Effective field theory for general baryon-number-violating nucleon decays

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Wei-Qi Fan, Yi Liao, **XDM**, Hao-Lin Wang, arXiv: 2412.20774 (PLB 862 (2025) 139335)
Yi Liao, **XDM**, Hao-Lin Wang, arXiv: 2504.14855 (Accepted by PRL)
Yi Liao, **XDM**, Hao-Lin Wang, arXiv: 2506.05052 (PRD 112, L031704 (2025))
Wei-Qi Fan, Yi Liao, **XDM**, Hao-Lin Wang, arXiv:2507.11844
XDM, Michael Schmidt, Wei-Hang Zhang, arXiv:2510.xxxxx
+ ongoing works

The 2025 Beijing Particle Physics and Cosmology Symposium (BPCS 2025)
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Outline

- Introduction
- General BNV nucleon decay interactions in the LEFT
- Chiral realizations
- Applications
- Summary

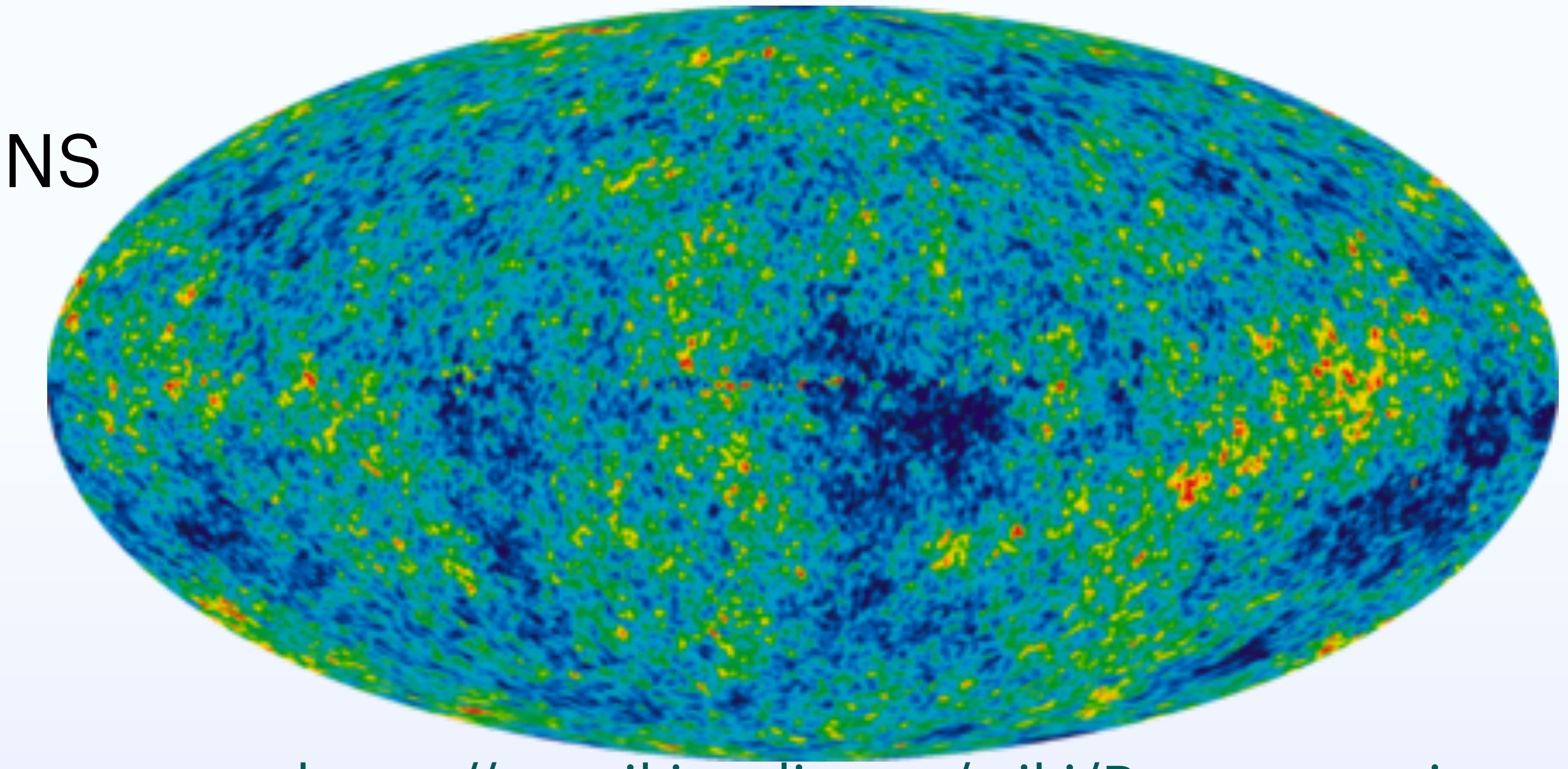
Baryon number violation (BNV) is related to many BIG questions

- Baryogenesis

Sakharov's conditions: BNV; C, CP violation; Out of thermal equilibrium

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 6 \times 10^{-10}$$

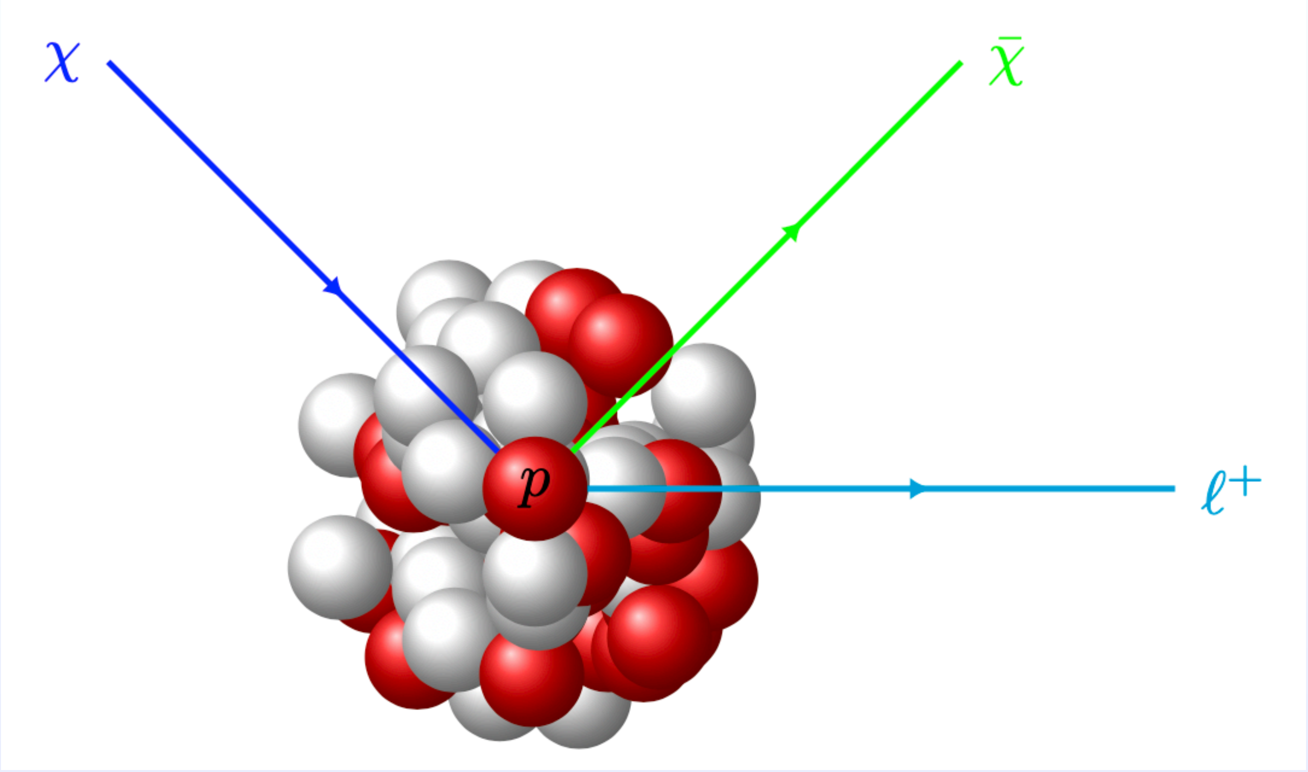
Sakharov, 1967



https://en.wikipedia.org/wiki/Baryogenesis

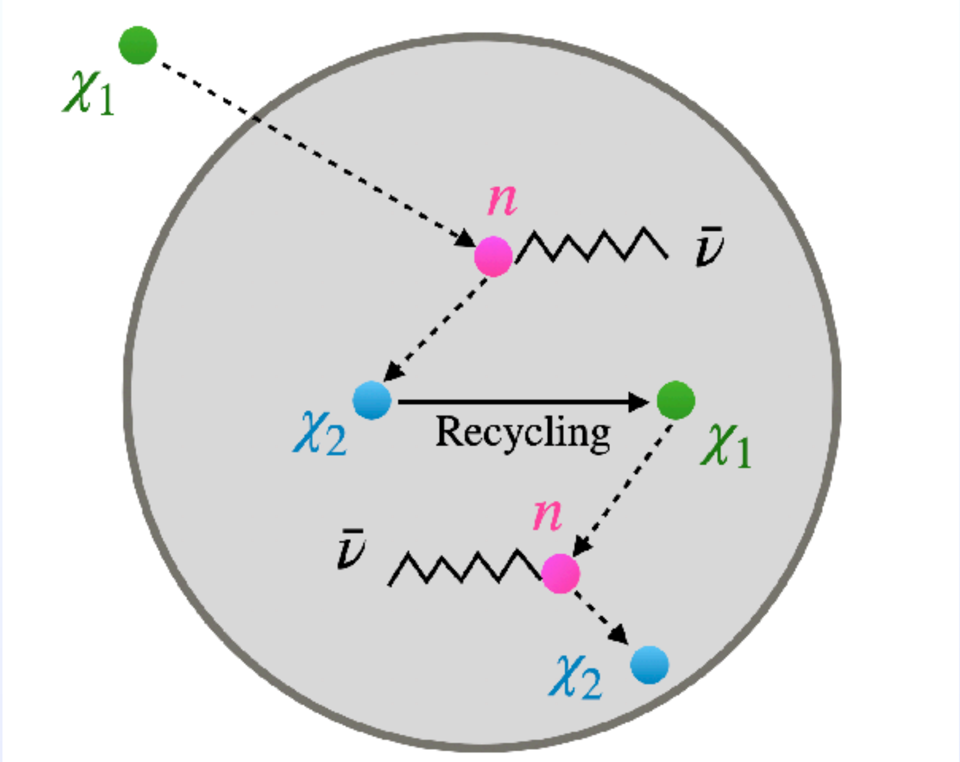
- Dark matter

Nucleon consumption induced by DM



S.-F. Ge and XDM: 2406.00445

DM-catalyzed baryon destruction inside a NS

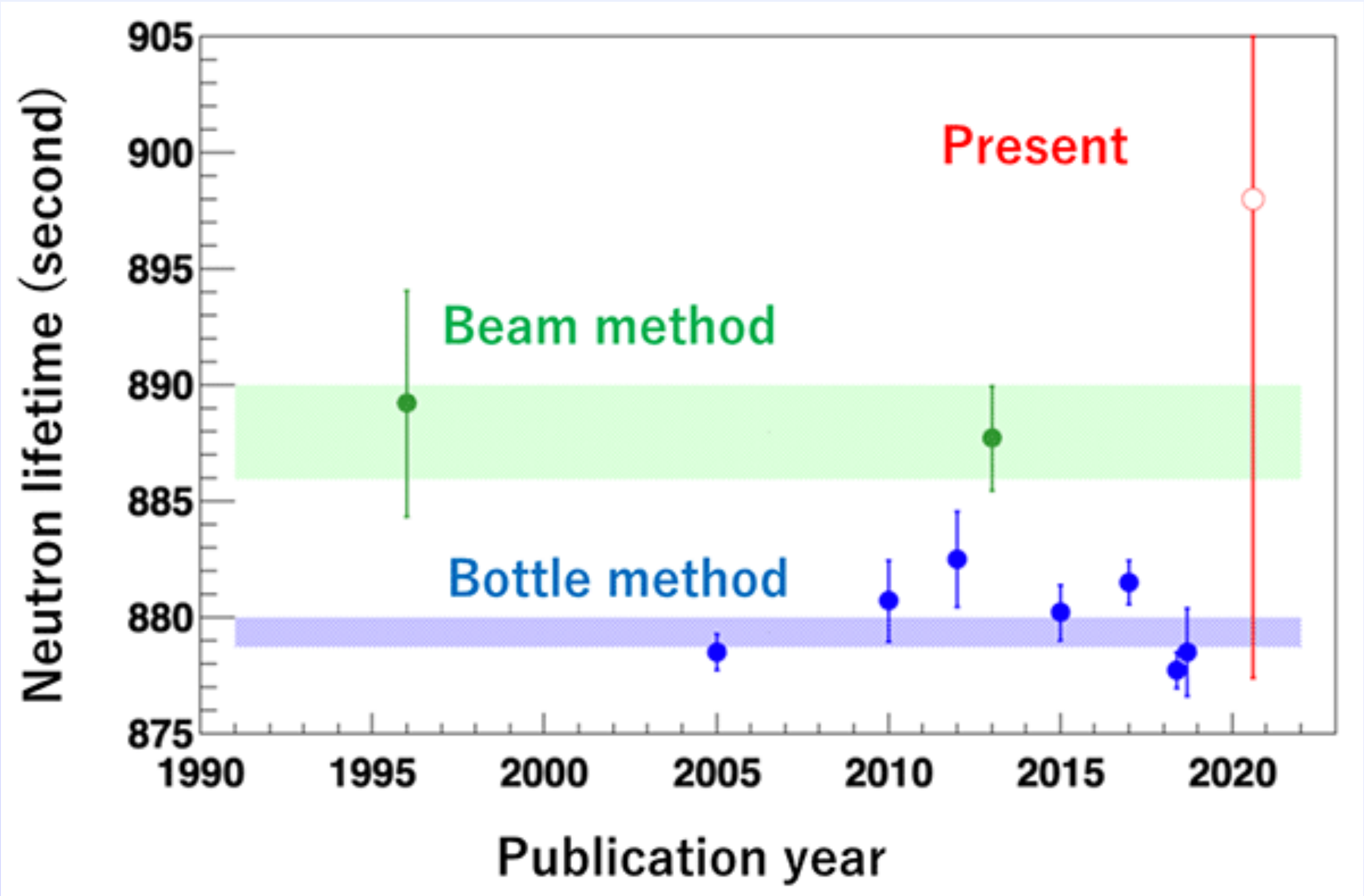


Y. Ema, R. McGehee, M. Pospelov, and A. Ray, 2405.18472

+ many many works along this direction

- Grand unified theories: SU(5), SO(10), ⋯
- Neutron lifetime anomaly: Neutron dark decay

B. Fornal and B. Grinstein: 1801.01124; 1810.00862

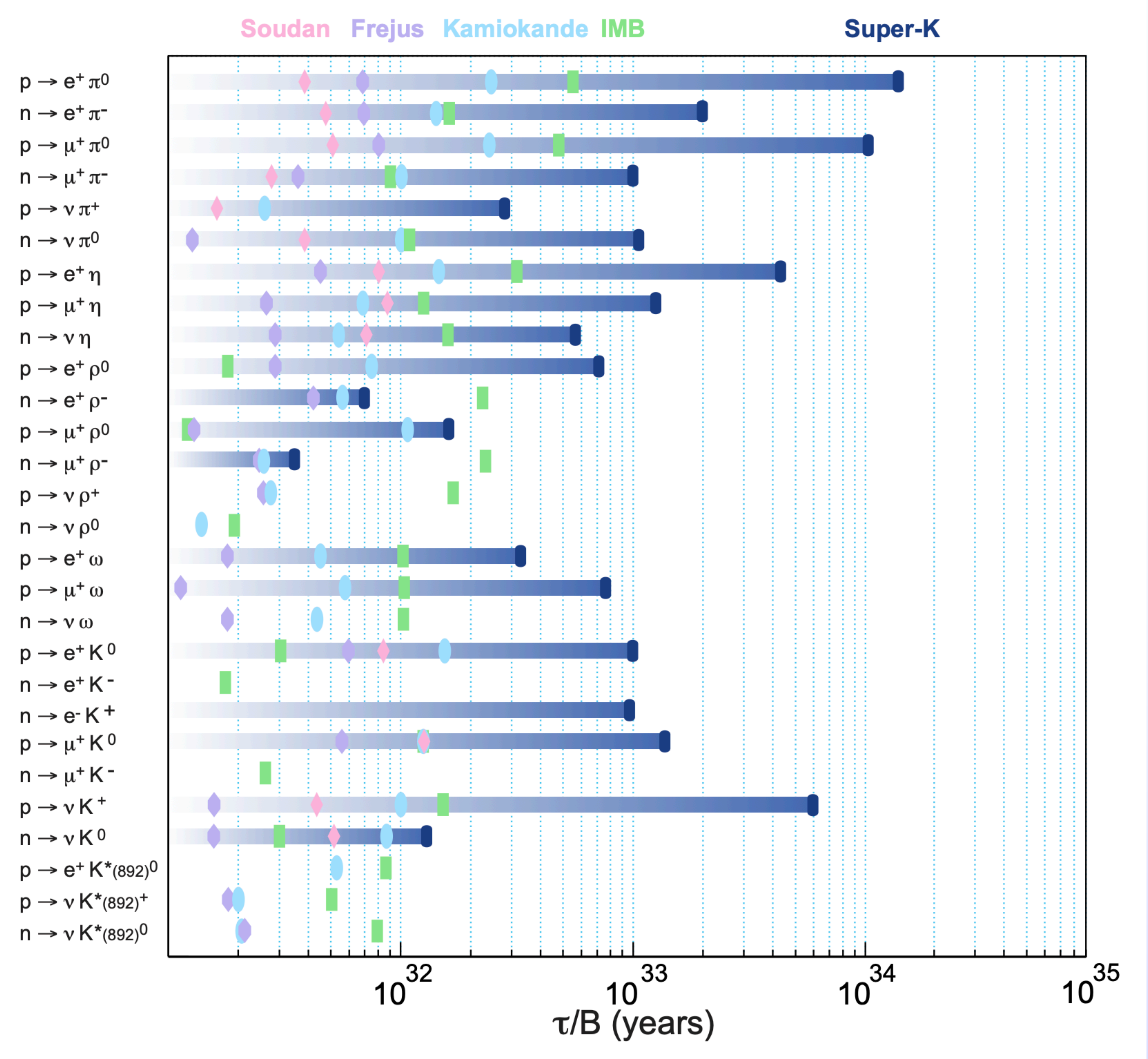


Low energy probes of BNV signals

$\Delta B = 1$ ✔

- The most sensitive probe of BNV is through nucleon decay
- A lot of experimental efforts in the past: IMB, SNO+, KamLAND, Super-Kamiokande, ...

→ Null result but stringent bound

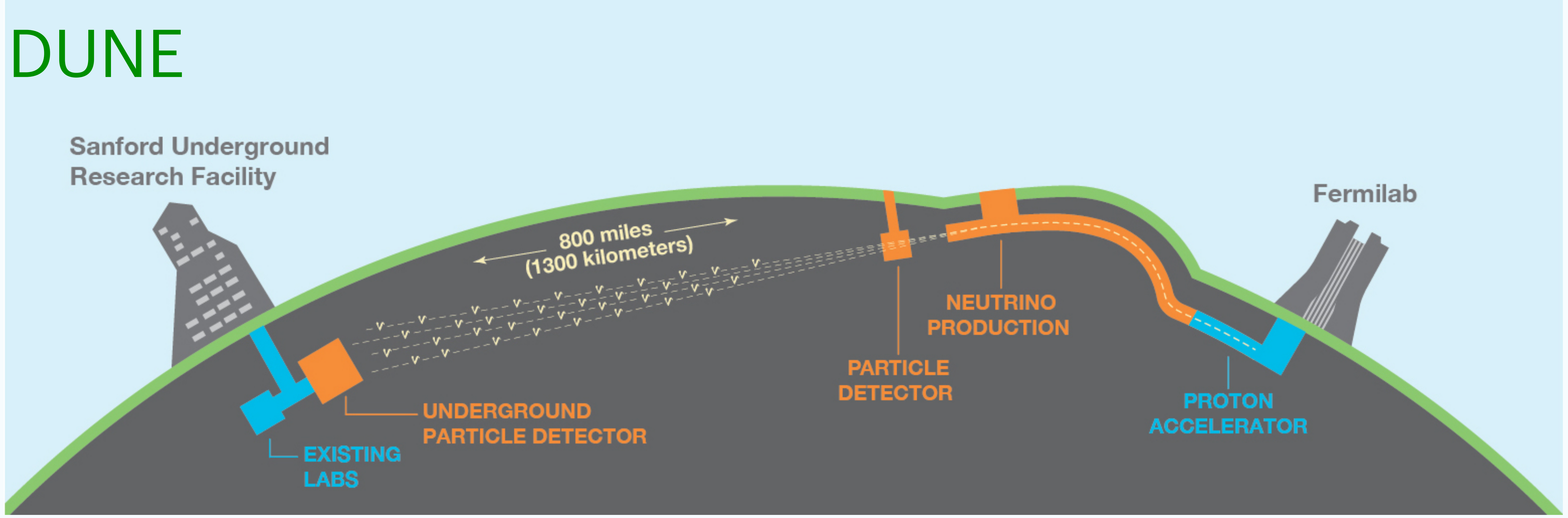


Snowmass 2013, arXiv: 1311.5285

$\Delta B = 2$

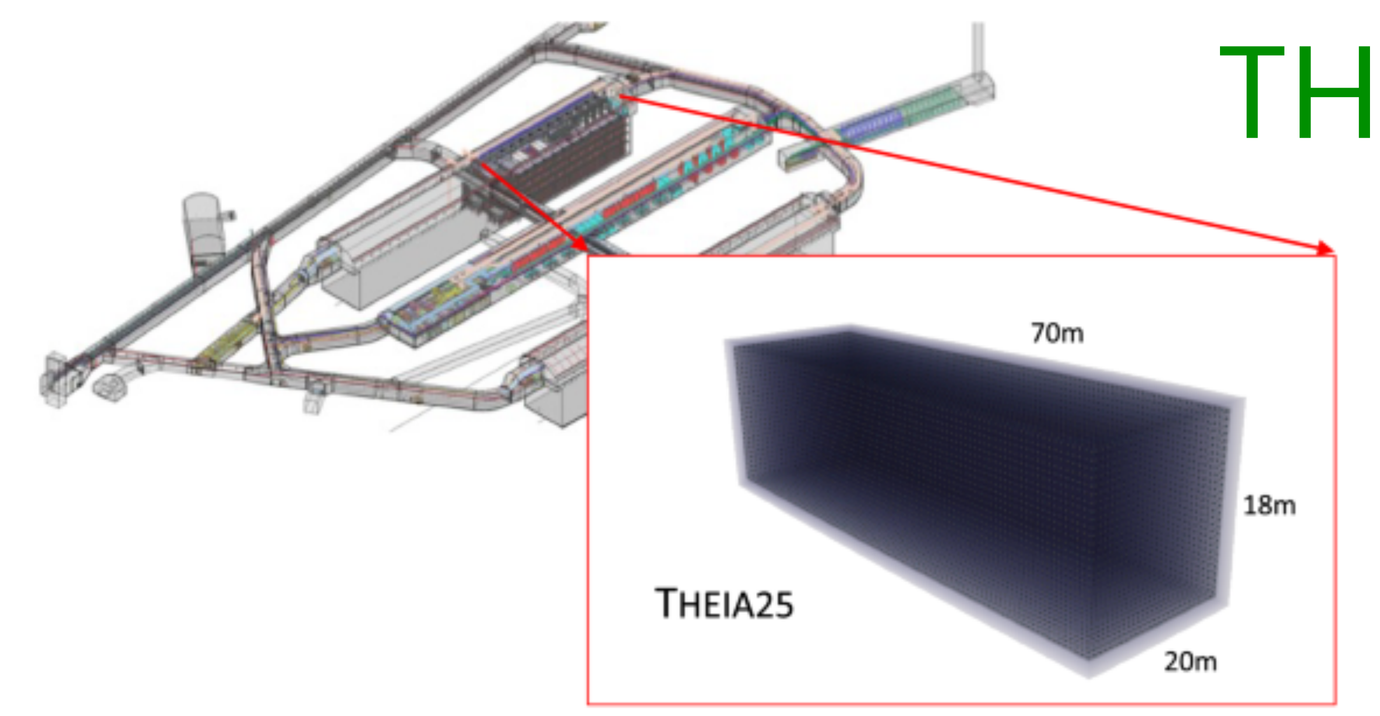
- $n - \bar{n}$ oscillation D.G. Phillips et al, 1410.1100
- $H - \bar{H}$ oscillation Feinberg, Goldhaber and Steigman, 1978
- Dinucleon decays: $NN' \to MM', \ell\ell', \ell\nu', \nu\nu'$ Xiao-Gang He and XDM, 2102.02562

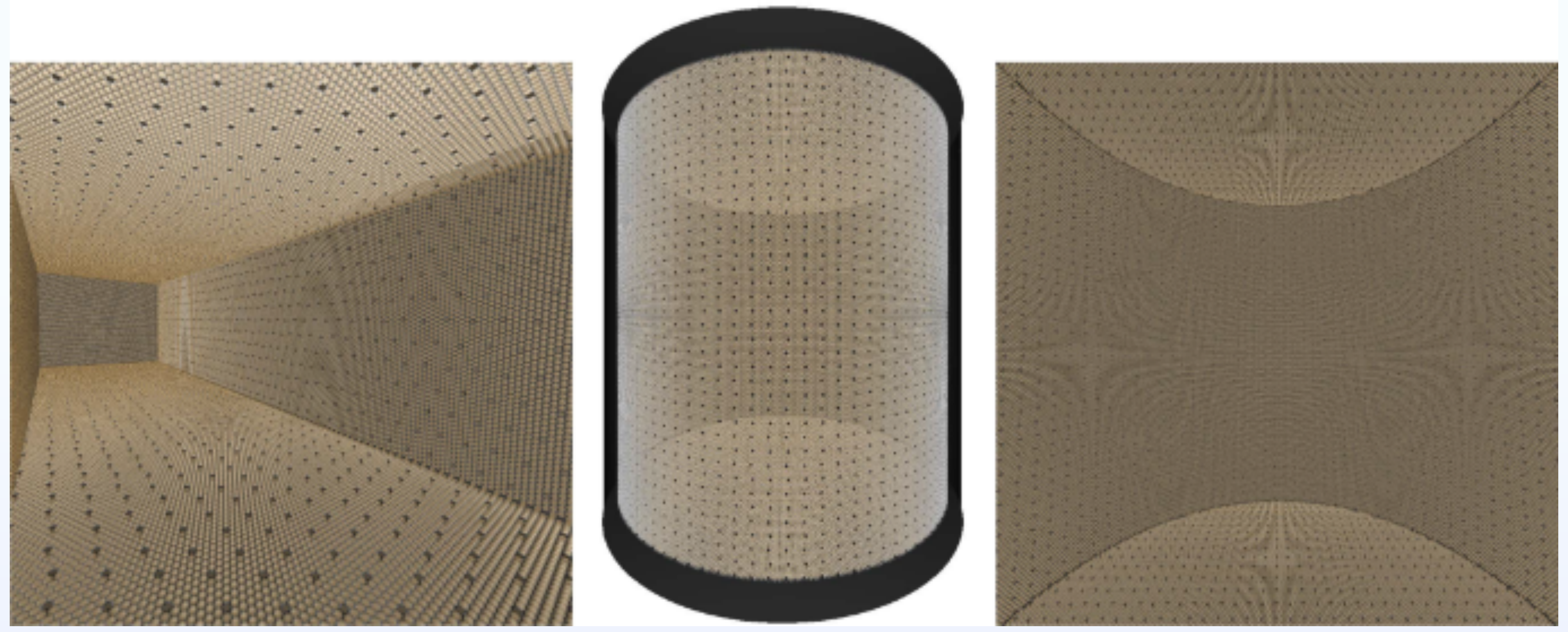
Nucleon decay search as experimental frontiers



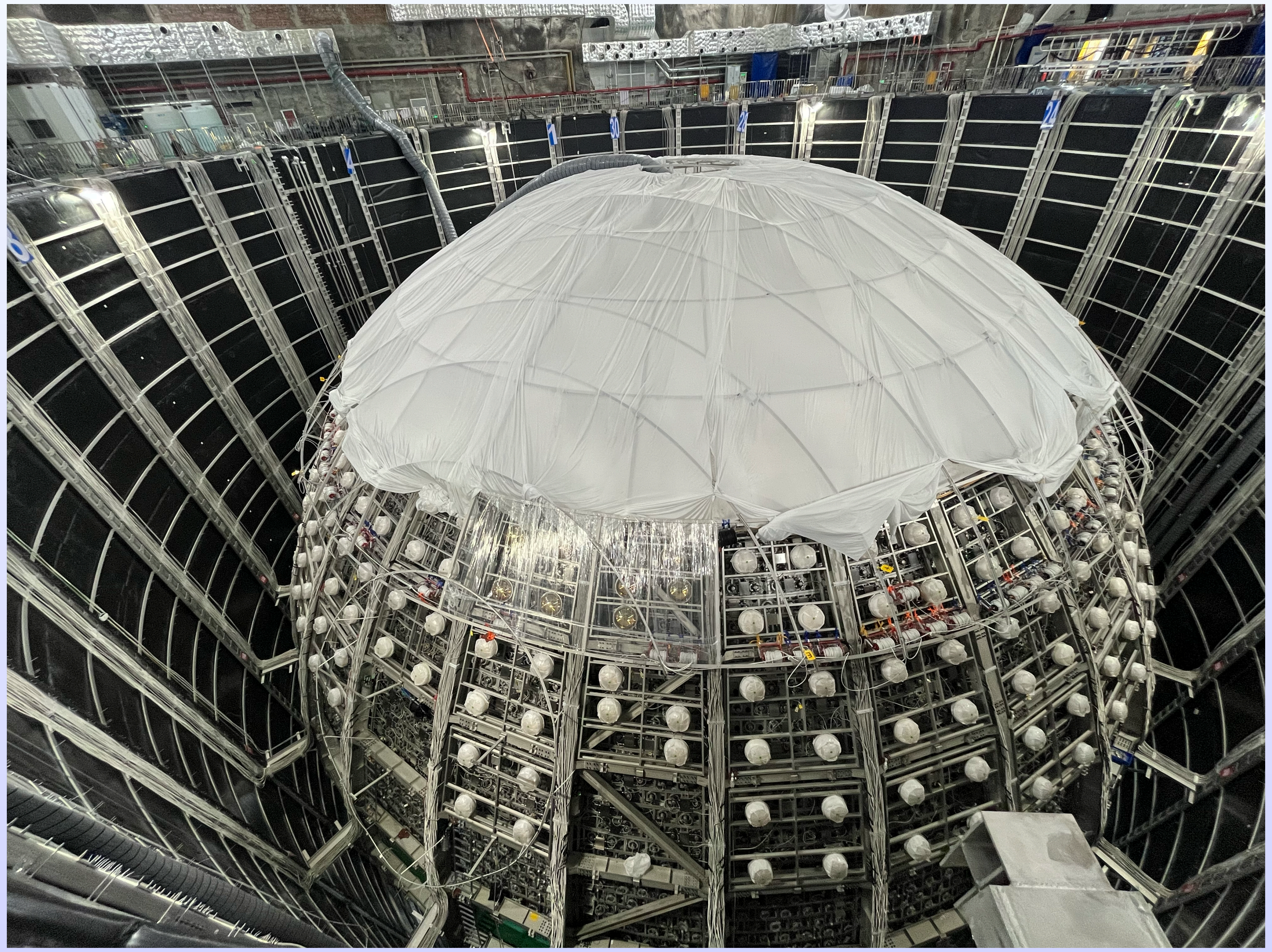
https://www.dunescience.org/

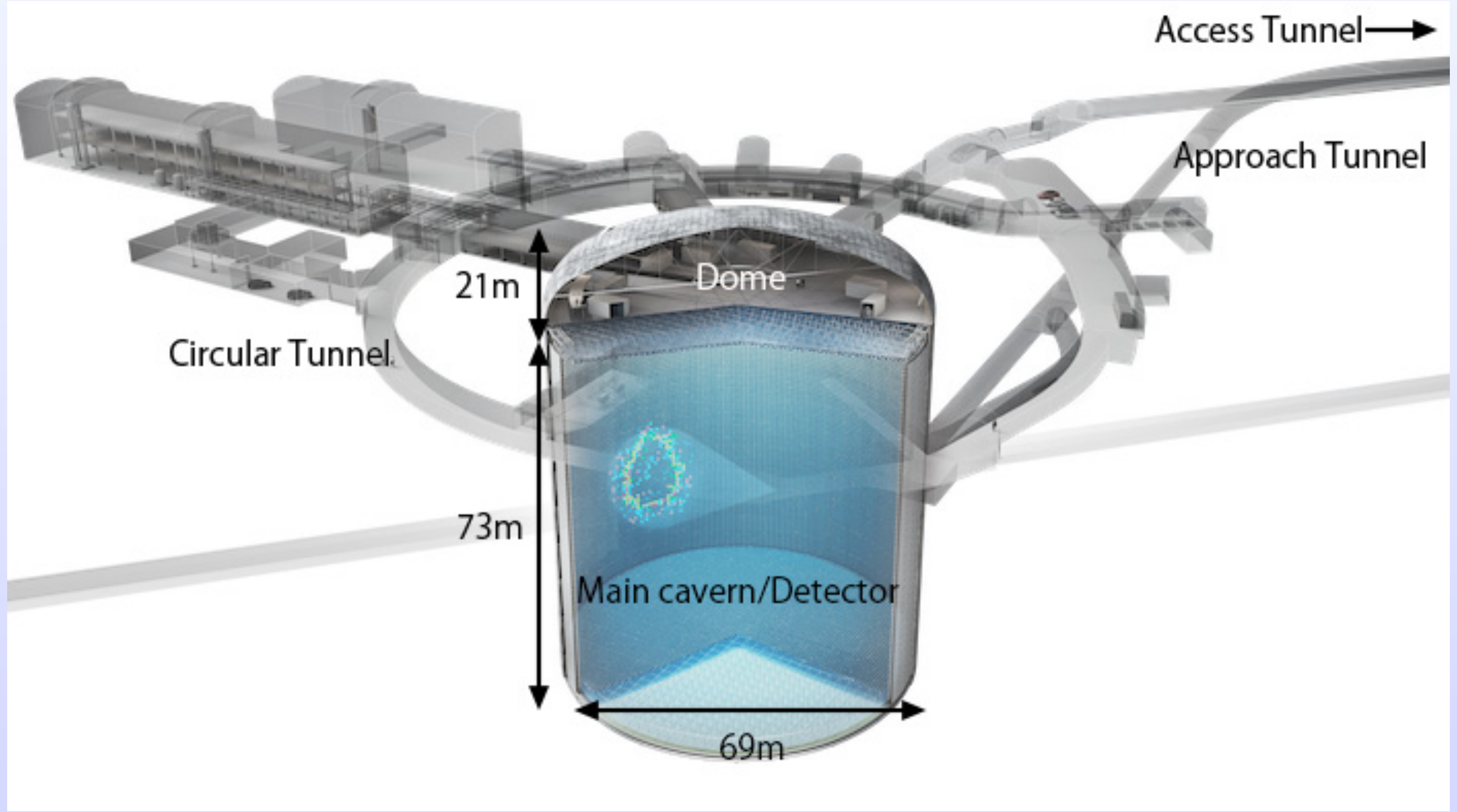
THEIA





JUNO



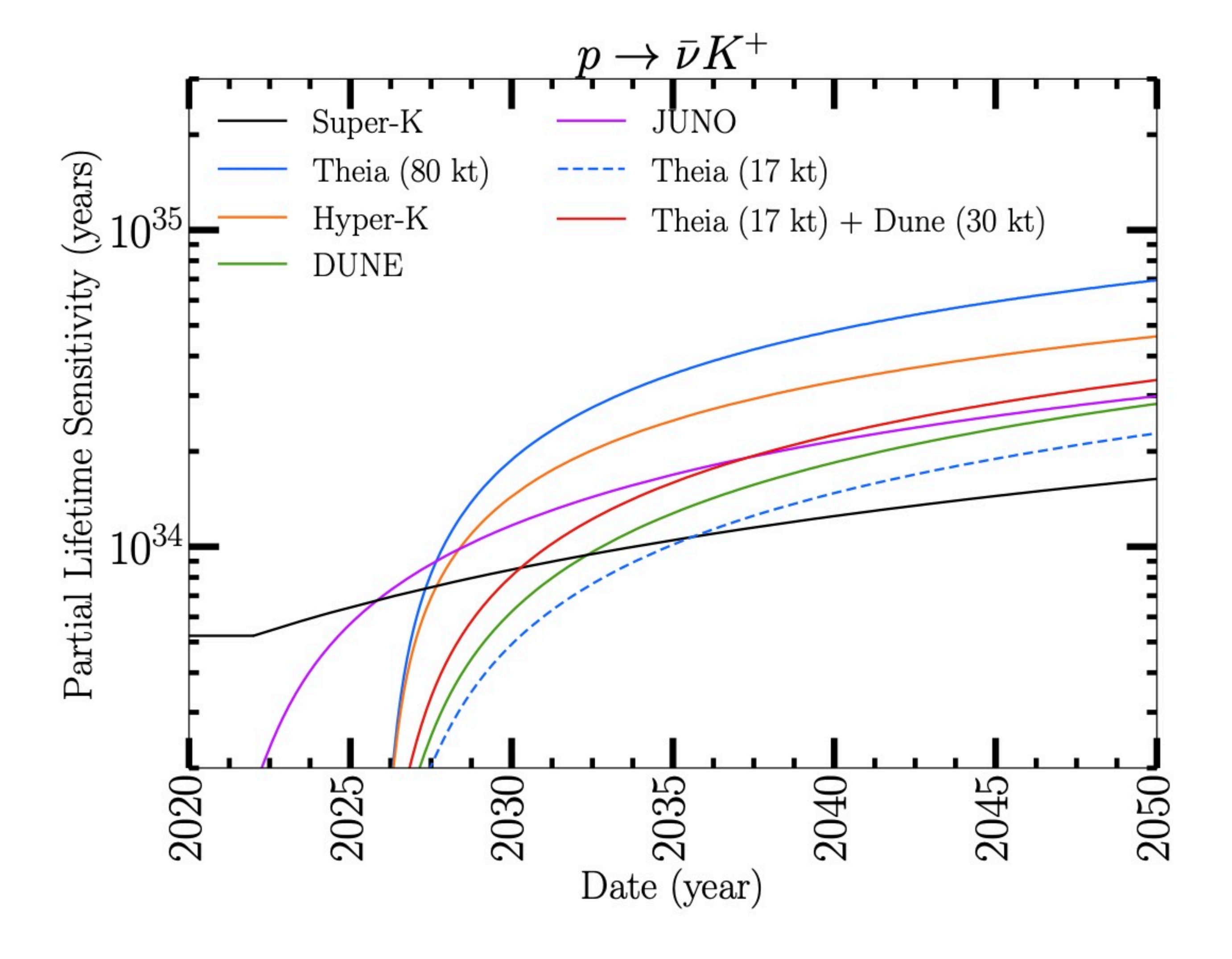


Hyper-K

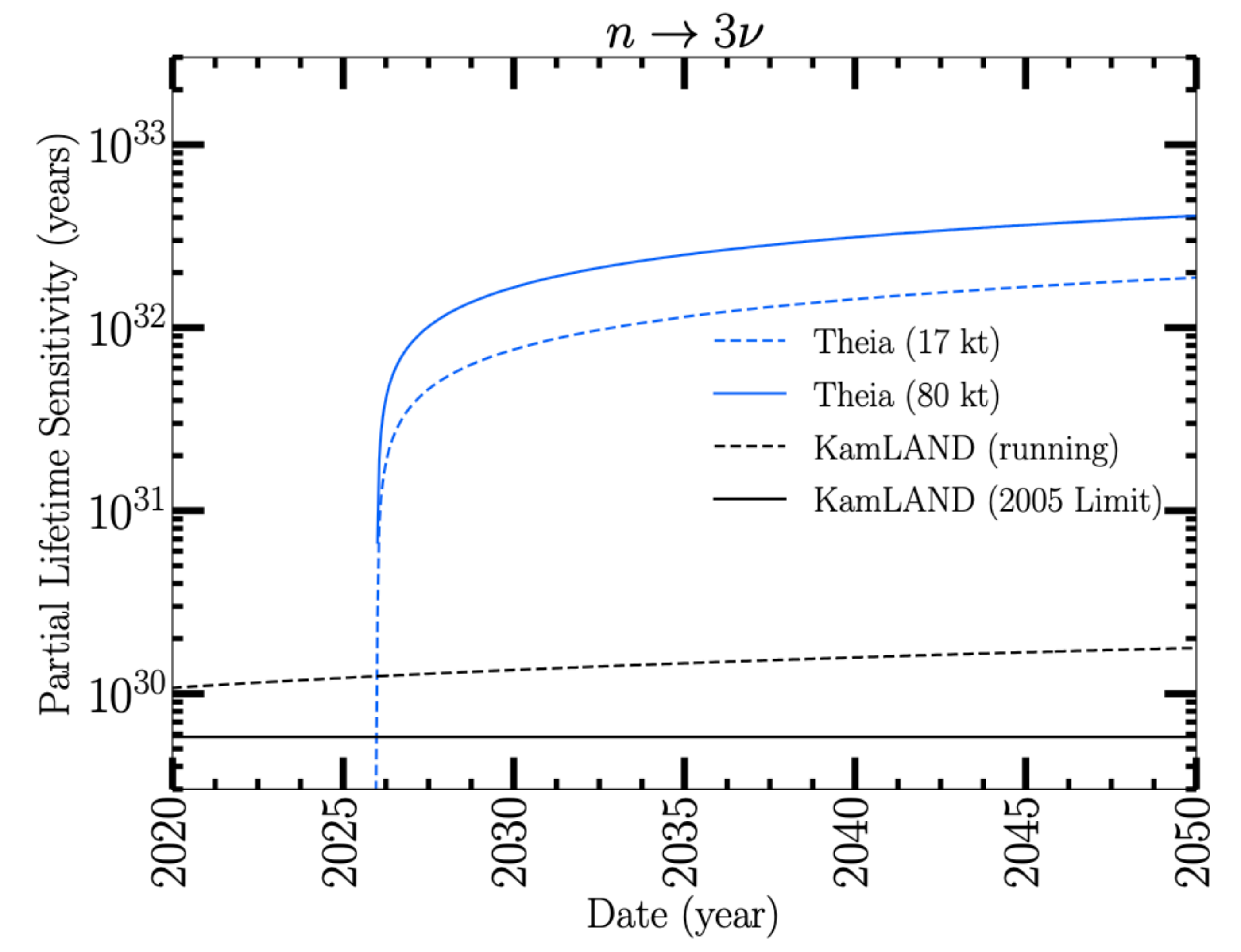
https://www-sk.icrr.u-tokyo.ac.jp/en/news/detail/684

Experiments meet theory

- Improving sensitivity to conventional modes



- Searching for exotic modes



All possible decay channels should be attempted

conventional and exotic

- 2-body vs 3-body modes
- Pseudoscalar vs vector meson modes
- SM particles vs new light particles
- ……

Needing a complete theoretical framework

THEIA, 2202.12839

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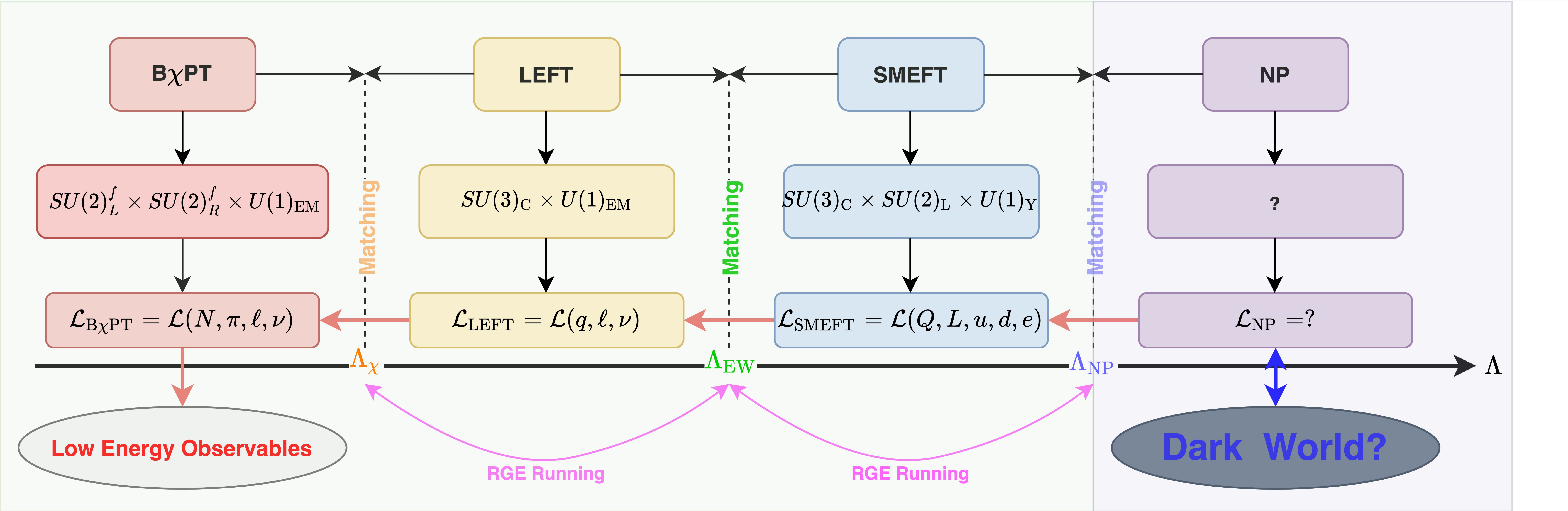
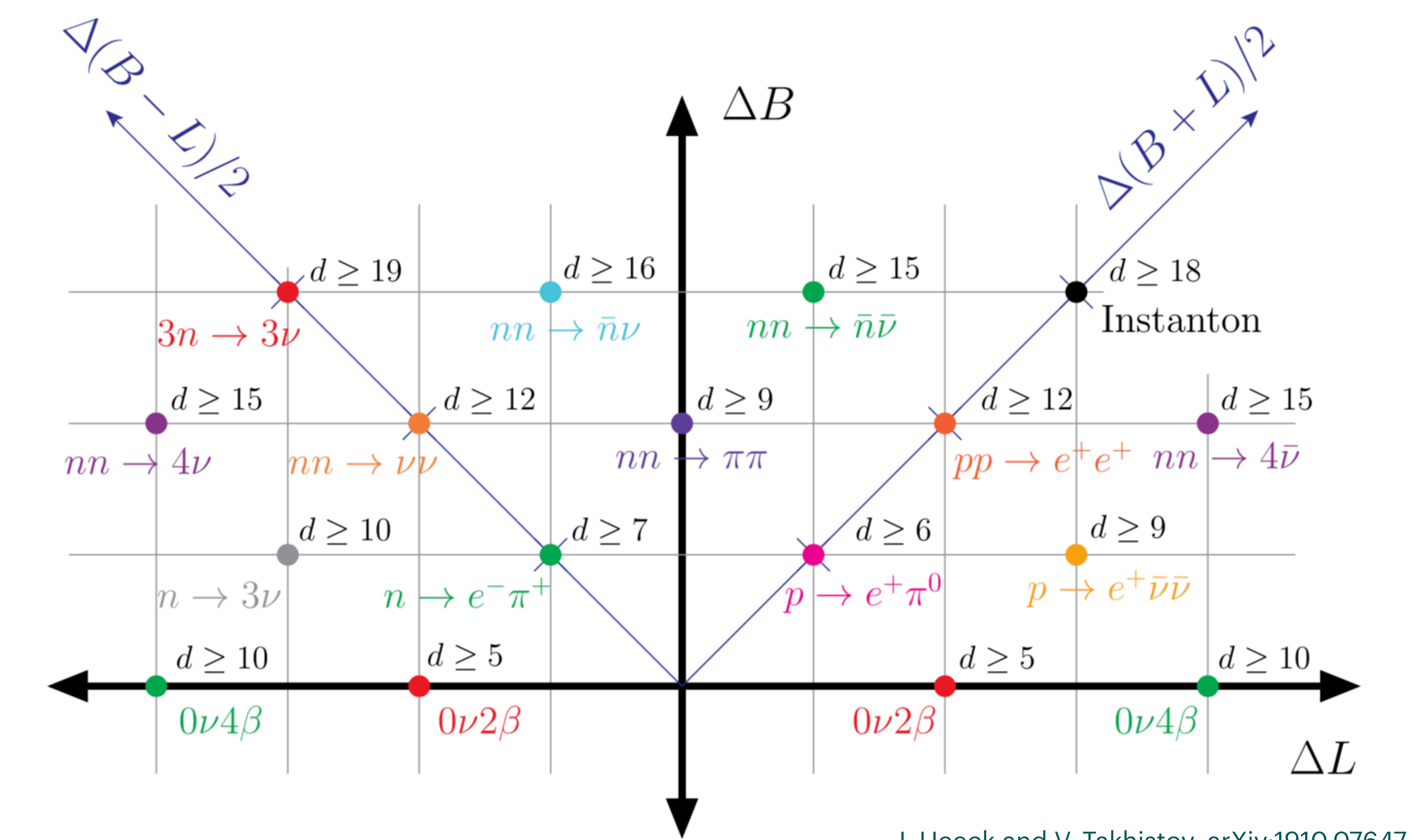
Nucleon decay in the effective field theory (EFT) landscape



Xiao-Gang He and XDM, 2102.02562

Hadron level: ChPT → quark level 1: LEFT → quark level 2: SMEFT

BNV in the SMEFT framework



J. Heeck and V. Takhistov, arXiv:1910.07647

- Dim-6 case: $\Delta(B-L) = 0$

  $p \to e^+\pi^0,\ p \to \bar{\nu}K^+,\ \ldots$

- Dim-7 case: $\Delta(B+L) = 0$

  $n \to e^-\pi^+,\ p \to \nu K^+,\ \ldots$

- Exotic nucleon decay modes beyond dim 6 & 7

  $n \to 3\nu,\ p \to \ell_1^+\ell_2^+\ell_3^-,\ \ldots$

Working framework: low energy effective field theory (LEFT)

- Fields: $u,\ d,\ s,\ \not{c},\ \not{b};\ e,\ \mu,\ \tau;\ \nu_e,\ \nu_\mu,\ \nu_\tau$
- Symmetry: $\mathrm{SU}(3)_c \times \mathrm{U}(1)_{em}$
- Power counting: canonical dimension d
- Range: $\ll \Lambda_{EW}$

$\Delta(B-L)=0$		$\Delta(B+L)=0$	
$\mathcal{O}^{LL}_{\nu dud}$	$(\overline{\nu^C_L} d^\alpha_L)(\overline{u^{\beta C}_L} d^\gamma_L)\epsilon_{\alpha\beta\gamma}$	$\mathcal{O}^{LL}_{\bar\ell ddd}$	$(\overline{\ell_R} d^\alpha_L)(\overline{d^{\beta C}_L} d^\gamma_L)\epsilon_{\alpha\beta\gamma}$
$\mathcal{O}^{LL}_{\ell udu}$	$(\overline{\ell^C_L} u^\alpha_L)(\overline{d^{\beta C}_L} u^\gamma_L)\epsilon_{\alpha\beta\gamma}$	$\mathcal{O}^{RL}_{\bar\nu dud}$	$(\overline{\nu_L} d^\alpha_R)(\overline{u^{\beta C}_L} d^\gamma_L)\epsilon_{\alpha\beta\gamma}$
$\mathcal{O}^{RL}_{\ell duu}$	$(\overline{\ell^C_R} d^\alpha_R)(\overline{u^{\beta C}_L} u^\gamma_L)\epsilon_{\alpha\beta\gamma}$	$\mathcal{O}^{RL}_{\bar\nu udd}$	$(\overline{\nu_L} u^\alpha_R)(\overline{d^{\beta C}_L} d^\gamma_L)\epsilon_{\alpha\beta\gamma}$
$\mathcal{O}^{RL}_{\ell udu}$	$(\overline{\ell^C_R} u^\alpha_R)(\overline{d^{\beta C}_L} u^\gamma_L)\epsilon_{\alpha\beta\gamma}$	$\mathcal{O}^{RL}_{\bar\ell ddd}$	$(\overline{\ell_L} d^\alpha_R)(\overline{d^{\beta C}_L} d^\gamma_L)\epsilon_{\alpha\beta\gamma}$
$\mathcal{O}^{LR}_{\ell duu}$	$(\overline{\ell^C_L} d^\alpha_L)(\overline{u^{\beta C}_R} u^\gamma_R)\epsilon_{\alpha\beta\gamma}$	$\mathcal{O}^{LR}_{\bar\ell ddd}$	$(\overline{\ell_R} d^\alpha_L)(\overline{d^{\beta C}_R} d^\gamma_R)\epsilon_{\alpha\beta\gamma}$
$\mathcal{O}^{LR}_{\ell udu}$	$(\overline{\ell^C_L} u^\alpha_L)(\overline{d^{\beta C}_R} u^\gamma_R)\epsilon_{\alpha\beta\gamma}$	$\mathcal{O}^{RR}_{\bar\nu dud}$	$(\overline{\nu_L} d^\alpha_R)(\overline{u^{\beta C}_R} d^\gamma_R)\epsilon_{\alpha\beta\gamma}$
$\mathcal{O}^{LR}_{\nu ddu}$	$(\overline{\nu^C_L} d^\alpha_L)(\overline{d^{\beta C}_R} u^\gamma_R)\epsilon_{\alpha\beta\gamma}$	$\mathcal{O}^{RR}_{\bar\ell ddd}$	$(\overline{\ell_L} d^\alpha_R)(\overline{d^{\beta C}_R} d^\gamma_R)\epsilon_{\alpha\beta\gamma}$
$\mathcal{O}^{LR}_{\nu udd}$	$(\overline{\nu^C_L} u^\alpha_L)(\overline{d^{\beta C}_R} d^\gamma_R)\epsilon_{\alpha\beta\gamma}$		
$\mathcal{O}^{RR}_{\ell udu}$	$(\overline{\ell^C_R} u^\alpha_R)(\overline{d^{\beta C}_R} u^\gamma_R)\epsilon_{\alpha\beta\gamma}$		

Jenkins, Manohar, Stoffer, 2018

Jenkins, Manohar, Stoffer, 2018 — Li, Ren, Xiao, Yu, Zheng, 2020

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

Yi Liao, XDM, Quan-Yu Wang, 2020 — Murphy, 2020 — Yi Liao, XDM, Hao-Lin Wang, 2019

F. Wilczek and A. Zee, PRL 43 (1979)
J. R. Ellis, M. k. Gaillard, and D. V. Nanopoulos, PLB 88 (1979)
S.Weinberg, PRL 43 (1979) & PRD 22 (1980)
L. F. Abbott and M. B. Wise, PRD 22 (1980)

Easily to bridge with the SMEFT framework

Exotic nucleon decay involving new light particles

LEFT + new light particles ⇒ LEFT-like framework ⇒ SMEFT-like framework

- LEFT + sterile neutrino (N): $p \to N\pi^+,\ n \to N\pi^0, \cdots$

  $(\overline{N_R} d_L^\alpha)(\overline{u_L^{\beta C}} d_L^\gamma)\epsilon_{\alpha\beta\gamma}, \ \cdots$

- LEFT + ALP (a): $p \to e^+ a,\ n \to e^+\pi^- a, \cdots$

  $(\partial_\mu a)(\overline{e_L^C} u_L^\alpha)(\overline{u_L^{\beta C}} \gamma^\mu d_R^\gamma)\epsilon_{\alpha\beta\gamma}, \ \cdots$

- LEFT + dark photon (X): $p \to e^+ X,\ n \to e^+\pi^- X, \cdots$

  $X_{\mu\nu}(\overline{\ell_R} d_L^\alpha)(\overline{d_L^{\beta C}} \sigma^{\mu\nu} d_L^\gamma)\epsilon_{\alpha\beta\sigma}, \ \cdots$

- LEFT + scalar (φ): $p \to e^+\varphi,\ n \to e^+\pi^-\varphi, \cdots$

  $\varphi(\overline{\nu_L^C} d_L^\alpha)(\overline{u_L^{\beta C}} d_L^\gamma)\epsilon_{\alpha\beta\gamma}, \ \cdots$

Sandbox Studio, Chicago

General $\Delta B = 1$ nucleon decay operator structures

- Must involve an odd number of light quarks: $qqq,\ qqqG,\ qqqq\bar{q},\cdots$
- Leading-order interactions: involve only three light quarks
- Only four general triple-quark (without derivative) structures

$$\mathcal{O}_a^{yzw} = (\overline{\Psi}_a q^\alpha_{\mathrm{L},y})(\overline{q^{\beta\mathrm{C}}_{\mathrm{L},z}} q^\gamma_{\mathrm{L},w})\epsilon_{\alpha\beta\gamma}$$

$$\mathcal{O}_b^{yzw} = (\overline{\Psi}_b q^\alpha_{\mathrm{R},y})(\overline{q^{\beta\mathrm{C}}_{\mathrm{L},z}} q^\gamma_{\mathrm{L},w})\epsilon_{\alpha\beta\gamma}$$

$$\mathcal{O}_c^{yzw} = (\overline{\Psi}_{c,\mu} q^\alpha_{\mathrm{L},\{y})(\overline{q^{\beta\mathrm{C}}_{\mathrm{L},z\}}}\gamma^\mu q^\gamma_{\mathrm{R},w})\epsilon_{\alpha\beta\gamma}$$

$$\mathcal{O}_d^{yzw} = (\overline{\Psi}_{d,\mu\nu} q^\alpha_{\mathrm{L},\{y})(\overline{q^{\beta\mathrm{C}}_{\mathrm{L},z}}\sigma^{\mu\nu} q^\gamma_{\mathrm{L},w\}})\epsilon_{\alpha\beta\gamma}$$

Newly identified structures

+ their chiral partners with $\mathrm{L} \leftrightarrow \mathrm{R}$

- ❖ $\overline{\Psi}_a, \overline{\Psi}_b, \overline{\Psi}_{c,\mu}, \overline{\Psi}_{d,\mu\nu}$: combinations of non-QCD fields
- ❖ $y, z, w = 1,2,3$: quark flavor indices with $q_{1,2,3} = u, d, s$
- ❖ $\{y, z\}$ and $\{y, z, w\}$: total symmetrization of flavor indices

- Form a basis for any triple-quark operators

Yi Liao, XDM, Hao-Lin Wang, arXiv: 2504.14855

QCD running effect

- 1-loop RGE due to QCD correction

$$\frac{dC^{yzw}_{a,b}}{d\ln\mu} = -2\frac{\alpha_s}{2\pi}C^{yzw}_{a,b}, \quad \frac{dC^{yzw}_{c}}{d\ln\mu} = +\frac{2}{3}\frac{\alpha_s}{2\pi}C^{yzw}_{c}, \quad \frac{dC^{yzw}_{d}}{d\ln\mu} = +2\frac{\alpha_s}{2\pi}C^{yzw}_{d}$$

Known from dim-6 LEFT counterparts

E. E. Jenkins, A. V. Manohar, and P. Stoffer, arXiv:1711.05270v3

- No mixing: QCD interactions preserve chiral symmetry

- Running effects

$$C^{yzw}_{a,b}(\Lambda_\chi) \approx 1.32\, C^{yzw}_{a,b}(\Lambda_{\mathrm{EW}}), \quad C^{yzw}_{c}(\Lambda_\chi) \approx 0.91\, C^{yzw}_{c}(\Lambda_{\mathrm{EW}}), \quad C^{yzw}_{d}(\Lambda_\chi) \approx 0.76\, C^{yzw}_{d}(\Lambda_{\mathrm{EW}})$$

Enhancement by 30%

Suppression

Chiral structures

- 3-flavor ($u,\ d,\ s$) QCD has a global chiral symmetry: $\mathrm{SU}(3)_\mathrm{L} \otimes \mathrm{SU}(3)_\mathrm{R}$

in the massless limit

- Restrict to triple-quark sector

$$\mathcal{N}^{\mathrm{LL}}_{yzw} \equiv q^{\alpha}_{\mathrm{L,y}}(\overline{q^{\beta C}_{\mathrm{L,z}}} q^{\gamma}_{\mathrm{L,w}})\epsilon_{\alpha\beta\gamma} \in \mathbf{8}_\mathrm{L} \otimes \mathbf{1}_\mathrm{R}$$

$$\mathcal{N}^{\mathrm{RL}}_{yzw} \equiv q^{\alpha}_{\mathrm{R,y}}(\overline{q^{\beta C}_{\mathrm{L,z}}} q^{\gamma}_{\mathrm{L,w}})\epsilon_{\alpha\beta\gamma} \in \bar{\mathbf{3}}_\mathrm{L} \otimes \mathbf{3}_\mathrm{R}$$

$+\mathrm{L} \leftrightarrow \mathrm{R}$

$$\mathcal{N}^{\mathrm{LR},\mu}_{yzw} \equiv q^{\alpha}_{\mathrm{L},\{\mathrm{y}}(\overline{q^{\beta C}_{\mathrm{L,z}\}}} \gamma^{\mu} q^{\gamma}_{\mathrm{R,w}})\epsilon_{\alpha\beta\gamma} \in \mathbf{6}_\mathrm{L} \otimes \mathbf{3}_\mathrm{R}$$

$$\mathcal{N}^{\mathrm{LL},\mu\nu}_{yzw} \equiv q^{\alpha}_{\mathrm{L},\{\mathrm{y}}(\overline{q^{\beta C}_{\mathrm{L,z}}} \sigma^{\mu\nu} q^{\gamma}_{\mathrm{L,w}\}})\epsilon_{\alpha\beta\gamma} \in \mathbf{10}_\mathrm{L} \otimes \mathbf{1}_\mathrm{R}$$

Newly identified chiral structures

- Different isospin property

$\mathcal{N}^{\mathrm{LL}}_{yzw}$ and $\mathcal{N}^{\mathrm{RL}}_{yzw}$ $\Rightarrow \Delta I = 0,\ 1/2,\ 1$

$\mathcal{N}^{\mathrm{LR},\mu}_{yzw}$ and $\mathcal{N}^{\mathrm{LL},\mu\nu}_{yzw}$ $\Rightarrow \Delta I = 0,\ 1/2,\ 1,\ 3/2 \Rightarrow n \to e^-\pi^+,\ n \to \mu^-\pi^+$

Non-trivial Lorentz structures

- Usual structures—spin-1/2 objects:

$$\mathcal{N}_{\mathbf{8}_\mathrm{L}\otimes\mathbf{1}_\mathrm{R}},\ \mathcal{N}_{\mathbf{3}_\mathrm{L}\otimes\bar{\mathbf{3}}_\mathrm{R}} \in (1/2,\ 0), \qquad \mathcal{N}_{\mathbf{1}_\mathrm{L}\otimes\mathbf{8}_\mathrm{R}},\ \mathcal{N}_{\bar{\mathbf{3}}_\mathrm{L}\otimes\mathbf{3}_\mathrm{R}} \in (0,\ 1/2)$$

- New structures—spin-3/2 objects:

Vector-spinor object: $\mathcal{N}^{\mathrm{LR},\mu}_{yzw} \in (1,\ 1/2), \quad \mathcal{N}^{\mathrm{RL},\mu}_{yzw} \in (1/2,\ 1) \quad \gamma_\mu \mathcal{N}^{\mathrm{LR},\mu}_{yzw} = \gamma_\mu \mathcal{N}^{\mathrm{RL},\mu}_{yzw} = 0$

Tensor-spinor object: $\mathcal{N}^{\mathrm{LL},\mu\nu}_{yzw} \in (3/2,0), \quad \mathcal{N}^{\mathrm{RR},\mu\nu}_{yzw} \in (0,\ 3/2) \quad \gamma_\mu \mathcal{N}^{\mathrm{LL},\mu\nu}_{yzw} = \gamma_\mu \mathcal{N}^{\mathrm{RR},\mu\nu}_{yzw} = 0$

↓

Complicating the chiral matching ⟶ Needing proper Lorentz projectors

$$\Gamma^{\mathrm{L,R}}_{\mu\nu} \equiv \left(g_{\mu\nu} - \frac{1}{4}\gamma_\mu\gamma_\nu\right) P_{\mathrm{L,R}}$$

$$\Gamma^{\mathrm{L,R}}_{\mu\rho}\Gamma^{\mathrm{L,R}\,\rho}_{\nu} = \Gamma^{\mathrm{L,R}}_{\mu\nu} \qquad \gamma^\mu \Gamma^{\mathrm{L,R}}_{\mu\nu} = 0$$

$$\hat{\Gamma}^{\mathrm{L,R}}_{\mu\nu\alpha\beta} \equiv \frac{1}{24}\Big(2\{\sigma_{\mu\nu}, \sigma_{\alpha\beta}\} - [\sigma_{\mu\nu}, \sigma_{\alpha\beta}]\Big) P_{\mathrm{L,R}}$$

$$\hat{\Gamma}^{\mathrm{L,R}}_{\mu\nu\rho\sigma}\hat{\Gamma}^{\mathrm{L,R}\,\rho\sigma}_{\alpha\beta} = \hat{\Gamma}^{\mathrm{L,R}}_{\mu\nu\alpha\beta} \qquad \gamma^\mu \hat{\Gamma}^{\mathrm{L,R}}_{\mu\nu\alpha\beta} = 0$$

E. Delgado et al., EPJA 51 (2015)

The general LEFT Lagrangian involving triple quarks

Non-quark factor as spurion fields

$$\mathscr{L}_{q^3}^{\not B} = \sum_i C_i^{yzw} \mathscr{O}_i^{yzw} = \sum_i C_i^{yzw}\overline{\psi}\,\Gamma_1 q(\overline{q^{\mathrm{C}}}\Gamma_2 q)$$

Quark factor

$\equiv \mathscr{P}^i_{yzw}$ $\equiv \mathscr{N}^i_{yzw}$

$$\begin{aligned}\mathscr{L}_{q^3}^{\not B} = &\mathrm{Tr}\left[\mathscr{P}_{\mathbf{8}_\mathrm{L}\otimes\mathbf{1}_\mathrm{R}}\mathscr{N}_{\mathbf{8}_\mathrm{L}\otimes\mathbf{1}_\mathrm{R}} + \mathscr{P}_{\mathbf{1}_\mathrm{L}\otimes\mathbf{8}_\mathrm{R}}\mathscr{N}_{\mathbf{1}_\mathrm{L}\otimes\mathbf{8}_\mathrm{R}}\right]\\ &+\mathrm{Tr}\left[\mathscr{P}_{\mathbf{3}_\mathrm{L}\otimes\bar{\mathbf{3}}_\mathrm{R}}\mathscr{N}_{\bar{\mathbf{3}}_\mathrm{L}\otimes\mathbf{3}_\mathrm{R}} + \mathscr{P}_{\bar{\mathbf{3}}_\mathrm{L}\otimes\mathbf{3}_\mathrm{R}}\mathscr{N}_{\mathbf{3}_\mathrm{L}\otimes\bar{\mathbf{3}}_\mathrm{R}}\right]\\ &+\left[\mathscr{P}^{\{yz\}w,\mu}_{\bar{\mathbf{6}}_\mathrm{L}\otimes\bar{\mathbf{3}}_\mathrm{R}}\mathscr{N}^{\{yz\}w}_{\mathbf{6}_\mathrm{L}\otimes\mathbf{3}_\mathrm{R},\mu} + \mathscr{P}^{\{yz\}w,\mu}_{\bar{\mathbf{3}}_\mathrm{L}\otimes\bar{\mathbf{6}}_\mathrm{R}}\mathscr{N}^{\{yz\}w}_{\mathbf{3}_\mathrm{L}\otimes\mathbf{6}_\mathrm{R},\mu}\right]\\ &+\left[\mathscr{P}^{\{yzw\},\mu\nu}_{\overline{\mathbf{10}}_\mathrm{L}\otimes\mathbf{1}_\mathrm{R}}\mathscr{N}^{\{yzw\}}_{\mathbf{10}_\mathrm{L}\otimes\mathbf{1}_\mathrm{R},\mu\nu} + \mathscr{P}^{\{yzw\},\mu\nu}_{\mathbf{1}_\mathrm{L}\otimes\overline{\mathbf{10}}_\mathrm{R}}\mathscr{N}^{\{yzw\}}_{\mathbf{1}_\mathrm{L}\otimes\mathbf{10}_\mathrm{R},\mu\nu}\right]\\ &+\mathrm{h.c.}\end{aligned}$$

Matrix form for easy chiral realization

$$\mathscr{N}_{\mathbf{8}_\mathrm{L}\otimes\mathbf{1}_\mathrm{R}} = \begin{pmatrix}\mathscr{N}^{\mathrm{LL}}_{uds} & \mathscr{N}^{\mathrm{LL}}_{usu} & \mathscr{N}^{\mathrm{LL}}_{uud}\\ \mathscr{N}^{\mathrm{LL}}_{dds} & \mathscr{N}^{\mathrm{LL}}_{dsu} & \mathscr{N}^{\mathrm{LL}}_{dud}\\ \mathscr{N}^{\mathrm{LL}}_{sds} & \mathscr{N}^{\mathrm{LL}}_{ssu} & \mathscr{N}^{\mathrm{LL}}_{sud}\end{pmatrix} \qquad \mathscr{N}_{\bar{\mathbf{3}}_\mathrm{L}\otimes\mathbf{3}_\mathrm{R}} = \begin{pmatrix}\mathscr{N}^{\mathrm{RL}}_{uds} & \mathscr{N}^{\mathrm{RL}}_{usu} & \mathscr{N}^{\mathrm{RL}}_{uud}\\ \mathscr{N}^{\mathrm{RL}}_{dds} & \mathscr{N}^{\mathrm{RL}}_{dsu} & \mathscr{N}^{\mathrm{RL}}_{dud}\\ \mathscr{N}^{\mathrm{RL}}_{sds} & \mathscr{N}^{\mathrm{RL}}_{ssu} & \mathscr{N}^{\mathrm{RL}}_{sud}\end{pmatrix}$$

Wei-Qi Fan, Yi Liao, XDM, Hao-Lin Wang, 2412.20774

Chiral building blocks

$$\mathscr{P}_{\mathbf{8}_\mathrm{L}\otimes\mathbf{1}_\mathrm{R}} = \begin{pmatrix}0 & \mathscr{P}^{\mathrm{LL}}_{dds} & \mathscr{P}^{\mathrm{LL}}_{sds}\\ \mathscr{P}^{\mathrm{LL}}_{usu} & \mathscr{P}^{\mathrm{LL}}_{dsu} & \mathscr{P}^{\mathrm{LL}}_{ssu}\\ \mathscr{P}^{\mathrm{LL}}_{uud} & \mathscr{P}^{\mathrm{LL}}_{dud} & \mathscr{P}^{\mathrm{LL}}_{sud}\end{pmatrix} \qquad \mathscr{P}_{\mathbf{3}_\mathrm{L}\otimes\bar{\mathbf{3}}_\mathrm{R}} = \begin{pmatrix}\mathscr{P}^{\mathrm{RL}}_{uds} & \mathscr{P}^{\mathrm{RL}}_{dds} & \mathscr{P}^{\mathrm{RL}}_{sds}\\ \mathscr{P}^{\mathrm{RL}}_{usu} & \mathscr{P}^{\mathrm{RL}}_{dsu} & \mathscr{P}^{\mathrm{RL}}_{ssu}\\ \mathscr{P}^{\mathrm{RL}}_{uud} & \mathscr{P}^{\mathrm{RL}}_{dud} & \mathscr{P}^{\mathrm{RL}}_{sud}\end{pmatrix} \qquad \mathscr{P}^{\mathrm{LR},\mu}_{yzw} \qquad \mathscr{P}^{\mathrm{LL},\mu\nu}_{yzw}$$

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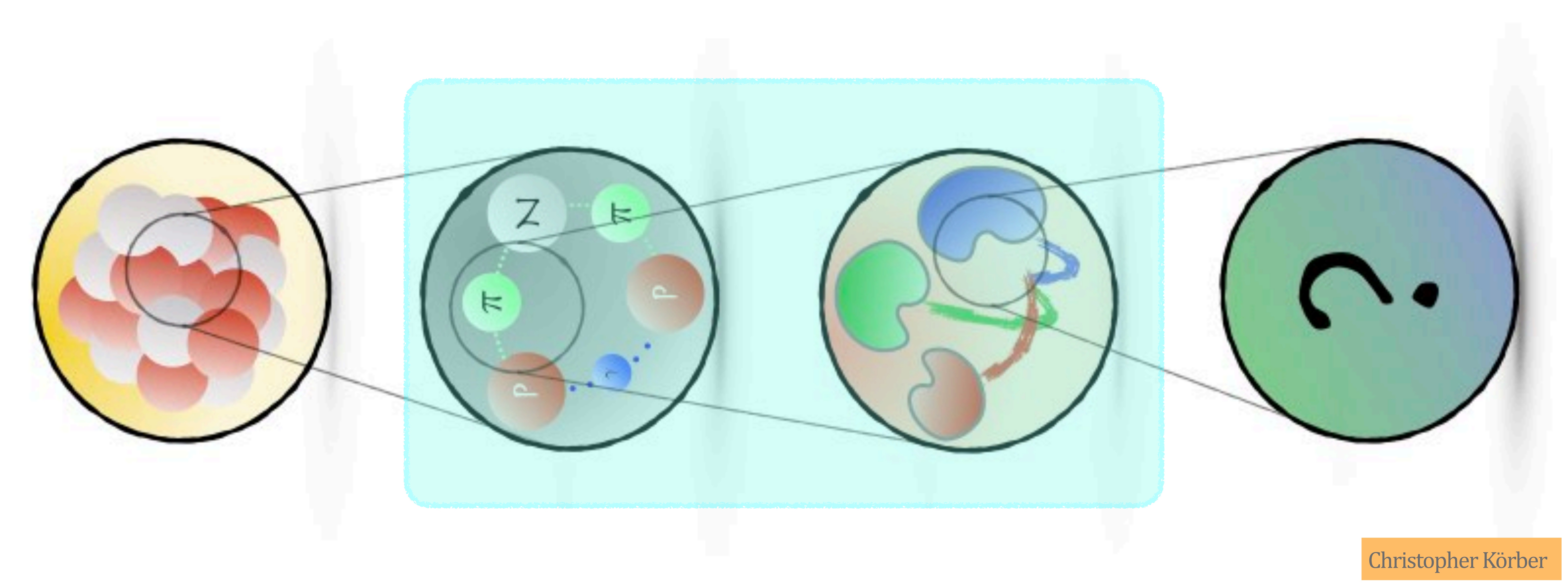
Chiral Perturbation Theory

$\mathrm{SU(3)_L \otimes SU(3)_R}$

u, d, s

Nucleon level operators

Quark level operators



Chiral matching procedures

- Building blocks in ChPT: Octet baryons, pseudoscalars, vector mesons + spurions

$$\Sigma(x) = \xi^2(x) = \exp\left(\frac{i\sqrt{2}\Pi(x)}{F_0}\right) \quad \Pi(x) = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}, \quad B(x) = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda^0}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda^0}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda^0 \end{pmatrix}, \quad V_\mu(x) = \begin{pmatrix} \frac{\rho^0_\mu}{\sqrt{2}} + \frac{\phi^{(8)}_\mu}{\sqrt{6}} & \rho^+_\mu & K^{*+}_\mu \\ \rho^-_\mu & -\frac{\rho^0_\mu}{\sqrt{2}} + \frac{\phi^{(8)}_\mu}{\sqrt{6}} & K^{*0}_\mu \\ K^{*-}_\mu & \bar{K}^{*0}_\mu & -\sqrt{\frac{2}{3}}\phi^{(8)}_\mu \end{pmatrix}$$

+ Spurion fields

$$\mathscr{P}_{\mathbf{8}_L\otimes\mathbf{1}_R} = \begin{pmatrix} 0 & \mathscr{P}^{LL}_{dds} & \mathscr{P}^{LL}_{sds} \\ \mathscr{P}^{LL}_{usu} & \mathscr{P}^{LL}_{dsu} & \mathscr{P}^{LL}_{ssu} \\ \mathscr{P}^{LL}_{uud} & \mathscr{P}^{LL}_{dud} & \mathscr{P}^{LL}_{sud} \end{pmatrix} \quad \mathscr{P}_{\mathbf{3}_L\otimes\bar{\mathbf{3}}_R} = \begin{pmatrix} \mathscr{P}^{RL}_{uds} & \mathscr{P}^{RL}_{dds} & \mathscr{P}^{RL}_{sds} \\ \mathscr{P}^{RL}_{usu} & \mathscr{P}^{RL}_{dsu} & \mathscr{P}^{RL}_{ssu} \\ \mathscr{P}^{RL}_{uud} & \mathscr{P}^{RL}_{dud} & \mathscr{P}^{RL}_{sud} \end{pmatrix} \quad \mathscr{P}^{LR,\mu}_{yzw} \quad \mathscr{P}^{LL,\mu\nu}_{yzw}$$

- Chiral symmetry: $SU(3)_L \otimes SU(3)_R$

- Chiral power counting: momentum p:

$$\{\Sigma, \xi, B, D_\mu B, V, D_\mu V\} \sim \mathcal{O}(p^0) \quad D_\mu\Sigma \sim \mathcal{O}(p^1)$$

- Low energy constant (LEC): associate an unknown LEC for each indep. operator

Leading-order chiral Lagrangian for nucleon decay

Yi Liao, XDM, Hao-Lin Wang, arXiv: 2504.14855

$$\mathcal{L}_B^{\not{B},0} = c_1 \mathrm{Tr}\left[\mathcal{P}_{\bar{\mathbf{3}}_\mathrm{L}\otimes\mathbf{3}_\mathrm{R}} \xi B_\mathrm{L} \xi - \mathcal{P}_{\mathbf{3}_\mathrm{L}\otimes\bar{\mathbf{3}}_\mathrm{R}} \xi^\dagger B_\mathrm{R} \xi^\dagger\right] + c_2 \mathrm{Tr}\left[\mathcal{P}_{\mathbf{8}_\mathrm{L}\otimes\mathbf{1}_\mathrm{R}} \xi B_\mathrm{L} \xi^\dagger - \mathcal{P}_{\mathbf{1}_\mathrm{L}\otimes\mathbf{8}_\mathrm{R}} \xi^\dagger B_\mathrm{R} \xi\right] + \frac{c_3}{\Lambda_\chi}\left[\mathcal{P}^{\mathrm{LR},\mu}_{yzi} \Gamma^\mathrm{L}_{\mu\nu} (\xi i D^\nu B_\mathrm{L} \xi)_{yj} \Sigma_{zk} \epsilon_{ijk} - \mathcal{P}^{\mathrm{RL},\mu}_{yzi} \Gamma^\mathrm{R}_{\mu\nu} (\xi^\dagger i D^\nu B_\mathrm{R} \xi^\dagger)_{yj} \Sigma^*_{kz} \epsilon_{ijk}\right] + \mathrm{h.c.},$$

$$\mathcal{L}_B^{\not{B},1} = \frac{c_4}{\Lambda_\chi^2}\left[\mathcal{P}^{\mathrm{LL},\mu\nu}_{yzw} \hat{\Gamma}^\mathrm{L}_{\mu\nu\alpha\beta} (\xi D^\alpha B_\mathrm{L} \xi)_{yi} \Sigma_{zj} (D^\beta \Sigma)_{wk} \epsilon_{ijk} - \mathcal{P}^{\mathrm{RR},\mu\nu}_{yzw} \hat{\Gamma}^\mathrm{R}_{\mu\nu\alpha\beta} (\xi^\dagger D^\alpha B_\mathrm{R} \xi^\dagger)_{iy} \Sigma^*_{jz} (D^\beta \Sigma)^*_{kw} \epsilon_{ijk}\right] + \mathrm{h.c.}\,.$$

Related to new structures

$$\Gamma^{\mathrm{L,R}}_{\mu\nu} \equiv \left(g_{\mu\nu} - \frac{1}{4}\gamma_\mu \gamma_\nu\right) P_{\mathrm{L,R}} \qquad \hat{\Gamma}^{\mathrm{L,R}}_{\mu\nu\alpha\beta} \equiv \frac{1}{24}\left(2\{\sigma_{\mu\nu}, \sigma_{\alpha\beta}\} - [\sigma_{\mu\nu}, \sigma_{\alpha\beta}]\right) P_{\mathrm{L,R}}$$

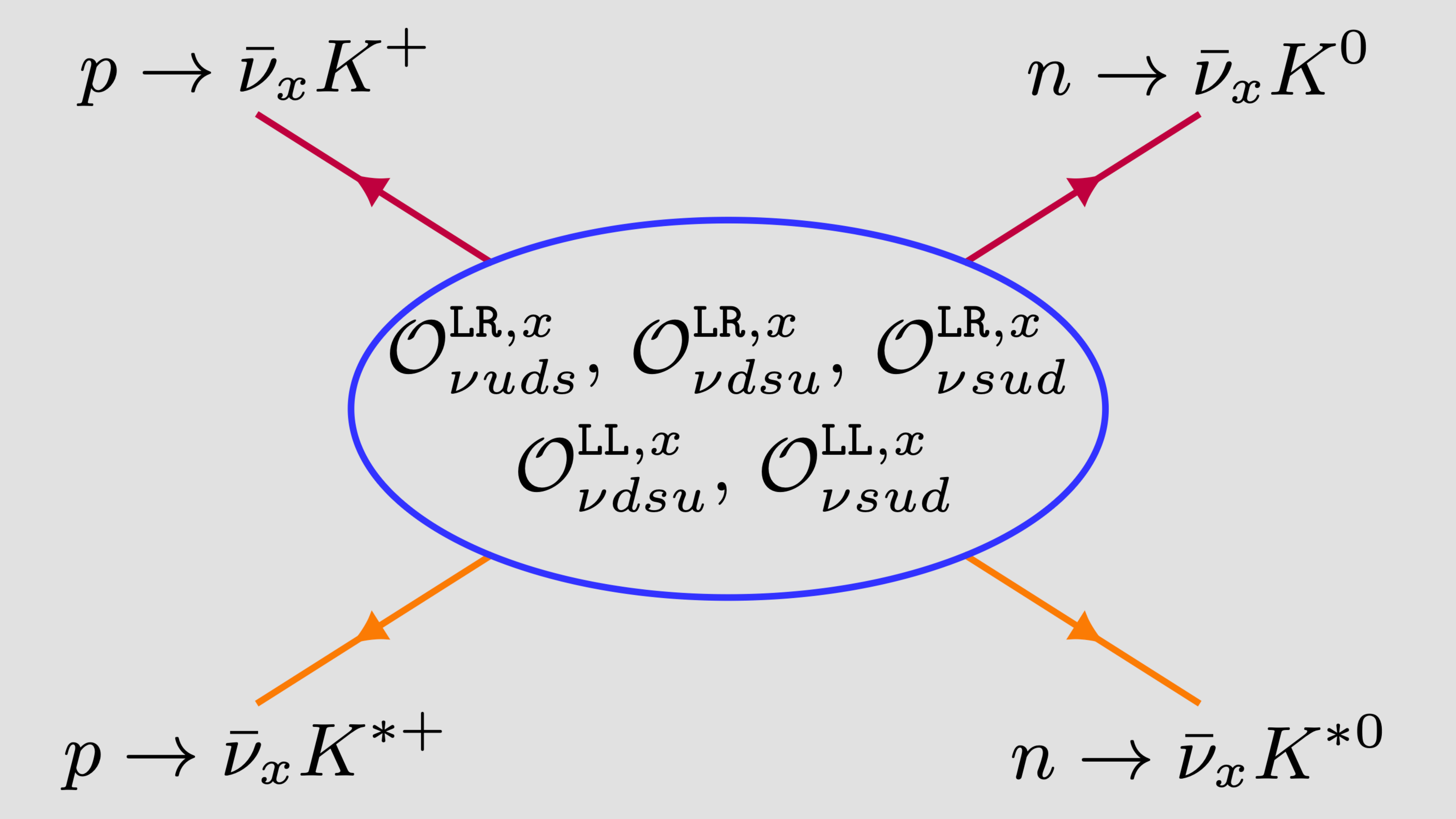
Expanding these Lagrangian terms lead to relevant interacting vertices, then the relevant amplitude can be computed as simple as in the perturbative QFT

Chiral Lagrangian involving octet vector mesons

$$
\begin{aligned}
\mathcal{L}^{\not{B}}_{BV} = {} & d_1 \mathrm{Tr}\big[\mathcal{P}_{\bar{\mathbf{3}}_{\mathrm{L}}\otimes\mathbf{3}_{\mathrm{R}}}\xi\gamma_\mu V^\mu B_{\mathrm{R}}\xi - \mathcal{P}_{\mathbf{3}_{\mathrm{L}}\otimes\bar{\mathbf{3}}_{\mathrm{R}}}\xi^\dagger\gamma_\mu V^\mu B_{\mathrm{L}}\xi^\dagger\big] \\
& + d_1' \mathrm{Tr}\big[\mathcal{P}_{\bar{\mathbf{3}}_{\mathrm{L}}\otimes\mathbf{3}_{\mathrm{R}}}\xi\gamma_\mu B_{\mathrm{R}} V^\mu \xi - \mathcal{P}_{\mathbf{3}_{\mathrm{L}}\otimes\bar{\mathbf{3}}_{\mathrm{R}}}\xi^\dagger\gamma_\mu B_{\mathrm{L}} V^\mu \xi^\dagger\big] \\
& + d_2 \mathrm{Tr}\big[\mathcal{P}_{\mathbf{8}_{\mathrm{L}}\otimes\mathbf{1}_{\mathrm{R}}}\xi\gamma_\mu V^\mu B_{\mathrm{R}}\xi^\dagger - \mathcal{P}_{\mathbf{1}_{\mathrm{L}}\otimes\mathbf{8}_{\mathrm{R}}}\xi^\dagger\gamma_\mu V^\mu B_{\mathrm{L}}\xi\big] \\
& + d_2' \mathrm{Tr}\big[\mathcal{P}_{\mathbf{8}_{\mathrm{L}}\otimes\mathbf{1}_{\mathrm{R}}}\xi\gamma_\mu B_{\mathrm{R}} V^\mu \xi^\dagger - \mathcal{P}_{\mathbf{1}_{\mathrm{L}}\otimes\mathbf{8}_{\mathrm{R}}}\xi^\dagger\gamma_\mu B_{\mathrm{L}} V^\mu \xi\big] \\
& + d_3 \big[\mathcal{P}^{\mathrm{LR},\mu}_{yzi}\Gamma^{\mathrm{L}}_{\mu\nu}(\xi B_{\mathrm{L}}\xi)_{yj}(\xi V^\nu \xi)_{zk}\epsilon_{ijk} \\
& - \mathcal{P}^{\mathrm{RL},\mu}_{yzi}\Gamma^{\mathrm{R}}_{\mu\nu}(\xi^\dagger B_{\mathrm{R}}\xi^\dagger)_{yj}(\xi^\dagger V^\nu \xi^\dagger)_{kz}\epsilon_{ijk}\big] \\
& + d_3' \big[\mathcal{P}^{\mathrm{LR},\mu}_{yzi}\Gamma^{\mathrm{L}}_{\mu\nu}(\xi V^\nu B_{\mathrm{L}}\xi)_{yj}\Sigma_{zk}\epsilon_{ijk} \\
& - \mathcal{P}^{\mathrm{RL},\mu}_{yzi}\Gamma^{\mathrm{R}}_{\mu\nu}(\xi^\dagger V^\nu B_{\mathrm{R}}\xi^\dagger)_{yj}\Sigma^*_{kz}\epsilon_{ijk}\big] \\
& + d_3'' \big[\mathcal{P}^{\mathrm{LR},\mu}_{yzi}\Gamma^{\mathrm{L}}_{\mu\nu}(\xi B_{\mathrm{L}} V^\nu \xi)_{yj}\Sigma_{zk}\epsilon_{ijk} \\
& - \mathcal{P}^{\mathrm{RL},\mu}_{yzi}\Gamma^{\mathrm{R}}_{\mu\nu}(\xi^\dagger B_{\mathrm{R}} V^\nu \xi^\dagger)_{yj}\Sigma^*_{kz}\epsilon_{ijk}\big] \\
& + \frac{d_4}{\Lambda_\chi}\big[\mathcal{P}^{\mathrm{LL},\mu\nu}_{yzw}\hat{\Gamma}^{\mathrm{L}}_{\mu\nu\alpha\beta}(\xi D^\alpha B_{\mathrm{L}}\xi)_{yi}\Sigma_{zj}(\xi V^\beta \xi)_{wk}\epsilon_{ijk} \\
& - \mathcal{P}^{\mathrm{RR},\mu\nu}_{yzw}\hat{\Gamma}^{\mathrm{R}}_{\mu\nu\alpha\beta}(\xi^\dagger D^\alpha B_{\mathrm{R}}\xi^\dagger)_{yi}\Sigma^*_{jz}(\xi V^\beta \xi)^*_{kw}\epsilon_{ijk}\big] \\
& + \mathrm{h.c.},
\end{aligned}
$$

Yi Liao, XDM, Hao-Lin Wang, 2506.05052

Complementarity between pseudoscalar and vector meson



Comparison to known results: ~40 years ago

Octet pseudoscalar case

CHIRAL LAGRANGIAN FOR DEEP MINE PHYSICS*

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Received 25 August 1981

The chiral lagrangian for baryon number violating nucleon decay is derived and applied to nucleon decays into strange and non-strange final states. The uncertainties in our predictions are discussed.

with SU(3)×SU(2)×U(1) symmetry are [5, 6]

$$O^{(1)}_{abcd} = (d_{\alpha a R} u_{\beta b R})(q_{i\gamma c L} l_{jdL})\varepsilon_{\alpha\beta\gamma}\varepsilon_{ij}\,, \quad (1a)$$

$$O^{(2)}_{abcd} = (q_{i\alpha a L} q_{j\beta b L})(u_{\gamma c R} l_{dR})\varepsilon_{\alpha\beta\gamma}\varepsilon_{ij}\,, \quad (1b)$$

$$O^{(3)}_{abcd} = (q_{i\alpha a L} q_{j\beta b L})(q_{k\gamma c L} l_{ldL})\varepsilon_{\alpha\beta\gamma}\varepsilon_{il}\varepsilon_{jk}\,, \quad (1c)$$

$$O^{(4)}_{abcd} = (d_{\alpha a R} u_{\beta b R})(u_{\gamma c R} l_{dR})\varepsilon_{\alpha\beta\gamma}\,. \quad (1d)$$

$$\begin{aligned}\mathscr{L}^{|\Delta B|=1} = \alpha \sum_{d=1}^{2} \{ & C^{(1)}_d [e_{dL}\,\mathrm{Tr}\, O\xi B_L \xi - \nu_{dL}\,\mathrm{Tr}\, O'\xi B_L\xi] \\ & + C^{(2)}_d e_{dR}\,\mathrm{Tr}\, O\xi^+ B_R \xi^+ + \tilde{C}^{(1)}_d [e_{dL}\,\mathrm{Tr}\,\tilde{O}\xi B_L\xi - \nu_{dL}\,\mathrm{Tr}\,\tilde{O}'\xi B_L \xi] \\ & + \tilde{C}^{(2)}_d e_{dR}\,\mathrm{Tr}\,\tilde{O}\xi^+ B_R \xi^+ + \tilde{C}^{(5)}_d \nu_{dL}\,\mathrm{Tr}\,\tilde{O}''\xi B_L\xi\} \\ & + \beta \sum_{d=1}^{2} \{ C^{(3)}_d [e_{dL}\,\mathrm{Tr}\, O\xi B_L\xi^+ - \nu_{dL}\,\mathrm{Tr}\, O'\xi B_L \xi^+] \\ & + C^{(4)}_d e_{dR}\,\mathrm{Tr}\, O\xi^+ B_R\xi + \tilde{C}^{(3)}_d [e_{dL}\,\mathrm{Tr}\,\tilde{O}\xi B_L\xi^+ - \nu_{dL}\,\mathrm{Tr}\,\tilde{O}'\xi B_L\xi^+] \\ & + \tilde{C}^{(4)}_d e_{dR}\,\mathrm{Tr}\,\tilde{O}\xi^+ B_R\xi + \tilde{C}^{(6)}_d \nu_{dL}\,\mathrm{Tr}\,\tilde{O}''\xi B_L\xi^+\} + \text{h.c.}\,, \end{aligned} \quad (16)$$

Only for dim-6 $\Delta(B-L)=0$ case

Octet vector meson case

PHYSICAL REVIEW D VOLUME 29, NUMBER 9 1 MAY 1984

Chiral Lagrangian for proton decay

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(Received 6 June 1983)

We extend the recent chiral model of Claudson, Wise, and Hall to include vector and axial-vector mesons as gauge bosons of an $SU(3)_L \times SU(3)_R$ chiral symmetry. The resulting baryon-number-violating interaction Lagrangian contains an additional free parameter and modifies significantly the two-body branching ratios of protons. Without some experimental input, it is not possible to predict

$$\begin{aligned}\mathscr{L}^{\Delta B=1}_{(2)} = \frac{\gamma}{M_p}\sum_d \{ & \overline{e^+_{dR}} i\gamma_\mu \mathrm{Tr}[\underline{C}^{(1)}_d \underline{\xi}(D^\mu \underline{B})\underline{\xi}] - \overline{e^+_{dL}} i\gamma_\mu \mathrm{Tr}[\underline{C}^{(2)}_d \underline{\xi}^\dagger (D^\mu \underline{B})\underline{\xi}^\dagger] - \overline{\nu^c_{dR}} i\gamma_\mu \mathrm{Tr}[\underline{F}^{(1)}_d \underline{\xi}(D^\mu \underline{B})\underline{\xi}]\} + \text{H.c.} \\ + \frac{\delta}{M_p}\sum_p \{ & \overline{e^+_{dR}} i\gamma_\mu \mathrm{Tr}[\underline{C}^{(3)}_d \underline{\xi}(D^\mu \underline{B})\underline{\xi}^\dagger] \overline{e^+_{dL}} i\gamma_\mu \mathrm{Tr}[\underline{C}^{(4)}_d \underline{\xi}^\dagger (D^\mu \underline{B})\underline{\xi}] - \overline{\nu^c_{dR}} i\gamma_\mu \mathrm{Tr}[\underline{F}^{(3)}_d \underline{\xi}(D^\mu \underline{B})\underline{\xi}^\dagger]\} + \text{H.c.}\end{aligned} \quad (3.7)$$

Not complete, double counting issues, ...

Our results provide a complete and consistent framework for more precise calculations of a variety of nucleon decay amplitudes.

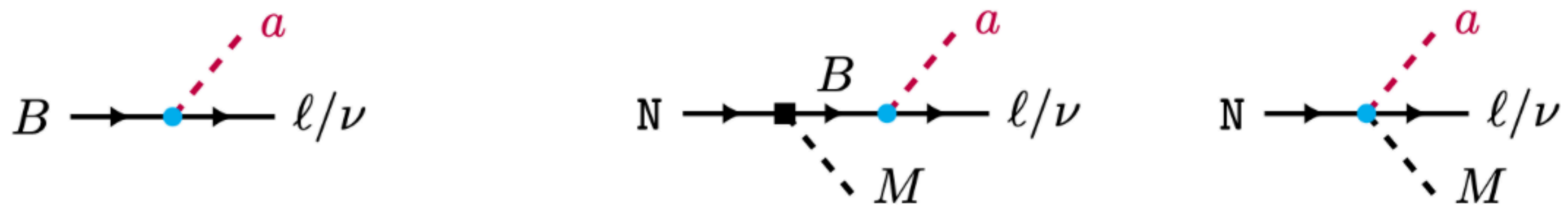
- ~~Introduction~~
- ~~General BNV nucleon decay interactions in the LEFT~~
- ~~Chiral realizations~~
- **Applications**
- Summary

Calculation of relevant transition matrix element and decay rate

Standard ChPT interactions

$$\mathcal{L}_{\text{ChPT}}^{B,0} \supset \frac{D}{2}\mathrm{Tr}(\bar{B}\gamma^{\mu}\gamma_5\{u_{\mu}, B\}) + \frac{F}{2}\mathrm{Tr}(\bar{B}\gamma^{\mu}\gamma_5[u_{\mu}, B]) + \mathrm{G_D}\mathrm{Tr}(\bar{B}\gamma_{\mu}\{V^{\mu}, B\}) + \mathrm{G_F}\mathrm{Tr}(\bar{B}\gamma_{\mu}[V^{\mu}, B]), \quad (11)$$

Expanding the chiral Lagrangian → $\mathscr{L} \supset M^n(\mathscr{P}B)$ → Draw diagram and calculate



(a) (b)

Triple-lepton example: $p \to e^+e^+\mu^-, \mu^+\mu^+e^-$

- Among the experimentally most constrained proton decay processes
- They can only be mediated by dim-9 and higher LEFT operators
- Associated with irreps $\mathbf{6}_{\mathrm{L(R)}} \otimes \mathbf{3}_{\mathrm{R(L)}}$

dim-10 or higher in SMEFT

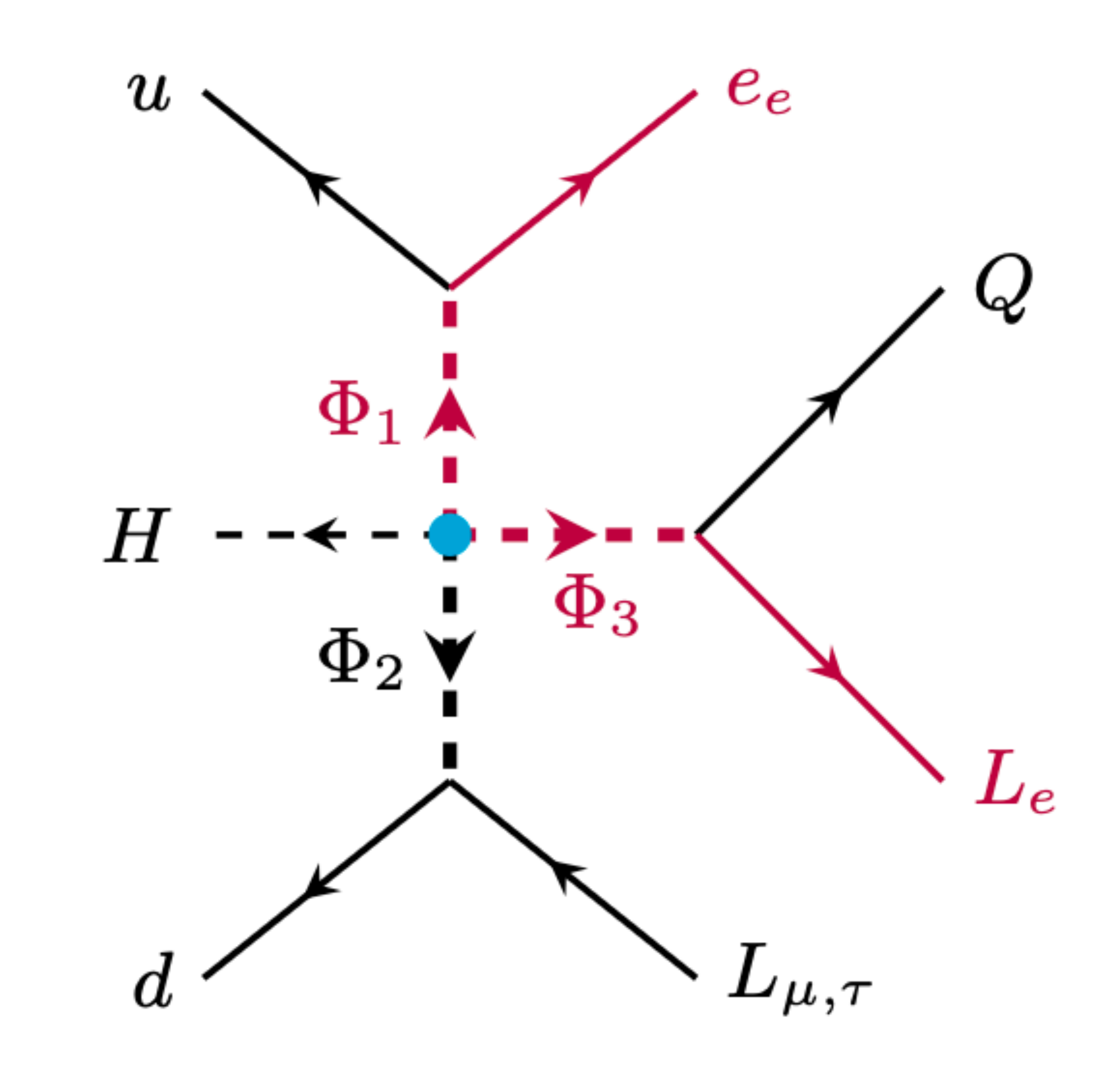
$$\mathcal{O}_{\ell\ell'} = (\overline{\ell^{\mathrm{C}}_{\mathrm{L}}}\gamma_\mu \ell_{\mathrm{R}})(\overline{\ell'_{\mathrm{R}}} u^\alpha_{\mathrm{L}})(\overline{u^{\beta\mathrm{C}}_{\mathrm{L}}}\gamma^\mu d^\gamma_{\mathrm{R}})\epsilon_{\alpha\beta\gamma}$$

$$\downarrow$$

$$\mathcal{P}^{\mathrm{LR},\mu}_{uud} = \Lambda^{-5}_{\ell\ell'}(\overline{\ell^{\mathrm{C}}_{\mathrm{L}}}\gamma^\mu \ell_{\mathrm{R}})\overline{\ell'_{\mathrm{R}}}$$

$$\downarrow$$

$$\Gamma(p \to e^+e^+\mu^-/\mu^+\mu^+e^-) \sim \frac{1}{10^{34}\ \mathrm{yr}}\left(\frac{4\times 10^5\,\mathrm{GeV}}{\Lambda_{\mu e}}\right)^{10}$$

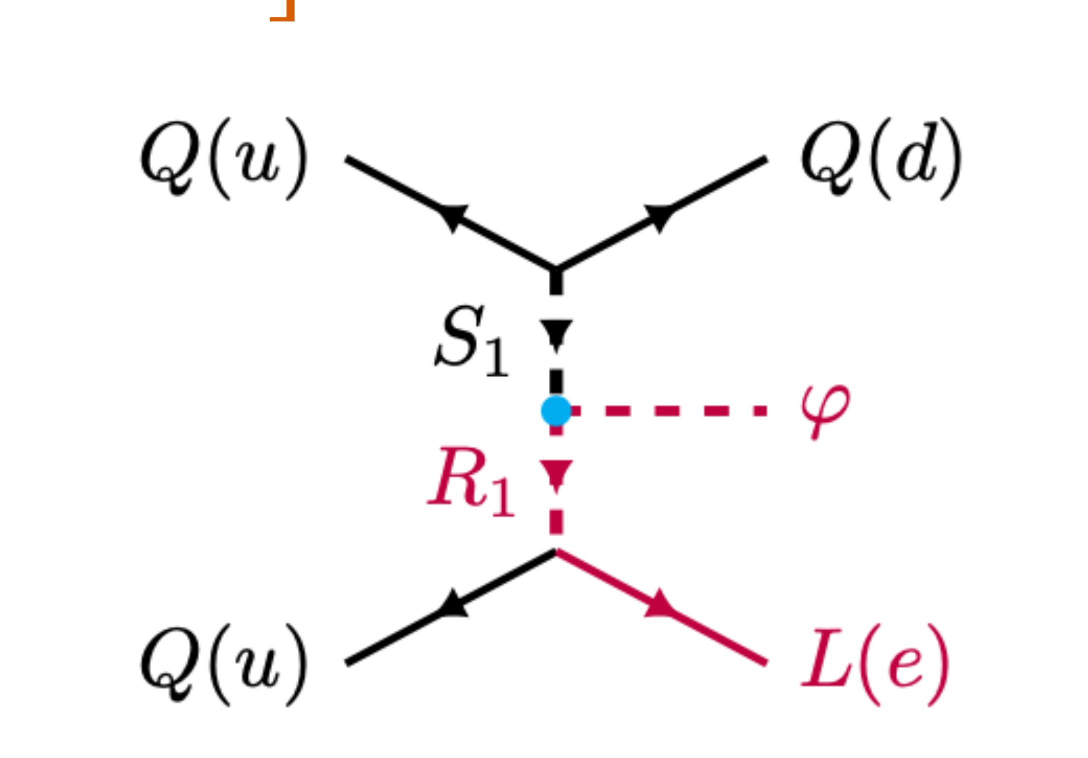


Leptoquark model

Nucleon decay with a light scalar: $\mathbb{N} \to l\varphi$

$$\mathscr{L} \supset \left[R_1^\dagger(y_{Lpr}\overline{Q_p^{i\mathbb{C}}}\epsilon_{ij}L_r^j + y_{Rpr}\overline{u_p^{\mathbb{C}}}e_r) + S_1^\alpha(z_{Lpr}\overline{Q_p^{i\beta\mathbb{C}}}\epsilon_{ij}Q_r^{j\gamma} + z_{Rpr}\overline{u_p^{\beta\mathbb{C}}}d_r^\gamma)\epsilon_{\alpha\beta\gamma} - \kappa R_1^\dagger S_1\varphi + \mathrm{h.c.}\right],$$

Leptoquark model



$\mathbb{Z}_2$ symmetry

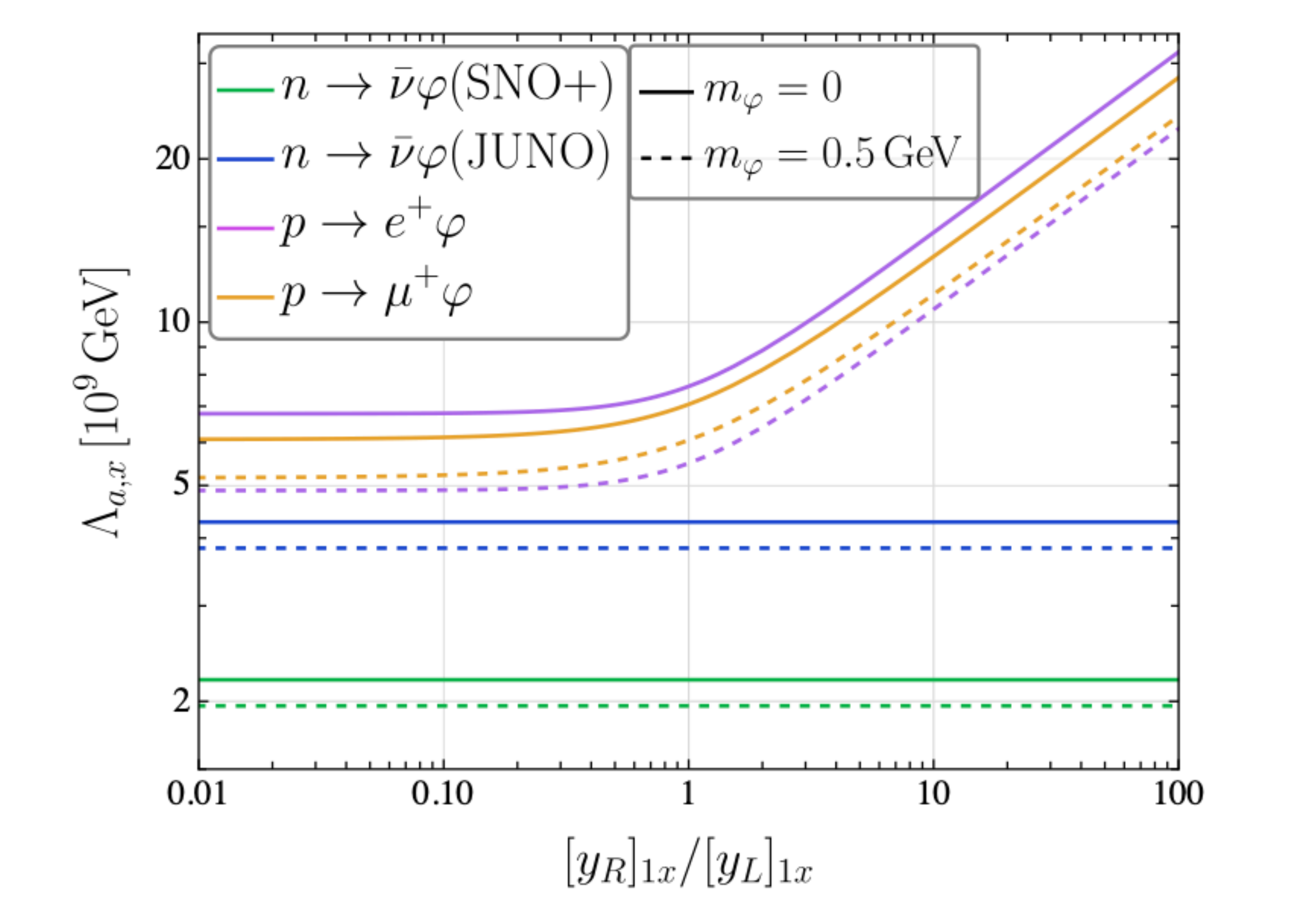
No dim-6 SMEFT

Dim-7 in φSMEFT

$$C_{LQdu\varphi}^{prst} = -\frac{\kappa^*[y_L]_{rp}[z_R]_{ts}}{m_S^2 m_R^2}, \qquad C_{euQQ\varphi}^{prst} = -\frac{\kappa^*[y_R]_{rp}[z_L]_{st}}{m_S^2 m_R^2},$$
$$C_{LQQQ\varphi}^{prst} = \frac{2\kappa^*[y_L]_{rp}[z_L]_{st}}{m_S^2 m_R^2}, \qquad C_{eudu\varphi}^{prst} = \frac{\kappa^*[y_R]_{rp}[z_R]_{ts}}{m_S^2 m_R^2}.$$

Dim-7 in φLEFT

$$C_{\varphi\nu dud}^{\mathrm{LR},x} = 1.32\frac{\kappa^*[y_L]_{1x}[z_R]_{11}}{m_S^2 m_R^2}, \; C_{\varphi\ell uud}^{\mathrm{LR},x} = -C_{\varphi\nu dud}^{\mathrm{LR},x}, \; C_{\varphi\ell uud}^{\mathrm{RL},x} = -1.32\frac{2\kappa^*[y_R]_{1x}[z_L]_{11}}{m_S^2 m_R^2},$$
$$C_{\varphi\nu dud}^{\mathrm{LL},x} = 1.32\frac{2\kappa^*[y_L]_{1x}[z_L]_{11}}{m_S^2 m_R^2}, \; C_{\varphi\ell uud}^{\mathrm{LL},x} = -C_{\varphi\nu dud}^{\mathrm{LL},x}, \; C_{\varphi\ell uud}^{\mathrm{RR},x} = -1.32\frac{\kappa^*[y_R]_{1x}[z_R]_{11}}{m_S^2 m_R^2},$$



Spurion fields

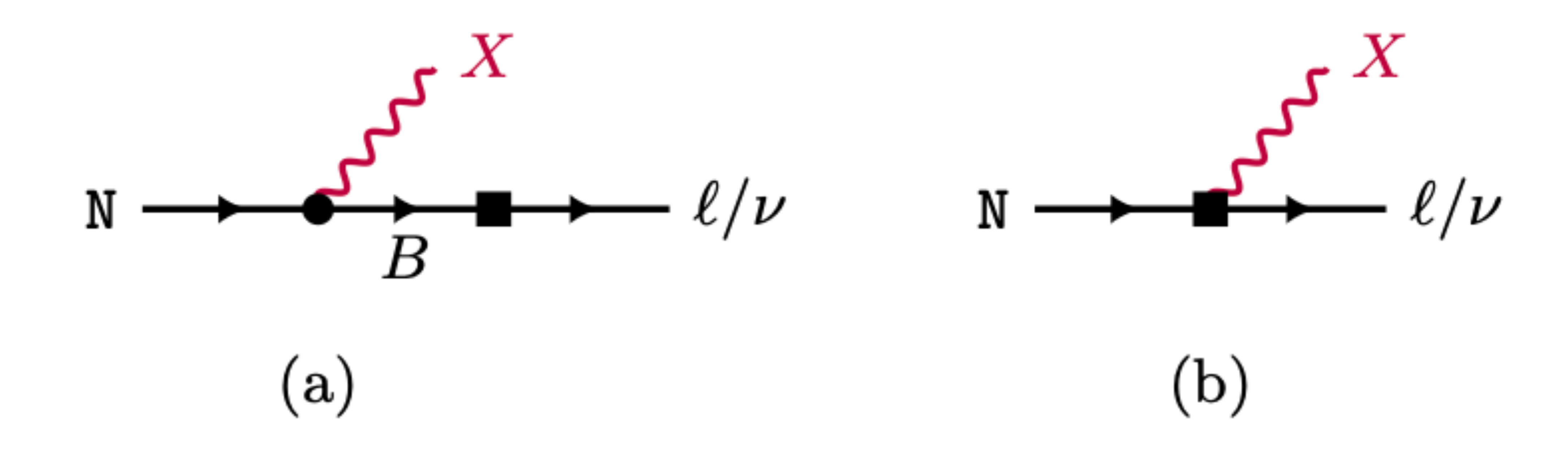
$\mathscr{N}_{yzw}^{\mathrm{LL}}$ and $\mathscr{N}_{yzw}^{\mathrm{RL}}$ + L <—>R

XDM, Michael Schmidt, Wei-Hang Zhang, arXiv:2510.xxxxx

$\Lambda_{a,x} \equiv (m_S^2 m_R^2/|\kappa^*[y_L]_{1x}([z_R]_{11} - 2[z_L]_{11})|)^{1/3}$

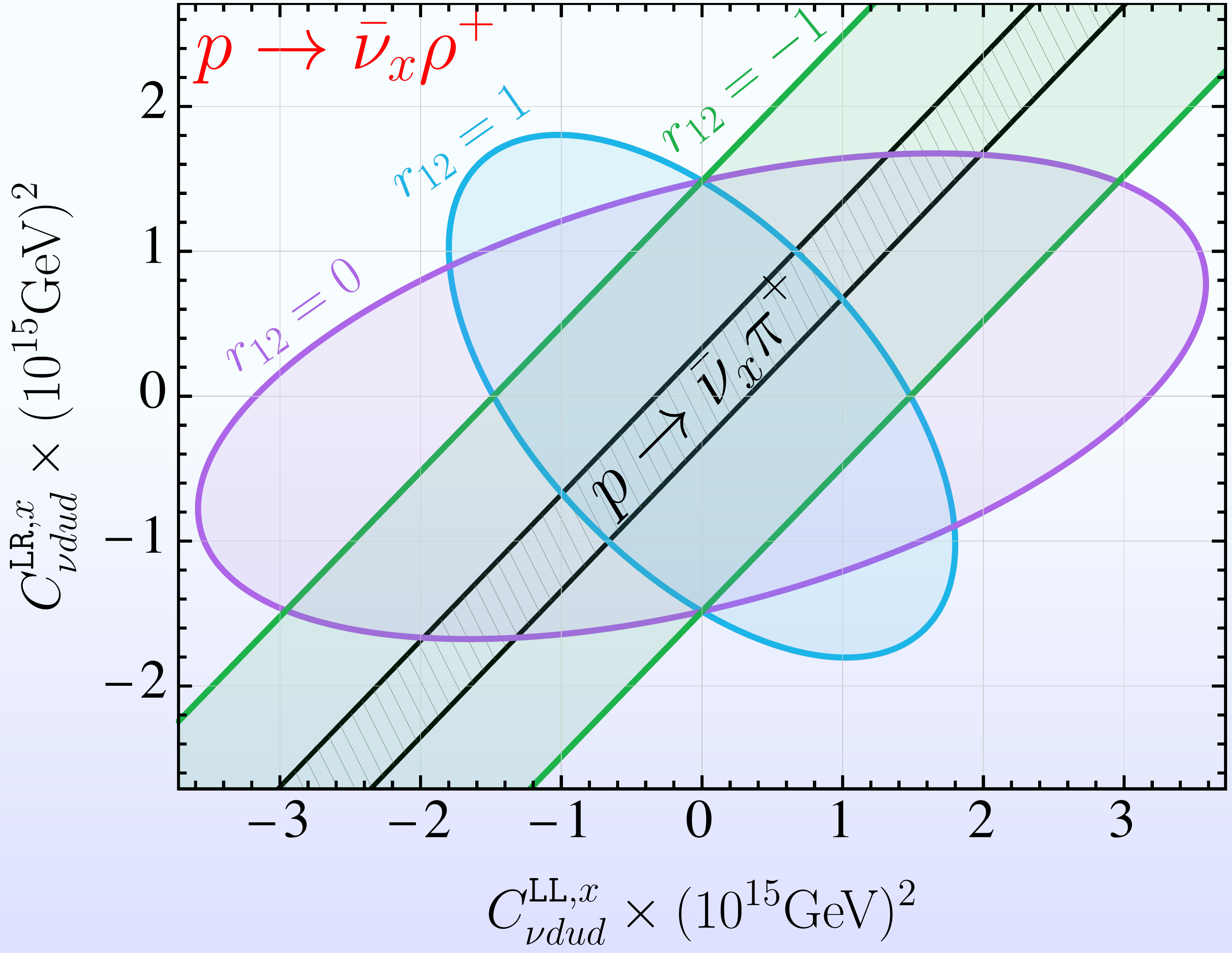
Vector meson modes help breaking degeneracy

Yi Liao, XDM, Hao-Lin Wang, 2506.05052



$$\Gamma_{p\to\bar{\nu}_x\rho^+} = \frac{m_p(1-3x_\rho^2+2x_\rho^3)}{32\pi\, x_\rho}\Big(\big|d_1 C^{\mathrm{LR},x}_{\nu dud} + d_2 C^{\mathrm{LL},x}_{\nu dud}\big|^2 + \frac{\mathrm{G}_\mathrm{F}^2}{m_n^2}\big|c_1 C^{\mathrm{LR},x}_{\nu dud} + c_2 C^{\mathrm{LL},x}_{\nu dud}\big|^2\Big), \qquad (15a)$$

$$\Gamma_{p\to\bar{\nu}_x\pi^+} = \frac{m_p(1-x_\pi)^2[1+(D+F)m_p m_n^{-1}]^2}{64\pi\, F_0^2} \times \big|c_1 C^{\mathrm{LR},x}_{\nu dud} + c_2 C^{\mathrm{LL},x}_{\nu dud}\big|^2. \qquad (15b)$$



Complementarity between the pseudoscalar and vector modes

Summary

- General triple-quark interactions without a ∂ related to nucleon decay are identified: $\bar{\mathbf{3}}_{\mathrm{L(R)}} \otimes \mathbf{3}_{\mathrm{R(L)}}$, $\mathbf{8}_{\mathrm{L(R)}} \otimes \mathbf{1}_{\mathrm{R(L)}}$, $\mathbf{6}_{\mathrm{L(R)}} \otimes \mathbf{3}_{\mathrm{R(L)}}$ and $\mathbf{10}_{\mathrm{L(R)}} \otimes \mathbf{1}_{\mathrm{R(L)}}$;
- Their LO chiral matching are realized, and the new LECs are estimated by the NDA;
- For the nucleon decay involving a vector meson, this is the first consistent chiral framework;
- Our results provide a reliable framework for further experimental and theoretical search.

Thanks for your attention!