Title: Big Crunch to Big Bang with AdS/CFT

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Abstract:

From Big Crunch to Big Bang with AdS/CFT

Perimeter Institute

March 2008

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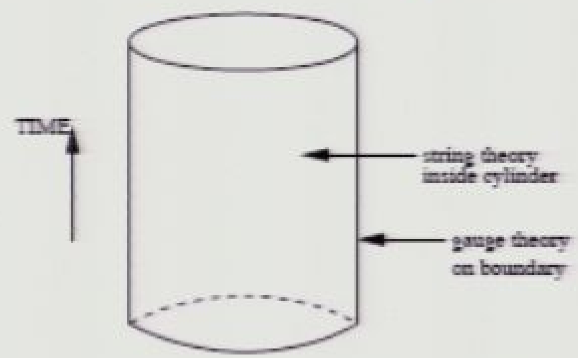
w/ Ben Craps, Neil Turok
arXiv:0711.1824; arXiv:0712.4180 [hep-th]

AdS/CFT duality

String theory with anti-de Sitter boundary conditions is equivalent to certain gauge theories living on the boundary of the AdS cylinder. [Maldacena '97]



e.g. String theory on $AdS_5 \times S^5$ is dual to $\mathcal{N} = 4$ super Yang-Mills theory on $\mathbb{R} \times S^3$ with $SU(N)$, where

$$R^4/l_s^4 \leftrightarrow g_{YM}^2 N = g_t, \qquad g_s \leftrightarrow 1/N$$

The finite N gauge theory is viewed as a *nonperturbative definition* of string theory with AdS boundary conditions.

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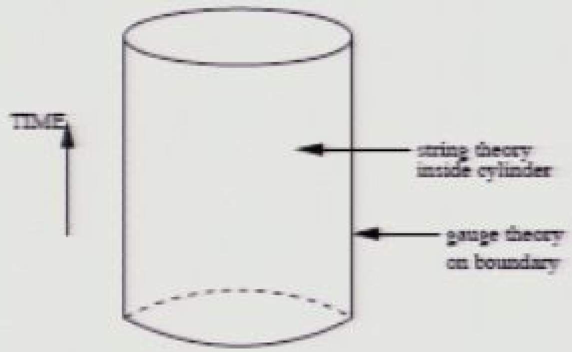

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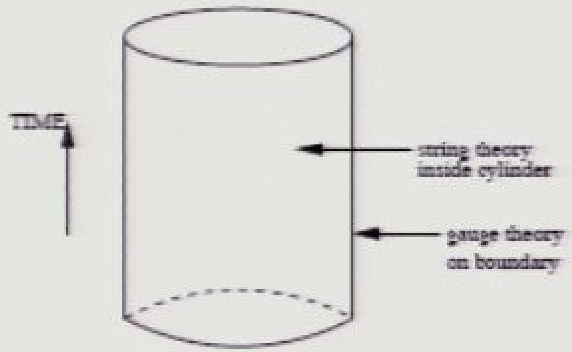

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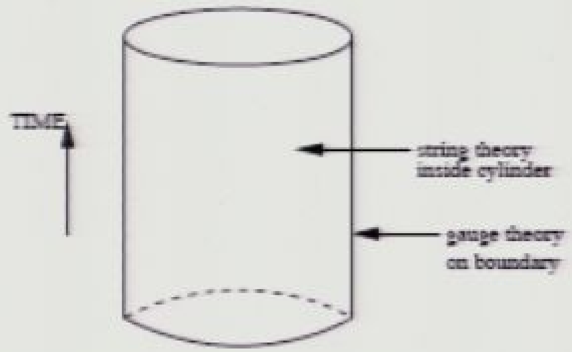

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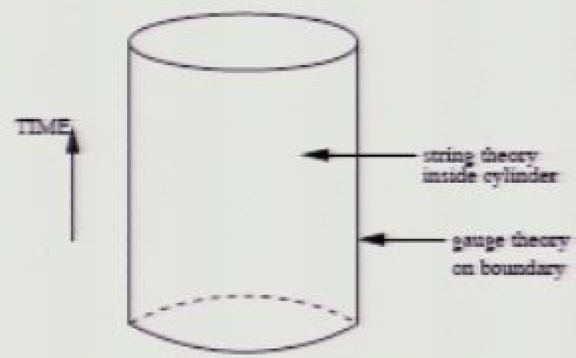

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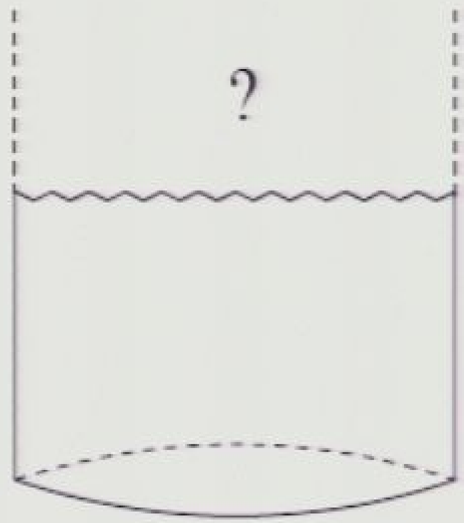
Holographic Cosmology

Generalization: SUGRA solutions where smooth asymptotically AdS initial data evolve to a big crunch in the future [TH, Horowitz '04].



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2. If so, what is the typical bulk spacetime at late times?

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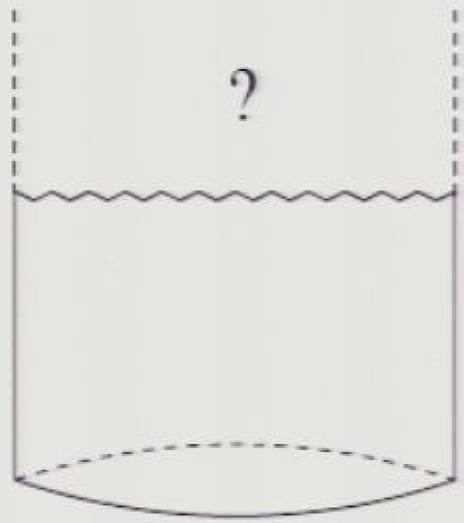

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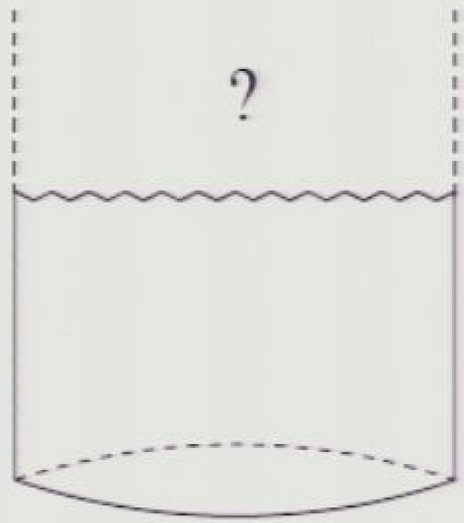

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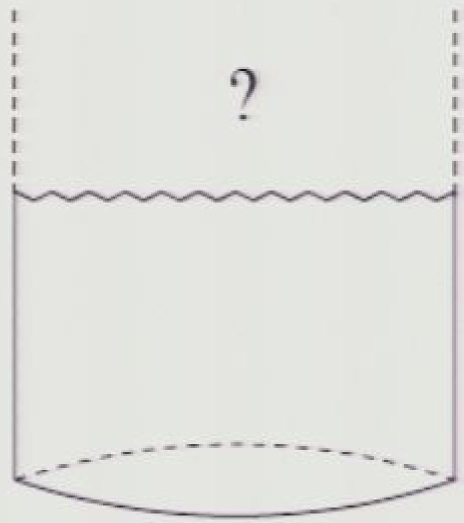

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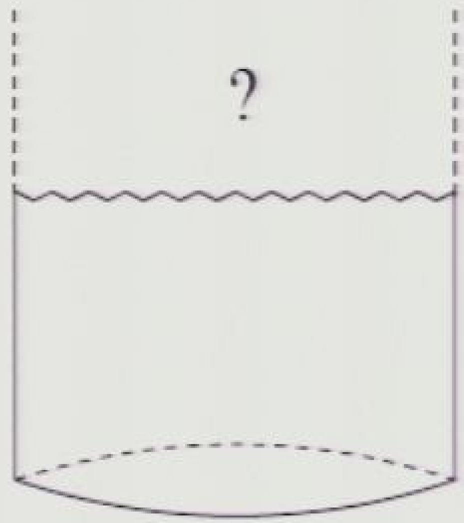

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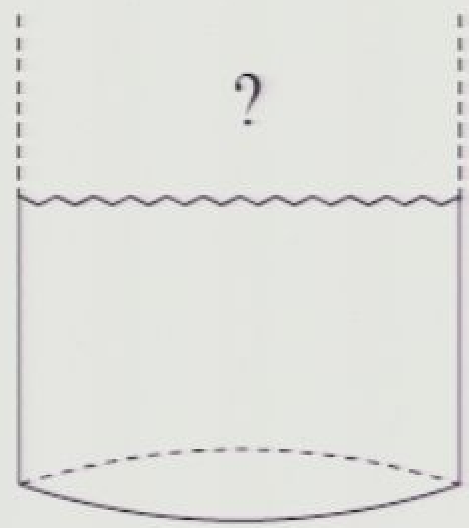

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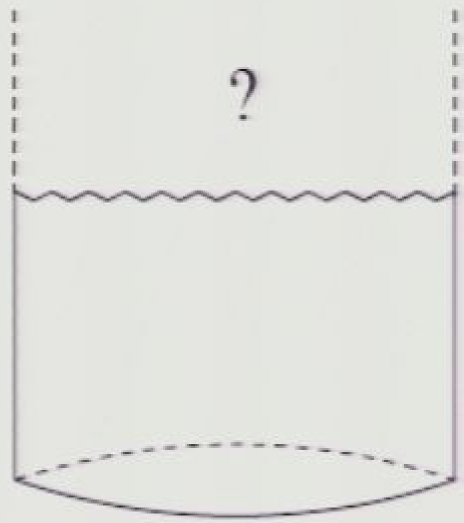

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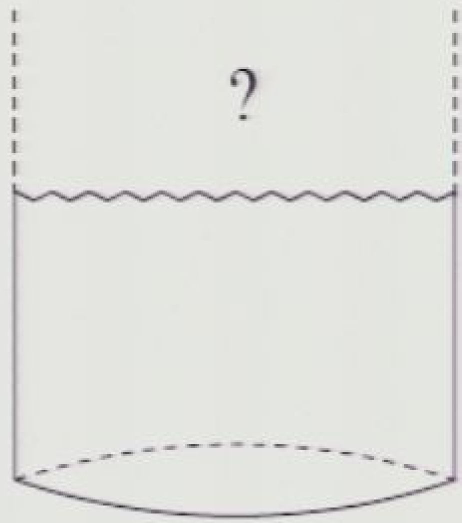

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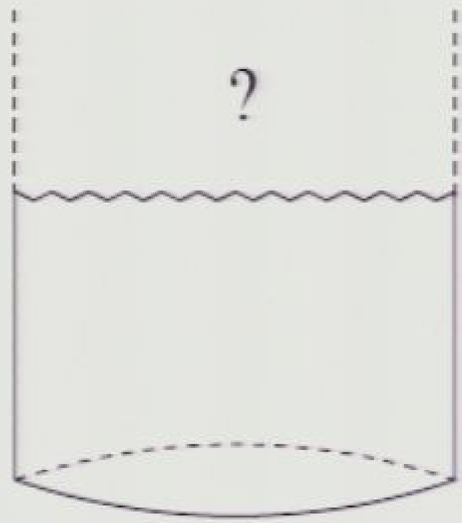

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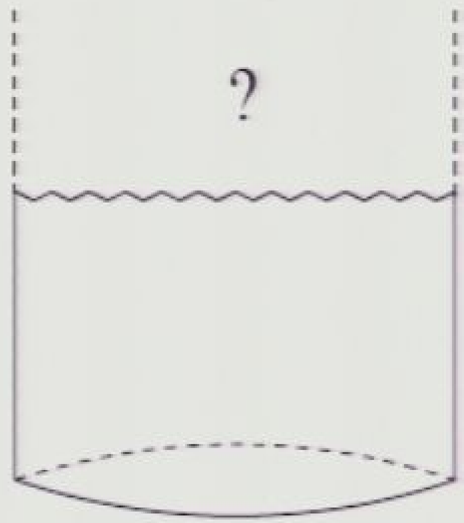

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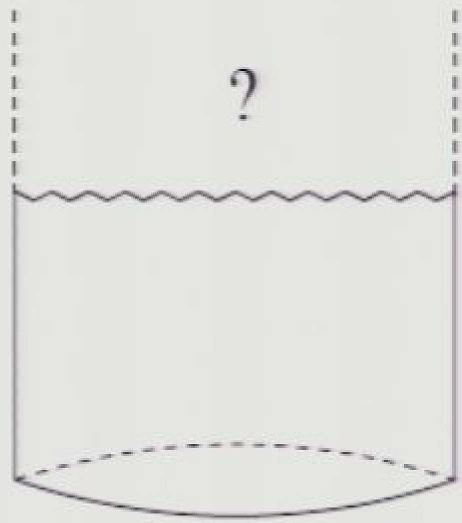

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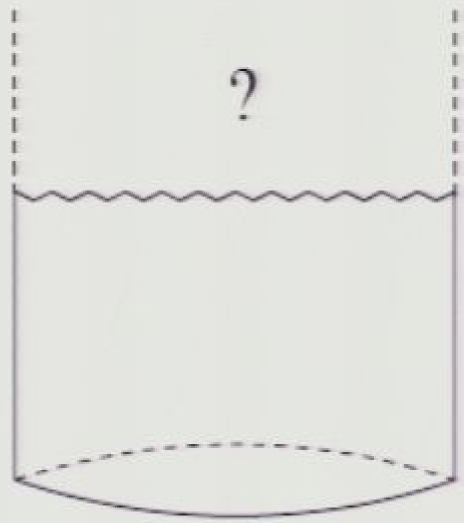

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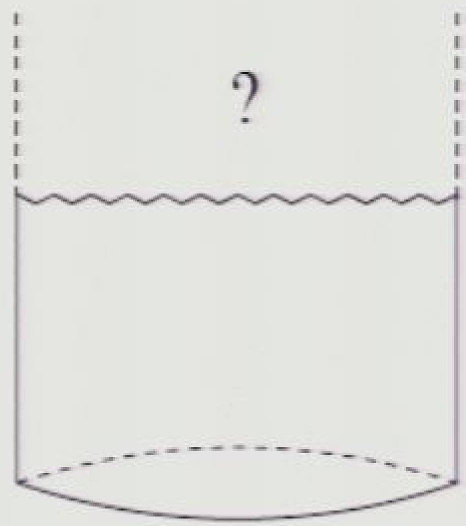

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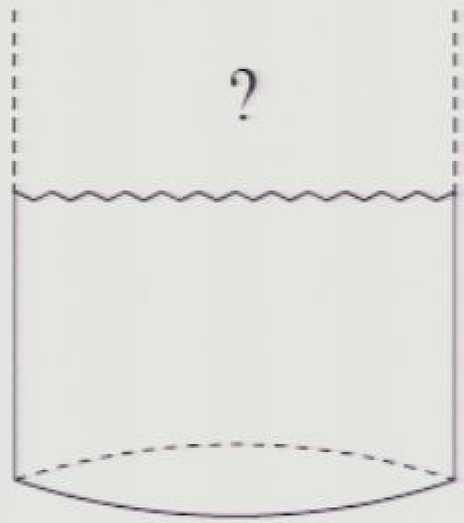

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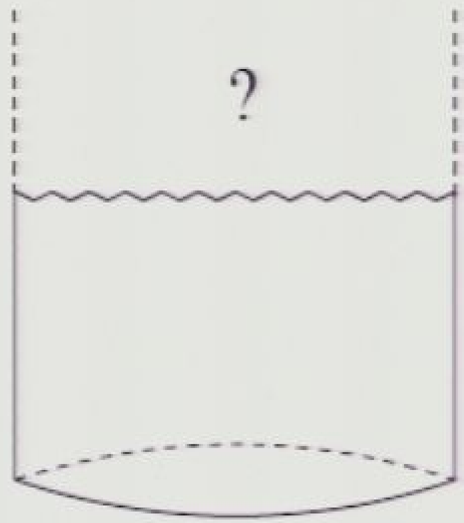

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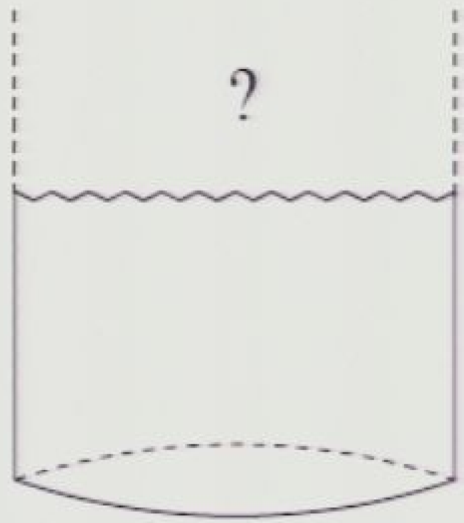

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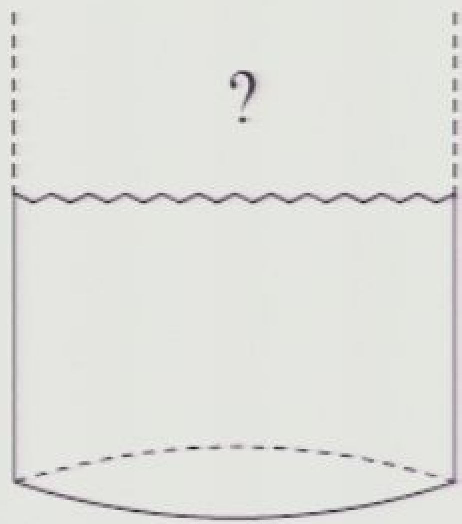

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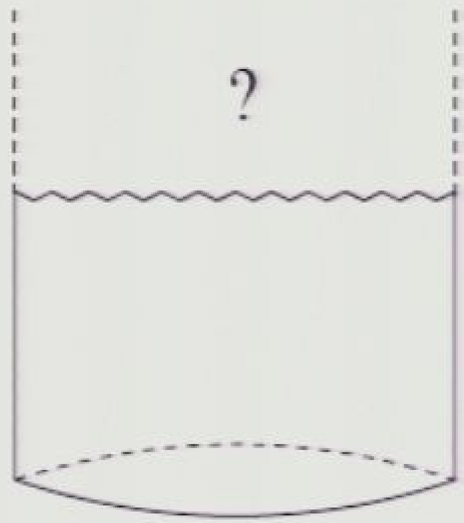

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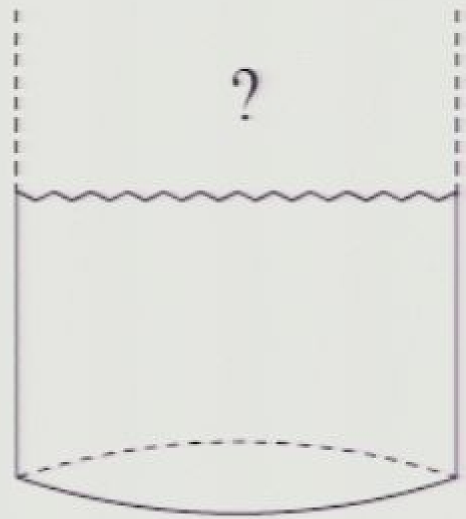

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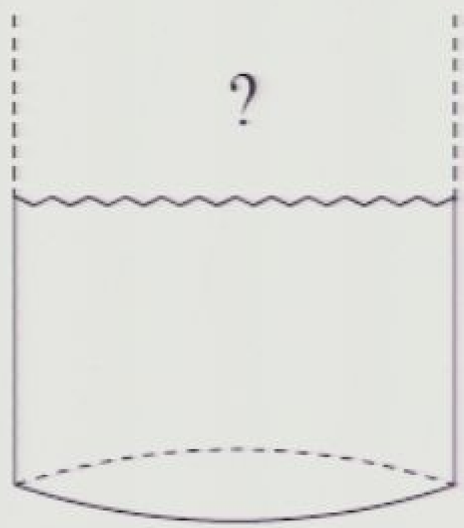

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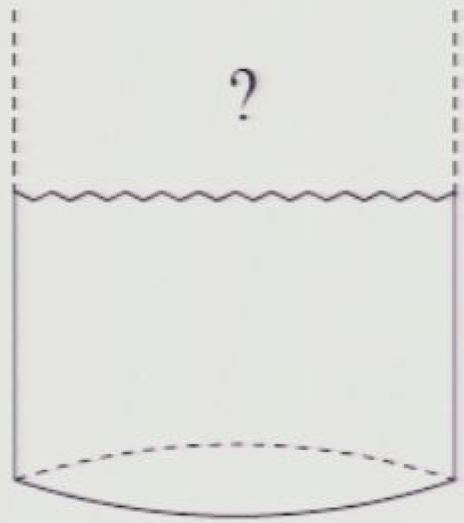

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- Bulk theory: string theory on $AdS_5 \times S^5$ with modified boundary conditions.
- Boundary theory: $\mathcal{N} = 4$ SYM with unstable double trace deformation.
- Boundary evolution: ultralocality and self-adjoint extensions.
- Quantum Evolution of homogeneous component.
- Particle creation $\rightarrow$ bounce or not?

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Bulk Setup

Consider a consistent truncation of 10d type IIB SUGRA compactified on S^5 involving only gravity and a single scalar field with potential

$$V = -\frac{15}{4}e^{2\gamma\varphi} - \frac{5}{2}e^{-4\gamma\varphi} + \frac{1}{4}e^{-10\gamma\varphi}, \quad \gamma = \sqrt{2/15}$$

The scalar φ has $\quad m^2 = -4 = m^2_{BF}$

AdS cylinder: $\quad ds^2 = -(1+r^2)dt^2 + \frac{dr^2}{1+r^2} + r^2 d\Omega_3$

Near the boundary (at large radius r) of the anti-de Sitter cylinder φ decays as

$$\varphi(t,r,\Omega) = \frac{\alpha(t,\Omega)\ln r}{r^2} + \frac{\beta(t,\Omega)}{r^2}$$

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The scalar φ has $m^2 = -4 = m^2_{BF}$

AdS cylinder: $ds^2 = -(1+r^2)dt^2 + \frac{dr^2}{1+r^2} + r^2 d\Omega_3$

Near the boundary (at large radius r) of the anti-de Sitter cylinder φ decays as

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The scalar φ has $\quad m^2 = -4 = m_{BF}^2$

AdS cylinder: $\quad ds^2 = -(1+r^2)dt^2 + \frac{dr^2}{1+r^2} + r^2 d\Omega_3$

Near the boundary (at large radius r) of the anti-de Sitter cylinder φ decays as

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Dynamics Depends on Boundary Conditions $\alpha(\beta)$ on timelike boundary AdS cylinder.

No Signal

VGA-1

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Take boundary conditions $\alpha = f\beta, \qquad f > 0$

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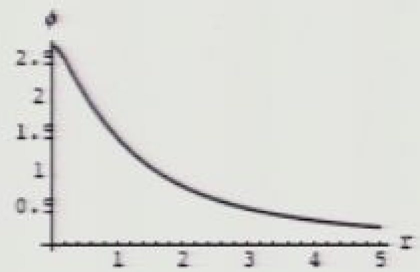
For $f > 0$ there are smooth $M \approx 0$ initial data that evolve to a singularity which extends to the boundary of AdS in finite global time.



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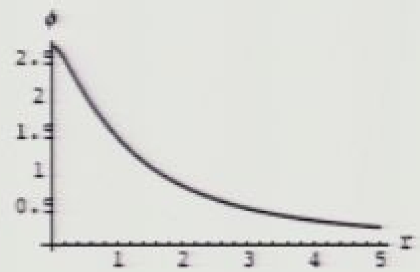

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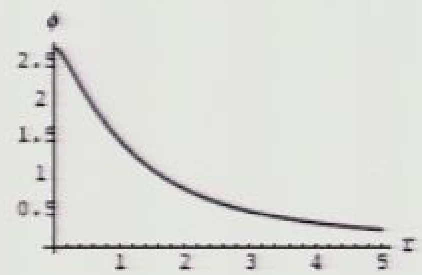

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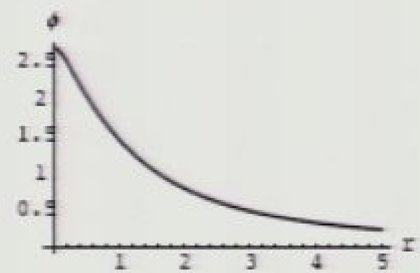

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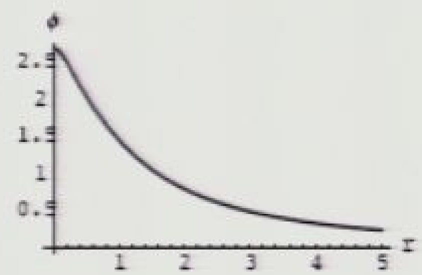

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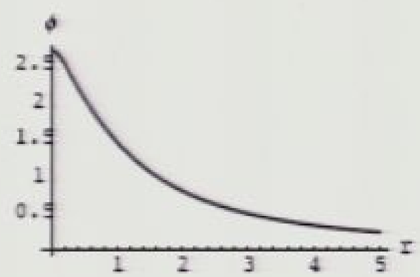

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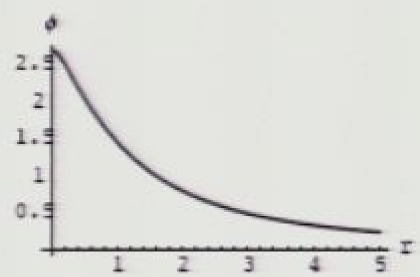

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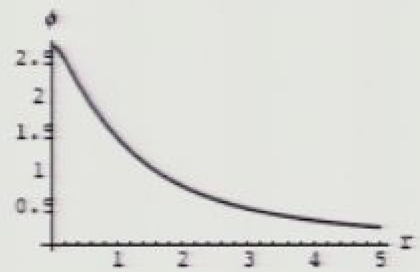

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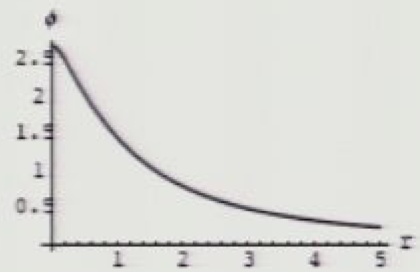

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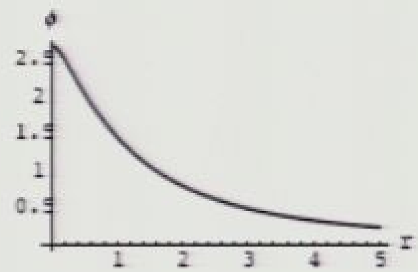

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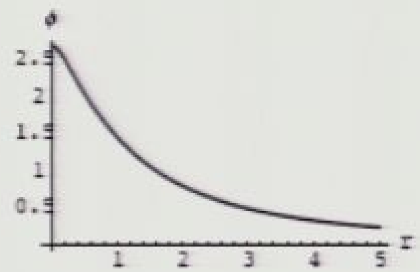

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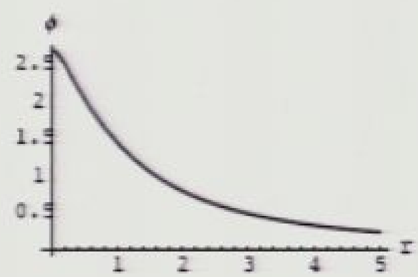

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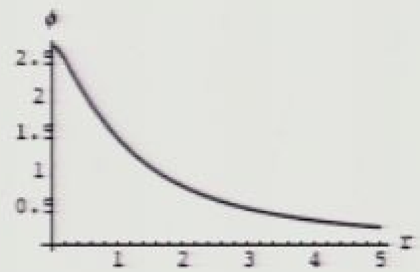

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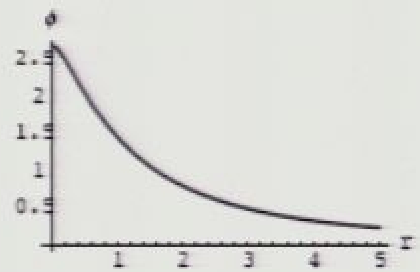

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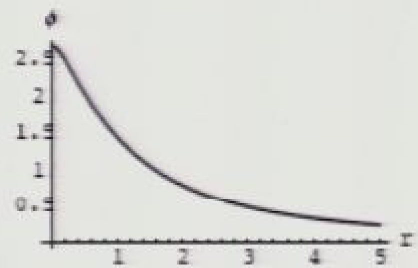

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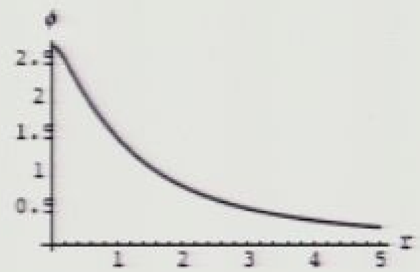

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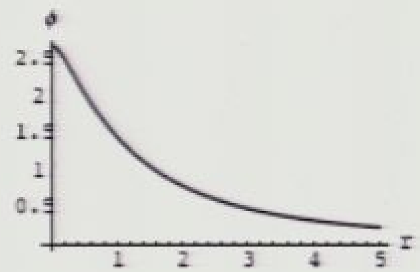

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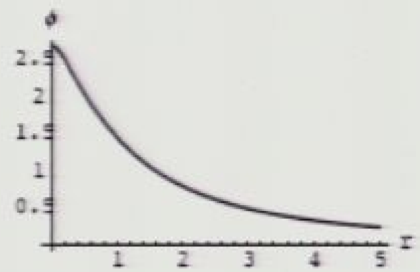

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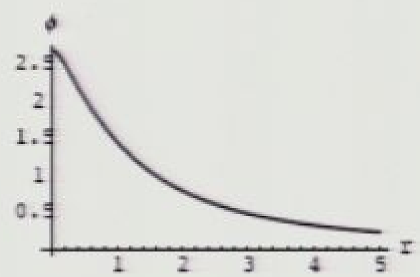

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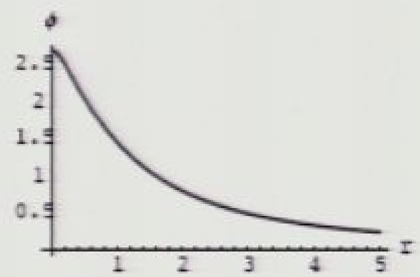

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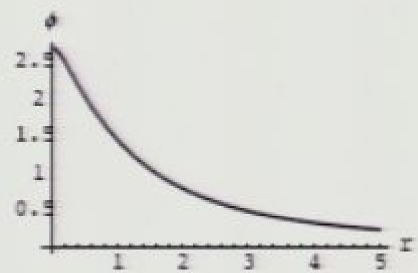

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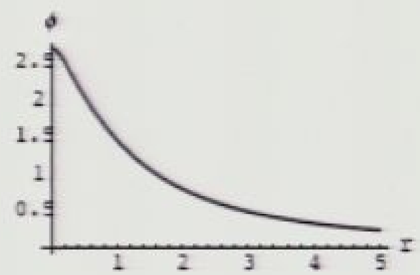

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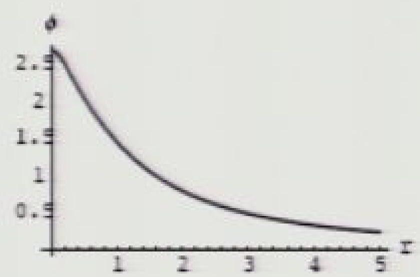

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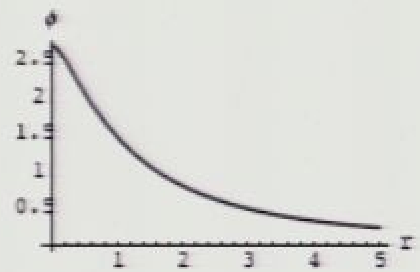

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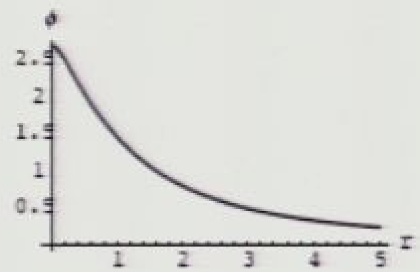

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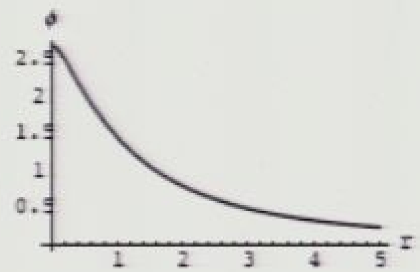

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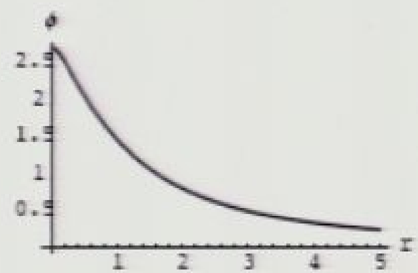

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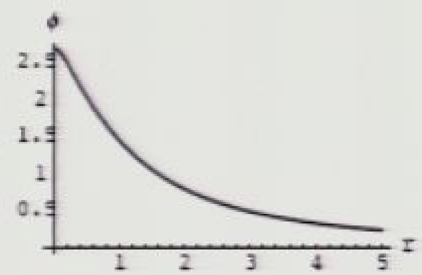

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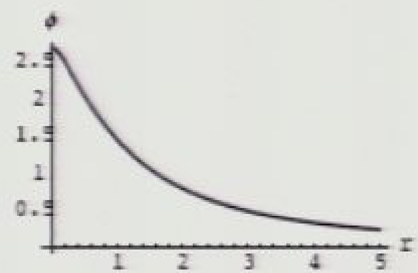

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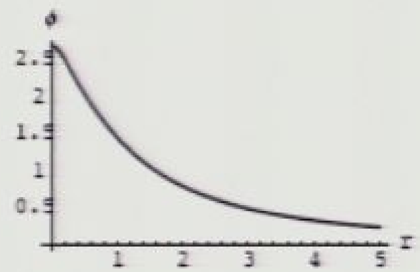

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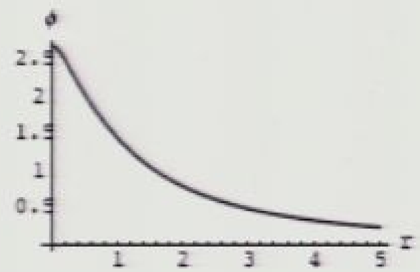

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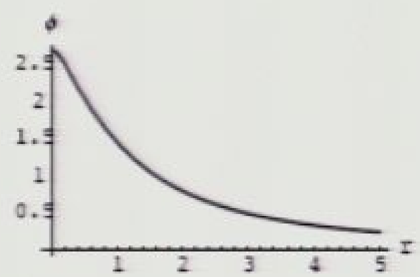

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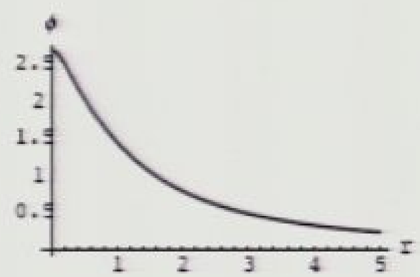

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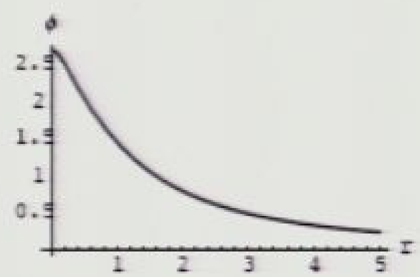

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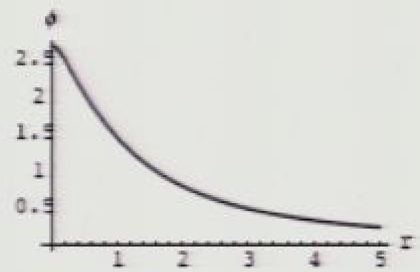

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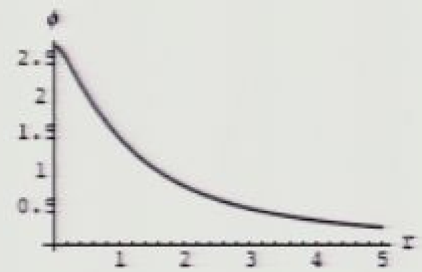

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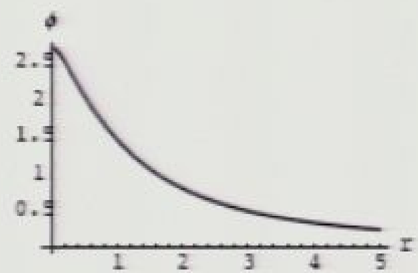

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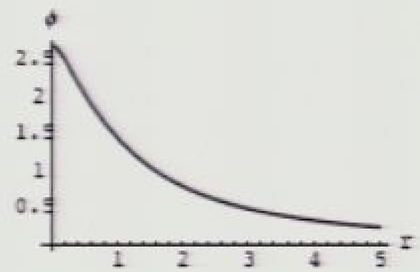

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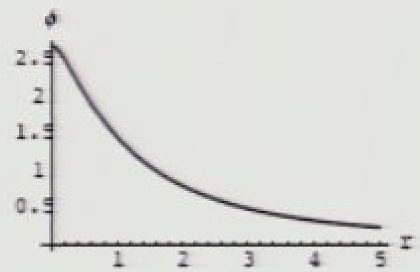

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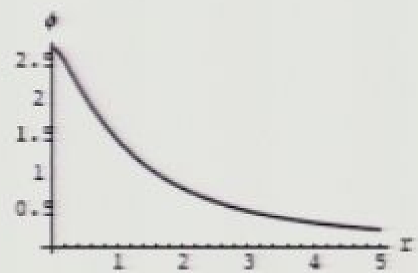

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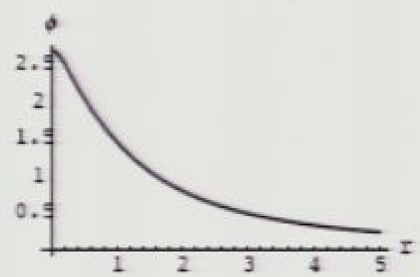

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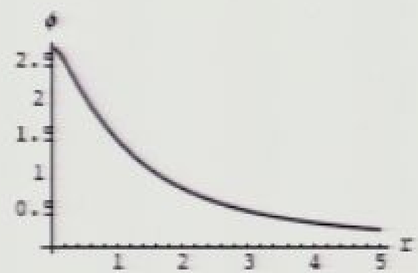

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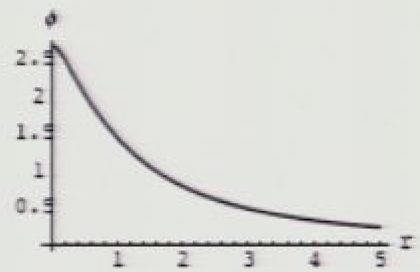

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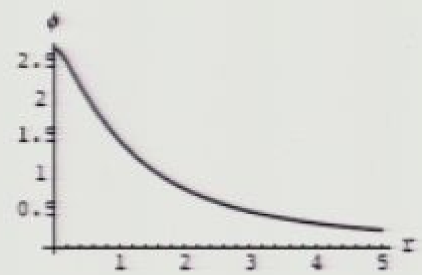

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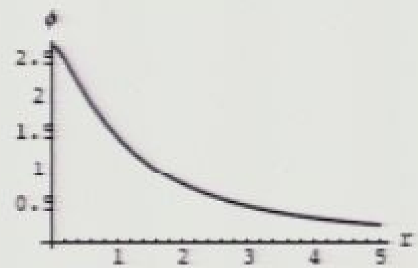

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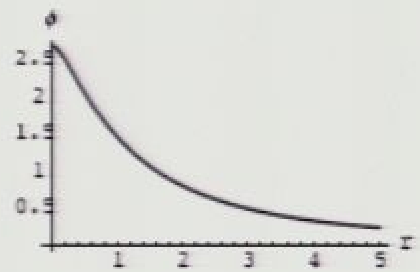

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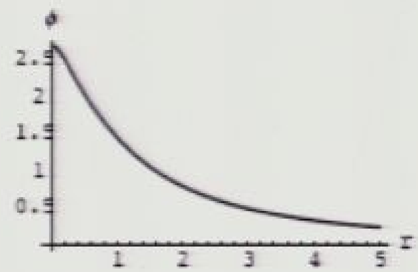

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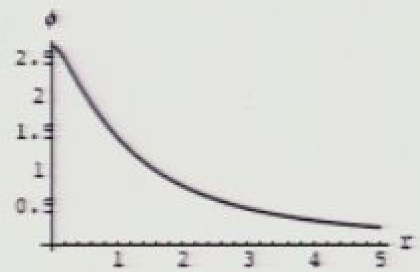

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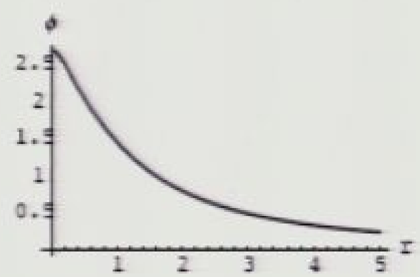

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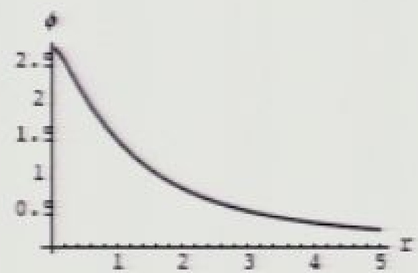

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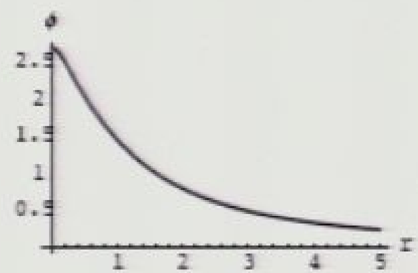

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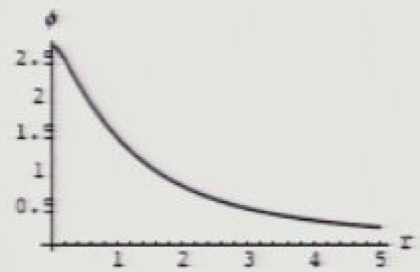

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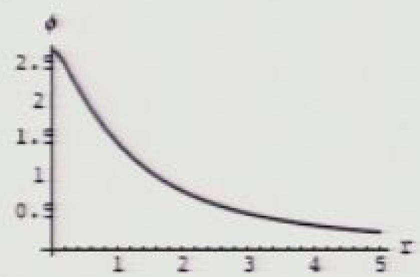

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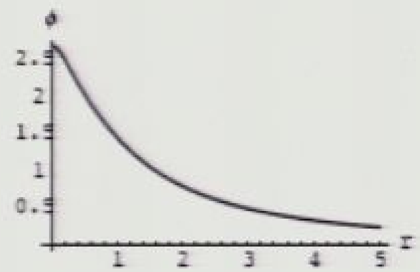

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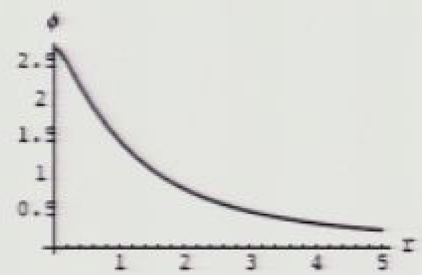

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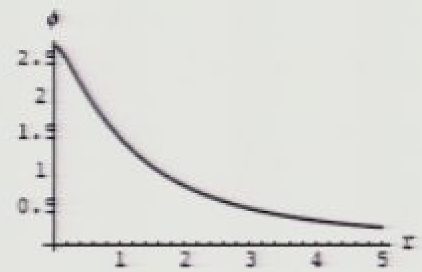

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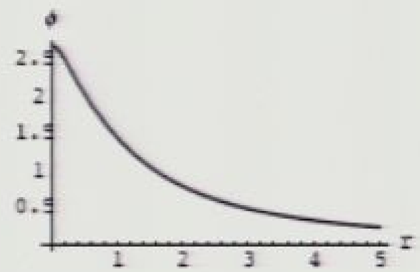

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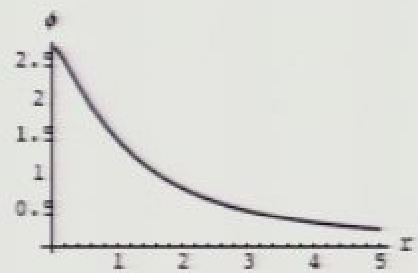

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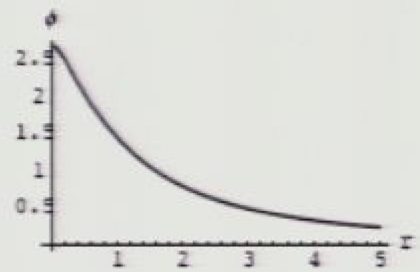

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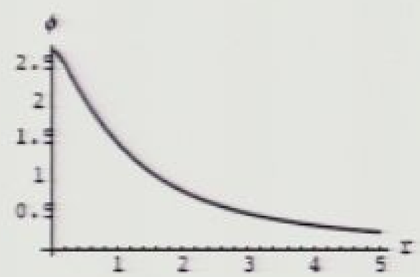

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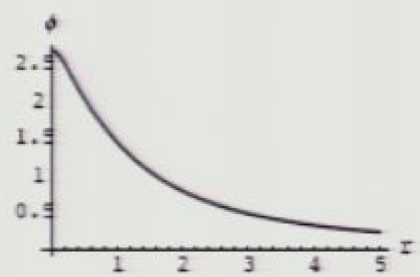

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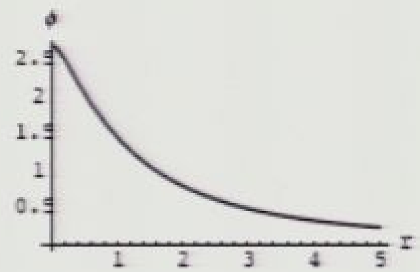

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String theory with $AdS_5 \times S^5$ boundary conditions is dual to $\mathcal{N}=4$ super Yang-Mills theory in $D=4$.

- For $\alpha = 0$, $\varphi \sim \beta/r^2$ is dual to $\Delta = 2$ operator $\mathcal{O}$,

$$\mathcal{O} = \frac{1}{N} Tr \left[\phi^2 - \frac{1}{5} \sum_{i=2}^{6} \phi_i^2 \right]$$

and

$$\beta \leftrightarrow \langle \mathcal{O} \rangle$$

- Taking $\alpha(\beta) \neq 0$ corresponds to adding a multitrace interaction $\int W(\mathcal{O})$ to the CFT, such that [Witten '02, Berkooz et al. '02]

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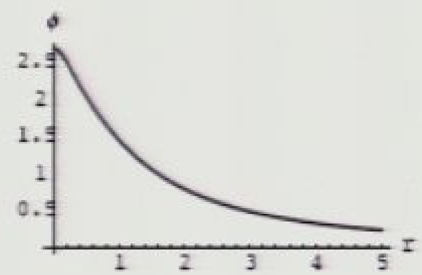

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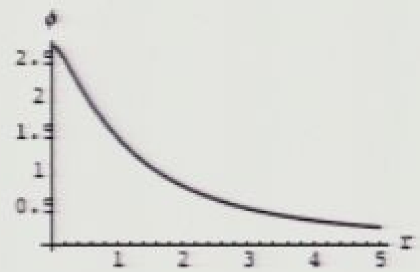

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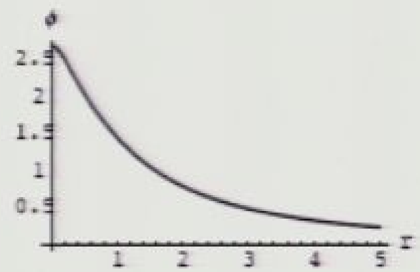

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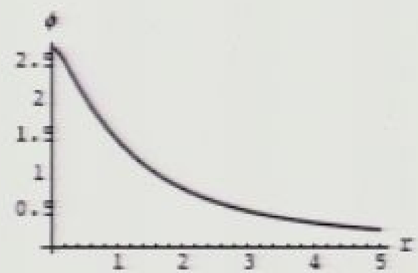

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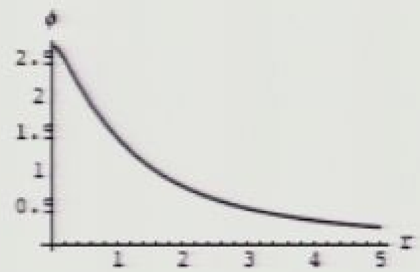

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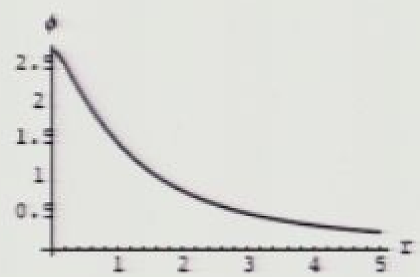

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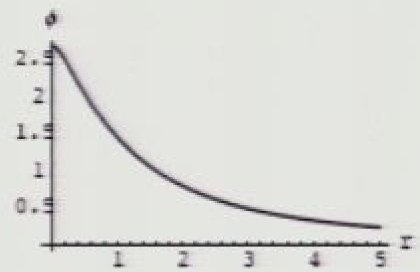

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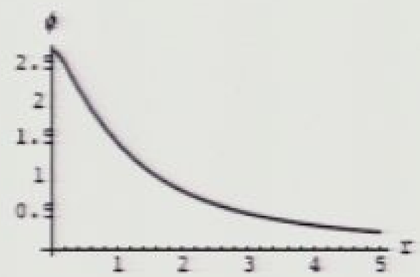

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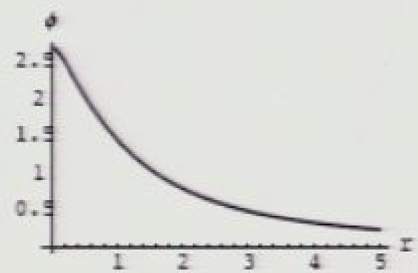

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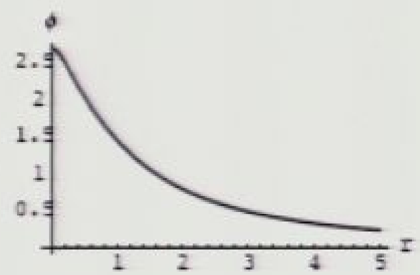

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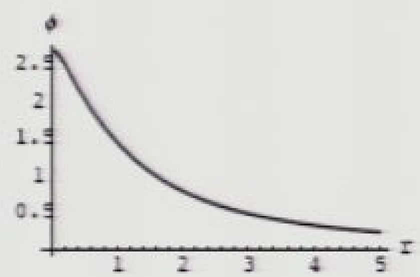

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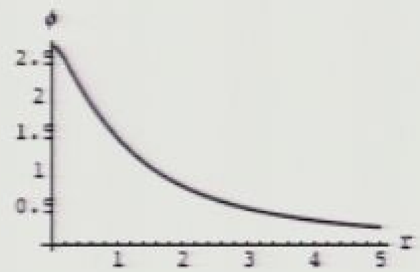

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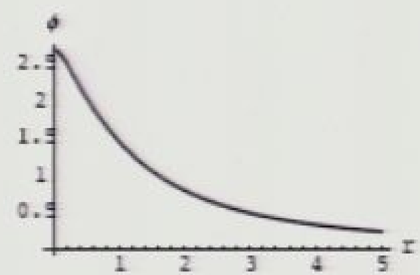

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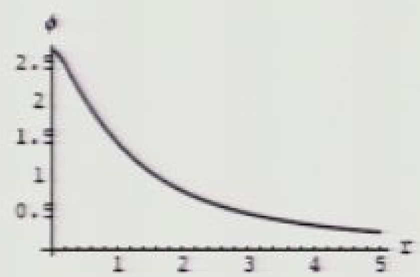

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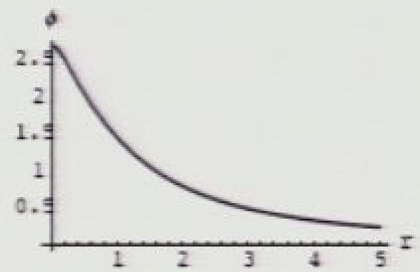

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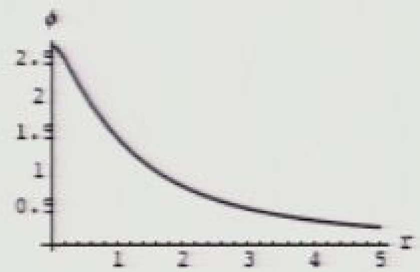

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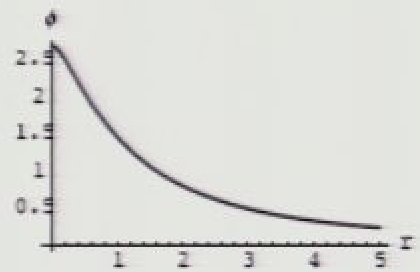

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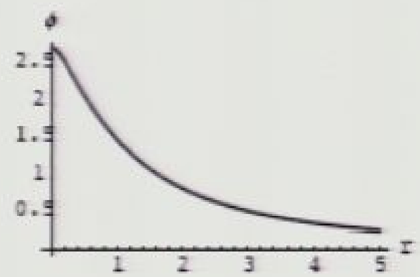

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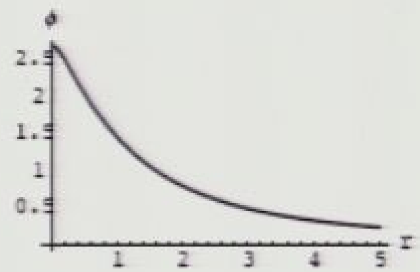

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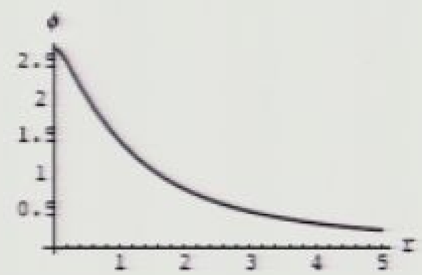

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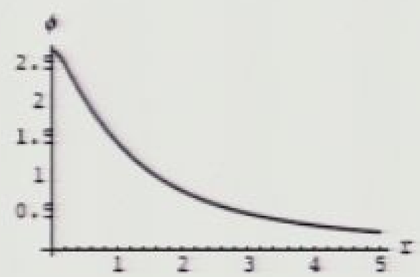

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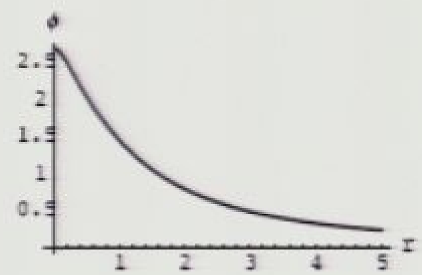

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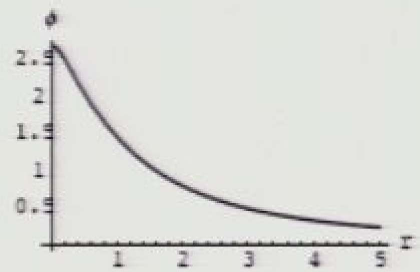

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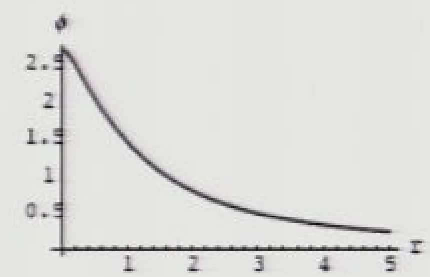

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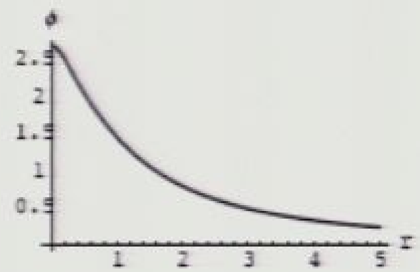

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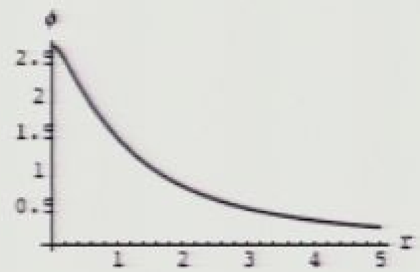

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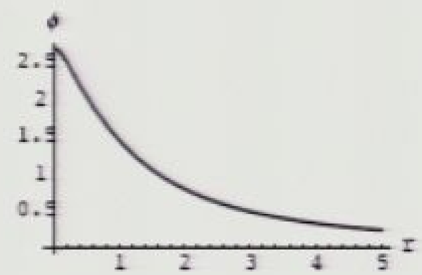

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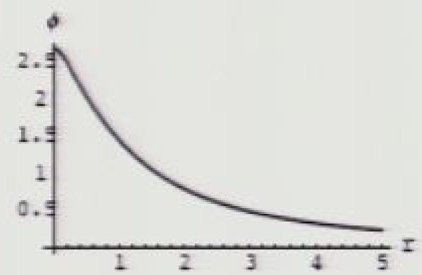

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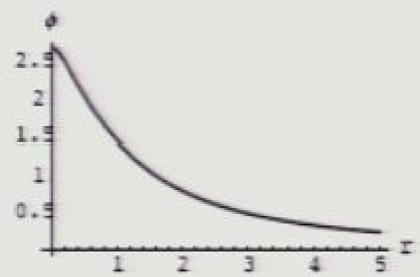

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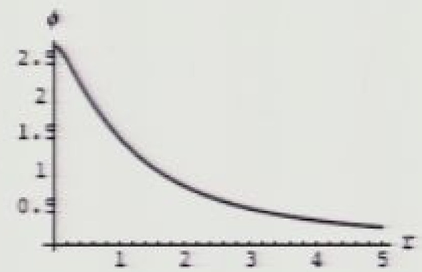

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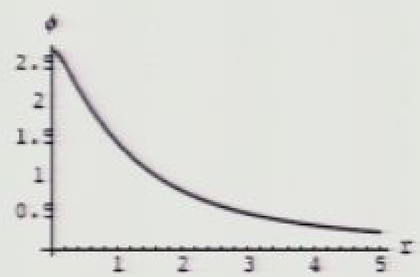

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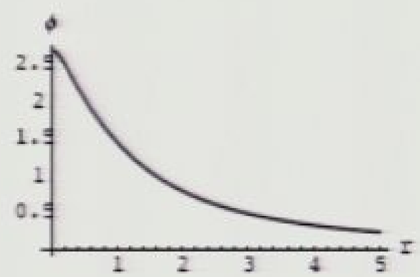

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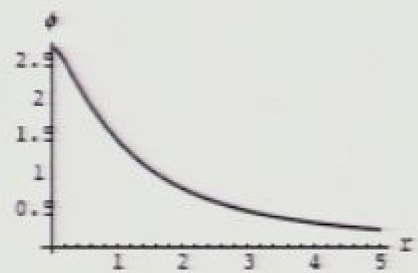

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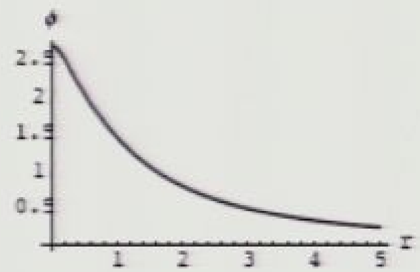

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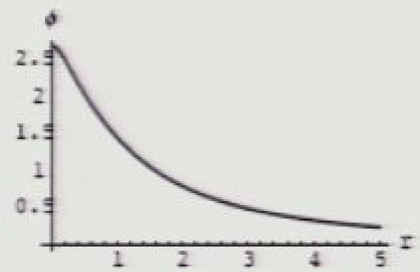

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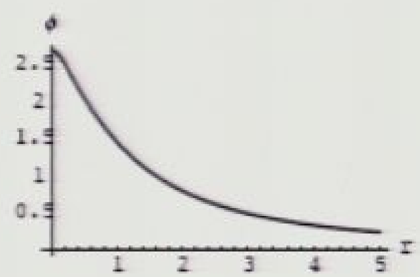

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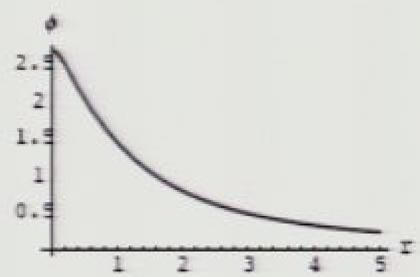

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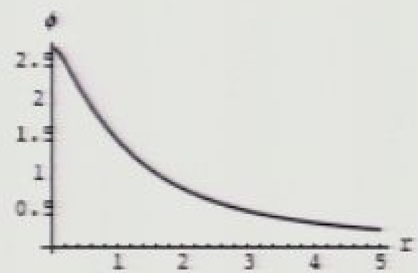

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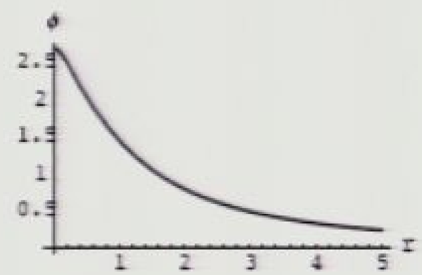

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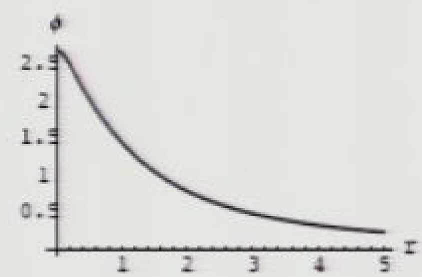

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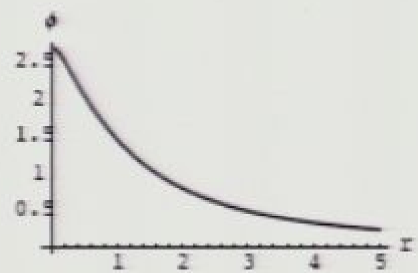

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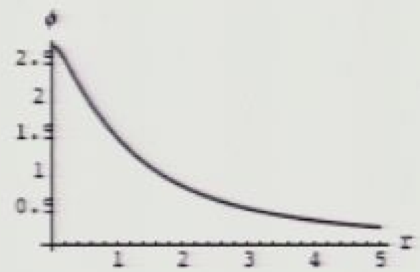

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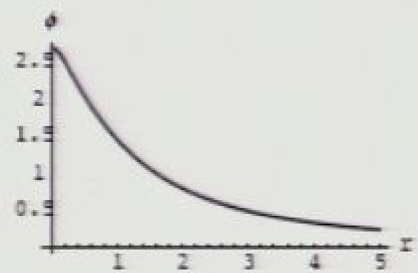

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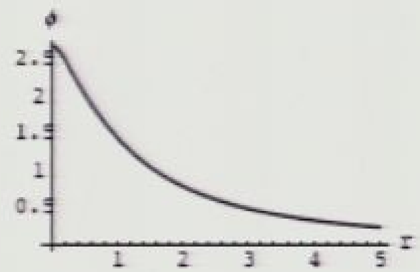

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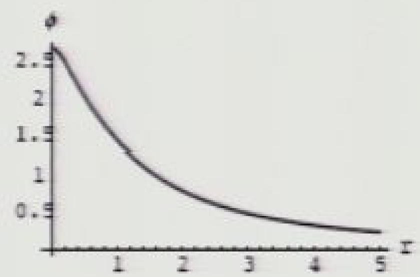

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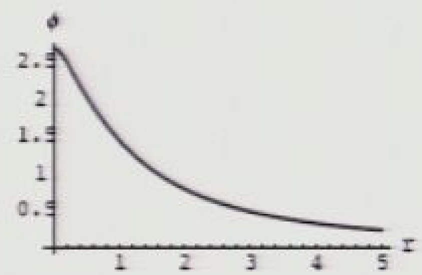

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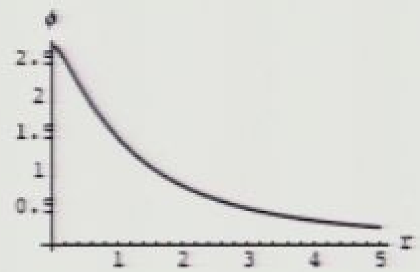

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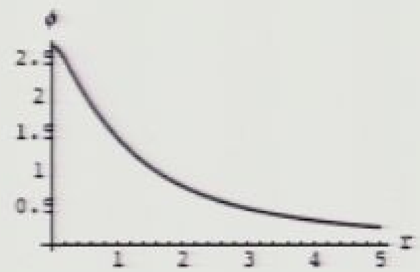

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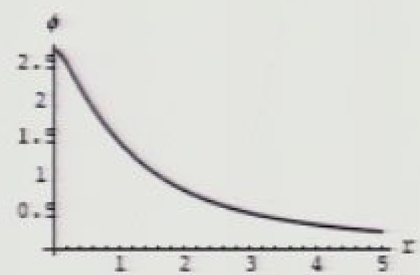

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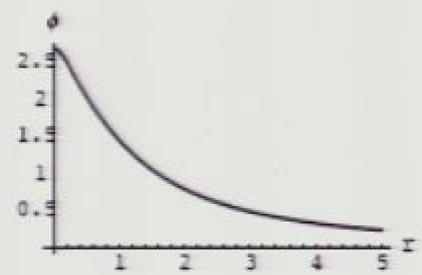

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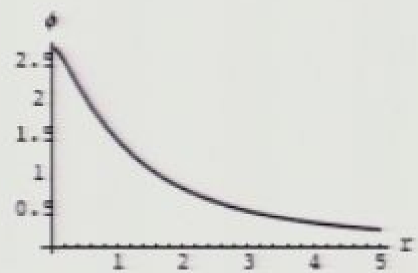

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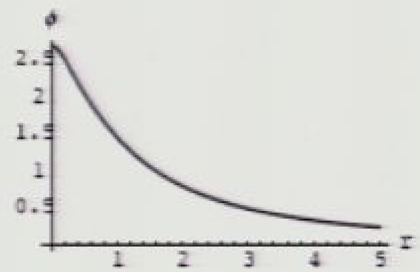

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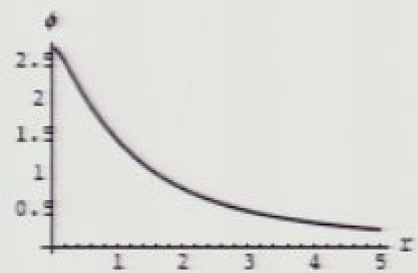

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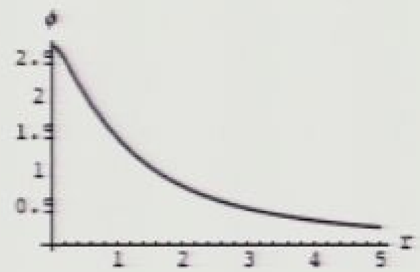

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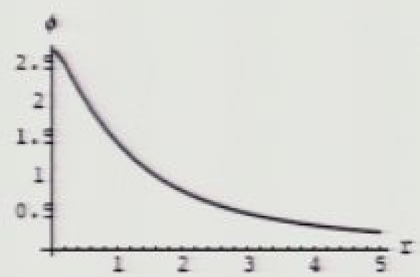

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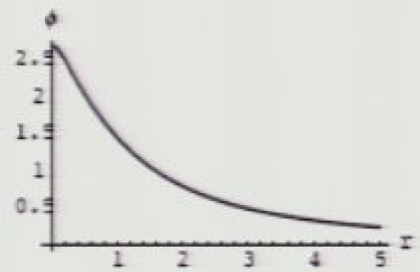

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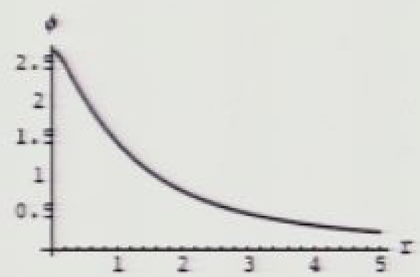

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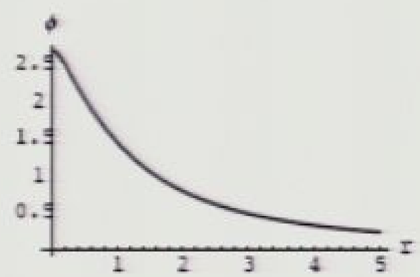

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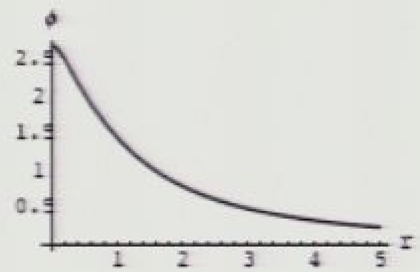

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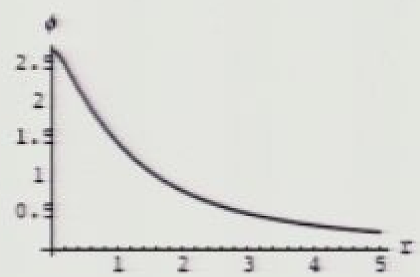

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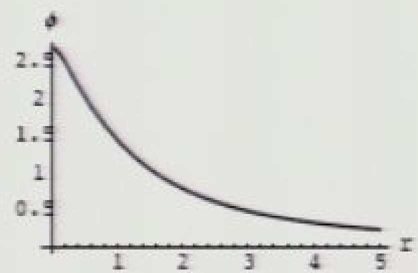

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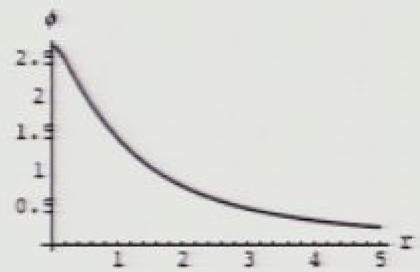

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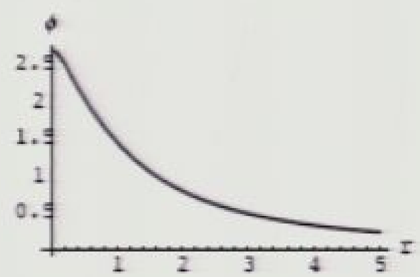

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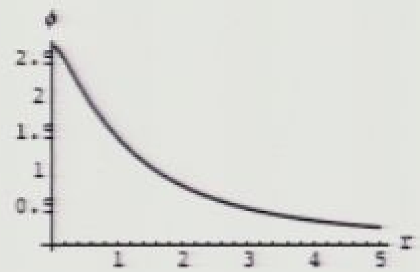

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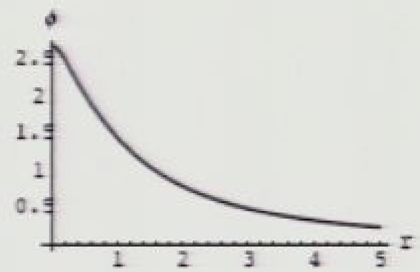

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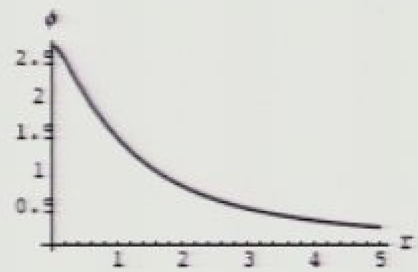

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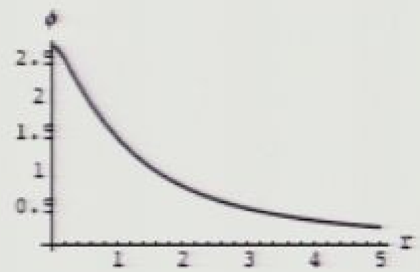

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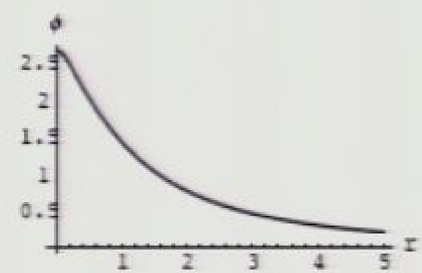

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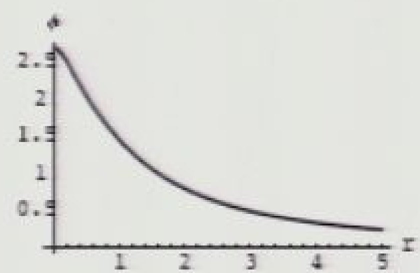

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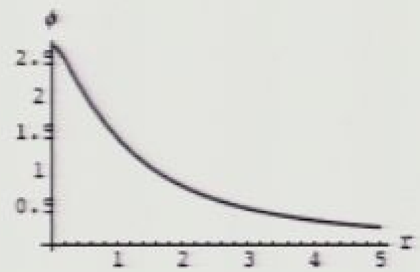

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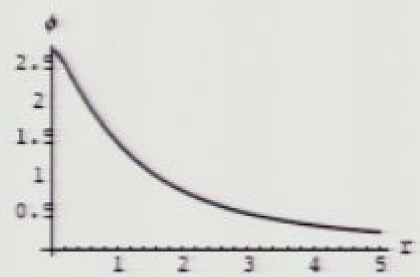

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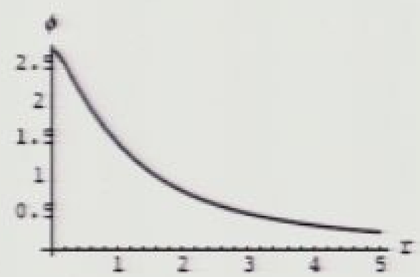

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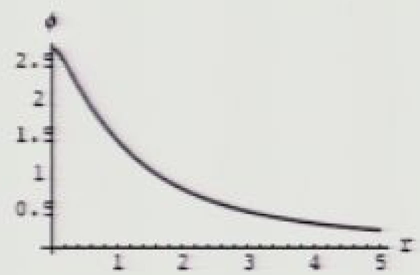

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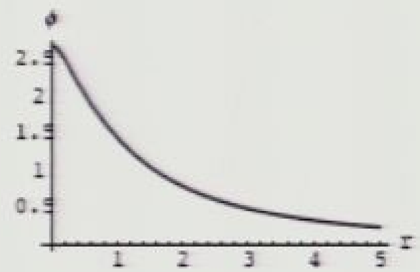

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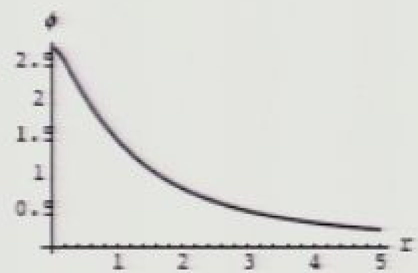

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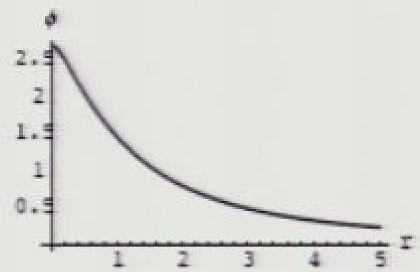

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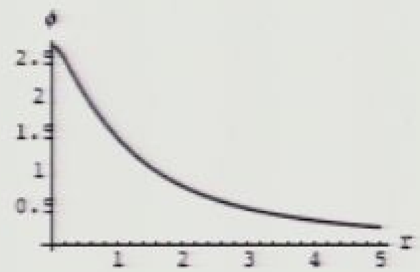

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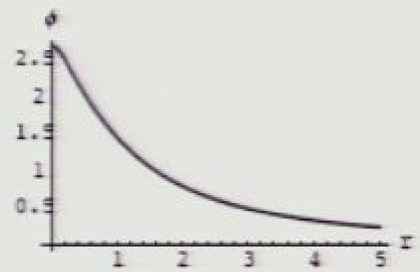

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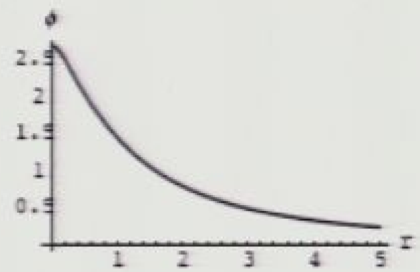

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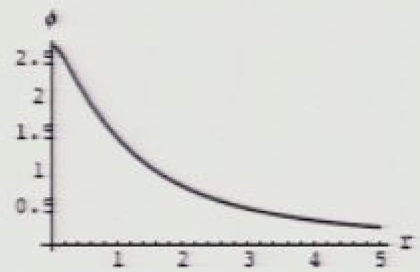

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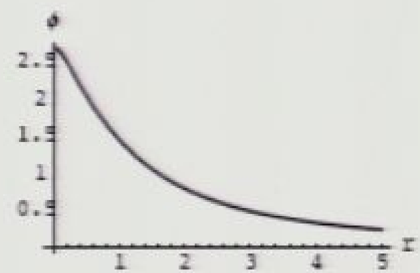

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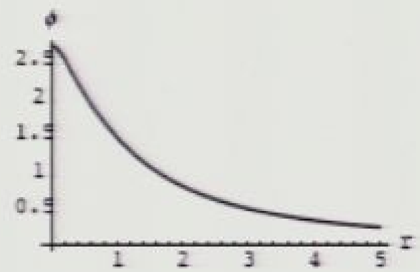

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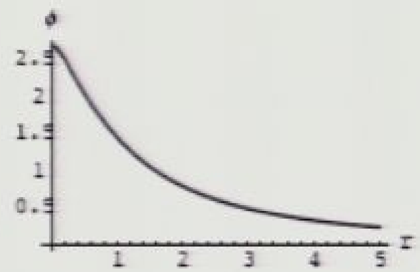

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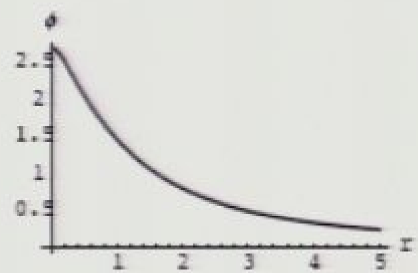

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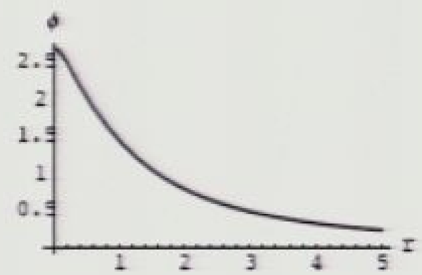

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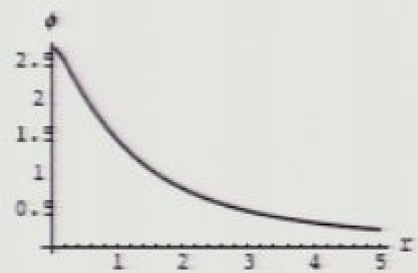

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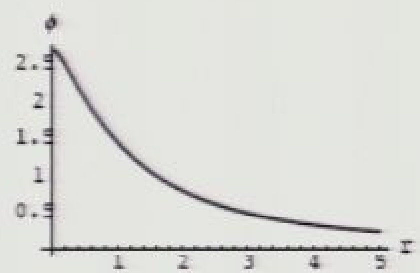

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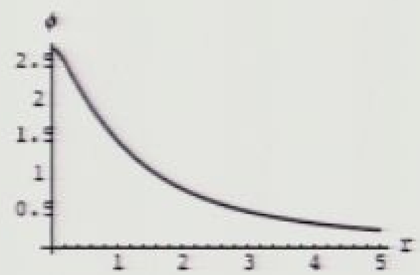

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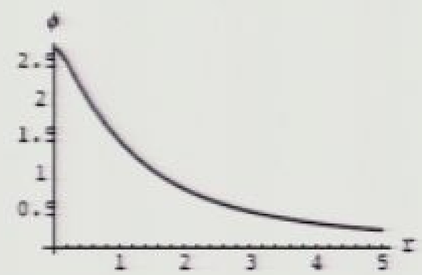

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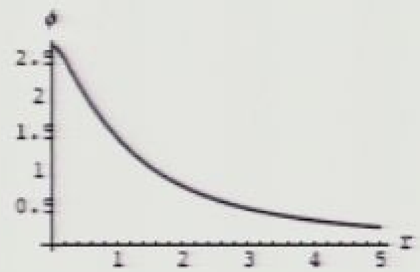

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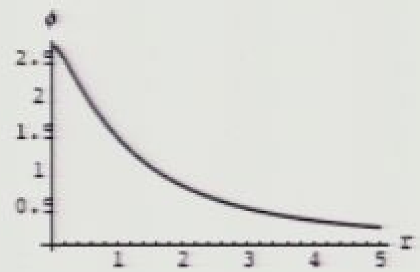

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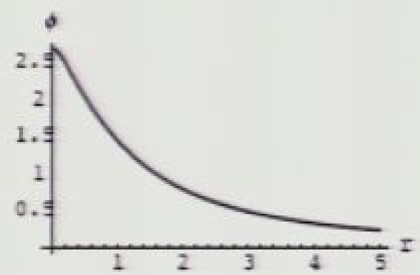

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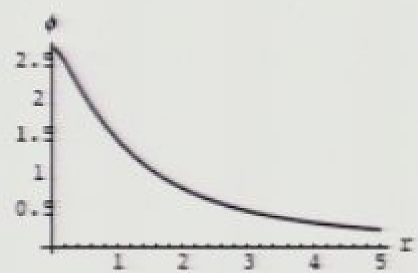

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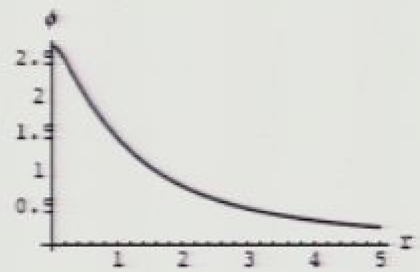

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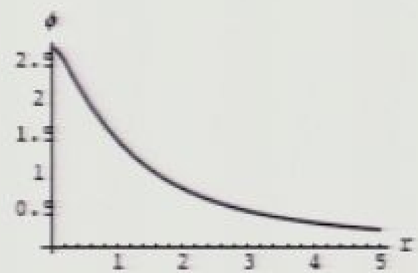

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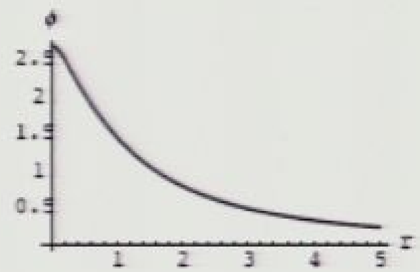

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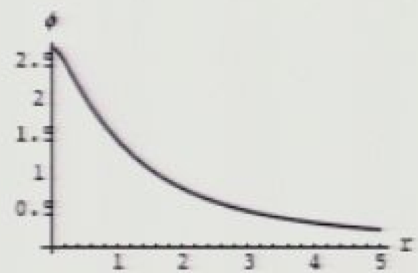

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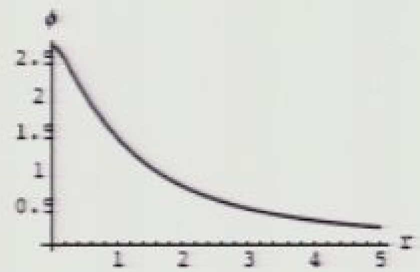

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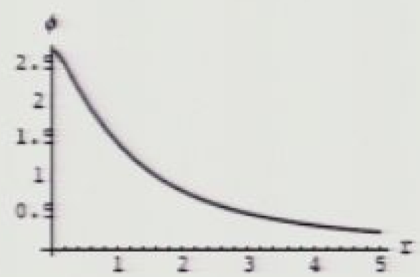

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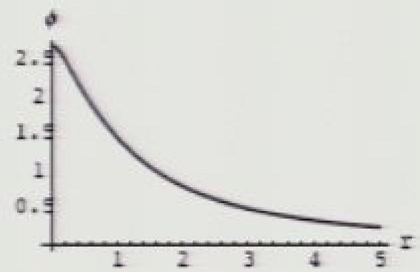

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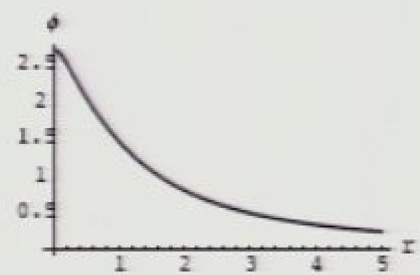

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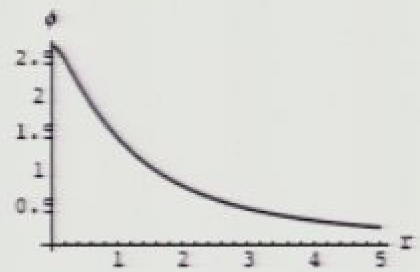

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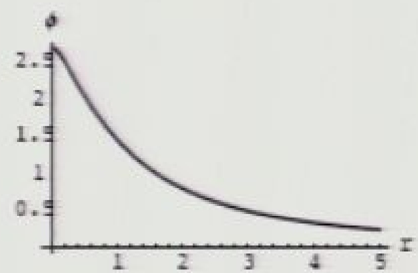

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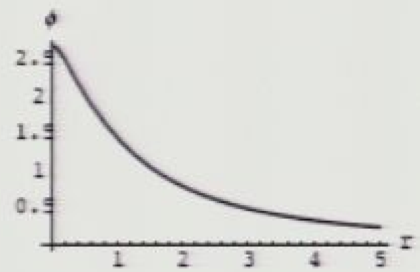

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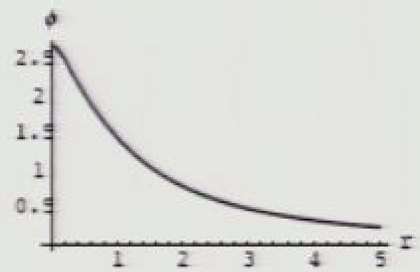

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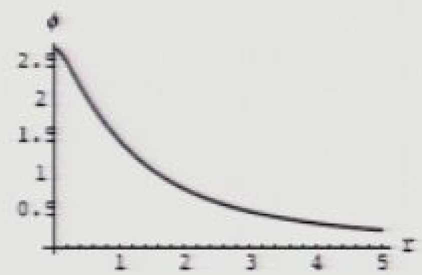

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Take boundary conditions $\alpha = f\beta, \qquad f > 0$

Conserved charges remain finite but asymptotic conformal invariance is logarithmically broken.

For $f > 0$ there are smooth $M \approx 0$ initial data that evolve to a singularity which extends to the boundary of AdS in finite global time.

Asymptotically (at large r) one has

$$\varphi \approx \frac{\beta(t)}{r^2}(1 + f \ln r) + \mathcal{O}(r^{-3}), \qquad \beta(t) = \frac{\beta(0)}{\cos^2 t}$$

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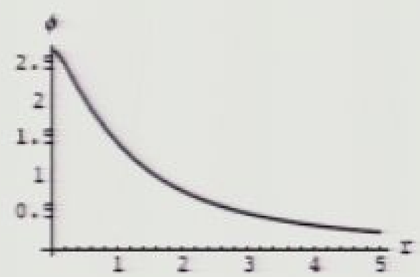

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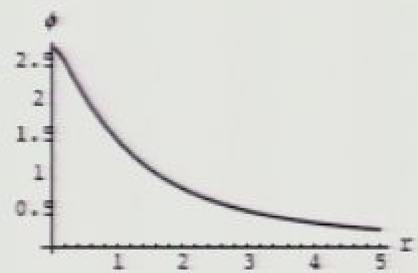

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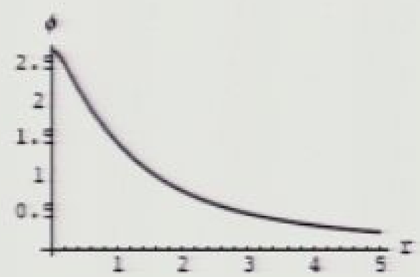

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- Taking $\alpha(\beta) \neq 0$ corresponds to adding a multitrace interaction $\int W(\mathcal{O})$ to the CFT, such that [Witten '02, Berkooz et al. '02]

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

Boundary Field Theory

String theory with $AdS_5 \times S^5$ boundary conditions is dual to $\mathcal{N}=4$ super Yang-Mills theory in $D = 4$.

- For $\alpha = 0$, $\varphi \sim \beta/r^2$ is dual to $\Delta = 2$ operator $\mathcal{O}$,

$$\mathcal{O} = \frac{1}{N} Tr \left[\phi^2 - \frac{1}{5} \sum_{i=2}^{6} \phi_i^2 \right]$$

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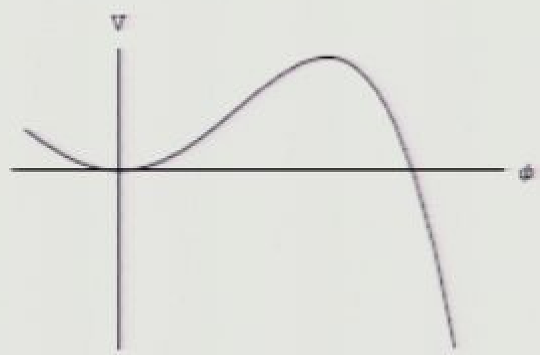
$$S = S_{YM} + \frac{f}{2}\int \mathcal{O}^2$$



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The dual description of AdS cosmologies involves field theories with effective potentials $\mathcal{V}(\langle\mathcal{O}\rangle)$ that are unbounded from below in certain directions.

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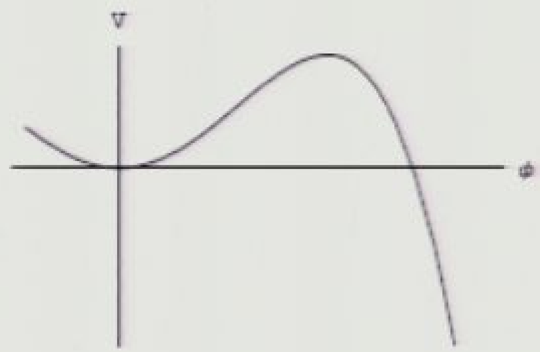

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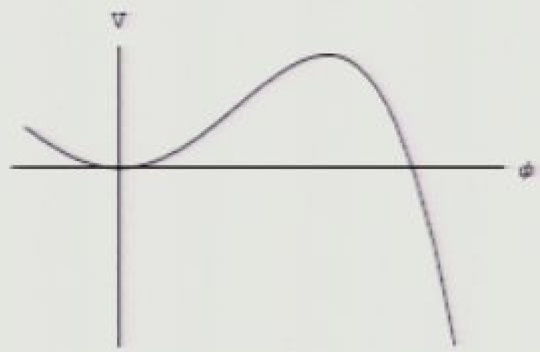

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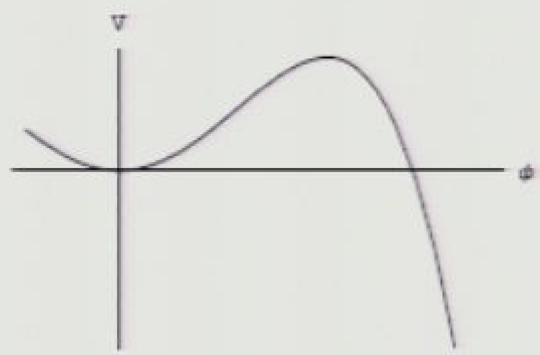

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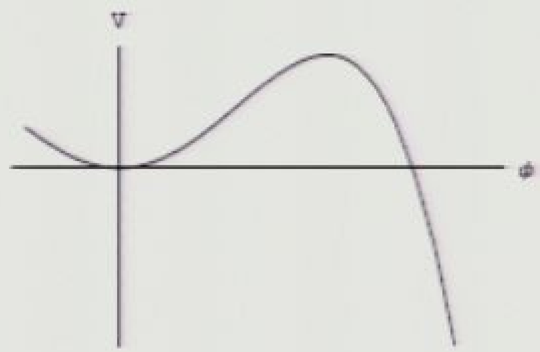

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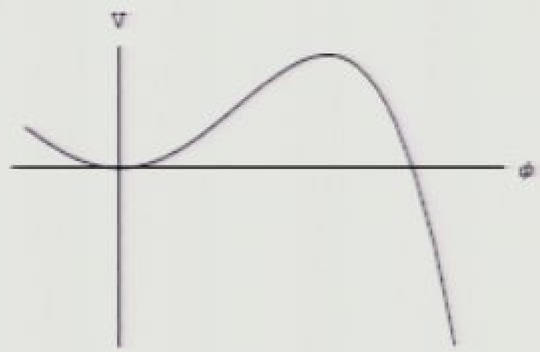

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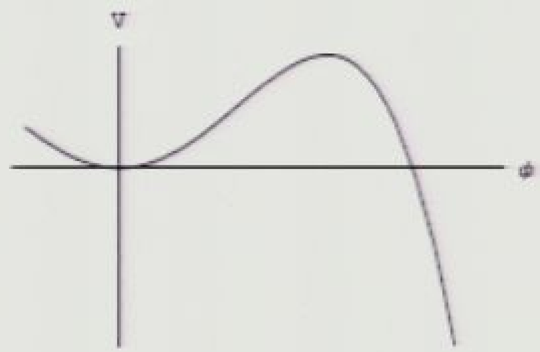

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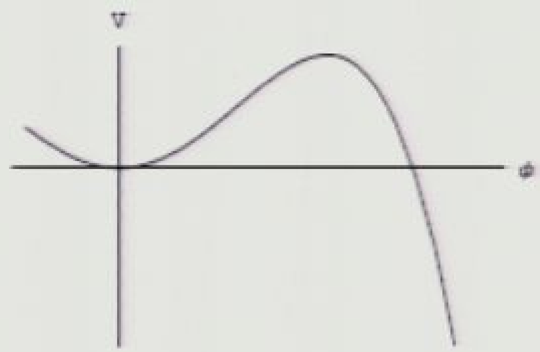

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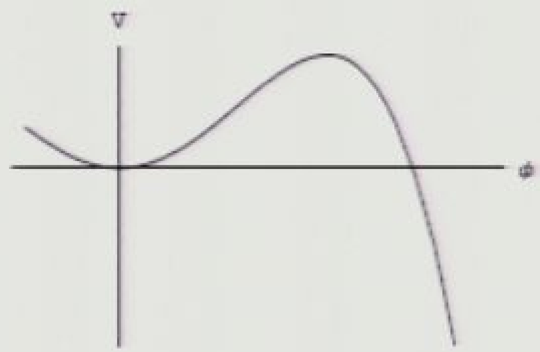

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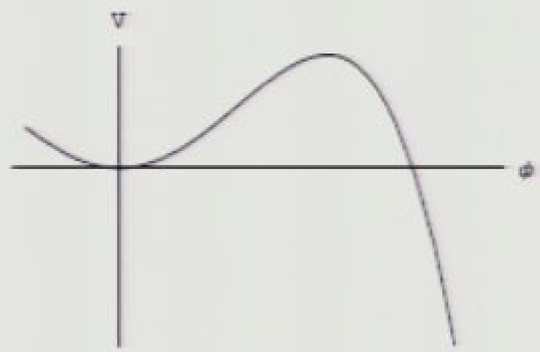

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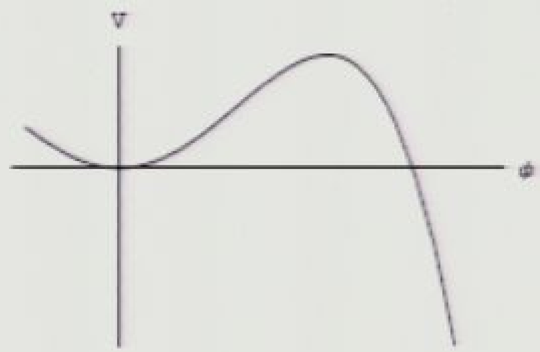

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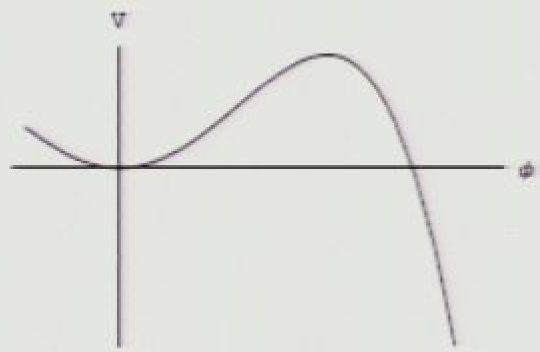

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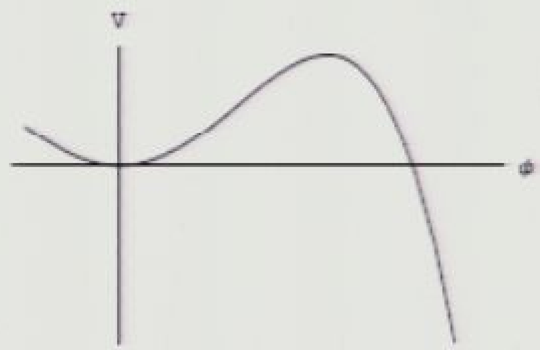

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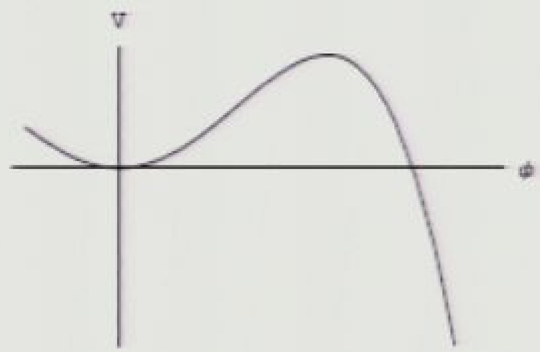

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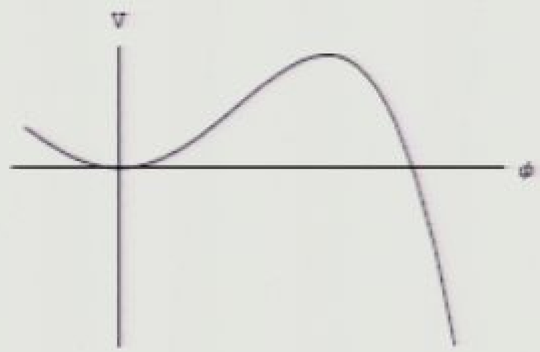

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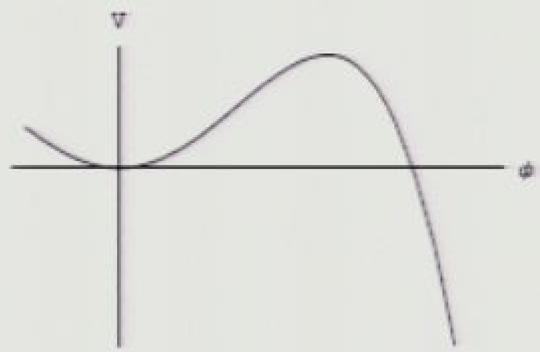

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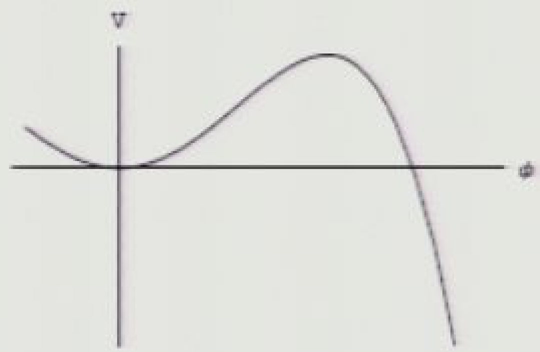

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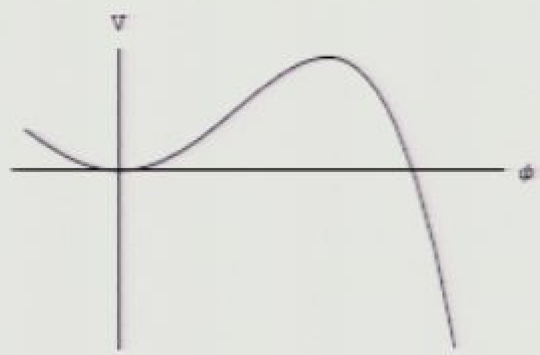

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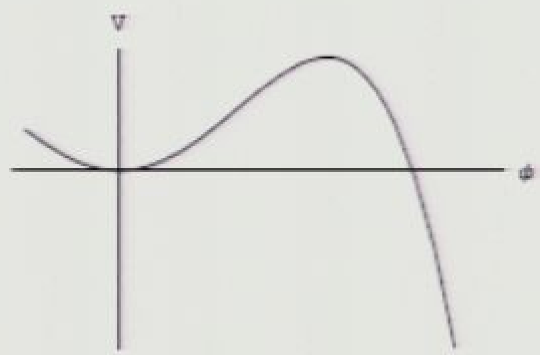

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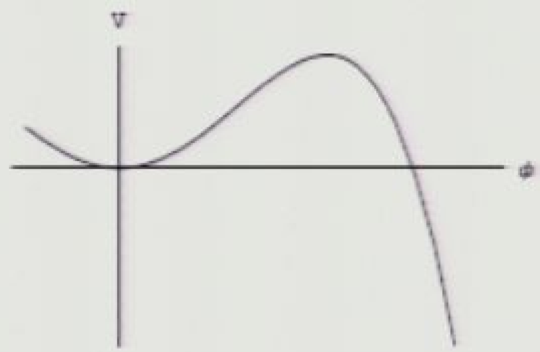

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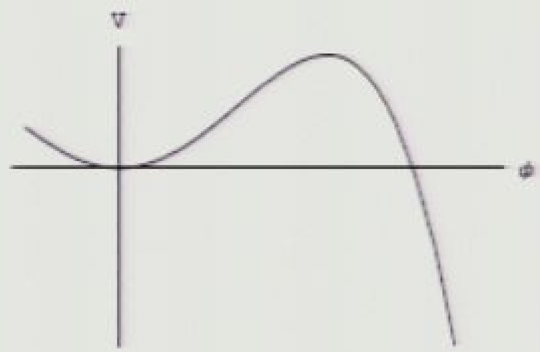

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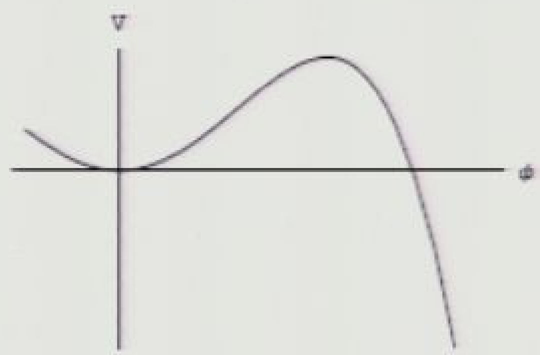

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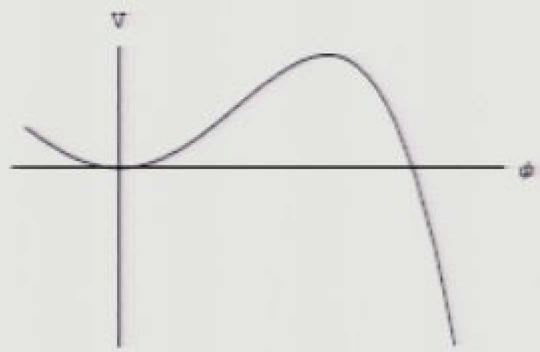

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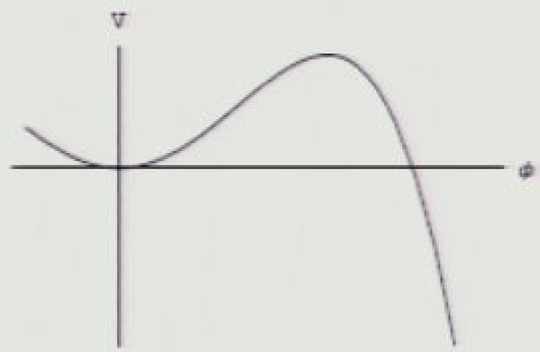

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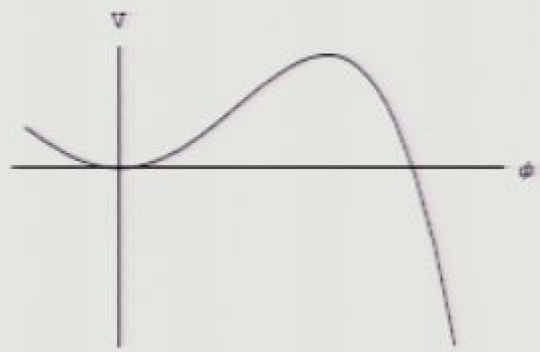

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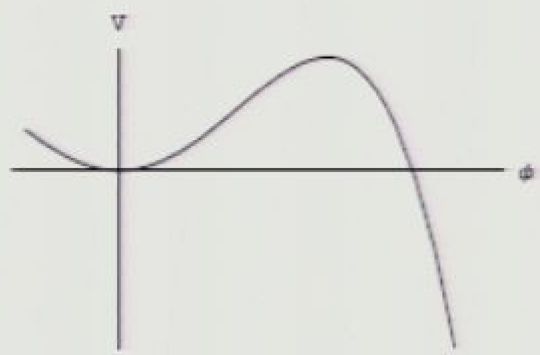

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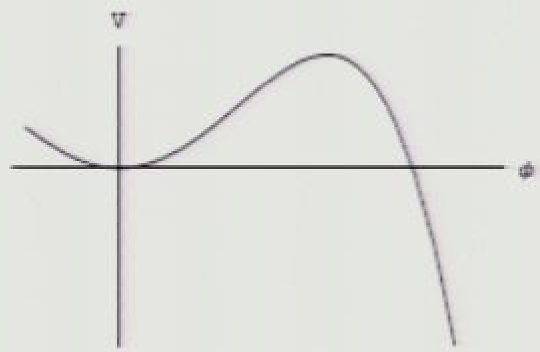

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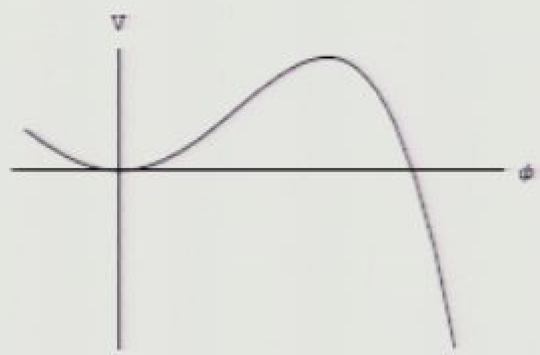

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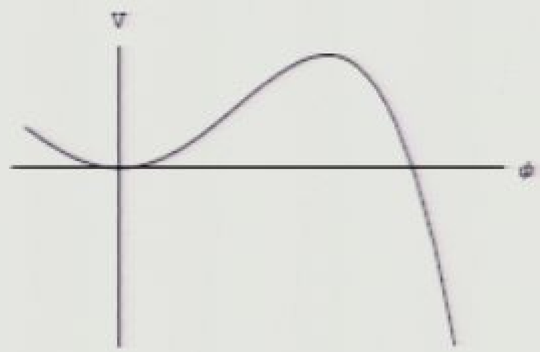

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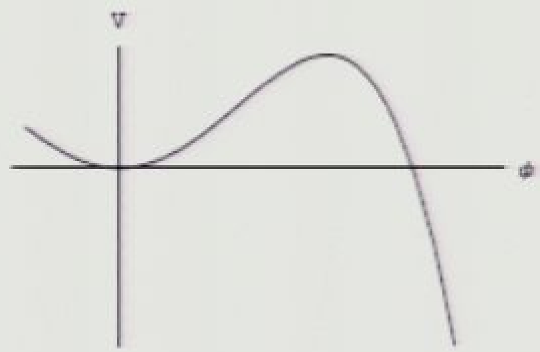

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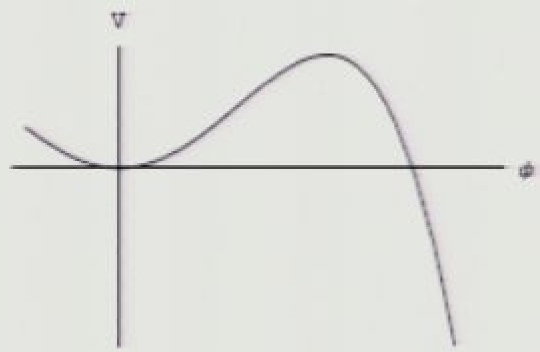

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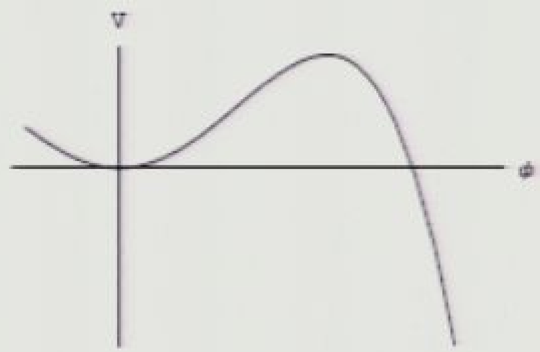

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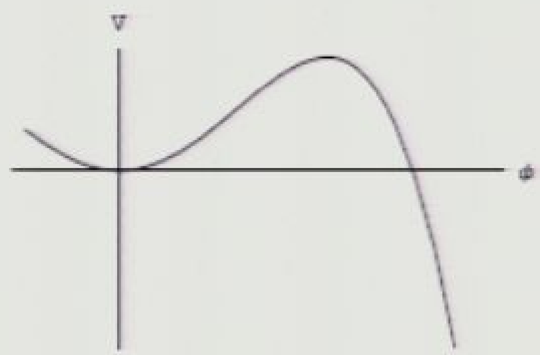

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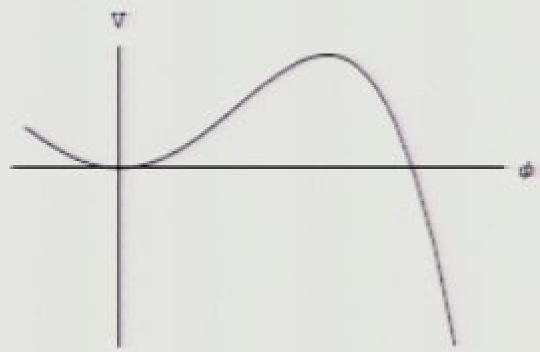

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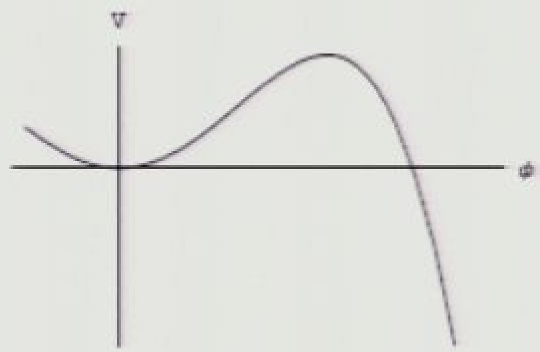

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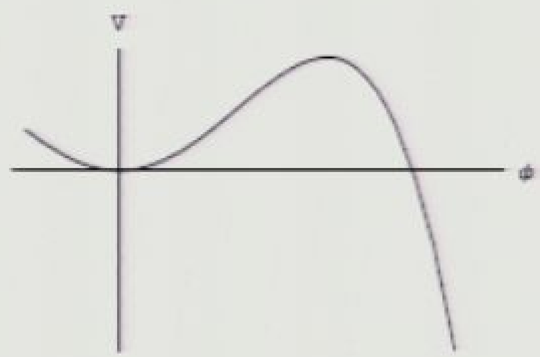

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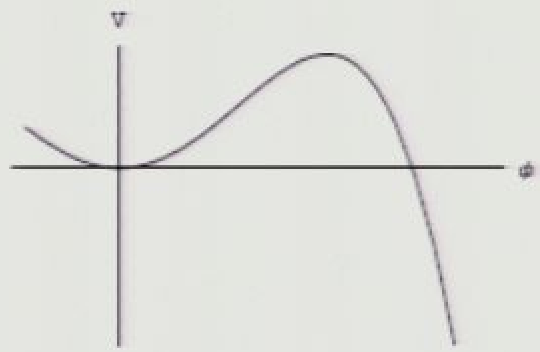

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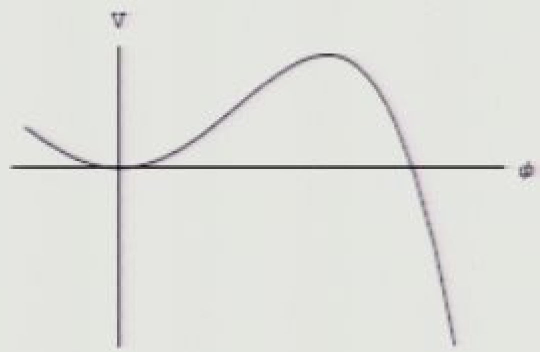

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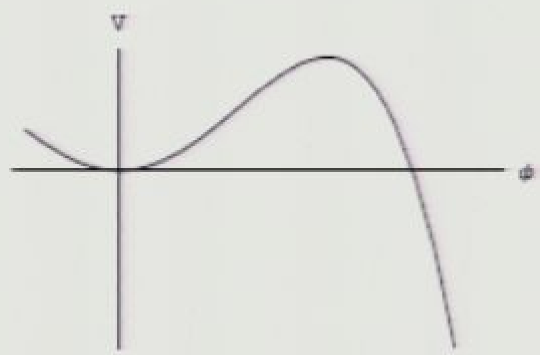

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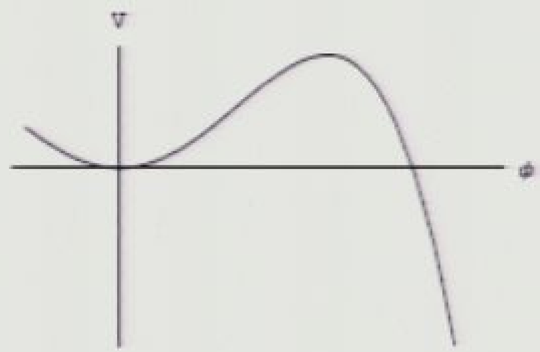

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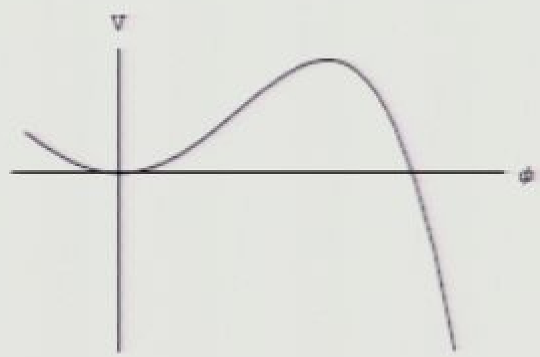

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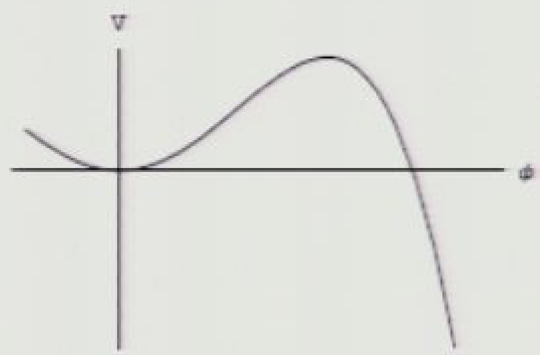

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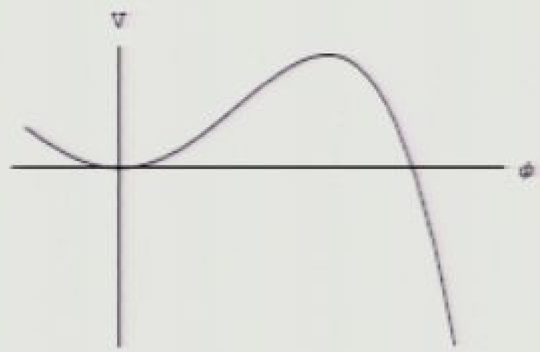

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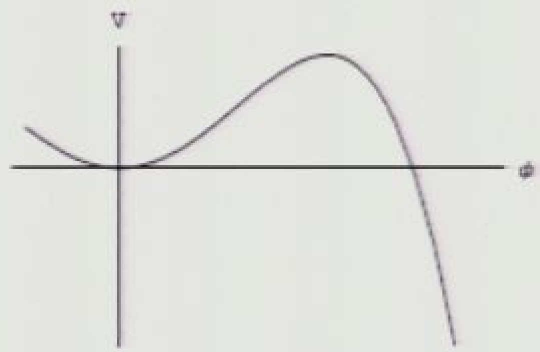

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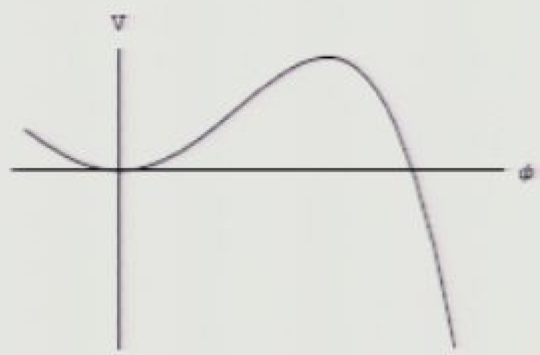

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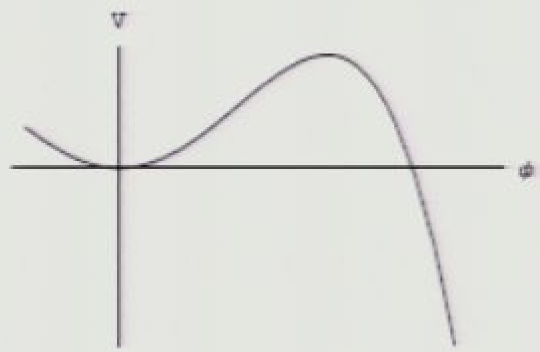
With $\alpha = f\beta$,

$$S = S_{YM} + \frac{f}{2}\int \mathcal{O}^2$$



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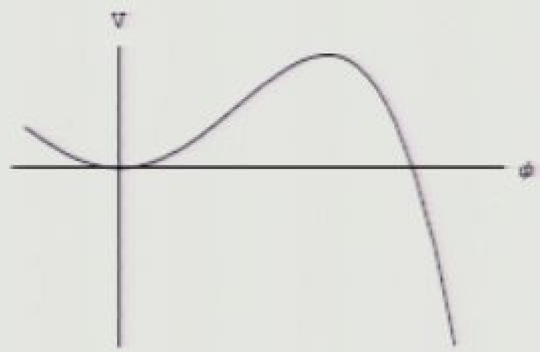

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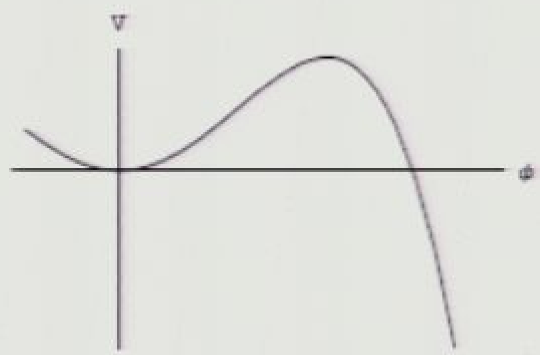

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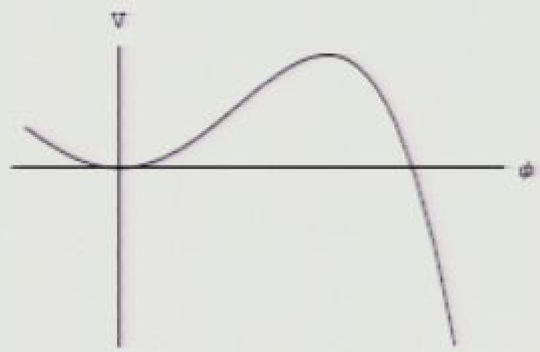

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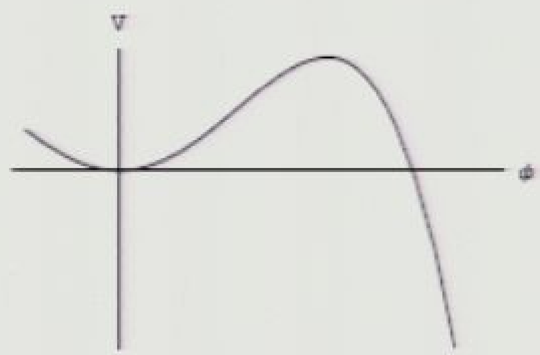

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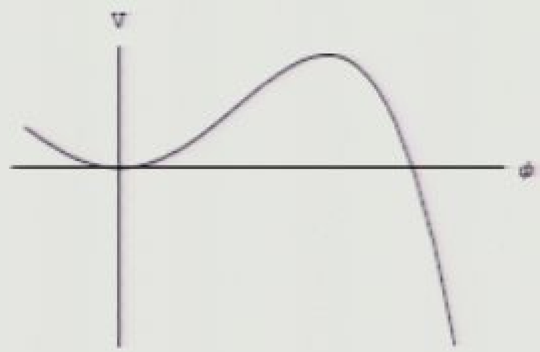

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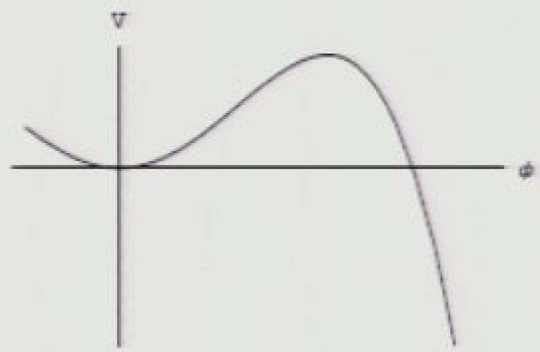

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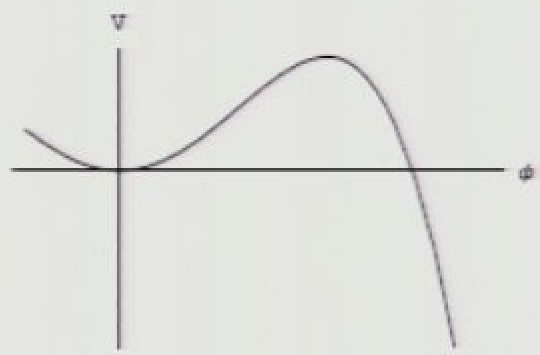

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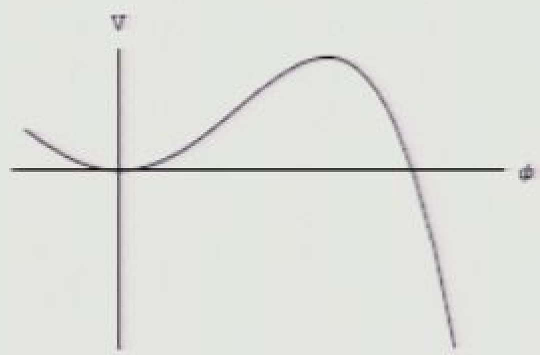

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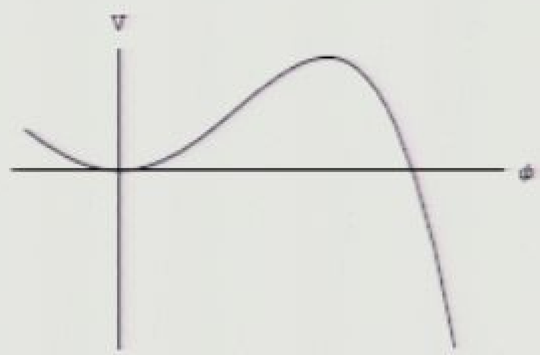

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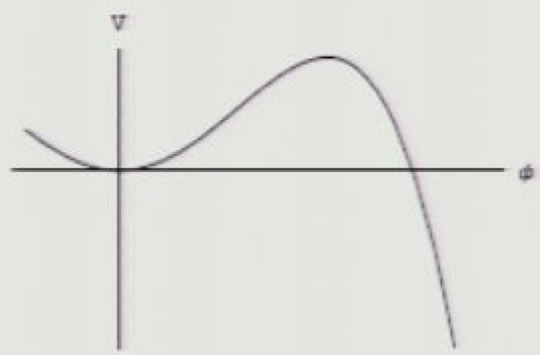

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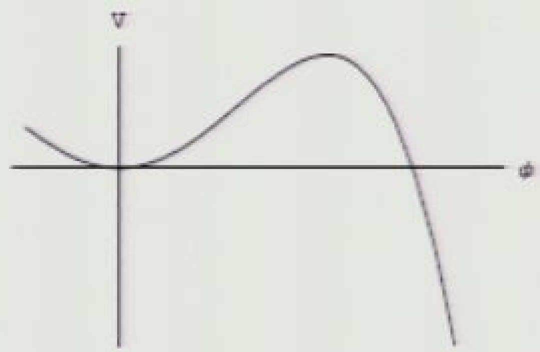

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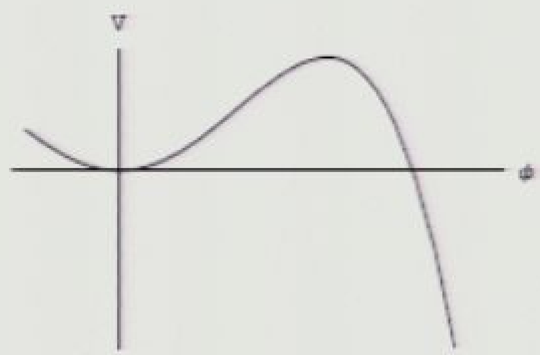

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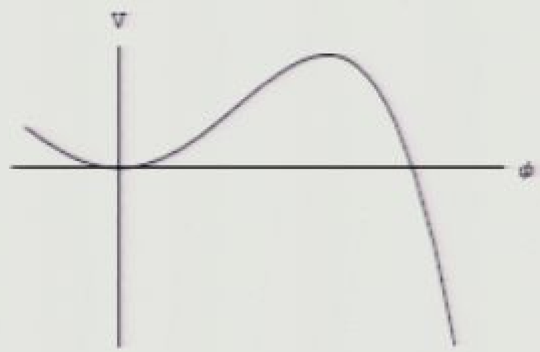

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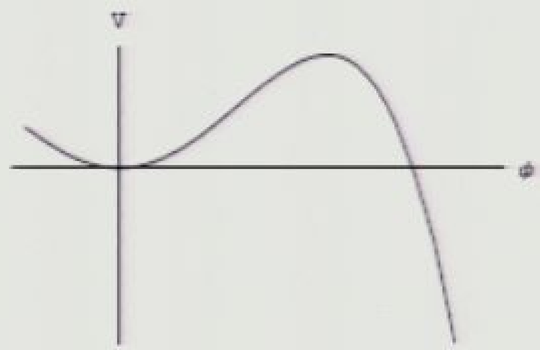

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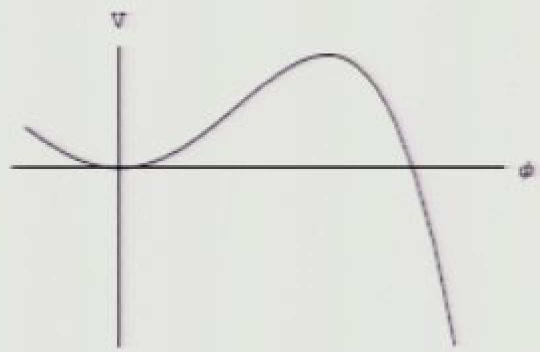

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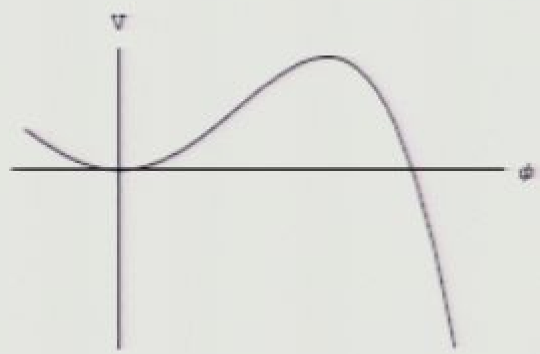

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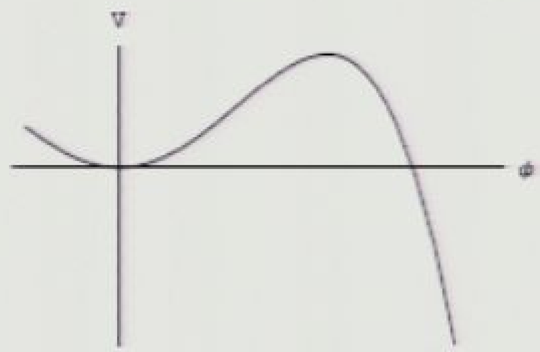

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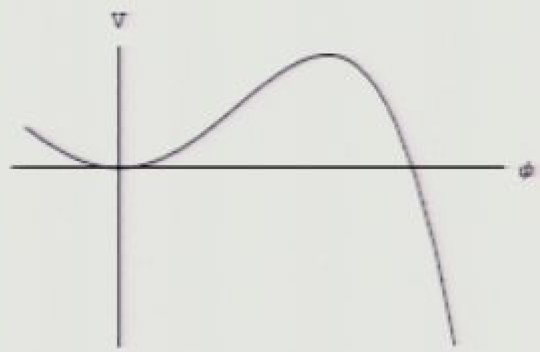

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Note: logarithmic running λ_ϕ consistent with asymptotic behavior of bulk scalar, $\alpha = f\beta$ [Witten '02]

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→ Ben's talk!

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$$\varphi = \alpha \frac{\ln r}{r^2} + \frac{\beta}{r^2}$$

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In particular it appears this is also a feature of analogous cosmologies in four dimensions.
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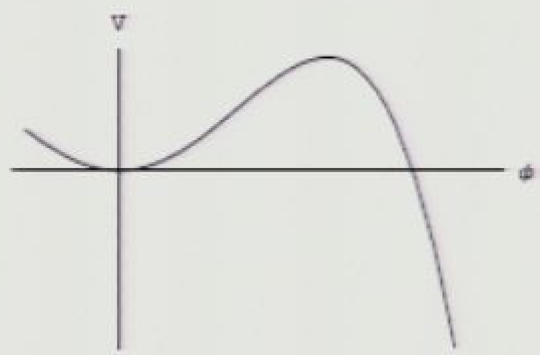
With $\alpha = f\beta$,

$$S = S_{YM} + \frac{f}{2}\int \mathcal{O}^2$$



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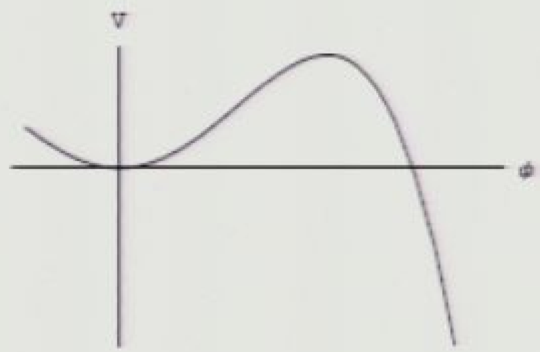

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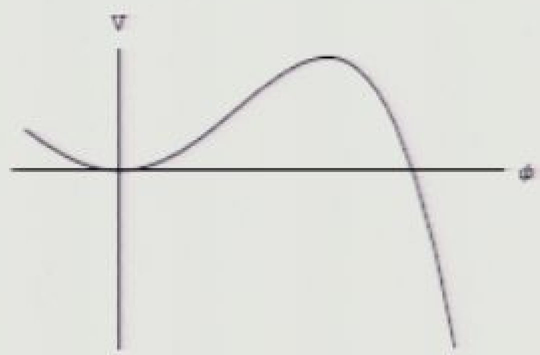

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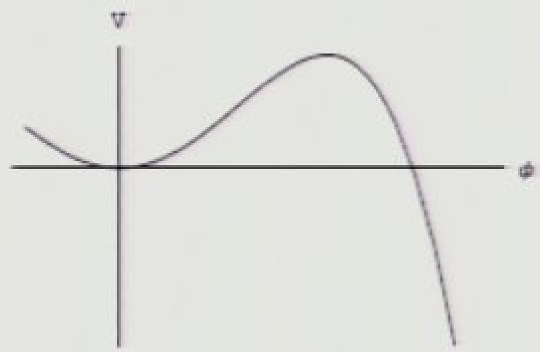

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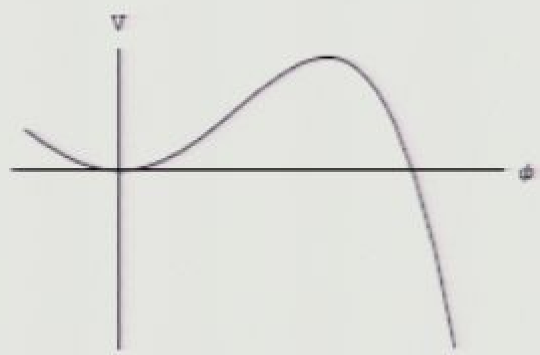

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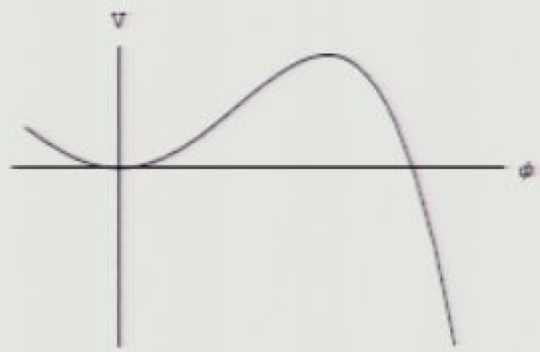

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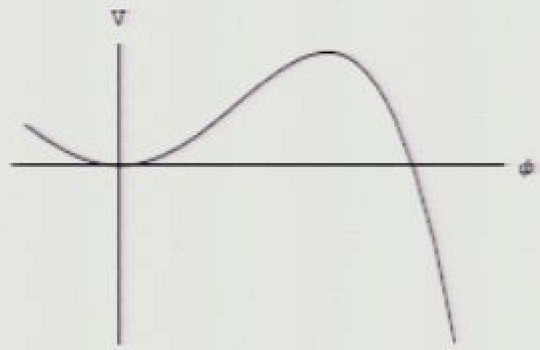

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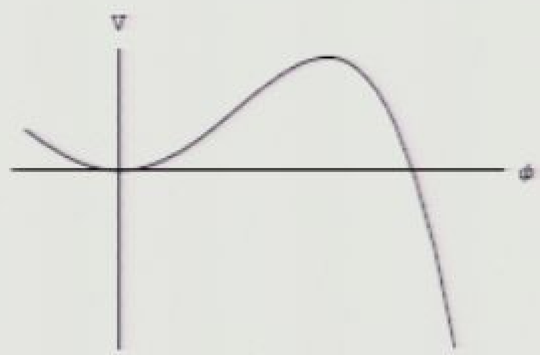

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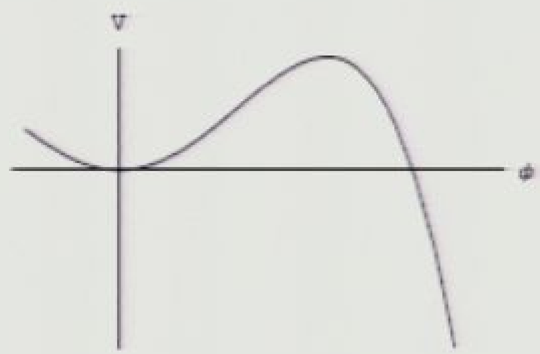

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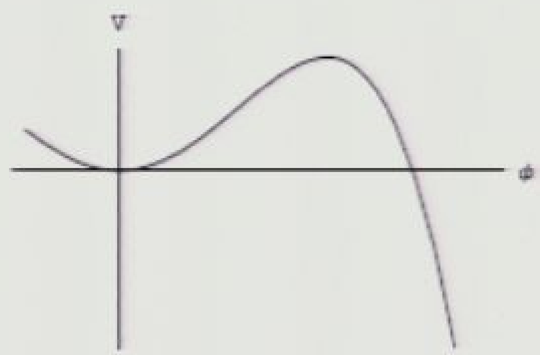

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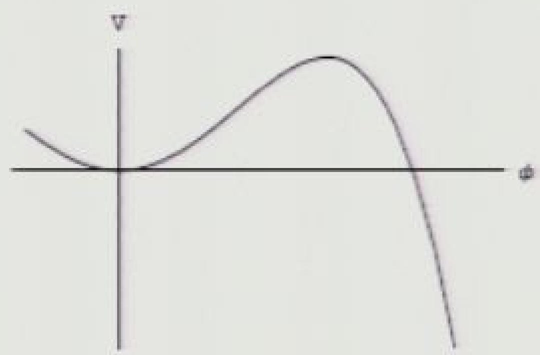

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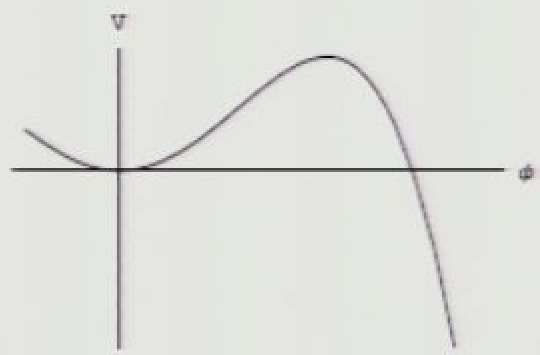

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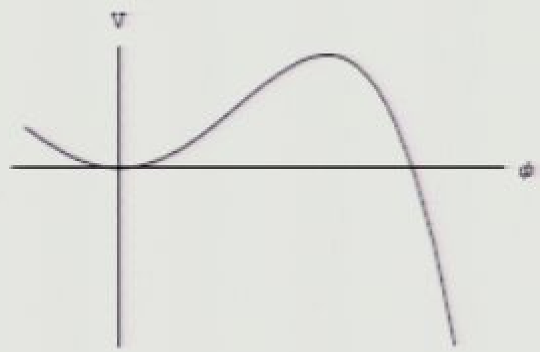

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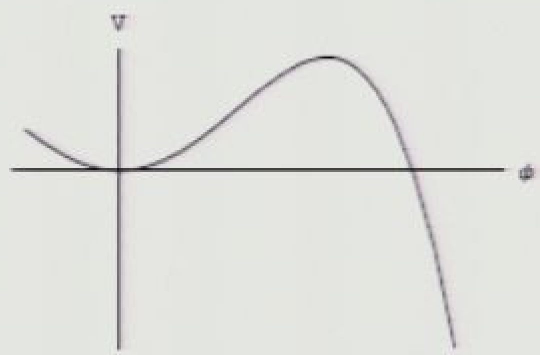

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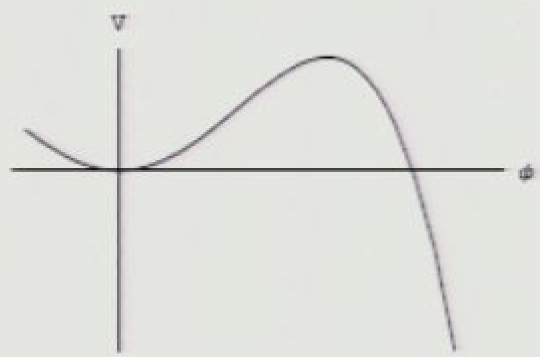

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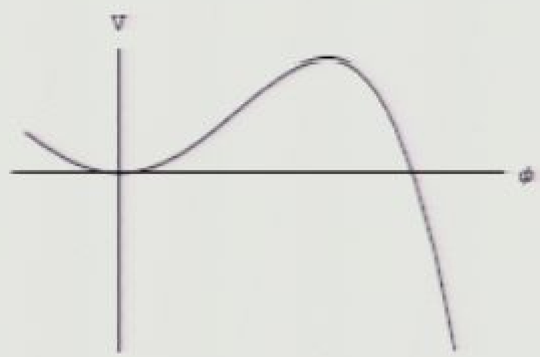

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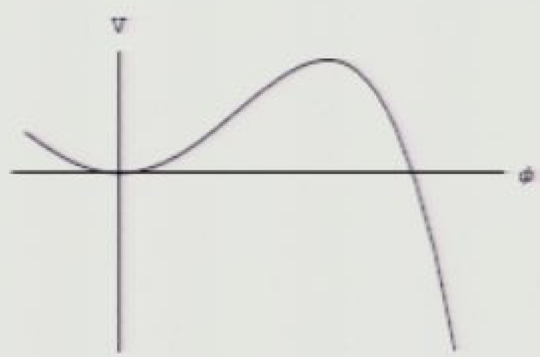

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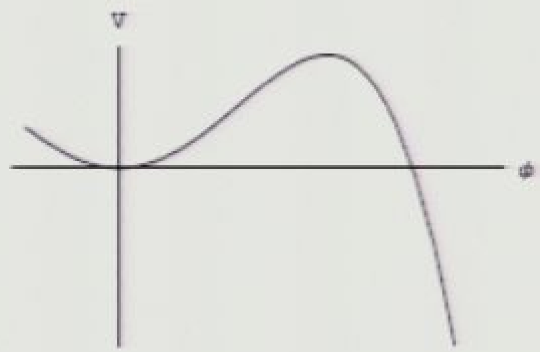

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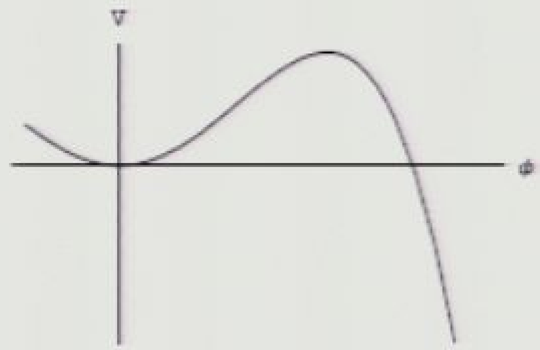

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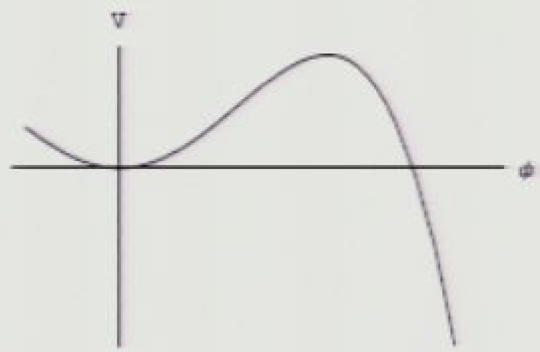

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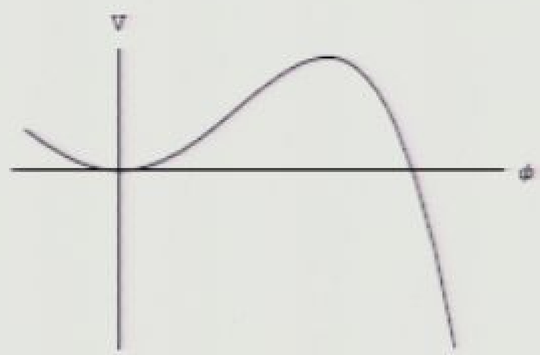

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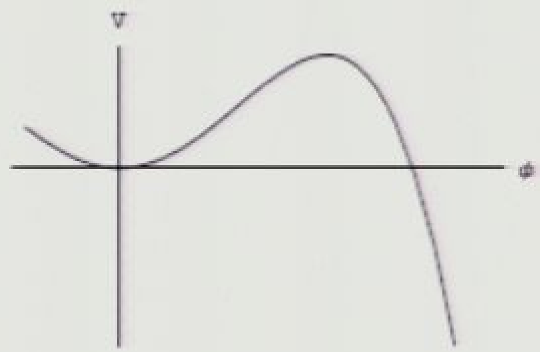

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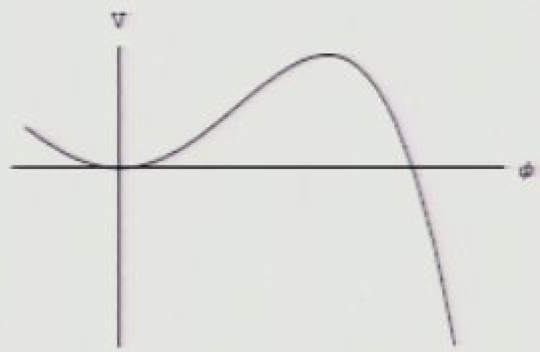

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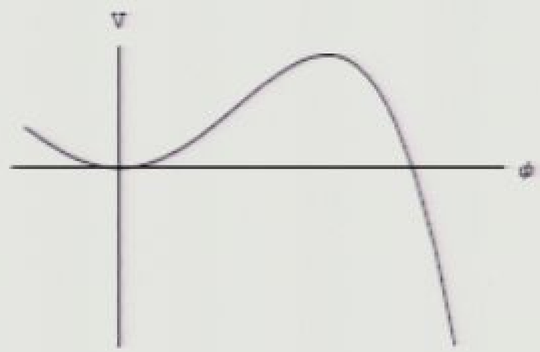

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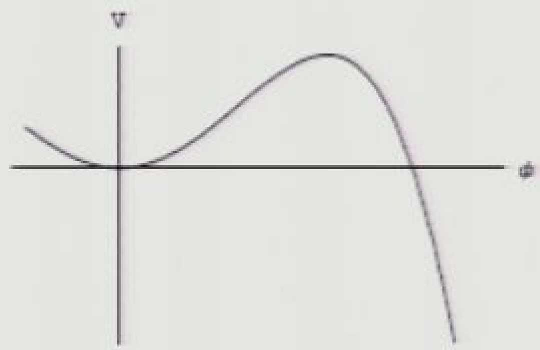

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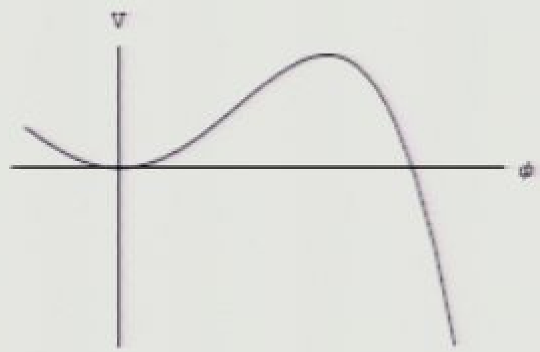

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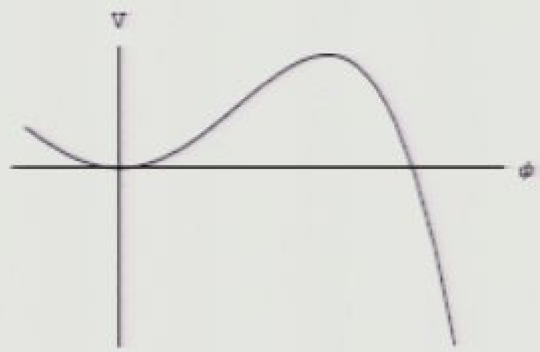

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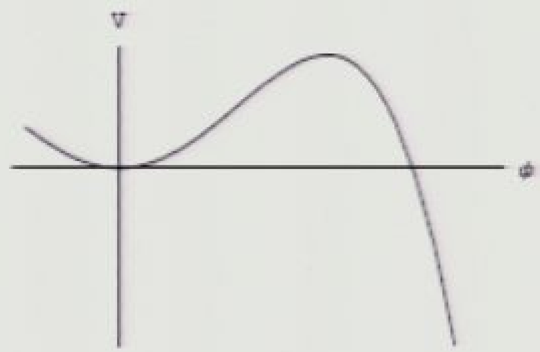

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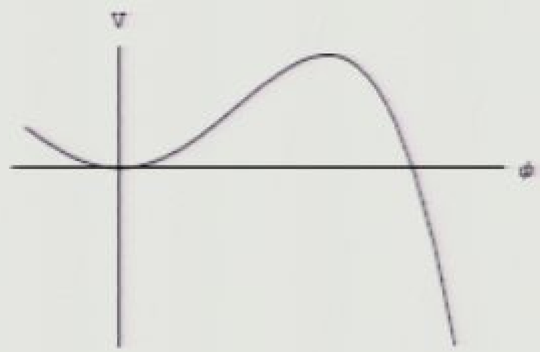

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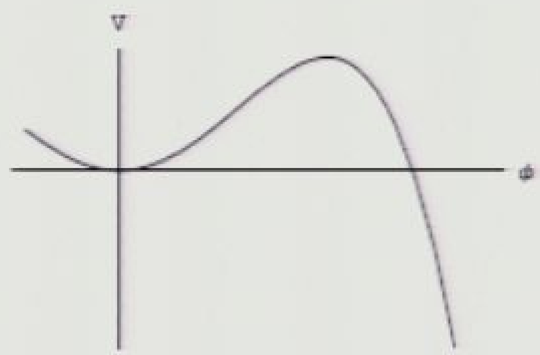

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This remains true at small 't Hooft coupling

$\rightarrow$ Ben's talk!

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Dual field theory is renormalizable and asymptotically free in f, β_f is one-loop exact at large N so that effective potential is under excellent control at large $\mathcal{O}$,

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Hence $\mathcal{V}(\mathcal{O}) \rightarrow -\infty$ for $\mathcal{O} \rightarrow \infty$

Note: logarithmic running λ_ϕ consistent with asymptotic behavior of bulk scalar, $\alpha = f\beta$
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This remains true at small 't Hooft coupling

$\rightarrow$ Ben's talk!

$$S = S_{YM} + \frac{f}{2}\int \mathcal{O}^2$$

Dual field theory is renormalizable and asymptotically free in f, β_f is one-loop exact at large N so that effective potential is under excellent control at large $\mathcal{O}$,

$$\mathcal{V}(\mathcal{O}) = -\frac{\mathcal{O}^2}{\ln(\mathcal{O}/M^2)} \rightarrow -\frac{\phi^4}{N^2 \ln(\phi/M)} \equiv -\lambda_\phi \phi^4,$$

Hence $\mathcal{V}(\mathcal{O}) \rightarrow -\infty$ for $\mathcal{O} \rightarrow \infty$

Note: logarithmic running λ_ϕ consistent with asymptotic behavior of bulk scalar, $\alpha = f\beta$
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In particular it appears this is also a feature of analogous cosmologies in four dimensions.
[T.H. & Horowitz '04]

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Consider first steepest unstable direction: $V = -\frac{\lambda}{4}\varphi^4$.

Homogeneous background solution: $\varphi = \sqrt{2/\lambda}|t|^{-1}$.

General classical solution near spacelike singular hypersurface $t_*(x)$

$$\chi \equiv \sqrt{2/\lambda}\varphi^{-1} \sim [t - t_*(\bar{x})$$

$$+\tfrac{1}{6}(t-t_*)^2\nabla^2 t_* + ... + \rho(\bar{x})(t-t_*)^5 + ...]$$

is fully determined by "time delay" $t_*(\bar{x})$ and "energy perturbation" $\rho(\bar{x})$.

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Instability

This instability is a universal feature of the dual description of AdS cosmologies: the field theory directly "sees" the gravitational instability associated with singularity formation.

In particular it appears this is also a feature of analogous cosmologies in four dimensions.
[T.H. & Horowitz '04]

→ the AdS/CFT duality maps the problem of cosmological singularities to the problem of understanding field theories with unbounded potentials.

What are the principles?

Effective Potential

This remains true at small 't Hooft coupling

$\longrightarrow$ Ben's talk!

$$S = S_{YM} + \frac{f}{2}\int \mathcal{O}^2$$

Dual field theory is renormalizable and asymptotically free in f, β_f is one-loop exact at large N so that effective potential is under excellent control at large $\mathcal{O}$,

$$\mathcal{V}(\mathcal{O}) = -\frac{\mathcal{O}^2}{\ln(\mathcal{O}/M^2)} \rightarrow -\frac{\phi^4}{N^2\ln(\phi/M)} \equiv -\lambda_\phi \phi^4,$$

Hence $\mathcal{V}(\mathcal{O}) \rightarrow -\infty$ for $\mathcal{O} \rightarrow \infty$

Note: logarithmic running λ_ϕ consistent with asymptotic behavior of bulk scalar, $\alpha = f\beta$
[Witten '02]

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Strategy

1. Describe quantum field background by set of independent quantum mechanical systems, one for each point in space.

2. Take in account gradient degrees of freedom perturbatively.

3. Calculate energy in created particles and verify if backreaction is small

Quantum Mechanics

A right-moving wave packet in $V(x) = -a^2 x^p$ (for $x > 0$ and $p > 2$) reaches infinity in finite time, which would seem to lead to loss of probability.

Restore unitarity by restricting domain of allowed wavefunctions such that Hamiltonian is self-adjoint [Reed & Simon 70's].

In fact, without a "self-adjoint extension" evolution is not even defined in these theories.

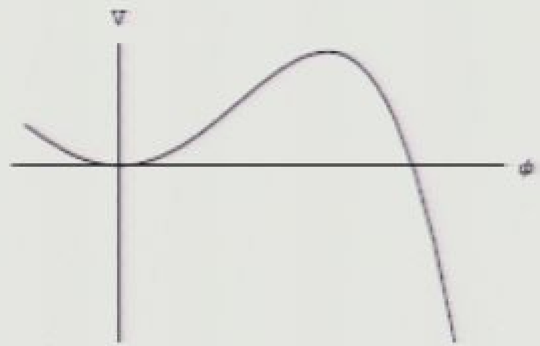
A basis can be constructed by taking the linear combination of the WKB energy eigenfunctions that for large x behaves as

$$\Psi_E \sim (2a^2 x^p)^{-1/4} \cos\left[\frac{\sqrt{2} a x^{p/2+1}}{p/2+1} + \alpha\right]$$

$$|\Psi_E|^2 \sim x^{-2} \quad \text{at large } x$$

Ultralocality: self-adjoint extension point by point.

Homogeneous Rolling Field



Decompose: $\phi(t,x) = \bar{\phi}(t) + \delta\phi(t,x)$

Kinetic term homogeneous mode: $V_3 \int dt \frac{1}{2} \dot{\bar{\phi}}^2$

→ Finite volume S^3 acts as mass, so that even homogeneous mode will undergo quantum spreading.

This will give rise to UV cutoff on creation of particles, since background remains regular.

Field Theory Evolution

Consider semiclassical expansion

$$\Psi(\bar{\phi}_f, t_f) = A(\bar{\phi}_f, t_f) e^{iS(\bar{\phi}_f, t_f)/\hbar}$$

Solving Schrodinger eq in expansion of $\hbar$ one finds $S = S_{cl}(\bar{\phi}_f, t_f)$, where S_{cl} is the action of the classical solution that obeys

1. Initial condition: $\bar{\phi} + 2i\hbar^{-1}\pi_{\bar{\phi}}(\Delta\bar{\phi})^2 = \bar{\phi}_c, \quad t = t_i$

i.e. Gaussian wavepacket with spread $\Delta\phi$ around $\bar{\phi}_c$ just over potential barrier.

$$\Psi(\bar{\phi}, t_i) \sim e^{-\frac{(\bar{\phi}-\bar{\phi}_c)}{4(\Delta\bar{\phi})^2}}$$

2. Final condition:

$\Psi(\bar{\phi}_f, t_f)$ with $\bar{\phi}_f \sim \bar{\phi}_c$ at time $t_f \sim t_i + 2R$.

$\rightarrow$ *relevant classical solutions are generally complex.*

Field Theory Evolution

Unitary boundary conditions: implemented via method of images, by adding "mirror" wave packet with

$$\bar{\phi} + 2i\hbar^{-1}\pi_{\bar{\phi}}(\Delta\bar{\phi})^2 = -\bar{\phi}_c, \quad t = t_i$$

$\rightarrow$ *Quantum spread and unitarity mean* $\Psi(\bar{\phi}, t)$ *determined by two complex classical solutions.*

$$\Psi(\bar{\phi}_f, t_f) = \left(A_1 e^{iS_1(\bar{\phi}_f, t_f)/\hbar} + A_2 e^{i\alpha} e^{iS_2(\bar{\phi}_f, t_f)/\hbar}\right)$$

In terms of $\bar{\chi} = \sqrt{2/\lambda}\bar{\phi}^{-1}$, mirror classical solution is

Imaginary part $-i\epsilon$ near $t \approx 0$ depends on final argument $\bar{\phi}_f$ of Ψ. Typically $\epsilon \sim (\Delta\phi)^3$.

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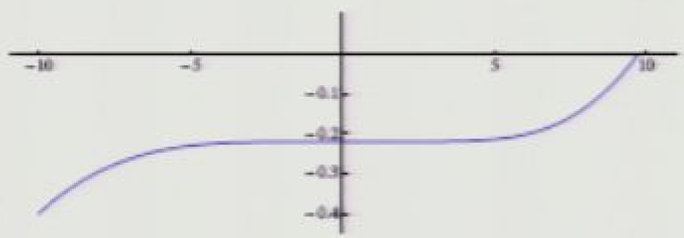

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Does the universe bounce?

$$\Psi(\bar{\phi}_f, t_f) = \left(A_1 e^{iS_1(\bar{\phi}_f, t_f)/\hbar} + A_2 e^{i\alpha} e^{iS_2(\bar{\phi}_f, t_f)/\hbar}\right)$$

Early times: S_1 dominates, wave packet rolling down.

Late times: S_2 dominates, wave packet rolling up.

Intermediate times: Interference

Self-adjoint extension would seem to imply that $\bar{\phi}$ rolls up the hill again, returning to its original configuration $\rightarrow$ bouncing cosmology.

But inhomogeneous modes $\delta\phi$ may be created and drain energy out of $\bar{\phi}$.

Do inhomogeneities prevent wave packet from rolling up the hill again?

Particle creation

To leading order, inhomogeneities evolve in the complex backgrounds.

→ extend method complex classical solutions

$$\Psi(\bar{\phi}, \delta\phi, t) = \left(A_1 e^{iS_1/\hbar} + A_2 e^{i\alpha} e^{iS_2/\hbar}\right)$$

with

$$S_i = S_{i,cl}(\bar{\phi}, t) + \delta S_i^{(2)}(\bar{\phi}, \delta\phi, t)$$

We have calculated $\delta S_i^{(2)}(\bar{\phi}, \delta\phi, t)$ for fluctuations inititally in ground state.

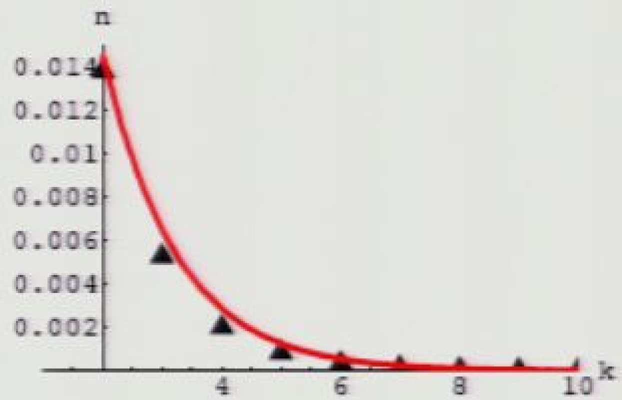
→ Ben's talk!

Particle creation from mode mixing across bounce, so that at late times

$$\langle n \rangle = \frac{|\beta|^2}{|\alpha|^2 - |\beta|^2}$$

UV Cutoff

At large k, $\langle n_k \rangle = \frac{|\beta_k|^2}{|\alpha_k|^2 - |\beta_k|^2} \sim e^{-4k\epsilon}$



→ backreaction negligible over entire bounce for sufficiently wide wave packets (remember $\epsilon \sim (\Delta\bar{\phi})^3$)

$$\phi_{end} - \phi_{start} << \phi_{start}.$$

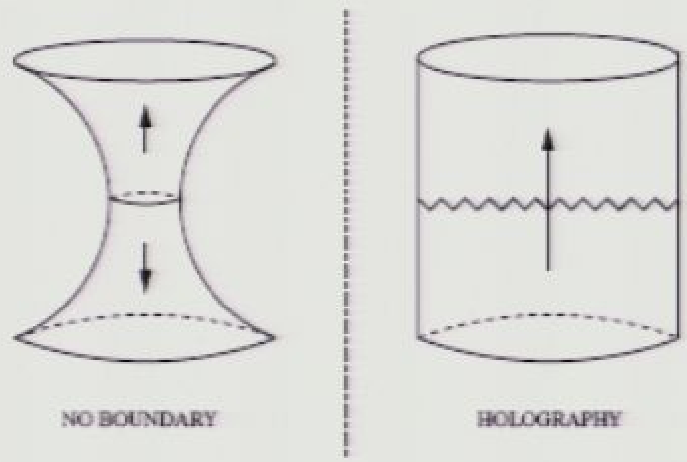
Bulk interpretation : class of cosmologies with a transition from big crunch to big bang.

Conclusion

- A 'holographic' description of (AdS) cosmology involves unstable conformal field theories.
- The ultralocality of the field theory evolution near the singularity means one can specify consistent unitary quantum evolution on the boundary by imposing a self-adjoint extension point by point.
- The quantum spread of the unstable homogeneous mode provides a UV cutoff on particle creation.
- For a certain range of parameters, and for certain states, this leads to a high probability for the homogeneous field to roll back up.
- It is natural to interpret this in the bulk as a quantum transition from a big crunch to a big bang.

Conclusion

- The extension of these results to realistic models may lead to interesting cosmologies that bounce and have an arrow of time pointing in the same direction everywhere.



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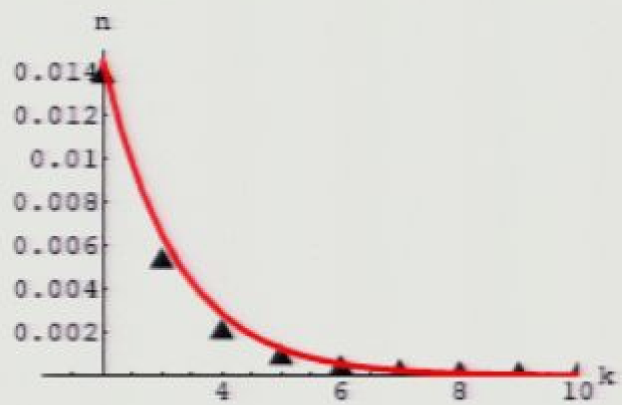

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