Super Entropic Black Hole in 5d $U(1)^3$ Gauged Supergravity

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    - 4d Fayet-Iliopoulos gauged supergravities : non-compact event horizon of finite area [D.Klemm et al. 1311.1795]

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- Ultraspinning Black hole
- Thermodynamics in extended phase space

Ultraspinning Black Holes

- Stability of Myers-Perry black holes in the limit of large angular momentum [Emparan, Myeres, 2003]
- $a \to l$, keeping the physical mass M fixed. [Caldarelli et al. 2008]

- Hyperboloid membrane limit

Super-entropic limit

Ultraspinning limit technique which leads to super entropic black hole

$$[R.Hennigar, R.BMann, D.Kubiznak, 1411.4309]$$

Super Entropic limit

Super Entropic limit

- Kerr-AdS Black Hole (written in Asymptotic rotating frame)

$$ds^2 = -\frac{\Delta_a}{\Sigma_a}\left[dt - \frac{a\sin^2\theta}{\Xi}d\phi\right]^2 + \frac{\Sigma_a}{\Delta_a}dr^2 + \frac{\Sigma_a}{\Delta_\theta}d\theta^2 + \frac{\Delta_\theta\sin^2\theta}{\Sigma_a}\left[adt - \frac{r^2+a^2}{\Xi}d\phi\right]^2$$

$$\Xi = 1 - \frac{a^2}{l^2}, \qquad \Delta_\theta = 1 - \frac{a^2}{l^2}\cos^2\theta$$

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- Ultraspinning limit (speed of light $a \to l$)
  - i) Change coordinate $\phi \to \varphi = \frac{\phi}{\Xi}$
  - ii) $a \to l$

$$ds^2 = -\frac{\Delta_l}{\Sigma_l}\left[dt - l\sin^2\theta d\varphi\right]^2 + \frac{\Sigma_l}{\Delta_l}dr^2 + \frac{\Sigma_l}{\sin^2\theta}d\theta^2 + \frac{\sin^4\theta}{\Sigma_l}\left[ldt - (r^2+l^2)d\varphi\right]^2$$

  - iii) Compactify new coordinate $\varphi \to \varphi + \mu$

Horizon of obtained geometry

- Let us consider the geometry of constant (t, r) surfaces

$$ds_h^2 = \frac{r_+^2 + l^2\cos^2\theta}{\sin^2\theta} d\theta^2 + \frac{l^2\sin^4\theta}{r_+^2 + l^2\cos^2\theta} d\varphi^2.$$

- This metric appears to be ill-defined for $\theta = 0, \pi$

$$k = l(1 - \cos\theta)$$

- Obtained horizon metric for small k

$$ds_h^2 = (r_+^2 + l^2)\left[\frac{dk^2}{4k^2} + \frac{4k^2}{l^2} d\varphi^2\right]$$

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- A metric of constant negative curvature on a hyperbolic space $\mathcal{H}^2$
- ***Horizon is non-compact.***

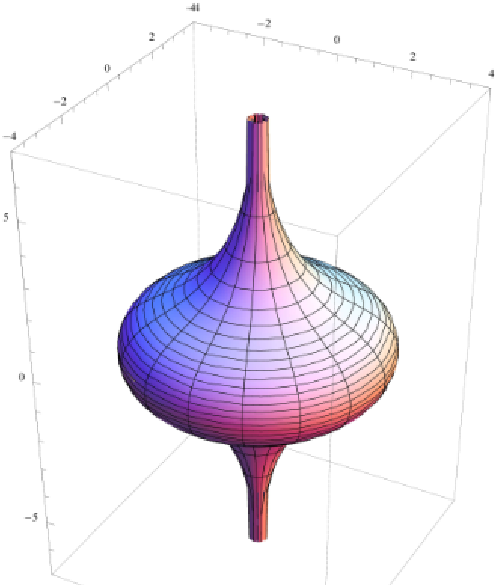
Visualize the horizon

- $A = 2\mu(l^2 + r_+^2)$
- $V = \frac{r_+ A}{3}$
- $M = \frac{\mu m}{2\pi}$
- $J = Ml$
- $\Omega = \frac{l}{r_+^2 + l^2}$

- The isoperimetric ratio

$$\mathcal{R} = \left(\frac{r_+^2}{r_+^2 + l^2}\right)^{1/6} < 1$$

- is ***super-entropic*** BH.



Thermodynamics in extended phase space

Extended phase space

- Cosmological constant Λ identified with the thermodynamic pressure

$$P = \frac{1}{8\pi}\Lambda = \frac{(d-1)(d-2)}{16\pi l^2} = < \chi >$$

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- AdS/CFT : $R = \sqrt{-6/\Lambda}$, $(R/l_s)^4 = g_{YM}^2 N$
- Extended first law of BH thermodynamics

$$\partial M = T\partial S + \sum_i \Omega_i \partial J_i + \sum_j \Phi_j \partial Q_j + \Theta d\Lambda$$

- M is now the enthalpy of the spacetime.
- Θ is thermodynamic conjugate of Λ

$$\partial M = T\partial S + \sum \Omega_i \partial J_i + \sum \Phi_j \partial Q_j + V dP$$

Thermodynamic Volume

- V is an effective volume given by Θ. $V = -\frac{16\pi}{D-2}\Theta$
- Θ is the boundary integrals of the ***Killing potential*** at ***infinity*** and the ***Killing potential*** at the ***horizon***.
- $\Theta = V_{BH} - V_{AdS}$, (***finite*** and ***negative***.)
- $V = -\Theta$ gives a measure of the volume excluded from the spacetime by the black hole horizon.

- In Euclidean (D-1) Space

$$R \equiv \left(\frac{(D-1)V^{\frac{1}{D-1}}}{\omega_{D-2}}\right)^{\frac{1}{D-1}} \left(\frac{\omega_{D-2}}{A}\right)^{\frac{1}{D-2}} \leq 1$$

- For a wide variety of BH's $R \geq 1$. (M. Cvetic, G.W. Gibbons et al. 2011)
- ***Some Ultraspinning solution :*** $R \leq 1$
- Such black holes are ***Super-entropic***

$5d$ gauged supergravity

The particular class of black holes considered here are solutions to the $U(1)^3$ $5d$ gauged supergravity whose bosonic action is

$$e^{-1}L = R - \frac{1}{2}\partial\vec{\phi}^2 - \frac{1}{4}\sum_{i=1}^{3} X_i^{-2}(F^i)^2 + \frac{4}{l^2}\sum_{i=1}^{3} X_i^{-1} + \frac{1}{24}\epsilon_{ijk}\epsilon^{\mu\nu\rho\sigma\lambda}F^i_{\mu\nu}F^j_{\rho\sigma}A^k_{\lambda},$$

$$X_1 = e^{-\frac{1}{\sqrt{6}}\phi_1 - \frac{1}{\sqrt{2}}\phi_2}, X_2 = e^{-\frac{1}{\sqrt{6}}\phi_1 + \frac{1}{\sqrt{2}}\phi_2}, X_3 = e^{\frac{2}{\sqrt{6}}\phi_1} \quad (1)$$

- Its most general asymptotically AdS_5 BH's Solution form a six parameter family of solutions.
- We consider the 5 parameter subclass: ***two spins, mass and two equal electric charge*** with the third charge a function of the remaining charges.
- These solutions were first constructed in [arXiv:hep-th/0505112]

5d Gauged supergravity

Metric

$$ds^2 = H^{-\frac{4}{3}}\Big[-\frac{X}{\rho^2}(dt - a\sin^2\theta\frac{d\phi}{\Xi_a} - b\cos^2\theta\frac{d\psi}{\Xi_b})^2$$

$$+\frac{C}{\rho^2}(\frac{ab}{f_3}dt - \frac{b}{f_2}\sin^2\theta\frac{d\phi}{\Xi_a} - \frac{a}{f_1}\cos^2\theta\frac{d\psi}{\Xi_b})^2 + \frac{Z\sin^2\theta}{\rho^2}(\frac{a}{f_3}dt - \frac{1}{f_2}\frac{d\phi}{\Xi_a})^2$$

$$+\frac{W\cos^2\theta}{\rho^2}(\frac{b}{f_3}dt - \frac{a}{f_1}\frac{d\psi}{\Xi_b})^2\Big] + H^{\frac{2}{3}}(\frac{\rho^2}{X}dr^2 + \frac{\rho^2}{\Delta_\theta}d\theta^2)$$

$$\Xi_a = 1 - \frac{a^2}{l^2}, \qquad \Xi_b = 1 - \frac{b^2}{l^2}, \qquad \Delta_\theta = 1 - \frac{a^2}{l^2}\cos^2\theta - \frac{b^2}{l^2}\sin^2\theta,$$

$$A^1 = A^2 = \frac{\sqrt{q^2 + 2mq}}{\tilde{\rho^2}}\left(dt - a\sin^2\theta\frac{d\phi}{\Xi_a} - \cos^2\theta\frac{d\psi}{\Xi_b}\right),$$

$$A^3 = \frac{q}{\rho^2}(b\sin^2\theta\frac{d\phi}{\Xi_a} + a\cos^2\theta\frac{d\psi}{\Xi_b})$$

Ultra-Spinning limit $a \to l$

$$ds^2 = H^{-\frac{4}{3}} \Big[-\frac{X}{\rho^2}(dt - a\sin^2\theta \frac{d\phi}{\Xi_a} - b\cos^2\theta \frac{d\psi}{\Xi_b})^2$$

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New ultraSpinning limit

- Is written in the asymptotic rotating frame, $\Omega_\infty = -a/l^2$
- i) Change coordinate $\phi \to \varphi = \frac{\phi}{\Xi_a}$
- ii) $a \to l$
- iii) $\varphi \sim \varphi + \mu$

Obtained geometry

New rotating BH solution

$$ds^2 = \tilde{H}^{-\frac{4}{3}}\Big[-\frac{\tilde{X}}{\rho^2}(dt - l\sin^2\theta d\varphi - b\cos^2\theta\frac{d\psi}{\Xi_b})^2$$

$$+\frac{\tilde{C}}{\rho^2}(\frac{lb}{\tilde{f}_3}dt - \frac{b}{\tilde{f}_2}\sin^2\theta d\varphi - \frac{l}{\tilde{f}_1}\cos^2\theta\frac{d\psi}{\Xi_b})^2 + \frac{\tilde{Z}\sin^2\theta}{\rho^2}(\frac{l}{\tilde{f}_3}dt - \frac{1}{\tilde{f}_2}d\varphi)^2$$

$$+\frac{\tilde{W}\cos^2\theta}{\rho^2}(\frac{b}{\tilde{f}_3}dt - \frac{l}{\tilde{f}_1}\frac{d\psi}{\Xi_b})^2\Big] + H_s^{\frac{2}{3}}(\frac{\rho^2}{\tilde{X}}dr^2 + \frac{\rho^2}{\Xi_b\sin^2\theta}d\theta^2),$$

$$\Xi_b = 1 - \frac{b^2}{l^2}, \qquad \rho^2 = r^2 + l^2\cos^2\theta + b^2\sin^2\theta,$$

- The super-entropic limit in ψ direction (instead of ϕ) would be analogous.
- It is not possible to take successively super-entropic limits in several directions.

Horizon Topology

$$ds_h^2 = \tilde{H}^{-\frac{4}{3}}\left[\frac{\tilde{C}}{\rho^2}(\frac{b}{\tilde{f}_2}\sin^2\theta d\varphi + \frac{l}{\tilde{f}_1}\cos^2\theta\frac{d\psi}{\Xi_b})^2 + \frac{\tilde{Z}\sin^2\theta}{\rho^2}\frac{1}{\tilde{f}_2^{\,2}}d\varphi^2\right.$$

$$\left.+\frac{\tilde{W}\cos^2\theta}{\rho^2}(\frac{l}{\tilde{f}_1}\frac{d\psi}{\Xi_b})^2\right] + \tilde{H}^{\frac{2}{3}}\frac{\rho^2}{\Xi_b\sin^2\theta}d\theta^2,$$

- $0 \leq \theta \leq \pi/2$
- It seems metric to be ill-defined for $\theta = 0$,
- Let us examine metric in the small θ, or $k = l(1-\cos\theta)$ for small k

$$ds_h^2 = \frac{\rho_+}{\Xi_b}\left[\frac{dk^2}{4k^2} + 4k^2\mathcal{O}_1 d\varphi^2 + k\mathcal{O}_2 d\varphi d\psi\right] + \frac{2m}{\rho_+^2\Xi_b}d\psi^2$$

Constant negative curvature on a hyperbolic space $\mathbb{H}^2$, ($\psi = const.$)

$$ds_h^2 = \frac{\rho_+}{\Xi_b}\left[\frac{dk^2}{4k^2} + 4k^2\Theta_1 d\varphi^2\right]$$

Non-Compact horizon with finite area

Horizon

- $ds_h^2 = \frac{\rho_+}{\Xi_b}\left[\frac{dk^2}{4k^2} + 4k^2\mathcal{O}_1 d\varphi^2\right]$
- Entropy $S_{BH} = \frac{\mu\pi[(r_+^2+l^2)(r_+^2+b^2)+qr_+^2]}{4r_+\Xi_b}$

Conformal boundary

- conformal factor : l^2/r^2

$$ds_{bdry}^2 = -dt^2 - l\sin^2\Theta dtd\varphi - \frac{b\cos^2\theta}{\Xi_b}dtd\psi$$
$$+\frac{l^2\cos^2\theta}{\Xi_b}d\psi^2 + \frac{bl\sin 2\theta}{\Xi_b}d\psi + d\varphi + \frac{l^2}{\Xi_b\sin^2\theta}d\theta.$$

- $k = l(1-\cos\theta)$, the small k limit :

$$-dt^2 - 4kdtd\varphi + \frac{l^3}{4k^2\Xi_b}dk^2,$$

AdS_3 written as a Hopf-like fibration over $\mathbb{H}$

Conserved charges

- Angular momenta

$$J = \frac{1}{16\pi}\int_{s^3} *dK,$$

On Killing vector $\partial\varphi, \quad \partial\psi$

$$J_\varphi = \frac{\mu l(2m + q\Xi_b)}{4\Xi_b}, \qquad J_\psi = \frac{\mu b(2m+q)}{4\Xi_b^2}$$

- Total electric charges are given by Gaussian integrals

$$Q = \frac{1}{16\pi}\int_{s^3} X_i^{-2} * F^i - \frac{1}{2}\epsilon_{ijk}A^j \wedge A^k,$$

$$Q_1 = Q_2 = \frac{\mu\sqrt{q^2+2mq}}{8\Xi_b}, \qquad Q_3 = -\frac{\mu lbq}{8l^2\Xi_b}$$

- Mass

$$E = \frac{\mu[2m(2+\Xi_b) + q(2+\Xi_b^2+\Xi_b)]}{16\Xi_b^2},$$

Thermdynamics Quantities

- Temperature

$$T_H = \frac{2r_+^6 + r_+^4(2l^2 + b^2 + 2q) - b^2 l^4}{2\pi r_+ l^2[(r_+^2 + l^2)(r_+^2 + b^2) + q r_+^2]},$$

- Angular velocities

$$\Omega_a = \frac{l(b^2 + r_+^2)}{b^2(l^2 + r_+^2) + r^2(l^2 + r_+^+ q)}, \qquad \Omega_b = \frac{b(r_+^4 + 2r_+^2 l^2 + r_+^2 q + l^4)}{l^2(r_+^2 + l^2)(r_+^2 + b^2) + q l^2 r_+^2},$$

- Electrostatic potentials

$$\Phi_1 = \Phi_2 = \frac{r_+^2\sqrt{q^2 + 2mq}}{(l^2 + r_+^2)(b^2 + r_+^2) + q r_+^2}, \qquad \Phi_3 = \frac{qlb}{(l^2 + r_+^2)(b^2 + r_+^2) + q r_+^2}$$

- Entropy

$$S_{BH} = \frac{\mu\pi[(r_+^2 + l^2)(r_+^2 + b^2) + q r_+^2]}{4 r_+ \Xi_b}$$

Thermodynamics in extended phase space

$$\partial M = T\partial S + \sum_i \Omega_i \partial J_i + \sum_j \Phi_j \partial Q_j + VdP$$

Thermodynamic volume

$$V = \frac{\mu\pi}{12 l^2 r_+^2 \Xi_b^2}\Big[b^4(l^2 - 2r_+^2)(l^2 + r_+^2) - 2b^2 r_+^2 (r_+^4 + q r_+^2 - 2l^4 - l^2 r_+^2) + l^2 r_+^2 (q^2 + 4q r_+^2 + 3r_+^2(l^2 + r_+^2))\Big]$$

All thermodynamic quantities satisfy both the first law and the Smarr relation.

$$\frac{D-3}{D-2}M = TS + \sum_i \Omega_i J_i + \frac{D-3}{D-2}\Phi Q - \frac{2}{D-2}VP$$

Isoperimetric inequality

$$SuperEntropicBH \quad \mathcal{R} \equiv \left(\frac{(D-1)V^{\frac{1}{D-1}}}{\omega_{D-2}} \right)^{\frac{1}{D-1}} \left(\frac{\omega_{D-2}}{A} \right)^{\frac{1}{D-2}} < 1$$

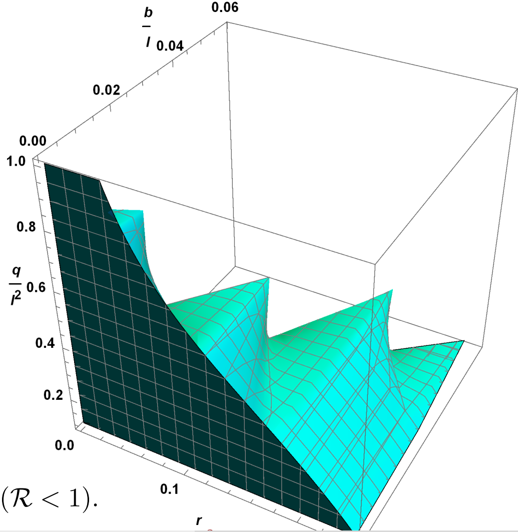
$$\omega_d = \frac{\mu \pi^{\frac{d-1}{2}}}{\Gamma(\frac{d+1}{2})}$$

Isoperimetric inequality for our obtained BH

$$\mathcal{R} = \frac{\mathcal{O}_1 \left(\frac{(l^2 - 2r_+^2)\rho^2 - \mathcal{O}_2}{r_+^2 \Xi_b^2} \right)^{1/4}}{\left(\frac{q r_+^2 + (b^2 + r_+^2)\rho^2}{r_+ \Xi_b} \right)^3} < 1$$

$$\mathcal{O}_1 = (\frac{1}{3})^{1/4} (\frac{\mu\pi}{4})^{2/3}$$

$$T_H >= 0$$



There is a range of parameters that ($\mathcal{R} < 1$).

Extrimality under supre-entropic limit

Extrimality under Supere-entropic limit

Kerr-AdS Black Hole

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A: i)Ex. ii)SE.

- Extrimality condition ($T_H = 0$)

$$m = -\sqrt{3/2}\frac{a^2(10l^2+\delta_0) - a^4 - l^2(1-\delta_0)}{9l^2\delta_0}, \qquad \delta_0 = \sqrt{a^4 + 14a^2l^2 + l^4}$$

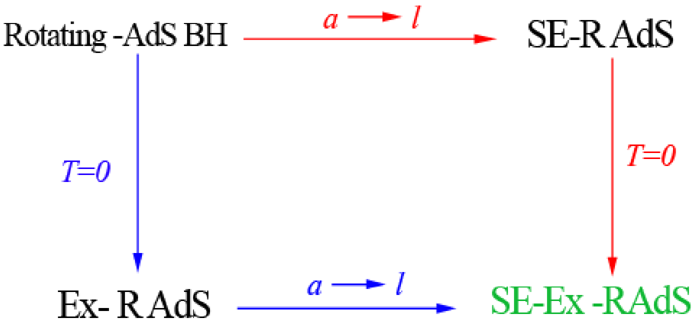
- SE. limit: $a \to l \qquad \longrightarrow m = \frac{8l}{3\sqrt{3}}$

B: i)SE. ii)Ex.

- SE. limit $a \to l \qquad \longrightarrow T_H = \frac{1}{r\pi r_+}\left(3\frac{r_+^2}{l^2} - 1 - \frac{q^2}{l^2+r_+^2}\right)$
- Extrimality condition ($T_H = 0$) $\longrightarrow m = \frac{8l}{3\sqrt{3}}$

Extrimality under Supere entropic limit

- Kerr-Newmann-Ads BH
- 5d Myers-Perry BH
- Minimal gauged supergravity
- 5d $U(1)^3$ gauged supergravity



BPS limit under supre-entropic limit

BPS limit under ultraspinning

The BPS limit can be found by looking at the eigenvalues of the Bogomol'nyi matrix coming from the anticommutators of the supercharges of the AdS superalgebraas.

5d Minial gauged supergravity

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$E + J_a/l + J_b/l - \sqrt{3}Q = 0,$ [hep-th/0504080]

- $A :$ i) BPS limit, ii) $a \to l$ $q = \frac{lm}{2l+b}$

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- $B:$ i) $a \to l$ ii) BPS limit , $q = \frac{ml(l-b)}{b^2+3bl+4l^2}$

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5d $U(1)^3$ gauged supergravity

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5d $U(1)^3$ gauged supergravity

$E + J_a/l + J_b/l - \sum_i Q_i = 0,$

- $A :$ i) BPS limit, ii) $a \to l$ $q = \frac{l^2 m}{(l^2-b^2)}$
- $B :$ i) $a \to l$ ii) BPS limit $q = m\frac{2(l^2(3l-b)+\delta_1)^2}{\delta_2(\delta_2+2l^2(b-3l)-2\delta_1)}$

$$\delta_1 = (b-l)^2 l^2 \sqrt{9b^2 - 12bl - l^2}, \qquad \delta_2 = 3b^3 - 5b^2 l + 2bl^2 + 2l^3$$

Summary

- We find a new super entropic BH solution in 5d $U(1)^3$ gauged supergravity
- The horizon of obtained BH is non-compact with finit area
- We finde some region in parameter space that leads to Super entropic

- Extrimality condition preserve under ultraspinning limit
- BPS limit deos not commute with ultraspinning limit. They lead to two different new black hole solutions

Thank you for your attention