Asymptotic Grand Unified Models

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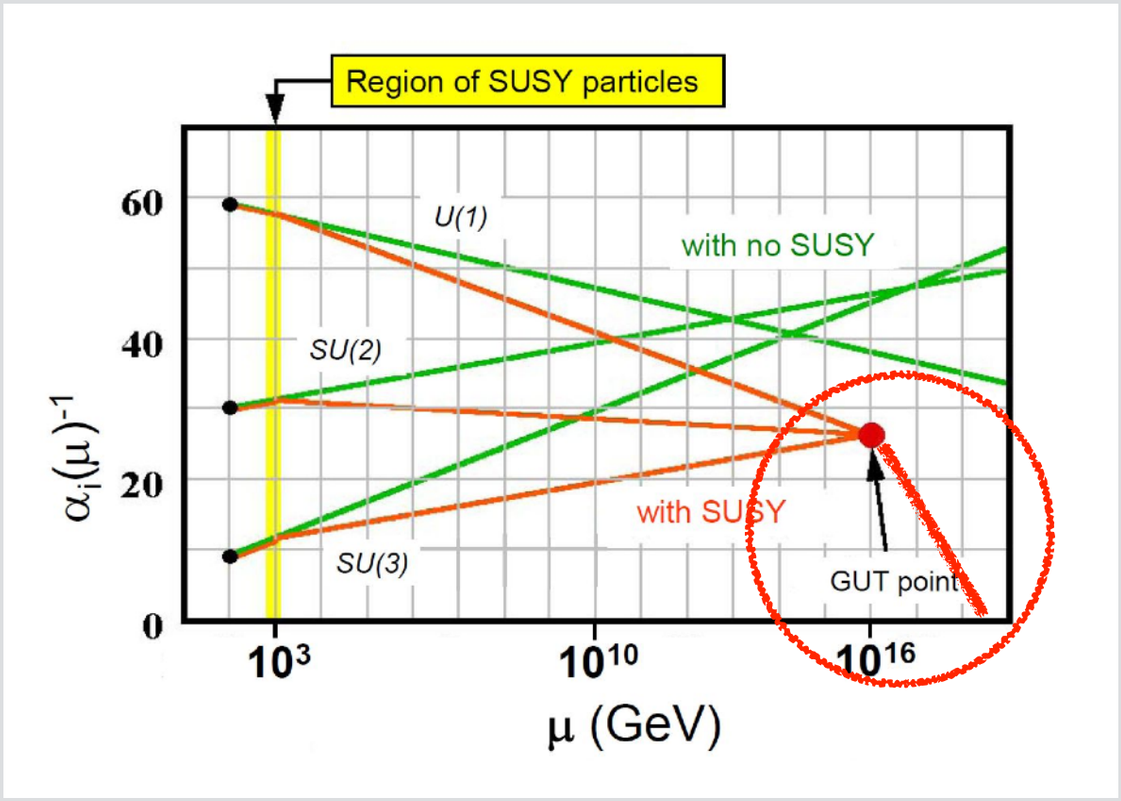
based on works with T.Alezraa, G.Cacciapaglia, C.Cot, A.Cornell, W.Isnard, R.Pasechnik, A.Preda, Z.-W.Wang

Standard unification

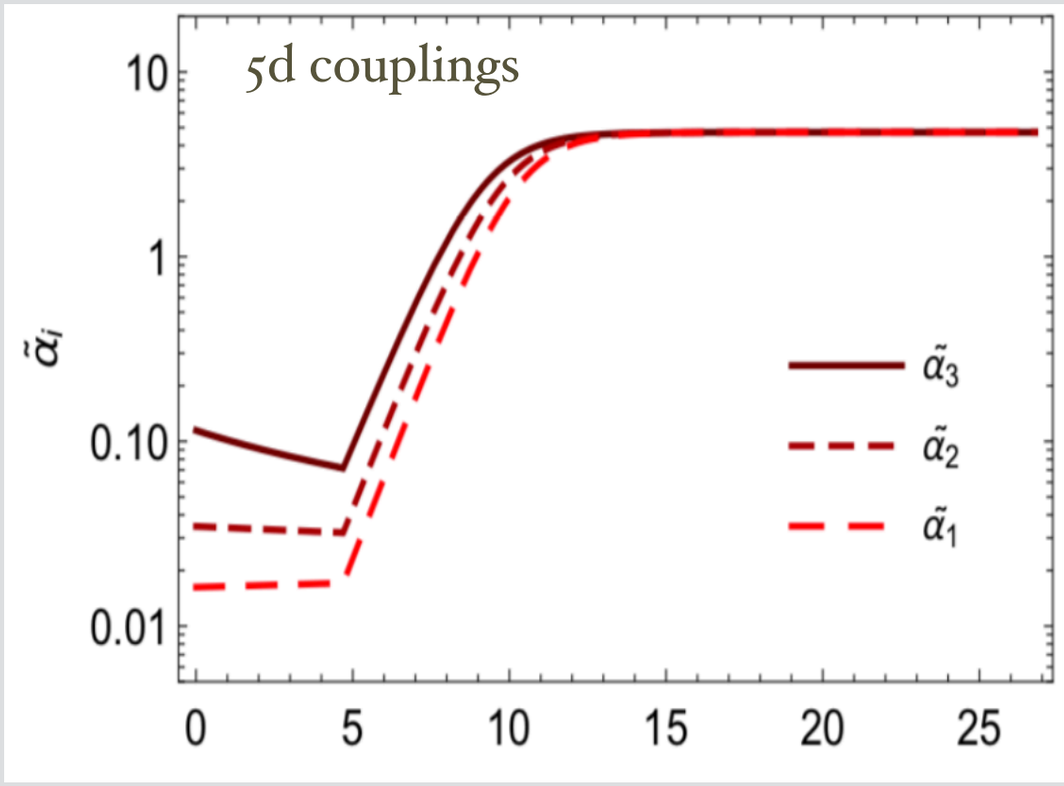
- SM gauge couplings become equal at the GUT scale
- Supersymmetry usually needed for realistic models
- Proton decay present and typically constraining
- Large matter representations to break the gauge symmetry
- Landau poles present in the UV



- Problem?
- Effective theory?
- Strings/Gravity?

Paths to asymptotic unification

1. Asymptotically Safe (AS) theories with large Nf
   (see Molinaro et al, 1807.03669)
2. Asymptotic Safety via perturbative fixed points and SUSY
   (see Bajic et al, 1610.09681 and 2308.13311)
3. Extra compact dimensions
   Gies, PRD 68 (2003) Morris, JHEP 01 (2005) 002



Paths to asymptotic unification

In the following AS via compact extra dimensions

$$2\pi \frac{d\alpha}{d\log\mu} = \mu R\, b_5\, \alpha^2$$

fixed point

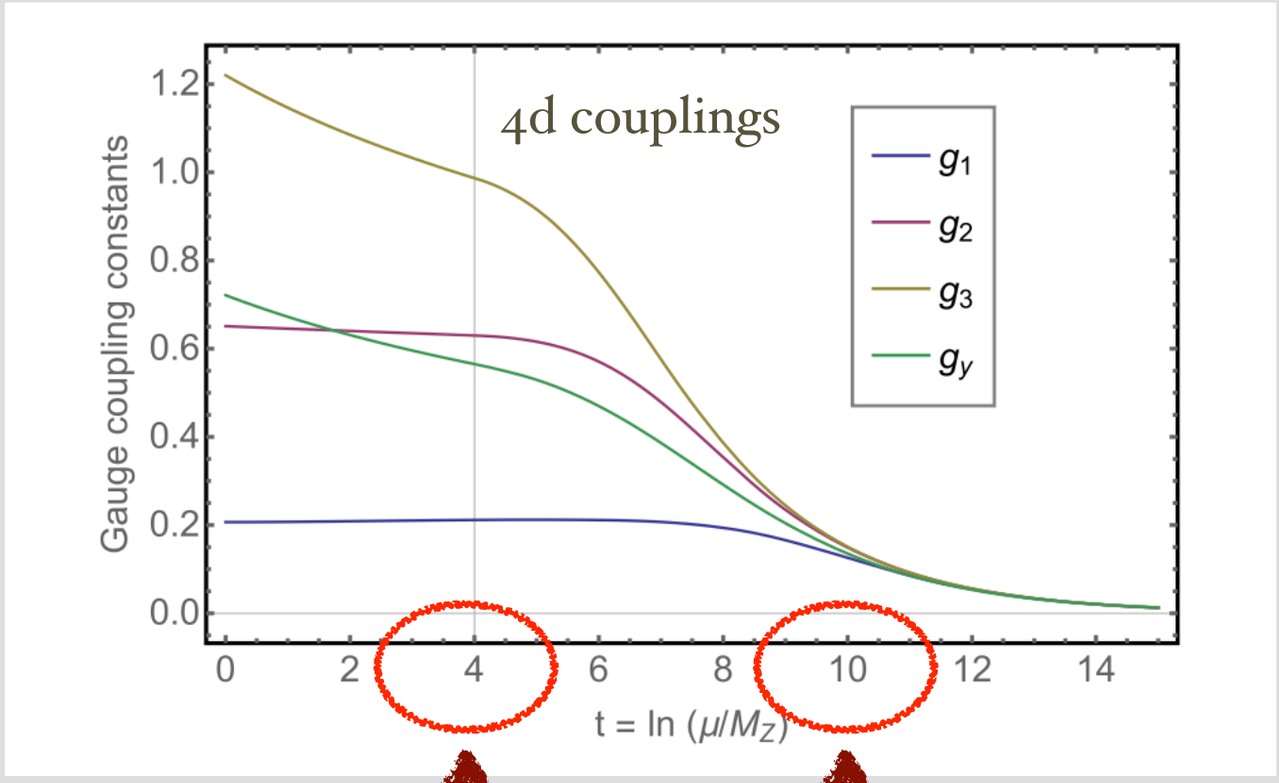
$\tilde{\alpha} = \mu R \alpha$ 5d 't Hooft coupling

$$2\pi \frac{d\tilde{\alpha}}{d\log\mu} = 2\pi\tilde{\alpha} + b_5\, \tilde{\alpha}^2 \qquad \rightarrow \qquad \tilde{\alpha}_{UV} = -\frac{2\pi}{b_5}$$

see the following talk by Roman for details on the UV behaviour

Asymptotic unification

Gauge couplings unification requires a specific scale and "crossing" of the evolution of couplings.
Asymptotic unification is not unification in the usual sense, rather at high energies, flow towards an UV fixed point.



Toy example in the EW sector with SU(3) ⊃ SU(2)xU(1) for gauge and Yukawa couplings
(5D model)

see 1706.02313
with A.Abdalgabar et al.

1st KK mode kicks in at t ~4
"unification" sets around t~10 (~200 KK-modes)

A gauge scalar from extra dimensions

$$A_M = (A_\mu, A_5)$$

Under orbifold projection vectors and scalars have opposite parity

$$A_M^+ = (A_\mu^+, A_5^-)$$

Contains a zero mode vector

$$A_M^- = (A_\mu^-, A_5^+)$$

Contains a zero mode scalar

5D gauge symmetry broken by parity projection (but 4D preserved)

Higgs scalar "protected" by the gauge symmetry (Hosotani mechanism), vev "geometrisation" → Yukawa coupling linked to gauge coupling

A SU(3) toy model

SU(2) U(1)

$$A_M^+ : \frac{1}{\sqrt{2}} \begin{bmatrix} W_3/2 & W^+/\sqrt{2} & 0 \\ W^-/\sqrt{2} & -W_3/2 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad \frac{1}{2\sqrt{3}} \begin{bmatrix} B & 0 & 0 \\ 0 & B & 0 \\ 0 & 0 & -2B \end{bmatrix}$$

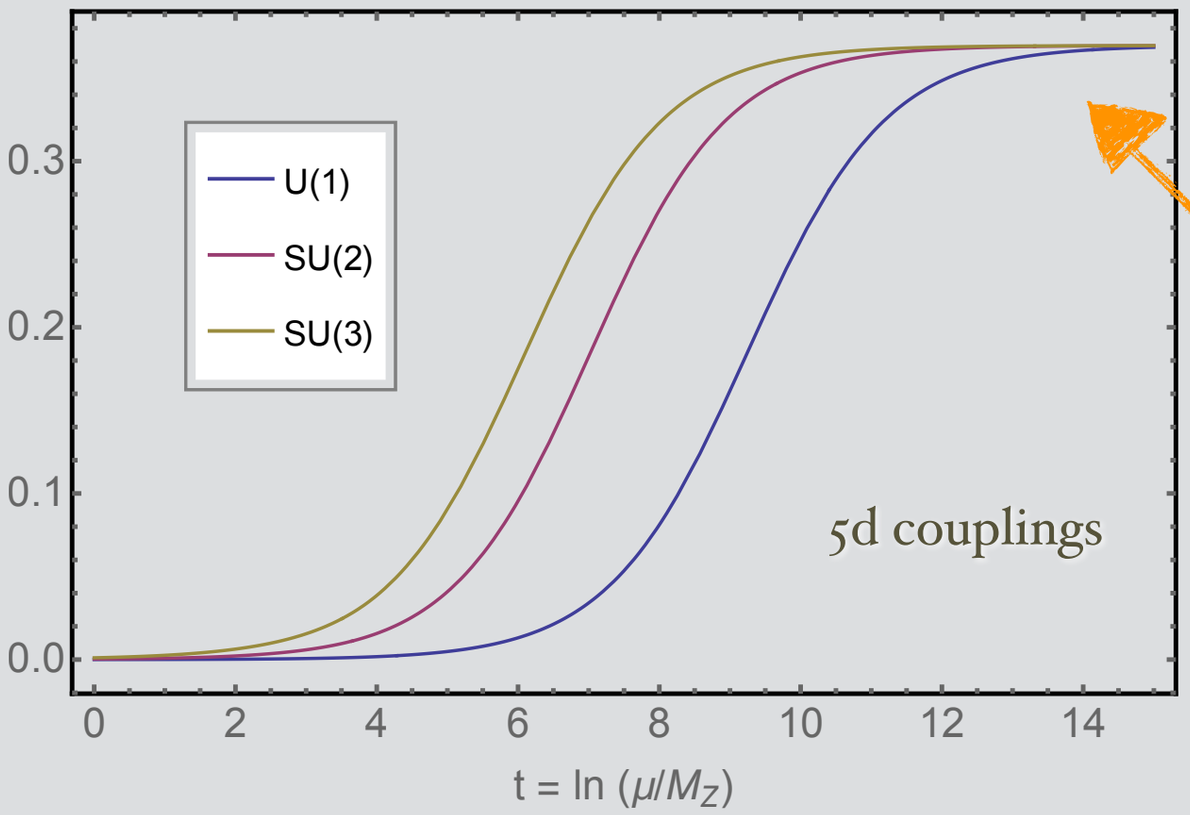
Higgs

$$A_M^- : \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 0 & h^+ \\ 0 & 0 & h^0 \\ h^- & h^{0*} & 0 \end{bmatrix}$$

Fermion matter
bulk triplet

Running of the gauge couplings

$$16\pi^2 \frac{dg_i}{dt} = b_i^{\rm SM}\ g_i^3 + (S(t)-1)\, b_i^{\rm GHU}\ g_i^3$$



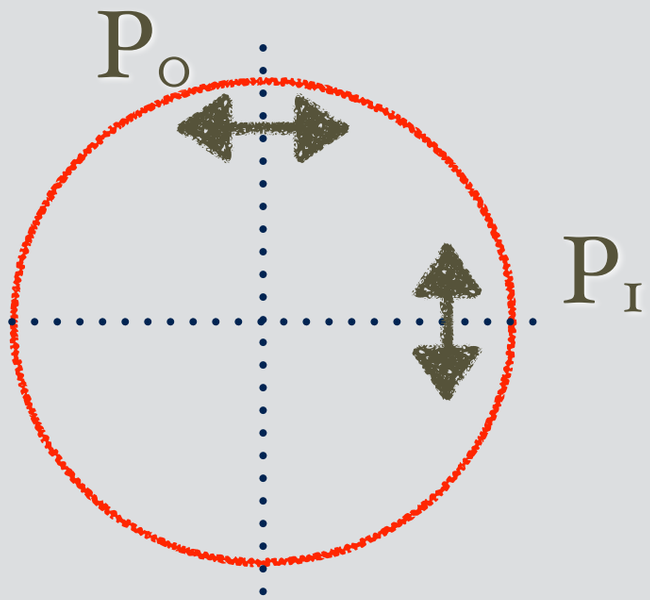
S(t) encodes the sum of the KK contributions to the running

5d coupling is going to a constant ~ α_4 E (asymptotically safe)

$$b_i^{SM} = \left[\frac{41}{10}, -\frac{19}{6}, -7\right], \quad b_i^{SU(3)} = \left[-\frac{17}{6}, -\frac{17}{2}, -\frac{17}{2}\right]$$

Simplest aGUT : SU(5) embedding

- SU(5) gauge symmetry in the bulk, broken to SM, via orbifold boundary conditions

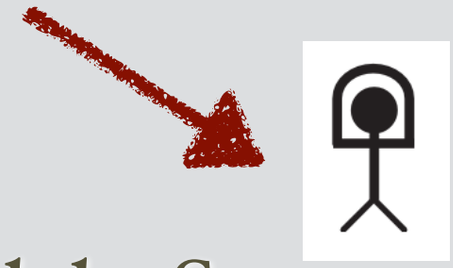


$$P_O = diag(+,+,+,-,-)$$
$$P_1 = diag(+,+,+,+,+)$$

- A single extra dimension compactified on an orbifold $S^1/\mathbb{Z}_2 \times \mathbb{Z}_2'$
- SM matter multiplets are NOT the usual SU(5) ones due to boundary conditions, need to duplicate the usual structure $\overline{5} + 10$

Fermion non-unification

- Capital letter fields are the new "Indalo" fields
- Baryon and Lepton charge conserved
- No proton decay
- Dark matter candidate → Lightest Indalo S



$$\psi_{1_{L/R}} = N, \qquad \psi_{5_{L/R}} = \begin{pmatrix} b \\ L^c \end{pmatrix}_{L/R}, \qquad \psi_{\bar{5}_{L/R}} = \begin{pmatrix} B^c \\ l \end{pmatrix}_{L/R},$$

$$\psi_{10_{L/R}} = \frac{1}{\sqrt{2}} \begin{pmatrix} T^c & q \\ & \mathcal{T}^c \end{pmatrix}_{L/R}, \qquad \psi_{\overline{10}_{L/R}} = \frac{1}{\sqrt{2}} \begin{pmatrix} t & Q^c \\ & \tau \end{pmatrix}_{L/R},$$

Particle content overview

Field	$(\mathbb{Z}_2, \mathbb{Z}_2')$	SM	Zero mode?	KK mass
l	$(+,+)$	$(\mathbf{1},\mathbf{2},-1/2)$	✓	$2/R$
L	$(+,-)$		–	$1/R$
τ	$(-,-)$	$(\mathbf{1},\mathbf{1},-1)$	✓	$2/R$
$\mathcal{T}$	$(-,+)$		–	$1/R$
N	$(-,-)$	$(\mathbf{1},\mathbf{1},0)$	✓	$2/R$
q	$(+,+)$	$(\mathbf{3},\mathbf{2},1/6)$	✓	$2/R$
Q	$(+,-)$		–	$1/R$
t	$(-,-)$	$(\mathbf{3},\mathbf{1},2/3)$	✓	$2/R$
T	$(-,+)$		–	$1/R$
b	$(-,-)$	$(\mathbf{3},\mathbf{1},-1/3)$	✓	$2/R$
B	$(-,+)$		–	$1/R$
ϕ_h	$(+,+)$	$(\mathbf{1},\mathbf{2},1/2)$	✓	$2/R$
H	$(-,+)$	$(\mathbf{3},\mathbf{1},-1/3)$	–	$1/R$
B_μ		$(\mathbf{1},\mathbf{1},0)$		
W_μ^a	$(+,+)$	$(\mathbf{1},\mathbf{3},0)$	✓	$2/R$
G_μ^i		$(\mathbf{8},\mathbf{1},0)$		
A_X^μ	$(-,+)$	$(\mathbf{3},\mathbf{2},-5/6)$	–	$1/R$

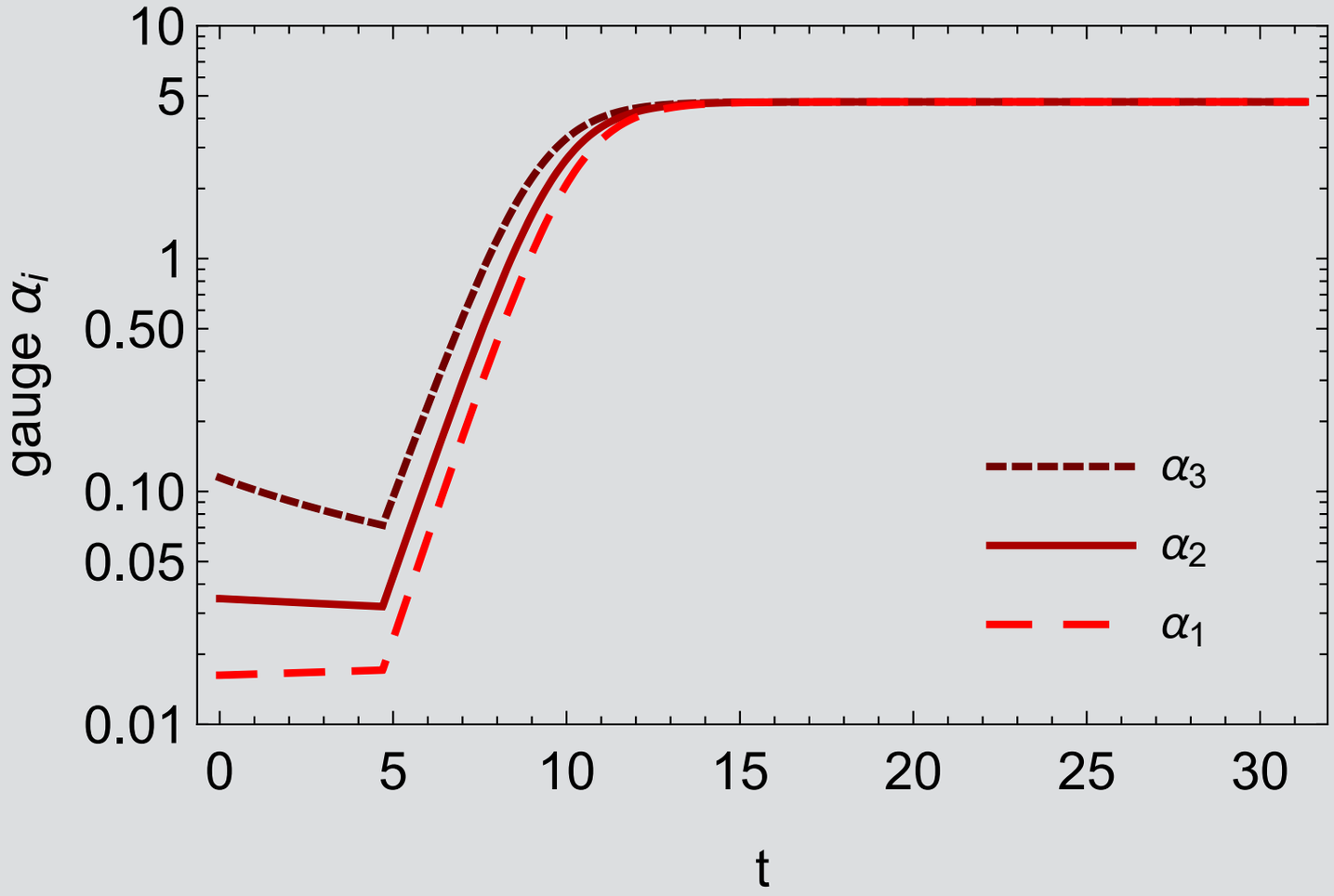
Non-SM components carry unusual B and L charges

So they cannot decay into SM states

States with mass 1/R stable

RGE SU(5) aGUT running

- All couplings constants flow to the same non-zero UV fixed point (- 2π/b5) asymptotically.
- Extra-dimensional one-loop factor is perturbative



$$b_5 = -\frac{52}{3} + \frac{16}{3} n_{\rm g}$$

$n_{\rm g}$ number of fermion generations in the bulk

Yukawa (non-)unification

$$\overline{\psi_1}\psi_{\bar{5}}\phi_5 = \overline{N}\phi_h l + \overline{N}H\mathcal{B}^c,$$

$$\sqrt{2}\bar{\psi}_5\psi_{10}\phi_5^* = \bar{b}\phi_h^* q - \bar{L}^c H^* q - \bar{L}^c\phi_h^*\mathcal{T}^c + \epsilon_3\bar{b}H^*T^c,$$

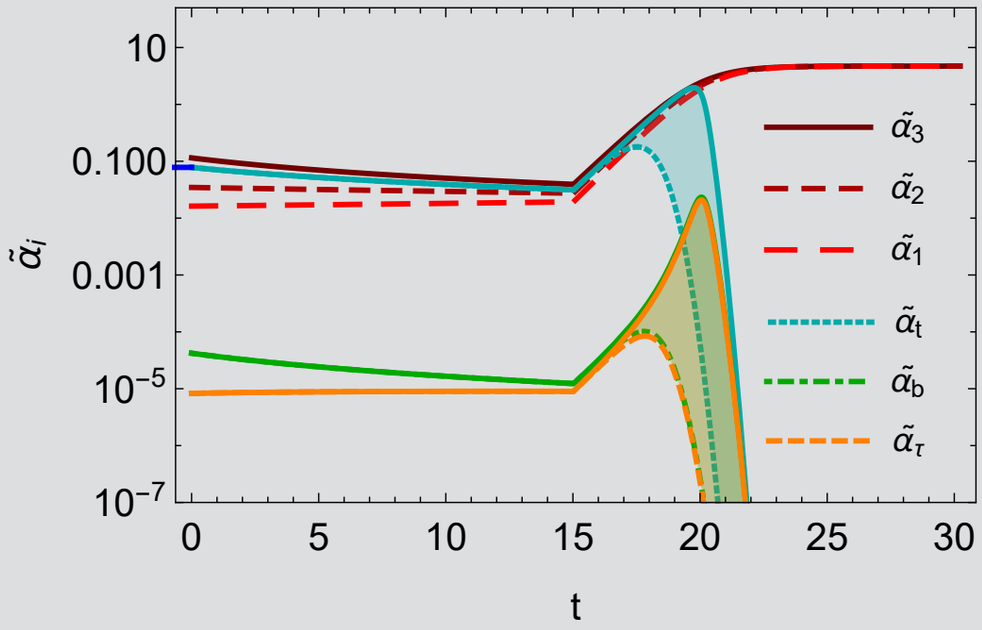
$$\sqrt{2}\overline{\psi_{\overline{10}}}\psi_{\bar{5}}\phi_5^* = -\bar{\tau}\phi_h^* l - \bar{Q}^c H^* l + \bar{Q}^c\phi_h^* B^c - \epsilon_3\bar{t}H^*B^c,$$

$$\frac{1}{2}\epsilon_5\overline{\psi_{\overline{10}}}\psi_{10}\phi_5 = \bar{t}\phi_h q + \bar{t}H\mathcal{T}^c + \bar{\tau}HT^c + \overline{Q^c}\phi_h T^c + \epsilon_3\bar{Q}^c Hq,$$

4 independent couplings, one for each SM Yukawa term

Behaviour of Yukawa couplings

Bulk fermion Yukawas do not systematically go to the fixed point: for small values of the KK they run to Landau poles, for higher values of the KK scale they may go to zero or unify.



Limiting case to avoid Landau poles: $R^{-1} > 3 \times 10^5$ TeV

Instead localized Yukawas always run to zero in the UV

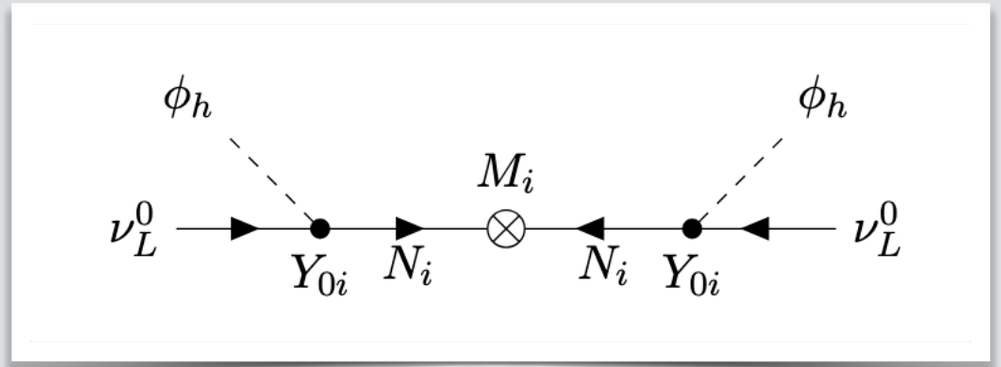
Leptogenesis and Baryogenesis in SU(5)

see 2503.14397

- See-saw mechanism can be embedded in the model thanks to a localised Majorana mass for the bulk right-handed neutrinos plus some bilinear boundary terms to ensure correct boundary conditions and decoupling :

$$S_{Maj} = -\int_{\mathscr{M}} d^4x\, dy\, \delta(y-L)\frac{L}{2}\left(\overline{\psi^c_{1}}_R M \psi_{1R}\right)$$

- Corrections to the masses and a mixing with the KK modes in ν_L will be generated via the bulk Higgs coupling giving Majorana mass of the SM neutrino :

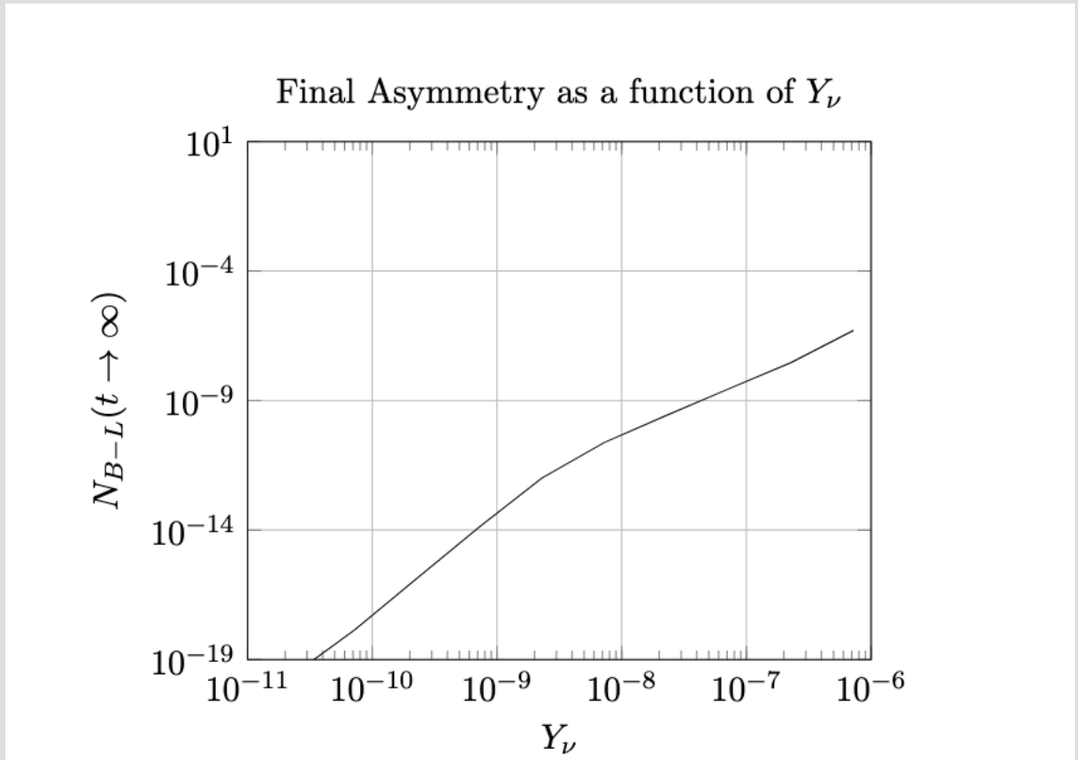


Leptogenesis and Baryogenesis in SU(5)

- source of asymmetry in the decays of the KK modes of the singlet N, generated by a CP violating phase in the Yukawa coupling Y_ν.
- B - L asymmetry as a function of Y_ν using the benchmark values $L^{-1} = 10^8$ GeV$= 2/(\pi R)$, $M = 10^{10}$ GeV is :

$$\eta_B \equiv \frac{n_B}{n_\gamma} = (6.12 \pm 0.04) \cdot 10^{-10}$$

$$\eta_B \sim 10^{-2}\, N_{B-L}$$



Leptogenesis can provide sufficient baryon asymmetry at the price of raising the scale of the extra dimensions well above the TeV scale

Classification of the gauge groups

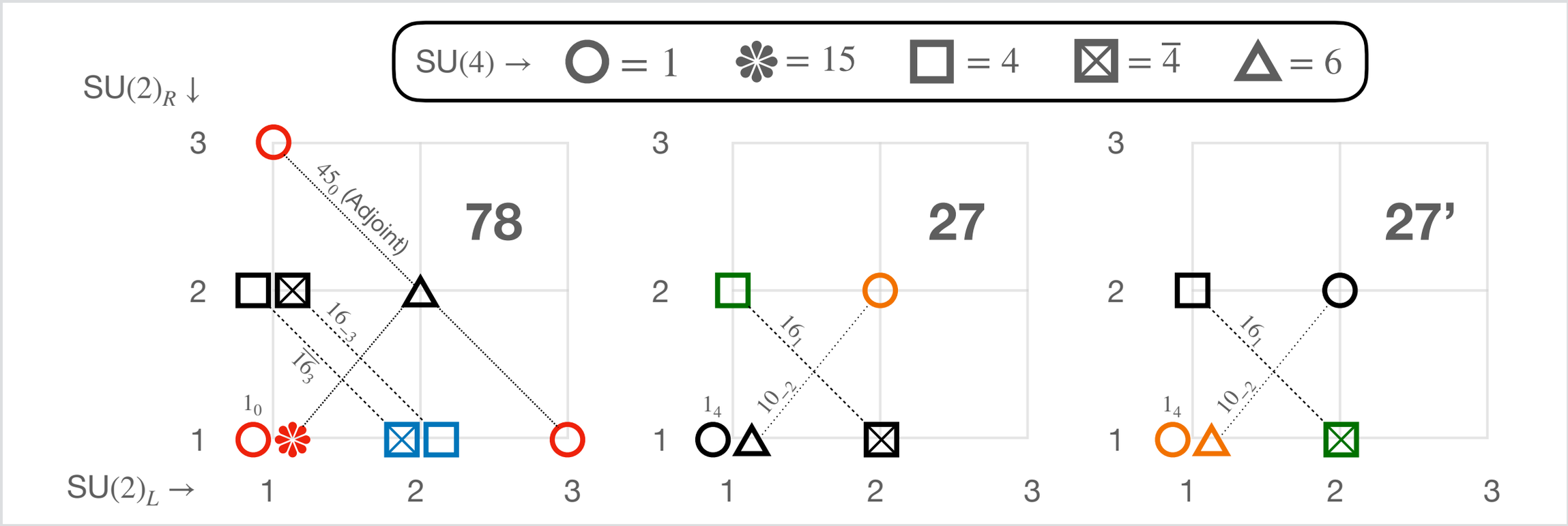
see 2309.10098

- Define a bulk gauge $\mathcal{G} \supset \mathcal{G}_{\rm SM}$ with parity breaking group $\mathcal{G} \to \mathcal{H} \supset \mathcal{G}_{\rm SM}$
- Find parities $P_i \times P_j$ such that $\mathcal{H}i \cap \mathcal{H}j = \mathcal{G}_{\rm SM} + X$
- Find minimal set of bulk fermions that contain SM zero modes and preserve the UV fixed point
- Check if the Yukawa couplings have fixed points in the UV
- Check if stable orbifold, i.e. not destabilised by a vacuum expectation value (VEV) of the massless gauge-scalars
- Check if gauge-Higgs unification occurs

see the following talk by Roman for details on the classification

E6 : the exceptional case

- Supersymmetry allows to generate fermions as gauge fields (gauginos)
- In E6, the adjoint 78 contains the right states (but in vector-like pairs)
- Bulk interactions preserve Baryon number

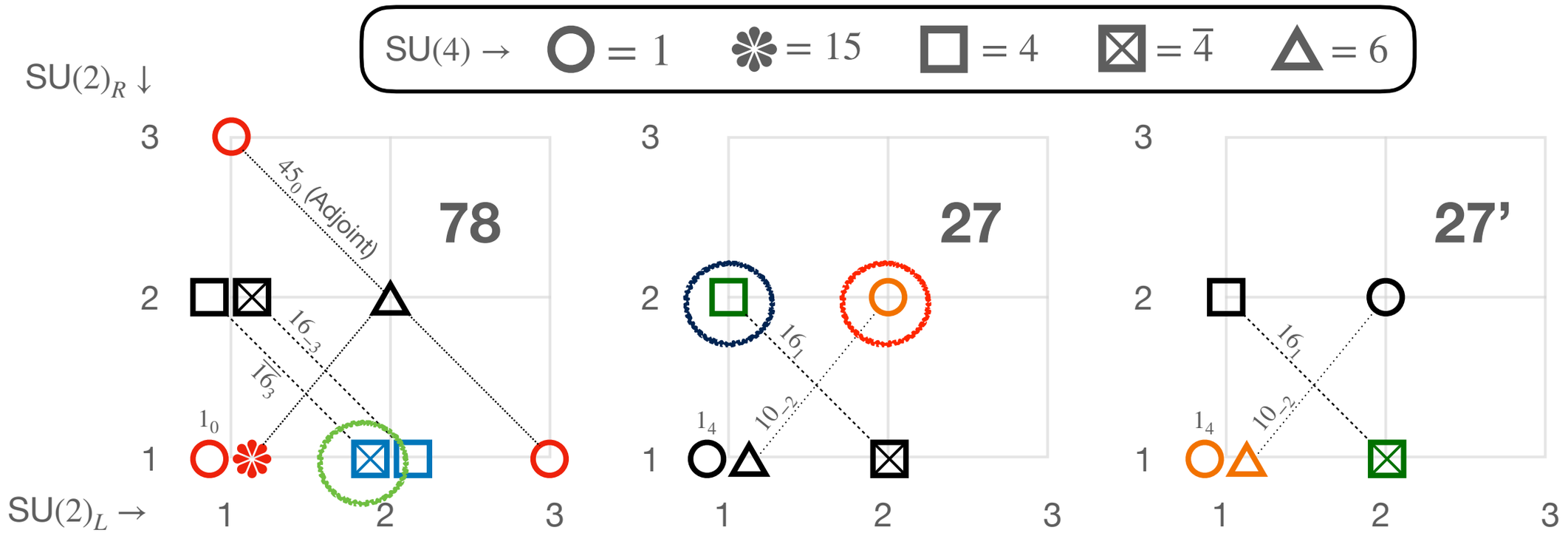


see 2302.11671 , 2501.13118 and also Kobayashi, Raby, Zhang, Nucl. Phys. B704, 3 (2005) but without UV fixed point

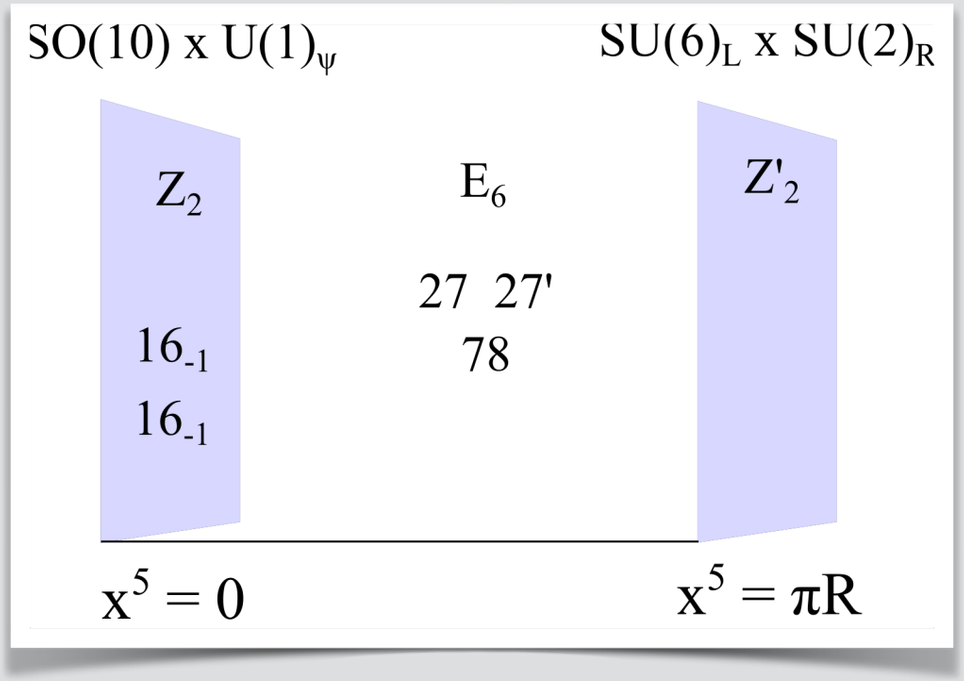
E6 : the exceptional case

SM Yukawa couplings →

$$g\ \Phi^c_{27}\Phi_{78}\Phi_{27} \supset \frac{g}{\sqrt{2}}(\mathbf{1},\mathbf{2},\mathbf{2})_2\,(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})_{-3}\,(\mathbf{4},\mathbf{2},\mathbf{1})_1$$



E6 : breaking pattern



The orbifold projection breaks N =2 SUSY to N =1 in 4D and also the gauge symmetry.

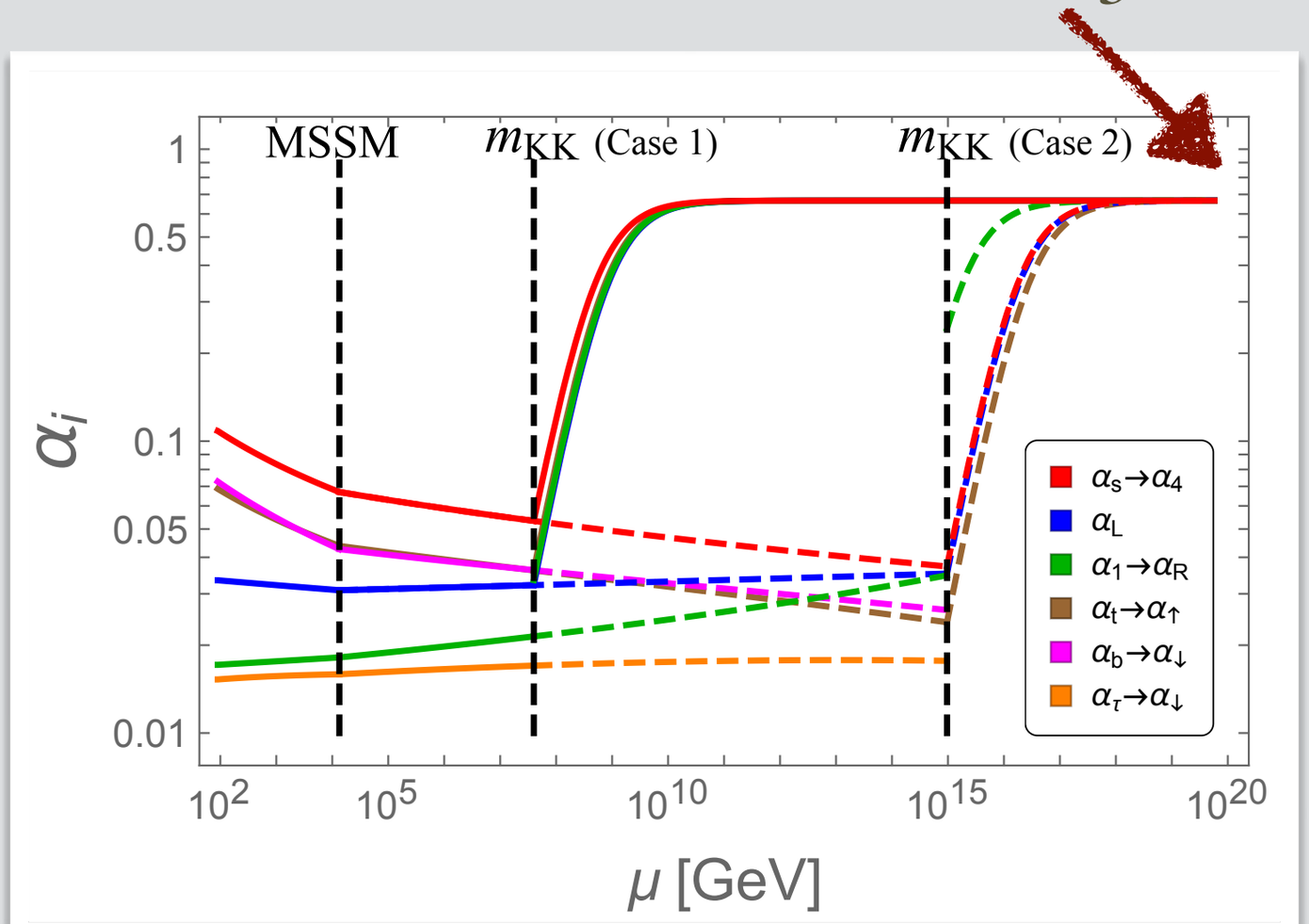
- Right-handed SM fermions from the adjoint
- Left-handed and Higgs(es) from the 27
- 27' to give mass to unwanted states
- PS breaking with gauge-scalar
- U(1) breaking by singlet in 27'

4D gauge symmetry $\underbrace{SU(4) \times SU(2)_L \times SU(2)_R}_{\text{Pati-Salam}} \times U(1)_\psi$

E6 : the UV fixed point

$$b_5 = -\frac{\pi}{2}\left(C(G) - \sum_i T_i(R_i)\right) = -3\pi$$

$$C(G) = 12 \quad T(27) = 3 \qquad \tilde{\alpha}_{UV} = \frac{2}{3}$$



- Only 1 generation allowed in the bulk
- Model 1: Two 10 for massive states, while the light generations are localised on the other boundary.
- Model 2: Two 16 for the two SM light generations. Baryon number is violated by the localised interactions.

Conclusions

- New paradigm for (asymptotic) unification (aGUT)
- 5D aGUT models are very constrained and successful cases can be classified
- Baryogenesis requires a high enough compactification scale
- SU(5) aGUT is a sample model, SU(6), SO(10) and other options are being studied for realistic phenomenology
- E6 model allows to unify gauge and Yukawa couplings (for one generation)