RG Flows Across Dimensions and Holography

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RG flows across dimensions

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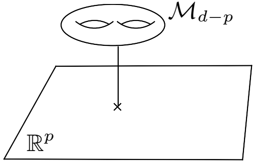

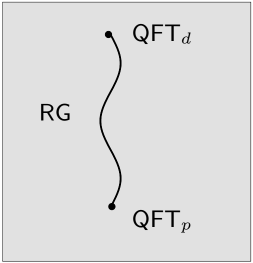

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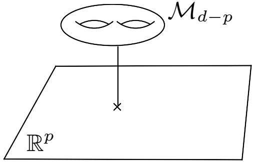

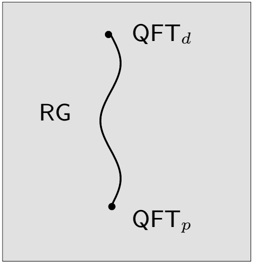

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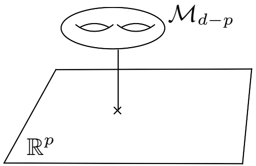

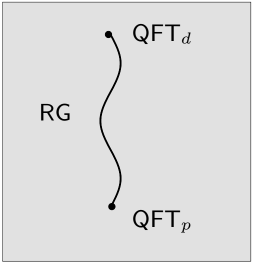

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Employ supersymmetry to simplify the problem.

Motivation

- Construct and explore large classes of interacting p-dimensional superconformal field theories (SCFTs) obtained from a d-dimensional theory "compactified" on the manifold $\mathcal{M}_{d-p}$. [Vafa-Witten], [Witten], [Bershadsky-Johansen-Sadov-Vafa], [Klemm-Lerche-Mayr-Vafa-Warner], [Maldacena-Núñez], [Kapustin], [Gaiotto], [Gaiotto-Moore-Neitzke], [Dimofte-Gukov-Gaiotto], [Cecotti-Córdova-Vafa], [Gadde-Gukov-Putrov], [Benini-NB], [Bah-Beem-NB-Wecht], ...

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- This setup leads to interesting "correpondences" between the p-dimensional SCFT and a ("topological") theory on $\mathcal{M}_{d-p}$. [Alday-Gaiotto-Tachikawa], [Gadde-Pomoni-Rastelli-Razamat], [Dimofte-Gaiotto-Gukov], [Cecotti-Córdova-Vafa], ...

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- Obtain insight into the original d-dimensional theory and RG flows across dimensions.

- The p-dimensional SCFTs typically admit a "large N" limit and have holographic duals which can be explicitly constructed. New examples of AdS/CFT. [Maldacena-Núñez], ...

Tools

- Anomaly matching ['t Hooft]
- Anomaly polynomials [Alvarez-Gaumé-Ginsparg], [Witten], [Harvey-Minasian-Moore], ...
- Topological twists [Witten], ...
- a-maximization [Intriligator-Wecht], F-maximization [Jafferis], [Closset-Dumitrescu-Fesctuccia-Komargodski-Seiberg], c-extremization [Benini-NB]
- Supersymmetric lozalization [Witten], [Moore], [Nekrasov], [Pestun],...
- Unitarity bounds [Hofman-Maldacena]
- Wrapped branes [Bershadsky-Sadov-Vafa], [Maldacena-Núñez], [Gauntlett-Waldram et al.], ...
- Holography [Maldacena], [GKP], [Witten], ...

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Disclaimer: Here I always take $\mathcal{M}_{d-p}$ to be compact and (in holography) with an Einstein metric. Generalizations are possible and very interesting!
[Anderson-Beem-NB-Rastelli]; [Gaiotto-Maldacena], [Bah]

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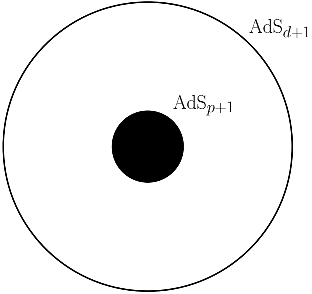

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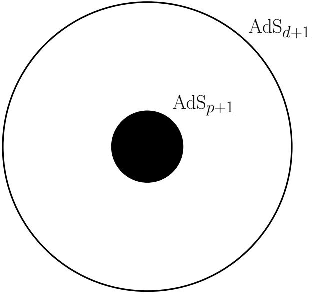

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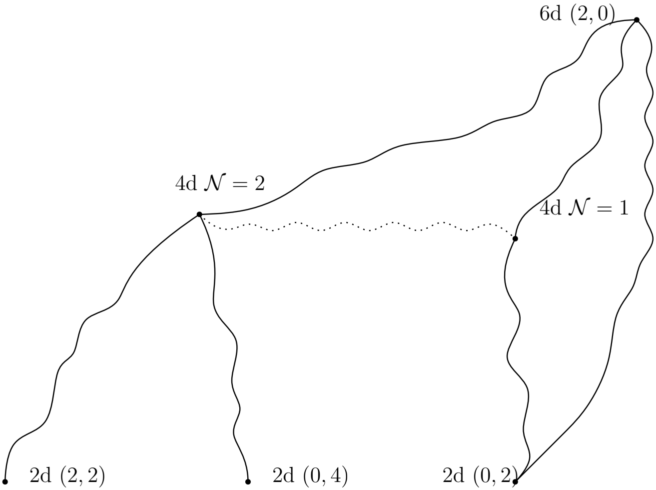
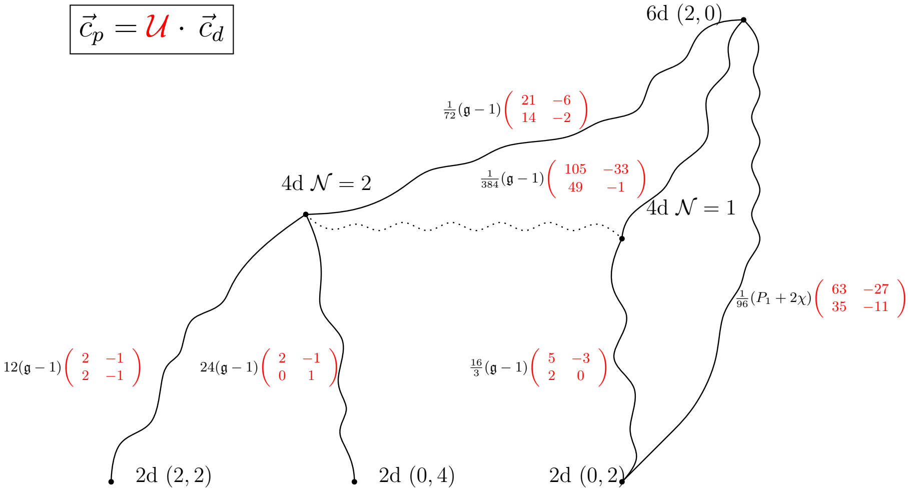
Numerous holographic RG flows of this type can be explicitly constructed and embedded in string theory by using branes wrapped on $\mathcal{M}_{d-p}$.

Universal flows across even dimensions



Universal flows across even dimensions

$$\boxed{\vec{c}_p = \mathcal{U} \cdot \vec{c}_d}$$



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3d $\mathcal{N} = 2$ on Σ_g

At large N one finds $F_{S^1 \times \Sigma_{\mathfrak{g}}} = (\mathfrak{g} - 1) F_{S^3}$

1d SUSY QM

- In holography this maps to a (magnetically charged) black hole in AdS_4. Microscopic counting of the BH entropy!

4d $\mathcal{N} = 1$ SCFTs on $\Sigma_{\mathfrak{g}}$

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$$\mathcal{A}^R_\mu = -\frac{1}{4}\omega_\mu \ , \qquad \rightarrow \qquad \widetilde{\nabla}_\mu \epsilon = \left(\partial_\mu + \frac{1}{4}\omega_\mu + \mathcal{A}^R_\mu\right)\epsilon = \partial_\mu \epsilon = 0 \ .$$

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General background fluxes in the Cartan of G_F do not break additional supersymmetry. The construction depends on the details of the 4d $\mathcal{N} = 1$ theory, i.e. non-universal $\rightarrow$ Rich families of 2d $\mathcal{N} = (0, 2)$ SCFTs.
[Almuhairi-Polchinski], [Kutasov-Lin], [Franco-Lee-Vafa et al.], [Schäfer-Nameki-Weigand], [Amariti-Cassia-Penati]...

4d $\mathcal{N} = 1$ SCFTs on $\Sigma_{\mathfrak{g}}$

The anomaly polynomials in 4d and 2d are

$$\mathcal{I}_6 = \frac{k_{RRR}}{6} c_1(\mathcal{F}_R^{(4)})^3 - \frac{k_R}{24} c_1(\mathcal{F}_R^{(4)}) p_1(\mathcal{T}_4) + I_6^F \ ,$$

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Superconformal Ward identities relate conformal and 't Hooft anomalies

[Anselmi-Freedman-Grisaru-Johansen]

$$a = \frac{9}{32} k_{RRR} - \frac{3}{32} k_R \ , \quad c = \frac{9}{32} k_{RRR} - \frac{5}{32} k_R \ , \quad c_r = 3k_{RR} \ , \quad c_r - c_l = k \ .$$

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Use ($\kappa = 1$ for S^2, $\kappa = 0$ for T^2, and $\kappa = -1$ for H^2)

$$\mathcal{F}_R^{(4)} \to \mathcal{F}_R^{(2)} - \frac{\kappa}{2} t_{\mathfrak{g}} \ , \qquad \text{and} \qquad \mathcal{I}_4 = \int_{\Sigma_{\mathfrak{g}}} \mathcal{I}_6 \ ,$$

to extract the 2d conformal anomalies

$$\boxed{\begin{pmatrix} c_r \\ c_l \end{pmatrix} = \frac{16}{3} (\mathfrak{g} - 1) \begin{pmatrix} 5 & -3 \\ 2 & 0 \end{pmatrix} \begin{pmatrix} a \\ c \end{pmatrix}}$$

4d $\mathcal{N} = 1$ SCFTs on $\Sigma_{\mathfrak{g}}$

Comments:

- The R-charges have to be properly quantized (i.e. rational) in order to be able to perform the universal twist.
- Notice that 't Hooft anomaly matching amounts to

$$k_{RR} = (\mathfrak{g} - 1)k_{RRR} \,, \qquad\qquad k = (\mathfrak{g} - 1)k_R \,.$$

- Unitarity implies that $\mathfrak{g} > 1$. In addition we should have

$$\frac{3}{5} < \frac{a}{c} \,, \quad \text{compatible with} \quad \frac{1}{2} \leq \frac{a}{c} \leq \frac{3}{2} \quad \text{[Hofman-Maldacena]} \,.$$

  Are there any interacting 4d $\mathcal{N} = 1$ SCFTs with $\frac{1}{2} < \frac{a}{c} < \frac{3}{5}$?

- For $a = c$ we have $c_r = c_l = \frac{32}{3}(\mathfrak{g} - 1)a$. To be tested holographically!

The holographic dual

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There is a BPS black string solution of the 5d theory [Klemm-Sabra], [Benini-NB]

$$ds^2 = e^{2f(r)}(-dt^2 + dz^2 + dr^2) + e^{2h(r)}\frac{dx^2+dy^2}{y^2} \, , \qquad A = \frac{dx}{y}$$

- Analytic solution for $f(r)$ and $h(r)$. Here $\Sigma_\mathfrak{g} = \mathbb{H}^2/\Gamma$.
- Asymptotically locally AdS_5 background at $r \to \infty$.
- $AdS_3 \times \Sigma_\mathfrak{g}$ background at $r \to 0$.

The holographic dual

Using standard holographic technology one finds

$$c_r = c_l = \frac{3L_{AdS_3}}{2G_N^{(3)}} = \frac{32}{3}(\mathfrak{g}-1)\frac{\pi L_{AdS_5}^3}{8G_N^{(5)}} = \frac{32}{3}(\mathfrak{g}-1)a.$$

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Uplift of this simple solution to many distinct string and M-theory backgrounds by using supergravity uplift formulas. [Gauntlett-Varela]

Particular examples:

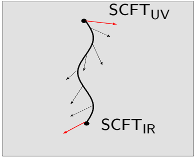
- IIB compactifications on SE_5 manifolds, i.e. 4d $\mathcal{N}=1$ quiver gauge theories. [Klebanov-Witten], [Morrison-Plesser], [Gauntlett-Martelli-Sparks-Waldram]...
- M-theory compactifications of the Maldacena-Núñez type, i.e. 4d $\mathcal{N}=1$ "class $\mathcal{S}$" SCFTs. [Bah-Beem-NB-Wecht]

4d $\mathcal{N} = 1$ on $\Sigma_{\mathfrak{g}}$

More general twists. Turn on fluxes for G_F → non-universal flows

$$\mathcal{A}_{\text{back}} = \mathcal{A}^R + b_i \mathcal{A}^i \, , \qquad \to \qquad R_{IR} = R_{UV} + \epsilon_i(b) F^i$$

Mixing between the flavor and R-symmetries along the RG flow!



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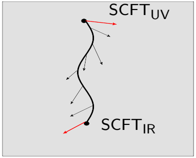

Consider a trial R-current Ω_μ^{tr}

$$\Omega_\mu^{\text{tr}}(t) = \Omega_\mu + \sum_{i \neq R} t_i J_\mu^i \, .$$

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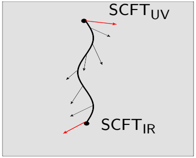

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Construct a trial $c_r^{\text{tr}}(t)$ from the anomaly of the trial R-symmetry. For unitary SCFTs one finds c-extremization [Benini-NB]

$$\frac{\partial c_r^{\text{tr}}(t^*)}{\partial t^i} = 0 \,, \quad \forall\, i \neq R \,, \quad \rightarrow \quad c_r^{\text{tr}}(t^*) = c_r \,.$$

Similar to a-maximization in 4d and F-maximization in 3d. [Intriligator-Wecht], [Jafferis], [Closset-Dumitrescu-Festuccia-Komargodski-Seiberg]

4d $\mathcal{N} = 1$ on $\Sigma_{\mathfrak{g}}$

Explicit examples from string theory: 4d $\mathcal{N} = 1$ SCFTs from D3-branes at conical singularities [Klebanov-Witten], [Morrison-Plesser],...

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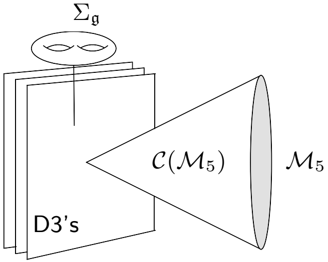
- Transverse space $\mathbb{R}_+ \times \mathcal{M}_5 = \mathcal{C}(\mathcal{M}_5)$.
- $\mathcal{M}_5$ is Sasaki-Einstein $\Rightarrow \mathcal{C}(\mathcal{M}_5)$ is Calabi-Yau.
- $\mathcal{M}_5 = S^5 \Rightarrow \mathcal{N} = 4$ SYM.
- $\mathcal{M}_5 = Y^{1,0} \Rightarrow \mathcal{N} = 1$ KW.
- More examples based on $Y^{p,q}$ [Gauntlett-Martelli-Sparks-Waldram] and dP_n surfaces.



One can analyze in the same way the Leigh-Strassler $\mathcal{N} = 1$ mass deformation of $\mathcal{N} = 4$ SYM. [Gubser-Freedman-Pilch-Warner], [NB-Pilch-Vasilakis]

A new feature: "Baryonic" and R-symmetries can mix along such RG flows.

Holographic description

Example: $Y^{p,0}$ on $\Sigma_{\mathfrak{g}>1}$ with baryonic flux b ($\mathbb{Z}_p$ orbifold of the KW theory).

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Field theory: Apply anomaly matching and c-extremization to find

$$c_r = \frac{32}{3}(\mathfrak{g}-1)a(Y^{p,0}) + 24(\mathfrak{g}-1)p^3 b^2 N^2 - 2p(\mathfrak{g}-1)$$

For $b = 0 \rightarrow$ universal twist.

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Field theory: Apply anomaly matching and c-extremization to find

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For $b=0 \to$ universal twist.

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where $v = \frac{1+4pb}{1-4pb}$.

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Notice that $\frac{1}{3}\alpha + \frac{4}{3}\beta$ is the "universal" twist with 2d $\mathcal{N} = (0,2)$ supersymmetry.

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Comments

- Unitarity implies that $\mathfrak{g} > 1$ and

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- No AdS_3 solution for the β-twist. Maybe no normalizable vacuum? Similarities with the $\mathcal{N} = (4,4)$ twist of 4d $\mathcal{N} = 4$ SYM where one finds a 2d σ-model onto the Hitchin moduli space [Bershadsky-Johansen-Sadov-Vafa]?

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$$\begin{pmatrix} c_r \\ c_l \end{pmatrix} = \frac{1}{96}(P_1 + 2\chi) \begin{pmatrix} 63 & -27 \\ 35 & -11 \end{pmatrix} \begin{pmatrix} a_{6d} \\ c_{6d} \end{pmatrix}$$

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- This setup corresponds to M5-branes wrapped on a Kähler 4-cycle in CY_4. Different from the MSW $\mathcal{N} = (0, 4)$ CFT. [Maldacena-Strominger-Witten]
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There are many other possible twists for the $(2,0)$ theory on various $\mathcal{M}_4$. Generically one has to rely on c-extremization to compute the correct central charges. [Benini-NB], [Gadde-Gukov-Putrov]

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To study this theory use the "topologically twisted index" [Benini-Zaffaroni], [Closset-Kim], [Benini-Hristov-Zaffaroni]. Computed by localization in the same spirit as the S^3 partition function. [Kapustin-Willett-Yaakov], [Drukker-Marino-Putrov], [Jafferis-Klebanov-Pufu-Safdi]

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At large N a simple relation between the two partition functions [Hosseini-Zaffaroni]

$$F_{S^1\times\Sigma_{\mathfrak{g}}}(\Delta_I,\mathfrak{n}_I) = (\mathfrak{g}-1)F_{S^3}(\Delta_I/\pi) + \sum_I \left(\frac{\mathfrak{n}_I}{1-\mathfrak{g}} - \frac{\Delta_I}{\pi}\right)\frac{\pi}{2}\partial_{\Delta_I}F_{S^3}(\Delta_I/\pi)$$

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The universal twist amounts to: $\mathfrak{n}_I = (1-\mathfrak{g})\Delta_I/\pi$

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Black holes in AdS_4

A simple supersymmetric BH solution of 4d minimal gauged supergravity

[Romans], [Caldarelli-Klemm]

$$ds_4^2 = -\left(\rho - \frac{1}{2\rho}\right)^2 dt^2 + \left(\rho - \frac{1}{2\rho}\right)^{-2} d\rho^2 + \rho^2 ds^2_{\Sigma_\mathfrak{g}} \ , \qquad F = \frac{1}{2\sqrt{2}} \mathrm{vol}_{\Sigma_\mathfrak{g}}$$

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In massive IIA: a new solution! Deformation of a recently constructed AdS_4 vacuum in massive IIA [Guarino-Jafferis-Varela], [Fluder-Sparks]

$$ds^2_{10} = e^{2\lambda} L^2 \left(ds_4^2 + ds_6^2 \right)$$

with

$$ds_6^2 = \omega_0^2 \left[e^{\varphi - 2\phi} X^{-1} d\alpha^2 + \sin^2\alpha (\Delta_1^{-1} ds^2_{\mathsf{KE}_4} + X^{-1} \Delta_2^{-1} \eta^2) \right]$$
$$e^{2\lambda} \equiv (\cos(2\alpha) + 3)^{1/2} (\cos(2\alpha) + 5)^{1/8}\, ,$$

and $L, \omega_0, \varphi, \phi$ - constants. Nontrivial F_2, H_3, and F_4 fluxes in massive IIA.

Large class of new massive IIA solutions with CFT duals.

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For the black hole entropy one finds

$$S_{\mathsf{BH}} = \frac{\pi}{2G_N^{(4)}}(\mathfrak{g} - 1) = (\mathfrak{g} - 1)F_{S^3}$$

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Comments:

- At large N one has $F_{S^1 \times \Sigma_{\mathfrak{g}}} \sim N^{3/2}$ in M-theory and $F_{S^1 \times \Sigma_{\mathfrak{g}}} \sim N^{5/3}$ in massive IIA.
- To generalize this setup turn on background flux for the G_F global symmetry of the CFT. Find the correct R-symmetry in the IR by extremizing the "twisted index". [Benini-Hristov-Zaffaroni]
- The holographic dual construction is realized by M2-branes at the tip of a conical singularity wrapping $\Sigma_{\mathfrak{g}}$. A large landscape of AdS_2 vacua in M-theory. [Azzurli-NB-Crichigno-Min-Zaffaroni]
- One can also add electric charges to these 4d black holes and modify correspondingly the "twisted index" [Benini-Hristov-Zaffaroni], [in progress]

Other flows

- This general setup is applicable to SCFTs in other dimensions and on other manifolds. A prominent example is the 6d $(2,0)$ theory on 4-manifolds. [Benini-NB], [Gadde-Gukov-Putrov], [Ganor]...
- The field theory tools are less developed for 5d $\mathcal{N}=1$ SCFTs on $\mathbb{R}^3 \times \Sigma_{\mathfrak{g}}$ or $\mathbb{R}^2 \times \mathcal{M}_3$ (absence of anomalies or localization results).
- A holographic analysis in "minimal" gauged supergravity always yields an AdS vacuum. Suggestive results and "predictions" from holography.
- Interpretation in terms of wrapped branes in string/M-theory.

Summary

- Evidence for many new SCFTs arising from RG flows across dimensions.
- Understanding of some of their properties through nonperturbative QFT tools.
- Explicit "top-down" holographic constructions that are dual to the SCFTs at hand.
- Useful spin-off: microscopic entropy counting for AdS black holes.

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- Holographic/geometric dual of c-extremization. Is there some "generalized volume" minimization? [Martelli-Sparks-Yau]

THANK YOU!