Recent advances in precision holography

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Motivation

- AdS/CFT provides a gauge theory description of string or M-theory on asymptotically locally AdS backgrounds. Immediate consequence:

$$Z_{\mathrm{CFT}}[J] = Z_{\mathrm{string/M}}[\phi]$$

- Tested thoroughly in the large N limit.

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- At strong coupling, CFT observables encode information about supergravity. Corrections teach us about string/M-theory beyond the low-energy limit.
- Studying and understanding corrections on both sides of the duality:

Precision Holography

Precision holography

- Need concrete realizations where we can test and make predictions
  $\rightarrow$ use supersymmetry to gain computational mileage.

SCFT

Localization gives exact results

Solving the matrix models yields $1/N$ expansion to any order

Various techniques available

Analytic & numeric

Supergravity

Exact results out of reach*

Work order-by-order in the derivative expansion

Can also study one-loop effects

LO, NLO, NNLO tests

*except special low-d settings

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- New handle on AdS vacua of string/M-theory with non-trivial fluxes.

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- This talk: recent progress in precision holography for $\mathrm{AdS}_4/\mathrm{CFT}_3$.

AdS_4/CFT_3 from M2 branes

- Study 3d $\mathcal{N} \geq 2$ SCFTs arising from low-energy limit of N M2 branes.
- No λ in M-theory $\rightarrow$ easier to study the correspondence.

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- M-theory engineers many dual pairs:

3d Chern-Simons-matter theories

$\Updownarrow$

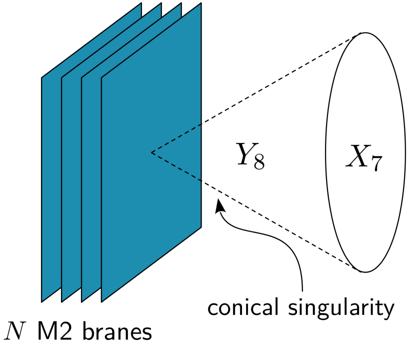
M-theory on $\text{AlAdS}_4 \times X_7$

Take X_7 to be Sasaki-Einstein $\rightarrow$ CSm

$$X_7 = S^7/\mathbb{Z}_k \text{ (free)} \rightarrow \text{ABJM}$$

$$X_7 = S^7/\mathbb{Z}_r \text{ (f.p.)} \rightarrow \text{ADHM}$$

$$X_7 = N^{010},\ V^{52},\ Q^{111},\ \ldots$$



- Put the gauge theory on compact M_3 and study susy partition functions. Use localization to compute them exactly for various (X_7, M_3).

ABJM on the squashed sphere: $M_3 = S_b^3$

- Let us start with simple $X_7 = S^7/\mathbb{Z}_k$ that gives rise to ABJM theory $\rightarrow U(N)_k \times U(N)_{-k}$ CSm with bifundamental chirals and a superpotential.

[Aharony,Bergman,Jafferis,Maldacena'08]

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- The partition function on S_b^3 localizes to a matrix model.

- For $\mathcal{F} = \begin{cases} k \geq 1 \ \& \ b = 1 \\ k = 1 \ \& \ b = \sqrt{3} \end{cases}$ matrix model reduces to a free Fermi gas.

  [Mariño,Putrov'11; Hatsuda'16]

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- Fully solved using refined topological string on toric non-compact CYs.

  [Grassi,Hatsuda,Mariño'15]

- All perturbative terms in the large N limit resum to an Airy function:

$$Z_{\mathcal{F}}(N) = e^{A} C^{-\frac{1}{3}} \,\mathrm{Ai}\big[C^{-\frac{1}{3}}(N - B)\big] + \mathcal{O}(e^{-\sqrt{N/k}}, e^{-\sqrt{Nk}})$$

with (k, b)-dependent coefficients (A, B, C) explicitly known.

Dual supergravity

- Systematic expansion of the free energy at large N:

$$-\log Z_{\mathcal{F}}(N) = \frac{2}{3\sqrt{C}} N^{\frac{3}{2}} - \frac{B}{\sqrt{C}} N^{\frac{1}{2}} + \frac{1}{4}\log N + \mathcal{O}(N^0)$$

- Dual to 4d minimal supergravity solutions (g_4, A) with $\Lambda < 0$ and $\partial\mathcal{M} = S_b^3$

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- Dual to 4d minimal supergravity solutions (g_4, A) with $\Lambda < 0$ and $\partial\mathcal{M} = S^3_b$
- LO $N^{\frac{3}{2}}$ term matches the two-derivative regularized on-shell actions.
  [Emparan,Johnson,Myers'99; Martelli,Passias,Sparks'11]
- NLO $N^{\frac{1}{2}}$ term reproduced by including bulk four-derivative terms.
  [Bobev,Charles,Hristov,VR'21]
- NNLO $\log N$ term is a one-loop effect from summing over the KK modes around the 11d backgrounds. [Bhattacharyya,Grassi,Mariño,Sen'12]

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- Precision holography → prediction for all higher-derivative and higher-loop effects in the bulk!

Beyond the ABJM Fermi gas?

- For general (k, b) there is no known Fermi gas.
- Conjecture: we again have an Airy function [Bobev,Hong,VR'22; Hristov'22]

$$Z_{k,b}(N) = e^{A} C^{-\frac{1}{3}} \,\mathrm{Ai}\big[C^{-\frac{1}{3}}(N-B)\big] + \mathcal{O}(e^{-\sqrt{N/k}}, e^{-\sqrt{Nk}})$$

$$C = \frac{32}{\pi^2 k} Q^{-4} \quad \text{and} \quad B = \frac{k}{24} - \frac{2}{k}\Big(\frac{1}{3} - 2Q^{-2}\Big)$$

with $Q = b + b^{-1}$.

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- Consistent with dual supergravity results up to and including log terms.
- Consistent with ongoing detailed numerical studies of the matrix model. Can even access the large-k expansion of the prefactor:

$$A = \big[(b - b^{-1})^2 - 4\big] \frac{\zeta(3)}{32\pi^2} \, k^2 + \mathcal{O}(k^0)$$

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- Question: what structure produces this Airy function in M-theory? Is there a Fermi gas or topological string picture? Something new?

A word on correlators

- The conjecture has implications for ABJM dynamics since the squashing parameter b couples to the stress tensor.
- $\mathcal{N} = 2$ Ward identities imply [Closset,Dumitrescu,Festuccia,Komargodski'12]

$$\langle T_{\mu\nu}(x)\, T_{\rho\sigma}(0)\rangle = C_T\, \mathcal{T}_{\mu\nu\rho\sigma}(x) \quad \text{and} \quad C_T = \frac{\partial^2 \log Z_{k,b}}{\partial b^2}\Big|_{b=1} .$$

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- Taking more derivatives gives access to integrated correlators of stress tensors over the round 3-sphere.
- Flat space limit gives a way to study scattering amplitudes in M-theory. [Chester,Pufu,Yin'18]

ABJM on $M_3 = S^1 \times \Sigma_{\mathfrak{g}}$

- Turn on flux for exact R-sym $\int_{\Sigma_{\mathfrak{g}}} dA_R = 2\pi(1-\mathfrak{g}) \rightarrow$ topological twist.
- Use localization to compute the Topologically Twisted Index (TTI).

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$$Z_{S^1\times\Sigma_{\mathfrak{g}}}(N) = \sum_{\{x_i,\tilde{x}_j\}\in \text{BAE}} \mathcal{B}(x_i,\tilde{x}_j)$$

Sum over solutions to transcendental eqs called Bethe Ansatz Equations.

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Sum over solutions to transcendental eqs called Bethe Ansatz Equations.

- Amenable to numerical evaluation:
  - Use known large N solution as `init`
  - Numerically solve BAE $\to x_i = x_i^\star$ and $\tilde{x}_j = \tilde{x}_j^\star$
  - Evaluate $\mathcal{B}(x_i^\star, \tilde{x}_j^\star)$ numerically to high precision
  - Fit with respect to (N, k) and (hopefully) infer analytic expressions

The ABJM twisted index

- Detailed numerics → we can propose an analytic formula: [Bobev,Hong,VR'22]

$$-\log Z_{S^1\times\Sigma_\mathfrak{g}}(N) = (1-\mathfrak{g})\frac{\pi\sqrt{2k}}{3}\left(\widehat{N}^{\frac{3}{2}} - \frac{3}{k}\widehat{N}^{\frac{1}{2}}\right) + \frac{1-\mathfrak{g}}{2}\log\widehat{N} + (1-\mathfrak{g})\,f(k) + \mathcal{O}(e^{-\sqrt{N/k}}, e^{-\sqrt{Nk}})$$

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$$f(k) = \frac{3\zeta(3)}{8\pi^2}k^2 - \frac{7}{6}\log k + \mathcal{O}(k^0)$$

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- Expand at large $N \rightarrow N^{\frac{3}{2}}$, $N^{\frac{1}{2}}$, $\log N$ terms... and all perturbative corrections.
- Useful for precision holography.

Dual supergravity

- The index captures the path integral of M-theory on the 11d background

$$ds^2_{11} = \frac{L^2}{4} ds^2_4 + L^2 ds^2_{\mathbb{CP}_3} + L^2 \Big(d\psi + \sigma + \frac{1}{4} A \Big)^2$$
$$G_4 = \frac{3L^3}{8} \mathrm{vol}_4 - \frac{1}{4} \star_4 F \wedge J$$

with $(g_4, F = dA)$ the Euclidean Romans solution of 4d $\mathcal{N} = 2$ minimal gauged supergravity. [Romans'92; Genolini,Ipiña,Sparks'19; Bobev,Charles,Min'20]

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- LO, NLO and NNLO for BH entropy match the corresponding terms in TTI. [Benini,Hristov,Zaffaroni'16; Bobev,Hong,VR'22; Liu,Pando Zayas,Rathee,Zhao'17]

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- Precision holography → prediction for the corrected Bekenstein-Hawking entropy of this BPS black hole to all orders in $1/N$.

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- $\mathcal{N} = 4$ with $X_7 = S^7/\mathbb{Z}_r \to \widehat{N} = N + \frac{7r}{24} + \frac{1}{3r}$ and

$$\frac{\log Z_{S^1\times\Sigma_{\mathfrak{g}}}}{\mathfrak{g}-1} = \frac{\pi\sqrt{2r}}{3}\left(\widehat{N}^{\frac{3}{2}} - \left(\frac{r}{2} + \frac{5}{2r}\right)\widehat{N}^{\frac{1}{2}}\right) + \frac{1}{2}\log\widehat{N} + g(r)$$

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- $\mathcal{N} = 3$ with $X_7 = N^{010}/\mathbb{Z}_k \to \widehat{N} = N + \frac{5k}{48} + \frac{1}{3k}$ and

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- In all cases, black hole solution exists $\to$ prediction for entropy at finite N.

Conclusions

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  - solutions coupled to matter multiplets [Bobev,Hong,VR'22]
- Reorganize the large N expansion into a genus expansion at fixed $\lambda = N/k$
  $\rightarrow$ predictions for type IIA string theory on $\mathcal{M}_4 \times \mathrm{KE}_6$ to all orders in α'

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  - solutions coupled to matter multiplets [Bobev,Hong,VR'22]
- Reorganize the large N expansion into a genus expansion at fixed $\lambda = N/k$
  $\rightarrow$ predictions for type IIA string theory on $\mathcal{M}_4 \times \mathrm{KE}_6$ to all orders in α'
- Develop bulk/string computations to match SCFT results to all orders?
  cf. [Hristov,Lodato,VR'17-18; Hristov'22]
- Logarithmic terms currently under investigation.

Conclusions

- Localized partition functions in SCFTs can be studied very precisely.
- Precision holography uncovers structures in M-theory: Airy, "shifted" N...
- Tests and predictions for AdS vacua, including AdS black holes.
- Can also study
  - rotating black holes [Bobev,Choi,Hong,VR'22]
  - solutions coupled to matter multiplets [Bobev,Hong,VR'22]
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Thank you for your attention