Sterile neutrinos in effective field theory

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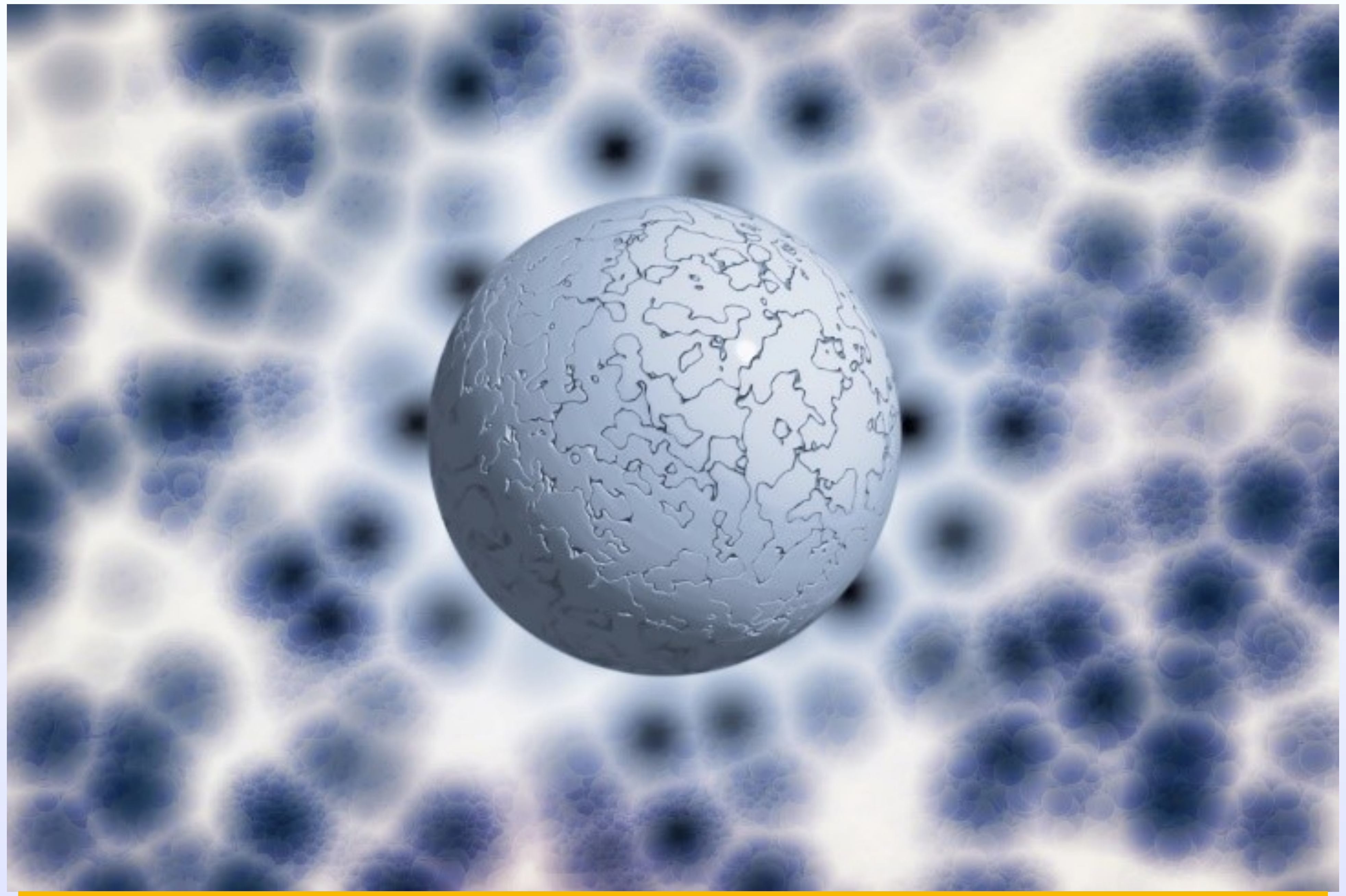
Outline

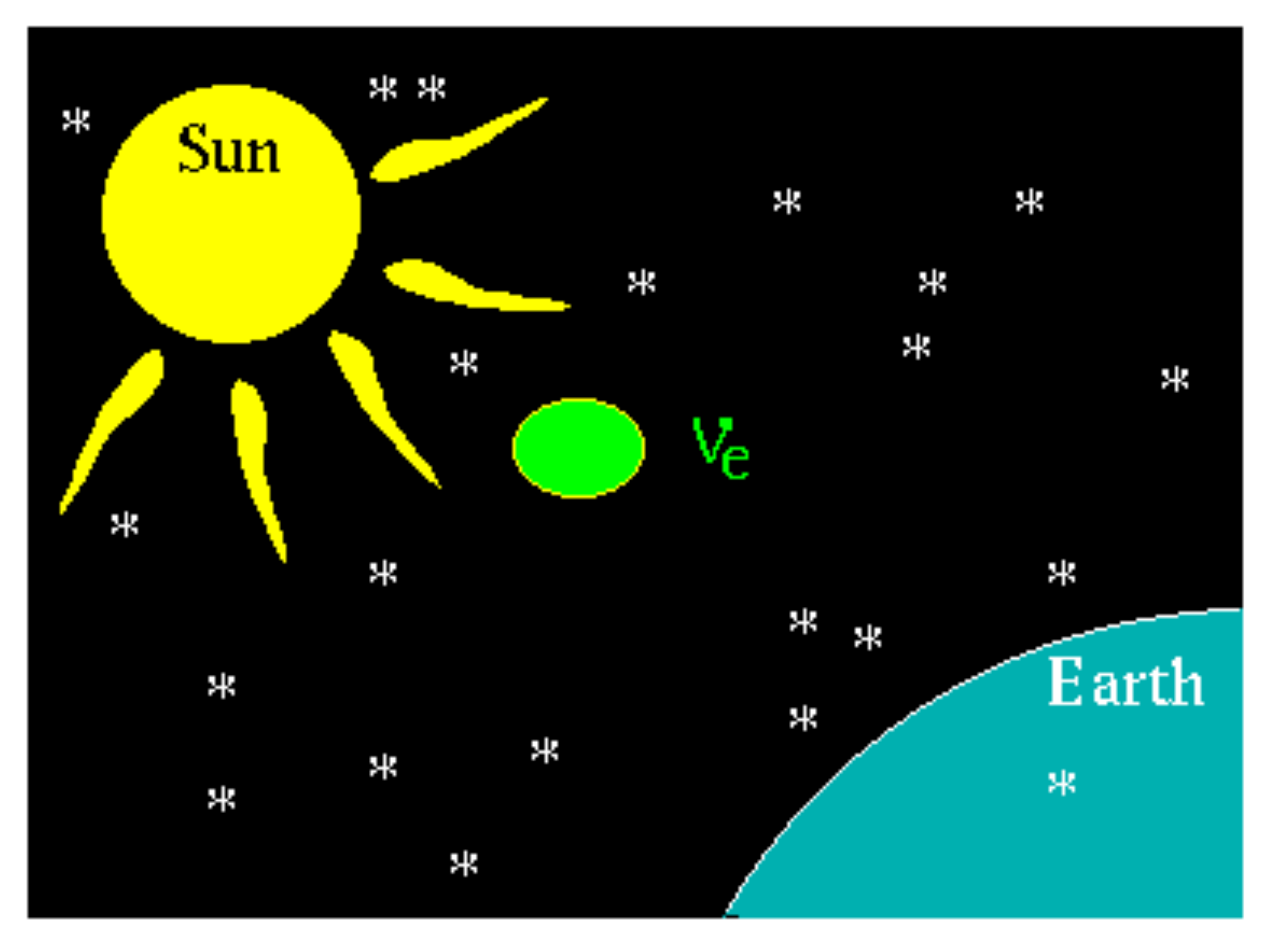
- Introduction
- Bottom-up EFT: νSMEFT, νLEFT, RGE connection
- UV completion of EFT operators
- Top-down EFT: matching UV models onto EFTs
- Summary

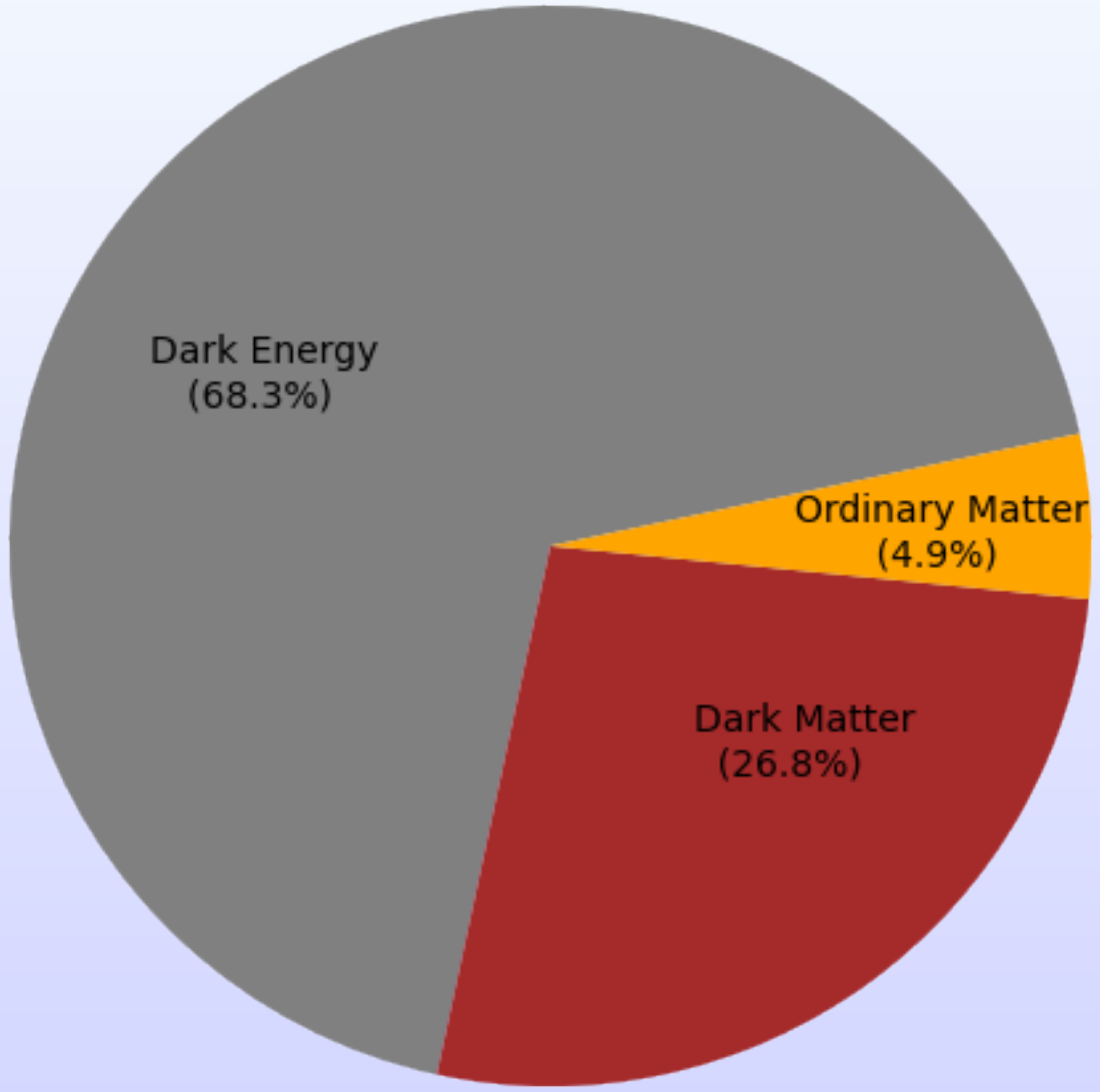
Neutrinos hold the key to big questions

- Neutrino mass
- Dark matter
- Baryon asymmetry
- Anomalies
  - Neutron lifetime τ_n
  - $B \to K\nu\bar{\nu}$
  - $K \to \pi\nu\bar{\nu}$
  - MiniBooNE ν_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 νSMEFT

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

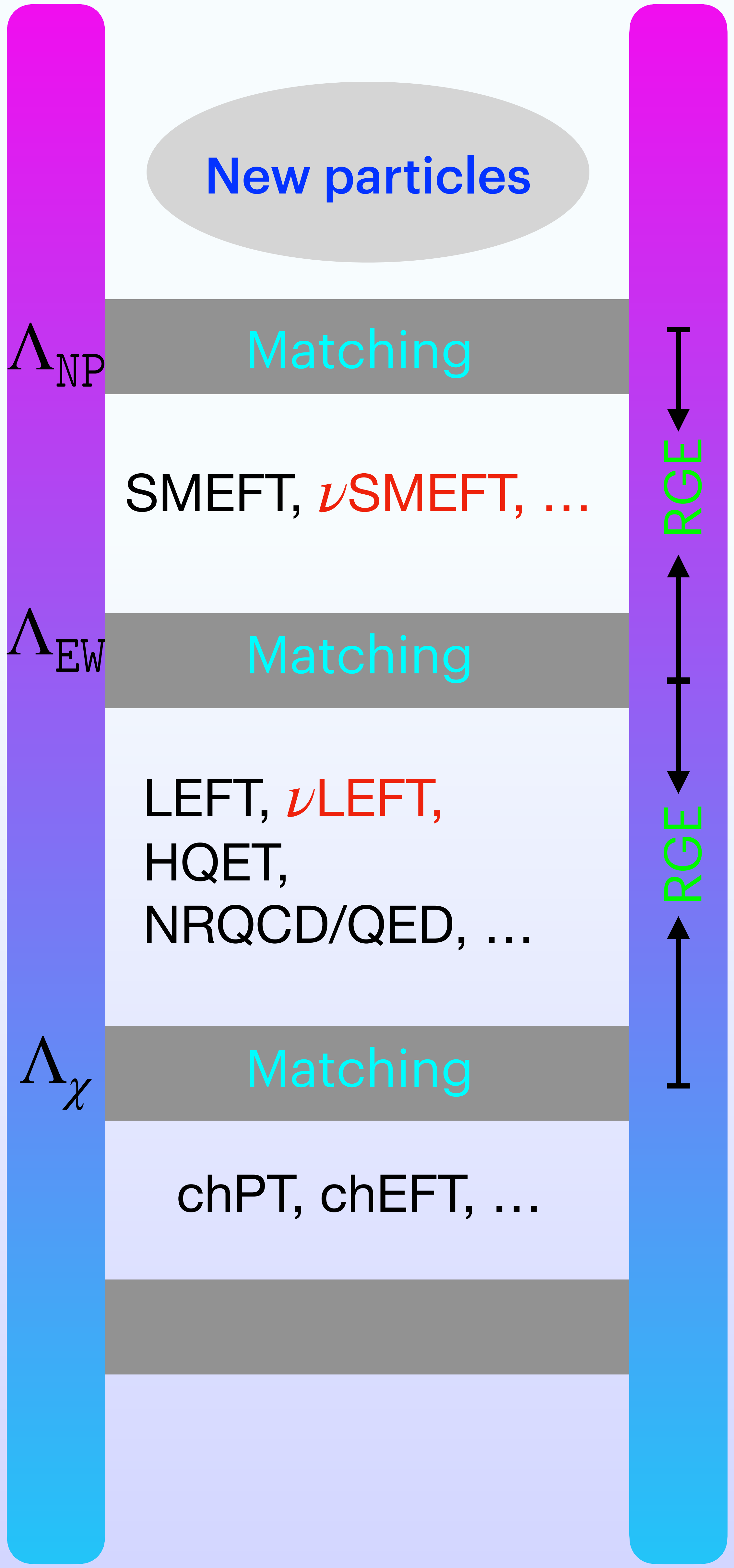
- Neutrino mass model as an EFT

Integrate out heavy NP states and match onto some EFTs

- Neutrino-participated processes in the EFTs

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

Bottom-up EFT



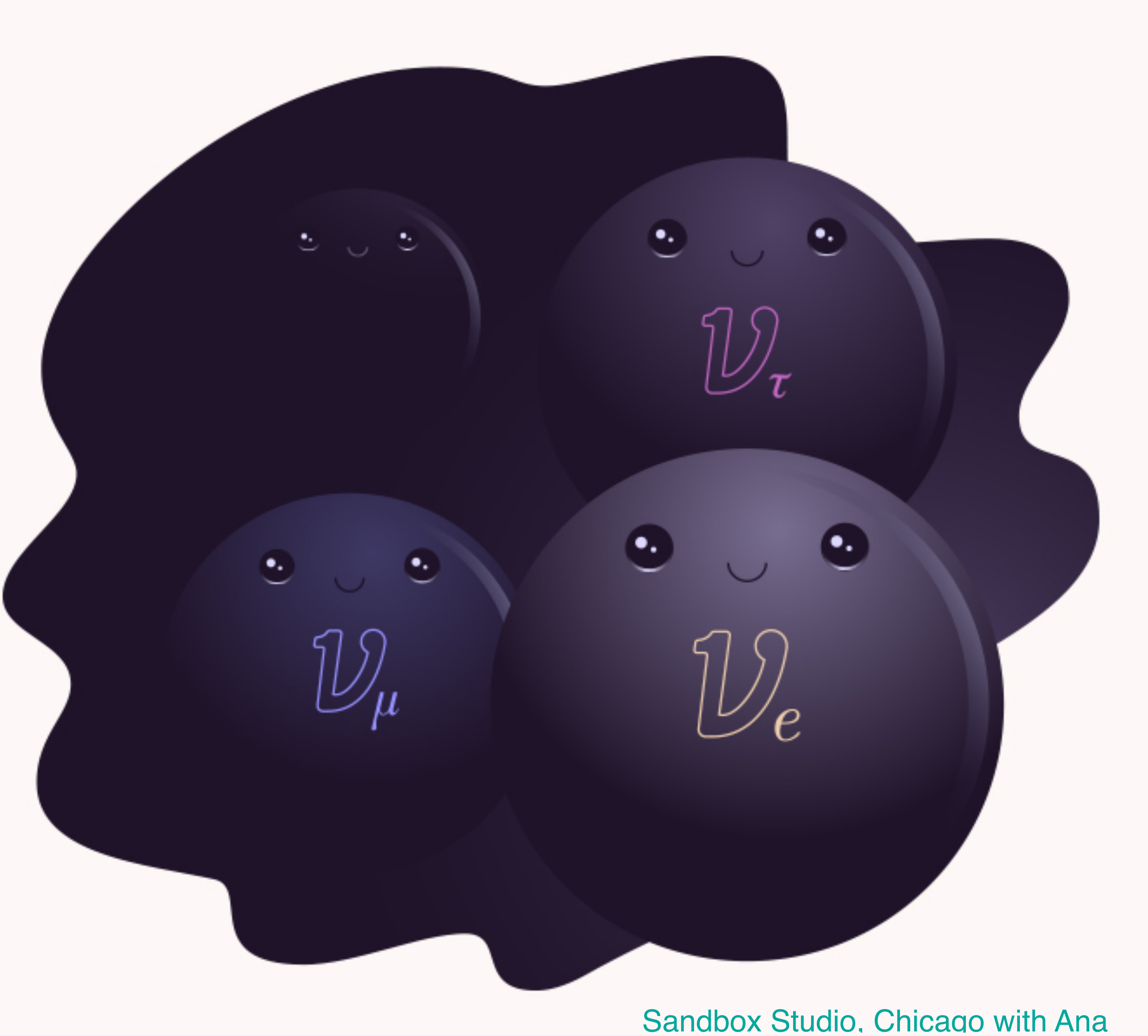
Assumption: scales are well separated with $\Lambda_{\mathrm{NP}} \gg \Lambda_{\mathrm{EW}}$

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

SMEFT-like framework

Study the NP effects in low energy observables indirectly

Why sterile neutrinos ?



- Neutrino mass — Dirac/Majorana mass
- Dark matter
- Baryogenesis
- LSND MiniBooNE— ν_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)

ν**SMEFT = SMEFT + sterile neutrinos** (N)

Operator basis of the νSMEFT

Liao, Ma, 1612.04527

$$\mathscr{L}_{\nu\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SMEFT}} + \boxed{\mathscr{L}^{N}_{\mathrm{dim5}}} + \boxed{\mathscr{L}^{N}_{\mathrm{dim6}} + \mathscr{L}^{N}_{\mathrm{dim7}}} + \boxed{\mathscr{L}^{N}_{\mathrm{dim8}} + \mathscr{L}^{N}_{\mathrm{dim9}}} + \cdots$$

Aparici et al, 0904.3244

del Aguila et al, 0806.0876
Bhattacharya, Wudka, 1505.05264

Li et al, 2105.09329

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

Dimension 6

Y. Liao & X.D. Ma, 1612.04527

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

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

$(\overline{L}L)(\overline{R}R)$	
$\mathcal{O}_{LN}$	$(\overline{L}\gamma^\mu L)(\overline{N}\gamma_\mu N)$
$\mathcal{O}_{QN}$	$(\overline{Q}\gamma^\mu Q)(\overline{N}\gamma_\mu N)$
$(\cancel{L}\cap B)(+\text{h.c.})$	
$\mathcal{O}_{NNNN}$	$(\overline{N^C}N)(\overline{N^C}N)$
$(\cancel{L}\cap \cancel{B})(+\text{h.c.})$	
$\mathcal{O}_{QQdN}$	$\epsilon_{ij}\epsilon_{\alpha\beta\sigma}(\overline{Q^{i,C}_\alpha}Q^j_\beta)(\overline{d^C_\sigma}N)$
$\mathcal{O}_{uddN}$	$\epsilon_{\alpha\beta\sigma}(\overline{u^C_\alpha}d_\beta)(\overline{d^C_\sigma}N)$

- Studied in A. Aparici, K. Kim, A. Santamaria, J. Wudka, 0806.0876

Many redundant operators + some missing ones

- First to obtain a complete and independent basis

- Neutrino non-standard interactions
- Coherent elastic neutrino-nucleus scattering
- Many neutrino-participated processes

- Phenomenological study: have to include SMEFT operators for consistency

Dimension 7

$N\psi H^3 D$	
$\mathcal{O}_{NL1}$	$\epsilon_{ij}(\overline{N^C}\gamma_\mu L^i)(iD^\mu H^j)(H^\dagger H)$
$\mathcal{O}_{NL2}$	$\epsilon_{ij}(\overline{N^C}\gamma_\mu L^i)H^j(H^\dagger i\overleftrightarrow{D}^\mu H)$
$N\psi H^2 D^2$	
$\mathcal{O}_{NeD}$	$\epsilon_{ij}(\overline{N^C}\overleftrightarrow{D}^\mu e)(H^i D^\mu H^j)$
$N\psi H^2 X$	
$\mathcal{O}_{NeW}$	$g_2(\epsilon\tau^I)_{ij}(\overline{N^C}\sigma^{\mu\nu}e)(H^i H^j)W^I_{\mu\nu}$
$N\psi H D X$	
$\mathcal{O}_{NLB1}$	$g_1\epsilon_{ij}(\overline{N^C}\gamma^\mu L^i)(D^\nu H^j)B_{\mu\nu}$
$\mathcal{O}_{NLB2}$	$g_1\epsilon_{ij}(\overline{N^C}\gamma^\mu L^i)(D^\nu H^j)\tilde{B}_{\mu\nu}$
$\mathcal{O}_{NLW1}$	$g_2(\epsilon\tau^I)_{ij}(\overline{N^C}\gamma^\mu L^i)(D^\nu H^j)W^I_{\mu\nu}$
$\mathcal{O}_{NLW2}$	$g_2(\epsilon\tau^I)_{ij}(\overline{N^C}\gamma^\mu L^i)(D^\nu H^j)\tilde{W}^I_{\mu\nu}$
$N^2 H^4$	
$\mathcal{O}_{NH}$	$(\overline{N^C}N)(H^\dagger H)^2$
$N^2 H^2 D^2$	
$\mathcal{O}_{NHD1}$	$(\overline{N^C}\overleftrightarrow{\partial}_\mu N)(H^\dagger\overleftrightarrow{D}^\mu H)$
$\mathcal{O}_{NHD2}$	$(\overline{N^C}N)(D_\mu H)^\dagger D^\mu H$
$N^2 H^2 X$	
$\mathcal{O}_{NHB}$	$g_1(\overline{N^C}\sigma_{\mu\nu}N)(H^\dagger H)B^{\mu\nu}$
$\mathcal{O}_{NHW}$	$g_2(\overline{N^C}\sigma_{\mu\nu}N)(H^\dagger\tau^I H)W^{I\mu\nu}$

$N\psi^3 D$	
$\mathcal{O}_{eNLLD}$	$\epsilon_{ij}(\bar{e}\gamma_\mu N)(\overline{L^{i,C}}i\overleftrightarrow{D}^\mu L^j)$
$\mathcal{O}_{duNeD}$	$(\bar{d}\gamma_\mu u)(\overline{N^C}i\overleftrightarrow{D}^\mu e)$
$\mathcal{O}_{QuNLD}$	$(\bar{Q}i\overleftrightarrow{D}_\mu u)(\overline{N^C}\gamma^\mu L)$
$\mathcal{O}_{dQNLD}$	$\epsilon_{ij}(\bar{d}i\overleftrightarrow{D}_\mu Q^i)(\overline{N^C}\gamma^\mu L^j)$
$N^2\psi^2 D$	
$\mathcal{O}_{LND}$	$(\bar{L}\gamma_\mu L)(\overline{N^C}i\overleftrightarrow{\partial}^\mu N)$
$\mathcal{O}_{QND}$	$(\bar{Q}\gamma_\mu Q)(\overline{N^C}i\overleftrightarrow{\partial}^\mu N)$
$\mathcal{O}_{eND}$	$(\bar{e}\gamma_\mu e)(\overline{N^C}i\overleftrightarrow{\partial}^\mu N)$
$\mathcal{O}_{uND}$	$(\bar{u}\gamma_\mu u)(\overline{N^C}i\overleftrightarrow{\partial}^\mu N)$
$\mathcal{O}_{dND}$	$(\bar{d}\gamma_\mu d)(\overline{N^C}i\overleftrightarrow{\partial}^\mu N)$
$N^4 D$	
$\mathcal{O}_{NND}$	$(\bar{N}\gamma_\mu N)(\overline{N^C}i\overleftrightarrow{\partial}^\mu N)$
$N\psi^3 H$	
$\mathcal{O}_{LNLH}$	$\epsilon_{ij}(\bar{L}\gamma_\mu L)(\overline{N^C}\gamma^\mu L^i)H^j$
$\mathcal{O}_{QNLH1}$	$\epsilon_{ij}(\bar{Q}\gamma_\mu Q)(\overline{N^C}\gamma^\mu L^i)H^j$
$\mathcal{O}_{QNLH2}$	$\epsilon_{ij}(\bar{Q}\gamma_\mu Q^i)(\overline{N^C}\gamma^\mu L^j)H$
$\mathcal{O}_{eNLH}$	$\epsilon_{ij}(\bar{e}\gamma_\mu e)(\overline{N^C}\gamma^\mu L^i)H^j$
$\mathcal{O}_{dNLH}$	$\epsilon_{ij}(\bar{d}\gamma_\mu d)(\overline{N^C}\gamma^\mu L^i)H^j$
$\mathcal{O}_{uNLH}$	$\epsilon_{ij}(\bar{u}\gamma_\mu u)(\overline{N^C}\gamma^\mu L^i)H^j$
$\mathcal{O}_{duNLH}$	$\epsilon_{ij}(\bar{d}\gamma_\mu u)(\overline{N^C}\gamma^\mu L^i)\tilde{H}^j$
$\mathcal{O}_{dQNeH}$	$\epsilon_{ij}(\bar{d}Q^i)(\overline{N^C}e)H^j$
$\mathcal{O}_{QuNeH1}$	$(\bar{Q}u)(\overline{N^C}e)H$
$\mathcal{O}_{QuNeH2}$	$(\bar{Q}\sigma_{\mu\nu}u)(\overline{N^C}\sigma^{\mu\nu}e)H$

$N^2\psi^2 H$	
$\mathcal{O}_{LNeH}$	$(\bar{L}N)(\overline{N^C}e)H$
$\mathcal{O}_{eLNH}$	$H^\dagger(\bar{e}L)(\overline{N^C}N)$
$\mathcal{O}_{QNdH}$	$(\bar{Q}N)(\overline{N^C}d)H$
$\mathcal{O}_{dQNH}$	$H^\dagger(\bar{d}Q)(\overline{N^C}N)$
$\mathcal{O}_{QNuH}$	$(\bar{Q}N)(\overline{N^C}u)\tilde{H}$
$\mathcal{O}_{uQNH}$	$\tilde{H}^\dagger(\bar{u}Q)(\overline{N^C}N)$
$N^3\psi H$	
$\mathcal{O}_{LNNH}$	$(\bar{L}N)(\overline{N^C}N)\tilde{H}$
$\mathcal{O}_{NLNH}$	$\tilde{H}^\dagger(\bar{N}L)(\overline{N^C}N)$
$\not{B}$: $N\psi^3 D$ & $N\psi^3 H$	
$\mathcal{O}_{uNdD}$	$\epsilon_{\alpha\beta\sigma}(\bar{u}_\alpha\gamma_\mu N)(\bar{d}_\beta i\overleftrightarrow{D}^\mu d^C_\sigma)$
$\mathcal{O}_{dNQD}$	$\epsilon_{ij}\epsilon_{\alpha\beta\sigma}(\bar{d}_\alpha\gamma_\mu N)(\bar{Q}_{i\beta}i\overleftrightarrow{D}^\mu Q^C_{j\sigma})$
$\mathcal{O}_{QNdH}$	$\delta_{ij}\epsilon_{\alpha\beta\sigma}(\bar{Q}_{i\alpha}N)(\bar{d}_\beta d^C_\sigma)\tilde{H}^j$
$\mathcal{O}_{QNQH}$	$\epsilon_{ij}\epsilon_{\alpha\beta\sigma}(\bar{Q}_{i\alpha}N)(\bar{Q}_{j\beta}Q^C_\sigma)H$
$\mathcal{O}_{QNudH}$	$\epsilon_{\alpha\beta\sigma}(\bar{Q}_\alpha N)(\bar{u}_\beta d^C_\sigma)H$
$N^2 X^2$	
$\mathcal{O}_{NB1}$	$\alpha_1(\overline{N^C}N)B_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{NB2}$	$\alpha_1(\overline{N^C}N)B_{\mu\nu}\tilde{B}^{\mu\nu}$
$\mathcal{O}_{NW1}$	$\alpha_2(\overline{N^C}N)W^I_{\mu\nu}W^{I\mu\nu}$
$\mathcal{O}_{NW2}$	$\alpha_2(\overline{N^C}N)W^I_{\mu\nu}\tilde{W}^{I\mu\nu}$
$\mathcal{O}_{NG1}$	$\alpha_3(\overline{N^C}N)G^A_{\mu\nu}G^{A\mu\nu}$
$\mathcal{O}_{NG2}$	$\alpha_3(\overline{N^C}N)G^A_{\mu\nu}\tilde{G}^{A\mu\nu}$

- $\Delta|L-B| = 2$
- # of operators: 47 + 5
- SMEFT: 12+6 operators
- Neutrino NSI
- Nucleon BNV
- ....

Dim-8/9 operators

Li et al, 2105.09329

νSMEFT-dim6 RGE

Datta et al: 2010.12109, 2103.04441

- Resum the large logs from perturbative expansion $\Rightarrow$ to improve perturbative expansion

- The dominant contributions are from the 1-loop SM correction
- The renormalization group equation: $16\pi^2 \frac{d\vec{C}}{d\ln\mu} = \hat{\gamma}\vec{C}$

- Operator mixing effect: non-diagonal $\hat{\gamma}$

- Important to precisely interpret the experimental data

- Non-trivial structure in QFT

ν**LEFT** = **LEFT + sterile neutrinos** (N)

LEFT and νLEFT

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

Important to parametrize many key low energy observables:

> Flavor physics: mesons and baryons

> Lepton physics: tau and muon

> BNV, LNV, LFV processes

> ……

Dimension 6

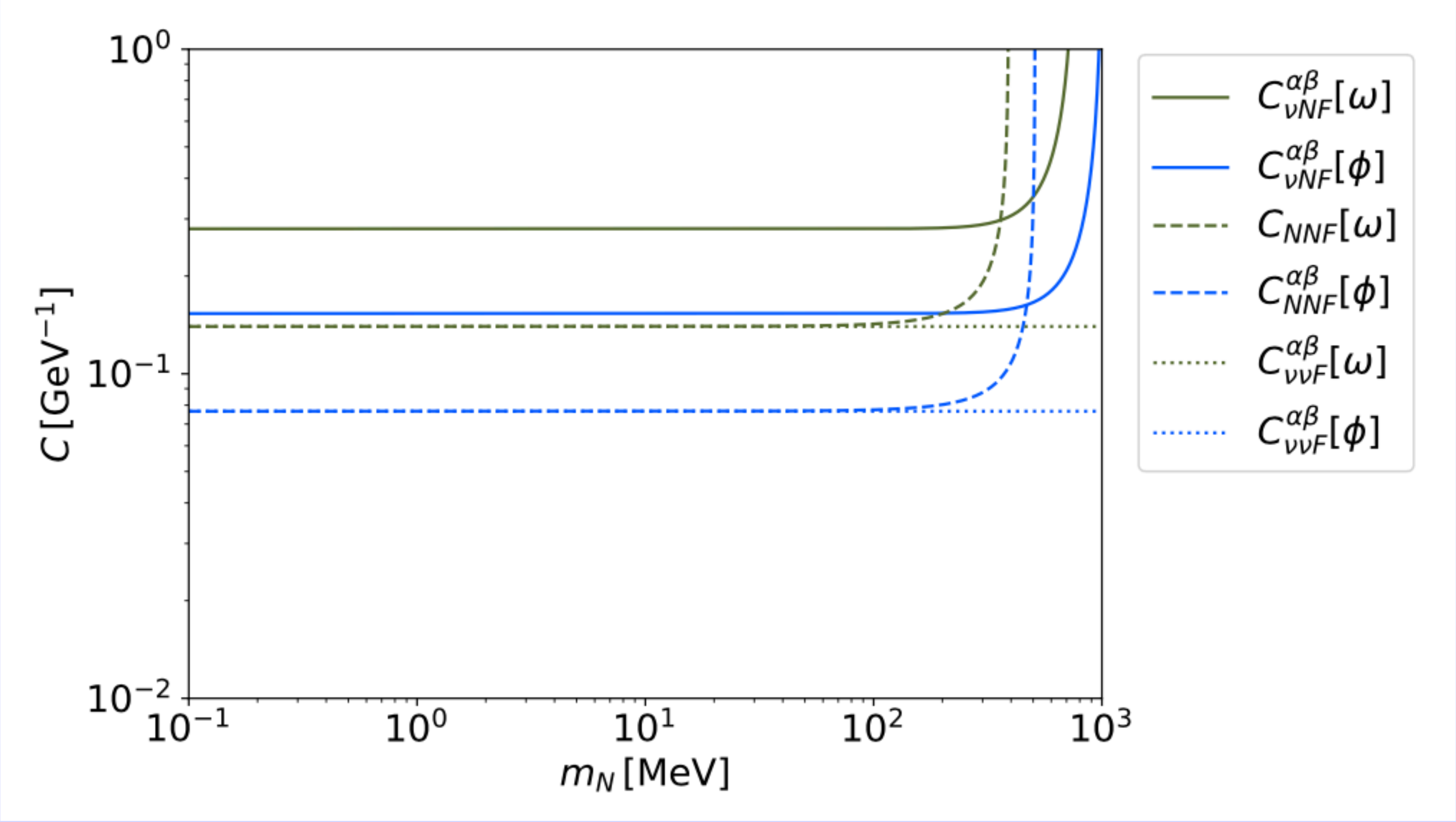
T. Li, X.D. Ma, M. A. Schmidt, 2005.01543

Operator	Specific form	$\#(n_f,\ n_u)$	Operator	Specific form	$\#(n_f,\ n_u)$
$(\Delta L, \Delta B) = (0,\ 0)$					
$(\overline{L}L)(\overline{R}R)$			$(\overline{R}R)(\overline{R}R)$		
$\mathcal{O}^V_{eN1}(\star\star)(\mathrm{H})$	$(\overline{e_L}\gamma_\mu e_L)(\overline{N}\gamma_\mu N)$	n_f^4	$\mathcal{O}^V_{eN2}(\star\star)(\mathrm{H})$	$(\overline{e_R}\gamma_\mu e_R)(\overline{N}\gamma_\mu N)$	n_f^4
$\mathcal{O}^V_{dN1}(\star\star)(\mathrm{H})$	$(\overline{d_L}\gamma_\mu d_L)(\overline{N}\gamma_\mu N)$	n_f^4	$\mathcal{O}^V_{dN2}(\star\star)(\mathrm{H})$	$(\overline{d_R}\gamma_\mu d_R)(\overline{N}\gamma_\mu N)$	n_f^4
$\mathcal{O}^V_{uN1}(\star\star)(\mathrm{H})$	$(\overline{u_L}\gamma_\mu u_L)(\overline{N}\gamma_\mu N)$	$n_f^2 n_u^2$	$\mathcal{O}^V_{uN2}(\star\star)(\mathrm{H})$	$(\overline{u_R}\gamma_\mu u_R)(\overline{N}\gamma_\mu N)$	$n_f^2 n_u^2$
$\mathcal{O}^V_{udeN1}(\star)$	$(\overline{u_L}\gamma^\mu d_L)(\overline{e_R}\gamma_\mu N)$	$n_f^3 n_u$	$\mathcal{O}^V_{udeN2}(\star)$	$(\overline{u_R}\gamma^\mu d_R)(\overline{e_R}\gamma_\mu N)$	$n_f^3 n_u$
$\mathcal{O}^V_{\nu N}(\star\star)(\mathrm{H})$	$(\overline{\nu}\gamma_\mu \nu)(\overline{N}\gamma_\mu N)$	n_f^4	$\mathcal{O}^V_{N}(\star\star\star\star)(\mathrm{H})$	$(\overline{N}\gamma_\mu N)(\overline{N}\gamma_\mu N)$	$\frac{1}{4}n_f^2(n_f+1)^2$
$(\overline{L}R)(\overline{L}R)$			$(\overline{R}L)(\overline{L}R)$		
$\mathcal{O}^S_{e\nu N1}(\star)$	$(\overline{e_L}e_R)(\overline{\nu}N)$	n_f^4	$\mathcal{O}^S_{e\nu N2}(\star)$	$(\overline{e_R}e_L)(\overline{\nu}N)$	n_f^4
$\mathcal{O}^T_{e\nu N}(\star)$	$(\overline{e_L}\sigma^{\mu\nu}e_R)(\overline{\nu}\sigma_{\mu\nu}N)$	n_f^4			
$\mathcal{O}^S_{d\nu N1}(\star)$	$(\overline{d_L}d_R)(\overline{\nu}N)$	n_f^4	$\mathcal{O}^S_{d\nu N2}(\star)$	$(\overline{d_R}d_L)(\overline{\nu}N)$	n_f^4
$\mathcal{O}^T_{d\nu N}(\star)$	$(\overline{d_L}\sigma^{\mu\nu}d_R)(\overline{\nu}\sigma_{\mu\nu}N)$	n_f^4			
$\mathcal{O}^S_{u\nu N1}(\star)$	$(\overline{u_L}u_R)(\overline{\nu}N)$	$n_f^2 n_u^2$	$\mathcal{O}^S_{u\nu N2}(\star)$	$(\overline{u_R}u_L)(\overline{\nu}N)$	$n_f^2 n_u^2$
$\mathcal{O}^T_{u\nu N}(\star)$	$(\overline{u_L}\sigma^{\mu\nu}u_R)(\overline{\nu}\sigma_{\mu\nu}N)$	$n_f^2 n_u^2$			
$\mathcal{O}^S_{udeN1}(\star)$	$(\overline{u_L}d_R)(\overline{e_L}N)$	$n_f^3 n_u$	$\mathcal{O}^S_{udeN2}(\star)$	$(\overline{u_R}d_L)(\overline{e_L}N)$	$n_f^3 n_u$
$\mathcal{O}^T_{udeN}(\star)$	$(\overline{u_L}\sigma^{\mu\nu}d_R)(\overline{e_L}\sigma_{\mu\nu}N)$	$n_f^3 n_u$			
$\mathcal{O}^S_{\nu N\nu N}(\star\star)$	$(\overline{\nu}N)(\overline{\nu}N)$	$\frac{1}{2}n_f^2(n_f^2+1)$	M. Chala , A. Titov, 2001.07732		
$(\Delta L, \Delta B) = (2,\ 0)$					
$(\overline{L}L)(\overline{R}R)$			$(\overline{R}R)(\overline{R}R)$		
$\mathcal{O}^V_{e\nu N1}(\star)$	$(\overline{e_L}\gamma_\mu e_L)(\overline{\nu^C}\gamma_\mu N)$	n_f^4	$\mathcal{O}^V_{e\nu N2}(\star)$	$(\overline{e_R}\gamma_\mu e_R)(\overline{\nu^C}\gamma_\mu N)$	n_f^4
$\mathcal{O}^V_{d\nu N1}(\star)$	$(\overline{d_L}\gamma_\mu d_L)(\overline{\nu^C}\gamma_\mu N)$	n_f^4	$\mathcal{O}^V_{d\nu N2}(\star)$	$(\overline{d_R}\gamma_\mu d_R)(\overline{\nu^C}\gamma_\mu N)$	n_f^4
$\mathcal{O}^V_{u\nu N1}(\star)$	$(\overline{u_L}\gamma_\mu u_L)(\overline{\nu^C}\gamma_\mu N)$	$n_f^2 n_u^2$	$\mathcal{O}^V_{u\nu N2}(\star)$	$(\overline{u_R}\gamma_\mu u_R)(\overline{\nu^C}\gamma_\mu N)$	$n_f^2 n_u^2$
$\mathcal{O}^V_{dueN1}(\star)$	$(\overline{d_L}\gamma_\mu u_L)(\overline{e_L^C}\gamma_\mu N)$	$n_f^3 n_u$	$\mathcal{O}^V_{dueN2}(\star)$	$(\overline{d_R}\gamma_\mu u_R)(\overline{e_L^C}\gamma_\mu N)$	$n_f^3 n_u$
$\mathcal{O}^V_{\nu\nu N}(\star)$	$(\overline{\nu}\gamma_\mu \nu)(\overline{\nu^C}\gamma_\mu N)$	$\frac{1}{2}n_f^3(n_f+1)$	$\mathcal{O}^V_{N\nu N}(\star\star\star)$	$(\overline{N}\gamma_\mu N)(\overline{\nu^C}\gamma_\mu N)$	$\frac{1}{2}n_f^3(n_f+1)$

- Dim-5:

$$\mathcal{O}_{NNF} = (\overline{N^C}\sigma_{\mu\nu}N)F^{\mu\nu},$$
$$\mathcal{O}_{\nu NF} = (\overline{\nu}\sigma_{\mu\nu}N)F^{\mu\nu},$$

- non-standard interactions
- Coherent elastic neutrino-nucleus scattering
- Meson invisible decay



Operator	Specific form	$\#(n_f,\ n_u)$	Operator	Specific form	$\#(n_f,\ n_u)$
$(\overline{L}R)(\overline{L}R)$			$(\overline{R}L)(\overline{L}R)$		
$\mathcal{O}^S_{eN1}(\star\star)$	$(\overline{e_L}e_R)(\overline{N^C}N)$	$\frac{1}{2}n_f^3(n_f+1)$	$\mathcal{O}^S_{eN2}(\star\star)$	$(\overline{e_R}e_L)(\overline{N^C}N)$	$\frac{1}{2}n_f^3(n_f+1)$
$\mathcal{O}^T_{eN}(\star\star)$	$(\overline{e_L}\sigma_{\mu\nu}e_R)(\overline{N^C}\sigma^{\mu\nu}N)$	$\frac{1}{2}n_f^3(n_f-1)$			
$\mathcal{O}^S_{dN1}(\star\star)$	$(\overline{d_L}d_R)(\overline{N^C}N)$	$\frac{1}{2}n_f^3(n_f+1)$	$\mathcal{O}^S_{dN2}(\star\star)$	$(\overline{d_R}d_L)(\overline{N^C}N)$	$\frac{1}{2}n_f^3(n_f+1)$
$\mathcal{O}^T_{dN}(\star\star)$	$(\overline{d_L}\sigma_{\mu\nu}d_R)(\overline{N^C}\sigma^{\mu\nu}N)$	$\frac{1}{2}n_f^3(n_f-1)$			
$\mathcal{O}^S_{uN1}(\star\star)$	$(\overline{u_L}u_R)(\overline{N^C}N)$	$\frac{1}{2}n_u^2n_f(n_f+1)$	$\mathcal{O}^S_{uN2}(\star\star)$	$(\overline{u_R}u_L)(\overline{N^C}N)$	$\frac{1}{2}n_f(n_f+1)n_u^2$
$\mathcal{O}^T_{uN}(\star\star)$	$(\overline{u_L}\sigma_{\mu\nu}u_R)(\overline{N^C}\sigma^{\mu\nu}N)$	$\frac{1}{2}n_u^2n_f(n_f-1)$			
$\mathcal{O}^S_{dueN1}(\star)$	$(\overline{d_L}u_R)(\overline{e_R^C}N)$	$n_f^3n_u$	$\mathcal{O}^S_{dueN2}(\star)$	$(\overline{d_R}u_L)(\overline{e_R^C}N)$	$n_f^3n_u$
$\mathcal{O}^T_{dueN}(\star)$	$(\overline{d_L}\sigma^{\mu\nu}u_R)(\overline{e_R^C}\sigma_{\mu\nu}N)$	$n_f^3n_u$	$(\overline{R}L)(\overline{R}L)$		
$\mathcal{O}^S_{\nu NN}(\star\star\star)$	$(\overline{\nu}N)(\overline{N^C}N)$	$\frac{1}{3}n_f^2(n_f^2-1)$	$\mathcal{O}^S_{N\nu\nu}(\star)$	$(\overline{N}\nu)(\overline{\nu^C}\nu)$	$\frac{1}{3}n_f^2(n_f^2-1)$
$(\Delta L, \Delta B) = (4,\ 0)$					
$(\overline{L}R)(\overline{L}R)$			$(\overline{R}L)(\overline{L}R)$		
$\mathcal{O}^S_{N}(\star\star\star\star)$	$(\overline{N^C}N)(\overline{N^C}N)$	$\frac{1}{12}n_f^2(n_f^2-1)$	$\mathcal{O}^S_{\nu N}(\star\star)$	$(\overline{\nu^C}\nu)(\overline{N^C}N)$	$\frac{1}{4}n_f^2(n_f+1)^2$
$(\Delta L, \Delta B) = (1,\ -1)$					
$(\overline{R}R)(\overline{R}R)$			$(\overline{L}R)(\overline{L}R)$		
$\mathcal{O}^V_{dduN1}(\star)$	$(\overline{d_R}\gamma^\mu d_L^C)(\overline{u_R}\gamma_\mu N)$	$n_f^3n_u$	$\mathcal{O}^S_{uddN1}(\star)$	$(\overline{u_L}d_L^C)(\overline{d_L}N)$	$n_f^3n_u$
$(\overline{R}L)(\overline{L}R)$					
$\mathcal{O}^S_{dduN1}(\star)$	$(\overline{d_R}d_R^C)(\overline{u_L}N)$	$\frac{1}{2}n_f^2(n_f-1)n_u$			
$(\Delta L, \Delta B) = (1,\ 1)$					
$(\overline{L}L)(\overline{R}R)$			$(\overline{L}R)(\overline{L}R)$		
$\mathcal{O}^V_{dduN2}(\star)$	$(\overline{d_R^C}\gamma^\mu d_L)(\overline{u_L^C}\gamma_\mu N)$	$n_f^3n_u$	$\mathcal{O}^V_{uddN2}(\star)$	$(\overline{u_R^C}d_R)(\overline{d_R^C}N)$	$n_f^3n_u$
$(\overline{R}L)(\overline{L}R)$					
$\mathcal{O}^S_{dduN2}(\star)$	$(\overline{d_L^C}d_L)(\overline{u_R^C}N)$	$\frac{1}{2}n_f^2(n_f-1)n_u$			

More operators violating lepton/baryon number

Matching @ Λ_{EW}

νSMEFT $\longleftrightarrow$ νLEFT

Integrate out heavy h, W, Z, t

Tree-level matching @dim5/6

LNC	$C^{V,pr\alpha\beta}_{u\nu1} = D_{px}D^*_{ry}\big(C^{(1),\alpha\beta xy}_{lq} + C^{(3),\alpha\beta xy}_{lq}\big) - \frac{\bar{g}_Z^2}{M_Z^2}[Z_{u_L}]_{pr}[Z_\nu]_{\alpha\beta}$	$C^{V,pr\alpha\beta}_{u\nu2} = C^{\alpha\beta pr}_{lu} - \frac{\bar{g}_Z^2}{M_Z^2}[Z_{u_R}]_{pr}[Z_\nu]_{\alpha\beta}$
$\nu\nu$ case	$C^{V,pr\alpha\beta}_{d\nu1} = C^{(1),\alpha\beta pr}_{lq} - C^{(3),\alpha\beta pr}_{lq} - \frac{\bar{g}_Z^2}{M_Z^2}[Z_{d_L}]_{pr}[Z_\nu]_{\alpha\beta}$	$C^{V,pr\alpha\beta}_{d\nu2} = C^{\alpha\beta pr}_{ld} - \frac{\bar{g}_Z^2}{M_Z^2}[Z_{d_R}]_{pr}[Z_\nu]_{\alpha\beta}$
LNC	$C^{V,pr\alpha\beta}_{uN1} = D_{px}D^*_{ry}C^{xy\alpha\beta}_{QN} - \frac{\bar{g}_Z^2}{M_Z^2}[Z_{u_L}]_{pr}[Z_N]_{\alpha\beta}$	$C^{V,pr\alpha\beta}_{uN2} = C^{pr\alpha\beta}_{uN} - \frac{\bar{g}_Z^2}{M_Z^2}[Z_{u_R}]_{pr}[Z_N]_{\alpha\beta}$
NN case	$C^{V,pr\alpha\beta}_{dN1} = C^{pr\alpha\beta}_{QN} - \frac{\bar{g}_Z^2}{M_Z^2}[Z_{d_L}]_{pr}[Z_N]_{\alpha\beta}$	$C^{V,pr\alpha\beta}_{dN2} = C^{pr\alpha\beta}_{dN} - \frac{\bar{g}_Z^2}{M_Z^2}[Z_{d_R}]_{pr}[Z_N]_{\alpha\beta}$
	$C^{\alpha\beta}_{\nu NF} = +\frac{v}{\sqrt{2}}e\big(C^{\alpha\beta}_{NB} + C^{\alpha\beta}_{NW}\big)$	
LNC	$C^{S,pr\alpha\beta}_{u\nu N1} = 0$	$C^{S,pr\alpha\beta}_{u\nu N2} = +D^*_{rx}C^{xp\beta\alpha *}_{QuNL}$
νN case	$C^{S,pr\alpha\beta}_{d\nu N1} = +C^{\alpha\beta pr}_{LNQd} - \frac{1}{2}C^{\alpha rp\beta}_{LdQN}$	$C^{S,pr\alpha\beta}_{d\nu N2} = 0$
	$C^{T,pr\alpha\beta}_{u\nu N} = 0$	$C^{T,pr\alpha\beta}_{d\nu N} = -\frac{1}{8}C^{\alpha rp\beta}_{LdQN}$
	$C^{\alpha\beta}_{\nu\nu F} = +\frac{1}{4}v^2 e\big(2C^{\alpha\beta}_{LHB} + C^{\beta\alpha}_{LHW} - C^{\alpha\beta}_{LHW}\big)$	
LNV	$C^{S,pr\alpha\beta}_{u\nu1} = 0$	$C^{S,pr\alpha\beta}_{u\nu2} = +\frac{v}{2\sqrt{2}}D_{px}\big(C^{xr\alpha\beta}_{\bar{Q}uLLH} + C^{xr\beta\alpha}_{\bar{Q}uLLH}\big)$
$\nu\nu$ case	$C^{S,pr\alpha\beta}_{d\nu1} = -\frac{v}{4\sqrt{2}}\big(C^{p\alpha r\beta}_{\bar{d}LQLH1} + C^{p\beta r\alpha}_{\bar{d}LQLH1}\big)$	$C^{S,pr\alpha\beta}_{d\nu2} = 0$
	$C^{T,pr\alpha\beta}_{u\nu} = 0$	$C^{T,pr\alpha\beta}_{d\nu} = +\frac{v}{16\sqrt{2}}\big(C^{p\alpha r\beta}_{\bar{d}LQLH1} - C^{p\beta r\alpha}_{\bar{d}LQLH1}\big)$
	$C^{\alpha\beta}_{NNF} = +\frac{1}{2}v^2 e\big(C^{\alpha\beta}_{NHB} - C^{\alpha\beta}_{NHW}\big)$	
LNV	$C^{S,pr\alpha\beta}_{uN1} = -\frac{v}{4\sqrt{2}}D_{px}\big(C^{x\alpha\beta r}_{QNuH} + C^{x\beta\alpha r}_{QNuH}\big)$	$C^{S,pr\alpha\beta}_{uN2} = +\frac{v}{\sqrt{2}}D^*_{rx}C^{px\alpha\beta}_{uQNH}$
NN case	$C^{S,pr\alpha\beta}_{dN1} = -\frac{v}{4\sqrt{2}}\big(C^{p\alpha\beta r}_{QNdH} + C^{p\beta\alpha r}_{QNdH}\big)$	$C^{S,pr\alpha\beta}_{dN2} = +\frac{v}{\sqrt{2}}C^{pr\alpha\beta}_{dQNH}$
	$C^{T,pr\alpha\beta}_{uN} = +\frac{v}{16\sqrt{2}}D_{px}\big(C^{x\alpha\beta r}_{QNuH} - C^{x\beta\alpha r}_{QNuH}\big)$	$C^{T,pr\alpha\beta}_{dN} = +\frac{v}{16\sqrt{2}}\big(C^{p\alpha\beta r}_{QNdH} - C^{p\beta\alpha r}_{QNdH}\big)$
LNV	$C^{V,pr\alpha\beta}_{u\nu N1} = -\frac{v}{\sqrt{2}}D_{px}D^*_{ry}C^{xy\beta\alpha}_{QNLH1} - \frac{\bar{g}_Z^2}{M_Z^2}[Z_{u_L}]_{pr}[Z_{\nu N}]_{\alpha\beta}$	$C^{V,pr\alpha\beta}_{u\nu N2} = -\frac{v}{\sqrt{2}}C^{pr\beta\alpha}_{uNLH} - \frac{\bar{g}_Z^2}{M_Z^2}[Z_{u_R}]_{pr}[Z_{\nu N}]_{\alpha\beta}$
νN case	$C^{V,pr\alpha\beta}_{d\nu N1} = -\frac{v}{\sqrt{2}}\big(C^{pr\beta\alpha}_{QNLH1} - C^{pr\beta\alpha}_{QNLH2}\big) - \frac{\bar{g}_Z^2}{M_Z^2}[Z_{d_L}]_{pr}[Z_{\nu N}]_{\alpha\beta}$	$C^{V,pr\alpha\beta}_{d\nu N2} = -\frac{v}{\sqrt{2}}C^{pr\beta\alpha}_{dNLH} - \frac{\bar{g}_Z^2}{M_Z^2}[Z_{d_R}]_{pr}[Z_{\nu N}]_{\alpha\beta}$

1-loop matching

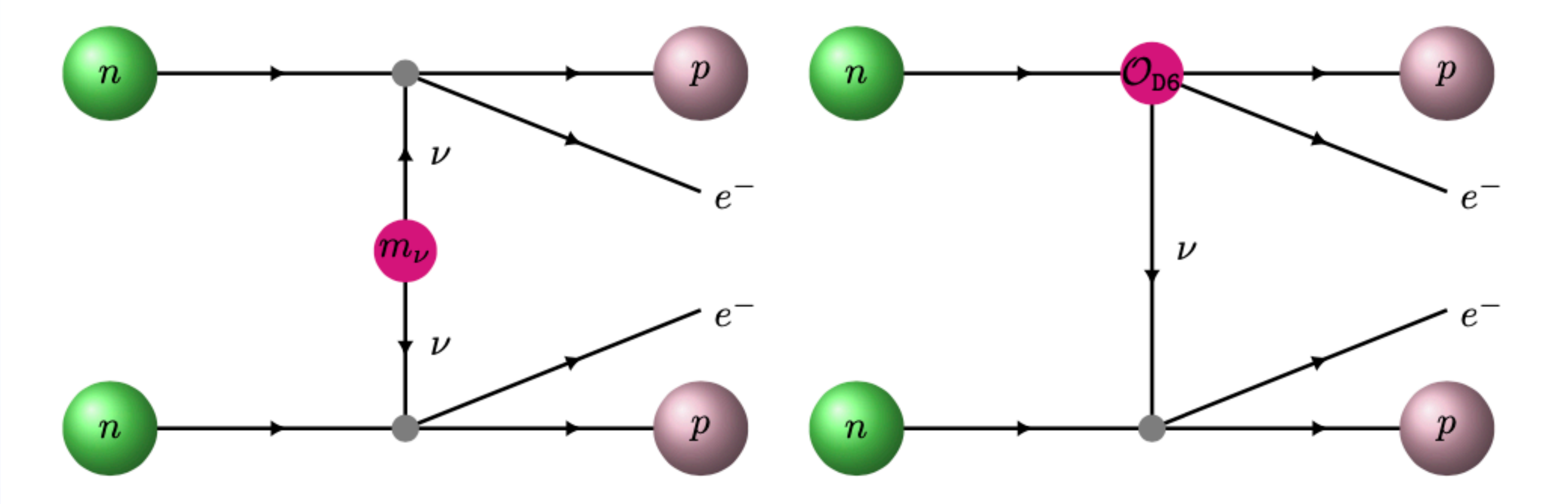
M. Chala , A. Titov, 2001.07732

Direct ν 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: $(\bar{\nu}\Gamma q)(q'C\Gamma'q''')$
- ...

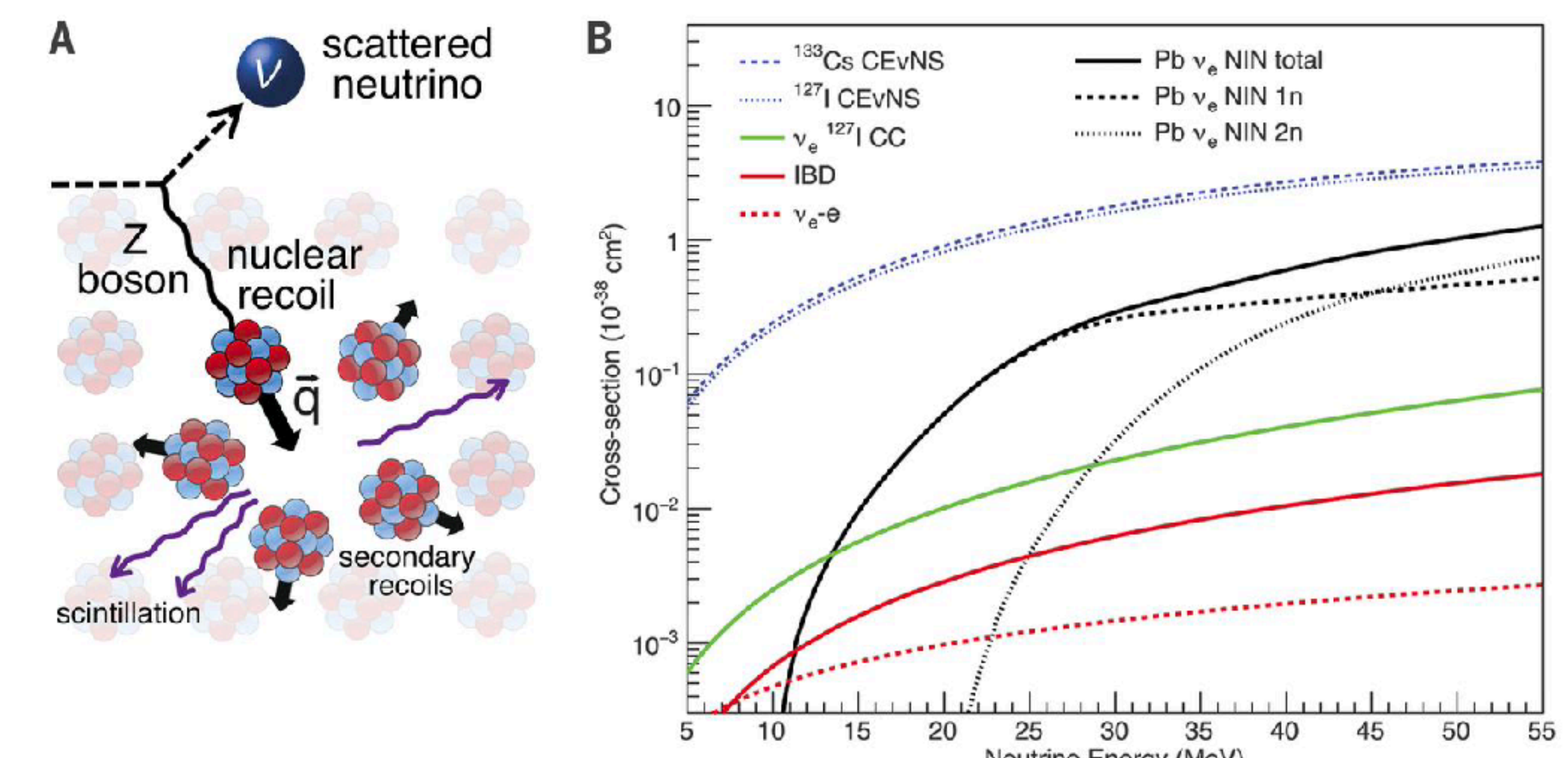
Indirect ν processes

- $0\nu\beta\beta$



Mass mechanism Long-distance

NSI and NGI (NC)



COHERENT: 1708.01294

coherent elastic scattering of neutrinos off nuclei (CEvNS)

- Freedman: PhysRevD.9.1389
- Enhanced by # of nucleons
- Sensitivity to TeV scale NPs

$$
\begin{aligned}
\mathcal{L}^{\epsilon}_{q\nu} \supset & -2\sqrt{2}G_F\epsilon^{\alpha\beta pr}_{L,q}\left(\overline{\nu_\alpha}\gamma_\mu P_L\nu_\beta\right)\left(\overline{q_p}\gamma^\mu P_L q_r\right) && -2\sqrt{2}G_F\tilde{\epsilon}^{\alpha\beta pr}_{L,q}\left(\overline{\nu_\alpha}\gamma_\mu P_R\nu_\beta\right)\left(\overline{q_p}\gamma^\mu P_L q_r\right)\\
& -2\sqrt{2}G_F\epsilon^{\alpha\beta pr}_{R,q}\left(\overline{\nu_\alpha}\gamma_\mu P_L\nu_\beta\right)\left(\overline{q_p}\gamma^\mu P_R q_r\right) && -2\sqrt{2}G_F\tilde{\epsilon}^{\alpha\beta pr}_{R,q}\left(\overline{\nu_\alpha}\gamma_\mu P_R\nu_\beta\right)\left(\overline{q_p}\gamma^\mu P_R q_r\right)\\
& -\sqrt{2}G_F\epsilon^{\alpha\beta pr}_{S,q}\left(\overline{\nu_\alpha}P_L\nu_\beta\right)\left(\overline{q_p}q_r\right) && -\sqrt{2}G_F\tilde{\epsilon}^{\alpha\beta pr}_{S,q}\left(\overline{\nu_\alpha}P_R\nu_\beta\right)\left(\overline{q_p}q_r\right)\\
& +\sqrt{2}G_F\epsilon^{\alpha\beta pr}_{P,q}\left(\overline{\nu_\alpha}P_L\nu_\beta\right)\left(\overline{q_p}\gamma_5 q_r\right) && +\sqrt{2}G_F\tilde{\epsilon}^{\alpha\beta pr}_{P,q}\left(\overline{\nu_\alpha}P_R\nu_\beta\right)\left(\overline{q_p}\gamma_5 q_r\right)\\
& -2\sqrt{2}G_F\epsilon^{\alpha\beta pr}_{T,q}\left(\overline{\nu_\alpha}\sigma_{\mu\nu}P_L\nu_\beta\right)\left(\overline{q_p}\sigma^{\mu\nu}P_L q_r\right) && -2\sqrt{2}G_F\tilde{\epsilon}^{\alpha\beta pr}_{T,q}\left(\overline{\nu_\alpha}\sigma^{\mu\nu}P_R\nu_\beta\right)\left(\overline{q_p}\sigma^{\mu\nu}P_R q_r\right),
\end{aligned}
$$

1907.00991,
Daya Bay: 1401.02901
Li: 1408.6301
Liao: 1612.01443, 1704.04711
Du et al: 2011.14292, 2106.15800
Farzan: 1710.09360,
.....

FCNC with neutrino pairs

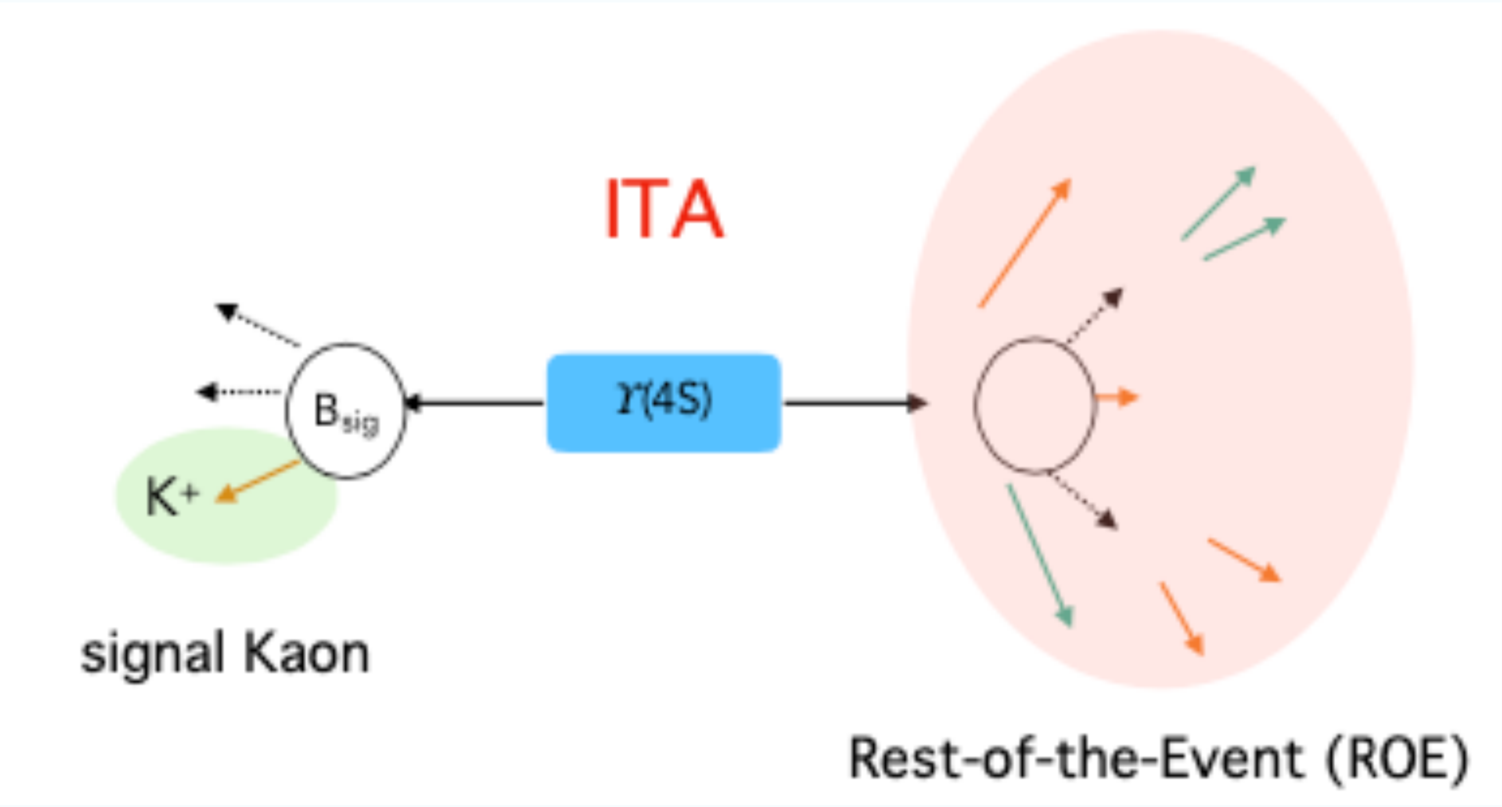
Observable	SM Br prediction:	90 % C.L. upper bound
$B^+ \to K^+\nu\bar{\nu}$	$(4.4 \pm 0.6) \times 10^{-6}$	1.6×10^{-5}
$B^0 \to K^0\nu\bar{\nu}$	$(4.1 \pm 0.6) \times 10^{-6}$	2.6×10^{-5}
$B^+ \to K^{*+}\nu\bar{\nu}$	$(1.0 \pm 0.1) \times 10^{-5}$	4.0×10^{-5}
$B^0 \to K^{*0}\nu\bar{\nu}$	$(9.5 \pm 1.0) \times 10^{-6}$	1.8×10^{-5}
$B^+ \to \pi^+\nu\bar{\nu}$	$(2.39^{+0.30}_{-0.28}) \times 10^{-7}$	1.4×10^{-5}
$B^0 \to \pi^0\nu\bar{\nu}$	$(1.2^{+0.15}_{-0.14}) \times 10^{-7}$	9.0×10^{-6}
$B^+ \to \rho^+\nu\bar{\nu}$	$(4.5 \pm 1.0) \times 10^{-7}$	3.0×10^{-5}
$B^0 \to \rho^0\nu\bar{\nu}$	$(2.0 \pm 0.4) \times 10^{-7}$	4.0×10^{-5}
$K^+ \to \pi^+\nu\bar{\nu}$	$(8.1 \pm 0.4) \times 10^{-11}$	$(1.14^{+0.40}_{-0.33}) \times 10^{-10}$
$K_L \to \pi^0\nu\bar{\nu}$	$(2.8 \pm 0.2) \times 10^{-11}$	4.9×10^{-9}

- KOTO anomaly in Kaon decay
- Baryon sector: $B_i \to B_f\nu\bar{\nu}$
- Other mesons:

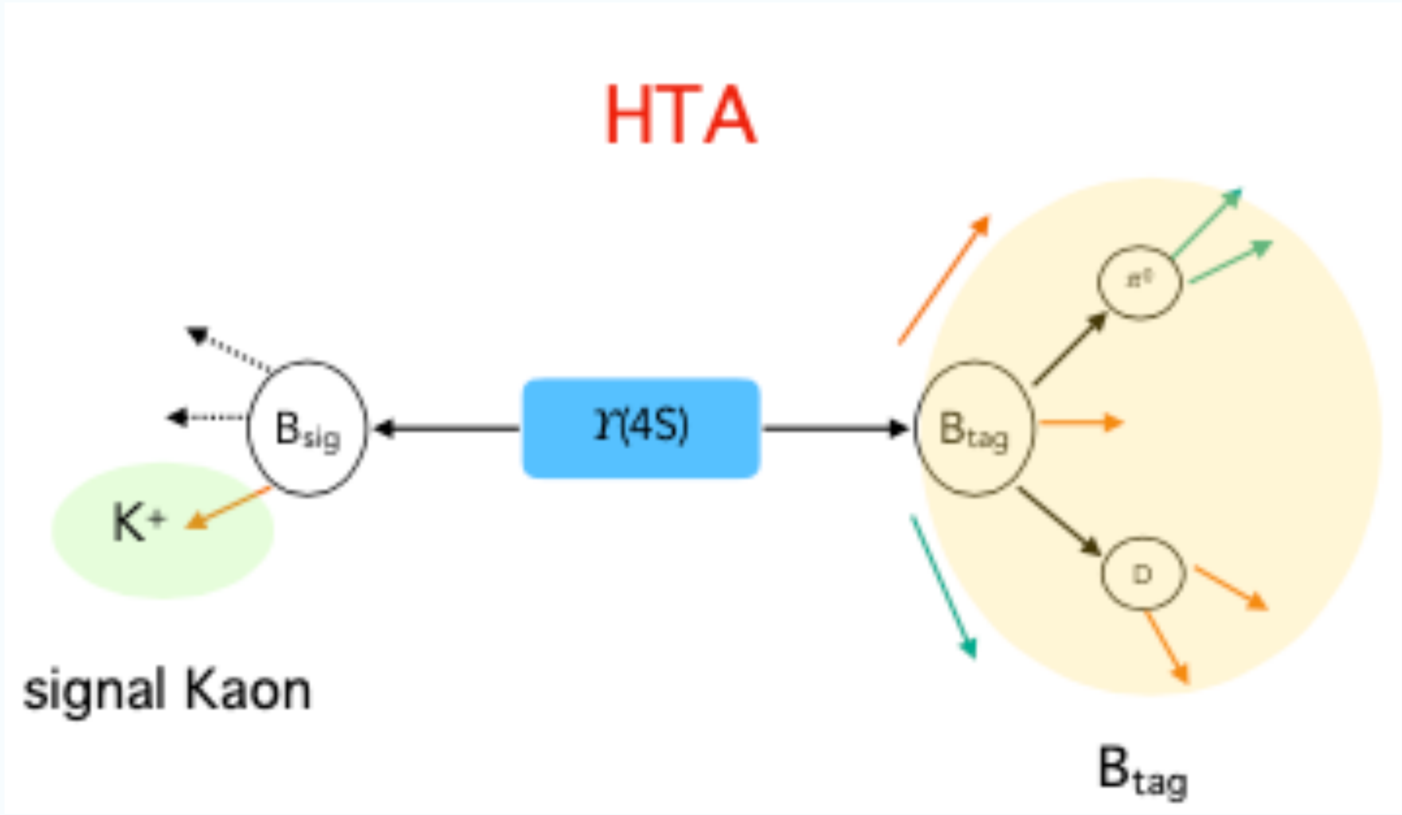
$$M_i \to M_f\nu\bar{\nu}, M \to \nu\bar{\nu}$$

NP related to neutrino sector

Recent Belle II result



Inclusive Tag analysis (ITA)
more sensitive



Hadronic Tag analysis (HTA)
more conventional

- Combination: $\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\rm exp} = (2.3 \pm 0.7) \times 10^{-5}$

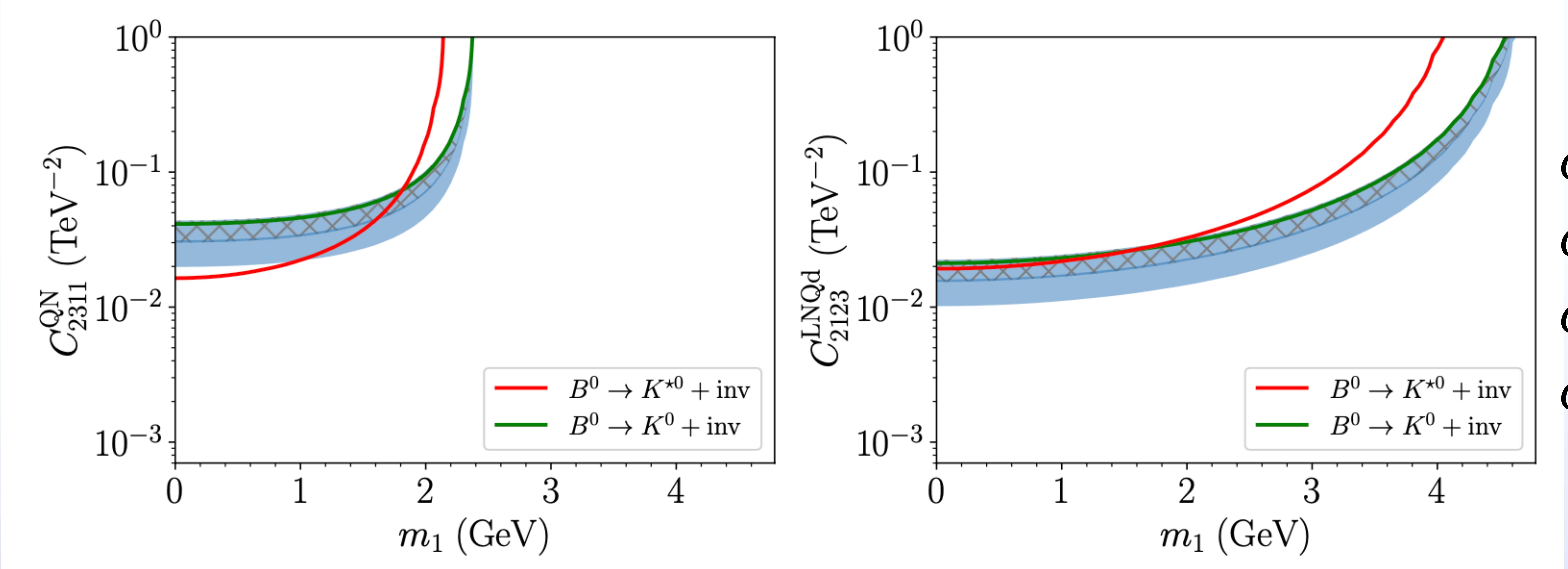
Belle-II Collaboration
2311.14647

- Combine Belle II 2021 data, $\mathscr{B}(B^+ \to K^+\nu\bar{\nu})^{\rm ave}_{\rm exp} = (1.3 \pm 0.4) \times 10^{-5}$

- $2.7\,\sigma$ higher than SM prediction $\Rightarrow$ New physics possibility

$B \to K + \nu(N) + N$

T. Felkl, A. Giri, R. Mohanta, and M. A. Schmidt, 2309.02940



$C^{QN}(\bar{Q}\gamma_\mu Q)(\bar{N}\gamma^\mu N)$

$C^{dN}(\bar{d}\gamma_\mu d)(\bar{N}\gamma^\mu N)$

$C^{LNQd}(\bar{L}^\alpha N)\epsilon_{\alpha\beta}(\bar{Q}^\beta d)$

$C^{LNQd,T}(\bar{L}^\alpha \sigma_{\mu\nu} N)\epsilon_{\alpha\beta}(\bar{Q}^\beta \sigma^{\mu\nu} d)$

- Assumption with a single operator dominant
- Tensor operator is almost excluded by $B^0 \to K^{*0} + \texttt{inv}$.
- The vector and scalar operators are viable

From EFTs to UV models

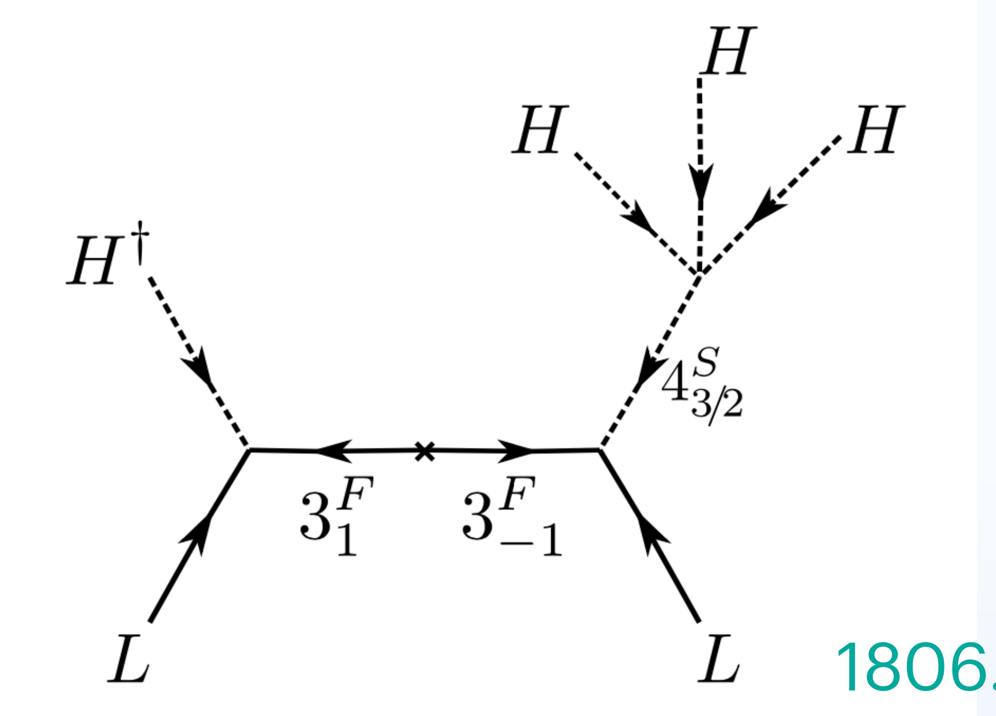
UV completion of EFT operators

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

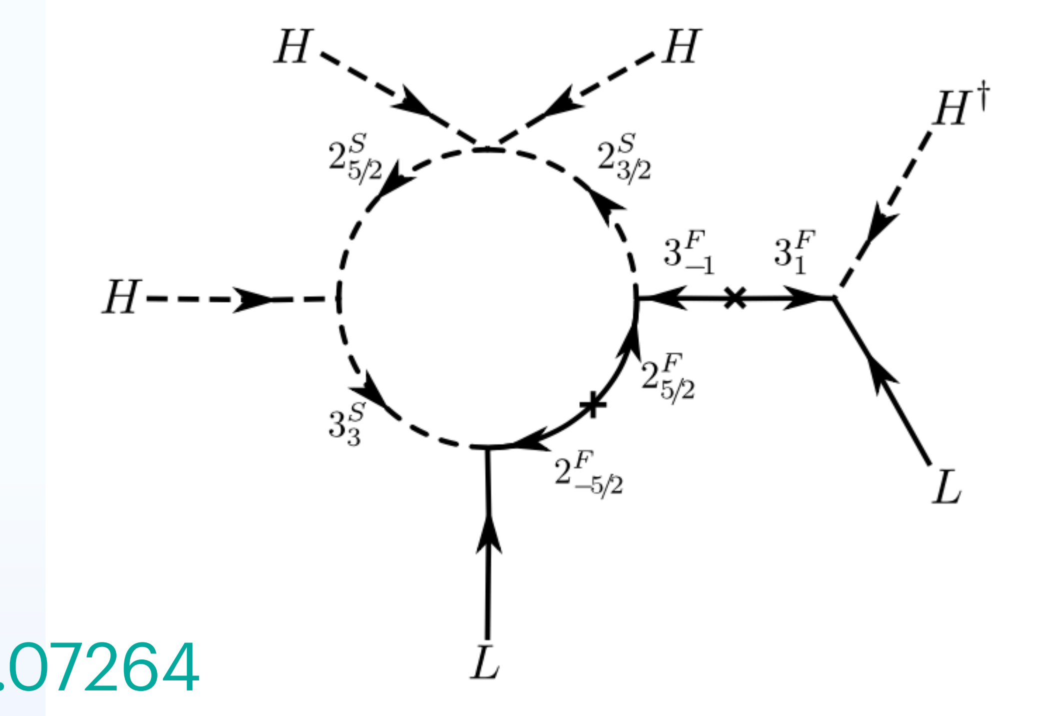
- Usually, assume the SM gauge symmetry intact
- Internal heavy fields: scalar, fermion, vector

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

- Dim-n Weinberg operator



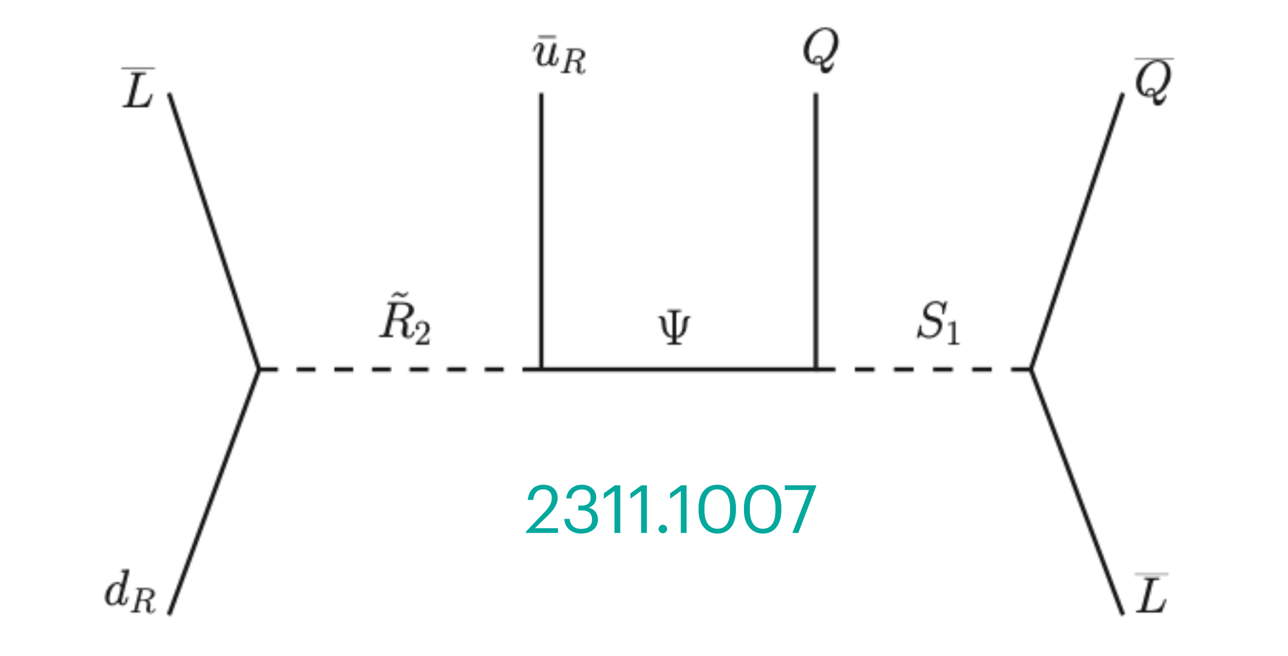
1806.07264



- 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

Dim <= 8:

Li et al: 2204.03660, 2307.10380, 2309.15933

UV completion of νSMEFT operators

R. Beltran, R. Cepedello, M. Hirsch, 2306.12578

Name	$\mathcal{S}$	$\mathcal{S}_1$	φ	Ξ	Ξ_1
Irrep	$(1,1,0)$	$(1,1,1)$	$(1,2,\frac{1}{2})$	$(1,3,0)$	$(1,3,1)$
$d=6$	$\circ$	$\circ$	$\circ$	$\circ$	$\circ$
Name	ω_1	ω_2	Π_1	Π_7	ζ
Irrep	$(3,1,-\frac{1}{3})$	$(3,1,\frac{2}{3})$	$(3,2,\frac{1}{6})$	$(3,2,\frac{7}{6})$	$(3,3,-\frac{1}{3})$
$d=6$	$\circ$	$\circ$	$\circ$		

Table 1: New scalars contributing to $d=6$ and $d=7$ N_RSMEFT operators at tree-level. Only fields marked with a circle contribute to $d=6$, the remaining ones appear in models for $d=7$ operators. Field names follow the conventions of [37].

Name	$\mathcal{N}$	E	Δ_1	Δ_3	Σ	Σ_1	
Irrep	$(1,1,0)$	$(1,1,-1)$	$(1,2,-\frac{1}{2})$	$(1,2,-\frac{3}{2})$	$(1,3,0)$	$(1,3,-1)$	
$d=6$	$\circ$		$\circ$		$\circ$	$\circ$	
Name	U	D	Q_1	Q_5	Q_7	T_1	T_2
Irrep	$(3,1,\frac{2}{3})$	$(3,1,-\frac{1}{3})$	$(3,2,\frac{1}{6})$	$(3,2,-\frac{5}{6})$	$(3,2,\frac{7}{6})$	$(3,3,-\frac{1}{3})$	$(3,3,\frac{2}{3})$
$d=6$							

Table 2: New vector-like fermions contributing to $d=6$, $d=7$ N_RSMEFT at tree-level.

Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{L}_1$	$\mathcal{L}_3$
Irrep	$(1,1,0)$	$(1,1,1)$	$(1,3,0)$	$(1,3,1)$	$(1,2,\frac{1}{2})$	$(1,2,-\frac{3}{2})$
$d=6$	$\circ$	$\circ$			$\circ$	
Name	$\mathcal{U}_1$	$\mathcal{U}_2$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$	
Irrep	$(3,1,-\frac{1}{3})$	$(3,1,\frac{2}{3})$	$(3,2,\frac{1}{6})$	$(3,2,-\frac{5}{6})$	$(3,3,\frac{2}{3})$	
$d=6$	$\circ$	$\circ$	$\circ$			

Table 3: New vector bosons contributing to $d=6$, $d=7$ N_RSMEFT at tree-level. Two fields, $\mathcal{L}_1$ and $\mathcal{U}_1$, are special cases, see text.

One-particle decompositions for dim-6 νSMEFT operators

Models	Operators
$\mathcal{S}$	$\mathcal{O}_{NN}$, $\mathcal{O}_{NNNN}$
$\mathcal{S}_1$	$\mathcal{O}_{LNLe}$, $\mathcal{O}_{eN}$
φ	$\mathcal{O}_{QuNL}$, $\mathcal{O}_{LNLe}$, $\mathcal{O}_{LNQd}$, $\mathcal{O}_{LN}$, $\mathcal{O}_{LNH^3}$
ω_1	$\mathcal{O}_{LNQd}$, $\mathcal{O}_{dN}$, $\mathcal{O}_{duNe}$
ω_2	$\mathcal{O}_{uN}$
Π_1	$\mathcal{O}_{LNQd}$, $\mathcal{O}_{QN}$
Δ_1	$\mathcal{O}_{NH^2D}$, $\mathcal{O}_{NeH^2D}$
$\mathcal{B}$	$\mathcal{O}_{NH^2D}$, $\mathcal{O}_{NN}$, $\mathcal{O}_{eN}$, $\mathcal{O}_{uN}$, $\mathcal{O}_{dN}$, $\mathcal{O}_{LN}$, $\mathcal{O}_{QN}$
$\mathcal{B}_1$	$\mathcal{O}_{NeH^2D}$, $\mathcal{O}_{eN}$, $\mathcal{O}_{duNe}$
$\mathcal{L}_1$	$\mathcal{O}_{LN}$
$\mathcal{U}_1$	$\mathcal{O}_{dN}$
$\mathcal{U}_2$	$\mathcal{O}_{QuNL}$, $\mathcal{O}_{uN}$, $\mathcal{O}_{duNe}$
$\mathcal{Q}_1$	$\mathcal{O}_{QuNL}$, $\mathcal{O}_{QN}$

Top-down EFT

UV model

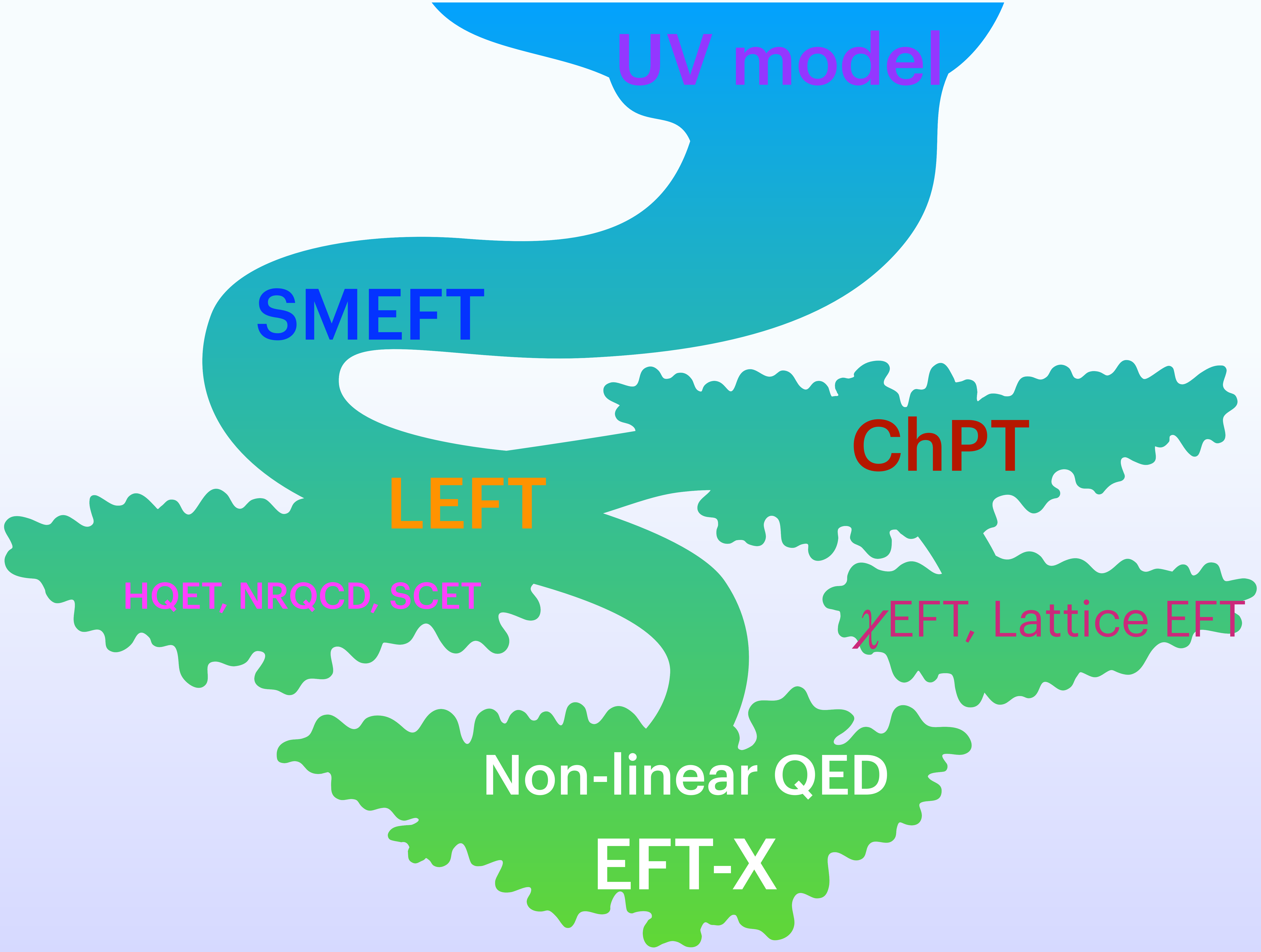
Integrate out
heavy dof

EFT1

Integrate out
heavy dof

EFT2

…



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: X. Li, S. 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)

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

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

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

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

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

- 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

From Green basis to Standard basis

- Double expansion: loop expansion and low energy expansion
- Background field method
- Threshold corrections: correction for dim<=4 terms
- Renormalization: treat the divergence
- Green basis: a redundant basis without applying EoM relations
- Convert to a standard basis via various identities and manipulations

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

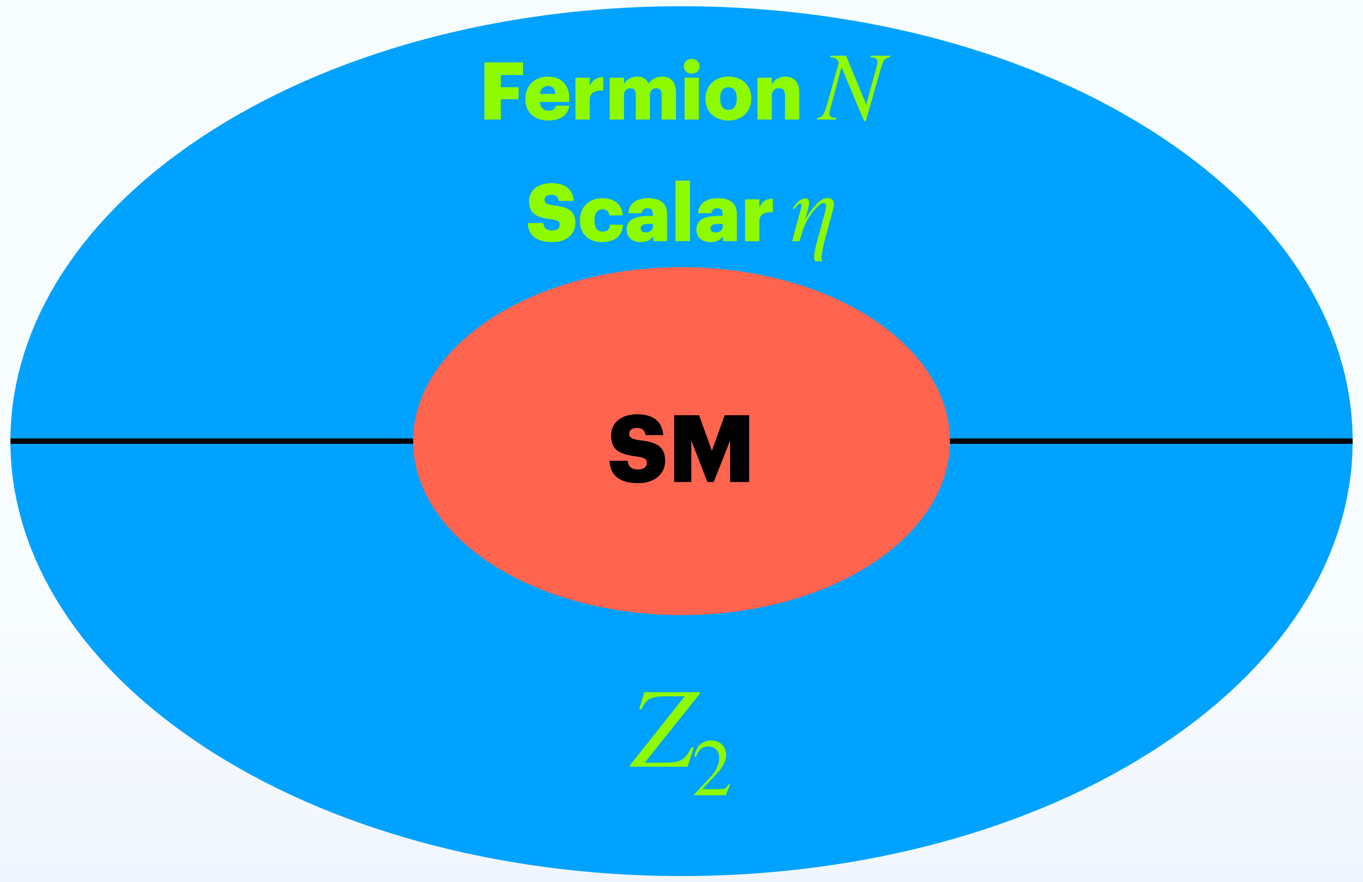
Leptoquark model

Singlet scalar model, etc

Matching scotogenic model onto (ν)SMEFT

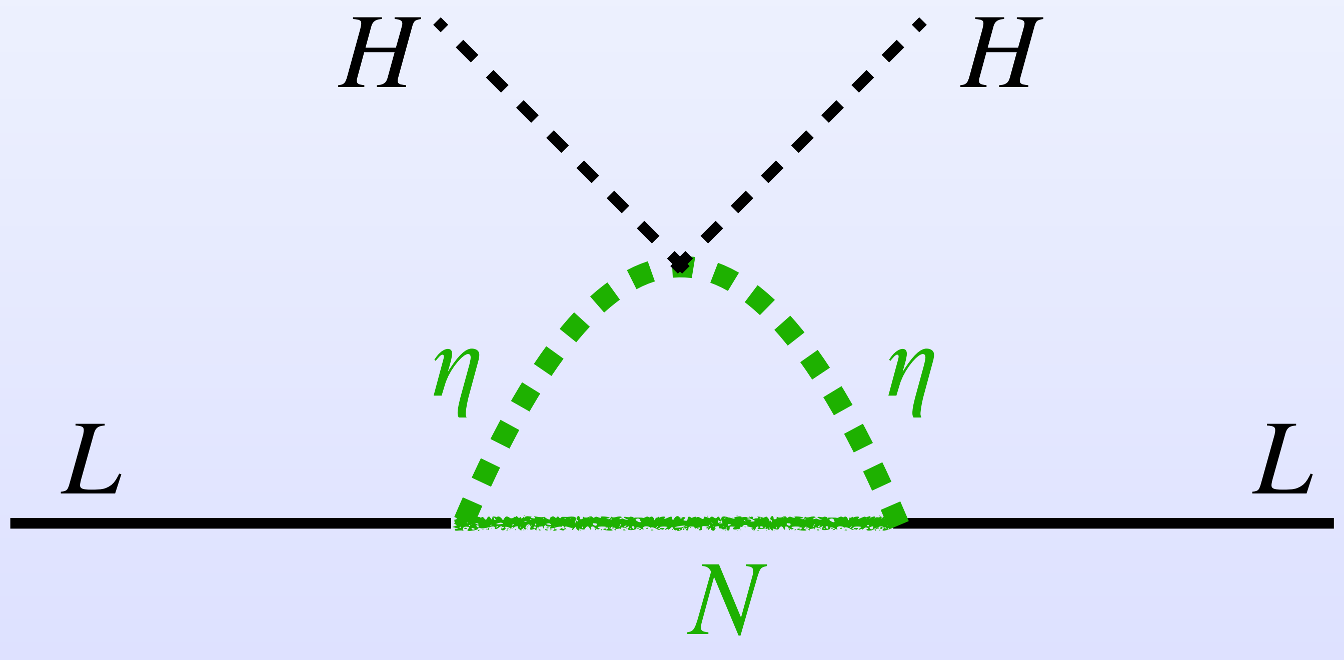
E. Ma, 0601225

Scotogenic model =



- **Neutrino mass**
- **Dark matter**
- **Testability @ collider**

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_{\mathtt{SM}} + \mathcal{L}_{N,\eta}, \\
\mathcal{L}_{N,\eta} &= \bar{N} i \partial\!\!\!/ N - \left(\frac{1}{2} \overline{N} m_N N^{\mathtt{C}} + \bar{L} \tilde{\eta} Y_\eta N + \text{h.c.} \right) + |D_\mu \eta|^2 - V(H,\eta), \\
V(H,\eta) &= m_\eta^2 \eta^\dagger \eta + \frac{1}{2} \lambda_2 (\eta^\dagger \eta)^2 + \lambda_3 (H^\dagger H)(\eta^\dagger \eta) \\
&\quad + \lambda_4 (H^\dagger \eta)(\eta^\dagger H) + \frac{1}{2} \lambda_5 [(H^\dagger \eta)^2 + (\eta^\dagger H)^2].
\end{aligned}
$$



Neutrino mass diagram

Matching scotogenic model onto SMEFT

Integrate out both N and η via functional method

$\Longrightarrow$ **SMEFT**

- $\mathbb{Z}_2$ symmetry: no tree-level matching result
- The non-trivial result begins at the one-loop level
- No neutrino transition moment
- LFV decays $\ell_i \to \ell_j \gamma, \mu \to 3e$

$$\mathcal{O}^{pr}_{LH,5} = \epsilon_{ij}\epsilon_{mn}(\overline{L^{c,i}_p} L^m_r) H^j H^n$$

$$C^{pr}_{LH,5} = -\frac{\lambda_5}{32\pi^2 m_\eta^2}\left\{\left[Y^*_\eta m_N G_1(x) Y^\dagger_\eta\right]_{pr} - \frac{\mu_H^2}{6m_\eta^2}\left[Y^*_\eta m_N G_4(x) Y^\dagger_\eta\right]_{pr}\right\}$$

$$\mathcal{O}^{pr}_{LH} = \epsilon_{ij}\epsilon_{mn}(\overline{L^{c,i}_p} L^m_r) H^j H^n (H^\dagger H)$$

$$C^{pr}_{LH} = \frac{\lambda_5}{32\pi^2 m_\eta^4}\left\{(\lambda_3+\lambda_4)\left[Y^*_\eta m_N G_2(x) Y^\dagger_\eta\right]_{pr} - \frac{\lambda_H}{3}\left[Y^*_\eta m_N G_4(x) Y^\dagger_\eta\right]_{pr}\right\}$$

$\Downarrow$ Neutrino mass matrix

$$M^{pr}_\nu = \frac{\lambda_5 v^2}{32\pi^2 m_\eta^2}\left\{Y^*_\eta m_N \left[G_1(x) - \frac{(\lambda_3+\lambda_4)v^2}{2m_\eta^2} G_2(x)\right] Y^\dagger_\eta\right\}$$

More efficient to systematically investigate the parameter space of the model

Matching scotogenic model onto νSMEFT

Y. Liao, X.D. Ma, D. Zhang, (in preparation)

Integrate out only η $\Longrightarrow$ ν**SMEFT**

- Tree-level matching result exists: $-\dfrac{1}{2m_\eta^2}(Y_\eta)_{pt}(Y_\eta^\dagger)_{sr}(\bar{L}_p\gamma_\mu L_r)(\bar{N}_s\gamma^\mu N_t)$
- $\mathbb{Z}_2$ symmetry: N appears in pairs
- Sterile neutrino magnetic moment:
- DM phenomenology:
  direct detection, relic density

Dim	Operator	WCs $[1/(16\pi^2)]$
5	$\mathcal{O}_{NH,5}^{pr}$	$-\frac{1}{4m_\eta^2}\left\{(2\lambda_3+\lambda_4)\left[Y_\eta^\dagger Y_\eta m_N\right]_{pr}+\left[Y_\eta^\dagger Y_e Y_e^\dagger Y_\eta m_N\right]_{pr}\right\}$
	$\mathcal{O}_{BN,5}^{pr}$	$-\frac{g_1}{8m_\eta^2}\left[Y_\eta^\dagger Y_\eta m_N\right]_{pr}$
6	$\mathcal{O}_{HN}^{pr}$	$\frac{1}{12}g_1^2(3+2L_\eta)\left[Y_\eta^\dagger Y_\eta\right]_{pr}+\frac{1}{2}(1+L_\eta)\left(Y_\eta^\dagger Y_e Y_e^\dagger Y_\eta\right)_{pr}$
	$\mathcal{O}_{uN}^{prst}$	$\frac{g_1^2}{9}(3+2L_\eta)\left[Y_\eta^\dagger Y_\eta\right]_{st}\delta_{pr}$
	$\mathcal{O}_{dN}^{prst}$	$-\frac{g_1^2}{18}(3+2L_\eta)\left[Y_\eta^\dagger Y_\eta\right]_{st}\delta_{pr}$
	$\mathcal{O}_{eN}^{prst}$	$-\frac{g_1^2}{6}(3+2L_\eta)\left[Y_\eta^\dagger Y_\eta\right]_{st}\delta_{pr}+\frac{1}{4}(3+2L_\eta)\left(Y_e^\dagger Y_\eta\right)_{pt}\left(Y_\eta^\dagger Y_e\right)_{sr}$
	$\mathcal{O}_{NN}^{prst}$	$-\frac{1}{4}\left(Y_\eta^\dagger Y_\eta\right)_{pr}\left(Y_\eta^\dagger Y_\eta\right)_{st}$
	$\mathcal{O}_{qN}^{prst}$	$\frac{1}{36}g_1^2(3+2L_\eta)\left[Y_\eta^\dagger Y_\eta\right]_{st}\delta_{pr}$
	$\mathcal{O}_{lN}^{prst}$	$-\frac{g_1^2}{12}(3+2L_\eta)\left[Y_\eta^\dagger Y_\eta\right]_{st}\delta_{pr}+\frac{1}{8m_\eta^2}(2L_\eta+1)\left[Y_\eta\right]_{pt}\left[Y_\eta^* m_N Y_\eta^\dagger Y_\eta \hat{m}_N\right]_{rs}$ $+\frac{1}{4}\left[\left(Y_\eta Y_\eta^\dagger\right)_{pr}\left(Y_\eta^\dagger Y_\eta\right)_{st}-6(1+L_\eta)\lambda_2\left(Y_\eta\right)_{pt}\left(Y_\eta^\dagger\right)_{sr}\right]$
7	$\mathcal{O}_{LNeH}^{prst}$	$\frac{1}{4m_\eta^4}(2L_\eta+3)\left[Y_\eta\right]_{pr}\left[Y_e^\intercal Y_\eta^* m_N Y_\eta^\dagger Y_\eta\right]_{st}$

Summary

- Sterile neutrinos are promising new particles to understand many big questions;
- Studying sterile neutrinos through EFT is a convenient way to reach the main physical insight;
- Various aspects of νEFT are discussed;
- Many other interesting topics are not covered:

HNL or LLP searches, $0\nu\beta\beta$, ….

Thank you for your time!