# Neutrino-participated interactions in effective field theories

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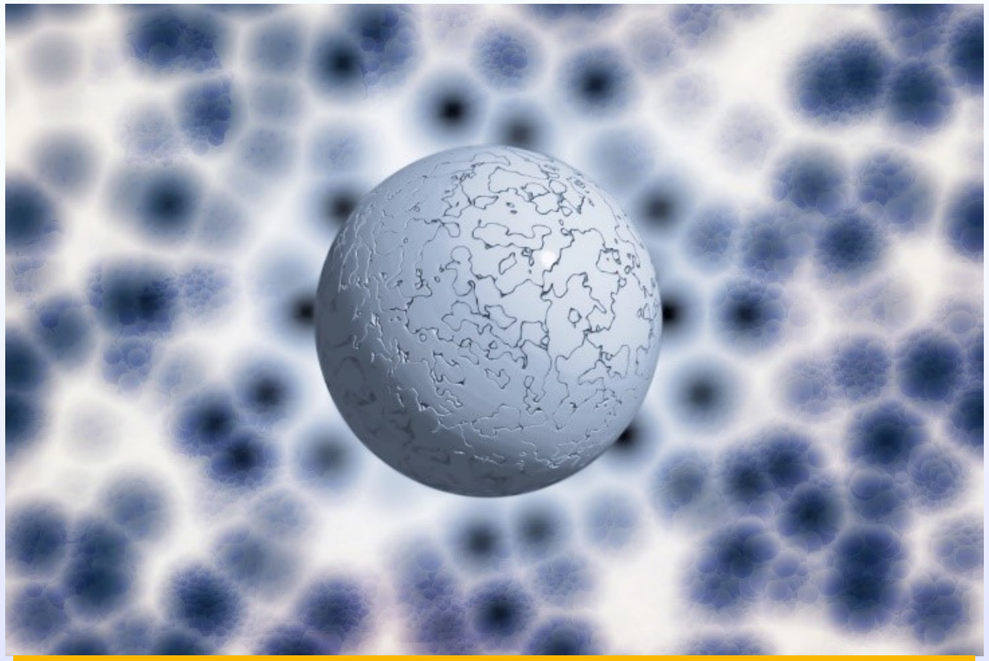
第2届 第二届中微子散射：理论、实验与唯象研讨会
2025年10月25日-29日，北京

# Outline

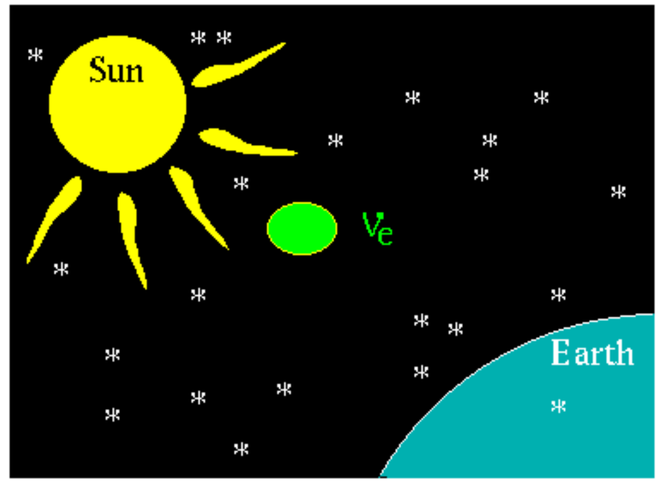
- Introduction
- Bottom up EFT: SMEFT, $\nu$SMEFT, LEFT, $\nu$LEFT
- UV completion of EFT operators
- Top down EFT: matching UV models onto EFTs
- Phenomenologies
- Summary

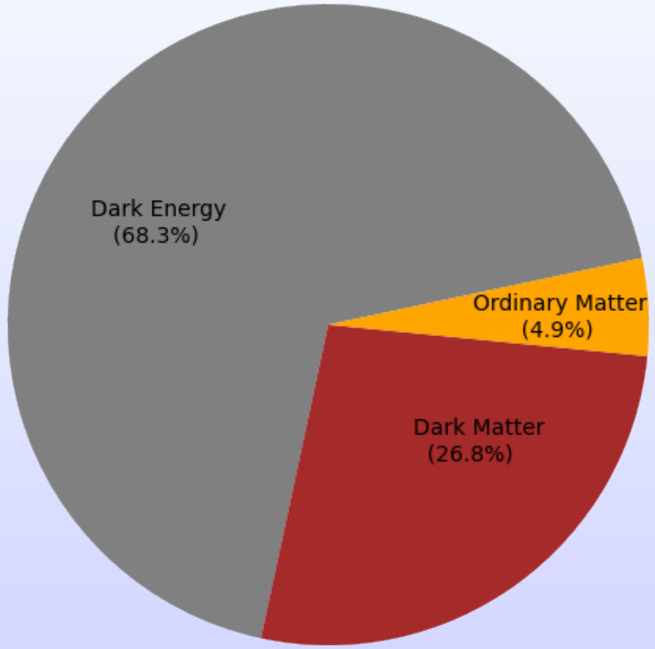
# Neutrinos hold the key to big questions

- Neutrino mass
- Dark matter
- Baryon asymmetry
- Anomalies
  - Neutron lifetime $\tau_n$
  - $B \to K\nu\bar{\nu}$
  - $K \to \pi\nu\bar{\nu}$
  - MiniBooNE $\nu_e$
  - Gallium anomaly
  - ……



https://www.iasgyan.in/daily-current-affairs/ghost-particles



# Neutrinos in the EFT paradigm

- Neutrino mass in the EFT framework — SMEFT or $\nu$SMEFT

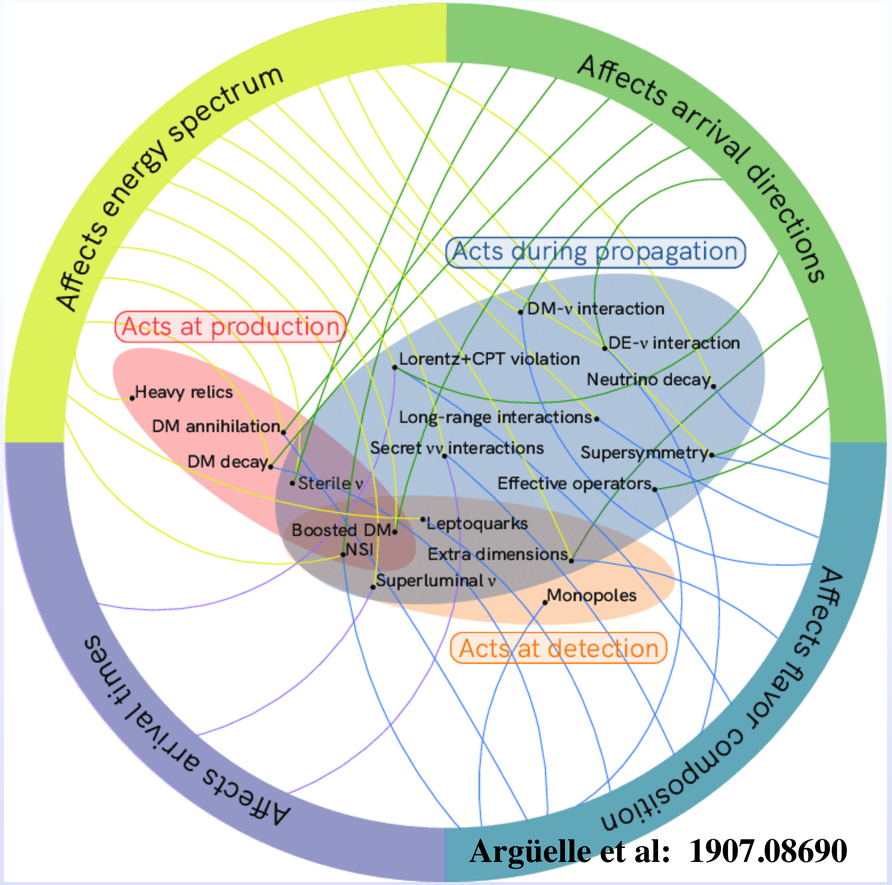
$$\mathscr{L}_{\nu}^{\text{mass}} \ni \frac{\hat{C}_{LH}}{\Lambda}\epsilon_{im}\epsilon_{jn}(\overline{L_i^{\text{C}}}L_j)\tilde{H}_n\tilde{H}_m + \text{h.c.} \Rightarrow m_\nu \bar{\nu}\nu$$

- Neutrino mass model as an EFT

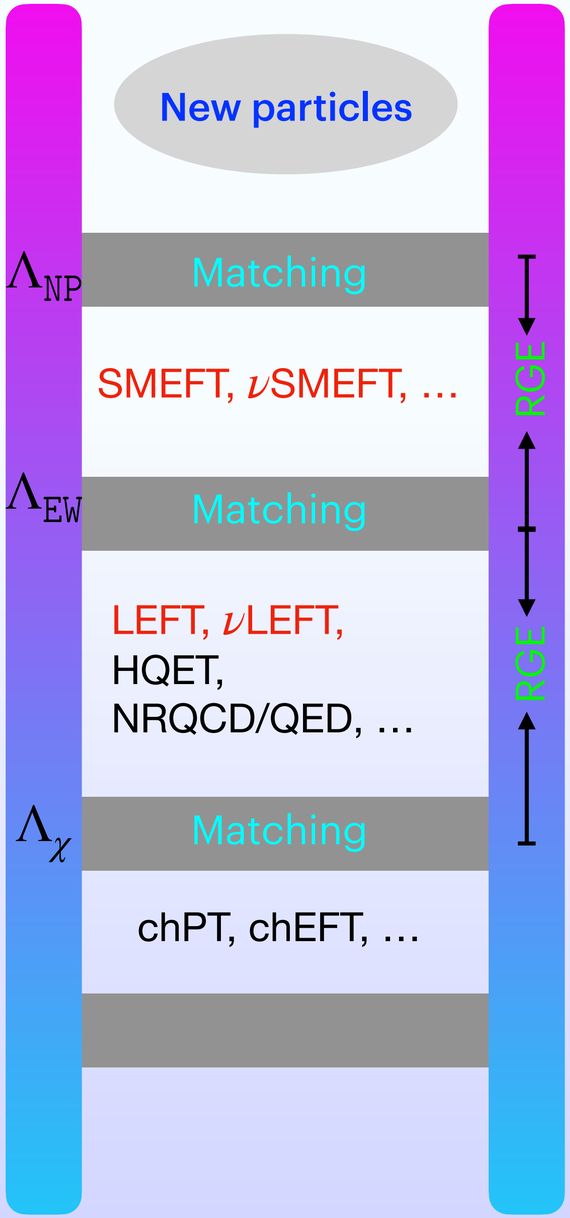
Integrate out heavy NP states and match onto some EFT

- Neutrino-participated processes in the EFTs

$$\nu - \gamma, \nu - \ell, \nu - q, \nu - \nu, \nu - \text{DM}, \cdots$$



# Bottom-up EFT



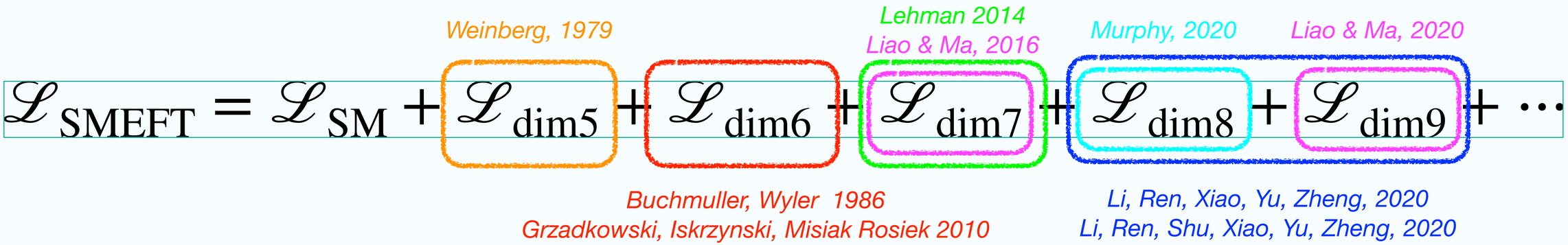

Assumption: scales are well separated with $\Lambda_{\rm NP} \gg \Lambda_{\rm EW}$

Parametrize the derivation of low energy observables w.r.t. the SM prediction by non-SM interactions based on SM particles and symmetries

SMEFT-like framework

**Study NP effect in low energy observables indirectly**

# State of art of SMEFT




**Hilbert series method:** ***Henning, Lu, Melia, Murayama 2015, 2017***

$$\mathscr{L}_{\rm dim5} = \frac{\hat{C}_{LH}}{\Lambda}\epsilon_{im}\epsilon_{jn}(\overline{L_i^C}L_j)\tilde{H}_n\tilde{H}_m + {\rm h.c.},$$

- $D \in$ even (odd) if $|B-L|/2$ is even (odd) for SMEFT Kobach: 1604.05726
- $D = 6 : |B-L| = 0$ vs $D = 7 : |B-L| = 2$
- $D \in$ odd: $B/L$ is violated

| $X^3$ | |
|---|---|
| $\mathcal{O}_G$ | $f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$ |
| $\mathcal{O}_{\tilde{G}}$ | $f^{ABC}\tilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$ |
| $\mathcal{O}_W$ | $\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$ |
| $\mathcal{O}_{\tilde{W}}$ | $\epsilon^{IJK}\tilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$ |
| $H^6$ | |
| $\mathcal{O}_H$ | $(H^\dagger H)^3$ |
| $H^4D^2$ | |
| $\mathcal{O}_{H\Box}$ | $(H^\dagger H)\Box(H^\dagger H)$ |
| $\mathcal{O}_{HD}$ | $(H^\dagger D_\mu H)^*(H^\dagger D_\mu H)$ |
| $X^2H^2$ | |
| $\mathcal{O}_{HG}$ | $H^\dagger H G_{\mu\nu}^A G^{A\mu\nu}$ |
| $\mathcal{O}_{H\tilde{G}}$ | $H^\dagger H \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$ |
| $\mathcal{O}_{HW}$ | $H^\dagger H W_{\mu\nu}^I W^{I\mu\nu}$ |
| $\mathcal{O}_{H\tilde{W}}$ | $H^\dagger H \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$ |
| $\mathcal{O}_{HB}$ | $H^\dagger H B_{\mu\nu} B^{\mu\nu}$ |
| $\mathcal{O}_{H\tilde{B}}$ | $H^\dagger H \tilde{B}_{\mu\nu} B^{\mu\nu}$ |
| $\mathcal{O}_{HWB}$ | $H^\dagger \tau^I H W_{\mu\nu}^I B^{\mu\nu}$ |
| $\mathcal{O}_{H\tilde{W}B}$ | $H^\dagger \tau^I H \tilde{W}_{\mu\nu}^I B^{\mu\nu}$ |

Dim6

| $\psi^2H^3+\text{h.c.}$ | |
|---|---|
| $\mathcal{O}_{eH}$ | $(H^\dagger H)(\bar{L}eH)$ |
| $\mathcal{O}_{uH}$ | $(H^\dagger H)(\bar{Q}u\tilde{H})$ |
| $\mathcal{O}_{dH}$ | $(H^\dagger H)(\bar{Q}dH)$ |
| $\psi^2XH+\text{h.c.}$ | |
| $\mathcal{O}_{eW}$ | $(\bar{L}\sigma^{\mu\nu}e)\tau^I H W_{\mu\nu}^I$ |
| $\mathcal{O}_{eB}$ | $(\bar{L}\sigma^{\mu\nu}e)H B_{\mu\nu}$ |
| $\mathcal{O}_{uG}$ | $(\bar{Q}\sigma^{\mu\nu}T^A u)\tilde{H}G_{\mu\nu}^A$ |
| $\mathcal{O}_{uW}$ | $(\bar{Q}\sigma^{\mu\nu}u)\tau^I\tilde{H}W_{\mu\nu}^I$ |
| $\mathcal{O}_{uB}$ | $(\bar{Q}\sigma^{\mu\nu}u)\tilde{H}B_{\mu\nu}$ |
| $\mathcal{O}_{dG}$ | $(\bar{Q}\sigma^{\mu\nu}T^A d)HG_{\mu\nu}^A$ |
| $\mathcal{O}_{dW}$ | $(\bar{Q}\sigma^{\mu\nu}d)\tau^I H W_{\mu\nu}^I$ |
| $\mathcal{O}_{dB}$ | $(\bar{Q}\sigma^{\mu\nu}d)HB_{\mu\nu}$ |
| $\psi^2H^2D$ | |
| $\mathcal{O}_{Hl}^{(1)}$ | $(H^\dagger i\overleftrightarrow{D_\mu}H)(\bar{L}\gamma^\mu L)$ |
| $\mathcal{O}_{Hl}^{(3)}$ | $(H^\dagger i\overleftrightarrow{D_\mu^I}H)(\bar{L}\gamma^\mu\tau^I L)$ |
| $\mathcal{O}_{He}$ | $(H^\dagger i\overleftrightarrow{D_\mu}H)(\bar{e}\gamma^\mu e)$ |
| $\mathcal{O}_{Hq}^{(1)}$ | $(H^\dagger i\overleftrightarrow{D_\mu}H)(\bar{Q}\gamma^\mu Q)$ |
| $\mathcal{O}_{Hq}^{(3)}$ | $(H^\dagger i\overleftrightarrow{D_\mu^I}H)(\bar{Q}\gamma^\mu\tau^I Q)$ |
| $\mathcal{O}_{Hu}$ | $(H^\dagger i\overleftrightarrow{D_\mu}H)(\bar{u}\gamma^\mu u)$ |
| $\mathcal{O}_{Hd}$ | $(H^\dagger i\overleftrightarrow{D_\mu}H)(\bar{d}\gamma^\mu d)$ |
| $\mathcal{O}_{Hud}+\text{h.c.}$ | $(\tilde{H}^\dagger iD_\mu H)(\bar{u}\gamma^\mu d)$ |

| $(\bar{L}L)(\bar{L}L)$ | |
|---|---|
| $\mathcal{O}_{ll}$ | $(\bar{L}\gamma_\mu L)(\bar{L}\gamma^\mu L)$ |
| $\mathcal{O}_{qq}^{(1)}$ | $(\bar{Q}\gamma_\mu Q)(\bar{Q}\gamma^\mu Q)$ |
| $\mathcal{O}_{qq}^{(3)}$ | $(\bar{Q}\gamma_\mu\tau^I Q)(\bar{Q}\gamma^\mu\tau^I Q)$ |
| $\mathcal{O}_{lq}^{(1)}$ | $(\bar{L}\gamma_\mu L)(\bar{Q}\gamma^\mu Q)$ |
| $\mathcal{O}_{lq}^{(3)}$ | $(\bar{L}\gamma_\mu\tau^I L)(\bar{Q}\gamma^\mu\tau^I Q)$ |
| $(\bar{R}R)(\bar{R}R)$ | |
| $\mathcal{O}_{ee}$ | $(\bar{e}\gamma_\mu e)(\bar{e}\gamma^\mu e)$ |
| $\mathcal{O}_{uu}$ | $(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$ |
| $\mathcal{O}_{dd}$ | $(\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)$ |
| $\mathcal{O}_{eu}$ | $(\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)$ |
| $\mathcal{O}_{ed}$ | $(\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)$ |
| $\mathcal{O}_{ud}^{(1)}$ | $(\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)$ |
| $\mathcal{O}_{ud}^{(8)}$ | $(\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)$ |
| $(\bar{L}L)(\bar{R}R)$ | |
| $\mathcal{O}_{le}$ | $(\bar{L}\gamma_\mu L)(\bar{e}\gamma^\mu e)$ |
| $\mathcal{O}_{lu}$ | $(\bar{L}\gamma_\mu L)(\bar{u}\gamma^\mu u)$ |
| $\mathcal{O}_{ld}$ | $(\bar{L}\gamma_\mu L)(\bar{d}\gamma^\mu d)$ |
| $\mathcal{O}_{qe}$ | $(\bar{Q}\gamma_\mu Q)(\bar{e}\gamma^\mu e)$ |
| $\mathcal{O}_{qu}^{(1)}$ | $(\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$ |
| $\mathcal{O}_{qu}^{(8)}$ | $(\bar{Q}\gamma_\mu T^A Q)(\bar{u}\gamma^\mu T^A u)$ |
| $\mathcal{O}_{qd}^{(1)}$ | $(\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$ |
| $\mathcal{O}_{qd}^{(8)}$ | $(\bar{Q}\gamma_\mu T^A Q)(\bar{d}\gamma^\mu T^A d)$ |
| $(\bar{L}R)(\bar{R}L)+\text{h.c.}$ | |
| $\mathcal{O}_{ledq}$ | $(\bar{L}e)(\bar{d}Q)$ |
| $(\bar{L}R)(\bar{L}R)+\text{h.c.}$ | |
| $\mathcal{O}_{quqd}^{(1)}$ | $\epsilon_{ij}(\bar{Q}^i u)(\bar{Q}^j d)$ |
| $\mathcal{O}_{quqd}^{(8)}$ | $\epsilon_{ij}(\bar{Q}^i T^A u)(\bar{Q}^j T^A d)$ |
| $\mathcal{O}_{lequ}^{(1)}$ | $\epsilon_{ij}(\bar{L}^i e)(\bar{Q}^j u)$ |
| $\mathcal{O}_{lequ}^{(3)}$ | $\epsilon_{ij}(\bar{L}^i\sigma_{\mu\nu}e)(\bar{Q}^j\sigma^{\mu\nu}u)$ |

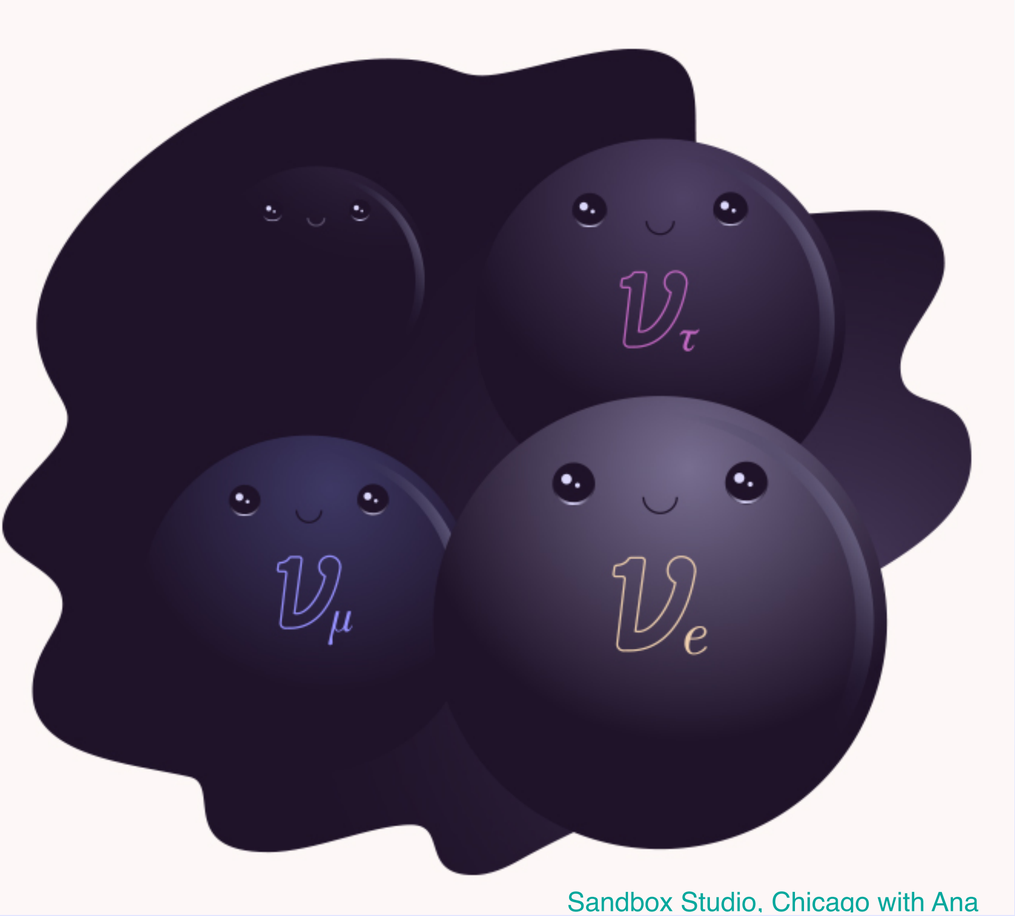
| $\psi^2H^4$ | |
|---|---|
| $\mathcal{O}_{LH}$ | $\epsilon_{ij}\epsilon_{mn}(\overline{L^{c,i}}L^m)H^jH^n(H^\dagger H)$ |
| $\psi^2H^2D^2$ | |
| $\mathcal{O}_{LDH1}\ (\star)$ | $\epsilon_{ij}\epsilon_{mn}(\overline{L^{c,i}}\overleftrightarrow{D_\mu}L^j)(H^mD^\mu H^n)$ |
| $\mathcal{O}_{LDH2}\ (\star)$ | $\epsilon_{im}\epsilon_{jn}(\overline{L^{c,i}}L^j)(D_\mu H^mD^\mu H^n)$ |
| $\psi^4D$ | |
| $\mathcal{O}_{\bar{d}uLDL}\ (\star)$ | $\epsilon_{ij}(\bar{d}\gamma_\mu u)(\overline{L^{c,i}}i\overleftrightarrow{D}^\mu L^j)$ |

Dim7

| $\psi^2H^3D$ | |
|---|---|
| $\mathcal{O}_{LeHD}$ | $\epsilon_{ij}\epsilon_{mn}(\overline{L^{c,i}}\gamma_\mu e)H^j(H^m iD^\mu H^n)$ |
| $\psi^2H^2X$ | |
| $\mathcal{O}_{LHB}$ | $g_1\epsilon_{ij}\epsilon_{mn}(\overline{L^{c,i}}\sigma_{\mu\nu}L^m)H^jH^nB^{\mu\nu}$ |
| $\mathcal{O}_{LHW}$ | $g_2\epsilon_{ij}(\epsilon\tau^I)_{mn}(\overline{L^{c,i}}\sigma_{\mu\nu}L^m)H^jH^nW^{I\mu\nu}$ |
| $\psi^4H$ | |
| $\mathcal{O}_{\bar{e}LLLH}$ | $\epsilon_{ij}\epsilon_{mn}(\bar{e}L^i)(\overline{L^{c,j}}L^m)H^n$ |
| $\mathcal{O}_{\bar{d}QLLH1}\ (\star)$ | $\epsilon_{ij}\epsilon_{mn}(\bar{d}Q^i)(\overline{L^{c,j}}L^m)H^n$ |
| $\mathcal{O}_{\bar{d}QLLH2}\ (\star)$ | $\epsilon_{ij}\epsilon_{mn}(\bar{d}\sigma_{\mu\nu}Q^i)(\overline{L^{c,j}}\sigma^{\mu\nu}L^m)H^n$ |
| $\mathcal{O}_{\bar{d}uLeH}\ (\star)$ | $\epsilon_{ij}(\bar{d}\gamma_\mu u)(\overline{L^{c,i}}\gamma^\mu e)H^j$ |
| $\mathcal{O}_{\bar{Q}uLLH}$ | $\epsilon_{ij}(\bar{Q}u)(\overline{L^c}L^i)H^j$ |

- All the SM $\nu$—involved operators must contain $L$
- Within the SMEFT, $\nu$—operators are quite limited

# $\nu$SMEFT = SMEFT + sterile neutrino $(N)$




Sandbox Studio, Chicago with Ana

- Neutrino mass — Dirac/Majorana mass
- Dark matter
- Baryogenesis
- LSND MiniBooNE— $\nu_e$ excess
- Gallium anomaly
- Portal to a dark sector
- Long-lived particle (heavy neutral leptons)

LSND (1998) —> MiniBooNE (2007) —> MINOS —> Daya Bay (2014) —> MINOS+—> IceCube (2016) —> MiniBooNE (2018) —> MicroBooNE (2021) —> BEST (2022) —> STEREO (2023)

Liao, Ma, 1612.04527

$$\mathscr{L}_{\nu\text{SMEFT}} = \mathscr{L}_{\text{SMEFT}} + \mathscr{L}^N_{\text{dim5}} + \mathscr{L}^N_{\text{dim6}} + \mathscr{L}^N_{\text{dim7}} + \mathscr{L}^N_{\text{dim8}} + \mathscr{L}^N_{\text{dim9}} + \cdots$$

Aparici et al, 0904.3244

del Aguila et al, 0806.0876
Bhattacharya, Wudka, 1505.05264

Li et al, 2105.09329

$$\mathscr{L}^N_{\text{dim5}} = \frac{\hat{C}_{NH}}{\Lambda}(\overline{N^C}N)H^\dagger H + \frac{\hat{C}_{NB}}{\Lambda}(\overline{N^C}\sigma_{\mu\nu}N)B^{\mu\nu} + \text{h.c.},$$

$\mathscr{L}^N_{\text{dim6}} =$

| $\psi^2H^3$ | |
|---|---|
| $\mathscr{O}_{LNH}(+\text{h.c.})$ | $(\bar{L}N)\tilde{H}(H^\dagger H)$ |
| $\psi^2H^2D$ | |
| $\mathscr{O}_{HN}$ | $(\bar{N}\gamma^\mu N)(H^\dagger i\overleftrightarrow{D}_\mu H)$ |
| $\mathscr{O}_{HNe}(+\text{h.c.})$ | $(\bar{N}\gamma^\mu e)(\tilde{H}^\dagger iD_\mu H)$ |
| $\psi^2HX(+\text{h.c.})$ | |
| $\mathscr{O}_{NB}$ | $(\bar{L}\sigma_{\mu\nu}N)\tilde{H}B^{\mu\nu}$ |
| $\mathscr{O}_{NW}$ | $(\bar{L}\sigma_{\mu\nu}N)\tau^I\tilde{H}W^{I\mu\nu}$ |
| $(\bar{L}R)(\bar{R}L)(+\text{h.c.})$ | |
| $\mathscr{O}_{QuNL}$ | $(\bar{Q}u)(\bar{N}L)$ |

| $(\bar{L}R)(\bar{L}R)(+\text{h.c.})$ | |
|---|---|
| $\mathscr{O}_{LNLe}$ | $(\bar{L}N)\varepsilon(\bar{L}e)$ |
| $\mathscr{O}_{LNQd}$ | $(\bar{L}N)\varepsilon(\bar{Q}d))$ |
| $\mathscr{O}_{LdQN}$ | $(\bar{L}d)\varepsilon(\bar{Q}N)$ |
| $(\bar{R}R)(\bar{R}R)$ | |
| $\mathscr{O}_{NN}$ | $(\bar{N}\gamma^\mu N)(\bar{N}\gamma_\mu N)$ |
| $\mathscr{O}_{eN}$ | $(\bar{e}\gamma^\mu e)(\bar{N}\gamma_\mu N)$ |
| $\mathscr{O}_{uN}$ | $(\bar{u}\gamma^\mu u)(\bar{N}\gamma_\mu N)$ |
| $\mathscr{O}_{dN}$ | $(\bar{d}\gamma^\mu d)(\bar{N}\gamma_\mu N)$ |
| $\mathscr{O}_{duNe}(+\text{h.c.})$ | $(\bar{d}\gamma^\mu u)(\bar{N}\gamma_\mu e)$ |

| $(\bar{L}L)(\bar{R}R)$ | |
|---|---|
| $\mathscr{O}_{LN}$ | $(\bar{L}\gamma^\mu L)(\bar{N}\gamma_\mu N)$ |
| $\mathscr{O}_{QN}$ | $(\bar{Q}\gamma^\mu Q)(\bar{N}\gamma_\mu N)$ |
| $(\not{L}\cap B)(+\text{h.c.})$ | |
| $\mathscr{O}_{NNNN}$ | $(\overline{N^C}N)(\overline{N^C}N)$ |
| $(\not{L}\cap \not{B})(+\text{h.c.})$ | |
| $\mathscr{O}_{QQdN}$ | $\varepsilon_{ij}\varepsilon_{\alpha\beta\sigma}(\overline{Q^{i,C}_\alpha}Q^j_\beta)(\overline{d^C_\sigma}N)$ |
| $\mathscr{O}_{uddN}$ | $\varepsilon_{\alpha\beta\sigma}(\overline{u^C_\alpha}d_\beta)(\overline{d^C_\sigma}N)$ |

# LEFT and $\nu$LEFT

- **Fields:** $u,\ d, s,\ c,\ b;\ \ e,\ \mu,\ \tau;\ \ \nu_e, \nu_\mu, \nu_\tau\ + N_i$ (sterile neutrino)
- **Symmetry:** $SU(3)_{\rm C} \times U(1)_{\rm em}$
- **Power counting: canonical dimension** $D$
- **Range:** $\ll \Lambda_{\rm EW}$

**Weak effective field theory can be treated as the LEFT of SM**

Buchalla, Buras and Lautenbacher, 1996

*Jenkins, Manohar, Stoffer, 2018*

*Li, Ren, Xiao, Yu, Zheng, 2020*

$$\mathscr{L}_{\text{LEFT}} = \mathscr{L}_{\dim\leq 4} + \sum_{\dim 5,i} \frac{\hat{C}_{5,i}}{\Lambda} Q^i_{\dim-5} + \sum_{\dim 6,i} \frac{\hat{C}_{6,i}}{\Lambda^2} Q^i_{\dim-6} + \sum_{\dim 7,i} \frac{\hat{C}_{7,i}}{\Lambda^3} Q^i_{\dim-7} + \sum_{\dim 8,i} \frac{\hat{C}_{8,i}}{\Lambda^4} Q^i_{\dim-8} + \sum_{\dim 9,i} \frac{\hat{C}_{9,i}}{\Lambda^5} Q^i_{\dim-9} + \cdots$$

*Liao, Ma, Wang, 2020*

*Murphy, 2020*

**All $D \geq 5$ operators $\Longleftrightarrow$ weak and/or NP interactions**

Important to parametrize many key low energy observables:

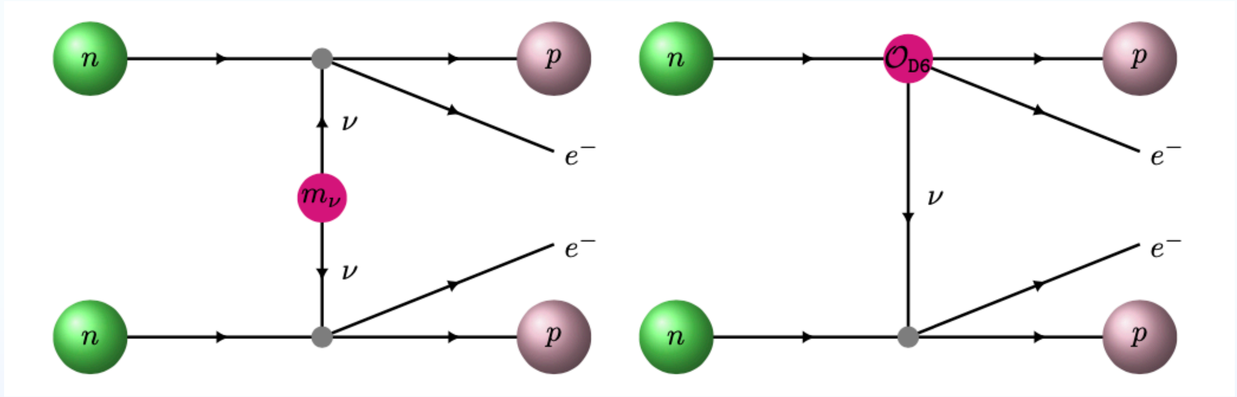
- Flavor physics: mesons and baryons
- Lepton physics: tau and muon
- BNV, LNV, LFV processes
- ……

# Direct $\nu$ processes

- Neutrino mass: $\bar{\nu}\nu'$
- Neutrino dipole moments: $\bar{\nu}\sigma_{\mu\nu}(i\gamma_5)\nu' F^{\mu\nu}$
- Neutrino NSI, LFV: $(\bar{\nu}\Gamma\nu')(\bar{\ell}\Gamma'\ell')$
- Neutrino NSI, FCNC: $(\bar{\nu}\Gamma\nu')(\bar{q}\Gamma'q')$
- Hadron decay: $(\bar{\nu}\Gamma\ell)(\bar{q}\Gamma'q')$
- Neutrino SI: $(\bar{\nu}\Gamma\nu')(\bar{\nu}''\Gamma'\nu''')$
- BNV: $(\bar{\nu}\Gamma q)(q'C\Gamma'q''')$
- ...

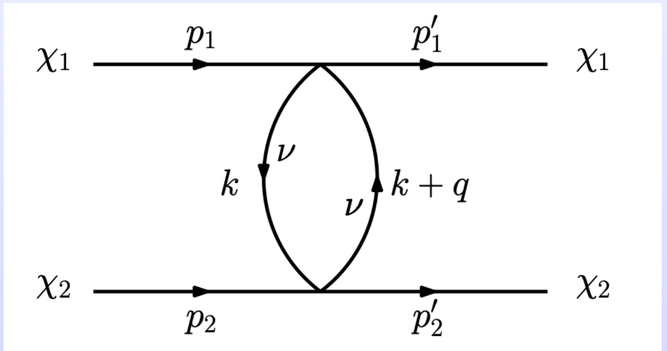
# Indirect $\nu$ processes

- $0\nu\beta\beta$




Mass mechanism  Long-distance

- Neutrino force




$\chi$: SM leptons/quarks

Mitrajyoti Ghosh, Yuval Grossman, Walter Tangarife, Xun-Jie Xu, Bingrong Yu, 2405.16801

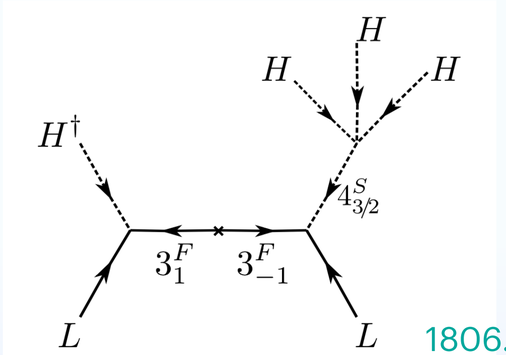
# UV completion of EFT operators

**Given an EFT operator, to construct some UV models by appealing to some heavy new fields**

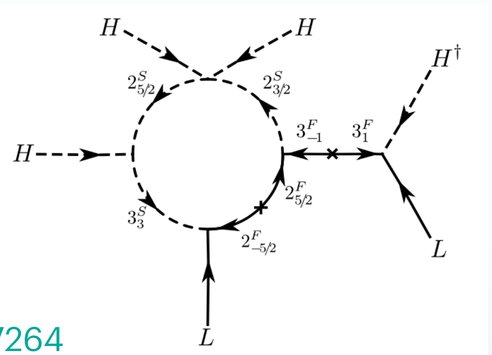
* Usually, assume the SM gauge symmetry intact
* Internal heavy fields: scalar, fermion, vector

- Generate topologies and diagrams
- Assign external and internal fields
- Select genuine topologies

- Dim-n Weinberg operator



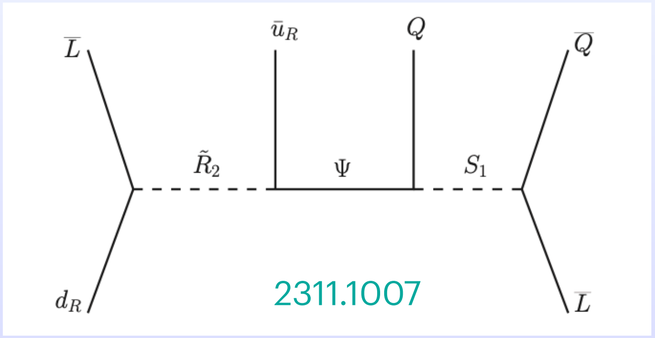

1806.07264




- Tree-level
- 1-loop
- 2-loop

Anamiati et al: 1806.07264
Bonnet et al: 1204.5862
Cai et a : 1706.08524
Hirsch1411.7038, ...

- $0\nu\beta\beta$ operators: dim-7 LD and dim-9 SD




2311.1007

Chen, Ding, Yao: 2110.15347, 2301.02503

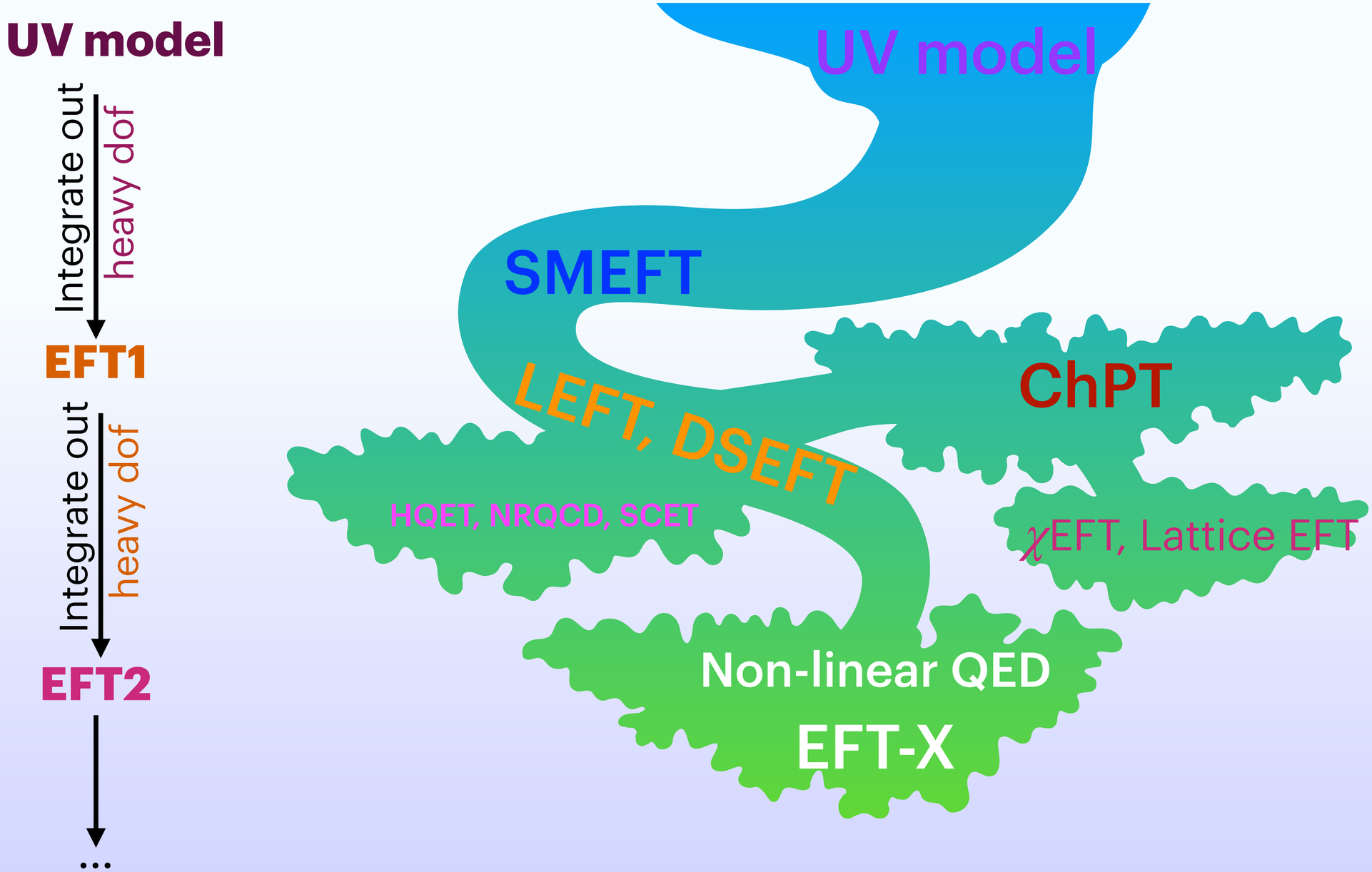
Li, Zhao, Yu: 2311.10079

$\nu$SMEFT: Beltran et al: 2306.12578

Dim <= 8:

Li et al: 2204.03660, 2307.10380, 2309.15933

# Top-down EFT


UV model
Integrate out
heavy dof
EFT1
Integrate out
heavy dof
EFT2
UV model
SMEFT
LEFT, DSEFT
ChPT
HQET, NRQCD, SCET
χEFT, Lattice EFT
Non-linear QED
EFT-X

# EFT for neutrino mass models

## Famous models

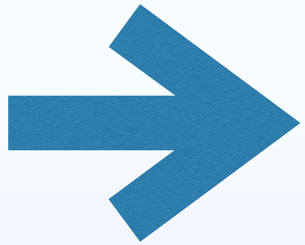
Type-I seesaw: SM + $F(1,1,0)$

Type-II seesaw: SM + $S(1,3,1)$

Type-III seesaw: SM + $F(1,3,1)$

Zee model: SM + $S(1,2,1/2) + S(1,1,1)$

Scotogenic model: SM + $\mathbb{Z}_2 + F(1,1,0)_{-1} + S(1,2,1/2)_{-1}$



Li, Zhang, Zhou, 2107.12133, 2201.05082, 2309.14702 (I, II, III)

Ohlsson , Pernow, 2201.00840 (I)

Coy, Frigerio, 2110.09126 (I, III, Zee)

Du, Li, Yu, 2201.04646 (I, II, III)

Liao, Ma, 2210.04270 (Scoto)

Two Higgs doublet model

Leptoquark model

Singlet scalar model, etc

# Matching techniques — diagrammatic approach

$$\mathscr{M}(\{i\} \to \{j\})_{\mathrm{UV}} = \mathscr{M}(\{i\} \to \{j\})_{\mathrm{EFT}}$$

- Design a complete set of Green's functions (operator basis)
- Compute them in both theories
- Identify the EFT WCs in terms of UV model parameters
- Automatic tools: *Matchmakereft*, 2112.10787

On-shell matching: Li, Zhou: 2309.10851

# Matching techniques — functional approach

Cohen, et al: 1912.08814, 2011.02484, 2012.07851
Fuentes-Martin et al: 2012.08506, 2212.04510 , 2311.13630 (Matchete)

$$\mathcal{O}_{\rm UV} \equiv -\frac{\delta^2 \mathcal{L}_{\rm UV}}{\delta\varphi^2}\Big|_{\varphi_c} = -\begin{pmatrix} \frac{\delta^2\mathcal{L}_{\rm UV}}{\delta\Phi^2}\Big|_{\varphi_c} & \frac{\delta^2\mathcal{L}_{\rm UV}}{\delta\Phi\delta\phi}\Big|_{\varphi_c} \\ \frac{\delta^2\mathcal{L}_{\rm UV}}{\delta\phi\delta\Phi}\Big|_{\varphi_c} & \frac{\delta^2\mathcal{L}_{\rm UV}}{\delta\phi^2}\Big|_{\varphi_c} \end{pmatrix} \equiv \begin{pmatrix} \Delta_\Phi & X_{\Phi\phi} \\ X_{\phi\Phi} & \Delta_\phi \end{pmatrix}.$$

$$\Gamma^{\rm tree}_{\rm L,UV}[\phi_c] = \int \mathrm{d}^d x \mathcal{L}_{\rm UV}[\varphi_c]\Big|_{\Phi_c=\Phi_c[\phi_c]}, \qquad \Gamma_{\rm EFT}[\phi_c] = \int \mathrm{d}^d x \mathcal{L}^{\rm tree}_{\rm EFT}[\phi_c],$$

$$\Gamma^{\text{1-loop}}_{\rm L,UV}[\phi_c] = \frac{i}{2}\mathrm{STr}[\ln(\mathcal{O}_{\rm UV})]\Big|_{\Phi_c=\Phi_c[\phi_c]}. \qquad \Gamma_{\text{1-loop}}[\phi_c] = \int \mathrm{d}^d x \mathcal{L}^{\text{1-loop}}_{\rm EFT}[\phi_c] + \frac{i}{2}\mathrm{STr}[\ln(\mathcal{O}_{\rm EFT})].$$

$$\mathcal{L}^{\rm tree}_{\rm EFT}[\phi_c] = \mathcal{L}_{\rm UV}[\Phi_c, \phi_c]\Big|_{\Phi_c=\Phi_c[\phi_c]},$$

$$\int \mathrm{d}^d x \mathcal{L}^{\text{1-loop}}_{\rm EFT}[\phi_c] = \frac{i}{2}\mathrm{STr}[\ln(\mathcal{O}_{\rm UV})]\Big|_{\Phi_c=\Phi_c[\phi_c]} - \frac{i}{2}\mathrm{STr}[\ln(\mathcal{O}_{\rm EFT})].$$

$$\int \mathrm{d}^d x \mathcal{L}^{\text{1-loop}}_{\rm EFT}[\phi] = \frac{i}{2}\mathrm{STr}\left[\ln(\boldsymbol{K})\right]\Big|_{\rm Hard} - \frac{i}{2}\sum_{n=1}^{\infty}\frac{1}{n}\mathrm{STr}\left[\left(\boldsymbol{K}^{-1}\boldsymbol{X}\right)^n\right]\Big|_{\rm Hard},$$

- 1 light particle irreducible amp.
- Covariant derivative expansion
- Integration by regions

Beneke and V.A. Smirnov: 9711391
Smirnov: Applied asymptotic expansions in momenta and masses

# A Quick tour for phenomenologies

Focus on a few cases we have toched upon recently.

# Neutrino EM property—without right-hand $\nu_R$

mdm: $\bar{\nu}\sigma_{\mu\nu}\nu F^{\mu\nu}$

edm: $\bar{\nu}i\sigma_{\mu\nu}\gamma_5\nu F^{\mu\nu}$

Charge radius: $\bar{\nu}\gamma_\mu\nu\partial_\nu F^{\mu\nu}$

Anapole moment: $\bar{\nu}\gamma_\mu\gamma_5\nu\partial_\nu F^{\mu\nu}$

polarizability: $\bar{\nu}(\gamma_5)\nu F_{\mu\nu}F^{\mu\nu}$

**Transition moments for Majorana neutrinos**

Terrestrial exp: DMDD ($\nu_\odot$), $\nu$ exp

Astrophysics: Stellar Cooling

Cosmology: BBN, CMB

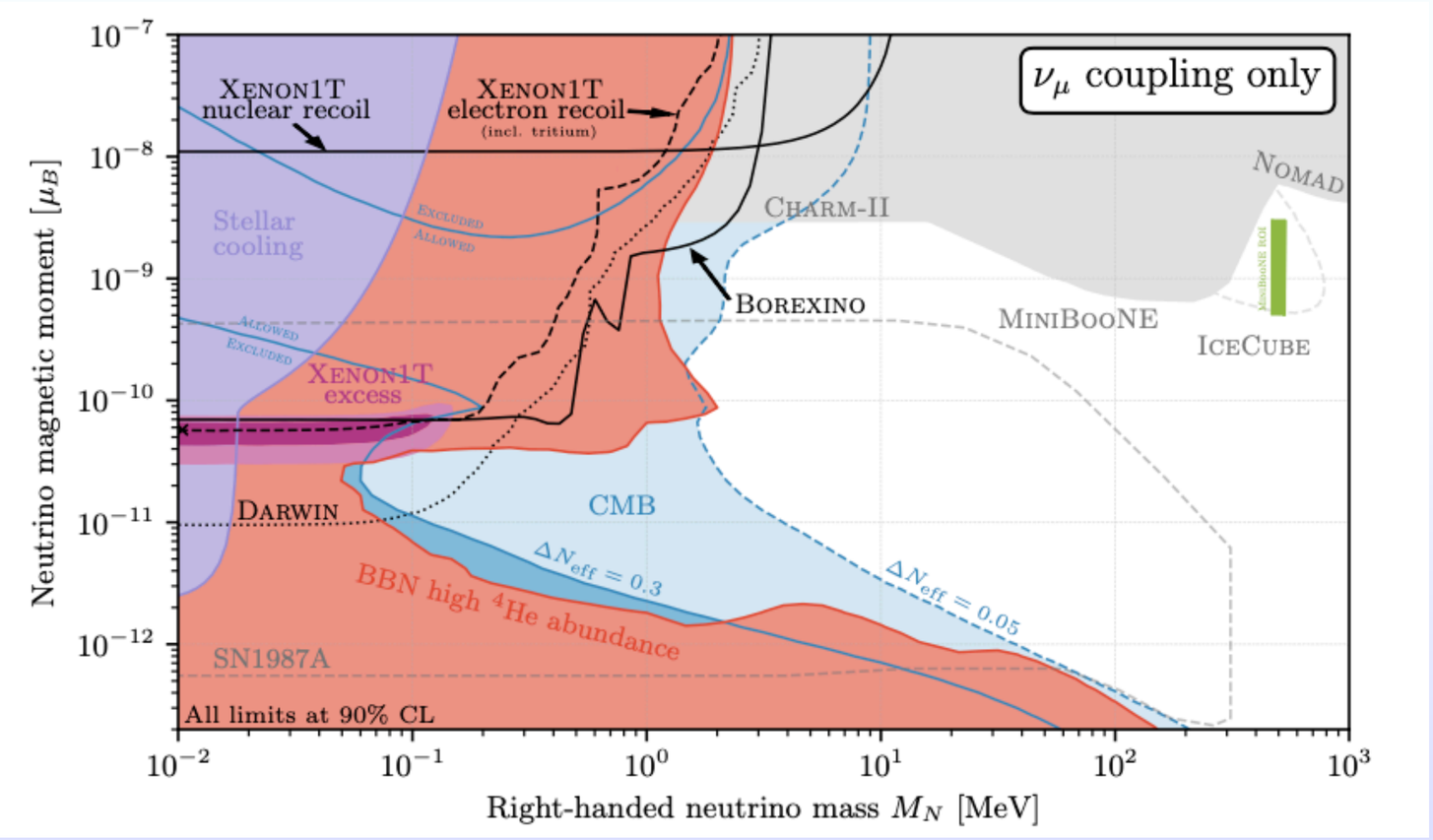
Accelerator:

Dicus, Repka, 1997, PRL $\bar{\nu}\gamma_\mu \overleftrightarrow{\partial}_\nu \nu F^{\mu\lambda}F^{\nu}{}_{\lambda}$ $\propto G_F^2$

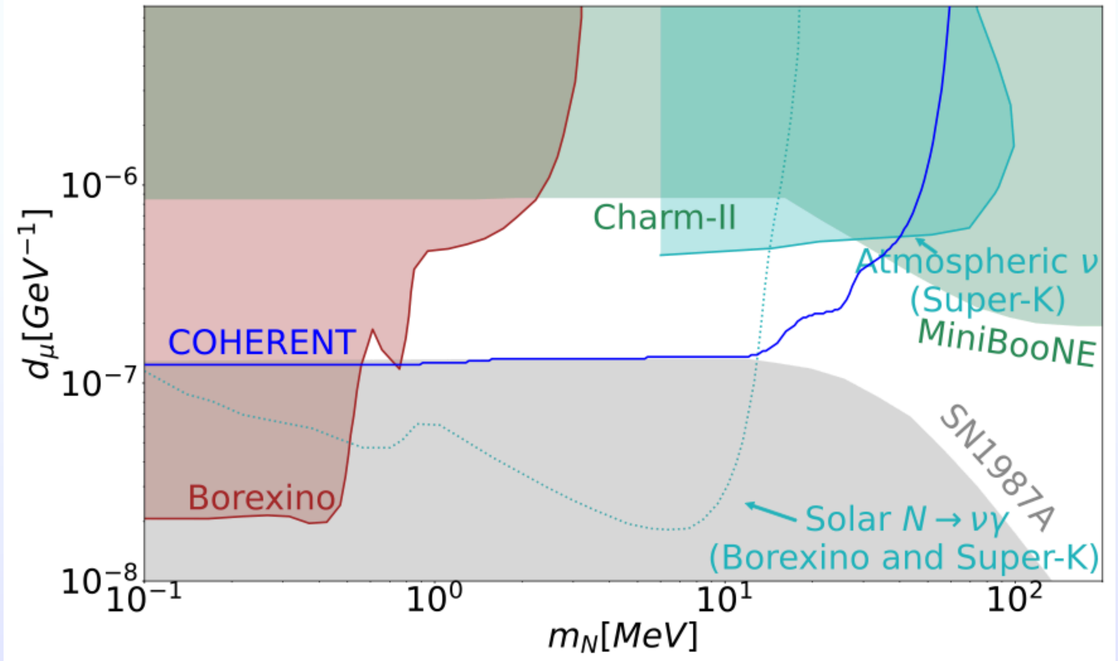
**SM:** $\partial_{[\mu}\bar{\nu}\gamma_{\nu]}\nu F^{\mu\nu}F_{\alpha\beta}F^{\alpha\beta}$, $\partial_{[\mu}\bar{\nu}\gamma_{\nu]}\nu F^{\mu}{}_{\alpha}F^{\alpha}{}_{\beta}F^{\beta\nu}$ $\propto G_F m_e^{-4}$

# Neutrino EM property—with right-hand $\nu_R$

$$\mathscr{L}_{\text{edm}} = \frac{1}{2} d_\mu \bar{N} \sigma_{\mu\nu} \nu_\mu F^{\mu\nu}$$



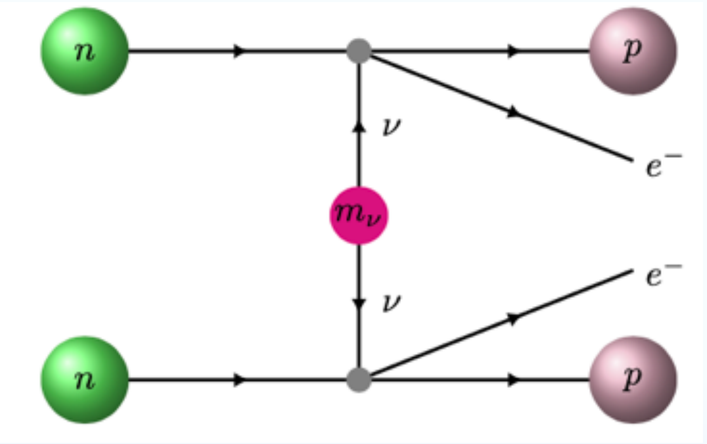

Brdar, Greljo, Kopp, Opferkuch: 2105.06846

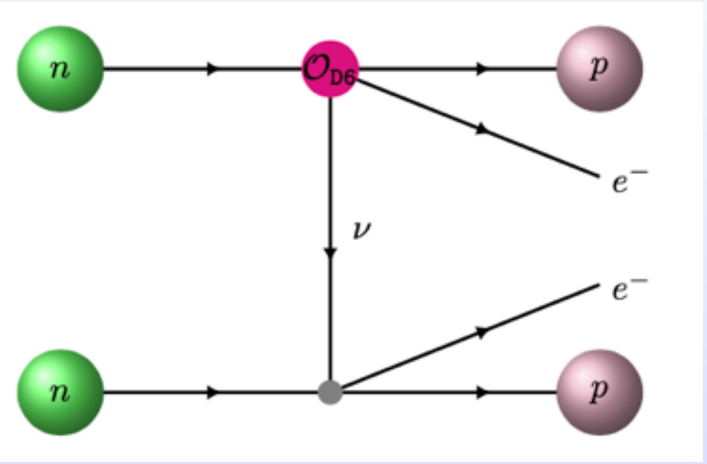



Recenet works by
Carlo Giunti, Konstantin Kouzakov, Yu-Feng Li, and Alexander Studenikin, 2411.03122
Ying-Ying Li, Yu-Feng Li, and Shuo-Yu Xia, arXiv:2406.07477v1

# LNV— $0\nu\beta\beta$ from SMEFT dim-7 interactions with loop effect

| Dim-7 SMEFT operators: $(\Delta B, \Delta L) = (0, 2)$ | | | | |
|---|---|---|---|---|
| Classes | Original operator basis in [17, 18] | Basis in [19, 20] | Relations of the two different notations | WC name in D7RGESolver |
| $\psi^2 H^4$ | $\mathcal{O}^{pr}_{LH} = \epsilon_{ij}\epsilon_{mn}\left(\overline{L^{i\mathtt{C}}_p} L^m_r\right) H^j H^n (H^\dagger H)$ | $\mathcal{O}^{pr}_{LH}$ | same | LH_pr |
| $\psi^2 H^3 D$ | $\mathcal{O}^{pr}_{LeHD} = \epsilon_{ij}\epsilon_{mn}\left(\overline{L^{i\mathtt{C}}_p}\gamma_\mu e_r\right) H^j H^m i D^\mu H^n$ | $\mathcal{O}^{pr}_{LeDH}$ | $= \mathcal{O}^{pr}_{LeHD}$ | LeDH_pr |
| $\psi^2 H^2 D^2$ | $\mathcal{O}^{pr}_{LHD1} = \epsilon_{ij}\epsilon_{mn}\left(\overline{L^{i\mathtt{C}}_p} D^\mu L^j_r\right) H^m D_\mu H^n$ | $\mathcal{O}^{pr}_{DLDH1}$ | $= \frac{1}{2}\left(\mathcal{O}^{pr}_{LHD1} + \mathcal{O}^{rp}_{LHD1}\right)$ | DLDH1_pr |
| | $\mathcal{O}^{pr}_{LHD2} = \epsilon_{im}\epsilon_{jn}\left(\overline{L^{i\mathtt{C}}_p} D^\mu L^j_r\right) H^m D_\mu H^n$ | $\mathcal{O}^{pr}_{DLDH2}$ | $= \frac{1}{2}\left(\mathcal{O}^{pr}_{LHD2} + \mathcal{O}^{rp}_{LHD2}\right)$ | DLDH2_pr |
| $\psi^2 H^2 X$ | $\mathcal{O}^{pr}_{LHB} = \epsilon_{ij}\epsilon_{mn}\left(\overline{L^{i\mathtt{C}}_p}\sigma_{\mu\nu} L^m_r\right) H^j H^n B^{\mu\nu}$ | $\mathcal{O}^{pr}_{LHB}$ | same | LHB_pr |
| | $\mathcal{O}^{pr}_{LHW} = \epsilon_{ij}(\epsilon\tau^I)_{mn}\left(\overline{L^{i\mathtt{C}}_p}\sigma_{\mu\nu} L^m_r\right) H^j H^n W^{I\mu\nu}$ | $\mathcal{O}^{pr}_{LHW}$ | same | LHW_pr |
| $\psi^4 H$ | $\mathcal{O}^{prst}_{\bar{e}LLLH} = \epsilon_{ij}\epsilon_{mn}\left(\overline{e_p} L^i_r\right)\left(\overline{L^{j\mathtt{C}}_s} L^m_t\right) H^n$ | $\mathcal{O}^{(\mathtt{S}),prst}_{\bar{e}LLLH}$ | $= \frac{1}{6}\left(\mathcal{O}^{prst}_{\bar{e}LLLH} + \mathcal{O}^{pstr}_{\bar{e}LLLH} + \mathcal{O}^{ptrs}_{\bar{e}LLLH}\right) + s \leftrightarrow t$ | eLLLHS_prst |
| | | $\mathcal{O}^{(\mathtt{A}),prst}_{\bar{e}LLLH}$ | $= \frac{1}{6}\left(\mathcal{O}^{prst}_{\bar{e}LLLH} + \mathcal{O}^{pstr}_{\bar{e}LLLH} + \mathcal{O}^{ptrs}_{\bar{e}LLLH}\right) - s \leftrightarrow t$ | eLLLHA_prst |
| | | $\mathcal{O}^{(\mathtt{M}),prst}_{\bar{e}LLLH}$ | $= \frac{1}{3}\left(\mathcal{O}^{prst}_{\bar{e}LLLH} + \mathcal{O}^{psrt}_{\bar{e}LLLH}\right) - t \leftrightarrow r$ | eLLLHM_prst |
| | $\mathcal{O}^{prst}_{\bar{d}LQLH1} = \epsilon_{ij}\epsilon_{mn}\left(\overline{d_p} L^i_r\right)\left(\overline{Q^{j\mathtt{C}}_s} L^m_t\right) H^n$ | $\mathcal{O}^{prst}_{\bar{d}LQLH1}$ | same | dLQLH1_prst |
| | $\mathcal{O}^{prst}_{\bar{d}LQLH2} = \epsilon_{im}\epsilon_{jn}\left(\overline{d_p} L^i_r\right)\left(\overline{Q^{j\mathtt{C}}_s} L^m_t\right) H^n$ | $\mathcal{O}^{prst}_{\bar{d}LQLH2}$ | same | dLQLH2_prst |
| | $\mathcal{O}^{prst}_{\bar{d}LueH} = \epsilon_{ij}\left(\overline{d_p} L^i_r\right)\left(\overline{u^{\mathtt{C}}_s} e_t\right) H^j$ | $\mathcal{O}^{prst}_{\bar{d}LueH}$ | same | dLueH_prst |
| | $\mathcal{O}^{prst}_{\bar{Q}uLLH} = \epsilon_{ij}\left(\overline{Q_p} u_r\right)\left(\overline{L^{\mathtt{C}}_s} L^i_t\right) H^j$ | $\mathcal{O}^{prst}_{\bar{Q}uLLH}$ | same | QuLLH_prst |
| $\psi^4 D$ | $\mathcal{O}^{prst}_{\bar{d}uLLD} = \epsilon_{ij}\left(\overline{d_p}\gamma_\mu u_r\right)\left(\overline{L^{i\mathtt{C}}_s} i D^\mu L^j_t\right)$ | $\mathcal{O}^{prst}_{\bar{d}uLDL}$ | $= \frac{1}{2}\left(\mathcal{O}^{prst}_{\bar{d}uLLD} + \mathcal{O}^{prts}_{\bar{d}uLLD}\right)$ | duLDL_prst |



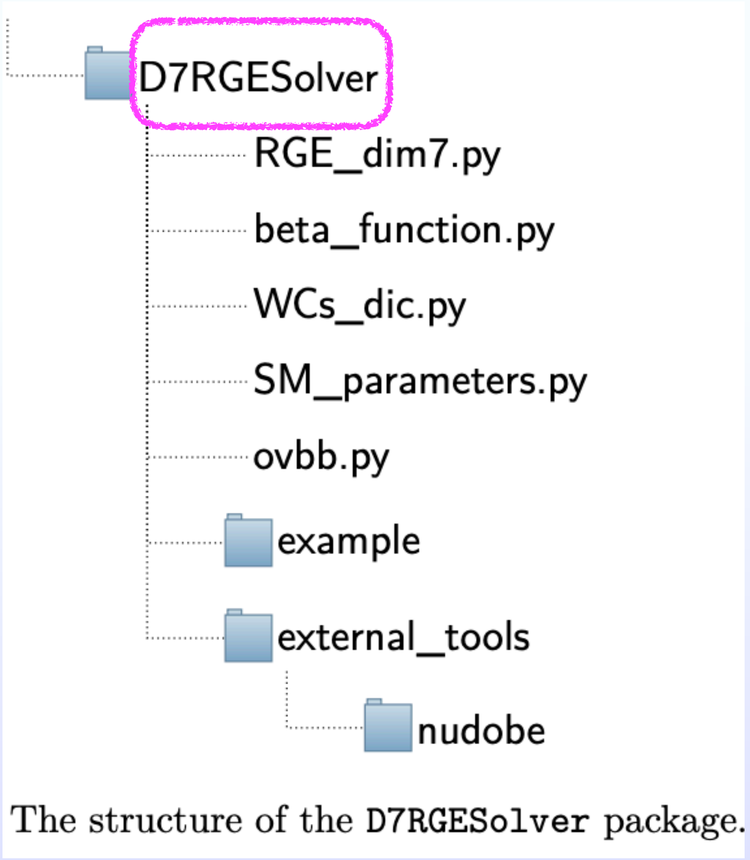




+ short-distance contribution

# LNV— $0\nu\beta\beta$ from SMEFT dim-7 interactions with loop effect

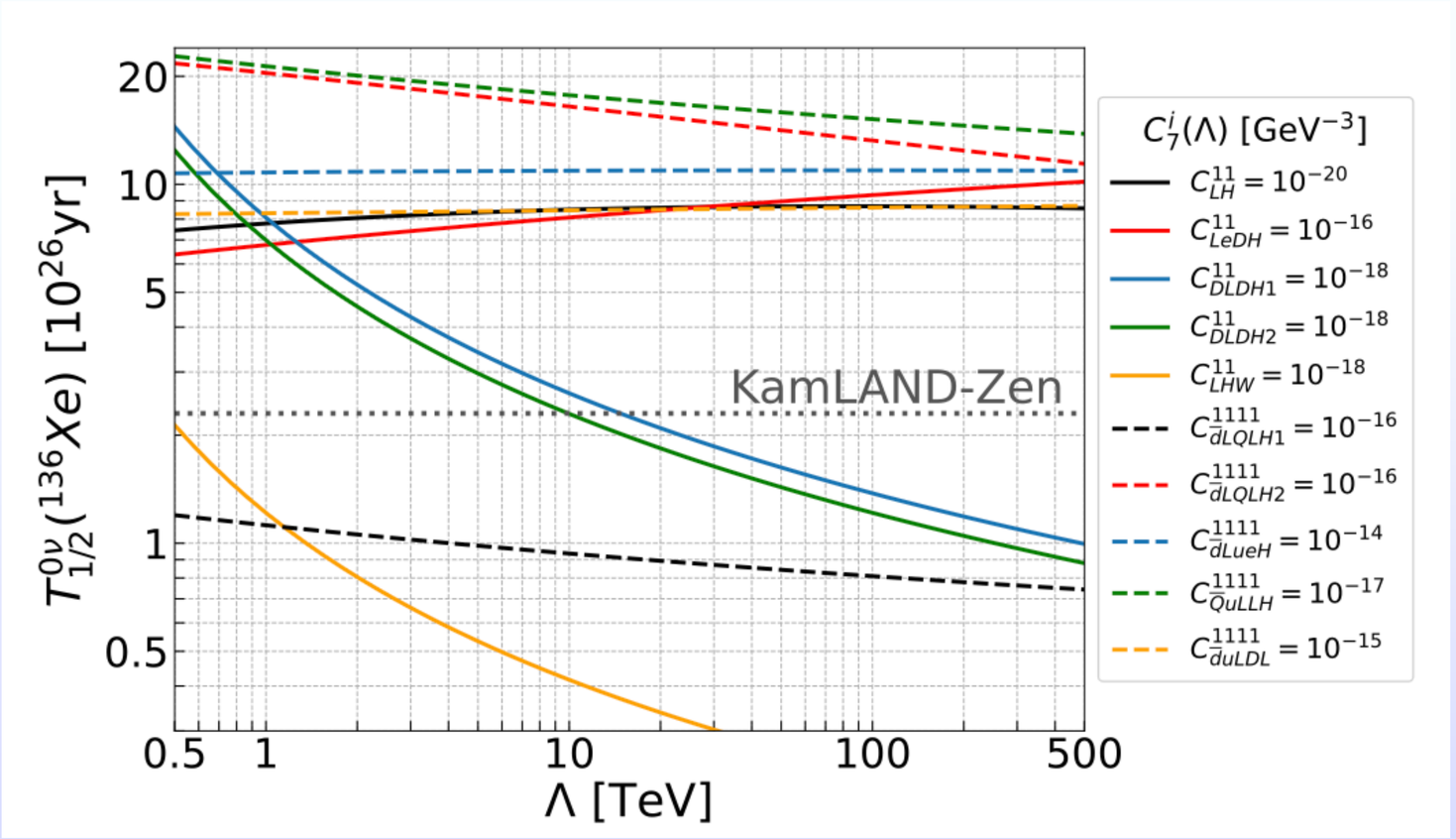
Yi Liao, XDM, Hao-Lin Wang, Xiang Zhao, 2505.06499

Solve the complete RGEs of dim-7 operators




The structure of the D7RGESolver package.

RG running effect on $0\nu\beta\beta$




O. Scholer, J. de Vries and L. Gráf, vDoBe, 2306.08709
Di Zhang, 2310.11055
L. Gráf, C. Hati, A. Martín-Galán and O. Scholer, 2504.00081

# LNV— $0\nu\beta\beta$ from SMEFT dim-7 interactions with loop effect

Yi Liao, XDM, Hao-Lin Wang, Xiang Zhao, 2505.06499

| RGE-improved constraints on the dimensionless WCs $c_7^i$ at $\Lambda = 10$ TeV | | | | |
|---|---|---|---|---|
| Operator | $\lvert c_7^i\rvert \equiv \lvert\Lambda^3 C_7^i(\Lambda)\rvert$ | Operator | $\lvert c_7^i\rvert \equiv \lvert\Lambda^3 C_7^i(\Lambda)\rvert$ | |
| | Same in both bases | | Up-quark flavor basis | Down-quark flavor basis |
| $\mathcal{O}_{LH}^{11}$ | $1.92 \times 10^{-8}$ | $\mathcal{O}_{\overline{Q}uLLH}^{1111}$ | $2.85 \times 10^{-5}$ | $2.78 \times 10^{-5}$ |
| $\mathcal{O}_{LeDH}^{11}$ | $1.88 \times 10^{-4}$ | $\mathcal{O}_{\overline{Q}uLLH}^{1211}$ | $8.58 \times 10^{5}$ | $4.48 \times 10^{-4}$ |
| $\mathcal{O}_{DLDH1}^{11}$ | $1.07 \times 10^{-6}$ | $\mathcal{O}_{\overline{Q}uLLH}^{1311}$ | $3.51$ | $6.50 \times 10^{-6}$ |
| $\mathcal{O}_{DLDH2}^{11}$ | $9.99 \times 10^{-7}$ | $\mathcal{O}_{\overline{Q}uLLH}^{2111}$ | $1.24 \times 10^{-4}$ | $2.65 \times 10^{-1}$ |
| $\mathcal{O}_{LHW}^{11}$ | $4.26 \times 10^{-7}$ | $\mathcal{O}_{\overline{Q}uLLH}^{2211}$ | $1.00 \times 10^{-4}$ | $1.03 \times 10^{-4}$ |
| $\mathcal{O}_{\overline{e}LLLH}^{(\mathrm{M}),2112}$ | $1.76 \times 10^{-3}$ | $\mathcal{O}_{\overline{Q}uLLH}^{2311}$ | $3.01 \times 10^{-1}$ | $1.43 \times 10^{-6}$ |
| $\mathcal{O}_{\overline{e}LLLH}^{(\mathrm{M}),3113}$ | $1.05 \times 10^{-4}$ | $\mathcal{O}_{\overline{Q}uLLH}^{3111}$ | $3.24 \times 10^{-3}$ | $5.38 \times 10^{-2}$ |
| $\mathcal{O}_{\overline{e}LLLH}^{(\mathrm{S}),1111}$ | $2.59 \times 10^{-1}$ | $\mathcal{O}_{\overline{Q}uLLH}^{3211}$ | $5.65 \times 10^{1}$ | $2.38 \times 10^{-3}$ |
| $\mathcal{O}_{\overline{e}LLLH}^{(\mathrm{S}),2112}$ | $1.25 \times 10^{-3}$ | $\mathcal{O}_{\overline{Q}uLLH}^{3311}$ | $5.90 \times 10^{-8}$ | $5.90 \times 10^{-8}$ |
| $\mathcal{O}_{\overline{e}LLLH}^{(\mathrm{S}),3113}$ | $7.44 \times 10^{-5}$ | | | |

RG mixing effects are important to constrain operators that cannot directly contribute to $0\nu\beta\beta$, especially the operators involving 3rd generation quarks

# Neutrino participated BNV processes

- $\Delta B = 1$: $p \to \pi^+\nu, K^+\nu\cdots$
- $\Delta B = 2$: $NN' \to \ell^+\nu, \bar{\nu}\nu$;
- $\Delta B = 2$ & $\Delta L = 2$: $pp \to pn \to \ell_\alpha^+\bar{\nu}_\beta, nn \to \bar{\nu}_\alpha\bar{\nu}_\beta$

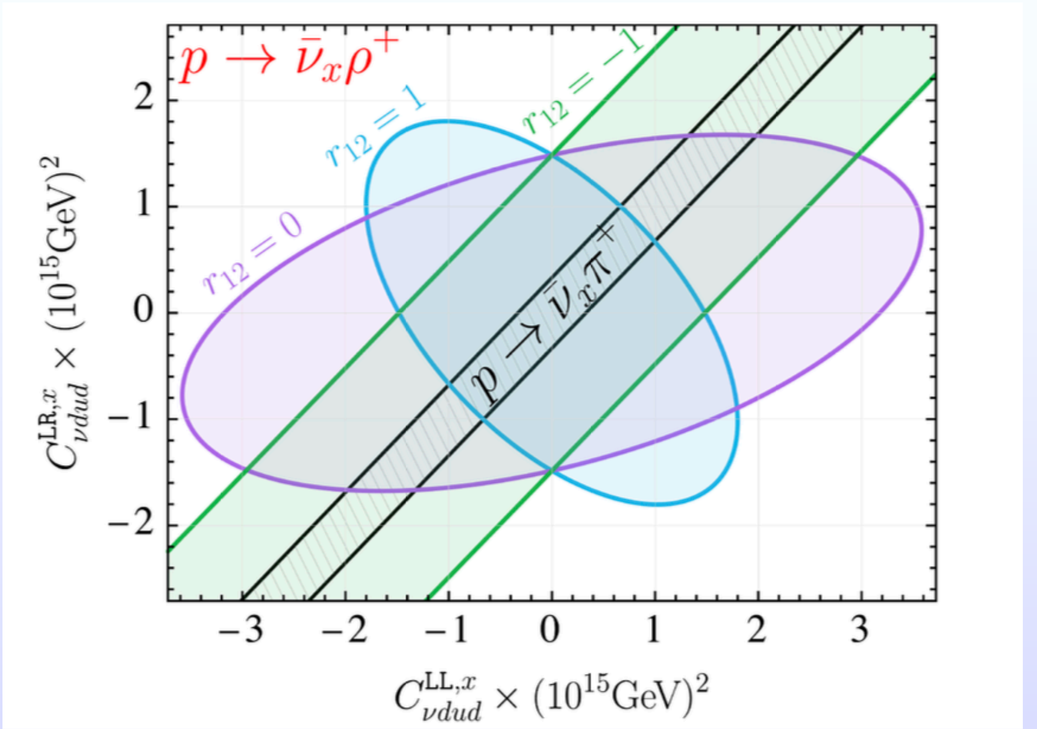
**$m_\nu$, BAU, GUTs,...**

Snowmass: 2203.08771, 2208.00010, 2210.04765
He, Ma: 2101.01405, 2102.02562
Schmidt et al: 2312.13361, 2401.04768

Conventional two-body modes: $\mathbb{N} \to \nu + M, M = \pi^0, \pi^\pm, K^0, \pm^\pm, \rho^0, \rho^\pm, \cdots$

Exotic two-body modes: $\mathbb{N} \to \nu + X$, a light scalar/boson

| $\Delta(B-L)=0$ | | $\Delta(B+L)=0$ | |
|---|---|---|---|
| $\mathcal{O}^{\rm LL}_{\nu dud}$ | $(\overline{\nu_{\rm L}^{\rm C}} d_{\rm L}^\alpha)(\overline{u_{\rm L}^{\beta{\rm C}}} d_{\rm L}^\gamma)\epsilon_{\alpha\beta\gamma}$ | $\mathcal{O}^{\rm LL}_{\bar{\ell}ddd}$ | $(\overline{\ell_{\rm R}} d_{\rm L}^\alpha)(\overline{d_{\rm L}^{\beta{\rm C}}} d_{\rm L}^\gamma)\epsilon_{\alpha\beta\gamma}$ |
| $\mathcal{O}^{\rm LL}_{\ell udu}$ | $(\overline{\ell_{\rm L}^{\rm C}} u_{\rm L}^\alpha)(\overline{d_{\rm L}^{\beta{\rm C}}} u_{\rm L}^\gamma)\epsilon_{\alpha\beta\gamma}$ | $\mathcal{O}^{\rm RL}_{\bar{\nu}dud}$ | $(\overline{\nu_{\rm L}} d_{\rm R}^\alpha)(\overline{u_{\rm L}^{\beta{\rm C}}} d_{\rm L}^\gamma)\epsilon_{\alpha\beta\gamma}$ |
| $\mathcal{O}^{\rm RL}_{\ell duu}$ | $(\overline{\ell_{\rm R}^{\rm C}} d_{\rm R}^\alpha)(\overline{u_{\rm L}^{\beta{\rm C}}} u_{\rm L}^\gamma)\epsilon_{\alpha\beta\gamma}$ | $\mathcal{O}^{\rm RL}_{\bar{\nu}udd}$ | $(\overline{\nu_{\rm L}} u_{\rm R}^\alpha)(\overline{d_{\rm L}^{\beta{\rm C}}} d_{\rm L}^\gamma)\epsilon_{\alpha\beta\gamma}$ |
| $\mathcal{O}^{\rm RL}_{\ell udu}$ | $(\overline{\ell_{\rm R}^{\rm C}} u_{\rm R}^\alpha)(\overline{d_{\rm L}^{\beta{\rm C}}} u_{\rm L}^\gamma)\epsilon_{\alpha\beta\gamma}$ | $\mathcal{O}^{\rm RL}_{\bar{\ell}ddd}$ | $(\overline{\ell_{\rm L}} d_{\rm R}^\alpha)(\overline{d_{\rm L}^{\beta{\rm C}}} d_{\rm L}^\gamma)\epsilon_{\alpha\beta\gamma}$ |
| $\mathcal{O}^{\rm LR}_{\ell duu}$ | $(\overline{\ell_{\rm L}^{\rm C}} d_{\rm L}^\alpha)(\overline{u_{\rm R}^{\beta{\rm C}}} u_{\rm R}^\gamma)\epsilon_{\alpha\beta\gamma}$ | $\mathcal{O}^{\rm LR}_{\bar{\ell}ddd}$ | $(\overline{\ell_{\rm R}} d_{\rm L}^\alpha)(\overline{d_{\rm R}^{\beta{\rm C}}} d_{\rm R}^\gamma)\epsilon_{\alpha\beta\gamma}$ |
| $\mathcal{O}^{\rm LR}_{\ell udu}$ | $(\overline{\ell_{\rm L}^{\rm C}} u_{\rm L}^\alpha)(\overline{d_{\rm R}^{\beta{\rm C}}} u_{\rm R}^\gamma)\epsilon_{\alpha\beta\gamma}$ | $\mathcal{O}^{\rm RR}_{\bar{\nu}dud}$ | $(\overline{\nu_{\rm L}} d_{\rm R}^\alpha)(\overline{u_{\rm R}^{\beta{\rm C}}} d_{\rm R}^\gamma)\epsilon_{\alpha\beta\gamma}$ |
| $\mathcal{O}^{\rm LR}_{\nu ddu}$ | $(\overline{\nu_{\rm L}^{\rm C}} d_{\rm L}^\alpha)(\overline{d_{\rm R}^{\beta{\rm C}}} u_{\rm R}^\gamma)\epsilon_{\alpha\beta\gamma}$ | $\mathcal{O}^{\rm RR}_{\bar{\ell}ddd}$ | $(\overline{\ell_{\rm L}} d_{\rm R}^\alpha)(\overline{d_{\rm R}^{\beta{\rm C}}} d_{\rm R}^\gamma)\epsilon_{\alpha\beta\gamma}$ |
| $\mathcal{O}^{\rm LR}_{\nu udd}$ | $(\overline{\nu_{\rm L}^{\rm C}} u_{\rm L}^\alpha)(\overline{d_{\rm R}^{\beta{\rm C}}} d_{\rm R}^\gamma)\epsilon_{\alpha\beta\gamma}$ | | |
| $\mathcal{O}^{\rm RR}_{\ell udu}$ | $(\overline{\ell_{\rm R}^{\rm C}} u_{\rm R}^\alpha)(\overline{d_{\rm R}^{\beta{\rm C}}} u_{\rm R}^\gamma)\epsilon_{\alpha\beta\gamma}$ | | |




Yi Liao, XDM, Hao-Lin Wang, 2506.05052

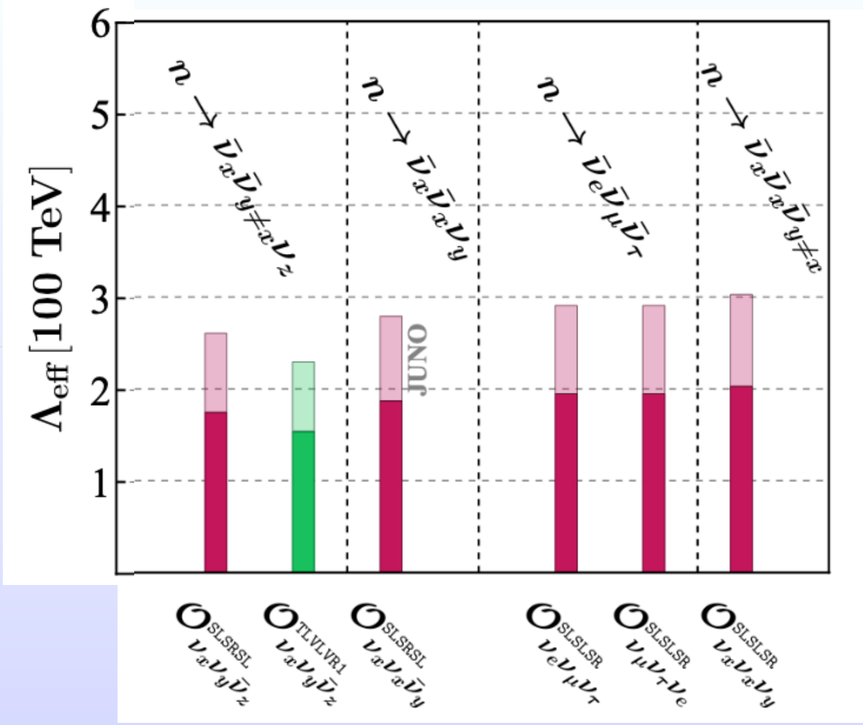
# BNV- exotic nucleon three-body decay

| Process | Exp. bound $\Gamma^{-1}$[yr] | Process | Exp. bound $\Gamma^{-1}$[yr] |
|---|---|---|---|
| $n \to e^- e^+ \hat{\nu}$ | $2.57 \times 10^{32}$ [15] | $p \to e^+ \hat{\nu}\hat{\nu}$ | $1.7 \times 10^{32}$ [16] |
| $n \to e^- \mu^+ \hat{\nu}$ | $8.3 \times 10^{31}$ [15] | $p \to \mu^+ \hat{\nu}\hat{\nu}$ | $2.2 \times 10^{32}$ [16] |
| $n \to \mu^- e^+ \hat{\nu}$ | $0.6 \times 10^{30}$ [15] | $n \to \hat{\nu}\hat{\nu}\hat{\nu}$ | $0.9 \times 10^{30}$ [17] |
| $n \to \mu^- \mu^+ \hat{\nu}$ | $7.9 \times 10^{31}$ [15] | | $(5 \times 10^{31}$ [18]) |
| | | | JUNO: 2405.17792 |

Liao Yi, XDM, Xiang Zhao, 2511.xxxxx

| $\Delta L = -1$ | $\Delta L = +1$ | $\Delta L = -3$ | $\Delta L = +3$ |
|---|---|---|---|
| $p \to \ell_x^+ \ell_y^+ \ell_z^-$ $(z = x, y)$ | $n \to \ell_x^- \ell_y^+ \nu_z$ $(y = x, z)$ | $p \to \bar{\nu}_x \bar{\nu}_y \ell_z^+$ | $n \to \nu_x \nu_y \nu_z$ |
| $n \to \ell_x^- \ell_y^+ \bar{\nu}_z$ $(x = y, z)$ | $p \to \nu_x \nu_y \ell_z^+$ $(z = y, z)$ | $n \to \bar{\nu}_x \bar{\nu}_y \bar{\nu}_z$ | |
| $p \to \nu_x \bar{\nu}_y \ell_z^+$ $(x = y, z)$ | $n \to \nu_x \nu_y \bar{\nu}_z$ $(z = x, y)$ | | |
| $n \to \bar{\nu}_x \bar{\nu}_y \nu_z$ $(z = x, y)$ | | | |

| | Notation | Operator | Chiral Irrep. | # of operators | Process |
|---|---|---|---|---|---|
| $\Delta L = -3$ | $\mathcal{O}^{\mathrm{SLSRSR}}_{\nu\nu\ell,xyz}$ | $(\overline{\nu^{\mathrm{C}}_{\mathrm{L}x}}\nu_{\mathrm{L}y})(\overline{\ell^{\mathrm{C}}_{\mathrm{R}z}}\mathcal{N}^{\mathrm{RR}}_{uud})$ | $\mathbf{1}_\mathrm{L} \otimes \mathbf{8}_\mathrm{R}$ | $\frac{1}{2}n_\ell n_\nu(n_\nu+1)$ [18] | $p \to \bar{\nu}_x \bar{\nu}_y \ell_z^+$ |
| | $\mathcal{O}^{\mathrm{SLSLSL}}_{\nu\nu\ell,xyz}$ | $(\overline{\nu^{\mathrm{C}}_{\mathrm{L}x}}\nu_{\mathrm{L}y})(\overline{\ell^{\mathrm{C}}_{\mathrm{L}z}}\mathcal{N}^{\mathrm{LL}}_{uud})$ | $\mathbf{8}_\mathrm{L} \otimes \mathbf{1}_\mathrm{R}$ | $\frac{1}{2}n_\ell n_\nu(n_\nu+1)$ [18] | |
| | $\mathcal{O}^{\mathrm{TLTLSL}}_{\nu\nu\ell,xyz}$ | $(\overline{\nu^{\mathrm{C}}_{\mathrm{L}x}}\sigma_{\mu\nu}\nu_{\mathrm{L}y})(\overline{\ell^{\mathrm{C}}_{\mathrm{L}z}}\sigma^{\mu\nu}\mathcal{N}^{\mathrm{LL}}_{uud})$ | $\mathbf{8}_\mathrm{L} \otimes \mathbf{1}_\mathrm{R}$ | $\frac{1}{2}n_\ell n_\nu(n_\nu-1)$ [9] | |
| | $\mathcal{O}^{\mathrm{TLSLTL}}_{\nu\nu\ell,xyz}$ | $(\overline{\nu^{\mathrm{C}}_{\mathrm{L}x}}\sigma_{\mu\nu}\nu_{\mathrm{L}y})(\overline{\ell^{\mathrm{C}}_{\mathrm{L}z}}\mathcal{N}^{\mathrm{LL},\mu\nu}_{uud})$ | $\mathbf{10}_\mathrm{L} \otimes \mathbf{1}_\mathrm{R}$ | $\frac{1}{2}n_\ell n_\nu(n_\nu-1)$ [9] | |
| | $\mathcal{O}^{\mathrm{SLSRSL}}_{\nu\nu\ell,xyz}$ | $(\overline{\nu^{\mathrm{C}}_{\mathrm{L}x}}\nu_{\mathrm{L}y})(\overline{\ell^{\mathrm{C}}_{\mathrm{R}z}}\mathcal{N}^{\mathrm{RL}}_{uud})$ | $\bar{\mathbf{3}}_\mathrm{L} \otimes \mathbf{3}_\mathrm{R}$ | $\frac{1}{2}n_\ell n_\nu(n_\nu+1)$ [18] | |
| | $\mathcal{O}^{\mathrm{TLVLVR1}}_{\nu\nu\ell,xyz}$ | $(\overline{\nu^{\mathrm{C}}_{\mathrm{L}x}}\sigma_{\mu\nu}\nu_{\mathrm{L}y})(\overline{\ell^{\mathrm{C}}_{\mathrm{R}z}}\gamma^\mu\mathcal{N}^{\mathrm{LR},\nu}_{udu})$ | $\mathbf{6}_\mathrm{L} \otimes \mathbf{3}_\mathrm{R}$ | $\frac{1}{2}n_\ell n_\nu(n_\nu-1)$ [9] | |
| | $\mathcal{O}^{\mathrm{TLVLVR2}}_{\nu\nu\ell,xyz}$ | $(\overline{\nu^{\mathrm{C}}_{\mathrm{L}x}}\sigma_{\mu\nu}\nu_{\mathrm{L}y})(\overline{\ell^{\mathrm{C}}_{\mathrm{R}z}}\gamma^\mu\mathcal{N}^{\mathrm{LR},\nu}_{uud})$ | $\mathbf{6}_\mathrm{L} \otimes \mathbf{3}_\mathrm{R}$ | $\frac{1}{2}n_\ell n_\nu(n_\nu-1)$ [9] | |
| | $\mathcal{O}^{\mathrm{SLSLSR}}_{\nu\nu\ell,xyz}$ | $(\overline{\nu^{\mathrm{C}}_{\mathrm{L}x}}\nu_{\mathrm{L}y})(\overline{\ell^{\mathrm{C}}_{\mathrm{L}z}}\mathcal{N}^{\mathrm{LR}}_{uud})$ | $\mathbf{3}_\mathrm{L} \otimes \bar{\mathbf{3}}_\mathrm{R}$ | $\frac{1}{2}n_\ell n_\nu(n_\nu+1)$ [18] | |
| | $\mathcal{O}^{\mathrm{TLTLSR}}_{\nu\nu\ell,xyz}$ | $(\overline{\nu^{\mathrm{C}}_{\mathrm{L}x}}\sigma_{\mu\nu}\nu_{\mathrm{L}y})(\overline{\ell^{\mathrm{C}}_{\mathrm{L}z}}\sigma^{\mu\nu}\mathcal{N}^{\mathrm{LR}}_{uud})$ | $\mathbf{3}_\mathrm{L} \otimes \bar{\mathbf{3}}_\mathrm{R}$ | $\frac{1}{2}n_\ell n_\nu(n_\nu-1)$ [9] | |
| | $\mathcal{O}^{\mathrm{SLSLSL}}_{\nu\nu\nu,xyz}$ | $(\overline{\nu^{\mathrm{C}}_{\mathrm{L}x}}\nu_{\mathrm{L}[y}})(\overline{\nu^{\mathrm{C}}_{\mathrm{L}z]}}\mathcal{N}^{\mathrm{LL}}_{dud})$ | $\mathbf{8}_\mathrm{L} \otimes \mathbf{1}_\mathrm{R}$ | $\frac{1}{3}n_\nu(n_\nu^2-1)$ [8] | $n\bar{n} \to \bar{\nu}\bar{\nu}\bar{\nu}$ |
| | $\mathcal{O}^{\mathrm{TLSLTL}}_{\nu\nu\nu,xyz}$ | $(\overline{\nu^{\mathrm{C}}_{\mathrm{L}[x}}\sigma_{\mu\nu}\nu_{\mathrm{L}y})(\overline{\nu^{\mathrm{C}}_{\mathrm{L}z]}}\mathcal{N}^{\mathrm{LL},\mu\nu}_{udd})$ | $\mathbf{10}_\mathrm{L} \otimes \mathbf{1}_\mathrm{R}$ | $\frac{1}{6}n_\nu(n_\nu-2)(n_\nu-1)$ [1] | |
| | $\mathcal{O}^{\mathrm{SLSLSR}}_{\nu\nu\nu,xyz}$ | $(\overline{\nu^{\mathrm{C}}_{\mathrm{L}x}}\nu_{\mathrm{L}[y}})(\overline{\nu^{\mathrm{C}}_{\mathrm{L}z]}}\mathcal{N}^{\mathrm{LR}}_{dud})$ | $\mathbf{3}_\mathrm{L} \otimes \bar{\mathbf{3}}_\mathrm{R}$ | $\frac{1}{3}n_\nu(n_\nu^2-1)$ [8] | |
| $\Delta L = +3$ | $\mathcal{O}^{\mathrm{SRSRSR}}_{\bar{\nu}\bar{\nu}\bar{\nu},xyz}$ | $(\overline{\nu_{\mathrm{L}x}}\nu^{\mathrm{C}}_{\mathrm{L}[y}})(\overline{\nu_{\mathrm{L}z]}}\mathcal{N}^{\mathrm{RR}}_{dud})$ | $\mathbf{1}_\mathrm{L} \otimes \mathbf{8}_\mathrm{R}$ | $\frac{1}{3}n_\nu(n_\nu^2-1)$ [8] | $nnn \to u$ |
| | $\mathcal{O}^{\mathrm{TRSRTR}}_{\bar{\nu}\bar{\nu}\bar{\nu},xyz}$ | $(\overline{\nu_{\mathrm{L}[x}}\sigma_{\mu\nu}\nu^{\mathrm{C}}_{\mathrm{L}y})(\overline{\nu_{\mathrm{L}z]}}\mathcal{N}^{\mathrm{RR},\mu\nu}_{udd})$ | $\mathbf{1}_\mathrm{L} \otimes \mathbf{10}_\mathrm{R}$ | $\frac{1}{6}n_\nu(n_\nu-2)(n_\nu-1)$ [1] | |
| | $\mathcal{O}^{\mathrm{SRSRSL}}_{\bar{\nu}\bar{\nu}\bar{\nu},xyz}$ | $(\overline{\nu_{\mathrm{L}x}}\nu^{\mathrm{C}}_{\mathrm{L}[y}})(\overline{\nu_{\mathrm{L}z]}}\mathcal{N}^{\mathrm{RL}}_{dud})$ | $\bar{\mathbf{3}}_\mathrm{L} \otimes \mathbf{3}_\mathrm{R}$ | $\frac{1}{3}n_\nu(n_\nu^2-1)$ [8] | |

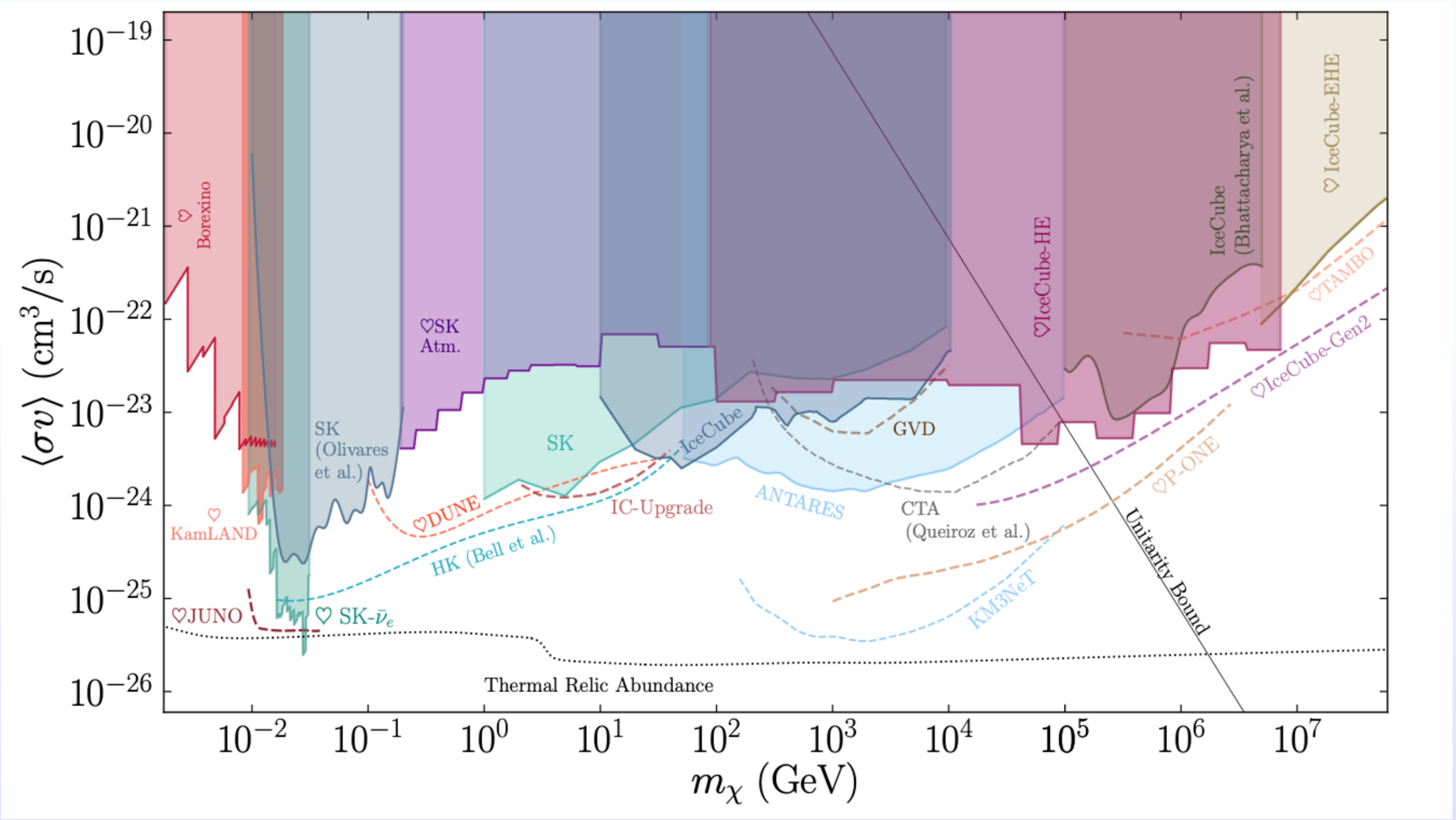



An alternative dim-9 LEFT BNV operator basis: H.-L. Li, Z. Ren, M.-L. Xiao, J.-H. Yu and Y.-H. Zheng, 2012.09188

# DM-neutrino interactions

Ongoing work.

| | |
|---|---|
| **Scalar DM case** | |
| $\mathcal{O}^{\mathrm{V},ij}_{\nu\phi}$ | $(\overline{\nu_{\mathrm{L}i}}\gamma^\mu\nu_{\mathrm{L}j})(\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi)$ (✗) |
| **Fermion DM case** | |
| $\mathcal{O}^{\mathrm{V},ij}_{\nu\chi1}$ | $(\overline{\nu_{\mathrm{L}i}}\gamma^\mu\nu_{\mathrm{L}j})(\overline{\chi}\gamma_\mu\chi)$ (✗) |
| $\mathcal{O}^{\mathrm{V},ij}_{\nu\chi2}$ | $(\overline{\nu_{\mathrm{L}i}}\gamma^\mu\nu_{\mathrm{L}j})(\overline{\chi}\gamma_\mu\gamma_5\chi)$ |
| **Vector DM case A** | |
| $\mathcal{O}^{\mathrm{V},ij}_{\nu X1}$ | $\frac{1}{2}[\overline{\nu_{\mathrm{L}i}}\gamma_{(\mu}i\overleftrightarrow{\partial_{\nu)}}\nu_{\mathrm{L}j}](X^{\mu\dagger}X^\nu + X^{\nu\dagger}X^\mu)$ |
| $\mathcal{O}^{\mathrm{V},ij}_{\nu X2}$ | $(\overline{\nu_{\mathrm{L}i}}\gamma_\mu\nu_{\mathrm{L}j})\partial_\nu(X^{\mu\dagger}X^\nu + X^{\nu\dagger}X^\mu)$ |
| $\mathcal{O}^{\mathrm{V},ij}_{\nu X3}$ | $(\overline{\nu_{\mathrm{L}i}}\gamma_\mu\nu_{\mathrm{L}j})(X^\dagger_\rho\overleftrightarrow{\partial_\nu}X_\sigma)\epsilon^{\mu\nu\rho\sigma}$ |
| $\mathcal{O}^{\mathrm{V},ij}_{\nu X4}$ | $(\overline{\nu_{\mathrm{L}i}}\gamma^\mu\nu_{\mathrm{L}j})(X^\dagger_\nu i\overleftrightarrow{\partial_\mu}X^\nu)$ (✗) |
| $\mathcal{O}^{\mathrm{V},ij}_{\nu X5}$ | $(\overline{\nu_{\mathrm{L}i}}\gamma_\mu\nu_{\mathrm{L}j})i\partial_\nu(X^{\mu\dagger}X^\nu - X^{\nu\dagger}X^\mu)$ (✗) |
| $\mathcal{O}^{\mathrm{V},ij}_{\nu X6}$ | $(\overline{\nu_{\mathrm{L}i}}\gamma_\mu\nu_{\mathrm{L}j})i\partial_\nu(X^\dagger_\rho X_\sigma)\epsilon^{\mu\nu\rho\sigma}$ (✗) |




arXiv:1912.09486v3

The operators depend on the spin of dark matter particle

# Summary

- EFT in neutrino physics is overviewed, including EFTs at different scales, matching, etc;
- EFT can help us to understand the origin of the neutrino mass;
- Low energy neutrino processes can be well described by EFT method.

**Thank you for your time!**