Axion

& other frameworks addressing the hierarchy problem

07.13 2021

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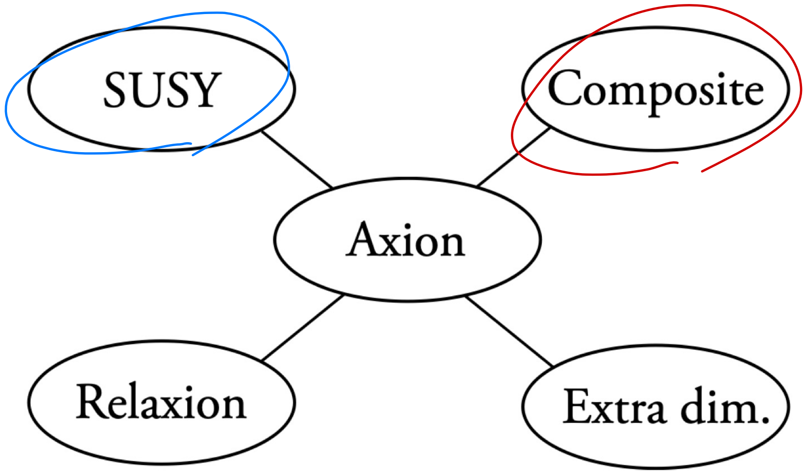
1. Overview



Hyungjin's note

sorry Geraldine

Axion + SUSY

- Brief recap of SUSY
  motivation, Wess-Zumino, Superpotential, F-term,
  SUSY breaking, μ-problem, ...
- Saxion & Axino : general properties
- SUSY DFSZ (Kim-Nilles '84)
- SUSY KSVZ (Asaka-Yamaguchi 9805449)

Axion + composite

- Recap of minimal $(+\alpha)$ composite axion
  (Kim '85, Choi-Kim '85)
- Composite axion in composite Higgs
  (Gherghetta & Nguyen 2007.10875)

2. Axion in SUSY

2-1. Recap of SUSY

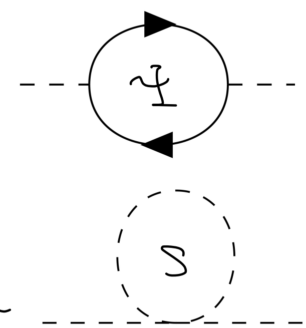
- Motivation : hierarchy prob. $M_{EW} \ll M_{GUT}, M_P$

- More precisely : $\mathcal{L}_{\rm toy} \supset -(y\Phi\bar{\Psi}\Psi + \text{h.c.}) - \lambda|\Phi|^2|S|^2.$

Dirac fermion (Ψ) Complex scalars (Φ, S)

1-loop mass correction

$-i\Delta m_\Phi^2 =$



$= i\,\dfrac{|y|^2}{8\pi^2}\Lambda_{UV}^2$

$= -i\,\dfrac{\lambda}{16\pi^2}\Lambda_{UV}^2$

So, naively $m_\Phi^2 \sim \Lambda_{UV}^2$ but we observe $m_\Phi^2 \sim M_{EW}^2$

Hierarchy problem

Solution? : Weyl fermion $\longleftrightarrow$ Complex scalar
(half dof of Dirac)

with $|y|^2 = \lambda$

- Simplest model : Wess-Zumino $\cancel{\mathcal{L}_{\mathrm{WZ?}} = -|\partial\phi|^2 + i\psi^\dagger\bar{\sigma}^\mu\partial_\mu\psi}$

$$\mathcal{L}_{\mathrm{WZ}} = -|\partial\phi|^2 + i\psi^\dagger\bar{\sigma}^\mu\partial_\mu\psi + |F|^2,$$

	ϕ	ψ	F
real dof (off shell)	2	4	2
real dof (on shell)	2	2	0

This model has a symmetry btwn. boson $\leftrightarrow$ fermion.

$$\delta\phi = \epsilon\psi, \quad \delta\psi = -i\sigma^\mu\epsilon^\dagger\partial_\mu\phi + \epsilon F, \quad \delta F = -i\epsilon^\dagger\bar{\sigma}^\mu\partial_\mu\psi.$$

SUSY transformation!

ε : infinitesimal parameter

complex, 2-component, anti-commuting, mass dim $-1/2$.

$\varepsilon \neq \varepsilon^*$ $\quad$ $\varepsilon_1, \varepsilon_2$ $\quad$ $\varepsilon_1\varepsilon_2 = -\varepsilon_2\varepsilon_1$

$\varepsilon_1^*, \varepsilon_2^*$

- Superpotential, F-term

Suppose we have many copies of (ϕ, ψ, F)

$$\mathcal{L}_{\rm free} = -(\partial^\mu \phi^{*i})(\partial_\mu \phi_i) + i\psi^{\dagger i}\bar{\sigma}^\mu \partial_\mu \psi_i + \boxed{F^{*i}F_i.}$$

What about interactions?

$$\mathcal{L}_{\rm int} = [((\text{dim }1)^{ij}\overbrace{\psi_i\psi_j}^{3} + \boxed{(\text{dim }2)^i \overbrace{F_i}^{2}} + \cancel{(\text{dim }0)^{ij}\overbrace{F_iF_j}^{4}}) + \boxed{\text{c.c.}}] - \cancel{(\text{dim }4)},$$

func. of $\{\phi_i\}$.

These functions cannot be arbitrary ∵ (because) SUSY transf.

$$(\text{dim }1)^{ij} = -\frac{1}{2}\frac{\partial^2 W}{\partial\phi_i\partial\phi_j}(\equiv W^{ij}), \quad \boxed{(\text{dim }2)^i = \frac{\partial W}{\partial \phi_i}(\equiv W^i).}$$

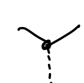
W is called SUPERPOTENTIAL

neglected.

$$W = \underbrace{\cancel{L^i\phi_i}}_{\text{dim. }3} + \frac{1}{2}\overset{1}{M^{ij}}\overbrace{\phi_i\phi_j}^{2} + \frac{1}{6}\overbrace{y^{ijk}}^{0}\overbrace{\phi_i\phi_j\phi_k}^{3}.$$

gives $\left\{\begin{array}{l}\text{scalar}\\ \text{fermion}\end{array}\right\}$ mass

gives $\left\{\begin{array}{l}\text{Yukawa}\\ \text{scalar quartic}\end{array}\right.$



What happens after integrating out $\{F_i\}$?

solution : $$F_i = -W_i^*$$

This gives rise to a scalar potential

$$\mathcal{L} \supset \underbrace{-\left|\frac{\partial W}{\partial \phi_i}\right|^2}_{} \left(= -|F_i|^2\right).$$

F-term contribution to the potential.

- Superspace formalism

Lagrangian above can be derived in one stroke. How?

→ Superspace formalism.

$$\mathcal{L} = \int d^2\theta d^2\theta^\dagger \ \Phi^{*i}\Phi_i + \left[\int d^2\theta \ W(\{\Phi\}) + \text{c.c.}\right]$$

What is θ ? What is Φ ?

θ : Grassmann coordinate. (on top of usual coordinate x^μ)

complex, 2-component, anti-commuting, dim $-1/2$.

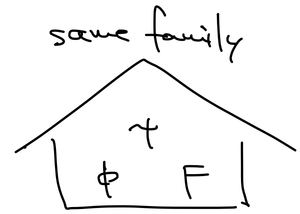
$\theta \neq \theta^\dagger$ $\quad \theta_1, \theta_2 \quad \theta_1\theta_2 = -\theta_2\theta_1$

θ_1^*, θ_2^*

(Left-chiral)

Real scalar — Weyl fermion — Auxiliary field

$$\Phi(x,\theta,\theta^\dagger) = \underline{\phi}(y) + \sqrt{2}\theta\underline{\psi}(y) + \theta\theta\underline{F}(y).$$



$$y^\mu \equiv x^\mu + \underbrace{i\theta^\dagger\bar{\sigma}^\mu\theta}_{\text{commuting, real.}}$$

trick.

$$\phi(y) = \phi(x) + \partial\phi\cdot i\theta^\dagger\bar{\sigma}\theta + \partial\partial\phi\cdot(i\theta^\dagger\bar{\sigma}\theta)^2 + \underbrace{\partial\partial\partial\phi\,(i\theta^\dagger\bar{\sigma}\theta)^3 + \cdots}$$

$$\theta\psi(y) = \theta\psi(x) + \theta\,\partial\psi\cdot i\theta^\dagger\bar{\sigma}\theta + \underbrace{\cdots}_{0}$$

$$\theta\theta F(y) = \theta\theta F(x) \underbrace{+\cdots}_{0}$$

zero ☹ too many θ

e.g. $\theta_1\theta_2\theta_1 = 0$

- To summarize, in order to have SUSY Lagrangian,

1. Fix your $W(\{\Phi\})$ (Don't use $\{\Phi^\dagger\}$)

2. Calculate $\mathcal{L} = \int d^2\theta d^2\theta^\dagger\ \Phi^{*i}\Phi_i + \left[\int d^2\theta\ W(\{\Phi\}) + \text{c.c.}\right]$

Scalar potential $U = \sum_i \left|\frac{\partial W}{\partial \Phi_i}\right|^2 \Bigg|_{\Phi_i \to \phi_i}$ (contains quartic $\sim y^2$)

Φ_i: multiplet, ϕ_i: scalar.

Yukawa $\sim \left.\frac{\partial^2 W}{\partial\Phi_i\partial\Phi_j}\right|_{\Phi\to\phi} \times \psi_i\psi_j$

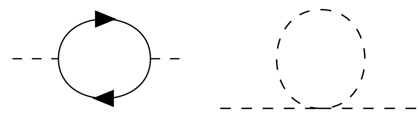
I will not talk about gauge & D-terms...

- SUSY breaking.

In reality, SUSY must be broken. (we don't observe any scalar at $m = 511\,\mathrm{keV}$)

But we want to break it softly.

If we break it badly,



will not cancel.

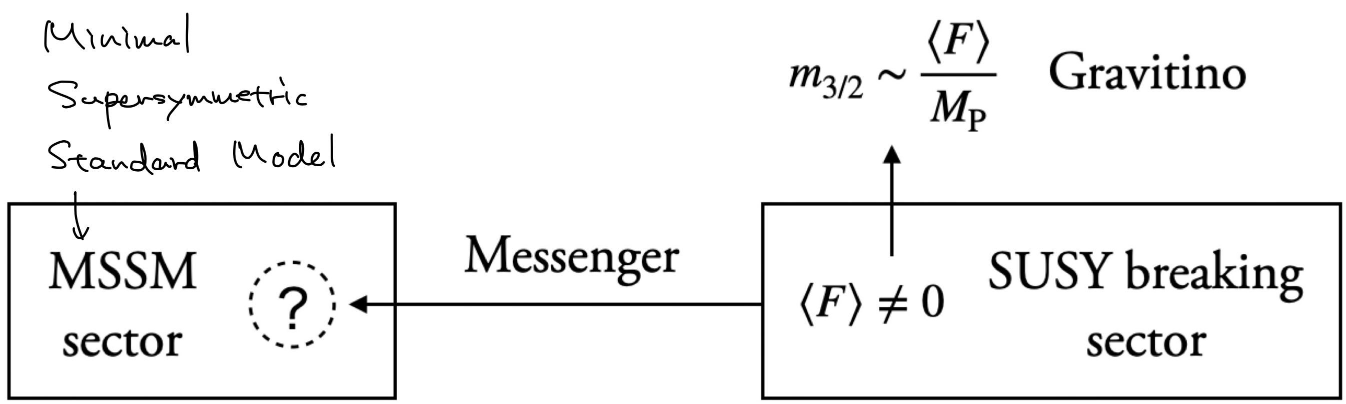
Meaning $\dfrac{\partial W}{\partial \Phi_i} = 0$ does not hold for all i at the same time

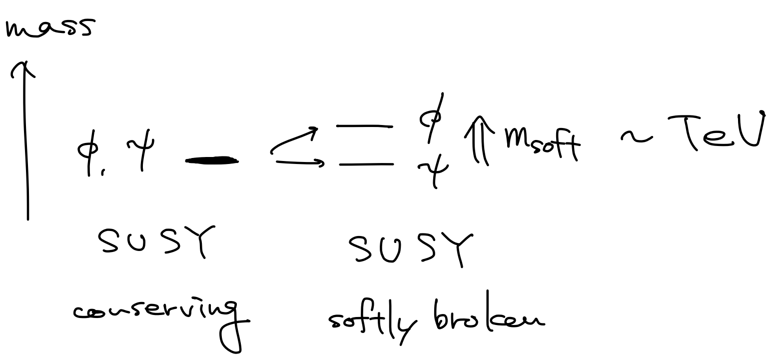
How is it possible?

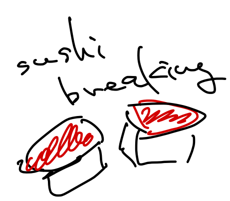
SUSY is spontaneously broken if some sector has $\langle F_i \rangle \neq 0$.

So, assume "~~SUSY~~ sector" $\langle F \rangle \neq 0$

and communicate the effect to our sector.







- MSSM Lagrangian & μ-problem.

We need 2 Higgses

$$W_{\mathrm{MSSM}} = \underline{\underline{\mathbf{y_u}}} Q H_u \bar{u} - \underline{\underline{\mathbf{y_d}}} Q H_d \bar{d} - \underline{\underline{\mathbf{y_e}}} L H_d \bar{e} + \underline{\underline{\mu}} H_u H_d$$

dimless dimless dimless

DIMENSION ONE

Needs to be $\lesssim$ TeV

gives { Yukawa, scalar quartic }

We recognize μ-problem

It's not unnatural to have $m_{soft} \sim$ TeV

☺ ~~SUSY~~ can be weakly communicated to our sector.

But why $\mu \sim$ TeV even though it's conserving SUSY part?

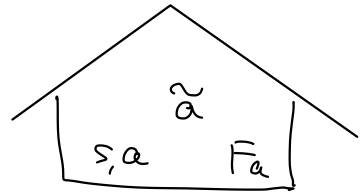
We wanted to <u>explain</u> that, right?

2-2. Saxion & Axino : general properties.

- In SUSY theories, axion lives in a multiplet.

saxion   axion   axino

$$A = \underbrace{\frac{s + ia}{\sqrt{2}}} + \sqrt{2}\theta\tilde{a} + \theta\theta F_a$$



axion superfield

auxiliary
(not the decay const.)

$\left\{\begin{array}{l}\text{saxion } s \\ \text{axion } a\end{array}\right\}$ form a complex scalar field.

- We expect s and $\tilde{a}$ to be <u>light</u>

because they are in the same multiplet as axion a

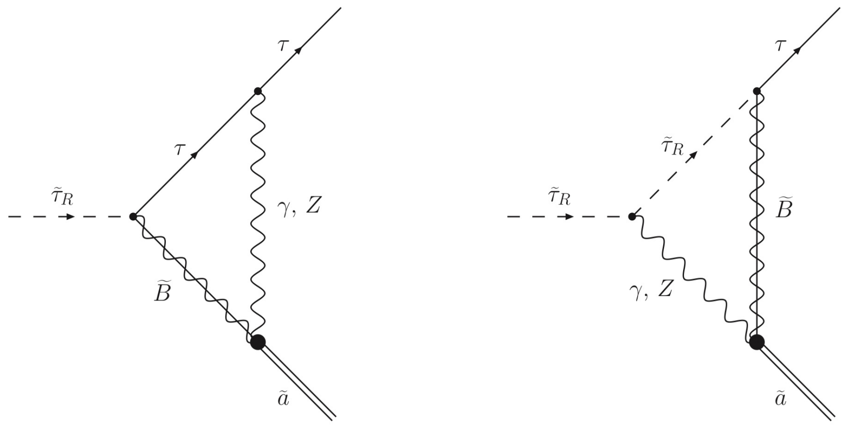
- Saxion s can be a cosmological problem

Why? $\left\{\begin{array}{l} \text{Light scalar fields tend to oscillate at late times} \\ \qquad\qquad \to \text{Energy domination} \\ \\ \text{It has couplings suppressed by } 1/f_a, \\ \text{mainly decaying into } aa \text{ or } \tilde{a}\tilde{a}\ (\to aa) \\ \qquad \to \text{Dark radiation constraints.}\end{array}\right.$

- Axino $\tilde{a}$

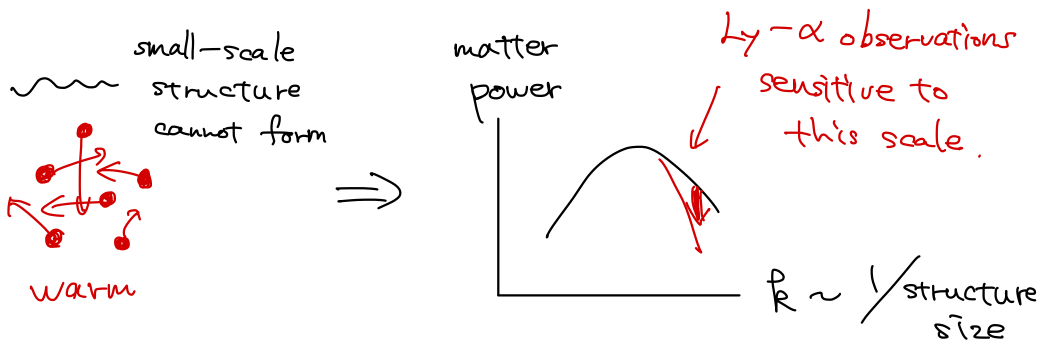
has couplings suppressed by $1/f_a$

→ behaves similarly to gravitino in colliders



can be (part of) dark matter.

→ if it's too light, it behaves as warm dark matter, and can be observed/excluded by small-scale structure



can pop up from thermal plasma

$$\Omega_{\tilde{a}} h^2 \sim \mathcal{O}(1) g_s^6 \left(\frac{m_{\tilde{a}}}{100\ \mathrm{MeV}}\right) \left(\frac{10^{11}\ \mathrm{GeV}}{f_a/N}\right)^2 \left(\frac{T_\mathrm{R}}{10^4\ \mathrm{GeV}}\right),$$

$$\Omega_{\tilde{G}} h^2 \sim \mathcal{O}(0.1) g_s^2 \left(1 + \frac{m_{\tilde{g}}^2}{3m_{\tilde{G}}^2}\right) \left(\frac{m_{\tilde{G}}}{100\ \mathrm{GeV}}\right) \left(\frac{T_\mathrm{R}}{10^{10}\ \mathrm{GeV}}\right).$$

- SUSY DFSZ (PQ - charged Higgs).

Kim - Nilles mechanism : solve $\left\{ \begin{array}{l} \text{strong CP} \\ \mu\text{ - problem} \end{array} \right\}$ at once.

$$W \supset \frac{\overset{O(1)}{\lambda} \overset{\text{New field}}{S^2}}{M_P} \underbrace{H_u H_d}_{\text{MSSM Higgs.}}$$

New field (scalar component develops VEV $\sim 10^{10}$ GeV)

	S	H_u	H_d
$U(1)_{PQ}$	+1	-1	-1

<u>Strong CP</u> : Same as (non - SUSY) DFSZ.

Recap. $\mathcal{L}_{DFSZ:II} \supset - y_u Q_L^\dagger H_u u_R - y_d Q_L^\dagger H_d d_R - y_e L_L^\dagger H_d e_R$

$- \lambda H_u H_d (\Phi^\dagger)^2$ - (other terms).

$\downarrow$

Integrate out Φ radial. $\quad \Phi \sim v_\Phi e^{ia/v_\Phi}$ $\quad$ radial $\to$ byebye, phase $\to$ alive

$\downarrow$

Integrate out H_u, H_d $\quad$ Eliminate phase in $\lambda H_u H_d v_\Phi^2 e^{-i2a/v_\Phi}$

$\to$ Phases in quark mass $\quad$ (* Otherwise non-decoupling effect appears)

$\downarrow$

(Optional) Rotate quarks $\quad$ Path integral measure $\to \dfrac{a}{v_\Phi} G\tilde{G}$

Axion!

$\underline{\mu\text{-problem}}$: Naturally explained if $\langle s \rangle \sim 10^{10}$ GeV.

$$\frac{\lambda \langle s \rangle^2}{M_p} H_u H_d \sim (\text{TeV}) \times H_u H_d .$$

* How can we explain $\langle s \rangle \sim 10^{10}$ GeV ?

Logic in the original paper

" If we solve strong CP with axion, then $f_a \sim 10^{10}$ GeV.

We can solve μ-problem with $\frac{\lambda s^2}{M_p} H_u H_d$

without any additional theoretical cost."

* Domain walls ?

N_{DW} = same as non-SUSY DFSZ = 6

Why? Higgs rotation affects all generations of quarks.

- SUSY KSVZ (PQ charged heavy quarks)

$$W \supset \lambda X Q \bar{Q}$$

heavy quarks.

"bar" does not mean any operation. $\bar{Q}$ is one object.

	X	Q	$\bar{Q}$
$U(1)_{PQ}$	1	$-\frac{1}{2}$	$-\frac{1}{2}$
$SU(3)_c$	$\mathbf{1}$	$\square$	$\bar{\square}$

Strong CP

X gets VEV $\langle x \rangle \sim f_a e^{i a/f_a}$

radial → bye

phase → alive

↓

$Q, \bar{Q}$ have a mass $\sim f_a e^{i a/f_a}$

Rotate $Q, \bar{Q}$ to eliminate the phase

(* otherwise non-decoupling effect)

↓

Path integral measure gives $\frac{a}{f_a} G \tilde{G}$

Axion!

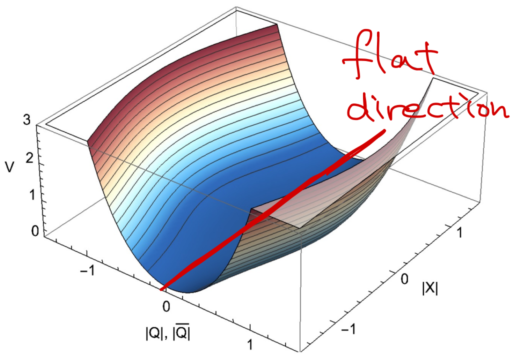
Saxion dynamics

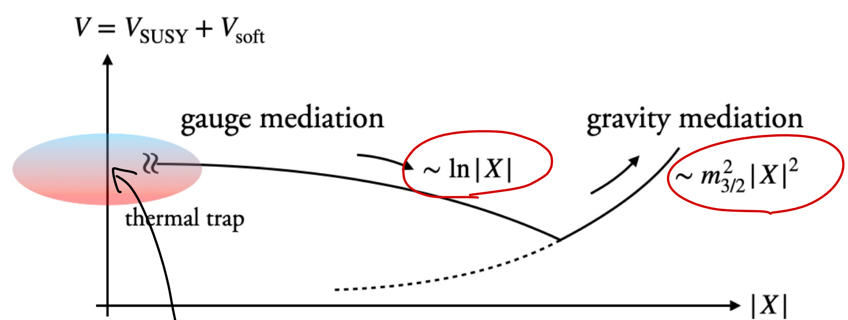
$$V_{\mathrm{SUSY}} \supset \left|\frac{\partial W}{\partial X}\right|^2 + \left|\frac{\partial W}{\partial Q}\right|^2 + \left|\frac{\partial W}{\partial \bar{Q}}\right|^2 = |Q|^2|\bar{Q}|^2 + |X|^2(|Q|^2 + |\bar{Q}|^2)$$

SUSY-conserving level

Where's saxion S ?

soft term mediated from $\langle F \rangle \neq 0$ sector





saxion = $|X|$ direction along $|Q| = |\bar{Q}| = 0$

usual soft mass from gauge med.

(saxion)

$\underbrace{\hphantom{xxxxxxxxxxxxxxxx}}$ SUSY-conserving level

$\underbrace{\hphantom{xxxxxxxxxxxxxxxx}}$ After including $\cancel{\mathrm{SUSY}}$

$*$ Assume gauge mediation, $m_{\mathrm{soft}} \sim \alpha \dfrac{\langle F_{\cancel{\mathrm{SUSY}}} \rangle}{M_{\mathrm{mess}}}$

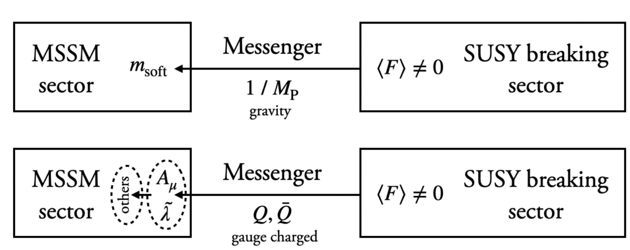
① At large $|X|$, $\sim \ln|X|$ term appears.

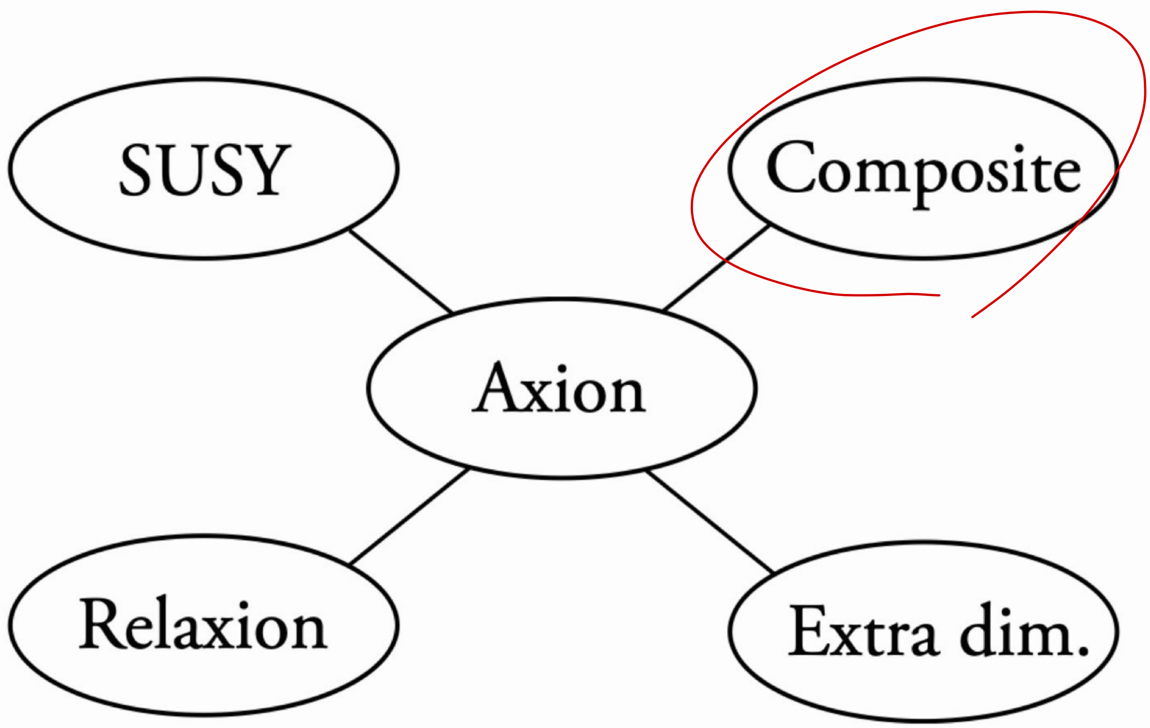
② We still have effect from gravity med. $m_{3/2}^2 |X|^2$

$\Rightarrow$ Balance btwn. ① & ②

can create $f_a \sim 10^{10}\,\mathrm{GeV}$

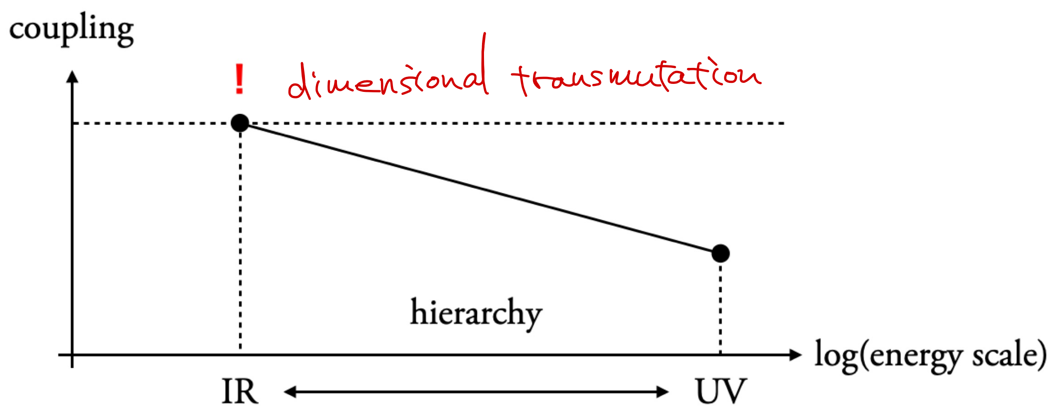
Asaka-Yamaguchi 9805449




SUSY
Composite
Axion
Relaxion
Extra dim.

3. Axion in composite Higgs

Motivation



3-1. Composite axion (not composite Higgs).

Minimal $(+\alpha)$ model.

Philip's talk

Minimal model

$\cancel{m\, Q^{A\alpha} Q_{A\alpha}}$

$\cancel{m\, \psi^{A} \psi_{A}}$

$$\mathcal{L} = i(Q^\dagger)_{A\alpha}\bar{\sigma}^\mu D_\mu Q^{A\alpha} + i(Q^\dagger)^{A\alpha}\bar{\sigma}^\mu D_\mu Q_{A\alpha} + i(\psi^\dagger)_\alpha \bar{\sigma}^\mu D_\mu \psi^\alpha + i(\psi^\dagger)^\alpha \bar{\sigma}^\mu D_\mu \psi_\alpha + \cdots .$$

		$Q^{A\alpha}$	$Q_{A\alpha}$	ψ^A	ψ_A
axicolor →	$SU(N)_a$	$\square$	$\overline{\square}$	$\square$	$\overline{\square}$
our color →	$SU(3)_c$	$\square$	$\overline{\square}$	$\mathbf{1}$	$\mathbf{1}$
axial symmetries	A_1	1	1	0	0
	A_2	0	0	1	1

$\square$: fundamental

$\overline{\square}$: anti-fund.

no $m\, Q^{A\alpha} Q_{A\alpha}$ no $m\, \psi^A \psi_A$

- Remember pions: $\underset{\text{flavor}}{U(2)_L} \times \underset{\text{flavor}}{U(2)_R} = SU(2)_V \times \cancel{SU(2)_A} \times U(1)_V \times \cancel{U(1)_A}$

spontaneously broken → pions

broken from the beginning

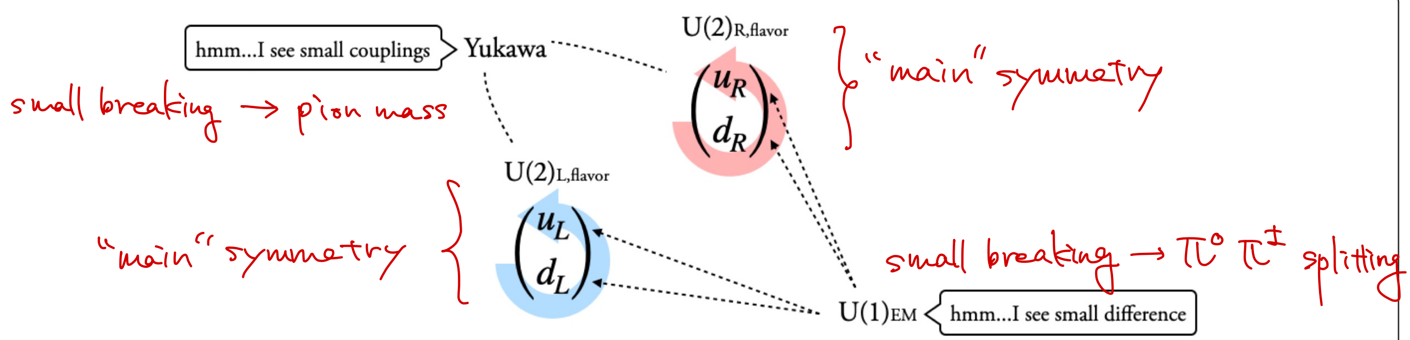


Figure 8: Approximate $U(2)_L \times U(2)_R$ and its small breaking seen by $U(1)_{EM}$ and Yukawas in QCD. On top of this, $U(1)_A$ is anomalous in reality.

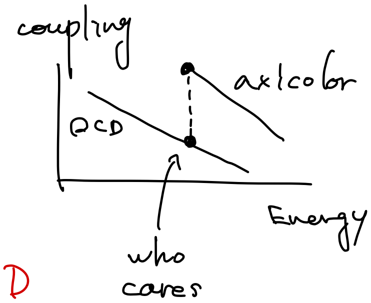
- In the present model

slight difference seen from axicolor.

$$q^A = \begin{pmatrix} Q^{A1} \\ Q^{A2} \\ Q^{A3} \\ \psi^A \end{pmatrix}, \quad q_A = \begin{pmatrix} Q_{A1} \\ Q_{A2} \\ Q_{A3} \\ \psi_A \end{pmatrix}$$

} feels QCD

} does not feel QCD



$$U(4)_L \times U(4)_R = SU(4)_V \times \cancel{SU(4)_A} \times U(1)_V \times \cancel{U(1)_A}$$

$4^2 - 1 = 15$ NG bosons.

$15 = 8 + 3 + \bar{3} + \underline{\underline{1}}$

decomposition under QCD

$$\begin{pmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & -3 \end{pmatrix}$$

direction of

axial $\begin{cases} \text{left} \quad q^A \to e^{i\varepsilon \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix}} q^A \\ q_A \to e^{i\varepsilon \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix}} q_A \quad \text{left} \end{cases}$

- After all, we have 2 rotations in the beginning $\left\{ \begin{matrix} Q \\ \psi \end{matrix} \right\}$,
  and one combination does not feel axicolor.

$$\delta\mathcal{L} = -\underbrace{\frac{2N\epsilon_1}{32\pi^2}G^{\alpha'}_{\mu\nu}\tilde{G}^{\alpha'\mu\nu}}_{\text{QCD}} - \underbrace{\frac{2(3\epsilon_1+\epsilon_2)}{32\pi^2}F^{A'}_{\mu\nu}\tilde{F}^{A'\mu\nu}}_{\text{axicolor}}$$

$$J^{5\mu}_{A_1-3A_2} = (Q^\dagger)_{A\alpha}\bar{\sigma}^\mu Q^{A\alpha} + (Q^\dagger)^{A\alpha}\bar{\sigma}^\mu Q_{A\alpha} - 3(\psi^\dagger)_\alpha\bar{\sigma}^\mu\psi^\alpha - 3(\psi^\dagger)^\alpha\bar{\sigma}^\mu\psi_\alpha$$

Strong CP is solved by this guy.

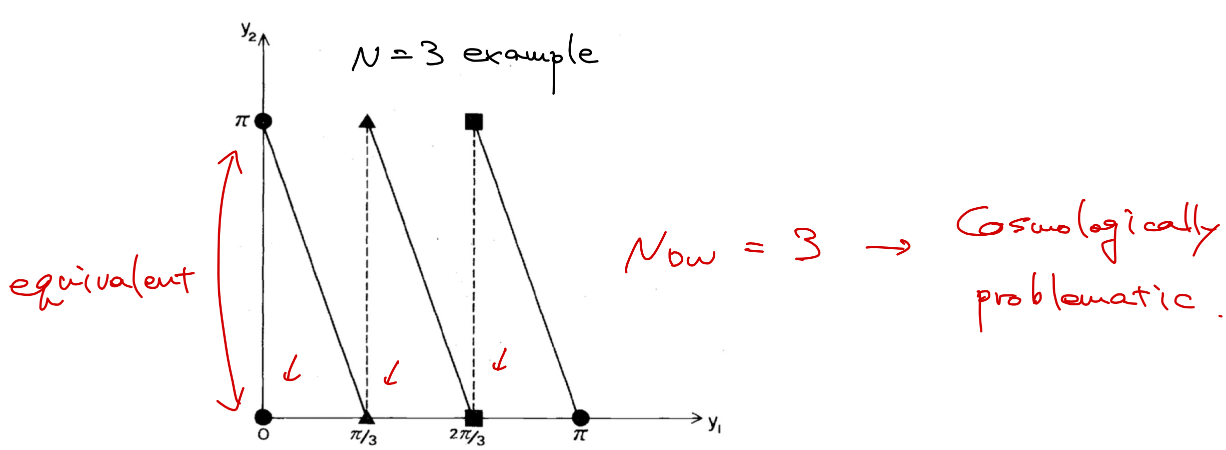
The other guy gets mass $\sim O(\Lambda_{axi})$ from axicolor instanton.

- Low-energy Lagrangian = KSVZ axion

- Problems ?

Problems We learned that several problems exist in the minimal model.

- Asymptotic freedom: Is the axicolor $\mathrm{SU}(N)_a$ really asymptotically free? In other words, does it really get strong at low energy?
- Domain walls: How can we design the model so that $N_{\rm DW} = 1$?
- Unwanted relics: How can we remove the unwanted bound states of the axicolor?



Minimal + α model

Choi & Kim '85

new guys

	$Q^{A\alpha}$	$Q_{A\alpha}$	q^{α}	q_{α}	ψ^A	ψ_A	ν	ν'
$SU(2)_a$	$\square = \mathbf{2}$	$\square = \mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\square = \mathbf{2}$	$\square = \mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
$SU(3)_c$	$\square = \mathbf{3}$	$\overline{\square} = \bar{\mathbf{3}}$	$\square = \mathbf{3}$	$\overline{\square} = \bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
A_1	1	1	-1	-1	0	0	0	0
A_2	0	0	0	0	1	1	-1	-1

QCD　　　　axicolor

$$\delta\mathcal{L} = -\frac{2\epsilon_1}{32\pi^2} G^{\alpha'}_{\mu\nu}\tilde{G}^{\alpha'\mu\nu} - \frac{6\epsilon_1 + 2\epsilon_2}{32\pi^2} G^{A'}_{\mu\nu}\tilde{G}^{A'\mu\nu}$$

cf. previously...

4 for $N=2$.

$$\delta\mathcal{L} = -\frac{2N\epsilon_1}{32\pi^2} G^{\alpha'}_{\mu\nu}\tilde{G}^{\alpha'\mu\nu} - \frac{2(3\epsilon_1 + \epsilon_2)}{32\pi^2} F^{A'}_{\mu\nu}\tilde{F}^{A'\mu\nu}$$

$$\begin{cases} 2\varepsilon_1 = 2\pi \times \text{integer} \\ 6\varepsilon_1 + 2\varepsilon_1 = 2\pi \times \text{integer} \end{cases} \quad \text{for} \quad \begin{matrix} 0 \le \varepsilon_1 < \pi \\ 0 \le \varepsilon_2 < \pi . \end{matrix}$$

$\Rightarrow$ Only $\varepsilon_1 = 0$, $\varepsilon_2 = 0$ $\Rightarrow$ $N_{DW} = 1$.

3-2. Axion in composite Higgs   Gherghetta & Nguyen '20

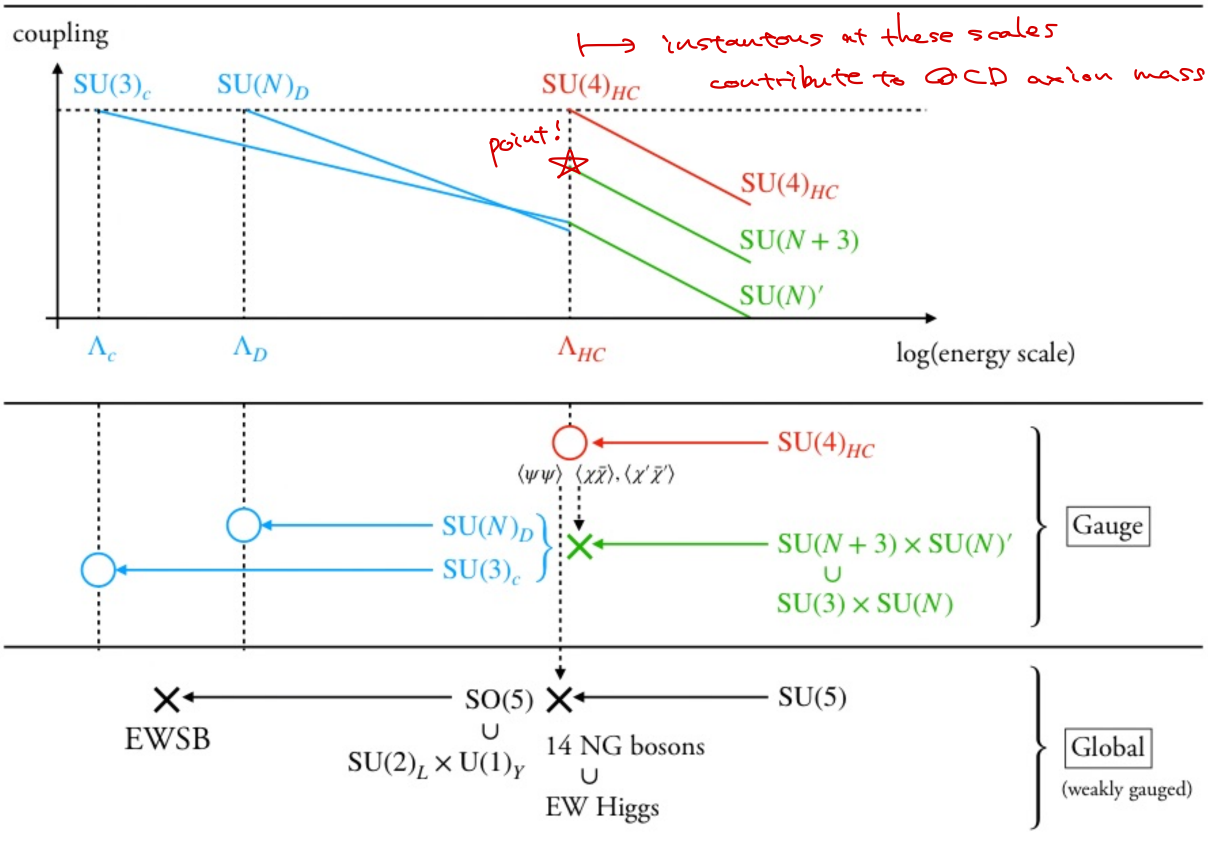


Figure 12: Symmetry breaking induced by the hypercolor confinement.

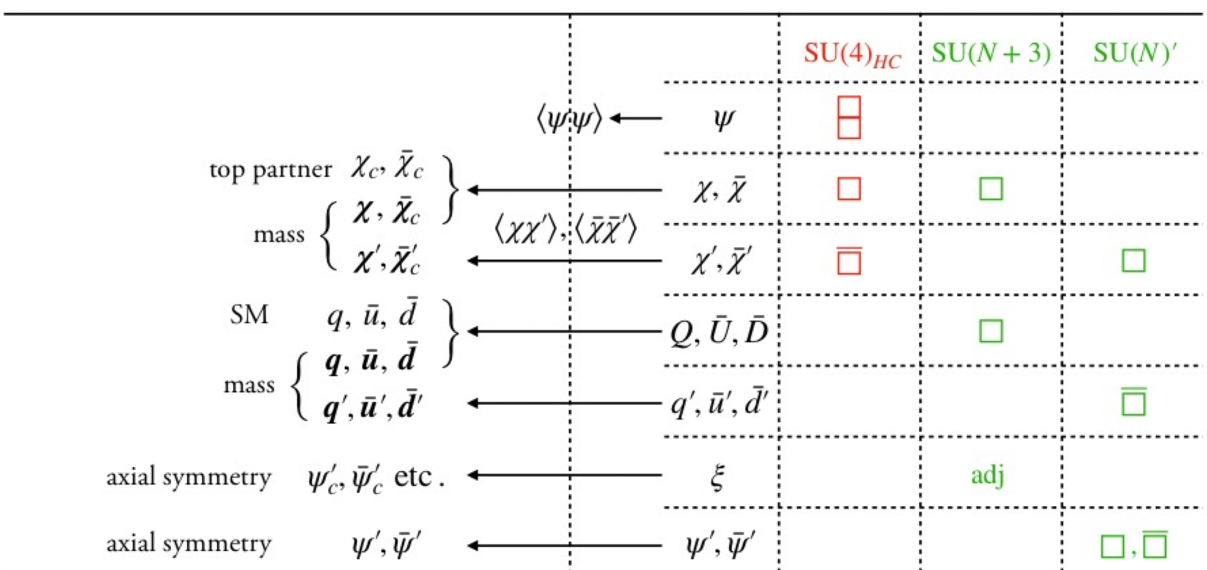


Figure 13: Fate of the particles.

	$SU(4)_{HC}$	$SU(N+3)$	$SU(N)$'	$SU(5)$
ψ	$\begin{smallmatrix}\square\\\square\end{smallmatrix} = \mathbf{6}$	$\mathbf{1}$	$\mathbf{1}$	$\square = \mathbf{5}$
χ	$\square = \mathbf{4}$	$\square = \mathbf{N+3}$	$\mathbf{1}$	$\mathbf{1}$
χ'	$\square = \mathbf{4}$	$\mathbf{1}$	$\square = \mathbf{N}$	$\mathbf{1}$
$\bar{\chi}$	$\overline{\square} = \bar{\mathbf{4}}$	$\overline{\square} = \overline{\mathbf{N+3}}$	$\mathbf{1}$	$\mathbf{1}$
$\bar{\chi}'$	$\overline{\square} = \bar{\mathbf{4}}$	$\mathbf{1}$	$\overline{\square} = \overline{\mathbf{N}}$	$\mathbf{1}$

Table 7: Charge assignments for particles relevant to the hypercolor confinement. They are all left-chiral. The first three groups are gauged, while the last is almost global, part of which is gauged. On top of this, χ and $\bar{\chi}$, and χ and $\bar{\chi}$, are assumed to have much smaller masses than Λ_{HC}.

	$SU(N+3)$	$SU(N)$'
Q	$\square = \mathbf{N+3}$	$\mathbf{1}$
$\bar{U}$	$\overline{\square} = \overline{\mathbf{N+3}}$	$\mathbf{1}$
$\bar{D}$	$\overline{\square} = \overline{\mathbf{N+3}}$	$\mathbf{1}$
$\bar{q}'$	$\mathbf{1}$	$\overline{\square} = \overline{\mathbf{N}}$
u'	$\mathbf{1}$	$\square = \mathbf{N}$
d'	$\mathbf{1}$	$\square = \mathbf{N}$
ξ	**adj**	$\mathbf{1}$
ψ'	$\mathbf{1}$	$\square = \mathbf{N}$
$\bar{\psi}'$	$\mathbf{1}$	$\overline{\square} = \overline{\mathbf{N}}$

$\rightarrow$

	$SU(3)_c$	$SU(N)_D$
q	$\square = \mathbf{3}$	$\mathbf{1}$
$\mathbf{q}$	$\mathbf{1}$	$\square = \mathbf{N}$
$\bar{u}$	$\overline{\square} = \bar{\mathbf{3}}$	$\mathbf{1}$
$\bar{\mathbf{u}}$	$\mathbf{1}$	$\overline{\square} = \overline{\mathbf{N}}$
$\bar{d}$	$\overline{\square} = \bar{\mathbf{3}}$	$\mathbf{1}$
$\bar{\mathbf{d}}$	$\mathbf{1}$	$\overline{\square} = \overline{\mathbf{N}}$
$\bar{\mathbf{q}}'$	$\mathbf{1}$	$\overline{\square} = \overline{\mathbf{N}}$
$\bar{\mathbf{u}}'$	$\mathbf{1}$	$\square = \mathbf{N}$
$\bar{\mathbf{d}}'$	$\mathbf{1}$	$\square = \mathbf{N}$
ψ'_c	$\square = \mathbf{3}$	$\overline{\square} = \overline{\mathbf{N}}$
$\bar{\psi}'_c$	$\overline{\square} = \bar{\mathbf{3}}$	$\square = \mathbf{N}$
λ_c	**adj**	$\mathbf{1}$
λ_D	$\mathbf{1}$	**adj**
ν'	$\mathbf{1}$	$\mathbf{1}$
ψ'	$\mathbf{1}$	$\square = \mathbf{N}$
$\bar{\psi}'$	$\mathbf{1}$	$\overline{\square} = \overline{\mathbf{N}}$

Table 8: Charge assignments for particles irrelevant to the hypercolor confinement. They are all left-chiral. The left and right tables are before and after the gauge breaking $SU(N+3) \times SU(N)' \rightarrow SU(3)_c \times SU(N)_D$ caused by the hypercolor confinement in the ψ and χ sector.

Interesting point !

QCD axion does not follow $m_a f_a \sim m_\pi f_\pi$

(solves strong CP)

$$\delta\mathcal{L} = -\underbrace{\frac{\Lambda_D^4}{2}\left((N+3)\frac{a_1}{f_D}+\frac{a_2}{f_D}\right)^2}_{\text{reasonable}} - \underbrace{\frac{\Lambda_c^4}{2}\left((N+3)\frac{a_1}{f_D}\right)^2}_{\text{reasonable}} - \boxed{\frac{\Lambda_I^4}{2}\left(\frac{a_2}{f_D}\right)^2}$$

!!

From small-scale instantons above Λ_{HC}

☆ The original idea is from Pablo's paper 1805.06465

☆ Then what's new about this paper?

They combined the idea with composite Higgs framework.

Hypercolor confinement $\xrightarrow{\text{trigger}}$ Gauge $SU(N+3)\times SU(N)' \to SU(3)_c \times SU(N)_D$

Hypercolor confinement $\xrightarrow{\text{trigger}}$ Global $SU(5) \to SO(5)$ (weakly gauged)