EuCAPT Astroneutino theory workshop/summer school
Prague, September 16-27 2024

BSM model building

(with special attention to neutrino physics aspects)

Michal Malinský

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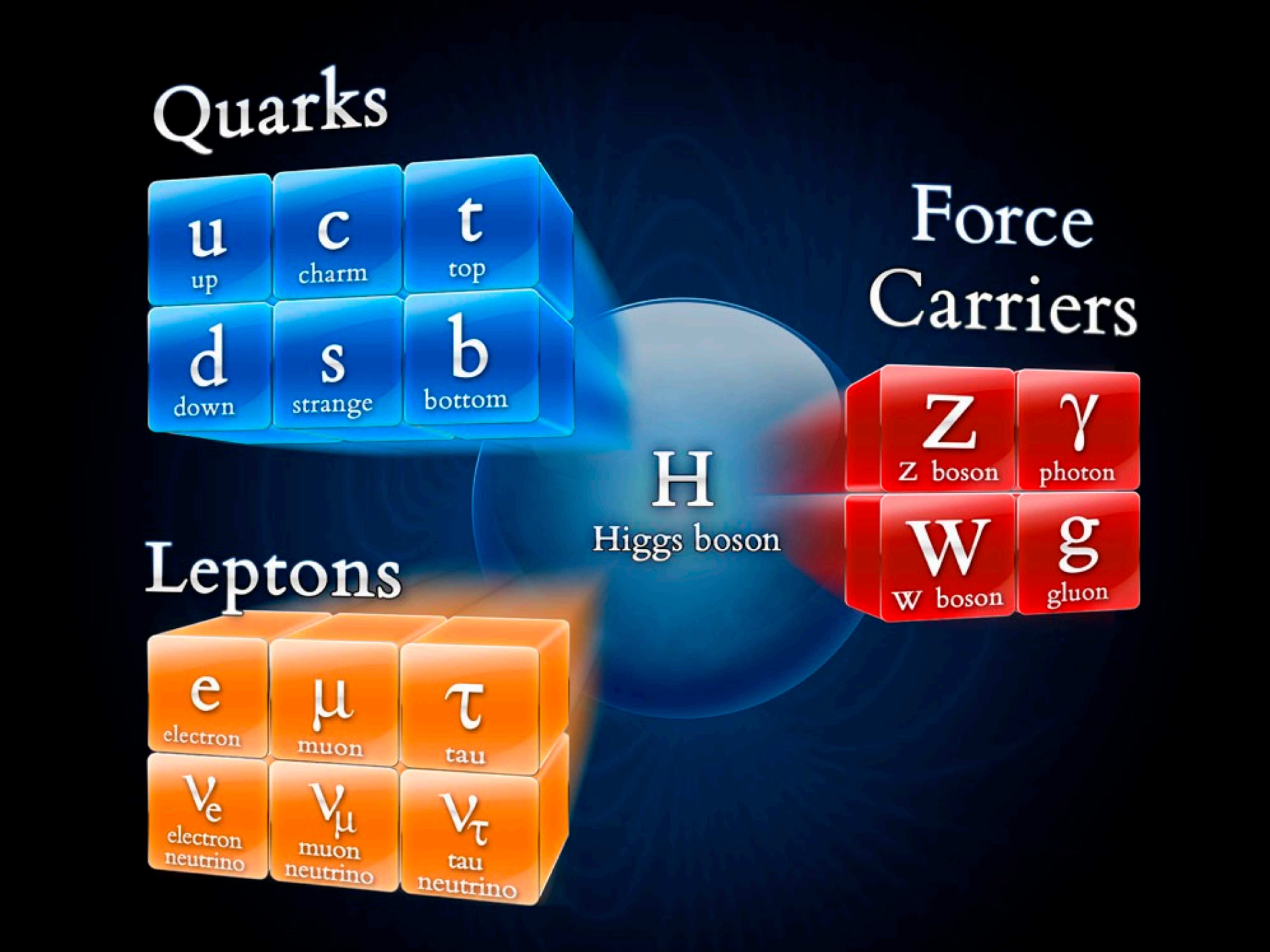
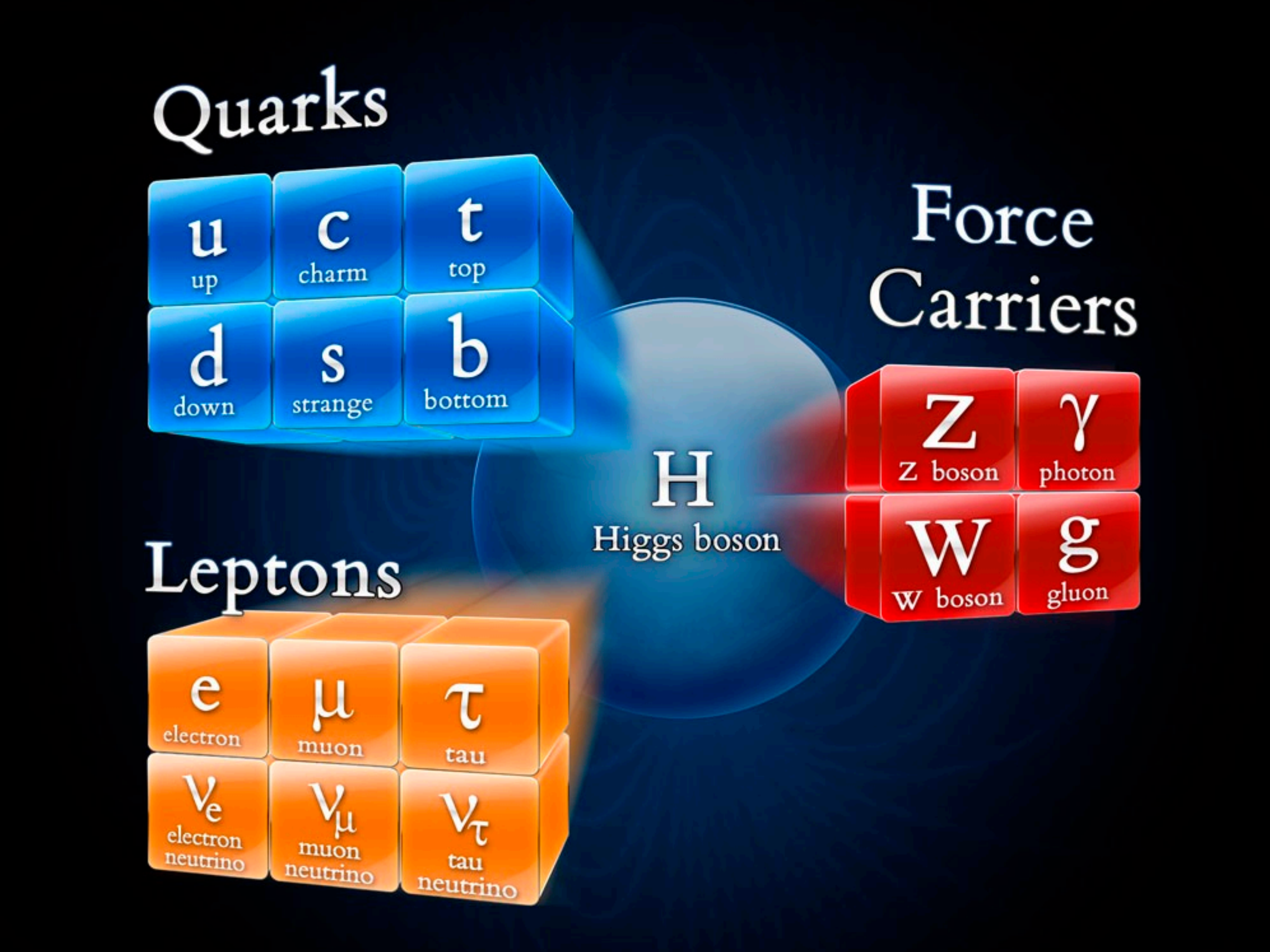


Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Force Carriers
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs boson
Leptons
e
electron
μ
muon
τ
tau
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino

Periodic Table of the Elements

1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 84.798
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

Lanthanide Series	57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]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Force Carriers
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W
W boson
g
gluon

Standard model matter fields

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

leptons

ν_e	e
ν_μ	μ
ν_τ	τ

quarks

u	u	u	d	d	d
c	c	c	s	s	s
t	t	t	b	b	b

Standard model matter fields

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

leptons			**quarks**					
ν_e	e	generation I	u	u	u	d	d	d
ν_μ	μ	generation II	c	c	c	s	s	s
ν_τ	τ	generation III	t	t	t	b	b	b

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			SU(3) triplets			SU(3) triplets		

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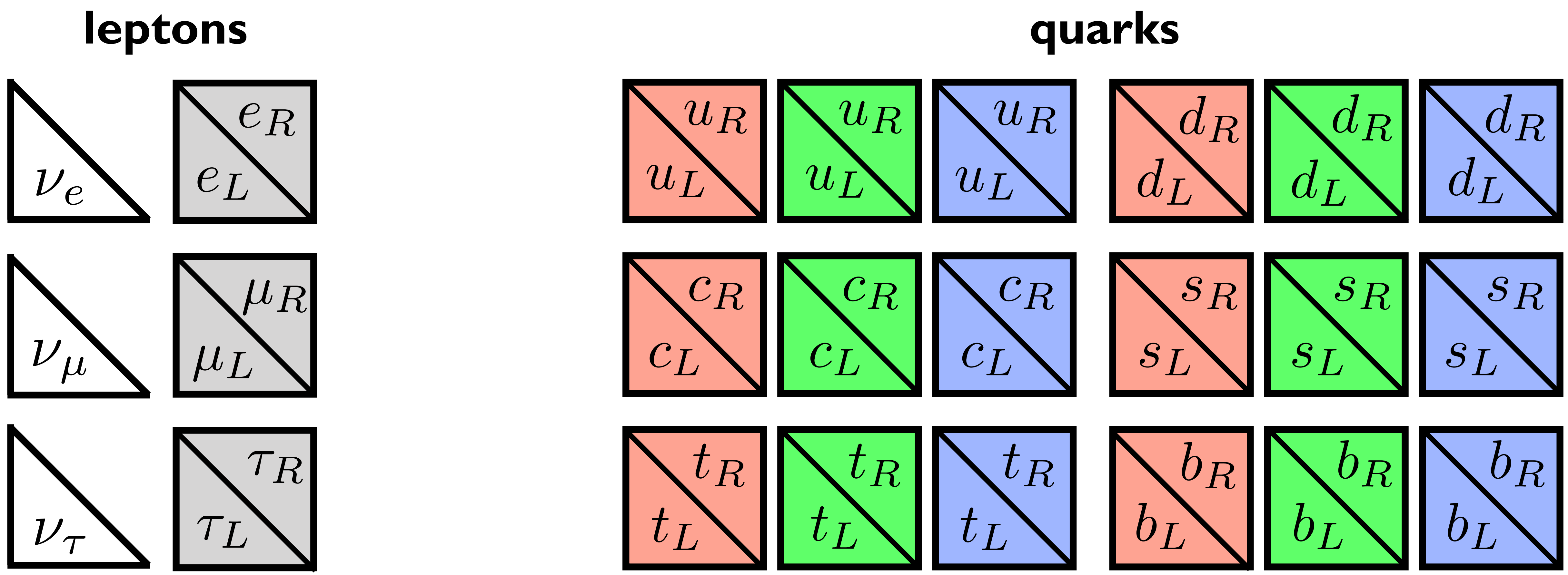

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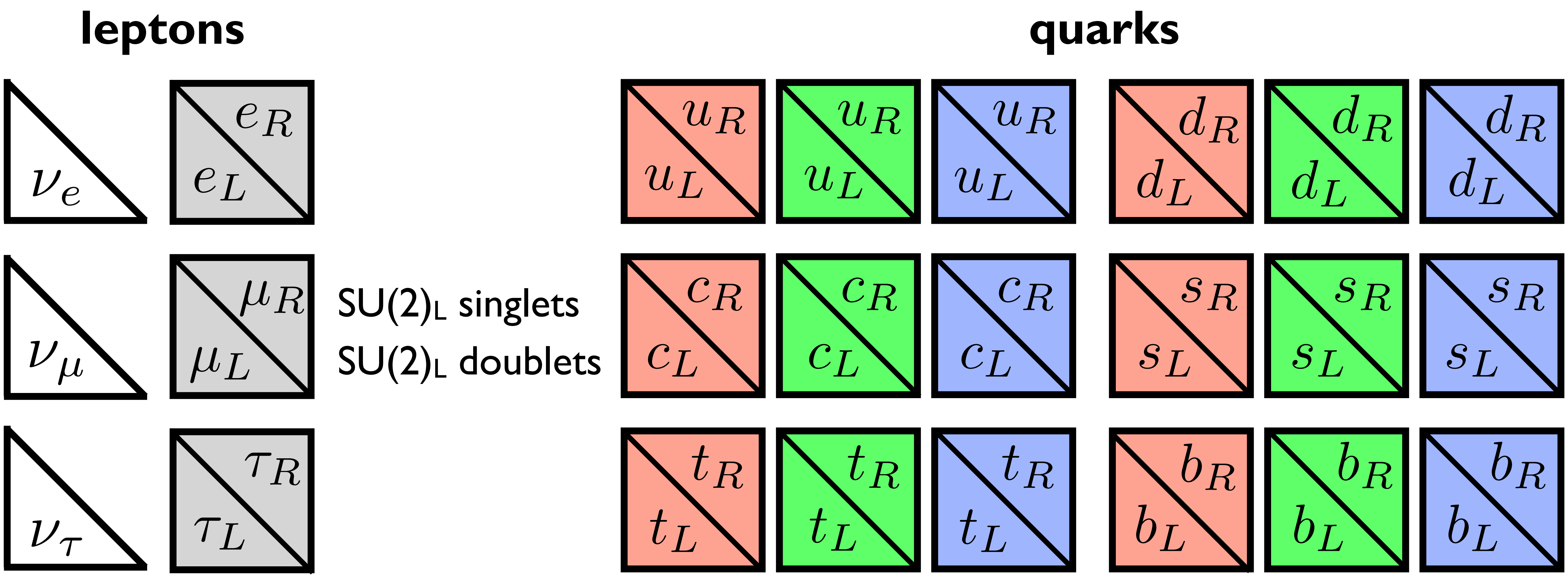

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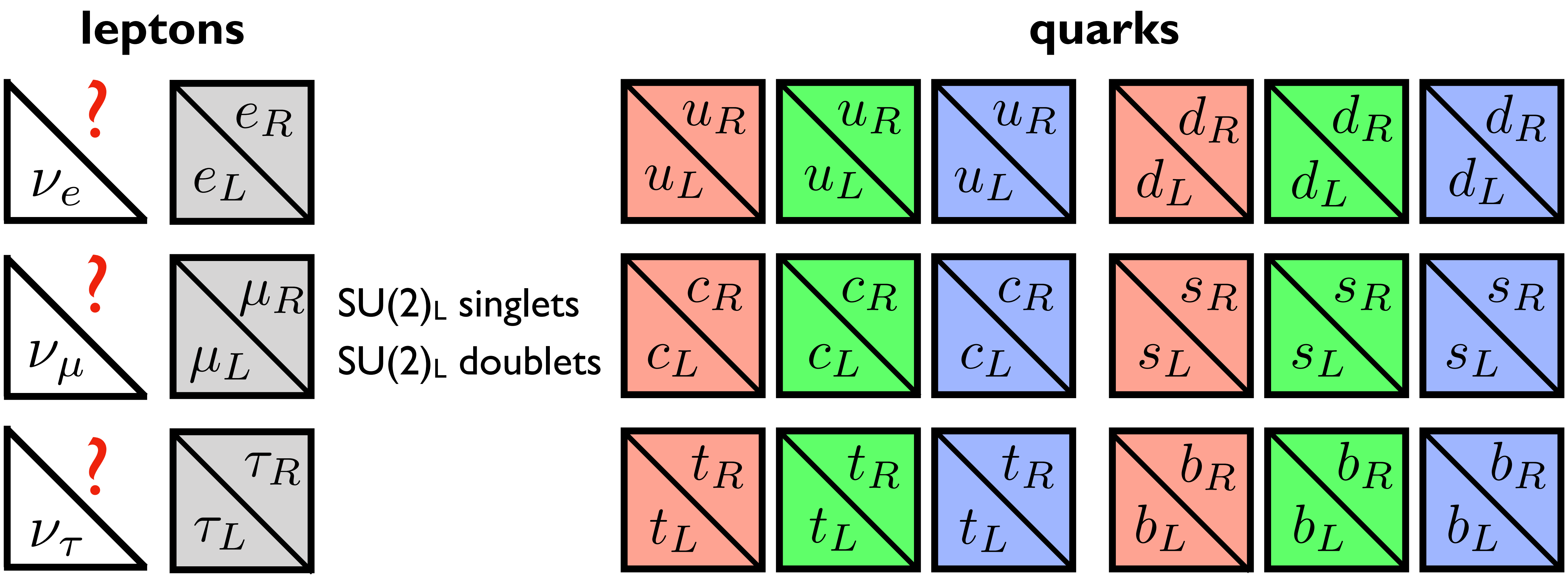

No right-handed neutrino components ?!

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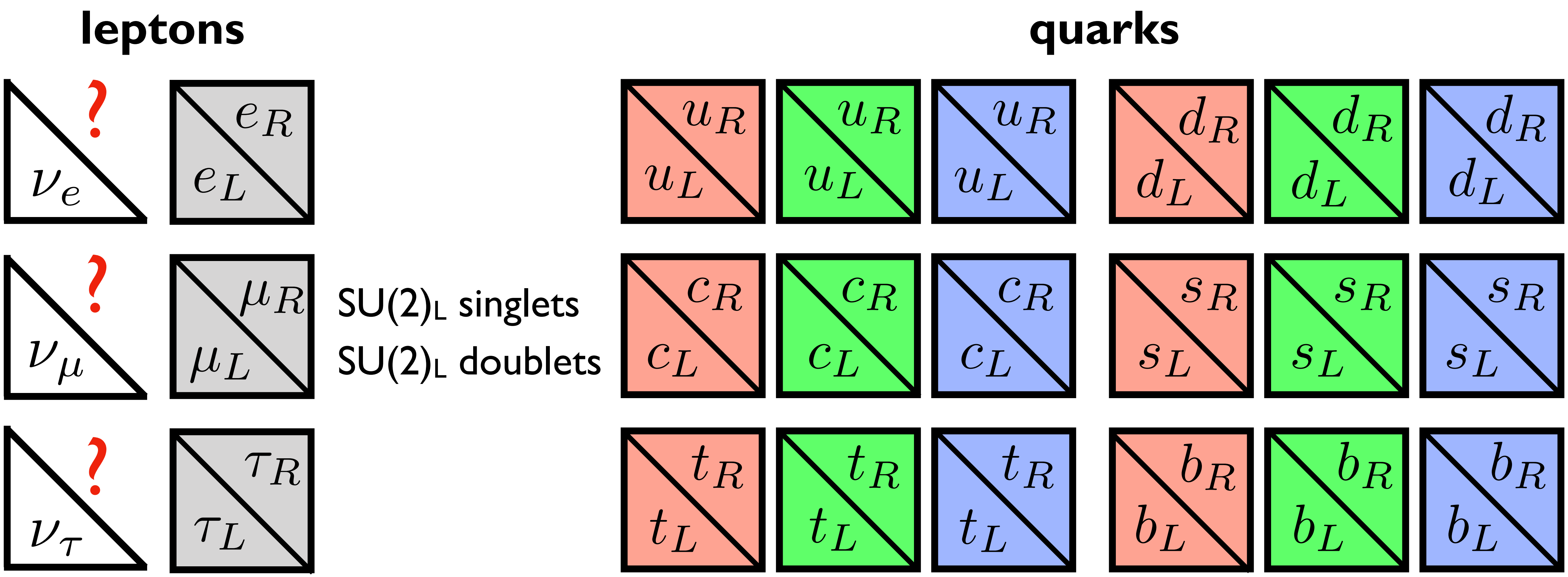

No right-handed neutrino components ?!

Neutrinos are Weyl spinors in the SM!

The likely course structure

Massive neutrinos - Dirac or Majorana?

- charge quantization in the SM with massive neutrinos
- B-L rules it all
- seesaw models, underlying dynamics, colliders?

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Extended gauge symmetries?

I. Structural aspects

  - B-L symmetry reloaded
  - LR models, parity restoration, B-L as 4th color

II. Scales

  - low-energy hints of a large BSM scale
  - theories with vastly different scales, decoupling, EFTs

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Very large scale dynamics?

- B & L violation in the SM @ d=6, mediators, SU(5)
- Neutrinos in SO(10) GUTs
- What else? Proton decay? Topological defects?

Massive neutrinos - Dirac or Majorana?

Standard model matter fields

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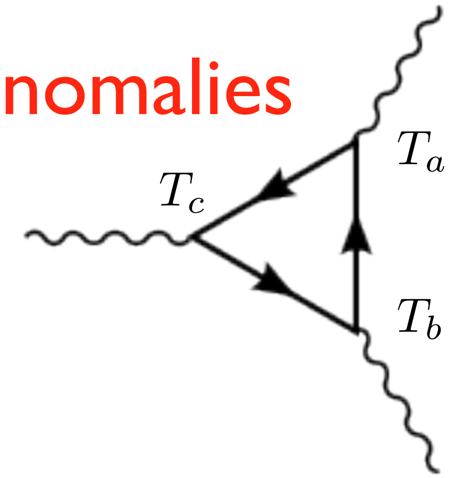
How about simply adding a RH neutrino component and going home?

This is actually far from trivial…

Charge quantization in the old good SM

Cancellation of the SU(3) x SU(2) x U(1) gauge anomalies

$$\mathcal{A}_c \propto \frac{1}{32\pi^2} \overset{L-R}{\mathrm{Tr}} \left(\{T_a, T_b\} T_c\right) \tilde{F}^a_{\mu\nu} F^{b\mu\nu}$$



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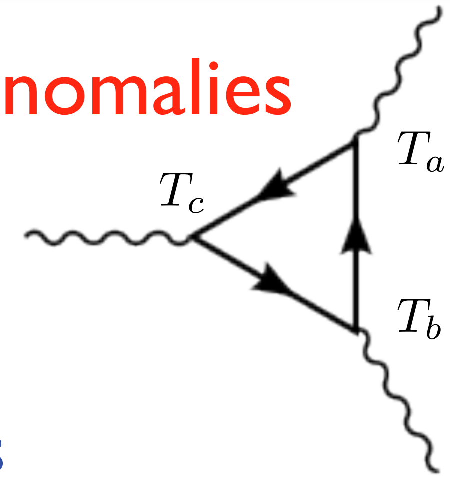

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Little trick: stick to SU(2)xU(1) and consider Yukawa interactions

$$\begin{aligned} Q_L &= (3,2,Y_Q) \\ u_R &= (3,1,Y_U) \\ d_R &= (3,1,Y_D) \\ L_L &= (1,2,Y_L) \\ e_R &= (1,1,Y_E) \end{aligned}$$

SU(2)² U(1): $6Y_Q + 2Y_L = 0$

U(1)³: $12Y_Q^3 + 4Y_L^3 - 6Y_U^3 - 6Y_D^3 - 2Y_E^3 = 0$

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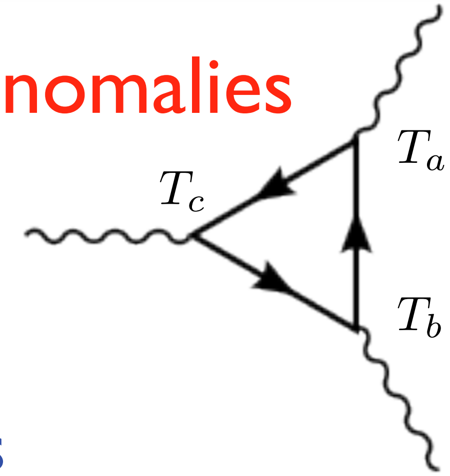

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Yukawas: $$Y_{Dij} \overline{Q_L}_i \langle H \rangle D_{Rj} + Y_{Uij} \overline{Q_L}_i \langle \tilde{H} \rangle U_{Rj} + Y_{Eij} \overline{L_L}_i \langle H \rangle E_{Rj}$$

$$H = (1, 2, Y_H)$$

$$-Y_Q + Y_D + Y_H = 0 \qquad -Y_Q + Y_U - Y_H = 0 \qquad -Y_L + Y_E + Y_H = 0$$

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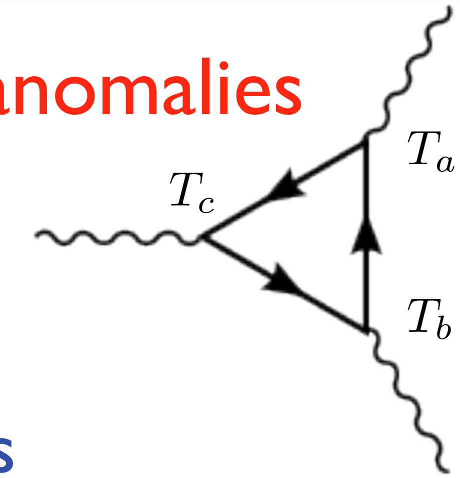

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$-Y_Q + Y_D + Y_H = 0 \qquad -Y_Q + Y_U - Y_H = 0 \qquad -Y_L + Y_E + Y_H = 0$

Solution: $\boxed{Y_Q = +\frac{1}{6},\ Y_U = +\frac{2}{3},\ Y_D = -\frac{1}{3},\ Y_L = -\frac{1}{2},\ Y_E = -1}$

Charge quantization in the SM is a consequence of anomaly cancellation!

Charge de-quantization in the SM with Dirac neutrinos

Cancellation of the SU(3) x SU(2) x U(1) gauge anomalies

Assume that there is a RH neutrino component added to the SM: $N_R = (1, 1, Y_N)$

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$$-Y_Q + Y_D + Y_H = 0 \qquad -Y_L + Y_E + Y_H = 0$$

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$$-Y_Q + Y_D + Y_H = 0 \qquad -Y_L + Y_E + Y_H = 0$$

$$-Y_Q + Y_U - Y_H = 0 \qquad -Y_L + Y_N - Y_H = 0$$

Solution: $$Y_Q = +\tfrac{1}{6} - \tfrac{1}{3}Y_N,\ Y_U = +\tfrac{2}{3} - \tfrac{1}{3}Y_N,\ Y_D = -\tfrac{1}{3} - \tfrac{1}{3}Y_N,$$
$$Y_L = -\tfrac{1}{2} + Y_N,\ Y_E = -1 + Y_N \qquad Y_N \in \mathbb{R}$$

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$-Y_Q + Y_D + Y_H = 0$ $\qquad$ $-Y_L + Y_E + Y_H = 0$

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Charge quantization is lost in the SM with Dirac neutrinos !!!

Charge de-quantization in the SM with Dirac neutrinos

A simple symmetry argument based on B & L symmetries

B & L - SM accidental global symmetries

$$
\begin{aligned}
\mathcal{L}_{SM} = &-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
&M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - \\
&Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
&\tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
&g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - \\
&2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
&\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
&\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - gMW^+_\mu W^-_\mu H - \\
&\tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
&\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
&M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - \\
&W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
&\tfrac{1}{4}g^2 W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) - \\
&\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \\
&\tfrac{1}{2}ig_s\,\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + \\
&igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - \\
&1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + (\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \\
&\tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
&\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
&\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa)\right) + \\
&\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa)\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
&\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda\,M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
&\overline{\tfrac{1}{4}\bar{\nu}_\lambda\,M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa} + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)\right) + \\
&\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \\
&\tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j)
\end{aligned}
$$

B & L - SM accidental global symmetries

$$
\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - \\
Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
\tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - \\
2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - gMW^+_\mu W^-_\mu H - \\
\tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\tfrac{1}{4}g^2 W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) - \\
\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \\
\tfrac{1}{2}ig_s\,\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + \\
igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - \\
1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + (\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} +
\end{gathered}
$$

$$
\begin{gathered}
\tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda\,M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
\tfrac{1}{4}\overline{\bar{\nu}_\lambda\,M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa} + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \\
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\end{gathered}
$$

B & L - SM accidental global symmetries

$$\frac{ig}{2\sqrt{2}}W_\mu^+\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa)+(\bar{u}_j^\lambda\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d_j^\kappa)\right)+$$
$$\frac{ig}{2\sqrt{2}}W_\mu^-\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda)+(\bar{d}_j^\kappa C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u_j^\lambda)\right)+$$
$$\frac{ig}{2M\sqrt{2}}\phi^+\left(-m_e^\kappa(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa)+m_\nu^\lambda(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right)+$$
$$\frac{ig}{2M\sqrt{2}}\phi^-\left(m_e^\lambda(\bar{e}^\lambda U^{lep\dagger}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa)-m_\nu^\kappa(\bar{e}^\lambda U^{lep\dagger}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right)-\frac{g}{2}\frac{m_\nu^\lambda}{M}H(\bar{\nu}^\lambda\nu^\lambda)-$$
$$\frac{g}{2}\frac{m_e^\lambda}{M}H(\bar{e}^\lambda e^\lambda)+\frac{ig}{2}\frac{m_\nu^\lambda}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda)-\frac{ig}{2}\frac{m_e^\lambda}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)-\frac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa-$$
$$\frac{1}{4}\overline{\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa}+\frac{ig}{2M\sqrt{2}}\phi^+\left(-m_d^\kappa(\bar{u}_j^\lambda C_{\lambda\kappa}(1-\gamma^5)d_j^\kappa)+m_u^\lambda(\bar{u}_j^\lambda C_{\lambda\kappa}(1+\gamma^5)d_j^\kappa\right)+$$
$$\frac{ig}{2M\sqrt{2}}\phi^-\left(m_d^\lambda(\bar{d}_j^\lambda C^\dagger_{\lambda\kappa}(1+\gamma^5)u_j^\kappa)-m_u^\kappa(\bar{d}_j^\lambda C^\dagger_{\lambda\kappa}(1-\gamma^5)u_j^\kappa\right)-\frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}_j^\lambda u_j^\lambda)-\frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}_j^\lambda d_j^\lambda)+$$
$$\frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}_j^\lambda\gamma^5 u_j^\lambda)-\frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}_j^\lambda\gamma^5 d_j^\lambda)$$

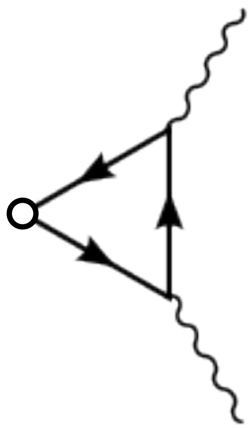
always a $\overline{\Psi}\Psi$ structure - B and also L are classical global symmetries of the SM

Charge de-quantization in the SM with Dirac neutrinos

A simple symmetry argument based on B & L symmetries

B and L anomalies in the presence of the RH neutrino:

$$\mathrm{Tr}(\{Y,Y\}(B-L))=0\,,\mathrm{Tr}(\{T^3_L,T^3_L\}(B-L))=0\,,$$



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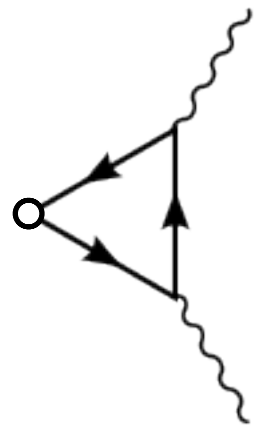

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B - L is a gaugeable symmetry !

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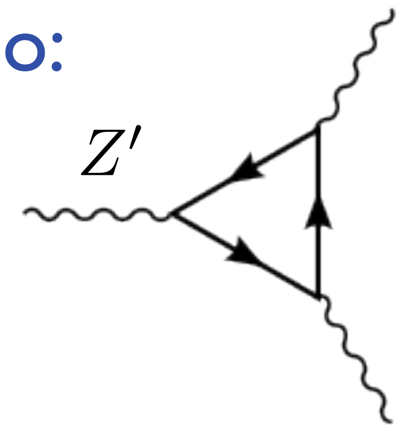

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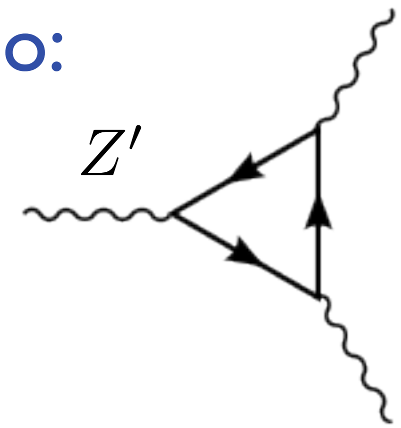

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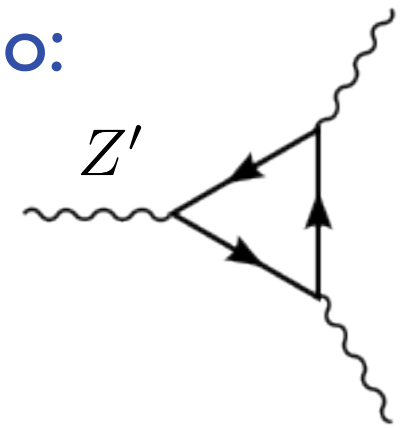

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Babu, Mohapatra, Phys.Rev. D41 (1990) 271

Experimentally (neutron neutrality): $|\varepsilon|<10^{-21}$

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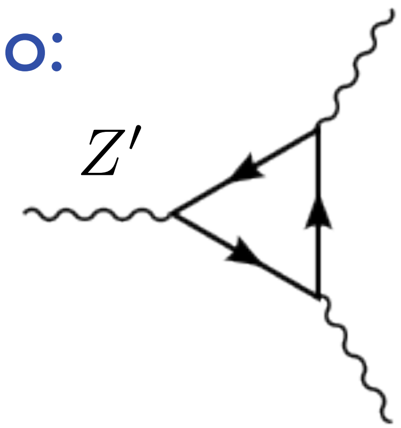

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The Dirac neutrino picture is not satisfactory...

Majorana mass term

E. Majorana 1937:

Neutral field can have a mass term even with 2 components only!!!

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Lagrangians (in Weyl notation): $\mathcal{L} = i\overline{\psi}_W \partial\!\!\!/ \psi_W - e^{i\phi} m \overline{\psi}_W \psi_W^c$

RH neutrinos equiped with Majorana mass term

RH neutrinos are completely SU(3)xSU(2) neutral Weyl spinors!

$$\mathcal{L} \ni \overline{L}_L Y_\nu N_R \tilde{H} + \frac{1}{2} N_R^T C M_R N_R + h.c.$$

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No free lunch principle: M_R is a new signet mass parameter!

Seesaw mechanism (type-I)

P. Minkowski, Phys. Lett. B67, 421 (1977)

$$\mathcal{L} \ni \overline{\nu}_L m_D N_R + \frac{1}{2} M_R N_R^T C N_R + h.c. = \frac{1}{2} n_L^T C \mathcal{M} n_L + h.c.$$

$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \qquad n_L = \begin{pmatrix} \nu_L \\ (N_R)^C \end{pmatrix}$$

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Suppose $m_D \ll M_R$:

$$m_1 = -\frac{m_D^2}{M_R} \qquad n_1 \propto \nu_L + \mathcal{O}\left(\frac{m_D}{M_R}\right)(N_R)^c$$

$$m_2 = M_R \qquad n_2 \propto (N_R)^c + \mathcal{O}\left(\frac{m_D}{M_R}\right)\nu_L$$

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P. Minkowski, Phys. Lett. B67, 421 (1977)

$$\mathcal{L} \ni \overline{\nu}_L m_D N_R + \frac{1}{2} M_R N_R^T C N_R + h.c. = \frac{1}{2} n_L^T C \mathcal{M} n_L + h.c.$$

$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \qquad n_L = \begin{pmatrix} \nu_L \\ (N_R)^C \end{pmatrix}$$

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M_R~$10^{12\text{-}14}$ GeV

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NB the argument is not water-tight - small Yukawas are natural…

$M_R \sim 10^{12\text{-}14}$ GeV

Effective lagrangian for neutrinos with $p^2 \ll M_R^2$

$$\mathcal{L} \ni \overline{L}_L Y_\nu N_R \tilde{H} + \frac{1}{2} N_R^T C M_R N_R + h.c.$$

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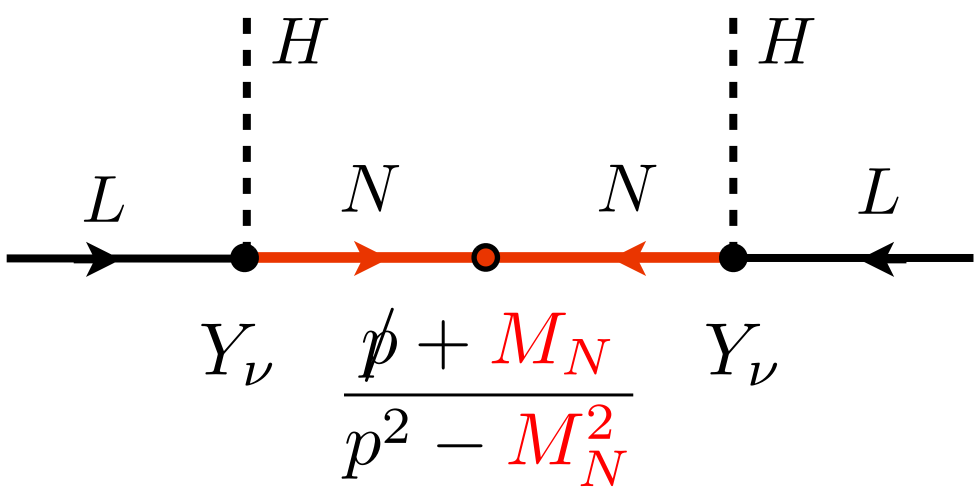

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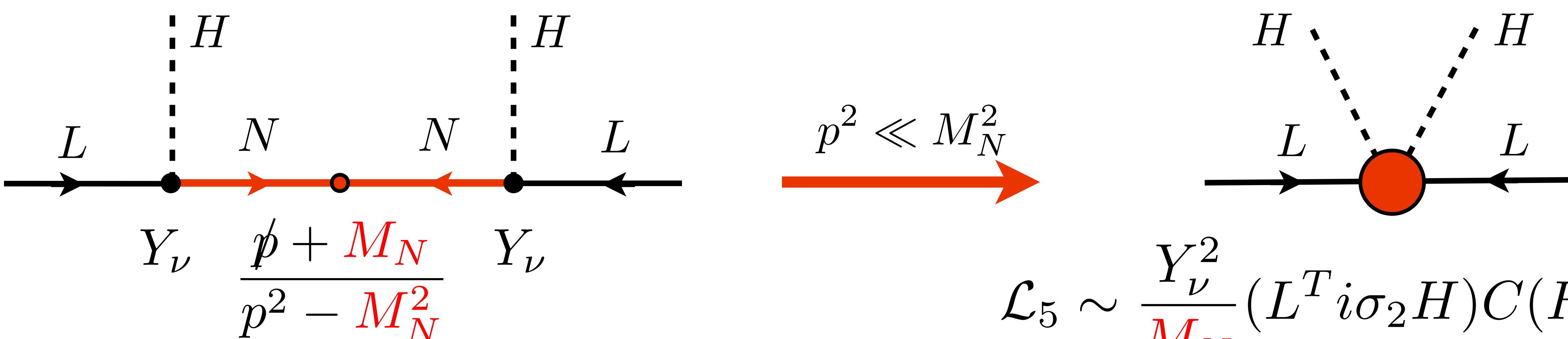

$$\mathcal{L}_5 \sim \frac{Y_\nu^2}{M_N} (L^T i\sigma_2 H) C (H^T i\sigma_2 L)$$

Weinberg's d=5 operator

S. Weinberg, PRL43, 1566 (1979)

SM as an effective theory - d=5

$$\mathcal{L}_5 \sim \frac{c}{\Lambda}(L^T i\sigma_2 H)C(H^T i\sigma_2 L)$$

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This operator is unique at d=5 in the SM!

By the way: it's great to have a complete Higgs doublet for the EFT business!

Renormalizable "openings" of the Weinberg operator

$$\mathcal{L}_5 \sim \frac{c}{\Lambda}(L^T i\sigma_2 H)C(H^T i\sigma_2 L)$$

Tree-level graphs (one mediator)

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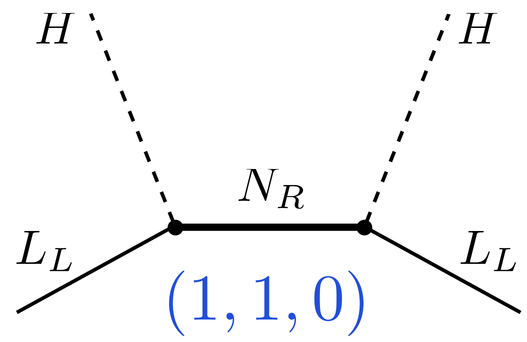

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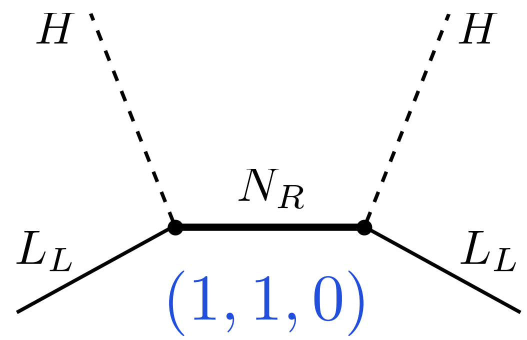

fermionic singlet
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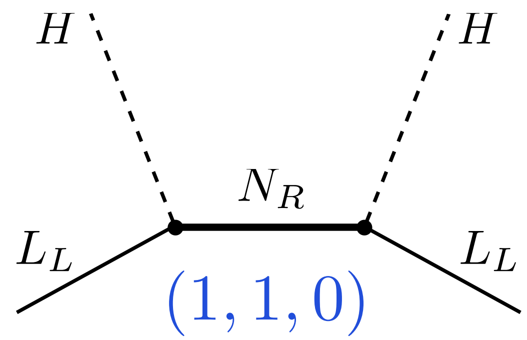
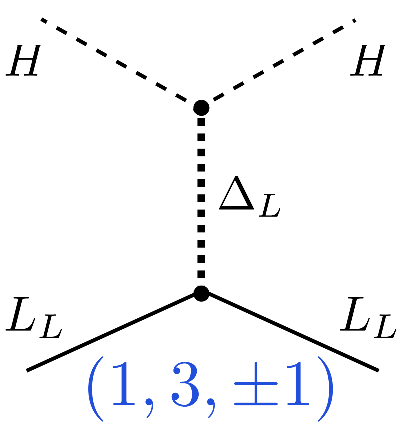


fermionic singlet
RH neutrino

seesaw type II



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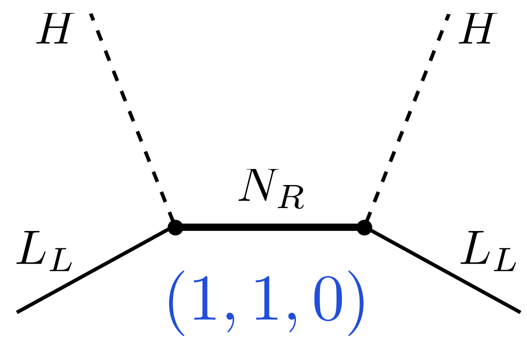

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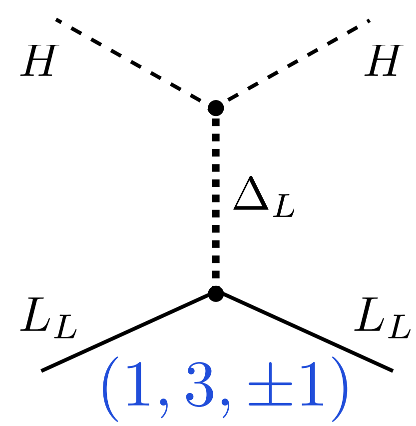

scalar triplet with a
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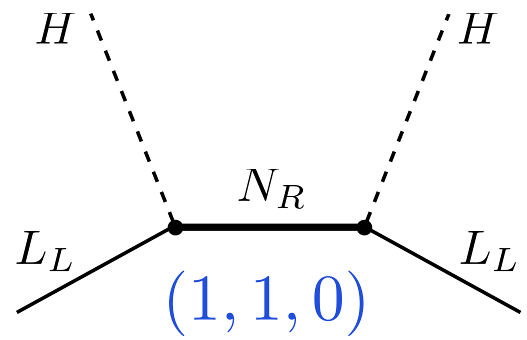

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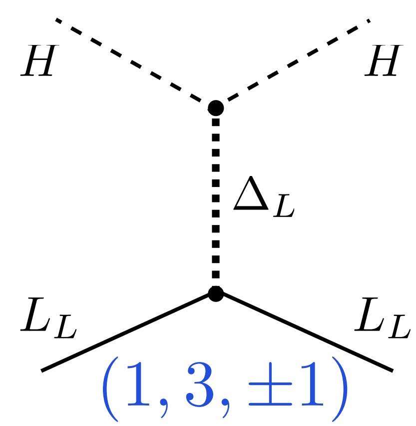

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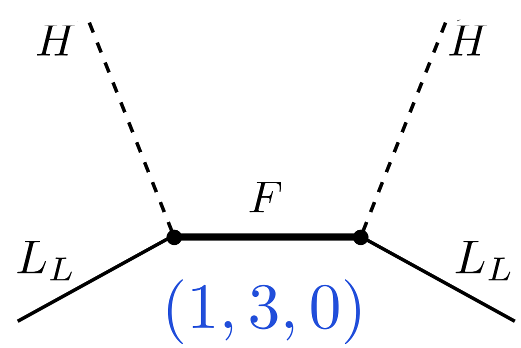

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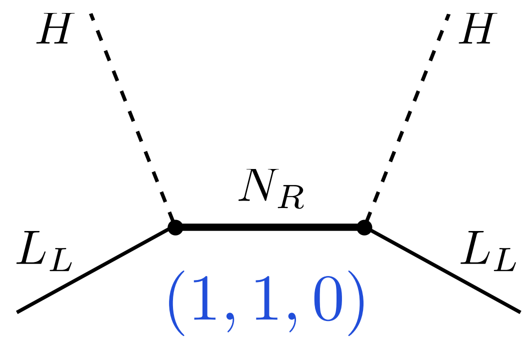

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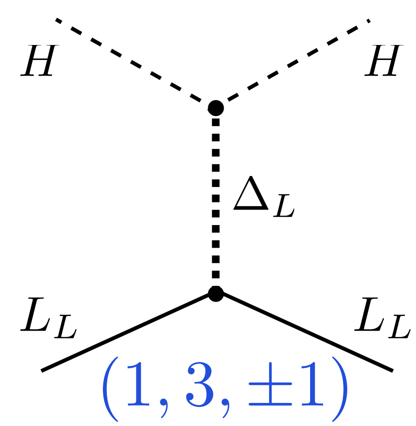

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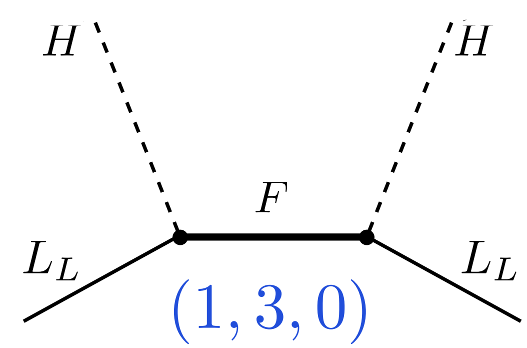
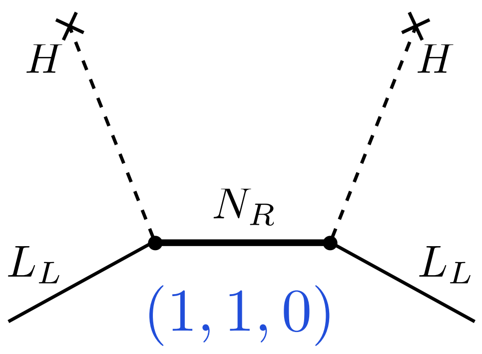


fermionic triplet

Majorana neutrinos @ colliders: "light" type-I seesaw?

Type-I seesaw:

review: arXiv:1001.2693 [hep-ph]



- generally problematic, Yukawa couplings small

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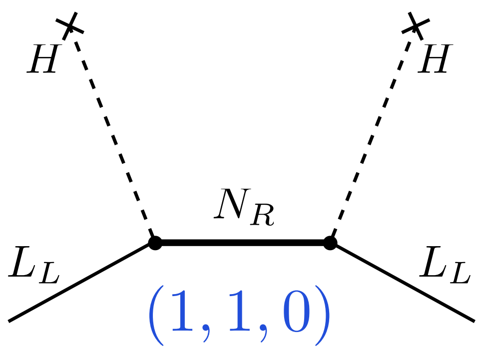

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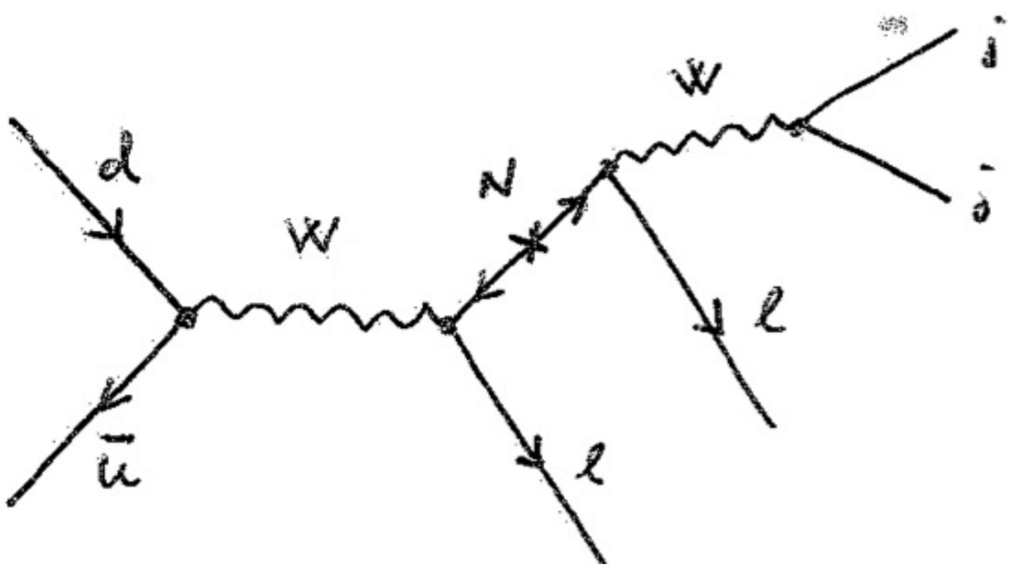
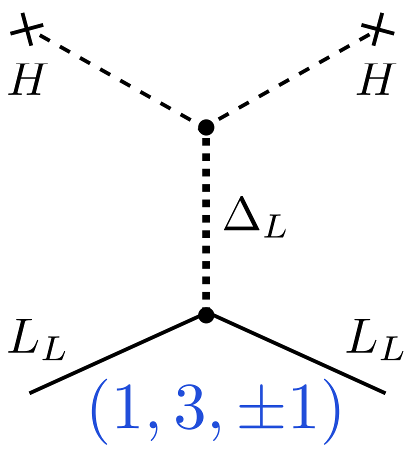


- gauge couplings of the RHN are also small!

Majorana neutrinos @ colliders: type-II seesaw?

Type-II seesaw:

review: arXiv:1001.2693 [hep-ph]



- doubly-charged scalar in the spectrum!

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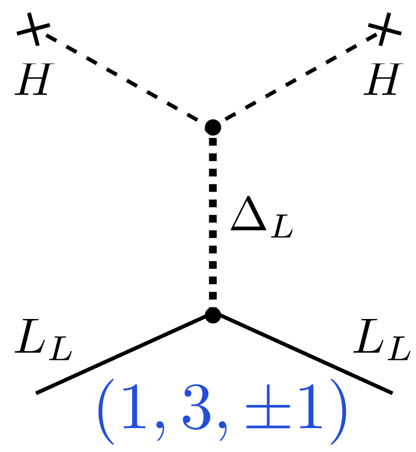

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$$Z^* \to \Delta^{++}\Delta^{--} \to (l^+ l^+)(l^- l^-)$$

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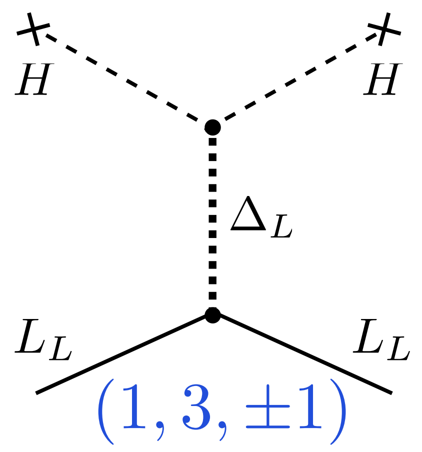

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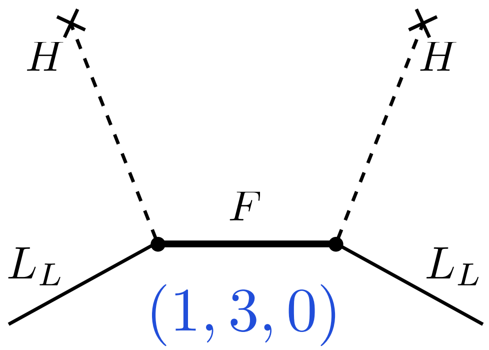
- small background in the SM !!!

Majorana neutrinos @ colliders: "light" type-III seesaw?

Type-III seesaw:

review: arXiv:1001.2693 [hep-ph]



- neutral and charged fermions in F

Majorana neutrinos @ colliders: "light" type-III seesaw?

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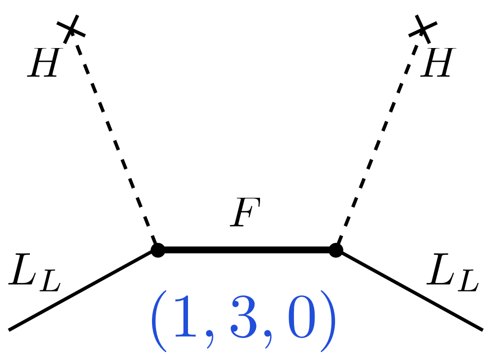

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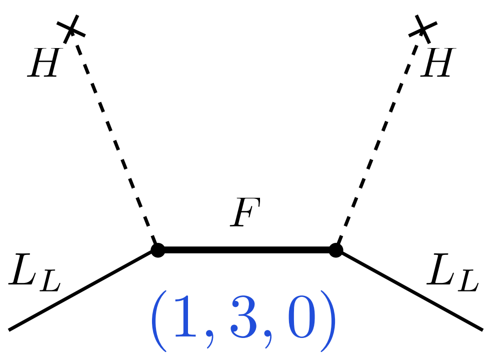

- neutral and charged fermions in F
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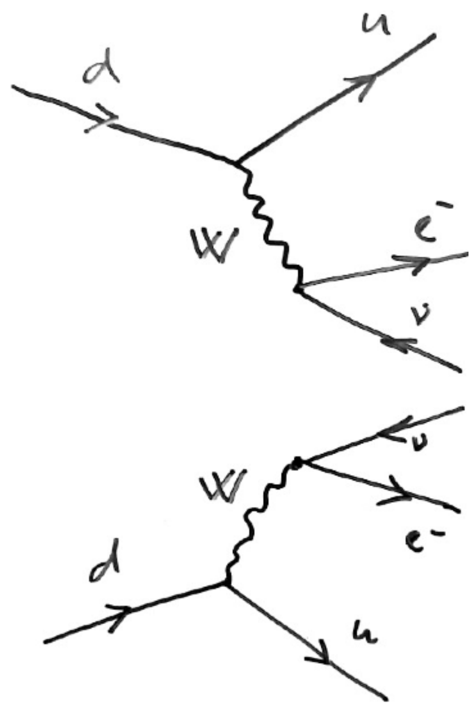
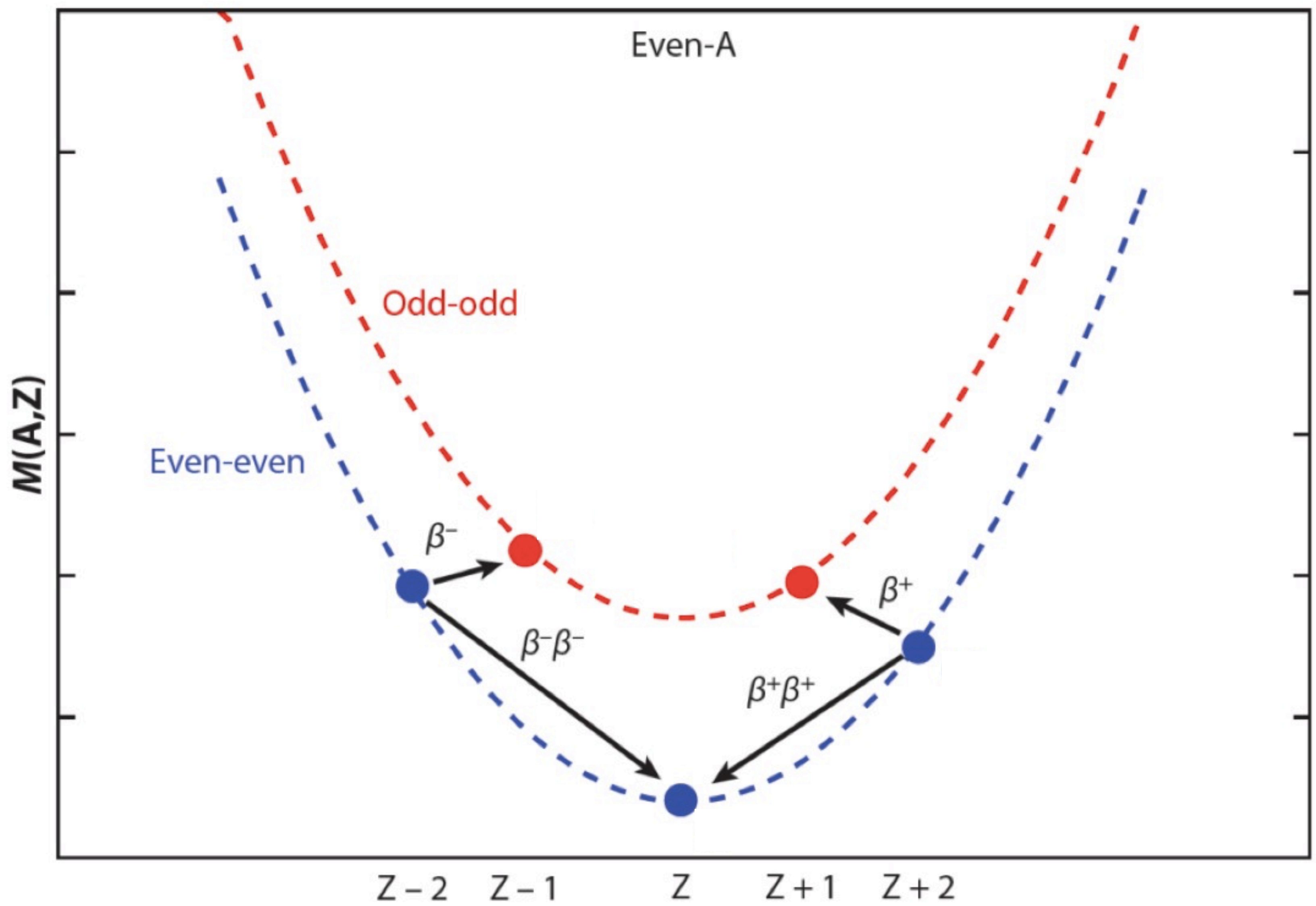
- multi-lepton channels like in type-II case

$$F^+ \to Z^* l^+ \to (l^+ l^-) l^+$$

- different kinematics, not as spectacular as type-II

Majorana neutrinos & double beta decay





"Standard" double beta decay: $$2n \rightarrow 2p^{+} + 2e^{-} + 2\overline{\nu}$$

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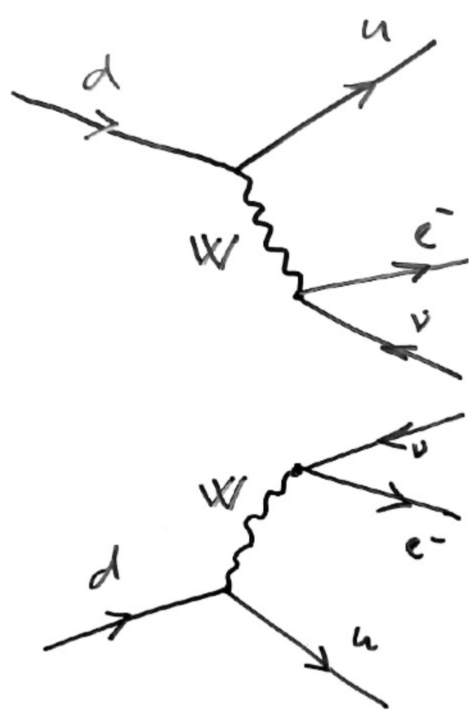

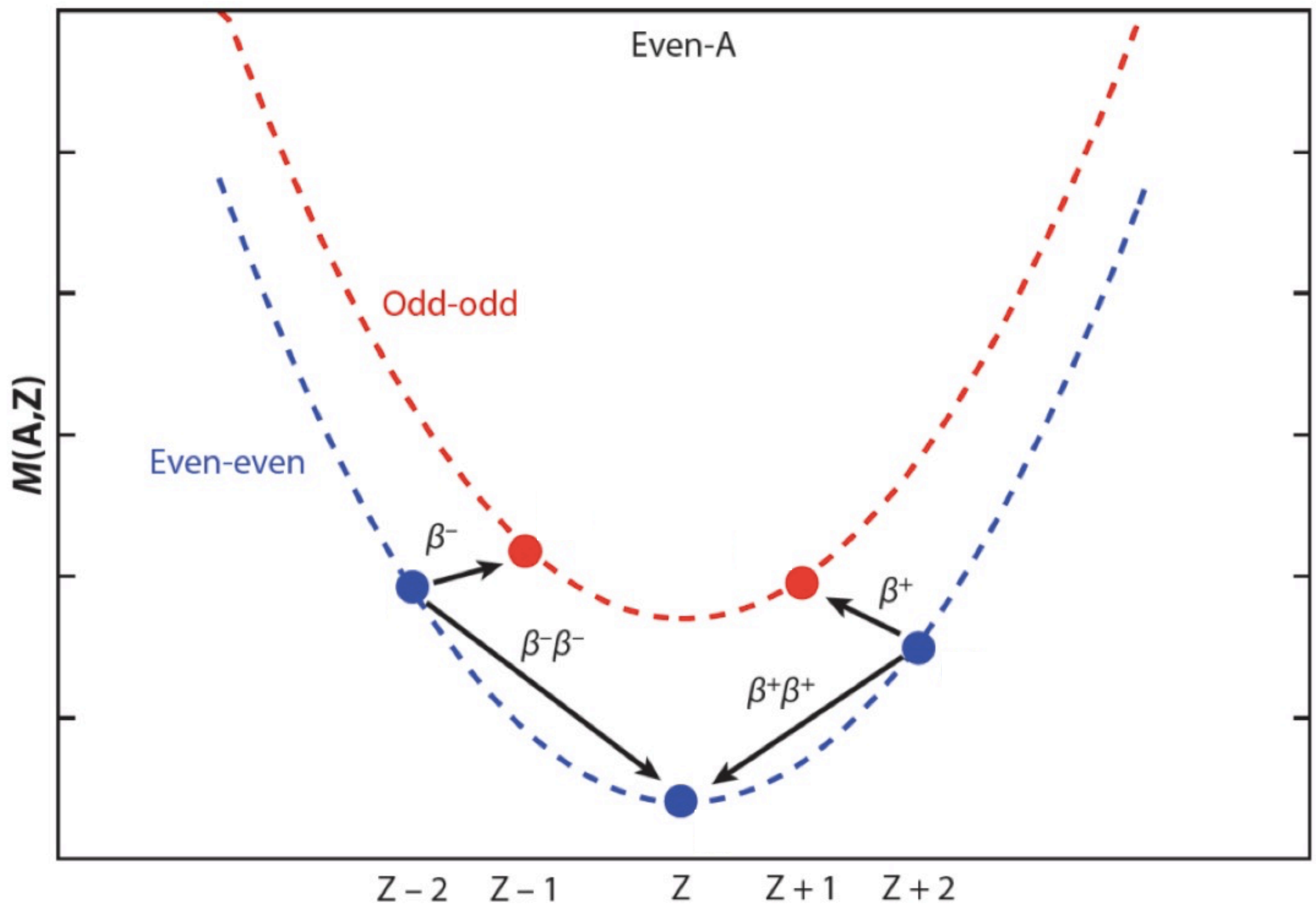

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Isotopes: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd

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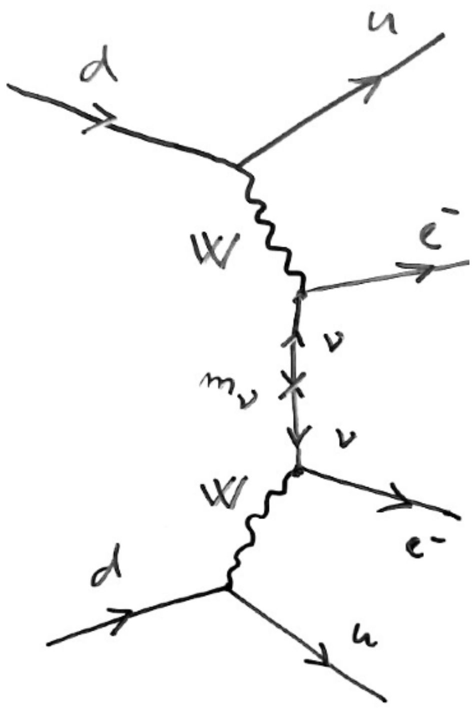

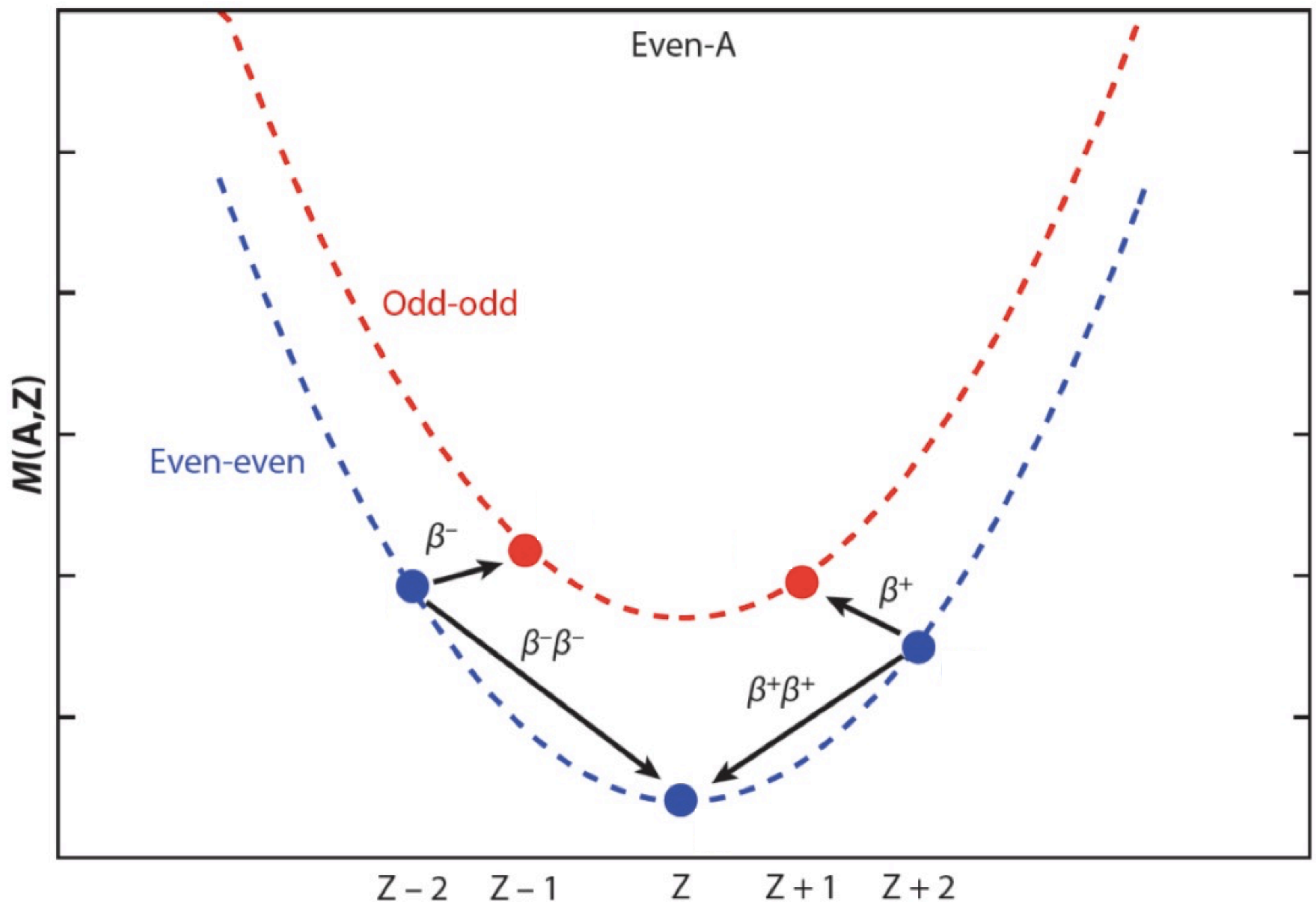

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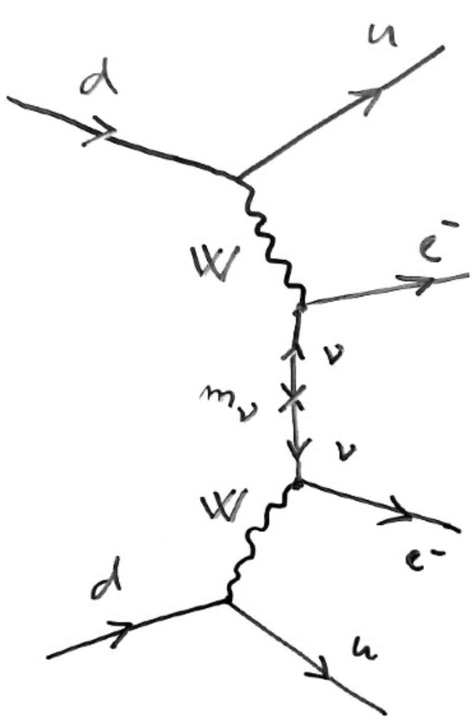
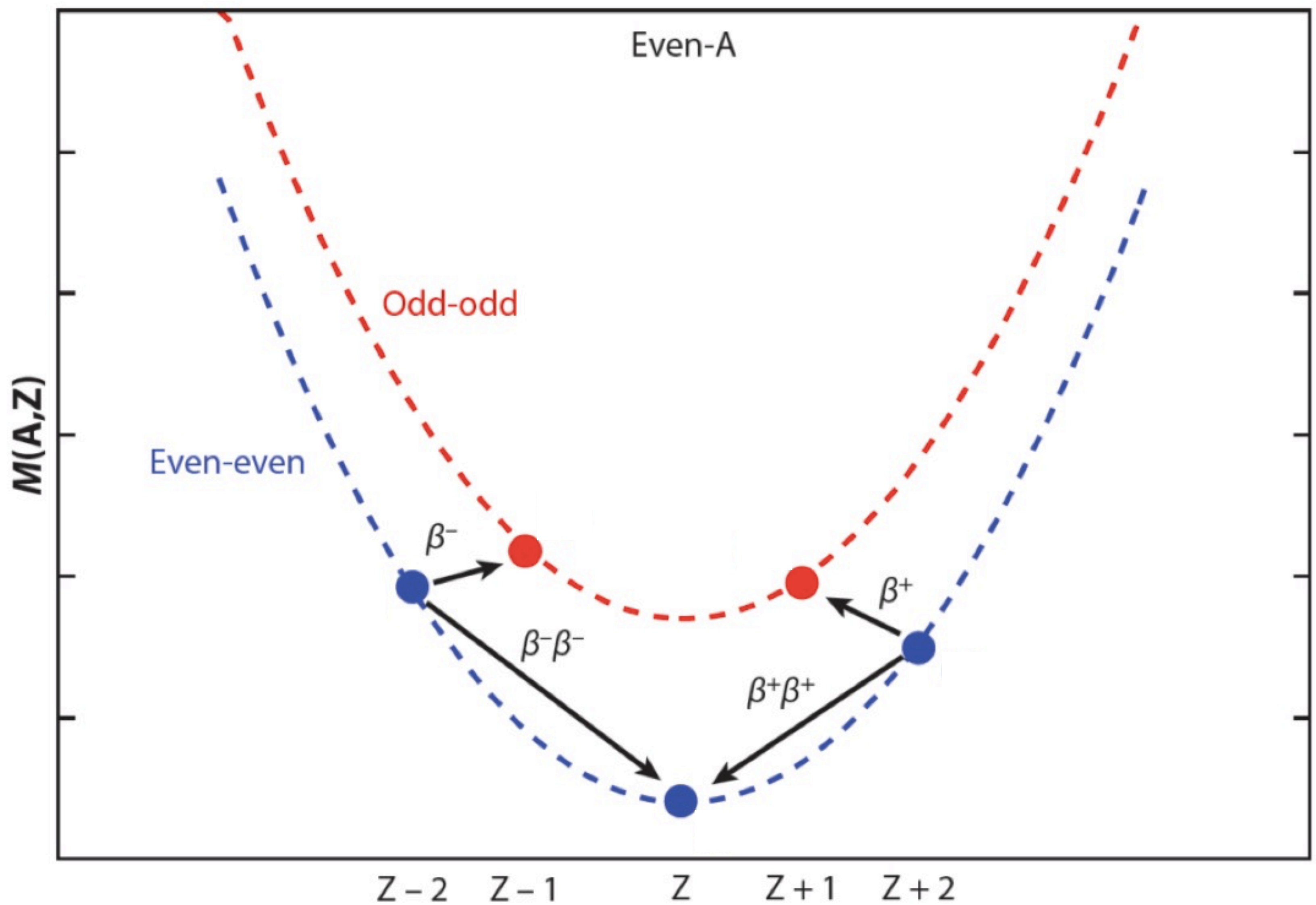




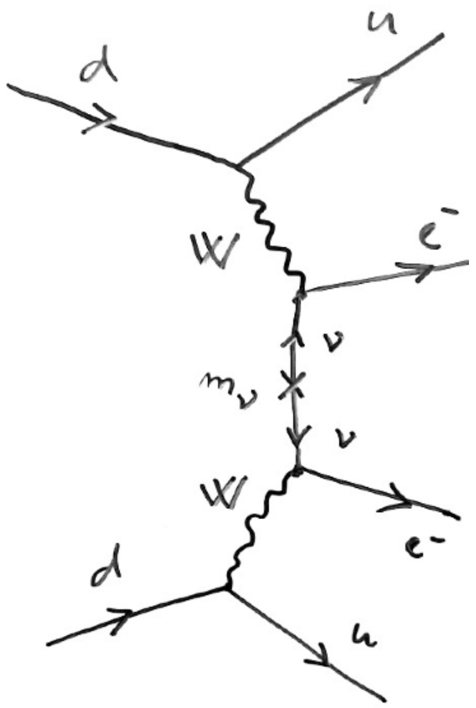
"Standard" double beta decay: $2n \to 2p^+ + 2e^- + 2\overline{\nu}$

Neutrinoless double beta decay: $2n \to 2p^+ + 2e^- + 0\overline{\nu}$

Isotopes: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd

Neutrinoless double beta decay - effective mass

Diagrammatics:



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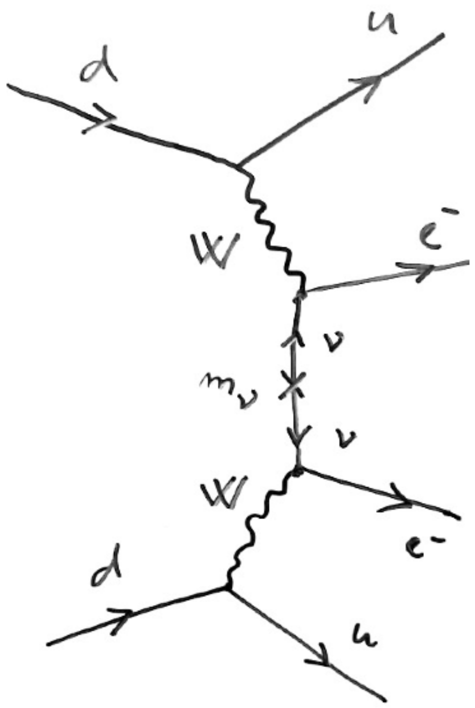

$$\mathcal{A} \propto g^4 \frac{\langle m \rangle}{q^2}$$

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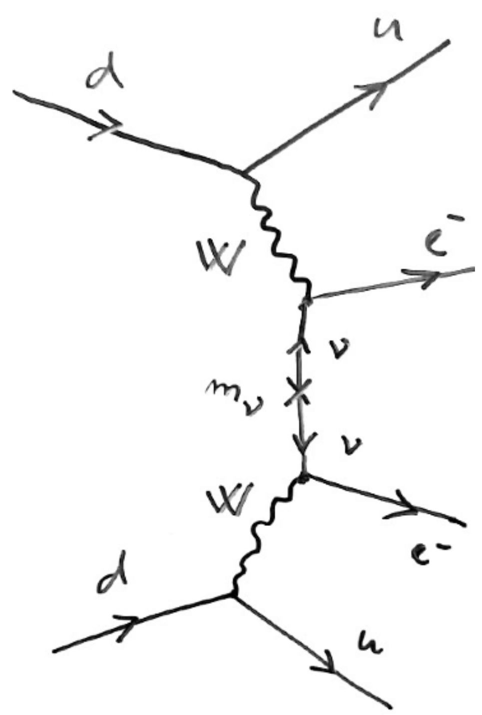

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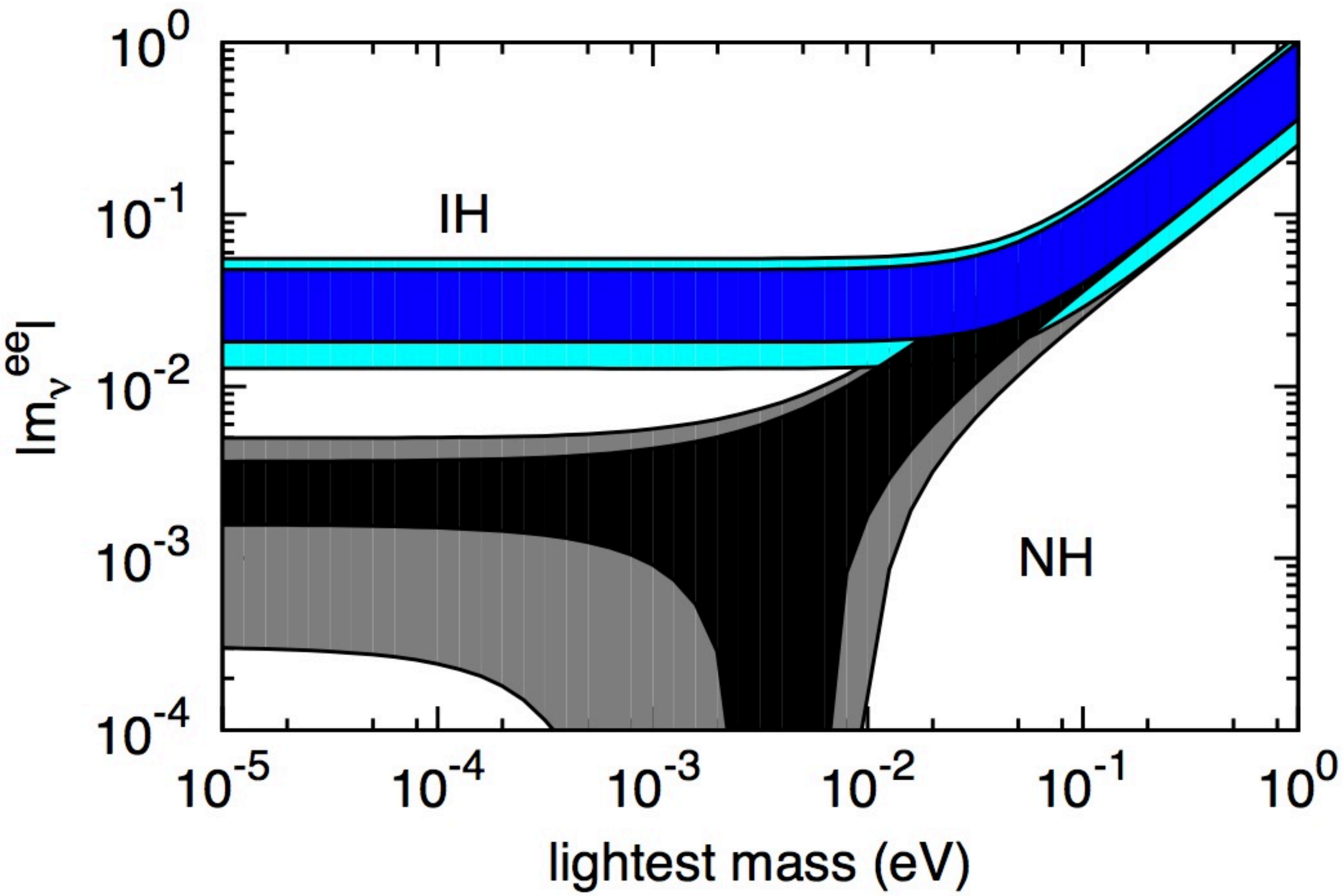

Figure from Chakrabortty et al., *JHEP* 08 (2012) 008

Is this a test of the Majorana nature of neutrinos?

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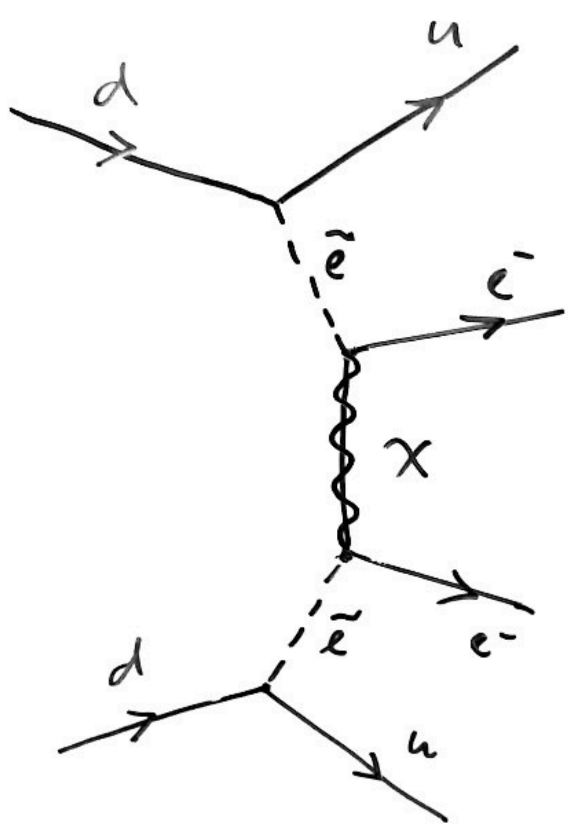

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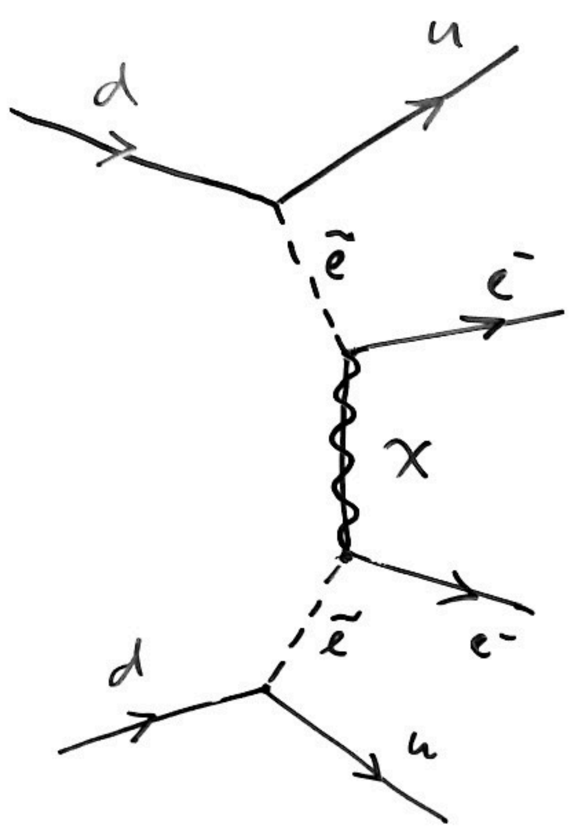
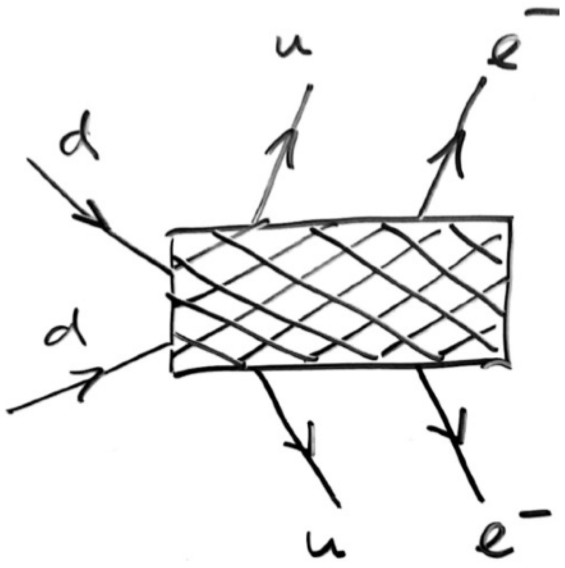


That actually does not make a difference...



J. Schechter, J. F. W. Valle, PRD 1982
Takasugi, PLB 1984

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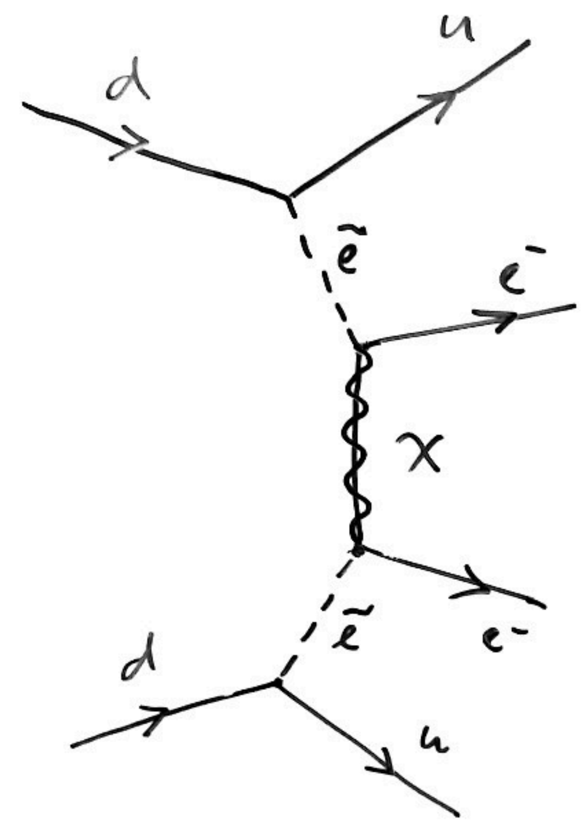

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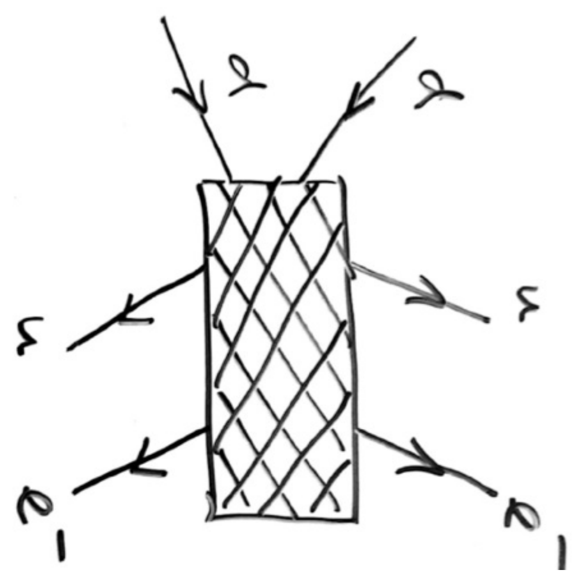

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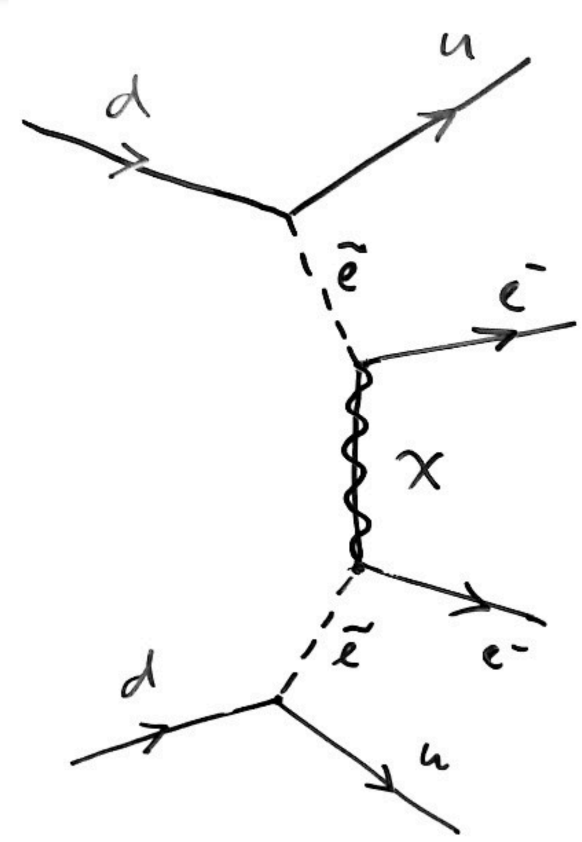

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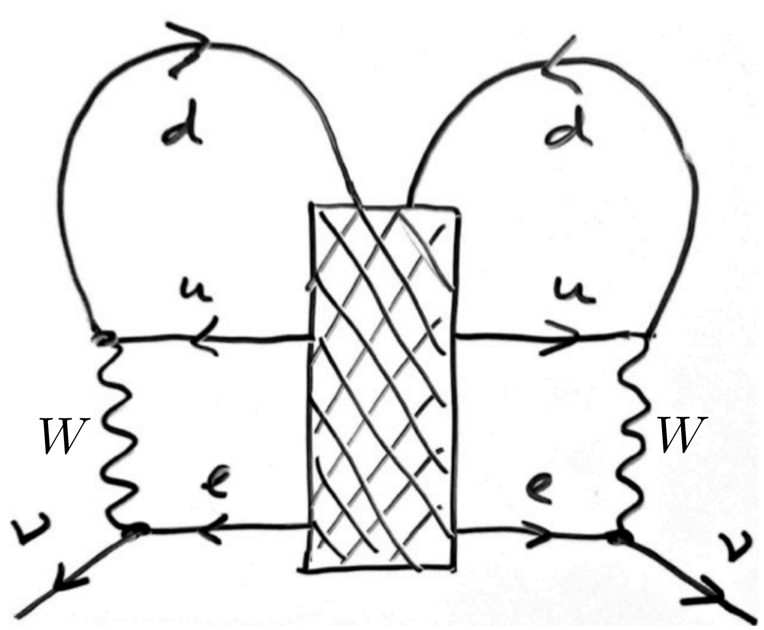

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If neutrinoless double beta decay is seen, neutrinos are inevitably Majorana...

Extended gauge symmetries?

Part 1: Structural aspects

Standard model matter fields + 3 RH neutrinos

	T_L^3	Y	Q
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$+\frac{1}{6}$	$+\frac{2}{3}$ $-\frac{1}{3}$
u_R	0	$+\frac{2}{3}$	$+\frac{2}{3}$
d_R	0	$-\frac{1}{3}$	$-\frac{1}{3}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$-\frac{1}{2}$	0 -1
ν_R	0	0	0
e_R	0	-1	-1

Standard model matter fields + 3 RH neutrinos

	T_L^3	Y	Q	$(B-L)/2$
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$+\frac{1}{6}$	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{1}{6}$
u_R d_R	0 0	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{1}{6}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$-\frac{1}{2}$	0 -1	$-\frac{1}{2}$
ν_R e_R	0 0	0 -1	0 -1	$-\frac{1}{2}$

Standard model matter fields + 3 RH neutrinos

	T_L^3	Y	Q	$(B-L)/2$	
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$+\frac{1}{2}$, $-\frac{1}{2}$	$+\frac{1}{6}$	$+\frac{2}{3}$, $-\frac{1}{3}$	$+\frac{1}{6}$	0
u_R	0	$+\frac{2}{3}$	$+\frac{2}{3}$	$+\frac{1}{6}$	
d_R	0	$-\frac{1}{3}$	$-\frac{1}{3}$		
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$+\frac{1}{2}$, $-\frac{1}{2}$	$-\frac{1}{2}$	0, -1	$-\frac{1}{2}$	0
ν_R	0	0	0	$-\frac{1}{2}$	
e_R	0	-1	-1		

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	T_L^3	Y	Q	$(B-L)/2$	
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$+\frac{1}{6}$	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{1}{6}$	0
u_R d_R	0 0	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{1}{6}$	$+\frac{1}{2}$ $-\frac{1}{2}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$-\frac{1}{2}$	0 -1	$-\frac{1}{2}$	0
ν_R e_R	0 0	0 -1	0 -1	$-\frac{1}{2}$	$+\frac{1}{2}$ $-\frac{1}{2}$

Standard model matter fields + 3 RH neutrinos

	T^3_L	Y	Q	$(B-L)/2$	T³-like generator for RH fields!
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$+\frac{1}{6}$	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{1}{6}$	0
u_R d_R	0 0	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{1}{6}$	$+\frac{1}{2}$ $-\frac{1}{2}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$-\frac{1}{2}$	0 -1	$-\frac{1}{2}$	0
ν_R e_R	0 0	0 -1	0 -1	$-\frac{1}{2}$	$+\frac{1}{2}$ $-\frac{1}{2}$

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u_R	0	$+\frac{2}{3}$	$+\frac{2}{3}$	$+\frac{1}{6}$	$+\frac{1}{2}$
d_R					$-\frac{1}{2}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$+\frac{1}{2}$, $-\frac{1}{2}$	$-\frac{1}{2}$	0, -1	$-\frac{1}{2}$	0
ν_R	0	0	0	$-\frac{1}{2}$	$+\frac{1}{2}$
e_R	0	-1	-1		$-\frac{1}{2}$

$$Q = T_L^3 + T_R^3 + \frac{1}{2}(B-L)$$

Left-right models

$$\begin{pmatrix} u \\ d \end{pmatrix}_L$$

$$u_R$$

$$d_R$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$$

$$\color{red}{\nu_R}$$

$$e_R$$

Left-right models

$$\begin{pmatrix} u \\ d \end{pmatrix}_L$$

$$\begin{matrix} u_R \\ d_R \end{matrix} \longrightarrow \begin{pmatrix} u \\ d \end{pmatrix}_R$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$$

$$\begin{matrix} \color{red}{\nu_R} \\ e_R \end{matrix} \longrightarrow \begin{pmatrix} \color{red}{\nu} \\ e \end{pmatrix}_R$$

Left-right models

$SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ gauge group

review: G. Senjanovic, Riv. Nuovo Cim. 034, 2011

$$\begin{pmatrix} u \\ d \end{pmatrix}_L$$

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High-scale parity restoration

- $SU(2)_R \times U(1)_{B-L}$ can be broken by a scalar triplet

$$\{\Delta^0, \Delta^+, \Delta^{++}\}$$

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Extra gauge bosons

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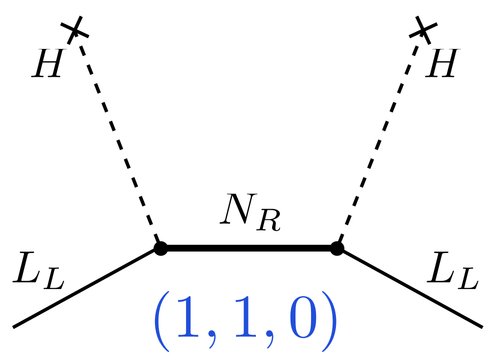
Yukawa "unification"

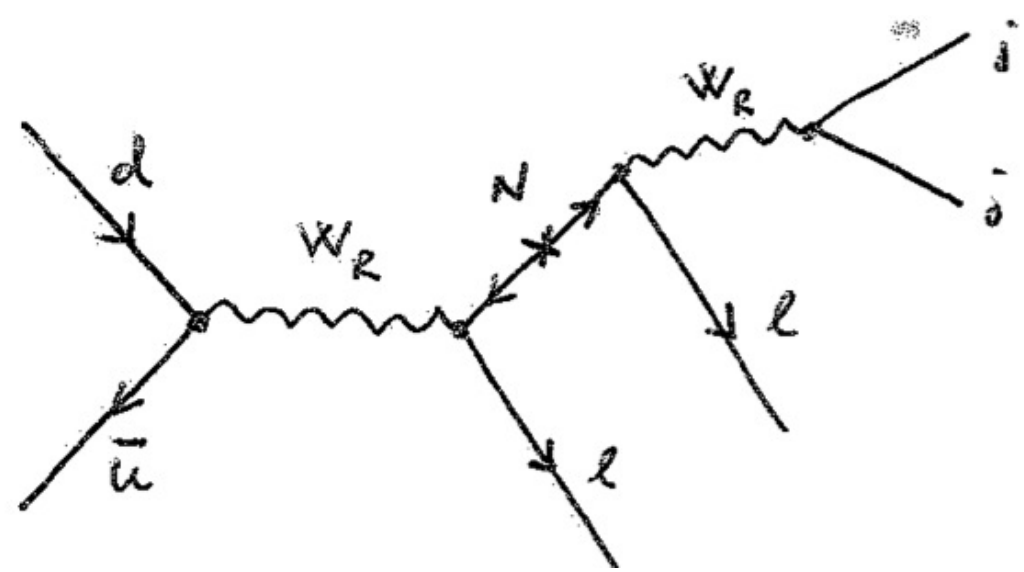
$$V_{CKM} \approx 1$$

RH neutrinos at colliders in LR models

Type-I seesaw:



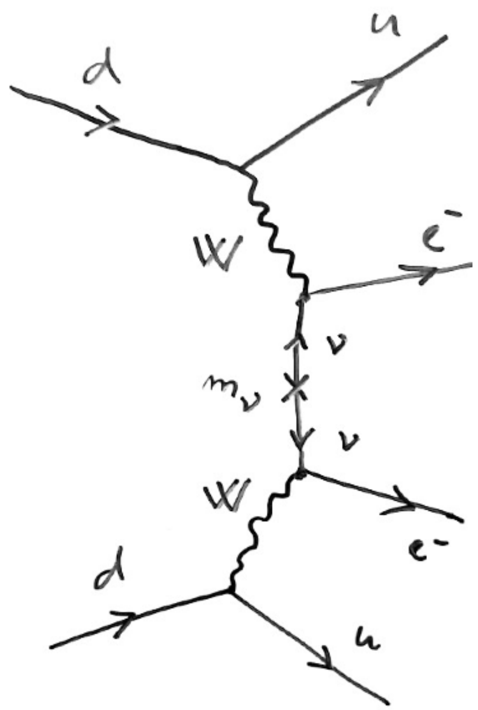
goes much better with right-handed currents



W.Y. Keung and G. Senjanovic, Phys. Rev. Lett. 50, 1427 (1983)

Neutrinoless double beta decay in LR models

Light neutrino mediation



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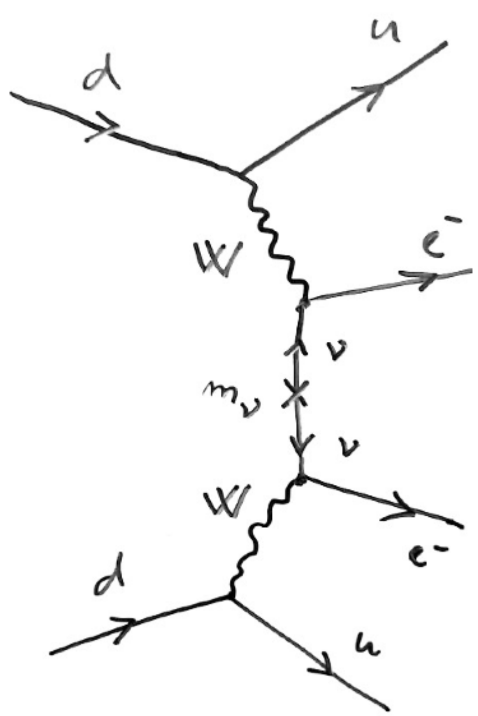

$$\mathcal{A} \propto g^4 \frac{\langle m \rangle}{q^2}$$

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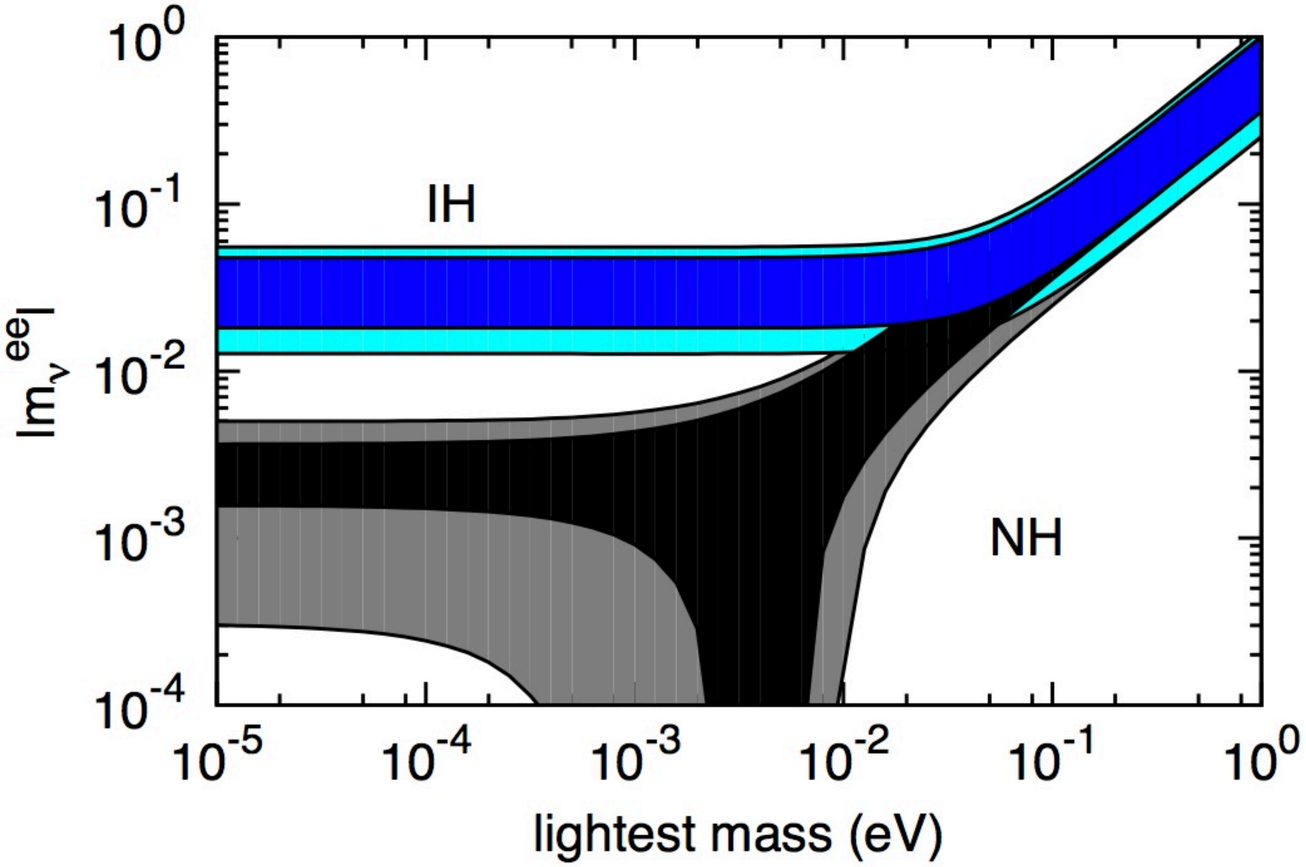

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Figures from Chakrabortty et al., *JHEP* 08 (2012) 008

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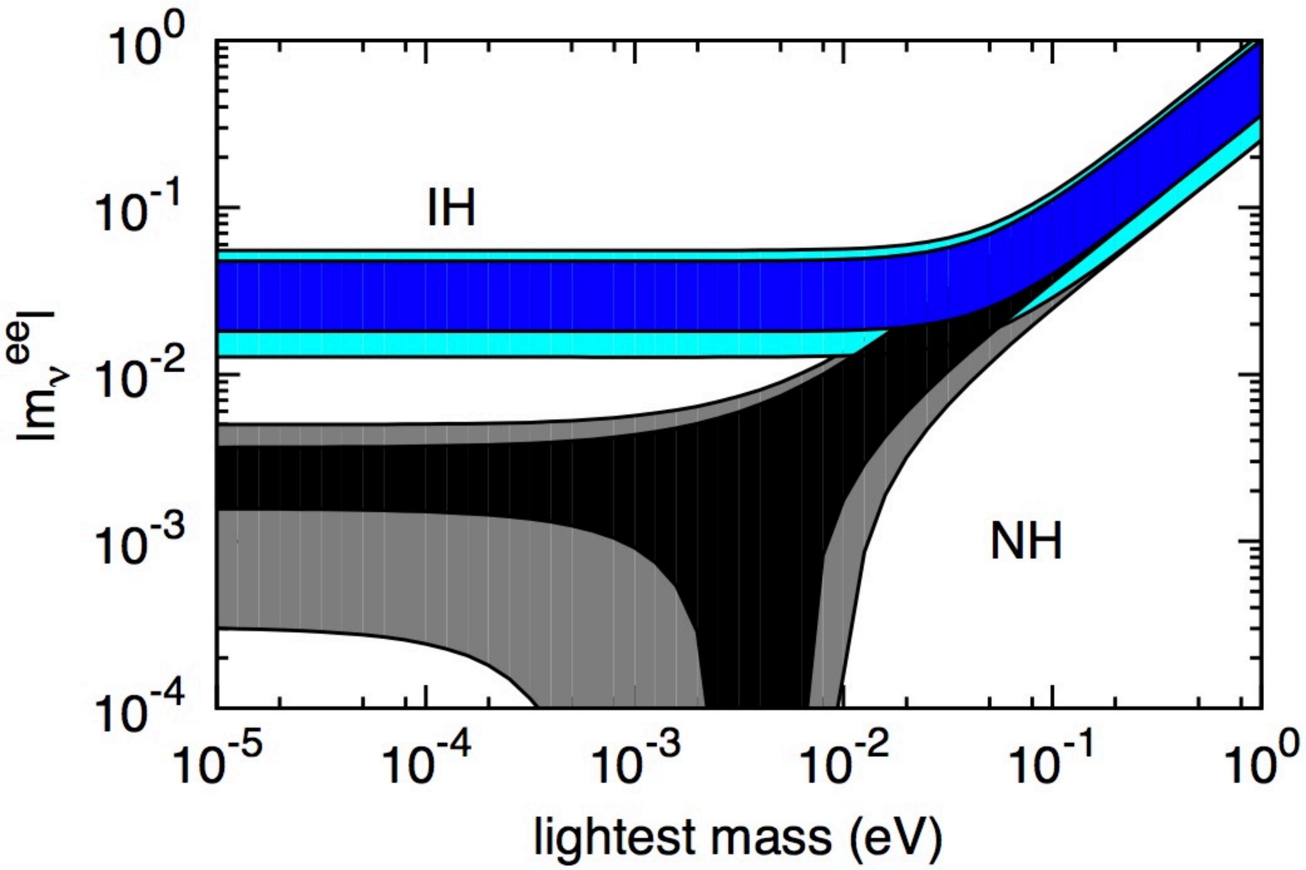

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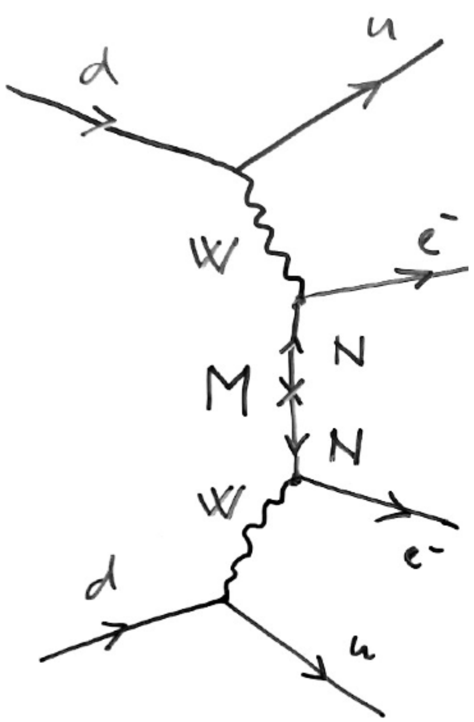
Heavy neutrinos also feel gauge interactions!



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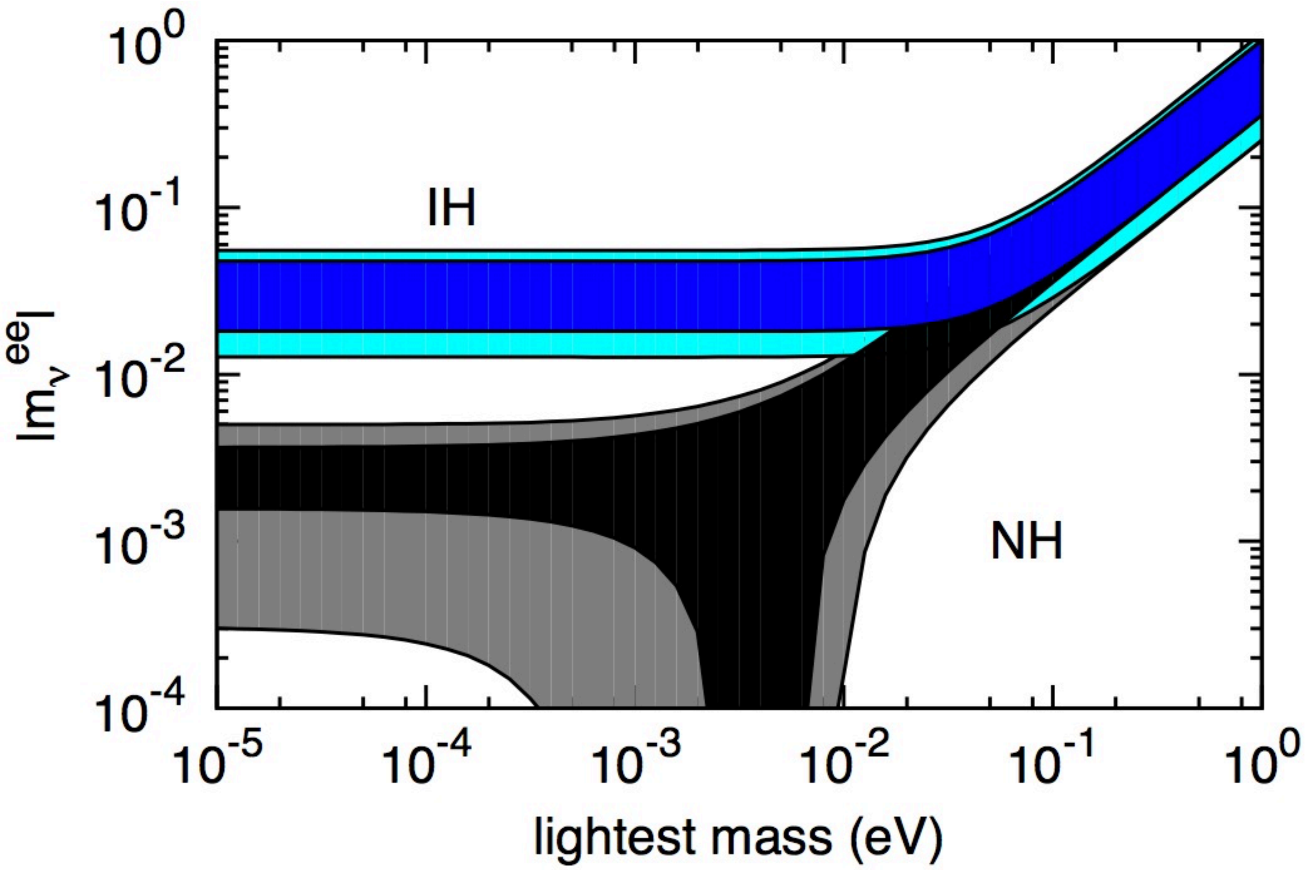

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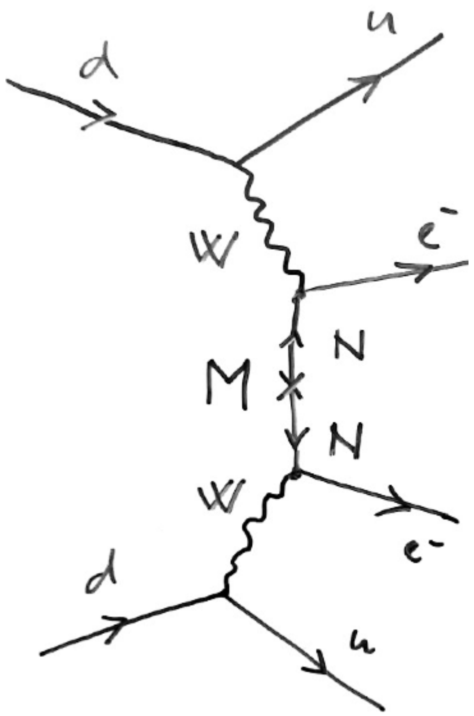

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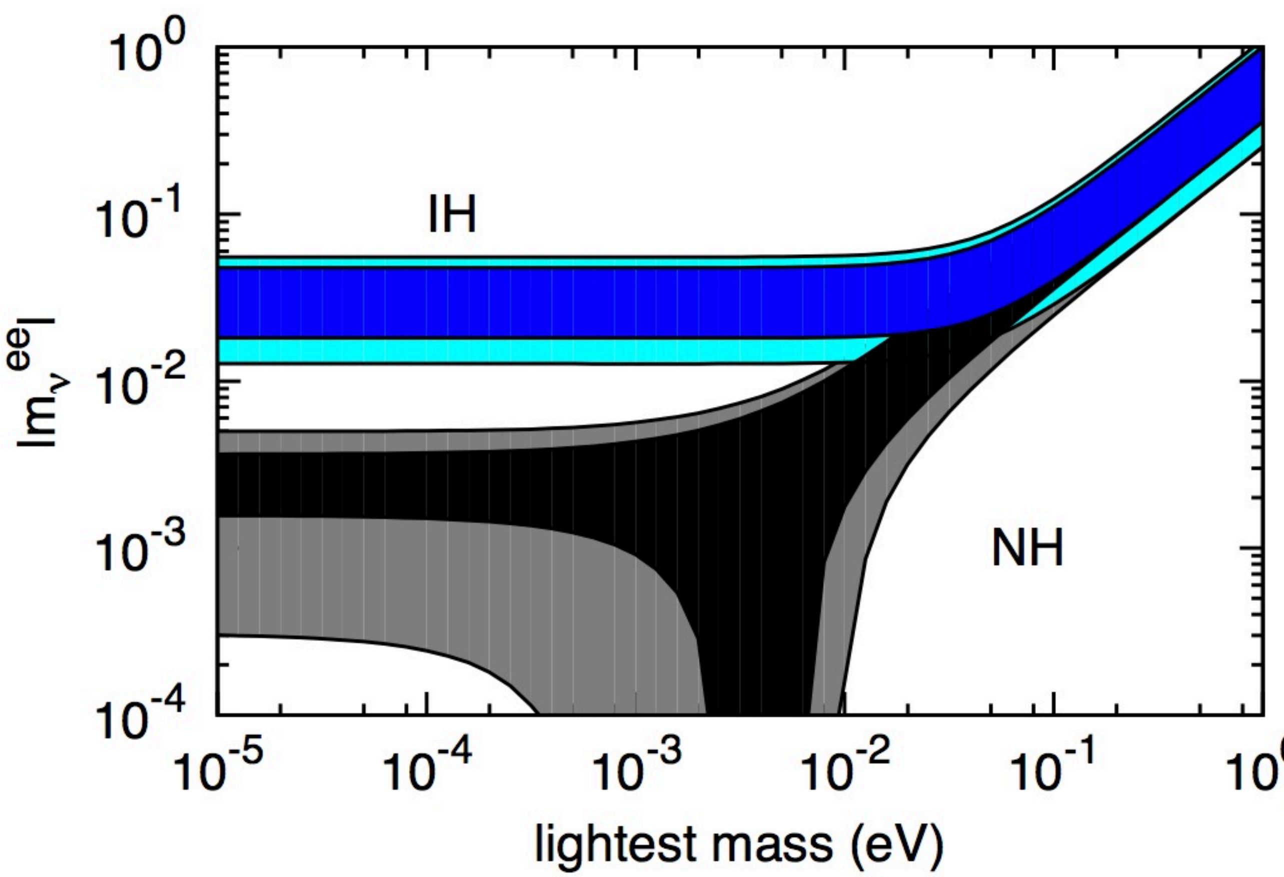

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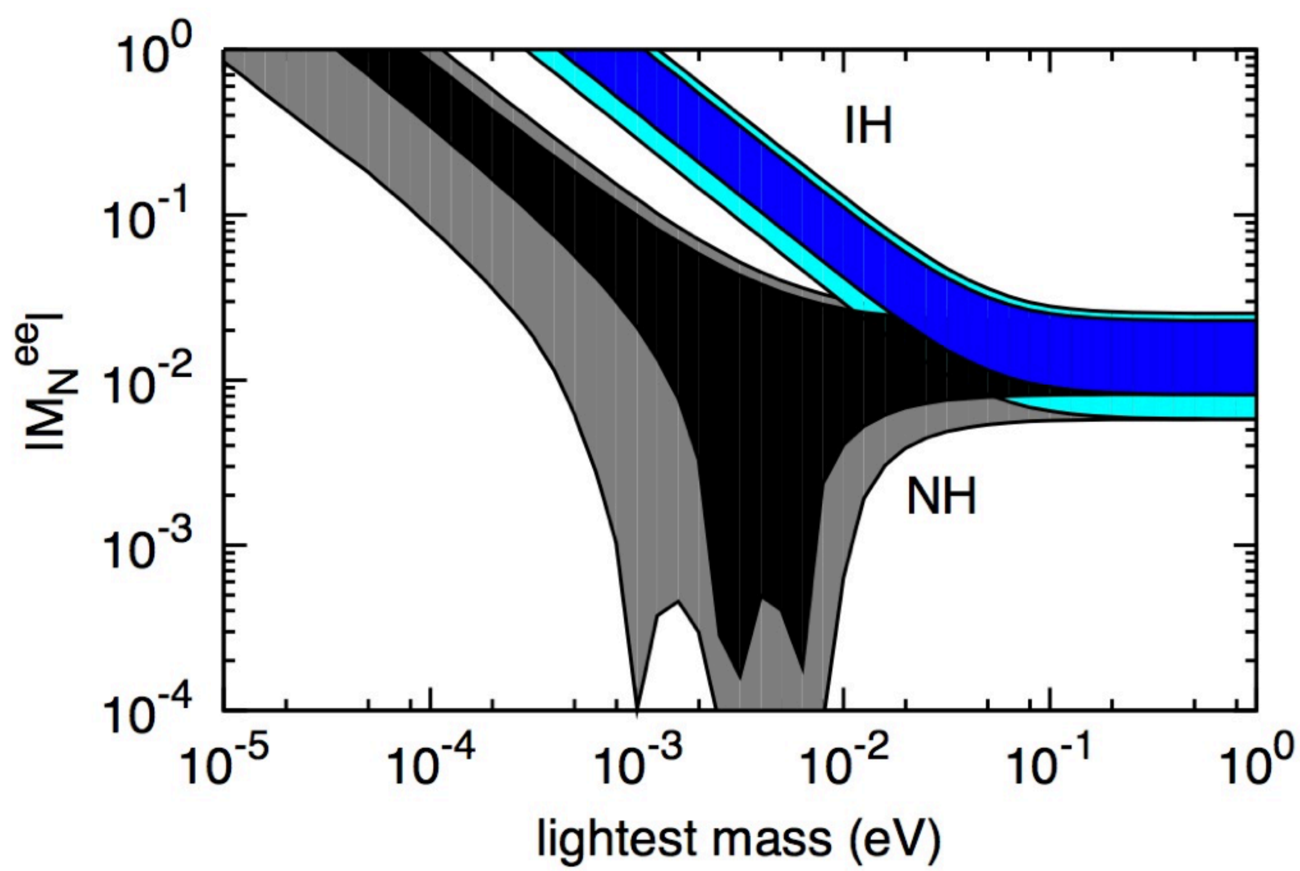

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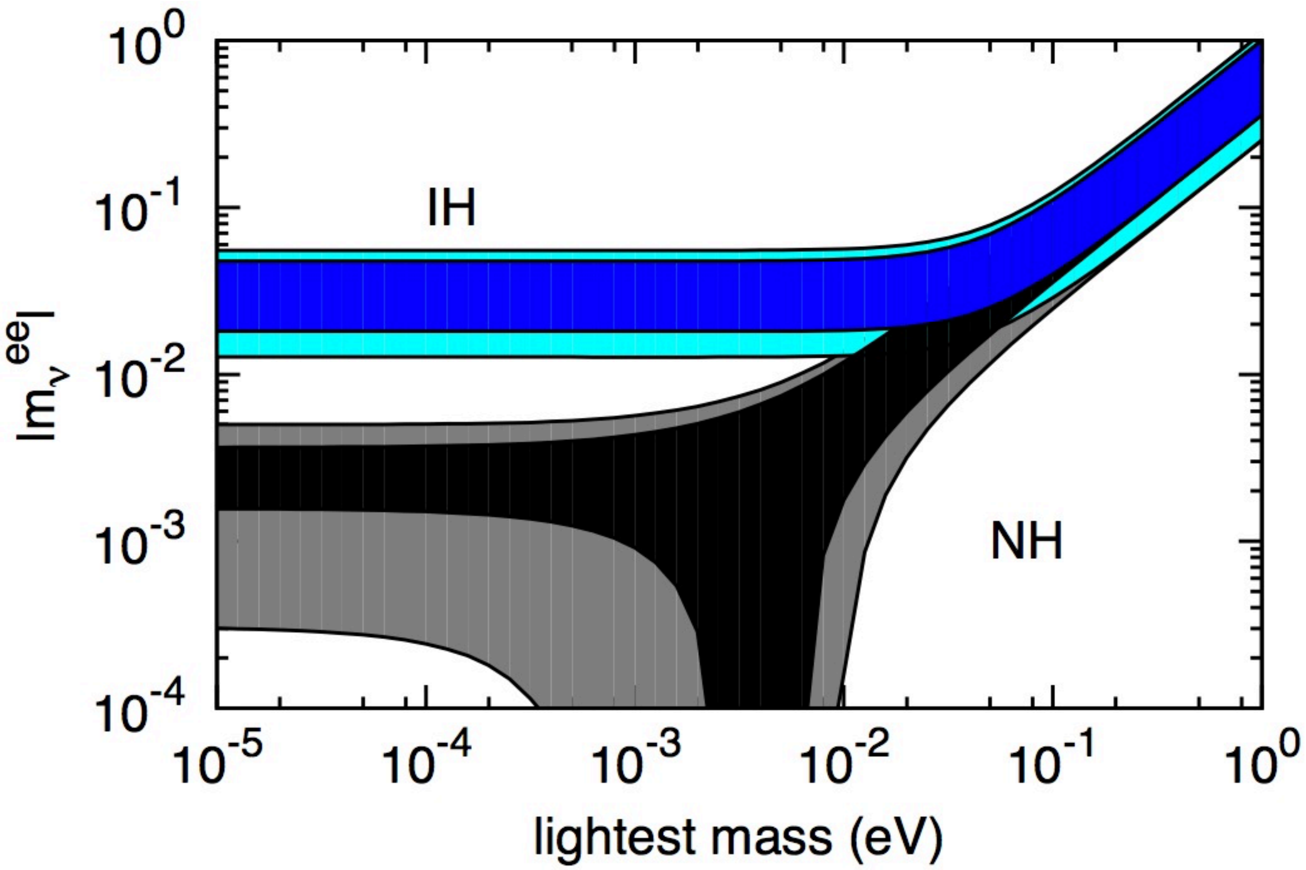

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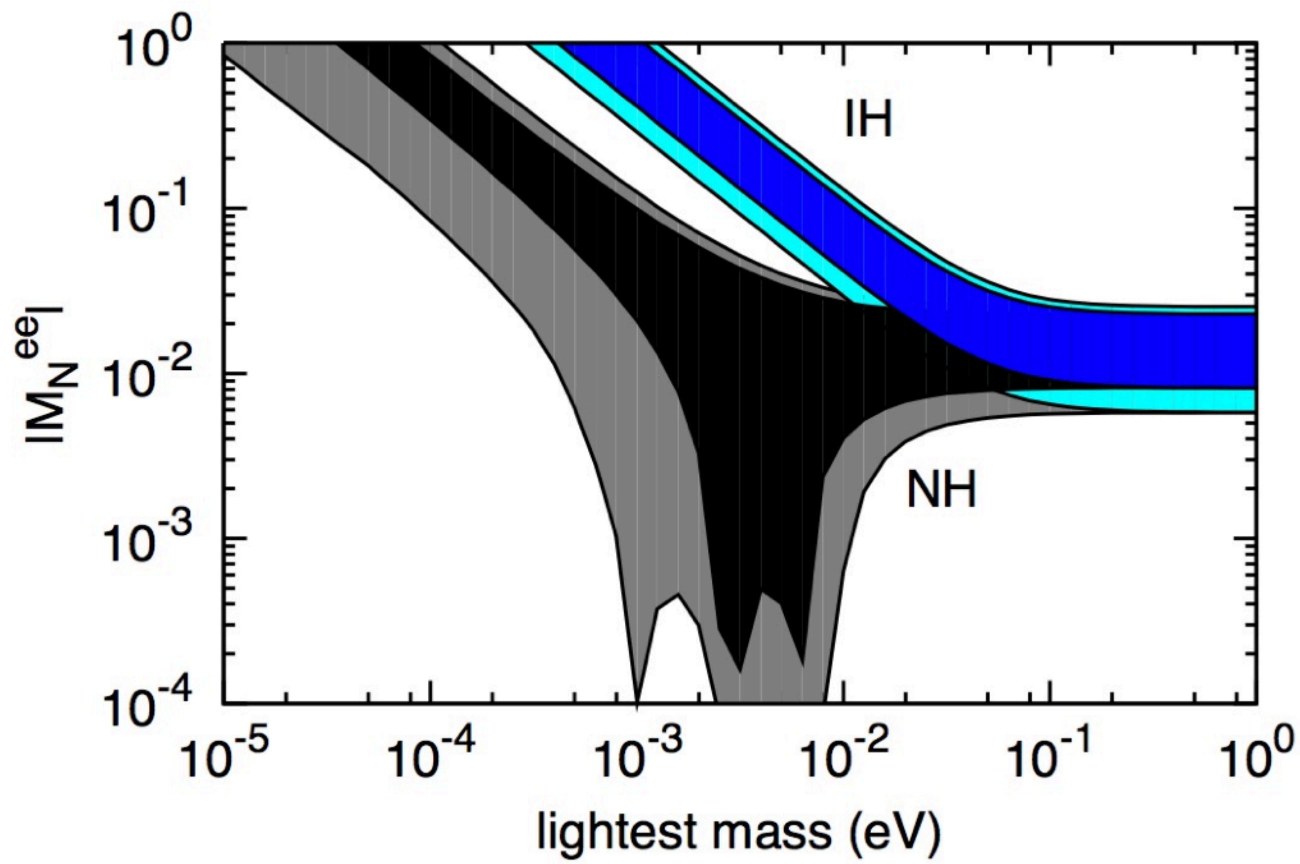

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$$m_{W_R} \gtrsim 1.3 \left(\frac{\langle m_N \rangle}{[1\mathrm{TeV}]} \right)^{-1/4} \mathrm{TeV}$$

“Lepton number as fourth color”

J. C. Pati, A. Salam, Phys. Rev. D 10, 275–289 (1974)

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$$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \qquad \begin{pmatrix} u \\ d \end{pmatrix}_R \begin{pmatrix} \nu \\ e \end{pmatrix}_R$$

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$$SU(3)_c \otimes U(1)_{B-L} \subset SU(4)_C$$

$$\downarrow \qquad\qquad \downarrow$$

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First attempt to unify quarks and leptons... (even before the charm discovery!)

Pati-Salam as a prototype rank-5 Q-L unification

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$$\begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}_{L,R} = (4,2,1) \oplus (\overline{4},1,2)^* \quad \text{of} \quad SU(4)_C \otimes SU(2)_L \otimes SU(2)_R$$

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Heavy singlet and coloured scalars

⇨ perturbative B and L violation (?)

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$$(10,1,3)_{PS} \ni (1,1,0)_{SM} \oplus (6,3,+\tfrac{1}{3})_{\rm SM} \oplus \ldots$$

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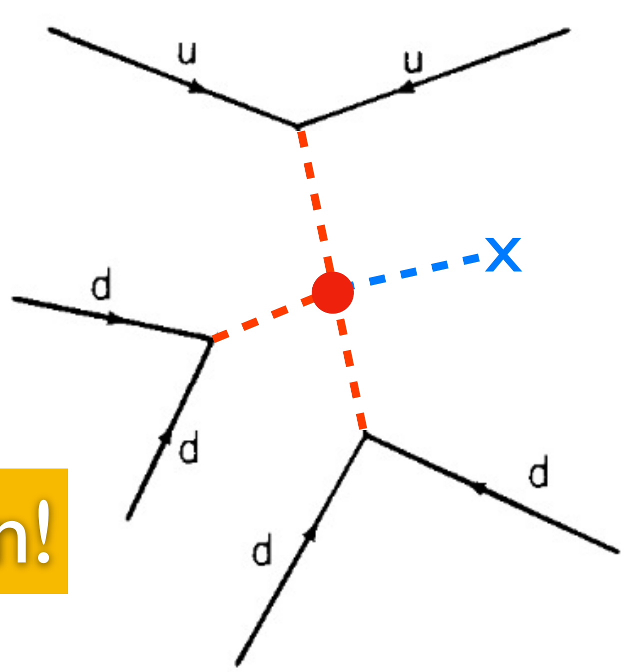

Majorana neutrino in PS implies Majorana neutron!

Extended gauge symmetries?

Part II: Scales

B-L breaking scale in type-I seesaw

$$\mathcal{L} \ni \overline{\nu}_L m_D N_R + \frac{1}{2} M_R N_R^T C N_R + h.c. = \frac{1}{2} n_L^T C \mathcal{M} n_L + h.c.$$

$$\mathcal{M} = \left(\begin{array}{cc} 0 & m_D^T \\ m_D & M_R \end{array} \right) \qquad n_L = \left(\begin{array}{c} \nu_L \\ (N_R)^C \end{array} \right)$$

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Seesaw formula: $$m_\nu = -m_D M_R^{-1} m_D^T$$

$$m_D = \frac{1}{\sqrt{2}} Y_\nu v \ll M_R$$

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Seesaw formula: $$m_\nu = -m_D M_R^{-1} m_D^T$$

$$m_D = \frac{1}{\sqrt{2}} Y_\nu v \ll M_R$$

For O(1) Yukawas: $M_R \sim 10^{12-14}$ GeV

Baryogenesis through leptogenesis - see Frank's lectures

Perturbative LNV + nonperturbative BNV
enough for baryogenesis

Fukugita, Yanagida, PLB174, 1986

$$\frac{n_B}{n_\gamma} \equiv \eta_B = (6.1 \pm 0.3) \times 10^{-10}$$

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1) Net L is generated in the heavy "RH" neutrino decays:

CP asymmetry: $$\epsilon_1 = \frac{\sum_\alpha [\Gamma(N_1 \to \ell_\alpha H) - \Gamma(N_1 \to \bar{\ell}_\alpha \overline{H})]}{\sum_\alpha [\Gamma(N_1 \to \ell_\alpha H) + \Gamma(N_1 \to \bar{\ell}_\alpha \overline{H})]}$$

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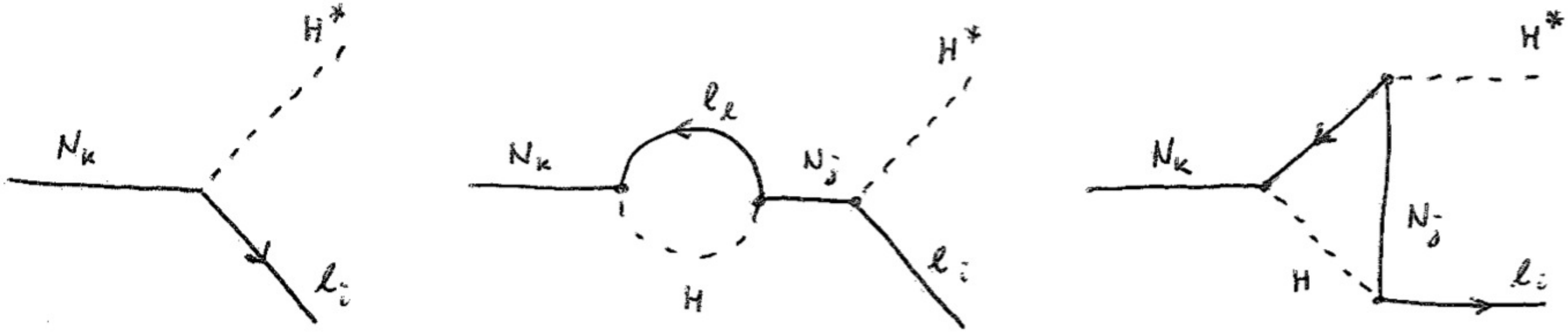
2) Sphalerons provide L to B transitions before EWPT

Kuzmin, Rubakov, Shaposhnikov, PLB155, 1985

Baryogenesis through leptogenesis - see Frank's lectures



CP asymmetry:

$$\epsilon_1 \approx -\frac{3}{8\pi}\frac{1}{(Y_N Y_N^\dagger)_{11}}\sum_{i=2,3} \mathrm{Im}\left[(Y_N Y_N^\dagger)^2_{1i}\right]\frac{M_1}{M_i}$$

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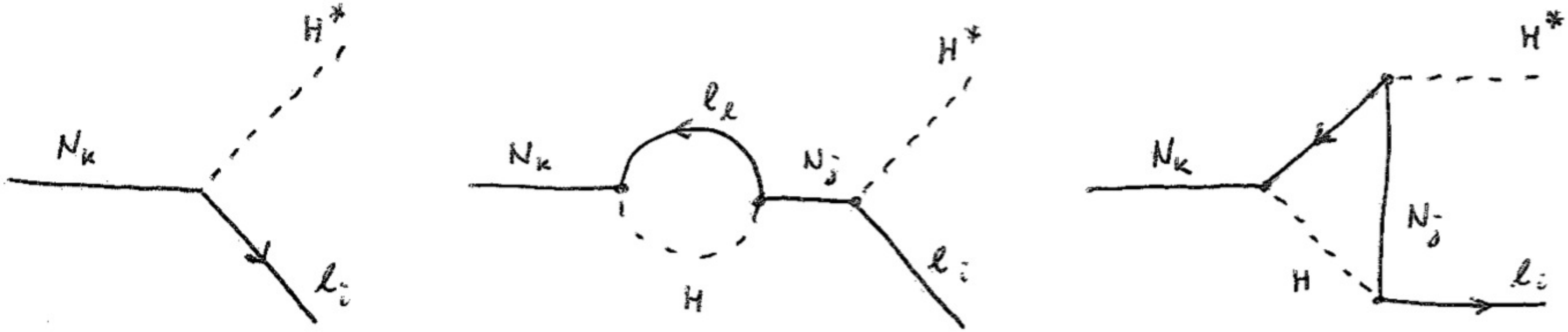

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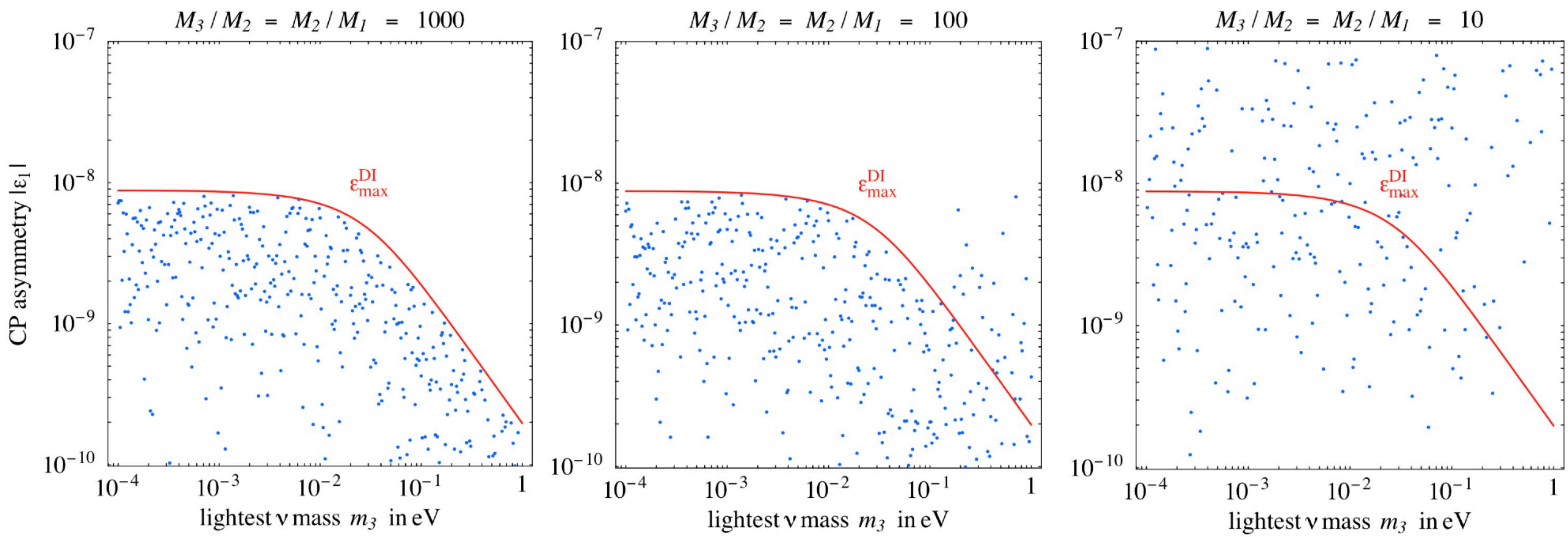
Davidson-Ibarra bound: S. Davidson and A. Ibarra, Phys. Lett. B535, 25 (2002)

$$|\epsilon_1| \leq \frac{3}{16\pi}\frac{M_1(m_3-m_2)}{v^2}$$

$M_1 > 10^9$ GeV

Baryogenesis through leptogenesis - see Frank's lectures

NB Strictness of the D-I limit



T. Hambye, Y. Lin, A. Notari, M. Papucci, A. Strumia, Nucl.Phys.B 695 (2004)

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The vacuum instability issue in the SM

With m_H=125 GeV the SM vacuum may be unstable

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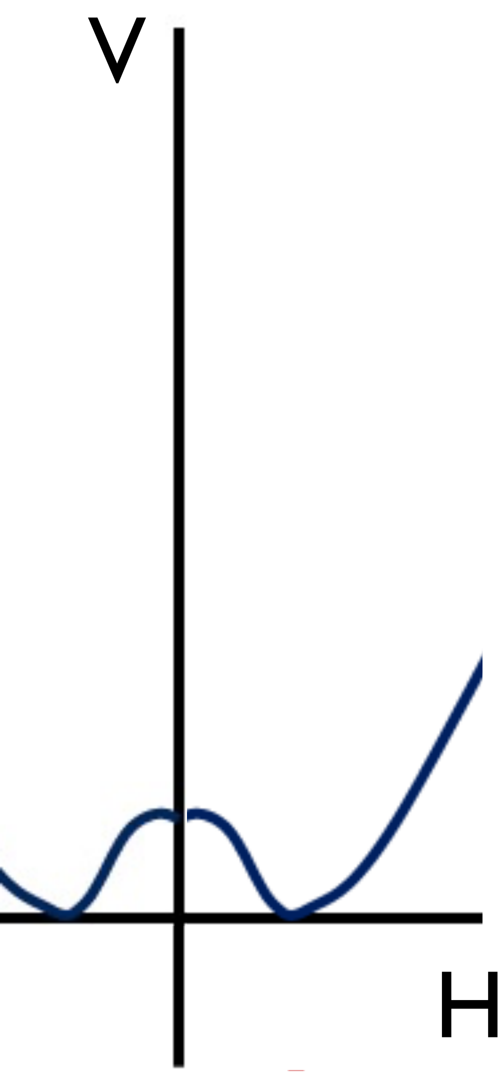

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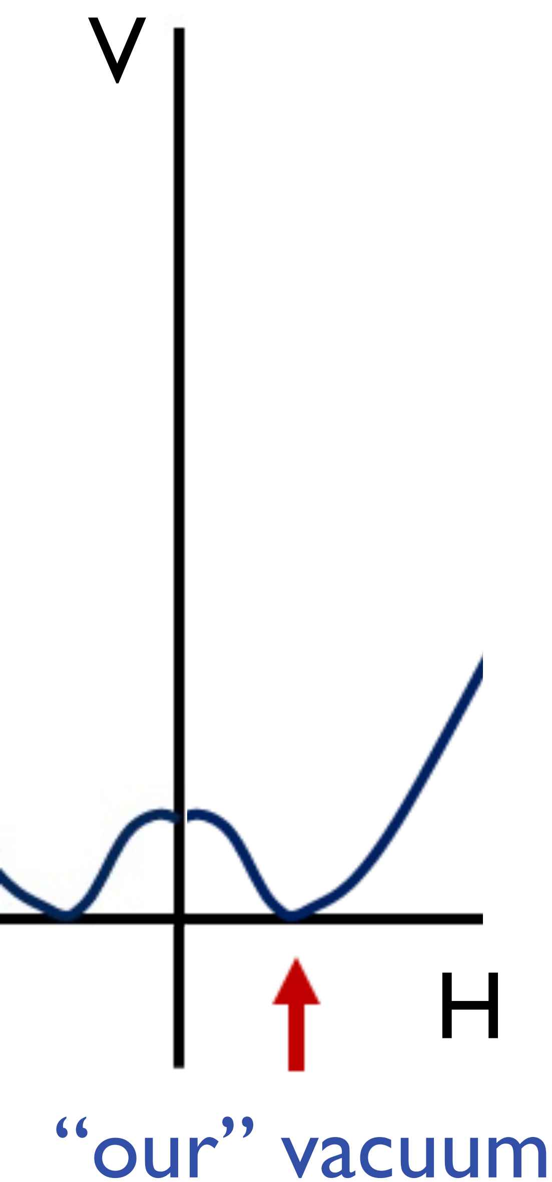

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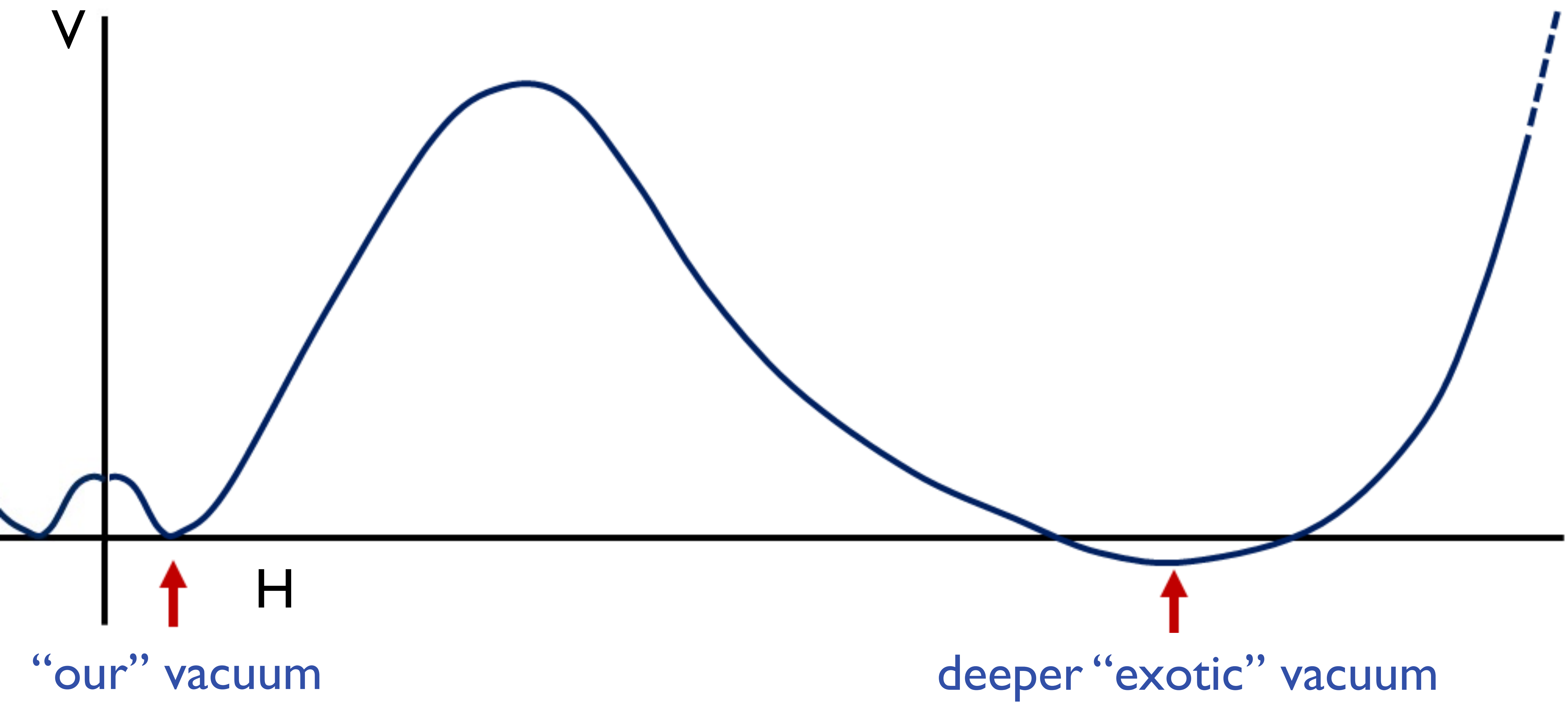
With m_H=125 GeV the SM vacuum may be unstable



The vacuum instability issue in the SM

$$16\pi^2\beta_\lambda^{1-loop} = 24\lambda^2 - 6y_t^4 + \frac{3}{8}(g'^2 + g^2)^2 + \frac{3}{4}g^4 + \lambda(-3g'^2 - 9g^2 + 12y_t^2)$$

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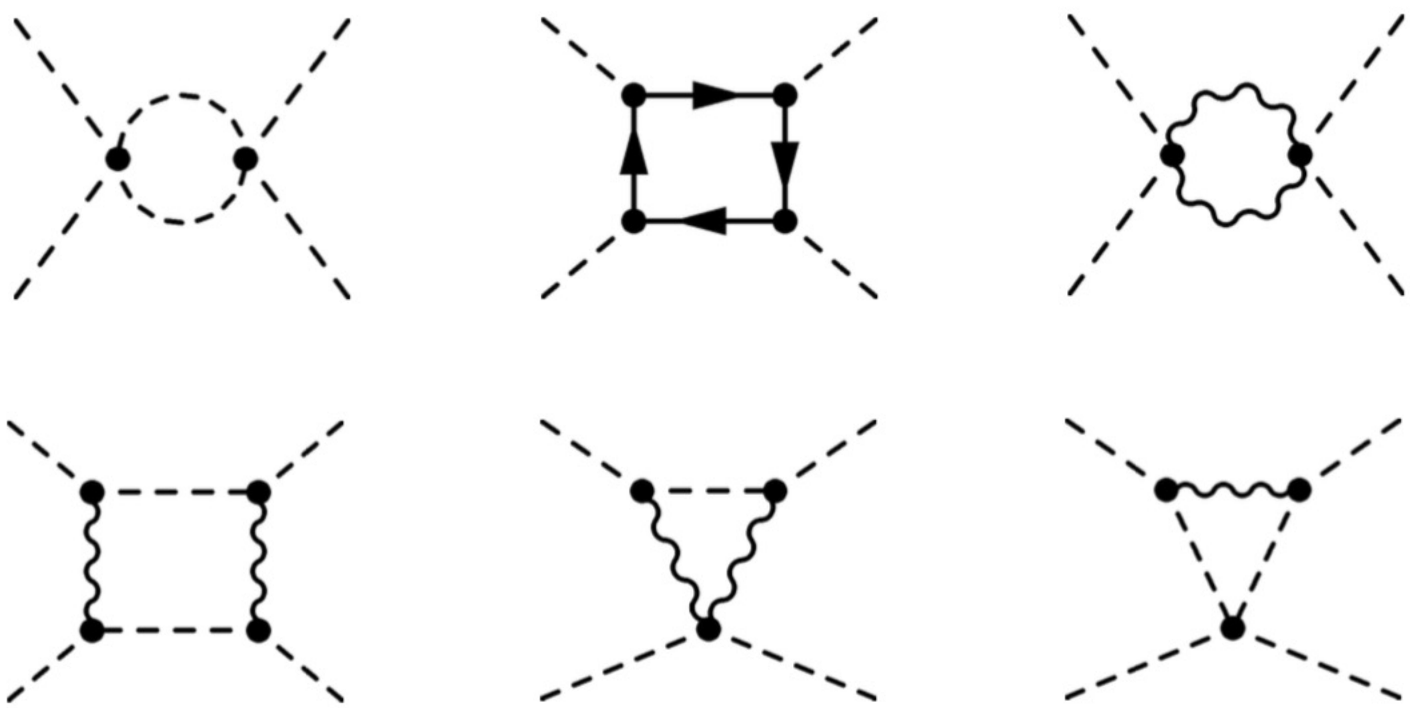

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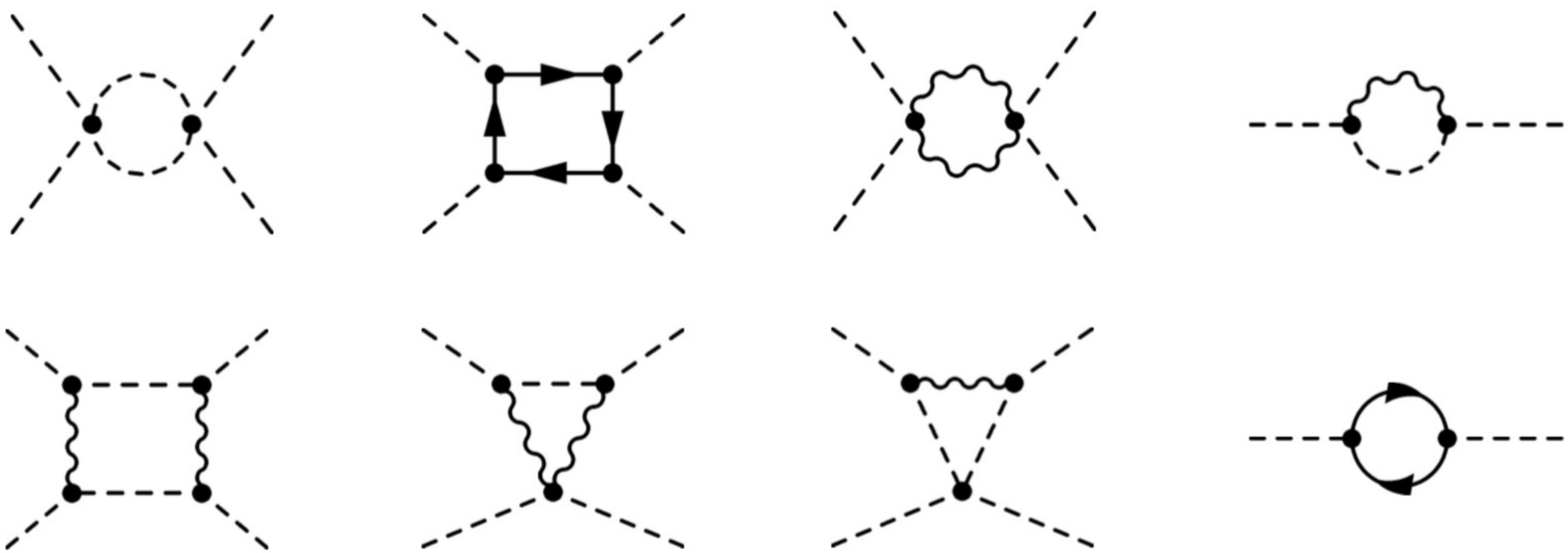

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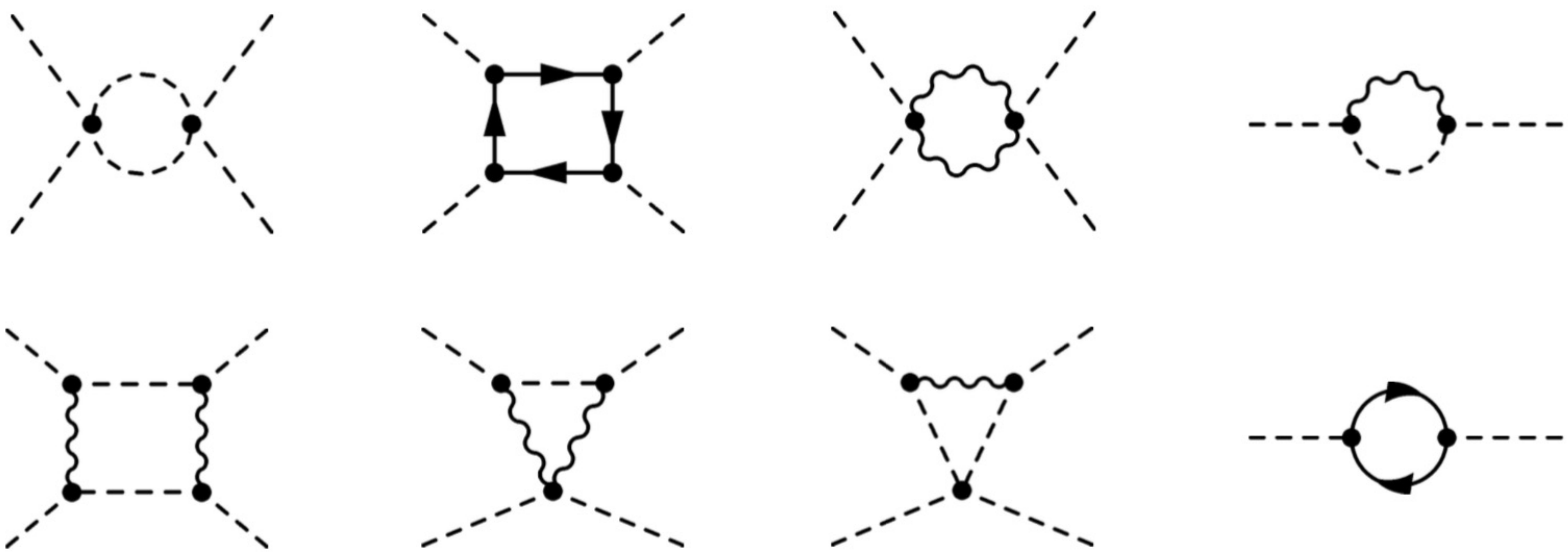

+ RHS terms: push λ up with increasing energy

\- RHS terms: push λ down with increasing energy

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D.Buttazzo, G.Degrassi, P. P.Giardino, G. F. Giudice, F.Sala, A.Salvio and A.Strumia, JHEP 1312, 089 (2013)

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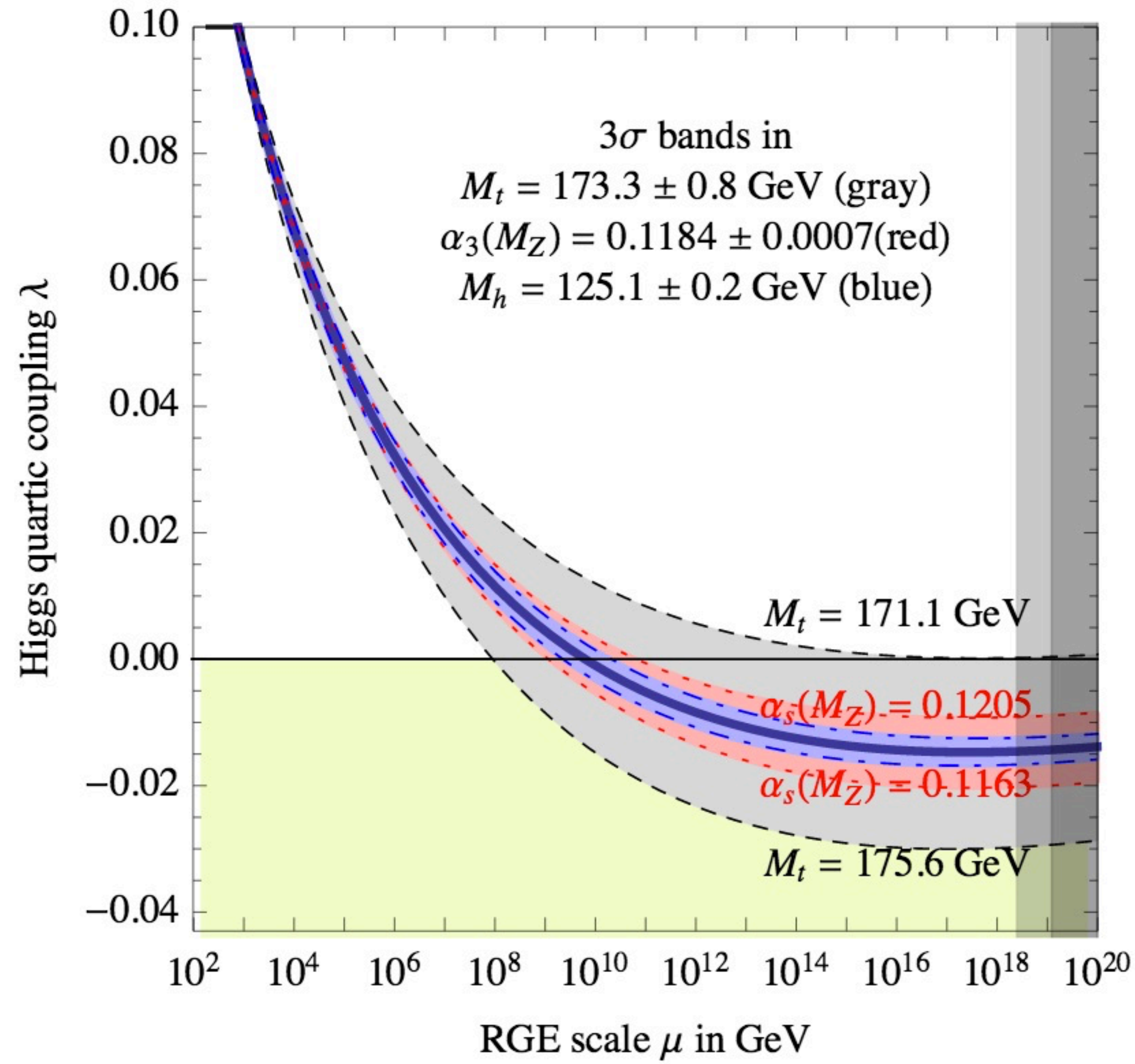

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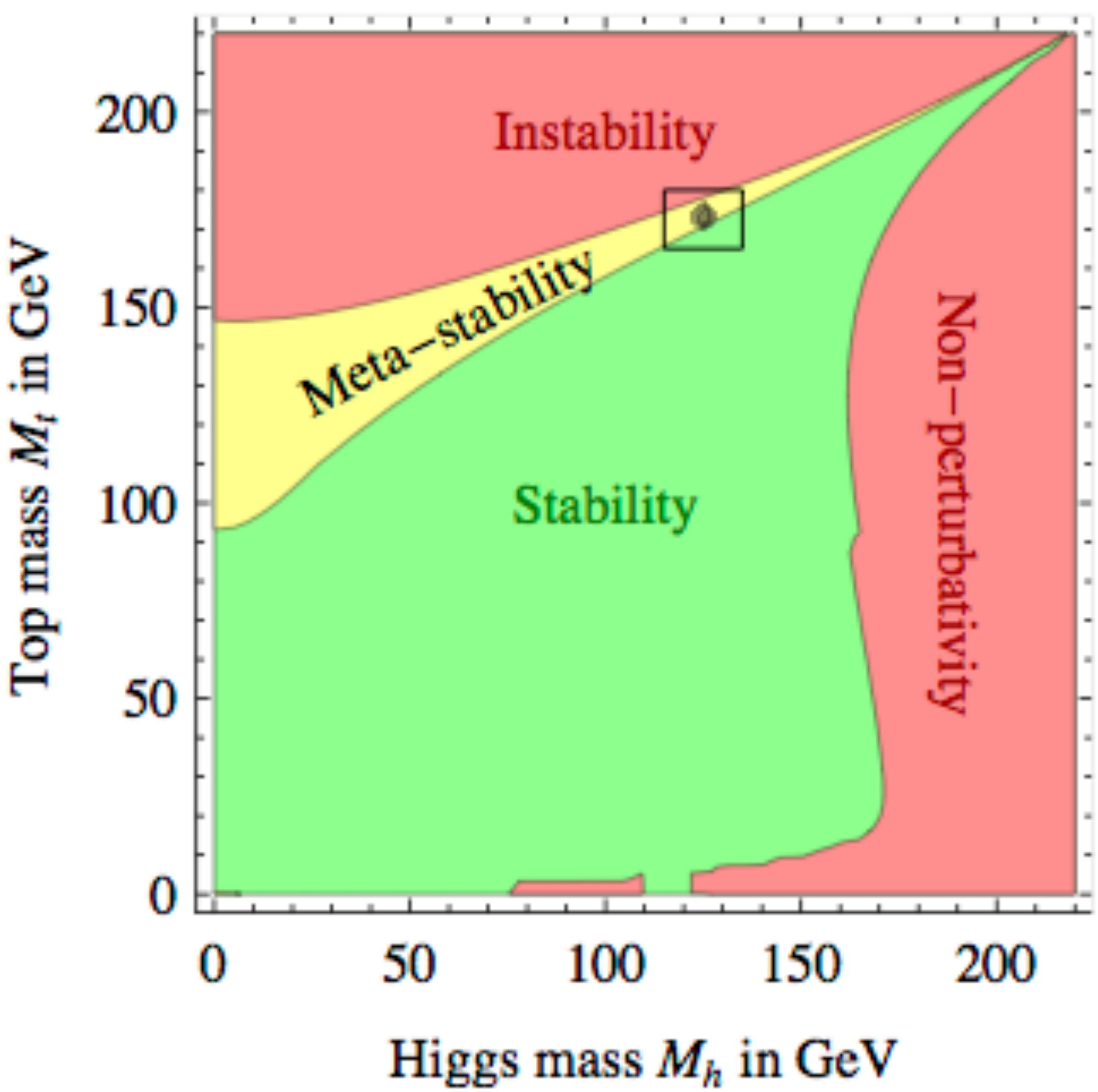

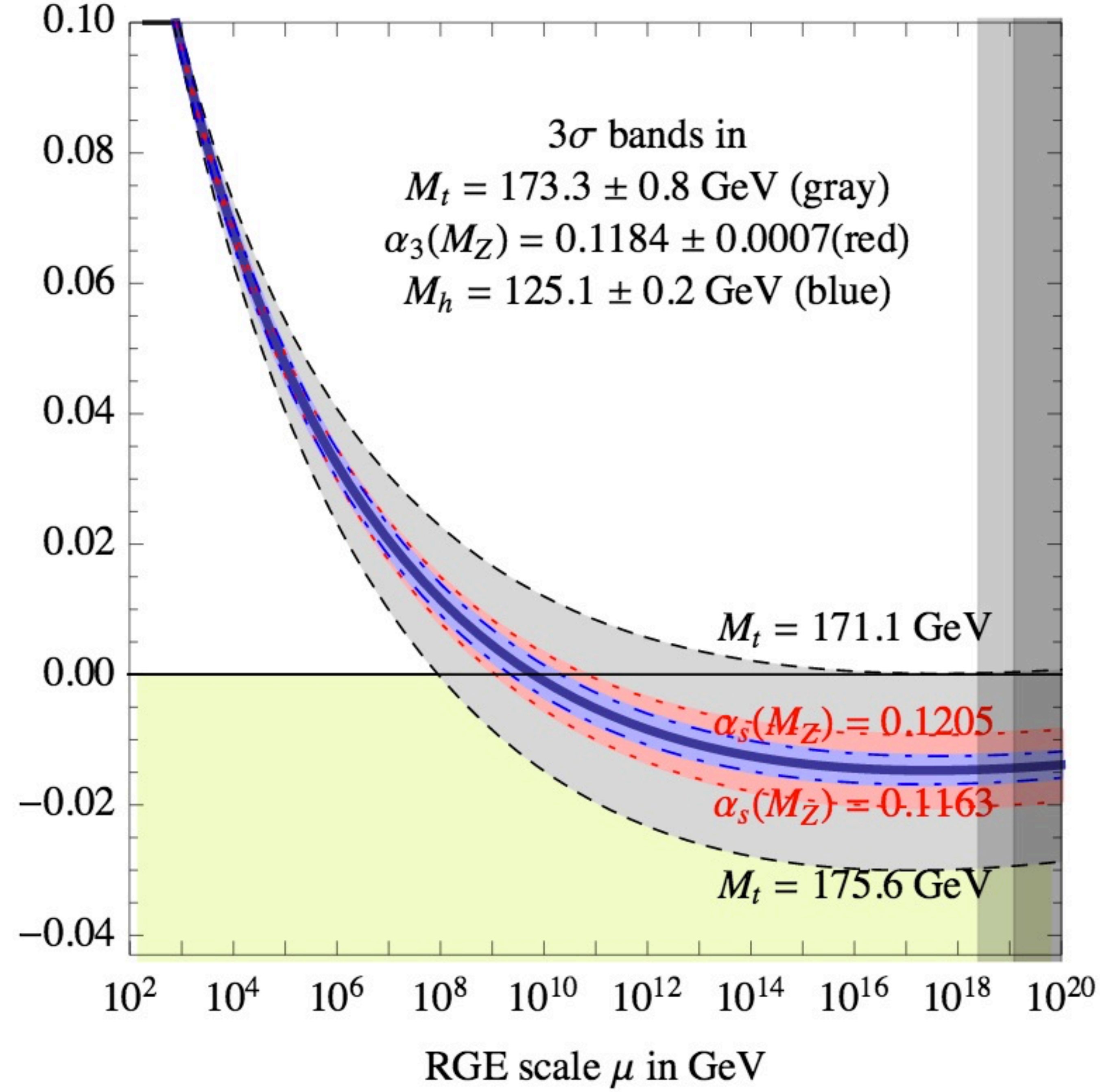

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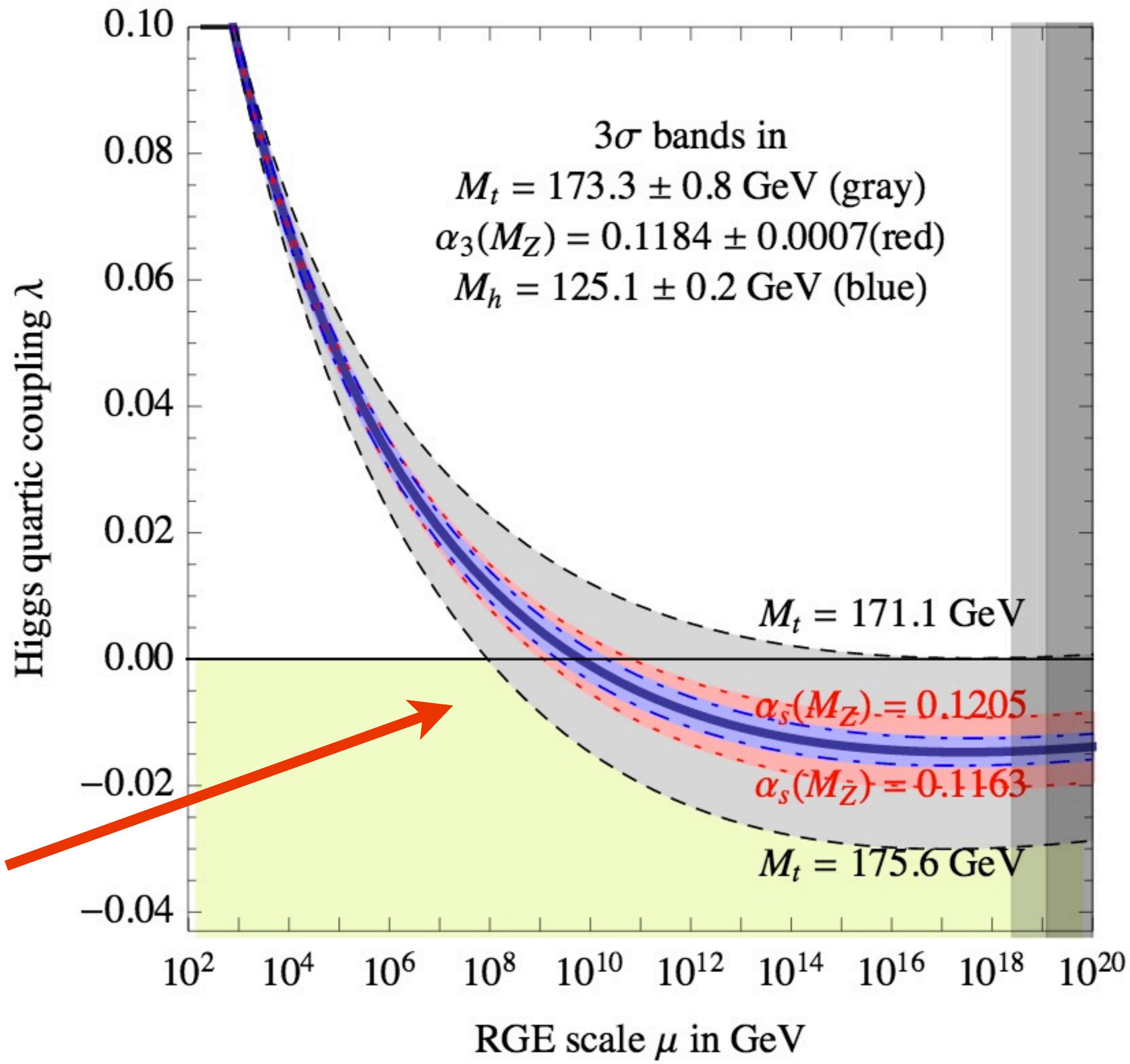

New physics may need to pop up before lambda gets significantly negative

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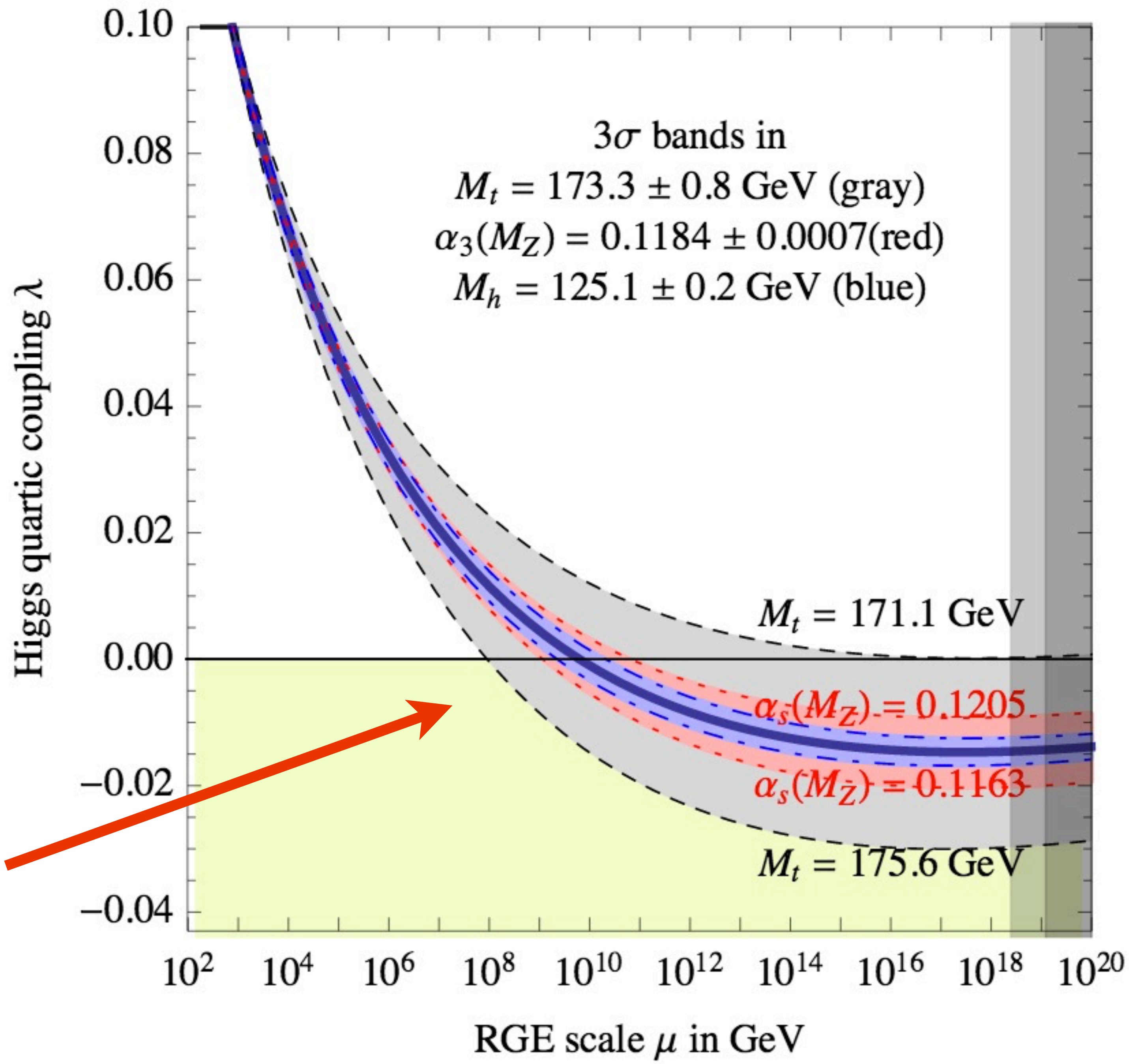

$M_{NP} < 10^{10\text{-}12}$ GeV(?)

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Vacuum stabilization in the seesaw models?

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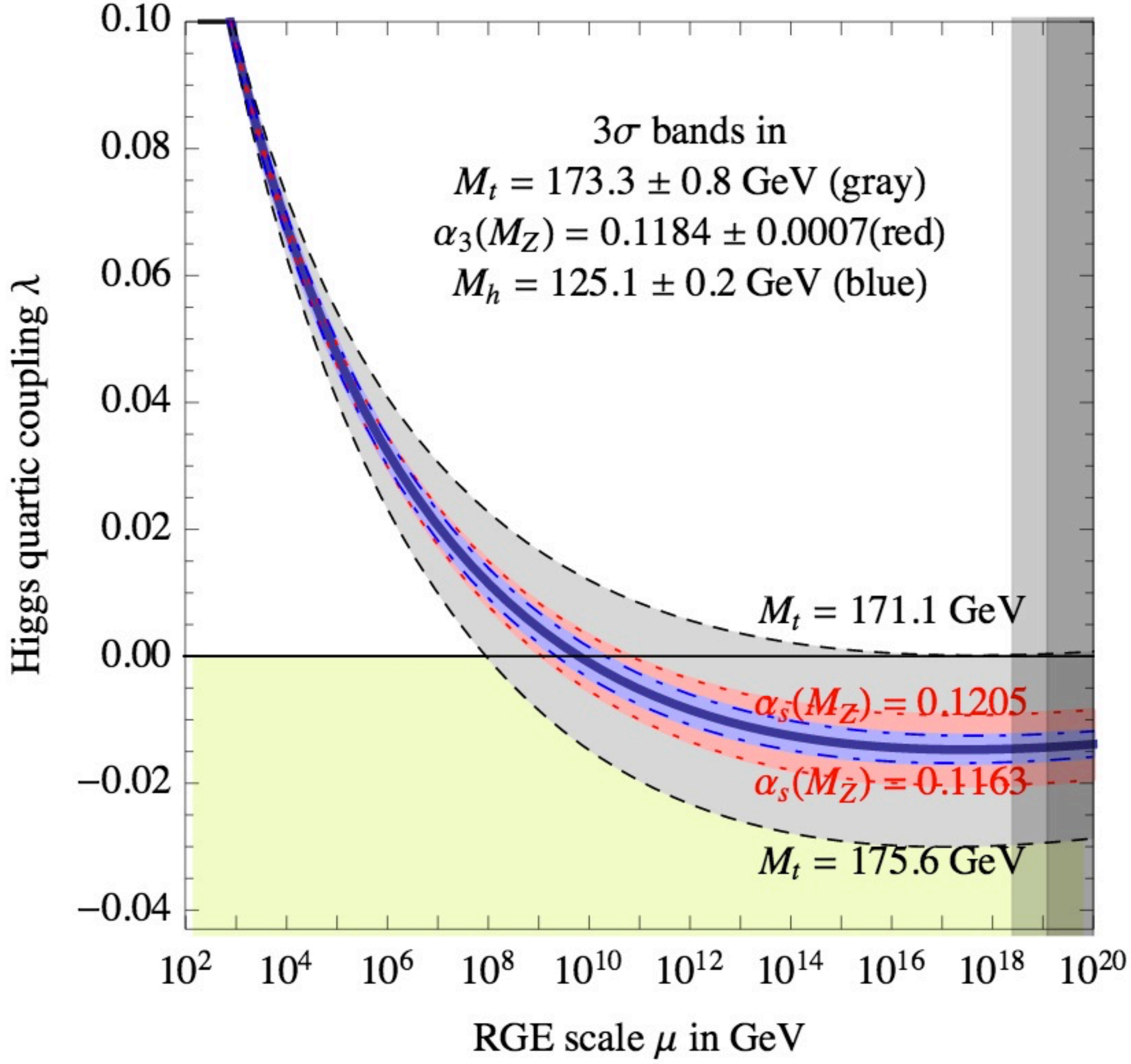

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Type-I seesaw: $\Delta\beta_\lambda^{1-loop} = -2y_\nu^4 + y_\nu^2\lambda$

may help if the effect kicks in "soon enough" and the Yukawa remains large

see, e.g., W. Rodejohann, H. Zhang JHEP 1206 (2012) 022 and references therein

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Type-II seesaw: $\Delta\beta_\lambda^{1-loop} = \sum_i p_i\lambda_i^2, \quad p_i > 0$ — - beta-function effect

$$\lambda^{>} = \lambda^{<} + \frac{\mu^2}{m_\Delta^2}$$

- matching effect

see, e.g., W. Rodejohann, H.Zhang JHEP 1206 (2012) 022 and references therein

In all these cases the new physics scale was huge!

(EFT time…)

SM as an effective theory: d=6 operators

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

B. Grzadkowski et al., JHEP 10 (2010) 085, arXiv: 1008.4884

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$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

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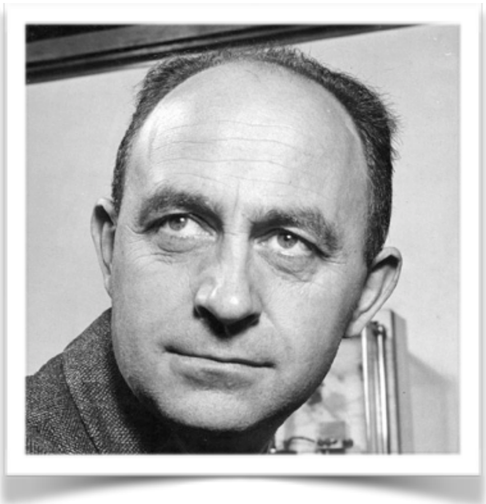
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu \tau^I l_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

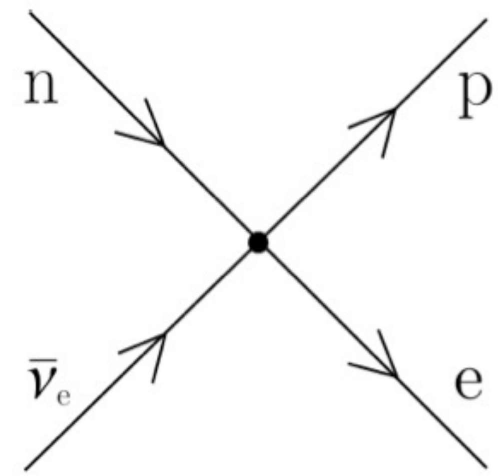
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating and also L-violating!	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

B. Grzadkowski et al., JHEP 10 (2010) 085, arXiv: 1008.4884

Renormalizable dynamics generating the d=6 BLNV operators?



Elementary vertex:



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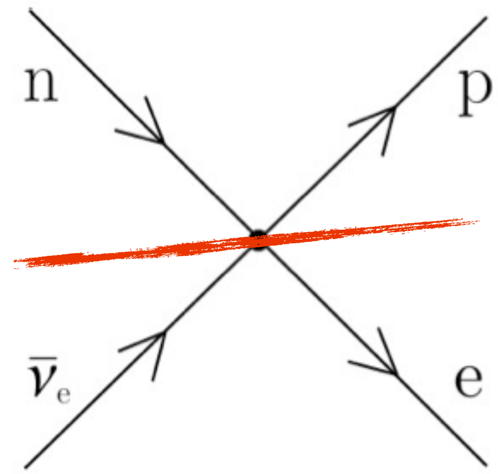
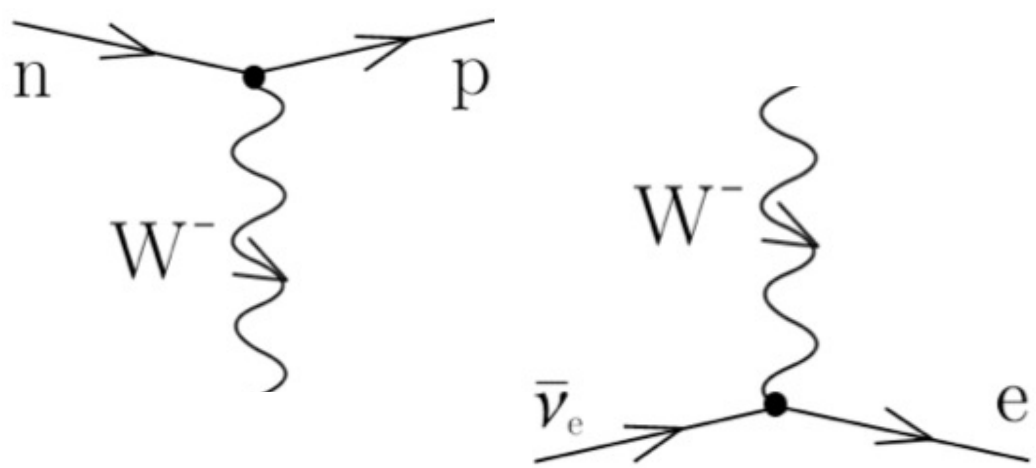
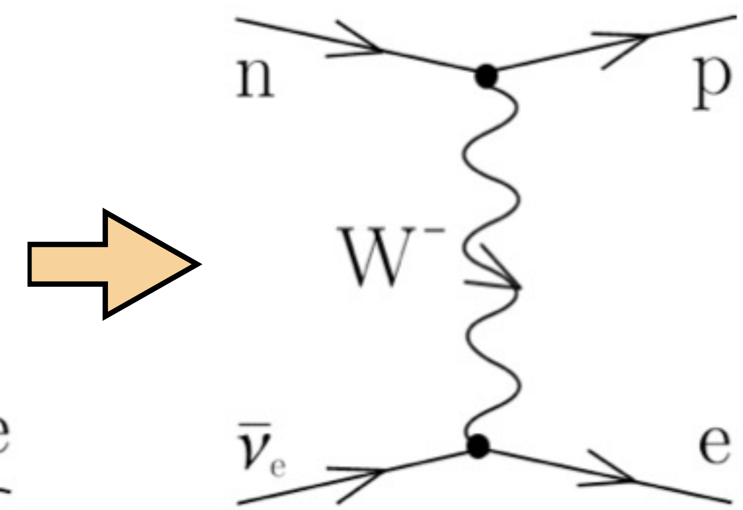


QED-like seed of
a renormalizable theory

Elementary vertices:





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Example: $(d_R^T C\, u_R)(Q_L^T C\, L_L)$

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Scalar exchange

$$(3,1,-\tfrac{1}{3}) \oplus (\overline{3},1,+\tfrac{1}{3})$$

$$\Delta$$

Renormalizable dynamics generating the d=6 BLNV operators?

Fierz

Example: $(d_R^T\, C\, u_R)(Q_L^T\, C\, L_L) = [\overline{(u_R)^c}\gamma_\mu Q][\overline{(d_R)^c}\gamma_\mu L]$

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X^μ

Renormalizable dynamics generating the d=6 BLNV operators?

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Example: $(d_R^T\, C\, u_R)\!\!\!/(Q_L^T\, C\, L_L) = [\overline{(u_R)^c}\gamma_\mu Q]\!\!\!/[\overline{(d_R)^c}\gamma_\mu L]$

Scalar exchange

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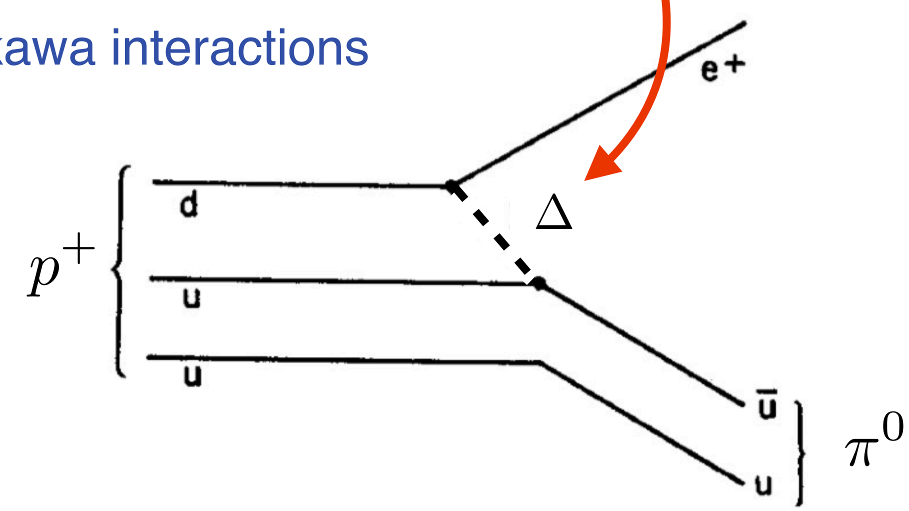
Proton instability!

new Yukawa interactions



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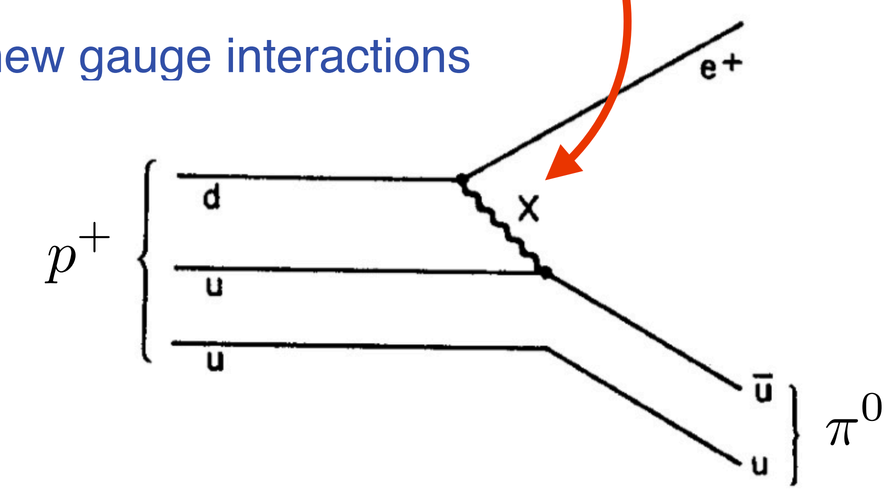

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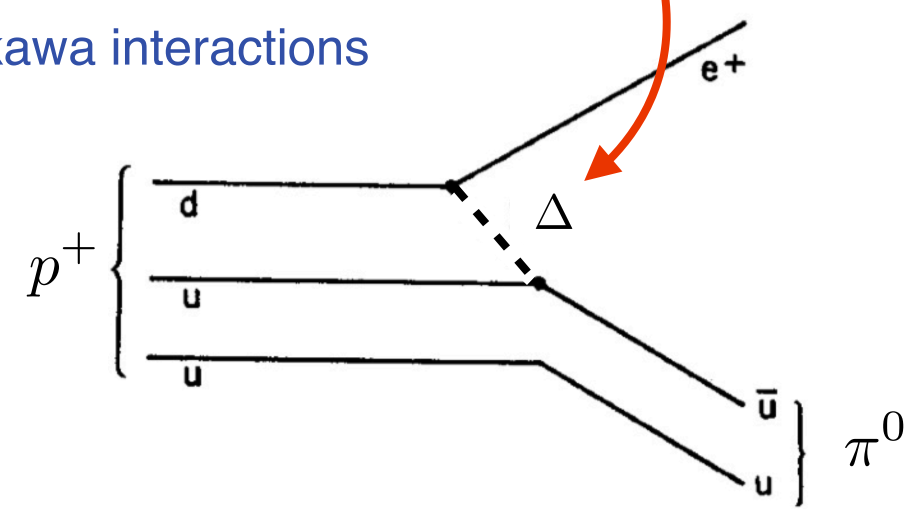

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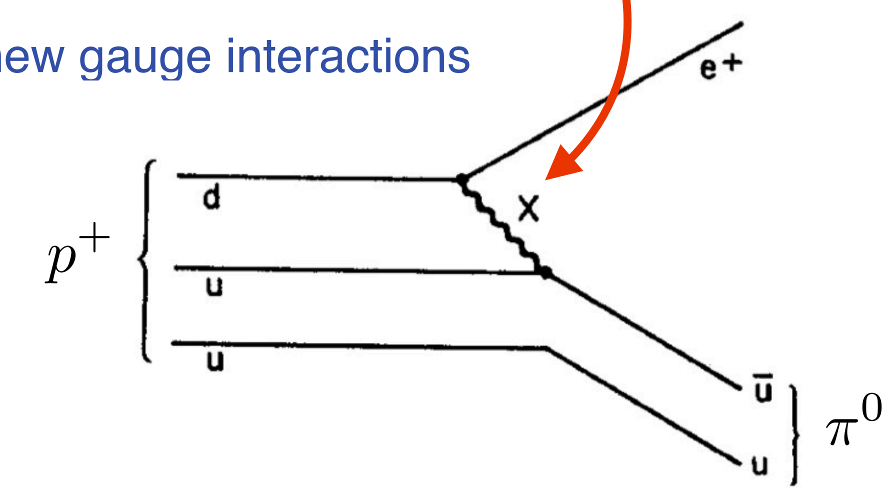


What do we know about the suppression scale of these operators?

Existing limits

1950's - M. Goldhaber

$$\tau(p^+) > 10^{18} y$$

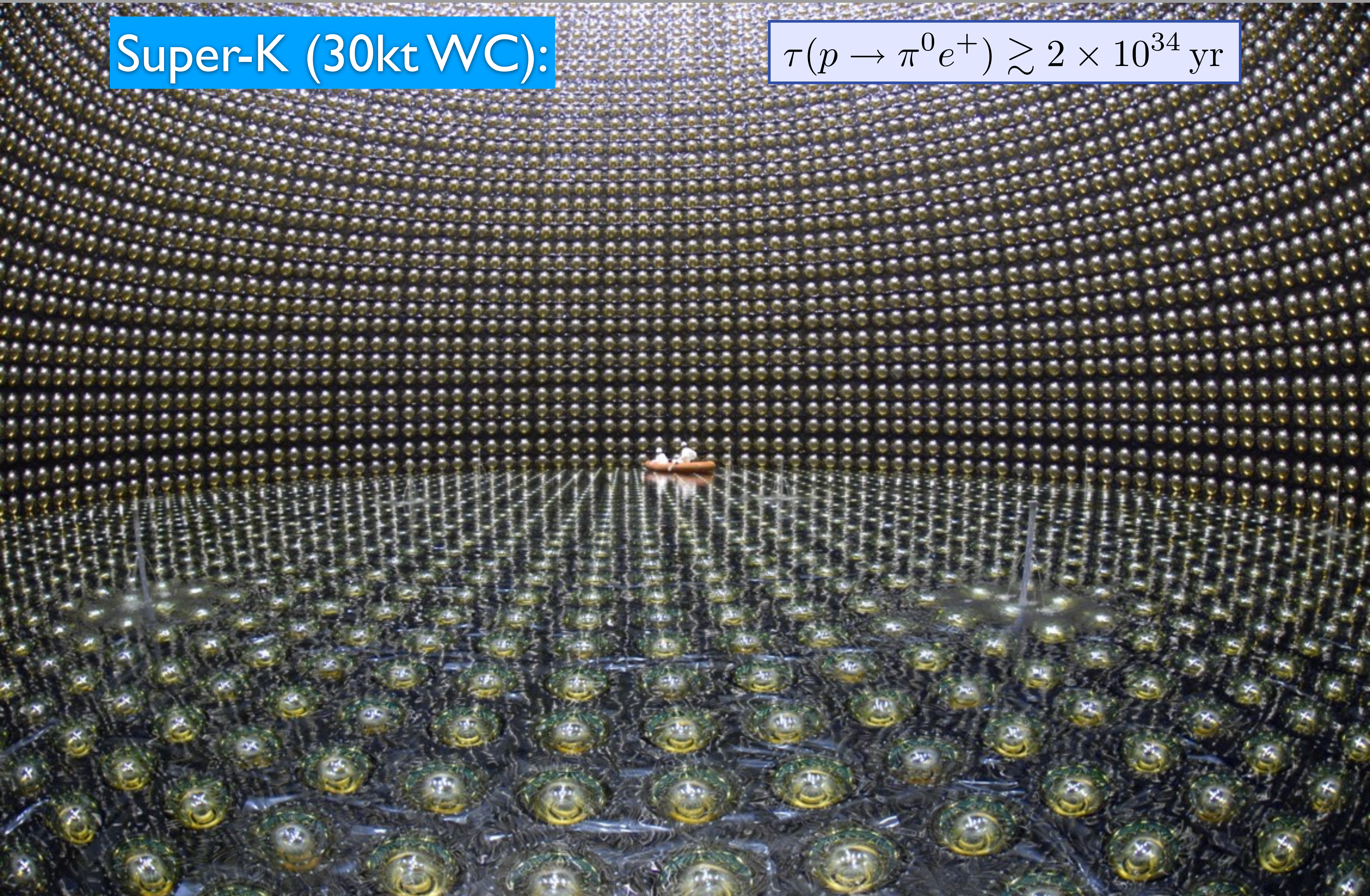
"Tickle in the bones" argument...

NB. 50% lethal dose is about $10^{14-15}\,\mathrm{MeV}/y$

Best limits - large WC detectors

Super-K (30kt WC):

$\tau(p \to \pi^0 e^+) \gtrsim 2 \times 10^{34}\,\mathrm{yr}$



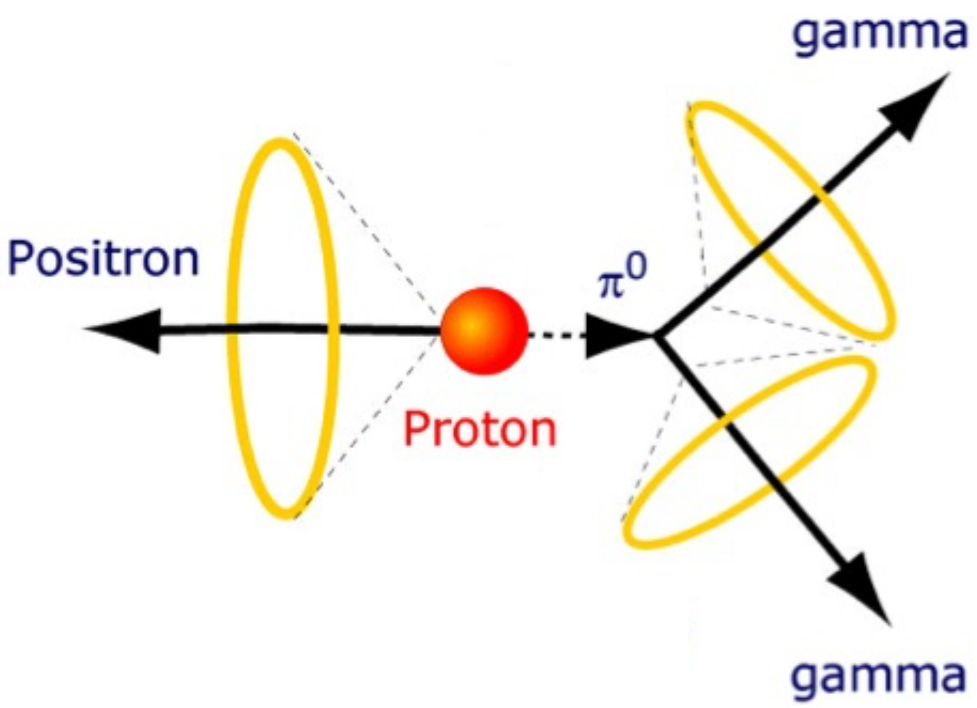
Proton decay in water

"Golden channel": $p \to \pi^0 e^+$

$\pi^0 \to 2\gamma$

$p_\pi = p_e = 459$ MeV

$p_{\gamma/\pi(rest)} = 68$ MeV



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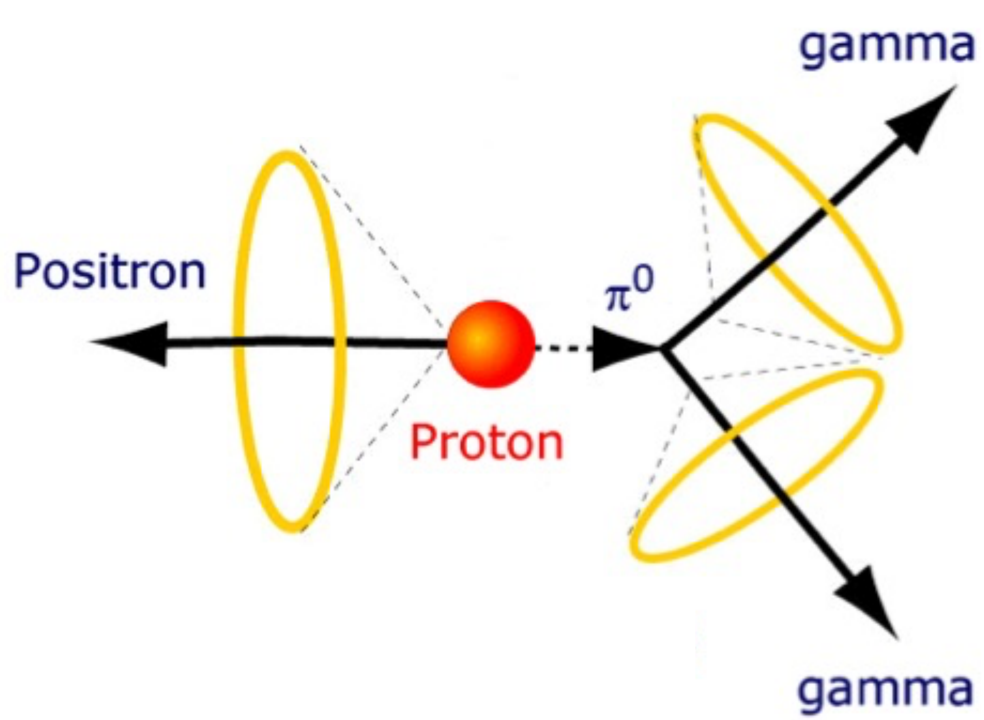

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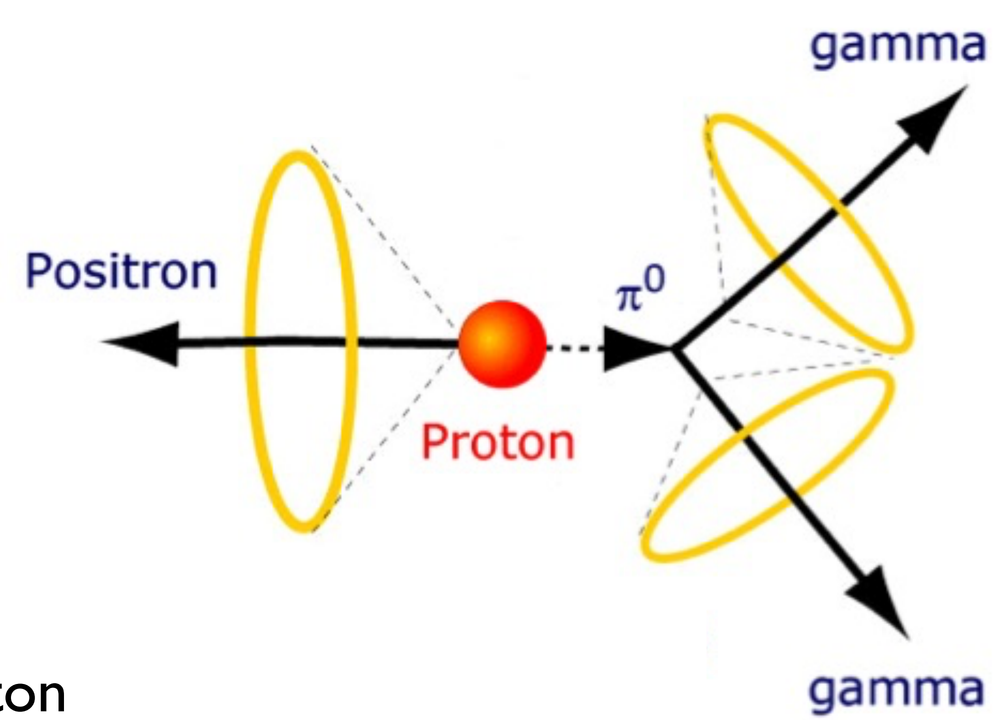
Other complication - nuclear effects

- majority of nucleons in oxygen
- Fermi motion
- pion charge exchange
- absorption



Other signals

- nuclear recombination - extra 6.3 MeV photon
- neutron capture at a dope (Gd, ...)

Proton decay in water

"Silver channel": $p \to K^+\nu$ p_K = 340 MeV

Proton decay in water

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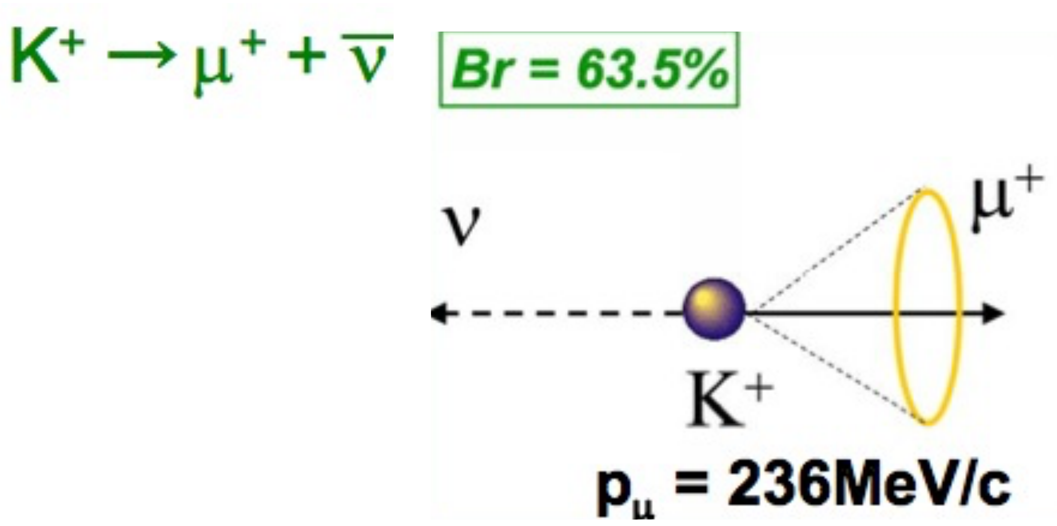
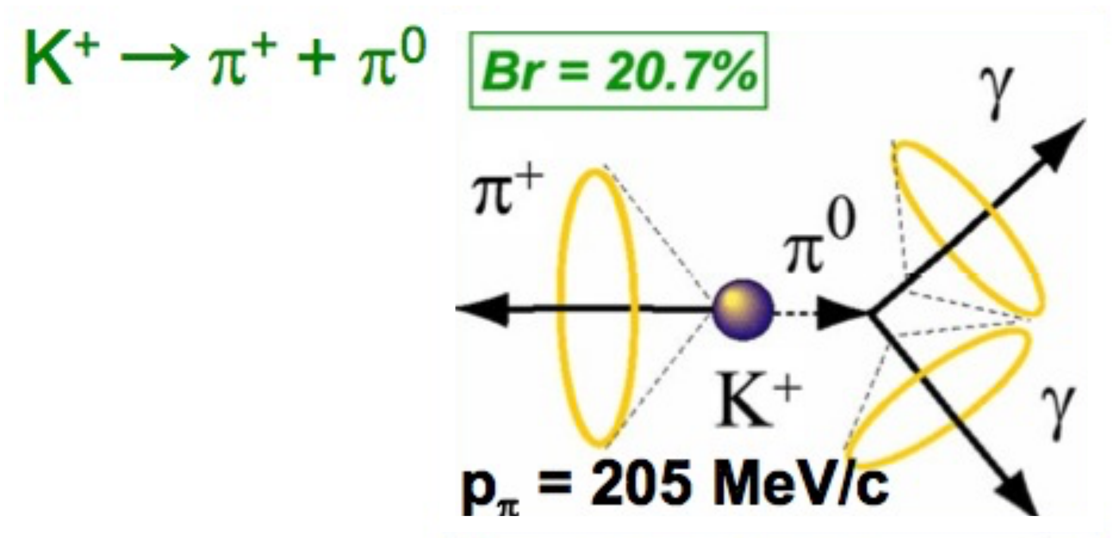


- single cone



- 2 EM cones
- little opposite-side activity

Proton decay in water

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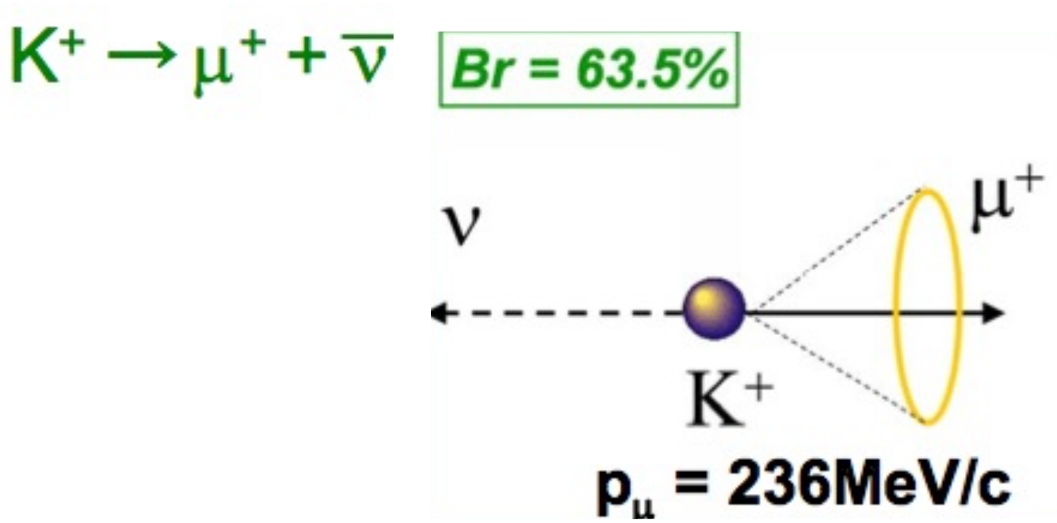

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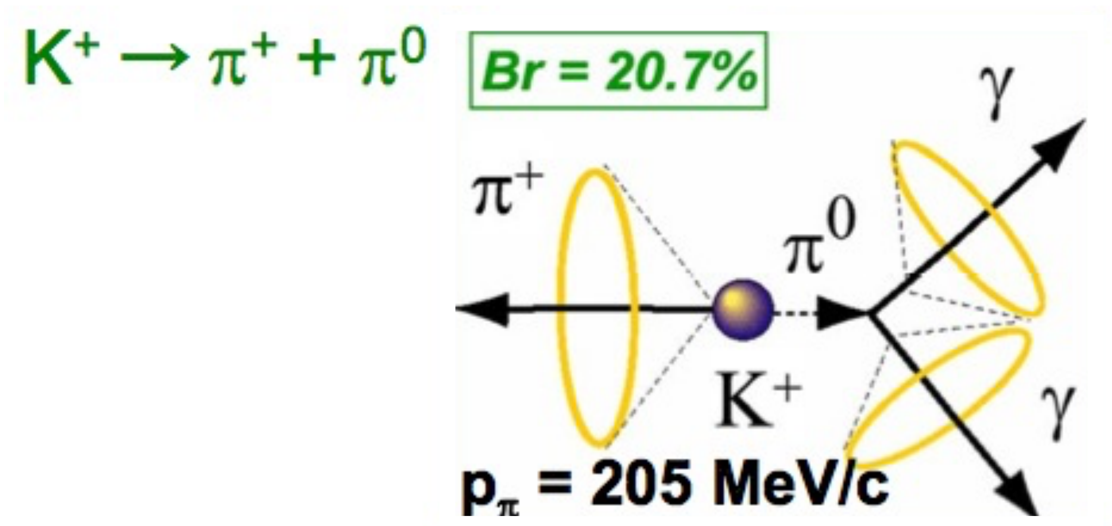


- 2 EM cones
- little opposite-side activity

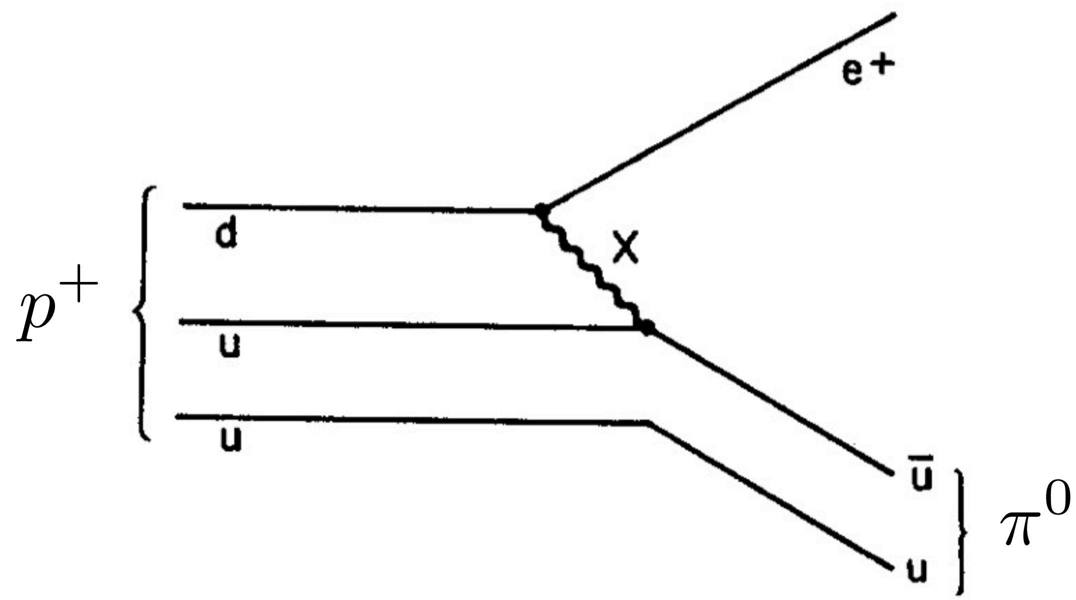
Less sensitive than $p \to \pi^0 e^+$

Current Super-K limits (d=6 p-decay)

Decay mode	SK detector	Exposure [kt-years]	Lifetime limit [years]
$p \to e^+\pi^0$	I–IV	450	2.4×10^{34}
$p \to \mu^+\pi^0$	I–IV	450	1.6×10^{34}
$p \to \nu\pi^+$	I–III	173	3.9×10^{32}
$n \to \nu\pi^0$	I–III	173	1.1×10^{33}
$p \to e^+\eta$	I–IV	373	1.4×10^{34}
$p \to \mu^+\eta$	I–IV	373	7.3×10^{33}
$p \to e^+\rho^0$	I–IV	316	7.2×10^{32}
$p \to \mu^+\rho^0$	I–IV	316	5.7×10^{32}
$p \to e^+\omega$	I–IV	316	1.6×10^{33}
$p \to \mu^+\omega$	I–IV	316	2.8×10^{33}
$n \to e^+\pi^-$	I–IV	316	5.3×10^{33}
$n \to \mu^+\pi^-$	I–IV	316	3.5×10^{33}
$n \to e^+\rho^-$	I–IV	316	3.0×10^{31}
$n \to \mu^+\rho^-$	I–IV	316	6.0×10^{31}
$p \to \nu K^+$	I–IV	365	8.2×10^{33}
$p \to \mu^+K^0$	I–IV	373	3.6×10^{33}
$p \to e^+K^0$	I	92	1.3×10^{33}
$p \to \mu^+K^0$	I	92	1.0×10^{33}

Shunichi Mine, talk at the 22nd Int. Workshop on Next Generation Nucleon Decay and Neutrino Detectors (NNN23) 2024

Suppression scale of d=6 BLNV operators



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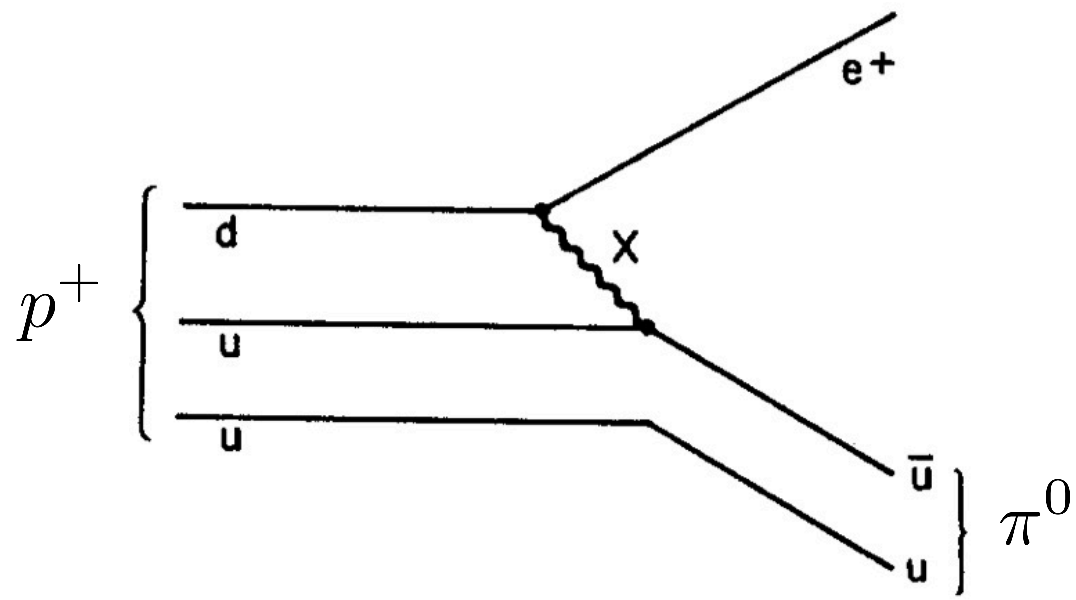

$$\Gamma_p \sim \frac{m_p^5}{M^4} \lesssim (10^{34} y)^{-1}$$

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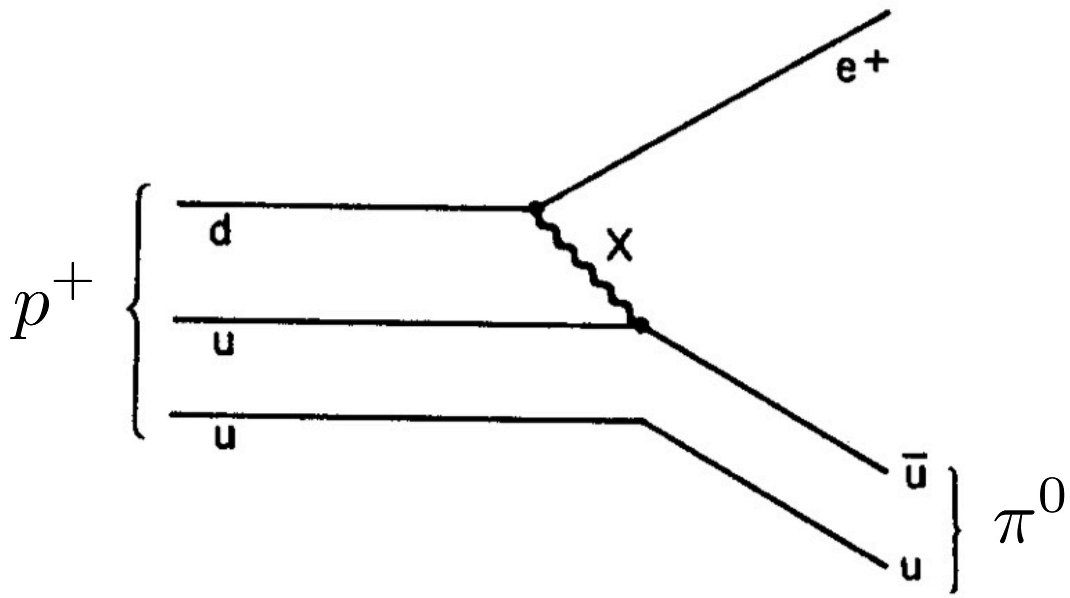

$$\Gamma_p \sim \frac{m_p^5}{M^4} \lesssim (10^{34}y)^{-1}$$

M $\gtrsim$ 10^{15} GeV

NB Higher-dimensional BLNV phenomenology

d=6 : proton decay (B-L conserving)

$$p \to \pi^0 e^+, \ldots$$

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d=8 : multibody p-decay (B-L conserving)

$$p \to \pi^+ \pi^- e^+, \ldots$$

NB Super-K limits for d=8 p-decay channels

$p \to e^+\pi^0\pi^0$	I–V	401	7.2×10^{33}
$p \to \mu^+\pi^0\pi^0$	I–V	401	4.5×10^{33}
$p \to e^+e^+e^-$	I–IV	373	3.4×10^{34}
$p \to \mu^+e^+e^-$	I–IV	373	2.3×10^{34}
$p \to \mu^-e^+e^+$	I–IV	373	1.9×10^{34}
$p \to e^+\mu^+\mu^-$	I–IV	373	9.2×10^{33}
$p \to e^-\mu^+\mu^+$	I–IV	373	1.1×10^{34}
$p \to \mu^+\mu^+\mu^-$	I–IV	373	1.0×10^{34}
$p \to e^+\nu\nu$	I–IV	273	1.7×10^{32}
$p \to \mu^+\nu\nu$	I–IV	273	2.2×10^{32}

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d=9 : (Majorana) neutron-antineutron oscillations,...

$$n \leftrightarrow \overline{n}, \ldots$$

...

Neutron-antineutron oscillations

$$H = \begin{pmatrix} E_n & \delta m \\ \delta m & E_{\bar{n}} \end{pmatrix}$$ in the $\{|n\rangle, |\bar{n}\rangle\}$ basis

Y. Kamyshkov, hep-ex/0211006

R. Mohapatra, J.Phys. G36 (2009) 104006

Neutron-antineutron oscillations

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in vacuum $\Delta E \to 0$

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Indirect searches: nuclear stability Super-K, SNO

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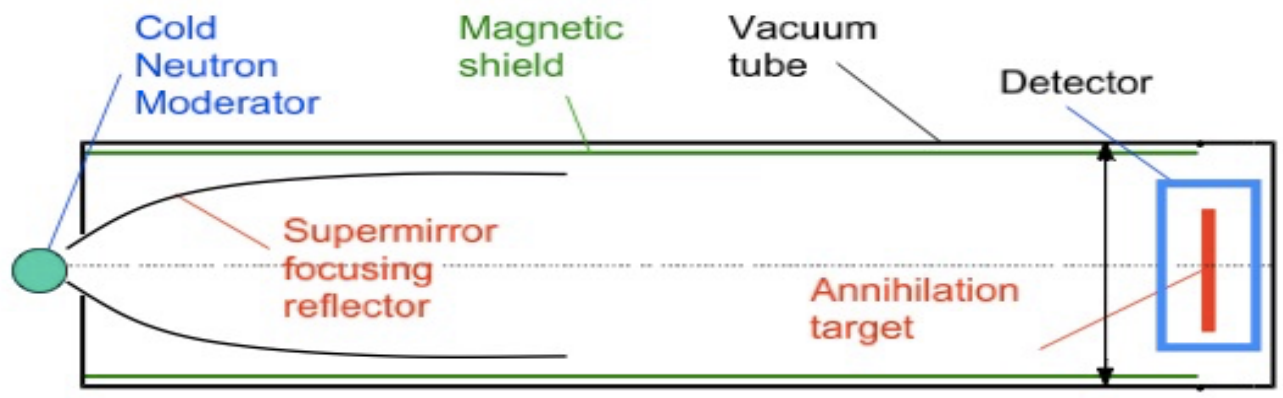
Direct searches with free neutrons:

Physics Reports 612 (2016)1-45



similar results

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$$\delta m \sim \frac{\Lambda_{QCD}^6}{M^5}$$

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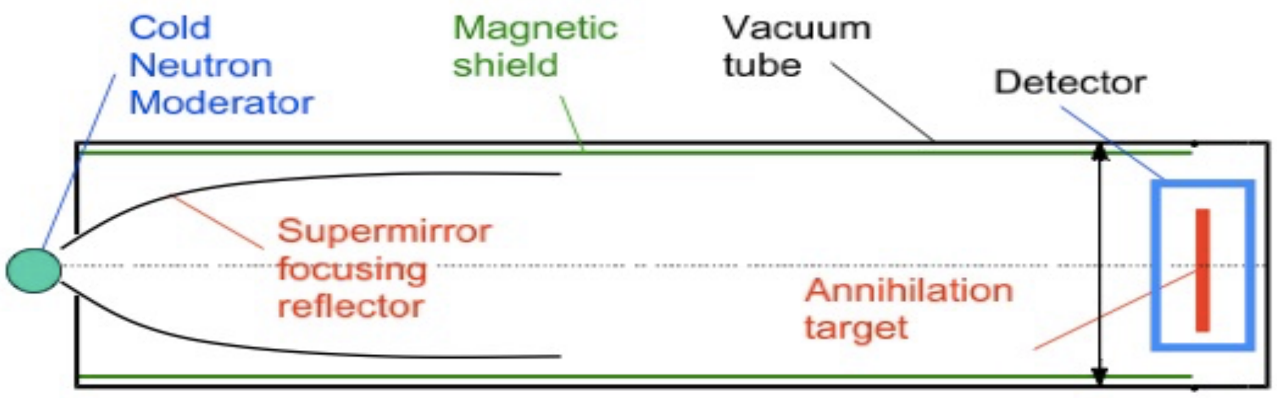

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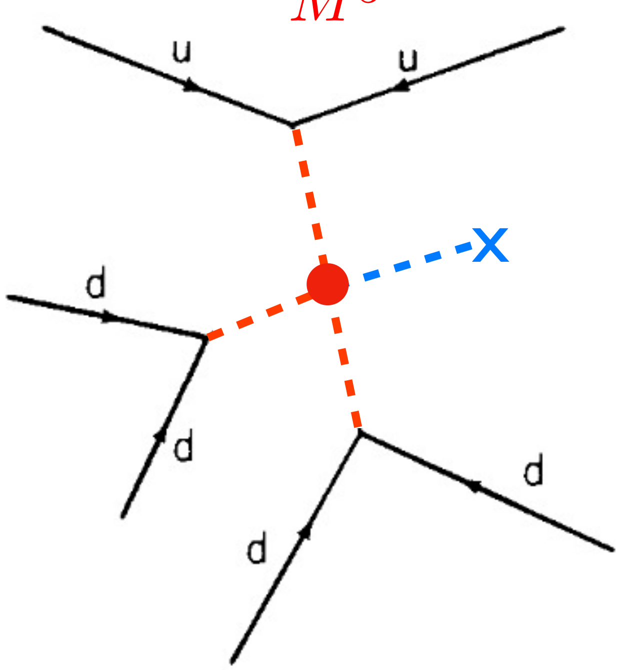

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$$H = \begin{pmatrix} E_n & \delta m \\ \delta m & E_{\bar{n}} \end{pmatrix}$$ in the $\{|n\rangle, |\bar{n}\rangle\}$ basis

Y. Kamyshkov, hep-ex/0211006
R. Mohapatra, J.Phys. G36 (2009) 104006

$$P(n \to \bar{n}) \sim \frac{4\delta m^2}{\Delta E^2 + 4\delta m^2} \sin^2(\sqrt{4\delta m^2 + \Delta E^2}\, t)$$

in vacuum $\Delta E \to 0$

$$P(n \to \bar{n}) \propto \sin^2(\delta m\, t)$$

in nuclei or in magnetic field

$$P(n \to \bar{n}) \sim \left(\frac{\delta m}{\Delta E}\right)^2 \sin^2(\Delta E\, t)$$

$$2\mu_n B_\oplus \sim 10^{-20}\mathrm{GeV}$$

Indirect searches: nuclear stability

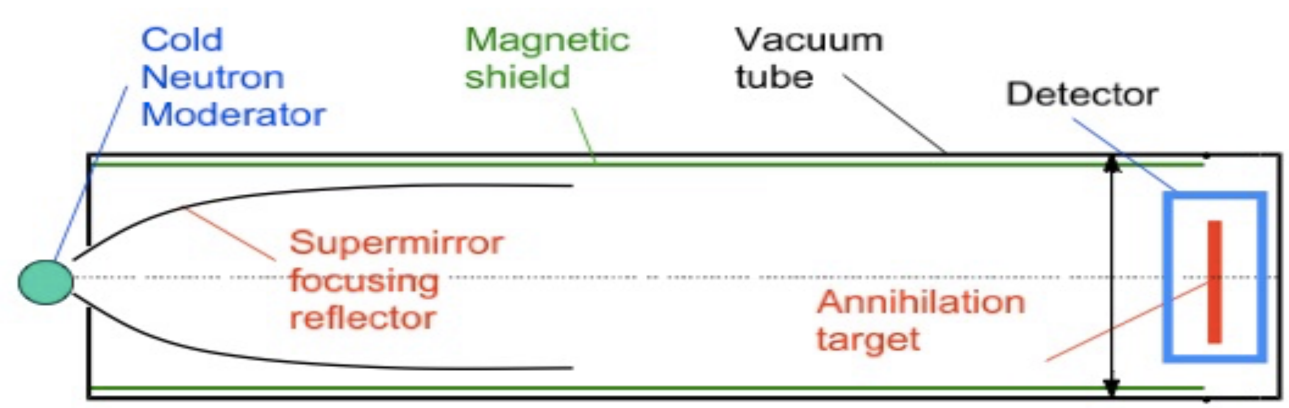
Super-K, SNO

$$\tau_{n-\bar{n}} \geq 10^8 \text{ s} \Rightarrow \delta m \lesssim 6 \times 10^{-33}\mathrm{GeV}$$

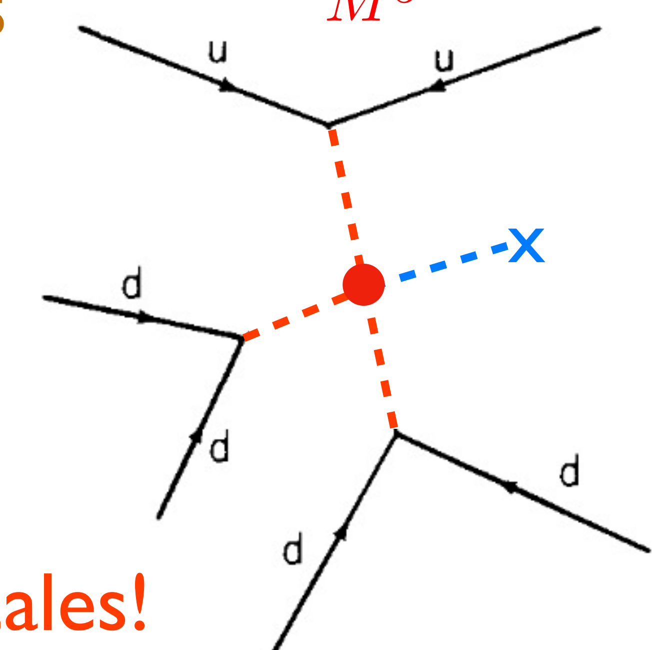
$$\delta m \sim \frac{\Lambda_{QCD}^6}{M^5}$$

Direct searches with free neutrons:

Physics Reports 612 (2016)1-45



similar results



Neutron-antineutron oscillations probe O(100 TeV) scales!

NB Higher-dimensional BLNV phenomenology

d=6 : proton decay (B-L conserving)

$$p \to \pi^0 e^+, \dots$$

d=7 : high-scale baryogenesis, p-decay exotics, ν masses (B-L violating)

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

d=8 : multibody p-decay (B-L conserving)

$$p \to \pi^+ \pi^- e^+, \dots$$

d=9 : (Majorana) neutron-antineutron oscillations,...

$$n \leftrightarrow \overline{n}, \dots$$

...

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d=9 : (Majorana) neutron-antineutron oscillations,...

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...

No predictivity without information on scales & couplings

Close-to-Planck-scale dynamics?

SM running gauge couplings

Running gauge couplings in the SM:

Gross, Wilczek, Politzer 1973
Georgi, Quinn, Weinberg 1974

$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} g = \beta(g, \ldots)$$

calculable in perturbation theory

$$\beta = \frac{g^3}{16\pi^2}\left(-\frac{11}{3}C_2(G) + \frac{2}{3}\sum_{f_W} T_2^G(R_{f_W}) + \frac{1}{3}\sum_{s_C} T_2^G(R_{s_C})\right) + \ldots$$

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Better coordinates: $\alpha_i \equiv \frac{g_i^2}{4\pi}$ $\quad t = \frac{1}{2\pi} \log \frac{\mu}{M_Z}$

$$\boxed{\frac{\mathrm{d}}{\mathrm{d}t} \alpha_i^{-1} = -b_i}$$

first order linear differential equation with constant coefficients (at the leading order)

SM running gauge couplings

Beta-function for the SM gauge couplings:

Georgi, Quinn, Weinberg 1974

$$\begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = -\frac{11}{3}\begin{pmatrix} 0 \\ 2 \\ 3 \end{pmatrix}_{gauge} + 2\begin{pmatrix} \frac{10}{3} \\ 2 \\ 2 \end{pmatrix}_{ferm.} + \frac{1}{3}\begin{pmatrix} \frac{1}{2} \\ \frac{1}{2} \\ 0 \end{pmatrix}_{scal.}$$

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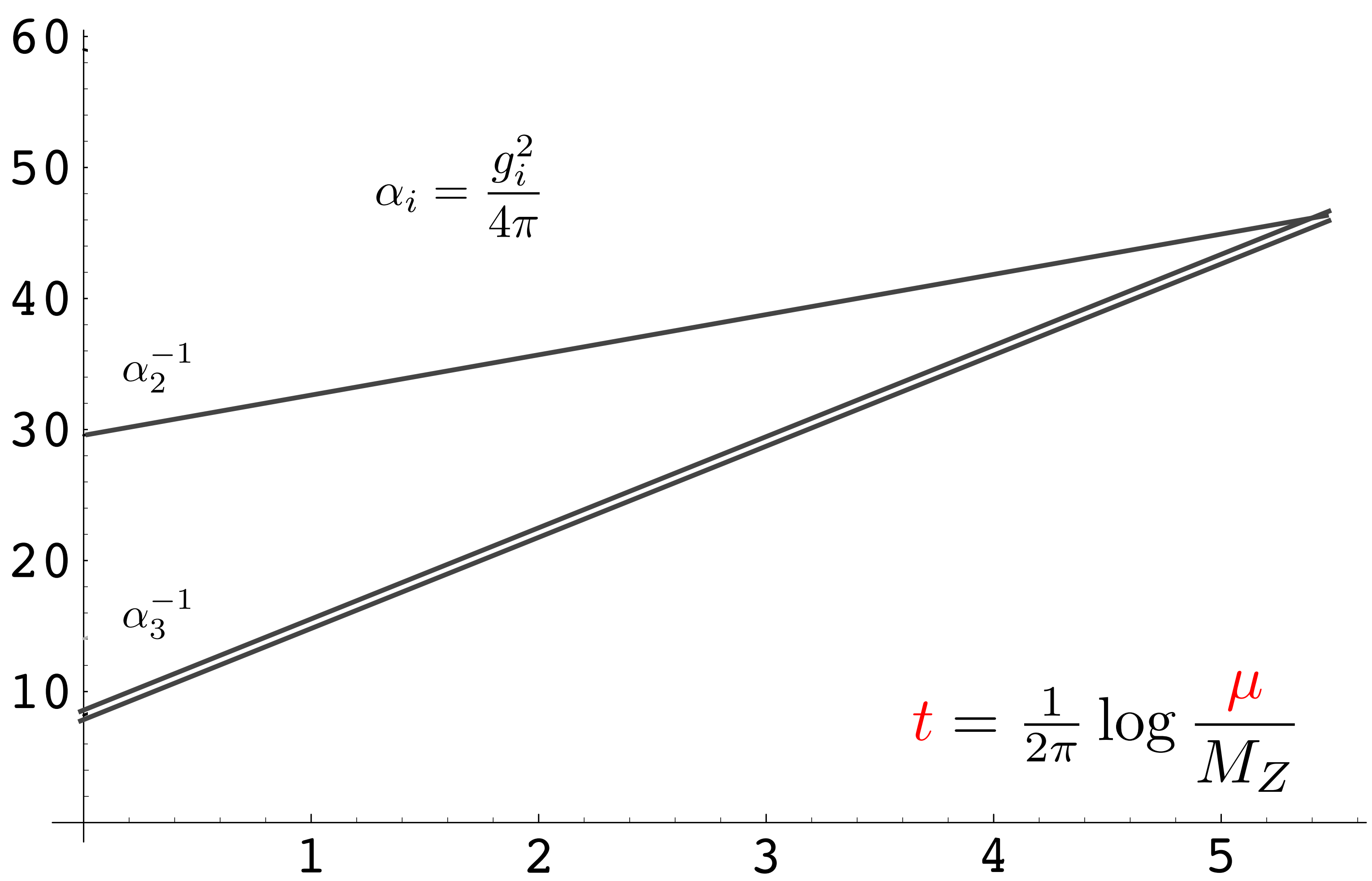

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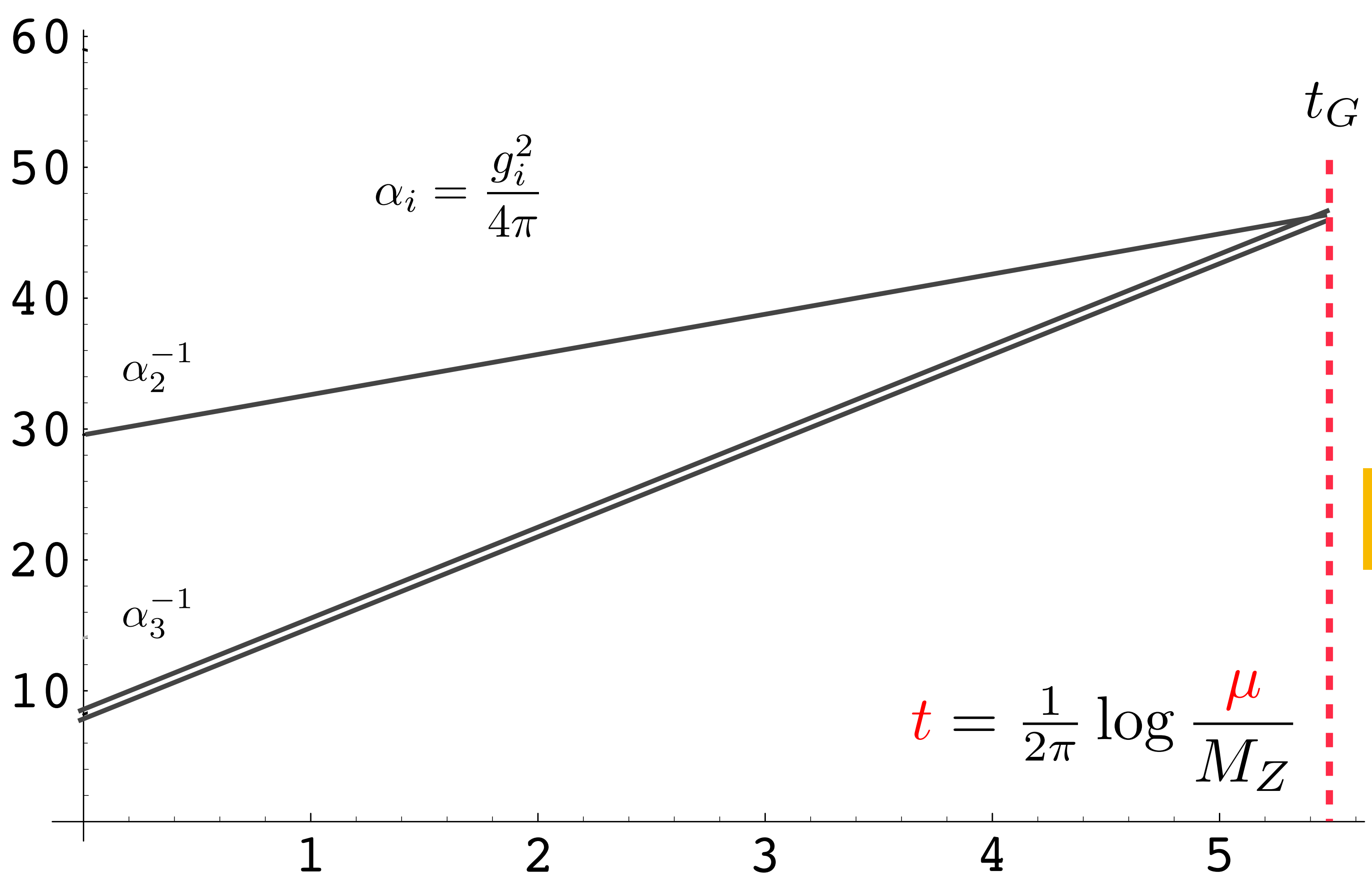


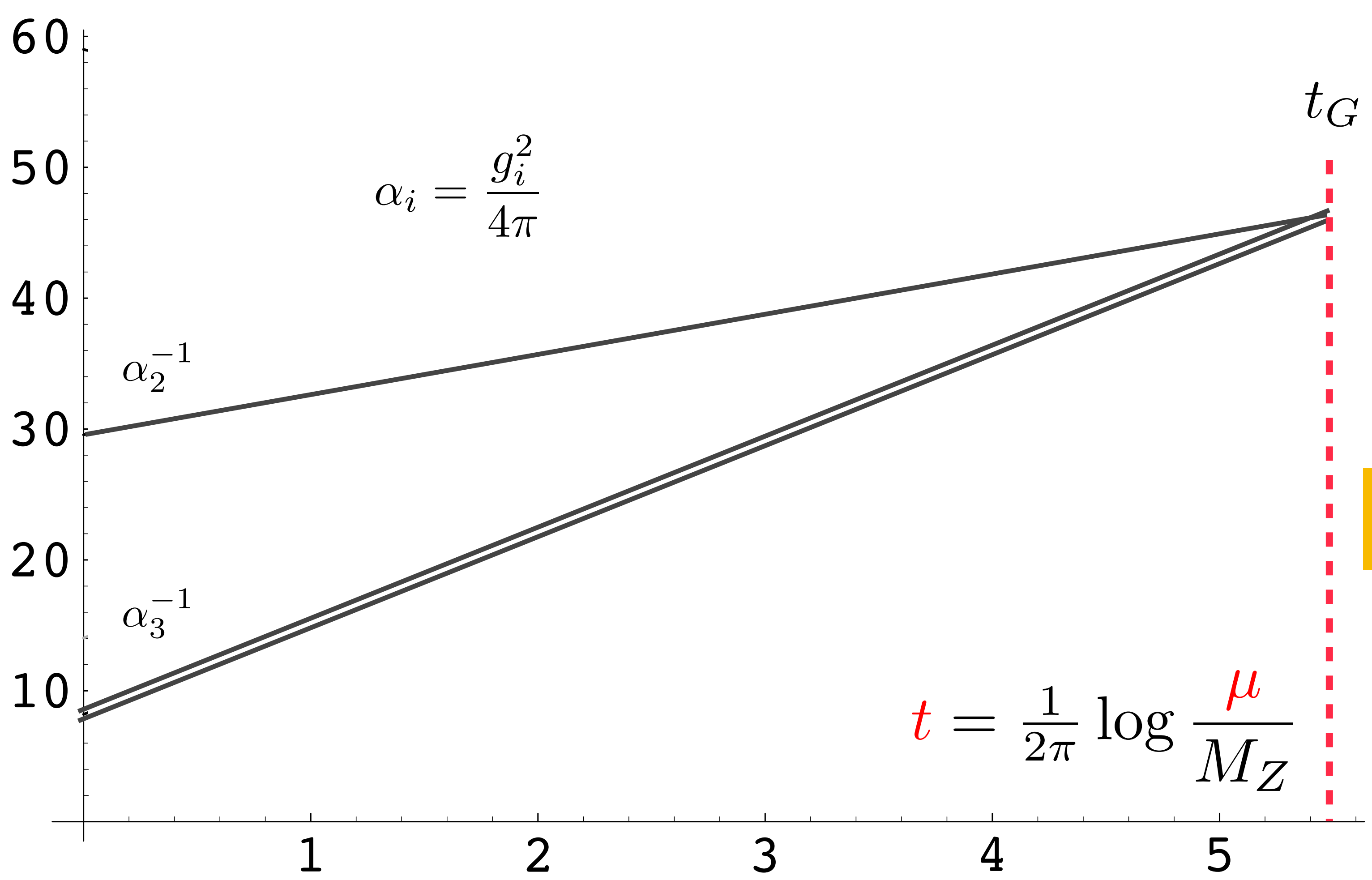
$M_G \sim 10^{16}$ GeV

SM running gauge couplings

Beta-function for the SM gauge couplings: $+X+\Delta$ d=6 BNV mediators

$$\begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = -\frac{11}{3}\begin{pmatrix} 0+\frac{25}{3} \\ 2+3 \\ 3+2 \end{pmatrix}_{gauge} + 2\begin{pmatrix} \frac{10}{3} \\ 2 \\ 2 \end{pmatrix}_{ferm.} + \frac{1}{3}\begin{pmatrix} \frac{1}{2}+\frac{1}{3} \\ \frac{1}{2} \\ 0+\frac{1}{2} \end{pmatrix}_{scal.}$$

$(3,2,-\frac{5}{6}) \oplus h.c.$ $(3,1,-\frac{1}{3})$



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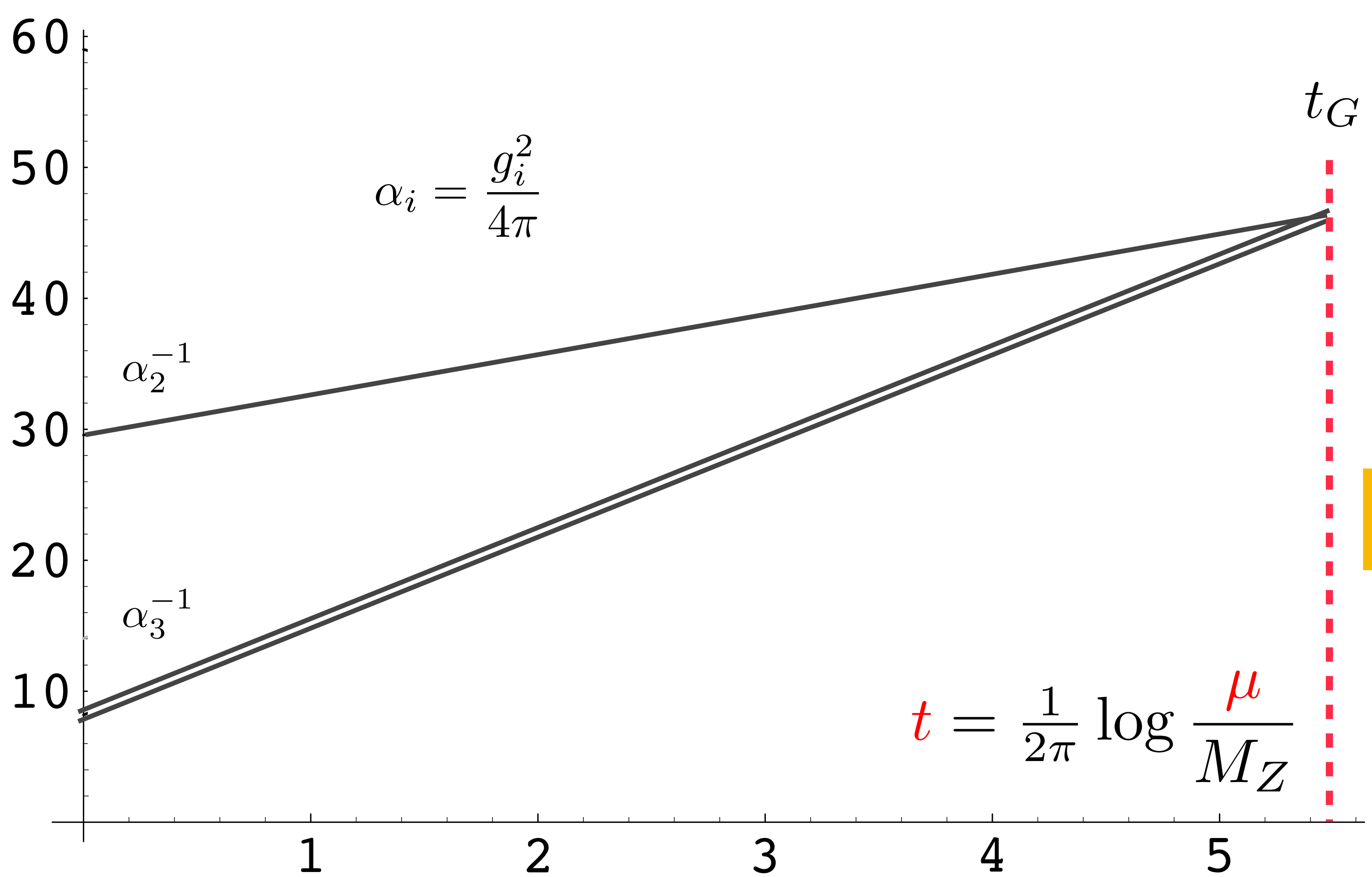

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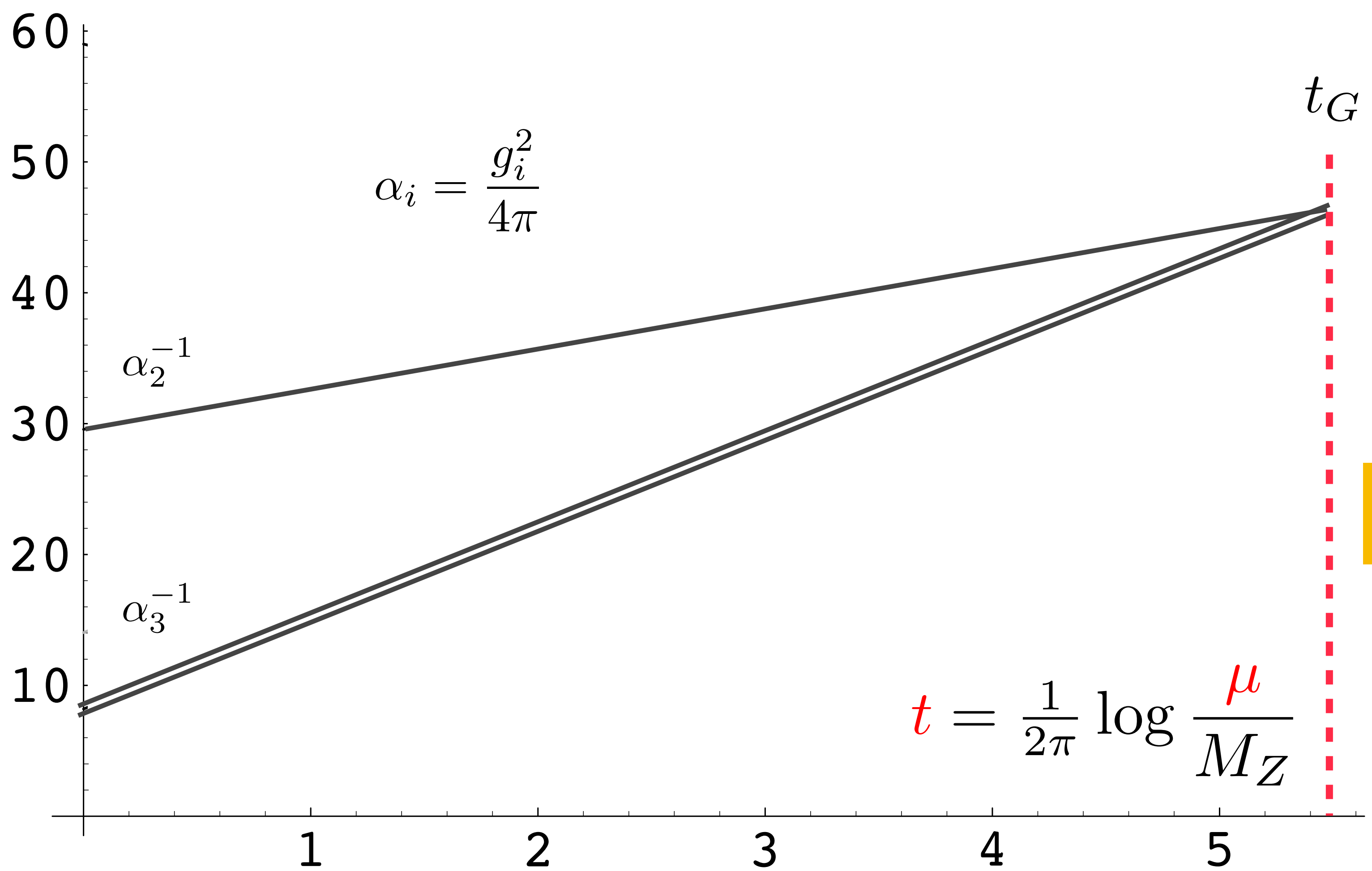

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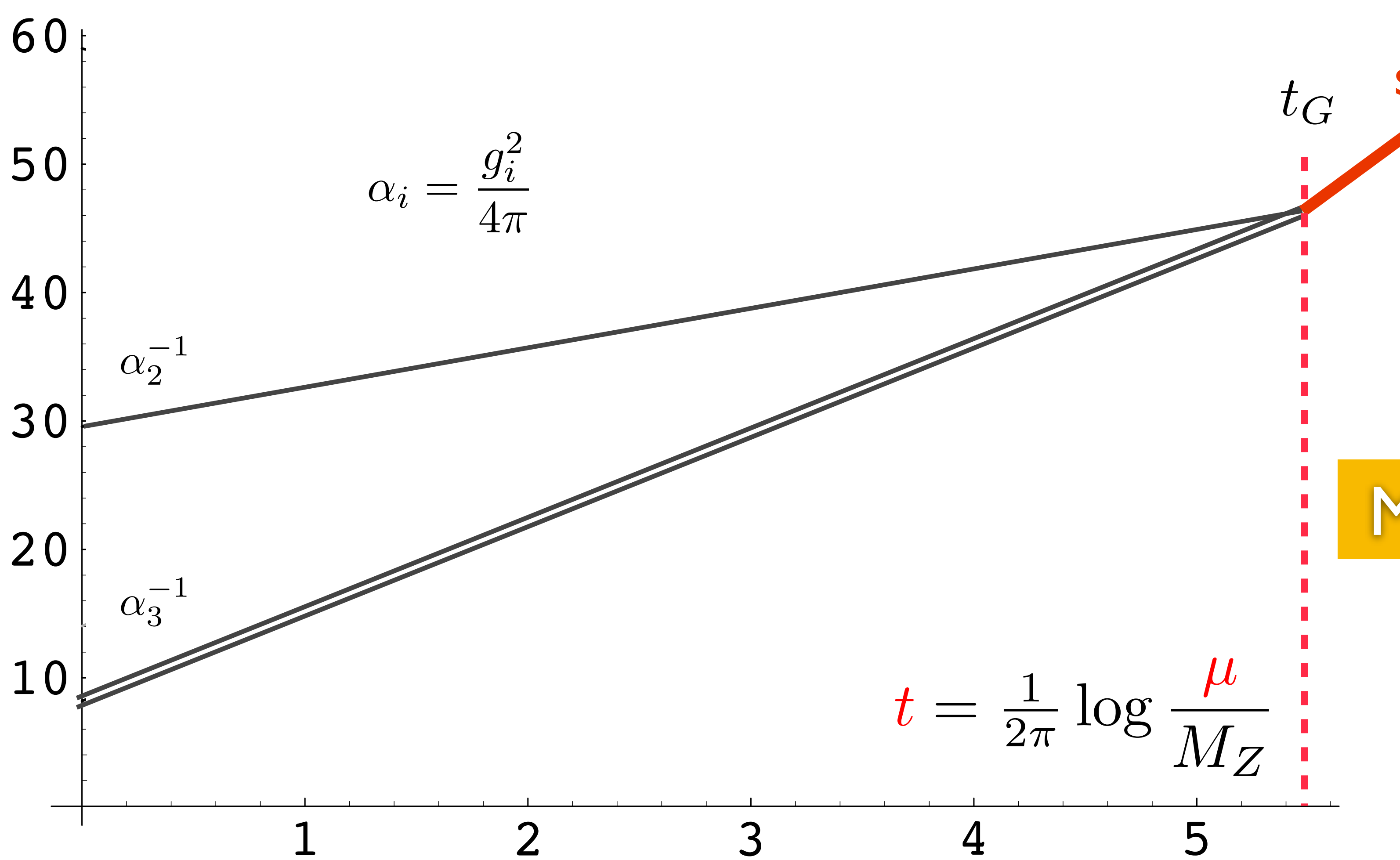

single coupling as in a **gauge theory with a simple gauge group**

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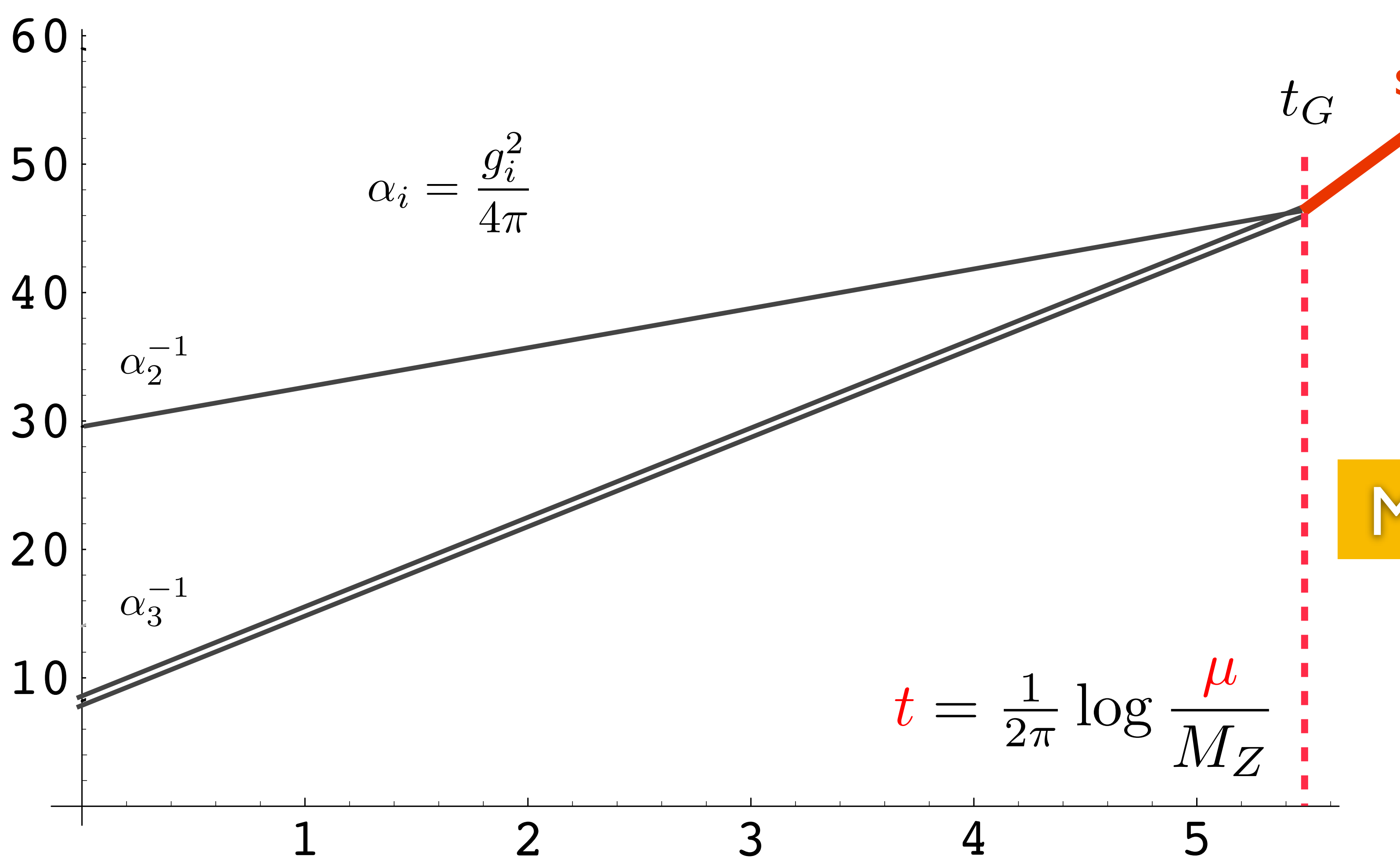

single coupling as in a **gauge theory with a simple gauge group**

$M_G \sim 10^{16}$ GeV

consistency determines the masses of X and Δ!

Grand unification of strong and electroweak interactions

The minimal SU(5) GUT

VOLUME 32, NUMBER 8 PHYSICAL REVIEW LETTERS 25 FEBRUARY 1974

Unity of All Elementary-Particle Forces

Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).

We present a series of hypotheses and speculations leading inescapably to the conclusion that SU(5) is the gauge group of the world—that all elementary particle forces (strong, weak, and electromagnetic) are different manifestations of the same fundamental interaction involving a single coupling strength, the fine-structure constant. Our hypotheses may be wrong and our speculations idle, but the uniqueness and simplicity of our scheme are reasons enough that it be taken seriously.

of the GIM mechanism with the notion of colored quarks[4] keeps the successes of the quark model and gives an important bonus: Lepton and hadron anomalies cancel so that the theory of weak and electromagnetic interactions is renormalizable.[5]

The next step is to include strong interactions. We assume that *strong interactions are mediated by an octet of neutral vector gauge gluons* associated with local color SU(3) symmetry, and that there are no fundamental strongly interacting scalar-meson fields.[6] This insures that

Uniqueness of SU(5) @ rank=4

The minimal SU(5) GUT

H.Georgi, S.Glashow, Phys.Rev.Lett. 30 (1974)

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$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

$$(1,2,-\tfrac{1}{2}) \quad \begin{pmatrix}\nu_e \\ e\end{pmatrix} \quad \begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix}$$

$$(1,1,+1) \quad e^c \quad \mu^c$$

$$(3,2,+\tfrac{1}{6}) \quad \begin{pmatrix}u \\ d\end{pmatrix} \quad \begin{pmatrix}c \\ s\end{pmatrix}$$

$$(\bar{3},1,-\tfrac{2}{3}) \quad u^c \quad c^c$$

$$(\bar{3},1,+\tfrac{1}{3}) \quad d^c \quad s^c$$

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$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \longrightarrow SU(5)$$

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$$(1,1,+1) \quad e^c \quad \mu^c$$

$$\overline{5} \quad \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ -e \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} s_1^c \\ s_2^c \\ s_3^c \\ -\mu \\ \nu_\mu \end{pmatrix}$$

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$$(\bar{3},1,-\tfrac{2}{3}) \quad u^c \quad c^c$$

$$(\bar{3},1,+\tfrac{1}{3}) \quad d^c \quad s^c$$

$$10 \quad \begin{pmatrix} 0 & u_3^c & -u_2^c & u^1 & d^1 \\ . & 0 & u_1^c & u^2 & d^2 \\ . & . & 0 & u^3 & d^3 \\ . & . & . & 0 & e^c \\ . & . & . & . & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & c_3^c & -c_2^c & c^1 & s^1 \\ . & 0 & c_1^c & c^2 & s^2 \\ . & . & 0 & c^3 & s^3 \\ . & . & . & 0 & \mu^c \\ . & . & . & . & 0 \end{pmatrix}$$

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The minimal SU(5) GUT

Gauge sector:

$$24 = (8,1,0) \oplus (1,3,0) \oplus (1,1,0) \oplus (3,2,-\tfrac{5}{6}) \oplus (\overline{3},2,+\tfrac{5}{6})$$

$$G^\mu \quad \left.\begin{matrix} A^\mu \\ B^\mu \end{matrix}\right\} W^\pm, Z, \gamma \qquad G^\mu \qquad A^\mu \qquad B^\mu \qquad X^\mu$$

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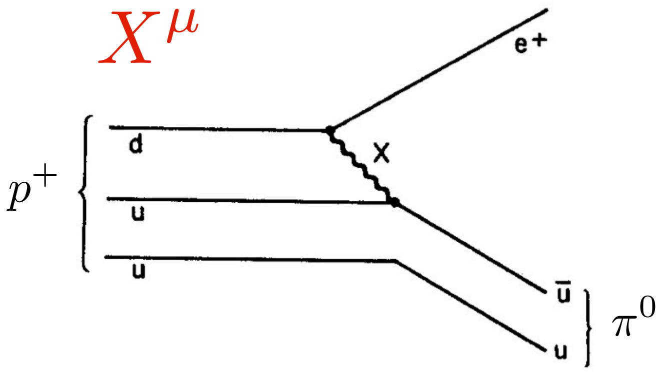

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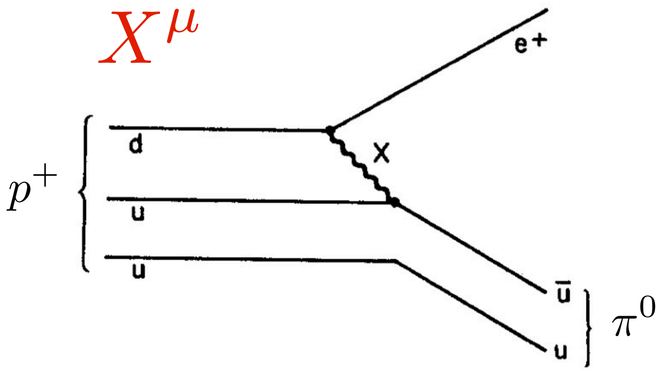

Scalar sector: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \rightarrow SU(3)_c \otimes U(1)_Q$

SM Higgs: $\overline{5} = (1,\overline{2},+\frac{1}{2}) \oplus (\overline{3},1,-\frac{1}{3})$

H Δ

The minimal SU(5) GUT

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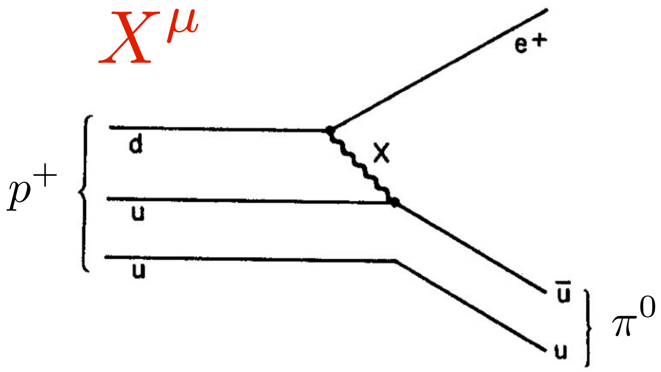

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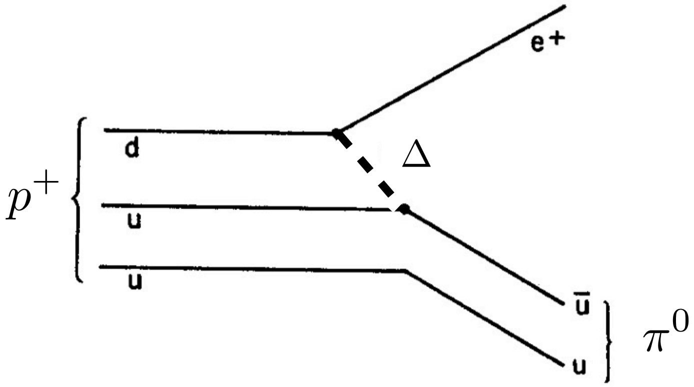

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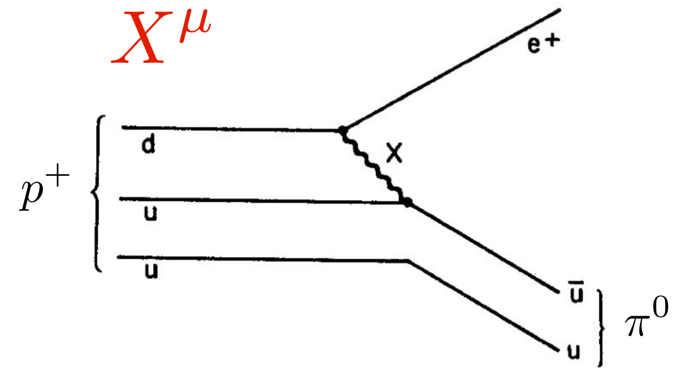

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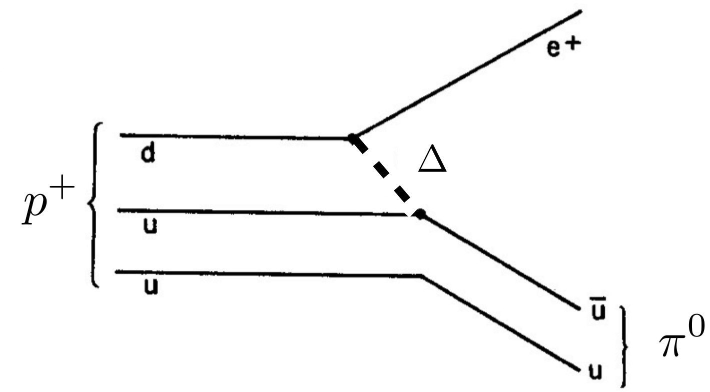

GUT-breaking scalars: $SU(5) \to SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

$$24 = (1,1,0) \oplus (8,1,0) \oplus (1,3,0) \oplus (3,2,-\tfrac{5}{6}) \oplus (\overline{3},2,+\tfrac{5}{6})$$

The SU(5) hypercharge issue

GUT-compatible hypercharge: $cY \equiv T_{24} \in SU(5)$

$$T_{24}^{\bar{\mathbf{5}}} \quad \propto \quad \begin{pmatrix} +\frac{1}{3} & & & & \\ & +\frac{1}{3} & & & \\ & & +\frac{1}{3} & & \\ & & & -\frac{1}{2} & \\ & & & & -\frac{1}{2} \end{pmatrix}$$

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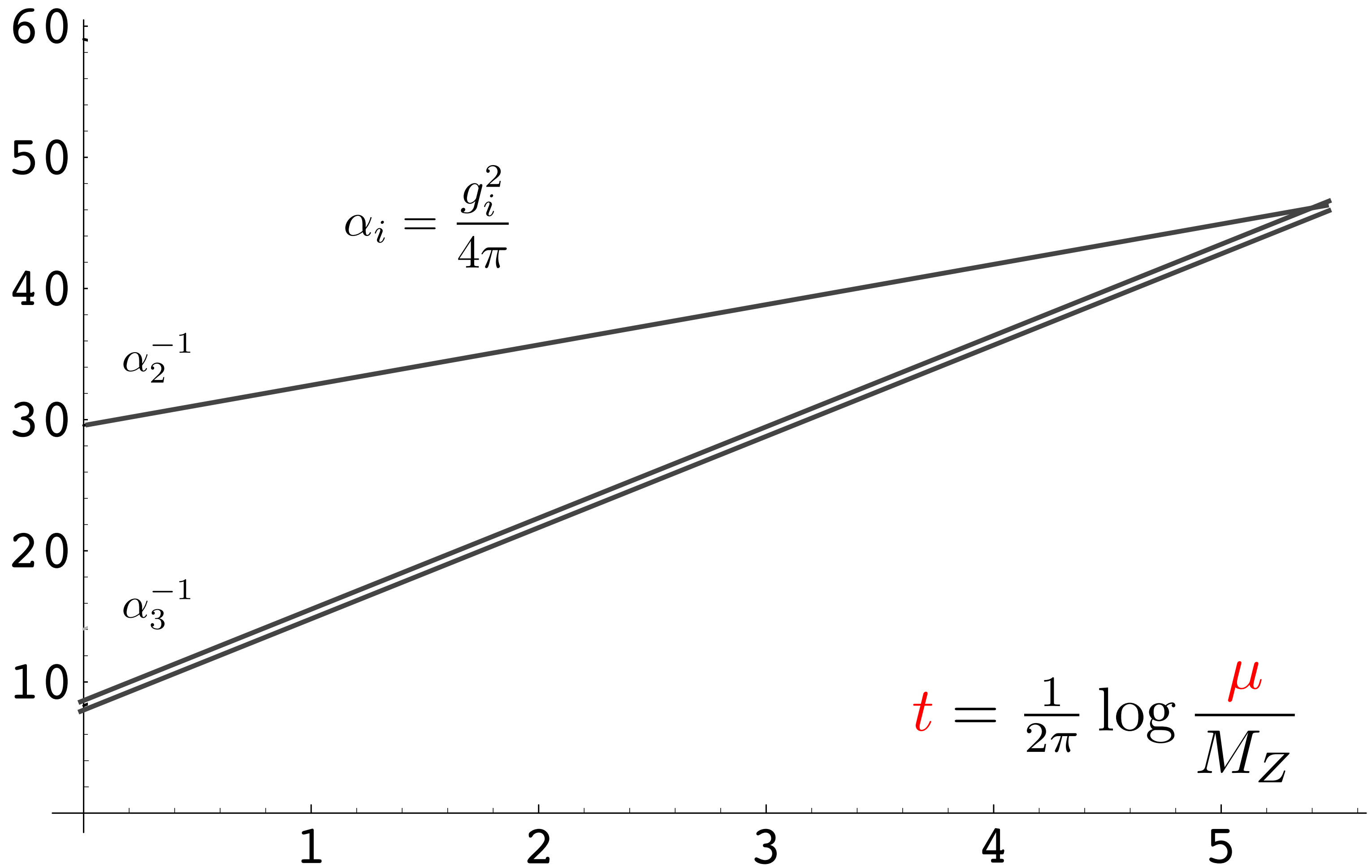

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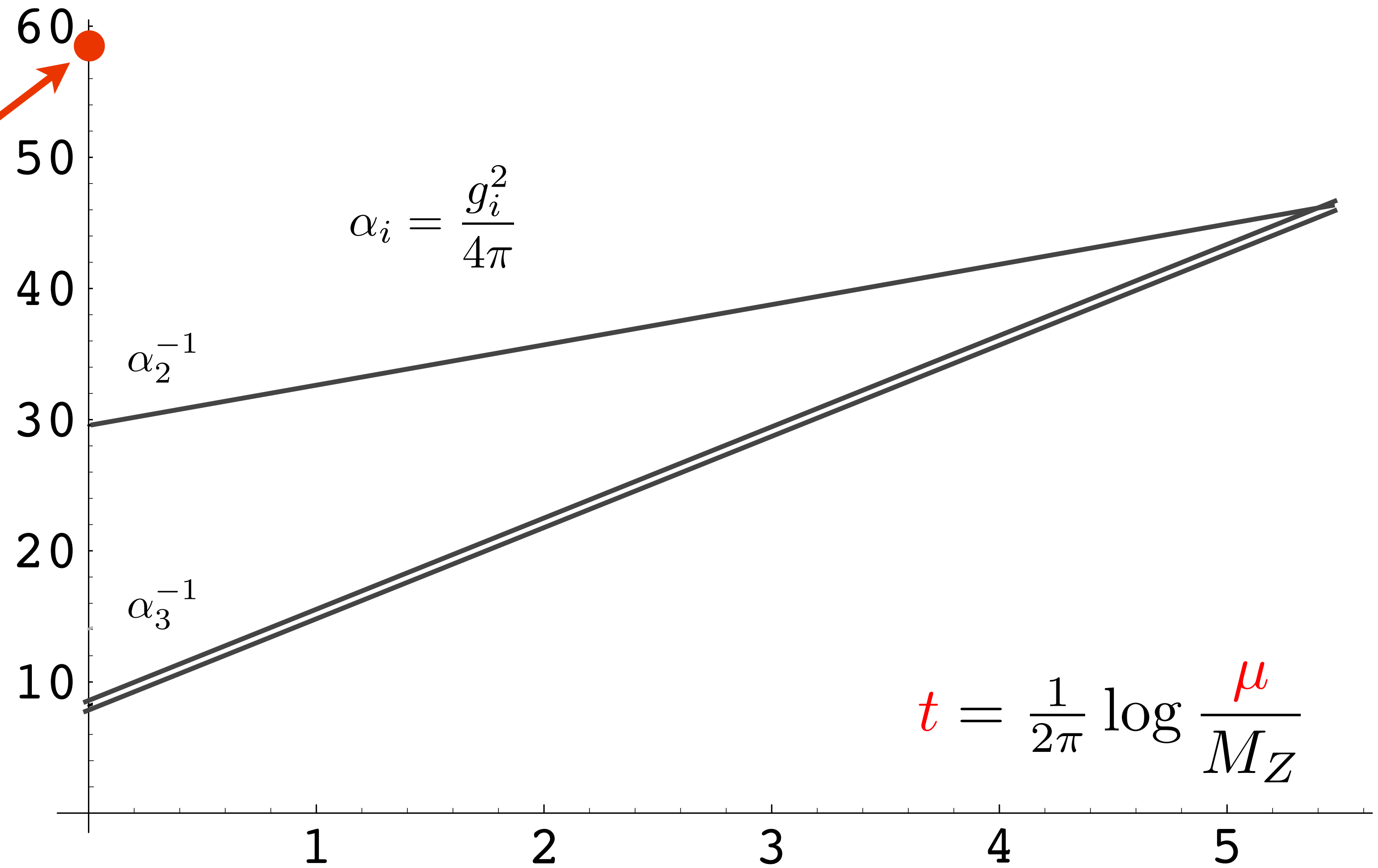
The SM g' @ Mz in GUT-normalization



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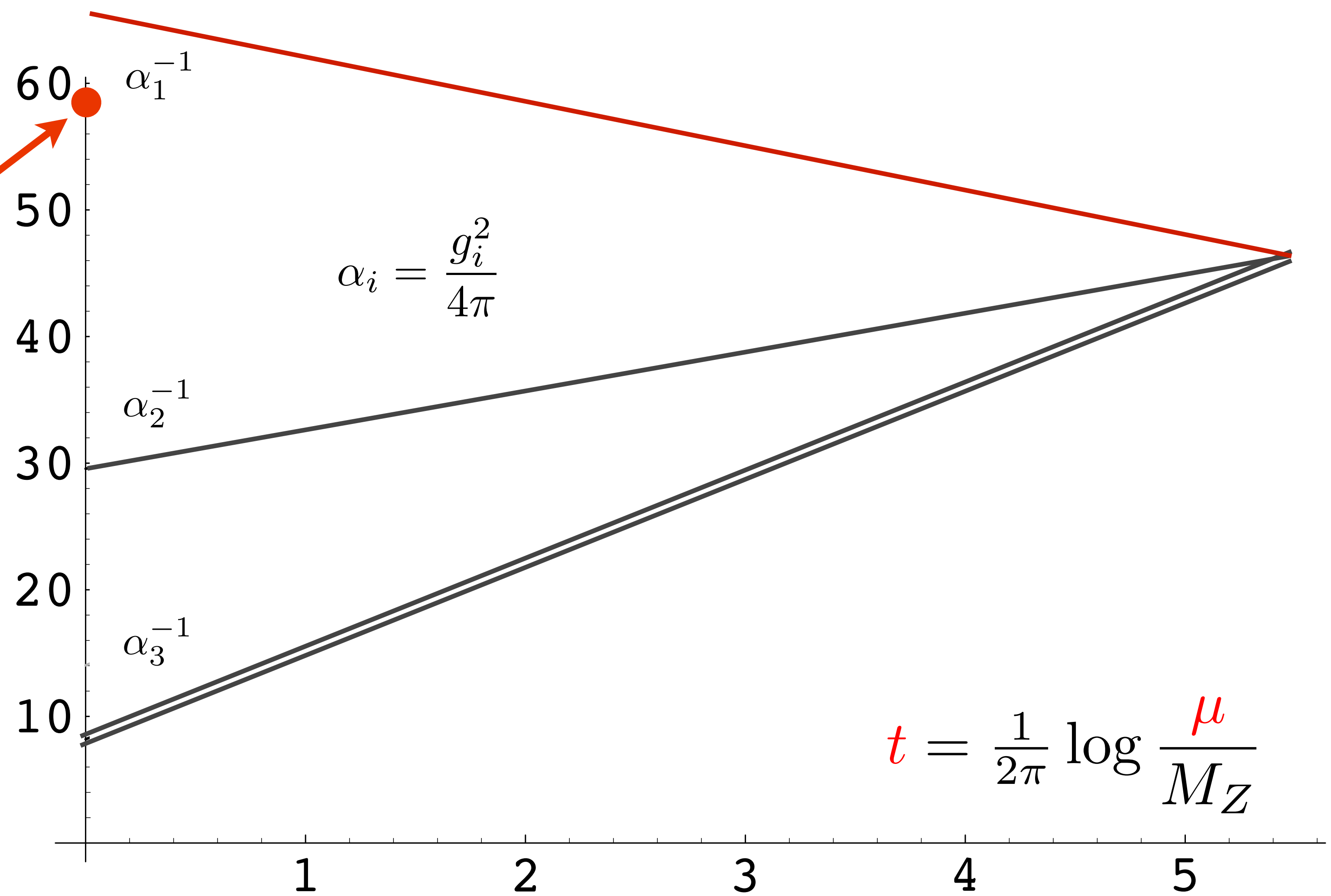
GUT-compatible hypercharge: $cY \equiv T_{24} \in SU(5)$

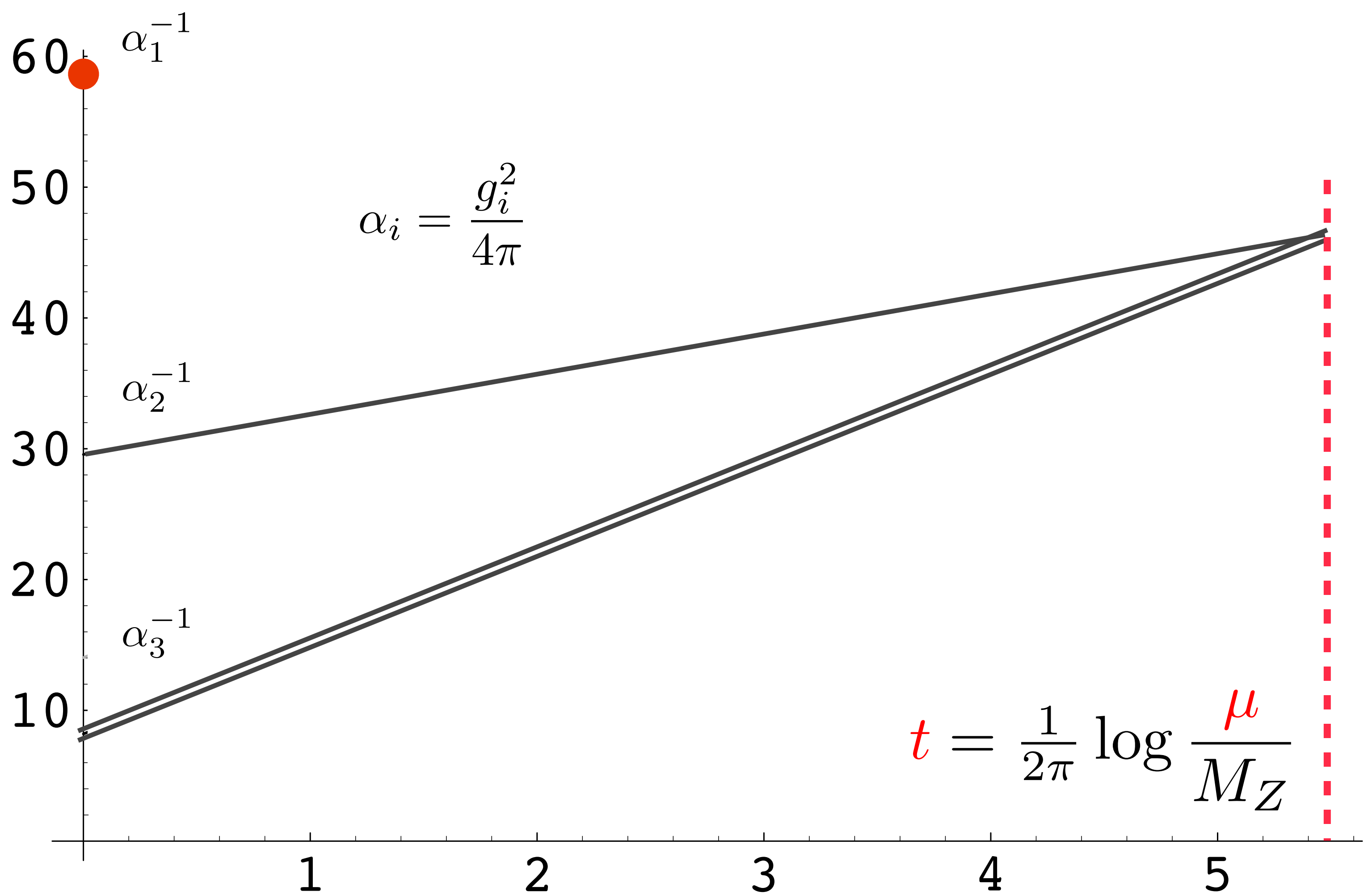
Normalization: $\mathrm{Tr}\{T_a, T_b\} = \frac{1}{2}\delta_{ab}$

$$T_{24}^{\bar{5}} = \sqrt{\frac{3}{5}} \begin{pmatrix} +\frac{1}{3} & & & & \\ & +\frac{1}{3} & & & \\ & & +\frac{1}{3} & & \\ & & & -\frac{1}{2} & \\ & & & & -\frac{1}{2} \end{pmatrix}$$

The SM g' @ Mz in GUT-normalization



Maybe the SM gauge couplings encode two scales !?



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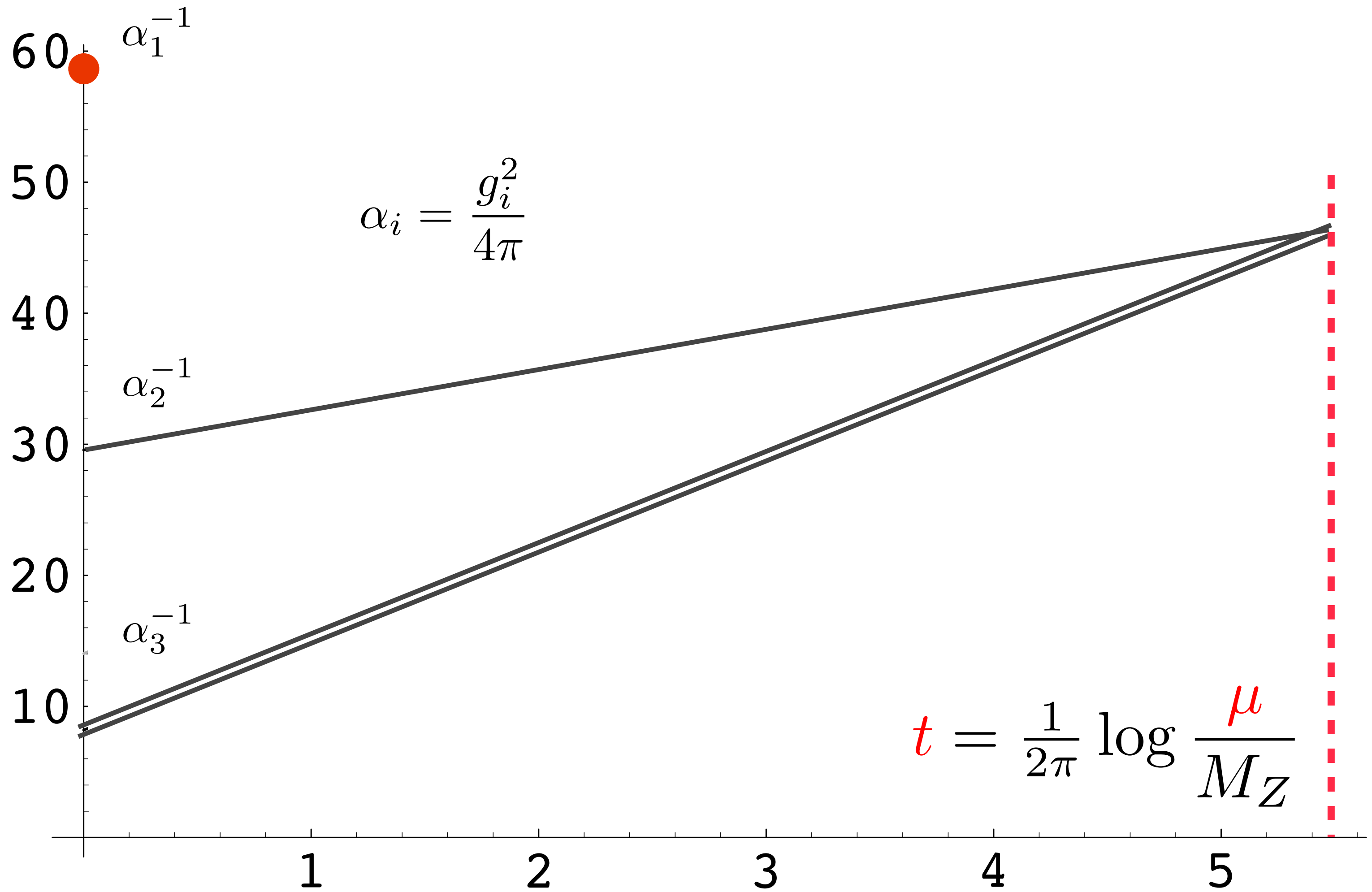
Evolution of gauge couplings in SO(10) GUT with intermediate LR

$SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$



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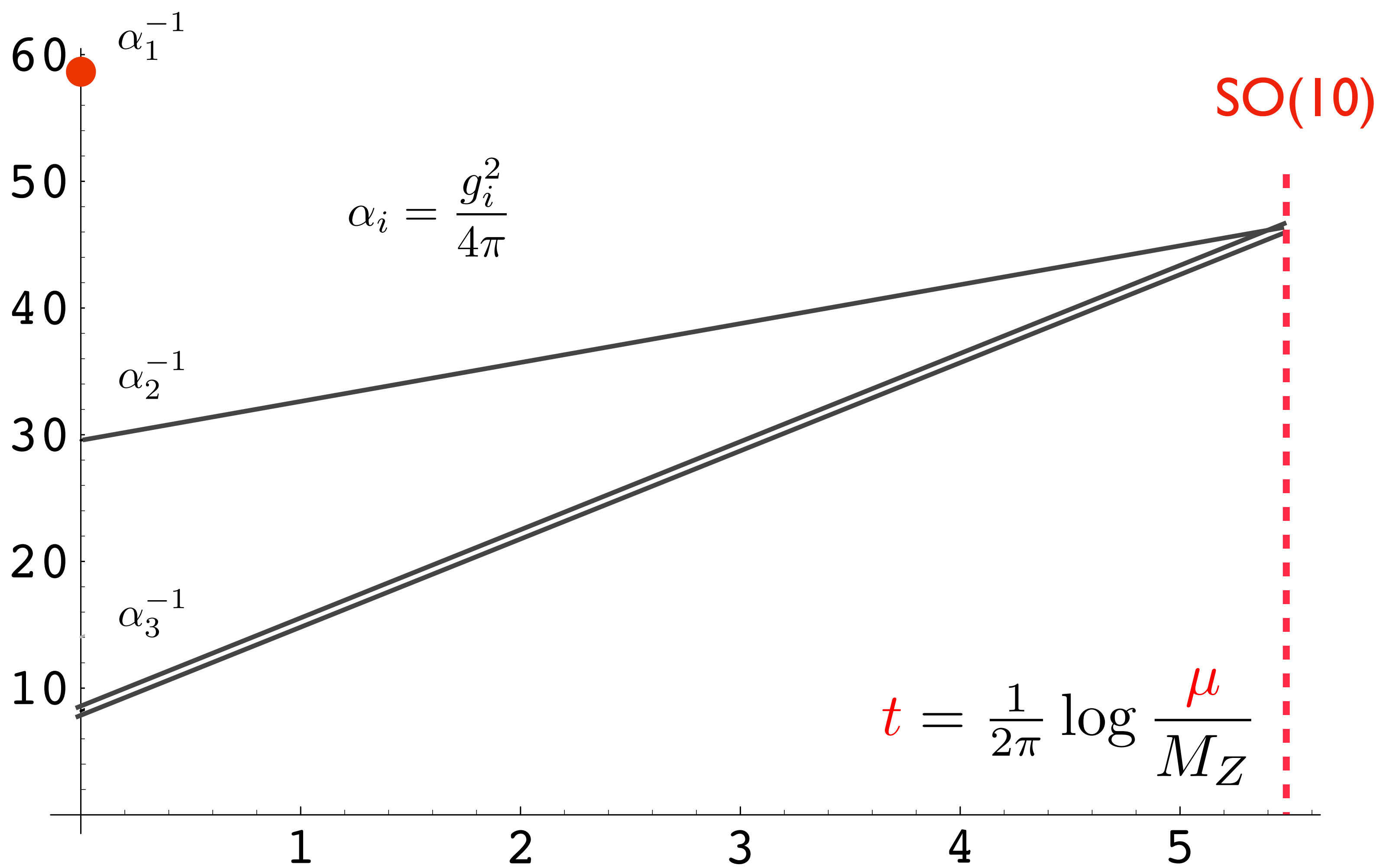

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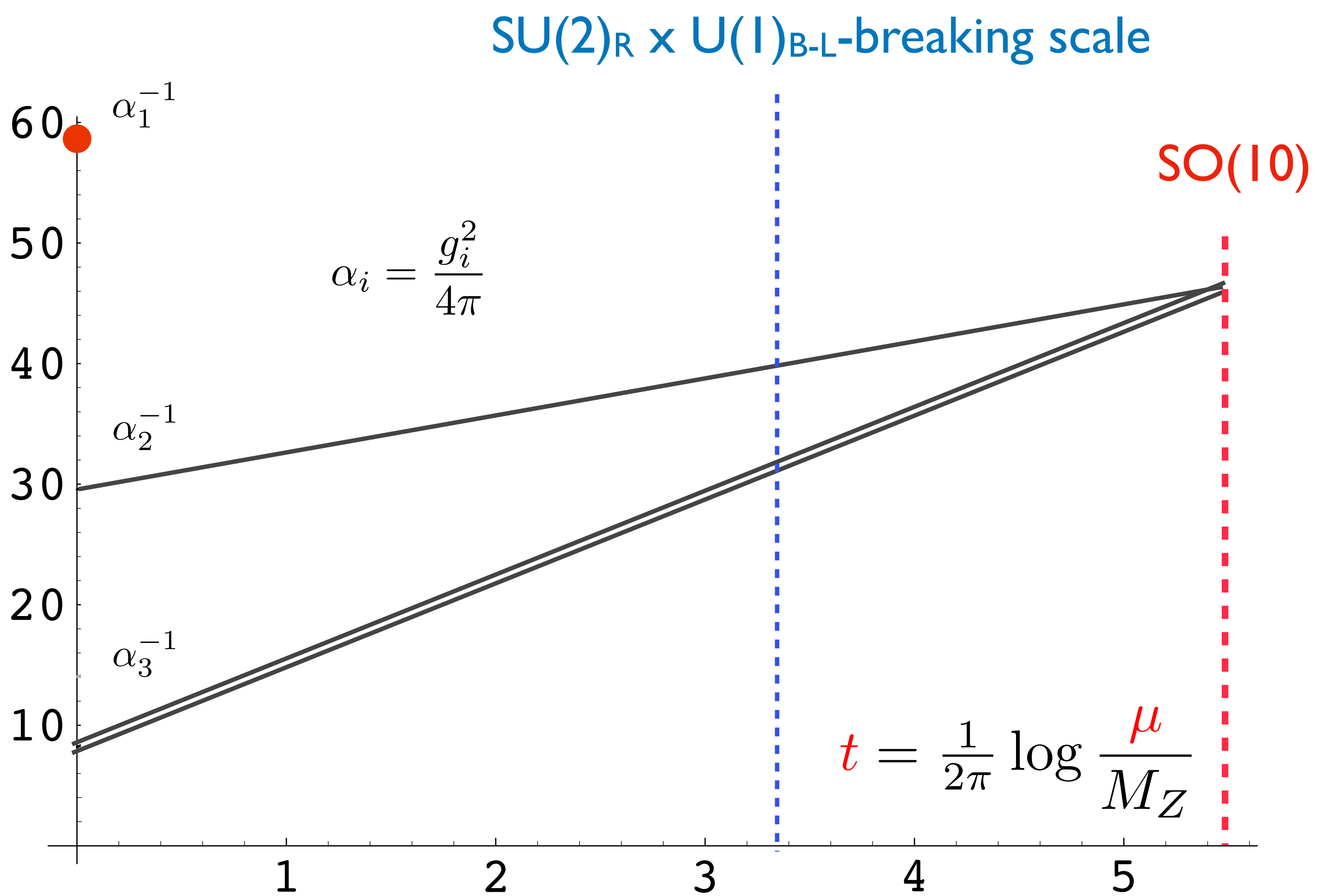

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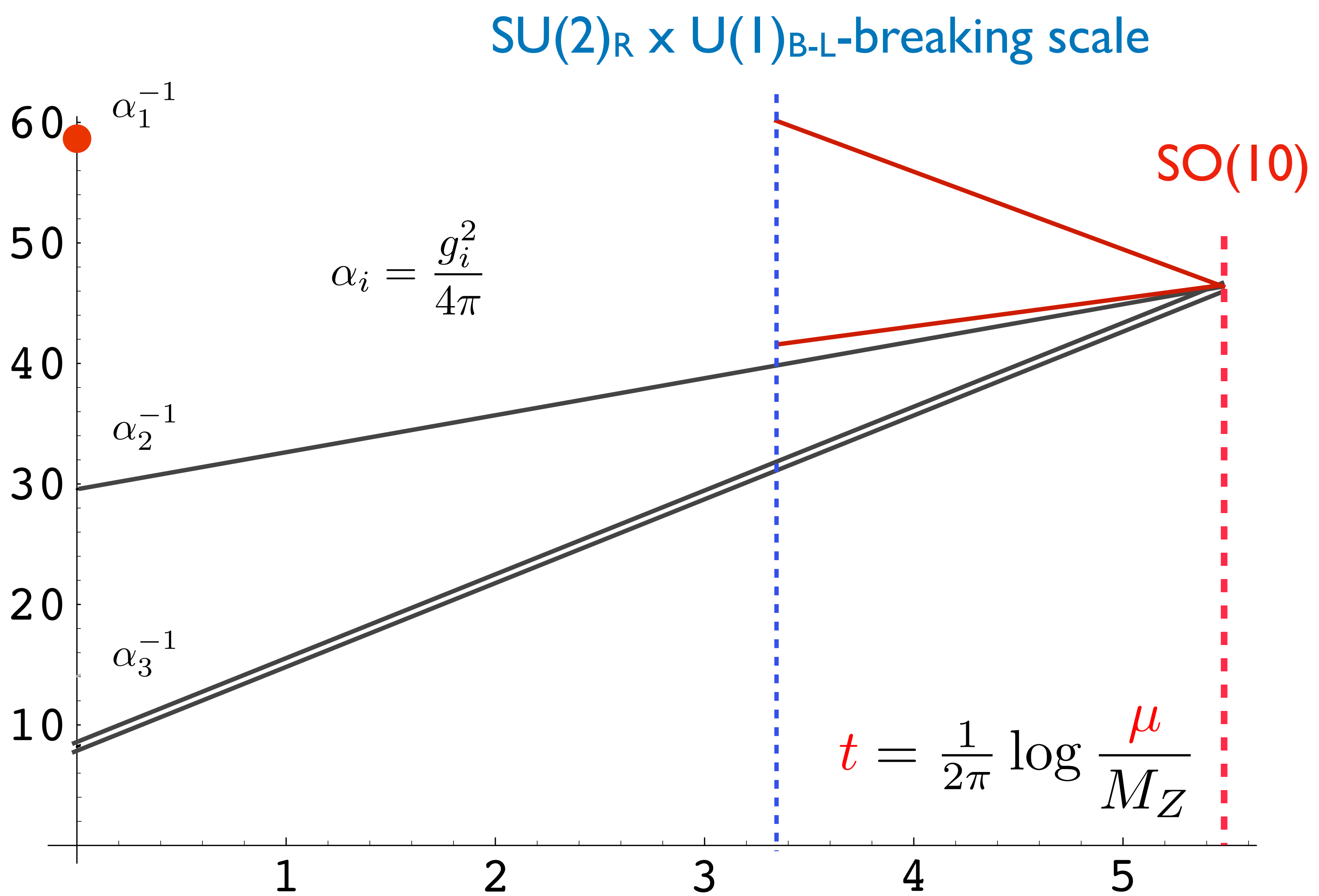

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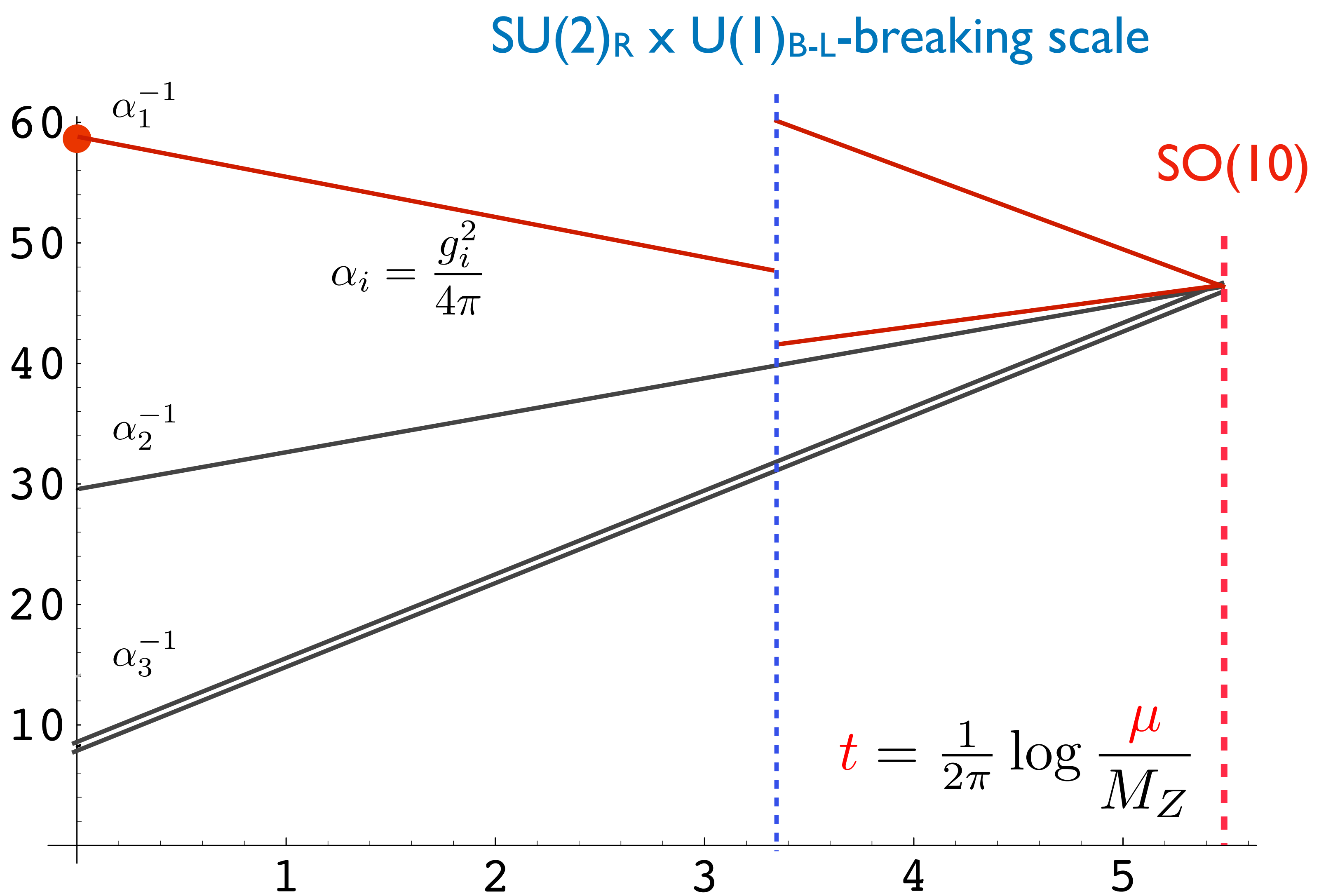
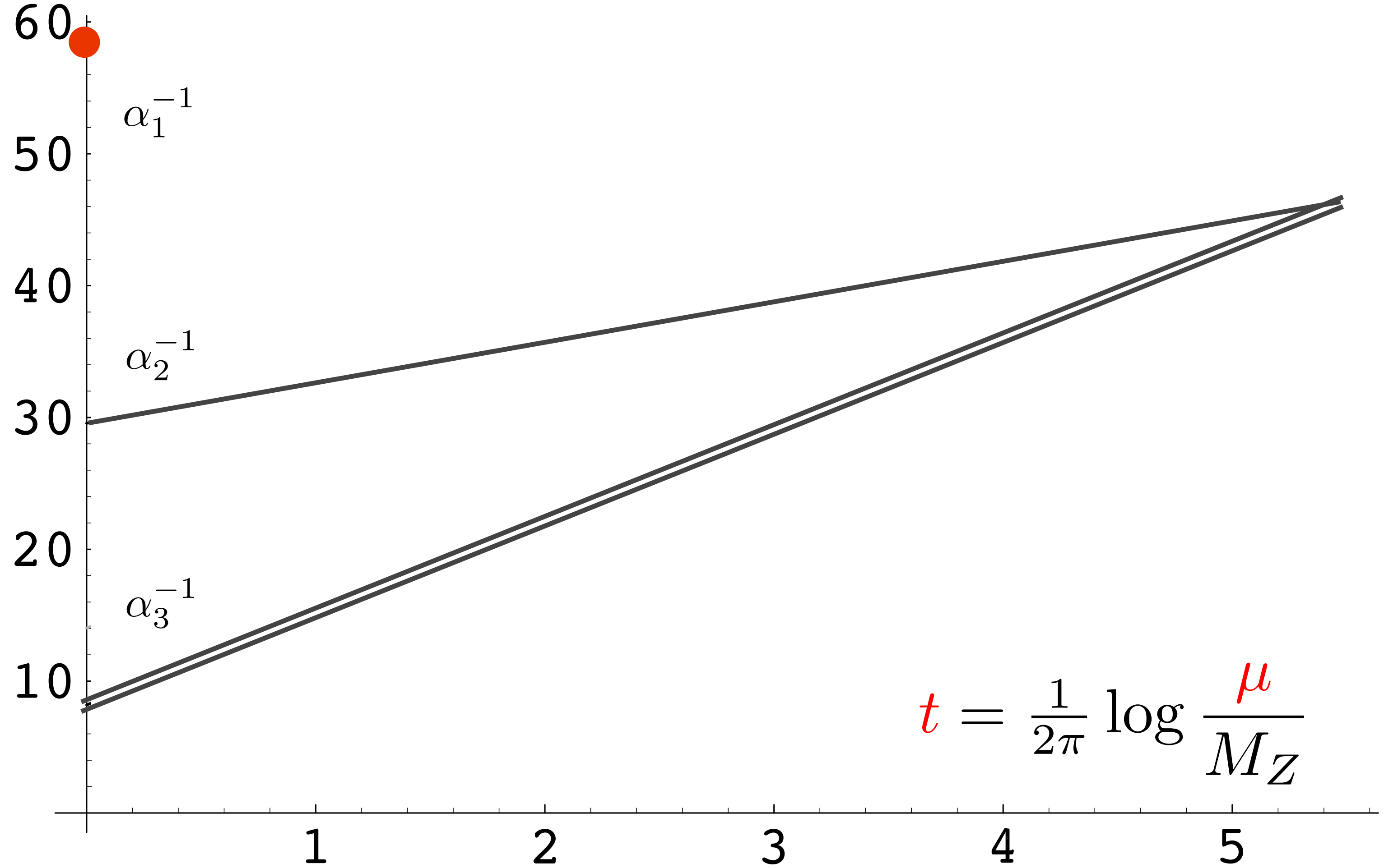


…or they may indicate a low-scale supersymmetry(?)



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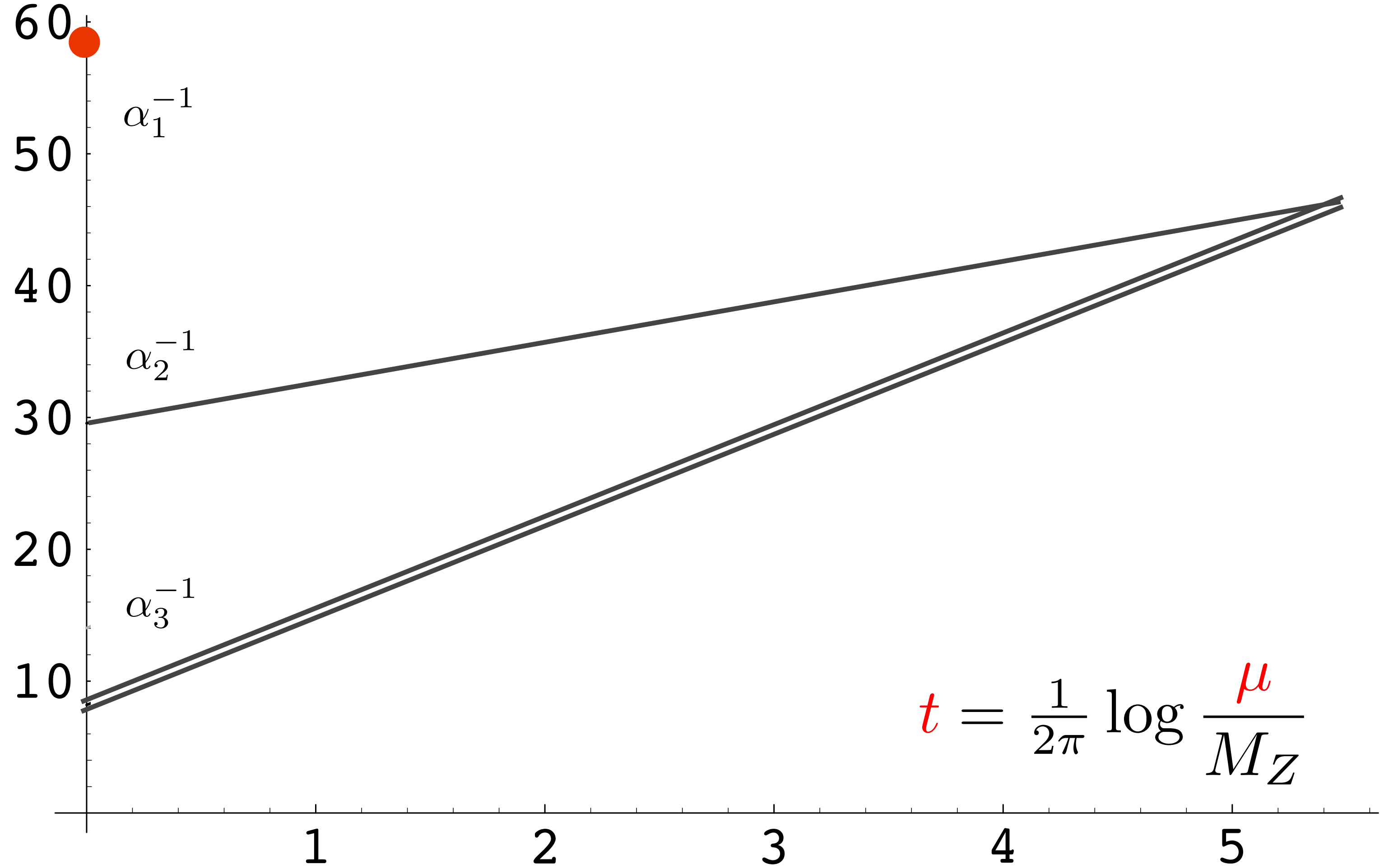
Evolution of gauge couplings in the MSSM



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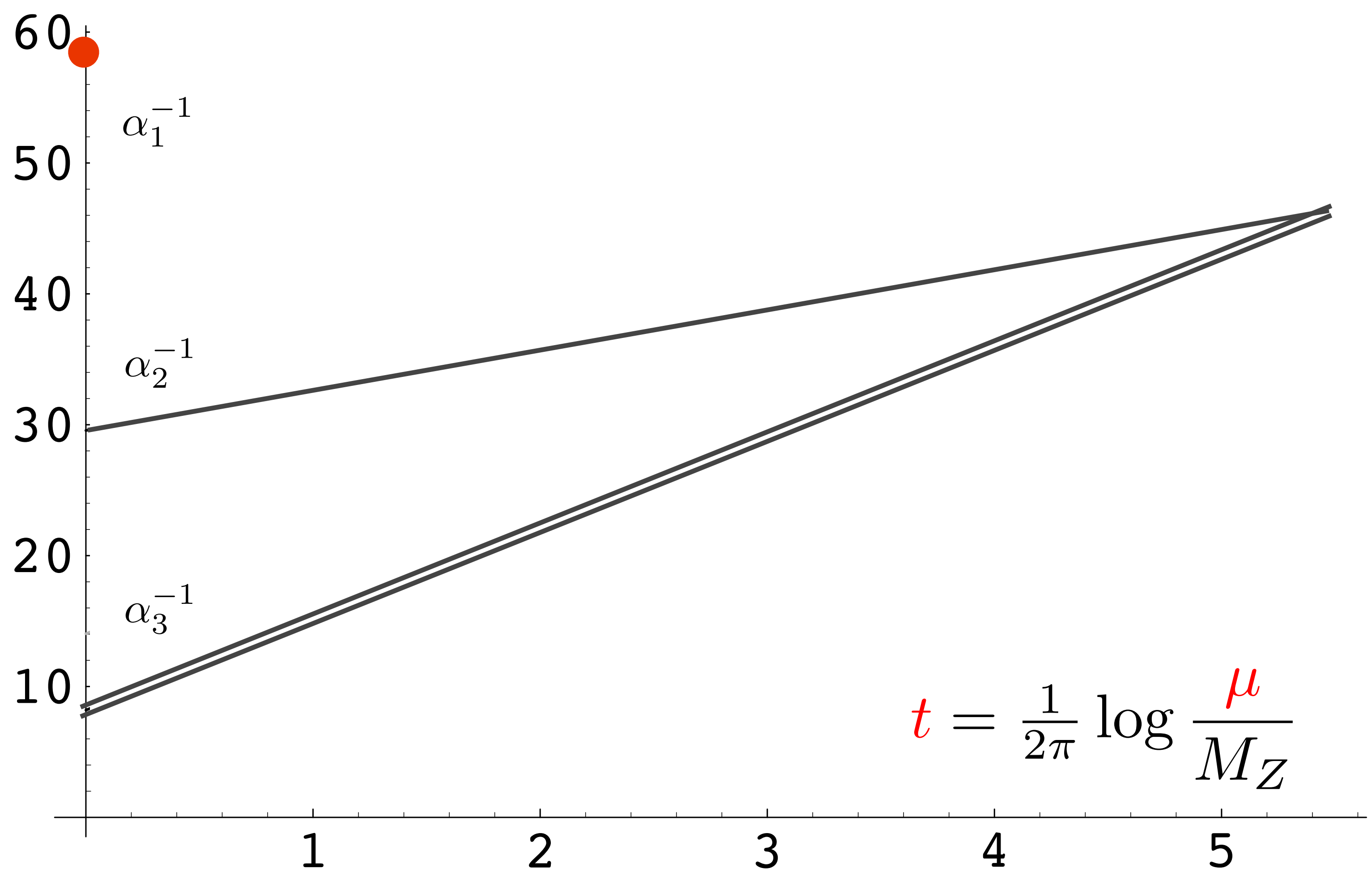
Evolution of gauge couplings in the MSSM (with TeV-scale SUSY)

+ gauginos

+ higgsinos

+ squarks and sleptons



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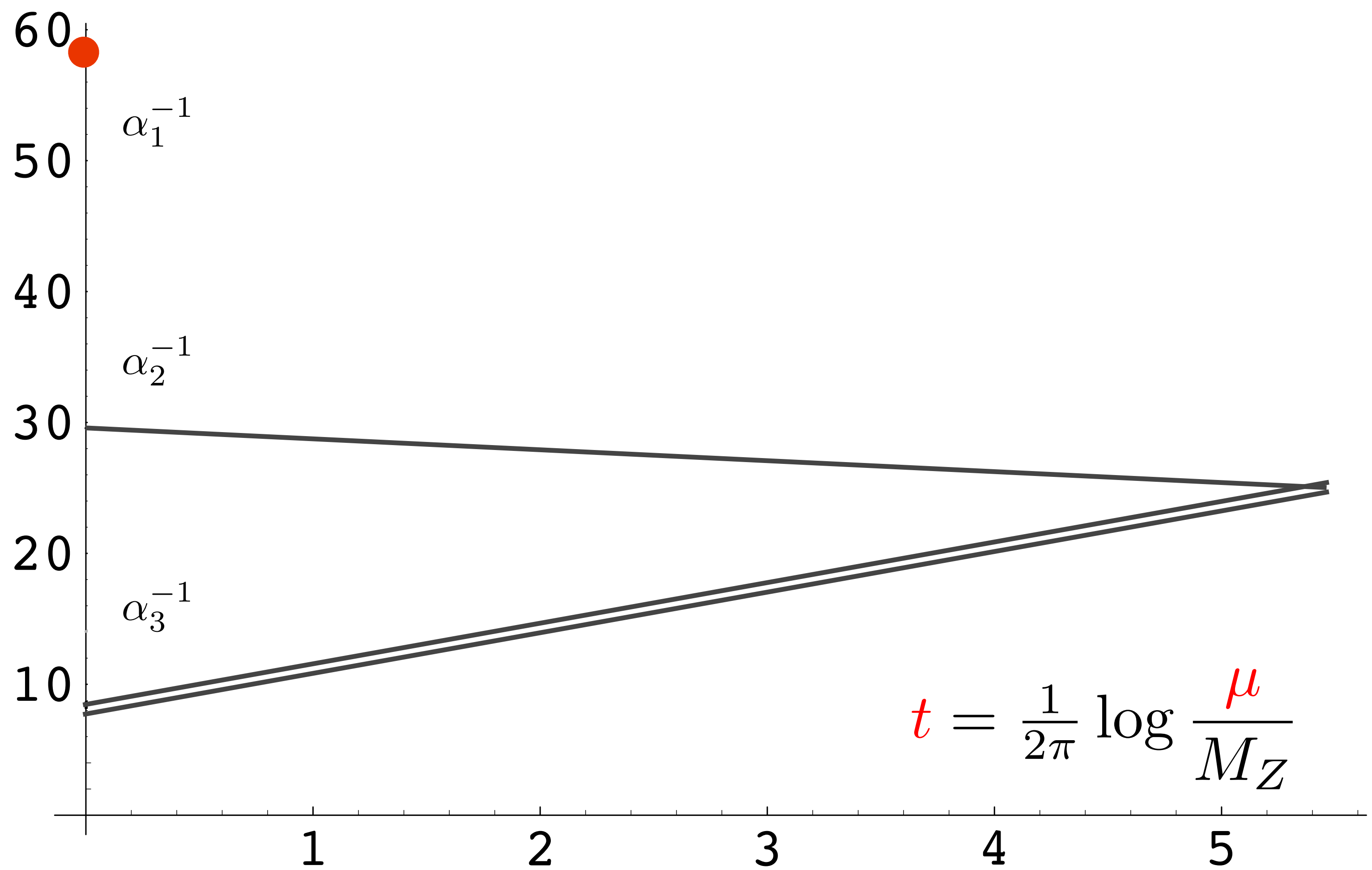

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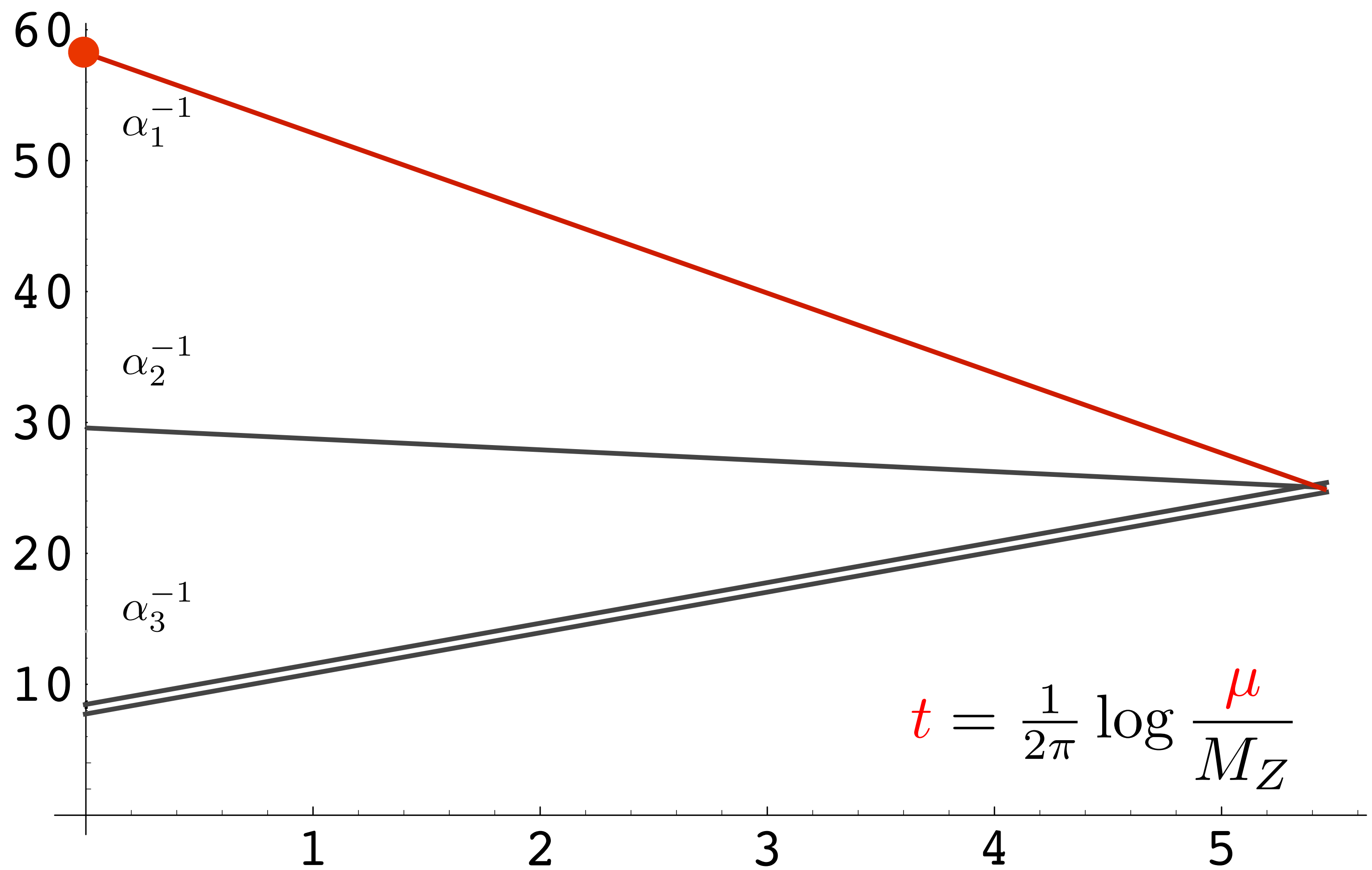

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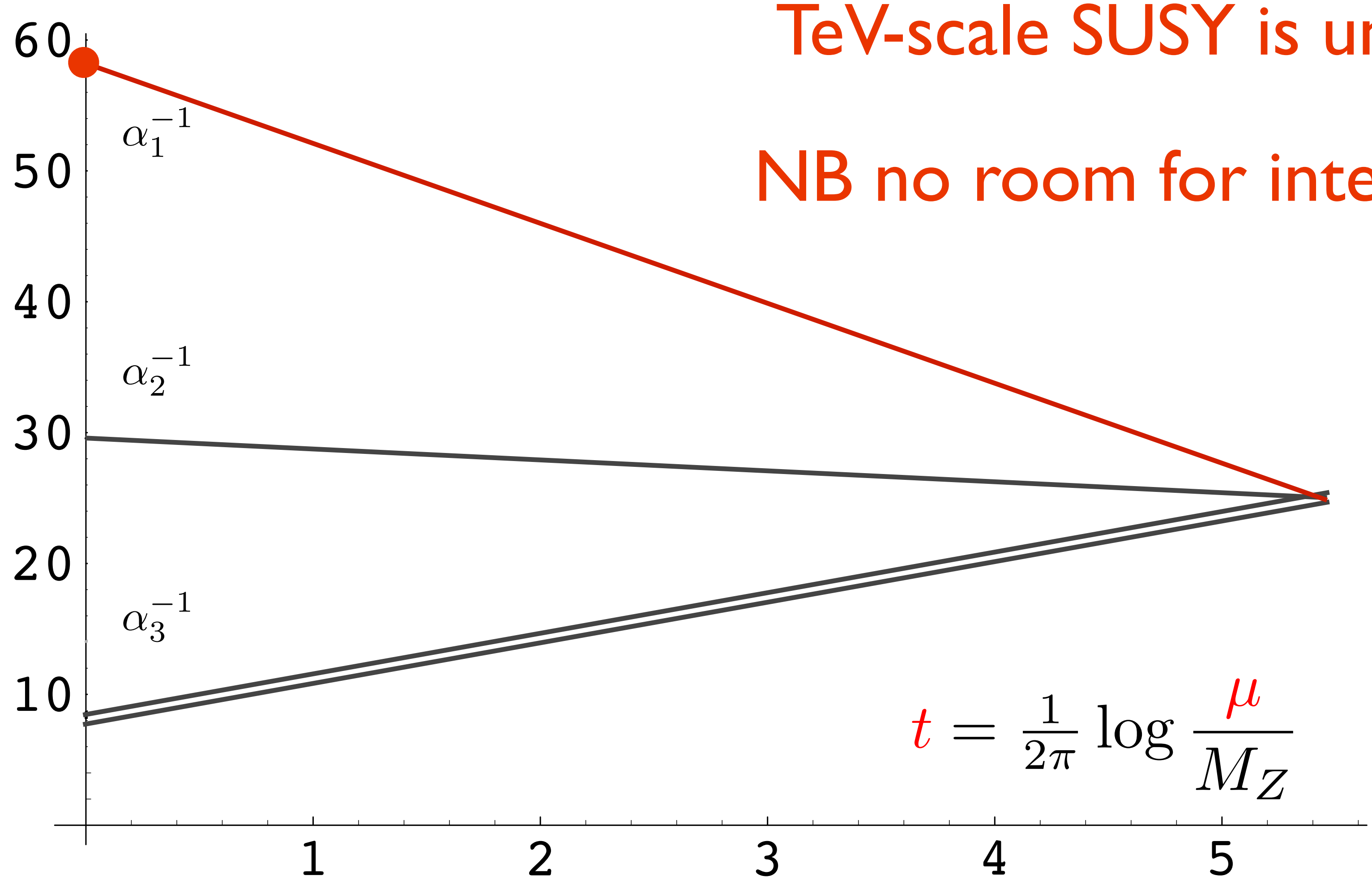

TeV-scale SUSY is unlikely though…

NB no room for intermediate stages!

Neutrinos in SO(10) GUTs