The gauge dual Standard Model:

A new approach to naturalness and the flavour puzzle

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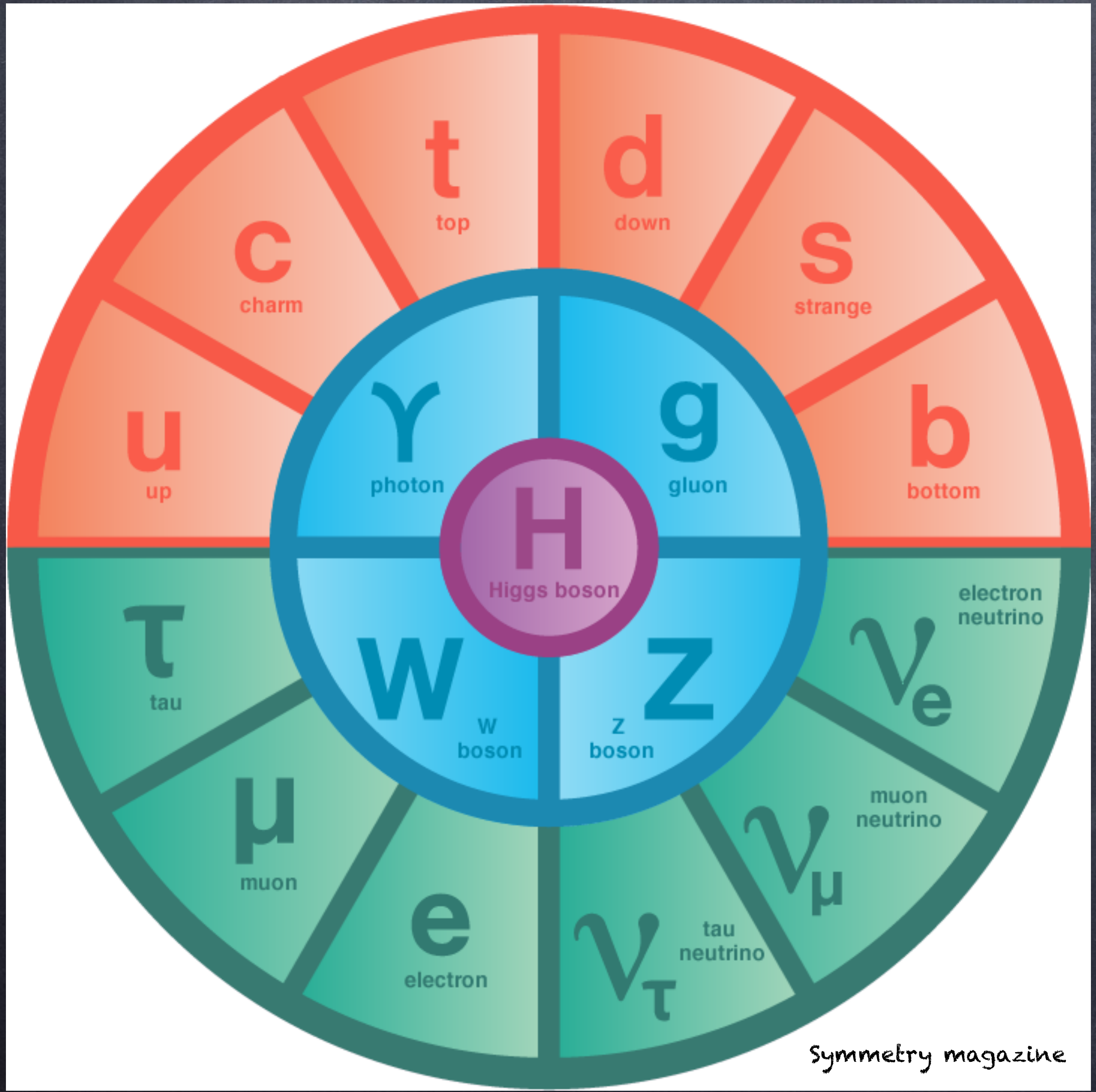
The Standard Model

- 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!

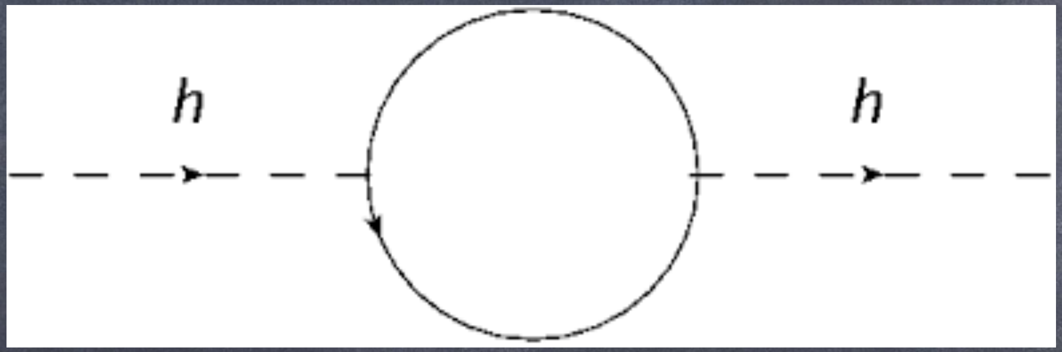
Beyond the Standard Model?

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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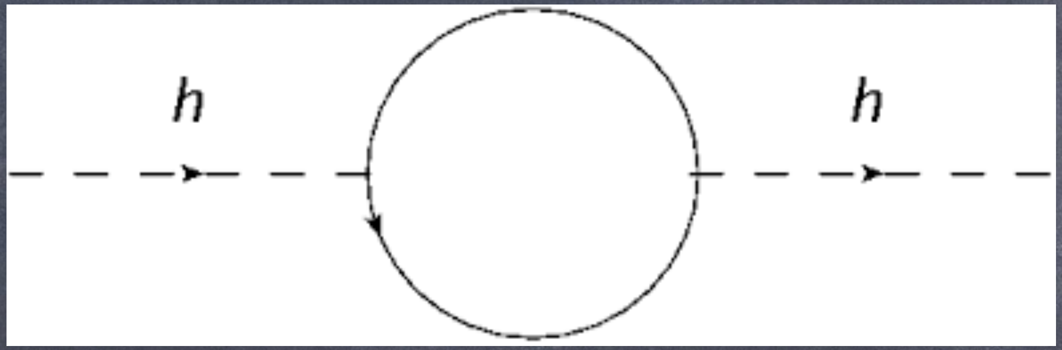
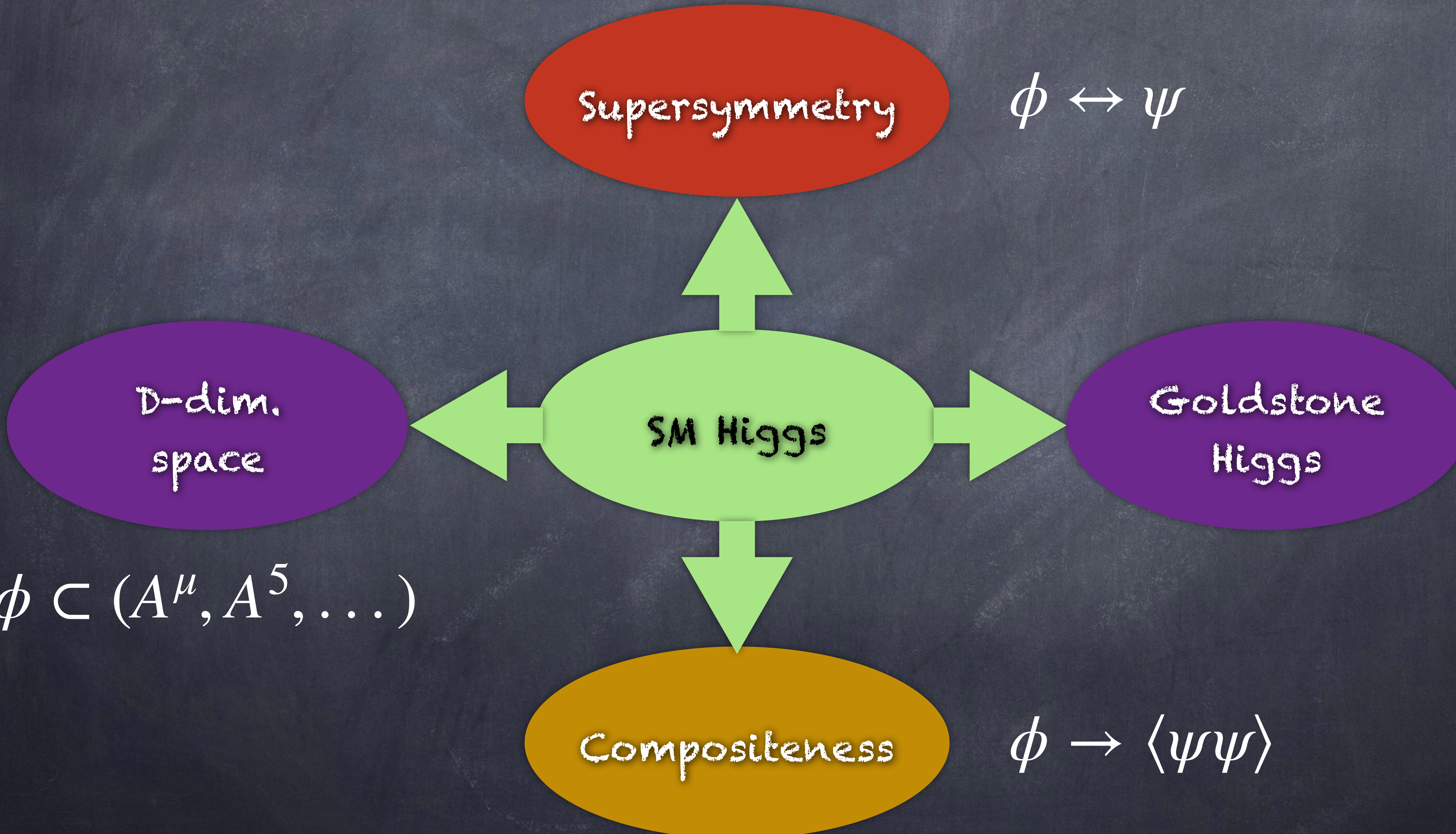


At quantum level: $$m_h^2\Big|_{1-loop} = m_h^2\left(1 + \frac{g^2}{16\pi^2}\frac{M^2}{m_h^2}\right)$$

Toward naturalness



$$\phi \leftrightarrow \psi$$

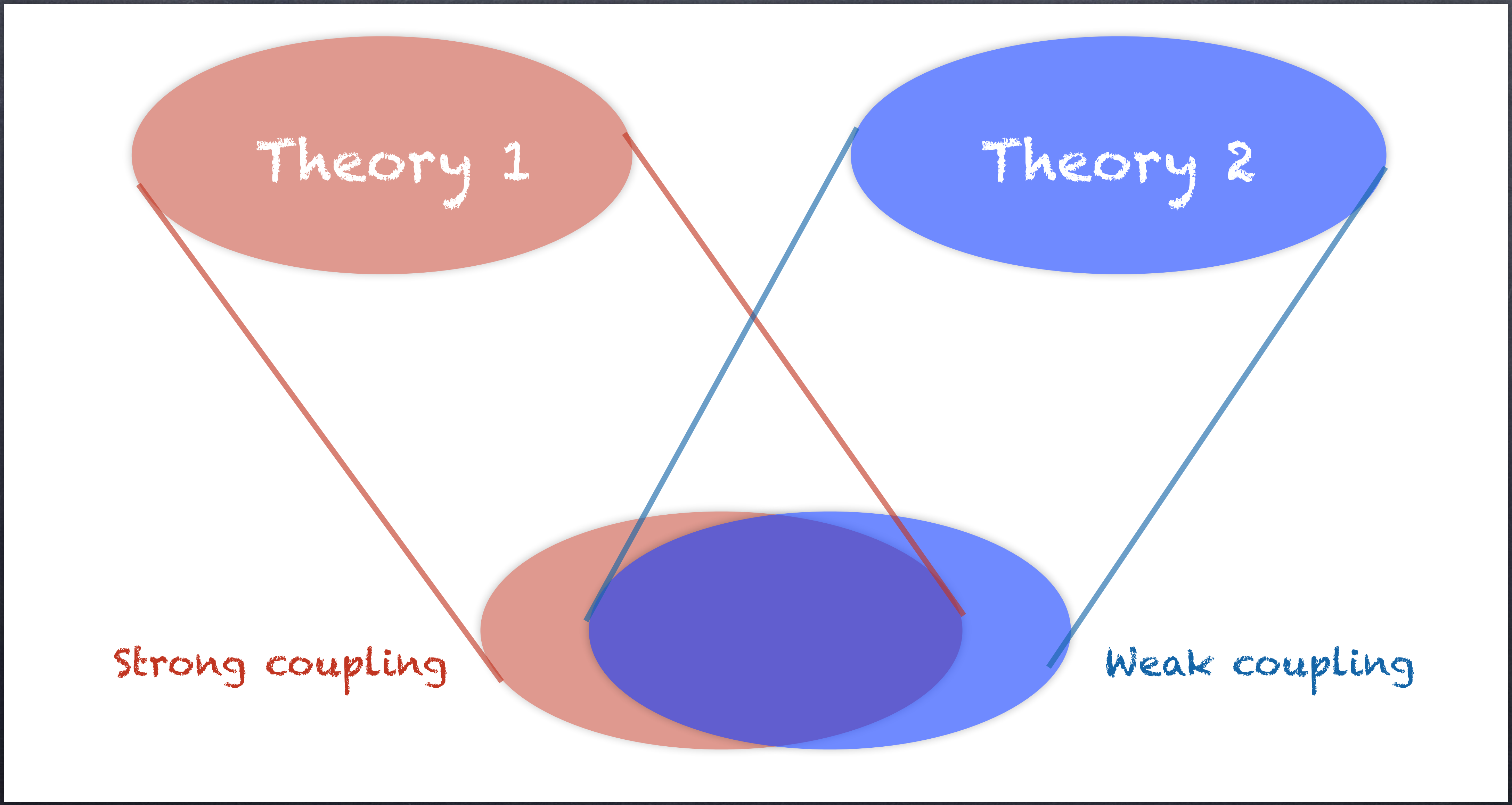
$$\phi \subset (A^\mu, A^5, \ldots)$$

$$\phi \to \langle \psi\psi \rangle$$


Dual SM

What is a duality?

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



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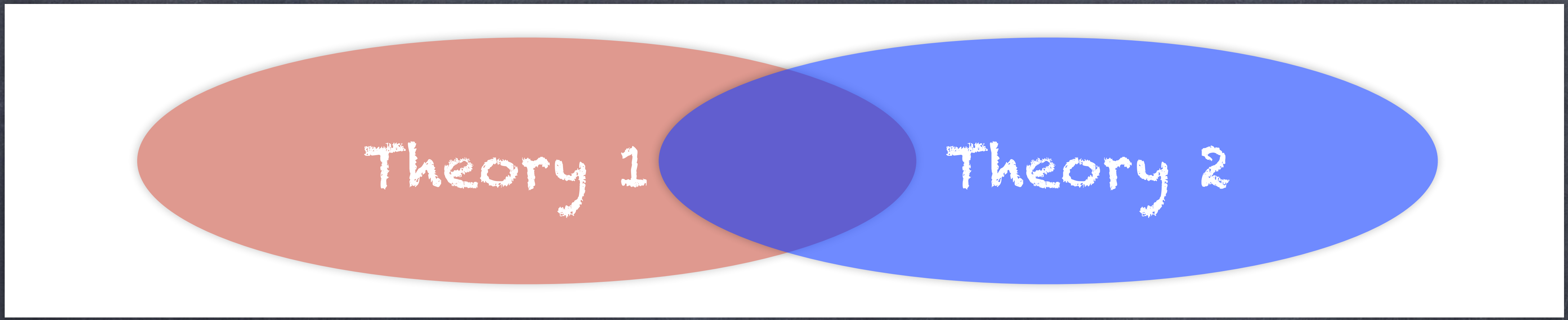

- Share the same global symmetries
- Anomaly matching
- Decoupling limits
- ...

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

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

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

Seiberg duality

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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 $\tilde{N}_C \to \tilde{N}_C - 1$

Seiberg-dual SM?

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

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

	$SU(\tilde{N}_C)$	$SU(N_F)_L$	$SU(N_F)_R$	$U(1)_B$	$U(1)_R$
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	$2(N_F - N_C)/N_F$

- Note that $SU(N_F)_{L/R} = SU(N_g) \times SU(2)_{L/R}$ for N_g families
- Hence, T^i_j contains 9+9 bidoublets – Higgs superfields
- 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!

Seiberg-dual SM: scorecard

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

The good:

- Composite quark Yukawas and Higgses emerge from a Higgs-less UV theory!
- Flavour hierarchies embedded in scalar mass patterns
- For $\tilde{N}_C = 3$, duality only exists for $N_g = 3,4,5$.

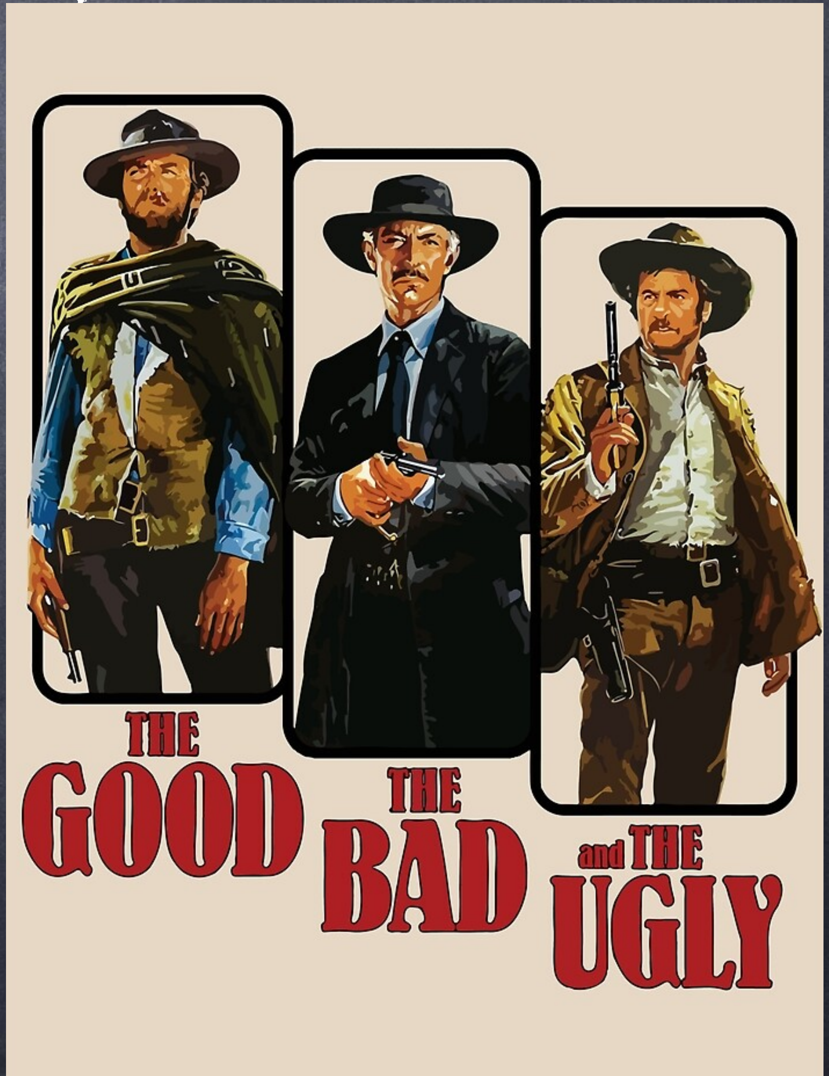
Sannino, 1102.5100

The bad:

- No Yukawas for leptons!
- Technically, the dual theory is conformal!

The ugly:

- SUSY must be broken!
- Does the duality hold?



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

$$X = N_f - N\,. \qquad (1)$$

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
$SU(2)_L \times U(1)_Y \subset SU(6)_L \times SU(6)_R \times U(1)_V$

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

Cacciapaglia et al, 2407.17281

Scalar-less theory above a certain energy scale!

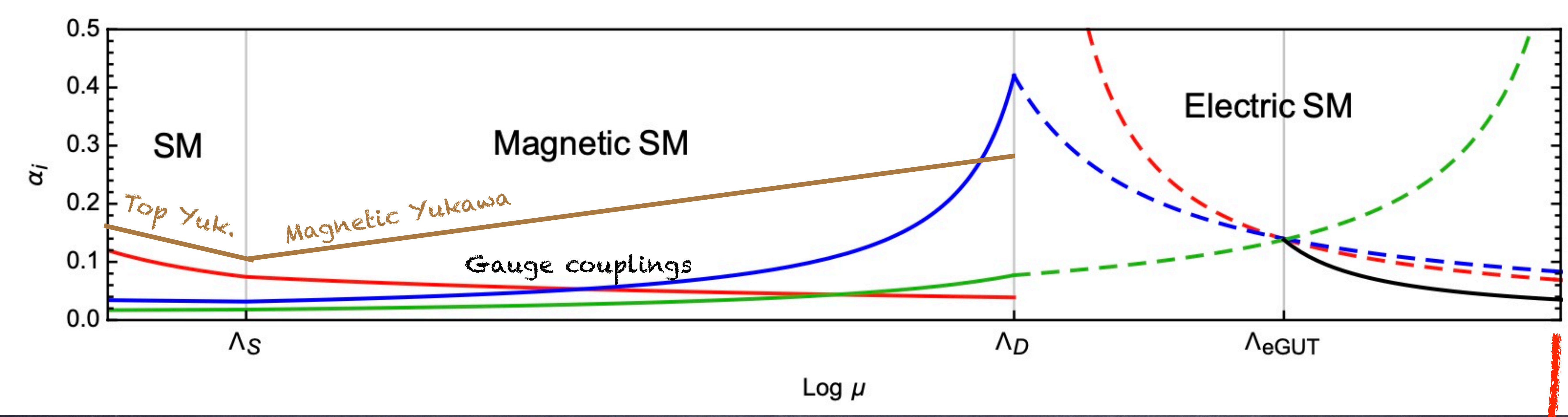
SM fermions

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

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:

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

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

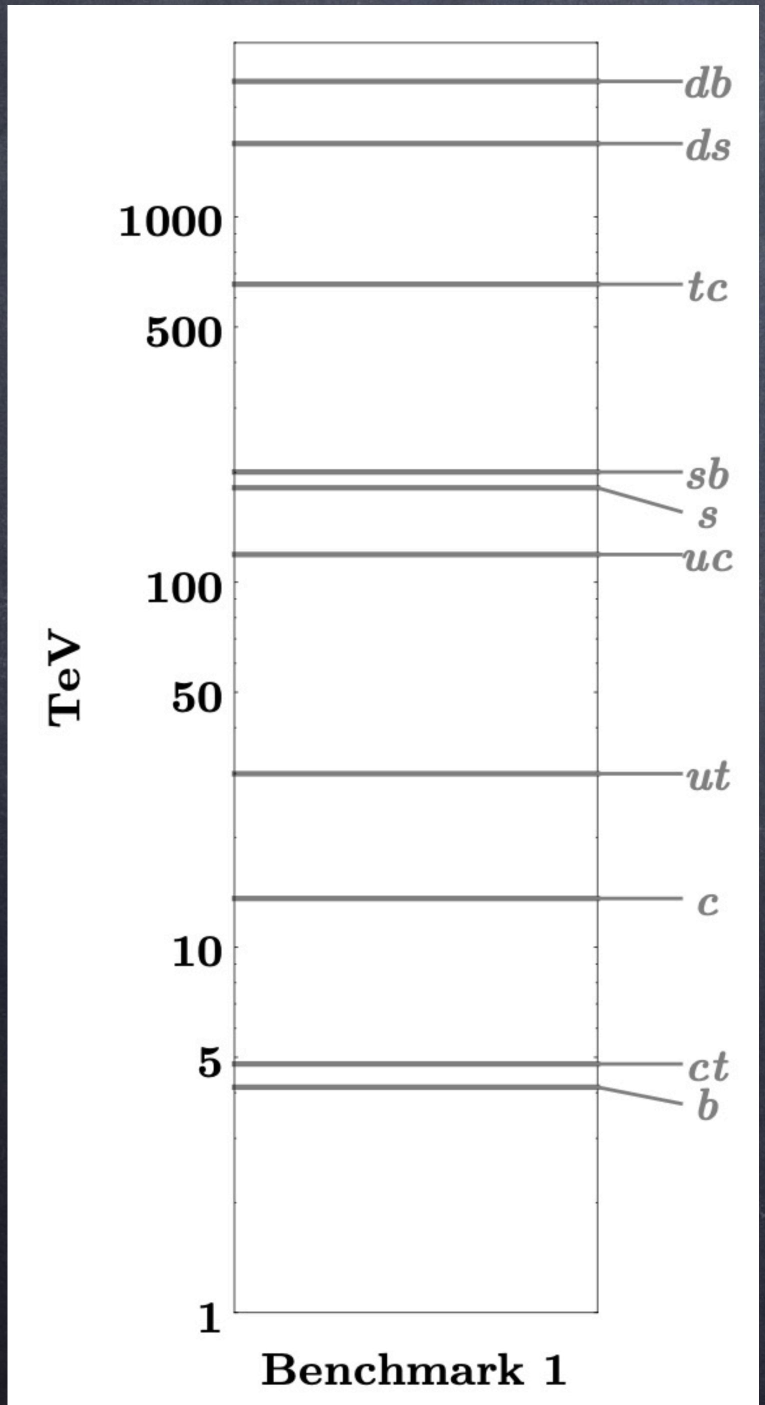
$$v^2 = \sum_{ij}\left(\langle H^u_{ij}\rangle^2 + \langle H^d_{ij}\rangle^2\right) = \frac{1}{2}(246\ \text{GeV})^2$$

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 μ^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:

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

$$\mu^2 \sim \xi \frac{\Lambda_D^4}{M_{\text{Pl}}^2} \longrightarrow \xi^{-1/4}\,\Lambda_D \sim \sqrt{\mu\, M_{\text{Pl}}} \sim 10^{11}\ \text{GeV}$$ 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!)

Origin of flavour in the electric theory

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

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

A detailed analysis of the electric SM EFT is under way!

Thanks to Leonardo Piacevole and Vigilante di Risi

GUT and generations

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

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

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

GUT and generations

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

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 $SU(7)_c$!

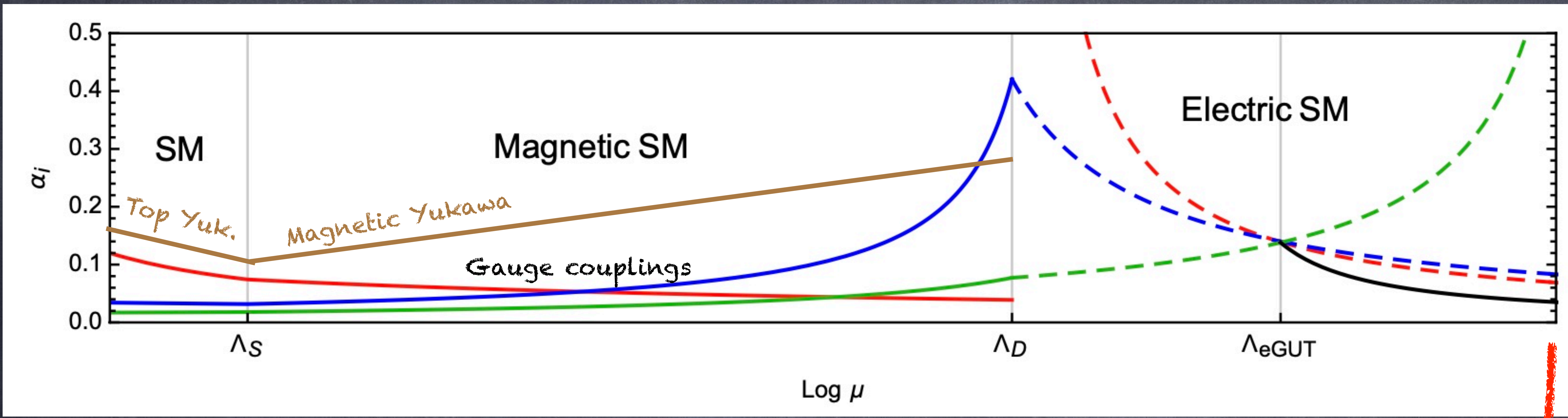
GUT and generations

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

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

Issue of GUT scalar sector for Yukawa couplings removed!

Phenomenology?



Mass of non-SM particles

TeV (LHC)

Scale of duality

Possible electric GUT

SUSY like spectrum, but with many Higgses and Higgsinos and no sleptons nor EW-inos

Origin of flavour physics at Planck scale

Correlations with electric EFT operators under study

Outlook

- Gauge duality offers a novel UV completion for the SM
- Higgses and Yukawas can be generated in the UV
- The flavour problem is recast into composite scalar masses, i.e. UV 4-fermi interactions
- GUT requires three generations in the SM
- Detailed studies of the dual SM phenomenology under way