Chiral models of composite axions and accidental Peccei-Quinn symmetry

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Based on
R. Contino, AP, F. Revello - arXiv: 2108.xxxxx

SUSY 21 - 26 August 2021

The Standard Model paradigm

- Gauge dynamics

- Global symmetries are accidental

  - renormalizable lagrangian
  - higher-dimensional operators become irrelevant in the IR
  - global symmetries emerge as accidental symmetries

    flavour symmetries and custodial $\mathrm{SO}(3)$

    Baryon number $\mathrm{U}(1)_\mathrm{B}$ and lepton number $\mathrm{U}(1)_\mathrm{L}$

+ [...]

- Fermions in chiral representations

  - bare fermion masses forbidden; generated dynamically

Bonus

- Unification of gauge couplings ?

  - fermions in complete GUT multiplets

Chiral gauge theories

the good

- Fermions in complex representations of the gauge group

No bare mass term $\delta\mathcal{L} = \mathcal{Q}^\dagger \sigma^\mu i D_\mu \mathcal{Q} - M\mathcal{Q}\mathcal{Q}$ ✗

- Dynamical generation of all energy scales
- Cancellation of gauge anomalies gives non-trivial constraints

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- Non-abelian simple gauge group: what happens at confinement ?
- No lattice simulations for chiral gauge theories

IR behaviour of theories with simple gauge group not understood

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Chiral gauge theories

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IR behaviour of theories with simple gauge group not understood

the bad

the ugly

- Consider chiral product gauge group with confining vector-like factor

A calculable model with a chiral sector and SM interactions

Consider a massless vector-like theory

	$\mathrm{SU(N_{DC})}$
ψ_1	$\square$
ψ_2	$\square$
χ_1	$\overline{\square}$
χ_2	$\overline{\square}$

Symmetry Breaking Pattern:

$$\mathrm{SU(2)} \times \mathrm{SU(2)} \times \mathrm{U(1)_V} \longrightarrow \mathrm{SU(2)_V} \times \mathrm{U(1)_V}$$

spontaneous

A calculable model with a chiral sector and SM interactions

and consider the weak gauging of a subgroup $U(1)_D$

	$\mathrm{SU(N_{DC})}$	$\mathrm{U(1)_D}$
ψ_1	$\square$	$+1$
ψ_2	$\square$	-1
χ_1	$\bar{\square}$	$-a$
χ_2	$\bar{\square}$	$+a$

chiral theory for $0 \leq a < 1$

Harigaya, Nomura - PRD 94 (2016) 035013

Co, Harigaya, Nomura - PRL 118 (2017) 101801

Symmetry Breaking Pattern:

$$\mathrm{SU(2)} \times \mathrm{SU(2)} \times \mathrm{U(1)_V} \longrightarrow \mathrm{SU(2)_V} \times \mathrm{U(1)_V}$$

explicit

$$\longrightarrow \mathrm{U(1)_{3V}} \times \mathrm{U(1)_V}$$

$\mathrm{U(1)_D}$ acquires a mass from the bilinear condensate $m_{\gamma_D} \sim f\, e_D$

A calculable model with a chiral sector and SM interactions

- chiral fermions should come in complete GUT multiplets

	$SU(N_{DC})$	$U(1)_D$	$SU(5)_{GUT}$
ψ_1	$\square$	$+1$	$\square$
ψ_2	$\square$	-1	$\square$
χ_1	$\overline{\square}$	$-a$	$\overline{\square}$
χ_2	$\overline{\square}$	$+a$	$\overline{\square}$

Contino, AP, Revello - JHEP 02 (2021) 091

99 NGBs :

pseudo   eaten by γ_D

$$24^{\pm} \oplus 24^{0} \oplus 24^{0\prime} \oplus 1^{\pm} \oplus 1^{0}$$

GUT breaking

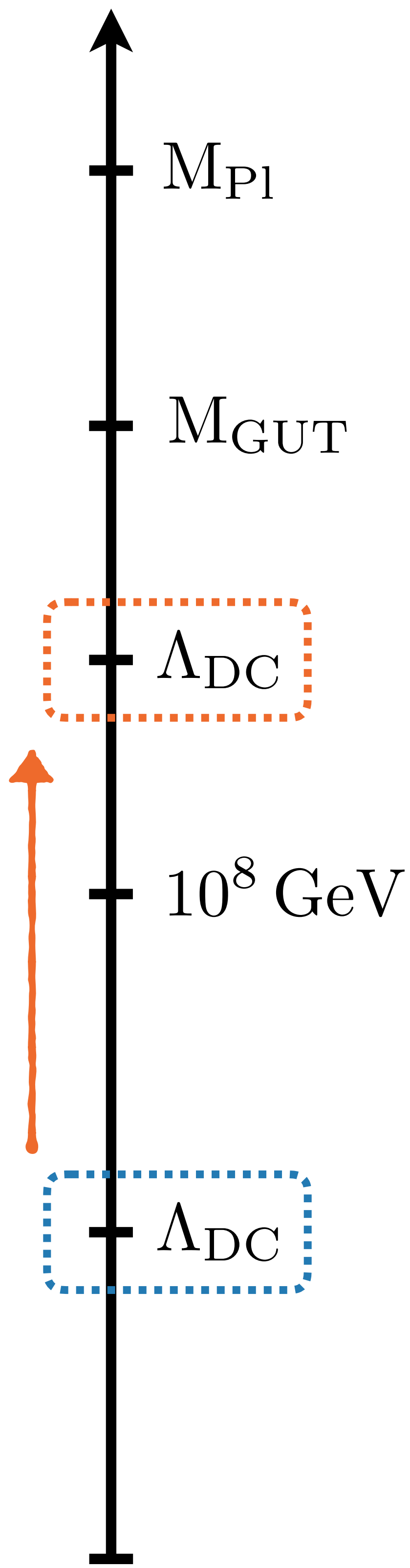
$$\supset 1^{0} \oplus 1^{0\prime}$$ SM singlets

one (combination) of the two singlets has anomalous couplings to SM

→ axion-like particle $$\delta m^2_{\tilde{a}} \sim \frac{g^2_{GUT}}{16\pi^2}\frac{\Lambda^4_{DC}}{M^2_{GUT}}$$ ✘ not QCD axion

GUT contribution

Accidental Peccei-Quinn symmetry



- raise the dynamical scale to PQ scale
- add SM singlets to obtain an exact QCD axion

	$SU(N_{DC})$	$U(1)_D$	$SU(5)_{GUT}$	$U(1)_{PQ}$
ψ_1	$\square$	$+1$	$\square$	$+1$
ψ_2	$\square$	-1	$\square$	$+1$
ψ_3	$\square$	$+1$	$\mathbf{1}$	-3
ψ_4	$\square$	-1	$\mathbf{1}$	-3
χ_1	$\overline{\square}$	$-a$	$\overline{\square}$	$+1$
χ_2	$\overline{\square}$	$+a$	$\overline{\square}$	$+1$
χ_3	$\overline{\square}$	$-a$	$\mathbf{1}$	-3
χ_4	$\overline{\square}$	$+a$	$\mathbf{1}$	-3

- accidental
- anomalous
- spont. broken

composite QCD axion

cfr.

Kim - PRD 31 (1985) 1733

Randall - PLB 284 (1992) 77

Dobrescu - PRD 55 (1997) 5826

+ [...]

The axion quality problem

UV effects : PQ breaking operator with dimension $\Delta_{\not{PQ}}$

↓

IR effect $$\Delta\theta \approx |c|\,\phi_{CP}\left(\frac{M_{\rm Pl}}{\Lambda_{\rm QCD}}\right)^4\left(\frac{f_a}{M_{\rm Pl}}\right)^{\Delta_{\not{PQ}}}$$

- neutron EDM experiment: $\Delta\theta \lesssim 10^{-10}$ nEDM - PRL 124 (2020) 8, 081803

for $f_a \lesssim 10^{12}\,\mathrm{GeV}$ → $\Delta_{\not{PQ}} \gtrsim 12$

- in the model we just defined: $\mathcal{O} = \psi_1\psi_2\chi_1\chi_2$ ✗

Selection rules on PQ violating operators

- Not every PQ violating operator is dangerous!
- A generic PQ violating operator generates a potential only if it has non vanishing matrix element with a state containing axions:

$$\langle \psi_a | \mathcal{O}_{\not{PQ}} | 0 \rangle \neq 0$$

- The operator must be an interpolating operator for the axion with vanishing vectorial charges.

→ $\mathcal{O}_{\not{PQ}}$ polynomial in $(\psi_r \chi_{\bar{r}}),\ (\psi_r \chi_{\bar{r}})^*, (\psi_r^\dagger \psi_r)$ and $(\chi_{\bar{r}}^\dagger \chi_{\bar{r}})$

caveat!

- It can be a composite operator built from the insertion of N local operators

$$d_{\text{eff}} = \sum_{i=1}^{N} d_i - 4(N-1)$$

High quality accidental PQ

Can we modify our construction to have an high quality composite axion? **Yes!**

	$SU(N_{DC})$	$U(1)_D$	G_{SM}	$U(1)_{PQ}$
ψ_1	$\square$	p_1	r_1	α
ψ_2	$\square$	p_2	r_2	β
ψ_3	$\square$	p_3	r_3	γ
χ_1	$\bar{\square}$	q_1	$\bar{r}_1$	α
χ_2	$\bar{\square}$	q_2	$\bar{r}_2$	β
χ_3	$\bar{\square}$	q_3	$\bar{r}_3$	γ

G_{SM}	r_1	r_2	r_3
$SU(5)_{GUT}$	$\mathbf{1}$	$\mathbf{5}$	$\mathbf{10}$
	$\mathbf{1}$	$\bar{\mathbf{5}}$	$\mathbf{10}$
$SU(3)_c$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{6}$
	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{6}$

- confining SU(N)
- perturbativity of SM up to MPl
- accidental PQ

with appropriate choices of U(1) charges PQ is protected up to dim 12

dim 12 operators always exist in these models as a consequence of anomaly cancellation

cfr: Dobrescu - PRD 55 (1997) 5826 Redi, Sato - JHEP 05 (2016) 104 Vecchi - arxiv: 2106.15224

High quality axion - GUT model

Robust model: high quality irrespectively of GUT scalar sector

$N_{\mathrm{DC}} = 5$

	SU(N_{DC})	U(1)$_D$	SU(5)$_{GUT}$	U(1)$_{PQ}$
ψ_1	$\square$	$+2$	$\mathbf{1}$	$+5$
ψ_2	$\square$	$+3$	$\bar{\mathbf{5}}$	$+1$
ψ_3	$\square$	-5	$\mathbf{10}$	-1
χ_1	$\overline{\square}$	$+3$	$\mathbf{1}$	$+5$
χ_2	$\overline{\square}$	-6	$\mathbf{5}$	$+1$
χ_3	$\overline{\square}$	$+6$	$\overline{\mathbf{10}}$	-1

+ others!

dim 12 PQ violating operator: $\mathcal{O}_1 = \psi_2\chi_2\left(\psi_3\chi_3\right)^3$

QCD axion low energy couplings

- Axion low energy couplings

  - well-predicted but not distinctive low energy couplings

    → common to "hadronic axion" models

$$m_a = 5.70(7) \left(\frac{10^{12}\,\text{GeV}}{f_a} \right) \mu\text{eV},$$

$$g_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_a} \left(\frac{E}{N} - 1.92(4) \right),$$

$$c_p = -0.47(3), \quad c_n = -0.02(3),$$

GUT models have fixed E/N = 8/3

Grilli di Cortona, Hardy, Vega, Villadoro - JHEP 05 (2016) 104

Cosmological evolution

- Cosmological evolution:

  - PQ breaking after the end of inflation is disfavoured for composite models

    → accidentally stable heavy resonances + domain walls ✗

  - PQ broken during inflation

    → axion populated with misalignment mechanism (possibly DM) ✓

  - in the GUT scenario, parametrically lighter metastable NGBs

$$\delta m_{\tilde{a}}^2 \sim \frac{g_{\rm GUT}^2}{16\pi^2} \frac{\Lambda_{\rm DC}^4}{M_{\rm GUT}^2}$$

→ can leave imprints in cosmological observables

High-quality axion summary

Summary:

- Chiral model with dynamical generation of scales
- Strong CP solved by the QCD axion
- PQ is an high quality accidental symmetry through gauge protection
- Possibly DM
- Compatibility with SU(5) unified dynamics

Outlook:

- Observational distinctive signatures from pseudo-NGB ?

Backup Slides

High quality axion models classification

GUT

n_{max}	$N_{\rm DC}=5$ 10	15	20	$N_{\rm DC}=4$ 10	15	20
AC solutions	77	189	341	77	189	341
HQ axions, $(\mathbf{1},\bar{\mathbf{5}},\mathbf{10})$	22	68	150	9	31	82
Robust HQ axions, $(\mathbf{1},\bar{\mathbf{5}},\mathbf{10})$	4	16	47	0	5	22
HQ axions, $(\mathbf{1},\mathbf{5},\mathbf{10})$	14	44	99	2	12	33
Robust HQ axions, $(\mathbf{1},\mathbf{5},\mathbf{10})$	3	16	36	0	7	21
No $d \leq 8$ operators	0	1	10	0	0	0

QCD

$n_{\rm max}$	$N_{\rm DC}=3$ 10	15	20
AC solutions	16	40	96
HQ axions, $(\mathbf{1},\bar{\mathbf{3}},\mathbf{6})$	3	14	50
HQ axions, $(\mathbf{1},\mathbf{3},\mathbf{6})$	4	17	50
No $d \leq 8$ operators	0	1	8