Black Holes in Higher Dimensions

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RESEARCH TRAINING GROUP Models of Gravity

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641. WE-Heraeus-Seminar

“Do Black Holes Exist? The Physics and Philosophy of Black Holes”

Bad Honnef

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Outline

1. Introduction
2. Vacuum Black Objects
   - Black Holes and Black Rings in $D = 5$
   - Black Holes and Black Rings in $D \geq 6$
   - Black Holes and Black Ringoids in $D \geq 7$
3. Adding Charge
4. Conclusions and Outlook

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Einstein–Maxwell Black Holes: $D = 4$

static spherically symmetric	Schwarzschild Reissner-Nordström	M M, Q
rotating axially symmetric	Kerr Kerr–Newman	M, J M, J, Q

- uniqueness

  black holes are uniquely determined by their mass M, angular momentum J, charges Q and P
- horizon topology

  black hole horizons have spherical topology
- staticity

  stationary black holes with non-rotating horizon are static
- ...

Generalization of $D = 4$ Black Holes: $D > 4$

Myers and Perry, Ann. Phys. (N.Y.) 172 (1986) 304

	static	rotating
$D = 4$	Schwarzschild (M)	Kerr (M, J)
$D > 4$	Tangherlini (M)	Myers-Perry $(M, J_1, ..., J_N)$

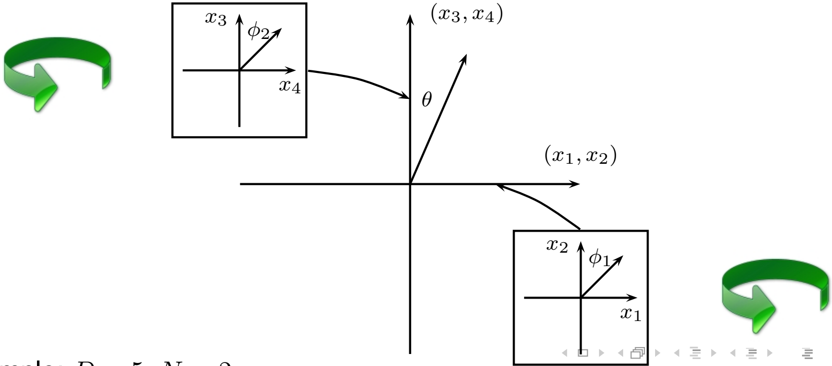
Myers-Perry Black Holes

Myers and Perry 1986

D: dimension of space-time

N: number of independent angular momenta J_i: $\quad N \equiv \left\lfloor \frac{D-1}{2} \right\rfloor$

N: number of independent planes



example: $D = 5$, $N = 2$

Myers-Perry Black Holes

metric

$$ds^2_{D,\mathrm{MP}} = -dt^2 + \frac{\Pi F}{\Pi - mr^{2-\varepsilon}} dr^2 + \sum_{i=1}^{N} (r^2 + a_i^2)(d\mu_i^2 + \mu_i^2 d\varphi_i^2)$$
$$+ \frac{mr^{2-\varepsilon}}{\Pi F} \left(dt - \sum_{i=1}^{N} a_i \mu_i^2 d\varphi_i \right)^2 + \varepsilon r^2 d\nu^2$$

$$F \equiv 1 - \sum_{i=1}^{N} \frac{a_i^2 \mu_i^2}{r^2 + a_i^2} \,, \quad \Pi = \prod_{i=1}^{N} (r^2 + a_i^2)$$

constraint

$$\sum_{i=1}^{N} \mu_i^2 + \varepsilon \nu^2 = 1$$

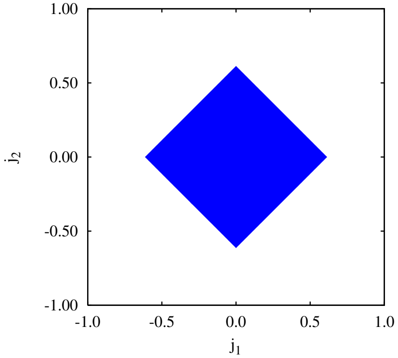
coordinate ν enters only in even dimensions: odd D : $\varepsilon = 0$

even D : $\varepsilon = 1$

mass M and angular momenta J_i:

$$M = m\,(1 + (D-3))\,A(S^{D-2})$$
$$J_i = 2m\,a_i A(S^{D-2})\,, \qquad i = 1, \dots, N$$

Myers-Perry Black Holes: Domain of Existence

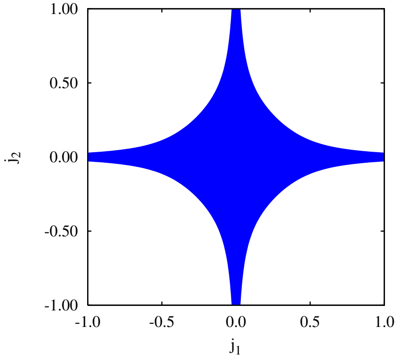


scaled angular momenta

$$j_1 = J_1/M^{(D-2)/(D-3)}$$
$$j_2 = J_2/M^{(D-2)/(D-3)}$$

- $D = 5$:
  - domain of existence is bounded

Myers-Perry Black Holes: Domain of Existence



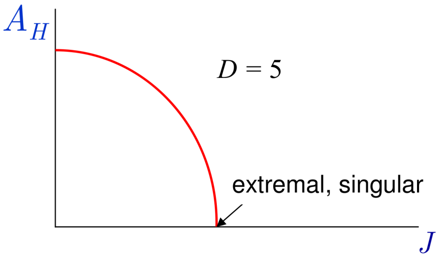
scaled angular momenta

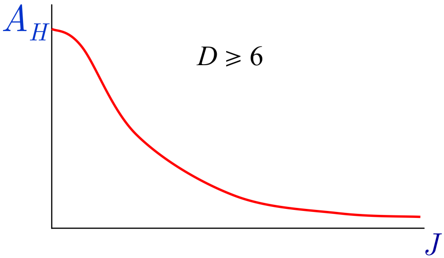
$$j_1 = J_1/M^{(D-2)/(D-3)}$$
$$j_2 = J_2/M^{(D-2)/(D-3)}$$

- $D = 5$:
  - domain of existence is bounded
- $D = 6$:
  - domain of existence is unbounded on axes:
    for $J_1 = J,\, J_2 = 0$
    for $J_1 = 0,\, J_2 = J$

Myers-Perry Black Holes: Domain of Existence

single angular momentum $J_1 = J$ $(J_i = 0,\, i > 1)$

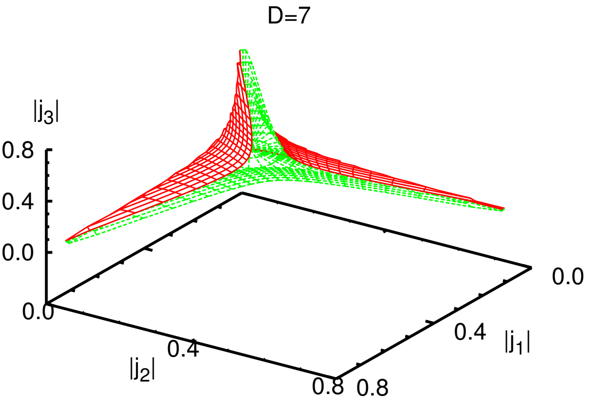




scaled horizon area A_H versus scaled angular momentum J

- $D = 5$: $J_1 = J$, $J_2 = 0$: domain bounded, singular extremal limit
- $D \geq 6$: $J_1 = J$, $J_i = 0$, $i > 1$: domain unbounded

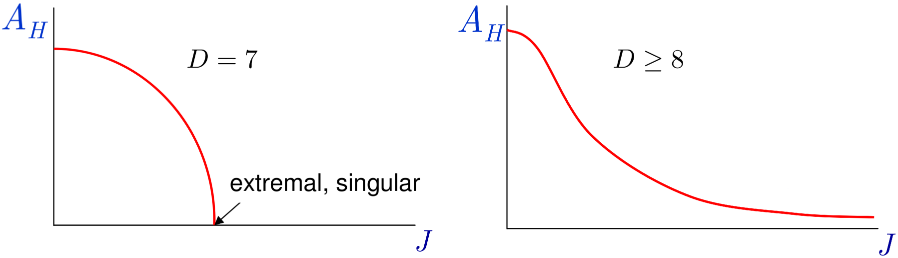
Myers-Perry Black Holes: Domain of Existence



- $J_1 = J_2 = J, J_3 = 0$: domain bounded, singular extremal limit
- $J_1 = J_2 = 0, J_3 = J$: domain unbounded

Myers-Perry Black Holes: Domain of Existence

two equal magnitude angular momenta $J_1 = J_2 = J$ $(J_i = 0,\, i > 2)$



scaled horizon area A_H versus scaled angular momentum J

- $D = 7$: $J_1 = J_2 = J$, $J_3 = 0$: domain bounded, singular extremal limit
- $D \geq 8$: $J_1 = J_2 = J$, $J_i = 0$, $i > 2$: domain unbounded

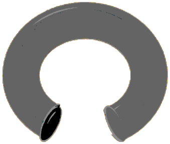
Black Rings and Further Beasts?

Myers and Perry, Ann. Phys. (N.Y.) 172 (1986) 304

‘construction’ of black rings:

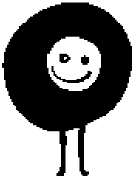
1. take a piece of black string

2. bend it



3. glue endpoints

Black Rings and Further Beasts?



e.g. Black Ringoids

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Black Rings in $D = 5$: Physical Picture

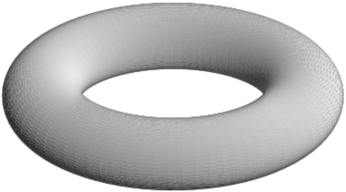
Emparan and Reall, PRD65 (2002) 084025, PRL 88 (2002) 101101

black rings

horizon topology $S^1 \times S^2$

static black rings

- attraction:
  gravity/string tension
  shrink rings
- repulsion:
  conical singularity
  inside: push
  outside: pull
- unbalanced black rings

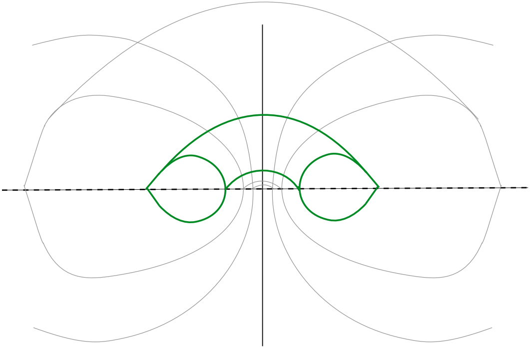


- attraction:
  gravity/string tension
- repulsion:
  rotation along S^1
  centrifugal force
- balanced black rings

Black Rings in $D = 5$: Physical Picture

Emparan and Reall, PRD65 (2002) 084025, PRL 88 (2002) 101101

static black ring: string pulling from outside the ring (shown: deficit)

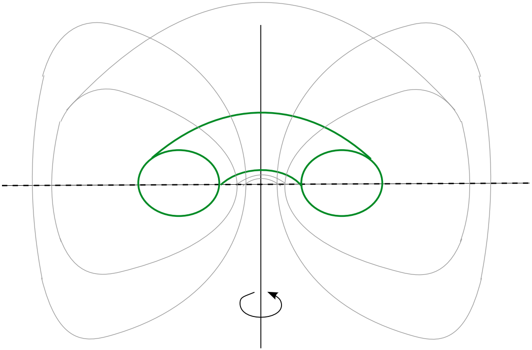


static black ring: strut pushing from inside the ring (not shown: excess)

Black Rings in $D = 5$: Physical Picture

Emparan and Reall, PRD65 (2002) 084025, PRL 88 (2002) 101101

rotating black ring:

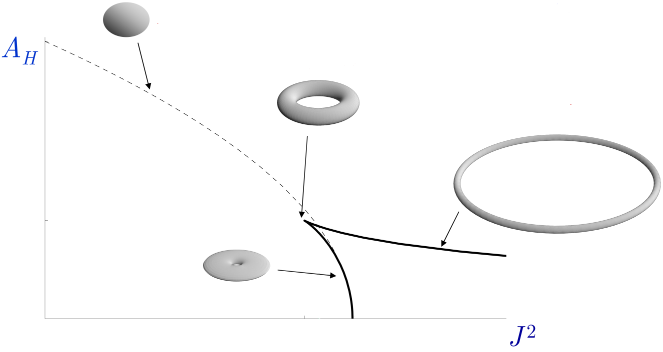


no conical singularity: appropriate horizon velocity

Black Rings in $D = 5$: Physical Picture

Emparan and Reall, PRD65 (2002) 084025, PRL 88 (2002) 101101

phase diagram: domain of existence



horizon area A_H vs. angular momentum J^2 at fixed mass

- black holes S^3
  maximal J
- black rings $S^1 \times S^2$
  minimal J
- nonuniqueness
  region with
  - MP black holes
  - fat black rings
  - thin black rings

Black Rings in $D = 5$: A Coordinate Choice

a parametrization of $4-$dimensional Euclidean space

$$ds^2 = d\rho^2 + \rho^2(d\Theta^2 + \cos^2\Theta d\phi^2 + \sin^2\Theta d\psi^2)$$

coordinate transformation

$$\rho = r\sqrt{U},\ \tan\Theta = \left(\frac{r^2+\rho^2+R^2}{r^2+\rho^2-R^2}\right)\tan\theta,$$

$$U = \sqrt{1 + \frac{R^4}{r^4} - \frac{2R^2}{r^2}\cos 2\theta}$$

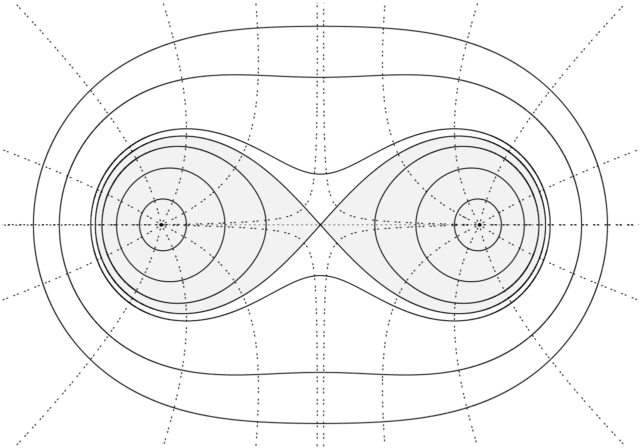
new metric

$$ds^2 = V_1(dr^2 + r^2 d\theta^2) + V_2 d\phi^2 + V_3 d\psi^2,$$

$$V_1 = \frac{1}{U},\ \ V_2 = r^2\left[\cos^2\theta - \frac{1}{2}(1+\frac{R^2}{r^2} - U)\right],\ \ V_3 = r^2\left[\sin^2\theta - \frac{1}{2}(1-\frac{R^2}{r^2} - U)\right],$$

$0 \le r < \infty$, $0 \le \theta \le \pi/2$, $0 \le \phi \le 2\pi$, $0 \le \psi \le 2\pi$, $R > 0$

Black Rings in $D = 5$: A Coordinate Choice



for $0 < r < R$: a surface of constant r has ring-like topology

Black Rings in $D = 5$: A Coordinate Choice

Euclidean metric

$$ds^2 = V_1(dr^2 + r^2 d\theta^2) + V_2 d\phi^2 + V_3 d\psi^2,$$

new metric ansatz for black rings

$$ds^2 = f_1(r,\theta)(dr^2 + r^2 d\theta^2) + f_2(r,\theta) d\phi^2 + f_3(r,\theta)(d\psi - W(r,\theta)dt)^2 - f_0(r,\theta) dt^2$$

- Emparan Reall solution can be expressed explicitly in these coordinates
- metric is well suited for numerical calculations
- new metric is easily generalized to more than 5 dimensions

Black Rings in $D = 5$: A Coordinate Choice

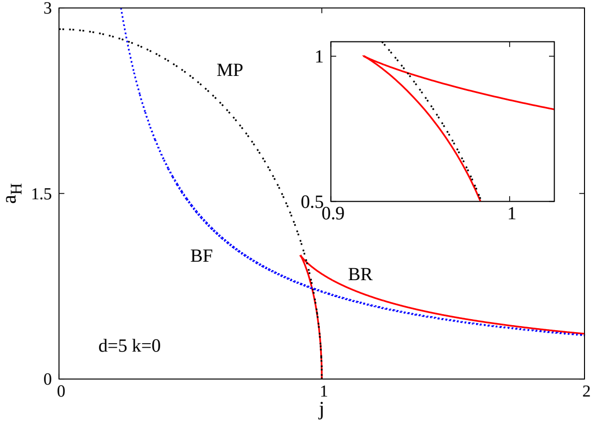
numerical schemes

- finite difference solver
- spectral solver

R	Ω_H	$M(num)$	$M(ex)$	$\|J(num)\|$	$\|J(ex)\|$	$A_H(num)$	$A_H(ex)$
1.61803	0.182574	24.0003	24.0000	109.547	109.545	773.616	773.605
1.93186	0.204124	16.0000	16.0000	58.7880	58.7878	446.647	446.645
2.18890	0.207020	13.3332	13.3333	45.0836	45.0843	332.911	332.909
2.41421	0.204124	12.0001	12.0000	39.1922	39.1918	273.514	273.518
2.80588	0.193649	10.6671	10.6667	34.4289	34.4265	210.552	210.563
3.14626	0.182574	9.99982	10.0000	32.8624	32.8634	176.553	176.555
3.45197	0.172516	9.59981	9.60000	32.4596	32.4607	154.723	154.726
3.99215	0.155902	9.14274	9.14286	32.9869	32.9877	127.614	127.616
4.46653	0.143019	8.88879	8.88889	34.1828	34.1834	110.970	110.973

accuracy: 10^{-5}

Black Rings in $D = 5$: A Coordinate Choice



MP: Myers-Perry, BR: black ring, BF: blackfold

Black Rings in $D = 5$: A Coordinate Choice

black ring metric in these coordinates:

$$ds^2 = f_1(r,\theta)(dr^2 + r^2 d\theta^2) + f_2(r,\theta)d\phi^2 + f_3(r,\theta)(d\psi - W(r,\theta)dt)^2 - f_0(r,\theta)dt^2$$

with functions:

$$f_0(r,\theta) = \frac{Q_2(r,\theta)}{Q_1(r,\theta)} U_1(r,\theta)U_2(r,\theta), \quad f_1(r,\theta) = \frac{r_H^2 R^4}{(R^4 - r_H^4)^2} \frac{U_1(r,\theta)Q_3(r,\theta)}{S(r,\theta)},$$

$$f_2(r,\theta) = \left(1 + \frac{r_H^2}{r^2}\right)^2 \frac{r^2 \sin^2 2\theta}{2U_2(r,\theta)}, \quad f_3(r,\theta) = \frac{r^2\left(1 - \frac{r_H^2}{r^2}\right)^2}{2\left(1 + \frac{r_H^2}{r^2}\right)^2} \frac{Q_1(r,\theta)}{Q_2(r,\theta)U_1(r,\theta)},$$

$$W(r,\theta) = \frac{4\sqrt{2}(r_H^2 + R^2)\sqrt{R^4 + r_H^4}}{R(R^2 - r_H^2)} \frac{\left(1 - \frac{r_H^2}{r^2}\right)^2}{r^2\left(1 + \frac{r_H^2}{r^2}\right)^2} \frac{Q_2(r,\theta)Q_4(r,\theta)}{Q_1(r,\theta)}.$$

Black Rings in $D = 5$: A Coordinate Choice

$$U_1(r,\theta) = \frac{(r_H^2 + R^4)}{r_H^2 R^2}\left(1 + \frac{4r_H^2}{r^2} + \frac{r_H^4}{r^4}\right) + \frac{4r_H^2}{r^2}\cos 2\theta - 2S(r,\theta),$$

$$U_2(r,\theta) = \frac{r_H^2 + R^4}{r^2 R^2} - (1 + \frac{r_H^4}{r^4})\cos 2\theta + S(r,\theta),$$

$$Q_1(r,\theta) = U_1^2(r,\theta)U_2(r,\theta) - \frac{4(r_H^2 + R^2)^2(r_H^4 + R^4)}{r^2 R^2 (R^2 - r_H^2)^2}\frac{\left(1 + \frac{r_H^2}{r^2}\right)^2}{\left(1 - \frac{r_H^2}{r^2}\right)^2} \times$$

$$\left[U_1(r,\theta) - \left(\frac{(r_H^2 - R^2)^2}{r_H^2 R^2} + \frac{r_H^2(r_H^2 - R^2)^2}{r^4 R^2} + \frac{2(r_H^2 + R^2)^2}{r^2 R^2} + \frac{4(r_H^4 + R^4)}{r^2 R^2}\right)\right]^2,$$

$$Q_2(r,\theta) = U_1(r,\theta) - \frac{8(r_H^4 + R^4)}{r^2 R^2},$$

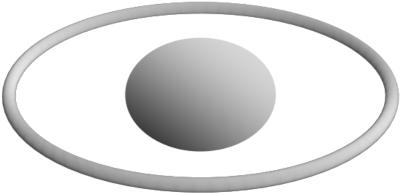
$$Q_3(r,\theta) = -U_1(r,\theta) + (1 + \frac{r_H^2}{r^2})^2 \frac{2(r_H^4 + R^4)}{r_H^2 R^2},$$

$$Q_4(r,\theta) = U_2(r,\theta) - 2(1 - \frac{r_H^2}{r^2})^2 \sin^2\theta,$$

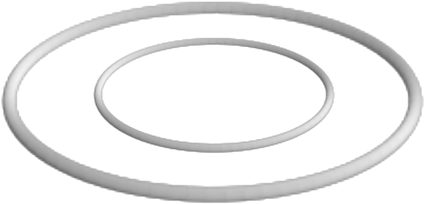
$$S(r,\theta) = \sqrt{\left(1 + \frac{R^4}{r^4} - \frac{2R^2}{r^2}\cos 2\theta\right)\left(1 + \frac{r_H^8}{r^4 R^4} - \frac{2r_H^4}{r^2 R^2}\cos 2\theta\right)}$$

A Zoo of Composite Species in $D = 5$

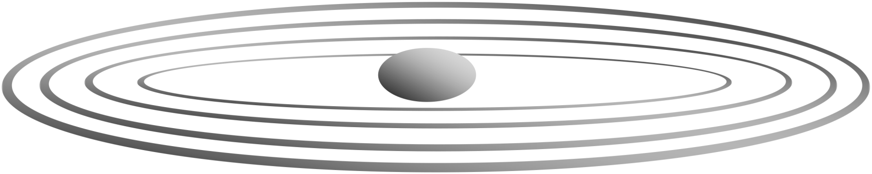
black Saturn



black dirings



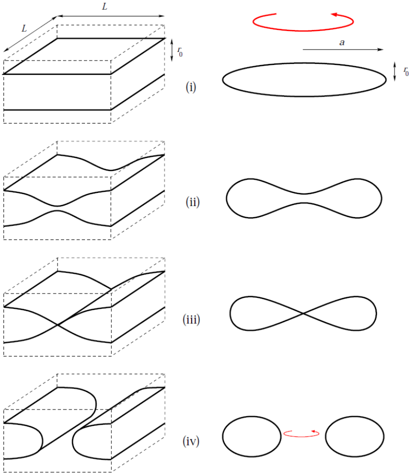
etc.



Outline

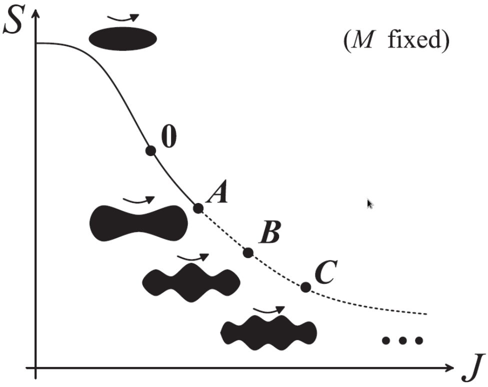
Myers-Perry Black Holes in $D \geq 6$

Emparan, Harmark, Niarchos, Obers, Rodriguez, JHEP 2007



Myers-Perry Black Holes in $D \geq 6$

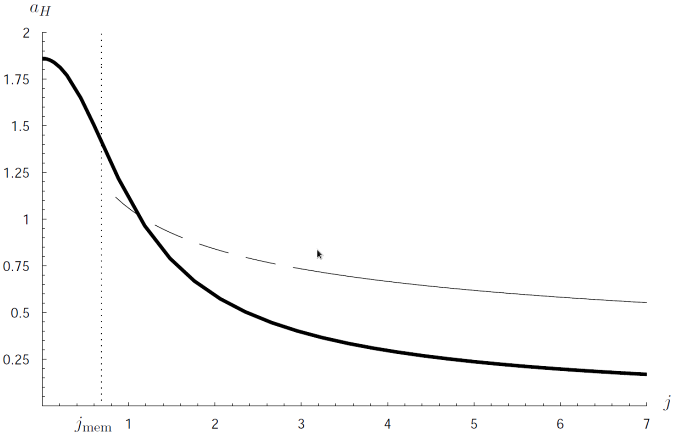
Dias, Figueras, Monteiro, Santos, Emparan, PRD 2009



unstable modes of Myers-Perry black holes: $D \geq 6$

Black Rings in $D > 5$: Perturbative Approach

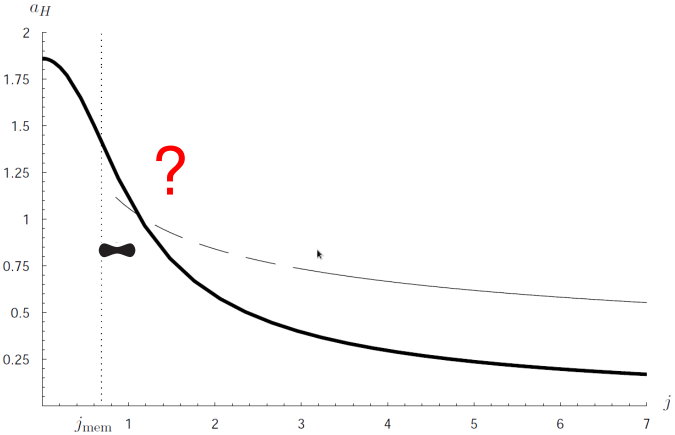
Emparan, Harmark, Niarchos, Obers, Rodriguez, JHEP 2007



perturbative approach: solutions for thin black rings in $D = 7$

Black Rings in $D > 5$: Perturbative Approach

Emparan, Harmark, Niarchos, Obers, Rodriguez, JHEP 2007



perturbative approach: solutions for thin black rings in $D = 7$

Black Rings in $D \geq 6$: New Coordinates

Kleihaus, Kunz, Radu, PLB 2013

a parametrization of $d-$dimensional Euclidean space (with $d = D - 1$)

$$ds^2 = d\rho^2 + \rho^2(d\Theta^2 + \cos^2\Theta d\Omega_{d-3}^2 + \sin^2\Theta d\psi^2)$$

coordinate transformation

$$\rho = r\sqrt{U}, \ \tan\Theta = (\frac{r^2 + \rho^2 + R^2}{r^2 + \rho^2 - R^2}) \tan\theta,$$

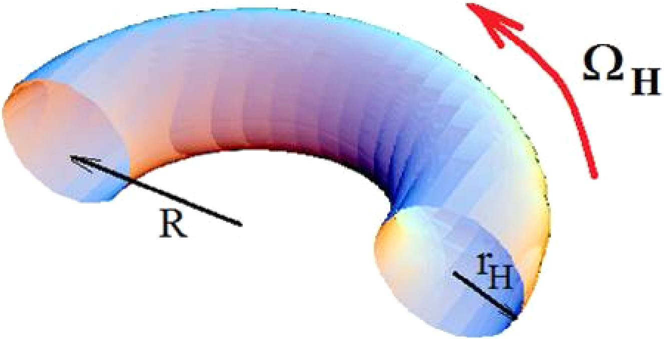
metric

$$ds_d^2 = V_1(dr^2 + r^2 d\theta^2) + V_2 d\Omega_{d-3}^2 + V_3 d\psi^2,$$

Ansatz for the $D-$dimensional black ring metric

$$ds^2 = f_1(r,\theta)(dr^2 + r^2 d\theta^2) + f_2(r,\theta)d\Omega_{D-4}^2 + f_3(r,\theta)(d\psi - W(r,\theta)dt)^2 - f_0(r,\theta)dt^2$$

Black Rings in $D \geq 6$: New Coordinates



regular solutions: adjust Ω_H for fixed r_H and R

in practice: $r_H = 1$, $R > r_H$

Black Rings in $D \geq 6$: New Coordinates

event horizon area

$$A_H = 2\pi r_H V_{D-4} \int_0^{\pi/2} d\theta \, \sqrt{f_1 f_2^{D-4} f_3}\Big|_{r=r_H}$$

temperature

$$T_H = \frac{1}{2\pi} \lim_{r \to r_H} \frac{1}{r - r_H} \sqrt{\frac{f_0}{f_1}}$$

mass and angular momentum

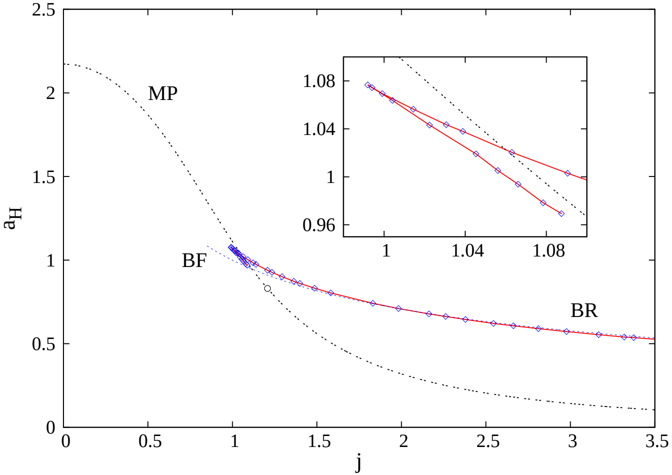
$$M = \frac{(D-2)V_{D-2}}{16\pi G} c_t \, , \quad J = \frac{V_{D-2}}{16\pi G} c_\psi$$

$$g_{tt} \to -1 + \frac{c_t}{r^{D-3}} + \dots \, , \quad g_{\psi t} \to \sin^2\theta \, \frac{c_\psi}{r^{D-3}} + \dots$$

Smarr formula

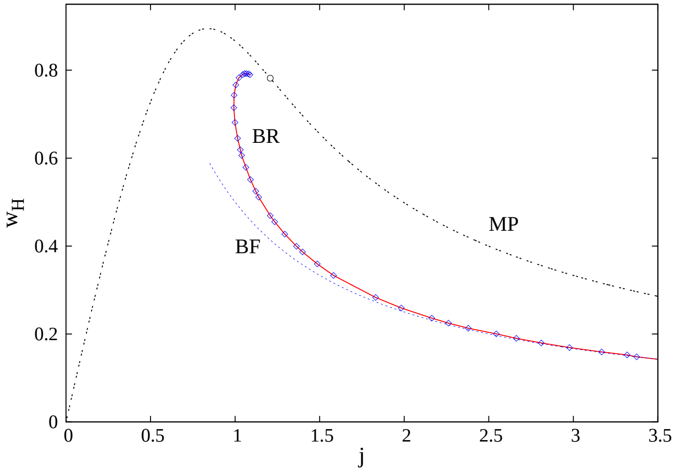
$$\frac{D-3}{D-2} M = \frac{T_H A_H}{4G} + \Omega_H J$$

Black Rings in $D = 6$: Results



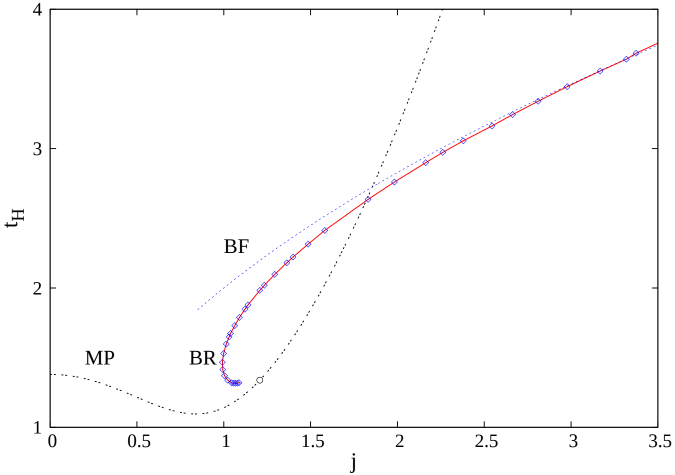
horizon area A_H vs. angular momentum J for fixed mass

Black Rings in $D = 6$: Results



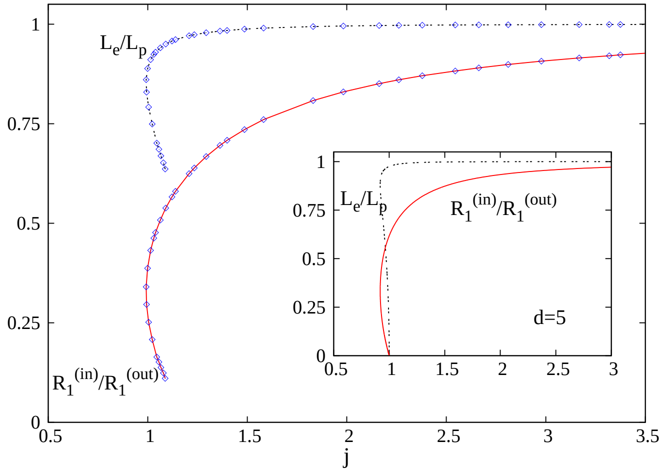
horizon angular velocity w_H vs. angular momentum J for fixed mass

Black Rings in $D = 6$: Results



temperature T_H vs. angular momentum J for fixed mass

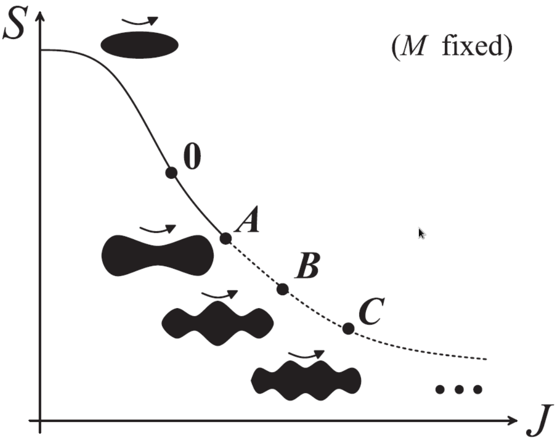
Black Rings in $D = 6$: Results



horizon geometry vs. angular momentum J for fixed mass

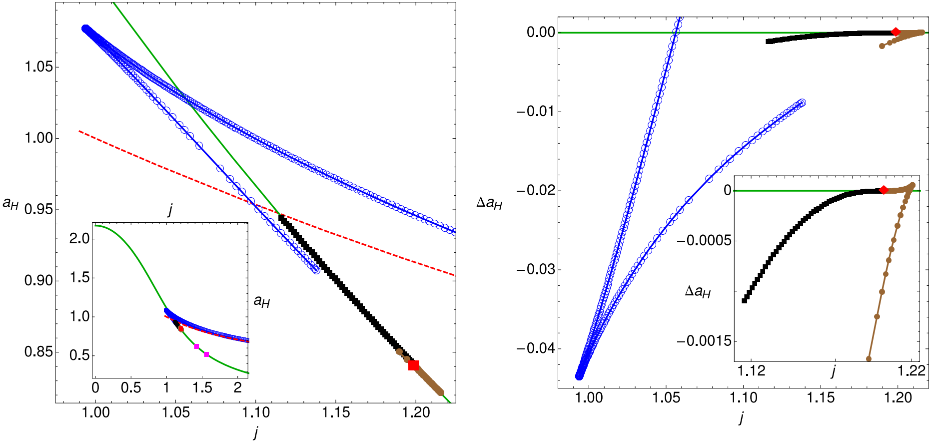
Black Rings and Pinched Black Holes

Dias, Figueras, Monteiro, Santos, Emparan, PRD 2009



Black Rings and Pinched Black Holes

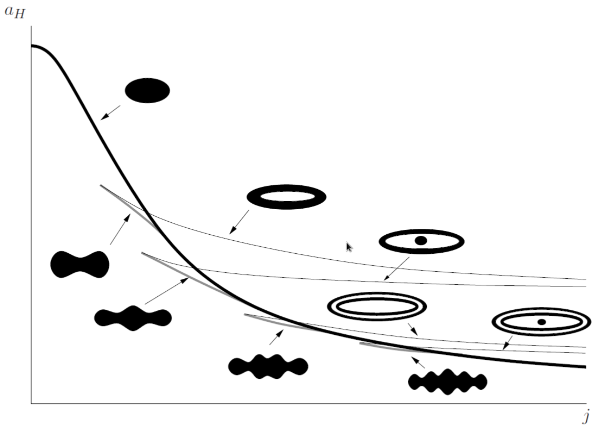
O. J. C. Dias, J. E. Santos and B. Way, JHEP 2014



- black rings and pinched black holes in $D = 6$
- extension to $D = 7$

A Phase Diagram in $D \geq 6$

Emparan, Figueras, JHEP 1011 (2010) 022



$D \geq 6$ horizon area vs. angular momentum at fixed mass

Outline

Black Ringoids: The Scheme

Kleihaus, Kunz, Radu, JHEP 2015

Balanced black objects with $S^{n+1} \times S^{2k+1}$ horizon topology

	spherical horizon	*black rings*	*black ringoids*		
	MP/'pinched'	$k = 0$	$k = 1$	$k = 2$	$k = 3$
$d = 5$	S^3	$\mathbf{S^2 \times S^1}$			
$d = 6$	S^4	$S^3 \times S^1$			
$d = 7$	S^5	$S^4 \times S^1$	$\mathbf{S^2 \times S^3}$		
$d = 8$	S^6	$S^5 \times S^1$	$S^3 \times S^3$		
$d = 9$	S^7	$S^6 \times S^1$	$S^4 \times S^3$	$\mathbf{S^2 \times S^5}$	
$d = 10$	S^8	$S^7 \times S^1$	$S^5 \times S^3$	$S^3 \times S^5$	
$d = 11$	S^9	$S^8 \times S^1$	$S^6 \times S^3$	$S^4 \times S^5$	$\mathbf{S^2 \times S^7}$

etc.

Black Ringoids: The Scheme

Euclidean metric

$$ds^2 = V_1(dr^2 + r^2 d\theta^2) + V_2 d\Omega_n^2 + V_3 d\Omega_p^2$$

surface of constant r: $\begin{cases} 0 < r < R: & S^{n+1} \times S^p \text{ topology} \\ r > R: & S^{n+1+p} \text{ topology} \end{cases}$

appropriate spatial coordinates for black objects with $S^{n+1} \times S^p$ topology

general case: difficult

simplification: $p = 2k+1, \quad k \geq 0$

$k+1$ equal magnitude angular momenta: $J_1 = J_2 = \cdots = J_k = J_{k+1} = J$

Black Ringoids: The Scheme

odd-dimensional sphere: as an S^1 fibration over $\mathbb{CP}^k$

$$d\Omega^2_{2k+1} = (d\psi + \mathcal{A})^2 + d\Sigma^2_k$$

$\mathcal{A} = A_i dx^i$: Kähler form $d\Sigma^2_k$: metric on the unit $\mathbb{CP}^k$

$$d\Omega^2_{2k+1} = \sum_i dz_i d\bar{z}_i$$

$k+1$ complex coordinates z_i with $\sum_i^{k+1} z_i \bar{z}_i = 1$, e.g.

$$z_i = e^{i(\psi+\phi_i)} \cos\theta_i \prod_{j<i} \sin\theta_j, \quad \text{for} \quad i = 1, \ldots, k, \quad \text{and} \quad z_{k+1} = e^{i\psi} \prod_{j=1}^{k} \sin\theta_j$$

$$\mathcal{A} = A_i dx^i = \sum_{i=1}^{k} \cos^2\theta_i \left[\prod_{j<i} \sin^2\theta_j \right] d\phi_i \ .$$

Black Ringoids: The Scheme

$S^{n+1} \times S^{2k+1}$ horizon topology

Ansatz for the metric of black ringoids: $k \geq 1$, $n \geq 1$

$$ds^2 = f_1(r,\theta)\left(dr^2 + r^2 d\theta^2\right) + f_2(r,\theta) d\Omega_n^2 - f_0(r,\theta) dt^2 + f_3(r,\theta)\big(d\psi + \mathcal{A} - W(r,\theta)dt\big)^2 + f_4(r,\theta) d\Sigma_k^2 \ ,$$

special case $n = 1$: $S^2 \times S^{2k+1}$ horizon topology

$$ds^2 = f_1(r,\theta)\left(dr^2 + \Delta(r) d\theta^2\right) + f_2(r,\theta) d\phi^2 - f_0(r,\theta) dt^2 + f_3(r,\theta)\big(d\psi + \mathcal{A} - W(r,\theta)dt\big)^2 + f_4(r,\theta) d\Sigma_k^2 \ ,$$

MP ($J_1 = ... = J_{k+1} = J$, $J_{k+2} = 0$): domain bounded, singular limit

general case $n > 1$:

MP ($J_1 = ... = J_{k+1} = J$, $J_i = 0$, $i > k+1$): domain unbounded

Black Ringoids: The Scheme

event horizon area

$$A_H = r_H V_n V_{2k+1} \int_0^{\pi/2} d\theta \, \sqrt{f_1 f_2^n f_3 f_4^{2k}}\Big|_{r=r_H}$$

temperature

$$T_H = \frac{1}{2\pi} \lim_{r \to r_H} \frac{1}{r - r_H} \sqrt{\frac{f_0}{f_1}}$$

mass and angular momentum

$$M = \frac{(D-2)V_{D-2}}{16\pi G} c_t \, , \quad J = \frac{V_{D-2}}{8\pi G} c_\psi$$

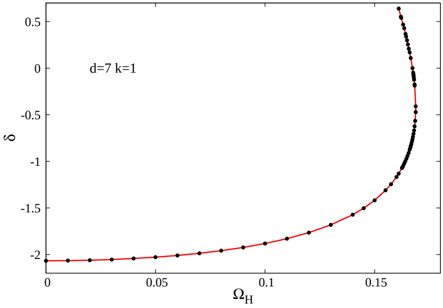
$$g_{tt} \to -1 + \frac{c_t}{r^{D-3}} + \dots \, , \quad g_{\psi t} \to \sin^2\theta \frac{c_\psi}{r^{D-3}} + \dots$$

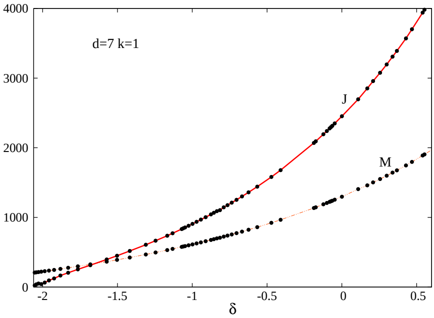
Smarr formula

$$\frac{D-3}{D-2} M = \frac{T_H A_H}{4G} + (k+1)\,\Omega_H J$$

Black Ringoids: Results

balancing the ringoids: variation of Ω_H

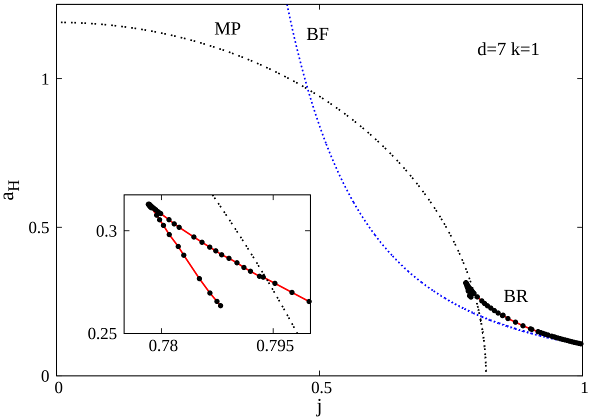




conical deficit/excess $\delta = 2\pi(1 - \lim_{\theta\to 0} \frac{f_2}{\theta^2 r^2 f_1})$

$d = 7,\ k = 1$ black ringoids ($r_H = 1$, $R = 4.6$)

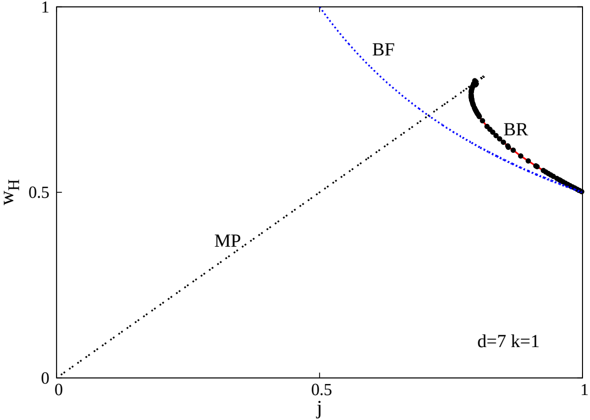
Black Ringoids: Results



area of balanced $D = 7$ ringoids with $S^2 \times S^3$ horizon topology

higher dimensional counterparts of $D = 5$ black rings

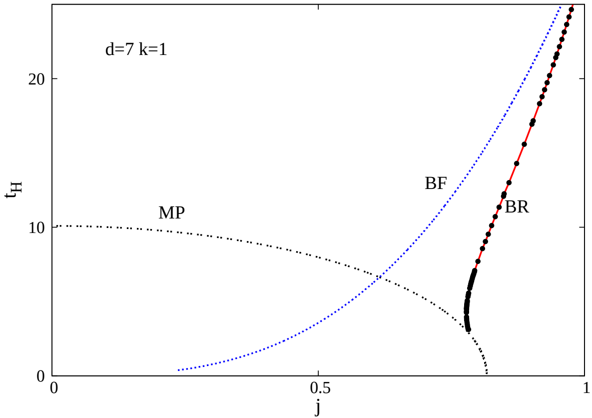
Black Ringoids: Results



$\Omega_{\rm H}$ of balanced $D = 7$ ringoids with $S^2 \times S^3$ horizon topology

higher dimensional counterparts of $D = 5$ black rings

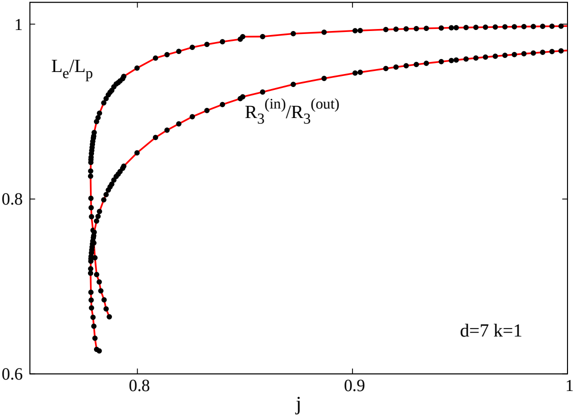
Black Ringoids: Results



temperature of balanced $D = 7$ ringoids with $S^2 \times S^3$ horizon topology

higher dimensional counterparts of $D = 5$ black rings

Black Ringoids: Results



geometry of balanced $D = 7$ ringoids with $S^2 \times S^3$ horizon topology

higher dimensional counterparts of $D = 5$ black rings

Black Ringoids: Results

Balanced black objects with $S^{n+1} \times S^{2k+1}$ horizon topology

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$d=8$	S^6	$S^5 \times S^1$	$S^3 \times S^3$		
$d=9$	S^7	$S^6 \times S^1$	$S^4 \times S^3$	$\mathbf{S}^2 \times \mathbf{S}^5$	
$d=10$	S^8	$S^7 \times S^1$	$S^5 \times S^3$	$S^3 \times S^5$	
$d=11$	S^9	$S^8 \times S^1$	$S^6 \times S^3$	$S^4 \times S^5$	$\mathbf{S}^2 \times \mathbf{S}^7$

etc.

Outline

Einstein-Maxwell-Dilaton Black Holes

Kaluza-Klein construction:

- embedding of the D-dimensional MP metric in $(D+1)$ spacetime with extra coordinate U

$$ds^2_{D+1} = dU^2 + ds^2_{D,\mathrm{MP}}$$

- boost in the $t-U$ plane with the 2×2 matrix

$$L = \begin{pmatrix} \cosh\alpha & \sinh\alpha \\ \sinh\alpha & \cosh\alpha \end{pmatrix}$$

- $(D+1)$-dimensional metric

$$ds^2_{D+1} = e^{2\iota\Phi} g_{\rho\sigma} dx^\rho dx^\sigma + e^{-2(D-2)\iota\Phi}(dU + A_\rho dx^\rho)^2$$

charged rotating black holes for the KK dilaton coupling constant h

$$h = \frac{D-1}{\sqrt{2(D-1)(D-2)}} = (D-1)\iota$$

Einstein-Maxwell-Dilaton Black Holes

asymptotic expansion and global charges

$$g_{tt} = -1 + \frac{M}{(D-2)A}\frac{1}{r^{D-3}} + \dots \qquad M = m\left(1 + (D-3)\cosh^2\alpha\right)A$$

$$g_{t\varphi_i} = -\frac{J_i}{2A}\mu_i^2\frac{1}{r^{D-3}} + \dots \qquad J_i = 2m\, a_i \cosh\alpha A$$

$$A_t = \frac{Q}{(D-3)A}\frac{1}{r^{D-3}} + \dots \qquad Q = (D-3)m\ \sinh\alpha\cosh\alpha A$$

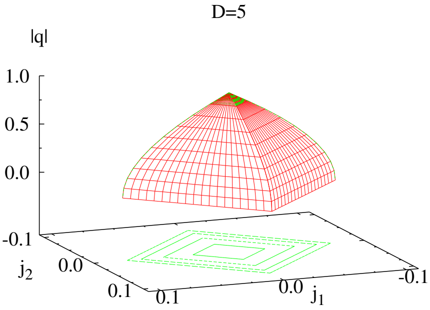
$$A_{\varphi_i} = -\frac{\mathcal{M}_i}{(D-3)A}\mu_i^2\frac{1}{r^{D-3}} + \dots \qquad \mathcal{M}_i = (D-3)m\, a_i \sinh\alpha A$$

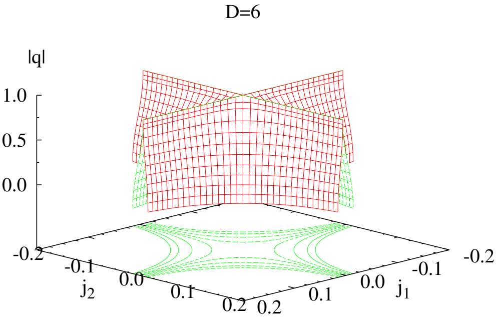
$$\Phi = \frac{\Sigma}{(D-3)A(S^{D-2})}\frac{1}{r^{D-3}} + \dots \qquad \Sigma = -\frac{(D-3)m\ \sinh^2\alpha}{2(D-2)\iota}A$$

where $A := A(S^{D-2})$

Einstein-Maxwell-Dilaton Black Holes

Myers-Perry black holes



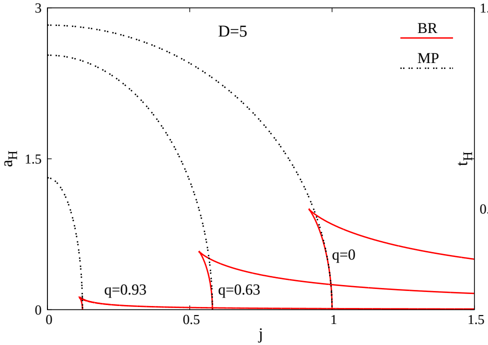


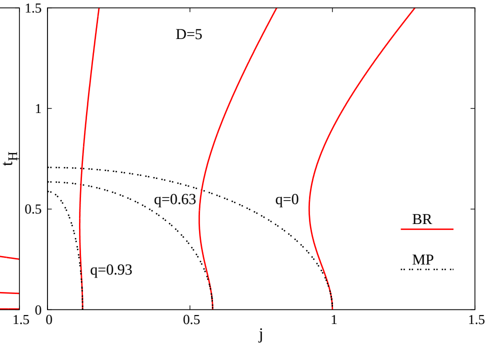
domain of existence of EMD MP black holes

scaled charge $|q| = \frac{|Q|}{M}$ vs scaled angular momenta $j_i = \frac{J_i}{M^{(D-2)/(D-3)}}$

Charged Black Rings and Ringoids

$D = 5$ black rings



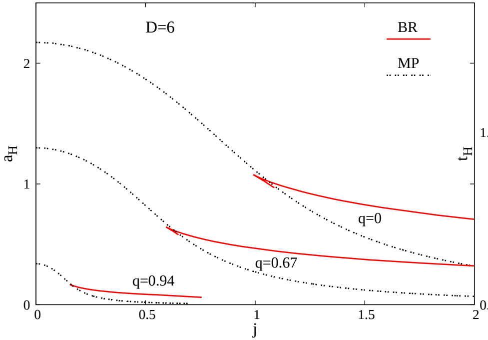


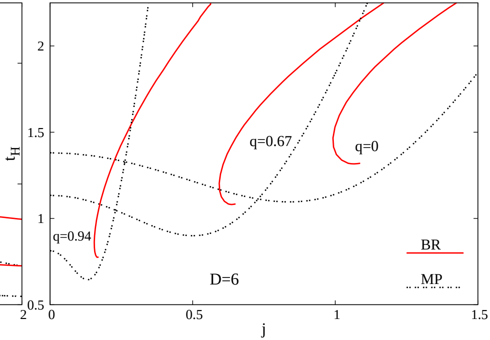
scaled area a_H scaled temperature t_H

vs scaled angular momentum j for fixed scaled charge q

Charged Black Rings and Ringoids

$D = 6$ black rings





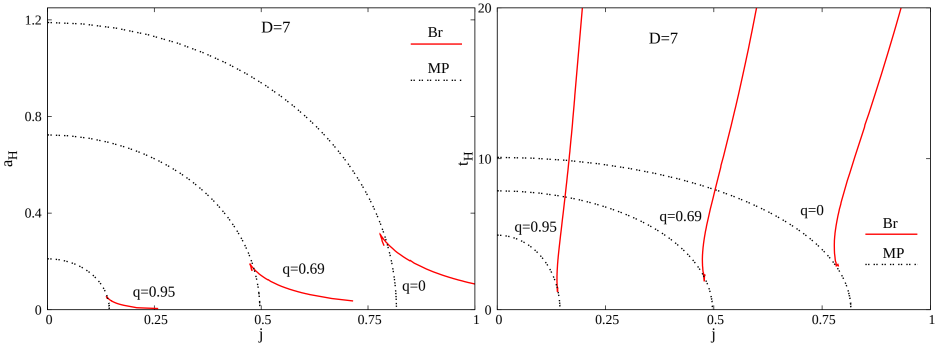
scaled area a_H

scaled temperature t_H

vs scaled angular momentum j for fixed scaled charge q

Charged Black Rings and Ringoids

$D = 7$ black ringoids

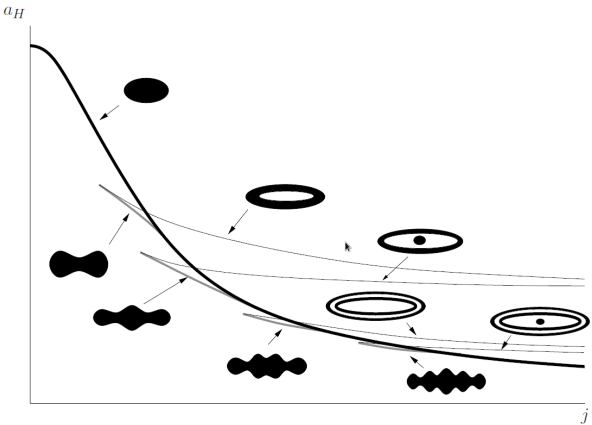


scaled area a_H scaled temperature t_H

vs scaled angular momenta j_i for fixed scaled charge q

Outline

Conclusions



$D = 5$: rings

- well-known

$D = 6$: rings

- horizon topology change?
- pinched black holes

$D = 7$: ringoids

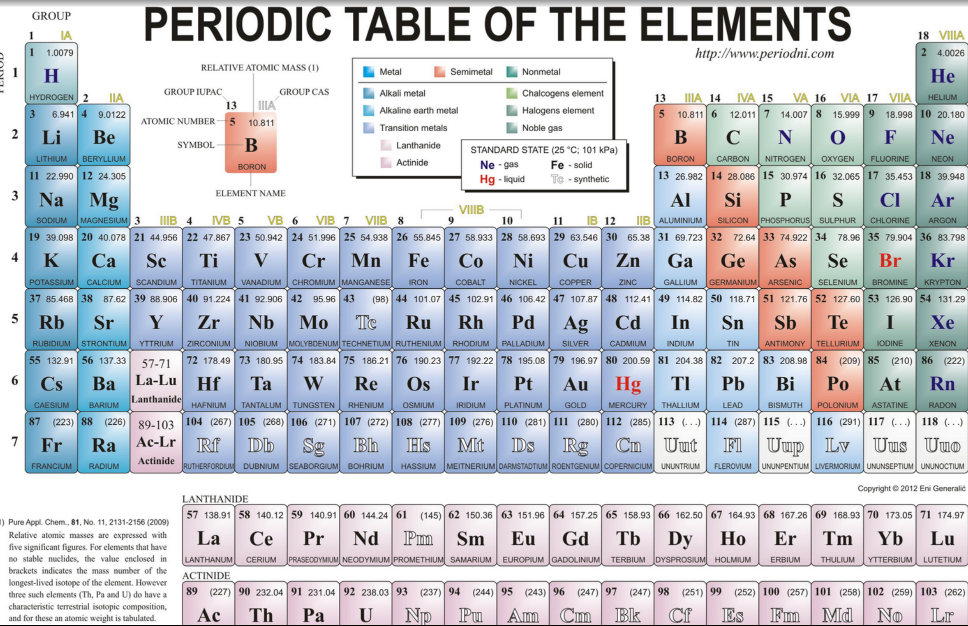
- analogous to $D = 5$

$D \geq 8$

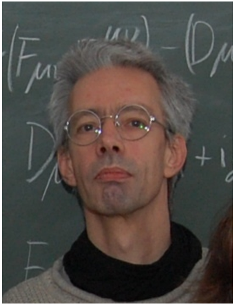
- systematic study to be done

A Black Hole Zoo

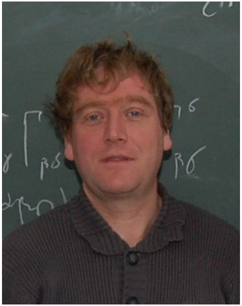
A Black Hole Zoo



THANKS



Burkhard Kleihaus



Eugen Radu

THANKS

Thank you very much
for your attention