Neutrinoless double beta decay with *light* sterile neutrinos

Kaori Fuyuto

Los Alamos National Laboratory

W. Dekens, J. de Vries, KF, E. Mereghetti, G. Zhou
JHEP06(2020)097

February 14, 2021
NDBD Workshop
LA-UR-21-21157

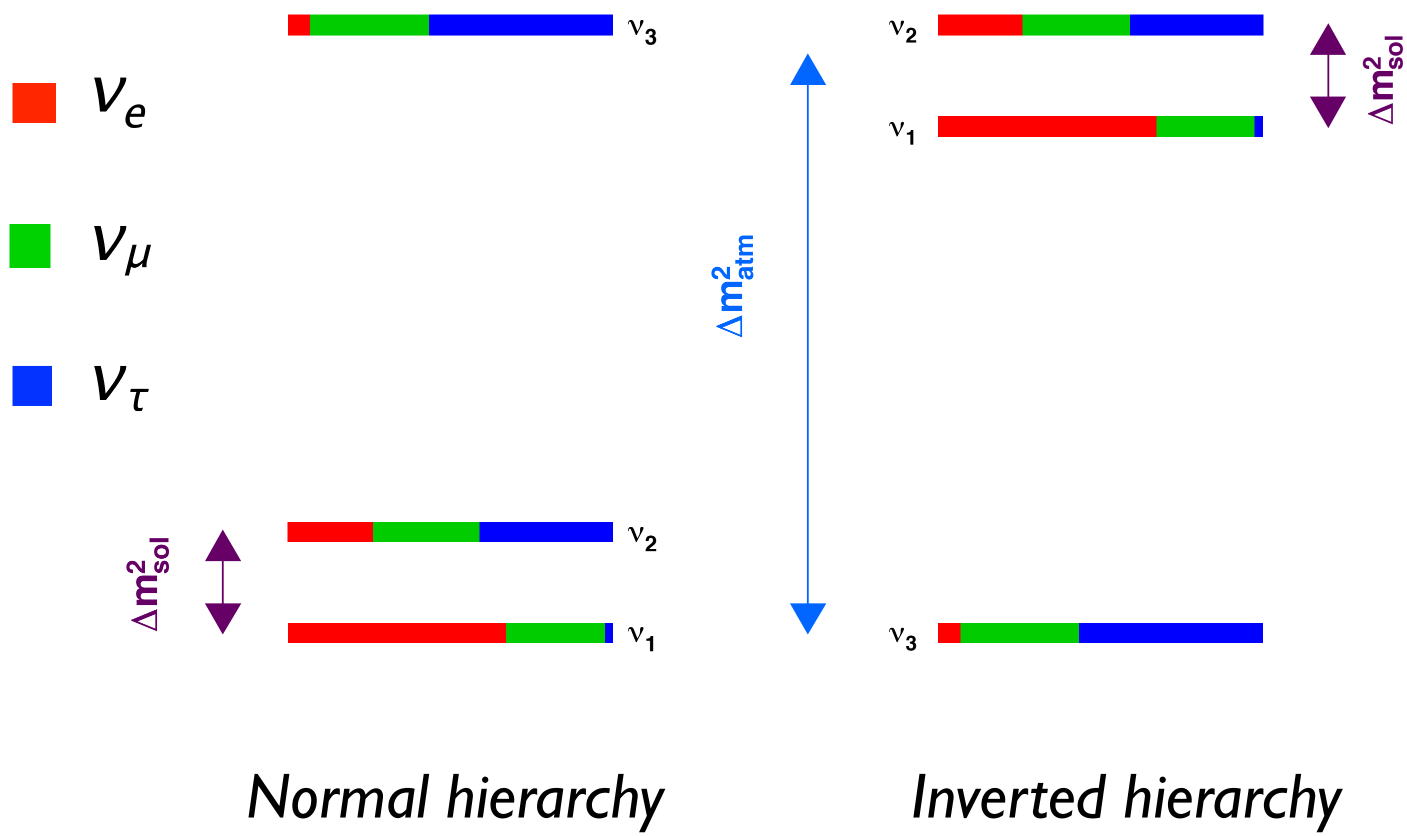
Outline :

1. Introduction
2. Neutrinoless double beta decay
   - *EFT approach with light sterile neutrino*
3. Standard vs Non-standard interactions
4. Summary

Introduction

Neutrino mass

The observation of neutrino oscillation confirms neutrinos have mass.

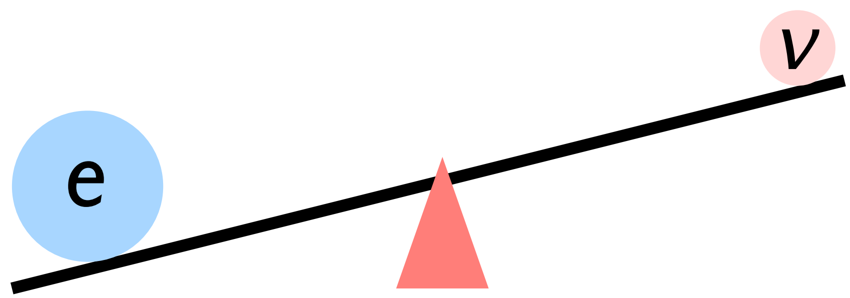


Neutrino mass

The observation of neutrino oscillation confirms neutrinos have mass.

Ex)

Electron : 0.5 MeV < 1eV



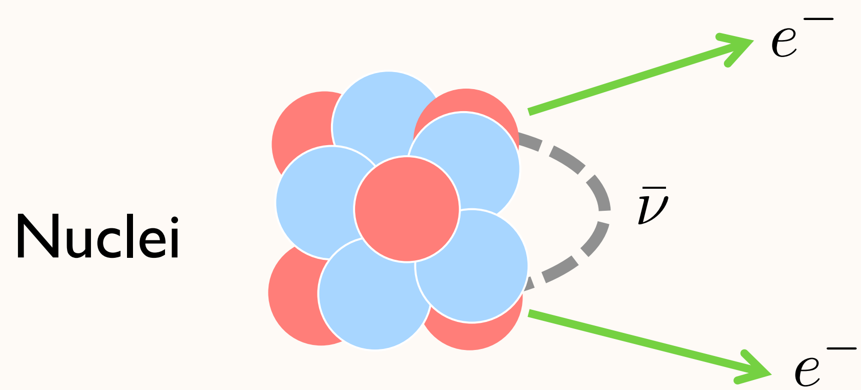
Open question :

What is the origin of the tiny but non-vanishing masses of the neutrinos?

Neutrinoless double beta decay

Double β decay without neutrino emission

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



The process can occur if neutrino is a *Majorana* particle.

Majorana mass

Right-handed neutrino : ν_R

~ Gauge singlet (Sterile neutrino)

Yukawa *Majorana Mass*

$$\mathcal{L}_{\nu_R} = -Y_\nu \bar{L} \tilde{H} \nu_R - \frac{1}{2} \overline{\nu_R^c} M_R \nu_R + \mathrm{H.C}$$

$$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad H = \begin{pmatrix} G^+ \\ \frac{1}{2}(v+h) \end{pmatrix}, \quad v \simeq 246 \text{ GeV}$$

$$\nu_R^c = C \overline{\nu_R}^T$$

C : charge conjugation matrix

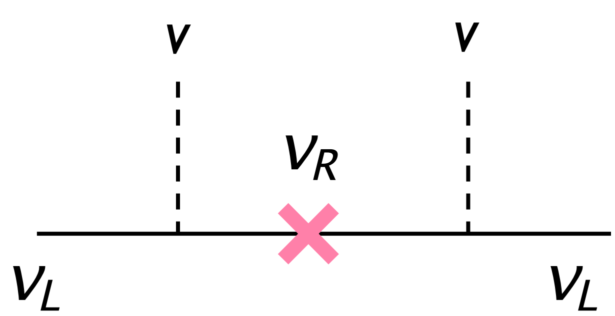
Majorana mass

Right-handed neutrino : ν_R

~ Gauge singlet (Sterile neutrino)

Yukawa *Majorana Mass*

$$\mathcal{L}_{\nu_R} = -Y_\nu \bar{L}\tilde{H}\nu_R - \frac{1}{2}\overline{\nu_R^c}M_R\nu_R + \mathrm{H.C}$$



✕ : Mass insertion

v : Higgs VEV

Majorana mass

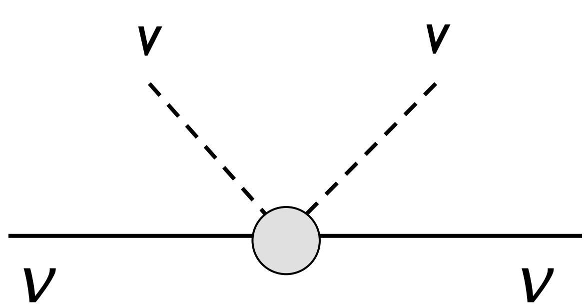
Right-handed neutrino : ν_R

~ Gauge singlet (Sterile neutrino)

Yukawa *Majorana Mass*

$$\mathcal{L}_{\nu_R} = -Y_\nu \bar{L}\tilde{H}\nu_R - \frac{1}{2}\overline{\nu_R^c}M_R\nu_R + \mathrm{H.C}$$

Majorana mass term is induced.



$$\mathcal{L}_{\mathrm{mass}} = -\frac{1}{2}\bar{\nu}m_\nu\nu$$

$$(\nu = \nu^c)$$

Majorana mass

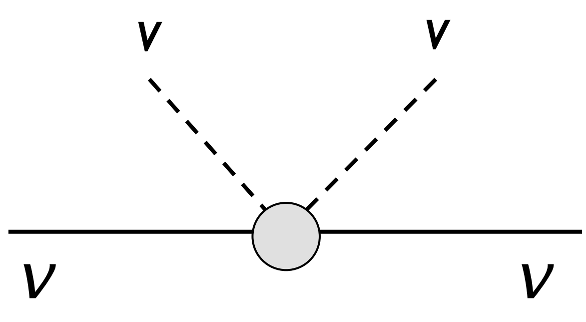
Right-handed neutrino : ν_R

~ Gauge singlet (Sterile neutrino)

Yukawa *Majorana Mass*

$$\mathcal{L}_{\nu_R} = -Y_\nu \bar{L}\tilde{H}\nu_R - \frac{1}{2}\overline{\nu_R^c}M_R\nu_R + \mathrm{H.C}$$

If M_R is much heavier than EW scale,



$$m_\nu \sim \frac{Y_\nu^2 v^2}{M_R}$$

Majorana mass

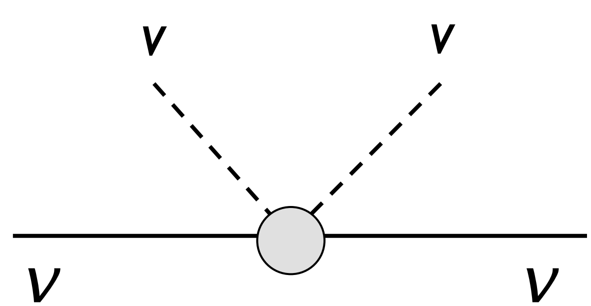
Right-handed neutrino : ν_R

~ Gauge singlet (Sterile neutrino)

Yukawa *Majorana Mass*

If neutrinos are Majorana particles, 0ν2β is induced.

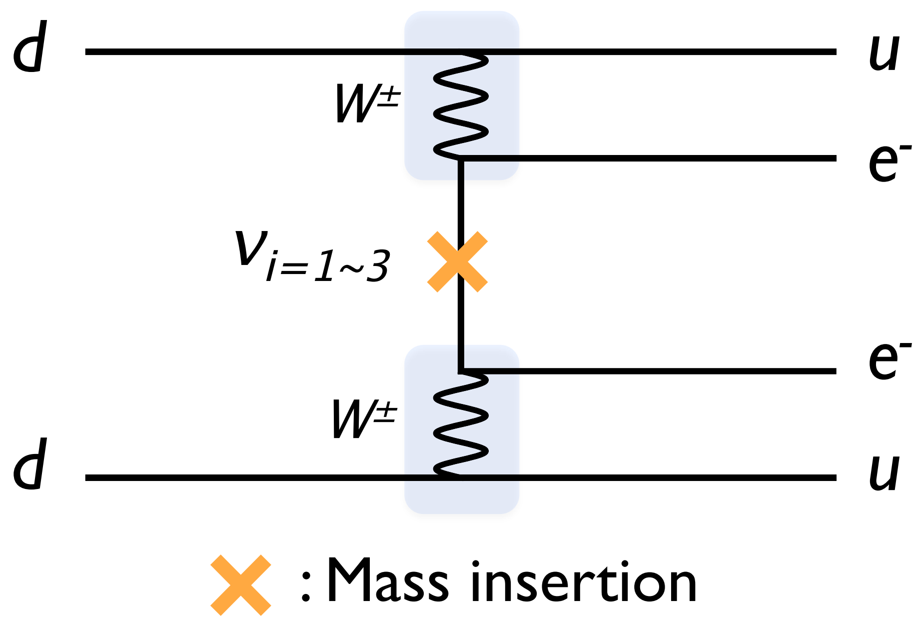
* *Three light Majorana neutrino case* $(M_R \gg v)$



$$m_\nu \sim \frac{Y_\nu^2 v^2}{M_R}$$

Standard case

Three light Majorana neutrinos : $\nu_{i=1\sim3}$

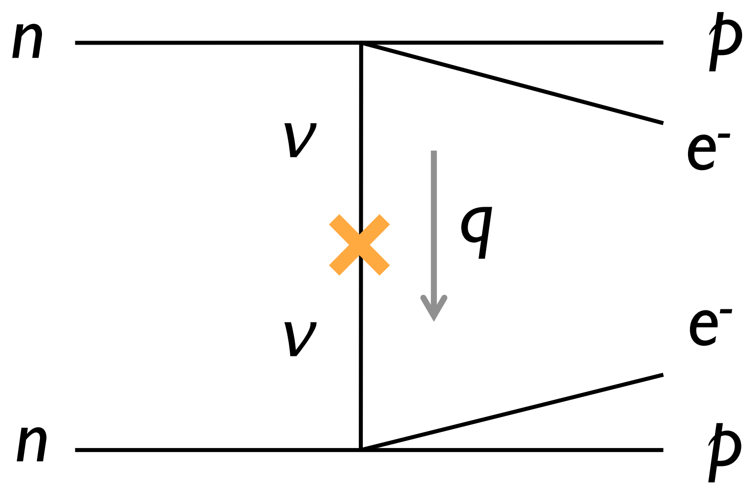


Left-handed vector operator :

$$\mathcal{L}^{(6)} = \frac{G_F}{\sqrt{2}} \bar{u}_L \gamma^\mu d_L \bar{e}_L \gamma_\mu C^{(6)}_{\rm VLL} \nu \quad \Big| \quad C^{(6)}_{\rm VLL} = -2 V_{ud} U_{ei}$$

Standard case

Three light Majorana neutrinos : $\nu_{i=1\sim3}$

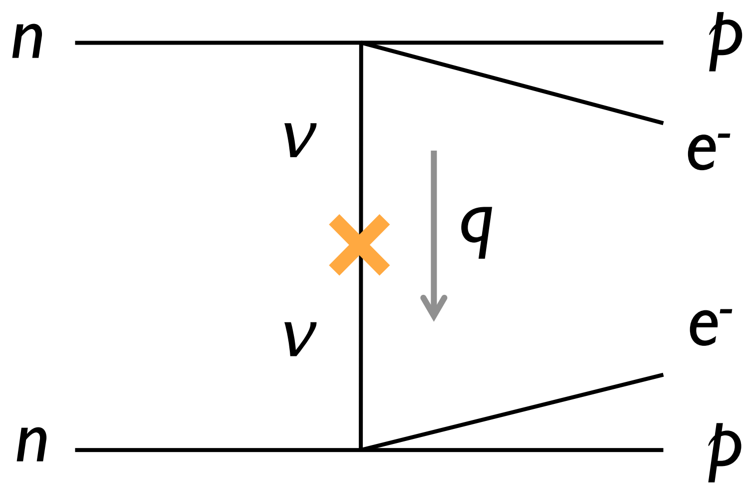


$$\mathcal{A}_{0\nu2\beta} \sim \sum_{i=1}^{3} U_{ei}^2 \frac{m_i}{\mathrm{q}^2 + m_i^2} \sim \frac{1}{\mathrm{q}^2}\left(\sum_{i=1}^{3} U_{ei}^2 m_i\right)$$

O(100) MeV

Standard case

Three light Majorana neutrinos : $\nu_{i=1\sim3}$



Oscillation data

$$\mathcal{A}_{0\nu2\beta} \sim \sum_{i=1}^{3} U_{ei}^2 \frac{m_i}{\mathrm{q}^2 + m_i^2} \sim \frac{1}{\mathrm{q}^2}\left(\sum_{i=1}^{3} U_{ei}^2 m_i\right)$$

O(100) MeV

Effective mass : $m_{\beta\beta}$

Standard case

Oscillation data : PRD98(2018)030001 [PDG]

$$U_{\rm PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \end{pmatrix}$$

$$\Delta m^2_{21} = m^2_2 - m^2_1 = 7.39 \times 10^{-5}\ [{\rm eV}^2]$$

$$\Delta m^2_{31} = m^2_3 - m^2_1 = \pm 2.5 \times 10^{-3}\ [{\rm eV}^2]$$

Ex) Normal hierarchy case

$$\mathcal{A}_{0\nu2\beta} \propto \left[c^2_{13} \left(m_1 c^2_{12} + e^{i\alpha} s^2_{12} \sqrt{m^2_1 + \Delta m^2_{21}} \right) + e^{i\beta} s^2_{13} \sqrt{m^2_1 + \Delta m^2_{31}} \right]$$

✔ *The amplitude is described by the lightest neutrino mass.*

Standard case

Oscillation data : PRD98(2018)030001 [PDG]

$$U_{\rm PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \end{pmatrix}$$

$$\Delta m_{21}^2 = m_2^2 - m_1^2 = 7.39 \times 10^{-5}\ [{\rm eV}^2]$$

$$\Delta m_{31}^2 = m_3^2 - m_1^2 = \pm 2.5 \times 10^{-3}\ [{\rm eV}^2]$$

Inverse half-life : $\left(T_{1/2}^{0\nu}\right)^{-1} = g_A^4 G_{0\nu} \left|\mathcal{A}_{0\nu 2\beta}\right|^2$

$g_A = 1.27,\ G_{0\nu}$: Phase space factor

Search for $0\nu 2\beta$

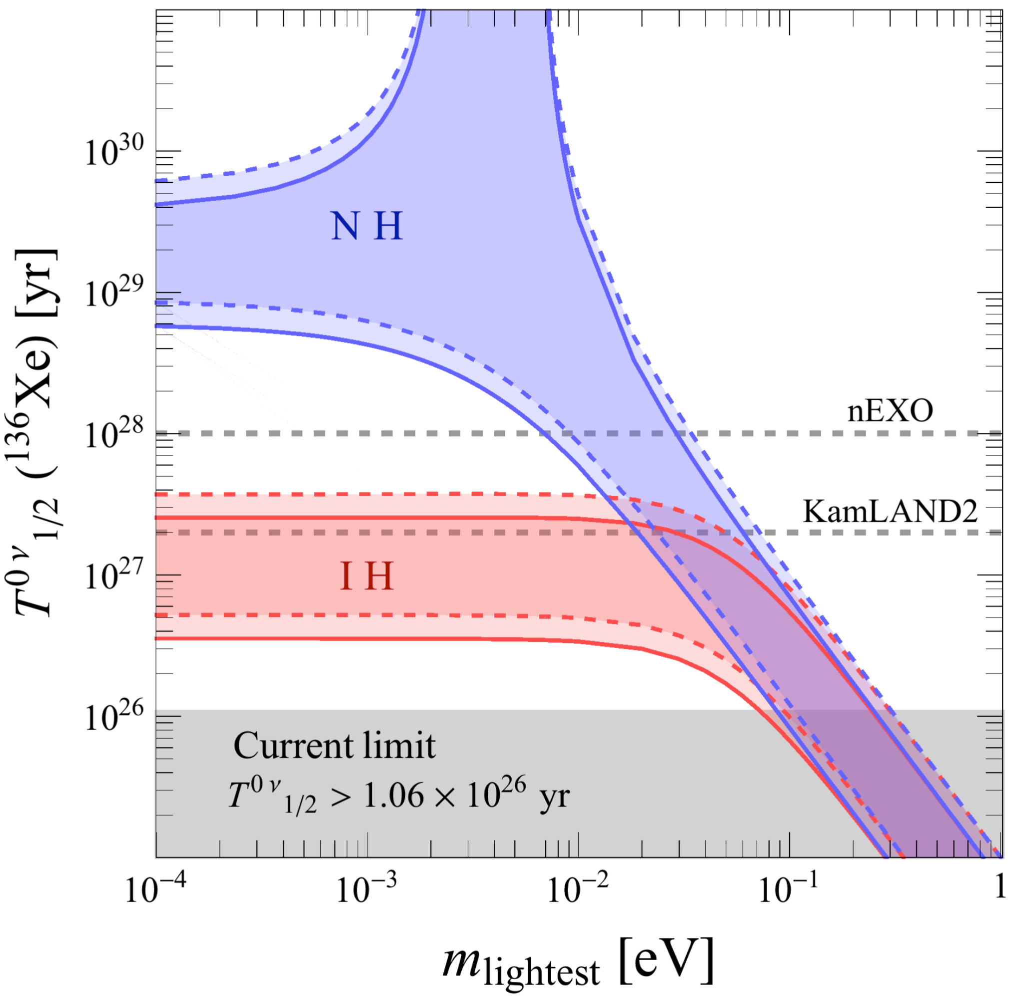
Isotope	Experiment	Current limit ($\times 10^{25}$yr)		Future sensitivity ($\times 10^{25}$yr)	
^{48}Ca	ELEGANT–IV	5.8×10^{-3}	[2]	–	
	CANDLES	6.2×10^{-3}	[23]	10^{-2}	[28]
	NEMO–3	2.0×10^{-3}	[9]		
^{76}Ge	MAJORANA DEMONSTRATOR	2.7	[22]	–	
	GERDA	9.0	[24]	–	
	LEGEND	–		10^{3}	[29]
^{82}Se	CUPID	3.5×10^{-1}	[25]		
	NEMO–3	2.5×10^{-2}	[20]		
	SuperNEMO	–		10	[30]
^{96}Zr	NEMO–3	9.2×10^{-4}	[3]		
^{100}Mo	NEMO–3	1.1×10^{-1}	[8]		
	CUPID–1T	–		9.2×10^{2}	[37]
	AMoRE	9.5×10^{-3}	[26]	5.0×10	[31]
^{116}Cd	NEMO–3	1.0×10^{-2}	[13]		
^{128}Te	–	1.1×10^{-2}	[1]	–	
^{130}Te	CUORE	3.2	[21]	9.0	[32]
	SNO+	–		1.0×10^{2}	[33]
^{136}Xe	KamLAND-Zen	10.7	[10]	2.0×10^{2}	
	EXO–200	3.5	[27]	10^{3}	[34]
	NEXT	–		2.0×10^{2}	[35]
	PandaX	–		1.0×10^{2}	[36]
^{150}Nd	NEMO–3	2.0×10^{-3}	[12]		

$$T_{1/2}^{0\nu}\left(^{136}\mathrm{Xe}\right) > 1.06 \times 10^{26}\ \mathrm{yr}$$

KamLAND-Zen
PRL117(2016) 082503

Current limit on half-life

Standard case



Normal Hierarchy (NH)

$$m_1 < m_2 < m_3$$

Inverted Hierarchy (IH)

$$m_3 < m_1 < m_2$$

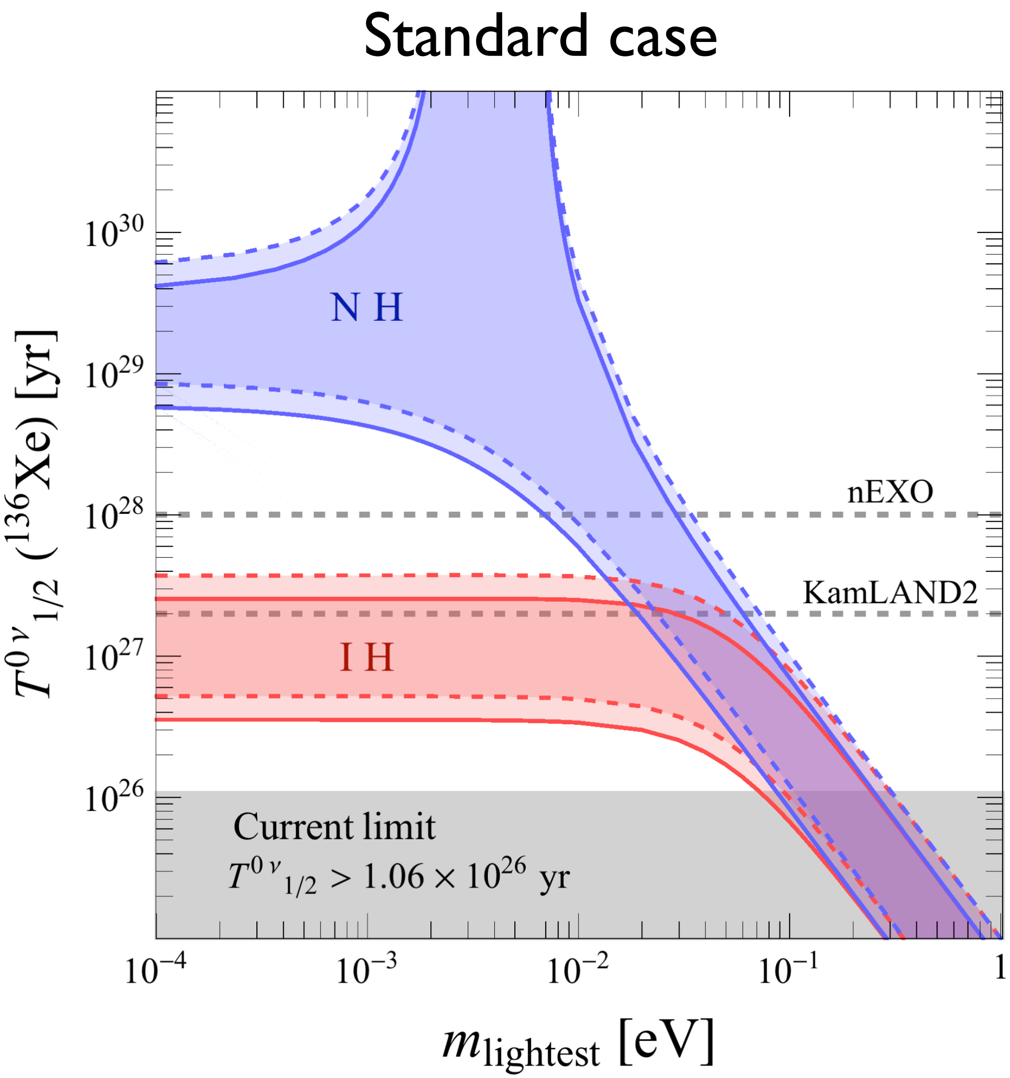
* *Bands*

1) Majorana phase
2) Matrix elements

— *QRPA*

- - - *Shell*

Current limit on half-life



Normal Hierarchy (NH)

$$m_1 < m_2 < m_3$$

Inverted Hierarchy (IH)

$$m_3 < m_1 < m_2$$

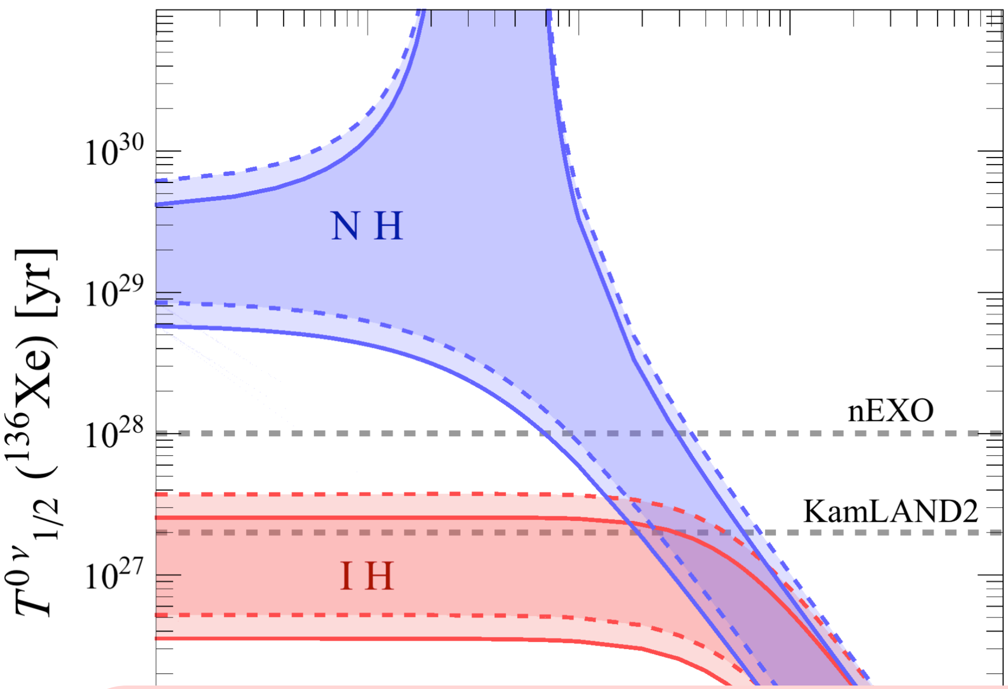
Future sensitivity

$\sim 10^{27}$ yr : KamLAND2-Zen

$\sim 10^{28}$ yr : nEXO

Current limit on half-life

Standard case



Normal Hierarchy (NH)

$$m_1 < m_2 < m_3$$

Inverted Hierarchy (IH)

$$m_3 < m_1 < m_2$$

Future sensitivity

Zen

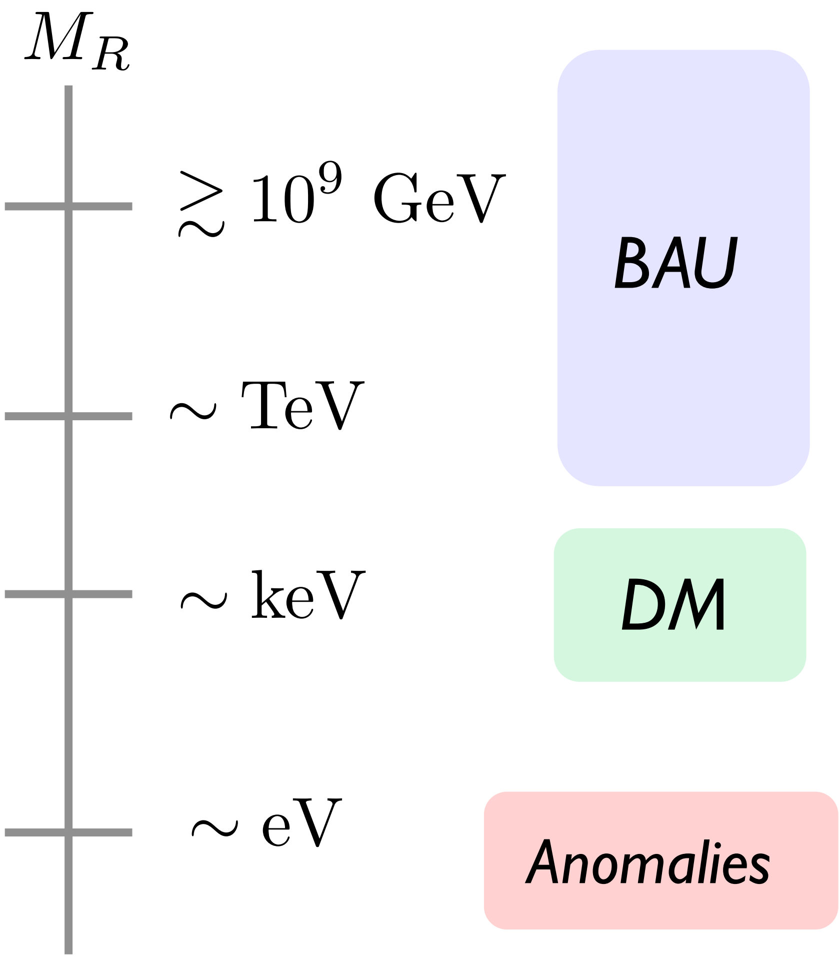
Standard case : Three light Majorana neutrinos $(M_R \gg v)$

What about light M_R *case?*

Beyond the standard case

For more details, see M. Drewes, 1303.6912

Other phenomenological aspects:



Wide mass range!

Leptogenesis

W. Buchmuller, et al , Ann.Rev.Nucl.Part.Sci. 55 (2005)311,

E. K. Akhmedov, et al, PRL81(1998)1359
T. Asaka, et al, PLBB620, 17 (2005),

DM candidate

S. Dodelson, L. M. Widrow, PRL72(1994)17

T. Asaka, et al, PLBB638, 401 (2006),

Short-baseline neutrino oscillation

LSND : PRD64(2001)112007
MiniBooNE : PRL110(2013)161801
Reactor anomaly : PRD83(2011)073006

$\bar{\nu}_\mu \to \bar{\nu}_e$

MiniBooNE : PRL121(2018)221801
PRL102(2009)101802

$\nu_\mu \to \nu_e$

Beyond the standard case

For more details, see
M. Drewes, 1303.6912

* *Need theoretical analysis in light of light sterile neutrinos*

M_R

$\gtrsim 10^9$ GeV — **BAU** — *Leptogenesis*

W. Buchmuller, et al , Ann.Rev.Nucl.Part.Sci. 55 (2005)311,

$\sim$ TeV

E. K. Akhmedov, et al, PRL81(1998)1359
T. Asaka, et al, PLBB620, 17 (2005),

$\sim$ keV — **DM** — *DM candidate*

S. Dodelson, L. M. Widrow, PRL72(1994)17

$\sim$ eV — **Anomalies** — *Short-baseline neutrino oscillation*

LSND : PRD64(2001)112007
MiniBooNE : PRL110(2013)161801
Reactor anomaly : PRD83(2011)073006

$\bar{\nu}_\mu \to \bar{\nu}_e$

MiniBooNE : PRL121(2018)221801
PRL102(2009)101802

$\nu_\mu \to \nu_e$

Our study

- Model-independent analysis in the light ν_R scenario

  ~ *Effective Field Theory*

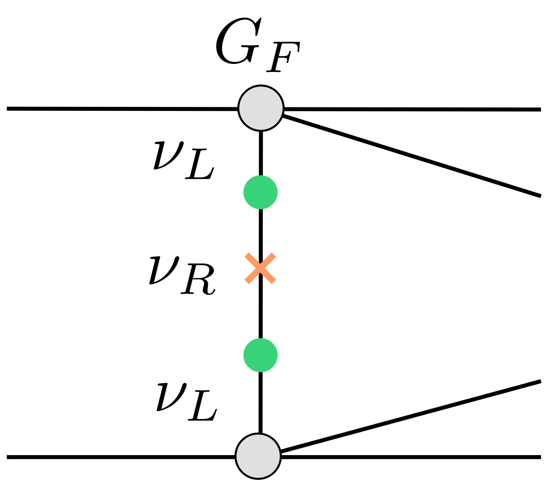
Our study

Model-independent analysis in the light ν_R scenario

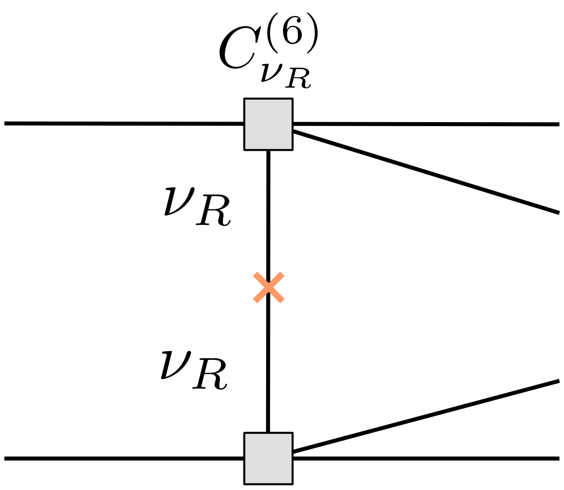
~ *Effective Field Theory*

* Non-standard interactions (d = 6)

$$\mathcal{L} = -Y_\nu \bar{L}\tilde{H}\nu_R - \frac{1}{2}\overline{\nu_R^c} M_R \nu_R + \frac{1}{\Lambda^2} C_{\nu_R}^{(6)} \mathcal{O}^{(6)}$$



VS



Our study

Model-independent analysis in the light ν_R scenario

~ *Effective Field Theory*

* Non-standard interactions (d = 6)

$$\mathcal{L} = -Y_\nu \bar{L}\tilde{H}\nu_R - \frac{1}{2}\overline{\nu_R^c}M_R\nu_R + \frac{1}{\Lambda^2}C^{(6)}_{\nu_R}\mathcal{O}^{(6)}$$

* Derive the master formula depending on M_R

Mass range : M_R

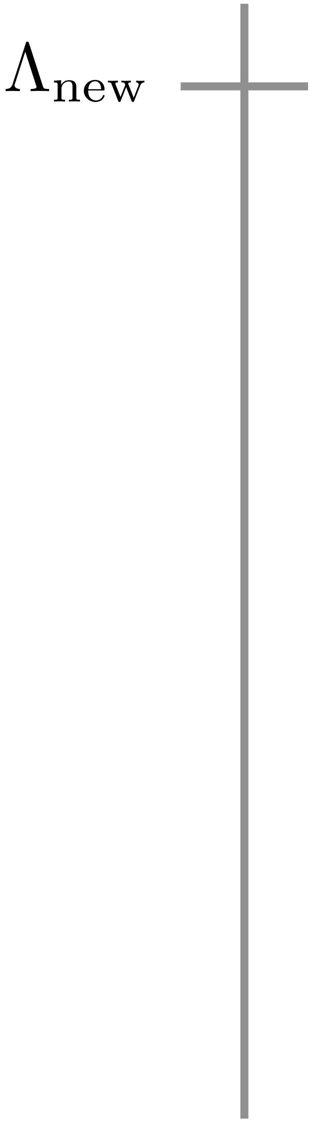
$\mathrm{eV} \longleftrightarrow 10^{15}\mathrm{GeV}$

Capture the behavior of light- and high-mass neutrino

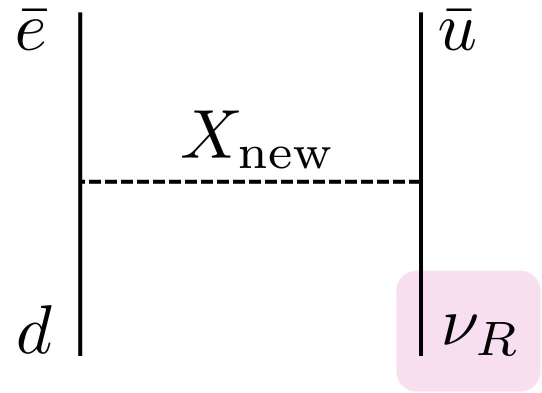
SM + Light sterile neutrinos EFT

EFT approach

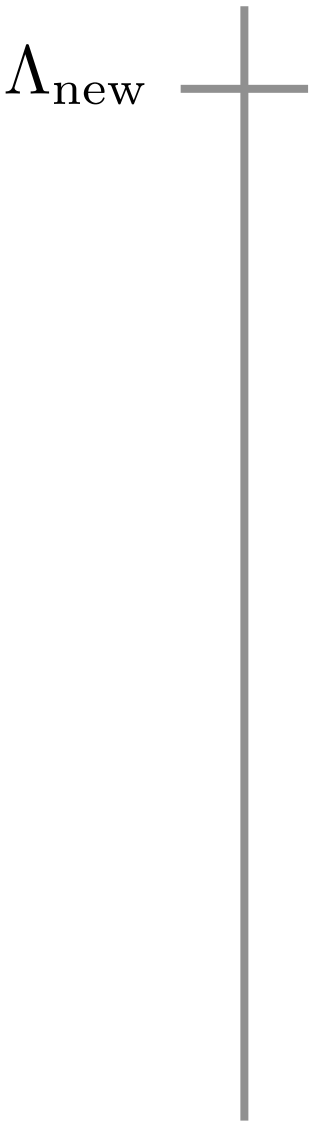
G. Prezeau, M. Ramsey-Musolf, and P. Vogel, PRD68, 034016 (2003)
V. Cirigliano, W. Dekens, J. de Vries, M. L. Graesser, and E. Mereghetti, JHEP 12, 082(2017)
V. Cirigliano, W. Dekens, J. de Vries, M. L. Graesser, and E. Mereghetti, JHEP 12, 097(2018)



New Physics



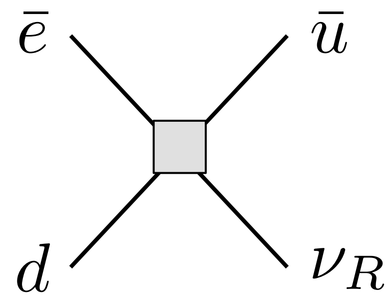
EFT approach



New Physics

SM + sterile neutrino EFT

Ex)



$$C^{(6)}_{\nu_R} \sim \frac{1}{m_X^2}$$

EFT approach

Λ_{new}

New Physics

SM + sterile neutrino EFT

LNC dim 6 operators

$\left(\bar{L}\nu_R\right)\tilde{H}\left(H^\dagger H\right)$	$\left(\bar{d}\gamma^\mu u\right)\left(\bar{\nu}_R\gamma_\mu e\right)$
$\left(\bar{\nu}_R\gamma^\mu e\right)\left(\tilde{H}^\dagger iD_\mu H\right)$	$\left(\bar{Q}u\right)\left(\bar{\nu}_R L\right)$
$\left(\bar{L}\sigma_{\mu\mu}\nu_R\right)\tau^I\tilde{H}W^I$	$\left(\bar{L}\nu_R\right)\epsilon\left(\bar{Q}_R d\right)$
	$\left(\bar{L}d\right)\epsilon\left(\bar{Q}_R\nu_R\right)$

** 7 independent operators*

Y. Liao and X.-D. Ma, Phys. Rev. D96, 015012 (2017)

EFT approach

Λ_{new} — *New Physics*

SM + sterile neutrino EFT

~ 100 GeV — *Mixing*

$$\mathcal{L}_{\mathrm{mass}} = -\frac{1}{2}\overline{N^c} M_\nu N + \mathrm{h.c.}$$

$$N = \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}, \qquad M_\nu = \begin{pmatrix} 0 & M_D^* \\ M_D^\dagger & M_R^\dagger \end{pmatrix}$$

✔ *Diagonalize M_ν with an unitary matrix U*

✔ *Integrate out heavy SM particles*

EFT approach

Λ_{new} — *New Physics*

SM + sterile neutrino EFT

$\sim 100\ \text{GeV}$ — *Mixing*

Ex) $$\mathcal{L}^{(6)} = \frac{G_F}{\sqrt{2}}\left[\bar{u}_L\gamma^\mu d_L\bar{e}_L\gamma_\mu C^{(6)}_{\text{VLL}}\nu + \bar{u}_L d_R\bar{e}_L C^{(6)}_{\text{SRR}}\nu\right]$$

$$C^{(6)}_{\text{VLL}} \supset -2V_{ud}U_{ij} \qquad (i = 1, 2, 3)$$

Unitary matrix

$$C^{(6)}_{\text{SRR}} \supset \frac{v^2}{2}C^{(6)}_{LdQ\nu}U^*_{kl} \qquad \left(\mathcal{O}^{(6)}_{LdQ\nu} = \bar{L}^a d\epsilon_{ab}\bar{Q}^b_R\nu_R\right)$$

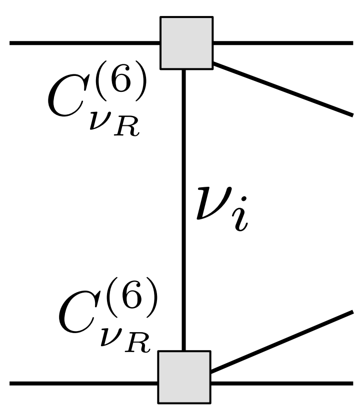
EFT approach

Λ_{new} — *New Physics*

SM + sterile neutrino EFT

$\sim 100\ \text{GeV}$ — *Mixing*

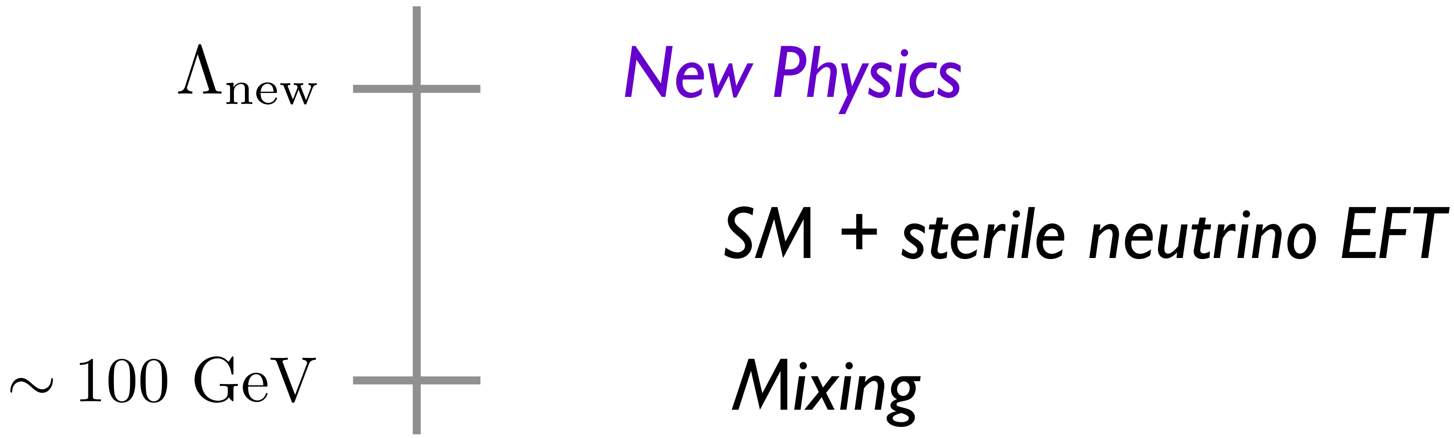
If $1\ \text{GeV} \lesssim m_i \lesssim v$, ν_i should also be integrated out.



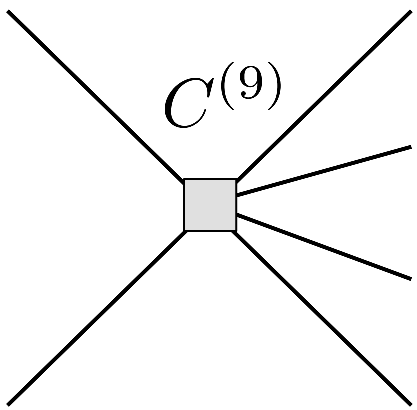
$$\sim \left[C^{(6)}_{\nu_R}\right]^2 \frac{m_i}{q^2 + m_i^2}$$

Sterile neutrino mass

EFT approach



If $1\ \text{GeV} \lesssim m_i \lesssim v$, ν_i should also be integrated out.



$$C^{(9)} \sim \left[C^{(6)}_{\nu_R}\right]^2 \frac{1}{m_i}$$

* *Described by Dim 9 operator*

EFT approach

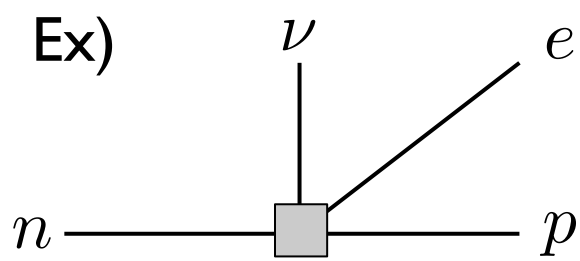
$\sim 1\ \mathrm{GeV}$

Nucleon and pion interactions

~ *Chiral Perturbation Theory*

G. Prezeau, M. Ramsey-Musolf, and P. Vogel, PRD68, 034016 (2003)

Ex)



$\sim g_{\mathrm{LEC}}\ C^{(6)}$

↑ Low energy constant

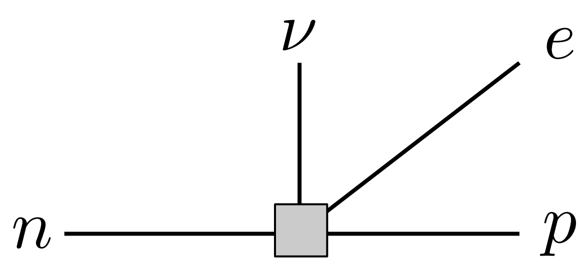
EFT approach

~ 1 GeV

Nucleon and pion interactions

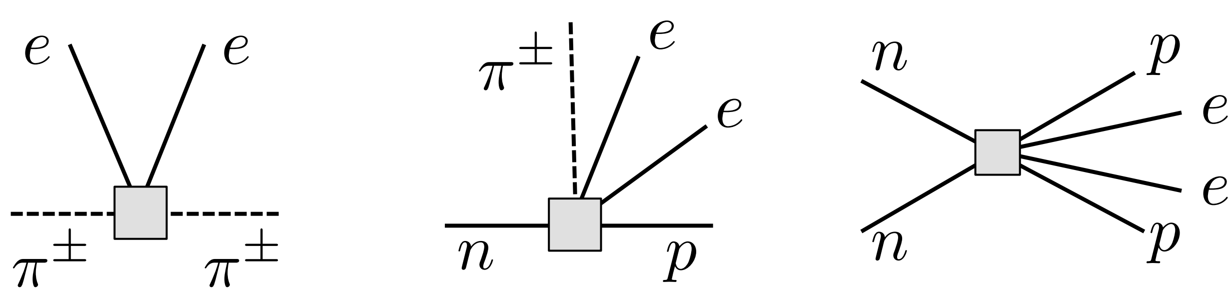
~ Chiral Perturbation Theory

G. Prezeau, M. Ramsey-Musolf, and P. Vogel, PRD68, 034016 (2003)



$\sim g_{\rm LEC}\ C^{(6)}$

Short-range contributions



* Hard-neutrino contributions:
V. Cirigliano, et al., PRL120(2018)20, 202001; PRC100(2019)055504

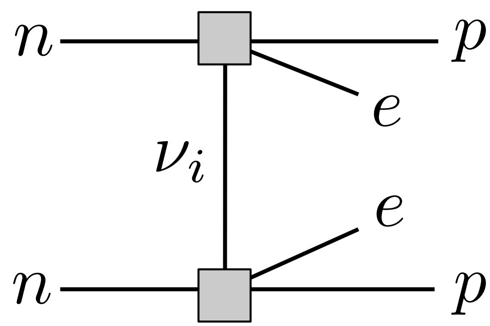
EFT approach

$\sim 1\ \mathrm{GeV}$

Nucleon and pion interactions

~ Chiral Perturbation Theory

G. Prezeau, M. Ramsey-Musolf, and P. Vogel, PRD68, 034016 (2003)



$$\mathcal{A}_{nn\to ppee}\left(g_{\mathrm{LEC}}, C^{(6)}\right)$$

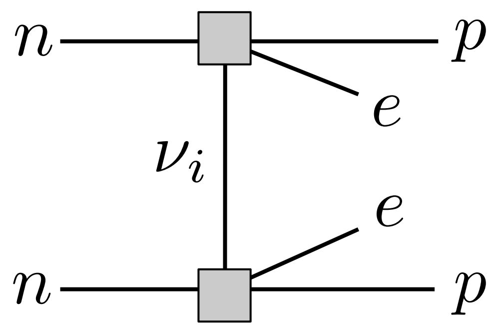
EFT approach

$\sim 1\ \mathrm{GeV}$

Nucleon and pion interactions

~ Chiral Perturbation Theory

G. Prezeau, M. Ramsey-Musolf, and P. Vogel, PRD68, 034016 (2003)



$$\mathcal{A}_{nn\to ppee}\left(g_{\mathrm{LEC}}, C^{(6)}\right)$$

$\sim 1\ \mathrm{MeV}$

Transition amplitudes :

$$\mathcal{A}_{0\nu2\beta} = \left\langle 0^{+} \left| \mathcal{A}_{nn\to ppee} \right| 0^{+} \right\rangle$$

Initial and final nuclei states

EFT approach

$\sim 1\ \mathrm{GeV}$

Nucleon and pion interactions

~ Chiral Perturbation Theory

G. Prezeau, M. Ramsey-Musolf, and P. Vogel, PRD68, 034016 (2003)

$\sim 1\ \mathrm{MeV}$

Transition amplitudes :

$$\mathcal{A}_{0\nu 2\beta}\left(g_{\mathrm{LEC}}, C^{(6)}, M_{\mathrm{NME}}\right)$$

↑

Nuclear matrix element
(Many-body methods)

EFT approach

$\sim 1\ \mathrm{GeV}$

Nucleon and pion interactions

~ Chiral Perturbation Theory

G. Prezeau, M. Ramsey-Musolf, and P. Vogel, PRD68, 034016 (2003)

$\sim 1\ \mathrm{MeV}$

Transition amplitudes :

$$\mathcal{A}_{0\nu 2\beta}\left(g_{\mathrm{LEC}}, C^{(6)}, M_{\mathrm{NME}}\right)$$

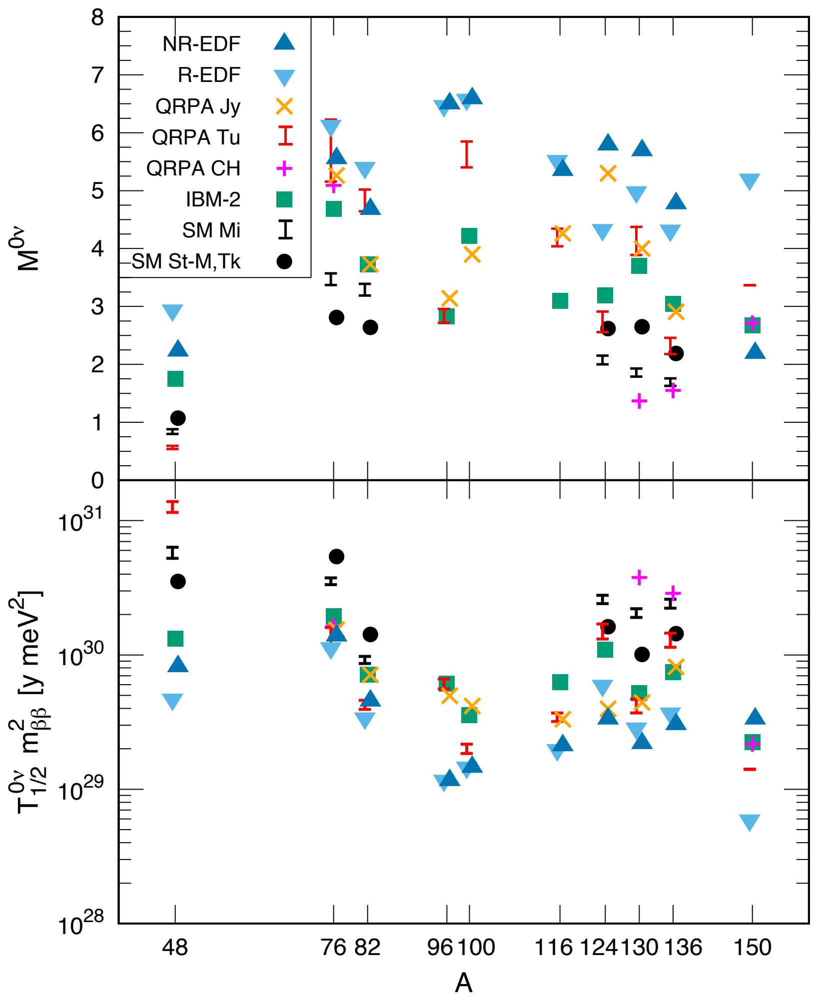
Inverse half-life :

$$\left(T^{0\nu}_{1/2}\right)^{-1} = g_A^4 G_{0\nu} \left|\mathcal{A}_{0\nu 2\beta}\right|^2$$

$$g_A = 1.27,\ \ G_{0\nu} : \text{Phase space factor}$$

NMEs

NMEs obtained with different nuclear-structure approaches differ by factors of two or three.



J. Engel, J. Menendez
Rept.Prog.Phys. 80(2017)046301

LECs

Well determined by experiments or Lattice

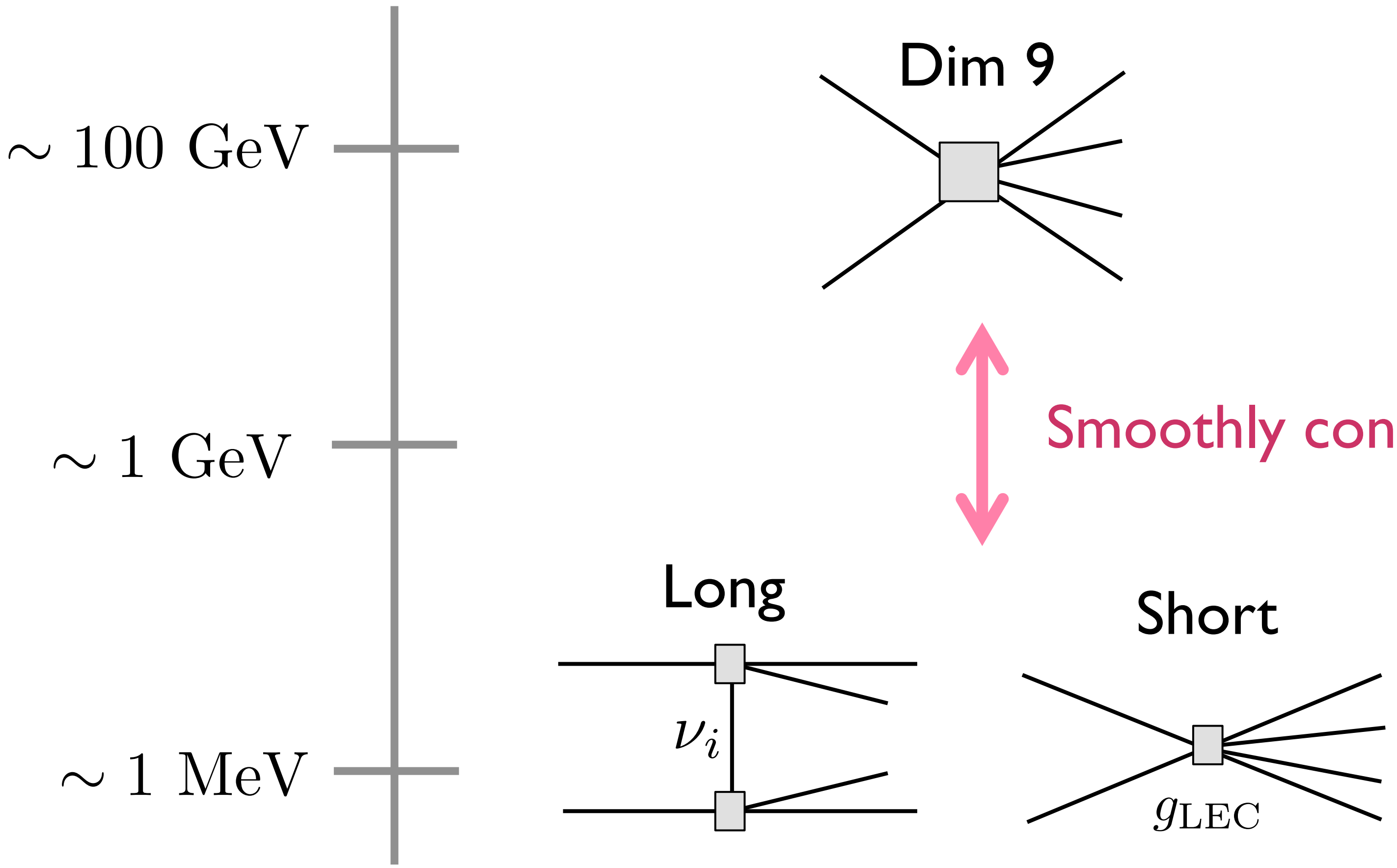
Lattice

$n \to pe\nu,\ \pi \to e\nu$		$\pi\pi \to ee:\quad \mathcal{O}^{(9)}$	
g_A	1.271 ± 0.002 [122]	$g_1^{\pi\pi}$	0.36 ± 0.02 [112]
g_S	1.02 ± 0.10 [114, 115]	$g_2^{\pi\pi}$	$2.0 \pm 0.2\ \ \mathrm{GeV}^2$ [112]
g_M	4.7 [122]	$g_3^{\pi\pi}$	$-0.62 \pm 0.06\ \ \mathrm{GeV}^2$ [112]
g_T	0.99 ± 0.03 [114, 115]	$g_4^{\pi\pi}$	$-1.9 \pm 0.2\ \ \mathrm{GeV}^2$ [112]
$\lvert g_T' \rvert$	$\mathcal{O}(1)$	$g_5^{\pi\pi}$	$-8.0 \pm 0.6\ \ \mathrm{GeV}^2$ [112]
B	$2.7\,\mathrm{GeV}$		
$n \to p\pi ee:\ \mathcal{O}^{(9)},\ \mathcal{O}^{(6,7)} \otimes \mathcal{O}^{(6,7)}$		$\pi\pi \to ee:\quad \mathcal{O}^{(6,7)} \otimes \mathcal{O}^{(6,7)}$	
$\lvert g_i^{\pi N} \rvert$	$\mathcal{O}(1)$	$\lvert g_{\mathrm{T,VLL}}^{\pi\pi} \rvert, \lvert g_{\mathrm{S,VLL}}^{\pi\pi} \rvert, \lvert g_{\mathrm{T,VRL}}^{\pi\pi} \rvert, \lvert g_{\mathrm{S,VRL}}^{\pi\pi} \rvert$	$\mathcal{O}(1)$
		$\lvert g_{\mathrm{LR}}^{\pi\pi} \rvert, \lvert g_{\mathrm{S1,S2}}^{\pi\pi} \rvert$	$\mathcal{O}(F_\pi^2)$
		$\lvert g_{\mathrm{TT}}^{\pi\pi} \rvert, \lvert g_{\mathrm{TL}}^{\pi\pi} \rvert, \lvert g_{\mathrm{TL,TR}}^{\pi\pi} \rvert$	$\mathcal{O}(F_\pi^2)$
$nn \to pp\,ee:\quad \mathcal{O}^{(9)}$		$nn \to pp\,ee:\quad \mathcal{O}^{(6,7)} \otimes \mathcal{O}^{(6,7)}$	
$\lvert g_{1,6,7}^{NN} \rvert$	$\mathcal{O}(1)$	$\lvert g_\nu^{NN} \rvert, \lvert g_{\mathrm{LR}}^{NN} \rvert, \lvert g_{\mathrm{S1}}^{NN} \rvert$	$\mathcal{O}(1/F_\pi^2)$
$\lvert g_{2,3,4,5}^{NN} \rvert$	$\mathcal{O}((4\pi)^2)$	$\lvert g_{\mathrm{S2}}^{NN} \rvert, \lvert g_{\mathrm{TT}}^{NN} \rvert, \lvert g_{\mathrm{SLL,VLL}}^{NN} \rvert$	$\mathcal{O}(1/F_\pi^2)$
		$\lvert g_{\mathrm{TLL,VLL}}^{NN} \rvert, \lvert g_{\mathrm{TL}}^{NN} \rvert, \lvert g_{\mathrm{TL,TR}}^{NN} \rvert$	$\mathcal{O}(1/F_\pi^2)$
		$\lvert g_{\mathrm{TL,T}}^{NN} \rvert, \lvert g_{\mathrm{TR,T}}^{NN} \rvert$	$\mathcal{O}(1/\Lambda_\chi^2)$
		$\lvert g_{\mathrm{S,VLL}}^{NN} \rvert, \lvert g_{\mathrm{T,VLL}}^{NN} \rvert\, \lvert g_{\mathrm{VLL,VLR}}^{NN} \rvert$	$\mathcal{O}(1)$
		$\lvert g_{\mathrm{S,VRL}}^{NN} \rvert, \lvert g_{\mathrm{T,VRL}}^{NN} \rvert$	$\mathcal{O}(1)$
		$\lvert g_{\mathrm{T,SRL}}^{NN} \rvert, \lvert g_{\mathrm{T,SLL}}^{NN} \rvert, \lvert g_{\mathrm{TL,V}}^{NN} \rvert, \lvert g_{\mathrm{TR,V}}^{NN} \rvert$	$\mathcal{O}((4\pi)^2)$

Several LECs are still unknown.

EFT approach

Interpolation formula of $M_{\mathrm{NME}}(m_i)$ and $g_{\mathrm{LEC}}(m_i)$

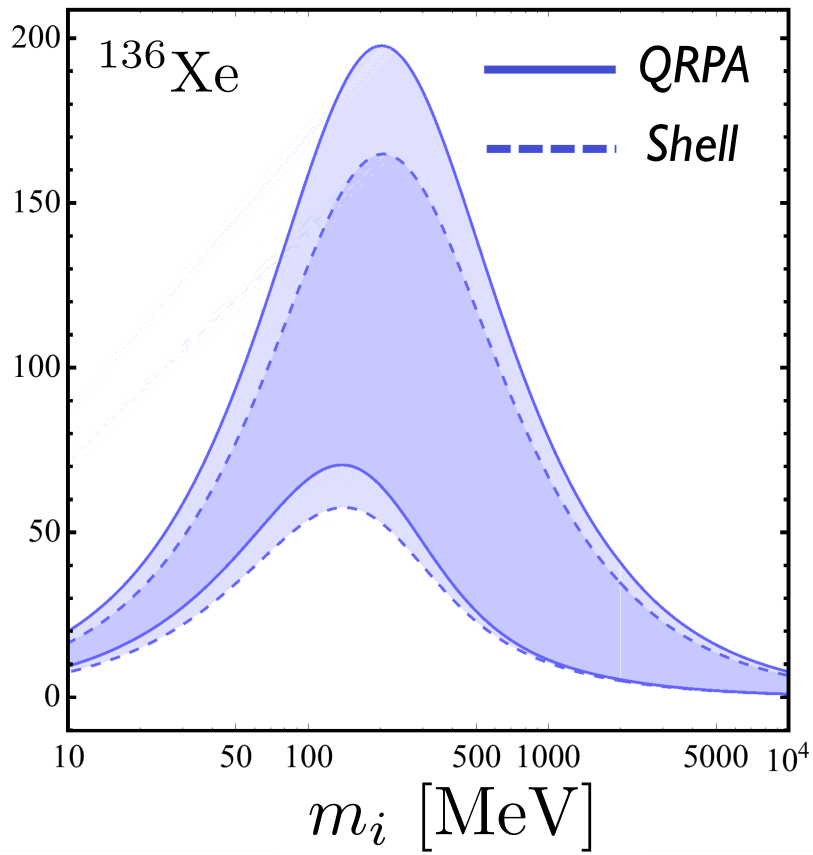


** This makes it possible to analyze NDBD in any mass spectrum.*

NMEs and LECs

Mass dependence of the amplitude : $|\mathcal{A}_{0\nu 2\beta}(m_i)|_{^{136}\mathrm{Xe}}$

$\bar{u}_L \gamma^\mu d_L \bar{e}_L \gamma_\mu \nu$



- Two different NMEs

- Peak around O(100) MeV

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

O(100) MeV

- Similar behavior in literature

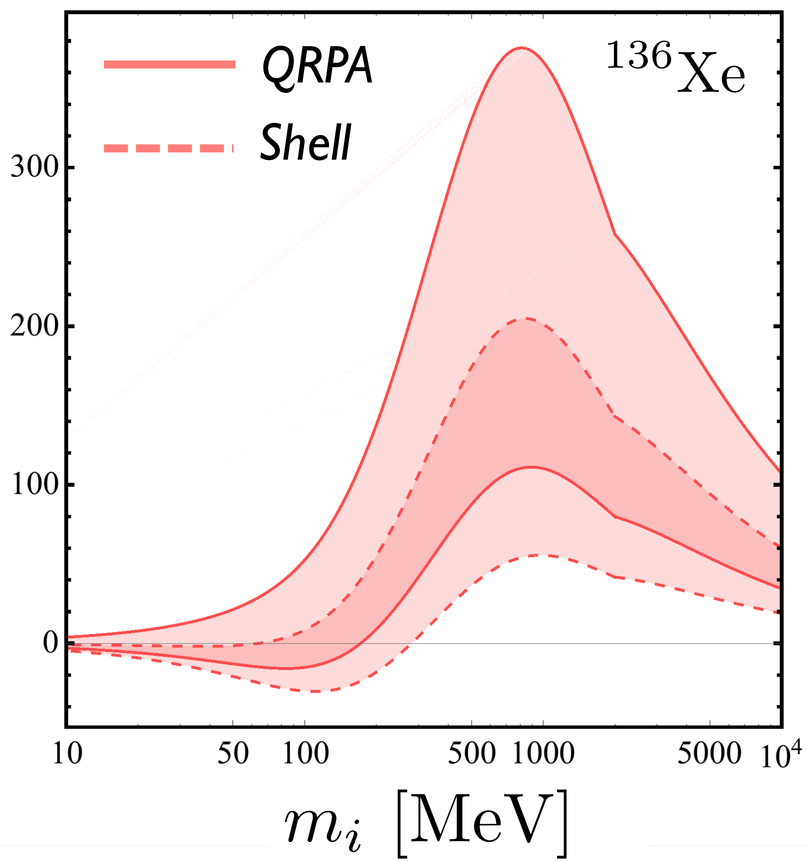
J.Barea, et al PRD92(2015)093001

- Large uncertainty in LECs

NMEs and LECs

Mass dependence of the amplitude : $|\mathcal{A}_{0\nu 2\beta}(m_i)|_{^{136}\mathrm{Xe}}$

$(\bar{u}_L \gamma^\mu d_L \times \bar{u}_R \gamma^\mu d_R)\, \bar{e}_L \gamma_\mu \nu$



- Two different NMEs
- Peak around O(1) GeV
  * Nontrivial behavior due to LECs
- Not discussed in literature
- Large uncertainty in LECs

3 + 1 Standard vs Non-standard case

(Leptoquark)

3+1 scenario

One sterile neutrino : m_4

$$\mathcal{L}_{\nu_R} = -Y_\nu \bar{L}\tilde{H}\nu_R - \frac{1}{2}\overline{\nu_R^c}M_R\nu_R + \mathrm{H.C}$$

* Standard interactions

3+1 scenario

One sterile neutrino : m_4

$$\mathcal{L}_{\rm mass} = -\frac{1}{2}\overline{N^c} M_\nu N + {\rm h.c.} \qquad N = \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}$$

Assumption : Two parameters M_D and M_R

$$M_\nu = \begin{pmatrix} 0 & 0 & 0 & M_D^* \\ 0 & 0 & 0 & M_D^* \\ 0 & 0 & 0 & M_D^* \\ M_D^* & M_D^* & M_D^* & M_R \end{pmatrix}$$

Yukawa

Majorana

$$m_1 = m_2 = 0$$

$$m_{3,4} = \frac{1}{2}\left[\sqrt{|M_R|^2 + 12|M_D|^2} \pm |M_R|\right] \qquad (m_4 > m_3)$$

3+1 scenario

One sterile neutrino : m_4

$$\mathcal{L}_{\rm mass} = -\frac{1}{2}\overline{N^c} M_\nu N + {\rm h.c.} \qquad N = \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}$$

Assumption : Two parameters M_D and M_R

$$M_\nu = \begin{pmatrix} 0 & 0 & 0 & M_D^* \\ 0 & 0 & 0 & M_D^* \\ 0 & 0 & 0 & M_D^* \\ M_D^* & M_D^* & M_D^* & M_R \end{pmatrix}$$

Yukawa

Majorana

* *Not satisfy oscillation data but good example to understand behaviors of $0\nu2\beta$*

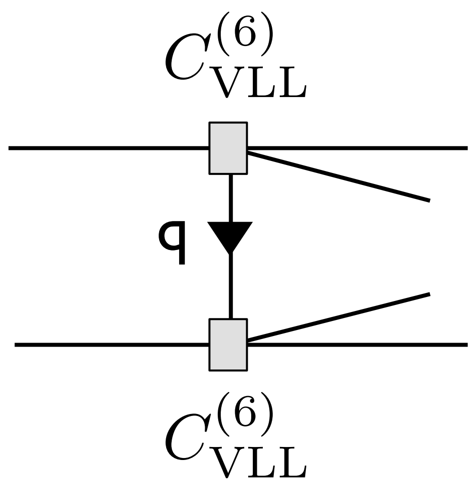
3+1 scenario

One sterile neutrino : m_4

$$\mathcal{L}^{(6)} = \frac{2G_F}{\sqrt{2}} \bar{u}_L \gamma^\mu d_L \bar{e}_L \gamma_\mu C^{(6)}_{\mathrm{VLL}} \nu \qquad C^{(6)}_{\mathrm{VLL}} = -2V_{ud}U_{ij}$$

** Cancellation of LO contribution in light-mass region*

M. Blennow, et al, JHEP07(2010)096



$\mathrm{q} \sim O(100)\mathrm{MeV}$

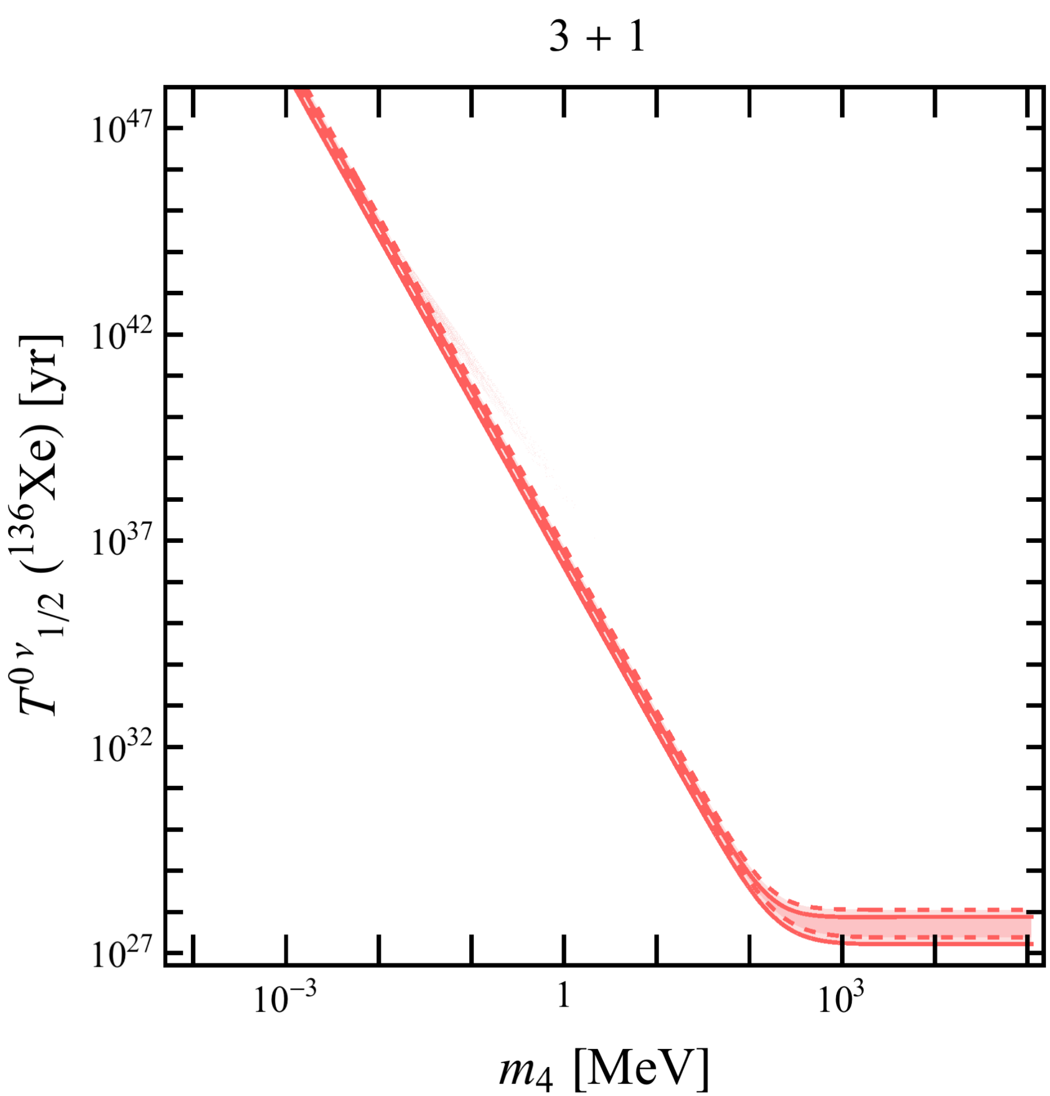
For $\mathrm{q}^2 \gg m_i^2$

$$\sim \frac{m_i}{\mathrm{q}^2} U_{ei}^2 \left(1 + \frac{m_i^2}{\mathrm{q}^2} + \cdots \right)$$

↑ LO vanishes

$$m_i U_{ei}^2 = (M_\nu)_{11} = 0$$

m_4 vs Half-life (^{136}Xe)



The half-life is well above experimental reach.

Leptoquark

J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 88, 035009 (2013)
J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 87, 075004 (2013)
I. Dorsner, S. Fajfer, A. Greljo, J. F. Kamenik and N. Kosnik, Phys. Rept. 641, 1 (2016)

Leptoquark (LQ) couples to the SM quark and lepton

+ sterile neutrinos (1, 2 flavors)

Leptoquark

J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 88, 035009 (2013)
J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 87, 075004 (2013)
I. Dorsner, S. Fajfer, A. Greljo, J. F. Kamenik and N. Kosnik, Phys. Rept. 641, 1 (2016)

Leptoquark (LQ) couples to the SM quark and lepton

+ sterile neutrinos (1, 2 flavors)

Scalar LQ : $\tilde{R}\,(\mathbf{3}, \mathbf{2}, 1/6)$ All possible scalar LQs: PRD43(1991)225

$$\mathcal{L}_{\rm LQ} = -y^{RL}\bar{d}_R\tilde{R}\epsilon L + y^{\overline{LR}}\bar{Q}\tilde{R}\nu_R$$

Leptoquark

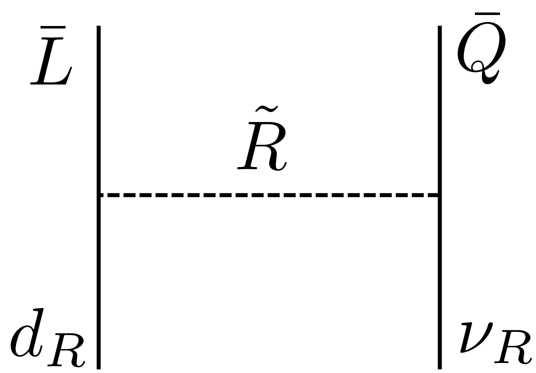
J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 88, 035009 (2013)
J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 87, 075004 (2013)
I. Dorsner, S. Fajfer, A. Greljo, J. F. Kamenik and N. Kosnik, Phys. Rept. 641, 1 (2016)

Leptoquark (LQ) couples to the SM quark and lepton

+ sterile neutrinos (1, 2 flavors)

Scalar LQ : $\tilde{R}\,(\mathbf{3}, \mathbf{2}, 1/6)$

$$\mathcal{L}_{\rm LQ} = -y^{RL}\bar{d}_R\tilde{R}\epsilon L + y^{\overline{LR}}\bar{Q}\tilde{R}\nu_R$$



Gauge-invariant dim6 operator:

$$\mathcal{L}^{(6)}_{\nu_R} = C^{(6)}_{LdQ\nu}\left(\bar{L}d_R\right)\epsilon\left(\bar{Q}\nu_R\right)$$

$$C^{(6)}_{LdQ\nu} = \frac{1}{m^2_{LQ}}y^{\overline{LR}}y^{RL*}$$

Leptoquark

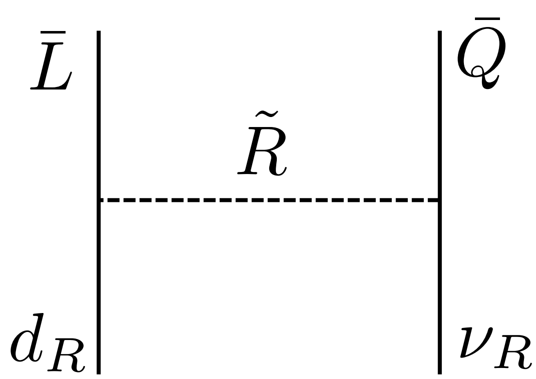
J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 88, 035009 (2013)
J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 87, 075004 (2013)
I. Dorsner, S. Fajfer, A. Greljo, J. F. Kamenik and N. Kosnik, Phys. Rept. 641, 1 (2016)

Leptoquark (LQ) couples to the SM quark and lepton

\+ sterile neutrinos (1, 2 flavors)

Scalar LQ : $\tilde{R}\,(\mathbf{3}, \mathbf{2}, 1/6)$

$$\mathcal{L}_{\rm LQ} = -y^{RL}\bar{d}_R\tilde{R}\epsilon L + y^{\overline{LR}}\bar{Q}\tilde{R}\nu_R$$



LQ parameters :

$$m_{\rm LQ} = 10\ {\rm TeV} \quad y^{\overline{LR}}y^{RL*} = 1.0$$

Leptoquark

Scalar and tensor operators show up below EW scale:

$$\mathcal{L}^{(6)} = \frac{2G_F}{\sqrt{2}}\left[\bar{u}_L d_R \bar{e}_L C^{(6)}_{\rm SRR}\nu_i + \bar{u}_L\sigma^{\mu\nu} d_R \bar{e}_L \sigma_{\mu\nu} C^{(6)}_{\rm TRR}\nu_i\right]$$

$$C^{(6)}_{\rm SRR} = 4C^{(6)}_{\rm TRR} = \frac{v^2}{2} C^{(6)}_{LdQ\nu}\, U^*_{Ni}$$

$N = 4(5)$

$i = 1 \sim 4(5)$

Leptoquark

Scalar and tensor operators show up below EW scale:

$$\mathcal{L}^{(6)} = \frac{2G_F}{\sqrt{2}}\left[\bar{u}_L d_R \bar{e}_L C^{(6)}_{\mathrm{SRR}} \nu_i + \bar{u}_L \sigma^{\mu\nu} d_R \bar{e}_L \sigma_{\mu\nu} C^{(6)}_{\mathrm{TRR}} \nu_i\right]$$

$$C^{(6)}_{\mathrm{SRR}} = 4C^{(6)}_{\mathrm{TRR}} = \frac{v^2}{2} C^{(6)}_{LdQ\nu} U^*_{Ni} \qquad N = 4(5), \quad i = 1 \sim 4(5)$$

$$+\frac{2G_F}{\sqrt{2}} \bar{u}_L \gamma^\mu d_L \bar{e}_L \gamma_\mu C^{(6)}_{\mathrm{VLL}} \nu$$

← Induced by mixing (No LQ interaction)

$$C^{(6)}_{\mathrm{VLL}} = -2V_{ud} U_{ij} \qquad i = 1 \sim 3, \; j = 1 \sim 4(5)$$

Leptoquark

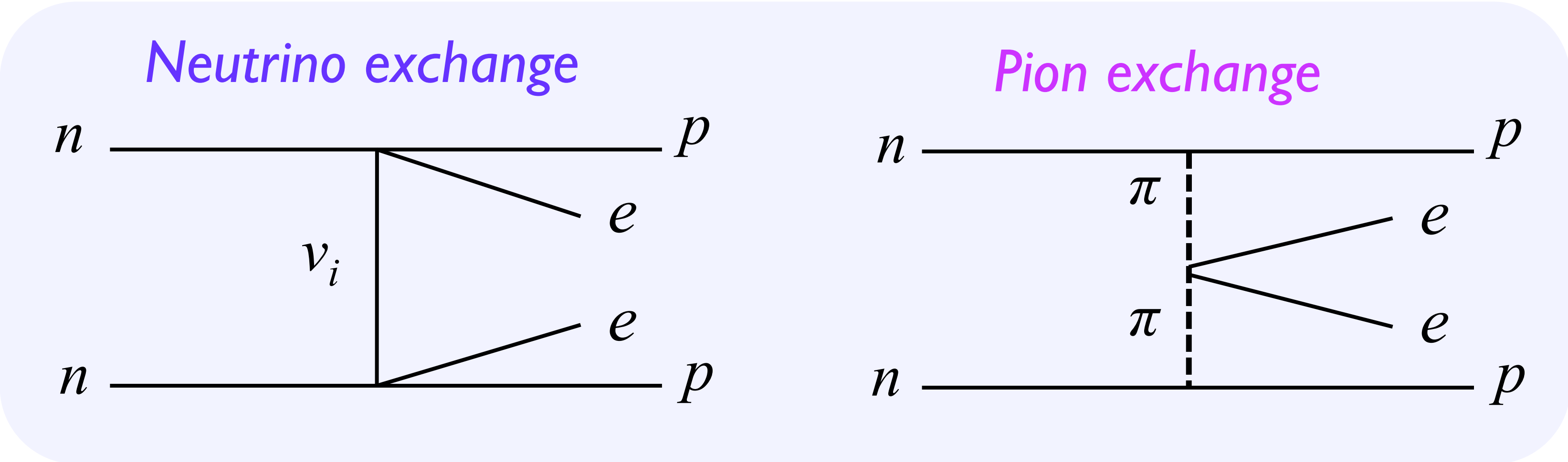
Scalar and tensor operators show up below EW scale:

$$\mathcal{L}^{(6)} = \frac{2G_F}{\sqrt{2}}\left[\bar{u}_L d_R \bar{e}_L C^{(6)}_{\mathrm{SRR}} \nu_i + \bar{u}_L \sigma^{\mu\nu} d_R \bar{e}_L \sigma_{\mu\nu} C^{(6)}_{\mathrm{TRR}} \nu_i\right]$$

$$C^{(6)}_{\mathrm{SRR}} = 4C^{(6)}_{\mathrm{TRR}} = \frac{v^2}{2} C^{(6)}_{LdQ\nu}\, U^*_{Ni}$$

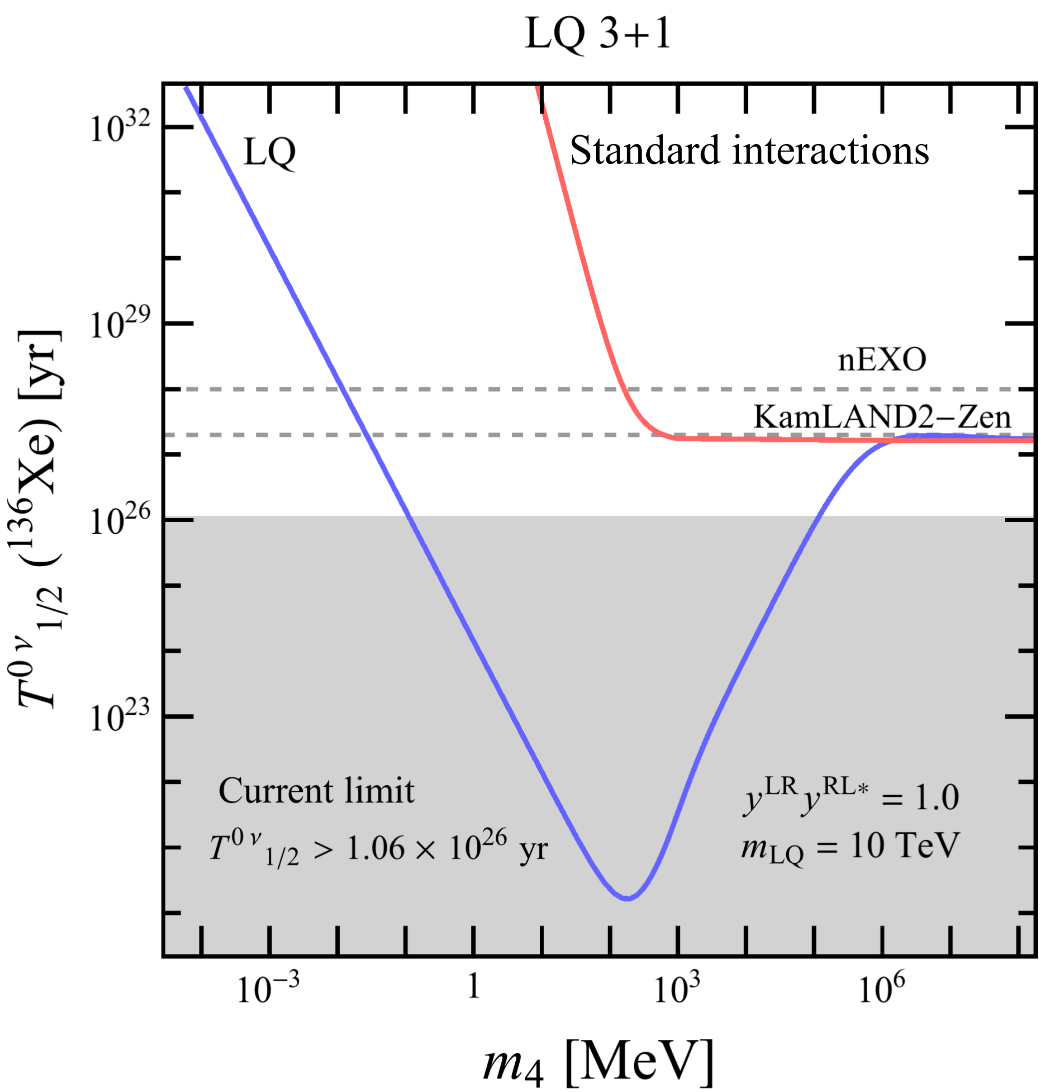
$N = 4(5)$

$i = 1 \sim 4(5)$

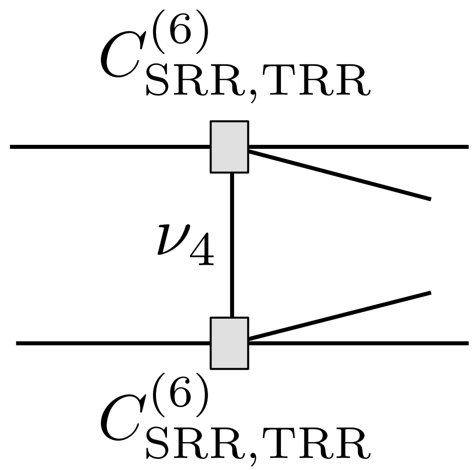


* πN and NN interactions are neglected in our analyses.

3+1 : m_4 vs Half-life



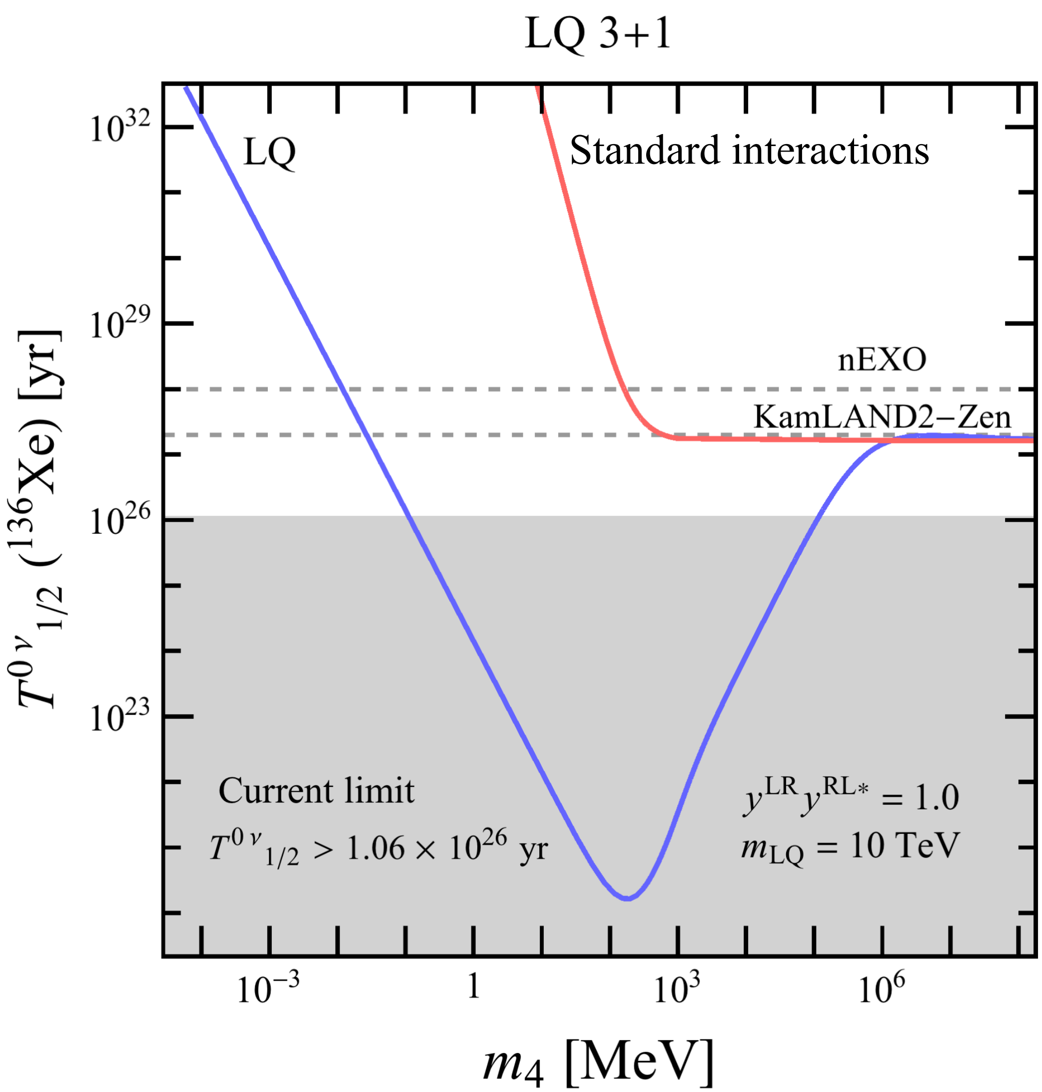
* *Dominant contribution : m_4*



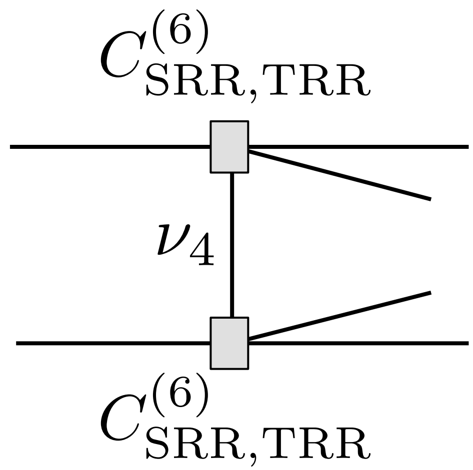
Pink : No LQ interaction (vector contribution)

* *LQ interactions dominate over standard contributions.*

3+1 : m_4 vs Half-life



** Dominant contribution : m_4*



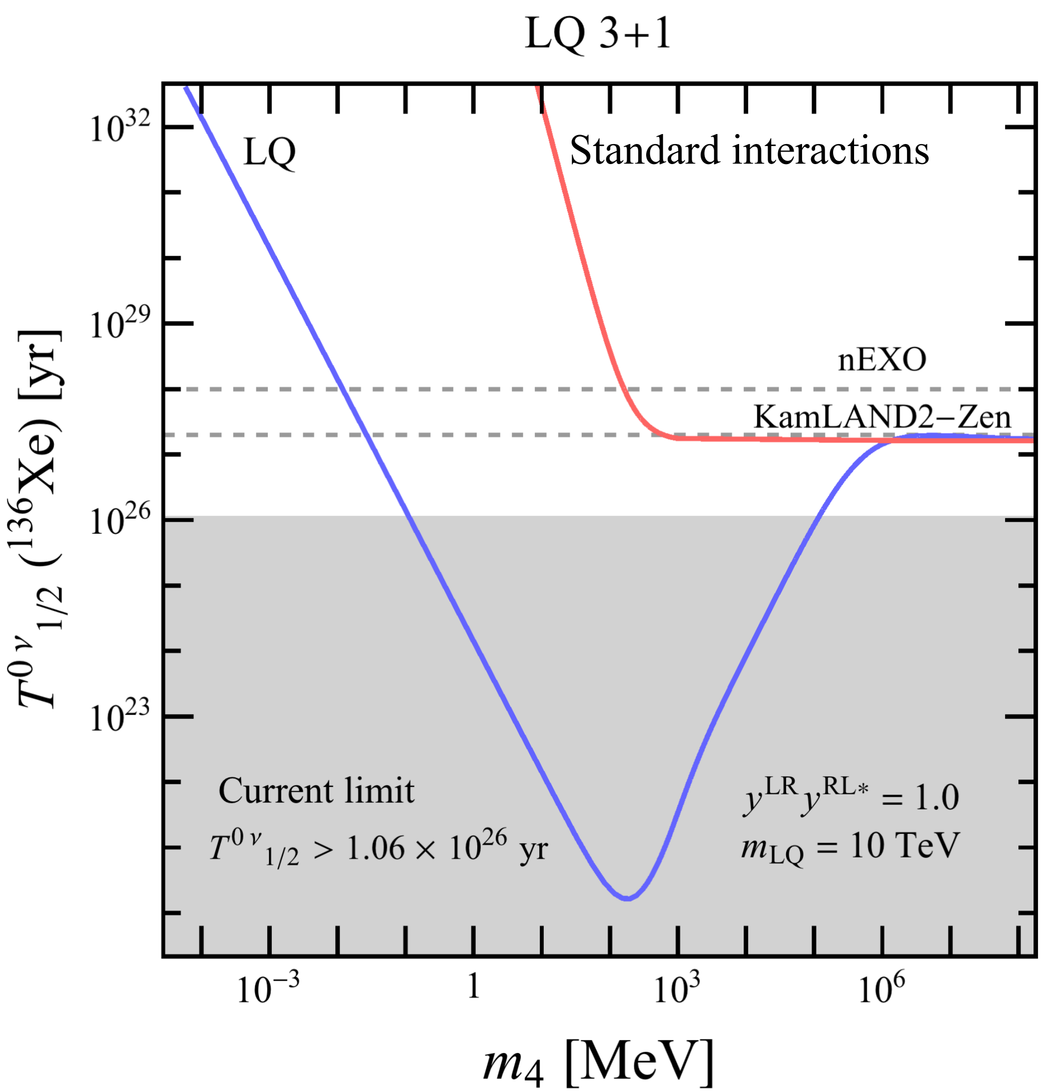
$$T^{0\nu}_{1/2}\left({}^{136}\mathrm{Xe}\right) > 1.06 \times 10^{26}\ \mathrm{yr}$$

KamLAND-Zen : PRL117(2016) 082503

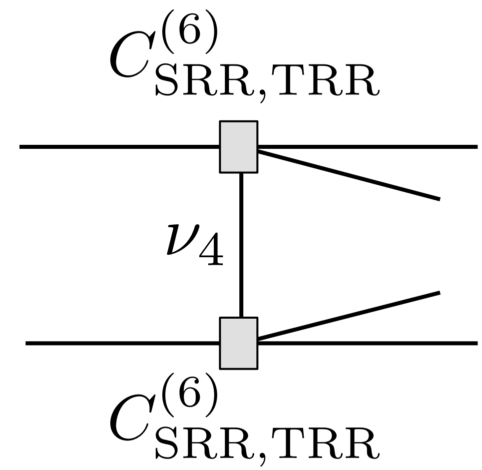
Ruled out

$$0.1\ \mathrm{MeV} \lesssim m_4 \lesssim 100\ \mathrm{GeV}$$

3+1 : m_4 vs Half-life



** Dominant contribution : m_4*



Future sensitivity

$\sim 10^{27}$ yr : KamLAND2-Zen

$\sim 10^{28}$ yr : nEXO

$m_4 \gtrsim 10$ keV

3 + 2 Standard vs Non-standard case

(Leptoquark)

3 + 2 scenario

Two sterile neutrinos : m_4 *and* m_5

* Normal hierarchy is assumed.

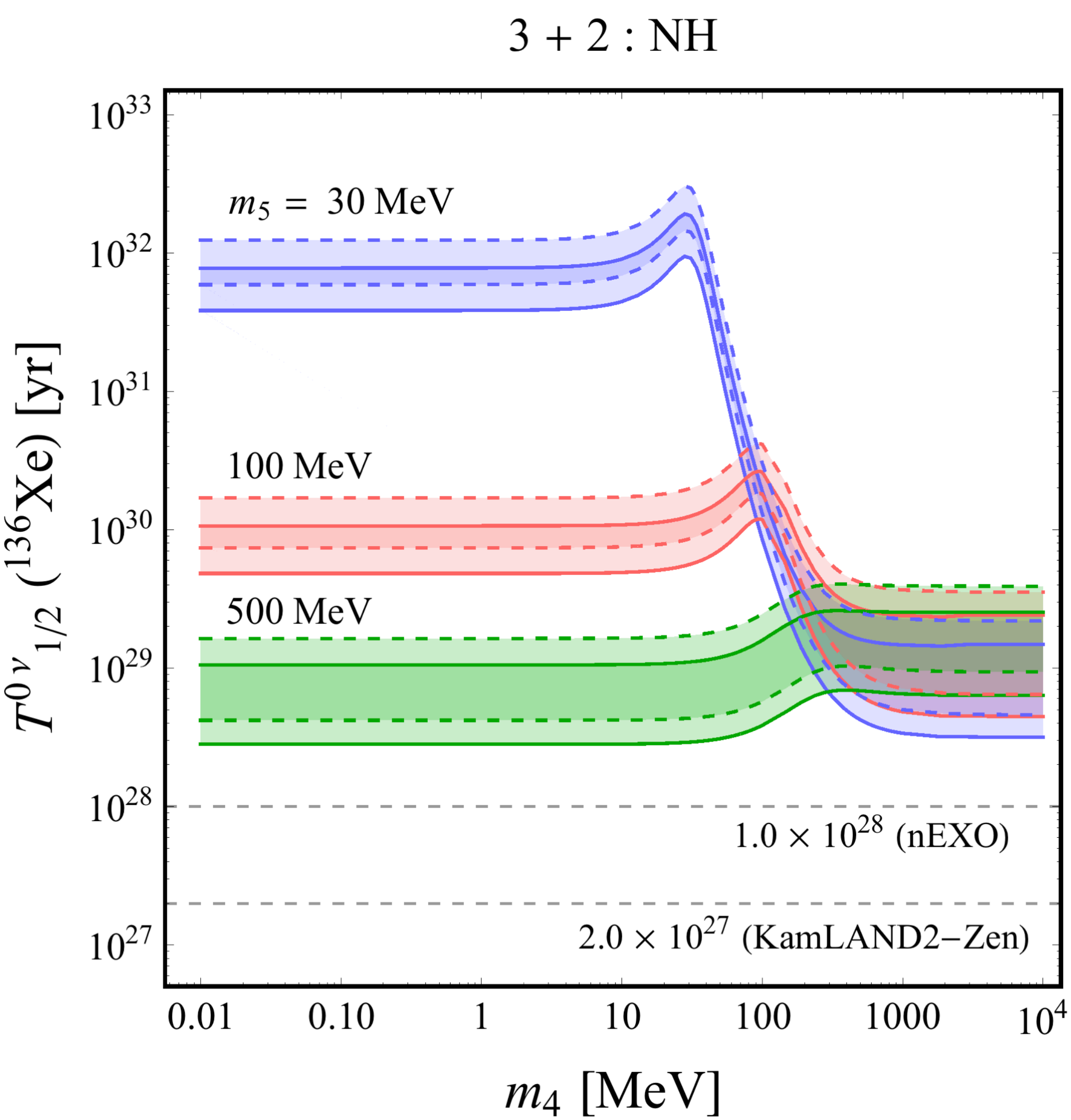
Oscillation parameters [PDG]PRD98, 030001(2018) and update (2019)

$\Delta m^2_{21} = 7.39 \cdot 10^{-5}$ [eV^2]	$\Delta m^2_{32} = 2.5 \cdot 10^{-3}$ [eV^2]
$\sin^2\theta_{12} = 3.10 \cdot 10^{-1}$	$\sin^2\theta_{23} = 5.58 \cdot 10^{-1}$
$\sin^2\theta_{13} = 2.241 \cdot 10^{-2}$	$\delta_{\mathrm{Dirac}} = 1.23\pi$

[3 + 2] $\theta_{45} = \pi/8$ $\gamma_{45} = 0.5$ Majorana phases $= 0$

$m_{4,5}$: free parameters

3+2 standard : m_4 vs Half-life



Three choices of m_5:

Blue : $m_5 = 30$ MeV

Pink : $m_5 = 100$ MeV

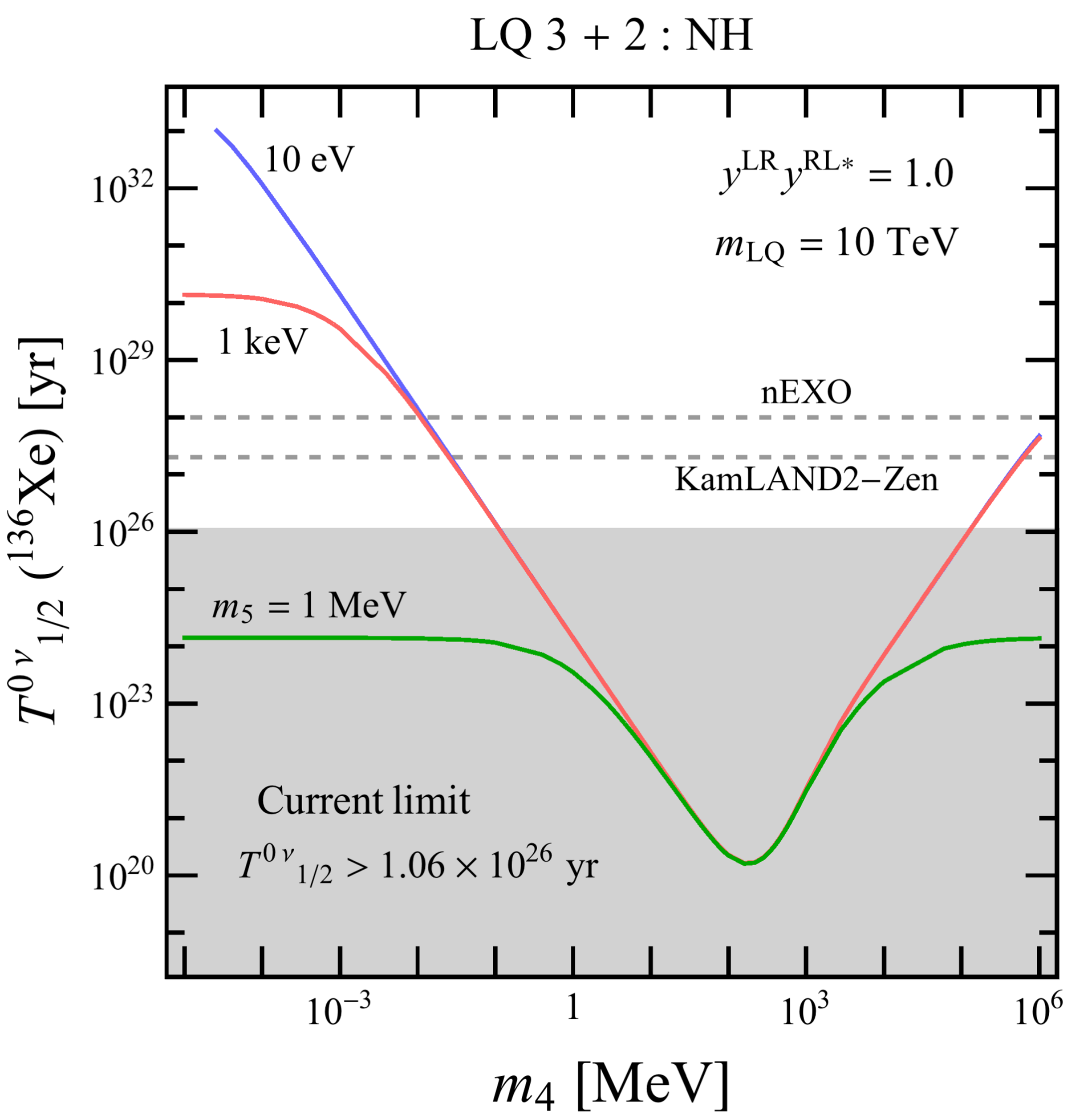
Green : $m_5 = 500$ MeV

Future sensitivity

$\sim 10^{28}$ yr : nEXO

$\sim 10^{27}$ yr : KamLAND2-Zen

3+2 LQ : m_4 vs Half-life



Three choices of m_5 :

Blue : $m_5 = 10\ \mathrm{eV}$

Red : $m_5 = 1\ \mathrm{keV}$

Green : $m_5 = 1\ \mathrm{MeV}$

For the two-light cases, the excluded region is

$$0.1\ \mathrm{MeV} \lesssim m_4 \lesssim 100\ \mathrm{GeV}$$

Summary

Search for neutrinoless double beta decay is a probe of Majorana mass.

Sterile neutrinos are motivated by various phenomena.

Mass range : M_R

eV ⟷ $10^{15}\mathrm{GeV}$

Our study : Model-independent analyses with light ν_R

- Possible to analyze NDBD in any mass spectrum with interpolation formulae
- Non-standard interactions can dominate

✔ *Applicable to models with light sterile neutrinos!*