New Directions Beyond the Standard Model of Particle Physics

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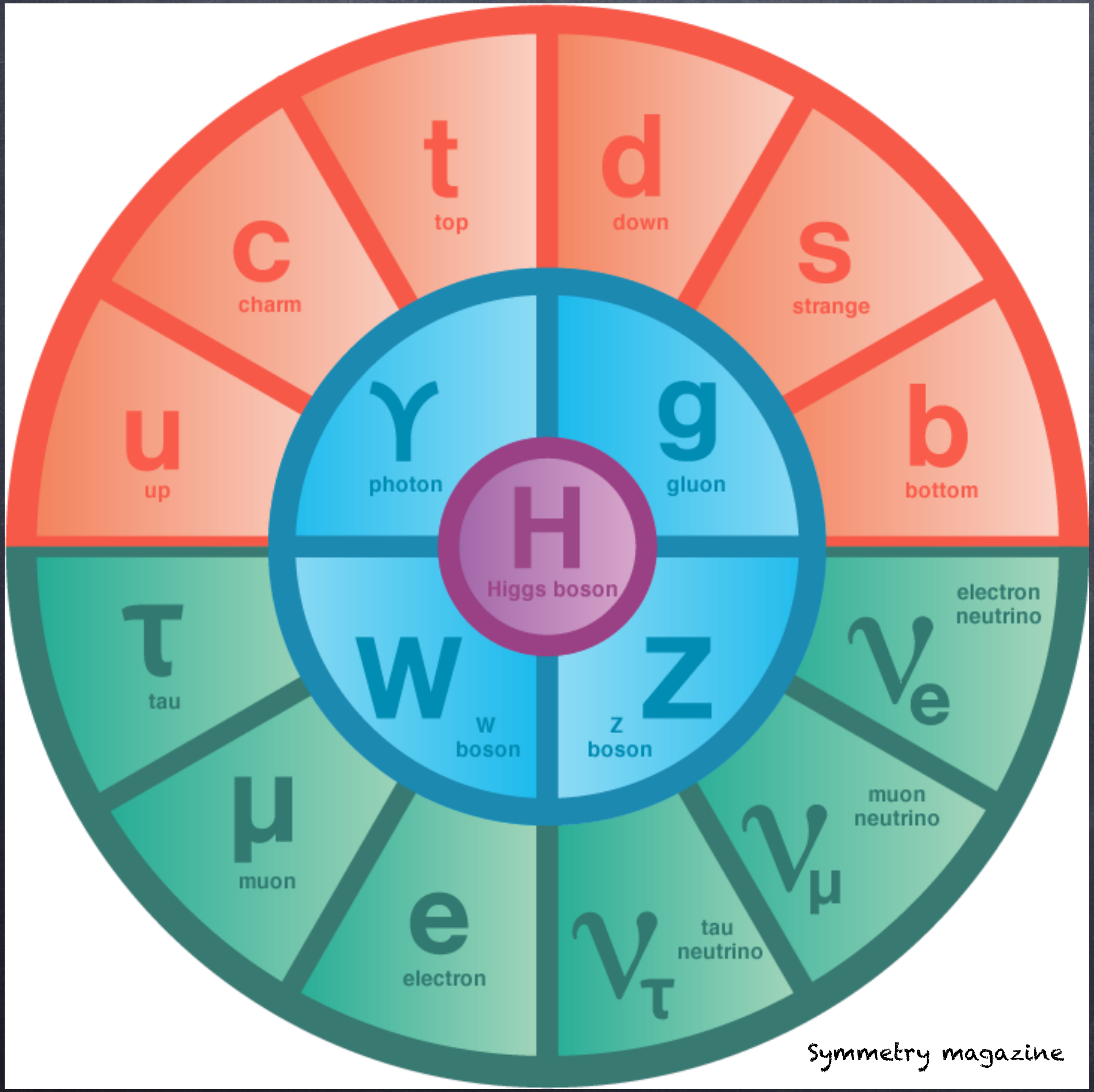
Who am I?

Recently moved from IP2I Lyon to LPTHE.

- Particle Model Building (BSM)
- Properties of strong dynamics
- Collider phenomenology – FCC programme at CERN
- Inflation
- Black Hole physics
- Models for epidemiology and viral genomics
- …

The Standard Model

- Since 2012, the Standard Model of Particle Physics is complete!



The discovery of the Higgs boson completes the puzzle.

Yet, it's not the end of the story!

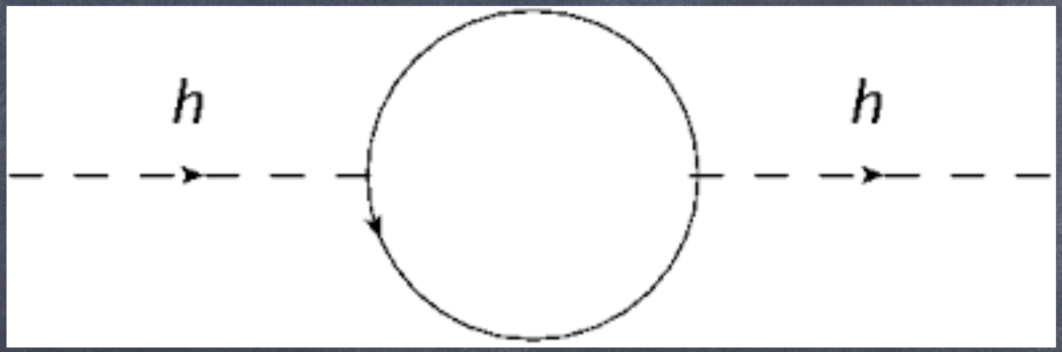
Beyond the Standard Model?

Many questions still open:

- What is the nature of the Higgs boson?
- What gives mass to neutrinos? (Maybe the Higgs Yukawas – Dirac neutrino masses)
- What is Dark Matter? (Maybe PBHs)
- What caused inflation? (Maybe the Higgs, with non-minimal gravity)
- Is it there a strong CP problem? (Maybe not)
- ...

The questionable naturalness of the Higgs boson

- Spin-0 particles are special: their mass is not protected by space-time symmetries!



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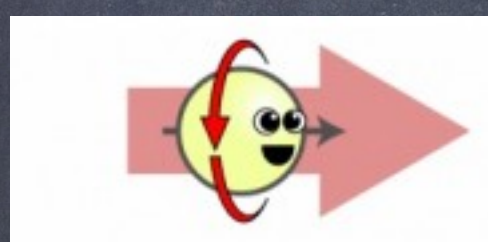

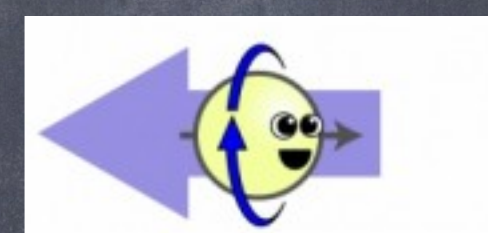

$v_{car} \gg v_{particle}$

Car rest frame

This is only possible for massive particles!

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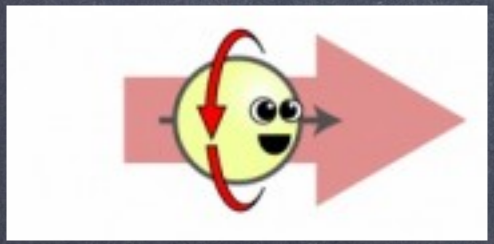

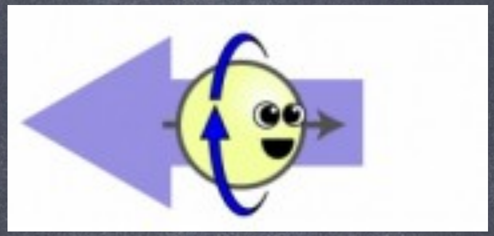

For massless particles ($v = c$), the two spin-configs are independent fields with separate properties.

At quantum level: $$m_f \Big|_{1-loop} = m_f \left(1 + \frac{g^2}{16\pi^2} \right)$$

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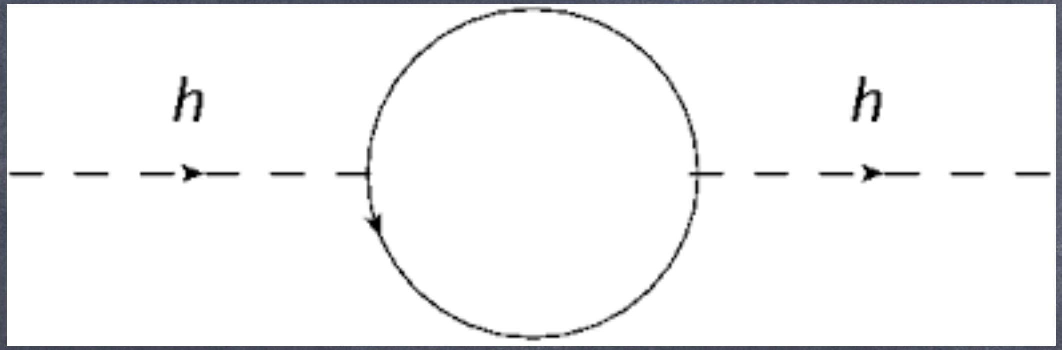
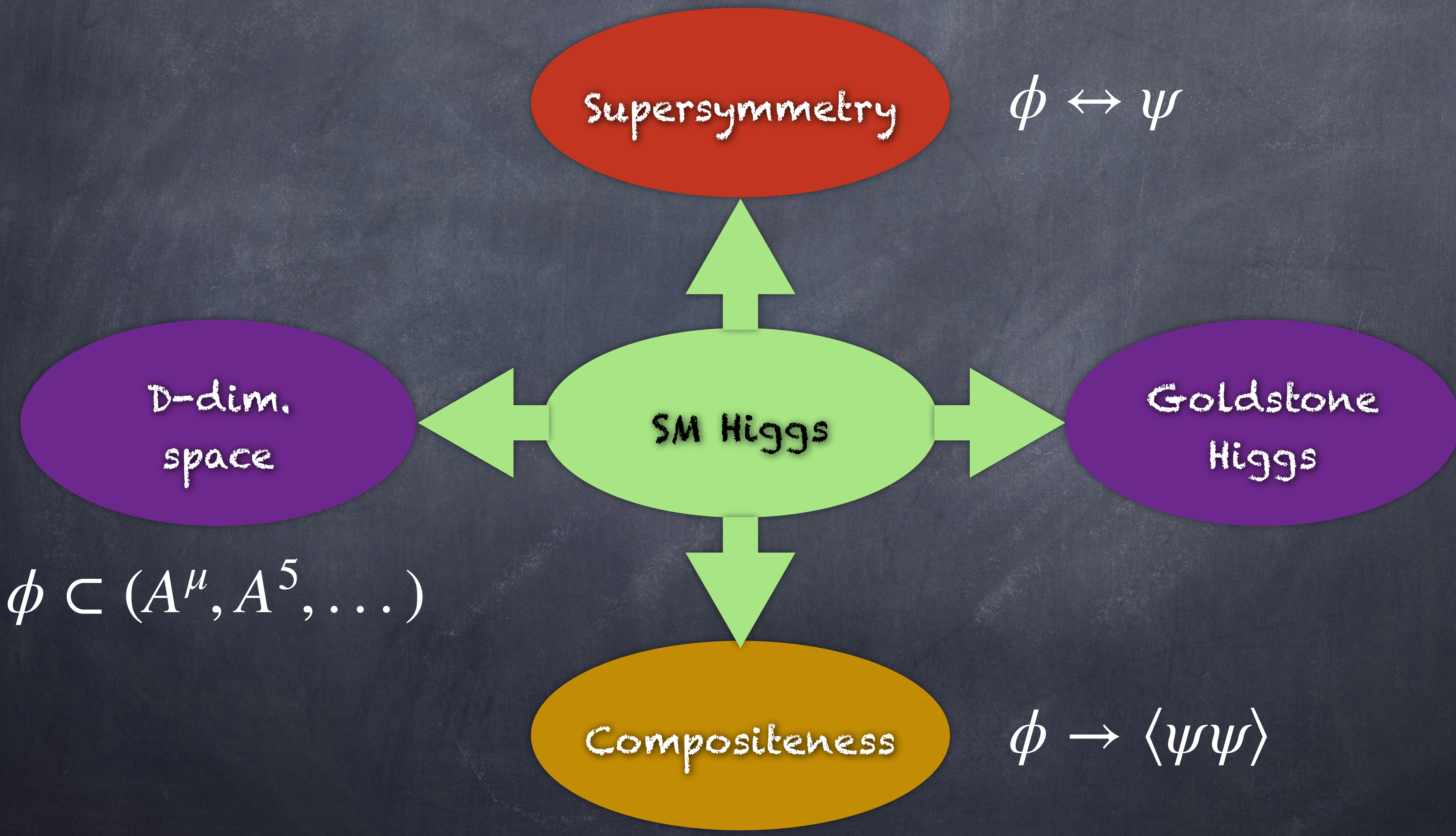


At quantum level:
$$m_h^2\Big|_{1-loop} = m_h^2\left(1 + \frac{g^2}{16\pi^2}\frac{M^2}{m_h^2}\right)$$

Toward naturalness



New directions:

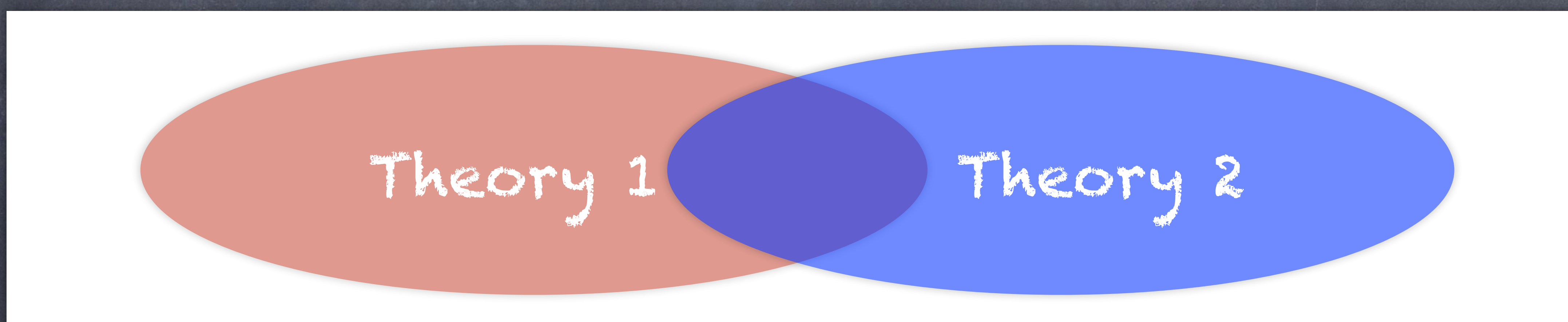
1. Dual Standard Model via Gauge Dualities

2. Asymptotic Grand Unification in 5 dimensions


Dual SM

What is a duality?

Two different theories that describe the same physics



- Share the same global symmetries
- Anomaly matching
- Decoupling limits
- ...

What is a duality?

$$X = N_f - N\,. \tag{1}$$

Electric theory (UV)					
Fields	$SU(N)$	$SU(N_f)_L$	$SU(N_f)_R$	$U(1)_V$	$U(1)_{AF}$
λ	Adj	1	1	0	1
Q	F	F	1	1	$-N/N_f$
$\tilde{Q}$	$\bar{F}$	1	$\bar{F}$	-1	$-N/N_f$

Magnetic theory (IR)					
Fields	$SU(X)$	$SU(N_f)_L$	$SU(N_f)_R$	$U(1)_V$	$U(1)_{AF}$
λ_m	Adj	1	1	0	1
q	F	$\bar{F}$	1	N/X	$-X/N_f$
$\tilde{q}$	$\bar{F}$	1	F	$-N/X$	$-X/N_f$
M	1	F	$\bar{F}$	0	$-1+2X/N_f$
ϕ	F	$\bar{F}$	1	N/X	$1-X/N_f$
$\tilde{\phi}$	$\bar{F}$	1	F	$-N/X$	$1-X/N_f$
Φ_H	1	F	$\bar{F}$	0	$2X/N_f$

Scalar-less theory valid at high energies

Equivalent theory valid at low energies

Can this one be related to the Standard Model?

Dual SM

EW symmetry contained in
$SU(2)_L \times U(1)_Y \subset SU(6)_L \times SU(6)_R \times U(1)_V$

Cacciapaglia et al, 2407.17281

Electric theory (UV)					
Fields	SU(3)	$SU(6)_L$	$SU(6)_R$	$U(1)_V$	$U(1)_{AF}$
λ	Adj	1	1	0	1
Q	F	F	1	1	$-1/2$
$\tilde{Q}$	$\bar{F}$	1	$\bar{F}$	-1	$-1/2$
L	1	F	1	-3	0
$\tilde{L}$	1	1	$\bar{F}$	3	0

Magnetic theory (IR)					
Fields	SU(3)	$SU(6)_L$	$SU(6)_R$	$U(1)_V$	$U(1)_{AF}$
λ_m	Adj	1	1	0	1
q	F	$\bar{F}$	1	1	$-1/2$
$\tilde{q}$	$\bar{F}$	1	F	-1	$-1/2$
$l \equiv L$	1	F	1	-3	0
$\tilde{l} \equiv \tilde{L}$	1	1	$\bar{F}$	3	0
M	1	F	$\bar{F}$	0	0
ϕ	F	$\bar{F}$	1	1	$1/2$
$\tilde{\phi}$	$\bar{F}$	1	F	-1	$1/2$
Φ_H	1	F	$\bar{F}$	0	1

Scalar-less theory above a certain energy scale!

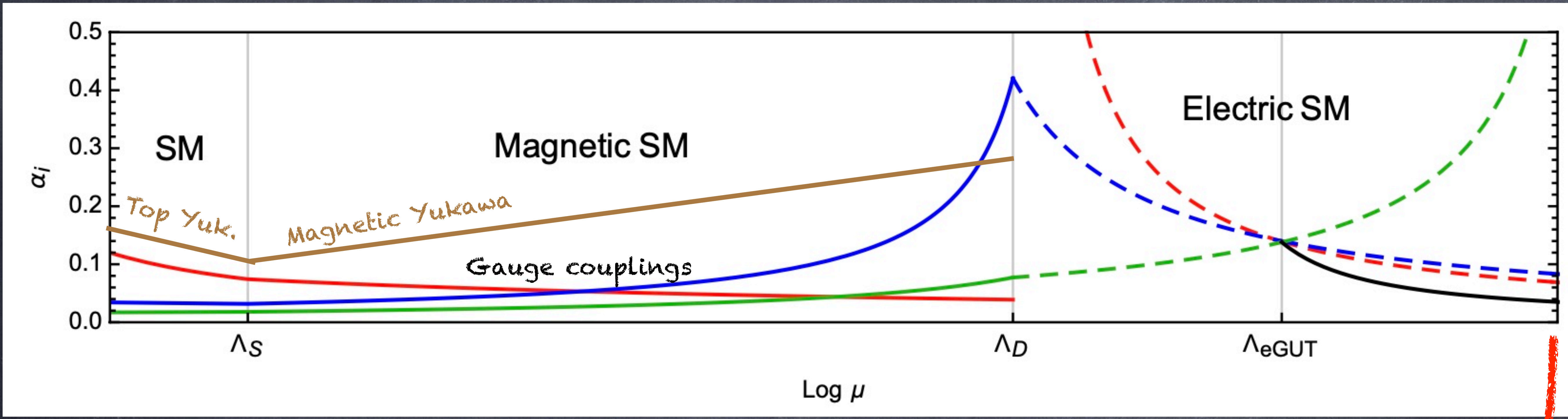
SM fermions

$$\mathscr{L} \subset y q \tilde{q} \Phi_H$$

Contains (many) Higgses

Dual SM

Cacciapaglia et al, 2407.17281



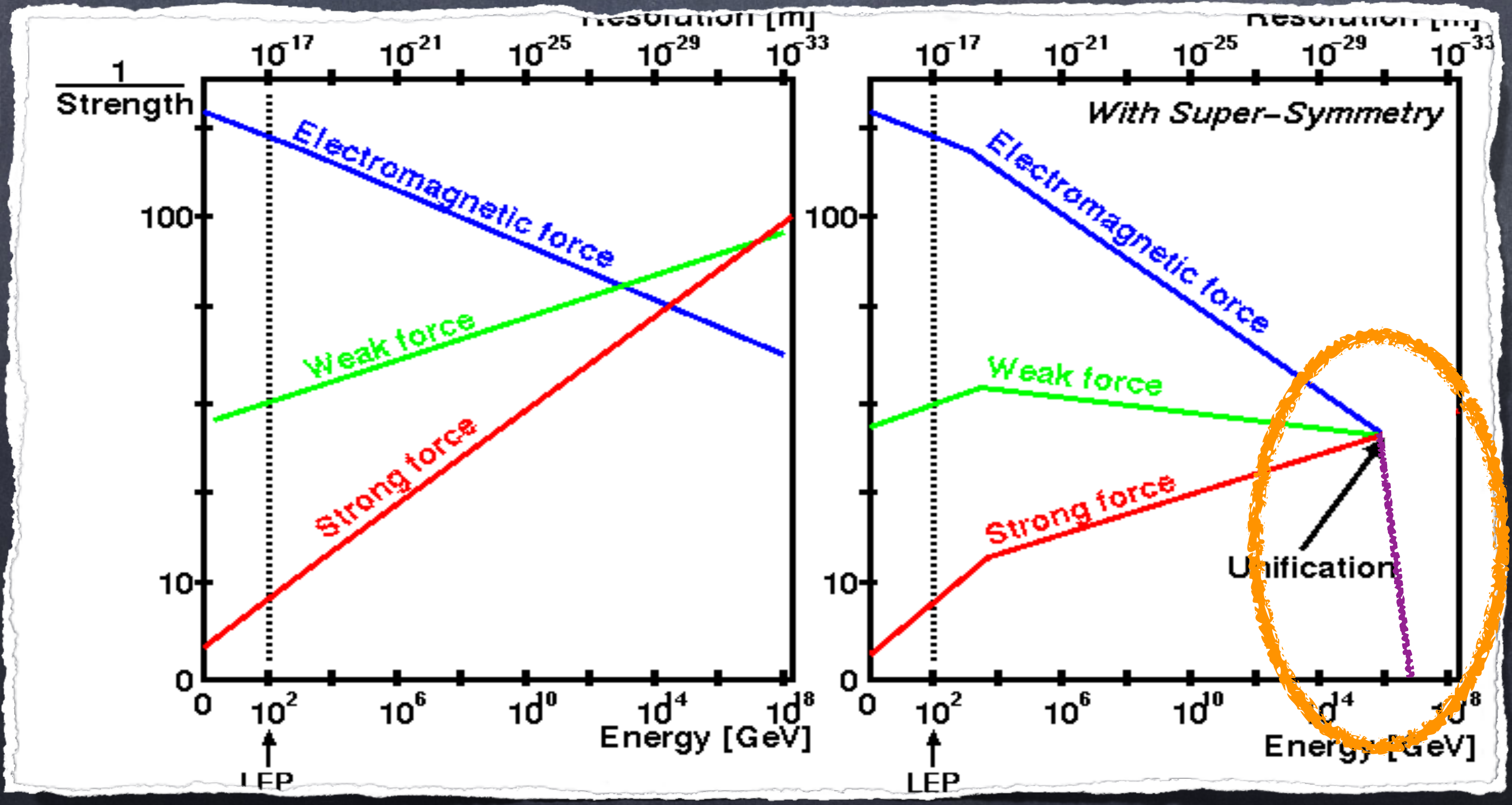
Mass of non-SM particles	Scale of duality	Possible electric GUT	
TeV (LHC)	10^{11} GeV (Neutrinos)		Origin of flavour physics at Planck scale

aGUTs,

aka Asymptotic GUTs

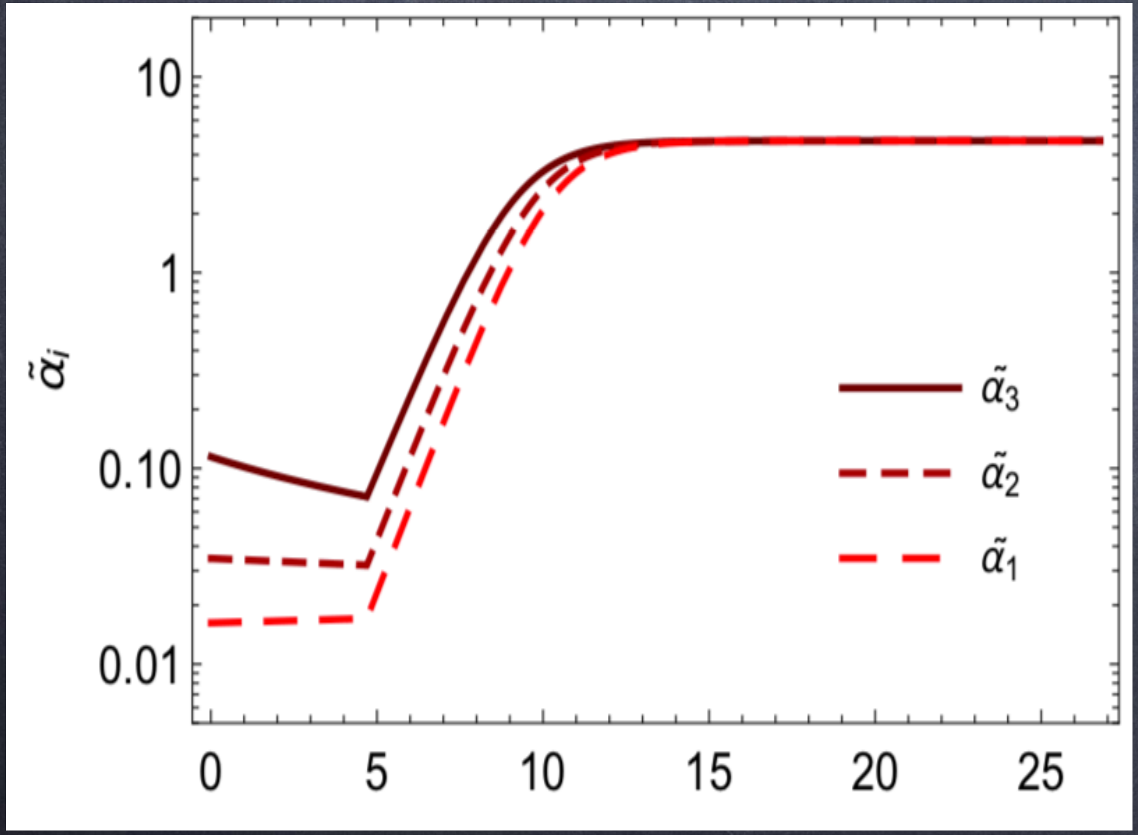
Traditional GUTs

- SM gauge couplings expected to be equal at the GUT scale
- supersymmetry helps building "realistic" models
- proton decay hard to avoid!



asymptotic GUT (aGUT)

- Gauge couplings are never equal, but tend to the same UV fixed point!



B) Extra compact dimensions

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

$\tilde{\alpha} = \mu R\, \alpha$ ('t Hooft coupling in 5D)

$$2\pi \left(\tilde{\alpha} + \frac{d\tilde{\alpha}}{d\ln\mu} \right) = b_5\, \tilde{\alpha}^2$$

$$\tilde{\alpha}_{UV} = -\frac{2\pi}{b_5}$$

Gies, PRD 68 (2003)
Morris, JHEP 01 (2005) 002

aGUT model building

- Many constraints from the UV behaviour: finite number of feasible models.
- We just completed a full classification of aGUTs!

The most ambitious model:

- Based on exceptional group E6
- Supersymmetry allows to generate fermions as gauge fields (gauginos)
- In E6, the adjoint 78 contains the right states (but in vector-like pairs)

See Kobayashi, Raby, Zhang, Nucl. Phys. B704, 3 (2005)

The exceptional case

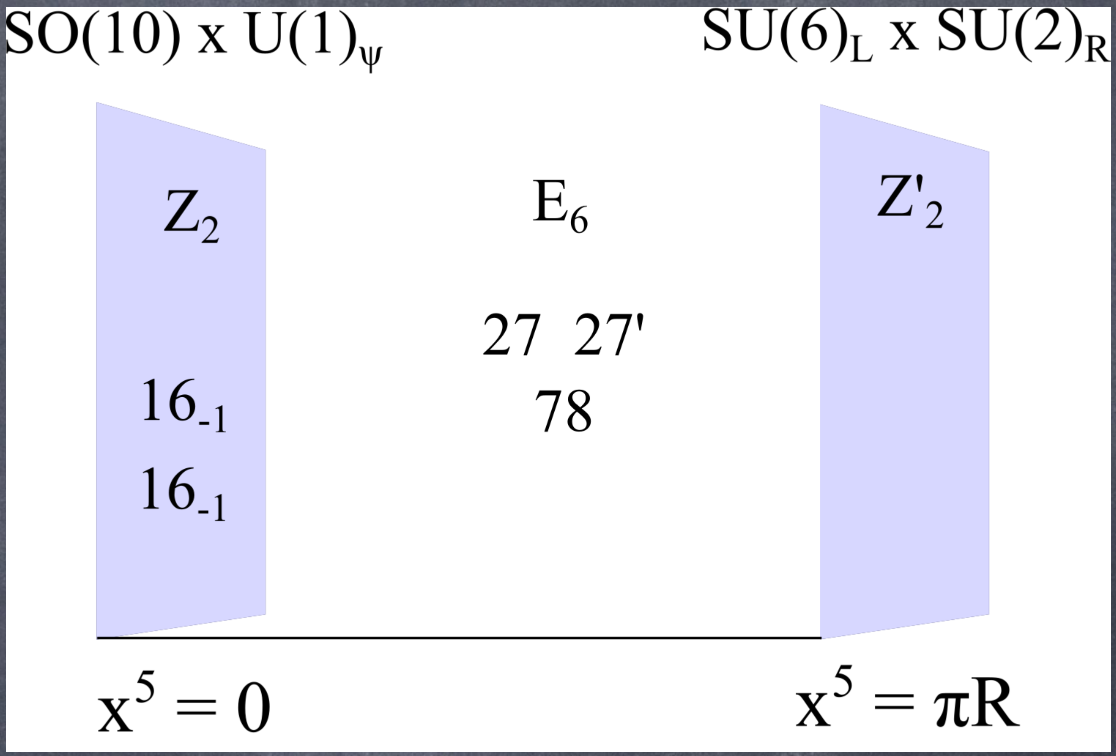
Cacciapaglia et al, 2302.11671

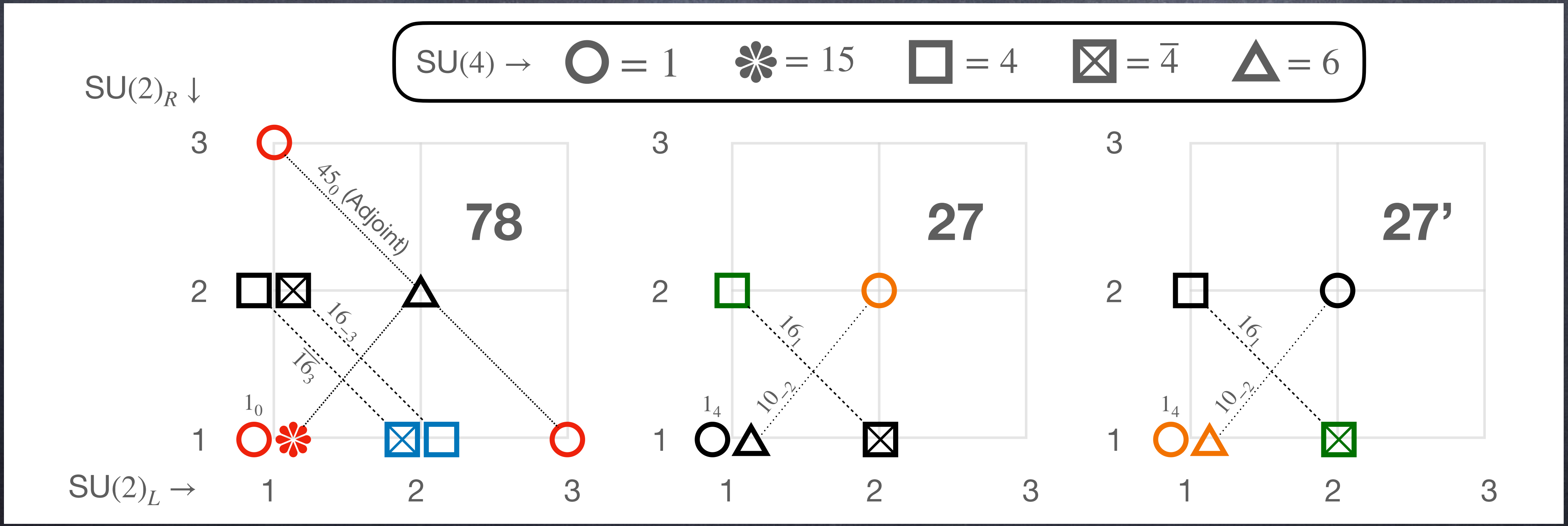
$$E_6 \to PS \times U(1)_\psi$$

- The zero modes generate an anomaly for the U(1) gauge symmetry:

$$\mathscr{A}_{16_1} - \mathscr{A}_{10_{-2}+1_4} = 2\mathscr{A}_{16_1}$$

- Add exactly two generations on the SO(10) boundary!





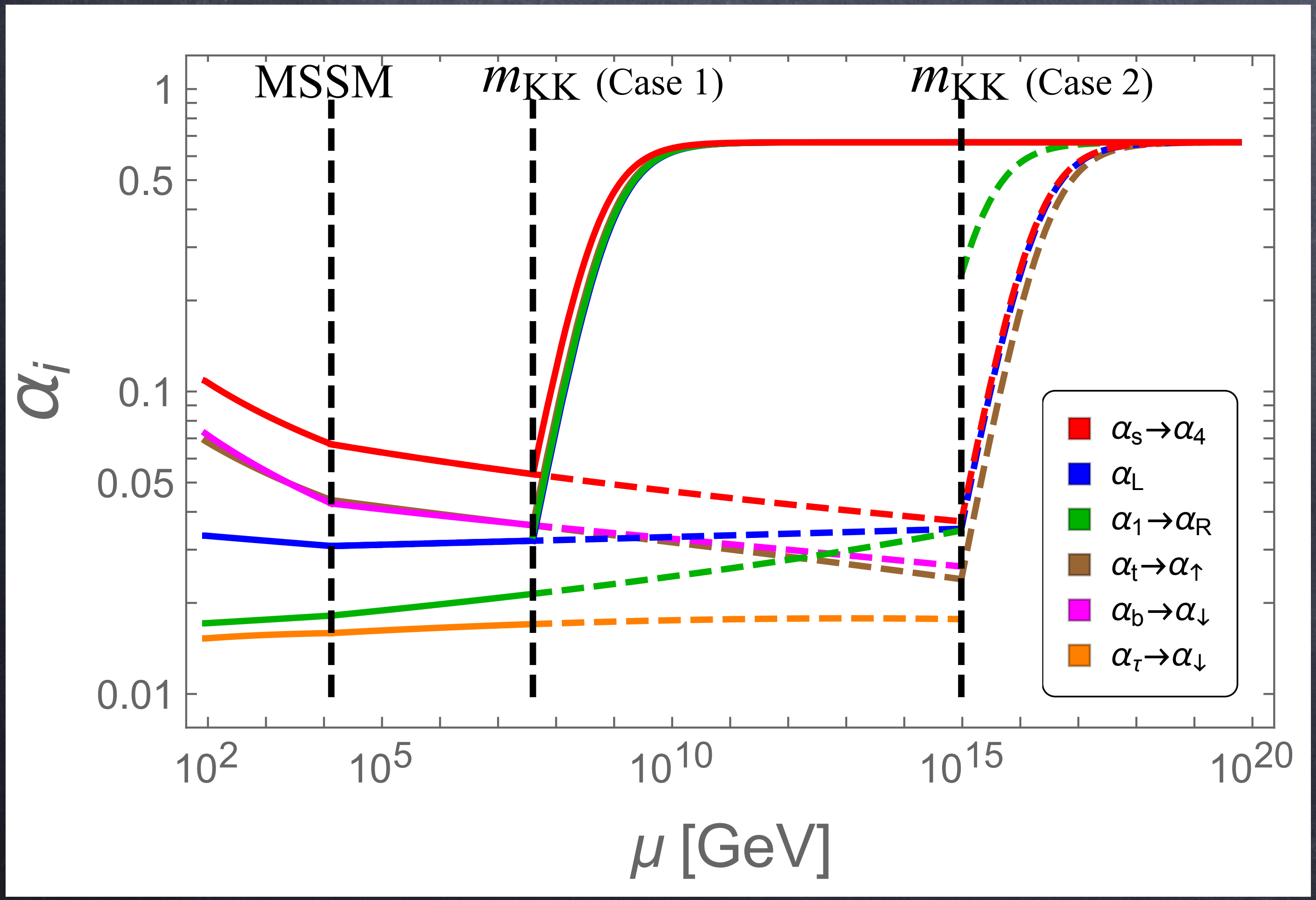
The fixed point

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

$$C(G) = 12 \quad T(27) = 3$$

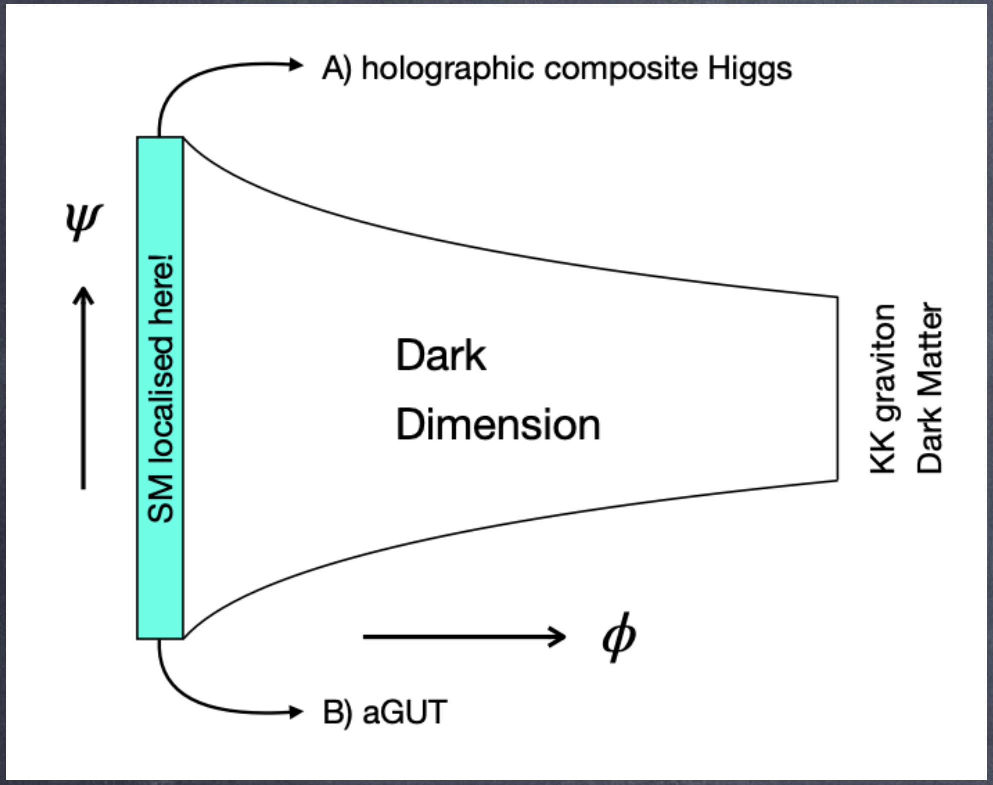
$$\tilde{\alpha}^* = \frac{2}{3}$$

No more than one generation allowed in the bulk!



- PS breaking due to a gauge-scalar
- U(1) breaking by singlet in 27′
- SUSY breaking to be studied

aGUT out of the Swampland



- The Dark Dimension conjecture relates the Cosmological constant (cc) to an meV extra dimension.
- By warping the DD, we can compute the 5D cc to be:

$$\Lambda_5 = -\,24\,k^3\,M_{Pl}^2 \sim (100\ GeV)^5$$

- Hence, Λ_5 can be related to a 6th warped extra dimension, with parameters of the order of the fundamental scale $\sim 10^{10}\ GeV$.

$$ds_6^2 = e^{-2\tilde{k}\tilde{r}_c|\psi|}\left(e^{-2kr_c|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\phi^2\right) + \tilde{r}_c^2 d\psi^2$$

Double-warped extra dimensions.

$$m_5 = \lambda'^{-1}\sqrt[5]{\Lambda_5} \sim \lambda'^{-1}\lambda^{-3/5}\Lambda^{3/20}M_{\rm Pl}^{2/5}$$

TeV scale naturally emerging from the cc And Planck!

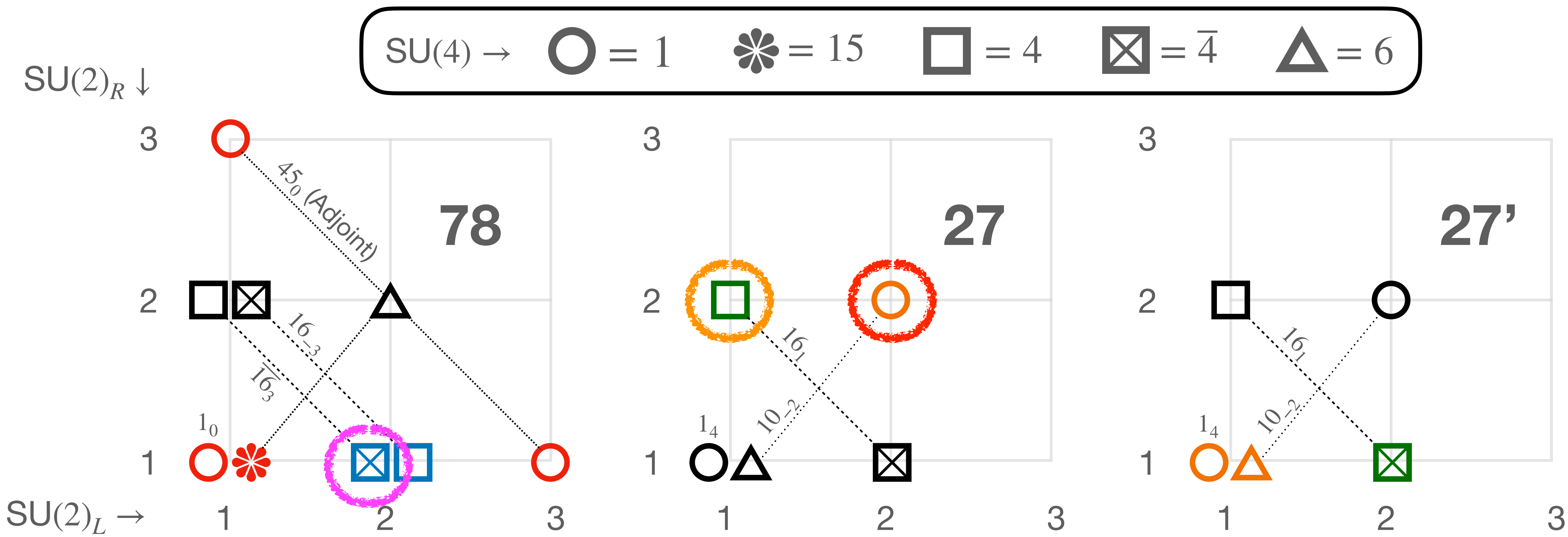
Conclusions

- We still do not know what the Higgs boson is: more experimental efforts needed.
- BSM is still welcome!
- New directions:

  1. Dual SM: use gauge duality to define a "new SM" at high energies
  2. aGUT: asymptotic unification in 5 dimensions

In both cases, the nature of the SM is profoundly changed at high scales!

The exceptional case



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

-> SM Yukawa couplings!

$$g\ \Phi^c_{27'}\Phi_{78}\Phi_{27'} \supset -\frac{g}{\sqrt{2}}(\mathbf{1},\mathbf{1},\mathbf{1})_{-4}\ (\mathbf{4},\mathbf{1},\mathbf{2})_3\ (\bar{\mathbf{4}},\mathbf{1},\mathbf{2})_1 + \frac{g}{\sqrt{2}}(\mathbf{6},\mathbf{1},\mathbf{1})_2\ (\bar{\mathbf{4}},\mathbf{1},\mathbf{2})_{-3}\ (\bar{\mathbf{4}},\mathbf{1},\mathbf{2})_1$$

-> Gives mass to unwanted Chiral states via U(1) breaking

Bulk interactions preserve Baryon number!