String Corrections To Black Holes In Five Dimensions

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Introduction

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- Motivation: e.g. $S = k \log \Omega$

Bekenstein-Hawking $S = \dfrac{A}{4}$

Wald $S \propto \displaystyle\int_H d^{d-2}x \sqrt{|h|} \frac{\delta \mathcal{L}}{\delta R_{\mu\nu\rho\sigma}} \epsilon^{\mu\nu} \epsilon^{\rho\sigma}$

[Castro et al. *String theory effects on five-dimensional black-hole physics*]

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- Another motivation: AdS/CFT

gravity side	SU(N) side
higher orders in curvature	$1/N$ effects

[Cremonini et al. *Black holes in five-dimensional gauged supergravity with higher derivatives*]

$\mathcal{N} = 2$, $D = 5$ supergravity with vector multiplets

- Pure gravity
  - bosons: e_μ^a
  - fermions: ψ_μ^i
- $n_V + 1$ gauge fields $G = \mathrm{U}(1)^{n_V+1}$
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- Bosonic action: $S=\frac{1}{16\pi G}\int d^5x\sqrt{|g|}\mathcal{L}$

$$\mathcal{L}=-R-G_{IJ}\left(\tfrac{1}{2}F^I_{\mu\nu}F^{J\mu\nu}-\nabla_\mu M^I\nabla^\mu M^J\right)+\frac{1}{24\sqrt{|g|}}c_{IJK}\epsilon^{\mu\nu\rho\sigma\tau}F^I_{\mu\nu}F^J_{\rho\sigma}A^K_\tau$$

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- *Very special geometry constraint* & graviphoton

$$\frac{1}{3!}c_{IJK}M^I M^J M^K = 1 \qquad A_{\text{gr.ph.}} \propto c_{IJK}M^I M^J A^K$$

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- Motivation: dimensional reduction from $D=11$ on Calabi-Yau

Off-shell formalism

- String theory calculations $\rightarrow$ supersymmetry considerations

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- Resulting lagrangian: $\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_1$

$$
\begin{aligned}
\mathcal{L}_0 = {} & \tfrac{1}{2} D(\mathcal{N} - 1) - \tfrac{1}{4}(\mathcal{N} + 3)R + (3\mathcal{N} + 1)v^2 + 2\mathcal{N}_I v \cdot F^I + \\
& + \mathcal{N}_{IJ} \left(\tfrac{1}{4} F^I \cdot F^J - \tfrac{1}{2} \partial M^I \cdot \partial M^J \right) + \\
& + \frac{1}{24} \frac{1}{\sqrt{|g|}} c_{IJK} \epsilon^{\mu\nu\rho\sigma\tau} A^I_\mu F^J_{\nu\rho} F^K_{\sigma\tau}
\end{aligned}
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$$
\mathcal{L}_1 = \frac{c_{2I}}{24} \cdot \left\{ \frac{1}{16} \epsilon^{abcde} A^I_a C_{bcfg} C_{de}{}^{fg} + \text{supersymmetric completion} \right\}
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- $\mathcal{L}_1$ encodes one-loop string corrections

Modified very special geometry constraint

- Let us focus on D-terms:

$$\mathcal{L} = \frac{1}{2} D \left(\mathcal{N} - 1 \right) + \frac{c_{2I}}{24} \cdot \frac{1}{6} D \left(\frac{1}{2} M^I D + v \cdot F^I \right) + \dots$$

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- Equation of motion of D field

$$\mathcal{N} = 1 - \frac{c_{2I}}{24} \cdot \frac{1}{3} \left(M^I D + v \cdot F^I \right)$$

BPS conditions

some fraction of supersymmetry is preserved $\Leftrightarrow$ $\exists\, \epsilon(x) \neq 0$ such that

$$\delta\psi_\mu \equiv \left\{ \nabla_\mu + \frac{1}{2} v^{ab} \gamma_{\mu ab} - \frac{1}{3} v^{ab} \gamma_\mu \gamma_{ab} \right\} \epsilon = 0$$

$$\delta\chi \equiv \left\{ D - 2\gamma^c \gamma^{ab} \nabla_a v_{bc} - 2\gamma^a \epsilon_{abcde} v^{bc} v^{de} + \frac{4}{3} (v \cdot \gamma)^2 \right\} \epsilon = 0$$

$$\delta\Omega^I \equiv \left\{ -\frac{1}{4} F^I_{ab} \gamma^{ab} - \frac{1}{2} \gamma^\mu \partial_\mu M^I - \frac{1}{3} M^I v^{ab} \gamma_{ab} \right\} \epsilon = 0$$

Spinorial geometry techniques

- Killing spinor equation: $\nabla\epsilon + \mathcal{O}\epsilon = 0$ or $\mathcal{O}\epsilon = 0$

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- Killing spinor equation: $\nabla\epsilon + \mathcal{O}\epsilon = 0$ or $\mathcal{O}\epsilon = 0$
- Systematic study:
  1. find the orbits of Spin(1,4) on the spinor module Δ
  2. determine a standard representative for each orbit
  3. exploit invariance under LLT's to cast ϵ in standard form:

$$\exp\left\{\tfrac{1}{4}\lambda^{ab}(x)\gamma_{ab}\right\}\epsilon(x) = \epsilon^{\mathrm{std}}(x)$$

  4. choose a basis for spinor module: $\Delta = \mathrm{span}(\lambda_1, \lambda_2, \lambda_3, \lambda_4)$
  5. write down Killing equation in components:

$$0 = \left(\nabla\epsilon^{\mathrm{std}} +\right)\mathcal{O}\epsilon^{\mathrm{std}} = \sum_{i=1}^{4} C_i\lambda_i \quad \Rightarrow \quad C_i = 0$$

  6. study geometrical properties of 0-,1-,2-forms constructed out of the Killing spinor

Orbits and k-forms

- Standard representatives ($\psi = \sum_{i=1}^4 C_i\lambda_i \neq 0$):

$$q(\psi) := |C_1|^2 + |C_2|^2 - |C_3|^2 - |C_4|^2$$

$$\psi \sim \begin{cases} \sqrt{q(\psi)}\,\lambda_1 & \text{if } q(\psi) > 0 \\ \lambda_1 + \lambda_3 & \text{if } q(\psi) = 0 \\ \sqrt{-q(\psi)}\,\lambda_3 & \text{if } q(\psi) < 0 \end{cases}$$

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- Killing spinors to be studied

$$\epsilon^{\text{std}}(x) = e^{\phi(x)}\lambda_1 \ , \quad \epsilon(x)^{\text{std}} = e^{\phi(x)}\lambda_3 \ , \quad \epsilon(x)^{\text{std}} = \lambda_1 + \lambda_3$$

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- 0-,1-,2-forms out of spinor bilinears

$$\Omega^{ij}_{(0)} = \bar{\epsilon}^i \epsilon^j \ , \quad \Omega^{ij}_{(1)} = \bar{\epsilon}^i \gamma_\mu \epsilon^j \ dx^\mu \ , \quad \Omega^{ij}_{(2)} = \tfrac{1}{2}\ \bar{\epsilon}^i \gamma_{\mu\nu} \epsilon^j \ dx^\mu \wedge dx^\nu$$

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- real parametrization

$$i\Omega^{ij}_{(0)} = \epsilon^{ij} S\ , \quad i\Omega^{ij}_{(1)} = \epsilon^{ij} V\ , \quad [\Omega_{(2)}]^i{}_j = \sum_{k=1}^3 X^{(k)} [\sigma^{(k)}]^i{}_j$$

BPS conditions for $\epsilon^{\rm std} = e^{\phi}1$ and $\epsilon^{\rm std} = e^{\phi}e_1$

Killing spinor $\epsilon^{\rm std} = e^{\phi}1$:

- V^{μ} is Killing and timelike $\Rightarrow V^{\mu} = (\partial/\partial t)^{\mu}$
- $ds^2 = e^{4\phi}(dt+\omega)^2 - e^{-2\phi}ds_B^2$
- B is hyper-Kähler with self-dual curvature:

$$\hat{\nabla}\hat{J}^{(k)} = 0 \qquad \hat{J}^{(k)} \circ \hat{J}^{(\ell)} = -\delta^{k\ell}\mathbb{I} + \epsilon^{k\ell m}\hat{J}^{(m)}$$

$$\hat{*}\hat{\mathbf{\Omega}}^{i}{}_{j} = +\hat{\mathbf{\Omega}}^{i}{}_{j} \qquad \text{remark: } \mathrm{Ric} = 0$$

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Killing spinor $\epsilon^{\mathrm{std}} = e^{\phi}e_1$: as above, although

- opposite self-duality
- v, D, F^{I}_{0i} are given by different functions of ϕ, ω

BPS conditions for $\epsilon^{\mathrm{std}} = 1 + e_1$

Killing spinor $\epsilon^{\mathrm{std}} = 1 + e_1$;

- V^μ is Killing and lightlike $\Rightarrow V^\mu = (\partial/\partial v)^\mu$
- 2-forms $X^{(k)}$ are closed $\Rightarrow dX^{(k)} = du \wedge dx^k$
- $ds^2 = e^U(\mathcal{F}du^2 + 2dudv) - e^{-2U}(d\vec{x} + \vec{a}du)^2$
- v, D are given in terms of $U, \vec{a}$
- Bianchi identity

$$dF^I = 0 \;\Rightarrow\; \begin{cases} M^I = e^U H^I \quad \text{with} \quad \vec{\nabla}^2 H^I = 0 \\ F^I \text{ is fixed modulo a gradient in } \mathbb{R}^3 \end{cases}$$

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- Example: if $\epsilon^{\text{std}} = e^{\phi} 1$

$$\begin{aligned} \mathcal{E}(A)_I^0 - \mathcal{E}(M)_I &= 0 \\ \mathcal{E}(A)_I^i &= 0 \\ \nabla^i \mathcal{E}(D) - \tfrac{1}{4}\mathcal{E}(v)^{0i} - \mathcal{E}(D) v^{0i} &= 0 \\ \tfrac{1}{4}\mathcal{E}(v)^{(-)ij} + \mathcal{E}(D) v^{(-)ij} &= 0 \\ \mathcal{E}(g)_{00} = \mathcal{E}(g)_{0i} = \mathcal{E}(g)_{ij} &= 0 \quad (*) \end{aligned}$$

$(*) \equiv$ other bosons on-shell

Example: magnetic attractor ($\epsilon^{\rm std} = 1 + e_1$)

- Ansatz: $\vec{a} = 0$, $\mathcal{F} = 0$, $F^I_{+i} = 0$;
- Ansatz: no u-dependence; radial $\vec{x}$-dependence
- *Modified very special geometry constraint*

$$e^{-3U} = \frac{1}{3!} c_{IJK} H^I H^J H^K + \frac{c_{2I}}{24} \cdot \left[\frac{1}{2} U' H^{I\prime} + H^I \frac{1}{r^2} \left(r^2 U' \right)' \right]$$

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- Magnetic attractor: $H^I = \frac{p^I}{2r}$
- Geometry:

$$AdS_3 \times S^2 \text{ with } \ell_A = 2\ell_S \ \Rightarrow \ \text{maximal supersymmetry}$$

- Only non-vanishing components: $F^I_{\theta\phi}$ $\Rightarrow$ magnetic field
- Radius and charges

$$2\ell_S = \frac{1}{3!} c_{IJK} p^I p^J p^K + \frac{c_{2I}}{24} \cdot 2p^I$$

magnetic attractor $\equiv$ exact solution approximating near-horizon geometry of a magnetically chaged black string

Example: "small" magnetic string

$$2\ell_S = \frac{1}{3!} c_{IJK} p^I p^J p^K + \frac{c_{2I}}{24} \cdot 2p^I$$

- "Small" string $\rightarrow c_{IJK} p^I p^J p^K = 0$
- $c_{2I} = 0 \Rightarrow \ell_S = 0 \rightarrow$ degenerate horizon $\rightarrow$ naked singularity

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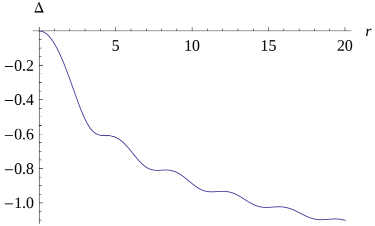
- $c_{2I} = 0 \Rightarrow \ell_S = 0 \rightarrow$ degenerate horizon $\rightarrow$ naked singularity
- $c_{2I} \neq 0 \Rightarrow \ell_S \neq 0 \rightarrow$ an interpolating solution exists

$$e^{-3U} \sim \begin{cases} (\ell_S/r)^3 e^{-6\Delta} & \text{if } r \ll p^1 \\ 1 + \frac{p^1}{2r} & \text{if } r \gg p^1 \end{cases}$$



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- Corrections smooth out singularity!

Conclusions & Perspectives

- Analysis of the most general supersymmetric solution:
  - off-shell formalism VS on-shell formalism
  - spinorial geometry techniques VS Fierz identities
  - supersymmetry constraints are independent of dynamics
  - can corrections smooth all singularities?

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  - off-shell formalism VS on-shell formalism
  - spinorial geometry techniques VS Fierz identities
  - supersymmetry constraints are independent of dynamics
  - can corrections smooth all singularities?
- Possible developments:
  - multiple Killing spinors $\rightarrow$ classification of solutions
  - computation of entropy corrections
  - gauged supergravity, AdS/CFT