Recent developments in $\mathrm{AdS}_6/\mathrm{CFT}_5$

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Holography, Generalized Geometry and Duality
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Why 5d SCFTs?

Higher-dimensional SCFTs integral part in general understanding of (susy) QFT, many insights into lower-dimensional theories:

- new $d \leq 4$ QFTs (4d class $\mathcal{S}$, 3d class $\mathcal{F}$, . . .)
- new dualities, natural explanations for known relations (S-duality, AGT, Argyres-Seiberg duality, . . .)

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5d SCFTs: higher-dimensional perspective with close relations to Lagrangian gauge theories

5d SCFTs from gauge theories

Existence of interacting QFTs in $d > 4$ surprise from perturbative perspective: $d > 4$ gauge theories non-renormalizable ($\sim$ 4d GR).

May flow to non-perturbative UV fixed point $\sim$ asymptotic safety.

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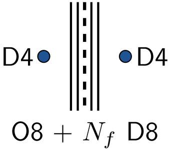

(i) convex prepotential on Coulomb Branch

(ii) construction in Type I' string theory

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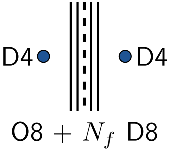


(i) convex prepotential on Coulomb Branch

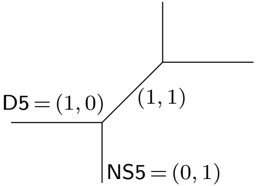
(ii) construction in Type I' string theory

Gauge theories with (i) classified in [Intriligator,Morrison,Seiberg].
Even more theories realized by (p, q) 5-brane webs in Type IIB...

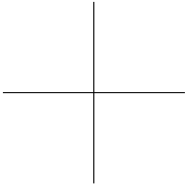
5-brane webs in Type IIB

[Aharony,Hanany,Kol '97]

5-brane web: planar arrangement of (p,q) 5-branes at angles fixed by (p,q), junctions w/ conserved charges



$\longrightarrow$



free massive hypermultiplet

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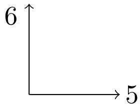
	0	1	2	3	4	5	6	7	8	9
D5	×	×	×	×	×	×				
NS5	×	×	×	×	×		×			



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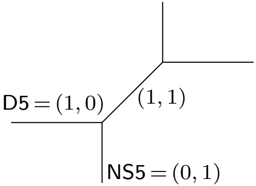
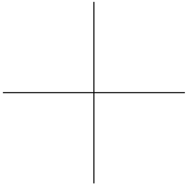


free massive hypermultiplet

$\longrightarrow$



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Length scales in brane web $\leftrightarrow$ mass parameters in field theory.
UV fixed point: all lengths $\to 0$, intersection at a point.

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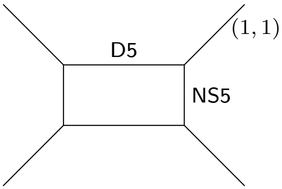
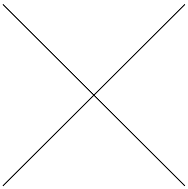


SU(2) Coulomb branch
finite gauge coupling

$\longrightarrow$



UV fixed point SCFT

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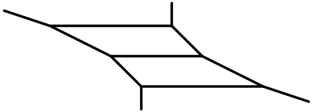
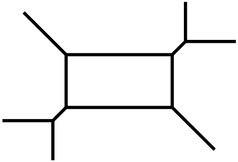
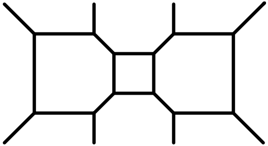
5d SCFTs from 5-brane junctions



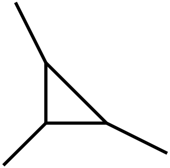
SU(3), CS$= 0$



SU(2) + 2 flavors



SU(2)×SU(2)×SU(2) quiver

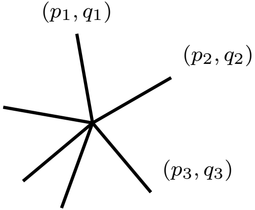


E_0 theory

Landscape of 5d gauge theories, enhanced symmetries, dualities,. . .

5d SCFTs from 5-brane junctions

General picture: any planar 5-brane junction realizes a 5d SCFT on the intersection point



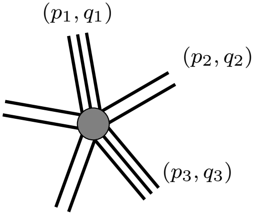
$p_i, q_i \in \mathbb{Z}$

$$\sum p_i = \sum q_i = 0$$

Characterized entirely by external 5-brane charges. No standard Lagrangian. May or may not have gauge theory deformations.

5-brane junctions with 7-branes [DeWolfe,Hanany,Iqbal,Katz '99]

More general theories realized by 5-junctions with 7-branes:



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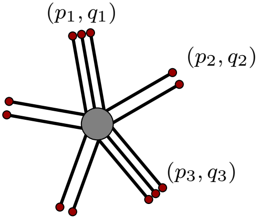

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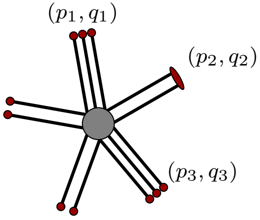

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- multiple 5-branes ending on same 7-brane $\rightarrow$ s-rule constraints [Benini,Benvenuti,Tachikawa]
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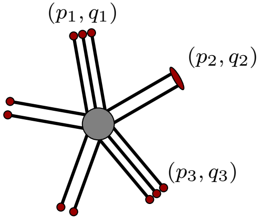

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Additional data for 5-brane junctions w/ 7-branes: partition of like-charged 5-branes into subgroups ending on same 7-brane

Recent developments in $\mathrm{AdS}_6/\mathrm{CFT}_5$

Outline

- $\mathrm{AdS}_6/\mathrm{CFT}_5$ dualities in Type IIB
- Matching "stringy" operators
- Sphere partition functions
- Counting black hole microstates

AdS_6/CFT_5 dualities in Type IIB

Holographic duals for 5d SCFTs

AdS/CFT for quantitative access to superconformal fixed points?
Needs AdS_6 solutions in Type IIB:

– Unique superconformal algebra $F(4)$, 8_Q supercharges.

– Fully localized brane intersections – expect physical singularities from brane sources.

BPS equations studied by [Apruzzi, Fazzi, Passias, Rosa, Tomasiello '14; Kim, Kim, Suh '15; Kim, Kim '16].

Symmetries and ansatz [D'Hoker,Gutperle,Karch,CFU arXiv:1606.01254]

$$\mathrm{AdS}_6 + 16 \text{ susies} \;\rightarrow\; \mathrm{F}(4) \;\supset\; \text{bosonic } \underbrace{\mathrm{SO}(2,5)}_{\mathrm{AdS}_6} \oplus \underbrace{\mathrm{SO}(3)}_{\mathrm{S}^2}$$

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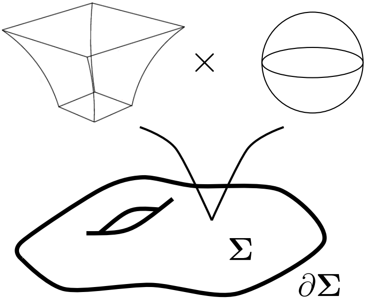
AdS$_6$ S^2



General ansatz: AdS$_6$ and S^2 warped over Riemann surface Σ

$$ds^2 = f_6(w,\bar{w})^2 ds^2_{\mathrm{AdS}_6} + f_2(w,\bar{w})^2 ds^2_{\mathrm{S}^2} + 4\rho(w,\bar{w})^2 |dw|^2$$

$$C_{(4)} = 0 \qquad B_2 + iC^{\mathrm{RR}}_{(2)} = \mathcal{C}(w,\bar{w})\mathrm{vol}_{\mathrm{S}^2} \qquad \tau = \tau(w,\bar{w})$$

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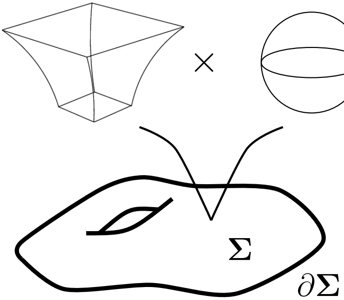

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BPS eq: non-linear PDEs on Σ

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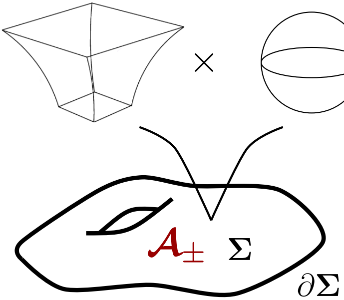

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General solution parametrized by locally holomorphic $\mathcal{A}_\pm : \Sigma \rightarrow \mathbb{C}$

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General local solution [D'Hoker,Gutperle,Karch,CFU arXiv:1606.01254]

General local solution to BPS eq. parametrized by two locally holomorphic functions $\mathcal{A}_\pm$ on Σ:

$$f_6^2 = \sqrt{6\mathcal{G}T} \qquad f_2^2 = \frac{1}{9}\sqrt{\frac{6\mathcal{G}}{T^3}} \qquad \rho^2 = \kappa^2\sqrt{\frac{T}{6\mathcal{G}}}$$

$$B = \frac{1+i\tau}{1-i\tau} = \frac{\partial_w\mathcal{A}_+\,\partial_{\bar w}\mathcal{G} - R\,\partial_{\bar w}\bar{\mathcal{A}}_-\partial_w\mathcal{G}}{R\,\partial_{\bar w}\bar{\mathcal{A}}_+\partial_w\mathcal{G} - \partial_w\mathcal{A}_-\partial_{\bar w}\mathcal{G}}$$

$$\mathcal{C} = \frac{2i}{3}\left(\frac{\partial_{\bar w}\mathcal{G}\partial_w\mathcal{A}_+ + \partial_w\mathcal{G}\partial_{\bar w}\bar{\mathcal{A}}_-}{3\kappa^2T^2} - \bar{\mathcal{A}}_- - \mathcal{A}_+\right)$$

with composite quantities

$$\kappa^2 = -|\partial_w\mathcal{A}_+|^2 + |\partial_w\mathcal{A}_-|^2 \qquad \partial_w\mathcal{B} = \mathcal{A}_+\partial_w\mathcal{A}_- - \mathcal{A}_-\partial_w\mathcal{A}_+$$

$$\mathcal{G} = |\mathcal{A}_+|^2 - |\mathcal{A}_-|^2 + \mathcal{B} + \bar{\mathcal{B}} \qquad T^2 = \left[\frac{1+R}{1-R}\right]^2 = 1 + \frac{2\kappa^2\,\mathcal{G}}{3|\partial_w\mathcal{G}|^2}$$

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Real geometry with consistent spacetime signature, $\mathrm{Im}(\tau) > 0$ at interior points of Σ, smoothly collapse S^2 on boundary points:

$$\begin{array}{lll} \kappa^2 > 0 & \mathcal{G} > 0 & \text{on } \mathrm{int}(\Sigma) \\ \kappa^2 = 0 & \mathcal{G} = 0 & \text{on } \partial\Sigma \end{array}$$

$\rightarrow \Sigma$ needs a boundary ($\partial_w\partial_{\bar{w}}\mathcal{G} = -\kappa^2$). To be realized by locally holomorphic $\mathcal{A}_\pm$...

Solution strategy

[D'Hoker,Gutperle,CFU arXiv:1703.08186]

Solution strategy: regular κ^2 from auxiliary electrostatics potential

$$\Phi \equiv -\ln\left|\frac{\partial_w \mathcal{A}_+}{\partial_w \mathcal{A}_-}\right|^2 \qquad\qquad \Phi\Big|_{\mathsf{int}(\Sigma)} > 0 \qquad\qquad \Phi\Big|_{\partial\Sigma} = 0$$

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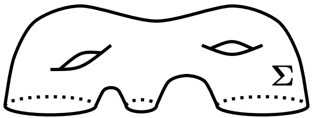

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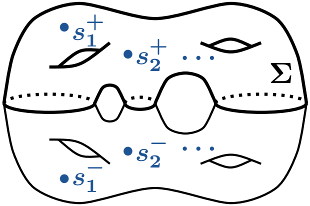

Arbitrary distribution of positive charges in Σ, negative mirror charges in doubled surface

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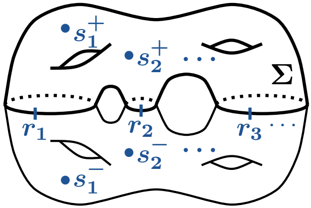

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$\mathcal{A}_\pm$ from holomorphic splitting: charges become zeros of $\partial\mathcal{A}_\pm$.
Meromorphic differentials need **poles r_ℓ** on $\partial\Sigma$

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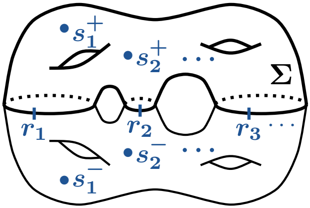

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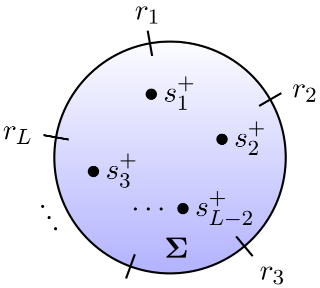
Regularity of $\mathcal{G}$ imposes further constraints on the resulting $\mathcal{A}_\pm$.

Regular solutions on the disc [D'Hoker,Gutperle,CFU arXiv:1703.08186]

Worked out for Σ =disc/upper half plane. $\mathcal{A}_\pm$ from potential Φ:



$$\mathcal{A}_\pm = \mathcal{A}_\pm^0 + \sum_{\ell=1}^{L} Z_\pm^\ell \ln(w - r_\ell)$$

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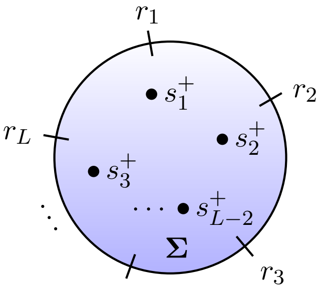

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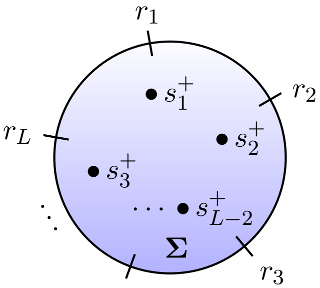

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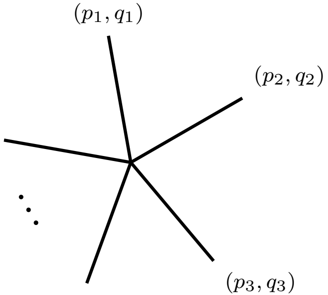
$L \geq 3$ poles. Remaining regularity conditions leave $2L-2$ free real parameter $\sim$ choice of Z_+^ℓ with $\sum Z_+^\ell = 0$.

Solutions regular except at poles. Near pole, solution matches near horizon limit of (p,q) 5-brane solution [Lu,Roy '98] w/ $q + ip \sim Z_+^m$.

5-brane picture and AdS/CFT

Supergravity solutions for fully localized (p, q) 5-brane junctions:



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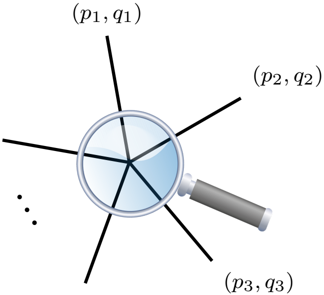

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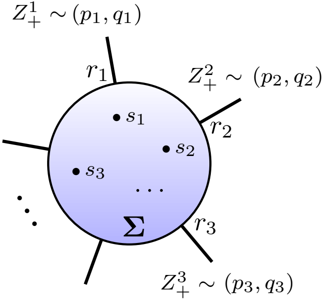

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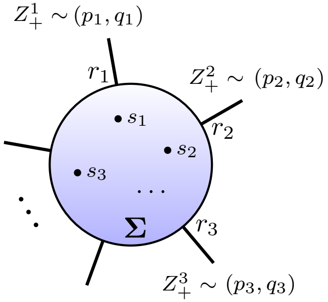

- 5-branes $\leftrightarrow$ poles in $\partial\mathcal{A}_\pm$
  charges $\leftrightarrow$ residues Z_+^ℓ
- both parametrized by choice of residues mod charge cons.
- $\mathrm{AdS}_6 + 16$ susies $= F(4)$
- need $L \geq 3$, p and q charge

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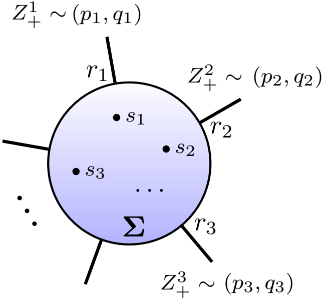

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- AdS$_6$ $+ 16$ susies $= F(4)$
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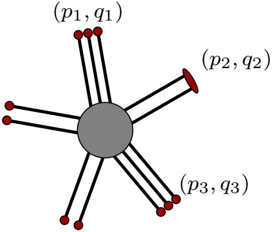
AdS$_6$/CFT$_5$: Type IIB string theory on warped AdS$_6$ solution $\cong$ 5d SCFT on associated (p, q) 5-brane junction.

"Large-N" classical supergravity limit: all $p_i, q_i \gg 1$. Generically, junctions of large groups of like-charged 5-branes (unconstrained).

Extension to constrained junctions [D'Hoker,Gutperle,CFU 1706.00433]

Supergravity solutions for "constrained" junctions with 7-branes:



– How to see 7-branes at intersection point?

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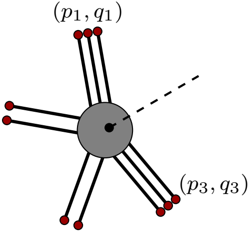

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Mass-deform to open up brane web, Hanany-Witten transitions to move 7-branes w/ multiple 5-branes into the web, take UV limit.

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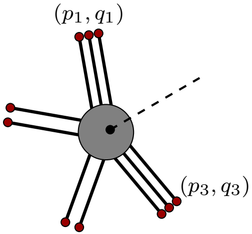


– How to see 7-branes at intersection point?

Mass-deform to open up brane web, Hanany-Witten transitions to move 7-branes w/ multiple 5-branes into the web, take UV limit.

$\rightarrow \Sigma =$ disc with punctures & $SL(2,\mathbb{R})$ monodromy $=$ 7-branes.
Works for punctures with commuting monodromies, so far.

Holographic duals for 5d SCFTs

General warped $\mathrm{AdS}_6 \times \mathrm{S}^2 \times \Sigma$ sol. with 16 susies in Type IIB.

Physically regular solutions for $\Sigma =$disc with single-valued $\mathcal{A}_\pm$.
Identified with unconstrained (p, q) 5-brane junctions.

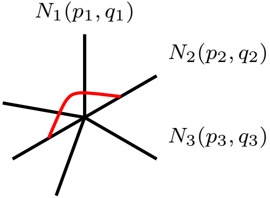
Physically regular solutions for punctured disc with commuting $SL(2, \mathbb{R})$ monodromies, describe constrained 5-brane junctions.

T-duals of AdS_6 in massive IIA realized with relaxed regularity conditions [Hong,Liu,Mayerson '18, Lozano,Macpherson,Montero '18]

– Matching stringy operators –

Matching stringy operators [Bergman,Rodriguez-Gomez,CFU 1806.07898]

5-brane picture: gauge invariant operators from strings and string junctions connecting external 5-branes



Supergravity: probe string (junctions) $\leftrightarrow \Delta = \mathcal{O}(N)$ operators

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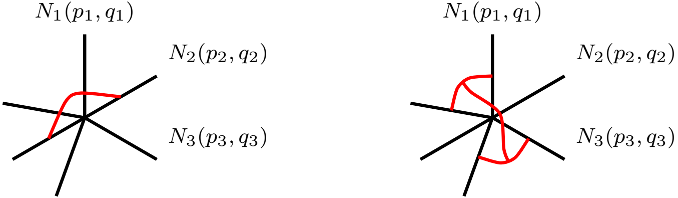
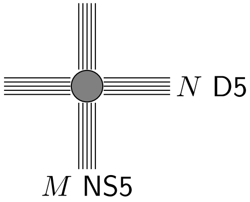


Supergravity: probe string (junctions) $\leftrightarrow \Delta = \mathcal{O}(N)$ operators

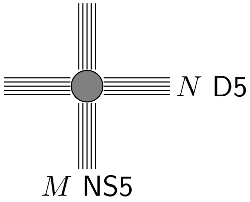
Strategy: identify stringy BPS operators in gauge theory deformations, extrapolate charges and scaling dim to SCFT

Matching stringy operators: $+_{N,M}$ theory



$\mathsf{SU}(N)^2 \times \mathsf{SU}(M)^2 \times \mathsf{U}(1)$
global symmetry

Matching stringy operators: $+_{N,M}$ theory



SU$(N)^2\times$SU$(M)^2\times$U(1)
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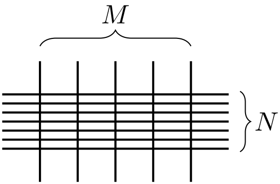

gauge theory deformation:

$$[N] \overset{x_1}{-} \mathrm{SU}(N) \overset{x_2}{-} \cdots \overset{x_{M-1}}{-} \mathrm{SU}(N) \overset{x_M}{-} [N]$$

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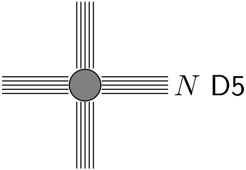

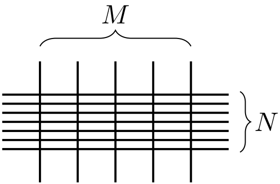

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$$M^i_j = (x^{(1)} \cdots x^{(M)})^i_j \qquad (\mathbf{N}, \bar{\mathbf{N}}, \mathbf{1}, \mathbf{1}) \qquad \Delta = \frac{3}{2}M \qquad Q = \frac{1}{2}M$$

$$B^{(k)} = \det(x^{(k)}) \qquad \subset (\mathbf{1}, \mathbf{1}, \mathbf{M}, \bar{\mathbf{M}}) \qquad \Delta = \frac{3}{2}N \qquad Q = \frac{1}{2}N$$

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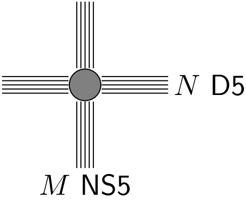

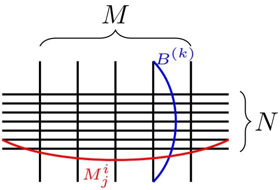

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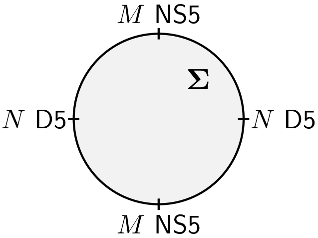
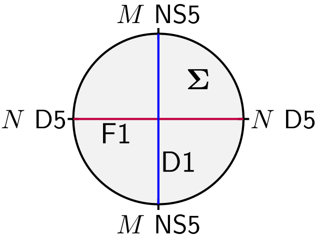
$M^i_j \sim$ F1 between D5, $B^{(k)} \subset$ D1 between NS5

Matching stringy operators: $+_{N,M}$ theory



Supergravity: 4-pole solution

Matching stringy operators: $+_{N,M}$ theory



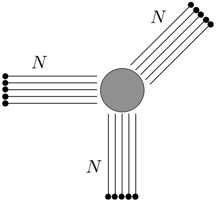
Supergravity: 4-pole solution

F1 between D5 poles, D1 between NS5 poles:

$$\Delta_{\mathrm{F1}} = \frac{3}{2}M \qquad\qquad \Delta_{\mathrm{D1}} = \frac{3}{2}N$$

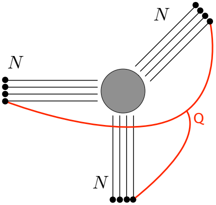
Solve EOM and are BPS, scaling dim. match field theory ✓✓

Matching stringy operators: T_N theory



5d T_N: reduce on S^1 to 4d T_N, global symmetry (at least) $SU(N)^3$

Matching stringy operators: T_N theory



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string junction in $(\mathbf{N}, \mathbf{N}, \mathbf{N}) \supset$ meson in

$$N - SU(N-1) - \ldots - SU(2) - 2$$

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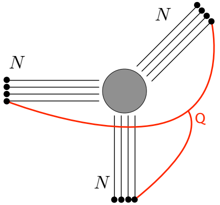

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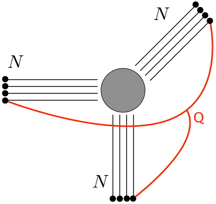

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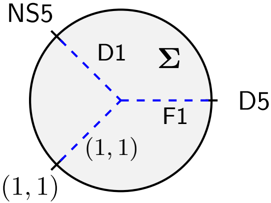
$$N - SU(N-1) - \ldots - SU(2) - 2$$

$$\Longrightarrow \ \Delta = \frac{3}{2}(N-1) \qquad Q = \frac{1}{2}(N-1)$$

Triple junction in supergravity:

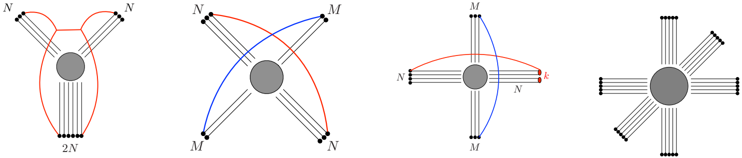
$$\Delta = \frac{3}{2}N \qquad Q = \frac{1}{2}N$$

Agrees with T_N operator at large N. ✓✓

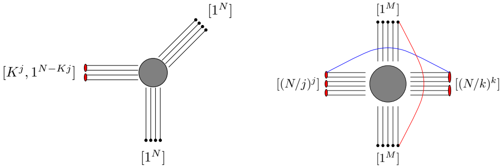


Matching stringy operators [Bergman,Rodriguez-Gomez,CFU 1806.07898]

Similar quantitative matches of field theory and supergravity for



and solutions w/punctures and only two poles [Chaney, CFU 1810.10592]



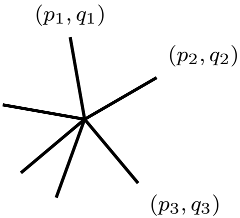
Predictions for operators not easily seen in gauge theory and more exotic junctions, e.g. $\Delta = \frac{9}{2}N$ in large-N E_0 theory.

– Sphere partition functions –

S^5 partition functions

[Gutperle,Marasinou,Trivella,CFU 1705.01561]

Holographically: on-shell action ($F_5 = 0$) or finite part of $S_{\mathrm{EE,disc}}$



– poles unproblematic for both

– generically non-trivial dependence of F_{S^5} on all (p, q) charges

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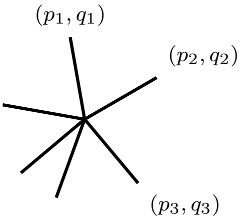


- poles unproblematic for both
- generically non-trivial dependence of F_{S^5} on all (p, q) charges

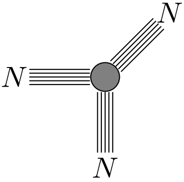
Homogeneous rescaling of all (p, q) charges:

$$(p_i, q_i) \to N(p_i, q_i) \quad \forall i \qquad \Longrightarrow \qquad \mathcal{F}(S^5) \to N^4 \mathcal{F}(S^5)$$

Unlike $N^{5/2}$ for $USp(N)$ theory from D4/D8/O8 [Jafferis,Pufu]

$+_{N,M}$ and T_N theories [Gutperle,Marasinou,Trivella,CFU 1705.01561]

Supergravity results for T_N and $+_{N,M}$ theories:



5d T_N theory w/ gauge theory deformation

$$N - SU(N-1) - \cdots - SU(2) - 2$$

$$\mathcal{F}_{\text{sugra}}(S^5) = -\frac{27}{8\pi^2}\,\zeta(3)N^4$$

$+_{N,M}$ and T_N theories

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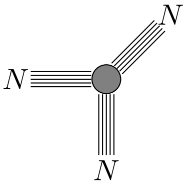

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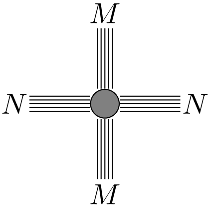
D5/NS5 intersection: $N - SU(N)^{M-1} - N$

$$\mathcal{F}_{\rm sugra}(S^5) = -\frac{189}{16\pi^2}\,\zeta(3)N^2M^2$$



$+_{N,M}$ and T_N in field theory [Fluder, CFU 1806.08374]

Supersymmetric localization in large-N gauge theory: instantons exponentially suppressed, saddle point approximation exact.

Extrapolate to SCFT assuming higher-dim operators Q-exact.

$+_{N,M}$ and T_N in field theory [Fluder, CFU 1806.08374]

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Zero-instanton partition function on squashed S^5 [Imamura '12]

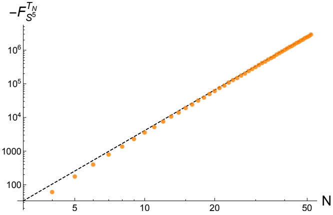
$$\mathcal{Z}_0 = \int \prod_{i,j} \mathrm{d}\lambda_i^{(j)} \exp\left(-\mathcal{F}\right)$$

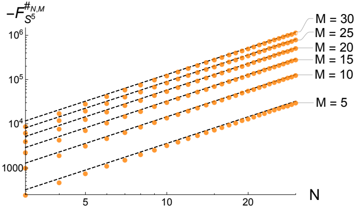
Long quivers with many gauge nodes, in general independent eigenvalue distributions.

$+_{N,M}$ and T_N in field theory [Fluder, CFU 1806.08374]

Numerical evaluation [Herzog,Klebanov,Pufu,Tesileanu]: Replace saddle point eq. by set of particles w/ coordinates $\lambda_i^{(j)}$ in potential $\mathcal{F}$

$\Rightarrow \mathcal{F}_{S^5}$ numerically, $N \leq 50$ for T_N, $N, M \leq 30$ for $+_{N,M}$





Confirms N^4 and $N^2 M^2$ scaling predicted from supergravity, coefficients of leading terms agree to $1‰$ ✓✓

– Counting AdS_6 black hole microstates –

Counting black hole microstates [Fluder,Hosseini,CFU 1902.05074]

Consistent KK reduction to 6d F(4) sugra based on these general AdS_6 solutions: [Hong,Liu,Mayerson; Malek,Samtleben,Vall Camell '18]

$\rightarrow$ any (bosonic) solution to 6d F(4) supergravity combined with any choice of $(\Sigma, \mathcal{A}_\pm)$ uplifts to 10d solution of Type IIB

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Magnetically charged AdS$_6$ black holes in 6d F(4) supergravity with AdS$_2 \times \Sigma_{\mathfrak{g}_1} \times \Sigma_{\mathfrak{g}_2}$ near-horizon limit [Suh '18] ([Naka '02])

$$ds^2 = ds^2_{AdS_2} + ds^2_{\Sigma_{\mathfrak{g}_1}} + ds^2_{\Sigma_{\mathfrak{g}_2}} \qquad \phi = \text{const}$$

$$F^3 \sim \text{vol}_{\Sigma_{\mathfrak{g}_1}} + \text{vol}_{\Sigma_{\mathfrak{g}_2}} \qquad B_2 \sim \text{vol}_{AdS_2}$$

$\Sigma_{\mathfrak{g}_i}$ constant curvature Riemann surfaces of genus $\mathfrak{g}_i > 1$.

Counting black hole microstates [Fluder,Hosseini,CFU 1902.05074]

Uplift to family of Type IIB AdS_6 black hole solutions, one for each choice $(\Sigma, \mathcal{A}_\pm)$, labeled by $(\mathfrak{g}_1, \mathfrak{g}_2)$. Bekenstein-Hawking entropy:

$$S_{\rm BH} = -\frac{8}{9}(1-\mathfrak{g}_1)(1-\mathfrak{g}_2)\mathcal{F}_{S^5}$$

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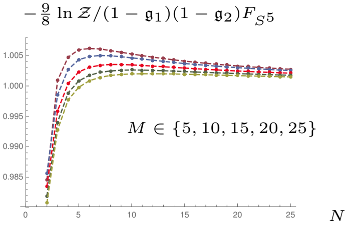
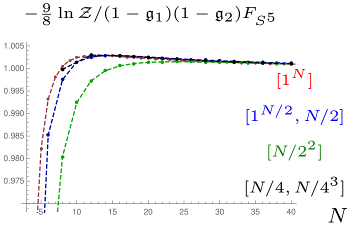
Near-horizon solution describes 5d SCFT characterized by $(\Sigma, \mathcal{A}_\pm)$ compactified on $\Sigma_{\mathfrak{g}_1} \times \Sigma_{\mathfrak{g}_2} \times S^1$ with topological twist.

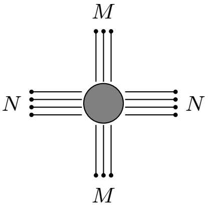
Partition function $\mathcal{Z}_{S^1 \times \Sigma_{\mathfrak{g}_1} \times \Sigma_{\mathfrak{g}_2}}$ from localization [Hosseini,Yaakov, Zaffaroni; Crichigno,Jain,Willett '18] $\sim$ 5d topologically twisted index.

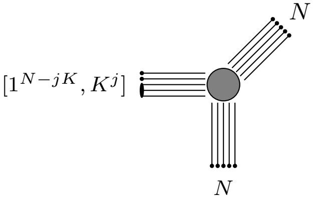
Counting black hole microstates [Fluder,Hosseini,CFU 1902.05074]

Large-N saddle point prescription of [Hosseini,Yaakov, Zaffaroni '18]:









Supports index computation, KK reductions, AdS$_6$/CFT$_5$ dualities.

– Summary & Outlook–

Summary

Supergravity solutions for fully localized 5-brane junctions in Type IIB. Holographic duals for the corresponding 5d SCFTs.

Quantitative tests of proposed $\mathrm{AdS}_6/\mathrm{CFT}_5$ dualities: spectrum of stringy operators, S^5 partition functions, top. twisted indices.

Supports existence of 5d SCFTs and SCFT interpretation of 5-brane junctions.

N^4 scaling of $\#$ d.o.f. from sphere partition functions, results consistent with conjectured 5d F-theorem

Outlook

More quantitative studies of 5d SCFTs: spectrum, correlators, non-local operators, finite T, ...

Lessons for $d \leq 4$: boundaries and defects, compactification, e.g. new "class $\mathcal{F}$" examples from AdS$_4 \times \Sigma_{\mathfrak{g}}$ in 6d $F(4)$, ...

Further solutions: RG flows, non-minimal truncations, mutually non-local 7-branes, ...

Similar story for closely related AdS$_2 \times$S$^6 \times \Sigma$ solutions?
[Corbino,D'Hoker,CFU 1712.04463], [Corbino,D'Hoker,Kaidi,CFU 1812.10206]

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Thank you!