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Proton decay theory and predictions

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Multi-kiloton neutrino facilities & proton decay

Abstract

We propose the Hyper-Kamiokande (Hyper-K) detector as a next generation underground water Cherenkov detector. It will serve as a far detector of a long baseline neutrino oscillation experiment envisioned for the upgraded J-PARC, and as a detector capable of observing – far beyond the sensitivity of the Super-Kamiokande (Super-K) detector – proton decays, atmospheric neutrinos, and neutrinos from astronomical origins. The baseline design of Hyper-K is based on the highly successful Super-K, taking full advantage of a well-proven technology.

Multi-kiloton neutrino facilities & proton decay

Abstract

We propose the Hyper-Kamiokande (Hyper-K) detector as a next generation underground water ... baseline neutrino oscillation experiment en- ... tivity ... from ... ng full

The **primary objectives** of LBNE, in priority order are the following experiments:

1. precision measurements of, the parameters that govern $\nu_\mu \to \nu_e$ oscillations; this includes precision measurement of the third mixing angle, measurement of the CP violating phase δ_{CP}, and determination of the mass ordering (the sign of Δm^2_{32}).
2. precision measurements of θ_{23} and $|\Delta m^2_{32}|$ in the ν_μ-disappearance channel.
3. *search for proton decay, yielding significant improvement in the current limits on the partial lifetime of the proton (τ/BR) in one or more important candidate decay modes, e.g. $p \to e^+\pi^0$ or $p \to K^+\nu$.*
4. *detection and measurement of the neutrino flux from a core-collapse supernova within our galaxy, should one occur during the lifetime of LBNE.*

Multi-kiloton neutrino facilities & proton decay

Abstract

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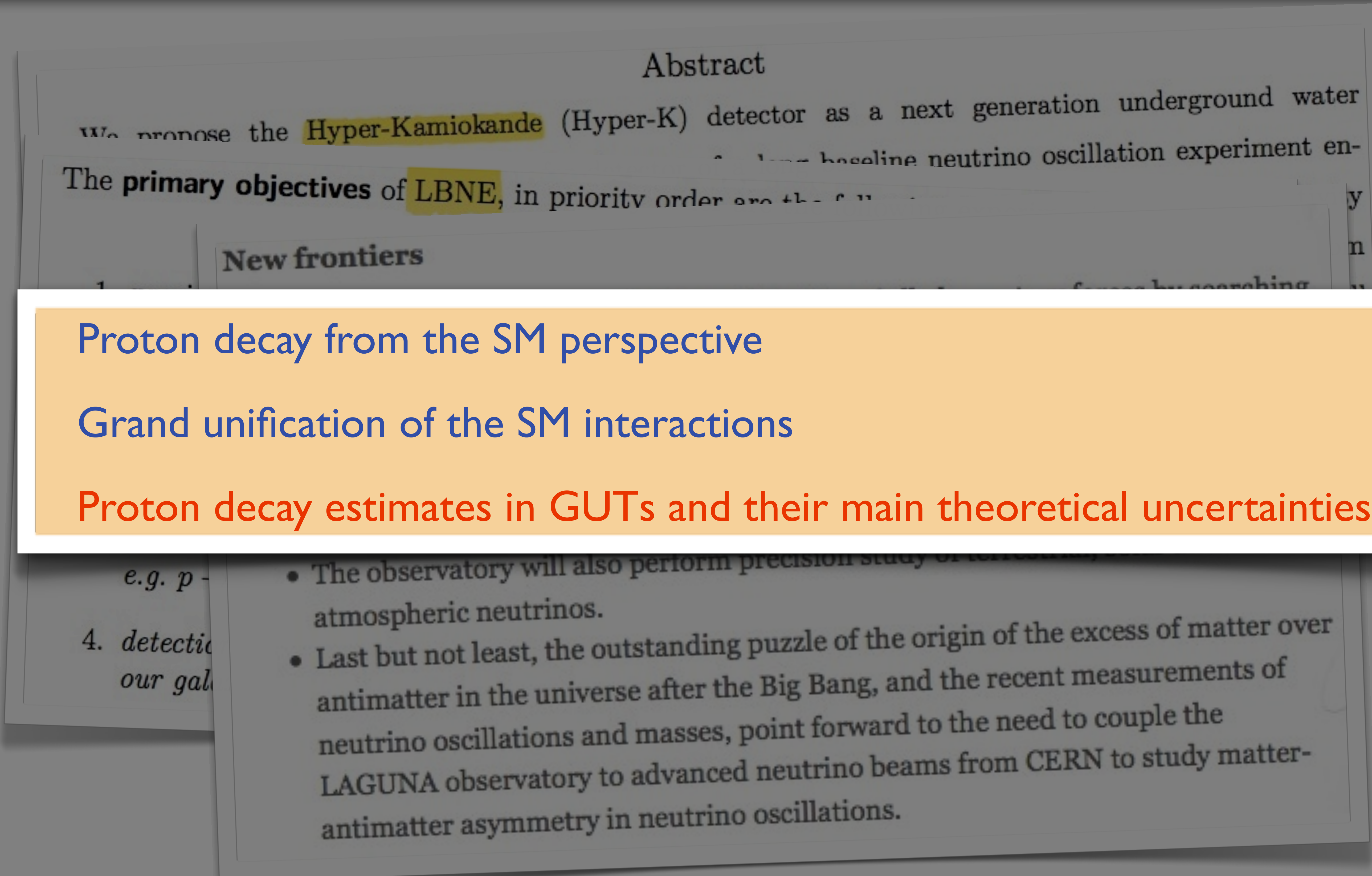
The **primary objectives** of LBNE, in priority order are the following:

1. precis… clude… lating…
2. precis…
3. *search … partial … e.g. p* …
4. *detectio… our gal…*

New frontiers

- The observatory will look for the unification of all elementary forces by searching for an extremely rare process called proton decay. Large size detectors like those envisioned in LAGUNA are the only way to address this question.
- The large size of the LAGUNA observatory will, in addition, allow the detection of a sufficiently large number of neutrinos from very distant galactic supernovae to understand their explosion mechanism.
- The observatory will also perform precision study of terrestrial, solar and atmospheric neutrinos.
- Last but not least, the outstanding puzzle of the origin of the excess of matter over antimatter in the universe after the Big Bang, and the recent measurements of neutrino oscillations and masses, point forward to the need to couple the LAGUNA observatory to advanced neutrino beams from CERN to study matter-antimatter asymmetry in neutrino oscillations.

Multi-kiloton neutrino facilities & proton decay


Abstract

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New frontiers

e.g. p ...

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- The observatory will also perform precision study of ... atmospheric neutrinos.
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Proton decay from the SM perspective

Grand unification of the SM interactions

Proton decay estimates in GUTs and their main theoretical uncertainties

Proton decay from the SM perspective

The SM lagrangian conserves B and L

$$
\begin{aligned}
\mathcal{L}_{SM} = & -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
& M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - \\
& Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)) - igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - \\
& W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)) - \\
& \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac12 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) - \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^2W^+_\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 g2\tfrac{m_\nu^\lambda}{M}H(\bar\nu^\lambda\nu^\lambda) - \\
& \tfrac g2\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\overline{\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 g2\tfrac{m_u^\lambda}{M}H(\bar u^\lambda_j u^\lambda_j) - \tfrac g2\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 conserves B and L

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

The SM lagrangian conserves B and L

$$
\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^5 e^\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^5 u_j^\lambda) - \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda)
\end{aligned}
$$

always a $\overline{\Psi}\gamma^\mu\Psi$ structure - B 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

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

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

- Sphalerons (at high T) make the tunneling more efficient ⇨ leptogenesis

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

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Renormalizability is nowadays considered a quantitative feature

SM as an effective theory at d=5 level

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

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

There is only one d=5 effective operator in the SM!

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

Baryon number violation from the SM perspective

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

Baryon number violation from the SM perspective

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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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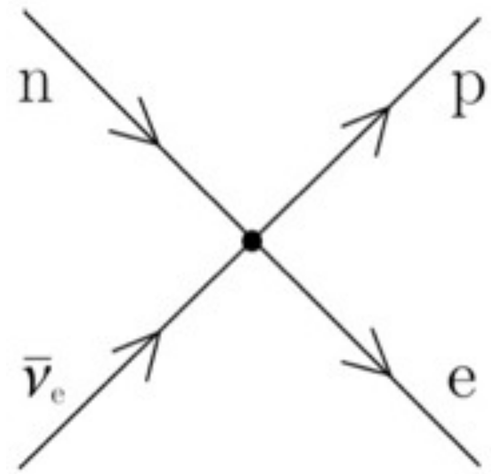
Renormalizable dynamics behind the SM d=6 BNV?

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

Elementary vertex:



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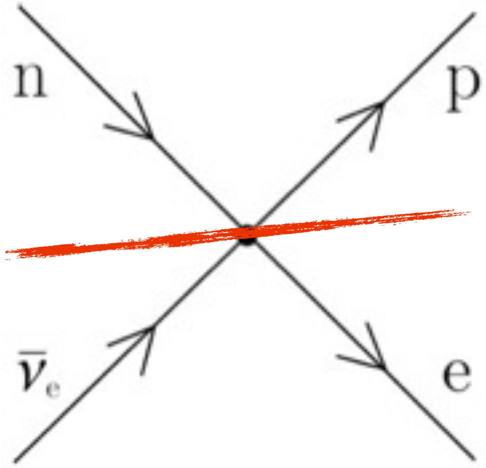
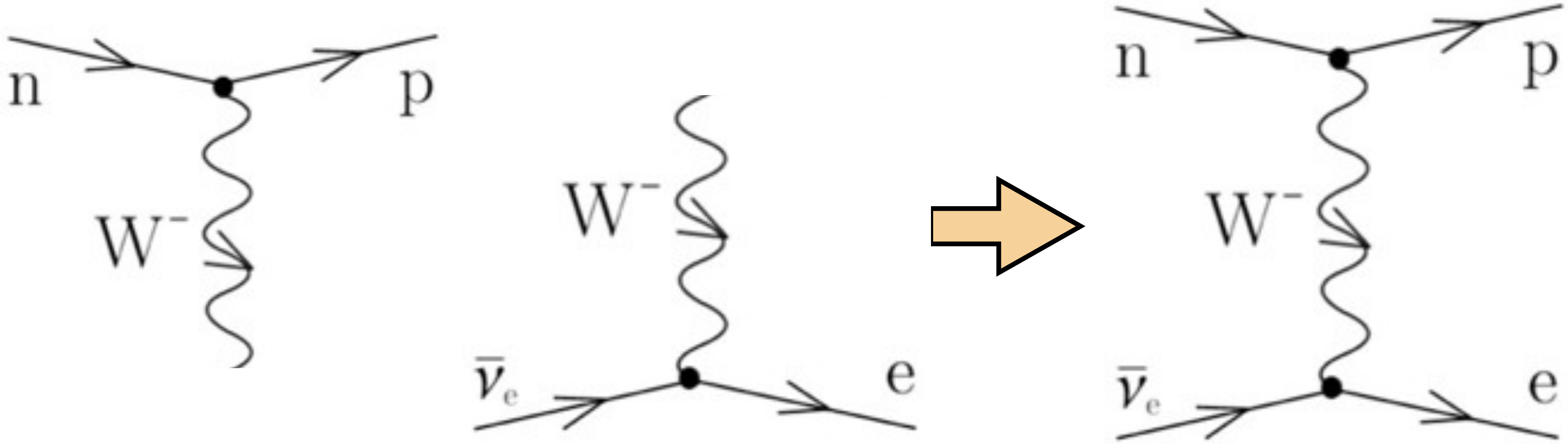


QED-like seed of
a renormalizable theory

Elementary vertices:



Renormalizable dynamics behind the SM d=6 BNV?

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

Renormalizable dynamics behind the SM d=6 BNV?

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

Scalar exchange

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

Δ

Renormalizable dynamics behind the SM d=6 BNV?

Fierz

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

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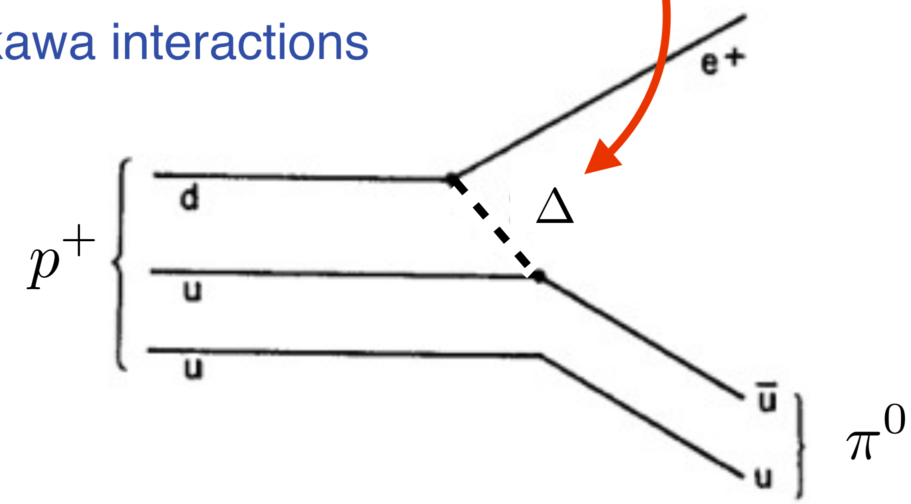
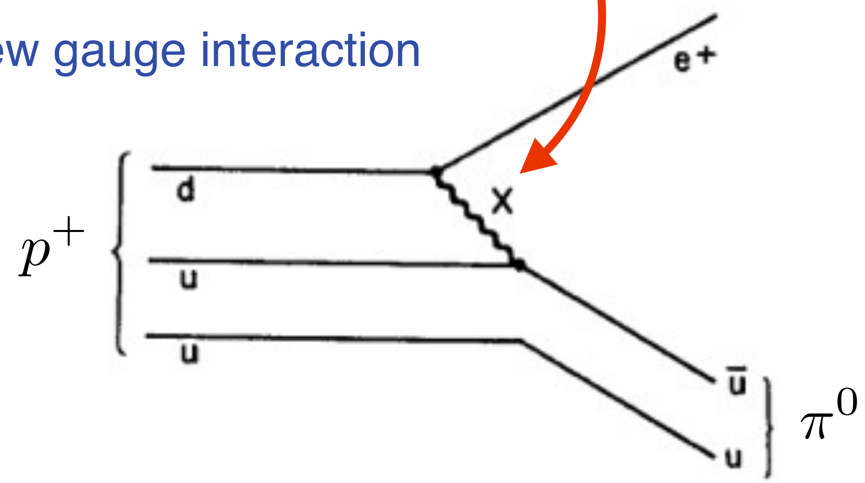
Proton instability:

new Yukawa interactions



new gauge interaction



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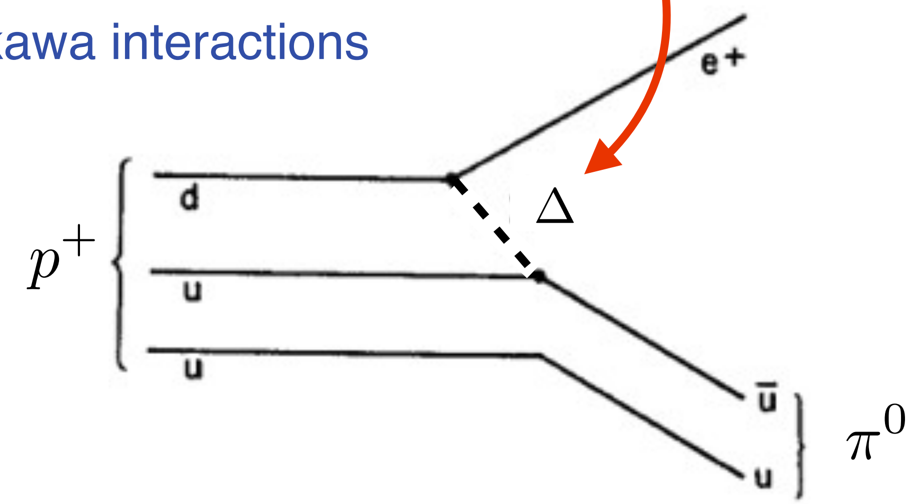

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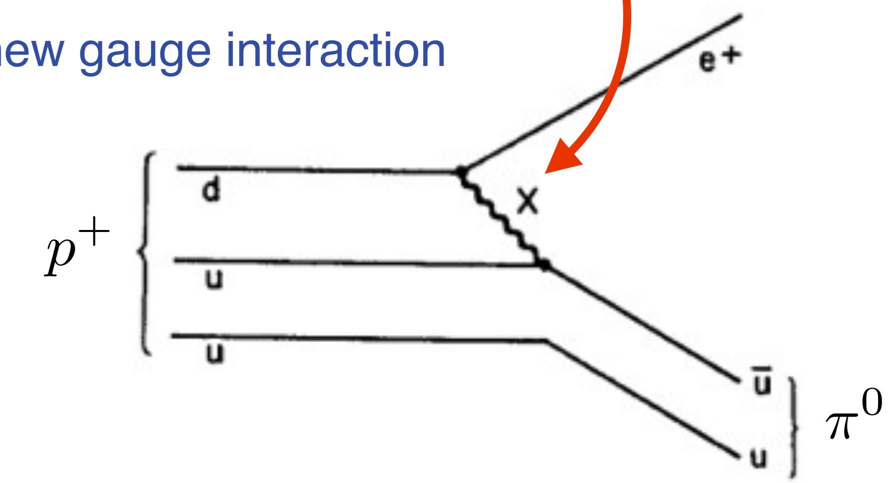

$\Gamma_p \sim \frac{m_p^5}{M^4} < (10^{34}\mathrm{y})^{-1}$ Such a new physics should be above 10^{15} GeV !??

SM running gauge couplings

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

Running gauge couplings in the SM:

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

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

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

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

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

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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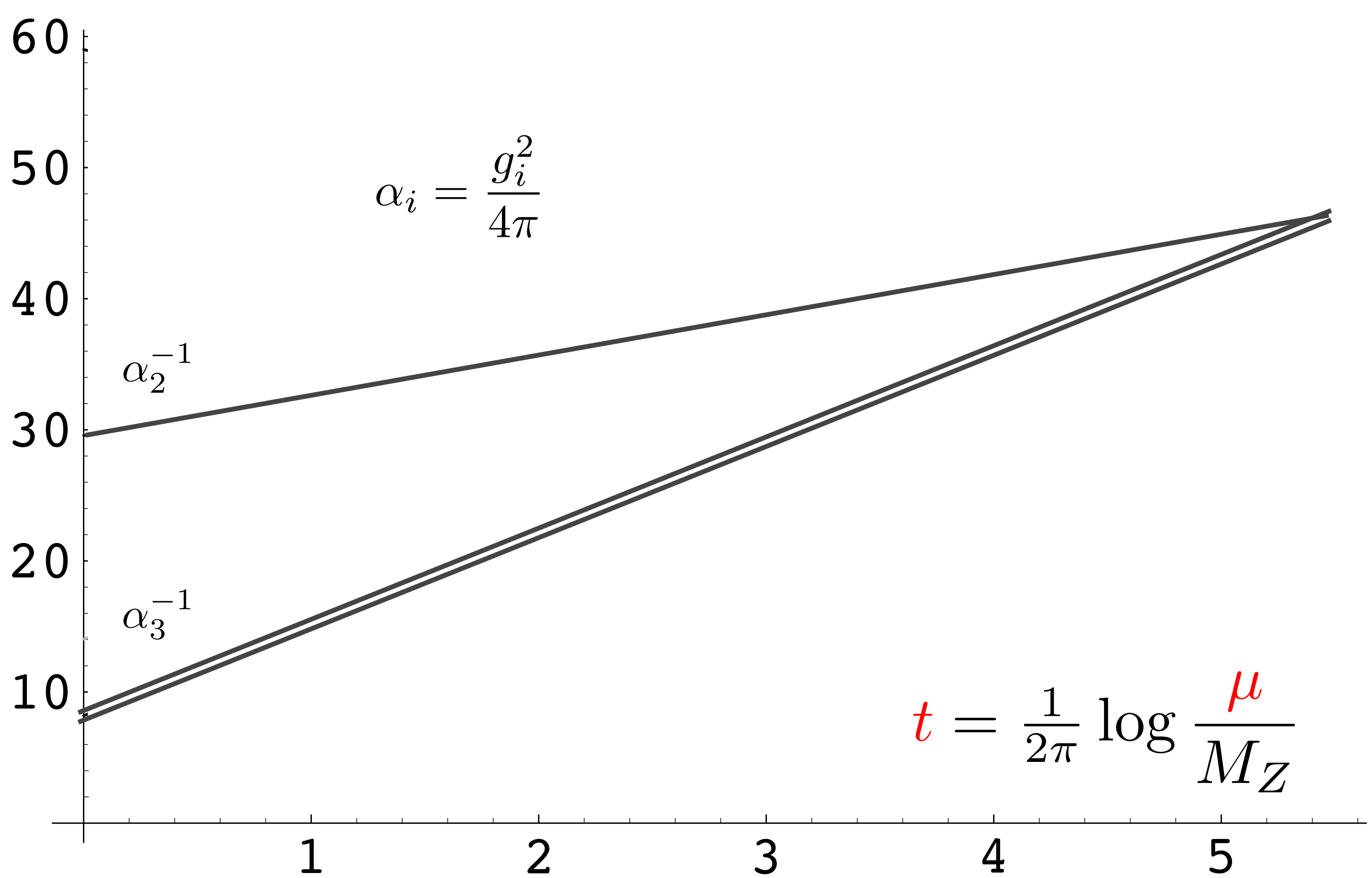

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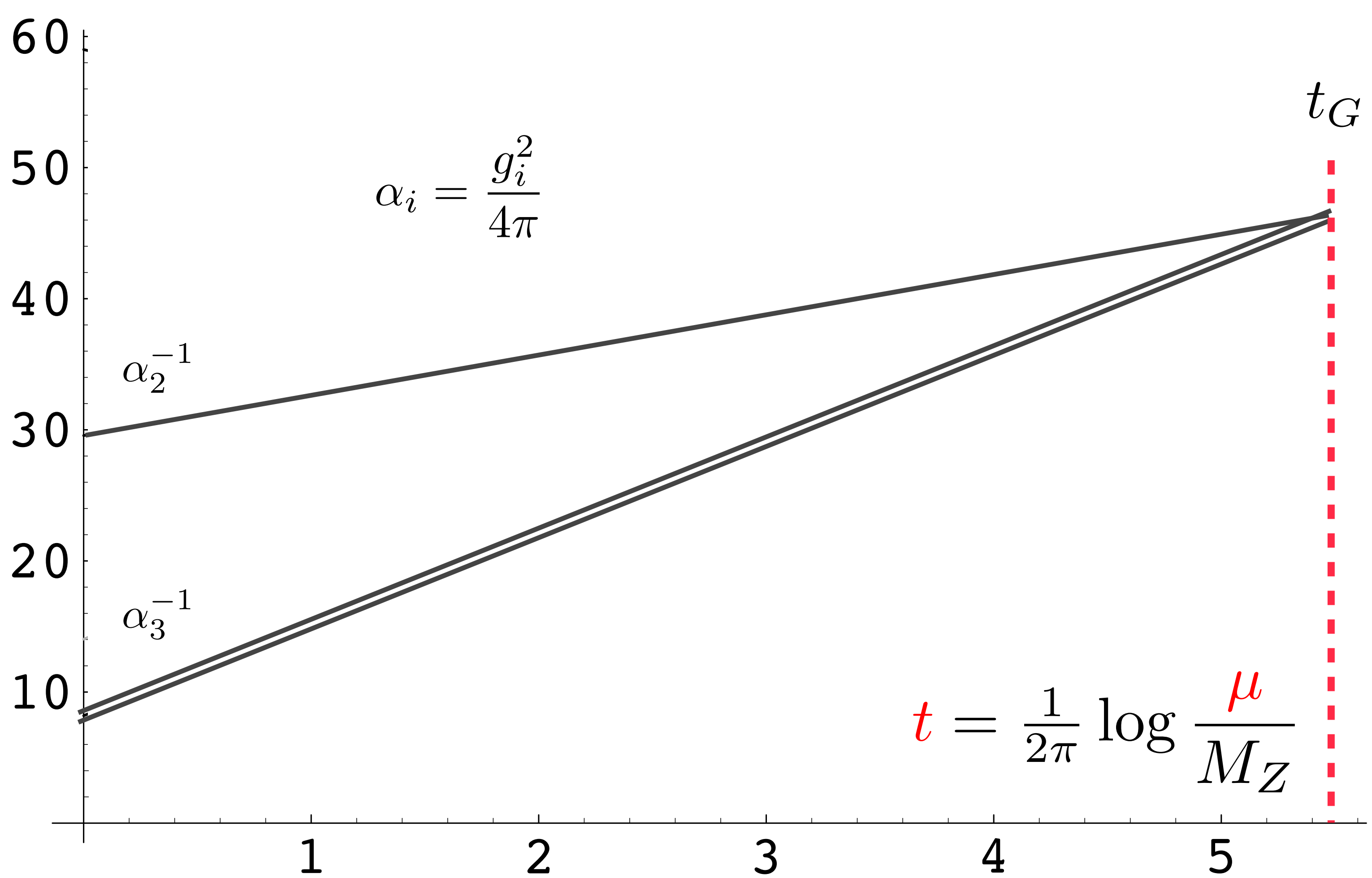

$M_G \sim 10^{16}\text{GeV}$

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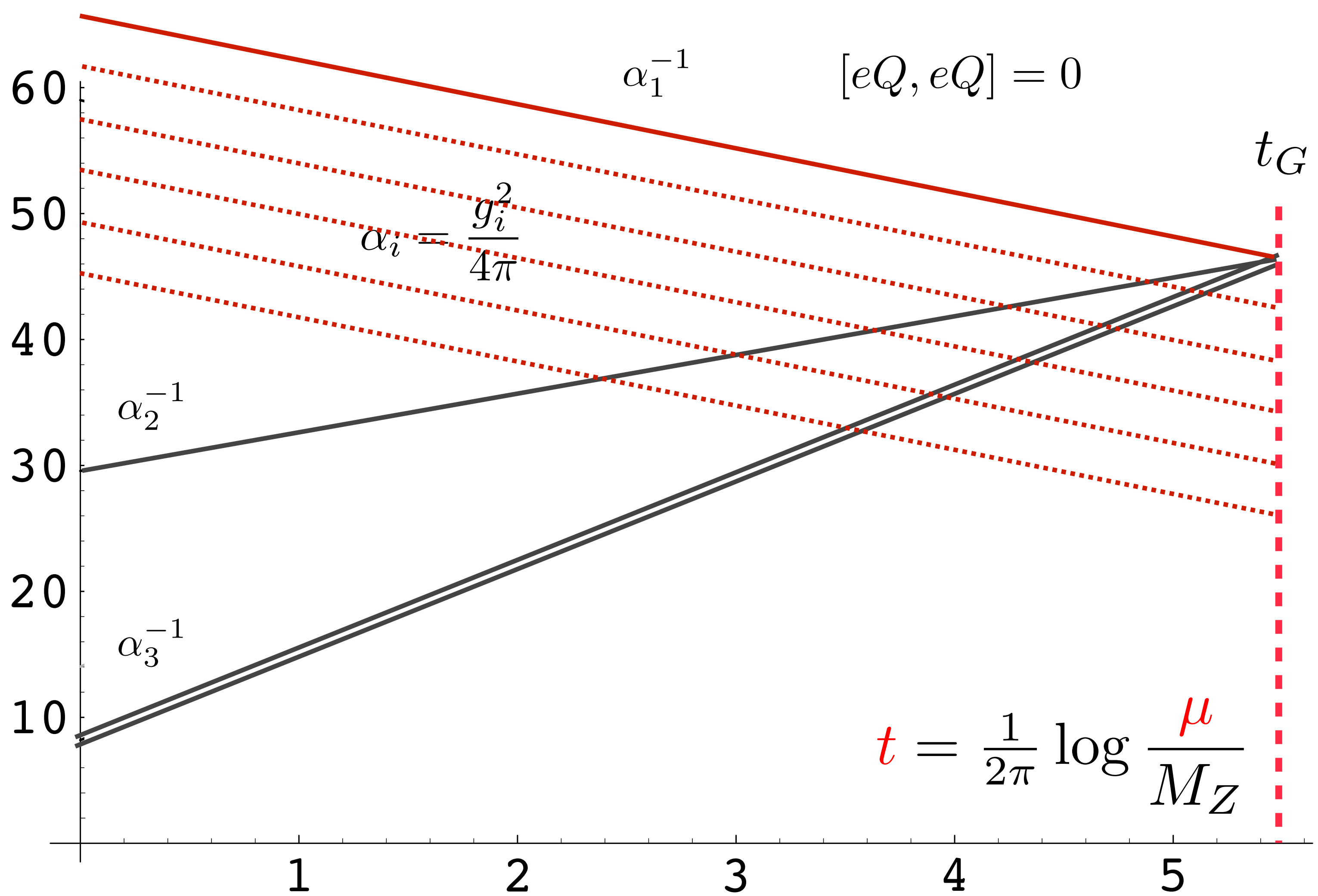

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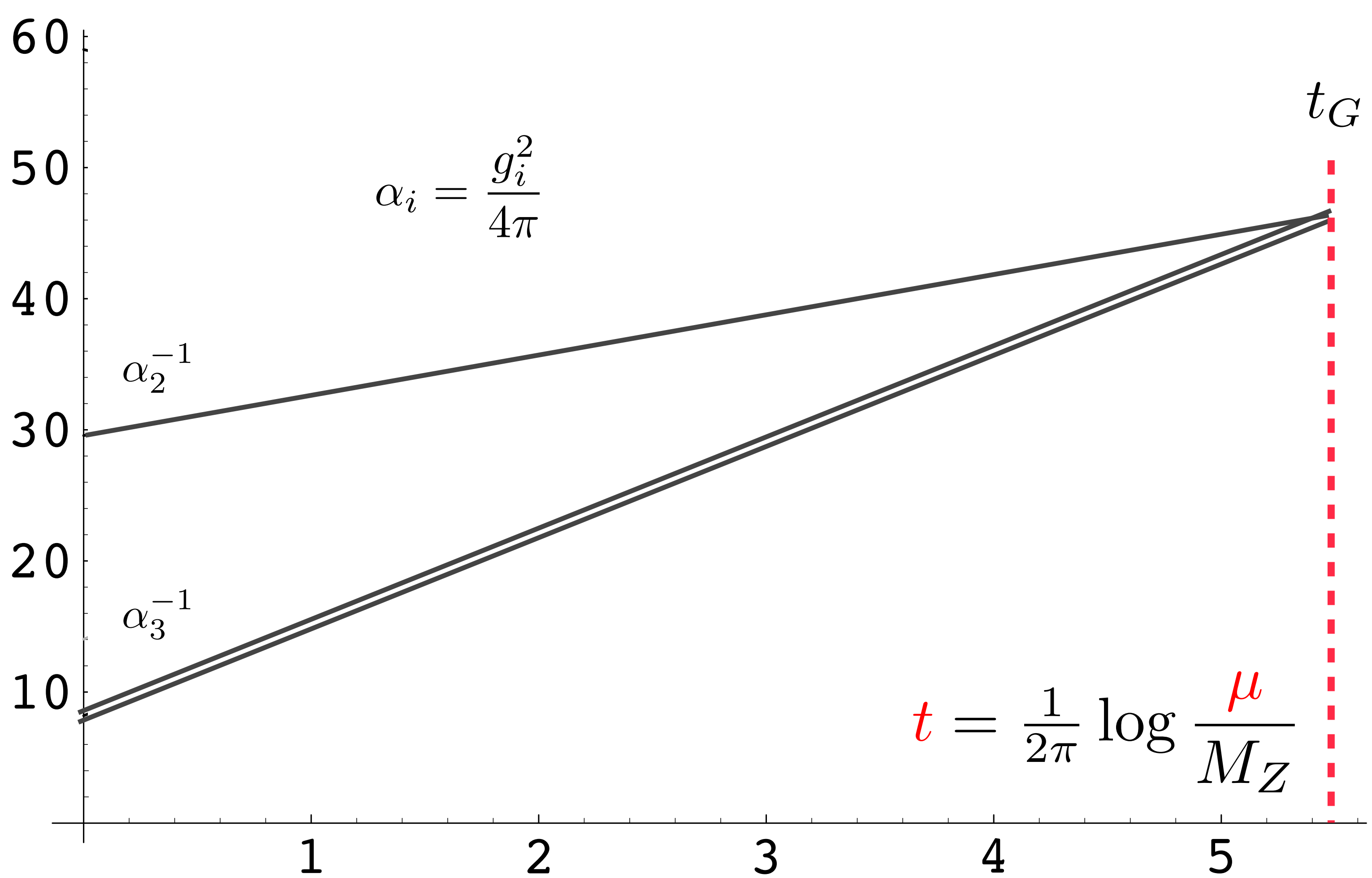

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Running gauge couplings in the SM

d=6 BNV mediators

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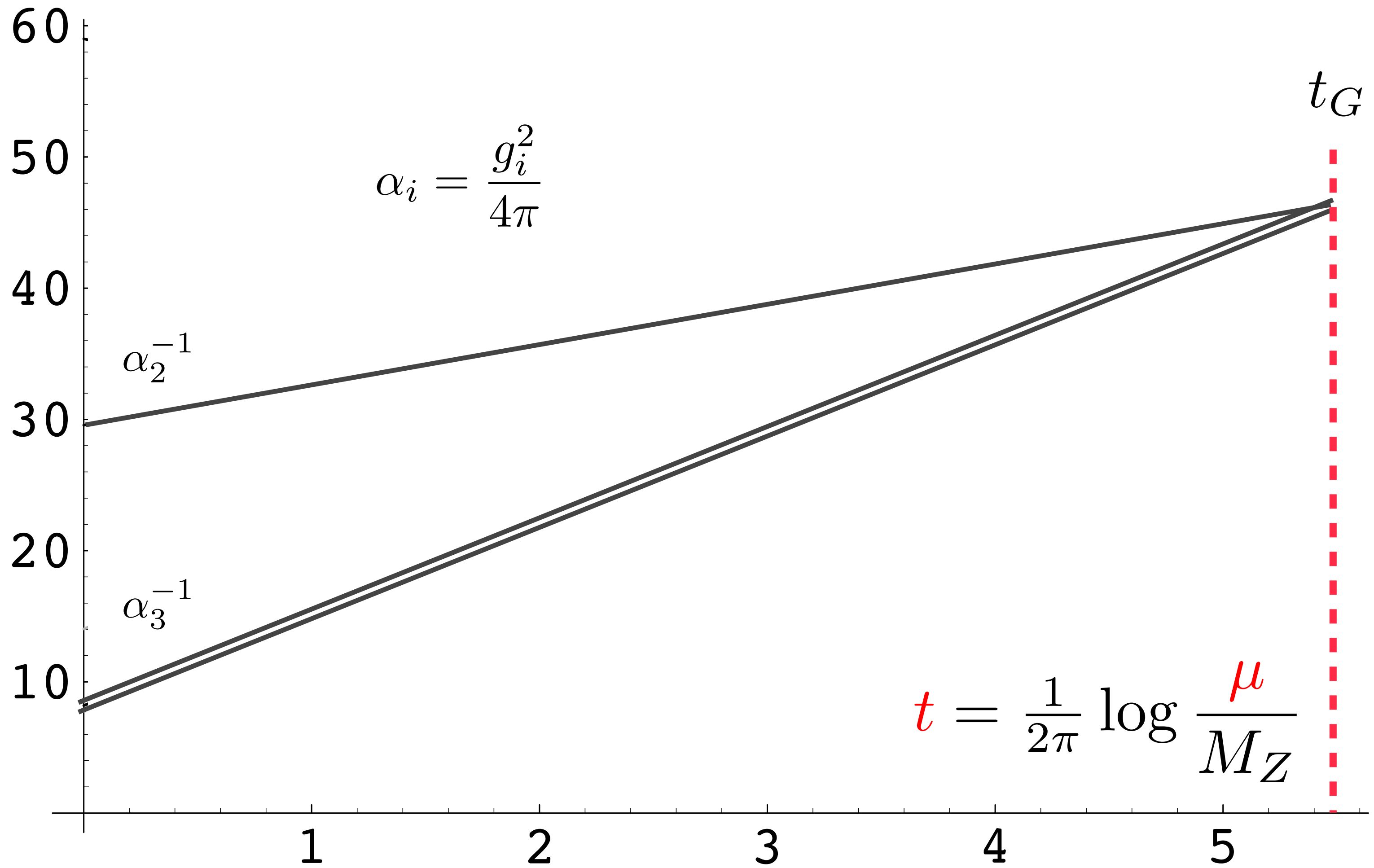

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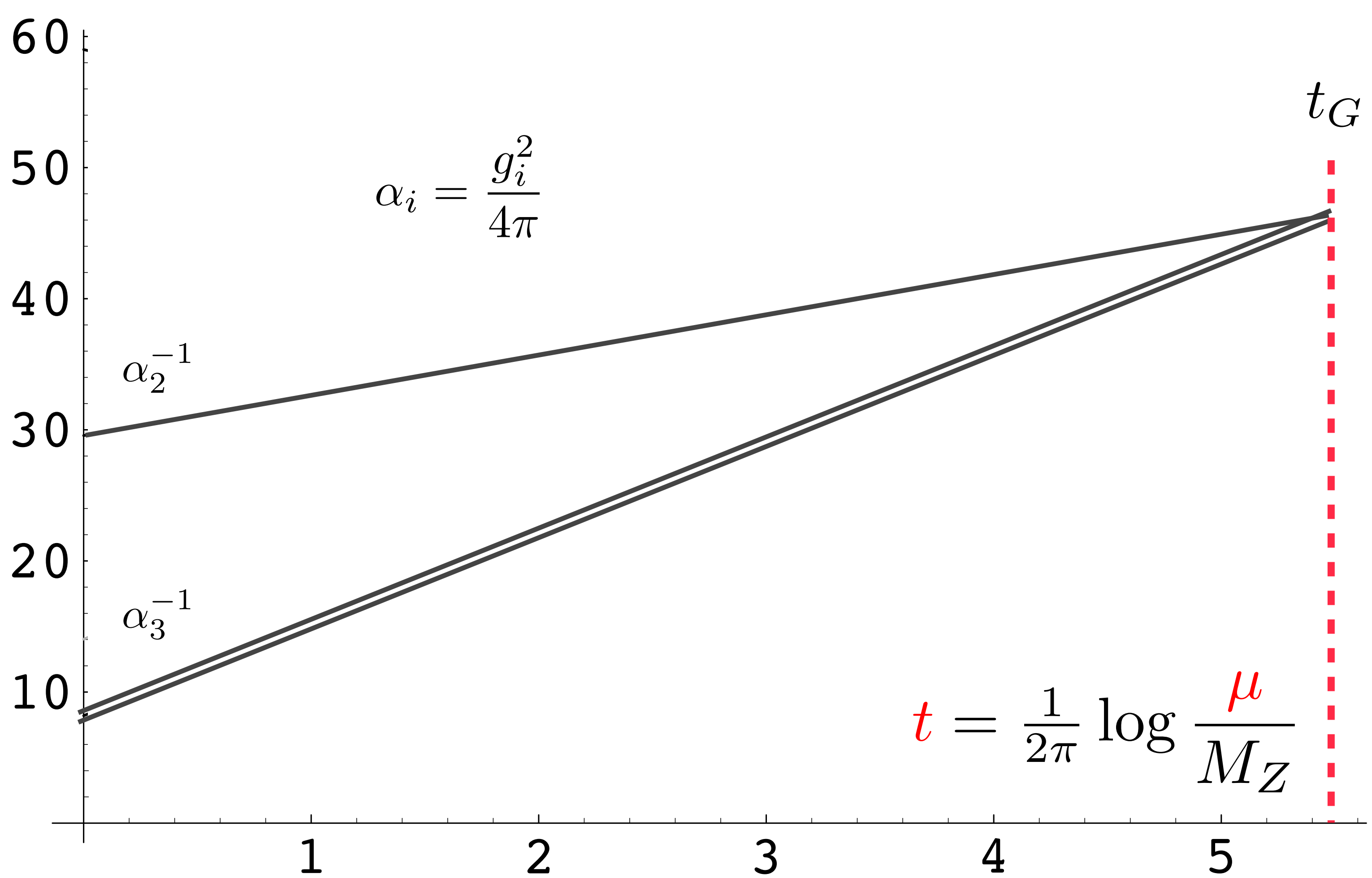
Running gauge couplings in the SM $+X+\Delta$ d=6 BNV mediators

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

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



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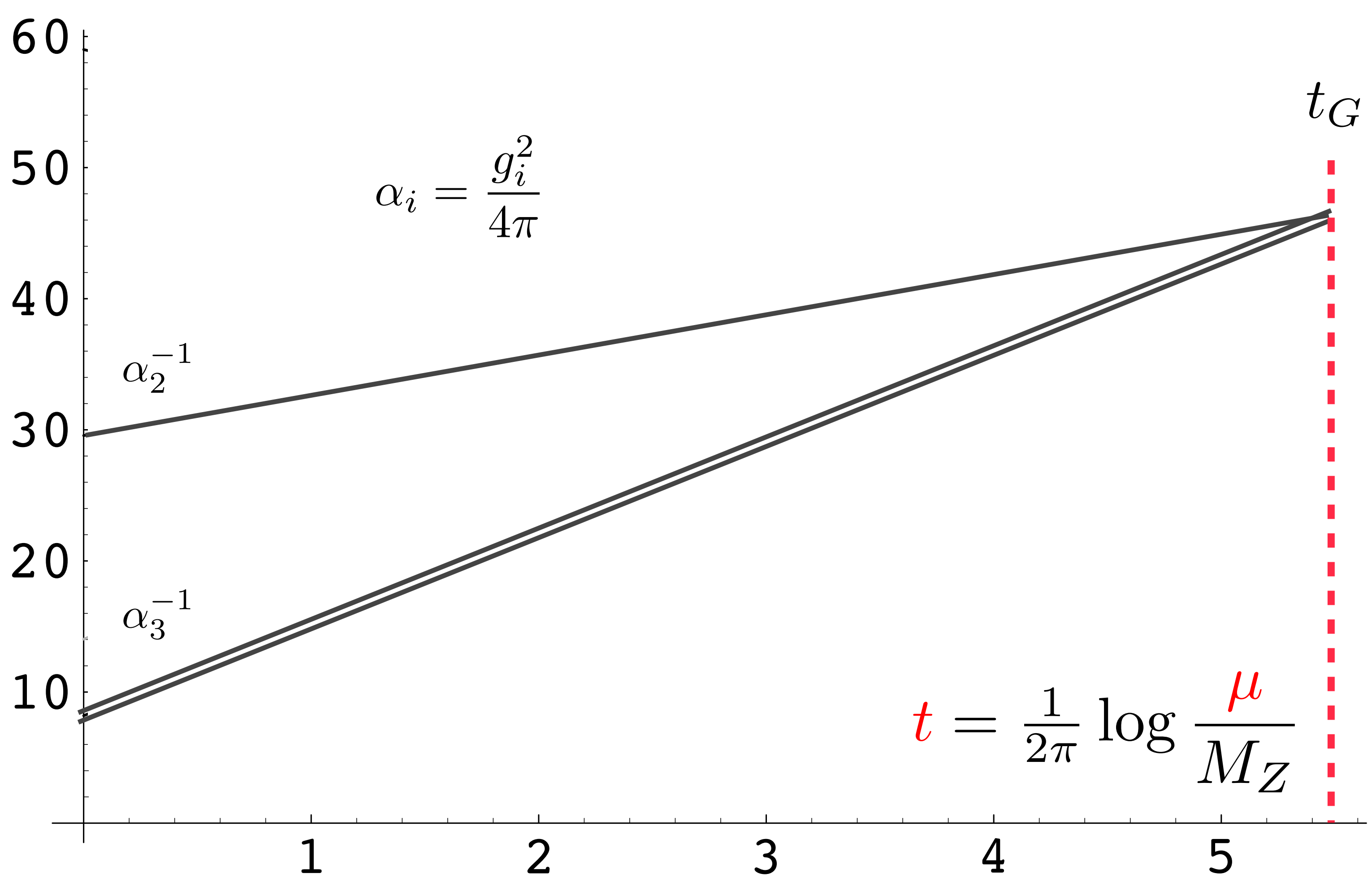
Running gauge couplings in the SM $+X+\Delta$ d=6 BNV mediators

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



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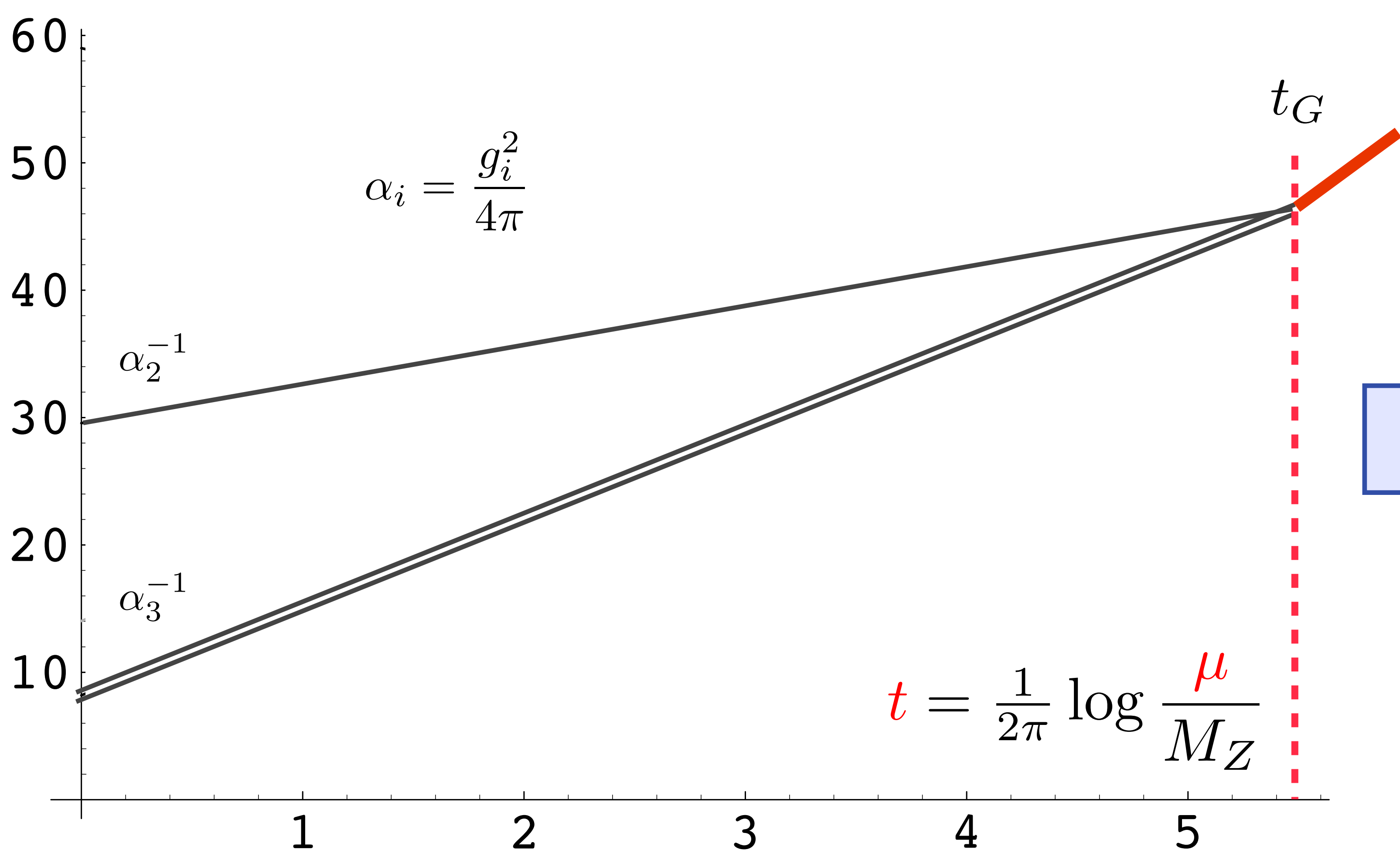
$$\begin{pmatrix} \frac{3}{5}b_1 \\ b_2 \\ b_3 \end{pmatrix} = -\frac{11}{3}\begin{pmatrix} 5 \\ 5 \\ 5 \end{pmatrix}_{gauge} + 2\begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix}_{ferm.} + \frac{1}{3}\begin{pmatrix} \frac{1}{2} \\ \frac{1}{2} \\ \frac{1}{2} \end{pmatrix}_{scal.}$$



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

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

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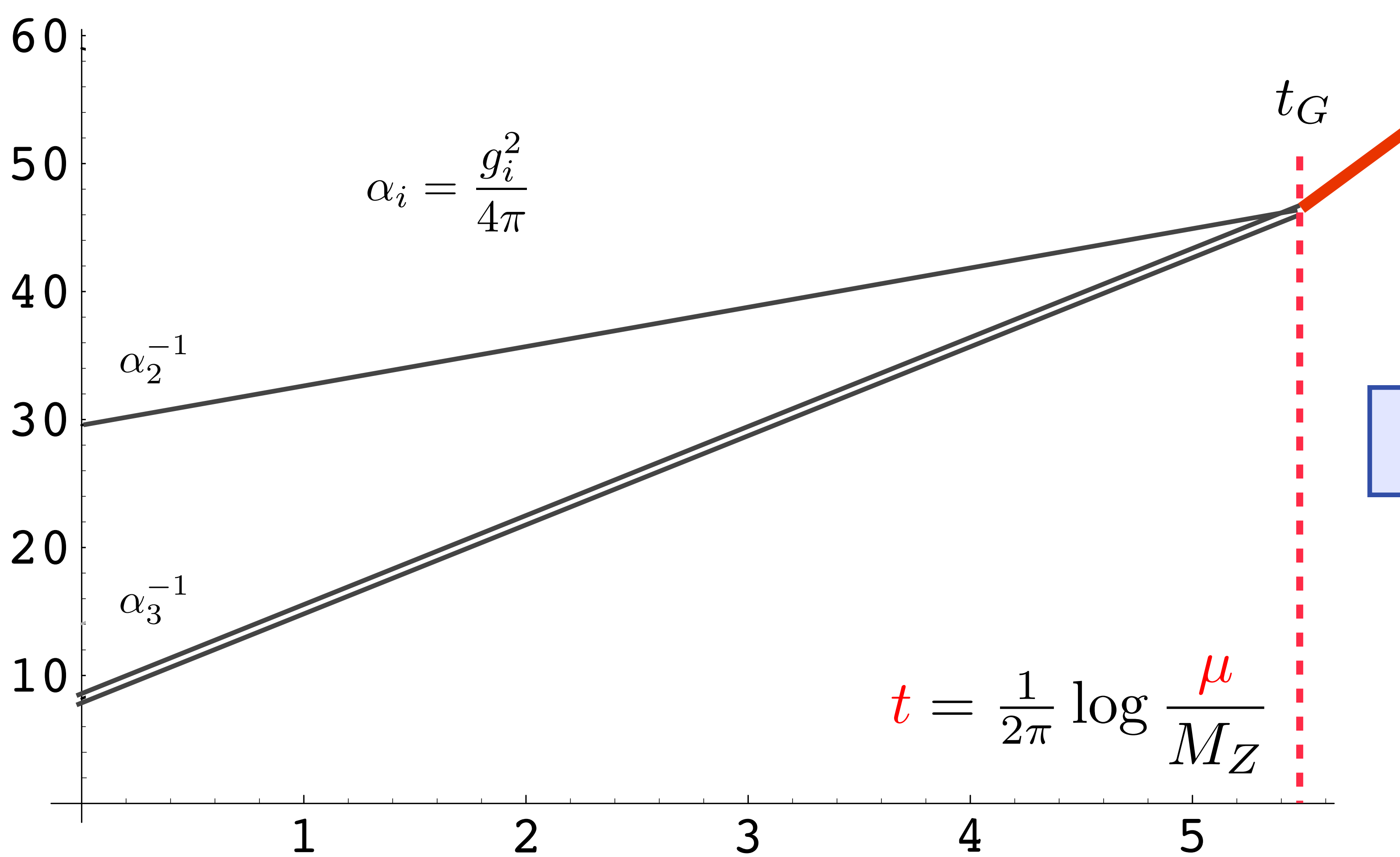

single gauge coupling like in an asymptotically free gauge theory with a simple gauge group

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

this tells us the BNV scale and also the gauge coupling

Grand unification of the EW & strong interactions

The minimal SU(5) GUT

VOLUME 32, NUMBER 8 PHYSICAL REVIEW LETTERS 25 FEBRUARY 1974

Unity of All Elementary-Particle Forces

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

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

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

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

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

Uniqueness of SU(5) @ rank=4

The minimal SU(5) GUT

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

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

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

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

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

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

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

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

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

$\overline{5}$:

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

10:

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G^μ $\left.\begin{array}{c} A^\mu \\ B^\mu \end{array}\right\} W^\pm, Z, \gamma$ G^μ A^μ B^μ X^μ

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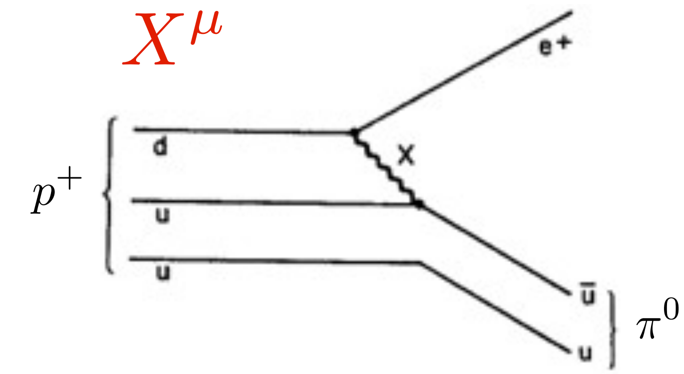

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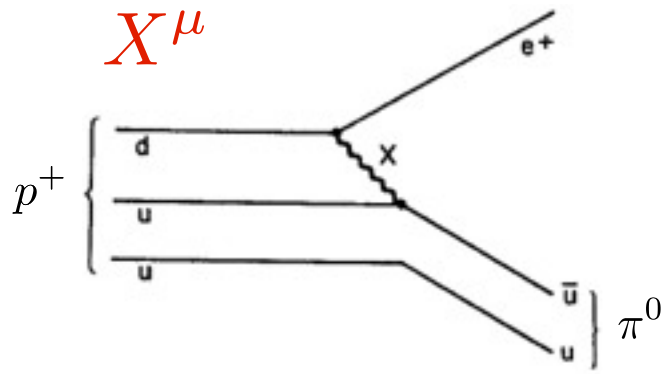

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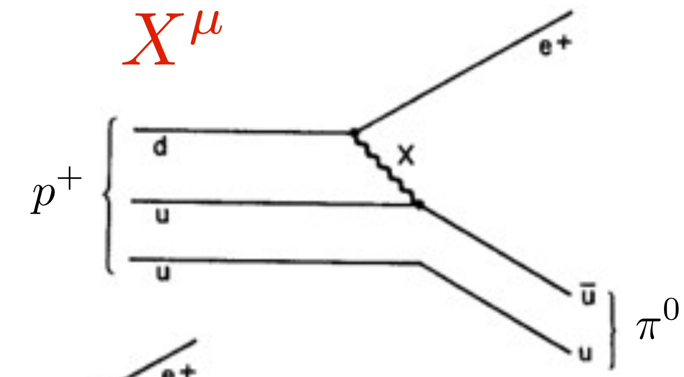

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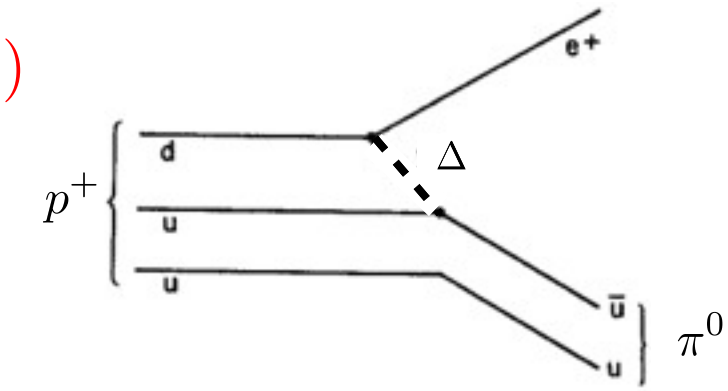

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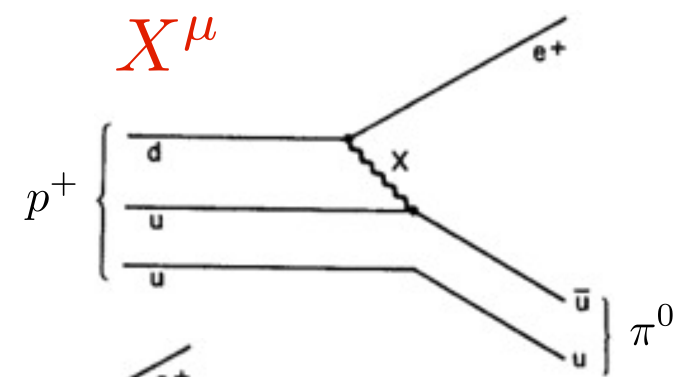

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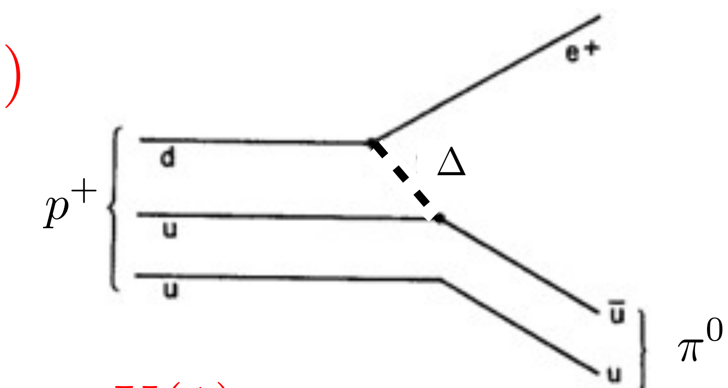


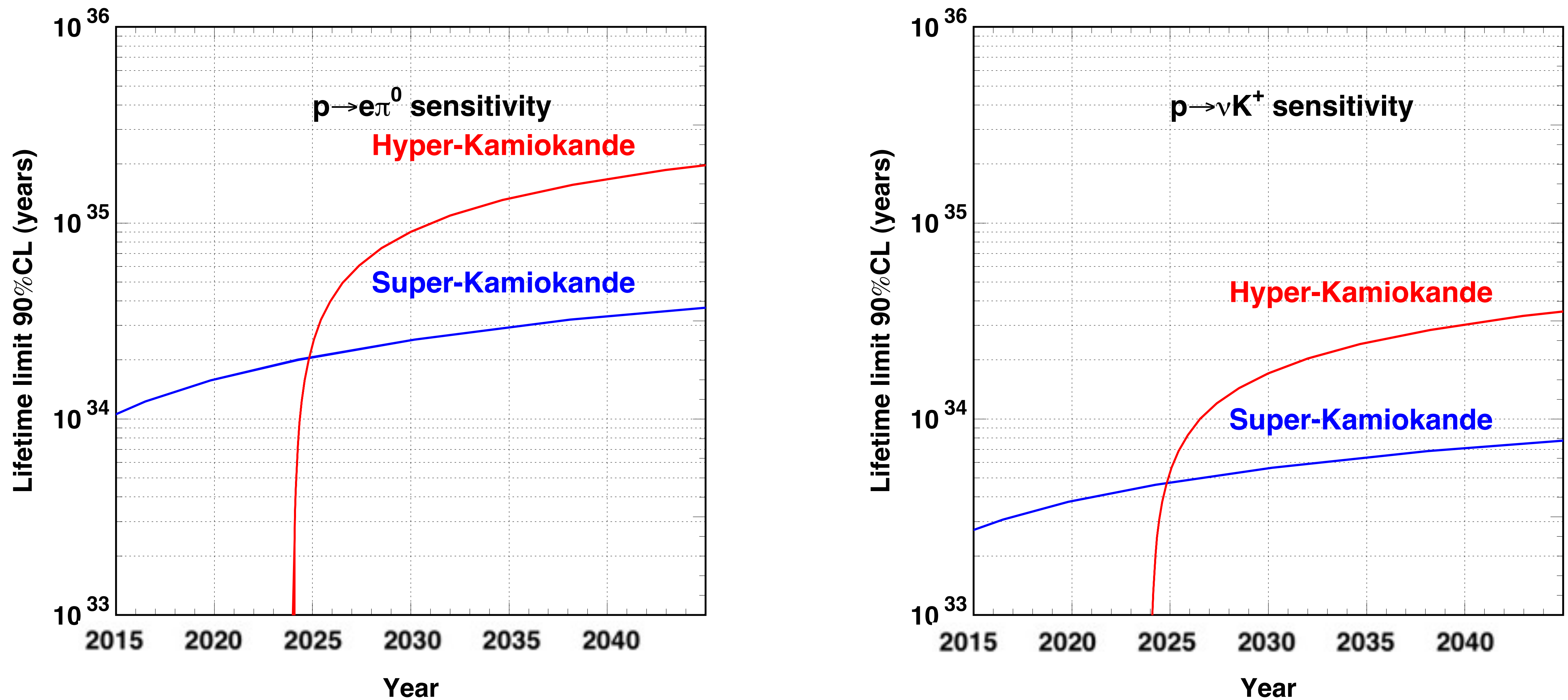
GUT-breaking scalars: $SU(5) \to SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

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

GUT proton lifetime estimates

Expected near(?) future sentsitivity improvements

Hyper-K p-decay sensitivity projection



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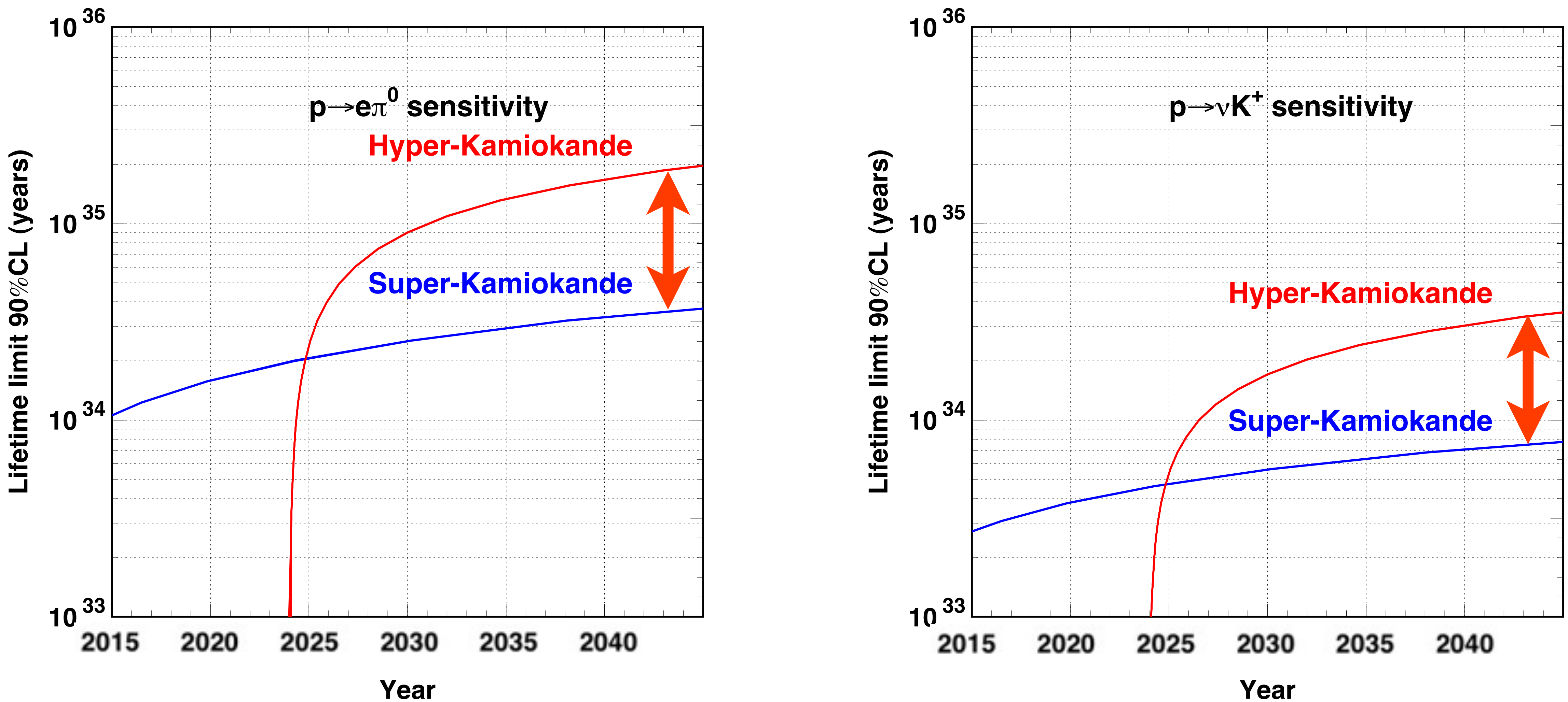

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Accuracy of a **factor of few** in Γ_p estimates needed to make a case !

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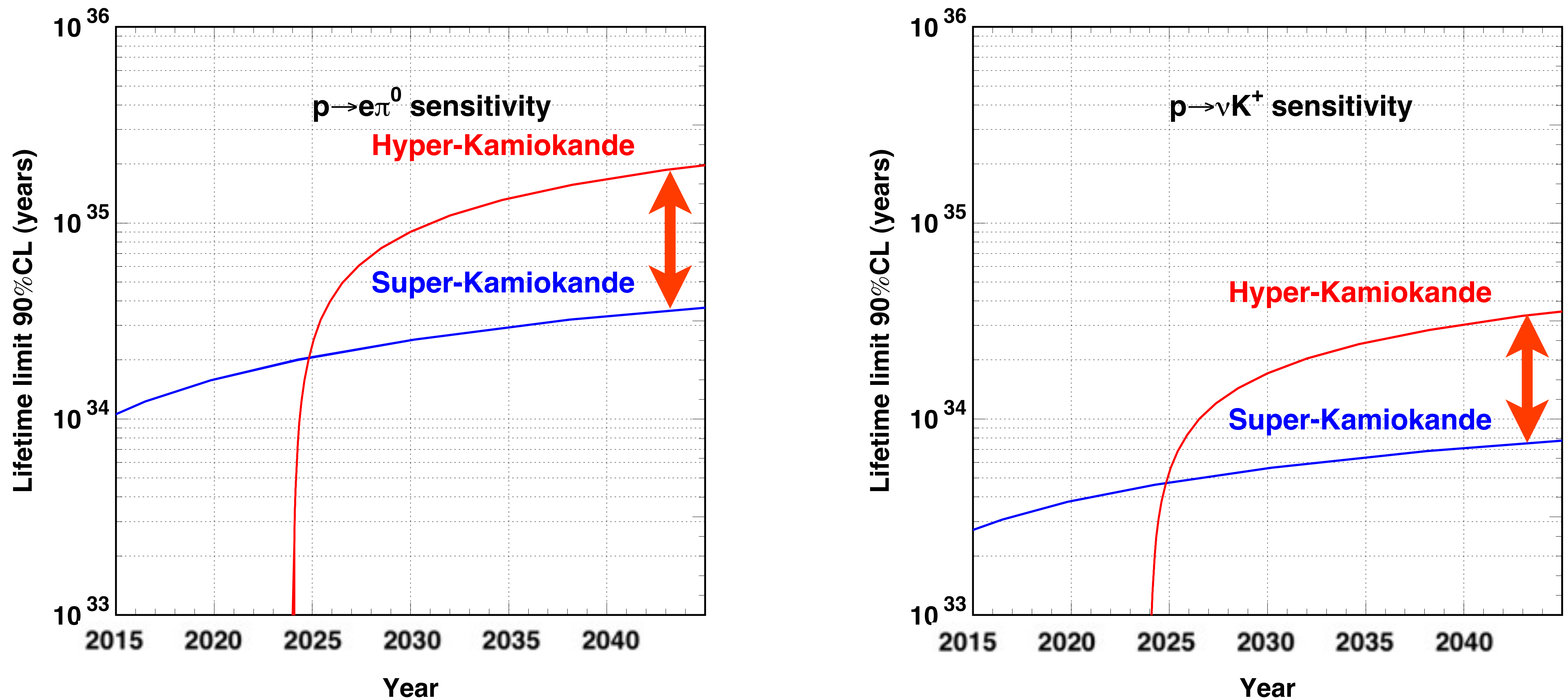

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Accuracy of a **factor of few** in Γ_p estimates needed to make a case !

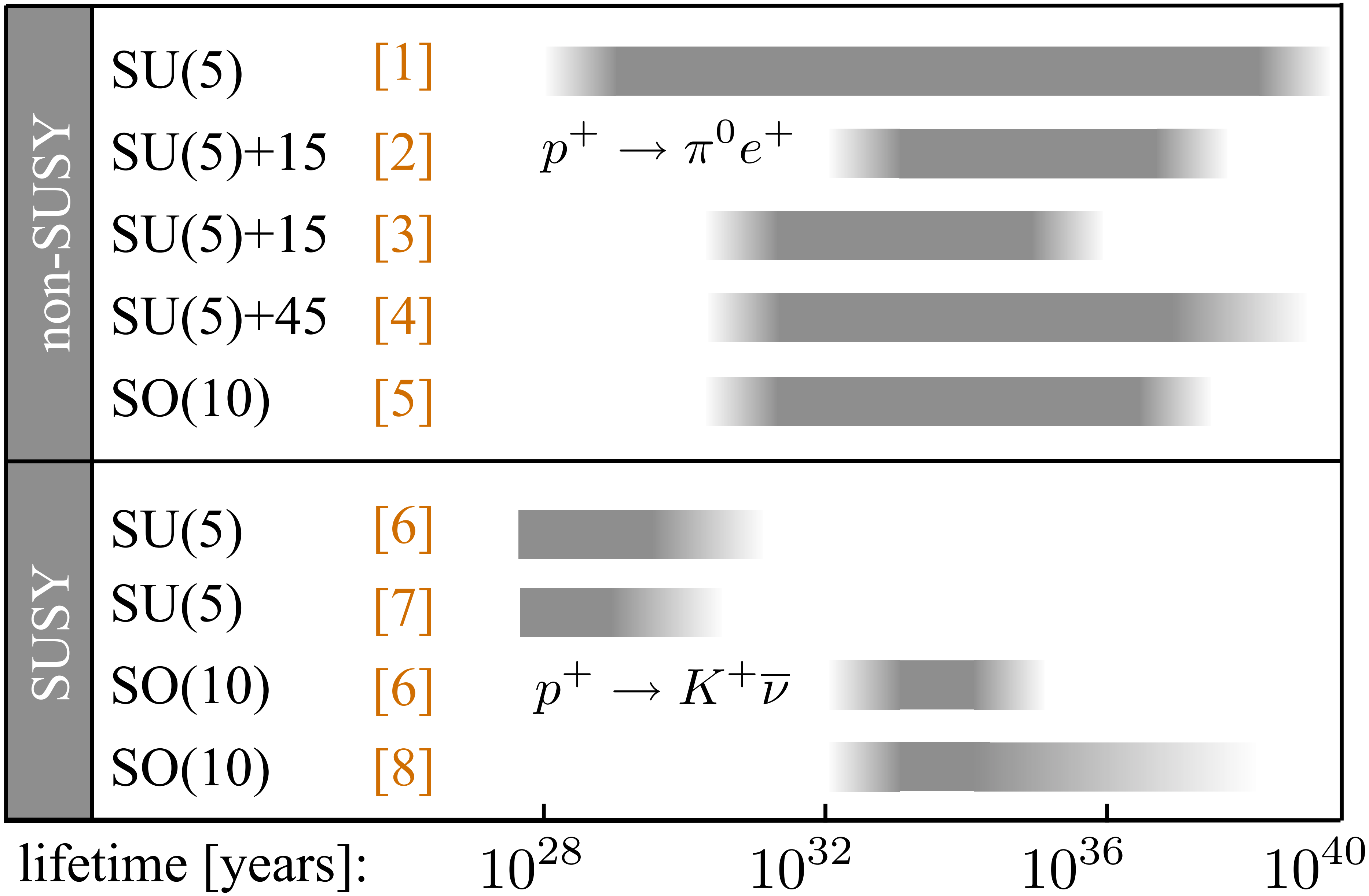
(At least) **NLO PRECISION REQUIRED**

Proton lifetime estimates in GUTs

Now I'll focus solely on the BNV **theory accuracy...**

... and leave dealing with the **accuracy of the low-energy inputs** aside

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)
[8] Dutta, Mimura, Mohapatra, PRL 94, 091804 (2005)
... and many more.

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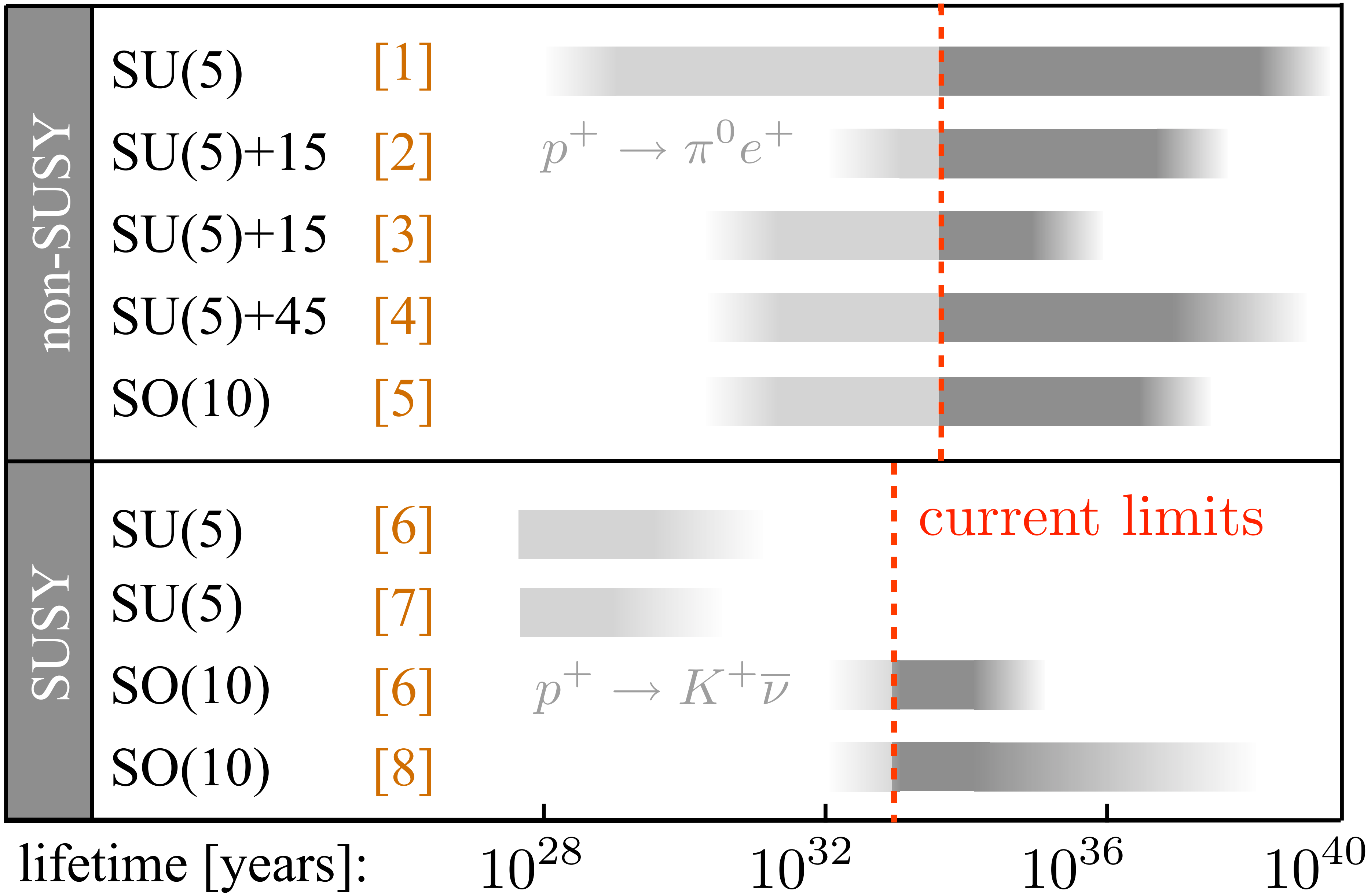

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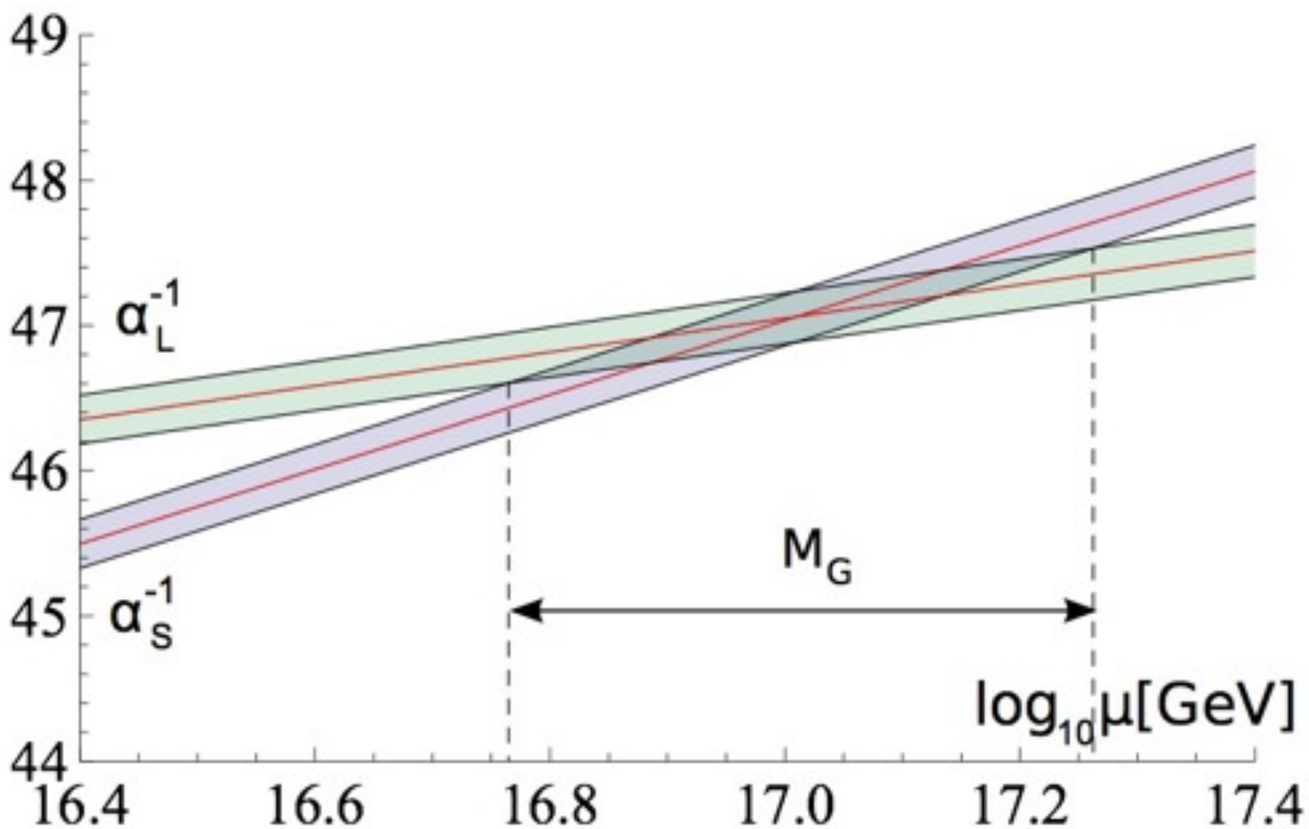
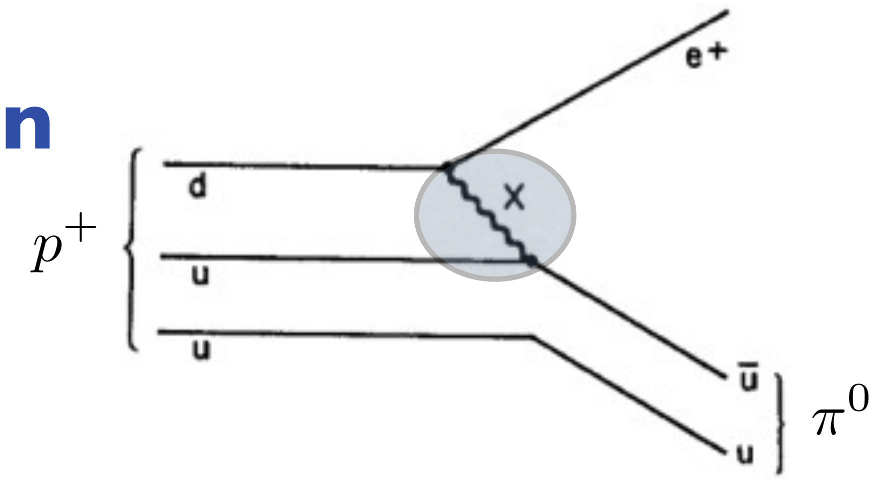
Main theoretical uncertainties in p-decay estimates

GUT scale determination

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



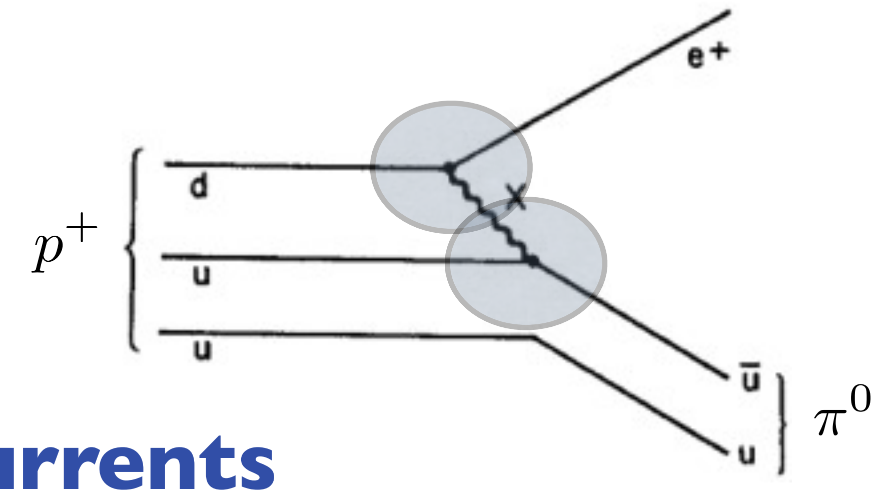


Credit: H. Kolesova

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

NB. SUSY is "schizophrenic" in this respect...

Main theoretical uncertainties in p-decay estimates



Flavour structure of the BLV currents

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

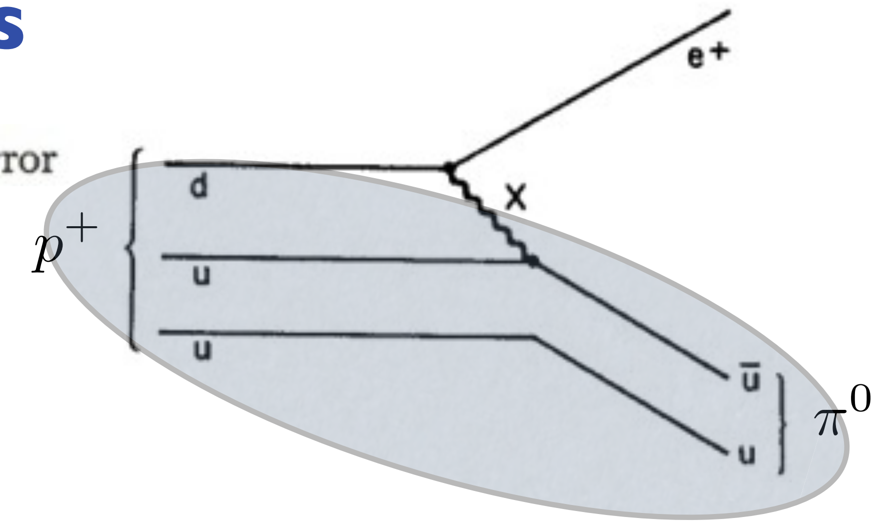
- RH rotations enter here

- simple Yukawa sector desirable!

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

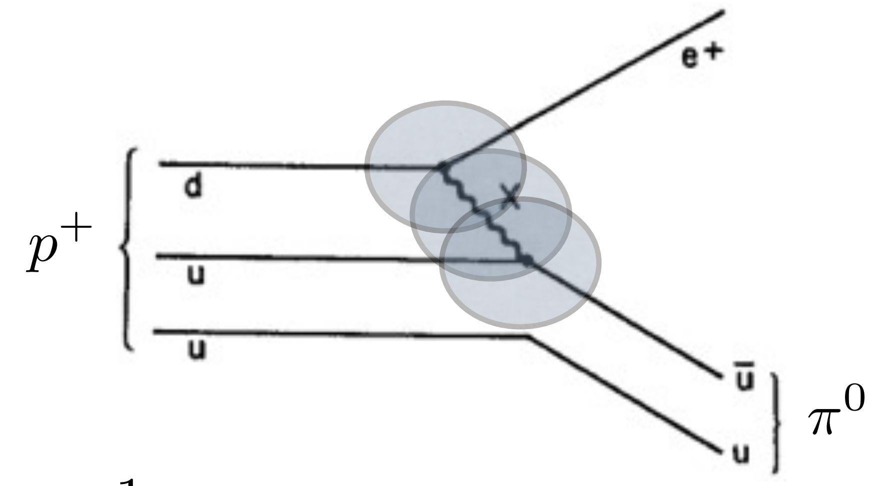


Y. Aoki, E. Shintani, A. Soni, Phys.Rev. D89 (2014) 014505 (lattice)

Main theoretical uncertainties in p-decay estimates

Planck scale effects

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



- finite shifts in the gauge matching, can be as large as $\Delta\alpha_i^{-1} \sim 1$

Larsen, Wilczek, NPB 458, 249 (1996)
G. Veneziano, JHEP 06 (2002) 051
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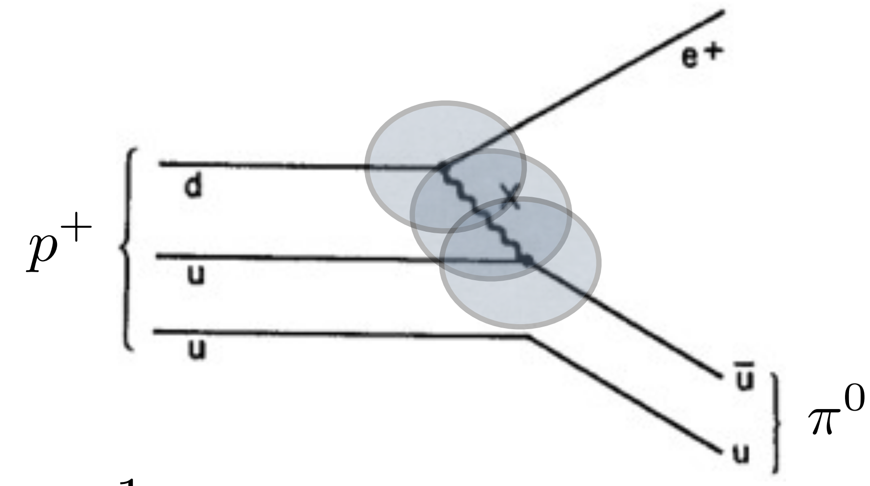

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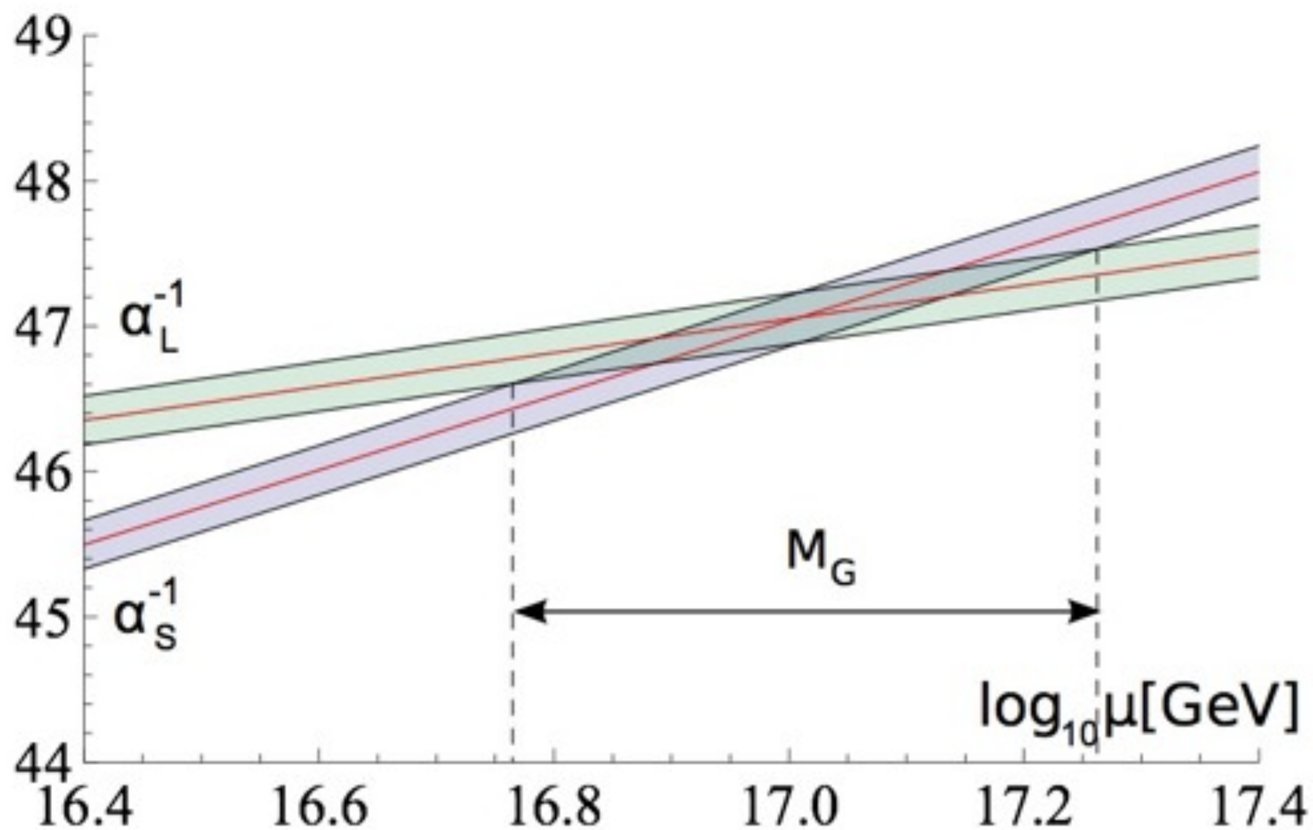

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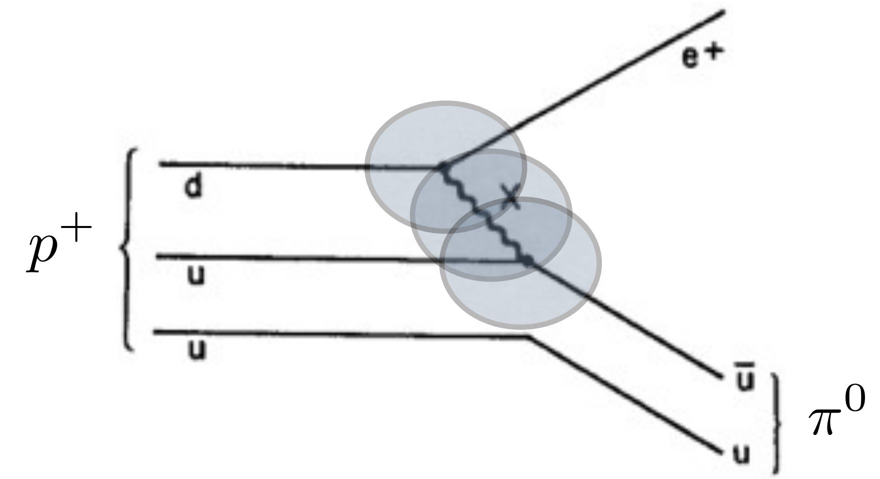

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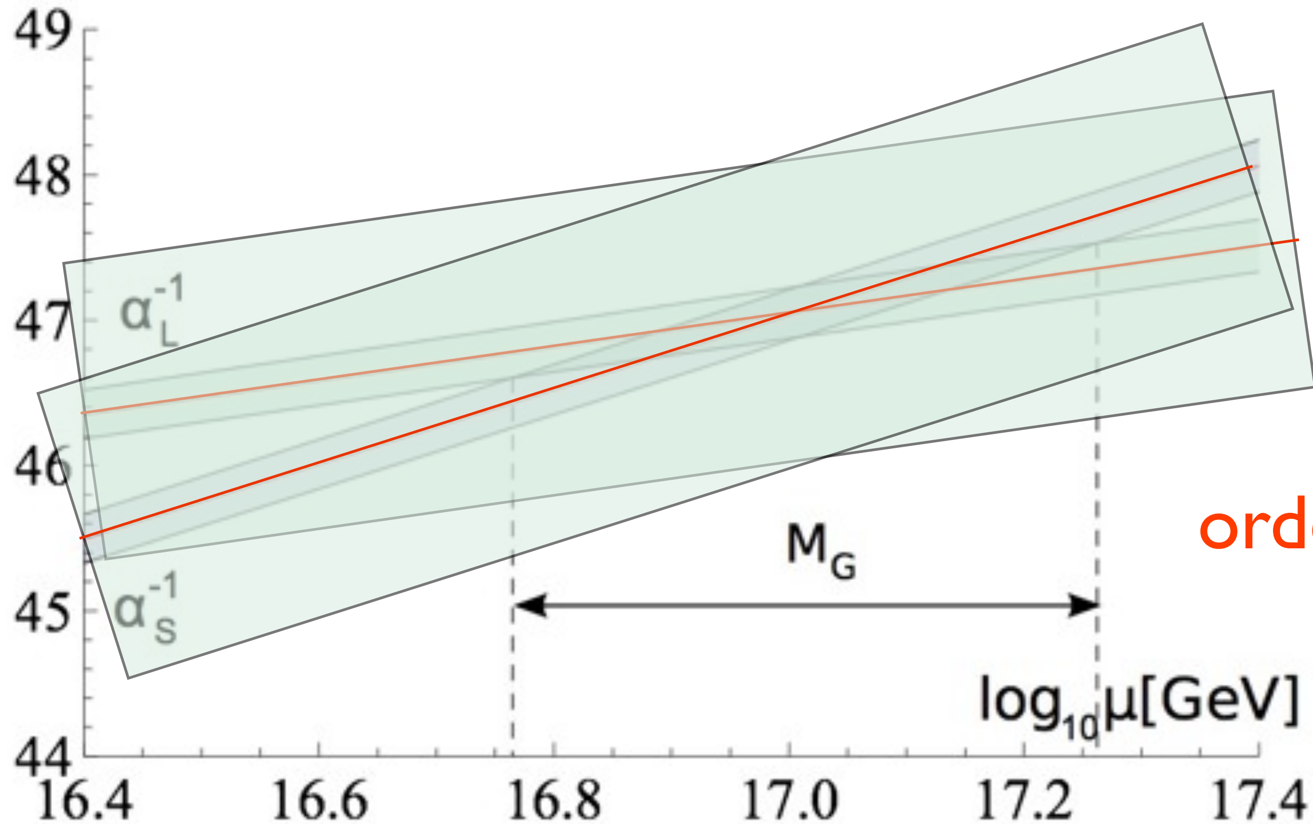

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orders of magnitude uncertainty in M_G!

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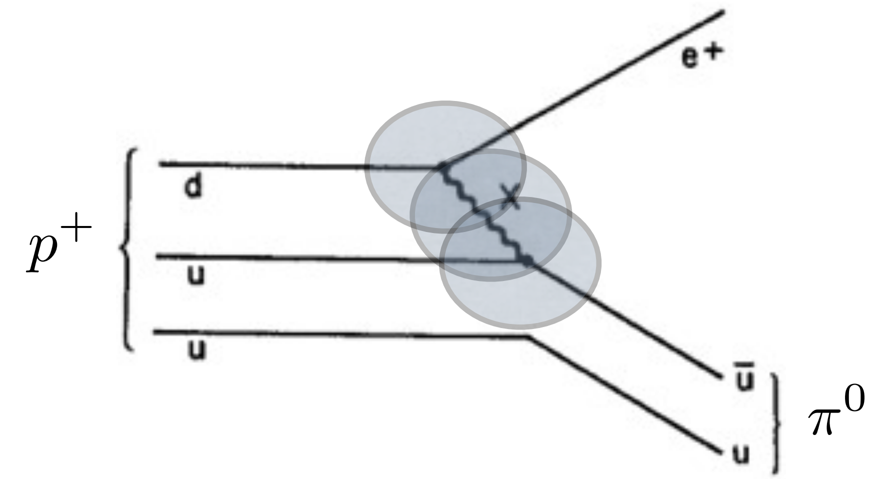
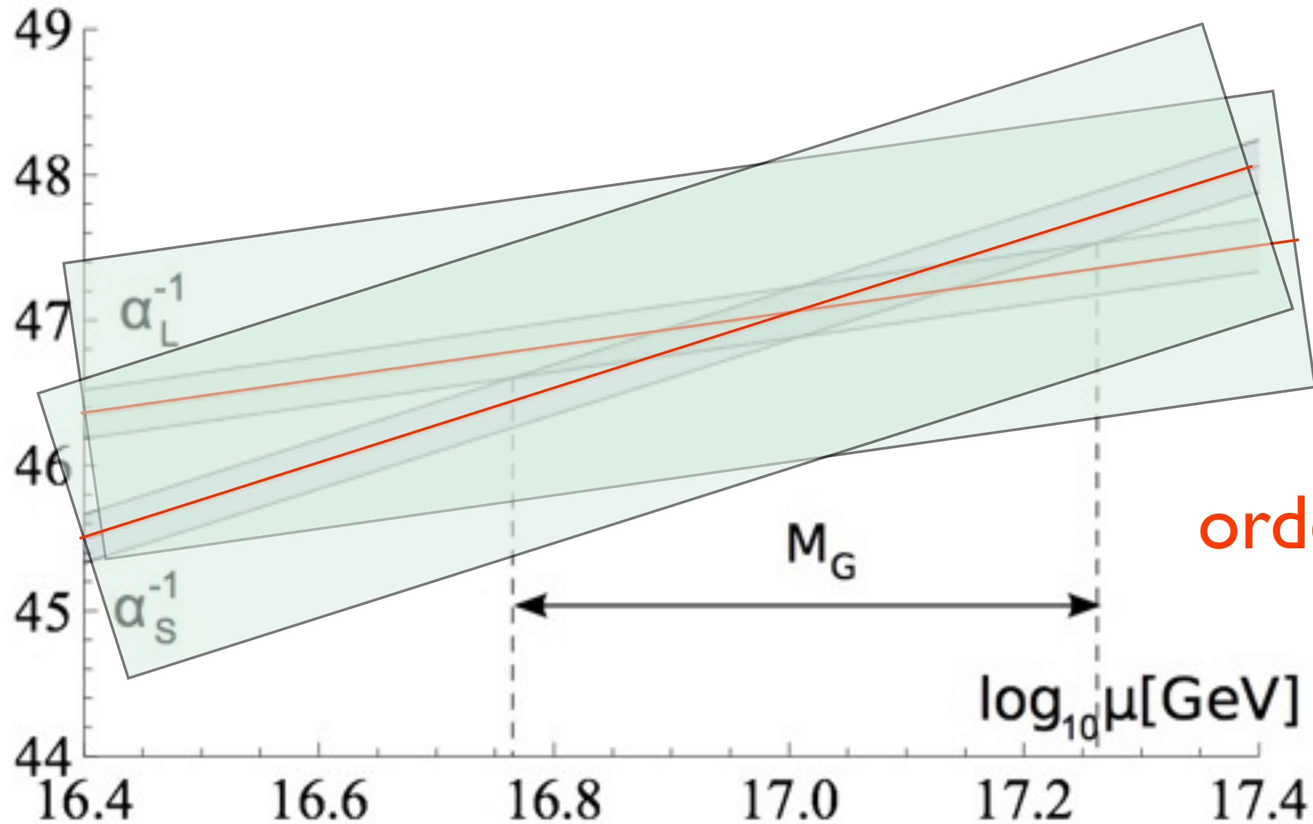


- finite shifts in the gauge matching, can be as large as $\Delta\alpha_i^{-1} \sim 1$



Larsen, Wilczek, NPB 458, 249 (1996)
G. Veneziano, JHEP 06 (2002) 051
Calmet, Hsu, Reeb, PRD 77, 125015 (2008)
G. Dvali, Fortsch. Phys. 58 (2010) 528-536

orders of magnitude uncertainty in M_G!

NO POINT IN WORKING @ 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:

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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:

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

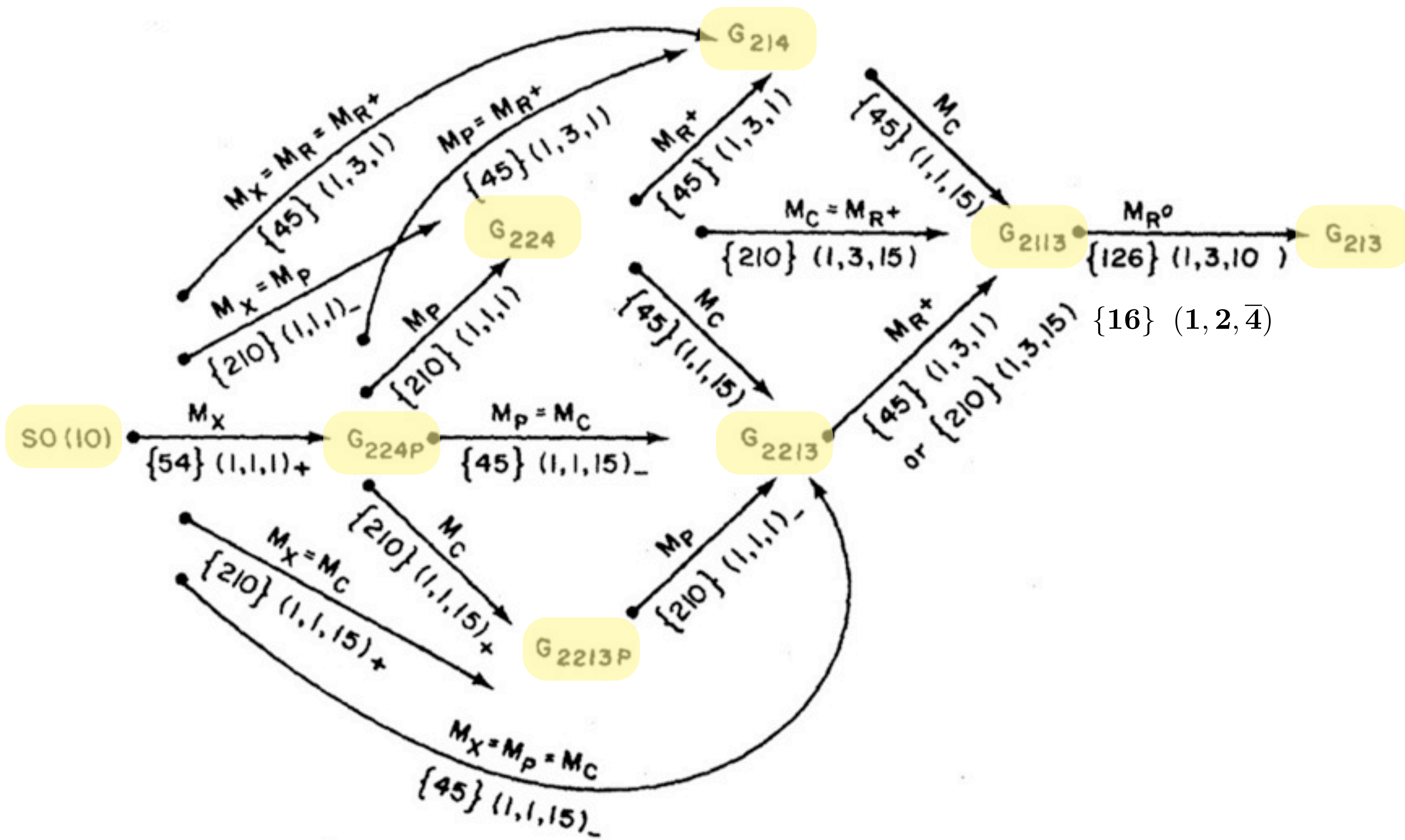
these, however, are the "usual" choices (**though not minimal**)...

Minimal SO(10) GUT

The minimal SO(10) unification

Chang, Mohapatra, Gipson, Marshak, Parida 1985

SU(5) branches omitted



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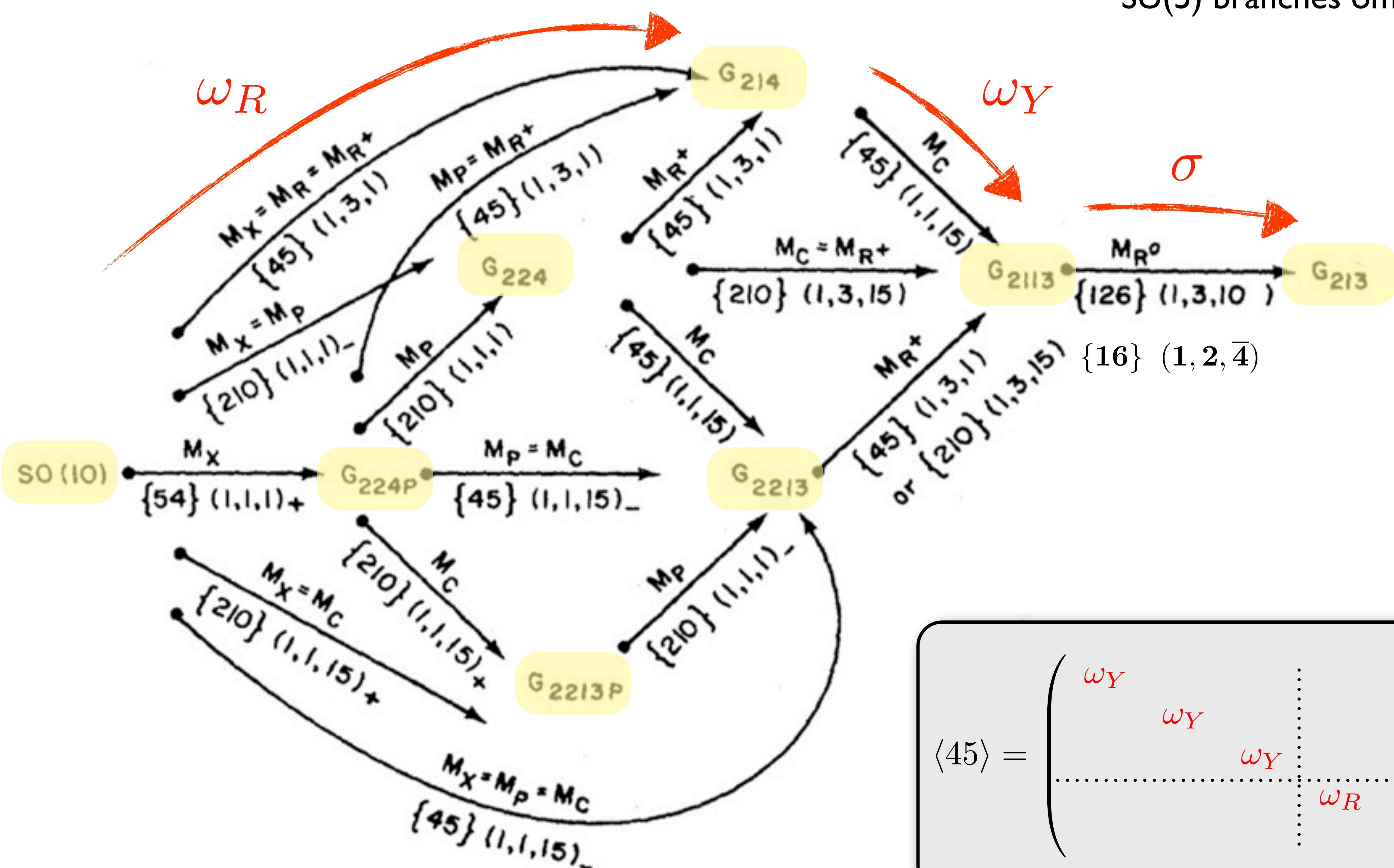

$$\langle 45\rangle = \begin{pmatrix} \omega_Y & & & & \\ & \omega_Y & & & \\ & & \omega_Y & & \\ & & & \omega_R & \\ & & & & \omega_R \end{pmatrix} \otimes \tau_2$$

The minimal SO(10) unification

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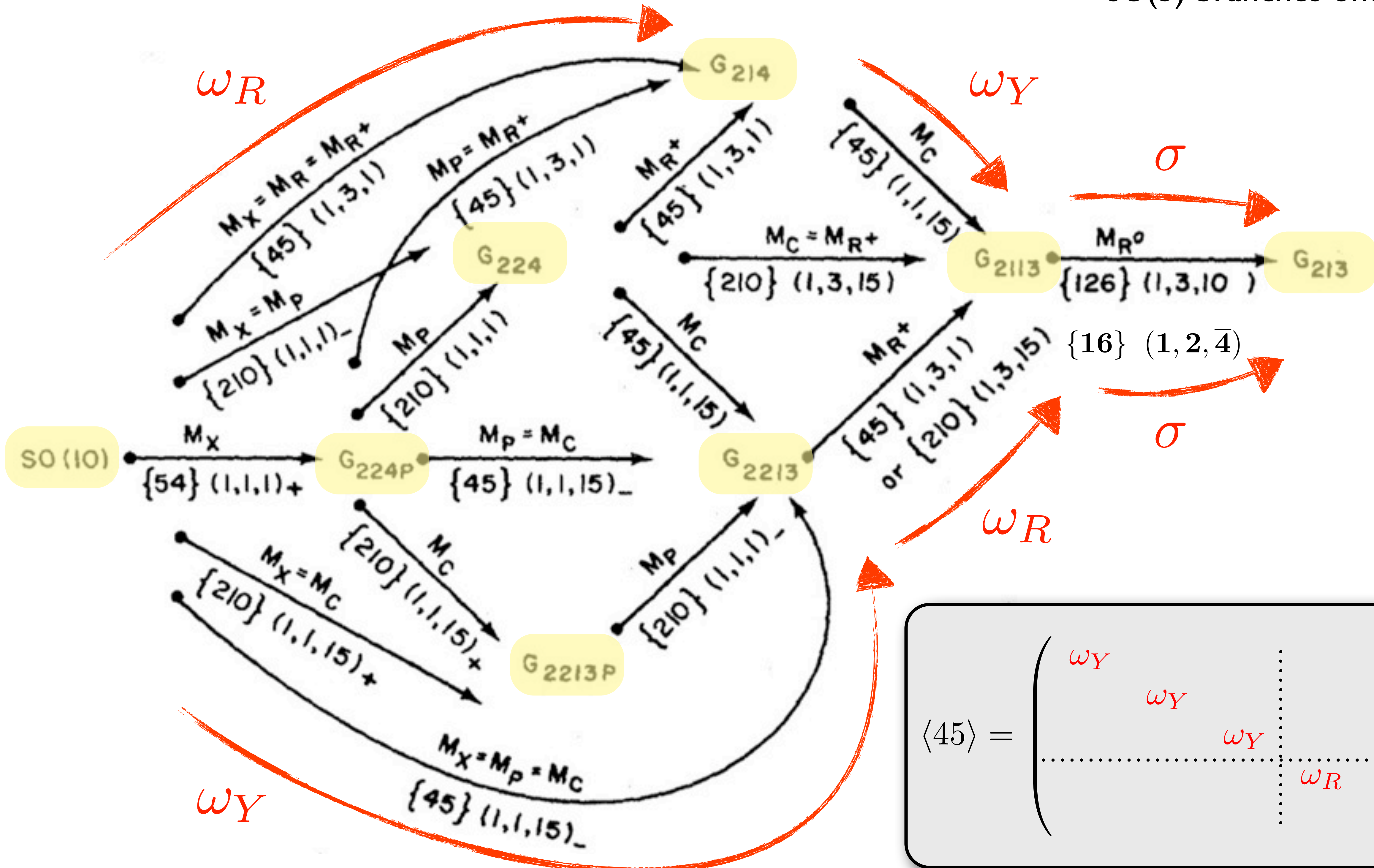

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Taming the Planck-scale effects in the minimal SO(10)

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

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

The minimal SO(10) unification

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

"Ruled out" in 1980's

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

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

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

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

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

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

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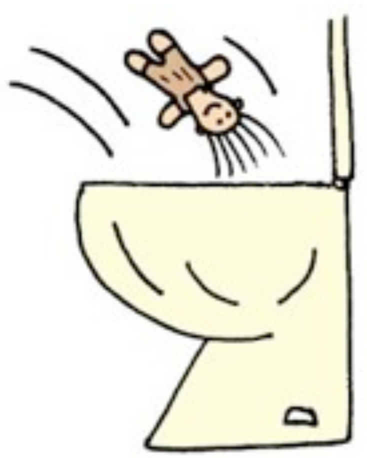
$$



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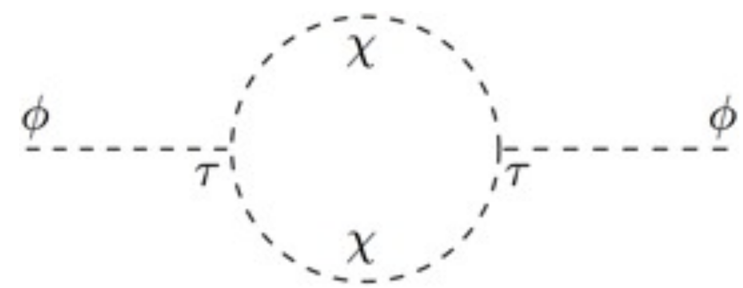
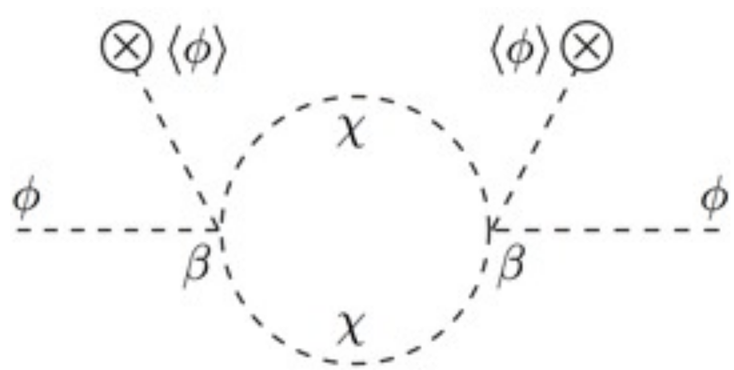
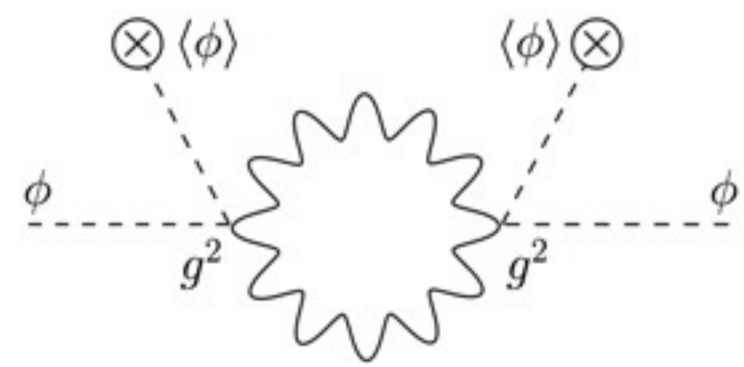
The minimal SO(10) ~~unification~~ nightmare

Quantum salvation in 2010

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)

The minimal SO(10) unification

Quantum salvation in 2010

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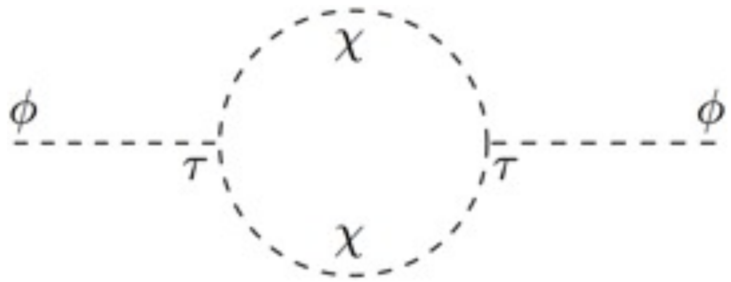

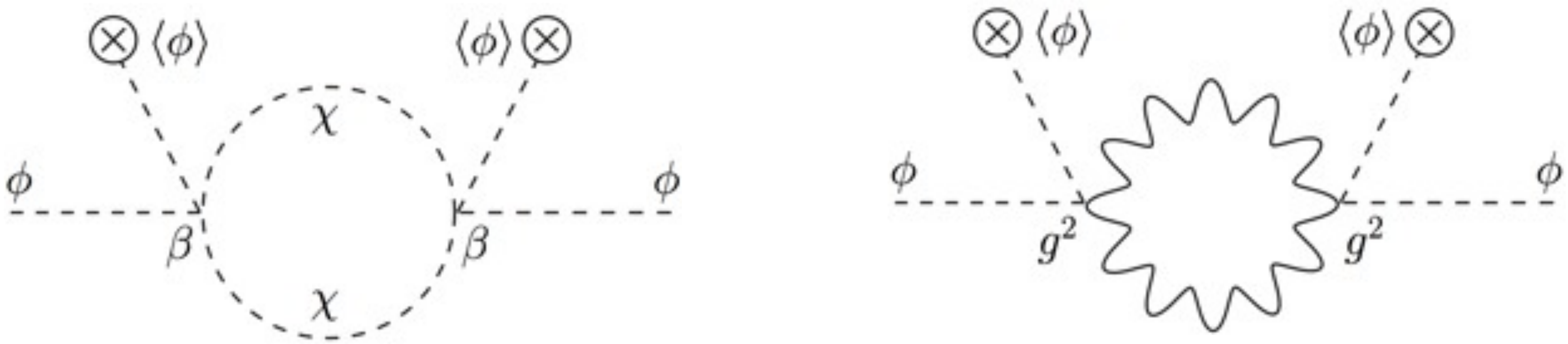

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Conclusions / outlook

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 scalar is the best hope.

Thanks for your kind attention!

Backup slides

The minimal consistent SO(10) unification

"Consistency is the last refuge of people without imagination"

Oscar Wilde

The minimal consistent SO(10) unification

Chang, Mohapatra, Gipson, Marshak, Parida (1985)
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Simple estimates: $M_{\rm seesaw} \sim 10^{10}\,{\rm GeV}$ $\Longrightarrow$ too heavy LH neutrinos!?

multiple Yukawa finetuning?

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Two other potentially realistic minimally fine-tuned & consistent scenarios with "light" scalars:

$(8, 2, +\frac{1}{2})$ $(6, 3, +\frac{1}{3})$

Bertolini, Di Luzio, MM, PRD85 095014 2012

Towards a consistent & potentially realistic SO(10) scenario

Case I: light $(8, 2, +\frac{1}{2})$ **@ one loop**

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

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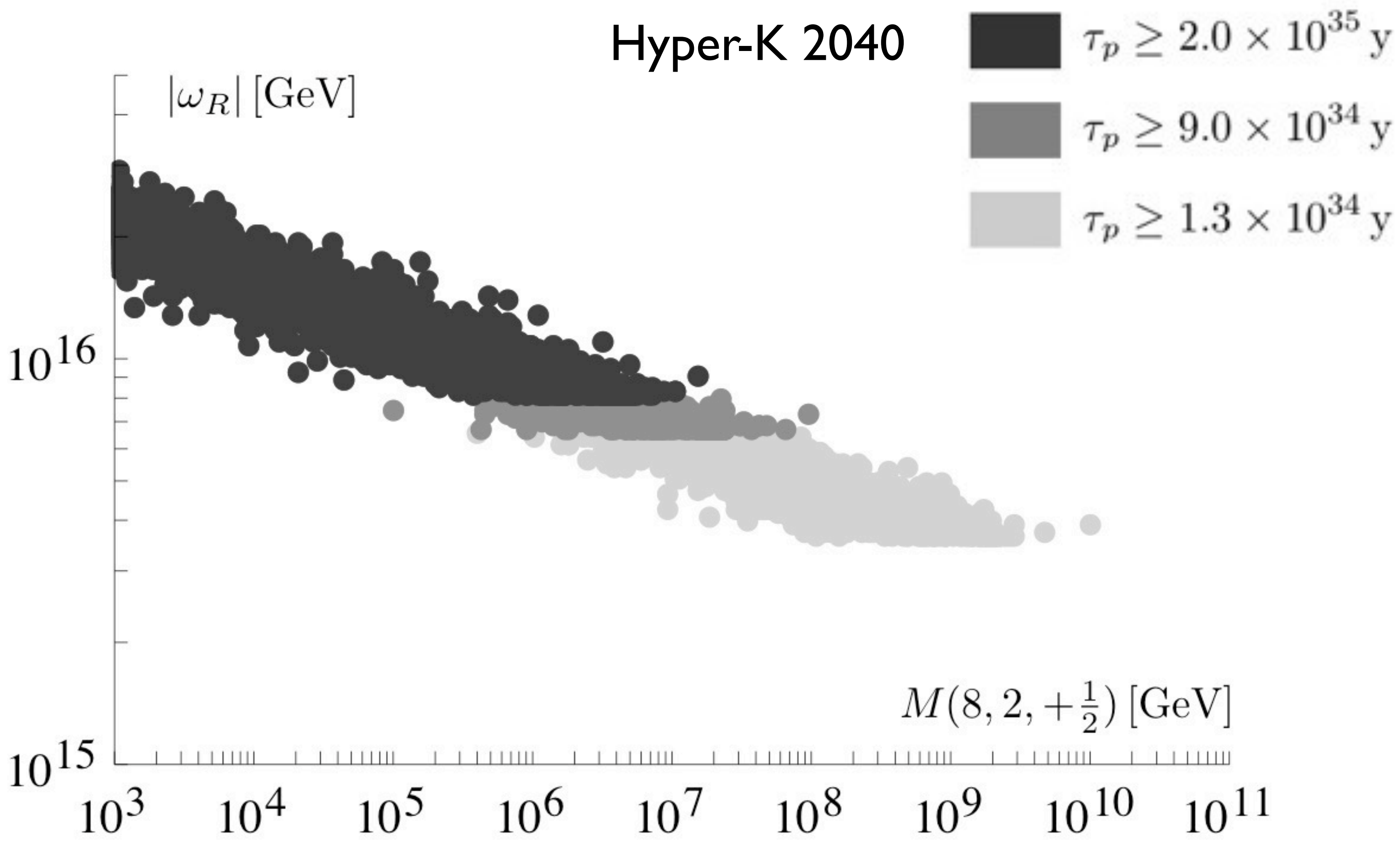

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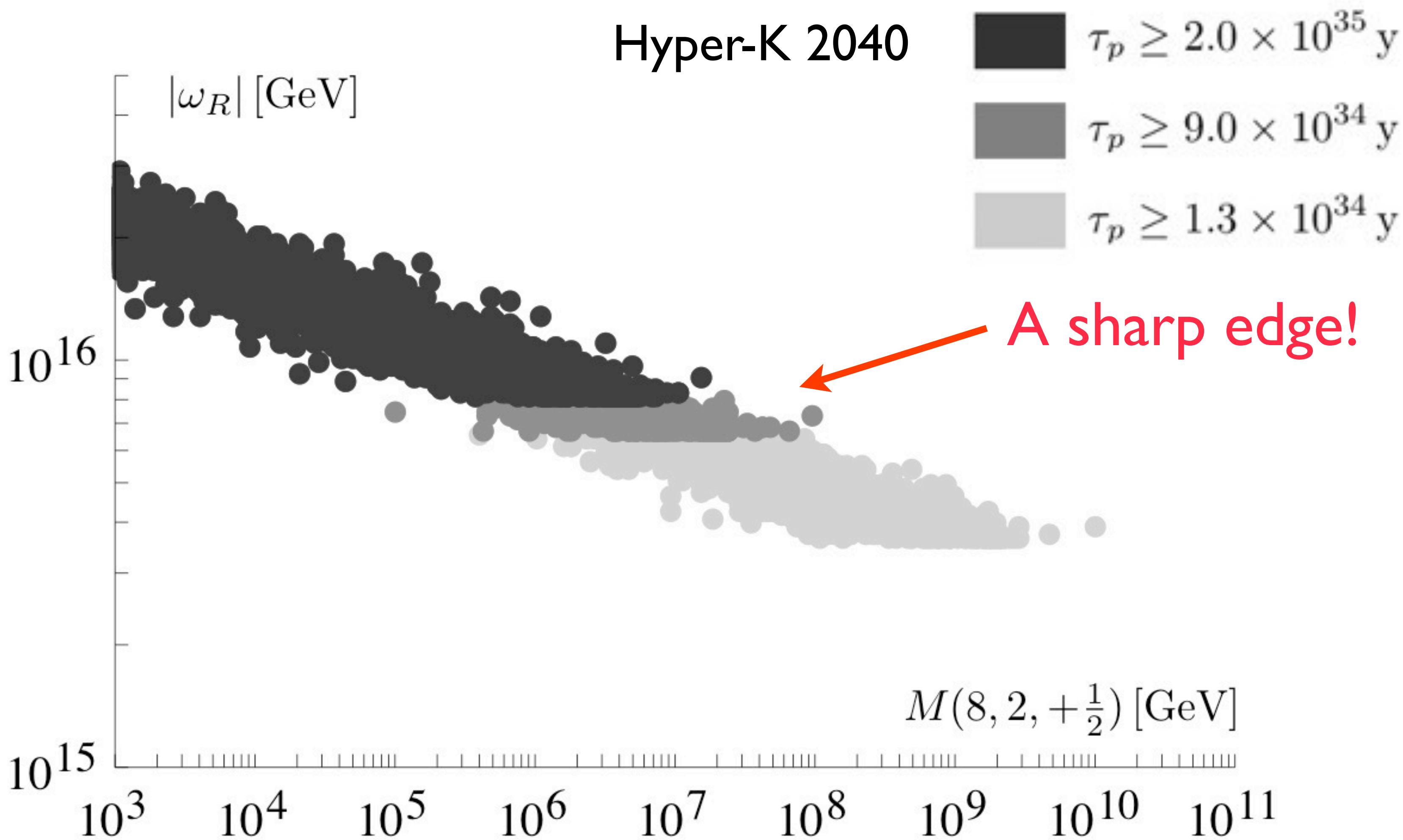

The octet should be light!!!

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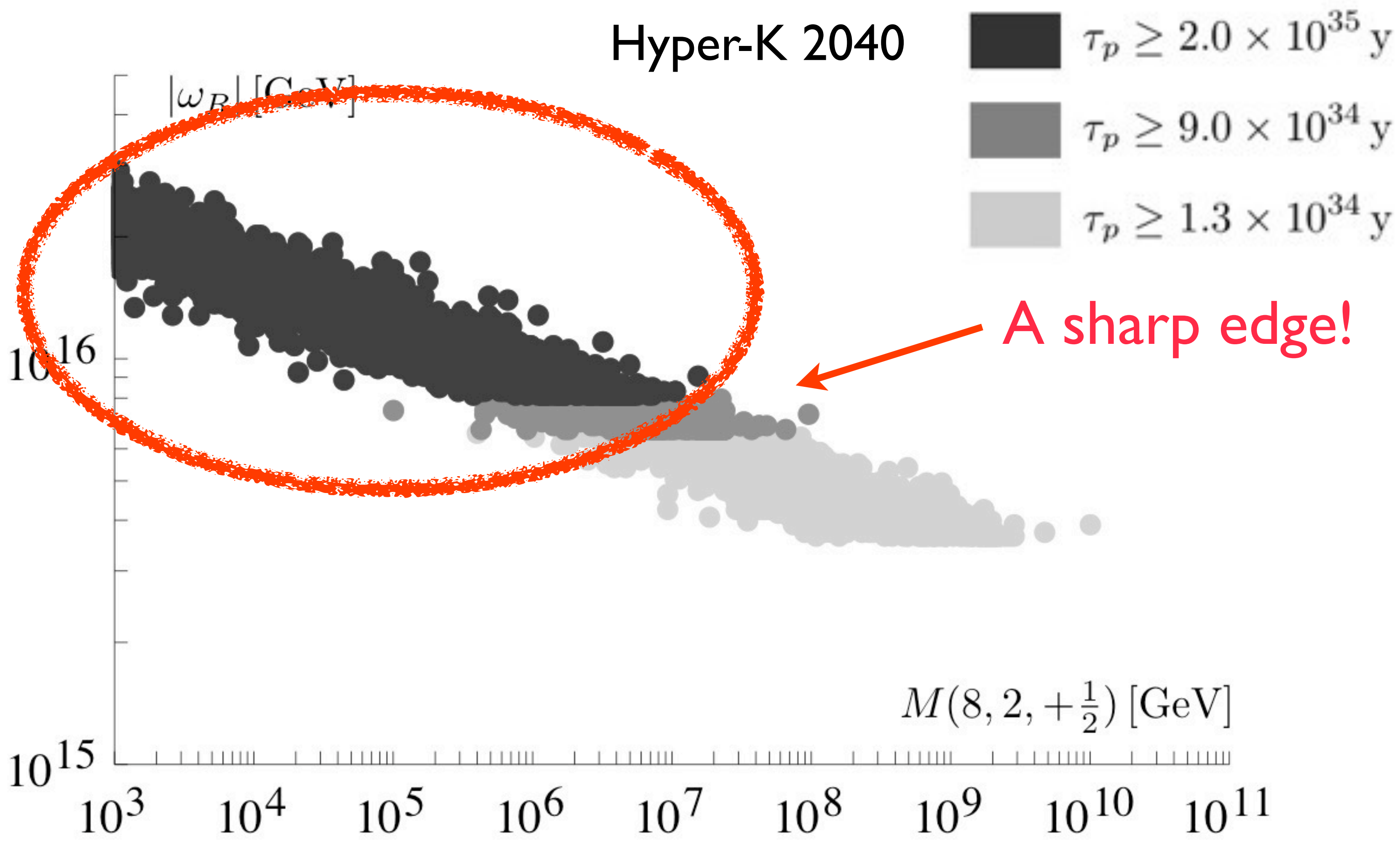
Bertolini, Di Luzio, MM, PRD 85, 095014 (2012)



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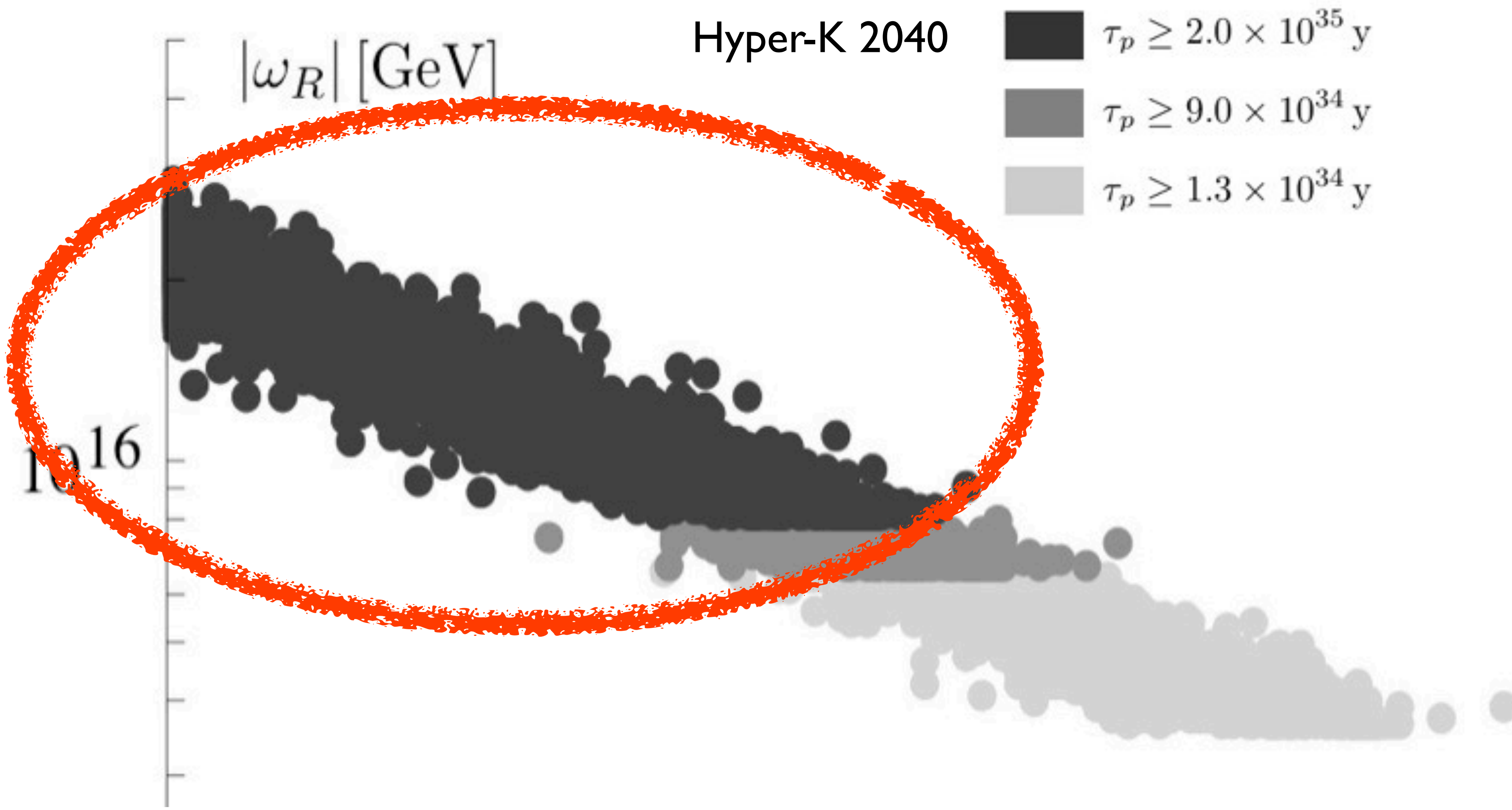
Bertolini, Di Luzio, MM, PRD 85, 095014 (2012)



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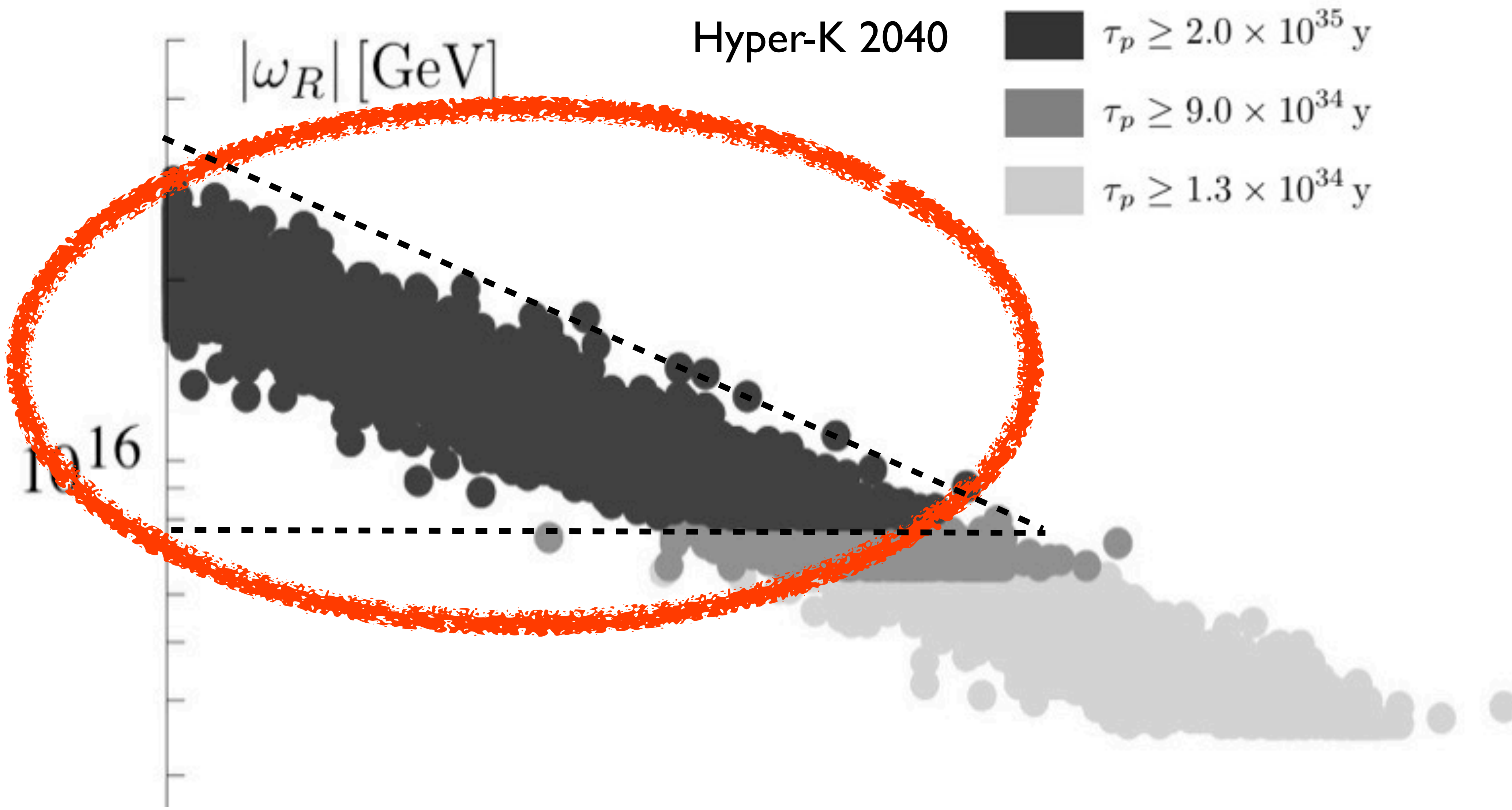

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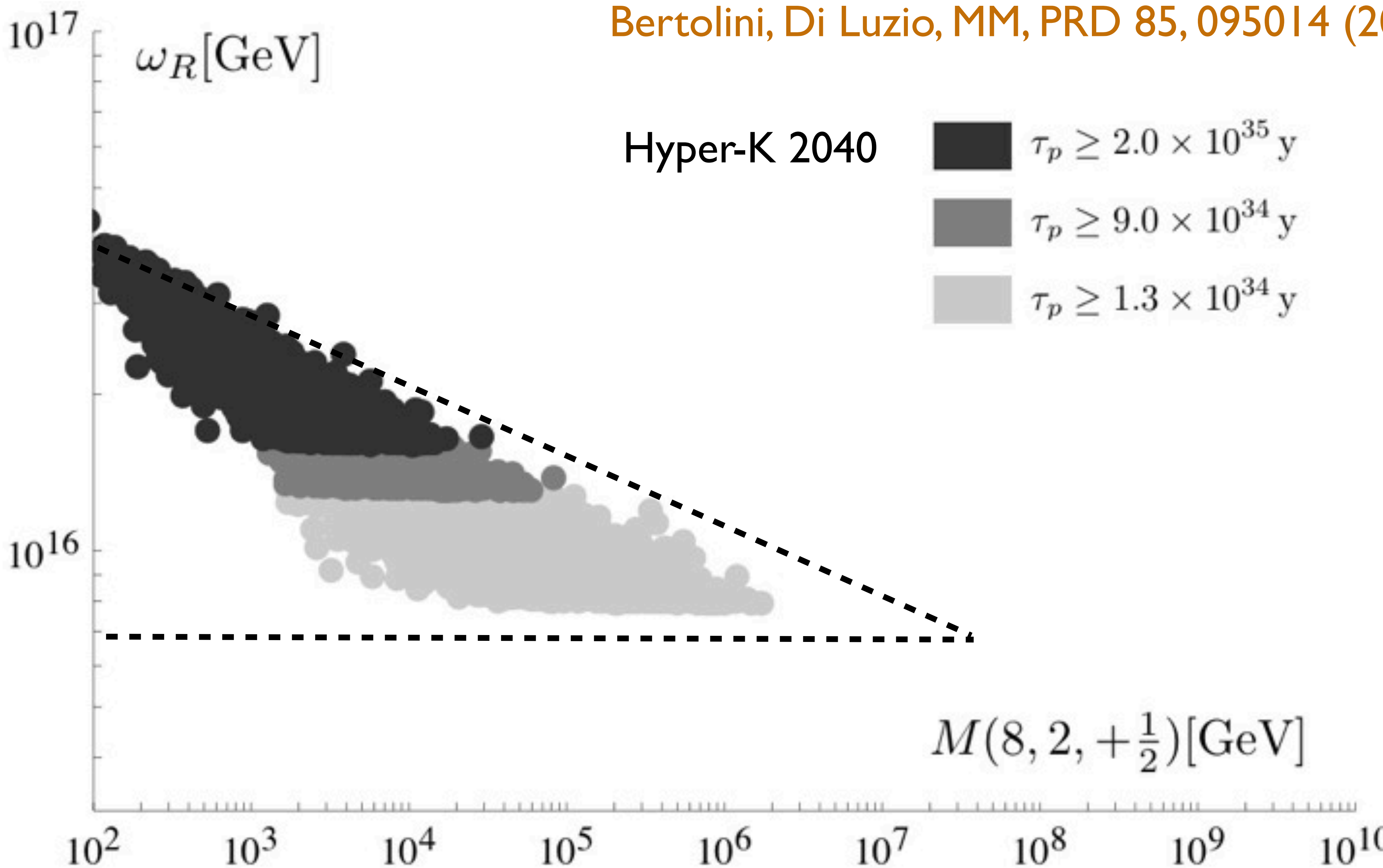
Bertolini, Di Luzio, MM, PRD 85, 095014 (2012)



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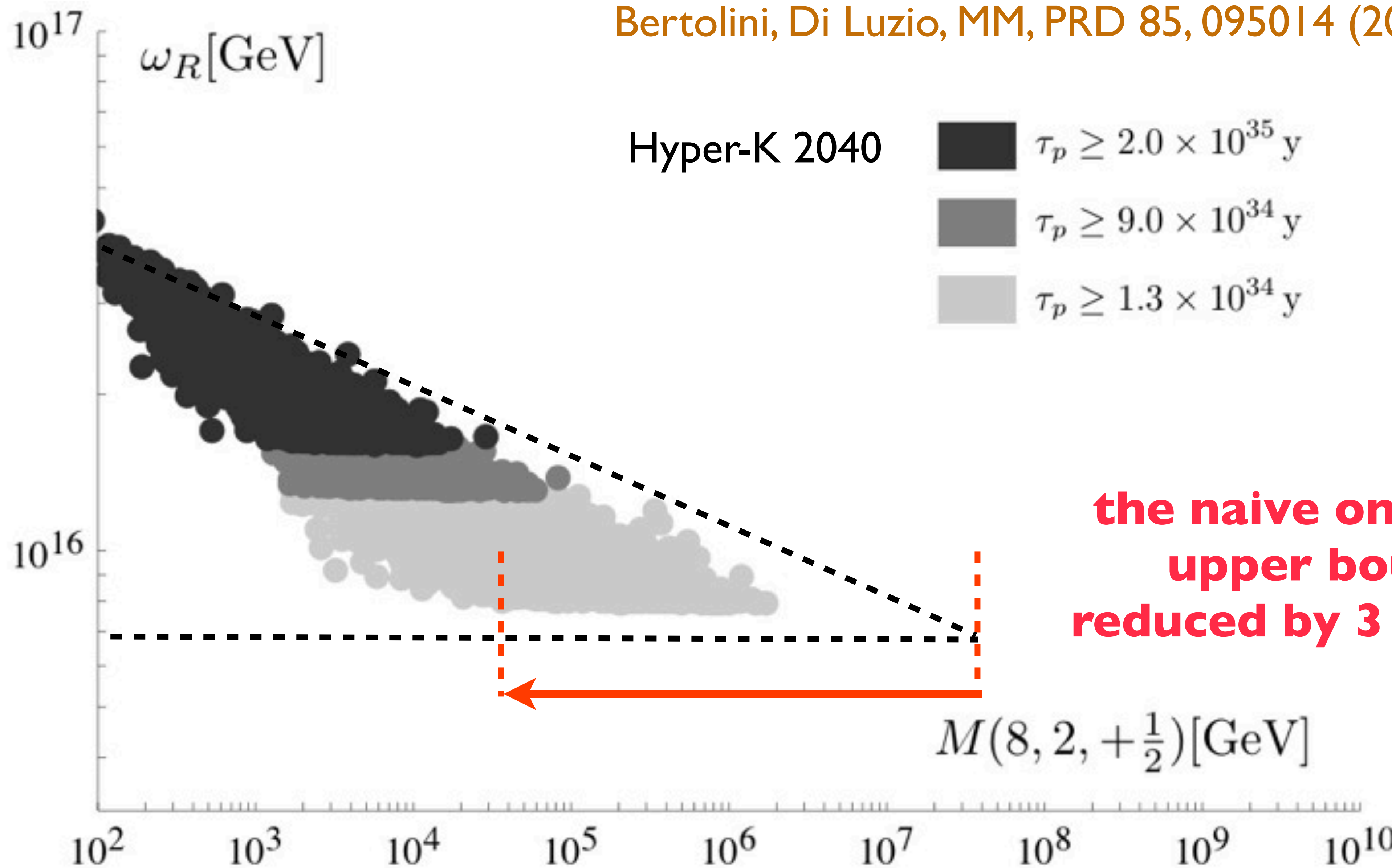

the naive one-loop upper bound reduced by 3 o.o.m. !

Towards a consistent & potentially realistic SO(10) scenario

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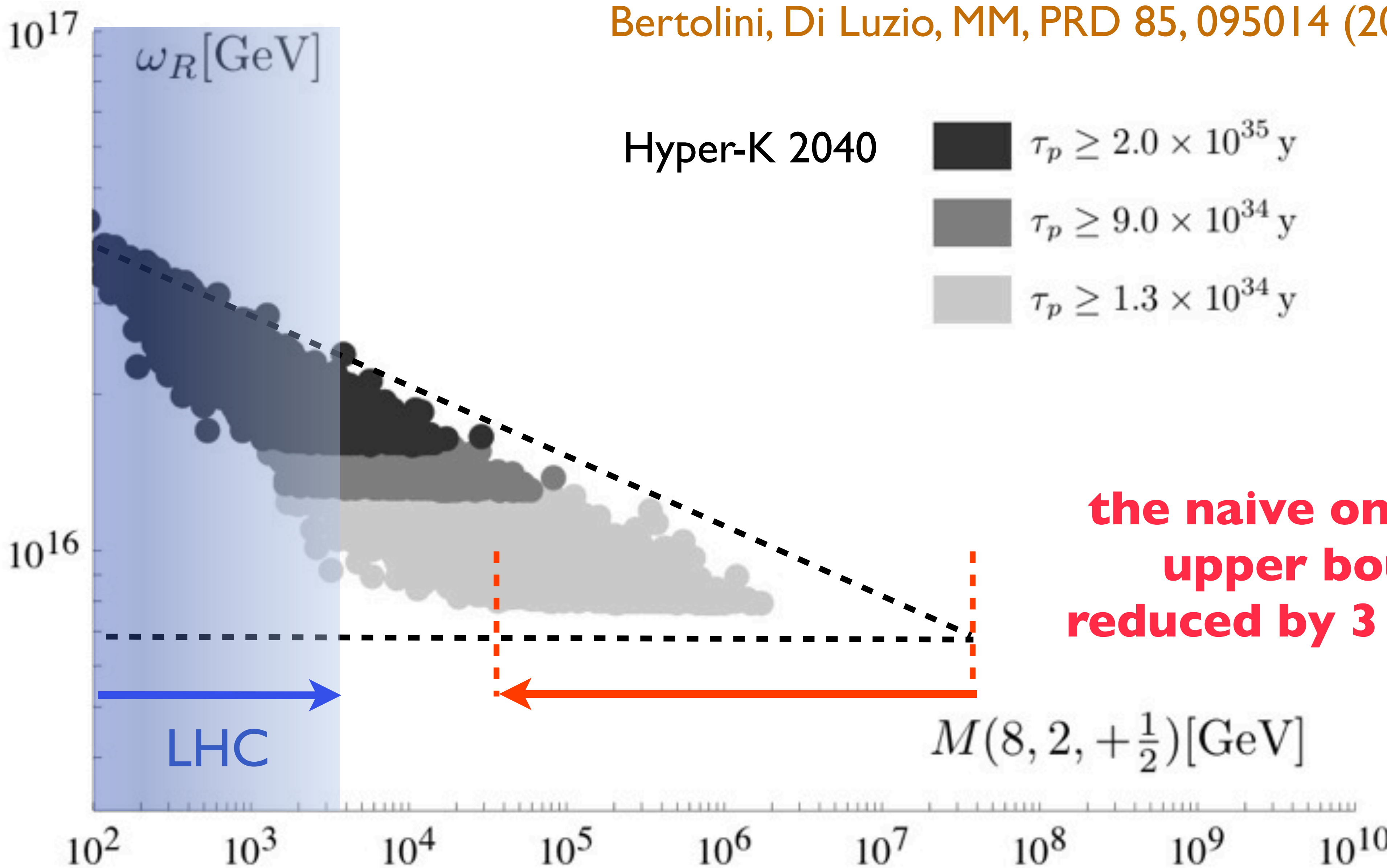
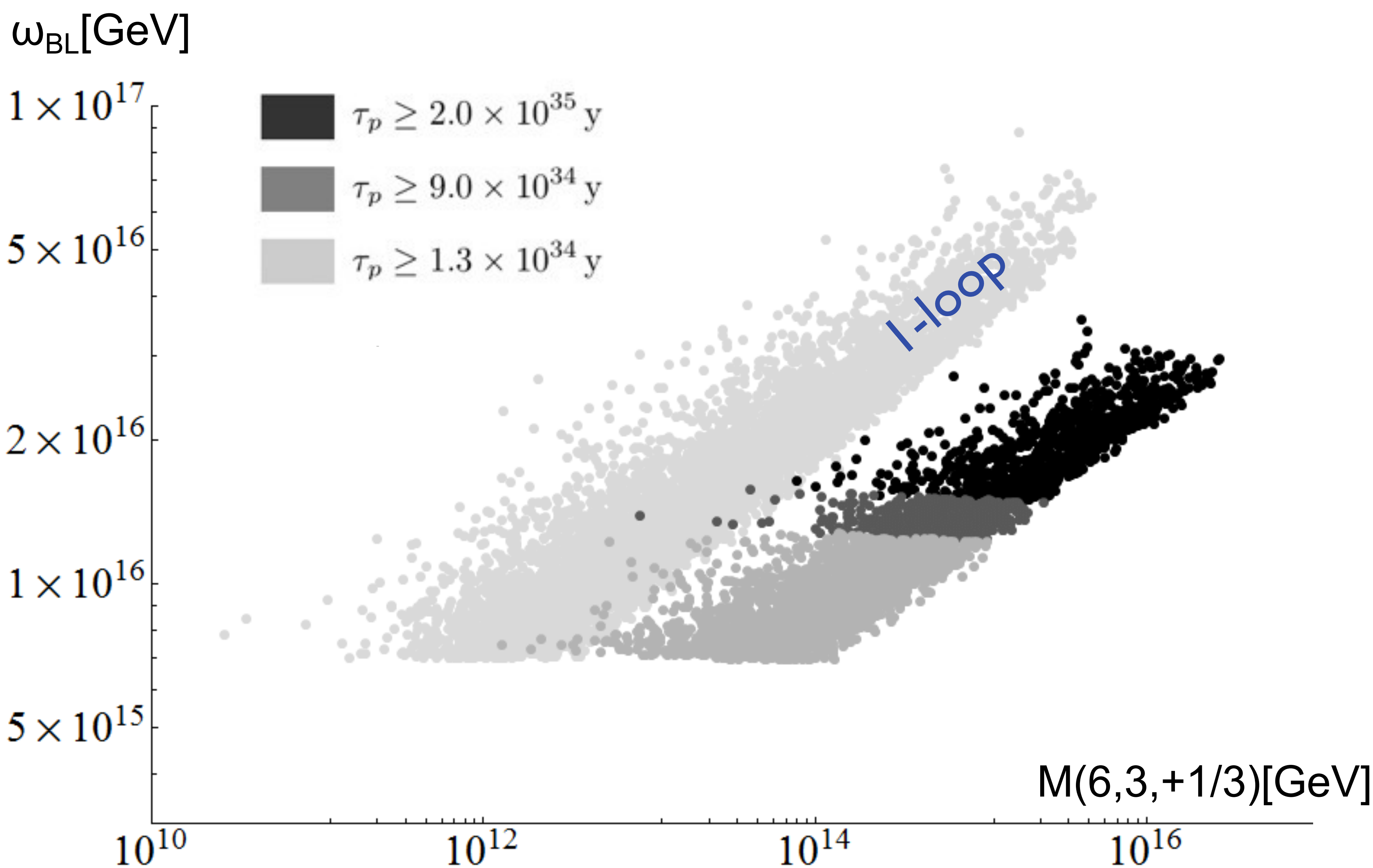


the naive one-loop upper bound reduced by 3 o.o.m. !

Towards a consistent & potentially realistic SO(10) scenario

Case II: light $(6,3,+\frac{1}{3})$**@ NLO**

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



Towards a consistent & potentially realistic SO(10) scenario

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