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GUTs and all that...

Proton lifetime in minimal gauge unifications

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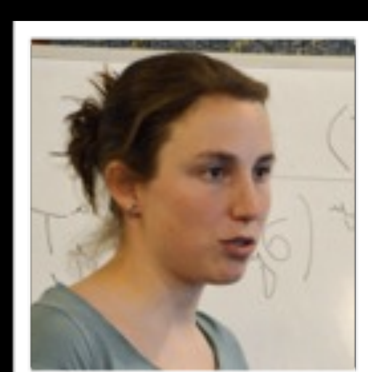
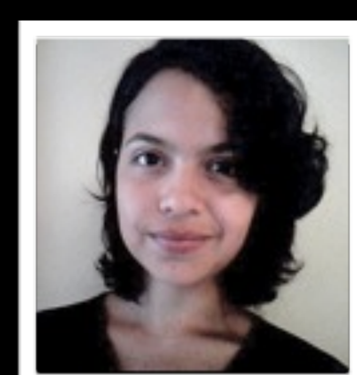


Outline

Proton decay from the SM perspective

Proton decay in BSM physics

Experimental situation

Grand unifications as theories of proton decay

Proton lifetime estimates in GUTs

Minimal "reasonably calculable" models (?)

Proton decay

from the GSW Standard model perspective

The SM lagrangian

$$
\begin{gathered}
\mathcal{L}_{SM} = -\frac{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 - \frac{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 - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \frac{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)) - \\
\frac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{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) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h \left(\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \frac{2M^4}{g^2}\alpha_h - g\alpha_h M \left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\frac{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)^2 H^2\right) - gMW^+_\mu W^-_\mu H - \\
\frac{1}{2} g \frac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \frac{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) + \\
\frac{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) + \frac{1}{2} g \frac{1}{c_w}(Z^0_\mu(H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
M \left(\frac{1}{c_w} Z^0_\mu \partial_\mu \phi^0 + W^+_\mu \partial_\mu \phi^- + W^-_\mu \partial_\mu \phi^+\right) - ig \frac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + igs_w M A_\mu (W^+_\mu \phi^- - \\
W^-_\mu \phi^+) - ig \frac{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^+) - \\
\frac{1}{4} g^2 W^+_\mu W^-_\mu \left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \frac{1}{8} g^2 \frac{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) - \\
\frac{1}{2} g^2 \frac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) - \frac{1}{2} ig^2 \frac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) + \frac{1}{2} ig^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \frac{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^- + \\
\frac{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) + \frac{2}{3}(\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j \gamma^\mu d^\lambda_j)\right) + \frac{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 (\frac{4}{3}s_w^2 - 1 - \gamma^5) d^\lambda_j) + (\bar{u}^\lambda_j \gamma^\mu (1 - \frac{8}{3}s_w^2 + \gamma^5) u^\lambda_j)\} + \\
\frac{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) + \\
\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}^\kappa_j C^\dagger_{\kappa\lambda} \gamma^\mu (1+\gamma^5) u^\lambda_j)\right) + \\
\frac{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) + \\
\frac{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) - \frac{g}{2}\frac{m^\lambda_\nu}{M} H(\bar{\nu}^\lambda \nu^\lambda) - \\
\frac{g}{2}\frac{m^\lambda_e}{M} H(\bar{e}^\lambda e^\lambda) + \frac{ig}{2}\frac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2}\frac{m^\lambda_e}{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^\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) + \\
\frac{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) - \frac{g}{2}\frac{m^\lambda_u}{M} H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m^\lambda_d}{M} H(\bar{d}^\lambda_j d^\lambda_j) + \\
\frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j \gamma^5 d^\lambda_j)
\end{gathered}
$$

The SM lagrangian

$$
\begin{aligned}
\mathcal{L}_{SM} = &-\tfrac12\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 - \tfrac14 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 - \tfrac12\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac12\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)) - \\
&\tfrac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac12 g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_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) - \tfrac12\partial_\mu H\partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - \tfrac12\partial_\mu\phi^0\partial_\mu\phi^0 - \\
&\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac12(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) - \\
&\tfrac18 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 - \\
&\tfrac12 g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac12 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) + \\
&\tfrac12 g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac12 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_wMA_\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_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
&\tfrac14 g^2 W^+_\mu W^-_\mu\left(H^2+(\phi^0)^2+2\phi^+\phi^-\right) - \tfrac18 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) - \\
&\tfrac12 g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac12 ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac12 g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) + \tfrac12 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^- + \\
&\tfrac12 ig_s\,\lambda^a_{ij}(\bar q^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar e^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar\nu^\lambda(\gamma\partial + m_\nu^\lambda)\nu^\lambda - \bar u^\lambda_j(\gamma\partial+m_u^\lambda)u^\lambda_j - \bar d^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + \\
&igs_wA_\mu\left(-(\bar e^\lambda\gamma^\mu e^\lambda) + \tfrac23(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac13(\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(\tfrac43 s_w^2 - 1 - \gamma^5)d^\lambda_j) + (\bar u^\lambda_j\gamma^\mu(1-\tfrac83 s_w^2+\gamma^5)u^\lambda_j)\} + \\
&\tfrac{ig}{2\sqrt2}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\sqrt2}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\sqrt2}\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) + \\
&\tfrac{ig}{2M\sqrt2}\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) - \tfrac{g}{2}\tfrac{m_\nu^\lambda}{M}H(\bar\nu^\lambda\nu^\lambda) - \\
&\tfrac{g}{2}\tfrac{m_e^\lambda}{M}H(\bar e^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m_\nu^\lambda}{M}\phi^0(\bar\nu^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m_e^\lambda}{M}\phi^0(\bar e^\lambda\gamma^5 e^\lambda) - \tfrac14\bar\nu_\lambda\, M^R_{\lambda\kappa}\,(1-\gamma_5)\hat\nu_\kappa - \\
&\tfrac14\bar\nu_\lambda\, M^R_{\lambda\kappa}\,(1-\gamma_5)\hat\nu_\kappa + \tfrac{ig}{2M\sqrt2}\phi^+\left(-m_d^\kappa(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)\right) + \\
&\tfrac{ig}{2M\sqrt2}\phi^-\left(m_d^\lambda(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\right) - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar u^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar d^\lambda_j d^\lambda_j) + \\
&\tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar u^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j)
\end{aligned}
$$

The SM lagrangian

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

always a $\overline{\Psi}\Psi$ structure - B & L perturbatively conserved

B & L violation in the SM

Only by anomalies (at the renormalizable level)

- Instantons (at zero T) cause $9q + 3l \leftrightarrow \emptyset$ with immeasurably small rates

$$^3He \to e^+\mu^+\overline{\nu}_\tau$$

$$\mathcal{A} \sim e^{-2\pi/\alpha} \sim 10^{-\mathcal{O}(100)}$$

- Sphalerons (at high T) make the tunneling more efficient $\Rightarrow$ leptogenesis

Kuzmin, V. Rubakov, M. Shaposhnikov, PLB155, 1985 Fukugita, Yanagida, PLB174, 1986

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neutrinos are massive, **renormalizability** may not be fundamental

Perturbative L violation

in the SM with massive neutrinos

Standard model with massive neutrinos

neutron neutrality + neutrino masses

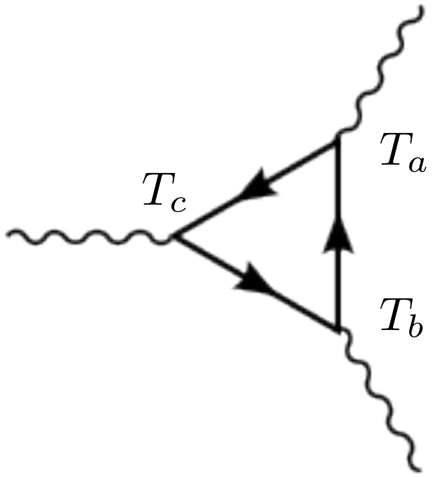
suggest

perturbative L violation

(Hyper)charge quantization in the Standard model

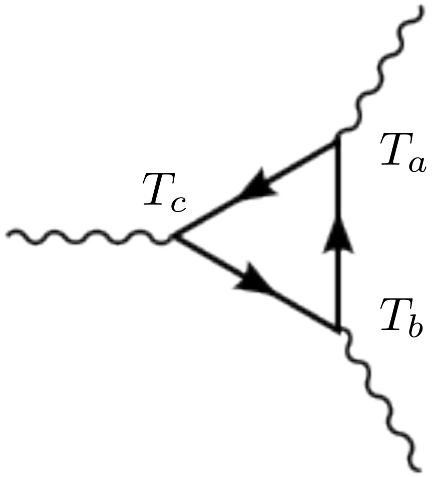
SU(3) x SU(2) x U(1) gauge anomalies

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



(Hyper)charge quantization in the Standard model

SU(3) x SU(2) x U(1) gauge anomalies $$\mathcal{A}_c \propto \frac{1}{32\pi^2}\mathrm{Tr}\left(\{T_a,T_b\}T_c\right)\tilde{F}^a_{\mu\nu}F^{b\mu\nu}$$



SU(2)^2 U(1): $$6Y_Q+2Y_L=0$$

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

(Hyper)charge quantization in the Standard model

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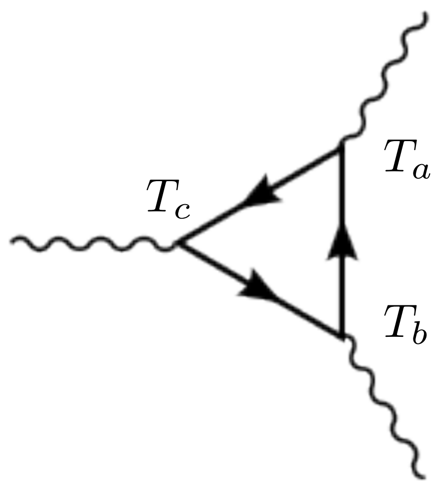


SU(2)^2 U(1): $6Y_Q + 2Y_L = 0$

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

Yukawas: $Y_{D ij}\overline{Q_L}_i\langle H\rangle D_{Rj} + Y_{U ij}\overline{Q_L}_i\langle \tilde{H}\rangle U_{Rj} + Y_{E ij}\overline{L_L}_i\langle H\rangle E_{Rj}$

$-Y_Q + Y_D + Y_H = 0$

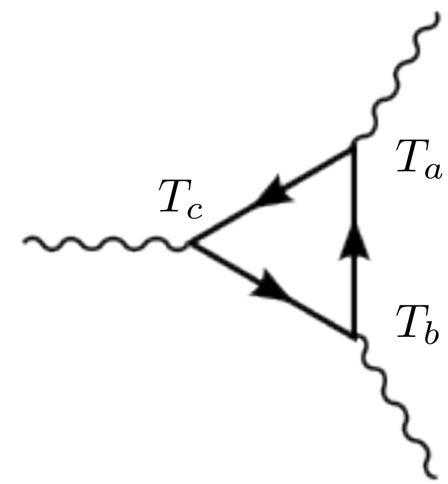
$-Y_L + Y_E + Y_H = 0$

$-Y_Q + Y_U - Y_H = 0$

(Hyper)charge quantization in the Standard model

SU(3) x SU(2) x U(1) gauge anomalies

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



SU(2)^2 U(1): $\quad 6Y_Q + 2Y_L = 0$

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

Yukawas: $\quad Y_{Dij}\overline{Q_{L}}_i\langle H\rangle D_{Rj} + Y_{Uij}\overline{Q_{L}}_i\langle\tilde{H}\rangle U_{Rj} + Y_{Eij}\overline{L_{L}}_i\langle H\rangle E_{Rj}$

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

$$-Y_Q + Y_U - Y_H = 0$$

Solution:

$$\boxed{\begin{array}{l} Y_Q = +\frac{1}{6}, \quad Y_U = +\frac{2}{3}, \quad Y_D = -\frac{1}{3}, \\ Y_L = -\frac{1}{2}, \quad Y_E = -1 \end{array}}$$

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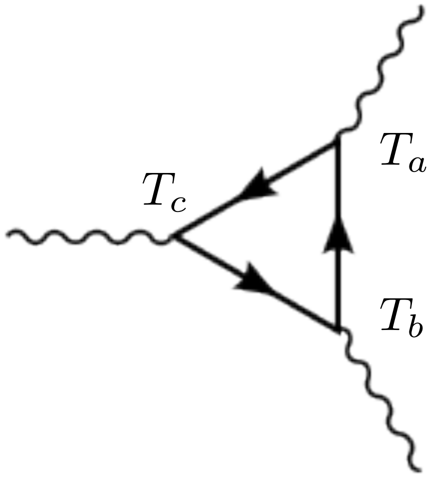
Assume Dirac neutrinos: $N_R = (1,1,Y_N)$



SU(2)[2] U(1): $6Y_Q + 2Y_L = 0$

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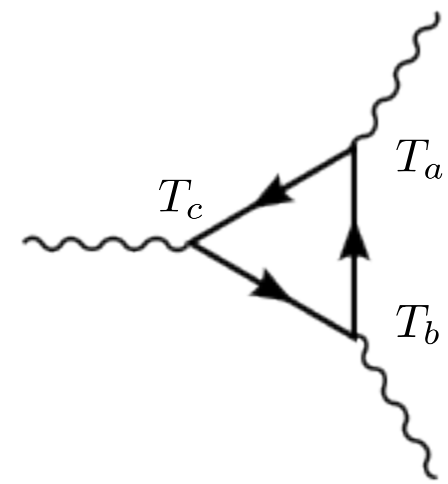

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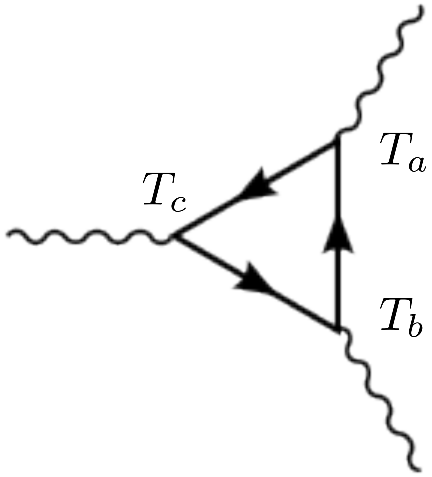

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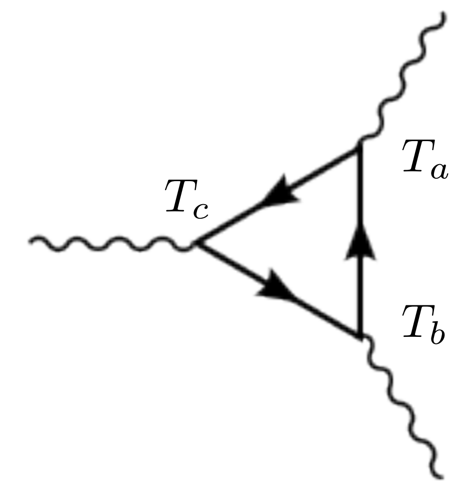

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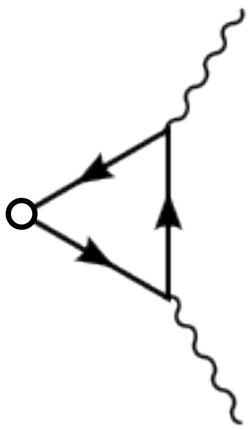
A simpler symmetry argument

B and L anomalies & RH neutrino

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



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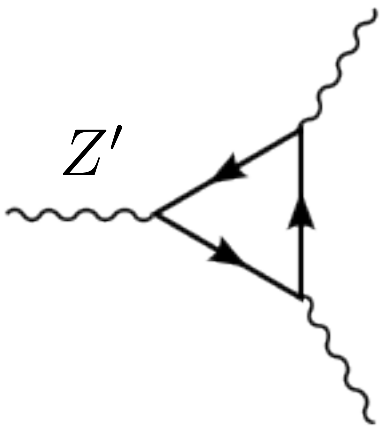

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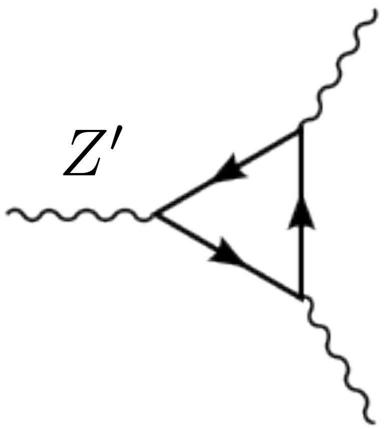

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"Fuzzy" hypercharge $\quad Y \to Y + \varepsilon(B-L) \qquad \varepsilon = -Y_N$

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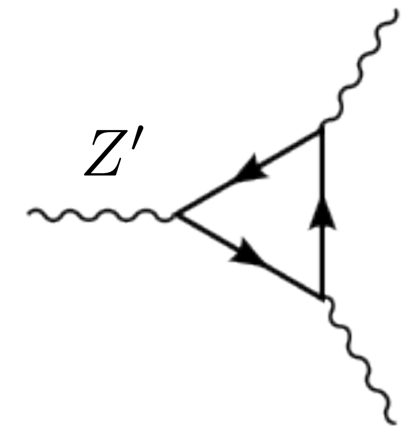

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Babu, Mohapatra, Phys.Rev. D41 (1990) 271

Foot, Lew, Volkas 1993

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

SM with massive neutrinos and quantized charges

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

E. Majorana 1937

Majorana neutrino mass = **perturbative L violation**

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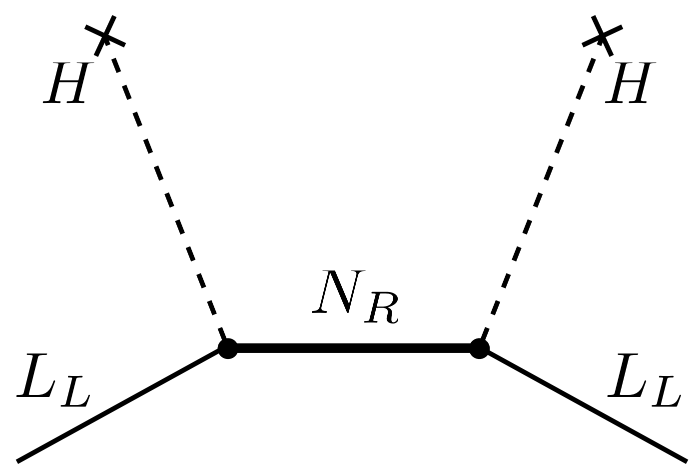
Seesaw:



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

Lepton number violation in oscillations

NB The first account of neutrino oscillations was indeed “L-violating”!

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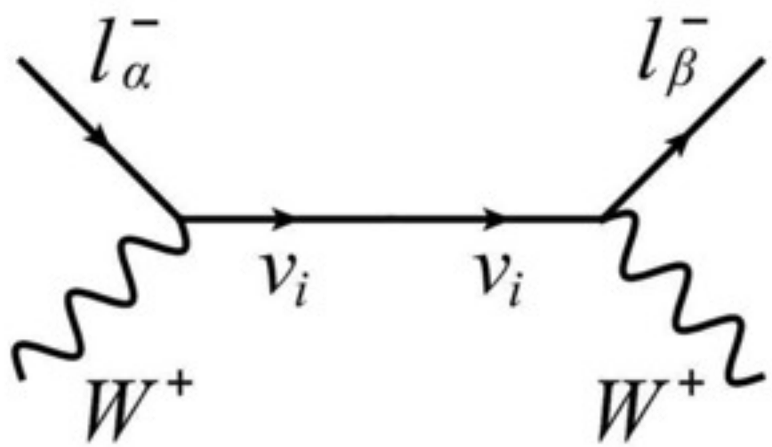

$$\mathcal{A}(\nu_\alpha \to \nu_\beta) \propto \sum_i U^*_{\alpha i} U^*_{\beta j} e^{-i\frac{m_i^2 L}{2E}}$$

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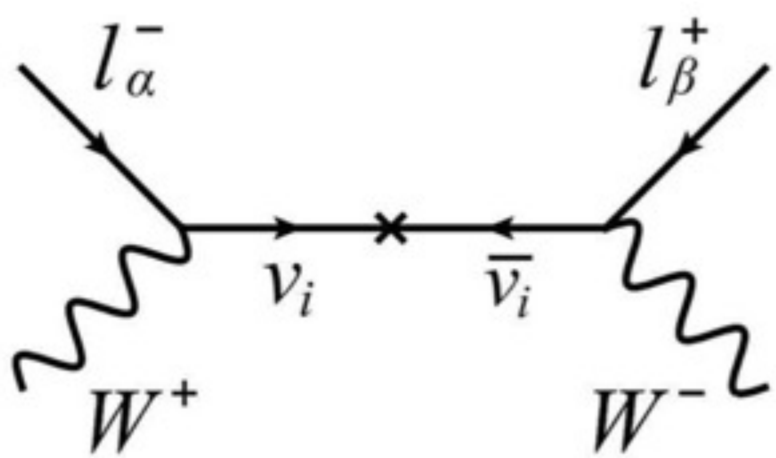

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suppressed...

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

SM as an effective theory

LNV in the SM at d=5 level

Weinberg's d=5 operator $\mathcal{L} \ni \frac{LLHH}{\Lambda}$ S.Weinberg, PRL43, 1566 (1979)

$$\boxed{\Lambda \sim (10^{12} - 10^{14})\ \mathrm{GeV}}$$

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

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

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}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	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

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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
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$(\bar{L}R)(\bar{R}L)$ 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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

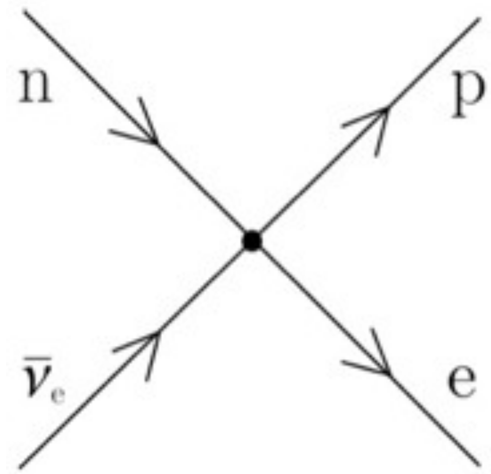
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	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 behind the SM d=6 BNV?

Let's do the same trick that Schwinger & co. played with the Fermi theory:

Elementary vertex:



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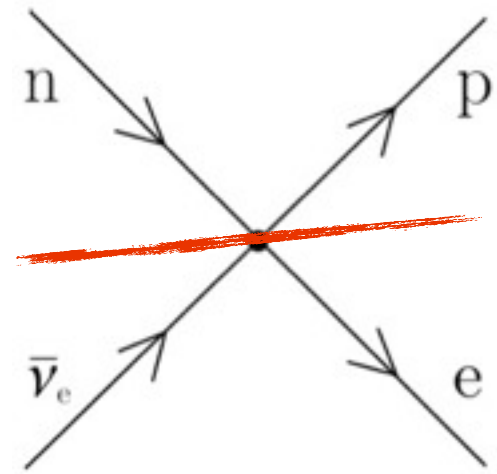
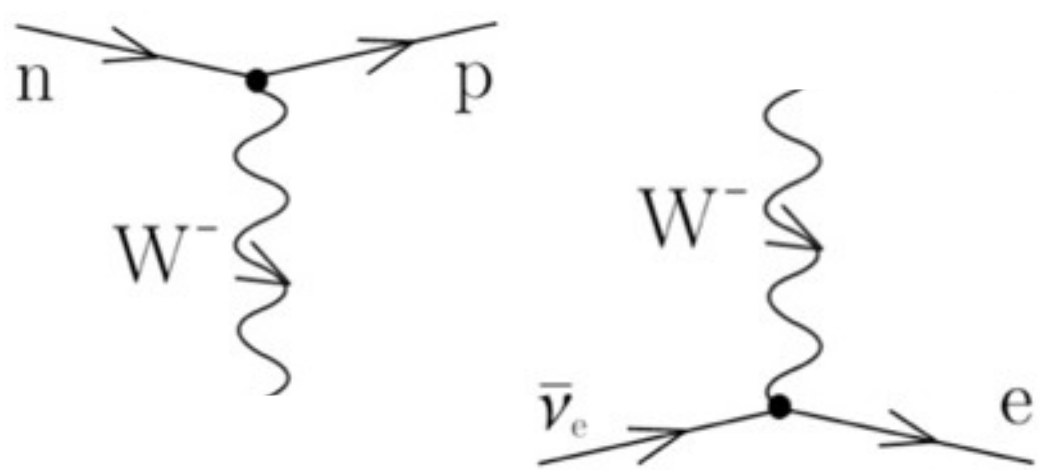
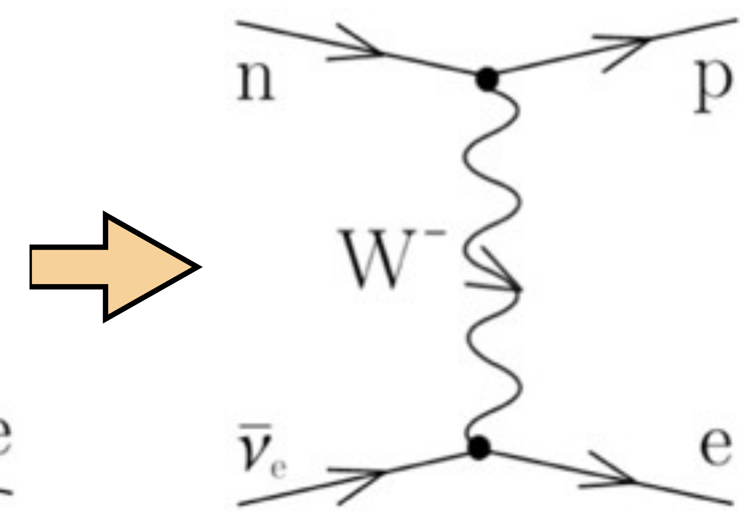


QED-like seed of
a renormalizable theory

Elementary vertices:





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Scalar exchange

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

Δ

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Fierz

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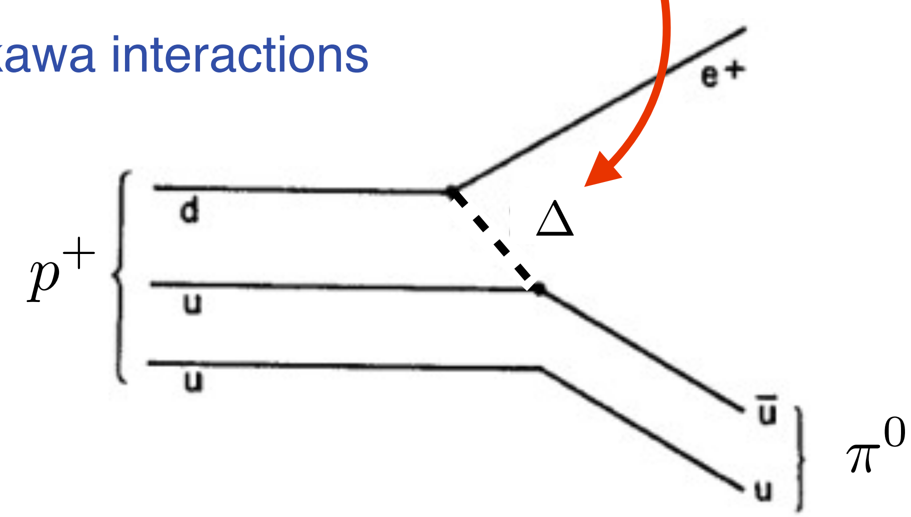
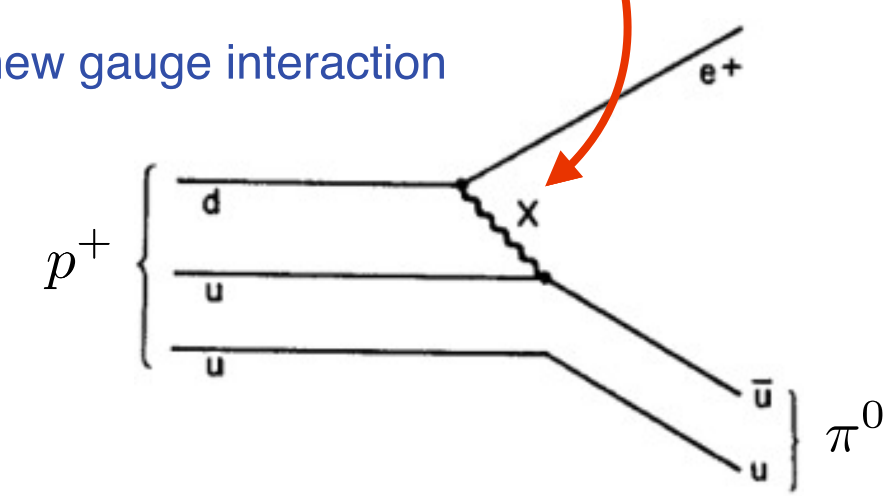
Proton instability:

new Yukawa interactions



new gauge interaction



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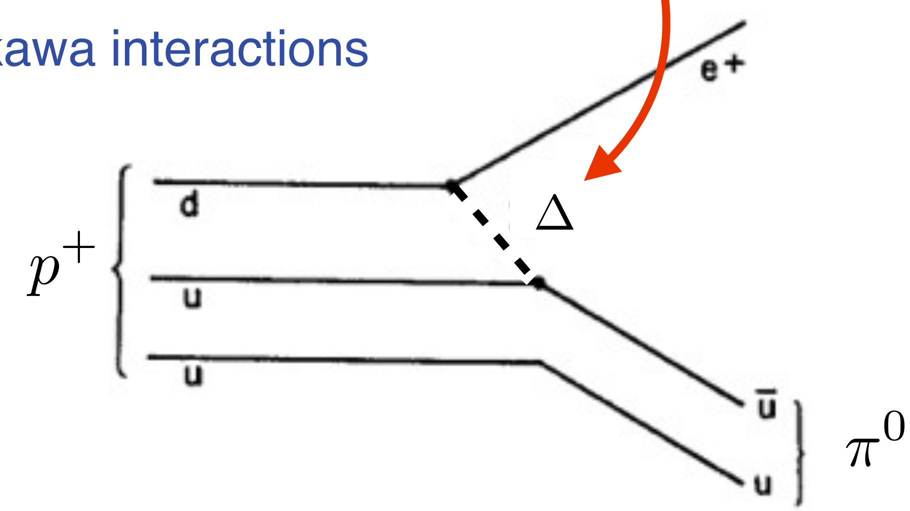

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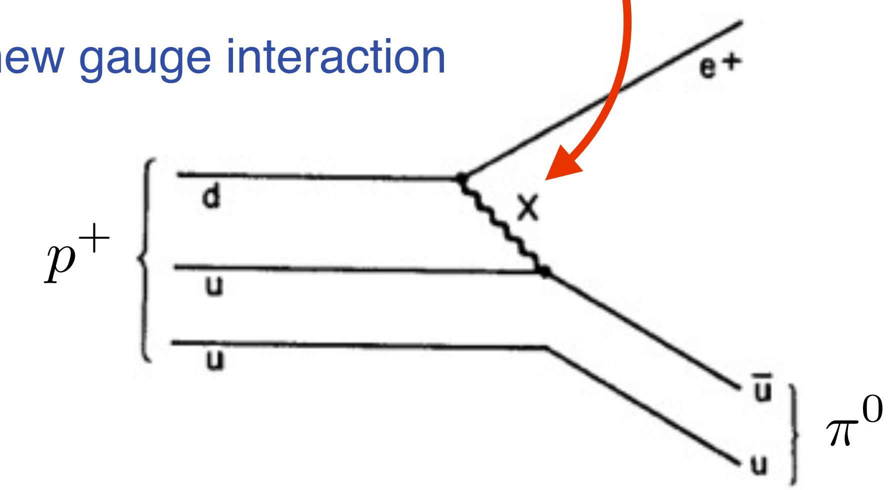

Useless without further info on the mediator masses and couplings...

Proton lifetime

experimental constraints I

First limits on proton lifetime

1950's - M. Goldhaber

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

"Tickle in the bones" argument...

NB. Lethal dose about $10^{14-15}\,\mathrm{MeV}/y$

First experiments

1954 - F. Reines, C.L. Cowan, M. Goldhaber

Reines, Cowan, Goldhaber, Phys. Rev. 96, 1157 (1954)

Experiment in Savannah River, SC

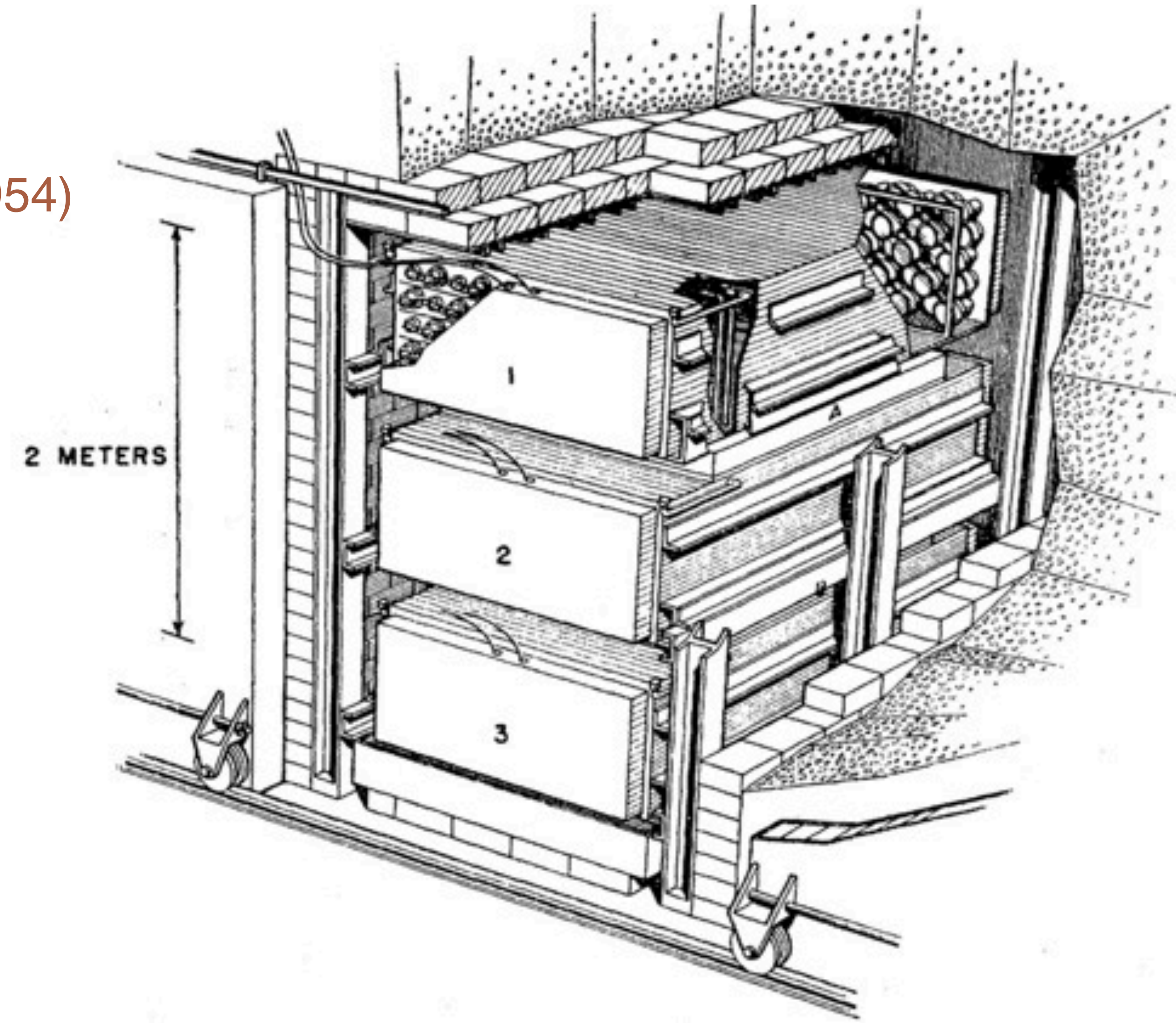

FIG. 2. Sketch of detectors inside their lead shield. The detector tanks marked 1, 2, and 3 contained liquid scintillator solution which was viewed in each tank by 110 5-in. photomultiplier tubes. The white tanks contained the water-cadmium chloride target, and in this picture are some 28 cm deep. These were later replaced by 7.5-cm deep polystyrene tanks, and detectors 1 and 2 were lowered correspondingly. A drip tank, not shown here, was later set underneath tank 3 in the event of a leak. Because of the weight it was necessary to move the lead doors with a hydraulic system.

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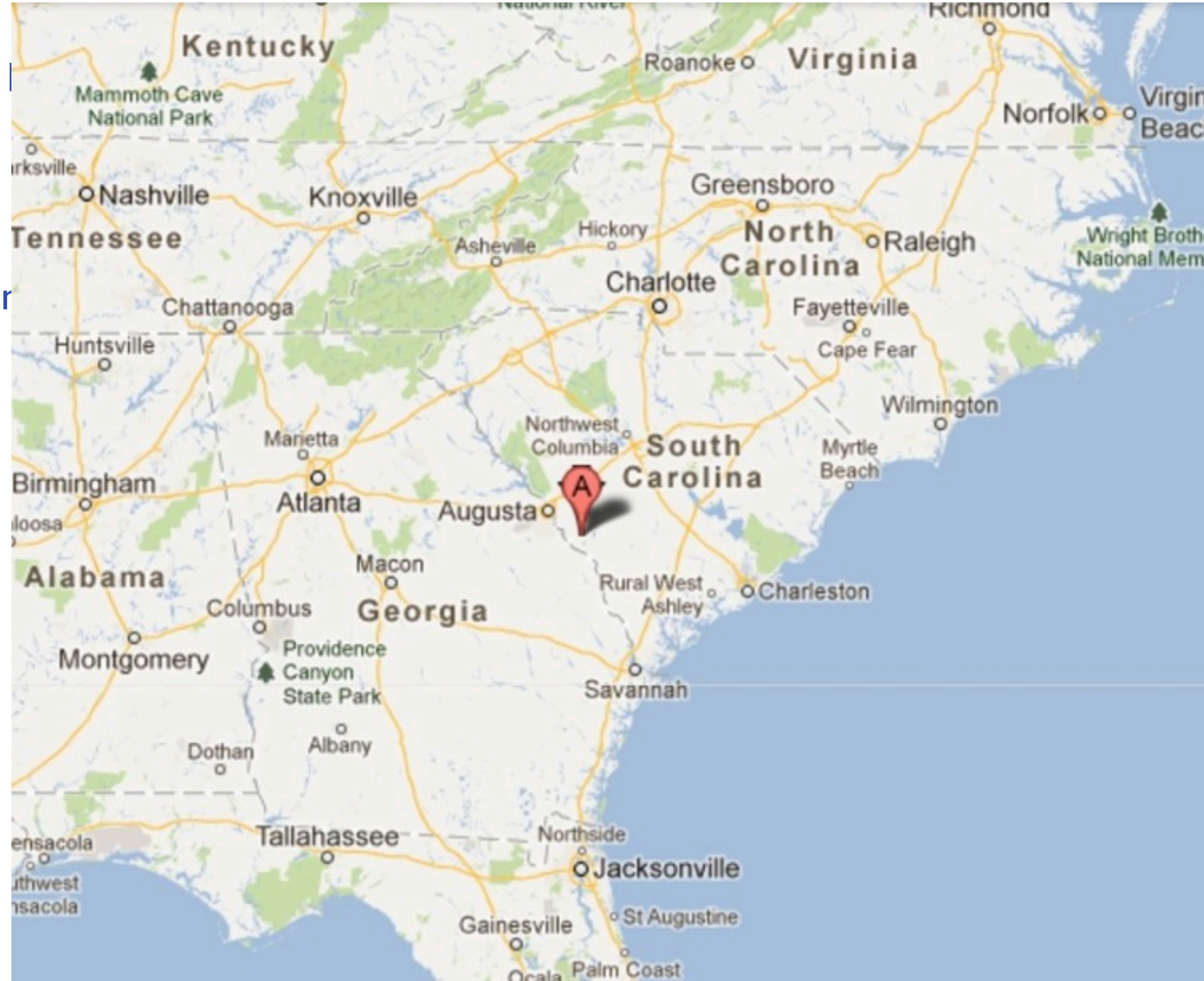
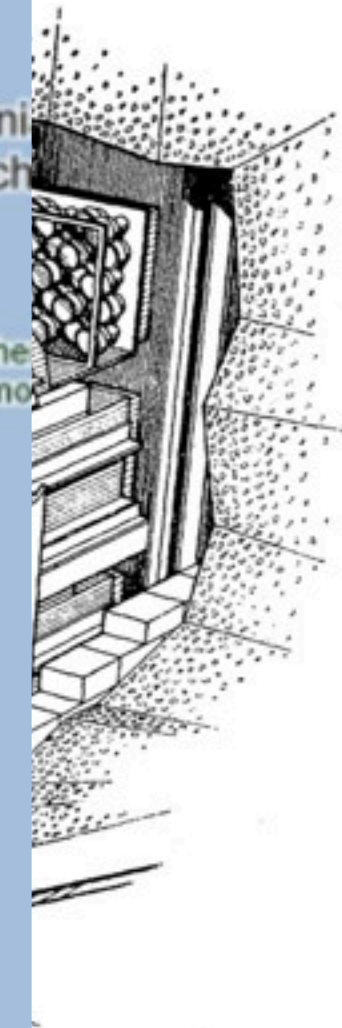
1954 - I

Reines,

Experir





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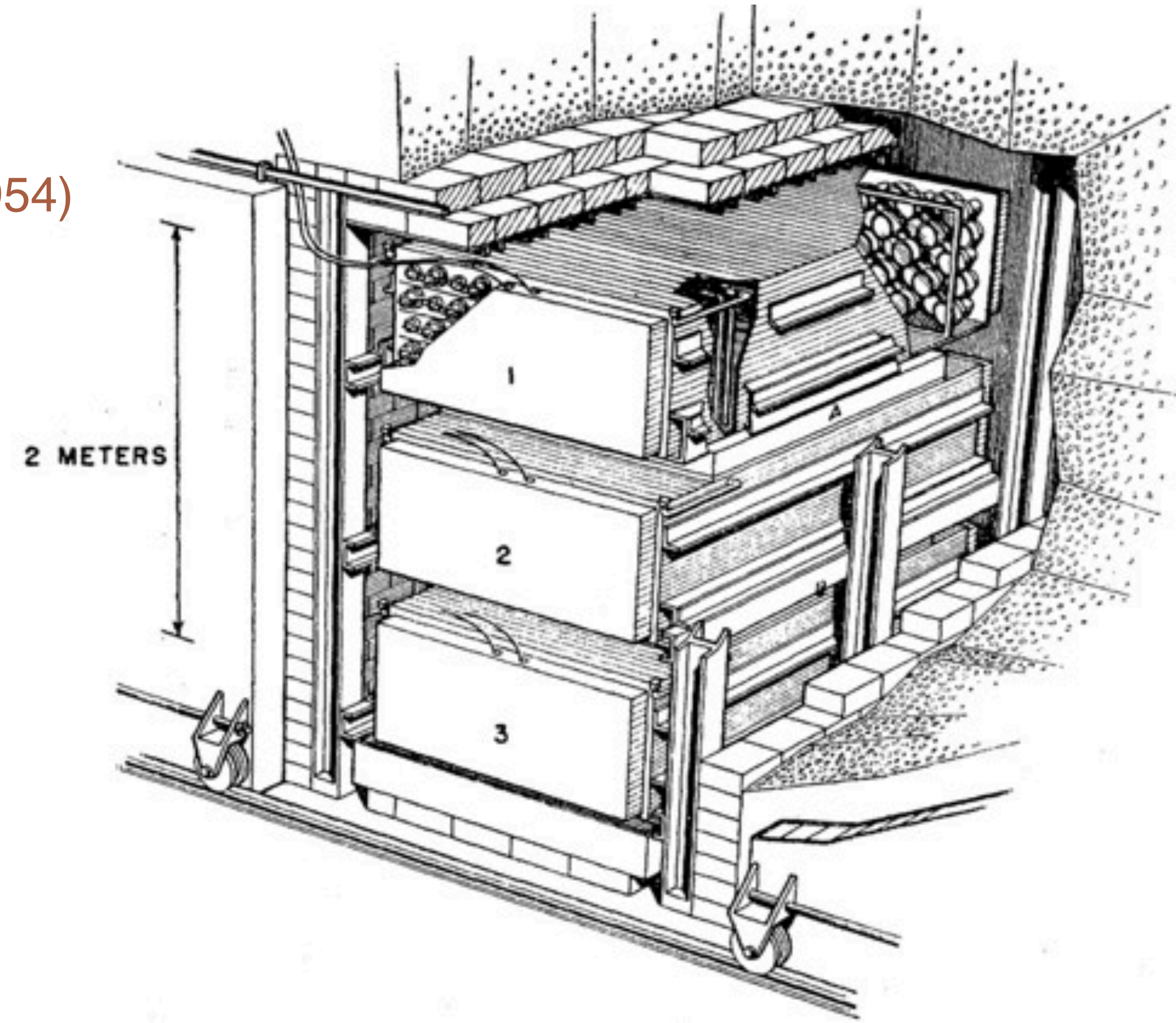
- detecting muons from inside the apparatus
- background about 6 Hz (30 meters)

$$\boxed{\tau(p^+) > 10^{21} y}$$



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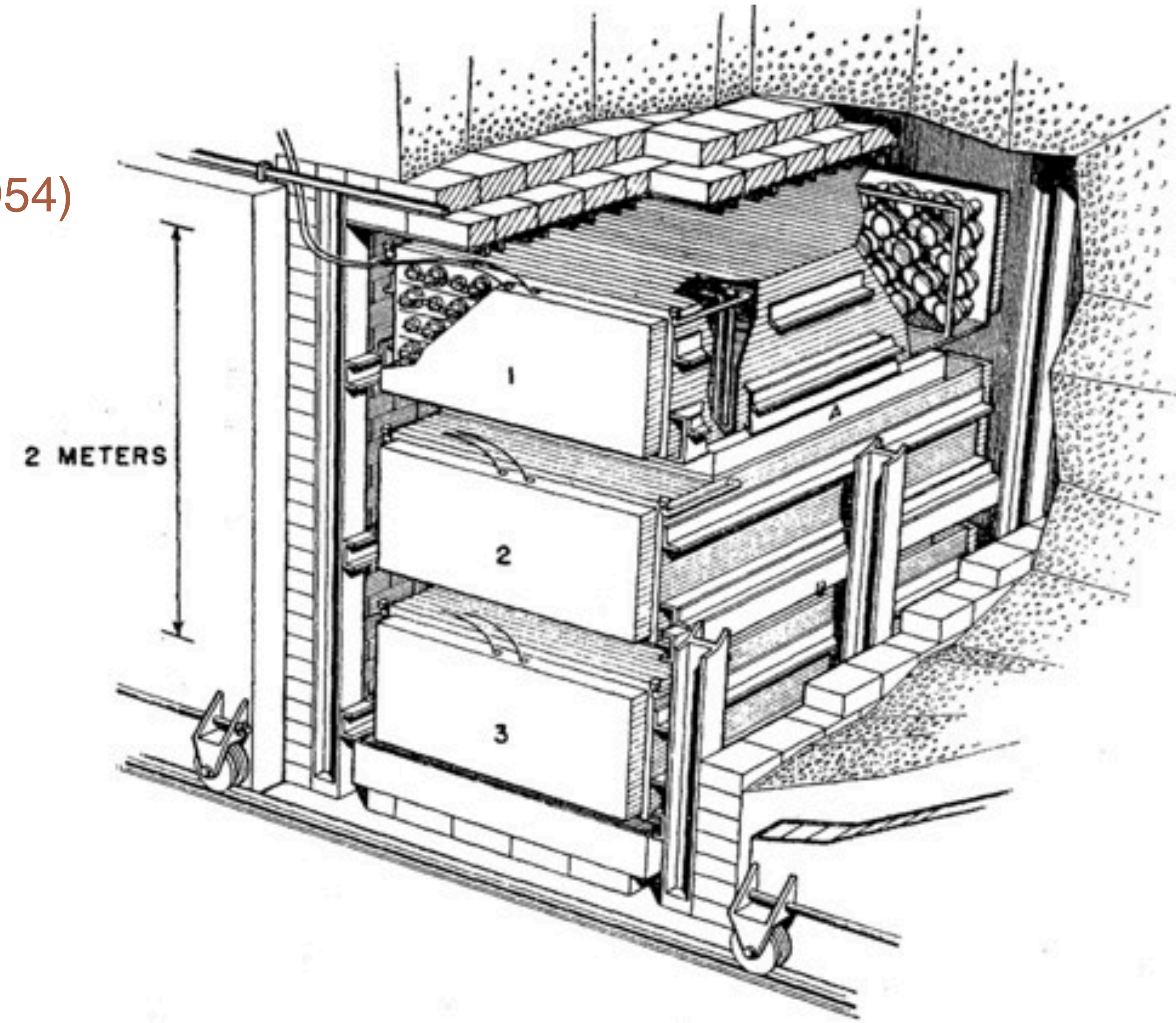
Neutrino discovery 1956 !

C.L. Cowan, F. Reines, F. B. Harrison, H.W. Kruse, A.D. McGuire, Science 124 (1956) 103-104



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3200 m deep!!!

muon background under control

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F. Reines, M. Crouch, PRL 32, 493 (1974)

F. Reines et al., PRD 4, 80 (1971)

1974 - F. Reines, M. Crouch et al.

- primarily a detector of atmospheric neutrinos

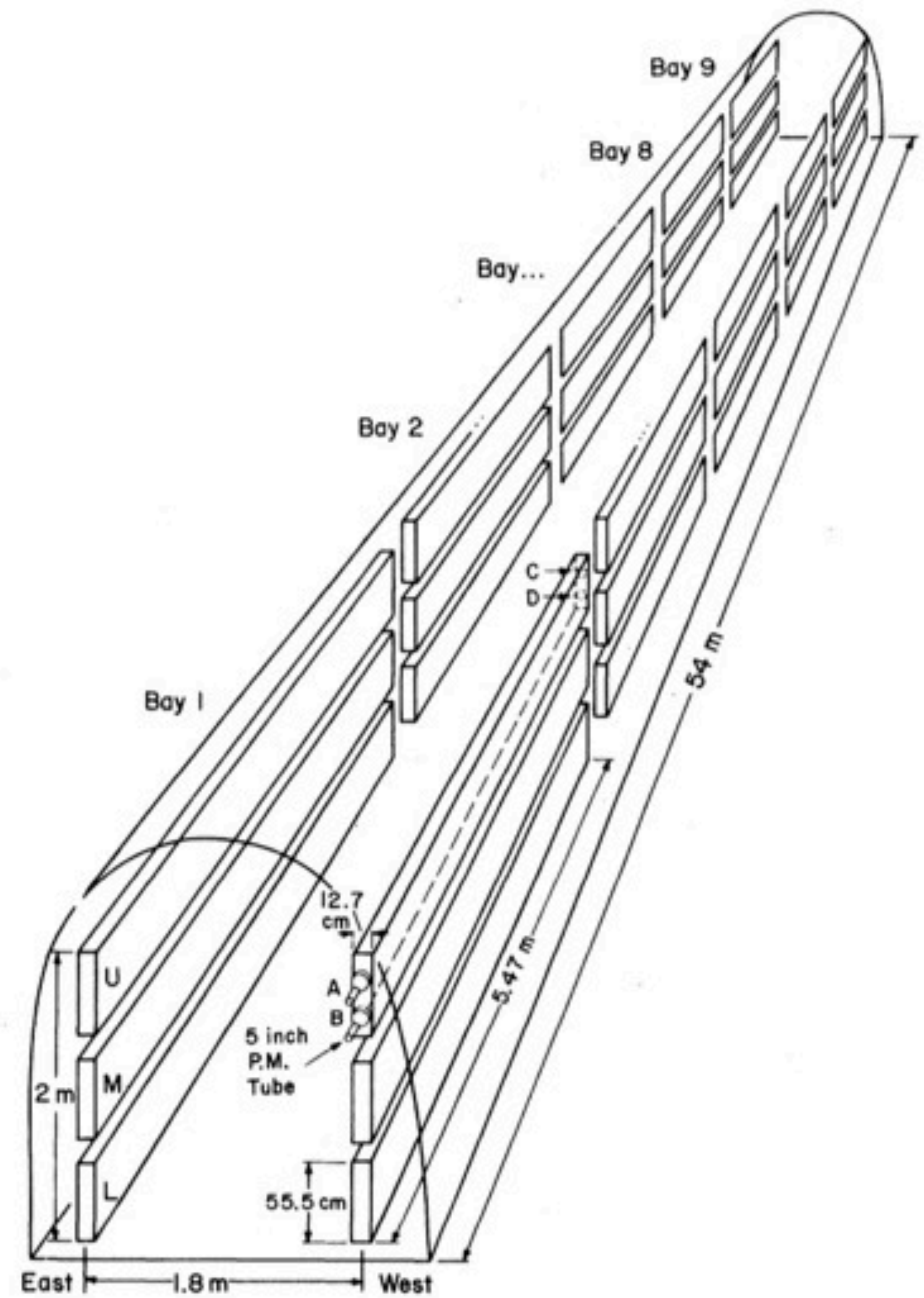

FIG. 1. Sketch of the detector array. Approximate array and element dimensions are given.

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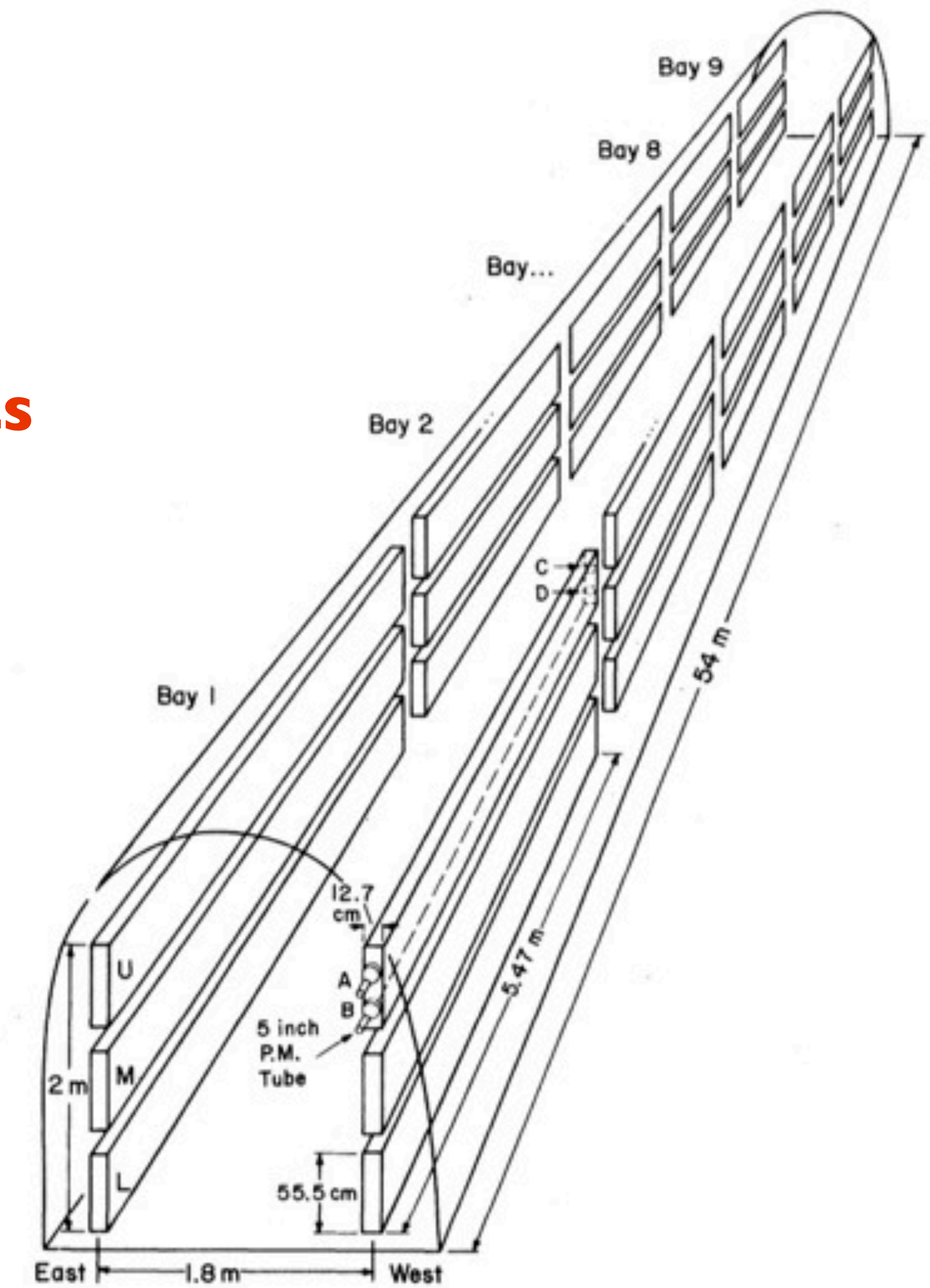
- p-decay signal = horizontal muon events

- exp. from atmospheric neutrinos: few/year

- atmospheric muon background suppressed: 10^{-9}



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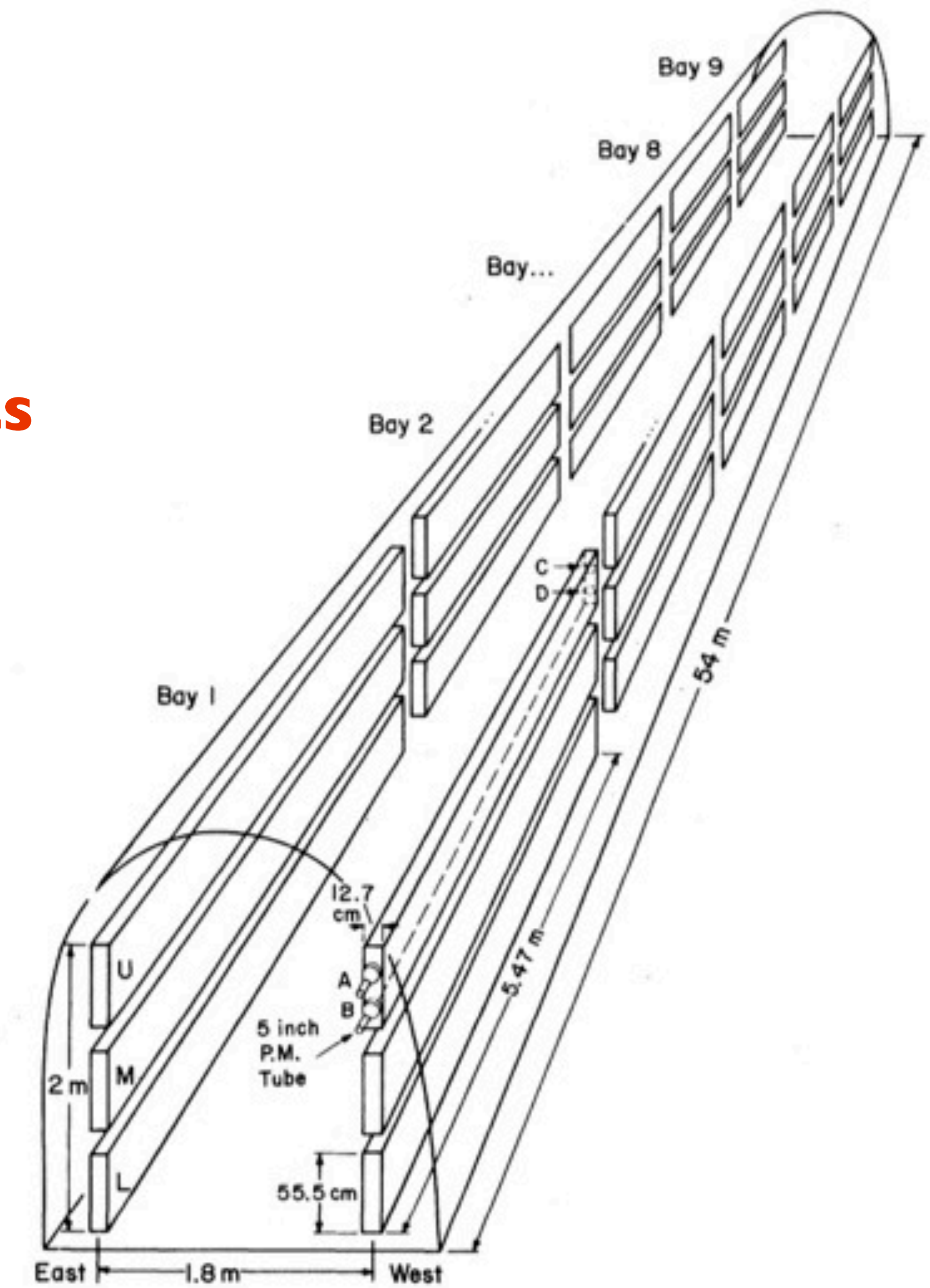
- p-decay signal = horizontal muon events

- exp. from atmospheric neutrinos: few/year

- atmospheric muon background suppressed: 10^{-9}

- compatibility with purely neutrino events:

$$\boxed{\tau_p \gtrsim 10^{30}\ \mathrm{yr}}$$



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1974

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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\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} \\
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$(1,1,+1)$ e^c μ^c

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

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

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The minimal SU(5) GUT

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

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

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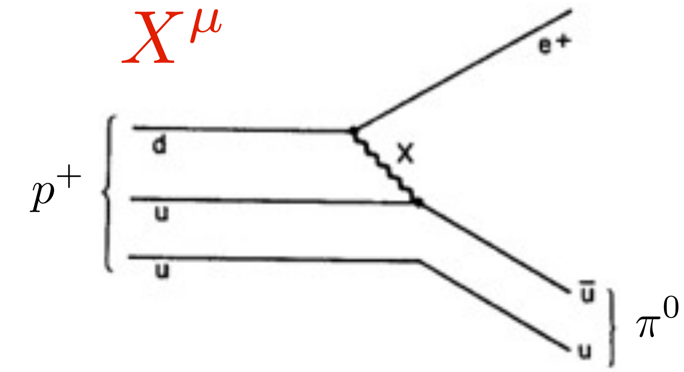

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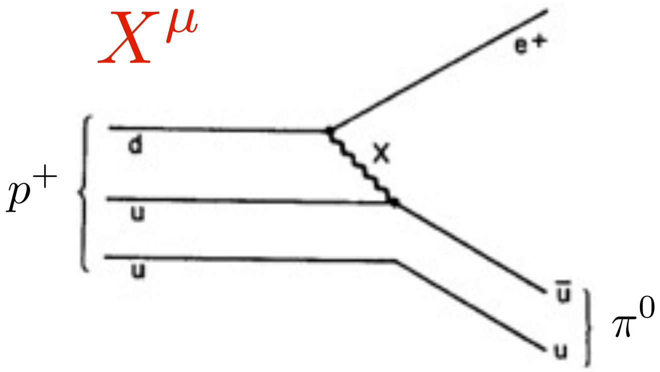

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$H \qquad \Delta$

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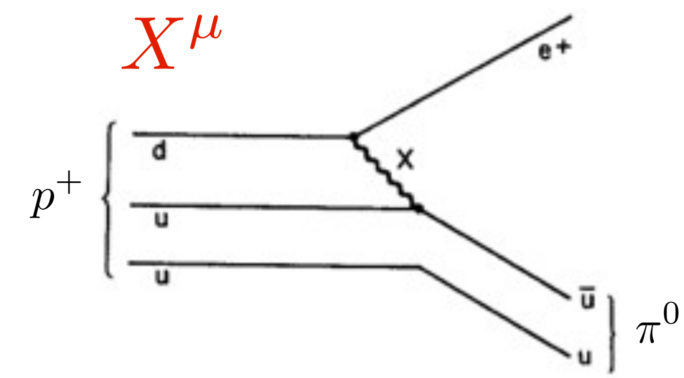

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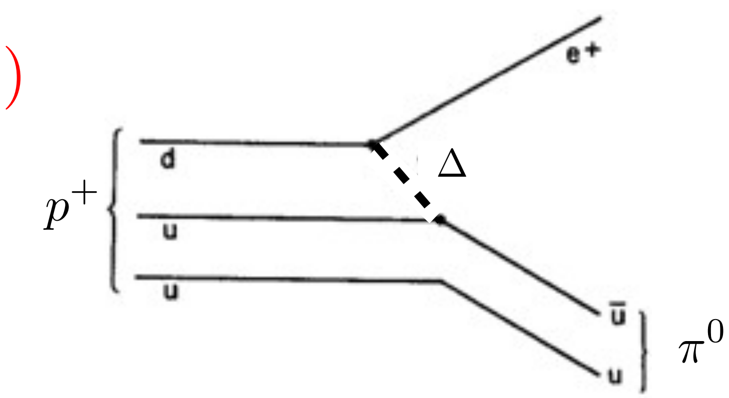

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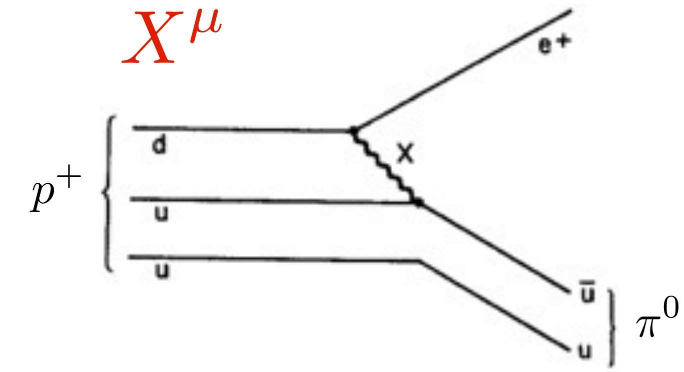

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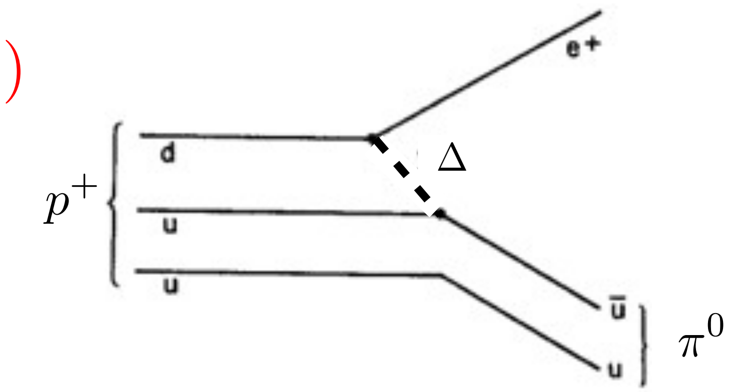
$H \qquad \Delta$



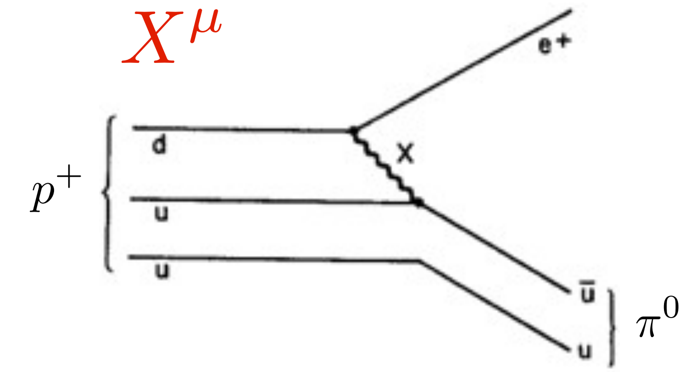
GUT-breaking scalars: $SU(5) \to SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

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

Gauge sector:

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

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



Scalar sector:

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

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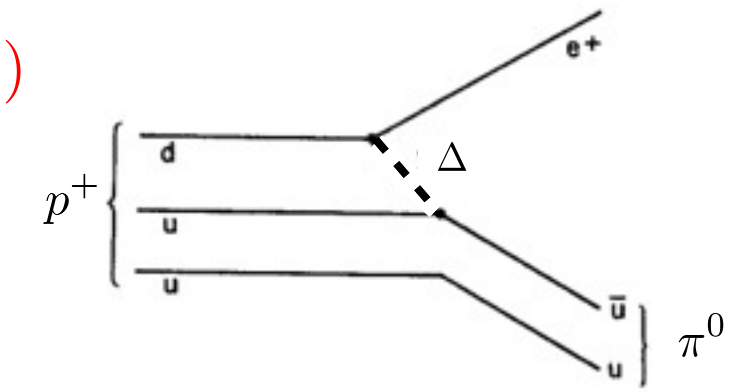

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Pure group theory, no dynamical picture **yet**...

SM running gauge couplings

SM running couplings

Running gauge couplings in the SM:

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

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

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)

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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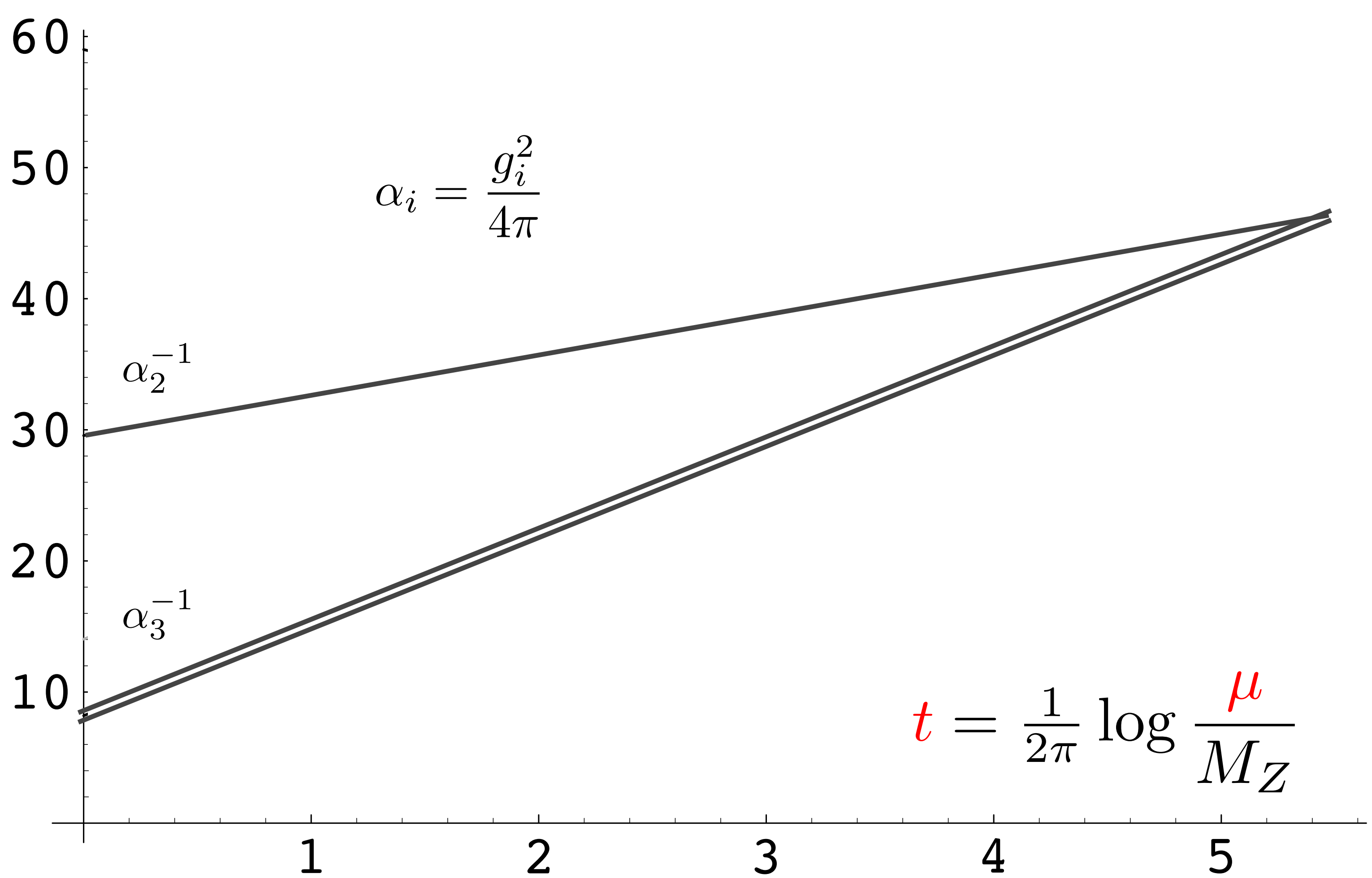

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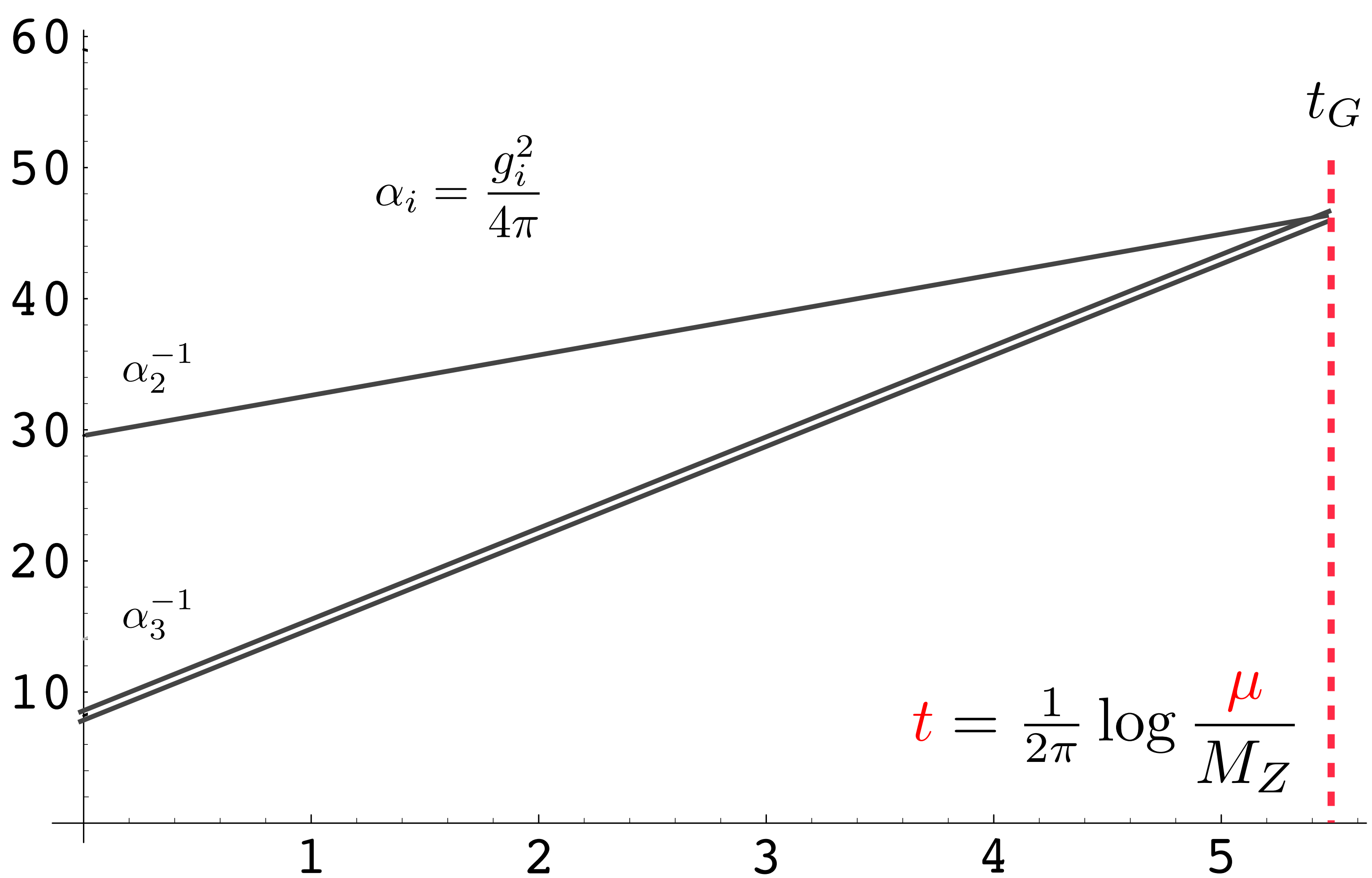

$M_G \sim 10^{16}\mathrm{GeV}$

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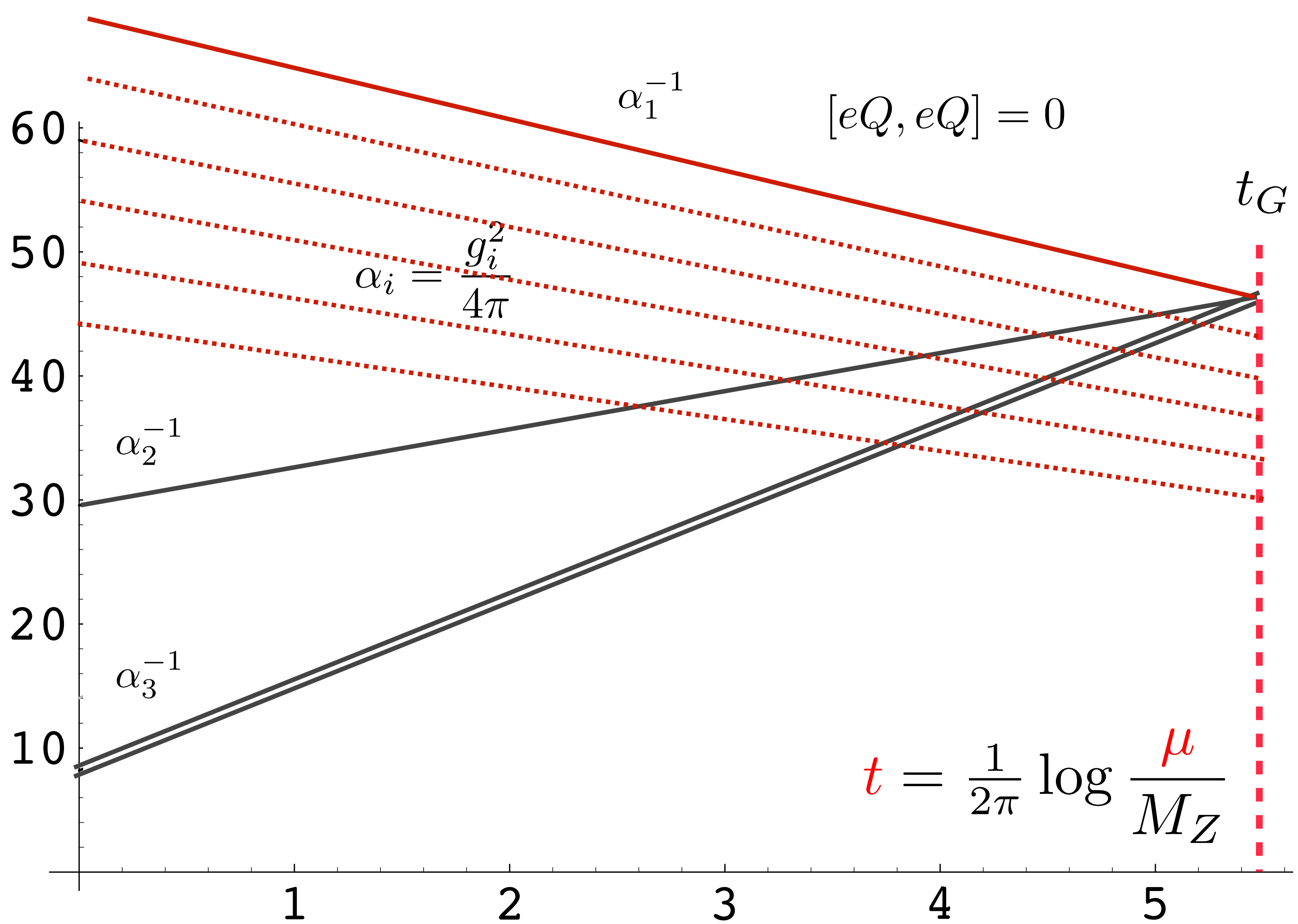

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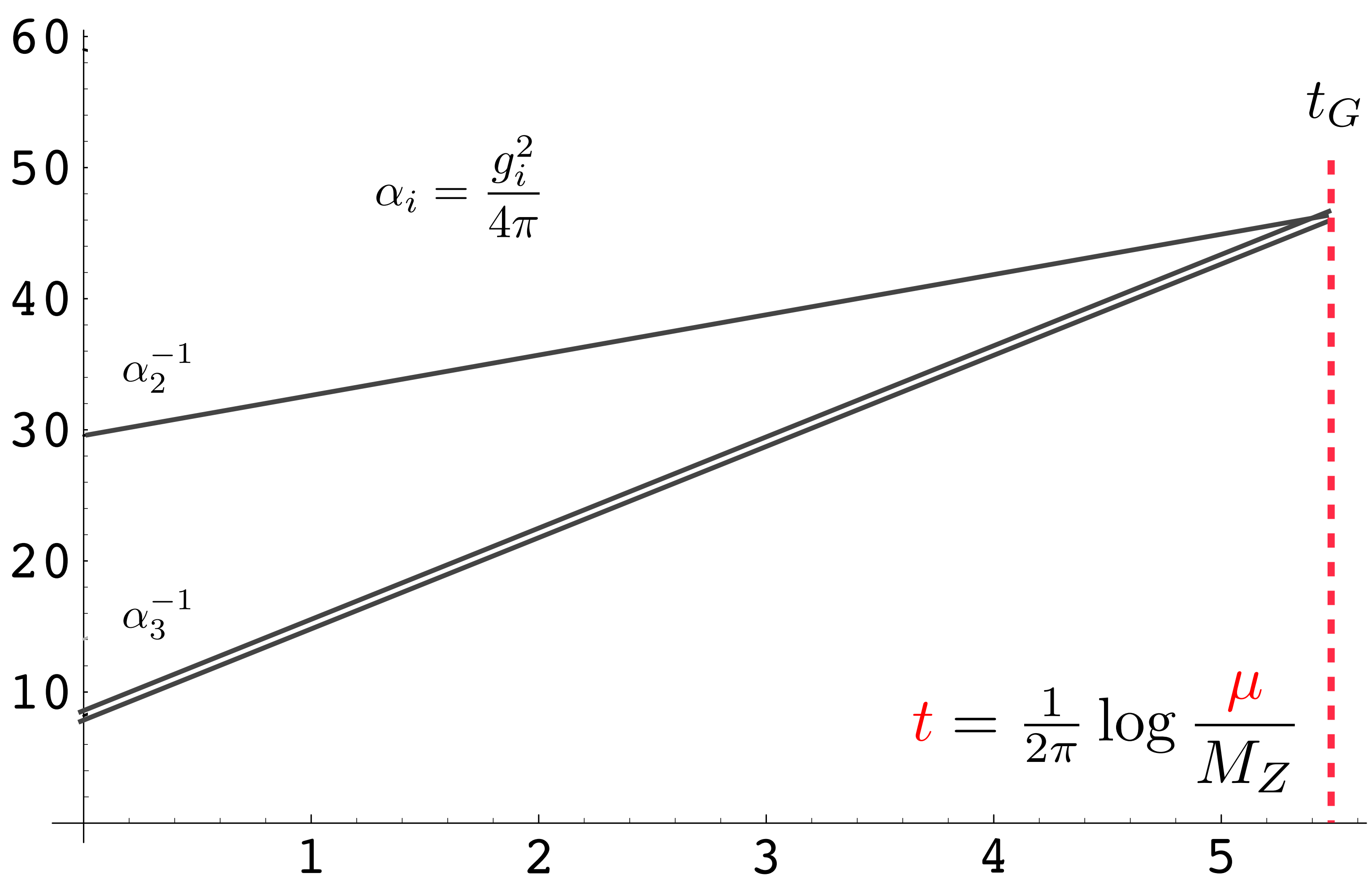

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Running gauge couplings in the SM

d=6 BNV mediators

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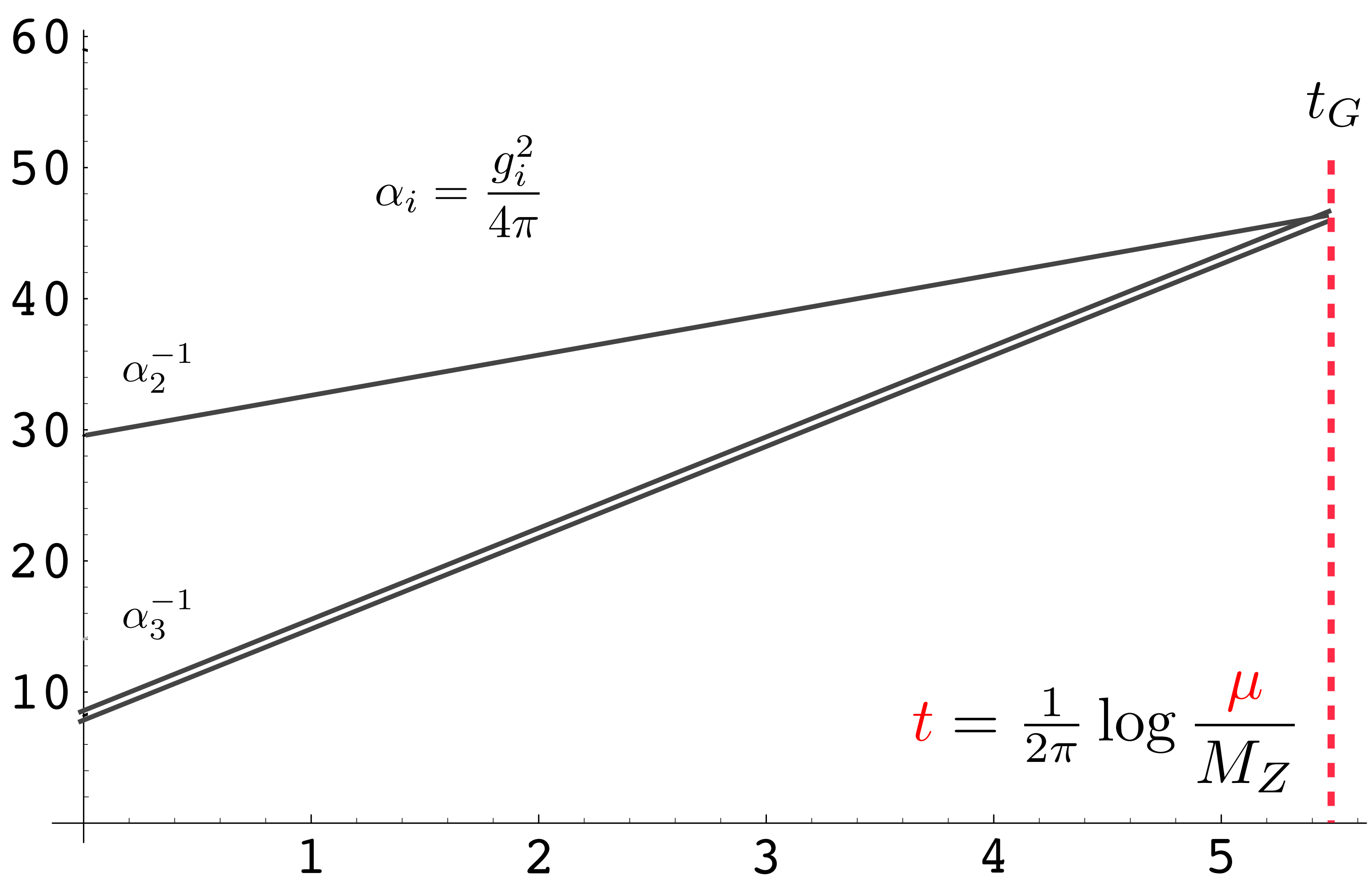

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Running gauge couplings in the SM $+X+\Delta$ d=6 BNV mediators

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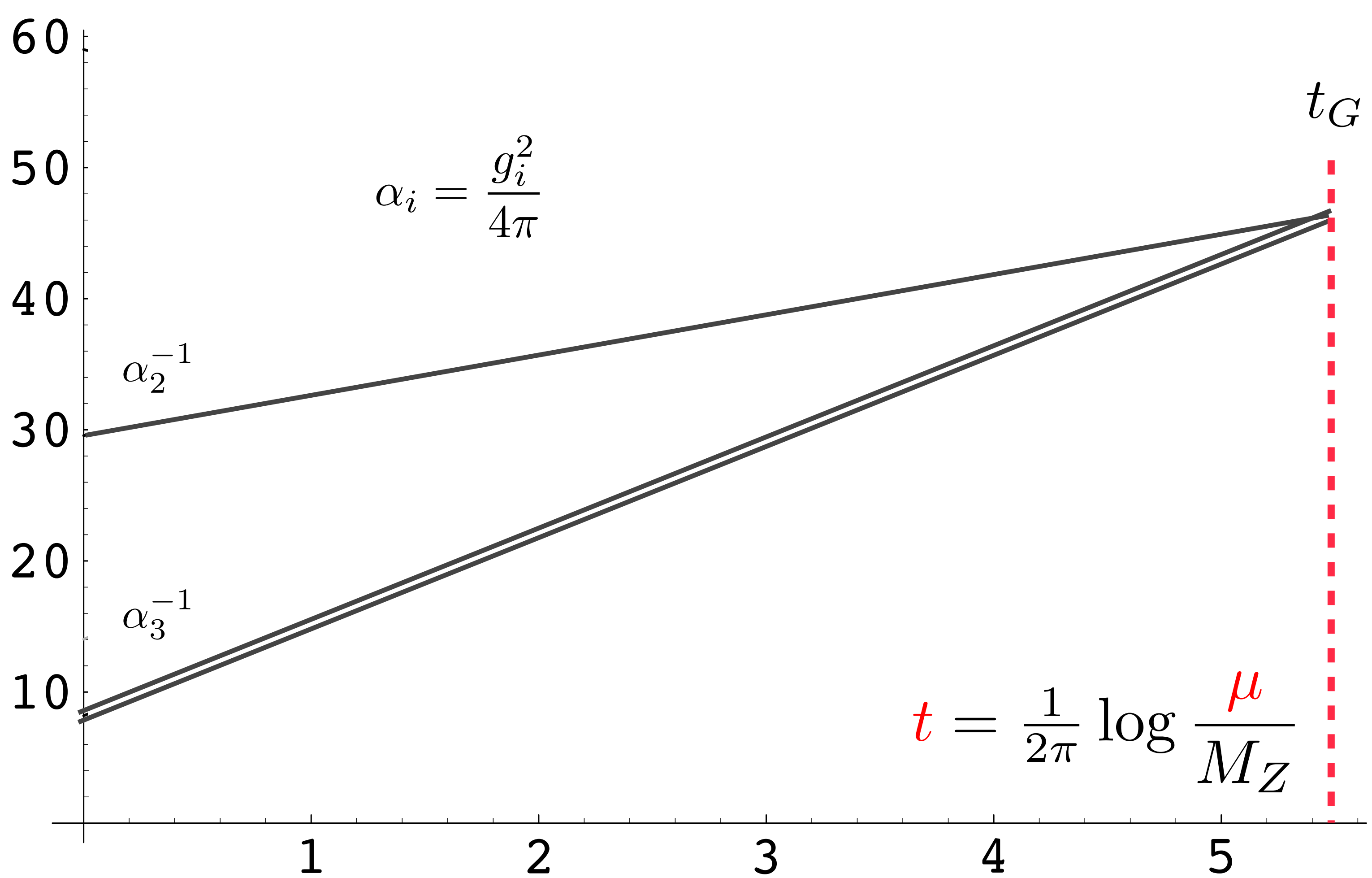
$(3,2,-\frac{5}{6})\oplus h.c.$ $\quad$ $(3,1,-\frac{1}{3})$



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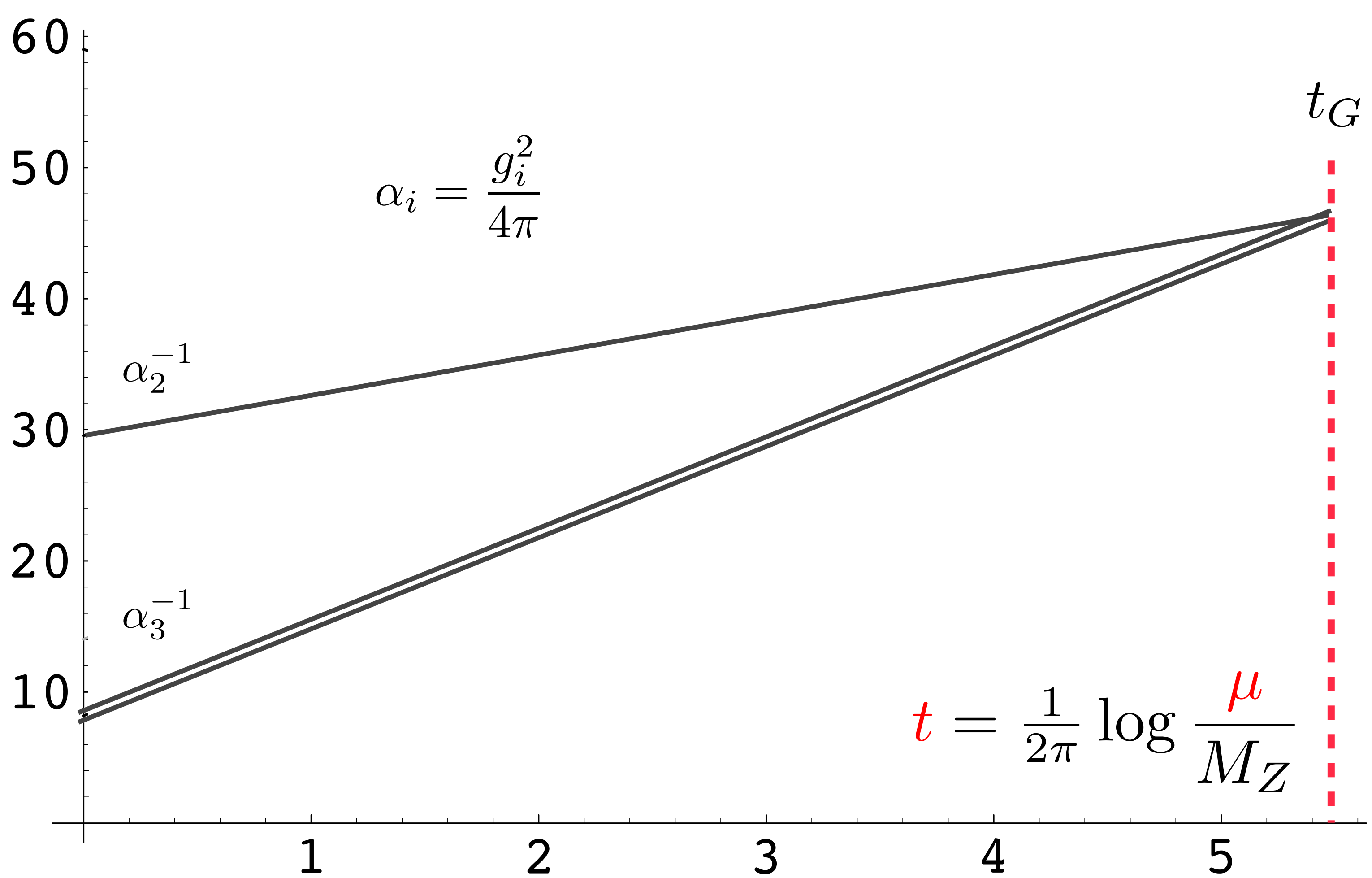

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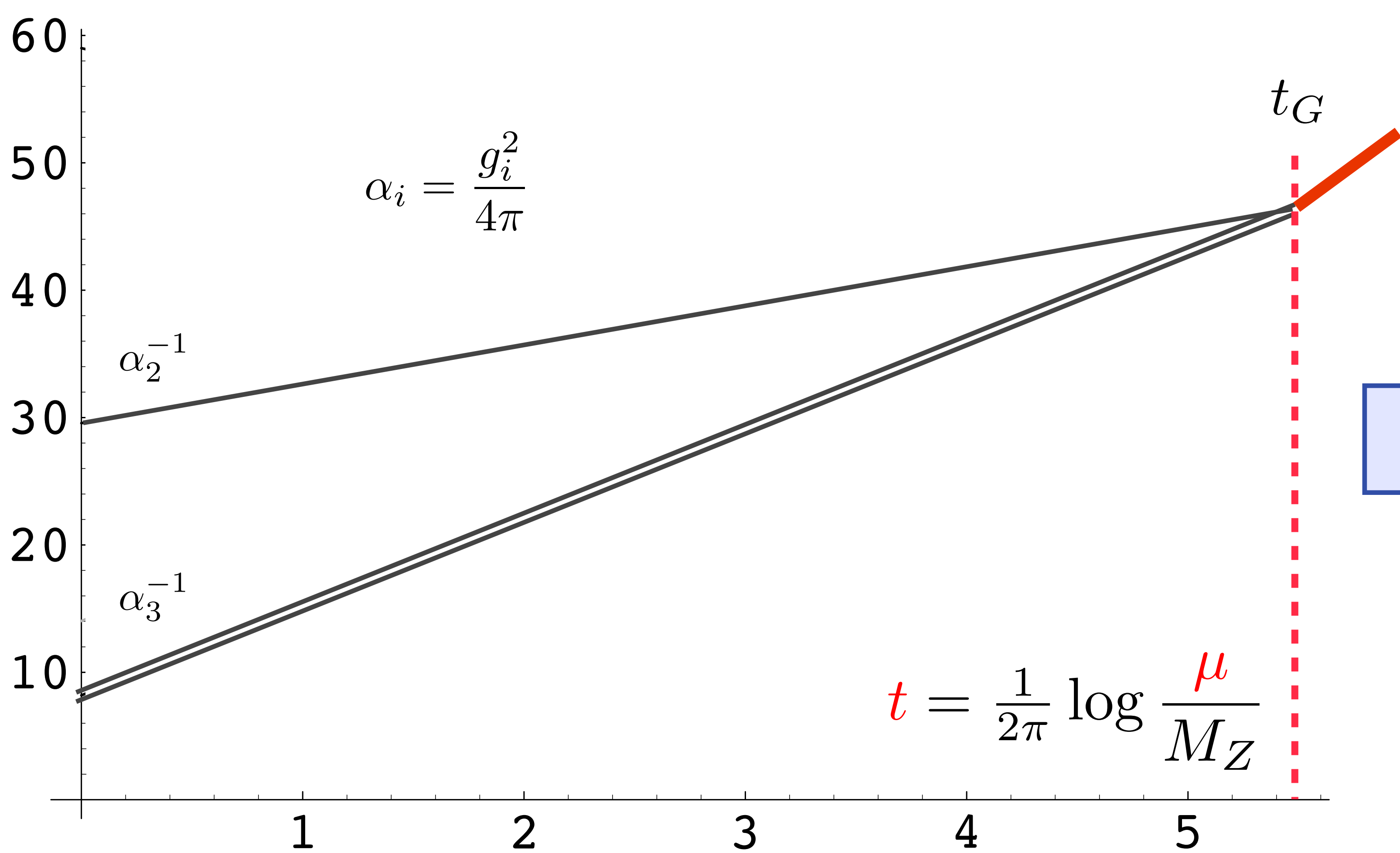

single gauge coupling like in an asymptotically free gauge theory with a **simple gauge group**

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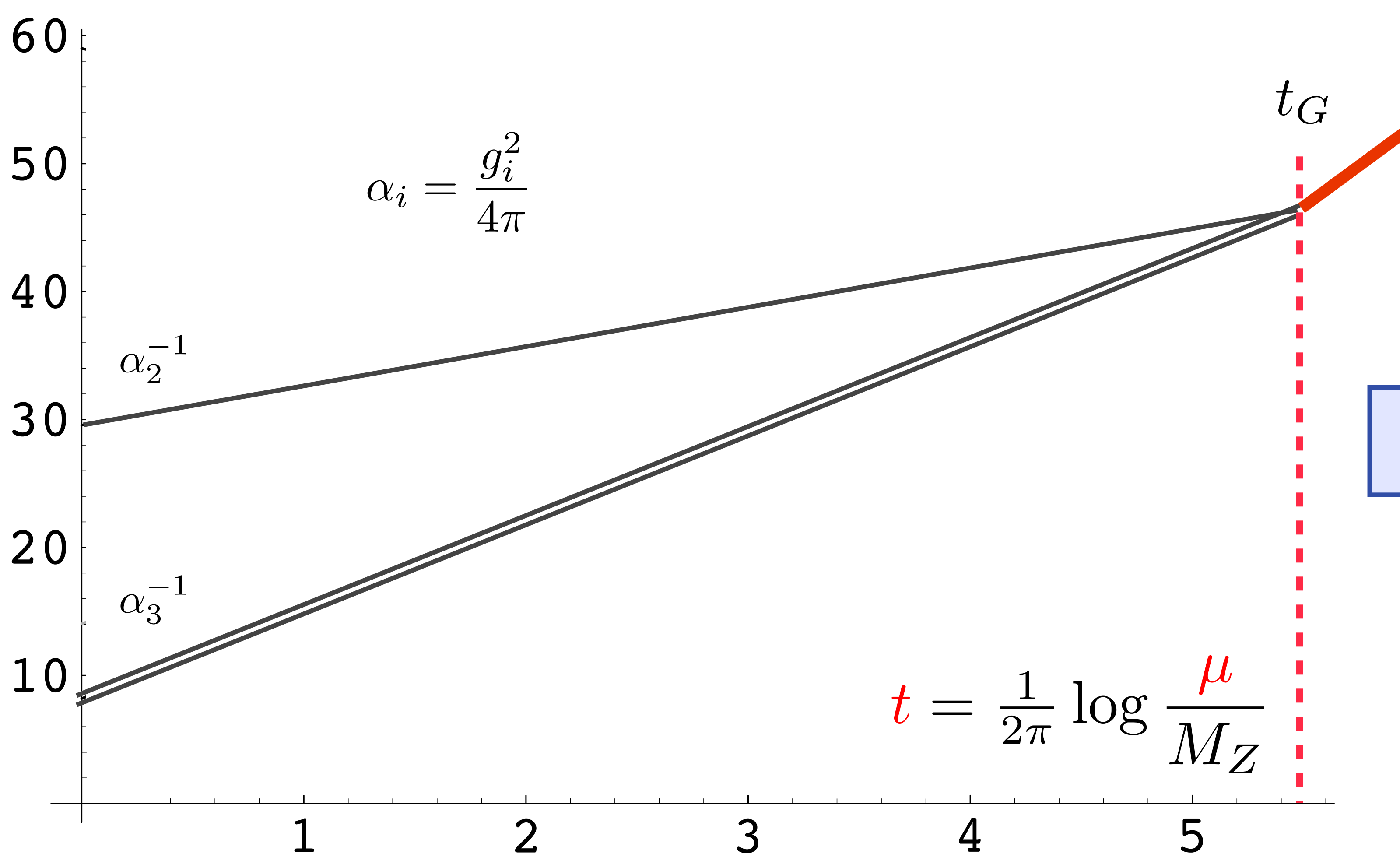

single gauge coupling like in an asymptotically free gauge theory with a **simple gauge group**

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

this tells the mediator scale and the gauge coupling!!!

Proton lifetime

experimental constraints II

Proton decay searches II

The proximity of the GQW result and the Reines, Crouch et al. limit:

$$\Gamma_p \sim \frac{m_p^5}{M^4} \lesssim (10^{30}\mathrm{y})^{-1}$$ corresponds to M ~ 10^{15} GeV !!!

Proton decay searches II

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This triggered a proton decay rush!

ASCENDING CHILCOOT PASS, MAY, 1898.

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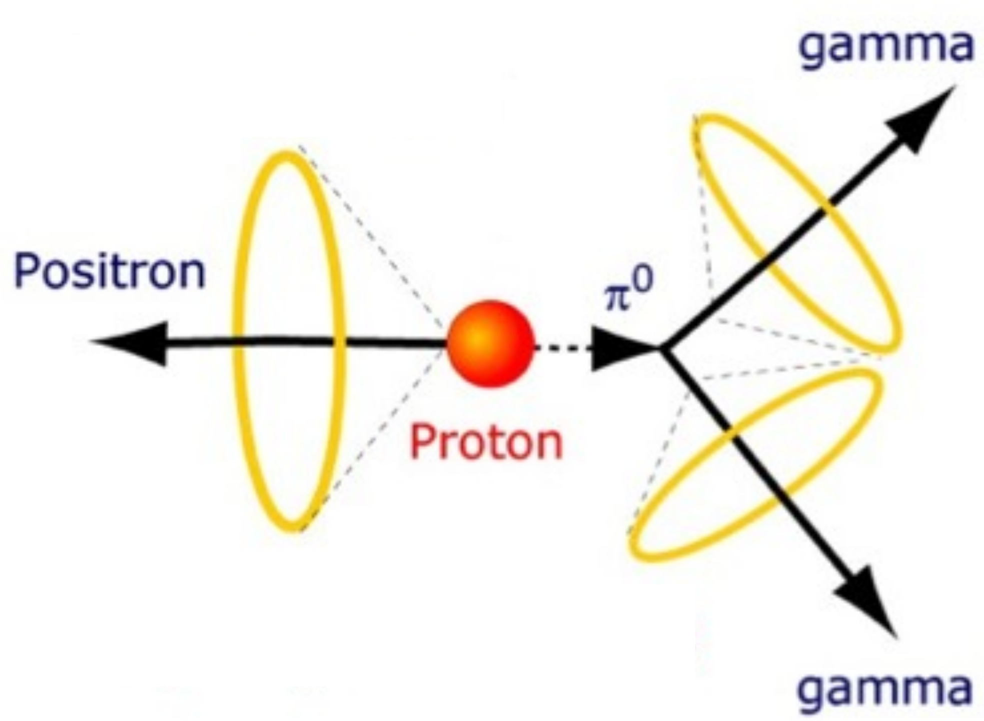
Proton decay in water

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

$\pi^0 \to 2\gamma$

$p_\pi = p_e = 459$ MeV

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



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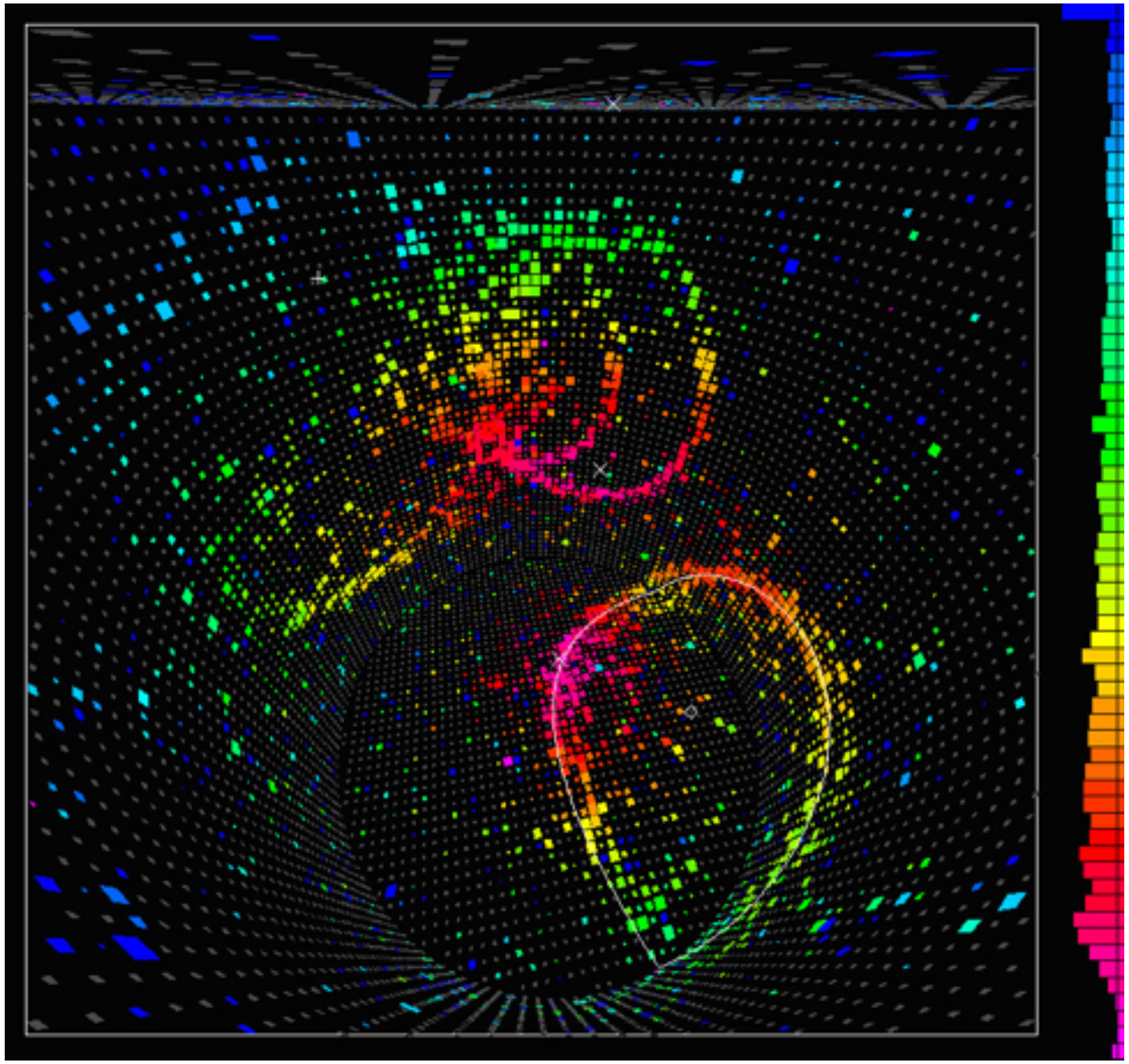

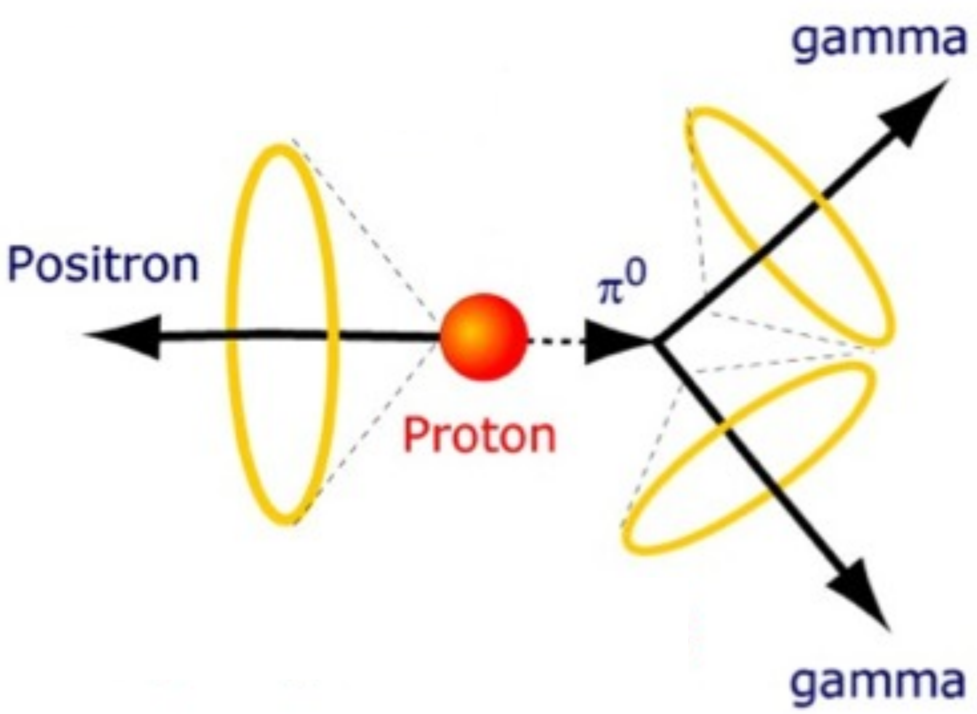

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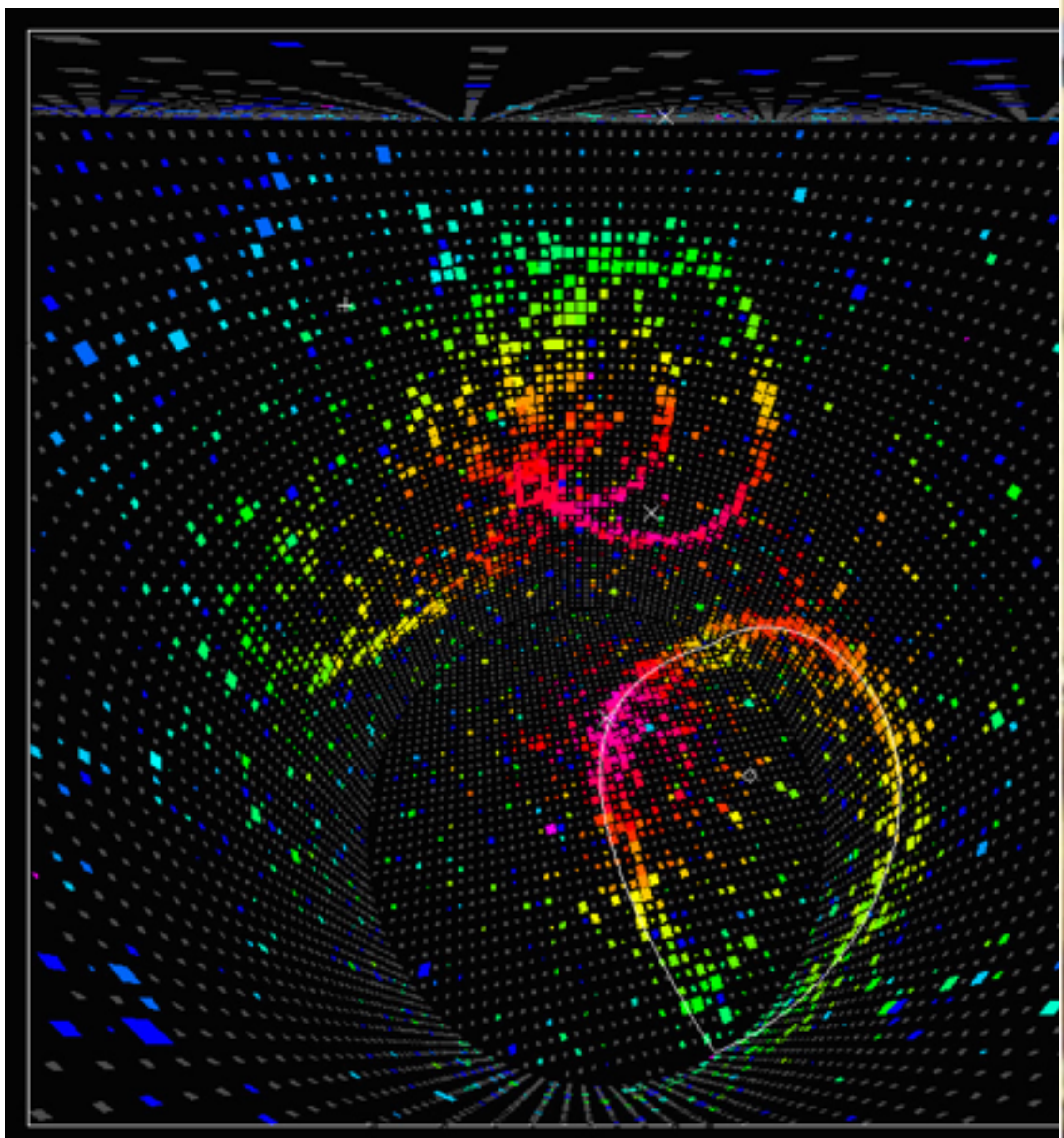

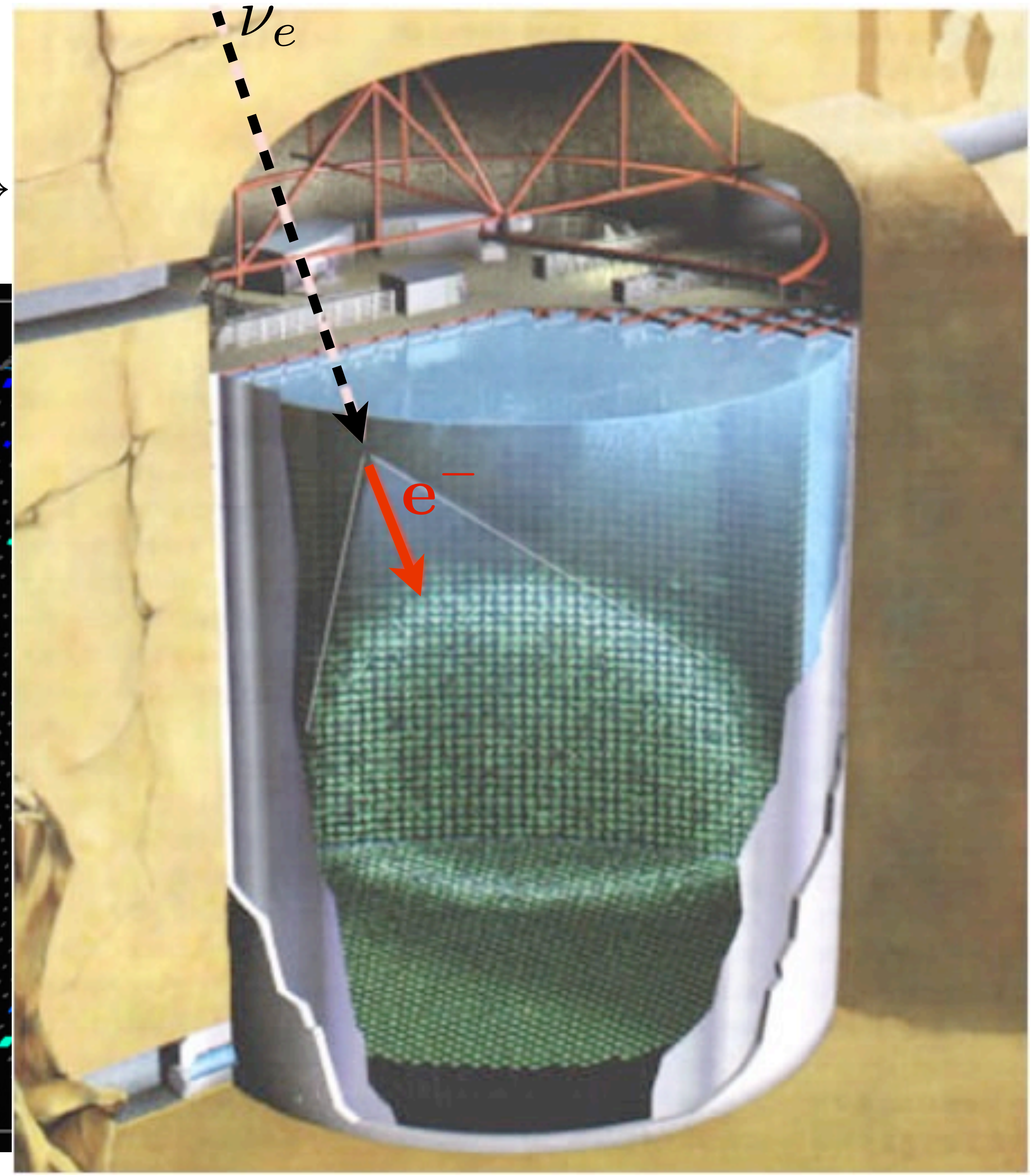

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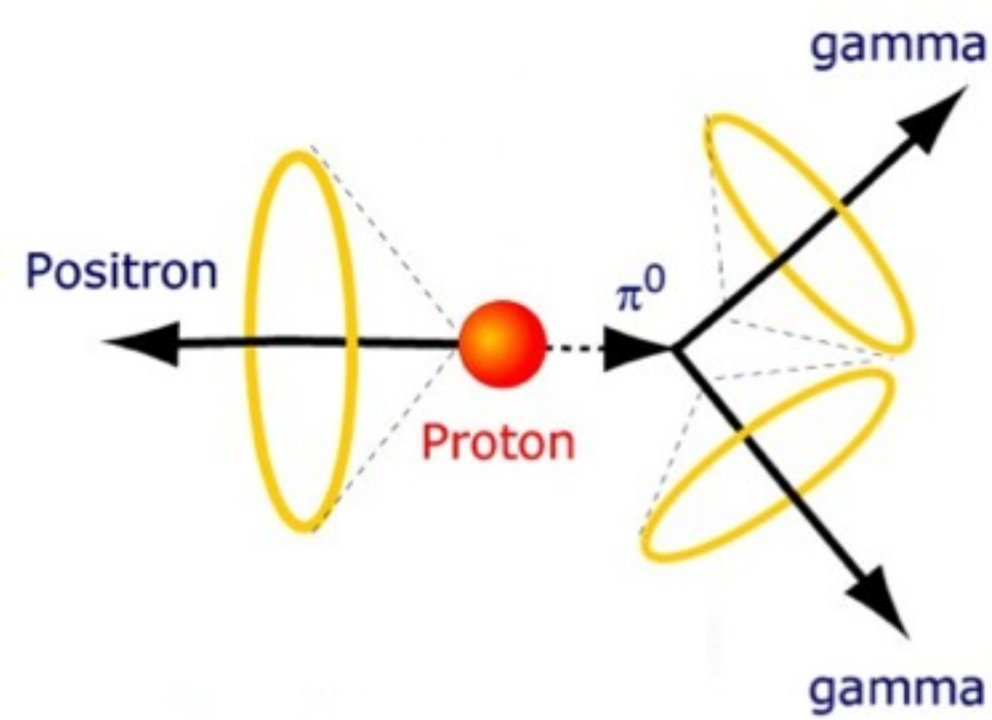
Main background: $\nu N \to N e^+ + \#\pi$ inelastic CC scattering of atmospheric neutrinos



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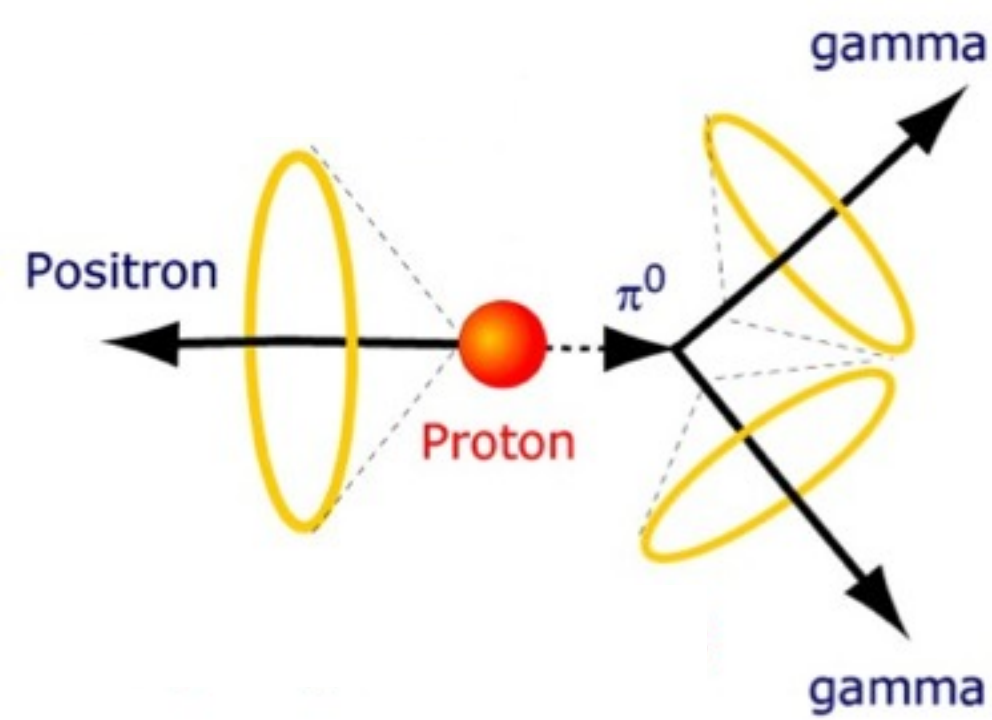
Other complication - nuclear effects

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



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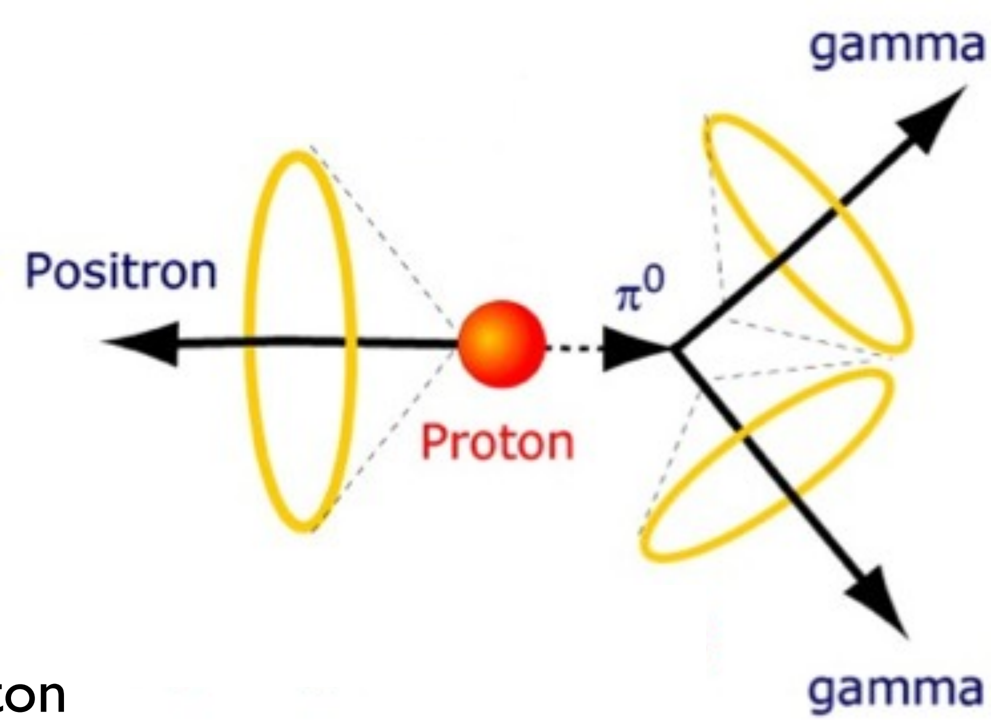

Other signals

- 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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p_K = 340 MeV

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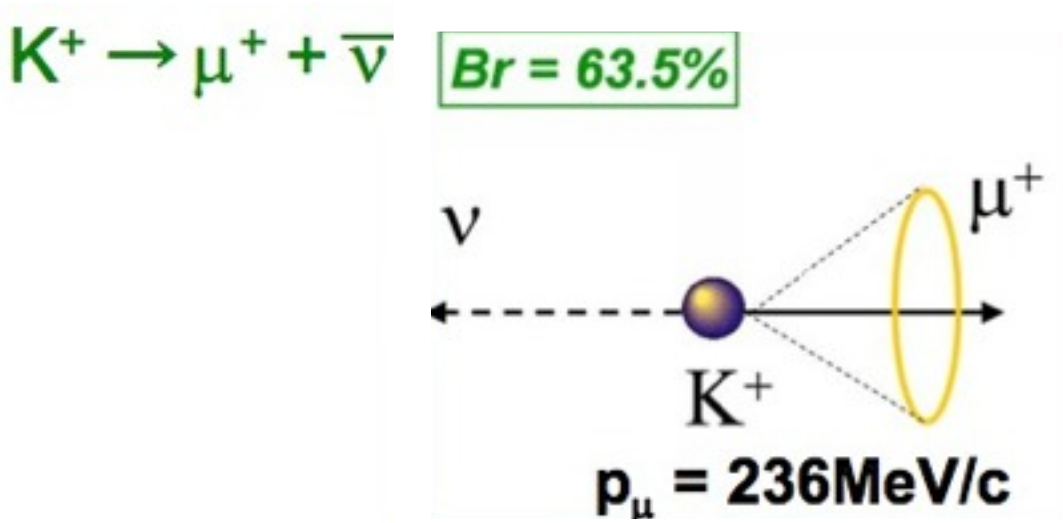

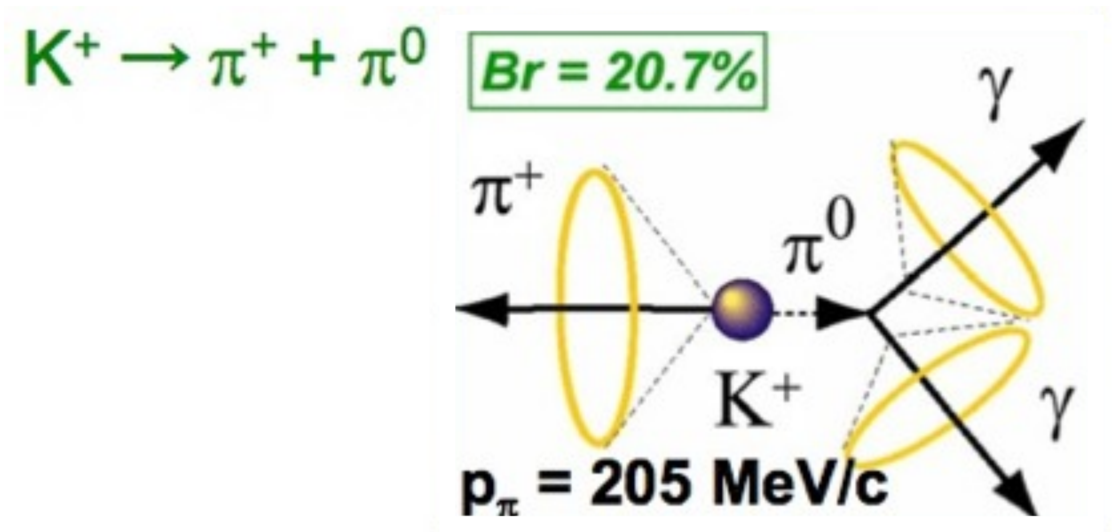

- single cone

- 2 EM cones
- little opposite-side activity

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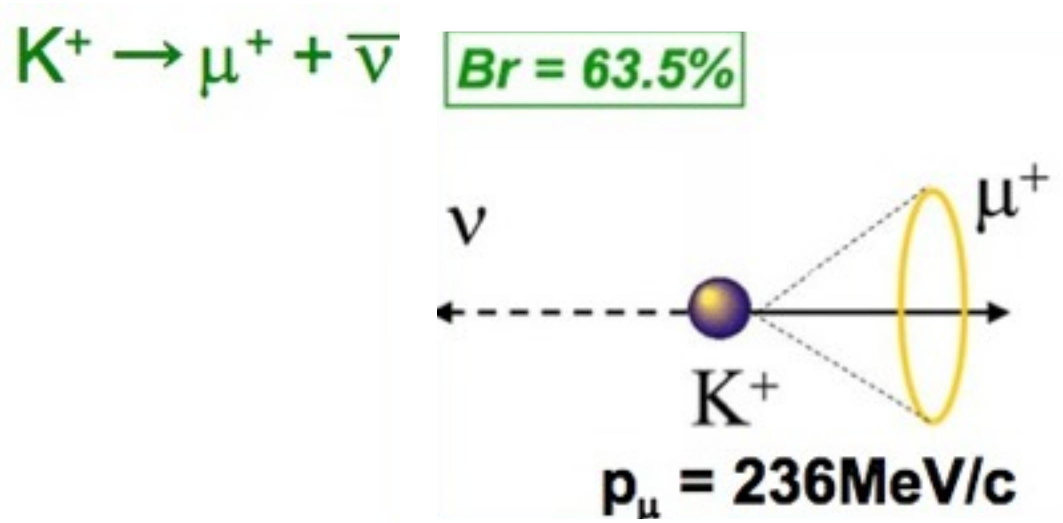

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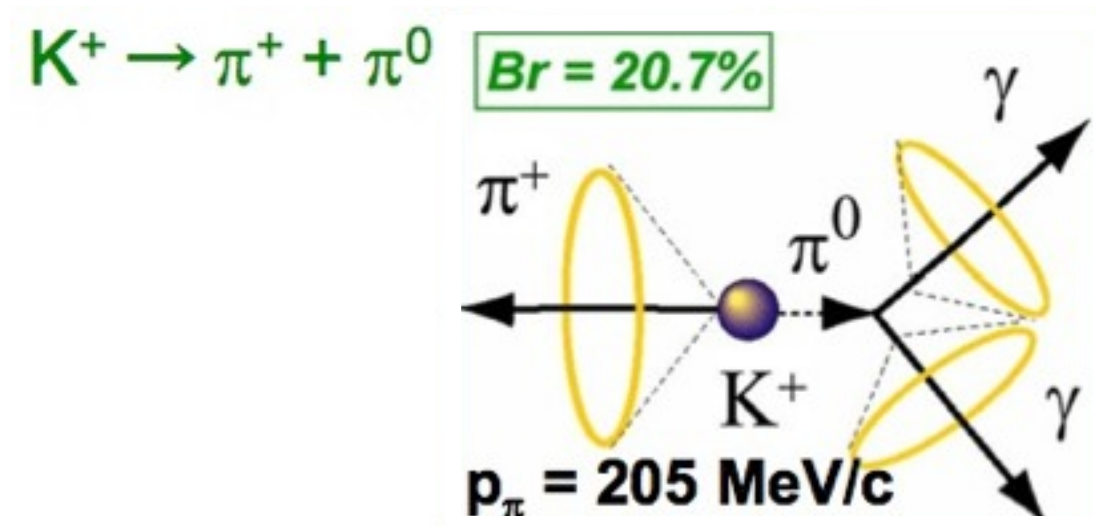


- 2 EM cones
- little opposite-side activity

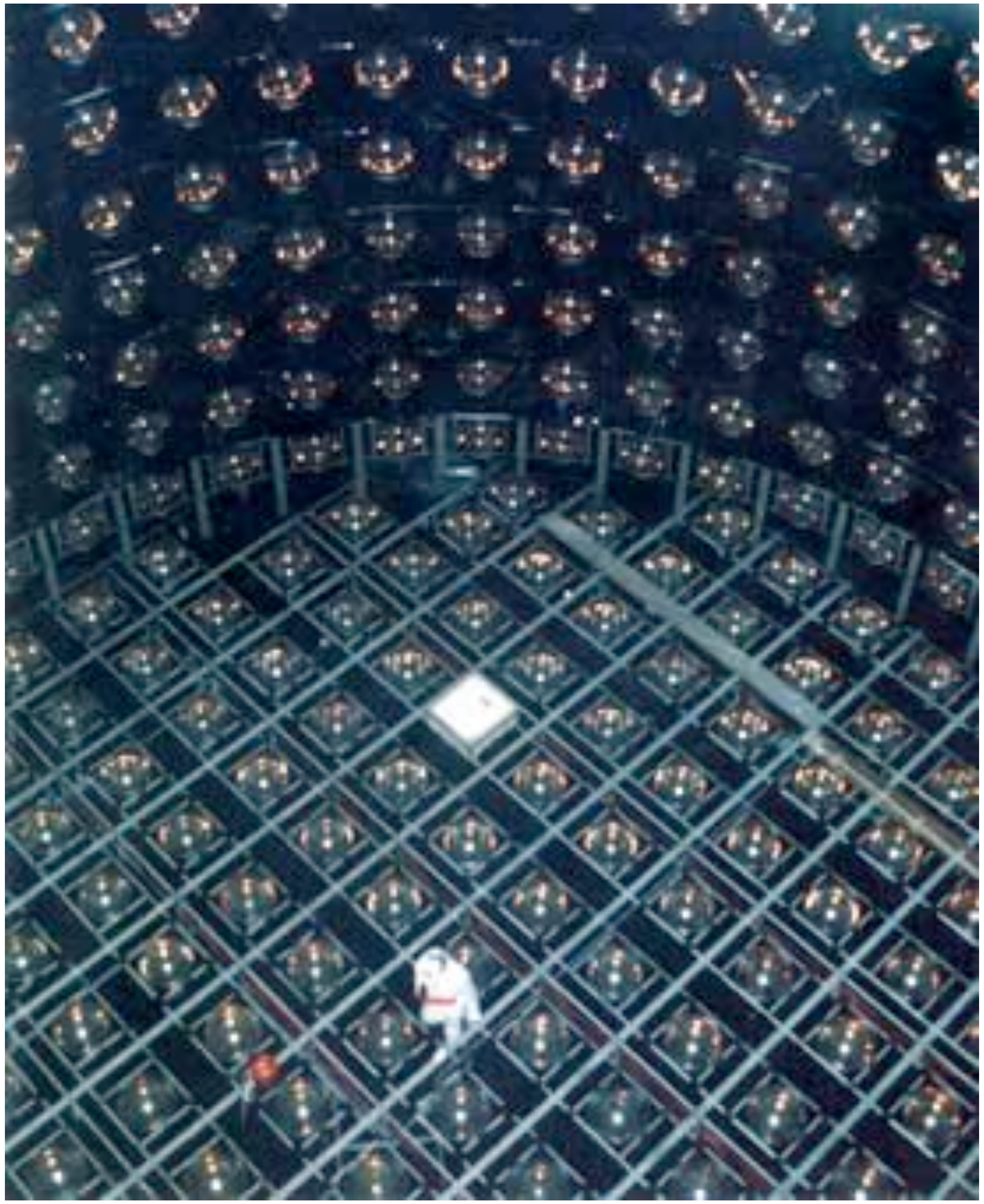
About one order of magnitude less sensitive than $p \to \pi^0 e^+$

First large water-Cherenkov detectors

KamiokaNDe

Kamioka-cho, Gifu, Japan

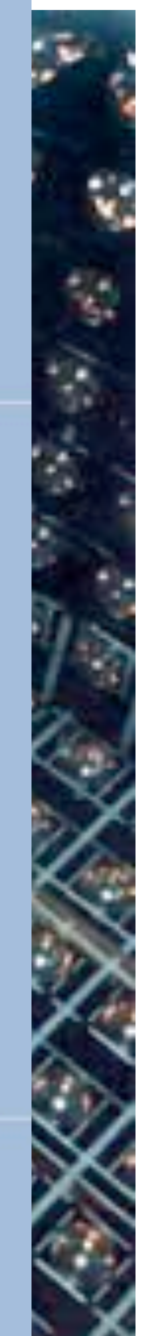
3,000 tons of pure water, about 1,000 PMs



First large water-Cherenkov detectors

Kamic

3,000



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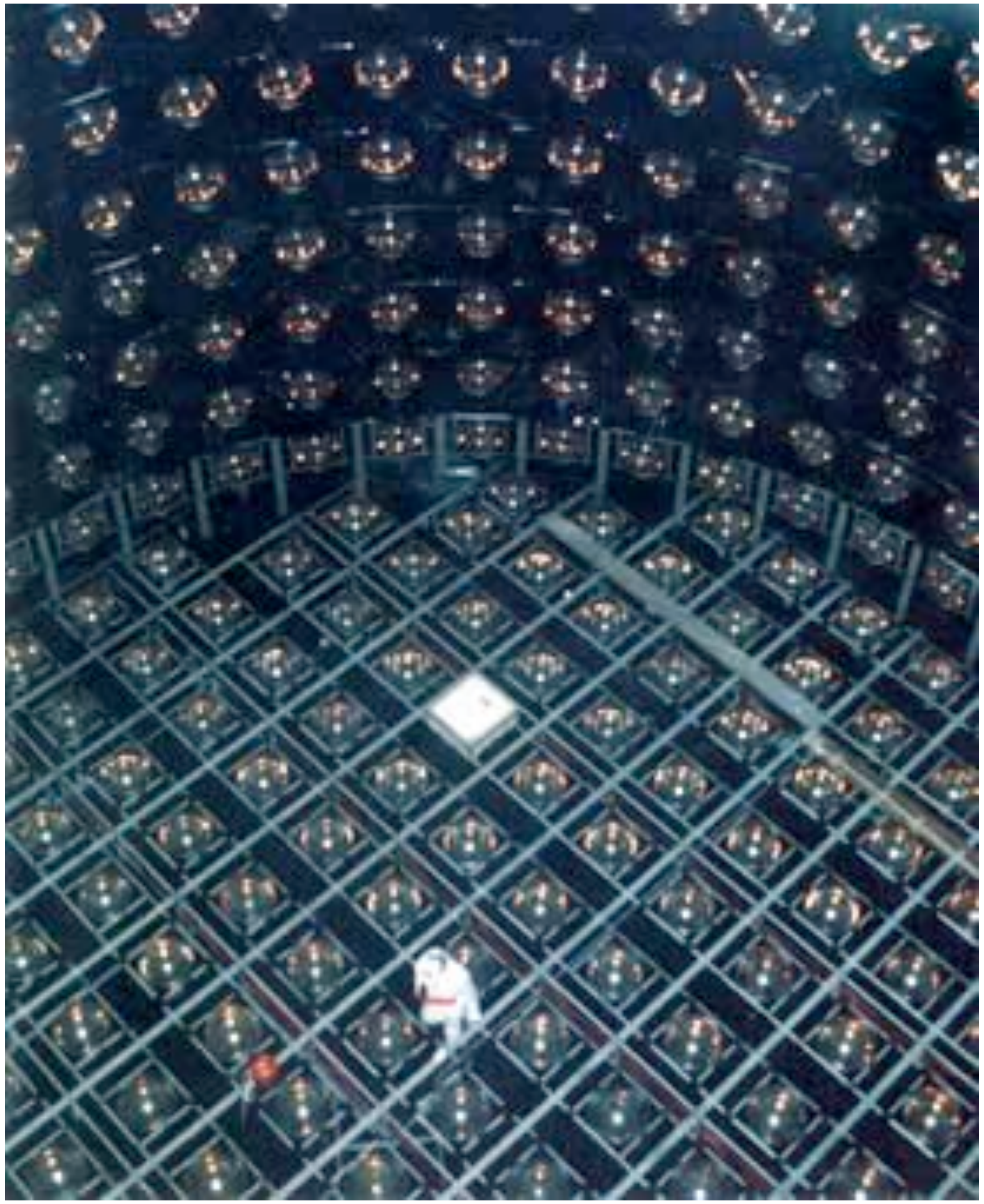

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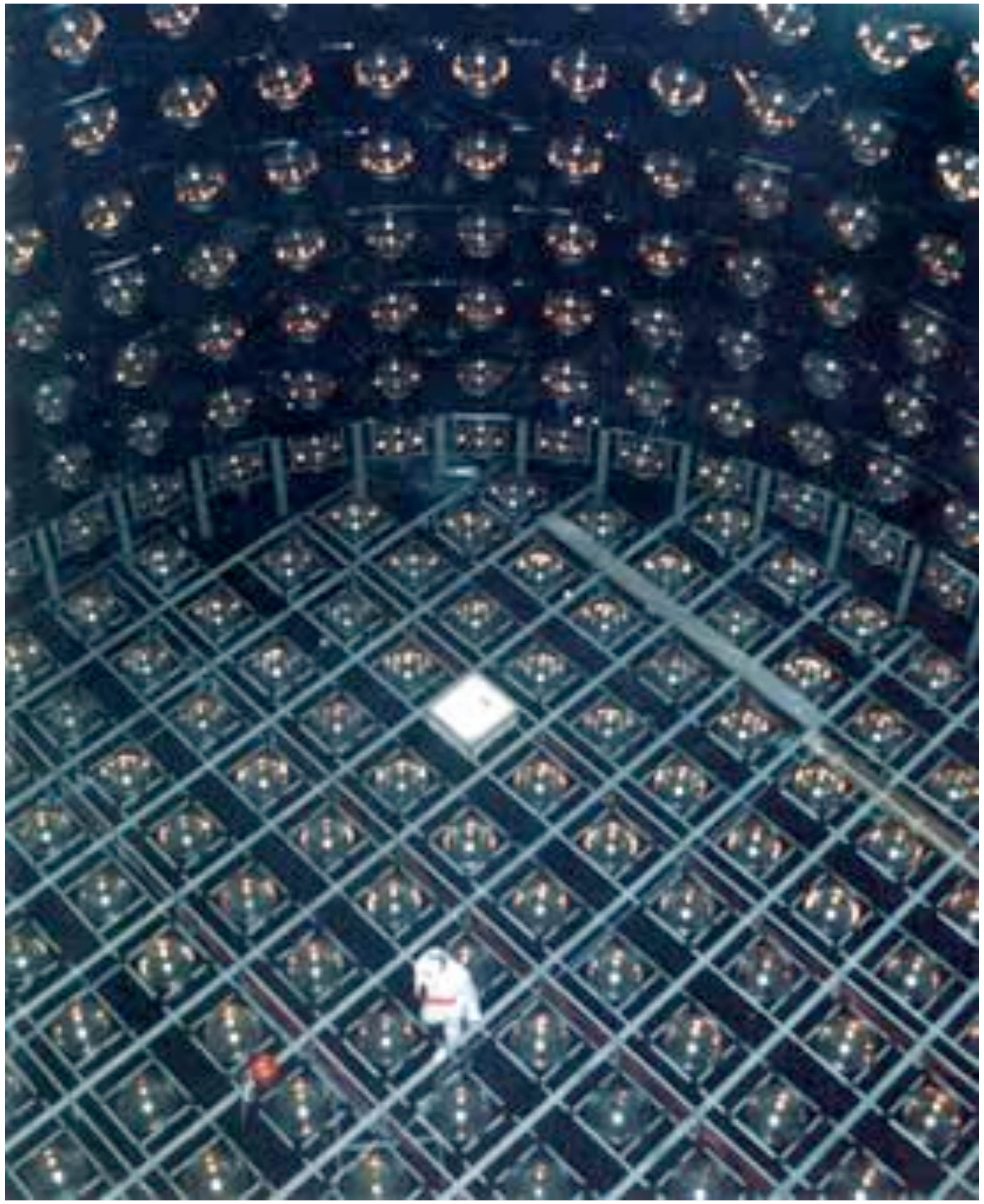

1983-1985 - first phase (proton decay focused)

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

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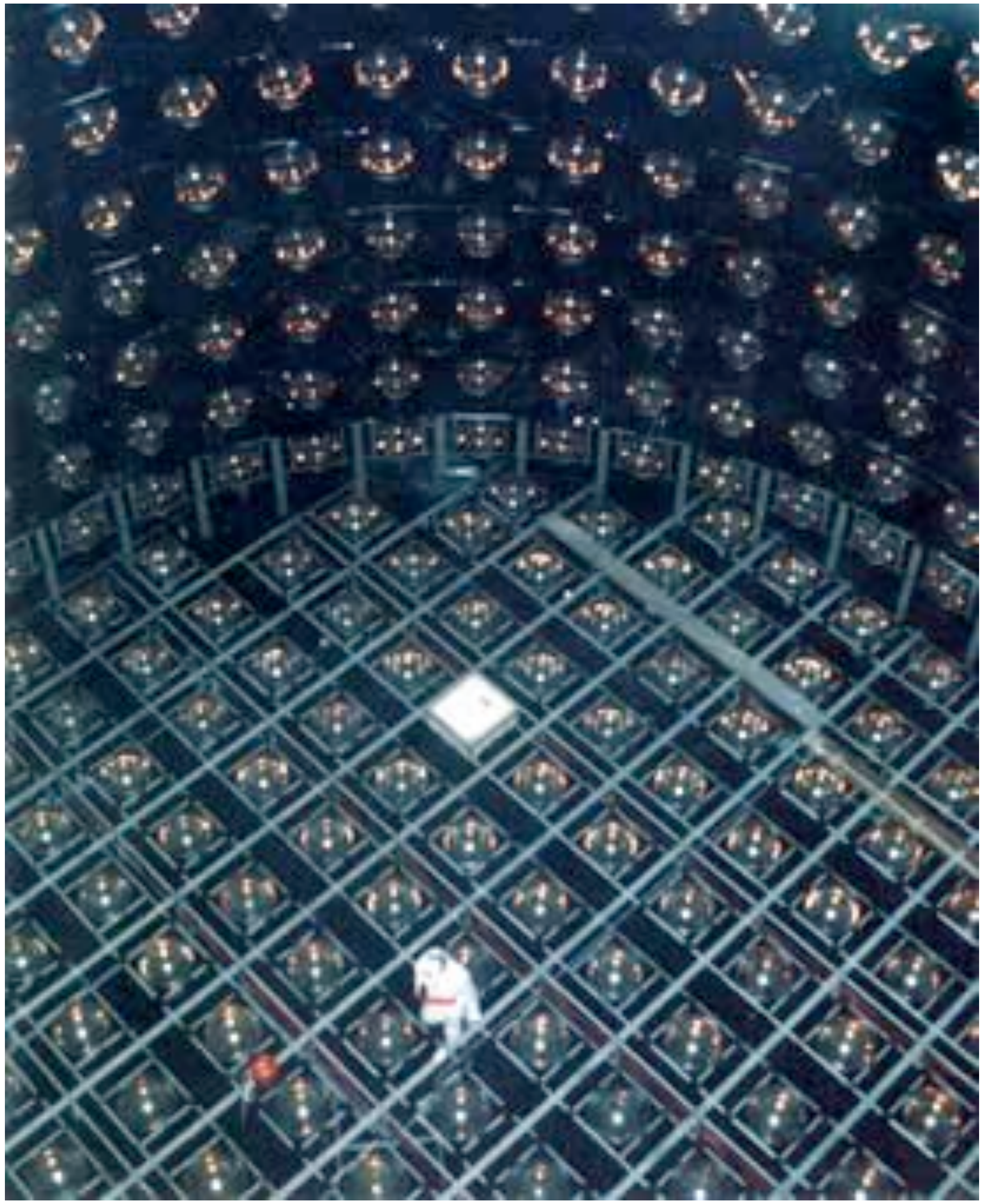
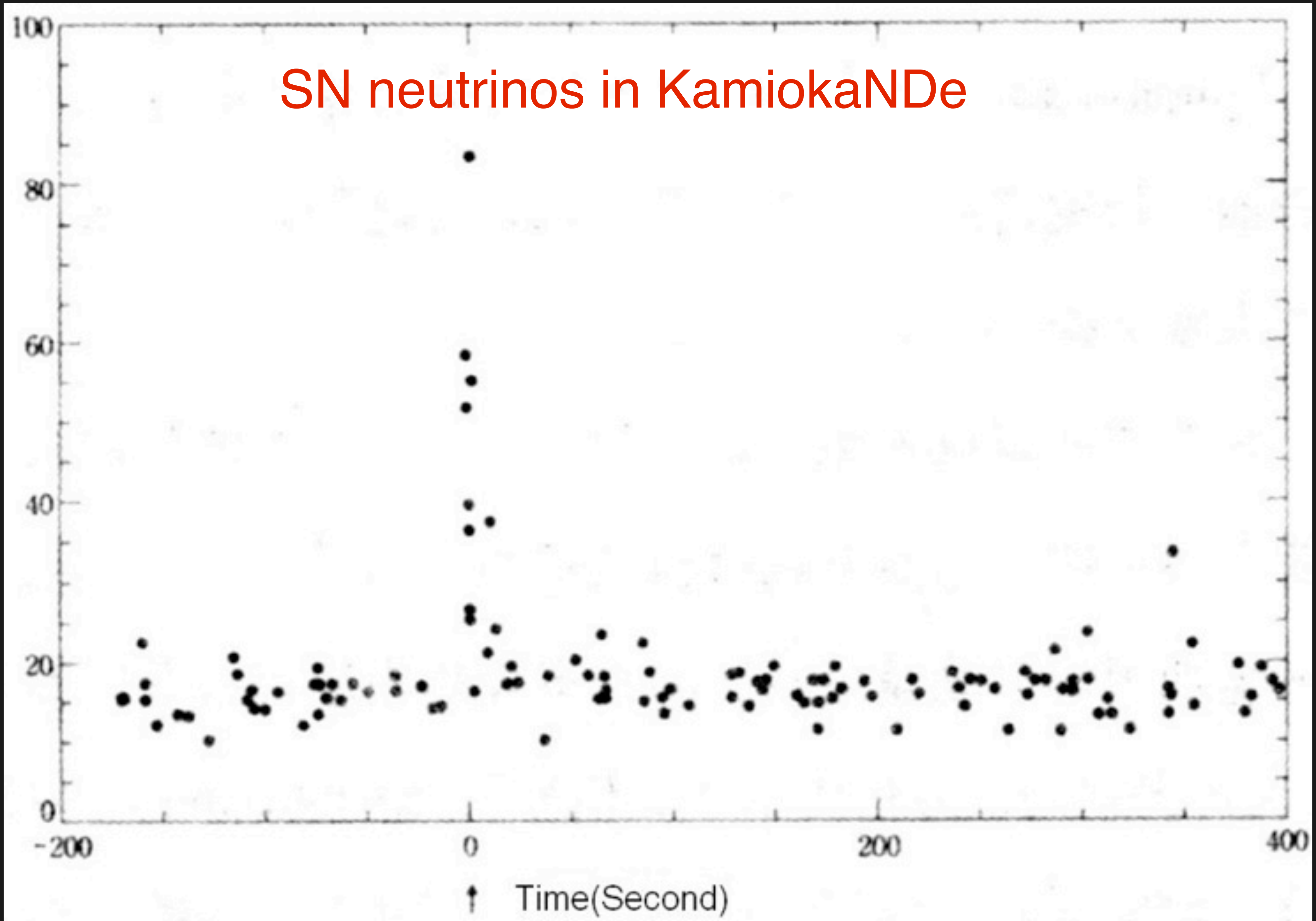
1987-1990 - solar neutrino deficit studies

1990 Solar neutrino deficit confirmation



2002 Nobel prize for Masatoshi Koshiba

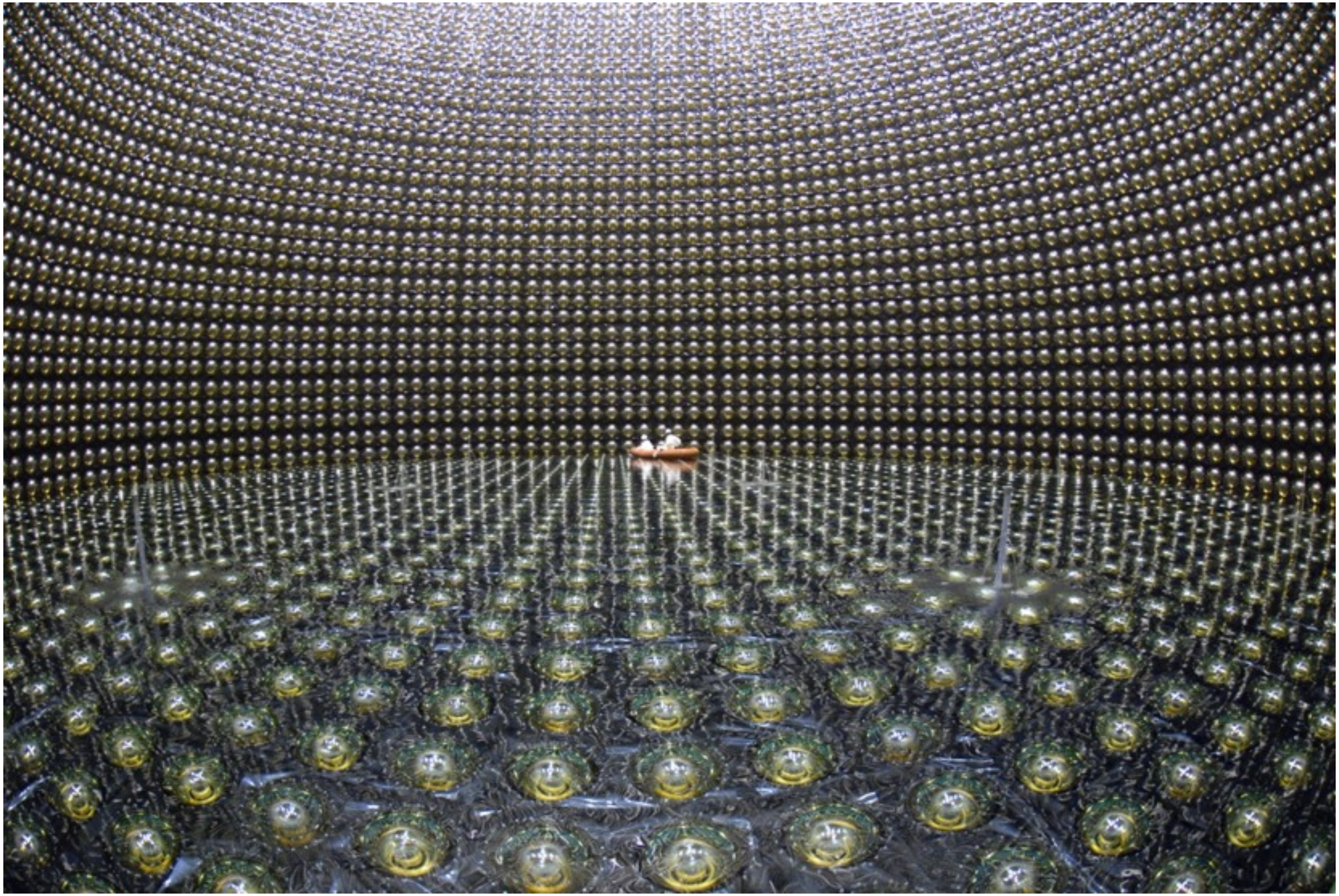
Feb 23 1987 07:35 UT


SN neutrinos in KamiokaNDe
100
80
60
40
20
0
-200
0
200
400
Time(Second)

Current limits

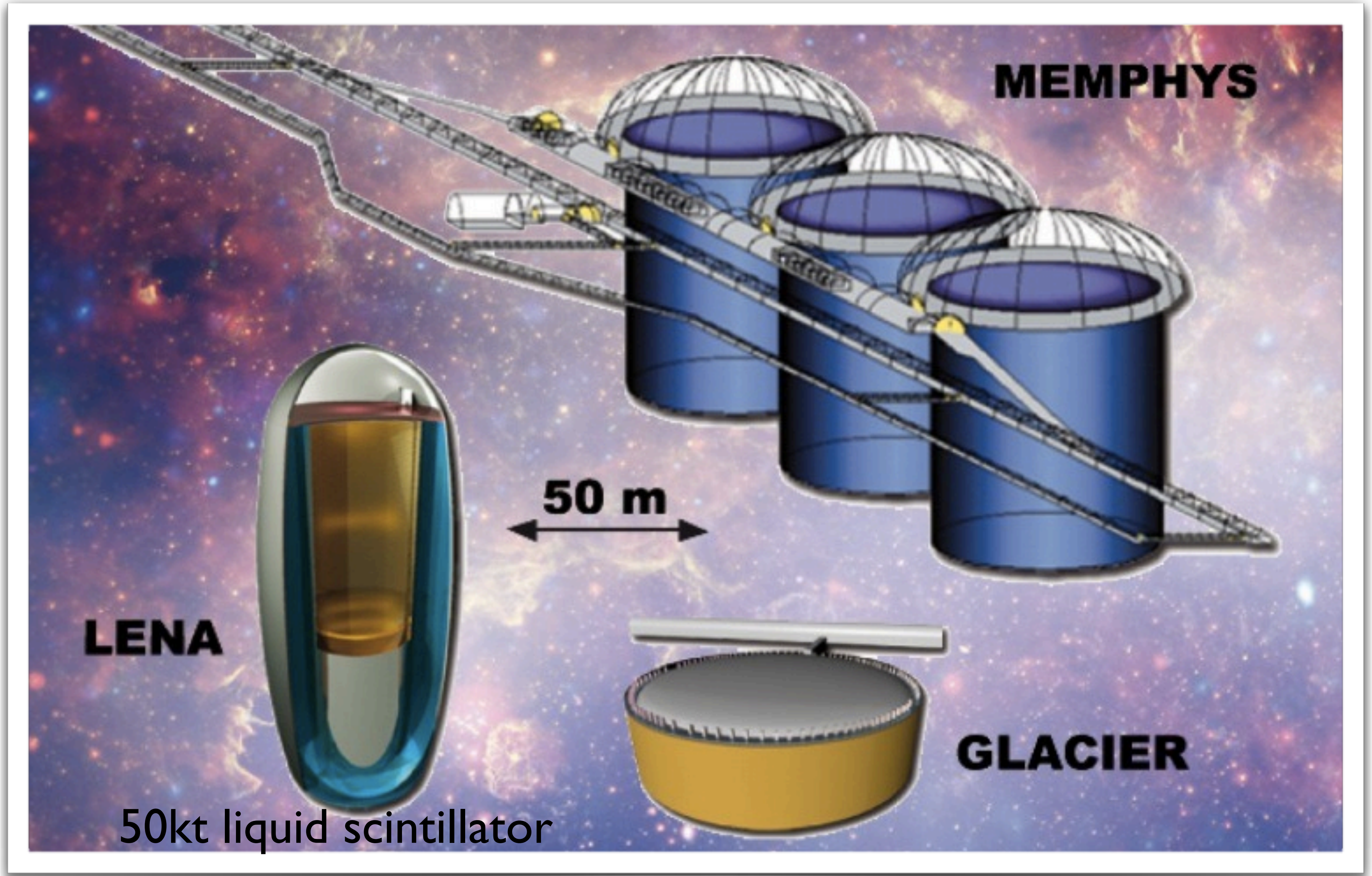
Super-K (30kt WC):

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



Future?

Large volume p-decay searches proposals



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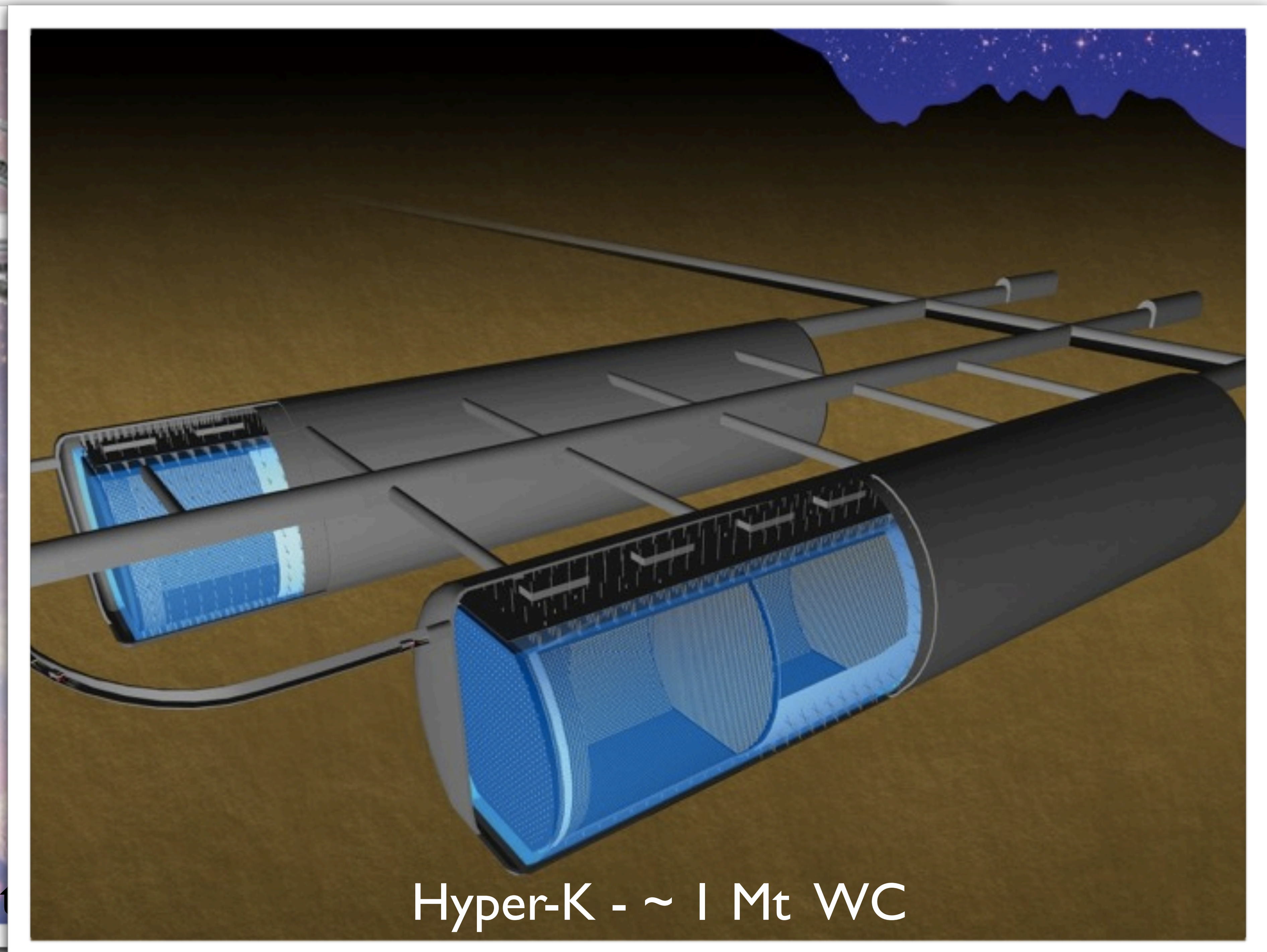

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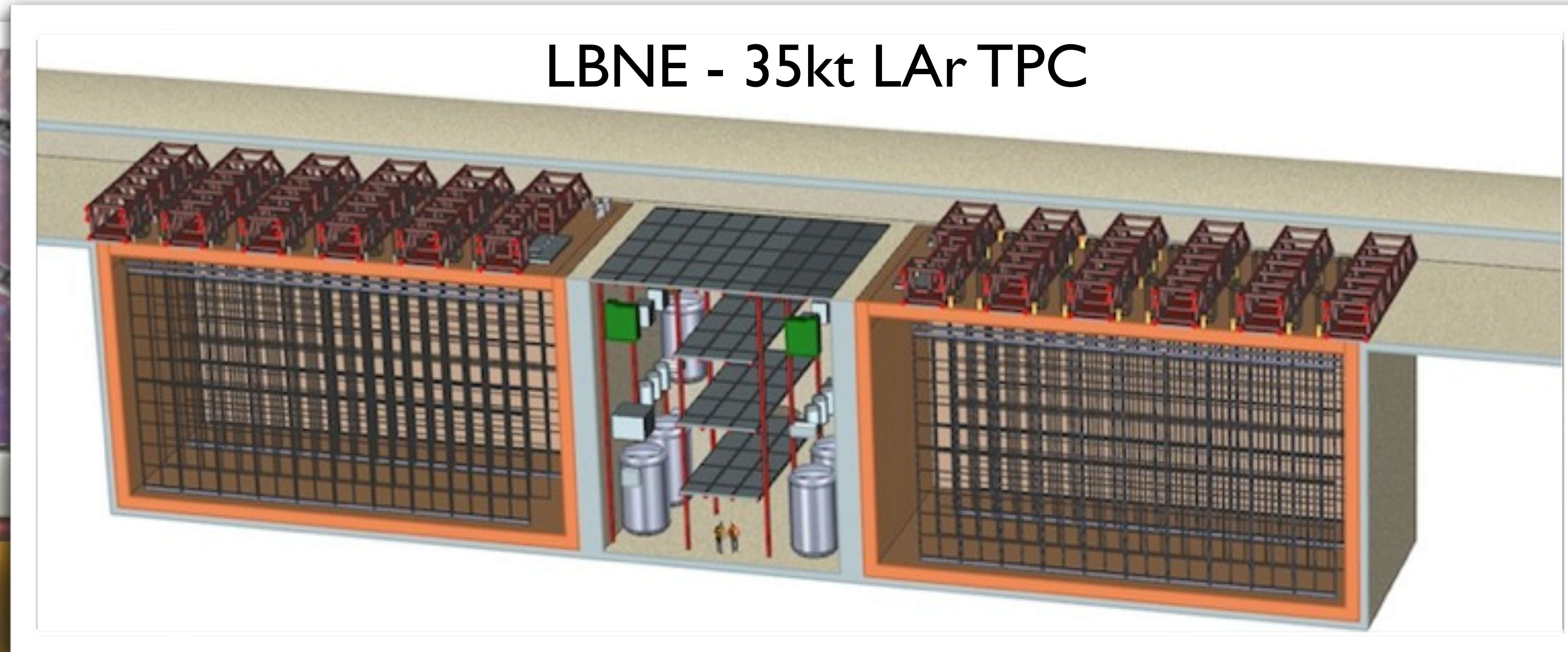

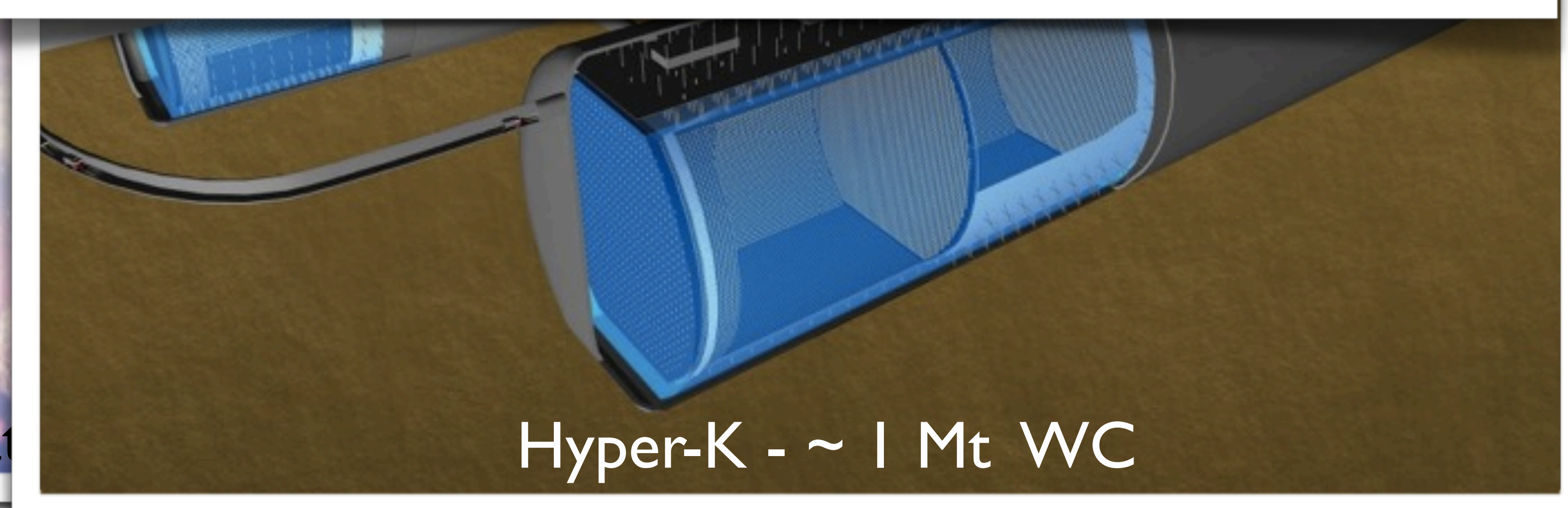

The prospects of getting the Hyper-K built are improving...

提　言

第 22 期学術の大型研究計画に関する
マスタープラン
（マスタープラン 2014）

平成２６年（２０１４年）２月２８日
日　本　学　術　会　議
科学者委員会
学術の大型研究計画検討分科会

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第 22 期学術の大型研究計画に関する
マスタープラン
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Japanese master plan for large scale research projects

SCIENCE COUNCIL OF JAPAN
日本学術会議

平成２６年（２０１４年）２月２８日
日　本　学　術　会　議
科学者委員会
学術の大型研究計画検討分科会

分野	計画番号	学術領域番号	計画名称	計画の概要	学術的な
物理学	85	23-2	大型先端検出器による核子崩壊・ニュートリノ振動実験	スーパーカミオカンデに代わる100万トン級水チェレンコフ検出器ハイパーカミオカンデを建設し、J-PARC加速器ニュートリノビームと組み合わせる事により、世界最先端の核子崩壊・ニュートリノ研究を行う。	ニュートリノにおけ (粒子・反粒子対称 探索し、ニュートリ 宙の進化論に対する る。さらに核子崩壊 せ、素粒子物理学の 超える物理の確立を
	86	23-2	高エネルギー重イオン衝突実験によるクォーク・グルーオン・プラズマ相の解明	高エネルギー重イオン衝突実験(RHIC-PHENIX/LHC-ALICE 実験)を国際協力の下で推進し、宇宙開びゃく直後の姿である新しい物質相QGP(クォーク・グルーオン・プラズマ)の物性科学を展開する。	ハドロン物質の相構 性の理解を通じて、 質相構造の理解が イラル対称性の自 クォークの閉じ込め 度場の物理、非線形 相関物性現象の解明
	87	23-2	光子ビームによるクォーク核物理研究	光子ビームによるクォーク核物理研究を推進し、量子色力学真空とハドロン内クォーク相関を究明する。東北大学電子光理学研究拠点と大阪大学サブアトミック科学研究拠点との拠点間連携研究計画である。	物質の質量の99.9% 担っており、その98% けるカイラル対称性 れによって創成され ており、学術的観点 複雑な階層の研究 れない。

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Hyper-K

- The HK/T2HK collaboration is excited and active
- MOU signed on January 31 2015
- The european part of the collaboration is just forming
- R&D funding secured (both the HK and T2K/J-PARC upgrade)
- A lively discussion about the near detector
- some 2 years delay w.r. to the LOI, realistic starting date 2025(?)

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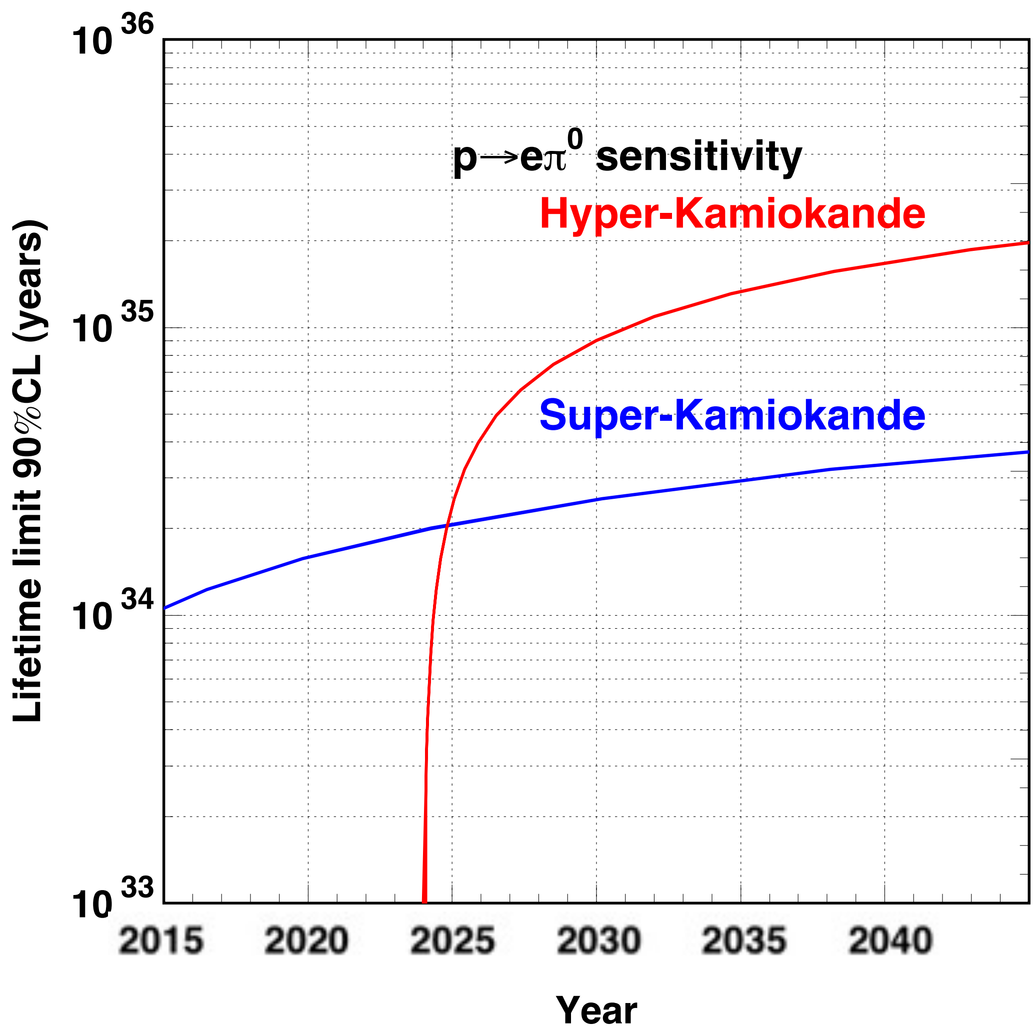
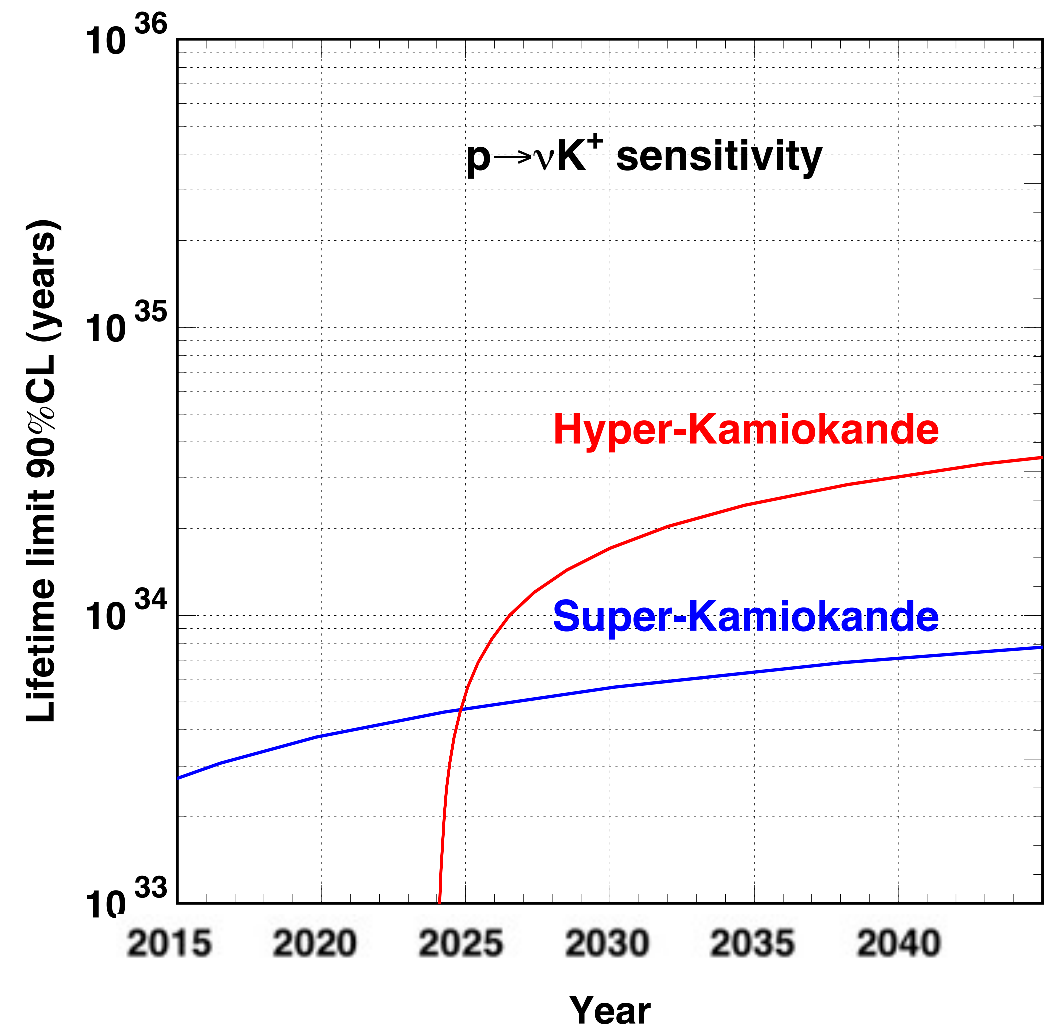
Regardless of what happens...

Hyper-K p-decay sensitivity projection





Abe et al., arXiv:1109.3262 [hep-ex]

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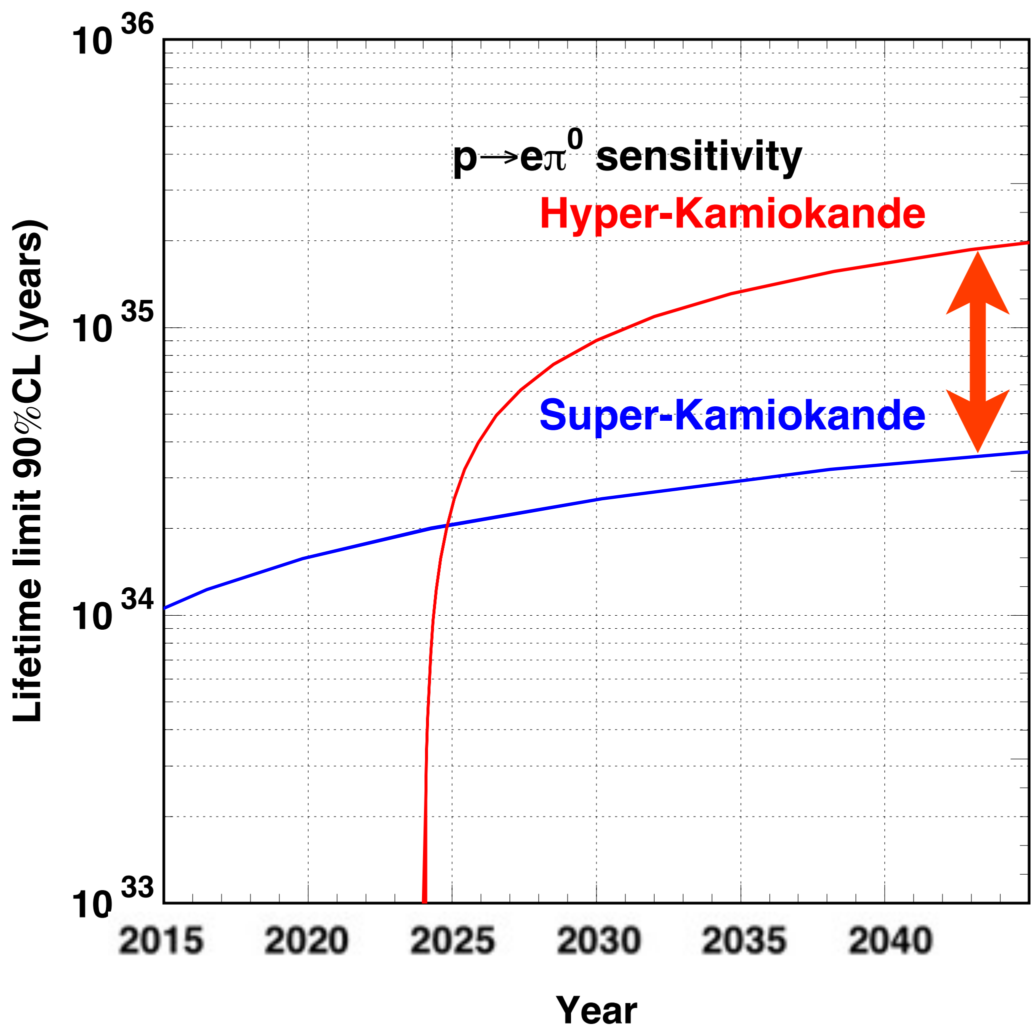

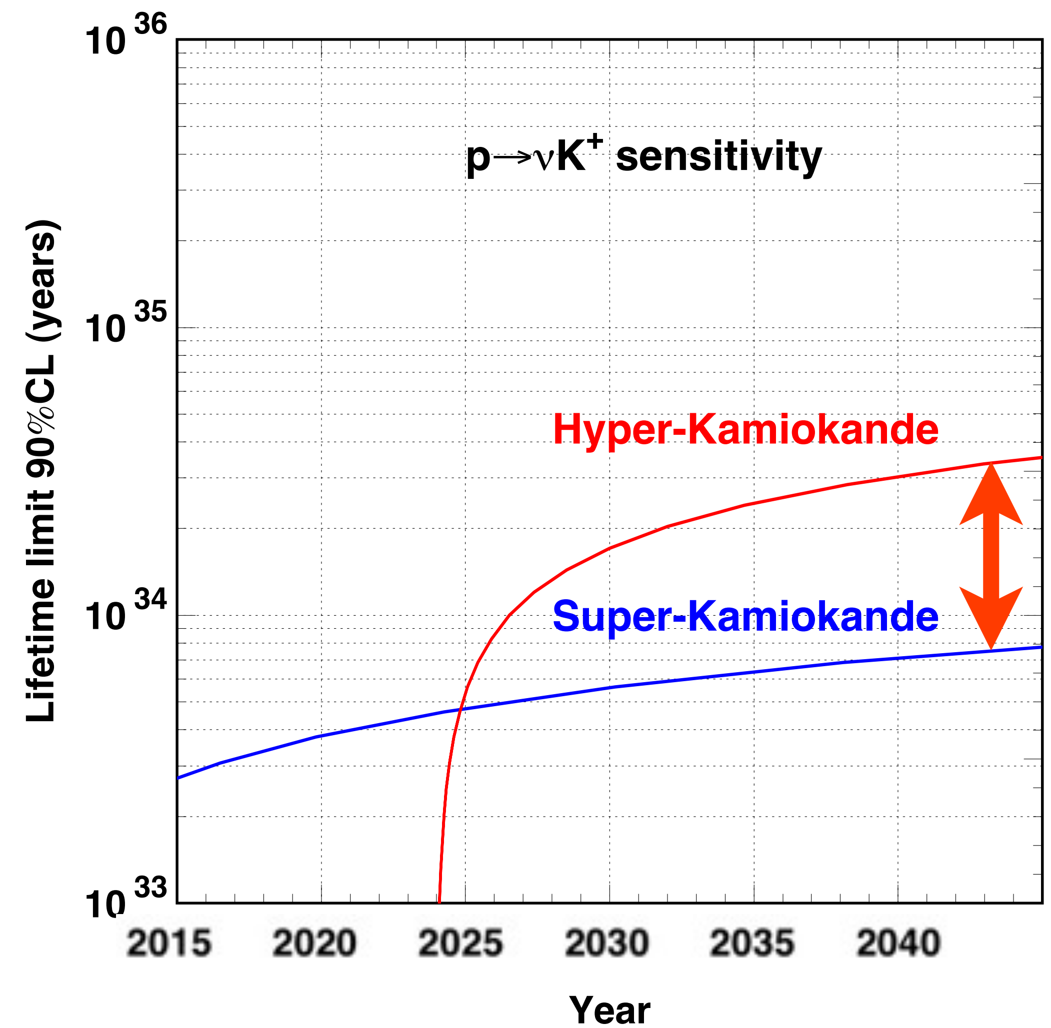

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Accuracy of a **factor of few** in Γ_p estimates needed to make a case !

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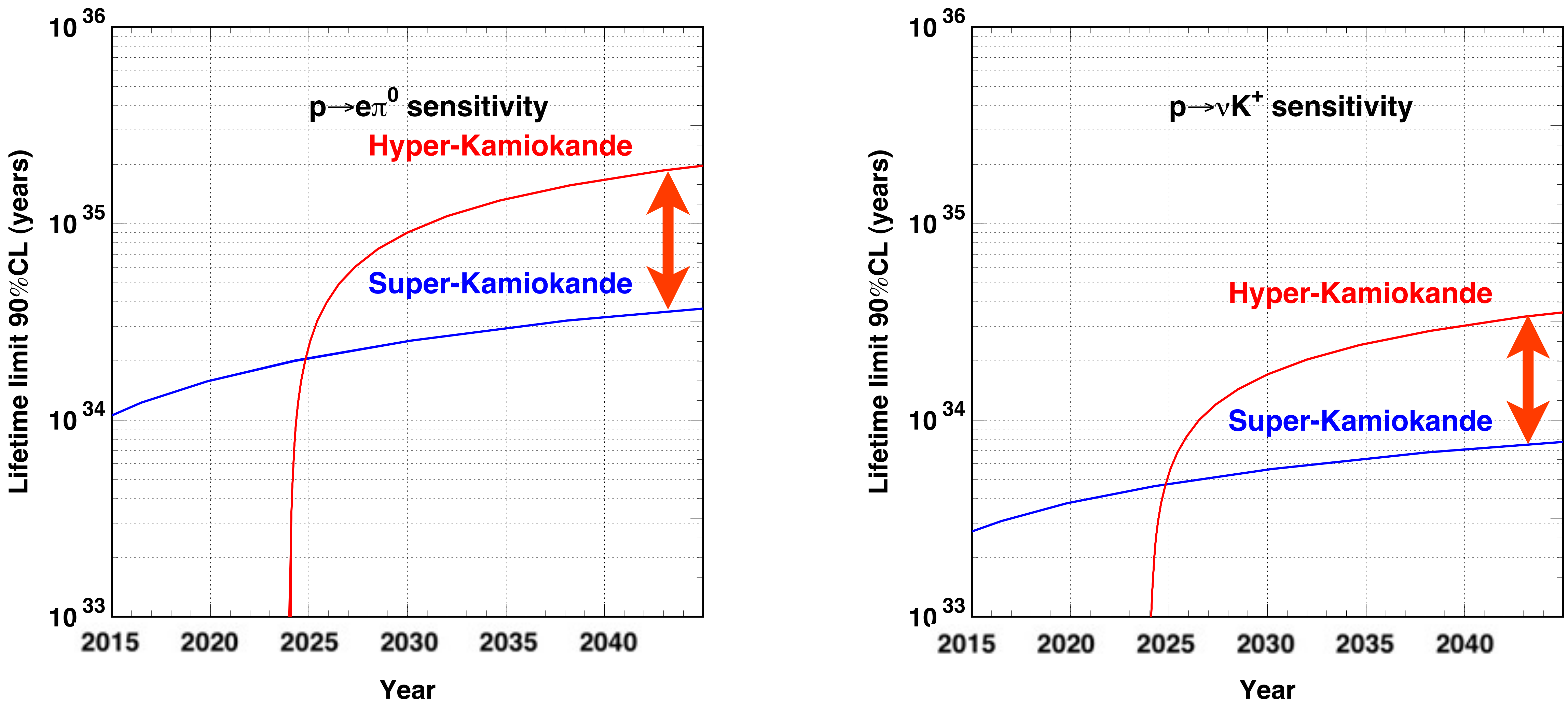


Abe et al., arXiv:1109.3262 [hep-ex]

Accuracy of a **factor of few** in Γ_p estimates needed to make a case !

(At least) **NLO theory precision required**

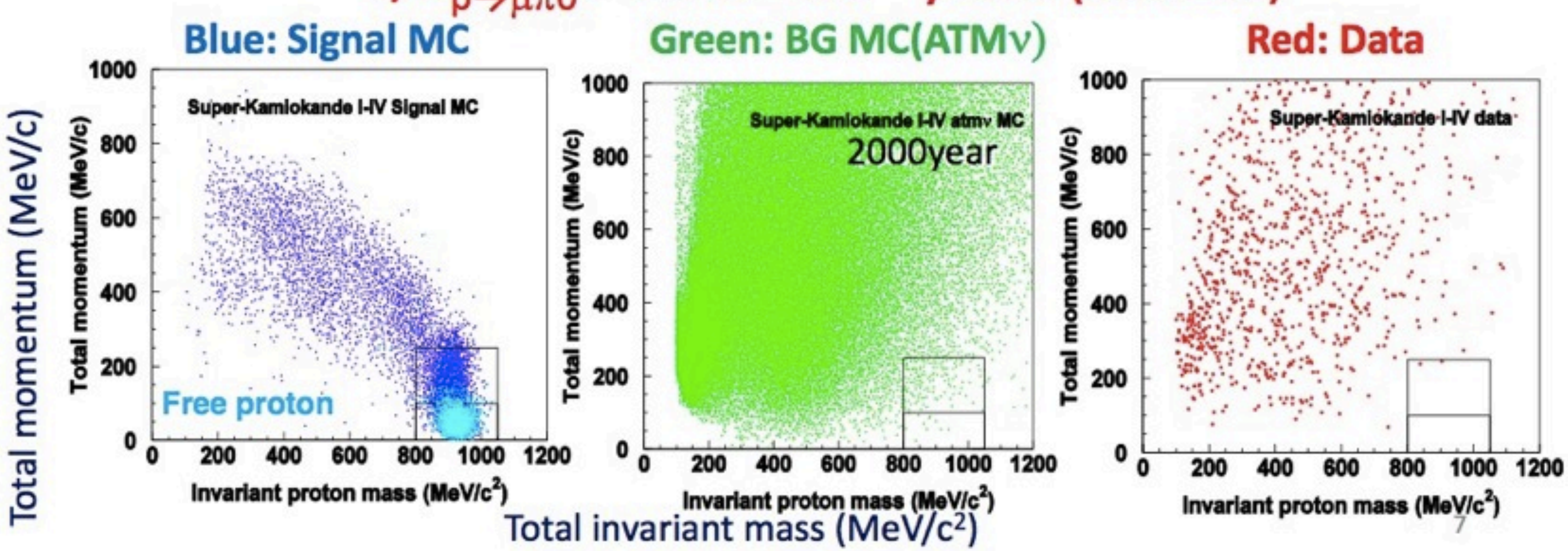
M.Ikeda for SK @ NNN2015 @ StonyBrook

Results of $p \rightarrow \mu^+\pi^0$

(analysis proceeds as with $e^+\pi^0$ with additional requirement of 1 Michel-e)

- 306.3 kton·yrs (SKI-IV) (220kt·yrs in PRD)
- signal $\varepsilon(P_{tot}<250\text{MeV/c})$: 30-40%
- total expected #BKG:
  - $P_{tot}<100$: ~0.05, $100 \leq P_{tot}<250$: ~0.82
- no significant data excess

$$\tau/B_{p\rightarrow\mu\pi 0} > 7.78 \times 10^{33} \text{ years (90\% CL)}$$

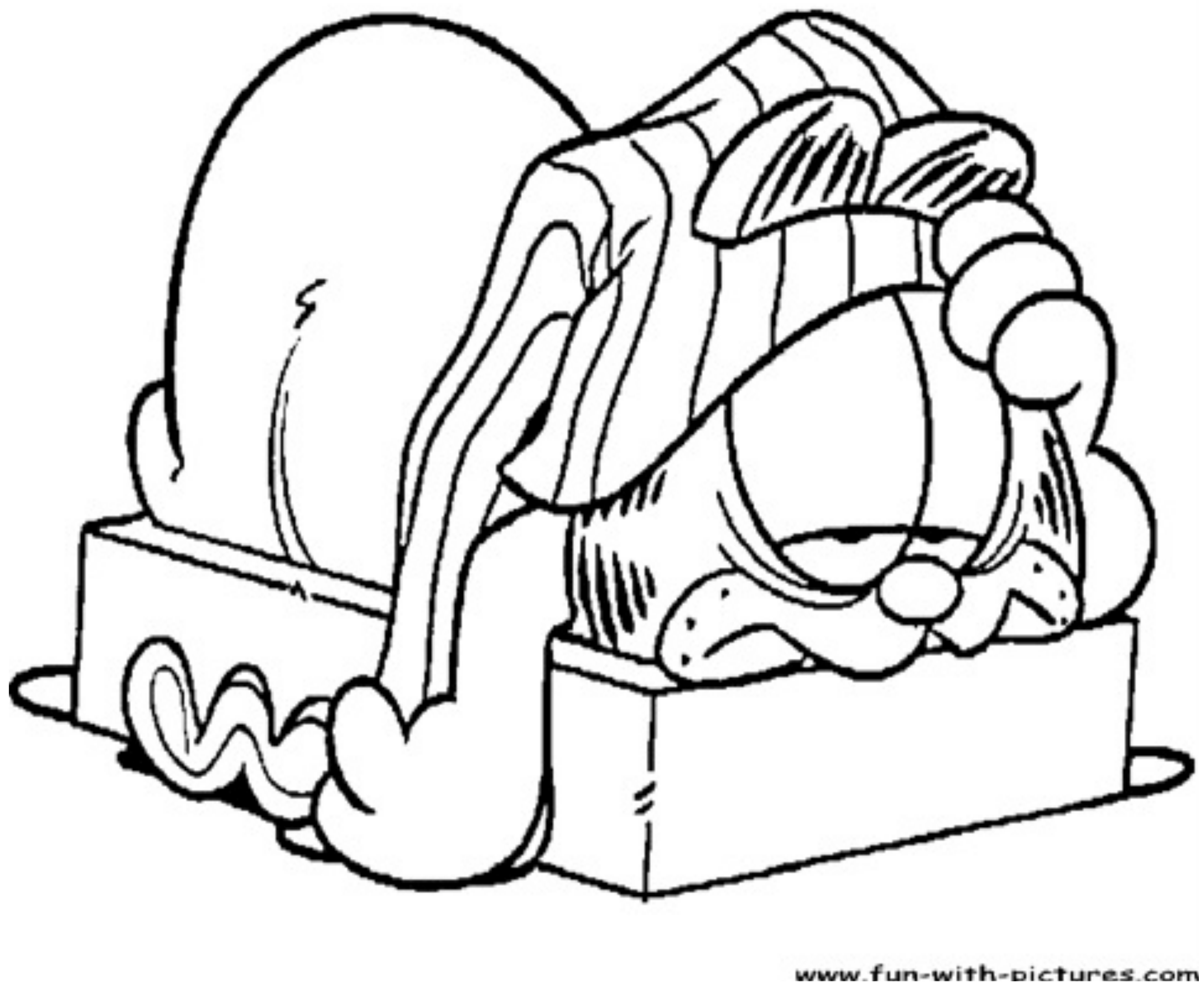


Regardless of what happens...

Optimistic scenario: Day 1

Regardless of what happens...

Optimistic scenario: Day 2

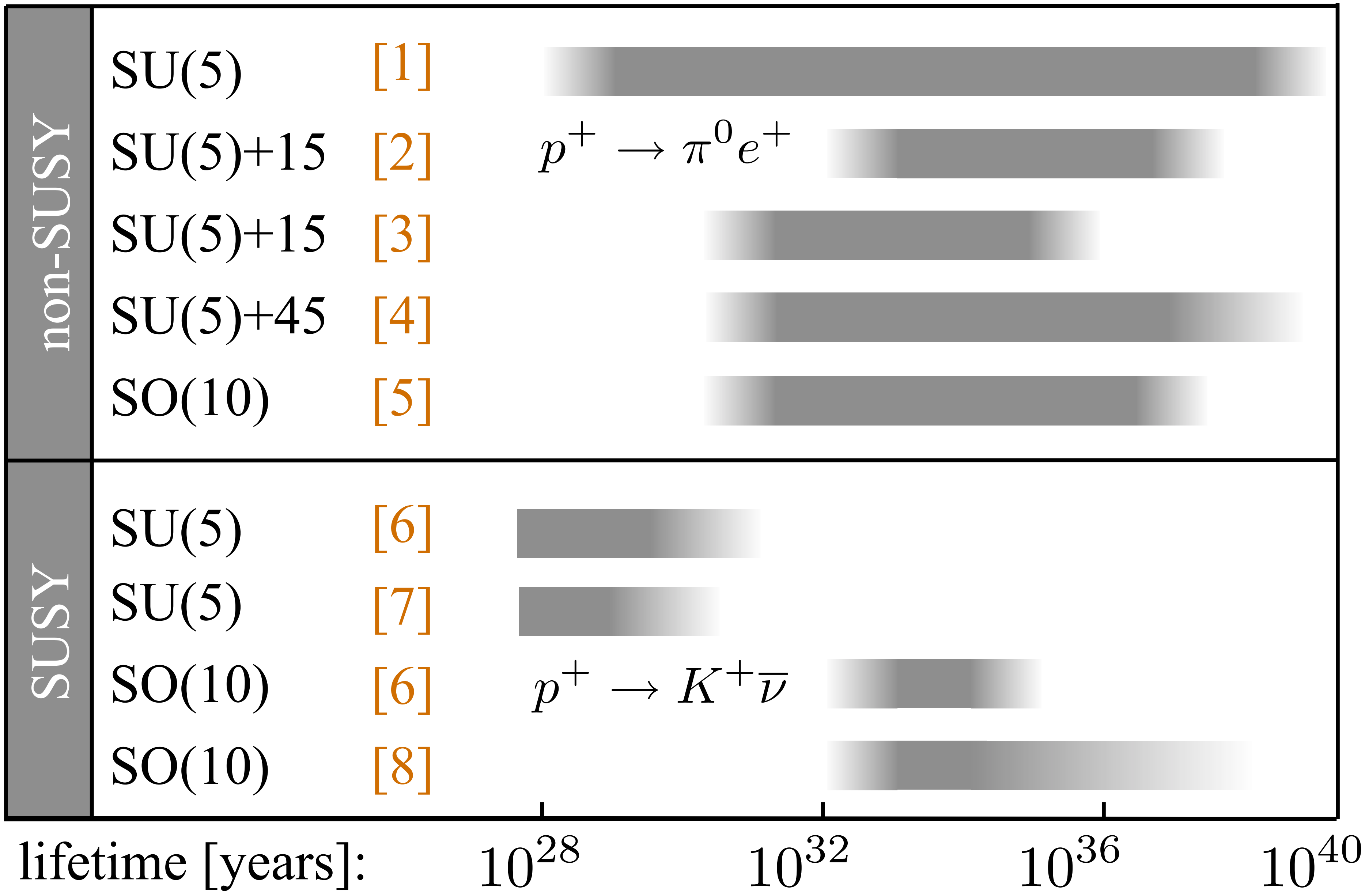


Optimistic scenario: Day 3

Are we in a position to discriminate among different GUTs ?

Proton lifetime estimates in GUTs

Proton lifetime estimates in GUTs



[1] Georgi, Quinn, Weinberg, PRL 33, 451 (1974)
[2] Dorsner, Fileviez Perez, NPB 723, 53 (2005)
[3] Dorsner, Fileviez Perez, Rodrigo, PRD75, 125007 (2007)
[4] Dorsner, Fileviez Perez, PLB 642, 248 (2006)
[5] Lee, Mohapatra, Parida, Rani, PRD 51 (1995)
[6] Pati, hep-ph/0507307
[7] Murayama, Pierce, PRD 65. 055009 (2002)
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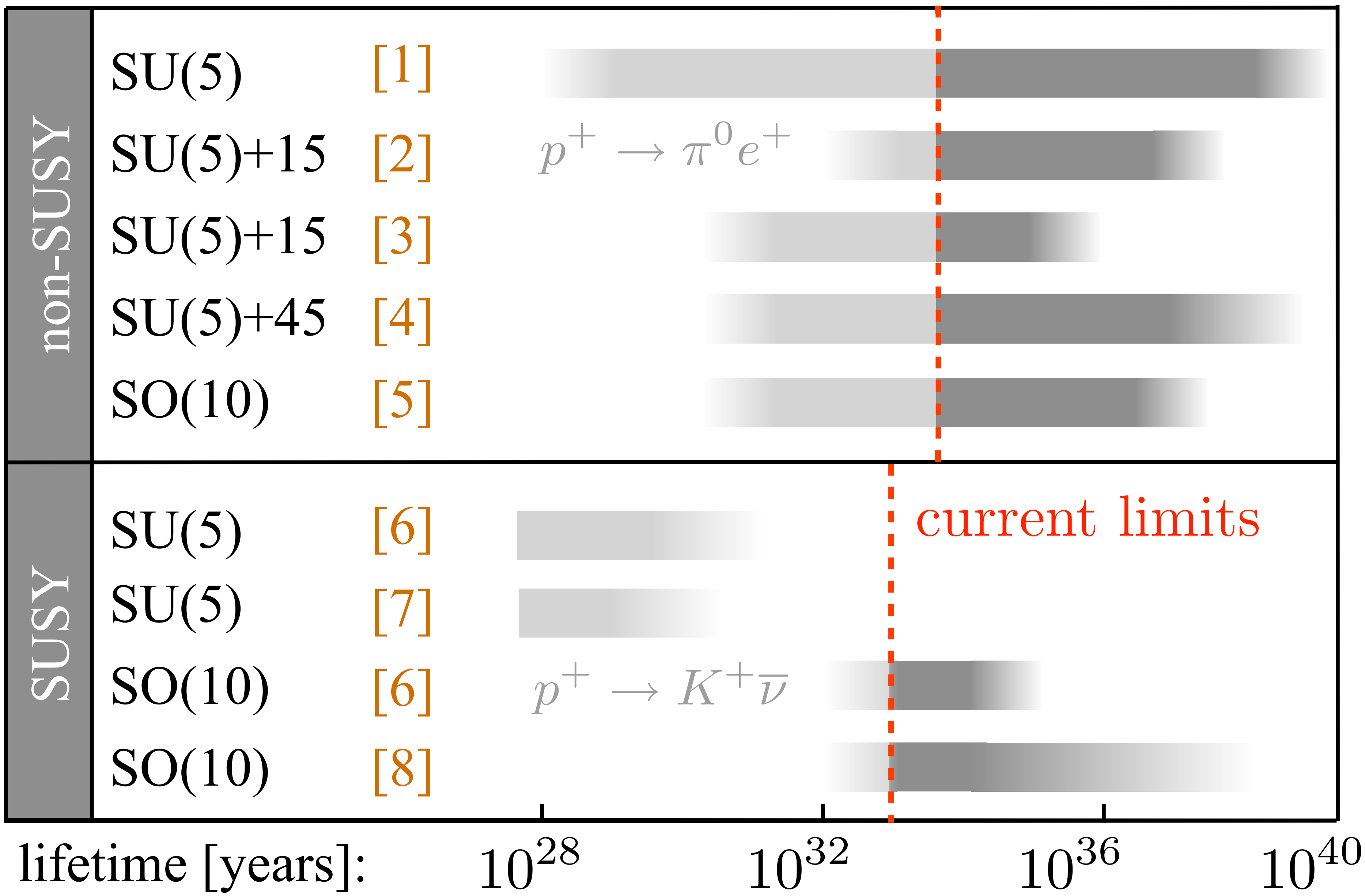

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Main theoretical uncertainties in p-decay estimates in GUTs

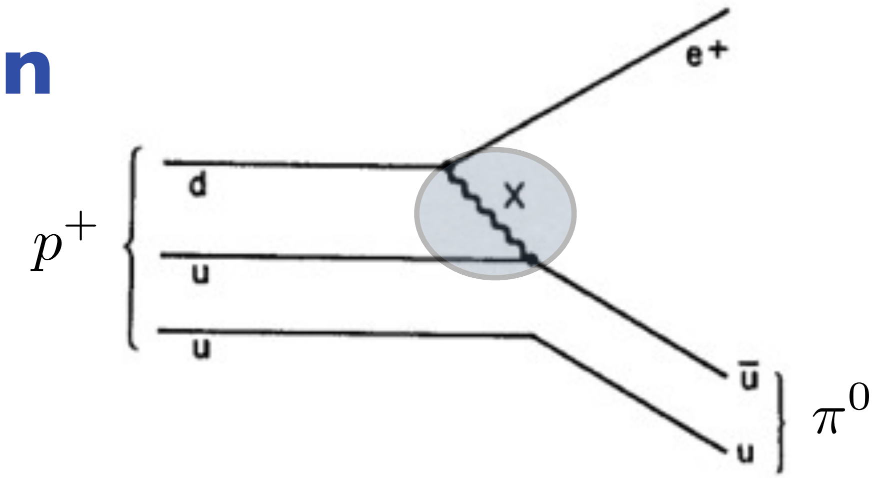
- **Hadronic matrix elements**

- **GUT-scale (= effective mediator mass) determination**
  - **one- vs. two-loop running (or even higher?)**
  - **scalar spectrum & threshold effects**
  - **Planck-scale effects**
    - gauge kinetic form = matching
    - effective cut-off in GUTs

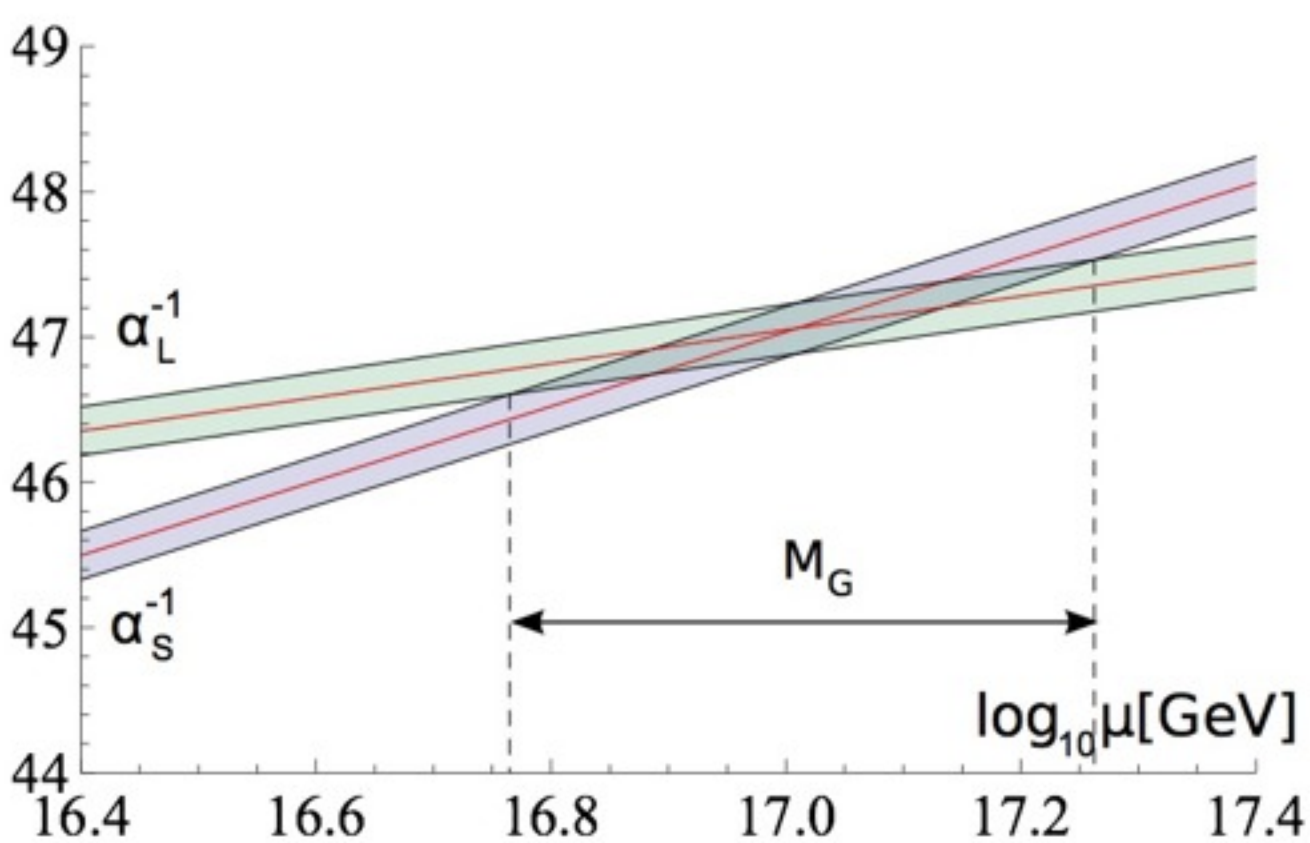
- **Flavor structure of the B & L violating currents**
  - **Yukawa sector fits**
  - **Planck-scale effects**
    - scalar & fermionic kinetic forms = matching
    - higher-order operators

Main theoretical uncertainties in p-decay estimates

GUT scale determination



- at least **two-loop** running necessary!

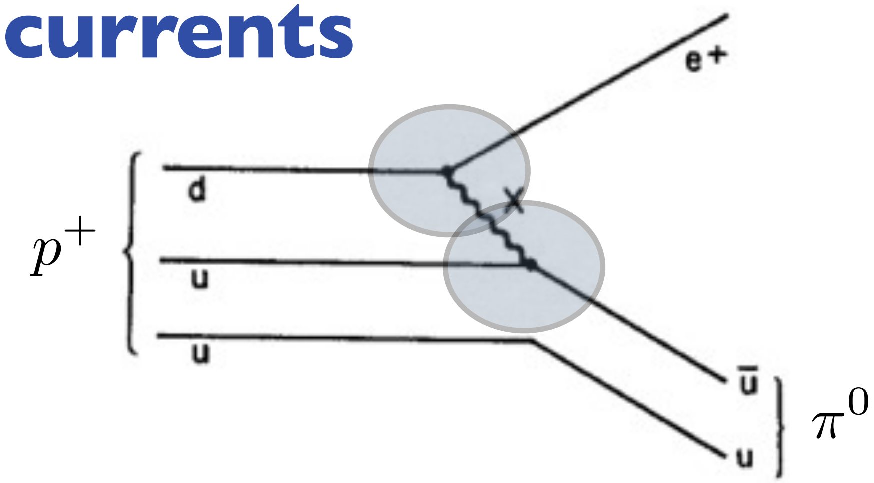


Credit: H. Kolesova

- requires a **very good** understanding of the **entire** spectrum

Main theoretical uncertainties in p-decay estimates

Flavour structure of the BLNV currents



Example: $$\frac{g^2}{M_{1/6}^2} C_{ijk}\, \overline{u^c}\gamma^\mu d_i\, \overline{d^c_j}\gamma_\mu \nu_k \qquad C_{ijk} = (V_{d^c}^\dagger V_d)_{ji}(V_{u^c}^\dagger V_\nu)_{1k}$$

- RH rotations enter here

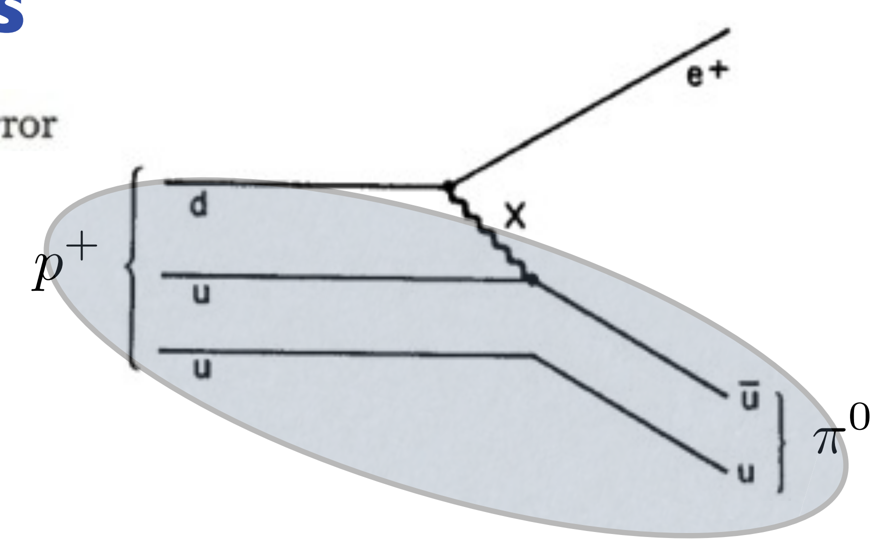
- simple Yukawa sector desirable!

- some channels are more "robust" than others

Main theoretical uncertainties in p-decay estimates

Hadronic matrix elements

Matrix element	$W_0(\mu = 2\text{GeV})$ GeV^2	(%) Total error
$\langle\pi^0\|(ud)_R u_L\|p\rangle$	-0.103 (23) (34)	40
$\langle\pi^0\|(ud)_L u_L\|p\rangle$	0.133 (29) (28)	30
$\langle\pi^+\|(ud)_R d_L\|p\rangle$	-0.146 (33) (48)	40
$\langle\pi^+\|(ud)_L d_L\|p\rangle$	0.188 (41) (40)	30
$\langle K^0\|(us)_R u_L\|p\rangle$	0.098 (15) (12)	20
$\langle K^0\|(us)_L u_L\|p\rangle$	0.042 (13) (8)	36
$\langle K^+\|(us)_R d_L\|p\rangle$	-0.054 (11) (9)	26
$\langle K^+\|(us)_L d_L\|p\rangle$	0.036 (12) (7)	39
$\langle K^+\|(ud)_R s_L\|p\rangle$	-0.093 (24) (18)	32
$\langle K^+\|(ud)_L s_L\|p\rangle$	0.111 (22) (16)	25
$\langle K^+\|(ds)_R u_L\|p\rangle$	-0.044 (12) (5)	30
$\langle K^+\|(ds)_L u_L\|p\rangle$	-0.076 (14) (9)	22
$\langle\eta\|(ud)_R u_L\|p\rangle$	0.015 (14) (17)	147
$\langle\eta\|(ud)_L u_L\|p\rangle$	0.088 (21) (16)	30



Y. Aoki, E. Shintani, A. Soni, Phys.Rev. D89 (2014) 014505 (lattice)

Main theoretical uncertainties in p-decay estimates

“Gravity smearing” effects

Larsen, Wilczek, NPB 458, 249 (1996)
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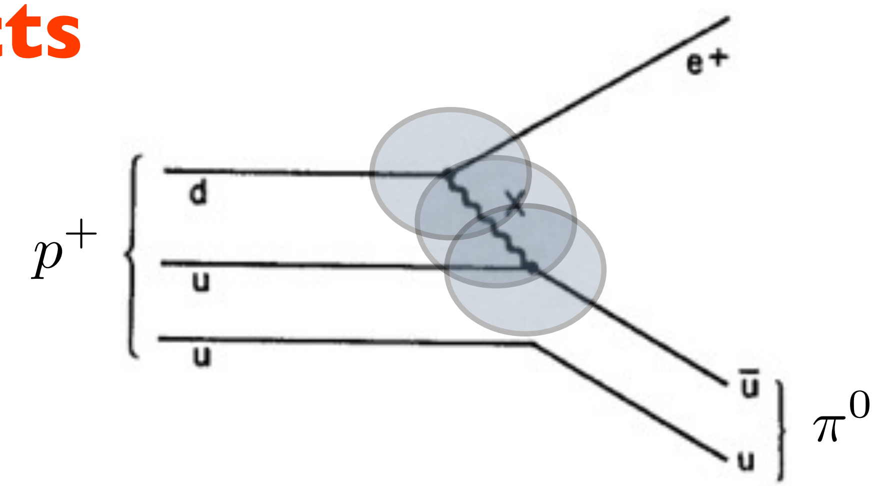
$$\mathcal{L} \ni \frac{\kappa}{\Lambda} F^{\mu\nu} \langle \Phi \rangle F_{\mu\nu}$$



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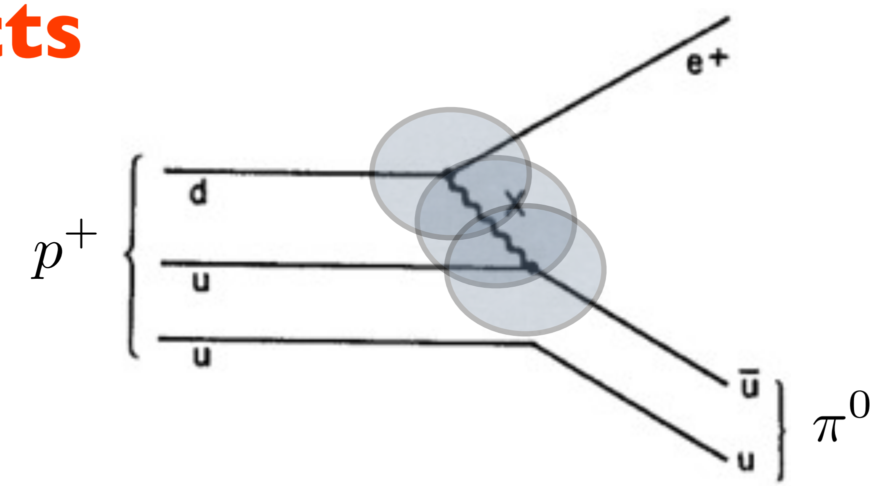

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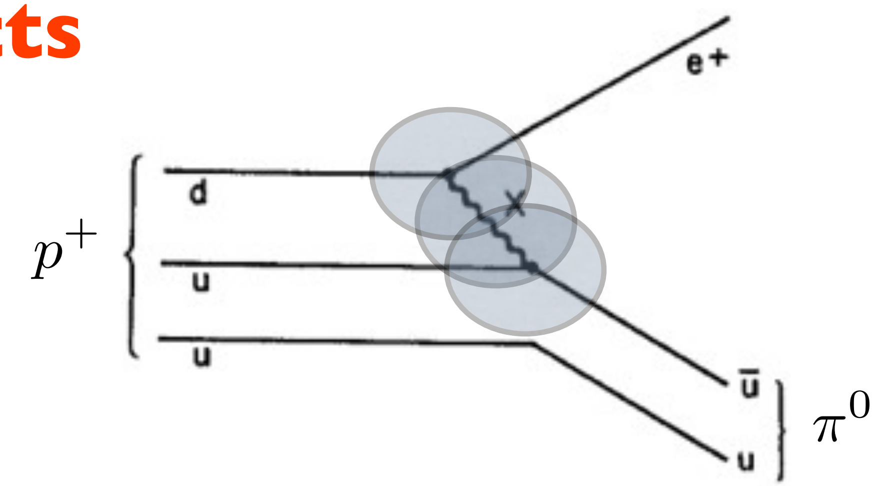

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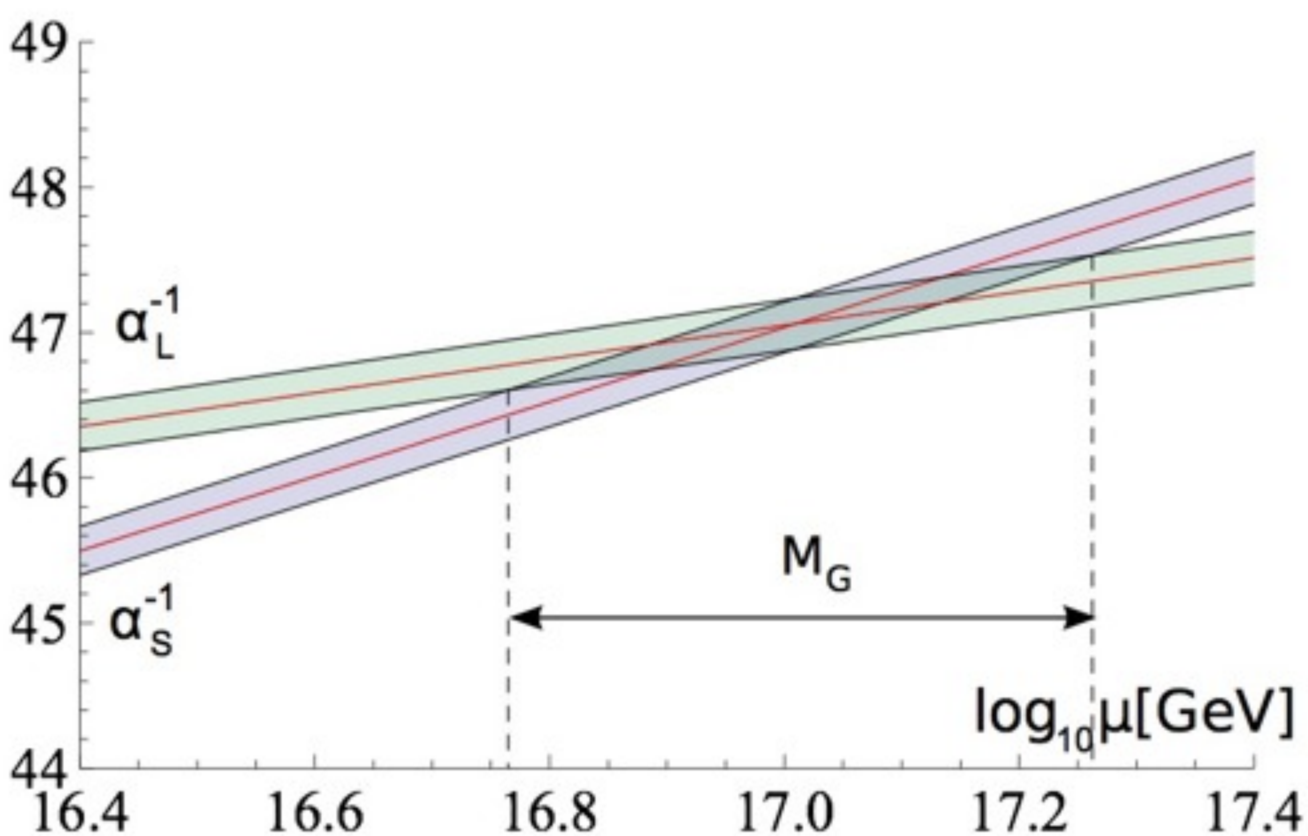

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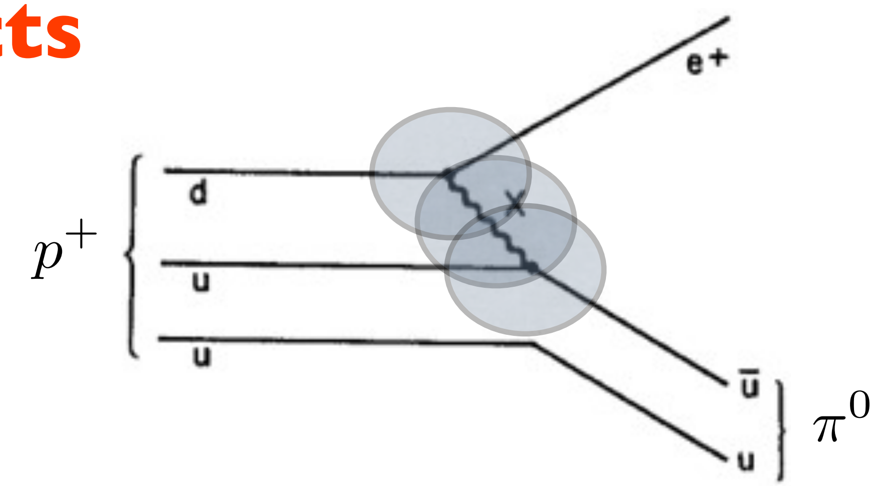

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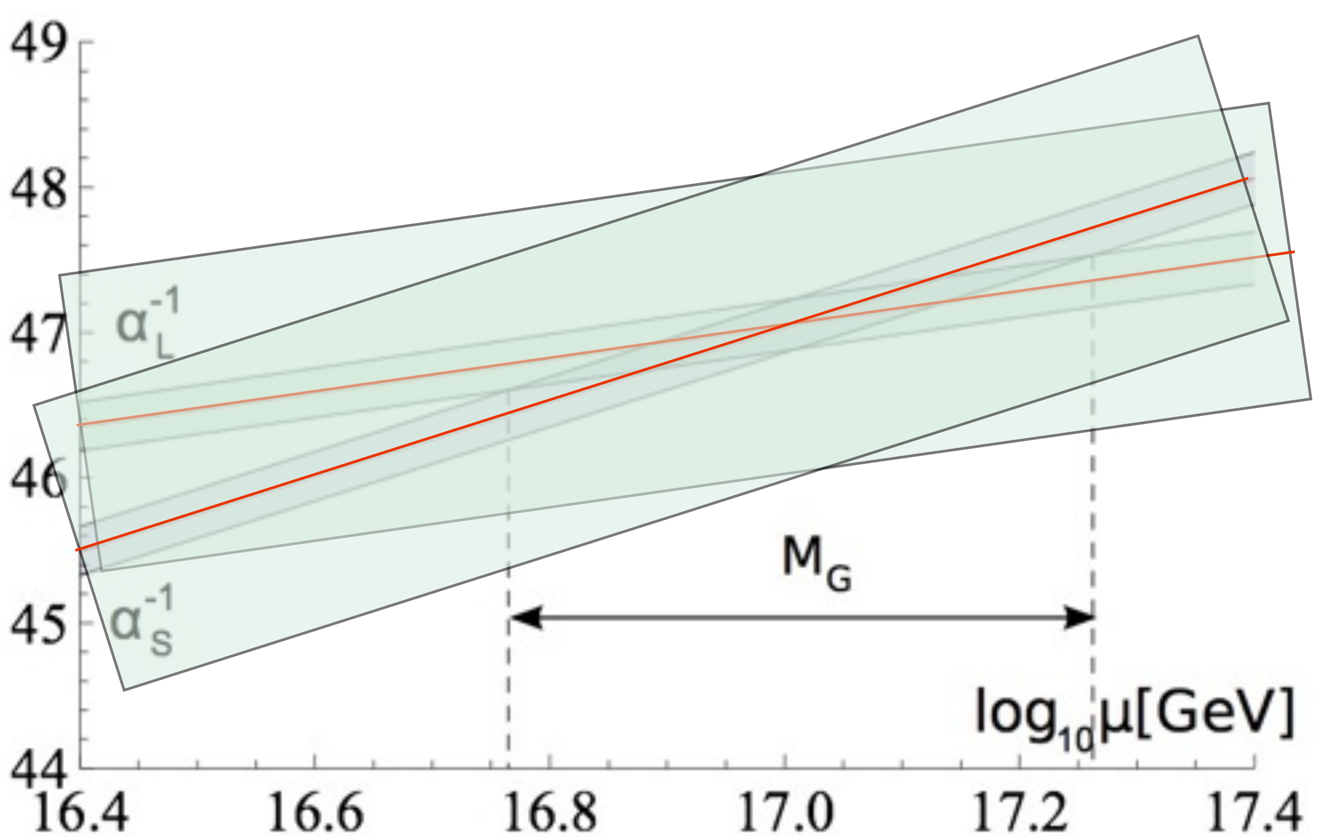

in principle orders
of magnitude uncertainty in M_G!

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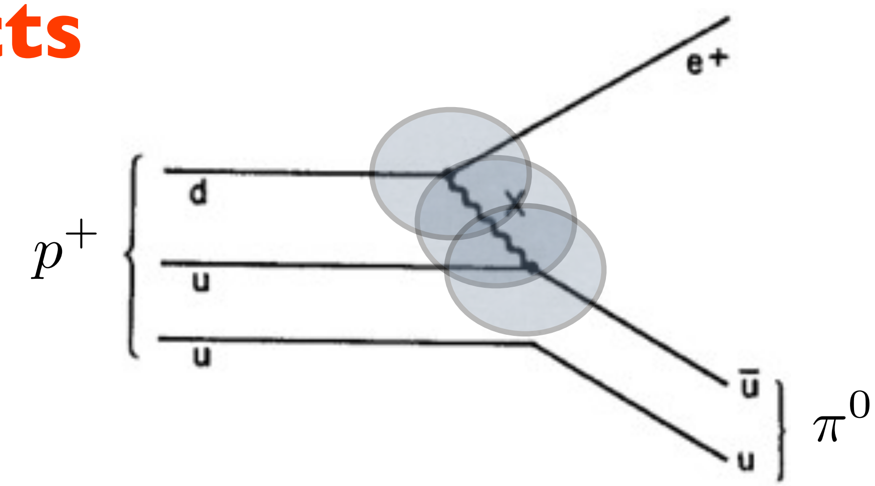

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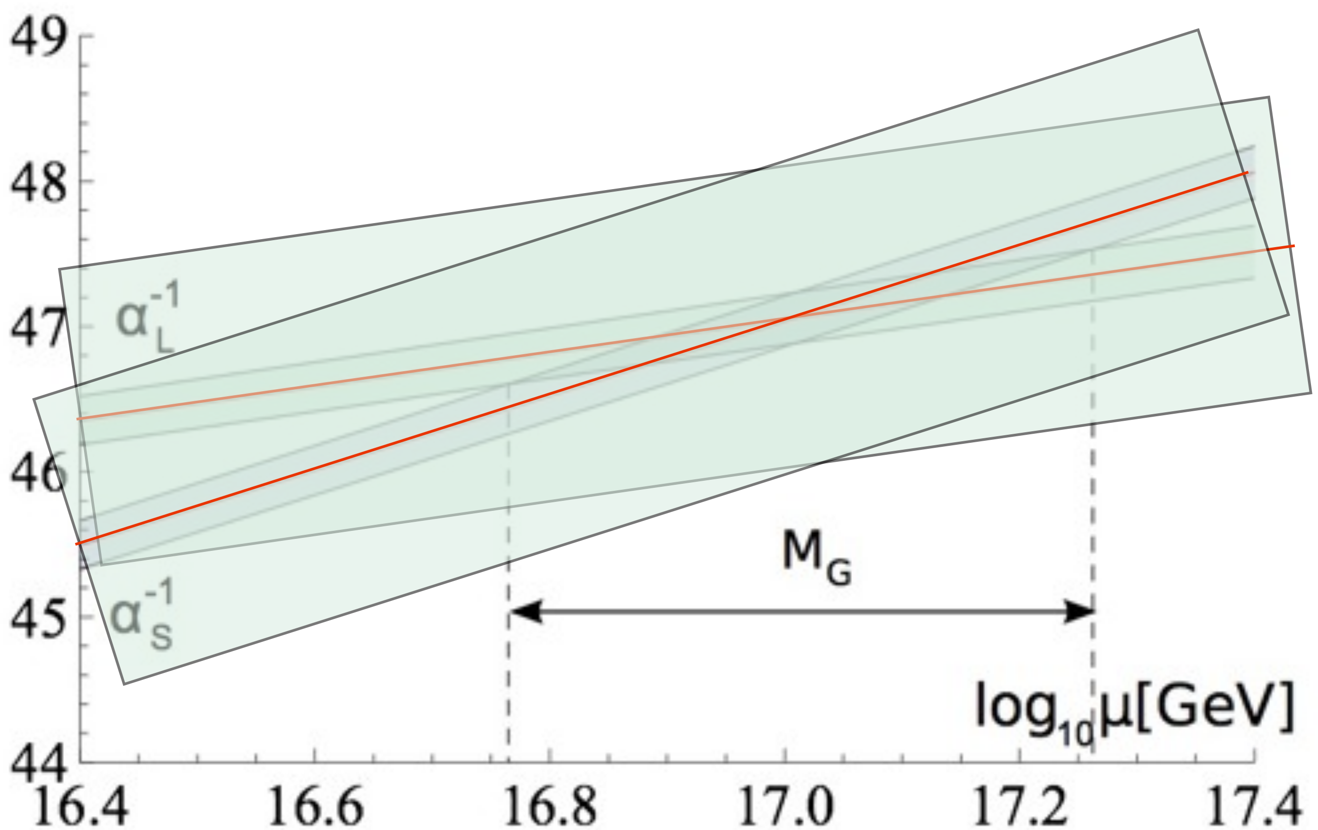

in principle orders
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No point in trying @ NLO without taming these!!!

What to do about the Planck-scale effects (in matching)?

$$\mathcal{L} \ni \frac{\kappa}{\Lambda} F^{\mu\nu} \langle \Phi \rangle F_{\mu\nu}$$

- absent @ d=5 if, e.g., Φ is not in $(Adj. \otimes Adj.)_{sym}$

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SU(5) GUTs:

$$(24 \otimes 24)_{sym} = 24 \oplus 75 \oplus 200$$

not many options - the rank should not get reduced...

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not many options - the rank should not get reduced...

SO(10) GUTs:

$$(45 \otimes 45)_{sym} = 54 \oplus 210 \oplus 770$$

these, however, are the "usual" choices (**though not minimal**)...

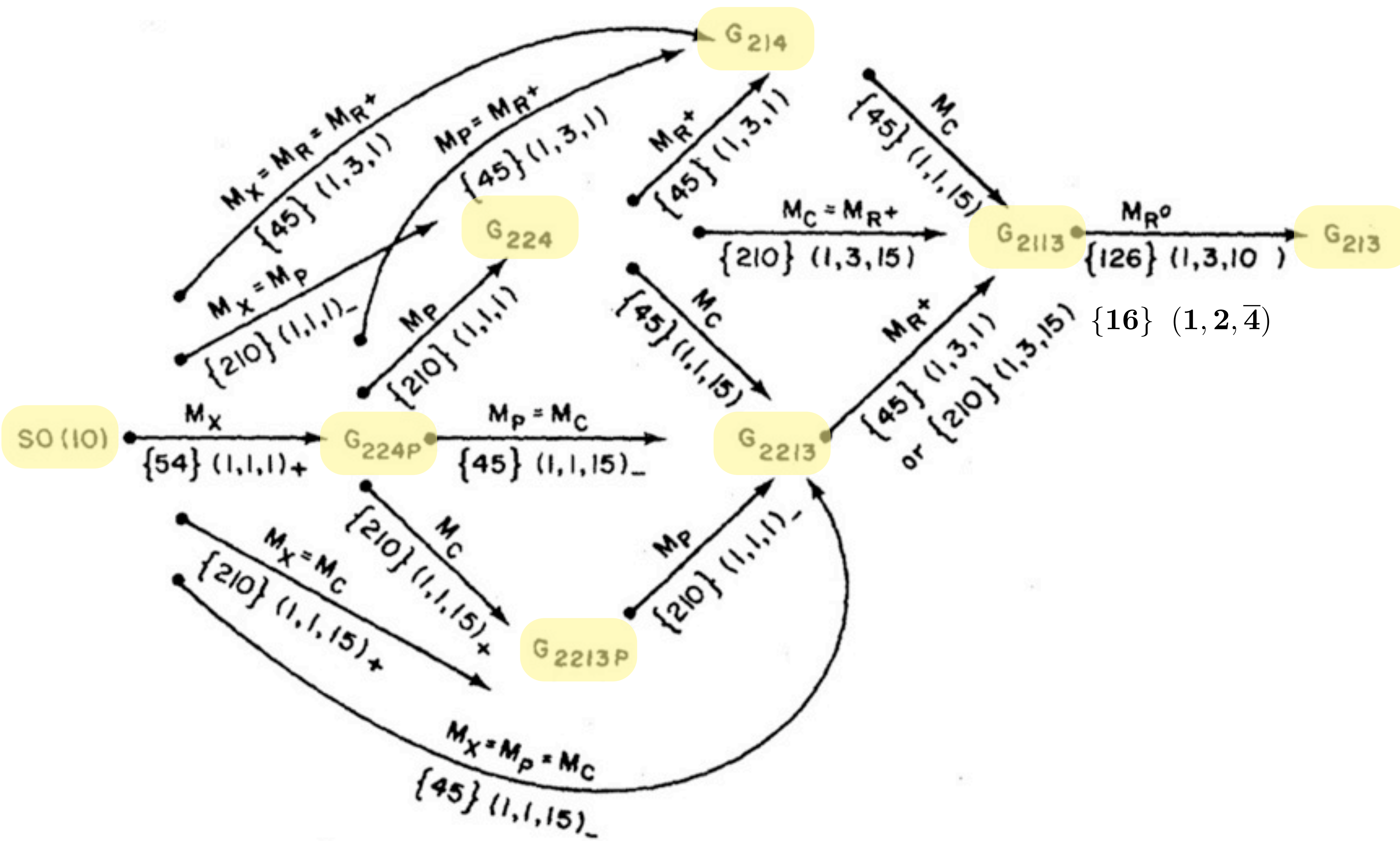
Minimal “reasonably calculable” unifications

The minimal SO(10) GUT

The minimal SO(10) Higgs model

Chang, Mohapatra, Gipson, Marshak, Parida 1985

SU(5) branches omitted



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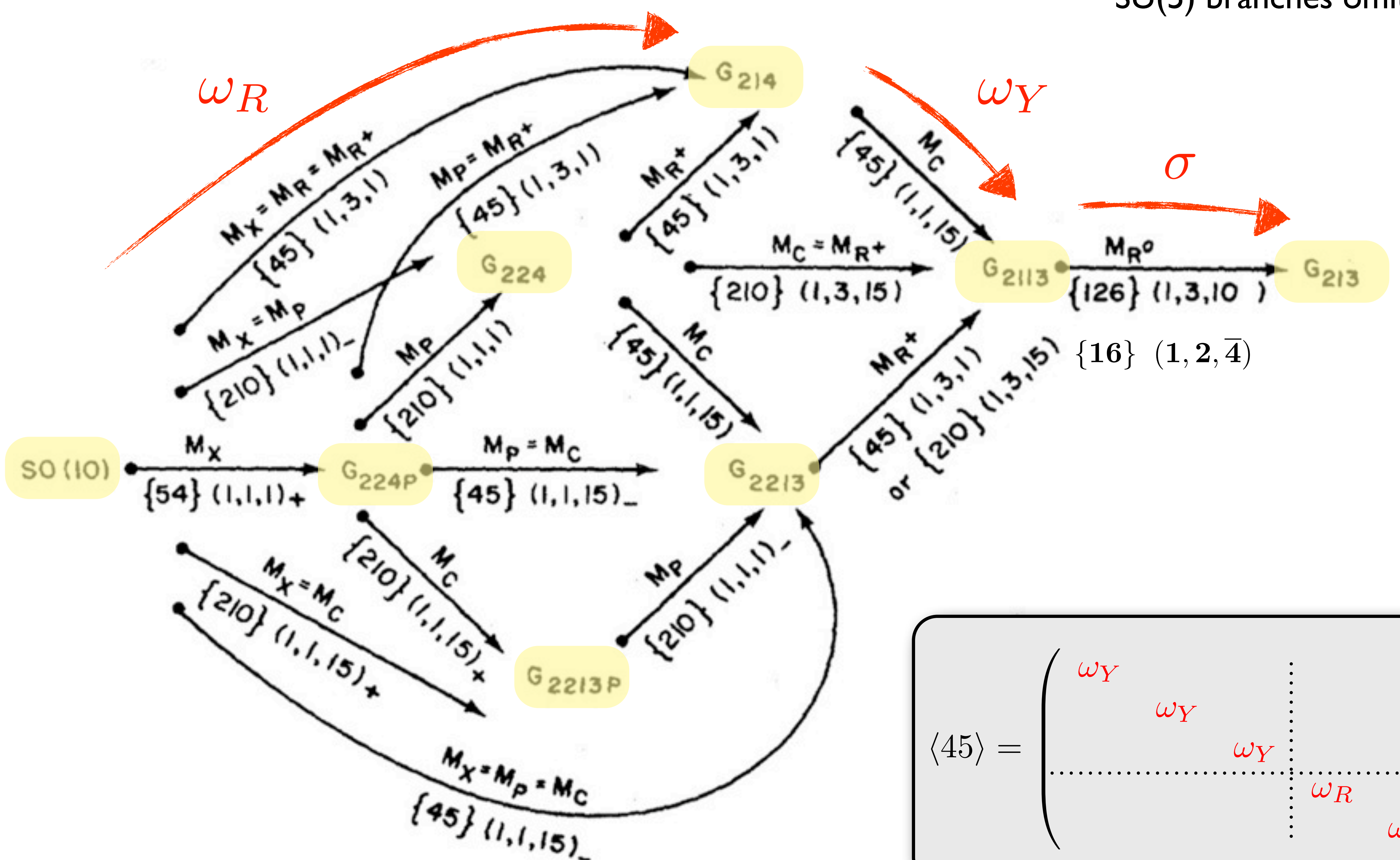

$$\langle 45\rangle = \left(\begin{array}{ccc|cc} \omega_Y & & & & \\ & \omega_Y & & & \\ & & \omega_Y & & \\ \hline & & & \omega_R & \\ & & & & \omega_R \end{array}\right) \otimes \tau_2$$

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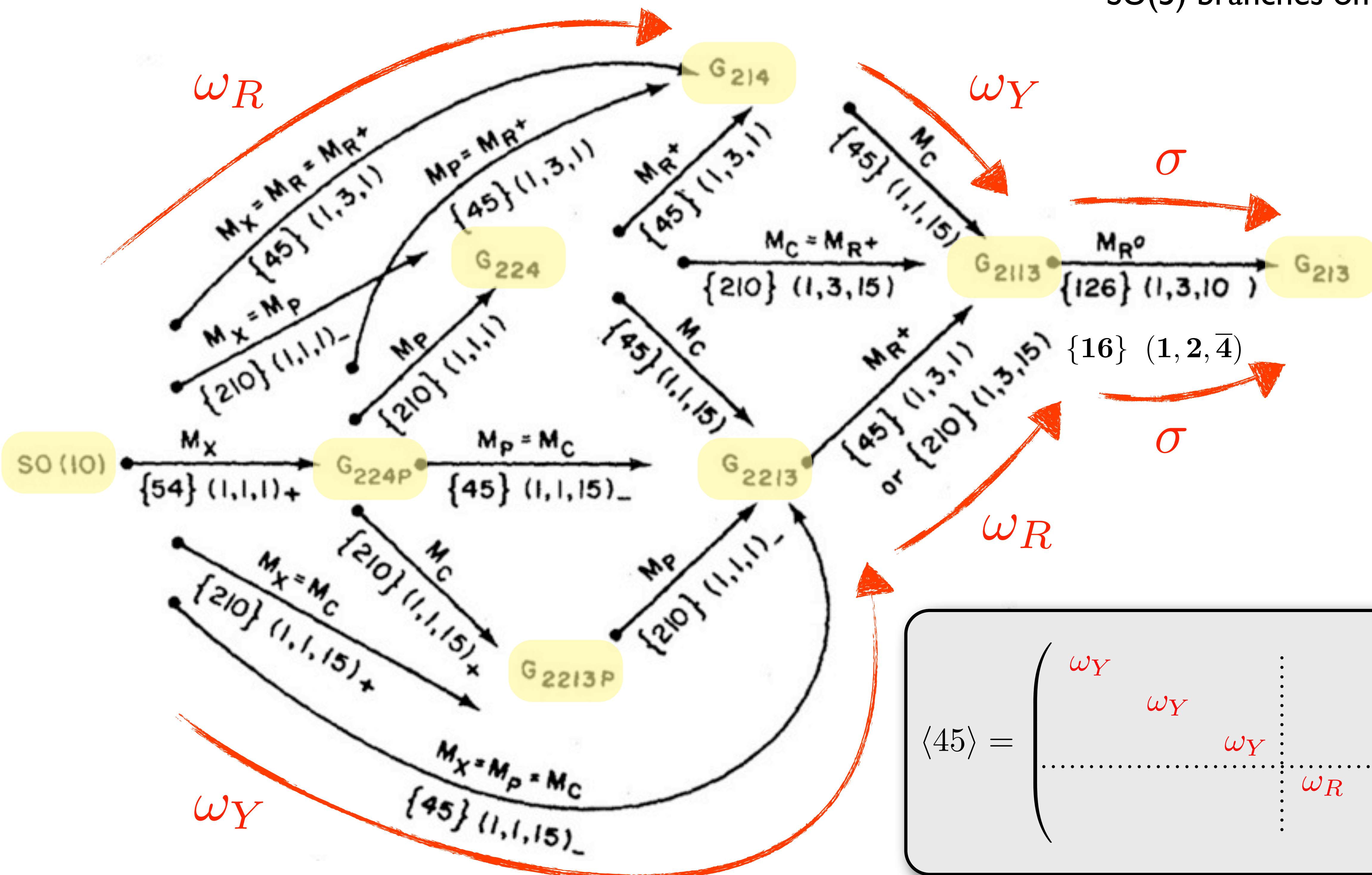

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Taming Planck effects in gauge matching in minimal SO(10)

$$\mathcal{L} \ni \frac{\kappa}{\Lambda} F^{\mu\nu} \langle 45 \rangle F_{\mu\nu} = 0$$

The leading Planck-scale effects in gauge matching absent from SO(10) GUTs broken by 45!

The minimal SO(10) Higgs model

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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The minimal SO(10) ~~Higgs model~~ nightmare

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

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

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

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

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

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

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

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

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The minimal SO(10) Higgs ~~model~~ 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

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

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

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

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

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\hline
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Quantum salvation of the 45-broken SO(10) Higgs model

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

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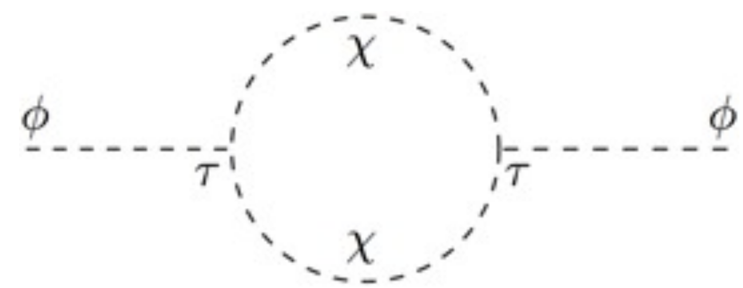
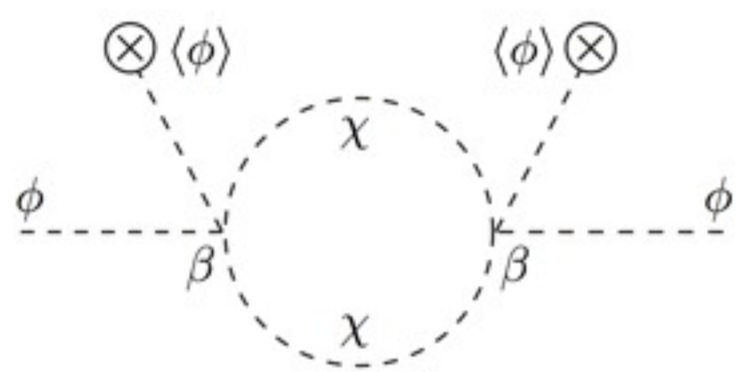
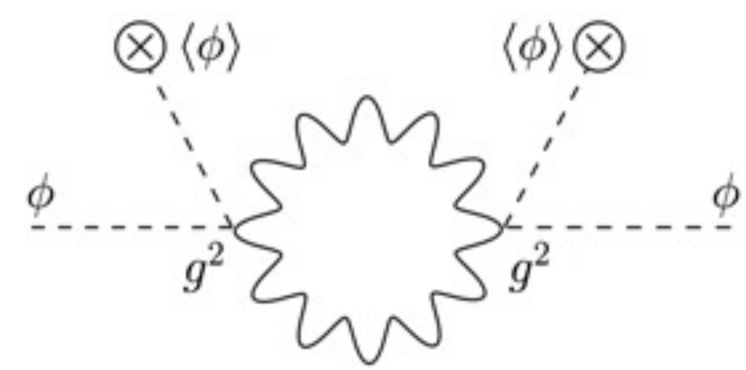
One-loop effective potential:







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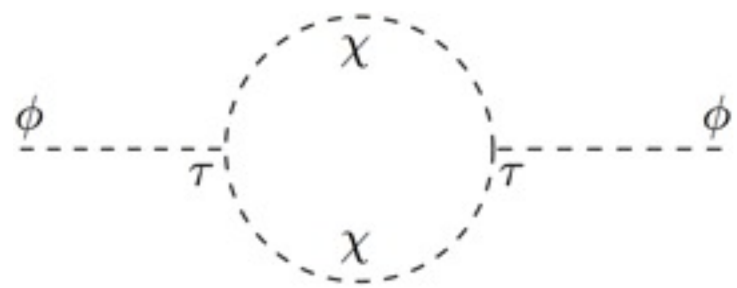

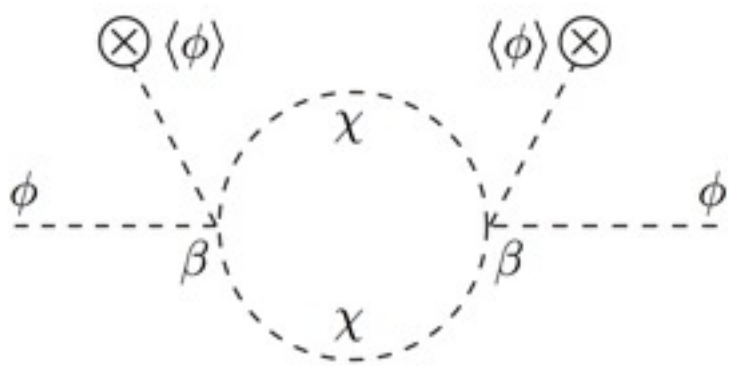

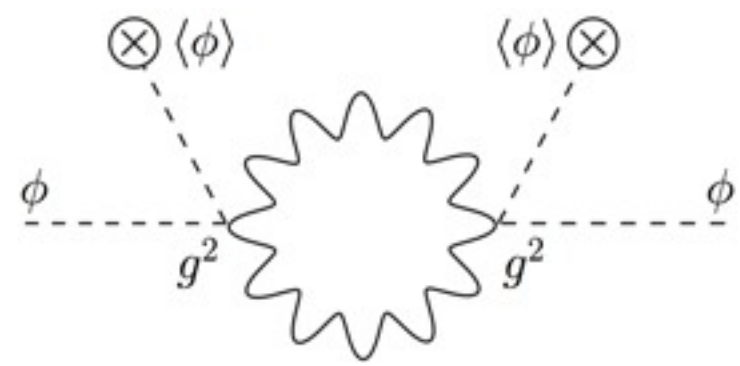

$$\Delta m^2_{(1,3,0)} = \frac{1}{4\pi^2}\left[\tau^2 + \beta^2(2\omega_R^2 - \omega_R\omega_Y + 2\omega_Y^2) + g^4\left(16\omega_R^2 + \omega_Y\omega_R + 19\omega_Y^2\right)\right] + \text{logs}\,,$$

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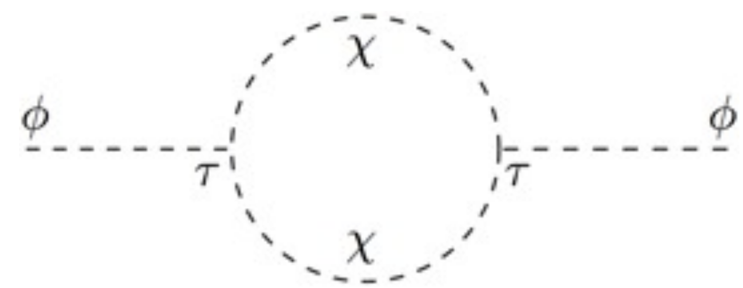

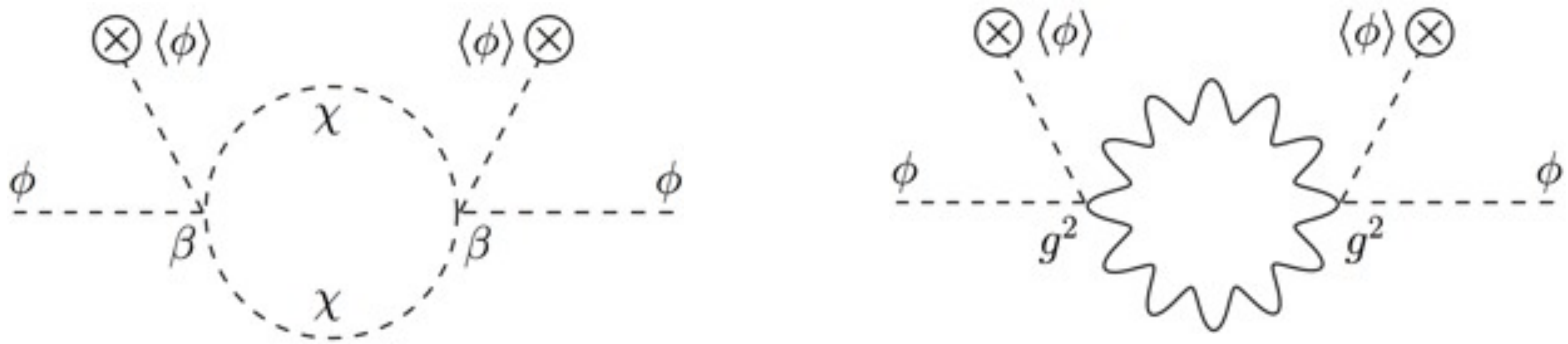

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Towards a consistent & potentially realistic SO(10) scenario

"Consistency is the last refuge
of people without imagination"

Oscar Wilde

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multiple Yukawa finetuning?

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Two other potentially realistic minimally fine-tuned & consistent scenarios with “light” scalars in the desert

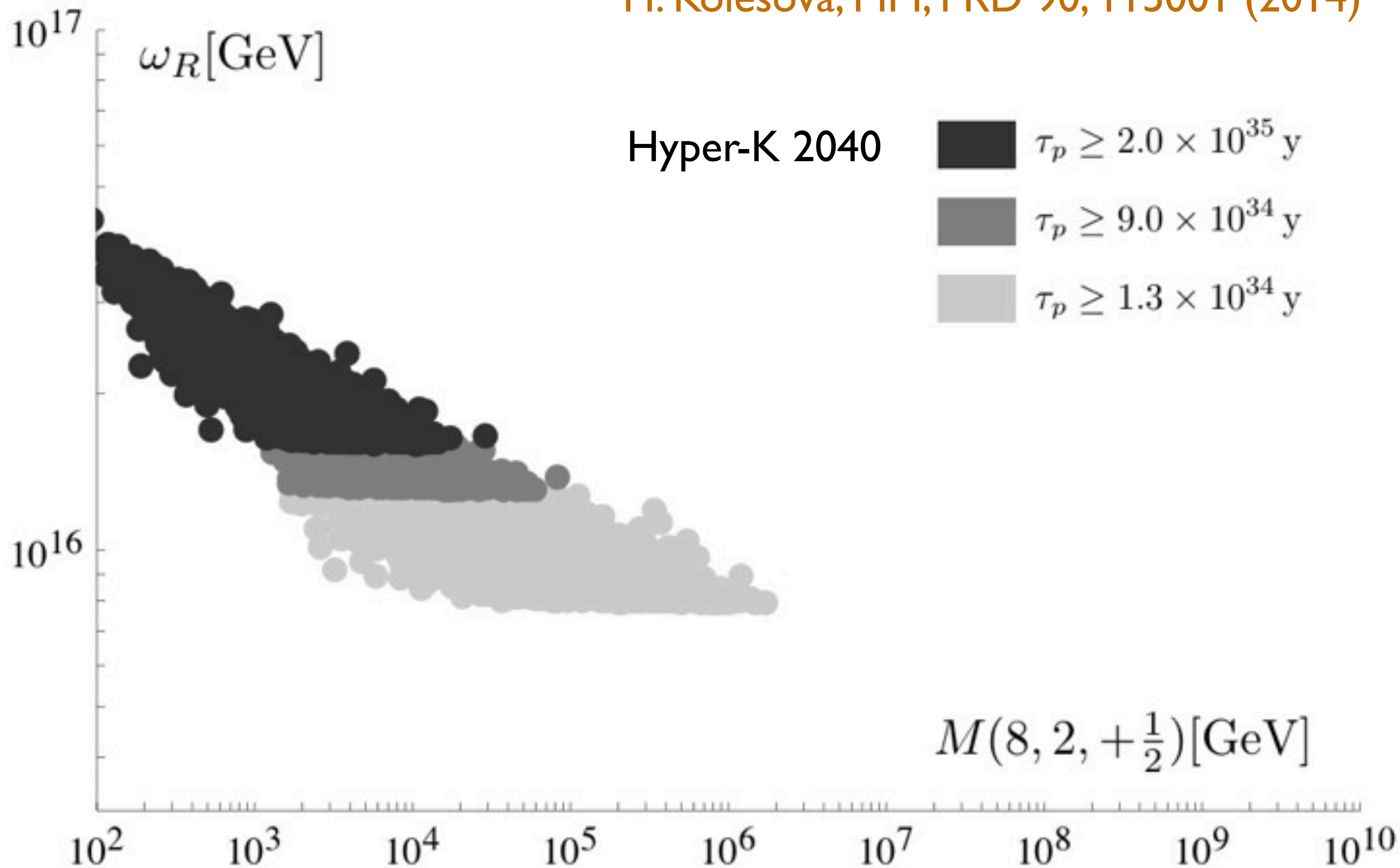
Bertolini, Di Luzio, MM, PRD85 095014 2012

Towards a consistent & potentially realistic SO(10) scenario

Example: light $(8, 2, +\frac{1}{2})$ @ NLO

Bertolini, Di Luzio, MM, PRD 85, 095014 (2012)

H. Kolešová, MM, PRD 90, 115001 (2014)



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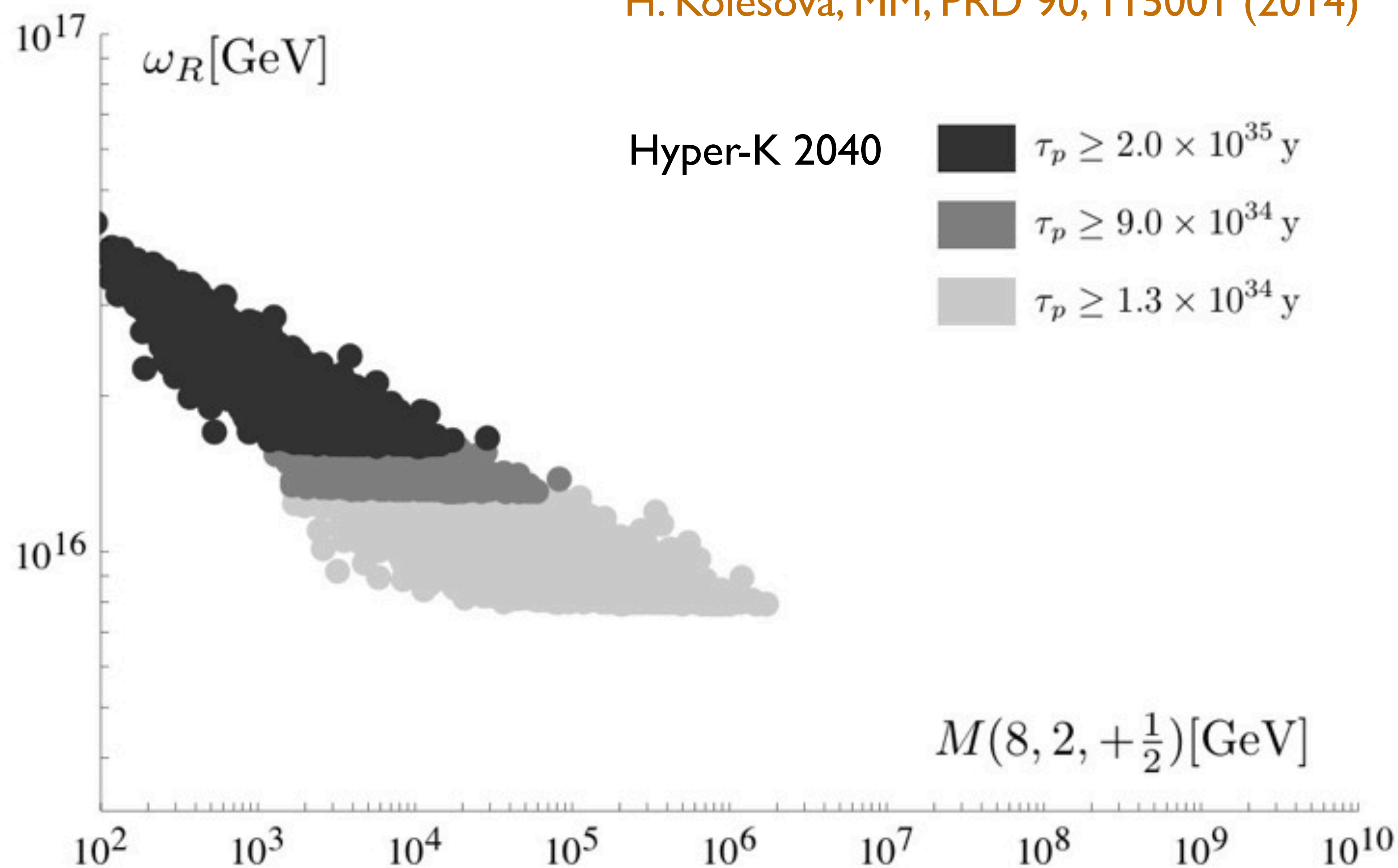

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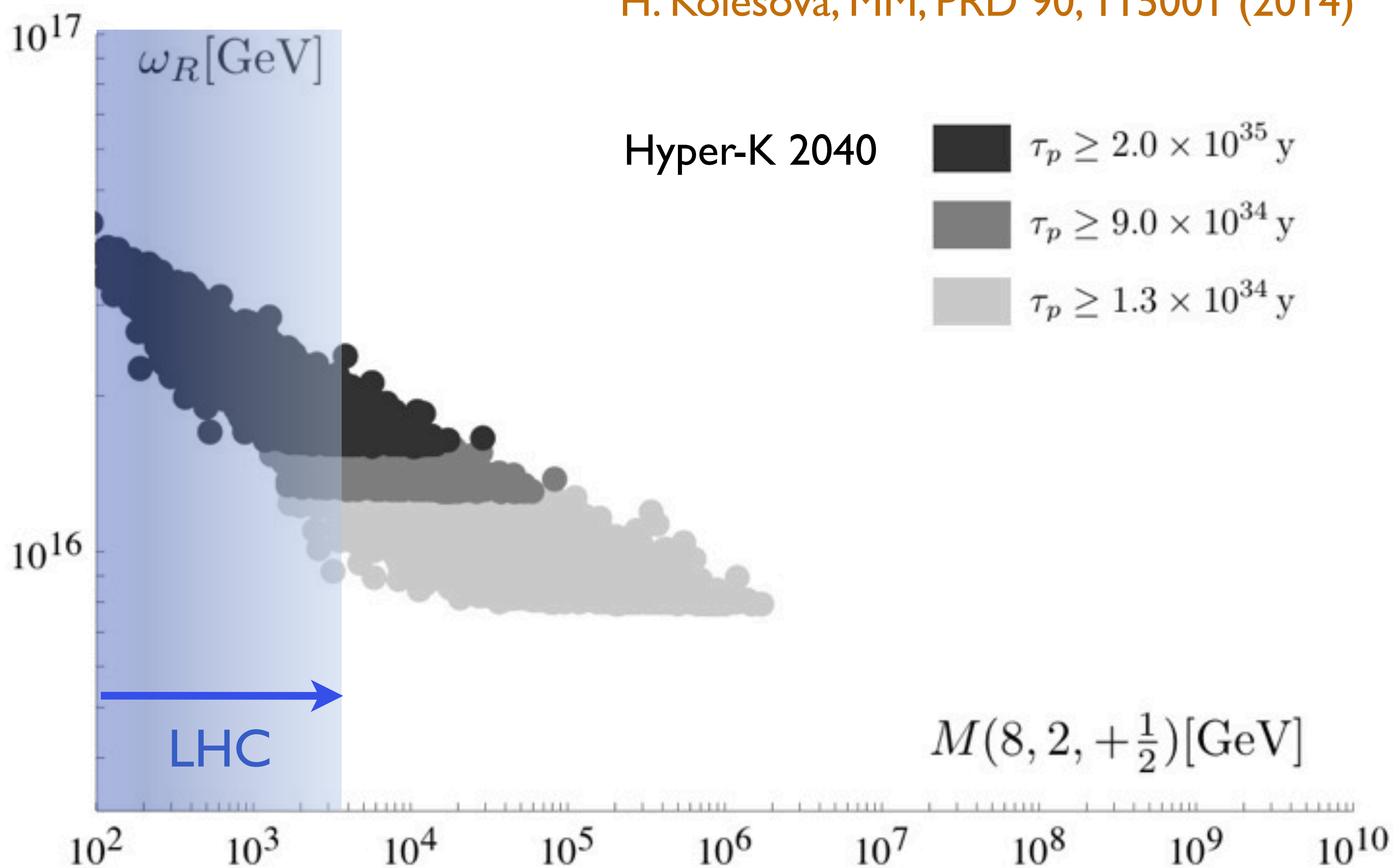

Minimal flipped SU(5) UT

a case for radiative neutrino mass generation

A brief flipped SU(5) recap

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SO(10) $\supset$ SU(5) x U(1)$_Z$

$$16_M \ni \quad (10,+1)_M \oplus (\overline{5},-3)_M \oplus (1,+5)_M$$

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$16_H \ni \quad (10,+1)_H$ SU(5) x U(1) to the SM

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  the VEV of (10,+1) = the mass of the X',Y' bosons - predictive!

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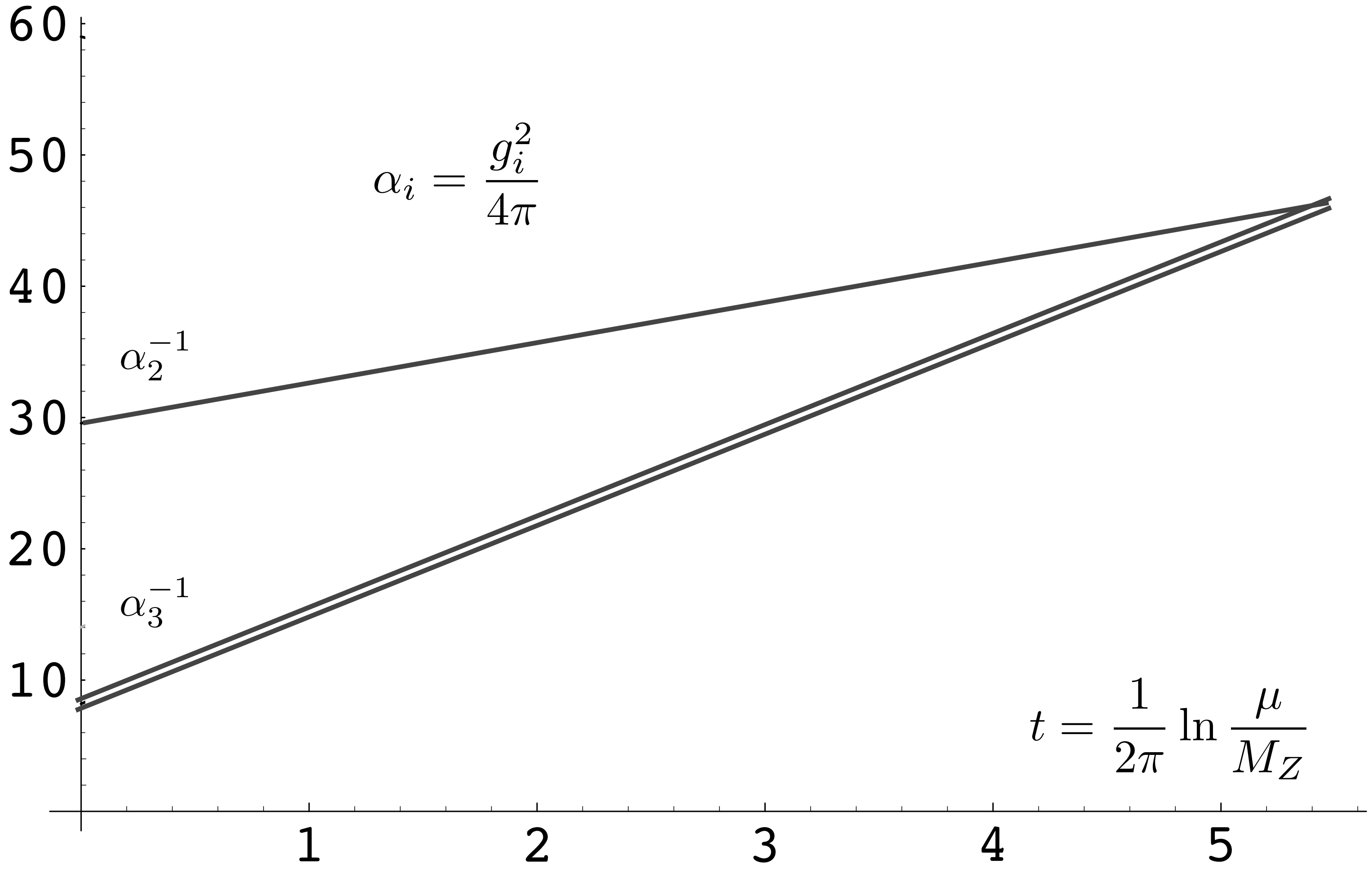

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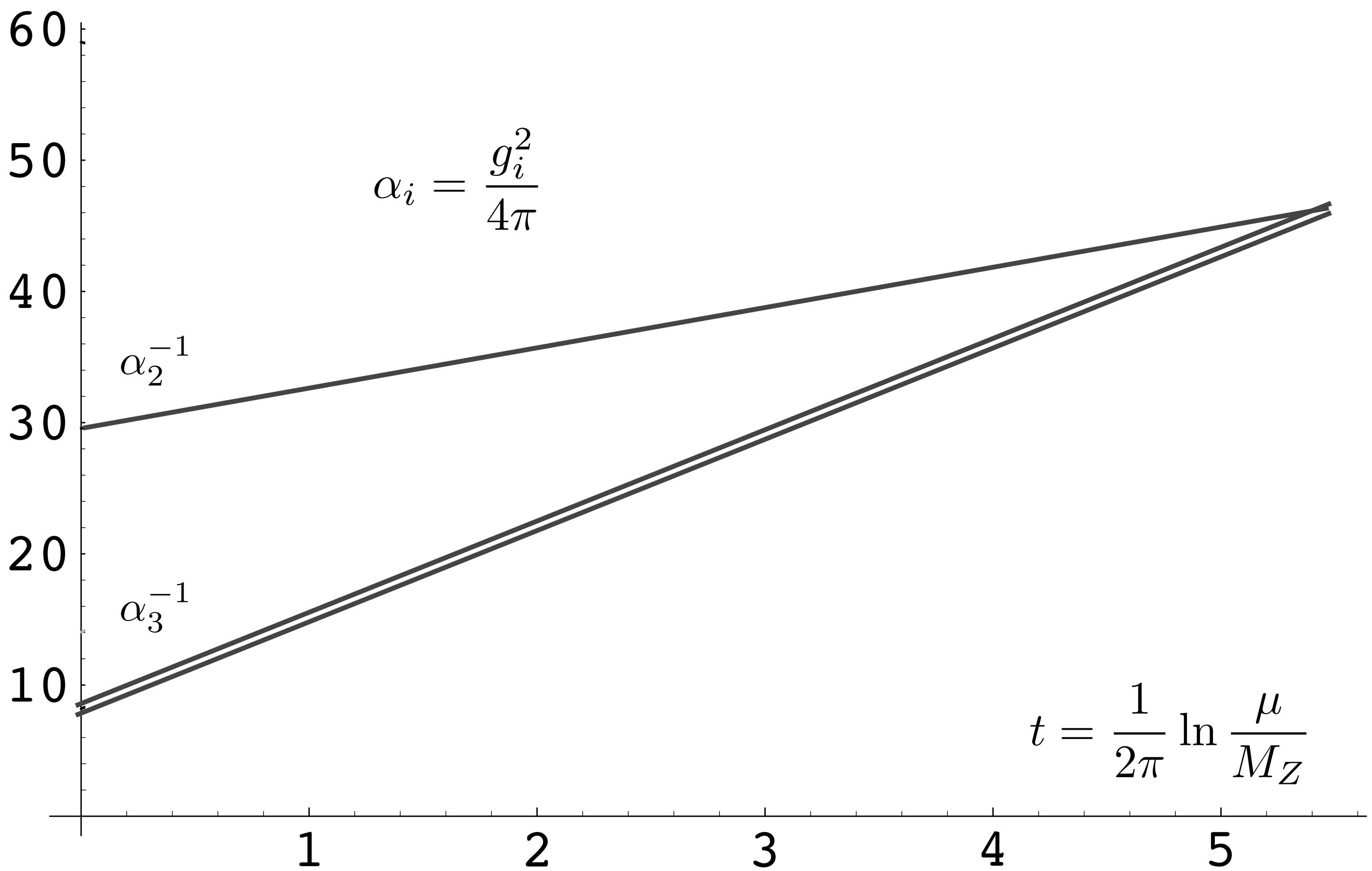

- monopoles absent $\pi_2(SU(5)\otimes U(1)/SU(3)\otimes SU(2)\otimes U(1))$

$$= \pi_2(SU(5)/SU(3)\otimes SU(2))$$

$$= \pi_1(SU(3)\otimes SU(2)) = 0$$

Taming Planck effects in gauge matching in the flipped SU(5)

$$\mathcal{L} \not\ni \frac{\omega}{M_{Pl}} F_{\mu\nu} \langle \Phi \rangle F^{\mu\nu}$$

The leading Planck-scale effects in gauge matching absent from the flipped SU(5) UT broken by (10,+1)!

The minimal flipped SU(5) flavor structure

rather different from the standard SU(5) one

$$\mathcal{L} \ni Y_{10} 10_M 10_M 5_H + Y_{\overline{5}} 10_M \overline{5}_M 5_H^* + Y_1 \overline{5}_M 1_M 5_H + h.c.$$

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$$M_d = M_d^T \propto Y_{10} \quad M_u = {M_\nu^D}^T \propto Y_{\overline{5}} \quad M_e \propto Y_1 \ \text{arbitrary} \qquad M_\nu^M = 0$$

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down-quark mass matrix is independent - unlike in SU(5) - and **symmetric!**

$$\boxed{\Gamma(p \to K^+ \overline{\nu})} = 0$$

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clearly incomplete: neutrinos massive, but **heavy & Dirac**

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$\mathbf{50_H}$ **usually added** to generate RH neutrino masses/seesaw at tree level...

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$$\frac{\Gamma(p \to \pi^0 e_\alpha^+)}{\Gamma(p \to \pi^+ \overline{\nu})} = \frac{1}{2} |(V_{CKM})_{11}|^2 |(U_{MNS} U_\nu)_{\alpha 1}|^2$$

$m_{LL}^\nu = {U_\nu}^T D_\nu U_\nu$ in the up-diagonal basis

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$$m^\nu_{LL} = {U_\nu}^T D_\nu U_\nu$$ in the up-diagonal basis

- in this approach U_ν is an independent structure
- little grip on the charged lepton channels

Witten's loop in the SO(10) GUTs

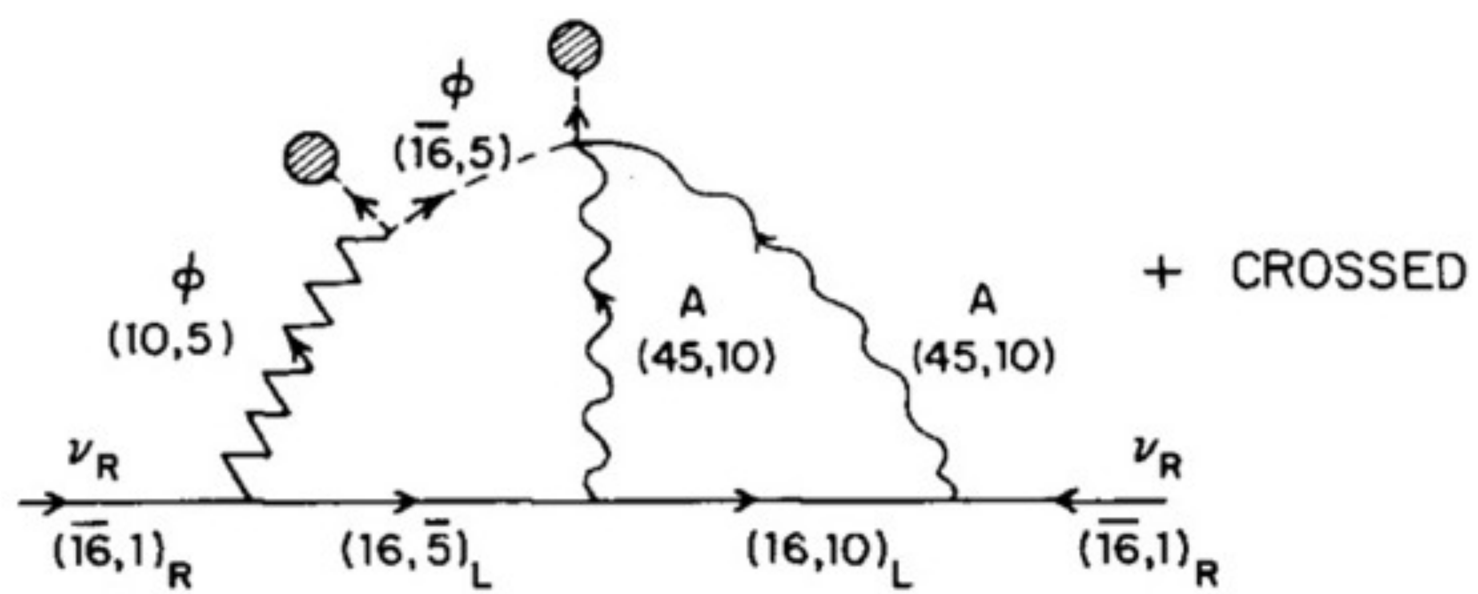
NEUTRINO MASSES IN THE MINIMAL O(10) THEORY ☆

Phys. Lett. B91 (1980) 81

Edward WITTEN [1]
Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

Received 6 December 1979

Neutrino masses are discussed in the context of the O(10) grand unified theory. In the "minimal" form of this theory, with minimal Higgs and fermion content, the right-handed neutrinos acquire masses at the two loop level. The left-handed neutrino masses are correspondingly *larger* by a factor roughly $(\alpha/\pi)^{-2}$ than they would be if the right-handed neutrino could acquire mass at the tree level. In the simplest form of this theory, the neutrino mass matrix is proportional to the up quark mass matrix, and the neutrino mixing angles equal the usual Cabibbo angles. The neutrino masses will be roughly in the range $10^{0\pm2}$ eV depending on the strength of O(10) symmetry breaking, and on certain unknown ratios of masses and couplings of superheavy particles.



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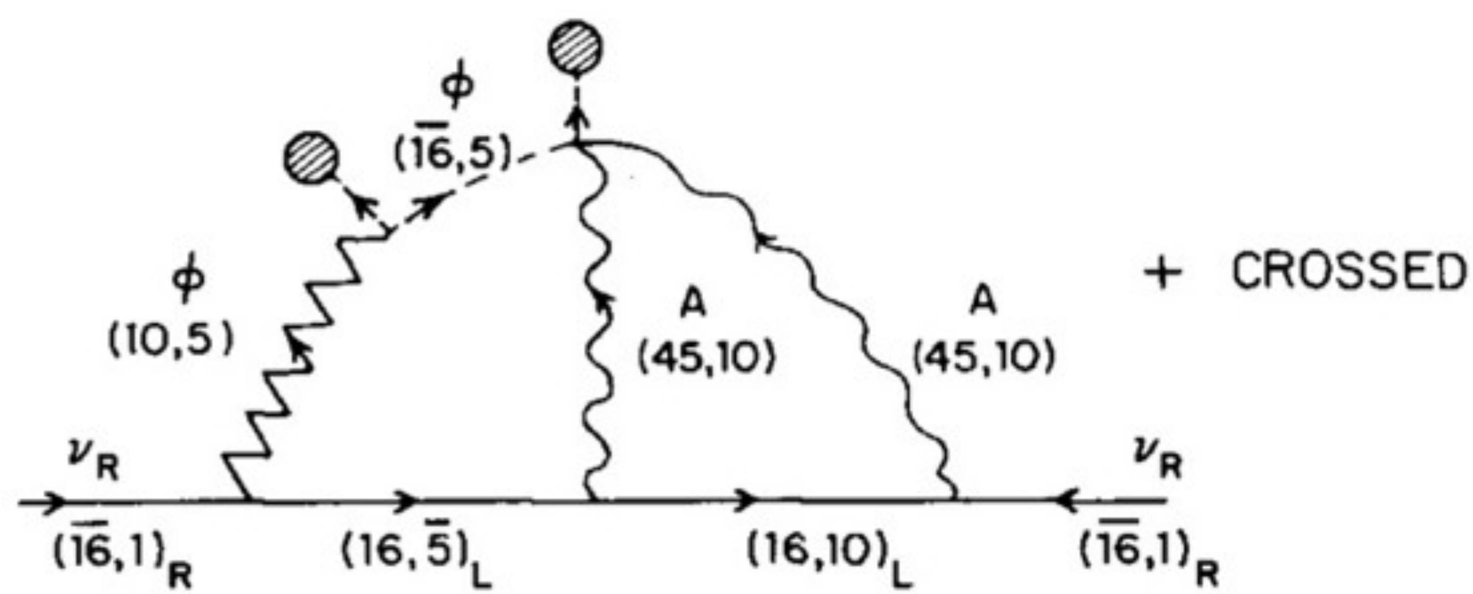
Neutrino masses are discussed in the context of the O(10) grand unified theory. In the "minimal" form of this theory, with minimal Higgs and fermion content, the right-handed neutrinos acquire masses at the two loop level. The left-handed neutrino masses are correspondingly *larger* by a factor roughly $(\alpha/\pi)^{-2}$ than they would be if the right-handed neutrino could acquire mass at the tree level. In the simplest form of this theory, the neutrino mass matrix is proportional to the up quark mass matrix, and the neutrino mixing angles equal the usual Cabibbo angles. The neutrino masses will be roughly in the range $10^{0\pm2}$ eV depending on the strength of O(10) symmetry breaking, and on certain unknown ratios of masses and couplings of superheavy particles.



Witten's loop in the SO(10) GUTs

NEUTRINO MASSES IN THE MINIMAL O(10) THEORY ☆

Phys. Lett. B91 (1980) 81

Edward WITTEN [1]
Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

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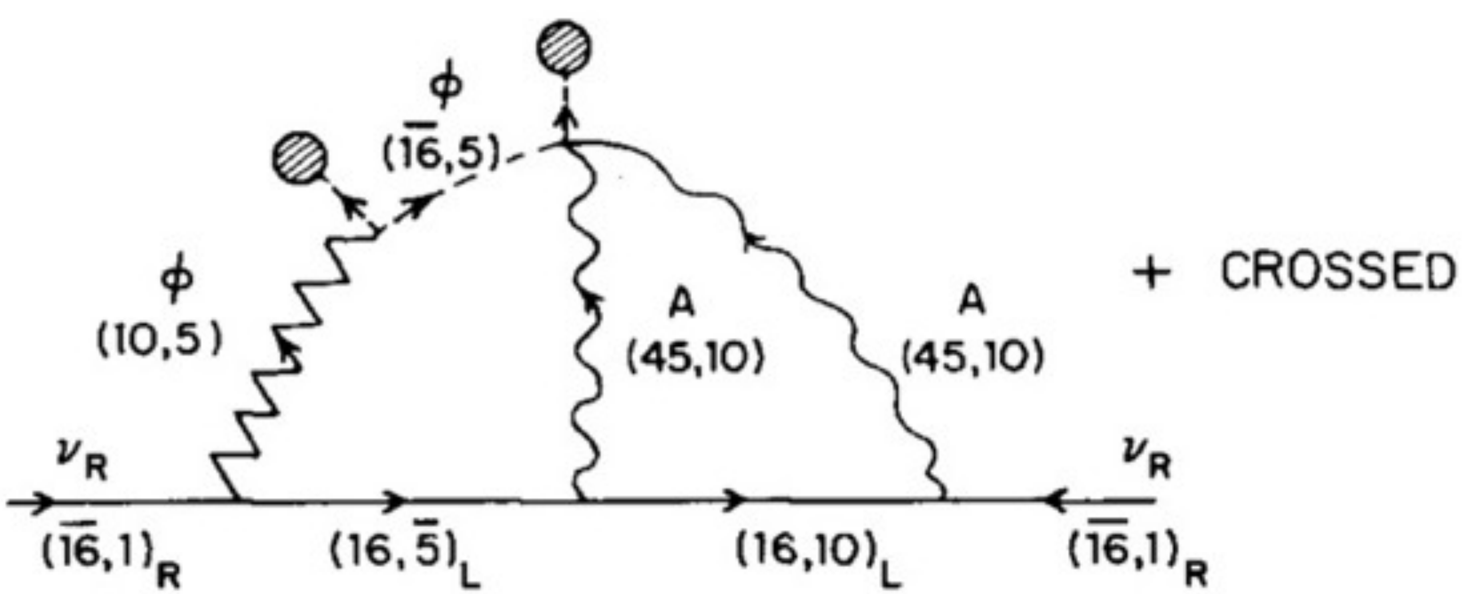


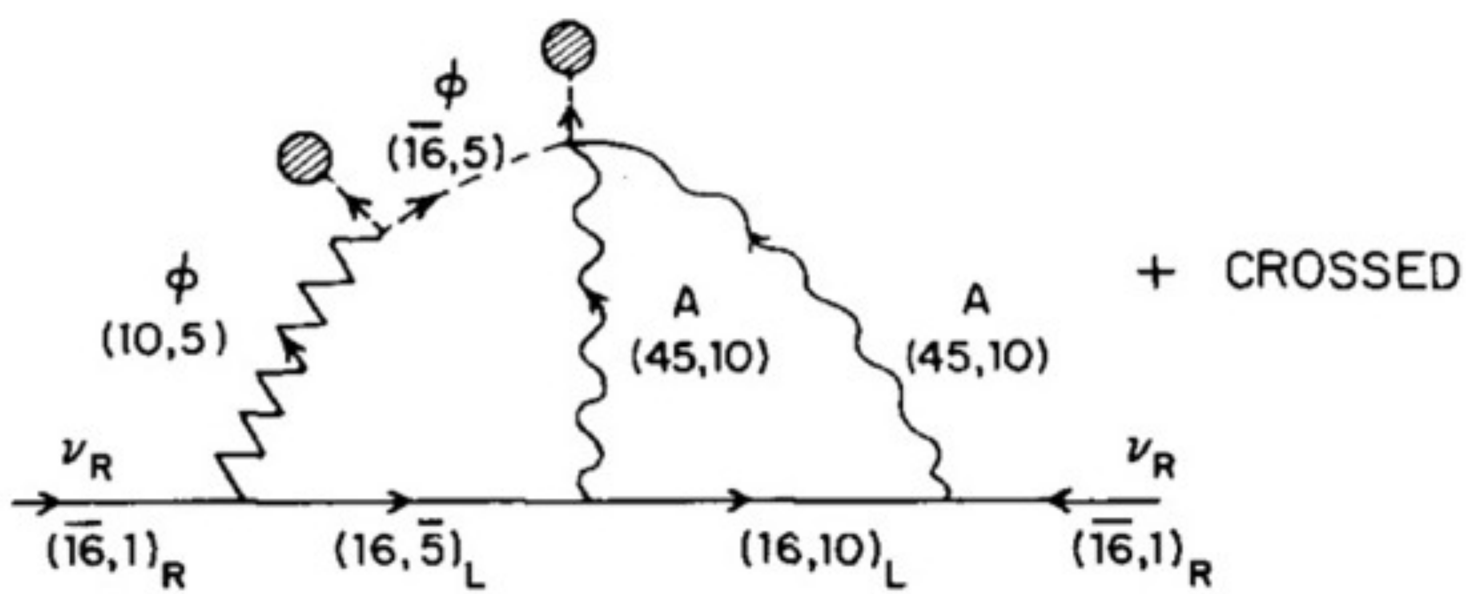
Witten's loop in the SO(10) GUTs

- the structure is pretty unique:

need to mimic 126_H, i.e., 5-index tensor with fields coupled to 16_M

these are 10_H, 45_G, the former has 1 and the latter has 2 indices

$10_H \times 45_G \times 45_G$



Witten's loop in the SO(10) GUTs

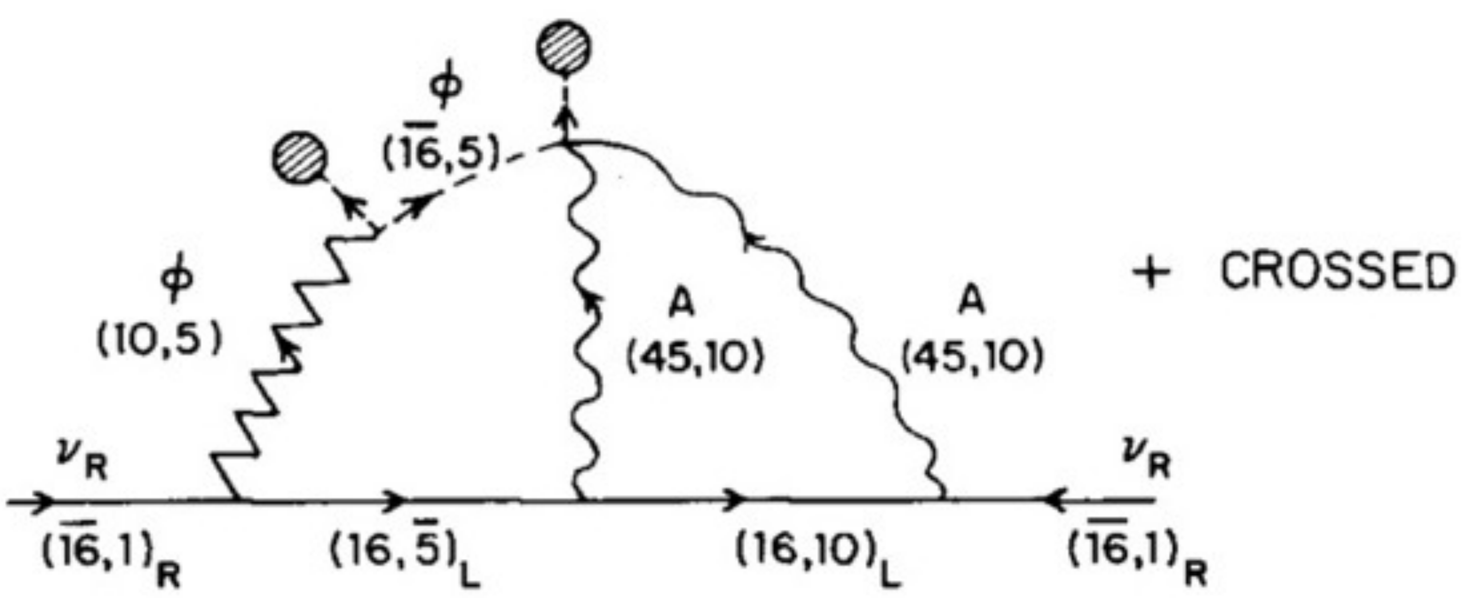
- not many true applications though!

1980: GUT scale known to be well above 10^{14} GeV

one-step unification OK

mid 1980's: one-step unification failure

TeV-scale SUSY comes to rescue



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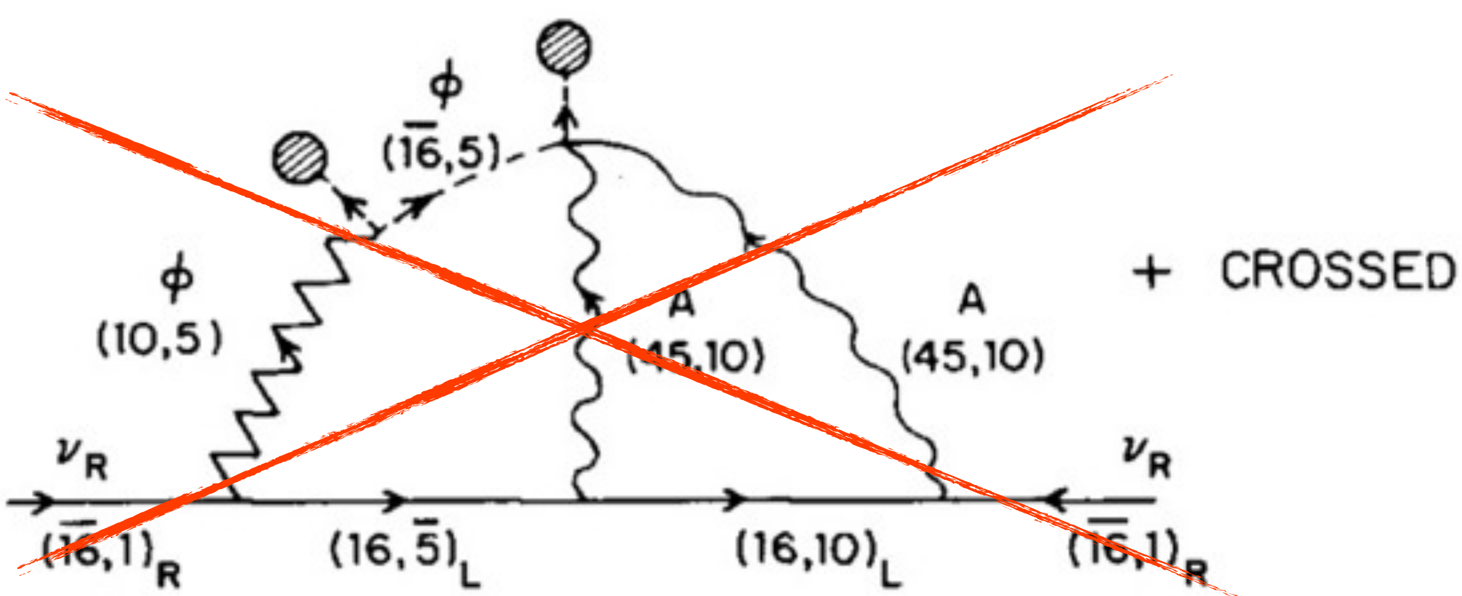

Witten's loop in the SO(10) GUTs

... yet several brave people have considered it...

Witten's loop in the SO(10) GUTs

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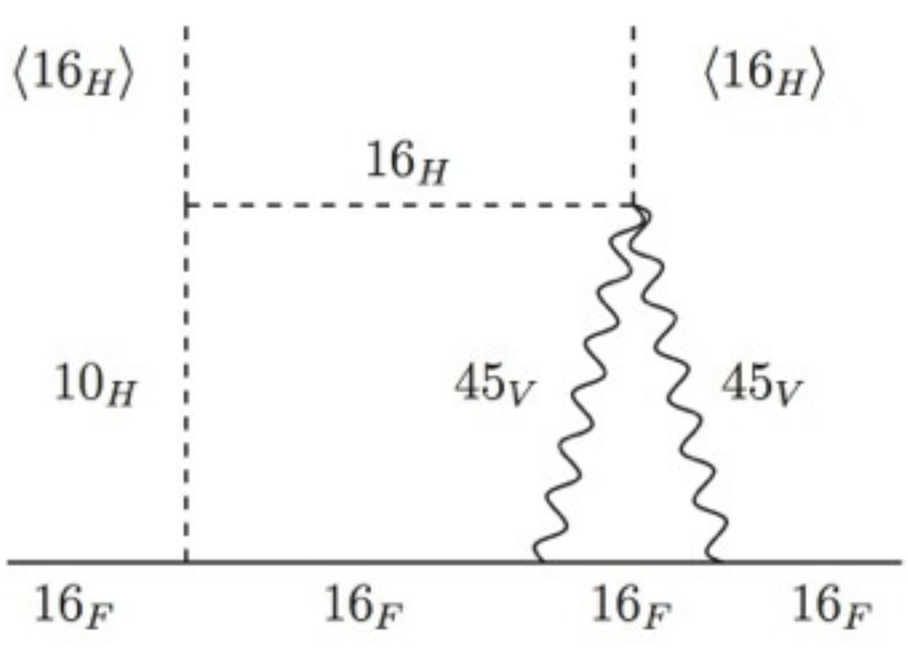
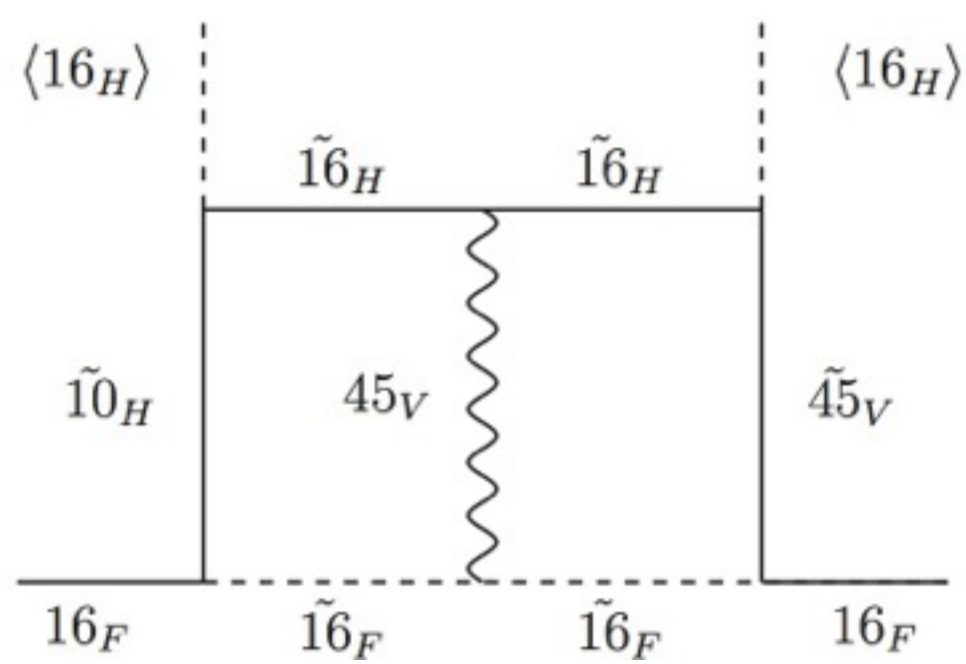
Extremely split SUSY: SUSY scalars at the GUT scale

one-step unification

loops not killed by SUSY

Bajc, Senjanovic, Phys. Lett.B610 (2005) 80





Witten's loop in the flipped SU(5)

C. Arbelaez Rodrigues, H. Kolešová, MM, PRD 89, 055003 (2014)

Witten's loop in the flipped SU(5)

C. Arbelaez Rodrigues, H. Kolešová, MM, PRD 89, 055003 (2014)

- works from scratch even in the minimal setting

- the VEV cares only about the SU(3) x SU(2) unification scale

- there **neutrino flavor structure correlated with quarks**

Witten's loop in the flipped SU(5)

C. Arbelaez Rodrigues, H. Kolešová, MM, PRD 89, 055003 (2014)

- works from scratch even in the minimal setting
- the VEV cares only about the SU(3) x SU(2) unification scale
- there **neutrino flavor structure correlated with quarks**

Given U_ν there would be a prediction for ALL proton decay channels!!!

$\Gamma(p \to \pi^0 \ell_\alpha^+)$	$\Gamma(p \to \pi^+ \overline{\nu})$	$\Gamma(n \to \pi^- \ell_\alpha^+)$	$\Gamma(n \to \pi^0 \overline{\nu})$
$\Gamma(p \to K^0 \ell_\alpha^+)$	$\Gamma(p \to K^+ \overline{\nu})$	$\Gamma(n \to K^- \ell_\alpha^+)$	$\Gamma(n \to K^0 \overline{\nu})$
$\Gamma(p \to \eta\, \ell_\alpha^+)$			$\Gamma(n \to \eta\, \overline{\nu})$

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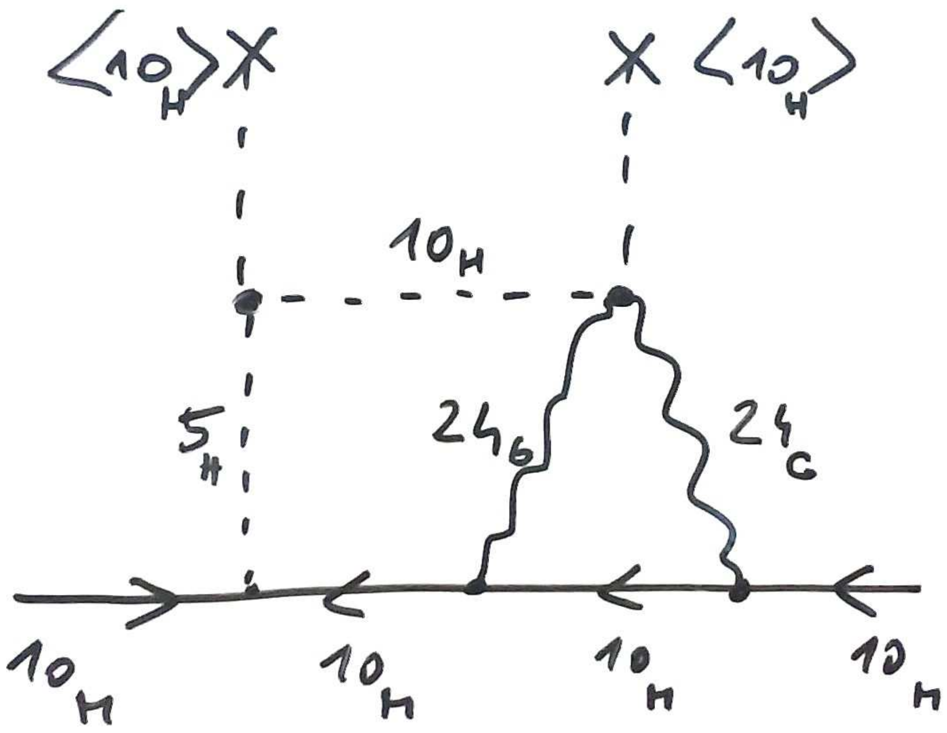

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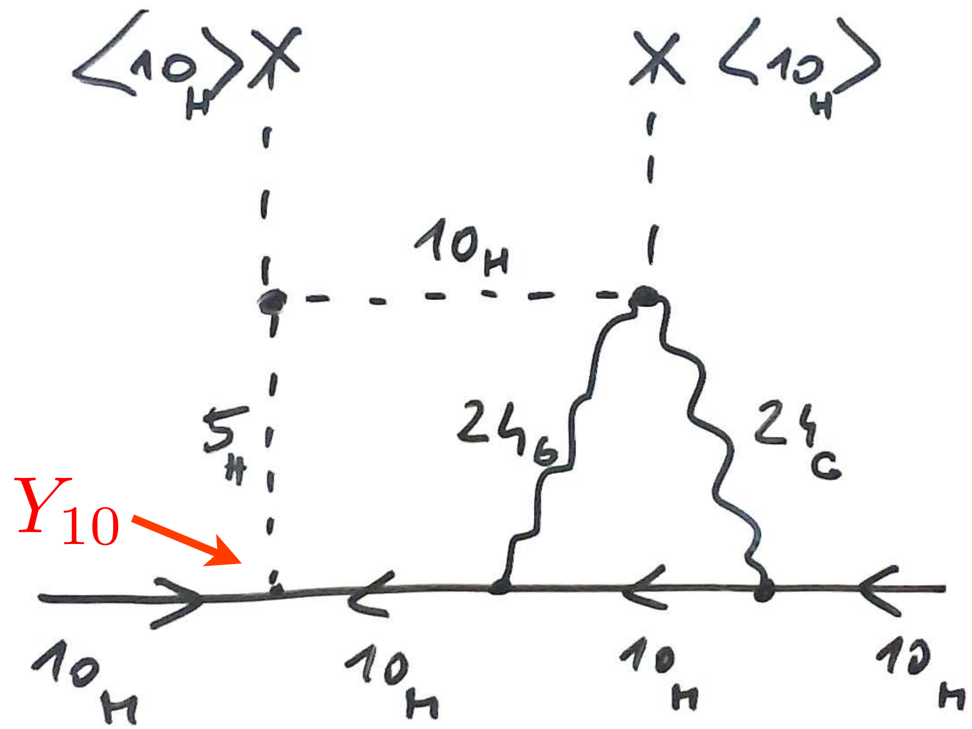
$10_M Y_{10} 10_M 5_H$



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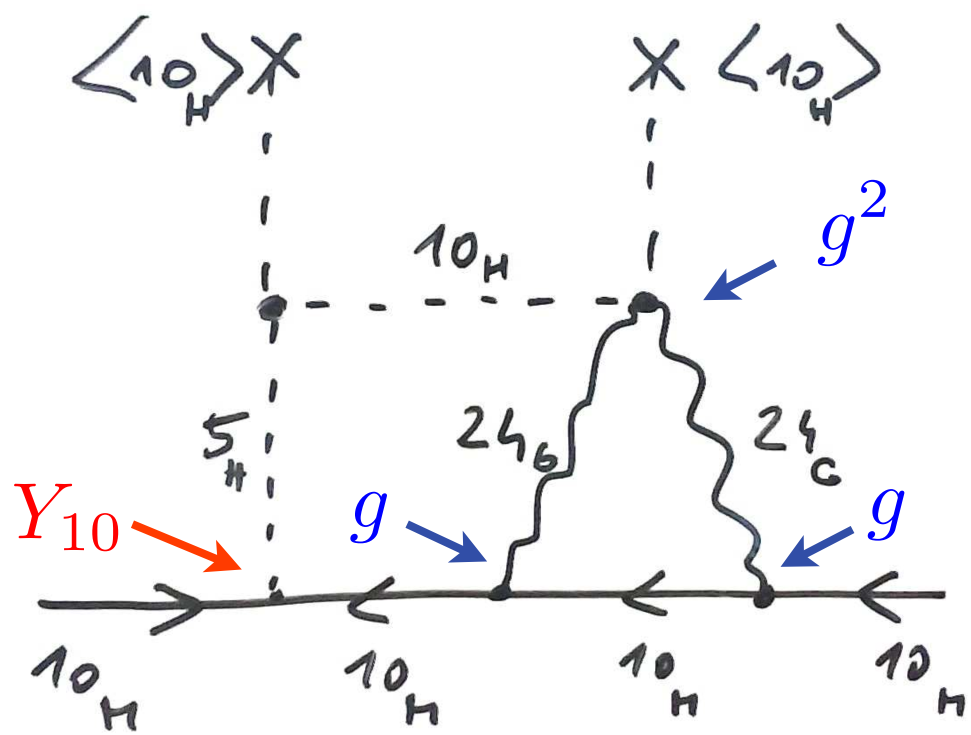

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$\mu\, 5_H 10_H 10_H$

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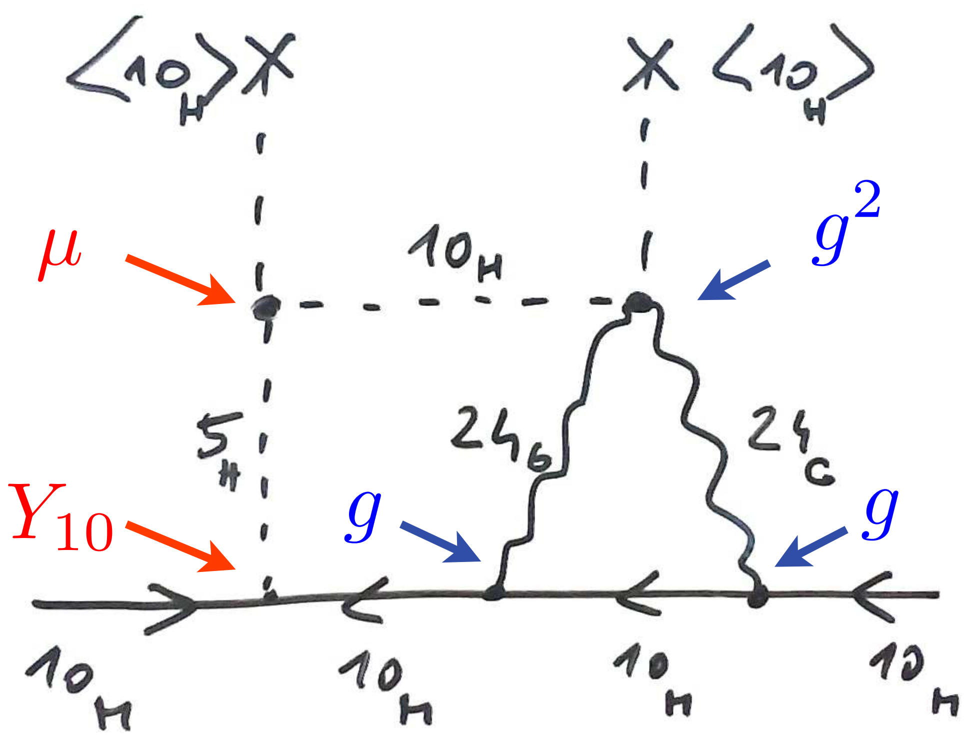

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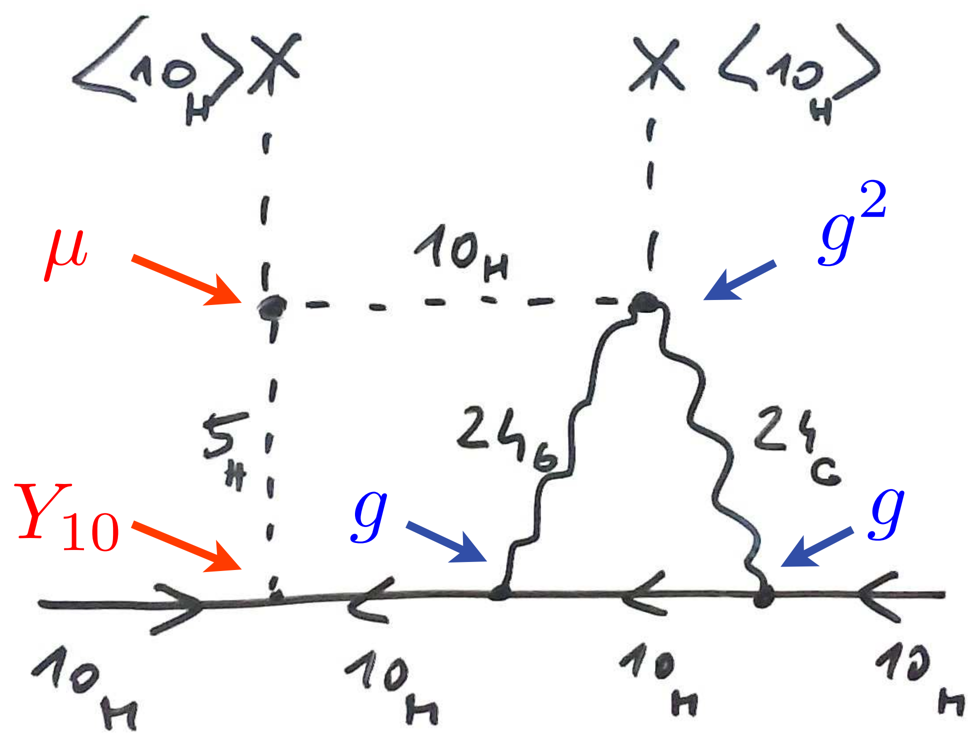

$$M_\nu^M = \left(\frac{1}{16\pi^2}\right)^2 g^4\, Y_{10}\, \mu \frac{\langle 10_H\rangle^2}{M_G^2} K(\ldots)$$

$K(\ldots)$ is an order 1 factor depending on the details of the heavy spectrum

MM, Catarina Simoes, work in progress

Perturbativity & stability constraints

C. Arbelaez Rodrigues, H. Kolešová, MM, PRD 89, 055003 (2014)

The scalar spectrum:

$$\begin{aligned} V &= \frac{1}{2}m_{10}^2 \mathrm{Tr}(10_H^\dagger 10_H) + m_5^2 5_H^\dagger 5_H + \frac{1}{4}(\mu\, \varepsilon_{ijklm} 10_H^{ij} 10_H^{kl} 5^m + h.c.) + \\ &+ \frac{1}{4}\lambda_1 [\mathrm{Tr}(10_H^\dagger 10_H)]^2 + \lambda_2 \mathrm{Tr}(10_H^\dagger 10_H 10_H^\dagger 10_H) + \lambda_3 (5_H^\dagger 5_H)^2 + \\ &+ \frac{1}{2}\lambda_4 \mathrm{Tr}(10_H^\dagger 10_H)(5_H^\dagger 5_H)^2 + \lambda_5 5_H^\dagger 10_H 10_H^\dagger 5_H \end{aligned}$$

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$$\begin{aligned}
m_i^2 &= 0\,, \quad i = 1, \ldots, 16\,, \\
m_{17}^2 &= \left[4\lambda_3 - \frac{(\lambda_4 + \lambda_5)^2}{\lambda_1 + 2\lambda_2}\right] v^2\,, \\
m_{18}^2 &= 4(\lambda_1 + 2\lambda_2) V_G^2\,, \\
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← 16 real Goldstones as expected

Perturbativity & stability constraints

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the potential tachyon

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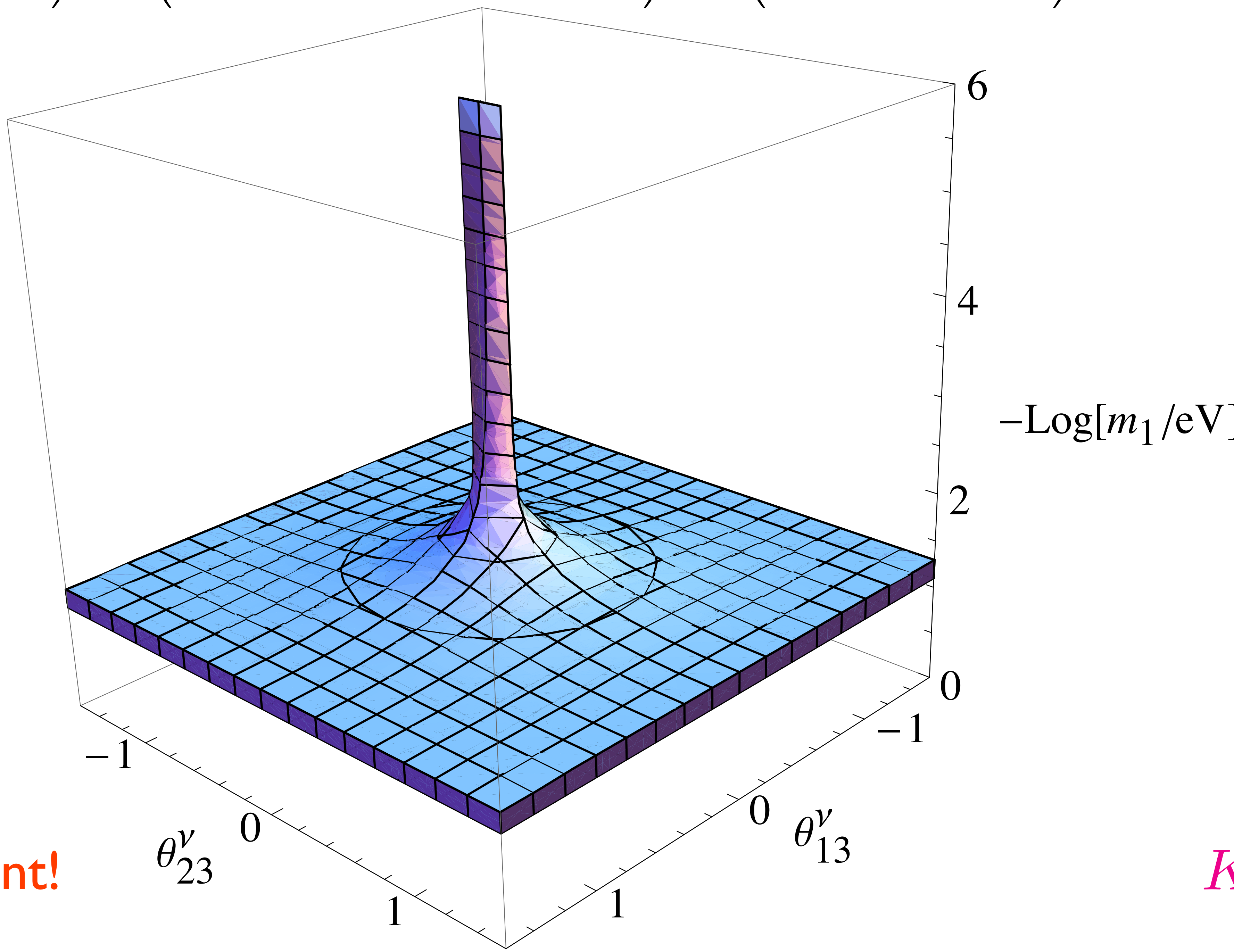
16 real Goldstones as expected

the potential tachyon

The QCD x QED vacuum is unstable unless $\mu^2 \leq \lambda_2\lambda_5 V_G^2$

Only some U_ν's allowed!

$$\begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix} U_\nu^\dagger \begin{pmatrix} 10^{10-\infty} & 0 & 0 \\ 0 & 10^{10-11} & 0 \\ 0 & 0 & 10^{10} \end{pmatrix} U_\nu^* \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix} \leq 10^{14}\mathrm{GeV}^2 K$$



θ_{12}-independent!

$K = 1$

Proton decay to neutral mesons+charged leptons

This should be superimposed over the observable(s) of our interest ...

$$\Gamma(p \to \pi^0 e^+) + \Gamma(p \to \pi^0 \mu^+)$$

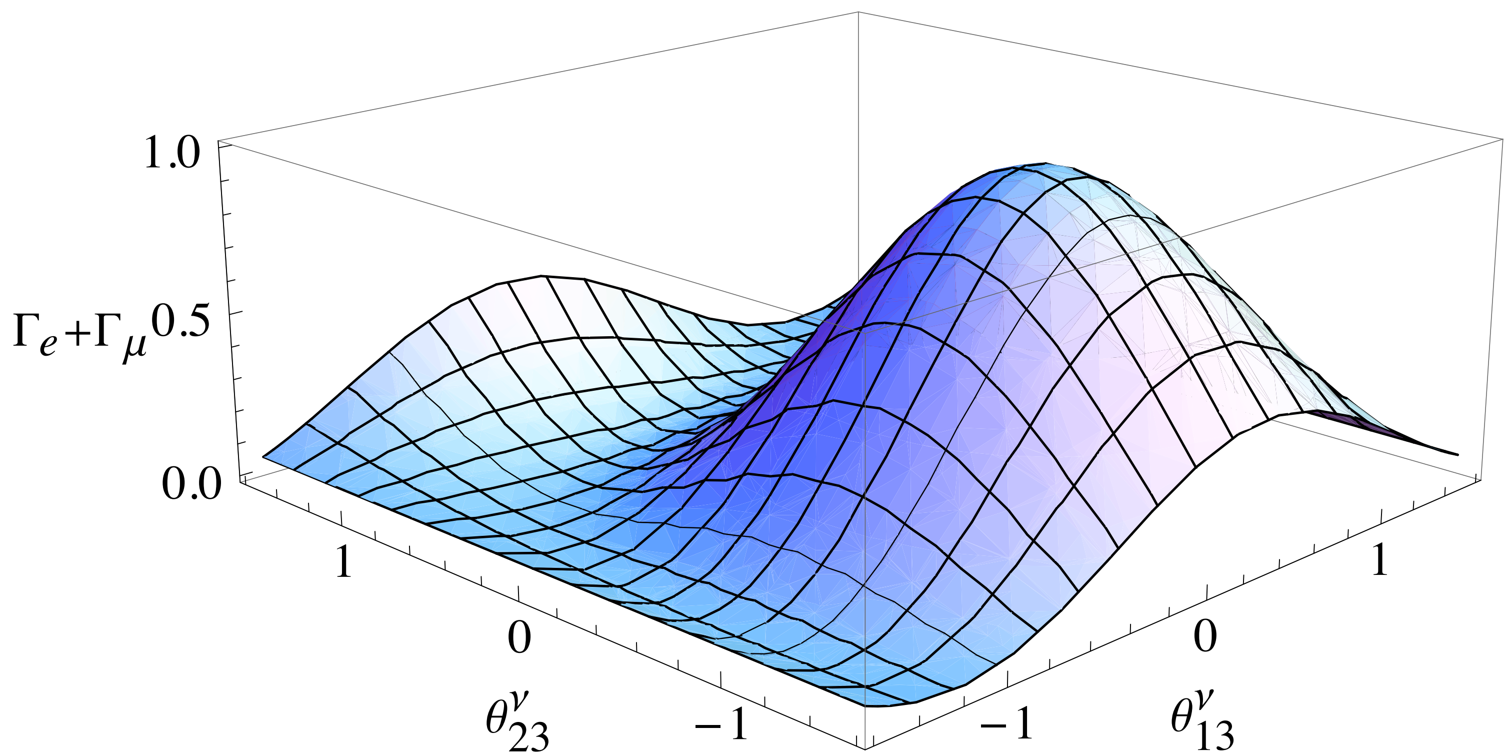
Proton decay to neutral mesons+charged leptons

This should be superimposed over the observable(s) of our interest ...

$\Gamma(p \to \pi^0 e^+) + \Gamma(p \to \pi^0 \mu^+)$

the minima of the sum of the matrix elements

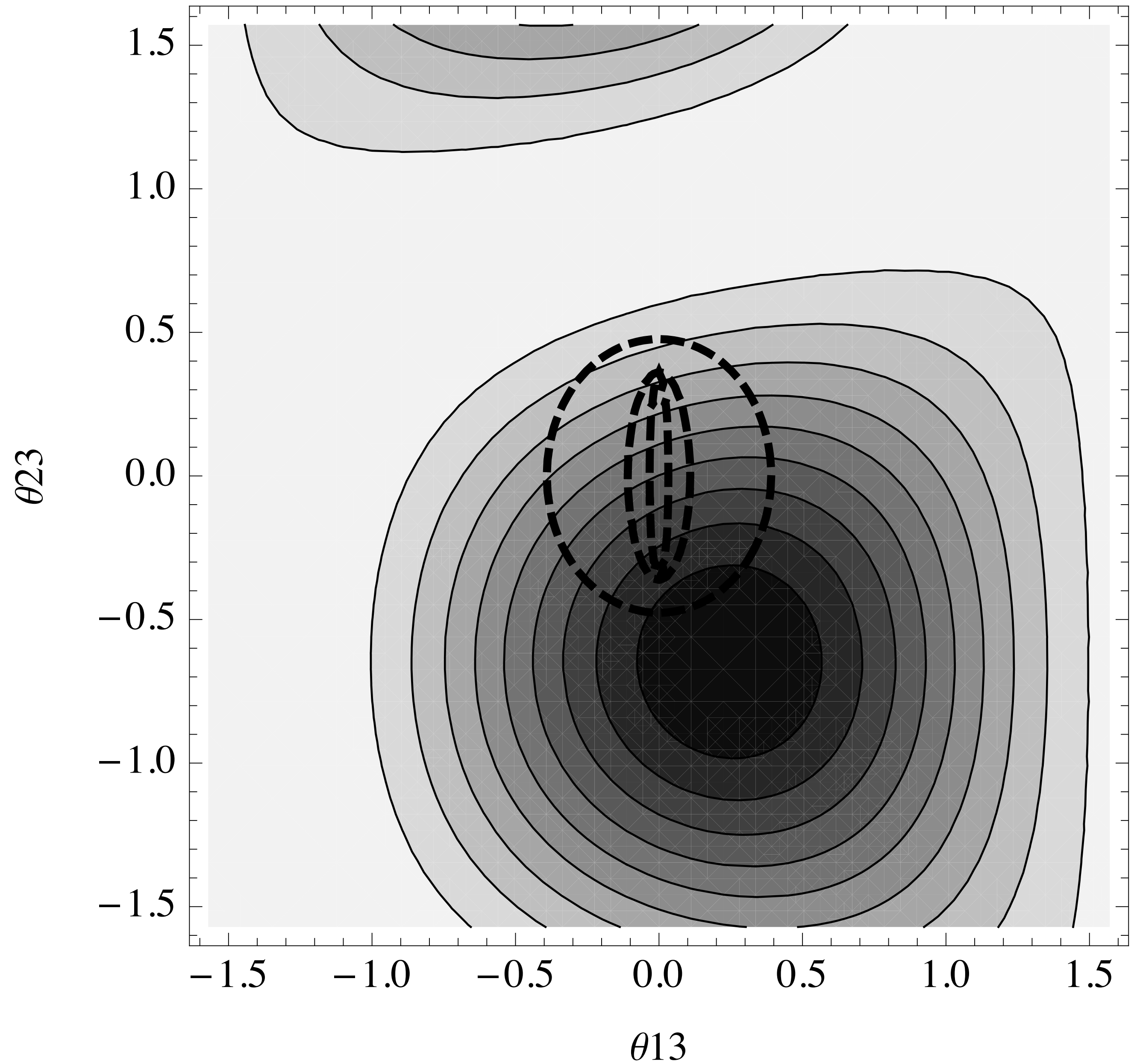
$$\Gamma(p \to \pi^0 \ell_\alpha^+) \propto |(V_{PMNS} U_\nu)_{\alpha 1}|^2$$



θ_{12}-dependent, analytic minimization with respect to θ_{12}

Proton decay to neutral mesons+charged leptons

Superimposing the two: $\Gamma(p \to \pi^0 e^+) + \Gamma(p \to \pi^0 \mu^+)$ in the perturbative mode



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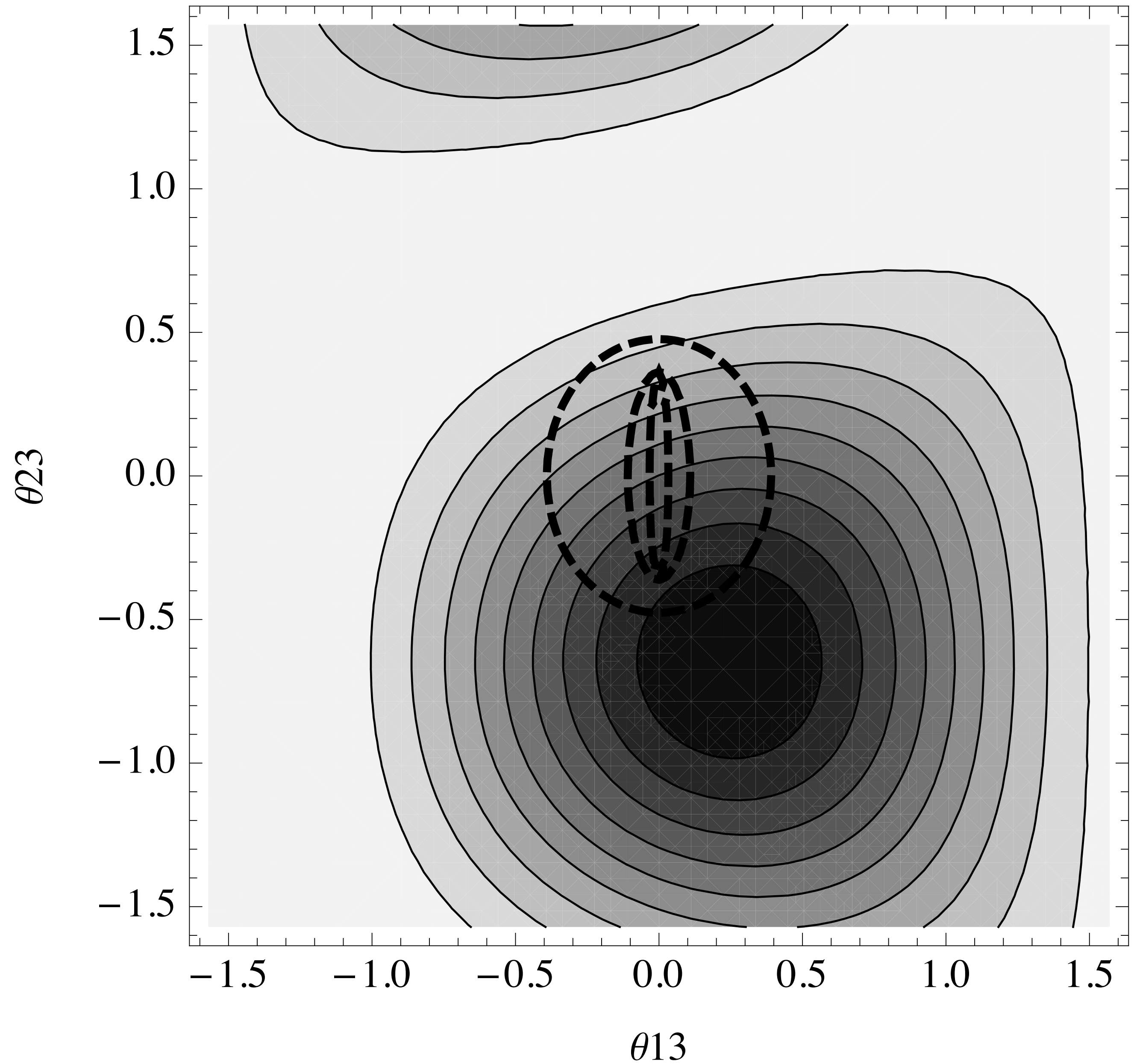

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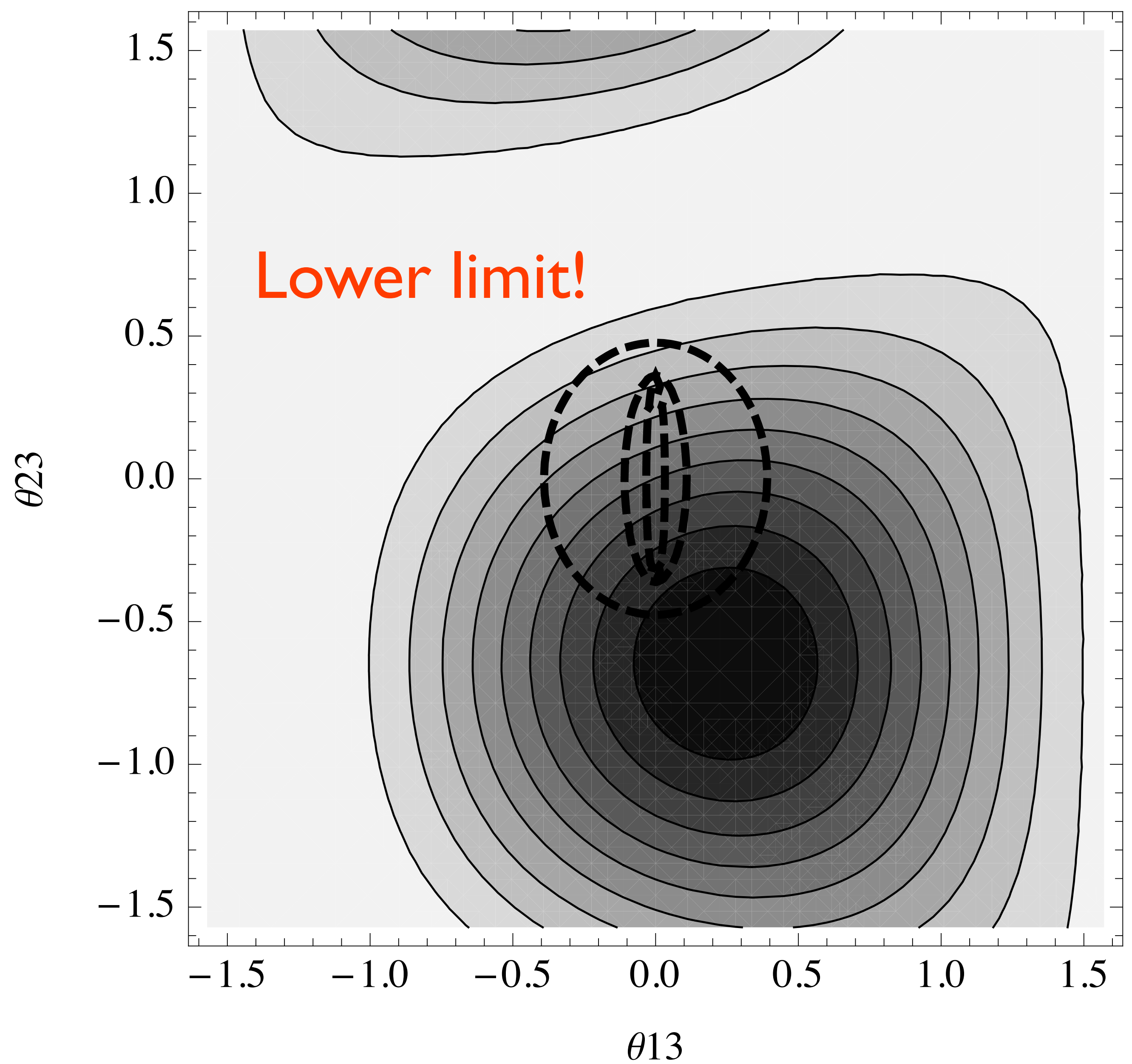
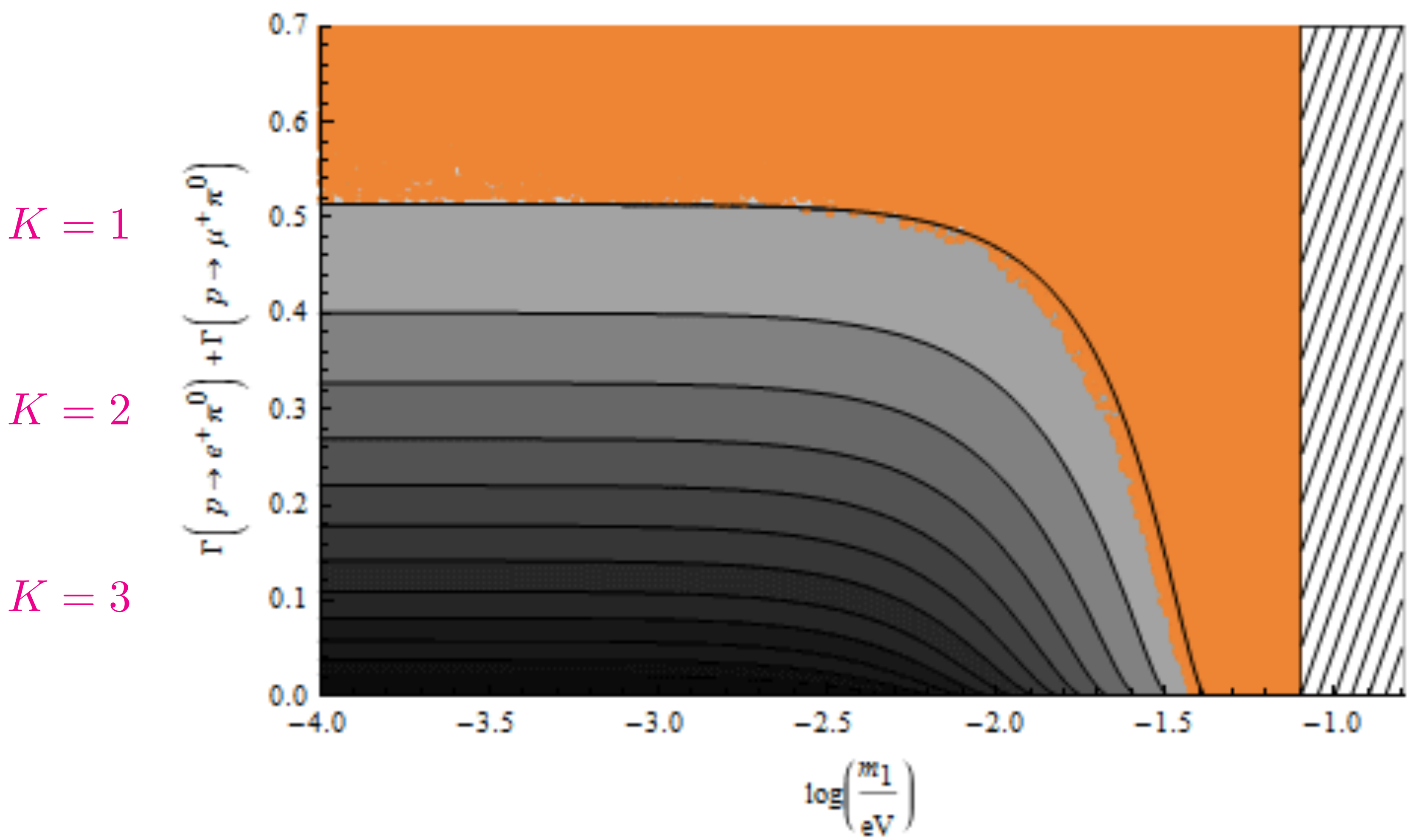


Proton decay to neutral mesons+charged leptons

Impossible to have both $\Gamma(p \to \pi^0 e^+)$ and $\Gamma(p \to \pi^0 \mu^+)$
arbitrarily suppressed in the perturbative regime !



C. Arbelaez Rodrigues, H. Kolešová, MM, PRD 89, 055003 (2014)

Conclusions / outlook

Proton decay is a classical yet still thrilling BSM signal

Lots of money/efforts spent in 6 decades of its searches

It's almost impossible to calculate the proton lifetime accurately enough to make a clear case...

The long-ago cursed (but recently resurrected) SO(10) GUT broken by the adjoint is a robust scenario!

Flipped SU(5) may be more predictive than expected!

Thanks for your kind attention!