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Aspects of black holes and holography in gauged supergravity

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Outline

1. Intro
    - *black holes in gauged supergravity*
    - *properties of BPS configurations in AdS4*
2. On shell action and Mass
    - *holographic renormalization*
    - *BPS black hole or domain wall flow?*
3. Thermodynamics and phase transitions
    - *Phase space at T=0 and a QCP*
    - *Phase space at finite T*

Motivations

Black holes as a Quantum Gravity Lab

- Charged Black holes and branes constituents
  - ➡ Microscopic entropy
- Holographic dual theories
  - ➡ Phase transitions

Two main areas of investigation:

1. String/M-theory BHs
2. AdS black holes

Motivations

Gauged Supergravity

Holography requires to go beyond Minkowski asymptotics

- The gauging introduces a potential that behaves as a cosmological constant of which AdS is a supersymmetric vacuum

$$V(\varphi) \neq 0 \ , \qquad \partial_\varphi V|_\infty = 0$$

- A Supergravity theory with gauging has charged particles and the vacuum may break supersymmetry spontaneously. New dynamics?

- What's the String/M-theory interpretation of a black hole in a Minkowski vacuum of a gauged SUGRA?

Supersymmetric solutions in N=2 SG

Vacua from String/M-theory

Interpolating geometries
AdS_d x S^d to flat space or another SUSY space

BPS black holes

Static background, abelian and scalar fields

$$S = \int d^4x \left(-\frac{R}{2} + g_{i\bar{\jmath}} \partial_\mu z^i \partial^\mu \bar{z}^{\bar{\jmath}} + \mathrm{Im}\mathcal{N}_{\Lambda\Sigma} F^\Lambda_{\mu\nu} F^{\Lambda\,\mu\nu} + \right.$$
$$\left. + \frac{1}{2\sqrt{-g}} \mathrm{Re}\mathcal{N}_{\Lambda\Sigma} \epsilon^{\mu\nu\rho\sigma} F^\Lambda_{\mu\nu} F^\Sigma_{\rho\sigma} - V_g \right)$$

Interpolating geometry + scalar fields

$$ds^2 = -e^{2U(r)} dt^2 + e^{-2U(r)} (dr^2 + e^{2\psi(r)} d\Omega^2)$$

BPS black holes as attractor points

[Ferrara, Gibbons, Kallosh, Strominger, '95,'96]

$$AdS_2 \times S^2 \longleftrightarrow \mathrm{R}^{1,3}$$

$$\partial_i |\mathcal{Z}(p, q, z^j, \bar{z}^j)| = 0$$

AdS4 BPS black holes as holographic RG flows

$$AdS_2 \times S^2 \longleftrightarrow AdS_4$$

[Cacciatori, Klemm '09]

Translates radial equations in algebraic relations that capture the physics of the (dual) theory

Gauged Supergravity

Introduces charged scalars

$$\partial_\mu z^i \to \partial_\mu z^i + g A_\mu^\Lambda k_\Lambda^i \,, \qquad \partial_\mu q^u \to \partial_\mu q^u + g A_\mu^\Lambda k_\Lambda^u$$

Scalar potential

$$V_g = (g_{ij^\star} k_\Lambda^i k_\Sigma^{j^\star} + 4 h_{uv} k_\Lambda^u k_\Sigma^v) \bar{L}^\Lambda L^\Sigma + (U^{\Lambda\Sigma} - 3 \bar{L}^\Lambda L^\Sigma) \mathcal{P}_\Lambda^x \mathcal{P}_\Sigma^x$$

- possible AdS geometries
- fermionic fields are charged
- em - duality invariance is broken

R-symmetry gauging for black holes

The gauging is specified by constant moment maps $\boxed{\mathcal{P}^0_\Lambda = 0 \qquad \mathcal{P}^x_\Lambda = \xi^x_\Lambda}$

It involves the abelian isometry $\quad U(1)_R \subset SU(2)_R \subset \mathcal{QM}$

For this particular choice the scalar potential is $\quad \mathcal{L} = g\mathcal{P}^x_M \mathcal{V}^M$

$$\boxed{V_g = g^{i\bar{\jmath}} D_i \mathcal{L} D_{\bar{\jmath}} \bar{\mathcal{L}} - 3\mathcal{L}\bar{\mathcal{L}}}$$

Scalar fields are still neutral and field strenghts abelian

$$\begin{array}{llcl} \text{line bundle} & \mathcal{Q} & \rightarrow & \widehat{\mathcal{Q}} = \mathcal{Q} + g\, A^\Lambda\, \cancel{\mathcal{P}^0_\Lambda} \\ SU(2)\ \text{bundle} & \omega^x & \rightarrow & \widehat{\omega}^x = \omega^x + g\, A^\Lambda\, \mathcal{P}^x_\Lambda \end{array}$$

R-symmetry gauging for black holes

Not only BHs are solution of the Euler-Lagrange equations, but, when the system preserves some supersymmetry, it obeys first order equations.

$$ds^2 = -e^{2U(r)}dt^2 + e^{-2U(r)}(dr^2 + e^{2\psi(r)}d\Omega^2)$$

The field equations satisfied by the BPS back hole are $\mathcal{Z} = \mathcal{Q}_M \mathcal{V}^M(z^i, \bar{z}^{\bar{\imath}})$

$$\begin{array}{rcl} U' &=& -e^{U-2\psi}\mathrm{Re}(e^{-i\alpha}\mathcal{Z}) + e^{-U}\mathrm{Im}(e^{-i\alpha}\mathcal{L}) \\ \psi' &=& 2e^{-U}\mathrm{Im}(e^{-i\alpha}\mathcal{L}) \\ \dot{z}^i &=& -e^{i\alpha}g^{i\bar{\jmath}}(e^{U-2\psi}\bar{D}_{\bar{\jmath}}\bar{\mathcal{Z}} + ie^{-U}\bar{D}_{\bar{\jmath}}\bar{\mathcal{L}}) \end{array}$$

It is in fact a Hamilton-Jacobi flow with the Hamiltonian constraint:

$$\langle \mathcal{G}, \mathcal{Q} \rangle = -1$$

BPS first order flow is driven by the superpotential

$$\boxed{W_{BH} = e^U |\mathcal{Z} - ie^{2(\psi-U)}\mathcal{L}|}$$

SUSY structure at the horizon

$AdS_2 \times S^2$	$g = 0$	$\partial_i \lvert\mathcal{Z}\rvert = 0$	$\mathcal{N} = 2$
	$g \neq 0$	$\partial_i \dfrac{\lvert\mathcal{Z}\rvert}{\lvert\mathcal{W}\rvert} = 0$	$\mathcal{N} = 1$

$$\mathcal{W} = g \mathcal{P}^x_M \mathcal{V}^M \qquad \mathcal{Z} = q_\Lambda L^\Lambda - p^M M_\Lambda$$

- Killing spinor equations at AdS_2 x S^2 show a topological twist at the horizon for the S^2 factor
- The Killing spinor does not depend on the S^2 coordinates

$$\hat{\nabla}_{\underline{a}} \epsilon^i_{\pm} \mp \frac{1}{2\ell_{AdS}} \epsilon^{ij} \gamma_{\underline{a}} \epsilon_{j\pm} = 0 \qquad AdS_2$$

$$\hat{\nabla}_{\hat{a}} \epsilon^i_{\pm} + \frac{1}{2} \mathcal{V}_{\hat{a}}{}^i{}_j \epsilon^j_{\pm} = 0 \qquad S^2$$

[de Wit, Van Zalk, ’11]

$\longrightarrow$ *No more Bertotti-Robinson geometry, only N=1 SUSY*

BPS AdS_4 black holes

[Cacciatori, Klemm '09]

Finite horizon SUSY Solution requires:

- magnetic charge
- or magnetic gauging

$$g_\Lambda p^\Lambda - \tilde{g}^\Lambda q_\Lambda = \kappa$$

$$AdS_2 \times \Sigma_\kappa$$

$AdS_2 x S_2 \longrightarrow mAdS_4$

1/4 BPS states

[Dall'Agata, AG, Hristov, Vandoren]

[Klemm, Vaughan] [Halmagyi, Erbin, Vanel]

[Klemm, Marrani, Petri, Rabbiosi, Santoli..]

[Chow, Compère]

Extensions/applications

- Microstate counting
- Holography [Benini, Hristov, Zaffaroni]
- Hypermultiplets
  [Meessen, Ortin] [Halmagyi, Petrini, Zaffaroni]
  [Chimento, Faedo, Klemm, Nozawa, Toldo, Monten]
- 10-11D Uplift
  [Tomasiello, Katmadas]

Holography at maximally symmetric points

$$AdS_2 \times S^2 \longleftrightarrow AdS_4$$

Each of the fixed point is holographically a superconformal fixed point.
The black hole geometry is a flow in parameter space.

$$\partial_i |\mathcal{Z}| = 0 \longleftrightarrow \partial_i |\mathcal{W}| = 0$$

- What is the minimization/maximization dual to the above extermination in supergravity?
  - ➡ Hristov, Benini, Zaffaroni, 2015
- Proposal: two point function à la Intriligator
  - ➡ Amariti, AG 2015

Dual SCFT
in 3d -
no anomalies

Holography at maximally symmetric points

$$\partial_i |\mathcal{Z}| = 0$$

$\boxed{\text{Attractor mechanism for AdS4 and AdS2}}$

$$\Longleftrightarrow \quad \partial_i |W| \big|_{\{q^{u*},\, z^{i*},\, \bar{z}^{i*}\}} = 0 \qquad \langle k^u(q^*), \mathcal{V}(z^*, \bar{z}^*) \rangle = 0$$

The BPS flow starts on the AdS4 vacuum by effect of the background magnetic fields:

$AdS_2 \times S^2$	$g = 0$	$\partial_i \lvert\mathcal{Z}\rvert = 0$	$\mathcal{N} = 2$
	$g \neq 0$	$\partial_i \dfrac{\lvert\mathcal{Z}\rvert}{\lvert\mathcal{W}\rvert} = 0$	$\mathcal{N} = 1$
AdS_4	$\partial_i \lvert\mathcal{W}\rvert = 0$	*unconstrained*	$\mathcal{N} = 2$
	$\partial_i \lvert\mathcal{W}\rvert = 0$	$g_\Lambda m^\Lambda = -1$	$\dfrac{1}{4} - BPS$

(no more a vacuum solution)

Study of Phase space of black branes in AdS4

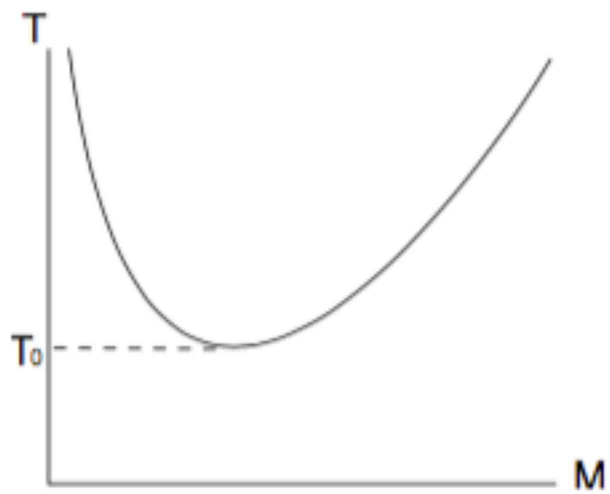
Applications to holography and dual 3D QFT

Overview

Black hole physics can teach about strongly coupled field theories

Investigate quantum critical phases of strongly coupled solid state systems

Hawking-Page transition for a black hole in anti de Sitter spacetime ['83]



Holographic interpretation as confinement/de-confinement phase transition [Witten '98]

Goal: analytic holographic studies of black branes in AdS_4

Branches of small/large black holes [Hristov, Vandoren, Toldo, '13]

Black branes phase transition in temperature [Caldarelli, Christodoulu, Papadimitriou, Skenderis, '16]

Finite temperature solutions in the t^3 model

[Klemm, Vaughan, Toldo, Vandoren, '12]

[AG, Toldo, '14]

General metric à la Duff-Liu

$$ds^2 = -e^K f(r) dt^2 + e^{-K} \left(\frac{dr^2}{f(r)} + r^2 d\Omega^2_{(2)} \right)$$

It can be extended to generic electric or magnetic gaugings, and for electric or magnetic solutions

$$\begin{aligned} e^{-K(r)} &= \sqrt{H_0 (H_1)^3}\ , \qquad f(r) = 1 + \frac{c_1}{r} + \frac{c_2}{r^2} + \ell_{AdS}^{-2} e^{-2K}\ , \\ H_\Lambda &= 1 + \frac{Q_\Lambda}{r}\ , \qquad \ell_{AdS} = \left(\frac{\sqrt{2} g_0^{1/4} g_1^{3/4}}{3^{3/4}} \right)^{-1} \end{aligned}$$

This is an equivalent parametrization, and its relation with the BPS formulation is given by

$$e^{\psi(r)} \equiv r \sqrt{f(r)}\ , \qquad e^{U(r)} = e^{K(r)/2} f(r)$$

Finite temperature solutions in the t^3 model

The solution has a real scalar and gauge fields

$$z(r) = \frac{3\xi_0}{\xi_1}\frac{Q_1 + r}{Q_0 + r}\,, \qquad A^\Lambda = -\ell_{AdS}\frac{\tilde{g}^\Lambda}{4}\sqrt{c_2 + Q_\Lambda(Q_\Lambda - c_1)}\cos\theta\, d\phi$$

satisfy the first order equations

$$\begin{aligned} z^{i\prime} &= -\frac{e^{K/2}}{r} g^{ij}\partial_j W_m \\ (r\, e^{-K/2})' &= W_m \end{aligned}$$

for a superpotential

$$W_{mag} = \mathrm{Im}\left(g_\Lambda \mathcal{I}_\infty^{\Lambda\Sigma} M_\Sigma\right)$$

- One recovers these first order equation from a squaring à la BPS of the action!
- First order equations are easier to solve than the second order equations of motion.

[AG, Toldo, '14]

Black holes or domain walls?

Solution with magnetic charges admits an extremal BPS limit, when the function f(r) has a double pole

$$r^2 f_0(r) \quad = \quad \frac{1}{\ell_{AdS^2}}(r^2 - r_h^2)^2$$

giving additional restrictions on the parameters c1 and c2.
The 1/4-BPS solution satisfies the Supersymmetric first order upon further constraint on the charges

$$g_\Lambda p^\Lambda - \tilde{g}^\Lambda q_\Lambda = \kappa$$

On-shell, the magnetic superpotential and the BPS one are identical functions of r, as expected

$$e^{-\psi(r)}\mathcal{W}(r) \equiv -\ell_{AdS} W_{mag}(r)$$

BPS black holes or supersymmetric domain walls ?

Black holes or domain walls?

There is an interesting characteristic of the BPS solutions that suggests they might be closely related to domain walls. For black brane, the supersymmetric constraint is simply

$$p^\Lambda g_\Lambda = 0 \ ,$$

so the zero charge limit is well defined, and independent of g. The first order flow then reduces to

$$\begin{aligned} U'(r) &= e^{-U}|\mathcal{L}| \ , \\ \psi'(r) &= 2e^{-U}|\mathcal{L}| \ , \\ \dot{z}^i &= -2g^{i\bar{\jmath}}e^{-U}\partial_{\bar{\jmath}}|\mathcal{L}| \end{aligned}$$

corresponding to the metric ansatz of a domain wall

$$ds^2_{Q=0} = e^{-2U}dr^2 + e^{2U}\left(-dt^2 + dx^2 + dy^2\right)$$

Holographic renormalization

Canonically normalized scalar field and Lagrangian

$$S = \int \sqrt{-g} d^4x \left(\frac{R}{2} + \frac{1}{2}\partial_\mu \varphi(r) \partial^\mu \varphi(r) - \left(\frac{3\xi_0}{\xi_1}\right)^{3/2} e^{\sqrt{6}\varphi} F^0_{\mu\nu} F^{0\,\mu\nu} + \right.$$
$$\left. -3 \left(\frac{3\xi_0}{\xi_1}\right)^{-1/2} e^{-\sqrt{2/3}\varphi} F^1_{\mu\nu} F^{1\,\mu\nu} - V(\phi) \right)$$

with potential $\quad V(\varphi) = -\frac{3}{\ell^2_{AdS}} \mathrm{Cosh}\left(\sqrt{\frac{2}{3}}\varphi\right) \qquad \ell^{-2}_{AdS} = g^2 \sqrt{\frac{4}{27}\xi_0 \xi_1^3}$

Dual operator conformal dimensions are $\quad \Delta_- = 1 \qquad \Delta_+ = 2$

corresponding to a scalar of mass $\quad m^2_\varphi \ell^2_{AdS} = -2$

we are in the window $\quad -9/4 \leq m^2_\varphi \ell^2_{AdS} \leq -9/4 + 1$

allows for mixed boundary conditions, both modes of the scalar fields are normalizable.

Holographic renormalization

Choice of canonical radius $$g_{tt} \sim \ell_{AdS}^{-2}(c + g^2 r^2 + \mathcal{O}(r^{-1}))$$

the metric asymptotes the AdS boundary as

$$ds^2 \sim d\tilde{r}^2 + e^{2\tilde{r}/\ell} h_{(0)ij}(x) dx^i dx^j$$

the field expansion in terms of the radial coordinate $$\frac{r}{\ell} = e^{\tilde{r}/\ell}$$

$$\varphi \sim e^{-\Delta_- \tilde{r}/\ell}(\varphi_-(x) + ...) + e^{-\Delta_+ \tilde{r}/\ell}(\varphi_+(x) + ...)$$

Multitrace deformation read by: $$\varphi_+ = \lambda \varphi_-^2 \qquad \lambda = \frac{\epsilon}{\sqrt{6}}$$

Only two points of a larger class found?

Holographic renormalization

Counterterm action $$I_{ct,can} = \int_{\partial\mathcal{M}_0} d^3x\sqrt{h}\ \left(W(\varphi) + W_0\mathcal{R}\right)$$

The Hamilton Jacobi equations imply the superpotential constraint

$$V(\phi) = \frac{1}{2}\left(\partial_\phi W^2 - \frac{3}{2}W^2\right)$$

A 1-parameter class of superpotential exists for the considered Lagrangian. They differ at cubic order in the fields expansion

$$W_\nu(\varphi) \quad = \quad -\frac{2}{\ell}\left(1 + \frac{\varphi^2}{4} + \frac{\nu}{6\sqrt{6}}\varphi^3 + \mathcal{O}(\varphi^4)\right)$$

Conditions for a well defined variational principle is that the superpotential has to be uniquely dependent on the value of lambda

[Papadimitriou, ‘07]

$$\nu(\lambda)\ , \qquad \varphi_+ = \lambda\varphi_-^2$$

Holographic renormalization

First order flow for the real scalar field

$$\begin{aligned} \varphi' &= \frac{\ell_{AdS}}{r} e^{K/2} \partial_\varphi W_{el,mag}(\varphi) \ , \\ (r e^{-K/2})' &= -\frac{1}{2} \ell_{AdS} W_{el,mag}(\varphi) \end{aligned}$$

the electric solution has $W_{el}(\varphi) = -\frac{2}{\ell_{AdS}} \left(\frac{3}{4} e^{\varphi/\sqrt{6}} + \frac{1}{4} e^{-\sqrt{3/2}\varphi} \right)$

while for the magnetic solution $W_{mag}(\varphi) = -\frac{2}{\ell_{AdS}} \left(\frac{3}{4} e^{-\varphi/\sqrt{6}} + \frac{1}{4} e^{\sqrt{3/2}\varphi} \right)$

corresponding to $\nu = \pm 1 \qquad \nu = \sqrt{6}\lambda$

This fixes uniquely the counterterm action, from which one can compute the mass of the solution as

$$Mass = -\frac{c_1}{2}$$

Domain wall as reference background

The computation of the mass in AdS can be obtained by subtraction of a reference background.

Holographic renormalization allows to check that the correct background for these solutions is the domain wall solutions

$$ds^2 = e^{-K} r^2 \left(-dt^2 + dx^2 + dy^2\right) + e^K \frac{dr^2}{r^2}$$

It is obtained from the black brane when $f(r) = r^2 e^{-2K}$

And it corresponds to the choice of parameters

$$c_1 = 0 \qquad\qquad c_2 = \frac{Q_1^2}{2}\left(1 + 6Q_1^2\right)$$

So it would correspond to a “zero mass” system, as given by the holographic renormalization.

Relations with String/M-theory

M-theory on $AdS_4 \times S_7$ $\longrightarrow$ dual to ABJM

effective theory:

N=8 4dim Supergravity with SO(8) gauging

truncation to $U(1)^4 \in SO(8)$

N=2 R-symmetry gauged supergravity with prepotential

$$F(X^\Lambda) = 2i\sqrt{X^0 X^1 X^2 X^3}$$

even simpler setup, one scalar field, two vectors

general T=0 solutions, might not be BPS

Known embedding in N=8 gives BF instabilities

[Donos, Gauntlett, Pantelidou, '11-'12]

Relations with String/M-theory

- Uplift solutions to String Theory in a generic N=2 setup

  Instead of an M-branes constructions, D-branes uplift could yield a clearer understanding

  construction of Killing spinors and geometry from bilinear forms

- Dual operator conformal dimensions $\Delta_- = 1\ , \qquad \Delta_+ = 2$

$$\varphi_+ = \lambda \varphi_-^2$$

The solutions of electric and magnetic black holes are dual to marginal multitrace deformations

Supersymmetry at the boundary of AdS4

N=8 SUGRA boundary term required
[Freedman et al. '16]

$$\delta S_{SUSY} \sim \lambda \int \mathcal{O}^3$$

Thermodynamic ensemble

Euclidean path integral formulation of gravity at the semiclassical level:

[Gibbons, Hawking '76 , York, '86]

$$Z = \int d[g_{\mu\nu}] d[\phi] \exp\{iI_e[g_{\mu\nu}, \phi]\}$$

The partition function defines a free energy, which, within a saddle point approximation, corresponds to the Euclidean on-shell action

$$-\beta F = \ln Z = iI_e[g^*, \phi^*]$$

What are the thermodynamic variables?

Thermodynamic ensemble

Electric configuration: the bare on-shell action corresponds to the free energy for the grand canonical ensemble F(T, χ)

$$F(T,\chi) = M - TS - q_\Lambda \chi^\Lambda$$

Magnetic configuration: the bare on-shell action corresponds to the free energy for the grand canonical ensemble F(T, p)

$$F(T,p^\Lambda) = M - TS$$

Adding boundary terms on the action changes the boundary conditions. In Supergravity, that corresponds to an *electric-magnetic duality rotation*

Good singularity

Planar black holes compete with a thermal gas solution

Black branes in the limit where the black hole coincide with the singularity [Gubser,2000]

$$g_{tt}(r_h) = 0 \qquad r_h \to r_s$$

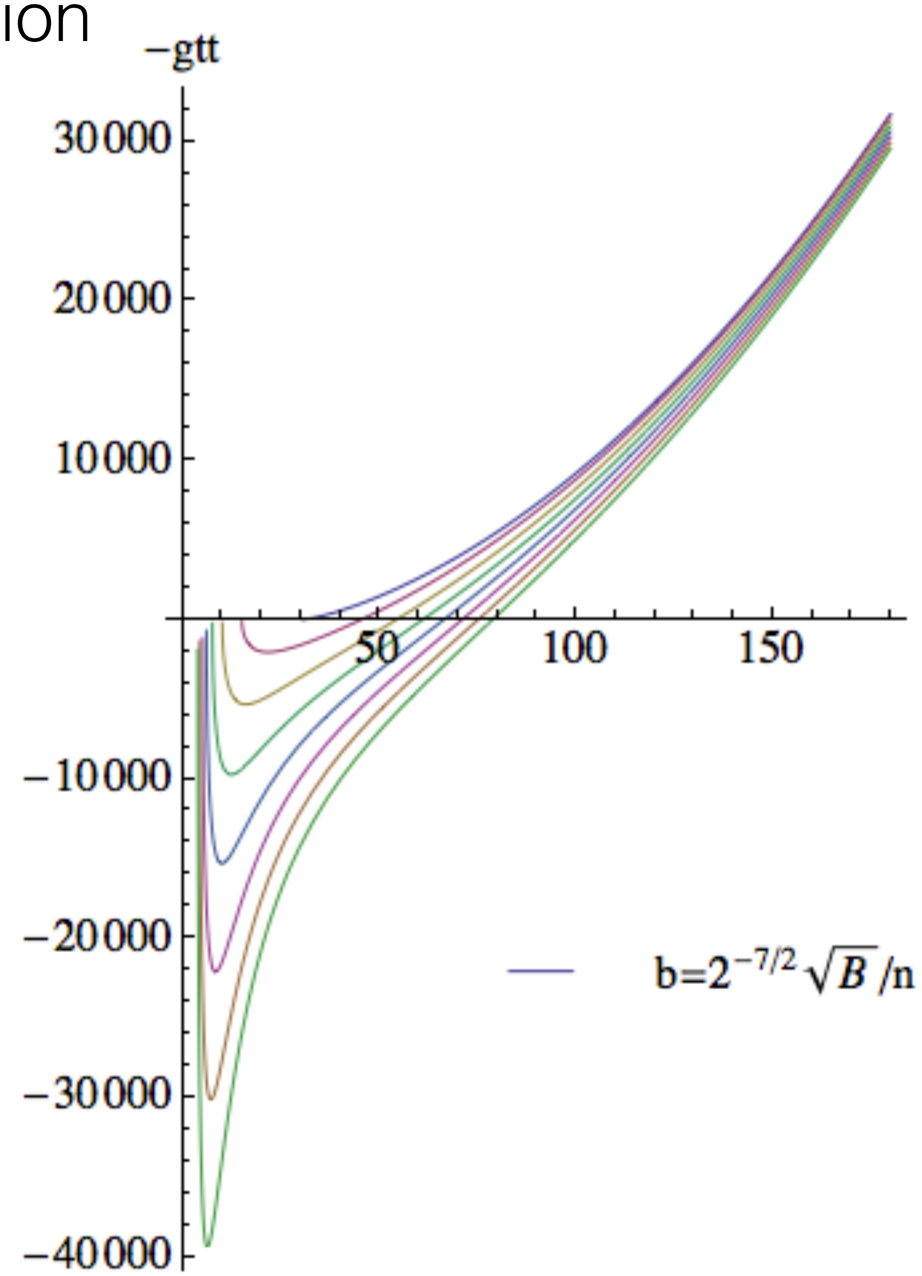
$$g_{xx} = g_{yy} = \sqrt{(r-3b)(r+b)^3}$$

Family of black branes with horizon $r_h = 3b + \epsilon$

Horizon condition $g_{tt}(3b+\epsilon) = 0$

$$|B| = 8\sqrt{2}b^2 + \frac{(6b^2+\chi^2)\epsilon}{\sqrt{2}b} + \mathcal{O}(\epsilon^2)$$

The electric charge of the solution is ***q = 0***



Good singularity

Define a thermal gas as the subset in parameter space where

$$|B| = 8\sqrt{2}b^2 \ , \qquad \chi \quad \text{finite}$$

Because of this relation the dependence on χ drops from the metric:

$$\begin{aligned} ds^2_{TG} \quad &= \quad e^{-\sqrt{6}\varphi}(r^2 + 6br + 21b^2)dt^2 - e^{\sqrt{6}\varphi}dr^2(r^2 + 6br + 21b^2)^{-1} + \\ & \quad\ -e^{\sqrt{6}\varphi}(r-3b)^2(dx^2 + dy^2) \ , \\ e^{\sqrt{6}\phi} \quad &= \quad \left(\frac{r+b}{r-3b}\right)^{3/2} \quad . \end{aligned}$$

Thermodynamic variables (B, χ, T)

In particular, temperature T and electric potential χ are moduli of the thermal gas solution

Possible resolution of the singularity from string theory

Black brane

$$F_{bb} = M_{bb} - TS_{bb} + q_{bb}\chi_{bb}$$

Mass $$M = \frac{B^2 - q^2}{4b}$$

Thermodynamic potential

$$dF_{bb} = -S_{bb}dT + q_{bb}d\chi_{bb} + m_{bb}dB$$

Thermal gas

$$b_{TG} = +2^{-\frac{7}{4}}\sqrt{|B|}$$

Free energy depends only on the magnetic charge B

$$F_{TG} = M_{TG} = \frac{B^2}{4b_{TG}} = 2^{-\frac{1}{4}}|B|^{\frac{3}{2}}$$

$$dF_{TG} = m_{TG}dB$$

Qualitative different magnetization

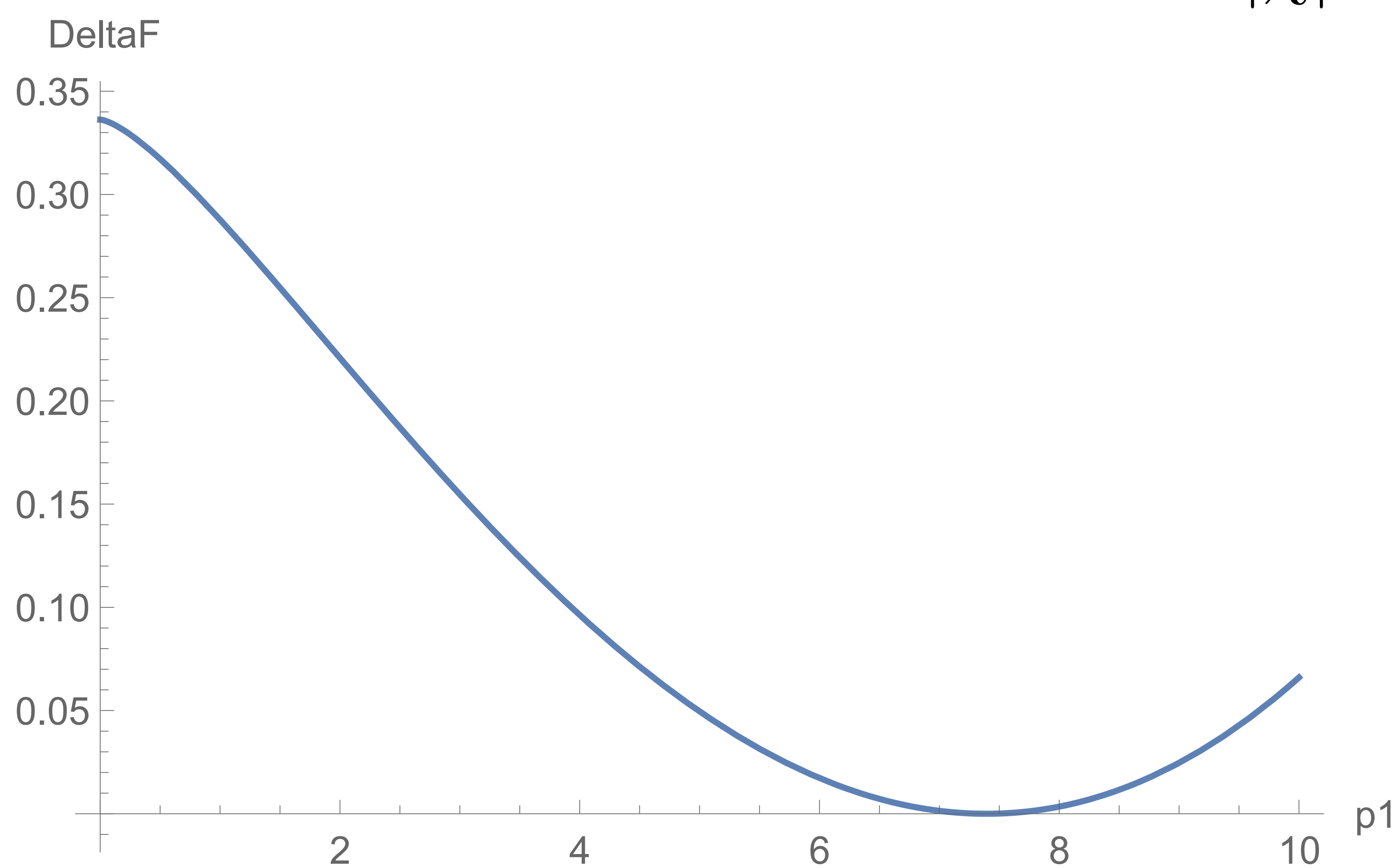
$$m_{bb} = \frac{\partial F_{bb}}{\partial B}\Big|_{\chi,T} = 3\sqrt{\frac{3}{2}}\,\frac{B}{|\chi|}$$

$$m_{TG} = 3\,2^{-\frac{5}{4}}\sqrt{|B|}\,\mathrm{sgn}(B)$$

Phase space, T=0

At T=0 it is possible to solve analytically for the free energy in terms of the thermodynamic variables

$$\Delta F = F_{bb} - F_{TG} = \frac{27B^2 + 32\chi^4}{24\sqrt{6}|\chi|} - 2^{-\frac{1}{4}}|B|^{\frac{3}{2}}$$



We find a critical point for every value of χ

$$|B_*| = \frac{4\sqrt{2}}{3}\chi^2$$

The QCP is second order

$$\Delta F = 3\sqrt{\frac{3}{2}}\frac{(B-B_*)^2}{|\chi|} + \mathcal{O}\left((B-B_*)^3\right)$$

Comments on the BPS point

BPS solution obtained by setting

$$g_{tt} = e^{K}(r^2 - r_h^2)^2 \ , \qquad g_\Lambda p^\Lambda - g^\Lambda q_\Lambda = 0$$

BPS black holes in ungauged supergravity are stable. They minimize the mass in the parameter space.

$$M \geq |Z|$$

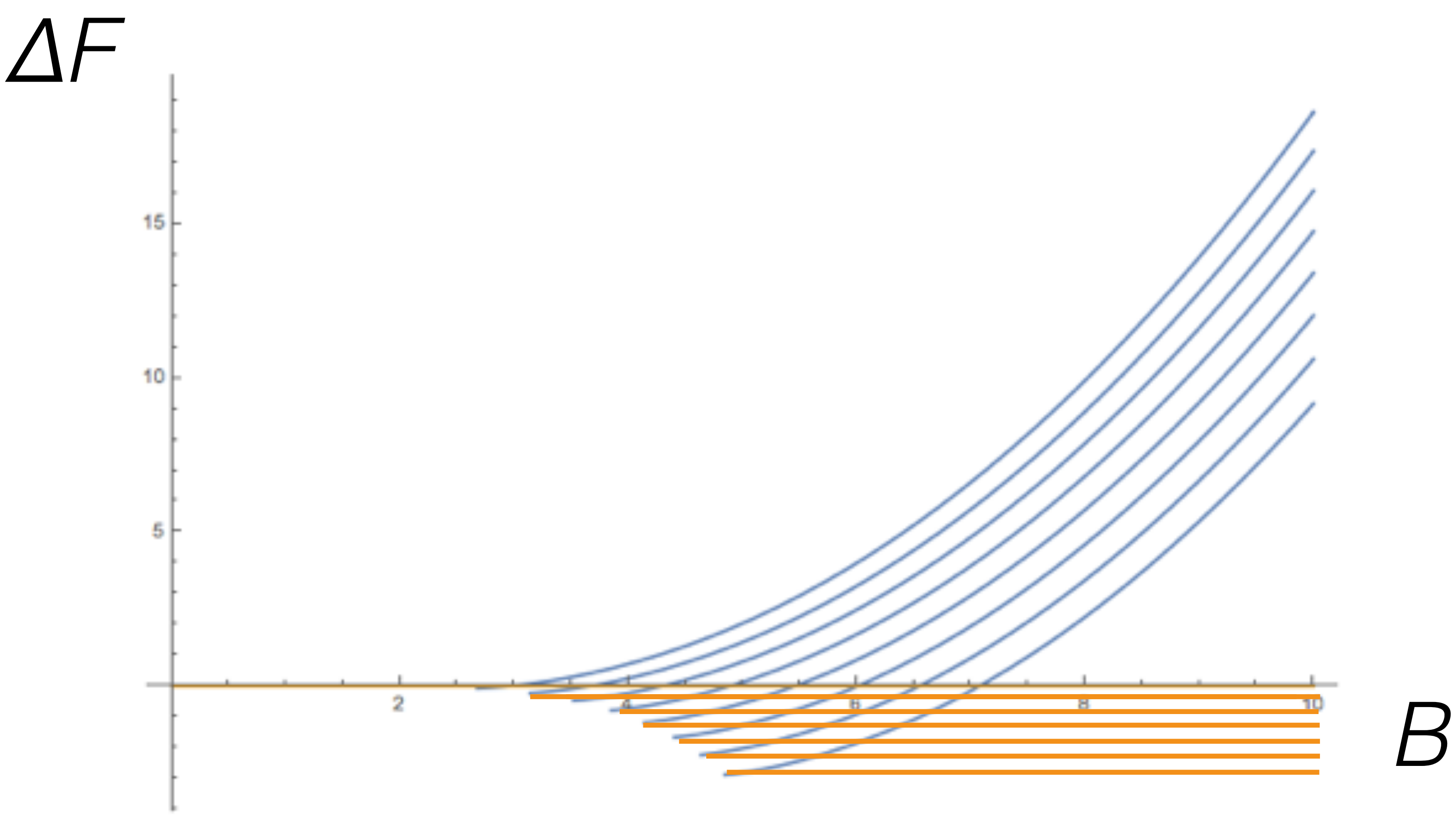
In the canonical ensemble the on-shell action at zero temperature is the mass, so it is consistent

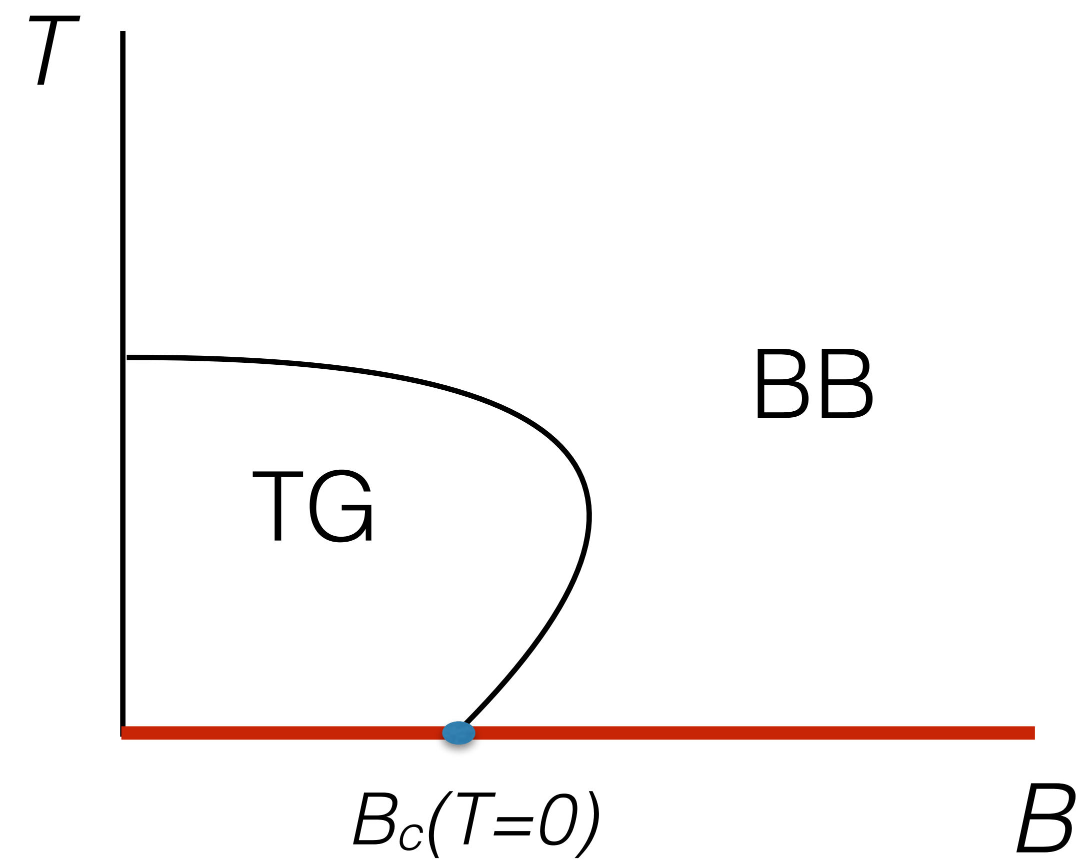
$$F(T=0) = M \qquad F_{extremized} \Leftrightarrow M_{extremized}$$

We work instead in a mixed ensemble, and we find a phase transition which thus seems to be related to the choice of different thermodynamical ensemble. No contradiction, in principle.

T > 0 phase space

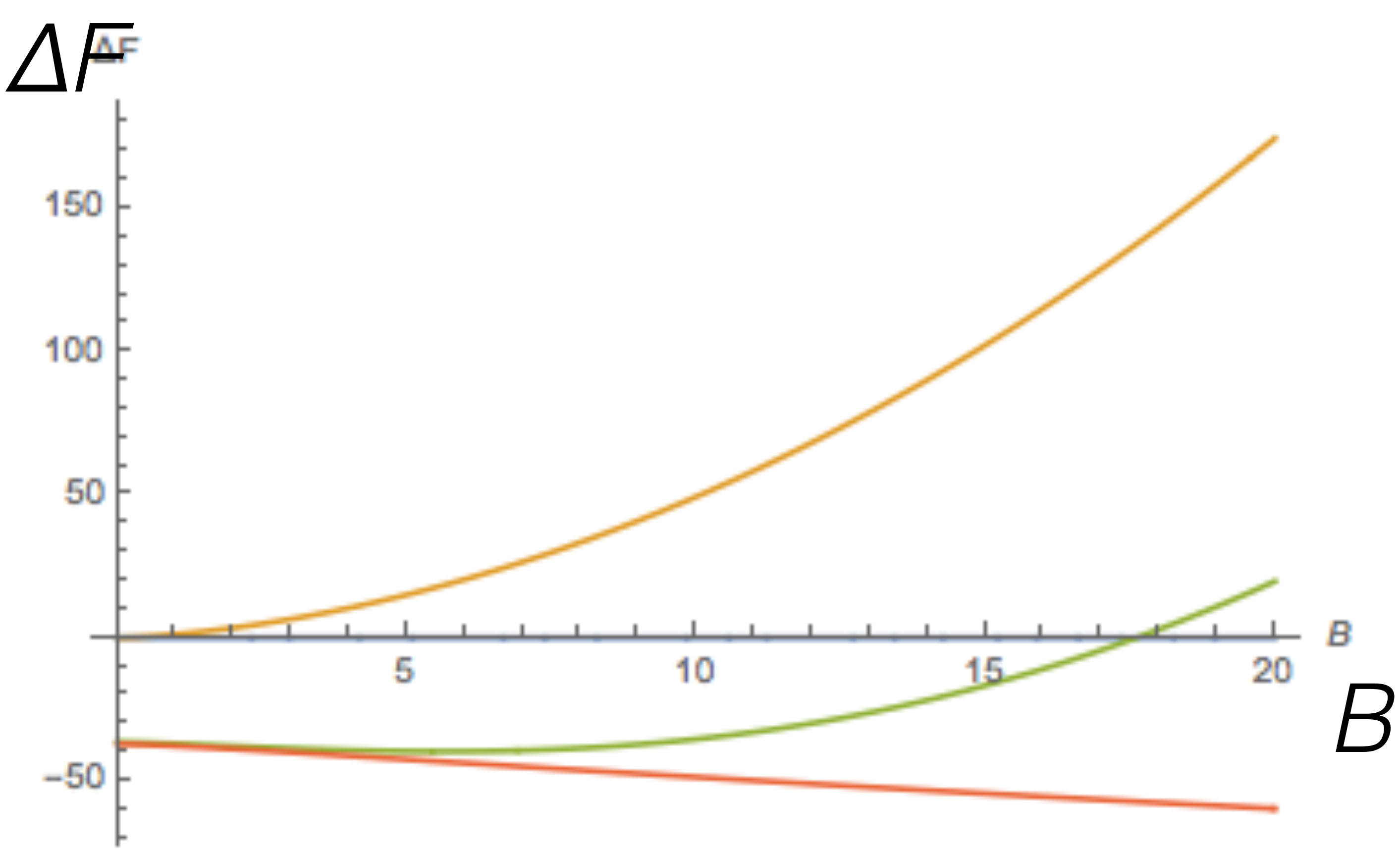
Low temperature

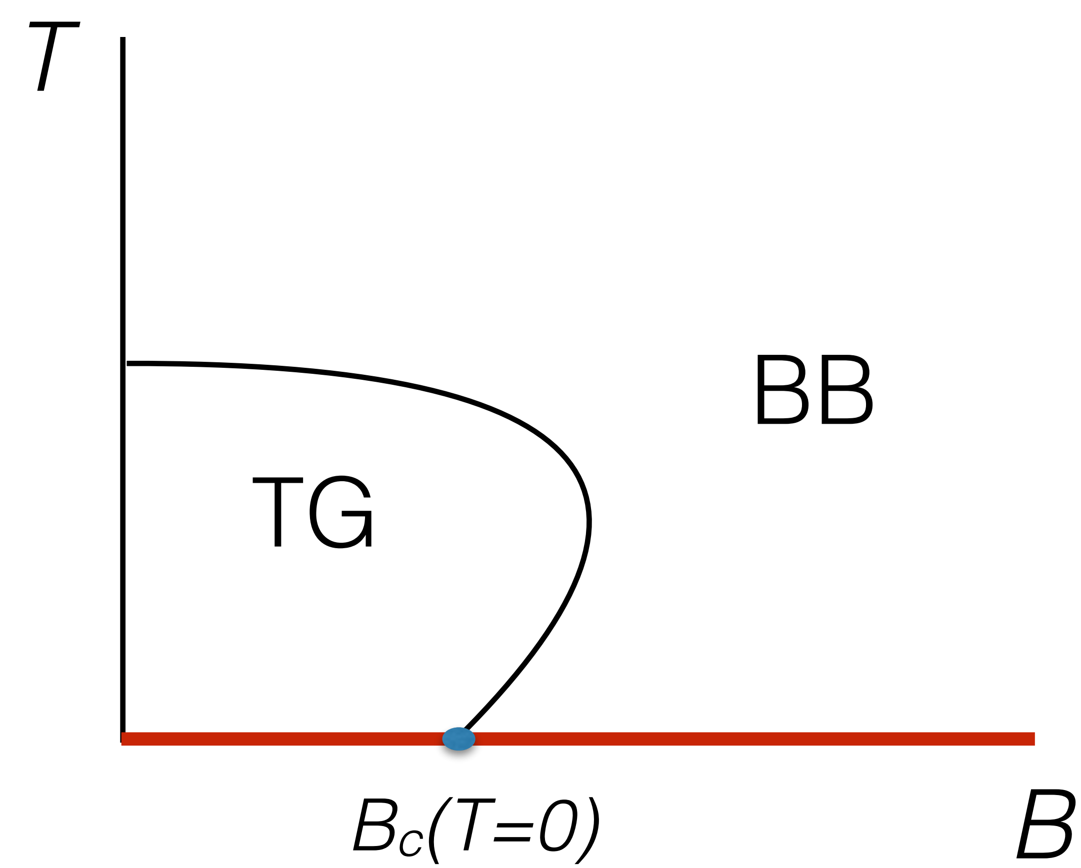




T > 0 phase space

High temperature





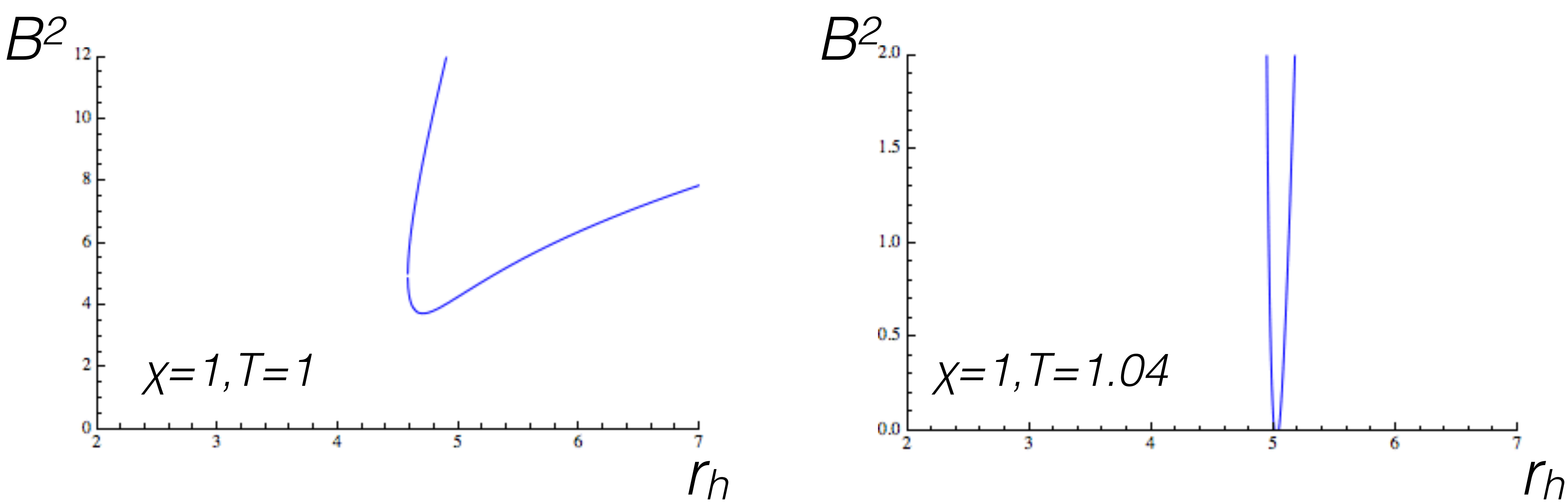
Bounds in parameter space

Temperature

$$4\pi T = \frac{(-3b + r_h)^{1/2}(3(b + r_h)^2 - 8\chi^2)}{(b + r_h)^{3/2}}$$

Horizon constraint

$$B^2 = 2(b + r_h)\left(b(b^2 - 6\chi^2) + 2(b^2 + \chi^2)r_h + br_h^2\right)$$



Analysis of QCP

Quantum criticality emerges at the locus B= Bc(χ)

Information on the nature of the critical point from spectrum of the dual theory
[Gursoy, Kiritsis, Nitti ’07]

Scalar fluctuations of the background: acting with a bosonic operator on vacuum, $\mathcal{O}_\Delta$

Holographically induce fluctuations of the corresponding bosonic bulk field on the background

Effective action for a scalar perturbation $m^2 = 0\ ,\ \phi(r,x) = \xi(r) e^{-i\omega t + \vec{k}\cdot\vec{x}}$

$$S_{fluc} = \int d^4x \sqrt{-g} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi^* =$$
$$= \int dr d^3x \sqrt{-g} \left\{ g^{rr} |\partial_r \xi_\omega(r)|^2 + \omega^2 g^{00} |\xi_\omega(r)|^2 \right\}$$

Eigenvalue problem for normalizable modes both in the UV and IR (singularity)

Analysis of QCP

- The thermal gas has no normalizable modes for arbitrary small ω: <u>gapped system</u>

$$\xi_0 \sim \epsilon^{-1} \qquad \epsilon = r - r_s$$

Crucial constraint on the TG: releasing the relation $|B| = 8\sqrt{2}b^2$ *introduces normalizable modes!!*

- Black branes have QNM spectrum discrete frequencies, the lowest **|ω|~T**

- Lowering the temperature one can reach arbitrary small energies **|ω|~ε**, with separations also **|Δω|~ε**.

- In the T→0 limit, the spectrum of QNM accumulates at the origin producing a branch-cut *as expected from a holographic perspective for retarded Green's functions in a strongly interacting CFT at zero temperature*

<u>gapless system</u>

We checked that there is no confinement/deconfinement phase transition

semi-local quantum criticality

[Iqbal, Liu, Mezei, '11]

"Understanding phases of matter for which there is no quasiparticle description"

- Interpretation of black branes horizons as a universal fractionalized intermediate-energy phase (due to instabilities)
- energy scale ~ order of the chemical potential

- finite spatial correlation length, but an infinite correlation time
- nontrivial scaling behavior in the time direction
- nonzero entropy density

- goal: semi-local quantum liquid arises universally from lower energy phases through deconfinement $\rightarrow$ fractionalization

semi-local quantum criticality

[Iqbal, Liu, Mezei, '11]
[Donos, Gauntlett, Pantelidou, '12]

η geometries, conformal to AdS2xS2

$$ds^2 = \frac{1}{\rho^{2\eta/(D-2)}}\left(-\frac{dt^2}{\rho^2} + \ell^2\frac{d\rho^2}{\rho^2} + dx^i dx^i\right)$$

$$t \to \zeta t\ , \qquad x^i \to x^i \qquad\qquad ds^2 \to \zeta^{-2\eta/(D-2)} ds^2$$
$$\rho \to \zeta\rho$$

Thermal gas defined with *T* as a modulus, *not only at T=0* !

Supersymmetric infrared region?

If the q-charge is zero, the BPS condition ***q* - 3*B* = 0** cannot be satisfied!

semi-local quantum criticality

[Iqbal, Liu, Mezei, '11]
[Donos, Gauntlett, Pantelidou, '12]

Finite entropy density as $T \to 0$, related to system instabilities

possibly associated with new branches of black hole solutions appearing at finite temperature, corresponding to new phases

Obtained from higher dimensions by reduction of the product of AdS or Lifshitz geometries with flat directions.

- Investigate the full space at finite temperature

conclusions and outlook

- Analytic study of black holes in holographic systems possible in gauged Supergravity

- Existence of a good singularity solution whose origin might me clarified by a string theory uplift

- Presence of a QCP between a gapped and a gapless phase

- clarify the relations with *intermediate* phases of quantum critical systems

- Extend the study to quantum critical region
- An N=2 supersymmetric field theory dual?

— Thank you!