Title: Fermions, holography, and consistent truncations

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Abstract: We discuss the coupling of fermions to holographic superconductors in 3+1 and 4+1 (bulk) dimensions. We do so from a top-down perspective, by considering the reduction of the fermionic sector in recently found consistent truncations of type IIB and D=11 supergravity on squashed Sasaki-Einstein manifolds, which notably retain a finite number of charged (massive) modes. The truncations in question also include the string/M-theory embeddings of various models which have been proposed to describe systems with non-relativistic scale invariance via holography. We show that the lower-dimensional effective action for the fermion modes includes certain interactions that had been discussed in bottom-up constructions, as well as a variety of new couplings that may be relevant for applications of holographic techniques to the study of condensed matter systems

Fermions, holography, and consistent truncations

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Based on:

arXiv:1008.1423
with I. Bah, A. Faraggi, R.G. Leigh, L. Pando Zayas

and

arXiv:1009.1615
with I. Bah, A. Faraggi, R.G. Leigh

Outline

1. Motivation
2. Consistent bosonic truncations
   - $D = 11$ supergravity
   - Type IIB supergravity
3. The fermionic sector
4. Outlook

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1. Motivation

2. Consistent bosonic truncations
   - $D = 11$ supergravity
   - Type IIB supergravity

3. The fermionic sector

4. Outlook

Motivation

- In recent years, there has been an increasing interest in applying holographic techniques to construct models which capture basic features of various condensed matter systems.
- Ultimately, we would like to access the strong-coupling regime of systems which can be engineered in the lab ("real life").
- It is fair to say that this goal has not been attained so far (lattice models?, *d*-wave superconductors?, etc).
- More modestly, we can still aim to describe generic properties of theories in the same universality class of a quantum critical point.

- These efforts have been largely of a phenomenological nature, where different configurations of bulk matter fields are devised to model particular phenomena.
  - Abelian bulk gauge fields give raise to chemical potential, charge density, magnetic fields, etc. in the dual field theory.
  - Charged scalars model (s-wave) superfluids/superconductors.
  - Non-Abelian gauge fields model p-wave superconductors.
- One of the first examples of these applications was the "HHH" holographic superconductor (Hartnoll, Herzog, Horowitz, 2008)

$$\mathcal{L}_{3+1} = R + \frac{6}{L^2} - \frac{1}{4} F^{ab} F_{ab} - |\nabla_a \phi - i\, q\, A_a\, \phi|^2 + \frac{2}{L^2} \phi^2 \,.$$

- Below a certain critical temperature T_c there are *"hairy"* black hole solutions with a non-trivial profile for ϕ (Gubser, 2008). This has the interpretation of a scalar operator condensing in the dual field theory.

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- These efforts have been largely of a phenomenological nature, where different configurations of bulk matter fields are devised to model particular phenomena.
  - Abelian bulk gauge fields give raise to chemical potential, charge density, magnetic fields, etc. in the dual field theory.
  - Charged scalars model (s-wave) superfluids/superconductors.
  - Non-Abelian gauge fields model p-wave superconductors.
- One of the first examples of these applications was the "HHH" holographic superconductor (Hartnoll, Herzog, Horowitz, 2008)

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- We will focus on fermions, because of their interest in CM systems (e.g. strongly interacting cold fermion gases, BCS superconductivity, etc.)
- So far, fermions have been added to the existent holographic models in an *ad hoc* way.
- Early examples include minimally coupled Dirac fermions in the extremal RN-AdS black hole background (Faulkner et. al., 2009). They found:
  - Fermi surfaces.
  - Emergent scaling behavior in the IR, of non-Fermi liquid type.
  - Features resembling the strange metal region in the phase diagram of the cuprate ("high T_c") superconductors.

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- Similarly, a *Majorana coupling* was introduced in the same background (Faulkner et. al., 2009)

$$S = S_{Dirac} + \int d^4x \sqrt{-g} \left(\beta \varphi^* \overline{\zeta^c} \Gamma^5 \zeta + \text{h.c}\right)$$

  In the $T = 0$ limit of the superconducting phase, this coupling introduces stable gapped quasiparticles in the spectrum.

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- The bosonic models of holographic superconductivity in $(2+1)$ and $(3+1)$ dimensions have been successfully embedded in String/M-theory.
- This has been also done for the duals of systems with non-relativistic conformal symmetry at both zero and finite temperature.
- The question we set ourselves to answer is: can we consistently add fermion modes to these compactifications? A: yes!
- These dimensionally reduced theories will display a rich structure. Moreover, even in bottom-up models we can gain useful guidance from looking at top-down constructions.

Outline

1. Motivation
2. Consistent bosonic truncations
   - $D = 11$ supergravity
   - Type IIB supergravity
3. The fermionic sector
4. Outlook

Some SUGRA jargon

- A *truncation* entails throwing away a certain number of modes arising in the compactification.
- If these are not sourced by the modes we kept, we call the truncation consistent.
- Equivalently, a consistent truncation is such that any solution of the lower-dimensional theory can be *uplifted* to a solution of the higher-dimensional theory we started with.
- For example, say that compactifying from $D = 11$ to $d = 4$ yields a theory containing a $U(1)$ gauge field and a real scalar h such that the eom for h is

$$d(*dh) + F \wedge F = 0$$

- In such a situation it is *not* consistent to set $h = 0$. If we do so, we need to restrict to configurations for which $F \wedge F = 0$.

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- Part of the supergravity lore is that it is inconsistent to keep a *finite* number of massive (charged) modes. Hence, most of the work in KK compactifications of 10 and 11-dimensional supergravity has been done by truncating to the *massless* sector.

- In this talk we will focus on KK compactifications of $D = 11$ supergravity on *squashed Sasaki-Einstein* seven-manifolds (SE_7), and type IIB supergravity on squashed SE_5.

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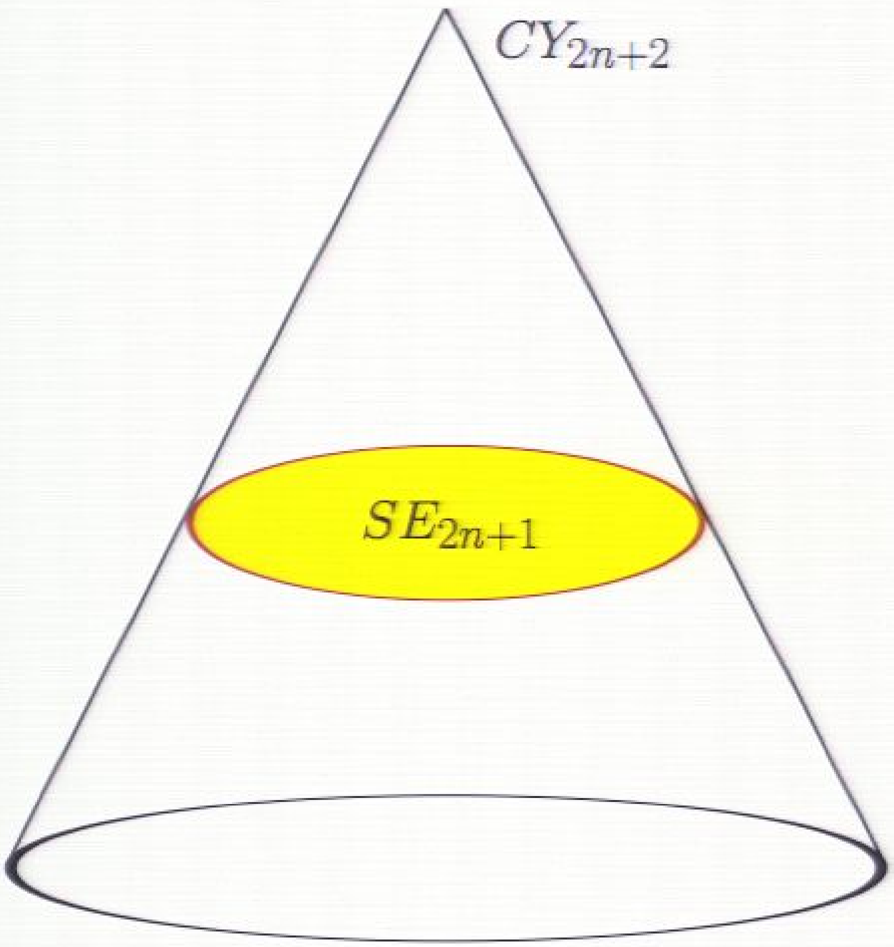
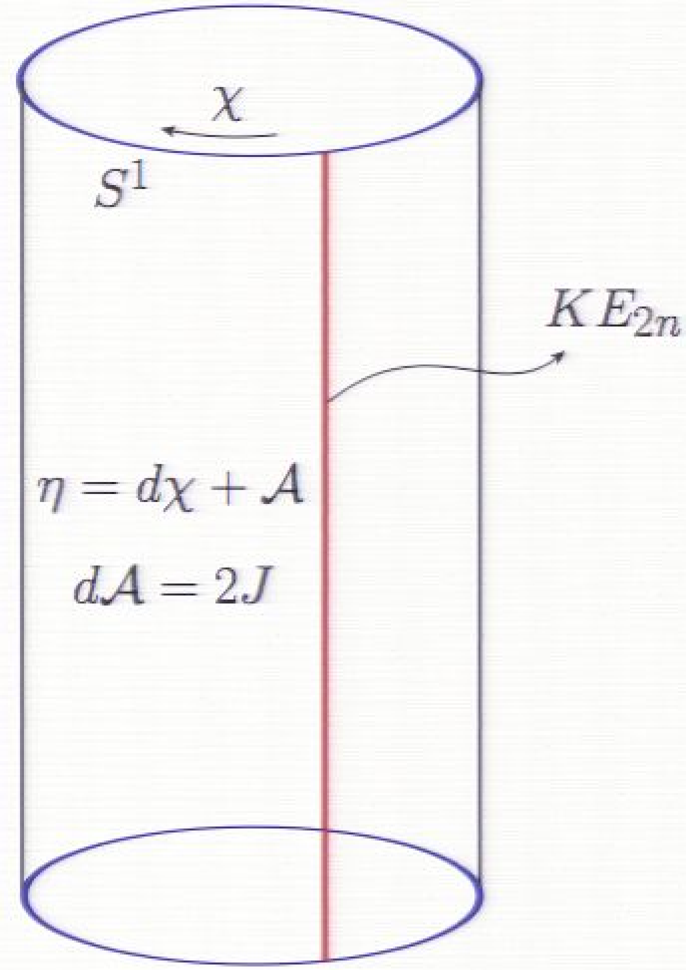
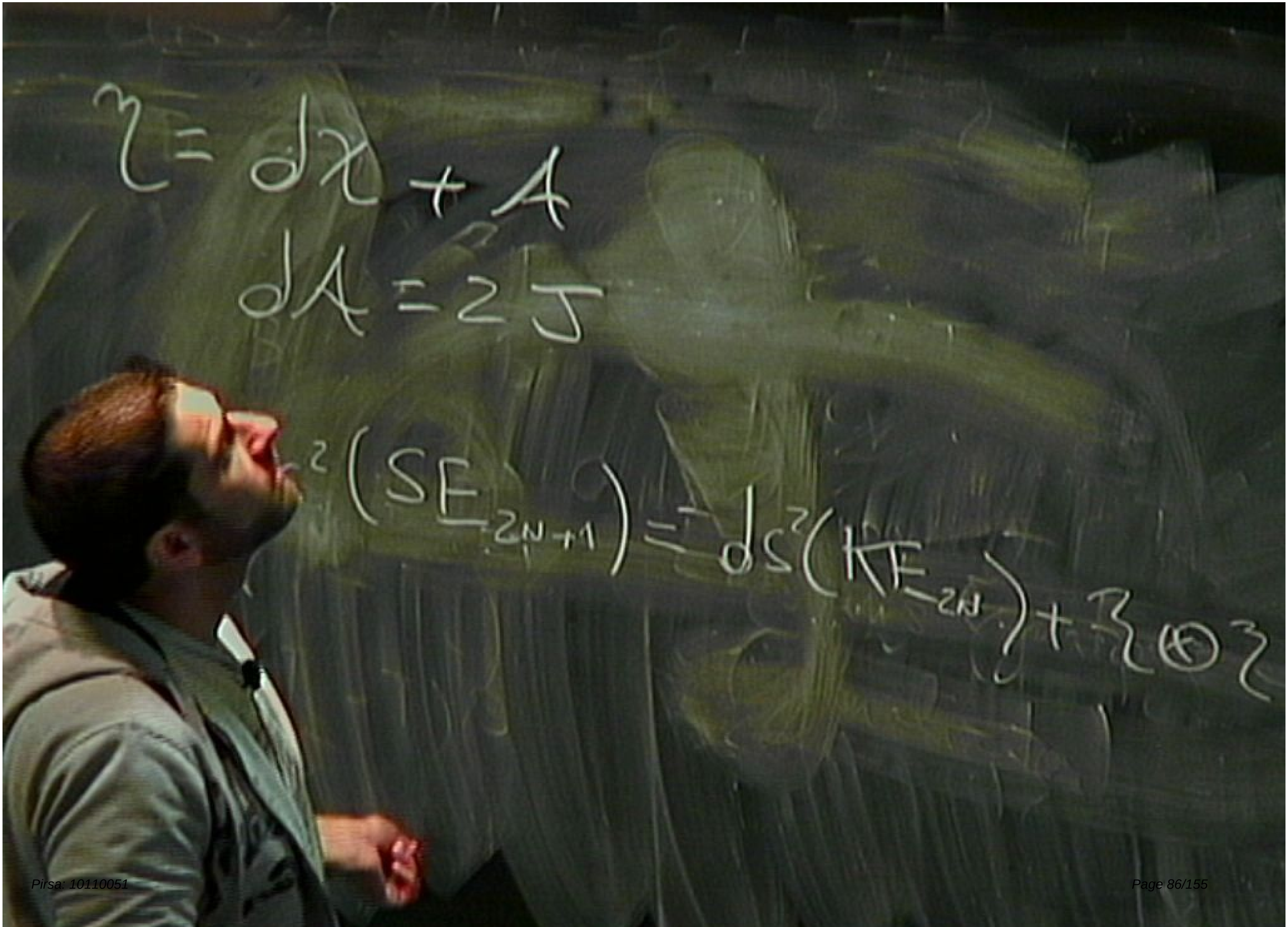
Sasaki-Einstein manifolds





$$ds^2(CY_{2n+2}) = dr^2 + r^2 ds^2(SE_{2n+1})$$

$$ds^2(SE_{2n+1}) = ds^2(KE_{2n}) + \eta \otimes \eta$$


η = dχ + A
dA = 2J
²(SE_{2N+1}) = ds²(KE_{2N}) + η ⊗ η

Breathing and squashing

- The metric ansatz in the KK reductions we study is of the form

KK metric ansatz

$$ds^2 = e^{2W(x)} ds^2_{(E)}(M) + e^{2U(x)} ds^2(KE) + e^{2V(x)}(\eta + A_1(x))^2$$

- For $D = 11$ we consider $dim(M) = 4$ (reduction on SE_7). In $D = 10$ we take $dim(M) = 5$ (reduction on SE_5).
- $U(x) - V(x)$ is the *squashing mode*, and $W(x)$ is proportional to the *breathing mode*. The pure SE case has $U = V = 0$ ($W = 0$).
- Archetypal examples: $S^5 = \mathbb{CP}_2 \times U(1)$, $S^7 = \mathbb{CP}_3 \times U(1)$. Upon squashing, the isometry gets reduced: $SU(4) \to SU(3) \times U(1)$ for S^5, and $Spin(8) \to SU(4) \times U(1)$ for S^7.

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- What about fluxes? $\Rightarrow$ the consistency is ensured by truncating to modes which are *singlets* under the structure group of the *KE* base.

- The KE_{2n} base is endowed with a Kähler form $J = d\mathcal{A}/2$ and a holomorphic $(n, 0)$-form Σ which are $SU(n)$ singlets:

$$J = e^1 \wedge e^2 + e^3 \wedge e^4 + \dots , \qquad \Sigma = (e^1 + ie^2) \wedge (e^3 + ie^4) \wedge \dots$$

- Lifting from the *KE* base to the *SE*, the relevant $(n, 0)$-form carries $U(1)$ charge: $\Omega = e^{iQ\chi}\Sigma$.

- Hence, the ansatz for the fluxes consists in building the most general forms of the given rank such that their "legs" in the internal directions are given by (η, J, Ω).

$D = 11$ supergravity

- The general $SU(3)$-singlet 4-form $\hat{F}_4$ in $D = 11$ sugra has the form (Gauntlett, Kim, Varela, Waldram, 2009)

$$\hat{F}_4 = f\,\mathrm{vol}_4^{(E)} + H_3 \wedge (\eta + A_1) + H_2 \wedge J + dh \wedge J \wedge (\eta + A_1) + 2hJ^2$$
$$+ \left[X(\eta + A_1) \wedge \Omega - \frac{i}{4}(dX - 4iA_1 X) \wedge \Omega + \text{c.c.} \right]$$

- So we have a real boson h, a charged boson X, the $U(1)$ gauge field A_1, a second $U(1)$ gauge field B_1, and an axion dual to H_3. The bosonic eom imply $f = 6e^W(\pm 1 + h^2 + |X|^2/3)$.

- The content is consistent with the bosonic sector of $N = 2$ gauged supergravity in $d = 4$, coupled to one vector multiplet and one hypermultiplet.

Relation to flux compactifications

- Viewing the SE_7 manifold as $KE_6 \times U(1)$, one can imagine reducing from M-theory to type IIA.

- The truncation then has the structure of a IIA reduction on a six-dimensional manifold of $SU(3)$ structure. Generically this yields $N = 2$ (ungauged) sugra coupled to a tensor multiplet and a vector multiplet.

- However, in our case we also have the background 4-form flux, the twisting of the $U(1)$ fiber, and the non-closure of the $(3, 0)$ form on KE_6: $d\Sigma = 4i\mathcal{A} \wedge \Sigma$.

- These features lead to the gauging of the $d = 4$ theory.

- The $f = +6e^W + \ldots$ theory has an $N = 2$ supersymmetric AdS vacuum which uplifts to an $AdS_4 \times SE_7$ solution (dual to $N = 2$ SCFT in $d = 3$). A possible further truncation of this theory yields minimal gauged $N = 2$ sugra.

- Reversing the orientation in the internal manifold, i.e. $f = -6e^W + \ldots$, the resulting theory has a non-supersymmetric AdS vacuum which uplifts to the so-called *"skew-whiffed"* $AdS_4 \times SE_7$ solution.

  A further truncation of this theory yields (Gauntlett, Sonner, Wiseman, 2009)

M-theory holographic superconductor

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\left[R - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{|DX|^2 - \frac{6}{L^2}\left(1 - \frac{2}{3}|X|^2\right)}{(1 - \frac{1}{2}|X|^2)^2}\right]$$

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$F \wedge F = 0$!!

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Type IIB supergravity

- In type IIB, the $SU(2)$-invariant ansatz for the fluxes reads (Gauntlett, Varela, 2010)

$$
\begin{aligned}
F_{(5)} &= 4e^{8W+Z}\mathrm{vol}_5^{(E)} + e^{4(W+U)} * K_2 \wedge J + K_1 \wedge J \wedge J \\
&\quad + \left[2e^{Z} J \wedge J - 2e^{-8U} * K_1 + K_2 \wedge J\right] \wedge (\eta + A_1) \\
&\quad + \left[e^{4(W+U)} * L_2 \wedge \Omega + L_2 \wedge \Omega \wedge (\eta + A_1) + \text{c.c.}\right]
\end{aligned}
$$

$$
\begin{aligned}
F_{(3)} &= G_3 + G_2 \wedge (\eta + A_1) + G_1 \wedge J + G_0\, J \wedge (\eta + A_1) \\
&\quad + \left[N_1 \wedge \Omega + N_0\, \Omega \wedge (\eta + A_1) + \text{c.c.}\right]
\end{aligned}
$$

$$
\begin{aligned}
H_{(3)} &= H_3 + H_2 \wedge (\eta + A_1) + H_1 \wedge J + H_0\, J \wedge (\eta + A_1) \\
&\quad + \left[M_1 \wedge \Omega + M_0\, \Omega \wedge (\eta + A_1) + \text{c.c.}\right]
\end{aligned}
$$

- The bosonic spectrum is consistent with $N = 4$ gauged supergravity in $d = 5$, coupled to two vector multiplets (Cassani, Dall' Agata, Faedo; Gauntlett, Varela; Liu, Szepietowski, Zhao, 2010) (see Skenderis, Taylor, Tsimpis, 2010 also.)

- This theory has an AdS_5 vacuum that breaks $N = 4 \to N = 2$ spontaneously, and uplifts to a class of $AdS_5 \times SE_5$ solutions (dual to $N = 1$ SCFTs in $d = 4$). It also has an AdS_5 vacuum which preserves no-supersymmetries.

- A further truncation of this theory yields the type IIB holographic superconductor (Gubser, Herzog, Pufu, Tesileanu, 2009)

Type IIB holographic superconductor

$$\mathcal{L}_{4+1} = R - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{12\sqrt{3}}A_\mu F_{\nu\rho}F_{\lambda\sigma}\epsilon^{\mu\nu\rho\lambda\sigma}$$
$$- 8(1-4|Y|^2)^{-2}\left[|DY|^2 - (3/2L^2)\left(1-6|Y|^2\right)\right]$$

Outline

1. Motivation
2. Consistent bosonic truncations
   - $D = 11$ supergravity
   - Type IIB supergravity
3. The fermionic sector
4. Outlook

Singlet spinors

- As we have discussed, we have to find a basis of $SU(n)$ singlet spinors to expand the various fermion modes.

- The *KE* base might not admit a spin structure (e.g. $\mathbb{CP}^2$). However, being Kähler, we can always define a *spin^c* bundle.

- Of crucial importance to us, the "gauge-covariantly constant" spinors ε are sections of the *spin^c* bundle satisfying

Gauge-covariantly constant spinors

$$\left(\nabla_\alpha^{KE} - ie\mathcal{A}_\alpha\right)\varepsilon(y) = 0$$

where e is the "charge".

- An integrability condition allows one to identify the $U(1)$ charge operator acting on the spinor states as $Q \sim i\not{J}$.
- In general, the operator $Q \sim i\not{J}$ has two $SU(n)$ singlet eigenvalues, corresponding to $\varepsilon_{\pm}$ with charge $e = \pm(n+1)/2$.
- For example, for a KE_6 base they are the $SU(3)$ singlets in the $\mathbf{4} \oplus \bar{\mathbf{4}}$ of $Spin(6) = SU(4)$.
- In the absence of squashing, the fact that $\varepsilon_{\pm}(y)$ are gauge-covariantly constant implies that $\epsilon_{\pm}(y,\chi) = e^{ie\chi}\varepsilon_{\pm}(y)$ are Killing spinors of the corresponding SE.
- From this point of view, it seems natural to use these spinors to construct the reduction ansatz for the squashed case.

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- From this point of view, it seems natural to use these spinors to construct the reduction ansatz for the squashed case.

$D = 11$ supergravity

- Since the 11-*d* gravitino is Majorana, the ansatz reads

KK ansatz for the 11-*d* gravitino

$$\Psi_a(x,y,\chi) = \psi_a(x) \otimes \varepsilon_+(y) e^{2i\chi} + \psi_a^{\mathbf{c}}(x) \otimes \varepsilon_-(y) e^{-2i\chi}$$
$$\Psi_\alpha(x,y,\chi) = \lambda(x) \otimes \gamma_\alpha \varepsilon_+(y) e^{2i\chi}$$
$$\Psi_{\bar{\alpha}}(x,y,\chi) = -\lambda^{\mathbf{c}}(x) \otimes \gamma_{\bar{\alpha}} \varepsilon_-(y) e^{-2i\chi}$$
$$\Psi_f(x,y,\chi) = \varphi(x) \otimes \varepsilon_+(y) e^{2i\chi} + \varphi^{\mathbf{c}}(x) \otimes \varepsilon_-(y) e^{-2i\chi}$$

- All in all we have a 5-*d* Dirac gravitino ψ_a, and two spin-1/2 Dirac fields λ and φ (and their charge conjugates). As usual, it is necessary to take linear combinations of these modes and an appropriate rescaling in order to have diagonal kinetic terms.

- In the present case,

$$\zeta_a = e^{W/2}\left[\psi_a - \frac{1}{2}\gamma_5\gamma_a(\varphi + 6\lambda)\right]$$
$$\eta = e^{W/2}(\varphi + 2\lambda)$$
$$\xi = 6e^{W/2}\lambda$$

- Reducing the 11-*d* SUSY variation of the gravitino, we identify η as the gaugino and ξ as the hyperino.

- Reducing the eom for the 11-*d* gravitino, we constructed an effective 4-*d* action, to quadratic order in the fermions, which fits in the general form of $N = 2$ gauged supergravity as given by (Andrianopoli et. al., 1996).

- The full action is complicated, but we will discuss some of its features that are probably relevant for holographic applications.

$$S_F = \kappa \int d^4x\sqrt{-g}\left[\bar{\zeta}_a\gamma^{abc}D_b\zeta_c + \frac{3}{2}\bar{\eta}\not{D}\eta + \frac{1}{2}\bar{\xi}\not{D}\xi + \mathcal{L}^{int}_{\bar{\psi}\psi} + \frac{1}{2}\left(\mathcal{L}^{int}_{\bar{\psi}\psi^c} + \text{c.c.}\right)\right]$$

$$\begin{aligned}
\mathcal{L}^{int}_{\bar{\psi}\psi} = &+ \frac{3}{4}i(\partial_b h)e^{-2U-V}\bar{\zeta}_a\gamma_5\gamma^{abc}\zeta_c + \frac{3}{8}ie^{-2U-V}\bar{\eta}\gamma_5(\not{\partial}h)\eta - \frac{3}{8}ie^{-2U-V}\bar{\xi}\gamma_5(\not{\partial}h)\xi \\
&+ \frac{1}{4}e^{-2W-V}H_3{}^{abc}\bar{\zeta}_a\gamma_5\gamma_b\zeta_c - \frac{3}{8}e^{-2W-V}\bar{\eta}\gamma_5\not{H}_3\eta + \frac{3}{8}e^{-2W-V}\bar{\xi}\gamma_5\not{H}_3\xi \\
&- \frac{i}{4}\bar{\zeta}_a\left[6(\not{\partial}U) + e^{-2W-V}\gamma_5\not{H}_3\right]\gamma^a\xi + \frac{i}{4}\bar{\xi}\gamma^a\left[6(\not{\partial}U) - e^{-2W-V}\gamma_5\not{H}_3\right]\zeta_a \\
&- \frac{3}{4}e^{-2U-V}\left[\bar{\zeta}_a\gamma_5(\not{\partial}T)\gamma^a\eta - \bar{\eta}\gamma_5\gamma^a(\not{\partial}T^\dagger)\zeta_a\right] \\
&+ \frac{3i}{4}e^{V-W}\bar{\eta}\left(\not{F} - i\gamma_5 e^{-V-2U}\not{H}_2\right)\eta - \frac{i}{8}e^{V-W}\bar{\xi}\left(\not{F} + 3i\gamma_5 e^{-V-2U}\not{H}_2\right)\xi \\
&+ \frac{i}{4}\bar{\zeta}_a\left[-e^{V-W}(F + i\gamma_5 * F)^{ac} + 3ie^{-W-2U}\gamma_5(H_2 + i\gamma_5 * H_2)^{ac}\right]\zeta_c \\
&+ \frac{3}{8}e^{V-W}\left[\bar{\zeta}_a\left(\not{F} - i\gamma_5 e^{-V-2U}\not{H}_2\right)\gamma^a\eta + \bar{\eta}\gamma^a\left(\not{F} - i\gamma_5 e^{-V-2U}\not{H}_2\right)\zeta_a\right] \\
&- 3ie^{W-4U}\bar{\zeta}_a\gamma_5 T^\dagger\gamma^{ac}\zeta_c + 3ie^{W-4U}\bar{\eta}\gamma_5 T^\dagger\eta + \frac{3}{2}e^{W-4U}\left(\bar{\zeta}_a\gamma^a\gamma_5 T\eta + \bar{\eta}T\gamma_5\gamma^a\zeta_a\right) \\
&- \frac{9i}{2}e^{W-4U}\bar{\xi}\gamma_5 T\xi - 3ie^{W-4U}(\bar{\eta}\gamma_5 T\xi + \bar{\xi}\gamma_5 T\eta) + 3e^{W-4U}\left(\bar{\zeta}_a\gamma^a\gamma_5 T\xi + \bar{\xi}T\gamma_5\gamma^a\zeta_a\right) \\
&+ \frac{1}{4}i\left(\tilde{f} - 8e^{W-V}\right)\left(i\bar{\zeta}_a\gamma^{ac}\zeta_c - 3i\bar{\eta}\eta + \frac{3}{2}\bar{\zeta}_a\gamma^a\eta + \frac{3}{2}\bar{\eta}\gamma^a\zeta_a\right) \\
&+ \frac{1}{8}\left(3\tilde{f} + 8e^{W-V}\right)\bar{\xi}\xi + \frac{3}{4}\tilde{f}\left(\bar{\eta}\xi + \bar{\xi}\eta\right) + \frac{1}{4}i\tilde{f}\left(\bar{\xi}\gamma^a\zeta_a + \bar{\zeta}_a\gamma^a\xi\right)
\end{aligned}$$

$$S_F = \kappa \int d^4x\sqrt{-g}\left[\bar{\zeta}_a\gamma^{abc}D_b\zeta_c + \frac{3}{2}i \right. + \mathcal{L}^{int}_{\bar{\psi}\psi} + \frac{1}{2}\left(\mathcal{L}^{int}_{\bar{\psi}\psi^{\mathbf{c}}} + \mathrm{c.c.}\right)$$

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& + \frac{1}{4}e^{-2W-V}H_3{}^{abc}\bar{\zeta}_a\gamma_5\gamma_b\zeta_c - \frac{3}{8}e^{-2W-V}\bar{\eta}\gamma_5 H\!\!\!/_3\eta + \frac{3}{8}e^{-2W-V}\bar{\xi}\gamma_5 H\!\!\!/_3\xi \\
& - \frac{i}{4}\bar{\zeta}_a\left[6\,(\partial\!\!\!/ U) + e^{-2W-V}\gamma_5 H\!\!\!/_3\right]\gamma^a\xi + \frac{i}{4}\bar{\xi}\gamma^a\left[6\,(\partial\!\!\!/ U) - e^{-2W-V}\gamma_5 H\!\!\!/_3\right]\zeta_a \\
& - \frac{3}{4}e^{-2U-V}\left[\bar{\zeta}_a\gamma_5(\partial\!\!\!/ T)\gamma^a\eta - \bar{\eta}\gamma_5\gamma^a(\partial\!\!\!/ T^\dagger)\zeta_a\right] \\
& + \frac{3i}{4}e^{V-W}\bar{\eta}\left(F\!\!\!/ - i\gamma_5 e^{-V-2U}H\!\!\!/_2\right)\eta - \frac{i}{8}e^{V-W}\bar{\xi}\left(F\!\!\!/ + 3i\gamma_5 e^{-V-2U}H\!\!\!/_2\right)\xi \\
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&+ \frac{1}{4} e^{-2W-V} H_3{}^{abc} \bar\zeta_a \gamma_5 \gamma_b \zeta_c - \frac{3}{8} e^{-2W-V} \bar\eta \gamma_5 H\!\!\!/_3 \eta + \frac{3}{8} e^{-2W-V} \bar\xi \gamma_5 H\!\!\!/_3 \xi \\
&- \frac{i}{4} \bar\zeta_a \left[6\,(\partial\!\!\!/ U) + e^{-2W-V} \gamma_5 H\!\!\!/_3 \right] \gamma^a \xi + \frac{i}{4} \bar\xi \gamma^a \left[6\,(\partial\!\!\!/ U) - e^{-2W-V} \gamma_5 H\!\!\!/_3 \right] \zeta_a \\
&- \frac{3}{4} e^{-2U-V} \left[\bar\zeta_a \gamma_5 (\partial\!\!\!/ T) \gamma^a \eta - \bar\eta \gamma_5 \gamma^a (\partial\!\!\!/ T^\dagger) \zeta_a \right] \\
&+ \frac{3i}{4} e^{V-W} \bar\eta \left(F\!\!\!/ - i\gamma_5 e^{-V-2U} H\!\!\!/_2 \right) \eta - \frac{i}{8} e^{V-W} \bar\xi \left(F\!\!\!/ + 3i\gamma_5 e^{-V-2U} H\!\!\!/_2 \right) \xi \\
&+ \frac{i}{4} \bar\zeta_a \left[-e^{V-W} (F + i\gamma_5 * F)^{ac} + 3ie^{-W-2U} \gamma_5 (H_2 + i\gamma_5 * H_2)^{ac} \right] \zeta_c \\
&+ \frac{3}{8} e^{V-W} \left[\bar\zeta_a \left(F\!\!\!/ - i\gamma_5 e^{-V-2U} H\!\!\!/_2 \right) \gamma^a \eta + \bar\eta \gamma^a \left(F\!\!\!/ - i\gamma_5 e^{-V-2U} H\!\!\!/_2 \right) \zeta_a \right] \\
&- 3ie^{W-4U} \bar\zeta_a \gamma_5 T^\dagger \gamma^{ac} \zeta_c + 3ie^{W-4U} \bar\eta \gamma_5 T^\dagger \eta + \frac{3}{2} e^{W-4U} \left(\bar\zeta_a \gamma^a \gamma_5 T \eta + \bar\eta T \gamma_5 \gamma^a \zeta_a \right) \\
&- \frac{9i}{2} e^{W-4U} \bar\xi \gamma_5 T \xi - 3ie^{W-4U} (\bar\eta \gamma_5 T \xi + \bar\xi \gamma_5 T \eta) + 3e^{W-4U} \left(\bar\zeta_a \gamma^a \gamma_5 T \xi + \bar\xi T \gamma_5 \gamma^a \zeta_a \right) \\
&\ldots \bar\eta \gamma^a \zeta_a \Big) \\
&\ldots + \bar\zeta_a \gamma^a \xi \Big)
\end{aligned}$$

$$+\frac{1}{8}\left(3e^{-3W} f + 18 e^{W+V-2U} + 8e^{W-V} \right) \bar\xi \xi$$

$$S_F = \kappa \int d^4x\sqrt{-g}\left[\bar\zeta_a\gamma^{abc}D_b\zeta_c + \frac{3}{2}i + \mathcal{L}^{int}_{\bar\psi\psi} + \frac{1}{2}\left(\mathcal{L}^{int}_{\bar\psi\psi^c} + \text{c.c.}\right)\right.$$

$$\begin{aligned}
\mathcal{L}^{int}_{\bar\psi\psi} = &+ \frac{3}{4}i(\partial_b h)e^{-2U-V}\bar\zeta_a\gamma_5\gamma^{abc}\zeta_c + \frac{3}{8}ie^{-2U-V}\bar\eta\gamma_5(\partial\!\!\!/ h)\eta - \frac{3}{8}ie^{-2U-V}\bar\xi\gamma_5(\partial\!\!\!/ h)\xi \\
&+ \frac{1}{4}e^{-2W-V}H_3{}^{abc}\bar\zeta_a\gamma_5\gamma_b\zeta_c - \frac{3}{8}e^{-2W-V}\bar\eta\gamma_5 H\!\!\!/_3\eta + \frac{3}{8}e^{-2W-V}\bar\xi\gamma_5 H\!\!\!/_3\xi \\
&- \frac{i}{4}\bar\zeta_a\left[6(\partial\!\!\!/ U) + e^{-2W-V}\gamma_5 H\!\!\!/_3\right]\gamma^a\xi + \frac{i}{4}\bar\xi\gamma^a\left[6(\partial\!\!\!/ U) - e^{-2W-V}\gamma_5 H\!\!\!/_3\right]\zeta_a \\
&- \frac{3}{4}e^{-2U-V}\left[\bar\zeta_a\gamma_5(\partial\!\!\!/ T)\gamma^a\eta - \bar\eta\gamma_5\gamma^a(\partial\!\!\!/ T^\dagger)\zeta_a\right] \\
&+ \frac{3i}{4}e^{V-W}\bar\eta\left(F\!\!\!/ - i\gamma_5 e^{-V-2U}H\!\!\!/_2\right)\eta - \frac{i}{8}e^{V-W}\bar\xi\left(F\!\!\!/ + 3i\gamma_5 e^{-V-2U}H\!\!\!/_2\right)\xi \\
&+ \frac{i}{4}\bar\zeta_a\left[-e^{V-W}(F + i\gamma_5 * F)^{ac} + 3ie^{-W-2U}\gamma_5(H_2 + i\gamma_5 * H_2)^{ac}\right]\zeta_c \\
&+ \frac{3}{8}e^{V-W}\left[\bar\zeta_a\left(F\!\!\!/ - i\gamma_5 e^{-V-2U}H\!\!\!/_2\right)\gamma^a\eta + \bar\eta\gamma^a\left(F\!\!\!/ - i\gamma_5 e^{-V-2U}H\!\!\!/_2\right)\zeta_a\right] \\
&- 3ie^{W-4U}\bar\zeta_a\gamma_5 T^\dagger \ldots \\
&- \frac{9i}{2}e^{W-4U}\bar\xi\gamma_5 T\xi \ldots \\
&\ldots \frac{3}{2}\bar\eta\gamma^a\zeta_a\Big) \\
&\ldots + \bar\zeta_a\gamma^a\xi\Big)
\end{aligned}$$

$$+\frac{1}{4}i\left(fe^{-3W} + 6e^{W+V-2U}\right)\left(\bar\xi\gamma^a\zeta_a + \bar\zeta_a\gamma^a\xi\right)$$

$$+\frac{1}{8}\left(3e^{-3W}f + 18e^{W+V-2U} + 8e^{W-V}\right)\bar\xi\xi$$

$$S_F = \kappa \int d^4x\sqrt{-g}\left[\bar{\zeta}_a\gamma^{abc}D_b\zeta_c + \frac{3}{2}i \right.$$

$$+\mathcal{L}^{int}_{\bar{\psi}\psi} + \frac{1}{2}\left(\mathcal{L}^{int}_{\bar{\psi}\psi^{\mathbf{c}}} + \mathrm{c.c.}\right)$$

$$\mathcal{L}^{int}_{\bar{\psi}\psi} = +\frac{3}{4}i(\partial_b h)e^{-2U-V}\bar{\zeta}_a\gamma_5\gamma^{abc}\zeta_c + \frac{3}{8}ie^{-2U-V}\bar{\eta}\gamma_5(\partial\!\!\!/ h)\eta - \frac{3}{8}ie^{-2U-V}\bar{\xi}\gamma_5(\partial\!\!\!/ h)\xi$$

$$+\frac{1}{4}e^{-2W-V}H_3{}^{abc}\bar{\zeta}_a\gamma_5\gamma_b\zeta_c - \frac{3}{8}e^{-2W-V}\bar{\eta}\gamma_5 H\!\!\!/_3\eta + \frac{3}{8}e^{-2W-V}\bar{\xi}\gamma_5 H\!\!\!/_3\xi$$

$$-\frac{i}{4}\bar{\zeta}_a\left[6(\partial\!\!\!/ U) + e^{-2W-V}\gamma_5 H\!\!\!/_3\right]\gamma^a\xi + \frac{i}{4}\bar{\xi}\gamma^a\left[6(\partial\!\!\!/ U) - e^{-2W-V}\gamma_5 H\!\!\!/_3\right]\zeta_a$$

$$-\frac{3}{\ }\ \ldots$$

$$+\frac{3i}{4}e^{V-W}\bar{\eta}\left(F\!\!\!/ - i\gamma_5 e^{-V-2U}H\!\!\!/_2\right)\eta$$

$$+ \ldots e^{-V-2U}H\!\!\!/_2)\,\xi$$

$$+\frac{i}{4}\bar{\zeta}_a\left[-e^{V-W}(F + i\gamma_5 * F)^{ac} + 3ie^{-W-2U}\gamma_5(H_2 + i\gamma_5 * H_2)^{ac}\right]\zeta_c$$

$$+\frac{3}{8}e^{V-W}\left[\bar{\zeta}_a\left(F\!\!\!/ - i\gamma_5 e^{-V-2U}H\!\!\!/_2\right)\gamma^a\eta + \bar{\eta}\gamma^a\left(F\!\!\!/ - i\gamma_5 e^{-V-2U}H\!\!\!/_2\right)\zeta_a\right]$$

$$-3ie^{W-4U}\bar{\zeta}_a\gamma_5 T^{\dagger\ ac}\ \ldots$$

$$-\frac{9i}{2}e^{W-4U}\bar{\xi}\gamma_5 T\xi$$

$$+\frac{1}{4}i\left(fe^{-3W} + 6e^{W+V-2U}\right)\left(\bar{\xi}\gamma^a\zeta_a + \bar{\zeta}_a\gamma^a\xi\right)$$

$$\ldots \frac{3}{2}\bar{\eta}\gamma^a\zeta_a\Big)$$

$$+\frac{1}{8}\left(3e^{-3W}f + 18e^{W+V-2U} + 8e^{W-V}\right)\bar{\xi}\xi$$

$$\ldots + \bar{\zeta}_a\gamma^a\xi\Big)$$

$$\mathcal{L}^{int}_{\bar{\psi}\psi^{\mathbf{c}}} = e^{-3U}\left\{-\frac{3i}{4}\bar{\eta}\gamma_5(\not{D}X)\eta^{\mathbf{c}} - \frac{i}{2}(D_bX)\bar{\zeta}_a\gamma_5\gamma^{abc}\zeta_c^{\mathbf{c}} - \frac{1}{4}\bar{\zeta}_a\gamma_5(\not{D}X)\gamma^a\xi^{\mathbf{c}} + \frac{1}{4}\bar{\xi}\gamma^a\gamma_5(\not{D}X)\zeta_a^{\mathbf{c}}\right\}$$

$$+ e^{W-V-3U}\left\{-6iX\bar{\eta}\gamma_5\eta^{\mathbf{c}} + 2iX\bar{\zeta}_a\gamma_5\gamma^{ac}\zeta_c^{\mathbf{c}} - X\bar{\zeta}_a\gamma_5\gamma^a\xi^{\mathbf{c}} + X\bar{\xi}\gamma^a\gamma_5\zeta_a^{\mathbf{c}}\right.$$

$$\left. - 3X\left[\bar{\zeta}_a\left(\gamma_5\gamma^a\right)\eta^{\mathbf{c}} + \bar{\eta}\left(\gamma_5\gamma^a\right)\zeta_a^{\mathbf{c}} + i\bar{\eta}\gamma_5\xi^{\mathbf{c}} + i\bar{\xi}\gamma_5\eta^{\mathbf{c}}\right]\right\},$$

$$\mathcal{L}^{int}_{\bar{\psi}\psi^{\mathbf{c}}} = e^{-3U}\left\{ -\frac{3i}{4}\bar{\eta}\gamma_5(\not{D}X)\eta^{\mathbf{c}} - \frac{i}{2}(D_b X)\bar{\zeta}_a\gamma_5\gamma^{abc}\zeta_c^{\mathbf{c}} - \frac{1}{4}\bar{\zeta}_a\gamma_5(\not{D}X)\gamma^a\xi^{\mathbf{c}} + \frac{1}{4}\bar{\xi}\gamma^a\gamma_5(\not{D}X)\zeta_a^{\mathbf{c}} \right\}$$

$$+e^{W-V-3U}\Big\{ -6iX\bar{\eta}\gamma_5\eta^{\mathbf{c}} + \dots \; {}^{c}\zeta_c^{\mathbf{c}} - X\bar{\zeta}_a\gamma_5\gamma^a\xi^{\mathbf{c}} + X\bar{\xi}\gamma^a\gamma_5\zeta_a^{\mathbf{c}}$$

$$-3X\left[\bar{\zeta}_a\left(\gamma_5\gamma^a\right)\eta^{\mathbf{c}} + \bar{\eta}\left(\gamma_5\gamma^a\right)\zeta_a^{\mathbf{c}} + i\bar{\eta}\gamma_5\xi^{\mathbf{c}} + i\bar{\xi}\gamma_5\eta^{\mathbf{c}}\right]\Big\},$$

$$\mathcal{L}^{int}_{\bar{\psi}\psi^{\mathbf{c}}} = e^{-3U}\Big\{ -\tfrac{3i}{4}\bar{\eta}\gamma_5(\not{D}X)\eta^{\mathbf{c}} + \dots \quad {}_a\gamma_5\gamma^{abc}\zeta_c^{\mathbf{c}} - \frac{1}{4}\bar{\zeta}_a\gamma_5(\not{D}X)\gamma^a\xi^{\mathbf{c}} + \frac{1}{4}\bar{\xi}\gamma^a\gamma_5(\not{D}X)\zeta_a^{\mathbf{c}}\Big\}$$

$$+e^{W-V-3U}\Big\{ -6iX\bar{\eta}\gamma_5\eta^{\mathbf{c}} + \dots \quad {}^c\zeta_c^{\mathbf{c}} - X\bar{\zeta}_a\gamma_5\gamma^a\xi^{\mathbf{c}} + X\bar{\xi}\gamma^a\gamma_5\zeta_a^{\mathbf{c}}$$

$$-3X\left[\bar{\zeta}_a\left(\gamma_5\gamma^a\right)\eta^{\mathbf{c}} + \bar{\eta}\left(\gamma_5\gamma^a\right)\zeta_a^{\mathbf{c}} + i\bar{\eta}\gamma_5\xi^{\mathbf{c}} + i\bar{\xi}\gamma_5\eta^{\mathbf{c}}\right]\Big\},$$

Type IIB supergravity

- We now have a chiral 10-d gravitino Ψ_M and a chiral 10-d dilatino λ of opposite chirality. The ansatz reads

KK ansatz for type IIB fermions

$$\Psi_a(x,y,\chi) = \psi_a^{(+)}(x) \otimes \varepsilon_+(y) e^{\frac{3}{2}i\chi} \otimes u_- + \psi_a^{(-)}(x) \otimes \varepsilon_-(y) e^{-\frac{3}{2}i\chi} \otimes u_-$$

$$\Psi_\alpha(x,y,\chi) = \rho^{(+)}(x) \otimes \gamma_\alpha \varepsilon_+(y) e^{\frac{3}{2}i\chi} \otimes u_-$$

$$\Psi_{\bar{\alpha}}(x,y,\chi) = \rho^{(-)}(x) \otimes \gamma_{\bar{\alpha}} \varepsilon_-(y) e^{-\frac{3}{2}i\chi} \otimes u_-$$

$$\Psi_f(x,y,\chi) = \varphi^{(+)}(x) \otimes \varepsilon_+(y) e^{\frac{3}{2}i\chi} \otimes u_- + \varphi^{(-)}(x) \otimes \varepsilon_-(y) e^{-\frac{3}{2}i\chi} \otimes u_-$$

$$\lambda(x,y,\chi) = \lambda^{(+)}(x) \otimes \varepsilon_+(y) e^{\frac{3}{2}i\chi} \otimes u_+ + \lambda^{(-)}(x) \otimes \varepsilon_-(y) e^{-\frac{3}{2}i\chi} \otimes u_+$$

- Unlike the $D = 11$ case, there is no reality condition on the $D = 10$ fermions. For example, $\lambda^{(+)}$ and $\lambda^{(-)}$ are now independent Dirac fermions in $d = 5$.

- As before, we take linear combinations and rescale the fields to obtain diagonal kinetic terms:

$$\tilde{\lambda}^{(\pm)} = e^{W/2}\lambda^{(\pm)}$$

$$\zeta_a^{(\pm)} = e^{W/2}\left[\psi_a^{(\pm)} - \frac{i}{3}\gamma_a\left(\varphi^{(\pm)} + 4\rho^{(\pm)}\right)\right]$$

$$\xi^{(\pm)} = 4e^{W/2}\rho^{(\pm)}$$

$$\eta^{(\pm)} = 2e^{W/2}\left(\rho^{(\pm)} + \varphi^{(\pm)}\right)$$

- By examining the susy variations of these modes and matching with the general structure of $N = 4$ gauged supergravity in $d = 5$ ((Dall' Agata,Herrmann, Zagermann, 2001; Schön, Weidner, 2006), for example) we learn that $\eta^{(\pm)}$ sit in the $N = 4$ gravity multiplet.

- These modes could be assembled into four symplectic-Majorana spinors, in the **4** of $USp(4) \simeq SO(5)$. The remaining spin-1/2 fermions $\xi^{(\pm)}$, $\tilde{\lambda}^{(\pm)}$ can then be arranged into an $SO(2)$ doublet of $USp(4)$ quartets, appropriate to the pair of vector multiplets.

- It is hard to display the full effective $d = 5$ action here. However, there are various possible further truncations.
- Examples include the minimal gauged $N = 4$ sugra in $d = 5$ and the type IIB holographic superconductor truncation.
- Quite interestingly, for the superconductor model we found a consistent truncation of the fermion sector which retains a single spin-1/2 mode:

A fermion truncation in the type IIB holographic superconductor

$$\mathcal{L}_{4+1} = \frac{1}{2}\bar{\tilde{\lambda}}^{(+)} \not{D} \tilde{\lambda}^{(+)} - \frac{1}{2}\bar{\tilde{\lambda}}^{(+)} \left(\frac{3}{2} + \frac{1}{4} i \not{F} + \frac{2 - 6|Y|^2 + Y^* \overleftrightarrow{\not{D}} Y}{1 - 4|Y|^2} \right) \tilde{\lambda}^{(+)}$$

Outline

1. Motivation
2. Consistent bosonic truncations
   - $D = 11$ supergravity
   - Type IIB supergravity
3. The fermionic sector
4. Outlook

- We have constructed top-down models that describe the coupling of fermions to the bosonic configurations that are relevant for AdS/CMT applications.
- For the type IIB holographic superconductor, we found a simple consistent truncation of the fermion sector containing a single spin-1/2 mode.
- In general, including the mixing of the spin-1/2 fermions with the gravitino might have interesting effects from the point of view of holography.
- Our effective Lagrangians can provide guidance for bottom-up models $\Rightarrow$ new couplings that may be relevant for "phenomenology" (e.g. Pauli couplings to gauge fields, derivative couplings to charged scalars, etc.).
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