2009-05-01

Black rings from fluid mechanics

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Subhaneil Lahiri
based on arXiv:0705.3404 [hep-th] with Shiraz Minwalla
and arXiv:0903.4734 [hep-th] with Jyotirmoy Bhattacharya
May 1, 2009

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Higher dimensional gravity
General relativity makes sense in any $\#$ of dimensions.
D is a parameter.
We vary parameters to understand the theory better: c.f. coupling constants, gauge groups, ...
Sometimes we need extra dimensions: string theory, large extra dimensions scenarios, ...
Is gravity the same in $D > 4$?

1. Why higher D gravity?
2. 1/D expansion
3. perturbation theory. SU(2), SU(infinity).

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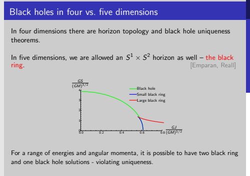
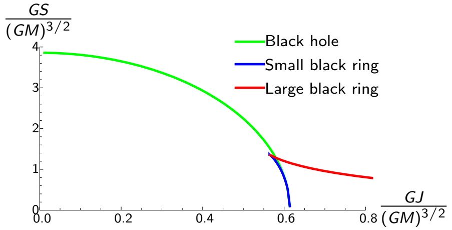


1/2 Black holes have thermodynamics. Plot phase diagBlack holes have thermodynamics. Plot phase diag

Black holes in four vs. five dimensions

In four dimensions there are horizon topology and black hole uniqueness theorems.

In five dimensions, we are allowed an $S^1 \times S^2$ horizon as well – the black ring. [Emparan, Reall]



For a range of energies and angular momenta, it is possible to have two black ring and one black hole solutions - violating uniqueness.

Black rings from fluid mechanics
└ Motivation
└ Higher dimensional gravity
└ Higher dimensions

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Higher dimensions

For $D \geq 6$: no exact solutions (except Myers-Perry). Approximate solutions for $R_{S^1} \gg R_{S^3}$.

[Emparan et al.]

1/3 One possible phase diag. ∃ another

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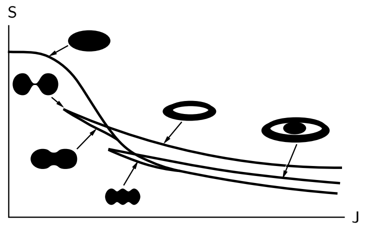

[Emparan et al.]

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- Motivation
  - Higher dimensional gravity
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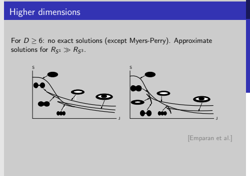

2/3 Common features: robust

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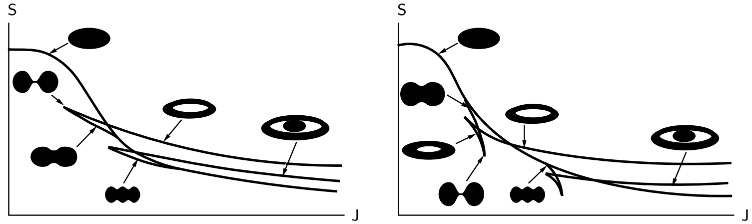

[Emparan et al.]

Black rings from fluid mechanics
└Motivation
  └Higher dimensional gravity
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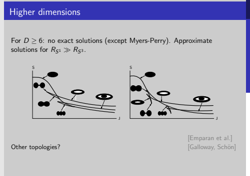

3/3 Positive Yamabe. Not every allowed exists: S^3/Γ

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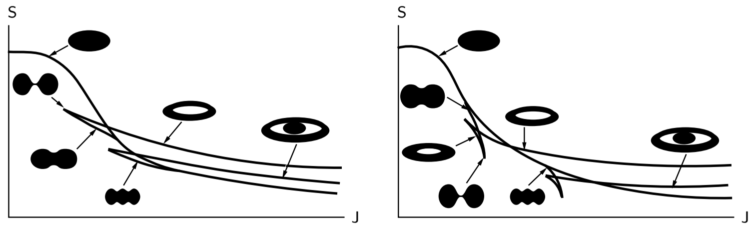
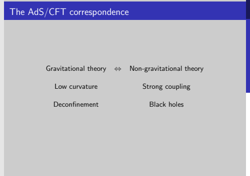


[Emparan et al.]
[Galloway, Schön]

Other topologies?



1. We'll look at deformed version: confining

The AdS/CFT correspondence

Gravitational theory	$\Leftrightarrow$	Non-gravitational theory
Low curvature		Strong coupling
Deconfinement		Black holes

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Black rings from fluid mechanics
└Motivation
└The AdS/CFT correspondence
└Black holes and fluid mechanics

Black holes and fluid mechanics

At long wavelengths, deconfined plasma described by fluid mechanics.

Only input: equation of state, transport coefficients. Also works at strong coupling.

1/2

1. Compute eos, trans, difficult in CFT.
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Equation of state: black hole thermodynamics, static case.
Transport coefficients: small fluctuations, e.g. $\eta/s = 1/4\pi$. [Son,Starinets]
$\Longrightarrow$ universal features of black holes at long wavelengths.

2/2

1. Compute eos, trans, difficult in CFT.
2. Once we know them, strong coupling doesn't matter
3. Take data from static. Predict features of non-static

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Outline

1. Motivation
2. Plasmaball setup
3. Relativistic fluid mechanics
4. Three dimensional configurations
5. Higher dimensional generalisations
6. Summary

Outline

Plasmaballs in confining theories

Plasmaballs are a bubbles of deconfined phase, surrounded by confined phase, held together by surface tension.

Focus on theories that come from compactifying conformal theories on a Scherk-Schwarz circle.

Leads to confining theory.

1. Why 1st order
2. with gravity dual
3. $l_{\rm mfp} \sim R_\theta$. Reduce - $D = d + 2$. $n - 1$ angular momenta.

Plasmaballs in confining theories

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Confined phase
At low temperatures, gravity dual: AdS soliton:
$$\mathrm{d}s^2 = \frac{R_{\text{AdS}}^2}{z^2}\left(-\mathrm{d}t^2 + F_{R_\theta}(z)\,\mathrm{d}\theta^2 + \mathrm{d}\vec{x}^2 + \frac{1}{F_{R_\theta}(z)}\,\mathrm{d}z^2\right),$$
where $F_a(u) = 1 - \left(\frac{\pi z}{a}\right)^4$ and $R_{\text{AdS}}^2 = \sqrt{\lambda}\alpha'$. [Witten]
Small z: Poincaré AdS_5 with one compact direction.
At $z = R_\theta/\pi$, the θ circle contracts: space stops.

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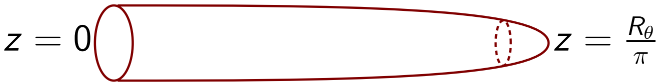

Deconfined phase
At high temperatures: the black brane:
$$\mathrm{d}s^2 = \frac{R_{\text{AdS}}^2}{z^2}\left(-F_\beta(z)\,\mathrm{d}t^2 + \mathrm{d}\theta^2 + \mathrm{d}\vec{x}^2 + \frac{1}{F_\beta(z)}\,\mathrm{d}z^2\right).$$
Horizon at $z = \frac{\beta}{\pi}$. Temperature: $\mathcal{T} = 1/\beta$.

1/2

1. Double Wick rotation

Deconfined phase

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Dominant phase above transition temperature, $\mathcal{T}_{\text{c}} = \frac{1}{R_\theta}$.

The equation of state of the dual plasma can be found from this gravity solution.

$$\mathcal{P} = \frac{\alpha}{\mathcal{T}_{\text{c}}}\left(\mathcal{T}^4 - \mathcal{T}_{\text{c}}{}^4\right).$$

2/2

1. Conformal.
2. Different reference.
3. Reduction.

Deconfined phase

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Plasmaball solutions
On the bulk side, deep interior looks like black brane. Far from the plasmaball, it looks like the AdS soliton. There is a domain wall that interpolates between the two.
In the limit of infinitely large radius, a numerical domain wall solution has been found. The surface tension and thickness can be computed from this solution. [Aharony, Minwalla, Wiseman]

1. Vertical Hawking - AdS
2. Horizontal Hawking - flat
3. between flat and AdS. $C < 0$.
4. Only $\sigma(\mathcal{T}_c)$. Ignore temp dep

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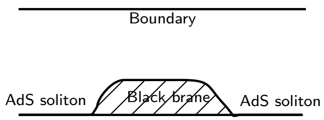

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Topology

The Scherk-Schwarz circle does not contract in the black brane region but does contract in the AdS soliton region.

Horizon topology: fibre circle over the plasmaball, contracting at surfaces.

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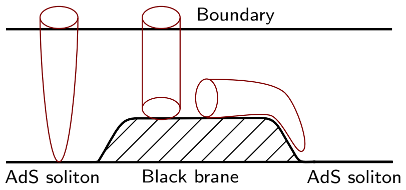

Horizon topology: fibre circle over the plasmaball, contracting at surfaces.

Fluid mechanics

The equations of motion are $\nabla_\mu T^{\mu\nu} = 0$. The dynamical input is in specifying $T^{\mu\nu}$.

For long wavelengths, we need only go up to one derivative terms: $T^{\mu\nu} = T^{\mu\nu}_{\text{perfect}} + T^{\mu\nu}_{\text{dissipative}}$.

Coefficients depend on $\mathcal{T}$. Determined from static black brane.

This approximation breaks down at surfaces – but at scales $\gg$ surface thickness we can replace these regions with a δ-function localised surface tension.

Benefit of fluid pic. Know deriv exp in gravity. Surf, puzzle solved centuries ago

1. equilibrium -¿ dissipative =0
2. rest frame temp

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Three dimensional configurations

Rigid rotation: $(u^t, u^r, u^\phi) = \gamma(1, 0, \Omega)$, where $\gamma = \frac{1}{\sqrt{1-v^2}}$.
Centripetal force provided by pressure gradient.

1/4

1. $\theta, \eta = 0$ - rotation + boost.
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Surfaces: $\mathcal{P} = \pm\frac{\sigma}{r}$. Relates $(\mathcal{T}/\gamma)$ to Ω and position of surface.

4/4

1. $\theta, \eta = 0$ - rotation + boost.
2. press grad - temp grad.
3. extra term in q
4. inner / outer.
5. 2 param.

Three dimensional configurations

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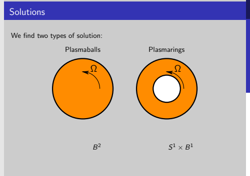
Black rings from fluid mechanics
└Three dimensional configurations
  └Solutions
    └Solutions

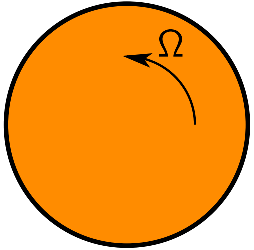


1/2

Solutions

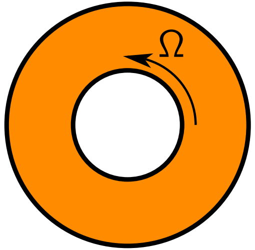
We find two types of solution:

Plasmaballs



B^2

Plasmarings



$S^1 \times B^1$

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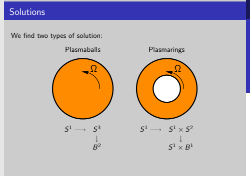
Black rings from fluid mechanics
└Three dimensional configurations
└Solutions
└Solutions



2/2

Solutions

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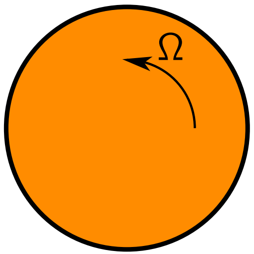
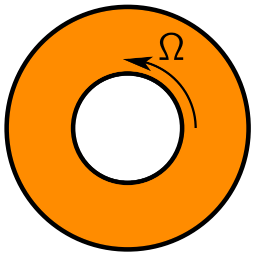
Plasmaballs



$$\begin{tikzcd} S^1 \arrow[r] & S^3 \arrow[d] \\ & B^2 \end{tikzcd}$$

Plasmarings



$$\begin{tikzcd} S^1 \arrow[r] & S^1 \times S^2 \arrow[d] \\ & S^1 \times B^1 \end{tikzcd}$$

Thermodynamics
We compute the thermodynamic properties of the whole solution with
$$E = \int \mathrm{d}^2 x \left(T^{tt}\right), \quad L = \int \mathrm{d}^2 x \left(r^2 T^{t\phi}\right), \quad S = \int \mathrm{d}^2 x \left(\gamma s\right).$$

1/2

1. include KE. Different to $\mathcal{E}$

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Then we compute an overall temperature and angular velocity via
$$\mathrm{d}E = T\mathrm{d}S + \Omega \mathrm{d}L,$$
we find
$$T = \frac{\mathcal{T}}{\gamma}, \qquad \Omega \text{ as before}.$$

2/2

1. include KE. Different to $\mathcal{E}$
2. Different to $\mathcal{T}$
3. Identify with Hawking temp. const on horizon.
4. redshift glueballs

Thermodynamics

We compute the thermodynamic properties of the whole solution with

$$E = \int \mathrm{d}^2x \left(T^{tt}\right),$$

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Black rings from fluid mechanics
└Three dimensional configurations
  └Thermodynamics
    └Phase diagram

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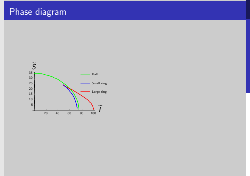
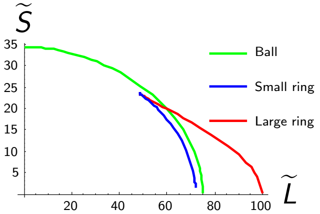


1/2

1. approx break down at ext
2. c.f. flat

Phase diagram



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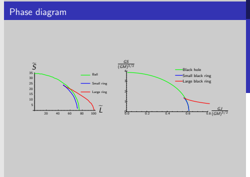
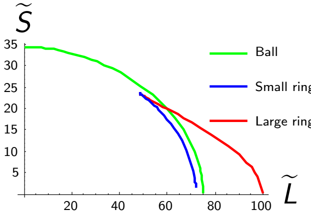
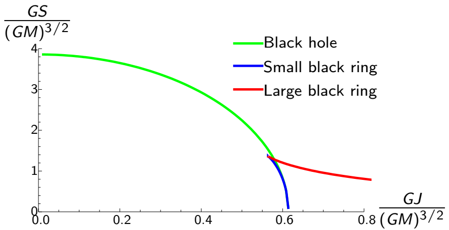


2/2

1. approx break down at ext
2. c.f. flat
3. upper bound on L
4. Precise and rigorous for SSAdS. Qualitative for flat.
5. Left, easy. Right - hard.

Phase diagram





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Black rings from fluid mechanics
└ Higher dimensional generalisations
  └ Six dimensional gravity
    └ Topologies in six dimensions

Topologies in six dimensions

S^4 $S^3 \times S^1$

$S^2 \times S^2$ $S^2 \times T^2$

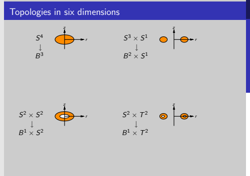
1/3

1. not full list. just ones we can imagine as fluids

Topologies in six dimensions

S^4 $S^3 \times S^1$

$S^2 \times S^2$ $S^2 \times T^2$

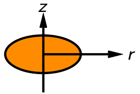


2/3

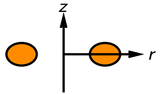
1. not full list. just ones we can imagine as fluids
2. cylindrical coords. Suppress ϕ

Topologies in six dimensions

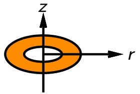
$$S^4 \downarrow B^3$$



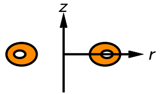
$$S^3 \times S^1 \downarrow B^2 \times S^1$$

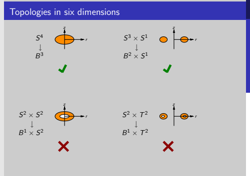


$$S^2 \times S^2 \downarrow B^1 \times S^2$$



$$S^2 \times T^2 \downarrow B^1 \times T^2$$



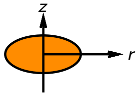


3/3

1. not full list. just ones we can imagine as fluids
2. cylindrical coords. Suppress ϕ

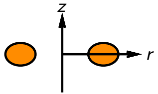
Topologies in six dimensions

$$S^4 \downarrow B^3$$



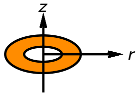
✓

$$S^3 \times S^1 \downarrow B^2 \times S^1$$



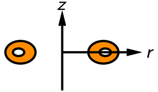
✓

$$S^2 \times S^2 \downarrow B^1 \times S^2$$



✗

$$S^2 \times T^2 \downarrow B^1 \times T^2$$



✗

Solving equations of motion

Again: rigid rotation $(u^t, u^r, u^\phi, u^z) = \gamma(1, 0, \Omega, 0)$.

Again: $\frac{\mathcal{T}}{\gamma} = T =$ constant.

Now: surface satisfies $\mathcal{P} = \sigma K^\mu_\mu$.

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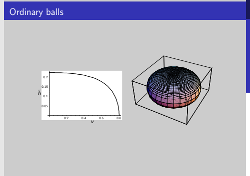
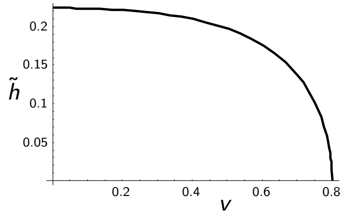
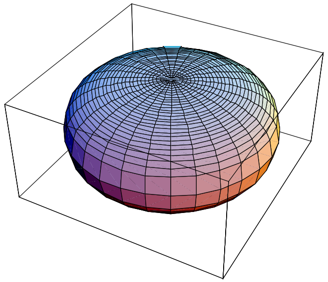
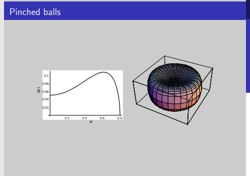


Increase Ω, $\mathcal{P}(0) \to 0$

Ordinary balls

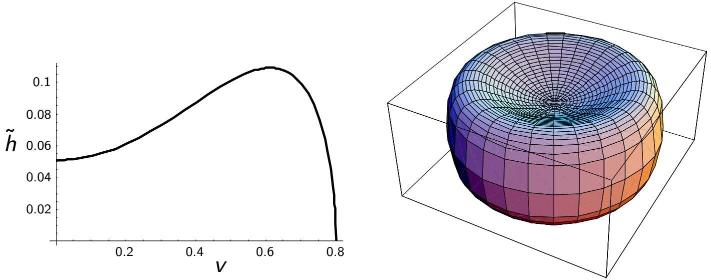






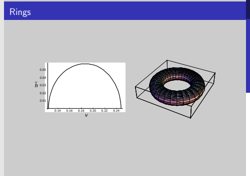
1. Emparan, Myers, wavy BH.
2. Increase Ω, $h(0) \to 0$

Pinched balls

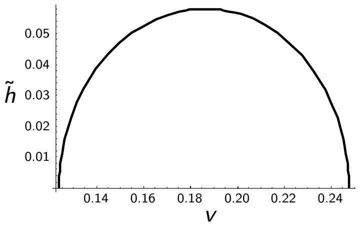


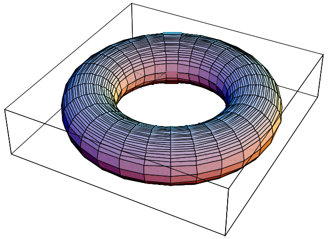
2009-05-01

Black rings from fluid mechanics
└ Higher dimensional generalisations
  └ Solutions in six dimensions
    └ Rings



Rings

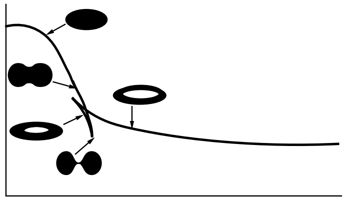




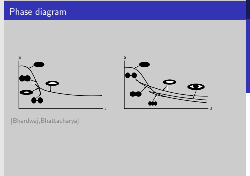
1/3

1. compare with proposals

Phase diagram



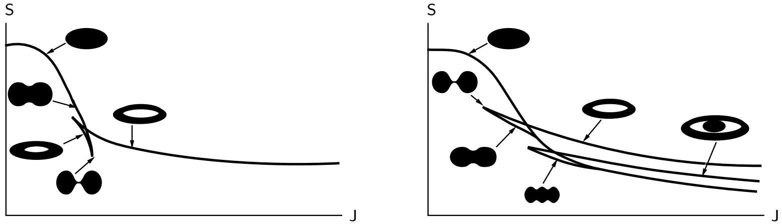
[Bhardwaj,Bhattacharya]



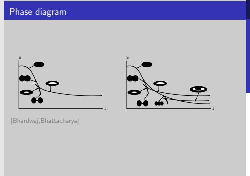
2/3

1. compare with proposals
2. not good

Phase diagram



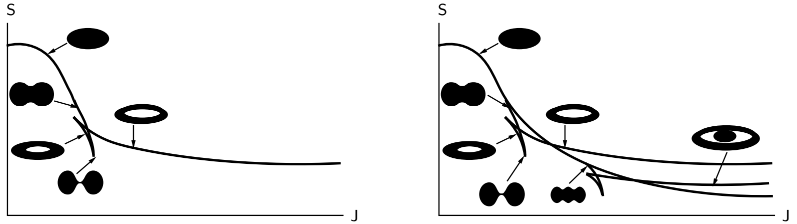
[Bhardwaj,Bhattacharya]



3/3

1. compare with proposals
2. not good
3. good. Myers-Perry continues past wavy BH

Phase diagram



[Bhardwaj,Bhattacharya]

Black rings from fluid mechanics
└Higher dimensional generalisations
└Seven dimensional gravity
└Topologies in seven dimensions

2009-05-01

Topologies in seven dimensions

S^5 $S^4 \times S^1$ $S^3 \times T^2$

$S^3 \times S^2$ $S^2 \times S^2 \times S^1$ $S^2 \times T^3$

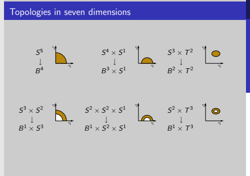
1/2

1. again not full list

Topologies in seven dimensions

S^5 $S^4 \times S^1$ $S^3 \times T^2$

$S^3 \times S^2$ $S^2 \times S^2 \times S^1$ $S^2 \times T^3$

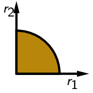


2/2

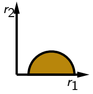
1. again not full list
2. Ball, ring, torus.
3. hollow exist?.

Topologies in seven dimensions

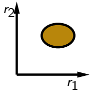
$$\begin{array}{c} S^5 \\ \downarrow \\ B^4 \end{array}$$



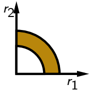
$$\begin{array}{c} S^4 \times S^1 \\ \downarrow \\ B^3 \times S^1 \end{array}$$



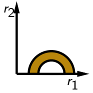
$$\begin{array}{c} S^3 \times T^2 \\ \downarrow \\ B^2 \times T^2 \end{array}$$



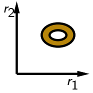
$$\begin{array}{c} S^3 \times S^2 \\ \downarrow \\ B^1 \times S^3 \end{array}$$



$$\begin{array}{c} S^2 \times S^2 \times S^1 \\ \downarrow \\ B^1 \times S^2 \times S^1 \end{array}$$



$$\begin{array}{c} S^2 \times T^3 \\ \downarrow \\ B^1 \times T^3 \end{array}$$



Approximate solutions

For ring, $B^3 \times S^1$, take $\epsilon = \frac{R_{B^3}}{R_{S^1}}$ small.

For 'torus', $B^2 \times T^2$, take $\epsilon = \frac{R_{B^2}}{R_{T^2}}$ small.

Expand in ϵ. At $\mathcal{O}(\epsilon^0)$ – just a tube.

Similar to black-fold construction of Emparan et al.

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2009-05-01

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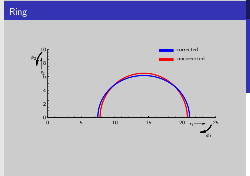
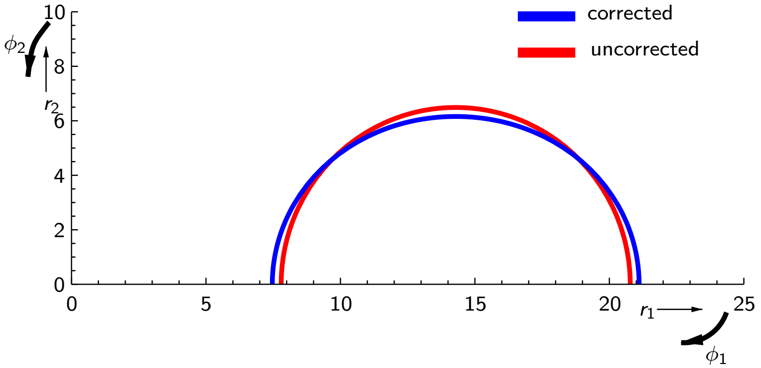
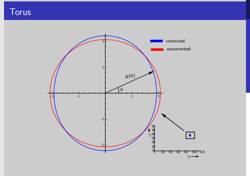
  └─Seven dimensional gravity
    └─Ring



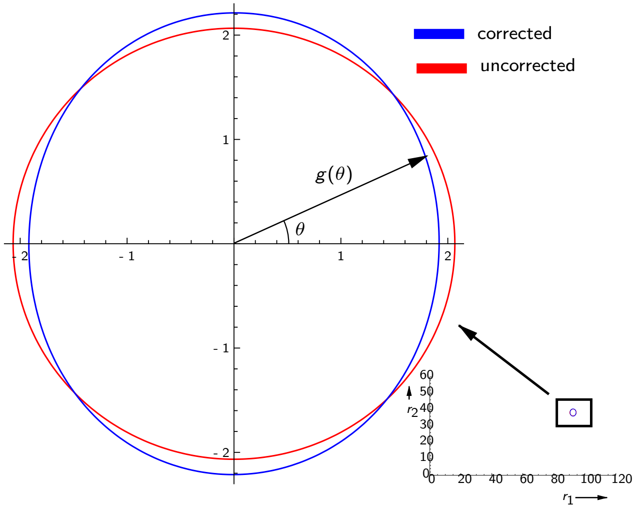
Ring





whole new topology

Torus



Summary

We can get insight to some problems in classical gravity from fluid mechanics in AdS/CFT.

In five dimensions – qualitative agreement with flat space gravity.

In six dimensions – proposal for phase diagram.

In seven dimensions – new topology.

Future: numerical solutions for $D = 7$, phase diagram.

Gregory-Laflamme vs. Plateau-Rayleigh. [Caldarelli et al.]

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