LA-UR-22-20967
Approved for public release; distribution is unlimited.

Title: Searching for new physics in violations of fundamental symmetries

Author(s): Fuyuto, Kaori

Intended for: Job interview at Argonne National Laboratory

Issued: 2022-02-04

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by Triad National Security, LLC for the National Nuclear Security Administration of U.S. Department of Energy under contract 89233218CNA000001. By approving this article, the publisher recognizes that the U.S. Government retains nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

Searching for New Physics in violations of fundamental symmetries

Kaori Fuyuto

Los Alamos National Laboratory

KF, WS. Hou, and E. Senaha, PLB 776 (2018) 402, PRD101(2020)011901
J. de Vries, P. Draper, **KF**, J. Kozaczuk, D. Sutherland, PRD015042(2019)99
J. de Vries, P. Draper, **KF**, B. Lillard, PRD104(2021)055039
W. Dekens, J. de Vries, **KF**, E. Mereghetti, G. Zhou, JHEP06(2020)097
V. Cirigliano, **KF**, C. Lee, E. Mereghetti, B. Yan, JHEP03(2021)256

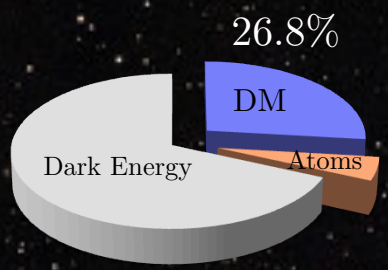
February 15, 2022
LA-UR-22-

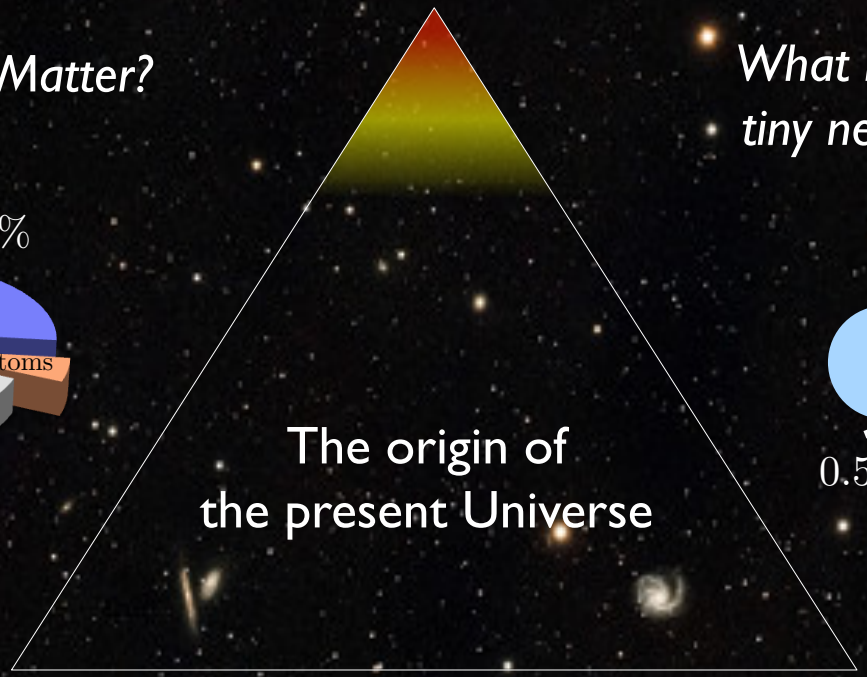
The Standard Model of Particle Physics is currently the best theory to describe the most basic building blocks of the Universe.

However, it does not explain the complete picture.

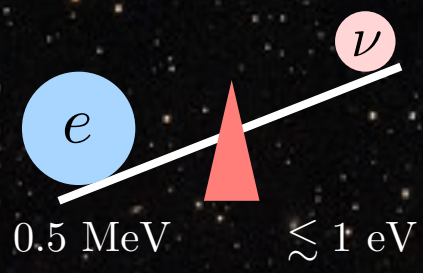
For example, the following questions are not answered by the SM

What is Dark Matter?





What is the origin of tiny neutrino mass ?

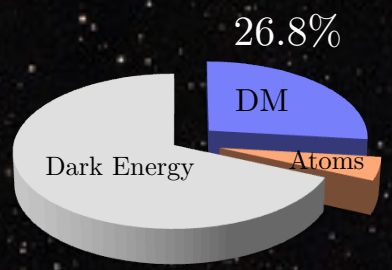


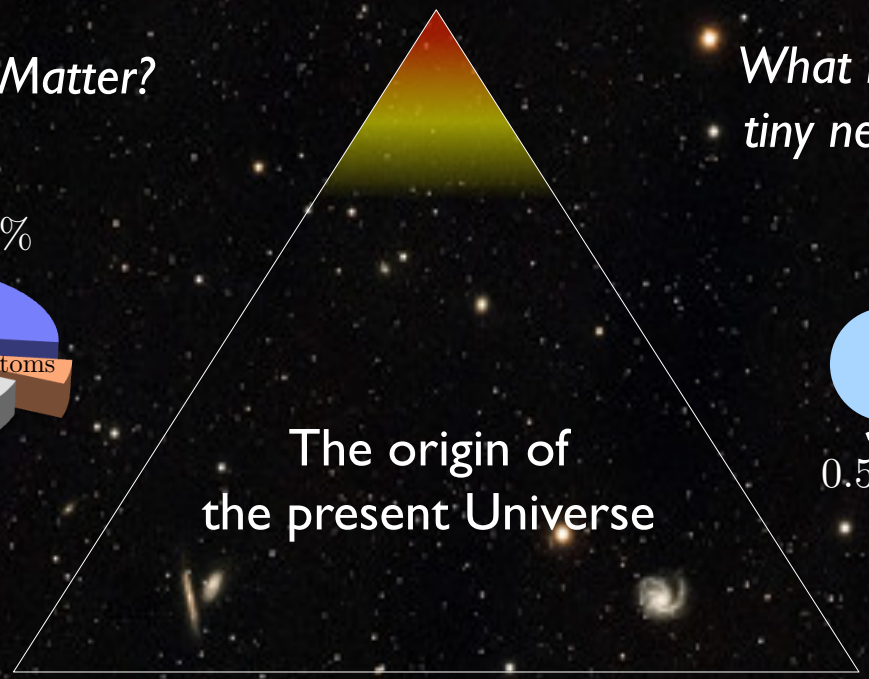
Why is there more matter than antimatter? $\frac{n_b - n_{\bar{b}}}{n_\gamma} = 6.1 \times 10^{-10}$

*We need physics beyond the Standard Model.
(BSM Physics)

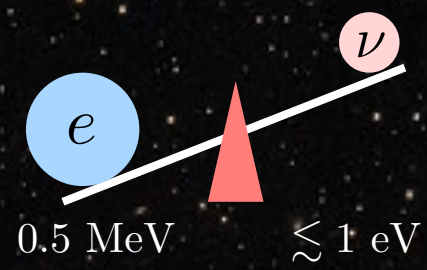
Key approach : Fundamental symmetry tests

What is Dark Matter?





What is the origin of tiny neutrino mass ?

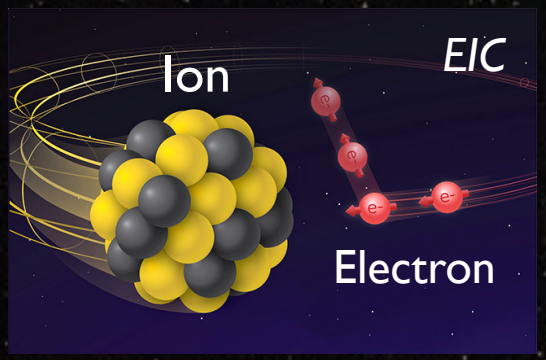


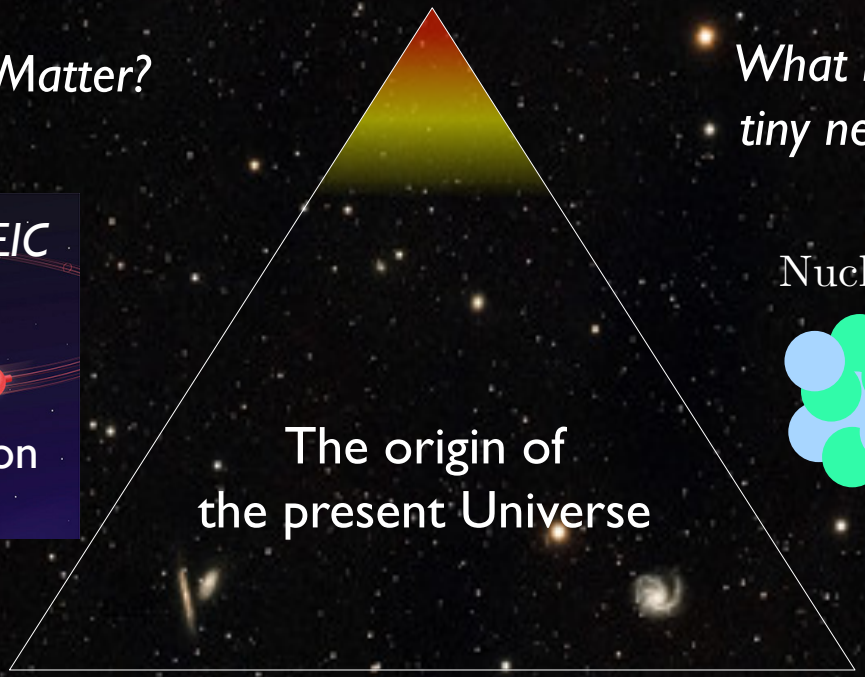
Why is there more matter than antimatter? $\frac{n_b - n_{\bar{b}}}{n_\gamma} = 6.1 \times 10^{-10}$

Ex) Search for CP violation, Lepton Flavor and Lepton-Number Violation

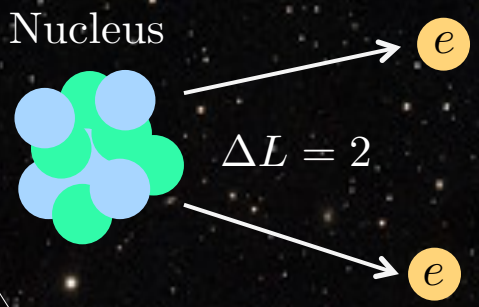
Key approach : Fundamental symmetry tests

What is Dark Matter?

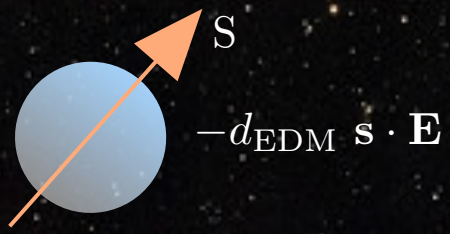




What is the origin of tiny neutrino mass ?



Why is there more matter than antimatter?



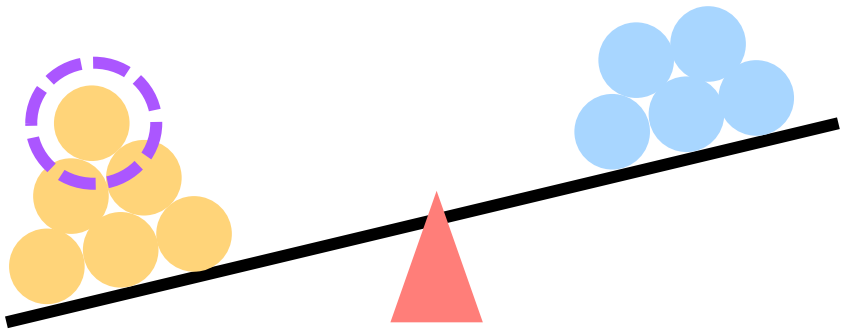
Ex) Search for CP violation, Lepton Flavor and Lepton-Number Violation

CP violation

Matter-antimatter asymmetry

A tiny imbalance of particle and antiparticle is needed to create the current Universe.

Particle : $10^{10} + 1$ Antiparticle : 10^{10}



$$\frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.105 \pm 0.055) \times 10^{-10}$$

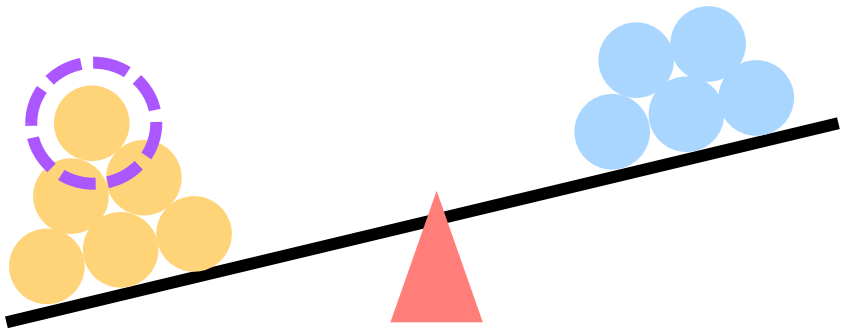
PDG: PTEP(2020)083C01

Matter-antimatter asymmetry

A tiny imbalance of particle and antiparticle is needed to create the current Universe.

Particle : $10^{10} + 1$

Antiparticle : 10^{10}



CP violation is necessary to create the imbalance.

Electric Dipole Moments

One CPV quantity is Electric Dipole Moment:

$$H_{\mathrm{EDM}} = -d\frac{\mathbf{s}}{|\mathbf{s}|}\cdot\mathbf{E}$$

$\mathbf{E}$: Electric field $\quad$ $\mathbf{s}$: Spin

$\mathrm{s} \underset{\mathrm{T}}{\rightarrow} (-\mathrm{s})$: Violation of Time-reversal symmetry

CP violation under CPT theorem

Electric Dipole Moments

One CPV quantity is Electric Dipole Moment:

$$H_{\mathrm{EDM}} = -d\frac{\mathbf{s}}{|\mathbf{s}|}\cdot\mathbf{E}$$

$\mathbf{E}$: Electric field $\quad \mathbf{s}$: Spin

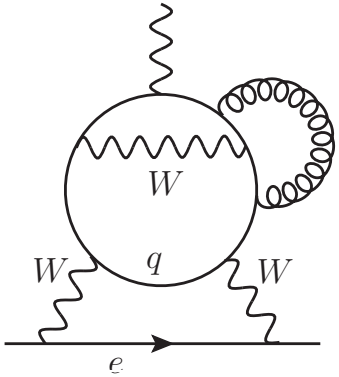
$\mathrm{s} \underset{\mathrm{T}}{\rightarrow} (-\mathrm{s})$: Violation of Time-reversal symmetry

CP violation under CPT theorem

Ex) Electron EDM in the SM

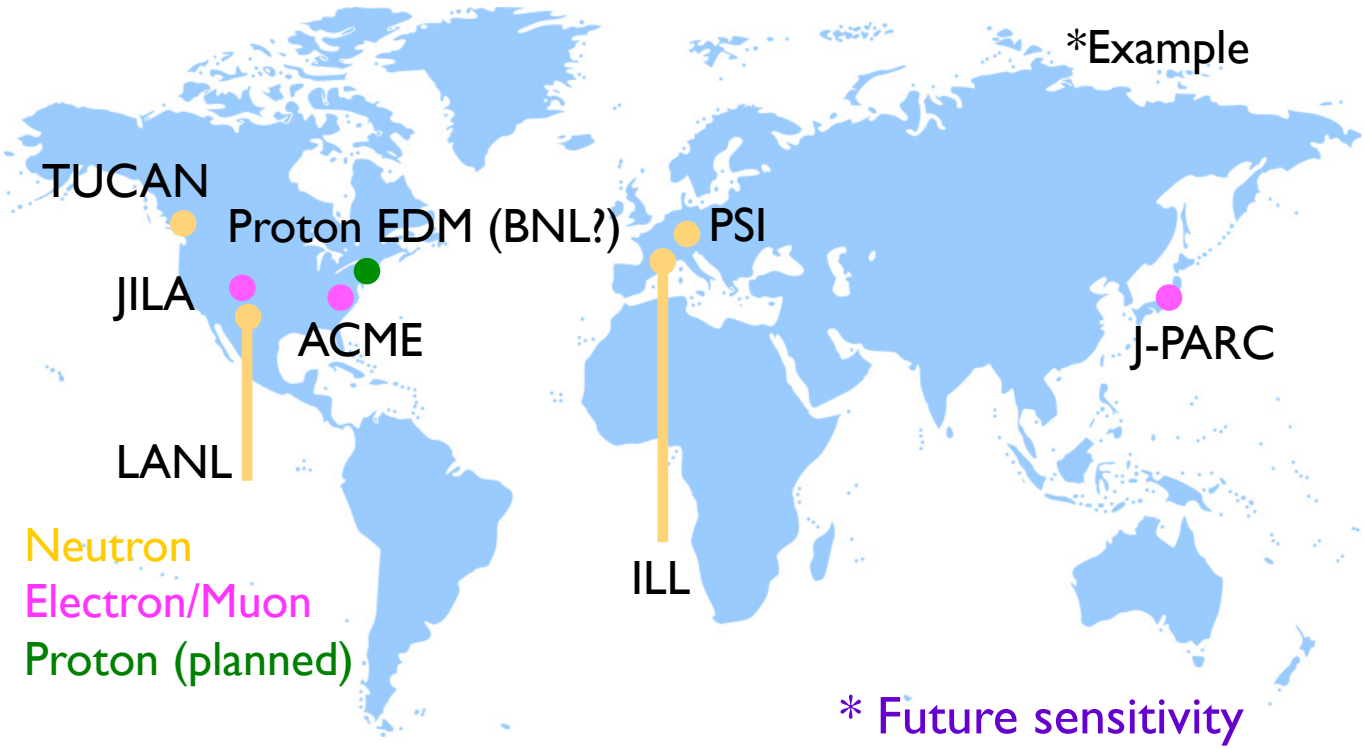
$$d_e^{\mathrm{CKM}} \sim O(10^{-44})\ e\ \mathrm{cm}$$

M. Pospelov, I.B. Khriplovich, SJNP53(1991)638, Yad. Fiz. 53(1991)1030
D. Ng, J. Ng, Mod. MPLA11(1996)211, W. Bernreuther, M. Suzuki, RMP63(1991)313
M. Pospelov and A. Ritz, PRD89(2014)056006



Various searches for EDMs

Various searches for EDMs are ongoing and planned.



* Future sensitivity

$$|d_e| < 1.1 \times 10^{-29}\ e\ \mathrm{cm}$$

ACME Collaboration : Nature 562(2018)7727

$$\sim 10^{-30}\ e\ \mathrm{cm}$$

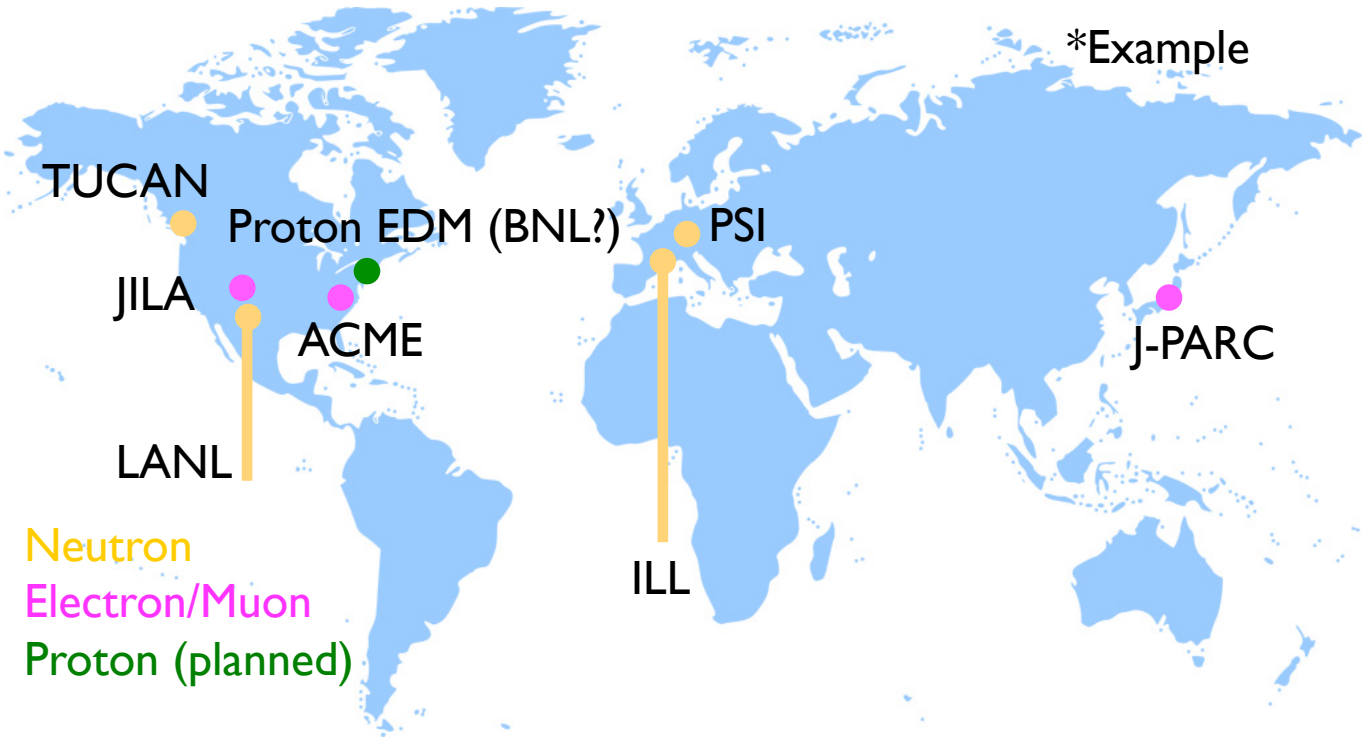
$$|d_n| < 1.8 \times 10^{-26}\ e\ \mathrm{cm}$$

nEDM Collaboration, PRL124(2020)081803

$$\sim 10^{-(27-28)}\ e\ \mathrm{cm}$$

Various searches for EDMs

Various searches for EDMs are ongoing and planned.



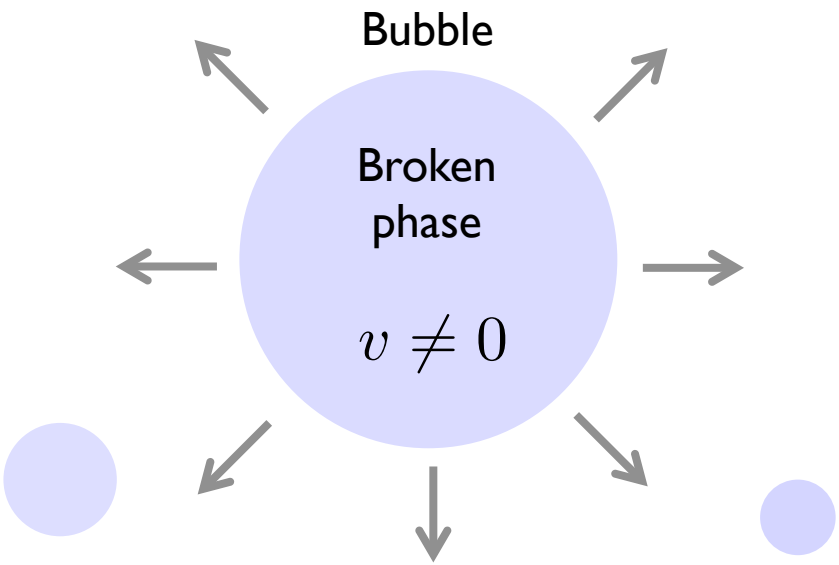
How do EDM searches play a role in solving the mystery of the BAU?

*One possible mechanism : Electroweak Baryogenesis

KF, WS. Hou, and E. Senaha, PLB 776 (2018) 402, PRD101(2020)011901

Electroweak Baryogenesis

Baryon asymmetry is created during EW phase transition.



Symmetric phase

$$v = 0$$

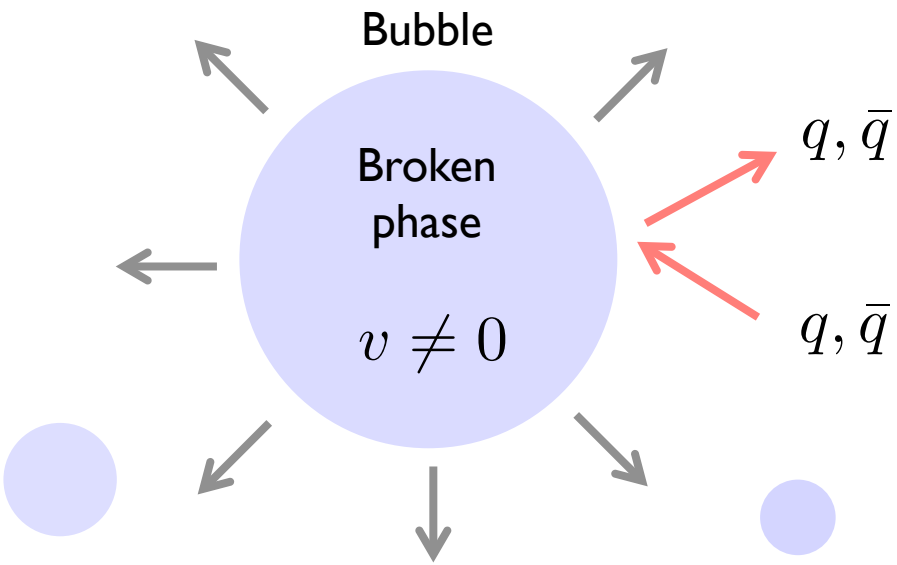
Boiling water

If EW phase transition is 1st order, bubbles can be nucleated.

✔ Higgs Physics

Electroweak Baryogenesis

Baryon asymmetry is created during EW phase transition.



$$n_b^{L(R)} - n_{\bar{b}}^{L(R)} \neq 0$$

✔ EDM searches

Particle and antiparticle numbers can be different if CPV exists.

One example : General Two Higgs Doublet Model

Two Higgs Doublet Model

KF, WS. Hou, and E. Senaha, PLB 776 (2018) 402

Two doublets H_1 and H_2

Yukawa interactions :

$$-\mathcal{L}_Y = \bar{q}_L \left(Y_1 \tilde{H}_1 + Y_2 \tilde{H}_2 \right) u_R + \text{h.c.}$$

$Y_1,\ Y_2$: Complex numbers

$$H_{1,2} = \begin{pmatrix} \phi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + i a_i) \end{pmatrix}$$

* 2HDM can cause the first-order EWPT.

KF, E. Senaha, PLB(2015)152,
KF, E. Senaha, CW. Chiang, PLB762(2016)315

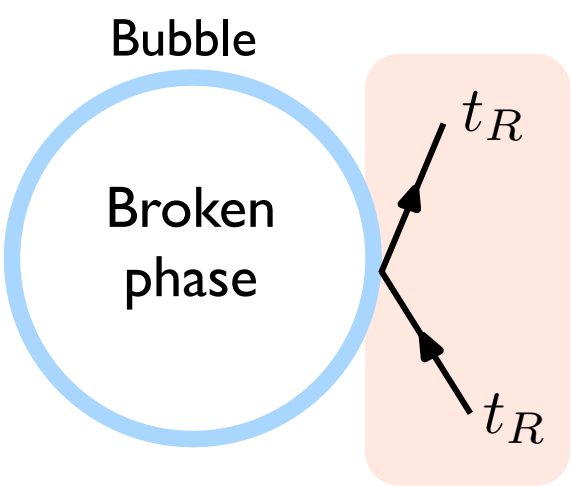
Two Higgs Doublet Model

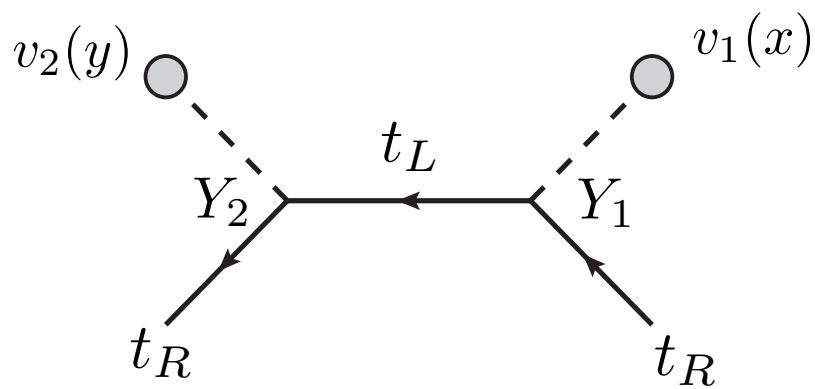
KF, WS. Hou, and E. Senaha, PLB 776 (2018) 402

Two doublets H_1 and H_2

Yukawa interactions :

$$-\mathcal{L}_Y = \bar{q}_L \left(Y_1 \, v_1 \; + Y_2 \, v_2 \right) u_R + \text{h.c.}$$





* Focus on top quark

Two Higgs Doublet Model

KF, WS. Hou, and E. Senaha, PLB 776 (2018) 402

Two doublets H_1 and H_2

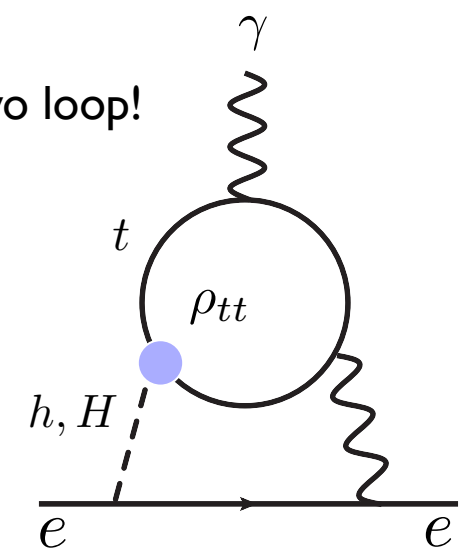
Yukawa interactions :

CPV : $|\rho_{tt}|e^{i\phi_{tt}}$

$$-\mathcal{L}_Y = \bar{t}_L \left[\frac{y_t}{\sqrt{2}} s_\alpha + \frac{1}{\sqrt{2}} \rho_{tt} c_\alpha \right] t_R h + \text{h.c.}$$

Yukawa : m_t/v

Two loop!



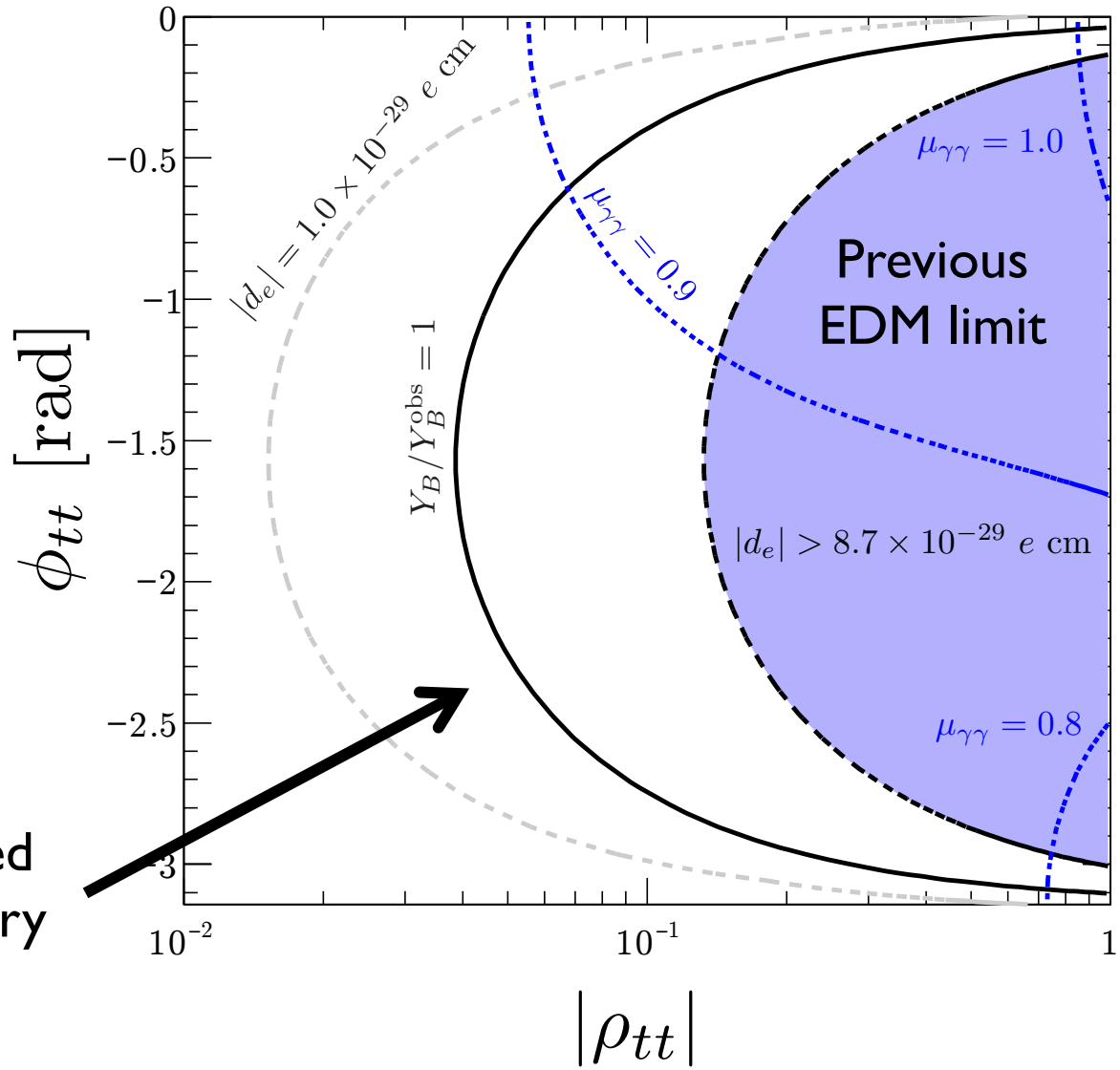
BAU : $n_B \propto y_t |\rho_{tt}| \sin\phi_{tt}$

EDM : $d_e \propto |\rho_{tt}| \sin\phi_{tt}$

Probed by EDM experiments !

Two Higgs Doublet Model

KF, WS. Hou, and E. Senaha, PLB 776 (2018) 402

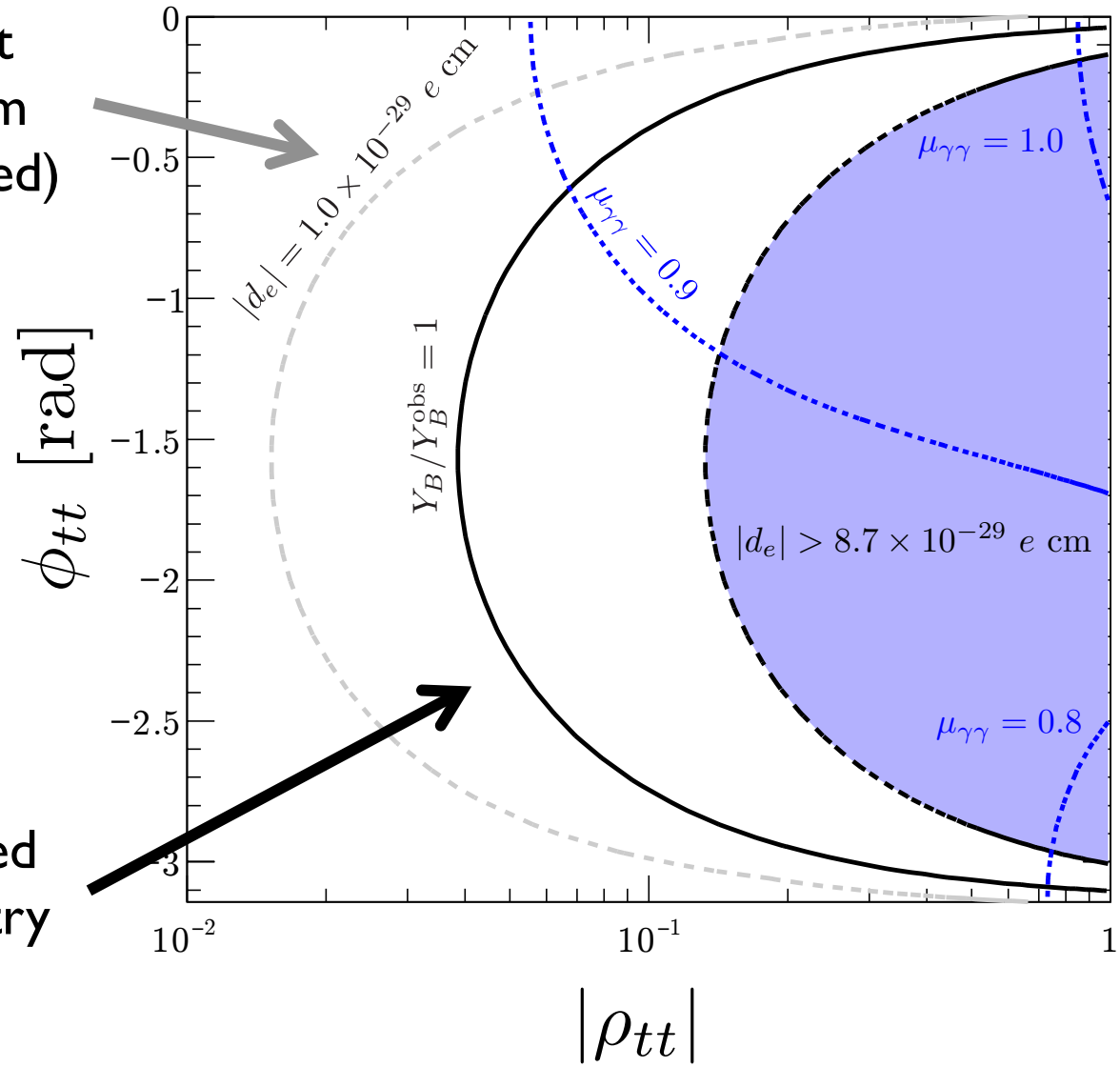


Observed asymmetry (Black)

Two Higgs Doublet Model

KF, WS. Hou, and E. Senaha, PLB 776 (2018) 402

New limit
~10^{-29} e cm
(Gray dashed)

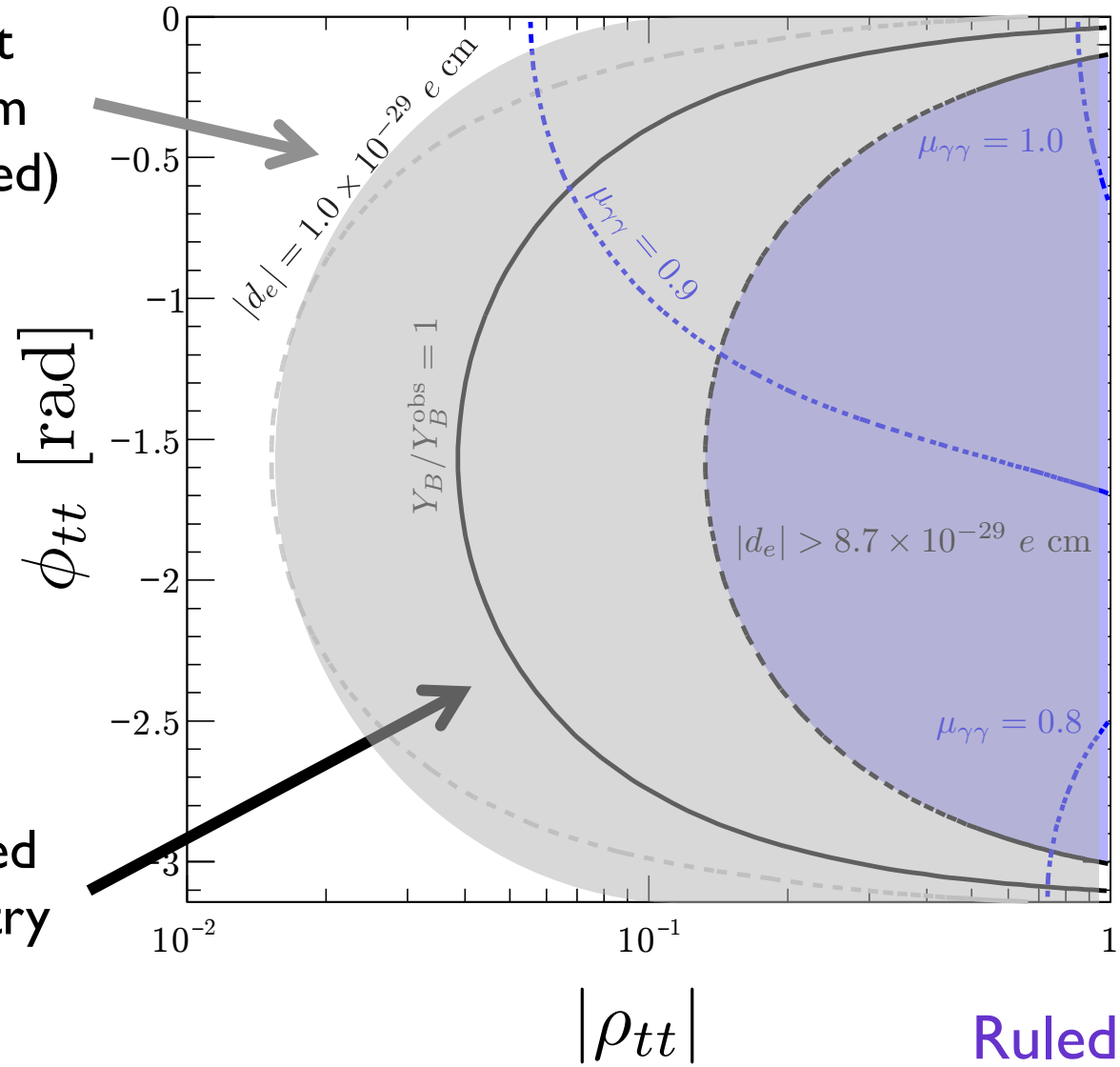


Observed
asymmetry
(Black)

Two Higgs Doublet Model

KF, WS. Hou, and E. Senaha, PLB 776 (2018) 402

New limit
~10^{-29} e cm
(Gray dashed)



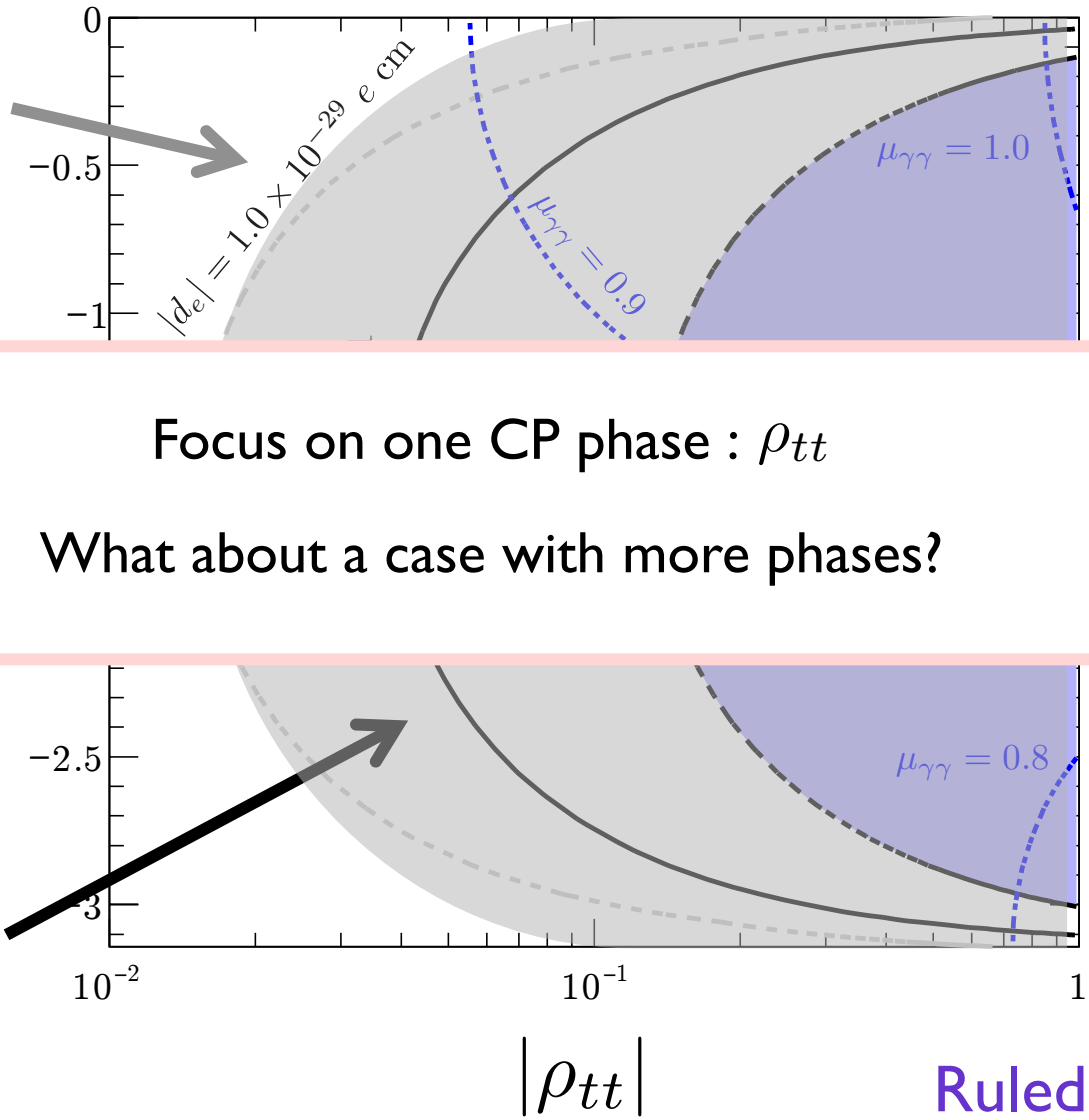
Observed
asymmetry
(Black)

Ruled out!

Two Higgs Doublet Model

KF, WS. Hou, and E. Senaha, PLB 776 (2018) 402

New limit
~10^{-29} e cm
(Gray dashed)



Focus on one CP phase : ρ_{tt}

What about a case with more phases?

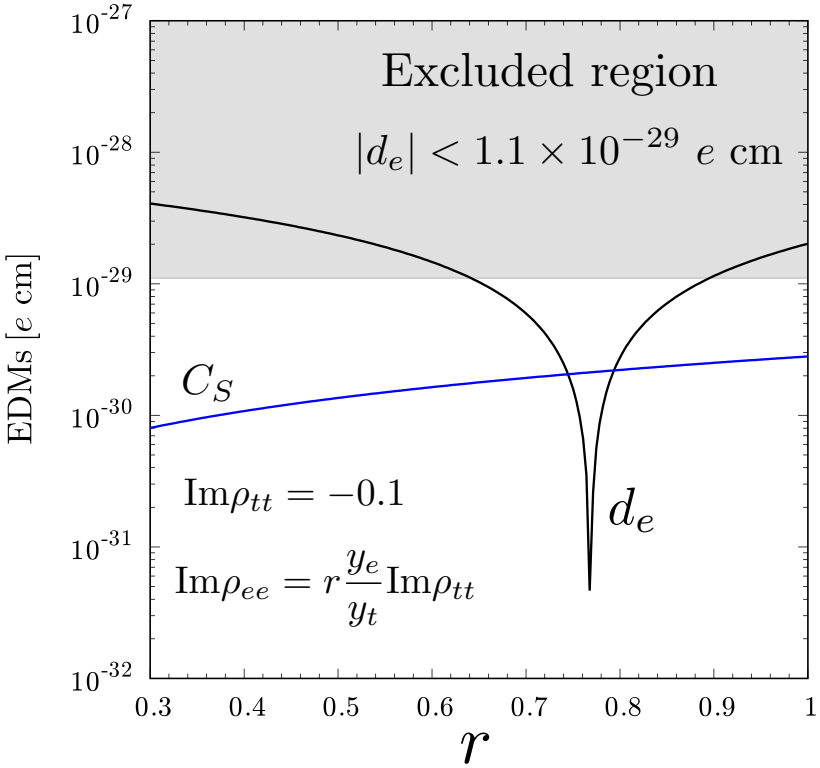
Observed
asymmetry
(Black)

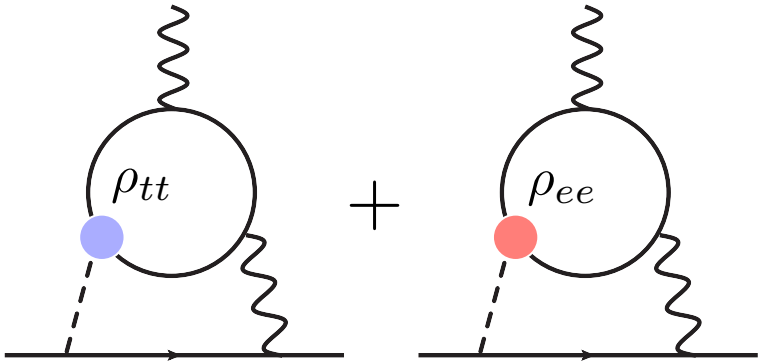
Ruled out!

Two Higgs Doublet Model

KF, WS. Hou, and E. Senaha, PRD101(2020)011901

Case with two phases : $\rho_{tt}, \ \rho_{ee}$





Cancellation occurs.

2HDM EWBG is still viable.

Multi-species EDM searches, e.g. nucleon EDMs, are necessary!

Implication for DM candidate

Axion is one attractive *DM candidate*.

Strong CP problem : $\theta \lesssim 10^{-10}$ | $\mathcal{L} = \theta \frac{\alpha_s}{8\pi} G_{\mu\nu} \tilde{G}^{\mu\nu}$

Peccei-Quinn Symmetry to absorb θ into axion field : $\theta \to a/f_a$

R. Peccei and H. R. Quinn, Phys.Rev.Lett. 38 (1977) 1440
R. Peccei and H. R. Quinn, Phys.Rev. D16 (1977) 1791{1797.
S.Weinberg, PRL40(1978)223,
F. Wilczek, PRL40(1978)279

Implication for DM candidate

Axion is one attractive *DM candidate*.

Strong CP problem : $\theta \lesssim 10^{-10}$ | $\mathcal{L} = \theta \frac{\alpha_s}{8\pi} G_{\mu\nu} \tilde{G}^{\mu\nu}$

Peccei-Quinn Symmetry to absorb θ into axion field : $\theta \to a/f_a$

R. Peccei and H. R. Quinn, Phys.Rev.Lett. 38 (1977) 1440
R. Peccei and H. R. Quinn, Phys.Rev. D16 (1977) 1791{1797.
S.Weinberg, PRL40(1978)223,
F. Wilczek, PRL40(1978)279

Another (UV) solution : P or CP symmetry to set $\theta = 0$ at UV

A.E. Nelson, PLB136 (1984) 387,
S. M. Barr, PRD30(1984)1805, PRD30(1984)1805
L. Bento, et al, PLB267(1991)95
M. Beg, et al, PRL41(1978)278, R. N. Mohapatra, et al, PLB79(1978)283
H. Georgei, Hadronic J. 1, 155 (1978), K. S. Babu and R. N. Mohapatra, PRD41(1990)1286
SM. Barr, et al, PRL67(1990)2765

Can we probe UV solution?

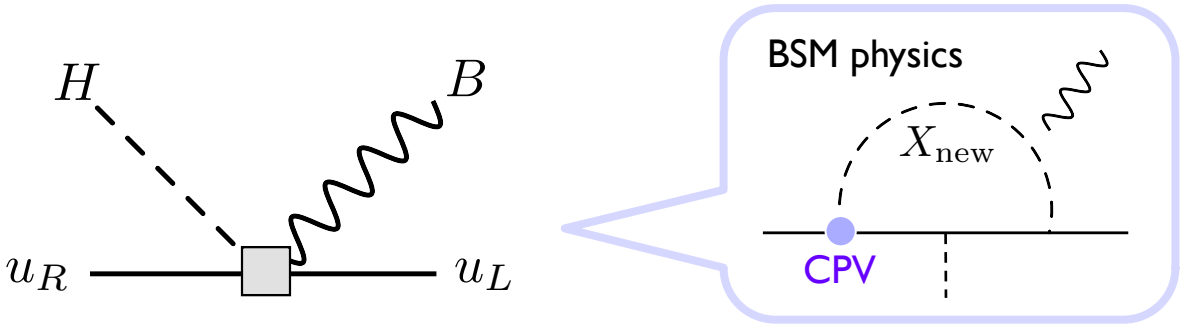
Implication for DM candidate

J. de Vries, P. Draper, **KF**, J. Kozaczuk, D. Sutherland, PRD015042(2019)99

UV solutions can be probed by looking for new CP sources.

Ex) d = 6 up-quark dipole operator

$$\mathcal{O}_{uB} = \bar{Q}\sigma^{\mu\nu} u_R \tilde{H} B_{\mu\nu}$$



Up-quark EDM: $d_u \sim \frac{v}{m_X^2} \mathrm{Im}(C_{uB})$

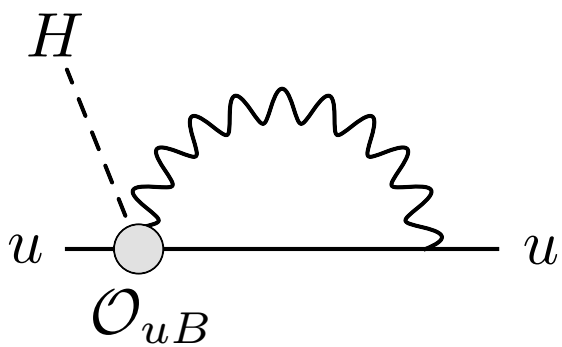
Implication for DM candidate

J. de Vries, P. Draper, **KF**, J. Kozaczuk, D. Sutherland, PRD015042(2019)99

UV solutions can be probed by looking for new CP sources.

Ex) d = 6 up-quark dipole operator

$$\mathcal{O}_{uB} = \bar{Q}\sigma^{\mu\nu}u_R\tilde{H}B_{\mu\nu}$$



$$\Delta\theta \sim \frac{1}{16\pi^2\Lambda^2}\mathrm{Im}(C_{uB})\Lambda^2 \gg 10^{-10}$$

Quadratic divergence

If any new CPV interactions are present,
UV solutions would not work.

*Threshold corrections to theta from dim=6 operators + search for top cEDM at pp collider
J. de Vries, P. Draper, **KF**, J. Kozaczuk, D. Sutherland, PRD015042(2019)99

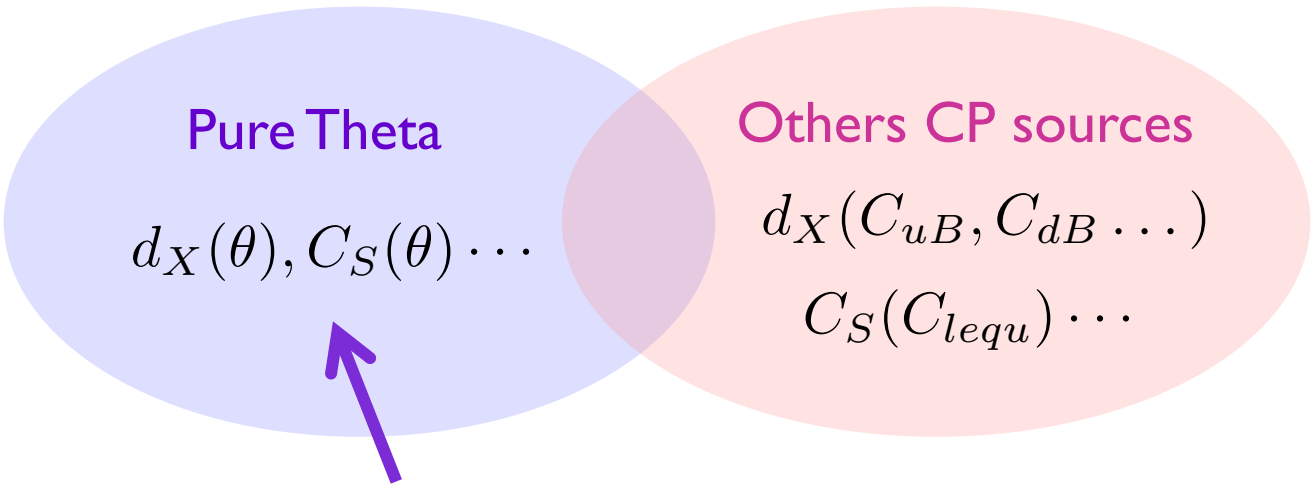
Implication for DM candidate

J. de Vries, P. Draper, **KF**, B. Lillard, PRD104(2021)055039

UV solutions can be probed by looking for new CP sources.

OR

by investigating "pure theta scenario"



Strategy : Rule out "pure theta scenario" with two EDMs

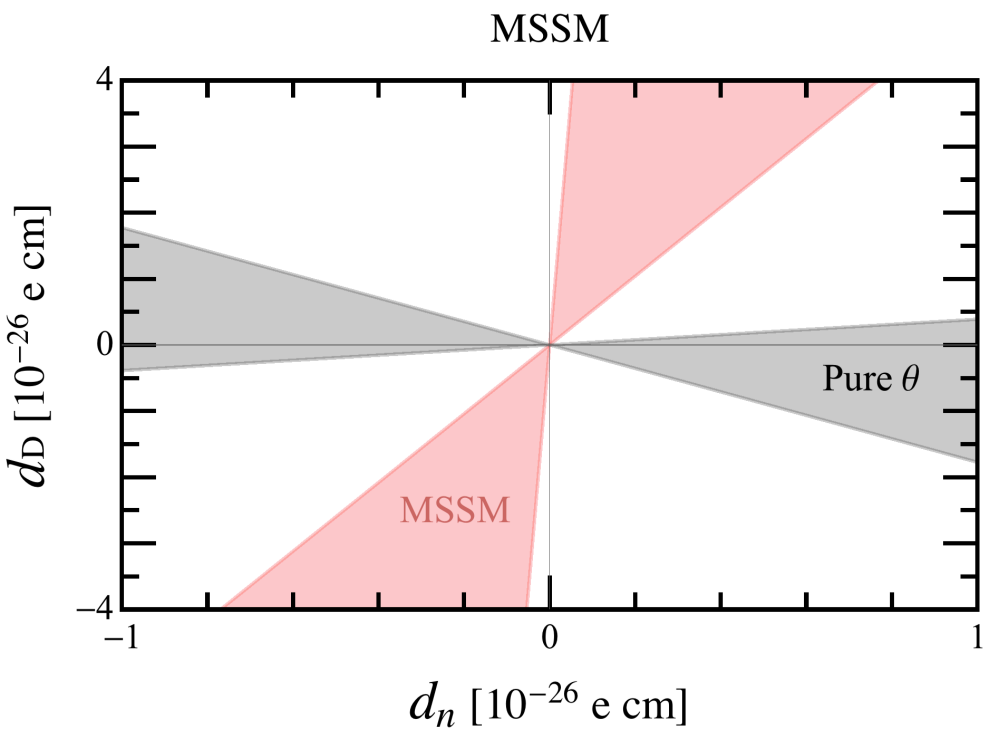
Predictions of EDMs in two scenario: Pure Theta vs BSM physics with another CPV
J. de Vries, P. Draper, **KF**, B. Lillard, PRD104(2021)055039

Neutron and Deuteron EDMs

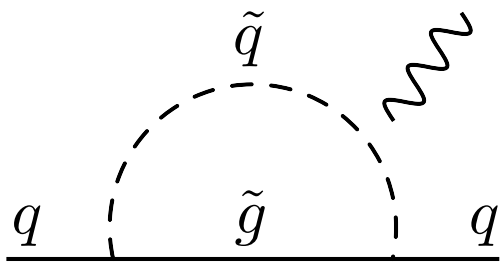
J. de Vries, P. Draper, **KF**, B. Lillard, PRD104(2021)055039

(Gray) Pure Theta Scenario

(Pink) Minimal SUSY Model (gluino mass phase)



* Quark EDMs/cEDMs



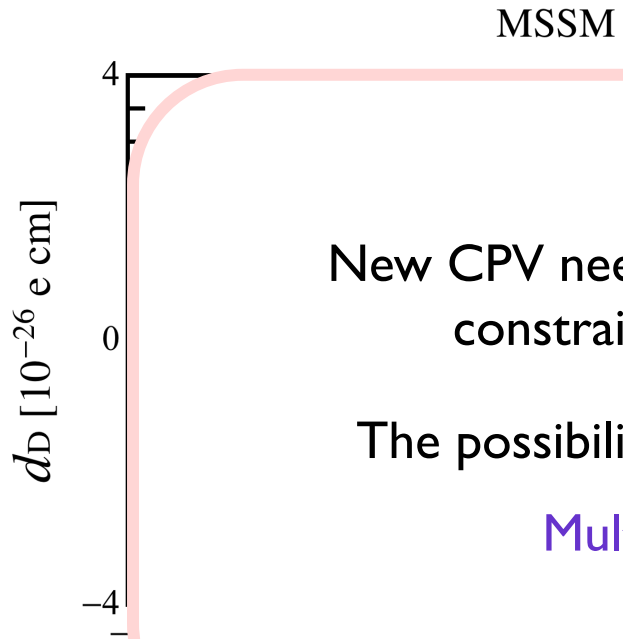
The prediction of d_D/d_n is different from pure theta case.

Neutron and Deuteron EDMs

J. de Vries, P. Draper, **KF**, B. Lillard, PRD104(2021)055039

(Gray) Pure Theta Scenario

(Pink) Minimal SUSY Model (gluino mass phase)



Short Summary

New CPV needed for creating the BAU is severely constrained by the electron EDM limit.

The possibility of scenarios with various CPV

Multi-species EDM searches

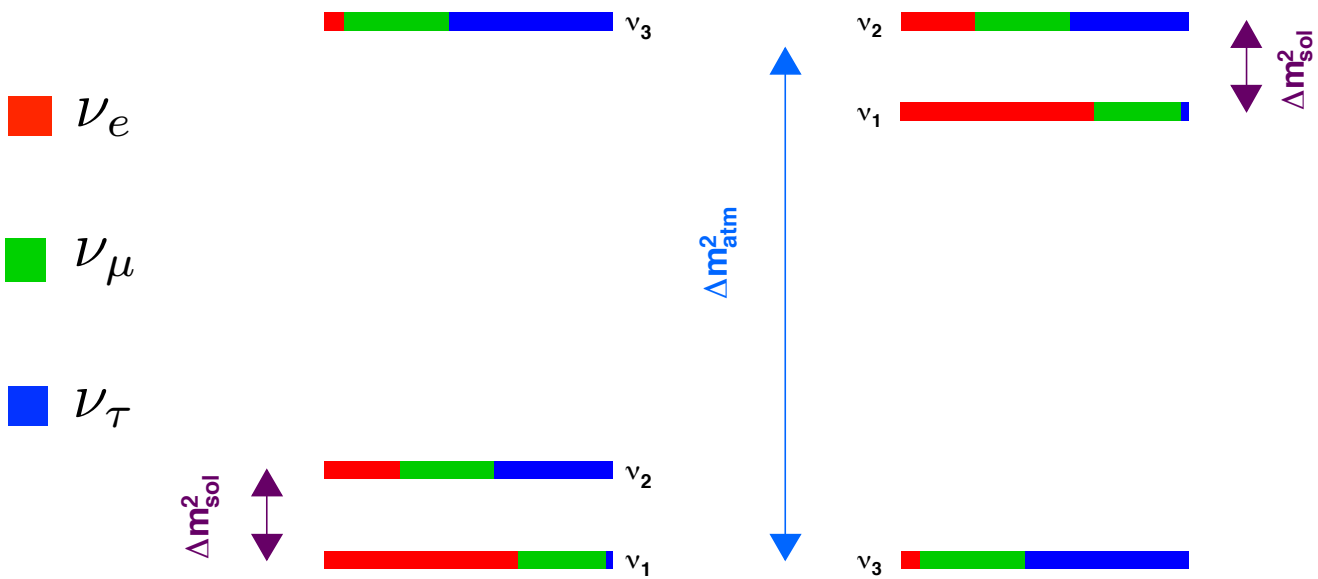
*Implication for strong CP ~ axion DM

The prediction of d_D/d_n is different from pure theta case.

Lepton Number Violation

Neutrino mass

The origin of the non-vanishing neutrino masses



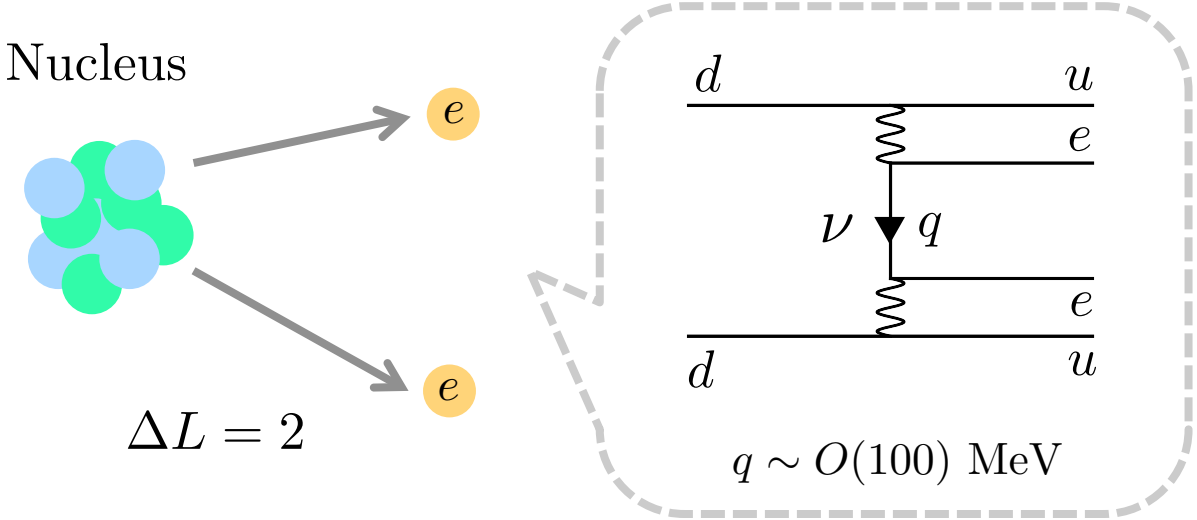
Normal hierarchy *Inverted hierarchy*

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

Neutrinoless Double Beta Decay

Double beta decay without neutrino emission

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



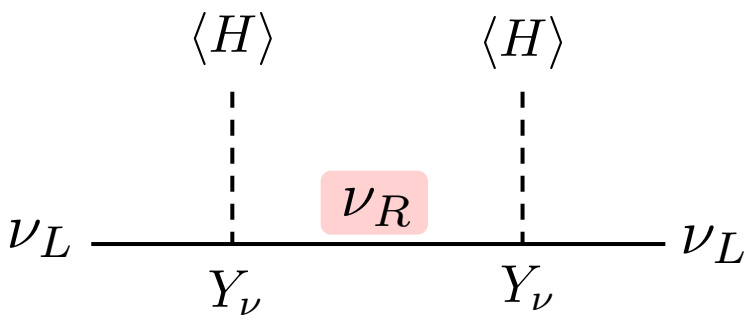
The process can occur if neutrino is a Majorana particle.

*Particle = Antiparticle

Neutrinoless Double Beta Decay

Right-handed neutrino : ν_R

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



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

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}\bar{\nu} m_\nu \nu \qquad (\nu = \nu^c)$$

Search for NDBD

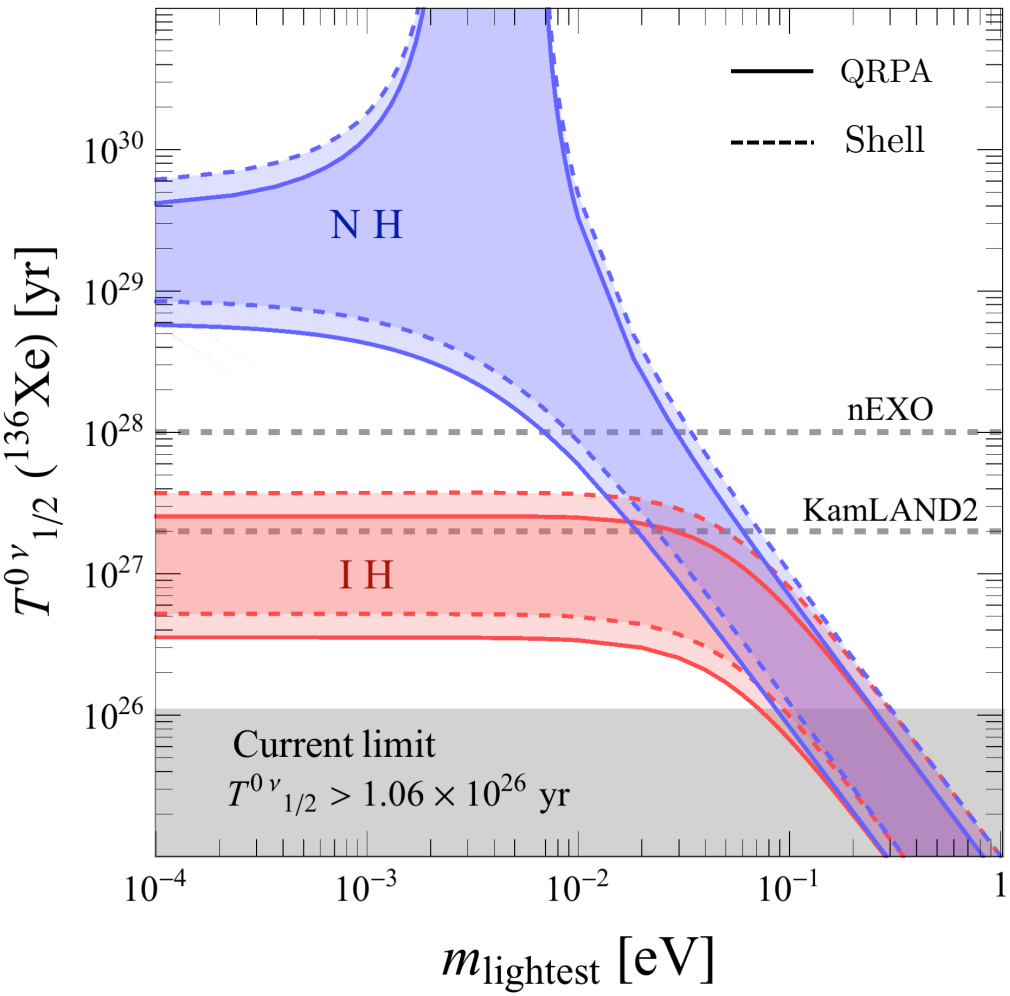
Isotope	Experiment	Current limit ($\times 10^{25}$yr)		Future sensitivity ($\times 10^{25}$yr)	
^{48}Ca	ELEGANT−IV	5.8×10^{-3}	[2]	–	
	CANDLES	6.2×10^{-3}	[23]	10^{-2}	[28]
	NEMO−3	2.0×10^{-3}	[9]		
^{76}Ge	MAJORANA DEMONSTRATOR	2.7	[22]	–	
	GERDA	9.0	[24]	–	
	LEGEND	–		10^{3}	[29]
^{82}Se	CUPID	3.5×10^{-1}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

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

KamLAND-Zen
PRL117(2016) 082503

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

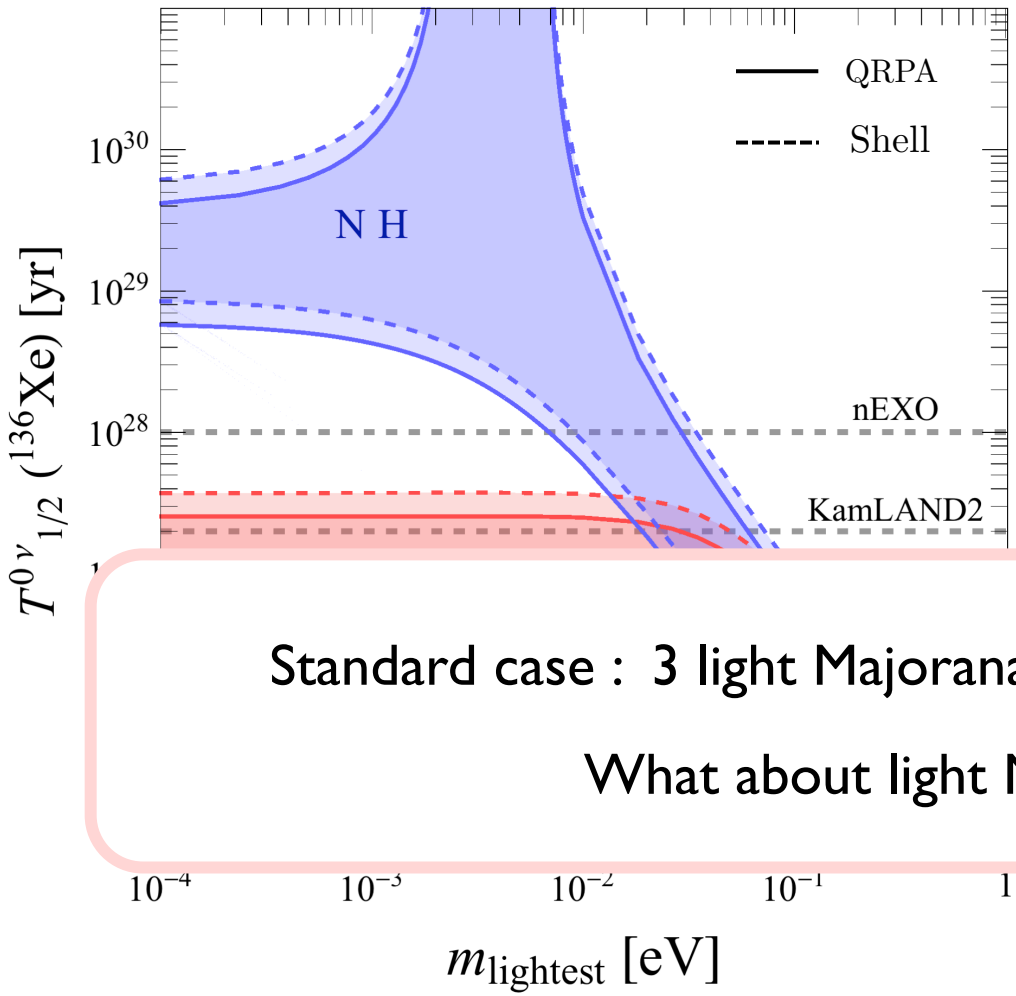
@KamLAND2 – Zen

$\sim 10^{28}$ 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:

M_R

$\gtrsim 10^9$ GeV

$\sim$ TeV

$\sim$ keV

$\sim$ eV

Wide mass range!

BAU

Thermal Leptogenesis

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

Resonant Leptogenesis

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 $\bar{\nu}_\mu \to \bar{\nu}_e$
Reactor anomaly : PRD83(2011)073006
MiniBooNE : PRL121(2018)221801 $\nu_\mu \to \nu_e$
PRL102(2009)101802

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

$\sim$ TeV

$\sim$ keV

$\sim$ eV

BAU

Thermal Leptogenesis

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

Resonant Leptogenesis

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 $\bar{\nu}_\mu \to \bar{\nu}_e$
Reactor anomaly : PRD83(2011)073006
MiniBooNE : PRL121(2018)221801 $\nu_\mu \to \nu_e$
PRL102(2009)101802

Wide mass range!

Light M_R case

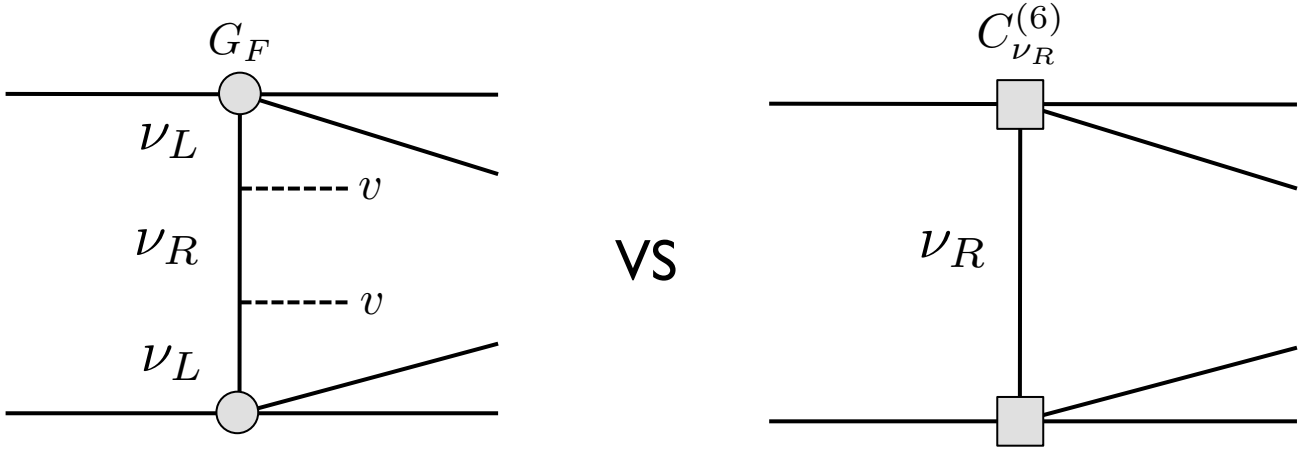
W. Dekens, J. de Vries, **KF**, E. Mereghetti, G. Zhou, JHEP06(2020)097

Model-independent analysis in the light ν_R scenario

~ Effective Field Theory

* Non-standard interactions (d = 6)

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



* Derive the master formula 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)

$\Lambda_{\rm new}$

SM + sterile neutrino EFT

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

~ 100 GeV

Neutrino mass

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

~ 1 GeV

~ 1 MeV

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)

$\Lambda_{\rm new}$

SM + sterile neutrino EFT

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

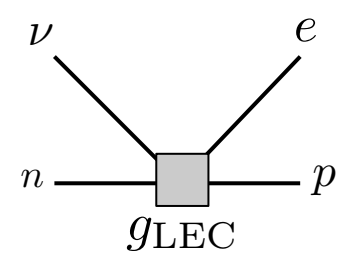
~ 100 GeV

Neutrino mass

Integrate out heavy SM particles + ν_R ($\geq$1 GeV)

~ 1 GeV

Chiral Perturbation Theory



~ 1 MeV

" Inverse half-life "

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

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

EFT approach

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

$\Lambda_{\rm new}$ — SM + sterile neutrino EFT

$g_{\rm LEC}(m_i)$ $M_{\rm NME}(m_i)$

~ 100 GeV — Neutrino mass

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

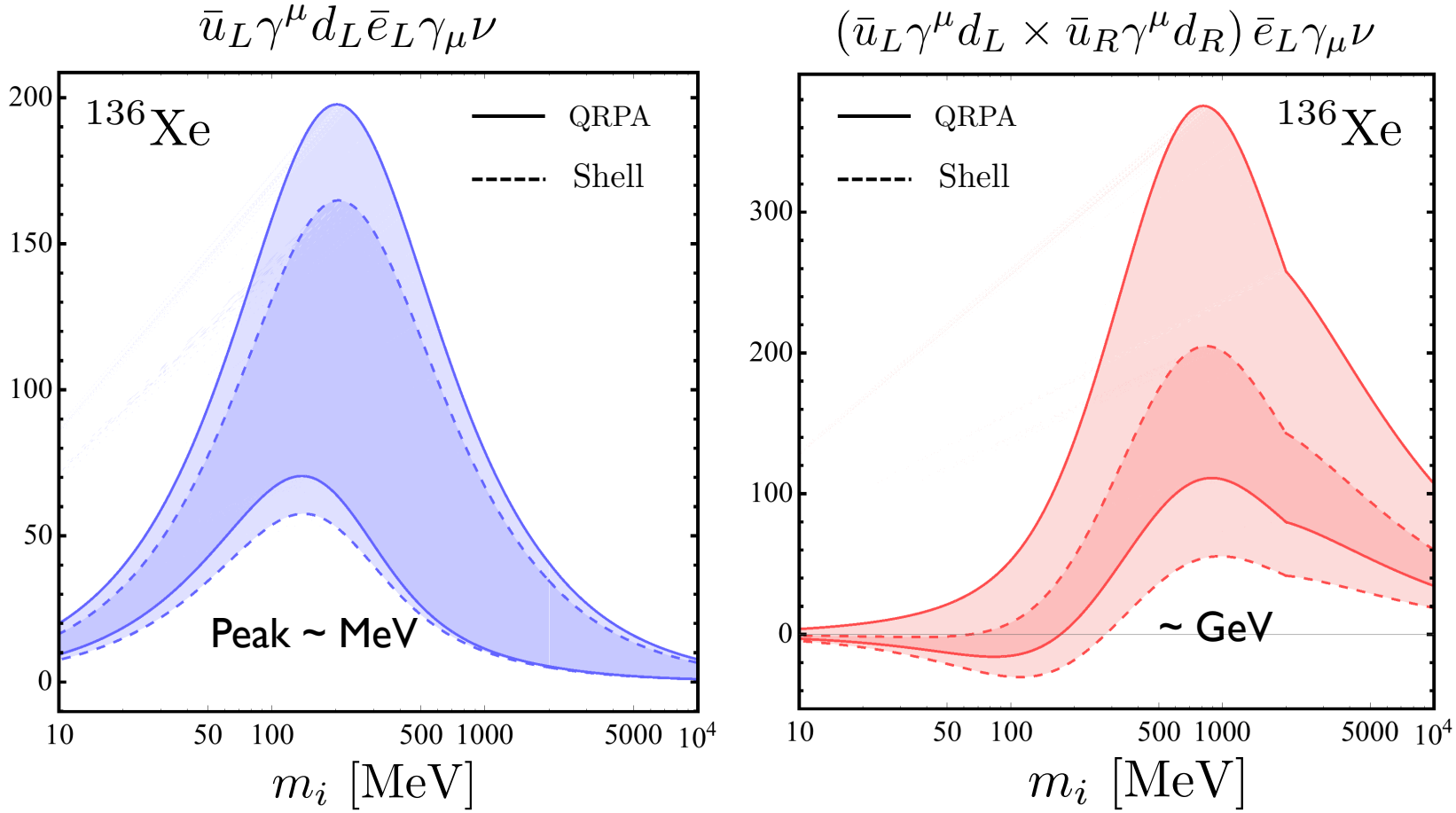
~ 1 GeV — Chiral Perturbation Theory

~ 1 MeV — " Inverse half-life "

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

"Interpolation formulae"

Mass dependence



* The master formulae make it possible to analyze NDBD in any mass spectrum.

✔ Underlying physics, i.e., BSM physics

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

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

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

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

Leptoquark

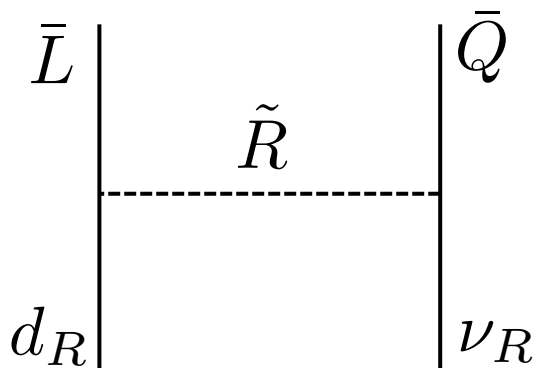
J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 88, 035009 (2013)
J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 87, 075004 (2013)
I. Dorsner, S. Fajfer, A. Greljo, J. F. Kamenik and N. Kosnik, Phys. Rept. 641, 1 (2016)

Leptoquark (LQ) couples to the SM quark and lepton

+ sterile neutrinos

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

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



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

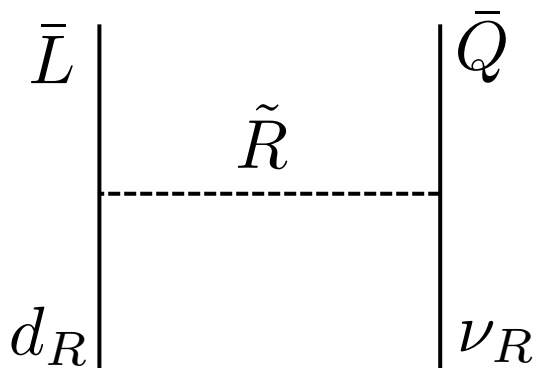
J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 88, 035009 (2013)
J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 87, 075004 (2013)
I. Dorsner, S. Fajfer, A. Greljo, J. F. Kamenik and N. Kosnik, Phys. Rept. 641, 1 (2016)

Leptoquark (LQ) couples to the SM quark and lepton

+ sterile neutrinos

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 :

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

Leptoquark

Scalar and tensor operators show up below EW scale:

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

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

Leptoquark

Scalar and tensor operators show up below EW scale:

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

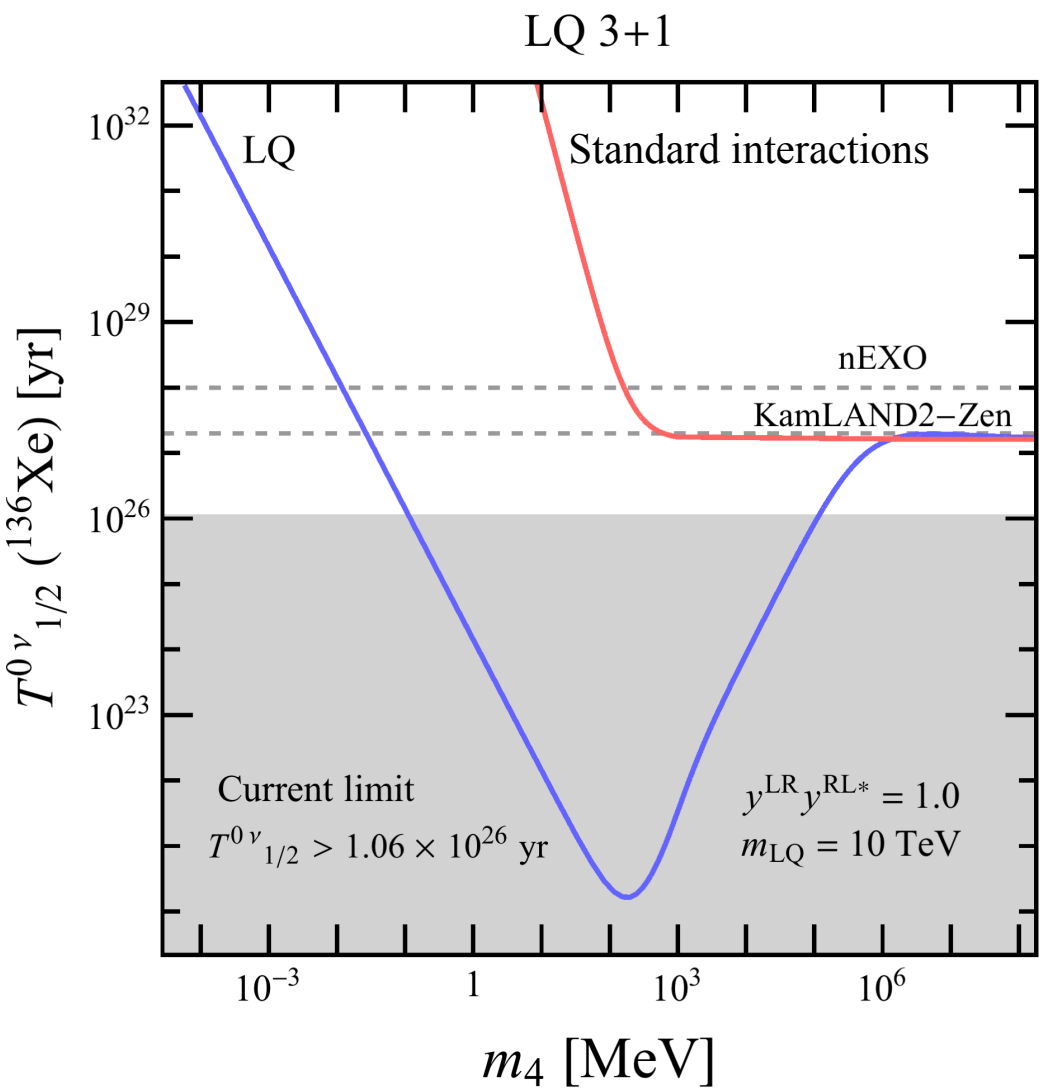
$$C^{(6)}_{\mathrm{SRR}} = 4C^{(6)}_{\mathrm{TRR}} = \frac{v^2}{2} C^{(6)}_{LdQ\nu} U^*_{4i} \qquad i = 1 \sim 4$$

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

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



Blue : LQ interaction

Pink : No LQ interaction (vector contribution)

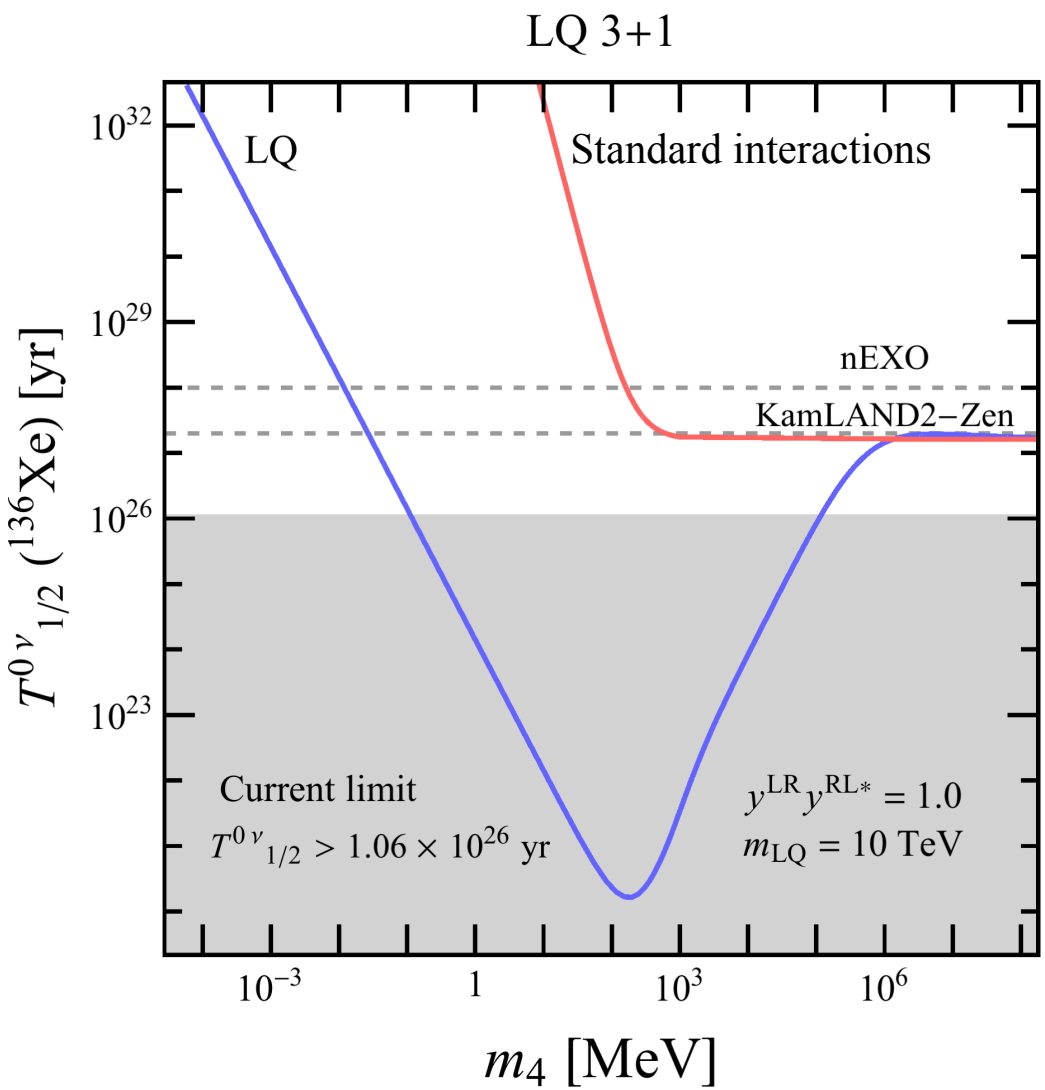
* LQ interactions dominate over standard contributions.

For $q^2 \gg m_i^2$

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

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

3+1 Leptoquark



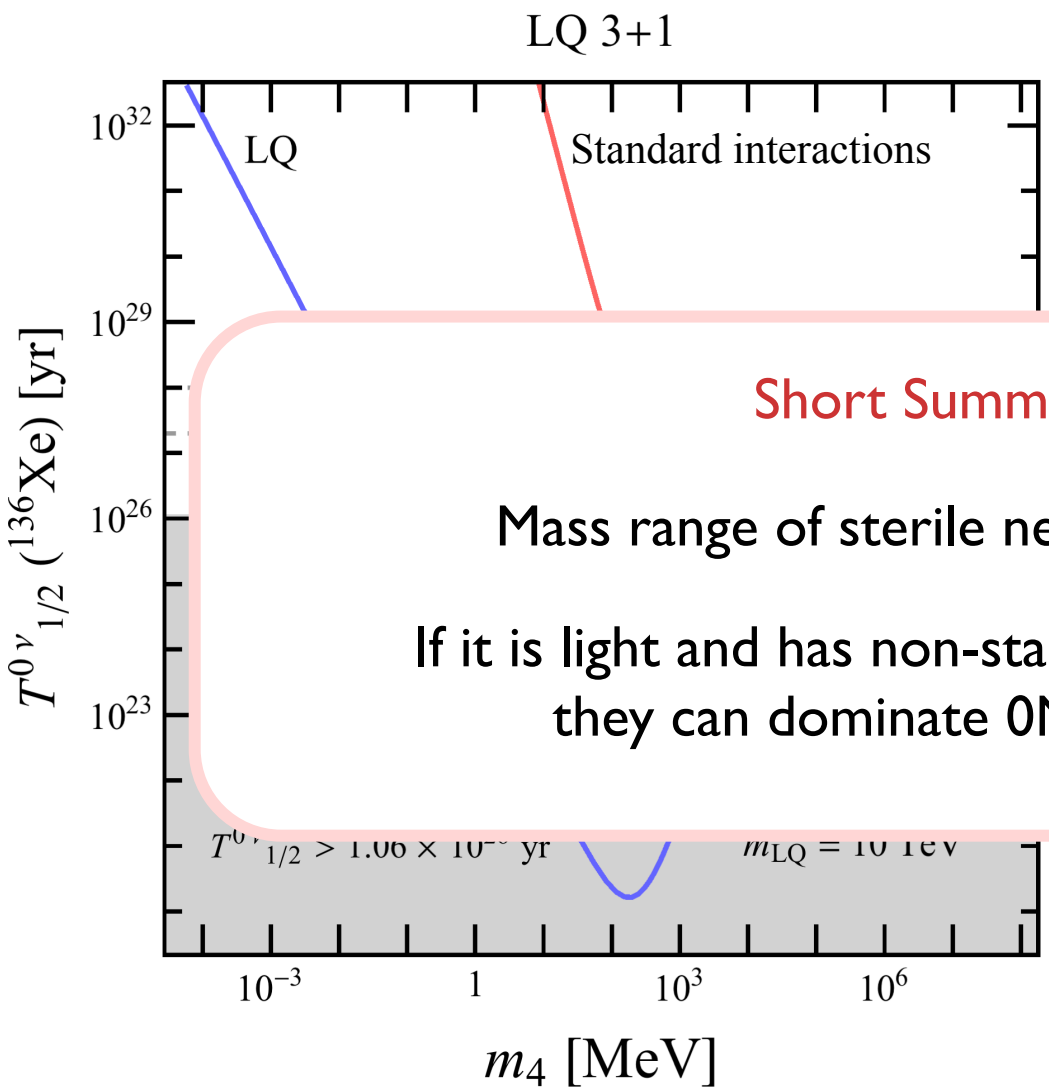
Blue : LQ interaction

Pink : No LQ interaction (vector contribution)

Ruled out

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

3+1 Leptoquark



2-Zen

Short Summary

Mass range of sterile neutrino is wide.

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

Charged Lepton Flavor Violation

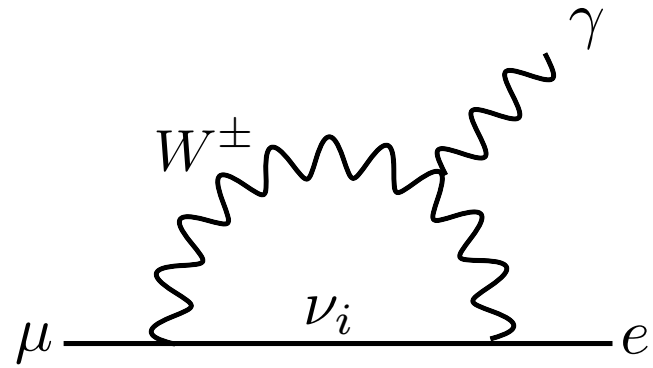
Charged Lepton Flavor Violation

Nonzero neutrino mass induces CLFV.

Ex) Minimal extension of the SM

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\nu-{\rm mass}}$$

Dirac or Majorana



Petcov '77, Marciano-Sanda '77 ....

$$\mathrm{Br}\,(\mu \to e\gamma) = \frac{3\alpha_{\rm em}}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{m_W^2}\right|^2 < 10^{-54}$$

Extremely small!

The predicted BR is too small to be observed.

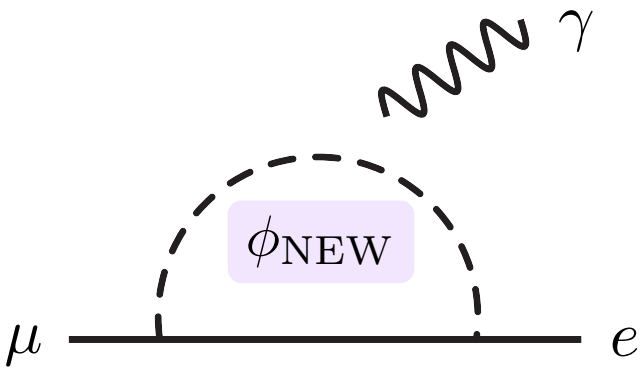
Charged Lepton Flavor Violation

Nonzero neutrino mass induces CLFV.

Ex) Minimal extension of the SM

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\nu-{\rm mass}}$$

Dirac or Majorana



$$\mathrm{Br}\,(\mu \to e\gamma) = \frac{3\alpha_{\rm em}}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{m^2_W}\right|^2 < 10^{-54}$$

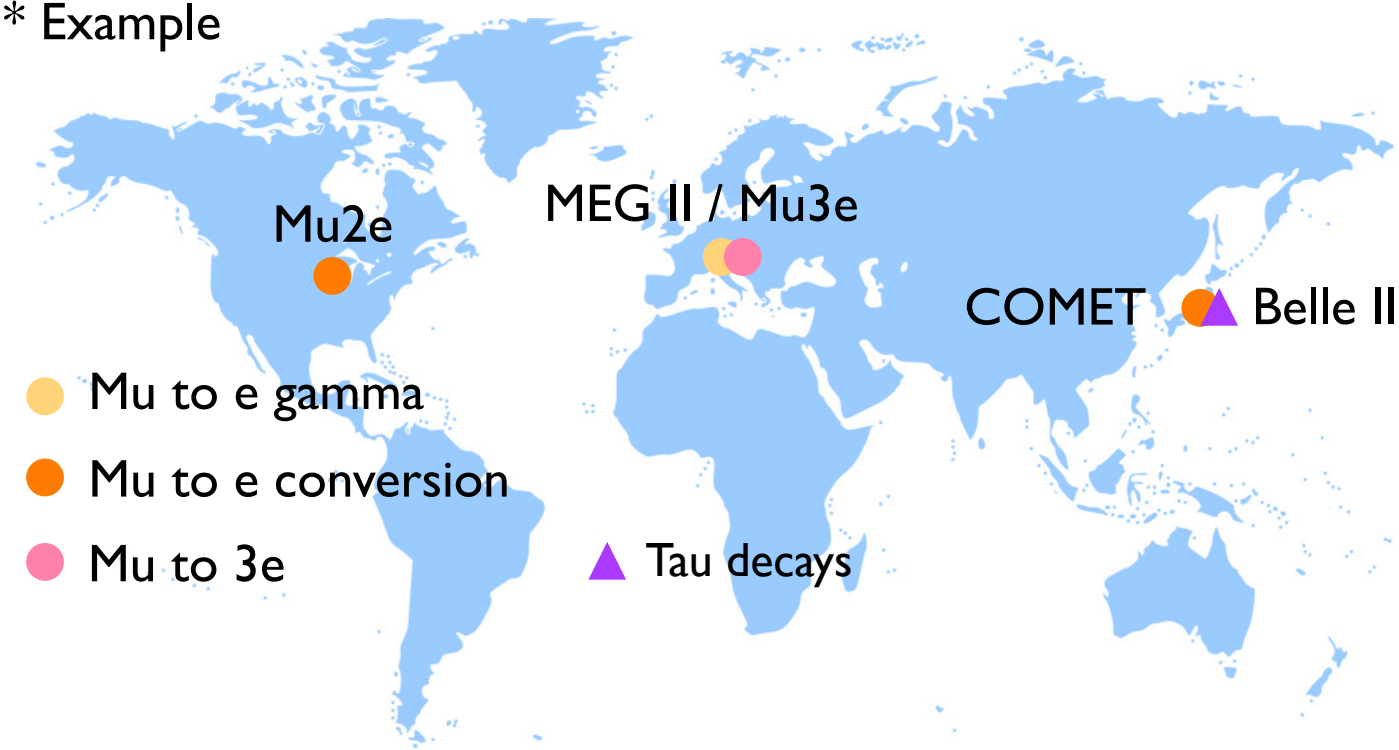
Extremely small!

The observation of CLFV would imply another contribution.

✔ Underlying physics, i.e., BSM physics

Searches for CLFV

* Example



$$\mathrm{BR}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$$

MEG Collaboration, Eur. Phys. J. C 76(8), 434 (2016).

$$\mathrm{BR}(\mu^- \ \mathrm{Au} \to e^- \ \mathrm{Au}) < 7 \times 10^{-13}$$

SINDRUM II, Eur. Phys. J. C 47(2), 337–346 (2006).

$$\mathrm{BR}(\tau \to e\gamma) < 3.3 \times 10^{-8}$$

BaBar, PRL104 (2010) 021802

$$\mathrm{BR}(\tau \to e\pi^+\pi^-) < 2.3 \times 10^{-8}$$

Belle, PLB719 (2013) 346-353

Searches for CLFV

$$\mathrm{BR}(\mu^- \mathrm{Al} \to e^- \mathrm{Al}) < O(10^{-17})$$

at Mu2e and COMET

* Example

"Next-to-leading order scalar contributions to mu to e conversion"
V. Cirigliano, **KF**, M. Ramsey-Musolf and **Evan Rule**, 2022.xxxxx

$$\mathcal{L} \supset \sum_{q=u,d} C_S \; \bar{e}\mu\bar{q}q$$

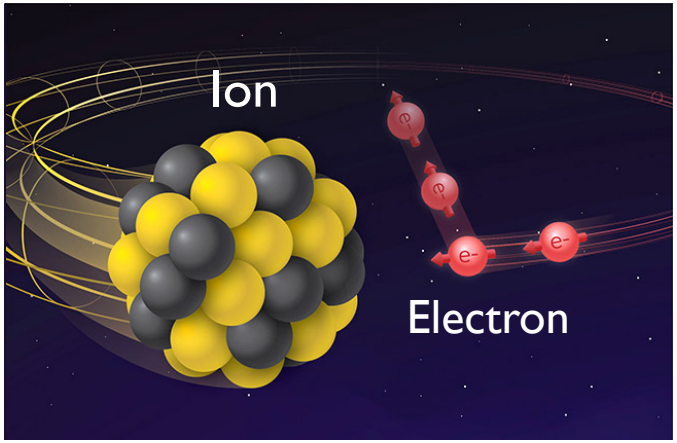
*NLO contributions can reduce the BR by 20% > ~10% uncertainty at LO

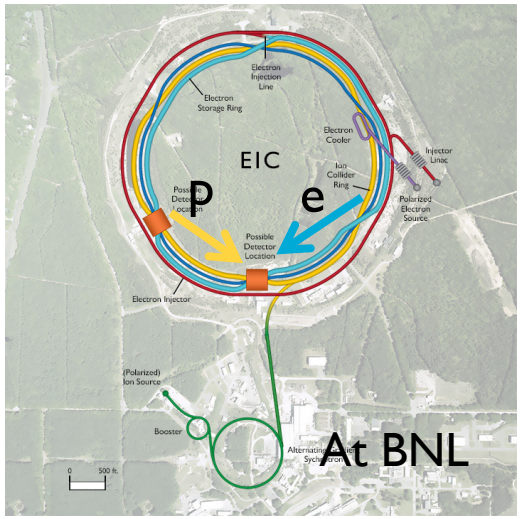
Electron-Ion Collider

EIC Detector Requirements and R&D Handbook
EIC Yellow report, arXiv:2103.05419

One potential probe : CLFV search at the EIC

Collide electrons and protons/heavy ions





$$\sqrt{S} = 20 \sim 100 \text{ GeV}$$

(Upgradable to 140 GeV)

$$\mathcal{L} \sim 10^{33-34} \text{ cm}^{-2}\text{s}^{-1}$$

$(10 - 100 \text{ fb}^{-1} \text{ per year})$

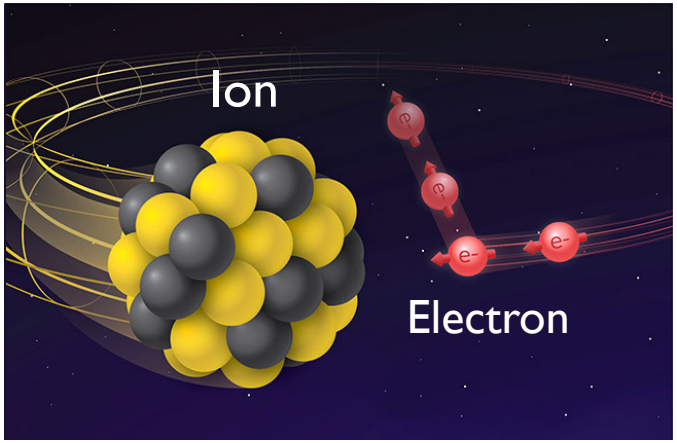
Map the structure of the proton and nuclei

Electron-Ion Collider

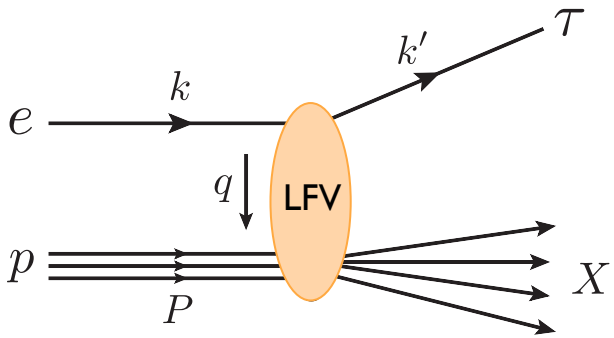
EIC Detector Requirements and R&D Handbook
EIC Yellow report, arXiv:2103.05419

One potential probe : CLFV search at the EIC

Collide electrons and protons/heavy ions



* Electron-Tau process



EIC vs low-energy tau decays and CLFV searches at LHC

Model-independent (EFT) analysis + application to Leptoquark Model
V. Cirigliano, **KF**, C. Lee, E. Mereghetti, B. Yan, JHEP03(2021)256

CLFV operators

V. Cirigliano, **KF**, C. Lee, E. Mereghetti, B. Yan
JHEP03(2021)256

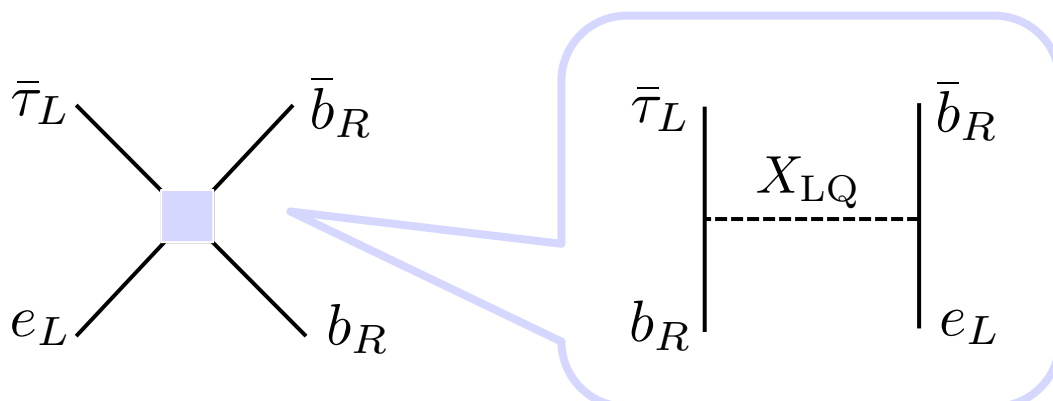
Model-independent way : 16 different operators in total

Ex) Four-fermion vector operator

$$\mathcal{L} \supset -\frac{4G_F}{\sqrt{2}} [C_{Ld}]_{\tau ebb} \bar{\tau}_L \gamma^\mu e_L \bar{b}_R \gamma_\mu b_R$$

VLR : bb element

Ex) Induced by Scalar Leptoquark Model



CLFV operators

V. Cirigliano, **KF**, C. Lee, E. Mereghetti, B. Yan
JHEP03(2021)256

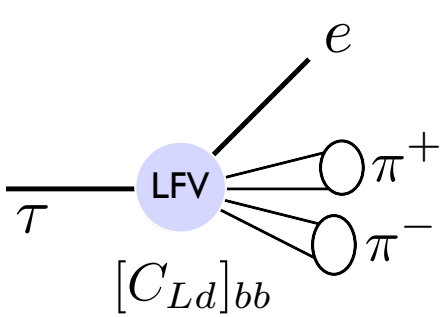
Model-independent way : 16 different operators in total

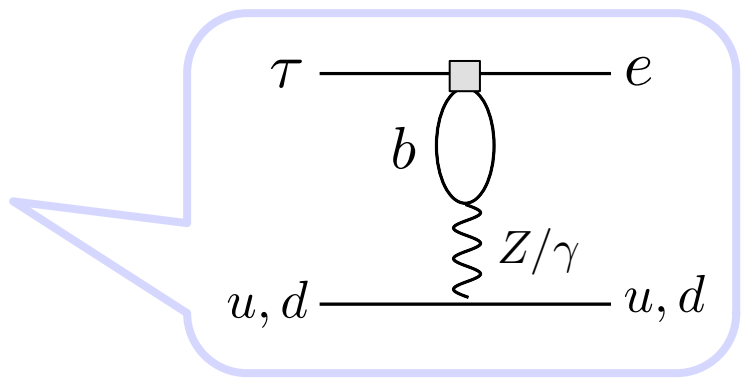
Ex) Four-fermion vector operator

$$\mathcal{L} \supset -\frac{4G_F}{\sqrt{2}} [C_{Ld}]_{\tau ebb} \bar{\tau}_L \gamma^\mu e_L \bar{b}_R \gamma_\mu b_R$$

VLR : bb element

Scale running effect : The renormalization group equation





$$\mathrm{BR}(\tau \to e\pi^+\pi^-) < 2.3 \times 10^{-8}$$

Belle, PLB719 (2013) 346-353

Loop effect $\sim 10^{-3}$

CLFV searches at LHC

LFV search	Upper limit
Z decay	$\mathrm{BR}(Z \to \tau e) < 8.1 \times 10^{-6}$ (95%C.L.) ATLAS Collaboration, Nature Phys. 17 (2021)7, 819-825
Higgs decay	$\mathrm{BR}(H \to e^-\tau^+ + \tau^- e^+) < 4.7 \times 10^{-3}$ (95%C.L.) ATLAS collaboration, PLB 800 (2020) 135069
Top decay	$\mathrm{BR}(t \to q\ell\ell') < 1.86 \times 10^{-5}$ (95%C.L.) ATLAS collaboration, ATLAS-CONF-2018-044
Bottom 4F operator	
Search for $pp \to \tau e$	Search for a heavy particle decaying into different-flavor dilepton pairs ATLAS Collaboration, PRD98(2018)092008

EIC analysis

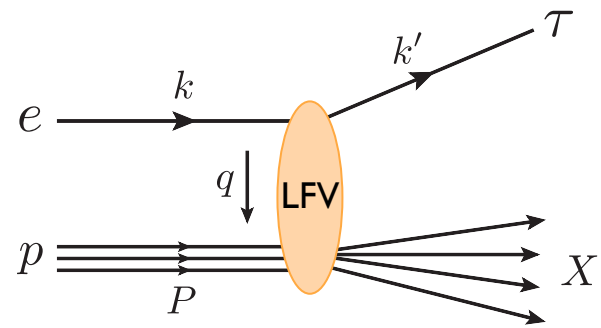
V. Cirigliano, **KF**, C. Lee, E. Mereghetti, B. Yan
JHEP03(2021)256

- Cross sections : $\mathcal{O}(1-10)$ pb at $\sqrt{S} = 141$ GeV

- Major backgrounds

  1) Neutral Current : $ep \to ej$

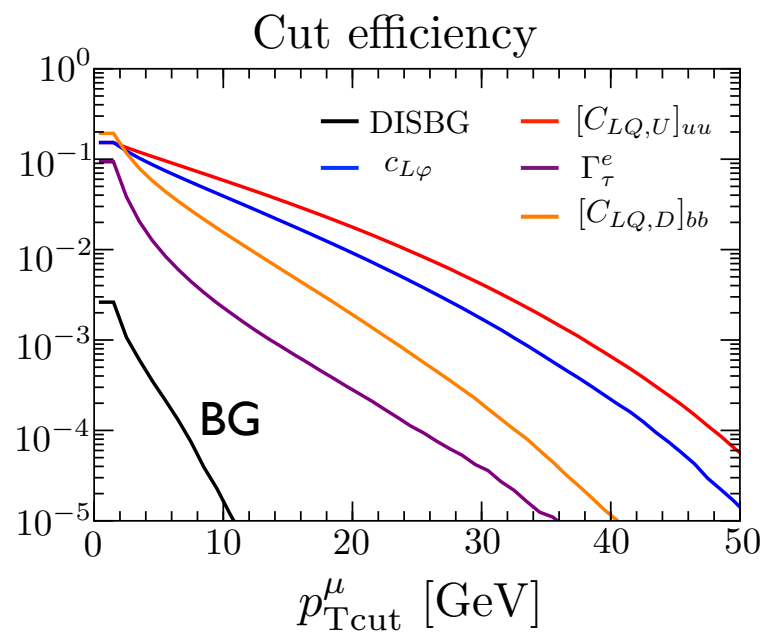
  2) Charged Current : $ep \to \nu_e j$



- Promising channel

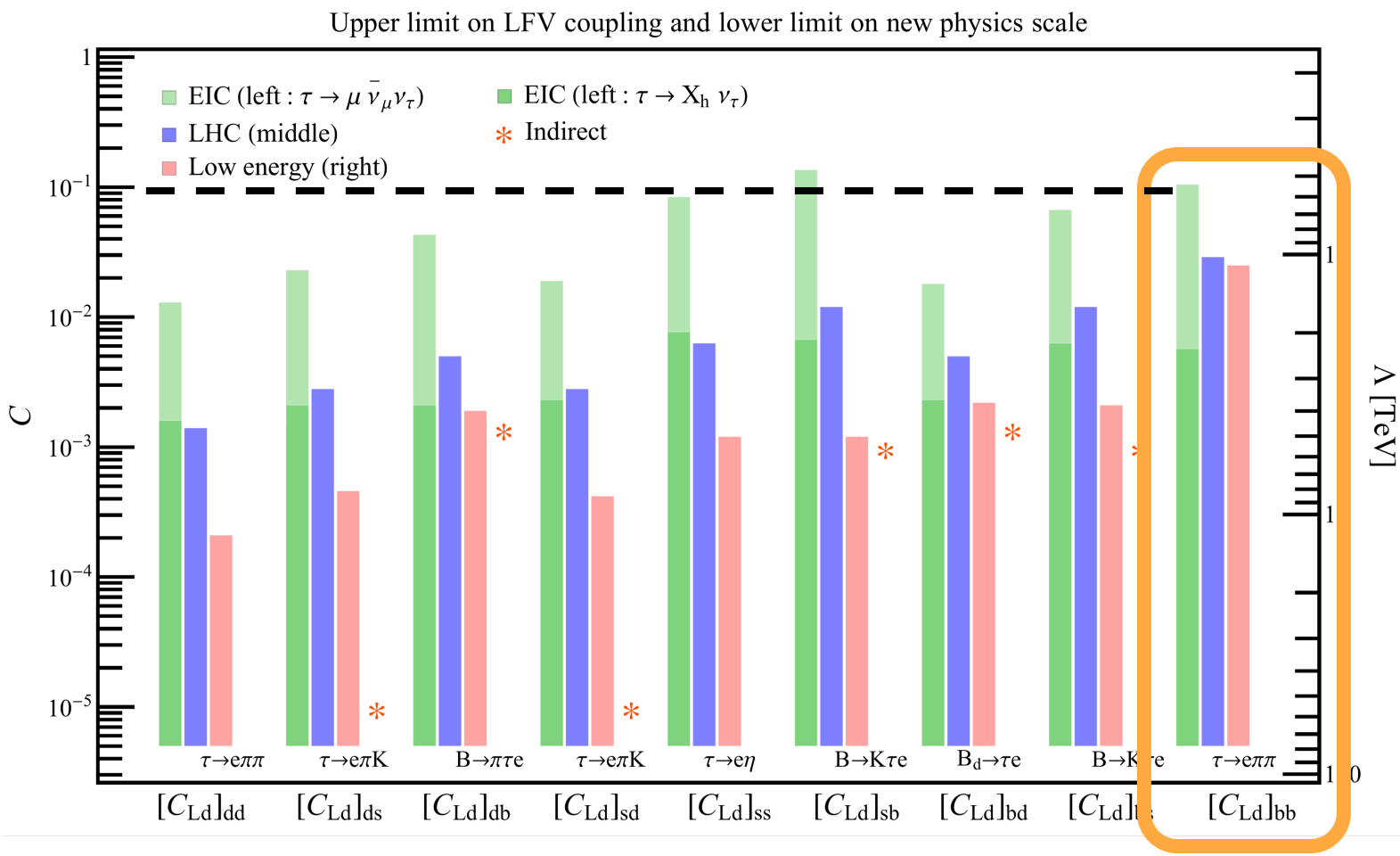
$$\mathrm{BR}\left(\tau \to \mu \bar{\nu}_\mu \nu_\tau\right) = 17.39\%$$

* Moderate cuts enable to eliminate all SM background



EIC vs Current limits

V. Cirigliano, **KF**, C. Lee, E. Mereghetti, B. Yan
JHEP03(2021)256



EIC : $[C_{Ld}]_{bb} < 0.1$ LHC, Tau decay : $[C_{Ld}]_{bb} < O(10^{-2})$

Competitive!

Multi-operator scenario

V. Cirigliano, **KF**, C. Lee, E. Mereghetti, B. Yan
JHEP03(2021)256

See the situation where 8 operators are nonzero

* Z couplings + down-type 4F operators

$$\mathcal{L}_{\rm LFV} \supset -\frac{g_2}{c_W}\left(c_{L\varphi}^{(1)} + c_{L\varphi}^{(3)}\right)\bar{\tau}_L\gamma^\mu Z_\mu e_L$$

$$-\frac{4G_F}{\sqrt{2}}\sum_{a=d,s,b}[C_{Ld}]_{aa}\bar{\tau}_L\gamma^\mu e_L\bar{d}_{Ra}\gamma_\mu d_{Ra}$$

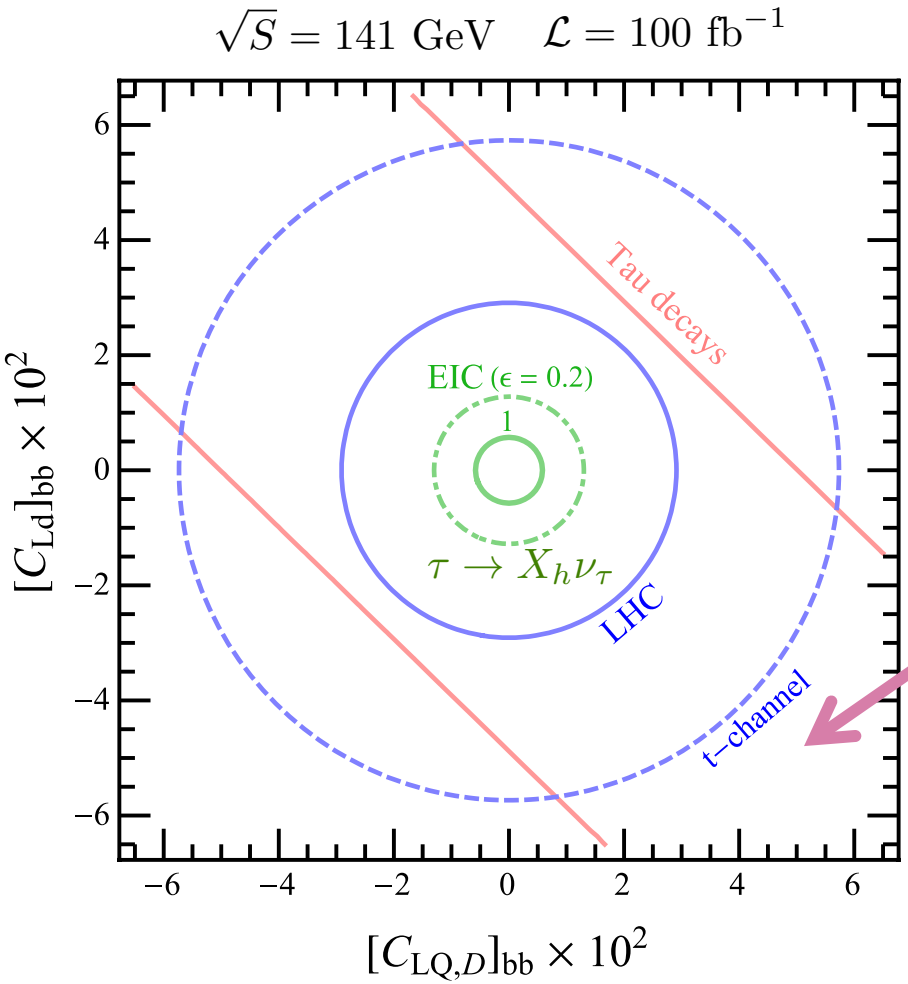
$$-\frac{4G_F}{\sqrt{2}}\sum_{a=d,s,b}[C_{LQ,D}]_{aa}\bar{\tau}_L\gamma^\mu e_L\bar{d}_{La}\gamma_\mu d_{La}$$

✔ Limits on $[C_{LQ,D}]_{bb}$ and $[C_{Ld}]_{bb}$ at 90% C.L.

The rest is marginalized.

Multi-operator scenario

V. Cirigliano, **KF**, C. Lee, E. Mereghetti, B. Yan
JHEP03(2021)256



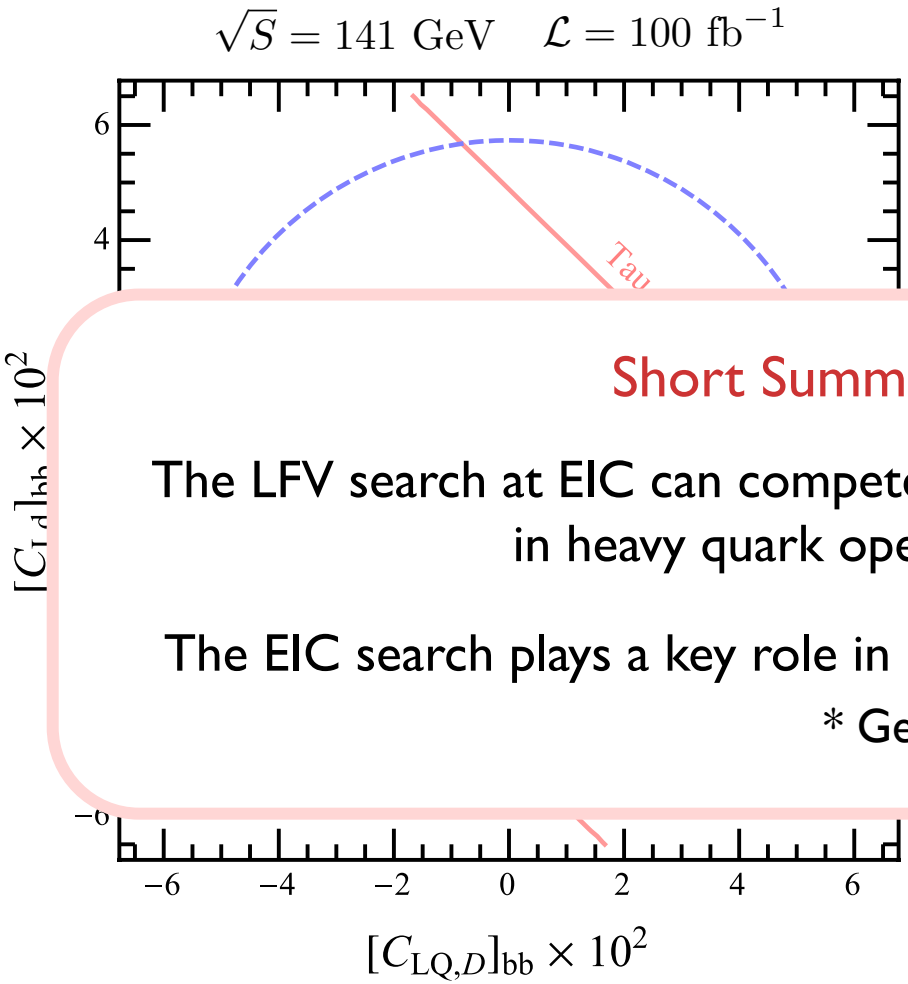
Free direction appears.

$$[C_{LQ,D}]_{bb} - [C_{Ld}]_{bb}$$

Collider probes are necessary to close the free direction.

Multi-operator scenario

V. Cirigliano, **KF**, C. Lee, E. Mereghetti, B. Yan
JHEP03(2021)256



Short Summary

The LFV search at EIC can compete with the current limits in heavy quark operators.

The EIC search plays a key role in multi-operator scenario.

* General BSM physics

Collider probes are necessary to close the free direction.

Future directions

✔ Comprehensive analysis of CPV in EDM and Collider experiments

e.g., Other CPV sources in 2HDM, $d_e(\rho_{tt}, \rho_{ee})$

Collider

✔ Phenomenology of light-sterile neutrinos with non-standard interactions

* Model-independent and -dependent ways

e.g., SB anomalies, The number of relativistic species : $N_{\rm eff}$

Impact on keV sterile neutrino (DM)

LNV/LFV effects on the BAU

✔ Global analysis of e to mu LNV/LFV at Colliders/Mu2e/COMET

e.g., Model-discriminating power

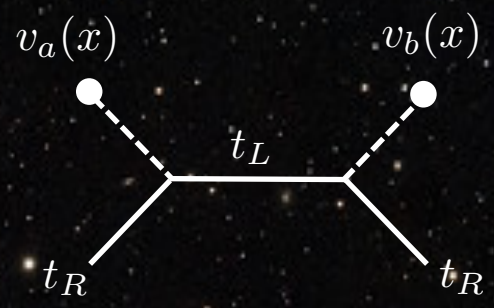
Future directions

✔ EIC analysis at NLO in QCD for heavy-quark operators (a factor of 2)

+ Hadronic decay channels in Tau

✔ Improvement of estimations of the BAU in EWBG

Beyond the lowest order in powers of v/T



✔ Nucleon EDMs

~ 50% uncertainties from quark-chromo EDMs

** LANL NP/Lattice group*

Workshops

1) "What's the matter? : a cross-frontier pursuit of the origin of matter"
Mainz Institute for Theoretical Physics, August 22 - September 9, 2022

2) "Searches for Electric Dipole Moments: from theory to experiment"
Nagoya University, Japan, 2022 or 2023

Conclusion

We still don't know much about our Universe.

Dark Matter

✔ Multi-species EDM searches

$$d_e,\ d_n,\ d_p \cdots$$

✔ CPV/LNV/LFV searches at colliders

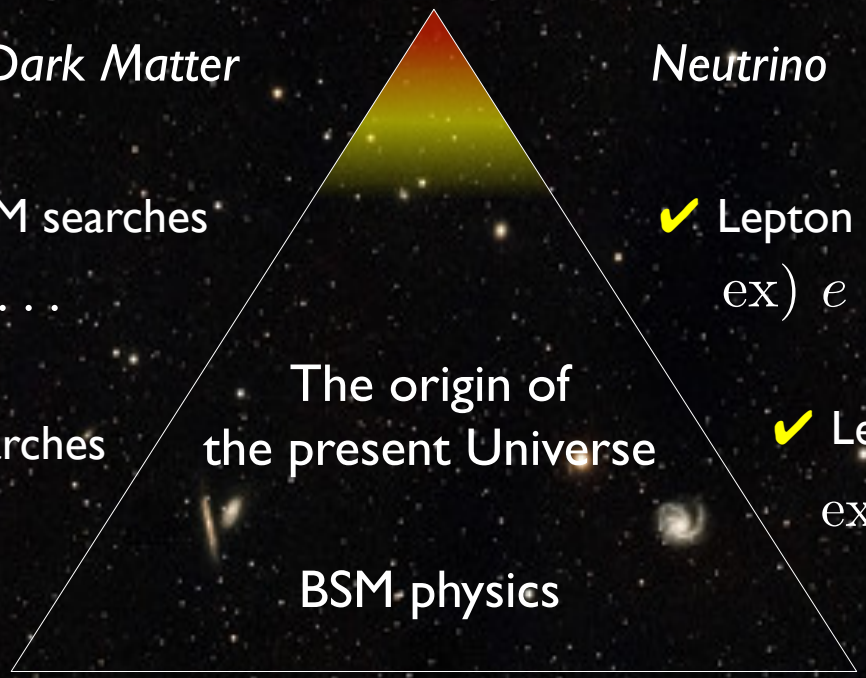
Neutrino

✔ Lepton Flavor Violation

$$\text{ex)}\ e \to \tau \text{ and } \mu \to e$$

✔ Lepton Number Violation

$$\text{ex)}\ 0\nu 2\beta \text{ and } e^- \to \mu^+$$



Matter-Antimatter Asymmetry

✦ Various fundamental symmetry tests to reveal the origin of the Universe

* *From low-energy to intensity and energy frontiers*