# Signatures of a SM duality

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(LPTHE)

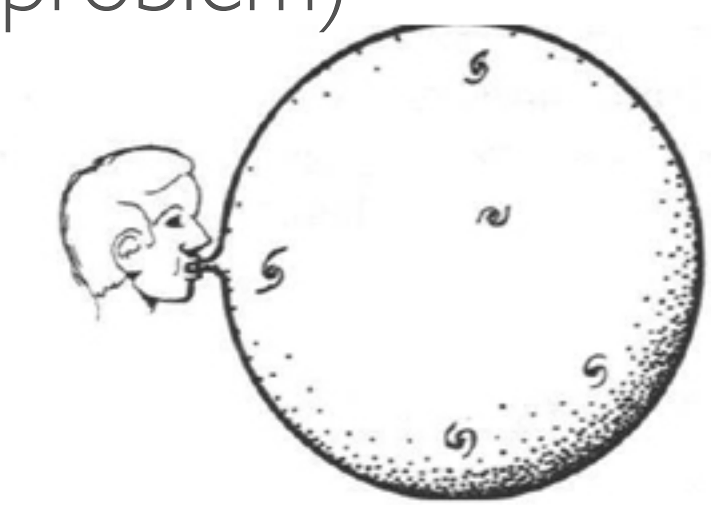
# Do we still need New Physics?

While the SM is complete and extremely successful, observational and theoretical needs for NPh remain.

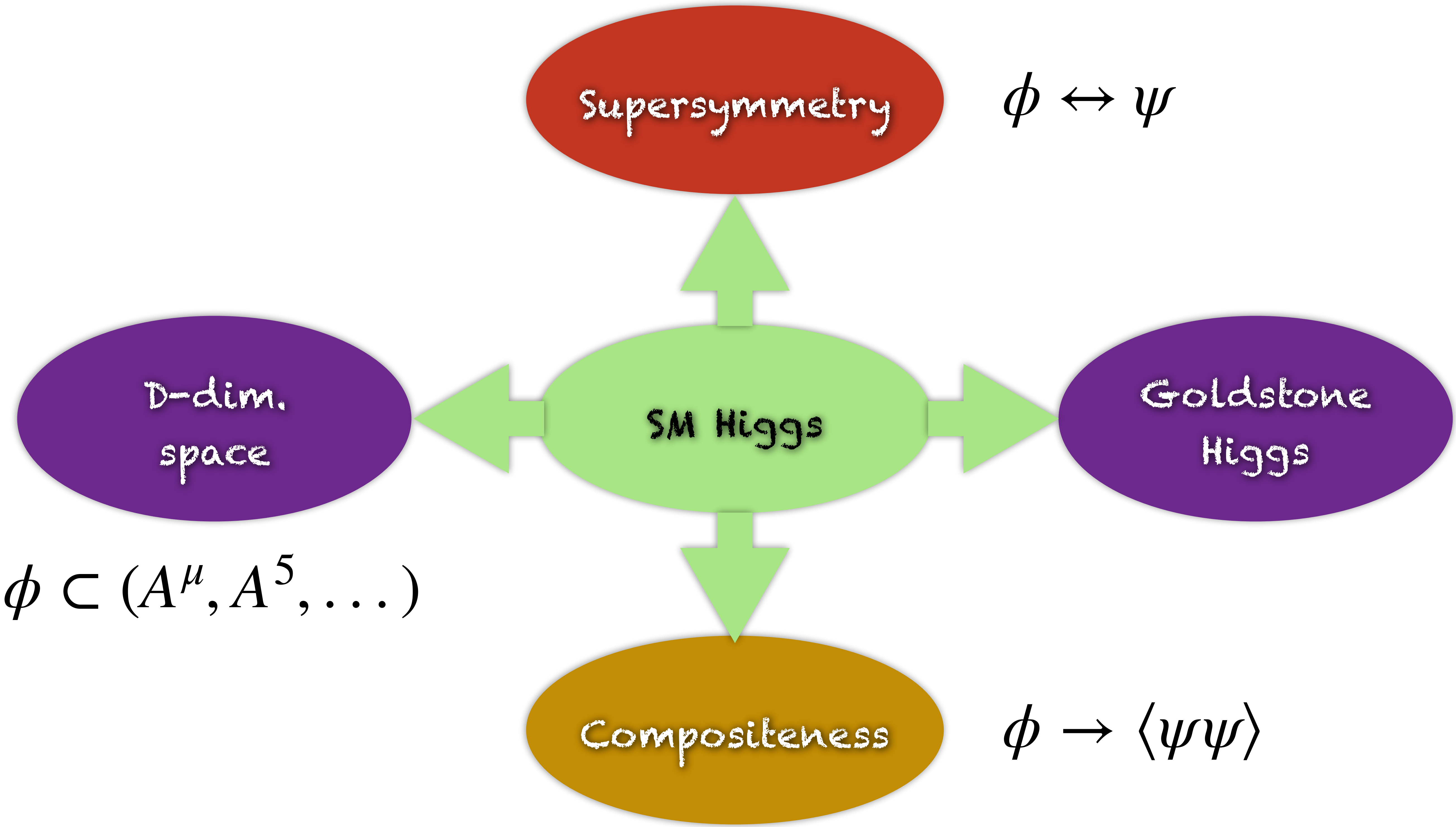
- Neutrino masses
- Dark Matter and Dark Energy
- Baryon asymmetry in the Universe
- Absence of strong CP violation
- …



- Naturalness of the EW scale (hierarchy problem)
- How to incorporate Inflation?
- Quantum gravity
- …



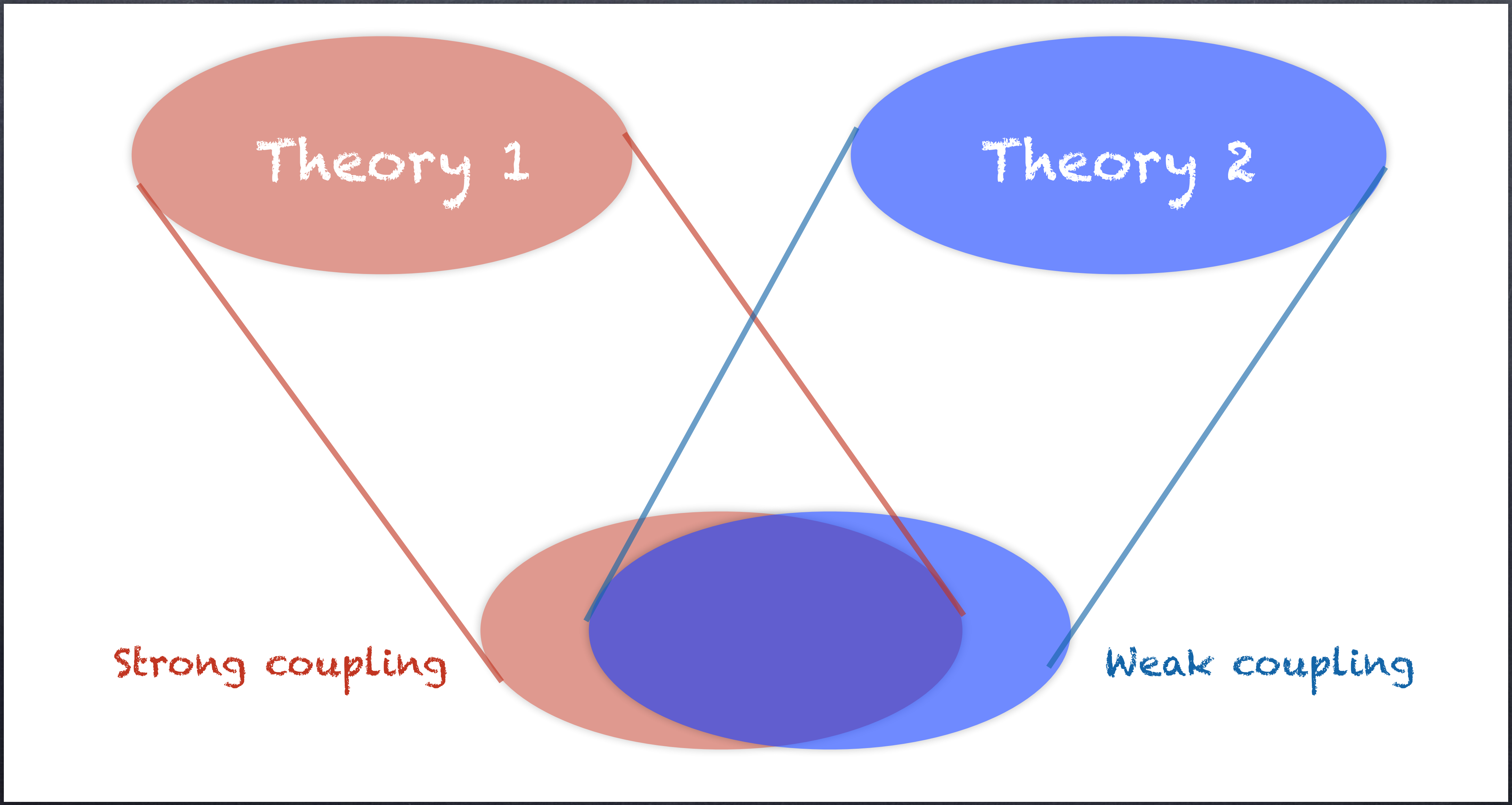
# Models of naturalness




Dual SM

# What is a duality?

Two different theories that describe the same physics in the IR:



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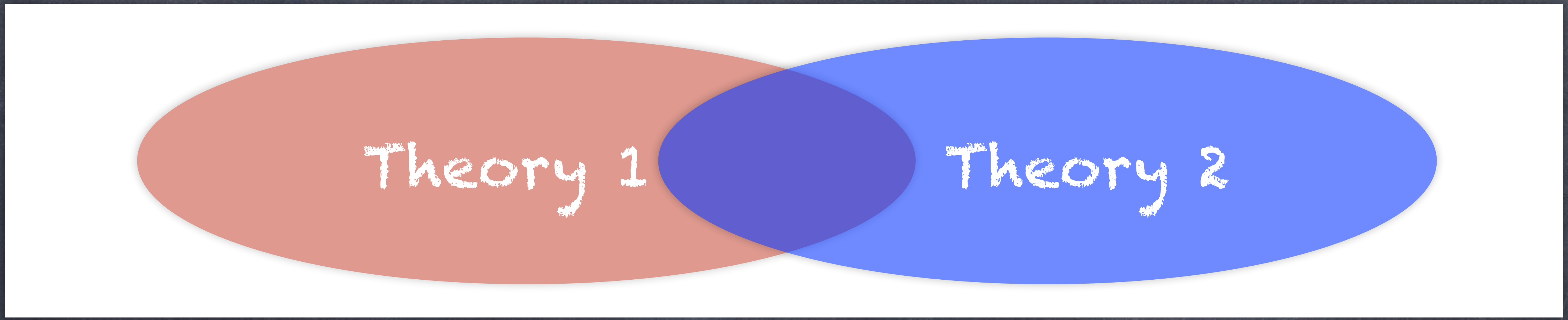


- Share the same global symmetries
- Anomaly matching
- Decoupling limits
- ...

# Seiberg duality

Seiberg, hep-th/9411149

Consider a supersymmetric SU(N) theory:

| | $SU(N_C)$ | $SU(N_F)_L$ | $SU(N_F)_R$ | $U(1)_B$ | $U(1)_R$ |
|---|---|---|---|---|---|
| $Q^i$ | $N_C$ | $N_F$ | 1 | 1 | $(N_F - N_C)/N_F$ |
| $\bar{Q}_j$ | $\bar{N}_C$ | 1 | $\bar{N}_F$ | $-1$ | $(N_F - N_C)/N_F$ |

IR fixed point exists for

$$\frac{1}{3}N_F < N_C < \frac{2}{3}N_F$$

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IR fixed point exists for

$$\frac{1}{3}N_F < N_C < \frac{2}{3}N_F$$

Anomaly matching requires

$$\tilde{N}_C = N_F - N_C$$

| | $SU(\tilde{N}_C)$ | $SU(N_F)_L$ | $SU(N_F)_R$ | $U(1)_B$ | $U(1)_R$ |
|---|---|---|---|---|---|
| $q_i$ | $\tilde{N}_C$ | $\bar{N}_F$ | $1$ | $N_C/(N_F - N_C)$ | $N_C/N_F$ |
| $\bar{q}^j$ | $\bar{\tilde{N}}_C$ | $1$ | $N_F$ | $-N_C/(N_F - N_C)$ | $N_C/N_F$ |
| $T^i_j$ | $1$ | $N_F$ | $\bar{N}_F$ | $0$ | $2(N_F - N_C)/N_F$ |

Superpotential: $y\, T^i_j q_i \bar{q}_j$

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Giving mass to one flavour, $M\, Q^1 \bar{Q}_1$,
reduces $N_F \to N_F - 1$

| | $SU(\tilde{N}_C)$ | $SU(N_F)_L$ | $SU(N_F)_R$ | $U(1)_B$ | $U(1)_R$ |
|---|---|---|---|---|---|
| $q_i$ | $\tilde{N}_C$ | $\bar{N}_F$ | 1 | $N_C/(N_F - N_C)$ | $N_C/N_F$ |
| $\bar{q}^j$ | $\bar{\tilde{N}}_C$ | 1 | $N_F$ | $-N_C/(N_F - N_C)$ | $N_C/N_F$ |
| $T^i_j$ | 1 | $N_F$ | $\bar{N}_F$ | 0 | $2(N_F - N_C)/N_F$ |

In the dual theory, giving a VEV to $\langle q_1 \rangle \sim \langle \bar{q}^1 \rangle \neq 0$
also reduces $N_F \to N_F - 1$ and $\tilde{N}_C \to \tilde{N}_C - 1$

# A duality without SUSY?

Sannino, 0909.4584, 0907.1364
Mojaza, Nardecchia, Pica, Sannino, 1101.1522

- The anomaly matching only involves fermions, not scalars.
- Without SUSY, calculability is lost.
- The IR dynamics is not forced to be conformal, i.e. fixed point may be absent!
- Scalars needed only to implement decouplings in the IR dual theory: emergent SUSY

Antipin, Mojaza, Pica, Sannino, 1101.1522

# A duality without SUSY?

Mojaza, Nardecchia, Pica, Sannino, 1101.1522

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

| Electric theory (UV) | | | | | |
|---|---|---|---|---|---|
| Fields | $SU(N)$ | $SU(N_f)_L$ | $SU(N_f)_R$ | $U(1)_V$ | $U(1)_{AF}$ |
| $\lambda$ | 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 | $SU(X)$ | $SU(N_f)_L$ | $SU(N_f)_R$ | $U(1)_V$ | $U(1)_{AF}$ |
| $\lambda_m$ | 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 | $-1+2X/N_f$ |
| $\phi$ | $F$ | $\bar{F}$ | 1 | $N/X$ | $1-X/N_f$ |
| $\tilde{\phi}$ | $\bar{F}$ | 1 | $F$ | $-N/X$ | $1-X/N_f$ |
| $\Phi_H$ | 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?

# Towards a dual SM?

Cacciapaglia, Sannino, 2407.17281

(Maekawa, Sato, hep-th/9509407 and hep-th/9511395)

Consider QCD, with $\tilde{N}_C = 3$ and $N_F = 6$ :
this leads to $N_C = 3$!

- Note that $SU(N_F)_{L/R} = SU(N_g) \times SU(2)_{L/R}$ for $N_g$ families
- Hence, $\Phi_H$ contains 9+9 bidoublets – Higgses
- Yukawa couplings are naturally generated in the IR dual theory
- One coupling $y \sim \mathcal{O}(1)$, hence flavour embedded in the Higgs VEV patterns!
- For $\tilde{N}_C = 3$, duality only exists for $N_g = 3,4,5$.

Sannino, 1102.5100

# 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)$_{AF}$ |
| $\lambda$ | 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)$_{AF}$ |
| $\lambda_m$ | 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 |
| $\phi$ | $F$ | $\bar{F}$ | 1 | 1 | $1/2$ |
| $\tilde{\phi}$ | $\bar{F}$ | 1 | $F$ | $-1$ | $1/2$ |
| $\Phi_H$ | 1 | $F$ | $\bar{F}$ | 0 | 1 |

Scalar-less theory above a certain energy scale!

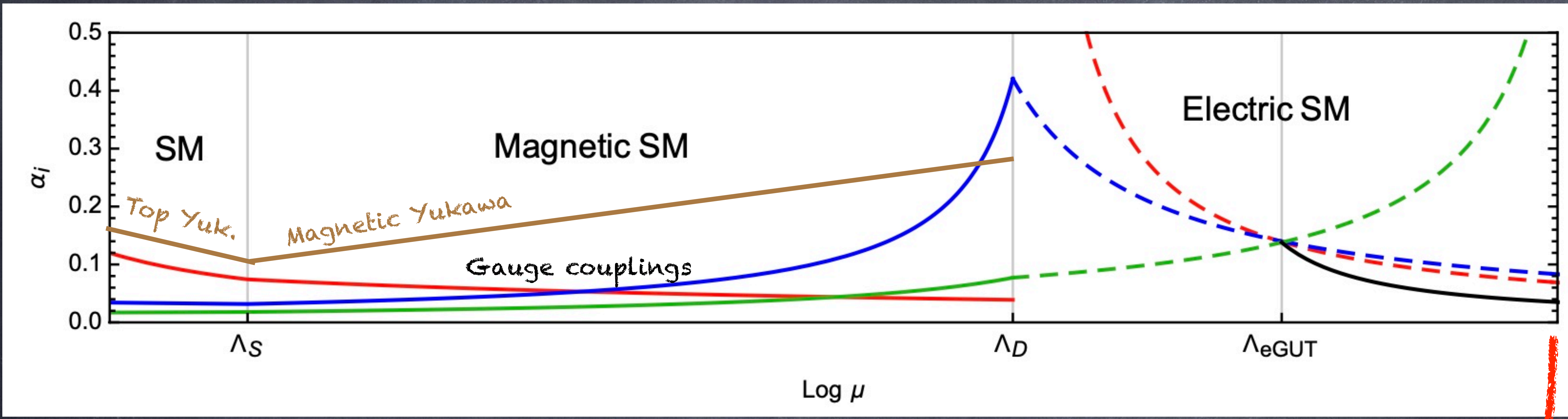
SM fermions

$$\mathcal{L}_m \supset y\, q\tilde{q}\Phi_H + y'\, q\tilde{\phi}M + \tilde{y}'\, \tilde{q}\phi M + \\ \xi_L\, \lambda_m q\phi^\dagger + \xi_R\, \lambda_m \tilde{q}\tilde{\phi}^\dagger + \text{h.c.}$$

Contains (many) Higgses

# Dual SM cartoon

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

# Quark flavour sector

Higgs doublets emerge as composites in the magnetic SM:

$$\Phi_H = \{H_{ij}\}\ , \quad i,j = 1,2,3\,,$$

$$H_{ij} = (H^u_{ij},\ H^d_{ij})\,,$$

9+9=18 doublets

A single composite Yukawa, with flavour structures encoded in the scalars:

$$y\ q\tilde{q}\Phi_H = y\sum_{i,j}\left(q^i_L u^j_R H^u_{ij} + q^i_L d^j_R H^d_{ij}\right)\ ,$$

$$Y^u_{ij} = y\frac{\langle H^u_{ij}\rangle}{v} \quad \text{and} \quad Y^d_{ij} = y\frac{\langle H^d_{ij}\rangle}{v}$$

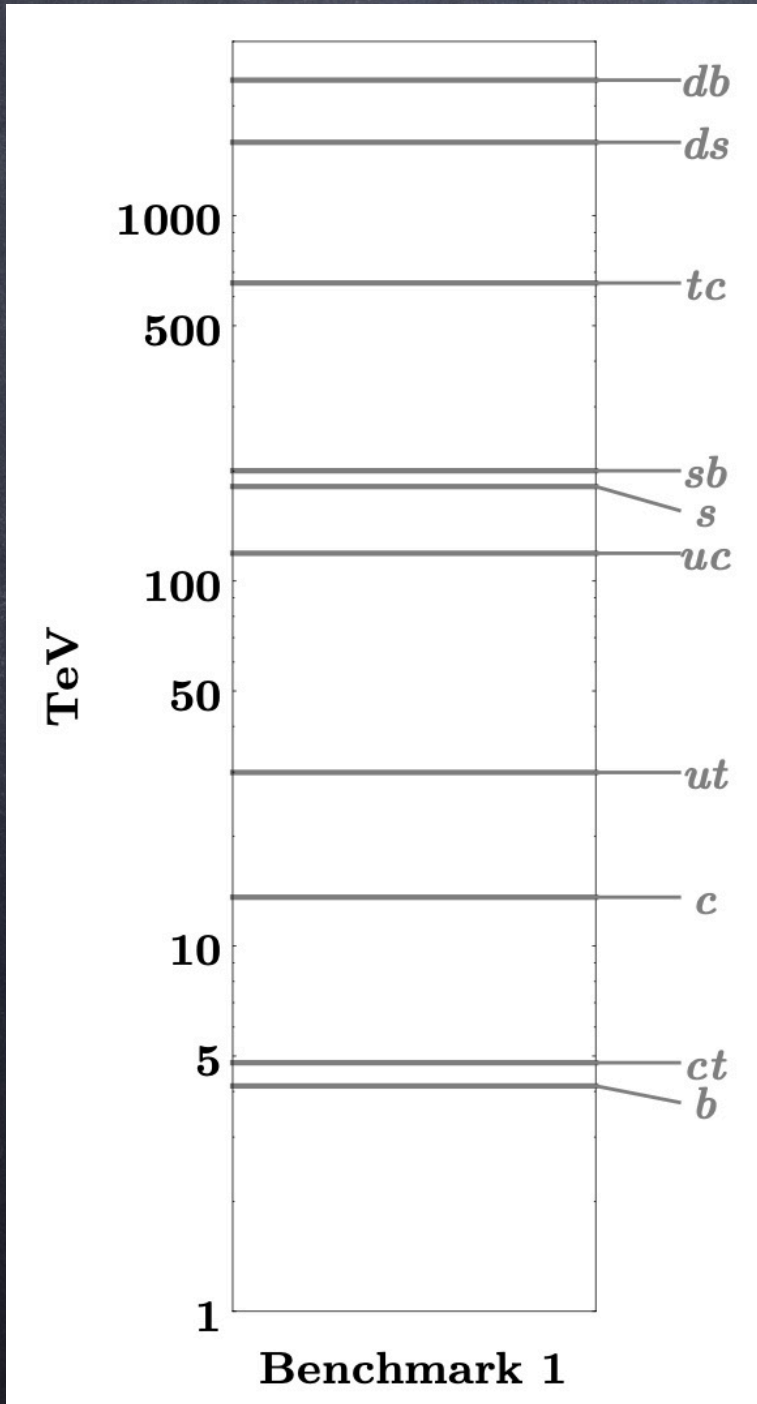
$$v^2 = \sum_{ij}\left(\langle H^u_{ij}\rangle^2 + \langle H^d_{ij}\rangle^2\right) = \frac{1}{2}(246\ \text{GeV})^2$$

We need hierarchical VEVs for the scalars!

# Scalar democracy

Hill, Machado, Anders, Turner, 1902.07214

This scenario has been proposed and studied in 2019:




$$V = M_H^2 H_0'^\dagger H_0' + \frac{\lambda}{2} |H_0'|^4 + H_a'^\dagger M_{ab}^2 H_b' - \left( H_a'^\dagger \mu_a^2 H_0' + \text{h.c.} \right),$$

- One doublets develops a large VEV, $H_0' = H_u^{33}$ with $\langle H_0' \rangle = v$
- Other Higgses inherit the VEV via (small) mixing terms $\mu^2$
- Hierachies generated by TeV-scale scalar masses
- Flavour bounds can be avoided!

# Origin of flavour in the electric theory

The duality offers a simple origin of the scalar masses within the electric theory:

$$\mathcal{L}_{\rm Planck} \supset \frac{c^{abcd}}{M_{\rm Pl}^2}(Q^a\tilde{Q}^b)(Q^c\tilde{Q}^d)^\dagger$$

$$\mu^2 \sim \xi\frac{\Lambda_D^4}{M_{\rm Pl}^2}$$ ⟶ $$\xi^{-1/4}\,\Lambda_D \sim \sqrt{\mu\, M_{\rm Pl}} \sim 10^{11}\ {\rm GeV}$$ for $\mu \sim 1$ TeV

Similarly, for leptons:

$$\mathcal{L}_e \supset \frac{h_l}{M^2}(L\tilde{L})(Q\tilde{Q})^\dagger$$

$$\mathcal{L}_m \supset h_l\mathcal{F}_\Phi\frac{\Lambda_D^2}{M^2}l\tilde{l}\Phi_H^\dagger\,,$$

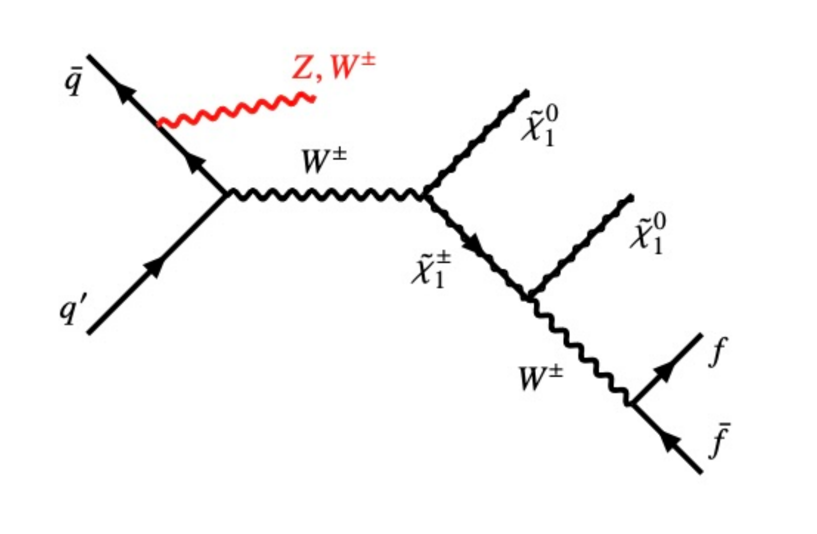
$$l\tilde{l}\Phi_H^\dagger = \sum_{i,j}\left(l_L^i\nu_R^j(H_{ij}^d)^\dagger + l_L^i e_R^j(H_{ij}^u)^\dagger\right)$$

(Bonus: the tau couples to the 'top' Higgs!)

# Phenomenology

Essentially, MSSM w/o EW gauginos and sleptons
18 $H_u/H_d$, $\tilde{h}_u/\tilde{h}_d$ pairs (flavoured).

Masses from Planck-operators (work in prog.),
Higgsinos expected to be the lightest.




Small mass splitting (absence of EWinos)
may hide the signal (e.g. 1107.5581)

+ more 'standard' squark signatures.

Work in progress!
More news soon.

# GUT and generations

- $N_g = 3 \Rightarrow N = 6 - 3 = 3$, hence $G_{SM,e} = SU(3)_c \times SU(2)_L \times U(1)_Y$
- $N_g = 4 \Rightarrow N = 8 - 3 = 5$, hence $G_{SM,e} = SU(5)_c \times SU(2)_L \times U(1)_Y$
- $N_g = 5 \Rightarrow N = 10 - 3 = 7$, hence $G_{SM,e} = SU(7)_c \times SU(2)_L \times U(1)_Y$

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Grand Unification in the electric theory only possible for $N_g = 3$!

Issue of GUT scalar sector for Yukawa couplings removed!

# Extras

# Seiberg duality

Seiberg, hep-th/9411149

Exact NSVZ beta function:

$$\beta(g) = -\frac{g^3}{16\pi^2}\frac{\beta_0 + N_F\gamma}{1 - N_C\frac{g^2}{8\pi^2}}$$

$$\beta_0 = 3N_C - N_F$$

Asymptotic freedom: $\beta_0 > 0 \Rightarrow N_C > \frac{1}{3}N_F$

Conformal windowsill: $\gamma^* = -\frac{\beta_0}{N_F} = 1 - 3\frac{N_C}{N_F}$ at the fixed point.

Unitarity bound: $D[\tilde{Q}Q] = 2 + \gamma^* = 3 - 3\frac{N_C}{N_F} \geq 1 \Rightarrow N_C \leq \frac{2}{3}N_F$

Consistency of the fixed point! ←

# A duality without SUSY?

Ryttov, Sannino, 0711.3745

$$\beta(g) = -\frac{g^3}{(4\pi)^2}\frac{\beta_0 - \frac{2}{3}T(r)\,N_f\,\gamma(g^2)}{1 - \frac{g^2}{8\pi^2}C_2(G)\left(1 + \frac{2\beta_0'}{\beta_0}\right)}$$

Improved version: Pica, Sannino, 1011.3832

- Estimated range of validity of the duality:

$$\frac{3}{2}N_C \leq N_F \leq \frac{9}{2}N_C$$

# GUT and generations

Like for Seiberg duality, the SM duality is only valid for $N_g = 3,4,5$!

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# GUT and generations

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The UV theory is a Higgsless SM! It can be unified to SU(5) or SU(10), with only scalars that break the gauge group to the SM one.

The QCD SU(3) gauge symmetry plays an important role for fermion unification: i.e., for SU(5)

$10 \to (3,2)_{1/6} \oplus (1,1)_1 \oplus (\bar{3},1)_{-2/3}$, where $\bar{3} = A^{ab}$ (two-index anti-sym)

This property does not hold for $SU(5)_c$ and $SU(7)_c$!