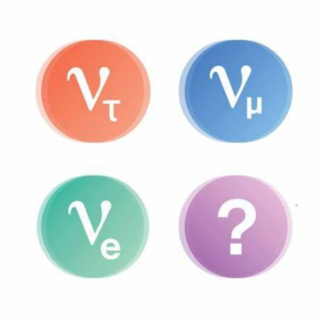


Sterile Neutrinos as a Window to New Physics

Gang Li (李刚)

School of Physics and Astronomy,
Sun Yat-sen University, Zhuhai

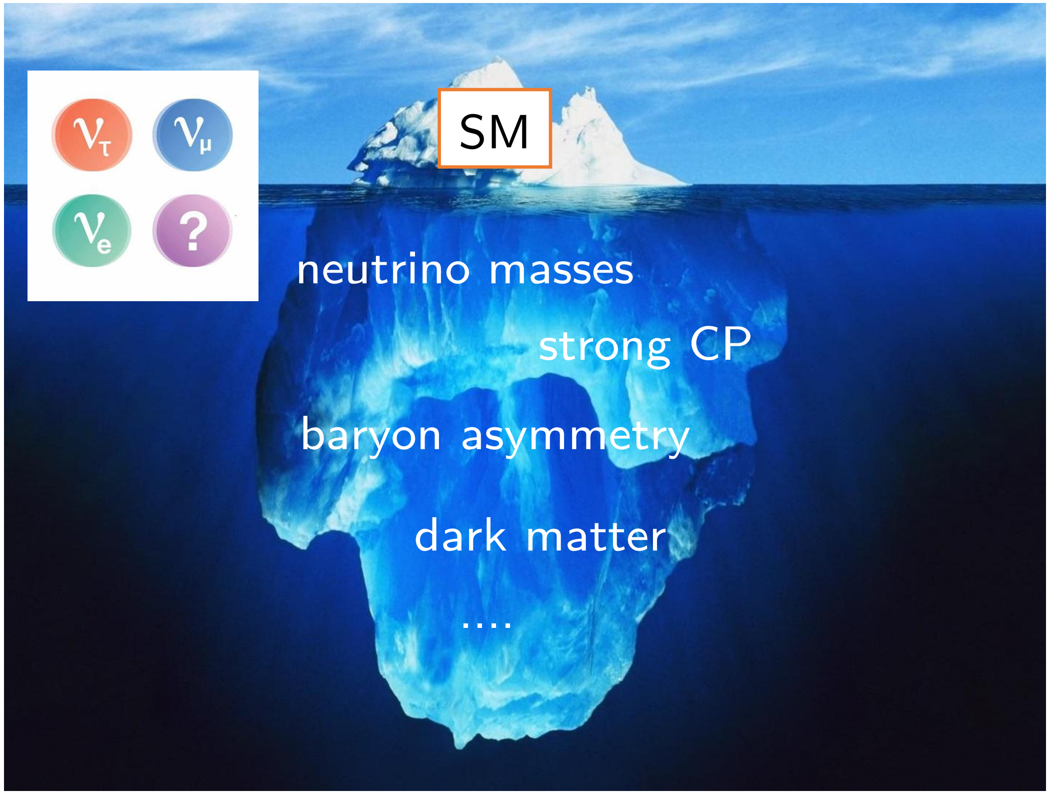
Based on 2202.01789 (PRD); 2209.03031 (JHEP); 2404.16740

2024年理论物理前沿与交叉科学研讨会（第二届彭桓武科教合作中心联席会议）

2024年4月27日

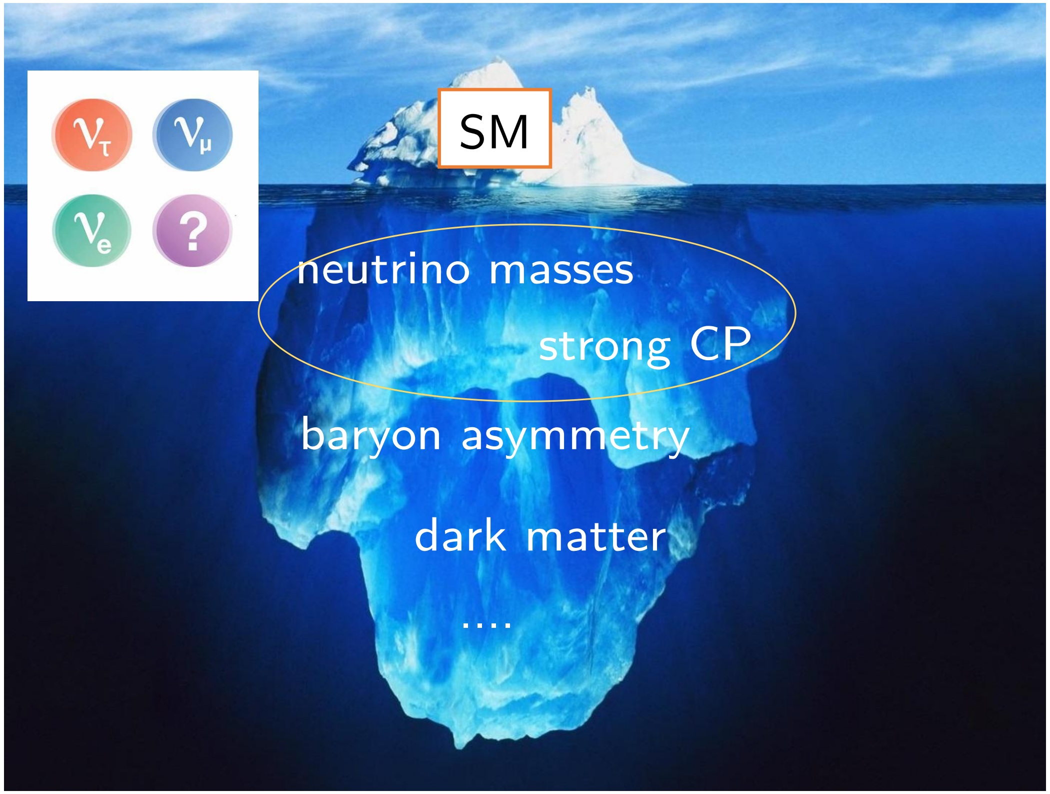
Tail of new physics

- Massive neutrinos



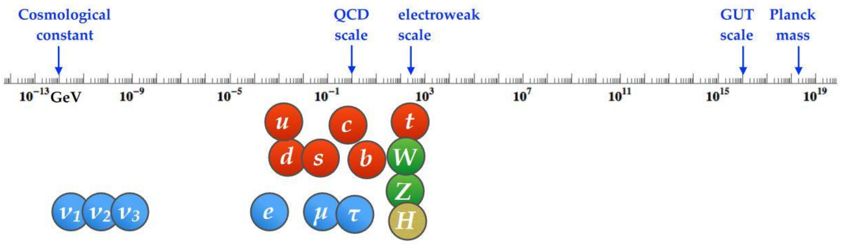
Tail of new physics

- Massive neutrinos

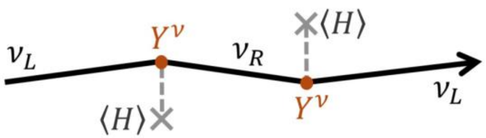


Neutrino masses

- How do neutrinos get tiny masses?



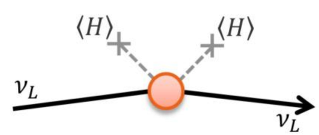
Dirac mass:



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

very small coupling

Majorana mass:



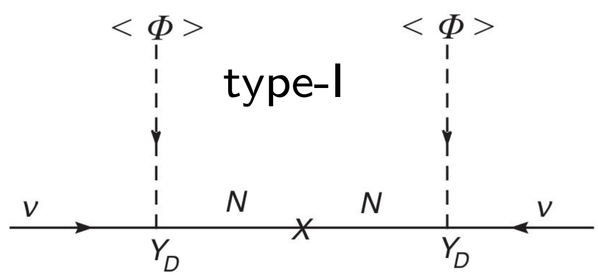
$$\mathcal{L}_M = \frac{C_5}{\Lambda}(\bar{L}^c \tilde{H}^*)(\tilde{H}^\dagger L) + \text{h.c.}$$

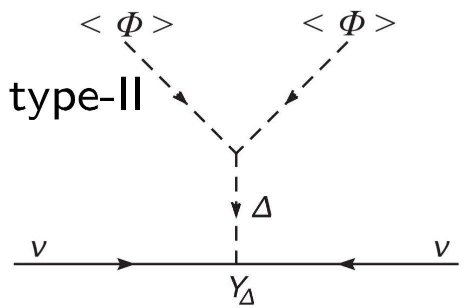
(very) large scale

a la eg. type-I, II, III seesaw

Neutrino masses

Seesaw mechanisms:





$$-M_D M_N^{-1} M_D^T$$

$$Y_\Delta \frac{\mu v^2}{M_\Delta^2}$$

(1) How do heavy neutrinos interact with the SM?

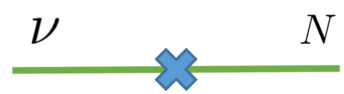
(2) How do heavy neutrinos get Majorana masses M_N?

Neutrino masses

(1) From flavor basis to mass basis, heavy neutrinos interact with the SM

$$\begin{pmatrix} \nu \\ N \end{pmatrix} \to \begin{pmatrix} 1 & \Theta^\dagger \\ -\Theta & 1 \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}$$

active-sterile mixing:



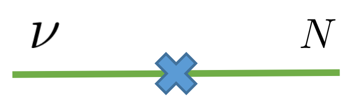
$$\Theta = \frac{1}{M_N} M_D \ll 1$$

Neutrino masses

(1) From flavor basis to mass basis, heavy neutrinos interact with the SM

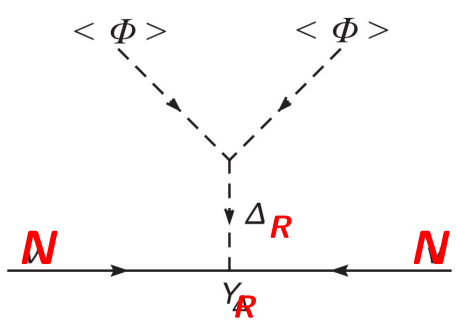
$$\begin{pmatrix} \nu \\ N \end{pmatrix} \to \begin{pmatrix} 1 & \Theta^\dagger \\ -\Theta & 1 \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}$$

active-sterile mixing:



$$\Theta = \frac{1}{M_N} M_D \ll 1$$

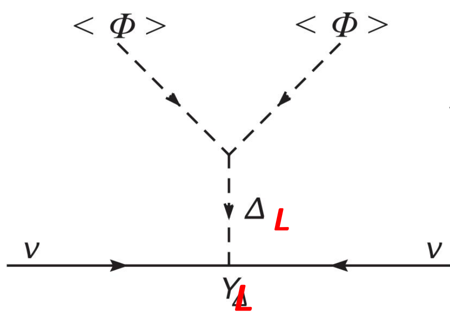
(2) Spontaneous symmetry breaking above the electroweak scale



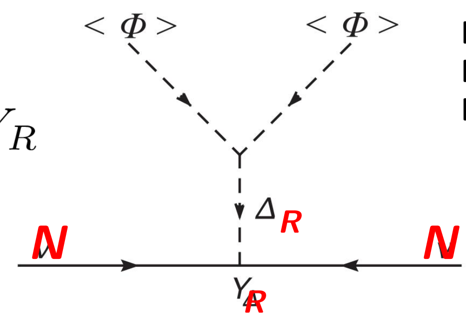
$$M_N = Y_R \langle \Delta_R \rangle$$

Left-Right Symmetric Model

The left-right symmetry $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$



$$Y_L = Y_R$$

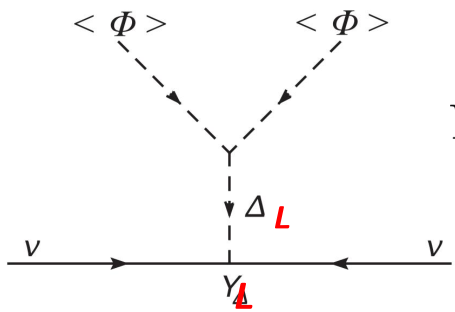


R. Mohapatra, G. Senjanovic,
Phys.Rev.Lett. 44 (1980) 912,
Phys.Rev.D 23 (1981) 165

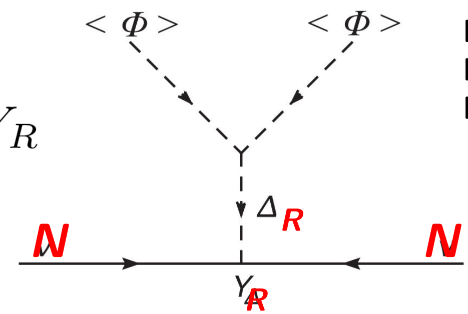
$$M_L = Y_L \langle \Delta_L \rangle \qquad M_N = Y_R \langle \Delta_R \rangle$$

Left-Right Symmetric Model

The left-right symmetry $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$



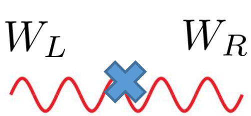
$$Y_L = Y_R$$



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

$$M_L = Y_L \langle \Delta_L \rangle \qquad\qquad M_N = Y_R \langle \Delta_R \rangle$$

Left-right symmetry is broken, leading to the left-right mixing



$$\zeta = \frac{M_W^2}{M_{W_R}^2} \sin(2\beta) \lesssim 10^{-4}$$

$$\langle \Phi \rangle = v \, \mathrm{diag}\left(c_\beta, -s_\beta e^{-i\alpha}\right)$$

Sterile neutrinos

General seesaw relation in the LRSM:

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

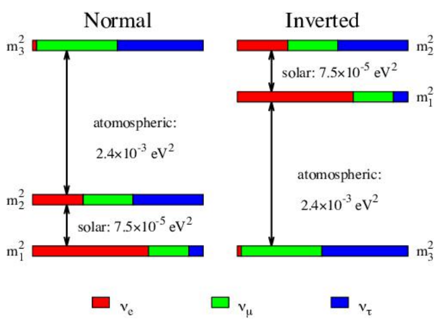
- Type-I seesaw dominance: $M_\nu = -M_D^T \frac{1}{M_N} M_D$
- Type-II seesaw dominance: $M_\nu = M_L = \frac{v_L}{v_R} M_N \qquad v_{L,R} \equiv \langle \Delta_{L,R} \rangle$

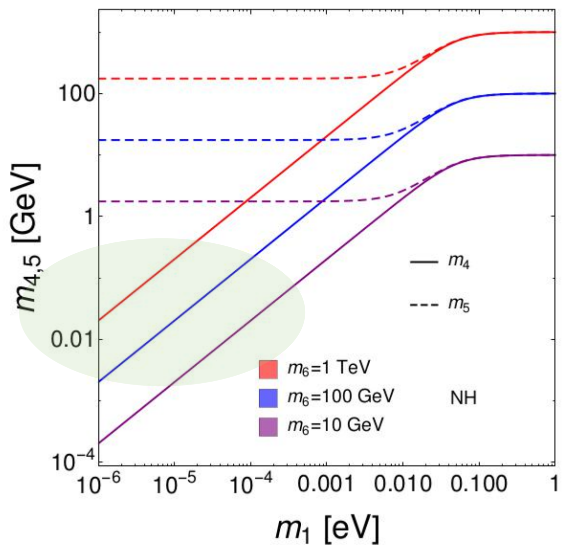
Sterile neutrinos

General seesaw relation in the LRSM:

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

- Type-I seesaw dominance: $M_\nu = -M_D^T \frac{1}{M_N} M_D$
- Type-II seesaw dominance: $M_\nu = M_L = \frac{v_L}{v_R} M_N \qquad v_{L,R} \equiv \langle \Delta_{L,R} \rangle$





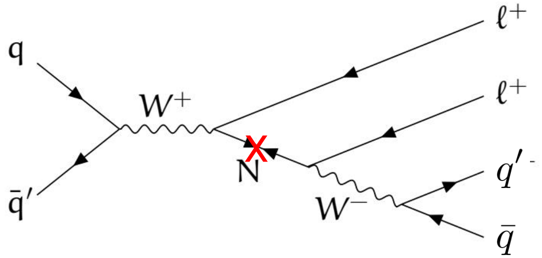
sterile neutrino can be very light

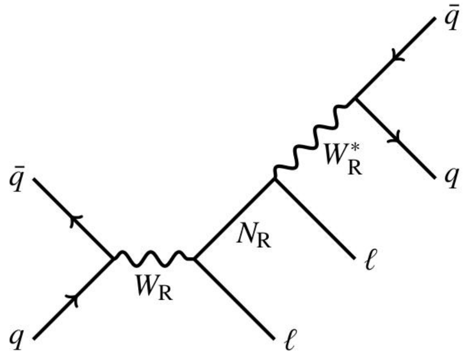
de Vries, GL, Ramsey-Musolf, Vasquez, 2209.03031 (JHEP)

Sterile neutrinos

Sterile neutrinos to elucidate the origin of neutrino masses:

- Direct searches (masses and couplings)





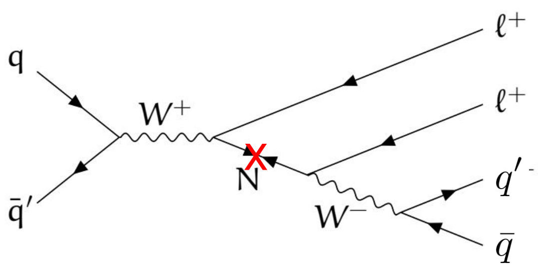
- active-sterile mixing Θ
- sensitive to light N

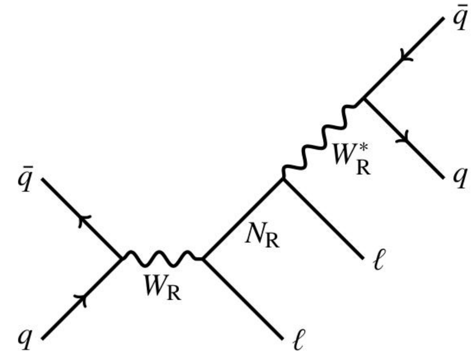
- suppression by W_R mass
- sensitive to heavy N

Sterile neutrinos

Sterile neutrinos to elucidate the origin of neutrino masses:

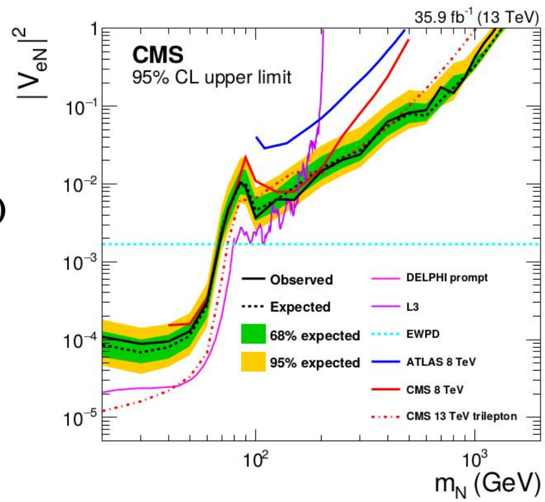
- Direct searches (masses and couplings)

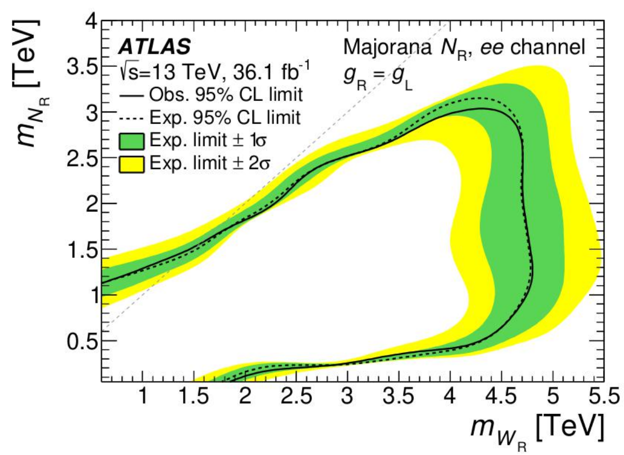




Keung-Senjanovic process

$$V_{eN} \sim \Theta$$

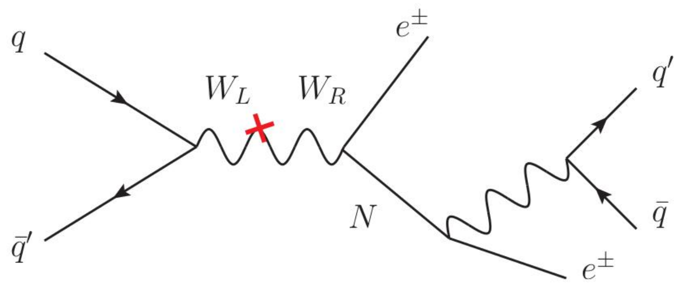




Sterile neutrinos

Sterile neutrinos to elucidate the origin of neutrino masses:

- Direct searches (masses and couplings)



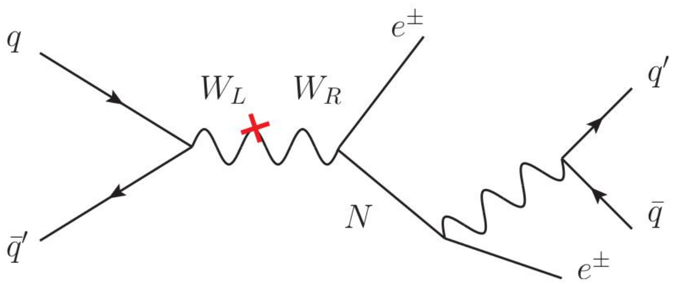
  - left-right mixing ζ
  - sensitive to light N

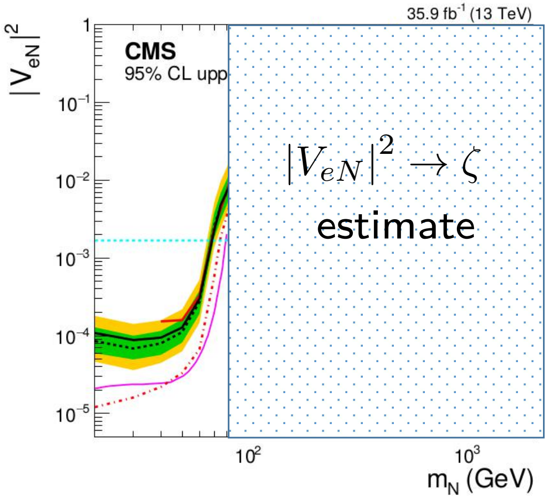
GL, Ramsey-Musolf, Vasquez, 2202.01789 (PRD)

Sterile neutrinos

Sterile neutrinos to elucidate the origin of neutrino masses:

- Direct searches (masses and couplings)





- left-right mixing ζ
- sensitive to light N

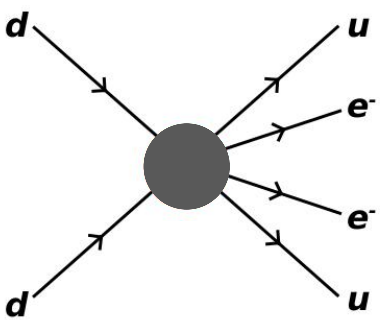
GL, Ramsey-Musolf, Vasquez, 2202.01789 (PRD)

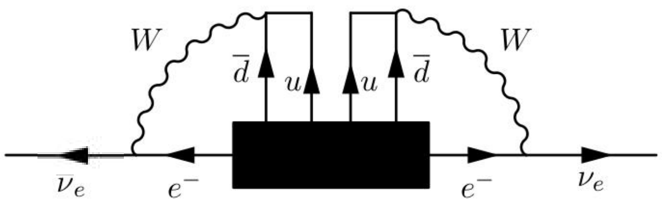
- sensitivity comparable to Keung-Senjanovic process $|V_{eN}|^2 \sim \zeta \sim 10^{-4}$
- new probe of light sterile neutrino in the LRSM

Sterile neutrinos

Sterile neutrinos to elucidate the origin of neutrino masses:

- Neutrinoless double beta decay (Majorana vs Dirac)



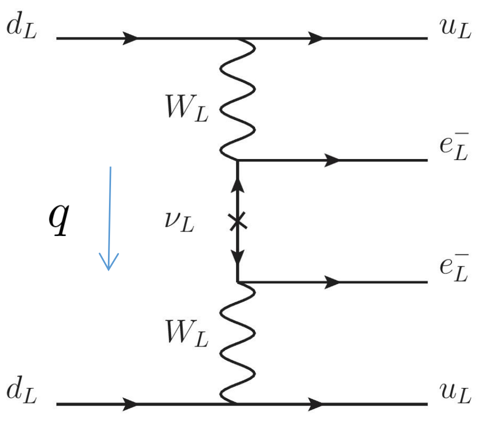


Schechter, Valle, Phys.Rev. D25 (1982) 774

Sterile neutrinos

Sterile neutrinos to elucidate the origin of neutrino masses:

- Neutrinoless double beta decay (Majorana vs Dirac)



$$-q^2 \sim (200\ \mathrm{MeV})^2$$

mass dependence:

$$P_L \frac{\not{q} + m_i}{q^2 - m_i^2} P_L = P_L \frac{m_i}{q^2 - m_i^2} P_L$$

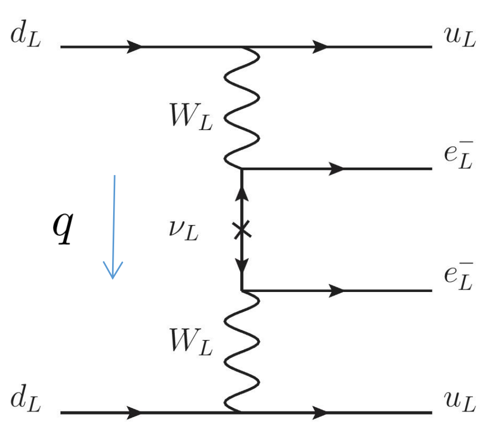
$$m_i^2 \ll -q^2$$

$$P_L \frac{m_i}{q^2} P_L$$

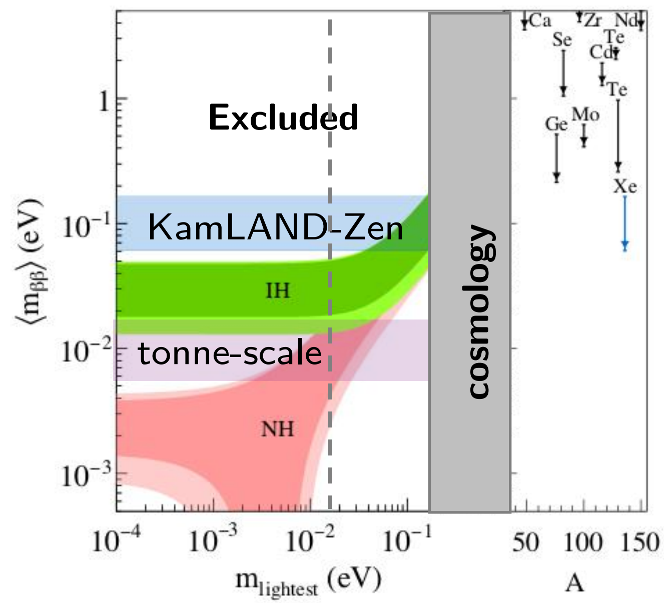
Sterile neutrinos

Sterile neutrinos to elucidate the origin of neutrino masses:

- Neutrinoless double beta decay (Majorana vs Dirac)



$$-q^2 \sim (200\ \mathrm{MeV})^2$$

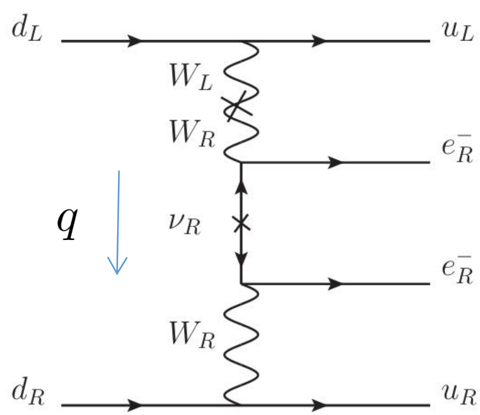


$$\langle m_{\beta\beta}\rangle = |\sum_i m_i U_{ei}^2|$$

Sterile neutrinos

Sterile neutrinos to elucidate the origin of neutrino masses:

- Neutrinoless double beta decay (Majorana vs Dirac)



$$-q^2 \sim (200\ \mathrm{MeV})^2$$

mass dependence:

$$P_R \frac{\not{q} + m_i}{q^2 - m_i^2} P_R = P_R \frac{m_i}{q^2 - m_i^2} P_R$$

$$m_i^2 \ll -q^2 \qquad\qquad m_i^2 \gg -q^2$$

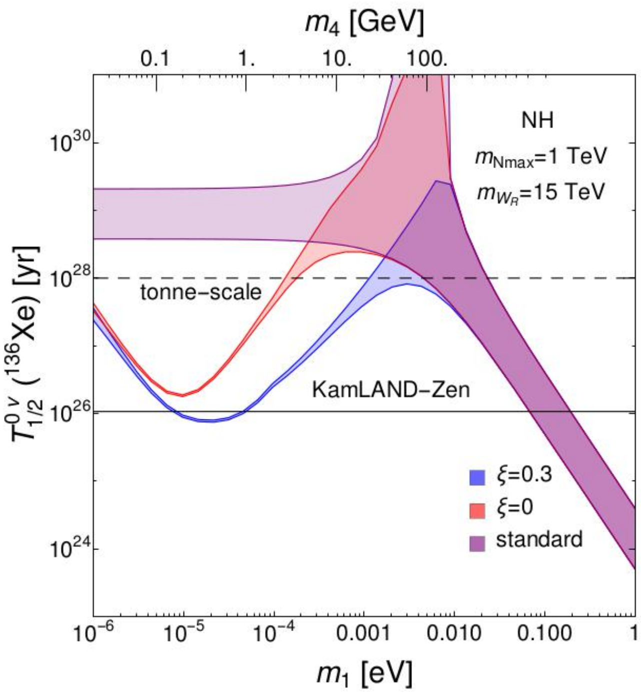
$$P_R \frac{m_i}{q^2} P_R \qquad\qquad -P_R \frac{1}{m_i} P_R$$

Sterile neutrinos with intermediate mass have the potential to make significant contributions

Sterile neutrinos

Sterile neutrinos to elucidate the origin of neutrino masses:

- Neutrinoless double beta decay (Majorana vs Dirac)



type-II seesaw dominance:

$$m_4 = \frac{m_1}{m_3} m_{N_{\max}} \qquad m_{N_{\max}} \equiv m_6$$

$$m_N \simeq 200 \text{ GeV} \cdot \frac{m_1}{0.01 \text{ eV}} \cdot \frac{m_{N_{\max}}}{1 \text{ TeV}}$$

de Vries, GL, Ramsey-Musolf, Vasquez, 2209.03031 (JHEP)

strong support for next-generation experimental searches

Left-Right Symmetric Model

The left-right symmetry $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

no QCD θ term due to parity (axionless solution)

$$\cancel{\delta \mathcal{L}_{\mathrm{QCD}} = \theta \frac{g_s^2}{32\pi^2} G\tilde{G}}$$

Mohapatra, Senjanovic 1978
Babu, Mohapatra 1989

Left-Right Symmetric Model

The left-right symmetry $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

no QCD θ term due to parity (axionless solution)

$$\cancel{\delta\mathcal{L}_{\mathrm{QCD}} = \theta \frac{g_s^2}{32\pi^2} G\tilde{G}}$$

Mohapatra, Senjanovic 1978
Babu, Mohapatra 1989

Strong CP problem: $\bar{\theta}^{\mathrm{exp}} \lesssim 10^{-10}$

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

Left-Right Symmetric Model

The left-right symmetry $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

no QCD θ term due to parity (axionless solution)

$$\cancel{\delta\mathcal{L}_{\rm QCD} = \theta\frac{g_s^2}{32\pi^2}G\tilde{G}}$$

Mohapatra, Senjanovic 1978
Babu, Mohapatra 1989

Strong CP problem: $\bar{\theta}^{\rm exp} \lesssim 10^{-10}$

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

For quark Yukawa interaction $\bar{Q}_L Y_Q \Phi Q_R$,

$$Q_L \leftrightarrow Q_R \quad \Phi \leftrightarrow \Phi^\dagger \quad Y_Q \leftrightarrow Y_Q^\dagger$$

Quark mass matrix $M_Q = Y_Q\langle\Phi\rangle$ is generally complex

$$\langle\Phi\rangle = v\,\mathrm{diag}\left(c_\beta, -s_\beta e^{-i\alpha}\right)$$

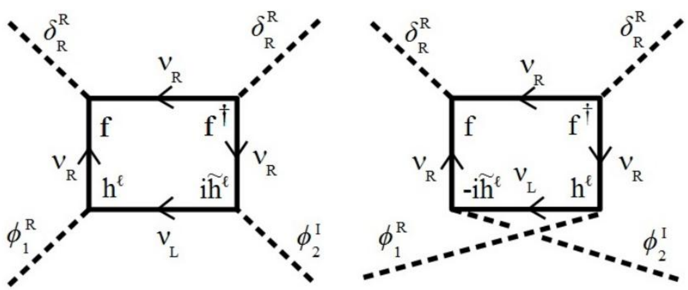
$$\bar{\theta} \simeq s_\alpha t_{2\beta} m_t / \left(2m_b\right)$$

tree-level, from CP violation in quark sector

Sterile neutrinos

Sterile neutrinos to address strong CP problem

Even if $s_\alpha t_{2\beta} \to 0$, $\bar{\theta}$ can be generated from leptonic CP violation at one-loop level



R. Kuchimanchi, 1408.6382 (PRD)

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

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

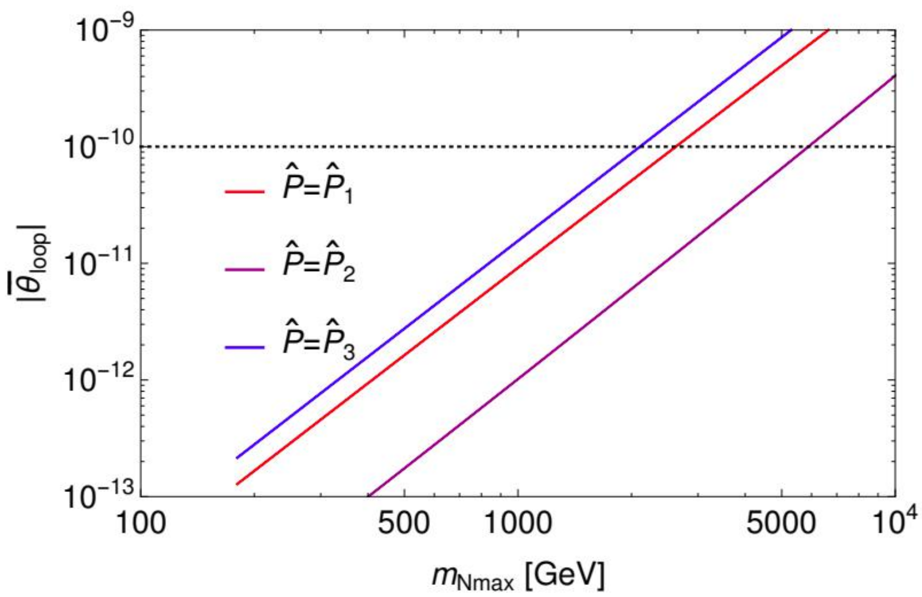
G. Senjanovic and V. Tello, 2004.04036 (IJMPA)

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

Sterile neutrinos

Sterile neutrinos to address strong CP problem

One-loop $\bar{\theta}$ is sensitive to the sterile neutrino masses, thereby $\theta_{loop} \lesssim 10^{-10}$ sets upper limits on the sterile neutrino masses



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

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

GL, Ding-Yi Luo, Xiang Zhao, 2404.16740

Summary

- Sterile neutrinos provide a unique insight into new physics, including the understanding of neutrino masses and resolution of the strong CP problem.

- Left-right symmetric model explains the origin of neutrino masse:

  - Light sterile neutrinos can be directly probed at the LHC and significantly contribute to $0\nu\beta\beta$ decay
  - Heavy sterile neutrino can address strong CP problem

- Outlook:
  - interplay of $0\nu\beta\beta$ decay and neutron EDMs
  - connections of sterile neutrinos to baryon asymmetry and dark matter

Thanks for your attention!