braneworld Black holes and the Gravity dual of $\mathcal{N}$=4 SYM on Schwarzschild

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based on work with J. Lucietti and T. Wiseman [1104.4489], [1105.2558],
[∞∞∞∞.∞∞∞∞]

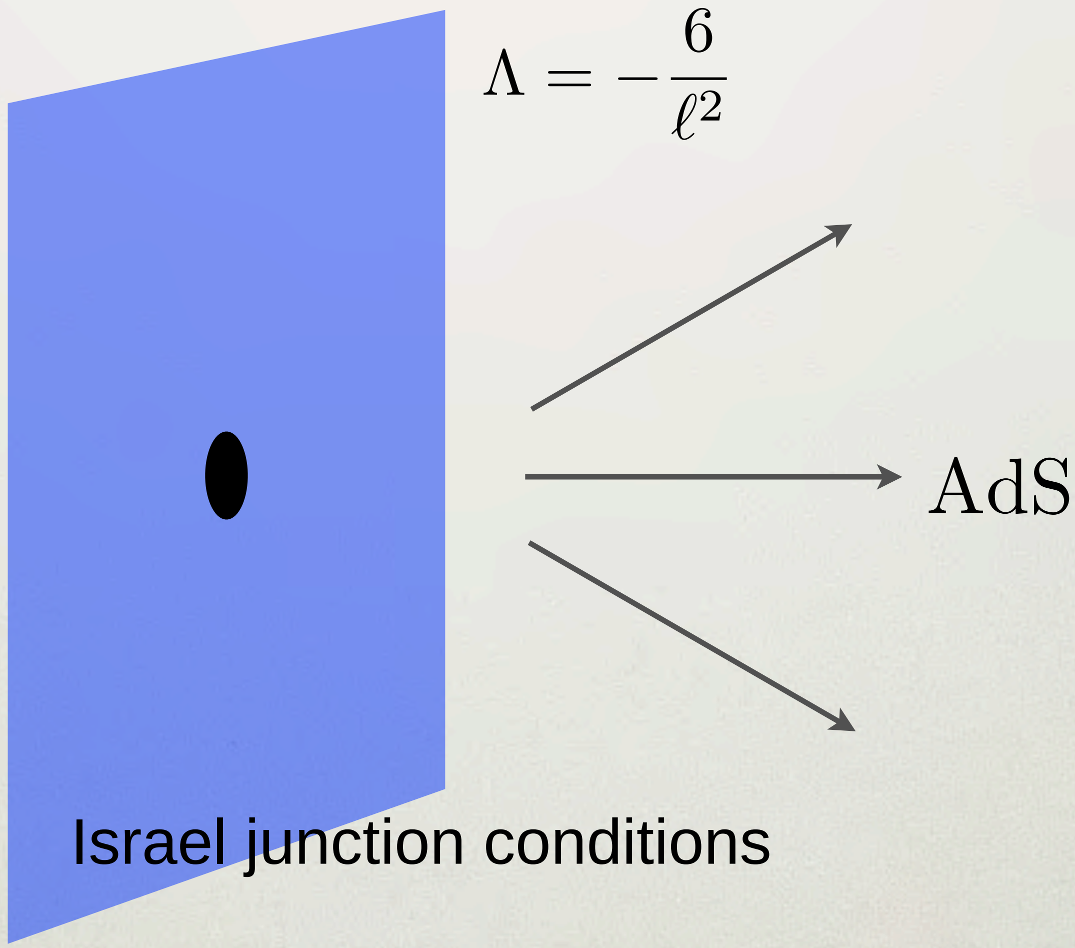
Novel Numerical Methods, KITP
28th of February, 2012

Outline of the Talk

- Review of RSII braneworlds
- The method
- Gravitational dual to $\mathcal{N} = 4$ SYM on Schwarzschild
- Braneworld black holes in RSII
- Summary

The Randall-Sundrum (RSII) model

Consider the 4+1 dimensional asymptotically AdS spacetime. Cut off the geometry near the boundary of AdS and glue a copy of it onto this surface.



All Standard Model fields are localised on the brane but gravity can propagate in all dimensions

The Randall-Sundrum (RSII) model

• The RSII model offers an alternative to the traditional Kaluza-Klein compactification: in the linear regime and on scales much larger than ℓ, 4d gravity is recovered.

• The gravitational potential on the brane goes like [Garriga and Tanaka; Giddings, Katz and Randall]

$$\bar{h}_{tt} \sim \frac{1}{r} + \frac{2\,\ell^2}{3\,r^3}$$

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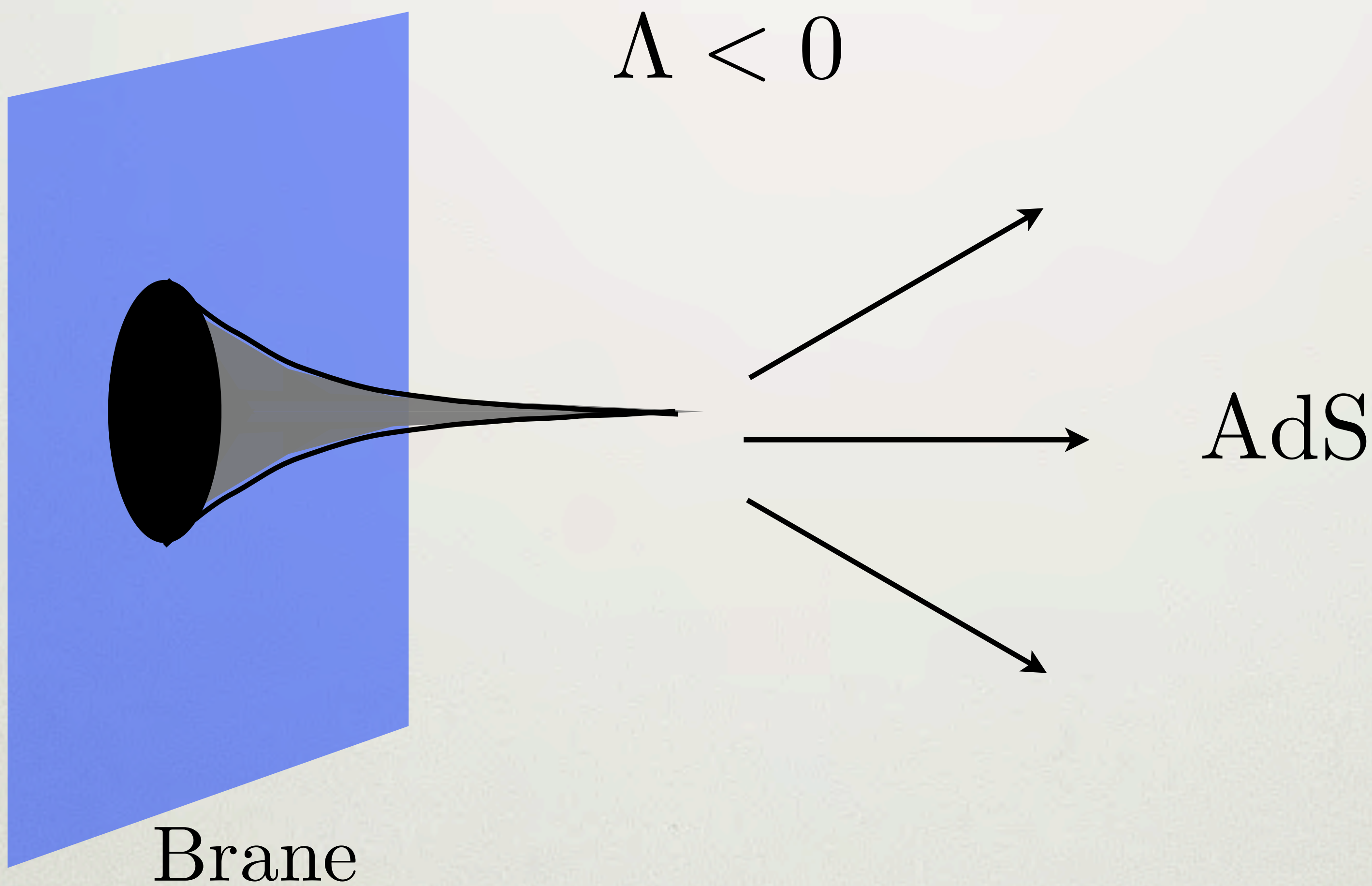
• What about in the strong field regime?

• How does a black hole look like in this model?

The Randall-Sundrum (RSII) model

- Expectation: [Chamblin, Hawking, Reall]



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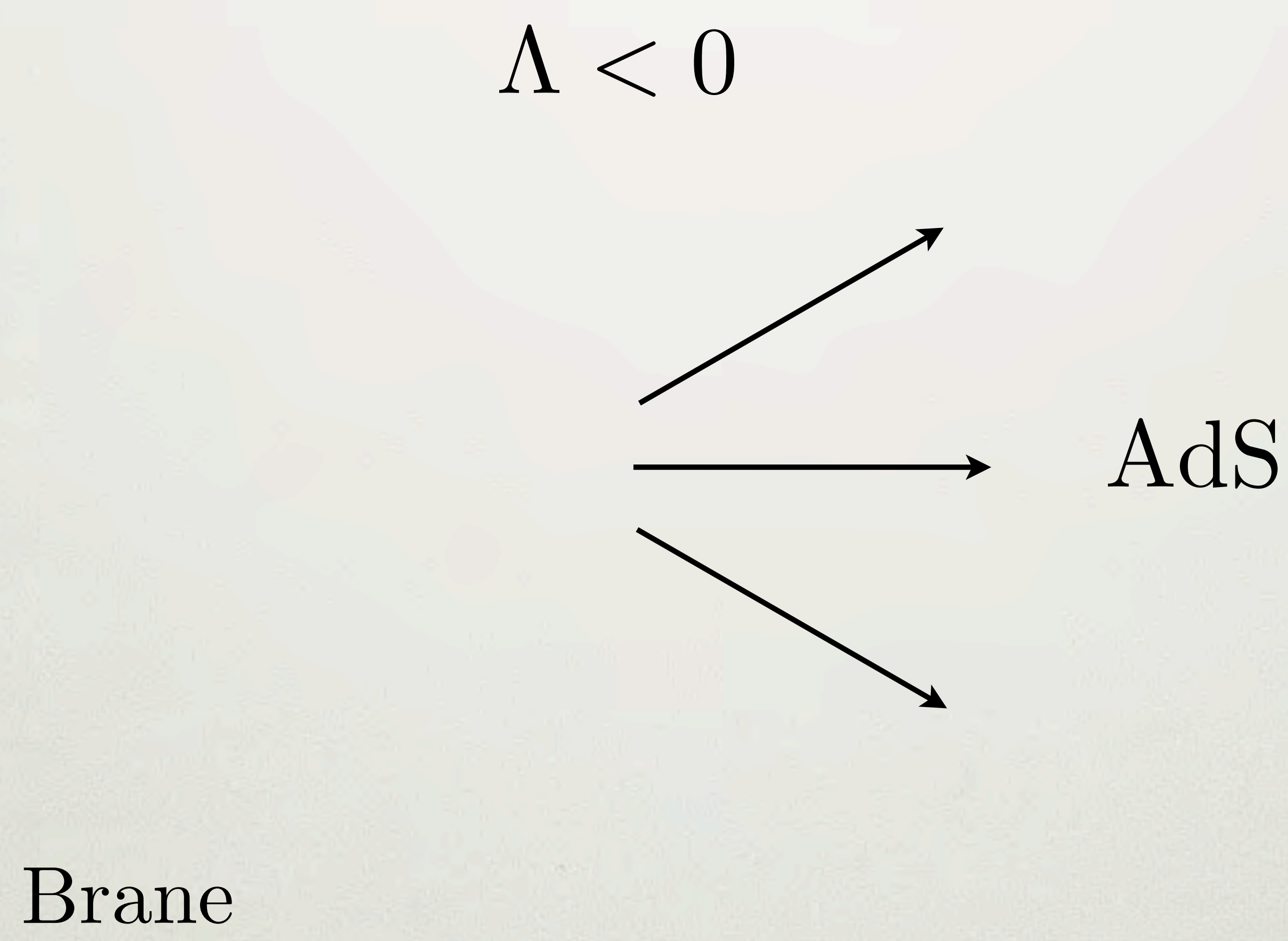

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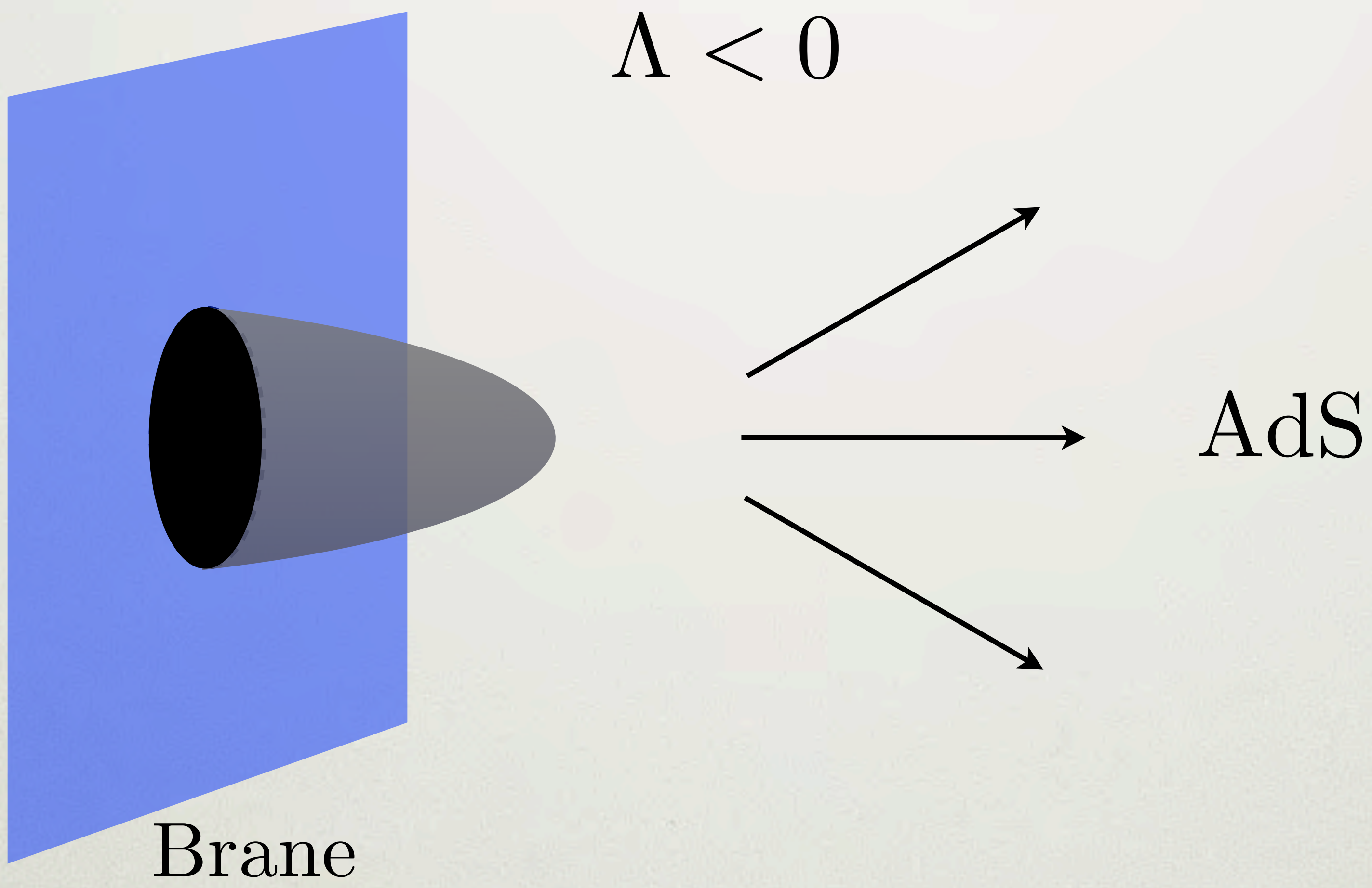

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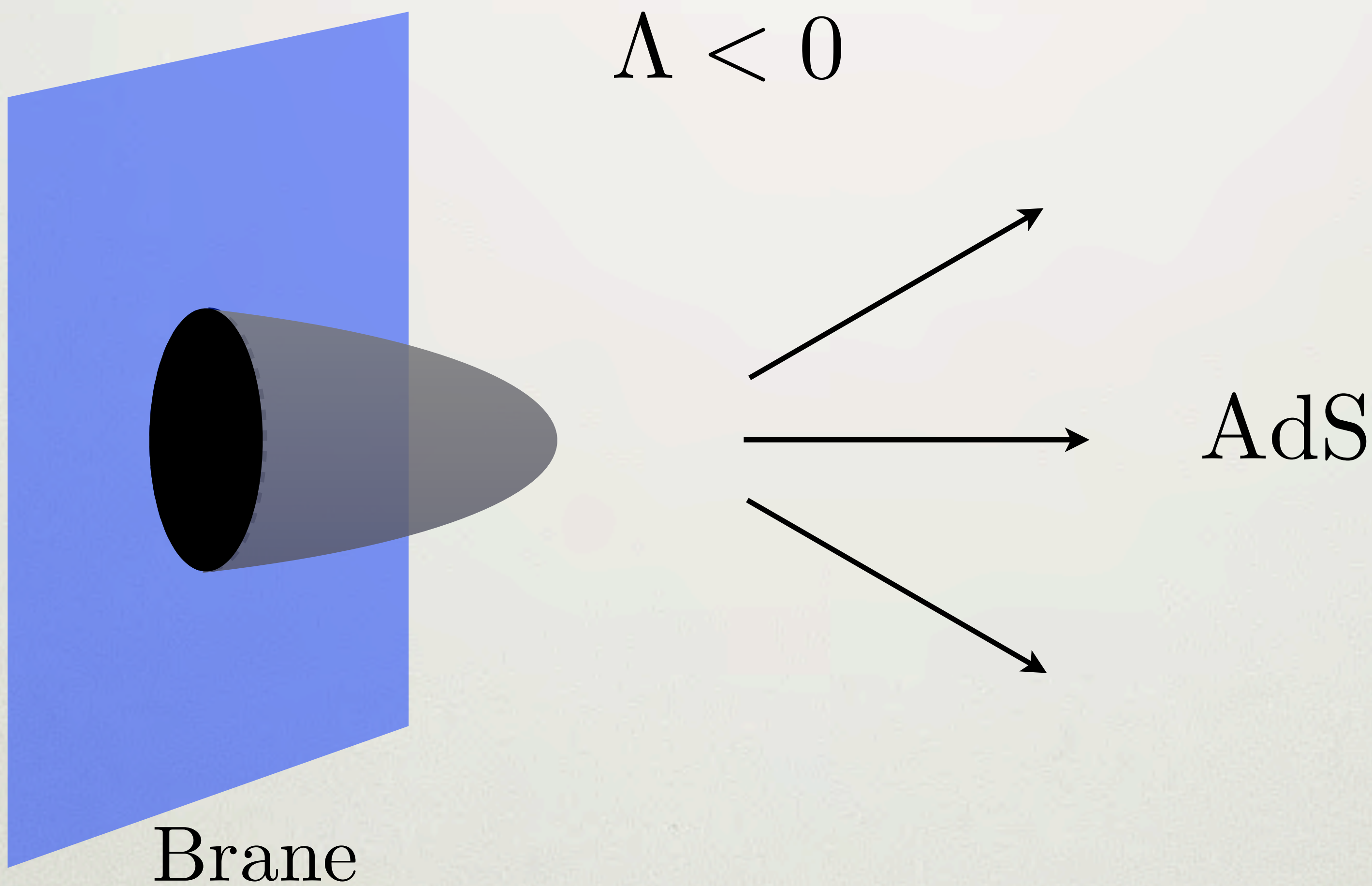

- For scales much smaller than ℓ, 5d gravity is recovered. In particular, a small ($R_4 << \ell$) black hole on the brane will look like 5d (AF) Schwarzschild.

- **Do we recover 4d gravity on the brane for large black holes?**

The Randall-Sundrum (RSII) model

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• An explicit solution is known in 3+1 dimensional bulk spacetime (2+1 dimensional black hole on the brane) [Emparan, Horowitz and Myers]:

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• Remarks:

- Standard 2+1 gravity on the brane is recovered at large scales: the spacetime is only locally asymptotically flat and the mass is given by the conical deficit angle
  $\Rightarrow$ the bulk spacetime is not asymptotically AdS far from the brane

- Black holes have a finite size horizon

- Large black holes look like “pancakes”

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• ***Ultimately we are interested in the 5d case...***

The Randall-Sundrum (RSII) model

• Interpretation in AdS/CFT: [Tanaka ; Emparan, Fabbri and Kaloper]

The black hole solutions localised on the brane in the RSII model which are found solving the classical bulk equations in AdS_{D+1} with brane boundary conditions correspond to quantum-corrected black holes in D-dimensions. [Tanaka ; Emparan, Fabbri and Kaloper]

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• The unsuccessful attempts to construct the 5d black hole analytically and numerically, led to the following conjecture:

Conjecture: ***No large, STATIC** (or stationary) **and NON-EXTREMAL black hole on the brane should exist because it should Hawking radiate*** [Tanaka ; Emparan, Fabbri and Kaloper].

• Simplified argument based on ***FREE*** field theory intuition:

Hawking radiation is an effect that goes like $\sim \hbar N_c^2$, and this remains finite in the large N_c and strong coupling limit

• The 2+1 braneworld black hole can be interpreted as a quantum corrected black hole

The Randall-Sundrum (RSII) model

Counter-arguments:

• Fitzpatrick, Randall and Wiseman pointed out that for gauge theories with gravity duals, a localised object with finite T need NOT necessarily be able to radiate all $O(N_c^2)$ dofs: out of the entire $O(N_c^2)$ perturbative states, only the $O(1)$ glueball states dual to the gravitational perturbations remain light in the strong coupling large N_c limit.

➡ reduction of the light glueball states dual to the decoupling of the string oscillator modes

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➡ reduction of the light glueball states dual to the decoupling of the string oscillator modes

• More recent picture by Hubeny, Marolf and Rangamani

• Although the above proposals may be logically self-consistent, a detailed microscopic understanding from first principles is lacking

The Randall-Sundrum (RSII) model

Summary of numerical previous work (Relativistic stars were constructed [Wiseman]):

• Kudoh, Tanaka and Nakamura ('03): only small ($R_4/\ell \leq 0.3$) black holes were found.
• Kudoh ('06): up to intermediate size black holes ($R_5/\ell \leq 2.$) were found in D=6.
• Yoshino ('08): no static black hole at all was found. One possible interpretation: no static black hole (no matter the size) on the brane exists.
• Kaus and Reall ('09): the near horizon geometry of *extremal* braneworld black holes of arbitrary size was found. (no Hawking radiation expected in this case anyway)

The Method

[Headrick, Kitchen and Wiseman; Adam, Kitchen and Wiseman]

In the context of solving the Einstein equations we are interested in two types of PDEs according the nature of the problem:

- Elliptic: boundary value problem.

- Hyperbolic: initial value problem.

The Method

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- Elliptic: boundary value problem.

- Hyperbolic: initial value problem.

We want to solve:

$$R_{\mu\nu} = 0$$

for a *static* black hole spacetimes $(\mathcal{M}, g)$ in D dimensions.

• The above equations of motion do ***NOT*** have a definite character (elliptic or hyperbolic) unless a suitable gauge fixing is introduced

The Method

Instead of considering the Einstein equations, we consider a characteristic version of it (the Harmonic Einstein equation) which is manifestly elliptic/hyperbolic:

$$R^H_{\mu\nu} = R_{\mu\nu} - \nabla_{(\mu}\xi_{\nu)} = 0 \qquad\qquad \xi^\mu = g^{\alpha\beta}(\Gamma^\mu_{\alpha\beta} - \bar{\Gamma}^\mu_{\alpha\beta})$$

where $\bar{\Gamma}$ is the Levi-Civita connection associated to a reference metric $\bar{g}$ on the manifold.

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Note:

- $R^H_{\mu\nu} = 0$ is manifestly elliptic/hyperbolic: $R^H_{\mu\nu} \sim -\frac{1}{2}\, g^{\alpha\beta}\partial_\alpha\partial_\beta g_{\mu\nu}$
- Analogous to harmonic gauge: $\xi^\mu = 0 \quad \Rightarrow \quad \Delta_g x^\mu = H^\mu = -g^{\alpha\beta}\bar{\Gamma}^\mu_{\alpha\beta}$
- There are no constraints to worry about and fully covariant

The Method

Comments/Remarks:

• Since the term proportional to Λ in the Einstein equations has no derivatives we can simply added to the Einstein Harmonic equation without affecting its character:

$$R^H_{\mu\nu} \equiv R_{\mu\nu} - \nabla_{(\mu}\xi_{\nu)} - \Lambda g_{\mu\nu} = 0$$

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Ultimately we want to find solutions to the original Einstein equations

How can we achieve $\xi^\mu = 0$?

The Method

- **Hyperbolic case**:

Choosing $\xi^\mu = 0$ and $\partial_t\, \xi^\mu = 0$ on a Cauchy surface Σ ensures that the solutions to $R^H{}_{\mu\nu} = 0$ are Einstein!

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• **Hyperbolic case**:

Choosing $\xi^\mu = 0$ and $\partial_t \xi^\mu = 0$ on a Cauchy surface Σ ensures that the solutions to $R^H{}_{\mu\nu} = 0$ are Einstein!

• **Elliptic case**:

Solve $R^H{}_{\mu\nu} = 0$ subject to BCs compatible with $\xi^\mu = 0 \Rightarrow$ ***solve simultaneously the Einstein equations and the gauge condition.***

A solution $R_{\mu\nu} = 0$ in the gauge $\xi^\mu = 0$ certainly implies $R^H{}_{\mu\nu} = 0$ but the converse is not true: there can be solutions $R^H{}_{\mu\nu} = 0$ with non-trivial ξ^μ called Ricci solitons.

What boundary conditions should we impose on ξ^μ in order to find Einstein metrics? Smoothness, asymptotics...

The Method

• In favourable circumstances one can in fact prove that only Einstein solutions exist on a given manifold:

- Bourguignon ('79) and Perelman ('02): no solitons exist on compact manifolds.
- For various asymptotics (AF, KK, AdS) and for static spacetimes one can prove that no Ricci solitons can exist. [PF, Lucietti and Wiseman]

• For the brane boundary conditions in the RSII model we ***cannot*** prove that no solitons exist (but they are compatible with non-existence of Ricci solitons).

• Since $R^H_{\mu\nu} = 0$ are elliptic and if the boundary conditions are compatible with the ellipticity of the problem, then every solution should be locally unique.
➡Therefore, an Einstein solution can always be distinguished from a Ricci soliton.

• We can use ξ^μ to monitor the numerical error

Solving the equations

• **Method 1**: local relaxation (diffusion) ⇒ Ricci-DeTurck flow

$$\frac{\partial}{\partial\lambda}\, g_{\mu\nu} = -2\, R^H_{\mu\nu}$$

➡ evolve the metric until one reaches a fixed point.

Comments:

• *Advantages*:

  • Very easy to implement!

  • It is diffeomorphic to Ricci flow, $\frac{\partial}{\partial\lambda}\, g_{\mu\nu} = -2\, R_{\mu\nu}$

  ⇒ the trajectory in the space of geometries is independent of the choice of reference metric!

• *Disadvantages*:

  • Attractive fixed points have no -ve eigenvalues of Δ_L, but many bhs of interest have -ve modes [Gross, Perry and Yaffe]

Solving the equations

Method 2: Newton's method (root finding). Iteratively replace

$$g_{\mu\nu} \to g_{\mu\nu} + h_{\mu\nu} \quad \text{with} \quad h_{\mu\nu} = -\Delta_H^{-1} R_{\mu\nu}^H$$

where Δ_H is the linearisation of R^H.

Comments:

• *Advantages*:
- Fast convergence.
- No problems with -ve modes (only zero modes cause trouble).

• *Disadvantages*:
- Harder to implement than Ricci Flow.
- Non-geometric in nature and the trajectory in the space of geometries depends on the choice of reference metric.
- The basin of attraction depends on the reference metric and in practice it can be rather small.

Numerical construction of the braneworld BH

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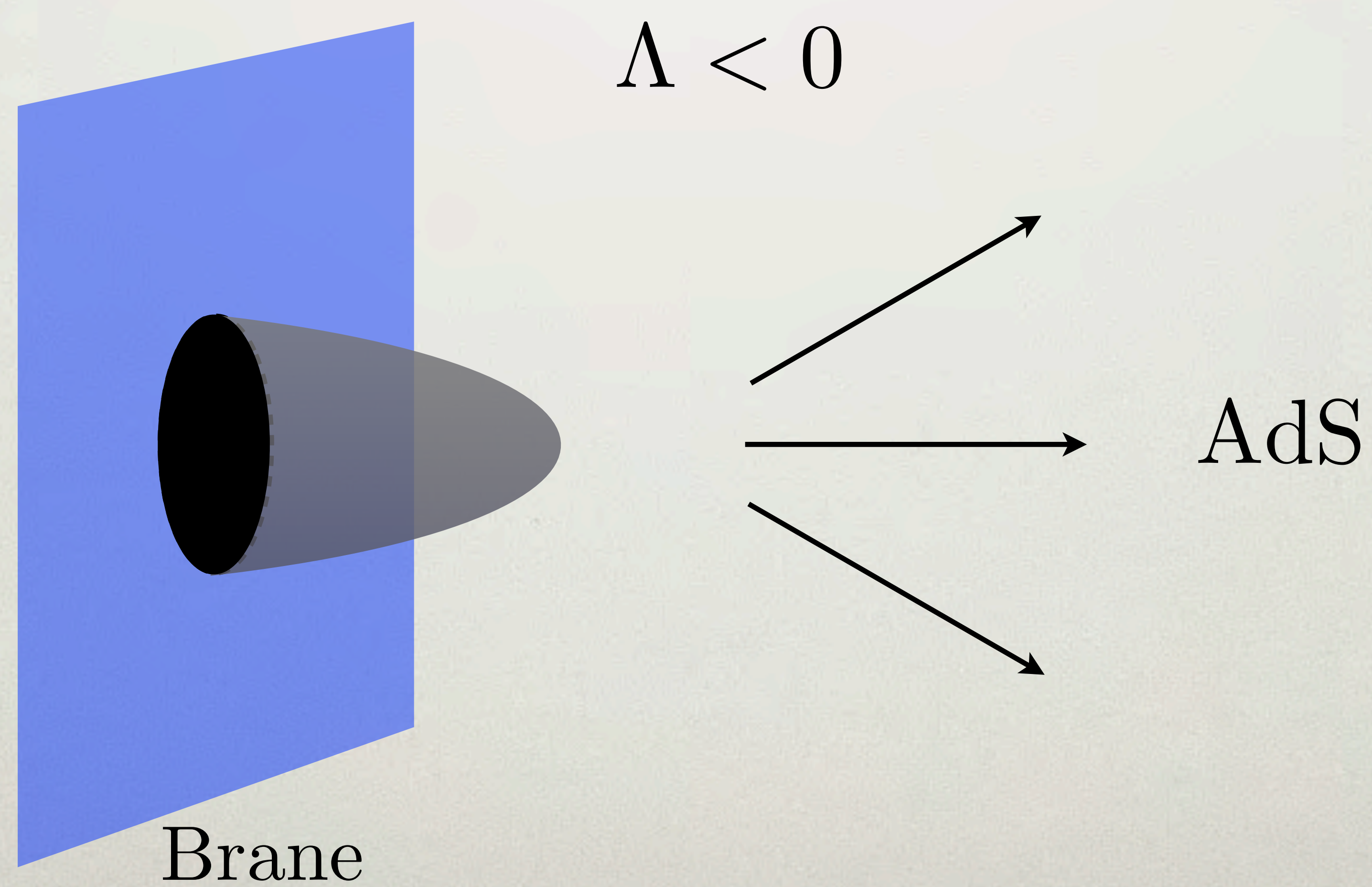
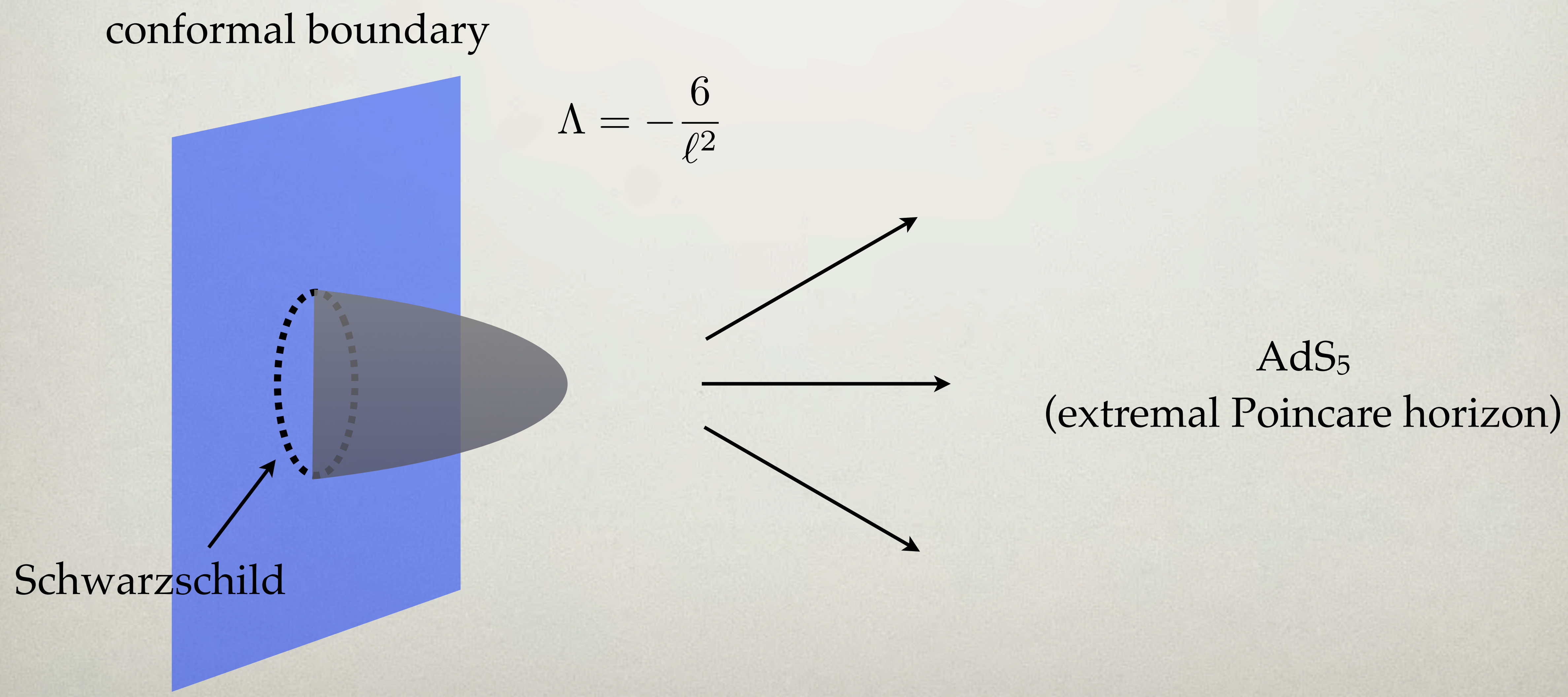
Goal: construct a spacetime with black hole localised on the brane and that far from the black hole tends to the Poincare horizon of pure AdS:



Gravity dual of $\mathcal{N}$=4 SYM on Schwarzschild

Simpler problem: use AdS/CFT to construct the gravitational dual of $\mathcal{N}$=4 SYM on Schwarzschild such that far from the black hole the theory is in a certain vacuum state.



Gravity dual of $\mathcal{N}$=4 SYM on Schwarzschild

Why this AdS/CFT solution is relevant to the braneworld black hole problem?

1. The arguments of non-existence of Tanaka and Emparan et al. apply to this case.
2. This solution turns out to be much cleaner and easy to find.
3. *One can prove analytically that no solitons can exist in this case!*
4. The AdS/CFT solution corresponds to the infinite radius limit of a braneworld black hole.

➡ it is more difficult to argue that it doesn’t exist!

Gravity dual of $\mathcal{N}$=4 SYM on Schwarzschild

We can choose coordinates in order to make the isometries manifest (∂_τ and axis of symmetry) to simplify the problem. This introduces fictitious boundaries at the fixed points and extra boundary conditions follow from requiring smoothness of the original metric.

$\Rightarrow$ compatible with non-existence of solitons.

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$\Rightarrow$ compatible with non-existence of solitons.

General metric ansatz:

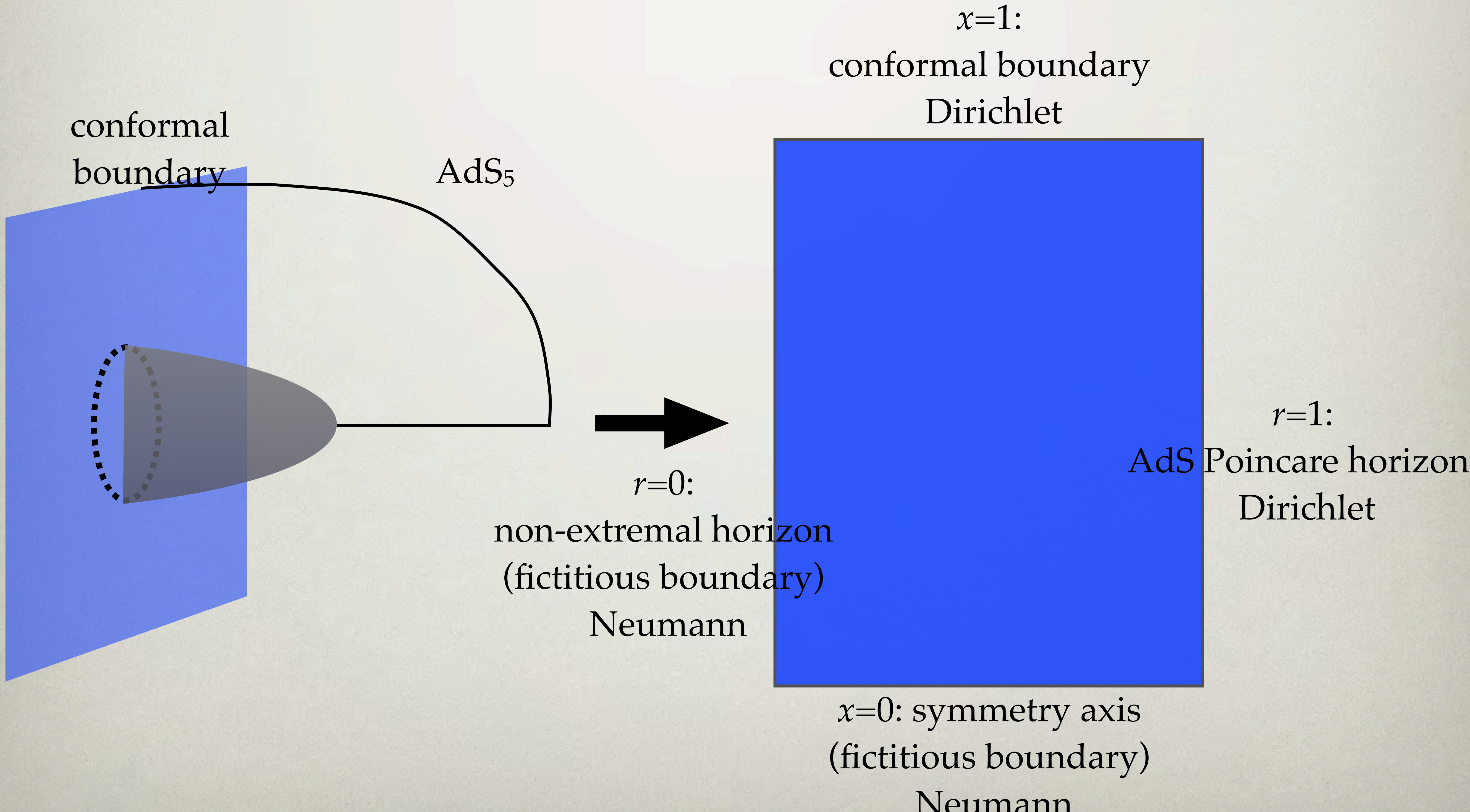
$$ds^2 = \frac{\ell^2}{(1-x^2)^2}\left(4r^2 f^2 e^T\, d\tau^2 + x^2 g\, e^S\, d\Omega^2_{(2)} + \frac{4}{f^2}\, e^{T+r^2 f\, A} dr^2 + \frac{4}{g}\, e^{S+x^2 B} dx^2 + \frac{2\, r\, x}{f}\, F\, dr\, dx\right)$$

$$f = 1 - r^2\,, \qquad g = 2 - x^2$$

- *T*, *S*, *A*, *B*, *F* are functions of *r* and *x* and these are the functions we are solving for.
- Without loss of generality we can choose $0 \leq r, x \leq 1$.
- Reference metric: $T = S = A = B = F = 0$.

Gravity dual of $\mathcal{N}$=4 SYM on Schwarzschild

Boundary conditions:



Gravity dual of $\mathcal{N}$=4 SYM on Schwarzschild

Remarks:

1. With the previous BCs we can analytically show that no Ricci soliton can exist.
2. There is no free parameter
3. There are no negative modes: the boundary black hole is non-dynamical.

➡ We can find the solution using Ricci Flow!

Gravity dual of $\mathcal{N}$=4 SYM on Schwarzschild

Embedding of the horizon geometry into hyperbolic space:

$$ds^2_H = \frac{1}{z^2}(dz^2 + dy^2 + y^2 d\Omega^2_{(2)})$$

$$y = y(z)$$

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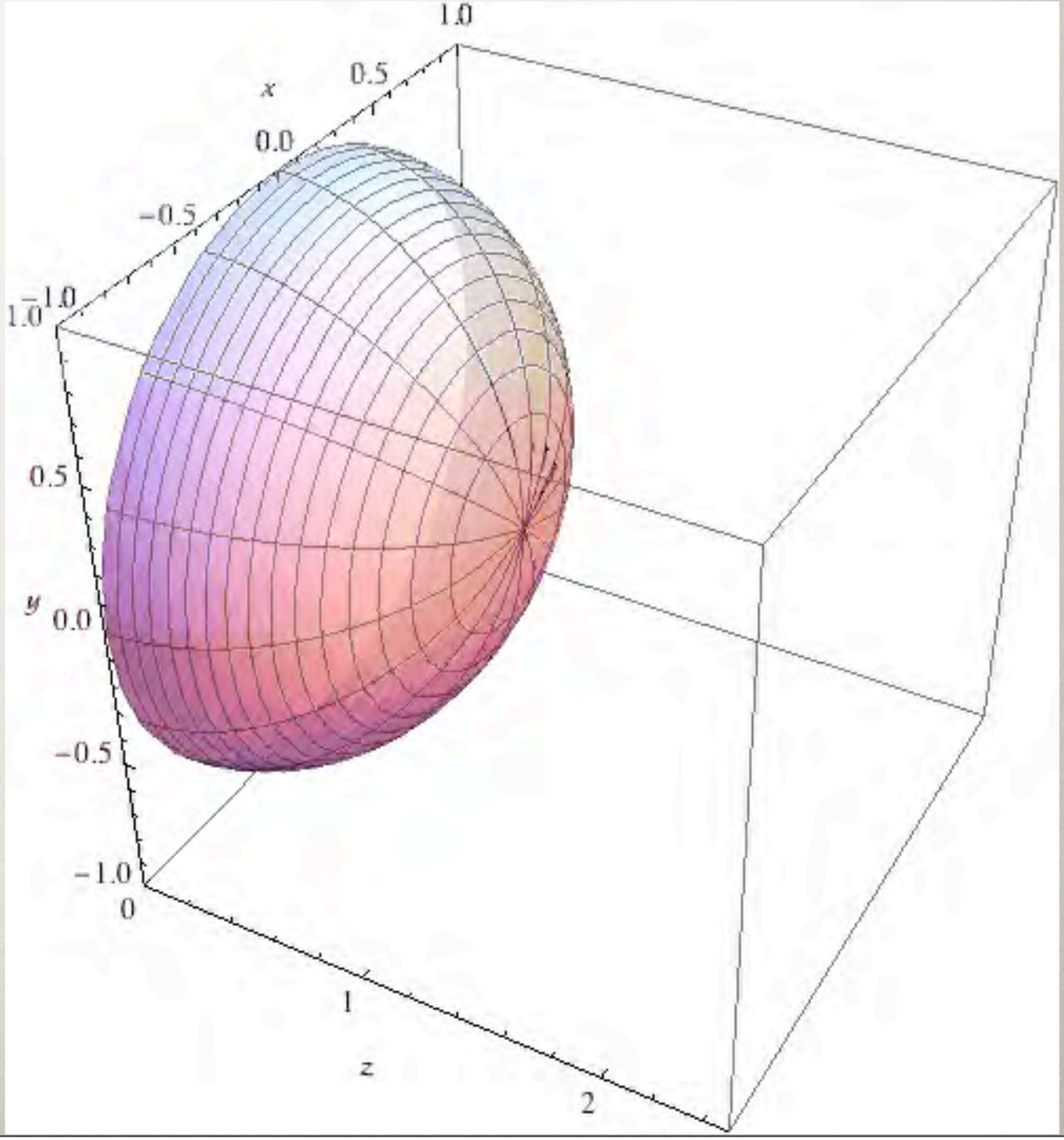

Gravity dual of $\mathcal{N}$=4 SYM on Schwarzschild

Embedding of the horizon geometry into hyperbolic space:

$$ds_H^2 = \frac{1}{z^2}(dz^2 + dy^2 + y^2 d\Omega_{(2)}^2)$$

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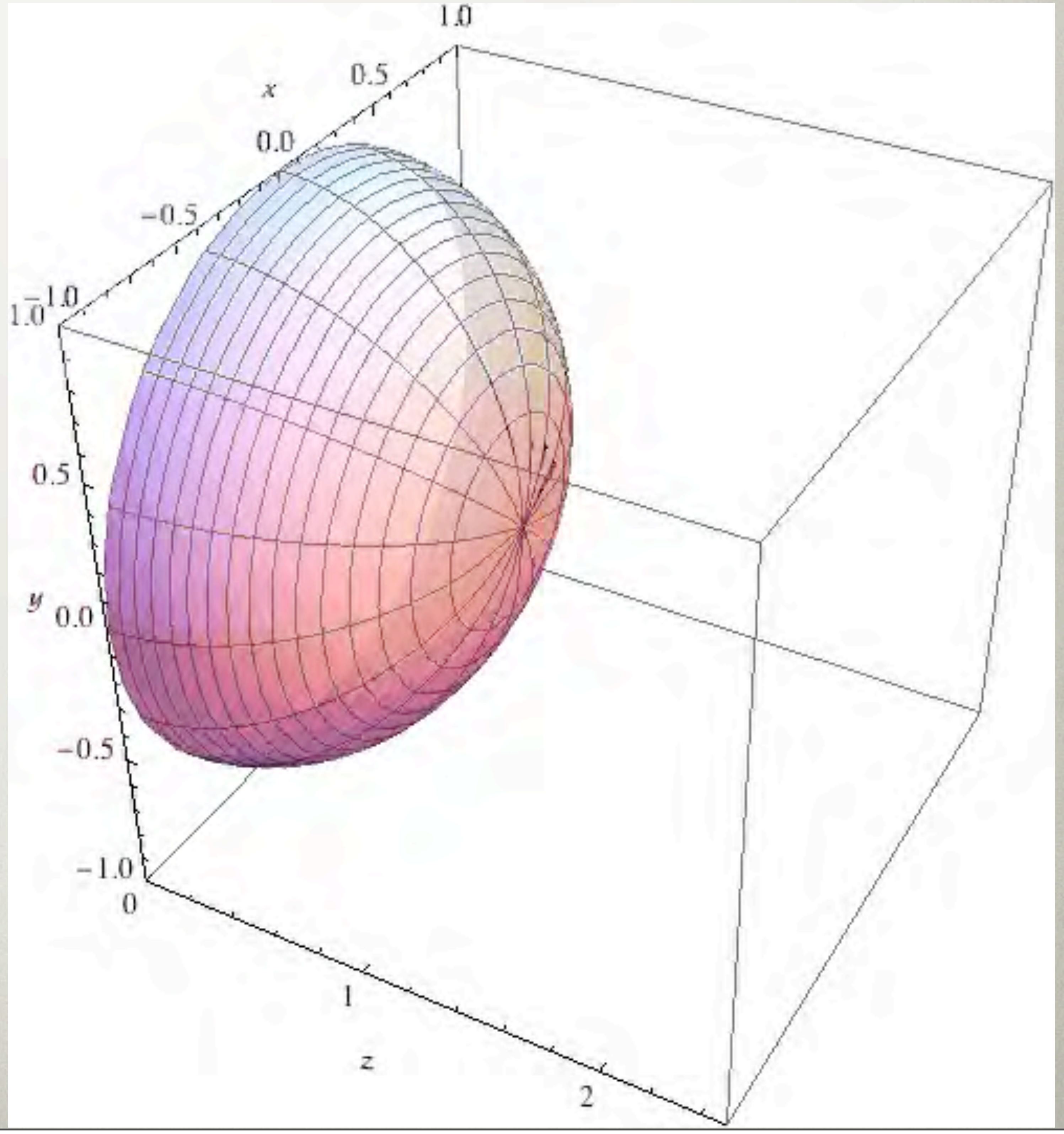
Note: the geometry only looks string-like in a small region near the boundary, too small for a GL type mode to fit on the horizon ⇒ the solution is presumably stable.

Ricci flow converges ⇒ no -ve modes



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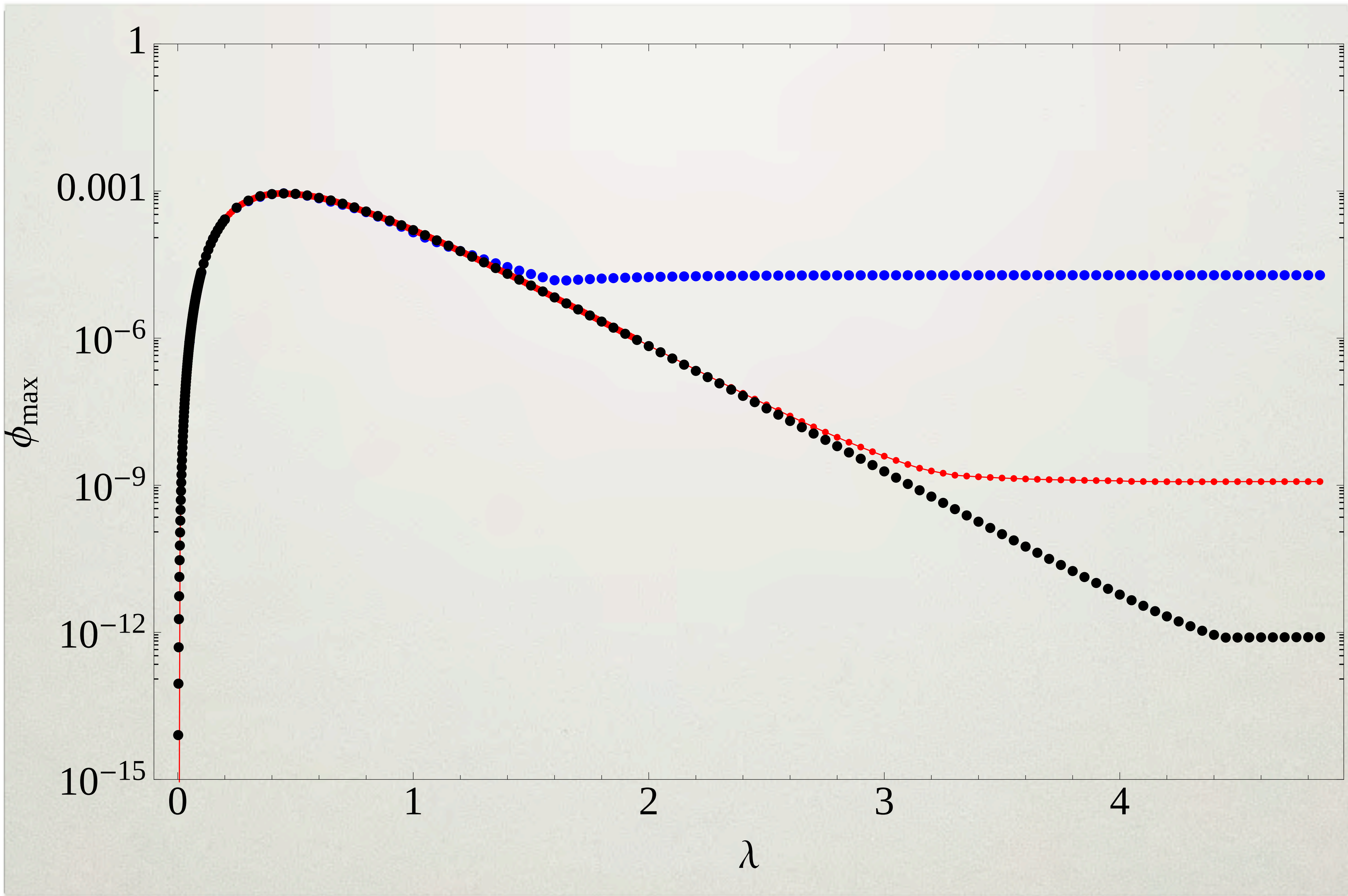
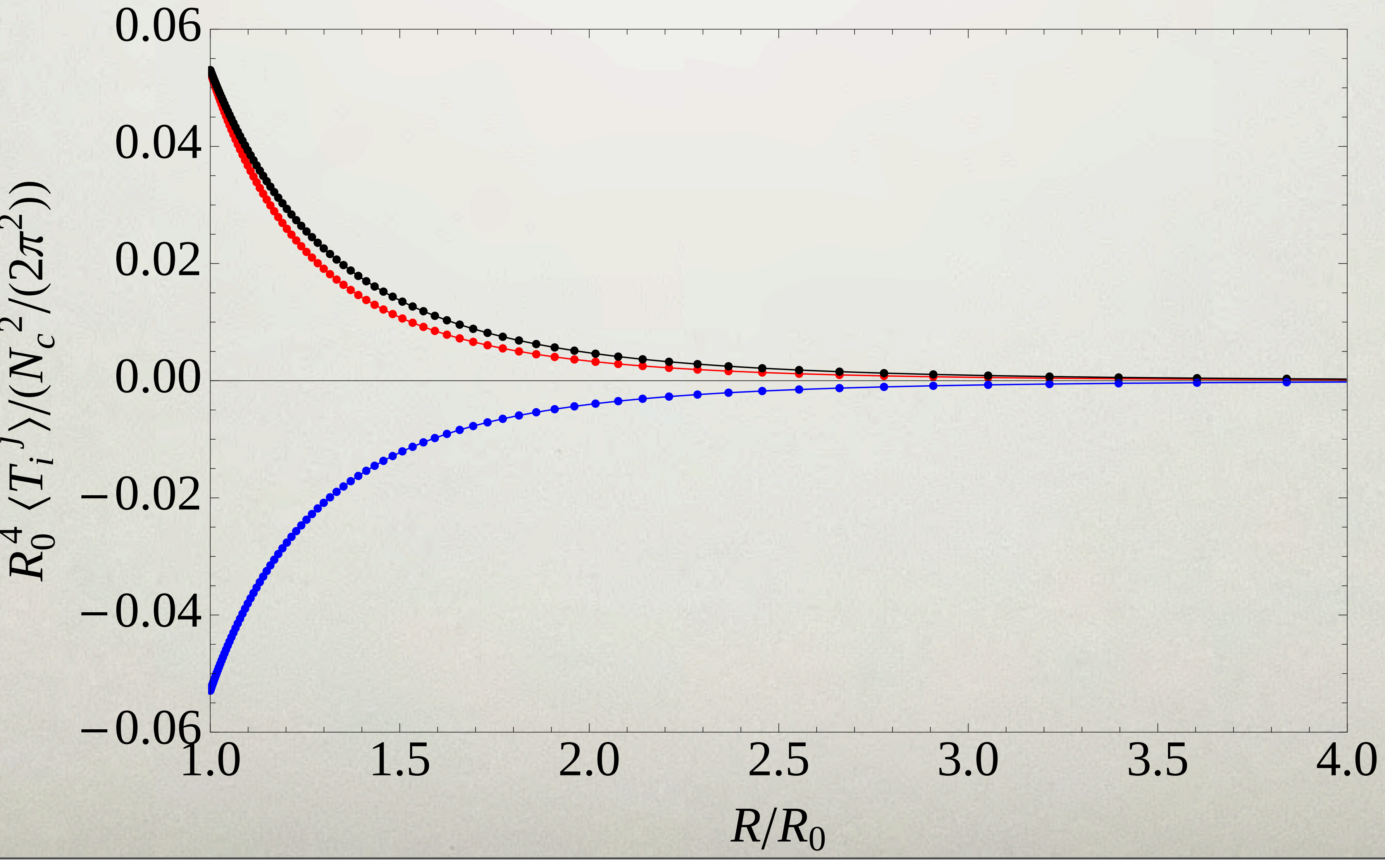


Note: we do not achieve the gauge $\xi^\mu = 0$ until we have reached the fixed point (i.e., solved the Harmonic Einstein equations)

Gravity dual of $\mathcal{N}$=4 SYM on Schwarzschild

$O(N_c^2)$ of the quantum stress tensor:

$$\frac{1}{N_c^2}\langle T_i{}^j\rangle = \frac{1}{2\pi^2}\,\frac{1}{R^4}\,\mathrm{diag}\left\{\frac{3\,R_0}{4\,R}\left(1-\frac{R_0}{R}\right)+t_4(R)\,,\ \frac{3\,R_0^2}{4\,R^2}-\big(t_4(R)+2\,s_4(R)\big)\,,\right.$$
$$\left.-\frac{3\,R_0}{8\,R}+s_4(R)\,,\ -\frac{3\,R_0}{8\,R}+s_4(R)\right\},$$



Gravity dual of $\mathcal{N}$=4 SYM on Schwarzschild

Main features and interpretation:

• Traceless: no conformal anomaly.

• Our solution corresponds to the gravitational dual of $\mathcal{N}$=4 SYM on the background of Schwarzschild in the Unruh vacuum.

• The dual classical geometry only captures the $O(N_c^2)$ of the full quantum stress tensor, and this piece is ***static and regular*** everywhere.
➡ ***there is no flux of radiation at infinity***. This is an $O(1)$ effect which cannot be captured in the gravity approximation

• To see the usual divergences on the past horizon in the Unruh vacuum one should include bulk quantum/string corrections.

Gravity dual of $\mathcal{N}$=4 SYM on Schwarzschild

Physical picture:

• The black hole acts as a heat source (of infinite energy) exciting the plasma around it, but far from the source the field theory should be in the confining vacuum ($T_{IR} = 0$)

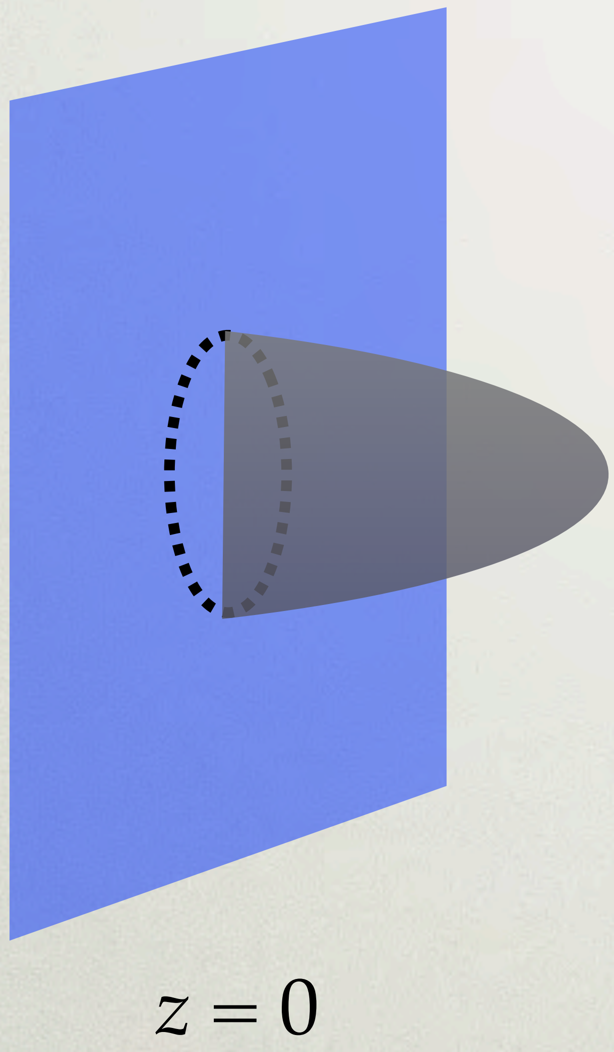
• The strong interactions of the plasma are attractive and want to collapse back into the black hole

• At $O(N_c^2)$ there is equilibrium between the radiation pressure and the attractive self-interactions of the plasma

• There is no flux of radiation at infinity. This is an $O(1)$ effect which cannot be captured in the gravity approximation
➡ there is no reason to expect that braneworld black holes cannot exist

Braneworld black holes

From the AdS/CFT we can construct perturbatively very large braneworld black holes:



$$ds^2 = \frac{\ell^2}{z^2}(dz^2 + \tilde{g}_{\mu\nu}(z,x)dx^\mu dx^\nu)$$

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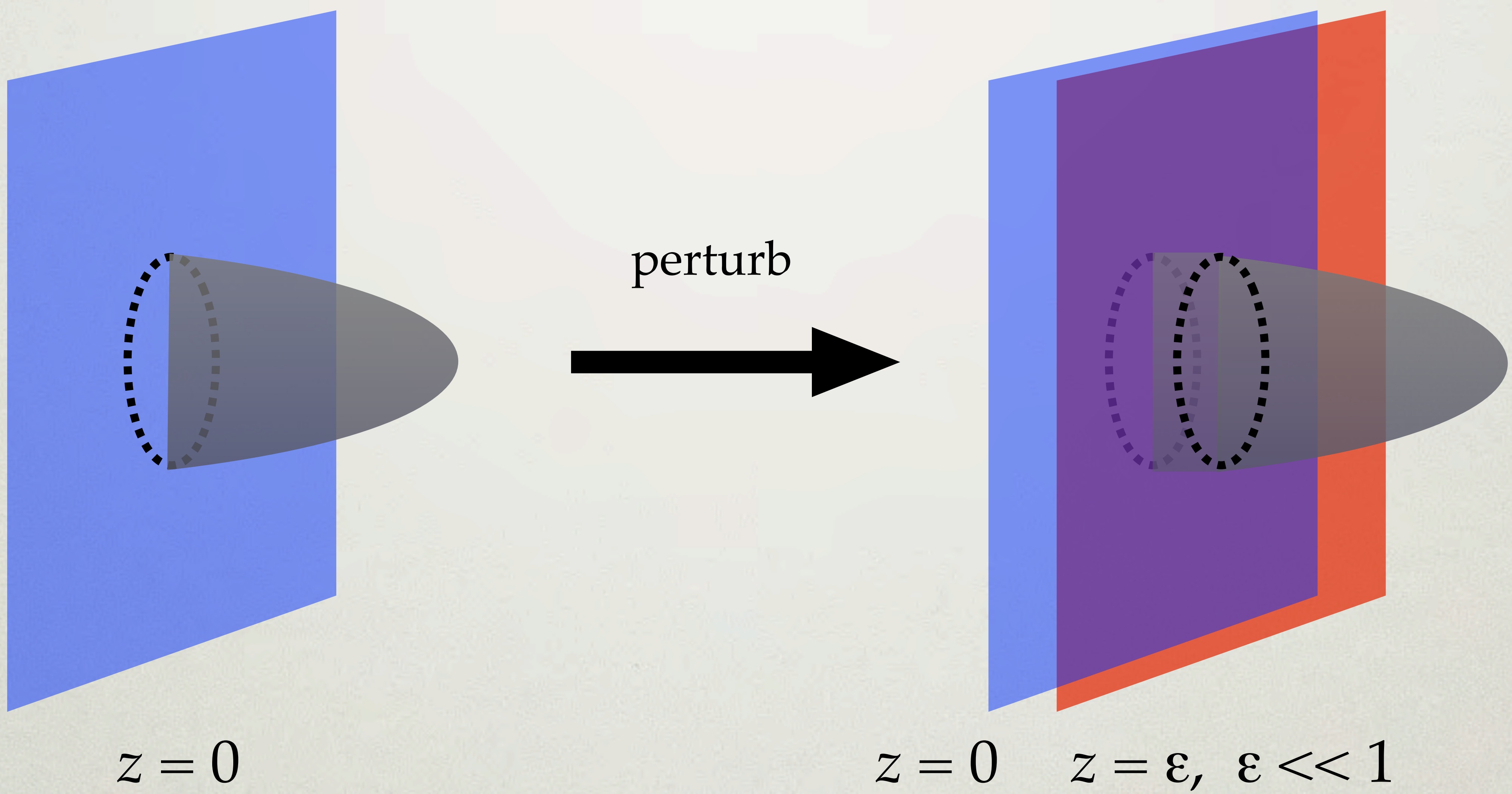

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Israel junction conditions

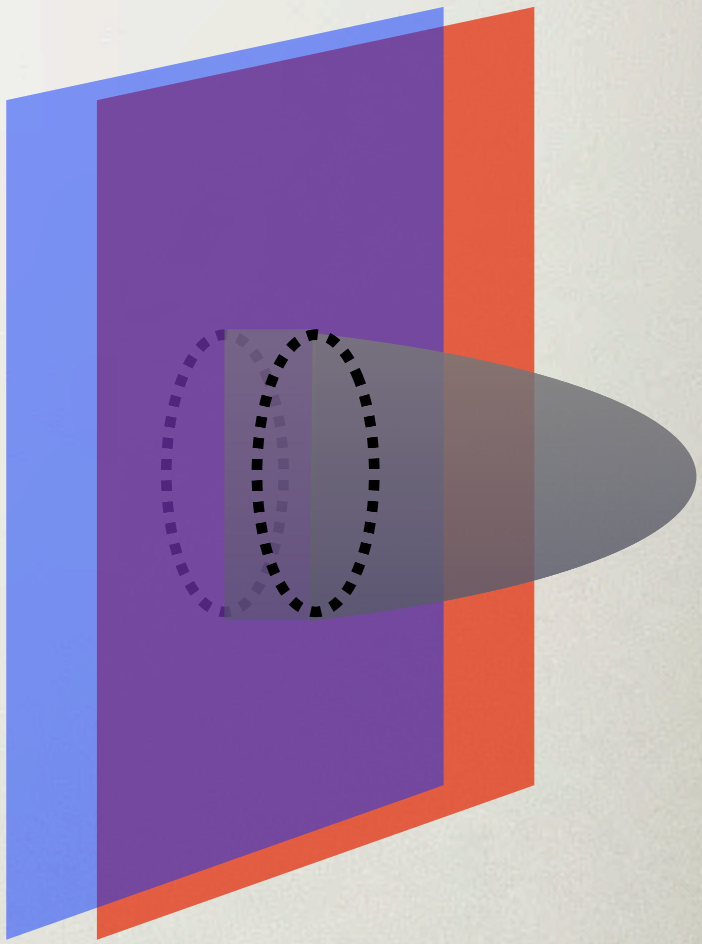
$$g_{\mu\nu} = g^{\rm Schw}_{\mu\nu} + \epsilon^2\, \delta g_{\mu\nu}$$

Braneworld black holes

Induced metric on the brane:

$$\gamma_{\mu\nu} = \frac{\ell^2}{\epsilon^2}(g_{\mu\nu}^{\rm Schw} + \epsilon^2\,\delta g_{\mu\nu})$$

$\Rightarrow$ the metric is approximately Schw. with a radius much larger than the AdS radius ℓ



$z = 0$ $z = \varepsilon,\ \varepsilon << 1$

Israel junction conditions

The perturbation satisfies:

$$\delta G_{\mu\nu} = 16\pi G_4 \langle T_{\mu\nu}^{\rm CFT}[g^{\rm Schw}]\rangle$$

Braneworld black holes

Metric ansatz for large black holes: "close" to the AdS/CFT solution but introduce a cut off near the boundary.

$$ds^2 = \frac{\ell^2}{\Delta^2}\left(4r^2 f^2 e^T\, d\tau^2 + x^2 g\, e^S\, d\Omega^2_{(2)} + \frac{4}{f^2}\, e^{T+r^2 A} dr^2 + \frac{4}{g}\, e^{S+x^2 B} dx^2 + \frac{2\,r\,x}{f}\, F\, dr\, dx\right)$$

$$\Delta = (1-x^2) + \epsilon(1-r^2)\,, \qquad f = 1 - r^2\,, \qquad g = 2 - x^2$$

- Place the brane at $x = 1$ (Δ remains finite there)
- In the limit $\varepsilon \rightarrow 0$ we recover the AdS/CFT solution.

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- Place the brane at $x = 1$ (Δ remains finite there)
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Metric ansatz for small black holes: "close" to 5d AF Schwarzschild

$$ds^2 = \frac{\ell^2}{\Delta^2}\left(4r^2 f(r)^2 g(r) e^T + x^2 g(x) e^S d\Omega^2_{(2)} + \frac{4}{f(r)^2 g(r)} e^{T+r^2 A} dr^2 + \frac{4}{g(x)} e^{S+x^2 B} dx^2 + \frac{2rx}{f(r)} F dr dx\right)$$

- In the limit $\varepsilon \to \infty$ we recover the 5d AF Schwarzschild solution

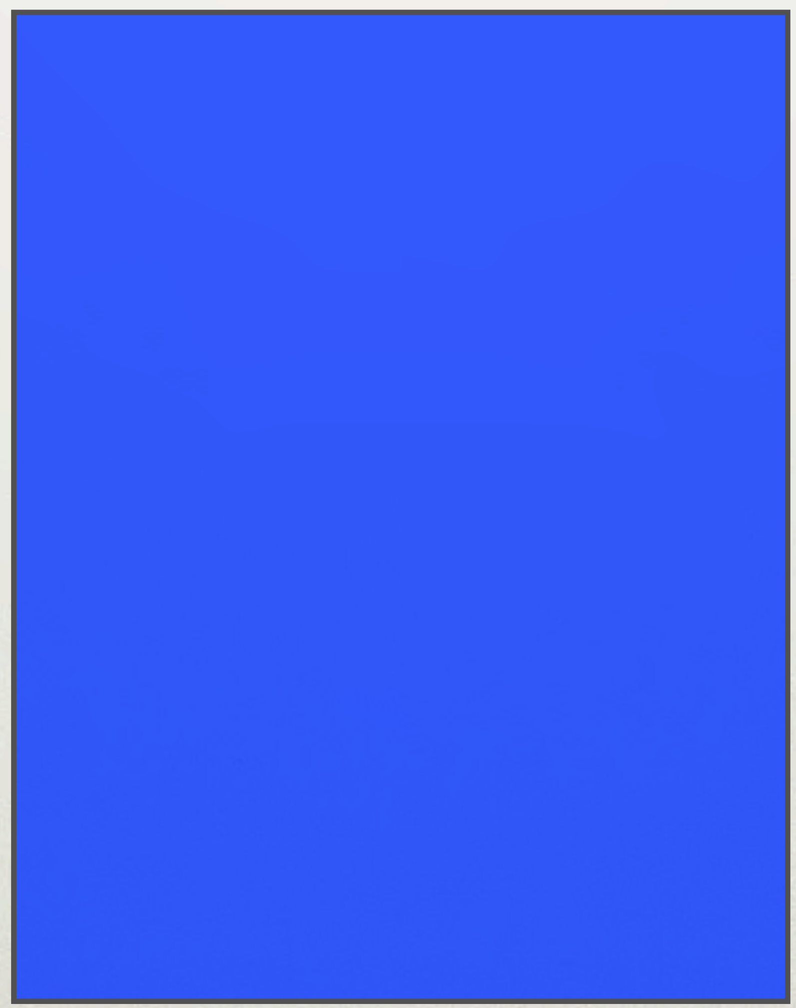
Braneworld black holes

x=1:
Brane

$$K_{ij} = \frac{1}{\ell}\,\gamma_{ij}\,,$$

$$\xi_x = 0\,, \quad F = 0\,, \quad \Rightarrow \quad \partial_x \xi_r = \frac{2}{\ell}\,\xi_r$$

r=0:
non-extremal horizon
(fictitious boundary)
Neumann



r=1:
AdS Poincare horizon.
Dirichlet

x=0: symmetry axis
(fictitious boundary)
Neumann

Braneworld black holes

Why is this problem harder than the AdS/CFT one?

• The Israel junction conditions + BCs on ξ^μ are a set of non-linear equations

• Our BCs are compatible with $\xi^\mu = 0$ but they do NOT imply it

• Gravity on the brane is dynamical and localised braneworld black holes are expected to have at least one negative mode

$\Rightarrow$ we cannot use Ricci flow in a straightforward manner: we have to introduce at least one parameter and tune it so as to kill the -ve modes (e.g., fix the radius of the horizon on the brane and vary the temperature)

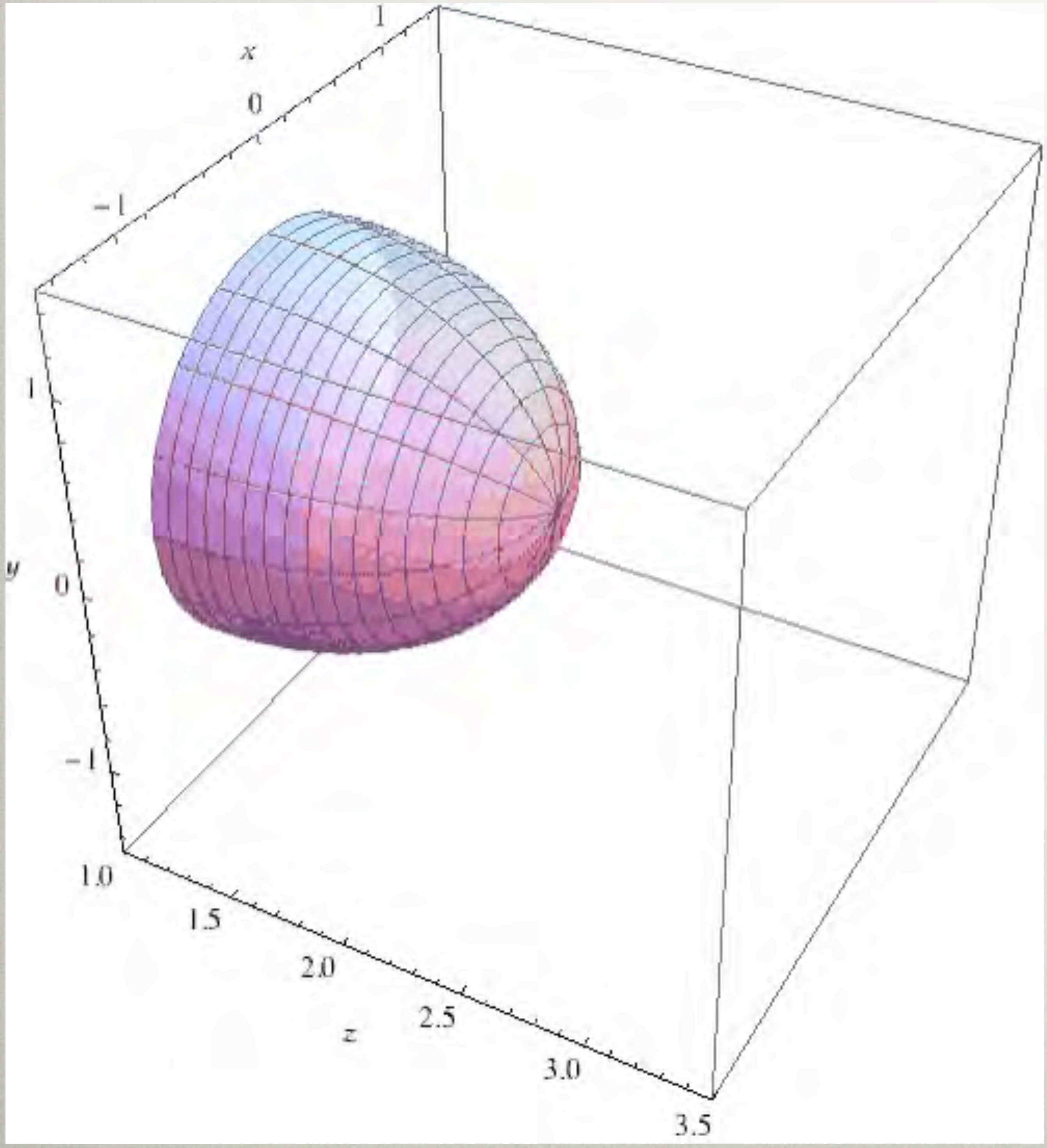
Braneworld black holes results

$\varepsilon = 1, t_0 = -3.9115$

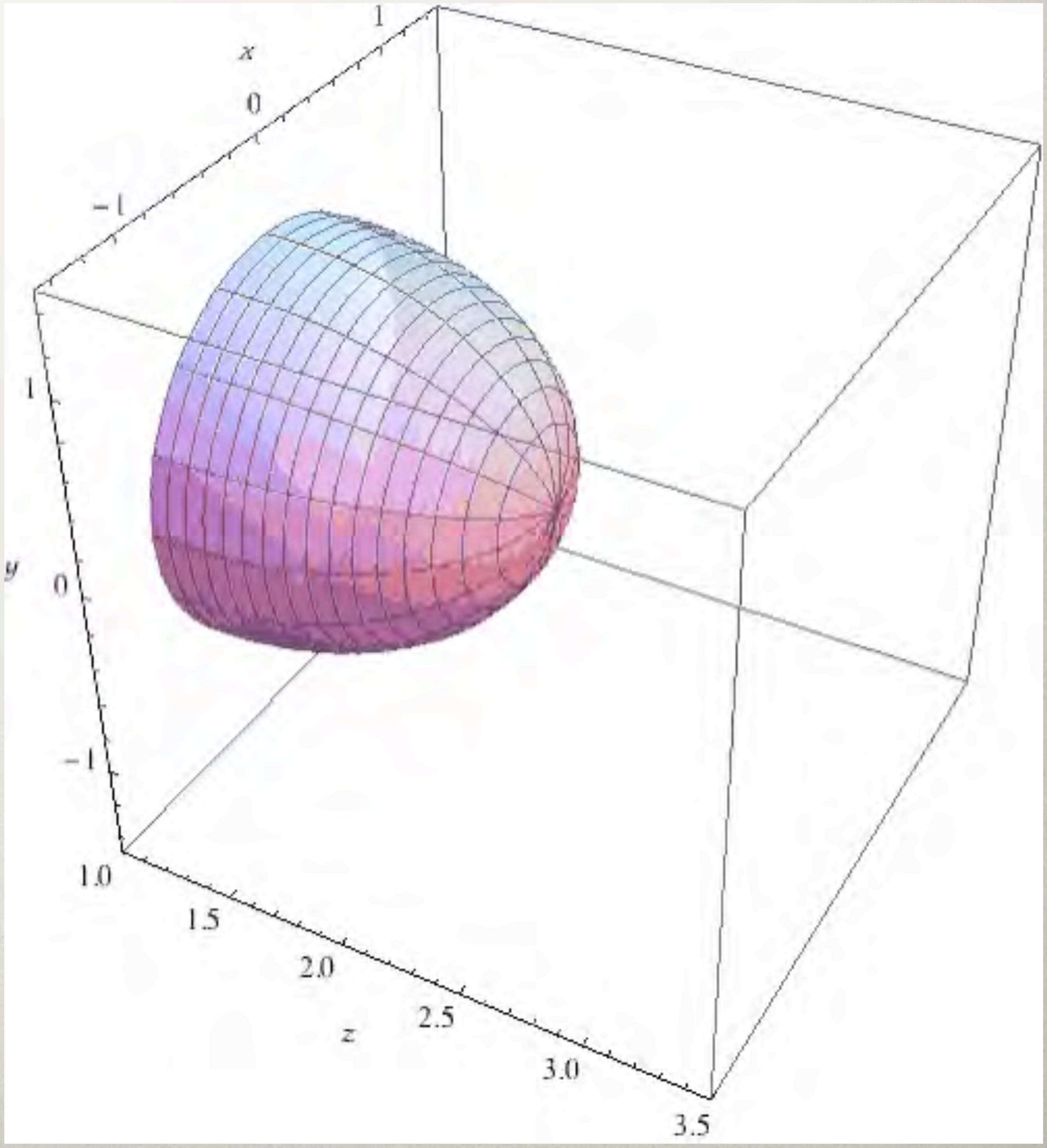
$\varepsilon = 1, t_0 = -3.9110$

Braneworld black holes results

$\varepsilon = 1$, $t_0 = -3.9115$

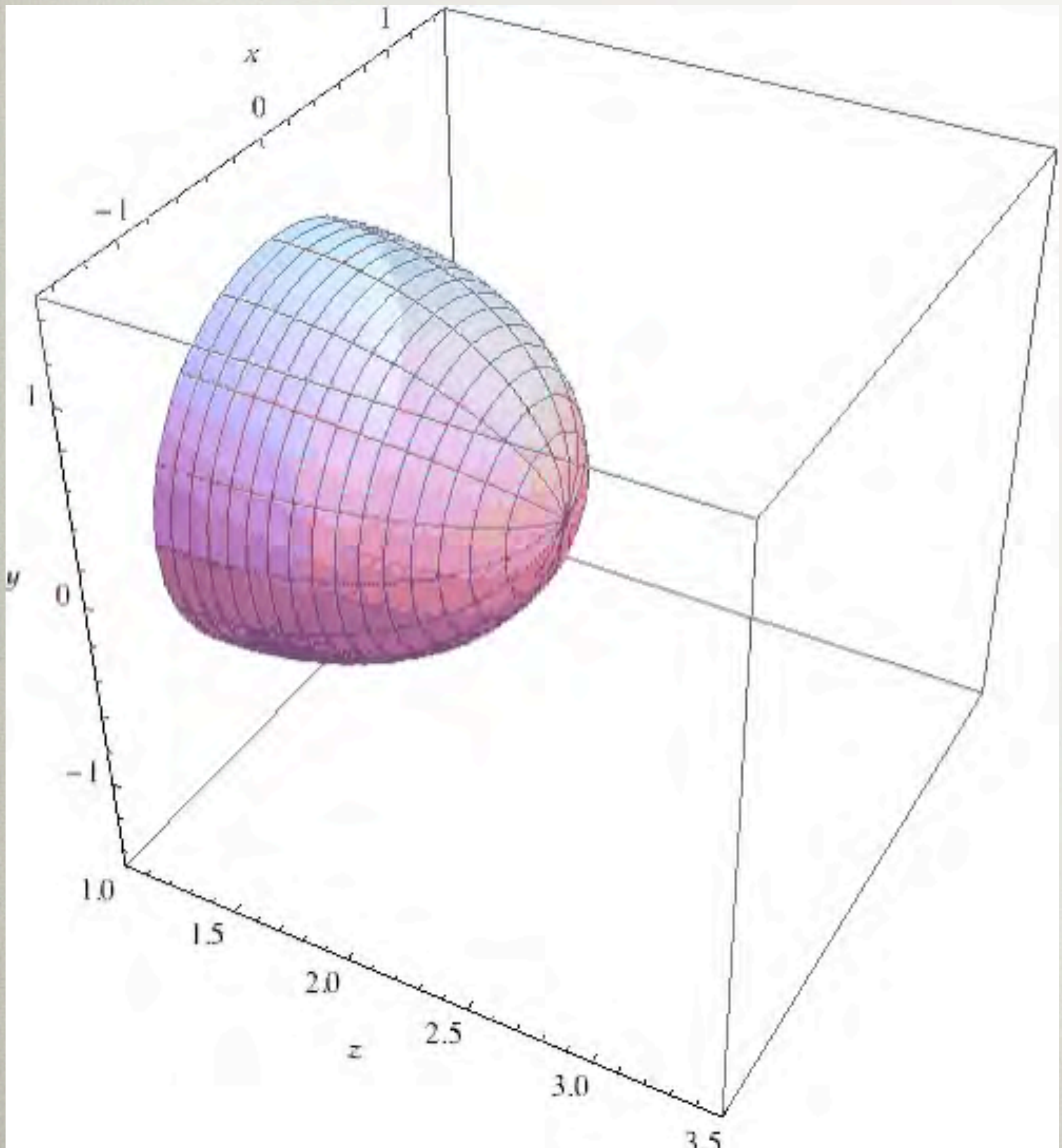


$\varepsilon = 1$, $t_0 = -3.9110$

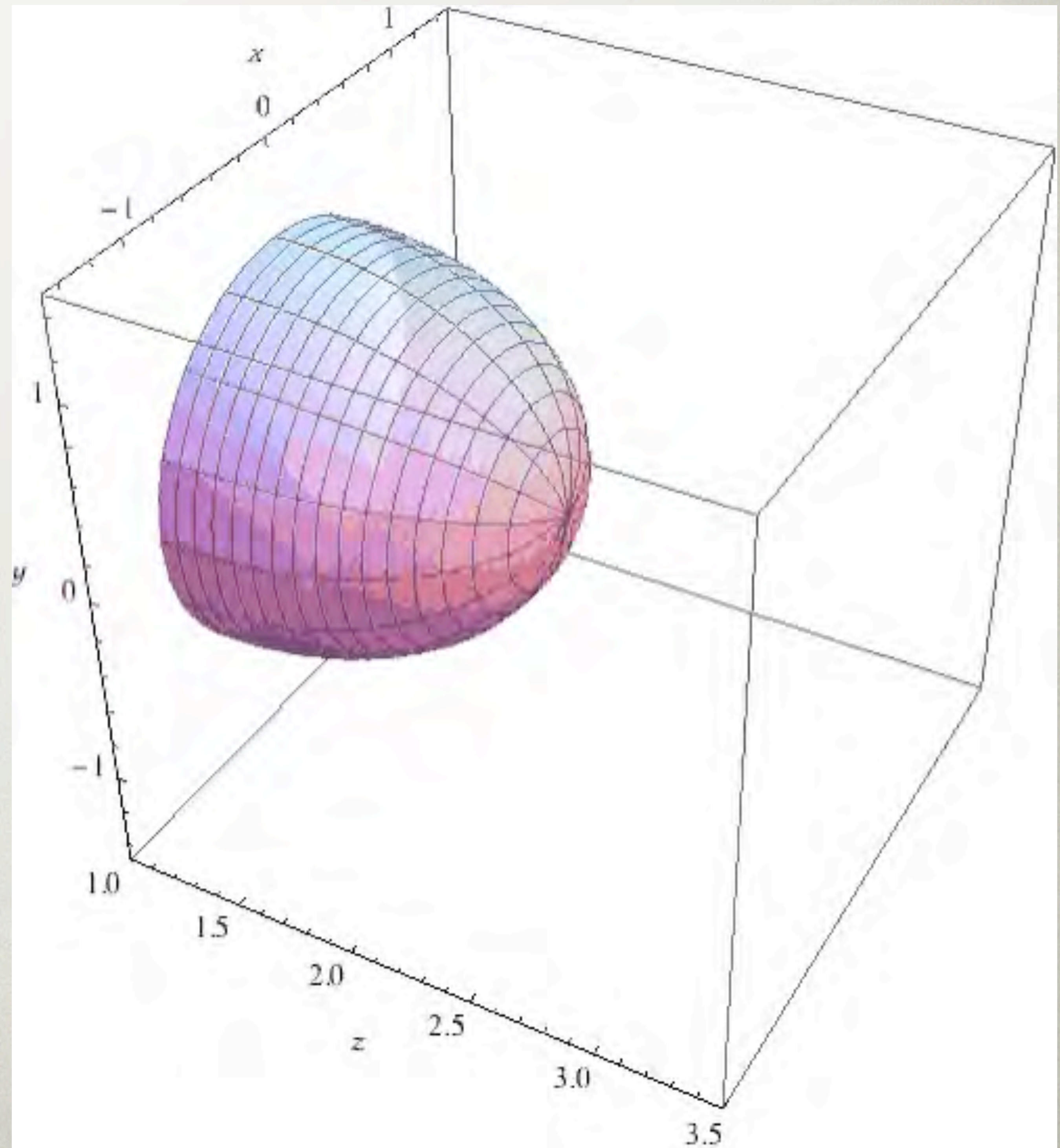


Braneworld black holes results

$\varepsilon = 1, t_0 = -3.9115$

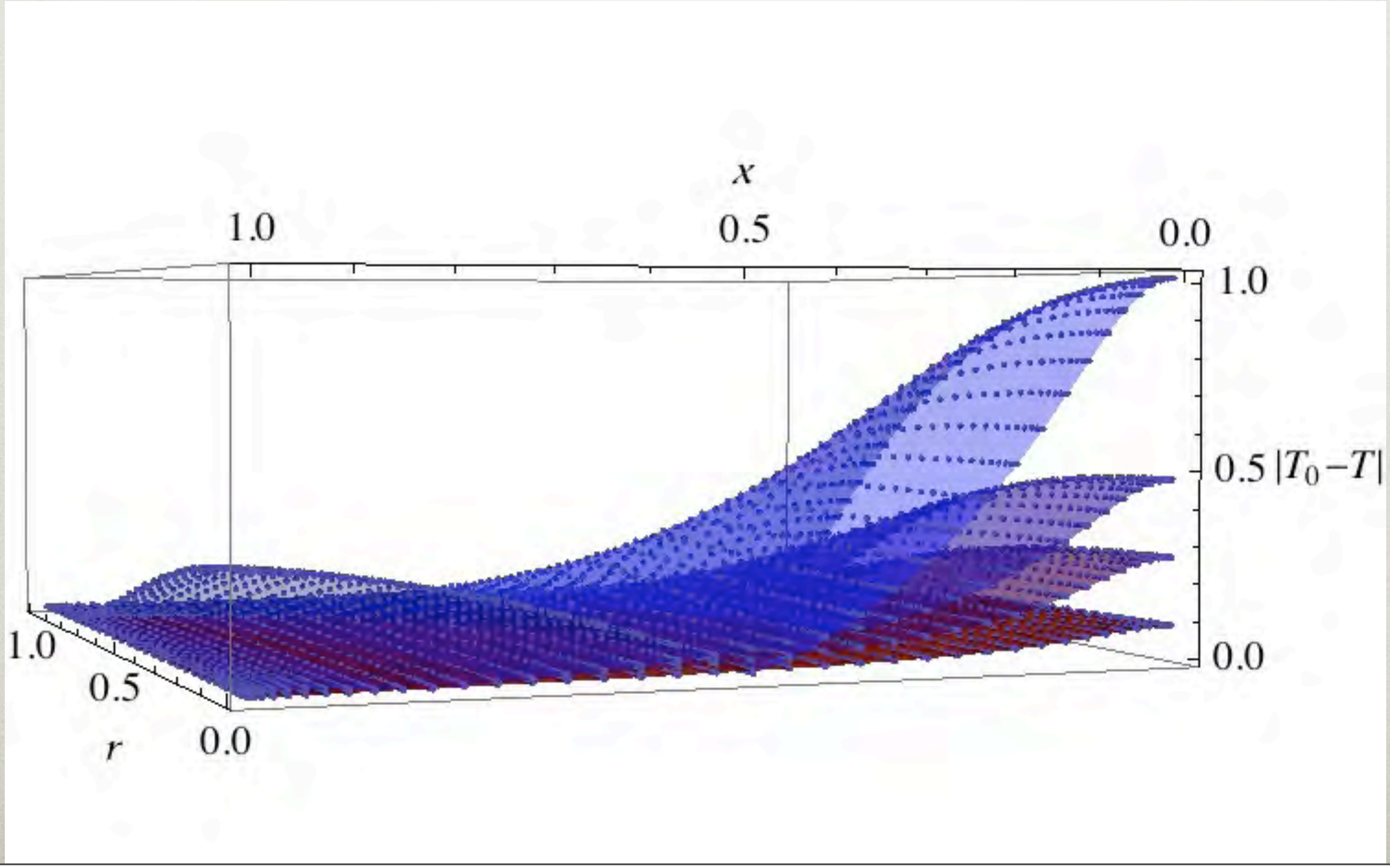


$\varepsilon = 1, t_0 = -3.9110$



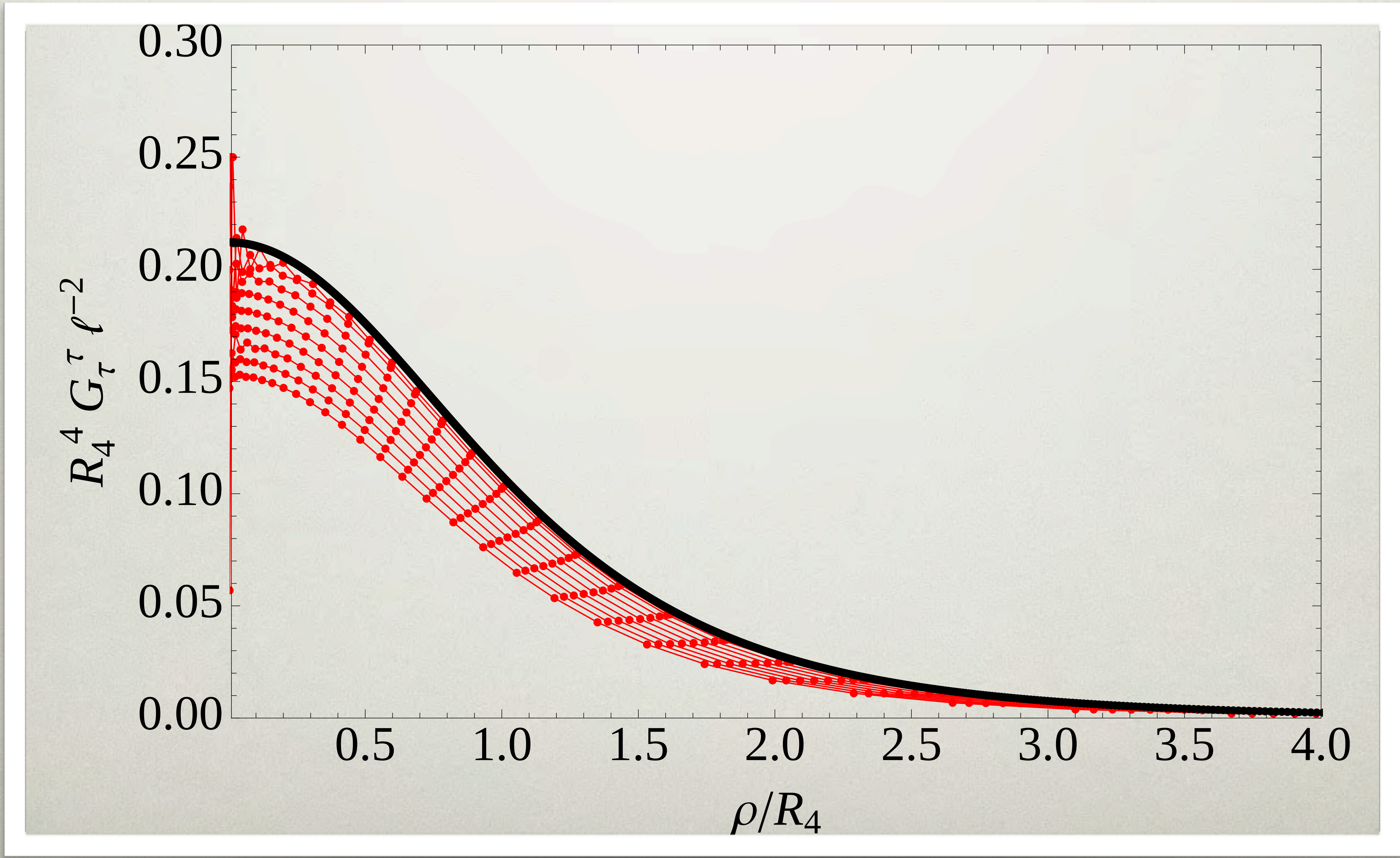
Braneworld black holes results

- Using Newton's method we can find black holes with $5 \times 10^{-3} \lesssim R_4/\ell \lesssim 100$
- Even though we cannot prove that solitons do not exist, we do NOT find any.
- Large braneworld black holes are "close" to the AdS/CFT solution.



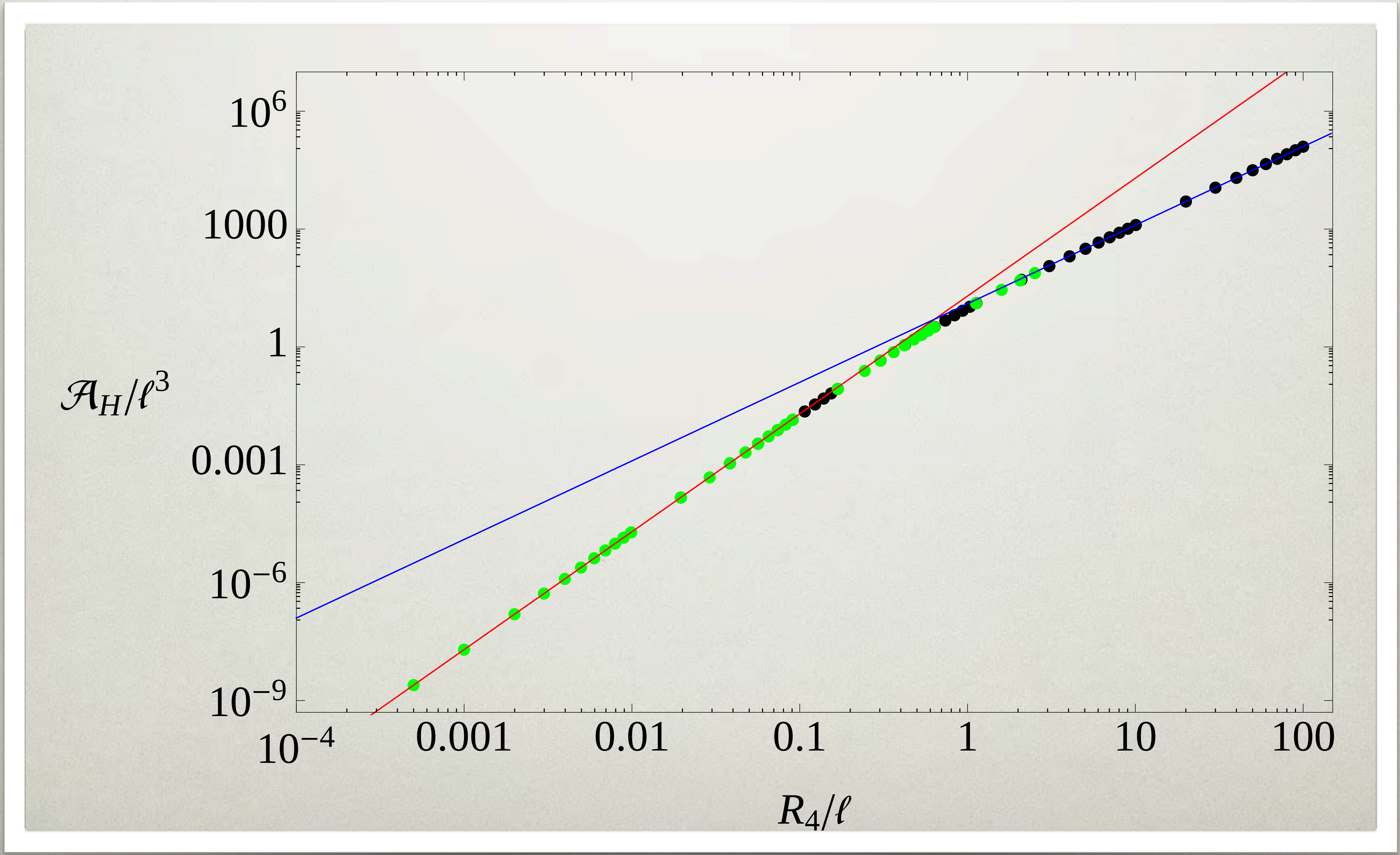
Braneworld black holes results

- Einstein tensor on the brane



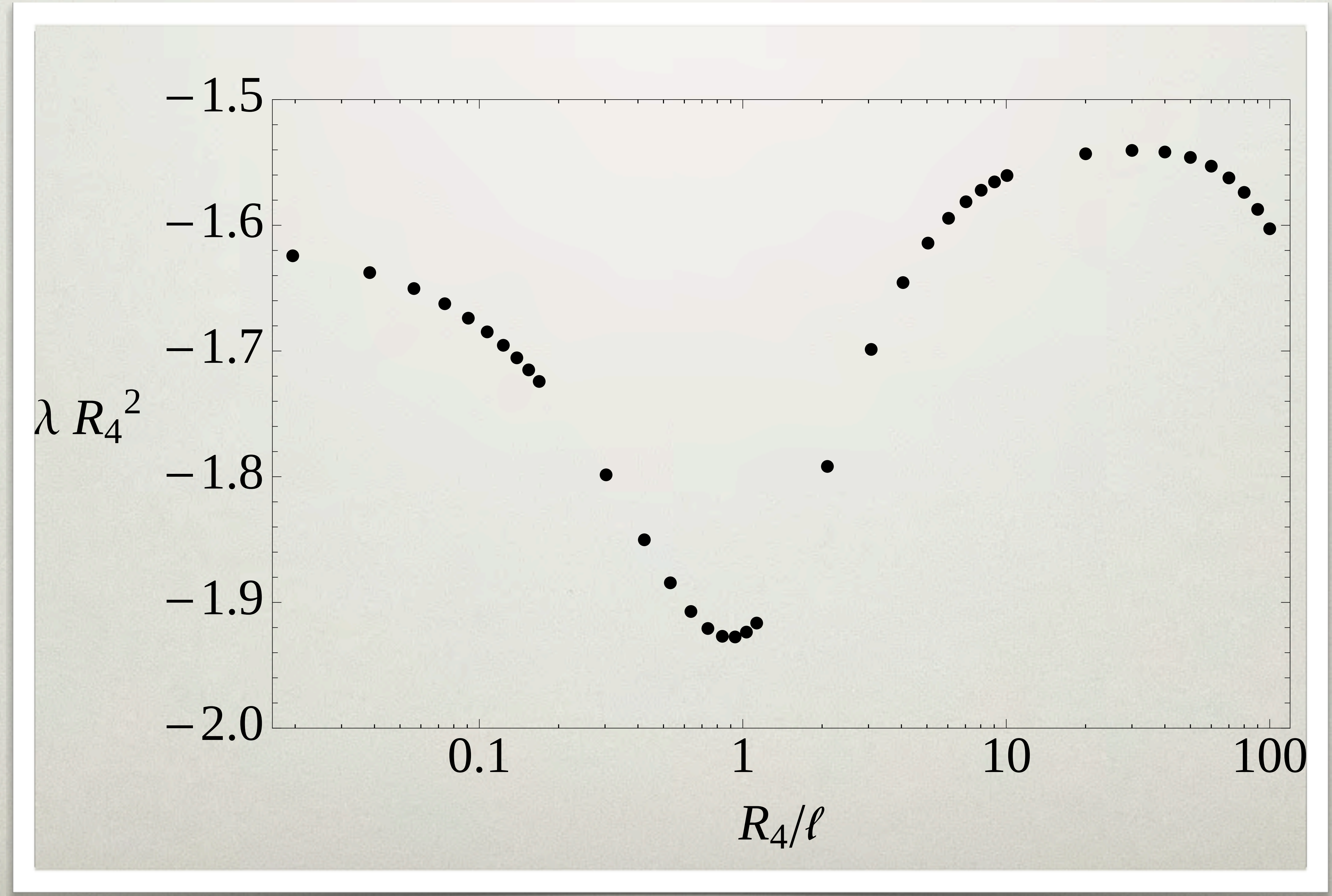
Braneworld black holes results

- 5d/4d behaviour



Braneworld black holes results

- Spectrum of Δ_L



Summary

• The method that we have used is based on a characteristic formulation of the Einstein equations:

- Numerical stability.
- A posteriori gauge fixing.
- No constraints.
- Fully covariant.

• We have found a solution in AdS/CFT which corresponds to $\mathcal{N}$=4 SYM in the background of Schwarzschild in the Unruh vacuum.

• The AdS/CFT solution with 4d Schwarzschild boundary metric allows to understand the existence of large braneworld black holes.

• We have found static non-extremal braneworld black holes of any size.

• Braneworld black holes are likely to be stable.

• 4d gravity is recovered on the brane for large black holes

THANK YOU!!!!