Chirality changing RG flows: dynamics and models

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arxiv:2303.08847
with S. Shukla, and M. Waterbury
arxiv:2109.01681,
with S. Ramos-Sánchez, M. Ratz, S. Shukla, and M. Waterbury

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Introduction

- Gapless spectrum and unbroken chiral symmetry are often linked and this association appears to be RG invariant. It is often assumed that a mass gap can only develop if chiral symmetry is broken, either spontaneously or explicitly
- Yet, it is well known that representations of the matter fields under unbroken chiral symmetries change as a result of RG evolution, e.g. in SUSY theories exhibiting confinement without chiral symmetry breaking.
- Razamat and Tong introduced examples of strongly coupled models with chiral matter content where mass gap was generated in the IR without chiral symmetry breaking
- These models are complimentary to Nelson-Strassler models where analogous dynamics resulted in an appearance of additional *composite* massless fields in the IR

- Our goal is to carefully analyze the dynamics of deformed s-confining models and clarify the condition under RG evolution may change chiral properties of the theory.
- These effects may be relevant model building, including string model building, where the number of the SM generations is typically used as an early selection criteria in search for viable compactifications.

A sketch

$$H \times G \longrightarrow G$$

- H is a strongly coupled group. G is a global or a weakly coupled symmetry.
- $H \times G$ matter content is chiral.
- Matter may or may not be chiral under H alone
- Matter contains spectators charged under G alone
- Model choice: Upon confinement H composites transform in reps conjugate to the spectator reps
- Choose the s-confining strongly coupled sector
- Introduce tree level terms whose IR dimension is 2
- Analyze non-perturbative dynamics to ensure chirally symmetric vacuum is not destabilized

References

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- D. Tong, arxiv:2104.03997

- M. Strassler, hep-ph/9510342
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s-confining SUSY QCD

- $SU(N)$ with $F = N + 1$ flavors

	$SU(N)$	$SU(F)_L$	$SU(F)_R$	$U(1)_B$	$U(1)_R$
Q	$\square$	$\square$	1	1	$\frac{F-N}{F}$
$\bar{Q}$	$\overline{\square}$	1	$\square$	-1	$\frac{F-N}{F}$

- D-term potential

$$V_D = \frac{1}{2g^2} \sum_a \left(Q_i^\dagger T^a Q_i - \bar{Q}_i^\dagger T^a \bar{Q}_i \right)^2$$

- Classical moduli space

$$Q = \begin{pmatrix} v_1 & 0 & \dots & & \dots \\ 0 & v_2 & & & \\ \vdots & & \ddots & & \\ & & & v_N & \dots \end{pmatrix} \quad \bar{Q} = \begin{pmatrix} \bar{v}_1 & 0 & \dots & & \dots \\ 0 & \bar{v}_2 & & & \\ \vdots & & \ddots & & \\ & & & \bar{v}_N & \dots \end{pmatrix}$$

$$Q_i^\dagger Q_j - \bar{Q}_i^\dagger Q_j = \alpha \delta_{ij}$$

s-confining SUSY QCD

	$SU(N)$	$SU(F)_L$	$SU(F)_R$	$U(1)_B$	$U(1)_R$
Q	$\square$	$\square$	1	1	$\frac{F-N}{F}$
$\bar{Q}$	$\overline{\square}$	1	$\square$	-1	$\frac{F-N}{F}$

- Classically, gauge and flavor invariant operators with R-charge 2 vanish identically

$$\det\left(\bar{Q}Q\right) \equiv 0\,, \quad \left(\bar{Q}^N\right)\left(\bar{Q}Q\right)\left(Q^N\right) \equiv 0$$

- Dynamical W not allowed
- Quantum and classical moduli spaces identical.
- At large VEV (weak coupling) $SU(N)$ is completely broken, Kähler potential canonical
- Near the origin $SU(N)$ is strongly coupled: Kähler potential not calculable

	$SU(N)$	$SU(F)_L$	$SU(F)_R$	$U(1)_B$	$U(1)_R$
Q	$\square$	$\square$	1	1	$\frac{F-N}{F}$
$\bar{Q}$	$\overline{\square}$	1	$\square$	-1	$\frac{F-N}{F}$
M	1	$\square$	$\square$	0	$\frac{2(F-N)}{F}$
B	1	$\overline{\square}$	1	F	$F-N$
$\bar{B}$	1	1	$\overline{\square}$	$-F$	$F-N$

- Moduli space of vacua parameterized by gauge invariant composites

$$M_{ij} \sim Q_i \bar{Q}_j \,, \quad B_i \sim Q^N \,, \quad \bar{B}_i \sim \bar{Q}^N$$

- Classical constraints in terms of (gauge invariant) moduli

$$\left(M^{-1}\right)_{ij} (\det M) - B_i \bar{B}_j = M_{ij} B_j = \bar{B}_i M_{ij} = 0$$

- Composites satisfy anomaly matching conditions
- Constraints implemented by a non-perturbative superpotential

$$W = \frac{1}{\Lambda^{2N-1}} \left(\bar{B} M B - \det M \right)$$

- K canonical in IR & near the origin
- Calculable but not canonical in UV & at large VEVs.

Mass gap in models with chiral matter

- Global symmetry G is chiral but the matter content is not
- Deform s-confining model
  - Weakly gauging a (sub-)group of G, e.g. $G_w = SU(F)_D$
  - Add spectators to cancel G_w^3 anomalies

	$SU(N)$	$SU(F)_D$	$U(1)_B$	$U(1)_R$
Q	$\square$	$\square$	1	$\frac{F-N}{F}$
$\bar{Q}$	$\overline{\square}$	$\square$	-1	$\frac{F-N}{F}$
M	1	$\square\!\square \oplus \begin{smallmatrix}\square\\\square\end{smallmatrix}$	0	$\frac{2(F-N)}{F}$
B	1	$\overline{\square}$	F	$F-N$
$\bar{B}$	1	$\overline{\square}$	$-F$	$F-N$
$\widetilde{M}$	1	$\overline{\square\!\square} \oplus \overline{\begin{smallmatrix}\square\\\square\end{smallmatrix}}$	0	$\frac{2N}{F}$
$\bar{X}$	1	$\square$	$-F$	$2+N-F$
X	1	$\square$	F	$2+N-F$

  - Note: other spectators reps allowed but don't lead to mass gap
  - Add tree level W

- Tree level W

$$W_{\text{tree}} = \tilde{M}\,(\bar{Q}Q) + \bar{X}\left(Q^N\right) + X\left(\bar{Q}^N\right)$$

- Full W in IR

$$W = \frac{1}{\Lambda^{2N+1}}\left(\bar{B}MB - \det M\right) + \widetilde{M}M + \bar{X}B + X\bar{B}$$

- $\det M$: irrelevant near the origin but important at large VEVs
- Analysis of the full W, including all dynamical terms, is required
- In this model: unique vacuum at the origin (as expected)
- Instructive to analyze dynamics in a weakly coupled regime at large $\widetilde{M}$.

Weak coupling analysis

- Spectator deformation changes the classical moduli space
  - All D-flat directions of $SU(N)$ are lifted
  - New flat directions appear. Parameterized by spectators.
- Can determine spectator superpotential in weak coupling regime
- At large $\widetilde{M}$ all matter fields are heavy
- Low energy theory is a pure $SU(N)$ SYM with

$$\Lambda_L^{3N} = \det\widetilde{M}\,\Lambda^{3N-F} \sim \widetilde{M}^F \Lambda^{3N-F}$$

- Gaugino condensate generates dynamical W in low energy theory

$$W = \Lambda_L^3 = \left(\det\widetilde{M}\,\Lambda^{3N-F}\right)^{1/N} \sim \widetilde{M}^{F/N}\Lambda^{(3N-F)/N}$$

- $F/N > 1$ and potential stabilized near the origin

Alternative viewpoint

- Start with spectators

	$SU(F)$	$SU(2F)$
$\widetilde{M} = \widetilde{A} \oplus \widetilde{S}$	$\overline{\begin{smallmatrix}\square\\ \square\end{smallmatrix}} \oplus \overline{\square\square}$	1
$Q, \overline{Q}, X, \overline{X}$	$\square$	$\square$

- $2F$ fundamentals of $SU(F)$ required by anomaly cancellation
- Model with one chiral $\widetilde{S}$ family and one chiral $\widetilde{A}$ family in UV
- Strongly gauge $SU(N) = SU(F-1)$ subgroup of global $SU(2F)$.
- Tree level (non-renormalizable) W consistent with symmetries
- $SU(N)$ dynamics generates mass gap.

What else can one do?

Models of chirality transmutation

- Replace $\widetilde{A}$ with $(F-4)$ $SU(F)$ antifundamentals $\bar{q}$

	$SU(F)$	$SU(2F)$	$SU(F-4)$
$\widetilde{S}$	$\bar{S}$	1	1
$Q, \overline{Q}, X, \overline{X}$	$\square$	$\square$	1
$\bar{q}$	$\overline{\square}$	1	$\square$

- Strongly gauge $SU(N) = SU(F-1)$ subgroup of $SU(2F)$
- Tree level plus dynamical superpotential

$$W = \frac{1}{\Lambda^{2N-1}}\left(\bar{B}MB - \det M\right) + \widetilde{S}S + XB + \bar{X}\bar{B}$$

- All $SU(N)$ quark superfields heavy at large $\widetilde{S}$.
- $\widetilde{S}$ stabilized at the origin
- Part of $SU(N)$ moduli space unlifted
- At the origin elementary $\tilde{S}$ and composite S become massive
- Composite A has no partner and remains massless
- Low energy theory at the origin: one chiral composite A flavor

Gapping anti-symmetrics: $SP(N)$ models

- A model with chiral antisymmetric flavor, even F

	$SU(F)$	$SU(F-4)$	$U(1)_R$
$\widetilde{A}$	$\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$	1	$\frac{2}{F-4}$
Q	$\overline{\Box}$	$\Box$	$\frac{2}{F-4}$

- Need strongly coupled sector with composites in $\overline{\begin{smallmatrix}\Box\\\Box\end{smallmatrix}}$ of $SU(F)$
- Gauge $SP(2N) \equiv SP(F-4)$ subgroup of $SU(F-4)$
- $SP(2N)$ s-confines, $M = Q^2$
- Dynamical & tree level superpotential generate mass gap

$$W = \frac{1}{\Lambda^{2N+1}} \mathrm{Pf} M + \widetilde{A} M$$

Fragile phase of $SO(N)$: no mass gap for symmetric

- Goal: mass gap for matter in chiral symmetric rep of $SU(N)$
- Composites of $SO(N)$ are symmetric
- Special case: $SO(N)$ with $N-4$ vectors ($G = SU(N-4)$)
- Vectors higgs $SO(N)$ to $SO(4) \equiv SU(2)_L \times SU(2)_R$
- Scale matching

$$\Lambda_L^6 = \Lambda_R^6 = \frac{16\Lambda^{2(N-1)}}{\det M}$$

- Dynamical superpotential

$$W = \Lambda_L^3 \pm \Lambda_R^3 = (1 \pm 1)\left(\frac{16\Lambda^{2(N-1)}}{\det M}\right)^{1/2}$$

- Two phases. Chirally symmetric point accessible in one phase
- Confining phase is analogous to
- s-confinement is *fragile*. Any deformation, e.g. mass term, destroys no-superpotential phase.

A failure mode: fragile s-confinement

- Spectators allow tree level IR superpotential

$$W_{\text{tree}} = \widetilde{S}_{ij} Q_i Q_j = \widetilde{S}_{ij} M_{ij}$$

- No dynamical W, naively there is a mass gap
- Need to check weakly coupled limits
- $\widetilde{S}$ is a classical flat direction
- At large $\widetilde{S}$ low energy physics is pure SYM $SO(N)$
- Scale matching

$$\Lambda_L^{3(N-2)} = \det \widetilde{S} \Lambda^{2N-2}$$

- Dynamical superpotential

$$W = \Lambda_L^3 = \left(\det \widetilde{S} \Lambda^{2N-2}\right)^{1/(N-2)} \sim \widetilde{S}^{(N-4)/(N-2)} \Lambda^{(2N-2)/(N-2)}$$

- Non-renormalization theorems imply that there is no SUSY vacuum near the origin unless Kähler potential is singular

Gapping symmetric: two s-confining sectors

Back to chirality transmutation model

	$SU(F)$	$SU(2F)$	$SU(F-4)$
$\widetilde{S}$	$\bar{S}$	1	1
$Q, \overline{Q}, X, \overline{X}$	$\square$	$\square$	1
$\bar{q}$	$\overline{\square}$	1	$\square$

- Strongly gauge $SU(N)$, $N = F - 1$ subgroup of $SU(2F)$. Quarks Q and $\bar{Q}$ form mesons and baryons containing S and A
- Strongly gauge $SP(M)$, $M = F - 4$ subgroup of $SU(F-4)$. Quarks $\bar{q}$ form mesons transforming as $\bar{A}$.
- Tree level superpotential

$$W_{\text{tree}} = \tilde{S}_{ij} Q_i \bar{Q}_j + \left(Q_{[i} \bar{Q}_{j]}\right) q_i q_j$$

- Composite $\bar{A}_{ij} = Q_{[i} \bar{Q}_{j]}$ picks up a mass with $A_{ij} = q_i q_j$

Other models

Csáki et al classified s-confining models. We expect that all models with non-Abelian global symmetries allow deformations exhibiting generation flow. Examples:

- $SU(N)$ with $\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$, $N\overline{\Box}$, $4\Box$
- $SU(N)$ with $\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$, $\overline{\begin{smallmatrix}\Box\\\Box\end{smallmatrix}}$, $3(\Box+\overline{\Box})$
- $SU(5)$ with $3(\overline{\begin{smallmatrix}\Box\\\Box\end{smallmatrix}}+\overline{\Box})$
- $SU(5)$ with $2\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$, $2\Box$, $4\overline{\Box}$
- $SU(6)$ with $2\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$, $5\overline{\Box}$, $\Box$
- $SU(7)$ with $2\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$, $6\overline{\Box}$
- $SP(6)$ with $\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$, $6\Box$
- Possibly a number of models with tree level W

Application: string model building

String model building:

- Choose framework, compactify to 4D
- Identify zero modes. Usually contain lots of exotics beyond SM matter
- Vectorlike exoctics can be decoupled
- Many models are not viable due to chiral exotics or wrong number of the SM flavors
- *Usually* non-perturbative QFT dynamics not considered at this stage

Chirality flow may change the number of generations. 3-generation models may acquire or loose generations in the IR. 2- or 4-generation models may flow to 3-generations in IR.

As illustration we identified semi-realistic compactifications of $E_8 \times E_{8'}$ which exhibit generation flow $2 \to 3$ and $4 \to 3$ generations.

Model scan:

- Orbifold geometry, $Z_4 \times Z_4$ $(1,1)$
- 4D gauge group contains $SU(5) \times SU(2)_s$.
- n $SU(5)_{\text{GUT}}$ reps with no $(10,2)$ and at least one $(5,2)$ or $(\bar{5},2)$
- At least one *flavon* in $(1,2)$
- Many $SU(5) \times SU(2)_s$ singlets needed to decouple non-chiral exotics
- Additional non-Abelian gauge factors under which $SU(5)$ charged fields transform as singlets are OK
- Additional $U(1)$ factors which can be broken without breaking $SU(5) \times SU(2)_s$ are OK

$4 \to 3$ model

$$G_{4D} = SU(5) \times SU(2)_s \times [SU(2)^5 \times U(1)^6]$$

$\#$	$irrep$	$label$
4	$(10, 1)$	A
4	$(\bar{5}, 1)$	$\bar{F}$
9	$(5, 1)$	F
7	$(\bar{5}, 1)$	$\bar{F}$
1	$(\bar{5}, 2)$	$\bar{F}$
170	$(1, 1)$	N
27	$(1, 2)$	ϕ

- If $SU(2)_s$ is broken the model has 4 chiral generations (+ vectorlike exotics)
- Unbroken $SU(2)_s$ has $4 \times (10, 1)$, $2 \times (\bar{5}, 1)$, $(\bar{5}, 2)$, and $(1, 2)$ (+ vectorlike exotics)
- All Yukawa's needed to gap one chiral generation are allowed
- $SU(5)$ and $SU(2)_s$ arise from different E_8's making it plausible that $SU(2)_s$ is more strongly coupled

$2 \to 3$ model

$$G_{4D} = SU(5) \times SU(2)_s \times [SU(2)^2 \times U(1)^9]$$

#	*irrep*	*label*
2	$(10, 1)$	A
2	$(\bar{5}, 1)$	$\bar{F}$
10	$(\bar{5}, 1)$	$\bar{F}$
8	$(5, 1)$	F
1	$(5, 2)$	F
240	$(1, 1)$	N
41	$(1, 2)$	ϕ

- If $SU(2)_s$ is broken the model has 2 chiral generations (+ vectorlike exotics)
- Unbroken $SU(2)_s$ has $2 \times (10, 1)$, $4 \times (\bar{5}, 1)$, $(\bar{5}, 2)$, and $(1, 2)$ (+ vectorlike exotics)
- All Yukawa's needed to gap one chiral generation are allowed
- $SU(5)$ and $SU(2)_s$ arise from different E_8's making it plausible that $SU(2)_s$ is more strongly coupled

Conclusions

- Performed a careful analysis of deformed s-confining models and clarified dynamics responsible for chirality transmustation/generation flow
- Formulate recipe for building models generating mass gap, massless composite matter, and more general chirality transmutations
- Constructed examples of string models where IR matter content, in particular, number of generations differs from naive UV expectations
- Future string model building must take strong QFT dynamics into account and existing promising models must be re-evaluated for a possibility of generation flow.