Holography and the dynamical breaking of Supersymmetry

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Outline

- Motivation
- New domain wall SUGRA solutions
- Holographic correlators
  - massless modes
  - massive resonances
- Applications to SUSY breaking hidden sectors
- Outlook

Based on:

Collaboration with Bertolini, Di Pietro, Musso, Porri and Redigolo

- **arXiv:1411.2658 [hep-th] AMR**
- arXiv:1412.6499 [hep-th] ABMPR
- see also arXiv:1205.4709 [hep-th], arXiv:1208.3615 [hep-th], arXiv:1310.6897 [hep-th] ABDPR

Motivation

Symmetry breaking by strongly coupled dynamics
is often crucial in physical theories

Some examples:

- Chiral symmetry in QCD
- Dynamical SUSY breaking $\leftrightarrow$ hierarchy problem
- High T_c superconductors
- Higher spin symmetry $\leftrightarrow$ string theory

In strongly coupled theories, both the fields responsible for symmetry breaking and the (pseudo)-Goldstone particles that result from it are typically composite, i.e. not elementary.

Here we will focus on SUSY breaking at strong coupling.

Our approach to strong coupling is through holography.

In a nutshell:

- Strongly coupled, large N 4d field theories from 5d near-AdS gravitational theories.
- Vacua of the gauge theories correspond to specific solutions (backgrounds) in the gravity theory.
- Gauge invariant (composite) operators correspond to classical fields in the bulk.
- Quantum correlators are computed from fluctuations over the background and a (classical) renormalization procedure.
- RG-flow from UV to IR in the quantum field theory is mapped to radial evolution from the boundary to the deep bulk in the gravity theory.

Motivated by the celebrated example of the correspondence between $\mathcal{N} = 4$ SYM and IIB string theory on $AdS_5 \times S^5$.

Models of SUSY breaking in holography:

Roughly, in order to recover situations where SUSY breaking is spontaneous (or soft), we need non-SUSY solutions that asymptote to SUSY ones near the boundary/UV.

Some examples:

- non SUSY versions of Klebanov-Strassler: anti-D3 branes (KPV), Kuperstein et al., ...
- $d \neq 4$ examples: Maldacena-Nastase, Massai et al.,...
- $T \neq 0$: many! (but not our focus here–$T = 0$ from now on)

- bottom-up: $\mathcal{N} = 2$ SUGRA in 5d

The complexity of the bottom-up model (and its reach towards top-down models) depends on the hyper- and vector-multiplet content.

$\Rightarrow$ it turns out $\mathcal{N} = 2$ SUGRA coupled to a universal hypermultiplet is already rich enough!

Given that we define the SUSY breaking strongly coupled theory through its holographic dual, how are we going to probe/characterize its SUSY breaking features?

Our aim will be to compute two-point correlators through holographic renormalization

This will give us information on several physical properties:

- Presence/absence of massless modes such as:
  - dilaton
  - R-axion
  - Goldstino
  - 't Hooft fermions
- Violation of SUSY Ward identities
- Spectrum of resonances
- Stability: no tachyonic resonances
- Can be directly useful for applications

New RG-flow SUGRA solutions

We restrict to solutions with at most two backreacting scalars.

We start form the action (choice of gauging!)

$$\mathcal{S} = \int d^5x\sqrt{G}\left[-\frac{1}{2}R + \partial_M\eta\partial^M\eta + \frac{1}{4}\cosh^2\eta\partial_M\phi\partial^M\phi \right.$$
$$\left. + \frac{3}{4}\left(\cosh^2 2\eta - 4\cosh 2\eta - 5\right)\right]$$

together with the 4d Poincaré invariant ansatz

$$ds^2 = \frac{1}{z^2}\left(dz^2 + F(z)\eta_{\mu\nu}dx^\mu dx^\nu\right) \qquad \eta = \eta(z) \qquad \phi = \phi(z)$$

The system of equations we have to solve boils down to

$$12\left(1-\frac{zF'}{2F}\right)^2+\frac{3}{2}\left(\cosh^2 2\eta-4\cosh 2\eta-5\right)=2z^2\eta'^2+\frac{1}{2}z^2\cosh^2\eta\phi'^2$$

$$\frac{z^5}{F^2}\partial_z\left(\frac{F^2}{z^3}\eta'\right)=\frac{1}{8}z^2\sinh 2\eta\phi'^2+\frac{3}{2}\sinh 2\eta(\cosh 2\eta-2)$$

$$\partial_z\left(\frac{F^2}{z^3}\cosh^2\eta\phi'\right)=0$$

[Note: we do not use any superpotential (true or fake)]

3-parameter worth of domain wall solutions, all are AdS near $z=0$:

$$\phi=\tilde{\phi}_4 z^4+\ldots \qquad \eta=\eta_0 z+\tilde{\eta}_2 z^3+\ldots$$

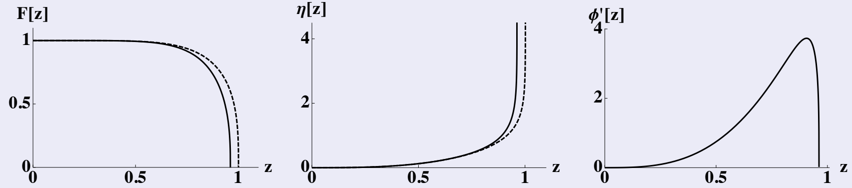
Most solutions are singular in the IR.

For some specific values of the parameters, we recover known solutions.

- For $\tilde{\phi}_4 = 0$ and $\eta_0 = 0$ we have the SUSY solution of GPPZ:

$$F(z) = \left(1 - z^6 \tilde{\eta}_2^2\right)^{\frac{1}{3}} \ , \qquad \eta(z) = \frac{1}{2} \ln\left(\frac{1 + \tilde{\eta}_2 z^3}{1 - \tilde{\eta}_2 z^3}\right)$$

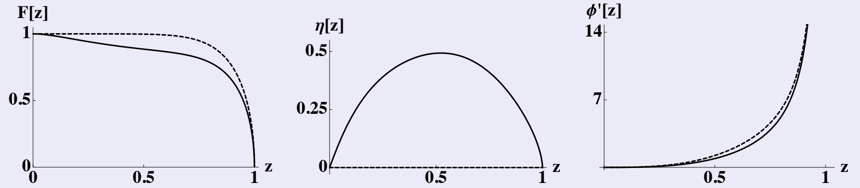
Our generic (numerical) solution is a non-SUSY generalization of it:



- For $\eta = 0$, we have the dilaton domain wall of Gubser, Kehagias-Sfetsos, Constable-Myers:

$$F(z) = \left(1 - \frac{\tilde{\phi}_4^2 z^8}{6}\right)^{1/2} , \qquad \phi(z) = \sqrt{6}\ \mathrm{arctanh}\left(\frac{\tilde{\phi}_4 z^4}{\sqrt{6}}\right)$$

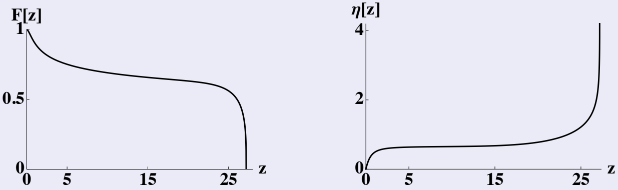
Again, we have a two-dimensional subspace of solutions generalizing it, with a non-trivial but non-singular profile for η:



- For $\phi = 0$ and $\tilde{\eta}_2$ a specific function of η_0, we also recover a family of numerical non-singular solutions, known as the Distler-Zamora solutions.

They are domain walls where η interpolates between the maximum and the minimum of the potential.

We generalize this family by “almost getting there": walking solutions



Holographic correlators

2-point correlators of gauge invariant operators $\langle \mathcal{O}(k)\mathcal{O}(-k)\rangle$ contain lots of information on the theory and on the vacuum in which it finds itself.

- Euclidean momentum $k^2 > 0$: UV and IR asymptotics
- Minkowskian momentum $k^2 < 0$: spectrum of theory (resonances)
- When SUSY is unbroken, different 2-point functions are related.
- When SUSY is broken the 2-point functions will differ at low momenta/large distances.

We will employ holographic renormalization to compute two-point functions in the gauge theories dual to our backgrounds.

The prescription relating quantum correlators to fluctuations of bulk fields is the following (in the large N, strong coupling limit):

$$Z_{\rm QFT}(\phi_0) \equiv \langle e^{-\int \phi_0 \mathcal{O}} \rangle = e^{-S_{\rm SUGRA}(\phi|_{z=0}=\phi_0)}$$

It follows that two-point correlators are obtained taking the second order variation of $S_{\rm SUGRA}$ with respect to the leading mode ϕ_0.

The on-shell action $S_{\rm SUGRA}$ reduces to a 4d boundary integral, which however diverges due to the infinite volume of AdS.

The procedure of holographic renormalization goes through regularization (introducing a $z = \epsilon$ surface), covariant counter-terms, and eventually leads to a renormalized action $S_{\rm ren}$.

More specifically, if the fluctuation of the bulk field ϕ dual to the dimension Δ operator $\mathcal{O}$ has a near-boundary expansion like

$$\phi = \phi_0 z^{4-\Delta} + \cdots + \tilde{\phi}_{2\Delta-4} z^{\Delta} + \ldots$$

then the renormalized action will be

$$S_{\text{ren}} \propto \int d^4x (\phi_0 \tilde{\phi}_{2\Delta-4} + \text{local terms})$$

Solving for the linear fluctuations of ϕ in the non-trivial background, including boundary conditions in the bulk, $\tilde{\phi}_{2\Delta-4}$ is typically a non-local but linear function of ϕ_0.

$\Rightarrow$ Eventually, the two point function is given by

$$\langle \mathcal{O}(k)\mathcal{O}(-k)\rangle = \frac{\delta^2 S_{\text{ren}}}{\delta \phi_0^2} = \frac{\delta \tilde{\phi}_{2\Delta-4}}{\delta \phi_0} + \text{local terms}$$

Note that sometimes the local terms are crucial!

Massless modes

As a warm up, we consider a toy model for the holographic realization of Goldstone bosons: 5d model with a vector and an axion-like scalar

[See also Bianchi, Freedman, Skenderis 01]

$$S = \int d^5x\sqrt{G}\left[\frac{1}{4}F^{MN}F_{MN} + \frac{1}{2}m(z)^2(\partial_M\alpha - A_M)(\partial^M\alpha - A^M)\right]$$

The bulk vector's $U(1)$ symmetry is broken by the profile

$$m(z) = m_0 z + \tilde{m}_2 z^3 \qquad (\Delta = 3 \text{ for simplicity})$$

From the boundary FT point of view:

- m_0 explicit breaking of global $U(1)$
- $\tilde{m}_2$ spontaneous breaking of global $U(1)$

[From the SUGRA point of view it is always spontaneous breaking.]

The correlator we will be probing is

$$\langle J_\mu(k) J_\nu(-k)\rangle = -(k^2\delta_{\mu\nu} - k_\mu k_\nu)C(k^2) - m_0^2 \frac{k_\mu k_\nu}{k^2} F(k^2)$$

In holographic renormalization, the transverse and longitudinal parts of A_μ are dual to the transverse and longitudinal parts of J_μ, respectively.

The longitudinal part of A_μ however mixes with α, which is dual to $\mathrm{Im}O_m$, i.e. the imaginary part of the operator that breaks the symmetry.

Expectations:

- spontaneous breaking: $F(k^2) = 0$, massless pole in $C(k^2)$, Schwinger term in $\langle J_\mu \, \mathrm{Im}O_m\rangle$
- explicit breaking: no massless poles, $F(k^2) \neq 0$, operator identity $\partial_\mu J^\mu = m_0 \, \mathrm{Im}O_m$

Holographic renormalization:

Spontaneous: $$S_{\rm ren} = -\int d^4k \left\{ a^t_{0\mu}\tilde{a}^t_{2\mu} + \tilde{m}_2^2\alpha_0(\tilde{\alpha}_2 + a^l_0) + \text{local} \right\}$$

- $a^t_{0\mu}\tilde{a}^t_{2\mu}$ term leads to $C(k^2)$. Massless pole appears because of bulk boundary conditions.
- $\tilde{m}_2^2\alpha_0 a^l_0$ term leads to the Schwinger term $\langle \partial_\mu J^\mu \, \mathrm{Im} O_m \rangle = \tilde{m}_2$, which leads to the massless pole $\langle J_\mu(k) \mathrm{Im}\, O_m(-k) \rangle = \tilde{m}_2 \frac{k_\mu}{k^2}$.

Explicit: $$S_{\rm ren} = -\int d^4k \left\{ a^t_{0\mu}\tilde{a}^t_{2\mu} + m_0^2(\alpha_0 - a^l_0)\tilde{\alpha}_2 + \text{local} \right\}$$

- massless pole in $C(k^2)$ can be cancelled by local terms $\propto m_0^2$ (cancels anyhow from full $\langle J_\mu J_\nu \rangle$)
- Operator identity consequence of $\mathcal{S}_{\rm ren}$ depending only on $\alpha_0 - a^l_0$ (bulk gauge symmetry):

$$\frac{\delta \mathcal{S}_{\rm ren}}{\delta a_{l0}} = -\frac{\delta \mathcal{S}_{\rm ren}}{\alpha_0} \qquad \Leftrightarrow \qquad \langle \partial_\mu J^\mu \rangle = m_0 \langle \mathrm{Im}\, O_m \rangle$$

In full $\mathcal{N}=2$ SUGRA models, these considerations apply to the R-axion and the dilaton.

The correlators are

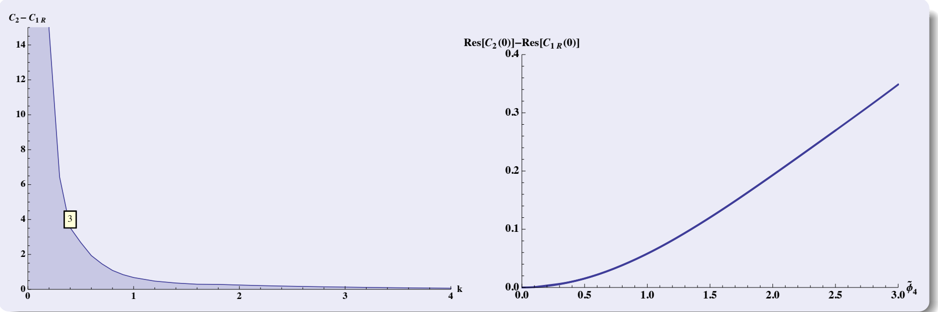
$$\langle T_{\mu\nu}(k)\, T_{\rho\sigma}(-k)\rangle = -\frac{1}{8} X_{\mu\nu\rho\sigma}\, C_2(k^2) - \frac{1}{12}\frac{m^2}{k^2}\, P_{\mu\nu}P_{\rho\sigma}\, F_2(k^2)$$

$$\langle j^R_\mu(k)\, j^R_\nu(-k)\rangle = -P_{\mu\nu}\, C_{1R}(k^2) - \frac{1}{3}\, m^2 \frac{k_\mu k_\nu}{k^2}\, F_1(k^2)$$

- $F_2 = 0 = F_1$ if conformal and R-symmetry are not explicitly broken.
- SUSY Ward identities require $C_2 = C_{1R}$ and $F_2 = F_1$ for a SUSY preserving RG-flow.
- $T_{\mu\nu}$ dual to h_{MN}, the graviton, and j^R_μ dual to R_M, the graviphoton, of the $\mathcal{N}=2$ gravity multiplet.

Both C_2 and C_{1R} have a massless pole when $\eta_0 = 0$.

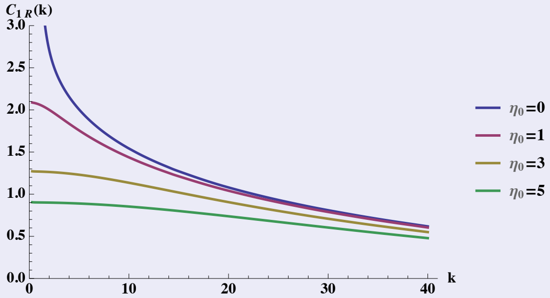
SUSY is recovered when also $\tilde{\phi}_4 = 0$.
In this case we expect $C_2 = C_{1R}$.



The pole in C_2 corresponds to the dilaton of broken conformal symmetry, and the pole in C_{1R} to the R-axion of broken R-symmetry.

In the SUSY limit, the R-axion and dilaton become superpartners.

The massless poles disappear when η_0 is turned on:



The R-axion acquires a mass proportional to η_0.

Goldstino

When SUSY is spontaneously broken, a massless fermion, the Goldstino is expected.

Problem: spontaneous SUSY breaking is allowed only when conformal symmetry is explicitly broken.

This is because spontaneous SUSY breaking is heralded by

$$\langle T_{\mu\nu} \rangle = -F^2 \eta_{\mu\nu}$$

This relation is impossible in a conformal theory in which we have the operator constraint $T^{\mu}_{\mu} = 0$.

$\Rightarrow$ We need a solution where conformal symmetry is broken by a SUSY source. [This requires a different gauged SUGRA–no details here]

Q: Where should the Goldstino massless pole appear?
A: in the correlator of the supercurrent!

More precisely, in a Schwinger term in this correlator.

$$\langle(\partial^\mu S_{\mu\alpha})(k)\bar{S}_{\nu\dot{\beta}}(-k)\rangle = -\langle\delta_\alpha \bar{S}_{\nu\dot{\beta}}\rangle = 2i\sigma^\nu{}_{\alpha\dot{\beta}}\,\langle T_{\mu\nu}\rangle \neq 0$$

implies

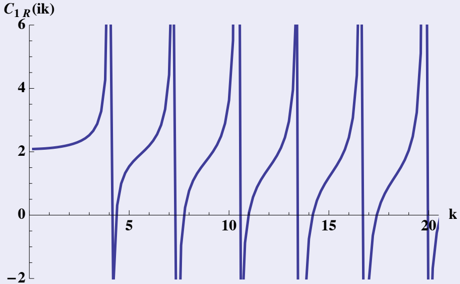
$$\langle S_{\mu\alpha}(k)\,\bar{S}_{\nu\dot{\beta}}(-k)\rangle = \cdots + F^2(\sigma_\mu\bar{\sigma}^\rho\sigma_\nu)_{\alpha\dot{\beta}}\frac{2k_\rho}{k^2}$$

$\Rightarrow$ boundary analysis in holographic renormalization is enough to find the Goldstino. [See Matteo's talk next week!]

Spectrum of resonances

The poles appearing in the correlators give the spectrum in the corresponding channel.

If all the poles lie on the $k^2 < 0$ axis, then no tachyonic resonance is present and the solution represents an RG-flow to a stable vacuum.



In the generic case the first pole corresponds to a mass of the order of the mass gap.

We have checked that there are no tachyonic poles in any channel for a sample of our class of solutions.

This does not mean that the solutions are stable also when enlarging the SUGRA model (for instance in string theory embeddings). However it is a check in principle of the stability of the solution.

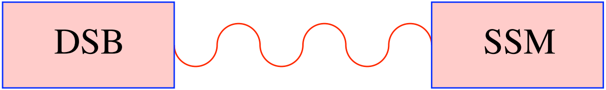
Note that tachyons in the QFT spectrum of resonances are not the same thing as scalars below the BF bound in the bulk!

- We look for tachyons that would occur in a channel associated to an operator with real dimension.
- Scalars below the BF bound would lead to complex dimensions $\rightarrow$ more drastic instability.

Application to SUSY breaking hidden sectors

Q: How are the soft terms in the SSM generated?

SUSY breaking must be communicated to the SSM through higher dimension operators. This leads to the mediation paradigm:



- hidden sector with (dynamical) SUSY breaking
- visible SSM sector
- mediating fields in between: one option is SM gauge fields (and superpartners) $\Rightarrow$ Gauge Mediation of SUSY breaking

The hidden sector has to have a global symmetry, which is then gauged by the SM gauge fields.

All data of interest from the hidden sector is contained in the 2-pt correlators of operators in the supermultiplet to which the conserved currents belongs to.

This is the formalism of General Gauge Mediation. [Meade, Seiberg, Shih 08]

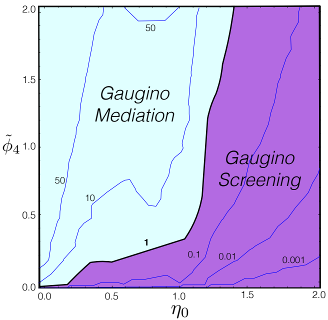
An early top-down attempt was Holographic Gauge Mediation.

[Benini et al, McGuirk et al 09]

- In our holographic set up, we need to add to our supergravity an $\mathcal{N} = 2$ vector multiplet dual to the conserved current supermultiplet.

Our results:

- Set up for holographic computation of correlators relevant for GGM.
- R-preserving cases $\eta = 0$: we find a composite 't Hooft fermion, leading to a Dirac mass for gauginos.
  A heavy gaugino leads to a gaugino mediation scenario.
- Turning on the R-breaking scalar η produces Majorana masses, eventually covering all GGM parameter space.
- For dominant η_0 gaugino masses are suppressed–'screened'.



Outlook

- New classes of SUGRA solutions representing SUSY-breaking RG-flows.
- Holographic realization of massless particles related to dynamical symmetry breaking.
- These particles arise as part of the spectrum of resonances, and also from Schwinger terms.

- More general and more realistic classes of solutions
  $\rightarrow$ more hyper- and vector multiplets in the $\mathcal{N} = 2$ SUGRA.
- Embedding in string theory/consistent truncations
  $\rightarrow$ top down models.
- Finding the Goldstino can be a useful discriminant to determine whether we have the gravity dual of spontaneous SUSY breaking.