中微子有效场论

华南师范大学

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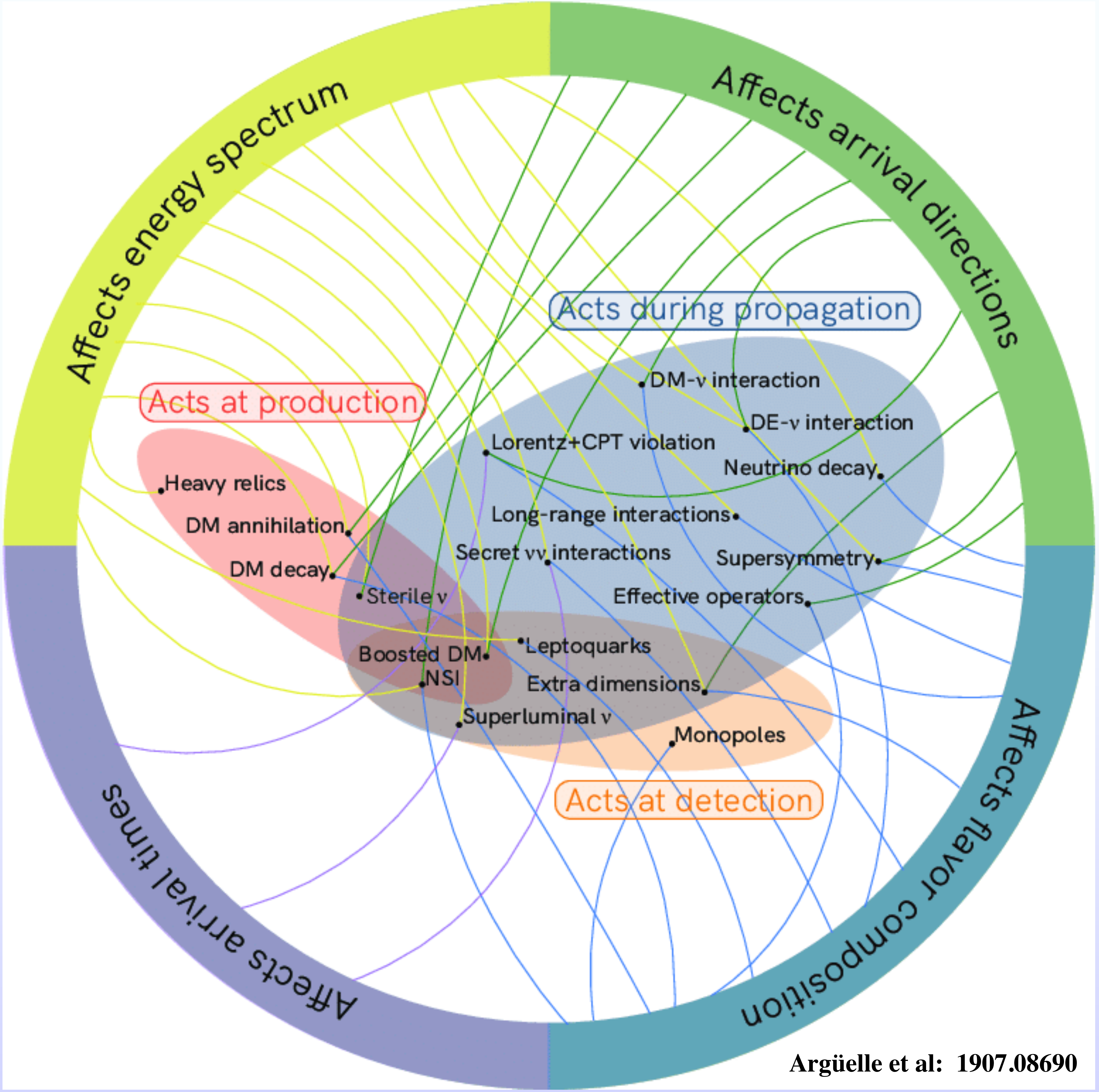
第27届 LHC Mini-Workshop
2024年1月19日-23日，珠海



Argüelle et al: 1907.08690

Neutrino world is wonderful,

full of mysteries and treasures,

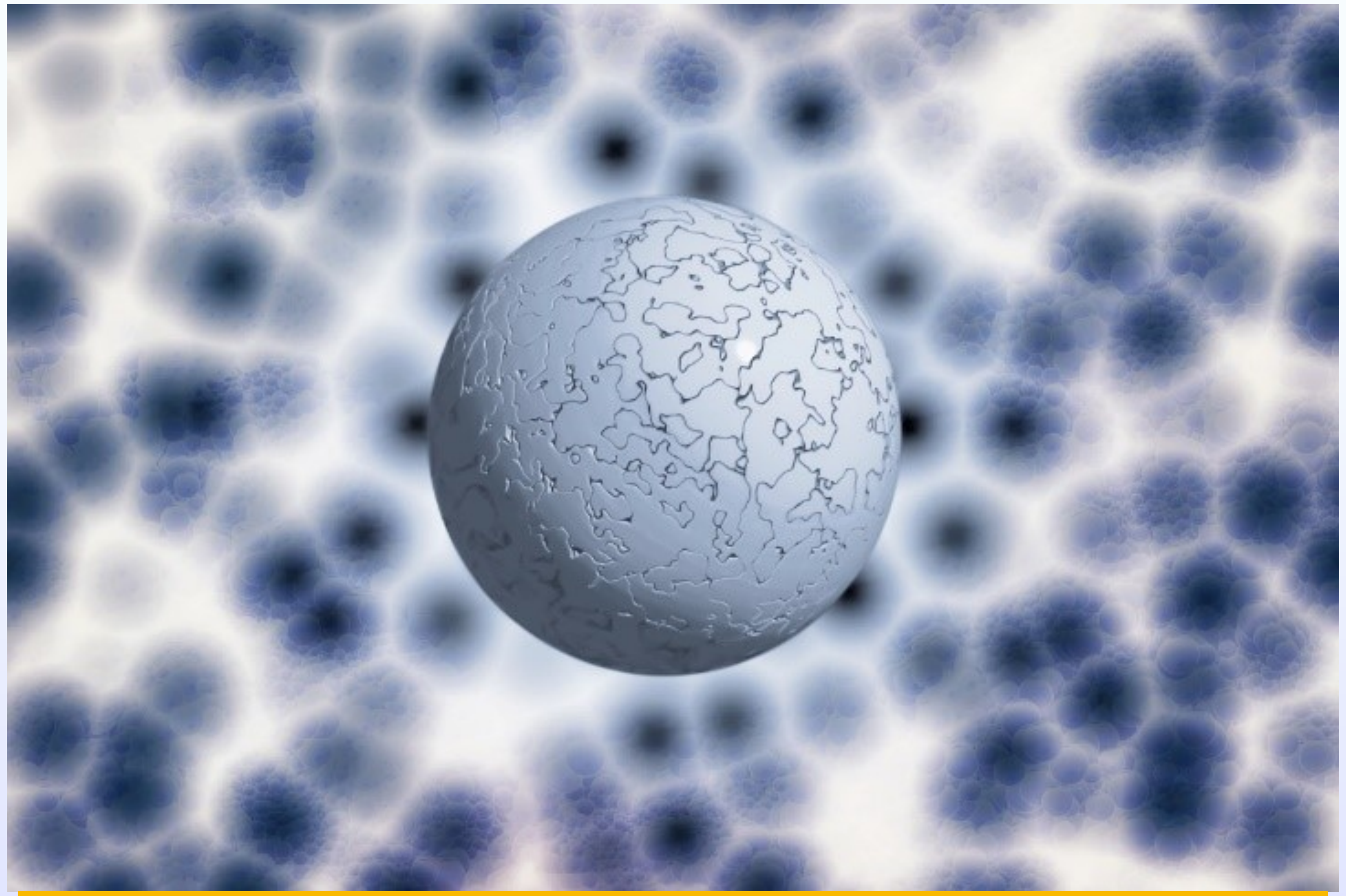
seducing us to explore.

Outline

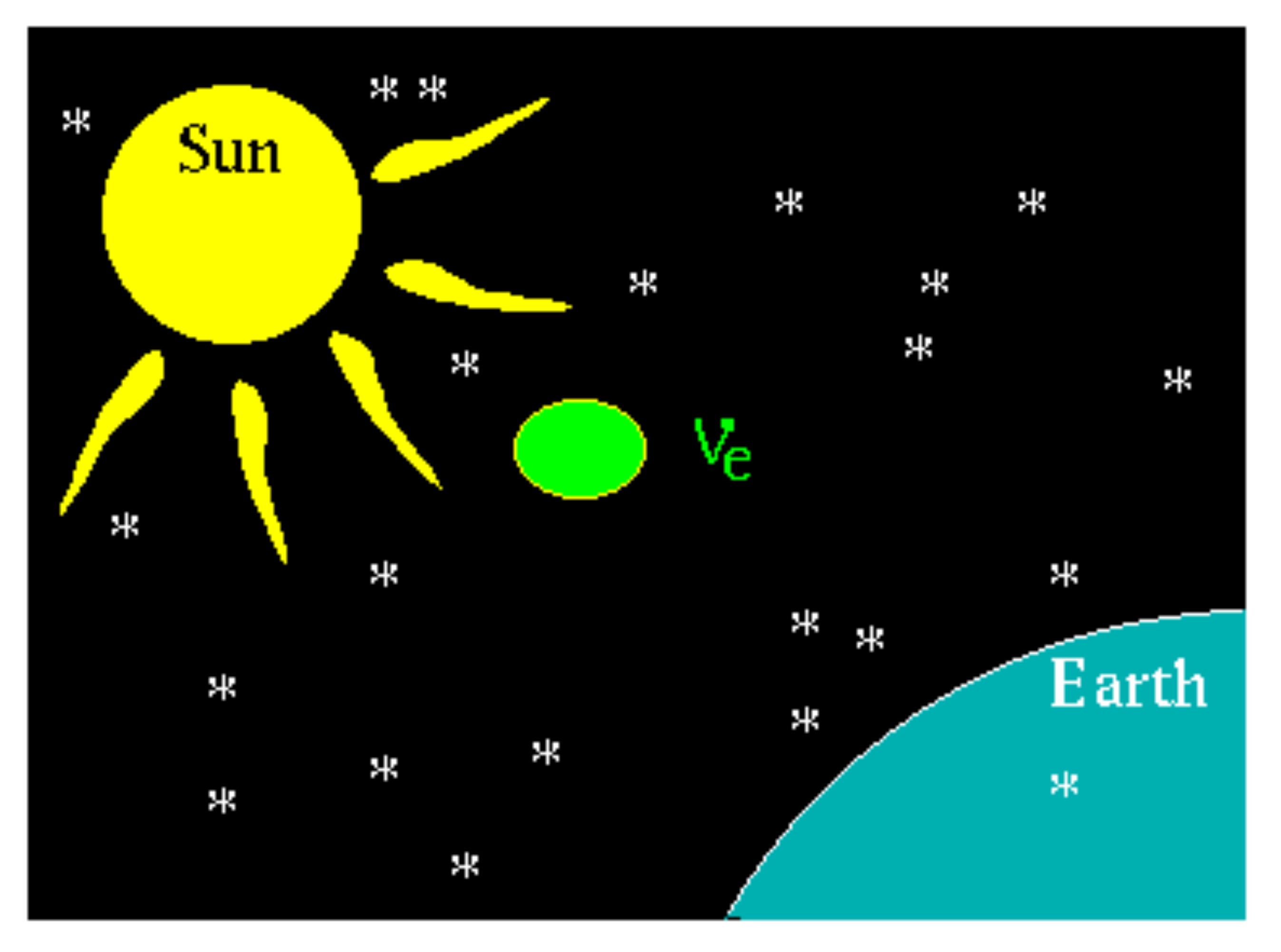
- Introduction
- Bottom up EFT: SMEFT, νSMEFT, LEFT, νLEFT
- RGE connection
- UV completion of EFT operators
- Top down EFT: matching UV models onto EFTs
- Phenomenologies
- Summary

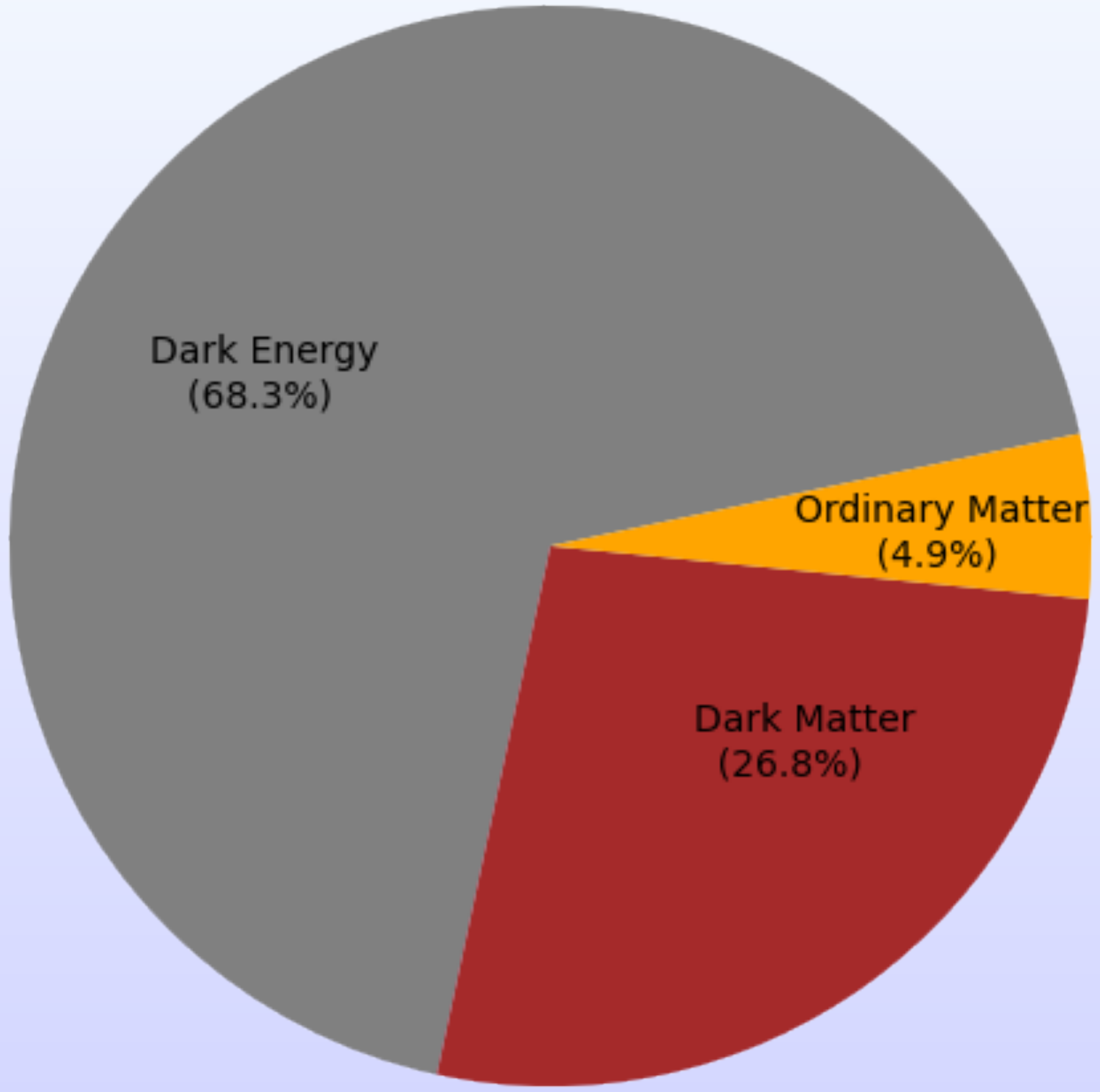
Neutrinos hold the key to big questions

- Neutrino mass
- Dark matter
- Baryon asymmetry
- Anomalies
  - Neutron lifetime 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

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

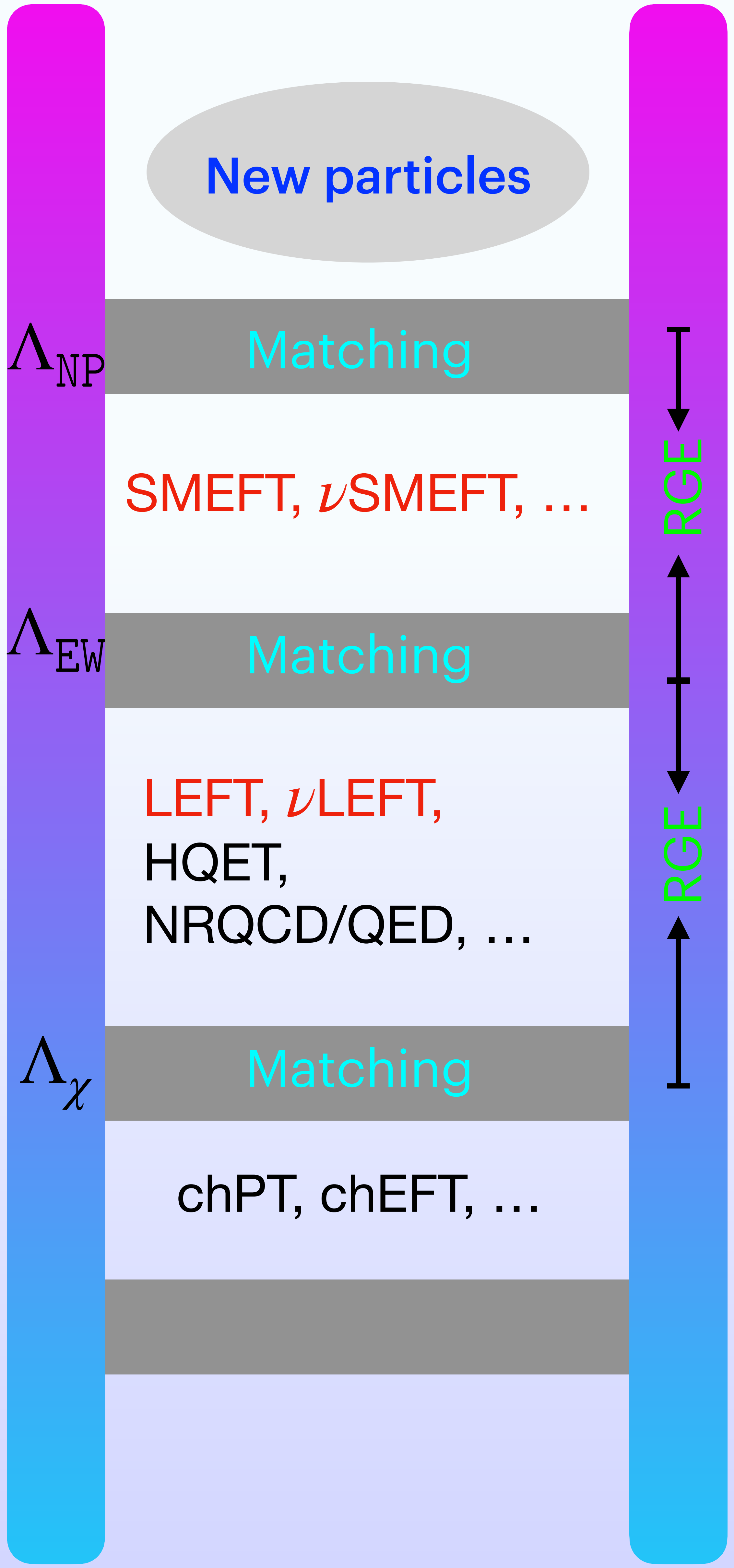
- Neutrino mass model as an EFT

Integrate out heavy NP states and match onto some EFT

- Neutrino-participated processes in the EFTs

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

Bottom-up EFT



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

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

Weinberg, 1979 — Lehman 2014 / Liao & Ma, 2016 — Murphy, 2020 — Liao & Ma, 2020

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \mathscr{L}_{\rm dim5} + \mathscr{L}_{\rm dim6} + \mathscr{L}_{\rm dim7} + \mathscr{L}_{\rm dim8} + \mathscr{L}_{\rm dim9} + \cdots$$

Buchmuller, Wyler 1986
Grzadkowski, Iskrzynski, Misiak Rosiek 2010

Li, Ren, Xiao, Yu, Zheng, 2020
Li, Ren, Shu, Xiao, Yu, Zheng, 2020

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

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

- $D \in$ 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

Dim6

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	
$\mathcal{O}_{HG}$	$H^\dagger H G^A_{\mu\nu}G^{A\mu\nu}$
$\mathcal{O}_{H\tilde G}$	$H^\dagger H \tilde G^A_{\mu\nu}G^{A\mu\nu}$
$\mathcal{O}_{HW}$	$H^\dagger H W^I_{\mu\nu}W^{I\mu\nu}$
$\mathcal{O}_{H\tilde W}$	$H^\dagger H \tilde W^I_{\mu\nu}W^{I\mu\nu}$
$\mathcal{O}_{HB}$	$H^\dagger H B_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{H\tilde B}$	$H^\dagger H \tilde B_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{HWB}$	$H^\dagger\tau^I H W^I_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{H\tilde W B}$	$H^\dagger\tau^I H \tilde W^I_{\mu\nu}B^{\mu\nu}$

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

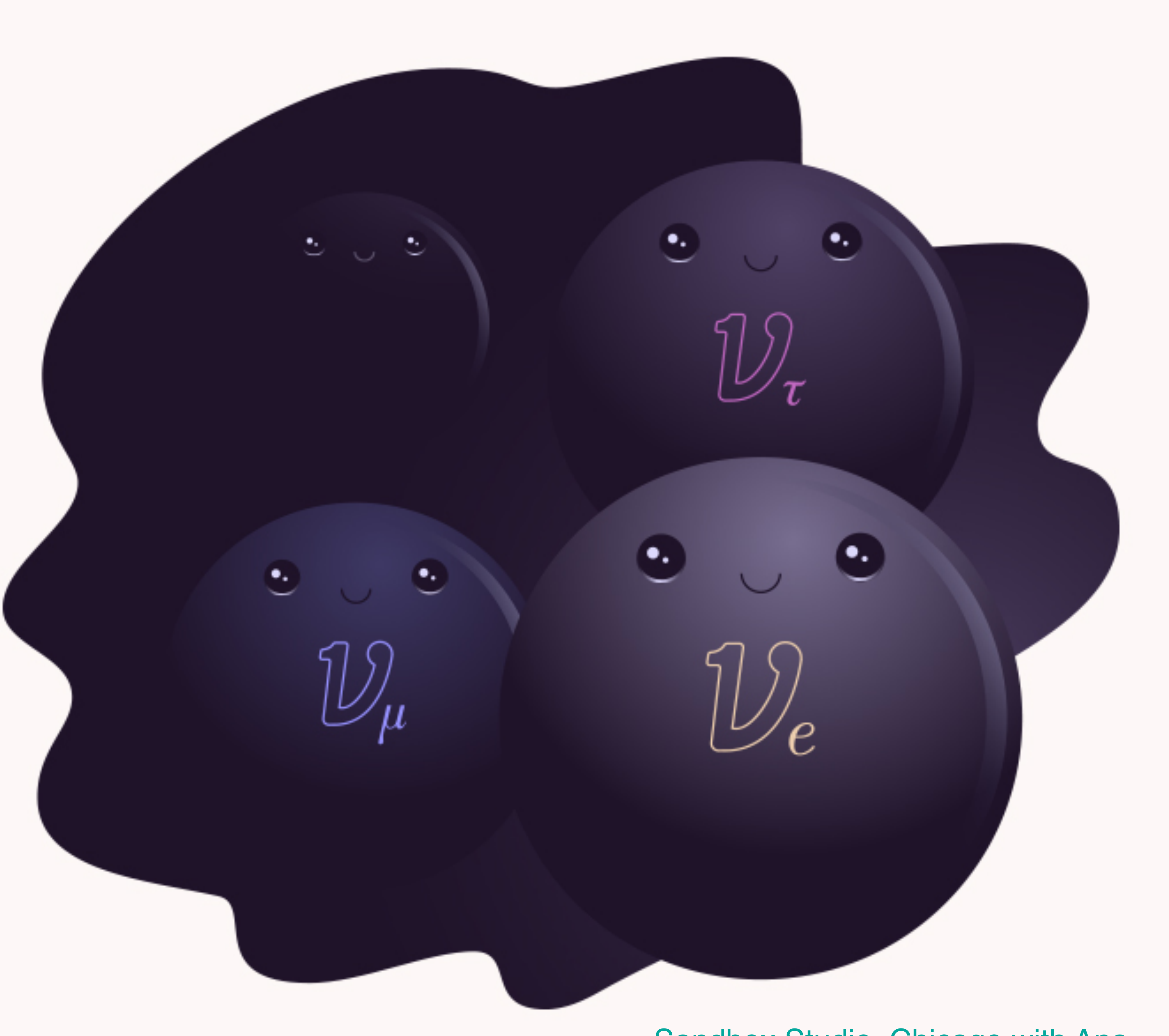
$(\bar LL)(\bar LL)$	
$\mathcal{O}_{ll}$	$(\bar L\gamma_\mu L)(\bar L\gamma^\mu L)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar Q\gamma_\mu Q)(\bar Q\gamma^\mu Q)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar Q\gamma_\mu\tau^I Q)(\bar Q\gamma^\mu\tau^I Q)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar L\gamma_\mu L)(\bar Q\gamma^\mu Q)$
$\mathcal{O}_{lq}^{(3)}$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

Dim7

ψ^2H^4	
$\mathcal{O}_{LH}$	$\epsilon_{ij}\epsilon_{mn}(\overline{L^{c,i}}L^m)H^jH^n(H^\dagger H)$
ψ^2H^3D	
$\mathcal{O}_{LeHD}$	$\epsilon_{ij}\epsilon_{mn}(\overline{L^{c,i}}\gamma_\mu e)H^j(H^m iD^\mu H^n)$
$\psi^2H^2D^2$	
$\mathcal{O}_{LDH1}$ $(\star)$	$\epsilon_{ij}\epsilon_{mn}(\overline{L^{c,i}}\overleftrightarrow{D}_\mu L^j)(H^m D^\mu H^n)$
$\mathcal{O}_{LDH2}$ $(\star)$	$\epsilon_{im}\epsilon_{jn}(\overline{L^{c,i}}L^j)(D_\mu H^m D^\mu H^n)$
ψ^2H^2X	
$\mathcal{O}_{LHB}$	$g_1\epsilon_{ij}\epsilon_{mn}(\overline{L^{c,i}}\sigma_{\mu\nu}L^m)H^jH^nB^{\mu\nu}$
$\mathcal{O}_{LHW}$	$g_2\epsilon_{ij}(\epsilon\tau^I)_{mn}(\overline{L^{c,i}}\sigma_{\mu\nu}L^m)H^jH^nW^{I\mu\nu}$
ψ^4D	
$\mathcal{O}_{\bar duLDL}$ $(\star)$	$\epsilon_{ij}(\bar d\gamma_\mu u)(\overline{L^{c,i}}i\overleftrightarrow{D}^\mu L^j)$
ψ^4H	
$\mathcal{O}_{\bar eLLLH}$	$\epsilon_{ij}\epsilon_{mn}(\bar e L^i)(\overline{L^{c,j}}L^m)H^n$
$\mathcal{O}_{\bar dQLLH1}$ $(\star)$	$\epsilon_{ij}\epsilon_{mn}(\bar d Q^i)(\overline{L^{c,j}}L^m)H^n$
$\mathcal{O}_{\bar dQLLH2}$ $(\star)$	$\epsilon_{ij}\epsilon_{mn}(\bar d\sigma_{\mu\nu}Q^i)(\overline{L^{c,j}}\sigma^{\mu\nu}L^m)H^n$
$\mathcal{O}_{\bar duLeH}$ $(\star)$	$\epsilon_{ij}(\bar d\gamma_\mu u)(\overline{L^{c,i}}\gamma^\mu e)H^j$
$\mathcal{O}_{\bar QuLLH}$	$\epsilon_{ij}(\bar Q u)(\overline{L^c}L^i)H^j$

- All the ν-involved operators must contain L
- From SMEFT, BSM operators with ν are quite limited
- Hard to probe due to ghost-like property
- Suitable for collider study: missing energy, ...

νSMEFT = SMEFT + sterile neutrino (N)



- 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)

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

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

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

$\psi^2 H^3$		$(\bar{L}R)(\bar{L}R)(+\text{h.c.})$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{LNH}(+\text{h.c.})$	$(\bar{L}N)\tilde{H}(H^\dagger H)$	$\mathcal{O}_{LNLe}$	$(\bar{L}N)\varepsilon(\bar{L}e)$	$\mathcal{O}_{LN}$	$(\bar{L}\gamma^\mu L)(\bar{N}\gamma_\mu N)$
$\psi^2 H^2 D$		$\mathcal{O}_{LNQd}$	$(\bar{L}N)\varepsilon(\bar{Q}d))$	$\mathcal{O}_{QN}$	$(\bar{Q}\gamma^\mu Q)(\bar{N}\gamma_\mu N)$
$\mathcal{O}_{HN}$	$(\bar{N}\gamma^\mu N)(H^\dagger i\overleftrightarrow{D}_\mu H)$	$\mathcal{O}_{LdQN}$	$(\bar{L}d)\varepsilon(\bar{Q}N)$	$(\not{L}\cap B)(+\text{h.c.})$	
$\mathcal{O}_{HNe}(+\text{h.c.})$	$(\bar{N}\gamma^\mu e)(\tilde{H}^\dagger iD_\mu H)$	$(\bar{R}R)(\bar{R}R)$		$\mathcal{O}_{NNNN}$	$(\overline{N^c}N)(\overline{N^c}N)$
$\psi^2 HX(+\text{h.c.})$		$\mathcal{O}_{NN}$	$(\bar{N}\gamma^\mu N)(\bar{N}\gamma_\mu N)$	$(\not{L}\cap \not{B})(+\text{h.c.})$	
$\mathcal{O}_{NB}$	$(\bar{L}\sigma_{\mu\nu}N)\tilde{H}B^{\mu\nu}$	$\mathcal{O}_{eN}$	$(\bar{e}\gamma^\mu e)(\bar{N}\gamma_\mu N)$	$\mathcal{O}_{QQdN}$	$\varepsilon_{ij}\varepsilon_{\alpha\beta\sigma}(\overline{Q^{i,c}_\alpha}Q^j_\beta)(\overline{d^c_\sigma}N)$
$\mathcal{O}_{NW}$	$(\bar{L}\sigma_{\mu\nu}N)\tau^I\tilde{H}W^{I\mu\nu}$	$\mathcal{O}_{uN}$	$(\bar{u}\gamma^\mu u)(\bar{N}\gamma_\mu N)$	$\mathcal{O}_{uddN}$	$\varepsilon_{\alpha\beta\sigma}(\overline{u^c_\alpha}d_\beta)(\overline{d^c_\sigma}N)$
$(\bar{L}R)(\bar{R}L)(+\text{h.c.})$		$\mathcal{O}_{dN}$	$(\bar{d}\gamma^\mu d)(\bar{N}\gamma_\mu N)$		
$\mathcal{O}_{QuNL}$	$(\bar{Q}u)(\bar{N}L)$	$\mathcal{O}_{duNe}(+\text{h.c.})$	$(\bar{d}\gamma^\mu u)(\bar{N}\gamma_\mu e)$		

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:** $\ll \Lambda_{\mathrm{EW}}$

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

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

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:

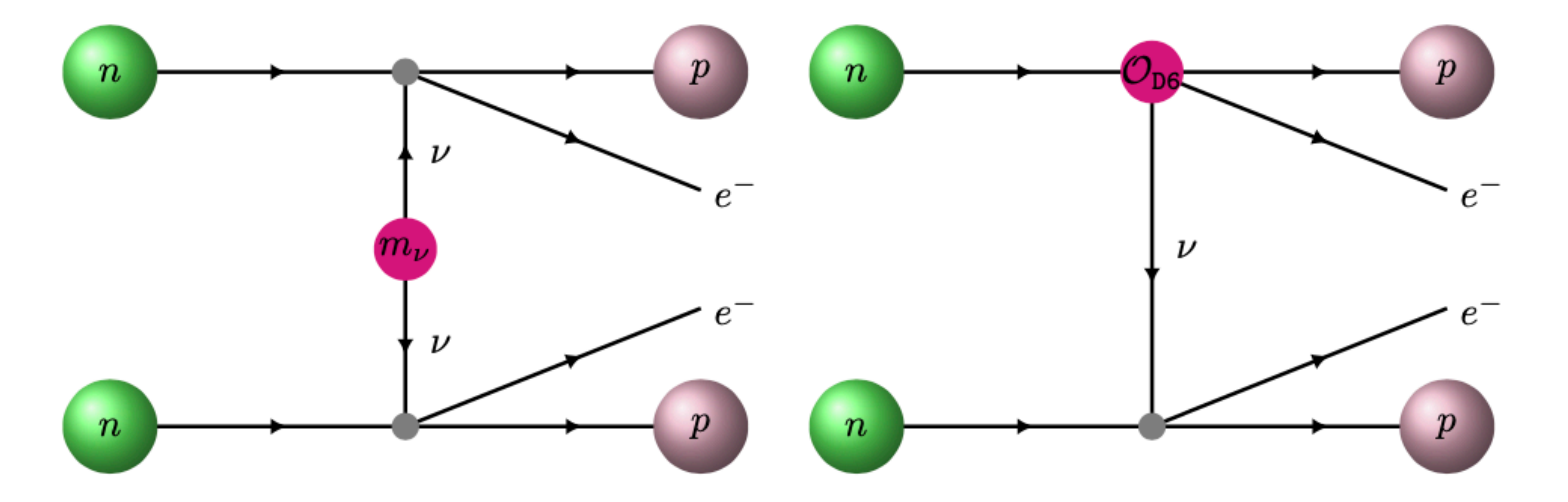
- Flavor physics: mesons and baryons
- Lepton physics: tau and muon
- BNV, LNV, LFV processes
- ……

Direct 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

RGEs

- Resum the large logs from perturbative expansion ⇒ 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

RGEs in SMEFT or νSMEFT

Dim5: Antusch et al: 0108005

Dim6: Jenkins et al: 1308.2627, 1310.4838, 1312.2014, 1405.0486; Elias-Miro et al: 1309.0819; Wang et al , 2302.08140

Dim7: Liao & Ma: 1607.07309, 1901.10302 ; Zhang, 2306.03008, 2310.11055

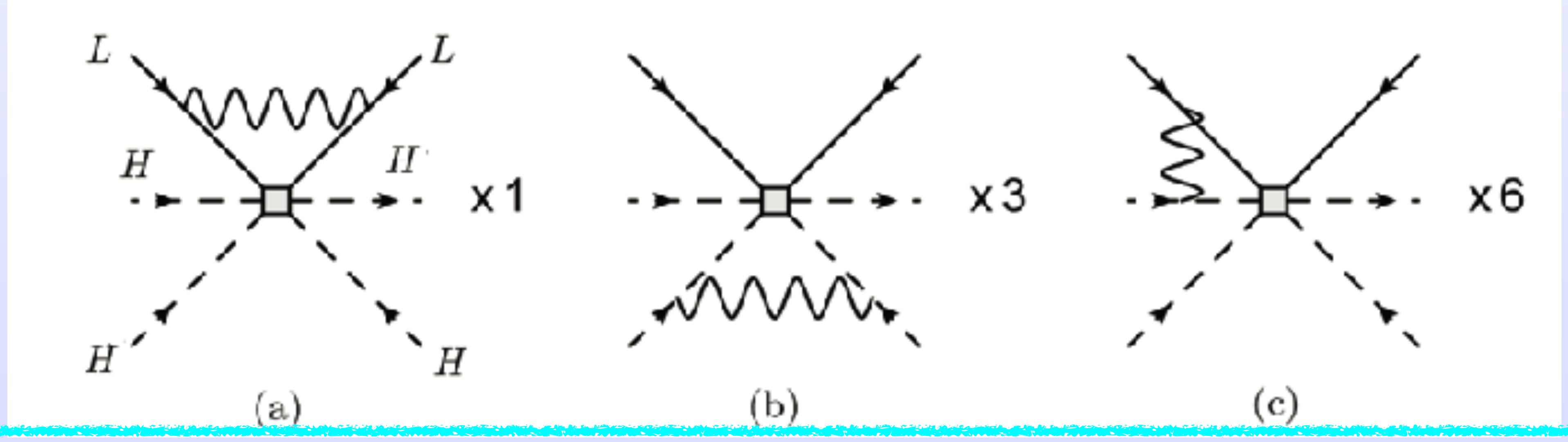
Dim8: Chala et al: 2106.05291, 2205.03301; Bakshi tal : 2301.07151; Assi et al: 2307.03187

SMEFT

νSMEFT-dim6: Datta et al: 2010.12109, 2103.04441

$$16\pi^2 \frac{dC_{LH}^{d\,pr}}{d\ln\mu} = \left[(3d^2-18d+19)\lambda - \frac{3}{4}(d-5)g_1^2 - \frac{3}{4}(3d-11)g_2^2 + (d-3)W_H\right] C_{LH}^{d\,pr} - \frac{3}{2}\left[(Y_eY_e^\dagger)_{vp}C_{LH}^{d\,vr} + (Y_eY_e^\dagger)_{vr}C_{LH}^{d\,pv}\right],$$

$$\mathcal{O}_{LH}^d = \epsilon_{im}\epsilon_{jn}(\overline{L_i^C}L_j)\tilde{H}_n\tilde{H}_m(H^\dagger H)^{(d-5)/2}$$



Liao & Ma: 1701.08019

Structure of γ, non-normalization theorem, on-shell calculation of γ, ...

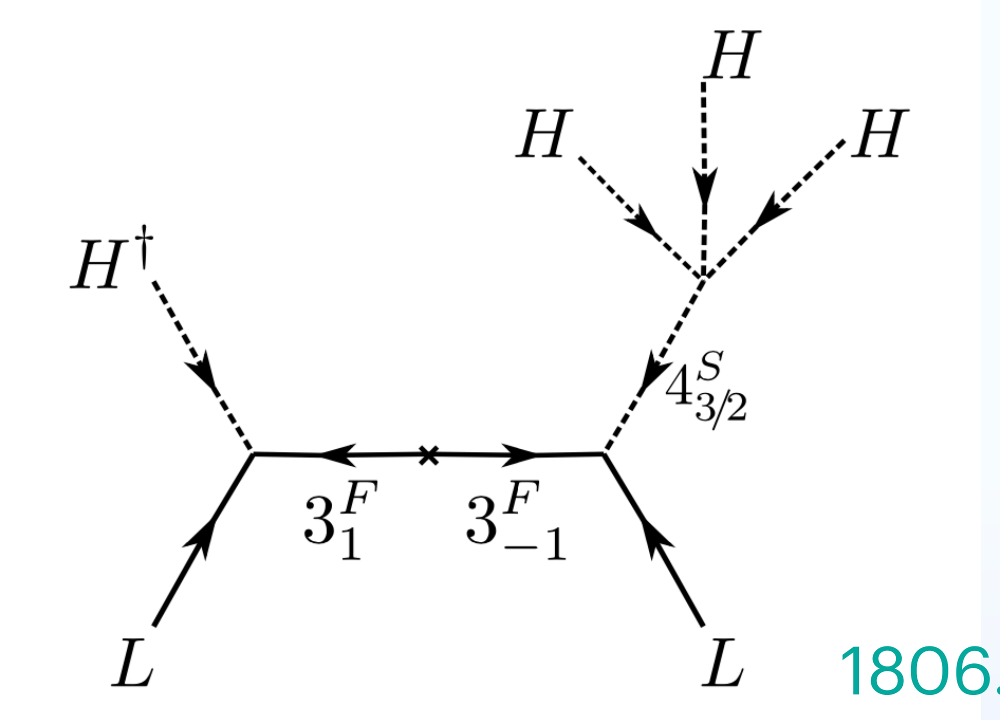
UV completion of EFT operators

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

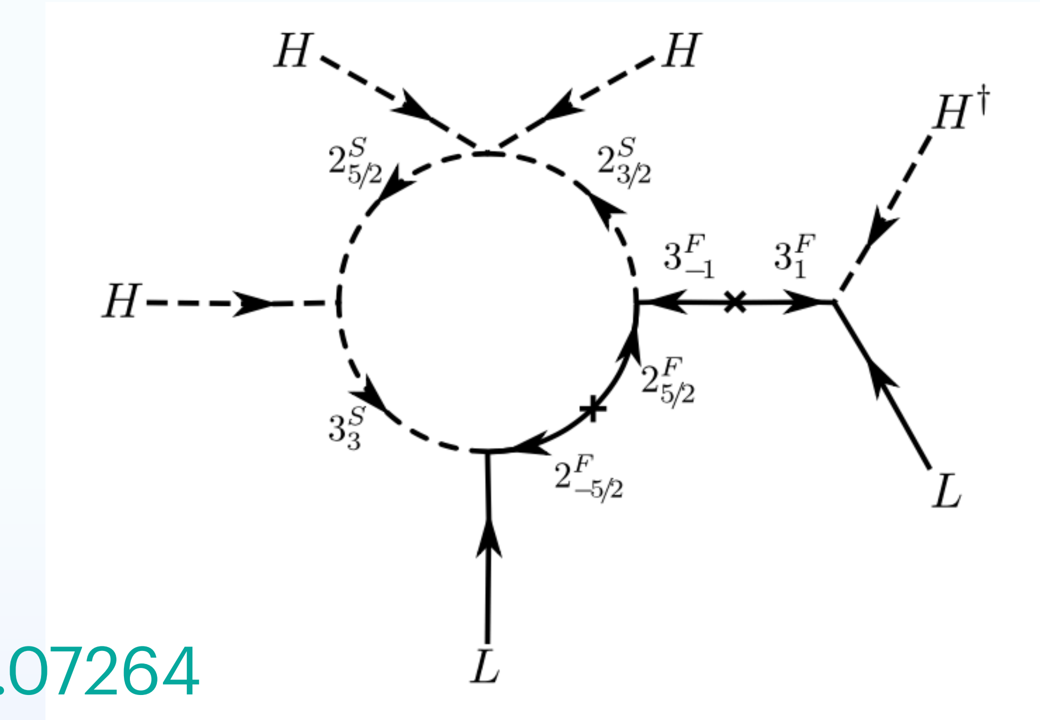
- ✱ Usually, assume the SM gauge symmetry intact
- ✱ Internal heavy fields: scalar, fermion, vector

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

- Dim-n Weinberg operator



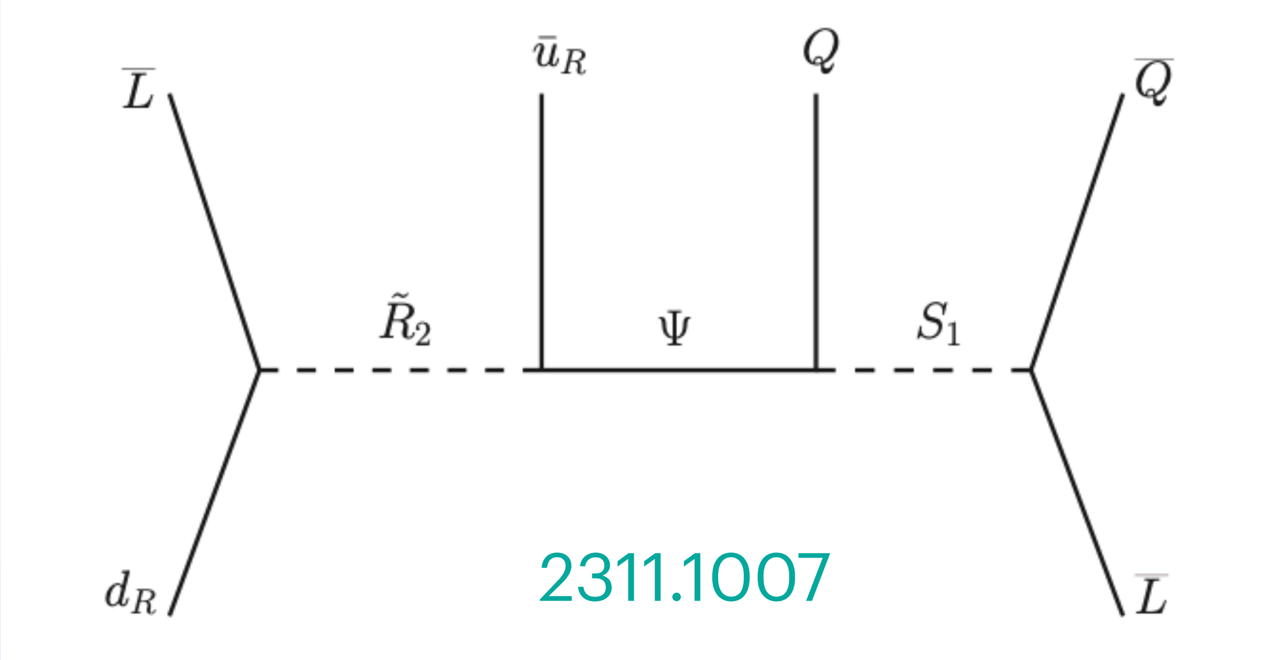
1806.07264



- 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



Chen, Ding, Yao: 2110.15347, 2301.02503

Li, Zhao, Yu: 2311.10079

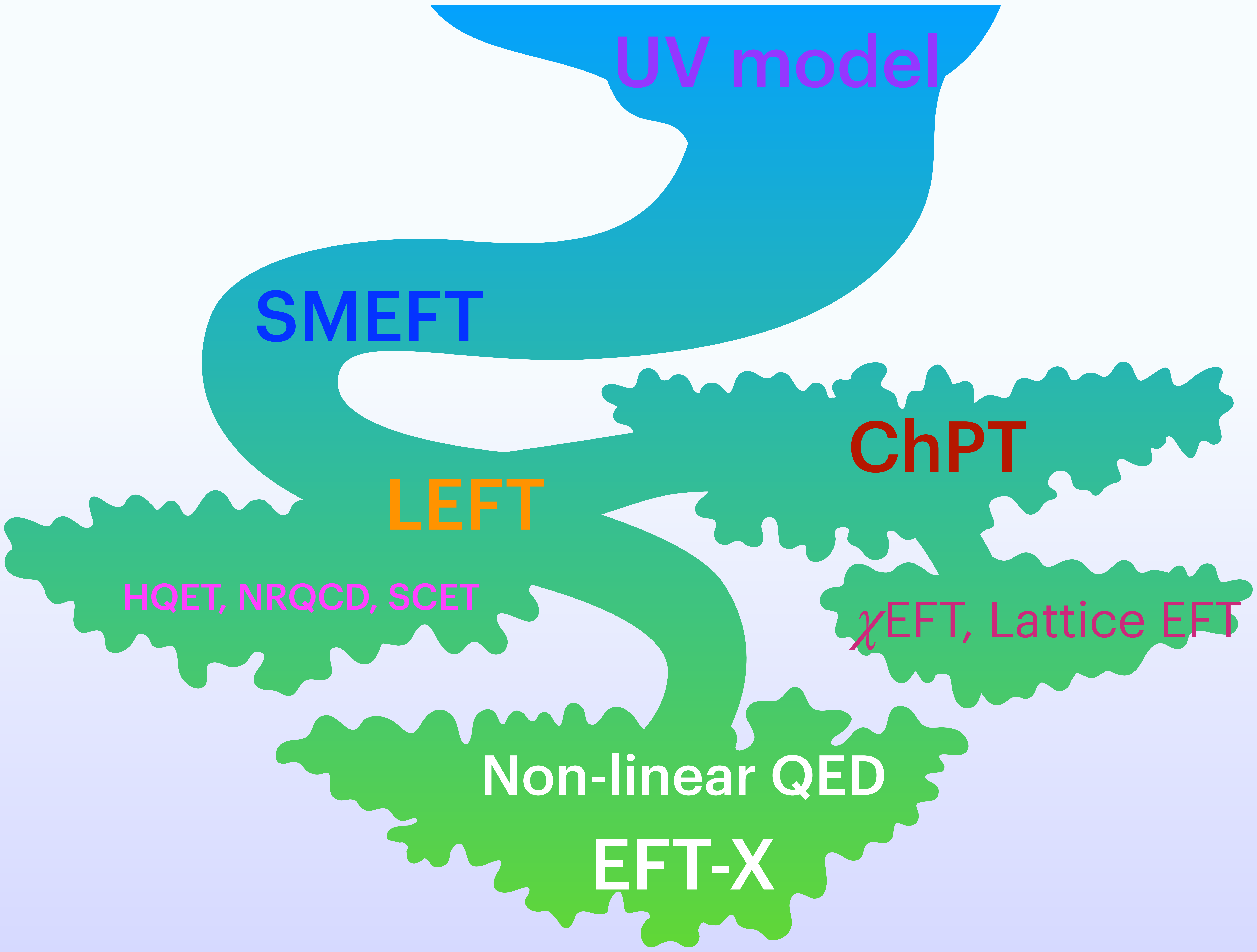
νSMEFT: Beltran et al: 2306.12578

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
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)

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

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

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

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

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

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

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

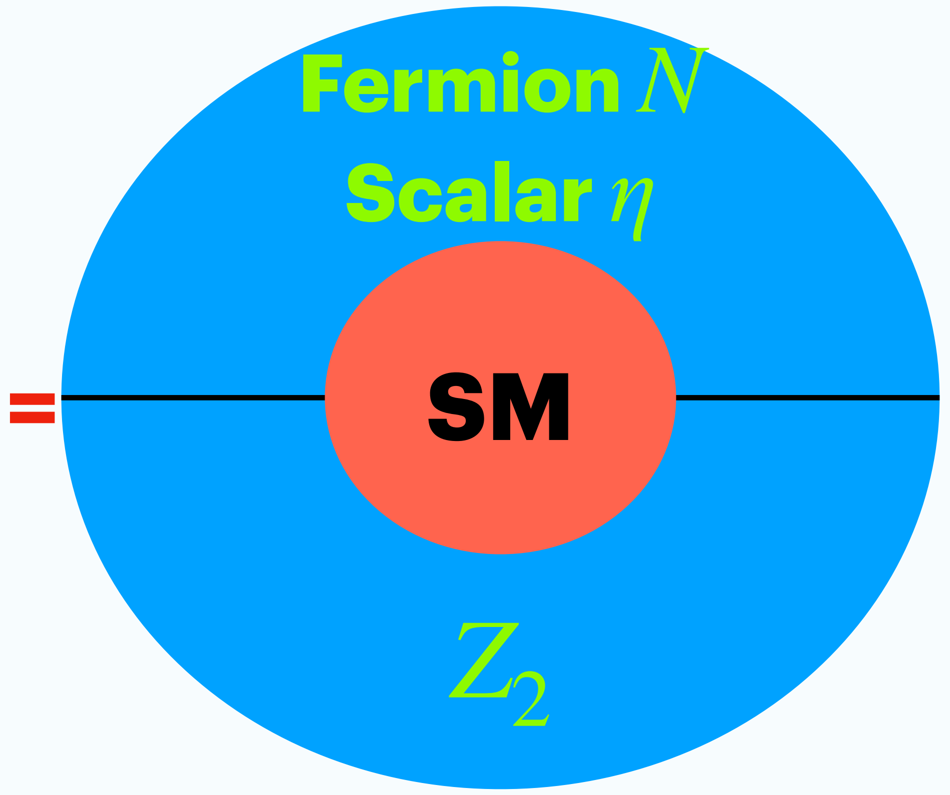
Beneke and V.A. Smirnov: 9711391
Smirnov: Applied asymptotic expansions in momenta and masses

From Green basis to Standard basis

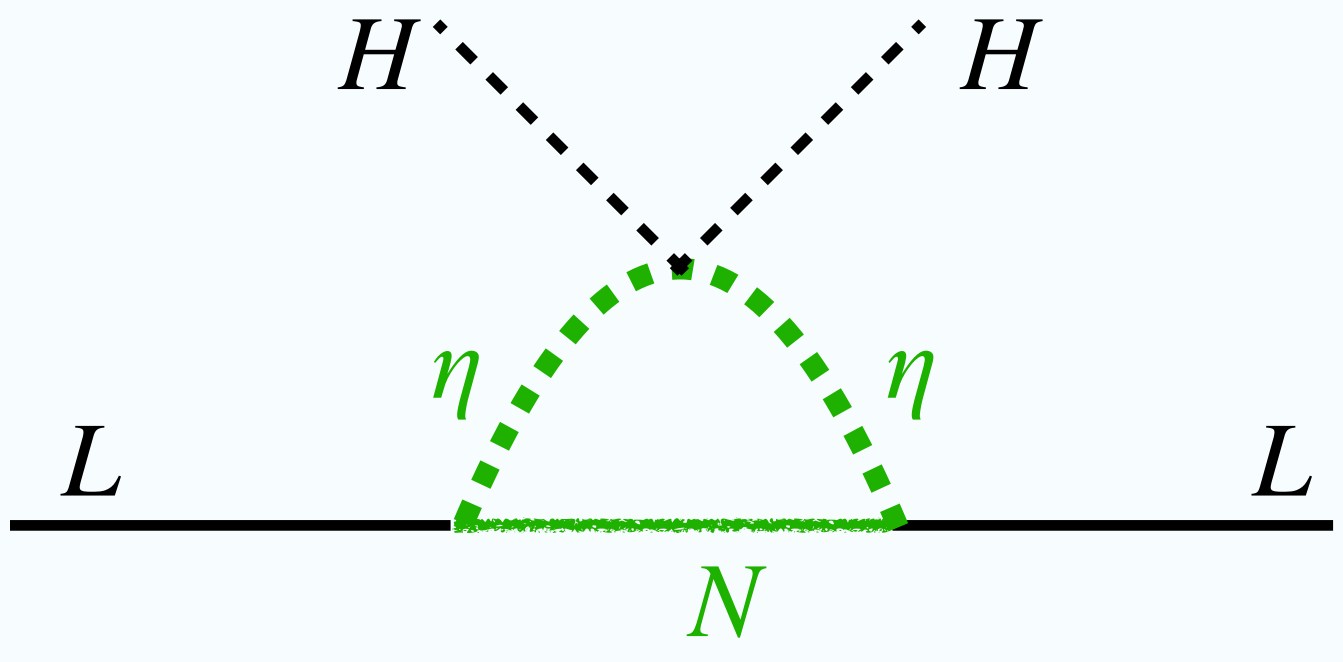
- Double expansion: loop expansion and low energy expansion
- Background field method
- Threshold corrections: correction for dim<=4 terms
- Renormalization: tame the divergence
- Green basis: a redundant basis without applying EoM relations
- Convert to standard basis via various identities and manipulations

Matching scotogenic model onto SMEFT

Scotogenic model =



- Neutrino mass
- Dark matter
- Testability @ collider



Integrate out N and η via functional method

SMEFT

Weinberg-like operator

$$\mathcal{O}_{LH,5}^{pr} = \epsilon_{ij}\epsilon_{mn}(\overline{L_p^{c,i}}L_r^m)H^jH^n$$

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

$$\mathcal{O}_{LH}^{pr} = \epsilon_{ij}\epsilon_{mn}(\overline{L_p^{c,i}}L_r^m)H^jH^n(H^\dagger H)$$

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

Neutrino mass matrix

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

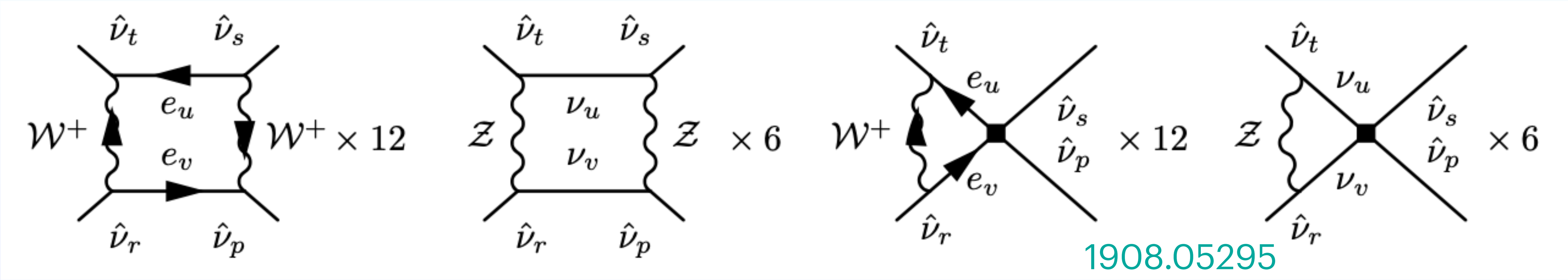
Matching between SMEFT and LEFT

Integrate out the SM heavy $h, Z, W^{\pm}, t$ particles from the SMEFT at electroweak scale

SMEFT
dim-5
dim-6
dim-7
dim-8

→ **Matching** →

LEFT
dim-3
dim-4
dim-5
dim-6
dim-7



1908.05295

Jenkins, Manohar, Stoffer: 1709.04486; Dekens and Stoffer 1908.05295
Liao, Ma, Wang: 2005.08013
Hamoudou, Kumar, London: 2207.08856

A Quick tour for phenomenologies

Neutrino EM property

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

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

Transition moments for Majorana neutrinos

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

Astrophysics: Stellar Cooling

Cosmology: BBN, CMB

Accelerator:

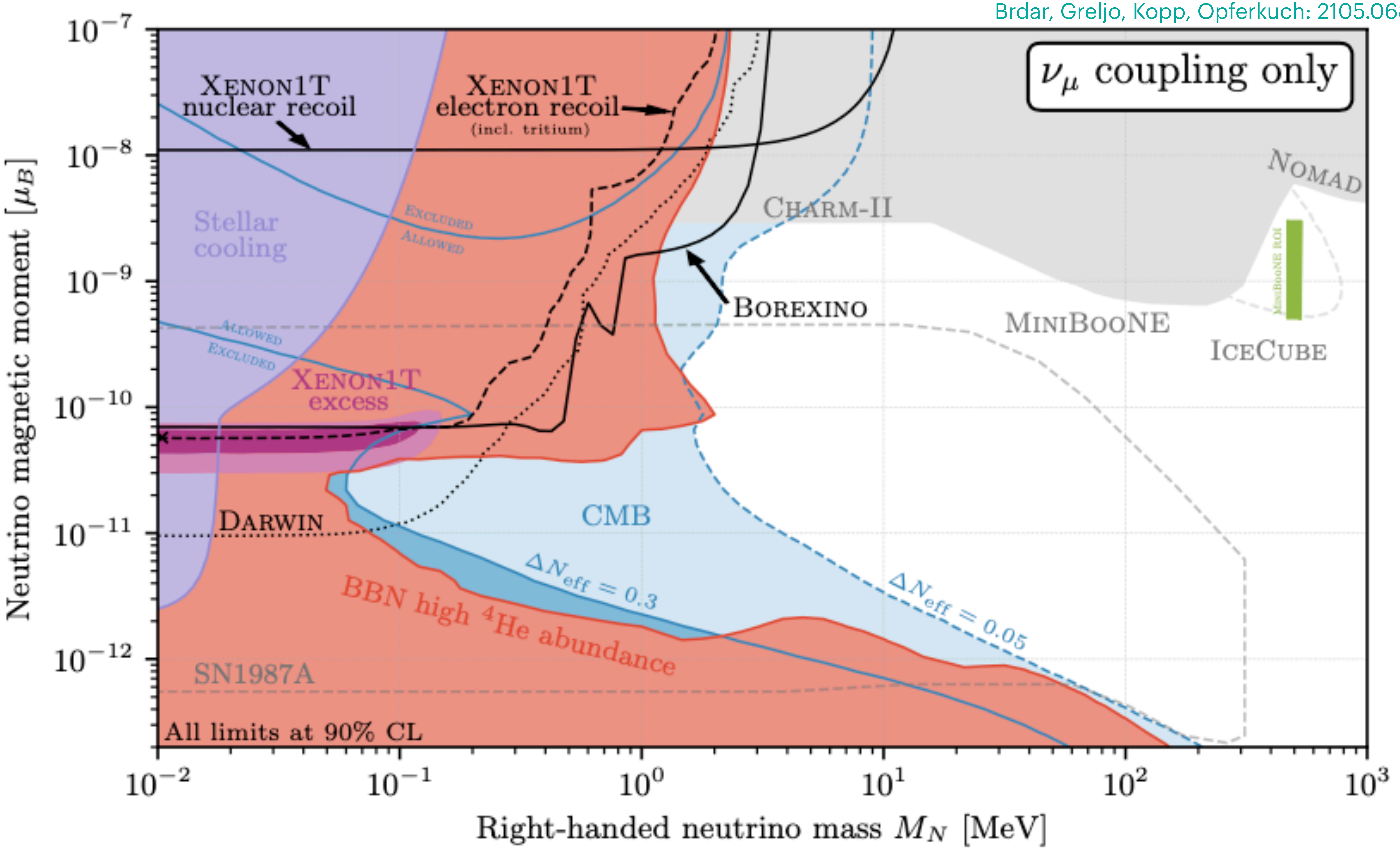
SM:

$\bar{\nu}\gamma_\mu \overleftrightarrow{\partial}_\nu \nu F^{\mu\lambda}F^\nu{}_\lambda$ $\propto G_F^2$

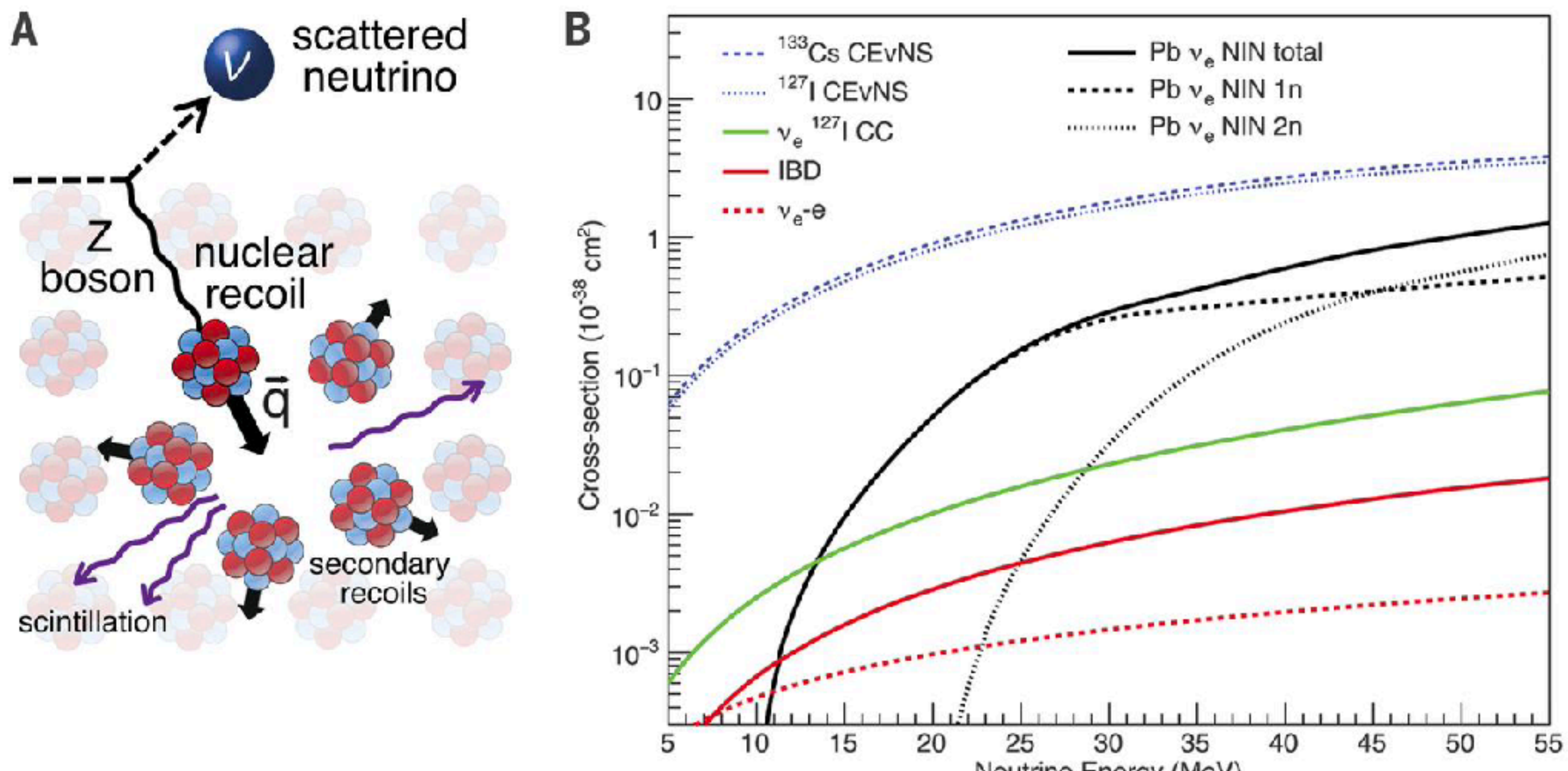
$\partial_{[\mu}\bar{\nu}\gamma_{\nu]}\nu F^{\mu\nu}F_{\alpha\beta}F^{\alpha\beta}, \quad \partial_{[\mu}\bar{\nu}\gamma_{\nu]}\nu F^\mu{}_\alpha F^\alpha{}_\beta F^{\beta\nu}$ $\propto G_F m_e^{-4}$

Dicus, Repka, 1997, PRL

Brdar, Greljo, Kopp, Opferkuch: 2105.06846



NSI and NGI (NC)



COHERENT: 1708.01294

coherent elastic scattering of neutrinos off nuclei (CEvNS)

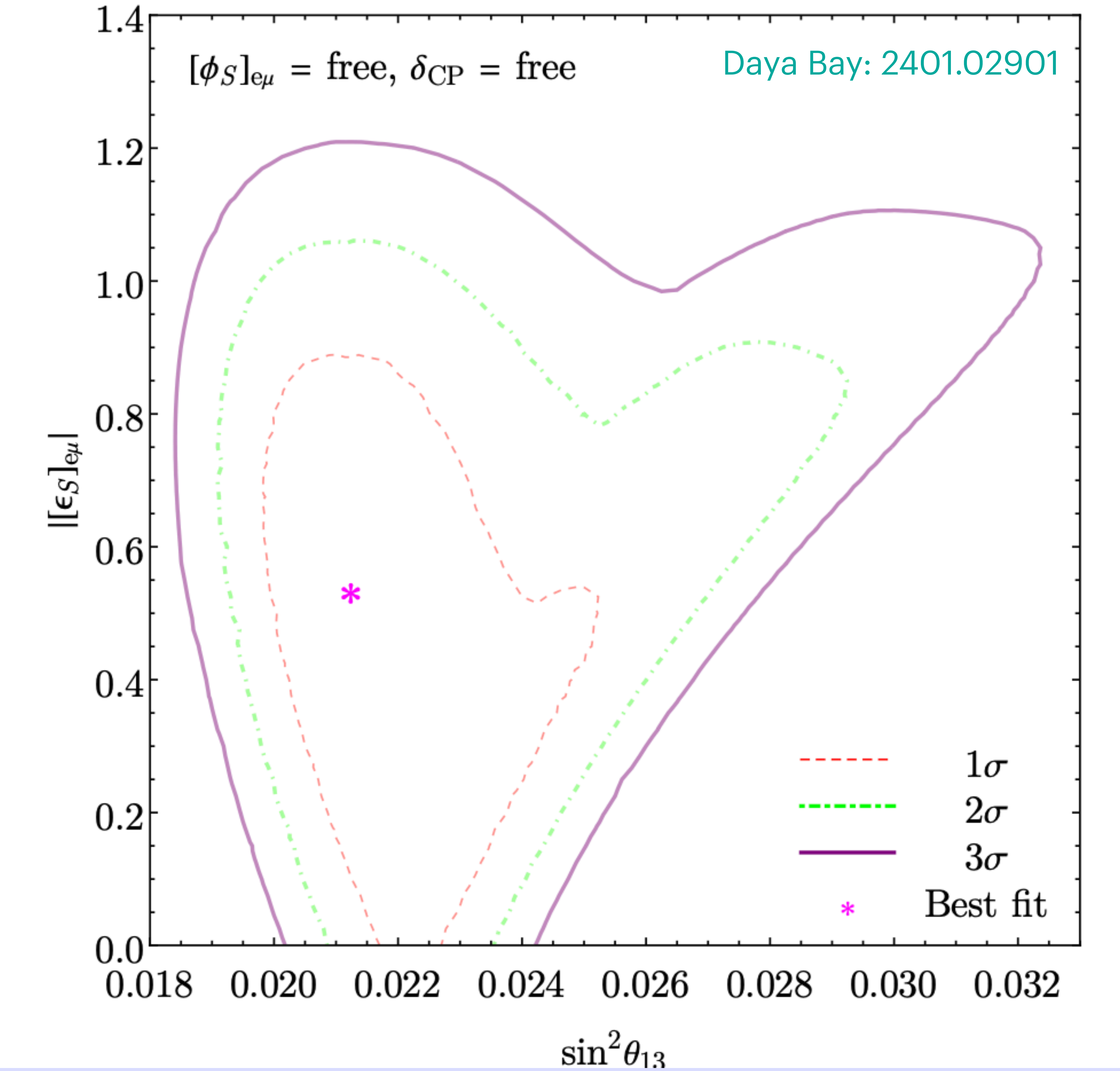
* Freedman: PhysRevD.9.1389
* Enhanced by # of nucleons
* Sensitivity to TeV scale NPs

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

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

NSI and NGI (CC)

$$\mathscr{L}_{\text{WEFT}} \supset -\frac{2V_{ud}}{v^2}\Big\{(1+\varepsilon_L)_{\alpha\beta}(\bar{u}\gamma^\mu P_L d)(\bar{l}_\alpha\gamma_\mu P_L \nu_\beta)$$
$$+ [\varepsilon_R]_{\alpha\beta}(\bar{u}\gamma^\mu P_R d)(\bar{l}_\alpha\gamma_\mu P_L \nu_\beta)$$
$$+ \frac{1}{2}[\varepsilon_S]_{\alpha\beta}(\bar{u}d)(\bar{l}_\alpha P_L \nu_\beta)$$
$$- \frac{1}{2}[\varepsilon_P]_{\alpha\beta}(\bar{u}\gamma_5 d)(\bar{l}_\alpha P_L \nu_\beta)$$
$$+ \frac{1}{4}[\varepsilon_T]_{\alpha\beta}(\bar{u}\sigma^{\mu\nu} P_L d)(\bar{l}_\alpha \sigma_{\mu\nu} P_L \nu_\beta) + h.c.\Big\}.$$



G_F

Unitarity of CKM matrix

Meson decays

Neutrino oscillations exp: the ν production, propagation and detection

FCNC with neutrino pairs

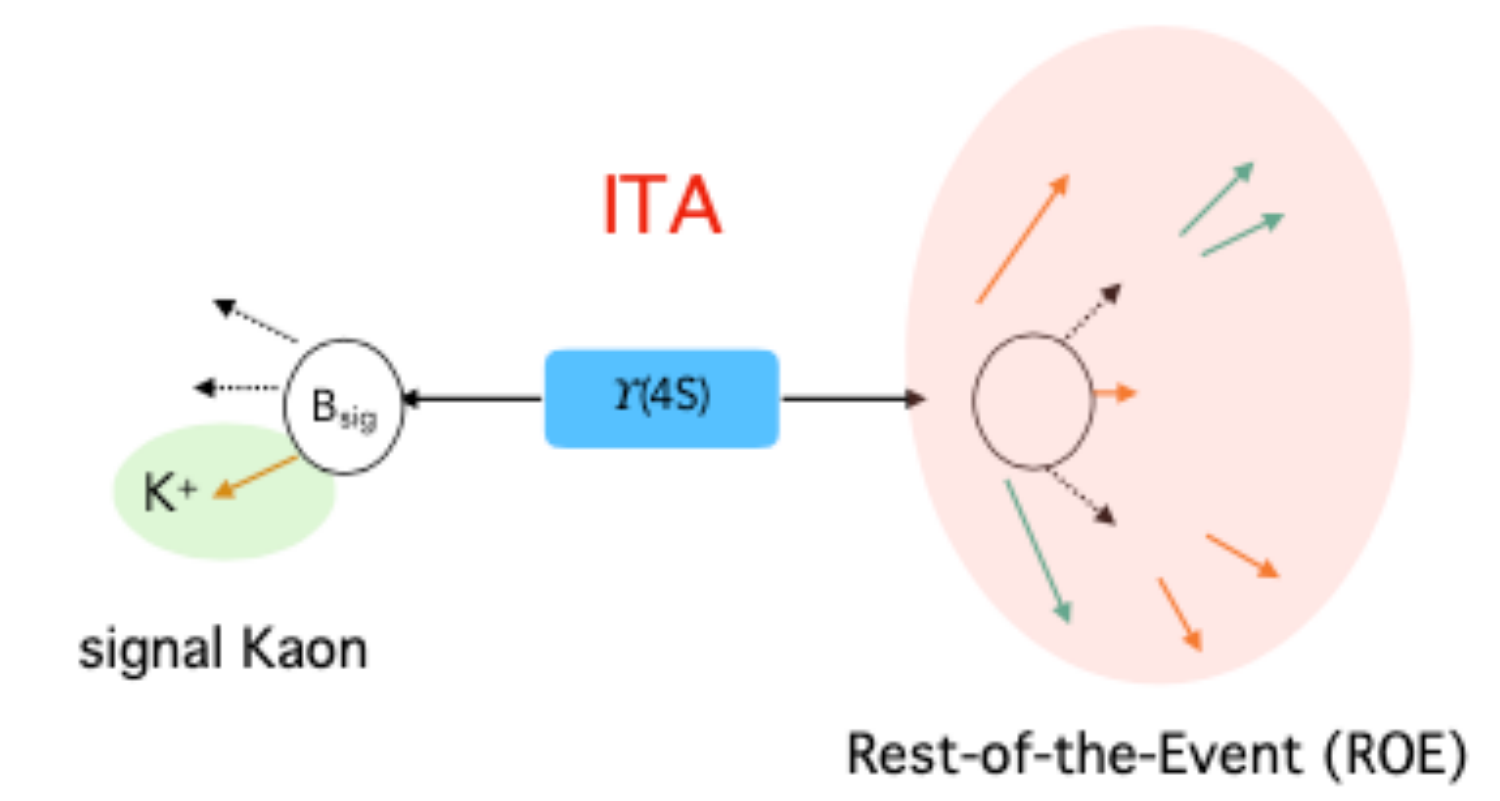
Observable	SM Br prediction:	90 % C.L. upper bound
$B^+ \to K^+ \nu\bar{\nu}$	$(4.4 \pm 0.6) \times 10^{-6}$	1.6×10^{-5}
$B^0 \to K^0 \nu\bar{\nu}$	$(4.1 \pm 0.6) \times 10^{-6}$	2.6×10^{-5}
$B^+ \to K^{*+} \nu\bar{\nu}$	$(1.0 \pm 0.1) \times 10^{-5}$	4.0×10^{-5}
$B^0 \to K^{*0} \nu\bar{\nu}$	$(9.5 \pm 1.0) \times 10^{-6}$	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}

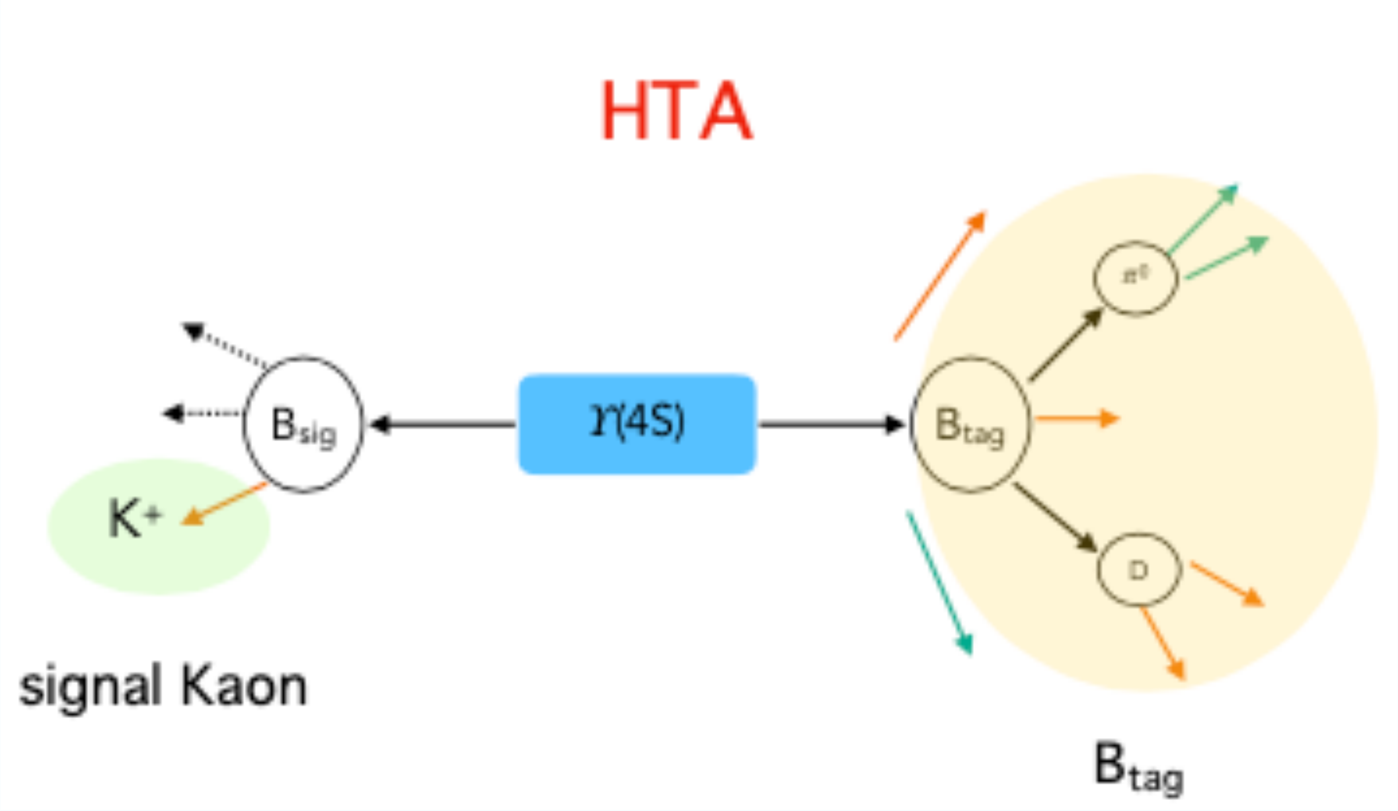
- KOTO anomaly in Kaon decay
- Baryon sector: $B_i \to B_f \nu\bar{\nu}$
- Other mesons:

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

NP related to neutrino sector

Recent Belle II result





Inclusive Tag analysis (ITA)
more sensitive

Hadronic Tag analysis (HTA)
more conventional

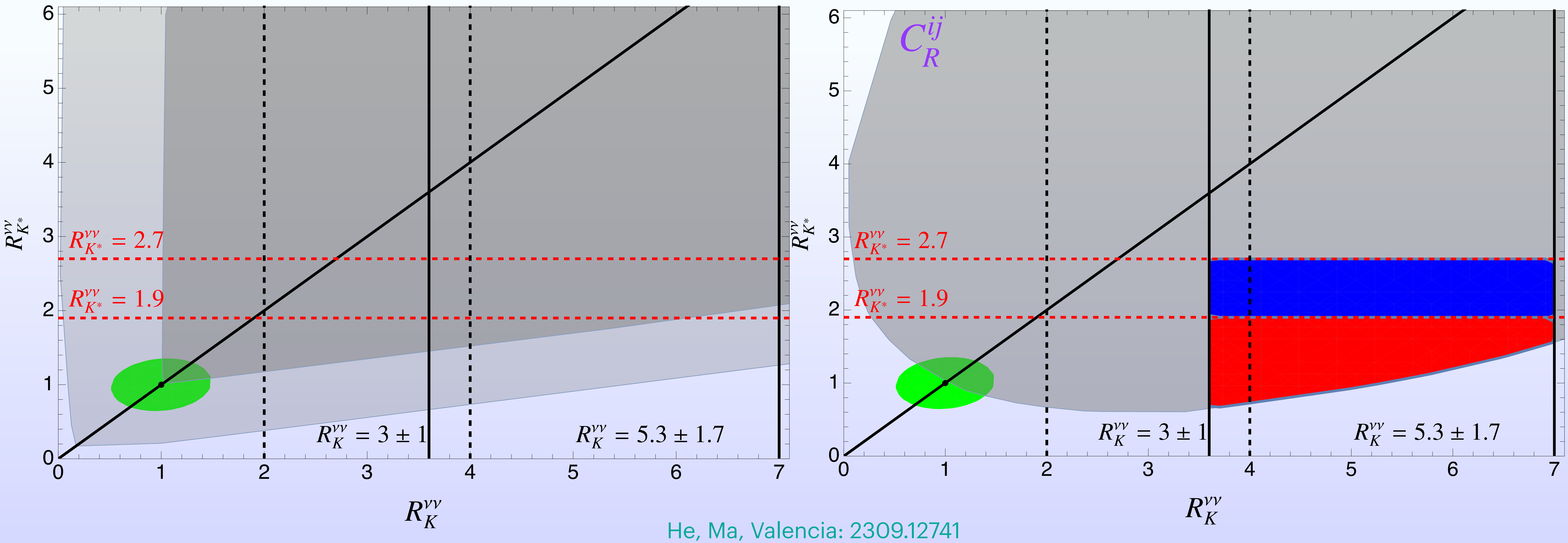
- Combination: $\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{exp}} = (2.3 \pm 0.7) \times 10^{-5}$
- SM prediction: $\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{SM}} = (4.43 \pm 0.31) \times 10^{-6}$
- $2.8\,\sigma$ higher than SM prediction $\Rightarrow$ New physics possibility

New contributions to $b \to s\nu\bar{\nu}$ with heavy new mediators

$$\mathscr{H}_{\mathrm{NP}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{\star} \frac{e^2}{16\pi^2} \sum_{ij} \left(C_L^{ij} \mathscr{O}_L^{ij} + C_R^{ij} \mathscr{O}_R^{ij} \right) + \mathrm{h.c.},$$

$$\mathscr{O}_L^{(\prime)ij} = (\bar{s}\gamma_\mu P_L d)(\bar{\nu}_i \gamma^\mu P_\mp \nu_j)$$

$$\mathscr{O}_R^{(\prime)ij} = (\bar{s}\gamma_\mu P_R d)(\bar{\nu}_i \gamma^\mu P_\mp \nu_j)$$



He, Ma, Valencia: 2309.12741

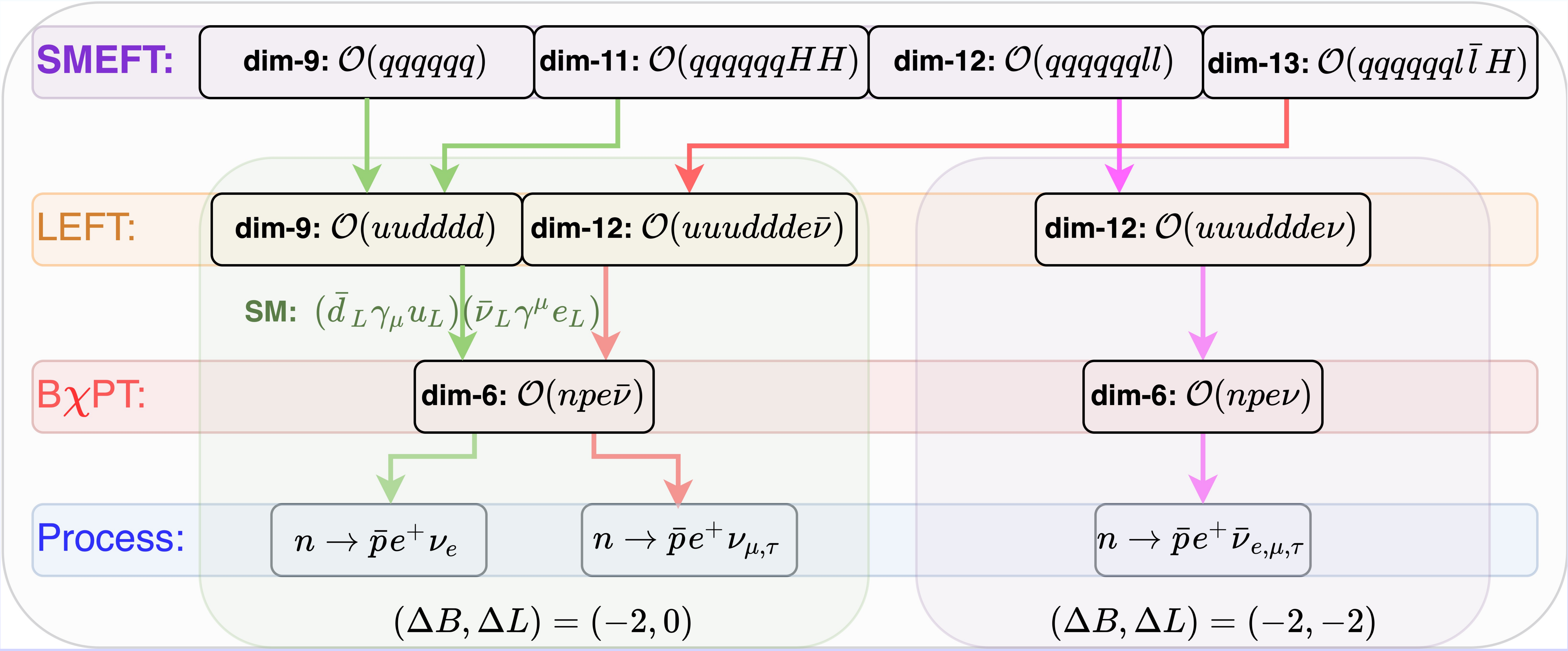
Neutrino participated BNV processes

- $\Delta B = 1$: $p \to \pi^+\nu, K^+\nu \cdots$
- $\Delta B = 2$: $NN' \to \ell^+\nu, \bar{\nu}\nu$;
- $\Delta B = 2$ & $\Delta L = 2$:

$pp \to pn \to \ell_\alpha^+\bar{\nu}_\beta, nn \to \bar{\nu}_\alpha\bar{\nu}_\beta$

m_ν, BAU, GUTs,...

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



Other interesting topics not covered

* $0\nu\beta\beta$
* NSI in cosmology: Neff   Du & Yu: 2101.10475
* Long-lived particle
* CP violation and flavor invariants   Yu & Zhou: 2203.10121
* Positivity bound   Li & Zhou: 2202.12907, 2203.10121
* Neutrino self-interaction
* …………

Summary

- EFT in neutrino physics is overviewed, including EFTs at different scales, their renormalization, 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!