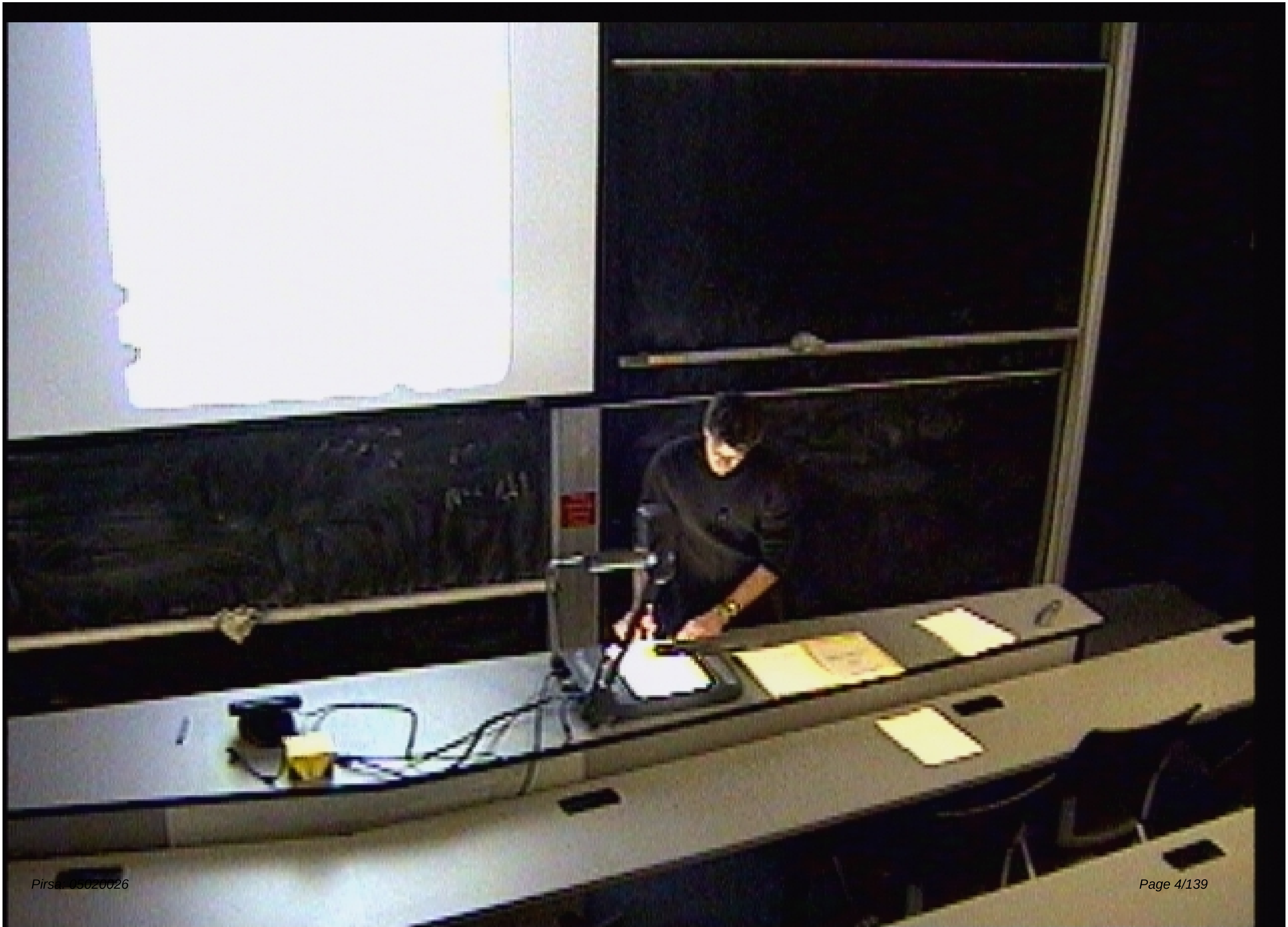
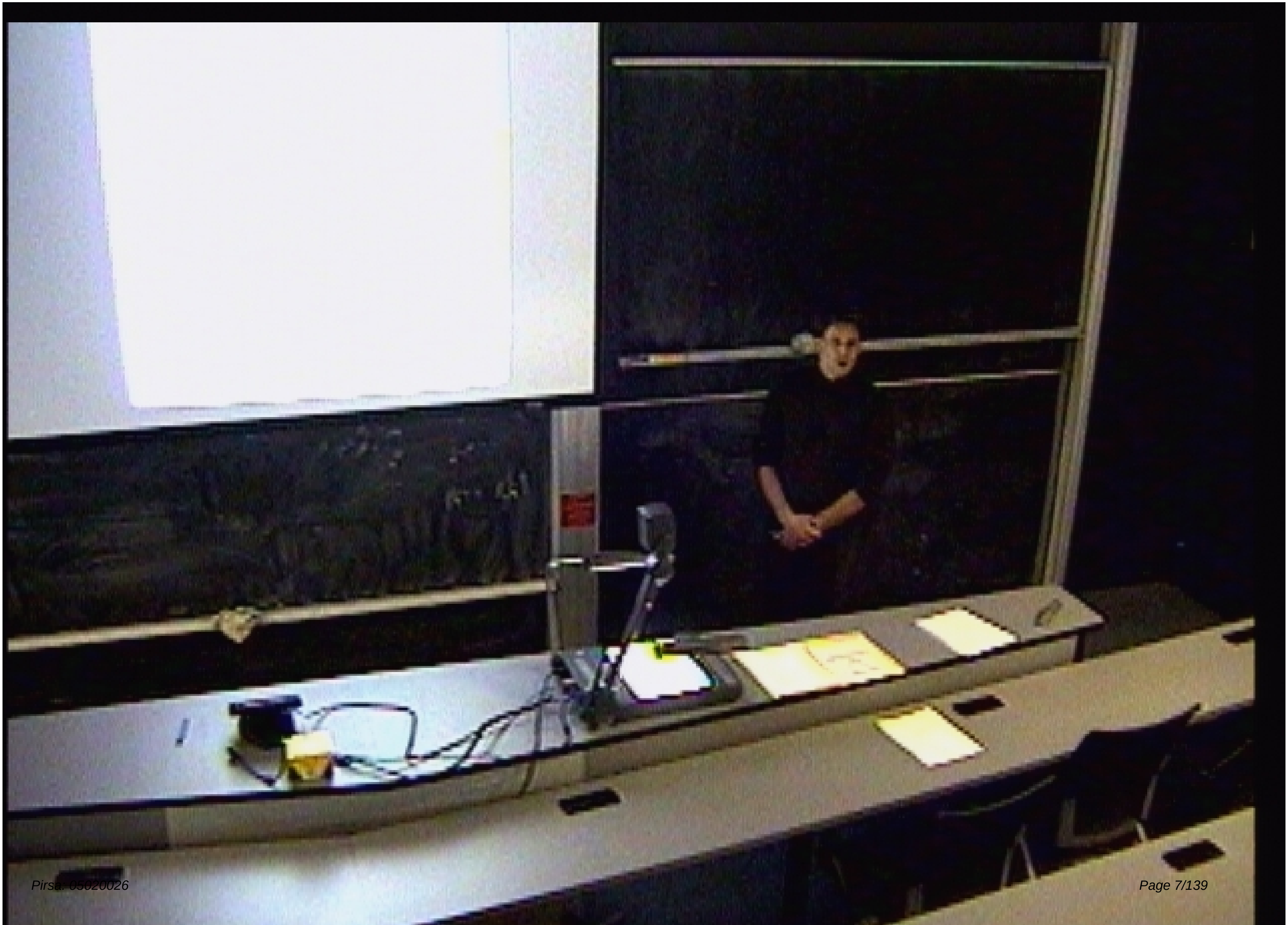
Title: Holographic description of AdS cosmologies

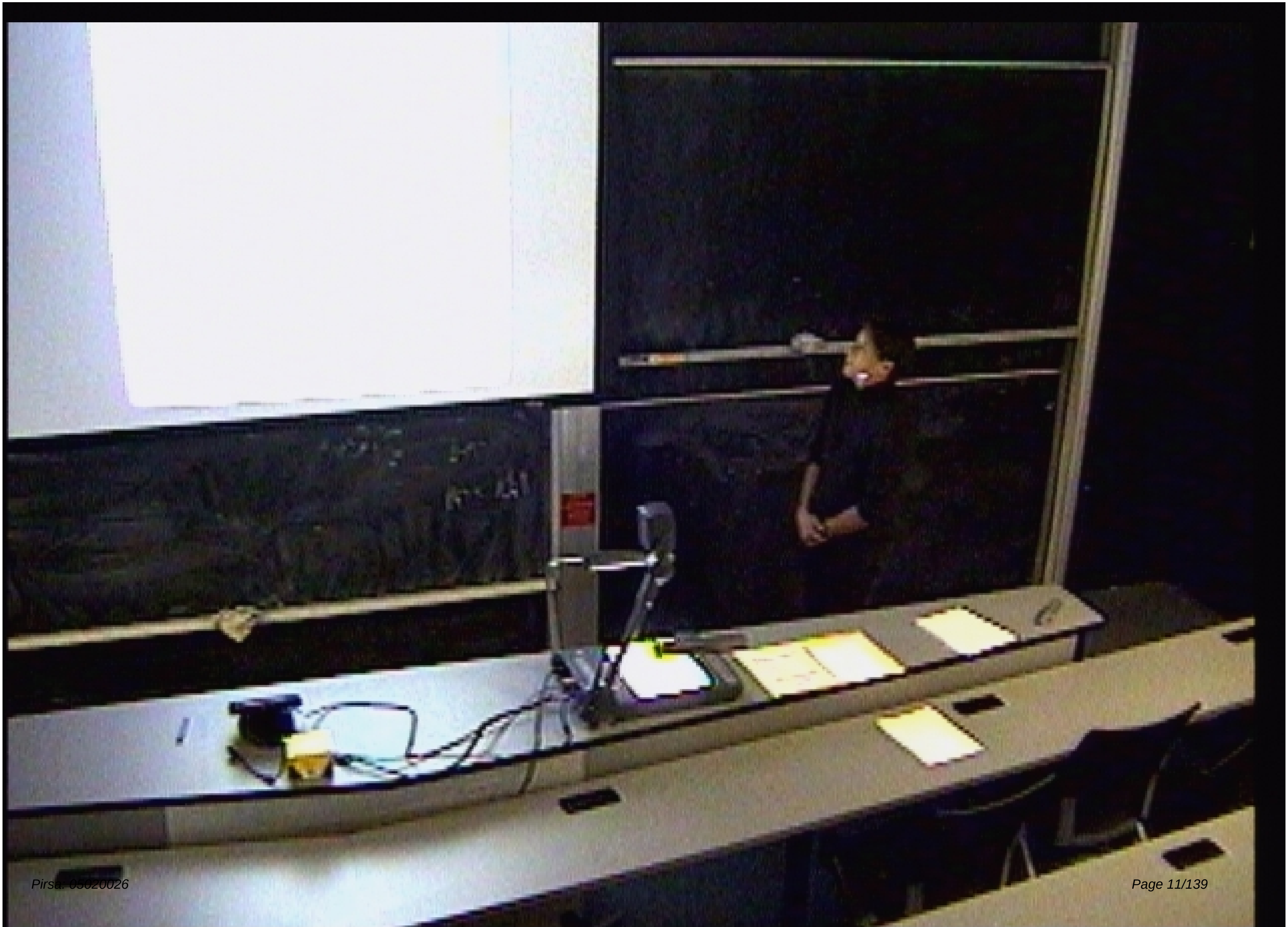
Date: Feb 22, 2005 11:00 AM

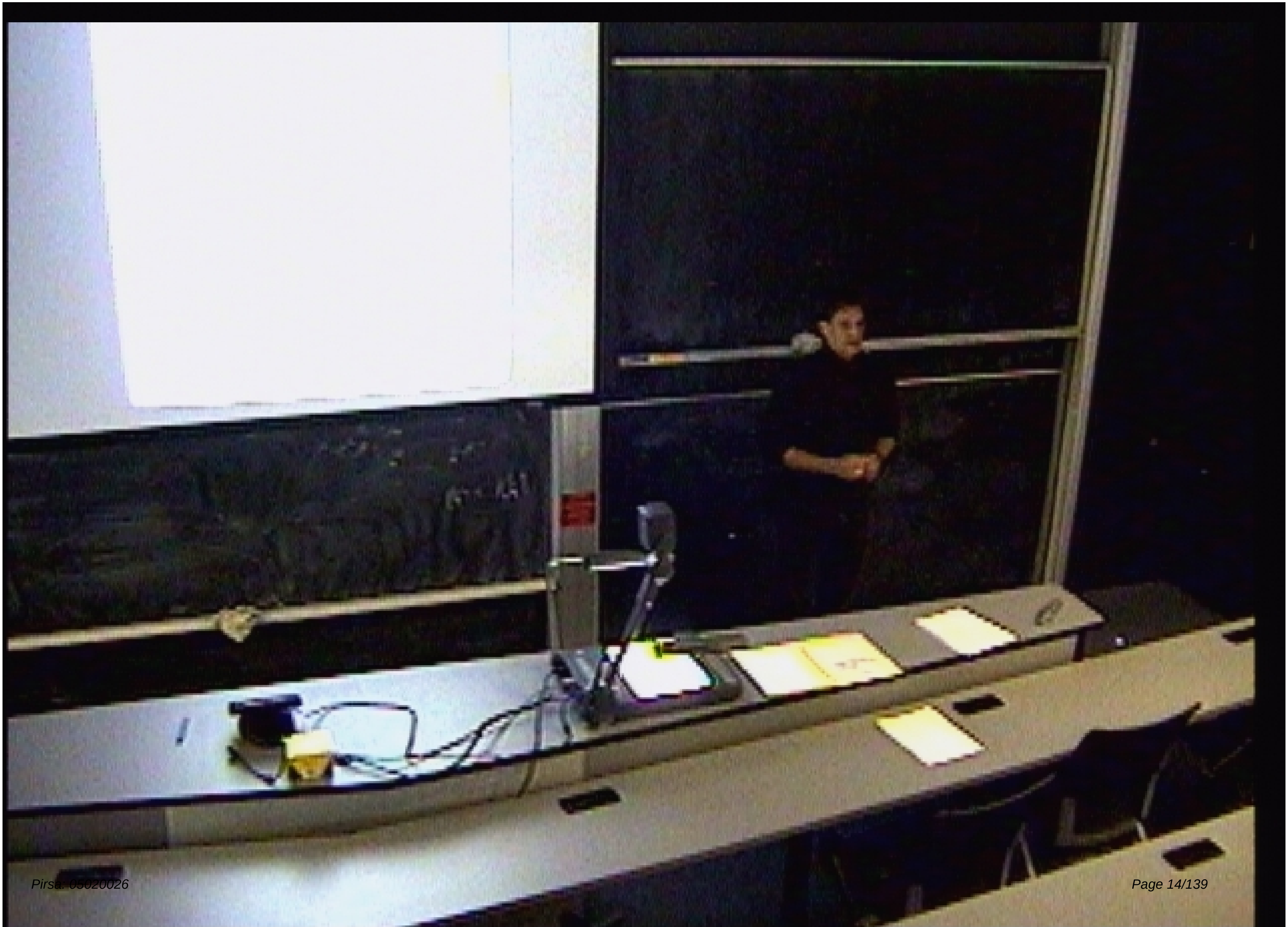
URL: http://pirsa.org/05020026

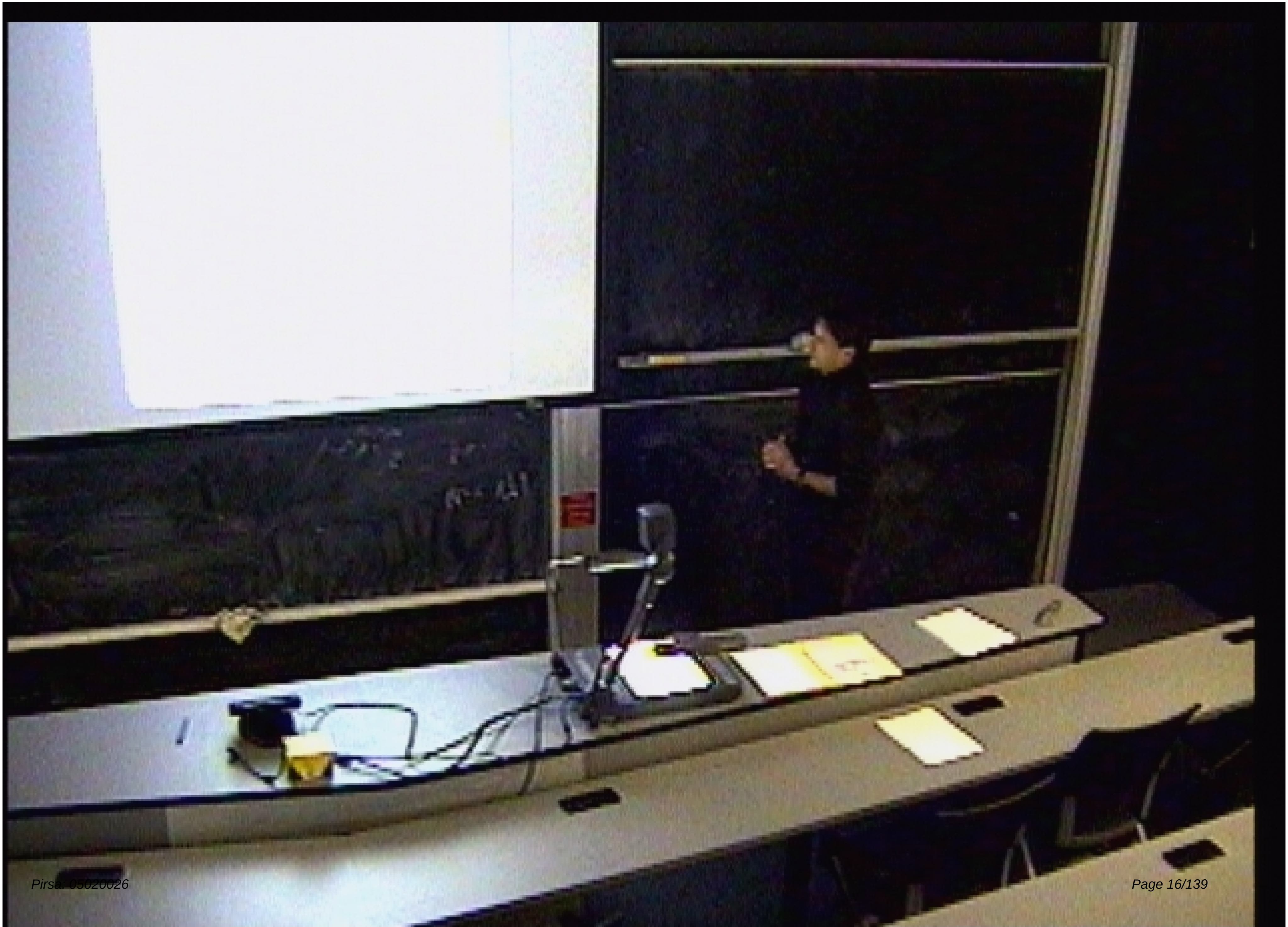
Abstract:











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AdS-invariant boundary conditions

Remarkably, the following class of boundary conditions are invariant under all AdS symmetries, [T.H & K. Maeda '04]

$$\bar{\beta} = k\alpha^2$$

Claim: For all $k \neq 0$ boundary conditions there exist smooth asymptotically AdS initial data that evolve to a singularity which extends to the boundary of AdS in finite global time.

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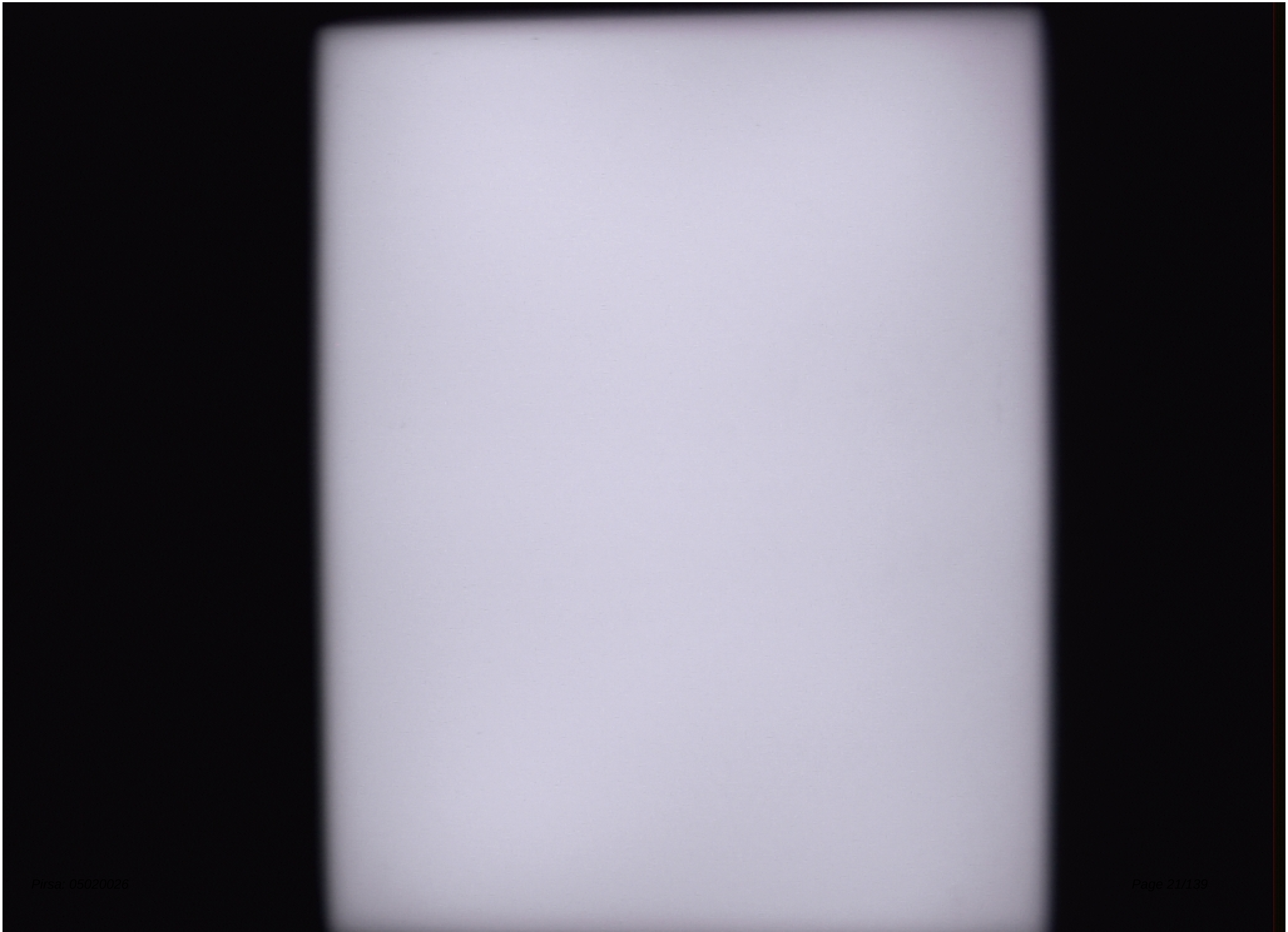


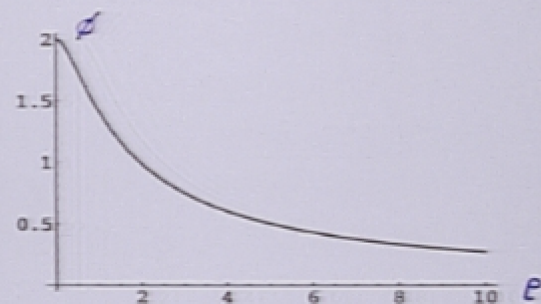
Example

The theory with $k \neq 0$ boundary conditions admits an $O(4)$-invariant Euclidean instanton solution,

$$ds^2 = \frac{d\rho^2}{b^2(\rho)} + \rho^2 d\Omega_3$$

and $\phi = \phi(\rho)$.

For $k = -1/4$, the scalar field profile is



and the field equations determine $b(\phi)$.

The slice through the instanton obtained by restricting to the equator of the S^3 defines zero mass, time symmetric initial data for a Lorentzian solution.

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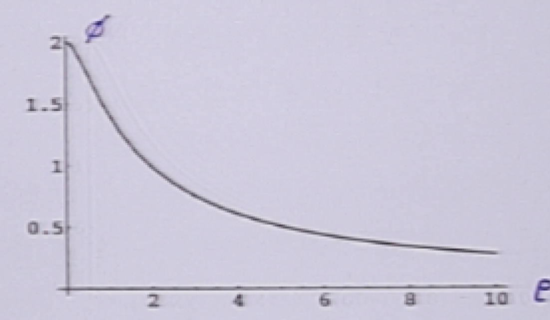

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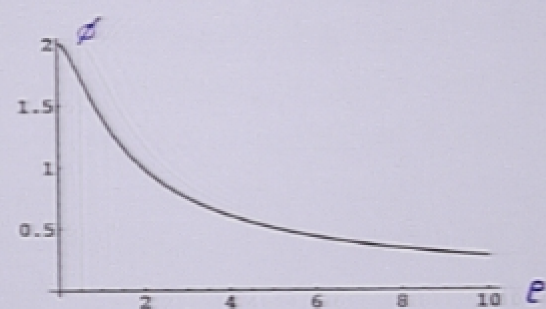

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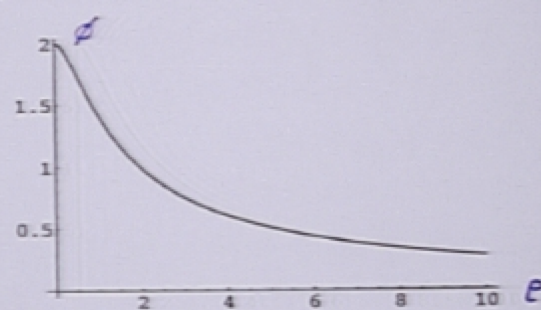

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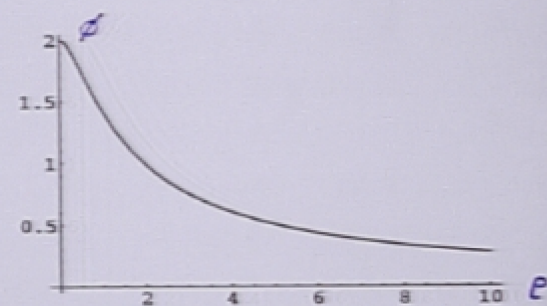

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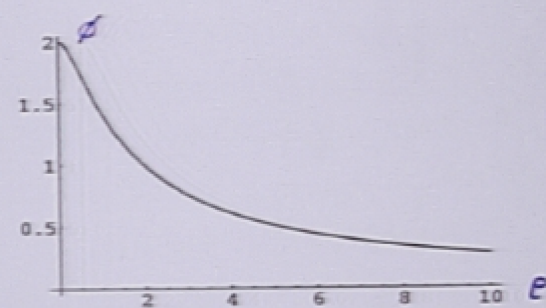

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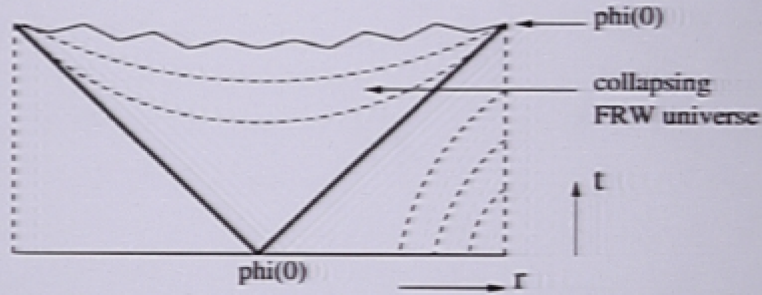
Evolution

The evolution of these initial data is obtained from the instanton by analytic continuation.



Inside the lightcone the solution produces a big crunch singularity, which hits the boundary as $t \to \pi/2$.

The asymptotic behavior of ϕ is given by

$$\phi(r) = \frac{\tilde{\alpha}}{r} + \frac{k\tilde{\alpha}^2}{r^2} + O(r^{-3})$$

where $\tilde{\alpha} = \alpha/\cos t \to \infty$ as $t \to \pi/2$.

The field ϕ itself, however, tends to a constant at the boundary, i.e. its value on the lightcone from $\phi(0)$.

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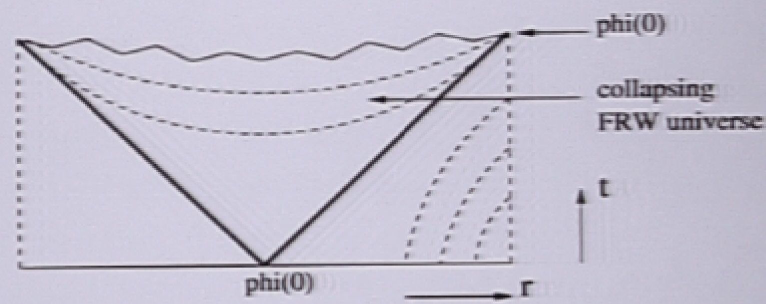

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Dual Field Theory

With $\beta = 0$ bulk boundary conditions, the dual theory is the 2+1 CFT on a stack of M2 branes. This contains dimension one operators,

$$\mathcal{O} = Tr T_{ij} \varphi^i \varphi^j$$

One of these operators is dual to our bulk scalar ϕ, so we identify $\alpha \leftrightarrow \langle \mathcal{O} \rangle$.

Imposing different boundary conditons $\beta(\alpha)$ corresponds to adding a multitrace interaction $\int W(\mathcal{O})$ to the CFT, such that [Witten '02]

$$\beta = \frac{\delta W}{\delta \alpha}$$

Hence the AdS-invariant boundary conditions $\bar{\beta} = k\alpha^2$ correspond to adding

$$S = S_0 + \frac{k}{3} \int \mathcal{O}^3$$

which is a marginal deformation.

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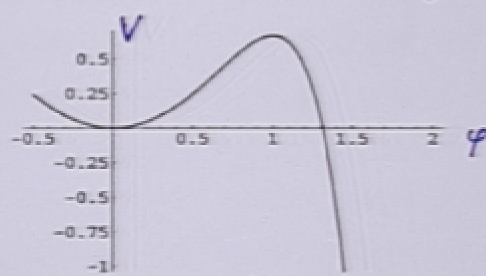
Classical Evolution

What is the dual field theory evolution that corresponds to our AdS cosmologies?

The multitrace term is not positive definite. Neglecting the nonabelian structure leads to $V = \frac{1}{8}\varphi^2 + \frac{k}{3}\varphi^6$,



The following homogeneous classical solution,

$$\varphi(t) \sim \frac{1}{k^{1/4}\cos^{1/2} t}$$

reproduces the time dependence and the scaling with k of the supergravity solution,

$$\varphi^2 \leftrightarrow \langle \mathcal{O} \rangle \leftrightarrow \bar{\alpha} = \frac{\alpha}{\cos t}.$$

Classically the field theory evolution ends in finite time.

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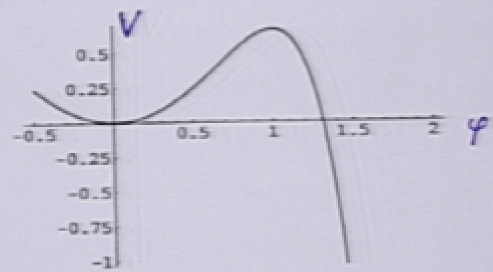

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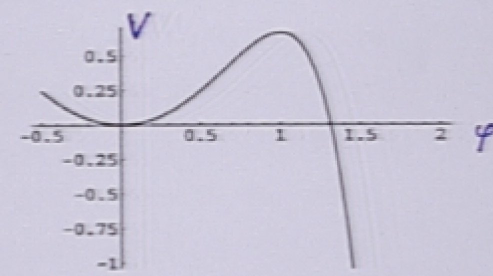

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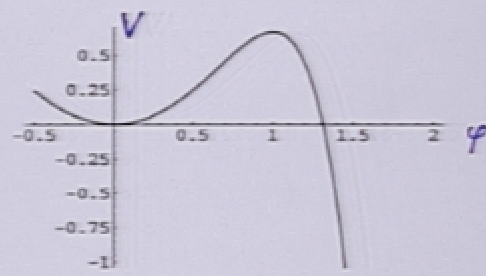

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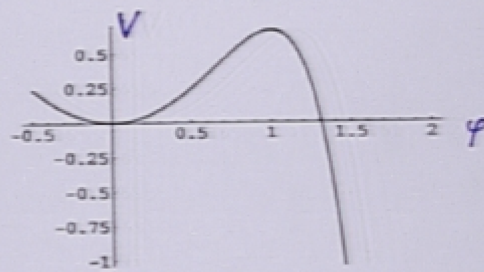

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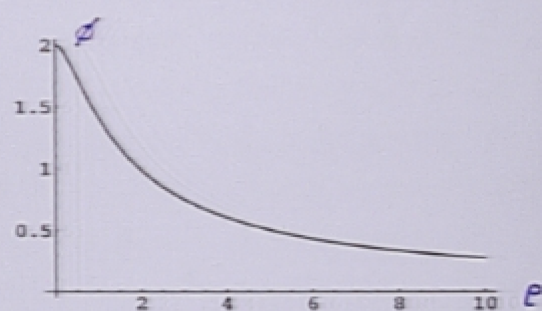

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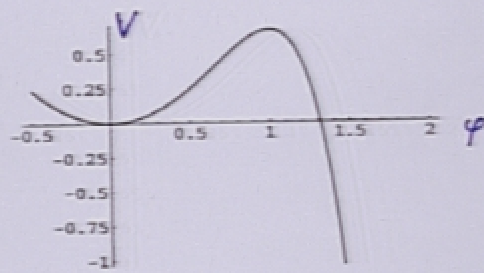

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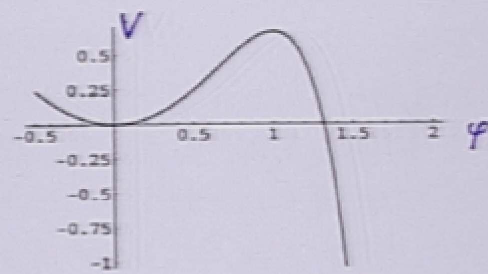

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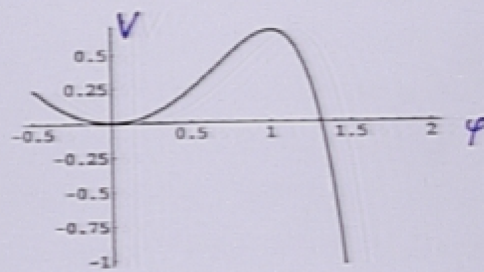

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The quantum mechanics of unbounded potentials of this type is well understood.

One constructs a self-adjoint extension of the Hamiltonian (by carefully specifying its domain) to ensure probability is not lost at infinity.

This guarantees unitary evolution for all time.

Yet the center of a wave packet follows essentially the classical trajectory. When it reaches infinity, however, it bounces back.

Have we found support from AdS/CFT for a big crunch/big bang transition, as envisioned in the cyclic universe models?

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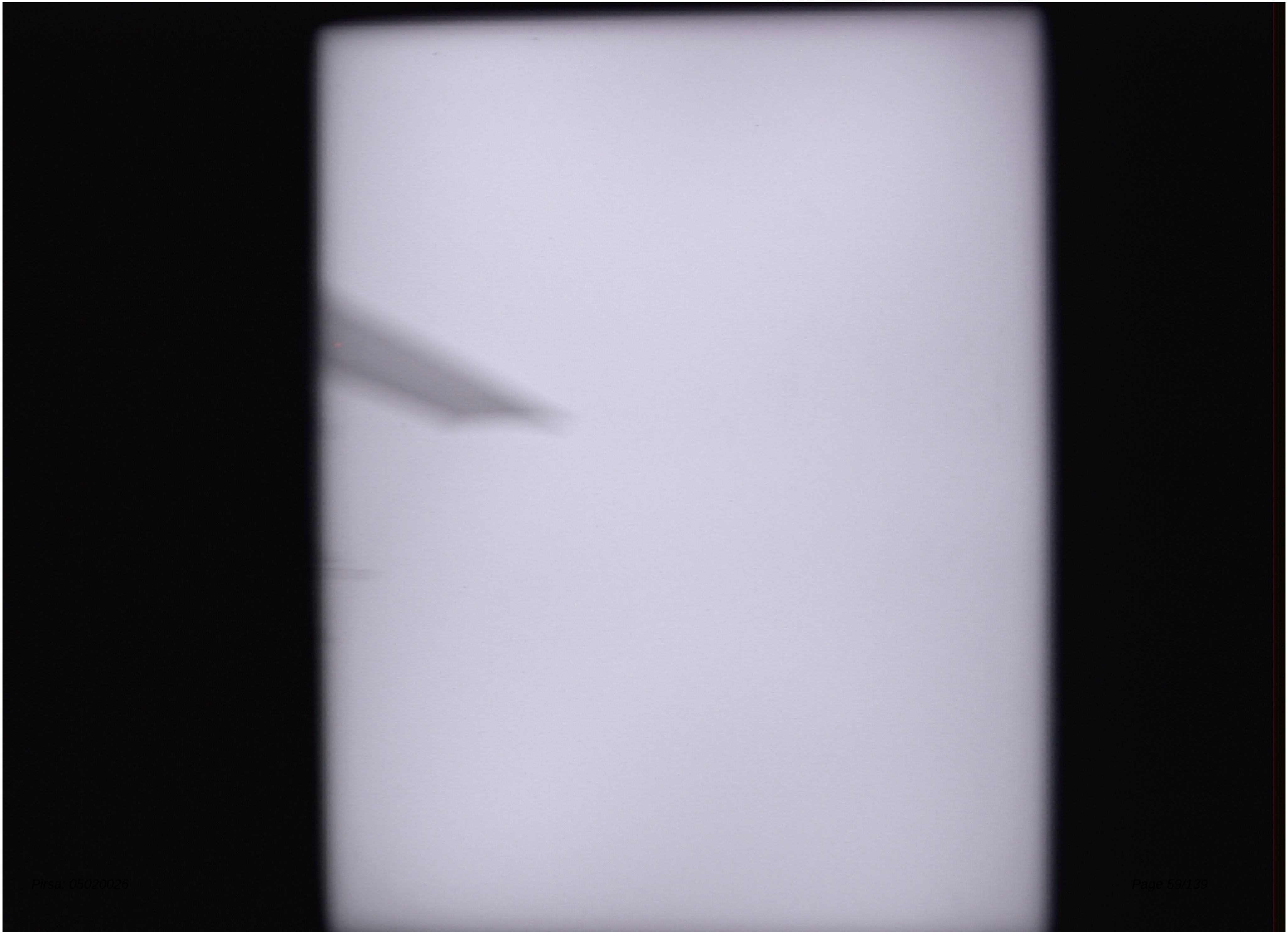

Tachyonic Preheating

Not really, since a bounce requires an exactly homogeneous initial state...

In the full field theory, particles are produced in great numbers while the field rolls down and the evolution becomes chaotic. [Kofman et al. '01]

A bounce through the singularity would require the miraculous conversion of all the gradient energy back in the homogeneous mode.

In summary, AdS/CFT suggests evolution does not end, but that generically a bounce does not occur.

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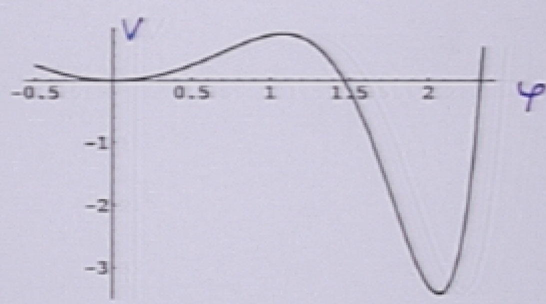
Regularization

To gain further insight we first regularize the field theory,

$$V = \frac{1}{8}\varphi^2 - \frac{k}{3}\varphi^6 + \frac{\epsilon}{4}\varphi^8$$



However, this regularization changes the bulk boundary conditions to

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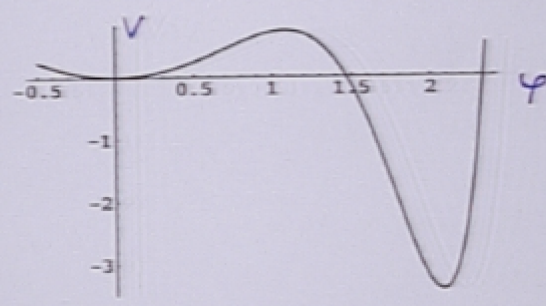

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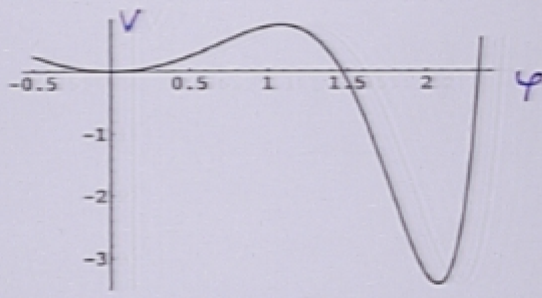

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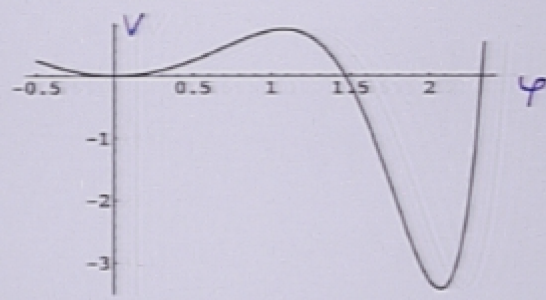

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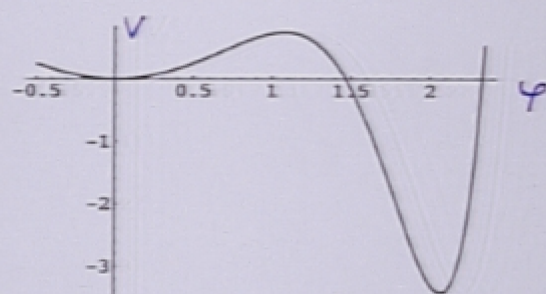

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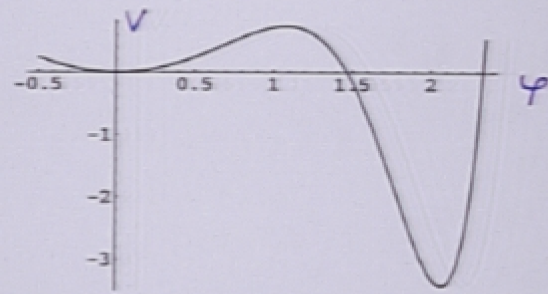

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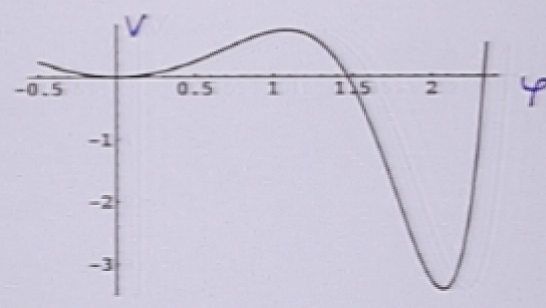

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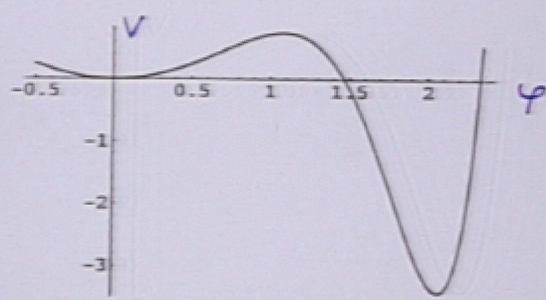

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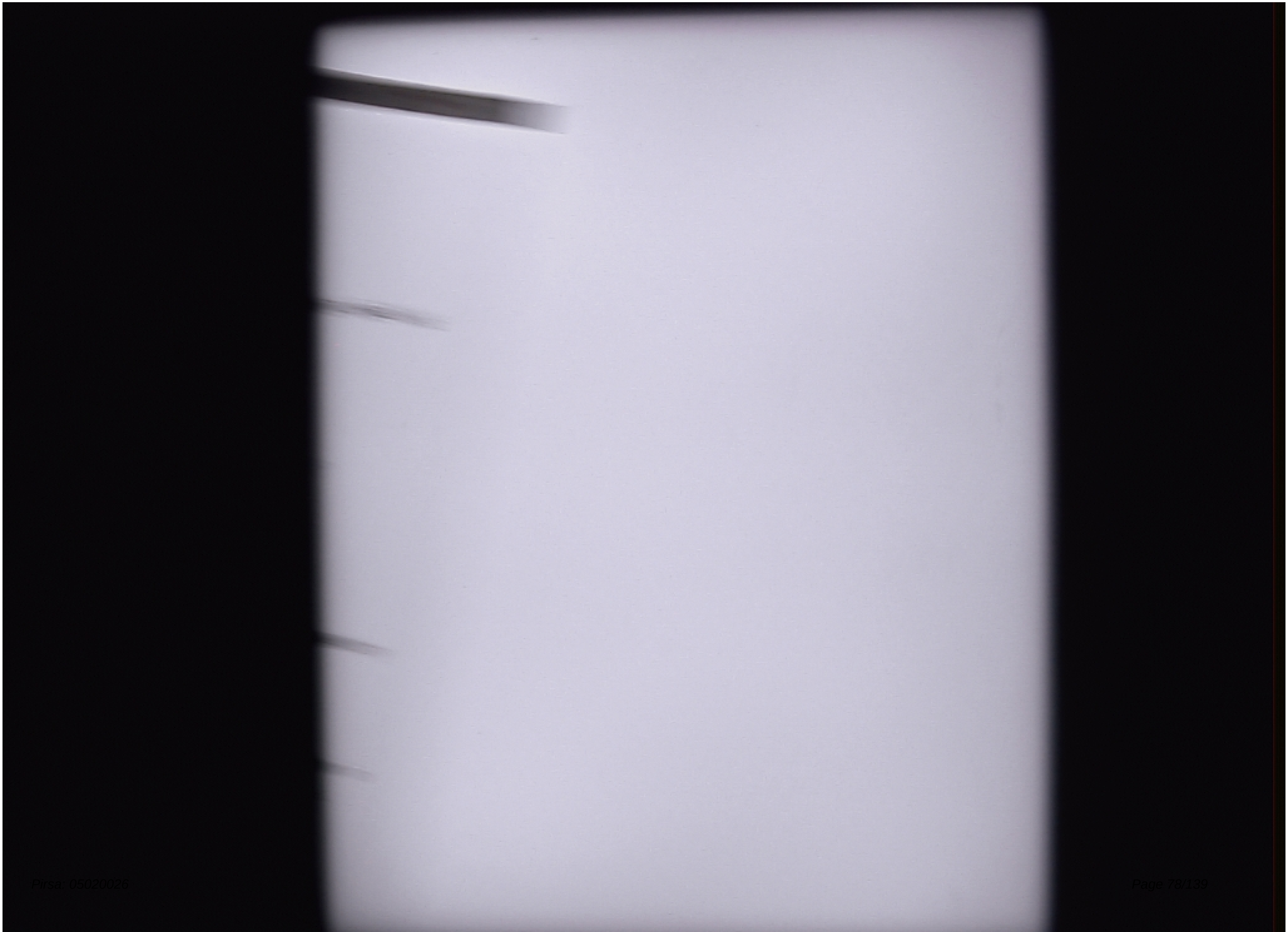

Black Holes with Scalar Hair

Writing the metric as

$$ds_4^2 = -h(r)e^{-2\delta(r)}dt^2 + h^{-1}(r)dr^2 + r^2 d\Omega_2^2$$

the field equations read

$$h\phi_{,rr} + \left(\frac{2h}{r} + \frac{r}{2}\phi_{,r}^2 h + h_{,r}\right)\phi_{,r} = V_{,\phi}$$

$$1 - h - rh_{,r} - \frac{r^2}{2}\phi_{,r}^2 h = r^2 V(\phi)$$

$$\delta_{,r} = -\frac{1}{2}\phi_{,r}^2$$

The scalar asymptotically generically behaves as,

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Therefore, integrating the field equations outward from the horizon yields a point in the (α, β) plane for each combination (R_e, ϕ_e) at the horizon.

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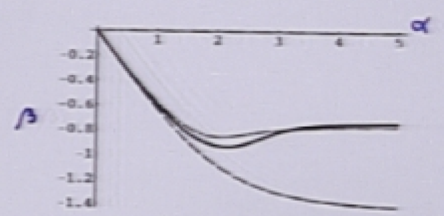

Given a choice of boundary conditions $\beta(\alpha)$, the hairy black holes are given by the intersection points,

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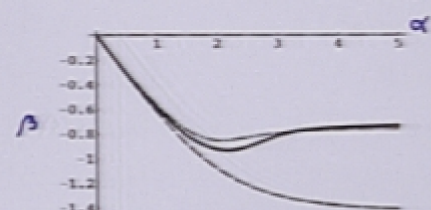

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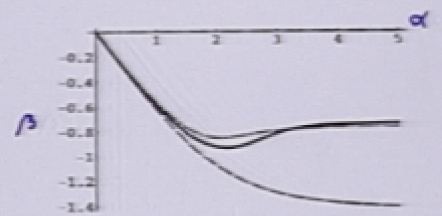

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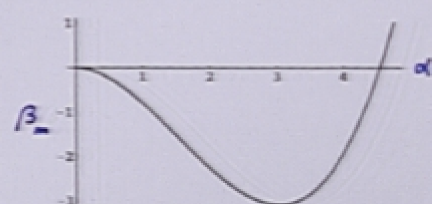

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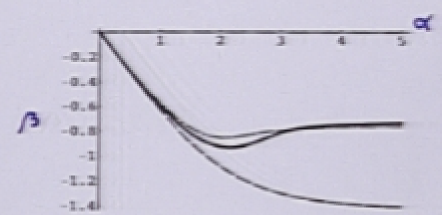

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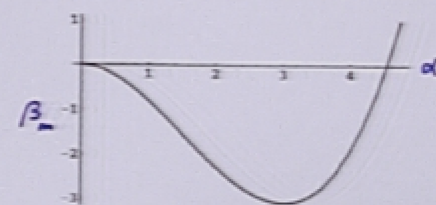

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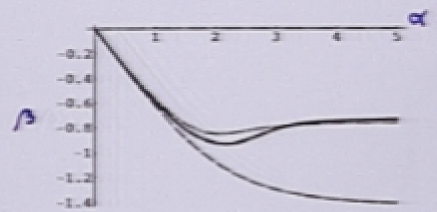

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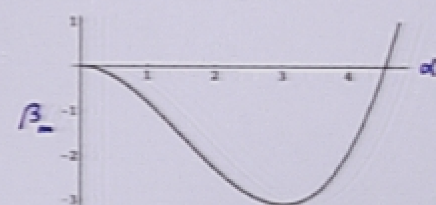

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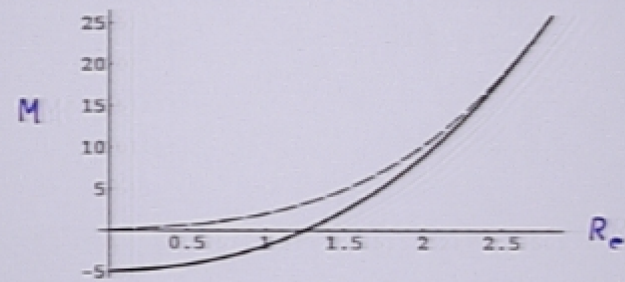
'Regularized' AdS Cosmologies

The mass of the hairy black holes:



The second branch contains a zero mass black hole, which is the natural endstate of evolution (with β_m boundary conditions) of our initial data.

Support for this comes from

$$\lim_{\epsilon\to 0}\phi_\epsilon \to \phi(0)$$

Hence we recover the big crunch of the original AdS cosmology (with $\bar{\beta}$ conditions) as the limit of a specific class of zero mass hairy black holes.

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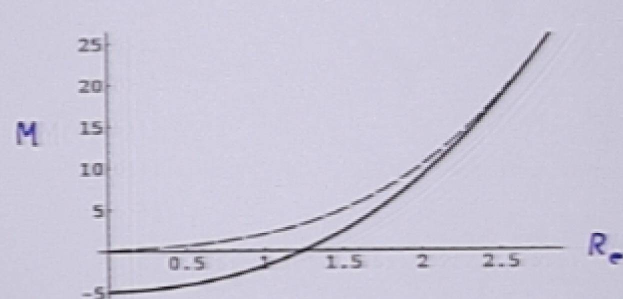

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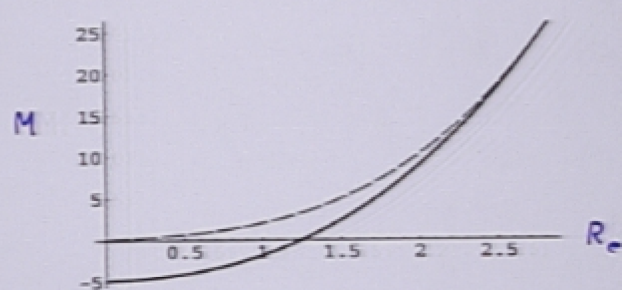

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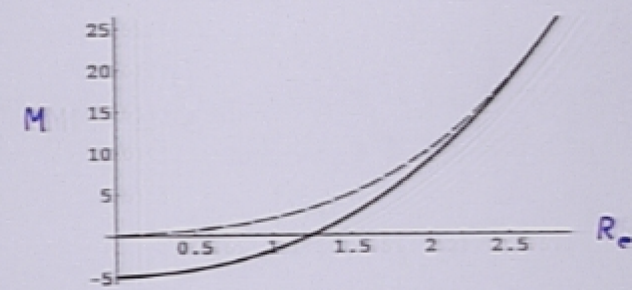

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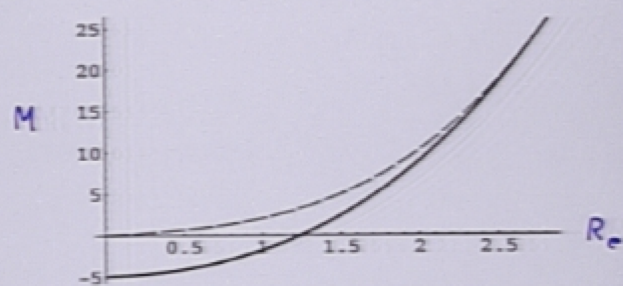

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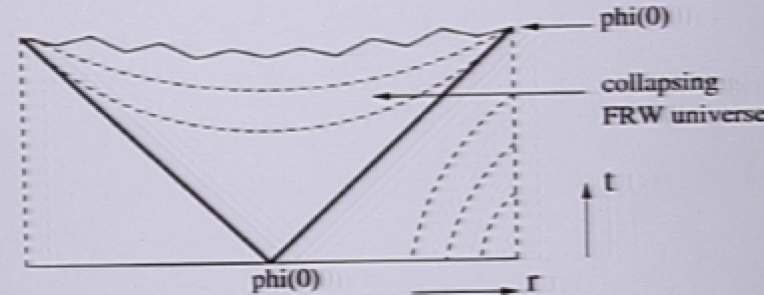
Evolution

The evolution of these initial data is obtained from the instanton by analytic continuation.



Inside the lightcone the solution produces a big crunch singularity, which hits the boundary as $t \to \pi/2$.

The asymptotic behavior of ϕ is given by

$$\phi(r) = \frac{\tilde{\alpha}}{r} + \frac{k\tilde{\alpha}^2}{r^2} + O(r^{-3})$$

where $\tilde{\alpha} = \alpha / \cos t \to \infty$ as $t \to \pi/2$.

The field ϕ itself, however, tends to a constant at the boundary, i.e. its value on the lightcone from $\phi(0)$.

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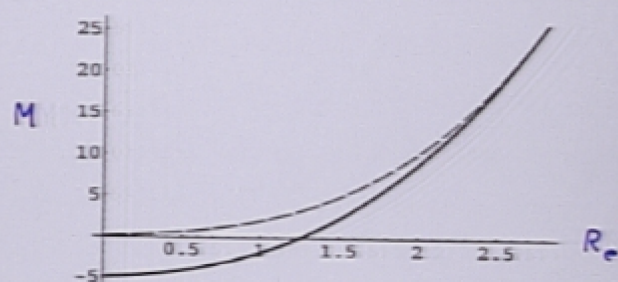

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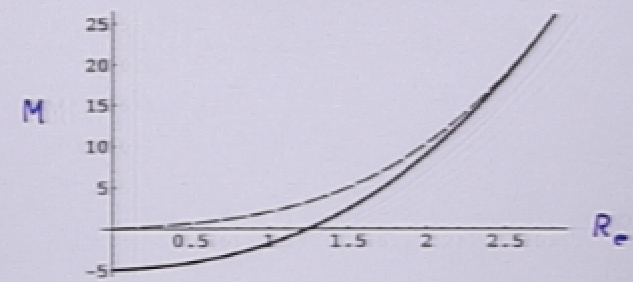

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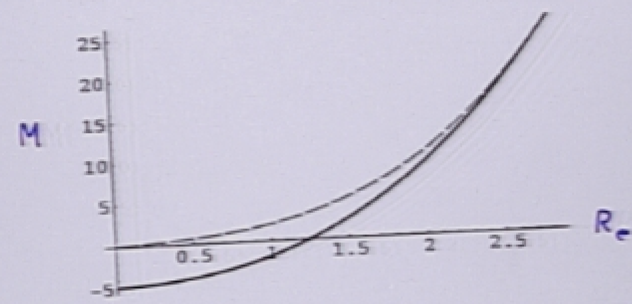

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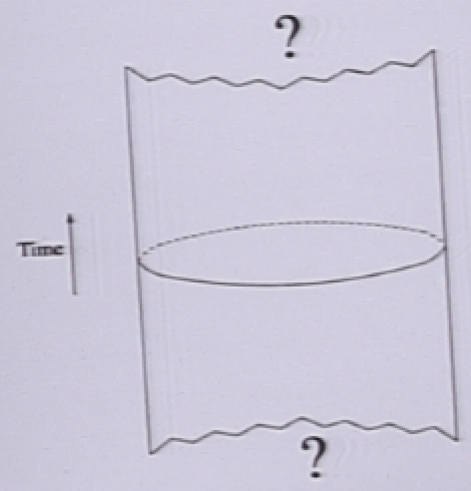
[T.H & G. Horowitz '04]



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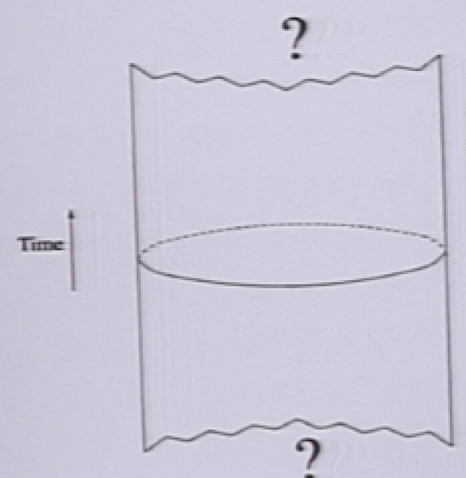

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Back to the Dual Field Theory

From the curves $\beta(R_e, \alpha)$ one can construct the effective potential for $\langle \mathcal{O} \rangle$ in field theory duals with arbitrary deformations $W(\mathcal{O})$. It is given by

$$\mathcal{V}_{R_e}(\alpha) = R_e(1 + R_e^2) - \int_0^\alpha \beta_{R_e}(\alpha) + W(\alpha)$$

- The extrema of $\mathcal{V}_{R_e}(\alpha)$ are in one-to-one correspondence with black holes of size R_e that obey $\beta = W'$: $\mathcal{V'}_{R_e}(\alpha) = 0 = -\beta_{R_e} + \beta$
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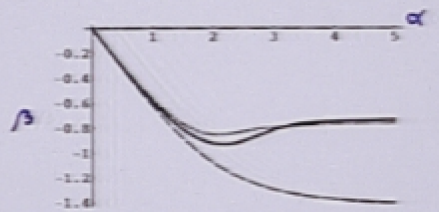
Black Holes with Scalar Hair

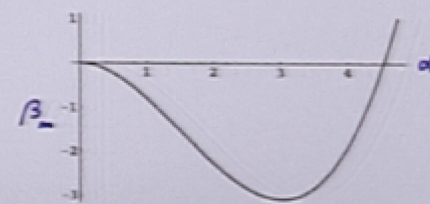
Some of the curves $\beta(R_e, \alpha)$ are



Given a choice of boundary conditions $\beta(\alpha)$, the hairy black holes are given by the intersection points,

$$\beta(R_e, \alpha) = \beta(\alpha)$$

Hence with our modified boundary conditions β_m,



there are two branches of hairy black holes.

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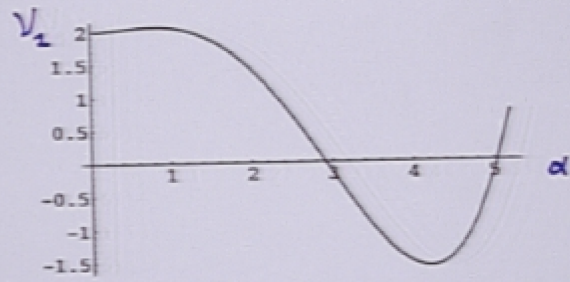
Hairy Black Holes in Field Theory

In our regularized field theory we obtain (for $R_c = 1$)



This provides a natural dual interpretation of the hairy black holes: Schwarschild-AdS black holes are dual to finite energy states in the usual $\alpha = 0$ vacuum, while the upper/lower branches of hairy black holes correspond to excited states in the two nontrivial vacua, respectively the local maximum and the global minimum of $\mathcal{V}$.

Thus the field theory description resolves this example of black hole non-uniqueness!

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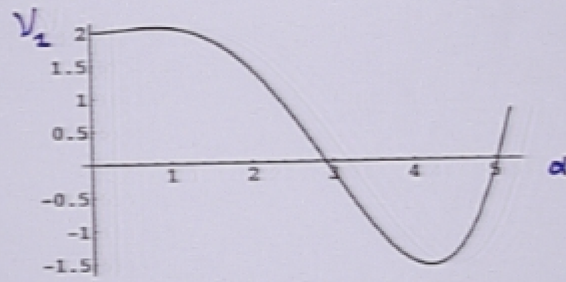

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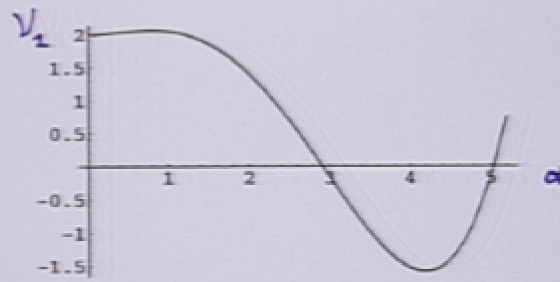

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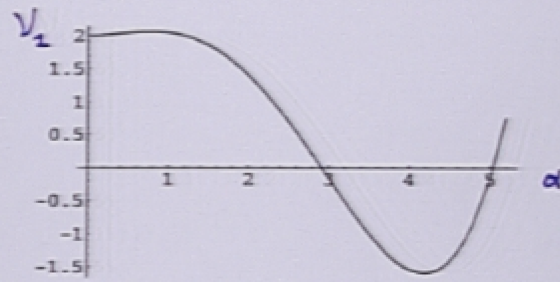

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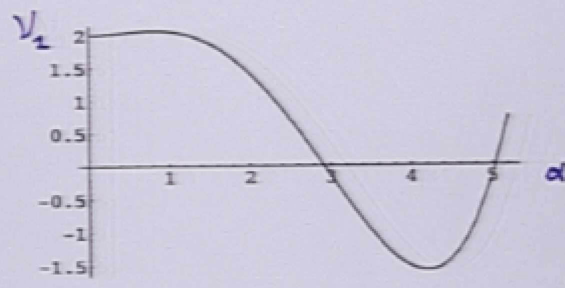

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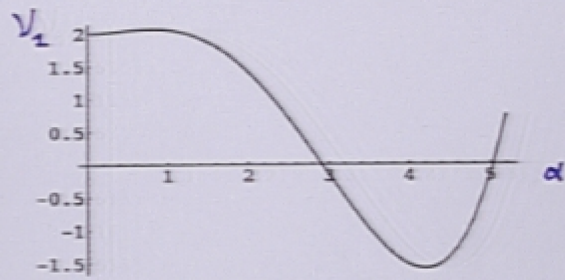

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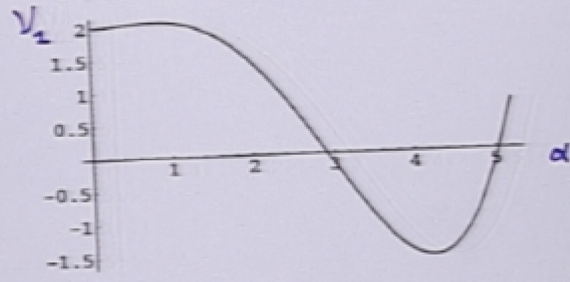

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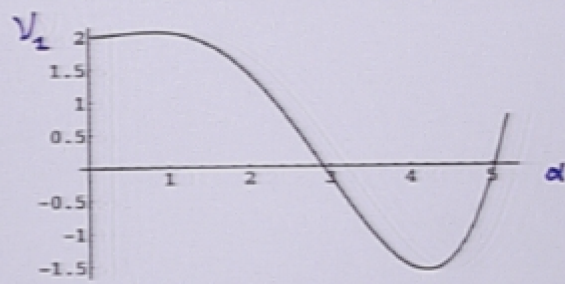

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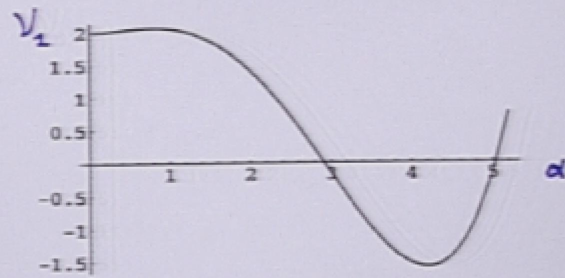

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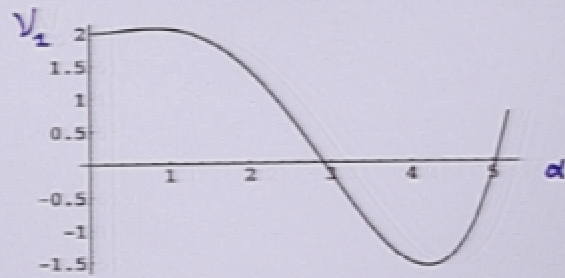

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Dual Field Theory Evolution of Regularized AdS Cosmologies

We understand the formation of a hairy black hole in the bulk as thermalization in the new global minimum of the field theory.

A rare fluctuation from this thermal state that causes the field to roll up the potential, dual to the sudden evaporation of the black hole, describes the emergence of the instanton initial data from the past singularity.

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