

# Effective field theory approach to $0\nu\beta\beta$ decay with light sterile neutrinos

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**GL**, Michael J. Ramsey-Musolf, Juan Carlos Vasquez, 2009.01257 (PRL)

Jordy de Vries, **GL**, Michael J. Ramsey-Musolf, Juan Carlos Vasquez, 2209.03031 (JHEP)

第十六届TeV物理工作组学术研讨会暨邝宇平院士学术思想研讨会  
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# Neutrinos: what we know

- Neutrinos in the SM are **massless**

$$L_i \rightarrow \begin{pmatrix} \nu_i \\ \ell_i \end{pmatrix} \quad m_\nu = 0$$

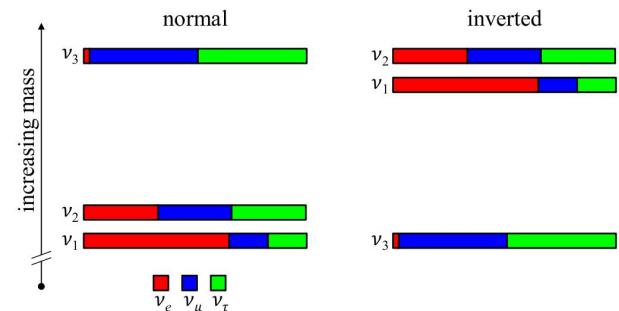
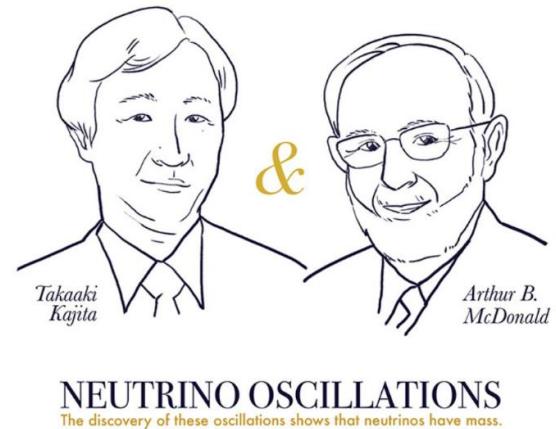
- Neutrino mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Neutrino oscillations require **massive neutrinos**

$$P(\nu_i \rightarrow \nu_j) \propto \Delta m_{ij}^2 \quad \Delta m_{21}^2 \approx 7.5 \times 10^{-5} \text{ eV}^2$$
$$|\Delta m_{31}^2| \approx 2.5 \times 10^{-3} \text{ eV}^2$$

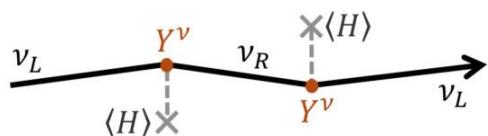
- Normal vs inverted hierarchy



# Neutrinos: what we do not know

- Mass origin and Majorana nature:
  - How do neutrinos get their masses?
  - Are they Dirac or Majorana fermions?

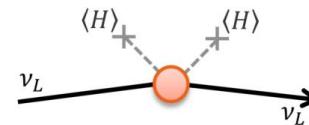
Dirac mass:



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

very small coupling

Majorana mass:



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

S. Weinberg 1979

(very) large scale

# Neutrinos and lepton number violation

- How can we test if neutrinos are Dirac or Majorana fermions?

Dirac mass:

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

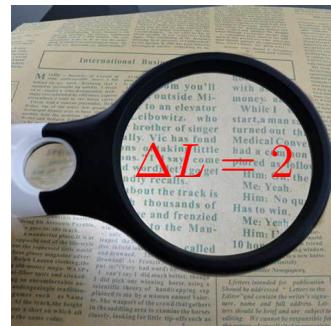
-1    +1

Majorana mass:

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

+1        +1

Lepton number is violated by two units  $\Delta L = 2$  if there exists Majorana neutrino mass

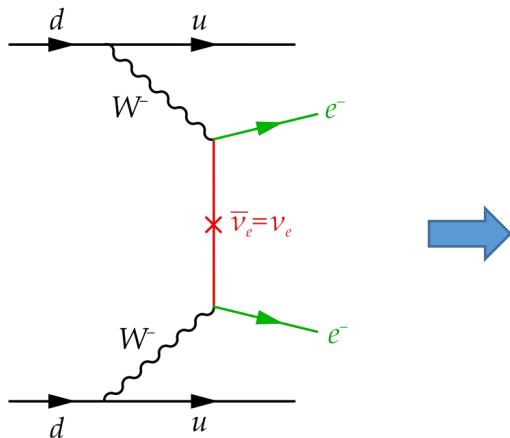


# Neutrinoless double beta decay

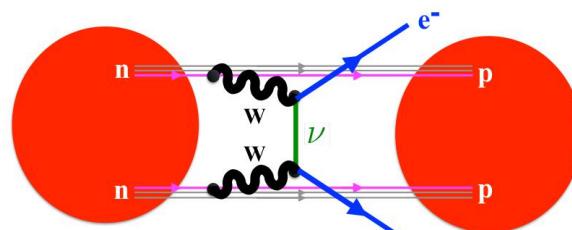
- Why search for  $0\nu\beta\beta$  decay?

If neutrino is Majorana fermion,  $0\nu\beta\beta$  decay process is induced

Majorana mass:



$0\nu\beta\beta$  decay:



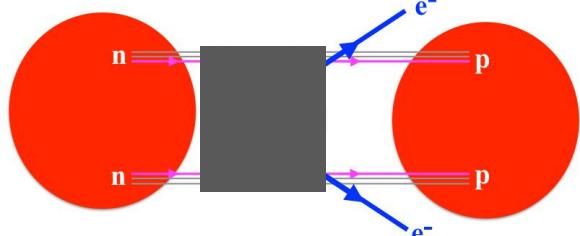
Furry, Phys. Rev. 56 (1939) 1184

# Neutrinoless double beta decay

- Why search for  $0\nu\beta\beta$  decay?

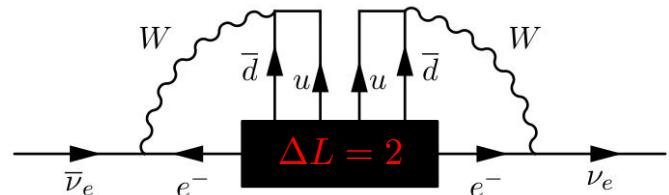
An observation of  $0\nu\beta\beta$  decay implies LNV  $\Delta L = 2$  and Majorana neutrino mass

$0\nu\beta\beta$  decay:



Majorana mass:

"Black box theorem"



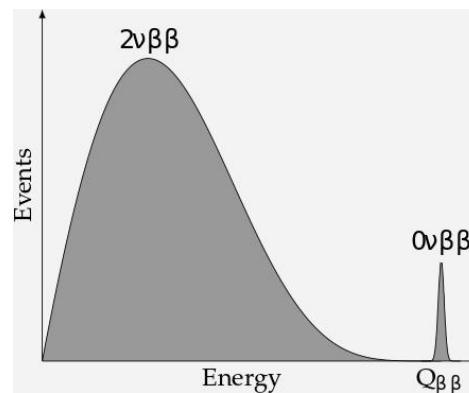
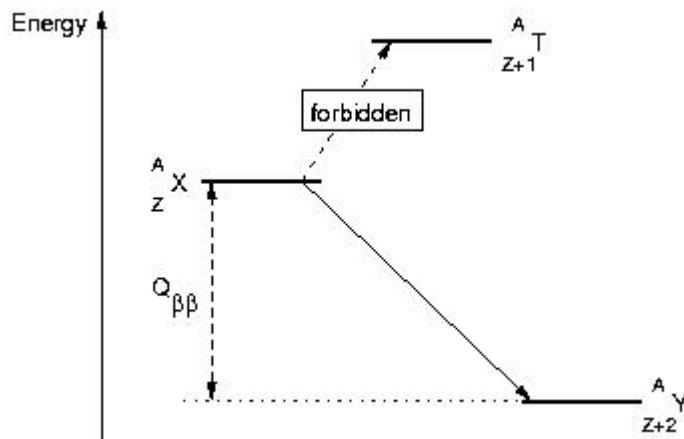
Schechter, Valle, Phys.Rev.  
D25 (1982) 774

# Neutrinoless double beta decay

Experimental searches for  $0\nu\beta\beta$  decay in nuclei  $^{136}\text{Xe}$ ,  $^{76}\text{Ge}$ , et al,

$$(A, Z) \rightarrow (A, Z + 2) + e^- + e^-$$

${}^A_Z X$      $A$ : mass number, # of  $p, n$   
 $Z$ : atomic number, # of  $p$



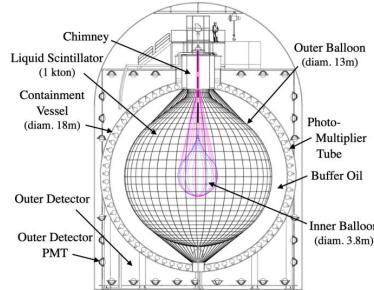
summed energy of  
electrons

$$Q_{\beta\beta} \sim 2 \text{ MeV}$$

# Neutrinoless double beta decay

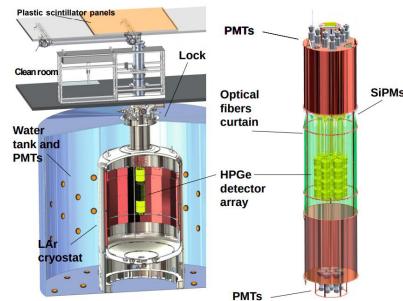
## Status of experiments

KamLAND-Zen:  $^{136}\text{Xe} \rightarrow ^{136}\text{Ba} + e^- + e^-$



$$T_{1/2}^{0\nu}(\text{Xe}) > 1.07 \times 10^{26} \text{ year}$$

GERDA:  $^{76}\text{Ge} \rightarrow ^{76}\text{Se} + e^- + e^-$



$$T_{1/2}^{0\nu}(\text{Ge}) > 1.8 \times 10^{26} \text{ year}$$

PandaX, CDEX, JUNO, ...



Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES-III	$^{48}\text{Ca}$	300 kg	$\text{CaF}_2$ scint. crystals	Prototype	Kamioka
GERDA	$^{76}\text{Ge}$	$\approx 35$ kg	$^{enr}\text{Ge}$ semicond. det.	Operating	LNGS
MAJORANA	$^{76}\text{Ge}$	26 kg	$^{enr}\text{Ge}$ semicond. det.	Operating	SURF
CDEX-IT	$^{76}\text{Ge}$	1 ton	$^{enr}\text{Ge}$ semicond. det.	Prototype	CJPL
LEGEND-200	$^{76}\text{Ge}$	200 kg	$^{enr}\text{Ge}$ semicond. det.	Construction	LNGS
LEGEND-1000	$^{76}\text{Ge}$	ton	$^{enr}\text{Ge}$ semicond. det.	Proposal	
CUPID-0	$^{82}\text{Se}$	5 kg	Zn $^{enr}\text{Se}$ scintillating bolometers	Prototype	LNGS
SuperNEMO-Dem	$^{82}\text{Se}$	7 kg	$^{enr}\text{Se}$ foils/tracking	Construction - 2019	Modane
SuperNEMO	$^{82}\text{Se}$	100 kg	$^{enr}\text{Se}$ foils/tracking	Proposal	Modane
CMOS Imaging	$^{82}\text{Se}$		$^{enr}\text{Se}$ , CMOS	Development	LNGS, LSM
				ion	YangYang
				n - 2019	YangYang
				n - 2020	Yomi
				n - 2020	Canfranc
				ment	LNGS, LSM
				ment	LNGS
				ion	LNGS
Tin,Tin	$^{124}\text{Sn}$	1 kg	Tin bolometers	Development	INO
CALDER	$^{130}\text{Te}$		$\text{TeO}_2$ bolometers with Cerenkov Light	Development	LNGS
CUORE	$^{130}\text{Te}$	1 ton	$\text{TeO}_2$ bolometers	Operating	LNGS
SNO+	$^{130}\text{Te}$	1.3 t	0.5% $^{enr}\text{Te}$ loaded liq. scint.	Construction - 2020	SNOLab
nEXO	$^{136}\text{Xe}$	5 t	Liq. $^{enr}\text{Xe}$ TPC/scint.	Proposal	
NEXT-100	$^{136}\text{Xe}$	100 kg	gas TPC	Prototype	Canfranc
AXEL	$^{136}\text{Xe}$		gas TPC	Prototype	
KamLAND-Zen	$^{136}\text{Xe}$	800 kg	$^{enr}\text{Xe}$ dissolved in liq. scint.	Operating	Kamioka
LZ	$^{136}\text{Xe}$		Dual phase Xe TPC	Construction - 2020	SURF
PANDAX-III	$^{136}\text{Xe}$	1 ton	Dual phase Xe TPC	Construction - 2019	CJPL
XENON1T	$^{136}\text{Xe}$	1 ton	Dual phase Xe TPC	Operating	LNGS
DARWIN	$^{136}\text{Xe}$	50 ton	Dual phase Xe TPC	Proposal	LNGS
NuDot	Various		Cherenkov and scint. detection in liq. scint.	Development	
FLARES	Various		Scint. crystals with Si photodetectors	Development	

tonne-scale experiments  $T_{1/2}^{0\nu} \gtrsim 10^{28}$  year

May 28, 2020

Elliott, BB Theory Workshop

# Neutrinoless double beta decay

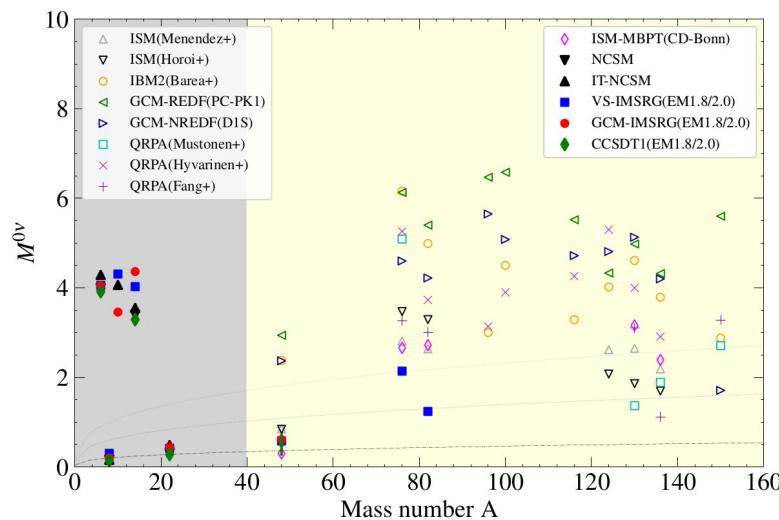
The theoretical inverse **half-life** is expressed as

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

$G_{0\nu}$ : phase space factor

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

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

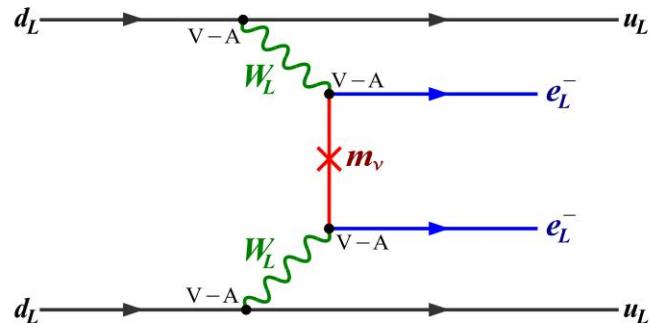


- Uncertainty in  $G_{0\nu}$  is about 10%
- $M_{0\nu}$  is being much improved

How about  $\langle m_{\beta\beta} \rangle$ ?

## Standard mechanism

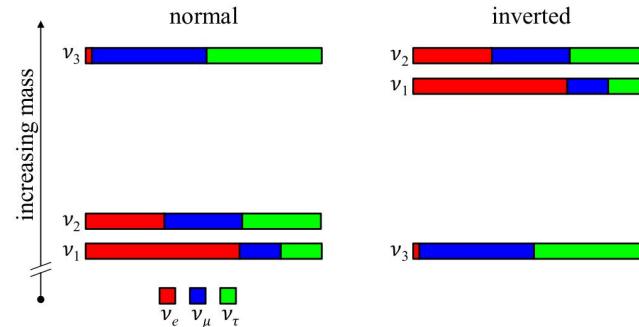
$0\nu\beta\beta$  decay is induced by the exchange of light Majorana neutrinos



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

absolute neutrino masses      PMNS matrix

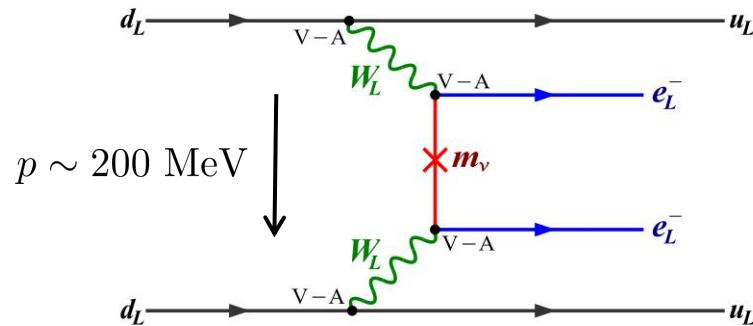
From neutrino oscillation  
 $\Delta m_{21}^2, |\Delta m_{31}^2|, \theta_{ij}, \delta$



The **lightest** neutrino mass, mass **hierarchy**, and **Majorana phases** are unknown

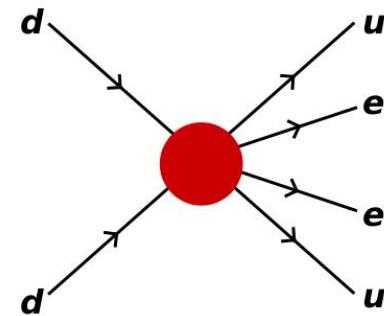
# Non-standard mechanisms

Standard mechanism:



$$\sim G_F^2 m_\nu / p^2$$

Non-standard mechanisms:



$$\sim c/\Lambda^5$$

$$\frac{c/\Lambda^5}{G_F^2 m_\nu^{ee} / p^2} = c \left( \frac{3.3 \text{ TeV}}{\Lambda} \right)^5 \frac{0.1 \text{ eV}}{m_\nu^{ee}}$$

$c$ : new coupling  
 $\Lambda$ : heavy particle mass

It is interesting to investigate it in more details in well-motivated  
neutrino mass models

# Minimal left-right symmetric model

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

Doublets:

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

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

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

Bidoublet:

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

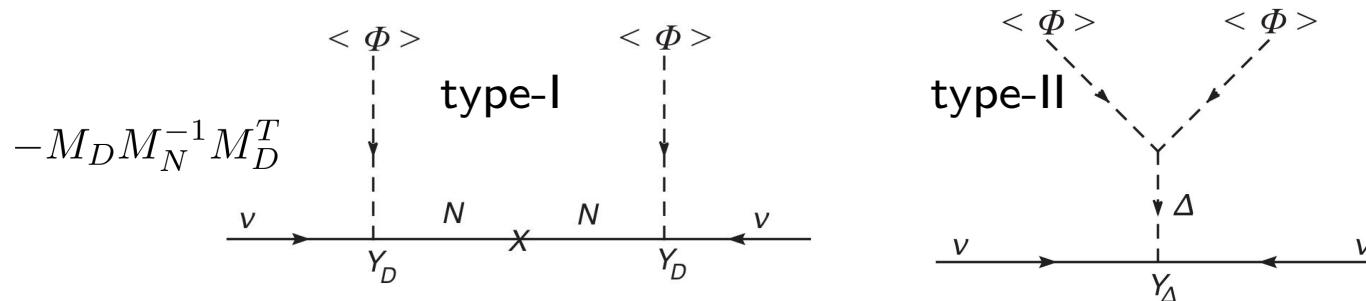
Triplets:

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

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

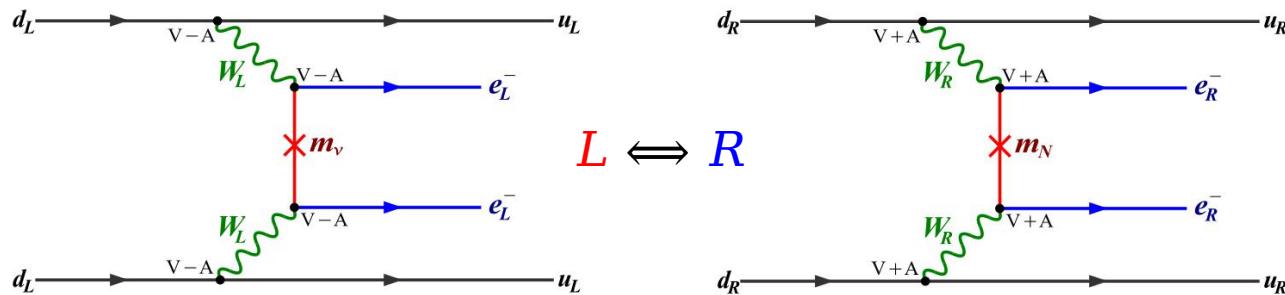
# Minimal left-right symmetric model

It provides natural origin of neutrino masses



$$\begin{aligned} M_L &= Y_\Delta \frac{\mu v^2}{M_\Delta^2} \\ &= \frac{v_L}{v_R} M_N \end{aligned}$$

It is the most studied BSM model for  $0\nu\beta\beta$  decay



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

Doi et al., Prog.Theor.Phys. 66 (1981) 1739

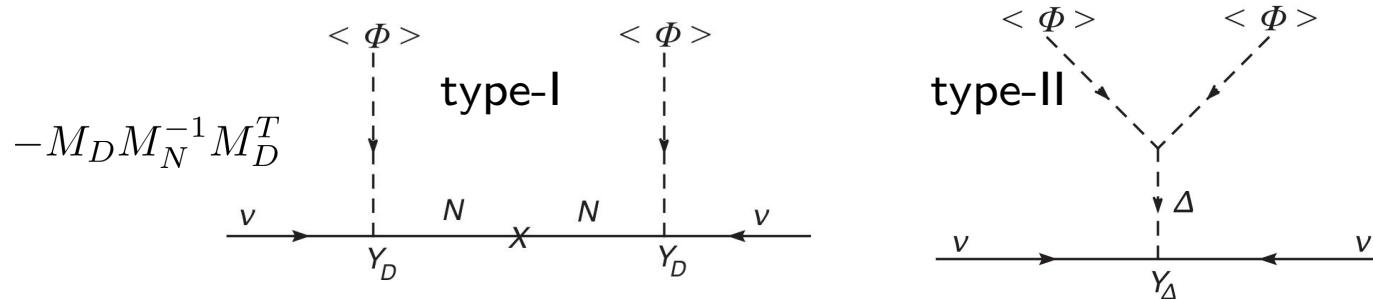
Tello et al., Phys.Rev.Lett. 106 (2011) 151801; S.-F. Ge, M. Lindner, S. Patra, 1508.07286

(JHEP); Bhupal Dev, Goswami, Mitra Phys.Rev.D 91 (2015) 113004

and many others

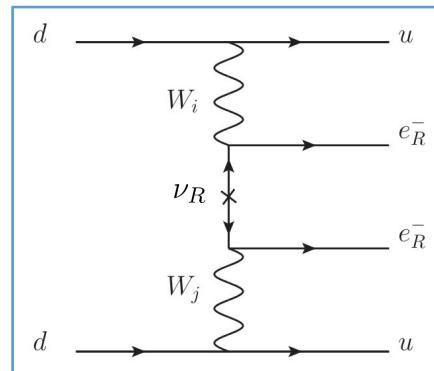
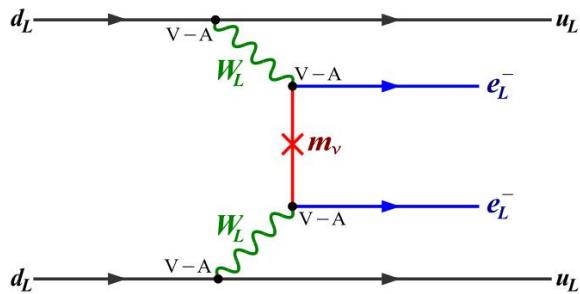
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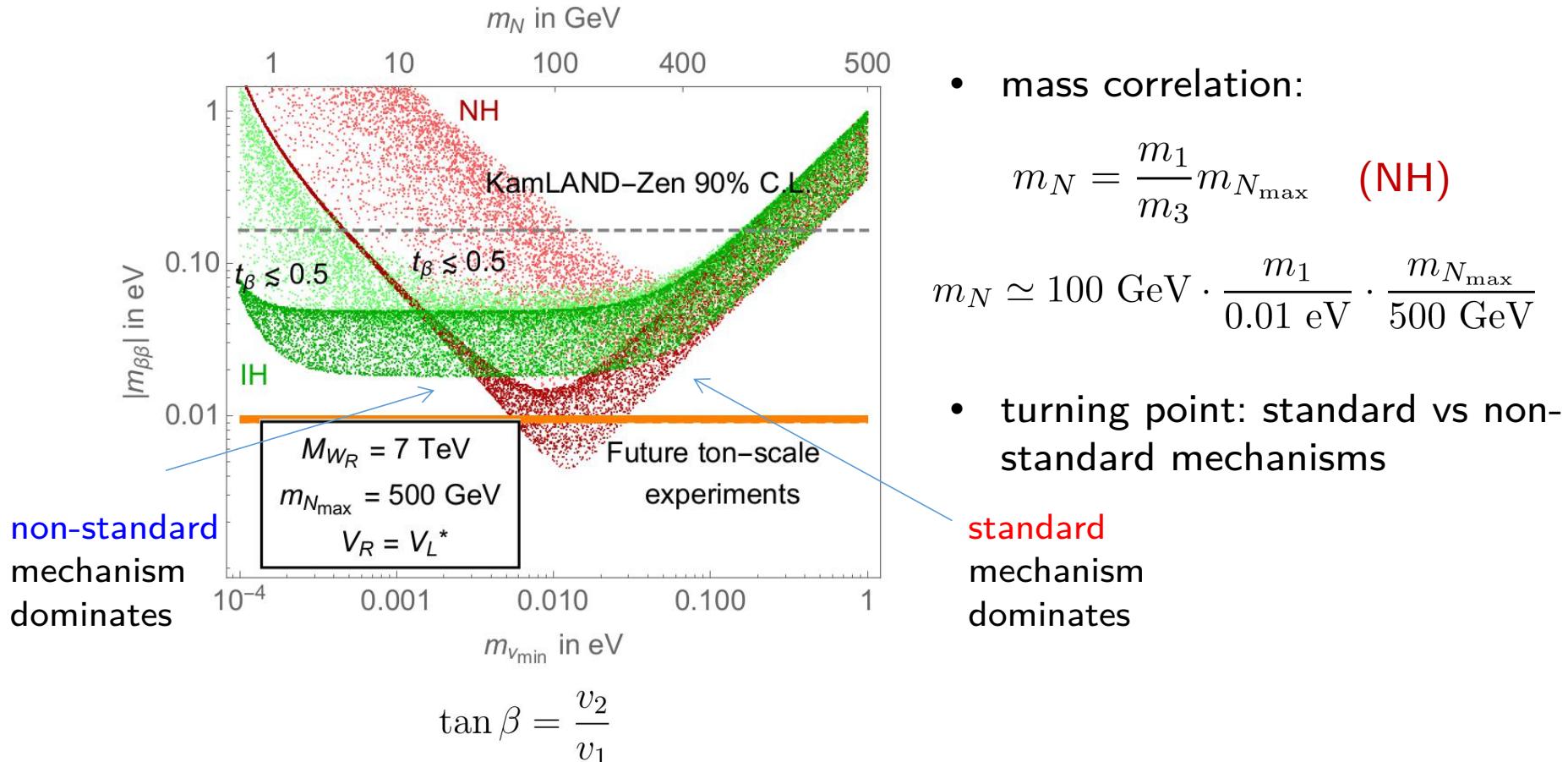
left-right mixing

(i,j)=(1,2)

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

# The leading contribution

Chiral **enhancement** comes from the left-right mixing



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

# Sterile neutrinos

From the flavor basis to the mass basis

$$N_m = \begin{pmatrix} \nu'_L \\ \nu'^c_R \end{pmatrix} = U^\dagger \begin{pmatrix} \nu_L \\ \nu^c_R \end{pmatrix} \quad U = \begin{pmatrix} U_{\text{PMNS}} & S \\ T & U_R \end{pmatrix}$$

Majorana states:  $\nu = (\nu_1, \dots, \nu_6)^T \equiv N_m + N_m^c$

active:  $\nu_a \equiv \nu'_L + \nu'^c_L = \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$

sterile:  $\nu_s \equiv \nu'_R + \nu'^c_R = \begin{pmatrix} \nu_4 \\ \nu_5 \\ \nu_6 \end{pmatrix}$

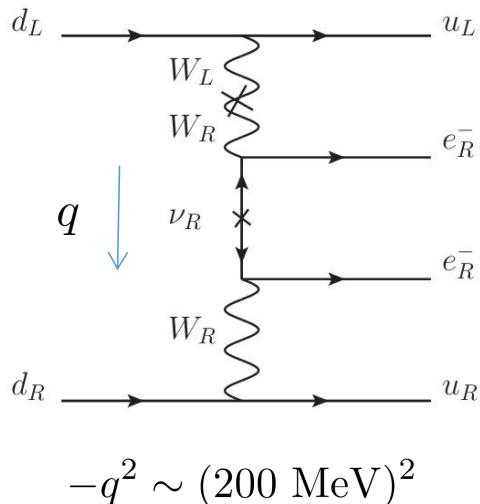
$\nu_s$  are sterile since they interact with  $W$  boson feebly, proportional to

- $S_{ei}$  ( $i = 1, 2, 3$ ) for  $\nu_4, \nu_5, \nu_6$ , respectively  $S = RU_R$   $R = M_D M_R^{-1}$
- the left-right mixing parameter  $\tan \zeta = \frac{M_W^2}{M_{W_R}^2} \sin(2\beta)$

# Sterile neutrinos

- How does the  $0\nu\beta\beta$  decay half-life or  $m_{\beta\beta}$  depend on the sterile neutrino mass  $m_i$  ( $i = 4,5,6$ )?

$0\nu\beta\beta$  decay amplitude



the mass dependence:

$$P_R \frac{q + m_i}{q^2 - m_i^2} P_R = P_R \frac{m_i}{q^2 - m_i^2} P_R$$

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

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

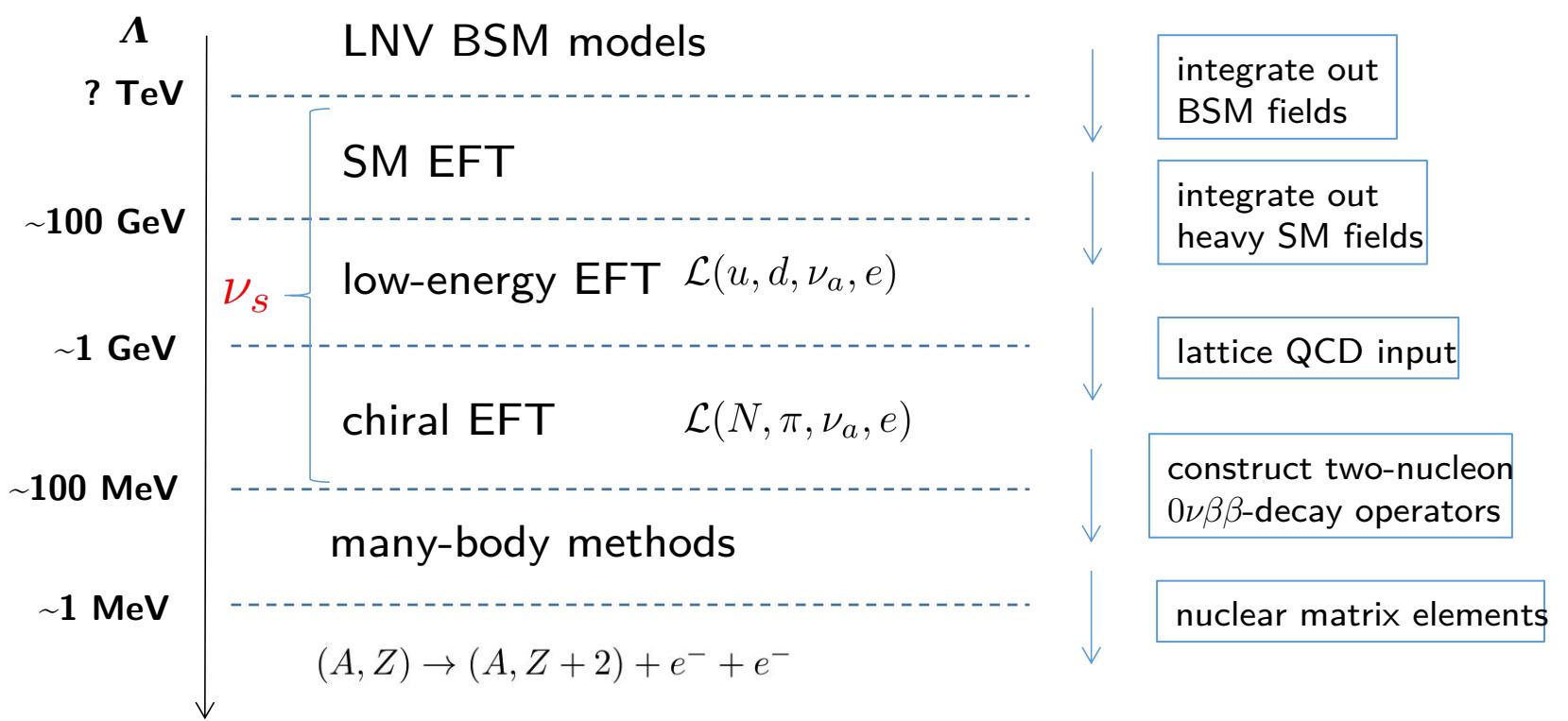
$$m_i^2 \gg -q^2$$

$$-P_R \frac{1}{m_i} P_R$$

For  $m_i^2 \gg -q^2$ , the decay amplitude is larger for a relatively lighter sterile neutrino

# EFT approach to $0\nu\beta\beta$ decay

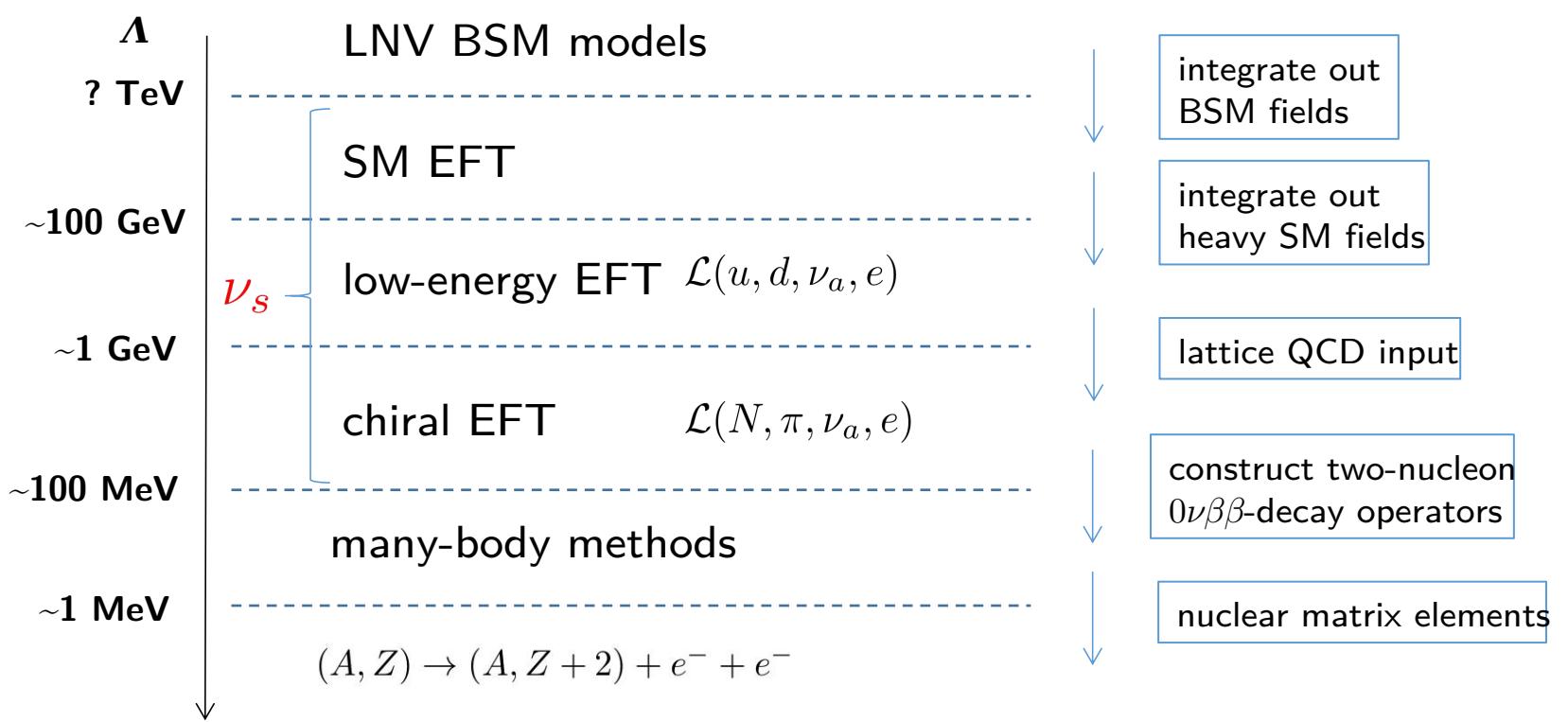
Describe contributions to  $0\nu\beta\beta$  decay systematically and consistently



SMEFT, LEFT,  $\nu$  SMEFT,  $\nu$  LEFT, ... which EFT?

# EFT approach to $0\nu\beta\beta$ decay

Describe contributions to  $0\nu\beta\beta$  decay systematically and consistently



We always keep  $\nu_s$ : RGE, nuclear matrix elements, low-energy constants

# EFT approach to $0\nu\beta\beta$ decay

We construct the effective Lagrangian in the mass basis

$$\mathcal{L}_{6,\nu\text{LEFT}} = \frac{2G_F}{\sqrt{2}} \left\{ \bar{u}_L \gamma_\mu d_L \left[ \bar{e}_L \gamma^\mu C_{\text{VLL}}^{(6)} \nu + \bar{e}_R \gamma^\mu C_{\text{VLR}}^{(6)} \nu \right] + \bar{u}_R \gamma_\mu d_R \bar{e}_R \gamma^\mu C_{\text{VRR}}^{(6)} \nu \right\}$$

$C_{\text{VLL}}^{(6)}(m_W) = -2V_{ud} PU,$ $C_{\text{VLR}}^{(6)}(m_W) = V_{ud} \left( v^2 C_L^{(6)}(m_{W_R}) \right) P_s U^*,$ $C_{\text{VRR}}^{(6)}(m_W) = \left( v^2 C_R^{(6)}(m_{W_R}) \right) P_s U^*.$	$C_L^{(6)}(m_{W_R}) = 2 \frac{\xi e^{-i\alpha}}{1 + \xi^2} \frac{C_R^{(6)}}{V_{ud}^R}$ $C_R^{(6)}(m_{W_R}) = -\frac{1}{v_R^2} V_{ud}^R$
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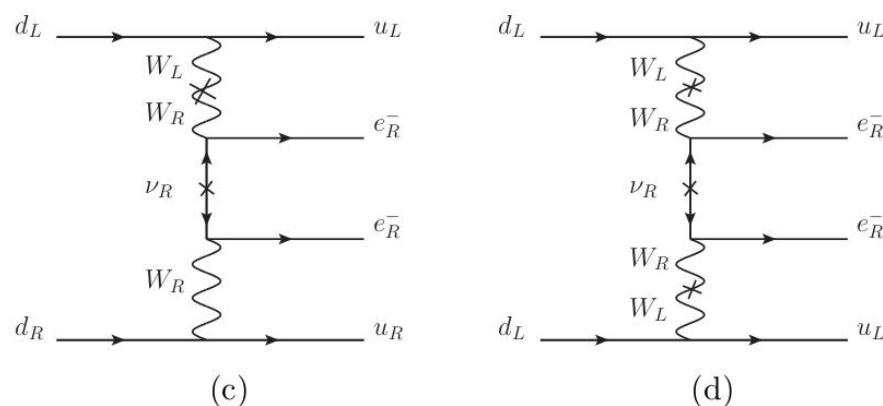
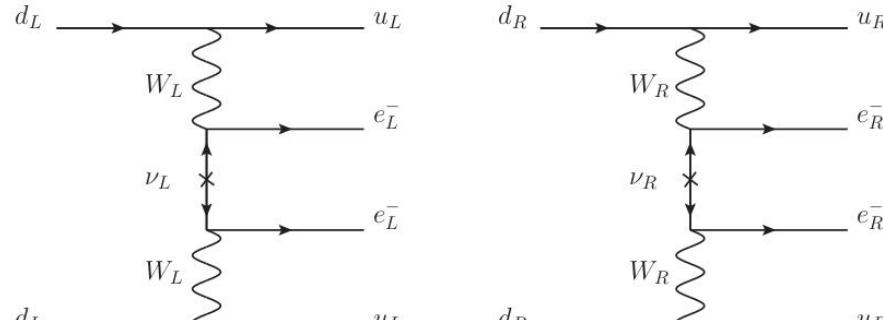
$$PU = (U_{\text{PMNS}}, S) \quad P_s U^* = (T^*, U_R^*)$$

Interestingly, all contributions to  $0\nu\beta\beta$  decay in the mLRSM can be described by these **three** Wilson coefficients

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

# Diagrams

Type-II:

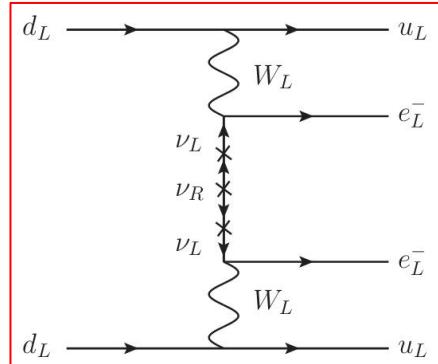


$$(a): P_L \frac{q + m_i}{q^2 - m_i^2} P_L = P_L \frac{m_i}{q^2 - m_i^2} P_L$$

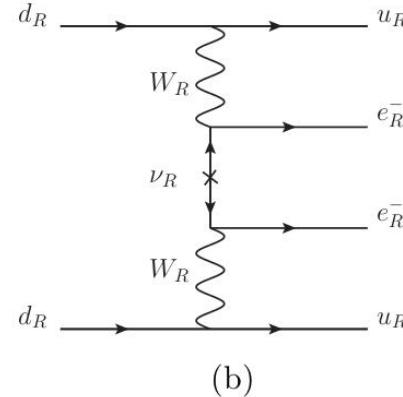
$$(b)(c)(d): P_R \frac{q + m_i}{q^2 - m_i^2} P_R = P_R \frac{m_i}{q^2 - m_i^2} P_R$$

# Diagrams

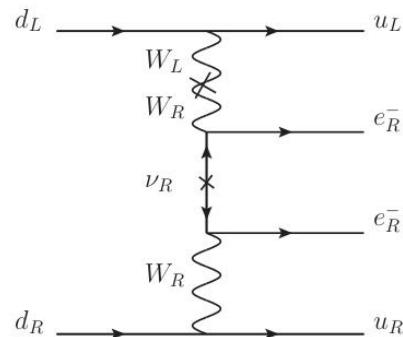
Type-I:



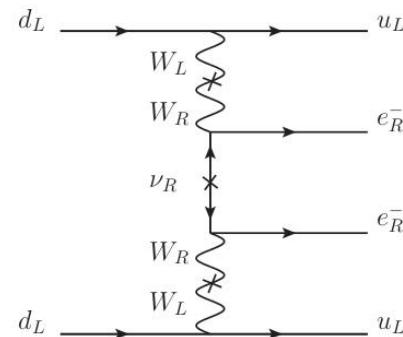
(a)



(b)



(c)



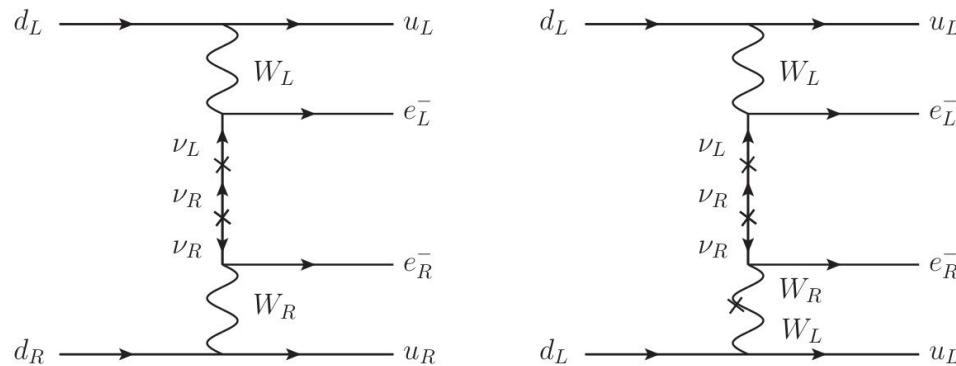
(d)

$$(a): P_L \frac{q + m_i}{q^2 - m_i^2} P_L = P_L \frac{m_i}{q^2 - m_i^2} P_L$$

$$(b)(c)(d): P_R \frac{q + m_i}{q^2 - m_i^2} P_R = P_R \frac{m_i}{q^2 - m_i^2} P_R$$

# Diagrams

Type-I:  $\lambda$  and  $\eta$  diagrams (Doi et al., 1983)

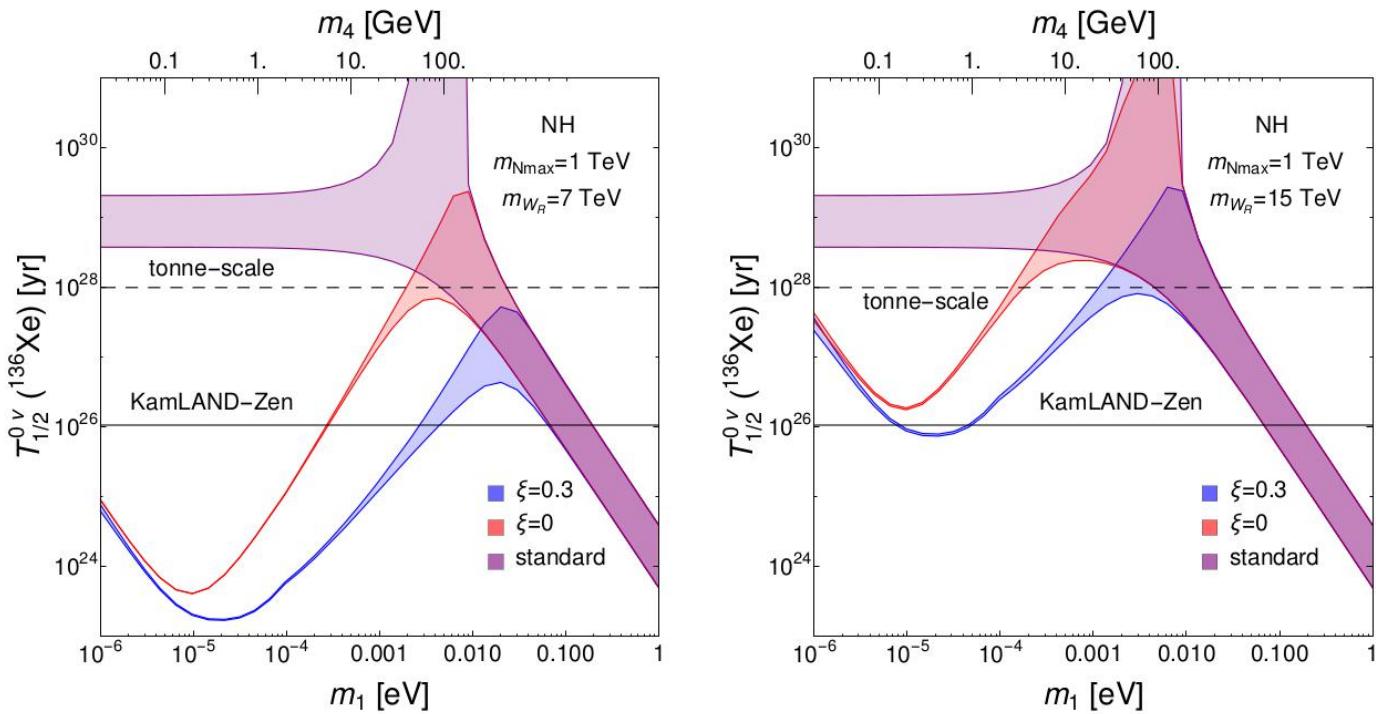


$$P_L \frac{q + m_i}{q^2 - m_i^2} P_R = P_L \frac{q}{q^2 - m_i^2} P_R$$

A complete EFT approach to  $0\nu\beta\beta$  decay half-life of the mLRSMS  
for any sterile neutrino mass

# Results

Type-II: sterile neutrino and active neutrino masses are related

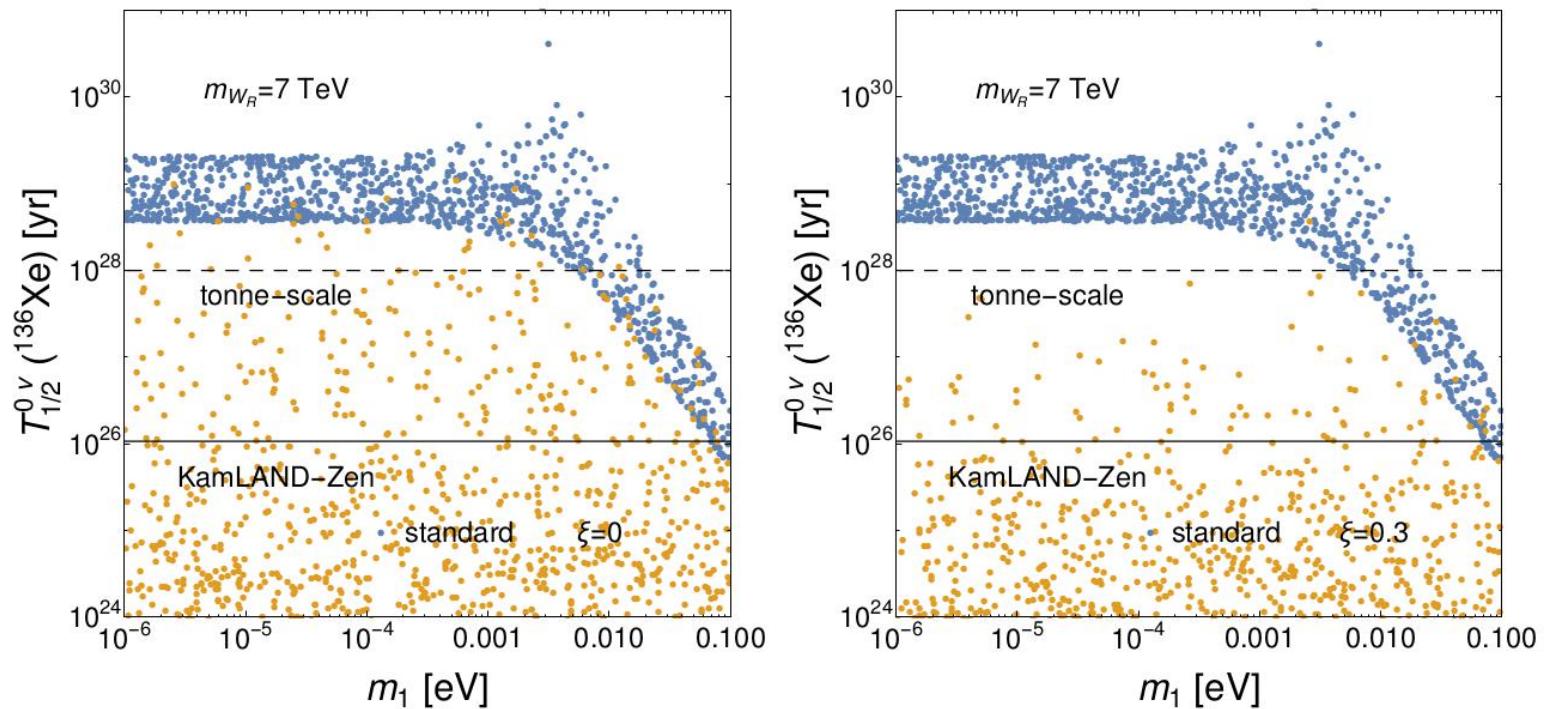


second turning point for  $m_4 \sim 200 \text{ MeV}$

$$\frac{m_4}{\mathbf{q}^2} \leftrightarrow \frac{1}{m_4}$$

# Results

Type-I: sterile neutrino masses are varied within [10 MeV, 1 TeV]



broader parameter space compared to type-II:  
cancellation between two lighter sterile neutrinos

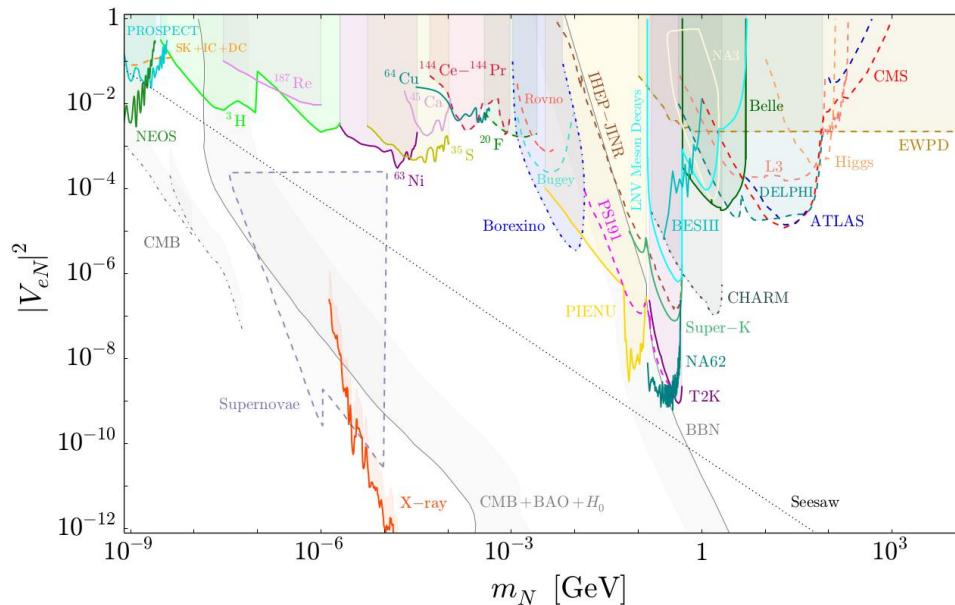
## Summary

- $0\nu\beta\beta$  decay in the mLRSM is considered with particluar attention to light sterile neutrinos
- A general EFT approach is developed, where all contributions are described by a few Wilson coefficients
- This formalism is suitable for  $0\nu\beta\beta$  decay experimental benchmarks and can be easily extended to other BSM models

# Sterile neutrinos

Current constraints:

Bolton, Deppisch, Bhupal Dev, 1912.03058 (JHEP)



The coupling of  $\nu_s$  to  $W$  boson is proportional to  $S_{ei}$  ( $i = 1, 2, 3$ ) for  $\nu_4, \nu_5, \nu_6$ , respectively

$$S = RU_R$$

$$\| R \| \lesssim \sqrt{0.1 \text{ eV}/10 \text{ MeV}} = 10^{-4}$$