Yukawa coupling unification in non-supersymmetric SO(10) models with an intermediate scale

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Outline

- Introduction & Motivation
- Left-right models
- Unification of Gauge couplings in SO(10) GUTs
- SO(10) symmetry breaking and the low-energy effective theory
- Yukawa couplings unification and E6 motivated Yukawa unification
- Conclusions

(Based on papers in collaboration with Abdelhak Djouadi and Martti Raidal, arXiv: 2106.15822, 2207.xxxxx)

Introduction & Motivation

What is the physics above the electroweak scale?

+ The supersymmetric models (e.g. MSSM)

- A hidden sector weakly interacted with the Standard model (e.g. 2HDM, …)

  § Vacuum stability

- The Left-Right models (e.g. PS, MLRSM, …)

  § Provides a simple solution to the Strong CP Problem and a dark matter candidate

  § Natural setting for small neutrino mass via seesaw mechanism

  § Explain the origin of parity violation.

+ The SO(10) Grand Unified Theory

The minimal left-right symmetric model

Basic idea: extend the gauge group of the SM with $SU(2)_R \times U(1)_{B-L}$ symmetry.

The right-handed symmetry is broken by the scalar triplets $\Delta_L(\mathbf{1},\mathbf{3},\mathbf{1},\mathbf{2}) \oplus \Delta_R(\mathbf{1},\mathbf{1},\mathbf{3},\mathbf{2})$ and bi-doublet $\phi(\mathbf{1},\mathbf{2},\mathbf{2},\mathbf{0})$. We can assign the correct vevs for both triplets and bi-doublets to trigger the right-handed symmetry breaking at right-handed scale v_R and electroweak symmetry breaking at v_{EW}:

$$\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} \kappa_1 & 0 \\ 0 & \kappa_2 e^{i\theta_2} \end{pmatrix}, \qquad \langle\Delta_L\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ v_L e^{i\theta_L} & 0 \end{pmatrix}, \qquad \langle\Delta_R\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}$$

(P. S. Bhupal Dev, et,al., arXiv: 1811.06869)

The seesaw mechanisms

If the vevs have the following relations, we can write down the mass matrix of neutrinos from a simple Yukawa interactions between the fermions and scalars.

$$\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$$

$$\downarrow$$

$$\langle \Delta_L^0 \rangle \simeq 0, \qquad \langle \Delta_R^0 \rangle = v_R \neq 0, \qquad M_\nu = \begin{pmatrix} 0 & 0 \\ 0 & v_R \end{pmatrix}$$

$$\downarrow$$

$$\mathrm{SU}(2)_L \times \mathrm{U}(1)$$

$$\downarrow$$

$$\langle \phi \rangle = \begin{pmatrix} k & 0 \\ 0 & k' \end{pmatrix}, \qquad M_\nu = \begin{pmatrix} 0 & \frac{1}{2}hk \\ \frac{1}{2}hk & fv_R \end{pmatrix}$$

$$\downarrow$$

$$\mathrm{U}(1)_{\mathrm{em}}.$$

$$m_\nu \simeq \frac{h^2 k^2}{2 f v_R},$$

$$m_N \simeq 2 f v_R,$$

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+ The Left-Right models (e.g. PS, MLRSM, …)

- The SO(10) Grand Unified Theories

  § Includes the right-handed symmetry as an intermediate symmetry

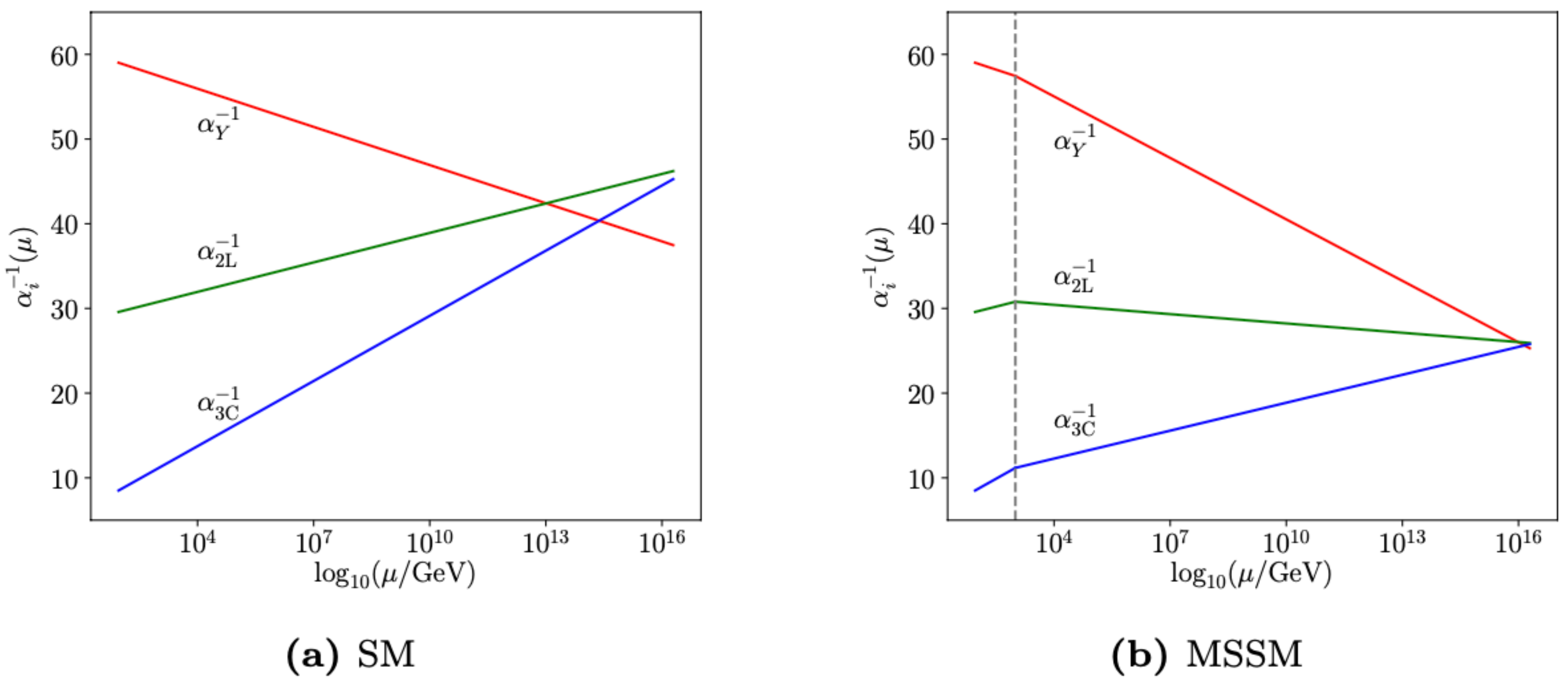
  § Reduce to 2HDM in low-energy

  § Solves the strong CP problem when including the axions

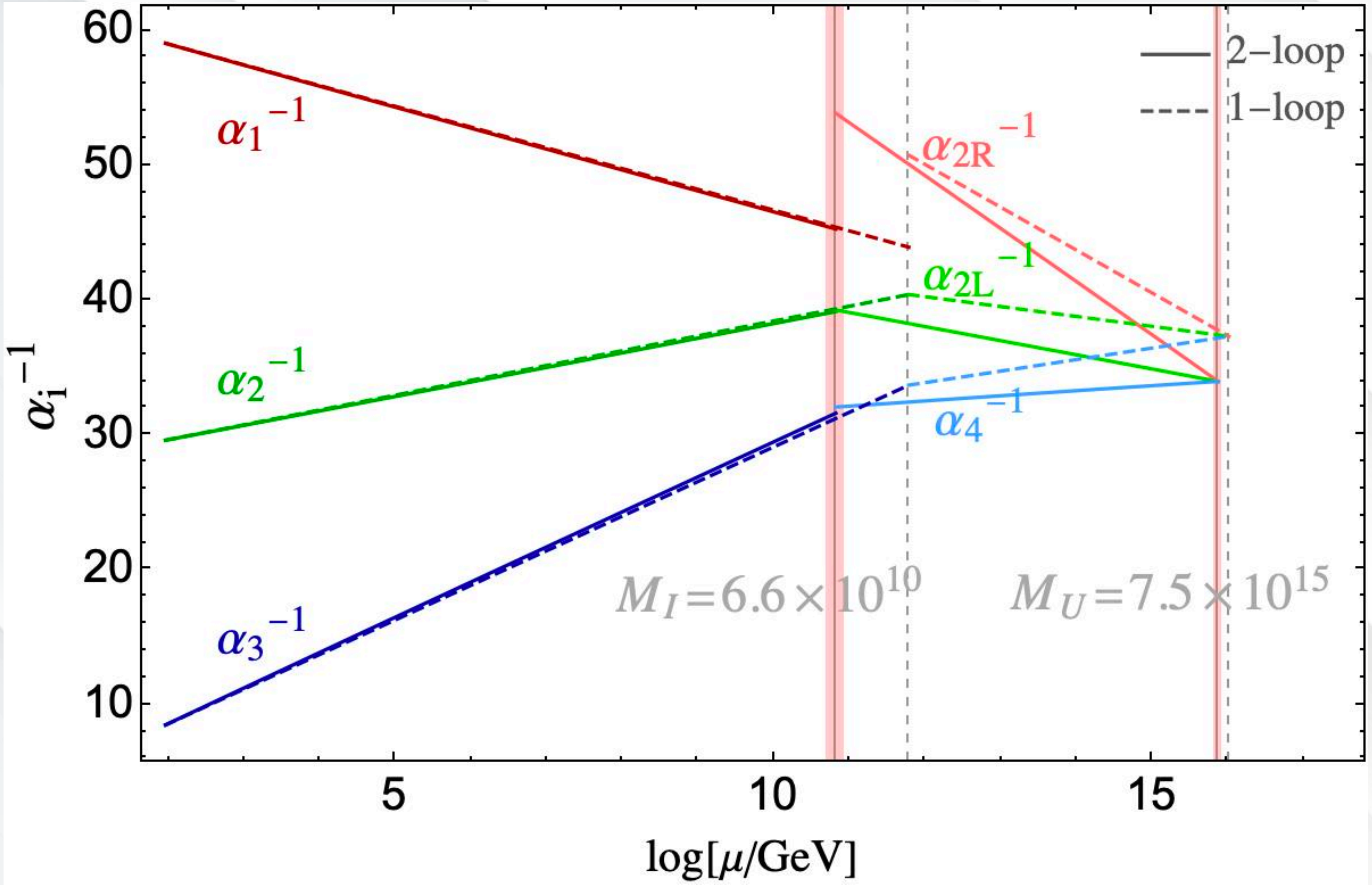
  § The grand unification of all gauge couplings can be achieved with/without SUSY

  § Many phenomenological predictions such as DM, cosmic strings, inflation, GW, etc.

Grand Unified Theory and the Magic of SUSY



Unification of gauge couplings in non-SUSY SO(10)



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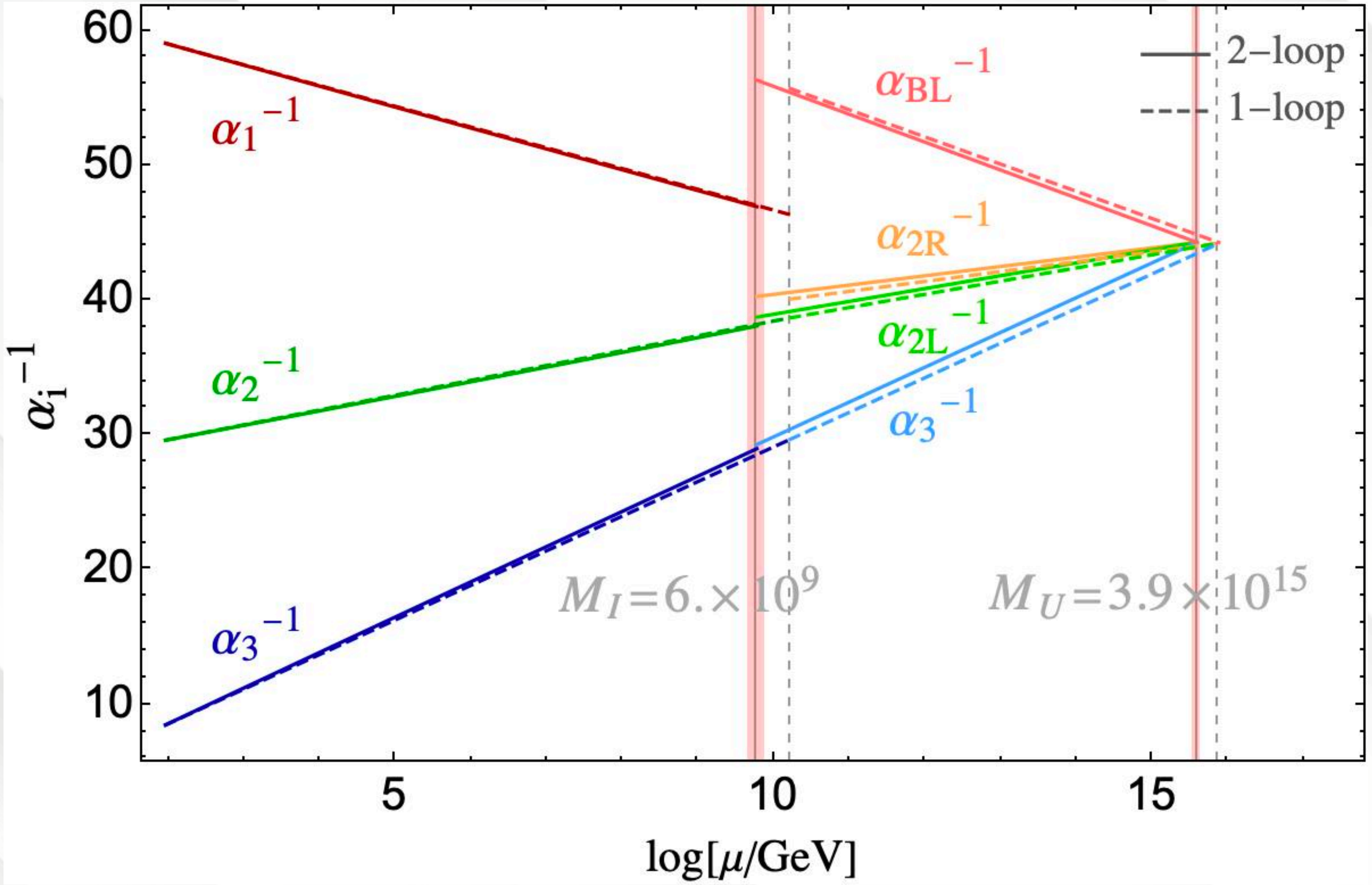

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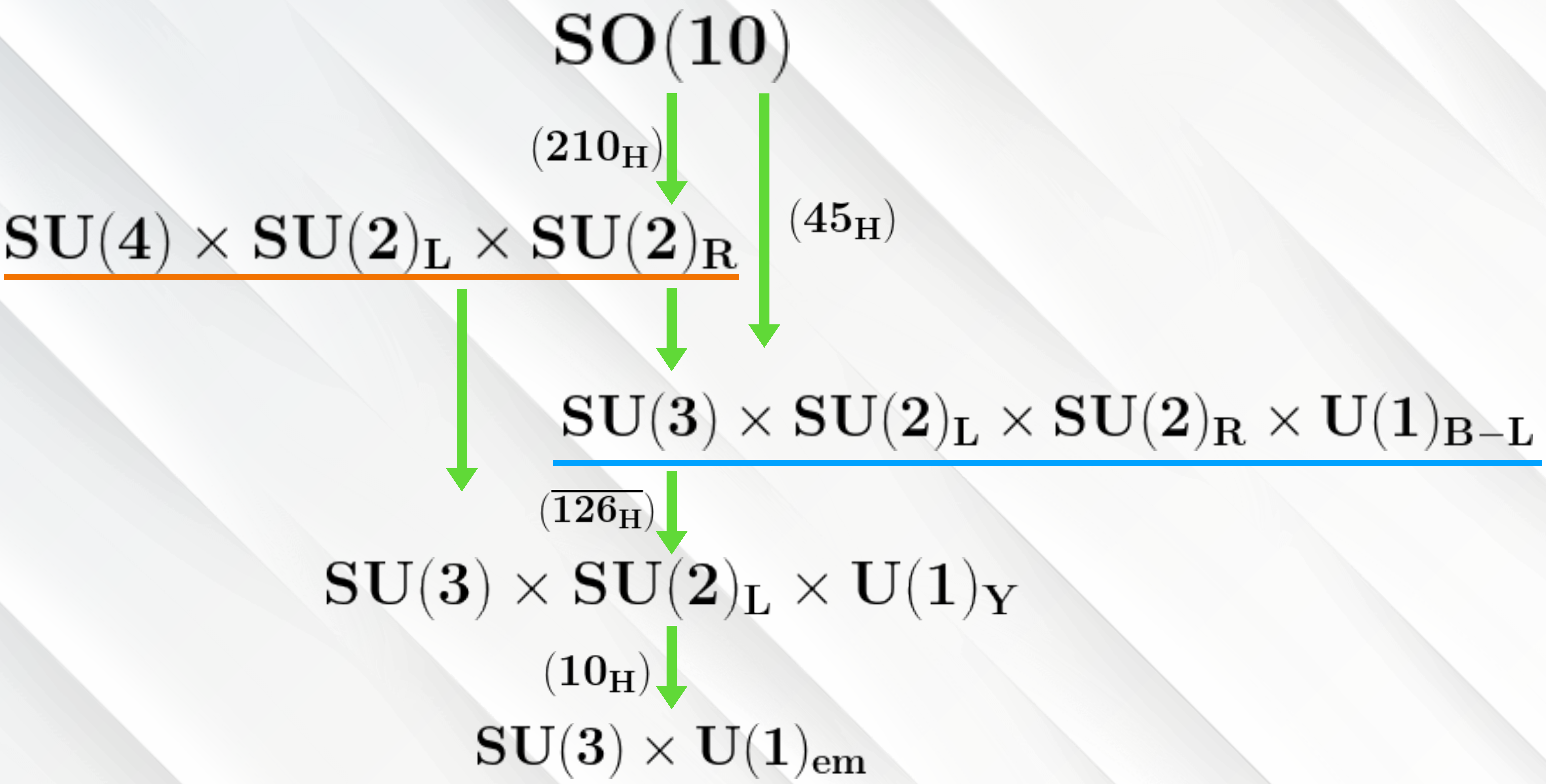
(A. Djouadi, M. Raidal, R. Ouyang, 2106.15822)

Some other advantages of SO(10) GUTs

Symmetry breaking of SO(10) GUT: SO(10) → Left-right model → SM

1. Unlike SU(5), SO(10) is a group of rank 5 with the extra diagonal generator of SO(10) being B–L as in the left–right symmetric groups.
2. All chiral fermions (including the right-handed neutrino) of a single generation, are embedded into one representation $16_{\mathbf{F}}$.
3. The gauge interactions of SO(10) conserve parity thus making parity a part of a continuous symmetry: this has the advantage that it avoids the cosmological domain wall problem associated with parity symmetry breakdown.
4. It is the minimal left–right symmetric grand unified model that gauges the B–L symmetry and is the only other simple grand unification group that does not need mirror fermions.

SO(10) symmetry breaking via intermediate step



$$\mathrm{PS}: \quad \mathrm{SO}(10)|_{M_U} \xrightarrow{\langle 210_H \rangle} \mathcal{G}_{422}|_{M_I} \xrightarrow{\langle \overline{126}_H \rangle} \mathcal{G}_{321}|_{M_Z} \xrightarrow{\langle 10_H \rangle} \mathcal{G}_{31} \qquad \mathrm{LR}: \quad \mathrm{SO}(10)|_{M_U} \xrightarrow{\langle 45_H \rangle} \mathcal{G}_{3221}|_{M_I} \xrightarrow{\langle \overline{126}_H \rangle} \mathcal{G}_{321}|_{M_Z} \xrightarrow{\langle 10_H \rangle} \mathcal{G}_{31}$$

Scalars in SO(10)

- The breaking chains we'd like to consider:

$$\text{PS}: \quad \text{SO}(10)|_{M_U} \xrightarrow{\langle \mathbf{210_H} \rangle} \mathcal{G}_{422}|_{M_I} \xrightarrow{\langle \overline{\mathbf{126}}_\mathbf{H} \rangle} \mathcal{G}_{321}|_{M_Z} \xrightarrow{\langle \mathbf{10_H} \rangle} \mathcal{G}_{31} \quad \text{LR}: \quad \text{SO}(10)|_{M_U} \xrightarrow{\langle \mathbf{45_H} \rangle} \mathcal{G}_{3221}|_{M_I} \xrightarrow{\langle \overline{\mathbf{126}}_\mathbf{H} \rangle} \mathcal{G}_{321}|_{M_Z} \xrightarrow{\langle \mathbf{10_H} \rangle} \mathcal{G}_{31}$$

- Survival hypothesis: all the scalar fields that do not participate in the symmetry breaking patterns by acquiring vevs will have masses of the order of the high scales (e.g. M_U).

- The fermions sector: $\mathbf{16_F} \otimes \mathbf{16_F} = \mathbf{10} + \mathbf{120} + \mathbf{126}$

$$-\mathcal{L}_Y = \mathbf{16_F}(Y_{10}\mathbf{10_H} + Y_{126}\overline{\mathbf{126}}_\mathbf{H} + Y_{120}\mathbf{120_H})\mathbf{16_F}$$

- Decomposition: $\mathbf{10_H} \supset (\mathbf{1}, \mathbf{2}, \mathbf{2})(\Phi_{10})$, $\overline{\mathbf{126}}_\mathbf{H} \supset (\mathbf{15}, \mathbf{2}, \mathbf{2})(\Phi_{10}) + (\mathbf{10}, \mathbf{1}, \mathbf{3})(\Delta_R)$

With these scalar contents, gauge symmetry, and the SM fermions plus one right-handed neutrino, we can obtain the interactions and RGEs for each intermediate scale model immediately.

Yukawa structure of SO(10)

- At the GUT scale: $-\mathcal{L}_Y = \mathbf{16_F}(Y_{10}\mathbf{10_H} + Y_{126}\overline{\mathbf{126}})\mathbf{16_F}$
- At the intermediate scale:

$$-\mathcal{L}_Y^{PS} = \bar{F}_L(Y_{PS}^{10}\Phi_{10} + Y_{PS}^{126}\Sigma_{126})F_R + F_R^T Y_{PS}^R C\overline{\Delta}_R F_R + \text{h.c.}$$

$$-\mathcal{L}_Y^{LR} = \bar{Q}_L(Y_{LR}^{10}\Phi_{10} + Y_{LR}^{126}\Sigma_{126})Q_R + \bar{L}_L(Y_{LR}^{10}\Phi_{10} + Y_{LR}^{126}\Sigma_{126})L_R + \frac{1}{2}L_R^T Y_{LR}^R i\sigma_2\Delta_R L_R + \text{h.c.}$$

- At Electroweak scale:

$$-\mathcal{L}_Y^{\text{2HDM}} = Y_u\bar{Q}_L H_u\, u_R + Y_d\bar{Q}_L H_d\, d_R + Y_e\bar{L}_L H_d\, e_R + \text{h.c.}$$

Physics at the intermediate scale: one bi-doublet split into two doublets, and only one combination of them become light. The threshold corrections coming from all heavy particles at this scale corrects the matching conditions and the RGEs.

Yukawa coupling unification

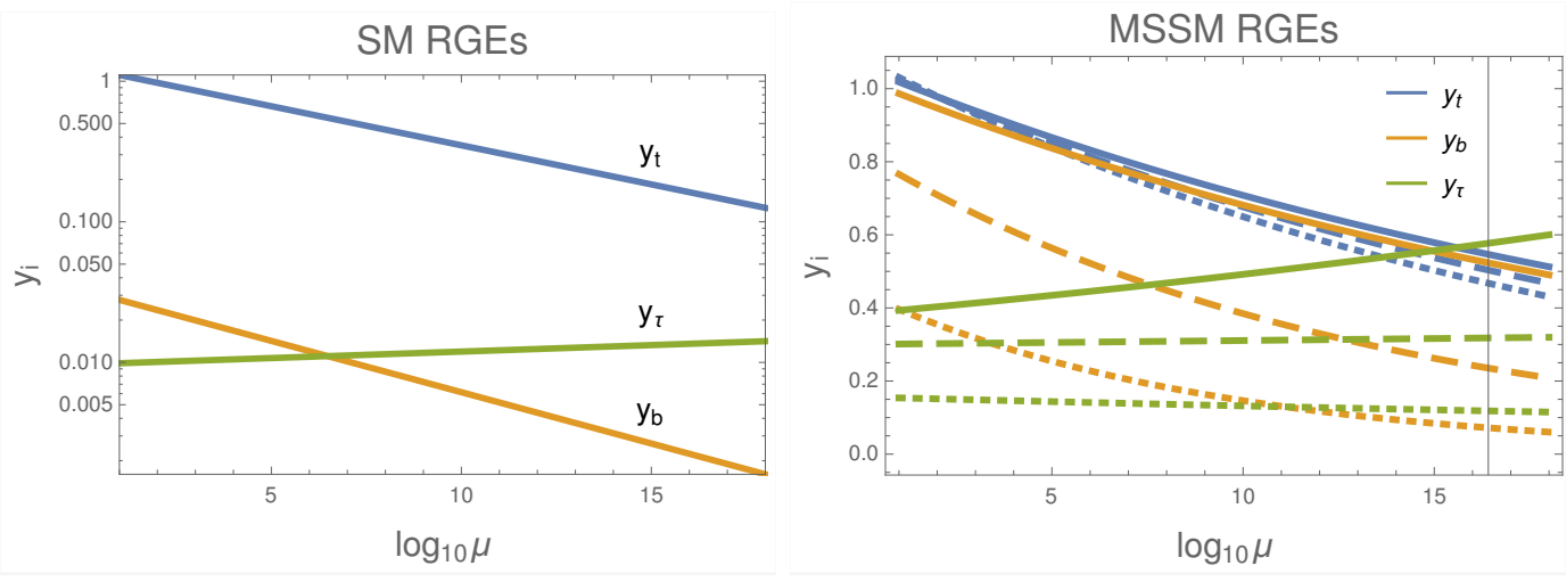


Figure 5: *One loop renormalisation group flow of the SM (left) and MSSM (right) Yukawa couplings, with* $m_0 = 2$ *TeV*, $m_{1/2} = 3$ *TeV*, $A_0 = 0$ *and* $\tan\beta = 40$ *(solid)*, $\tan\beta = 30$ *(dashed) and* $\tan\beta = 15$ *(dotted).*

(D. Croon, T. E. Gonzalo, L. Graf, N. Košnik, G.White, 1903.04977)

Matching conditions at the intermediate scale

- The fermion masses from the left-right models at M_I:

$$m_t=\frac{v_{10}Y_{10}^{PS}+v_{126}^{u}Y_{126}^{PS}}{\sqrt{2}},\ m_b=\frac{v_{10}Y_{10}^{PS}+v_{126}^{d}Y_{126}^{PS}}{\sqrt{2}},\ m_\tau=\frac{v_{10}Y_{10}^{PS}-3v_{126}^{d}Y_{126}^{PS}}{\sqrt{2}},$$

$$m_t=\frac{v_{10}Y_{10,q}^{LR}+v_{126}^{u}Y_{126,q}^{LR}}{\sqrt{2}},\ m_b=\frac{v_{10}Y_{10,q}^{LR}+v_{126}^{d}Y_{126,q}^{LR}}{\sqrt{2}},\ m_\tau=\frac{v_{10}Y_{10,l}^{LR}+v_{126}^{d}Y_{126,l}^{LR}}{\sqrt{2}}.$$

- The fermion masses from 2HDM at M_I:

$$m_t=\frac{1}{\sqrt{2}}Y_t v_u\,,\quad m_b=\frac{1}{\sqrt{2}}Y_b v_d\,,\quad m_\tau=\frac{1}{\sqrt{2}}Y_\tau v_d$$

Matching conditions at the GUT scale

- The fermion masses from the left-right models at M_U:

$$m_t = \frac{v_{10}Y_{10}^{PS} + v_{126}^u Y_{126}^{PS}}{\sqrt{2}}, \; m_b = \frac{v_{10}Y_{10}^{PS} + v_{126}^d Y_{126}^{PS}}{\sqrt{2}}, \; m_\tau = \frac{v_{10}Y_{10}^{PS} - 3v_{126}^d Y_{126}^{PS}}{\sqrt{2}},$$

$$m_t = \frac{v_{10}Y_{10,q}^{LR} + v_{126}^u Y_{126,q}^{LR}}{\sqrt{2}}, \; m_b = \frac{v_{10}Y_{10,q}^{LR} + v_{126}^d Y_{126,q}^{LR}}{\sqrt{2}}, \; m_\tau = \frac{v_{10}Y_{10,l}^{LR} + v_{126}^d Y_{126,l}^{LR}}{\sqrt{2}}.$$

- The fermion masses from SO(10) at M_U:

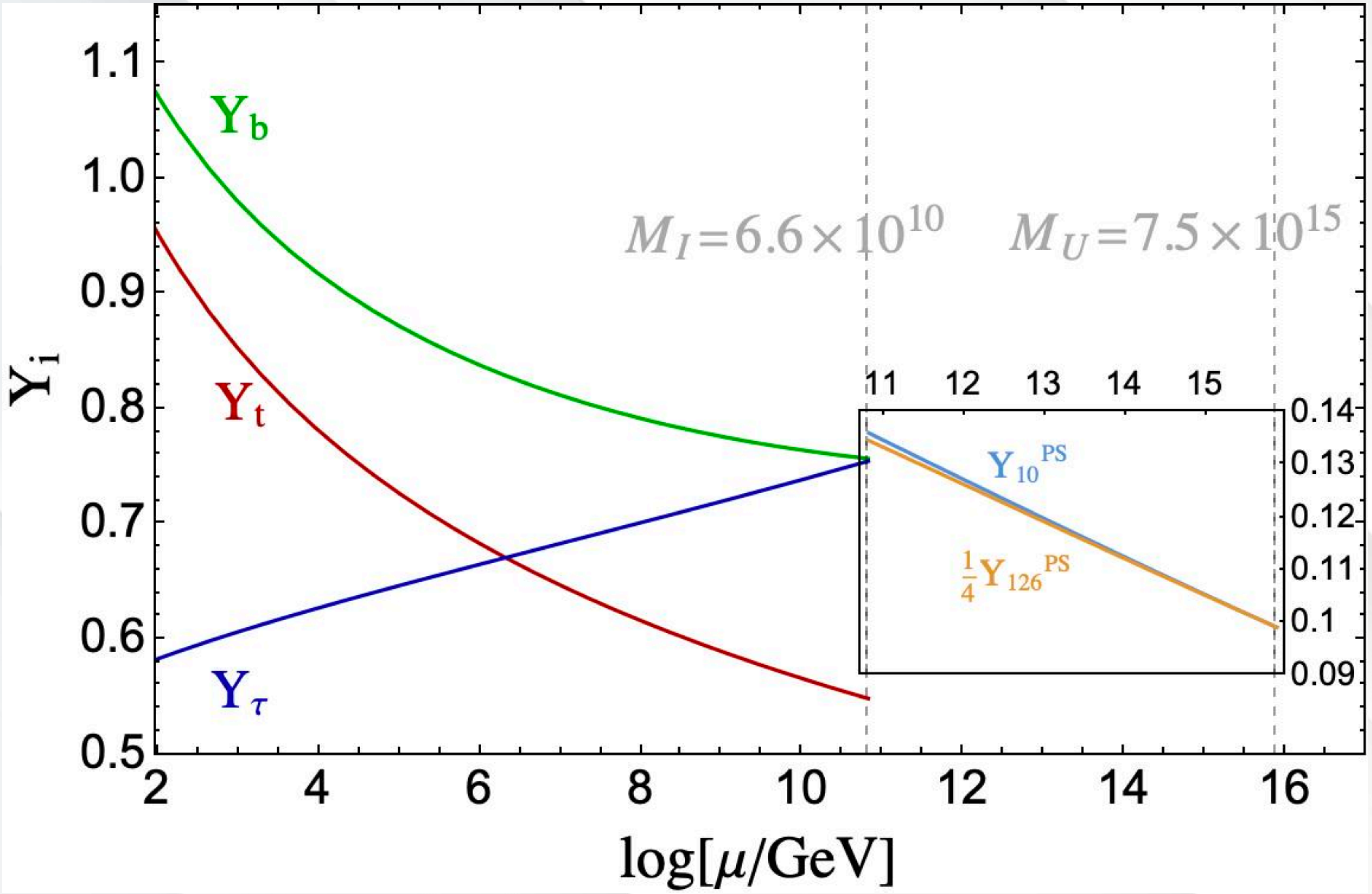
$$m_t = v_{10}Y_{10} + v_{126}^u Y_{126}\,, \; m_b = v_{10}Y_{10} + v_{126}^d Y_{126}\,, \; m_\tau = v_{10}Y_{10} - 3v_{126}^d Y_{126};$$

- At M_U, Yukawa unification means:

$$Y_f(M_U) \equiv Y_{10}^{PS}(M_U) = \frac{1}{4}Y_{126}^{PS}(M_U)\,,$$

$$Y_f(M_U) \equiv Y_{10,q}^{LR}(M_U) = \frac{1}{4}Y_{126,q}^{LR}(M_U) = Y_{10,l}^{LR}(M_U) = -\frac{1}{12}Y_{126,l}^{LR}(M_U)$$

Yukawa coupling unification in non-SUSY SO(10)



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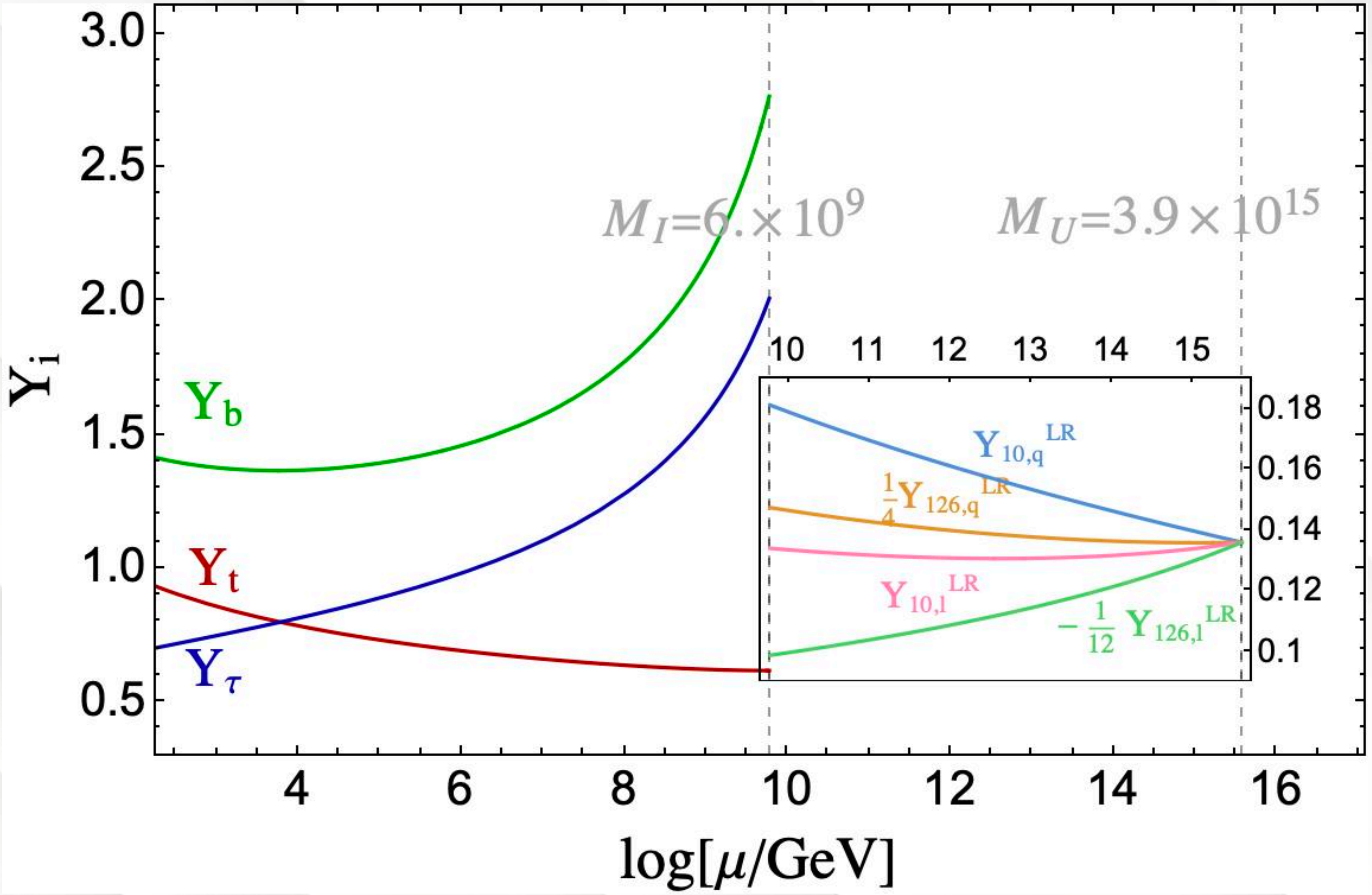

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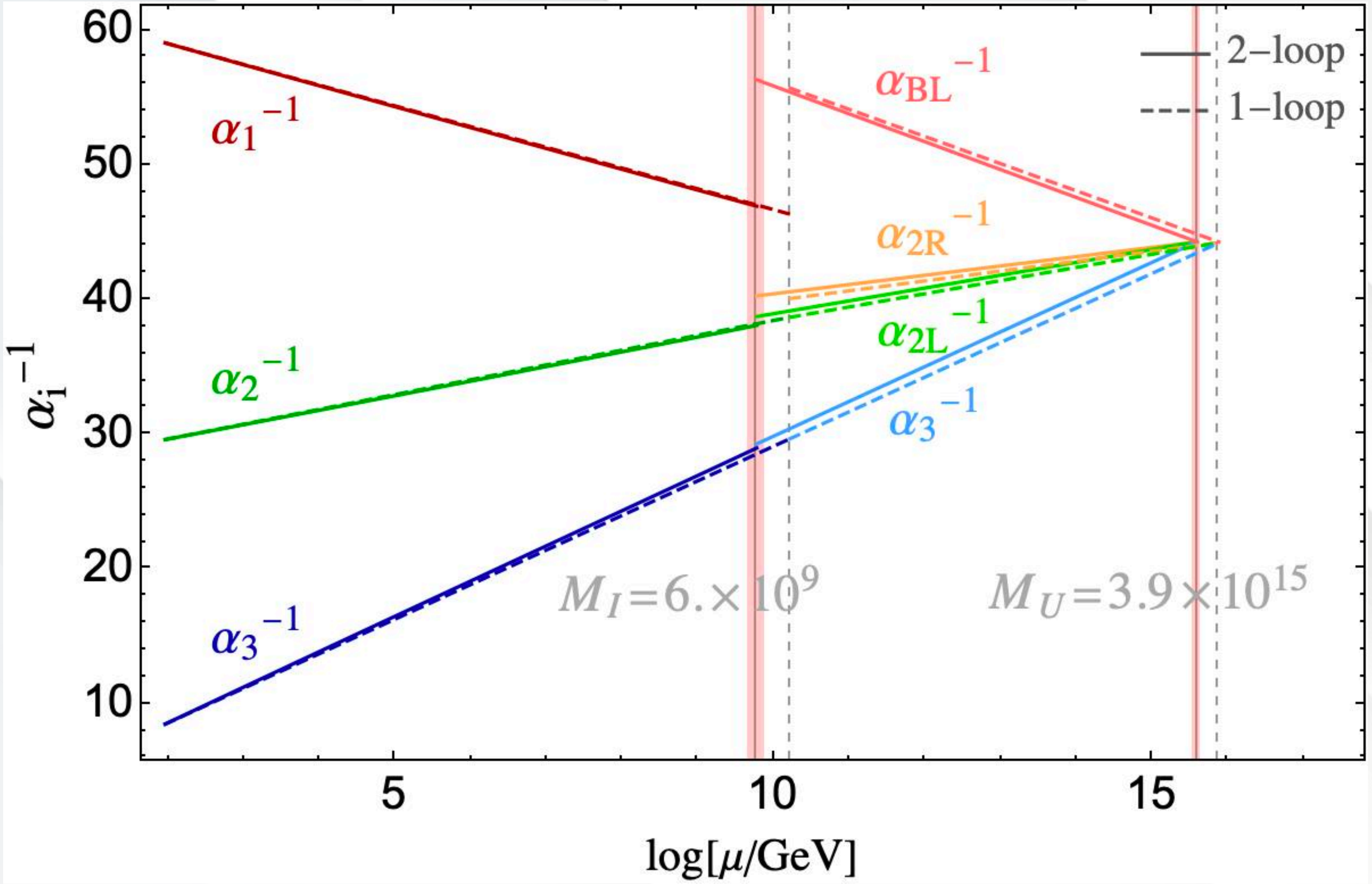
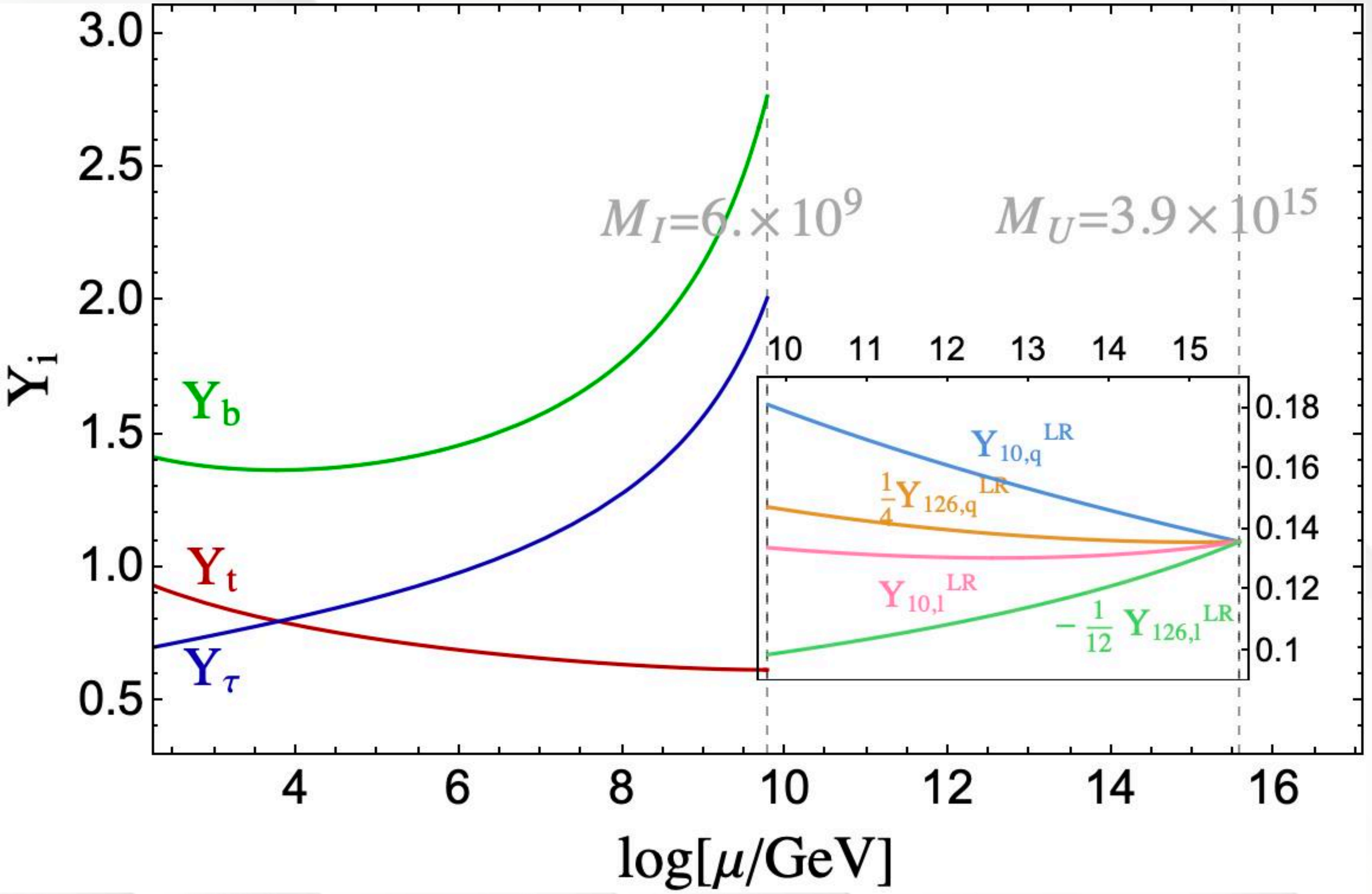
Gauge & Yukawa coupling unification in non-SUSY SO(10)





The E6 motivated Yukawa unification

- The GUT scale unification condition $Y_{10} = cY_{126}$, can be seen as emerging from decomposing the scalar representation in a E6 group, with the proper CG-coefficient in front:

$$\mathbf{351'} \supset \mathbf{10} \oplus \overline{\mathbf{126}} \oplus \ldots$$

- The Yukawa interaction $-\mathcal{L}_Y = \mathbf{16_F}(Y_{10}\mathbf{10_H} + Y_{126}\overline{\mathbf{126}})\mathbf{16_F}$ emerges from the term:

$$f\, \mathbf{27} \cdot \mathbf{351'} \cdot \mathbf{27}$$

In this sense, the unification of Yukawa couplings for different scalars can be interpreted as the Yukawa couplings are related with the CG coefficient from decomposing the scalar representation associated with the symmetry breaking.

Conclusions

- We discuss the non-SUSY SO(10) grand unified theories that is compatible with all the observables in SM while including the DM candidate and neutrinos.
- We require a 2HDM at low energy scale, as a consistency of the Yukawa sectors of SO(10) theory and is also important for the vacuum stability.
- The 2HDM also allows for a realization of the Yukawa unification in non-SUSY SO(10).
- The threshold corrections at the symmetry breaking scale is model-dependent and change the texture of Yukawa couplings. As a result, a discontinuity appears at the intermediate scale, just like the gauge couplings.
- We showed that it is possible to realize both the gauge and the Yukawa couplings to unify at the same scale, and thus explain the origin of all Yukawa couplings from decomposing the scalar multiplet in GUT models.

Additional material

For the Yukawa couplings of fermions of 1st/2nd generations?

§ How to explain the fermion mass hierarchies between 1st/2nd and 3rd generations?

- (One possible way is to generate Yukawas of 1st/2nd by radiation corrections)

(S. Fraser, E. Gabrielli, C. Marzo, L. Marzola, M. Raidal, 1904.09354)

§ The radiatively generated Yukawas can be also achieved, e.g.

(E. Gabrielli, L. Marzola, K. Müürsepp, R. Ouyang, 2106.09038)

§ About fine-tuning problem