Black holes in String Theory

Lesvos, 4th Aegean Summer School: Black Holes

September 20-21, 2007

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Introduction

Black holes in String Theory very broad subject

⇨ string theory gives rise to (more general) black hole solutions:
charged black branes + extremal (supersymmetric) versions of these

two main themes:
- use black branes in connection with gauge/gravity correspondence to learn about thermal phases of dual non-gravitational theories (e.g. super Yang-Mills theory) lliving on brane (holography)
- microscopic description of black hole entropy via string theory

◄ Focus in these lectures:
- black holes, strings and rings in higher dimensions (intimately connected to black objects in string theory)
- black branes in string theory (U-duality, thermodynamics, stability, ..)

Many other interesting recent developments in string theory:
- black hole entropy and attractors, relation to topological strings
- fuzzball conjecture (see lecture Mathur) .

Outline

- Introduction to black branes and their thermodynamics +
  relevance for the gauge/gravity correspondence

Part 1:

- Black objects in higher dimensional spaces
  - Kaluza-Klein black holes (spaces with extra compact directions)
  - rotating (stationary) black objects (in asymptotically flat space)
  - newly found connection between the phase structure of these two

Part 2:

- non-and near- extremal branes in string theory via boost/U-duality map
- applications of KK black holes to string theory:
  - correlated stability conjecture
    (relation between thermodynamic and classical stability)

See e.g. Review articles by: Kol (PhysRept)/Harmark,Niarchos,NO (CQG)
also Tasi lecture of Peet (+ various other reviews)

Motivation (higher D gravity + String Theory)

- Study black objects in higher dimensional gravity
  - richer phase structure
  - (non)-uniqueness theorems in higher dimensional gravity
  - new topologies of event horizons possible
  - gravitational phase transitions between different solutions with event horizons (topology change)
  - Gregory-Laflamme instability (new phases)
  - possible objects in universe/accelerators
  - + many ST applications (black branes, BH entropy, AdS/CFT)

► Two cases studied — most progress in recent years — less explored

- asymptotically flat spaces: (stationary solutions) — five dimensions — six and beyond
  - MP black holes, black rings, black Saturns, black di-rings,

- Kaluza-Klein spaces: (static solutions) — d-dim Minkowski x circle (tori) — other Ricci flat.. e.g. CY
  -non-uniform strings, localized black holes bubble-black hole sequences, merger point evolution of GL instability

String/Gauge Theory Motivations

- phase structure of Kaluza-Klein black holes related to objects and phenomena in string theory/gauge theory

Bostock,Ross/Aharony,Marsano,Minwalla,Wiseman/
Harmark,NO

→ phase structure of non- + near-extremal branes (with circle in transverse space)

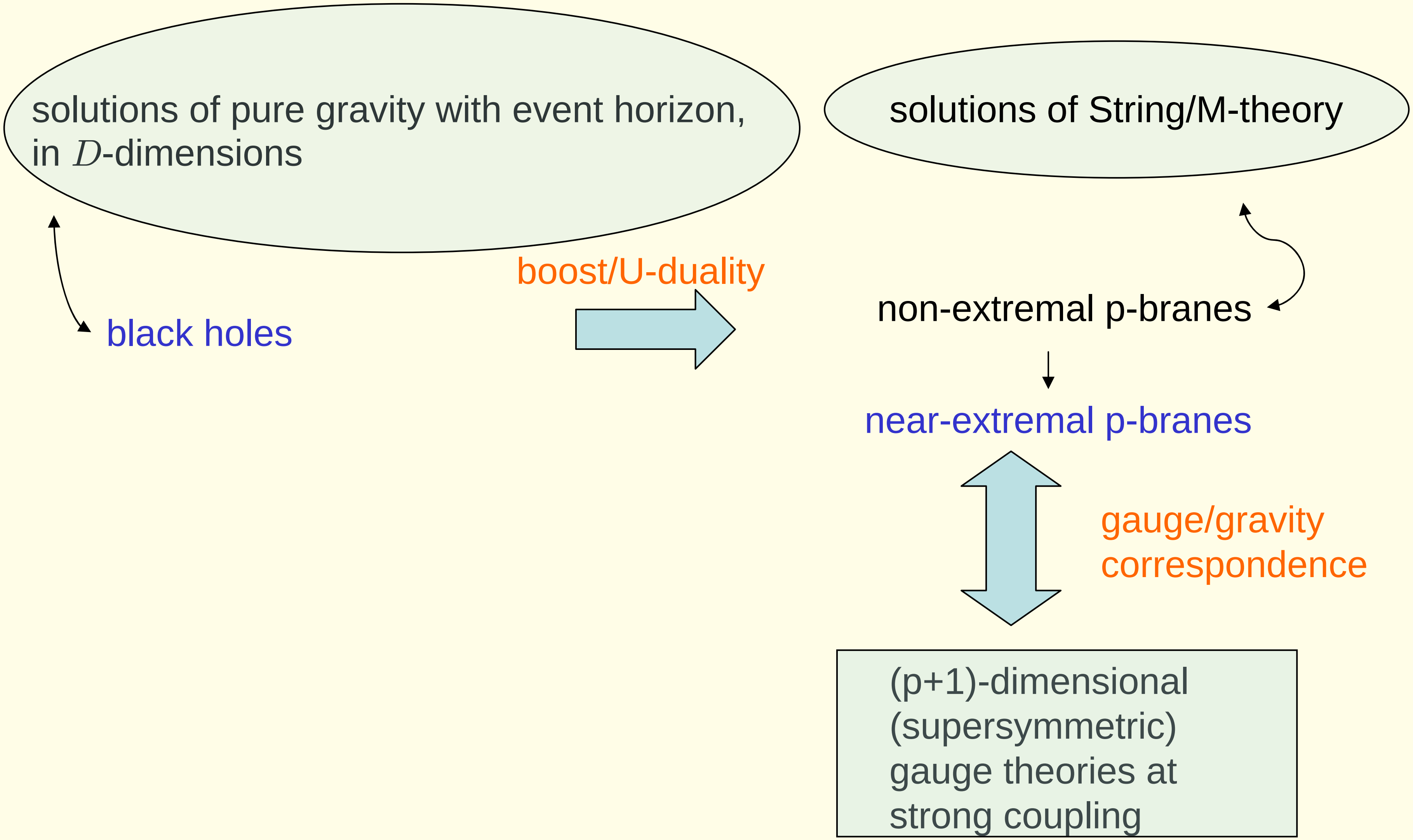
- new insights into phase structure of strongly coupled large N theories
  - qualitative/quantitative tests of gauge/gravity correspondence
- correlated stability conjecture
- new stable phase of LST
- entropy of 3-charge BHs on circle

- Black rings + supersymmetric cousins play important role in string theory

- supersymmetric black rings, supertubes
- microscopic counting of entropy, 4D-5D connection
- foaming black rings and fuzzball proposal
- plasma rings…..

From black hole to gauge theory thermodynamics

Black hole thermodynamics is intimately related to gauge theory dynamics in very precise way, via brane solutions in string theory



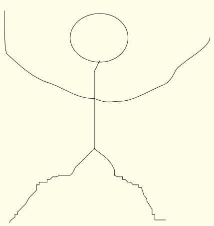
black holes in higher dimensions

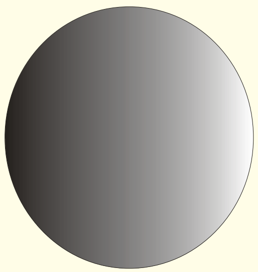
What do we know about black objects (i.e. with event horizon) in higher dimensional gravity

⇒ some, but still lot to discover

stationary black holes

$\mathcal{M}^D$





$\mathcal{M}^{D-1} \times S^1$

KK black holes

Black hole non-uniqueness

in 4 dimensions: given mass, angular momentum and charge:
unique black hole solution

for D–dimensional asymptotically flat space times:
only static and neutral black hole in pure gravity is Schwarzschild-Tangherlini black hole

$$ds^2 = -\left(1 - \frac{r_0^{d-3}}{r^{d-3}}\right) dt^2 + \left(1 - \frac{r_0^{d-3}}{r^{d-3}}\right)^{-1} dr^2 + r^2 d\Omega_{d-2}^2$$

event horizon at r_0

mass $M = \frac{\Omega_{d-2}(d-2)}{16\pi G} r_0^{d-3}$

Q: Does this uniqueness extend to higher dimensional GR ?

$\longrightarrow$ Recent years of research gives answer: No !

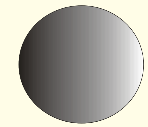
two examples of such non-uniqueness known:

Rotating ring in five dimensions

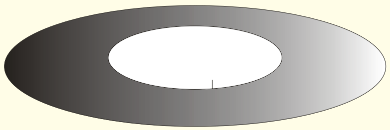
5D asymptotically flat rotating BH solutions

horizon topology

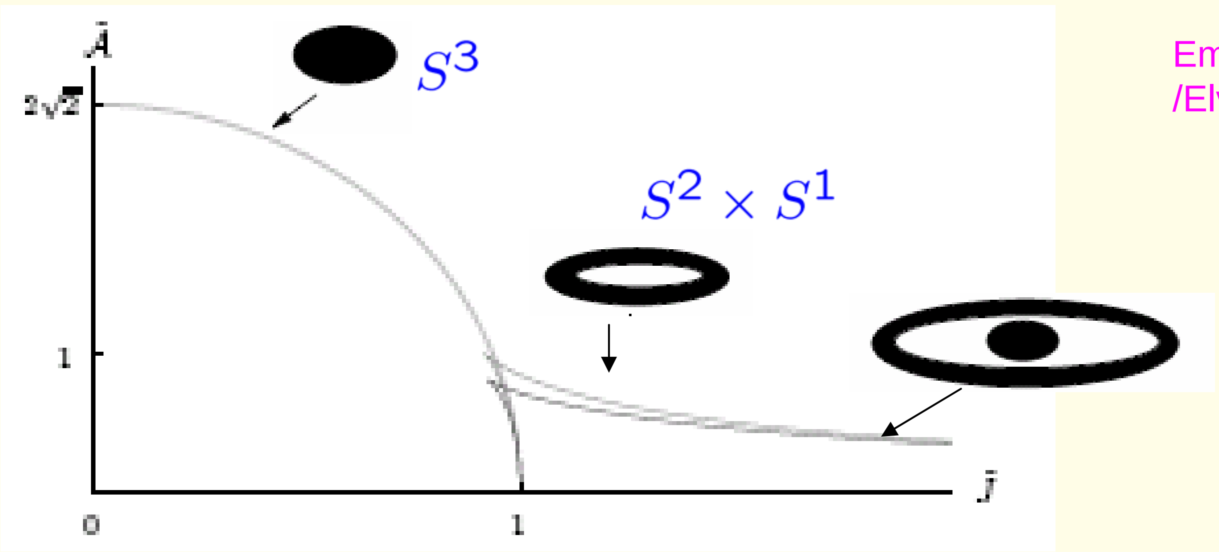
• Myers-Perry black hole
(generalizes 4D Kerr solution) S^3



• rotating black ring
(Emparan-Reall) $S^2 \times S^1$



+ black saturn, black di-rings etc. (exact solutions)



EmparanReall/Elvang,Figueras
/Elvang,Emparan,Figueras

infinite non-uniqueness
for configurations not
in thermal equilibrium

Elvang,Emparan,Mateos,Reall

non-uniqueness even persists for supersymmetric generalization in ST

Kaluza-Klein black holes

► black holes asymptoting to d-dimensional Minkowvski space times a circle (Kaluza-Klein spaces) = $\mathcal{M}^d \times S^1$
= time x d -dimensional cylinder $\mathbb{R}^{d-1} \times S^1$

circle direction breaks symmetry ⟶ gives rise to new possibilities of BH solutions

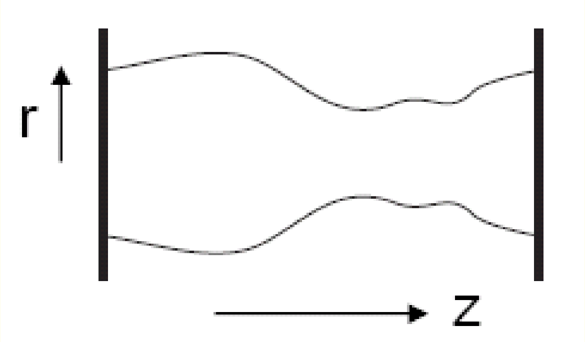
- what are the static & neutral BH solutions on the cylinder ?
- why richer phase structure ?
- how can we parameterize extra freedom ?

► consider case with spherical symmetry for $\mathbb{R}^{d-1}$ part of cylinder:

at ∞ can think of any BH solution as coming from Newtonian source located at origin of $\mathbb{R}^{d-1}$ but with mass distribution in circle direction: source $\rho(z)$

measure at horizon proper radius of S^{d-2} around cylinder ⟶ profile $r(z)$

- heuristically we can connect $r(z)$ to mass distrubution $\rho(z)$ by imagining d-dim static Sch BH for each value of z

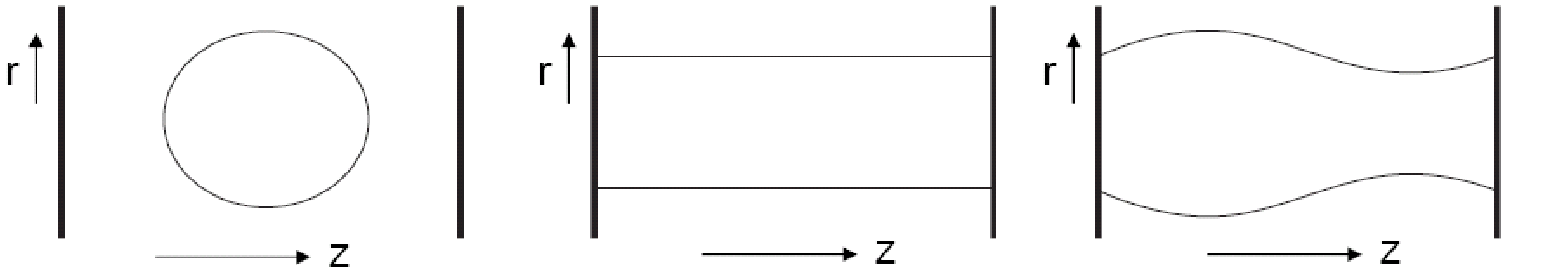


Possible BH solutions

► do all profile/mass distributions correspond to BH solutions ?

- clearly No – BH solution in GR automatically takes into account self-gravitation of the mass distribution, so not even for Newtonian matter would we expect that

what are possible BH solutions ?



Black hole localized on the cylinder

Uniform black string

Non-uniform black string

plus copies: repeat same profile number of times (e.g. 4 times)

these are presently known solutions on cylinder (assuming spherical symmetry)

Mass and tension for KK BHs

consider static solutions of vacuum Einstein equations

- coordinates for $\mathcal{M}^d \times S^1$ $(d \geq 4)$

$$ds^2 = -dt^2 + dr^2 + r^2 d\Omega_{d-2}^2 + dz^2 \qquad z \sim z + L$$

asymptotics
$$g_{tt} \simeq -1 + \frac{c_t}{r^{d-3}} \,, \quad g_{zz} \simeq 1 + \frac{c_z}{r^{d-3}}$$

→ 2 (gauge-invariant) asymptotic quantities

Harmark,NO/Kol,Sorkin,Piran/
Traschen,Fox/Towsend,Zamaklar

$$M = \frac{\Omega_{d-2} L}{16\pi G_N}\left[(d-2)c_t - c_z\right] \,, \quad \mathcal{T} = \frac{\Omega_{d-2}}{16\pi G_N}\left[c_t - (d-2)c_z\right]$$

mass → M, tension → $\mathcal{T}$

1st law of thermo $\delta M = T\delta S + \mathcal{T}\delta L$

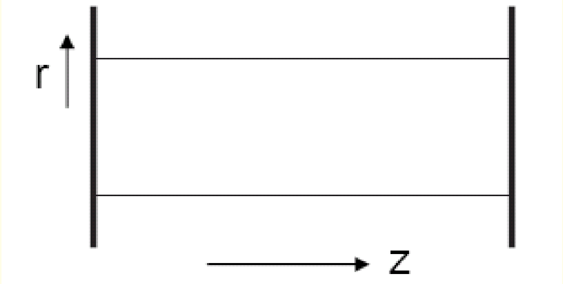
Smarr formula
$$TS = \frac{d-2}{d-1}M - \frac{\mathcal{T}L}{d-1}$$
using Komar integral (time-translation sym.)

dimensionless quantities:
$$\mu = \frac{16\pi G_N}{L^{d-2}} M \,, \quad n = \frac{\mathcal{T}L}{M} \qquad \mu \geq 0 \,, \quad 0 \leq n \leq d-2$$

Uniform black string (UBS) + Gregory-Laflamme instability

$$ds^2 = -f dt^2 + f^{-1} dr^2 + r^2 d\Omega_{d-2}^2 + dz^2$$

$$f = 1 - \frac{r_0^{d-3}}{r^{d-3}}$$



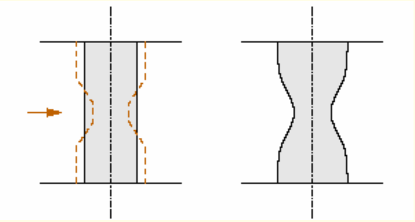
d-dim Schw-Tang. BH x flat compactified direction

GL found:

classically unstable $\mu < \mu_{GL}$ classically stable

Gregory,Laflamme

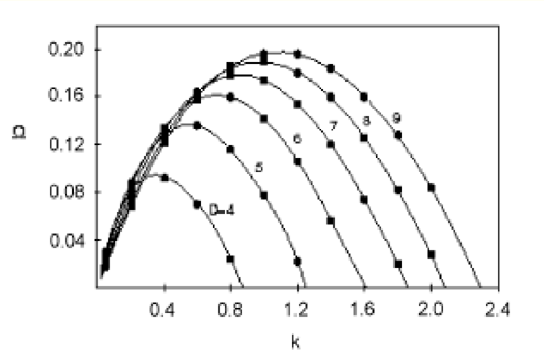
μ



$\delta g_{\mu\nu} \sim e^{ikz} e^{\Omega t}$

threshold mode $\Omega = 0$

non-uniform static solution emerges



long wave-length instability

– present when critical GL wavelength can fit in the compact direction

global thermodynamic argument:

$\mu \ll \mu_{GL}$, $S_{BH}(M) > S_{BS}(M)$

suggests that UBS decays to LBH

(subject of discussion)

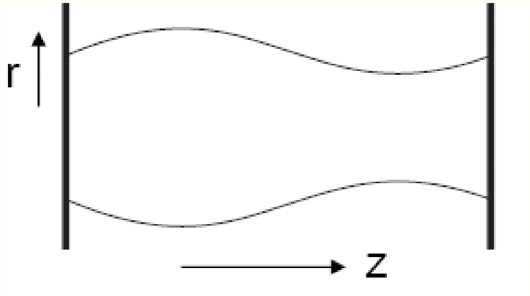
Horowitz,Maeda

Non-Uniform black string (NUBS)

▶ UBS has marginal mode at $\mu = \mu_{GL}$

⟶ new branch of solutions emerges from this point

- not translational invariant along circle direction



Gubser,/Wiseman,/Sorkin

Kleihaus,Kunz,Radu

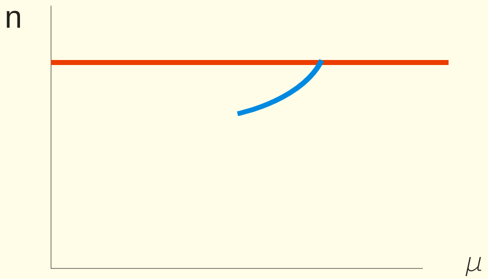
d <13 : branch numerically known

$$n(\mu) = \frac{1}{2} - 0.14(\mu - \mu_{GL}) + \mathcal{O}((\mu - \mu_{GL})^2)\,, \quad 0 \leq \mu - \mu_{GL} \ll 1$$

• critical dimension D=14: Sorkin

slope of non-uniform branch reverses

(2nd order transition instead of 1st order)

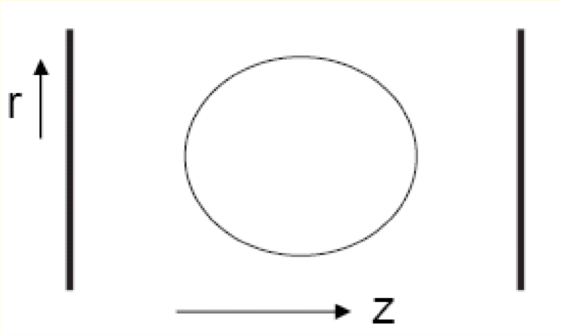


• analytical result: ansatz for metric of NUBS

Harmark,NO/Wiseman

Localized black hole on cylinder (LBH)

► for small mass (large circle radius) LBH becomes more and more like d+1 dimensional Schwarzschild-Tangherlini BH



tension vanishes in limit of vanishing mass

$$n \to 0 \quad \text{as} \quad \mu \to 0$$

• analytical results

Harmark,NO/Wiseman

-ansatz for metric

Harmark/Kol,Gorbonos

- first-order metric for LBH for $\mu \ll 1$
  (found using method of matched asymptotic expansion)

$$n(\mu) = \frac{(d-2)\zeta(d-2)}{2(d-1)\Omega_{d-1}}\mu + \mathcal{O}(\mu^2)$$

Karasik et al/Chu,Goldberger,Rothstein

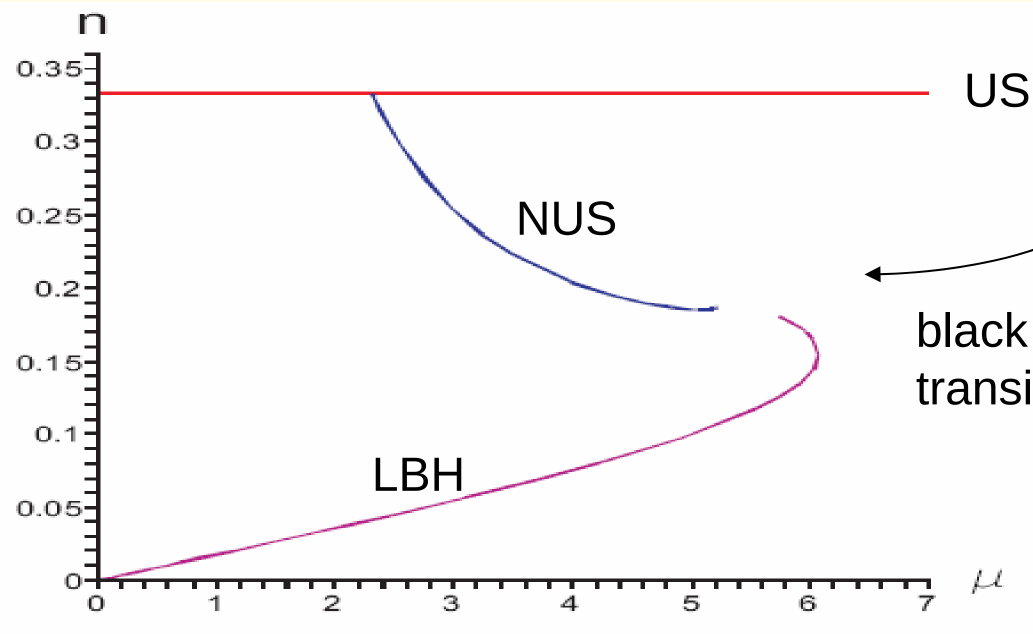
- higher order corrections to metric and thermodynamics

• numerical results

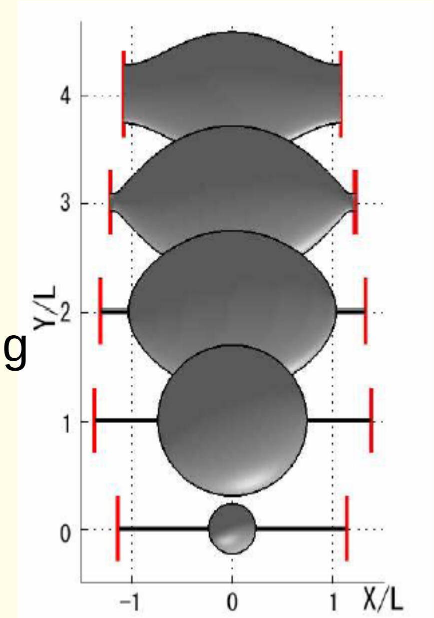
Sorkin,Kol,Piran/Kudoh,Wiseman

d=4,5: LBH solution found with impressive accuracy

Phase Diagram in six dimensions

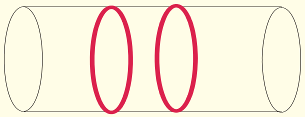


black hole/black string transition



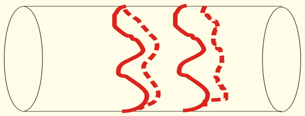
Koduh,Wiseman

•uniform black string
(US) $S^{d-2} \times S^1$



Schwarzschild (d) $\times$ S^1

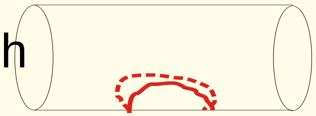
•non-uniform black string
(NUS) $S^{d-2} \times S^1$



emanates from uniform at Gregory-Laflamme point

Gregory,Laflamme/Gubser/Wiseman/Sorkin
motivated in part by: Horowitz,Maeda

•localized black hole branch
(LBH) S^{d-1}



Schwarzschild (d +1) + $\mathcal{O}$ (μ)

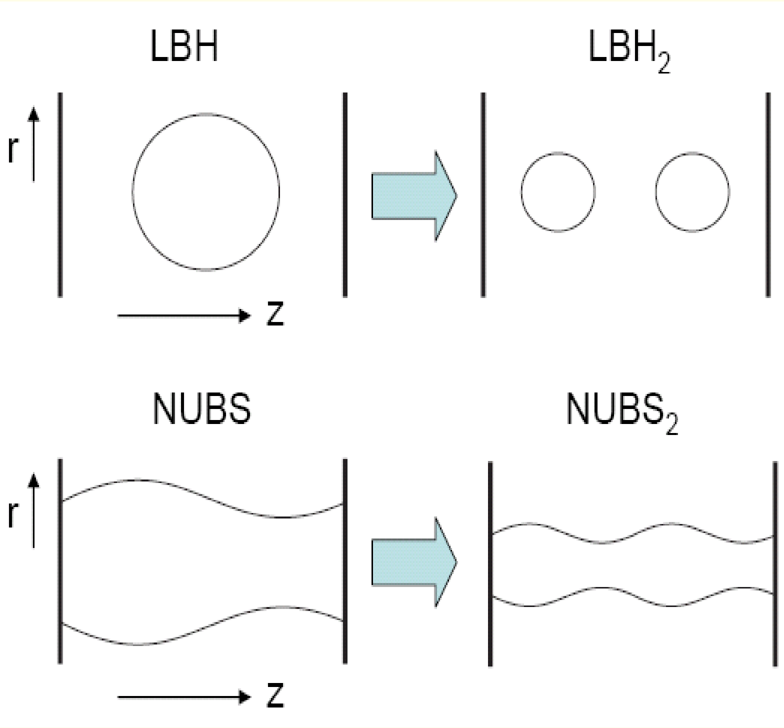
Harmark,NO/Harmar/Kol,Gorbonos/
Sorkin,Kol,Piran/Koduh,Wiseman

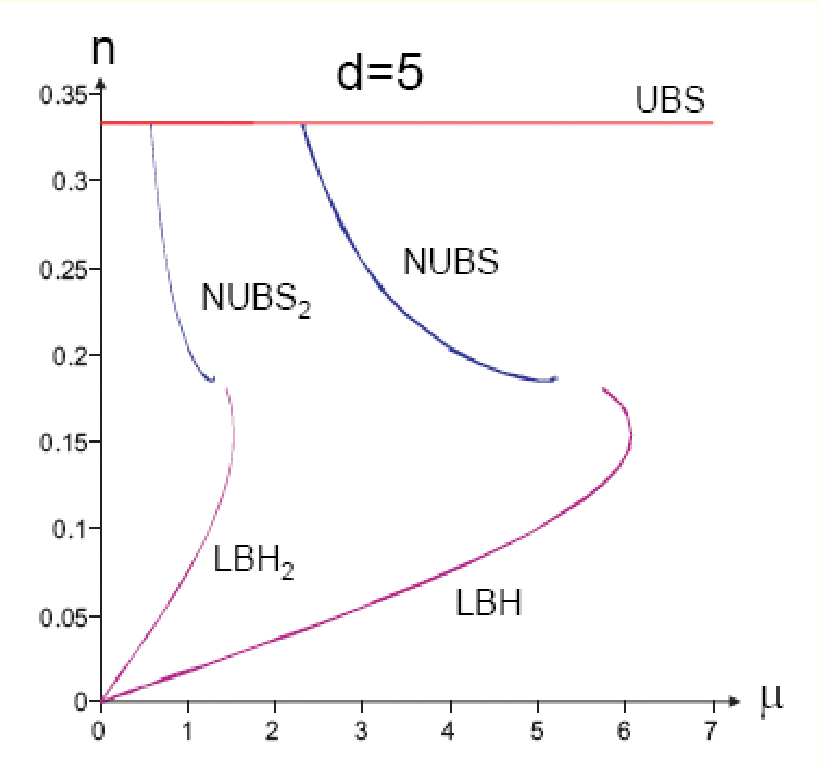
Copies of LBH and NUBS phases

• for solutions that vary in circle direction

Horowitz/Harmark,NO

⇨ can generate copies by copying k times on circle and scaling appropriately in $\mathbb{R}^{d-1}$ part





◄ from this we can argue existence of localized multi-black configurations of different mass/size

Dias.Harmark,MyersNO

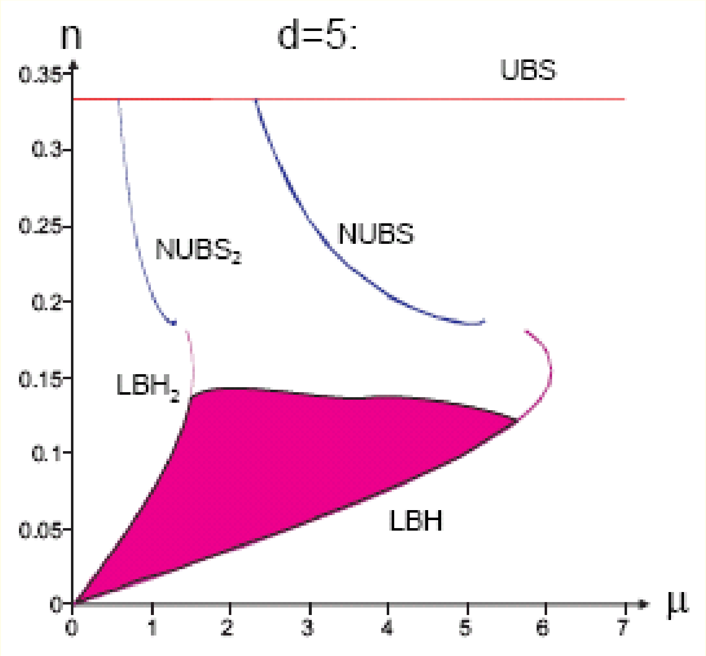
Multi-black hole configurations in phase diagram

► range of n is such that it can take all values between small LBH solution and the small LBH_k solution

continuous non-uniqueness for give mass μ

- takes infinite amount of continuous parameters to point to specific solution !

(non thermal equilibrium solutions)

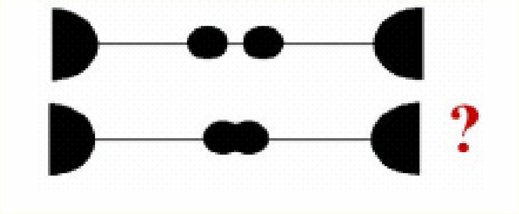


► multi BH solutions are in unstable mechanical equilibrium

in accordance with this: entropy of single BH is greater than entropy of mulit BH with k black holes (at same total mass)

$$S_k(\mu) < S(\mu)$$

► speculation: existence of (static) lumpy black holes (one big BH + two small BHs: small ones can merge into lumpy object before all horizons merge)

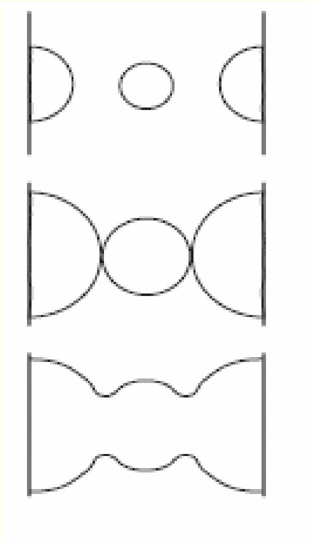


Consequences for non-uniform black strings

► what happens when we crank up mass for multi BH configuration

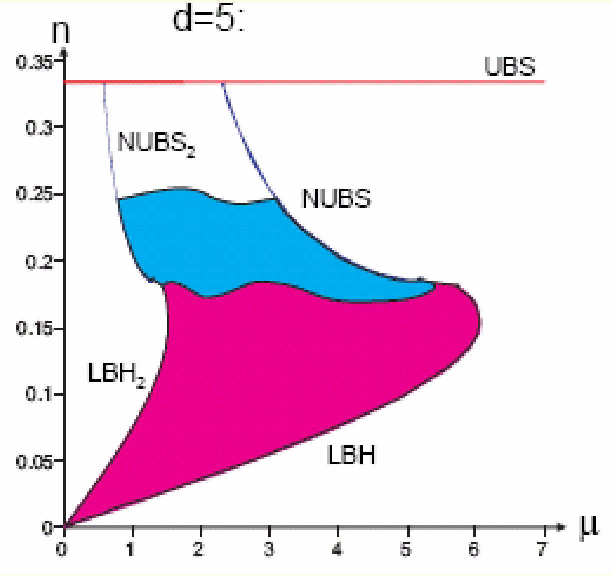
⇨ could point to existence of new non-uniform black strings (bumpy black strings)

Open Q: if exist, how connected to GL critical masses ?



possibility:
GL instability first decays to non-uniform black string, then bifurcation into new non-uniform black strings

⟶ could change our understanding of GL instability as happening between uniform black string and single black hole without any intermediate steps



Black rings and holes in higher dimensions

The non-uniqueness + phase structure of rotating rings in higher dimensions turns out to be intimately related to that of black hole solutions of vacuum Einstein equations in six or more dimensions

Emparan,Harmark,Niarchos,NO,Rodriguez

► construct thin rotating black rings in higher dimensions (D $\geq$ 6) with horizon topology $S^{D-3} \times S^1$

- matched asymptotic expansion   Harmark/Gorbonos,Kol
  - metric of thin black ring in linearized gravity
  - near-horizon metric (dipole perturbations corresponding to bending a boosted black string
  - match in overlap zone + require regular event horizon
  $\rightarrow$ zero pressure condition is required (balancing of ring)

► first steps to qualitatively complete phase diagram of asymptotically flat, neutral and rotating blackfolds

- exploit connection between black holes/strings/branes in KK spacetimes and higher-dim rotating black holes   Emparan,Myers
  - use the analogy and known phase structure of KK BHs to uncover the phase diagram of stationary BHs
  - conjecture existence of infinite number of pinched black holes connection to black Saturns configs thru merger transitions

Thin black rings from circular boosted black strings

- in limit of very large radius R of the S^1 of 5D black ring
  metric becomes that of a (critically) boosted 5D black string

Emparan/Hovdebo,Myers/
Emparan,Elvang,Virmani

aim: use perturbative approach to construct thin black rings in $\mathcal{M}^{n+4}$
starting from boosted black string in $\mathcal{M}^{n+4}$

horizon topology $S^1 \times S^{n+1}$
thin means: $R \gg r_0$

zeroth order solution in $1/R$: straight boosted black string

$$ds^2 = -\left(1 - \cosh^2\alpha \frac{r_0^n}{r^n}\right) dt^2 - 2\frac{r_0^n}{r^n}\cosh\alpha \sinh\alpha \, dt dz + \left(1 + \sinh^2\alpha \frac{r_0^n}{r^n}\right) dz^2 + \left(1 - \frac{r_0^n}{r^n}\right)^{-1} dr^2 + r^2 d\Omega_{n+1}^2$$

- distributional source of energy/momentum for thin black ring

$$T_{tt} = \frac{r_0^n}{16\pi G}\left(n\cosh^2\alpha + 1\right)\delta^{(n+2)}(r)$$

$$T_{tz} = \frac{r_0^n}{16\pi G} n \cosh\alpha \sinh\alpha \, \delta^{(n+2)}(r)$$

$$T_{zz} = \frac{r_0^n}{16\pi G}\left(n\sinh^2\alpha - 1\right)\delta^{(n+2)}(r)$$

Equilibrium condition

► boosted black string limit of black ring is described by three parameters

$$r_0 \ , \quad R \ , \quad \alpha$$

expect physically: two parameters (e.g. given radius and mass, spin is fixed)

dynamical balance condition relates the three parameters

$$K_{\mu\nu}{}^{\rho} T^{\mu\nu} = 0 \longrightarrow \frac{T_{zz}}{R} = 0 \longrightarrow \sinh^2\alpha = \frac{1}{n}$$

EOM for probe brane-like objects

Carter

critical boost:

enables computation of all leading order thermodynamic quantities !

$$M = \frac{\Omega_{n+1}}{8G} R\, r_0^n (n+2)$$

$$J = \frac{\Omega_{n+1}}{8G} R^2\, r_0^n \sqrt{n+1}$$

$$\mathcal{A} = \Omega_{n+1}\, 2\pi R\, r_0^{n+1} \sqrt{\frac{n+1}{n}}$$

$$R = \frac{n+2}{\sqrt{n+1}} \frac{J}{M}$$

valid in large J limit of black ring

crucial assumption: horizon remains regular when boosted black string is curved

■ important check: rederive equilibrium condition from regularity condition

⟶ shows how GR encodes EOM of BHs as regularity conditions on geometry

Matched asymptotic expansion

► MAE = systematic approach to iteratively construct solution given known solution in some limit + then correcting it in perturbative expansion

(applied e.g. to construct metric of small black holes on circle)

thin black rings:
two scales r_0 , R

r_0: S^{n+1} radius

asymptotic zone: $r \gg r_0$

near-horizon zone: $r \ll R$

r is distance from ring

• step 0: solution in near-horizon zone to 0th order in $1/R$
= boosted black string of infinite length

• step 1: solve Einstein eqs. in linearized approximation around flat space for appropriate source (circular distribution of given mass/angular momentum density)
-valid to first order in $r_0^n \propto GM/R$, $r_0 \ll r$

• step 2: find linear corrections to boosted black string for perturbation that is small in $1/R$, i.e. analyze effect of slightly bending the string
- BCs fixed by matching to step 2 in overlap region: $r_0 \ll r \ll R$
+ require regularity at horizon

• step 3: solve next-to-linearized solution in asymptotic zone + use BCs from step 2
- not necessary for phys. quantities, since can use corrections near horizon + Smarr

Solution method

Step 1a: find metric in the linearized approximation around flat space sourced by a thin black ring localized on circle of radius R

$$\Box \bar{h}_{\mu\nu} = -16\pi T_{\mu\nu} \qquad T_{tt} \neq 0 \;, \quad T_{t\psi} \neq 0 \qquad \psi \simeq \frac{z}{R}$$

$$r_0 \gg r \qquad\qquad T_{\mu\nu} \sim \delta(r)$$

Step 1b: Consider overlap region $r_0 \ll r \ll R$

- effect of curving thin black string into locally arc of constant curvature radius R

$$g_{\mu\nu} = \eta_{\mu\nu} + \frac{r_0^n}{r^n}\left(h_{\mu\nu}^{(0)} + \frac{r\cos\theta}{R} h_{\mu\nu}^{(1)}\right)$$

$\eta_{\mu\nu}$ = flat space metric in ring-adapted coords

Note: can explicitly check that regular solution requires $T_{\psi\psi} = 0$
expected: additional stresses lead to singularities

Step 2: Find general solution near black string (hardest part) $r_0 \leq r \ll R$
+ match to metric in overlap region

$$g_{\mu\nu} = g_{\mu\nu}^{(\mathrm{bs})} + \frac{\cos\theta}{R} h_{\mu\nu}(r)$$

- can be solved exactly in terms of hypergeometric functions
- invoves only dipole perturbations: thermodynamics not corrected thru this order (exception: five dimensions)

Dimensionless quantities

▶ meaningful comparison in terms of dimensionless quantities
classical GR does not posses intrinsic scale: use mass

$$j^{n+1} \propto \frac{J^{n+1}}{GM^{n+2}}\,, \quad a_H^{n+1} \propto \frac{\mathcal{A}^{n+1}}{(GM)^{n+2}}\,, \quad \omega_H \propto (GM)^{\frac{1}{n+1}}\Omega_H\,, \quad \mathfrak{t}_H \propto (GM)^{\frac{1}{n+1}}T_H$$

• thin black ring $\quad j^{n+1} \sim \left(\frac{R}{r_0}\right)^n$

j very large

• ultraspinning MP BH $\quad j^{n+1} \sim \left(\frac{a}{r_0}\right)^{n-1}$

(a is rotation parameter)

▶ compare the "phase structure" for large j

$$a_H(j)\,, \quad \omega_H(j)\,, \quad \mathfrak{t}_H(j)$$

same as studying $\mathcal{A}(M,J)$ at fixed M

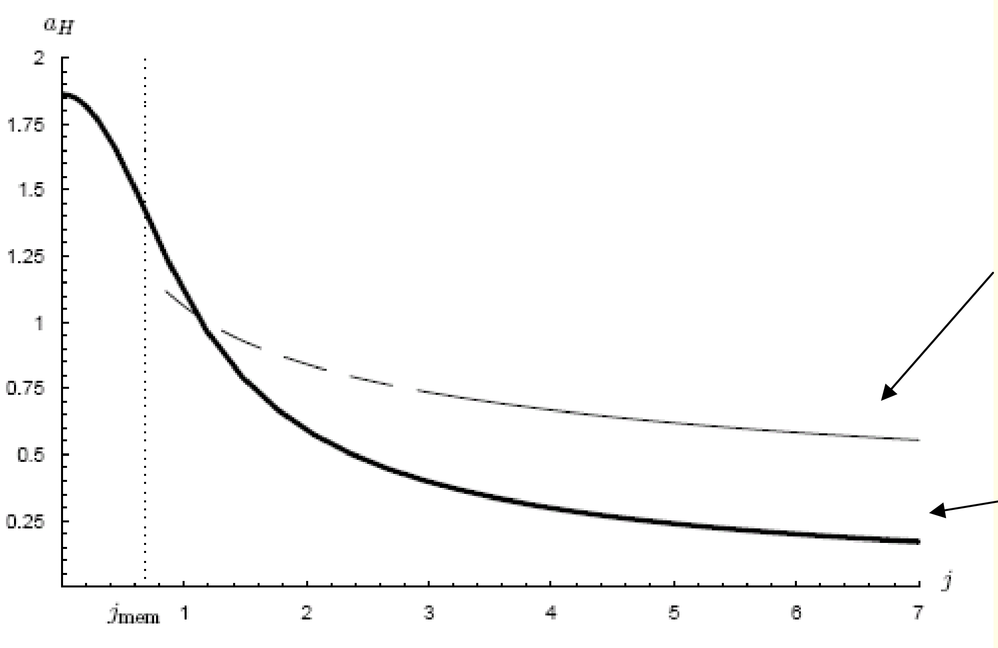
Higher-dimensional black rings vs. MP black holes

black ring | black hole

area $a_H \sim \frac{1}{j^{1/n}}$ | $a_H \sim \frac{1}{j^{2/(n-1)}}$

⇨ black rings dominate entropically in ultraspinning regime ($n > 1$)

e.g. in 7D



$$a_H^{\text{ring}} \sim \frac{1}{j^{1/3}}$$

$$a_H^{\text{hole}} \sim \frac{1}{j}$$

onset of membrane-like behavior of MP BH

Higher-dimensional black rings vs. MP black holes (cont'd)

	black ring	black hole
angular velocity	$\omega_H \sim \frac{1}{2j}$	$\omega_H \sim \frac{1}{j}$

► black ring has hole in middle (wheel), more efficient to carry spin than packaced MP BH (disk) $\longrightarrow$ ring rotates more slowly

temperature	$\mathfrak{t}_H \sim j^{1/n}$	$\mathfrak{t}_H \sim j^{2/(n-1)}$

► i.e. black ring cooler then MP BH at fixed mass:
same mass in a wheel makes it thicker than in a pancake
+ temperature inversely proportional to thickness

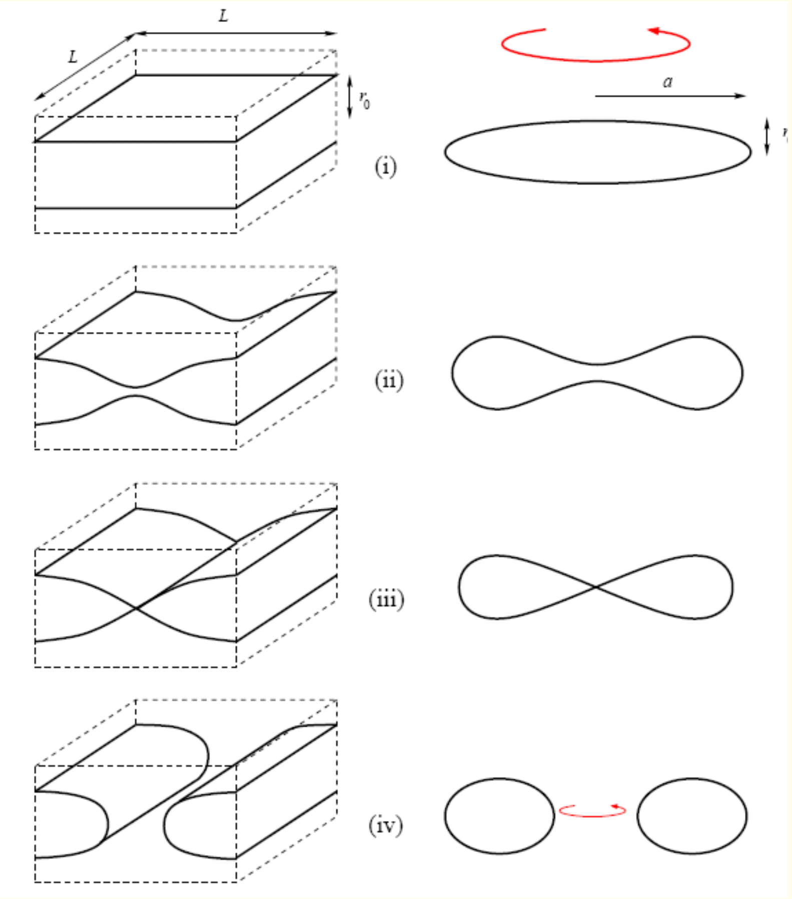
GL Instability of ultraspinning MP BH

MP BH approaches black membrane geometry $\mathbb{R}^2 \times S^n$ for large j

Emparan,Myers

$a \gtrsim r_0$ $a \sim J/M$

rotational axial symmetry so one translational symmetry along $\mathbb{T}^2$



uniform black membrane — ultraspinning MP black hole

pinched membrane (GL instability) non-uniform phase — lumpy (pinched) black holes

pinched-off membrane — pinched-off black hole

localized black string — black ring

Phase Diagram for Kaluza-Klein BHs on two-torus

- import knowledge of KK black holes on circle + add one uniform direction

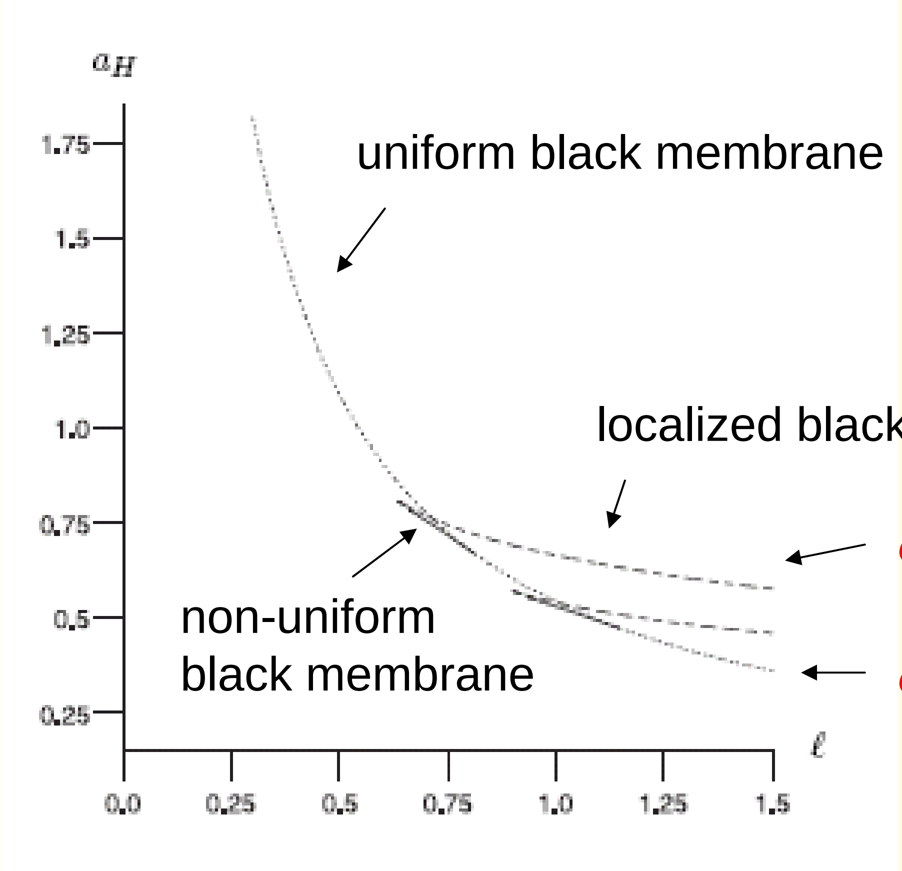
see e.g. review: Harmark,Niarchos,NO

• square two-torus sides L

identify: $j \leftrightarrow \ell$

$$\ell^{n+1} \propto \frac{L^{n+1}}{GM}$$

(measure linear size of horizon along rotation plane/torus for fixed mass)



example:
KK BHs in 7 dimensions
on $\mathcal{M}^5 \times \mathbb{T}^2$

$$a_H^{\text{lbs}}(\ell) \sim \ell^{-\frac{1}{n}}$$ (cf. thin BR)

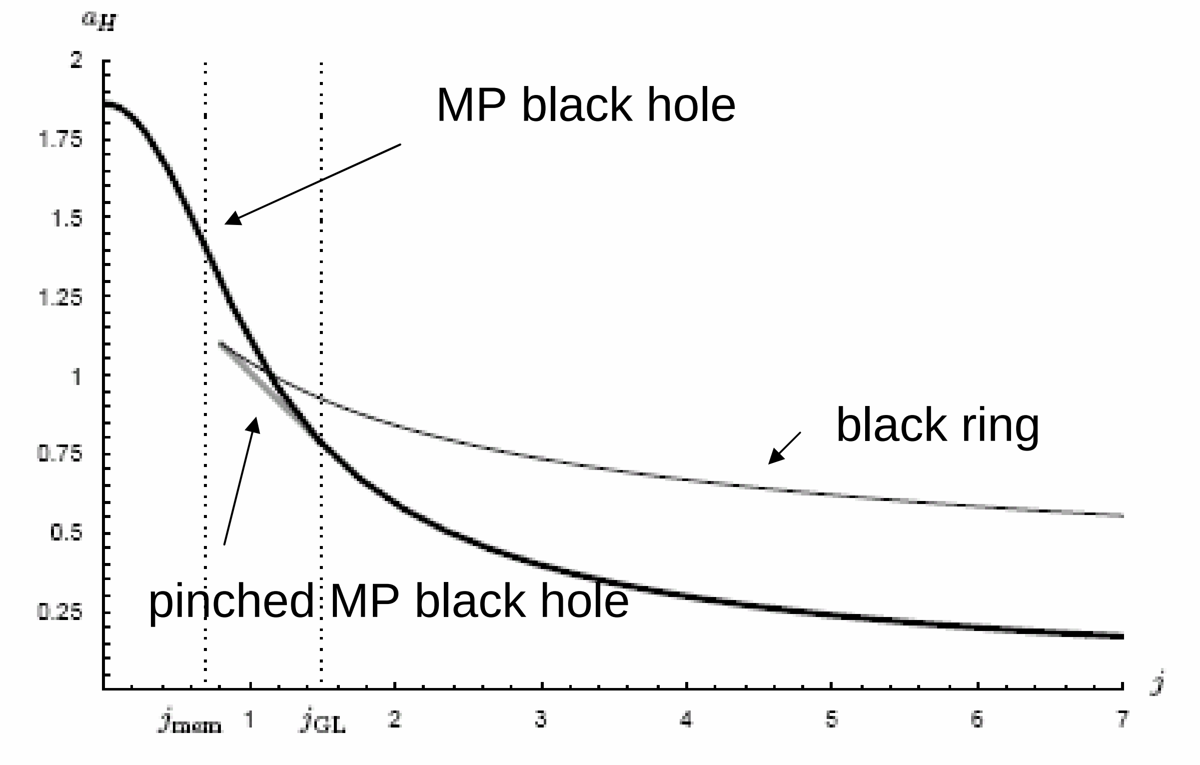
$$a_H^{\text{ubm}}(\ell) \sim \ell^{-\frac{2}{n-1}}$$ (cf ultraspinning MP BH)

+ copies by copying the solutions k times on the circle

Towards completing the phase diagram

◀ based on analogy with phase diagram for KK BHs on torus:
extrapolate to $j = \mathcal{O}(1)$ regime

- proposal for phase diagram of stationary BHs (one angular momentum)
in asymptotically flat space: main sequence = MP BH, pinched MP BH, black ring
(uniform, non-uniform, localized)

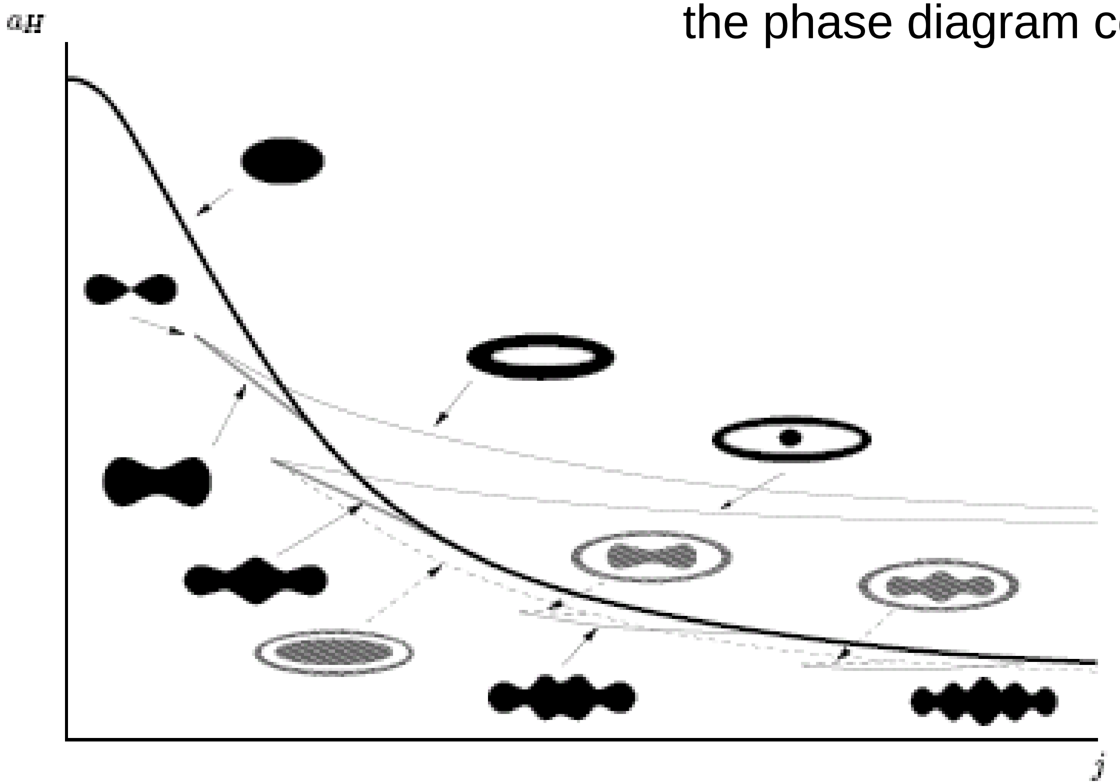


Black saturns and multi-pinches

most likely features

- main sequence: BH with pinch at rotation axis meets black ring phase
- infinite sequence of pinched BHs emanating from BH curve (from copies of the GL zero mode)
- upper black Saturn curve + merger to circular pinch

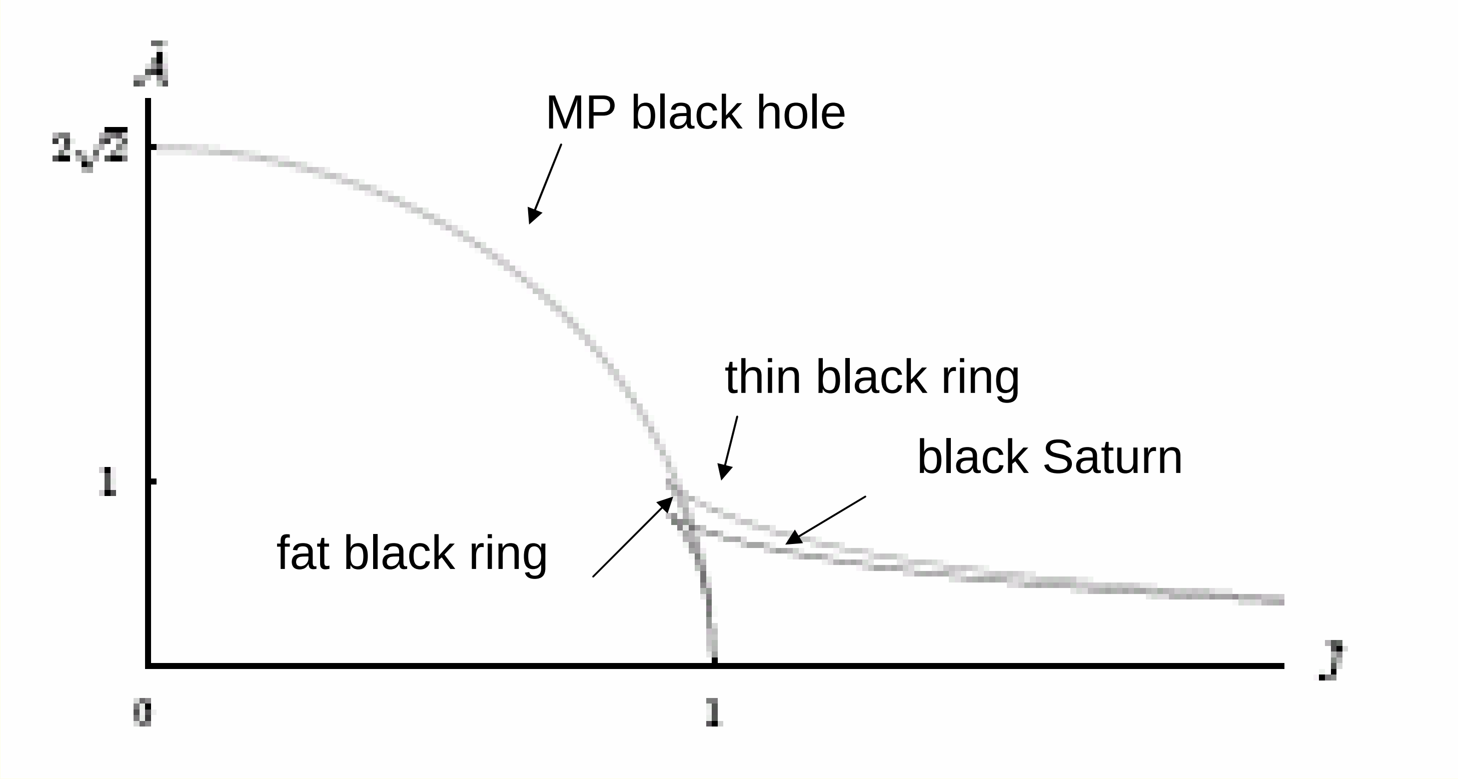
less compelling arguments for: pancaked + pinched black Saturns (but admit a simple and natural way for completing the phase diagram consistent with available info)



Comparison to five dimensions

5D : MP BHs have upper bound on j (black membranes do not exist in 5D)

- fat black ring instead of pinched MP (behave like drilled-through MP BH)
- only one type of black Saturn at large j



Further properties

◀ so far: thermal equilibrium phases (equal temperatures/angular velocities when more than one black object present)

non-thermal equilibrium phases perfectly valid as stationary multi-BH configurations of GR $\longrightarrow$ continuous families of solutions, e.g

.

more general black Saturns, di-rings etc.
(analogue of localized multi-BH solutions in KK space with unequal mass BHs)

Dias,Harmark,Myers,NO

◀ stability properties

(like in 5D) black rings at large j , GL-type instability creating ripples on S^1

fragments the ring into black holes flying apart

- MP BH + pinched BH could suffer from same type of instability

- black ring solutions below the cusp could be unstable towards radial perturbations causing collaps into MP BH

Future directions + outlook

► KK black holes

- further examine possibility of new non-uniform strings and lumpy black holes
- analyatical second order corrections, higher D compace spaces + adding J
  - apply effective FT technique of Chu, Goldberger, Rothstein
- numerical studies
  - extend into non-perturbative domain, temp. converge for multi BH ?
- applications to ST + dual gauge theories (see next time)
  - multiply gapped eigenvalue distributions as saddle points in finite T SYM ?
  - 3-charge multi BHs on circle + microscopic entropy Harmark,Kristjansen,NO,Roenne/ Chowdhurry,Giusto,Mathur
- examine fluid analogy

► higher D black rings

- black saturns, rings in (A)dS spaces, dipoles, etc.
- other topologies $S^2 \times S^2$, $S^2 \times T^2$, $S^2 \times \Sigma_{g>1}$ (in six dimensions)
  - boosted black p-branes: $S^{D-2-p} \times T^p$ (in progress)
- balance conditions, global properties (embedding of the different topologies)
- exact solutions ? - numerics, effective FT techniques for thermodynamics
- SUSY black rings + ST
- duality to plasma balls + rings in AdS (cf. Lahiri,Minwalla) – many similar features

► further explore relation between phase structure of KK BHs and rotating black objects