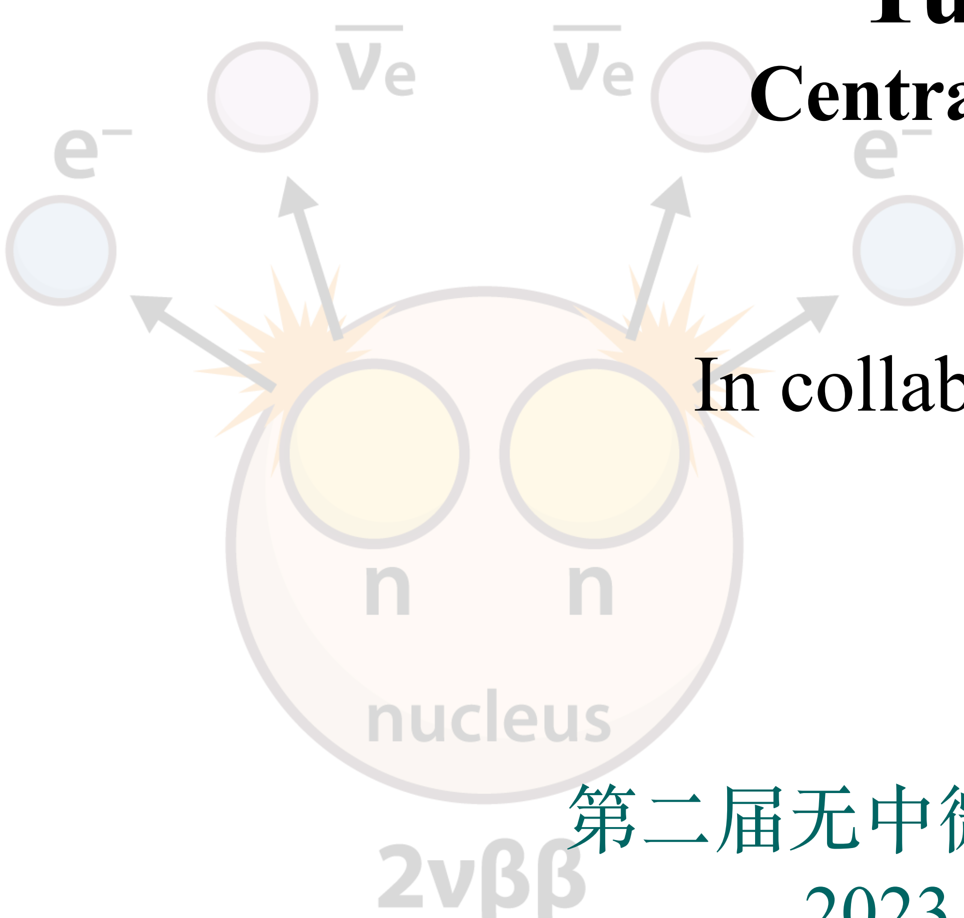
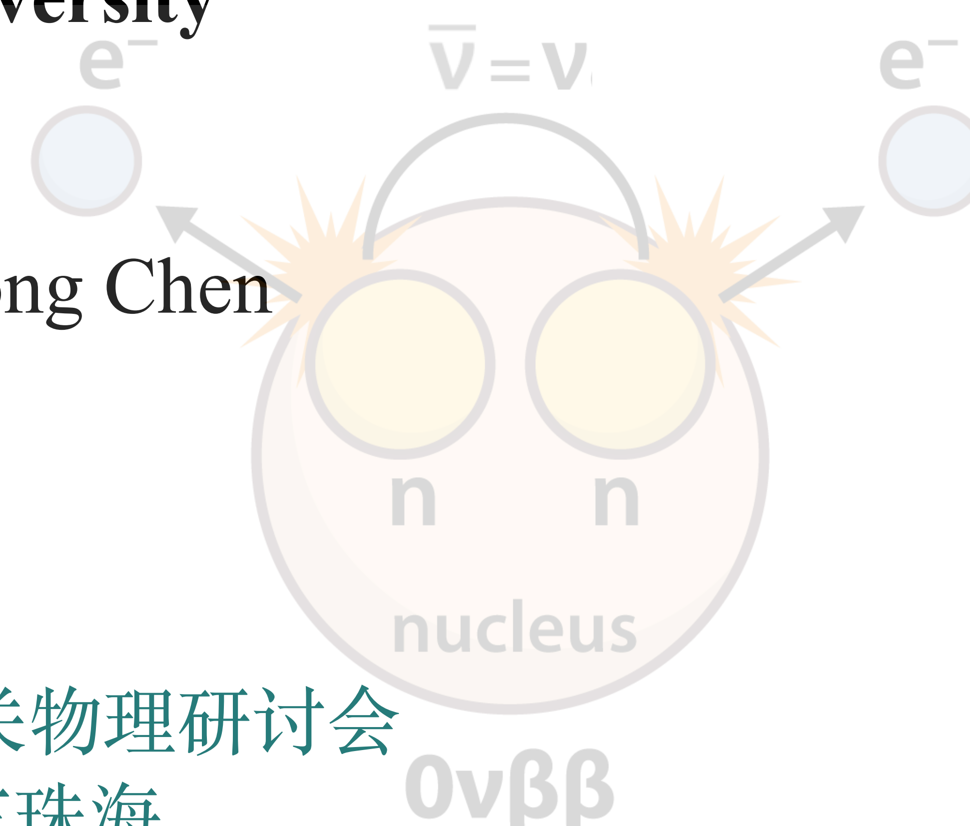
Neutrinoless Double Beta Decay in the Colored Zee-Babu Model

Yu-Qi Xiao（肖雨奇）
Central China Normal University





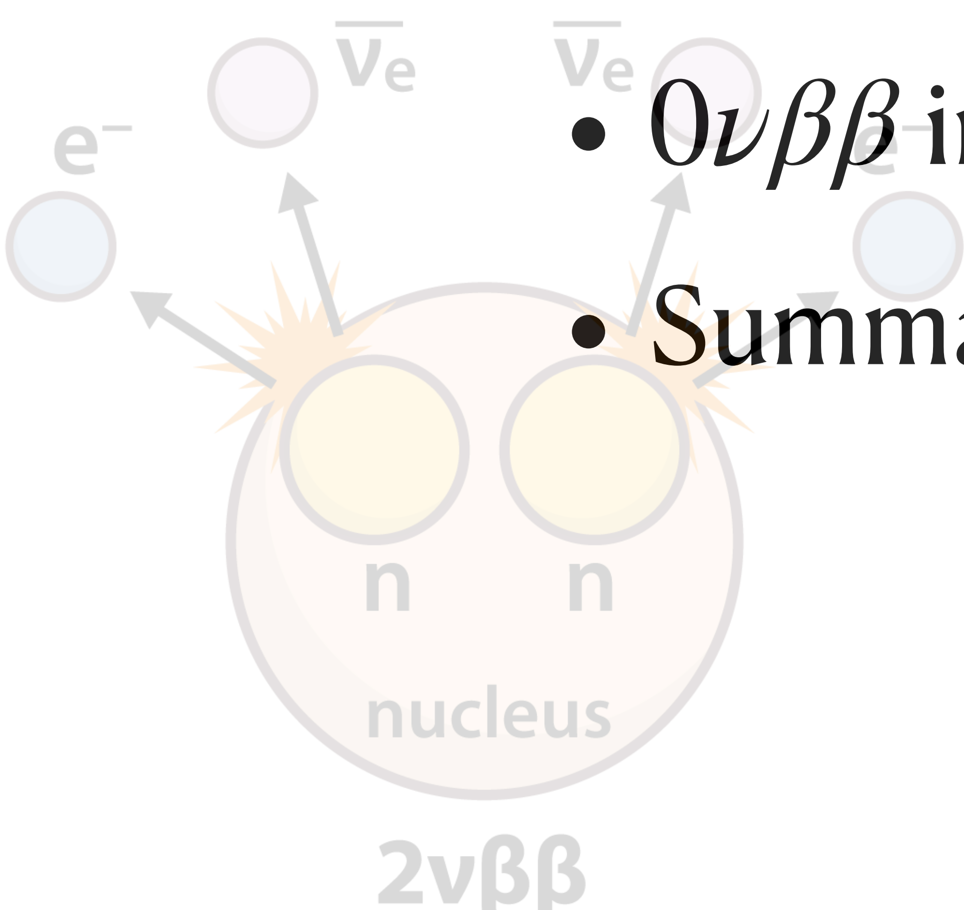
In collaboration with Shao-Long Chen

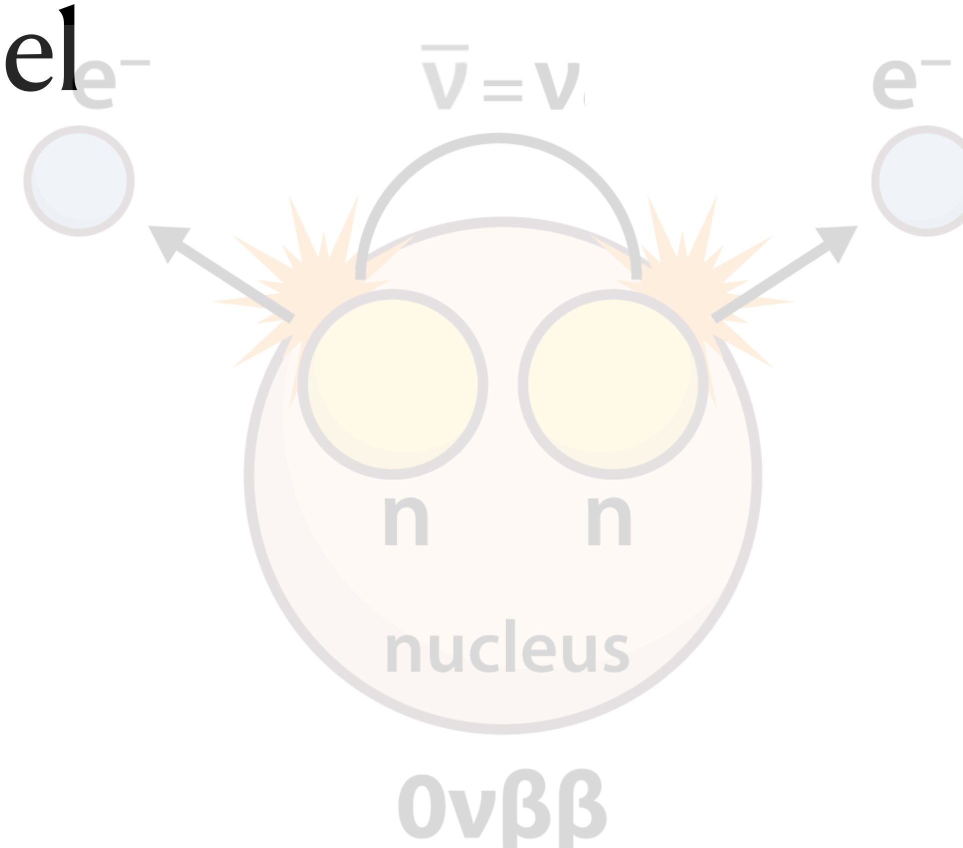
arXiv:2205.13118

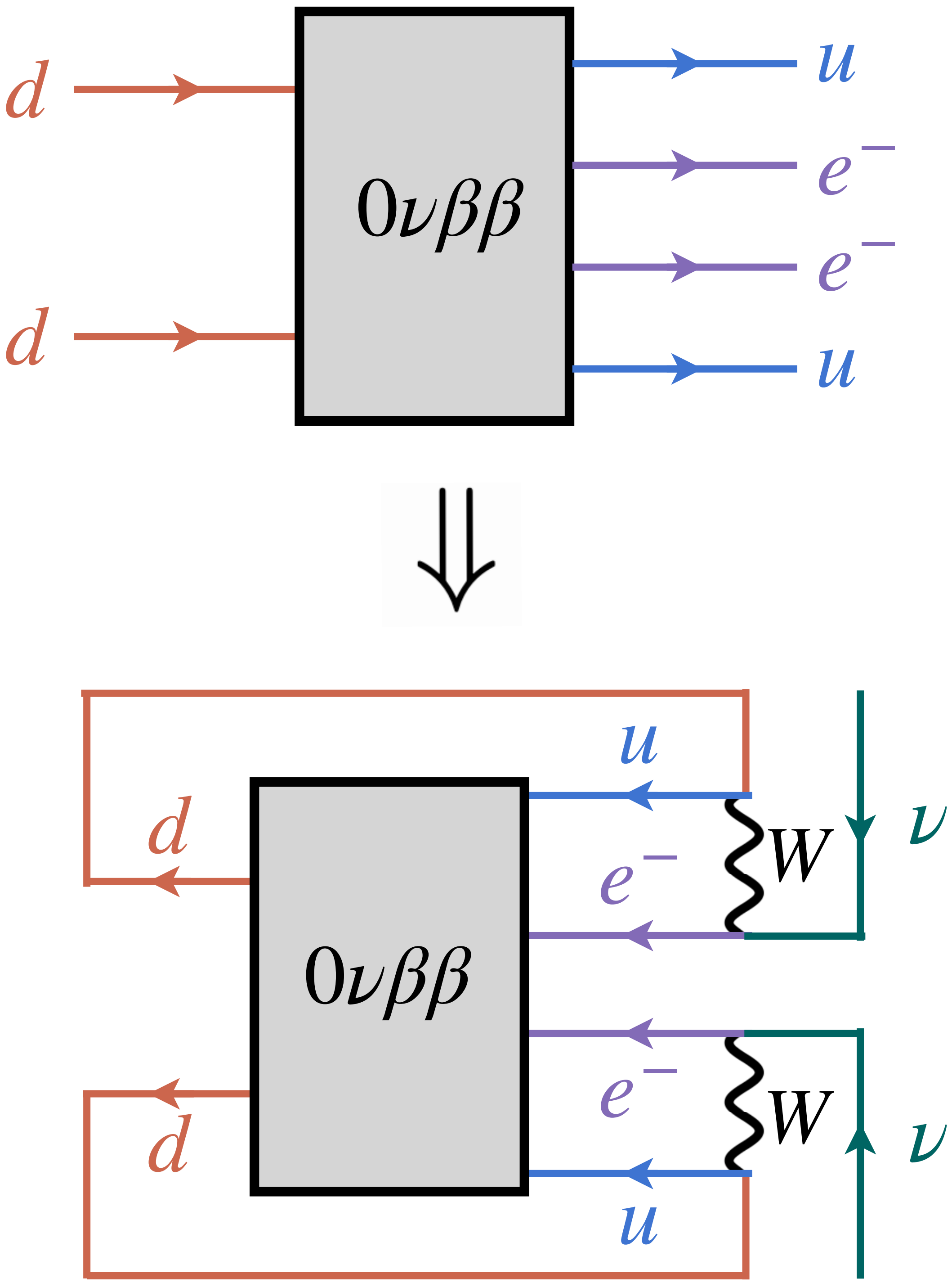
第二届无中微子双贝塔衰变及相关物理研讨会
2023.05.19-2023.05.23 广东珠海

OUTLINE

- Brief Introduction
- Short-Range mechanism of $0\nu\beta\beta$
- $0\nu\beta\beta$ in the cZB model
- Summary







J. Schechter,
J. W. F. Valle, 1982

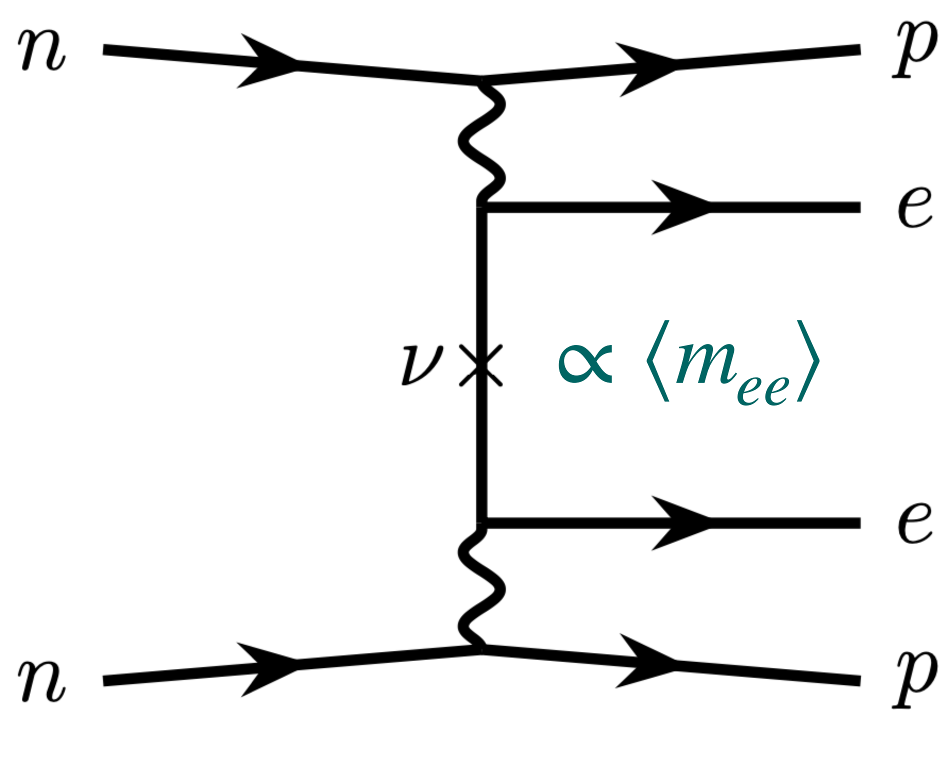
Probe the nature of neutrinos

Majorana neutrino or Dirac neutrino?

- Any neutrinoless double beta decay process induces a Majorana mass term.
- The Majorana mass term may be too small to account for the neutrino oscillation.

  M. Duerr, M. Lindner, A. Merle, **1105.0901**
- generate neutrino masses by the Majorana neutrino mass model or other mechanisms

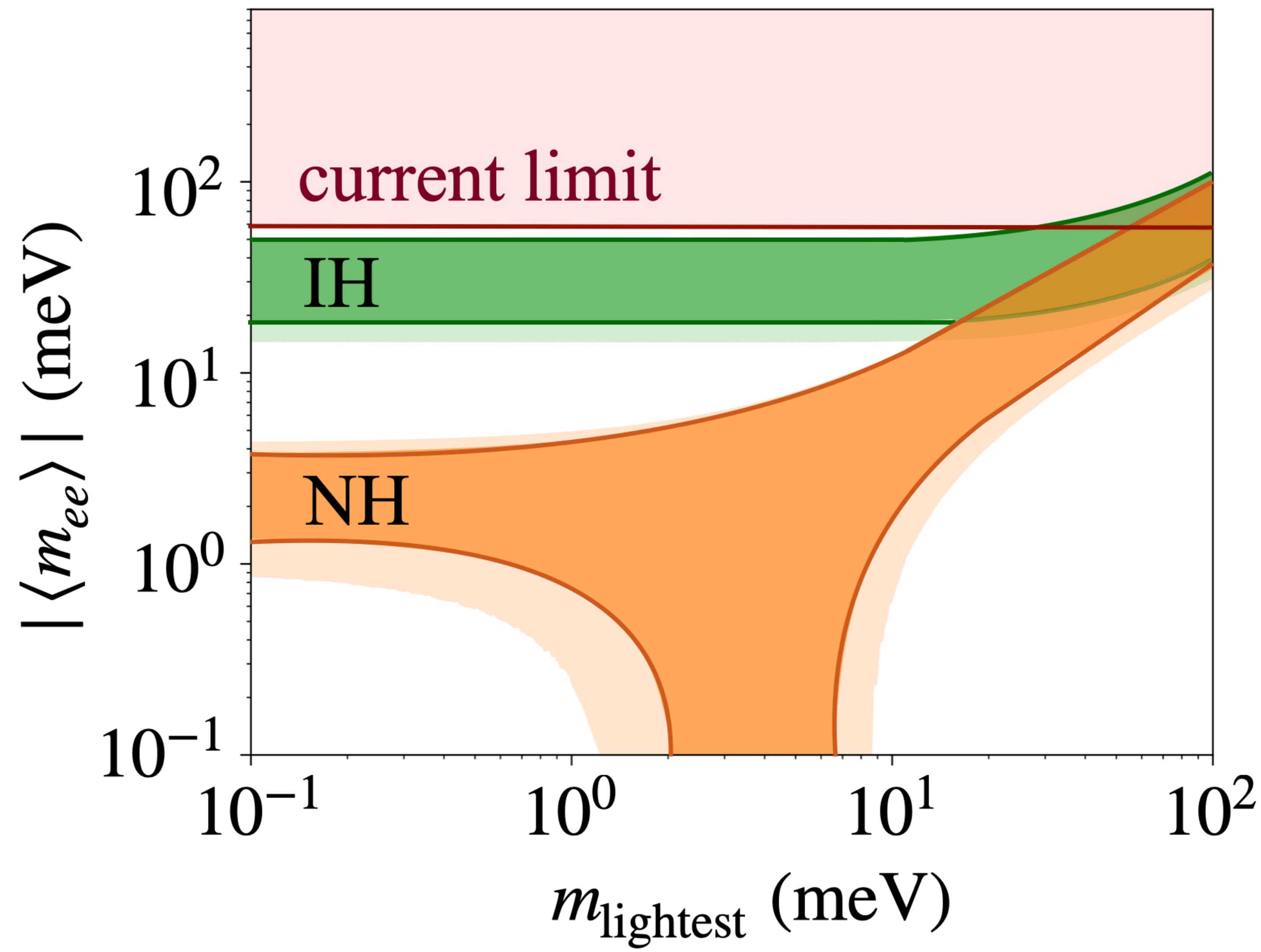
Brief Introduction



standard neutrino exchange

$$(T_{1/2}^{0\nu\beta\beta})^{-1} = G_{0\nu}|M_{0\nu}|^2 \frac{|\langle m_{ee}\rangle|}{m_e^2}$$

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



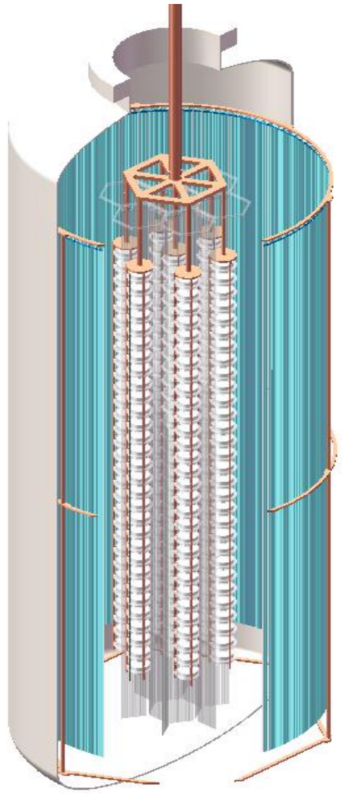
KamLAND-Zen (^{136}Xe) $T_{1/2}^{0\nu\beta\beta} > 1.07 \times 10^{26}$ yrs

GERDA (^{76}Ge) $T_{1/2}^{0\nu\beta\beta} > 1.8 \times 10^{26}$ yrs

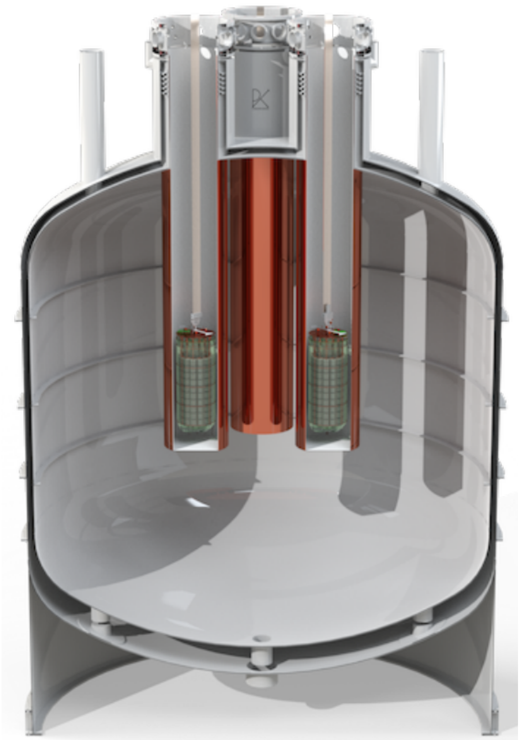
Brief Introduction

Possible isotopes ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, …

^{76}Ge
CDEX
LEGEND



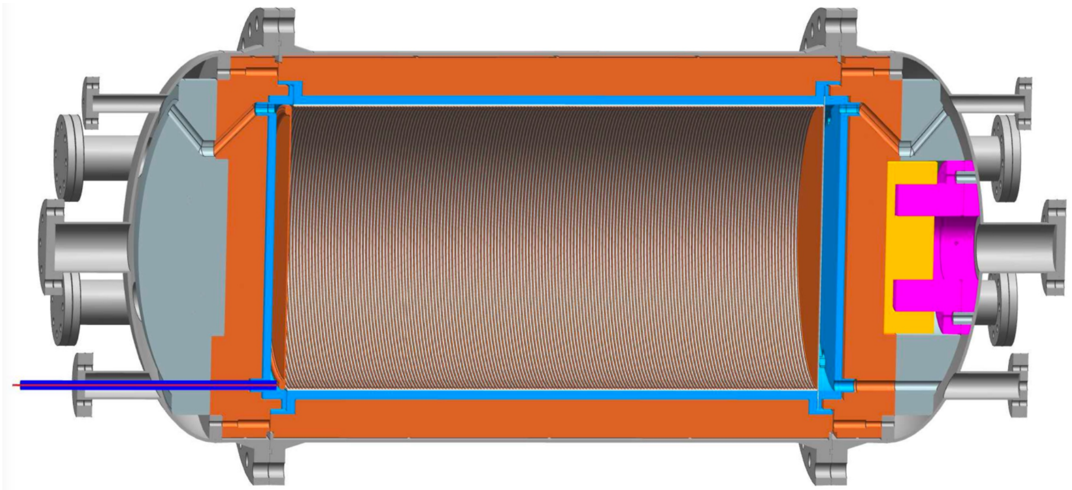
CDEX



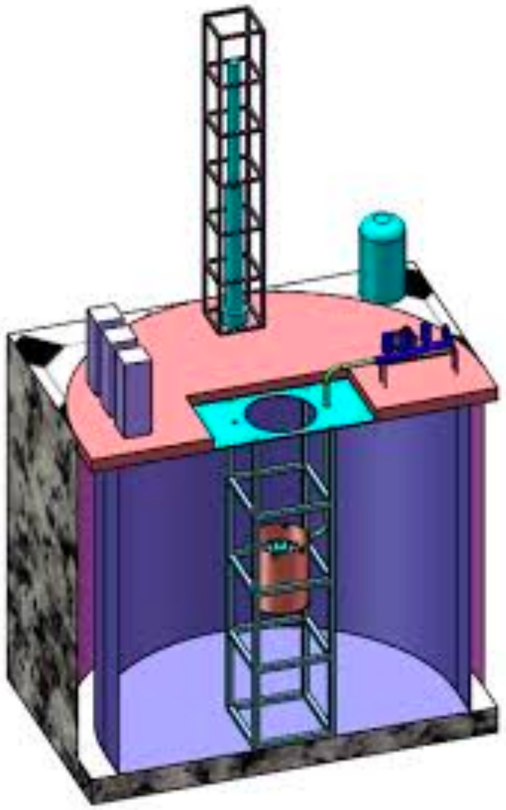
LEGEND-1000

^{100}Mo
CUPID-Mo

^{82}Se
NνDEx

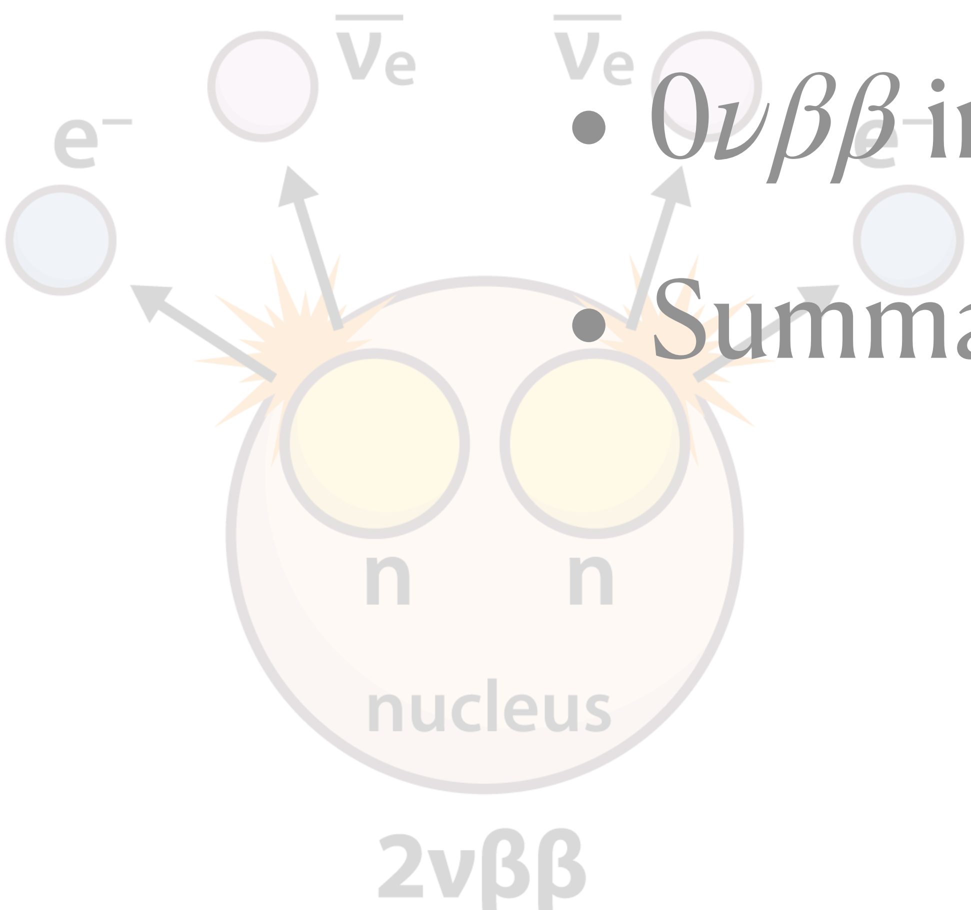


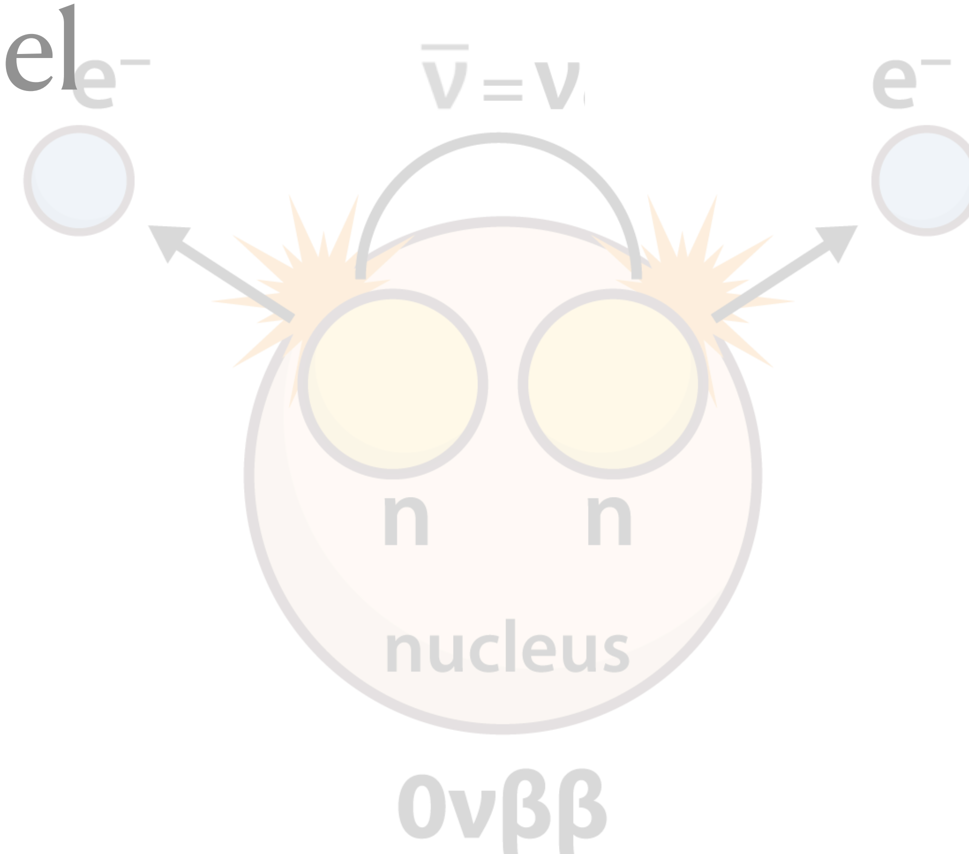
^{136}Xe
PandaX-4T



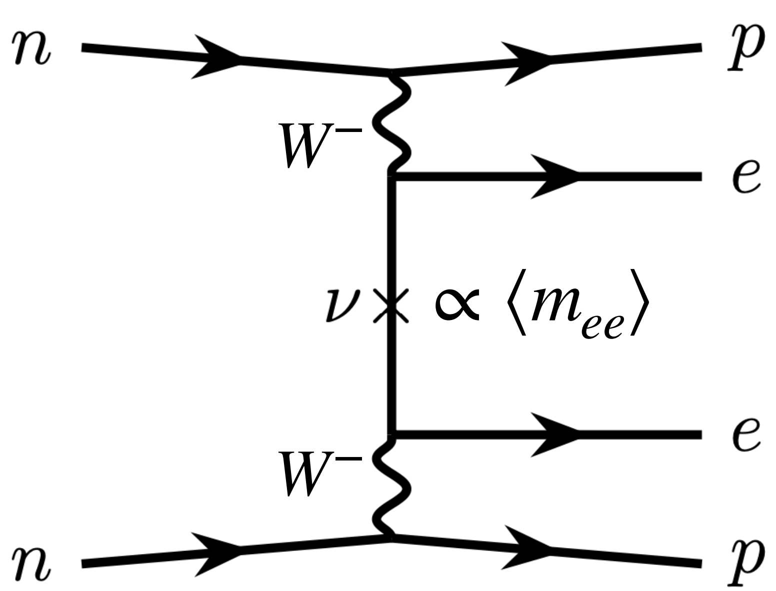
PART II

- Brief Introduction
- **Short-Range mechanism of $0\nu\beta\beta$**
- $0\nu\beta\beta$ in the cZB model
- Summary

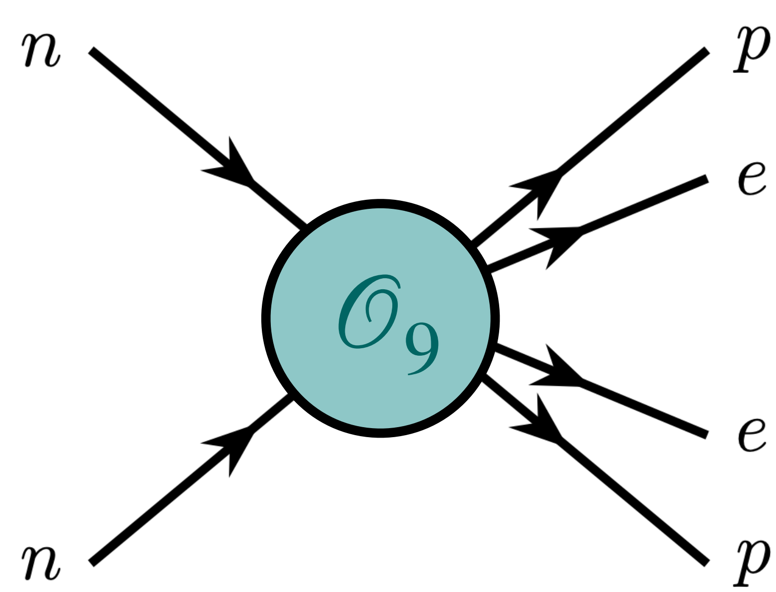




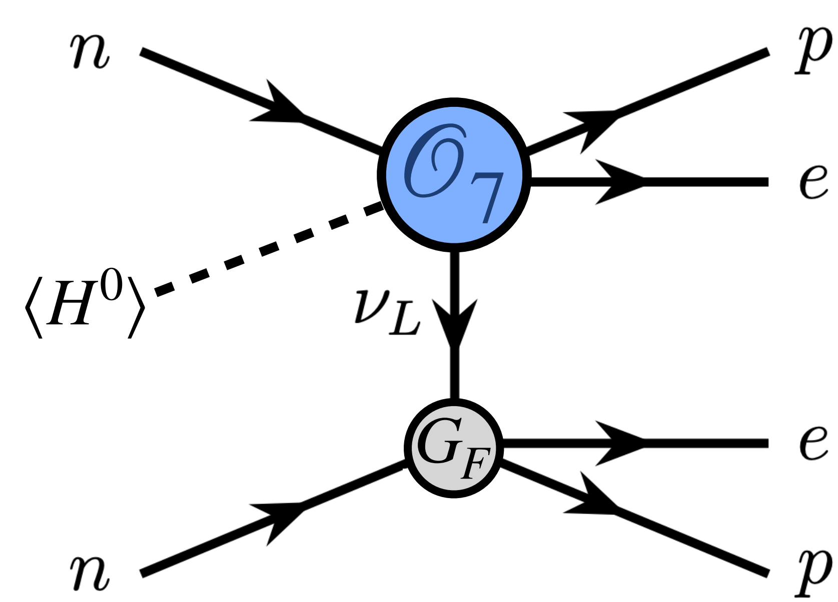
The Effective Field Theory Approach



standard neutrino exchange



short-range



long-range

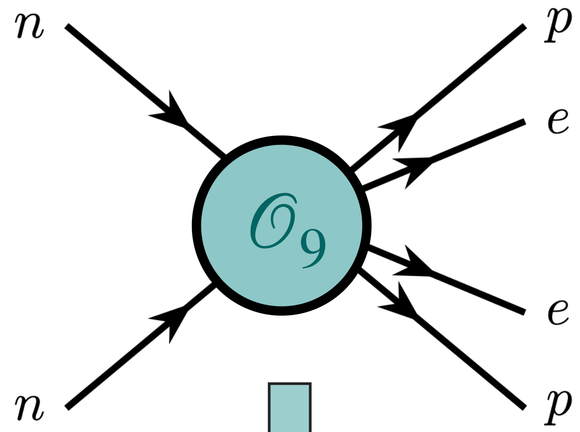
$$\mathcal{L}_{SR} = \frac{G_F^2 V_{ud}^2}{2m_p} \sum_{X,Y,Z} \Big(\epsilon_1^\chi J_X J_Y j_Z + \epsilon_2^\chi J_X^{\mu\nu} J_{Y,\mu\nu} j_Z + \epsilon_3^\chi J_X^\mu J_{Y,\mu} j_Z + \epsilon_4^\chi J_X^\mu J_{Y,\mu\nu} j^\nu + \epsilon_5^\chi J_X^\mu J_Y j_\mu \Big) + \text{h.c.}$$

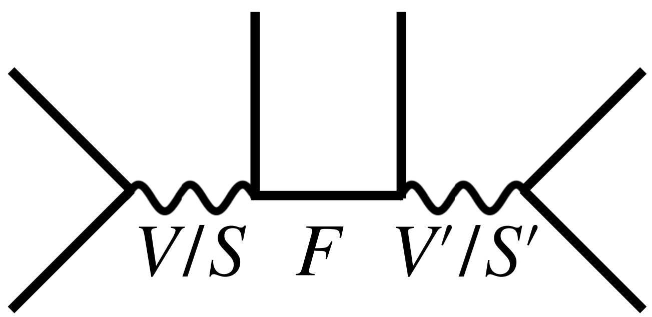
$$= \frac{G_F^2 V_{ud}^2}{2m_p} \sum_{\chi,i} \epsilon_i^\chi \mathcal{O}_{i,\chi}^{0\nu\beta\beta} + \text{h.c.}$$

H. Pas, M. Hirsch, *et al*.
hep-ph/0008182

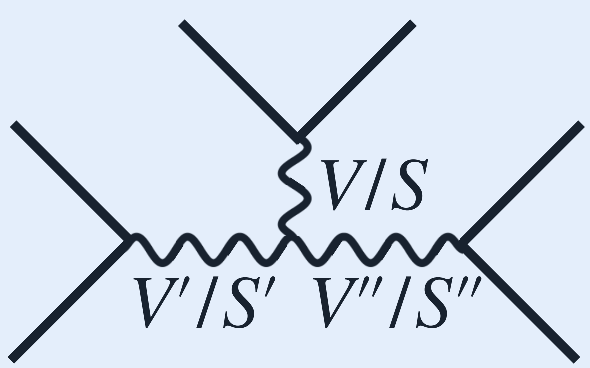
$$J_{R/L} = \overline{u}(1 \pm \gamma_5) d\,,$$
$$J^\mu_{R,L} = \overline{u}\gamma^\mu (1 \pm \gamma_5) d\,,$$
$$J^{\mu\nu}_{R/L} = \overline{u}\sigma^{\mu\nu}(1 \pm \gamma_5) d\,,$$
$$j_{R/L} = \overline{e}(1 \mp \gamma_5) e^c,$$
$$j^\mu = \overline{e}\gamma^\mu \gamma_5 e^c\,.$$

$\mathcal{O} \propto \bar{u}\bar{u}\, dd\, \bar{e}\bar{e}$





Topology I

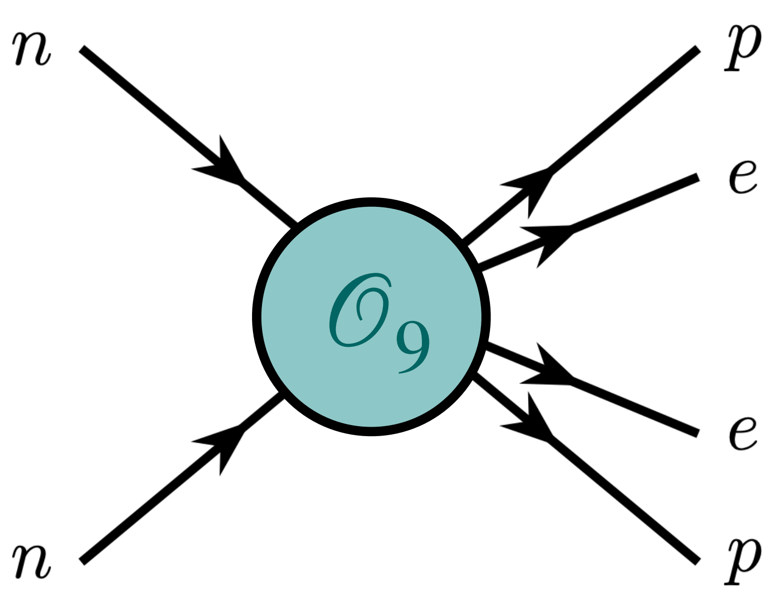


Topology II

F. Bonnet, M. Hirsch, T. Ota, W. Winter, **1212.3045**

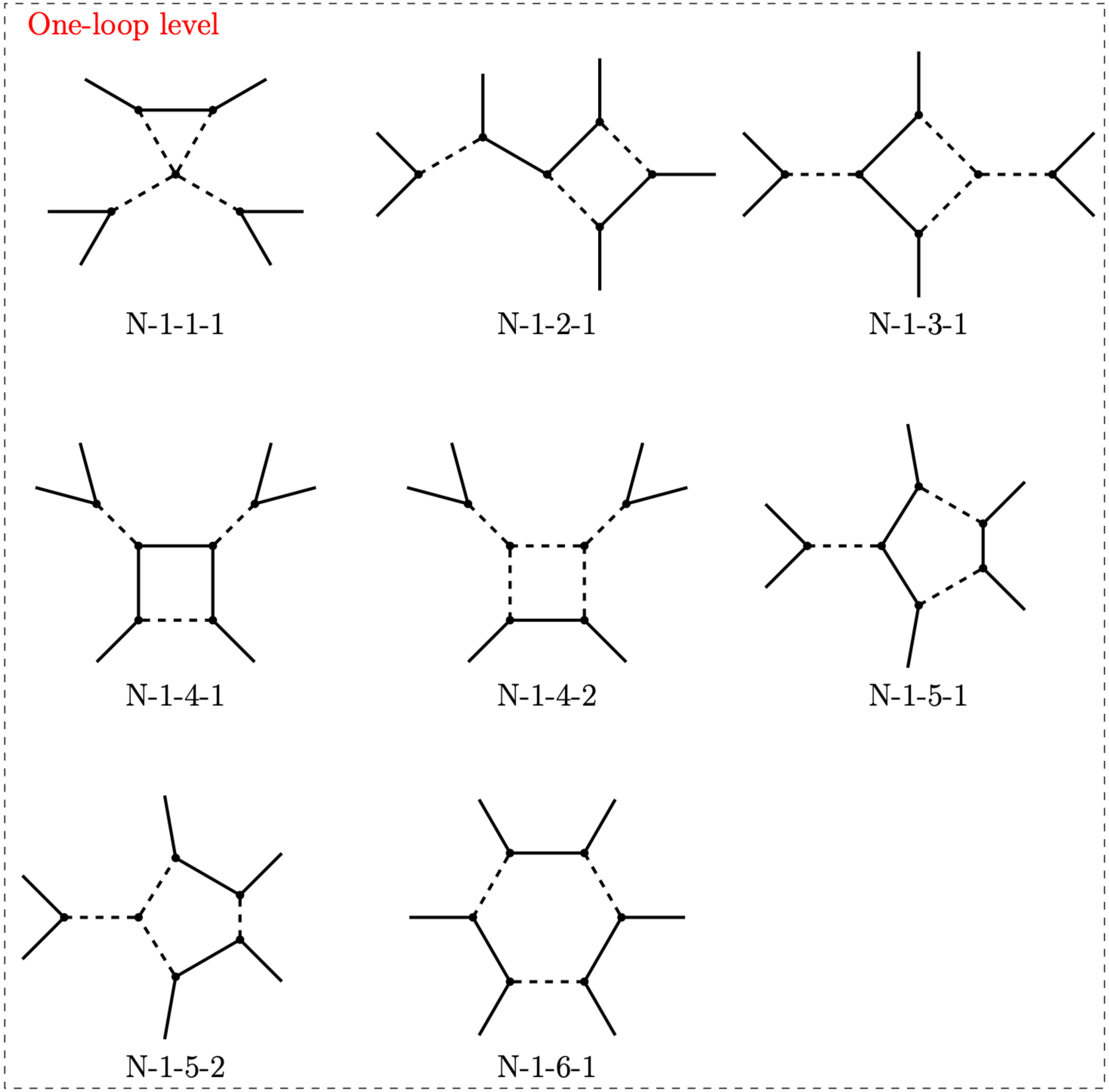
#	Operators	Mediators $(SU(3)_c, SU(2)_L)_{U(1)_Y}$ S	S'	S''
1	$(\overline{u_L}d_R)(\overline{u_L}d_R)(\overline{e_L}e_L)$	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{3})_{-1}$
		$(\mathbf{8},\mathbf{2})_{+1/2}$	$(\mathbf{8},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{3})_{-1}$
	$(\overline{u_R}d_L)(\overline{u_L}d_R)(\overline{e_L}e_L)$	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{3})_{-1}$
		$(\mathbf{8},\mathbf{2})_{+1/2}$	$(\mathbf{8},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{3})_{-1}$
	$(\overline{u_R}d_L)(\overline{u_R}d_L)(\overline{e_L}e_L)$	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{3})_{-1}$
		$(\mathbf{8},\mathbf{2})_{+1/2}$	$(\mathbf{8},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{3})_{-1}$
2	$(\overline{u_L}d_R)(\overline{u_L}e_L)(d_R\overline{e_L})$	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{3},\mathbf{1})_{-1/3}$	$(\bar{\mathbf{3}},\mathbf{2})_{-1/6}$
		$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{3},\mathbf{3})_{-1/3}$	$(\bar{\mathbf{3}},\mathbf{2})_{-1/6}$
		$(\mathbf{8},\mathbf{2})_{+1/2}$	$(\mathbf{3},\mathbf{1})_{-1/3}$	$(\bar{\mathbf{3}},\mathbf{2})_{-1/6}$
		$(\mathbf{8},\mathbf{2})_{+1/2}$	$(\mathbf{3},\mathbf{3})_{-1/3}$	$(\bar{\mathbf{3}},\mathbf{2})_{-1/6}$
	$(\overline{u_L}d_R)(\overline{u_R}e_R)(d_R\overline{e_L})$	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{3},\mathbf{1})_{-1/3}$	$(\bar{\mathbf{3}},\mathbf{2})_{-1/6}$
		$(\mathbf{8},\mathbf{2})_{+1/2}$	$(\mathbf{3},\mathbf{1})_{-1/3}$	$(\bar{\mathbf{3}},\mathbf{2})_{-1/6}$
	$(\overline{u_R}d_L)(\overline{u_L}e_L)(d_R\overline{e_L})$	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{3},\mathbf{1})_{-1/3}$	$(\bar{\mathbf{3}},\mathbf{2})_{-1/6}$
		$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{3},\mathbf{3})_{-1/3}$	$(\bar{\mathbf{3}},\mathbf{2})_{-1/6}$
		$(\mathbf{8},\mathbf{2})_{+1/2}$	$(\mathbf{3},\mathbf{1})_{-1/3}$	$(\bar{\mathbf{3}},\mathbf{2})_{-1/6}$
		$(\mathbf{8},\mathbf{2})_{+1/2}$	$(\mathbf{3},\mathbf{3})_{-1/3}$	$(\bar{\mathbf{3}},\mathbf{2})_{-1/6}$
	$(\overline{u_R}d_L)(\overline{u_R}e_R)(d_R\overline{e_L})$	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{3},\mathbf{1})_{-1/3}$	$(\bar{\mathbf{3}},\mathbf{2})_{-1/6}$
		$(\mathbf{8},\mathbf{2})_{+1/2}$	$(\mathbf{3},\mathbf{1})_{-1/3}$	$(\bar{\mathbf{3}},\mathbf{2})_{-1/6}$
3	$(\overline{u_L}u_L)(d_Rd_R)(\overline{e_L}e_L)$	$(\mathbf{6},\mathbf{3})_{+1/3}$	$(\bar{\mathbf{6}},\mathbf{1})_{+2/3}$	$(\mathbf{1},\mathbf{3})_{-1}$
	$(\overline{u_R}u_R)(d_Ld_L)(\overline{e_L}e_L)$	$(\mathbf{6},\mathbf{1})_{+4/3}$	$(\bar{\mathbf{6}},\mathbf{3})_{-1/3}$	$(\mathbf{1},\mathbf{3})_{-1}$
	$(\overline{u_R}u_R)(d_Rd_R)(\overline{e_R}e_R)$	$(\mathbf{6},\mathbf{1})_{+4/3}$	$(\bar{\mathbf{6}},\mathbf{1})_{+2/3}$	$(\mathbf{1},\mathbf{1})_{-2}$
4	$(\overline{u_L}u_L)(d_R\overline{e_L})(d_R\overline{e_L})$	$(\mathbf{6},\mathbf{3})_{+1/3}$	$(\bar{\mathbf{3}},\mathbf{2})_{-1/6}$	$(\bar{\mathbf{3}},\mathbf{2})_{-1/6}$
	$(\overline{u_R}u_R)(d_L\overline{e_R})(d_R\overline{e_L})$	$(\mathbf{6},\mathbf{1})_{+4/3}$	$(\bar{\mathbf{3}},\mathbf{2})_{-7/6}$	$(\bar{\mathbf{3}},\mathbf{2})_{-1/6}$
5	$(\overline{u_L}e_L)(\overline{u_L}e_L)(d_Rd_R)$	$(\mathbf{3},\mathbf{1})_{-1/3}$	$(\mathbf{3},\mathbf{1})_{-1/3}$	$(\bar{\mathbf{6}},\mathbf{1})_{+2/3}$
		$(\mathbf{3},\mathbf{3})_{-1/3}$	$(\mathbf{3},\mathbf{3})_{-1/3}$	$(\bar{\mathbf{6}},\mathbf{1})_{+2/3}$
	$(\overline{u_L}e_L)(\overline{u_R}e_R)(d_Rd_R)$	$(\mathbf{3},\mathbf{1})_{-1/3}$	$(\mathbf{3},\mathbf{1})_{-1/3}$	$(\bar{\mathbf{6}},\mathbf{1})_{+2/3}$
	$(\overline{u_R}e_R)(\overline{u_R}e_R)(d_Rd_R)$	$(\mathbf{3},\mathbf{1})_{-1/3}$	$(\mathbf{3},\mathbf{1})_{-1/3}$	$(\bar{\mathbf{6}},\mathbf{1})_{+2/3}$

The Short-Range Contribution

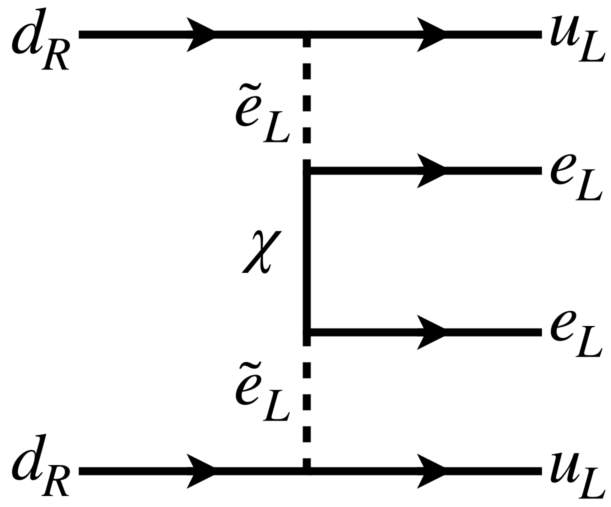


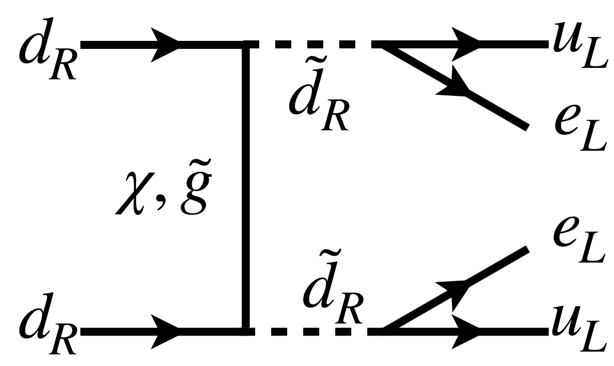
P.-T. Chen, G.-J. Ding, C.-Y. Yao,
2110.15347, 2301.02503

One-loop realization



MSSM with R-parity violating





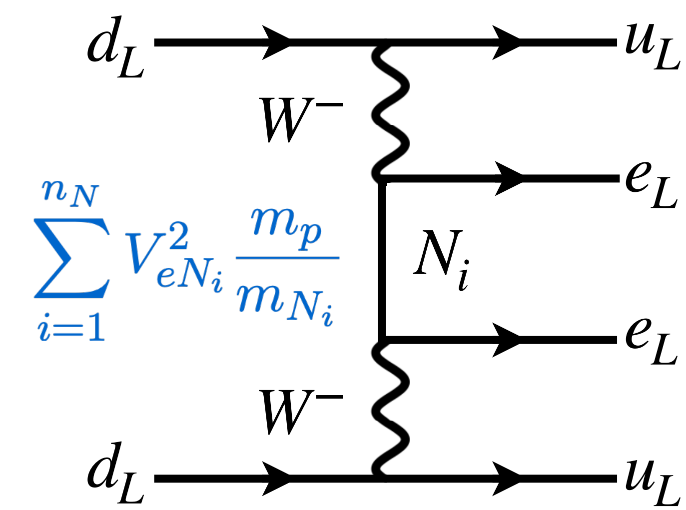
……

$$\frac{G_F^2 V_{ud}^2}{2m_p}\left(\epsilon_1^{RRL} J_R J_R + \epsilon_2^{RRL} J_{R^{\mu\nu}} J_{R,\mu\nu}\right) j_L + \text{ h.c.}$$

$$T_{\mathrm{SR},1/2}^{-1} = G_\nu \left|\frac{\langle m_{ee}\rangle}{m_e}\mathcal{M}_\nu + \epsilon_1^{RRL}\mathcal{M}_1^{RR} + \epsilon_2^{RRL}\mathcal{M}_2^{RR}\right|^2$$

Heavy RH neutrinos, Type-I seesaw

$m_{N_i} \gg 100$ MeV



$$\frac{G_F^2 V_{ud}^2}{2m_p}\epsilon_3^{LLL} J_L^\mu J_{L,\mu} j_L + \text{ h.c.}$$

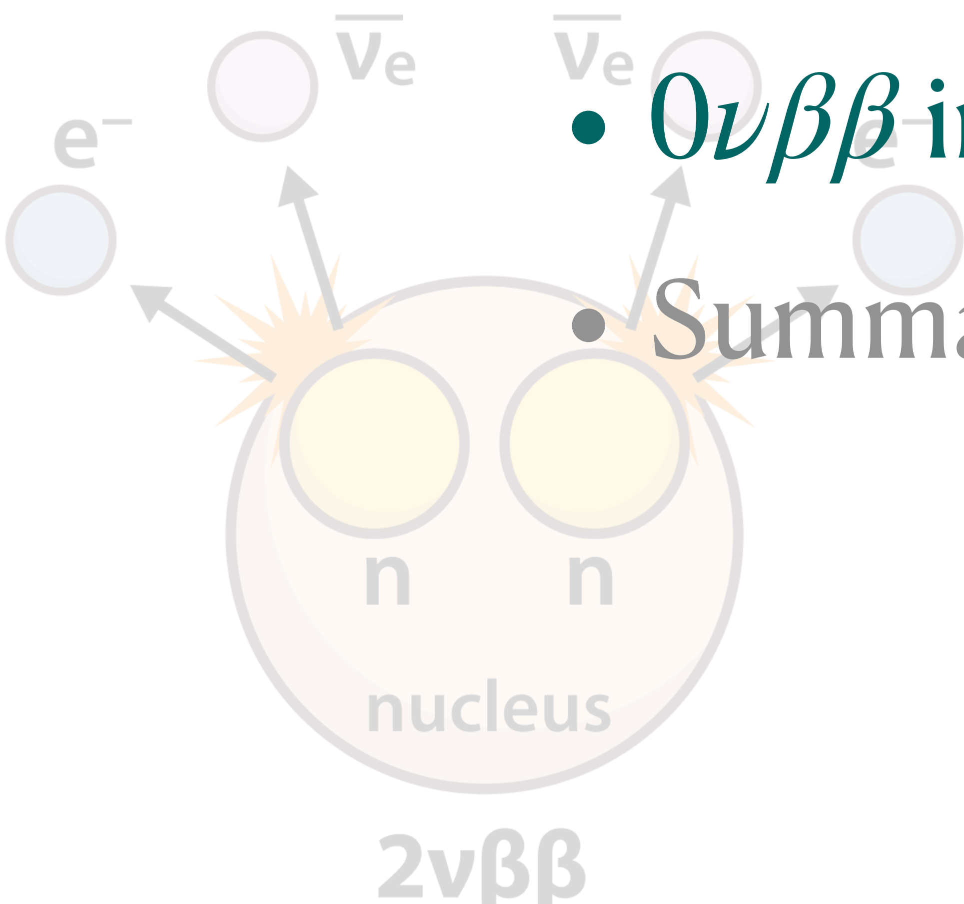
$$T_{1/2}^{-1} = G_\nu \left|\frac{\langle m_{ee}\rangle}{m_e}\mathcal{M}_\nu + \epsilon_3^{LLL}\mathcal{M}_3^{LL}\right|^2$$

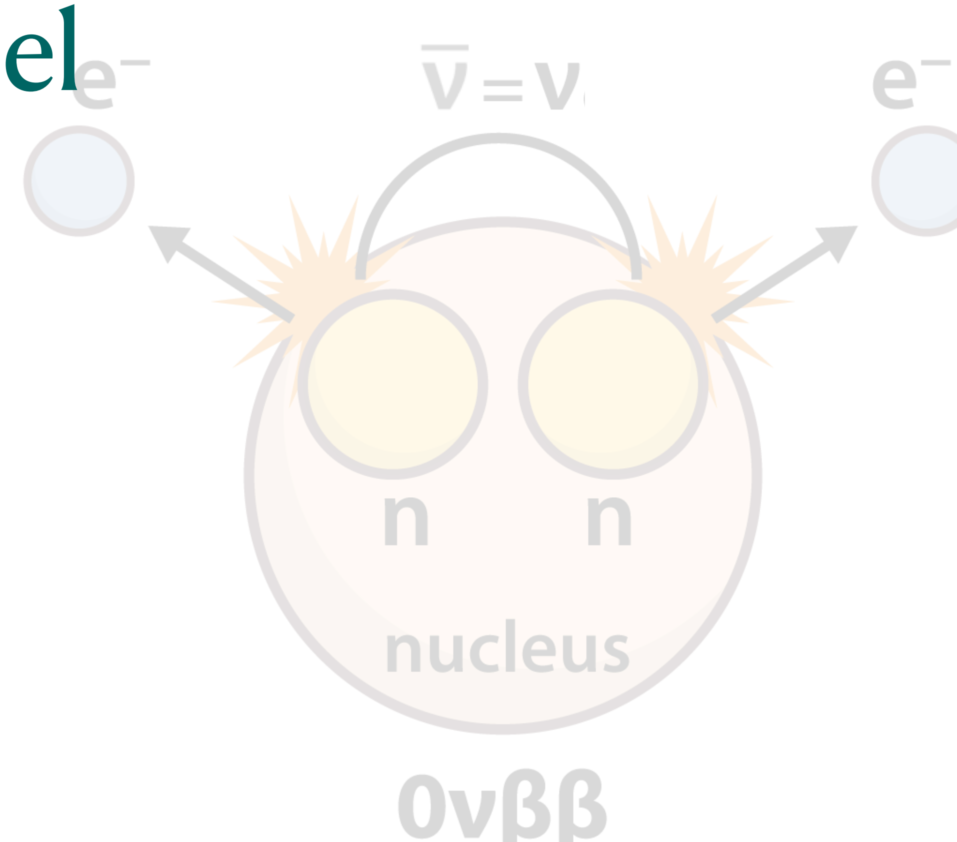
There is some interplay between
the standard mechanism and short-range contribution.

comprehensive analysis see F. F. Deppisch, L. Graf, F. Iachello, J. Kotila, **2009.10119**

PART III

- Brief Introduction
- Short-Range mechanism of $0\nu\beta\beta$
- $0\nu\beta\beta$ in the cZB model
- Summary

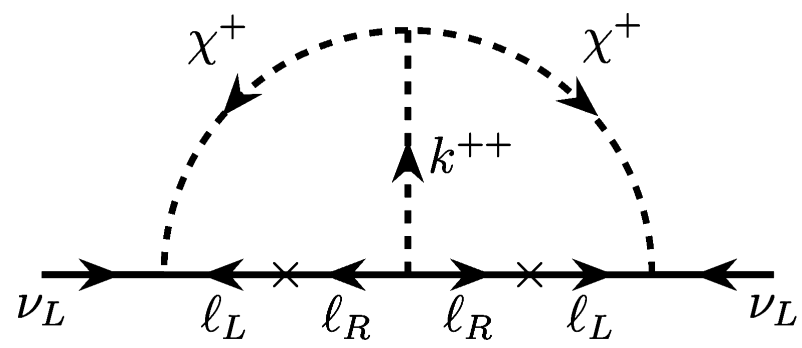




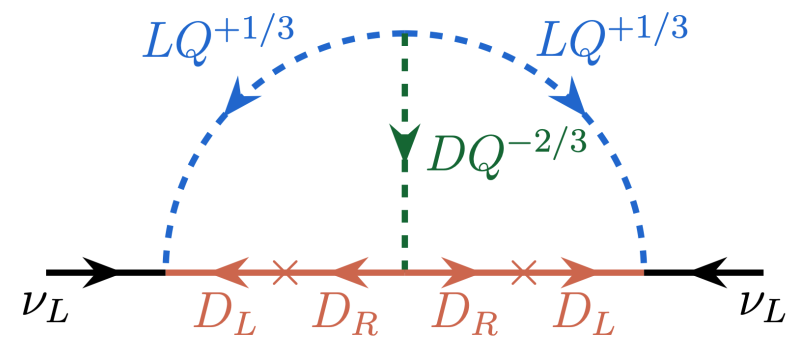
The Colored Zee-Babu Model

- The colored Zee-Babu (cZB) model requires leptoquarks and a diquark to generate the neutrino mass.

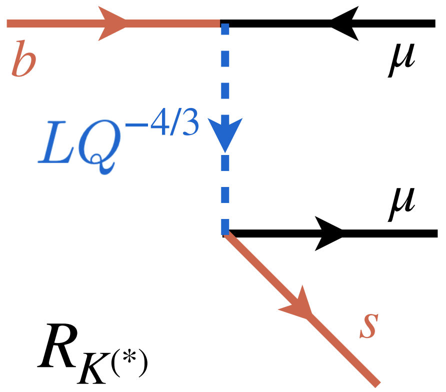
Zee, 1986; Babu, 1988

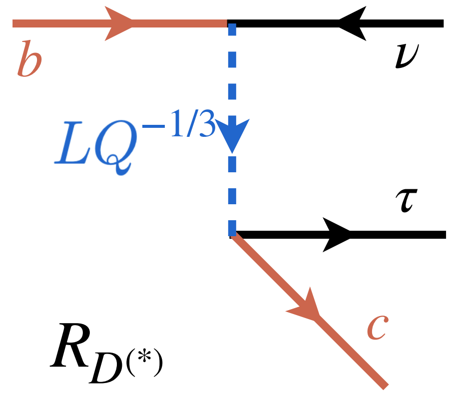


M. Kohda, H. Sugiyama, K. Tsumura, 2012.5622



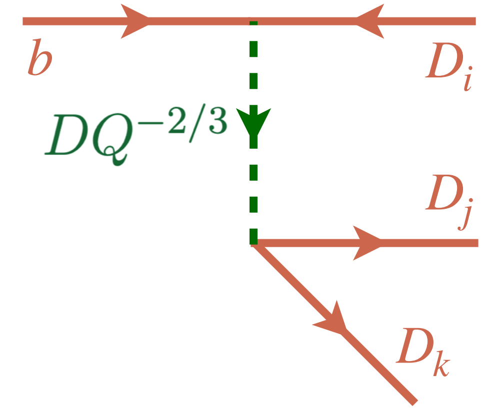
- solve B meson decays anomalies





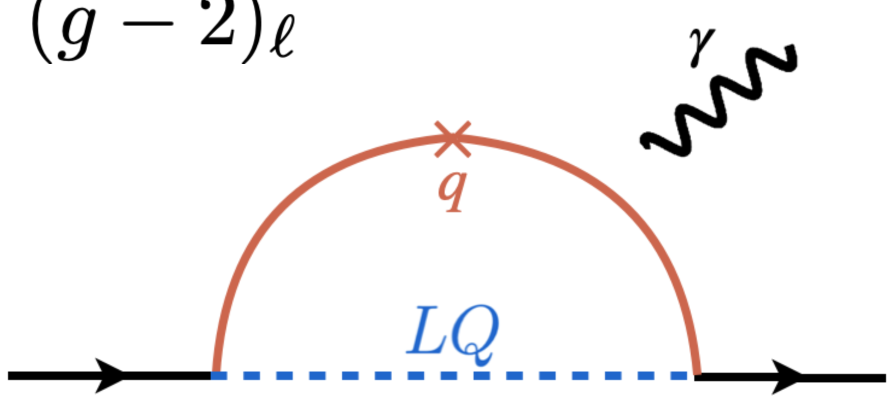
S. Saad, **2205.04352**; S.-Y. Guo, Z.-L. Han, B. Li, Y. Liao, X.-D. Ma, **1707.00522**, …

- $B \to \pi K$ puzzle



Datta, D. Sachdeva, J. Waite,**1905.04046**

- $(g-2)_\ell$

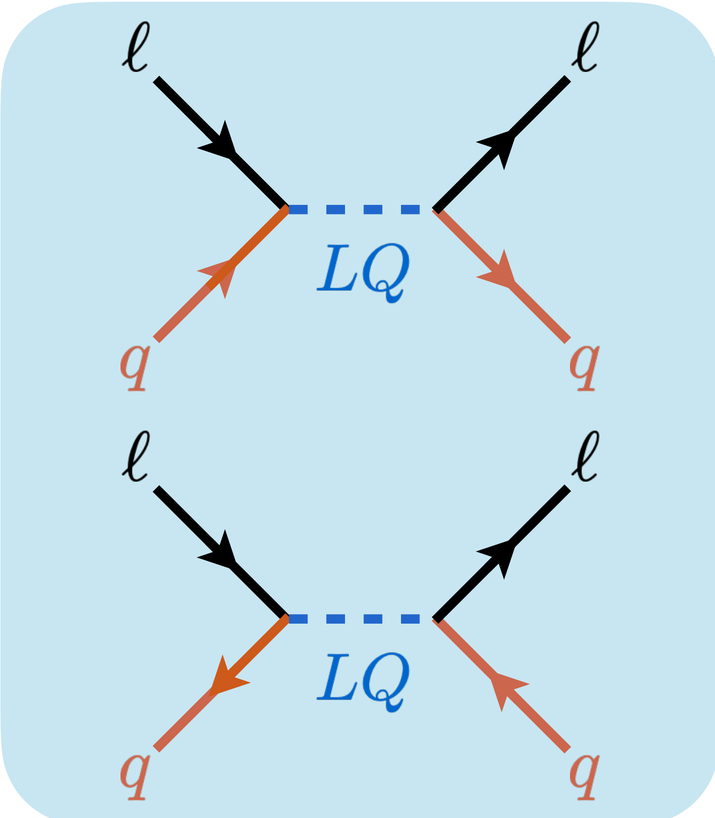


- The extension of cZB models

  e.g. +DM candidate $S + U(1)_{B-L}$, solve Fermi-LAT GC γ-ray excess

R. Ding, Z.-L. Han, L. Huang, Y. Liao,**1802.05248**

Constraints



tree-level flavor violation (four-fermion interaction)

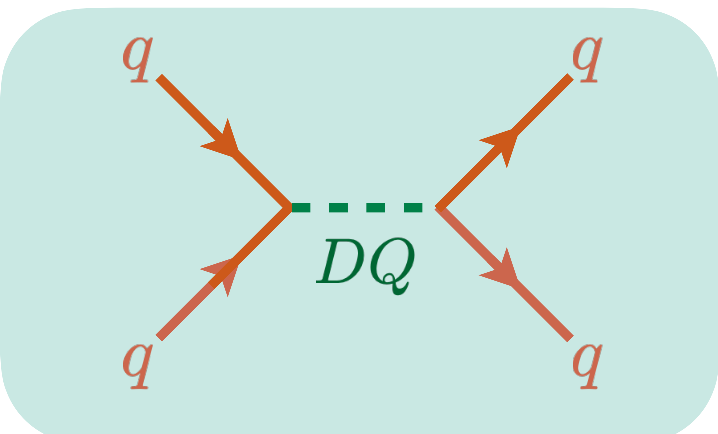
$$\epsilon_{ijkn} \equiv \frac{(Y_L)_{ik}(Y_L)_{jn}}{4\sqrt{2}G_F m_S^2}$$

model-independent analysis was done by M. Carpentier and S. Davidson, **1008.0280**

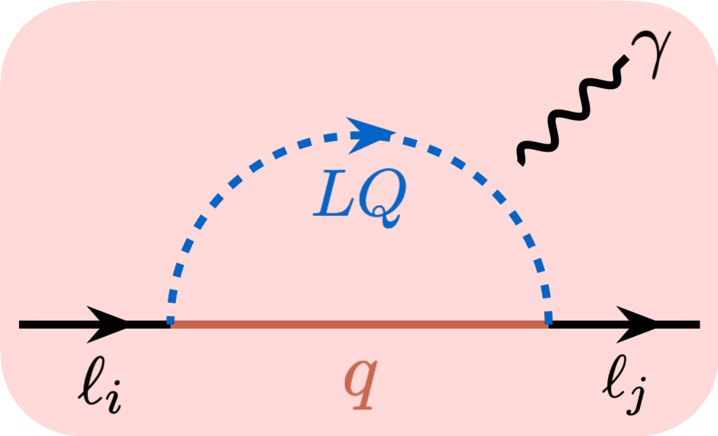
$$\mathcal{L}_{\text{eff},1} = \frac{1}{2M_{S_1}^2}\left\{(V^* y_{1SL})^{*ki}(V^* y_{1SL})^{nj}[\overline{E^i}\gamma_\mu P_L E^j][\overline{U^k}\gamma^\mu P_L U^n] + \ldots\right\}.$$

$$\mathcal{L}_{\text{eff},2} = \frac{1}{2M_{S_3}^2}\left\{(V^* y_{3S})^{*ki}(V^* y_{3S})^{nj}[\overline{E^i}\gamma^\mu P_L E^j][\overline{U^k}\gamma_\mu P_L U^n] + \ldots\right\}.$$

$$\mathcal{L}_{\text{eff},3} = -\frac{y_{2S}^{*ki} y_{2S}^{nj}}{2M_{S_2}^2}\left\{[\overline{E^i}\gamma^\mu P_L E^j][\overline{D^k}\gamma_\mu P_R D^n] + [\overline{\nu^i}\gamma^\mu P_L \nu^j][\overline{D^k}\gamma_\mu P_R D^n]\right\}.$$



$K-\overline{K}$, $B_d-\overline{B}_d$, $B_s-\overline{B}_s$ mixing



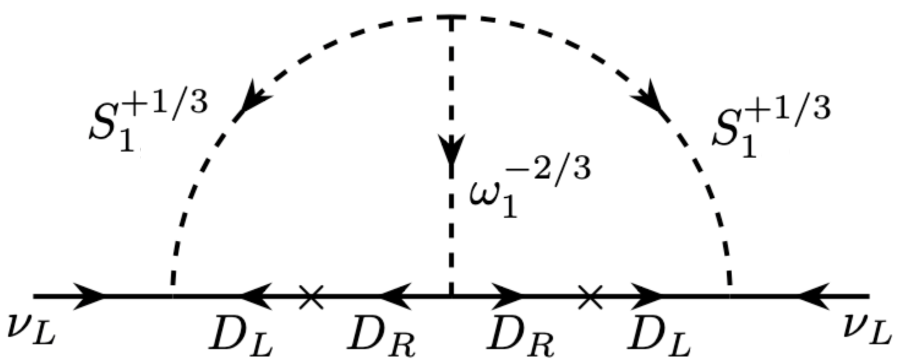
$(g-2)_l$, $l_i \to l_j\gamma$

$$\Delta a_\mu(S_1) \simeq \frac{3m_\mu^2}{8\pi^2 M_{S_1}^2}\frac{m_t}{m_\mu}\text{Re}[y_{1SR}^{32} y_{1SL}^{\prime *32}]\left[\frac{1}{3}f_1\left(\frac{m_t^2}{m_{S_1}^2}\right) + \frac{2}{3}f_2\left(\frac{m_t^2}{m_{S_1}^2}\right)\right]$$

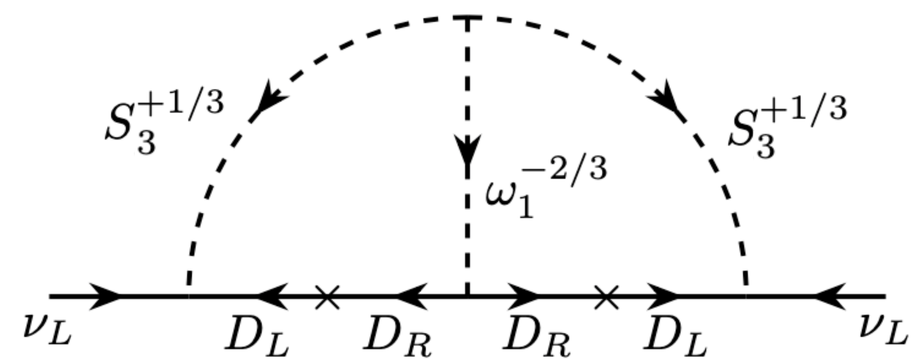
The Colored Zee-Babu Model

(one LQ + one DQ)

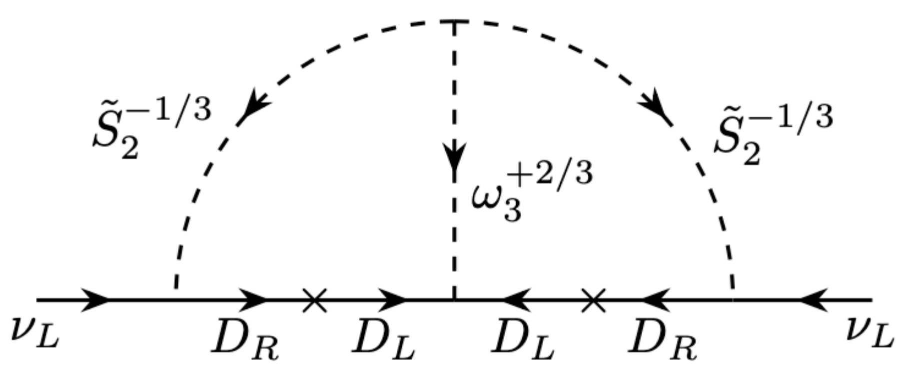
case 1: a singlet LQ $S_1 \sim (\bar{3}, 1, 1/3)$
a singlet DQ $\omega_1 \sim (6, 1, -2/3)$



case 2: a triplet LQ $S_3 \sim (\bar{3}, 3, 1/3)$
a singlet DQ $\omega_1 \sim (6, 1, -2/3)$



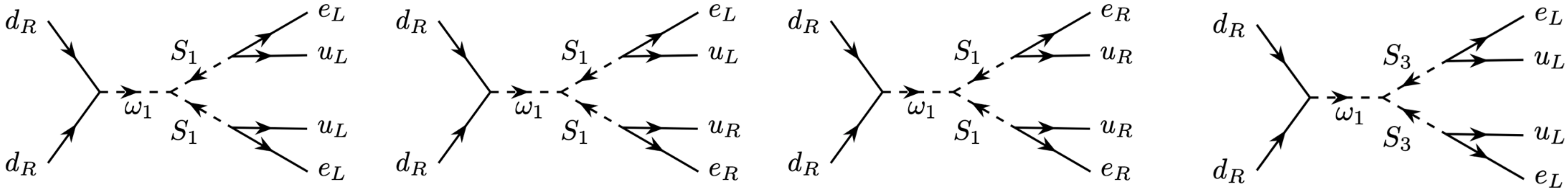
case 3: a doublet LQ $\tilde{S}_2 \sim (3, 2, 1/6)$
a triplet DQ $\omega_3 \sim (6, 3, 1/3)$

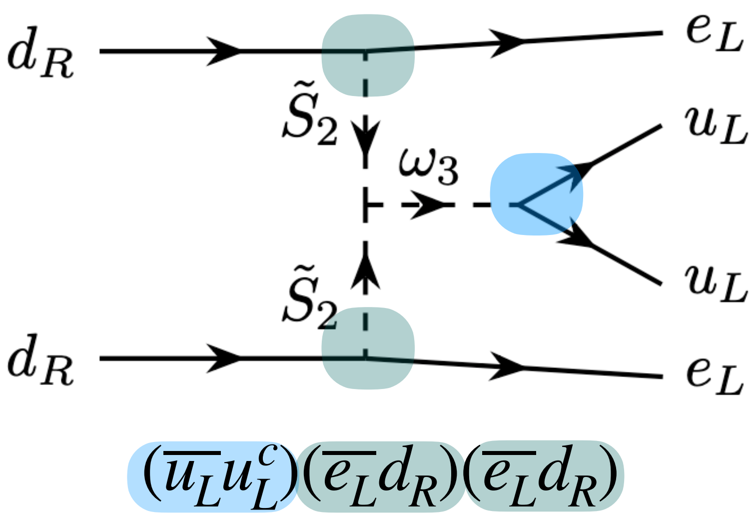


$$M_{\nu_a}^{kn} = 24\mu_a [y_{bS(L)}^T]^{kl} m_{D^l} z_{c\omega}^{lm} m_{D^m} y_{bS(L)}^{mn} \mathcal{I}_{lm}$$

$$\mathcal{I}_{lm} = \int \frac{d^4k}{(2\pi)^4} \int \frac{d^4q}{(2\pi)^4} \frac{1}{q^2 - m_{D^l}^2} \frac{1}{q^2 - M_S^2} \times \frac{1}{k^2 - M_S^2} \frac{1}{k^2 - m_{D^m}^2} \frac{1}{(k-q)^2 - M_\omega^2}$$

- **SR contributions**





$$(\overline{u_L u_L})(d_R \overline{e_L})(d_R \overline{e_L}) \to \frac{1}{48}\mathcal{O}_1^{RRL} - \frac{1}{192}\mathcal{O}_2^{RRL}$$

$$\epsilon_1^{RRL} = -\frac{1}{48}\frac{2m_p}{G_F^2 V_{ud}^2}\frac{4(y_{2S}^{*11})^2(V^* z_{3\omega} V^\dagger)^{11}\mu_3}{M_{S_2}^4 M_{\omega_3}^2}, \quad \epsilon_2^{RRL} = -\frac{1}{4}\epsilon_1^{RRL}.$$

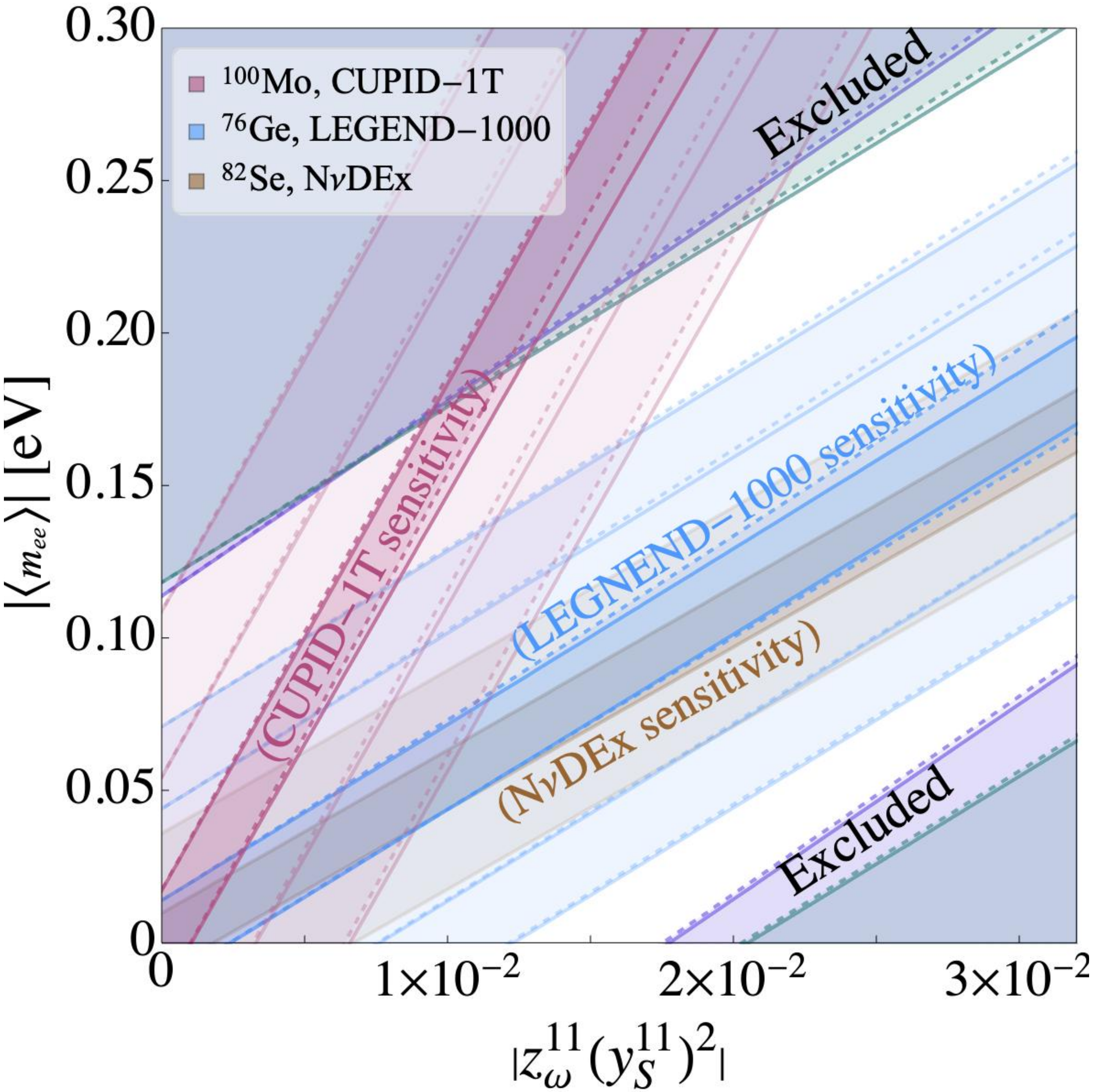
RGE μ-evolution matrix elements

M. Gonzalez, S.G. Kovalenko, M. Hirsch, 1511.03945

$$\hat{U}_{(12)}^{XX} = \begin{pmatrix} 2.39 & 0.02 \\ -3.83 & 0.35 \end{pmatrix}$$

$$\mathcal{M}_1^{XX} \to \beta_1^{XX} = 2.39\mathcal{M}_1^{XX} - 3.83\mathcal{M}_2^{XX}$$
$$\mathcal{M}_2^{XX} \to \beta_2^{XX} = 0.02\mathcal{M}_1^{XX} + 0.35\mathcal{M}_2^{XX}$$

Neutrinoless Double Beta Decay



The neutrinoless double beta decay **could be hidden**.

$$(y_S^{*11})^2 z_\omega^{11} \simeq 300 \times \frac{\mathcal{M}_\nu}{\beta_1 - \beta_2/4} \frac{\langle m_{ee}\rangle}{\text{eV}}$$

If there is no signal, the **survival region** will be reduced to the **overlap** area.

$$\frac{\mathcal{M}_\nu}{\beta_1 - \beta_2/4} \begin{cases} \text{similar ratio value in } ^{76}\text{Ge and } ^{136}\text{Xe} \\ \text{different in } ^{100}\text{Mo} \end{cases}$$

With the **high sensitivity** of future experiments, the survival band can be **examined comprehensively**.

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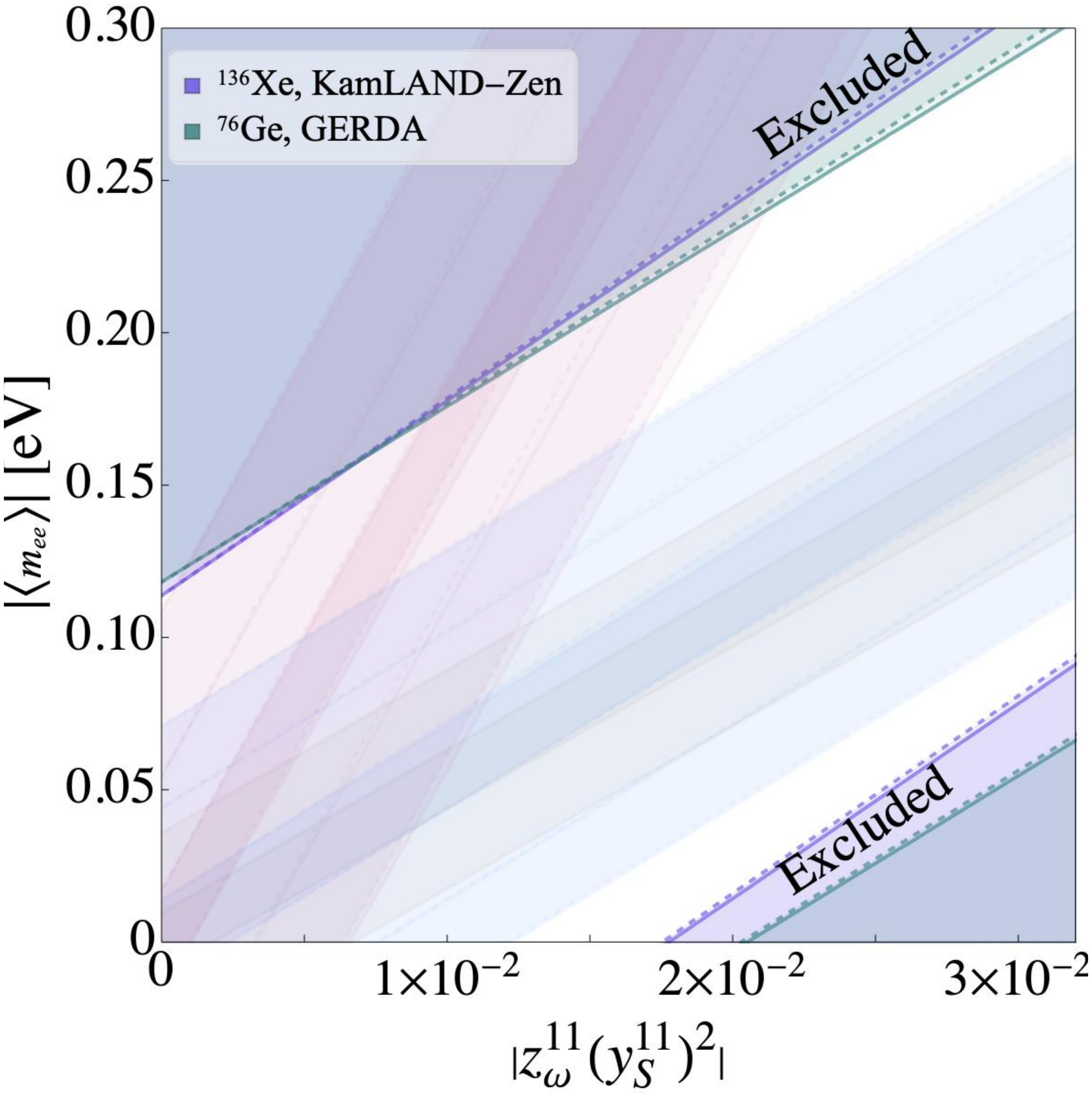

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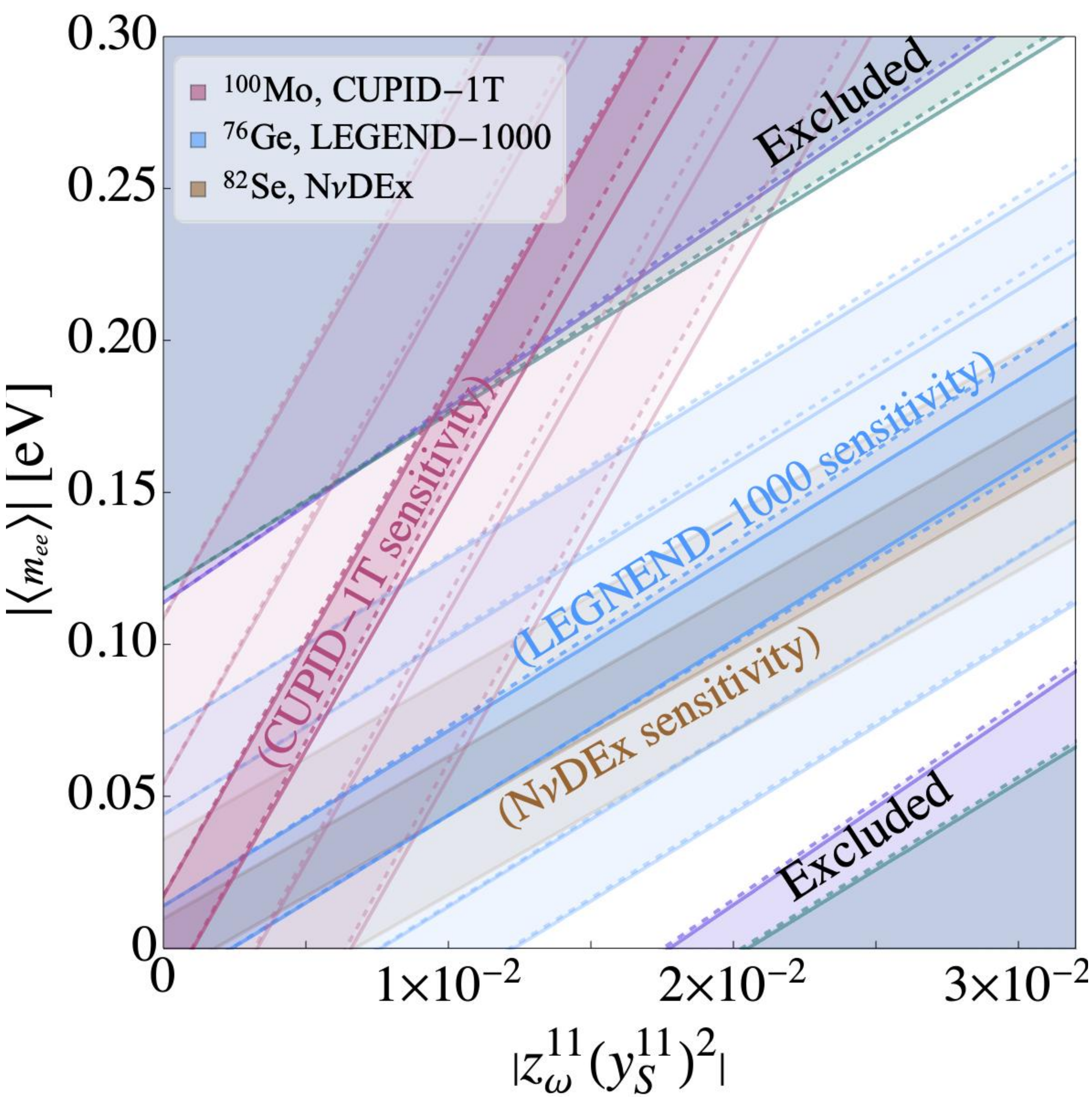

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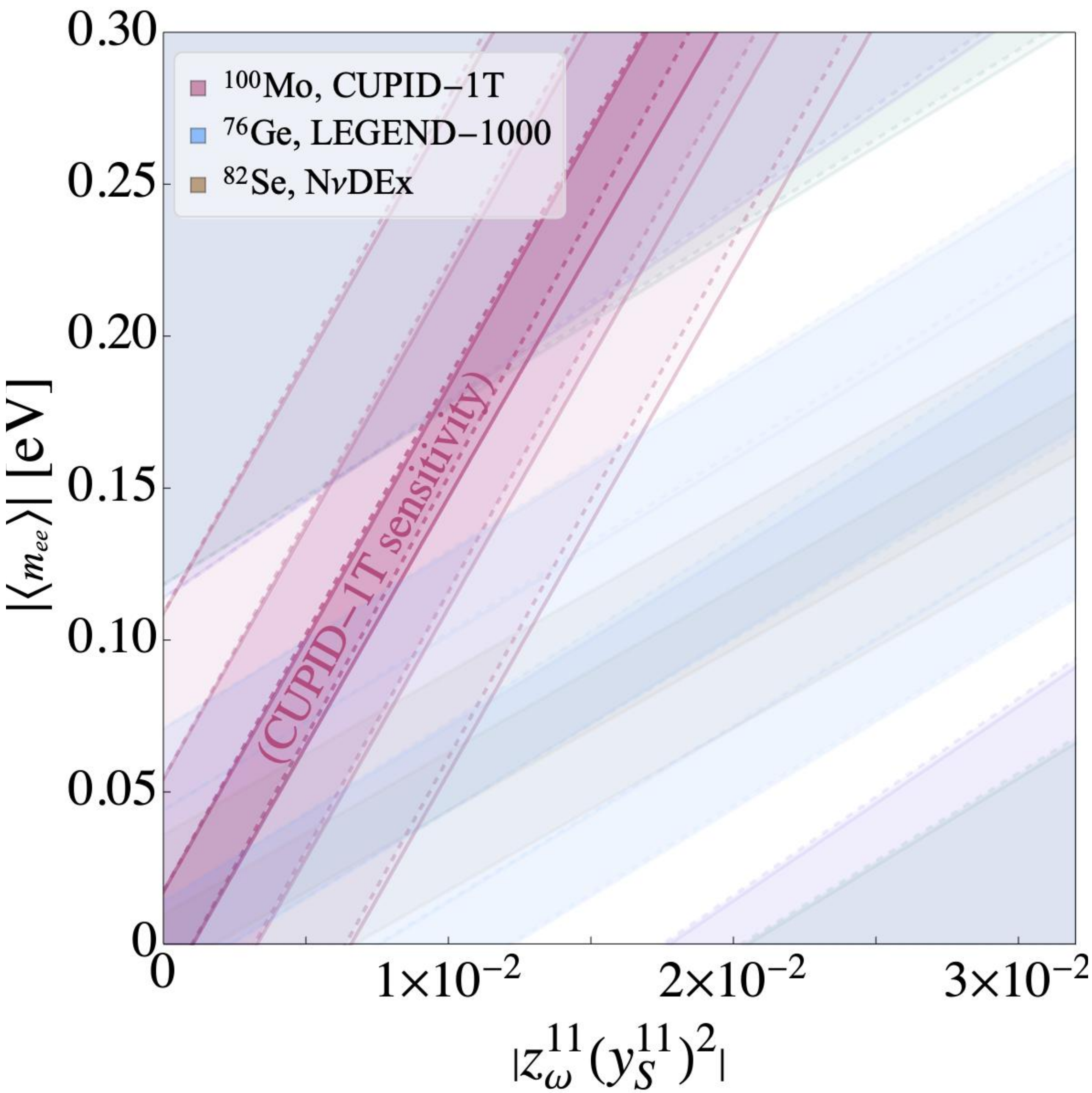

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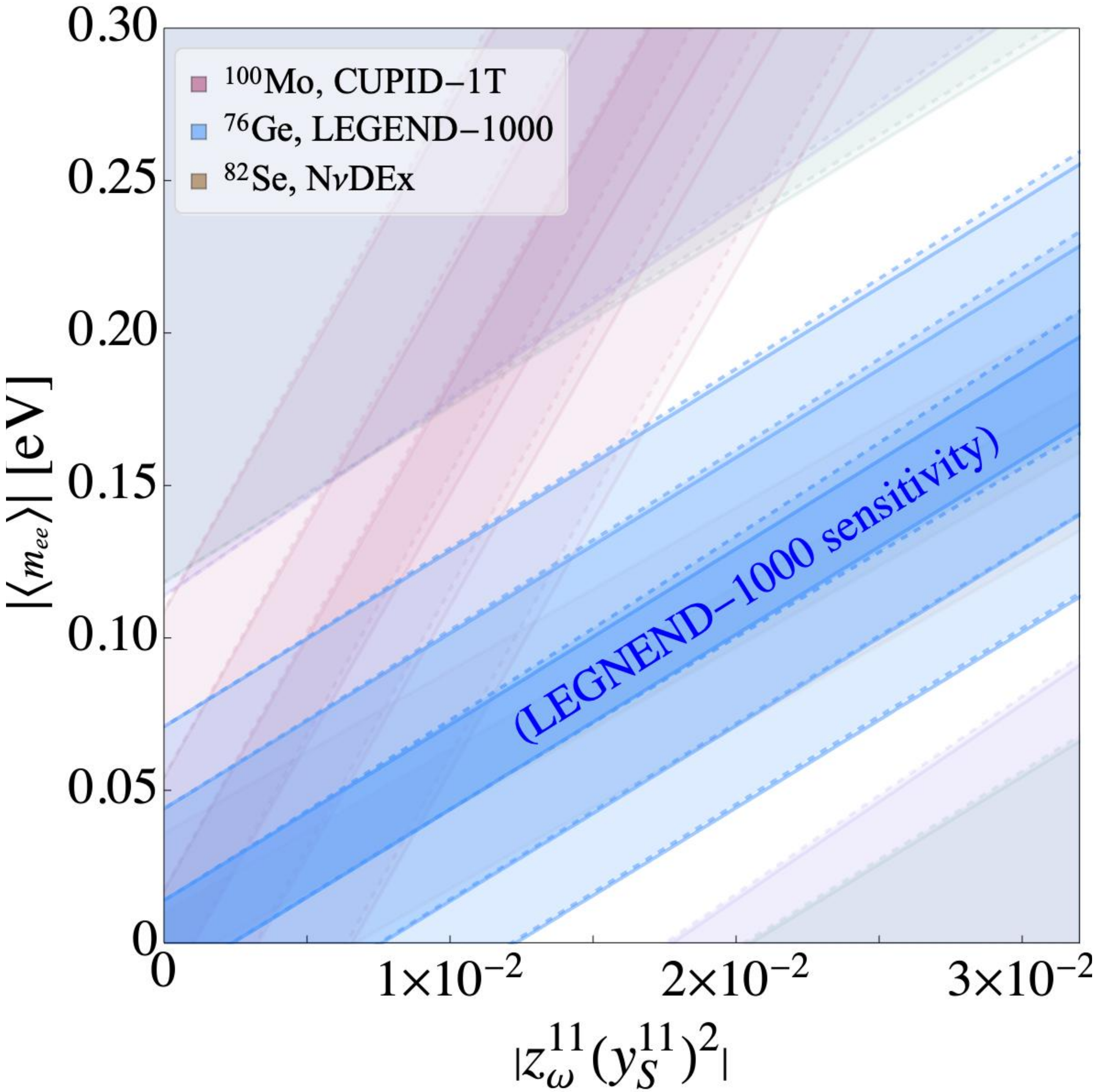

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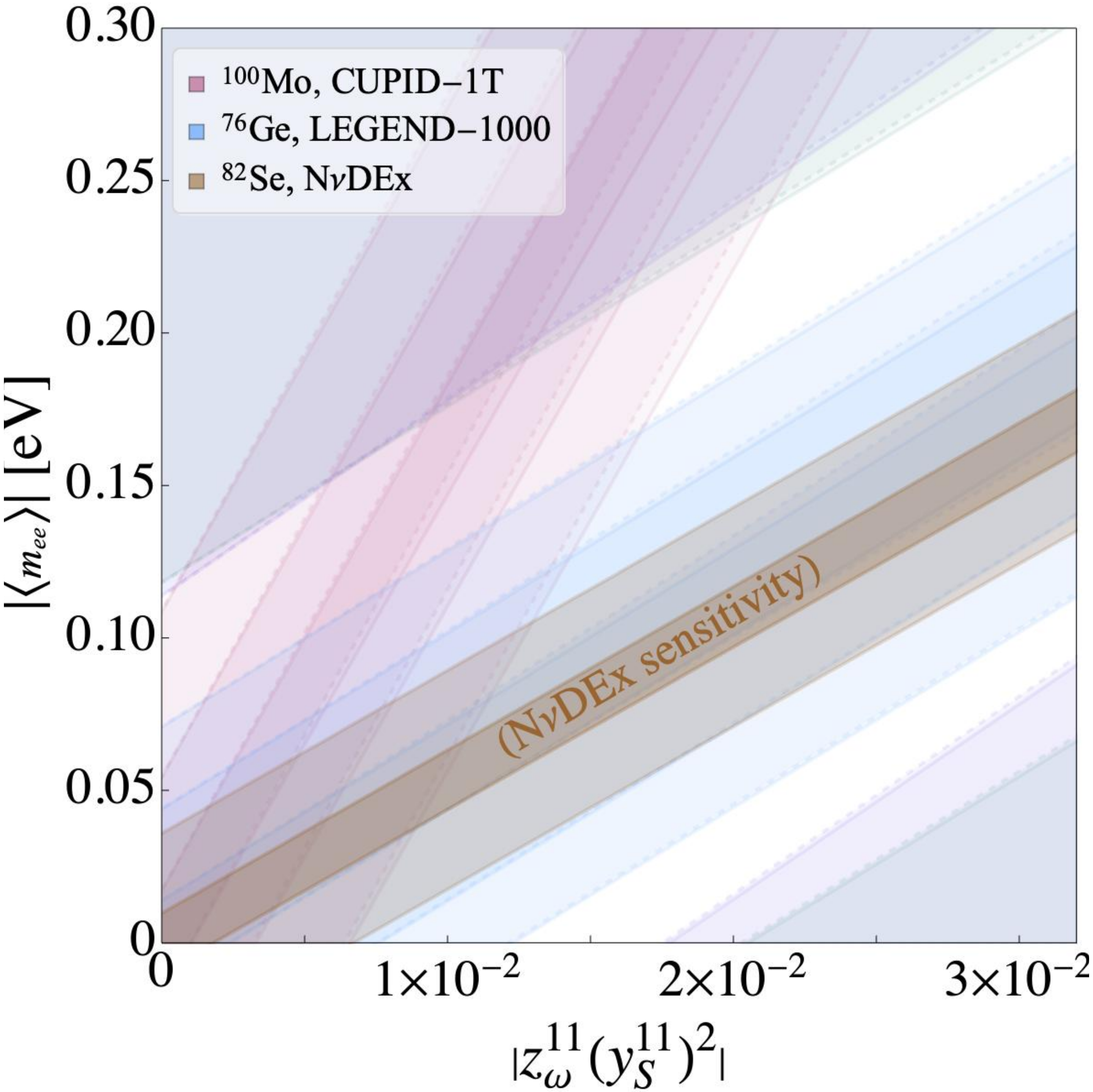

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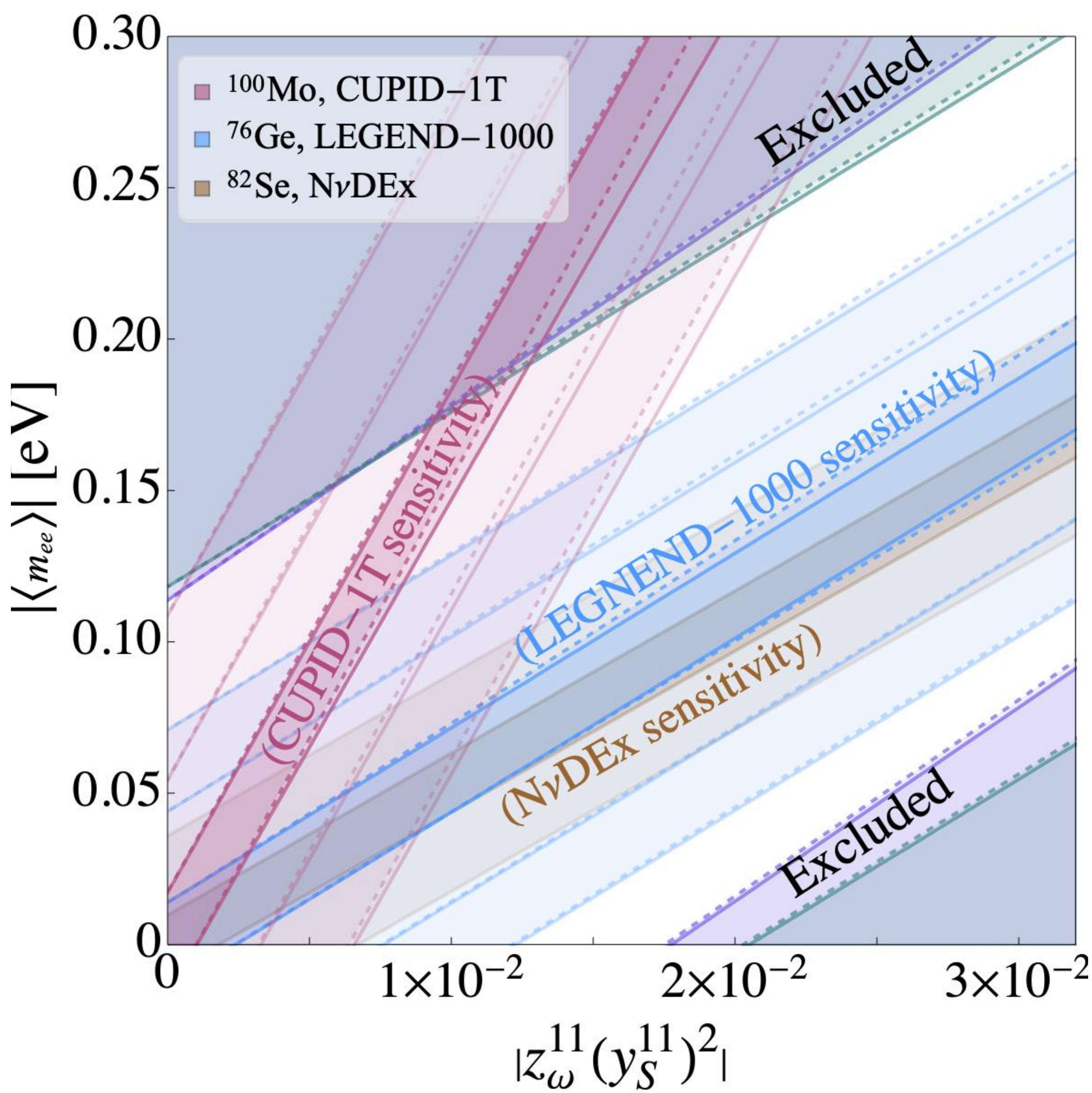

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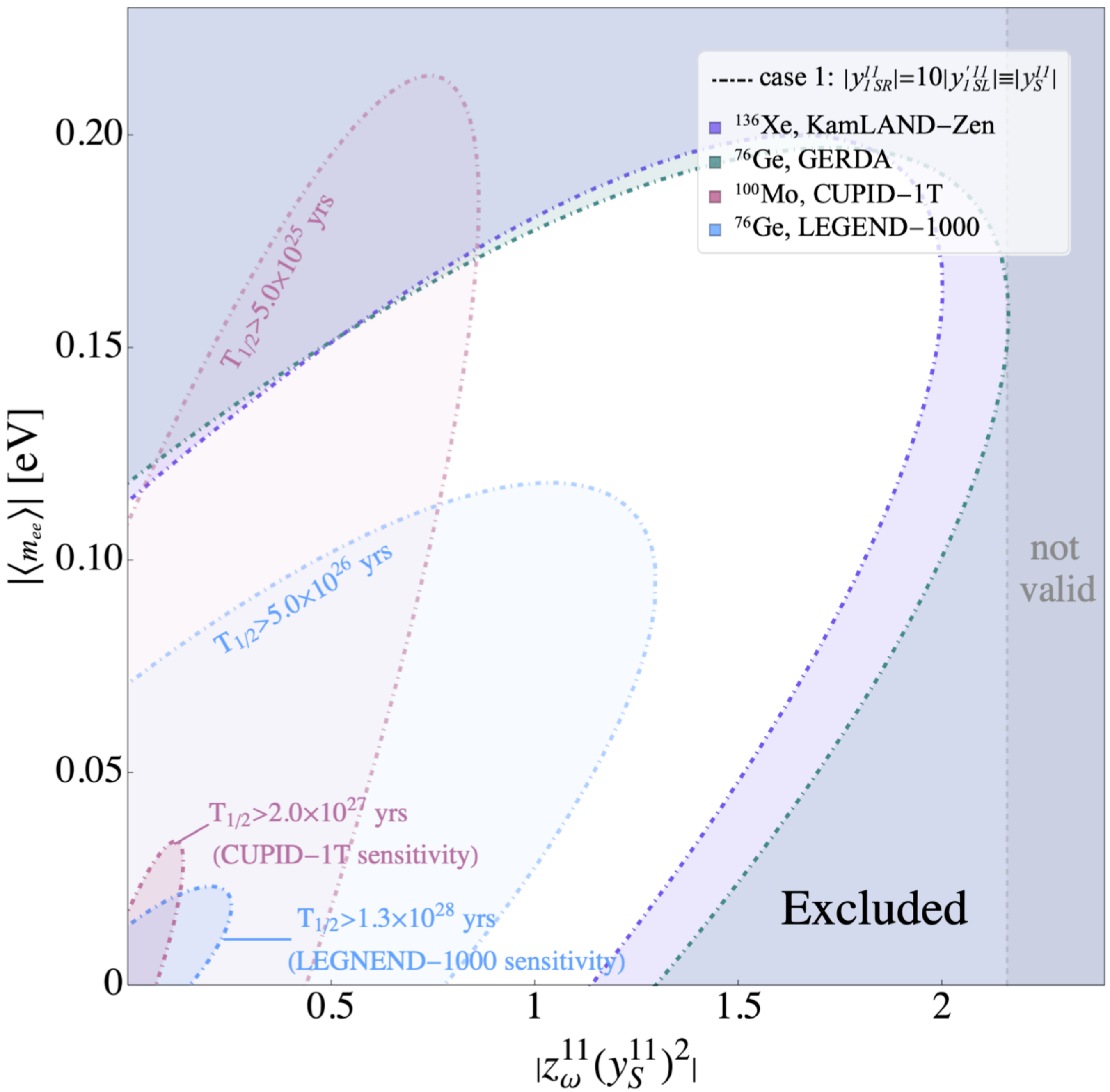
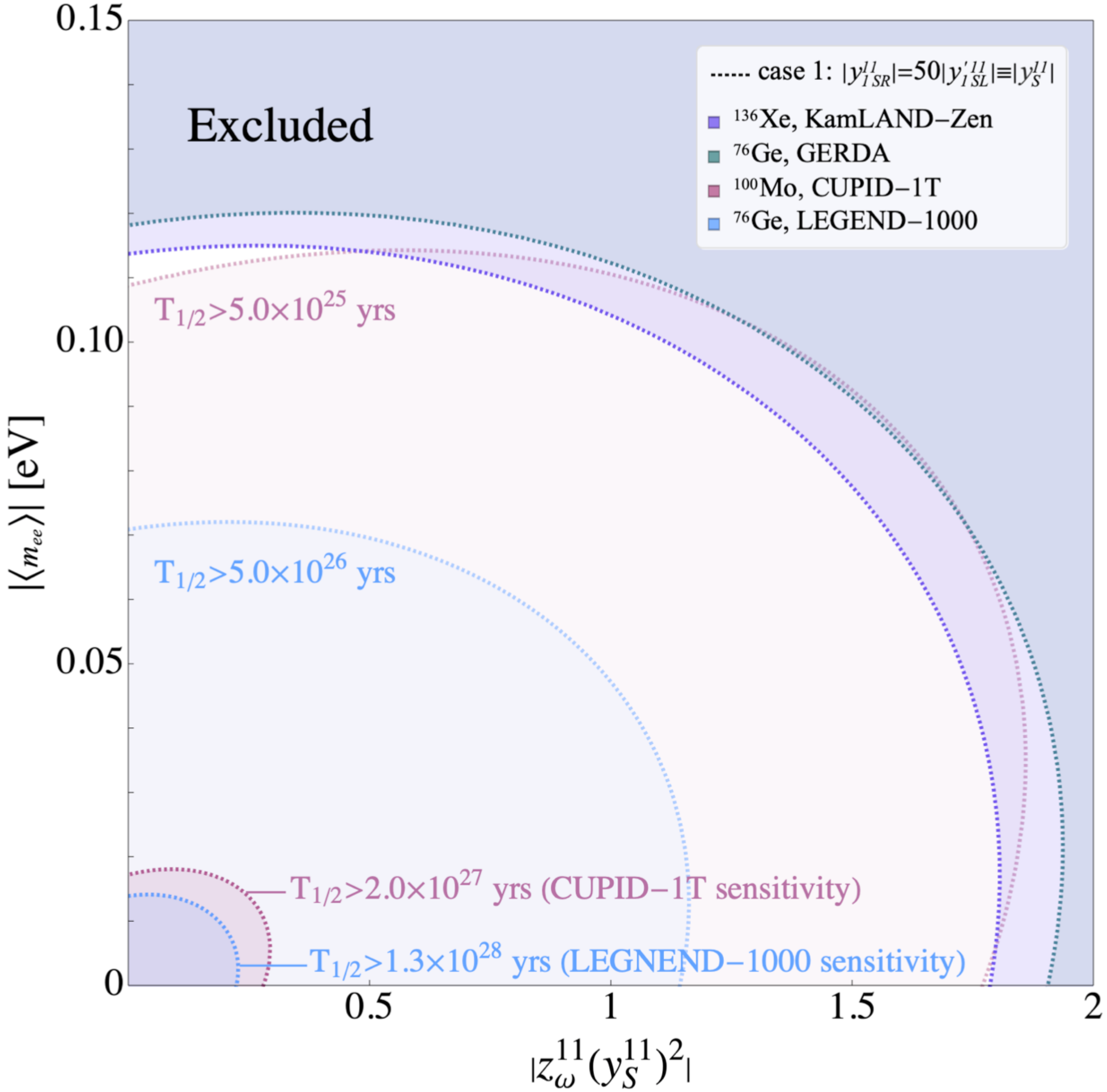




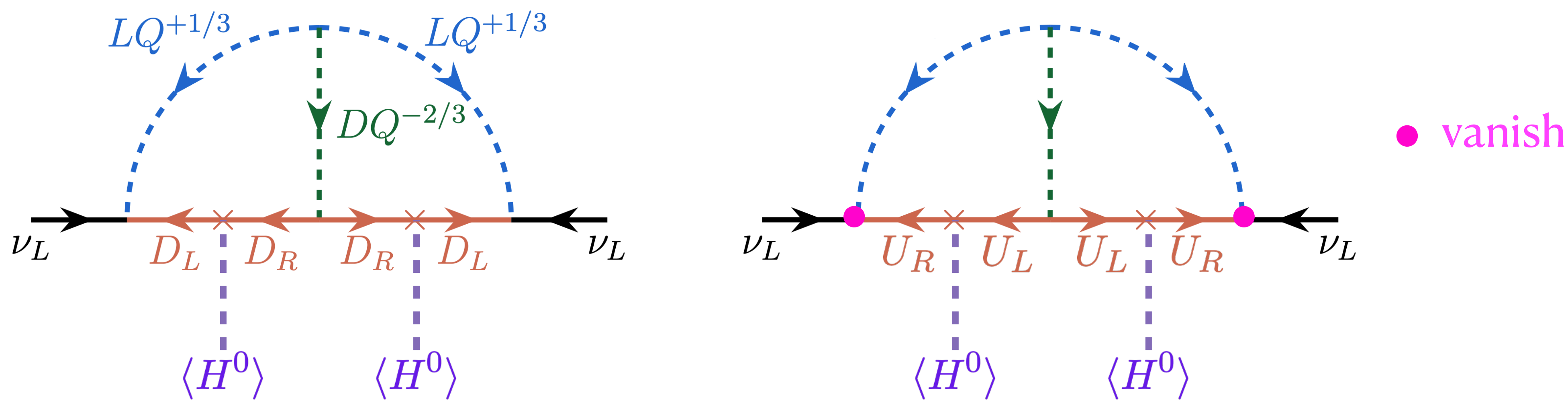
SUMMARY

- Consider three cases of the colored Zee-Babu model
- Focus on the interplay of standard neutrino exchange and short-range contribution of neutrinoless double beta decay
- Find that neutrinoless double beta decay can be hidden under certain condition
- The condition can be examined comprehensively by future complementary searches with different isotopes.

Thank you for your attention

BACKUP

✦ No up quarks?



✦ DQ color sextet?

If the color triplet, the vertex would vanish when involving repeated fields.

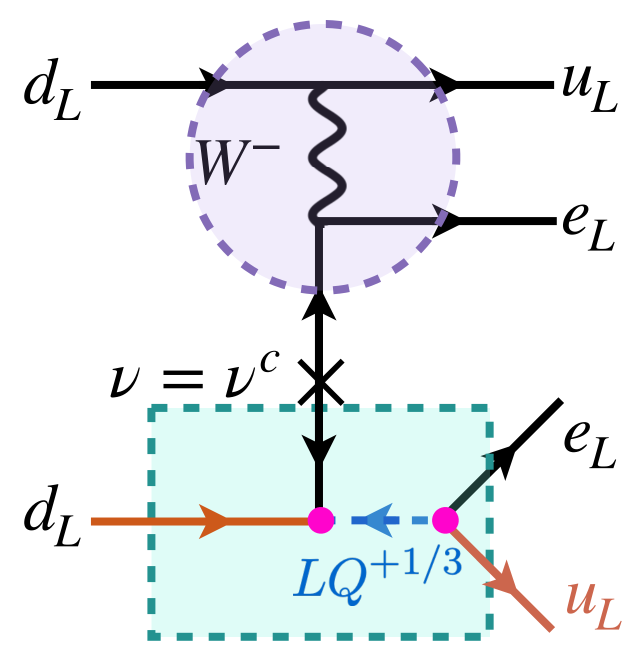
$$z^{ij}\overline{(D_R^{i\alpha})^c}D_R^{j\beta}\omega^\gamma\epsilon^{\alpha\beta\gamma} = z^{ij}\overline{(D_R^{j\beta})^c}D_R^{i\alpha}\omega^\gamma\epsilon^{\alpha\beta\gamma}$$

$$= -\,z^{ij}\overline{(D_R^{j\alpha})^c}D_R^{i\beta}\omega^\gamma = -z^{ji}\overline{(D_R^{i\alpha})^c}D_R^{j\beta}\omega^\gamma\epsilon^{\alpha\beta\gamma}$$

leads to $z^{11} = 0$

✦ Only LQ contribute?

- The LQ in case 3 cannot contribute to $0\nu\beta\beta$
- In case 1 and case 2: LQ contribution $\simeq 10^{-4} \times$ Standard contribution



$\propto G_F$

$\propto \frac{y_1 y_2}{M_{LQ}^2} \simeq \frac{0.1^2}{(1.5\ \text{TeV})^2} \simeq 4\times 10^{-9}\ \text{GeV}^{-2}$

BACKUP

Results Many-body model dependent?

MSSM with R-parity violating

$$T_{\mathrm{SR},1/2}^{-1} = G_\nu \left| \frac{\langle m_{ee} \rangle}{m_e} \mathcal{M}_\nu + \epsilon \mathcal{M}_{\mathrm{SR}} \right|^2$$

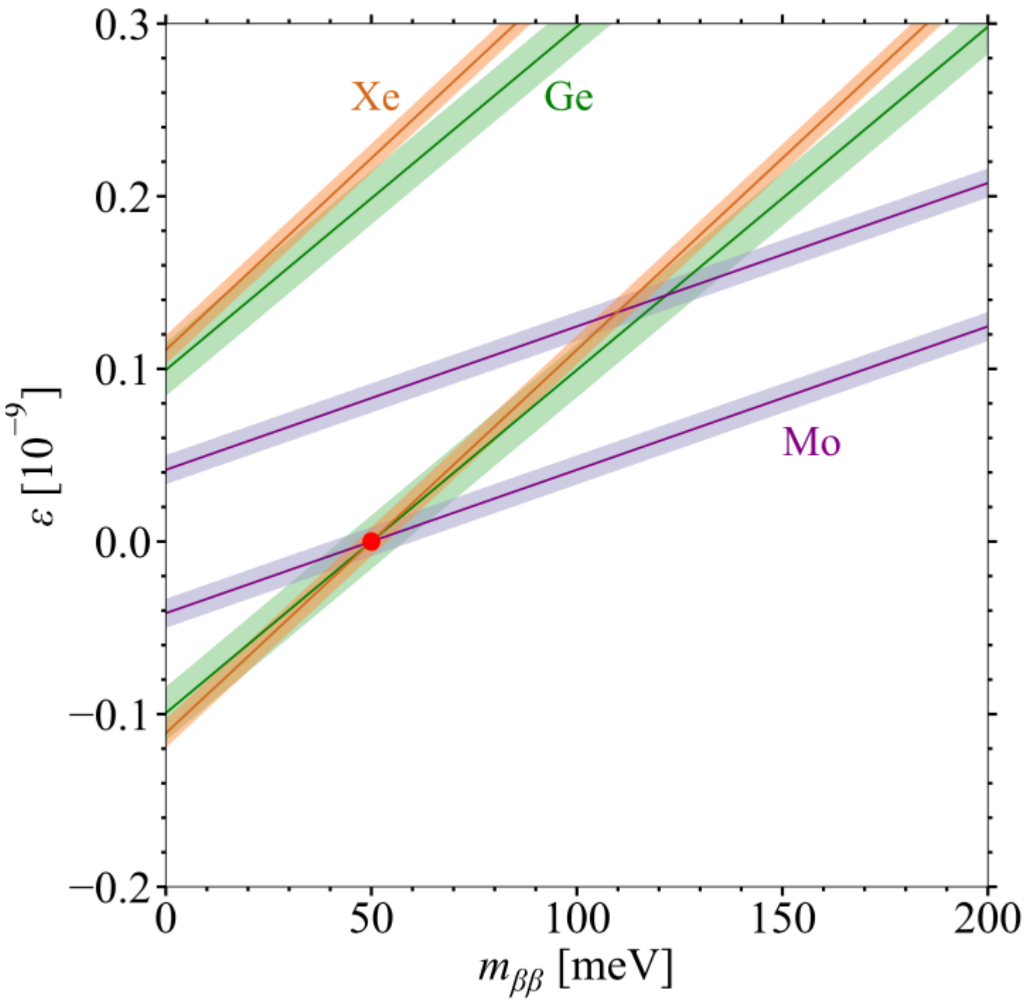
- The contributions cancel exactly

$$\epsilon = -\frac{\mathcal{M}_\nu}{\mathcal{M}_{\mathrm{SR}}} \frac{\langle m_{ee} \rangle}{m_e}$$

- For different isotopes X, the slopes are different.

$$\epsilon(X) = -\frac{\mathcal{M}_\nu(X)}{\mathcal{M}_{\mathrm{SR}}(X)} \frac{\langle m_{ee} \rangle}{m_e} \pm \left[T_{\mathrm{SR},1/2}(X) G_\nu(X)\right]^{-1/2}$$

M. Agostini, F. F. Deppisch, G. V. Goffrier, **2212.00045**



BACKUP

Nuclear Matrix Elements and their Estimation

Energy-density Functional (EDF) theory

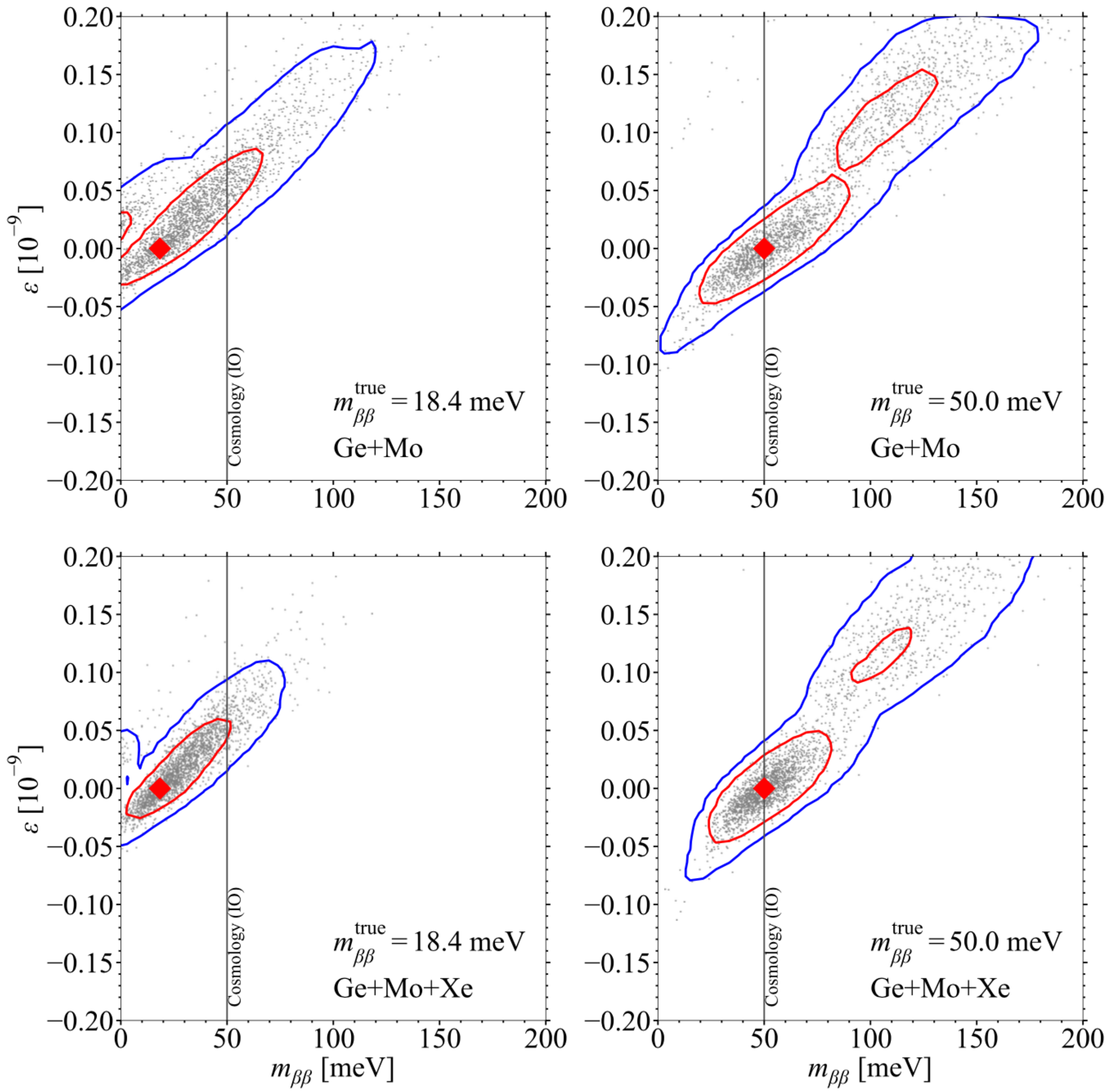
Interacting Boson Model (IBM)

Quasi-particle Random-Phase Approximation (QRPA)

Multivariate Gaussian distribution over the NMEs

$$\mathbf{m} = (M_\nu(^{76}\mathrm{Ge}), M_\nu(^{100}\mathrm{Mo}), M_\nu(^{136}\mathrm{Xe}))^T$$

$$\mathcal{N}(\mathbf{m}) = \frac{1}{\sqrt{(2\pi)^3 \det(\Sigma)}} \exp\left[-\frac{1}{2}(\mathbf{m}-\boldsymbol{\mu})^T \cdot \Sigma^{-1} \cdot (\mathbf{m}-\boldsymbol{\mu})\right]$$



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