

Title: Transdimensional Tunneling in the Multiverse

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Abstract: I will introduce a simple 6d model of flux compactification that shows a remarkable rich landscape of vacua with different number of large and compact dimensions. I will then describe the instantons interpolating between these different vacua as well as some the implications of a transdimensional multiverse of this form.

Transdimensional Tunneling in the Multiverse

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with:

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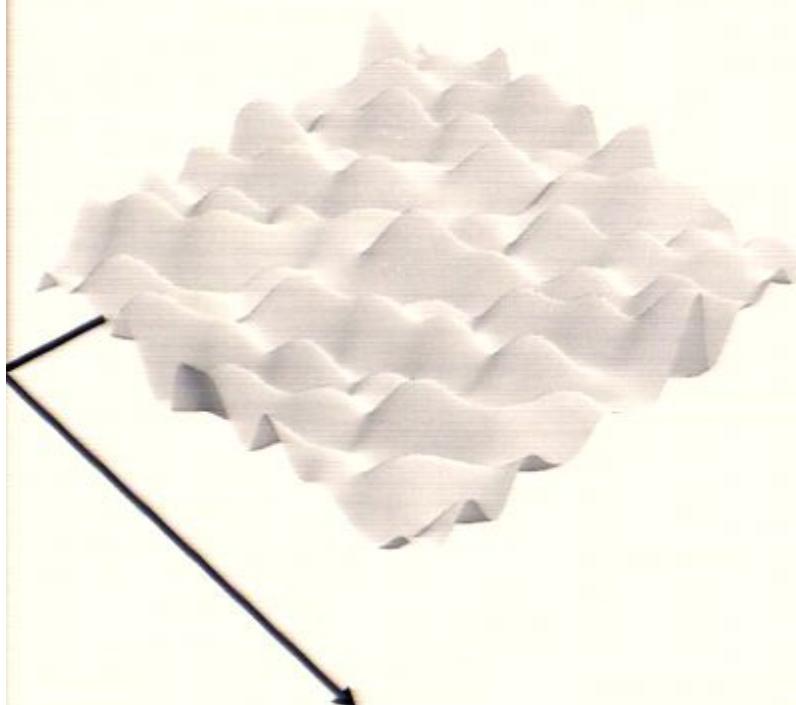
Outline of the talk

- Motivation.
- 6d Flux Compactification.
- Flux Tunneling transitions.
- Transdimensional Cosmology.
- Conclusions.

Introduction

- Models of Flux Compactifications have a long history.
- These ideas have been used recently in String Theory.

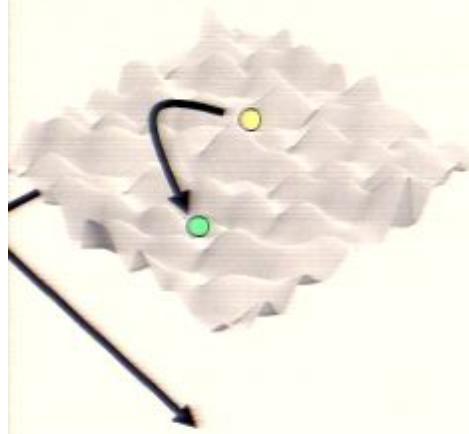
Potential



- These models have led us to a complicated 4d effective potential with many metastable minima.
- This has been described in the literature as the String Landscape.

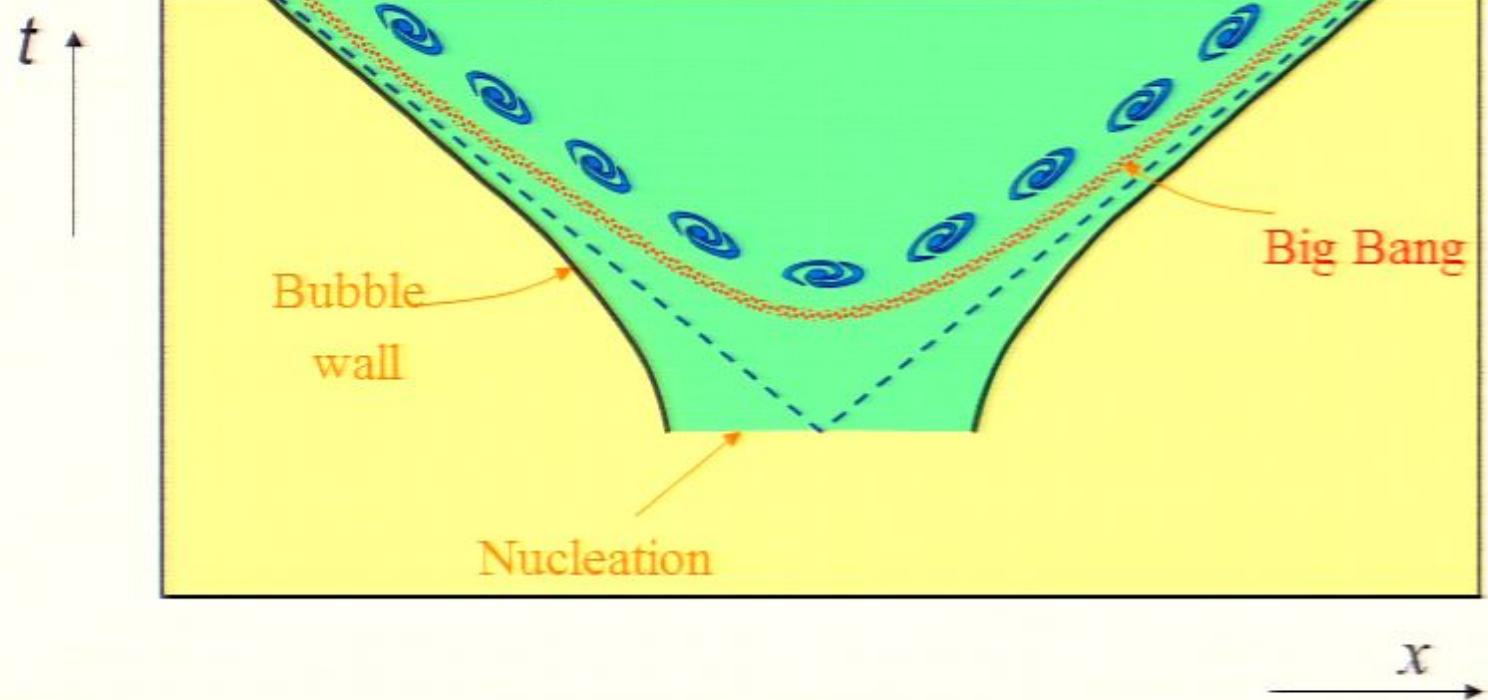
Spacetime of a Bubble Universe

Potential



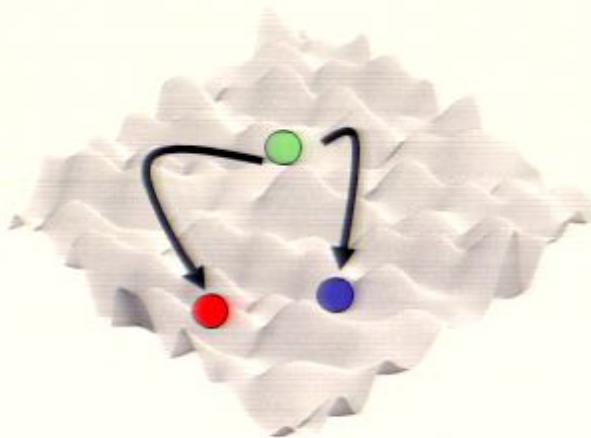
Moduli,
fluxes, etc

(Coleman & deLuccia, '80).



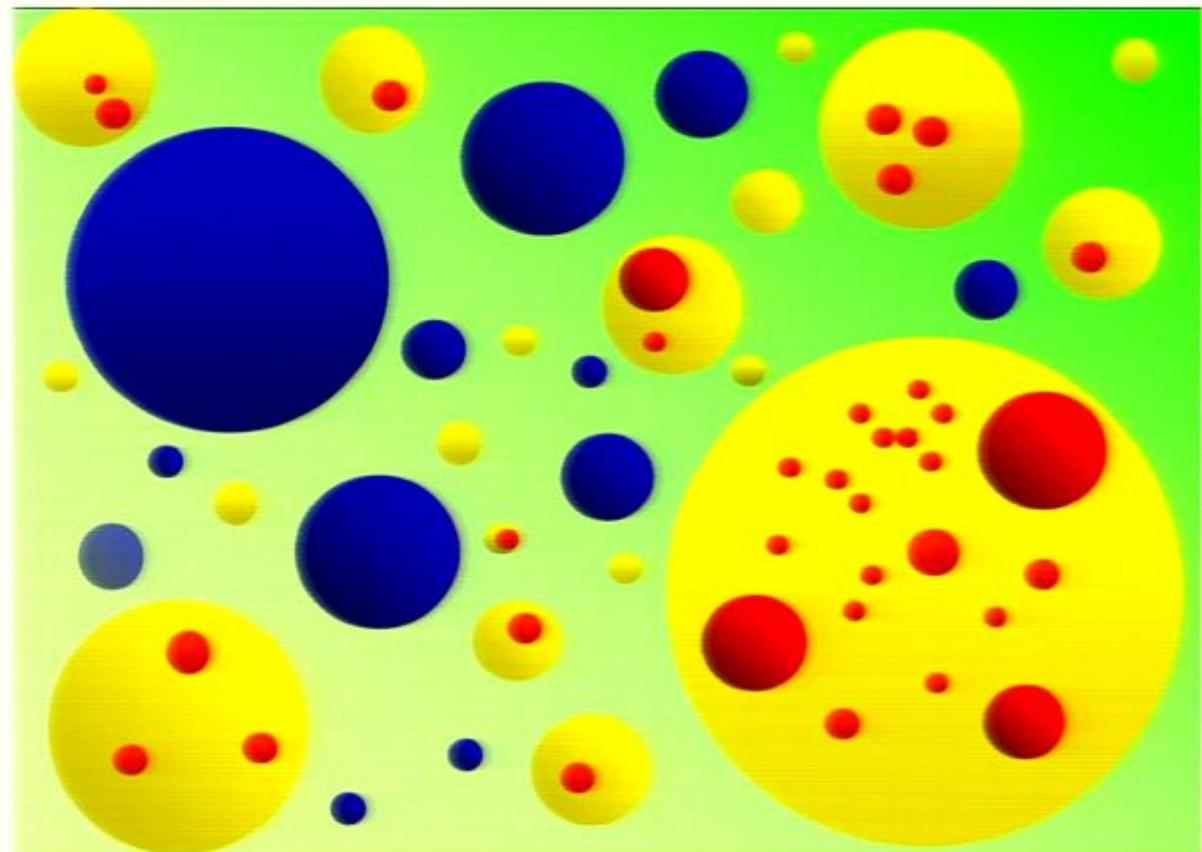
$$ds^2 = -dT^2 + a(T)^2(d\xi^2 + \sinh^2(\xi)d\Omega_2^2)$$

4d String Theory Multiverse



The universe is in fact, very homogeneous at the largest possible scales.

- Eternal Inflation allows one to explore other parts of the landscape.



The 6d Flux Compactification

(Freund and Rubin, '80).

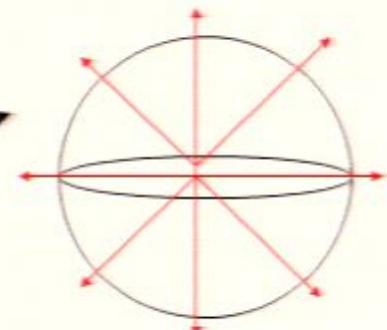
(Randjbar-Daemi et al., '83).

Let us consider the 6d theory:

$$S_6 = \int d\tilde{x}^6 \sqrt{-\tilde{g}} \left(\frac{M_{(6)}^4}{2} R^{(6)} - \frac{1}{4} F_{MN} F^{MN} - \Lambda \right)$$

Let us compactify on a 2-sphere:

$$ds^2 = \underbrace{\tilde{g}_{\mu\nu} dx^\mu dx^\nu}_{\text{4d spacetime}} + R^2 d\Omega_2^2$$



With a monopole magnetic field:

$$F_{\theta\phi} = \frac{n}{2e} \sin \theta$$

The 6d Flux Compactification

We can obtain the 4d effective theory by introducing the ansatz:

$$ds^2 = e^{-\psi/M_P} g_{\mu\nu} dx^\mu dx^\nu + e^{\psi/M_P} R^2 d\Omega_2^2$$

That gives the following 4d theory:

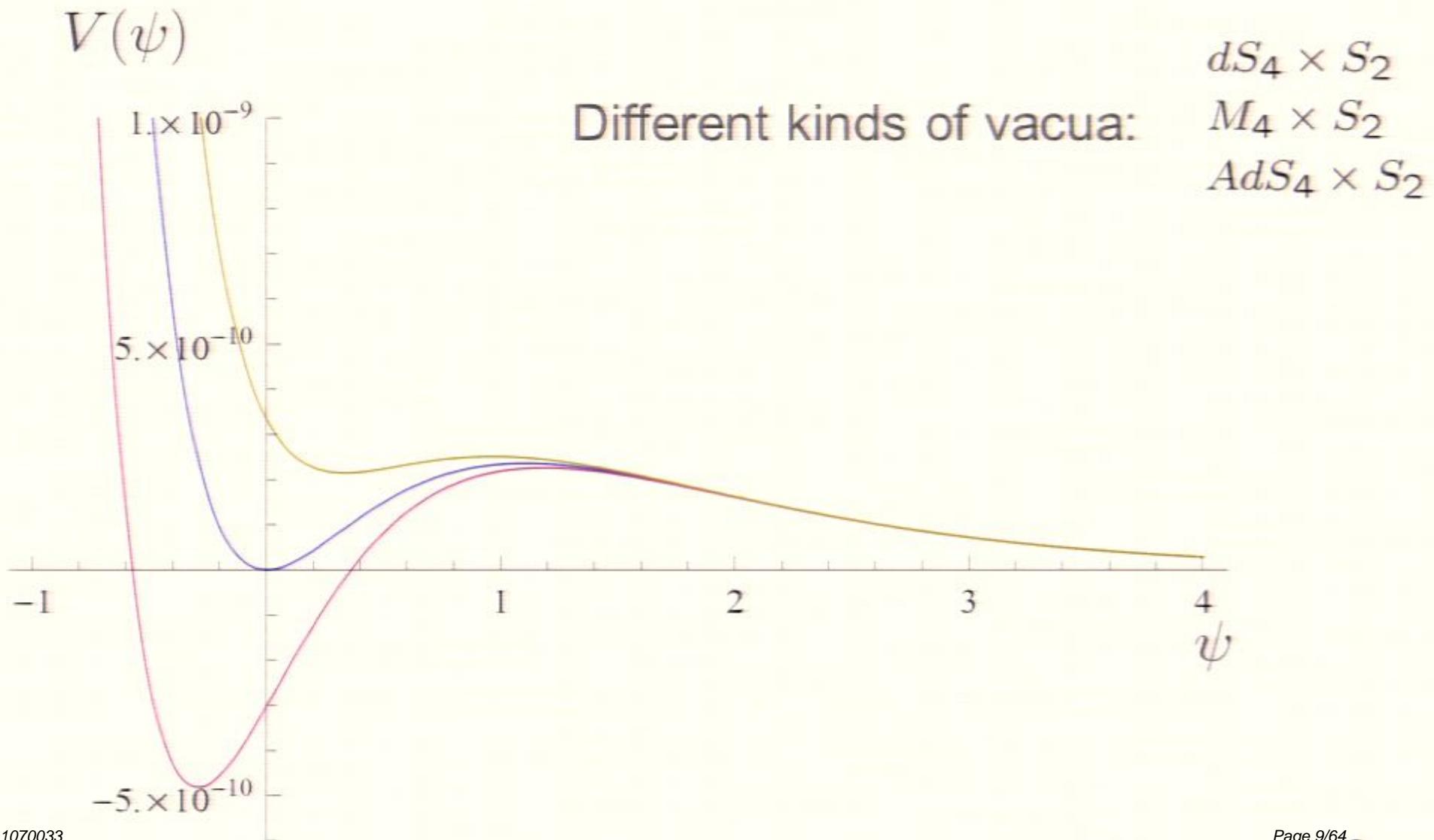
$$S_4 = \int dx^4 \sqrt{-g} \left(\frac{M_P^2}{2} R - \frac{1}{2} \partial_\mu \psi \partial^\mu \psi - V(\psi) \right)$$

$$V(\psi) = 4\pi M_{(6)}^4 \left(\frac{n^2}{8e^2 R^2 M_{(6)}^4} e^{-3\psi/M_P} - e^{-2\psi/M_P} + \frac{R^2 \Lambda}{M_{(6)}^4} e^{-\psi/M_P} \right)$$

Flux contribution Curvature of internal space 6d CC contribution

The 6d Flux Compactification

(B-P., Schwartz-Perlov and Vilenkin '09).



Magnetically Charged Branes

(Gibbons, Horowitz and Townsend '95).

(Gregory, '96).

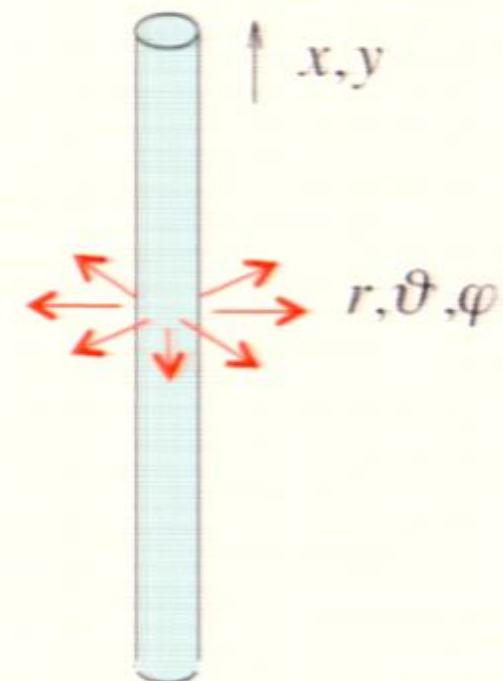
There are 2-brane solutions of our 6d theory. Generalizations of the monopole solutions in higher dimensions.

$$ds^2 = \left(1 - \frac{r_0}{r}\right)^{\frac{2}{3}} \underbrace{(-dt^2 + dx^2 + dy^2)}_{\text{Flat 2+1 worldvolume}} + \left(1 - \frac{r_0}{r}\right)^{-2} dr^2 + r^2 d\Omega_2^2$$

Flat 2+1 worldvolume

Magnetically charged

$$\left. \begin{array}{l} F_{\theta\phi} = \frac{g}{4\pi} \sin \theta \\ ge = 2\pi \end{array} \right\}$$

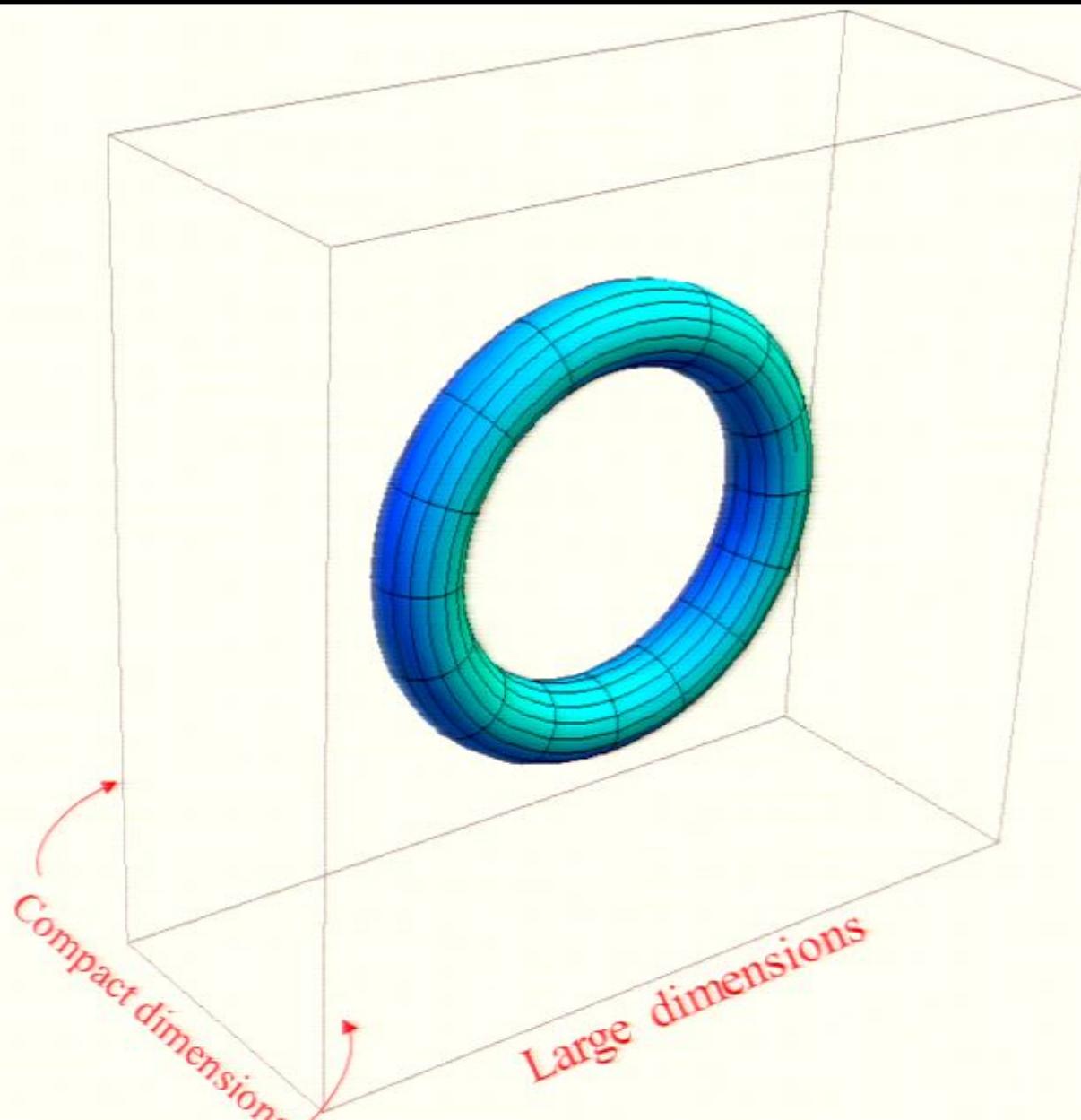


- In the extremal case we have,

$$r_0 = \frac{\sqrt{3}g}{8\pi M_{(6)}^2}$$

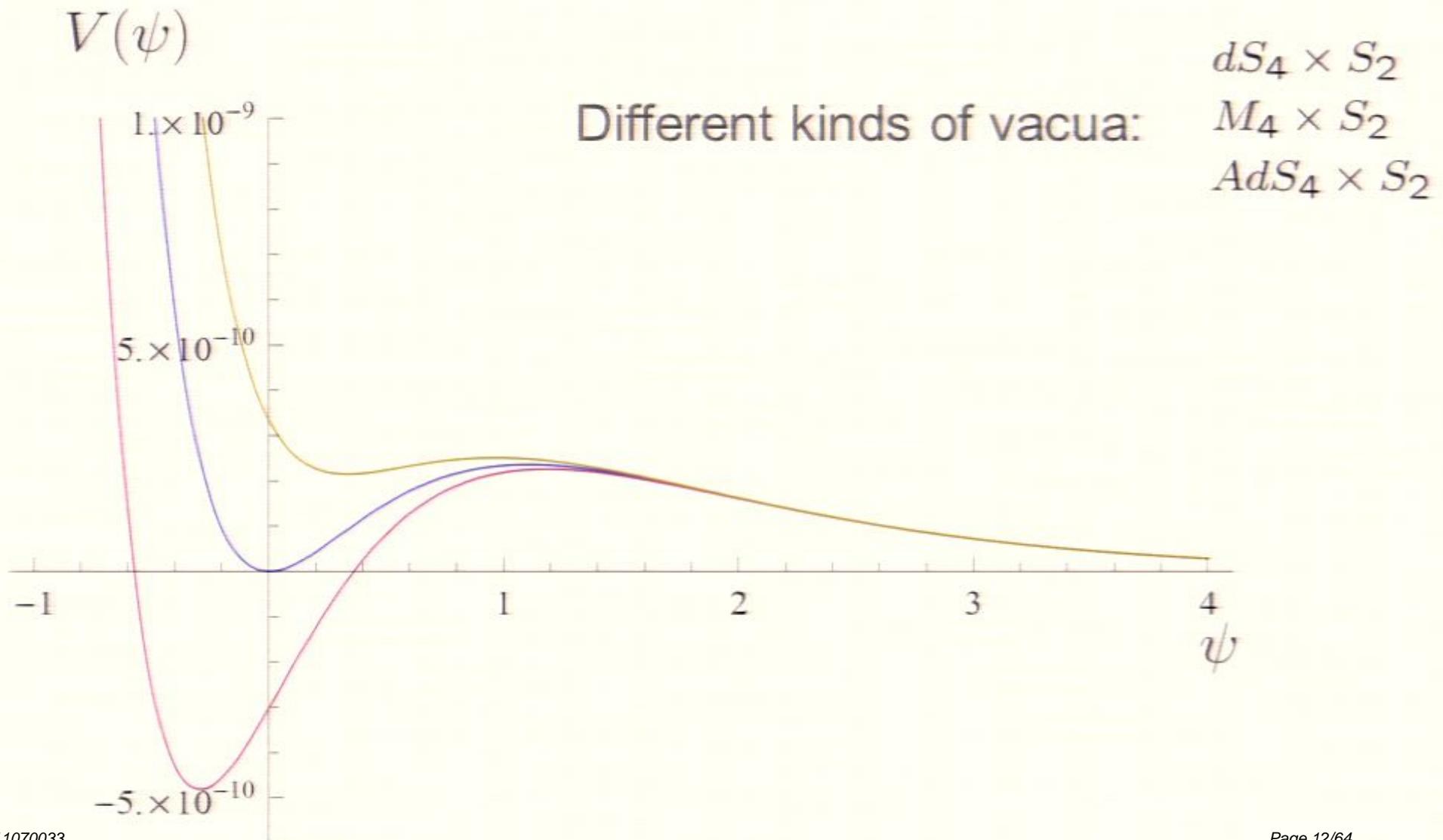
$$T_2 = \frac{2gM_{(6)}^2}{\sqrt{3}}$$

Flux Tunneling

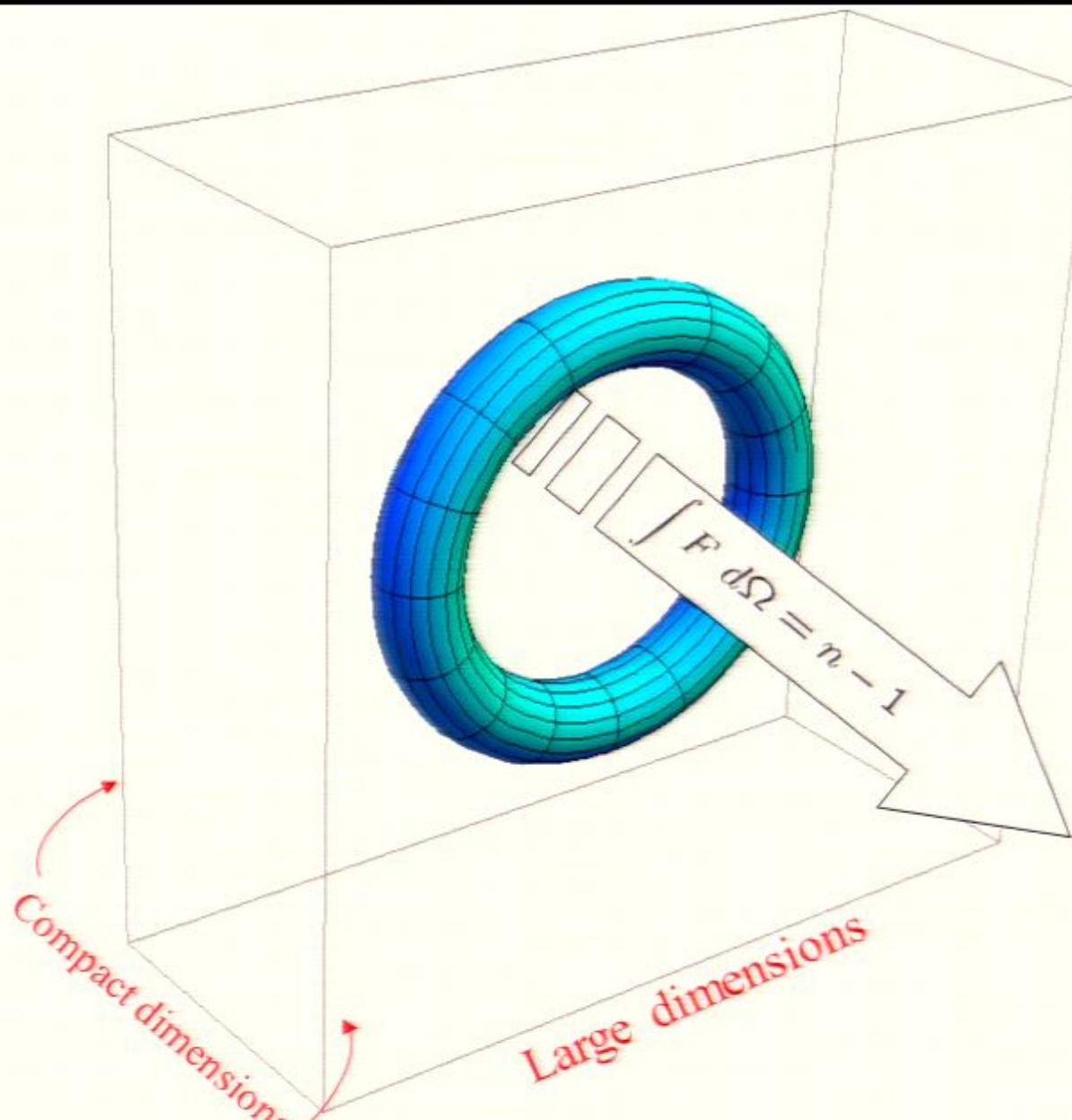


The 6d Flux Compactification

(B-P., Schwartz-Perlov and Vilenkin '09).

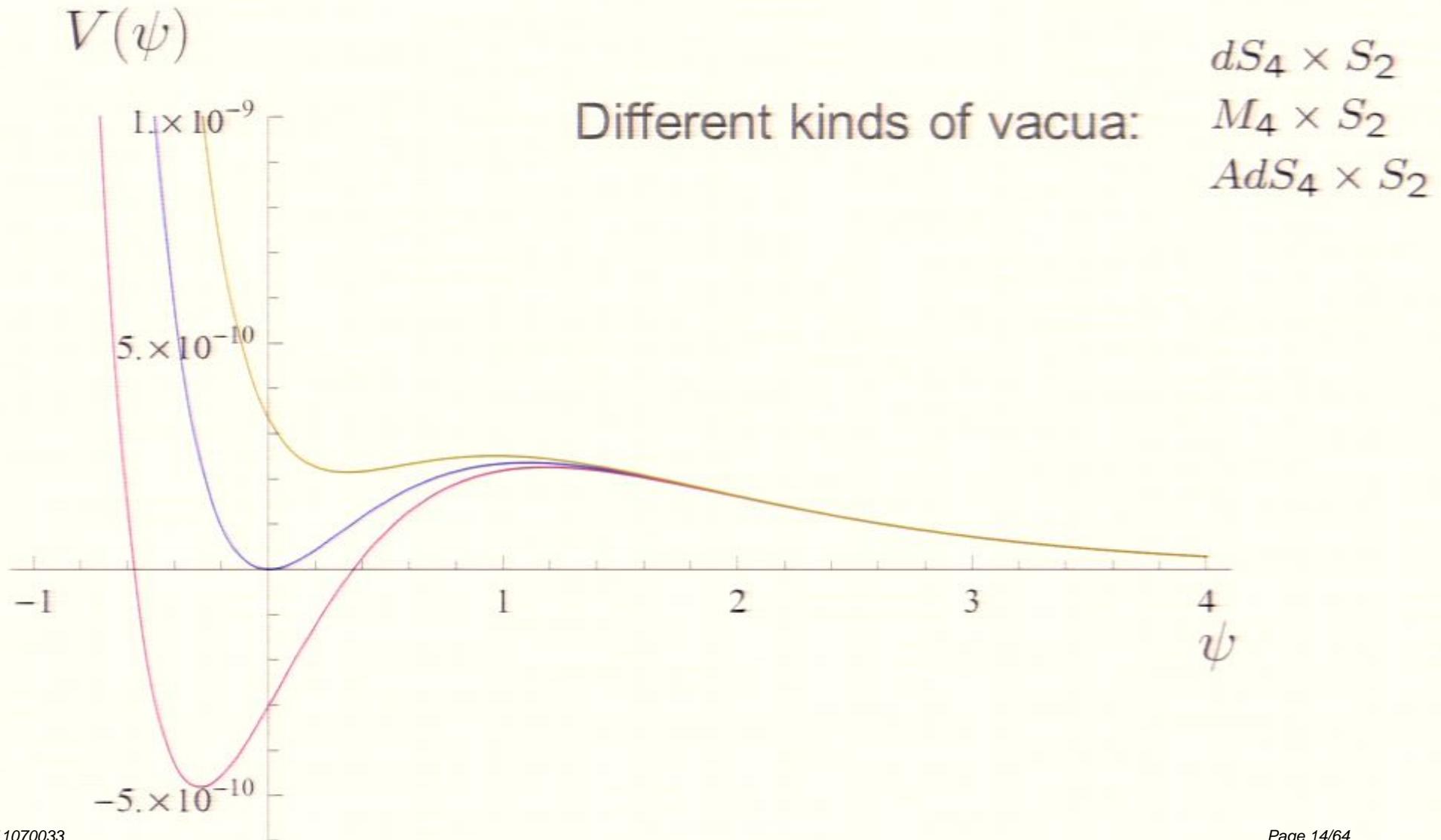


Flux Tunneling



The 6d Flux Compactification

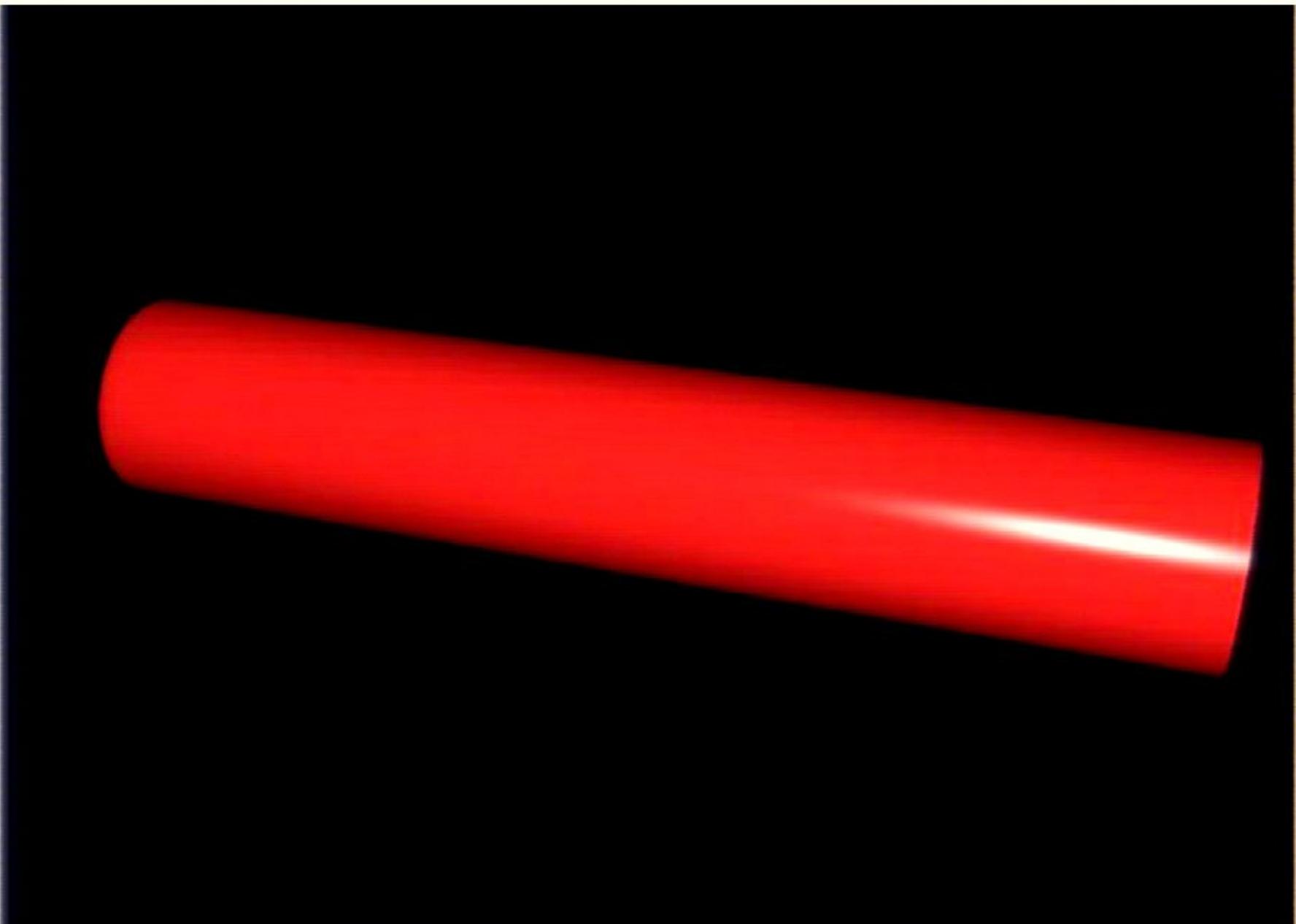
(B-P., Schwartz-Perlov and Vilenkin '09).

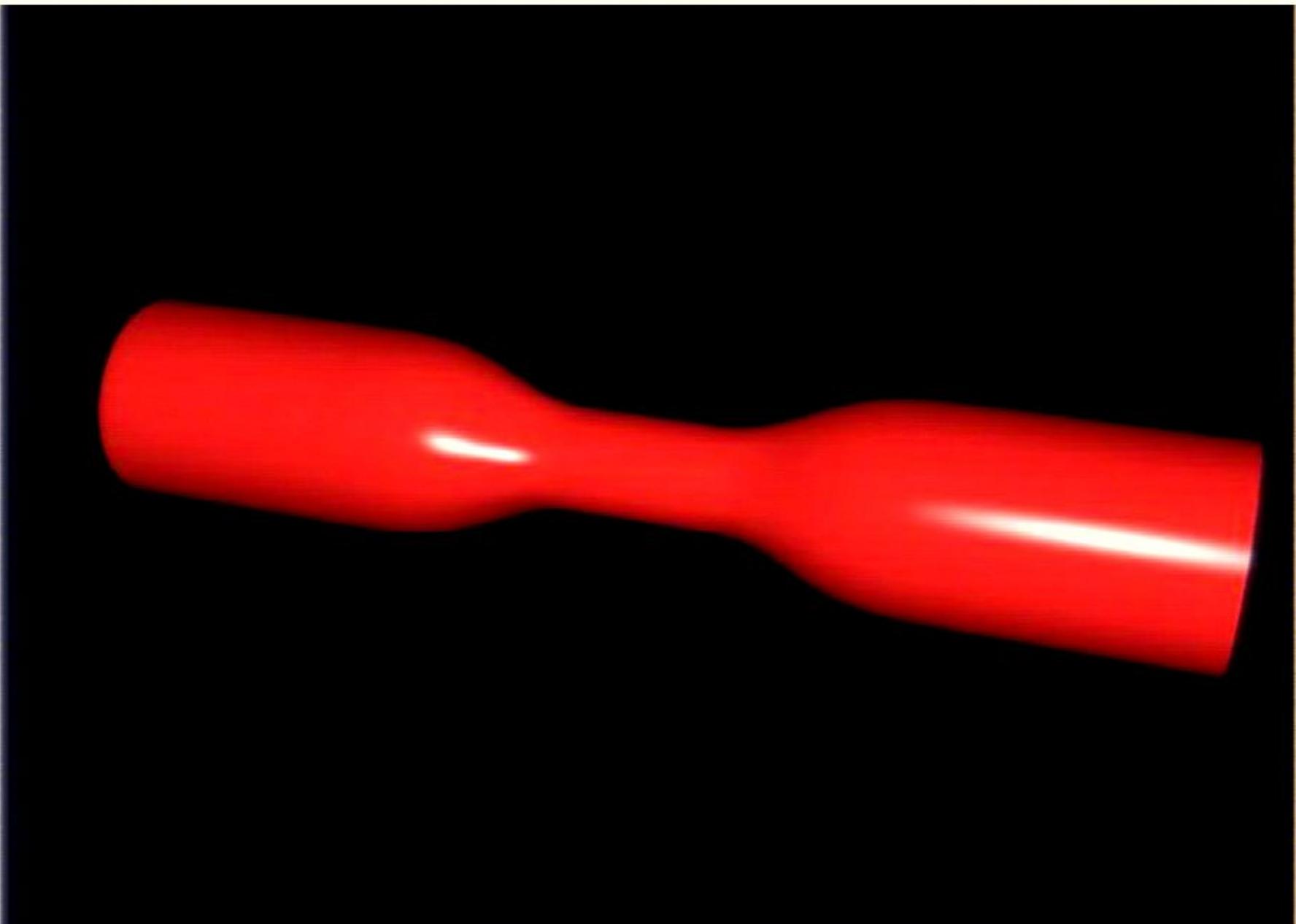


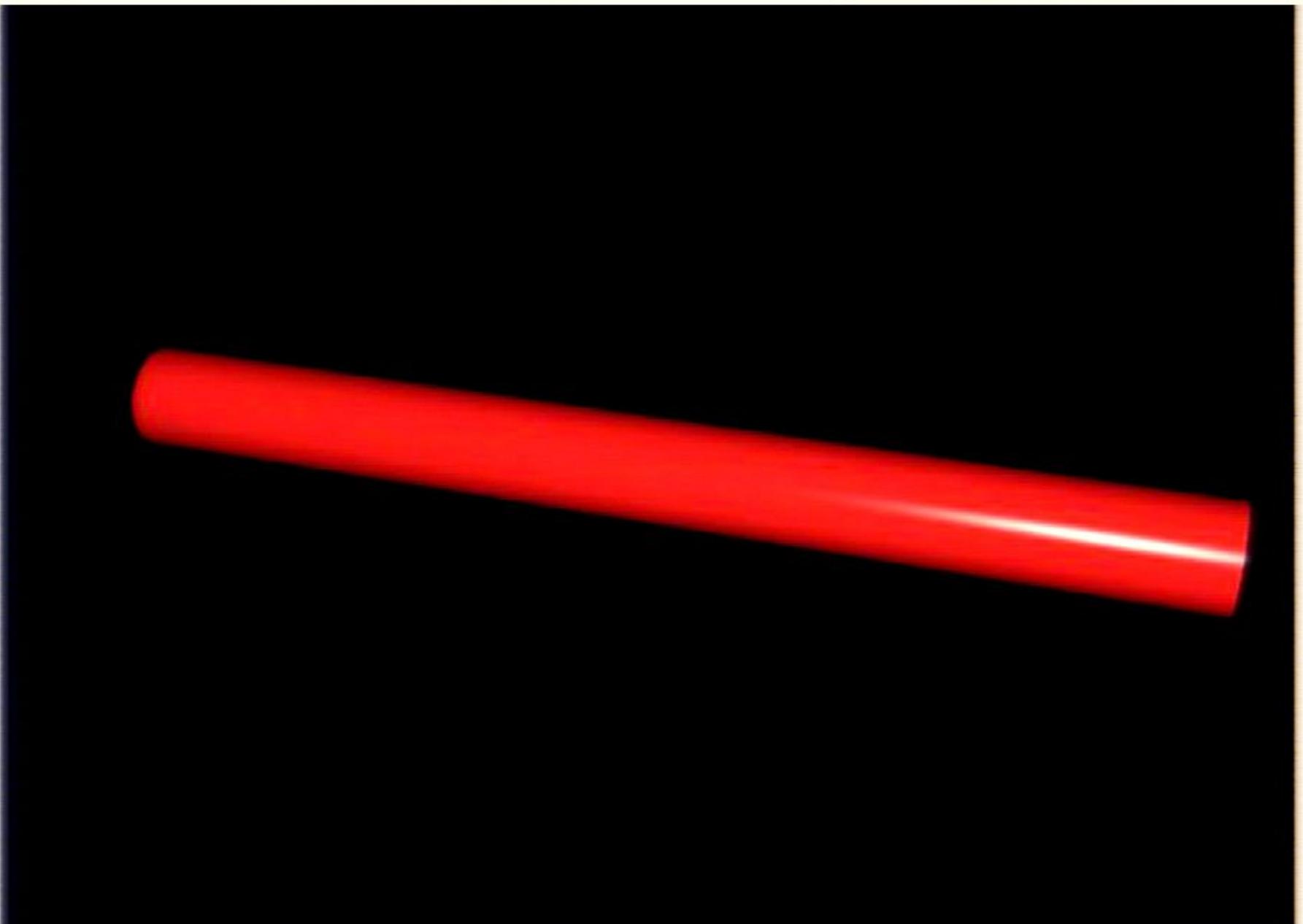
Compact dimensions

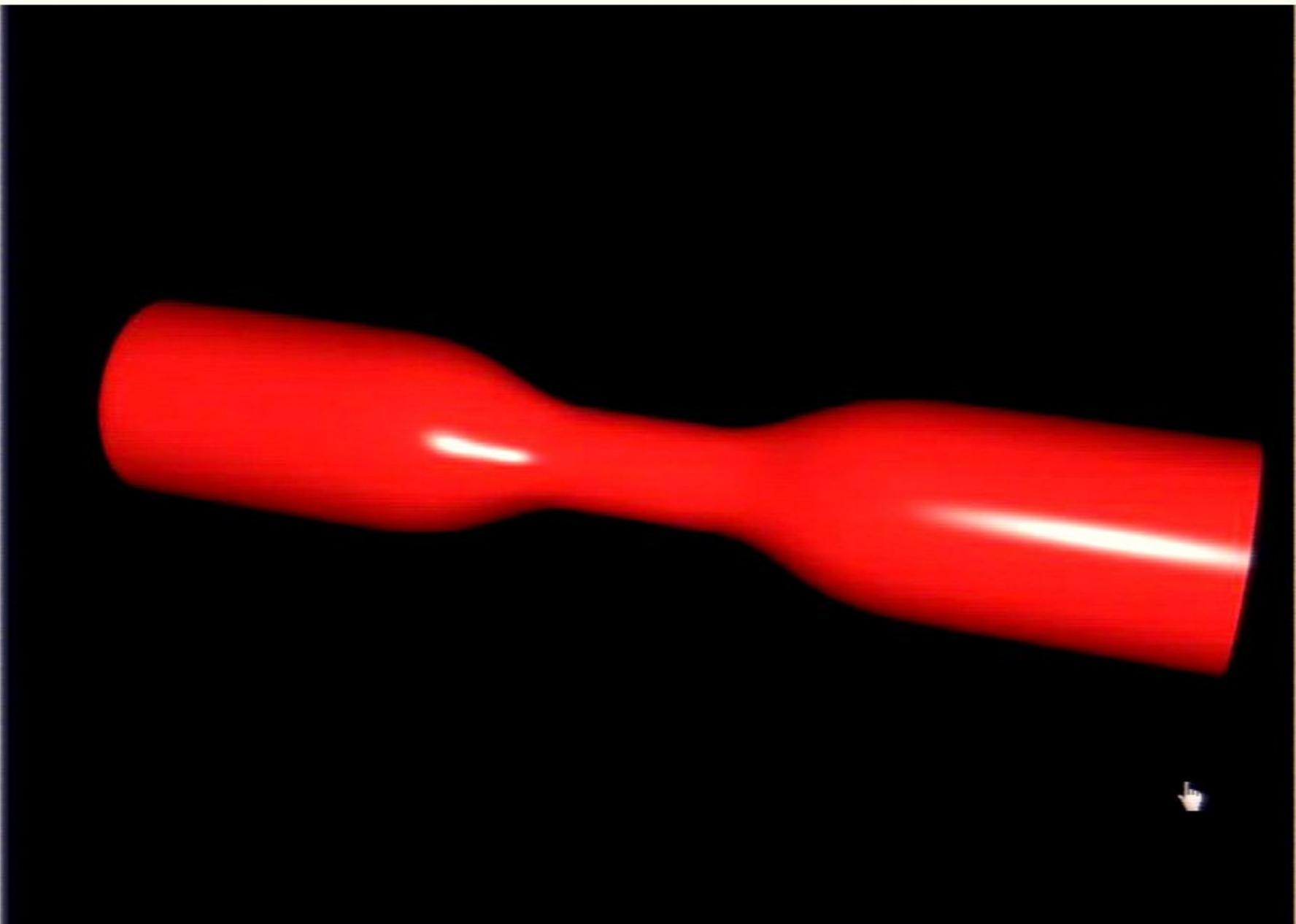


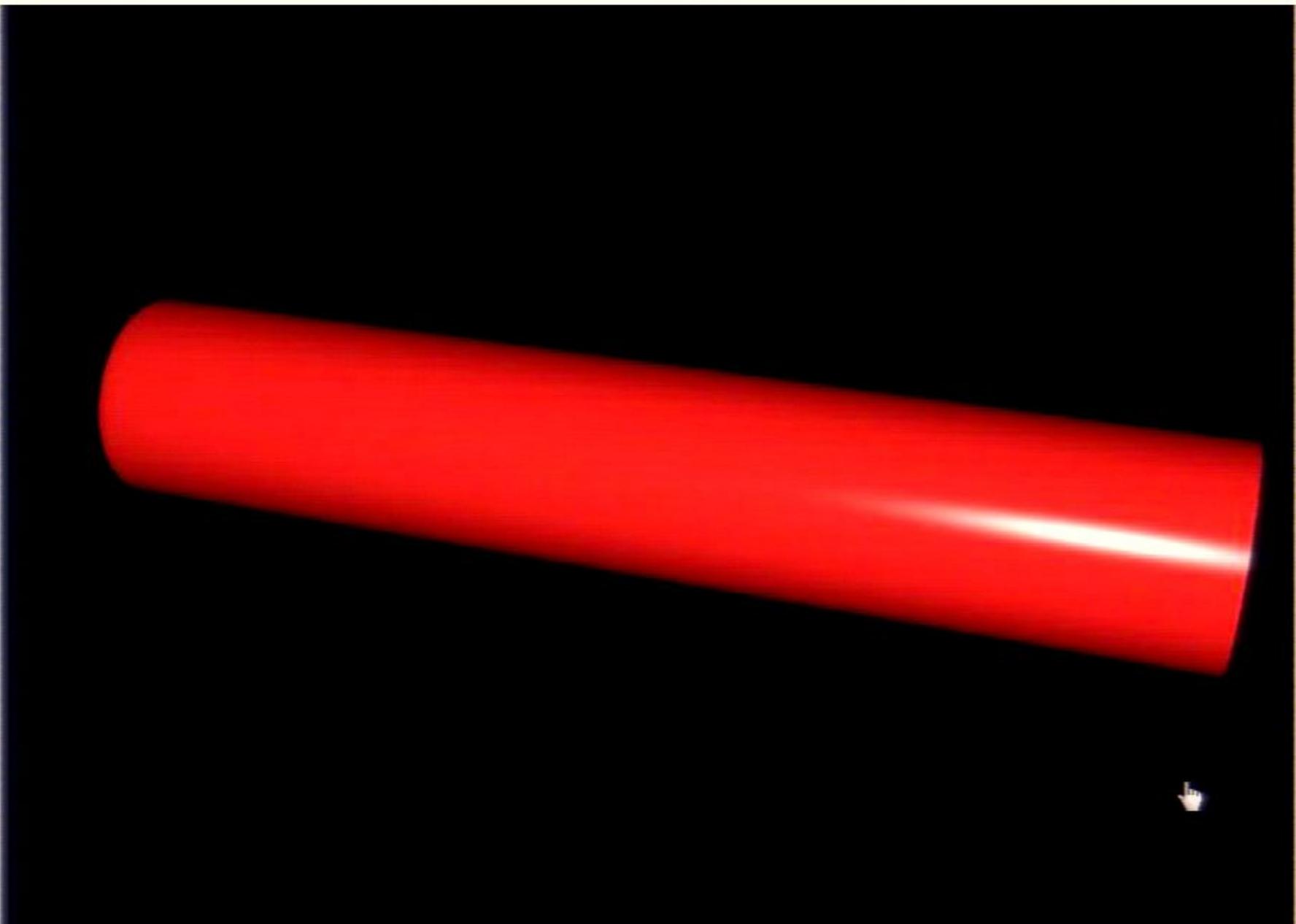
Large dimensions

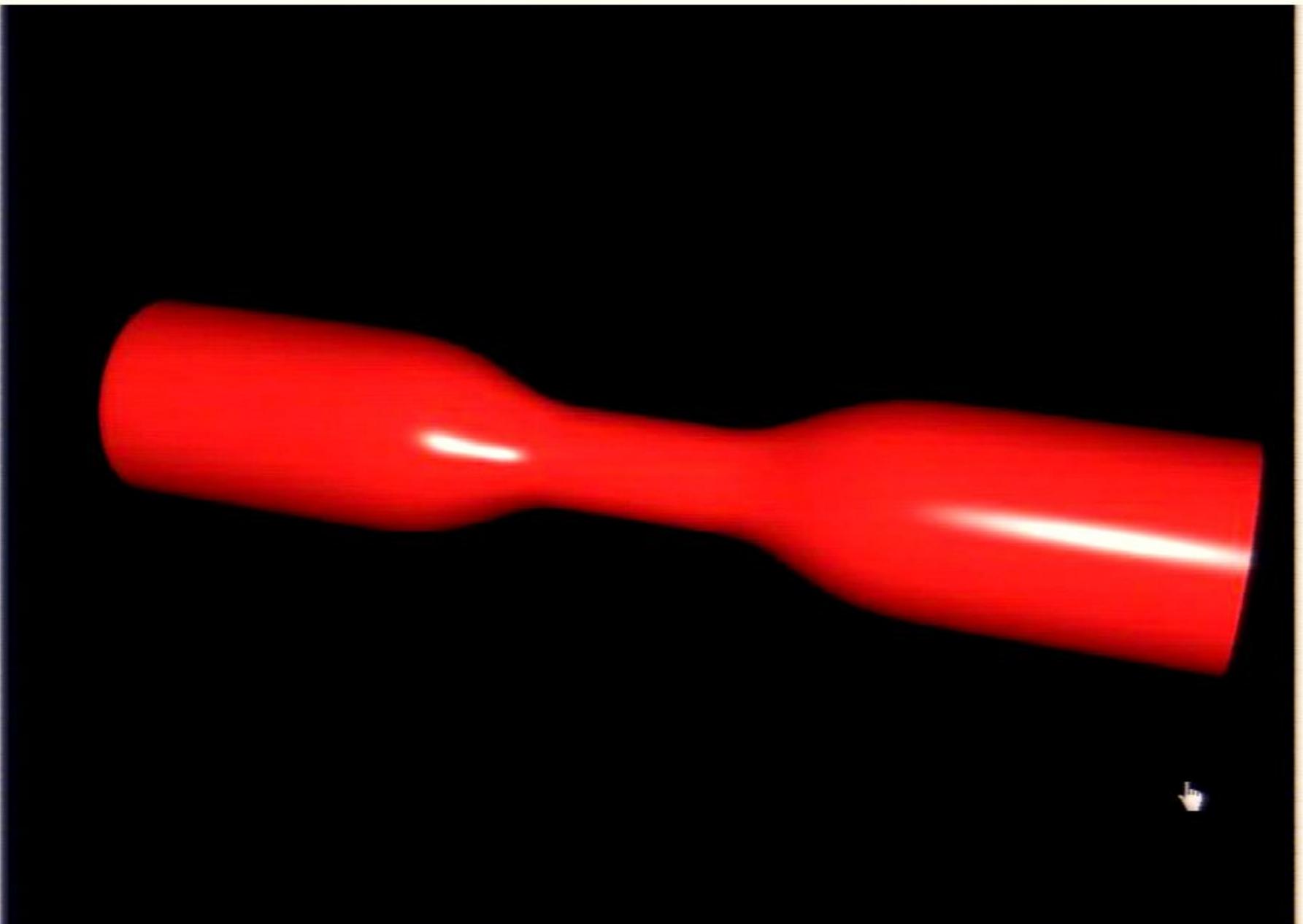


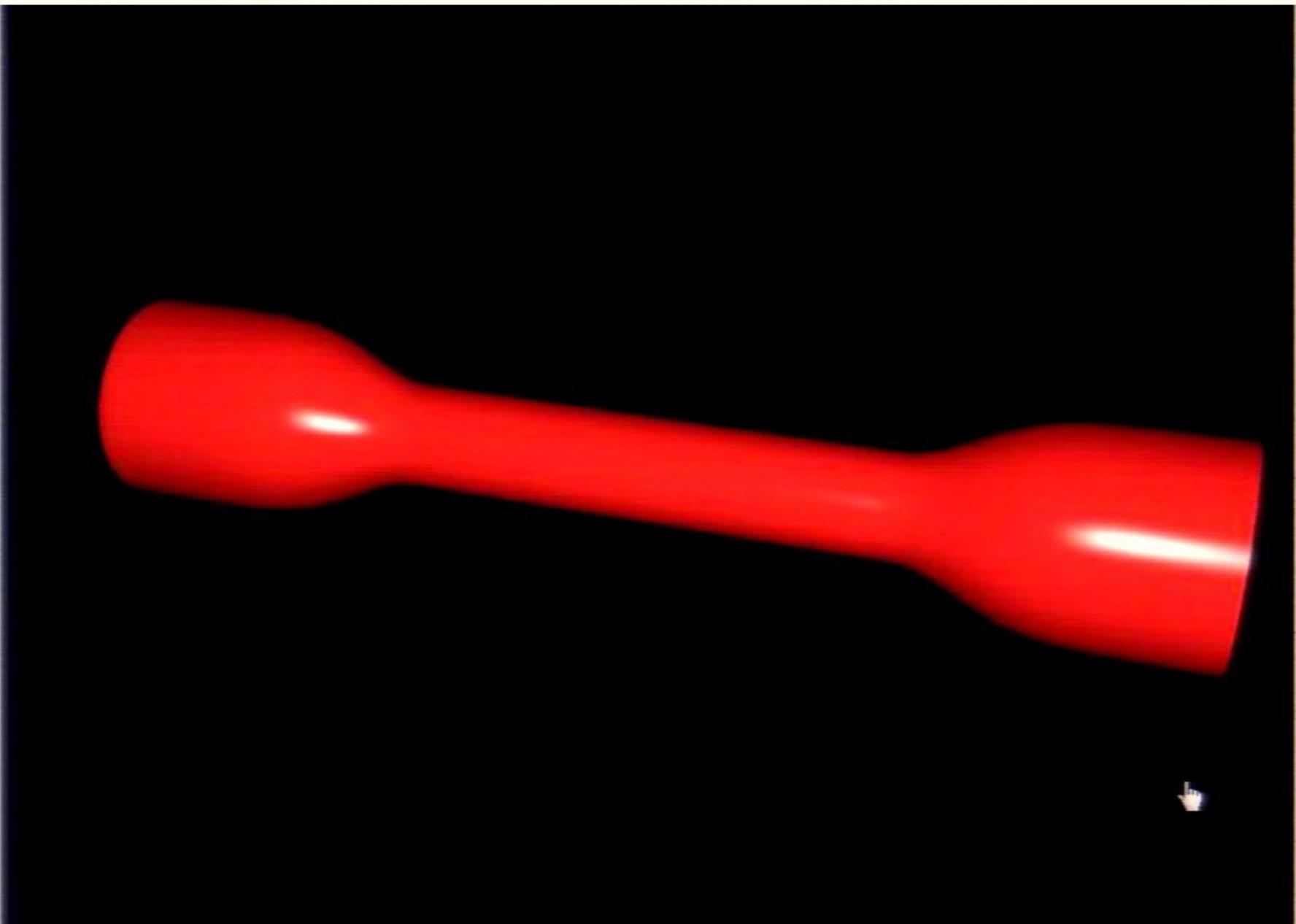


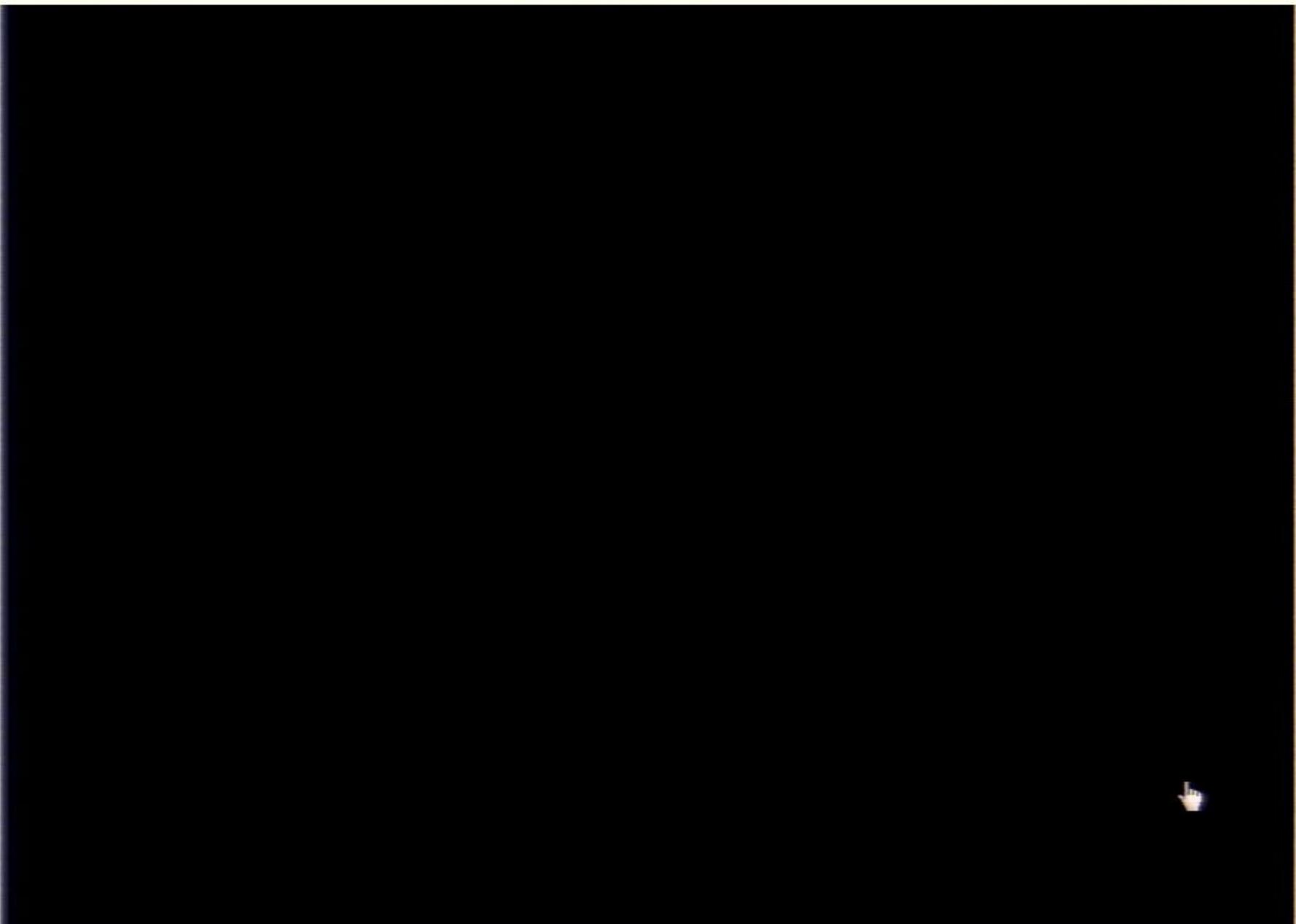




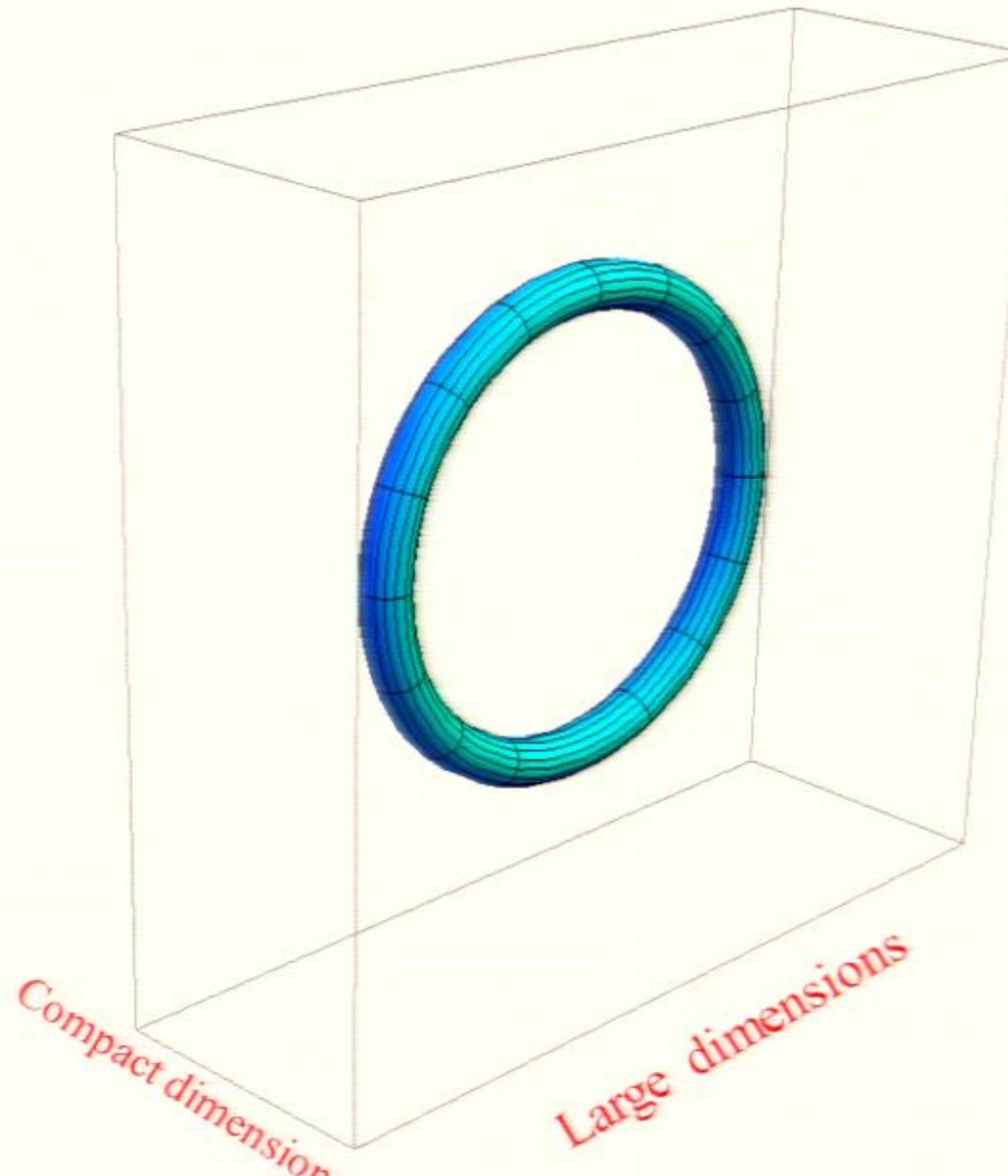




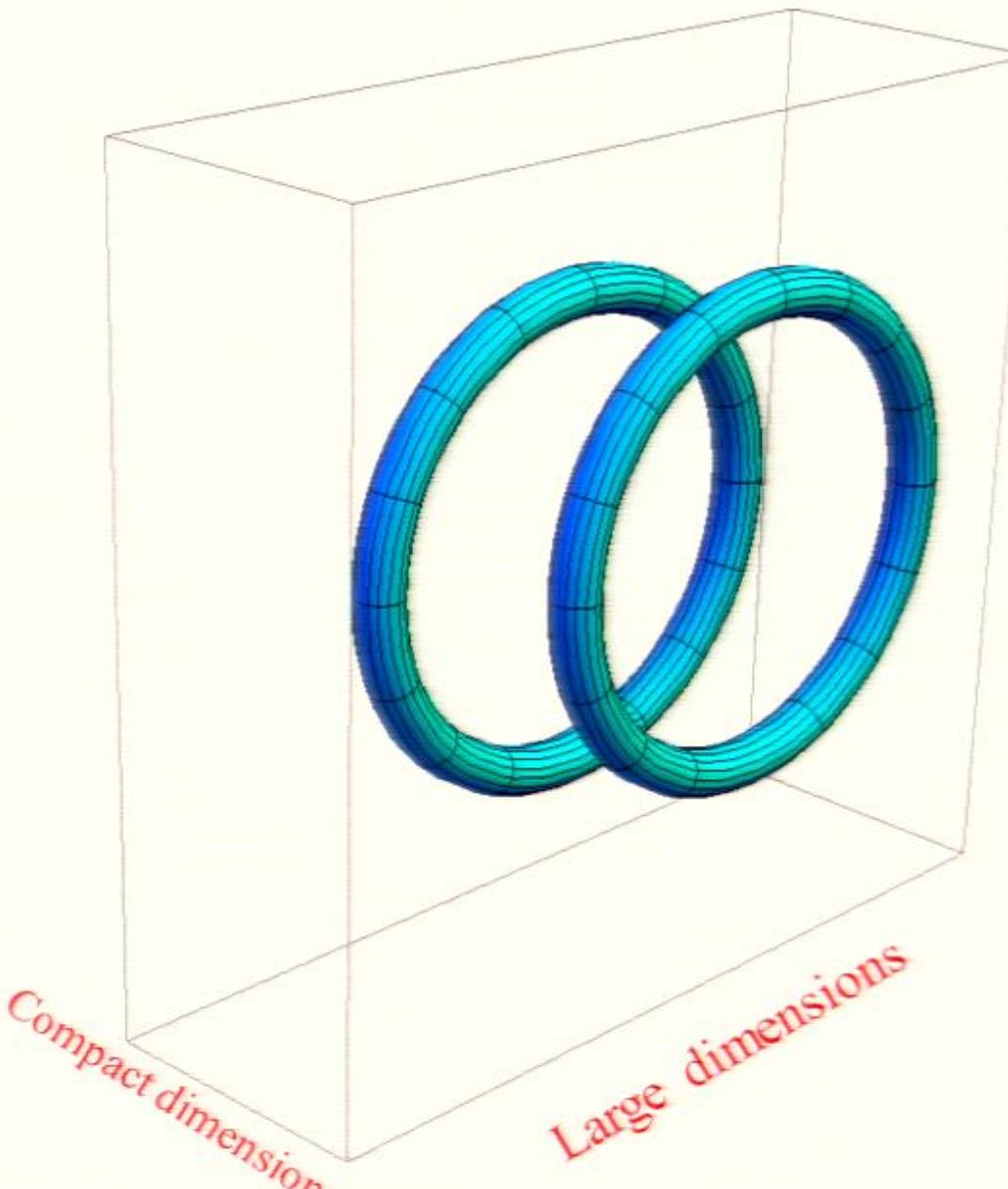




Bubble Ring Collisions



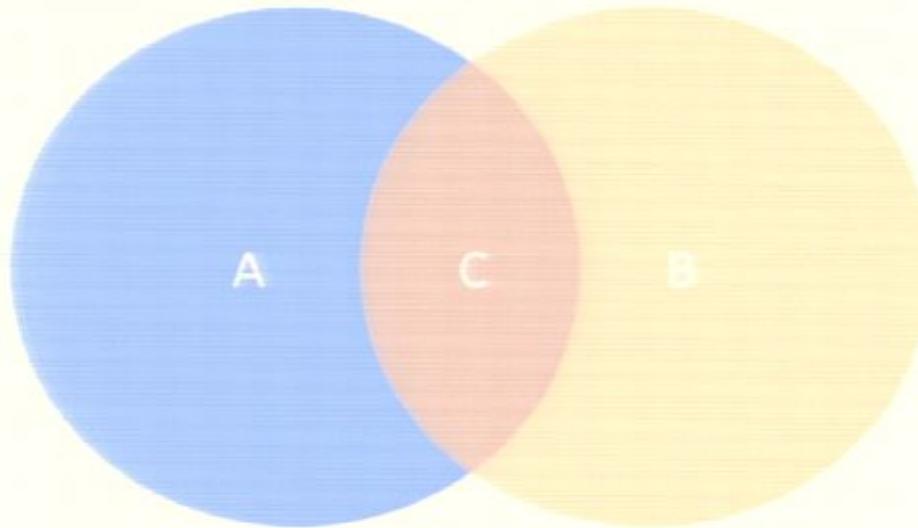
Bubble Ring Collisions



Bubble Collisions

(B-P., Schwartz-Perlov and Vilenkin '09).

From a 4d point of view bubbles can go through one another:



Our vacuum could be the result of this “collision” !!

(Similar to Johnson & Yang '10).

Another sectors of the model

B-P, Schwartz-Perlov and Vilenkin, (2009).

Within the same 6d:

$$S_6 = \int dx^6 \sqrt{-g} \left(\frac{M_{(6)}^4}{2} R^{(6)} - \frac{1}{4} F_{MN} F^{MN} - \Lambda \right)$$

We can look for flux other type of compactifications of the form:

$$ds^2 = \underbrace{g_{ab} dx^a dx^b}_{\text{2d spacetime}} + R^2 d\Omega_4^2$$

$$F_{tr} = \frac{q}{R^4} \sqrt{-g_2} \quad \text{Electric Sector}$$

- There is also a dS_6 sector where there is no charge.

Decompactification

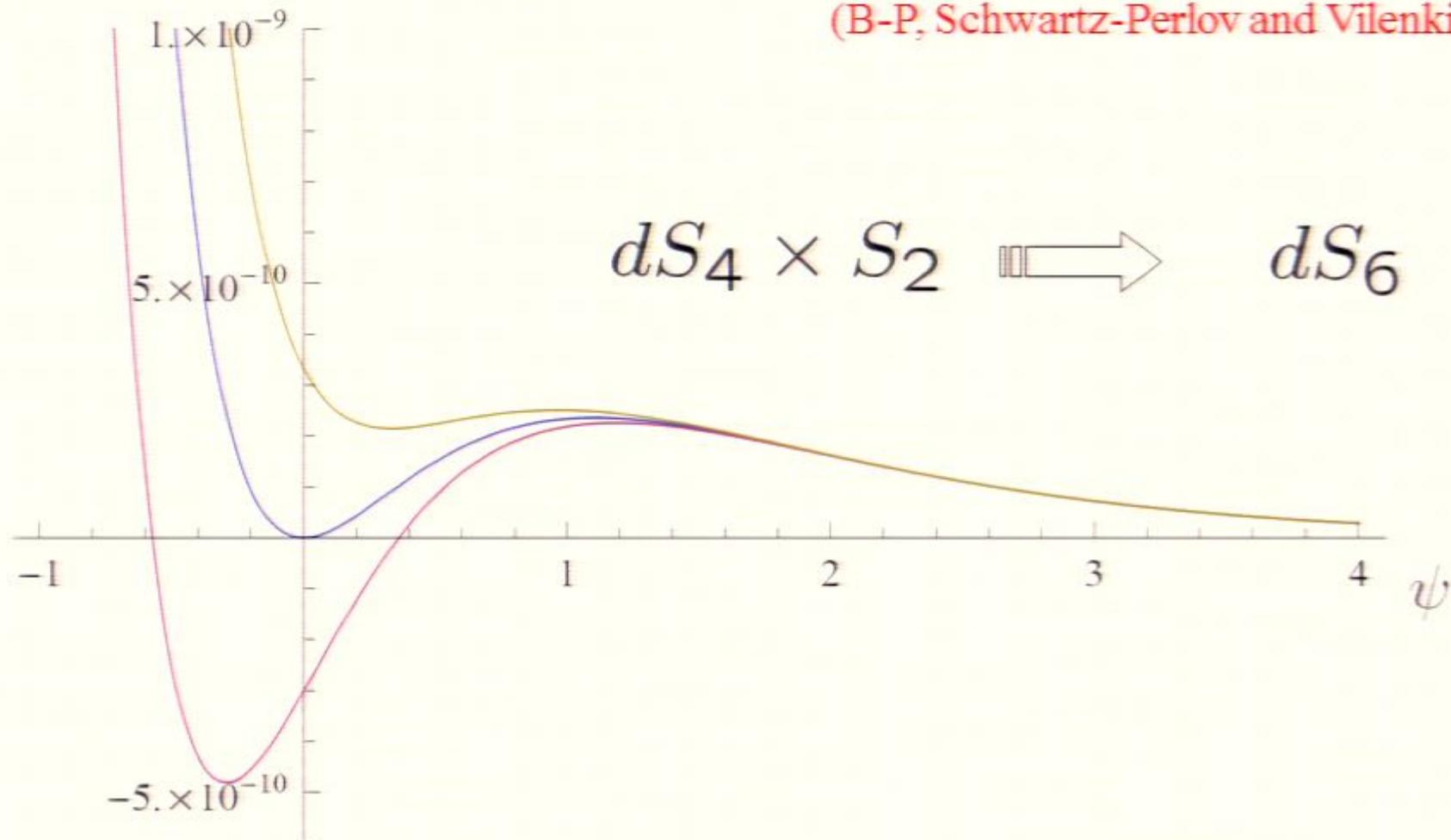
(Linde and Zelnikov, 1988).

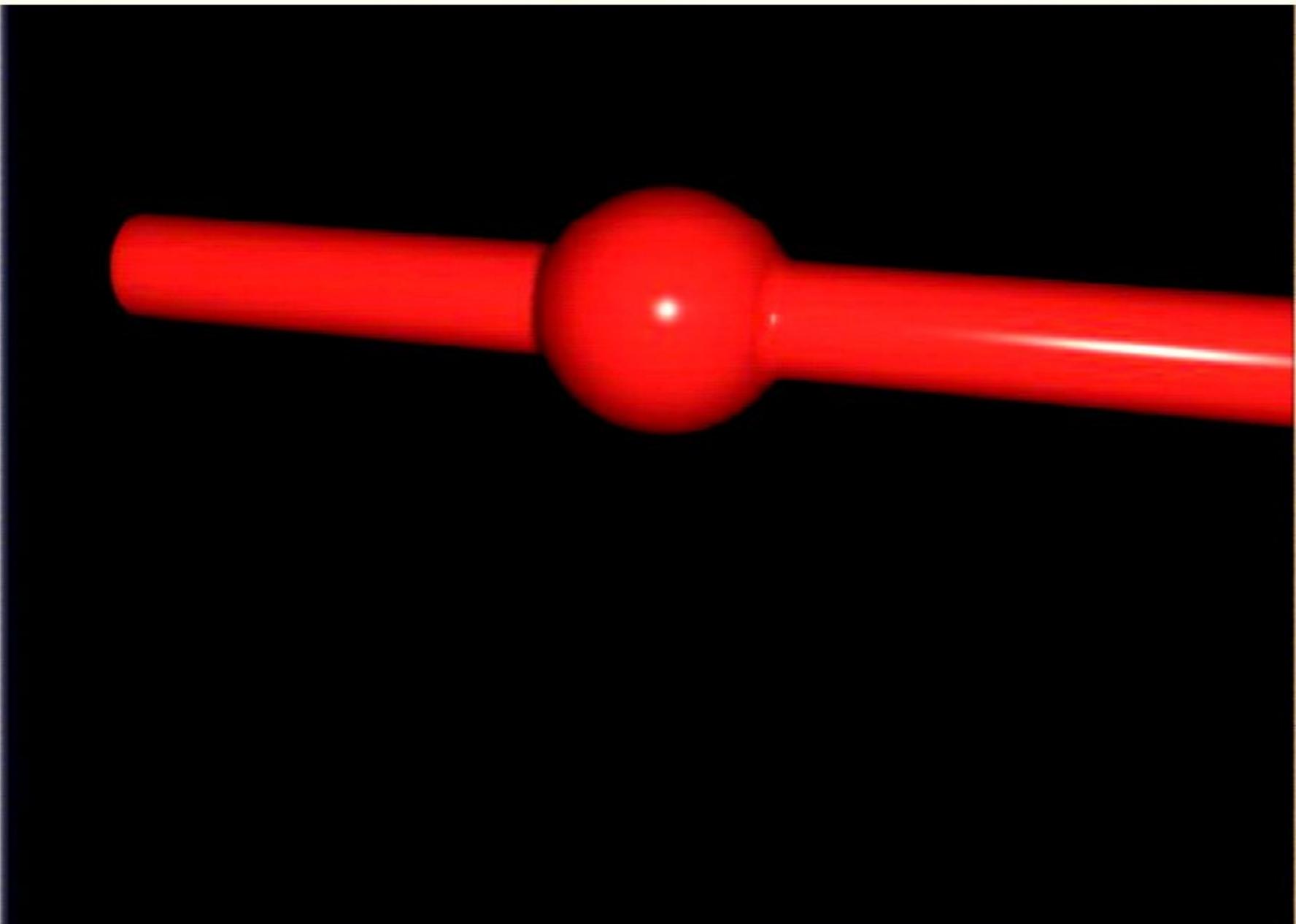
$V(\psi)$

(Giddings and Myers, 2004).

(B-P, Schwartz-Perlov and Vilenkin, 2009)

$$dS_4 \times S_2 \rightarrow dS_6$$

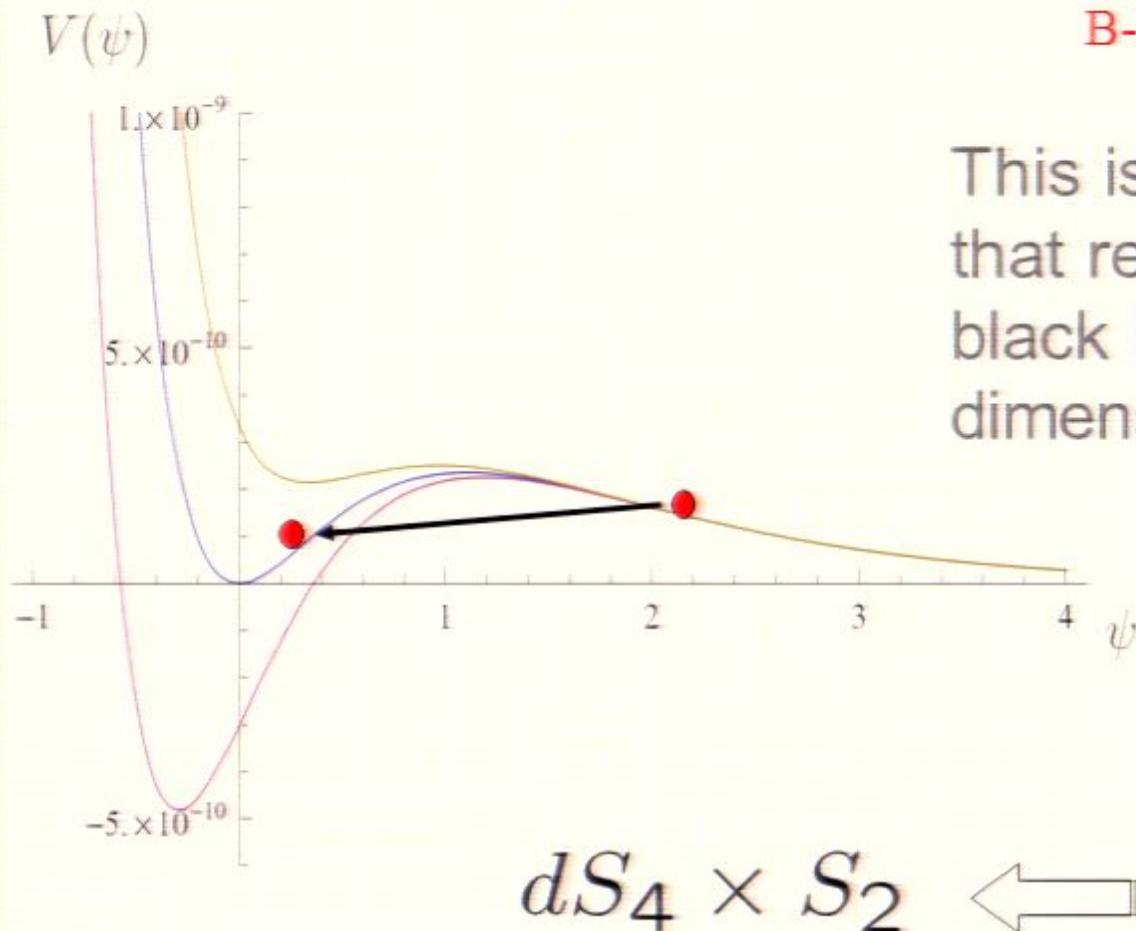




Dynamical compactification

Carroll, Johnson and Randall, (2009).

B-P, Schwartz-Perlov and Vilenkin, (2009).



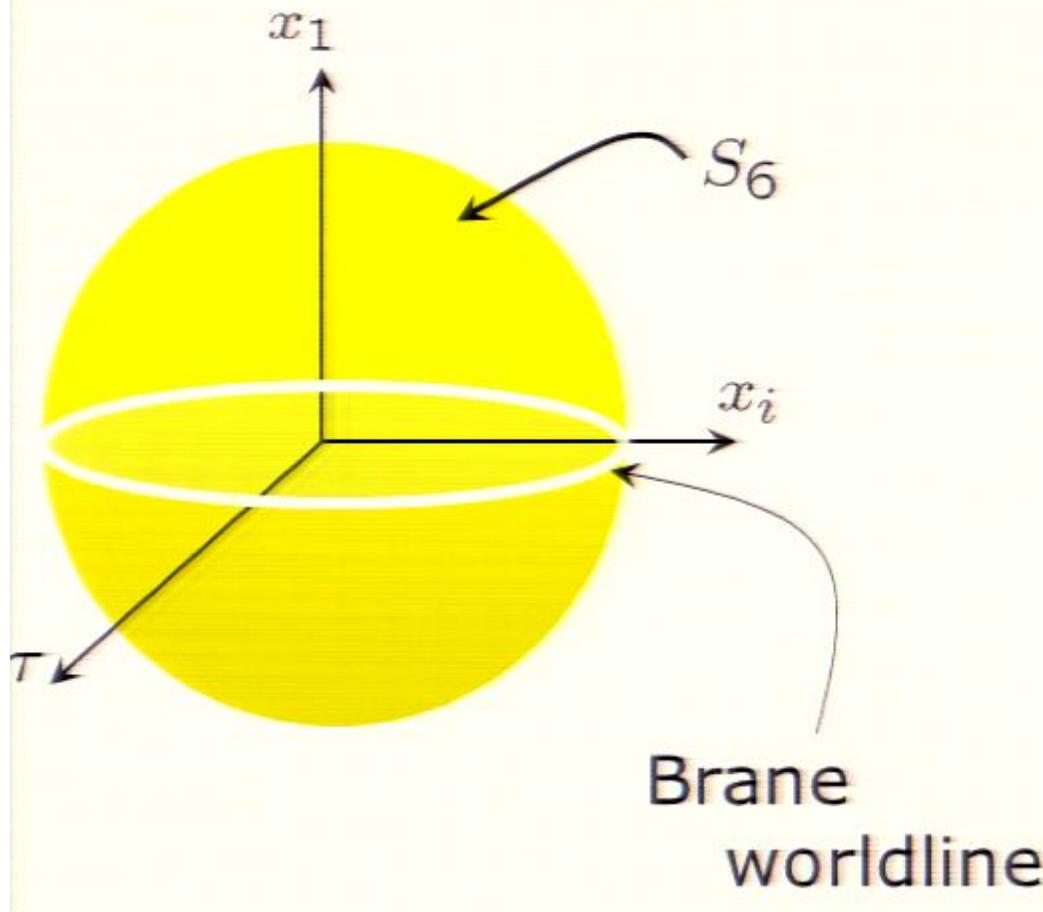
This is another kind of transition that represents the formation of black holes or branes in higher dimensional de Sitter space.

(Lee and Weinberg '87).

$$dS_4 \times S_2 \quad \longleftrightarrow \quad dS_6$$

Brane Nucleation in de Sitter

(Basu, Guth and Vilenkin '92).

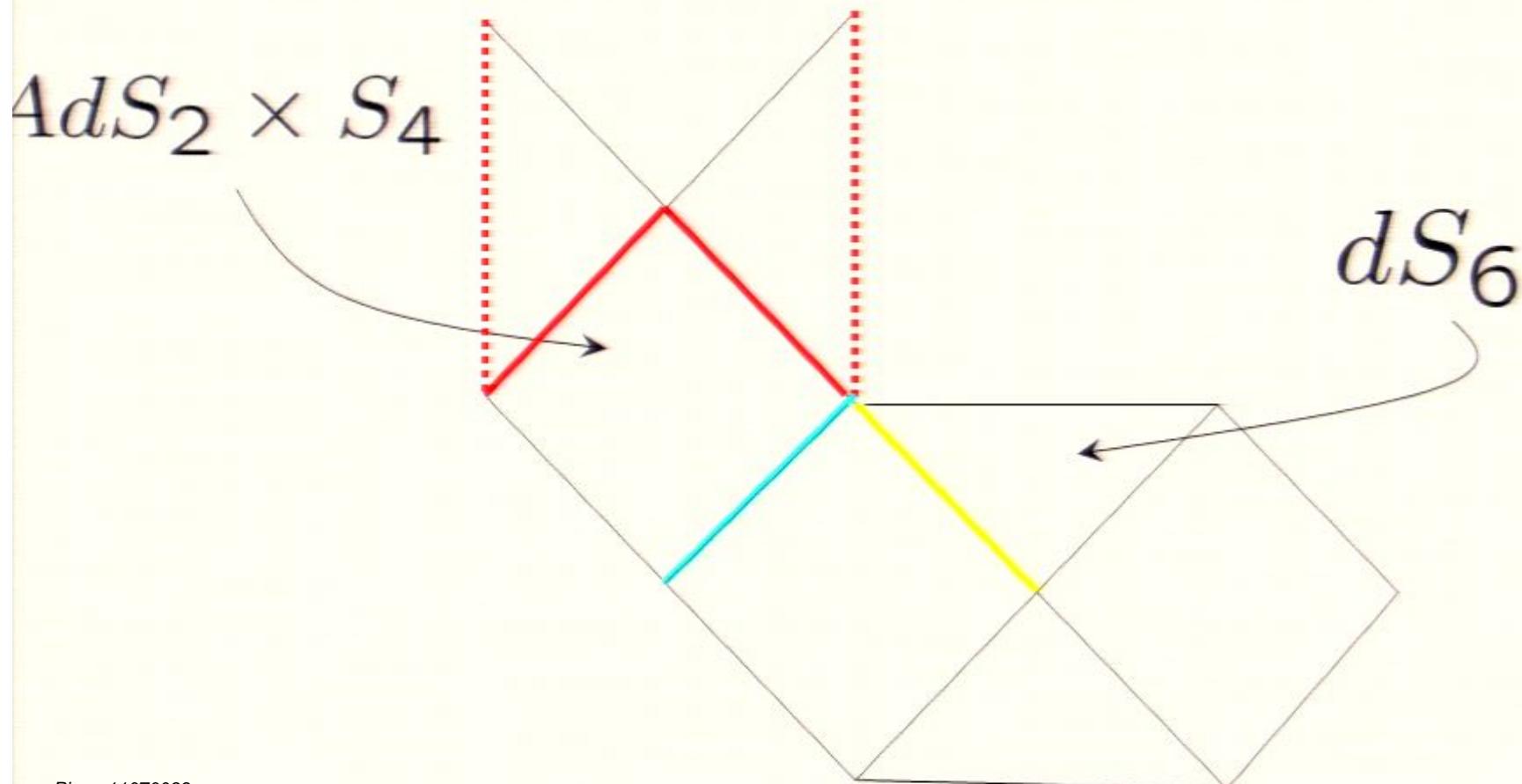


- Solution of the Euclidean equations of motion.
- Disregards backreaction on the geometry.
- In the Lorentzian part objects are stretched by the de Sitter expansion.
- In our case we have 2 types of objects: black holes and magnetic 2-branes.

Black Hole Pair Creation

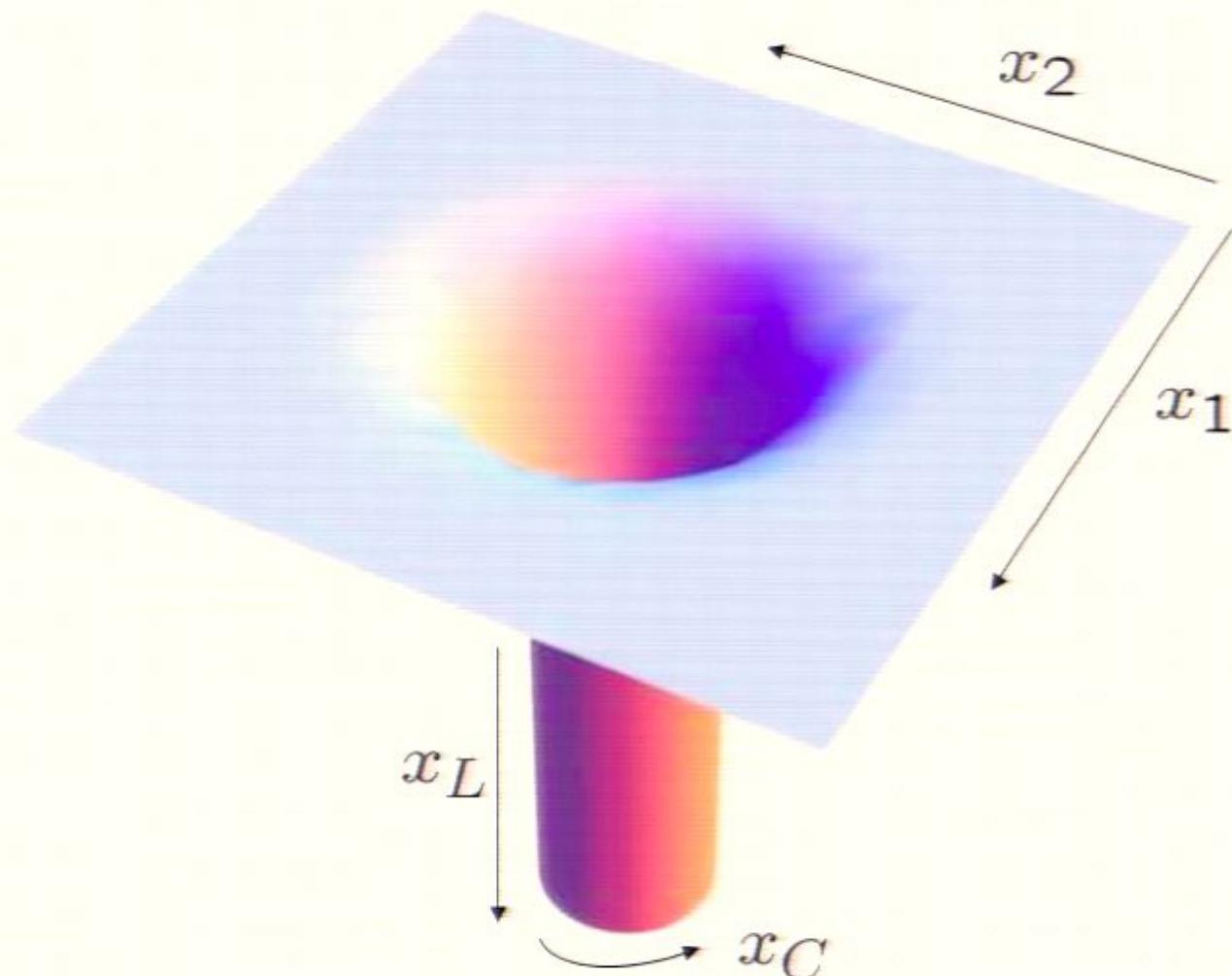
The creation of the pair of electrically charged black holes is a transition of the form:

Mellor and Moss, '89; Mann & Ross '95 ;
Bousso & Hawking '96; Dias & Lemos '04



Dynamical compactification

How can you reduce the number of large dimensions?



Inflating 2-brane

(B-P., Schwartz-Perlov and Vilenkin '10).

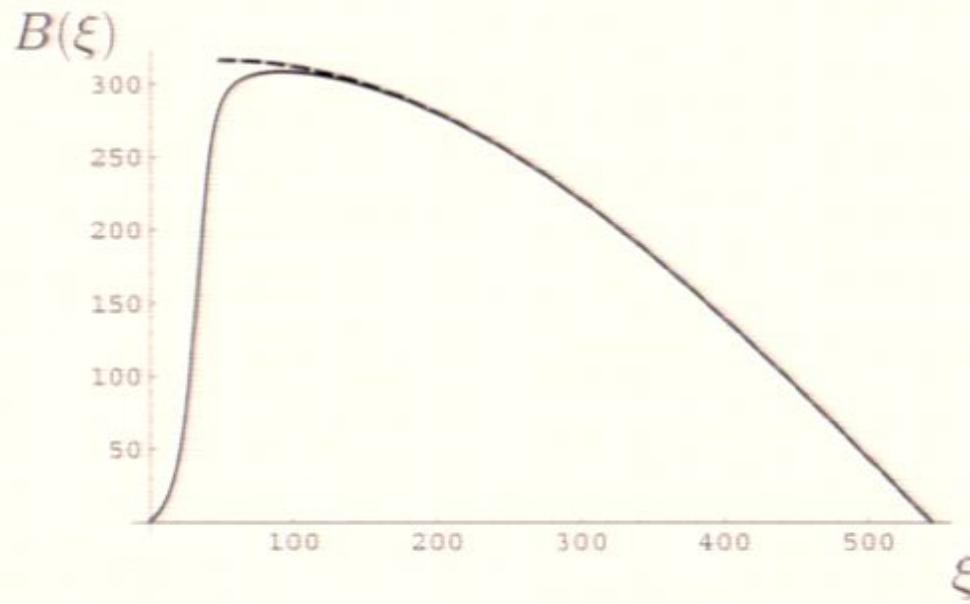
Look for solutions with the following ansatz:

$$\left\{ \begin{array}{l} ds^2 = B(\xi)^2 \underbrace{(-dt^2 + \cosh(t)^2 d\Omega_2^2)}_{\text{Inflating 2+1 worldvolume}} + d\xi^2 + r(\xi)^2 d\Omega_2^2 \\ F_{\theta\phi} = \frac{g}{4\pi} \sin \theta \end{array} \right. \quad \Rightarrow \quad \text{Magnetically charged}$$

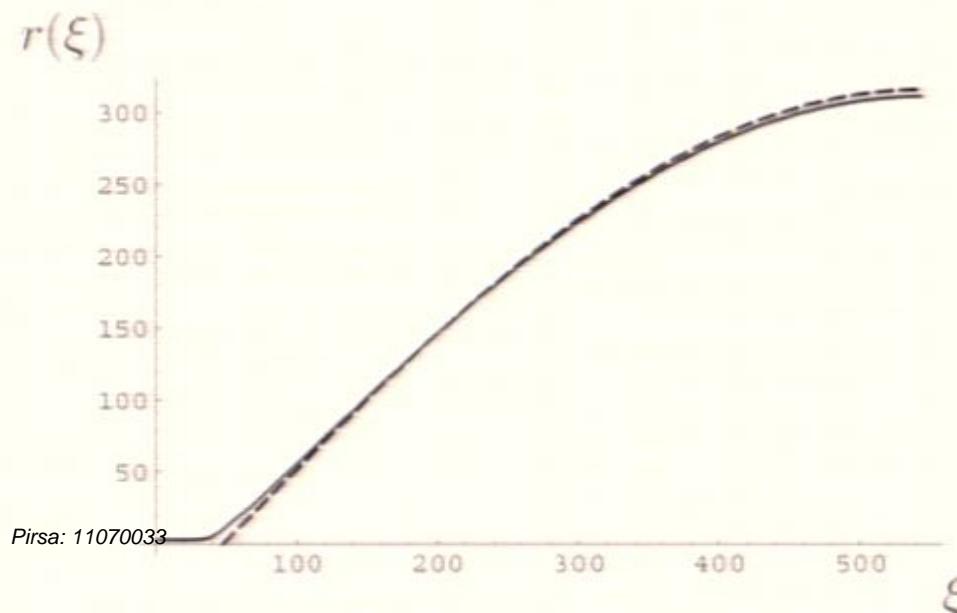
$$\left. \begin{array}{l} B(0) = B(\xi_{max}) = 0 \\ B'(0) = B'(\xi_{max}) = 1 \\ r'(0) = r'(\xi_{max}) = 0 \end{array} \right\} \quad \Rightarrow \quad \text{Smooth at the horizons}$$

$$\left. \begin{array}{l} r(\xi_{max}) = r_2 \\ r(0) = r_1 \end{array} \right\} \quad \Rightarrow \quad \text{One should find these values numerically}$$

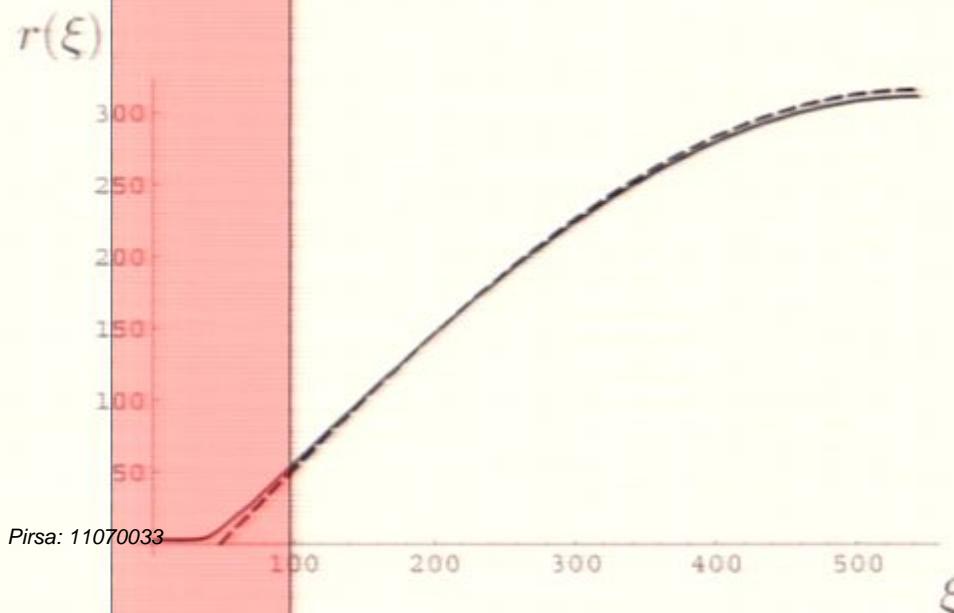
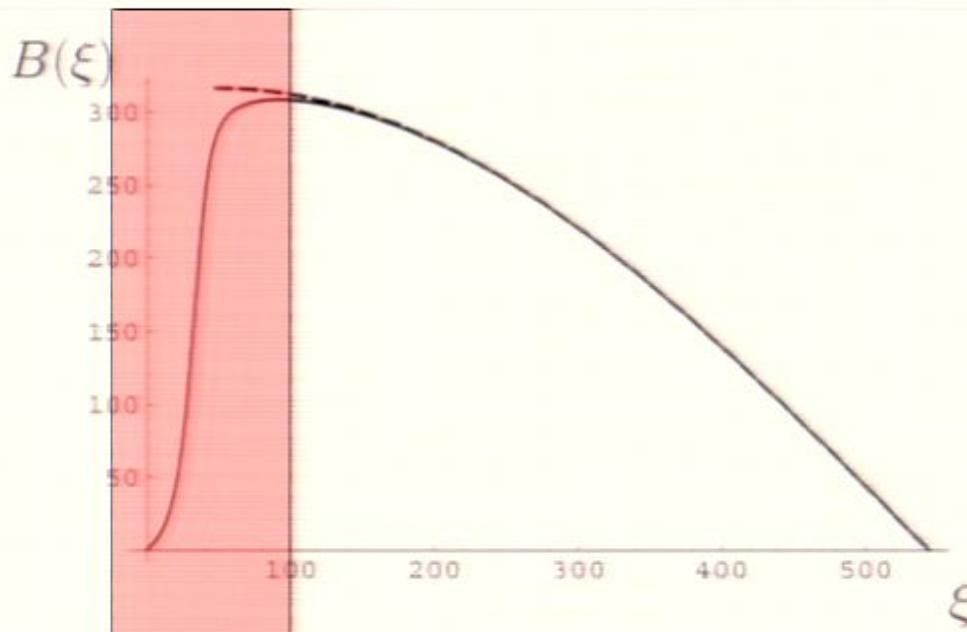
2-brane nucleation



In the small charge limit the backreaction on the background is concentrated to a region of the size of the black brane horizon.

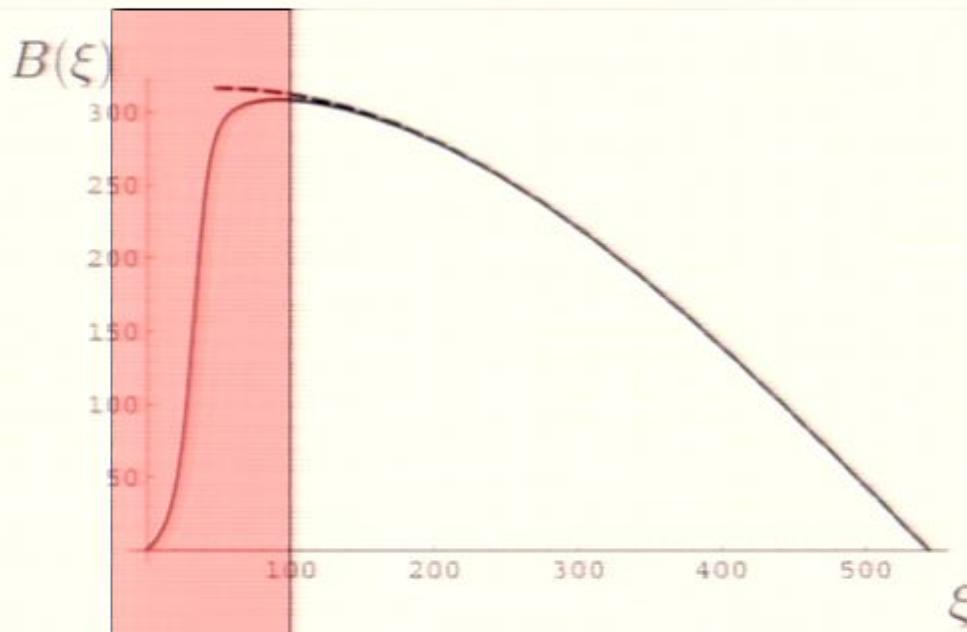


2-brane nucleation

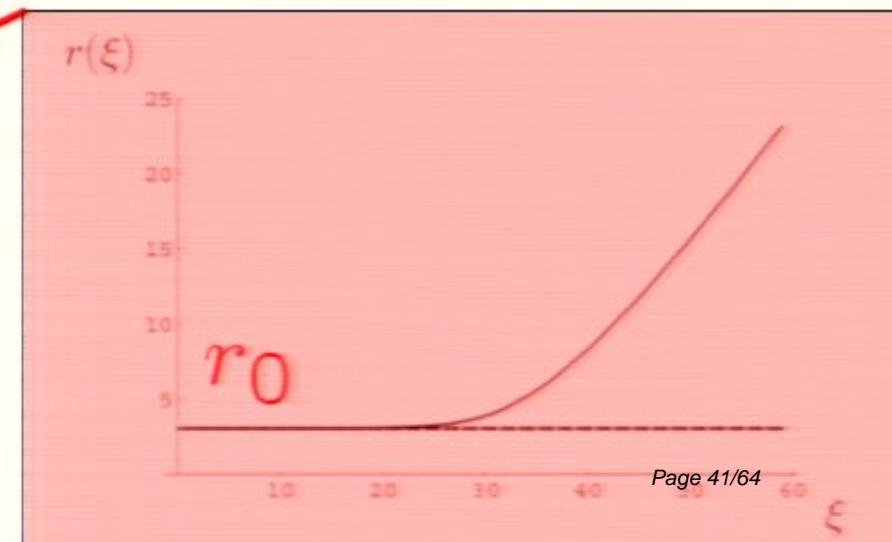
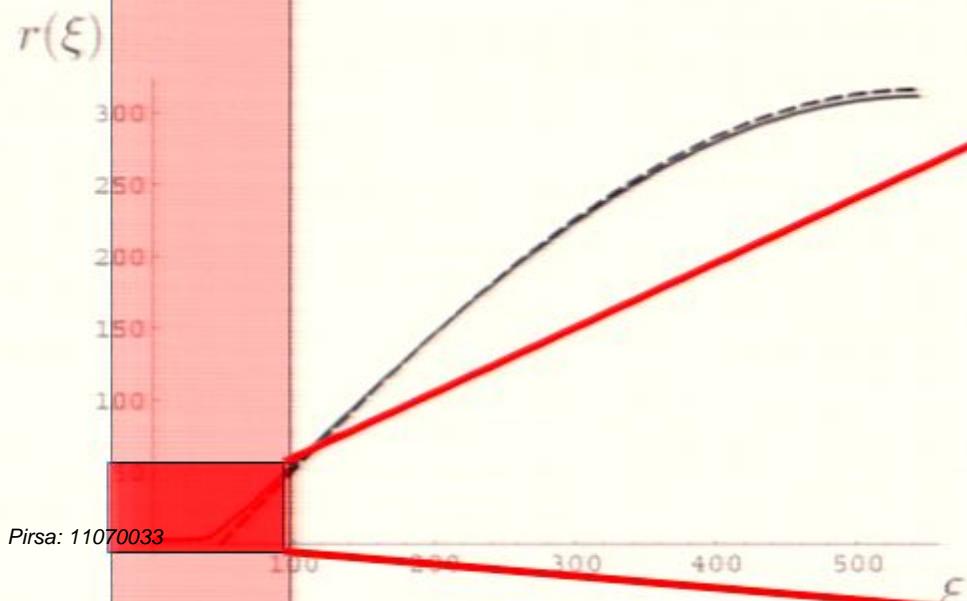


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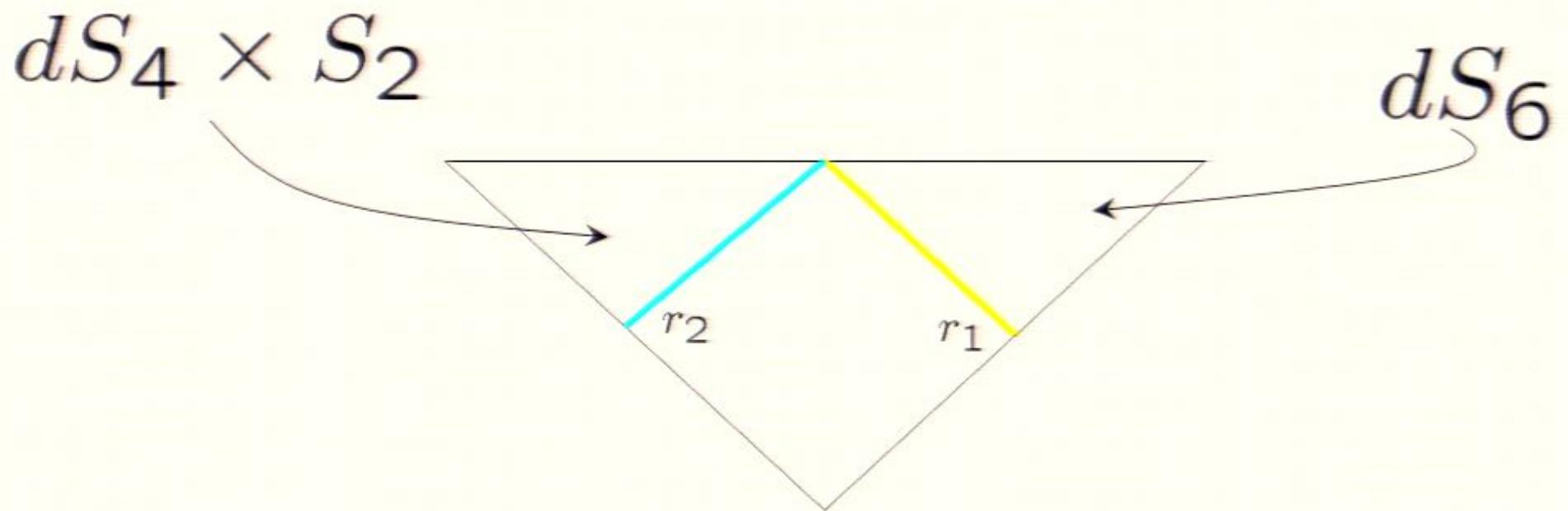
2-brane nucleation



In the small charge limit the backreaction on the background is concentrated to a region of the size of the black brane horizon.



Inflating branes mediate dynamical compactification



Bubbles of Nothing

Witten (82).

Are there other decay channels for compactification models?

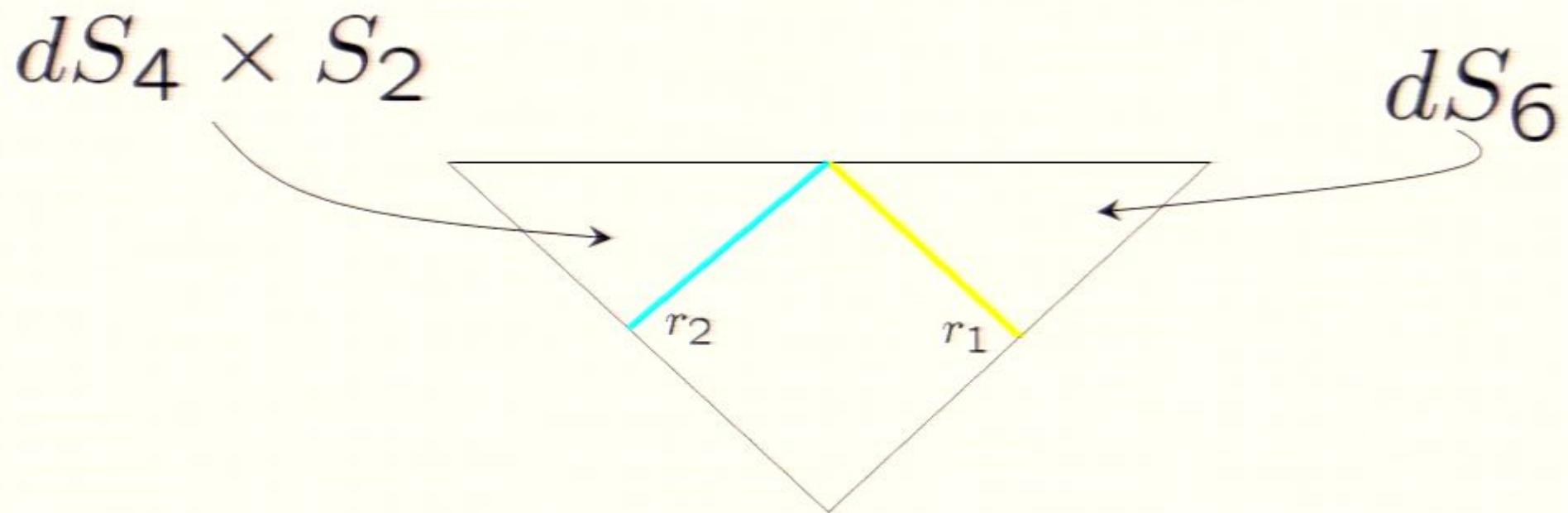
5d Kaluza-Klein model is non-perturbative stable and can decay into a bubble of nothing geometry.

Performing a double analytic continuation of Schwarzschild geometry in 5d we obtain:

$$y \equiv y + 2\pi$$

$$ds^2 = \underbrace{\frac{r^2}{1+r^2/l^2} dy^2 + dr^2}_{\text{Cigar geometry}} + (r^2 + l^2) \underbrace{(-dt^2 + \cosh(t)^2 d\Omega_2^2)}_{\text{Bubble geometry}}$$

Inflating branes mediate dynamical compactification



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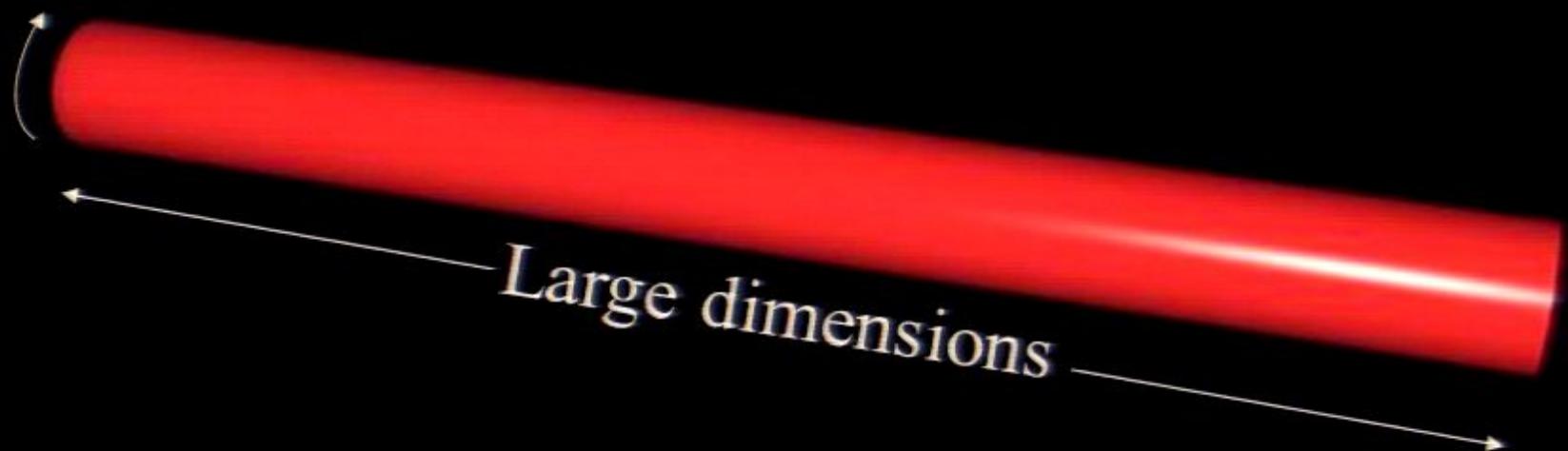
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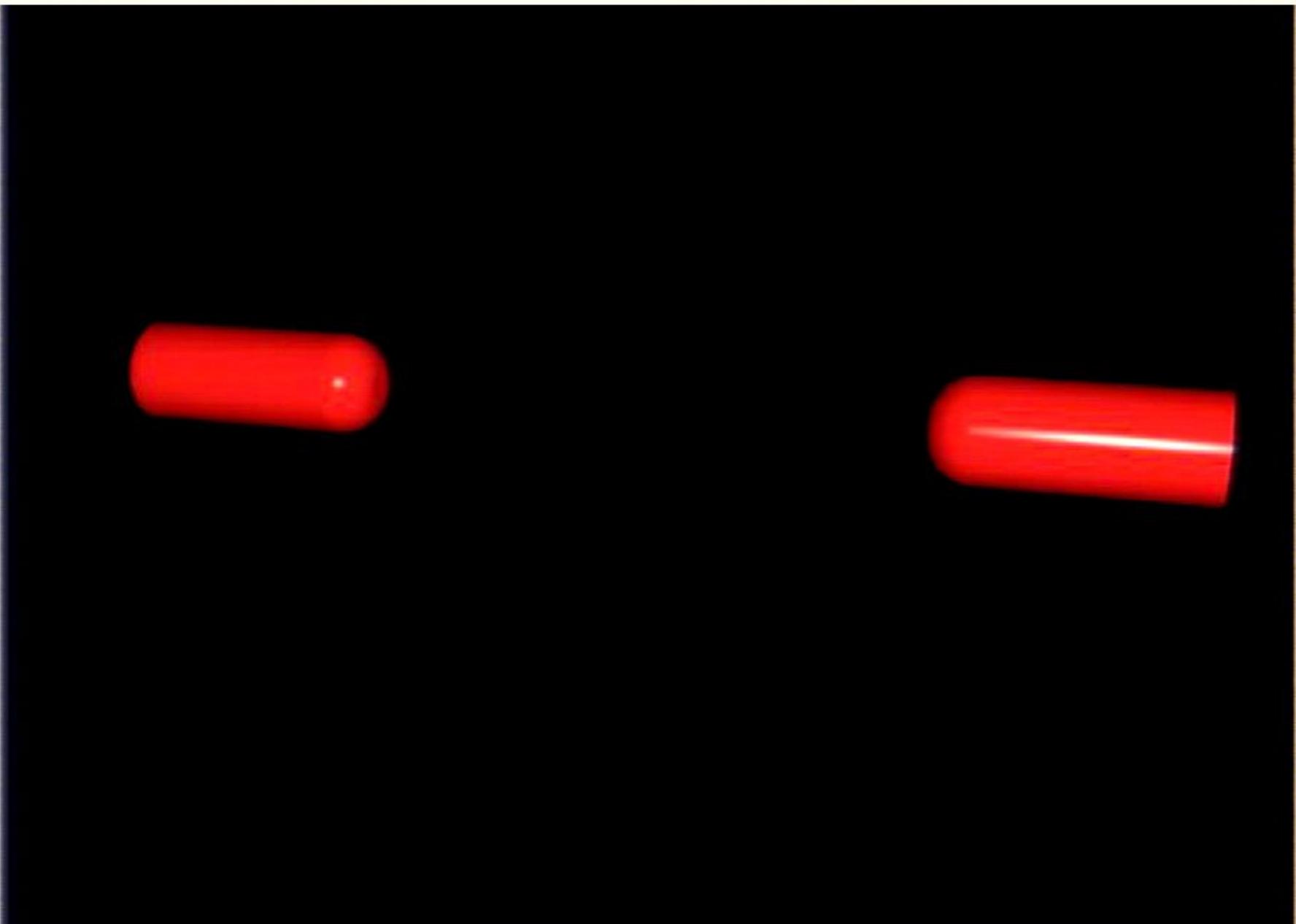
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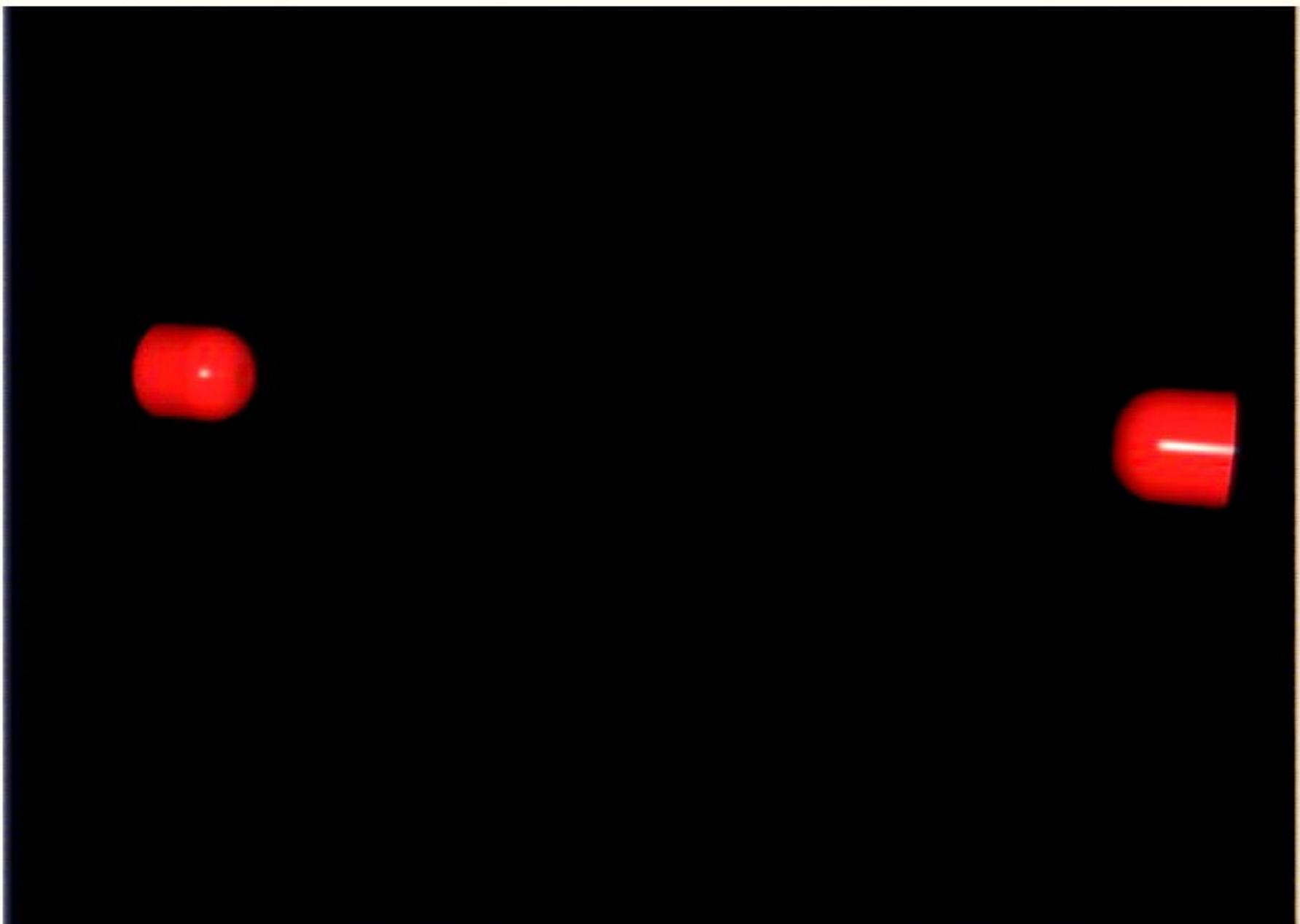
$$ds^2 = \underbrace{\frac{r^2}{1+r^2/l^2} dy^2 + dr^2}_{\text{Cigar geometry}} + (r^2 + l^2) \underbrace{(-dt^2 + \cosh(t)^2 d\Omega_2^2)}_{\text{Bubble geometry}}$$

Compact dimensions









Bubbles of Nothing in Flux Compactifications

B-P & Ben Shlaer (2010).

B-P, Handhika Ramadhan & Ben Shlaer (2010).

See also: I-Sheng Yang (2009) and A. Brown and A. Dahlen (2010) for a different approach

Are there similar decays in our 6d model ?

$$ds^2 = B(r)^2(-dt^2 + \cosh(t)^2 d\tilde{\Omega}_2^2) + dr^2 + C(r)^2 d\Omega_2^2$$

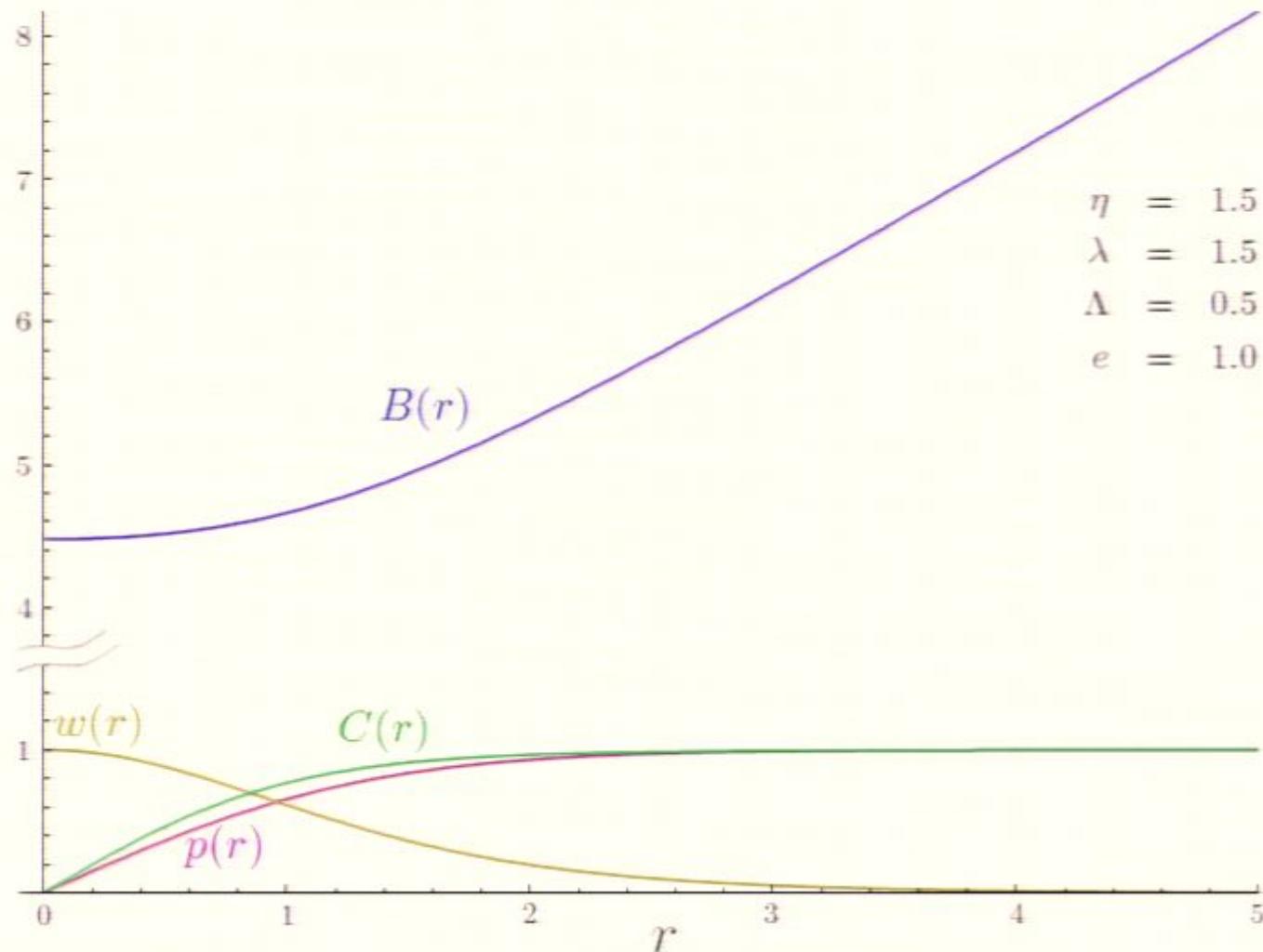
We need to regularize the tip of the cigar geometry so we upgrade our theory to an SU(2) version:

$$S = \int d^6x \sqrt{-g} \left(\frac{1}{2\kappa^2} R - \frac{1}{4} \mathcal{F}_{MN}^a \mathcal{F}^{aMN} - \frac{1}{2} D_M \Phi^a D^M \Phi^a - V(\Phi) - \Lambda \right)$$

This theory leads to the same landscape as the Einstein-Maxwell theory but smooth solitonic magnetically charged 2-branes.

Bubbles of Nothing in Flux Compactifications

B-P, Handhika Ramadhan & Ben Shlaer (2010).



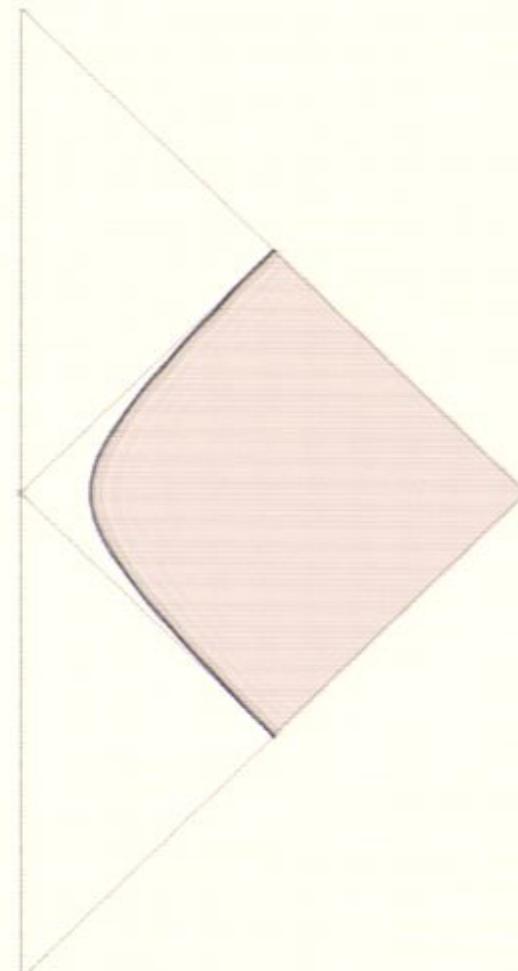
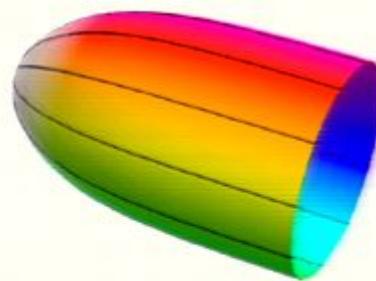
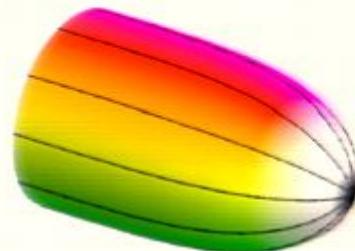
$$ds^2 = B(r)^2(-dt^2 + \cosh(t)^2 d\tilde{\Omega}_2^2) + dr^2 + C(r)^2 d\Omega_2^2$$

Bubbles of Nothing in Flux Compactifications

B-P, Handhika Ramadhan & Ben Shlaer (2010).

The solution can be thought of as an inflating brane.

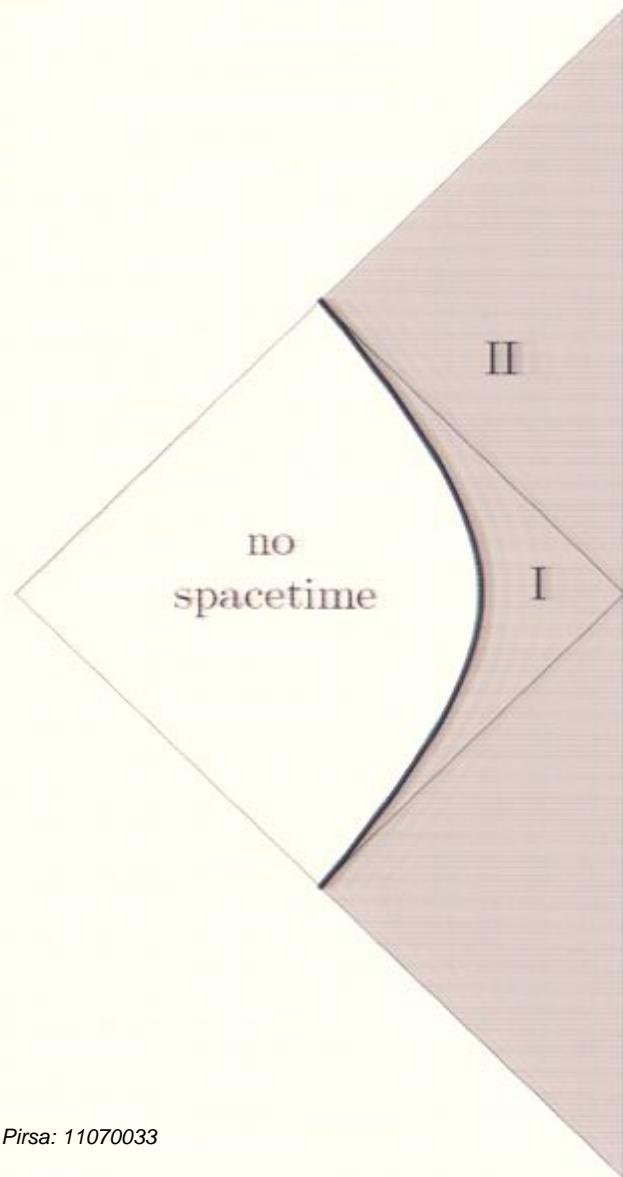
$$ds^2 = B(r)^2(-dt^2 + \cosh(t)^2 d\tilde{\Omega}_2^2) + dr^2 + C(r)^2 d\Omega_2^2$$



At some point these brane solutions become flat and the decay channel gets suppressed.

Bubbles from Nothing

B-P, Handhika Ramadhan & Ben Shlaer (2010).

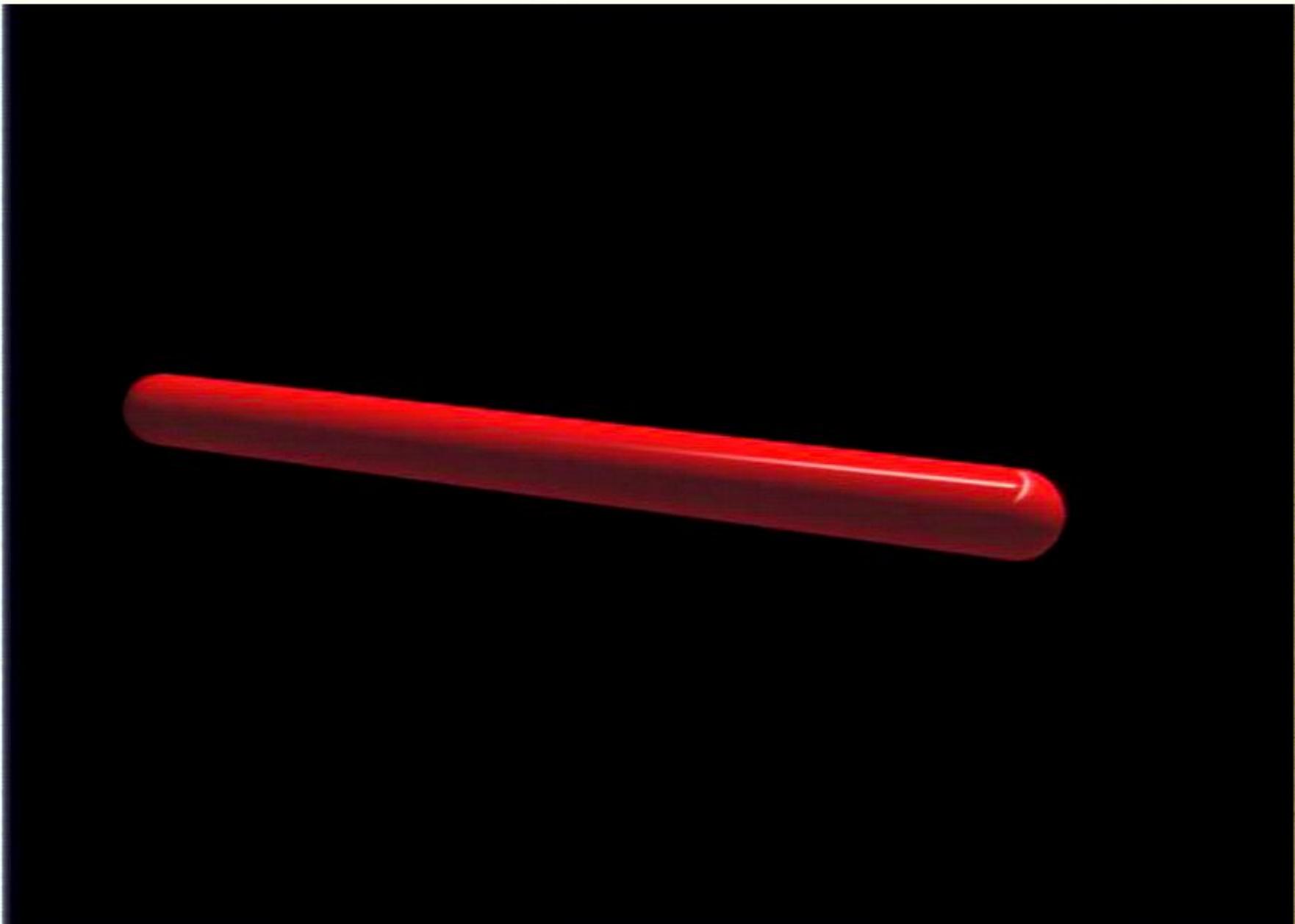


- Taking a different set of parameters allows us to find bubble from nothing geometries.
- Region II describes an open universe similar to the ideas of Hawking and Turok.

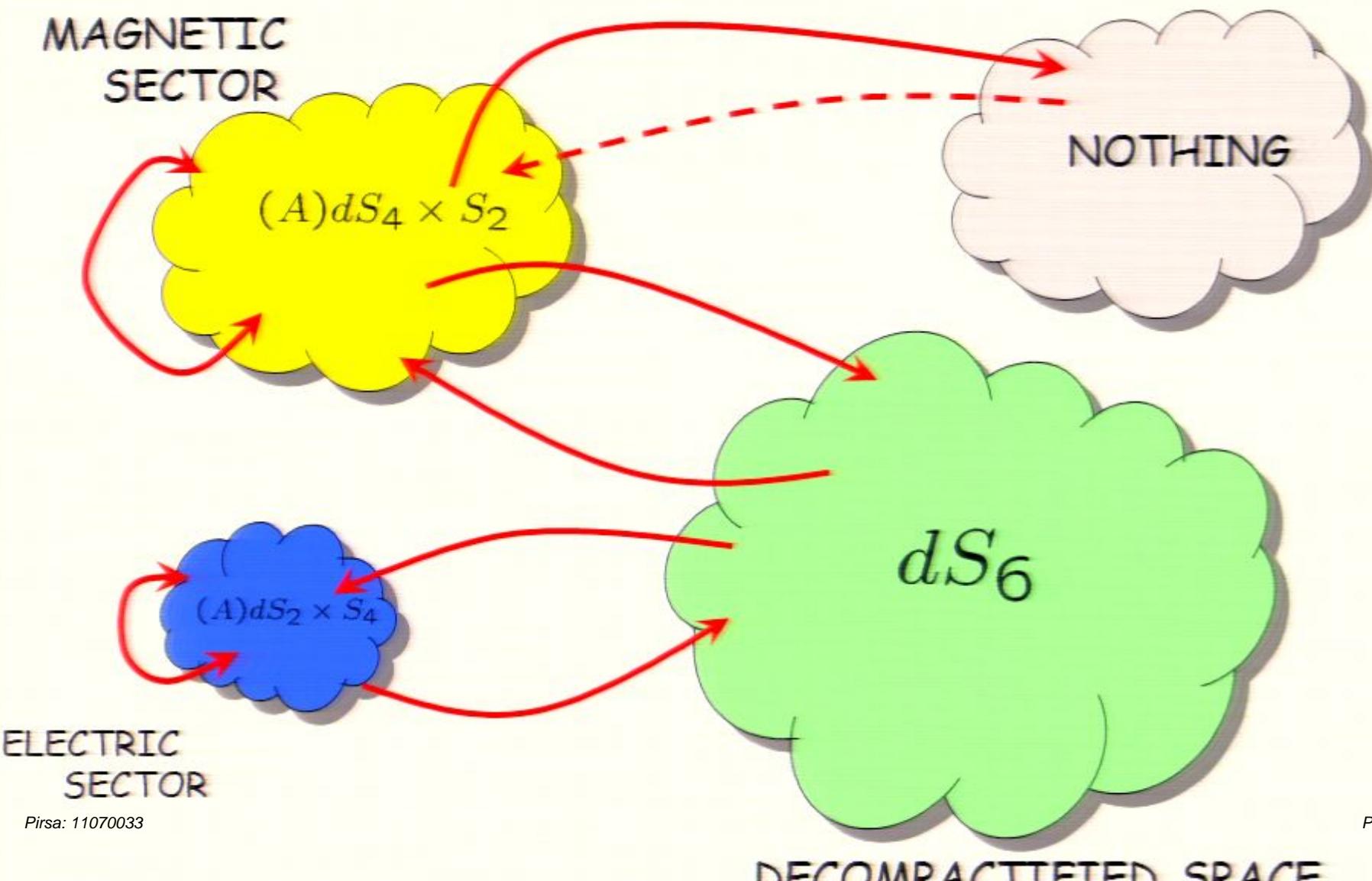
Hawking & Turok (1998).

- The singular region is replaced by a smooth solitonic solution in a higher dimensional setting.

Garriga (1998).



Transdimensional Tunneling



Observational Signatures

B-P & M. Salem (2010).

Our universe could be the result of one of these transdimensional transitions.

These transitions could leave some imprint on the spectrum of perturbations in the CMB.

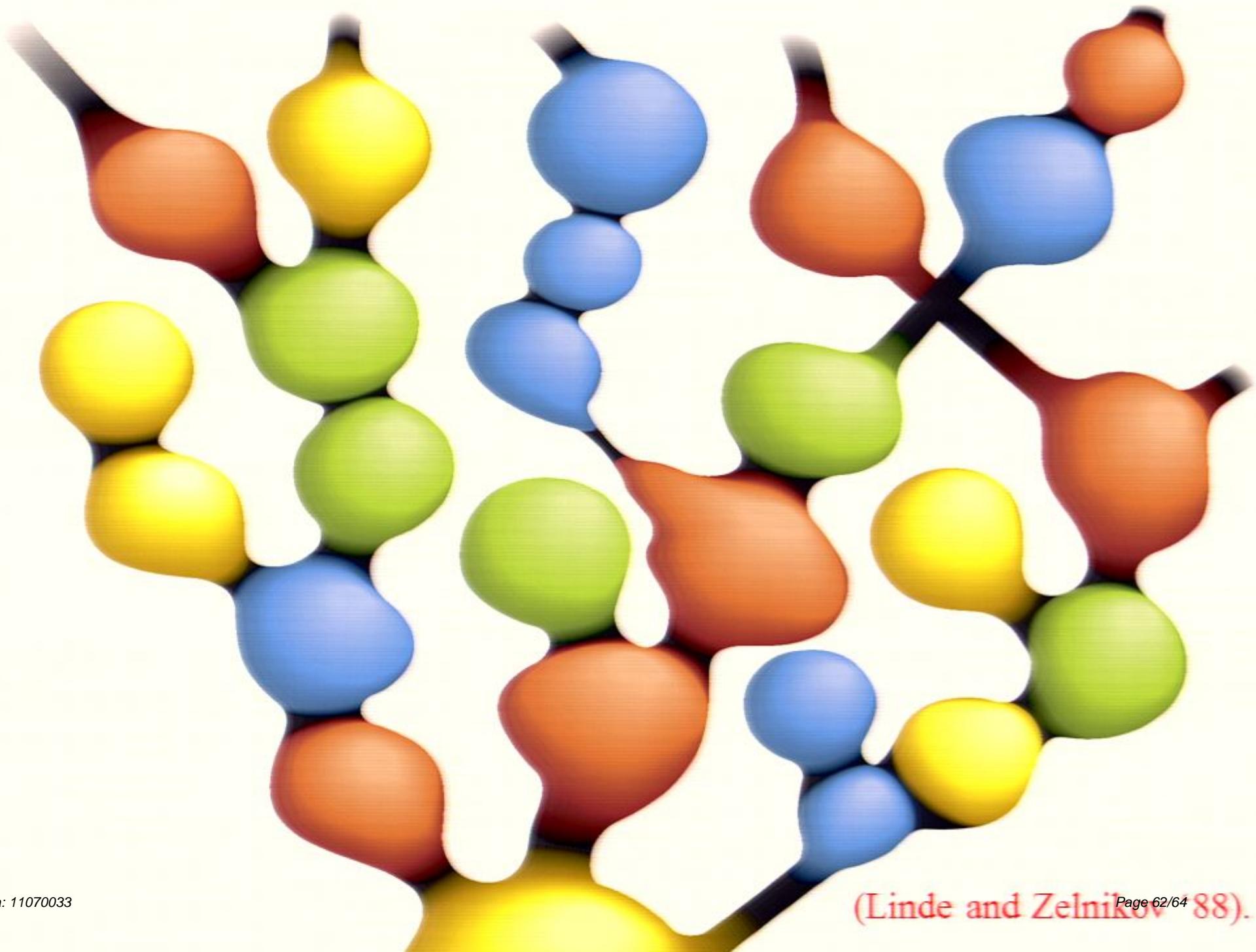
$$\text{Nothing} \quad \xrightarrow{\quad} \quad dS_4 \times S_2$$

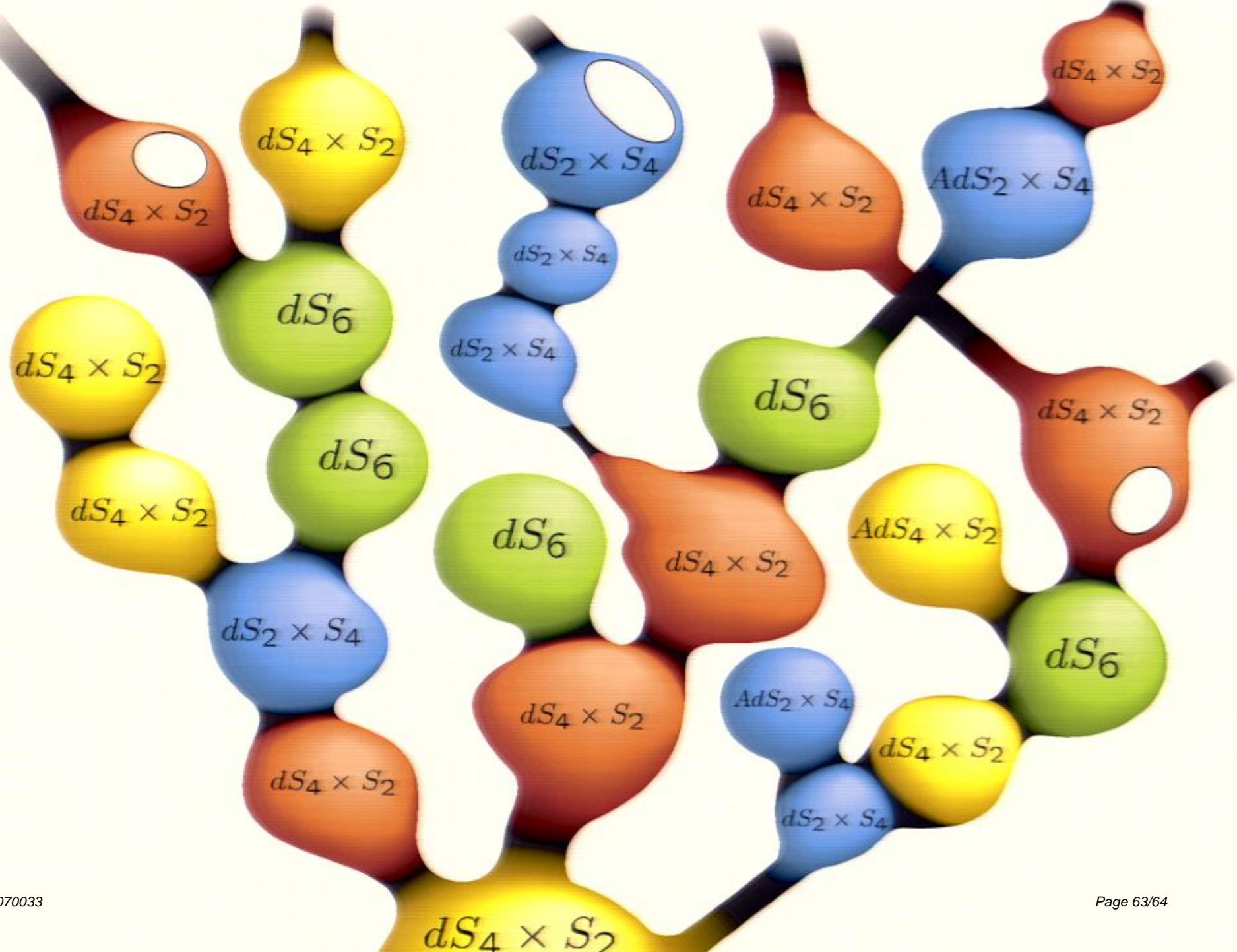
$$(A)dS_2 \times S_4 \quad \xrightarrow{\quad} \quad dS_4 \times S_2$$

$$dS_4 \times S_2 \quad \xrightarrow{\quad} \quad dS_4 \times S_2$$

$$dS_6 \quad \xrightarrow{\quad} \quad dS_4 \times S_2$$

What is the BIG PICTURE ?





Cosmology in models of extra dimensions could be much more complicated than we anticipated.