Black lenses

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Black holes in five dimensions

- String theoretic derivation of $S_{BH} = \frac{A}{4G}$ [Strominger, Vafa '96, ...]
  $D = 5$, asympt. flat, *supersymmetric* black holes: D1-D5 CFT

- Black hole non-uniqueness: S^3 black hole [Myers, Perry '86], $S^1 \times S^2$ black ring [Emparan, Reall '01]. What else?

  Open problem: classification of $D = 5$ *asymptotically flat*, stationary black hole solutions to Einstein equations.

- Horizon topology thrm [Galloway, Schoen '05]: $S^3, S^1 \times S^2, S^3/\Gamma$
  DOC topology: $H_2 \neq 0$ possible, e.g. solitons [Bena, Warner '05]

  But which topologies are actually realised?

$D = 5$, $U(1)^3$-supergravity

- Susy solutions [Gauntlett et al '02]. Time-like fibration over

$$ds^2_{\text{Gibbons-Hawking}} = H^{-1}(d\psi + \chi)^2 + H dx^i dx^i$$

$d\chi = \star_{\mathbb{R}^3} dH$. Full solution given by further 7 harmonic fns.

- Asympt flat $|x| \to \infty$: $H \to \frac{1}{|x|}$, $\chi \to \cos\theta d\phi$, $\psi \sim \psi + 4\pi$.
  - S^3 [BMPV '96], $S^1 \times S^2$ [Elvang et al '04; Bena Warner '04]: $H = \frac{1}{|x|}$, $|x| = 0$ regular event horizon
  - Smooth solitons [Bena, Warner '05], multi-centred solutions: $H = \frac{1}{|x|} - \frac{1}{|x-x_1|} + \frac{1}{|x-x_2|} + \dots$ 'centres' are points in $\mathbb{R}^4$

- Any other asymptotically flat (single) susy black holes?

Black lens [Kunduri, JL '14, '16]

- $H = \frac{2}{|x|} - \frac{1}{|x - x_1|}$. Can fix constants to ensure solution is asymptotically flat, smooth and CTC-free for $|x| > 0$.

- Regular event horizon $|x| = 0$. $H \sim \frac{2}{|x|}$, $\chi \sim 2 \cos\theta \mathrm{d}\phi$,

$$\mathrm{d}s^2_{\text{horizon}} = c_1 \left(\mathrm{d}\psi + 2\cos\theta \mathrm{d}\phi\right)^2 + c_2 \, \mathrm{d}\Omega_2^2$$

Near-horizon geometry locally of BMPV black hole [Reall '02].

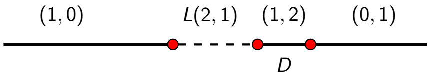
But *not* globally! $\psi \sim \psi + 4\pi \implies$ horizon is lens space

$$H \cong S^3/\mathbb{Z}_2 \cong \mathbb{R}P^3 \cong L(2,1)$$

First example of a regular asymptotically flat black hole solution with lens space horizon topology!

Black lens [Kunduri, JL '14, '16]

- 7-parameters: electric charges Q_i, angular momenta J_ψ, J_ϕ, magnetic dipoles q_i, constraint $J_\psi - J_\phi = q_i(Q_i - |\epsilon_{ijk}| q_j q_k)$
- Unequal J_i wrt orthogonal 2-planes (as for black ring) $\Longrightarrow$ no overlap with BMPV black hole
- Non-contractible disc D, end on horizon. Magnetic flux $\int_D F$. Equipotential surface D defines q_i [Kunduri, JL '13]



- Evades uniqueness theorem for locally S^3 horizon [Reall '02]: $\partial/\partial t$ not strictly timelike in DOC, null on 'ergosurfaces'

Black lenses in string theory [Kunduri, JL '16]

- IIB sugra uplift $S^1 \times T^4$: $\frac{1}{8}$-BPS black D1-D5-P solution

  Brane number/fluxes and momentum units $N_1, N_5, N_{\mathrm{P}} \sim Q_{1,2,3}$
  Quantized dipoles $n_1, n_5, n_{\mathrm{KK}} \sim q_{1,2,3}$. (KK-fibre $\implies n_{\mathrm{KK}} \in \mathbb{Z}$)

  Constraint: $J_\psi - J_\phi = n_1 N_5 + n_5 N_1 + n_{\mathrm{KK}} N_{\mathrm{P}} - 4 n_1 n_5 n_{\mathrm{KK}}$

  Entropy: [cf. BMPV $J_\phi = 0$, $S_{BH} = 2\pi\sqrt{N_1 N_5 N_{\mathrm{P}} - J_\psi^2}$]

$$S_{BH} = 2\pi\sqrt{2(N_1 - 2n_1 n_{\mathrm{KK}})(N_5 - 2n_5 n_{\mathrm{KK}})(N_{\mathrm{P}} - 2n_1 n_5) - (J_\psi + J_\phi - 4n_1 n_5 n_{\mathrm{KK}})^2}$$

  Microscopic derivation?

- **Decoupling limit**: asympt *global* $\mathrm{AdS}_3 \times S^3 \times T^4$,
  near-horizon *locally* $\mathrm{AdS}_3 \times S^3 \times T^4$, *not* a product in bulk

  $\mathrm{AdS}_3/\mathrm{CFT}_{\mathrm{UV}}$ ($c = \frac{3\ell_{\mathrm{UV}}}{2G_3} = 6N_1 N_5$) need KK modes on S^3
  [Skenderis, Taylor '08]

Near-horizon CFT [Kunduri, JL '16]

- **Near-horizon limit**: $L(2,1) \times T^4$ twisted over near-horizon geometry of extreme BTZ black hole
- Dimensionally reduce on $L(2,1) \times T^4$ to AdS$_3$-Einstein gravity. Central charge of near-horizon AdS$_3$:

$$\boxed{c = \frac{3\ell_{\text{IR}}}{2G_3} = 12(N_1 - 2n_1 n_{\text{KK}})(N_5 - 2n_5 n_{\text{KK}})}$$

$L_0 = \ell M \sim r_+^2$ deduced from horizon geometry:

$$L_0 = N_{\text{P}} - n_1 n_5 - \frac{(J_\psi + J_\phi - 4n_1 n_5 n_{\text{KK}})^2}{2(N_1 - 2n_1 n_{\text{KK}})(N_5 - 2n_5 n_{\text{KK}})}$$

$S_{\text{Cardy}} = 2\pi\sqrt{\frac{cL_0}{6}} = S_{BH} \implies$ CFT$_{\text{IR}}$ accounts for entropy!

(Appears to be not the case for black rings [Elvang et al '04])

Summary and future directions

- Asymptotically flat black holes with **lens space** topology exist!

  Non-extremal black lens? Vacuum black lens?

- **Entropy** accounted for by IR CFT of D1-D5-P system

  D1-D5 CFT description of black lenses?

- **Classification** of asymptotically flat $D = 5$ BPS black holes?

  $L(p, q)$ horizons ($q = 1$ [Tomizawa, Nozawa '16]),
  $H_2(DOC) \neq 0$ (see Kunduri talk)...

  Very rich moduli space expected!