Accidental Composite Axions

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Introduction

$$\frac{\theta}{32\pi^2}\int d^4x\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu} \qquad\qquad \theta < 10^{-10}$$

The strong CP problem is possibly the only tuning problem of the SM that requires a dynamical solution.

$$\theta \to \frac{a(x)}{f}$$

QCD dynamics automatically aligns the minimum of the potential so that CP is not broken. This requires the existence of a U(1) Peccei-Quinn symmetry only broken by QCD anomalies.

In the SM all global symmetries arise accidentally.
For example the proton is automatically stable due to accidental baryon number conservation.

Most axion models instead impose a global symmetry:

$$\mathcal{L}_{KSVZ} = \bar{\Psi}(i\gamma^\mu D_\mu - \cancel{m})\Psi + |\partial\Phi|^2 - \lambda(|\Phi|^2 - f_{PQ}^2)^2 + y\Phi\bar{\Psi}_L\Psi_R + h.c.$$

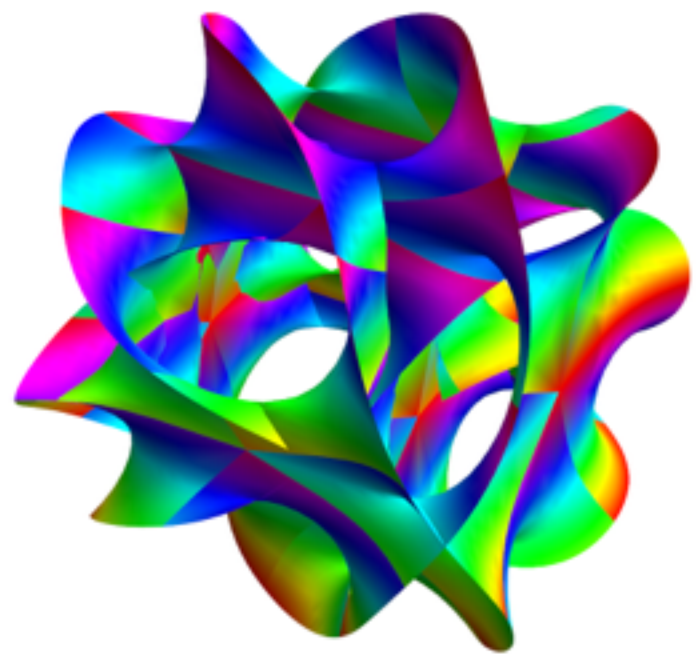
$$\Phi \to e^{i2\alpha}\Phi \qquad \Psi \to e^{i\alpha\gamma_5}\Psi$$

Fundamentally quantum gravity does not respect global symmetries:

$$\bar{\theta} \sim \frac{1}{m_\pi^2 f_\pi^2}\frac{\langle O_d\rangle}{M_p^{d-4}} \longrightarrow d > 12$$

In general a symmetry calls for an explanation.

Axions in string theory are naively better.



They originate from gauge fields wrapping non trivial cycles

$$B = \frac{1}{2\pi} \sum_{i=1}^{K} b^i(x) \omega_i(y) \qquad\qquad K = h^{(2)}(M_6)$$

Compactifications with complicated topology give rise to many axions.

Non-perturbative effects lift the axion potential

$$V_I \sim M^4 \exp(-S_{inst}) \cos(\theta + \theta_0)$$

$$S_{inst} > 200$$

Axions can acquire tree level mass from fluxes and branes

$$S_{DBI} = -\int \frac{d^{p+1}\xi}{(2\pi)^p} \alpha'^{-(p+1)/2} e^{-\Phi} \sqrt{\det\left(G_{MN} + B_{MN}\right) \partial_\alpha X^M \partial_\beta X^N}$$

The existence of axion-like particles is robust in string theory but the QCD axion is model dependent.

THIS TALK: Accidental QCD Axions in 4D

Ingredients:

- Accidental symmetries in 4D require massless gauge fields. Reducible reps give rise to accidental symmetries:

$$Q_i \to e^{i\alpha} Q_i$$

- We need U(1) anomalous under QCD. Theory should contain massless coloured fermions. U(1) must also be spontaneously broken.

- **weak coupling:** Axion is fundamental scalar. Unified theories can produce accidental symmetries.

Georgi, Hall, Wise '81

- **strong coupling:** Composite axion models.

Composite Axions

Choi, Kim '85

Take SU(N) confining gauge theory with massless (vectorial) coloured fermions and a singlet.

$$(N_c, 3) + (\bar{N}_c, \bar{3}) + (N_c, 1) + (\bar{N}_c, 1)$$

Same dynamics as QCD

$$\frac{SU(4) \times SU(4)}{SU(4)} \supset SU(3)_c$$

$$15 = 8 \oplus 3 \oplus \bar{3} \oplus 1 \qquad\qquad T_{PQ} = (\mathrm{Id}_3, \mathrm{Id}_3, -3, -3)$$

The singlet is anomalous under QCD.
If the fermion masses are set to 0 viable QCD axion.

In general we get a number of singlets equal to the number of SM reps. One combination is anomalous under QCD:

$$\mathcal{L}_a = \frac{1}{2}(\partial a)^2 - \frac{1}{32\pi^2}\frac{a}{f_{PQ}}\left[e^2 E\, F_{\mu\nu}\tilde{F}^{\mu\nu} + g_3^2\, N\, G_{\mu\nu}\tilde{G}^{\mu\nu}\right]$$

$$E = 4N_c\,\mathrm{Tr}(T_{PQ}Q^2)\ , \qquad \text{and} \qquad N\delta^{AB} = 4N_c\,\mathrm{Tr}\,(T_{PQ}T^A T^B).$$

Ex: 2 reps

$$\frac{E}{N} = \frac{d_2 E_1 - d_1 E_2}{d_2 N_1 - d_1 N_2}$$

	q_1	q_2	N	E/N
$D+L$	2	-3	$4N_c$	$-7/3$
$Q+E$	1	-6	$4N_c$	$-13/3$
$U+E$	1	-3	$2N_c$	$-10/3$
$U+V$	1	-1	$2N_c$	$-4/3$
$D+N$	1	-3	$2N_c$	$2/3$

Moose theory:

gauge

Georgi '85

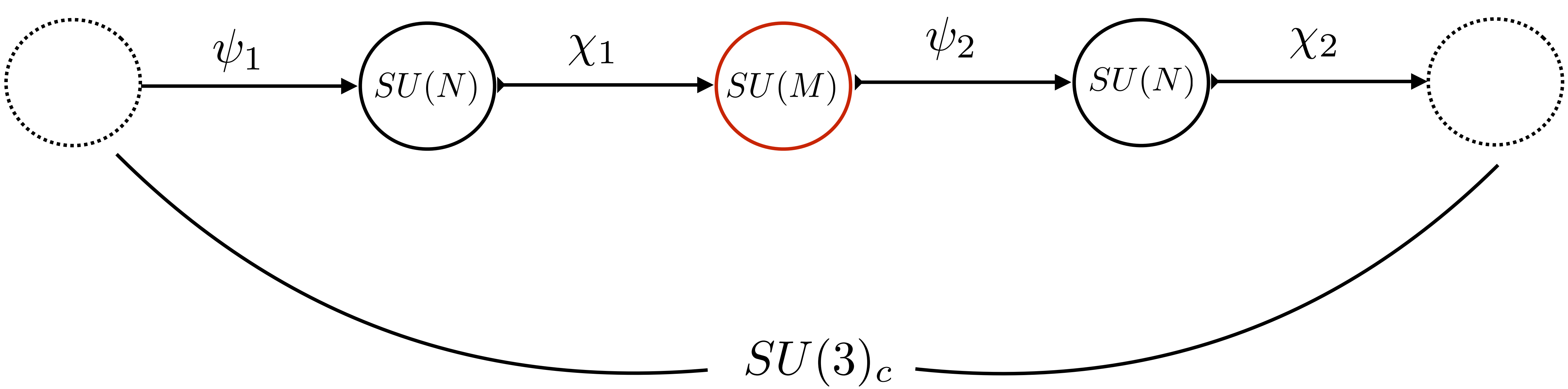
$$\frac{SU(M)_L \times SU(M)_{R_1}}{SU(M)_{L+R_1}} \quad + \quad \frac{SU(M)_{L_1} \times SU(M)_R}{SU(M)_{L_1+R}}$$

Global symmetry:

$$\frac{SU(M)_L \times SU(M)_R}{SU(M)_{L+R}}$$

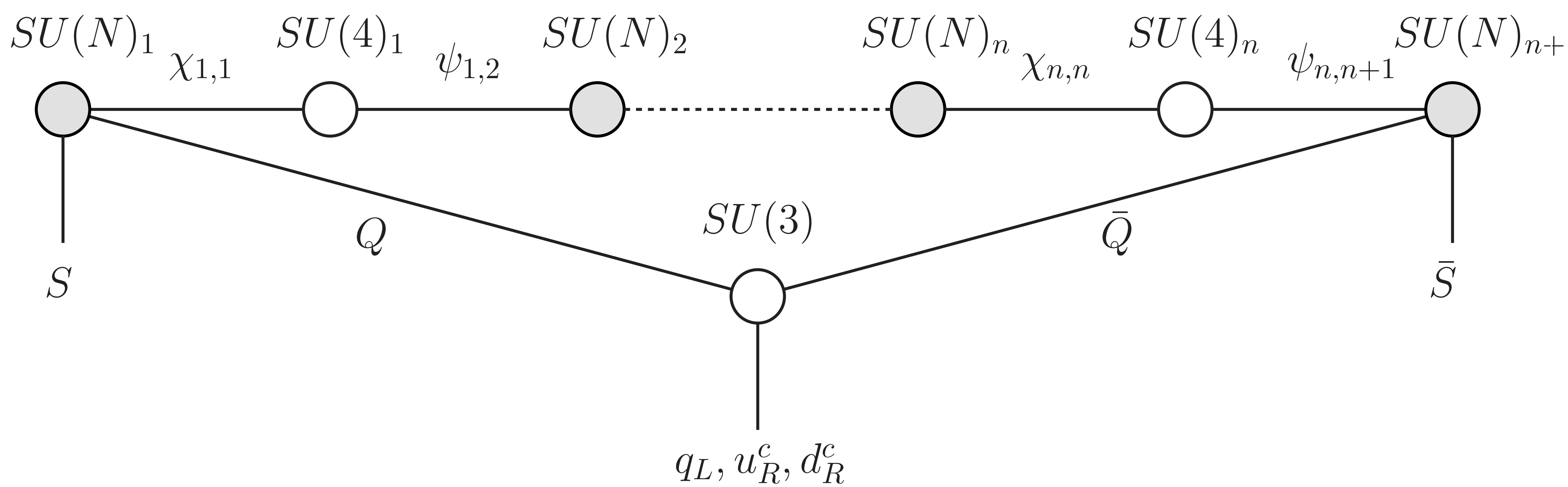
SU(N)xSU(M)xSU(N) gauge theory

$$\Psi = M(N,1,1) + (\bar{N},M,1) + (1,\bar{M},N) + M(1,1,\bar{N})$$



Mass terms are forbidden because the theory is chiral. Higher dim operators depend on the length of the moose:

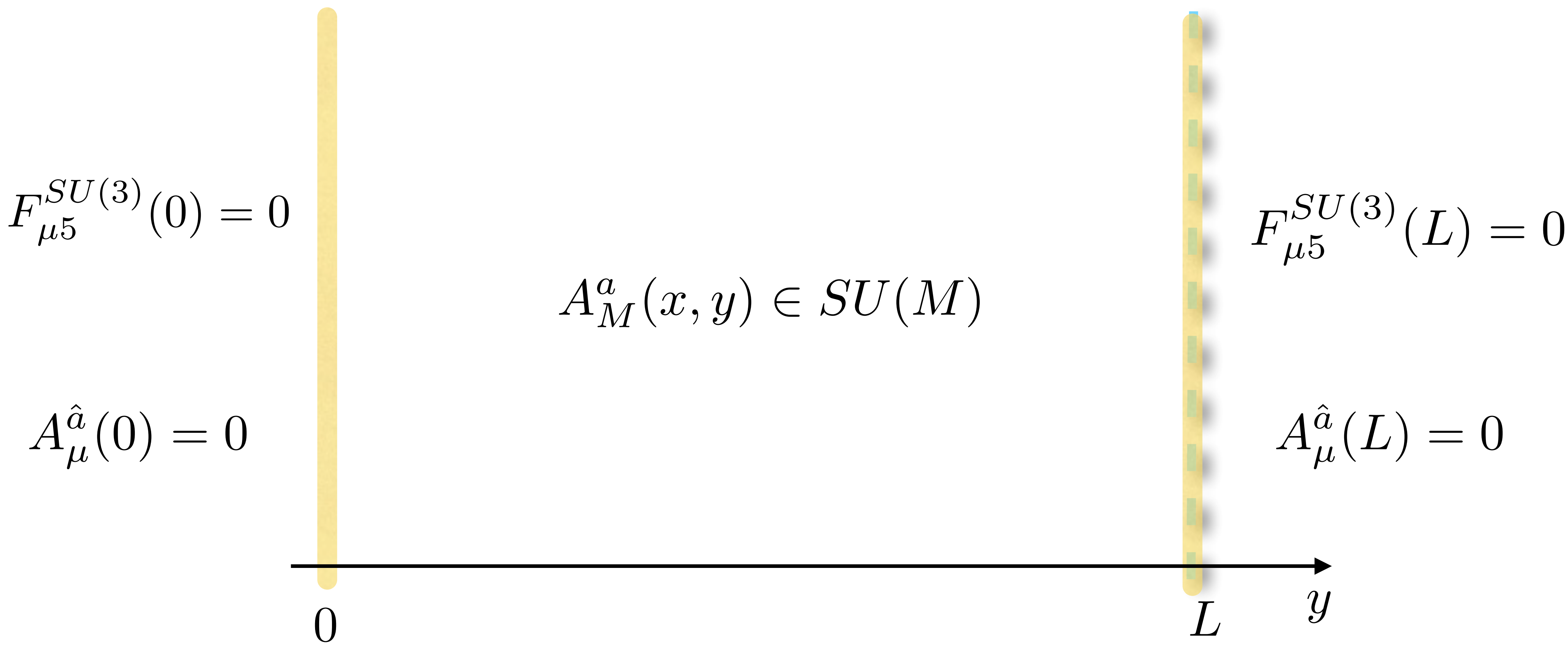
Dim=6 $\psi_1\chi_1\psi_2\chi_2$



$$\frac{1}{f^2} = \sum_{i=1}^{n} \frac{1}{f_i^2} \qquad\qquad \frac{1}{g_{SM}^2} = \frac{1}{g_0^2} + \sum_{i=1}^{n} \frac{1}{g_i^2}$$

$$n \ll 16\pi^2/g_{SM}^2$$

In the continuum limit one obtains a 5D gauge theory:



$$\text{Axion} = \int_0^L A_5^{PQ} dy$$

Choi '03

Anomalous couplings originate from Chern-Simons term:

$$S_{CS} = \frac{N_c}{96\pi^2} \int d^4x \int_0^L dz \epsilon^{MNOPQ} \mathrm{Tr}\left[A_M G_{NO} G_{PQ} + i A_M A_N A_O G_{PQ} - \frac{2}{5} A_M A_N A_O A_P A_Q\right]$$

“Axial” gauging:

$$\frac{SU(M)_L \times SU(M)_R}{SU(M)_{L+R}}$$

The SM could gauge chiral symmetry

$$\mathrm{Tr}(T_L^3) = \mathrm{Tr}(T_R^3)$$

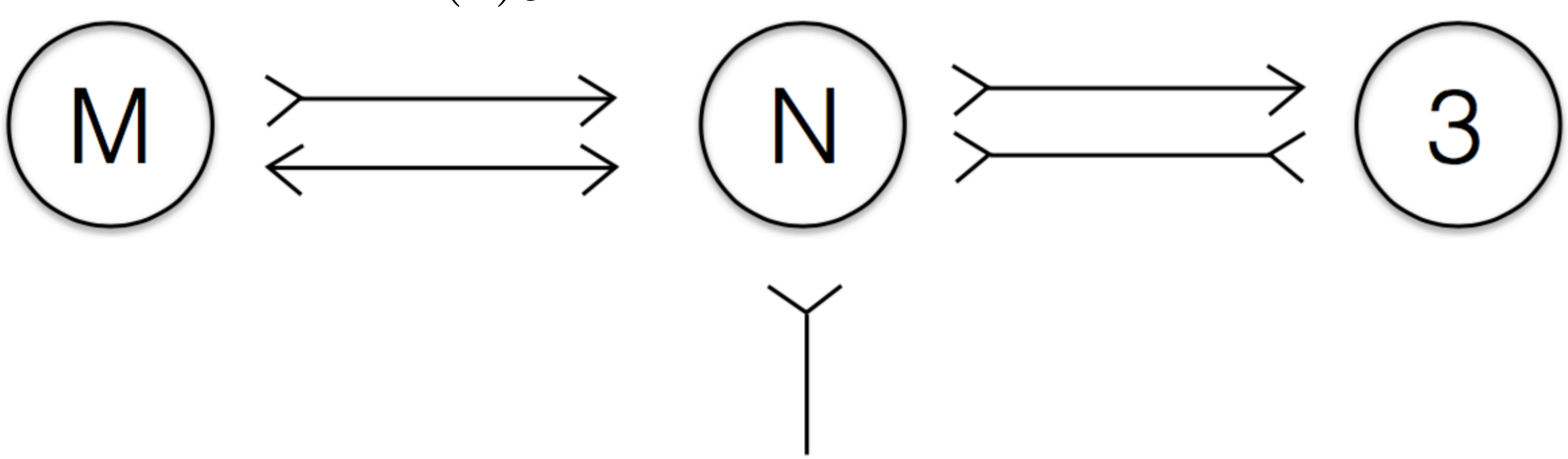
- $M = 2m$

$$SU(m)$$
$$2m = m + \bar{m}$$

$$SU(3)$$
$$2m = 3 + \bar{3} + (2m-6) \times 1$$

$$\frac{SU(2m)_L \times SU(2m)_R}{SU(2m)_{L+R}}$$

$$SU(3)_c$$



Ex: SU(N)xSU(4)xSU(3)

$$r_1 = (N, 4, 1)\,, \qquad r_2 = (\overline{N}, 1, \overline{3})\,, \qquad r_3 = (\overline{N}, 1, 1)$$
$$r_4 = (N, \overline{4}, 1)\,, \qquad r_5 = (\overline{N}, 1, 3)\,, \qquad r_6 = (\overline{N}, 1, 1)$$

Condensates:

$$r_1 r_2\,, \quad r_1 r_3\,, \quad r_4 r_5\,, \quad r_4 r_6$$

Invariant U(1):

$$U(1)_1: \quad (1, -1, -1, 0, 0, 0) \qquad\qquad A_1: \quad (0\,, N_c\,, -N_c)$$

Broken U(1):

$$U(1)_2: \quad (1, 1, 0, 0, 0, 0)\,, \qquad\qquad A_2: \quad (7\,, N_c\,, N_c)$$
$$U(1)_3: \quad (1, -1, 2, 0, 0, 0)\,, \qquad\qquad A_3: \quad (3, N_c, -N_c)$$

All topological terms eliminated. Extra Axion Like Particles.

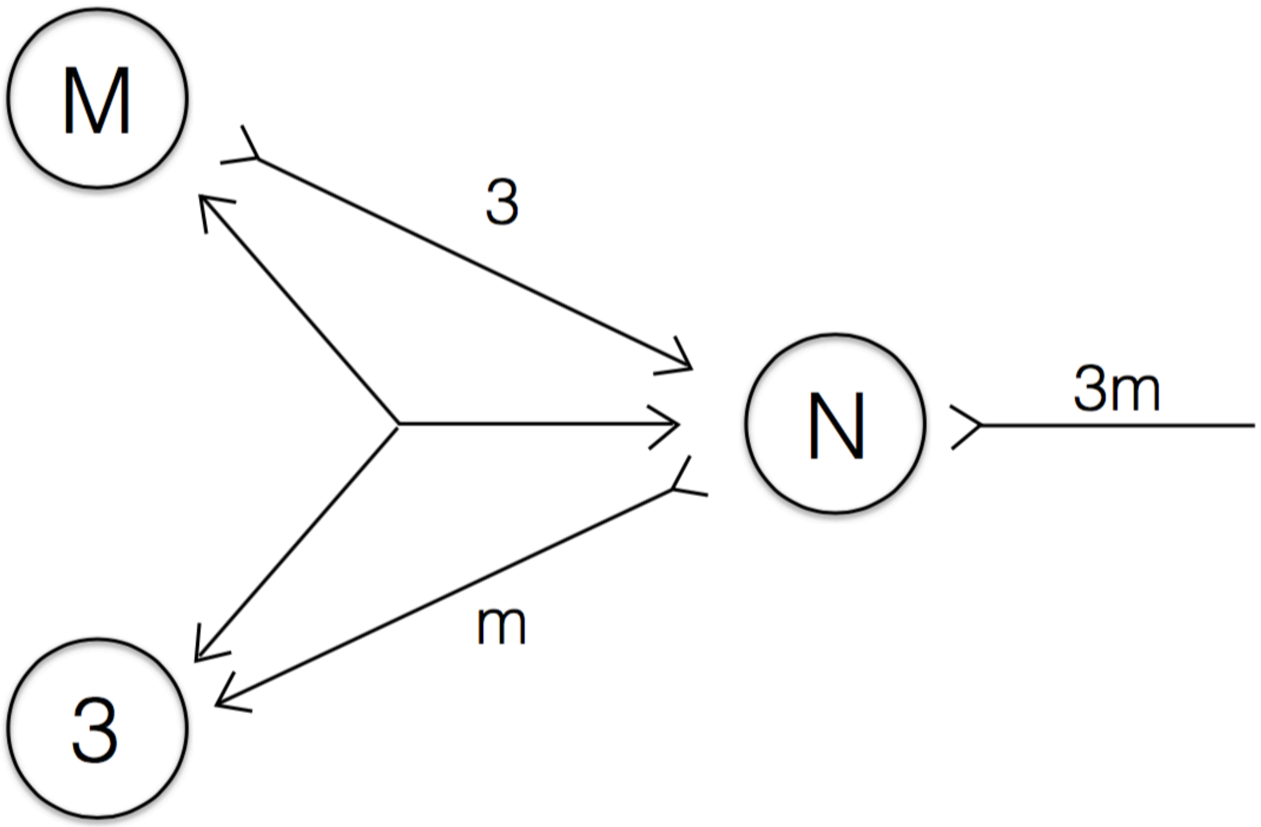
Axial gauging II:

Randall '92

Dovrescu '94

$$SU(N_c) \times SU(m) \times SU(3)$$

$$(N_c, m, 3) + 3(N_c, \bar{m}, 1) + m(\bar{N}_c, 1, \bar{3}) + 3m(\bar{N}_c, 1, 1)$$



$$SU(m) \subset \frac{SU(3m)_L \times SU(3m)_R}{SU(3m)_{L+R}} \supset SU(3)_c$$

Vacuum breaks SU(m) and preserves SU(3).

$$U(1)_{PQ} = (1\,, -1\,, 1\,, -1)$$

Higher dimensional operators controlled by m.
Strong constraints from Landau poles.

topological defects:

- **Baryons:**

If broken by dim 12 operators likely stable.

$$\tau \sim \frac{8\pi\, M_p^{16}}{m_B^{17}} \sim 10^{-40}\ \mathrm{s} \times \left(\frac{M_p}{4\pi f}\right)^{17} \qquad f > 10^{13}\,\mathrm{GeV}$$

- **Charged pions**

- **domain walls**

$$N = N_c$$

Inflation should be below PQ breaking scale:

$$H_{\mathrm{inf.}} < 10^7\ \mathrm{GeV}\left(\frac{f_{\mathrm{PQ}}}{10^{12}\ \mathrm{GeV}}\right)^{0.4} \qquad \text{(Planck)}$$

coupling to SM:

Villadoro et al. '15

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

$$-0.47(3)\frac{N}{2f_{PQ}}\partial_\mu a\,\bar{p}\gamma^\mu\gamma^5 p - 0.02(3)\frac{N}{2f_{PQ}}\partial_\mu a\,\bar{n}\gamma^\mu\gamma^5 n$$

axion-like particles:

$$V(a_{ALP}) \sim \frac{\langle\mathcal{O}_d\rangle}{M_p^{d-4}}\frac{a_{ALP}^2}{f_{\rm PQ}^2} \longrightarrow m_{\rm ALP} \sim \sqrt{\bar{\theta}}m_a < 10^{-5}\,m_a$$

$$\frac{\rho_{ALP}}{\rho_{DM}} \approx 1.6\sqrt{\frac{m_{ALP}}{\rm eV}}\left(\frac{f_{PQ}}{10^{11}\,\rm GeV}\right)^2\langle\theta^2\rangle$$

Arvanitaki et al. '09

$10^{-33}\,{\rm eV} < m_{\rm ALP} < 4\times 10^{-28}\,{\rm eV}$ CMB rotation

$10^{-18}\,{\rm eV} \lesssim m_{\rm ALP} \lesssim 10^{-10}\,{\rm eV}$ super-radiance

unification:

$$\Psi = 5 + 1 = D + L + N$$

$$T_{PQ} = D + L - 5N \qquad\qquad \frac{E}{N} = \frac{8}{3}$$

Incomplete SU(5) multiplets can improve unification ("unificaxion")

Giudice, Rattazzi, Strumia '12

$SU(5)$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	charge	name	ΔN	ΔE
1	1	1	0	0	N	0	0
$\bar{5}$	$\bar{3}$	1	$1/3$	$1/3$	D	$1/2$	$1/3$
	1	2	$-1/2$	$0, -1$	L	0	1
10	$\bar{3}$	1	$-2/3$	$-2/3$	U	$1/2$	$4/3$
	1	1	1	1	E	0	1
	3	2	$1/6$	$2/3, -1/3$	Q	1	$5/3$
15	3	2	$1/6$	$2/3, -1/3$	Q	1	$5/3$
	1	3	1	$0, 1, 2$	T	0	5
	6	1	$-2/3$	$-2/3$	S	$5/2$	$8/3$
24	1	3	0	$-1, 0, 1$	V	0	2
	8	1	0	0	G	3	0
	$\bar{3}$	2	$5/6$	$4/3, 1/3$	X	1	$17/3$
	1	1	0	0	N	0	0

Ex:

$$\Psi = D + L + Q + U$$

$$T_{PQ} = 9(D+L) - 5(Q+U)$$

$$\frac{E}{N} = \frac{6}{5}$$

$$\alpha_{\mathrm{GUT}} \approx 0.05$$

$$m_{\mathrm{GUT}} \approx 10^{17}\,\mathrm{GeV}$$

CONCLUSIONS

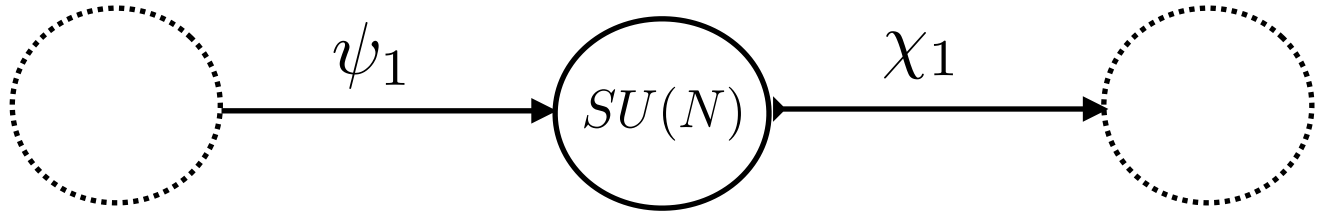
- While the axion seems the most plausible solution to the strong CP problem, an almost exact PQ symmetry is at odds with our understanding of symmetries in the SM.

- Composite axion models provide a natural framework to produce axions. Accidental QCD axions can be obtained making the theory chiral.

- Axion properties are predicted. QCD axion is often accompanied by extra light axion-like particles.

- Unification models can also provide accidental PQ symmetries. Difficult to suppress structurally higher dimensions operators.

Thaler '05



gauge: $H \subset SU(M)_L$

global: $\dfrac{SU(M)_R}{H}$

SU(m) fields eaten. Residual global symmetry:

$$\frac{SU(2m)\times U(1)}{SU(m)\times U(1)} \qquad SU(3)_c \subset SU(m)$$

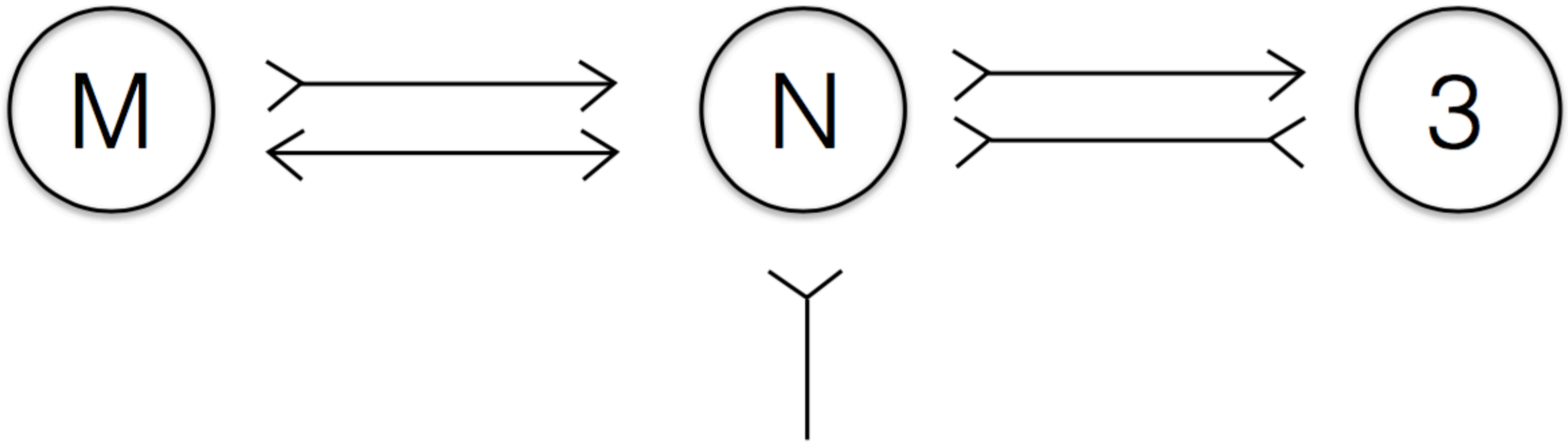
$$\mathbf{Adj}_{SU(2m)} = \mathbf{1} + \begin{array}{|c|}\hline \\ \hline \\ \hline\end{array} + \overline{\begin{array}{|c|}\hline \\ \hline \\ \hline\end{array}} + \begin{array}{|c|c|}\hline & \\ \hline\end{array} + \overline{\begin{array}{|c|c|}\hline & \\ \hline\end{array}} + \mathbf{2Adj}_{SU(m)}$$

Topological terms can be eliminated through chiral rotations if m>3:

$$U(1)\times SU(3): \qquad N_c q_{\overline{N3}} + N_c q_{\overline{N}3}$$

$$U(1)\times SU(m): \qquad N_c q_{Nm} + N_c q_{N\bar{m}}$$

$$U(1)\times SU(N_c): \qquad 3q_{\overline{N3}} + 3q_{\overline{N}3} + m q_{Nm} + m q_{N\bar{m}} + \sum_{i=1}^{2m-6} q_{\overline{N}^i}$$



Accidental PQ broken by dim-6

$$[(N_c, m, 1)(N_c, \bar{m}, 1)][(\bar{N}_c, 1, \bar{3})(\bar{N}_c, 1, 3)]$$

Extra suppression requires moose structure or more complicated gauging.