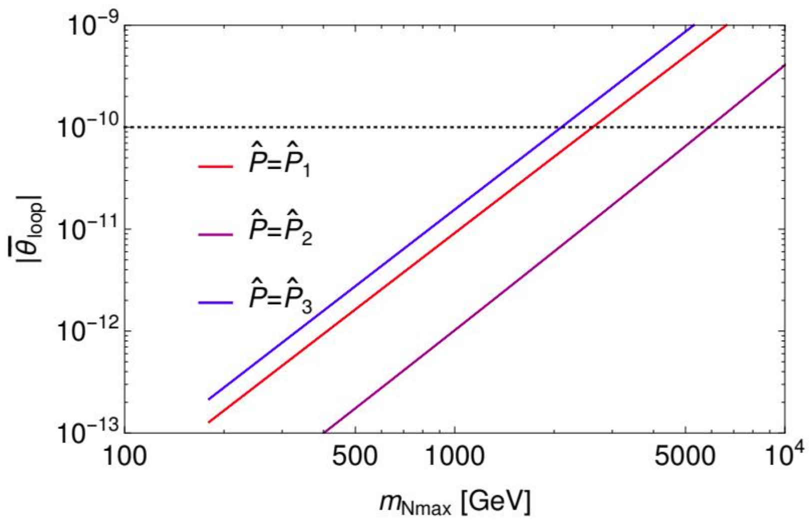
$$\hat{P}_3 = i\begin{pmatrix} \frac{1}{2} & \frac{1}{2} & -\frac{\sqrt{2}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{\sqrt{2}}{2} \\ -\frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & 0 \end{pmatrix}.$$

$$\bar{\theta}_{\rm loop} \propto (m_{\rm N\,max})^{5/2}$$

Upper bound on the heaviest sterile neutrino mass

Sterile neutrinos and strong CP problem

- TeV-scale sterile neutrino



GL, Ding-Yi Luo, Xiang Zhao, 2404.16740 (PRD)

Type I+II seesaw scenario:

$$m_1 = 10^{-3}\ \text{eV},\ v_L = 1\ \text{eV},\ v_R = 15\ \text{TeV}$$

For $\hat{P} = \hat{P}_1$,

$$m_N = \begin{pmatrix} 2.86\ \text{TeV} & 0 & 0 \\ 0 & 3.32\ \text{GeV} & 0 \\ 0 & 0 & 57.2\ \text{MeV} \end{pmatrix}$$

$$\Rightarrow \quad \bar{\theta}_{\rm loop} = -1.241335 \times 10^{-10}$$

MeV-GeV and TeV scale sterile neutrinos coexist

Summary

- Sterile neutrinos serve as an intriguing window to new physics
- In the context of left-right symmetric model,
  - MeV-GeV scale sterile neutrino gives significant contribution to $0\nu\beta\beta$ decay, which can assess the Majorana nature of neutrinos and lepton number violation
  - TeV scale sterile neutrino can account for the strong CP violation from the leptonic CP violation