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AdS_2 from D0-branes

arXiv: 1807.00555 with G. Dibitetto

arXiv: 2309.01714 with A. Legramandi and N. Macpherson

arXiv: 2503.23227 with Y. Lozano and N. Macpherson

arXiv: 26xx.xxxxx with N. Macpherson

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One of the most intriguing relations in theoretical physics is the Bekenstein–Hawking formula that expresses the entropy of a black hole in terms of the area of its event horizon.

A measure of success of any quantum theory of gravity is providing a statistical derivation of the black hole entropy, and identifying the corresponding microscopic degrees of freedom.

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Extremal black holes, which are black holes of zero temperature, play a key role as they allow for a tractable quantum description. They possess an AdS_2 factor in their near-horizon geometry, thus AdS_2 /CFT_1 correspondence is of particular interest.

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The fix, developed by [Almheiri, Polchinski], [Jensen], [Maldacena, Stanford, Yang] and [Engelsöy, Mertens, Verlinde], is to admit that the symmetry is always broken, and to make the breaking the whole content of the theory.

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All dynamics lives in and in the shape of the boundary. One works to leading order in a deviation from extremality: near-AdS_2, dual to a near-CFT_1.

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- The low-energy worldvolume theory for N D0-branes is maximally supersymmetric Yang–Mills dimensionally reduced from 10d to 0+1 dimensions: a $U(N)$ matrix quantum mechanics with nine Hermitian matrices and 16 supercharges.
- [Banks, Fischler, Shenker, Susskind] conjectured that this quantum mechanics, in the $N \to \infty$ limit, is M-theory in the infinite-momentum frame.

[Imamura]

branes	t	y	r	θ^1	θ^2	θ^3	θ^4	θ^5	θ^6	θ^7
D0	$\times$	—	—	—	—	—	—	—	—	—
F1	$\times$	$\times$	—	—	—	—	—	—	—	—
D8	$\times$	—	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$

$$
\begin{aligned}
ds_{10}^2 &= -S^{-1}K^{-1/2}dt^2 + S^{-1}K^{1/2}dy^2 + K^{\frac{1}{2}}(dr^2 + r^2 d\Omega_{(7)}^2) \\
e^{\Phi} &= g_s K^{3/4} S^{-1/2} \\
F_{(0)} &= m \\
C_{(1)} &= g_s^{-1} K^{-1} dt \\
B_{(2)} &= S^{-1} dt \wedge dy
\end{aligned}
$$

$$
\Delta_{(8)} S + \frac{1}{2}\frac{\partial^2}{\partial y^2} S^2 = 0 \,, \qquad \left\{ \begin{aligned} m g_s K - \frac{\partial S}{\partial y} &= 0 \\ \Delta_{(8)} K + S \frac{\partial^2}{\partial y^2} K &= 0 \end{aligned} \right.
$$

[Dibitetto, AP]

$$S = r^6\, G(y^2 r^4)\,, \qquad K = \frac{2}{m g_s} y r^2 G'(y^2 r^4)\,,$$

$$y \;\to\; 0\;,\; r \;\to\; \infty\;,\; \text{while}\;\; yr^2 \;\sim\; \text{finite}\;\;.$$

The metric becomes

$$ds^2_{10} = \left(\frac{\alpha}{\ddot{\alpha}}\right)^{1/2}\left(-\frac{1}{8}\frac{\alpha\ddot{\alpha}}{\alpha^2 - 2\alpha\ddot{\alpha}}\, ds^2(\mathrm{AdS}_2) + \frac{\ddot{\alpha}}{8\alpha}\, dz^2 \;+\; ds^2(\mathrm{S}^7)\right)\;, \qquad \ddddot{\alpha} = 0$$

The metric stays positive for $z \in [z_0, \infty]$

Near a double root z_0 of α the metric tends to

$$ds^2_{10} \sim \frac{3}{2^3\sqrt{2}} \frac{\ddot{\alpha}(z_0)}{\dddot{\alpha}} ds^2(\mathrm{AdS}_2) + \frac{1}{\sqrt{2}} \left(d\rho^2 + \rho^2 ds^2(S^7) \right)$$

where $\rho^2 \equiv z - z_0$. The internal space thus exhibits a regular zero.

The metric stays positive for $z \in [z_0, \infty]$

Near a stationary point of inflection of α the metric tends to

$$\mathrm{d}s_{10}^2 \sim (z-z_0)^{1/2}\frac{1}{8}\sqrt{\frac{\dddot{\alpha}}{\alpha(z_0)}}\mathrm{d}z^2 + (z-z_0)^{-1/2}\sqrt{\frac{\alpha(z_0)}{\dddot{\alpha}}}\left(\frac{1}{16}\mathrm{d}s^2(\mathrm{AdS}_2) + \mathrm{d}s^2(\mathrm{S}^7)\right)$$

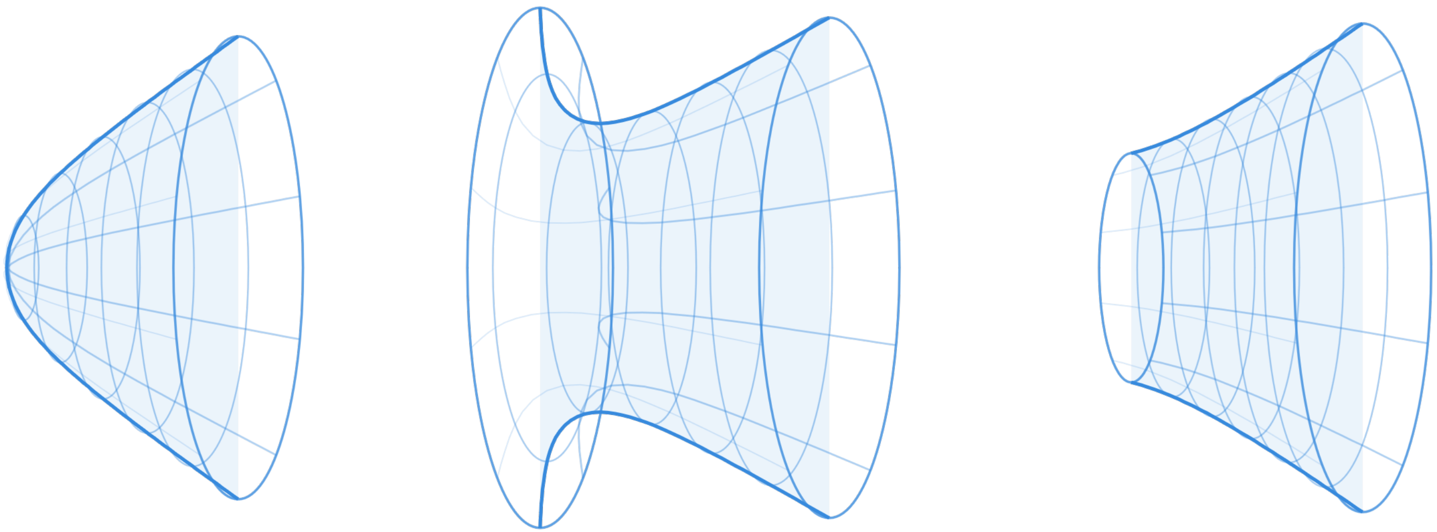
We recognise the singular, yet physical, behaviour as associated to a O8/D8–brane system extended in $\mathrm{AdS}_2\times\mathrm{S}^7$.

The metric stays positive for $z \in [z_0, \infty]$

Near a simple root of $2\alpha\ddot{\alpha} - \alpha^2$ the metric tends to

$$ds^2_{10} \sim \frac{1}{16}\frac{\sqrt{\alpha(z_0)\ddot{\alpha}(z_0)}}{\dddot{\alpha}}(z - z_0)^{-1}ds^2(\text{AdS}_2) + \frac{1}{8}\sqrt{\frac{\ddot{\alpha}(z_0)}{\alpha(z_0)}}dr^2 + \sqrt{\frac{\alpha(z_0)}{\ddot{\alpha}(z_0)}}ds^2(\text{S}^7)$$

This is the singularity associated to a localised OF1-plane extended in AdS_2 and backreacted on S^7.



$\mathbb{R}^8$ cap   O8/D8 system   OF1-plane

In [Dibitetto, Lozano, Ramirez] it was shown that the $\mathrm{AdS}_2 \times S^7$ solution corresponding to vanishing Romans mass originates from the ABJM M-theory solution.

Writing the metric of AdS_4 in the parametrisation

$$ds^2(\mathrm{AdS}_4) = \frac{1}{\sin^2\theta}\Big(d\theta^2 + ds^2(\mathrm{AdS}_3)\Big)$$

where

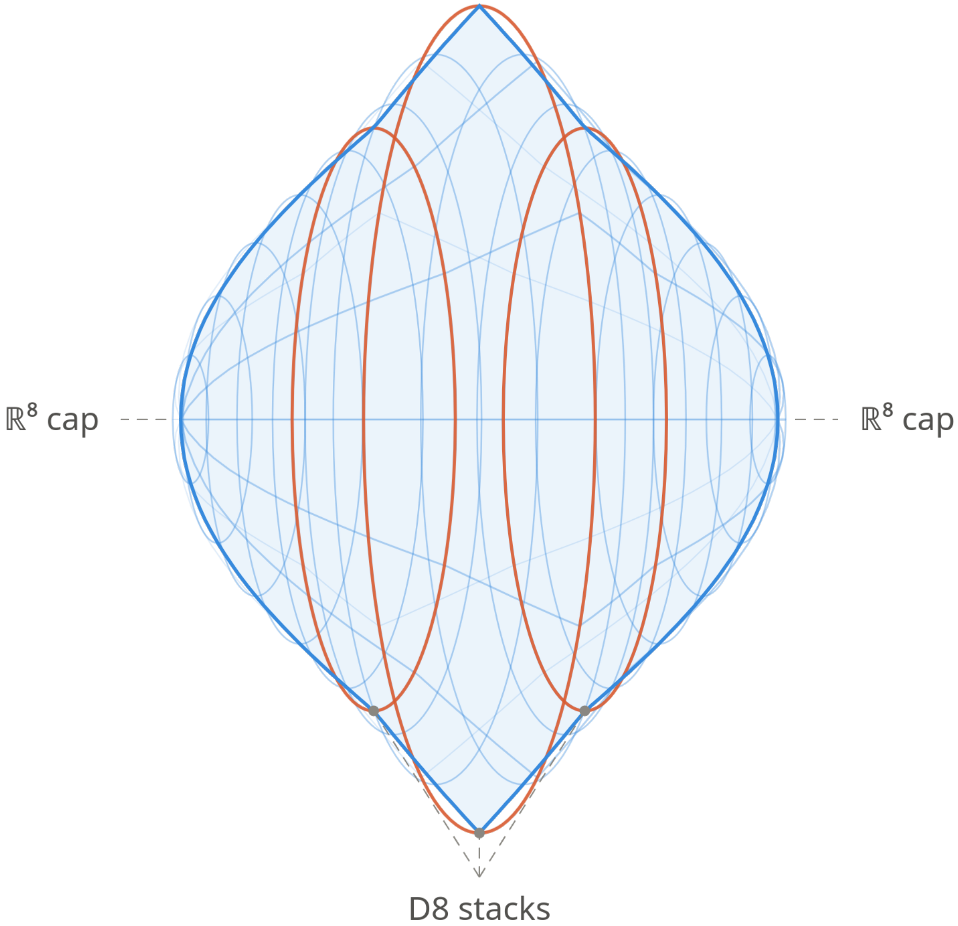
$$ds^2(\mathrm{AdS}_3) = \frac{1}{4}\Big[\Big(2dy + \eta\Big)^2 + ds^2(\mathrm{AdS}_2)\Big] \quad \text{with} \quad d\eta = -\mathrm{vol}(\mathrm{AdS}_2)$$

and $y \in [0, 2\pi]$, and reducing on y.

In [Lozano, Macpherson, AP] we revisited the solutions and generalized them in two ways:

1. $\mathsf{S}^7 \to \mathsf{S}^7/\mathbb{Z}_k$ breaking supersymmetry from $\mathcal{N}=8$ to $\mathcal{N}=6$
2. include D8-brane sources perpendicular to z-direction to construct compact internal spaces

$$ds^2(S^7/\mathbb{Z}_k) = \left(\frac{d\tau}{k} + \mathcal{A}\right)^2 + ds^2(\mathbb{CP}^3)$$



$\mathbb{R}^8$ cap
$\mathbb{R}^8$ cap
D8 stacks

$$
\begin{tikzcd}
 & \boxed{\mathrm{AdS}_4/\mathbb{Z}_{k'} \times S^7/\mathbb{Z}_k} \arrow[dl, "S^1/\mathbb{Z}_{k'}"'] \arrow[dr, "S^1/\mathbb{Z}_k"] & \\
\boxed{\mathrm{AdS}_2 \times S^7/\mathbb{Z}_k \times \mathrm{I}} \arrow[d, leftrightarrow, "T_{S^1/\mathbb{Z}_k}"] & & \boxed{\mathrm{AdS}_4/\mathbb{Z}_{k'} \times \mathbb{CP}^3} \arrow[d, leftrightarrow, "T_{S^1/\mathbb{Z}_{k'}}"] \\
\boxed{\mathrm{AdS}_2 \times \mathbb{CP}^3 \times S^1/\mathbb{Z}_k \times \mathrm{I}} \arrow[rr, leftrightarrow, "S"] & & \boxed{\mathrm{AdS}_2 \times \mathbb{CP}^3 \times S^1/\mathbb{Z}_{k'} \times \mathrm{I}}
\end{tikzcd}
$$

$$ds^2_{10} = e^{2A} ds^2(\mathrm{AdS}_2) + ds^2(M_8)$$

&

Φ, H, F_p

preserving the symmetries of AdS_2

$$\exists\ \epsilon_{1,2}\colon\ \delta_{\epsilon_{1,2}}\psi = 0 = \delta_{\epsilon_{1,2}}\lambda$$

$$\epsilon_1 = \zeta_+ \otimes \chi_{1+} + \zeta_- \otimes \chi_{1-} \,, \qquad \epsilon_2 = \zeta_+ \otimes \chi_{2\mp} + \zeta_- \otimes \chi_{2\pm} \,; \qquad \nabla_\mu \zeta_\pm = \frac{1}{2} m \gamma_\mu \zeta_\mp$$

$\mathrm{SO}(8)$

$\Downarrow$

G

stabilizer

M_8 acquires a G-structure characterized by a set of tensors constructed as bilinears of $\{\chi_1, \chi_2\}$

$$G = \begin{cases} SU(3)\,\{V_1,\ U_1,\ J_2,\ \Omega_3\} \\ \\ G_2\,\{V_1,\ \Phi_3\} \end{cases}$$

The exterior derivatives of the G-structure tensors determine its intrinsic torsion, which is parametrized by torsion classes

$$\psi \equiv \chi_1 \otimes \chi_2^\dagger, \hat{\psi} \equiv \hat{\gamma}\chi_1 \otimes \chi_2^\dagger$$

$$+$$

$$\chi_1 \otimes \chi_2^\dagger \propto \sum_p \chi_2^\dagger \gamma_{m_1 \dots m_p} \chi_1 \gamma^{m_1 \dots m_p}$$

$$+$$

$$\gamma^{m_1 \dots m_k} \to dx^{m_1} \wedge \cdots \wedge dx^{m_k}$$

$$\Downarrow$$

polyforms

$\psi, \hat{\psi}$(G-structure)

$$\delta_{\epsilon_{1,2}}\psi = 0 = \delta_{\epsilon_{1,2}}\lambda$$

$$\Downarrow$$

$$\text{constraints on } \{\chi_1, \chi_2\}$$

$$\Downarrow$$

Differential equations involving the polyforms and the fields. We obtain a set of constraints on the intrinsic torsion of the G-structure and expressions for the supergravity fields in terms of the geometric data.

Imposing a weak G_2 holonomy $d\Phi_3 = 4 \star \Phi_3$:

$$\frac{ds^2_{10}}{L^2} = \sqrt{\frac{h}{h''}}\left[\frac{hh''\sqrt{1-7\nu}}{8\Delta}ds^2(\mathrm{AdS}_2) + \left(\frac{h''}{8h\sqrt{1-7\nu}}d\rho^2 + \frac{\sqrt{1-7\nu}}{(\nu-1)^2}ds^2(\mathrm{M}_{\mathrm{WG}_2})\right)\right],$$

$$H = \frac{L^2}{8\sqrt{2}}d\left(\frac{hh'(1-7\nu)}{\Delta} - \rho\right) \wedge \mathrm{vol}(\mathrm{AdS}_2), \quad e^{-\Phi} = \frac{\sqrt{\Delta}(1-\nu)^{\frac{7}{2}}}{c_0 L^3 (1-7\nu)^{\frac{5}{4}}}\left(\frac{h''}{h}\right)^{\frac{3}{4}},$$

$$\Delta = 2hh'' - (1-7\nu)(h')^2,$$

$+ F_0, F_2, F_4$

$$h'''' = 0\,, \qquad v = \begin{cases} 0 \text{ [Dibitetto, AP]} \\ -\dfrac{1}{5} \end{cases}$$

Class 1 The range of r is $[r_-, r_+]$ where r_- and r_+ are roots of Δ. At the endpoints of the r-interval there are OF1 type singularities.

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Class 2. In this class

$$h = \delta_0 + +\frac{1}{6}\delta_3(r - r_0)^3, \tag{2}$$

where δ_0, δ_3 are constants and the Romans mass is proportional to δ_3. The range of r is $[r_0, r_+]$ where r_0 and r_+ are roots of Δ, with r_0 being also a double root of h'. Near r_0 there is an O8/D8 type singularity and near r_+ an OF1 type one.

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Class 3. In this class the Romans mass is zero and h is a quadratic polynomial. The range of r is $[r_-, r_+]$ where r_- and r_+ are the roots of Δ. At the endpoints of the r-interval there are OF1 type singularities.

- Construct a consistent truncation on S^7 to a two-dimensional supergravity.
- In [Lozano, Macpherson, AP] supersymmetric quantum mechanics were proposed as duals.

Test the correpondence by matching free energy

- Understand the brane configuration and the dual of the $\nu = -\frac{1}{5}$ case.
- Find solutions for non-constant ν.