

Composite Dynamics:

From CH to a Magnetic Standard Model

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On the many natures of the Higgs

RG (un)-naturalness

$$\mathcal{L} = \frac{1}{2}(\partial_\mu\phi_r)^2 - \frac{1}{2}m^2\phi_r^2 - \frac{\lambda}{4!}\phi_r^4 + \frac{\delta_Z}{2}(\partial_\mu\phi_r)^2 - \frac{\delta_m}{2}\phi_r^2 - \frac{\delta_\lambda}{4!}\phi_r^4$$

$$\phi_B \equiv \sqrt{Z}\phi_r \quad \delta_Z \equiv Z - 1 \quad m^2 \equiv m_0^2 Z - \delta_m \quad \delta_\lambda \equiv \lambda_0 Z^2 - \lambda$$

$$Z = 1 + f_1(\lambda, g_i) \log \frac{\Lambda^2}{m_0^2} + \dots$$

$$\delta_m = f_2(\lambda, g_i) \Lambda^2 + \dots$$

Shades of (un)naturality

$$m^2 = m_0^2 (1 + f_1(\lambda, g_i) \log \frac{\Lambda^2}{m_0^2}) - f_2(\lambda, g_i) \Lambda^2$$

Standard model

$$m^2 = m_0^2 (1 + f_1(\lambda, g_i) \log \frac{\Lambda^2}{m_0^2}) - f_2(\lambda, g_i) \Lambda^2$$

Standard model: cancel m_0 against cutoff Λ

Coleman Weinberg

$$m^2 = m_0^2 (1 + f_1(\lambda, g_i) \log \frac{\Lambda^2}{m_0^2}) - f_2(\lambda, g_i) \Lambda^2$$

Radiative EWSB, $m_0 = 0$ but unnatural as in SM

Veltman conditions

$$m^2 = m_0^2 (1 + f_1(\lambda, g_i) \log \frac{\Lambda^2}{m_0^2}) - f_2(\lambda, g_i) \Lambda^2$$

Delayed unnaturality: $f_2(\lambda, g_i) = 0$ perturbatively



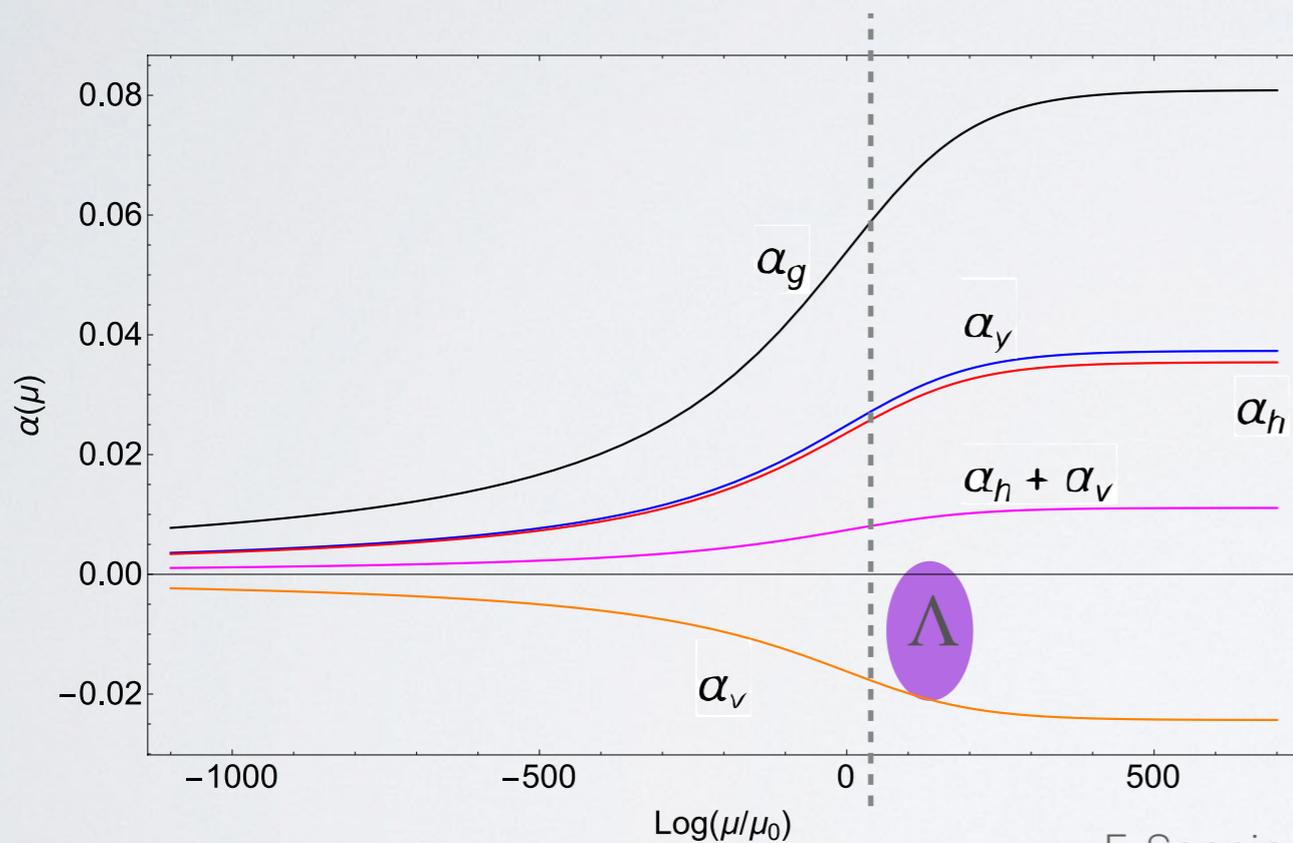
CW + Veltman conditions

$$m^2 = m_0^2 (1 + f_1(\lambda, g_i) \log \frac{\Lambda^2}{m_0^2}) - f_2(\lambda, g_i) \Lambda^2$$

Delayed unnaturality: $f_2(\lambda, g_i) = 0$ perturbatively + $m_0 = 0$ classically

Gauge Safe extensions

$$m^2 = m_0^2 (1 + f_1(\lambda, g_i) \log \frac{\Lambda^2}{m_0^2}) - f_2(\lambda, g_i) \Lambda^2$$



The Higgs:

Elementary via UV/CFT completeness

Light w.r.t. the RGI scale Λ

F. Sannino, Challenging Asymptotic Freedom, proc. 1511.09022

D. Litim, F. Sannino, JHEP 12 (2014) 178

S. Abel, F. Sannino, Phys.Rev.D 96 (2017) 5, 056028

Extra dimensional safety:

G. Cacciapaglia, T.Ma, S.Vatani, Y.Wu, EPJC 80 (2020) 11, 1088

G. Cacciapaglia et al., PRD 104 (2021) 7, 075012

Natural theories

$$m^2 = m_0^2 \left(1 + f_1(\lambda, g_i) \log \frac{\Lambda^2}{m_0^2} \right) - f_2(\lambda, g_i) \Lambda^2$$

- ◆ A (super) symmetry exists protecting

$$f_2 = 0$$

- ◆ Cutoff is physical as in composite models

$$m^2 = m_0^2 (1 + f_1(\lambda, g_i) \log \frac{\Lambda^2}{m_0^2}) - f_2(\lambda, g_i) \Lambda^2$$

Composite dynamics

Coleman Weinberg

SUSY

Veltman cond.s

CW + VCs

Gauge safety



Composite Higgs Dynamics

Partial Composite Goldstone Higgs

Higgs is a composite pseudo goldstone SM doublet

D.B. Kaplan & H. Georgi, 84

SM fermions masses via (effective) Lagrangian operators

D.B. Kaplan, 91

$f\mathcal{B}$

Extra-dim, no-lagrangian approaches, effective theories

Composite dynamics

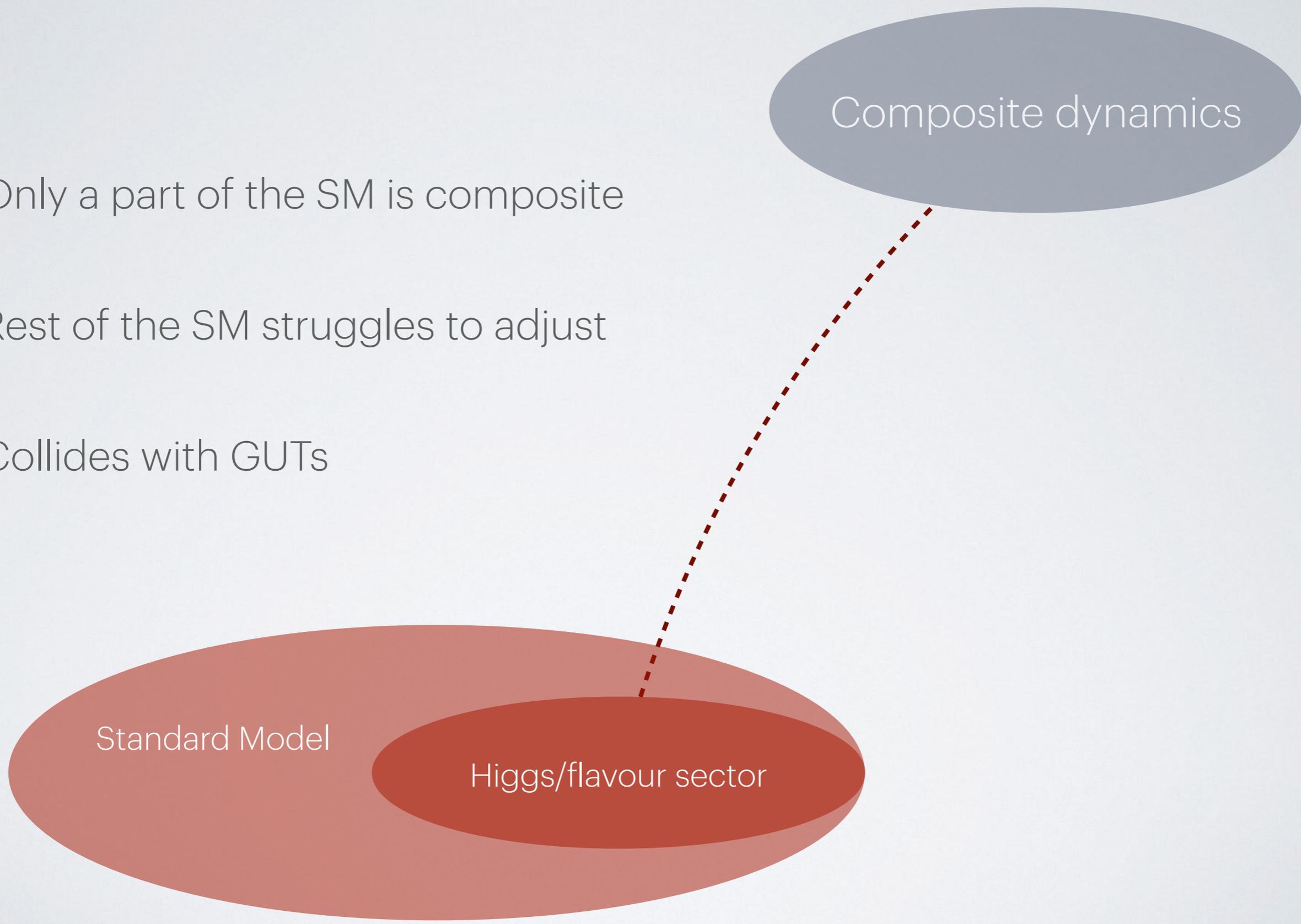
Only a part of the SM is composite

Rest of the SM struggles to adjust

Collides with GUTs

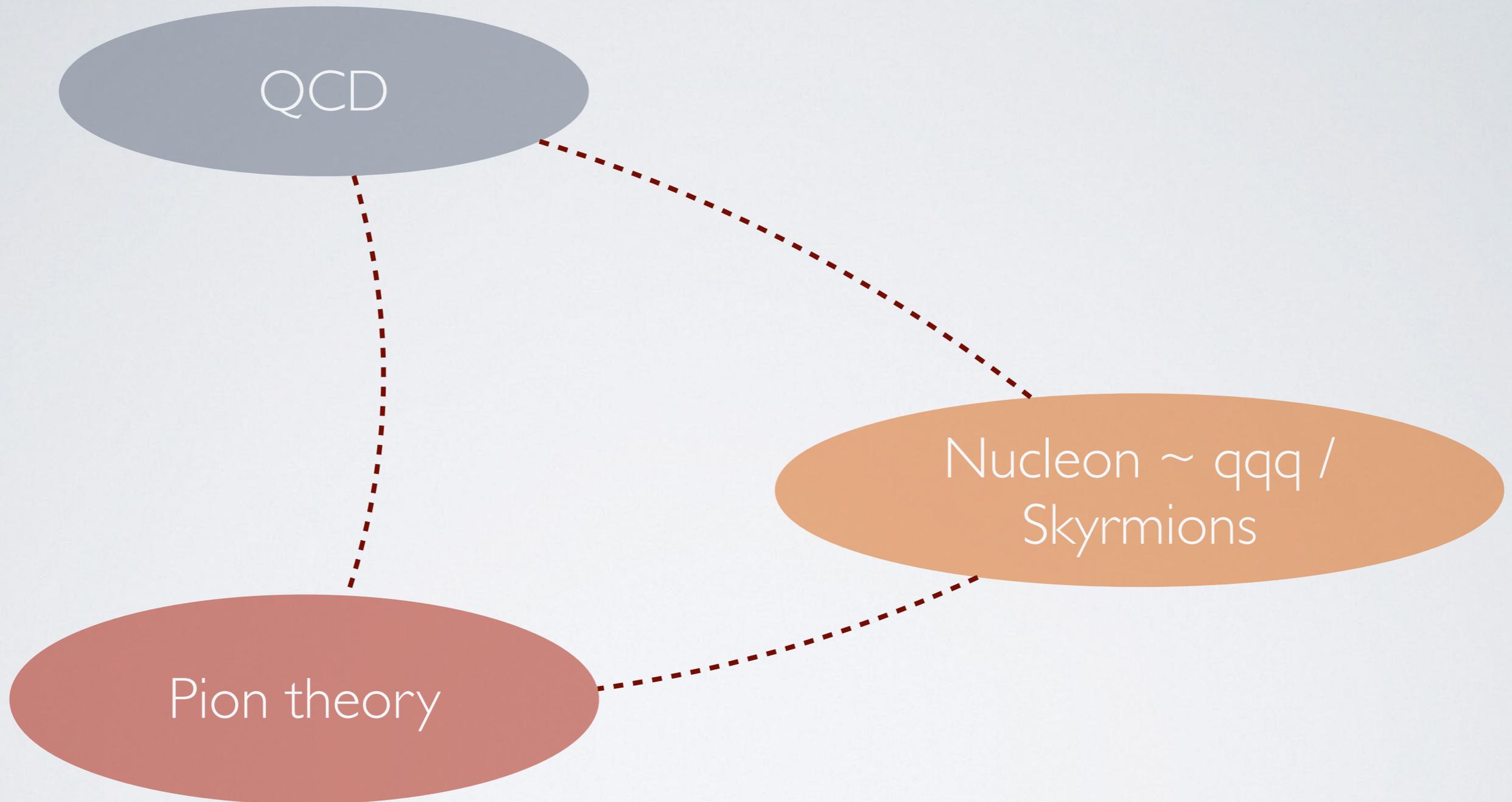
Standard Model

Higgs/flavour sector



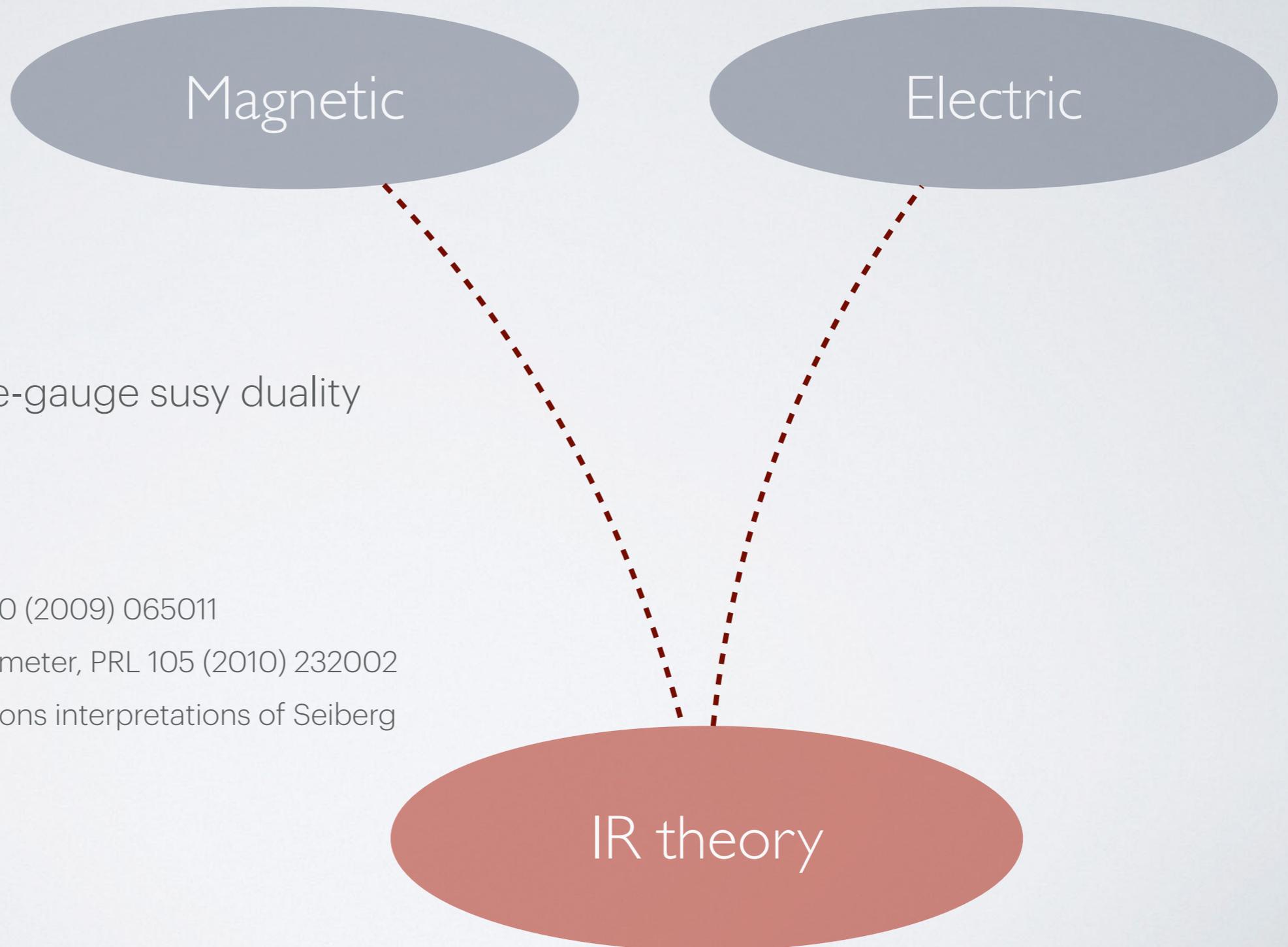
What if the whole SM were deeply composite?

Examples



Gauge symmetries are redundant descriptions of nature

Electro-Magnetic Duality



Seiberg's gauge-gauge susy duality

Non susy attempts:

- F. Sannino QCD Dual, PRD 80 (2009) 065011
- F. Sannino, Magnetic S-parameter, PRL 105 (2010) 232002
- Z. Komargodski, Vector Mesons interpretations of Seiberg Duality, JHEP 1102.019(2011)

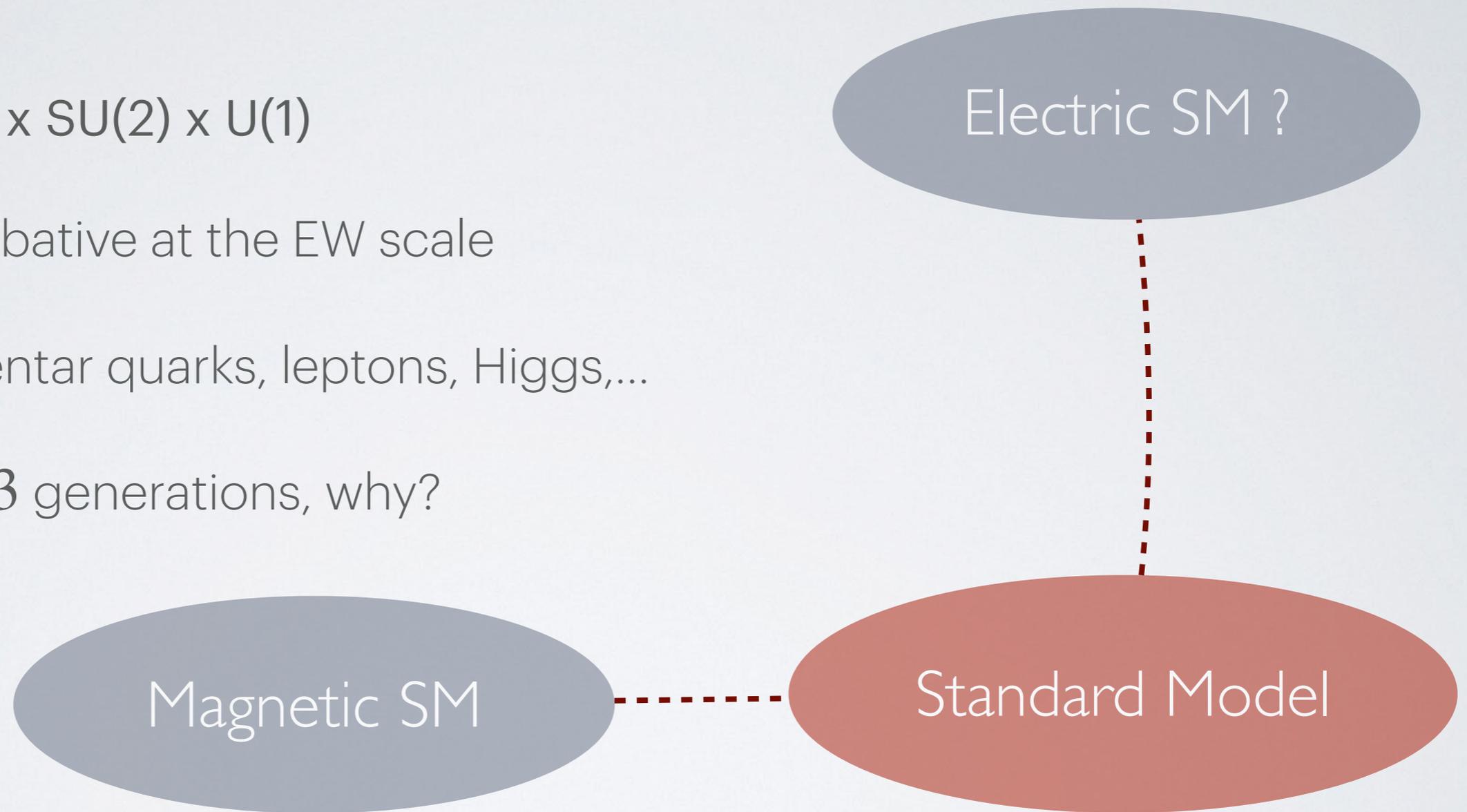
SM as magnetic theory

$SU(3) \times SU(2) \times U(1)$

Perturbative at the EW scale

Elementar quarks, leptons, Higgs,...

$n_g = 3$ generations, why?



SUSY/Extra Dim attempts

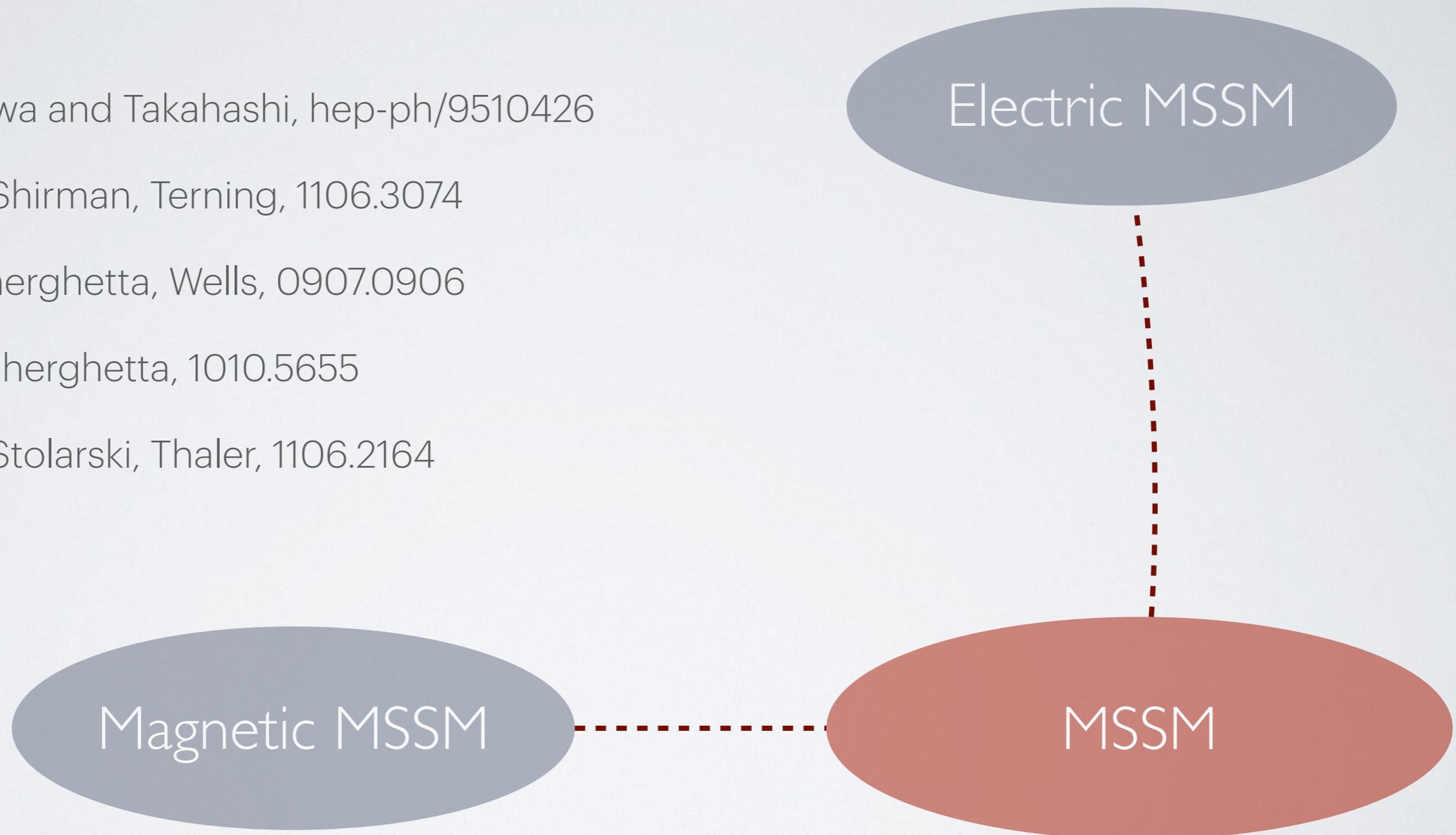
Maekawa and Takahashi, hep-ph/9510426

Csáki, Shirman, Terning, 1106.3074

Cui, Gherghetta, Wells, 0907.0906

Abel, Gherghetta, 1010.5655

Craig, Stolarski, Thaler, 1106.2164



SM toy example

| Fields | $[SU(3)]$ | $SU(N_f)_L$ | $SU(N_f)_R$ |
|-------------|----------------------|----------------------|----------------------|
| q | \square | $\overline{\square}$ | $\mathbf{1}$ |
| \tilde{q} | $\overline{\square}$ | $\mathbf{1}$ | \square |
| l | $\mathbf{1}$ | $\overline{\square}$ | $\mathbf{1}$ |
| \tilde{l} | $\mathbf{1}$ | $\mathbf{1}$ | \square |
| H | $\mathbf{1}$ | \square | $\overline{\square}$ |

$SU(3)$ is QCD

$N_f = 2n_g$ and n_g are generations

q, \tilde{q} left & right conjugated quarks

l, \tilde{l} left & right conjugated leptons

Weak interactions embedded in $SU(N_f)_L = SU(2n_g)_L$

Higgs doublet extended to a $N_f \times N_f$ complex matrix

Not the Standard Model but not too far either

Lepton as fourth color

| Fields | $[SU(4)]$ | $SU(N_f)_L$ | $SU(N_f)_R$ |
|-----------------|----------------------|----------------------|----------------------|
| p | \square | $\overline{\square}$ | $\mathbf{1}$ |
| \widetilde{p} | $\overline{\square}$ | $\mathbf{1}$ | \square |
| H | $\mathbf{1}$ | \square | $\overline{\square}$ |

Upgrade $SU(3)$ to Pati-Salam $SU(4)$

$$p = (q^1, q^2, q^3, \ell)$$

$B - L$ symmetry embedded as one of the $SU(4)$ generators

Pati-Salam allows for compact book keeping of d.o.f.

A minimal Pati-Salam model

| Fields | $[SU(4)]$ | $SU(N_f)_L$ | $SU(N_f)_R$ | $U(1)_p$ | $U(1)_{AF}$ |
|----------------------------|-----------------|-----------------|-----------------|---------------------|------------------------|
| λ_m | Adj | 1 | 1 | 0 | 1 |
| p | \square | $\bar{\square}$ | 1 | $\frac{2n_g-4}{4}$ | $-\frac{4}{2n_g}$ |
| \tilde{p} | $\bar{\square}$ | 1 | \square | $-\frac{2n_g-4}{4}$ | $-\frac{4}{2n_g}$ |
| Φ_p | \square | $\bar{\square}$ | 1 | $\frac{2n_g-4}{4}$ | $-\frac{2n_g-4}{2n_g}$ |
| $\tilde{\Phi}_{\tilde{p}}$ | $\bar{\square}$ | 1 | \square | $-\frac{2n_g-4}{4}$ | $-\frac{2n_g-4}{2n_g}$ |
| M | 1 | \square | $\bar{\square}$ | 0 | $-1 + \frac{8}{2n_g}$ |
| H | 1 | \square | $\bar{\square}$ | 0 | $\frac{8}{2n_g}$ |

$\Phi_p, \tilde{\Phi}_{\tilde{p}}$ scalars in fund/(antifund.) of $SU(4)$

't Hooft AC more restrictive with Weyl λ_m & M in Adj & bi-fundamental of $SU(4)$

F.S. MPLA 26 (2011) 1763-1769, e-print 1102.5100

Mojaza, Nardecchia, Pica, F.S. PRD 83 (2011), 065022

Antipin, Mojaza, Pica, F.S. JHEP 06 (2013) 037

Possible Electric Dual

| Fields | $SU(2n_g - 4)$ | $SU(2n_g)_L$ | $SU(2n_g)_R$ | $U(1)_p$ | $U(1)_{AF}$ |
|-------------|-----------------|--------------|-----------------|----------|------------------------|
| λ | Adj | 1 | 1 | 0 | 1 |
| P | \square | \square | 1 | 1 | $-\frac{2n_g-4}{2n_g}$ |
| \tilde{P} | $\bar{\square}$ | 1 | $\bar{\square}$ | -1 | $-\frac{2n_g-4}{2n_g}$ |

All 't Hooft ACs are all satisfied

$$H \sim P\lambda\tilde{P}$$

Consistent flavour decoupling

$$M \sim P\lambda\tilde{P}$$

Magnetic states are deep electric composites

Electric SM theory is gauge-fermionic

This duality can be tested

| Fields | $SU(2n_g - 4)$ | $SU(2n_g)_L$ | $SU(2n_g)_R$ | $U(1)_p$ | $U(1)_{AF}$ |
|-------------|-----------------|--------------|-----------------|----------|------------------------|
| λ | Adj | 1 | 1 | 0 | 1 |
| P | \square | \square | 1 | 1 | $-\frac{2n_g-4}{2n_g}$ |
| \tilde{P} | $\bar{\square}$ | 1 | $\bar{\square}$ | -1 | $-\frac{2n_g-4}{2n_g}$ |

Magnetic fixed points investigated in perturbation theory

$$H \sim P\lambda\tilde{P}$$

Electric theory to simulate on the lattice

$$M \sim P\lambda\tilde{P}$$

- IR conformality/compare to Magnetic results
- Spectrum,
- Chiral symmetry breaking patterns

F.S. MPLA 26 (2011) 1763-1769, e-print 1102.5100

Antipin, Mojaza, Pica, F.S. Magnetic Fixed Points and Emergent Supersymmetry, JHEP 06 (2013) 037

On the 3 generations?

No explanation from SM, MSSM, CH

Insight on the # of generations

The ED has *non-abelian* gauge group $SU(2n_g - 4)$

Non-abelian requirement

$$2n_g - 4 \geq 2 \quad \Rightarrow \quad n_g \geq 3$$

Asymptotic freedom bounds it from the above

$$3 \leq n_g \leq 6$$

Electric understanding of why at least 3 generations

What does the paradigm tell us?

Electric nature appears at high energies

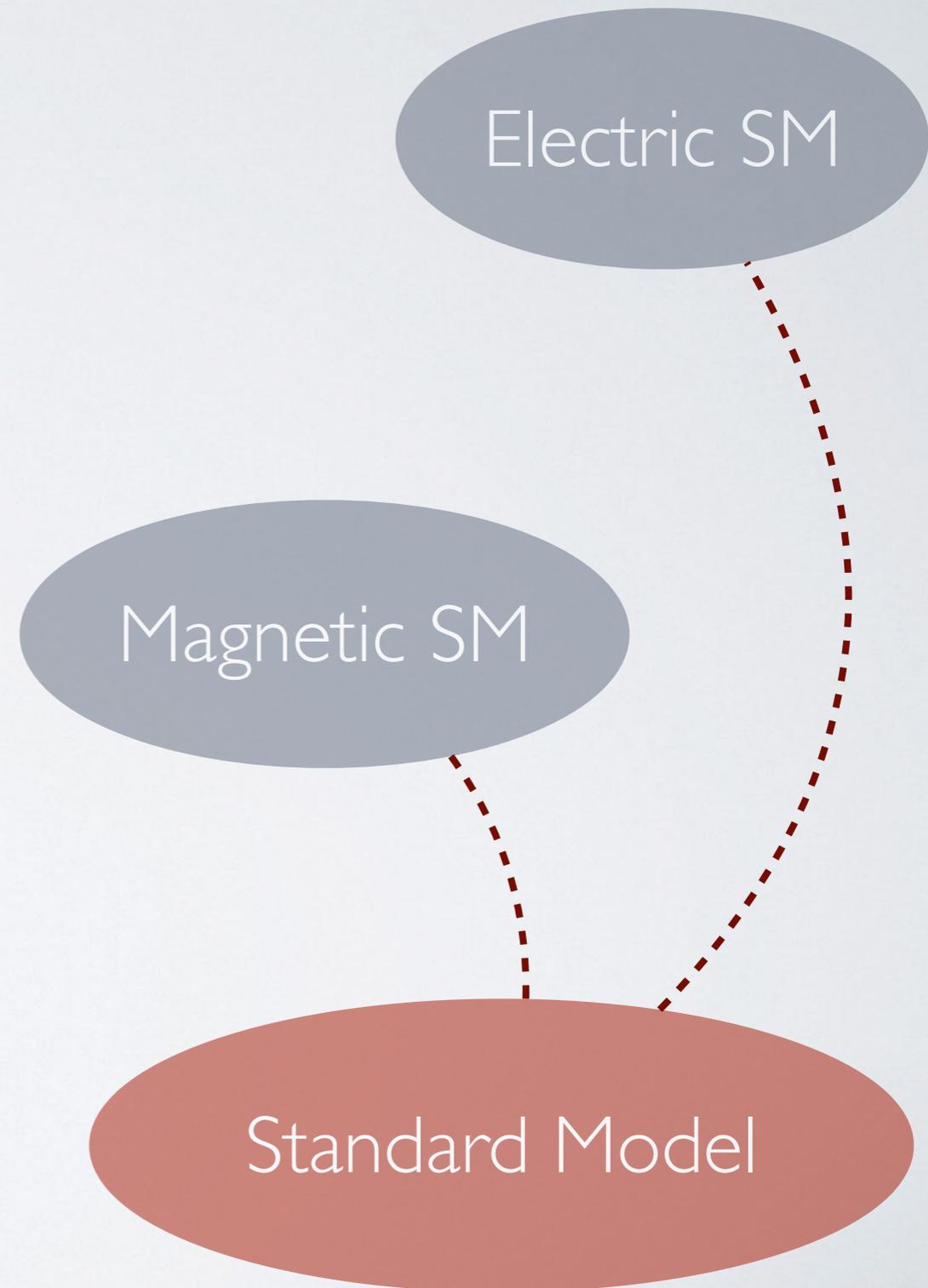
Quarks, leptons and Higgs are composite

Generation # is part of the gauge structure

Light Higgs because of:

- highly pert. nature of Magnetic Dual
- Possible near conformal Electric Dual
- PGB realisation in Electric Dual

SM is a natural theory in plain sight

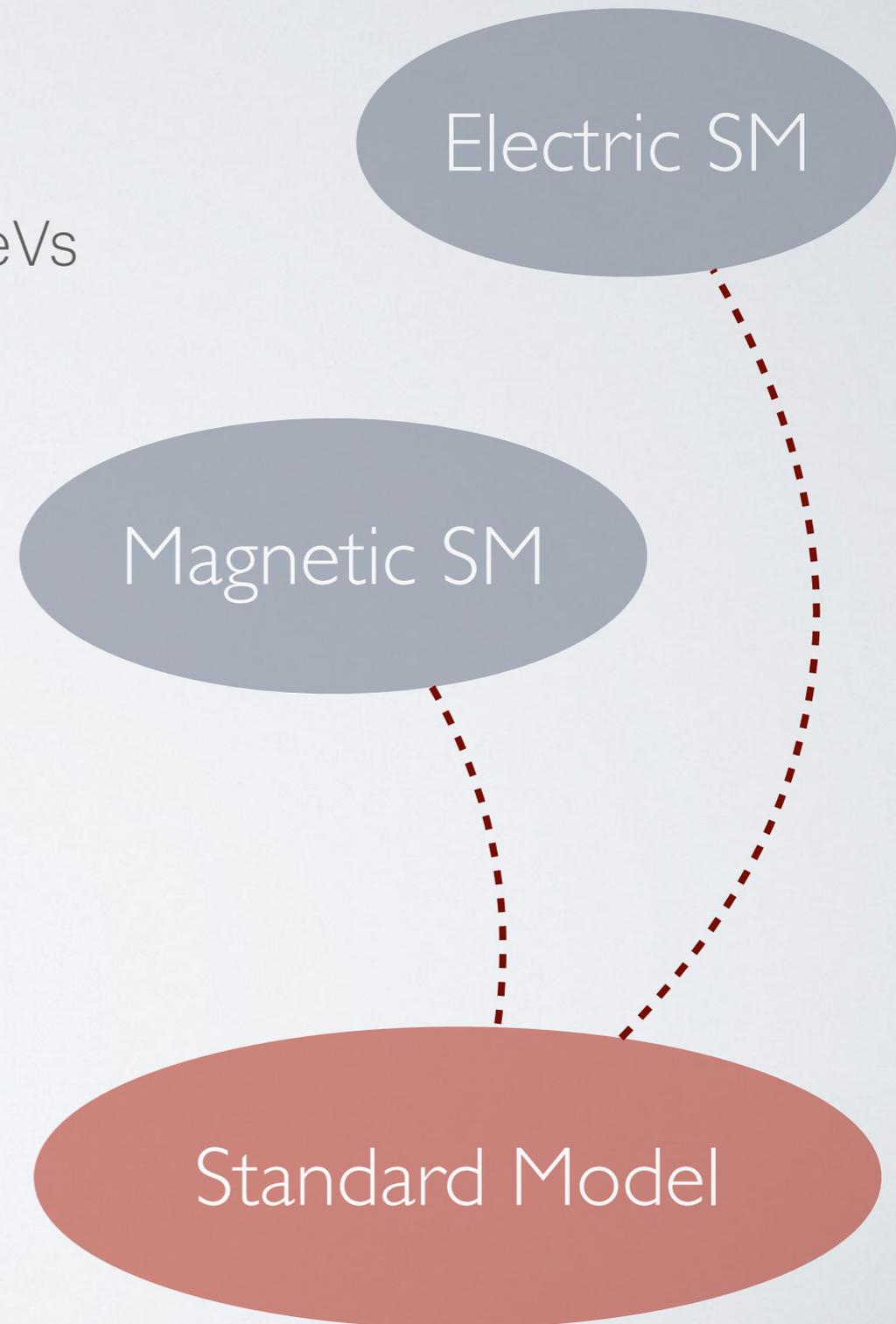


At colliders

Composites should appear within few-several TeVs

Quantum numbers via Electric/Magnetic duals

Quark and lepton substructure

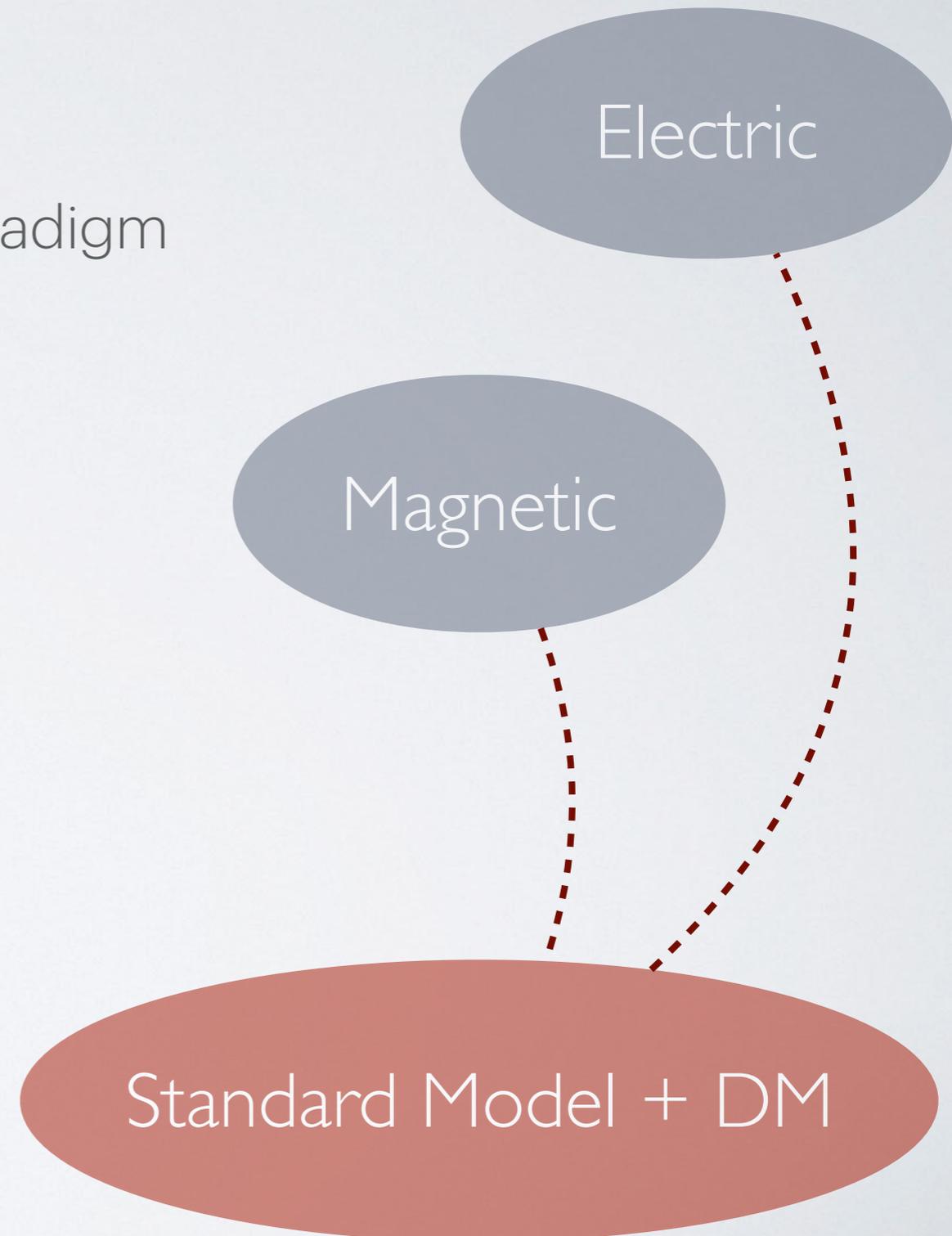


What about dark matter?

Can be part of the Magnetic/Electric paradigm

DM can contribute to the 't Hooft ACs

Much left to be investigated

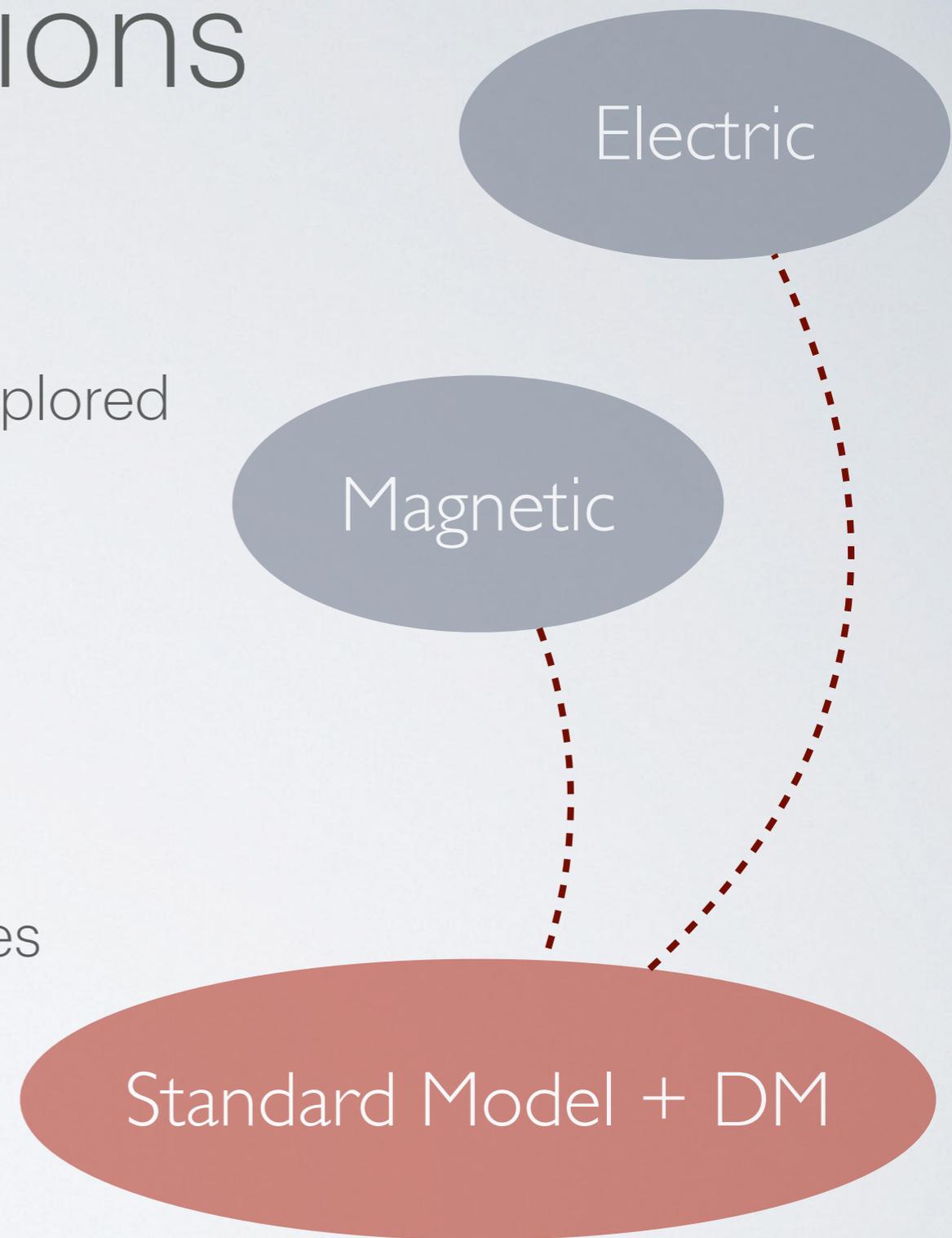


Conclusions

Electro Magnetic duality/modelling is unexplored

Strong dynamics is key to naturalness

Investigate duality for UV finite/safe theories



Solving strong dynamics is paramount for a deeper understanding of nature

Thank you

*"Others have seen what is and asked: Why is it?
I have seen what could be and asked: Why not?"*

Pablo Picasso