Asymptotic UV safe unification of gauge and Yukawa couplings

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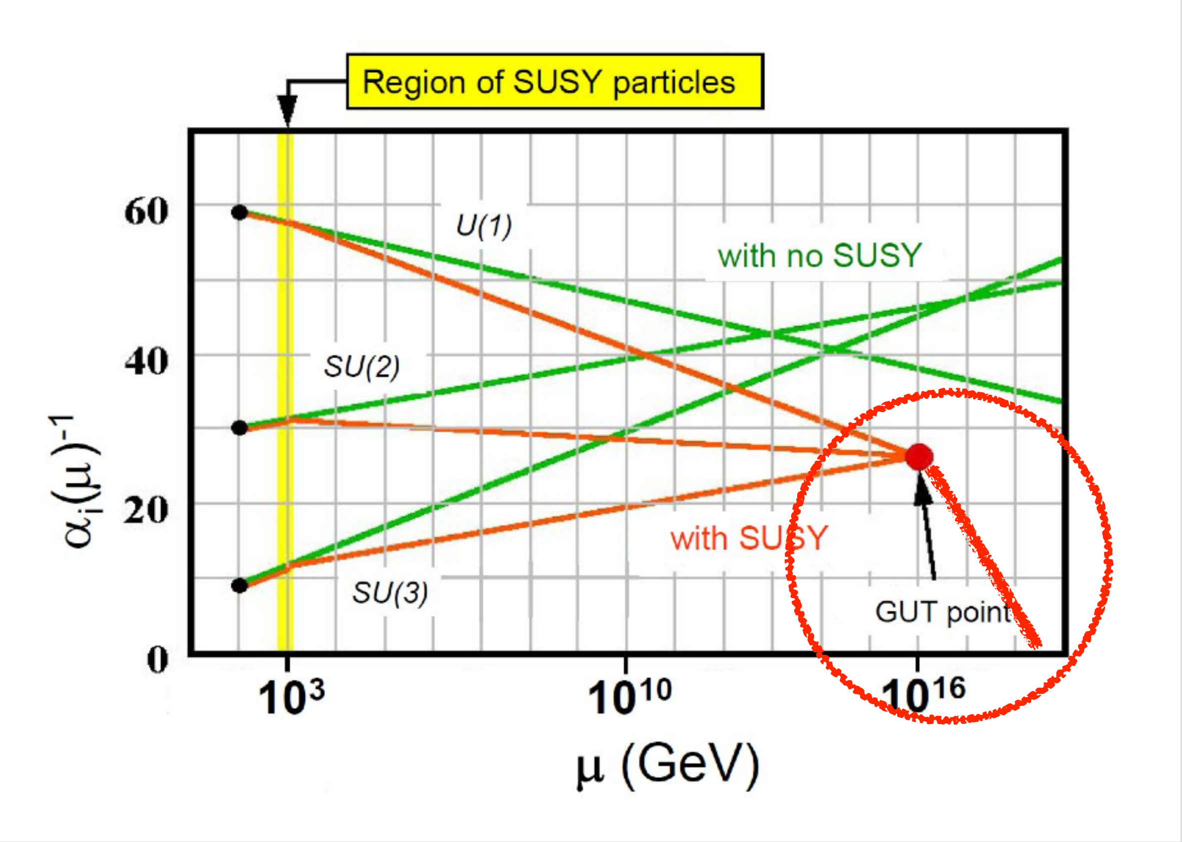
based on 2012.14732, 2302.11671 with G.Cacciapaglia, A.Cornell, C.Cot R.Pasechnik, Z.W.Wang and work in preparation (also with W.Isnard and A.Preda)

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
2. AS via perturbative fixed points and Susy
3. AS via extra compact dimensions:

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

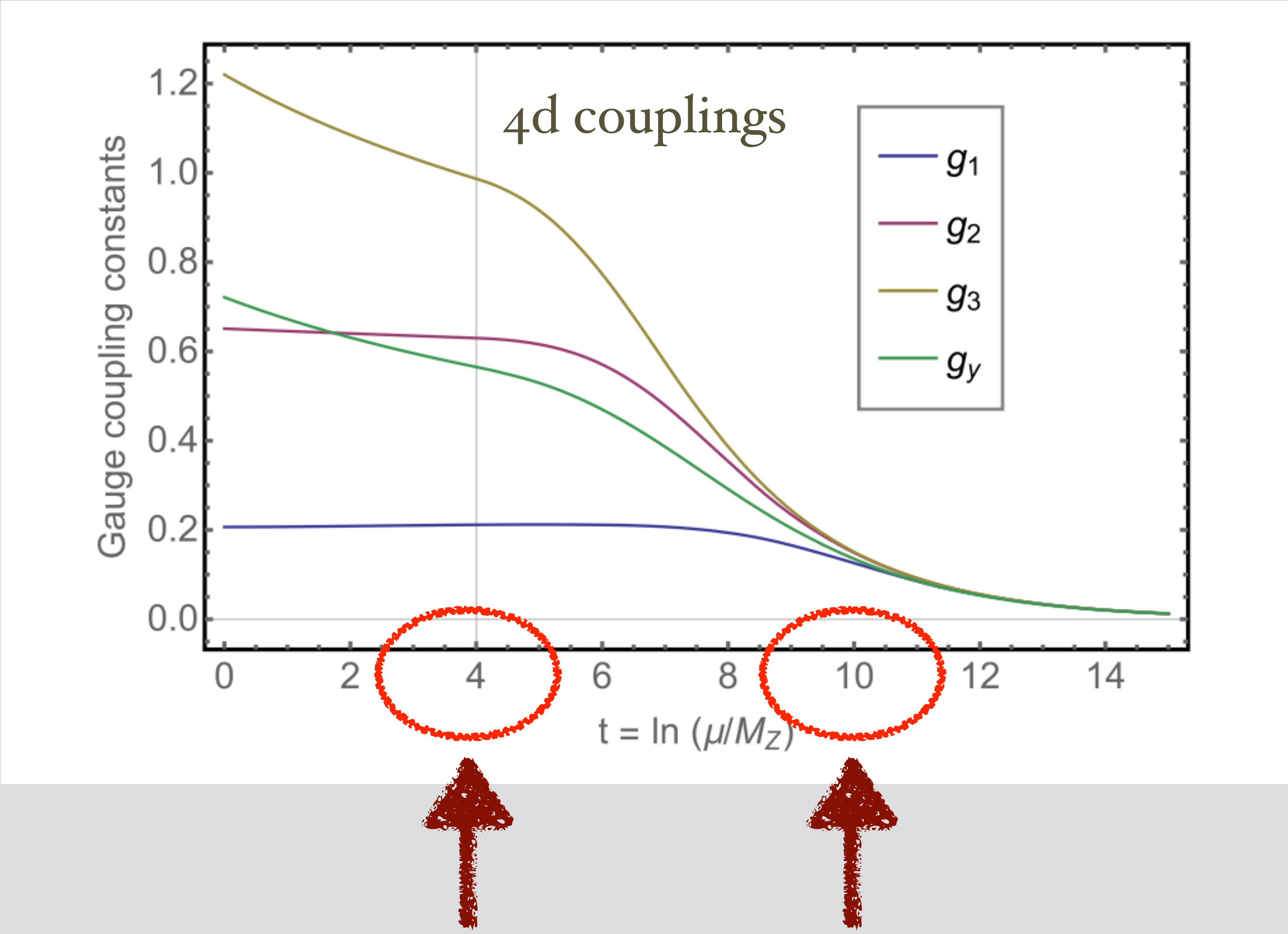
fixed point

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

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

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 SU(3) toy model

SU(2) U(1)

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

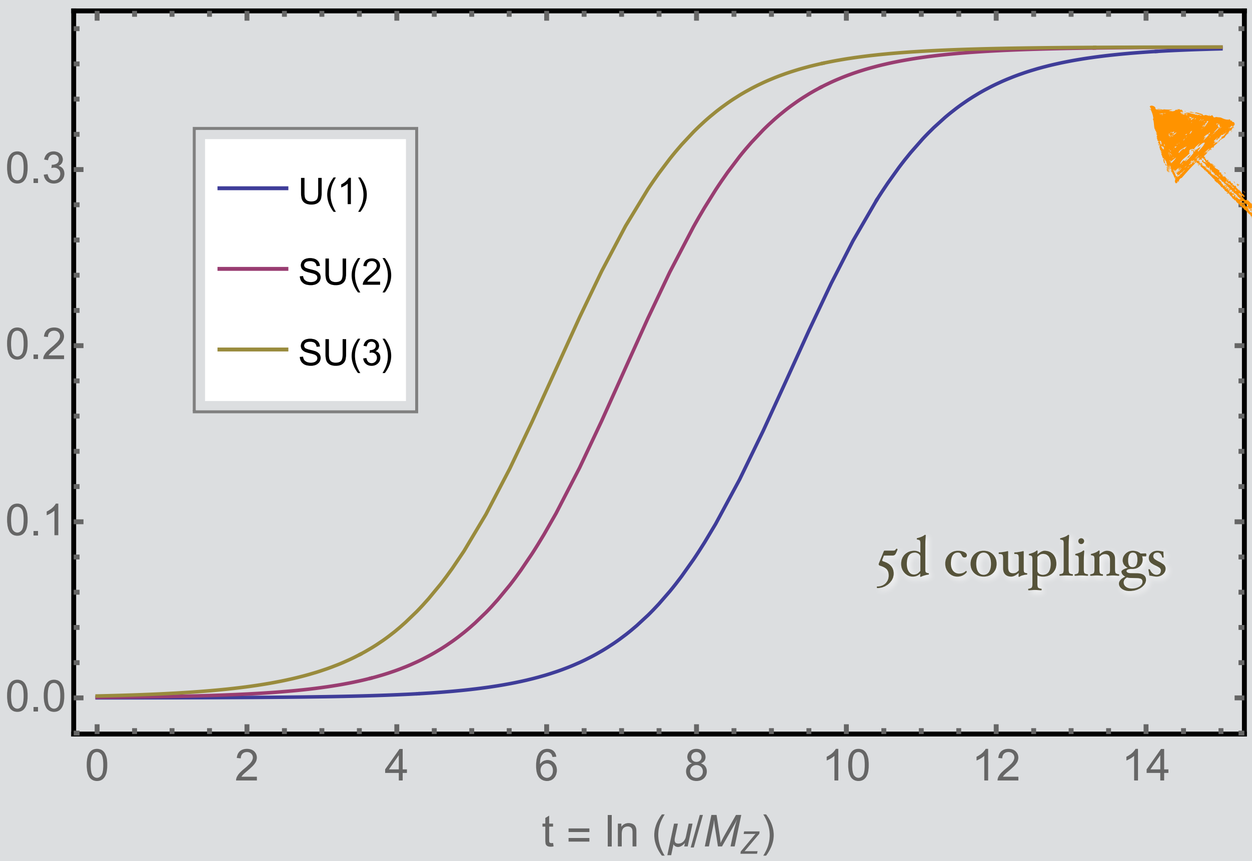
Higgs

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

Fermion matter
bulk triplet

Running of the gauge couplings

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



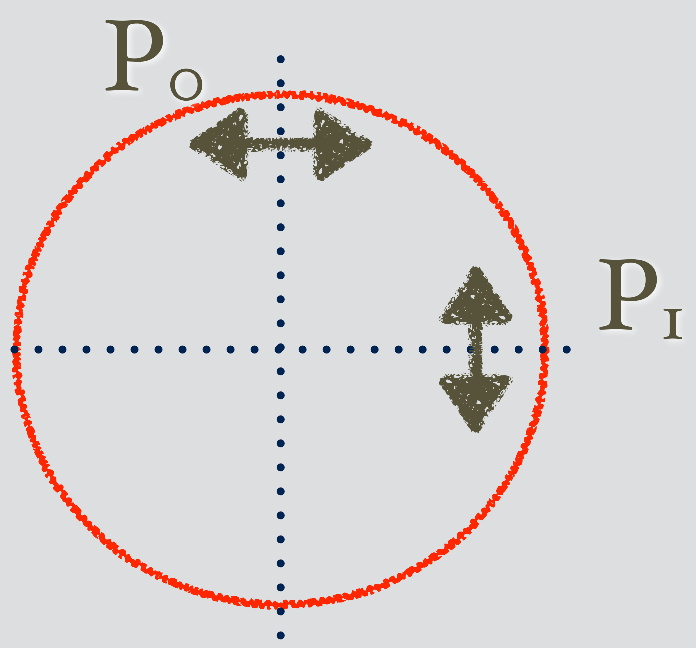
S(t) encodes the sum of the KK contributions to the running

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



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

- 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

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

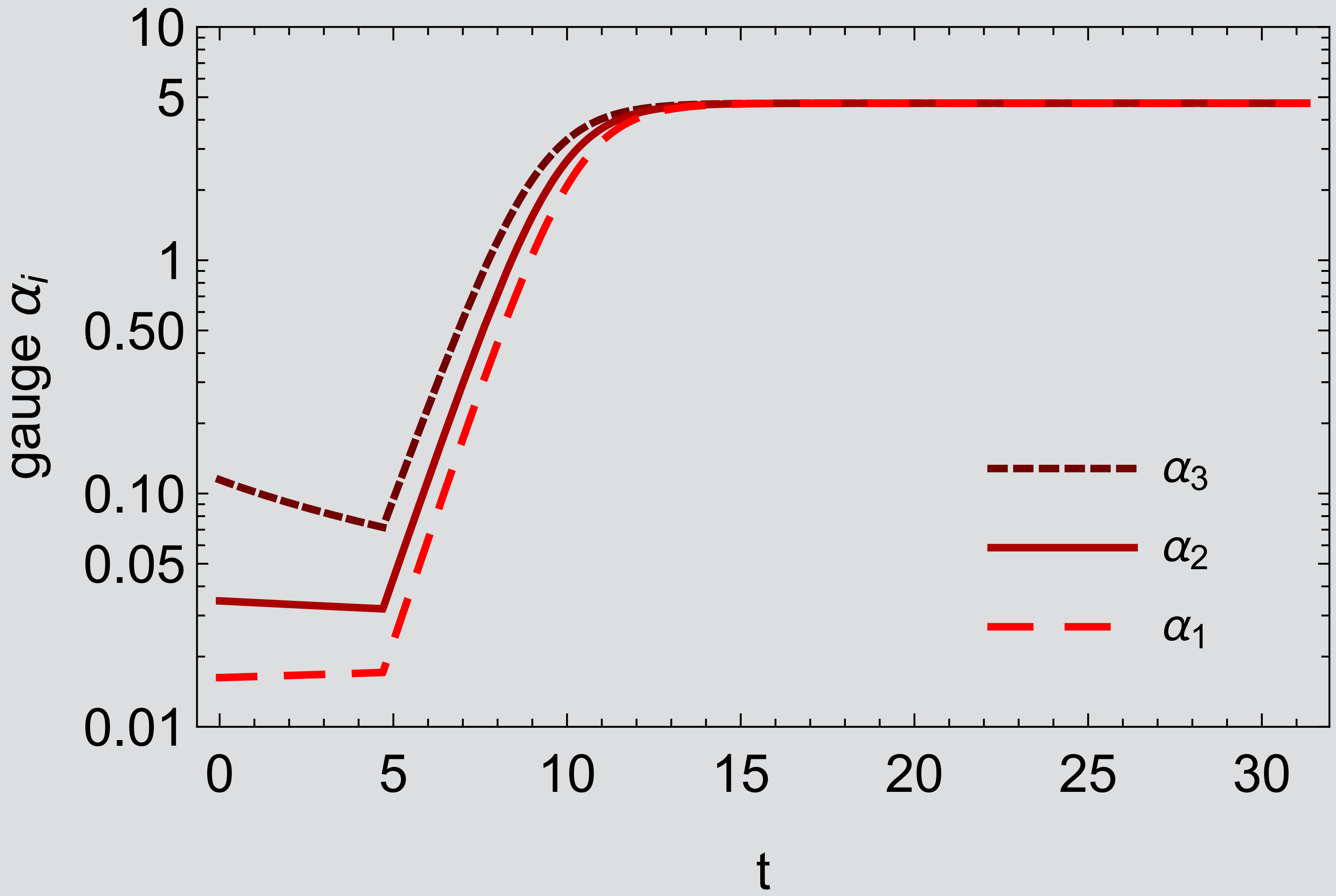
$$\psi_{10_{L/R}} = \frac{1}{\sqrt{2}} \begin{pmatrix} T^c & q \\ & \mathcal{T}^c \end{pmatrix}_{L/R}, \qquad \psi_{\overline{10}_{L/R}} = \frac{1}{\sqrt{2}} \begin{pmatrix} t & Q^c \\ & \tau \end{pmatrix}_{L/R},$$

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^a_μ	$(+,+)$	$(\mathbf{1}, \mathbf{3}, 0)$	✓	$2/R$
G^i_μ		$(\mathbf{8}, \mathbf{1}, 0)$		
A^μ_X	$(-,+)$	$(\mathbf{3}, \mathbf{2}, -5/6)$	–	$1/R$

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

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

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

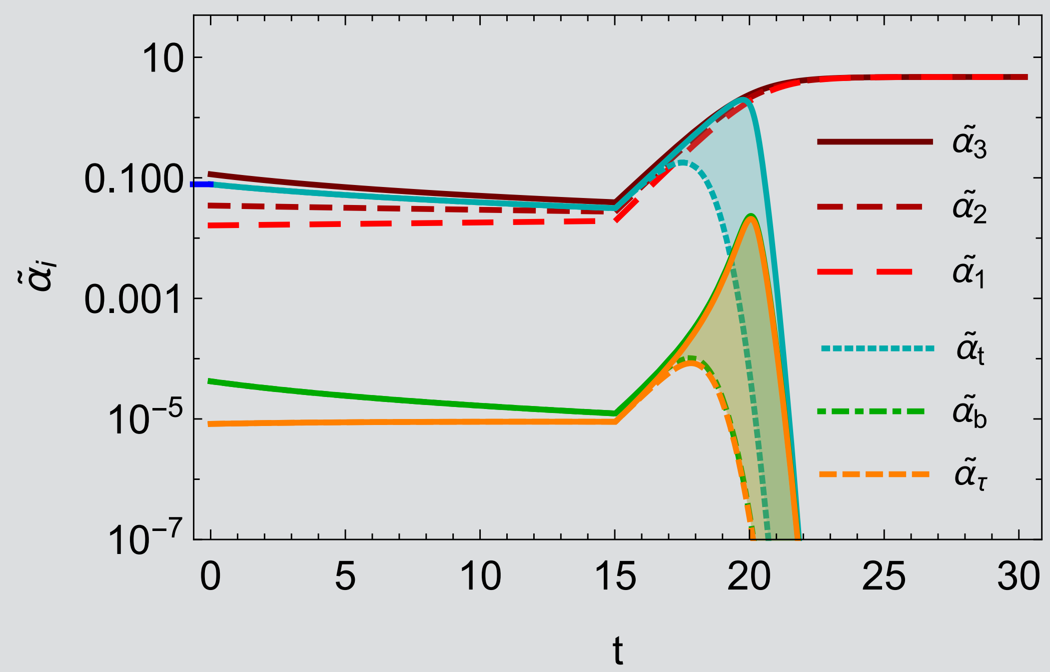
$$\sqrt{2}\overline{\psi_{\overline{10}}}\psi_{\bar{5}}\phi_5^* = -\bar{\tau}\phi_h^* l - \bar{Q}^c H^* l + \bar{Q}^c \phi_h^* B^c - \epsilon_3 \bar{t} H^* B^c,$$

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

4 independent couplings, one for each SM Yukawa term

Problems with 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.

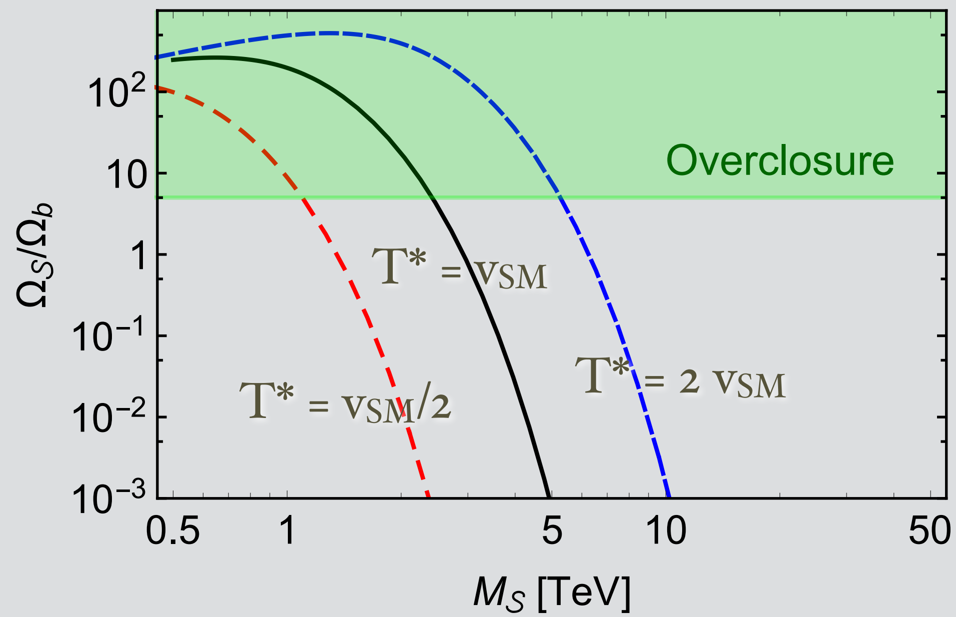


Limiting case to avoid Landau poles: $R^{-1} > 3\ 10^5$ TeV

Instead localized Yukawas always run to zero in the UV

see Cacciapaglia 2309.10098 for a classification in SU(N), ongoing study for SU(6)

Baryogenesis and DM



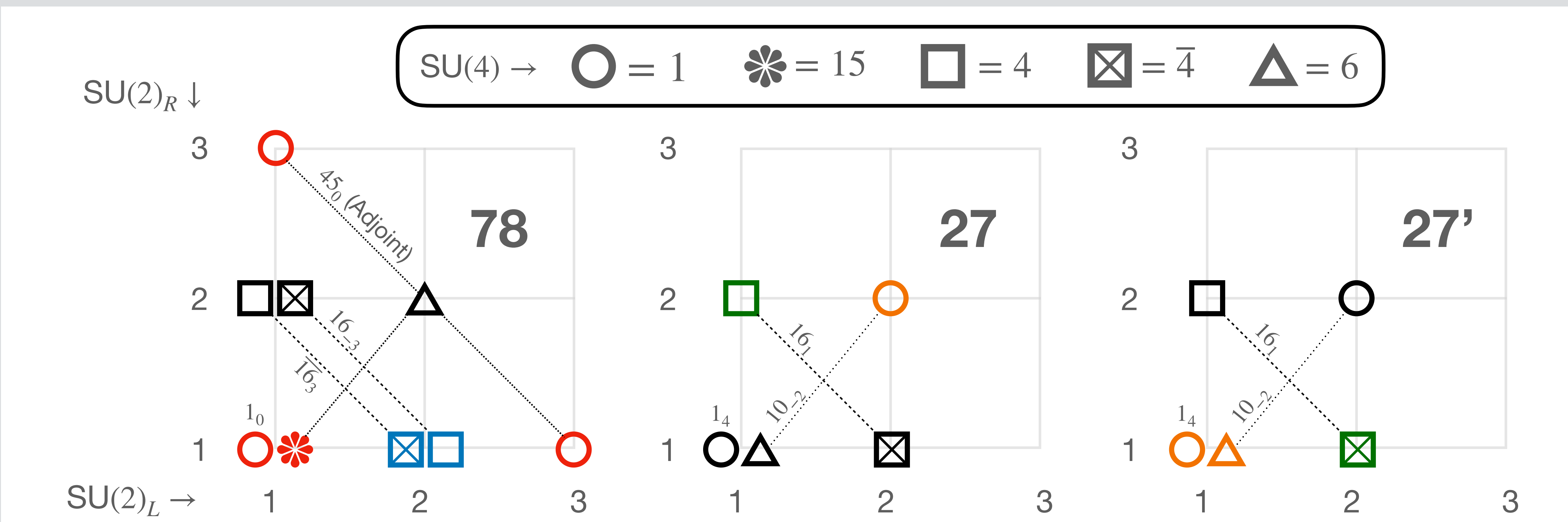
assuming 1st order phase transition

1/R ~ 2.4 TeV

- Indalo  particles carry both B and L charges, in values that are half of the SM unit charges
- It is not possible for them to decay into SM fields only and no proton decay
- The lightest state S is stable and a candidate for dark matter
- After the Indalo particles exit thermal equilibrium with the SM, they decay S + SM, and release some baryon number to the SM sector

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

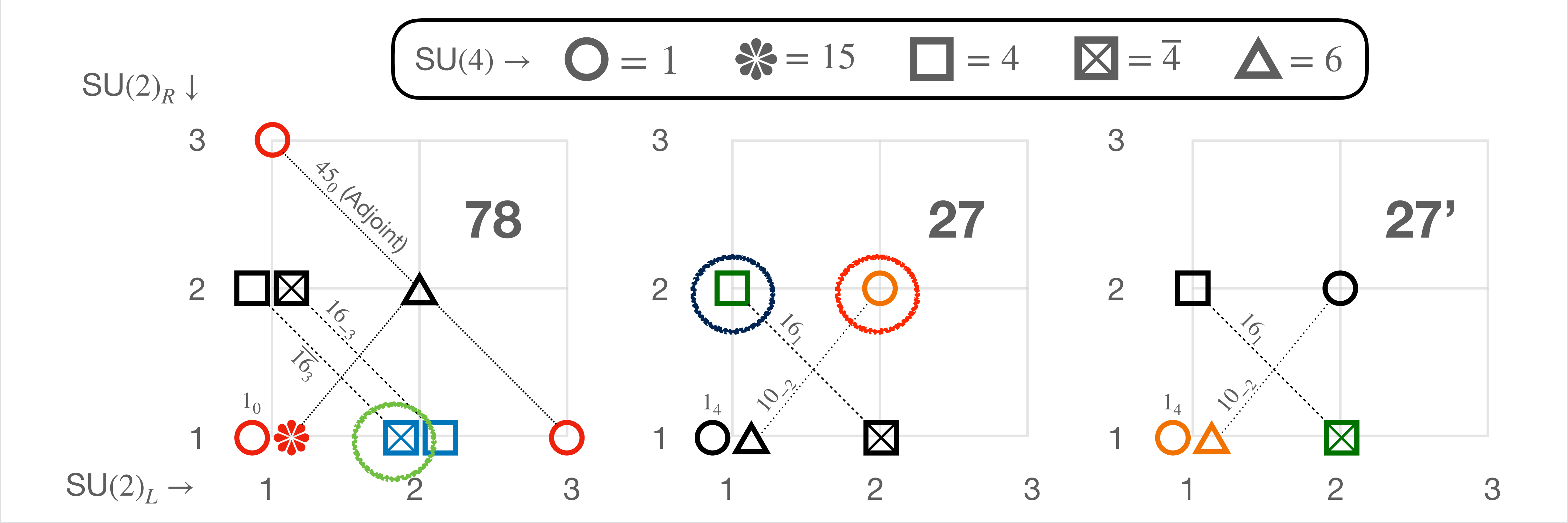


see also Kobayashi, Raby, Zhang, Nucl. Phys. B704, 3 (2005) but without UV fixed point

E6 : the exceptional case

SM Yukawa couplings →

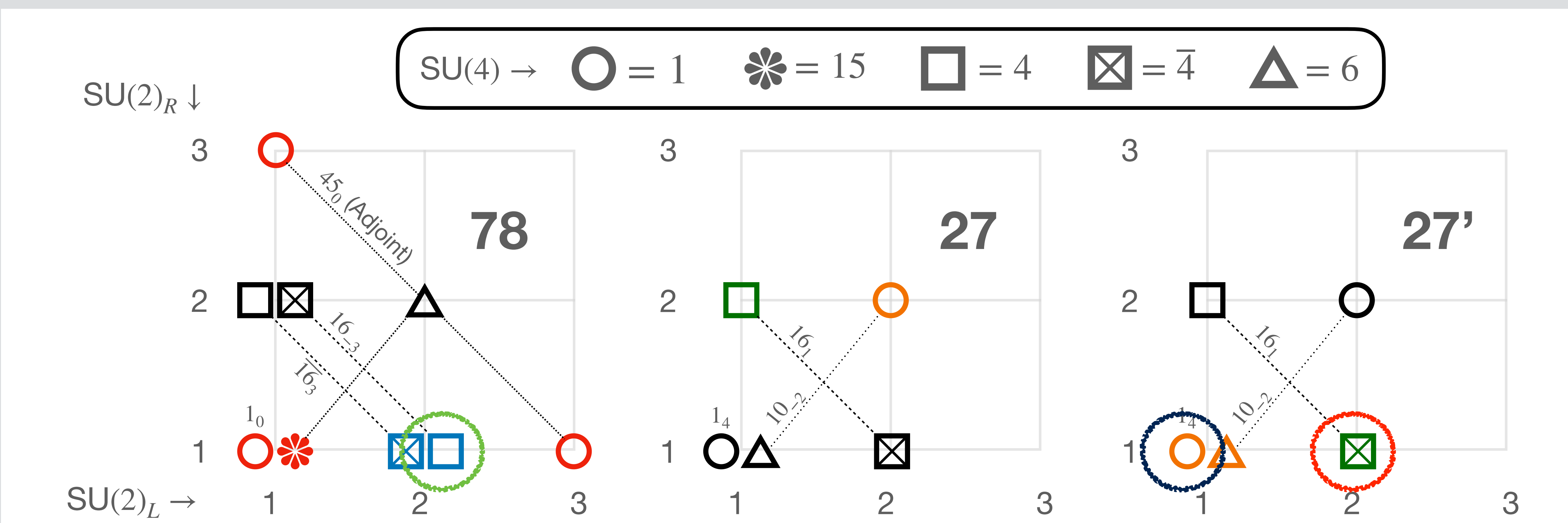
$$g\ \Phi^c_{27}\Phi_{78}\Phi_{27} \supset \frac{g}{\sqrt{2}}(\mathbf{1},\mathbf{2},\mathbf{2})_2\,(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})_{-3}\,(\mathbf{4},\mathbf{2},\mathbf{1})_1$$



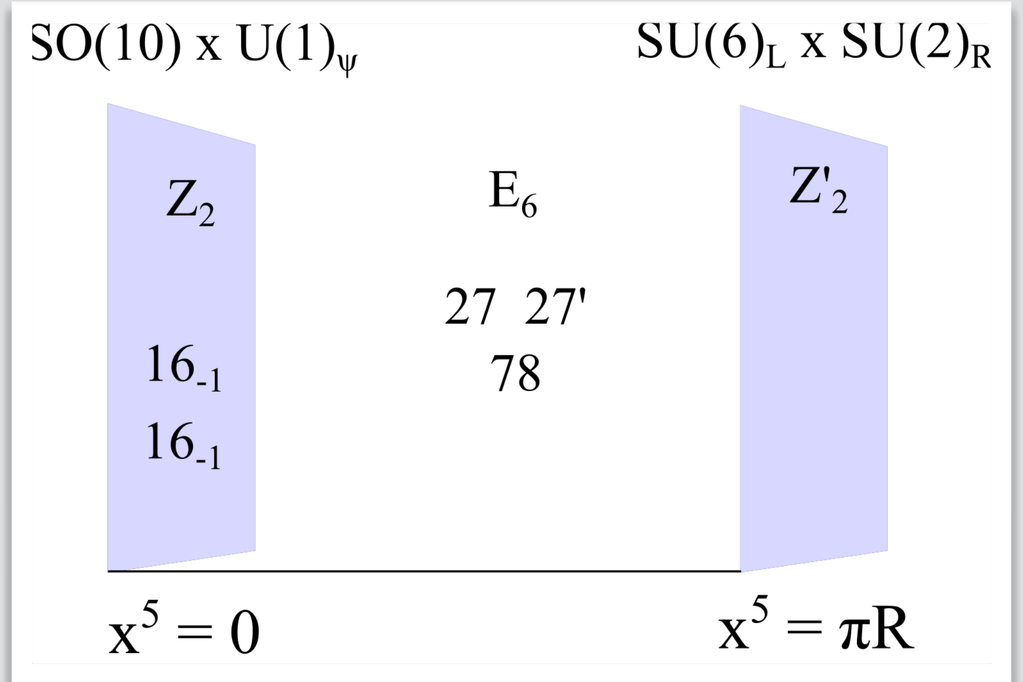
E6 : the exceptional case

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

heavy mass for unwanted chiral states



E6 : breaking pattern



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

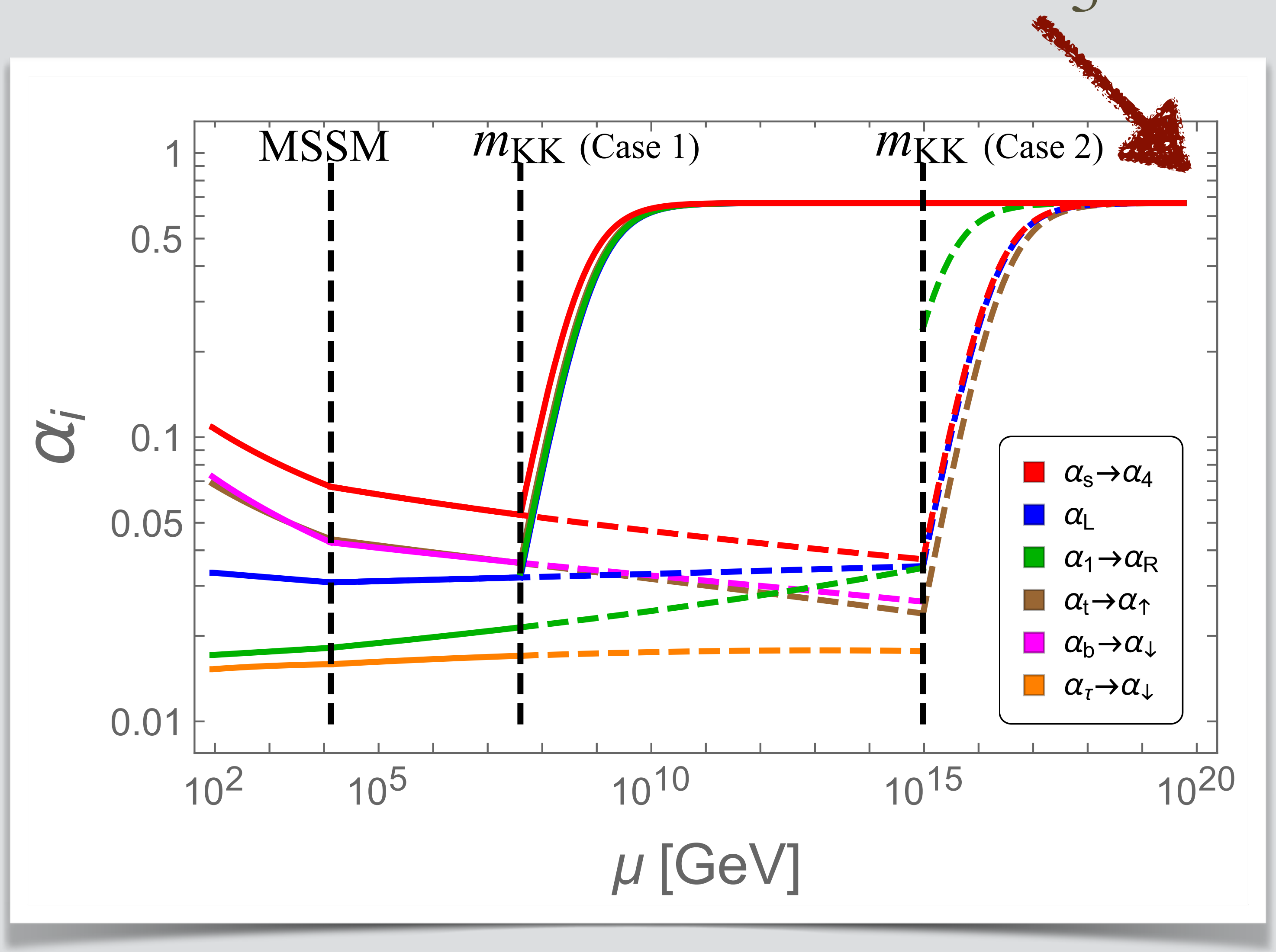
- Right-handed SM fermions from the adjoint
- Left-handed and Higgs(es) from the 27
- 27' to give mass to unwanted states
- PS breaking with gauge-scalar
- U(1) breaking by singlet in 27'

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)
- A dark Matter candidate (the lightest -field S)
- Baryogenesis can be reproduced (SU(5) model)
- E6 model allows to unify gauge and Yukawa couplings (for one generation)
- Lower scale allowed (Model 1) from PS breaking ($\sim 10^3$ TeV)
- Two light generation predicted by gauge anomalies on the SO(10) boundary (Model 2, high KK scale $\sim 10^{16}$ GeV)