LA-UR-23-24595

Neutrinoless double beta decay with *light* sterile neutrinos

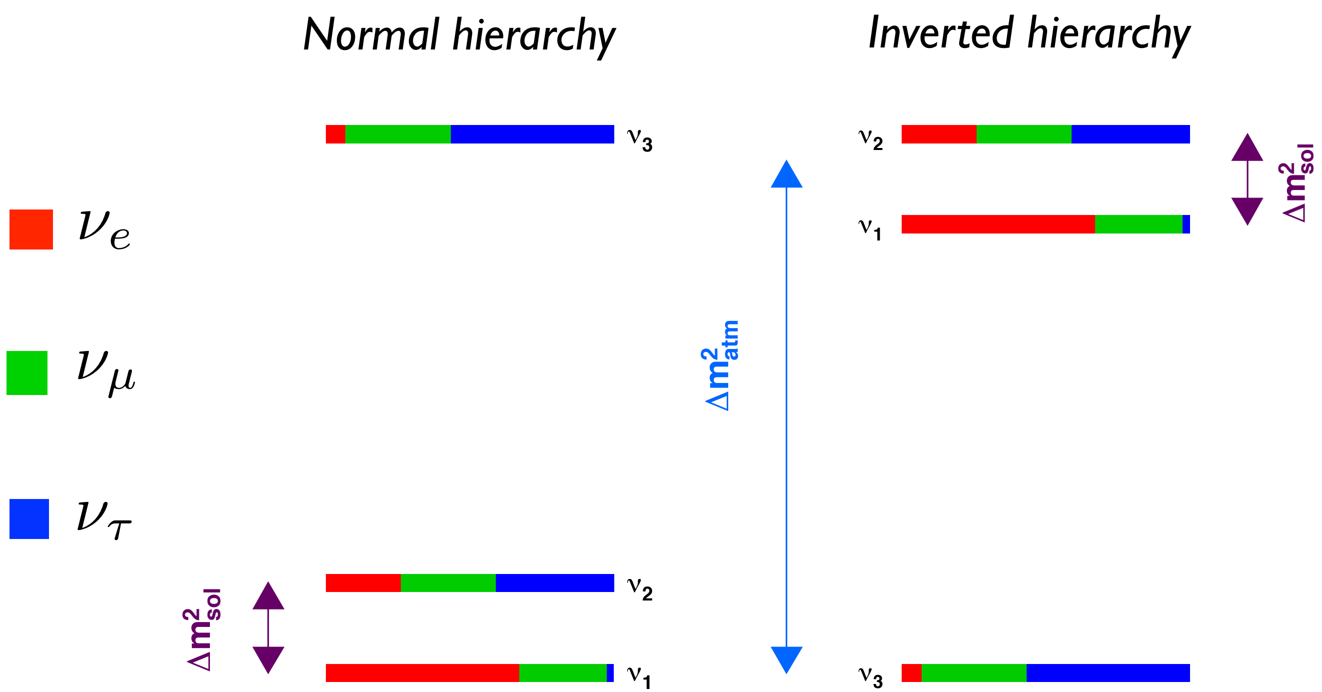
Kaori Fuyuto

Los Alamos National Laboratory

May 12, 2023 at INT
New Physics searches at the precision frontier

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

Neutrino mass



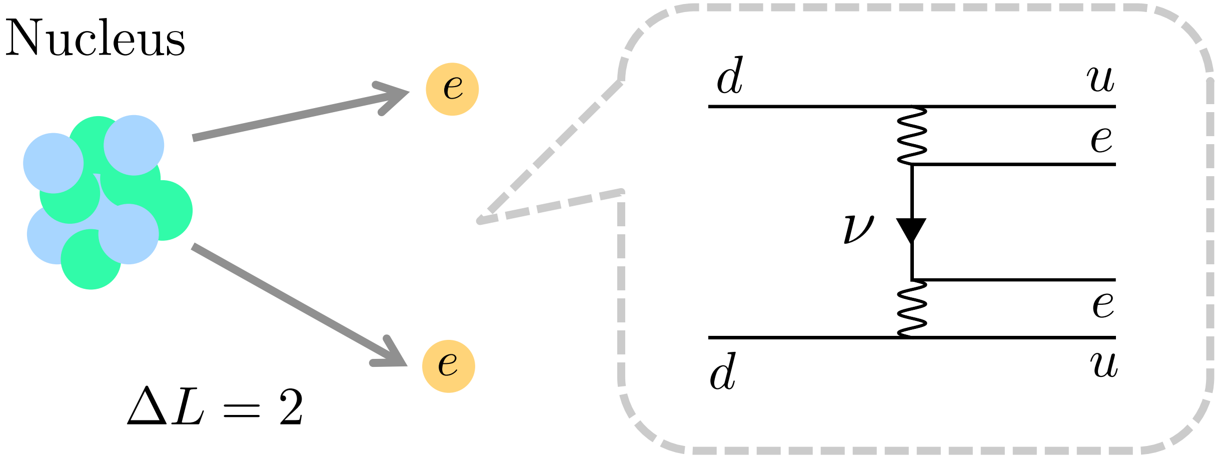
The origin of neutrino masses : Dirac or Majorana?

Neutrinoless Double Beta Decay : $\Delta L = 2$

Neutrinoless Double Beta Decay

Double beta decay without neutrino emission

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



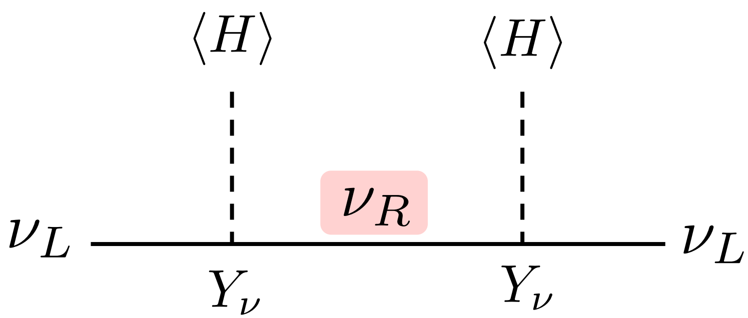
The process can occur if neutrino is a Majorana particle.

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

Neutrinoless Double Beta Decay

Right-handed neutrino : ν_R

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



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

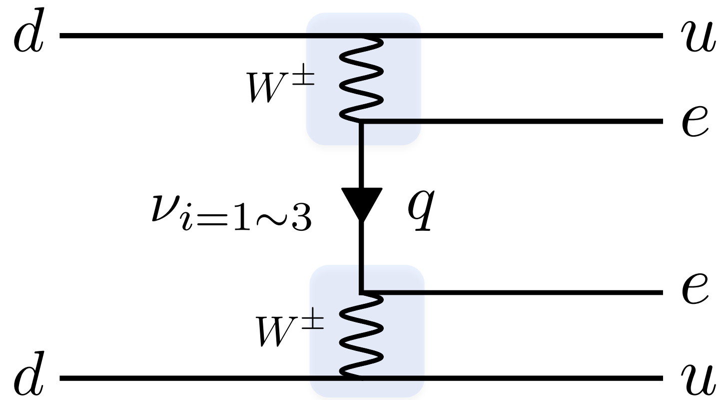
$$\mathcal{L}_{\mathrm{mass}} = -\frac{1}{2}\bar{\nu}m_\nu\nu$$

Majorana mass eigenstate

$$\nu = \nu^c$$

Standard case

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



$q \sim O(100)$ MeV

Left-handed vector operator

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

$$C^{(6)}_{\mathrm{VLL}} = -2 V_{ud} U_{ei}$$

Standard case

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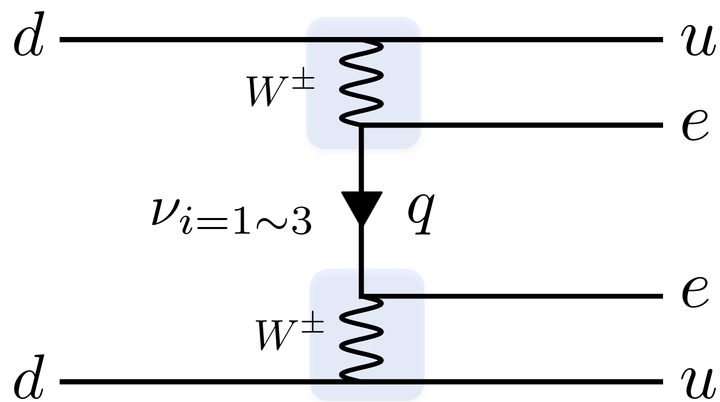

Left-handed vector operator

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

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

O(100) MeV

Standard case

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

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

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

$\sin^2\theta_{12} = 3.10\cdot 10^{-1}$	$\sin^2\theta_{23} = 5.58\cdot 10^{-1}$
$\sin^2\theta_{13} = 2.241\cdot 10^{-2}$	$\delta_{\text{Dirac}} = 1.23\pi$

$$\Delta m^2_{21} = m_2^2 - m_1^2 = 7.39\times 10^{-5}\ [\text{eV}^2]$$

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

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

O(100) MeV   Oscillation data

Standard case

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

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

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

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

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

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

Search for NDBD

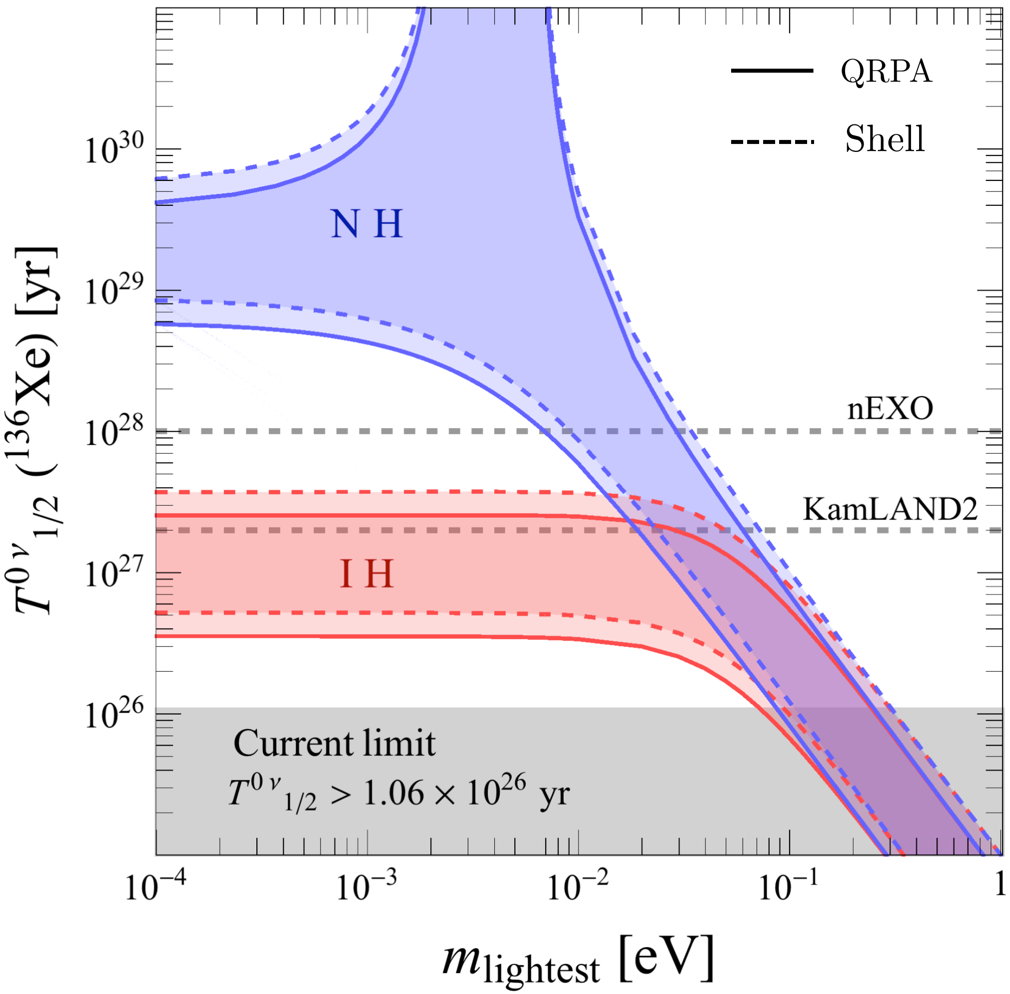
Isotope	Experiment	Current limit ($\times 10^{25}$yr)		Future sensitivity ($\times 10^{25}$yr)	
^{48}Ca	ELEGANT−IV	5.8×10^{-3}	[2]	–	
	CANDLES	6.2×10^{-3}	[23]	10^{-2}	[28]
	NEMO−3	2.0×10^{-3}	[9]		
^{76}Ge	MAJORANA DEMONSTRATOR	2.7	[22]	–	
	GERDA	9.0	[24]	–	
	LEGEND	–		10^3	[29]
^{82}Se	CUPID	3.5×10^{-1}	[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]		

$$T^{0\nu}_{1/2} > 2.3 \times 10^{26} \text{ yr}$$

KamLAND-Zen Collaboration
2203.02139

Current limit on half-life

Standard case : 3 light Majorana neutrinos $(M_R \gg v)$



Normal Hierarchy (NH)

$m_1 < m_2 < m_3$

Inverted Hierarchy (IH)

$m_3 < m_1 < m_2$

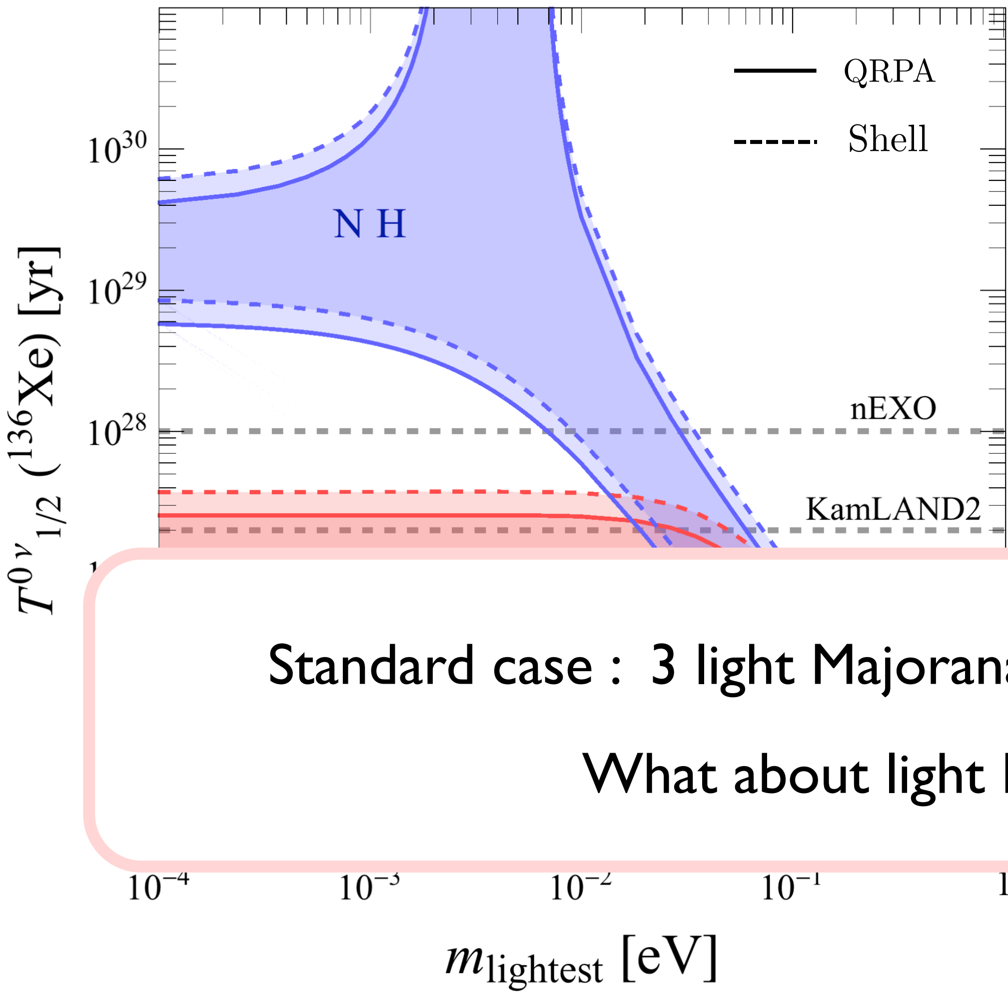
$\sim 10^{27}$ yr @KamLAND2 – Zen

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

*Future

Current limit on half-life

Standard case : 3 light Majorana neutrinos $(M_R \gg v)$



Normal Hierarchy (NH)

$$m_1 < m_2 < m_3$$

Inverted Hierarchy (IH)

$$m_3 < m_1 < m_2$$

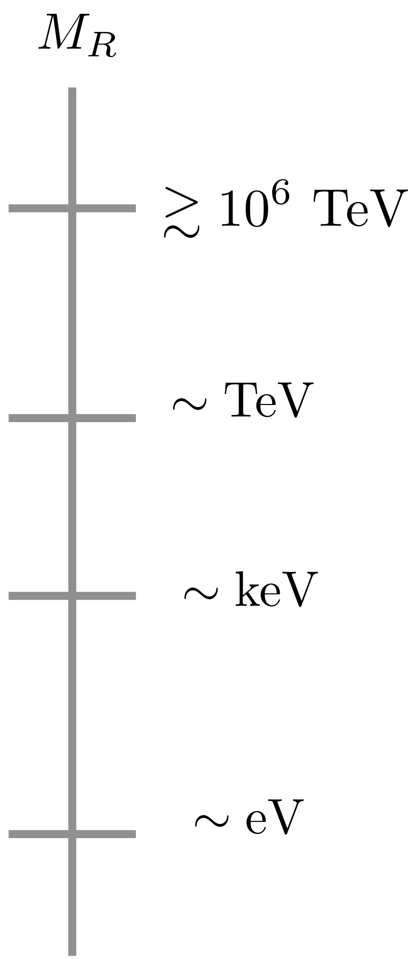
Standard case : 3 light Majorana neutrinos $(M_R \gg v)$

What about light M_R case?

Beyond the standard case

For more details, see M. Drewes, 1303.6912

Other phenomenological aspects:



Wide mass range!

BAU

Leptogenesis

W. Buchmuller, et al , Ann.Rev.Nucl.Part.Sci. 55 (2005)311
A. Pilaftsis, et al, Nucl. Phys. B692 (2004)303
E. K. Akhmedov, et al, PRL81(1998)1359

DM

DM candidate

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

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

$\nu_\mu \to \nu_e$

Beyond the standard case

For more details, see M. Drewes, 1303.6912

* Need theoretical analysis in light of light sterile neutrinos

M_R

$\gtrsim 10^6$ TeV

$\sim$ TeV

$\sim$ keV

$\sim$ eV

BAU

Leptogenesis

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PRL102(2009)101802

Wide mass range!

Light M_R case

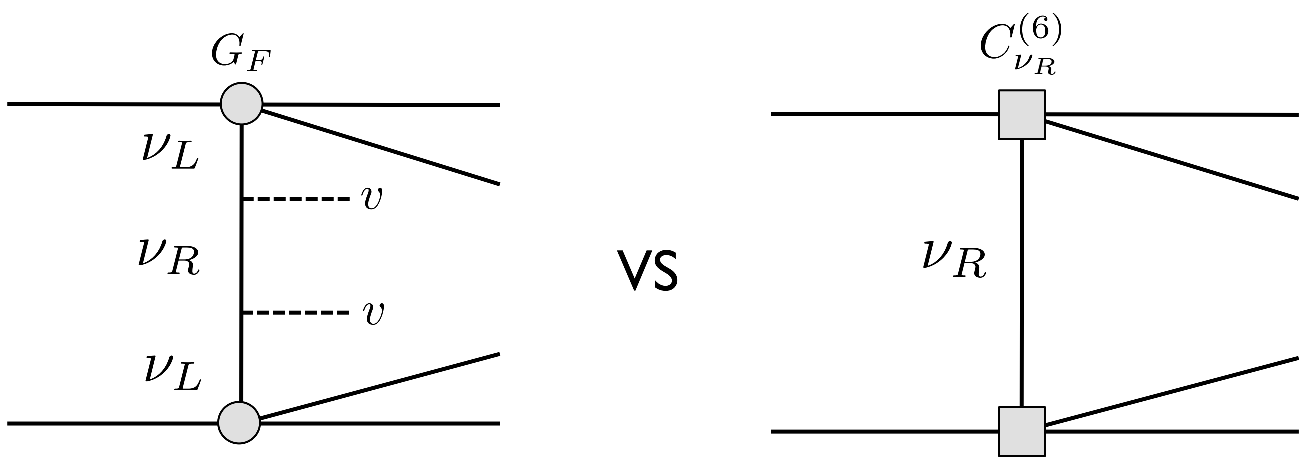
W. Dekens, J. de Vries, **KF**, E. Mereghetti, G. Zhou,
JHEP06(2020)097

Model-independent analysis in the light ν_R scenario

~ Effective Field Theory

* Non-standard interactions (d = 6)

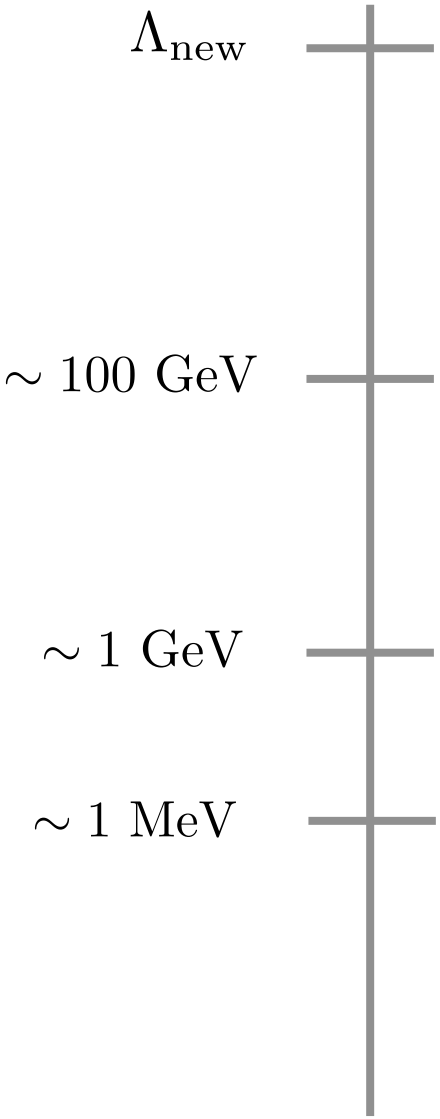
$$\mathcal{L} = -Y_\nu \bar{L}\tilde{H}\nu_R - \frac{1}{2}\overline{\nu_R^c} M_R \nu_R + \frac{1}{\Lambda^2} C^{(6)}_{\nu_R} \mathcal{O}^{(6)}$$



* Construct interpolation formulas for NMEs and LECs depending on M_R

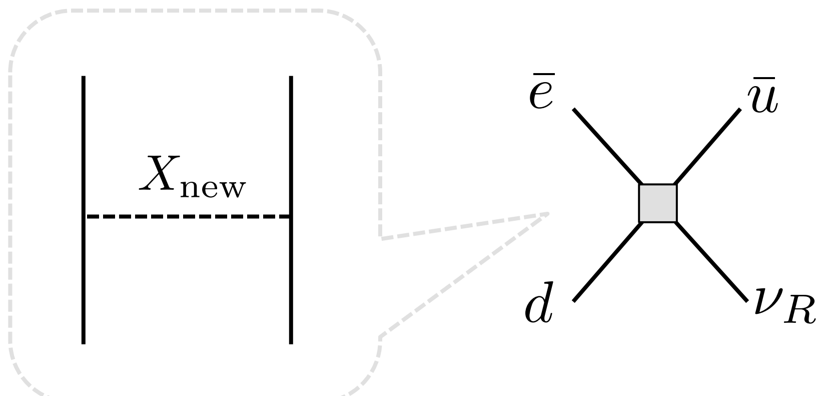
EFT approach

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)



SM + sterile neutrino EFT

$$\mathcal{L} = \mathcal{L}_{\rm SM+\nu_R} + \frac{1}{\Lambda^2} C^{(6)}_{\nu_R} \mathcal{O}^{(6)} + \cdots$$



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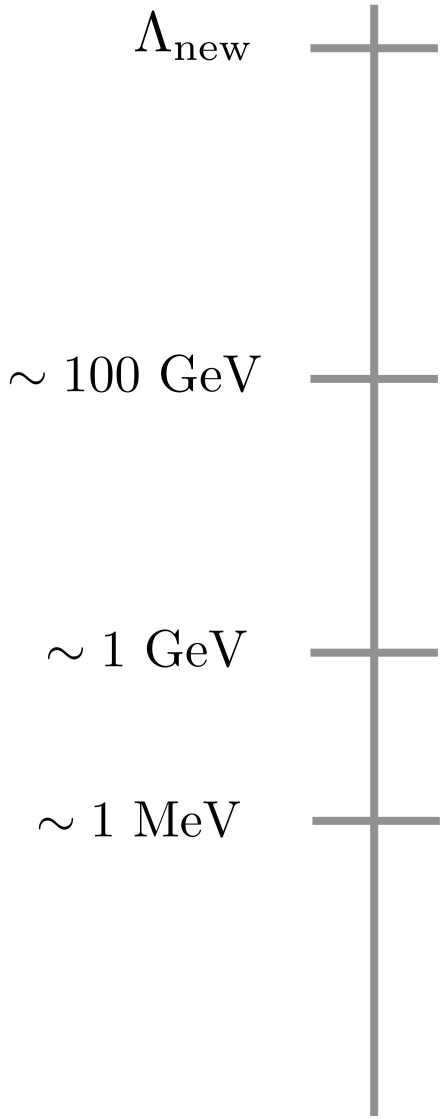

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Neutrino mass

Integrate out heavy SM particles + ν_R (≥1GeV)

EFT approach

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V. Cirigliano, W. Dekens, J. de Vries, M. L. Graesser, and E. Mereghetti, JHEP 12, 097(2018)

Λ_{new}

SM + sterile neutrino EFT

$$\mathcal{L} = \mathcal{L}_{\text{SM}+\nu_R} + \frac{1}{\Lambda^2} C^{(6)}_{\nu_R} \mathcal{O}^{(6)} + \cdots$$

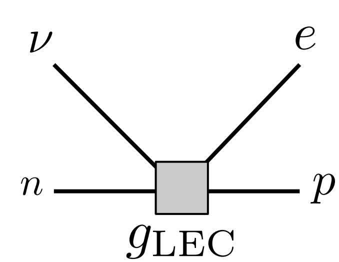
~ 100 GeV

Neutrino mass

Integrate out heavy SM particles + ν_R (≥1GeV)

~ 1 GeV

Chiral Perturbation Theory



~ 1 MeV

" Inverse half-life "

$$\left(T^{0\nu}_{1/2}\right)^{-1} = g_A^4 G_{0\nu} \left| \mathcal{A}_{0\nu 2\beta}\left(g_{\text{LEC}}, C^{(6)}_{\nu_R}, M_{\text{NME}}\right)\right|^2$$

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

EFT approach

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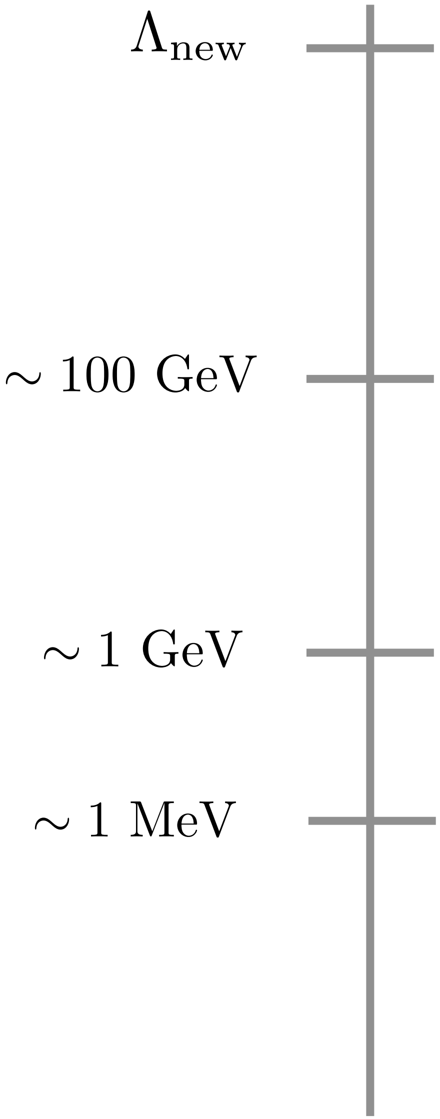

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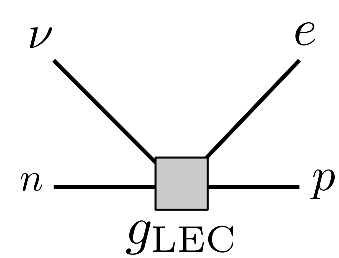
$$\mathcal{L} = \mathcal{L}_{\rm SM+\nu_R} + \frac{1}{\Lambda^2} C^{(6)}_{\nu_R} \mathcal{O}^{(6)} + \cdots$$

Neutrino mass

Integrate out heavy SM particles + ν_R (≥1GeV)

Chiral Perturbation Theory



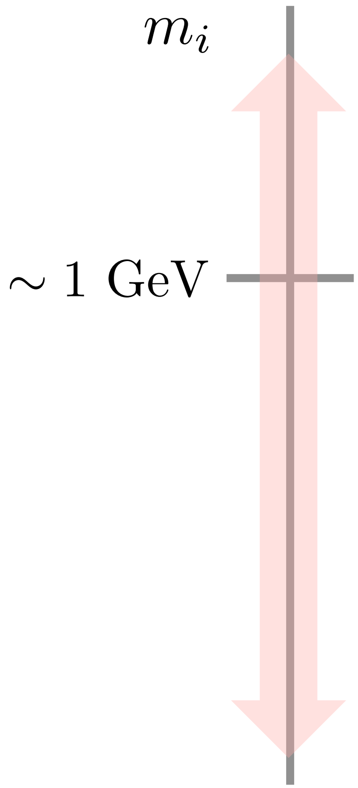
" Inverse half-life "

$$\left(T^{0\nu}_{1/2}\right)^{-1} = g_A^4 G_{0\nu} \left| \mathcal{A}_{0\nu 2\beta}\left(g_{\rm LEC}, C^{(6)}_{\nu_R}, M_{\rm NME}\right)\right|^2$$

"Interpolation formulae"

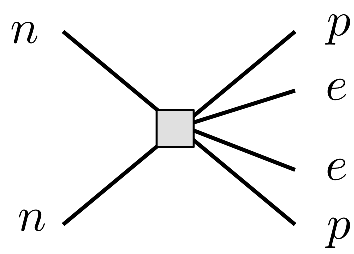
EFT approach

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



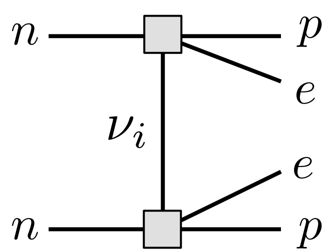
Ex)

Dim 9



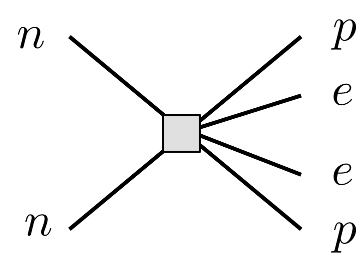
$g^{\mathrm{NN}} M_{F,sd}(0)$

Long distance



$M_F(m_i)$

Short distance



$g_\nu^{\mathrm{NN}}(m_i) M_{F,sd}(0)$

$$M_{\mathrm{NME}}(m_i) : \ \text{Pade approximation}$$

$$\mathcal{A}_{0\nu2\beta}(m_i)|_{m_i \gg \mathrm{GeV}} = \mathcal{A}^{(9)}_{0\nu2\beta}$$

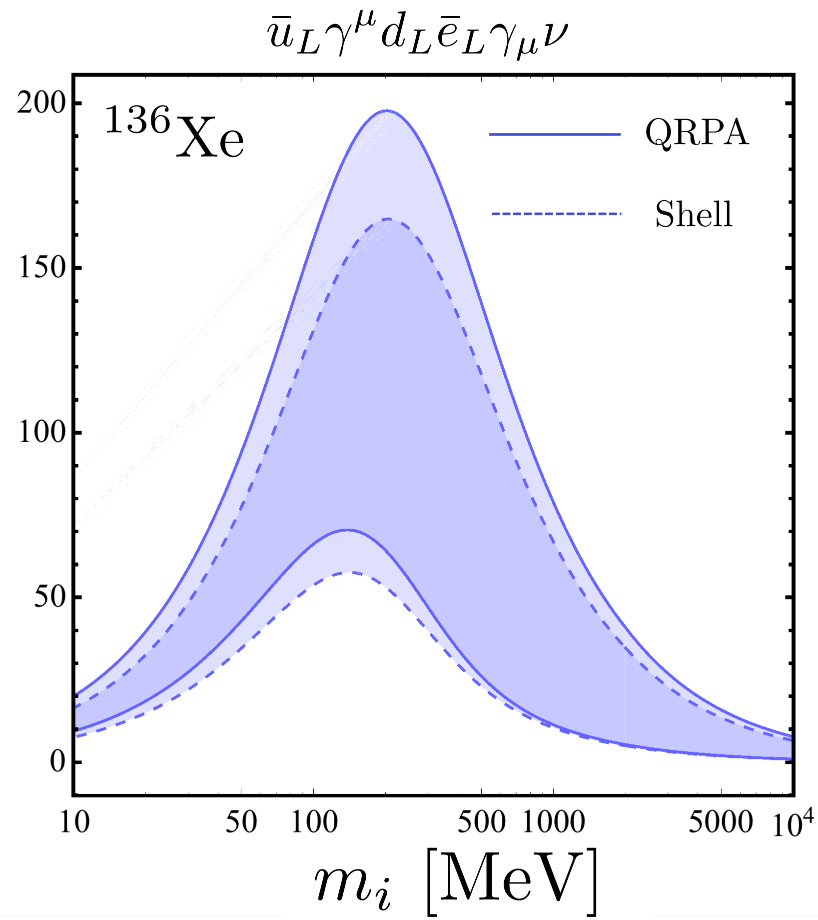
$$\lim_{m_i \to 0} M_F(m_i) = M_F(0)$$

$$\lim_{m_i \to \infty} M_F(m_i) = \frac{m_\pi^2}{m_i^2} M_{F,sd}(0)$$

EFT approach

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

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



- Two different NMEs

- Peak around O(100) MeV

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

O(100) MeV

- Similar behavior in literature

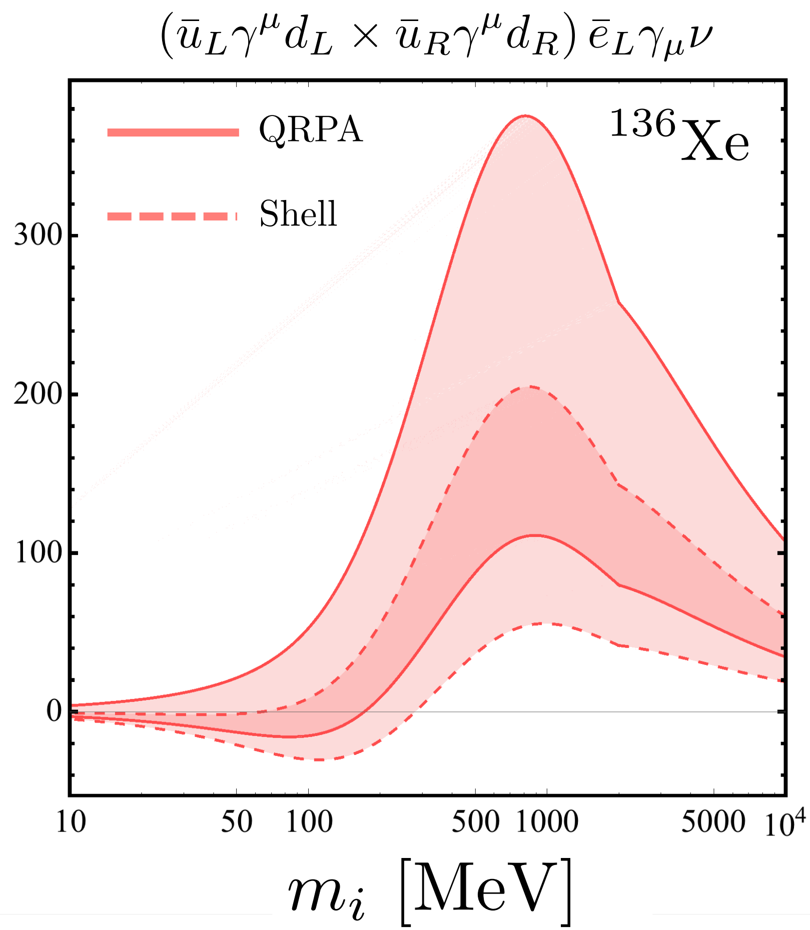
  J.Barea, et al PRD92(2015)093001

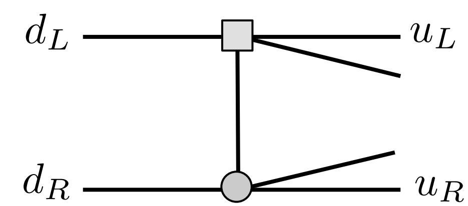
- Large uncertainty in LECs

EFT approach

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

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





- Peak around O(1) GeV

  * Nontrivial behavior due to LECs

- Not discussed in literature

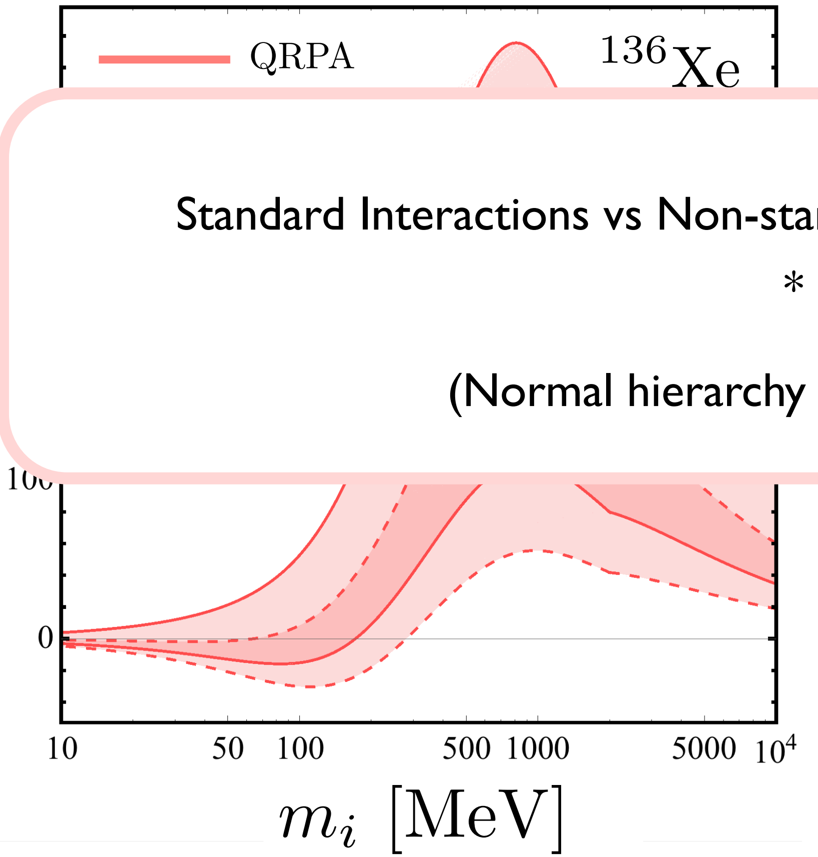
- Large uncertainty in LECs

EFT approach

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

Mass dependence of the amplitude : $|\mathcal{A}_{0\nu2\beta}(m_i)|_{^{136}\mathrm{Xe}}$

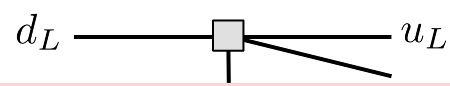
$(\bar{u}_L\gamma^\mu d_L \times \bar{u}_R\gamma^\mu d_R)\,\bar{e}_L\gamma_\mu\nu$



Standard Interactions vs Non-standard Interactions (dim = 6)

* Leptoquark Model

(Normal hierarchy is assumed)



ECs

- Not discussed in literature

- Large uncertainty in LECs

3+1 scenario

One sterile neutrino : m_4

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

* Standard interactions

Mass matrix : $(M_\nu)_{i4,4i} \neq 0$

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

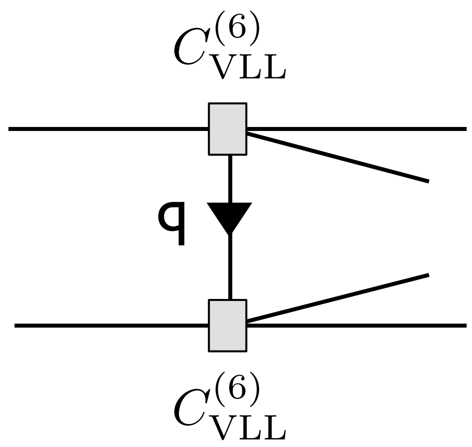
Yukawa

Majorana

3+1 scenario

One sterile neutrino : m_4

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



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

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

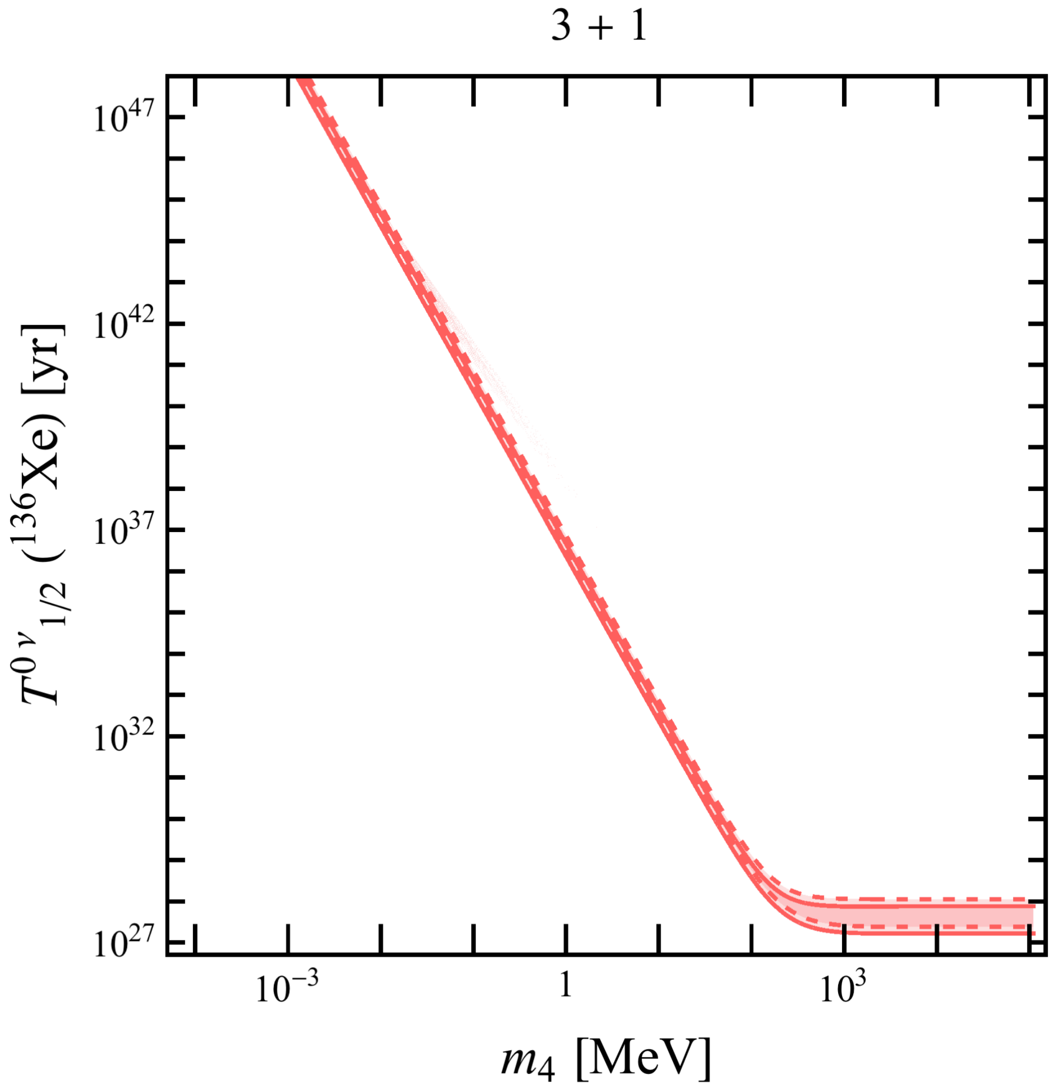
$$\sim \frac{m_i}{\mathrm{q}^2} U_{ei}^2 \left(1 + \frac{m_i^2}{\mathrm{q}^2} + \cdots \right)$$

LO vanishes

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

* Cancellation of LO contribution in light-mass region

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



3+1 Standard case : The half-life is well above experimental reach.

3+1 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

+ one sterile neutrino

3+1 Leptoquark

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+ one sterile neutrino

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

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

3+1 Leptoquark

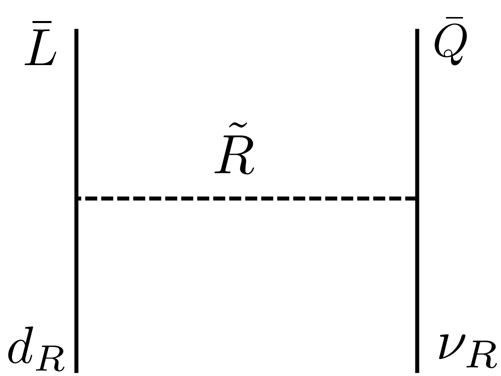
J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 88, 035009 (2013)
J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 87, 075004 (2013)
I. Dorsner, S. Fajfer, A. Greljo, J. F. Kamenik and N. Kosnik, Phys. Rept. 641, 1 (2016)

Leptoquark (LQ) couples to the SM quark and lepton

\+ one sterile neutrino

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:

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

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

3+1 Leptoquark

J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 88, 035009 (2013)
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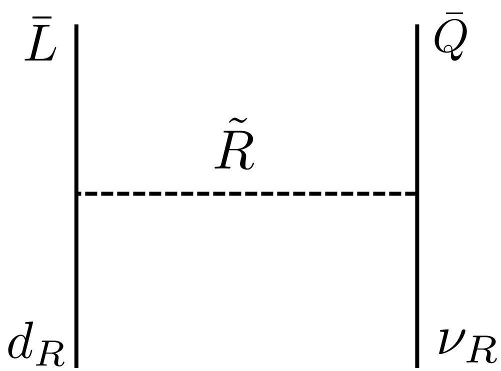

LQ parameters :

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

3+1 Leptoquark

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

Scalar and tensor operators show up below EW scale:

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

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

3+1 Leptoquark

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

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

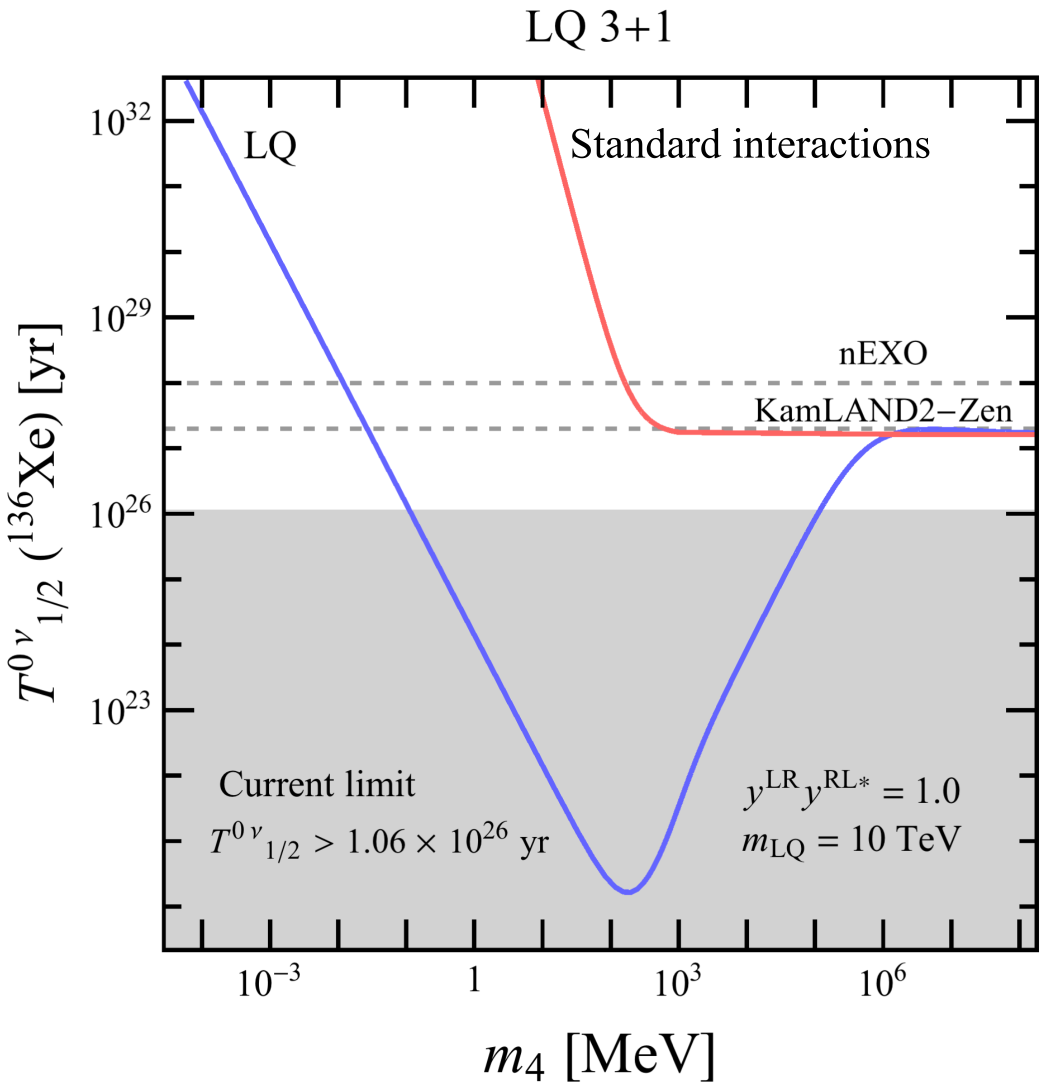
$$+\frac{2G_F}{\sqrt{2}} \bar{u}_L \gamma^\mu d_L \bar{e}_L \gamma_\mu C^{(6)}_{\mathrm{VLL}} \nu$$

← Induced by standard interaction (No LQ interaction)

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

3+1 Leptoquark

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



Blue : LQ interaction

Pink : No LQ interaction (vector contribution)

* LQ interactions dominate over standard contributions.

3+1 Leptoquark

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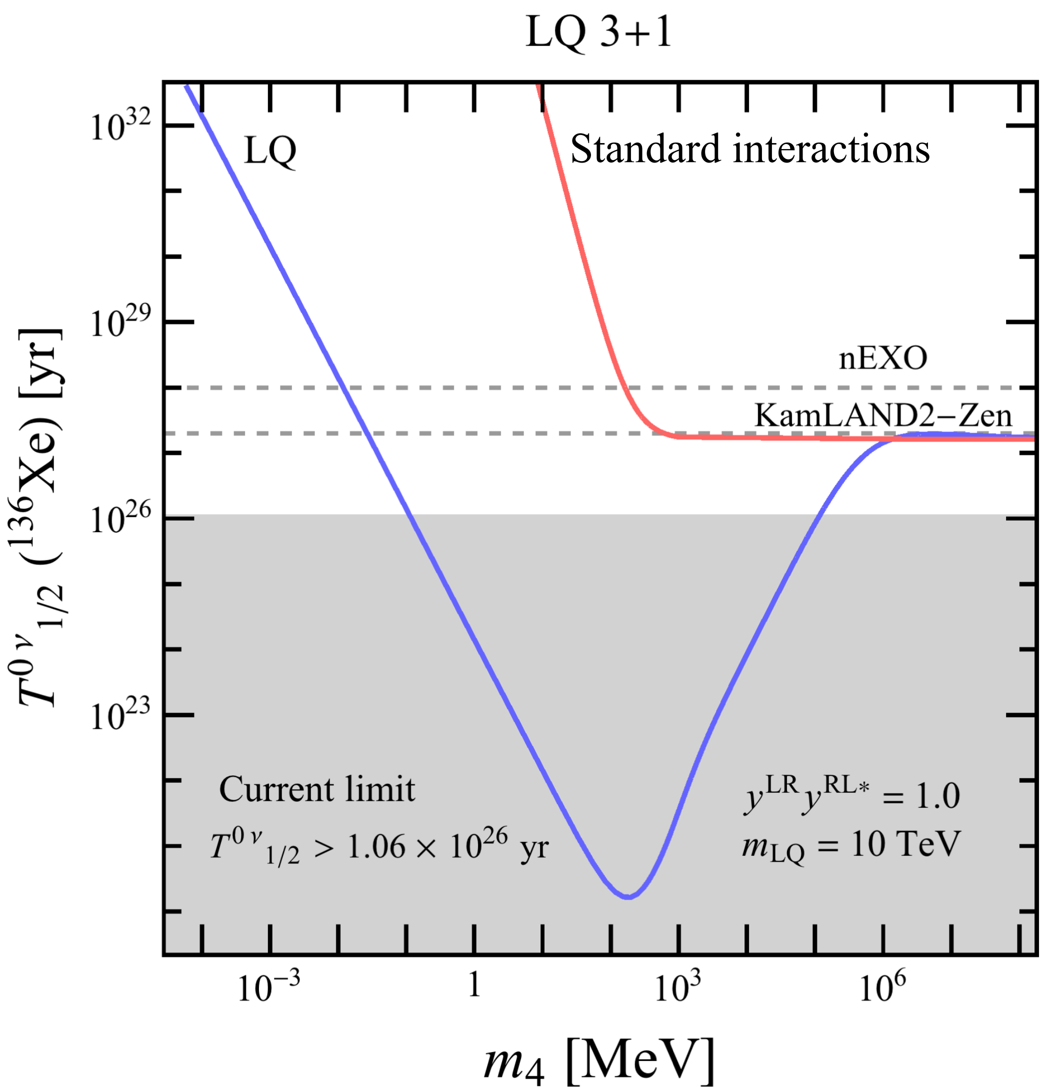


Blue : LQ interaction

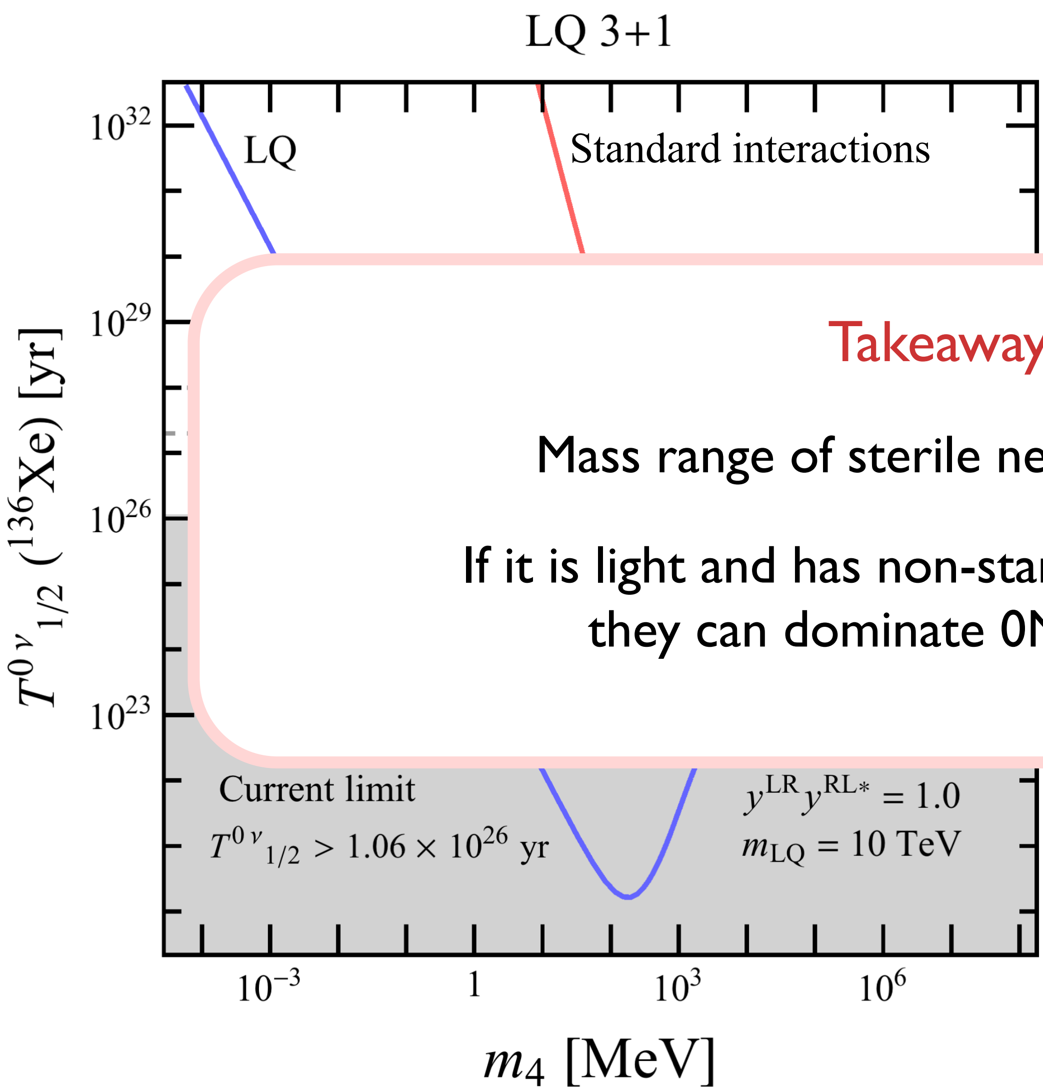
Pink : No LQ interaction (vector contribution)

Ruled out

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

3+1 Leptoquark

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



Blue : LQ interaction

…n

…ion)

Takeaway

Mass range of sterile neutrino is wide.

If it is light and has non-standard interactions, they can dominate 0N2B process.

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

3+2 leptoquark

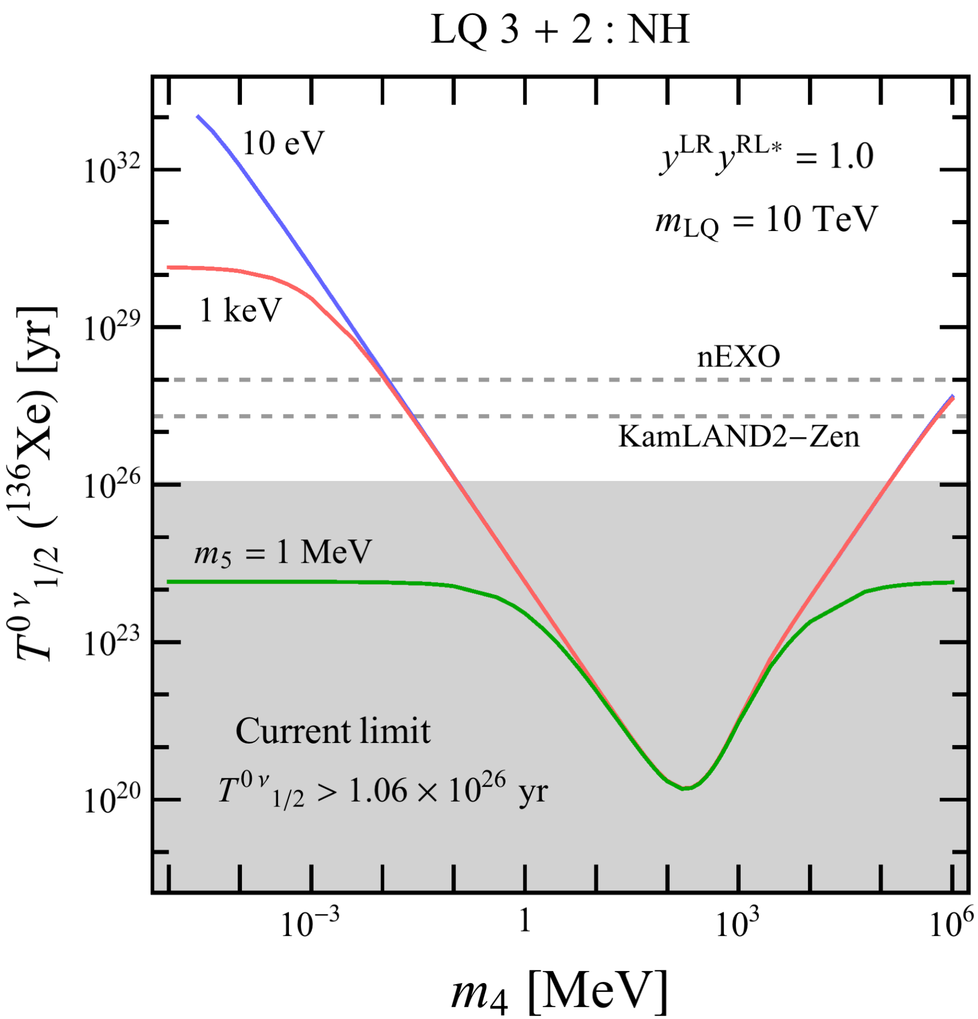
Two sterile neutrinos : m_4 and m_5

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

NH	$\Delta m^2_{21} = 7.39 \times 10^{-5}$ [eV^2]	$\Delta m^2_{32} = 2.5 \times 10^{-3}$ [eV^2]
	$\sin^2\theta_{12} = 3.1 \times 10^{-1}$	$\sin^2\theta_{13} = 2.241 \times 10^{-2}$
	$\sin^2\theta_{23} = 5.58 \times 10^{-1}$	$\delta_{\text{Dirac}} = 1.23\pi$
IH	$\Delta m^2_{21} = 7.39 \times 10^{-5}$ [eV^2]	$\Delta m^2_{32} = -2.5 \times 10^{-3}$ [eV^2]
	$\sin^2\theta_{12} = 3.1 \times 10^{-1}$	$\sin^2\theta_{13} = 2.261 \times 10^{-2}$
	$\sin^2\theta_{23} = 5.63 \times 10^{-1}$	$\delta_{\text{Dirac}} = 1.58\pi$
[3 + 2]	$\theta_{45} = \pi/8$	$m_{4,5}$: free parameters
	$\gamma_{45} = 0.5$	Majorana phases = 0

3+2 leptoquark

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



Three choices of m_5 :

Blue : $m_5 = 10$ eV

Pink : $m_5 = 1$ keV

Green : $m_5 = 1$ MeV

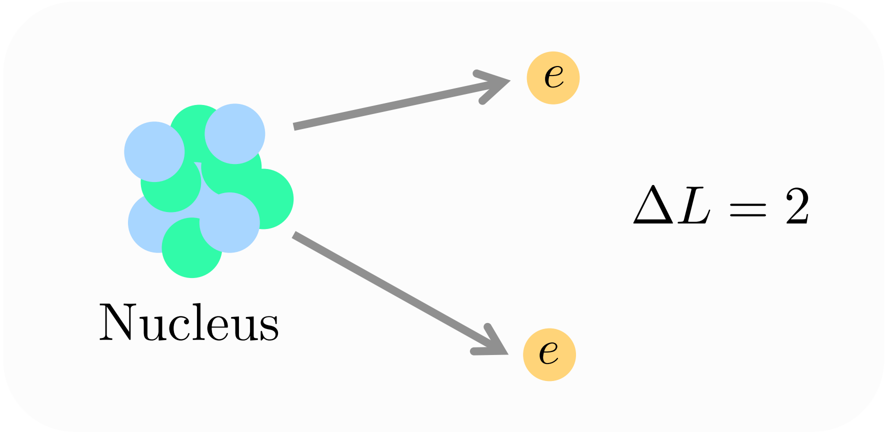
For the two light cases,

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

excluded.

Conclusion

Search for 0n2b is a probe of Majorana mass.



Our study : Model-independent analysis with light ν_R

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

✔ Applicable to phenomena involved in light sterile neutrinos (e.g., DM phenomenology and the BAU)