Title: Maximal supergravity, holography and the Romans mass

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Abstract: At large N, an important sector of the ABJM field theory defined on a stack of N M2-branes can be described holographically by the D=4 N=8 SO(8)-gauged supergravity of de Wit and Nicolai. Since its inception, the latter has been tacitly assumed to be unique. Recently, however, a one-parameter family of SO(8) gaugings of N=8 supergravity has been discovered, the de Wit-Nicolai theory being just a member in this class. I will explain how this overlooked family of SO(8)-gauged supergravities is deeply related to electric/magnetic duality breaking in four dimensions. I will then discuss some predictions that can be made about the family of dual large-N field theories that these supergravities define, focusing on the structure of superconformal phases and the RG flows between them. I will finally argue that when the gauging is chosen to be related, but different, to the SO(8) one, the D=4 N=8 family arises as consistent truncation of massive IIA on the six-sphere, with the Romans mass identified as the electric/magnetic duality-breaking parameter.

The holography of electric/magnetic duality breaking

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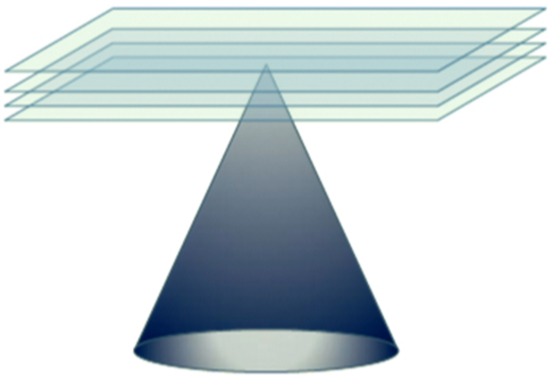
Outline

1. $\mathrm{AdS}_4/\mathrm{CFT}_3$ and gauged supergravity
2. Electric/Magnetic duality
3. The SU(3)–invariant sector of new $N = 8$ supergravity
   - All vacua with at least SU(3) invariance
   - Holographic RG flows
4. Outlook

N M2 branes at a conical singularity



- Place N M2 branes a the apex of a metric cone $(C(M_7), dr^2 + r^2 ds^2(M_7))$.
- Near the horizon, the $D = 11$ supergravity solution is [Freund, Rubin '80]

$$AdS_4 \times M_7$$
$$G_4 \sim \text{vol}(AdS_4)$$

with M_7 Einstein space with positive curvature.

- For $M_7 = S^7$, $C(S^7) = \mathbb{R}^8$ and the solution is $\mathcal{N} = 8$.

The field theory on the stack of N M2 branes

- The field theory on the stack of N M2 branes has been identified by BLG/ABJM

  [Bagger, Lambert '06, Gustavsson '07, Aharony, Begman, Jafferis, Maldacena '08]

- ABJM is a 3D Chern-Simons theory $\mathcal{L}_0$ with $\mathrm{U}(N)_k \times \mathrm{U}(N)_{-k}$ gauge group coupled to chiral multiplets.

- $\mathcal{L}_0$ is conformal and, for $k = 1, 2$, it is maximally supersymmetric and displays SO(8) global invariance:

$$\mathcal{L}_0 \quad \longleftrightarrow \quad \text{M-theory on } AdS_4 \times S^7/\mathbb{Z}_k$$

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Away from conformality

- Correspondence holds at a conformal fixed point. More interesting field theory regimes?

$$\mathcal{L}_0 + \mathcal{L}_1 \quad \longleftrightarrow \quad \text{M-theory on } AdS_4 \times S^7/\mathbb{Z}_k + \text{perturbations}$$

- Better control at large N:

$$\text{Large } N \ \mathcal{L}_0 + \mathcal{L}_1 \quad \longleftrightarrow \quad \text{11D sugra on } AdS_4 \times S^7/\mathbb{Z}_k + \text{perturbations}$$

- Closure:

Operators in $\mathcal{L}_1$ closed under OPE $\longleftrightarrow$ 'Well-defined' 4D perturbations above AdS_4

Gauged supergravity and AdS/CFT

Gauged supergravity is a powerful tool to explore interesting physics of the dual field theory:

Conformal phases	$\longleftrightarrow$	AdS critical points of the scalar potential
RG flows	$\longleftrightarrow$	Domain walls
Finite temperature effects	$\longleftrightarrow$	AAdS black holes
Chemical potentials	$\longleftrightarrow$	Non-trivial gauge field profiles
Non-relativistic phases	$\longleftrightarrow$	Deformations of AdS

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$D = 4$ $N = 8$ SO(8)-gauged supergravity

A prime gauged supergravity is the 4D $N = 8$ SO(8)-gauged supergravity [de Wit, Nicolai '82]

- Higher-dim origin: M-theory on S^7 [de Wit, Nicolai '87 ,'13; Pilch, Nicolai 12]
  Smaller truncations [Cvetic, Duff, Pope, et al.]

- Critical points lift to well-known $AdS_4 \times S^7$ M-theory backgrounds.
  - The $N = 8$ SO(8) point lifts to Freund-Rubin.
  - Other points with less susy lift to solutions with warped, stretched, squashed metrics on S^7 and fluxes, e.g. [Corrado, Pilch, Warner]

- Captures all possible mass deformations of $k = 1, 2$ ABJM:

$$\mathcal{L}_1 \sim m^2_{IJ} X^I X^J + m_{IJ} \psi^I \psi^J$$

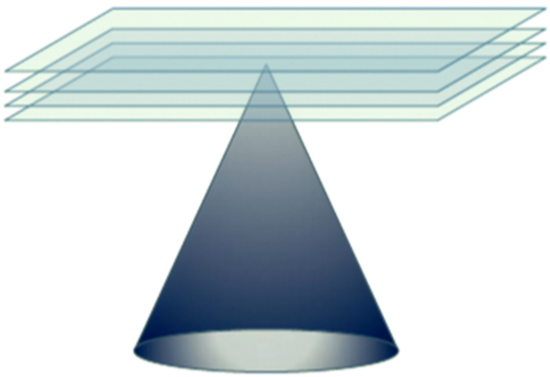
- SO(8) : Global symmetry of $k = 1, 2$ ABJM $\longleftrightarrow$ Gauge group of the supergravity $\longleftrightarrow$ Isometry of S^7

Gauged supergravity and AdS/CFT

Well defined: a consistent truncation of 11D sugra down to 4D gauged sugra exists.

- Truncation: Keep 4D fields above AdS_4, rather than 11D fields above $AdS_4 \times S^7$
- Consistent: 4D dynamics compatible with M-theory
- 4D gauged supergravity: gaugings arise due to truncation on a non-trivial internal space.
- Gaugings: interactions, including non-abelian gauge groups, a scalar potential, etc.

N M2 branes at a conical singularity



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$D = 4$ $N = 8$ SO(8)-gauged supergravity

But

Is the SO(8)-gauging of $N = 8$ supergravity unique?

The naive answer is yes.

Electric/Magnetic duality

Maxwell's equations

$$d * F = 0\,, \qquad dF = 0$$

are invariant under electric/magnetic duality transformations:

$$F \;\rightarrow\; \tilde{F} \equiv *F \qquad \Rightarrow \qquad d * \tilde{F} = 0\,, \qquad d\tilde{F} = 0.$$

All electric/magnetic duality frames are equivalent.

No EM duality in the presence of sources

In the presence of sources,

$$d * F = *j\,, \qquad dF = 0$$

Maxwell's equations are no longer EM duality invariant.

The physics now does depend on the duality frame.

EM duality for scalars coupled to abelian vectors

- The EM duality group of the $\mathrm{U}(1)^n$ theory

$$\mathcal{L} = \tfrac{1}{2}\delta_{IJ} F^I \wedge *F^J \, , \quad I = 1, \dots, n,$$

is $\mathrm{Sp}(2n, \mathbb{R})$. The eoms + Bianchis remain invariant under a symplectic rotation of the electric, F^I, and magnetic, $\tilde{F}_I = \dfrac{\partial \mathcal{L}}{\partial F^I}$, field strengths.

- When non-minimally coupled scalars are included,

$$\mathcal{L} = g_{ij} dz^i \wedge *dz^j + \tfrac{1}{2}\mathrm{Im}\mathcal{N}_{IJ} F^I \wedge *F^J + \tfrac{1}{2}\mathrm{Re}\mathcal{N}_{IJ} F^I \wedge F^J \, ,$$

the combined set of field equations + Bianchi identities remain invariant under the isometry group $G \subset \mathrm{Sp}(2n, \mathbb{R})$ of the scalar manifold.

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Gauged supergravity

Promote $G_0 \subset G \subset Sp(2n, \mathbb{R})$ to a local symmetry, while introducing minimal couplings:

$$d \to D = d + gA^I t_I$$

Add further terms, of order g (Yukawas) and g^2 (potential) to the lagrangian in order to restore susy.

EM invariance is broken. The physics depends on the symplectic frame.

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Gauged supergravity with magnetic charges

The gauge group G_0 needs to be a subgroup of the Eoms + Bianchis symmetry group G:

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Can magnetic charges be turned on?

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Yes!

- Magnetically charged scalars dualised into tensors.
- Duality-covariant formalism: embedding tensor

  [Nicolai, Samtleben '00; de Wit, Samtleben, Trigiante '05]

Example: Massive type IIA on Calabi-Yau. [Louis, Micu '02]

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(ungauged) $D = 4$ $N = 8$ supergravity

- $D = 4$ $N = 8$ supergravity has duality group $E_{7(7)} \subset Sp(56, \mathbb{R})$. [Cremmer, Julia '79]
- The scalars parametrise $E_{7(7)}/SU(8)$.

	$E_{7(7)}$	SU(8)
$g_{\mu\nu}$	**1**	**1**
$A_\mu^I, A_{\mu I}$	**56**	**1**
ϕ	**133 − 63**	**1**
ψ_μ^α	**1**	**8**
λ	**1**	**56**

- Higher dimensional origin: M-theory on T^7.

$D = 4$ $N = 8$ SO(8)-gauged supergravity

- Promote the **28** (electric) Abelian vectors featuring in the SL(8)-duality-frame lagrangian to gauge fields of SO(8). [de Wit, Nicolai '82]

- introduce minimal couplings

$$d \to D = d + gA^I t_I$$

- Introduce Yukawas ($O(g)$) and a scalar potential ($O(g^2)$).

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New $N = 8$ SO(8)-gauged supergravity

A one-parameter family of SO(8)-gaugings

[Dall'Agata, Inverso, Trigiante '12]

- Gauge SO(8) dyonically through electric and magnetic gauge fields:

$$d \to D = d + g \cos\omega A^I t_I + g \sin\omega \tilde{A}_I \tilde{t}^I$$

- ω reflects a one-parameter ambiguity of the SL(8) symplectic frame [de Wit, Nicolai '13; Dall'Agata, Inverso, Marrani '14]

$$\omega \in U(1) \subset Sp(56, \mathbb{R})/E_{7(7)}$$

- Recover de Wit-Nicolai for $\omega = 0$. Distinct theories for $\omega \in [0, \frac{\pi}{8}]$.

The physics depends on the symplectic frame:

the physics should depend on ω.

Electric/Magnetic duality

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The SU(3)-invariant sector

$N = 2$ supergravity + 1 VM + 1HM

$$E_{7(7)} \supset SU(1,1)_T \times SU(2,1) \times SU(3) \quad .$$

- Gravitini: SU(8) branches as

$$\mathbf{8} \rightarrow \mathbf{1} \oplus \mathbf{1} \oplus \mathbf{3} \oplus \overline{\mathbf{3}},$$

- Vectors:

$$\mathbf{56} \rightarrow (\mathbf{4},\mathbf{1},\mathbf{1}) \oplus \text{non-singlets}$$

- Scalars:

$$\mathcal{M}_{\rm SK} = \left(\frac{SU(1,1)}{U(1)}\right)_T \quad \text{and} \quad \mathcal{M}_{\rm QK} = \frac{SU(2,1)}{SU(2)_S \times U(1)_U} ,$$

The SU(3)-invariant sector: $\omega = 0$ vacuum structure

	$\omega = 0$	
	g.m.	V_*/g^2
$\mathcal{N} = 8$, SO(8)	1	-6
$\mathcal{N} = 2$, SU(3)×U(1)	1	-7.794
$\mathcal{N} = 1$, G_2	2	-7.192

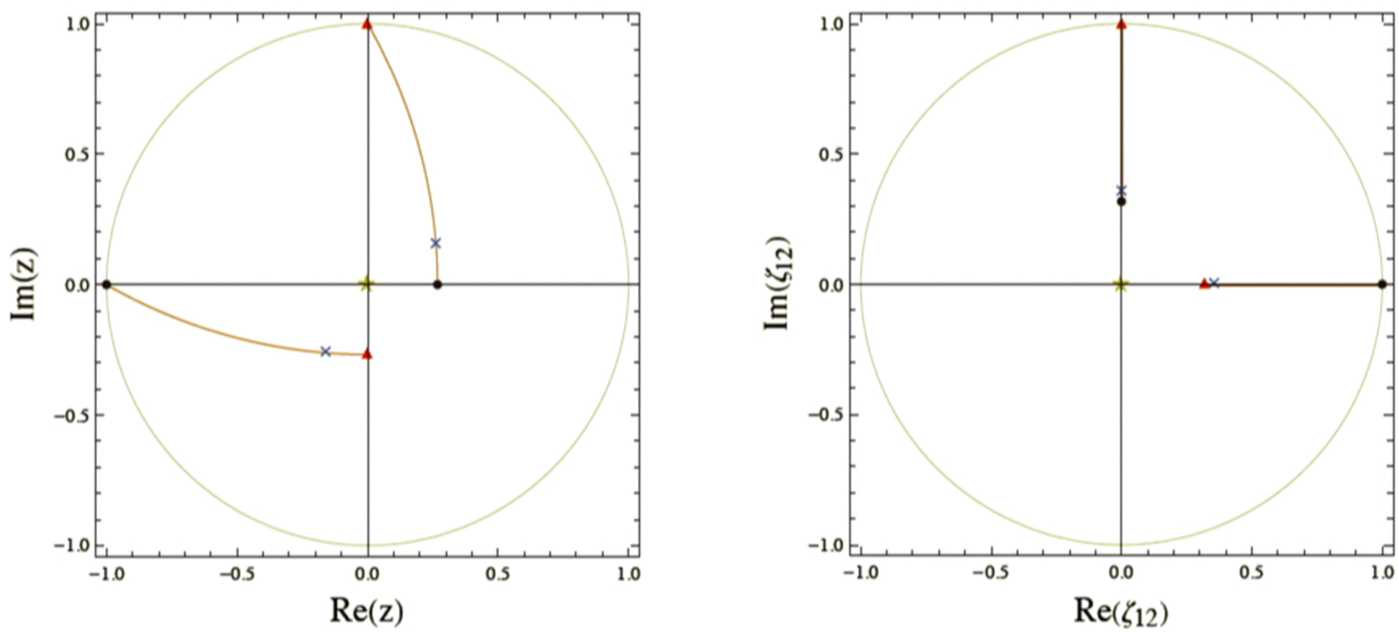
[Warner '83]

The SU(3)-invariant sector: $\omega \neq 0$ vacuum structure.

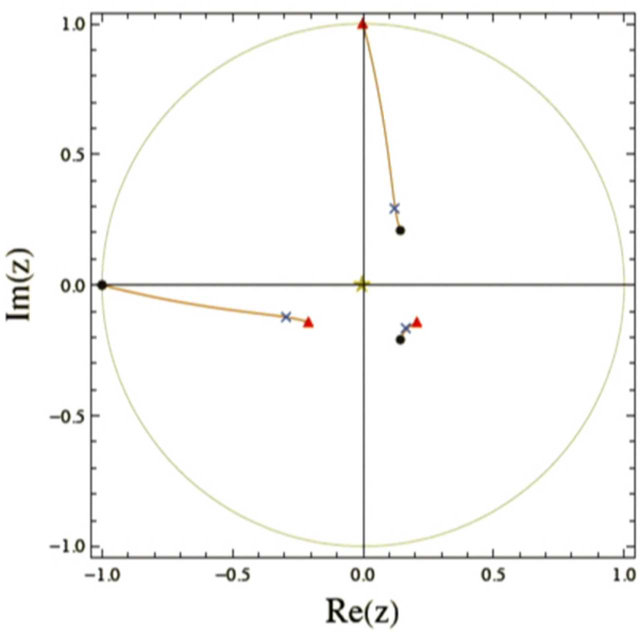
	$\omega = 0$		$\omega = \frac{\pi}{16}$		$\omega = \frac{\pi}{8}$	
	g.m.	V_*/g^2	g.m.	V_*/g^2	g.m.	V_*/g^2
$\mathcal{N} = 8$, SO(8)	1	-6	1	-6	1	-6
$\mathcal{N} = 2$, SU(3)×U(1)	1	-7.794	1	-7.912	2	-8.354
			1	-9.672		
$\mathcal{N} = 1$, G_2	2	-7.192	1	-7.075	1	-7.040
			1	-7.436	2	-7.943
			1	-9.264		
$\mathcal{N} = 1$, SU(3)	–	–	1	-11.353	1	-10.392

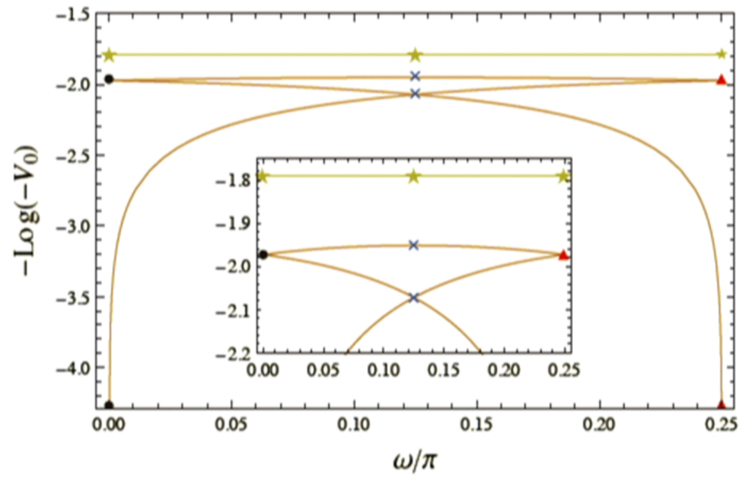
[Borghese, Dibitetto, Guarino, Roest, OV '12]

$\mathcal{N} = 2$ SU(3)×U(1) points run with ω

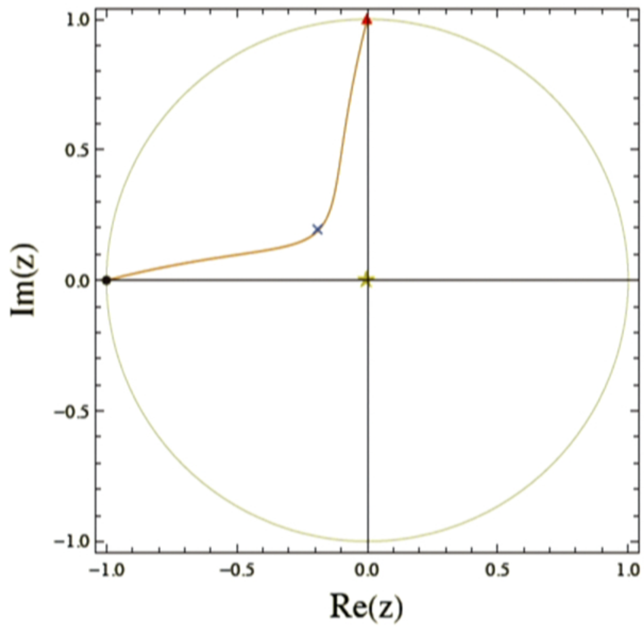


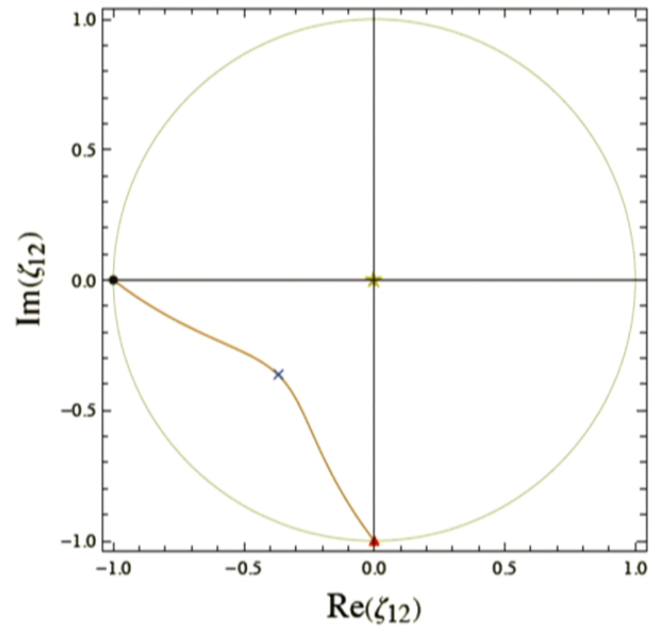
$N = 1$ G_2 points run with ω



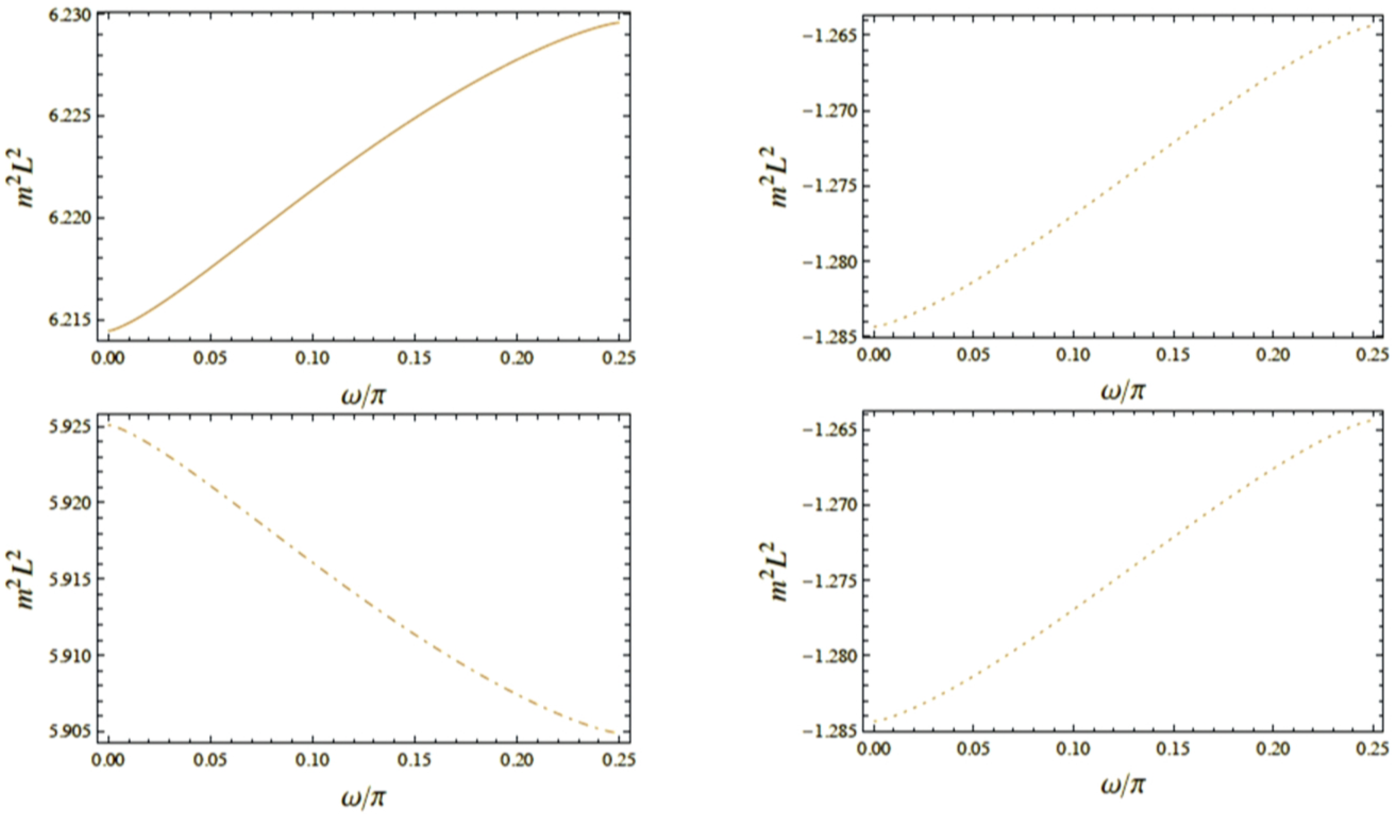


$\mathcal{N} = 1$ SU(3) point runs with ω





$N = 0$ SU(3) points: masses run with ω



The SU(3)-invariant sector: $\omega \neq 0$ vacuum structure.

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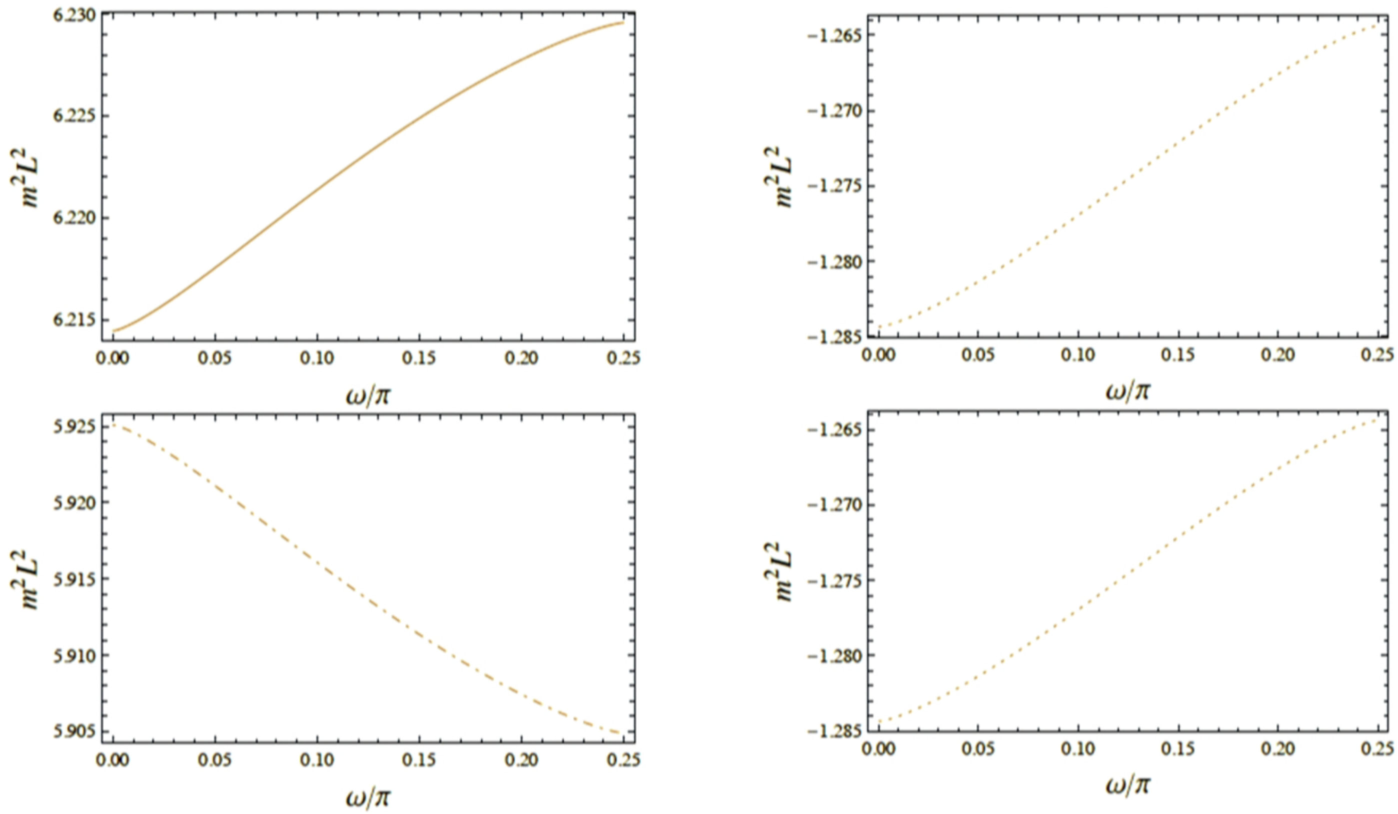
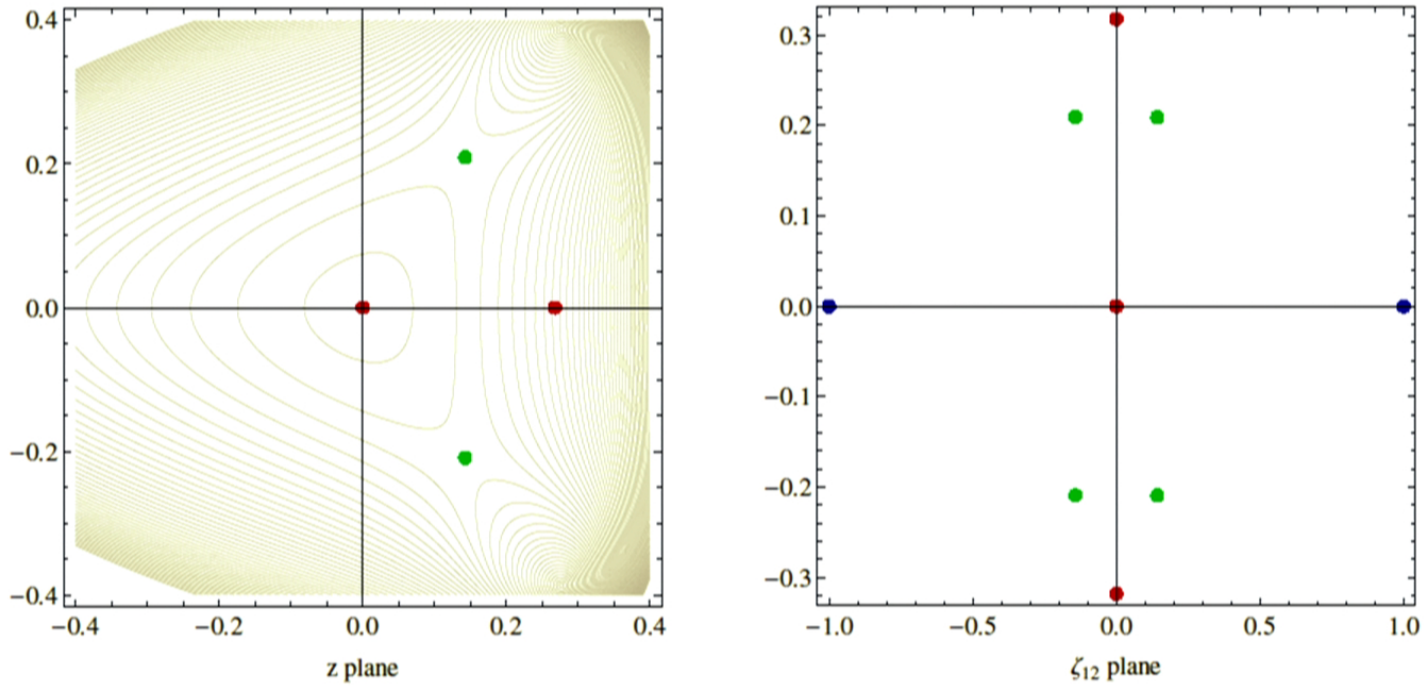


$\omega = 0$ supersymmetric critical points



[Warner '83]

Recap and outlook

- A new family of SO(8)-gauged $N = 8$ supergravities [Dall'Agata, Inverso, Trigiante '12]
  - Have charted the vacuum structure with at least SU(3) symmetry.
  - Interpolating domain walls.
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