Neutrino Mass Induced n–$\overline{n}$ Oscillation

Shaikh Saad

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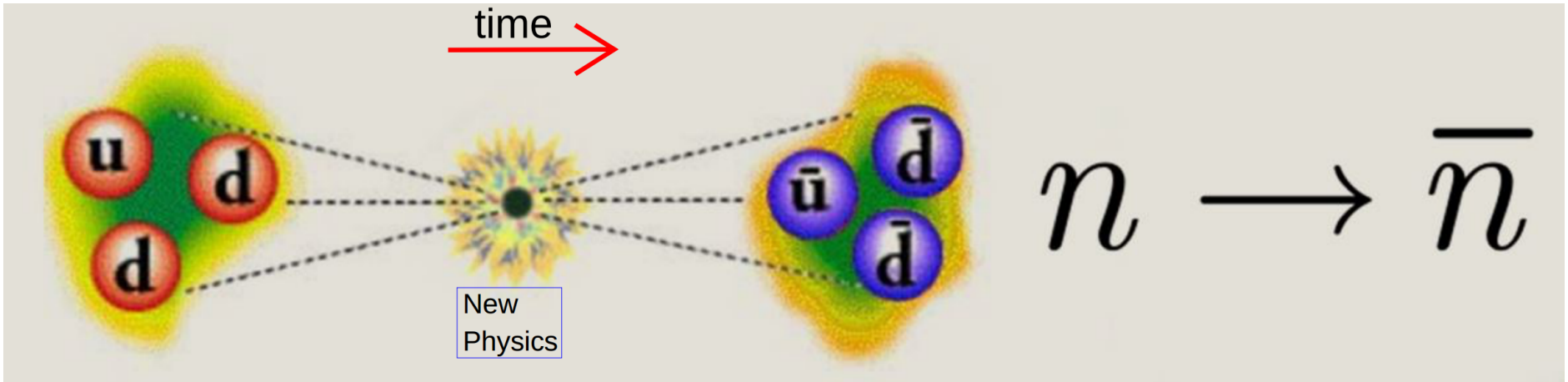
I. Doršner, S. Fajfer, S. Saad

Outline

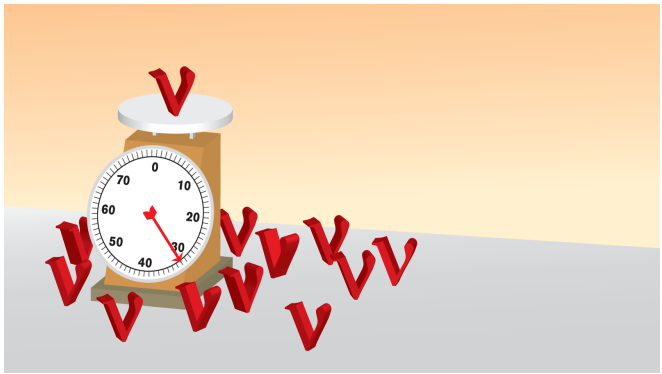
- Consequence of Grand Unification and Neutrino Mass
- Observable n–$\overline{n}$ Oscillation in UV Complete Seesaw Models

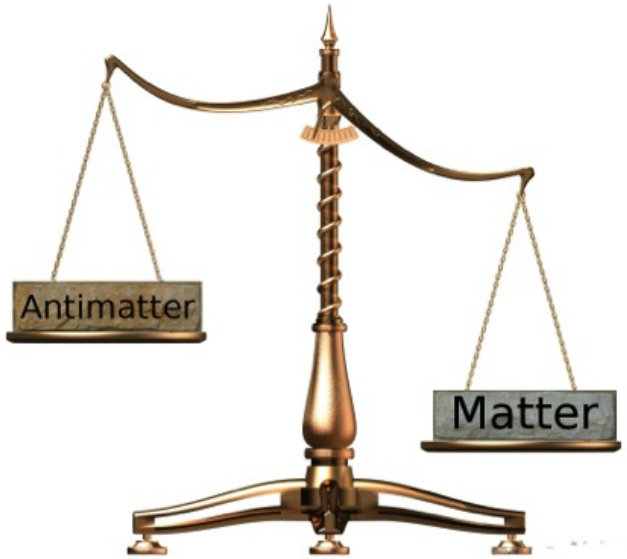


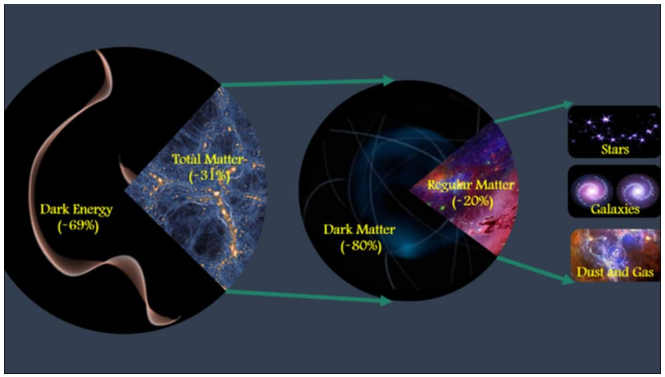
- n–$\overline{n}$ oscillation V. Kuzmin 1970
- Observable n–$\overline{n}$ in realistic GUTs Doršner, Fajfer, Saad 2025

Shortcoming of the SM

✗ Neutrino mass ✗ baryon asymmetry ✗dark matter



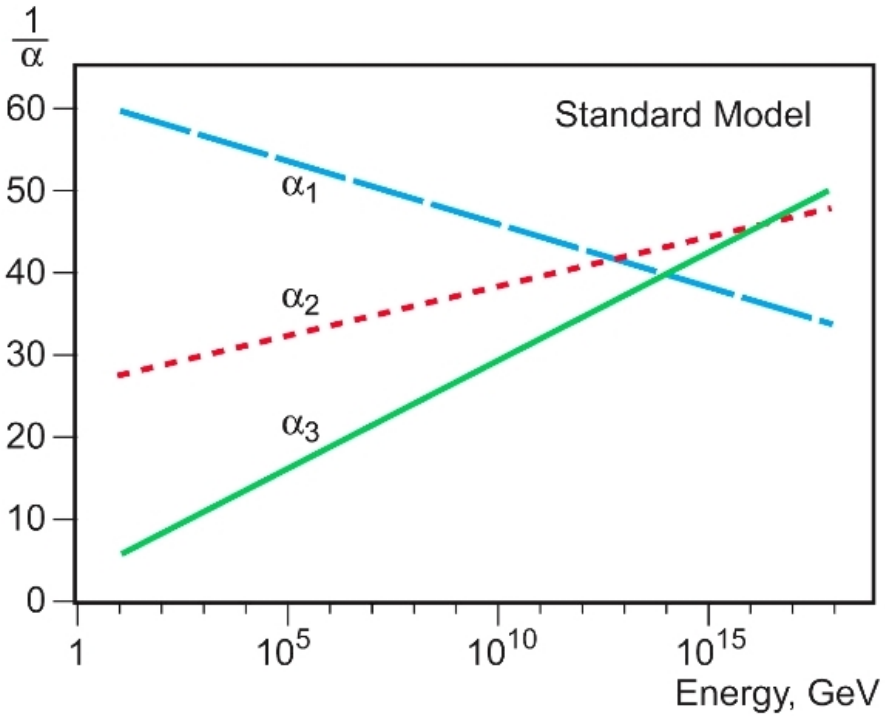




✓ Extension of the SM. → Guideline?

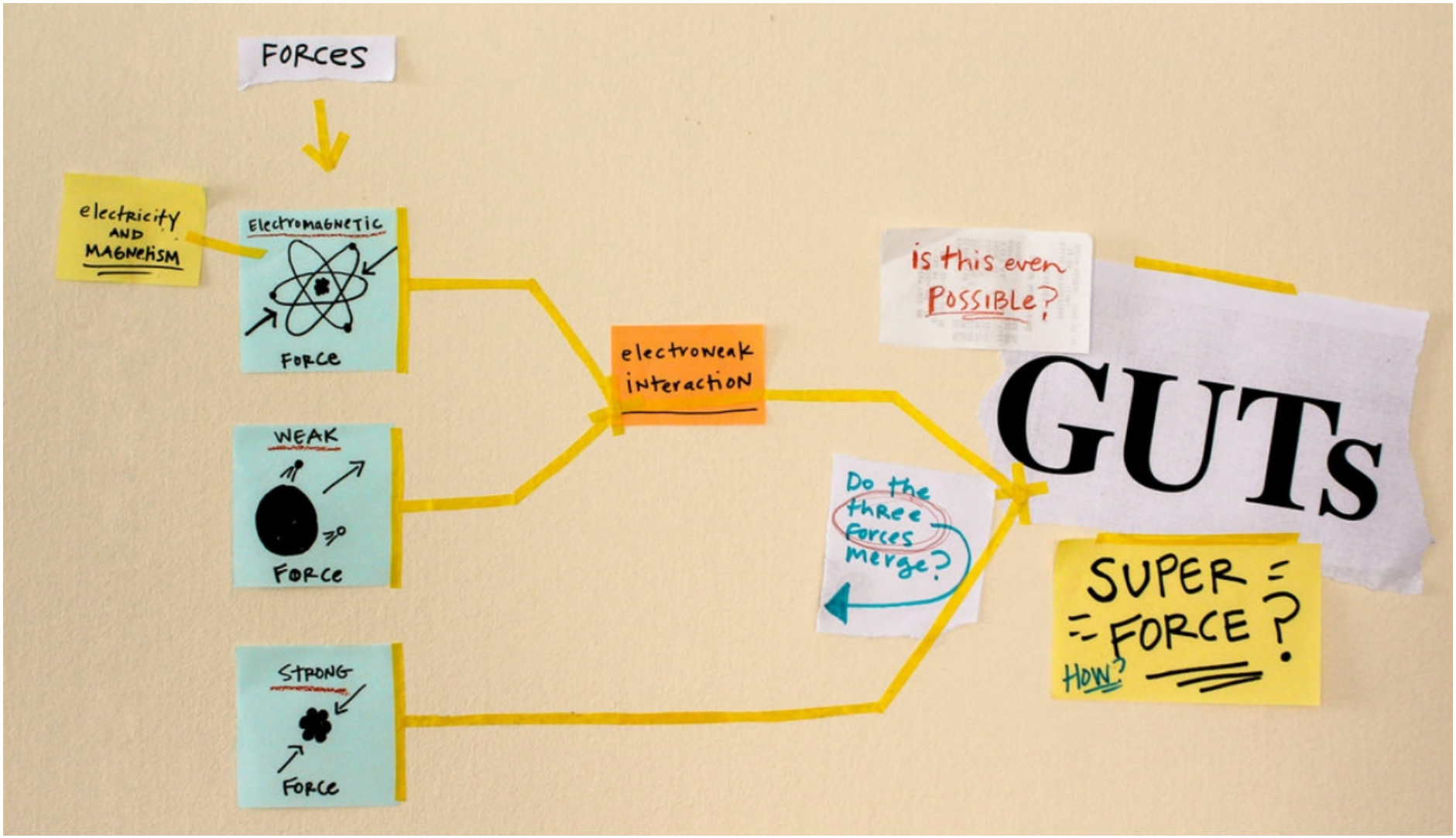
Coupling Constants in the Standard Model

- Group: $SU(3) \times SU(2) \times U(1)$ Strength of Forces: $\alpha_3, \alpha_2, \alpha_1$



$$SU(3) \times SU(2) \times U(1) \rightarrow \text{Bigger symmetry!}$$

Why Grand Unification Is a Natural Expectation



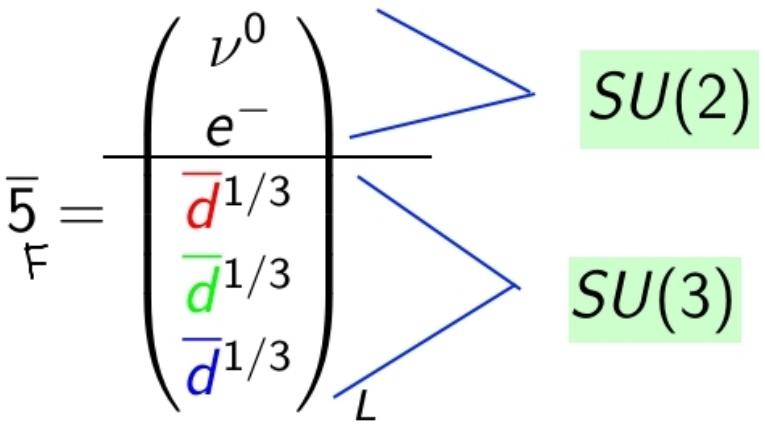
What is the Minimal GUT?

- $SU(3) \times SU(2) \times U(1) \subset SU(5)$

Georgi and Glashow 1974

$\rightarrow$ Only one unified force!

- $SU(5)$: Quark-Lepton unification



$$5_S = H(1, 2, \tfrac{1}{2}) + T(3, 1, -\tfrac{1}{3})$$

Georgi–Glashow model

- GG model: $\bar{5}_F + 10_F + 5_S + 24_S$

✗ $M_d = M_e^T$

✗ Gauge coupling unification

✗ $M_\nu = 0$

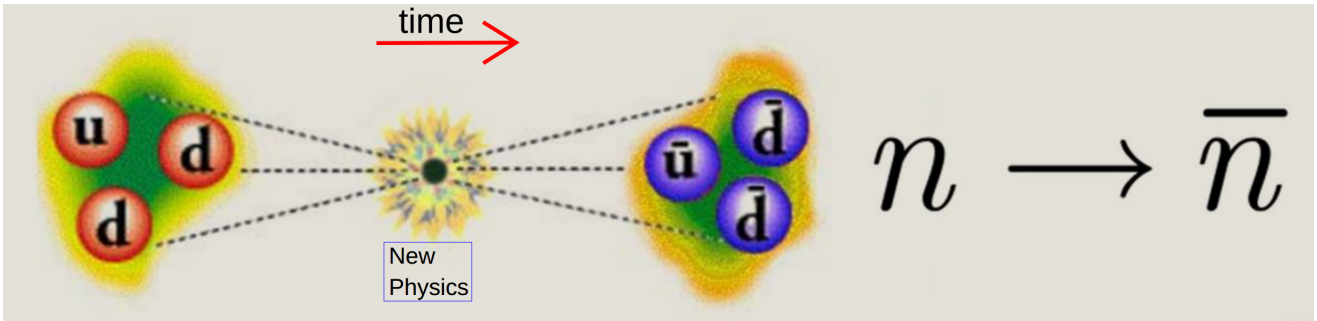
→ Accidental $B - L$ global symmetry

Neutrino Mass

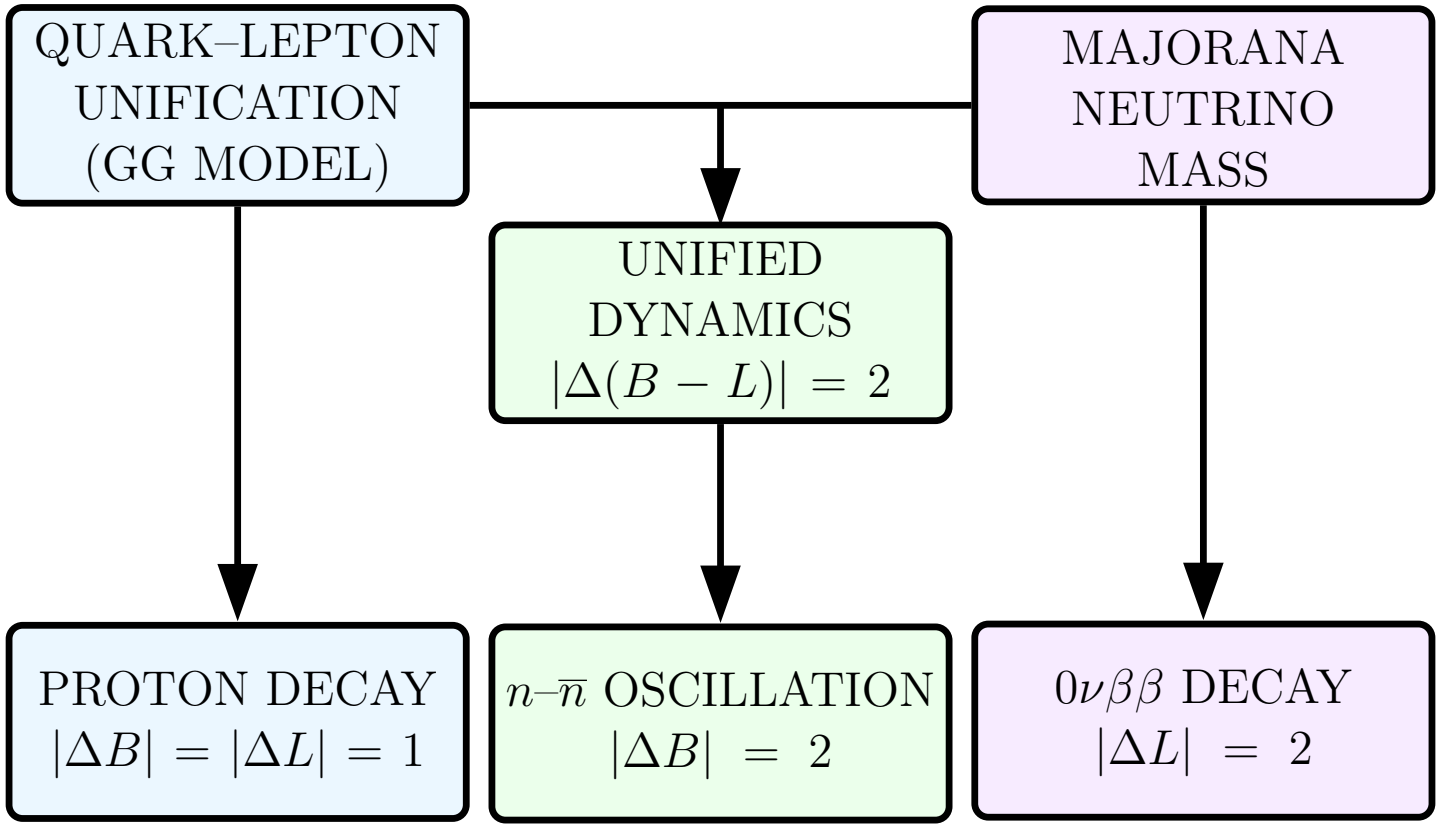
- Weinberg operator (Majorana neutrinos)

$$\mathcal{L}_5 = \frac{1}{\Lambda}\bar{5}_F\bar{5}_F 5_S 5_S = \frac{1}{\Lambda}\underbrace{\left(\underbrace{LLHH}_{\Delta L=+2} + \underbrace{d^c d^c TT}_{\Delta B=-2}\right)}_{\Delta(B-L)=-2}$$

$$\frac{1}{\Lambda} d^c d^c TT \to \frac{1}{\Lambda^5} d^c d^c \left(u^c d^c\right)\left(u^c d^c\right) \to n - \bar{n} \text{ oscillation}$$



Consequences



(Realistic) Neutrino Mass and n–$\bar{n}$ in $SU(5)$

MODEL	CONTENT	ν MASS	CLASS	TOPOLOGY	n–$\bar{n}$ MEDIATORS
Georgi–Glashow (GG)	$\bar{5}_{Fi} + 10_{Fi} + 5_S + 24_S$	–	–	–	–
Type I seesaw	GG $+ 1_F + 1_F$	tree-level	**I**	**B**	$S_1^{u^c d^c} = 5_S^*,\ F_1^{d^c} = 1_F$ $S_1 = (\bar{3},1,1/3),\ F_1 = (1,1,0)$
Type II seesaw	GG $+ 15_S$	tree-level	**II**	**A**	$S_1^{u^c d^c} = 5_S^*,\ S_2^{d^c d^c} = 15_S$ $S_1 = (\bar{3},1,1/3),\ S_2 = (6,1,-2/3)$
Type II seesaw (variant)	GG $+ 15_S + 45_S$	tree-level	**II**	**A**	$S_1^{u^c d^c} = 45_S^*,\ S_2^{d^c d^c} = 15_S$ $S_1 = (6,1,1/3),\ S_2 = (6,1,-2/3)$
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BNT	GG $+ 15_F + 35_S$	tree & one-loop	**III**	**C**	$S_1^{u^c d^c} = 5_S,\ S_2 = 35_S,\ F_1^{d^c} = 15_F$ $S_1 = (3,1,-1/3),\ S_2 = (\overline{10},1,1),$ $F_1 = (6,1,-2/3)$
Zee	GG $+ 10_S + 45_S$	one-loop	**II**	**AI**	$S_1^{u^c d^c} = 45_S^*,\ S_2^{d^c d^c} = 10_S$ $S_1 = (6,1,1/3),\ S_2 = (\bar{3},1,-2/3)$
Zee-Babu	GG $+ 10_S + 50_S$	two-loop	**II**	**AII**	$S_1^{d^c d^c} = 10_S,\ S_2^{u^c u^c} = 50_S$ $S_1 = (\bar{3},1,-2/3),\ S_2 = (6,1,4/3)$
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Zee-Babu (variant)	GG $+ 15_S + 50_S$	tree & two-loop	**II**	**A**	$S_1^{d^c d^c} = 15_S,\ S_2^{u^c u^c} = 50_S$ $S_1 = (6,1,-2/3),\ S_2 = (6,1,4/3)$ $S_1^{QQ} = 50_S^*,\ S_2^{d^c d^c} = 15_S$ $S_1 = (6,3,1/3),\ S_2 = (6,1,-2/3)$

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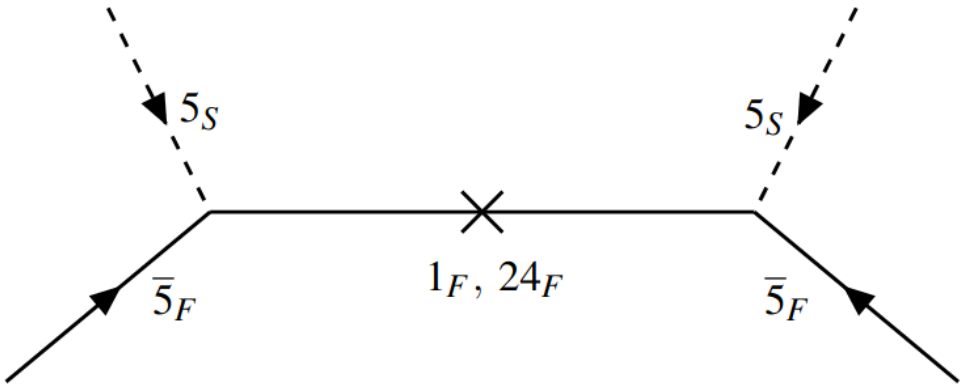
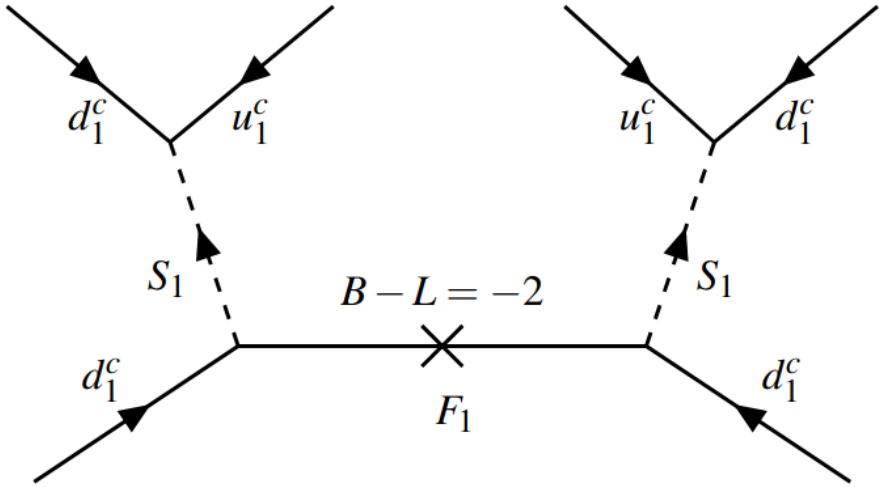
Type I/III mechanism in $SU(5)$



(a) Type I/III seesaw mechanisms in $SU(5)$.



(b) **TOPOLOGY B** for n–$\overline{n}$ ocillation.

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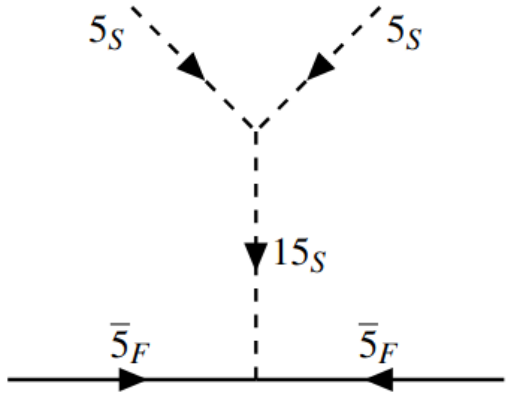
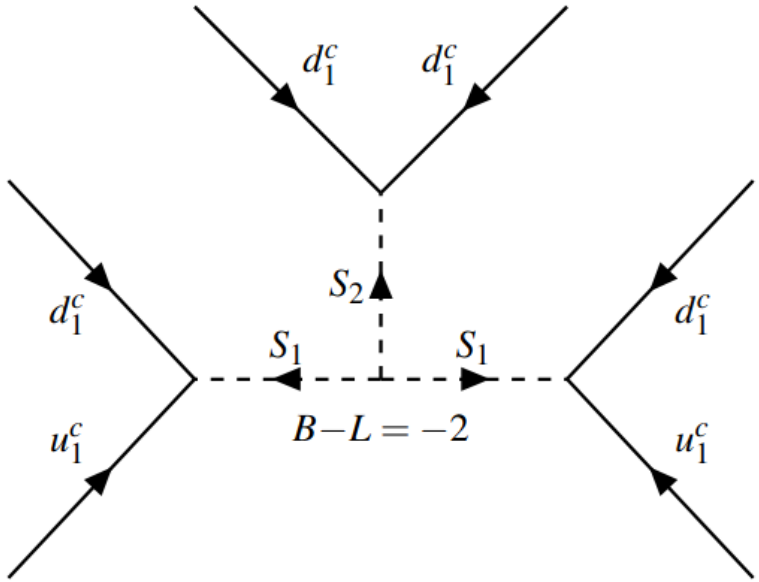
Type II mechanism in $SU(5)$



(a) Type II seesaw mechanism in $SU(5)$.



(b) **TOPOLOGY A** for n–$\bar{n}$ oscillation.

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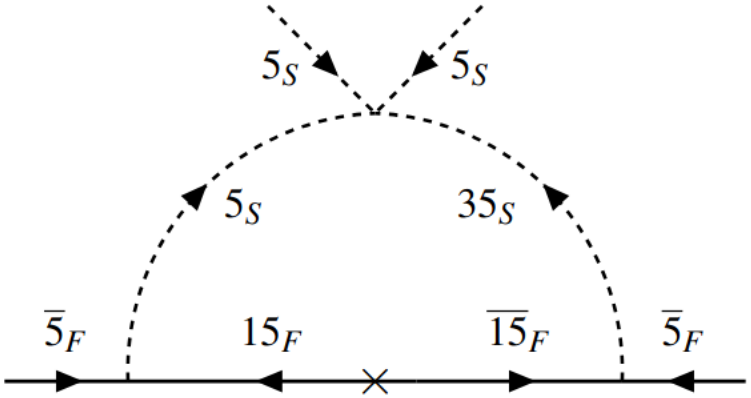
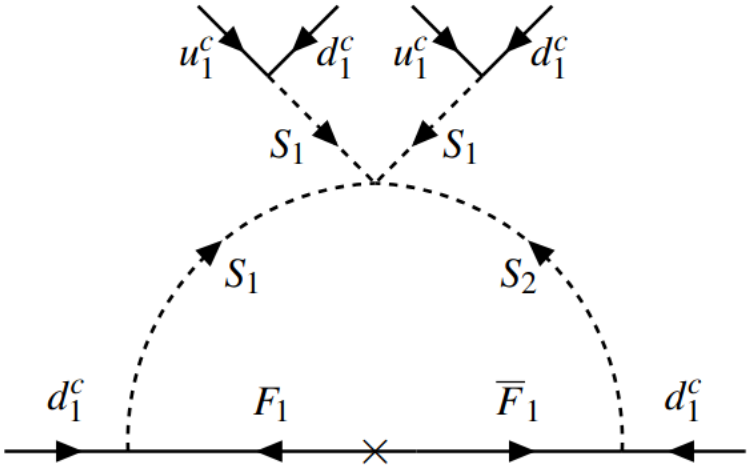
BNT mechanism in $SU(5)$



(a) BNT mechanism in $SU(5)$.



(b) **TOPOLOGY C** for n–$\overline{n}$ oscillation in the BNT embedding.

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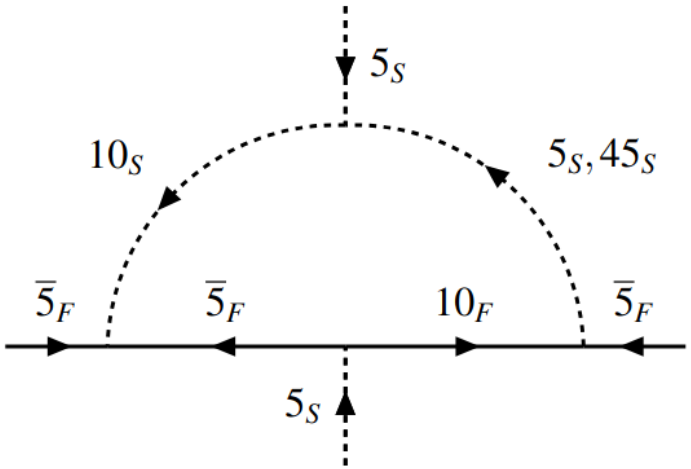
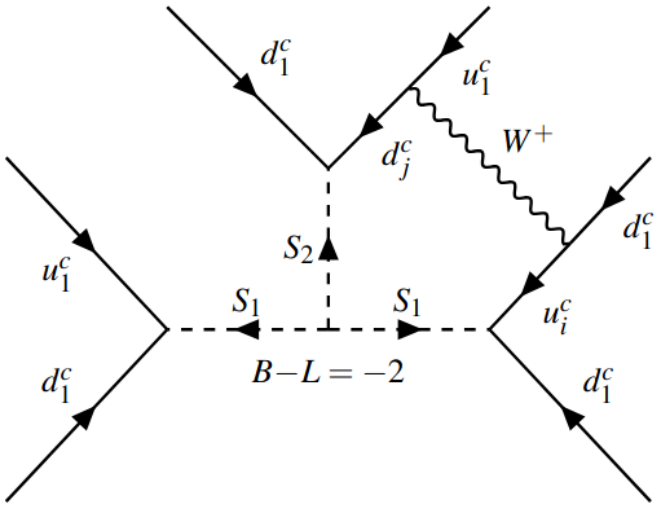
Zee mechanism in $SU(5)$



(a) Zee mechanism for neutrino mass generation in $SU(5)$.



(b) **TOPOLOGY AI** for n–$\overline{n}$ oscillation with $i = 1,2,3$ and $j = 2,3$.

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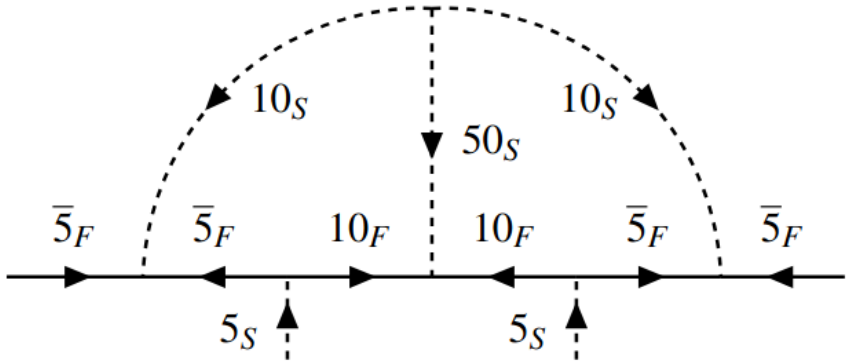
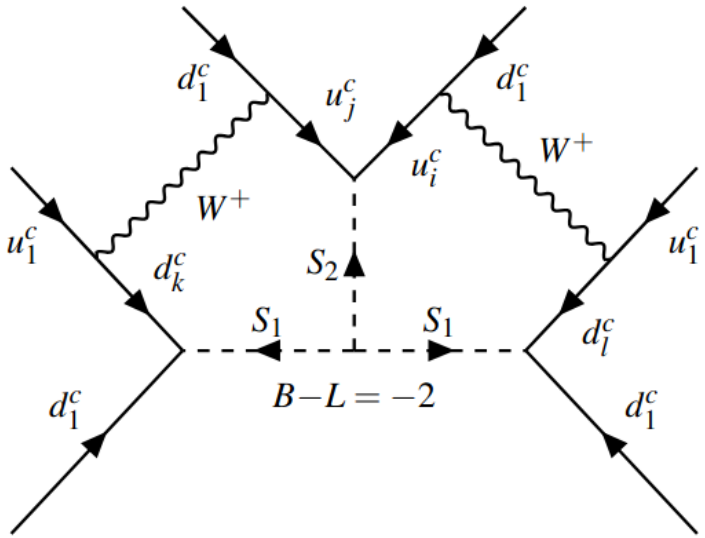
Zee-Babu mechanism in $SU(5)$



(a) Zee-Babu mechanism for neutrino mass generation in $SU(5)$.



(b) **TOPOLOGY AII** for n–$\overline{n}$ oscillation with $i, j = 1, 2, 3$ and $k, l = 2, 3$.

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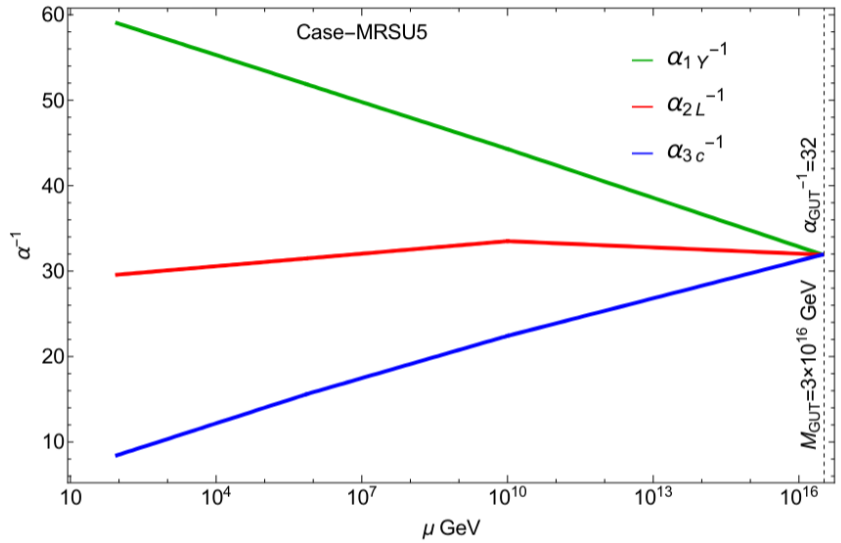
Realistic $SU(5)$ GUTs

- $\mathbf{5_H} \supset \phi_1(1,2,1/2), \qquad \mathbf{45_H} \supset \Sigma_1(1,2,1/2)$ Georgi, Jarlskog 1979
- $\mathcal{L}_Y \supset Y_1\ \bar{5}_F 10_F 5^*_H + Y_2\ \bar{5}_F 10_F 45^*_H$

$$M_E = \frac{1}{2} Y_1 v_5 + \frac{\sqrt{3}}{2\sqrt{2}} Y_2 v_{45}$$

$$M_D^T = \frac{1}{2} Y_1 v_5 - \frac{1}{2\sqrt{6}} Y_2 v_{45}$$



Doršner, Perez 2006; Saad 2019

☞ Type-II seesaw: GG+$\mathbf{45_H}$ + $\mathbf{15_H}$

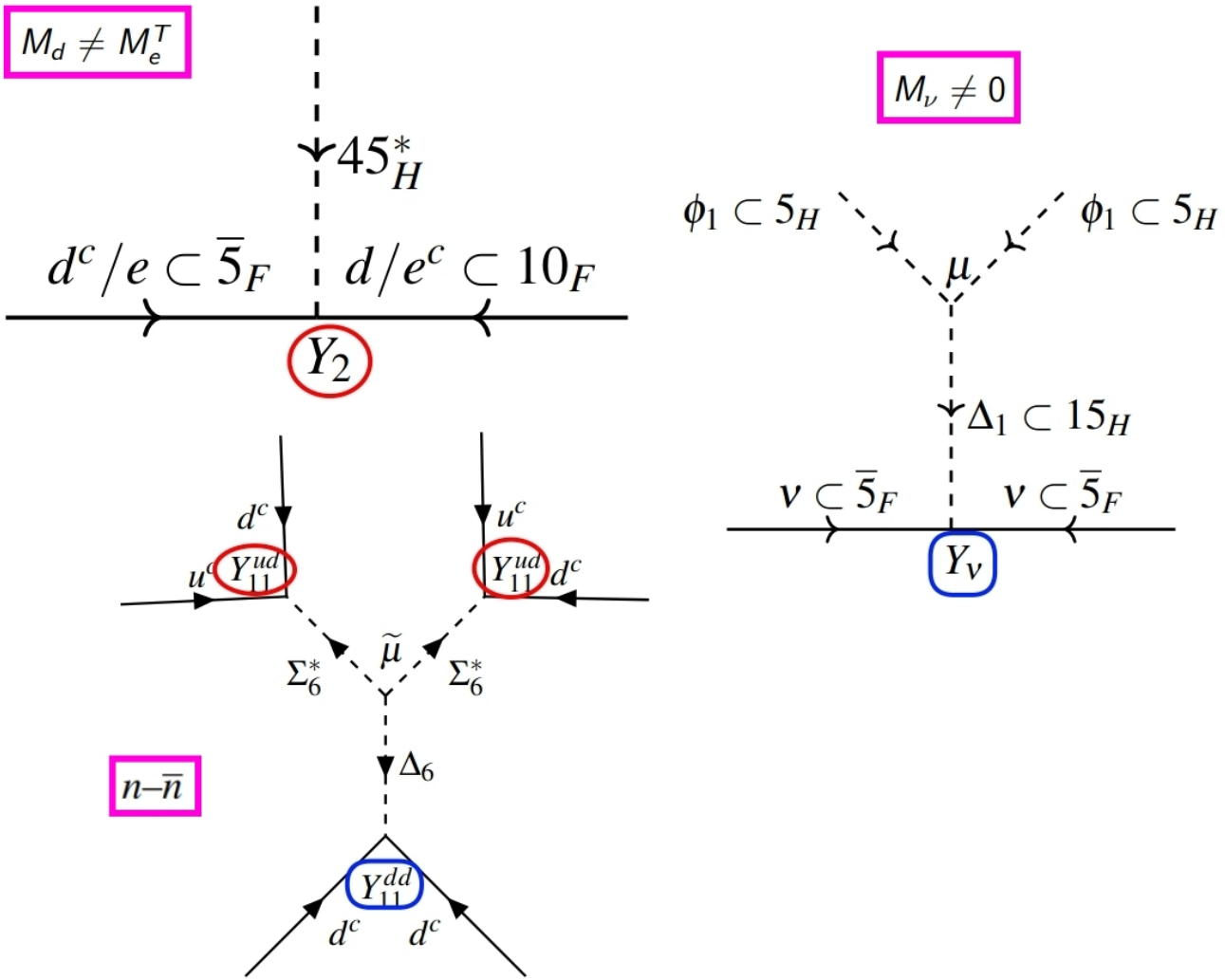
Doršner, Perez 2005; Doršner, Mocioiu 2008

☞ Type-I+III seesaw: GG+$\mathbf{45_H}$ + $\mathbf{24_F}$

Bajc, Senjanovic 2006; Doršner, Perez 2006; Perez 2007

$SU(5)$: Type-II Seesaw

$\mathbf{45_H} \supset \Sigma_6(\overline{6}, 1, -\frac{1}{3})$ $\quad$ $\mathbf{15_H} \supset \Delta_1(1,3,1) + \Delta_6(6,1,\frac{2}{3})$



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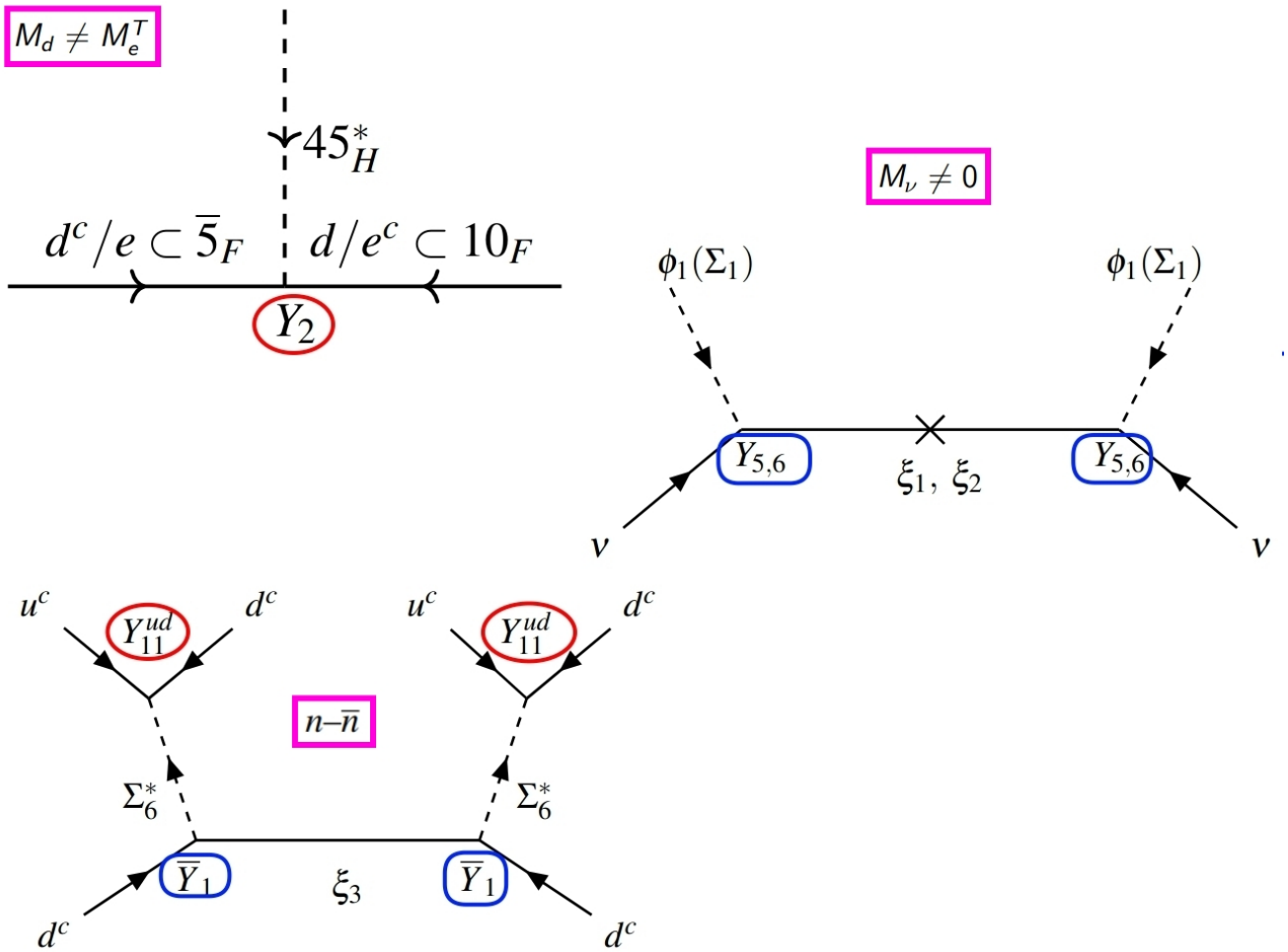
$SU(5)$: Type-I+III Seesaw

$\mathbf{45_H} \supset \Sigma_6(\overline{6}, 1, -\frac{1}{3})$, $\mathbf{24_F} \supset \xi_1(1,1,0) + \xi_2(1,3,0) + \xi_3(8,1,0)$



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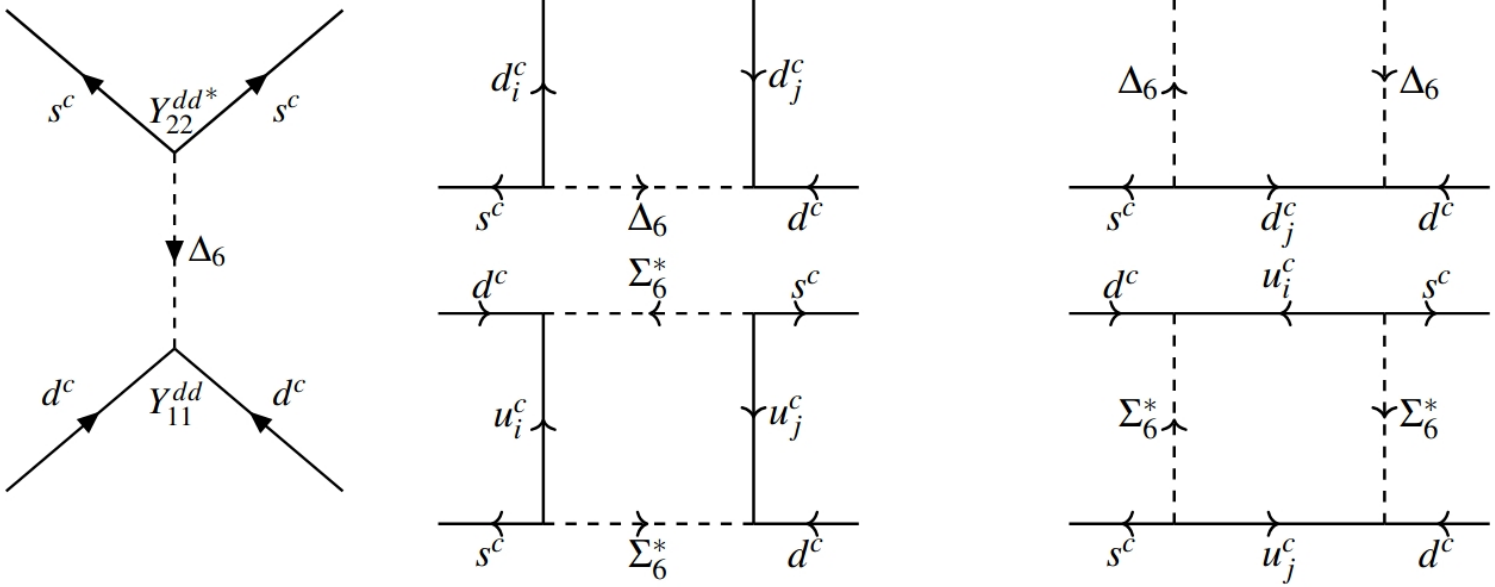
Seesaw in $SU(5)$

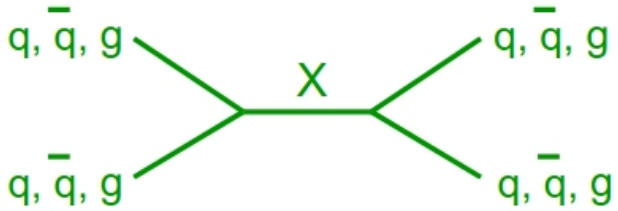
- $K^0 - \overline{K}^0$, $B^0 - \overline{B}^0$

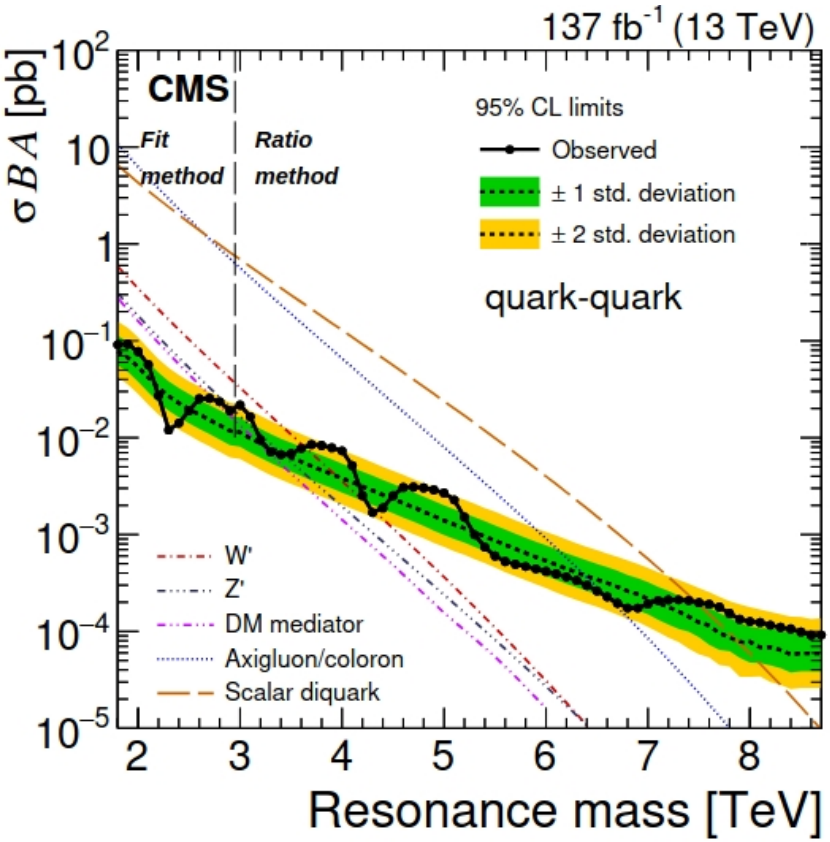


Fortes, Babu, Mohapatra 2013; Doršner, Fajfer, Saad 2025

Seesaw in $SU(5)$

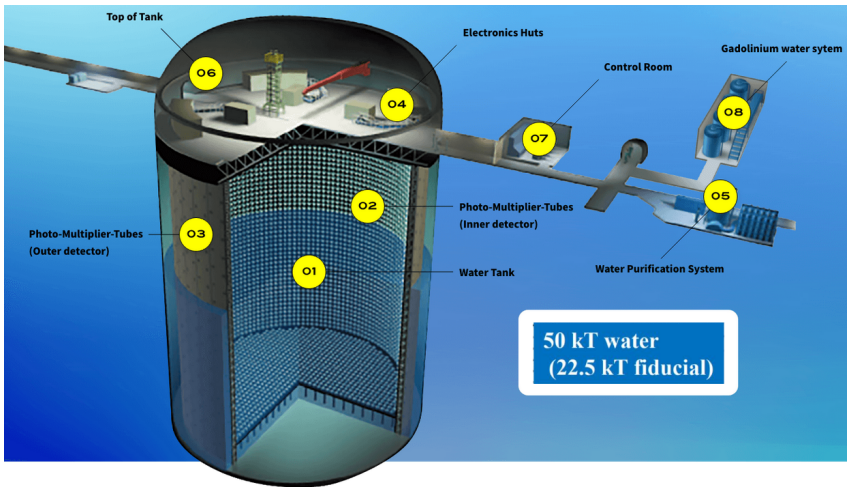
- Collider: dijet resonance

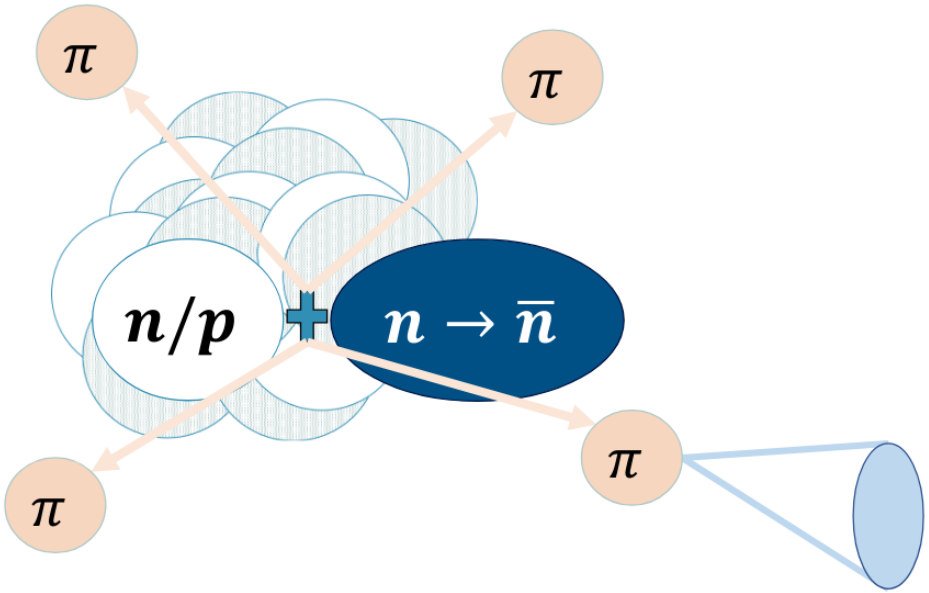




CMS 2019

Super-Kamiokande: bound neutrons

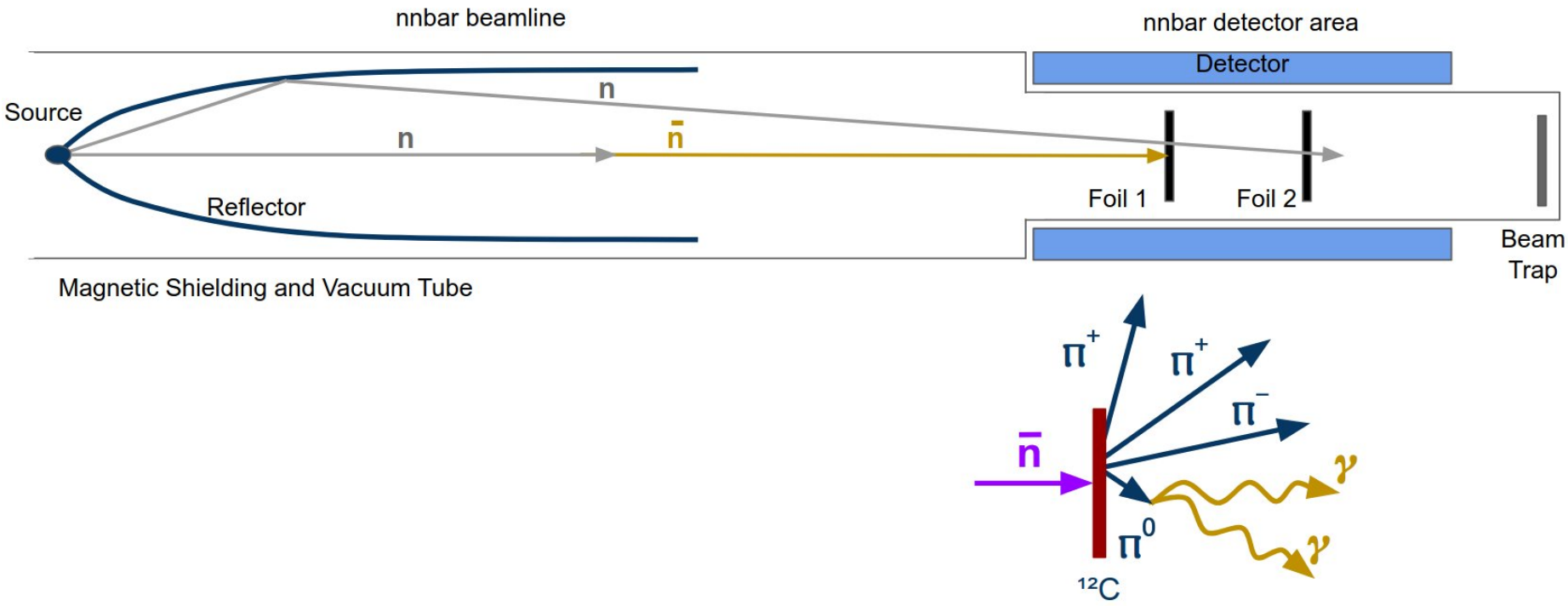




- $\Gamma_{\text{decay rate per neutron per sec}} = (R\tau^2_{n-\bar{n}})^{-1}$
- $N_{\text{events}} \sim N_n \times \Gamma \times t_{\text{SK}} \times \epsilon$
- $R \sim 0.5 \times 10^{23}/s,\ N_n \sim 10^{34} n,\ t_{\text{SK}} \sim 20 yrs$

$\tau^{\text{SK}}_{n-\bar{n}} \geq 4.7 \times 10^8\ \text{s}$ SK 2020

NNBAR Experiment: free neutrons



- $L \sim 200$ m $\Rightarrow$ $t \sim 0.4$ s.
- $P \sim t^2/\tau^2_{n-\bar{n}} \sim 7 \times 10^{-19}$; $\tau^{\rm SK}_{n-\bar{n}} \sim 15$ years.
- $N_n \sim 10^{11} n/s$. $N_{\rm events} \sim N_n \times P \sim$ few (in few years).

$\tau^{\rm NNBAR}_{n-\bar{n}} \geq 3 \times 10^9$ s ESS 2020

Type-II: benchmark fit

$$Y_1 = \begin{pmatrix} 1.3684752\times10^{-6} & 0 & 0 \\ 0 & 1.07234\times10^{-5} & 0 \\ 0 & 0 & 9.14325\times10^{-3} \end{pmatrix}$$

$$Y_2 = \begin{pmatrix} 0.04368\,e^{-0.42643i} & 0.04211\,e^{0.17418i} & 0.53368\,e^{1.54868i} \\ 0.00097\,e^{3.14136i} & 0.10053\,e^{-2.94176i} & 0.02185\,e^{0.02706i} \\ 0.24740\,e^{-1.72329i} & 0.66821\,e^{1.05058i} & 1.00000\,e^{0.61401i} \end{pmatrix}$$

$$Y_\nu = \begin{pmatrix} 0.30619\,e^{-2.97735i} & 0.25071\,e^{-3.13882i} & 0.05531\,e^{-0.02854i} \\ 0.25071\,e^{-3.13882i} & 1.00000\,e^{-2.23310i} & 0.80237\,e^{3.12855i} \\ 0.05531\,e^{-0.02854i} & 0.80237\,e^{3.12855i} & 0.51987\,e^{3.13948i} \end{pmatrix}$$

$$Y^{dd} = \begin{pmatrix} 0.5160\,e^{1.7476i} & 0.4641\,e^{1.1119i} & 0.2127\,e^{0.2517i} \\ 0.4641\,e^{1.1119i} & 1.5927\,e^{-0.4950i} & 0.9481\,e^{-2.2034i} \\ 0.2127\,e^{0.2517i} & 0.9481\,e^{-2.2034i} & 0.6666\,e^{-2.6527i} \end{pmatrix}$$

$$Y^{ud} = \begin{pmatrix} 0.0208\,e^{0.9978i} & 0.0706\,e^{0.7180i} & 0.3497\,e^{0.1300i} \\ 0.0486\,e^{1.4090i} & 0.1078\,e^{-0.9352i} & 0.2656\,e^{1.0054i} \\ 0.1185\,e^{-0.2162i} & 0.8000\,e^{1.8611i} & 0.9697\,e^{0.6558i} \end{pmatrix}$$

- ✓ $M_d \neq M_e^T$
- ✓ $M_\nu \neq 0$
- ✓ $g_1 = g_2 = g_3 = g_{\rm GUT}$
- ✓ $\tau(p \to \pi^0 e^+) > 2.4\times10^{34}$ years
- ✓ n–$\bar{n}$ oscillation
- ✓ Flavor & Collider constraints

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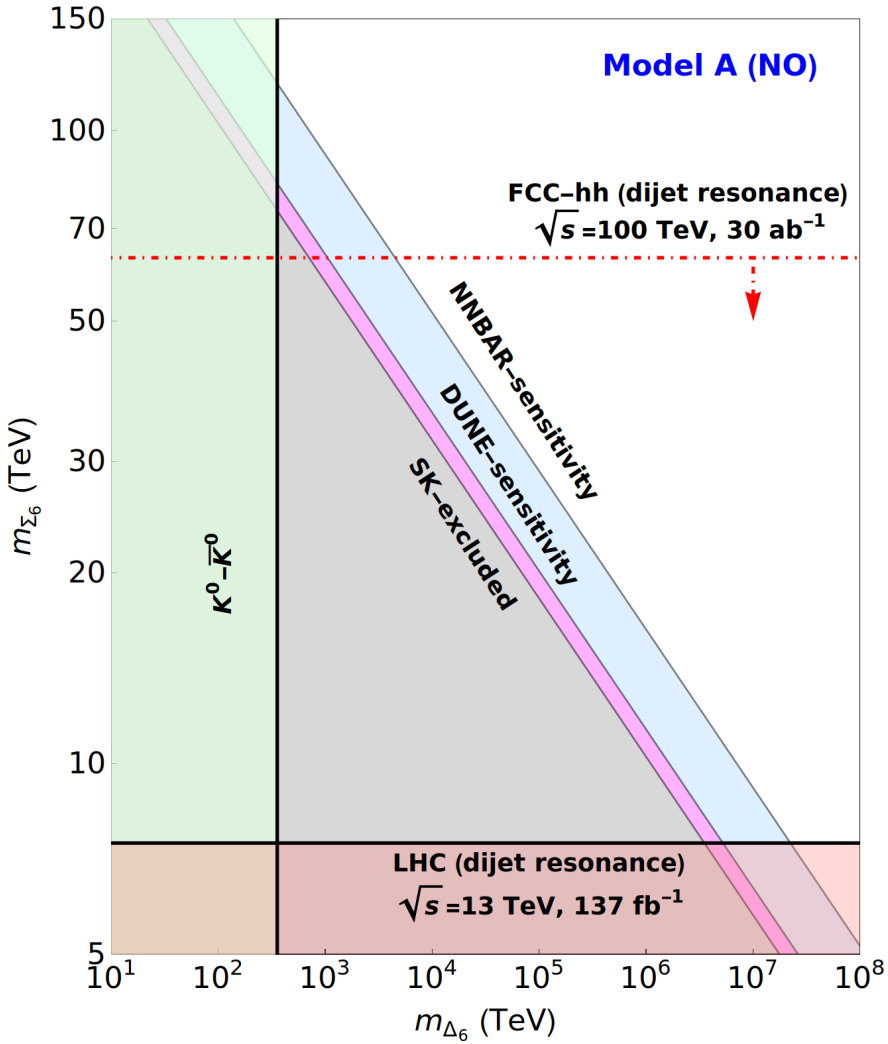
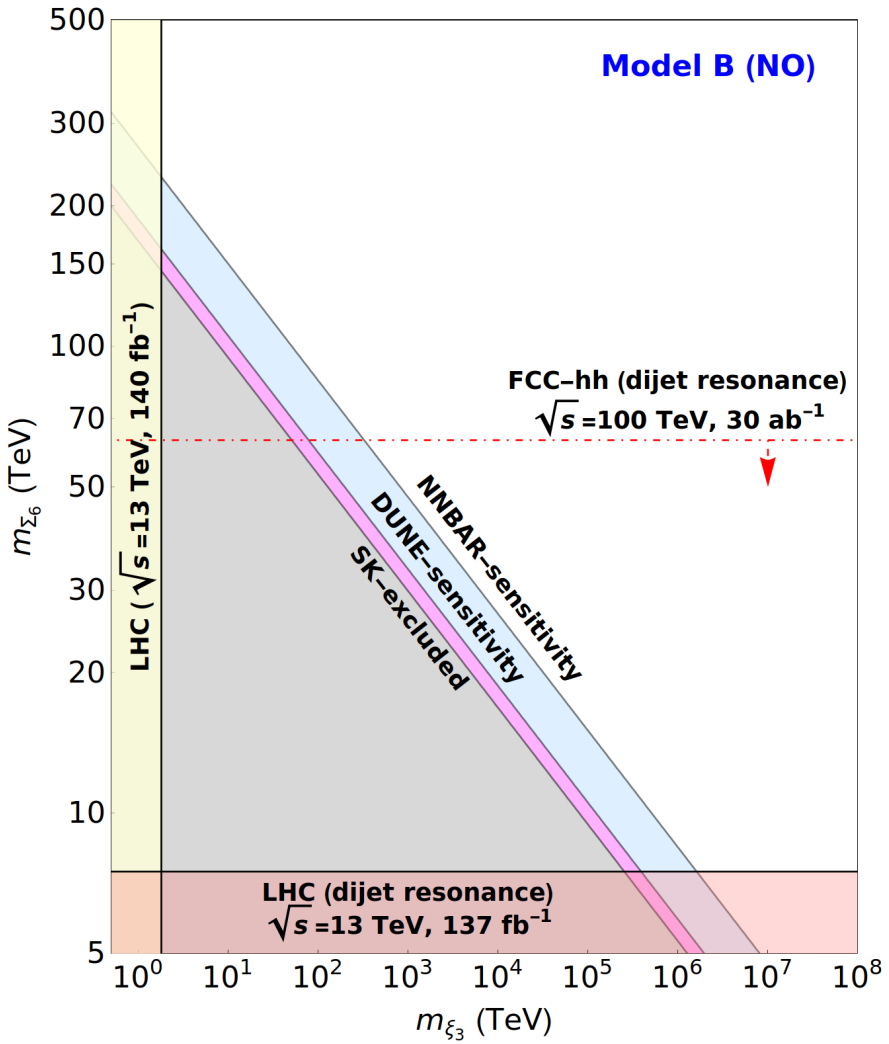
Observable n–$\bar{n}$: Type-II/III Seesaw

$\tau^{\rm SK}_{n-\bar{n}} \geq 4.7 \times 10^8\,{\rm s}$, $\tau^{\rm HK}_{n-\bar{n}} \geq (6-10) \times 10^8\,{\rm s}$, $\tau^{\rm DUNE}_{n-\bar{n}} \geq 7 \times 10^8\,{\rm s}$, $\tau^{\rm NNBAR}_{n-\bar{n}} \geq 3 \times 10^9\,{\rm s}$.





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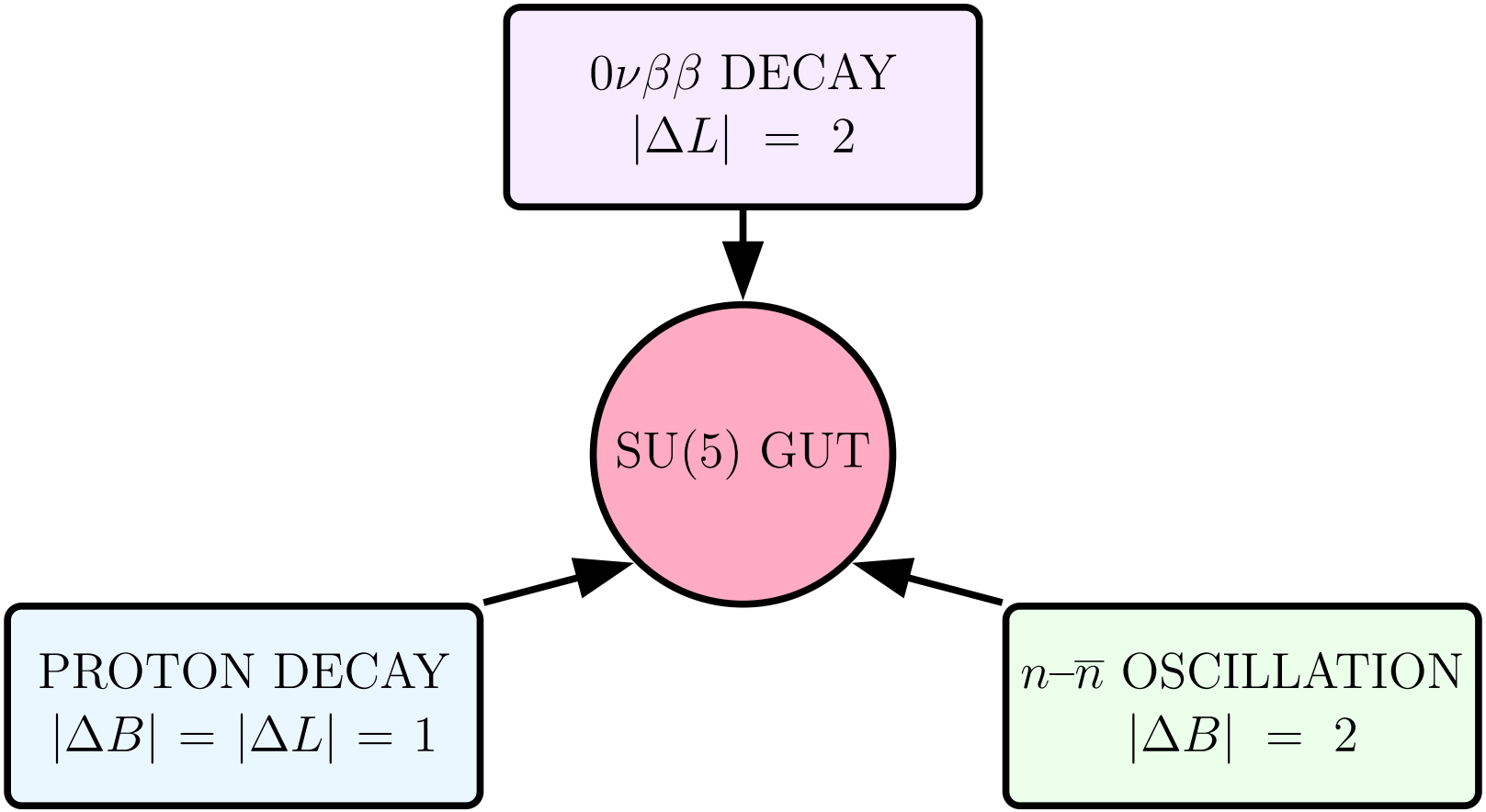
Upshot



THANK YOU!