LA-UR-24-24444

Phenomenology of Sterile Neutrino EFT

Kaori Fuyuto

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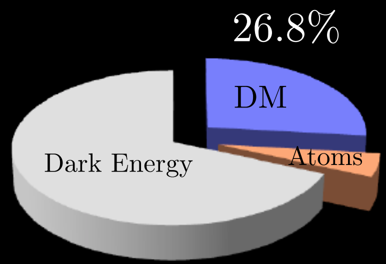
W. Dekens, J. de Vries, KF, E. Mereghetti, G. Zhou, JHEP06(2020)097
KF, J. Kumar, E. Mereghetti, S. Sandner, C. Sun, 2405.00119

May 7, 2024
N3AS seminar

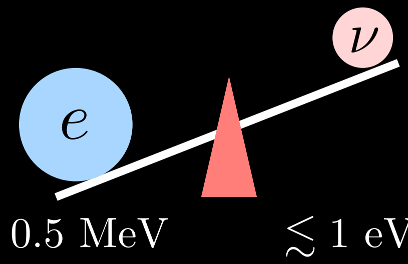
We still don't know much about our Universe.

What is Dark Matter?



The origin of
the present Universe

What is the origin of
tiny neutrino mass ?



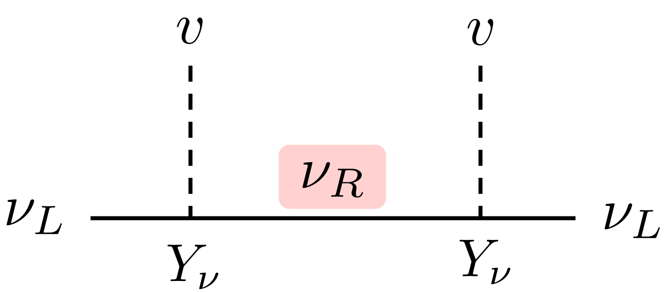
Why is there more matter than antimatter? $\dfrac{n_b - n_{\bar{b}}}{n_\gamma} = 6.1 \times 10^{-10}$

Need to extend the Standard Model, e.g., Sterile Neutrino

Sterile Neutrino

Right-handed neutrino with no SM charges

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



✔ SM Neutrino Mass

$$m_\nu \sim \frac{Y_\nu^2 v^2}{M_R} \quad (v \simeq 246 \text{ GeV})$$

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

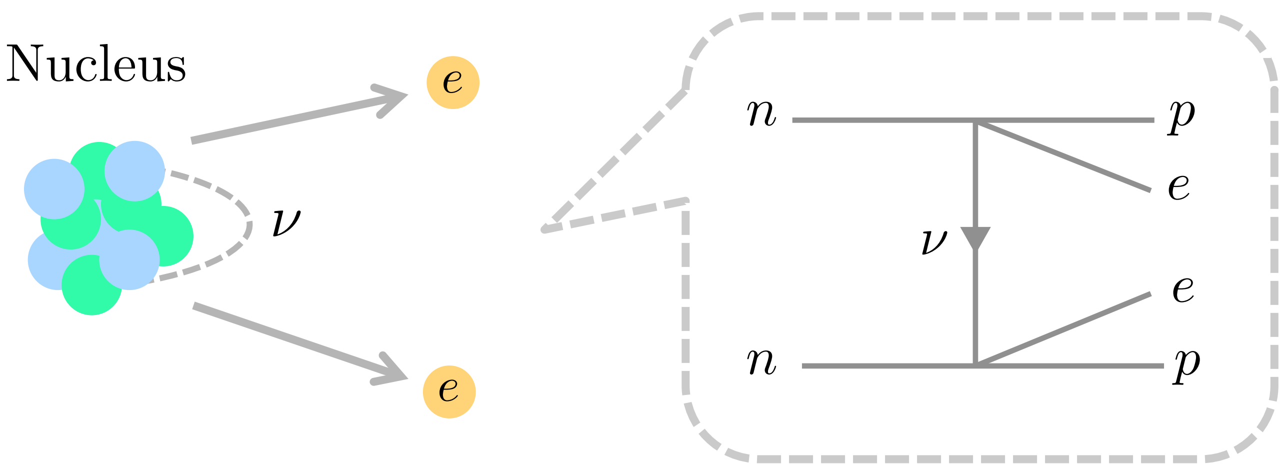
Majorana mass eigenstate

$$\nu = \nu^c$$

Sterile Neutrino

If neutrinos are Majorana particles, neutrinoless double beta decay can occur.

0N2B : Double beta decay without neutrino emission

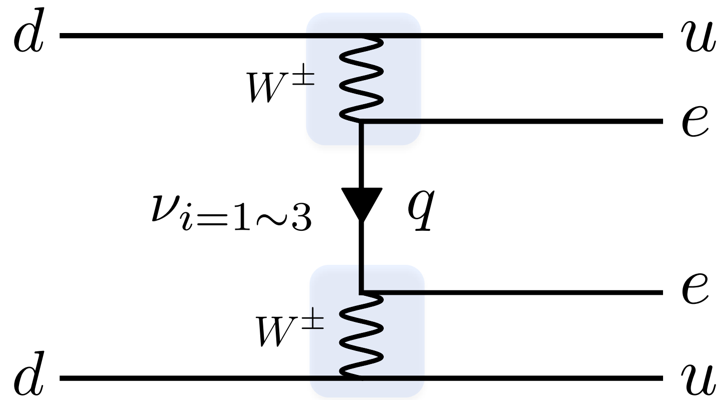


$$(A, Z) \to (A, Z+2) + 2e^-$$

*Lepton number is violated by two units.

0N2B : Standard Case

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



$q \sim O(100)$ MeV

Left-handed vector operator

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

0N2B : Standard Case

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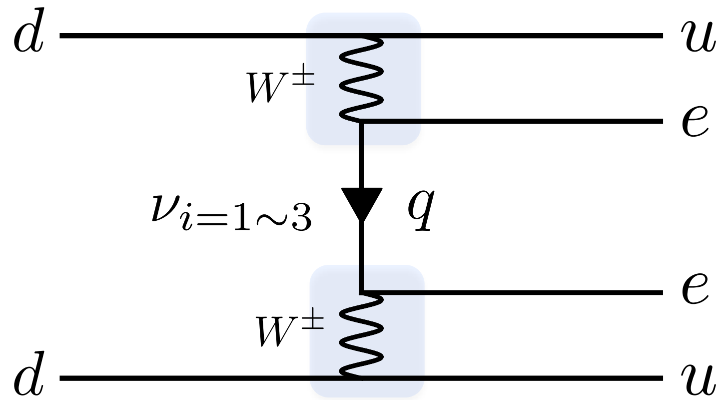

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$$\mathcal{A}_{0\nu2\beta} \sim \sum_{i=1}^{3} U_{ei}^2 \frac{m_i}{\mathrm{q}^2 + m_i^2} \sim \frac{1}{\mathrm{q}^2} \left(\sum_{i=1}^{3} U_{ei}^2 m_i \right)$$

O(100) MeV

0N2B : Standard Case

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

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

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

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

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

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

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

O(100) MeV — Oscillation data

0N2B : Standard Case

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

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

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Inverse half-life : $$\left(T^{0\nu}_{1/2}\right)^{-1} = g_A^4 G_{0\nu} \left|\mathcal{A}_{0\nu2\beta}\right|^2$$

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

Searches for 0N2B

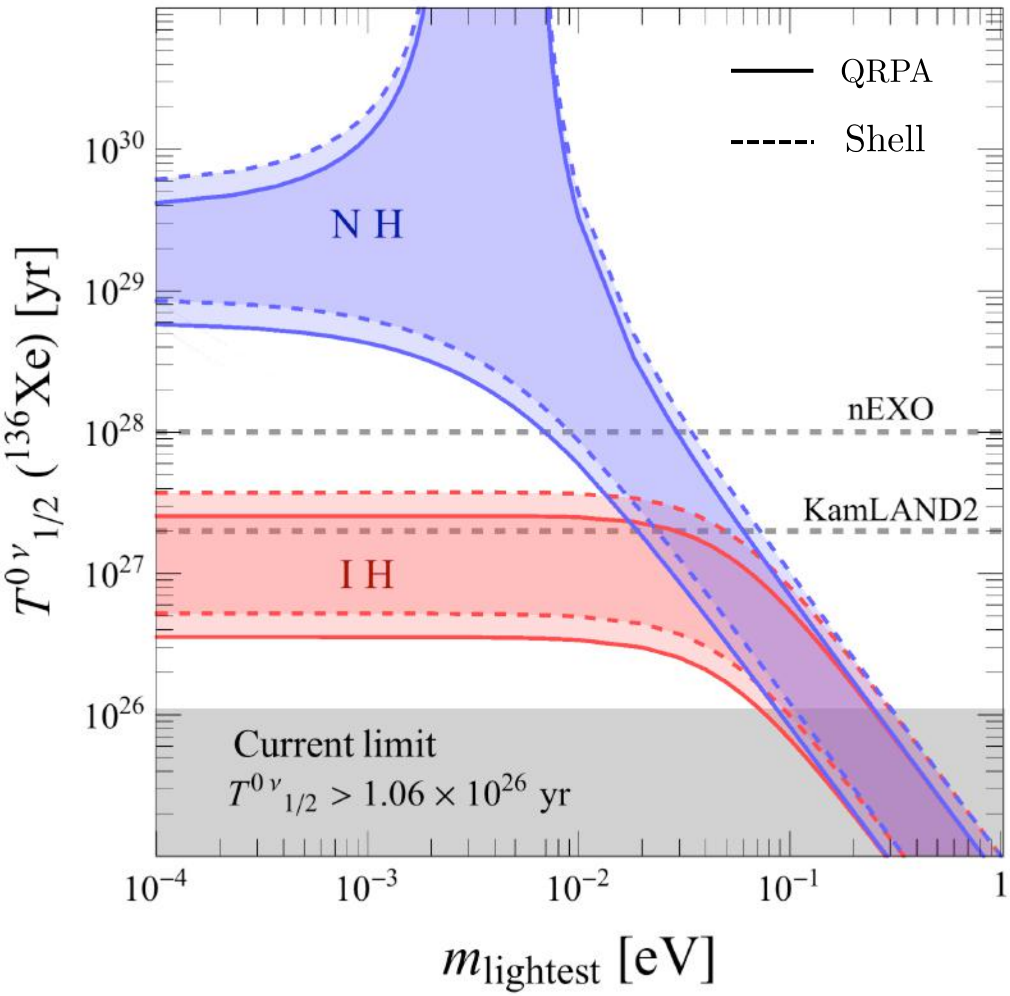
Isotope	Experiment	Current limit ($\times 10^{25}$yr)		Future sensitivity ($\times 10^{25}$yr)	
^{48}Ca	ELEGANT−IV	5.8×10^{-3}	[2]	–	
	CANDLES	6.2×10^{-3}	[23]	10^{-2}	[28]
	NEMO−3	2.0×10^{-3}	[9]		
^{76}Ge	MAJORANA DEMONSTRATOR	2.7	[22]	–	
	GERDA	9.0	[24]	–	
	LEGEND	–		10^{3}	[29]
^{82}Se	CUPID	3.5×10^{-1}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

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

KamLAND-Zen Collaboration
PRL130 (2023) 5, 051801

Current limit on half-life

Standard case : 3 light Majorana neutrinos



Normal Hierarchy (NH)

$$m_1 < m_2 < m_3$$

Inverted Hierarchy (IH)

$$m_3 < m_1 < m_2$$

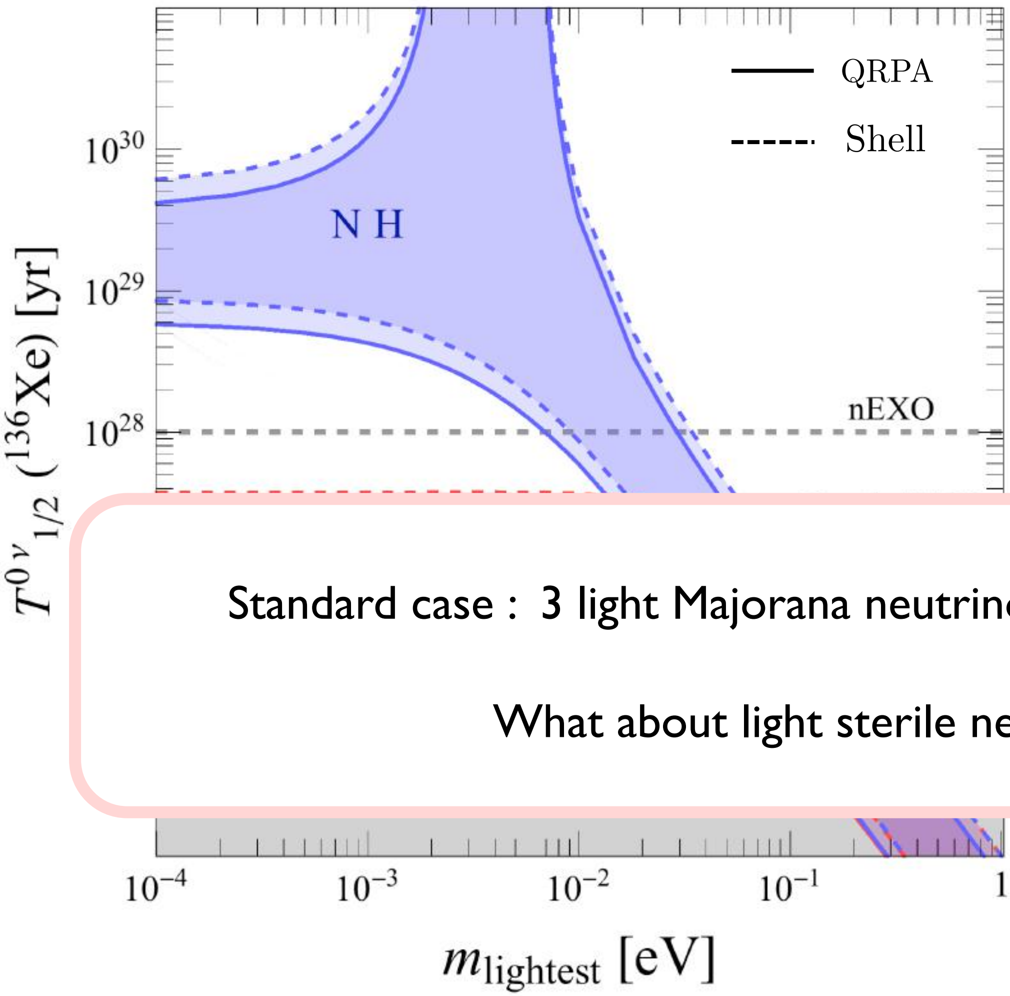
$\sim 10^{27}$ yr @KamLAND2 – Zen

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

*Future

Current limit on half-life

Standard case : 3 light Majorana neutrinos



Normal Hierarchy (NH)

$$m_1 < m_2 < m_3$$

Inverted Hierarchy (IH)

$$m_3 < m_1 < m_2$$

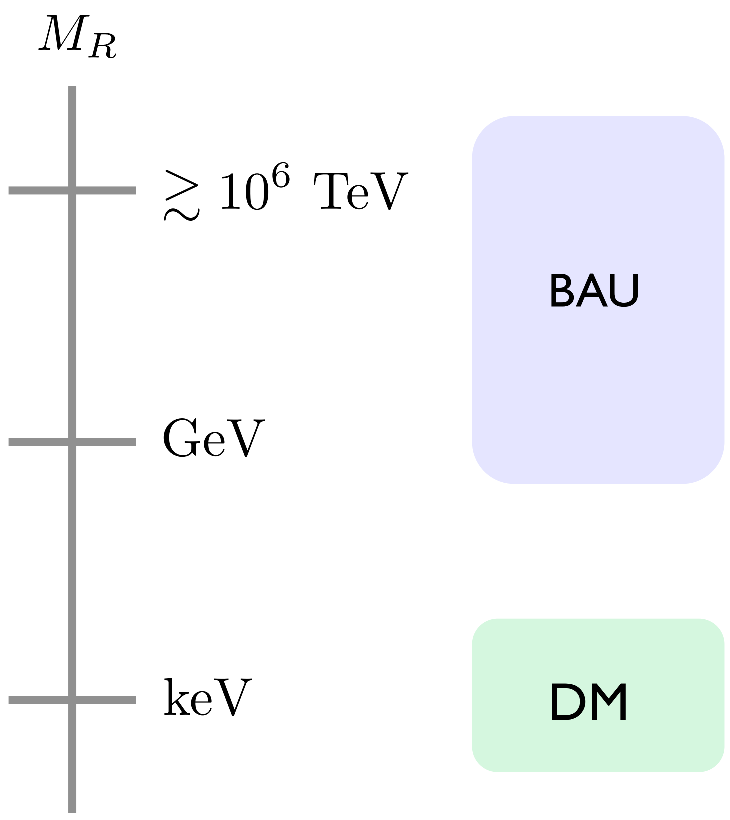
Standard case : 3 light Majorana neutrinos $M_R \gg \mathcal{O}(100)\ \mathrm{GeV}$

What about light sterile neutrino case?

Beyond the standard case

For more details, see M. Drewes, 1303.6912

Other phenomenological aspects:



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 candidate

S. Dodelson, L. M. Widrow, PRL72(1994)17
XD. Shi, G. Fuller, PRL82 (1999) 2832

Wide mass range!

Beyond the standard case

For more details, see M. Drewes, 1303.6912

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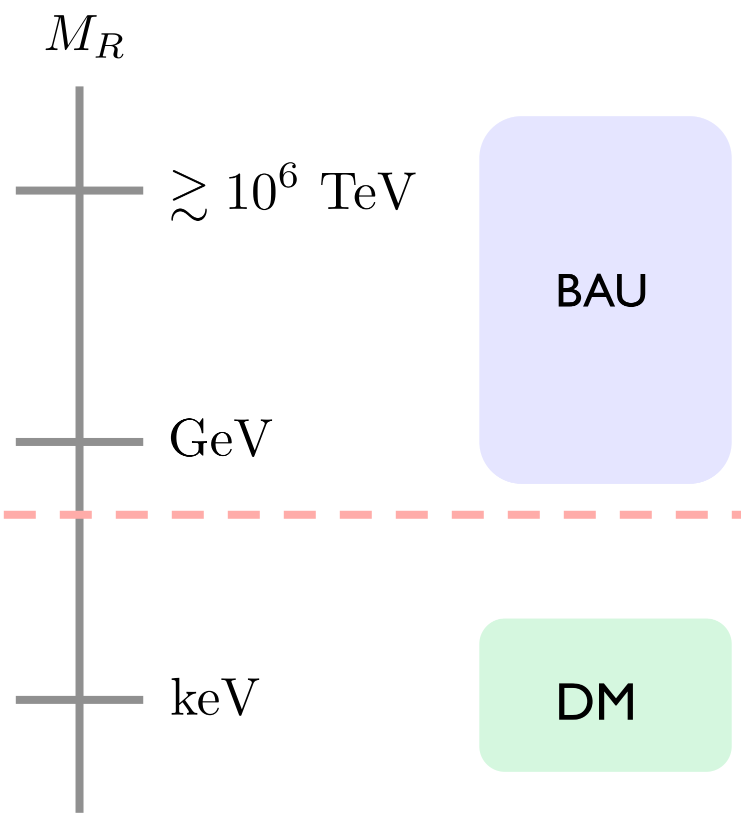

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* Need theoretical analysis of 0N2B in light of light sterile neutrinos

Nu-SMEFT

W. Dekens, J. de Vries, KF, E. Mereghetti, G. Zhou, JHEP06(2020)097
KF, J. Kumar, E. Mereghetti, S. Sandner, C. Sun, 2405.00119

- Systematic Analysis based on Effective Field Theory with ν_R

$$\mathcal{L} = \mathcal{L}_{\rm SM} - Y_\nu L\tilde{H}\nu_R - \frac{1}{2}\overline{\nu_R^c}M_R\nu_R + \frac{1}{\Lambda^{n-4}}C^{(n)}_{\nu_R}\mathcal{O}^{(n)}_{\nu_R}$$

*Higher dimensional operators

Nu-SMEFT

W. Dekens, J. de Vries, KF, E. Mereghetti, G. Zhou, JHEP06(2020)097
KF, J. Kumar, E. Mereghetti, S. Sandner, C. Sun, 2405.00119

Systematic Analysis based on Effective Field Theory with ν_R

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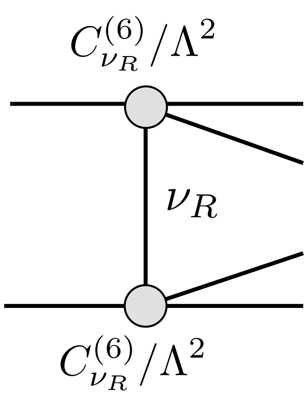
*Higher dimensional operators

✔ Contributions to 0N2B from non-standard (dim 6) interactions

New!

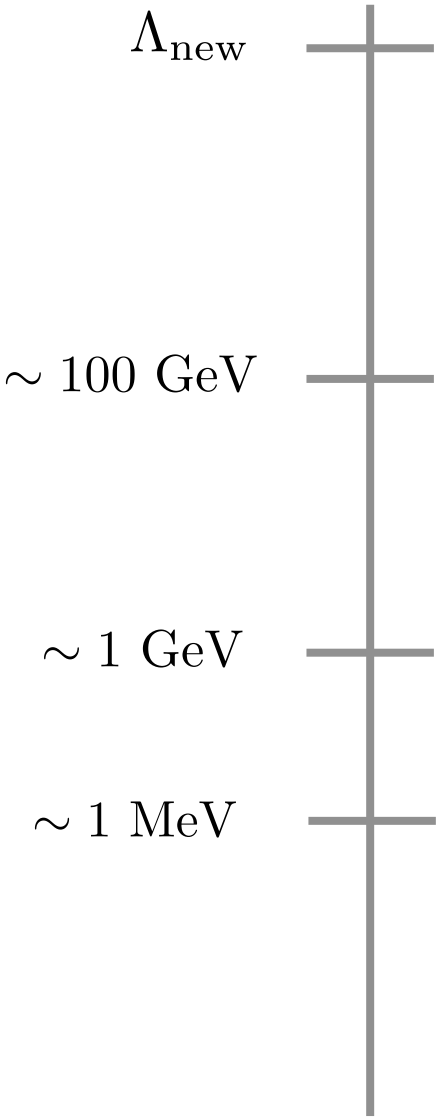


Ex) Dimension 6 operator

$$\frac{1}{\Lambda^2}C^{(6)}_{\nu_R}\ \bar{L}^i d_R \epsilon_{ij}\bar{Q}\nu_R$$

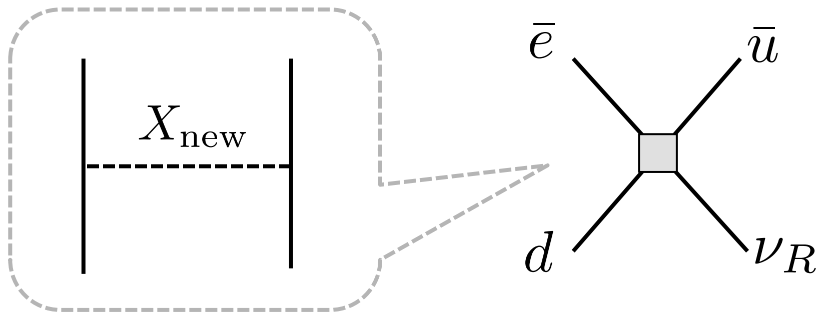
*Work for production of sterile neutrino DM

Nu-SMEFT Approach

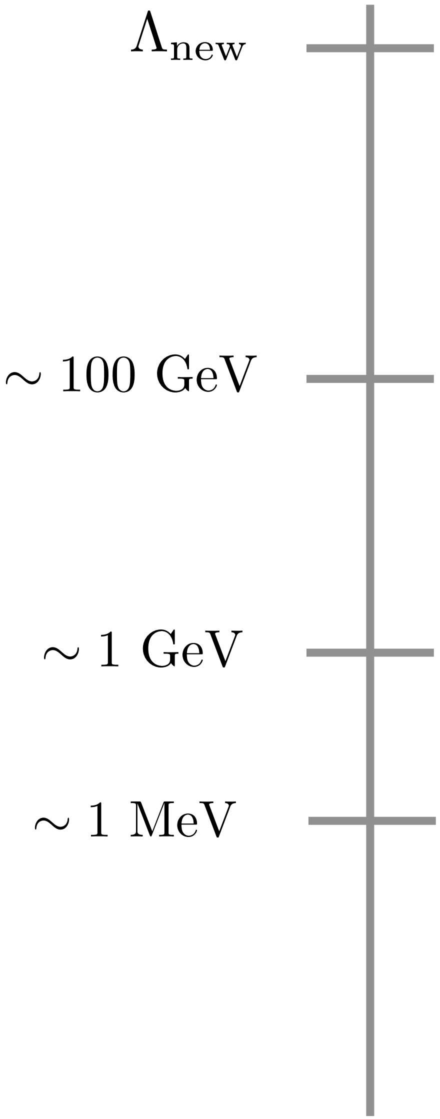


SM + sterile neutrino EFT

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



Nu-SMEFT Approach



SM + sterile neutrino EFT

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

Neutrino mass

Integrate out heavy SM particles

Nu-SMEFT Approach

G. Prezeau, M. Ramsey-Musolf, and P. Vogel, PRD68, 034016 (2003)
V. Cirigliano, W. Dekens, J. de Vries, M.L. Graesser, E. Mereghetti, JHEP12(2017)082, JHEP12(2018)097

Λ_{new}

SM + sterile neutrino EFT

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

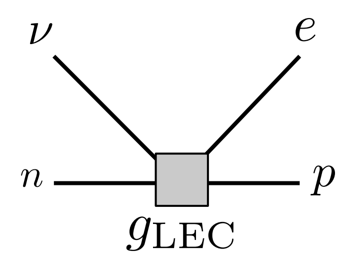
~ 100 GeV

Neutrino mass

Integrate out heavy SM particles

~ 1 GeV

Chiral Perturbation Theory



~ 1 MeV

" Inverse half-life "

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

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

Standard case vs Non-standard case

(dim 4) (dim 6)

3+1 Standard Scenario

*No dim 6 interaction

One Sterile Neutrino : m_4

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

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 Standard Scenario

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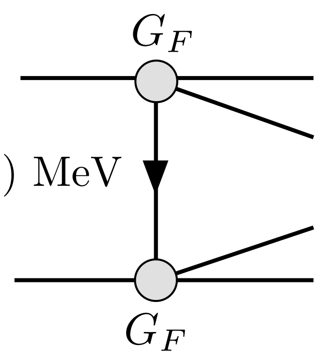
Yukawa

Majorana

$q \sim O(100)$ MeV



$$\propto \frac{m_i}{\mathrm{q}^2 + m_i^2} U_{ei}^2$$

3+1 Standard Scenario

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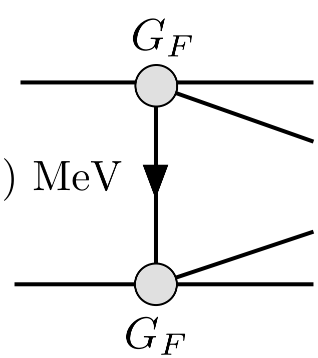
Yukawa

Majorana



$q \sim O(100)$ MeV

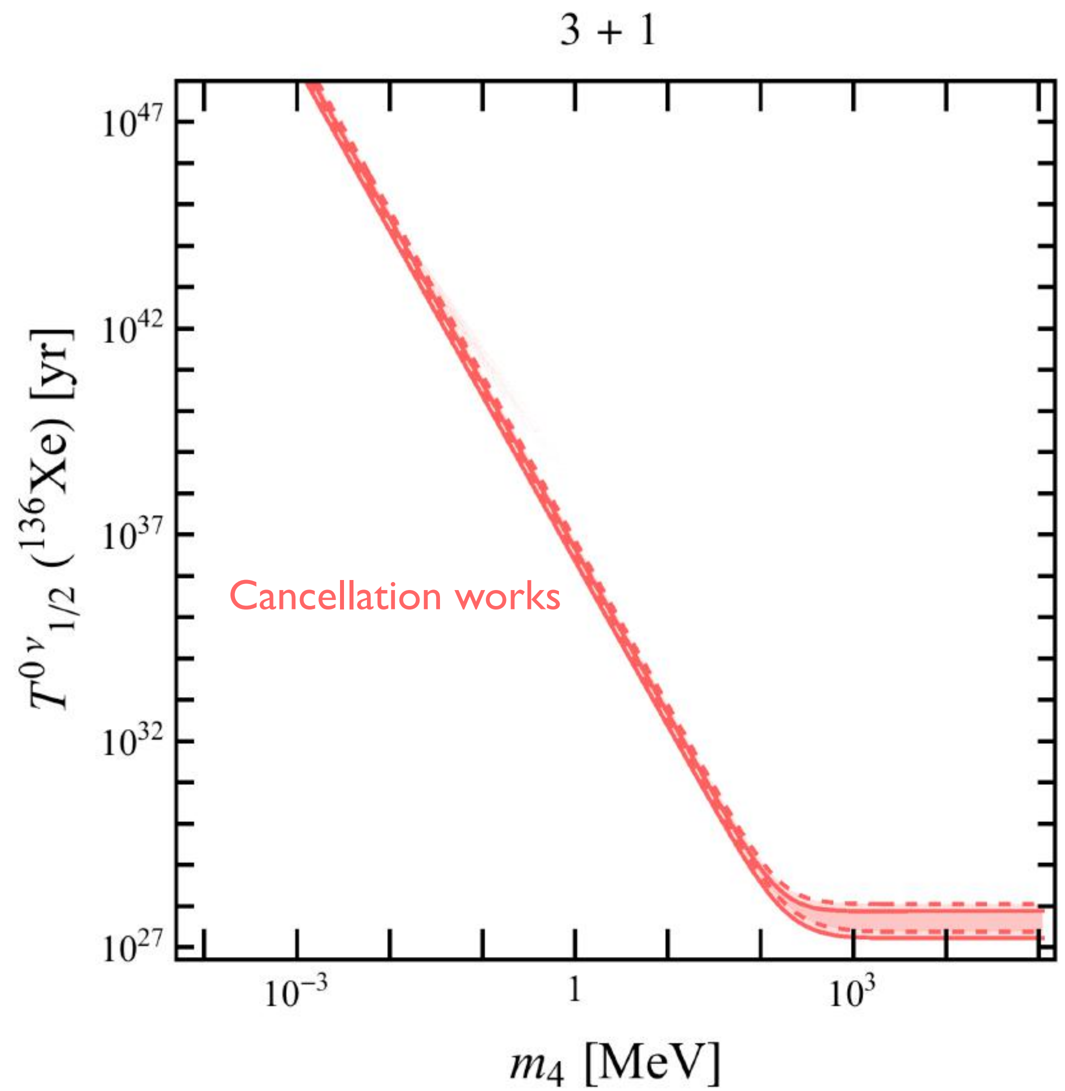
$q^2 \gg m_{1,2,3}^2$ and m_4^2

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

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

LO vanishes!

3+1 Standard Scenario

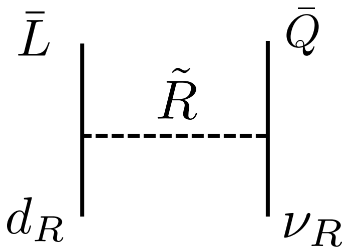


Standard case : The half-life is well above experimental reach.

3+1 Non-Standard Scenario

One sterile neutrino with dim 6 interaction

$$\mathcal{L} = -Y_\nu \bar{L}\tilde{H}\nu_R - \frac{1}{2}\overline{\nu_R^c}M_R\nu_R + \frac{1}{\Lambda^2}\bar{L}^i d_R \epsilon_{ij} \bar{Q}^j \nu_R$$



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

$\Lambda = m_{\rm LQ} = 10$ TeV

3+1 Non-Standard Scenario

One sterile neutrino with dim 6 interaction

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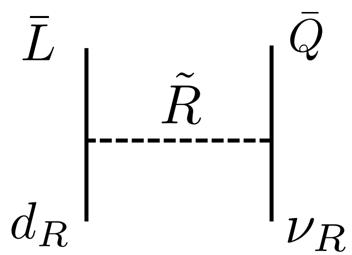
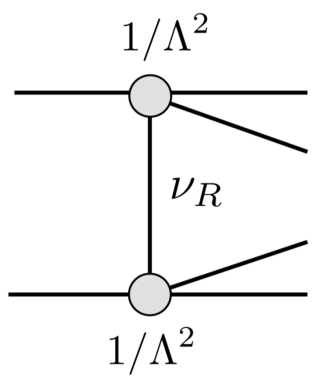
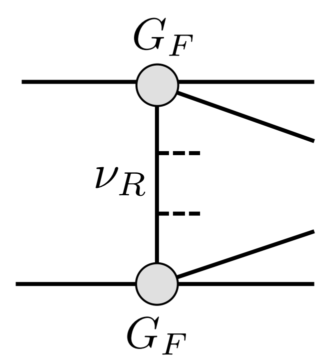


Leptoquark : $\tilde{R}(\mathbf{3}, \mathbf{2}, 1/6)$

$\Lambda = m_{\mathrm{LQ}} = 10 \ \mathrm{TeV}$

Non-standard

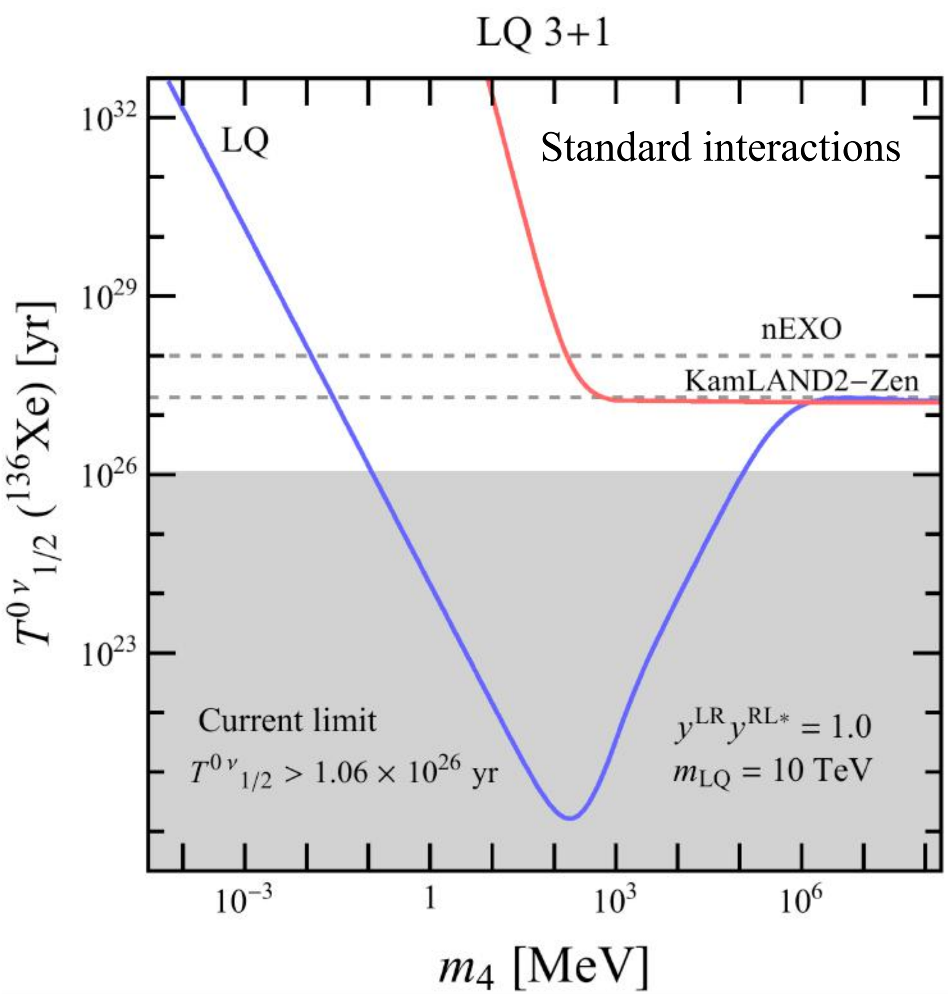




Standard

3+1 Non-Standard Scenario

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



Blue : Non-standard

Pink : Standard contribution

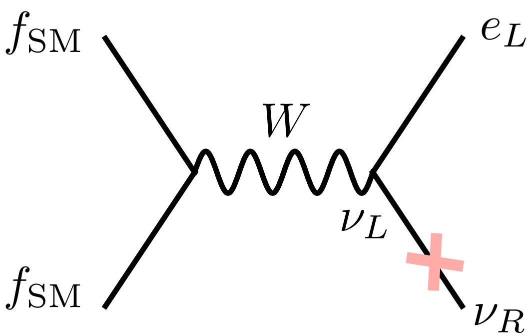
* Non-standard contributions dominate over standard contributions.

Application to DM phenomenology

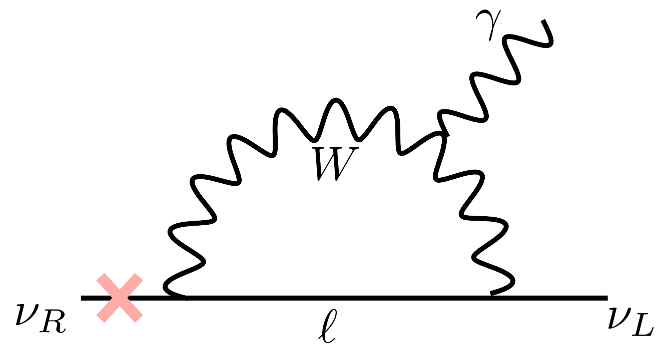
Sterile Neutrino DM

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

Minimal Scenario : Sterile Neutrino DM if M_R ~ O(keV)



$$\Omega_{\rm DM} \propto \theta^2$$



$$\Gamma(\nu_R \to \nu_L \gamma) \propto \theta^2$$

Photon Dipole Operator: $\mathcal{O}_{\nu F} = \bar{\nu}_L \sigma^{\mu\nu} \nu_R F_{\mu\nu}$

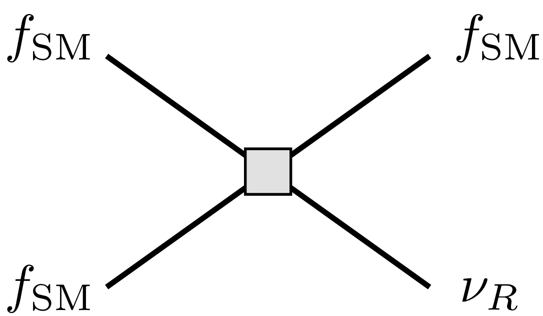
Excluded by non-observation of X-ray from the radiative decay

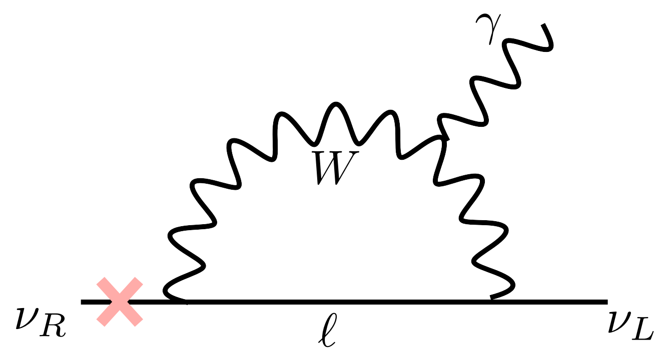
NuSTAR: PRD99(2019)083005, PRD107(2023)023009

Sterile Neutrino DM

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

Minimal Scenario : Sterile Neutrino DM if M_R ~ O(keV)





$$\mathcal{L}_{\nu\rm SMEFT} \supset \frac{1}{\Lambda^2} C_{\nu_R} \mathcal{O}_{\nu_R}$$

$$\Gamma(\nu_R \to \nu_L \gamma) \propto \theta^2$$

✔ New production mechanism via dimension 6 operators

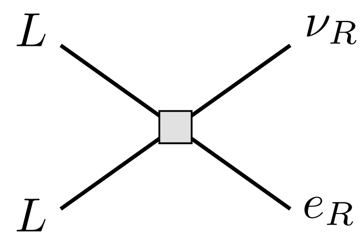
KF, J. Kumar, E. Mereghetti, S. Sandner, C. Sun, 2405.00119

Sterile Neutrino DM

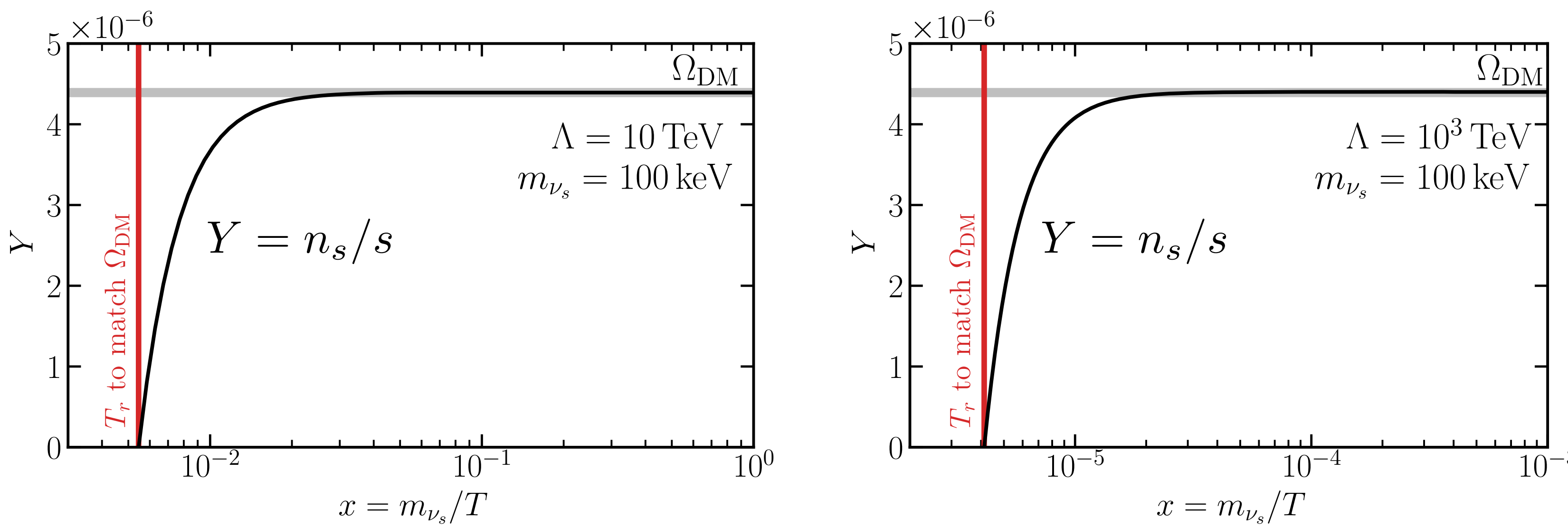
KF, J. Kumar, E. Mereghetti, S. Sandner, C. Sun
2405.00119

Ex) $\mathcal{O}_{L\nu Le} = (\bar{L}^i \nu_R)\epsilon_{ij}(\bar{L}^j e_R)$

*No Mixing



$\sim \frac{C^*_{L\nu Le}}{\Lambda^2}$



DM production dominantly occurs around reheating temperature T_r

Nu-SMEFT operators

KF, J. Kumar, E. Mereghetti, S. Sandner, C. Sun
2405.00119

(1) No dipole generated

(2) Photon dipole operator via the RGEs

Nu-SMEFT operators

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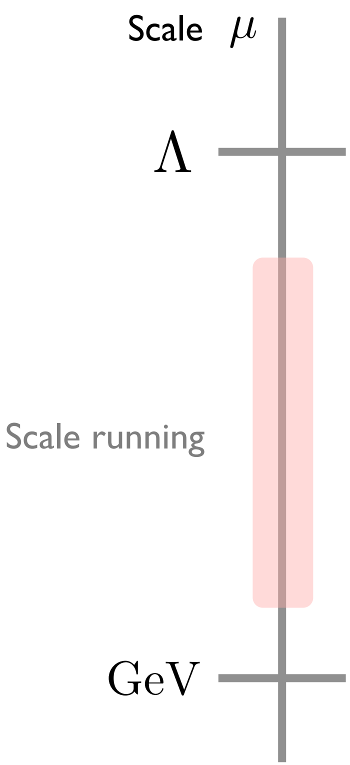
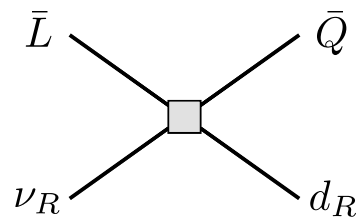
2405.00119

(1) No dipole generated

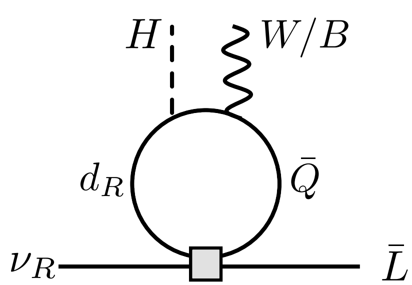
(2) Photon dipole operator via the RGEs





$$\mathcal{O}^{(3)}_{L\nu Qd} = (\bar{L}^i \sigma^{\mu\nu} \nu_R)\epsilon_{ij}(\bar{Q}^j \sigma_{\mu\nu} d_R)$$

Ex) Operator Mixing $\dfrac{dC_{\nu W}}{d\ln\mu} = \dfrac{2g_2}{(4\pi)^2} C^{(3)}_{L\nu Qd} Y_d$



$$\mathcal{O}_{\nu W} = (\bar{L}\sigma^{\mu\nu}\nu_R)\tau^I \tilde{H} W^I_{\mu\nu}$$

$$C_{\nu F} \propto \left(\frac{v}{\Lambda}\right)^2 (C_{\nu W} + C_{\nu B})$$

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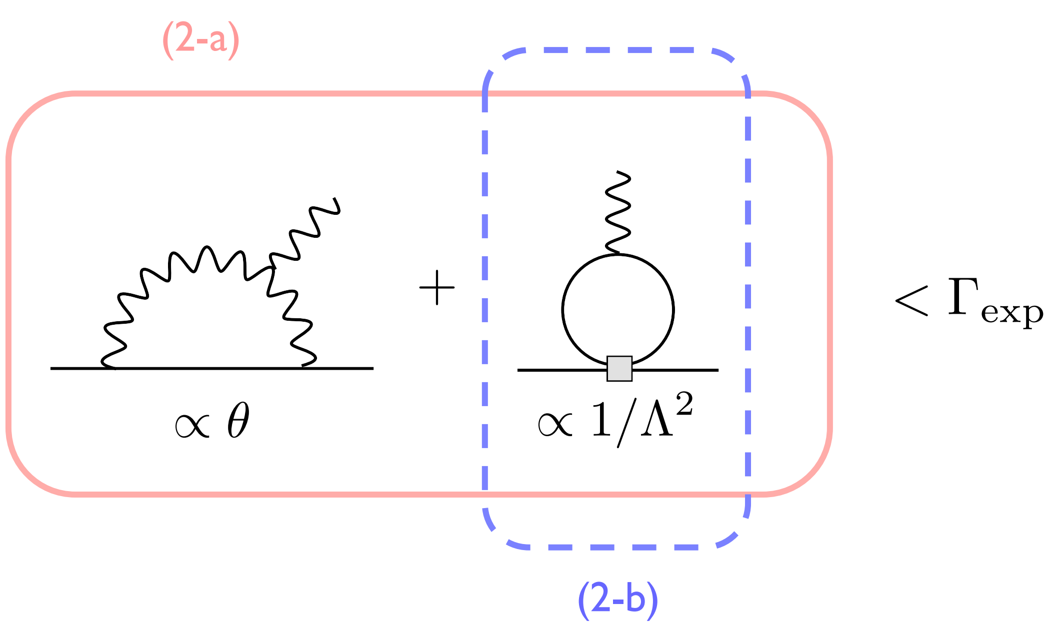
(1) No dipole generated : No X-ray contributions

(2) Photon dipole operator via the RGEs

(2-a) Nonzero active-sterile mixing (destructive contribution from dim 6)

(2-b) Zero mixing (only dim 6)



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Scale Λ and T_r for successful DM abundance

Case	Λ	T_r
(1) No dipole	$\gg \mathcal{O}(100)$ GeV	$\gg 5$ MeV
(2) Nonzero dipole		
$(2-a)$ nonzero mixing	$\mathcal{O}(10^2 - 10^3)$ TeV	$\mathcal{O}(10 - 100)$ GeV
$(2-b)$ zero mixing	$\gtrsim \mathcal{O}(10^3 - 10^4)$ TeV	$\gtrsim \mathcal{O}(10^2 - 10^3)$ GeV

$(m_{\nu_s} = 100 \text{ keV})$

Predict low-scale reheating temperature while high BSM scale

Nonzero mixing case : 0N2B

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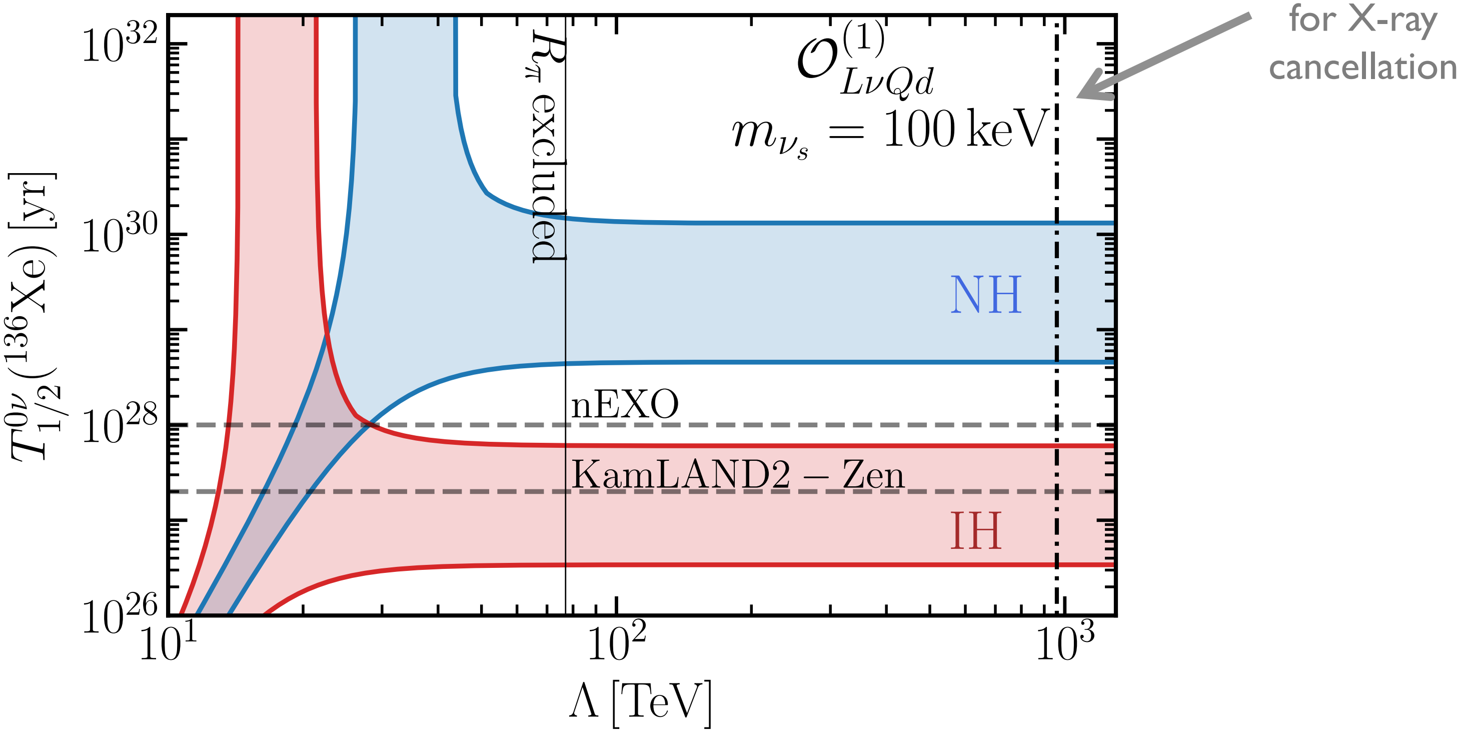
Ex) $\mathcal{O}^{(1)}_{L\nu Qd} = (\bar{L}^i \nu_R)\epsilon^{ij}(\bar{Q}^j d_R)$



$$R_\pi = \frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} \qquad R_\pi / R_\pi^{\mathrm{SM}} = 0.996 \pm 0.005$$

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Conclusion

Sterile neutrinos are one of the attractive hypothetical particles.

$\nu\mathrm{SMEFT}$: model-independent analysis of physical observables

Today

✔ 0N2B   Non-standard interactions can dominate 0N2B process

✔ Sterile Neutrino DM   Dimension 6 operators work for DM production

Predict low T_r and high BSM scale

Outlook/Discussion

How can we probe sterile neutrino DM scenarios?

Are there any ways to probe the range of reheating temperature?

If future ton-scale DBD experiment observe nonzero signals?

Any comments/thoughts/discussions would be appreciated!