Sequestered Conformal Anomaly Mediation (SCAM)

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Introduction

- Supersymmetry somewhat out of fashion
- Not found at LHC
- Been well studied

But

- Essential to string theory
- Likely essential to stable vacua
- Relevant to some axion models
- Tool to study strongly interacting theories

Intro Continued

- Supersymmetry breaking even less fashionable
- Messy and unsatisfying
- Need both to break susy and to communicate it
  - Often flavor a probem when susy broken
- But essential and interesting questions remain

- How to stabilize moduli
  - Moduli a feature of superymmetric theories

- How isolated can SUSY breaking be
  - Can superpartners be protected from supersymmetry-breaking

Anomaly-Mediation

- Anomaly mediation seemed to address latter
- Idea is that gravity mediates supersymmetry breaking universally
  - Always suppressed by gravity scale
  - In extra-dimensional context usually suppressed by volume
- Conformal compensator otoh couples to any violation of 4d scale invariance, no matter where in space
- So if conformal compensator has an F term, susy breaking loop-level masses for all
- Seems NOT suppressed by size of extra dimension
- More universal

Anomaly Mediation

Superpotenttial
Kahler potential but for sequestering f more natural

$$\frac{\mathcal{L}}{\sqrt{-g}} = \int d^4\theta |\mathbf{C}|^2 f\left(Q_i^\dagger, e^{-V}Q_i\right) + \left[\int d^2\theta \left(\mathbf{C}^3 W(Q_i) + \tau(Q_i)\mathcal{W}_\alpha \mathcal{W}^\alpha\right) + h.c.\right], \qquad (2.1)$$

where W is the superpontial and f is related to the Kähler potential K by

$$f = -3M_P^2 e^{-K/3}. \qquad (2.2)$$

Conformal compensator
Introduces spurious scale symmetry
Plays important role

The conformal compensator, $\mathbf{C}$, is a spurion superfield which is introduced to formally restore the scale invariance of the theory. Scale invariance is then explicitly broken by the gauge-fixing

$$\mathbf{C} = 1 + \theta^2 F_C. \qquad (2.3)$$

A non-zero F_C does not break supersymmetry by itself, in contrast to the F-components of physical chiral multiplets. One way this can be seen as it is responsible for generating the SUSY-preserving mass splittings in AdS space [28, 29, 31]. As we will show below, it is the only source of negative energy density in the potential, so must be of the same order as the SUSY-breaking F-terms if we are to end with a theory in Minkowski space after SUSY-breaking.

For now we focus on deriving the effective potential for the scalar components of the Q_i, neglecting the fermions and gauge fields. Solving for the F-terms gives

$$F_i^\dagger = (K^{-1})^{ij}\left(\frac{\partial W}{\partial q_j} + \frac{W}{M_P^2}\frac{\partial K}{\partial q_j}\right), \qquad (2.4)$$

$$F_C^\dagger = \frac{\partial K}{\partial q_j}\frac{F_j^\dagger}{3M_p^2} + e^{K/3}\frac{W}{M_P^2}, \qquad (2.5)$$

where K_{ij} is the Kähler metric

$$K_{ij} = \frac{\partial^2 K}{\partial q_i^\dagger \partial q_j}. \qquad (2.6)$$

Potential has kinetic term
Contributions from superpotential, gauge interactions

Plugging this into (2.1) and performing a Weyl rescaling to go the Eistein frame gives the following Lagrangian:

$$\frac{\mathcal{L}}{\sqrt{-g}} = K_{ij}(\partial q_i^\dagger)(\partial q_j) - V_F(q_i^\dagger, q_i) - V_D(q_i^\dagger, q_i), \qquad (2.7)$$

SUSY Potential and AM

where V_F is the potential from the F-terms and V_D the D-term potential coming from the couplings to gauge fields. These are given by

Notice the unique negative contribution

$$
\begin{aligned}
V_D(q_i^\dagger, q_i) &= \frac{1}{2}\sum_a D_a^2 = \sum_a \frac{g_a^2}{2}\left(\frac{\partial K}{\partial q_i} t^a q_i\right)^2 , \\
V_F(q_i^\dagger, q_i) &= e^K K^{ij} F_i^\dagger F_j - 3M_P^2 e^{K/3} |F_C|^2 , \qquad (2.8) \\
&= e^K \left[(K^{-1})^{ij} \left(\frac{\partial W^\dagger}{\partial q_i^\dagger} + \frac{W^\dagger}{M_P^2}\frac{\partial K}{\partial q_i^\dagger}\right)\left(\frac{\partial W}{\partial q_j} + \frac{W}{M_P^2}\frac{\partial K}{\partial q_j}\right) - 3\frac{|W|^2}{M_P^2}\right] ,
\end{aligned}
$$

where the sum over a in the first line is over the different gauge groups. Here we see that V_D is strictly positive and the only negative contribution to V_F comes from F_C. Tuning the cosmological constant to zero after SUSY breaking relates F_C to the SUSY-breaking energy density, regardless if it comes from F- or D-term breaking. This means that at the minimum

$$
M_P^2 |F_C|^2 = \frac{e^{2K/3}}{3} K^{ij} F_i^\dagger F_j + \frac{e^{-K/3}}{6} \sum_a D_a^2 . \qquad (2.9)
$$

While F_C is not responsible for breaking supersymmetry itself, it must be nonzero in any realistic model of SUSY breaking.

Compensator F term

- So we see that in the presence of a nonzero superpotential, the F_C term turns on
  - Value determined to cancel supersymmetry breaking energy to get flat space.

- Notice that F_C really has nothing to do with susy breaking. It's value is determined by susy breaking but its source is whatever generates negative energy through F_C.

- This leads to predictive susy breaking masses.

Take gaugino mass as an example

Important point is that masses through scale dependence

Virtually guaranteed in a physical field theory

$$\tau = \frac{1}{g_0^2} + 2b\log\left(\frac{\mu}{\Lambda_{uv}C}\right), \tag{2.10}$$

where Λ_{uv} is the UV cutoff and b is the 1-loop coefficient in the β-function for g:

$$\beta(g) = \frac{dg}{d\log(\mu)} = -bg^3. \tag{2.11}$$

Substituting equation (2.10) back into (2.1) we find that there is now a mass term for the gauginos which goes like

$$V_{\lambda,\,\mathrm{mass}} = -\frac{\beta(g)}{2g}F_C\lambda\lambda. \tag{2.12}$$

Mass proportional to beta function

Proportional to F_C

AM Most Interesting When Sequestering

- AM suppressed by gravity, loops
- If other sources of communication of SUSY breaking those likely dominate
  - AM might however be dominant source of gaugino mass in theories without singlets Randall, Sundrum/ Giudice Luty, Murayama, Rattazzi
- But unlikely to be dominant source of scalar mass in general
  - Expect direct interactions in Kahler potential
- Exception is sequestering; no direct interactions Randall, Sundrum
- Would be fine-tuned unless motivated by an extra dimension
- **So we study anomaly mediation in a five-dimensional setup**

Sequestering and an Extra Dimension

Without sequestering

$$\Delta\mathcal{L} \sim \int d^4\theta \, \frac{1}{M_P^2} |X|^2 |Q|^2 , \qquad (2.14)$$

his will lead to scalar masses of order

$$\Delta m_q^2 \sim \frac{|F_X|^2}{M_P^2} , \qquad (2.15)$$

vhich is generically larger than the anomaly mediated contribution which is suppressed by additional owers of $\beta(g)$. Anomaly mediation is typically only the dominant contribution to SUSY breaking vhen the Kähler potential and superpotential have a sequestered form

$$f = f_{\rm vis} + f_{\rm hid} , \qquad W = W_{\rm vis} + W_{\rm hid} , \qquad (2.16)$$

If this structure, direct interaction forbidden
Motivation for this structure is locality
Most natural with extra dimensions and branes
Need to communicate susy breaking through an extra dimension

Raises Several Puzzles

- When you have nontrivial geometry, why doesn't communication from 5d F- term depend on position (that is wavefunction)?
  - 4d result seems robust
- Physicists have assumed negative energy generated by superpotentials
  - on branes!
    - Seems natural; sequester susy breaking and sequester superpotential
- But: if you "generate" negative energy on one brane, why isn't susy breaking spectrum sensitive to location
- Also we know 4d cc same on every slice if warped; how does theory account for this?

More Puzzles

- As we will see you naturally have no-scale N=2 in bulk. Equation of motion for modulus sets F_C to zero!
- Has been argued this implies F_C term depends on stabilization mechanism for the extra dimension
  - By this logic, can't just ask about F_C; need to know what stabilizing field is doing too
- Also 5d with branes is a singular space
  - Do delta functions affect the answer?
- Final question is why has no one actually worked it out fully in 5d, given these uncertainties !!

Toy Models

- The answer to last question is probably that it’s messy
  - And didn’t seem necessary
  - 4d Theories seemed to suffice
- We will see this is not the case
- To illustrate, I’ll present two toy models
  - Model I: Problem from No-Scale
  - Model II: Problem from singular space

Toy Model I: Problem from No-Scale

- No-scale structure physically motivated
- Lowest component of Sigma is the radion
- $\Sigma \equiv \varphi_\Sigma - \theta\chi_\Sigma - \theta^2 F_\Sigma$
- $M_p^2 = M^3 r$
- So expect f scales like Sigma
- Recall $f = e^{-K/3}$

$$K = -3 \log \mathcal{V}_\Sigma = -3 \log \left(\Sigma + \Sigma^\dagger - \partial_y V\right)$$

Toy Model I: Compensator F term Vanishes!

$$\frac{\mathcal{L}_{\text{toy model}}}{\sqrt{-g}} = \int dy \left\{ -\int d^4\theta \, (\Sigma + \Sigma^\dagger)|\mathrm{C}|^{4/3} - \int d^2\theta \, \mathrm{C}^2 \left[W_{\text{bulk}} + \delta(y) W_0 + \delta(y-\pi) W_\pi \right] \right\}, \quad (2.17)$$

where $y \in [0, \pi]$ is the 5'th co-ordinate. C is the conformal compensator, and we note that the powers of C are different to those of equation (2.1) because the compensator has weight 3/2 in 5 dimensions. While there is no explicit kinetic term for the radion above, one is generated after going to the Einstein frame in 4d (see e.g. [37]).

The equation of motion for F_Σ is:

$$\frac{1}{\sqrt{-g}} \frac{\delta \mathcal{L}_{\text{toy model}}}{\delta F_\Sigma} = -C F_C^\dagger = 0, \quad (2.18)$$

and as the potential is proportional to F_C it vanishes identically. This result is due to the 'no-scale' form of the Kähler potential [84, 85]

[redacted]

Toy Model II: Potentially Dangerous Singularities

- Break No-Scale; eg at loop level

$$\frac{1}{\sqrt{-g}}\Delta\mathcal{L}_{\rm toy\ model} = -\beta\int dy\int d^4\theta\,(\Sigma+\Sigma^\dagger)^{-2}|C|^{4/3}$$

$$F_C^\dagger = \frac{\beta C^{5/3}}{(M_5 r)^4}\left(W_{\rm bulk}+\delta(y)W_0+\delta(y-\pi)W_\pi\right)\,,\qquad F_\Sigma^\dagger = -3C^{2/3}\left(W_{\rm bulk}+\delta(y)W_0+\delta(y-\pi)W_\pi\right)\,.$$

Proportional to β as you would expect

- Potential no longer vanishes
- However, it is badly singular

$$\frac{\mathcal{L}_{\rm singular}}{\sqrt{-g}} = \frac{2\beta\, C^{8/3}}{(M_5 r)^4}\left(|W_0\delta(y)|^2+|W_\pi\delta(y-\pi)|^2\right)$$

How to Handle Singular Terms?

1. Standard approach is to use eft at level of *superpotential*
   - Integrate over y; seems fine
   - However, standard eft applies at level of potential
   - There is no justification for this procedure (it's wrong)
2. Alternatively add counterterm
   - But delta squared counterterm leads to higher order in delta
   - Nonrenormalizable theory with arbitrary counterterms
3. Our approach; as with nonsusy theories solve for zero modes first
   - Apply same approach to auxiliary fields
   - Solve for bulk fields and integrate them ouut
   - But solve for auxiliary fields too
   - Derive *potential* of low-energy theory
     - What we would do in non-SUSY theories

Why Nontrivial

- Fields sourcing with delta function conventional
  - Fields are dynamical, delta function source and solve equation of motion for bulk field
- Auxiliary fields different
  - Nondynamical
  - Delta function in F term remains
  - At end all squares of such terms have to cancel
    - Usually in each F term individually
    - Which means sourcing bulk fields to cancel delta functions
- We will however see that it is possible for delta squared to cancel in potential
- When loop corrections break no-scale form, requires stabilizing bulk fields that adjust

Heads up on bottom line: Implication

- Boundary superpotentials generate zero or positive energy contributions
  - Not negative energy as expected from superpotential
    - So not responsible for 4d anomaly mediation!
      - But can generate susy breaking, “5d anomaly mediation”
- 4d Anomaly Mediation derives from bulk superpotential

However

- Can get brane anomaly-mediation in 5d
  - Suppressed by breaking of no-scale structure
- Such terms have to be added explicitly as susy-breaking terms in low-energy theory

- Note that compensator roles for anomaly-mediation and generating negative energy can decouple in 5d theory
- When this happens won't be captured in 4d EFT

- We now see how this works
  - Also see how brane superpotentials sometimes act as sources (even if nominally field-independent!
- See what is needed for negative energy
- Key will be breaking no-scale structure in bulk and bulk superpotential
  - Note difference to what is generally assumed

First: Add Source Terms to Stabilize Generalizes Goldberger-Wise to SUSY

$$C_4 = C_+^{2/3}$$

$$W|_{y=0} = -\frac{4J_0\Phi_+}{C_+}, \qquad W|_{y=\pi} = \frac{4J_\pi\Phi_+}{C_+},$$

$$\mathcal{L}_{\rm bdy} = 4e^{3\sigma}\left[-\delta(y)\int d^2\theta\, C_+ J_0 \Phi_+ + \delta(y-\pi)\int d^2\theta\, C_+ J_\pi \Phi_+ + h.c.\right],$$

$$= 4e^{3\sigma}\left[-\delta(y)\left(C J_0 F_{\Phi_+} + F_{C_+} J_0 \varphi_+\right) + \delta(y-\pi)\left(C J_\pi F_{\Phi_+} + F_{C_+} J_\pi \varphi_+\right) + h.c.\right]$$

Find Background Solution

$$F^\dagger_{\Phi_+} = -\frac{e^\sigma}{r}\left(\partial_y + \frac{3\dot\sigma}{2} - g_h M_5 r\right)\varphi_- + \frac{e^\sigma M_5^{3/2}}{r}\left[\delta(y)J_0 - \delta(y-\pi)J_\pi\right] + \mathcal{O}\left(\frac{|\varphi_\pm|^3}{M_5^3}\right)$$

terms in the F-term equation of motion for φ_-. To see this, we can write the odd field φ_-
$\varphi_- = \Theta(y)\overline{\varphi}_-$, where $\overline{\varphi}_-$ is even. y derivatives acting on φ_- then give δ-function terms:

$$\partial_y\varphi_- = 2\left[\delta(y) - \delta(y-\pi)\right]\overline{\varphi}_- + \Theta(y)\partial_y\overline{\varphi}_- \,. \qquad ($$

$$\overline{\varphi}_-(0) \simeq \frac{M_5^{3/2}J_0}{2}\,, \qquad \overline{\varphi}_-(\pi) \simeq \frac{M_5^{3/2}J_\pi}{2}\,.$$

Requiring that $F^\dagger_{\Phi_+} = 0$ with the above boundary conditions then leads to the solution

$$\overline{\varphi}_-(y) = \frac{M_5^{3/2}J_0}{2}\exp\left(-\frac{3\sigma(y)}{2} + rM_5 g_h y\right)\,,$$

the boundary condition on the IR brane is satisfied only if

$$J_0\exp\left(-\frac{3\sigma(\pi)}{2} + rM_5 g_h\pi\right) = J_\pi\,.$$

SUSY GW Stabilization!

SUSY GW

- Found a 5d supersymmetric solution for particular value of r

$$r = \frac{1}{(g_c + g_h) M_5 \pi} \log\left(\frac{J_\pi}{J_0}\right)$$

- If additional perturbations—energy for example—one has a nonsusy solution
- Then see full solution to second order eq (as with nonsusy)
- Necessary to satisfy both boundary conditions
- Supersymmetric if relation above satisfied and model has no additional terms

- Can also see in 4d: 4d EFT is mimimized for susy value of r

$$V_{\rm eff} = \frac{2M_5^4 (g_c - 3g_h) \left| J_\pi - J_0 e^{\pi M_5 r (g_c + g_h)} \right|^2}{3\left(e^{\frac{8}{3}\pi g_c M_5 r} - e^{2\pi M_5 r (g_c + g_h)}\right)}$$

Now Add Boundary Superpotentials

$$\mathcal{L}_{\rm bdy} = 4e^{3\sigma}\left[\delta(y)\int d^2\theta\ (\mathbf{C}_+^2 W_0 + \mathbf{C}_+ J_0 \Phi_+) - \delta(y-\pi)\int d^2\theta\ (\mathbf{C}_+^2 W_\pi + \mathbf{C}_+ J_\pi \Phi_+) + h.c.\right]$$

$$= 4e^{3\sigma}\Big[\delta(y)\left(C J_0 F_{\Phi_+} + F_{C_+}(J_0\varphi_+ + 2CW_0)\right) + h.c.$$

$$- \delta(y-\pi)\left(C J_\pi F_{\Phi_+} + F_{C_+}(J_\pi\varphi_+ + 2CW_\pi)\right) + h.c.\Big]. \qquad (4$$

- Nonzero radion auxiliary
  - This leads to Scherk-Schwartz supersymmetry breaking
    - Pomarol, Marti
    - F_Σ ~W, F_C~0
- No-scale still preserved so energy vanishes
- Since we are interested in anomaly mediation
- Need to break no-scale
  - Here we do it with a loop correction term

$$\mathcal{L}_{\mathrm{D}} = -3e^{2\sigma} \int d^4\theta \ \left(-\frac{8\beta}{9}\mathcal{V}_{\Sigma}^{-2} + \mathcal{V}_{\Sigma}\right) \left[\Sigma_a^{\dagger} \left(e^{-2g_c\sigma_3 V}\right)_b^a \Sigma^b - \Phi_a^{\dagger} \left(e^{-2g_h\sigma_3 V}\right)_b^a \Phi^b\right]^{2/3}$$

- Issue here is δ squared terms
- Because of form of no-scale potential ($F_C^+F_C+F_CF_\Sigma$+hc)
- F_Σ can turn on when F_C=0 (when F's~δ(r)
- Now with β term $F_\Sigma^+F_\Sigma$
- So $F_\Sigma$induces δ squared; need to eliminate
- We need hypermultiplet fields to turn on or adjust
- Find both compensator and radion have nonzero vevs
- But still zero energy at minimum!

Solve in presence of perturbation

$$V|_{\rm singular} = \frac{8}{M_5^4 r^5}\Big\{[\delta(y)]^2\left((M_5 r)^4\left|J_0 M_5^{3/2} + W_0\varphi_+^\dagger - \overline{\varphi}_-\right|^2 + \beta\left(\frac{1}{9}|J_0 M_5^{3/2} - \overline{\varphi}_-|^2 - 2|W_0|^2\right)\right) \quad (5.$$

$$+ [\delta(y-\pi)]^2\left((M_5 r)^3\left|J_\pi M_5^{3/2} + W_\pi\varphi_+^\dagger - \overline{\varphi}_-\right|^2 + \beta\left(\frac{1}{9}|J_\pi M_5^{3/2} - \overline{\varphi}_-|^2 - 2|W_\pi|^2\right)\right) \quad (5.$$

where we have kept terms up to quadratic in combinations of the W's, J's and $\varphi_\pm$'s. We have a
used $\varphi_- = \Theta(y)\overline{\varphi}_-$, as discussed in section 5.1. Setting $V|_{\rm singular} = 0$ does not have a unique soluti
but the one which minimizes the potential turns out to be for $\varphi_+ = 0$ and

$$\overline{\varphi}_-(0) = M_5^{3/2}\left(J_0 + \frac{\sqrt{2\beta}W_0}{(M_5 r)^2}\right), \qquad \overline{\varphi}_-(\pi) = M_5^{3/2}\left(J_\pi + \frac{\sqrt{2\beta}W_\pi}{(M_5 r)^2}\right). \quad (5.$$

As promised, there is a nonzero F-term for both the radion and compensator,

$$F_{C_+}^\dagger|_{\rm bdy} = -\frac{18\beta e^\sigma}{M_5^{3/2} r^4}\left(\delta(y)W_0 + \delta(y-\pi)W_\pi\right), \quad (5.$$

$$F_\Sigma^\dagger|_{\rm bdy} = -2e^\sigma M_5\left(\delta(y)W_0 + \delta(y-\pi)W_\pi\right) + \mathcal{O}(\beta), \quad (5.$$

which will lead to Scherk-Schwarz SUSY-breaking [74]. This agrees with the results of ref.'s [67, 70,

Effective Potential

$$V_{\text{eff}} = (4+2\epsilon)kM_5^3\rho^{(4+2\epsilon)}\left|J_0 + \frac{\sqrt{2}\beta W_0}{(M_5 r)^2} - \left(J_\pi + \frac{\sqrt{2}\beta W_\pi}{(M_5 r)^2}\right)\rho^{-\epsilon}\right|^2 + \mathcal{O}\left(\rho^8, \beta^2\rho^4\right) . \qquad (5.31)$$

We can also write it in a supersymmetric way, following the approach of section 5.2.1, which leads to the effective superpotential

$$W_{\text{eff}}(\rho) = \sqrt{6(2+\epsilon)}\left(\frac{k}{M_5}\right)^{3/2}\left(\frac{\left(J_0 + \frac{\sqrt{2}\beta W_0}{(M_5 r)^2}\right)\rho^{3+\epsilon}}{3+\epsilon} - \frac{\left(J_\pi + \frac{\sqrt{2}\beta W_\pi}{(M_5 r)^2}\right)\rho^3}{3}\right) . \qquad (5.32)$$

Note interesting phenomenon characteristic of Scherk Schwartz
We broke supersymmetry but can still find zero energy minimum
This is true even though we broke no-scale with beta!
Means more work if we want to get negative energy minimum (to cancel positive susy breaking energy)
Also note boundary superpotential acting as a correction to source term

Even Cooler

- We will show how to get what we want (negative energy) shortly
- But for now note the interesting phenomenon: **Sourced a field with a constant superpotential**
- Let's turn off J's and see if we can just source with superpotential alone (even though superficially field-independent!)
- Answer is yes and yields a supersymmetric stabilization

Superpotential as Source

- Set Js to zero for now
- Potential (without breaking no-scale)

$$V|_{\text{sing.}} = \frac{16}{r}\left([\delta(y)]^2 \left|\overline{\varphi}_- - W_0\varphi_+\right|^2 + [\delta(y-\pi)]^2 \left|\overline{\varphi}_- - W_\pi\varphi_+\right|^2\right) + \mathcal{O}\left(\frac{|\varphi|^4}{M_5^3 r}\right) .$$

- Clearly we can eliminate singularities with zero fields
- But we eliminate potential too in the process!
- Result of no-scale potential
- So we need to break no-scale
- Can happen naturally at loop level

Superpotential as Source -with No-Scale Breaking

$$\mathcal{L}_{\rm D} = -3e^{2\sigma}\int d^4\theta\ \left(-\frac{8\beta}{9}\mathcal{V}_\Sigma^{-2} + \mathcal{V}_\Sigma\right)\left[\Sigma_a^\dagger\left(e^{-2g_c\sigma_3 V}\right)_b^a\Sigma^b - \Phi_a^\dagger\left(e^{-2g_h\sigma_3 V}\right)_b^a\Phi^b\right]^{2/3}$$

- We can't solve all F terms=0 but can solve delta squared term in potential vanishes!

$$V|_{\rm sing.} = \frac{16}{r}\left([\delta(y)]^2\left|\overline{\varphi}_- - W_0\varphi_+\right|^2 + [\delta(y-\pi)]^2\left|\overline{\varphi}_- - W_\pi\varphi_+\right|^2\right) + \mathcal{O}\left(\frac{|\varphi|^4}{M_5^3 r}\right)$$

$$\Delta V|_{\rm sing.} = \frac{16\beta}{9M_5^3 r^4}\Big\{[\delta(y)]^2\left(|\overline{\varphi}_-|^2 - 17|W_0\varphi_+|^2 + 8W_0(\overline{\varphi}_-^\dagger\varphi_+^\dagger + \overline{\varphi}_-\varphi_+) - 9W_0^2M_5^3\right)$$
$$+ [\delta(y-\pi)]^2\left(|\overline{\varphi}_-|^2 - 17|W_\pi\varphi_+|^2 + 8W_\pi(\overline{\varphi}_-^\dagger\varphi_+^\dagger + \overline{\varphi}_-\varphi_+) - 9W_\pi^2M_5^3\right) + \mathcal{O}\left(\frac{|\varphi|^4}{M_5^3 r}\right)\Big\} \quad (4.$$

These terms can be made to cancel for $\varphi_+ = 0$ and

$$\overline{\varphi}_-(0) = r^{-3/2}W_0\sqrt{\beta}\,, \qquad \overline{\varphi}_-(0) = r^{-3/2}W_\pi\sqrt{\beta}\,. \quad (4.$$

$$V_{\rm eff} = \frac{4k\beta}{r^3}(4+2\epsilon)\rho^{(4+2\epsilon)}\left|W_0 - W_\pi\rho^{-\epsilon}\right|^2 + \mathcal{O}(\rho^8)\,.$$

W plays role of J!
SUSY soln so again
not neg energy

Status…

- We found a viable model with loop no-scale breaking and superpotentials on branes
- But that did not lead to negative energy

Now Finally: Negative Energy

- Reminder that conventional 4d anomaly mediation relies on negative energy that sources FC^2~V, where V is negative energy cancelling positive susy breaking energy

- We clearly need two things
  - Break No-Scale
  - ***Bulk*** superpotential
    - Solely boundary superpotentials doesn't work
- We present two types of breaking:
  - I: β kinetic term correction (as above) and W_{bulk}
  - II: W_{bulk} and condensate

Breaking No-Scale With Loop Corrections

- Add correction to kinetic term
  - Notice here we are assuming stabilizing through SUSY GW
  - As before, F_C no longer contrained to be ~0
    - $F_\Sigma$equation relates F_C to βF_Σ
- Also include constant *bulk* superpotential

The equation of motion for F_Σ no longer relates the F-terms of the comp
hypermultiplet F-terms, and can now be solved to determine F_Σ. The result is:

$$F_\Sigma = \frac{g_h M_5^3 r^5}{\beta} \varphi_+^\dagger \varphi_-^\dagger e^\sigma + \frac{(r\beta + 3M_5^4 r^5)}{6\beta M_5^2} (F_{C_+} C - F_{\Phi_+} \varphi_+^\dagger - F_{\Phi_-} \varphi_-^\dagger)$$

Assuming $\varphi_\pm$ vanish, the F-terms for Σ and the compensator are given by

$$F_\Sigma = -M_5^2 r W_{\text{bulk}}\, e^{\sigma(y)} + \mathcal{O}(\beta)\,,$$

$$F_{C_+}^\dagger = -\frac{2\beta\, W_{\text{bulk}}}{M_5^{3/2} r^4}\, e^{\sigma(y)} + \mathcal{O}(\beta^2)\,.$$

The leading correction to the potential from the bulk superpotential is then:

$$\Delta V_{\text{eff}} = -\frac{M_5 \beta}{k r^4} \left(1 - e^{-4k\pi r_c}\right) |W_{\text{bulk}}|^2 + \mathcal{O}(\beta^2)\,.$$

This term is negative for $\beta > 0$ due to the constant F_C in the bulk, generatin

Success! Negative energy

Alternative: Break No-Scale: Gaugino Condensate

- Previous model assumes that radion independenty stabilized
  - **One important lesson is that stabilizing radion is not the same as breaking no-scale**
- Next model we stabilize both at same time
- Add gauge group to bulk
- Assume gaugino condensation
  - Strange in 5d
  - Makes sense only at low energy below KK scale
  - So 5d bulk potential constant related to zero mode

Model

$$\delta\mathcal{L} = \frac{3}{2}\left[\int d^2\theta\, i\Sigma\, W^\alpha W_\alpha + \text{h.c.}\right]$$

$$\Delta\mathcal{L}_\lambda = -2e^{3\sigma}\left[\int d^2\theta\ \mathrm{C}_+^2 W_\lambda e^{-\alpha\Sigma} + h.c.\right]$$

Also include constant superpotential in bulk

$$F^\dagger_{C_+} = \alpha e^{\sigma(y)-M_5 r\alpha} M_5^{5/2} W_\lambda \quad F^\dagger_\Sigma = -\frac{M_5 e^{\sigma(y)}}{3}\left(3M_5 r W_{\text{bulk}} + e^{-M_5 r\alpha} W_\lambda (3+2M_5 r\alpha)\right)$$

α indicates no-scale breaking

$$V_{\text{gc I}} = \frac{\alpha M_5^4}{6kr}\left(1-e^{-4k\pi r}\right)e^{-M_5 r\alpha}\left(3M_5 r W^\dagger_{\text{bulk}} W_\lambda + |W_\lambda|^2(3+\alpha M_5 r)e^{-M_5 r\alpha} + h.c.\right)$$

Potential at minimum

- Note *FC,* negative energy both set by no-scale breaking gaugino condensate
- Also note we can stabilize radion without hypermultiplets

$$2|W_\lambda|^2 e^{-M_5 r\alpha}(3 + 6M_5 r\alpha + 2(M_5 r\alpha)^2) + 3(M_5 r\alpha)^2 \left(W_\lambda^\dagger W_{\text{bulk}} + W_\lambda W_{\text{bulk}}^\dagger\right) = 0$$

$$V_{\text{gc I}}|_{\text{min}} \simeq -\frac{\alpha^2 M_5^5}{3k} e^{-2M_5 r\alpha} |W_\lambda|^2$$

Again, success; negative energy

Gaugino Condensate with Brane Superpotential

$$F_\Sigma^\dagger = -\frac{M_5 e^{\sigma(y)}}{3}\left[W_\lambda e^{-M_5 r\alpha}(3+2M_5 r\alpha) + 6W_0\delta(y)\right]$$

$$V_{\mathrm{gc\,II}} = \frac{\alpha M_5^4}{3kr} e^{-M_5 r\alpha}\left(6krW_\lambda^\dagger W_0 + \frac{1}{2}(3+\alpha M_5 r)|W_\lambda|^2 e^{-M_5 r\alpha} + h.c.\right)$$

$$V_{\mathrm{gc\,II}}|_{\min} = -\frac{\alpha^2 M_5^5 e^{-M_5 r\alpha}|W_\lambda|^2}{3k} = -\frac{\left|\langle e^{-\sigma}F_{C_+}\rangle\right|^2}{3k}$$

- Minimum like before
- But here we find supersymmetry breaking
- Surprising aspect is that integral of F_Σ vanishes
- So low-energy theory very similar to bulk superpotential case

Effective Theory and 4d Anomaly Mediation

- Note that the only case where our low-energy theory matches “naïve EFT” where we integrate over superpotential is flat extra dimensions
  - Low-energy (4d) theory remains no-scale
  - Superpotential constant in bulk
- All other cases would give wrong low-energy theory

EFT and Anomaly Mediation

- Also note that boundary superpotentials can yield brane field “anomaly mediation”
  - Not communicating between branes, just local to wherever W sits
- Such terms must be included explicitly in 4d theory
- Same when F_Σ nonvanishing

4d EFT

- However, 4d EFT **does** generate conventional anomaly mediation
- We see how and why it accommodates universal form
- In the 5d theory associated with constant superpotential and constant F_C
  - Up to possible warp factor

So Back to Original Question

- How is 5d result consistent with 4d EFT
- Answer is 4d theory reproduces only anomaly-mediation that arises from a bulk superpotential
  - Since has definite y dependence not so surprising it can be consistent with single FC in 4d theory
- However, in 4d theory FC determines both anomaly-mediation and negative energ
  - Not true in 5d theory
- There are nonzero F terms whose effects must already be included in 5d theory
  - Boundary FC or Fsigma
- These supersymmetry breaking terms not generated in 4d theory

Comment on KKLT

- This model was *not* KKLT
- We had radion, gaugino condensate in bulk
- KKLT has brane radion, brane condensate
- They assume no-scale structure of bulk not present
  - Integrated out all other moduli
- We are doing a toy model to work this out too
- Seems you do get SUSY breaking in our toy model, unlike claim from 4d EFT (stay tuned)

Conclusions

- In reality, we did full N=2 broken to N=1 on orbifolds
- Showed constraints imposed by bulk no-scale structure
- Included breaking through loop effects or gaugino condensate
- Found **EFT must be derived at level of potential**
  - Exception flat case when supersymmetry preserved
- Also included superpotential
  - Showed needed superpotential to be in bulk to get negative energy
  - Boundary superpotentials are essentially sources (but can also lead to Scherk Schwartz supersymmetry breaking
  - **Associated with positive or zero energy**
- For future, points to correct way to deal with supersymmetry on singular spaces, including string theory