Holographic Gauge Mediation

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Based on: arXiv:0903.0619: Benini, Dymarsky, Franco, Kachru, Simic and Verlinde

(and in progress)

Outline

- Strongly coupled models of SUSY breaking
- Geometrizing the hidden sector
- An explicit model
- Soft Terms
- Compositeness
- Single sector SUSY-breaking
- Geometric constraints

SUSY breaking and its mediation

- Stabilization of Weak/Planck hierachy ⟶ Supersymmetry
- Spontaneous SUSY breaking within MSSM ⟶ Squarks lighter than u-quarks

Dimopoulos, Georgi

Gravity mediation ⟶ heavy (Planck scale) fields

Gauge mediation ⟶ massive fields with SM charges

Minimal Gauge Mediation

Messengers: $(\Phi, \tilde{\Phi})$ charged under SM $\boxed{W_{mess} = X\tilde{\Phi}\Phi}$ $\boxed{X = M + \theta^2 F}$

- Gauge mediation solves the SUSY flavor problem (flavor blind)
- Recently: interest in generalizations that include more general possibilities for messengers and their interaction with the hidden sector

e.g.: Cheung, Fitzpatrick, Shih Seiberg, Volansky, Wecht

Strongly coupled models of SUSY breaking

- In this talk: we explore new possibilities, with strongly coupled hidden sectors, that are calculable via gauge/gravity duality. Ultimate goal: composite models. We consider a 4D QFT with:

See also Nomura 2004

$$\mathcal{L} = \mathcal{L}_{\text{visible}} + \mathcal{L}_{\text{hidden}} + \mathcal{L}_{\text{int}}$$

Visible: SUSY extension of the SM. We assume visible, hidden and messenger matter in complete SU(5) representations.

Hidden: strongly coupled SUSY field theory with metastable SUSY breaking at $\Lambda_S > 1$ TeV. It has a global symmetry $G \supset SU(5)$.

They interact via:

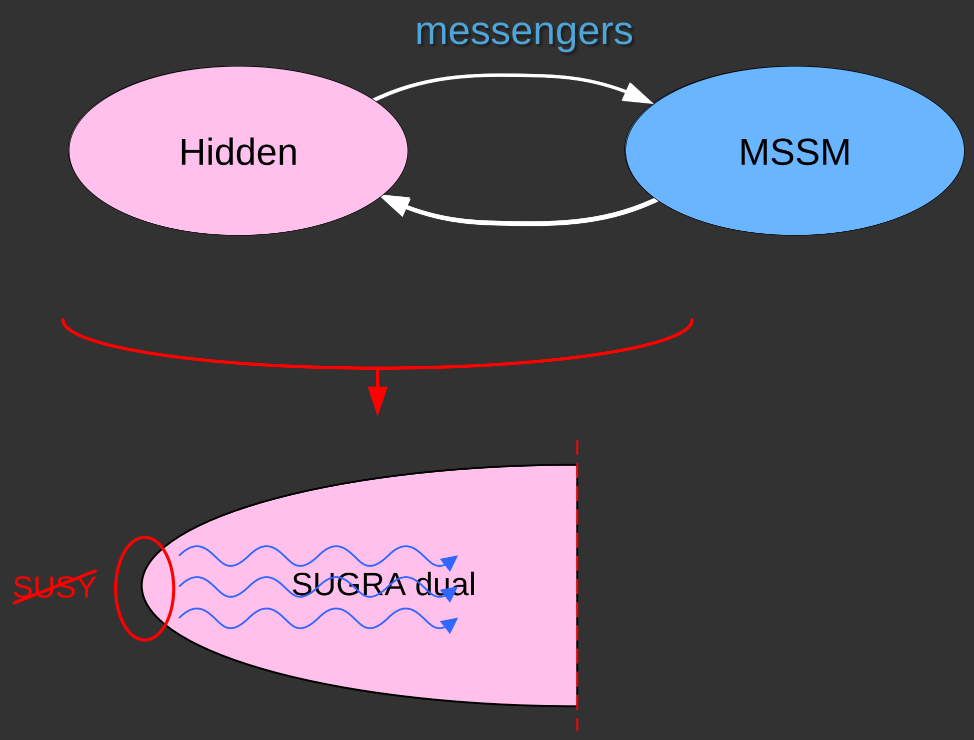
$$\mathcal{L}_{\text{int}} = \int d^4\theta \, g \mathcal{V} \hat{\mathcal{J}}_h$$

- In this General Gauge Mediation formalism, soft masses are parametrized by $\mathcal{J}_h$ 2-point functions

Meade, Seiberg and Shih

Geometrizing the hidden sector

- If the hidden gauge group has sufficiently large t' Hooft coupling and rank, we can trade the field theory for a classical supergravity theory



- The SUSY-breaking dynamics is localized in the IR region of the throat, and is communicated to the visible sector via supergravity fields that extend throughout the 5D bulk

Building the model: Hidden Sector

- Starting point: we want to study a strongly coupled hidden sector with a SUSY breaking metastable state at an exponentially small scale

Gravity side

- Most explicit dual of a confining gauge theory — Klebanov, Strassler

- Deformed conifold

$$z_1^2 + z_2^2 + z_3^2 + z_4^2 = \epsilon^2$$

→ finite size S^3 at tip

with fluxes

$$\int_A F_3^{RR} = M \qquad \int_B H_3^{NS} = -k$$

- Constructed from N = kM D3-branes and M wrapped D5-branes at the conifold

- These fluxes source a superpotenial

Gukov, Vafa, Witten

$$W = \int (F_3^{RR} + \tau H_3^{NS}) \wedge \Omega$$

Using the conifold periods:

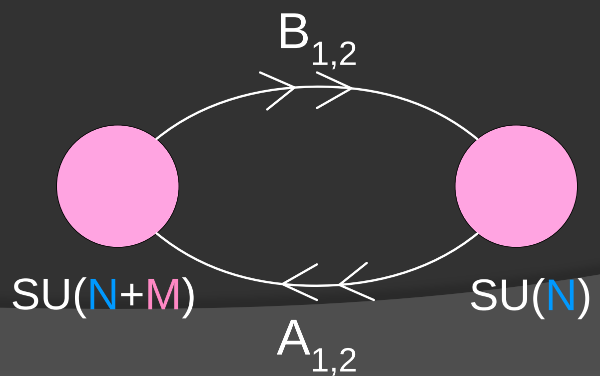
$$\int_A \Omega = z \qquad \int_B \Omega = \frac{z}{2\pi i} \log z + \text{regular}$$

- The size of the 3-sphere is dynamically fixed:

$$\epsilon \sim \exp(-4\pi k / 3 g_s M)$$

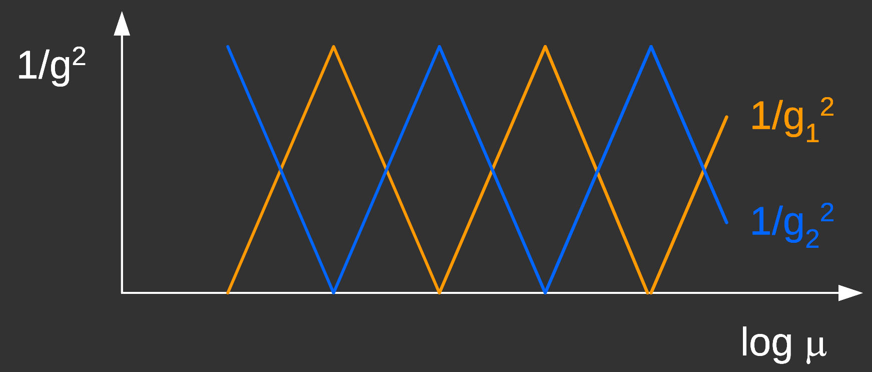
Gauge theory dual

- Dual to the following gauge theory:



$$W = \lambda \, \epsilon^{ij} \epsilon^{kl} \, \mathrm{Tr} \, A_i B_k A_j B_l$$

- The difference of ranks due to the D5-branes breaks conformal invariance and the theory undergoes a cascade of Seiberg dualities Klebanov,Strassler



Move beyond infinite coupling by switching to an alternative Seiberg dual description

- Each step in the duality cascade reduces N (the effective number of colors) by M units

- This QFT interpretation of the RG flow is supported by the existence of gravity duals reproducing this kind of behavior in a variety of theories Klebanov,Strassler
  Franco, He, Herzog, Walcher Ejaz, Herzog, Klebanov

- The cascade terminates in confinement in the IR. Dual to the deformation.

Zooming onto the IR tip

- Close to the IR tip, the metric simplifies to:

$$ds^2 = a_0^2\, dx_4^2 + g_s M\, b_0^2 \left(dr^2 + d\Omega_3^2 + r^2 d\Omega_2^2\right)$$

confinement   finite S^3 $S^2 \to 0$

$$a_0 \sim \exp(-4\pi k/3 g_s M) \qquad b_0 \sim \mathcal{O}(1)$$

- Confinement: minimal area surface localizes close to the tip. This results in the area law for the Wilson loop.

$$T_s = \frac{1}{2^{4/3} a_0^{1/2} \pi} \frac{\varepsilon^{4/3}}{(\alpha')^2 g_s M}$$

- With RR 3-form flux:

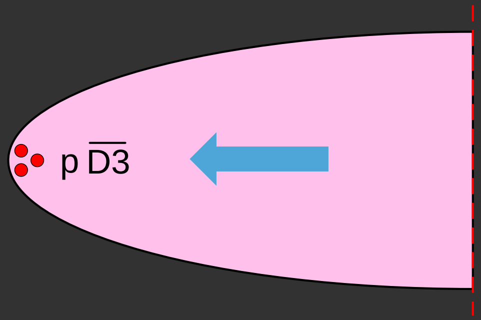
$$F_{ijk} \sim f\, \epsilon_{ijk} \qquad f \sim \frac{1}{b_0^3 \sqrt{g_s^3 M}}$$

SUSY-breaking state

- The KS throat gives rise to an exponentially small scale at its IR tip. Can we use it to generate exponentially small SUSY-breaking? → add $\overline{\text{D3}}$-branes

Kachru, Pearson and Verlinde

Argurio, Bertolini, Franco, Kachru



$$g_s V_{\rm eff}(\Phi) \simeq \sqrt{\det(G_{\parallel})}\left(p - i\frac{4\pi^2}{3}F_{kjl}\mathrm{Tr}\Big([\Phi^k,\Phi^j]\Phi^l\Big) - \frac{\pi^2}{g_s^2}\mathrm{Tr}\Big([\Phi^i,\Phi^j]^2\Big) + \dots\right)$$

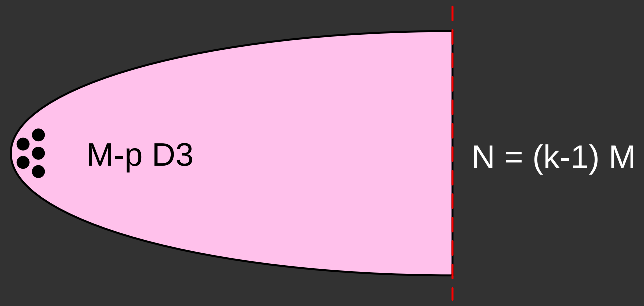
$$[[\Phi^i,\Phi^j],\Phi^j] - i g_s^2 f \epsilon_{ijk}[\Phi^j,\Phi^k] = 0$$

→ p-dimensional SU(2) representation

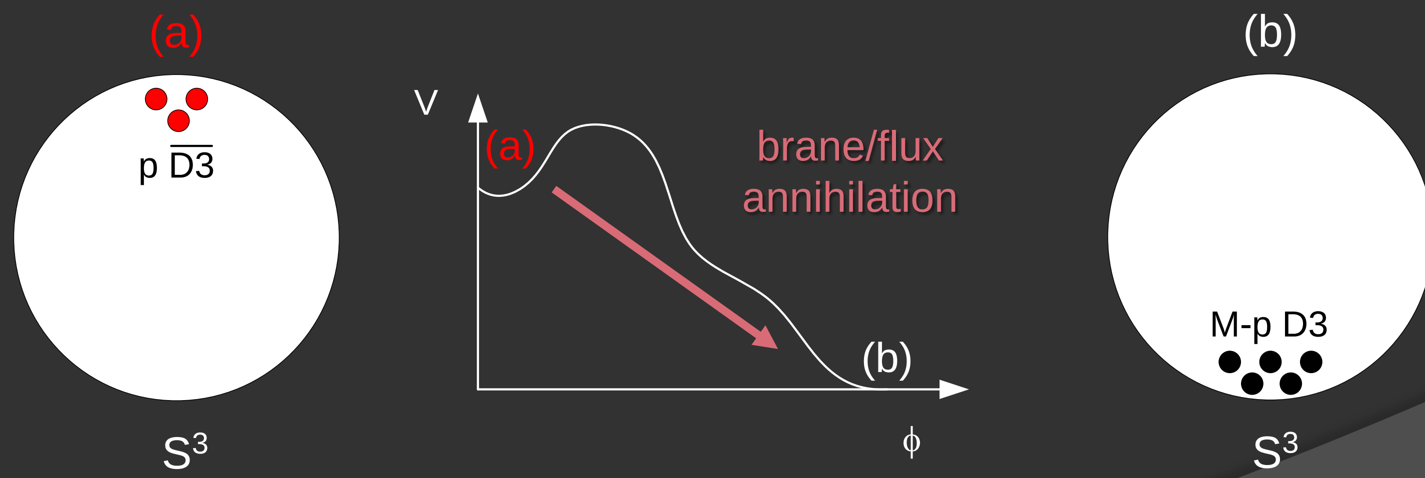
- The $\overline{\text{D3}}$-branes expand to a radius: $R^2 \sim 4\pi^2 \frac{p^2}{M^2} R^2_{S^3}$

- Vacuum energy: $V_0 \sim p\, T_{\overline{\text{D3}}}\, e^{-\frac{8\pi k}{3 g_s M}}$

- In addition, there is a SUSY state with the same charges



- The SUSY-breaking state can decay into the SUSY one by a brane/flux annihilation transition



$\int_B H_3 = k$

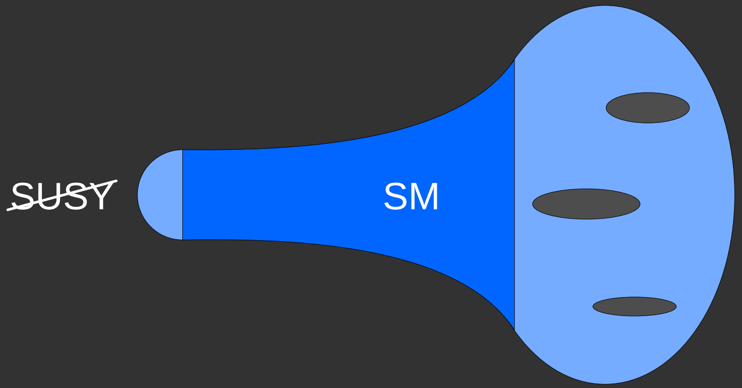
$\int_B H_3 = (k-1)$

- The $\overline{D3}$-branes are metastable for p << M

Gravity dual of the SUSY-breaking state

- Open string probe brane analysis: the meta-stable state corresponds to expanded $\overline{\text{D3}}$-branes at the tip of the throat

- Our final goal is to construct a configuration of the form:



- The SUSY-breaking effects away from the tip are captured by a non-SUSY gravity solution

- For $r \gg \varepsilon^{2/3}$, the corresponding non-SUSY background is a generalization of the Klebanov-Tseytlin (UV) solution

- The supergravity dual for the non-SUSY states (DKM) takes the form:

DeWolfe, Kachru and Mulligan

$$ds^2 = r^2 e^{2a(r)} \eta_{\mu\nu} dx^\mu dx^\nu + e^{-2a(r)} \left(\frac{dr^2}{r} + \sum_{i=1}^{2} (e_{\theta_i}^2 + e_{\phi_i}^2) + e^{2b(r)} e_\psi^2 \right)$$

$$\begin{aligned} e^{-4a} &= \frac{1}{4} g_s \bar{N} + \frac{1}{8}(g_s \bar{M})^2 + \frac{1}{2}(g_s \bar{M})^2 \log r \\ &\quad + \frac{1}{r^4} \left[\left(\frac{1}{32} g_s \bar{N} + \frac{13}{64}(g_s \bar{M})^2 + \frac{1}{4}(g_s \bar{M})^2 \log r \right) \mathcal{S} - \frac{1}{16}(g_s \bar{M})^2 \phi \right] \\ e^{2b} &= 1 + \frac{1}{r^4} \mathcal{S} \\ k &= g_s \bar{M} \log r + \frac{1}{r^4} \left[\left(\frac{3}{8} \frac{\bar{N}}{\bar{M}} + \frac{11}{16} g_s \bar{M} + \frac{3}{2} g_s \bar{M} \log r \right) \mathcal{S} - \frac{1}{4} g_s \bar{M} \phi \right] \\ \Phi &= \log g_s + \frac{1}{r^4} [\phi - 3\mathcal{S} \log r] \end{aligned}$$

$$\mathcal{S} \sim \frac{p}{N} e^{\left(-\frac{8\pi N}{3 g_s M^2}\right)}$$

Vacuum Energy

- Normalizable perturbation → spontaneous SUSY breaking

SUSY breaking in the field theory

R-symmetry:

- KS background: $U(1)_R \longrightarrow \mathbb{Z}_{2M}$ due to C_2 $\xrightarrow{\text{deformation}}$ $\mathbb{Z}_2$
- DKM $\longrightarrow$ no further R-symmetry breaking
- Hence, either D or F-term breaking

Expectation values:

- Holographic renormalization for cascading theories: Aharony, Buchel, Yarom

$$\langle T_{\mu\nu} \rangle = -\frac{3\eta_{\mu\nu}}{2}\mathcal{S} \qquad \langle \mathcal{O}_+ \rangle = -3\mathcal{S} - 4\phi \qquad \langle \mathcal{O}_- \rangle = \frac{12}{\bar{M}}\mathcal{S}$$

- Quantum violation of conformal invariance due to running of the coupling associated to O_-

$$\langle T^\mu_\mu \rangle = -\frac{1}{2}\bar{M}\langle \mathcal{O}_- \rangle$$

- Three couplings: λ, g_1 and g_2
- Two invariant combinations:

Strassler

  - Non-conformal: $M \neq 0$:

$$J = \lambda^{2N+M} \Lambda_1^{3M+N} \Lambda_2^{N-2M}$$

↓ O_+

$$I = \lambda^{3M} \frac{\Lambda_2^{N-2M}}{\Lambda_1^{3M+N}} \left[\epsilon^{ij}\epsilon^{kl} \mathrm{Tr}\left(A_i B_k A_j B_l\right)\right]^{2M}$$

↓ O_- — no W in CFT limit

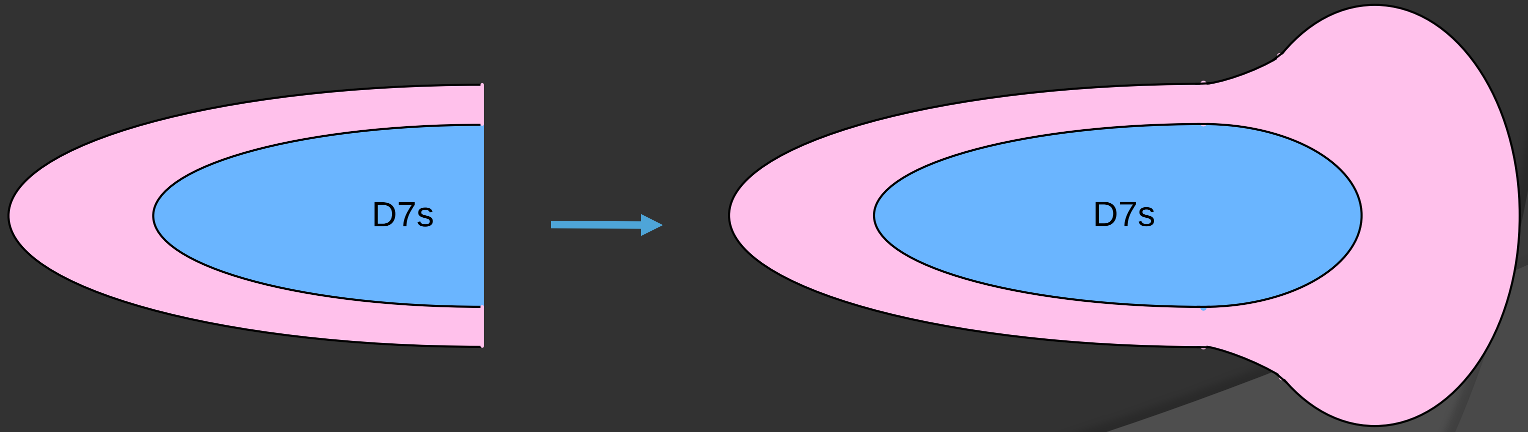
- In the conformal limit (i.e. M = 0) → only auxiliary fields in vector multiplet → D-term
- But the SUSY breaking vacuum does not exist in this limit
- Away from conformal limit → D and F-term mixing

DeWolfe, Kachru, Mulligan

Coupling the ~~SUSY~~ sector to the SM

Introducing the SM gauge group

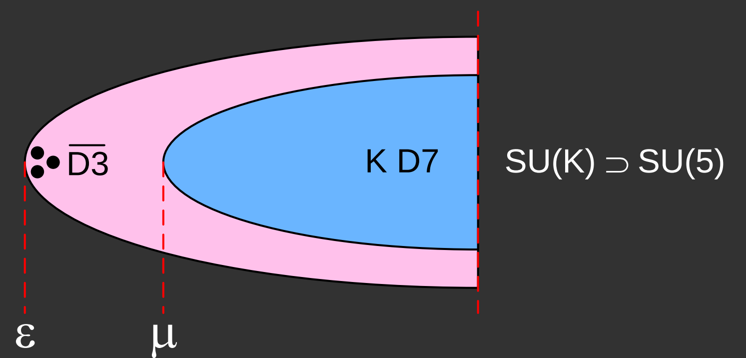
- The SM group is weakly gauged compared to the strongly coupled KS sector
- Hence, we embed it in the throat as a global symmetry
- In type IIB, this is achieved with a stack of D7-branes extending radially



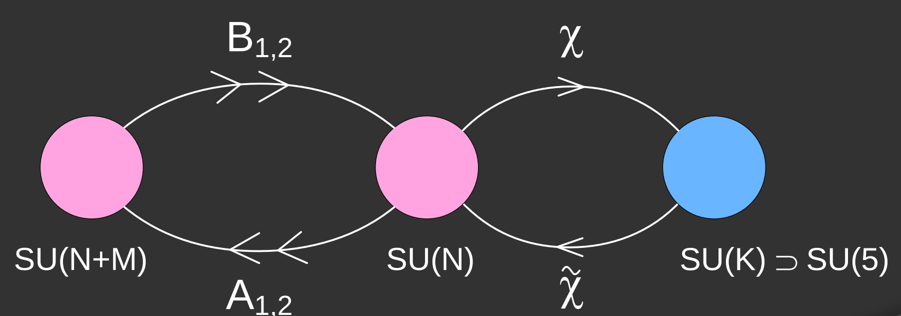
non-compact: $g^{D7}_{YM} = 0$ compact: small g^{D7}_{YM}

- Furthermore, we want a SUSY SM or GUT → SUSY D7 embedding
- Simplest possibility, Kuperstein embedding:

$$z_1^2 + z_2^2 + z_3^2 + z_4^2 = \epsilon^2 \quad \longrightarrow \quad z_4 = \mu$$



Gauge theory dual:



$$W = \epsilon^{ij}\epsilon^{kl} A_i B_k A_j B_l + \tilde{\chi}^a \left(A_1 B_1 + A_2 B_2\right) \chi_a + \mu\, \tilde{\chi}^a\, \chi_a$$

breaks R-symmetry

Gaugino mass: General expectations

- Let us determine the expected parametric dependence on: g_{SM}, $\mathcal{S}$ and μ

  - 1-loop of messengers: $\dfrac{g_{SM}^2 K}{16\pi^2}$
  - SUGRA background gets corrected at order $\mathcal{S}$
  - Mass dimensions: $[\mathcal{S}] = 4$ and $[\mu] = 2/3$

$$m_\lambda \sim \frac{g_{SM}^2 K}{16\pi^2} \frac{\mathcal{S}}{\mu^2}$$

- Leading correction: (ε/μ) suppressed

Soft Terms

Gaugino mass: explicit calculation

Step 1: Direct gaugino mass

- Anti D3-brane SUSY breaking state (DKM) at O($\mathcal{S}$):
  - Squashed metric
  - (1,2) RR flux
  - Running dilaton
- Do they result in a gaugino mass from the DBI action for the D7-branes?
- Gaugino masses on D7-branes come from (0,3) RR flux

Graña, Camara et. al., Jockers et. al.

No gaugino mass at tree level

Step 2: SUSY-breaking splitting of mesons: $\Phi_n = \tilde{\chi}\mathcal{O}_h^n\chi$

$$\mathcal{L} = \int d^4\theta\ \Phi_n\bar{\Phi}_n + \int d^2\theta\ X_n\Phi_n\Phi_n + c.c.$$

$$X_n = M_n + \theta\theta\ F_n$$

SUSY mass (M_n), splitting (F_n)

Let us consider D7-branes with Kuperstein embedding: $(z_4 - \mu)^K = 0$

a) No SUSY breaking: Klebanov-Tseytlin background

$$S = -\frac{\mu_7}{g_s}\int d^8\sigma\sqrt{|\gamma|}\ \left(g_{4\bar{4}}\ \gamma^{ab}\partial_a X^4\partial_b X^{\bar{4}} + \gamma^{ac}\gamma^{bd}F_{cb}F_{da}\right)$$

Kaluza-Klein reduction: $X^4 = \sum \phi_n(x)\,\xi_n(y)$

x : $M^{1,3}$

y : Σ_4

$$M_n \propto n\frac{|\mu|^{2/3}}{\sqrt{4\pi\lambda_{\text{eff}}(\mu)}}$$

b) SUSY breaking: DKM

The DKM solution contains (0,2) and (2,0) perturbations of the metric

$$\delta S_{\rm DKM} = -\frac{\mu_7}{g_s}\int d^8\sigma\sqrt{|\gamma|}\,\left(g_{44}\;g^{ab}\partial_a X^4\partial_b X^4 + g_{\bar{4}\bar{4}}\;g^{ab}\partial_a X^{\bar{4}}\partial_b X^{\bar{4}}\right)$$

$$\tilde{g}_{44} = h^{-1/2} g_{44} \sim \bar{\mu}^2\frac{\mathcal{S}}{r^8}$$

Meson spectrum:

$$M_n \propto n\frac{|\mu|^{2/3}}{\sqrt{4\pi\lambda_{\rm eff}(\mu)}}$$

$$F_n \propto n^2\frac{\bar{\mu}^2\mathcal{S}}{|\mu|^{10/3}4\pi\lambda_{\rm eff}(\mu)}$$

Step 3: Gaugino mass from meson loops

The ϕ_n transform in the adjoint representation of the gauge group. We then get a gaugino mass at 1-loop:

$$m_\lambda \sim \frac{g_{SM}^2 K}{16\pi^2} \frac{\mathcal{S}}{\mu^2\sqrt{4\pi\lambda_{\rm eff}}} \sum n = \frac{g_{SM}^2 K}{16\pi^2} \frac{\mathcal{S}}{\mu^2} \sqrt{4\pi\lambda_{\rm eff}}$$

Matter soft terms

- Our model realizes gaugino mediation (MSSM matter separated from SUSY breaking sector in extra dimensions, with gauge multiplet in the bulk)
- The direct contribution to scalar masses and A-terms is negligible

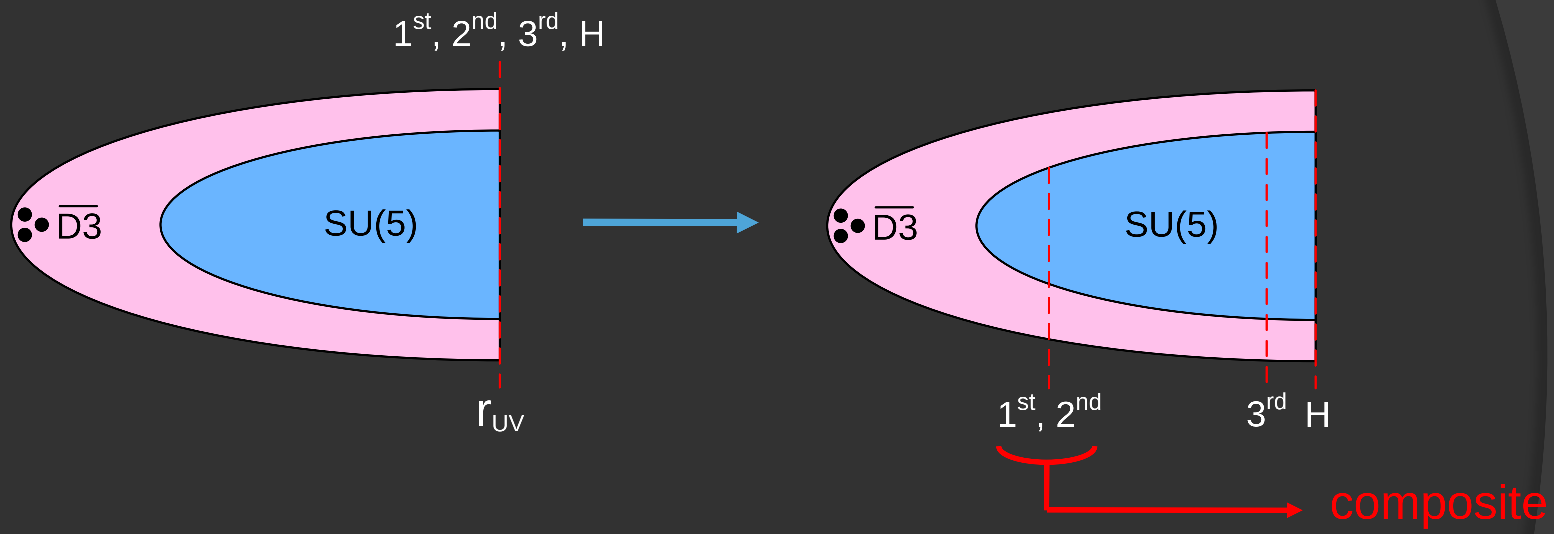
Kaplan et. al., Chacko et. al.

- Instead, they are generated by RG running

$$m^2 \sim \alpha_{SM}\; m_\lambda^2\; \log(\Lambda_{UV}/M_Z)$$

Compositeness

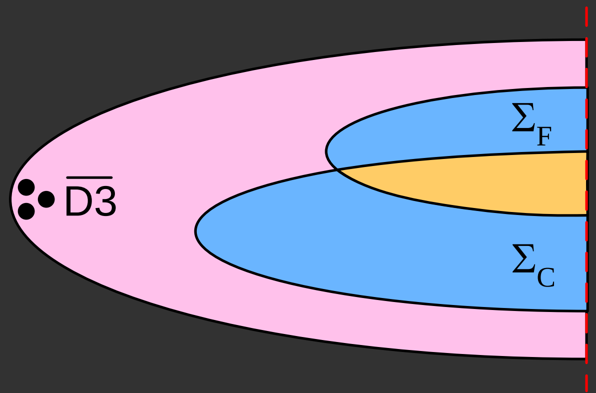
- So far, we have considered the SM matter to be UV localized in the throat
- Natural extension → allow the position of matter to vary



$$\mathcal{L}_{4D} = \ldots + \frac{f}{\Lambda^{\Delta_{\mathcal{O}}-3}} \, \phi \, \mathcal{O}^h + \ldots$$

- Compositeness can (partially) explain some issues about flavor physics
- Warped extra dimensions not only explain SUSY-breaking scale but also size of Yukawas via wavefunction overlap

- We can obtain composites at intersections with other D7-brane stacks



$$\int_{\Sigma_C \cap \Sigma_F} (F_C - F_F) \neq 0$$

Single Sector SUSY Breaking

- Idea: exploit compositeness to construct less modular models

SM matter emerging as composite of the SUSY-breaking field theory

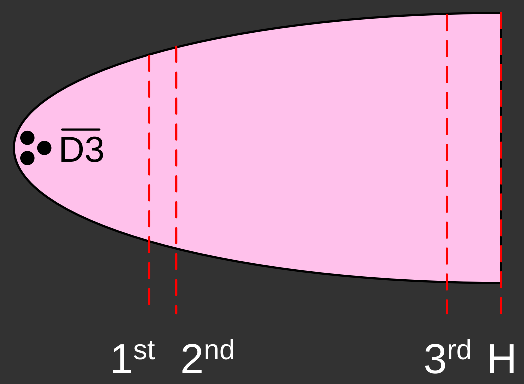
Arkani-Hamed, Luty and Terning

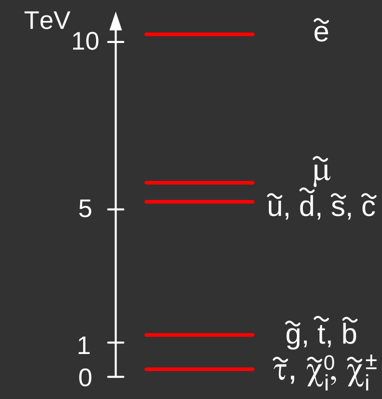
Gabella, Gherghetta and Giedt

- Known field theory examples are non-calculable

e.g.: SU(4)×SU(18) ×[SU(18)]

Single sector SUSY breaking in the throat



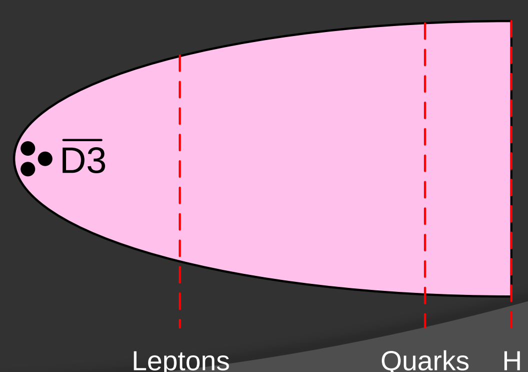


Gabella, Gherghetta
Giedt

- Correlation: small Yukawas → large sparticle masses

Other scenarios

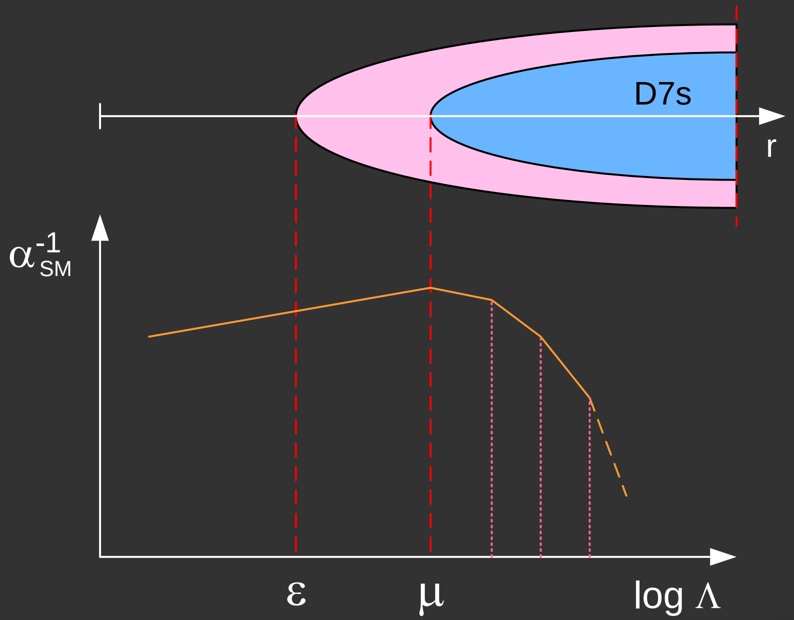
- This construction can interpolate among interesting phenomenologies



Maybe: composite leptons to cure tachyonic sleptons of anomaly mediation

Geometric constraints

- Large N sector → large N additional matter charged under SM!
- To avoid a Landau pole
  - Limit RG running by making messengers heavy
  - Equivalently, restrict extension of SM D7-branes
- From the perspective of the D7-branes, we have (k M) flavors



$$\alpha_{\rm IR}^{-1} - \alpha_{\rm UV}^{-1} \sim \frac{1}{4g_s}(k_{\rm UV}^2 - k_{\rm IR}^2)$$

- Reproduced in gravity by D7 volume
- Constraint easily relaxed, e.g. by orbifolding

Conclusions

- It is possible to geometrize models of strongly coupled gauge mediation using confining examples of AdS/CFT with massive flavors
- The flavors provide messenger mesons that lead to models of semi-direct gauge mediation Seiberg, Volansky and Wecht
- Generalizations with different positions of matter fields inside the throat. Calculable, composite models with single sector SUSY breaking
- Interesting to explore the interplay of compositeness contributions to soft terms with other mediation mechanisms, e.g. possible solution to tachyonic sleptons of anomaly mediation, μ/Bμ problem, etc