O’Raifeartaigh models with spontaneous R-symmetry breaking

Luca Ferretti

SISSA/ISAS

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Why O’Raifeartaigh models?

Interest:

- Historically: good models of stable SUSY breaking with $\langle F_X \rangle$
- Recent interest: ISS model (Intriligator, Seiberg, Shih)
  → Metastable non-SUSY vacua in $\mathcal{N} = 1$ SQCD!

Low energy theory (Seiberg dual)

$$W = \tilde{q}_{i\alpha} M_{ij} q_{j\alpha} + \mu^2 M_{ii} \quad i = 1 \ldots N_F, \quad \alpha = 1 \ldots N_F - N_C$$

→ (Weakly gauged) O’Raifeartaigh-like model

Original O’Raifeartaigh model:

- Chiral superfields $X, \phi^{(2)}, \phi^{(0)}$
- Canonical Kahler potential
- Superpotential $W = f X + n X \phi^{(0)}_2 + m \phi^{(2)}_0 \phi^{(0)}$
- R-symmetry $R(X) = R(\phi^{(2)}) = 2, R(\phi^{(0)}) = 0$
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O’Raifeartaigh models of SUSY breaking

- Fields $X_n, \phi_i$ with $n = 1 \ldots n_X, i = 1 \ldots n_\phi$
- R-charges
  \[
  R(X_n) = 2, \quad R(\phi_i) = 0
  \]
- Superpotential:
  \[
  W = \sum_n X_n g_n(\phi_i)
  \]
- Vacuum equations
  \[
  g_n(\phi_i) = 0, \quad \sum_n X_n \partial_j g_n(\phi_i) = 0
  \]
- SUSY spontaneously broken if $n_X > n_\phi$
- $(n_X - n_\phi)$-dimensional space of flat directions parametrized by $X_1 \ldots X_{n_X - n_\phi}$. Complexified R-symmetry acts as a dilatation:
  \[
  X_n \rightarrow \alpha X_n, \quad \alpha \in \mathbb{C}
  \]
- Coleman-Weinberg 1-loop effective potential: true minimum at $X_n = 0$
SUSY breaking and R-symmetry

R-symmetry plays an important role in O’Raifeartaigh models

- **Nelson-Seiberg argument:**
  Generic superpotential and SUSY breaking \(\Rightarrow\) R-symmetry

  - No R-symmetry \(\Rightarrow\) \(k\) equations in \(k\) variables \(\Rightarrow\) SUSY vacuum

  - R-symmetry \(\Rightarrow\) \(k\) equations in “\(k - 1\)” variables \(\Rightarrow\) If no solution SUSY broken

- **ISS argument:**
  *Metastable* SUSY breaking \(\leftrightarrow\) *approximate* R-symmetry
Explicit and spontaneous R-symmetry breaking

Gaugino masses $\gtrsim 100$ GeV $\Rightarrow$ R-symmetry must be broken

Two possibilities:
- Explicit breaking: vacuum metastability
- Spontaneous breaking: R-axion problem

How to achieve spontaneous breaking?
- Gauge interactions
- Perturbative dynamics of O’Raifeartaigh models (Shih model)
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The Shih model

Choose R-charges different from $R = 2, 0$

- **Fields:** $X$, $\phi(-1)$, $\phi(1)$, $\phi(3)$
- **R-charges:** $R(X) = 2$, $R(\phi(k)) = k$
- **Superpotential**

$$W = fX + NX\phi(1)\phi(-1) + M_3\phi(3)\phi(-1) + \frac{M_1}{2}\phi^2(1)$$

- **Vacuum equations $\Rightarrow$ SUSY breaking**

$$f + N\phi(1)\phi(-1) = 0$$

$$M_3\phi(3) + NX\phi(1) = 0$$

$$M_1\phi(1) + NX\phi(-1) = 0$$

$$M_3\phi(-1) = 0$$

- For $f$ small, there is a flat direction of non-SUSY minima at $\phi(-1) = \phi(1) = \phi(3) = 0$ parametrized by $X$
The Shih model

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- **Vacuum equations $\Rightarrow$ SUSY breaking**

$$f + N\phi(1)\phi(-1) = 0 \quad M_3\phi(3) + NX\phi(1) = 0$$
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Coleman-Weinberg potential in the Shih model

Flat directions are lifted by 1-loop effective potential:

\[ V_{\text{eff}}^{(1-\text{loop})}(X) = \frac{1}{64\pi^2} \text{Tr} \left( \mathcal{M}_B^4(X) \ln \frac{\mathcal{M}_B^2(X)}{\Lambda^2} - \mathcal{M}_F^4(X) \ln \frac{\mathcal{M}_F^2(X)}{\Lambda^2} \right) \]

This potential has the form

\[ V_{\text{eff}}^{(1-\text{loop})}(X) = V_0 + m_X^2 |X|^2 + \lambda_X |X|^4 + \ldots \]

where (for f small)

\[ m_X^2 = \frac{f^2}{32\pi^2} \text{Tr} \int_0^\infty dv \, v^3 \left[ \mathcal{M}_1(v)\mathcal{M}_1^\dagger(v) - \mathcal{M}_2(v)\mathcal{M}_2^\dagger(v) \right] \]

Note that \( m_X^2 \) is not positive-definite!
\[ M_1(v) = \frac{1}{\sqrt{v^2 + \hat{M}^2}} \hat{N} \left( \frac{\sqrt{2}v}{v^2 + \hat{M}^2} \right) \hat{N} \frac{1}{\sqrt{v^2 + \hat{M}^2}} \]

\[ M_2(v) = \frac{1}{\sqrt{v^2 + \hat{M}^2}} \hat{N} \left( \frac{2\hat{M}}{v^2 + \hat{M}^2} \right) \hat{N} \frac{1}{\sqrt{v^2 + \hat{M}^2}} \]

\[ \hat{N} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & N & 0 \\ 0 & 0 & 0 & N & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & N & 0 & 0 & 0 & 0 & 0 \\ N & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} , \quad \hat{M} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & M_3 \\ 0 & 0 & 0 & 0 & 0 & M_1 & 0 \\ 0 & 0 & 0 & M_3 & 0 & 0 & 0 \\ 0 & 0 & M_1 & 0 & 0 & 0 & 0 \\ M_3 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \]

The two contributions to \( m_X^2 \) are of the same order \( \rightarrow R' \) if \( m_X^2 < 0 \)

In usual O’Raifeartaigh models \( M_2 = 0 \) \( \rightarrow \) No \( R' \)
Choose the couplings such that $M_3 \lesssim 0.5 M_1$

Coleman-Weinberg potential:

Minimum with $|\langle X \rangle| \sim M_3, M_1$

Non-hierarchical R-symmetry breaking

($\mathbb{Z}_2$ unbroken)
Runaway directions in the Shih model

Go back to the classical potential

\[ V = \left| f + N \phi(1) \phi(-1) \right|^2 + \left| M_1 \phi(1) + N X \phi(-1) \right|^2 + \left| M_3 \phi(3) + N X \phi(1) \right|^2 + \left| M_3 \phi(-1) \right|^2 \]

There is a \textit{runaway direction}:

\[ \phi(1) = -\frac{f}{\lambda \phi(-1)} \quad , \quad X = \frac{m_2 f}{\lambda^2 \phi(-1)} \quad , \quad \phi(3) = \frac{m_2 f^2}{m_1 \lambda^2 \phi(-1)} \quad , \quad \phi(-1) \rightarrow 0 \]

Along this direction \( V \rightarrow 0 \) (supersymmetric runaway vacuum)

- This direction corresponds to a complexified R-charge rescaling:
  \[ \varphi(\epsilon) = \epsilon^{-R(\varphi)} \varphi \quad , \quad \epsilon \rightarrow 0 \]

- Vacua previously found are only metastable!
O’Raifeartaigh models with general R-charges

Class of models with SUSY breaking

\[ W = fX + \frac{1}{2} N^{ij} X \phi_i \phi_j + \frac{1}{2} M^{ij} \phi_i \phi_j \left( + \frac{1}{2} Q^{ij}_a Y_a \phi_i \phi_j \right) \]

Conditions: \( R(X) = R(Y_a) = 2 \), \( M^{ij}, N^{ij}, Q^{ij}_a \) symmetric, \( \det M \neq 0 \)

\( M^{ij} \neq 0 \Rightarrow R(\phi_i) + R(\phi_j) = 2 \)
\( N^{ij}, Q^{ij}_a \neq 0 \Rightarrow R(\phi_i) + R(\phi_j) = 0 \)

Vacuum equations:

\[ (M^{ij} + XN^{ij} + Y_a Q^{ij}_a) \phi_j = 0 \]
\[ f + \frac{1}{2} N^{ij} \phi_i \phi_j = 0 \]
\[ \det(M + XN + Y_a Q_a) = \det M \neq 0 \Rightarrow \text{SUSY broken} \]

For \( f \) small, non-SUSY flat directions at \( \phi_j = 0 \) parametrized by pseudomoduli \( X, Y_a \)
Spontaneous R-symmetry breaking

Quadratic part of 1-loop potential (for small $f$):

$$V_{\text{quad}}(X, Y_a) = \frac{f^2}{32\pi^2} \text{Tr} \int_0^\infty dv \, v^3 \left[ M_1(v) M_1^\dagger(v) - M_2(v) M_2^\dagger(v) \right]$$

$$M_1(v) = \frac{1}{\sqrt{v^2 + \hat{M}^2}} \left( \hat{N} \frac{\sqrt{2}v}{v^2 + \hat{M}^2} \hat{Y} \right) \frac{1}{\sqrt{v^2 + \hat{M}^2}}$$

$$M_2(v) = \frac{1}{\sqrt{v^2 + \hat{M}^2}} \left( \hat{N} \frac{\hat{M}}{v^2 + \hat{M}^2} \hat{Y} + \hat{Y} \frac{\hat{M}}{v^2 + \hat{M}^2} \hat{N} \right) \frac{1}{\sqrt{v^2 + \hat{M}^2}}$$

$$\hat{M} = \begin{pmatrix} 0 & M^\dagger \\ M & 0 \end{pmatrix}, \quad \hat{N} = \begin{pmatrix} 0 & N^\dagger \\ N & 0 \end{pmatrix}, \quad \hat{Y} = \begin{pmatrix} 0 & (NX + Q^a Y_a)^\dagger \\ NX + Q^a Y_a & 0 \end{pmatrix}$$

$\rightarrow$ Spontaneous R-symmetry breaking in a range of couplings
Flavor and gauge symmetries needed for ultraviolet completion, SUSY-breaking mediation. . .
No relevant changes in Coleman-Weinberg potential

- Easy to introduce *real representations* in the Shih model, for example SO(N) fundamentals:

\[ W = fX + NX\phi_{(1)}^{\alpha} \phi_{(-1)}^{\alpha} + M_3 \phi_{(3)}^{\alpha} \phi_{(-1)}^{\alpha} + \frac{1}{2} M_1 \phi_{(1)}^{\alpha} \phi_{(1)}^{\alpha} \]

- The simplest model with *complex representations*, for example U(N) fundamentals:

\[ W = fX + XN_5 \phi_{(5)}^{\alpha} \phi_{(-5)}^{\alpha} + XN_3 \phi_{(3)}^{\alpha} \phi_{(-3)}^{\alpha} + M_7 \phi_{(7)}^{\alpha} \phi_{(-7)}^{\alpha} + M_5 \phi_{(5)}^{\alpha} \phi_{(-5)}^{\alpha} + M_3 \phi_{(3)}^{\alpha} \phi_{(-3)}^{\alpha} \]

This model also shows spontaneous R-symmetry breaking
Runaway directions

Many models $W(\varphi_j)$ with generic R-charges have runaway directions

- Vacuum equations $\partial_i W(\varphi_j) = 0$ can be classified by R-charges:
  
  \[
  \begin{align*}
  \partial_i W &= 0, \quad R(\varphi_i) < 2 & R &> 0 \\
  \partial_i W &= 0, \quad R(\varphi_i) = 2 & R &= 0 \\
  \partial_i W &= 0, \quad R(\varphi_i) > 2 & R &< 0
  \end{align*}
  \]

- R-symmetry $\Rightarrow$ this set of equations cannot be solved . . .

  . . . but it can be possible to solve the *subset* with $R \geq 0$

- The form of the potential $V = V_{R<0} = \sum_{R(\varphi_i) > 2} |\partial_i W|^2$ does not change under complex R-symmetry transformations

- Rescaling $\varphi(\epsilon) = \epsilon^{-R(\varphi)} \varphi$ corresponds to a runaway direction:
  
  $V(\varphi(\epsilon)) \rightarrow 0$ , $\epsilon \rightarrow 0$
Runaway directions

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- Vacuum equations $\partial_i W(\varphi_j) = 0$ can be classified by R-charges:
  - $\partial_i W = 0, \ R(\varphi_i) < 2 \quad R > 0$
  - $\partial_i W = 0, \ R(\varphi_i) = 2 \quad R = 0$
  - $\partial_i W = 0, \ R(\varphi_i) > 2 \quad R < 0$

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There is a runaway direction:

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- Vacua previously found are only metastable!
Models with a single pseudomodulus

\[ W = fX + \frac{1}{2} N^{ij} X \phi_i \phi_j + \frac{1}{2} M^{ij} \phi_i \phi_j \]

Vacuum equations with \( R > 0 \):

\[
\begin{align*}
N X \phi_{(k-2)j} + M \phi_{(k)j} & = 0 \\
N X \phi_{(k-4)j} + M \phi_{(k-2)j} & = 0 \\
\ldots \\
N X \phi_{(-1)j} + M \phi_{(1)j} & = 0
\end{align*}
\]

Equations with \( R > 0 \) can be solved if \( \det M \neq 0 \) (← SUSY breaking condition)
Then the \( R = 0 \) equation \( f + N^{ij} \phi_i \phi_j = 0 \) can be solved by rescaling all \( \phi \)s.

⇒ Runaway directions exist in all generic models of this class
Most models have SUSY or non-SUSY runaway directions. Example:

\[ W = fX + (\lambda X + \eta Y)\phi_{(1)}\phi_{(-1)} + m_1\phi_{(3)}\phi_{(-1)} + \frac{1}{2}m_2\phi_{(1)}^2 \]

Here no SUSY runaway vacua, because \( R = 0 \) equations cannot be solved:

\[ f + \lambda\phi_{(1)}\phi_{(-1)} = 0 \quad \eta\phi_{(1)}\phi_{(-1)} = 0 \]

However, there is a non-SUSY runaway direction:

\[ \lambda' \equiv \frac{|\lambda|^2+|\eta|^2}{\lambda} \]

\[ \phi_{(1)} = -\frac{f}{\lambda'\phi_{(-1)}}, \quad X + \frac{\eta}{\lambda}Y = \frac{m_2f}{\lambda'^2\phi_{(-1)}^2}, \quad \phi_{(3)} = \frac{m_2f^2}{m_1\lambda'^2\phi_{(-1)}^3}, \quad \phi_{(-1)} \to 0 \]

by minimizing \( V_{R=0} \) and solving \( R > 0 \) equations
Models with more pseudomoduli

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by minimizing \( V_{R=0} \) and solving \( R > 0 \) equations.
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Metastability and remnants of SUSY vacua

ISS argument

Small explicit R-symmetry breaking terms restore supersymmetry:

\[ W_{\varepsilon} = W + \varepsilon_r W^R_r \quad R(\varepsilon_r) \neq 0 \]

SUSY vacua are pushed to infinity as \( \varepsilon_r \to 0 \)

\[
V(\tilde{\phi}_a(\varepsilon)) = \sum_b |\partial_b W(\tilde{\phi}_a(\varepsilon))|^2 = \sum_b |\varepsilon_r \partial_b W^R_r (\tilde{\phi}_a(\varepsilon))|^2
\]

Usually no control because \( \phi \sim 1/\varepsilon^k \), but for some R-breaking terms \( \varepsilon_r \to 0 \) can be thought of as an R-charge rescaling:

- Runaway directions \( \leftrightarrow \) Positions of SUSY vacua for \( \varepsilon_r \neq 0 \)
- Runaway vacuum \( \leftrightarrow \) SUSY vacuum pushed to infinity

Example: \( W^R = \sum_{R(\phi_j) > 2} \varepsilon_j \phi_j \)
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Example: \( W^R = \sum_{R(\phi_j) > 2} \varepsilon_j \phi_j \)
Conclusions

- Spontaneous R-symmetry breaking often occurs in O’Raifeartaigh models with general R-charge assignment.
- Flavor symmetries can be easily introduced.
- These models often have runaway directions (both SUSY and non-SUSY).

Recent developments (last month):

Existence of runaway directions is welcome, because they can be lifted by 1-loop effects leading to metastable vacua with broken R-symmetry (*pseudo-runaway*) (Essig, Sinha, Torroba).

There are interesting models with $R \neq 0, 2$ and spontaneous R-symmetry breaking, based on ISS model.
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Recent developments

- Essig, Sinha, Torroba: next talk

\[ W = \Phi \text{tr} M + \text{tr} q M \tilde{q} + \Phi \text{tr} P \tilde{P} + (\det P \tilde{P})^{-\frac{1}{N_c - N_f}} \]

SUSY runaway direction lifted by CW potential

- Cho, Park: ISS + singlets
  Same as Shih model

- Abel, Durnford, Jaeckel, Khoze: ISS + baryonic term

\[ W = \tilde{q}_{i\alpha} M_{ij} q_{j\alpha} + \mu^2 M_{ii} + m \epsilon^{rs} \epsilon^{\alpha\beta} q_{r\alpha} q_{s\beta} \]

Non-SUSY runaway direction lifted by CW potential

⇒ Spontaneous R-symmetry breaking more generic than expected!