Prague, January 29 2014

Baryon and lepton number violation in the Standard model and beyond

Michal Malinský

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Outlook

BSM perturbative L violation

- Dirac neutrinos and charge de-quantization in SM
- Majorana neutrinos and related phenomena

BSM perturbative B violation

- proton decay and grand unification

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Comments on the TeV-scale SUSY paradigm

- the "Higgs anti-discrimination act"

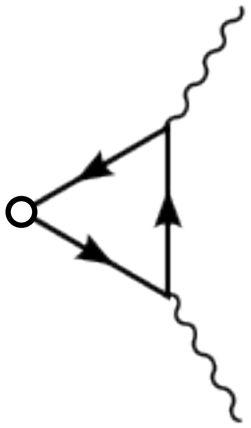
Recent developments in non-SUSY SO(10) GUTs

The GSW Standard Model

(non-perturbative B & L violation)

Expected at some point (non-perturbative):

Chiral anomalies: $\mathcal{A} \propto \frac{1}{32\pi^2} \mathrm{Tr}\left(\{T_a, T_b\} T\right) \tilde{F}^a_{\mu\nu} F^{b\mu\nu}$



B & L violation in the Standard model

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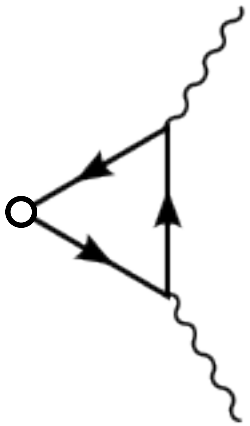

$$\mathrm{Tr}\left(\{Y,Y\}L\right) = \mathrm{Tr}\left(\{Y,Y\}B\right) = -\tfrac{1}{2} \quad \mathrm{Tr}\left(\{T^3_L, T^3_L\}L\right) = \mathrm{Tr}\left(\{T^3_L, T^3_L\}B\right) = \tfrac{1}{2}$$

$$\boxed{\partial^\mu J^L_\mu = \partial^\mu J^B_\mu \neq 0}$$

$$\partial^\mu J^{B-L}_\mu = 0 \qquad \boxed{\partial^\mu J^{B+L}_\mu \neq 0}$$

B & L violation in the Standard model

B+L non-conservation: $B + L = i \int \mathrm{d}^3x \, J^0_{B+L}(x)$

$$\Delta(B+L) = N_f(\Delta N_{\mathrm{CS}} - \Delta n_{\mathrm{CS}})$$

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Chern-Simons numbers:

$$\begin{aligned} N_{\mathrm{CS}} &= -\frac{g_2^2}{16\pi^2}\int d^3x\, 2\epsilon^{ijk}\,\mathrm{Tr}\left[\partial_i A_j A_k + i\frac{2}{3}g_2 A_i A_j A_k\right] \\ n_{\mathrm{CS}} &= -\frac{g_1^2}{16\pi^2}\int d^3x\, \epsilon^{ijk}\,\partial_i B_j B_k, \end{aligned}$$

B & L violation in the Standard model

Vacuum structure of non-abelian (Yang-Mills) gauge theories

$F^{\mu\nu}=0$ attained for pure gauge configurations $A^\mu = U\partial^\mu(U^\dagger)$

$$U\in SU(2)$$

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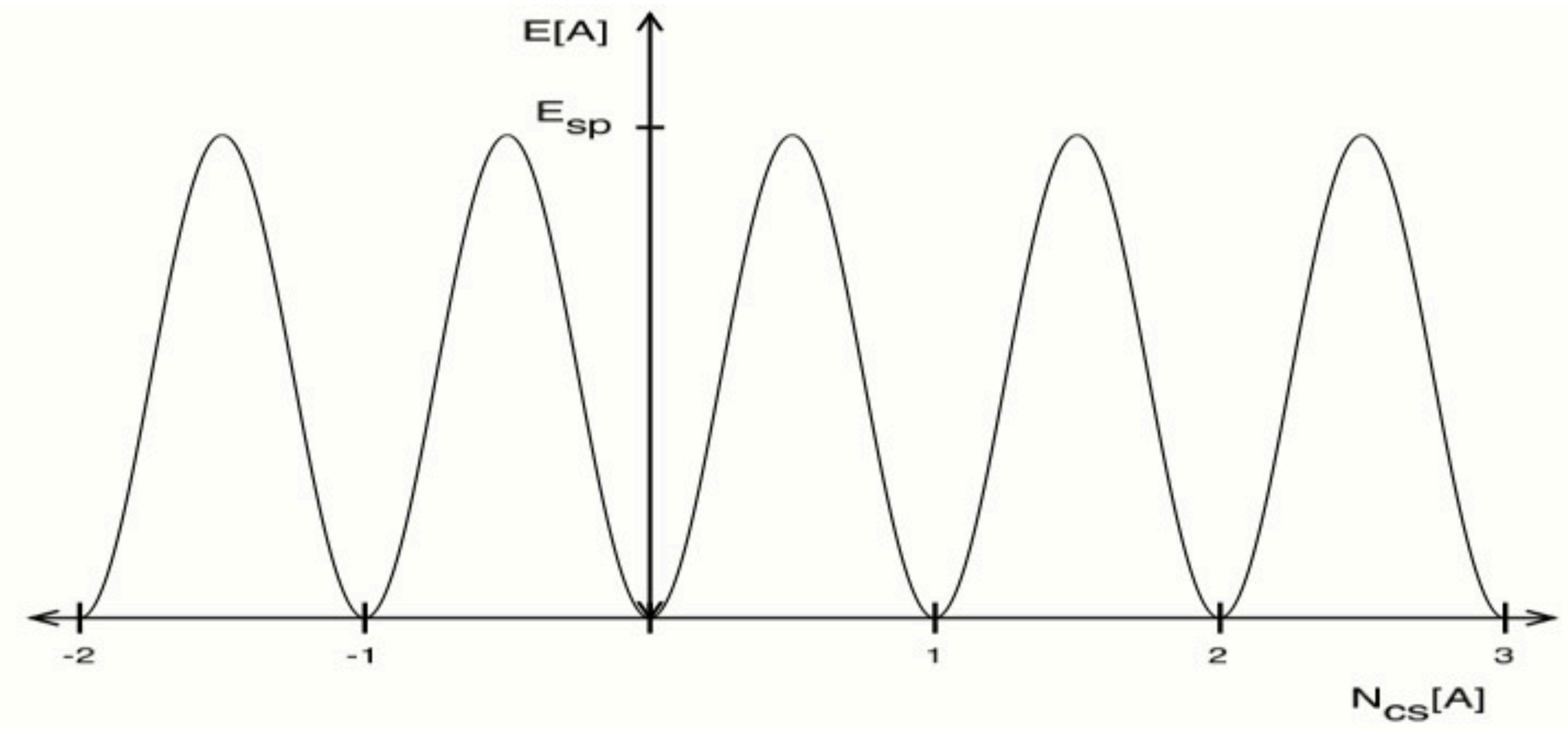
$$\pi_3[SU(2)]=\mathbb{Z}$$



B & L violation in the Standard model

Winding number of SU(2) transformations:

$$n = \frac{1}{24\pi^2} \int d^3x \,\mathrm{Tr}\left[(\partial_i U)U^{-1}(\partial_j U)U^{-1}(\partial_k U)U^{-1}\right] \epsilon^{ijk}$$

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Tunneling between minima with different n's: instantons

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Rates heavily suppressed...

$$\mathcal{A} \sim e^{-2\pi/\alpha_w} \sim 10^{-80}$$

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"Instanton effects" in the SM

$9q + 3l \leftrightarrow \emptyset$ $\quad {}^3He \to e^+ \mu^+ \overline{\nu}_\tau$

Rates heavily suppressed...

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Perturbative L violation

(in the SM with massive neutrinos)

Standard model with massive neutrinos

charge quantization

and

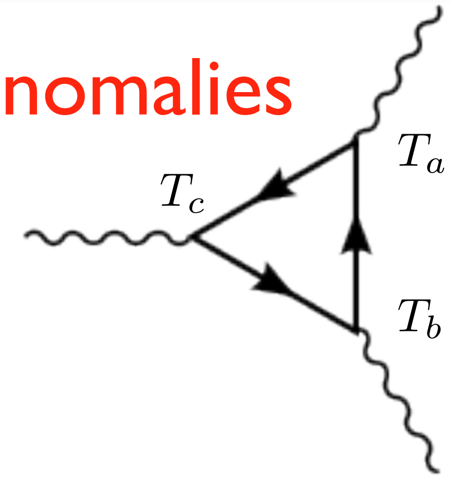
neutrino masses

imply

perturbative L violation

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

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



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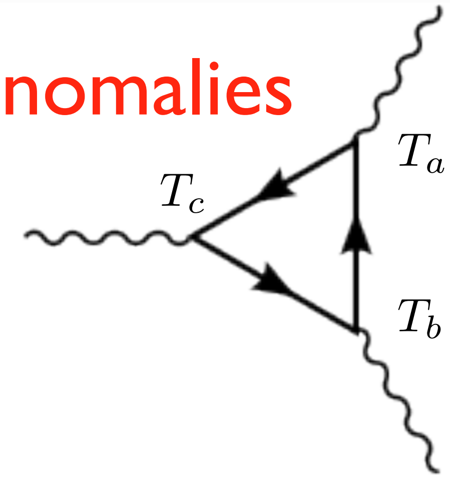

Trick: stick to just SU(2)xU(1) and consider Yukawa interactions

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

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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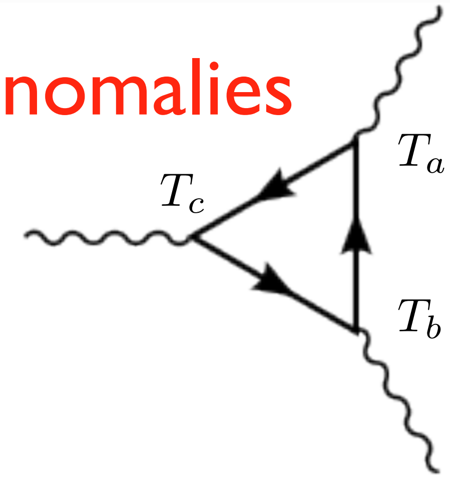

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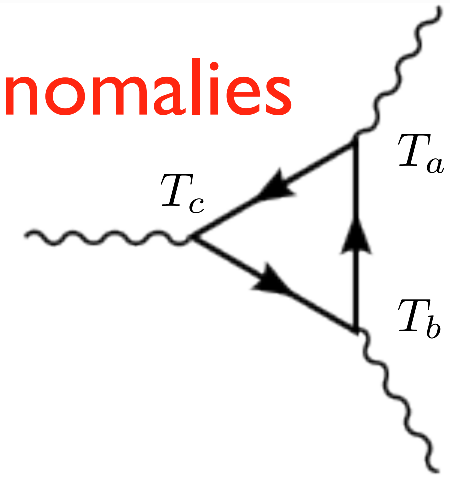

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$-Y_Q + Y_D + Y_H = 0$ $-Y_Q + Y_U - Y_H = 0$ $-Y_L + Y_E + Y_H = 0$

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!

(Hyper)charge de-quantization in the Standard model
with massive (Dirac) neutrinos

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

Assume that neutrinos are massive (Dirac) fermions: needs $N_R = (1, 1, Y_N)$

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Solution:

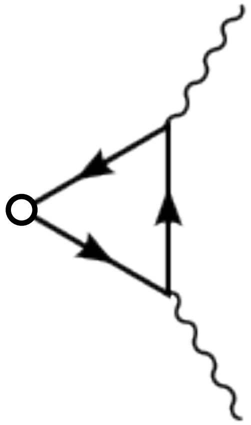
$$\boxed{\begin{array}{l} Y_Q = +\frac{1}{6} - \frac{1}{3}Y_N,\ Y_U = +\frac{2}{3} - \frac{1}{3}Y_N,\ Y_D = -\frac{1}{3} - \frac{1}{3}Y_N, \\ Y_L = -\frac{1}{2} + Y_N,\ Y_E = -1 + Y_N \qquad Y_N \in \mathbb{R} \end{array}}$$

Charge quantization is lost!

A simple symmetry argument

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

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



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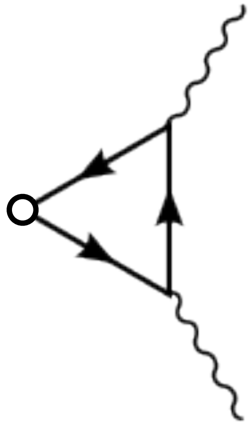

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B - L can be gauged !

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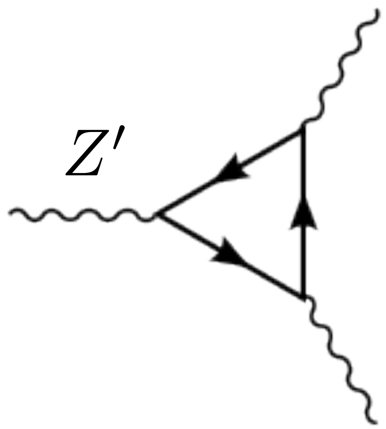

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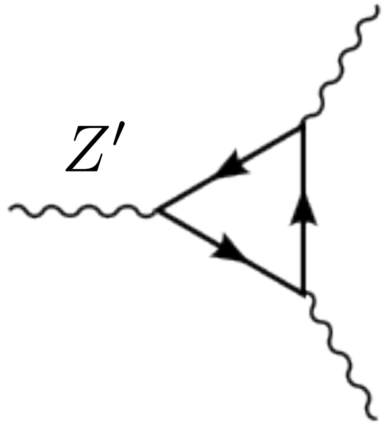

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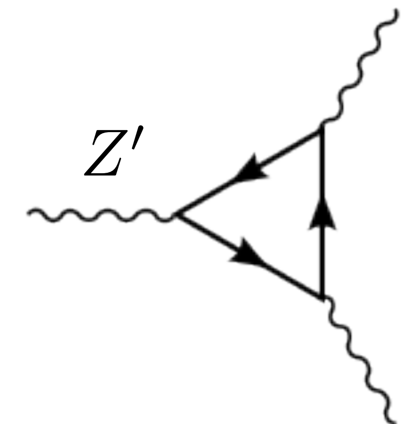

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Babu, Mohapatra, Phys.Rev. D41 (1990) 271

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

Foot, Lew, Volkas 1993

Standard model with massive neutrinos and quantized charges

This suggests that neutrinos are better not Dirac!

Massive but not Dirac = Majorana = strictly neutral = **L violation**

E. Majorana 1937

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Example: RH neutrino with an explicit Majorana mass term:

$$Y_{Dij}\overline{Q_L}_i\langle H\rangle D_{Rj}+Y_{Uij}\overline{Q_L}_i\langle\tilde{H}\rangle U_{Rj}+Y_{Eij}\overline{L_L}_i\langle H\rangle E_{Rj}+Y_{Nij}\overline{L_L}_i\langle\tilde{H}\rangle N_{Rj}+h.c.$$

$$+\tfrac{1}{2}M_{Rij}\overline{N^c_{Ri}}N_{Rj}+h.c.$$

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$$+\tfrac{1}{2} M_{Rij}\overline{N^c_{Ri}} N_{Rj} + h.c.$$

$$M_\nu = \begin{pmatrix} 0 & Y_N v \\ Y_N^T v & M_R \end{pmatrix} \qquad m_\nu = Y_N {M_R}^{-1} v^2 Y_N^T$$

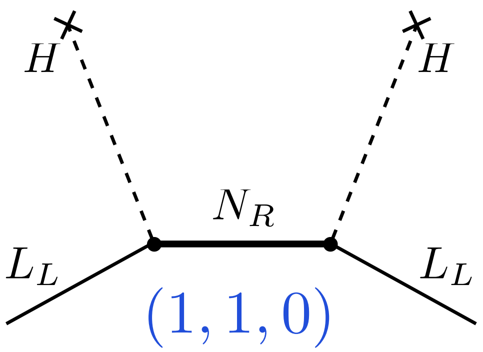
"seesaw mechanism"

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

Three kinds of tree-level renormalizable seesaw

Three kinds of tree-level renormalizable seesaw

type-I seesaw



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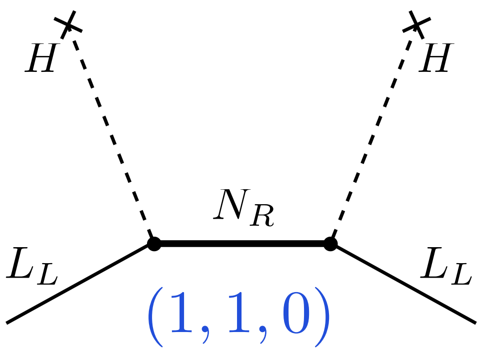

RHN with a large Majorana mass term

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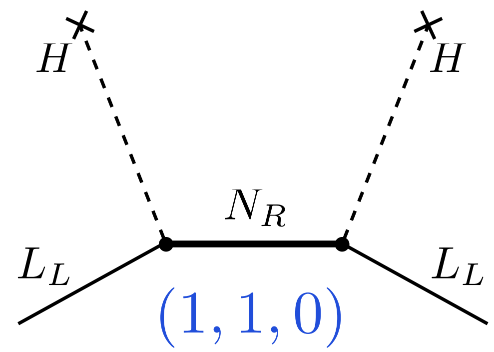
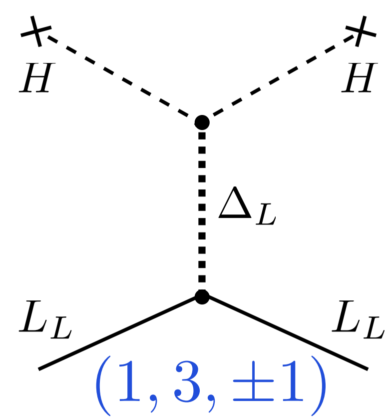


RHN with a large Majorana mass term

type-II seesaw



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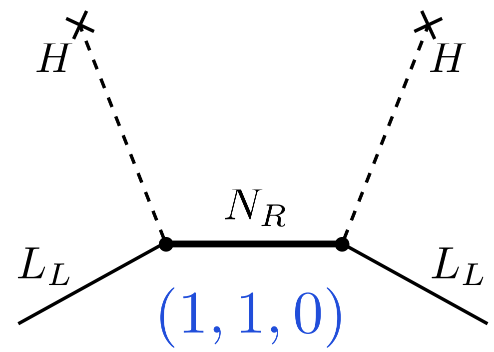

RHN with a large
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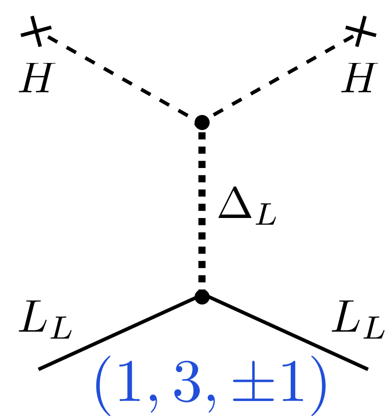

Heavy scalar triplet
with a dimensionful
trilinear scalar coupling

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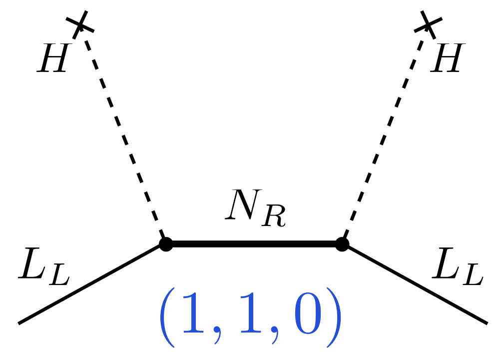

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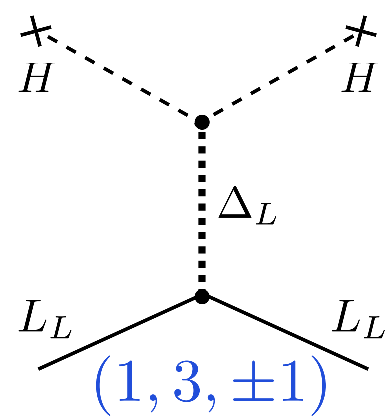
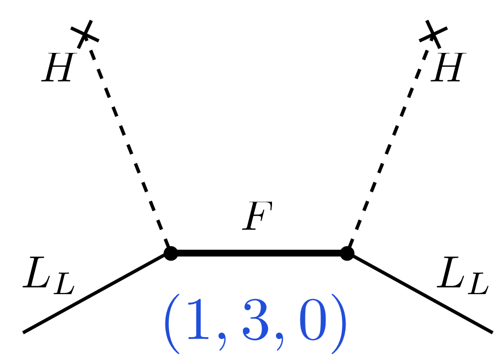


Heavy scalar triplet with a dimensionful trilinear scalar coupling

type-III seesaw



Three kinds of tree-level renormalizable seesaw

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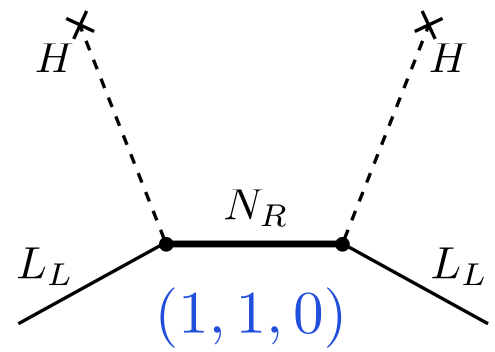

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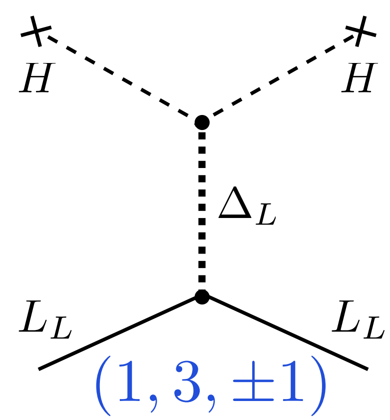

Heavy scalar triplet with a dimensionful trilinear scalar coupling

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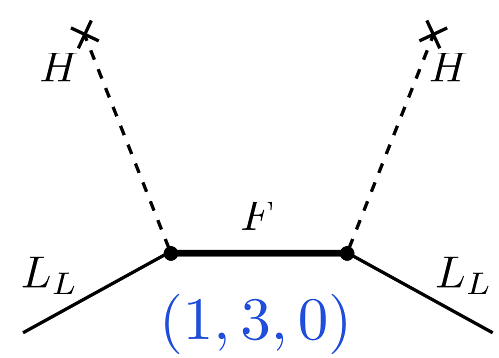

Fermionic triplet with a large Majorana mass term

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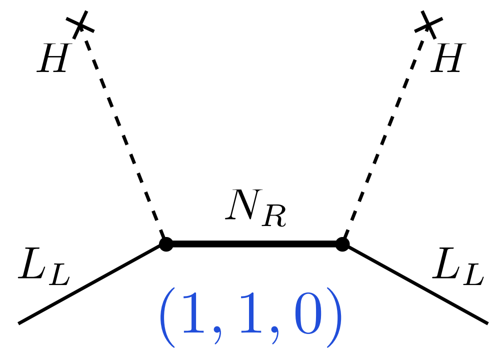

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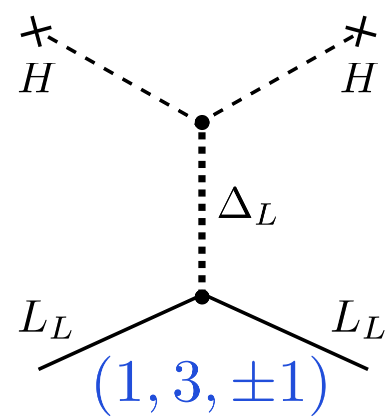
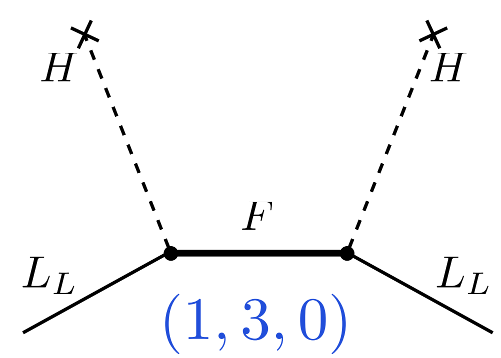


Heavy scalar triplet with a dimensionful trilinear scalar coupling

In all cases the SM neutrino is a light Majorana fermion

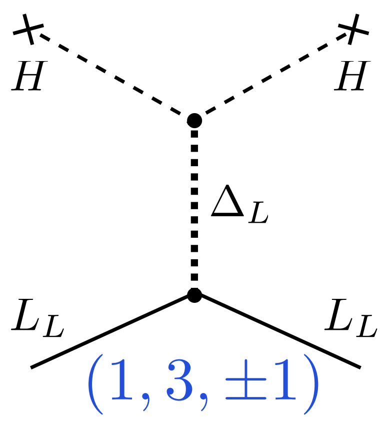
type-III seesaw



Fermionic triplet with a large Majorana mass term

review: arXiv:1001.2693 [hep-ph]

Type-II seesaw: - doubly-charged scalar in the spectrum!



Lepton number violation at colliders
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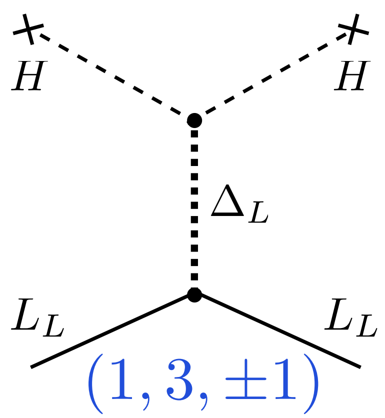

$$Z^* \to \Delta^{++}\Delta^{--} \to (l^+ l^+)(l^- l^-)$$

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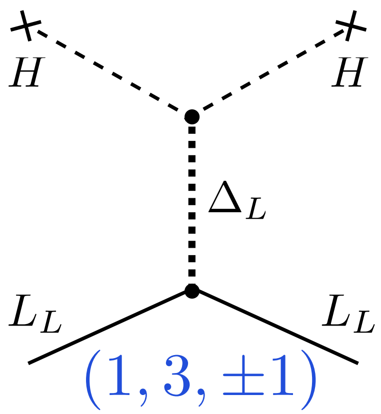


- doubly-charged scalar in the spectrum!

- same sign dilepton pairs (boosted)

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

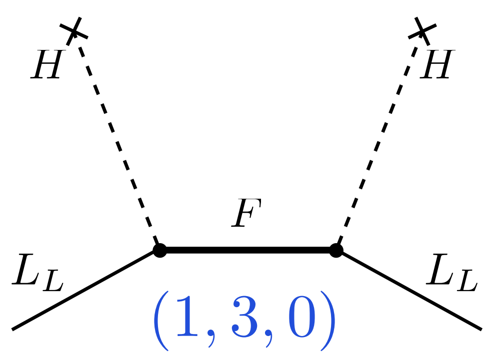
- decays rely on the size of the triplet Yukawa couplings

- flavour structure correlated to neutrino mixing

“light” type-III seesaw

review: arXiv:1001.2693 [hep-ph]

Type-III seesaw: - neutral and charged fermions



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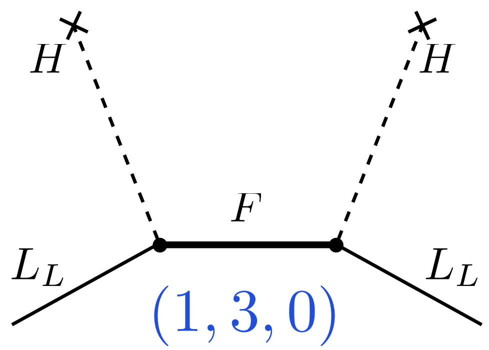

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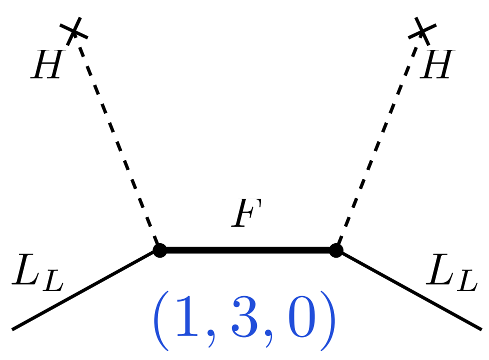

- neutral and charged fermions
- triplet feels the SM gauge bosons - better than singlet!
- multi-lepton channels as in type-II

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

- kinematics different, not so spectacular...

Lepton number violation in oscillations

LNV is a really old story...

The first approach to neutrino oscillations was indeed "L-violating"!

B. Pontecorvo, Sov.Phys.JETP 6 (1957) 429

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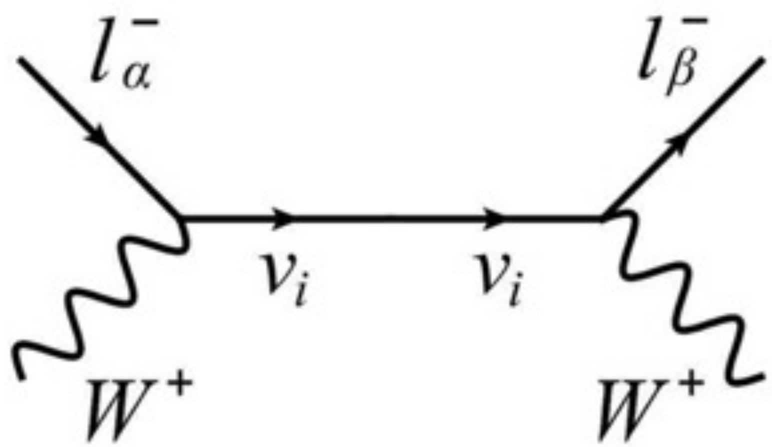
Diagrammatics:

see e.g. E. Akhmedov, J. Kopp, JHEP 1004 (2010) 008



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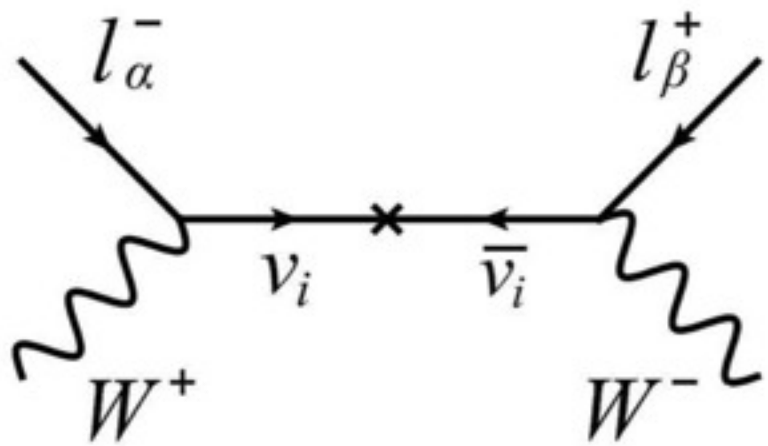

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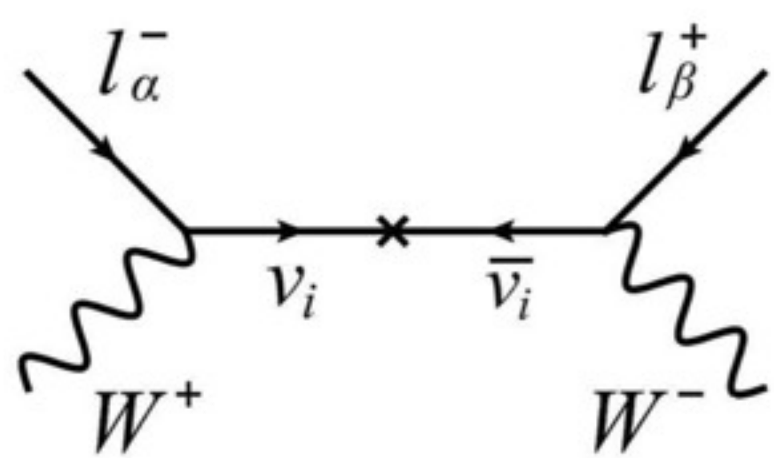

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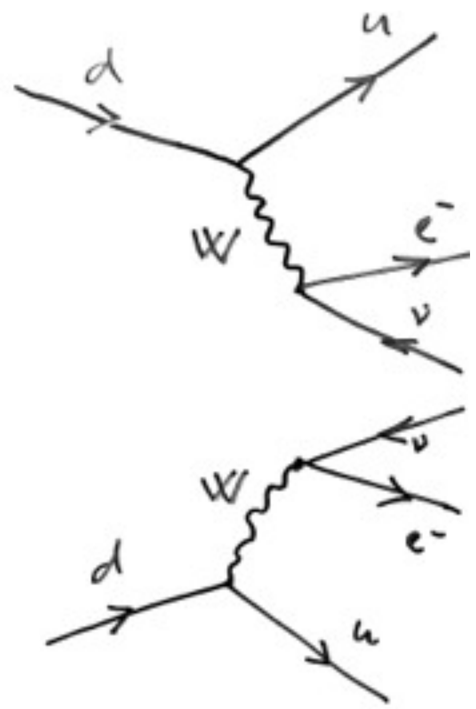
Nowadays mostly academic... see e.g. Z-z. Xing, arXiv:1301.7654v2

Neutrinoless double beta decay

Diagrammatics:



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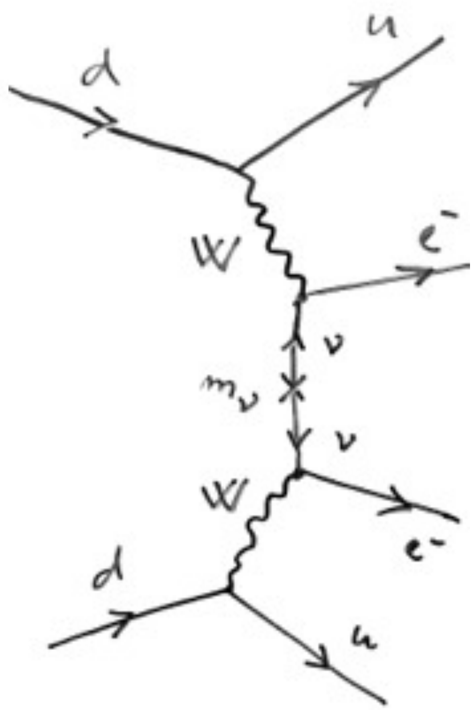

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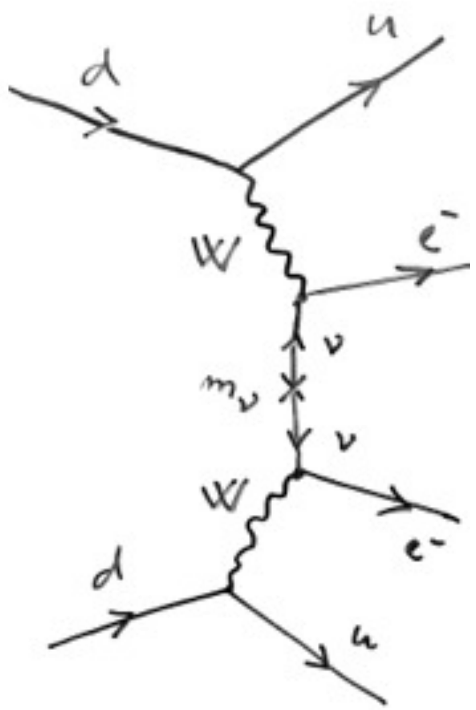

$$\mathcal{A} \propto g^4 \frac{\langle m \rangle}{q^2}$$

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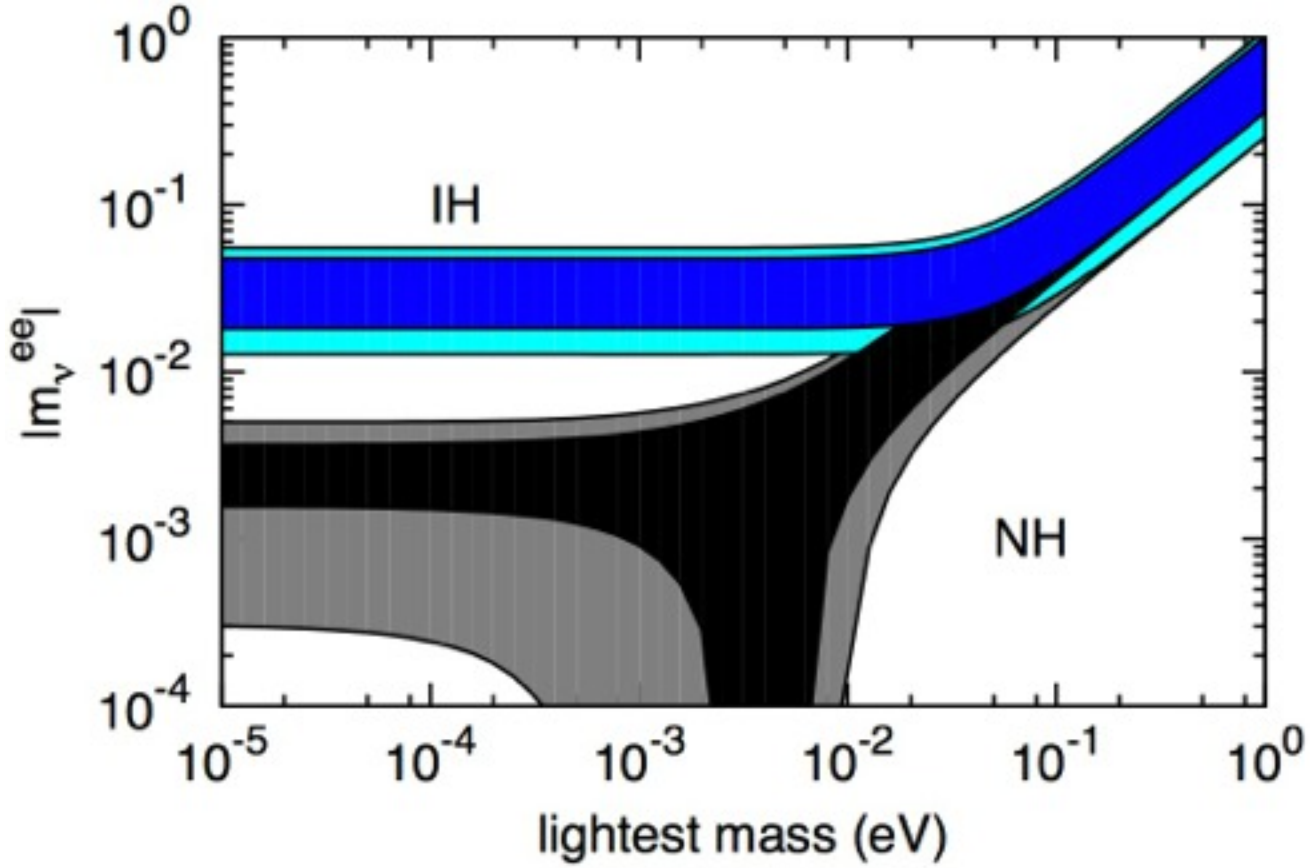

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Figures from Chakrabortty et al., 2012

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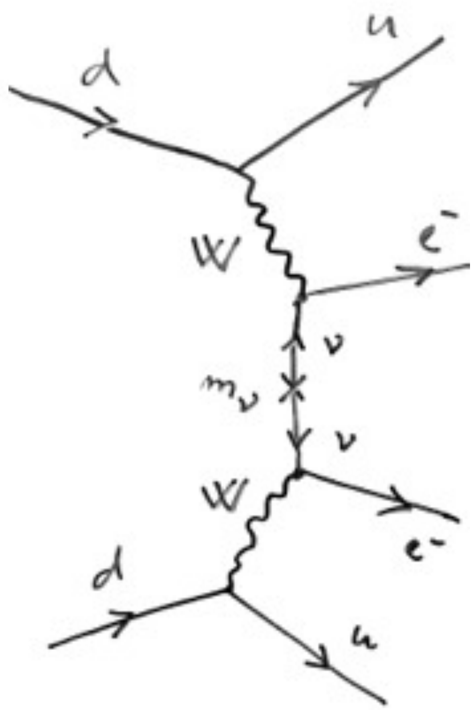

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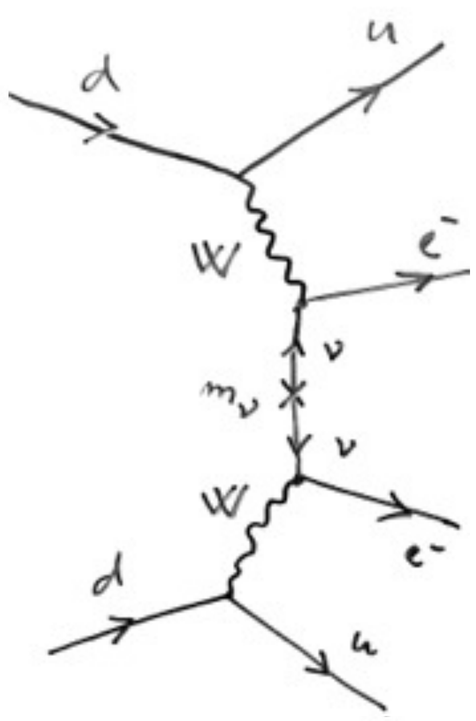

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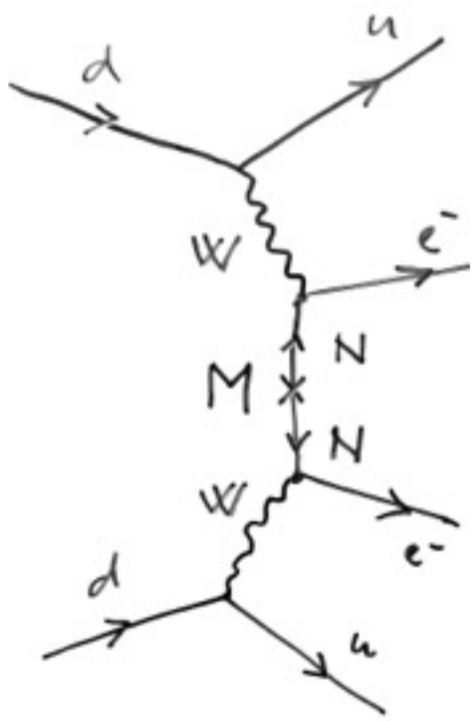
Heavy neutrinos also feel gauge interactions!



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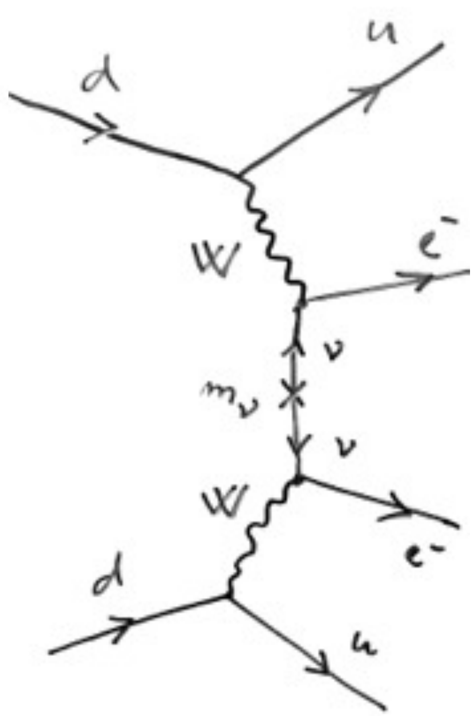

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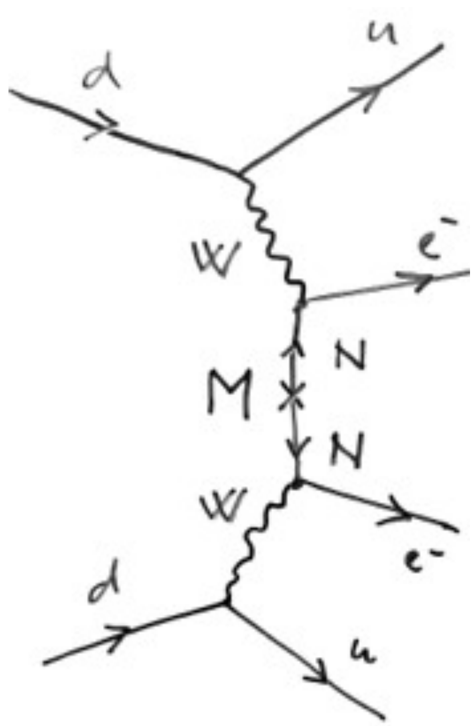

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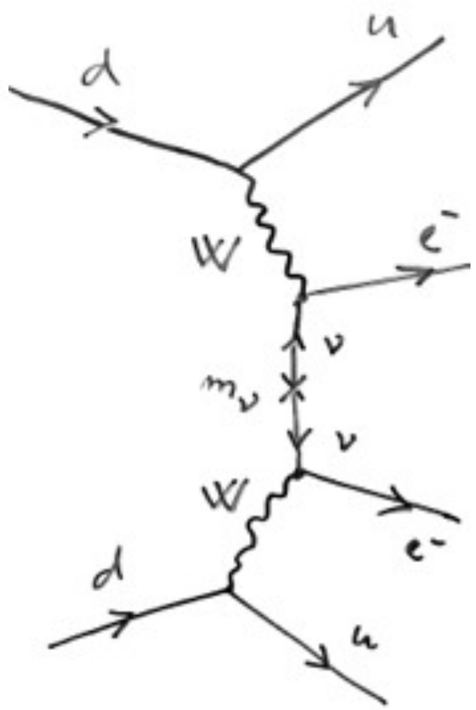

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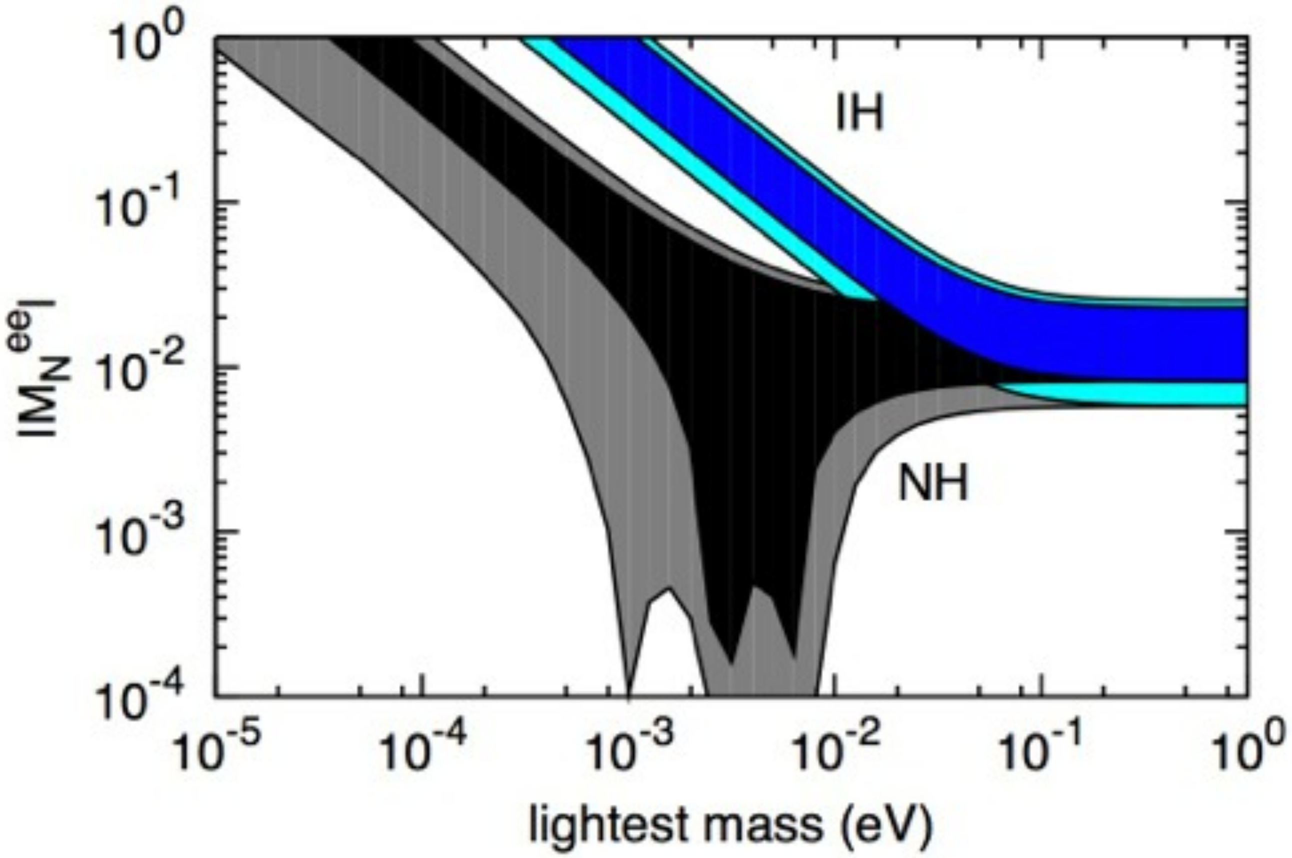

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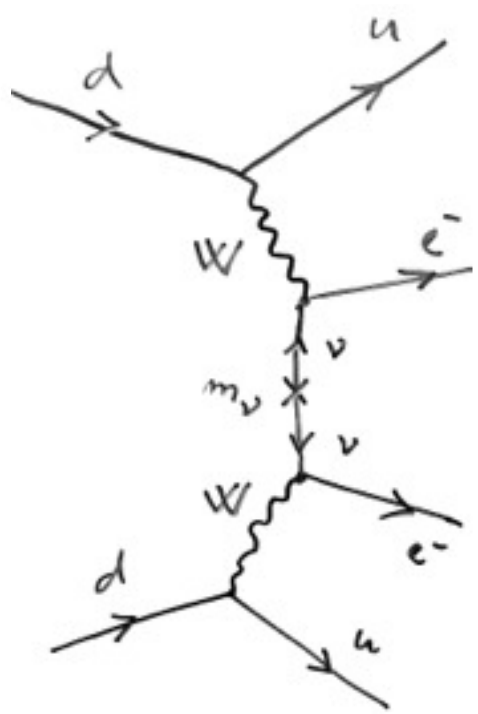

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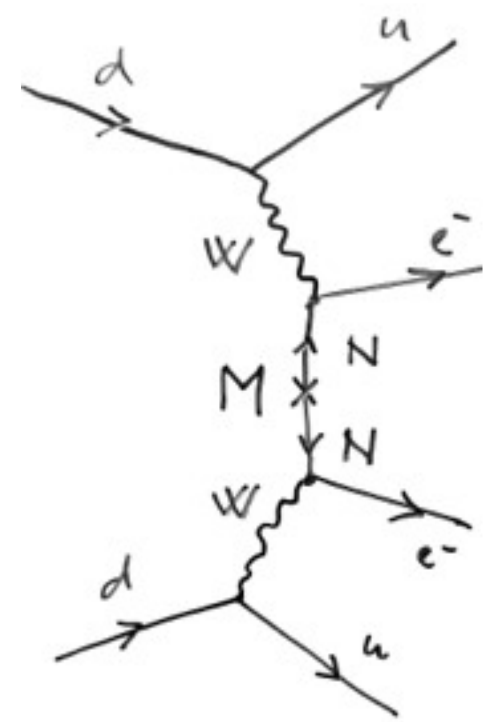

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This may even dominate if M is in the TeV region
or if there are RH currents around TeV

Neutrinoless double beta decay

But what if there is something else?

Neutrinoless double beta decay

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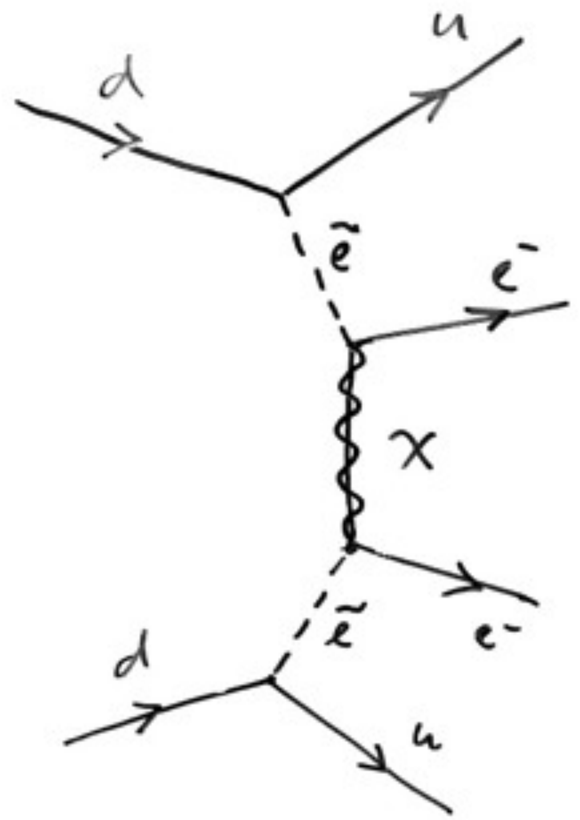

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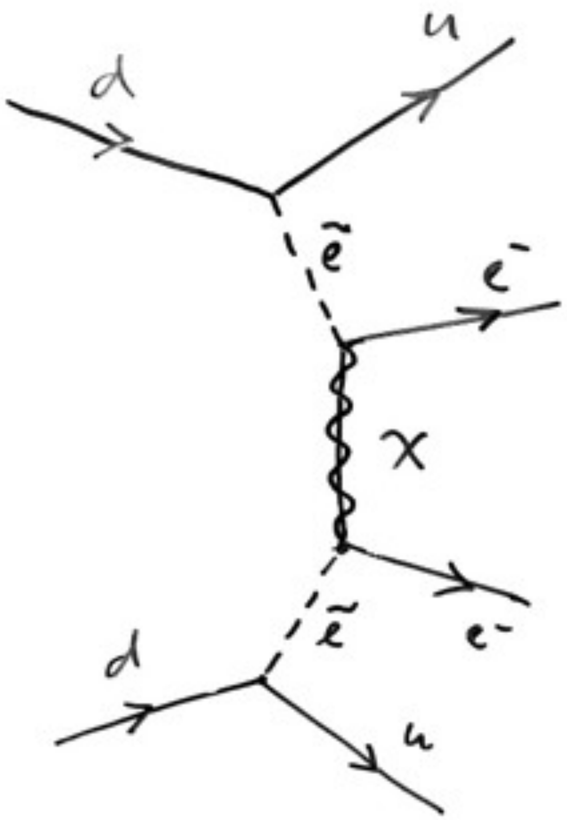
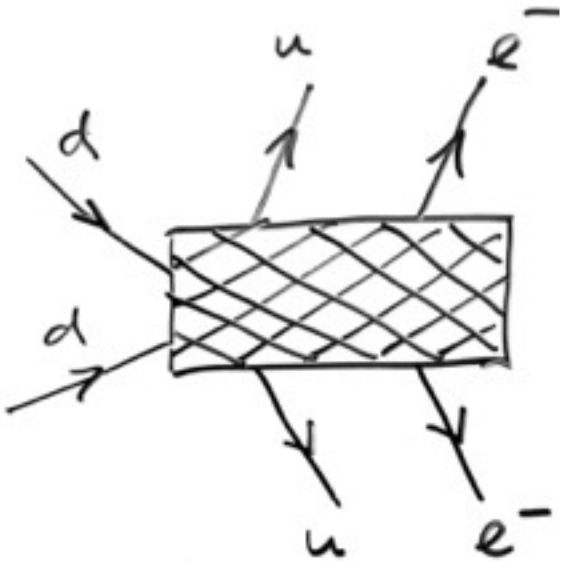


Schechter - Valle mechanism:



J. Schechter, J. F. W. Valle, PRD 1982
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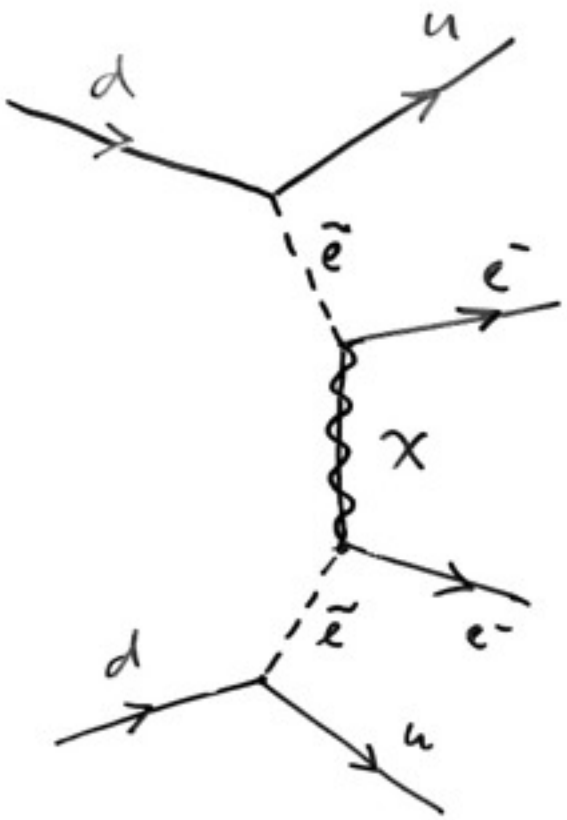

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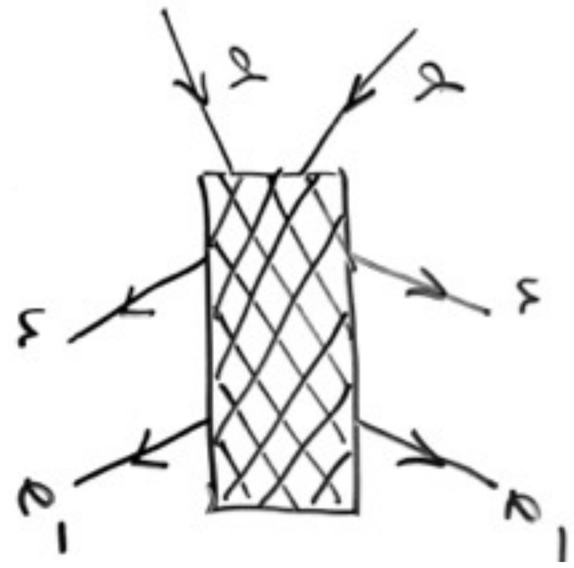

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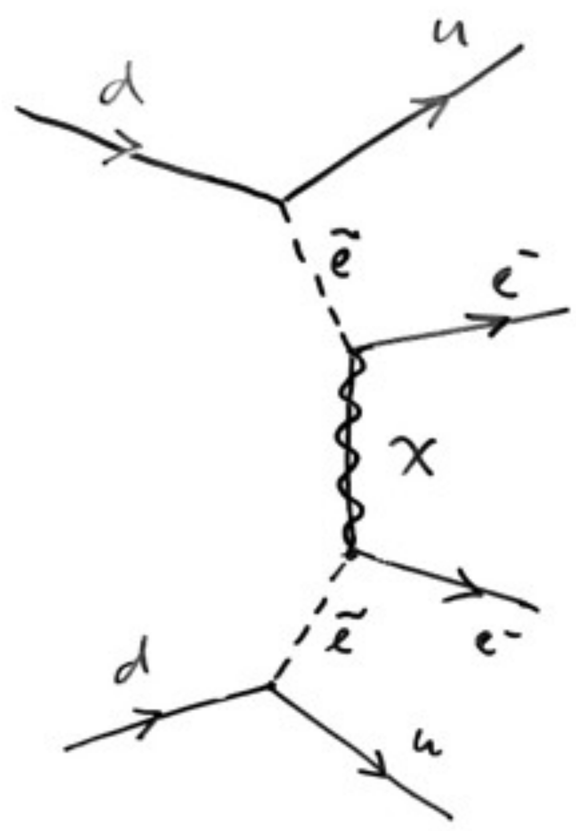

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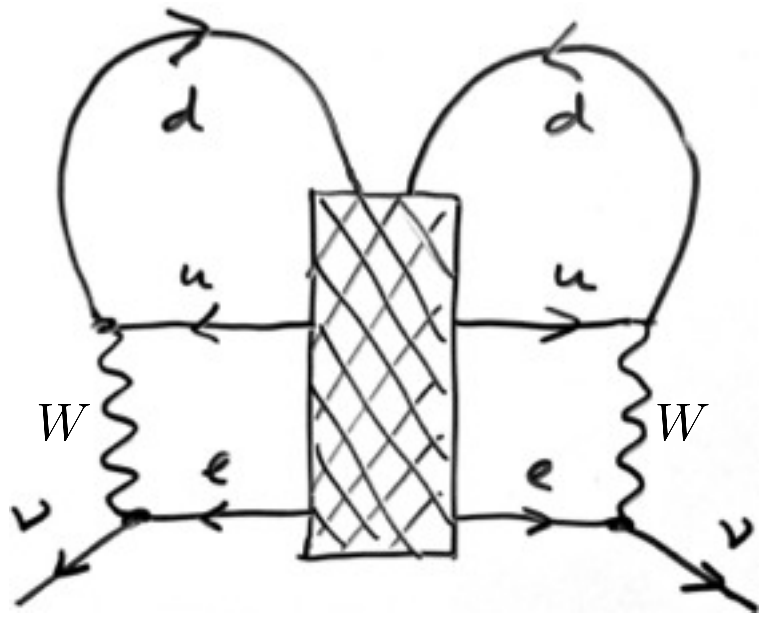

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If neutrinoless double beta decay is seen, neutrinos are inevitably Majorana...

Lepton number violation in cosmology - leptogenesis

Perturbative + nonperturbative LNV very handy for baryogenesis

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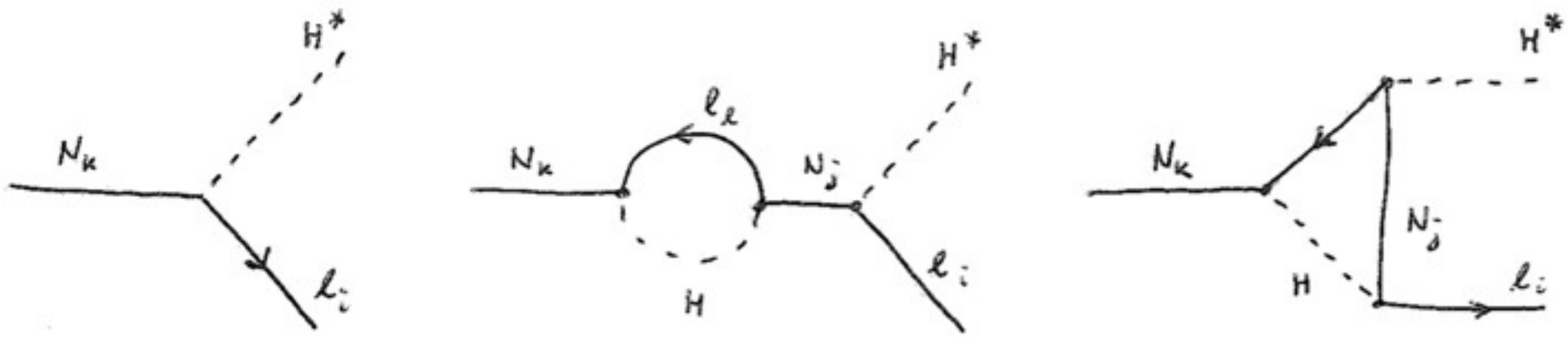
Generating net L in the type-I seesaw:

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

Lepton number violation in cosmology - leptogenesis



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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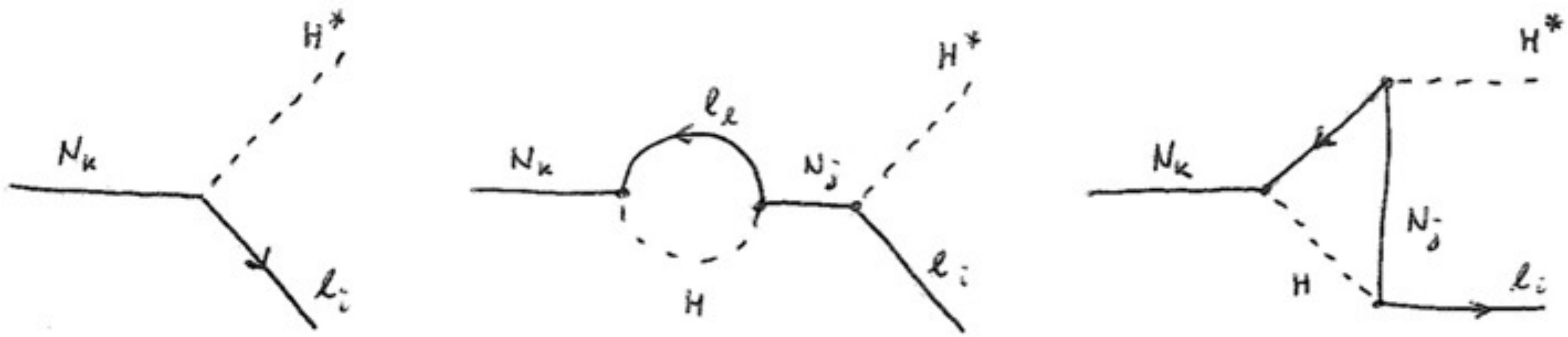

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Davidson-Ibarra bound: S. Davidson and A. Ibarra, Phys. Lett. B535, 25 (2002)

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

$$\boxed{M_1 \gtrsim 10^9\,\mathrm{GeV}}$$

SM as an effective theory

LOWER

- Neutrino oscillations: $\Delta m^2_\odot = (8.0 \pm 0.3) \times 10^{-5} \mathrm{eV}^2$

  $|\Delta m^2_A| = (2.5 \pm 0.3) \times 10^{-3} \mathrm{eV}^2$

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BTW: good to have the "complete Higgs doublet" :-)

(If you prefer LABEHGHKW you rather read "HIGGS"...)

Perturbative B violation

(in gauge extensions of the SM)

SM as an effective theory at d=6 level

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}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
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$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	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

SM as an effective theory at d=6 level

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	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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$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
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d=6 baryon number violation mediators

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

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Scalar exchange

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

d=6 baryon number violation mediators

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

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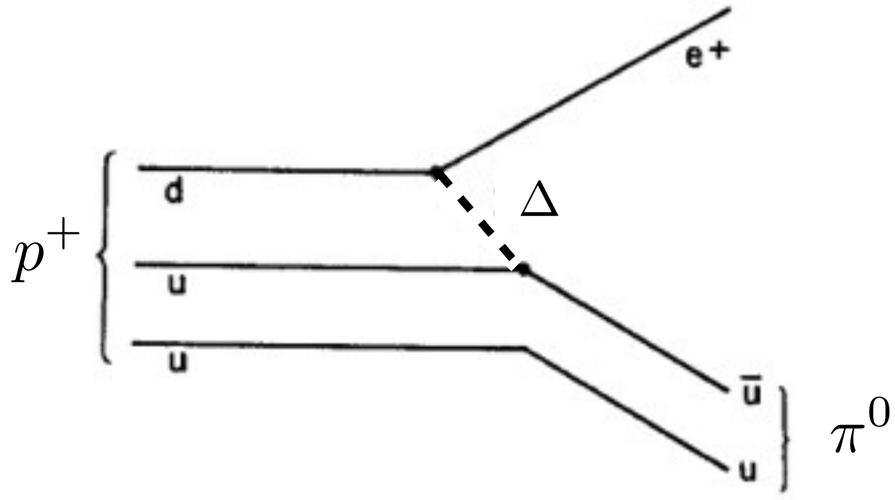
Proton instability: $\Gamma_p \sim \dfrac{m_p^5}{M^4} < (10^{34}\mathrm{y})^{-1}$

new Yukawa interactions?



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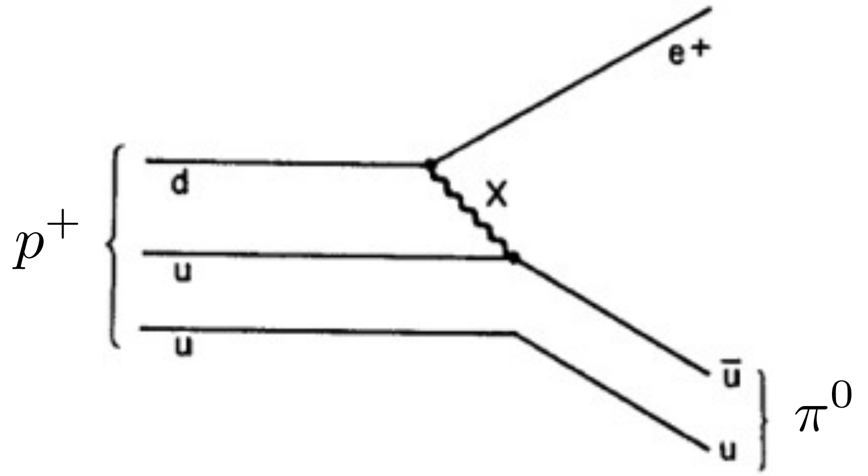

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Fierz

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Scalar exchange	Vector exchange
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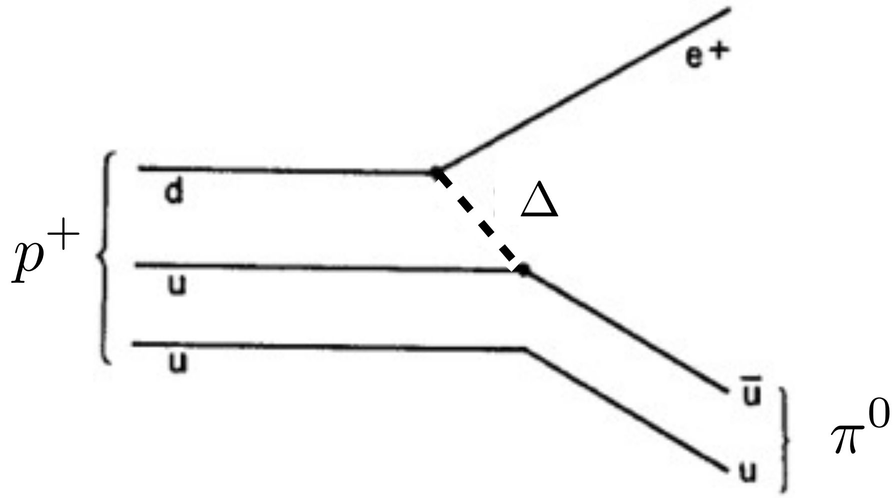

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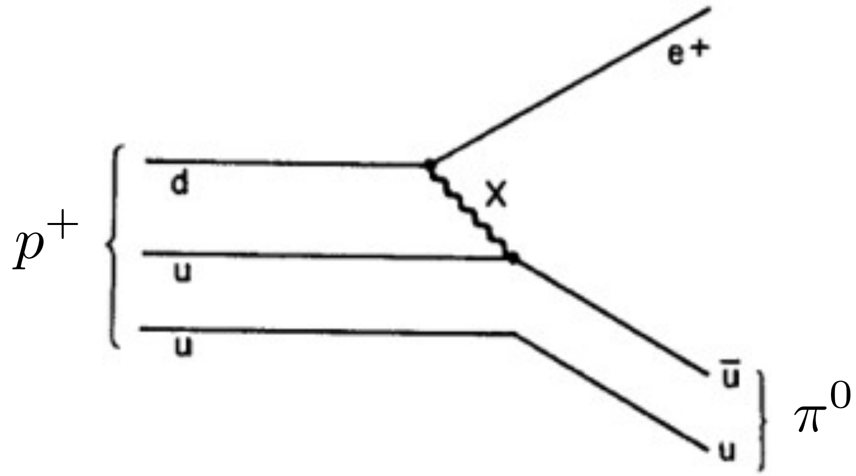

Such a new physics should be above 10^{15} GeV !??

Can SM tell us anything about such a huge-scale dynamics?

Running gauge couplings in the SM:

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

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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)

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Running gauge couplings in the SM

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

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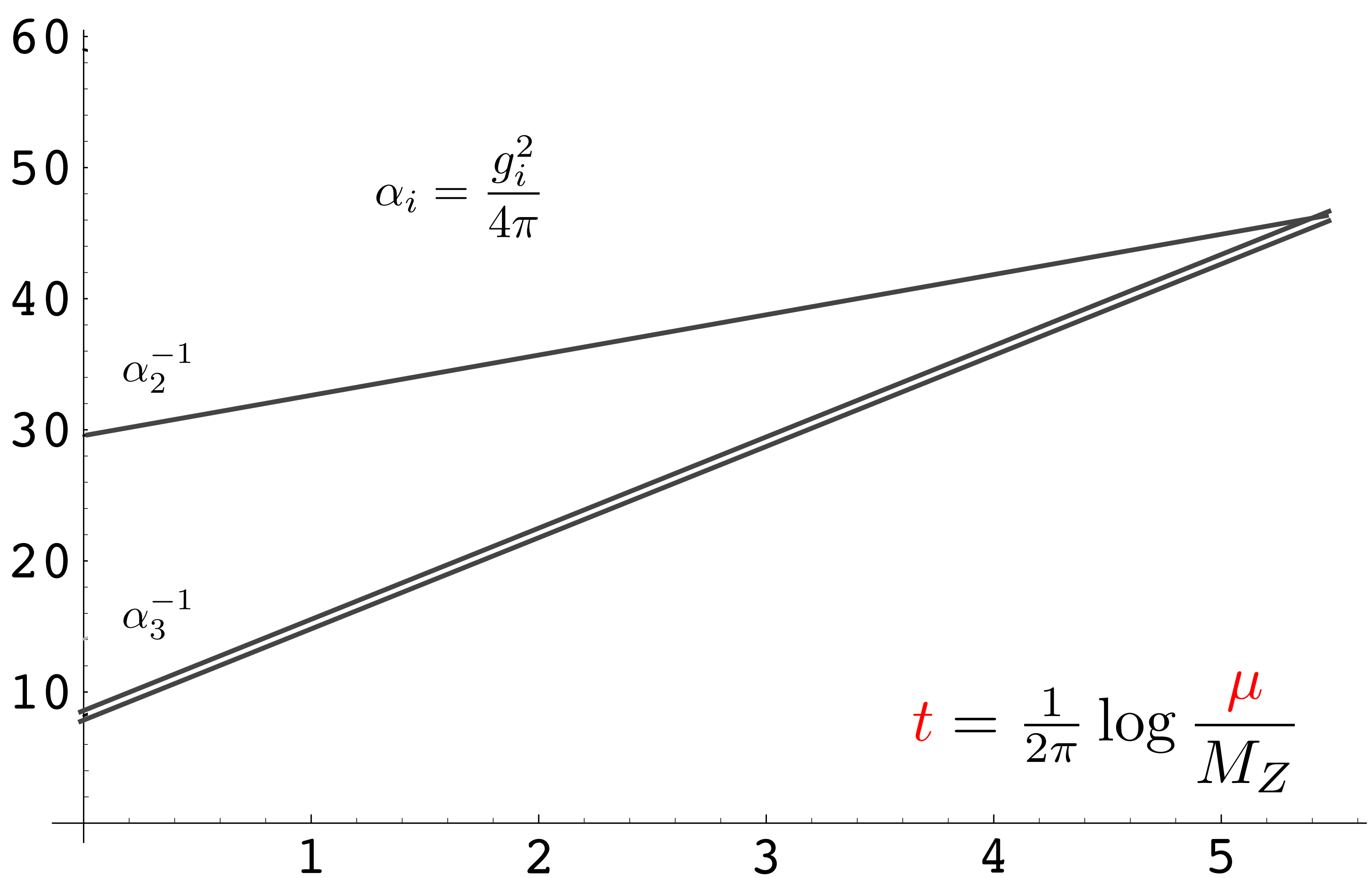

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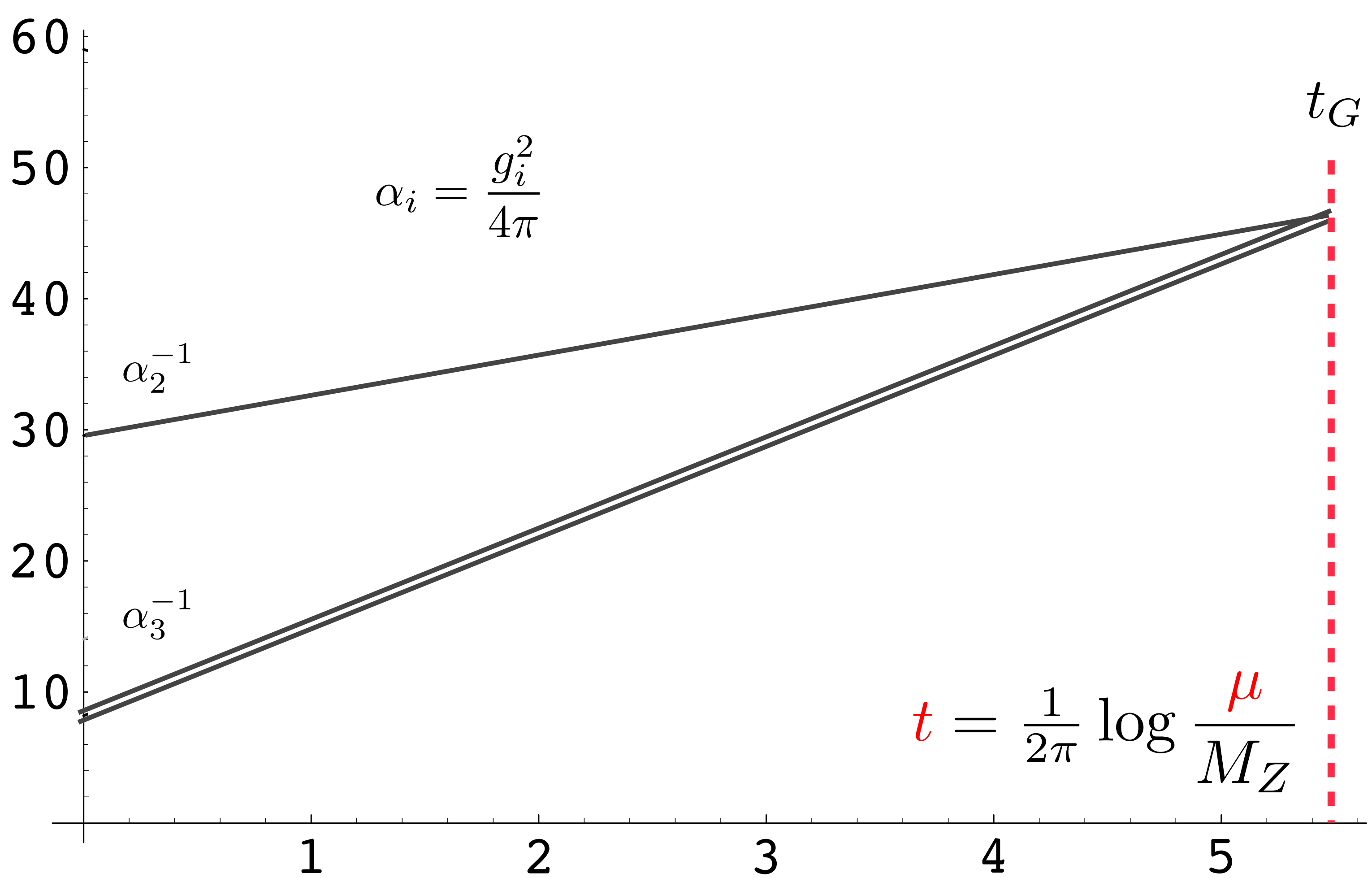

$M_G \sim 10^{16}\mathrm{GeV}$

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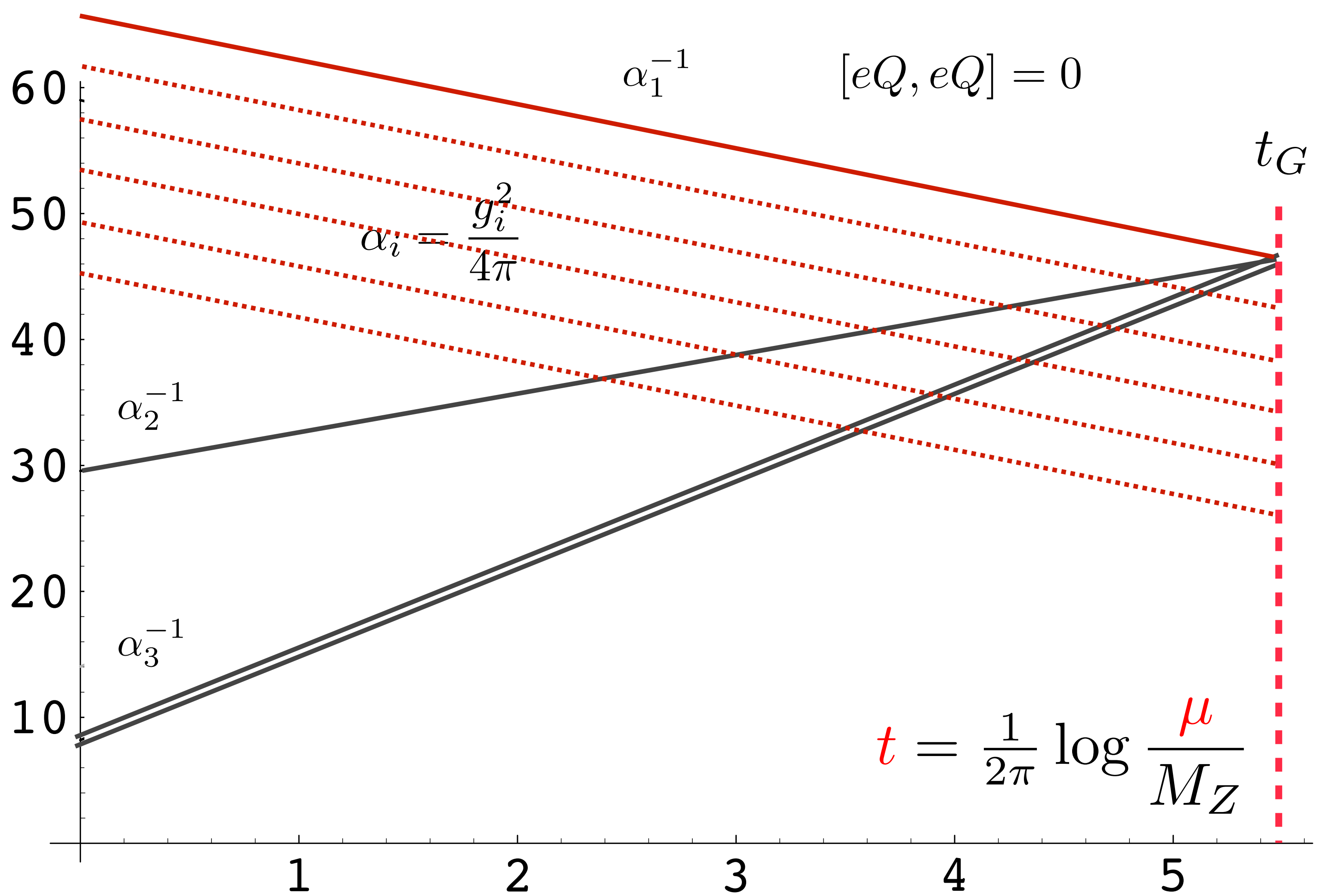

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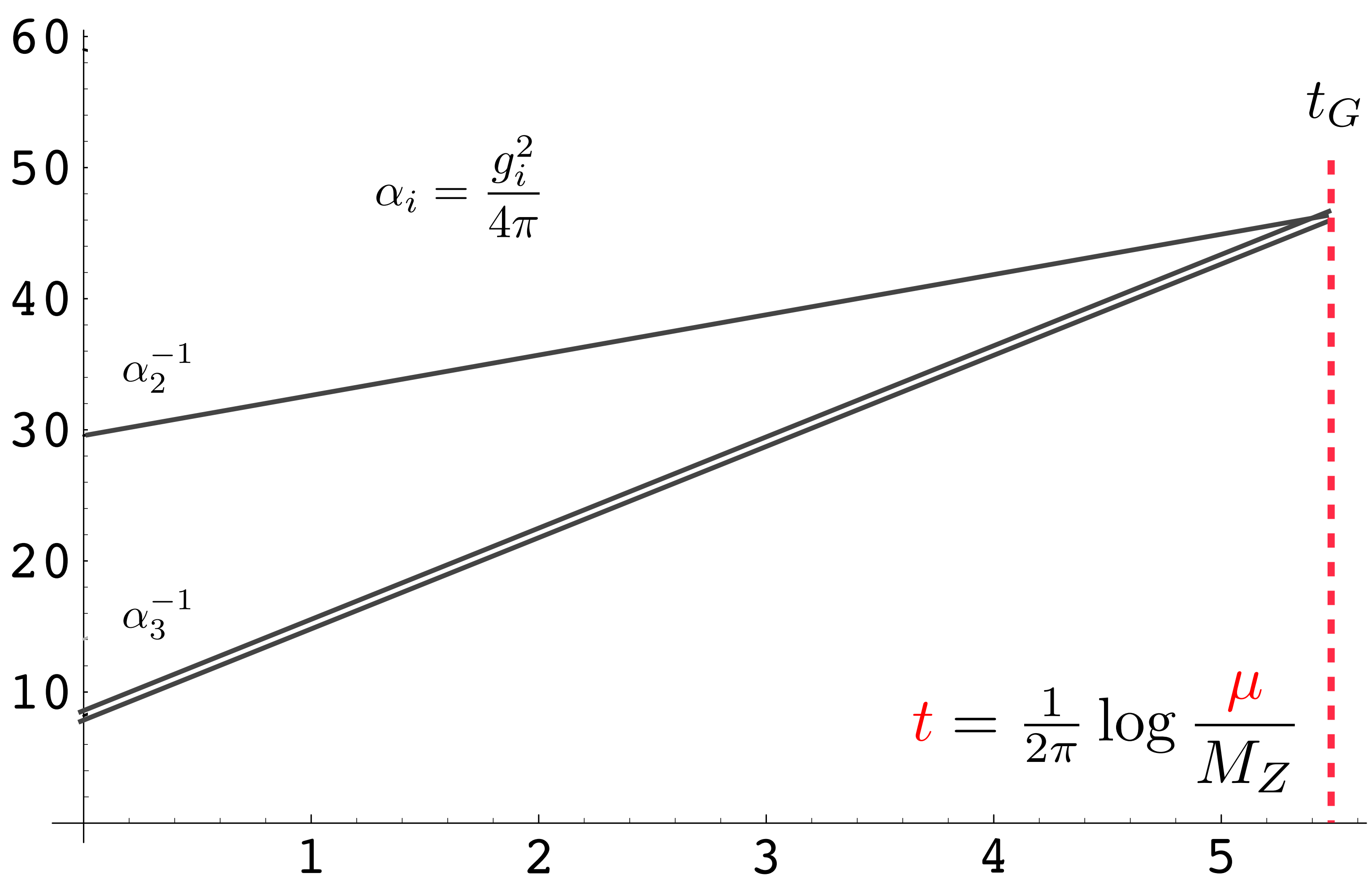

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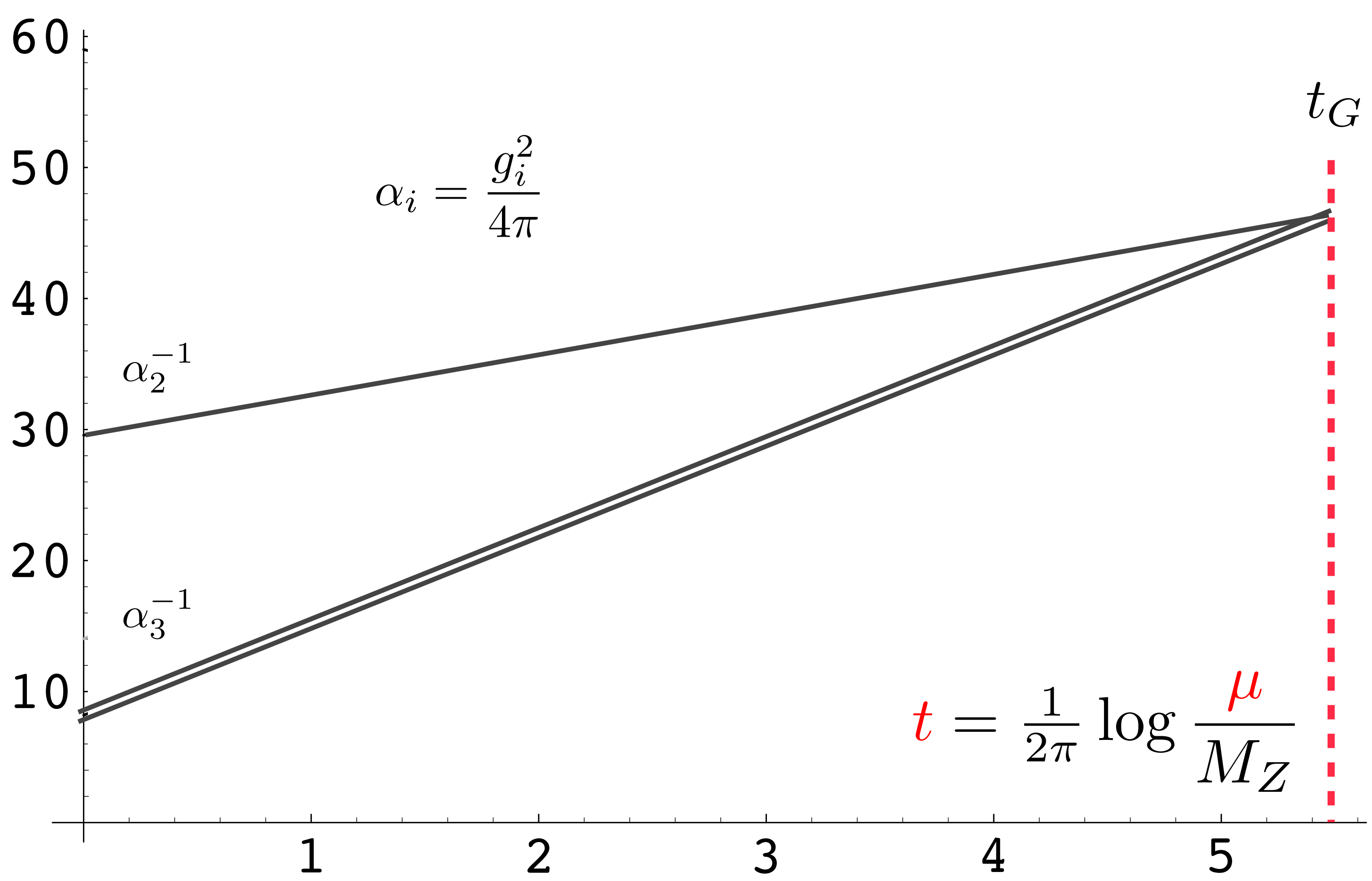

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Running gauge couplings in the SM $+X+\Delta$

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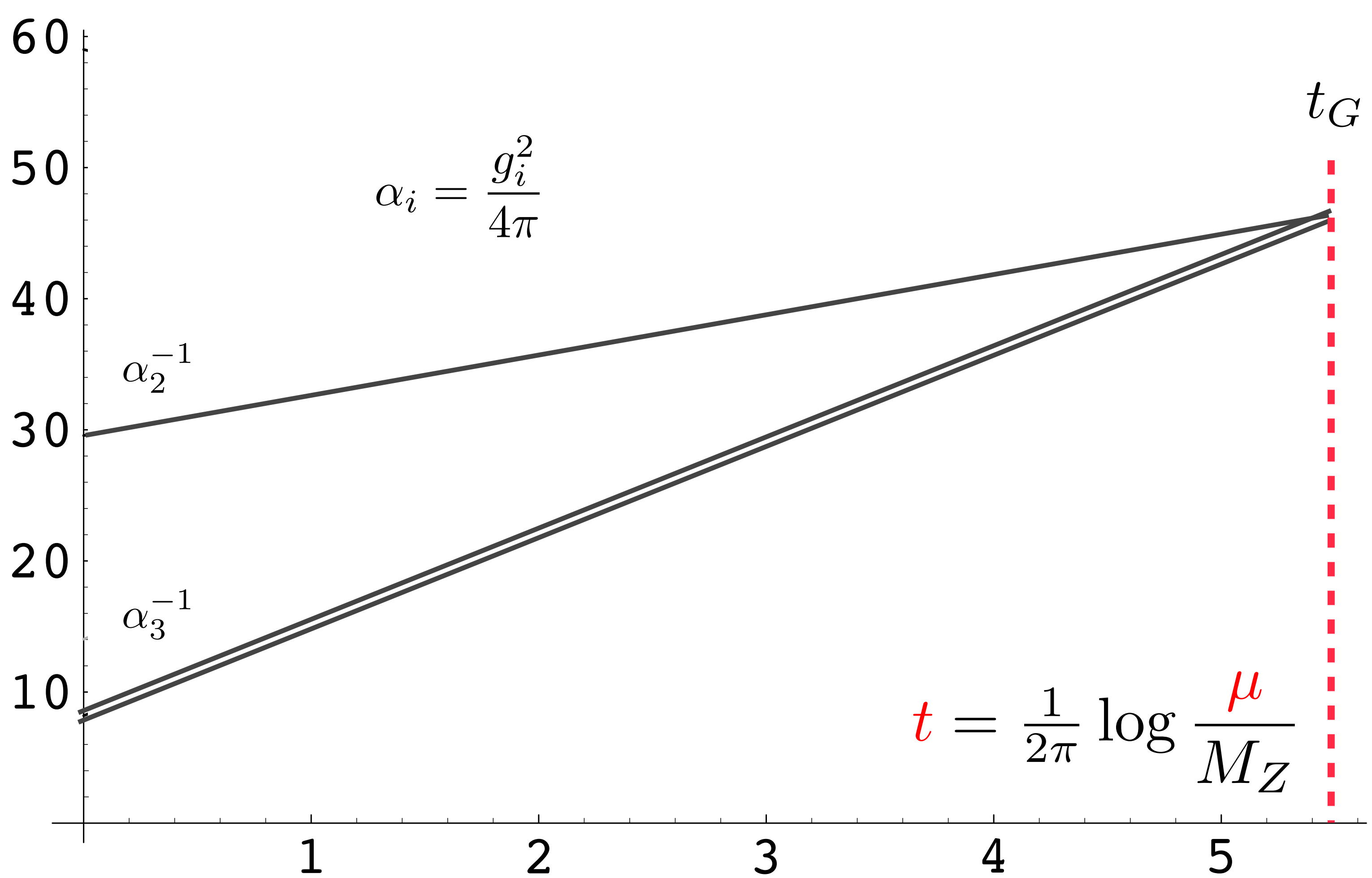
$(3,2,-\frac{5}{6}) \oplus h.c.$ $\qquad$ $(3,1,-\frac{1}{3})$



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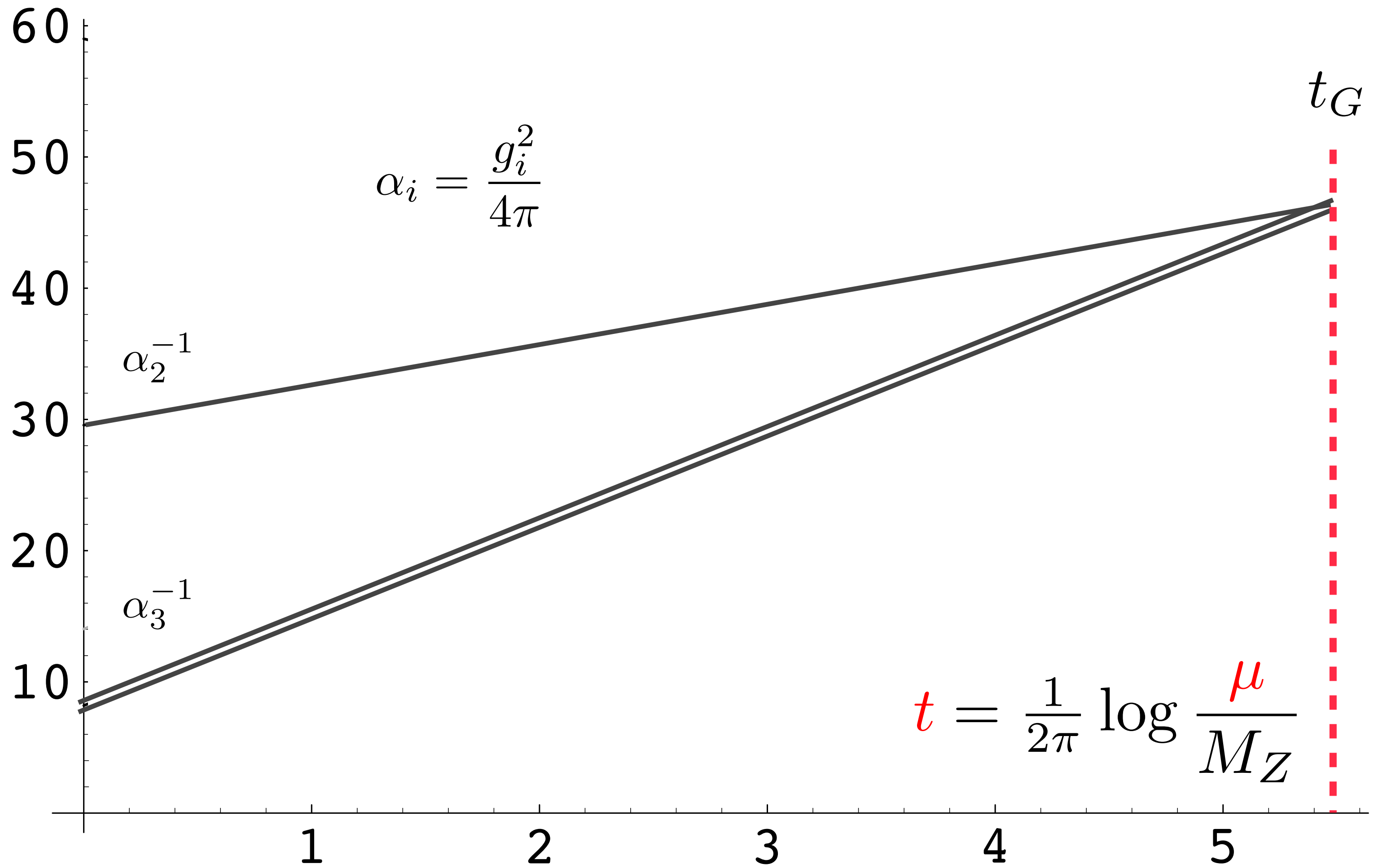
$$\begin{pmatrix} \frac{3}{5}b_1 \\ b_2 \\ b_3 \end{pmatrix} = -\frac{11}{3}\begin{pmatrix} 5 \\ 5 \\ 5 \end{pmatrix}_{gauge} + 2\begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix}_{ferm.} + \frac{1}{3}\begin{pmatrix} \frac{1}{2} \\ \frac{1}{2} \\ \frac{1}{2} \end{pmatrix}_{scal.}$$



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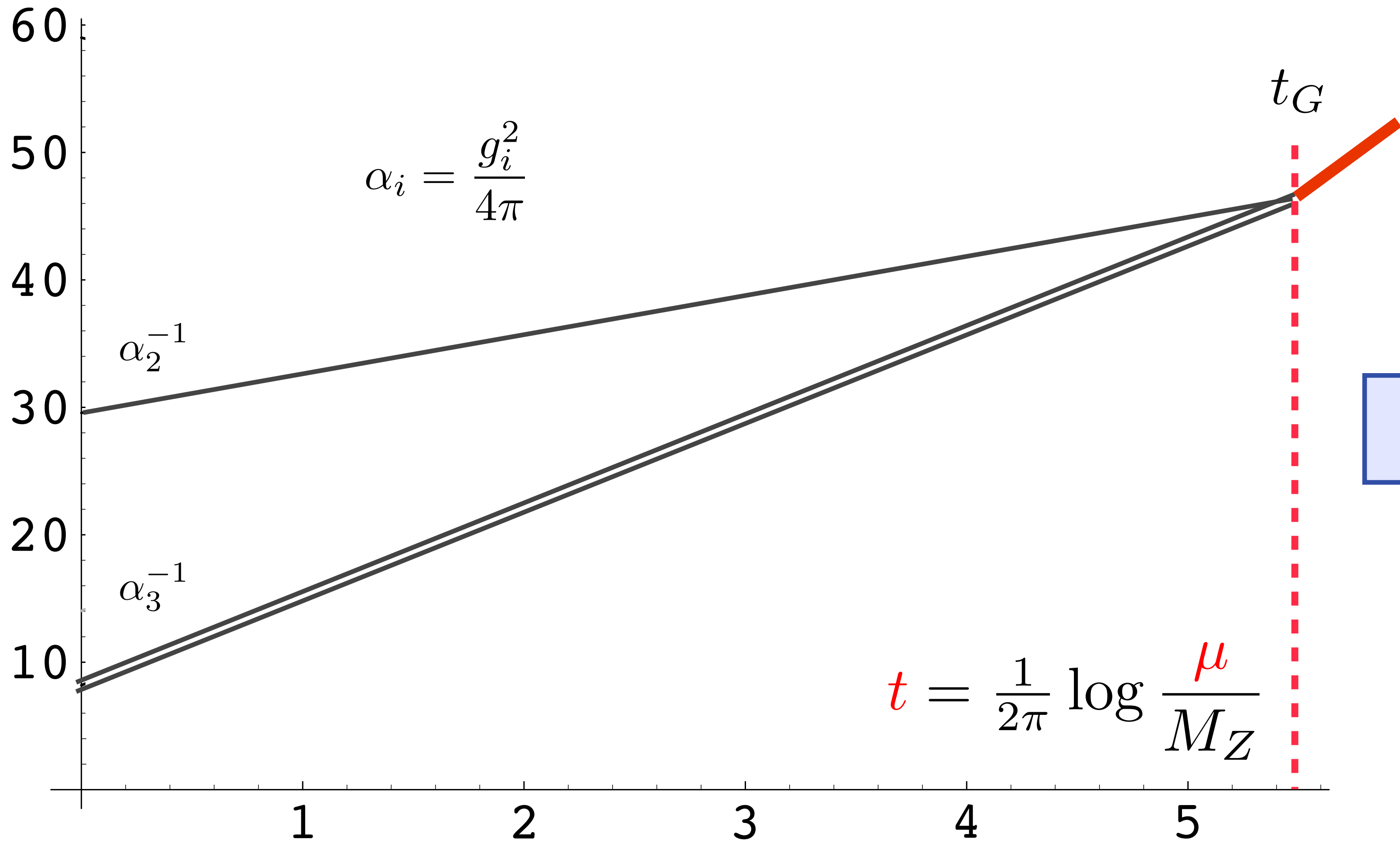

single gauge coupling like in an asymptotically free gauge theory with a simple gauge group

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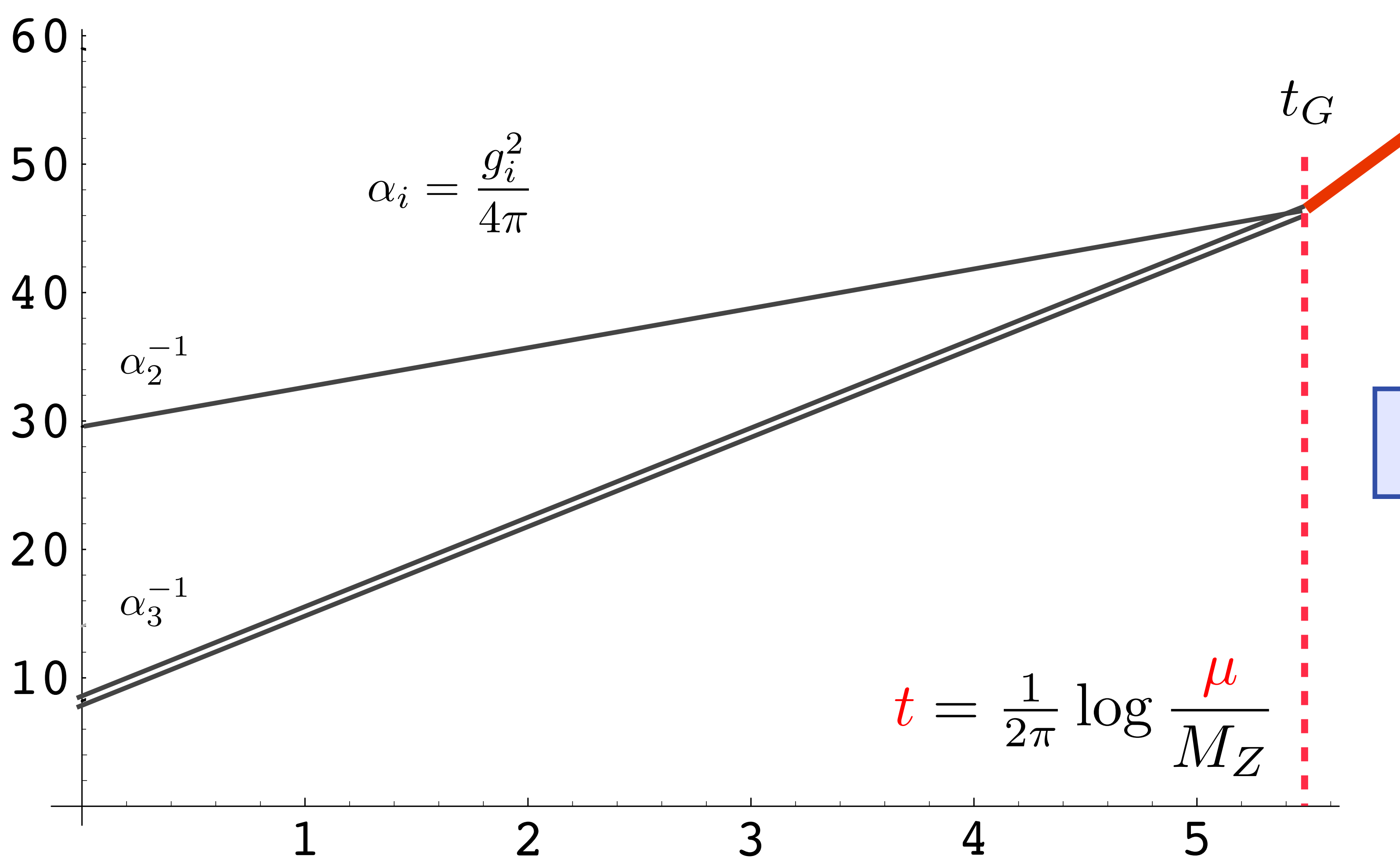

single gauge coupling like in an asymptotically free gauge theory with a simple gauge group

$$\boxed{M_G \sim 10^{16}\mathrm{GeV}}$$

tells us the BNV scale and also the gauge coupling

Grand Unifications

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

GUTs are spontaneously broken BSM gauge theories based on simple compact gauge groups

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They also look like theories of the d=6 BNV operators in the SM...

...and other stuff: magnetic monopoles, charge quantization, LNV etc.

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

- What Georgi and Glashow showed was the uniqueness of SU(5) @ rank=4

The minimal SU(5) GUT

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

$$
\begin{array}{ccc}
(1,2,-\frac{1}{2}) & \begin{pmatrix}\nu_e \\ e\end{pmatrix} & \begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix} \\
(1,1,+1) & e^c & \mu^c
\end{array}
$$

$$
\begin{array}{ccc}
(3,2,+\frac{1}{6}) & \begin{pmatrix}u \\ d\end{pmatrix} & \begin{pmatrix}c \\ s\end{pmatrix} \\
(\bar{3},1,-\frac{2}{3}) & u^c & c^c \\
(\bar{3},1,+\frac{1}{3}) & d^c & s^c
\end{array}
$$

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

$$(1,2,-\tfrac{1}{2}) \quad \begin{pmatrix}\nu_e \\ e\end{pmatrix} \quad \begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix} \qquad\qquad \overline{5} \quad \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ -e \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} s_1^c \\ s_2^c \\ s_3^c \\ -\mu \\ \nu_\mu \end{pmatrix}$$

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

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

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

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

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

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

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

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

H extra coloured scalar Δ

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

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

variety of other (heavy) scalars

The devil is in the detail...

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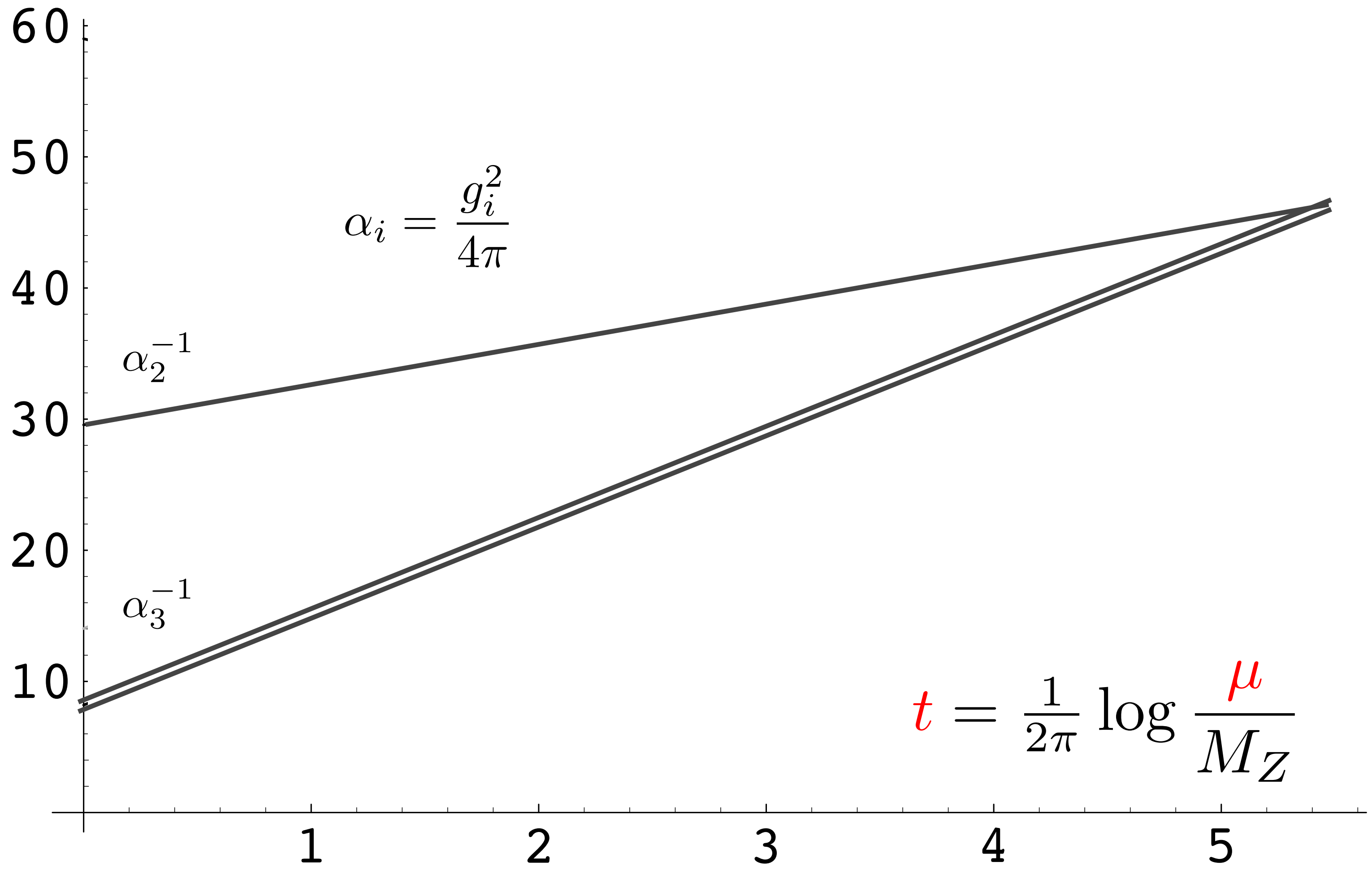
Hypercharge embedding: $cY \equiv T_{24} \in SU(5)$

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

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



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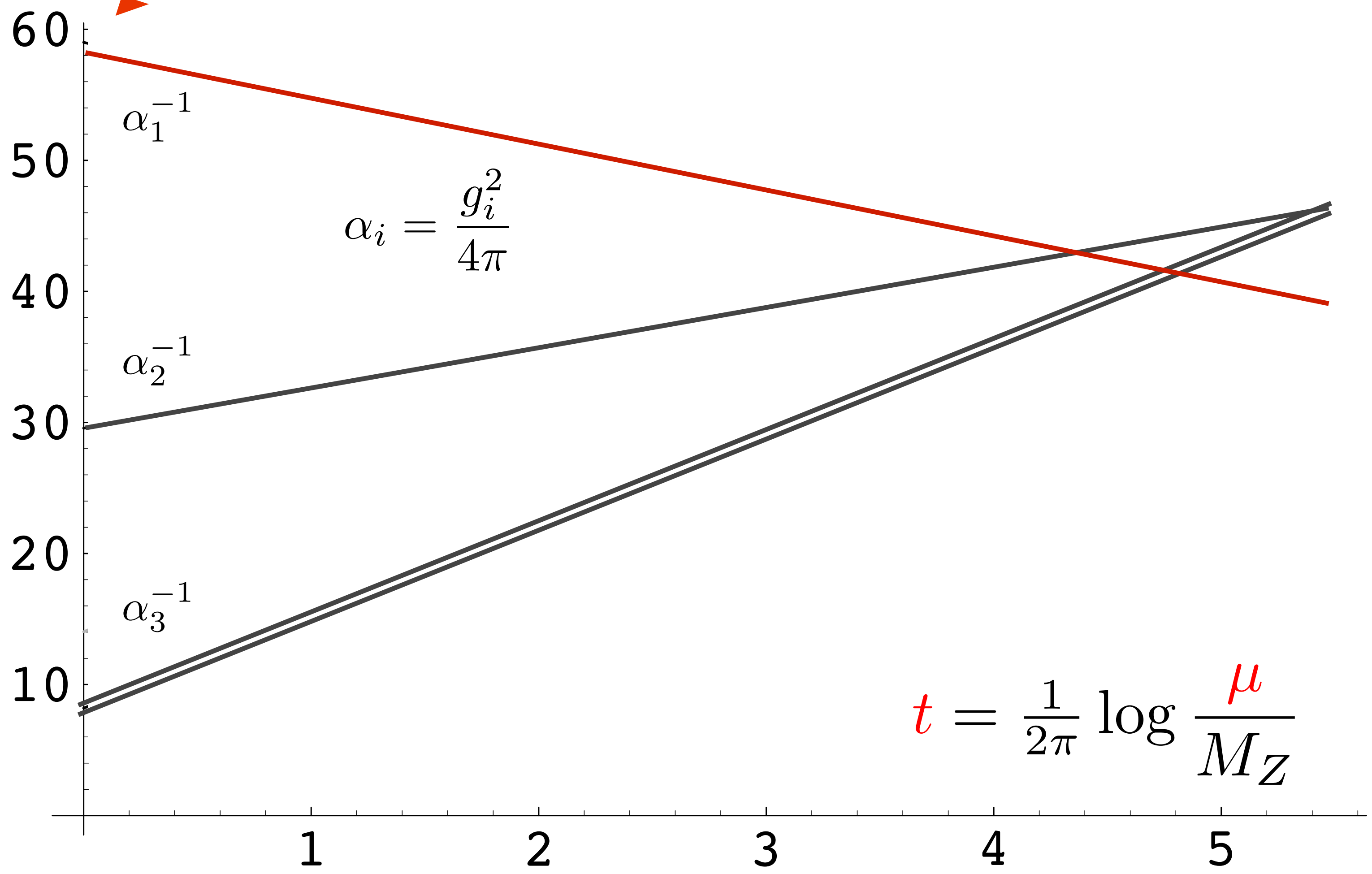
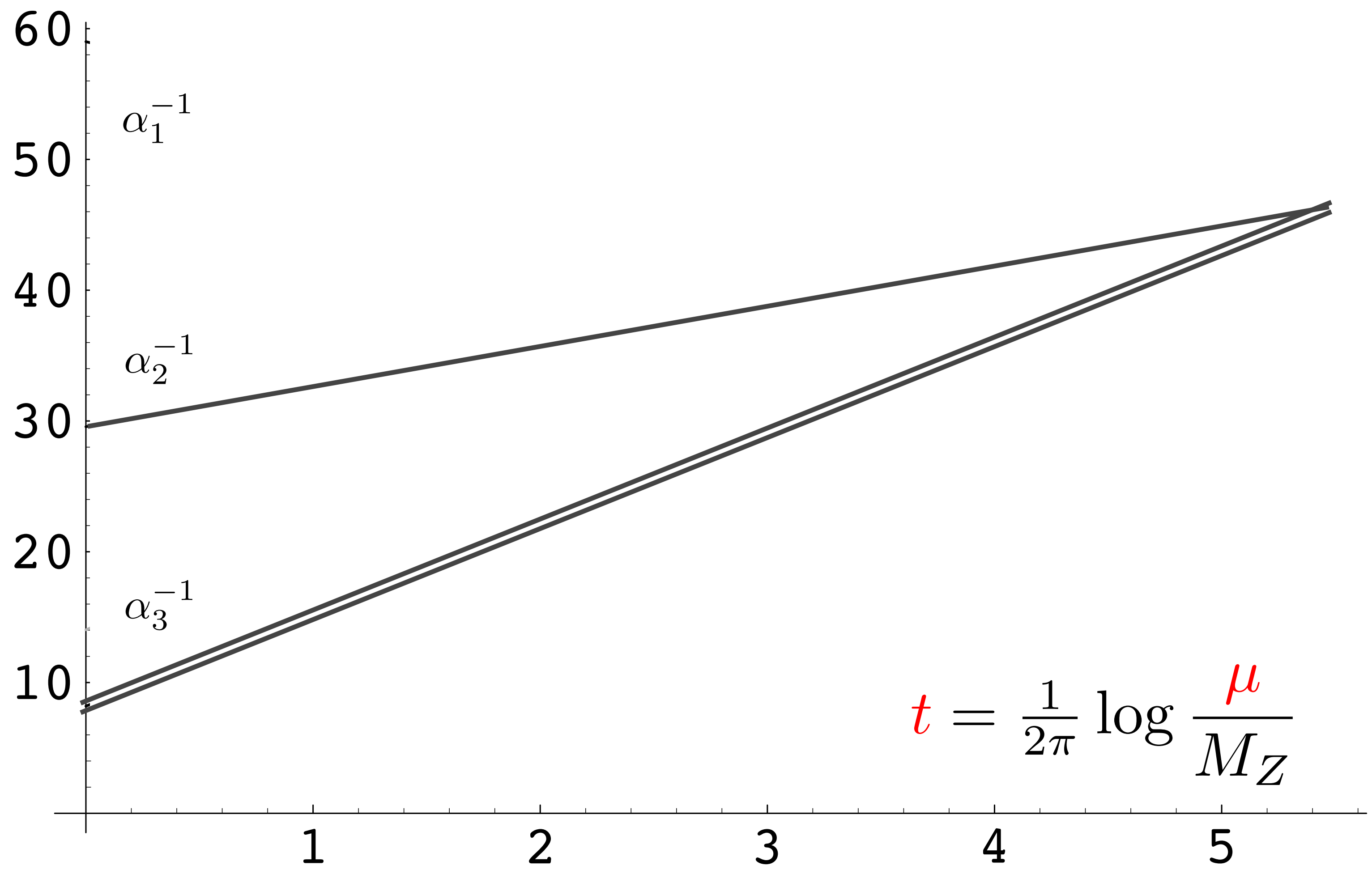
this sets the initial condition for the U(1) coupling



TeV-scale supersymmetry...

Running gauge couplings in the SM $+X+\Delta$



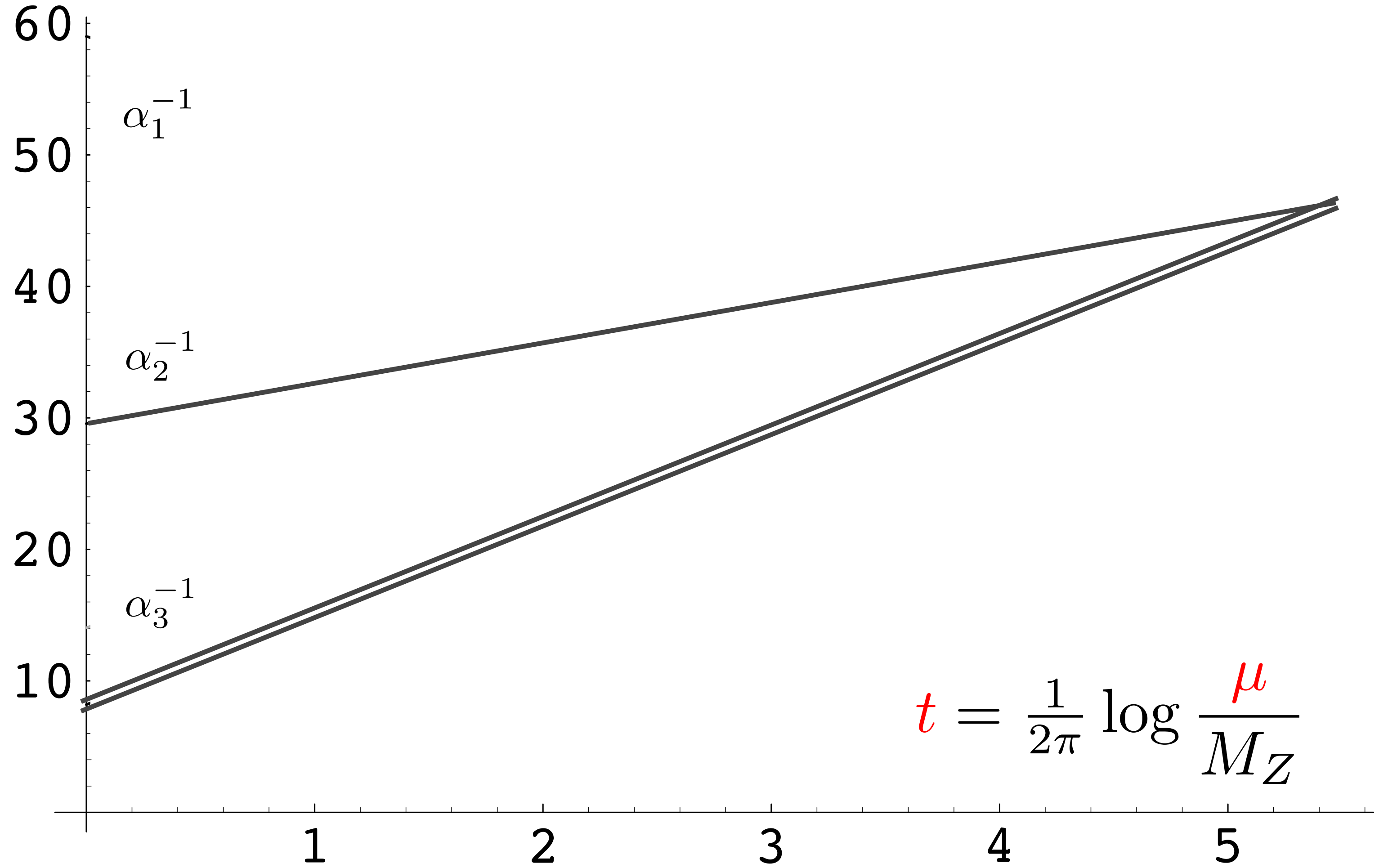
TeV-scale supersymmetry...

Running gauge couplings in the SM $+X+\Delta$ and a TeV-scale supersymmetry

+ gauginos

+ higgsinos

+ squarks and sleptons



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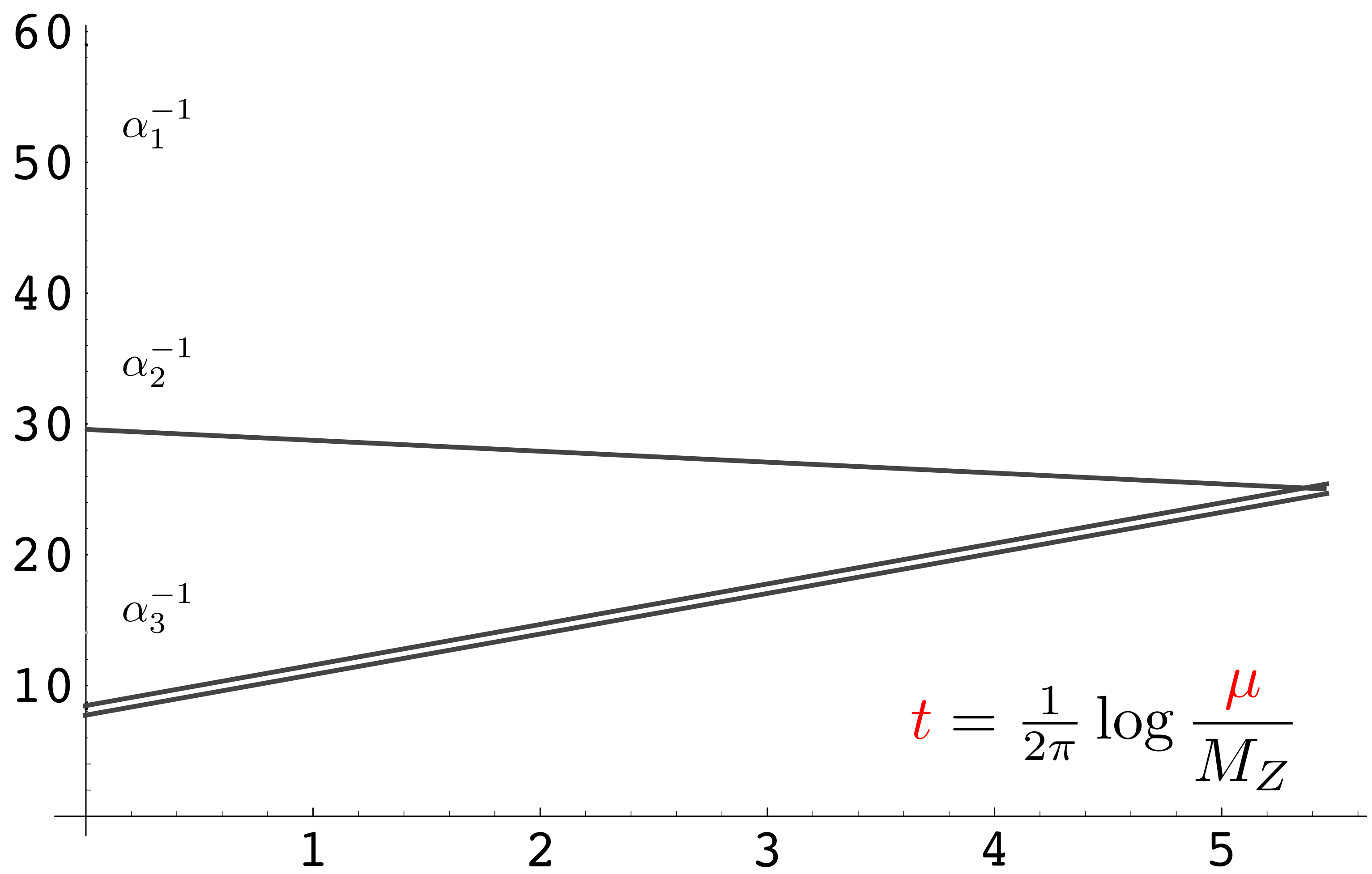

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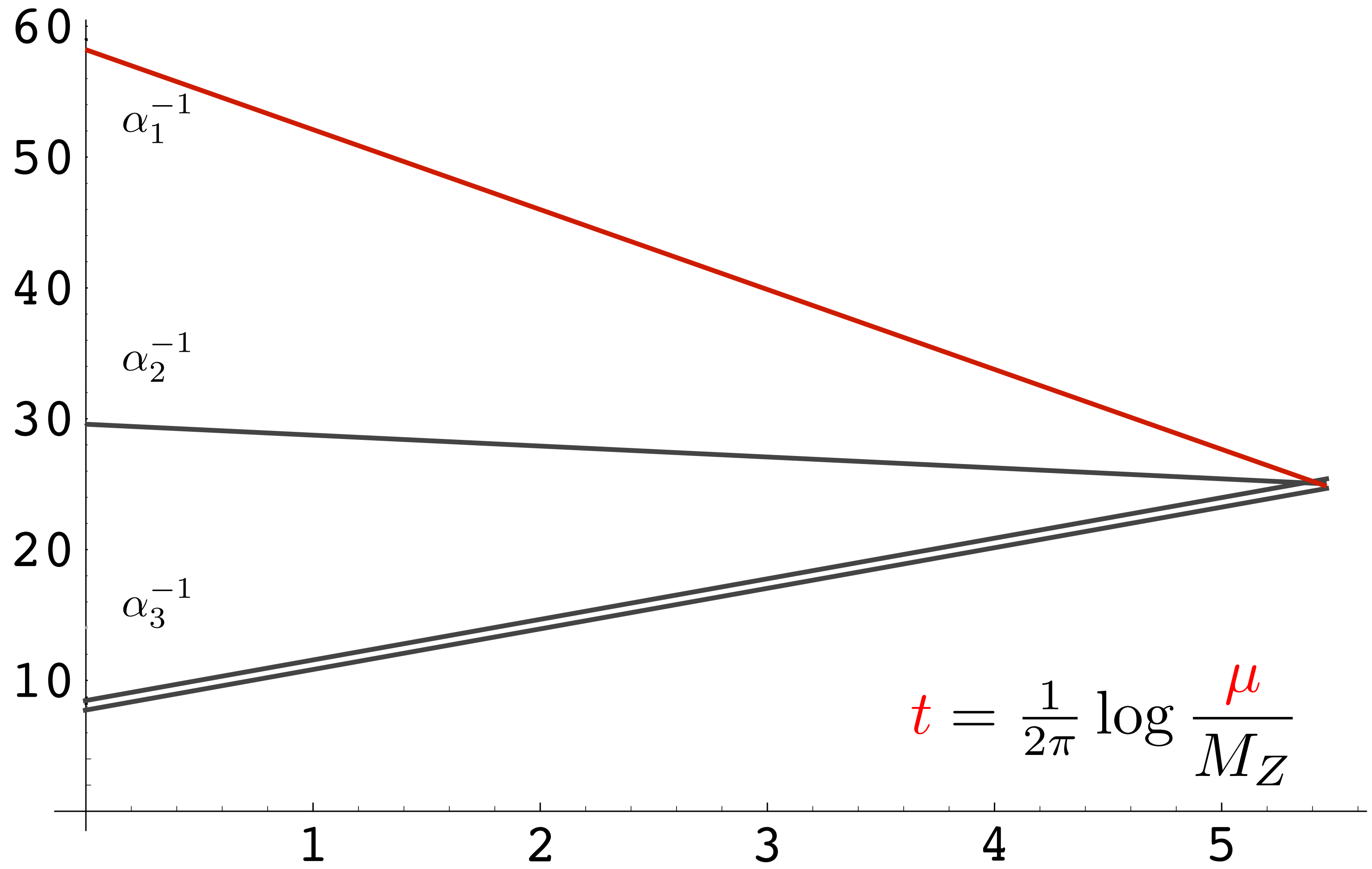

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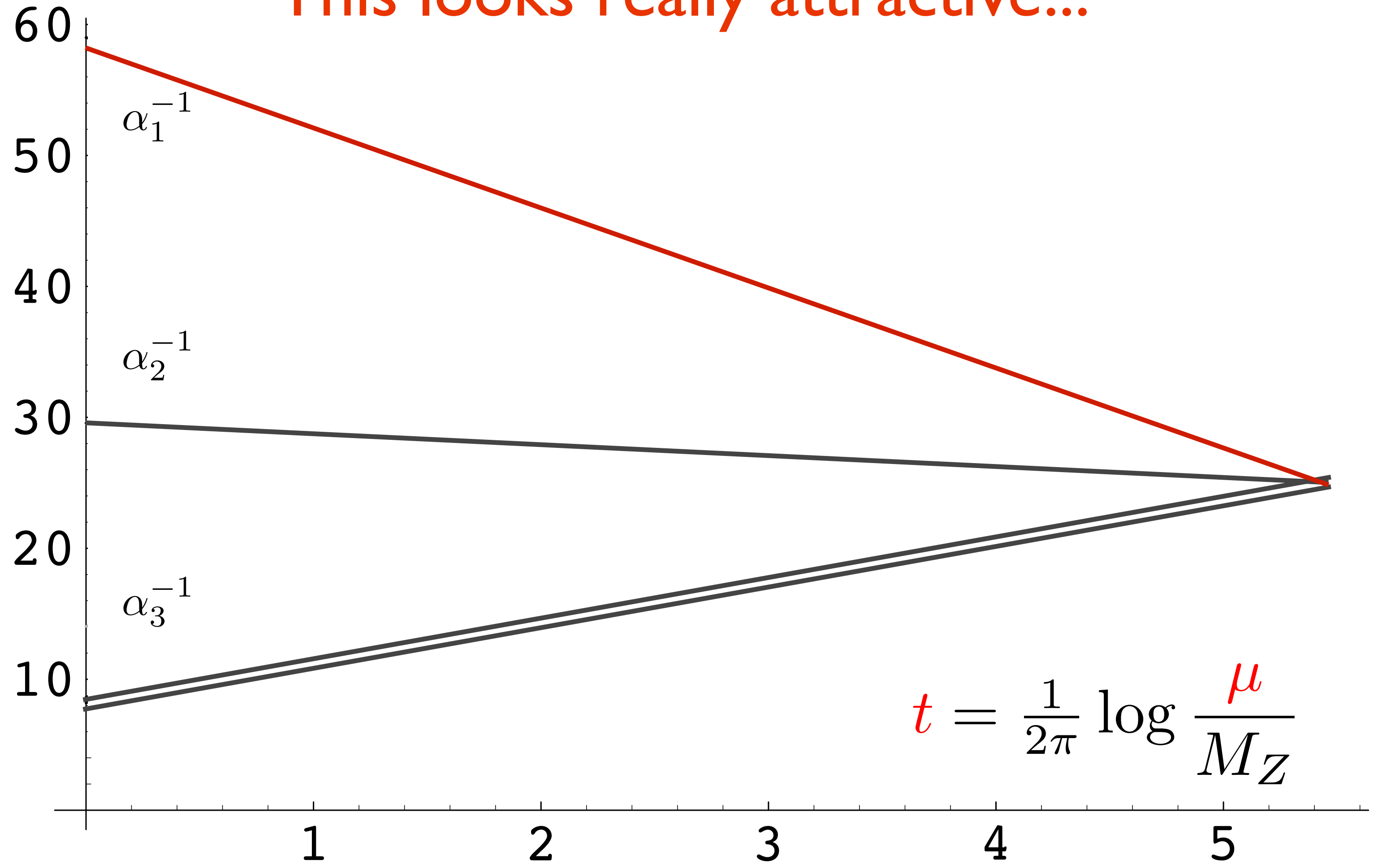
This looks really attractive...



My very personal view on the TeV-scale supersymmetry

brief version

TeV-scale supersymmetry...

People seem to really fancy it...

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The "instability" is a truncated perturbation theory artifact.
The **physical** Higgs mass is stable even without SUSY.
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Only with extra symmetries imposed (external assumptions)

Current situation and recent developments

in non-SUSY SO(10) GUTs

SO(10) basics

Georgi & Glashow 1974
Fritzsch & Minkowski 1975

- Matter family in a single spinor

$$16_F = (3,2,+\tfrac{1}{6}) \oplus (1,2,-\tfrac{1}{2}) \oplus (\bar{3},1,+\tfrac{1}{3}) \oplus (\bar{3},1,-\tfrac{2}{3}) \oplus (1,1,+1) \oplus (1,1,0)$$

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- Strongly correlated Yukawa's:

$$10_H = (1,2,-\tfrac{1}{2}) \oplus (1,2,+\tfrac{1}{2}) \oplus (\bar{3},1,+\tfrac{1}{3}) \oplus (3,1,-\tfrac{1}{3})$$

$16_F 16_F 10_H \ni$ Dirac masses for everybody can be obtained with a single coupling!

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- RH neutrinos automatic, renormalizable type I+II seesaw natural

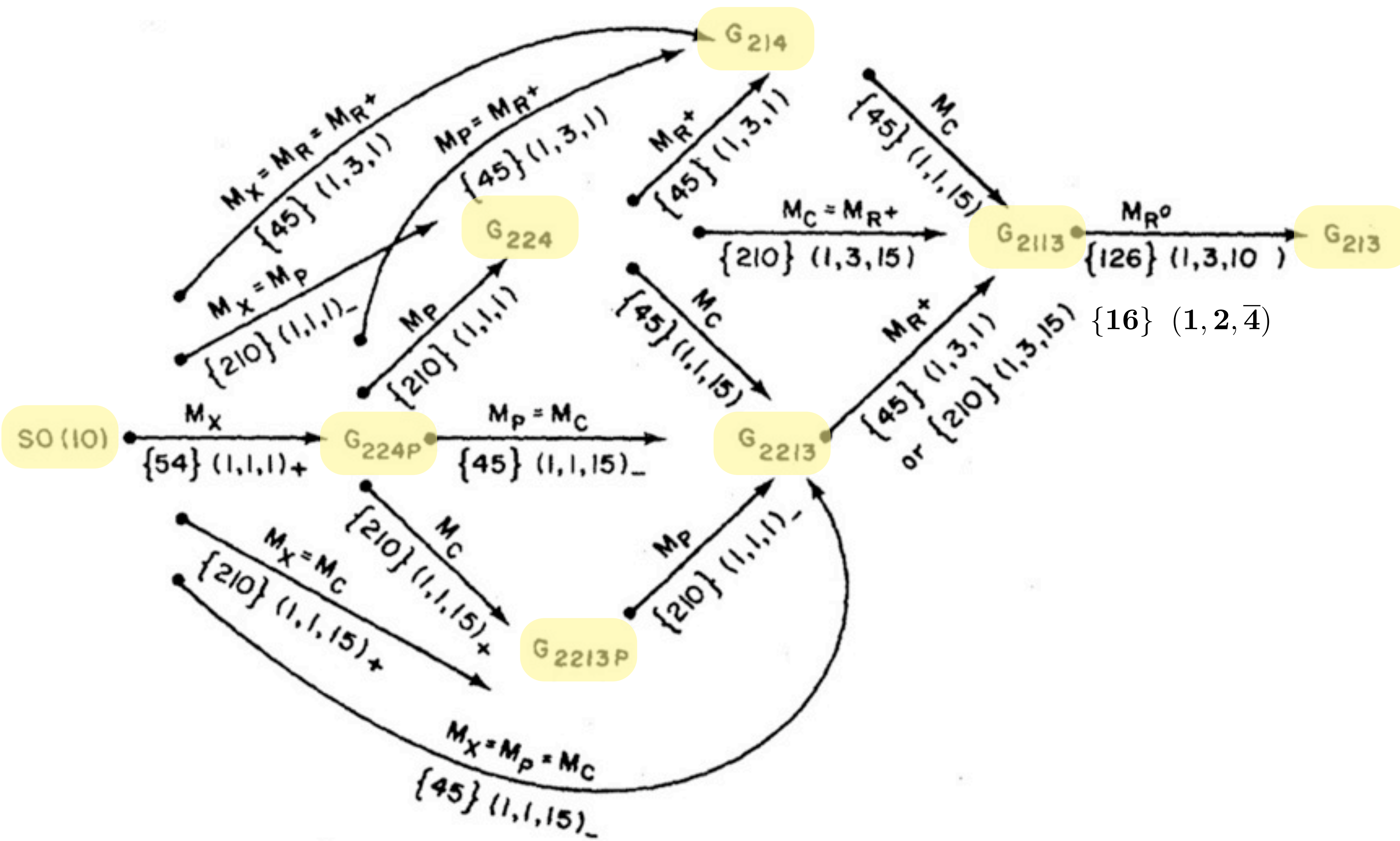
$$\overline{126}_H \ni (1,2,-\tfrac{1}{2}) \oplus (1,2,+\tfrac{1}{2}) \oplus (1,1,0) \oplus (1,3,+1) \oplus \ldots$$

$16_F 16_F \overline{126}_H \ni$ LH and RH Majorana neutrino masses, extra Dirac contributions

SO(10) Higgsology

Chang, Mohapatra, Gipson, Marshak, Parida 1985

SU(5) branches omitted



$\{16\} \quad (\mathbf{1}, \mathbf{2}, \overline{\mathbf{4}})$

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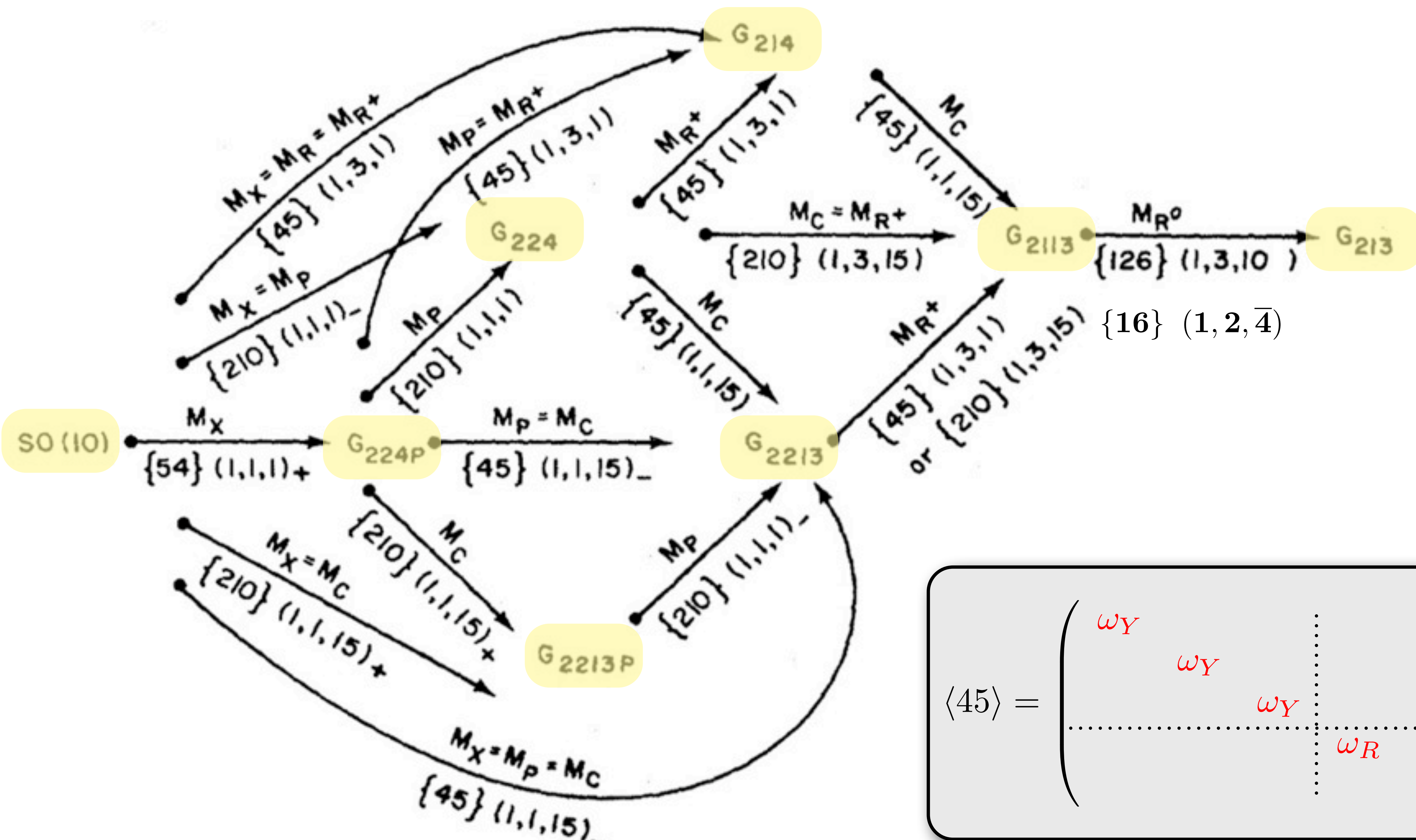
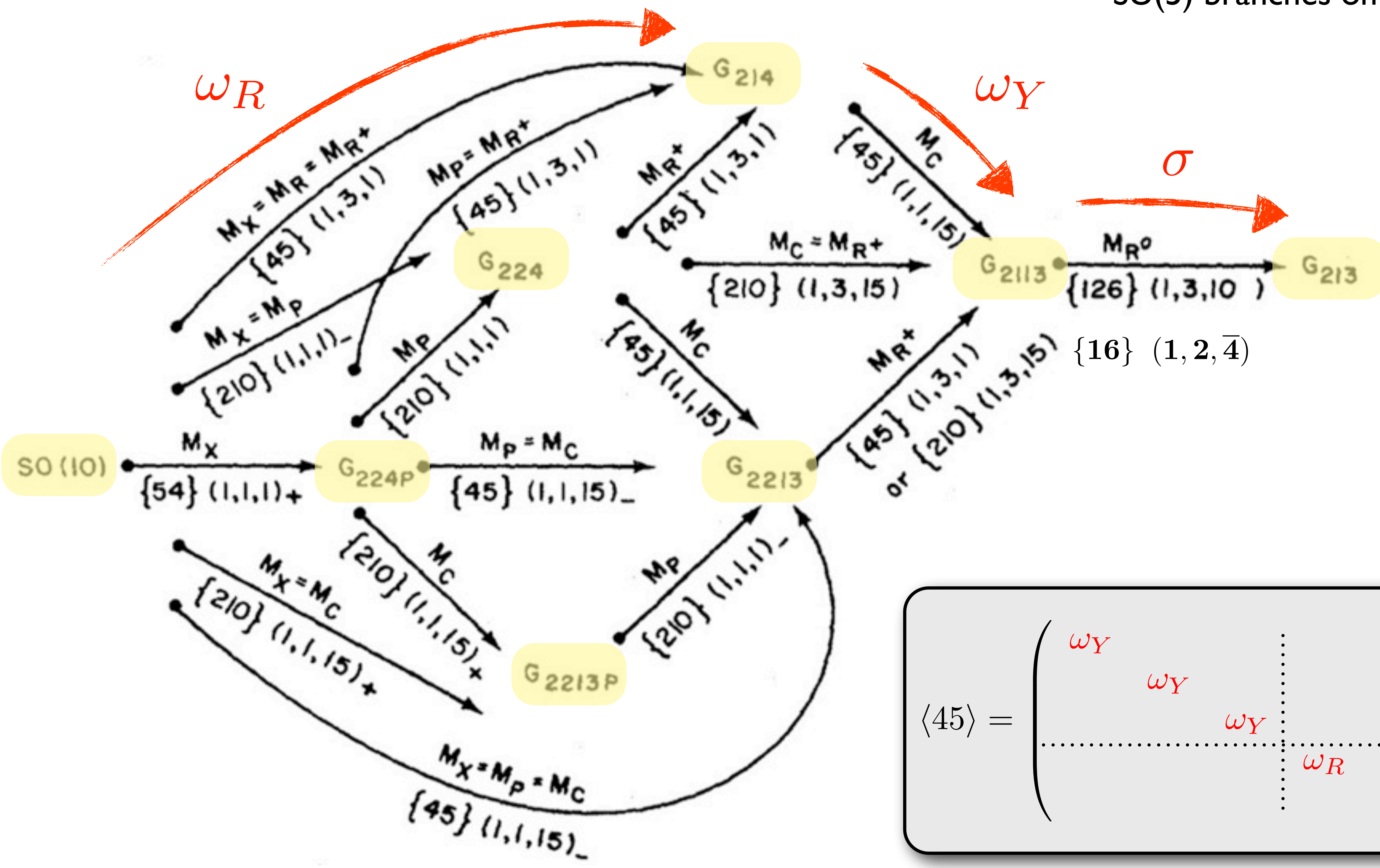


$$\langle 45\rangle = \begin{pmatrix} \omega_Y & & & & \\ & \omega_Y & & & \\ & & \omega_Y & & \\ & & & \omega_R & \\ & & & & \omega_R \end{pmatrix} \otimes \tau_2$$

SO(10) Higgsology

Chang, Mohapatra, Gipson, Marshak, Parida 1985

SU(5) branches omitted



$$\langle 45\rangle = \left(\begin{array}{ccc:cc} \omega_Y & & & & \\ & \omega_Y & & & \\ & & \omega_Y & & \\ \hdashline & & & \omega_R & \\ & & & & \omega_R \end{array}\right) \otimes \tau_2$$

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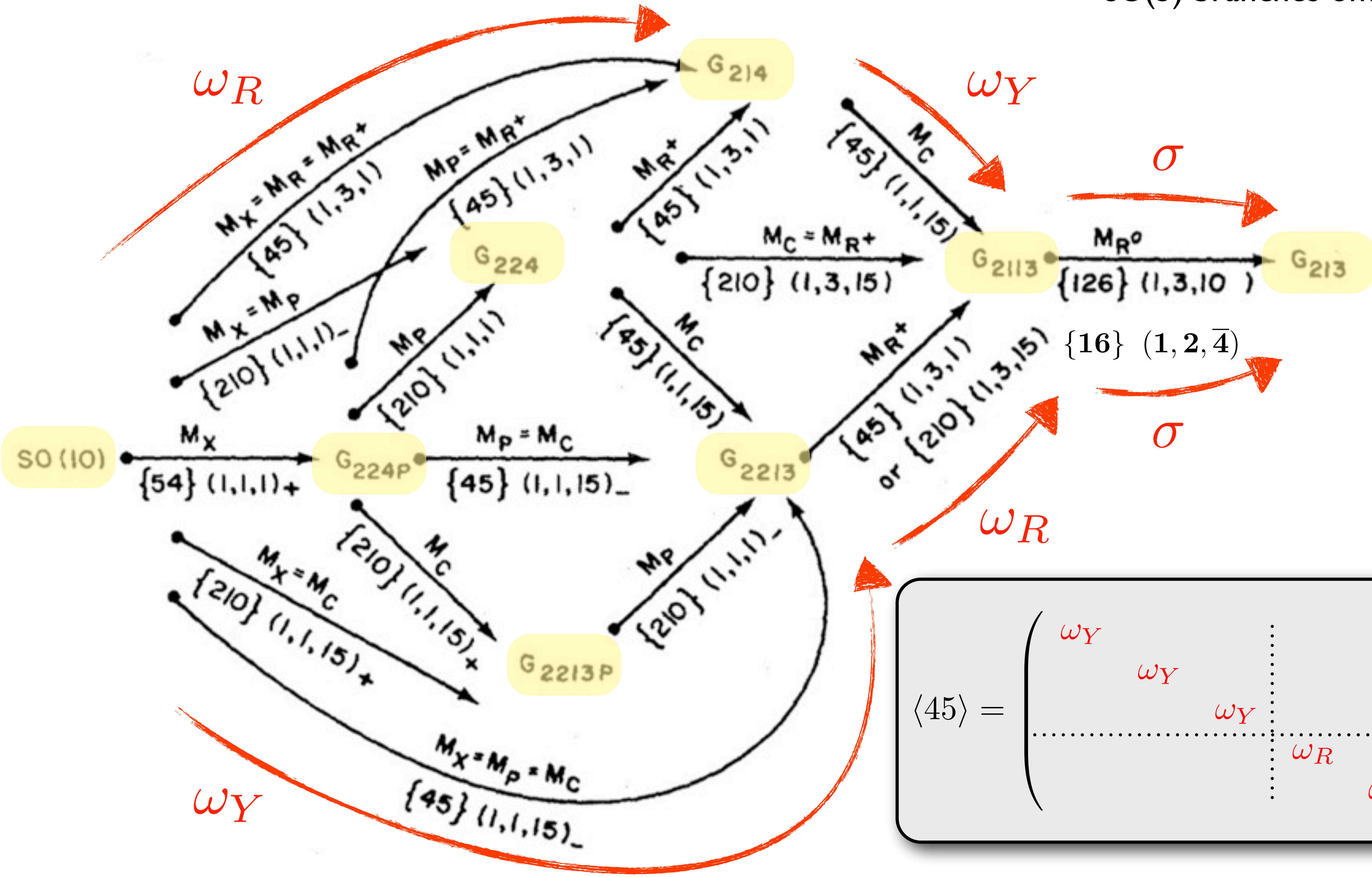

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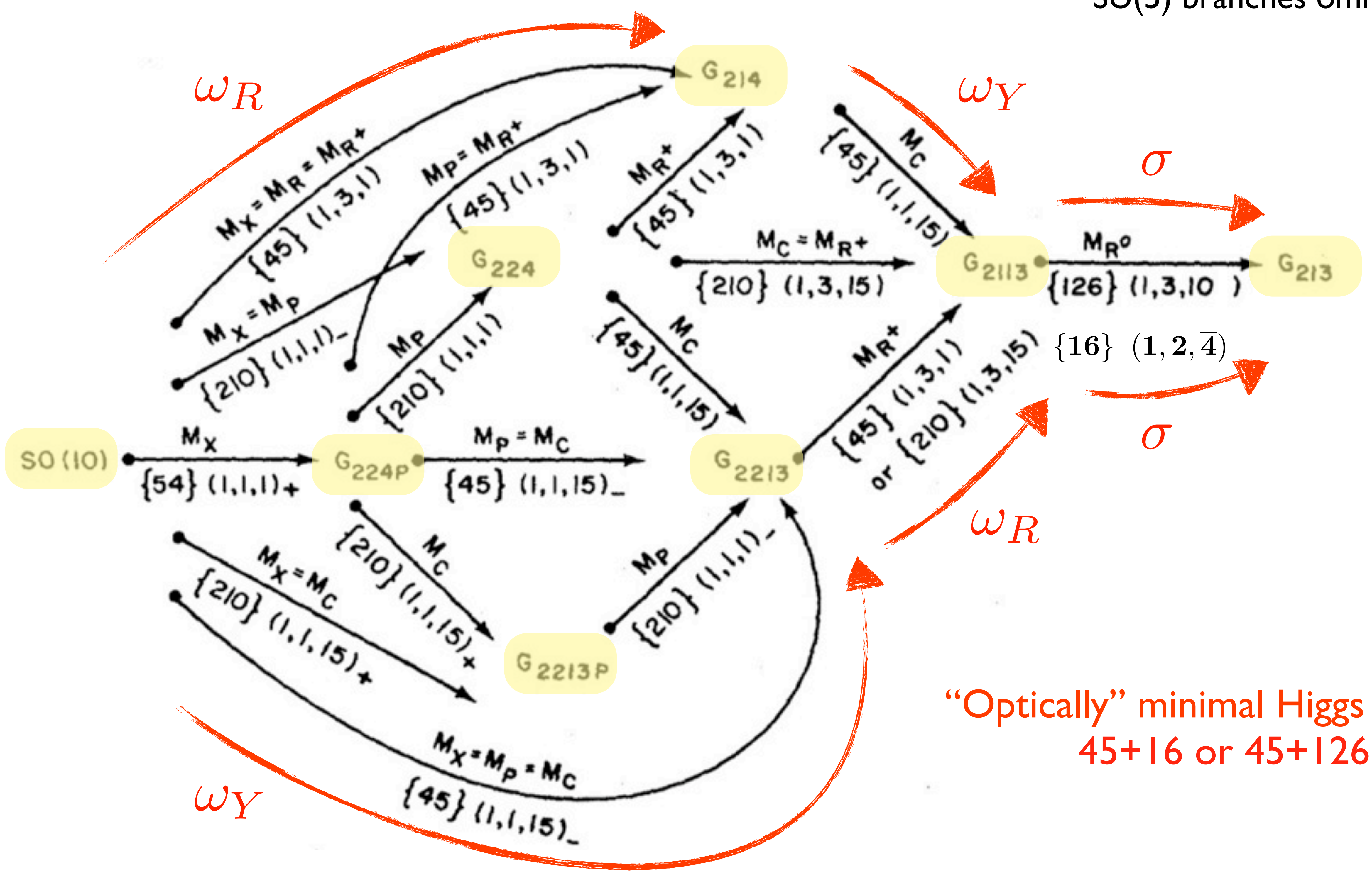

"Optically" minimal Higgs models:
45+16 or 45+126

The minimal SO(10)

SO(10) broken by 45, rank reduced by 126

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Scalar potential: $V = V_{45} + V_{126} + V_{\mathrm{mix}}$

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$$V_{45} = -\frac{\mu^2}{2}(\phi\phi)_0 + \frac{a_0}{4}(\phi\phi)_0(\phi\phi)_0 + \frac{a_2}{4}(\phi\phi)_2(\phi\phi)_2\,,$$

$$\begin{aligned}
V_{126} = & -\frac{\nu^2}{5!}(\Sigma\Sigma^*)_0 \\
& + \frac{\lambda_0}{(5!)^2}(\Sigma\Sigma^*)_0(\Sigma\Sigma^*)_0 + \frac{\lambda_2}{(4!)^2}(\Sigma\Sigma^*)_2(\Sigma\Sigma^*)_2 \\
& + \frac{\lambda_4}{(3!)^2(2!)^2}(\Sigma\Sigma^*)_4(\Sigma\Sigma^*)_4 + \frac{\lambda_4'}{(3!)^2}(\Sigma\Sigma^*)_{4'}(\Sigma\Sigma^*)_{4'} \\
& + \frac{\eta_2}{(4!)^2}(\Sigma\Sigma)_2(\Sigma\Sigma)_2 + \frac{\eta_2^*}{(4!)^2}(\Sigma^*\Sigma^*)_2(\Sigma^*\Sigma^*)_2\,,
\end{aligned}$$

$$\begin{aligned}
V_{\text{mix}} = & \frac{i\tau}{4!}(\phi)_2(\Sigma\Sigma^*)_2 + \frac{\alpha}{2\cdot 5!}(\phi\phi)_0(\Sigma\Sigma^*)_0 \\
& + \frac{\beta_4}{4\cdot 3!}(\phi\phi)_4(\Sigma\Sigma^*)_4 + \frac{\beta_4'}{3!}(\phi\phi)_{4'}(\Sigma\Sigma^*)_{4'} \\
& + \frac{\gamma_2}{4!}(\phi\phi)_2(\Sigma\Sigma)_2 + \frac{\gamma_2^*}{4!}(\phi\phi)_2(\Sigma^*\Sigma^*)_2\,.
\end{aligned}$$

$$(\phi\phi)_0(\phi\phi)_0 \equiv \phi_{ij}\phi_{ij}\phi_{kl}\phi_{kl}$$

$$(\phi\phi)_2(\phi\phi)_2 \equiv \phi_{ij}\phi_{ik}\phi_{lj}\phi_{lk}$$

$$(\phi\phi)_0 \equiv \phi_{ij}\phi_{ij}\,,\quad (\Sigma\Sigma^*)_0 \equiv \Sigma_{ijklm}\Sigma^*_{ijklm}$$

$$(\Sigma\Sigma^*)_0(\Sigma\Sigma^*)_0 \equiv \Sigma_{ijklm}\Sigma^*_{ijklm}\Sigma_{nopqr}\Sigma^*_{nopqr}$$

$$(\Sigma\Sigma^*)_2(\Sigma\Sigma^*)_2 \equiv \Sigma_{ijklm}\Sigma^*_{ijkln}\Sigma_{opqrm}\Sigma^*_{opqrn}$$

$$(\Sigma\Sigma^*)_4(\Sigma\Sigma^*)_4 \equiv \Sigma_{ijklm}\Sigma^*_{ijkno}\Sigma_{pqrlm}\Sigma^*_{pqrno}$$

$$(\Sigma\Sigma^*)_{4'}(\Sigma\Sigma^*)_{4'} \equiv \Sigma_{ijklm}\Sigma^*_{ijkno}\Sigma_{pqrln}\Sigma^*_{pqrmo}$$

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$$(\phi)_2(\Sigma\Sigma^*)_2 \equiv \phi_{ij}\Sigma_{klmni}\Sigma^*_{klmnj}$$

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$$(\phi\phi)_4(\Sigma\Sigma^*)_4 \equiv \phi_{ij}\phi_{kl}\Sigma_{mnoij}\Sigma^*_{mnokl}$$

$$(\phi\phi)_{4'}(\Sigma\Sigma^*)_{4'} \equiv \phi_{ij}\phi_{kl}\Sigma_{mnoik}\Sigma^*_{mnojl}$$

$$(\phi\phi)_2(\Sigma\Sigma)_2 \equiv \phi_{ij}\phi_{ik}\Sigma_{lmnoj}\Sigma_{lmnok}$$

$$(\phi\phi)_2(\Sigma^*\Sigma^*)_2 \equiv \phi_{ij}\phi_{ik}\Sigma^*_{lmnoj}\Sigma^*_{lmnok}$$

The minimal SO(10) nightmare

SO(10) broken by 45, rank reduced by 126

Scalar potential: $V = V_{45} + V_{126} + V_{\rm mix}$

$$V_{45} = -\frac{\mu^2}{2}(\phi\phi)_0 + \frac{a_0}{4}(\phi\phi)_0(\phi\phi)_0 + \frac{a_2}{4}(\phi\phi)_2(\phi\phi)_2\,,$$

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???

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$$(\Sigma\Sigma^*)_0(\Sigma\Sigma^*)_0 \equiv \Sigma_{ijklm}\Sigma^*_{ijklm}\Sigma_{nopqr}\Sigma^*_{nopqr}$$

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$$(\Sigma\Sigma^*)_4(\Sigma\Sigma^*)_4 \equiv \Sigma_{ijklm}\Sigma^*_{ijkno}\Sigma_{pqrlm}\Sigma^*_{pqrno}$$

$$(\Sigma\Sigma^*)_{4'}(\Sigma\Sigma^*)_{4'} \equiv \Sigma_{ijklm}\Sigma^*_{ijkno}\Sigma_{pqrln}\Sigma^*_{pqrmo}$$

$$(\Sigma\Sigma)_2(\Sigma\Sigma)_2 \equiv \Sigma_{ijklm}\Sigma_{ijkln}\Sigma_{opqrm}\Sigma_{opqrn}$$

$$(\phi)_2(\Sigma\Sigma^*)_2 \equiv \phi_{ij}\Sigma_{klmni}\Sigma^*_{klmnj}$$

$$(\phi\phi)_0(\Sigma\Sigma^*)_0 \equiv \phi_{ij}\phi_{ij}\Sigma_{klmno}\Sigma^*_{klmno}$$

$$(\phi\phi)_4(\Sigma\Sigma^*)_4 \equiv \phi_{ij}\phi_{kl}\Sigma_{mnoij}\Sigma^*_{mnokl}$$

$$(\phi\phi)_{4'}(\Sigma\Sigma^*)_{4'} \equiv \phi_{ij}\phi_{kl}\Sigma_{mnoik}\Sigma^*_{mnojl}$$

$$(\phi\phi)_2(\Sigma\Sigma)_2 \equiv \phi_{ij}\phi_{ik}\Sigma_{lmnoj}\Sigma_{lmnok}$$

$$(\phi\phi)_2(\Sigma^*\Sigma^*)_2 \equiv \phi_{ij}\phi_{ik}\Sigma^*_{lmnoj}\Sigma^*_{lmnok}$$

The minimal SO(10) nightmare

Ruled out in 1980's

The minimal SO(10) nightmare

Ruled out in 1980's

$$
\begin{aligned}
m^2_{(8,1,0)} &= 2a_2(\omega_R - \omega_Y)(\omega_R + 2\omega_Y) \\
m^2_{(1,3,0)} &= 2a_2(\omega_Y - \omega_R)(\omega_Y + 2\omega_R)
\end{aligned}
$$

Yasuè 1981, Anastaze, Derendinger, Buccella 1983, Babu, Ma 1985

$$
\langle 45 \rangle = \begin{pmatrix} \omega_Y & & & & \\ & \omega_Y & & & \\ & & \omega_Y & & \\ & & & \omega_R & \\ & & & & \omega_R \end{pmatrix} \otimes \tau_2
$$

The minimal SO(10) nightmare

Ruled out in 1980's

$$m^2_{(8,1,0)} = 2a_2(\omega_R - \omega_Y)(\omega_R + 2\omega_Y)$$
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Yasuè 1981, Anastaze, Derendinger, Buccella 1983, Babu, Ma 1985

$$\langle 45 \rangle = \begin{pmatrix} \omega_Y & & & & \\ & \omega_Y & & & \\ & & \omega_Y & & \\ & & & \omega_R & \\ & & & & \omega_R \end{pmatrix} \otimes \tau_2$$

$\omega_Y \gg \omega_R$

$$SO(10) \underset{\omega_Y}{\overset{45}{\rightarrow}} SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \underset{\omega_R}{\overset{45}{\rightarrow}} SU(3)_c \otimes SU(2)_L \otimes U(1)_R \otimes U(1)_{B-L} \overset{16}{\rightarrow} SM$$

The minimal SO(10) nightmare

Ruled out in 1980's

$$\begin{aligned} m^2_{(8,1,0)} &= 2a_2(\omega_R - \omega_Y)(\omega_R + 2\omega_Y) \\ m^2_{(1,3,0)} &= 2a_2(\omega_Y - \omega_R)(\omega_Y + 2\omega_R) \end{aligned}$$

Yasuè 1981, Anastaze, Derendinger, Buccella 1983, Babu, Ma 1985

$$\langle 45 \rangle = \begin{pmatrix} \omega_Y & & & & \\ & \omega_Y & & & \\ & & \omega_Y & & \\ & & & \omega_R & \\ & & & & \omega_R \end{pmatrix} \otimes \tau_2$$

$\omega_Y \gg \omega_R$

$$SO(10) \underset{\omega_Y}{\overset{45}{\to}} SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \underset{\omega_R}{\overset{45}{\to}} SU(3)_c \otimes SU(2)_L \otimes U(1)_R \otimes U(1)_{B-L} \overset{16}{\to} SM$$

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$$SO(10) \underset{\omega_R}{\overset{45}{\to}} SU(4)_C \otimes SU(2)_L \otimes U(1)_R \otimes U(1)_{B-L} \underset{\omega_Y}{\overset{45}{\to}} SU(3)_c \otimes SU(2)_L \otimes U(1)_R \otimes U(1)_{B-L} \overset{16}{\to} SM$$

The minimal SO(10) nightmare

Ruled out in 1980's

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\begin{aligned}
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Yasuè 1981, Anastaze, Derendinger, Buccella 1983, Babu, Ma 1985

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\langle 45 \rangle = \begin{pmatrix} \omega_Y & & & & \\ & \omega_Y & & & \\ & & \omega_Y & & \\ & & & \omega_R & \\ & & & & \omega_R \end{pmatrix} \otimes \tau_2
$$

Aaarrrggh... tachyonic spectrum unless $\frac{1}{2} < |\omega_Y/\omega_R| < 2$

The minimal SO(10) nightmare

Ruled out in 1980's

$$
\begin{aligned}
m^2_{(8,1,0)} &= 2a_2(\omega_R - \omega_Y)(\omega_R + 2\omega_Y) \\
m^2_{(1,3,0)} &= 2a_2(\omega_Y - \omega_R)(\omega_Y + 2\omega_R)
\end{aligned}
$$

Yasuè 1981, Anastaze, Derendinger, Buccella 1983, Babu, Ma 1985

$$
\langle 45 \rangle = \begin{pmatrix} \omega_Y & & & & \\ & \omega_Y & & & \\ & & \omega_Y & & \\ & & & \omega_R & \\ & & & & \omega_R \end{pmatrix} \otimes \tau_2
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Aaarrrggh... tachyonic spectrum unless $\frac{1}{2} < |\omega_Y/\omega_R| < 2$

SU(5)-like vacua only, not far from the "wrong SM running"!

The minimal SO(10) nightmare

Ruled out in 1980's

$$
\begin{aligned}
m^2_{(8,1,0)} &= 2a_2(\omega_R - \omega_Y)(\omega_R + 2\omega_Y) \\
m^2_{(1,3,0)} &= 2a_2(\omega_Y - \omega_R)(\omega_Y + 2\omega_R)
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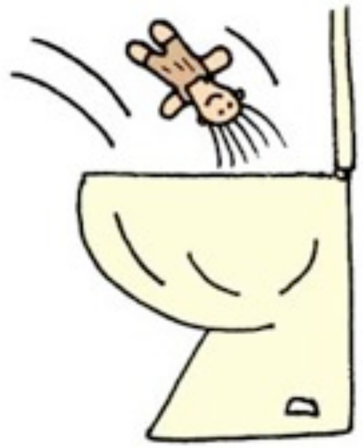
Yasuè 1981, Anastaze, Derendinger, Buccella 1983, Babu, Ma 1985

$$
\langle 45 \rangle = \begin{pmatrix} \omega_Y & & & & \\ & \omega_Y & & & \\ & & \omega_Y & & \\ & & & \omega_R & \\ & & & & \omega_R \end{pmatrix} \otimes \tau_2
$$



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\end{aligned}
$$

???

Yasuè 1981, Anastaze, Derendinger, Buccella 1983, Babu, Ma 1985

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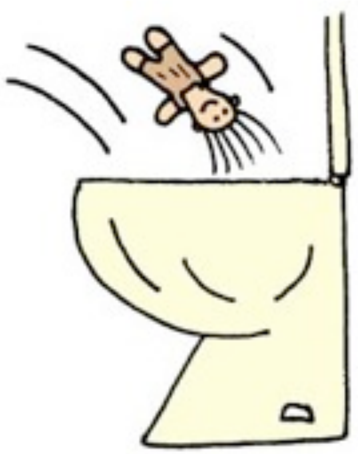
$$



Aaarrrggh... tachyonic spectrum unless $\frac{1}{2} < |\omega_Y/\omega_R| < 2$

SU(5)-like vacua only, not far from the "wrong SM running"!

The minimal SO(10) nightmare

“Do not trust arguments based on the lowest order of perturbation theory.”

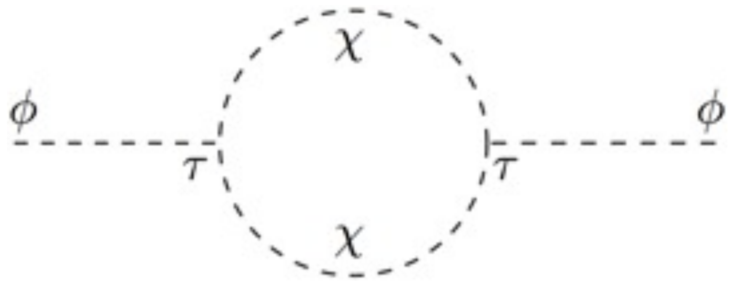
S.Weinberg ,“Why RG is a good thing”
in “Asymptotic Realm of Physics”, MIT press 1983

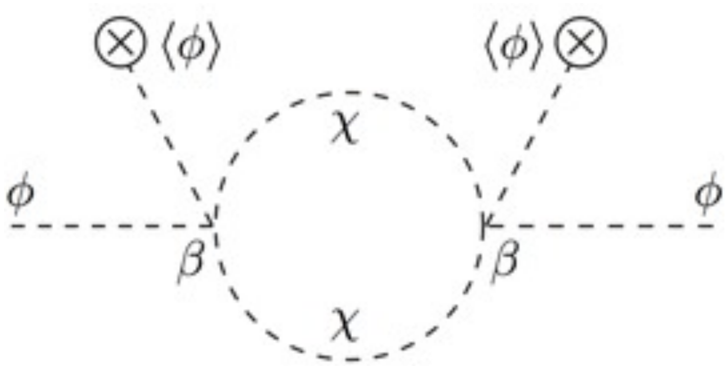
The minimal SO(10) ~~nightmare~~ blessing

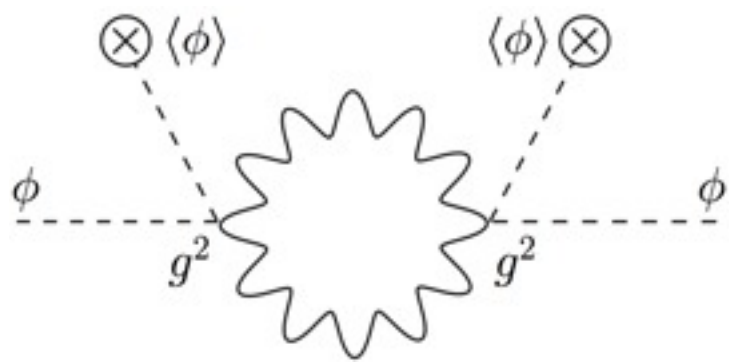
Quantum salvation of the minimal SO(10) GUT

Quantum salvation of the minimal SO(10) GUT

One-loop effective potential:







$$\Delta m^2_{(1,3,0)} = \frac{1}{4\pi^2}\left[\tau^2 + \beta^2(2\omega_R^2 - \omega_R\omega_Y + 2\omega_Y^2) + g^4\left(16\omega_R^2 + \omega_Y\omega_R + 19\omega_Y^2\right)\right] + \text{logs}\,,$$

$$\Delta m^2_{(8,1,0)} = \frac{1}{4\pi^2}\left[\tau^2 + \beta^2(\omega_R^2 - \omega_R\omega_Y + 3\omega_Y^2) + g^4\left(13\omega_R^2 + \omega_Y\omega_R + 22\omega_Y^2\right)\right] + \text{logs}\,,$$

Bertolini, Di Luzio, MM, PRD 81, 035015 (2010)

Thank you for your kind attention!

My very personal view on the TeV-scale supersymmetry

extended version

TeV-scale supersymmetry...

People seem to really fancy it...

TeV-scale supersymmetry...

People seem to really fancy it...

“It protects the Higgs mass from large corrections!”

TeV-scale supersymmetry...

People seem to really fancy it...

"It protects the Higgs mass from large corrections!"

"It is just behind the corner!"

TeV-scale supersymmetry...

People seem to really fancy it...

“It protects the Higgs mass from large corrections!”

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“It makes the gauge unification work better!”

TeV-scale supersymmetry...

People seem to really fancy it...

“It protects the Higgs mass from large corrections!”

“It is just behind the corner!”

“It makes the gauge unification work better!”

“It provides an excellent WIMP dark matter candidate!”

TeV-scale supersymmetry...

People seem to really fancy it...

"It protects the Higgs mass from large corrections!"

"It is just behind the corner!"

"It makes the gauge unification work better!"

"It provides an excellent WIMP dark matter candidate!"

I object!

... actually, all of these.

“TeV-scale SUSY protects the Higgs mass from large corrections!”

The standard argument:

$\Gamma_{hh} \propto$

$p^2 - m_H^2$

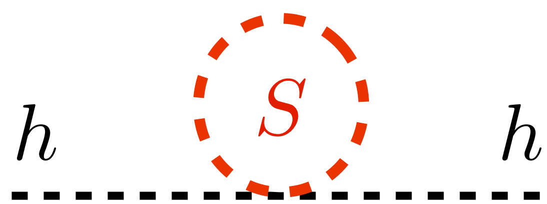
“TeV-scale SUSY protects the Higgs mass from large corrections!”

The standard argument:

$\Gamma_{hh} \propto$

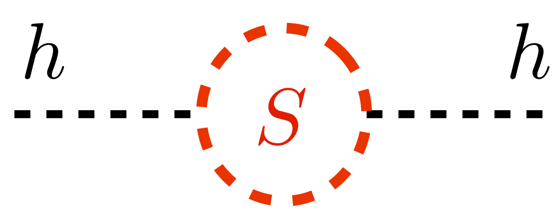
$$p^2 - m_H^2$$

$+$



$$\frac{1}{16\pi^2} M_S^2 \left(C_{UV} - 1 + \log \frac{M_S^2}{\mu^2}\right)$$

$+$



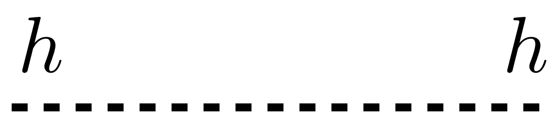
$$\frac{1}{16\pi^2} v^2 \left(C_{UV} - \int_0^1 \mathrm{d}x \log \frac{M_S^2 - x(1-x)p^2}{\mu^2}\right)$$

$+ \ldots$

“TeV-scale SUSY protects the Higgs mass from large corrections!”

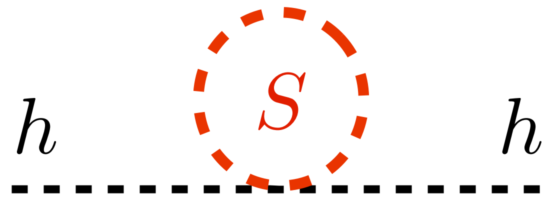
The standard argument:

$\Gamma_{hh} \propto$



$$p^2 - m_H^2$$

$+$



$$\frac{1}{16\pi^2} M_S^2 \left(C_{UV} - 1 + \log \frac{M_S^2}{\mu^2}\right)$$

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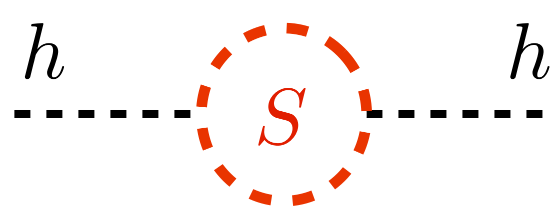


$$\frac{1}{16\pi^2} v^2 \left(C_{UV} - \int_0^1 \mathrm{d}x \log \frac{M_S^2 - x(1-x)p^2}{\mu^2}\right)$$

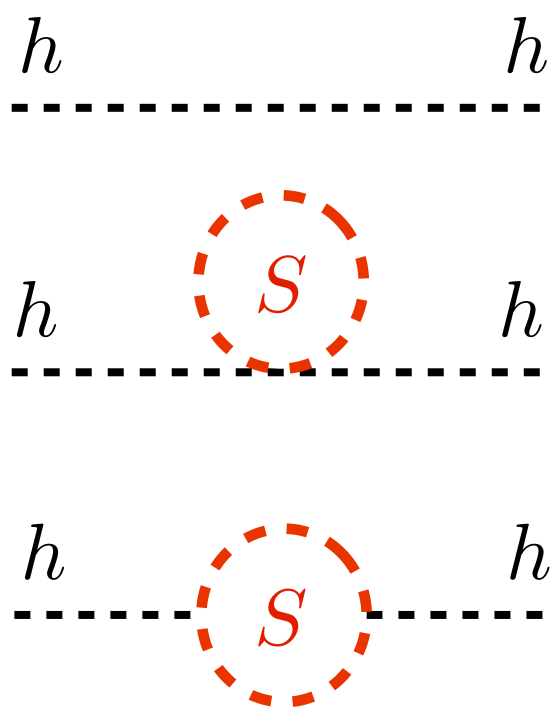
$+\ldots$

For large M_S^2 the root shifts enormously:

$$m_H^2 \rightarrow m_H^2 + \frac{1}{16\pi^2} M_S^2 \left(1 - \log \frac{M_S^2}{\mu^2}\right) + \ldots$$

“TeV-scale SUSY protects the Higgs mass from large corrections!”

The standard argument:



$\Gamma_{hh} \propto$

$$p^2 - m_H^2$$

$$+ \frac{1}{16\pi^2} M_S^2 \left(C_{UV} - 1 + \log \frac{M_S^2}{\mu^2} \right)$$

$$+ \frac{1}{16\pi^2} v^2 \left(C_{UV} - \int_0^1 \mathrm{d}x \log \frac{M_S^2 - x(1-x)p^2}{\mu^2} \right)$$

$+ \ldots$

For large M_S^2 the root shifts enormously:

$$m_H^2 \to m_H^2 + \frac{1}{16\pi^2} M_S^2 \left(1 - \log \frac{M_S^2}{\mu^2} \right) + \ldots$$

so the tree-level mass must be carefully readjusted order by order...

The “hierarchy problem”

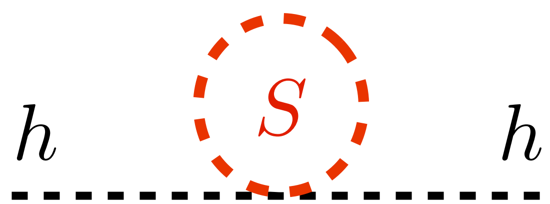
“TeV-scale SUSY protects the Higgs mass from large corrections!”

The standard argument:

$\Gamma_{hh} \propto$

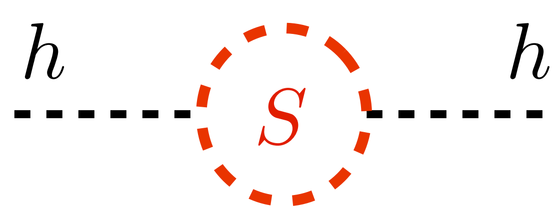
$$p^2 - m_H^2$$

$+$



$$\frac{1}{16\pi^2} M_S^2 \left(C_{UV} - 1 + \log \frac{M_S^2}{\mu^2} \right)$$

$+$



$$\frac{1}{16\pi^2} v^2 \left(C_{UV} - \int_0^1 \mathrm{d}x \log \frac{M_S^2 - x(1-x)p^2}{\mu^2} \right)$$

“TeV-scale SUSY protects the Higgs mass from large corrections!”

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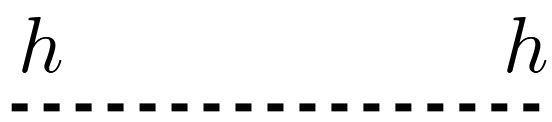
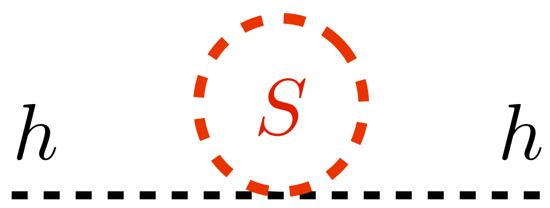


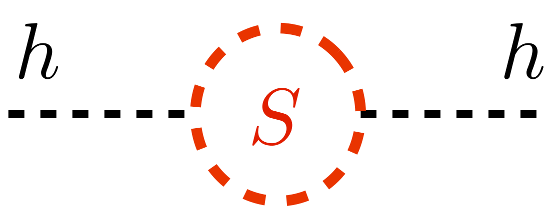
$$p^2 - m_H^2$$

$+$



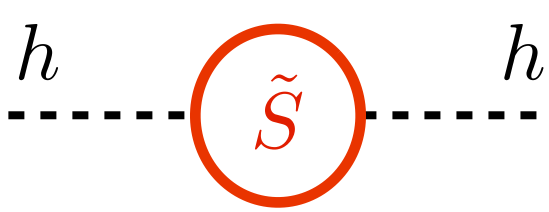
$$\frac{1}{16\pi^2} M_S^2 \left(C_{UV} - 1 + \log \frac{M_S^2}{\mu^2} \right)$$

$+$



$$\frac{1}{16\pi^2} v^2 \left(C_{UV} - \int_0^1 \mathrm{d}x \log \frac{M_S^2 - x(1-x)p^2}{\mu^2} \right)$$

SUSY: $+$

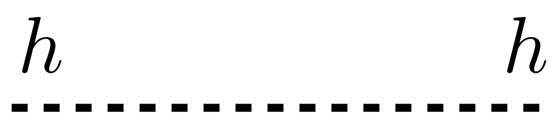


$$-\frac{1}{16\pi^2} M_S^2 \left(C_{UV} - 1 - \int_0^1 \mathrm{d}x \log \frac{M_S^2 - x(1-x)p^2}{\mu^2} \right) + p^2 \text{ terms}$$

$+\ldots$

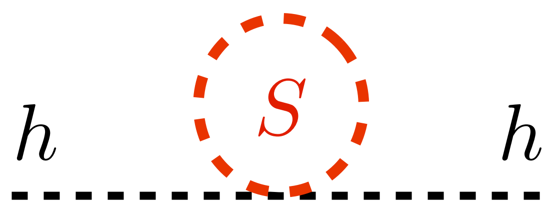
The standard argument:

$\Gamma_{hh} \propto$



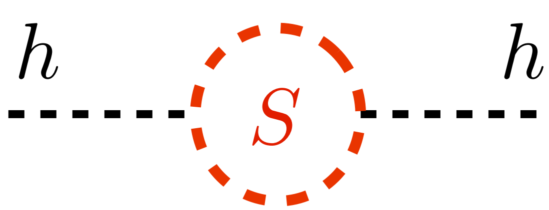
$$p^2 - m_H^2$$

$+$



$$\frac{1}{16\pi^2} M_S^2 \left(C_{UV} - 1 + \log \frac{M_S^2}{\mu^2} \right)$$

$+$



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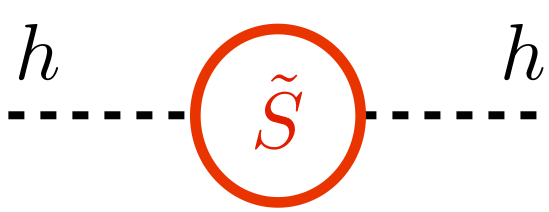

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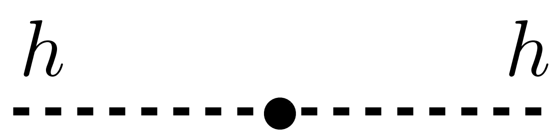
$+ \ldots$

The shift of the root is small even for large M_S^2

"The hierarchy among the two scales is stabilized if SUSY is near M_Z"

The trouble with the "standard argument":

$\Gamma_{hh} \propto$



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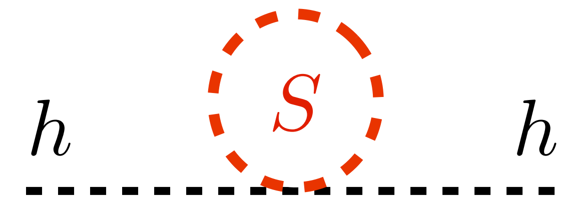


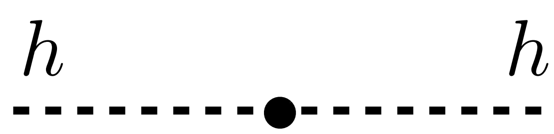
$+ \ldots$

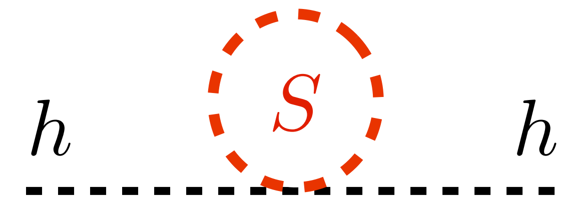
$$p^2 - m_H^2$$

$$\frac{1}{16\pi^2} M_S^2 \left(C_{UV} - 1 + \log \frac{M_S^2}{\mu^2} \right)$$

Is there anything to protect?

The trouble with the "standard argument":

$\Gamma_{hh} \propto$ 

$+$ 

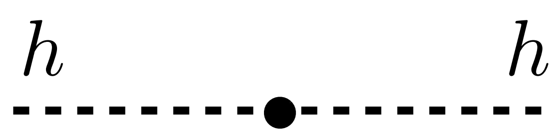
$+ \ldots$

$$p^2 - m_H^2 \qquad\qquad \frac{1}{16\pi^2} M_S^2 \left(C_{UV} - 1 + \log \frac{M_S^2}{\mu^2} \right)$$

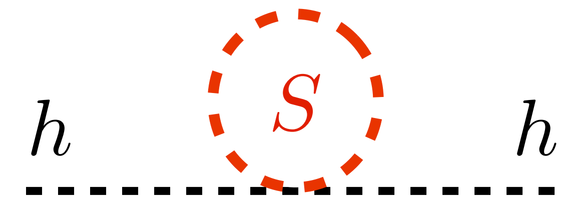
The root is **not the physical mass** - perturbation theory contrived!!!

The trouble with the "standard argument":

$\Gamma_{hh} \propto$



$+$



$+\ldots$

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The root is **not the physical mass** - perturbation theory contrived!!!

Mind the one-point function!

The trouble with the "standard argument":

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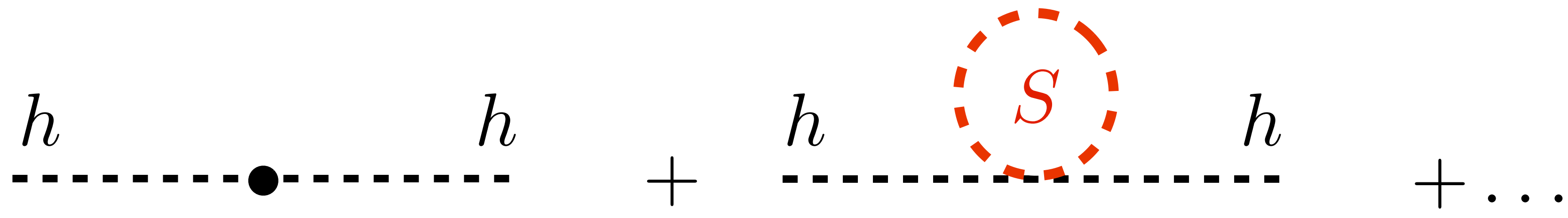

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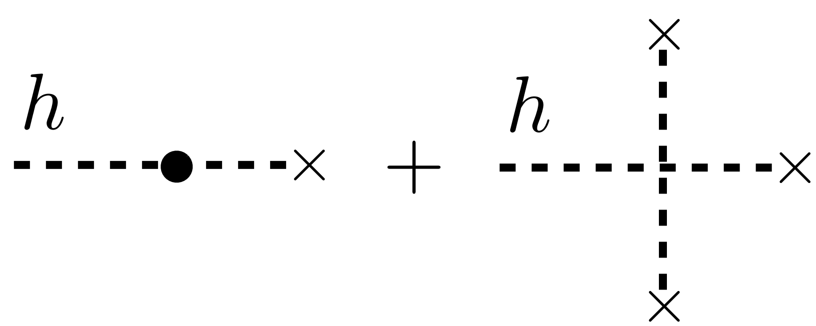
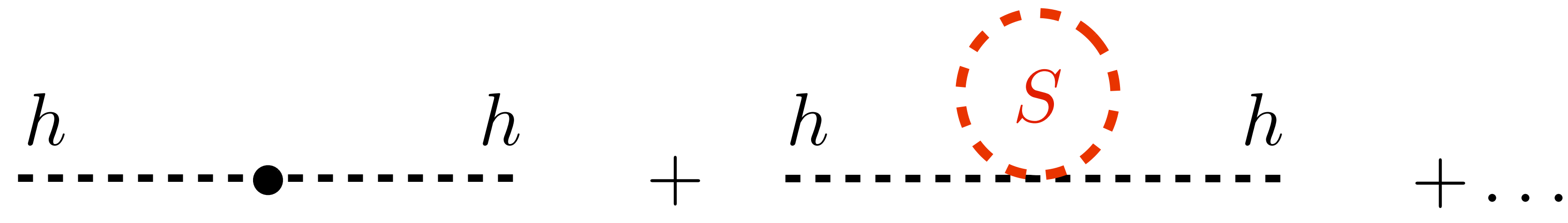
$\Gamma_h \propto$



$$m_H^2 v \qquad\qquad \lambda v^3$$

The trouble with the "standard argument":

$\Gamma_{hh} \propto$

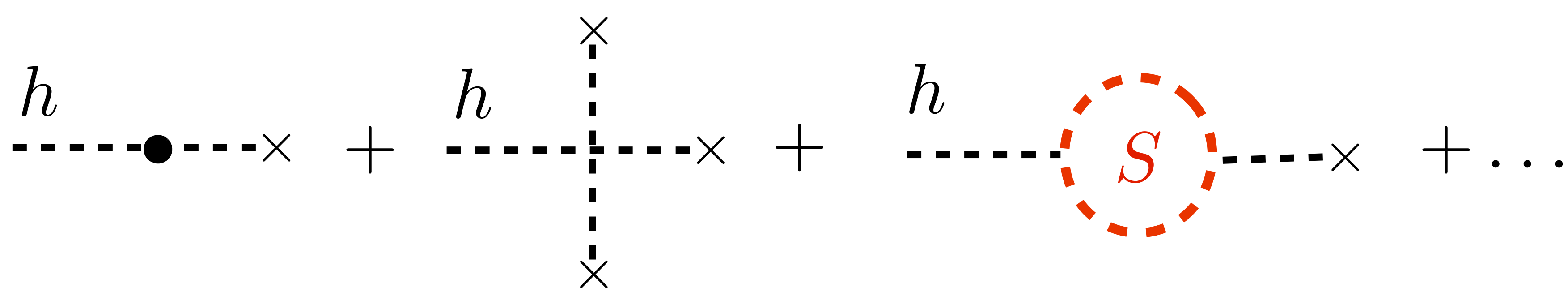


$$p^2 - m_H^2 \qquad\qquad \frac{1}{16\pi^2} M_S^2 \left(C_{UV} - 1 + \log \frac{M_S^2}{\mu^2} \right)$$

The root is **not the physical mass** - perturbation theory contrived!!!

Mind the one-point function!

$\Gamma_h \propto$



$$m_H^2 v \qquad\qquad \lambda v^3$$

Is there anything to protect?

The trouble with the “standard argument”:

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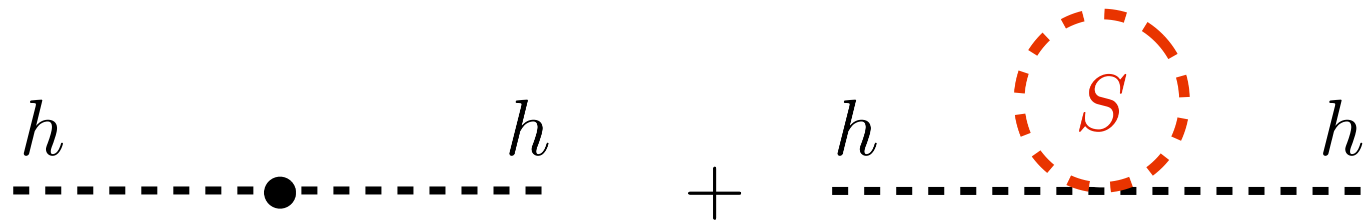

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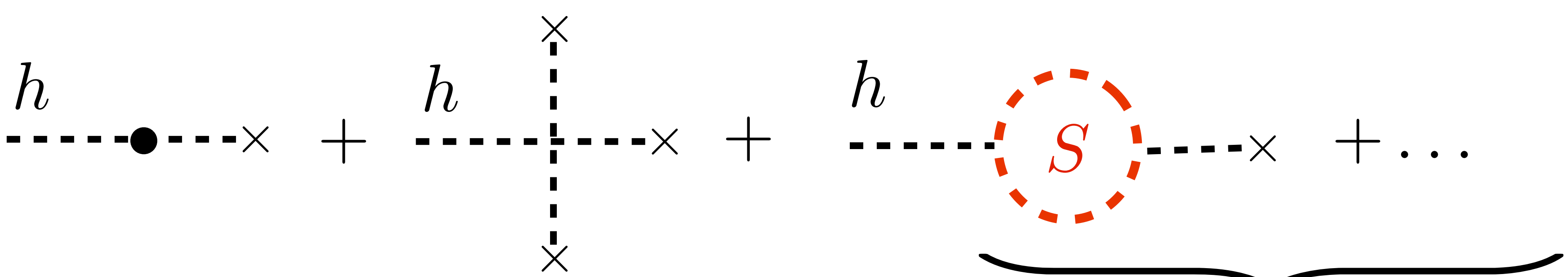

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“Higgs anti-discrimination act”

Full one-loop effective potential level approach: MM, EPJ C73 (2013) 2415, arXiv:1212.4660

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“Higgs anti-discrimination act”

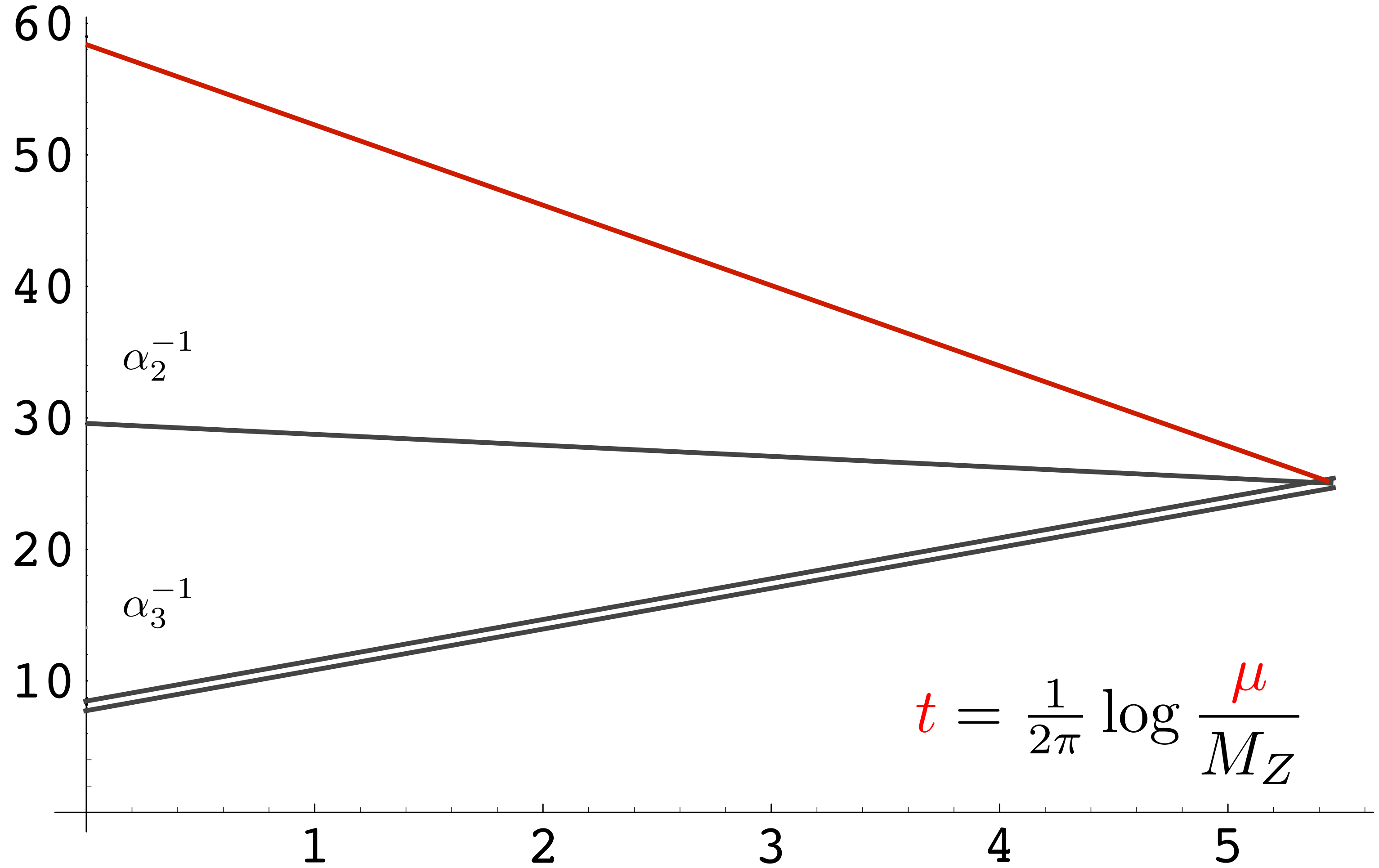
Who cares? Do you mind getting rid of the UV divergences?

Correlations among observables are stable!

Full one-loop effective potential level approach: MM, EPJ C73 (2013) 2415, arXiv:1212.4660

Why the TeV-scale SUSY does not make the unification work better

Unification "works" if it is internally consistent, accommodates all existing data and provides testable predictions (typically BNV)



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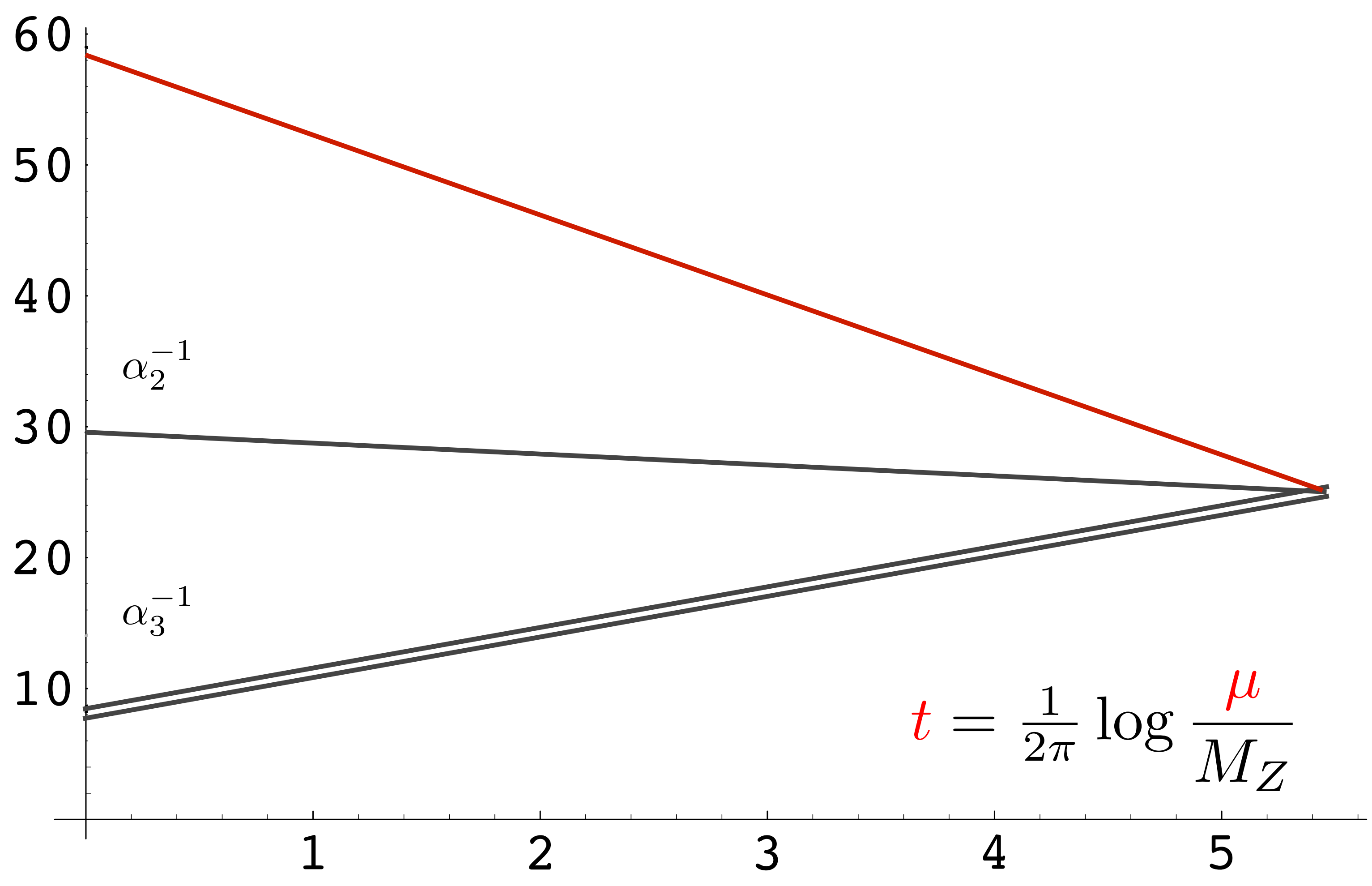

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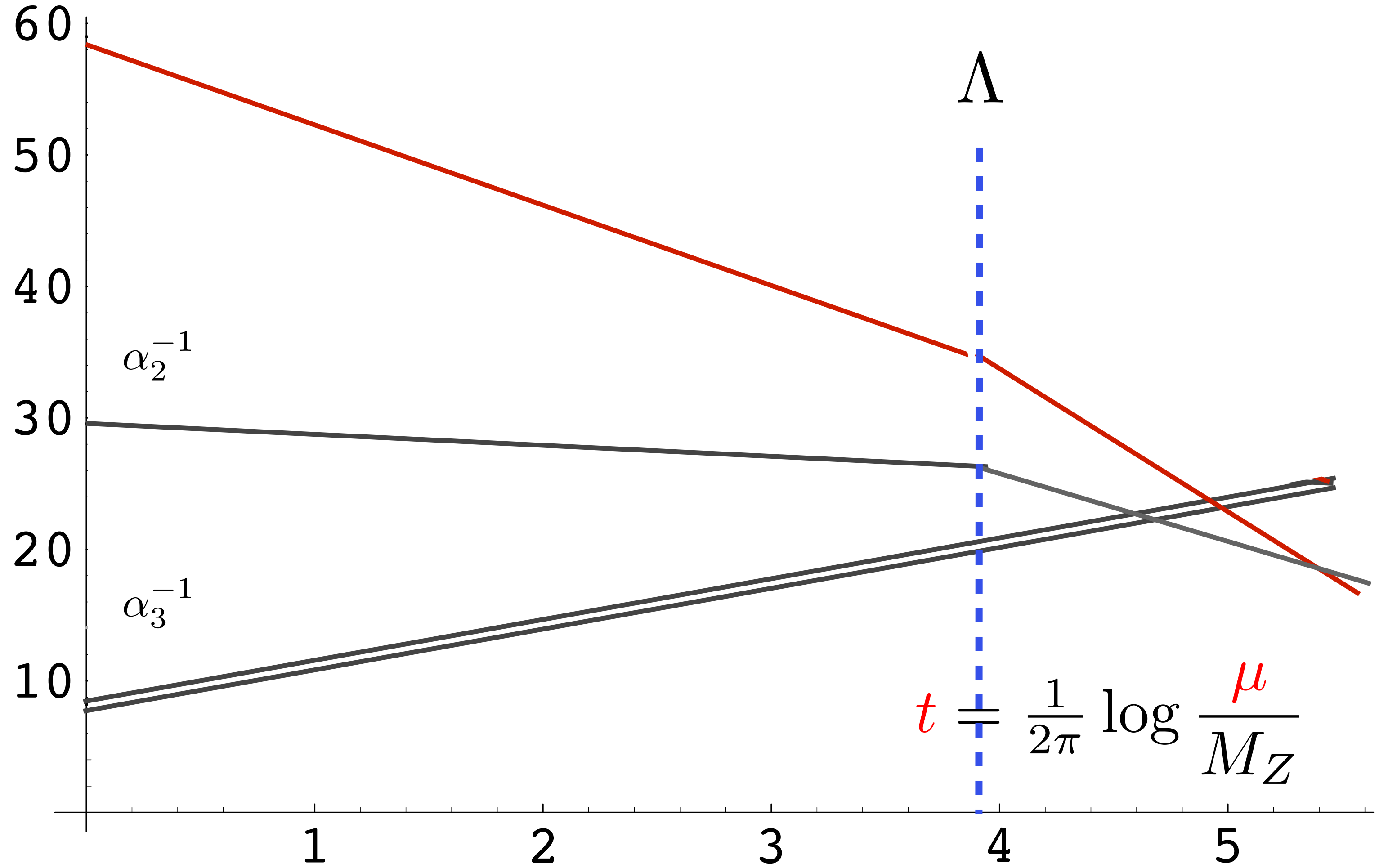

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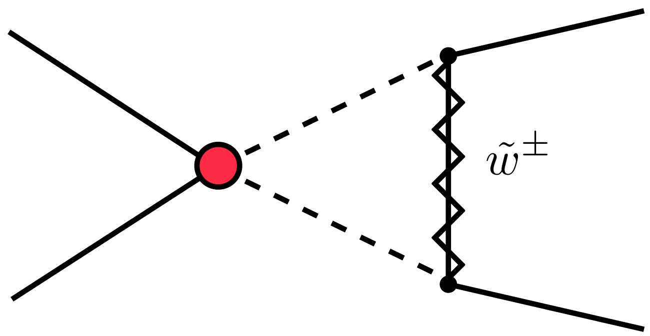
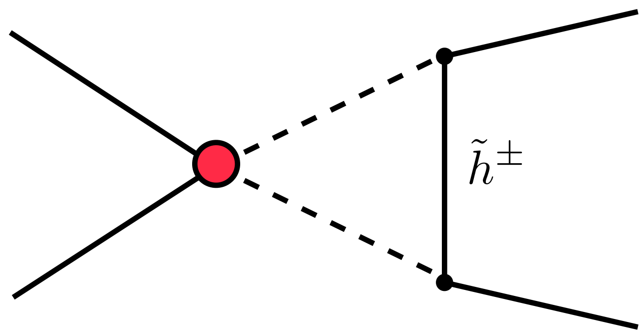
d=5 proton decay in SUSY:





$$W_L \sim \frac{c_L}{M_{\Delta_c}} \hat{Q}\hat{Q}\hat{Q}\hat{L} \qquad W_R \sim \frac{c_R}{M_{\Delta_c}} \hat{u}^c\hat{u}^c\hat{d}^c\hat{e}^c$$

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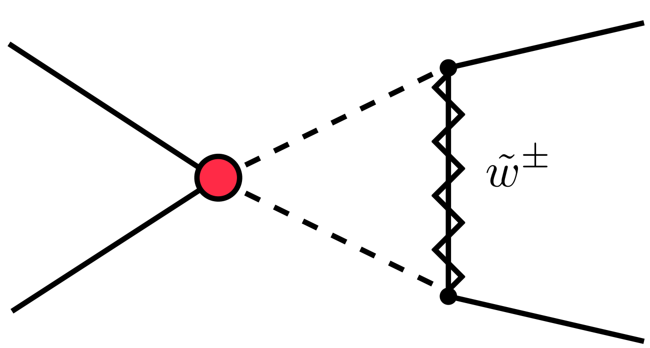

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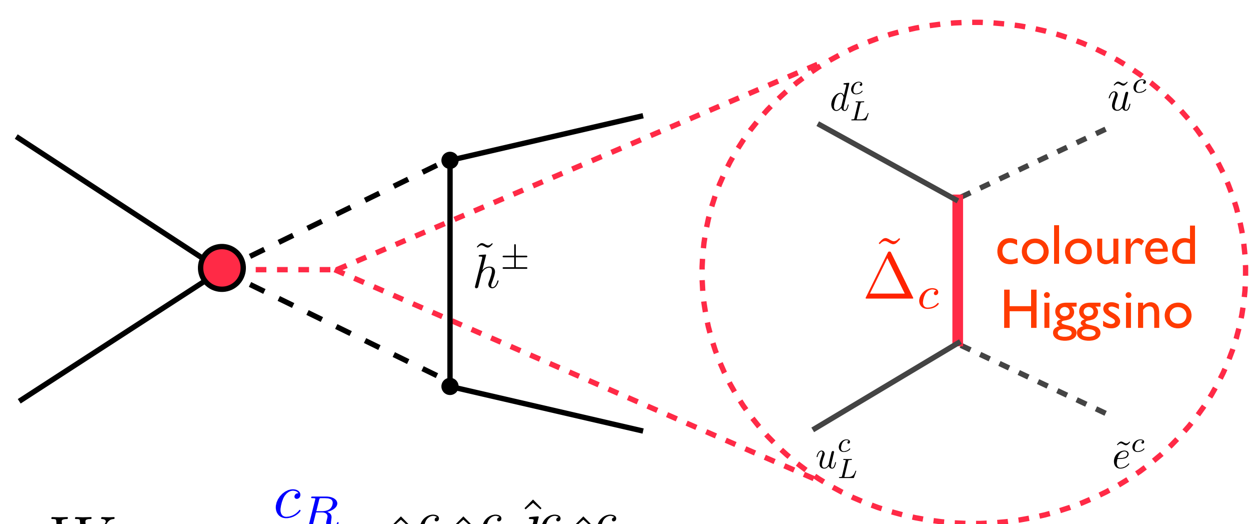

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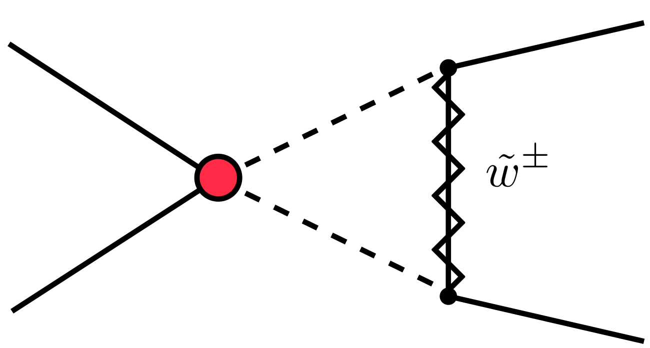
d=5 proton decay in SUSY:

Kaons favoured: $p^+ \to K^+ \bar{\nu}\,, \ldots$!!!



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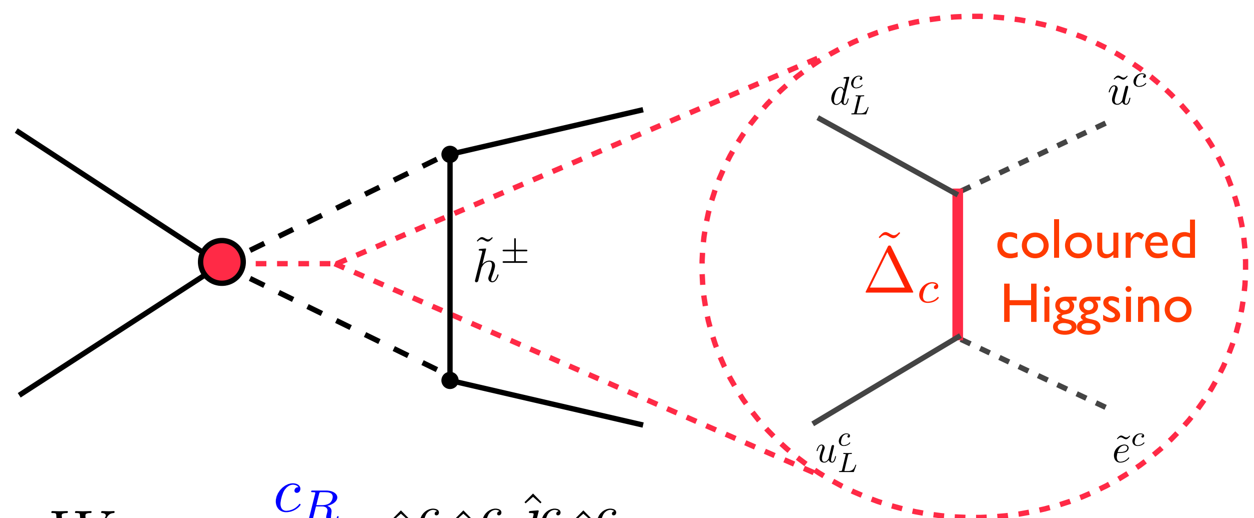

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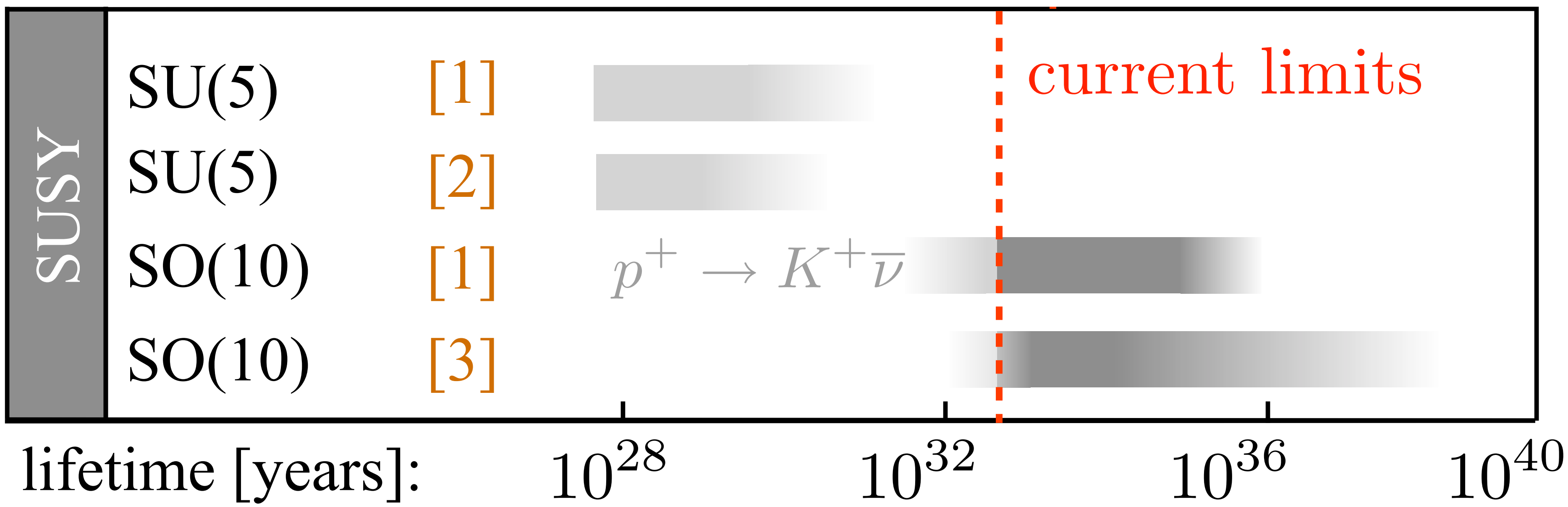


[1] Pati, hep-ph/0507307
[2] Murayama, Pierce, PRD 65. 055009 (2002)
[3] Dutta, Mimura, Mohapatra, PRL 94, 091804 (2005)
... and many more.

Experimental affairs

First large water-Cherenkov detectors

KamiokaNDE

Kamioka-cho, Gifu, Japan

3,000 tons of pure water, about 1,000 PMs

1983-1985 - first phase (proton decay focused)

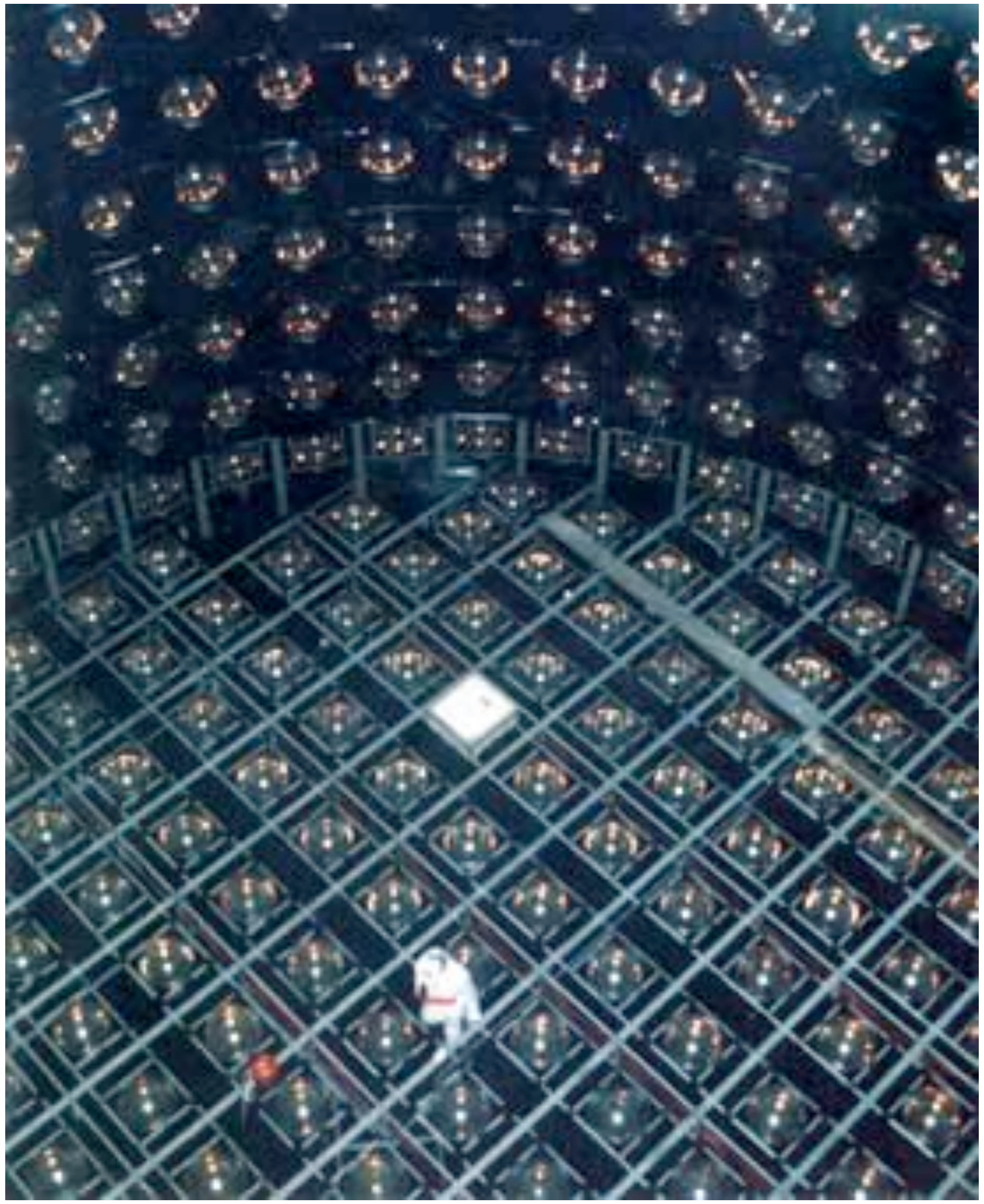
1987-1990 - solar neutrino deficit measurements

Feb. 23 1987 07:35 - 12 out of 10^{58} neutrinos

from SN 1987A (170,000 ly)

1989 $\boxed{\tau_p \gtrsim 2.6 \times 10^{32}\ \mathrm{yr}}$

1990 Solar neutrino deficit confirmation



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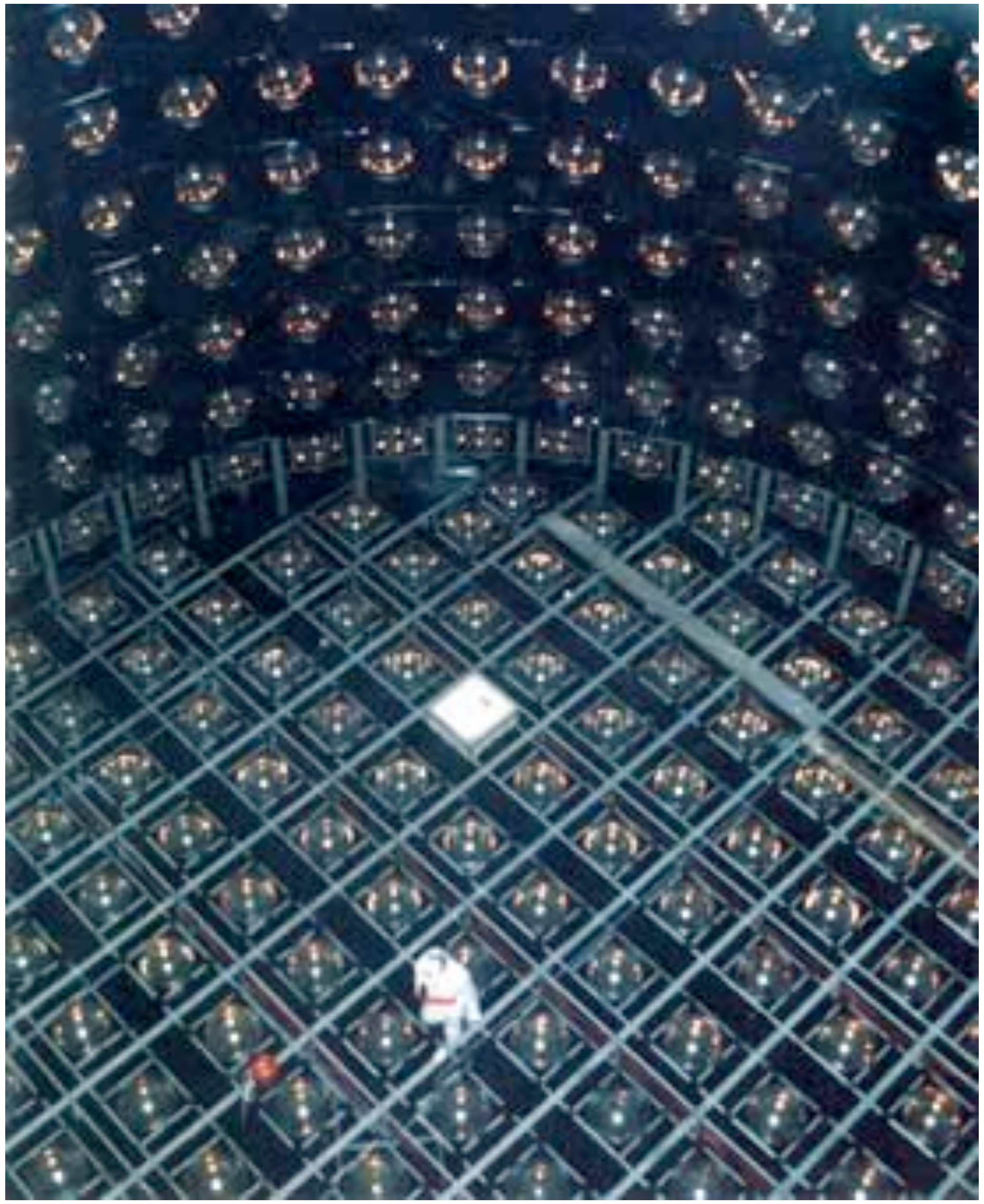

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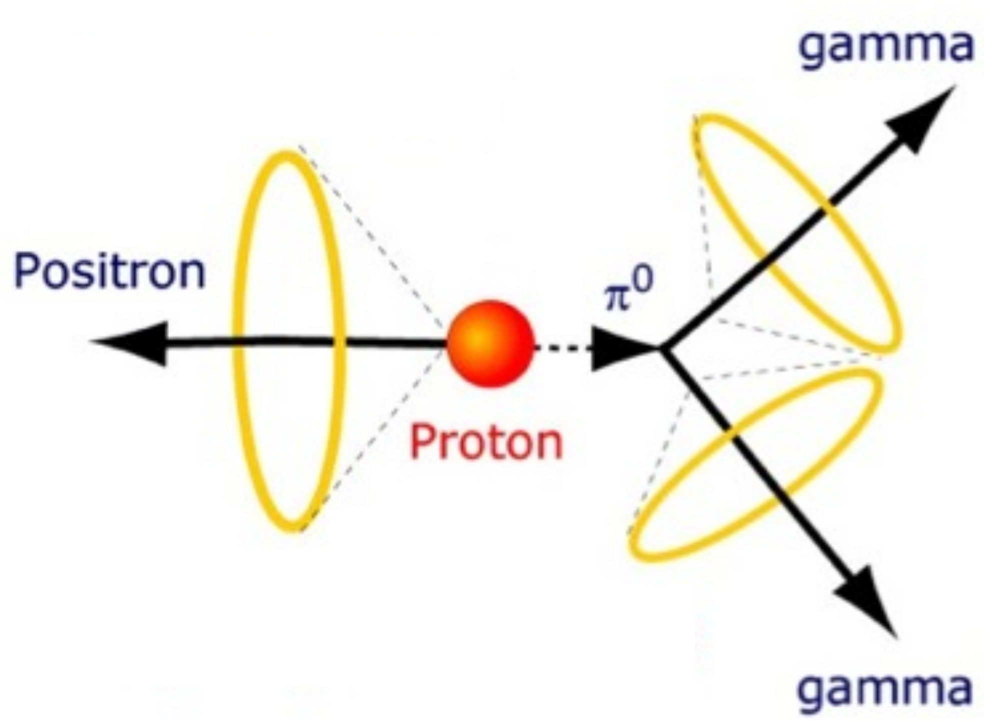
Proton decay in water

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

$\pi^0 \to 2\gamma$

$p_\pi = p_e = 459$ MeV

$p_{\gamma/\pi R} = 68$ MeV



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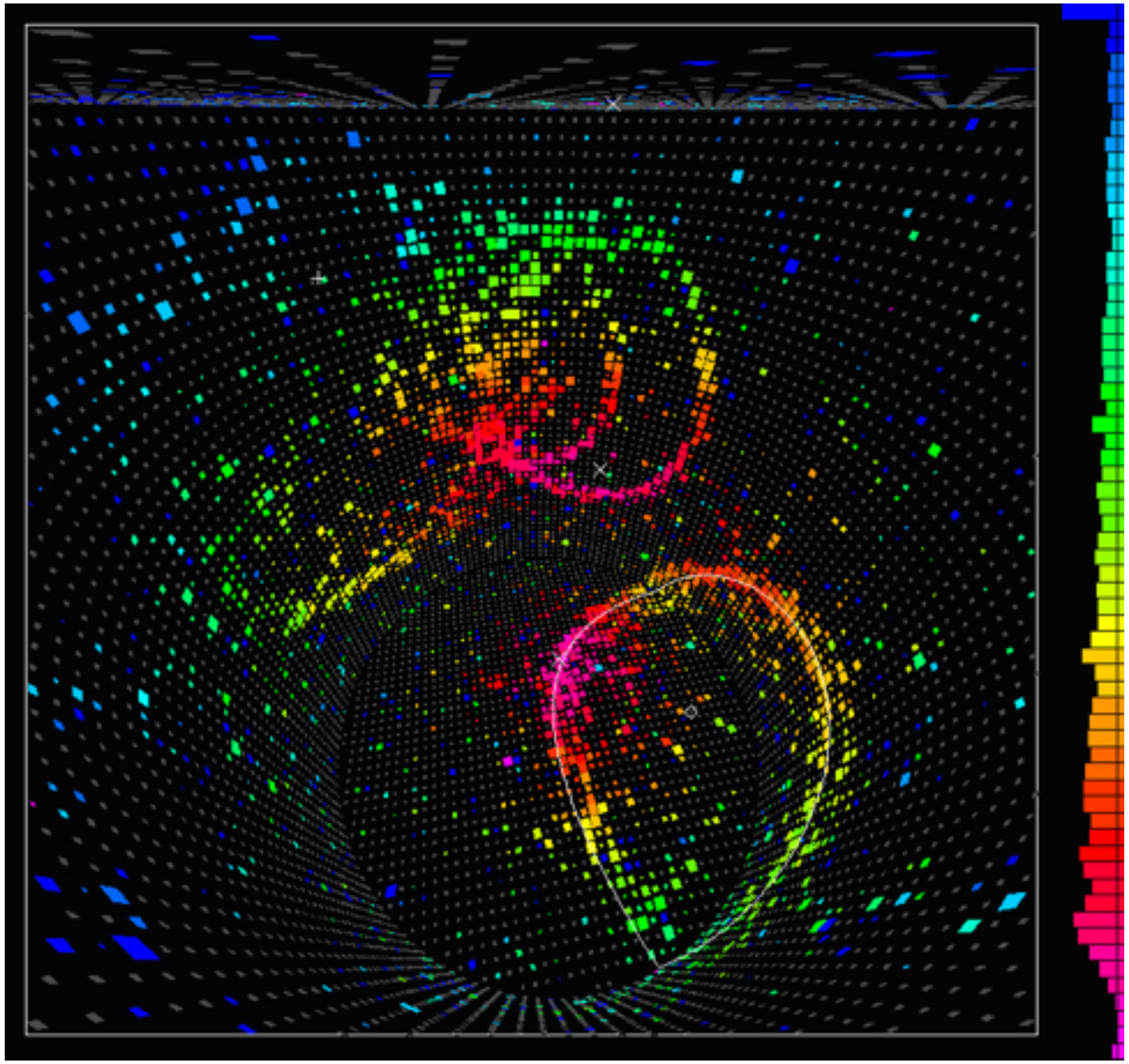

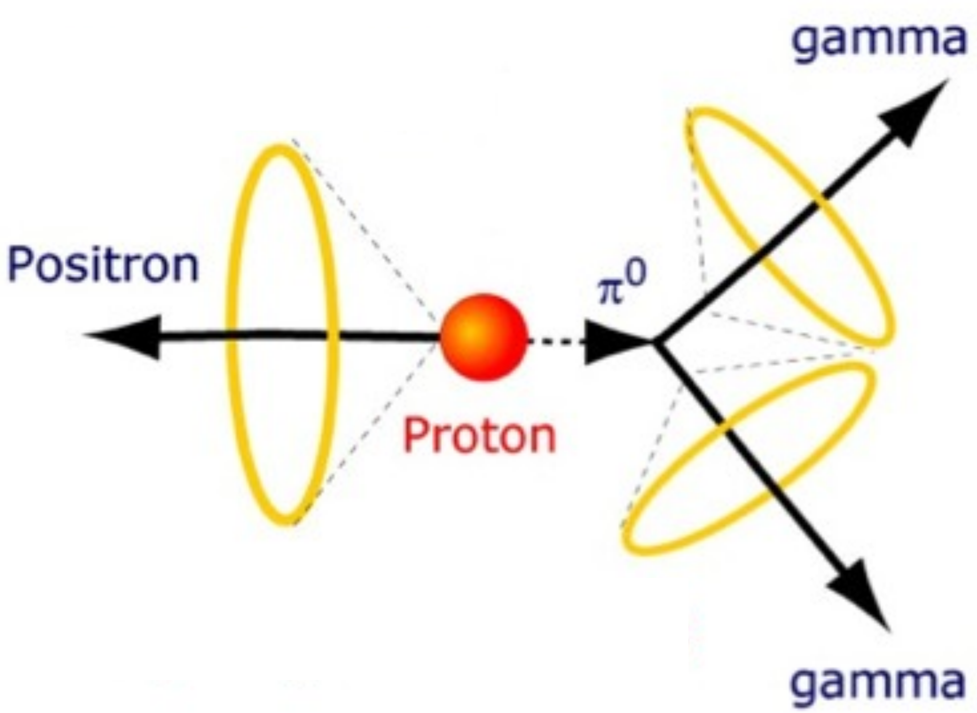

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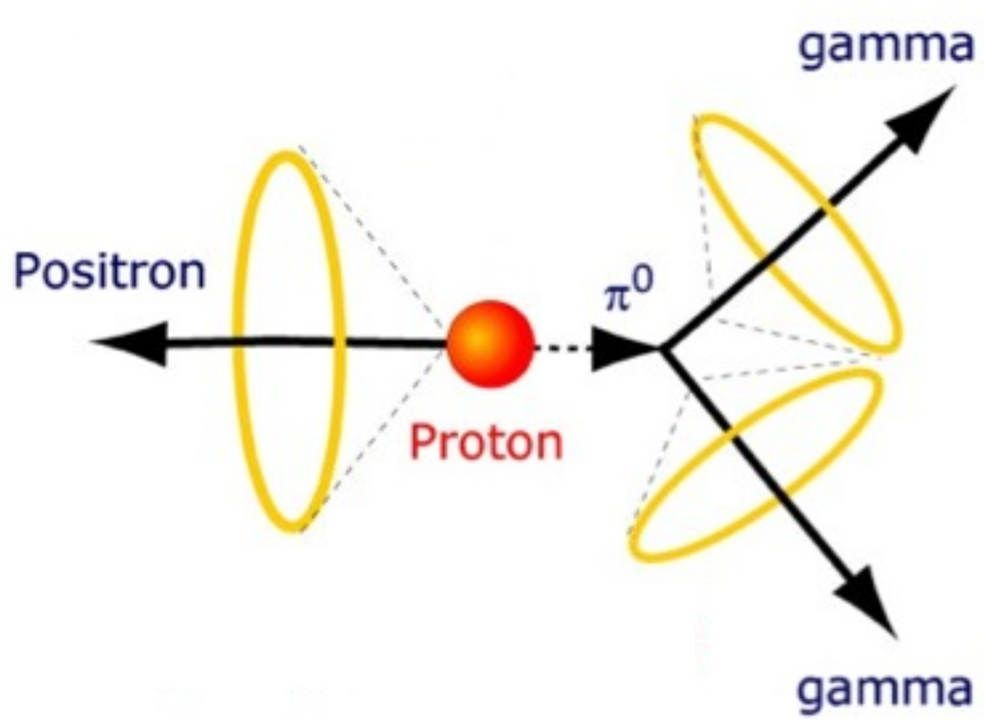

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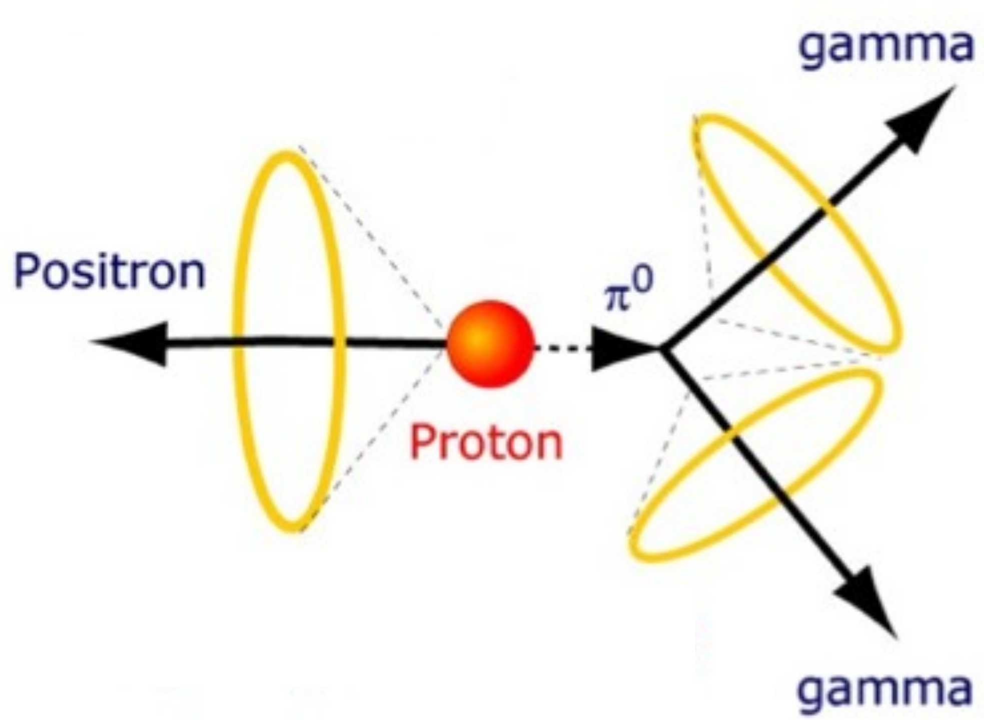
- majority of nucleons in oxygen
- Fermi motion
- pion charge exchange
- absorption



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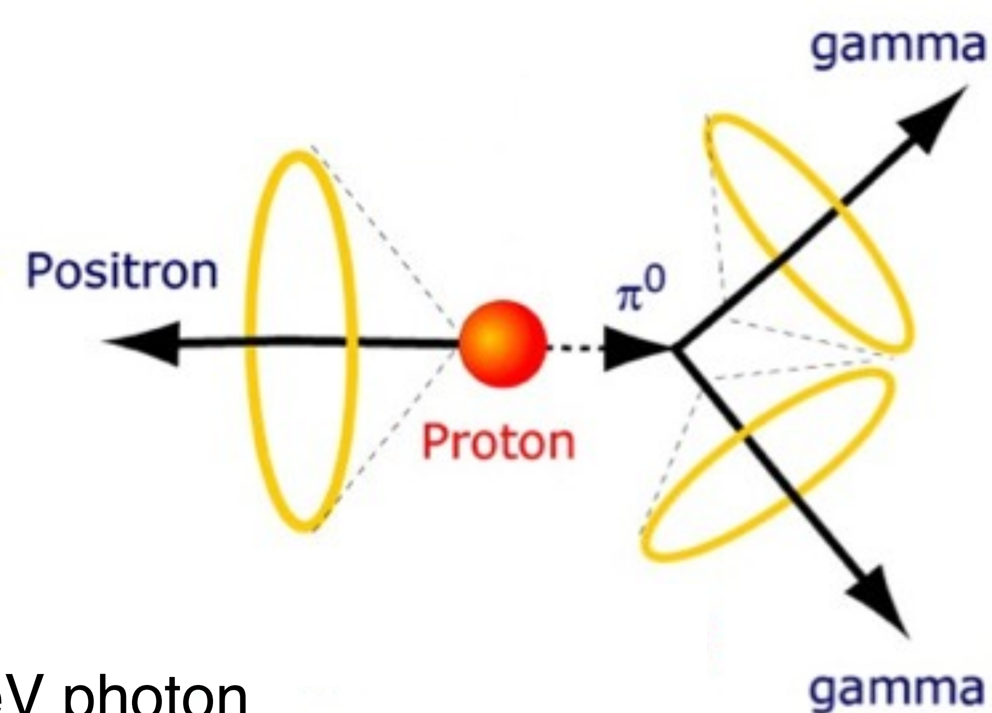
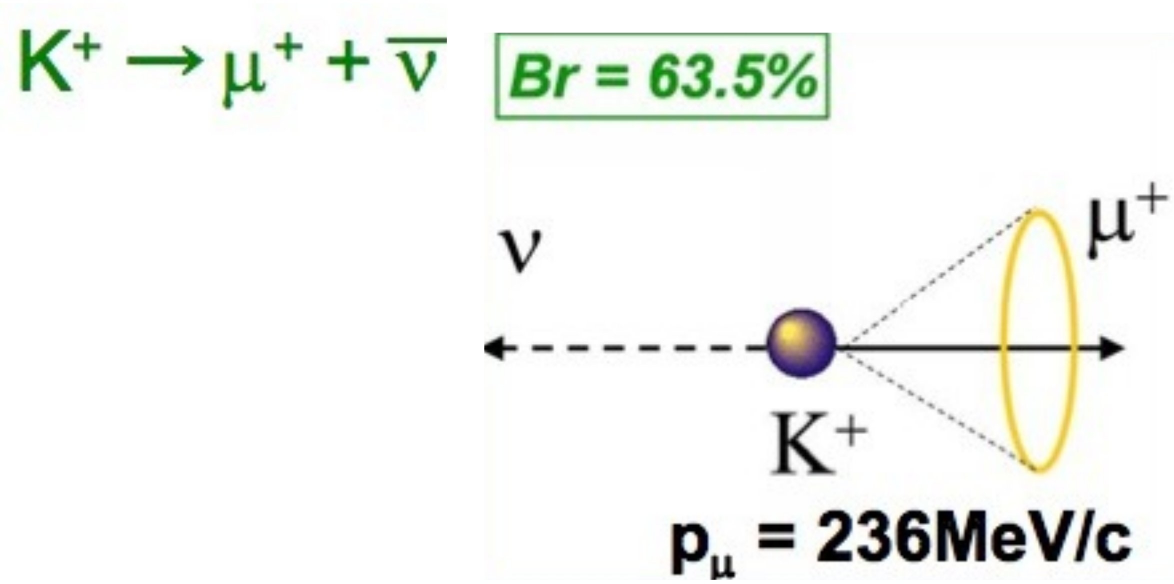


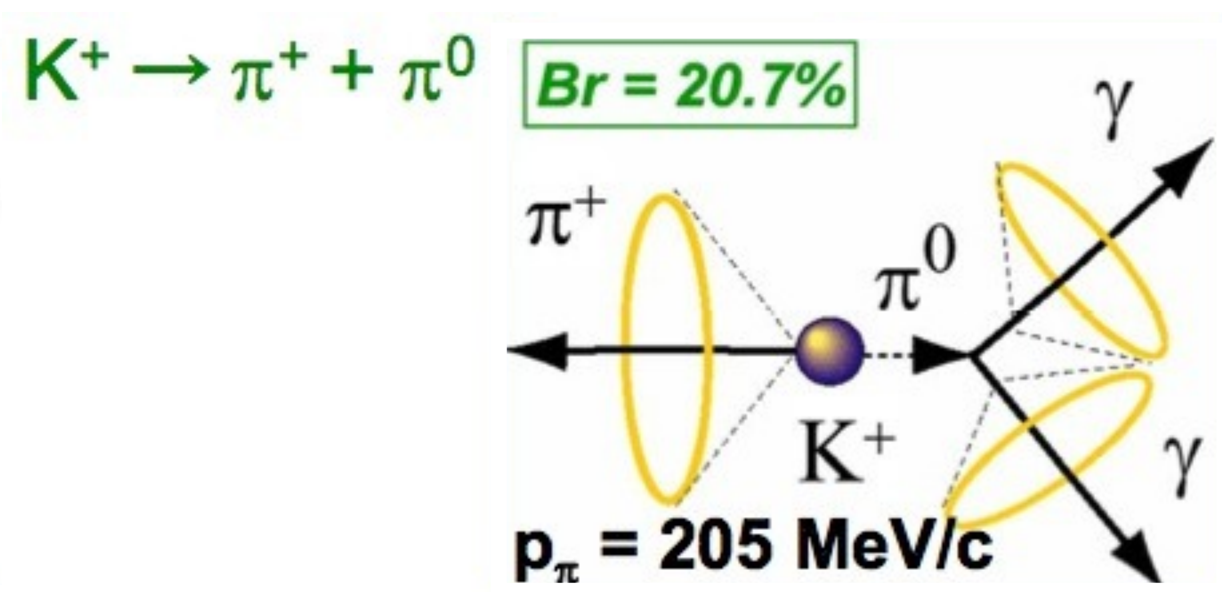
Other signals

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

Proton decay in water

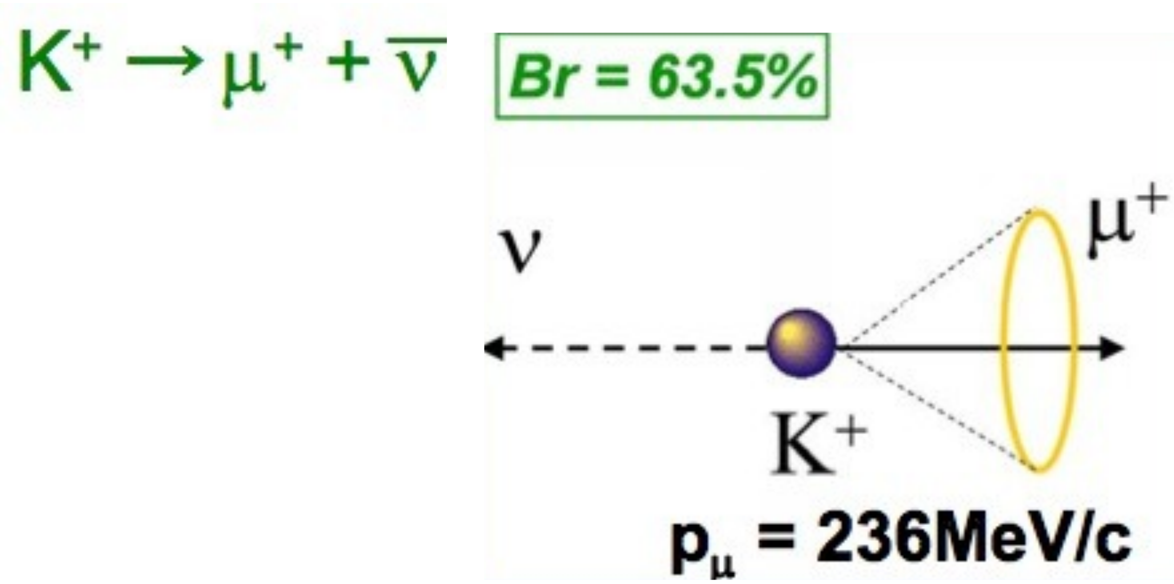
"Silver channel": $p \to K^+ \nu$ p_K = 340 MeV





Proton decay in water

“Silver channel”: $p \to K^+ \nu$ p_K = 340 MeV Kaons don’t shine !



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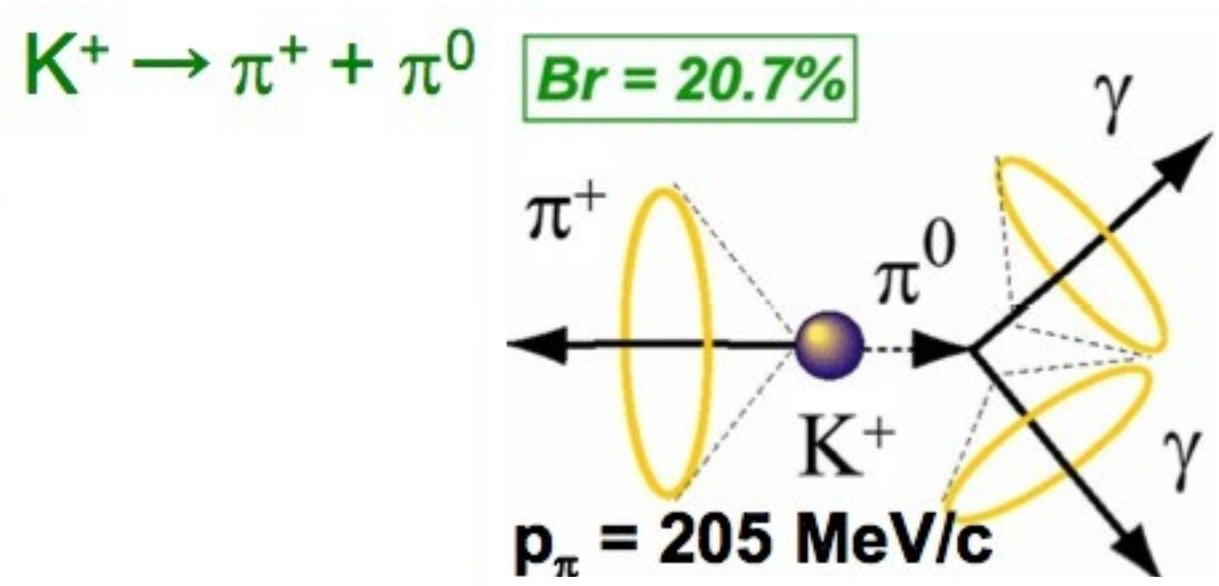

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- little opposite-side activity

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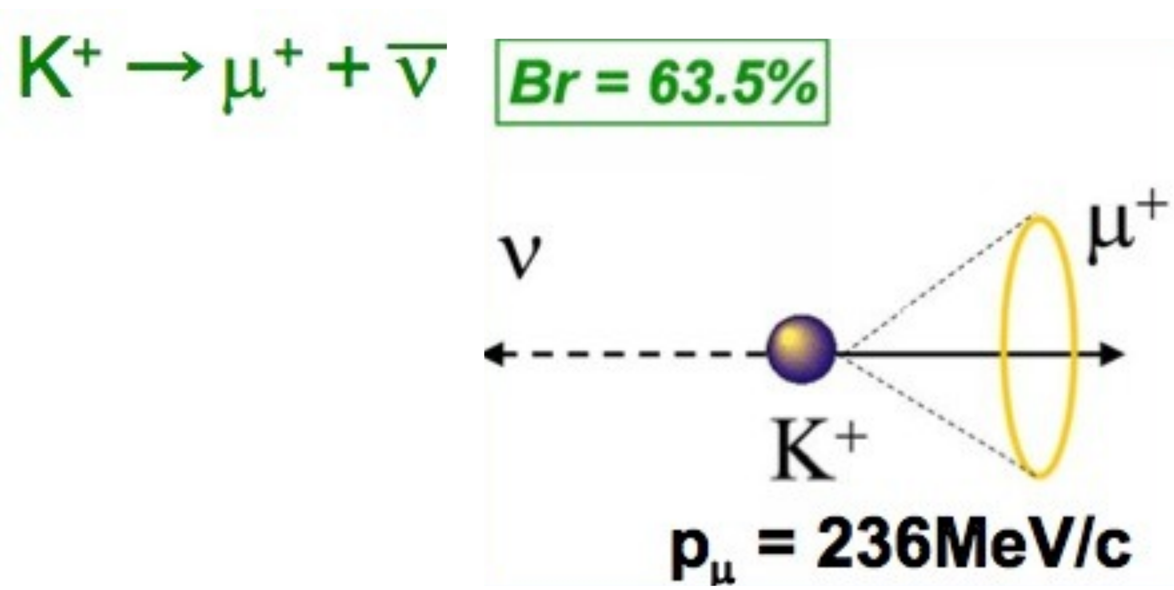

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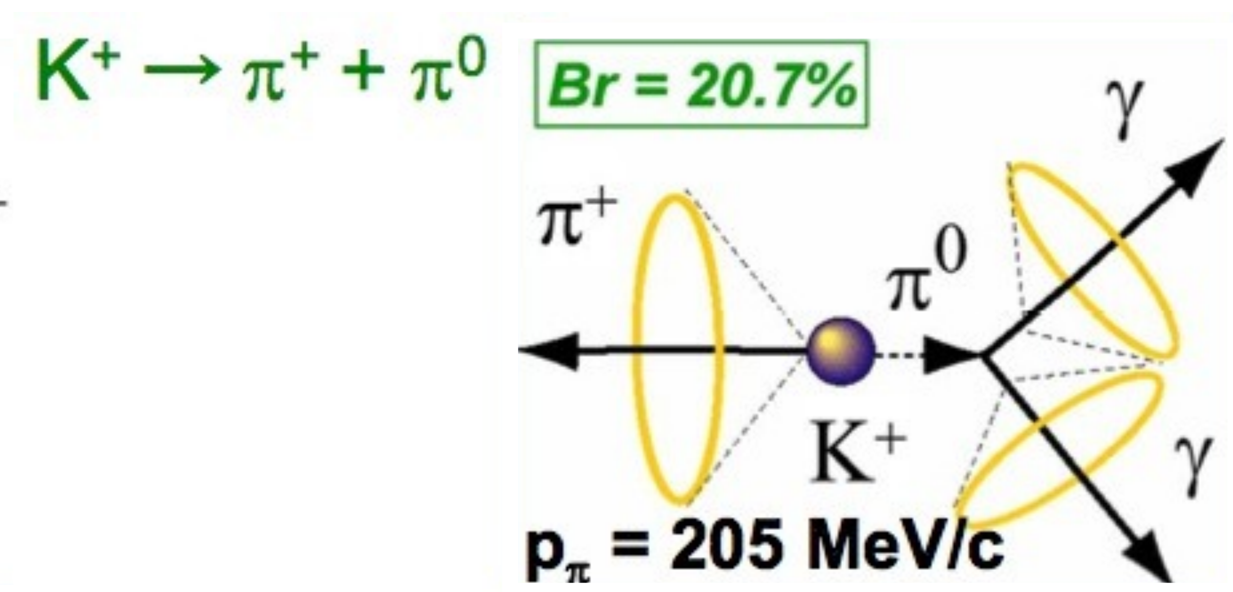

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About one order of magnitude less sensitive than $p \to \pi^0 e^+$

Monopoles

No way to produce in lab, only cosmics + Callan-Rubakov effect

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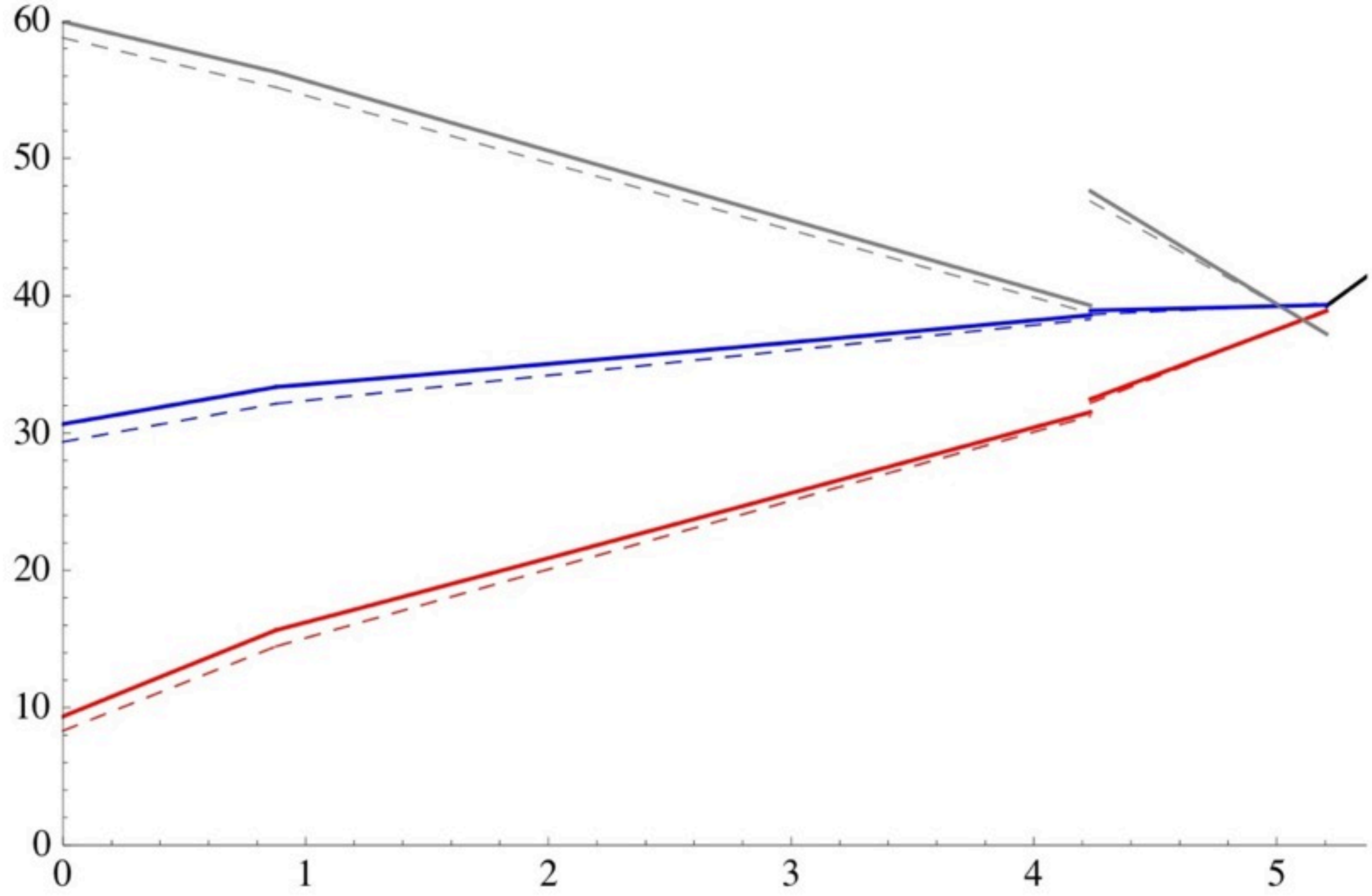
N.B. early (fake) monopole-like events — Price et al., 1975 PRL August 25

Backup slides

Sample 2-loop running



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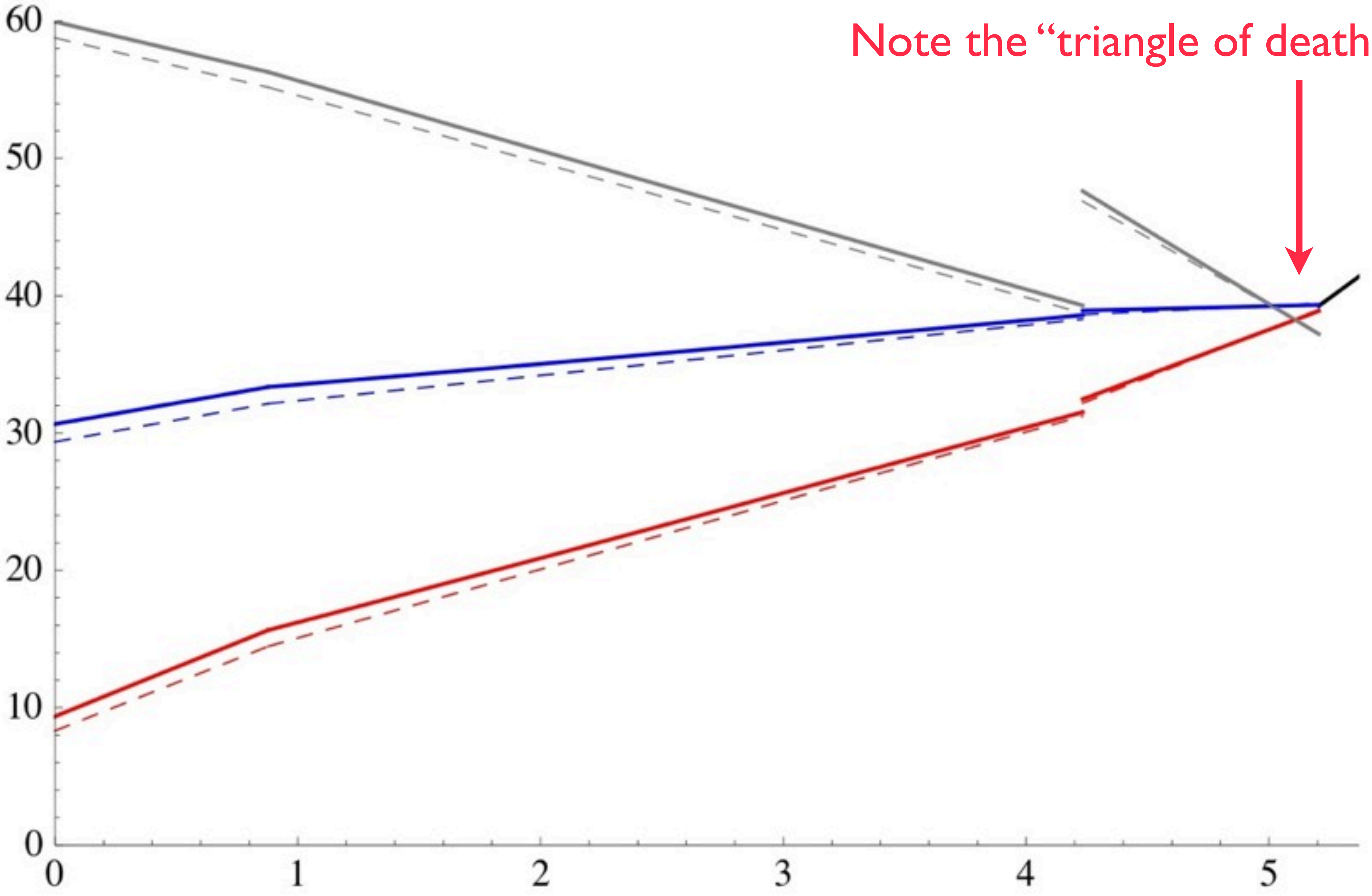

Note the "triangle of death"