Title: Transdimensional Tunneling in the Multiverse

Date: Jul 13, 2011 04:00 PM

URL: http://pirsa.org/11070033

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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Tufts Institute of Cosmology

with:
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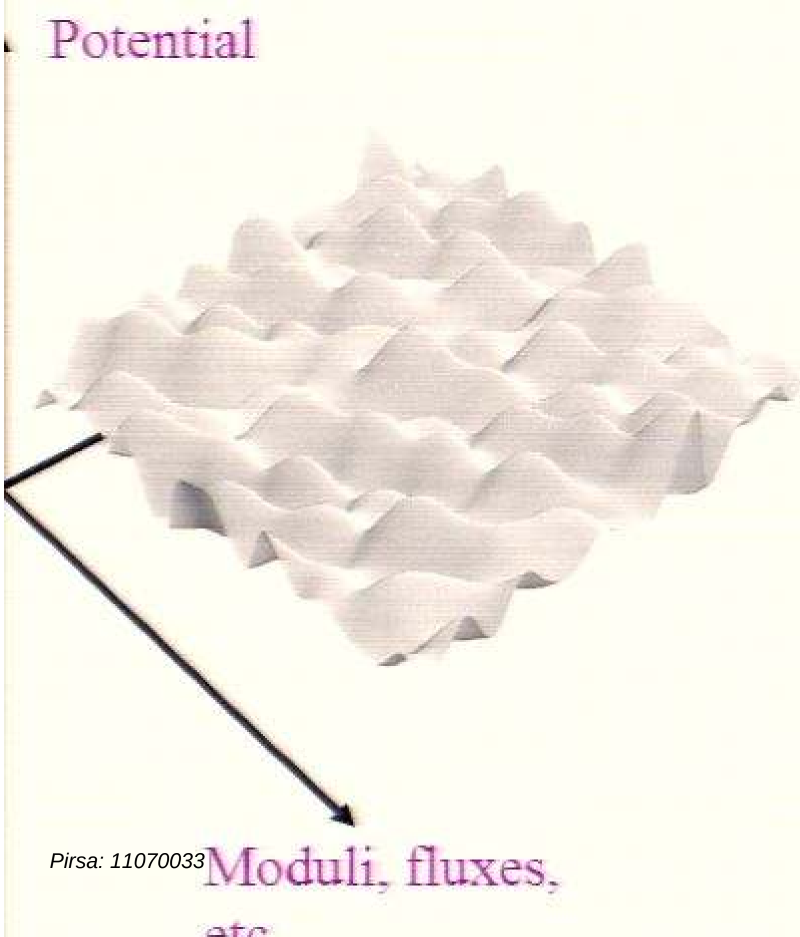
Mike Salem
Delia Schwartz-Perlov
Ben Shlaer
Alex Vilenkin

Outline of the talk

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

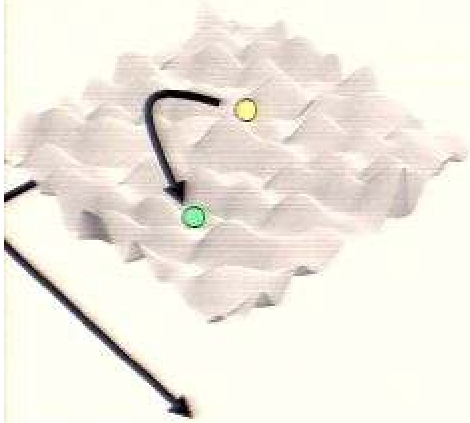
Introduction

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

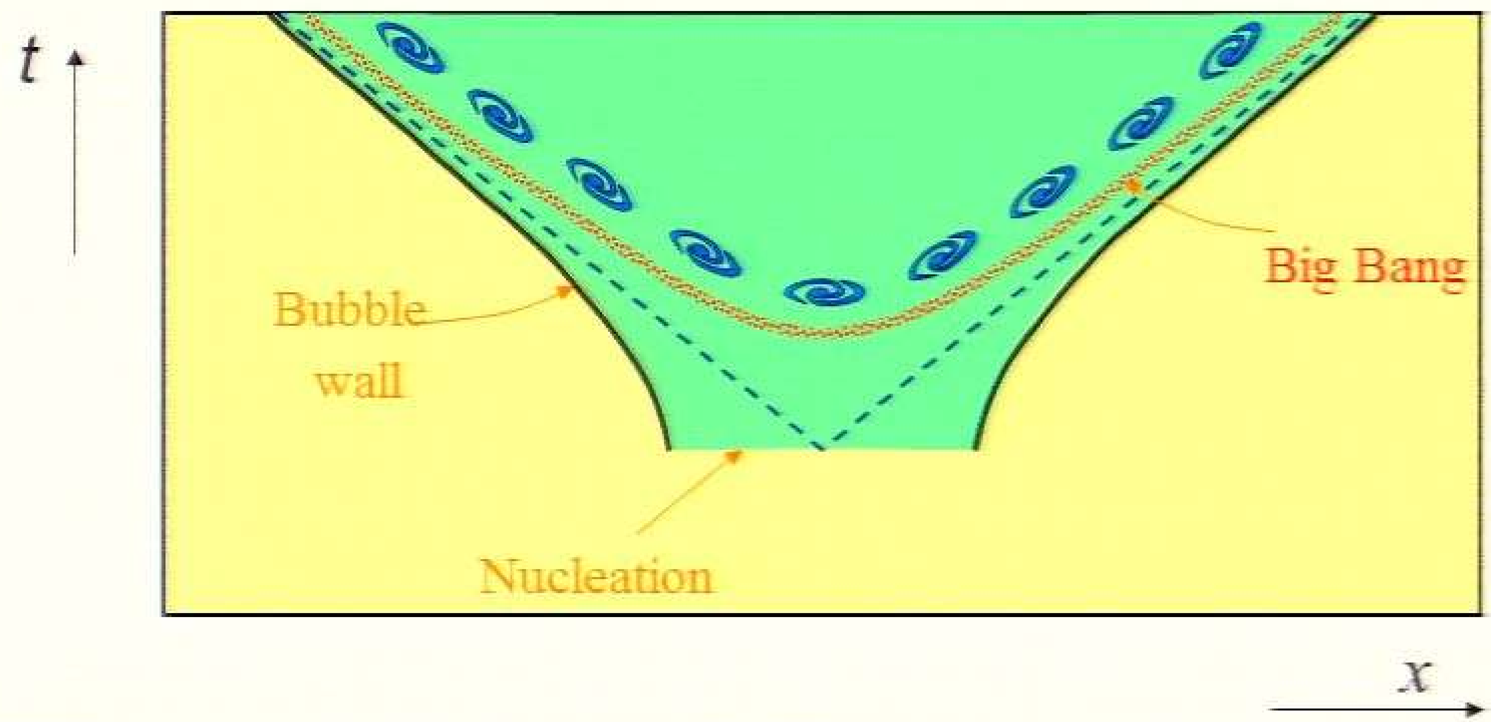


- These models have led us to a complicated 4d effective potential with many metastable minima.
- This has been described in the literature as the String Landscape.

Spacetime of a Bubble Universe

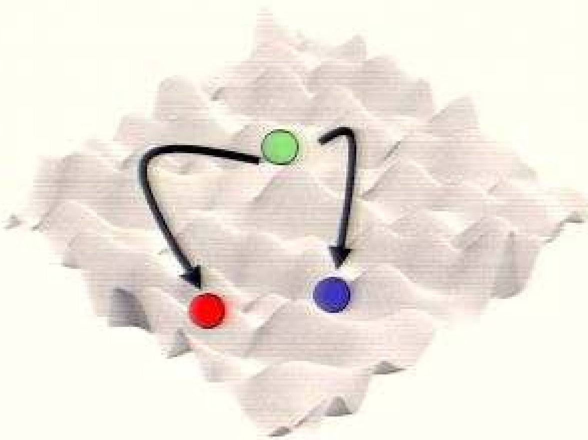


(Coleman & deLuccia, '80).

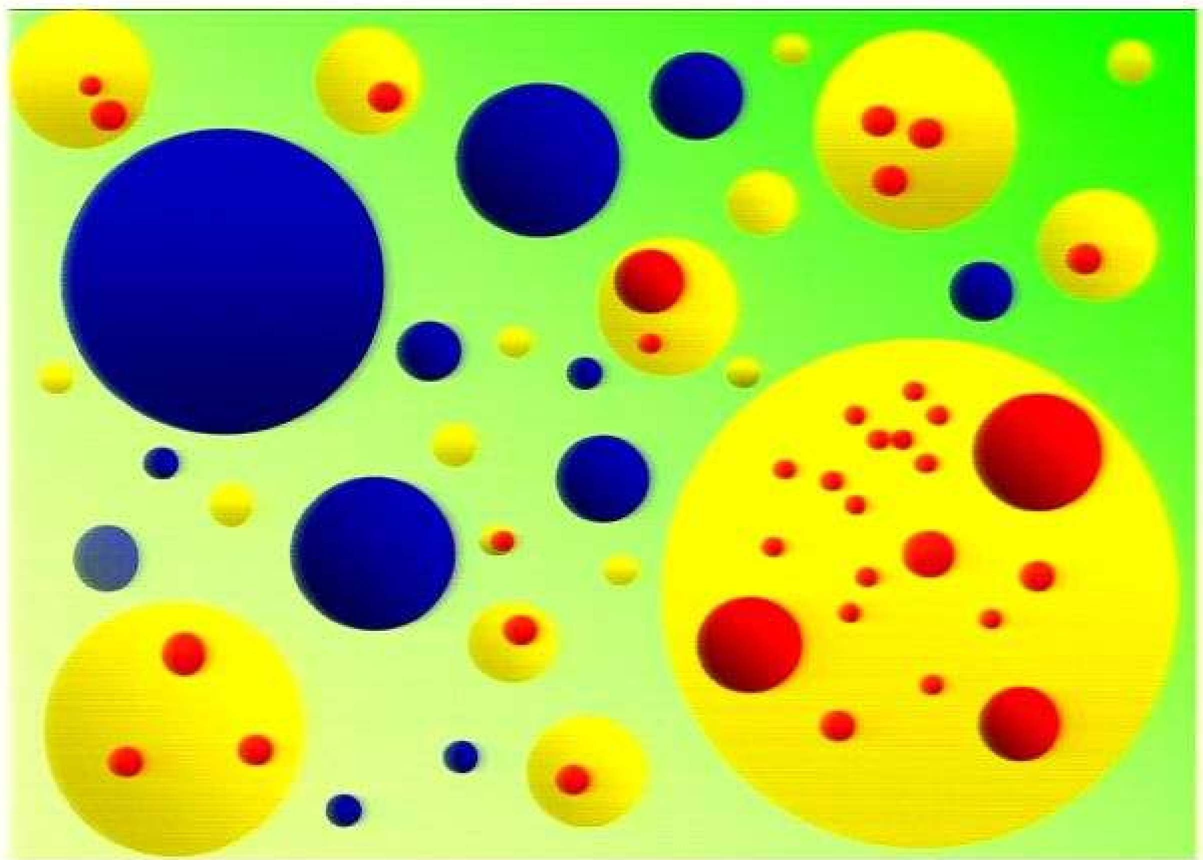


$$ds^2 = -dT^2 + a(T)^2(d\xi^2 + \sinh^2(\xi)d\Omega_2^2)$$

4d String Theory Multiverse



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



he universe is in fact, very
homogeneous at the largest
ossible scales.

The 6d Flux Compactification

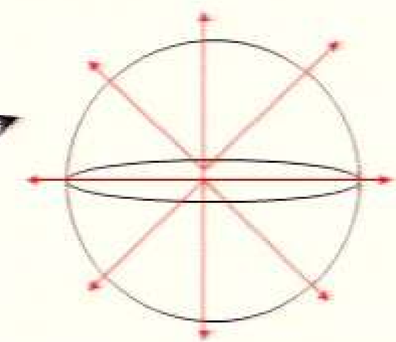
(Freund and Rubin, '80).
(Randjbar-Daemi et al., '83).

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:

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

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

6d CC contribution

Curvature of internal space

Flux contribution

The 6d Flux Compactification

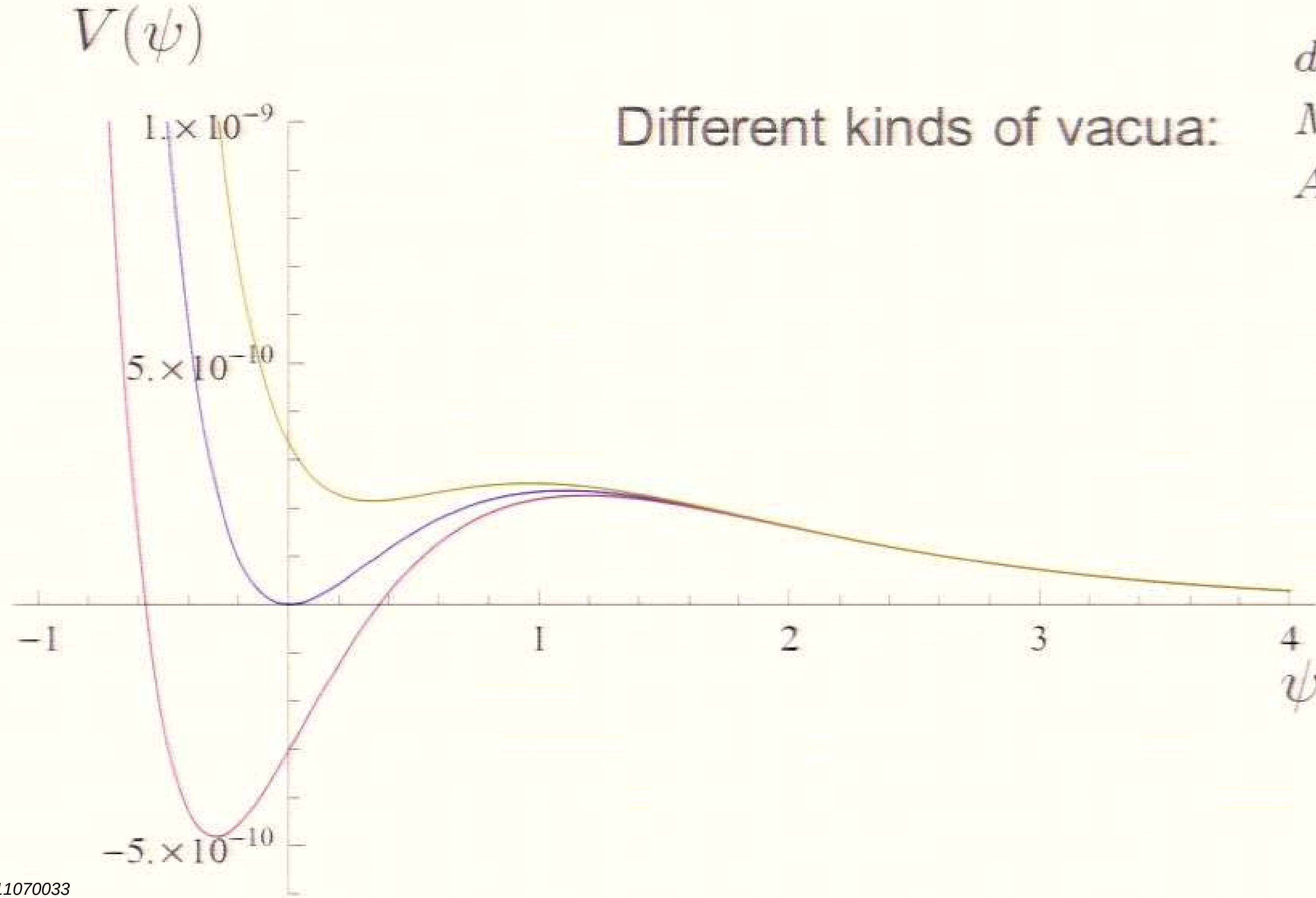
(B-P., Schwartz-Perlov and Vilenkin '09).

Different kinds of vacua:

$dS_4 \times S_2$

$M_4 \times S_2$

$AdS_4 \times S_2$



Magnetically Charged Branes

(Gibbons, Horowitz and Townsend '95).

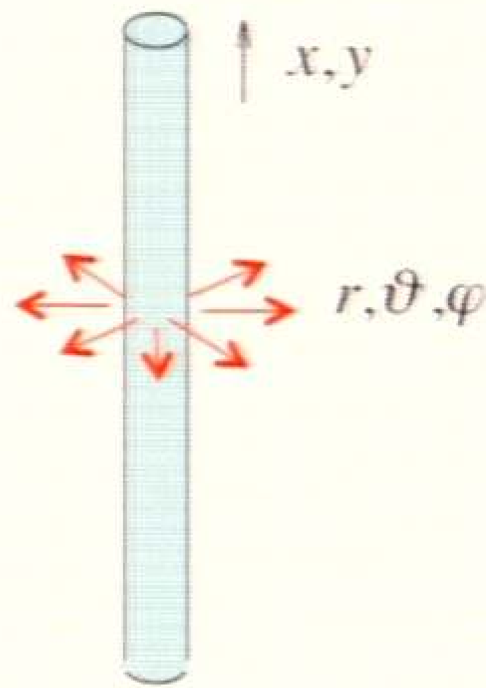
(Gregory, '96).

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

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

Magnetically charged

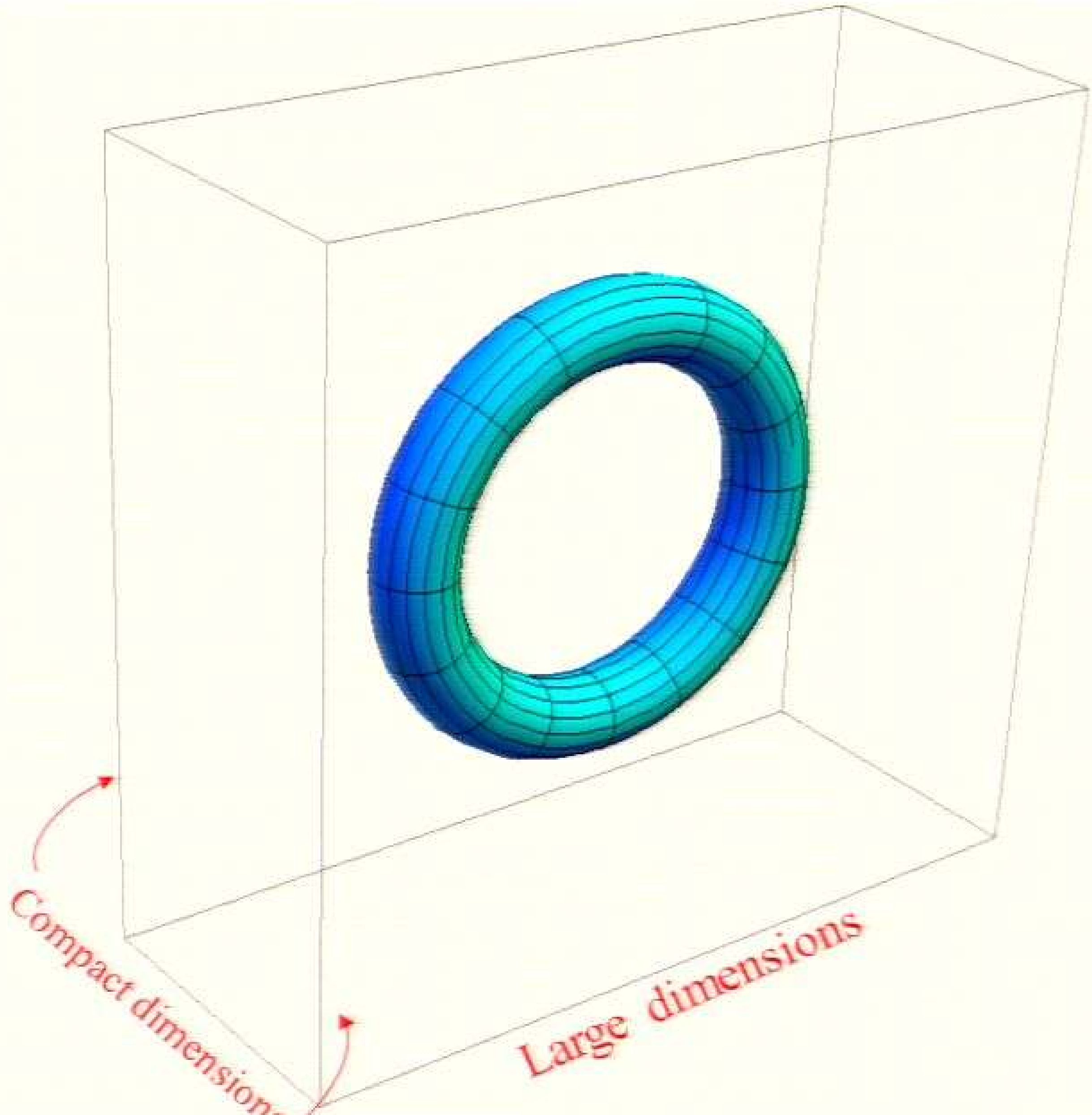
$$\left\{ \begin{array}{c} F_{\theta\phi} = \frac{g}{4\pi} \sin\theta \\ ge = 2\pi \end{array} \right\}$$



- In the extremal case we have,

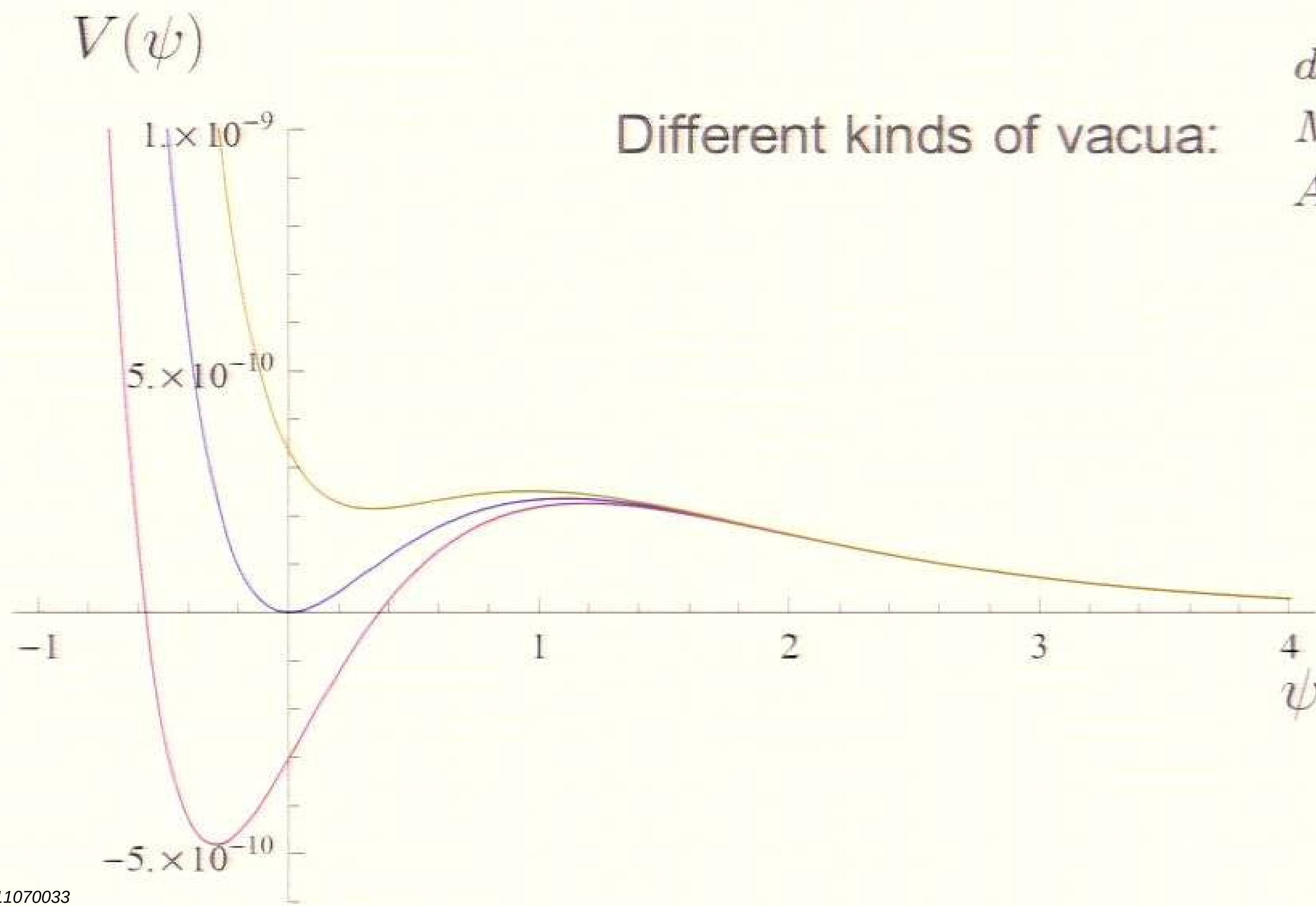
$$r_0 = \frac{\sqrt{3} g}{8\pi M_{(6)}^2} \qquad T_2 = \frac{2 g M_{(6)}^2}{\sqrt{3}}$$

Flux Tunneling



The 6d Flux Compactification

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



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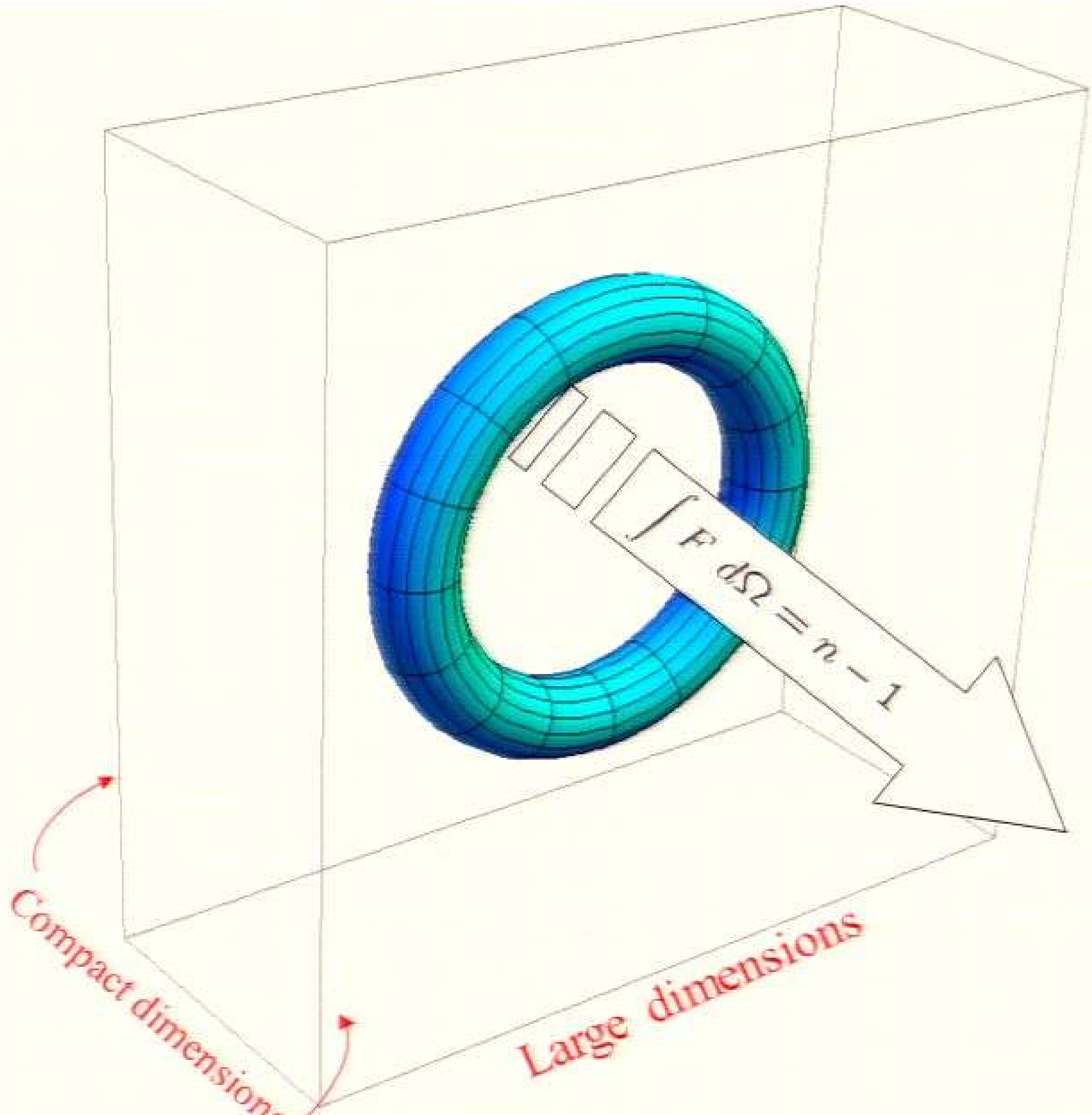
$M_4 \times S_2$

$AdS_4 \times S_2$

Flux Tunneling



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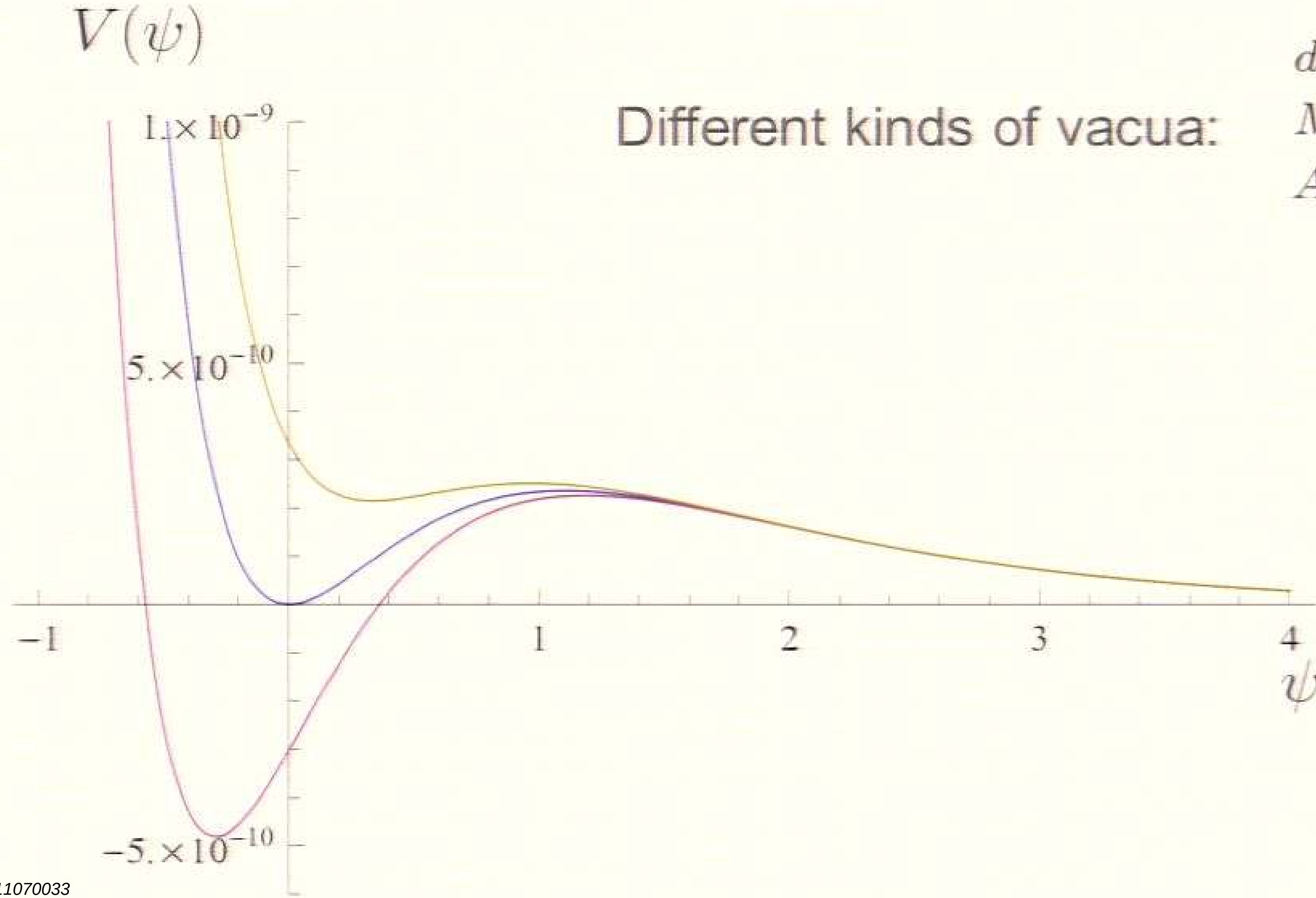

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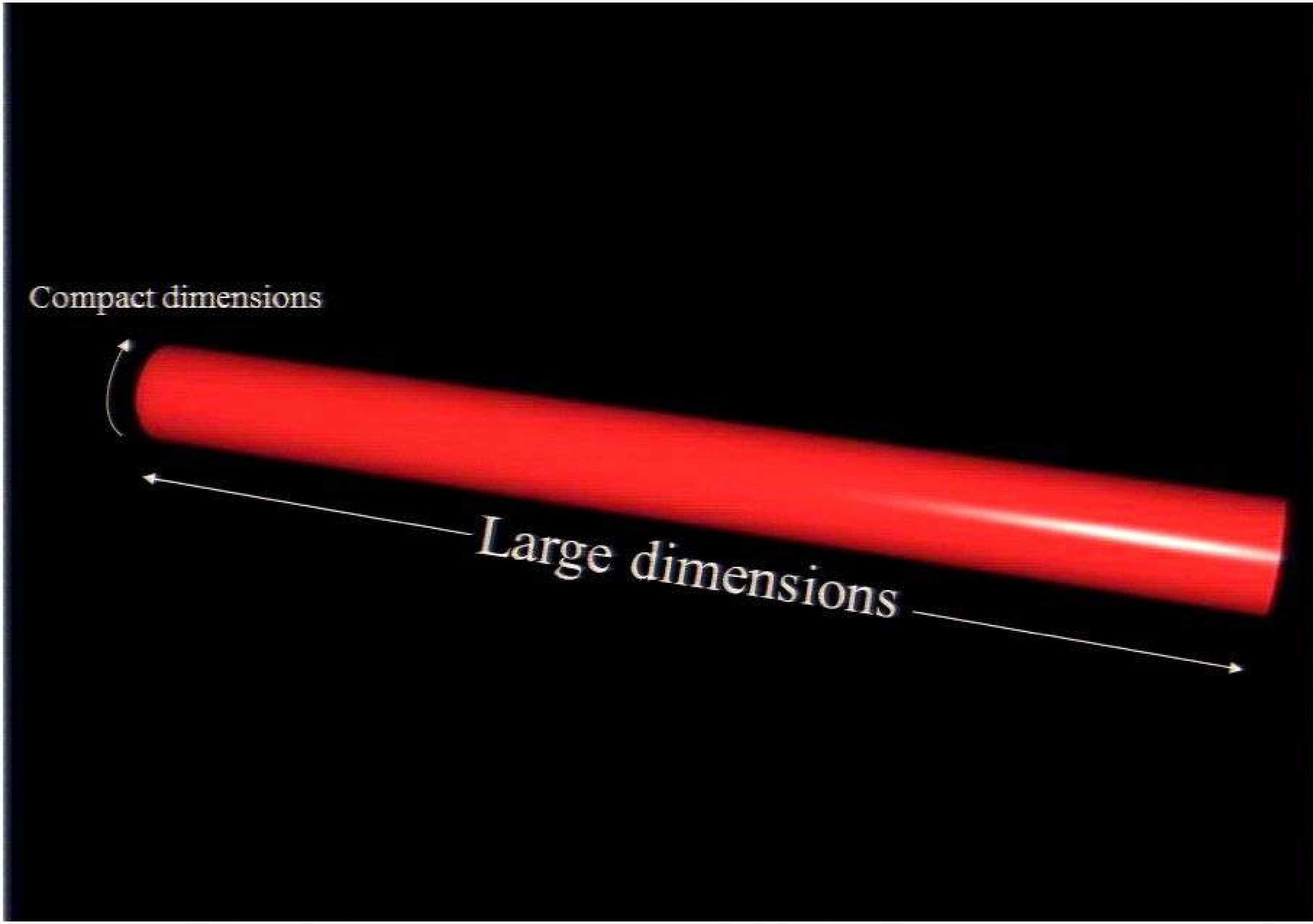
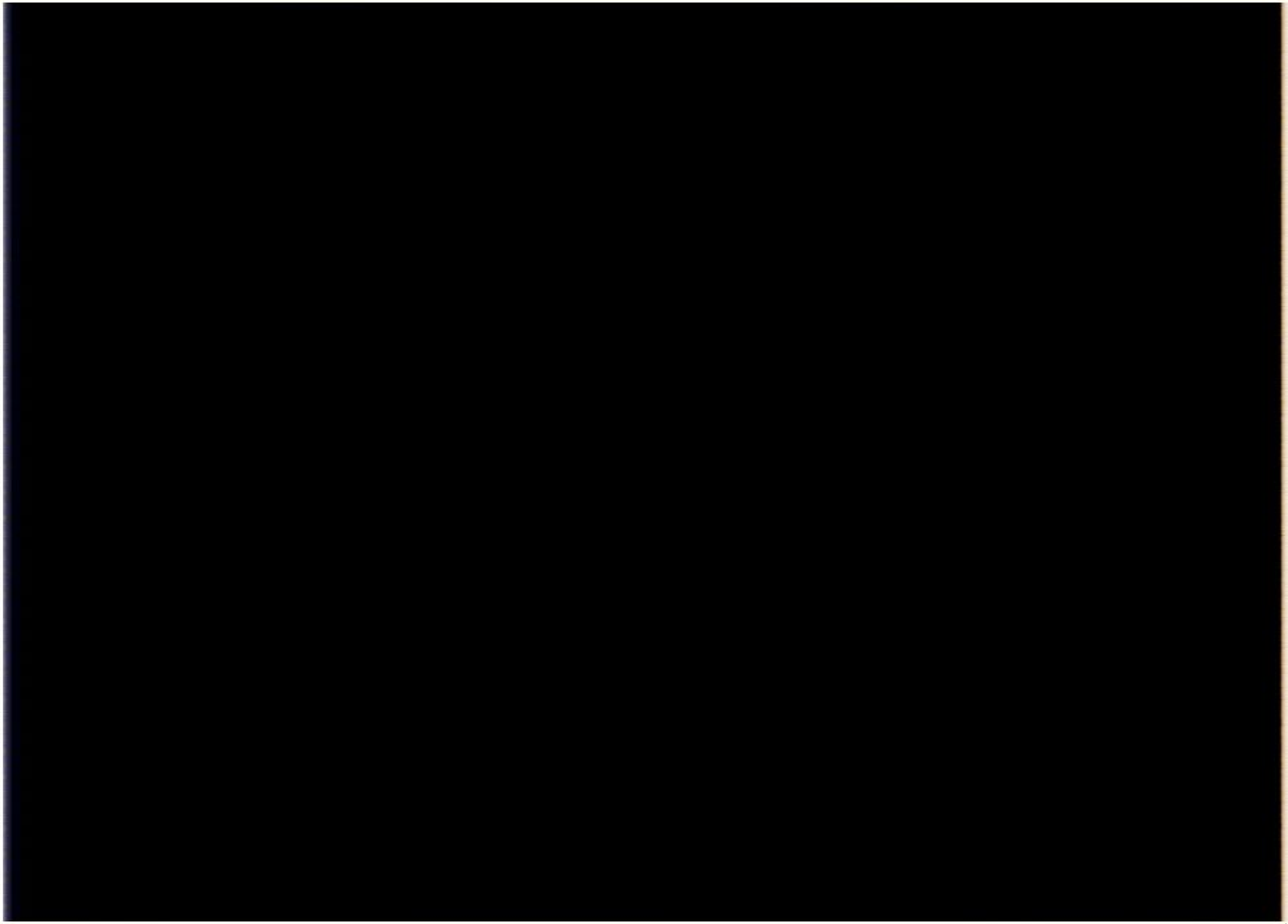
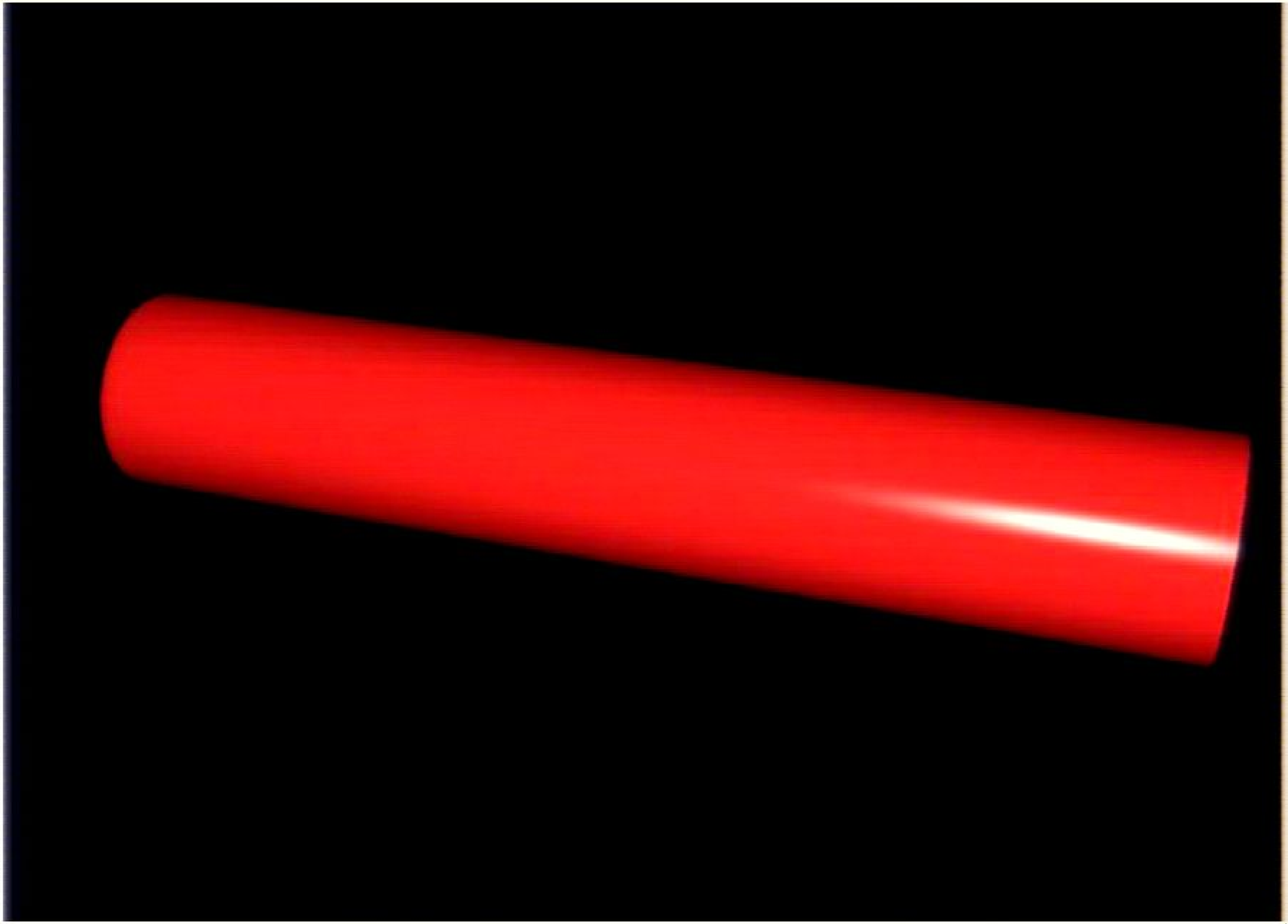
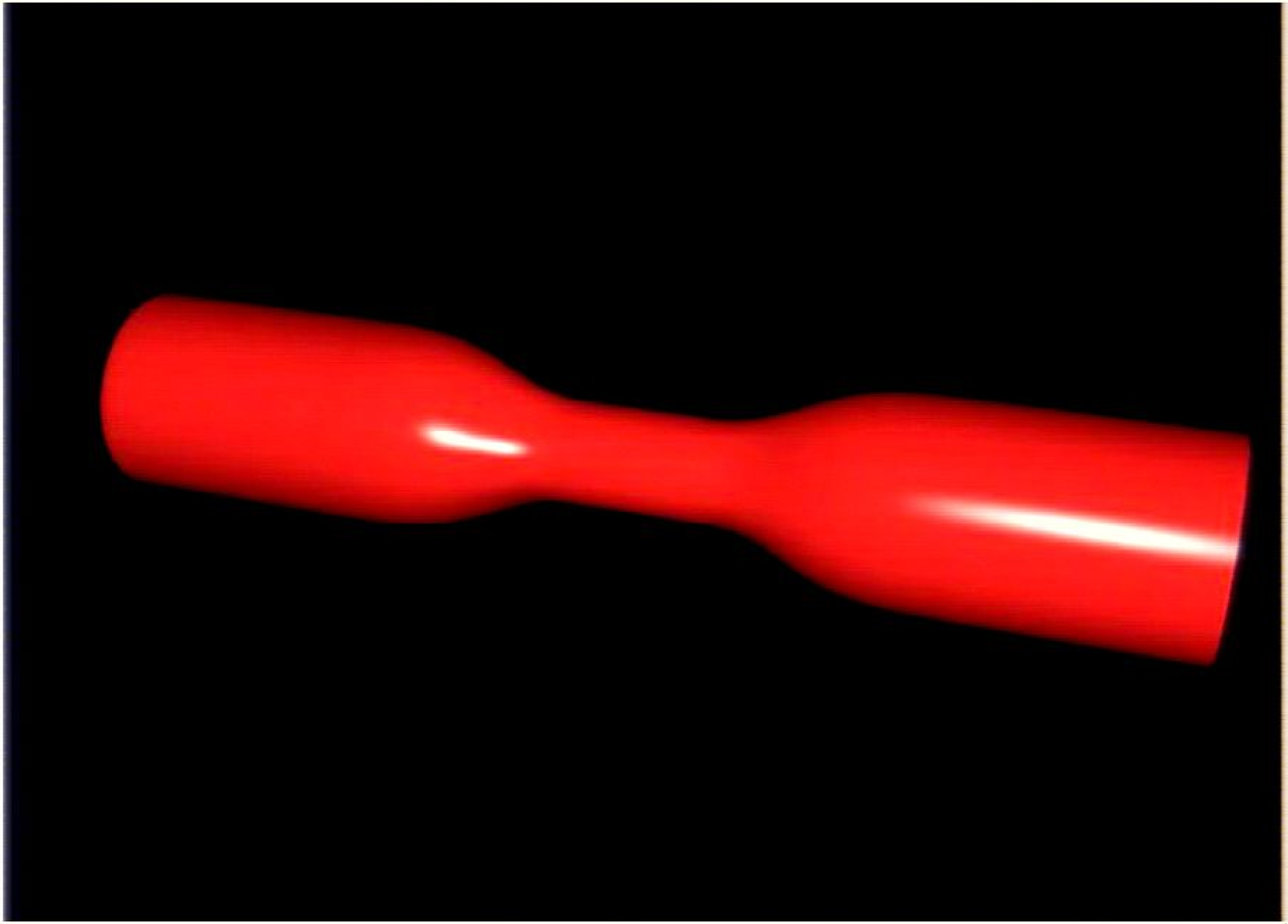
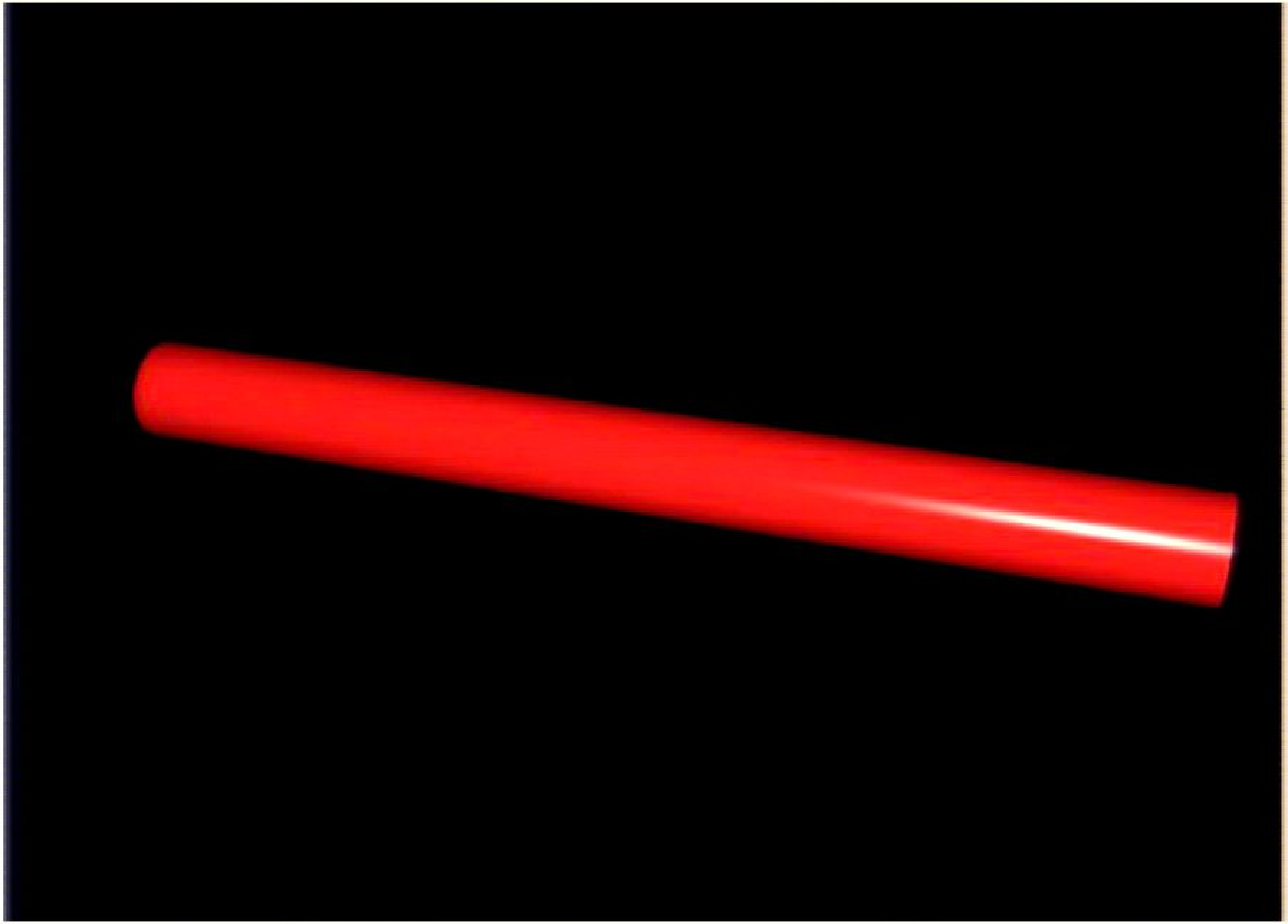
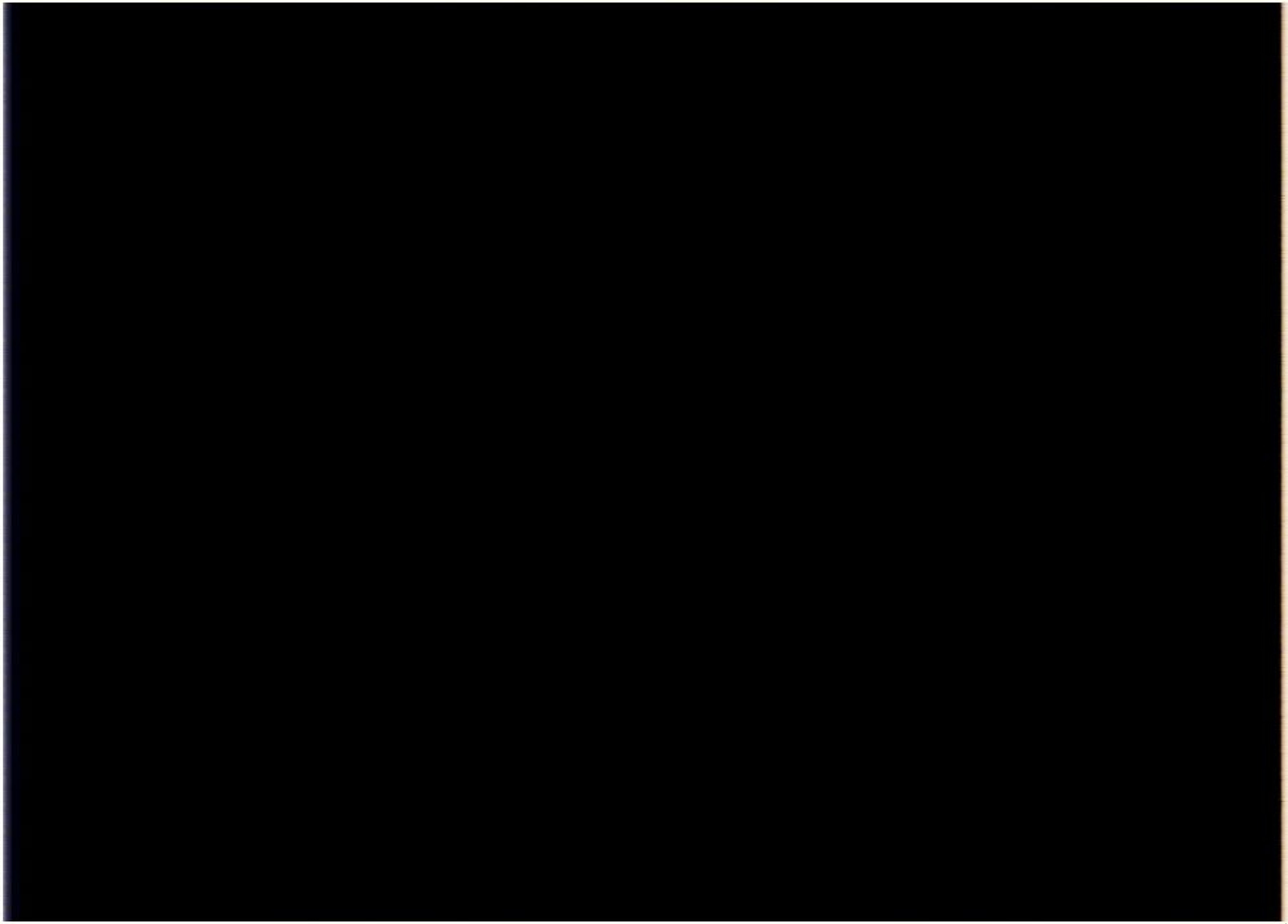

Compact dimensions
Large dimensions

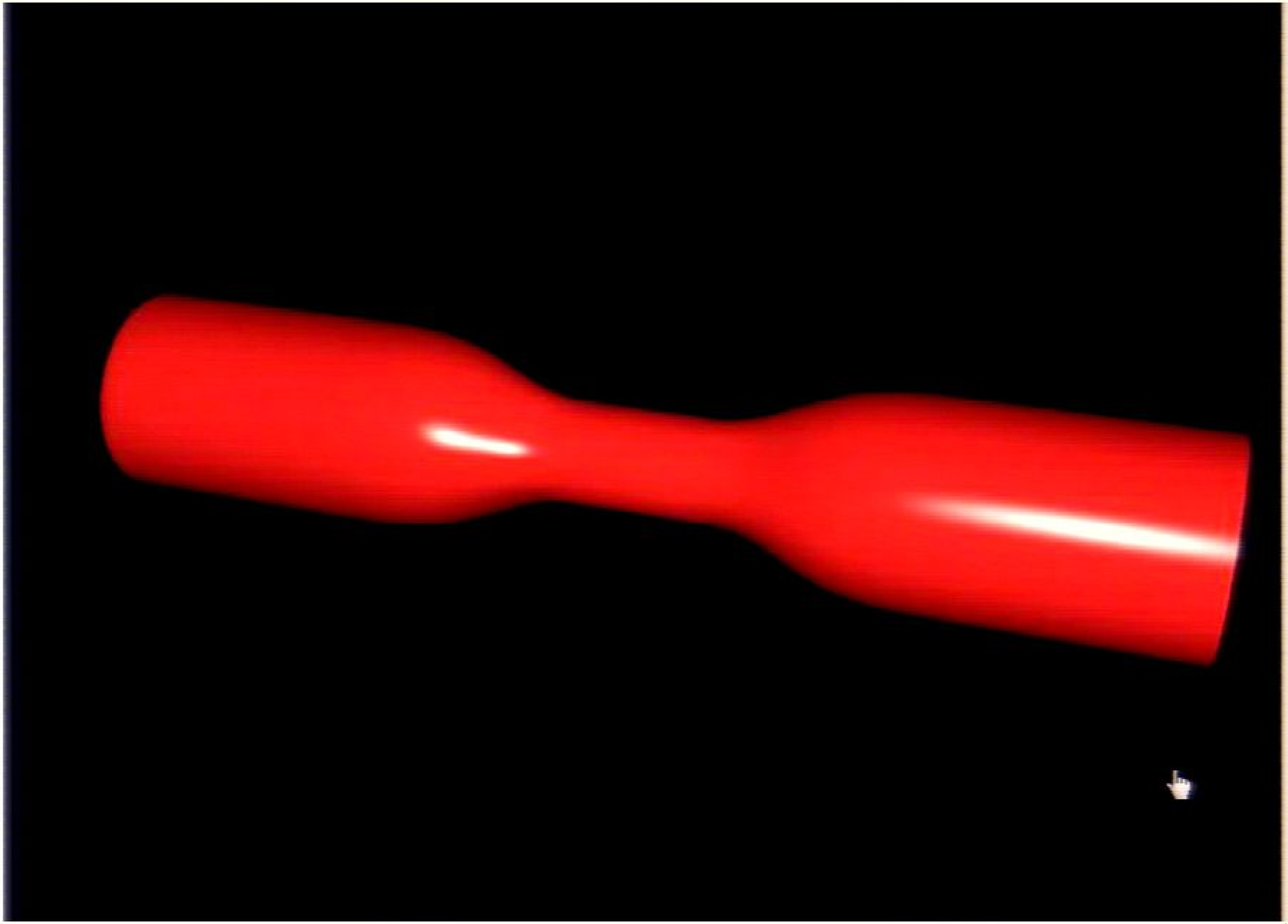


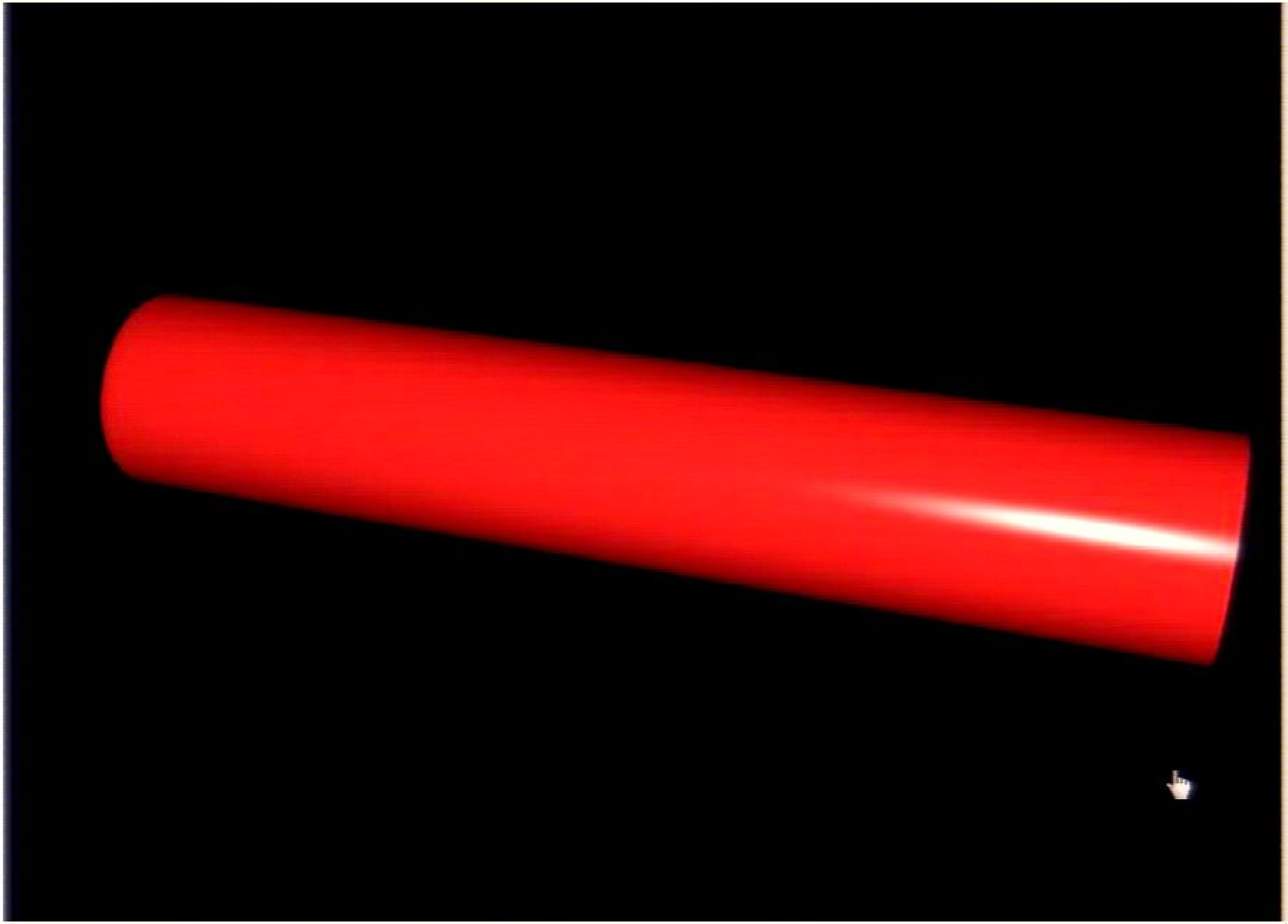


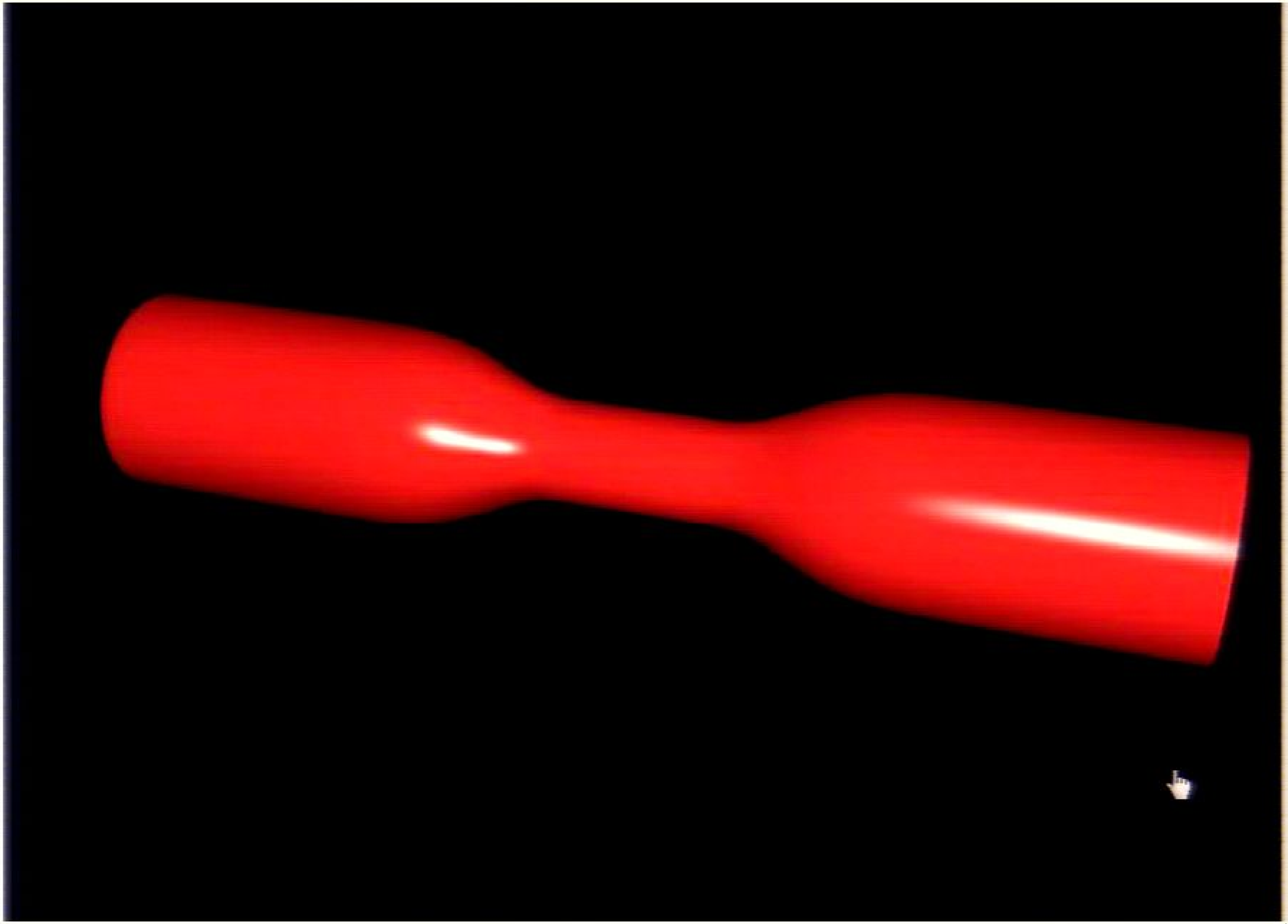


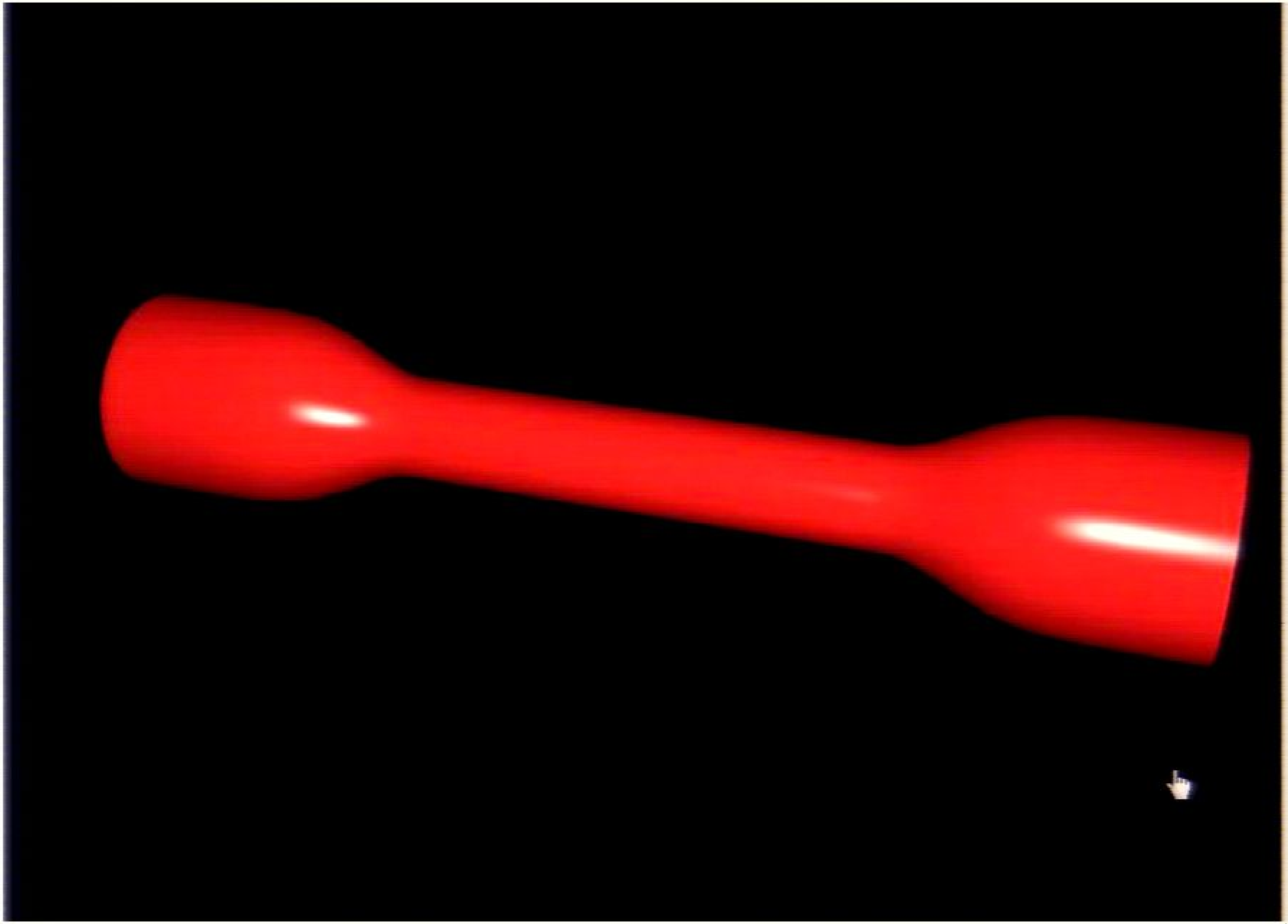


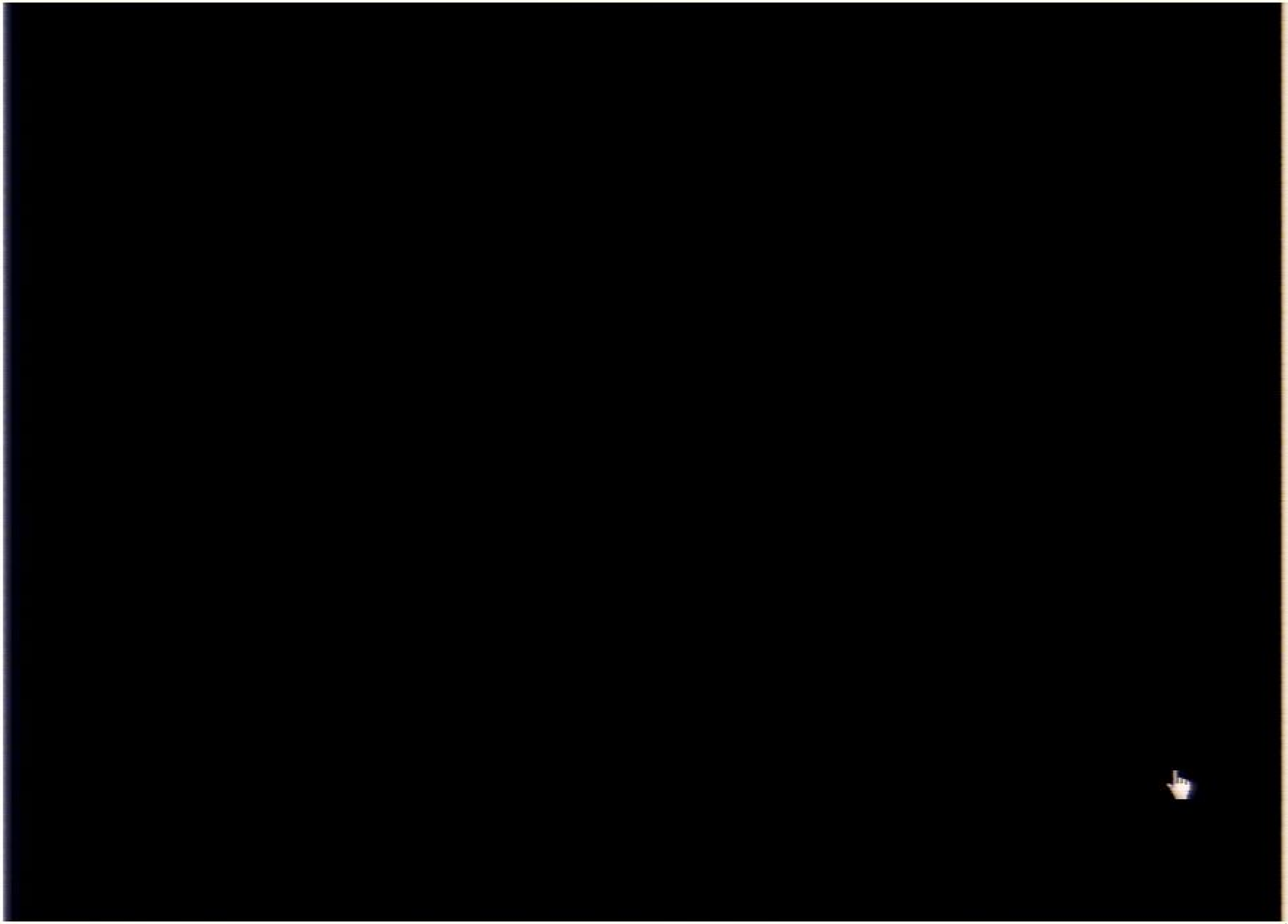




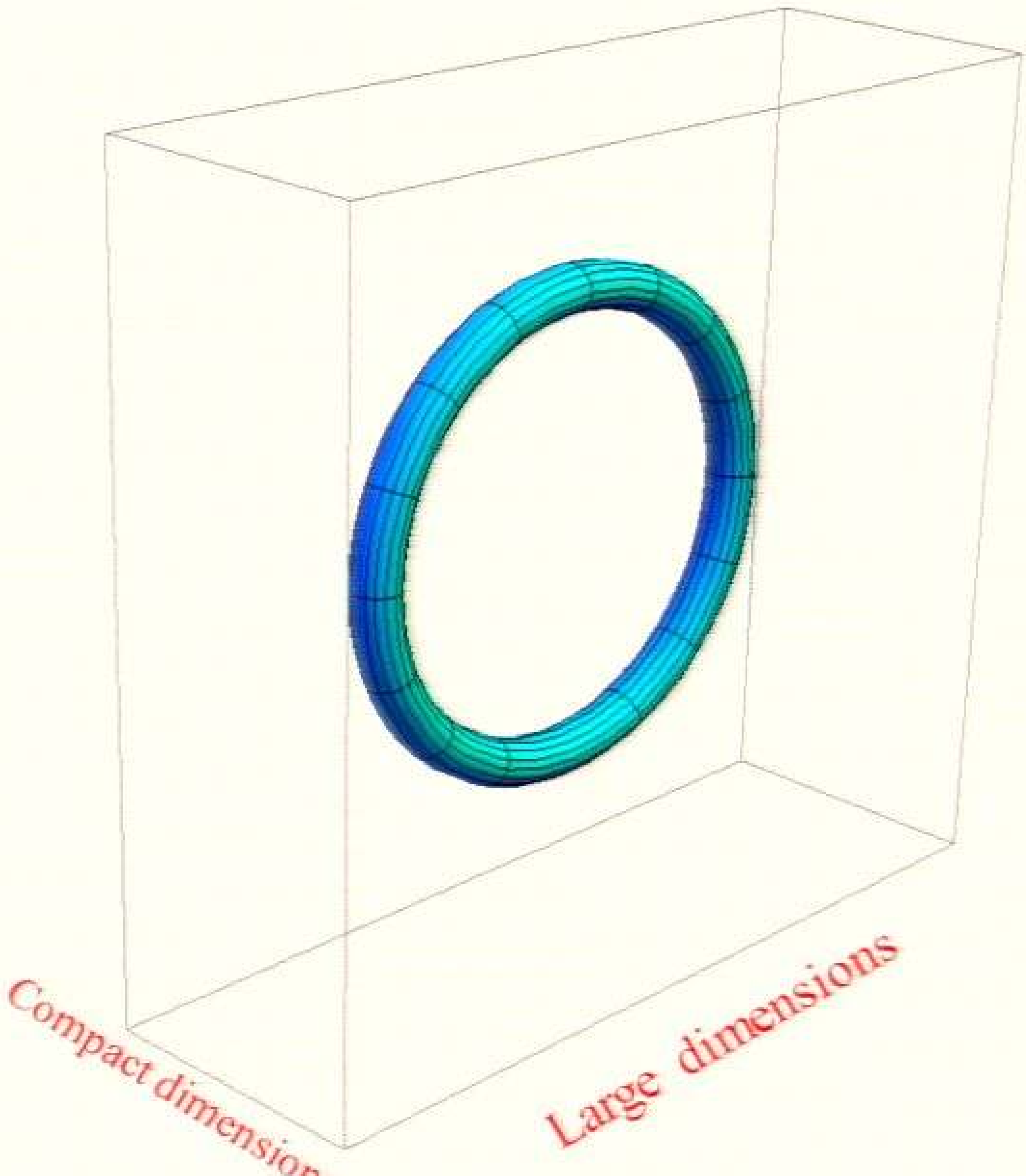




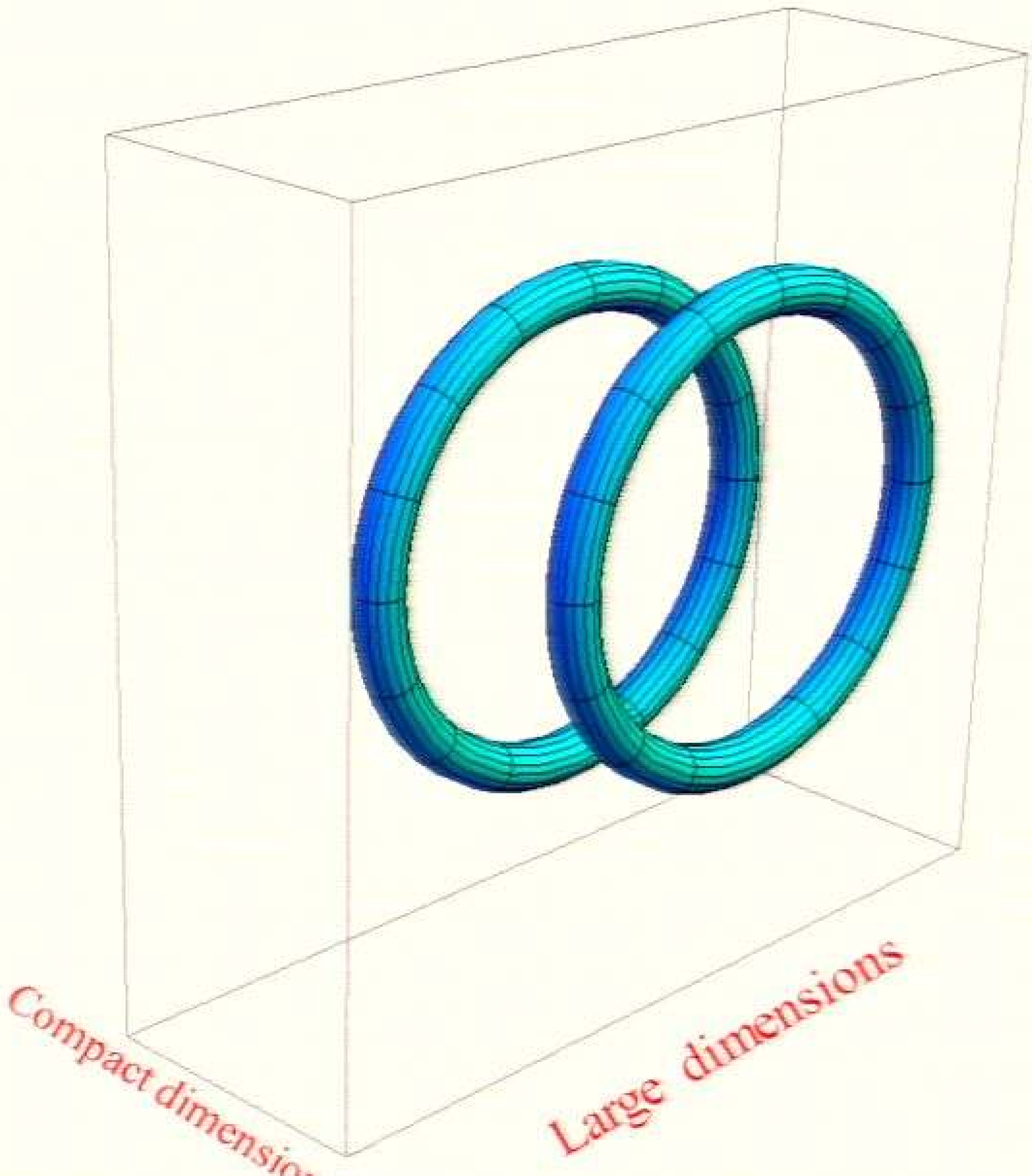




Bubble Ring Collisions



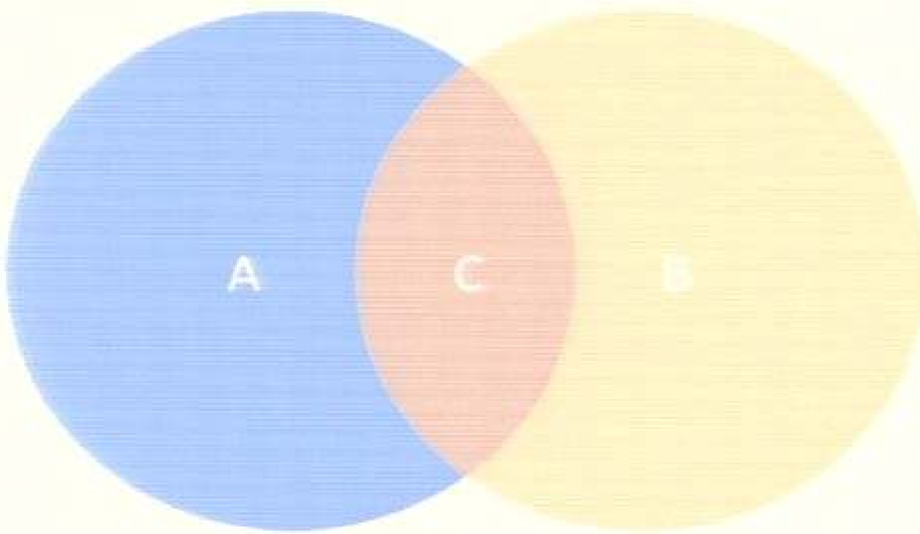
Bubble Ring Collisions



Bubble Collisions

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

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



Our vacuum could 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:

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

$$F_{tr} = \frac{q}{R^4} \sqrt{-g_2}$$

Electric Sector

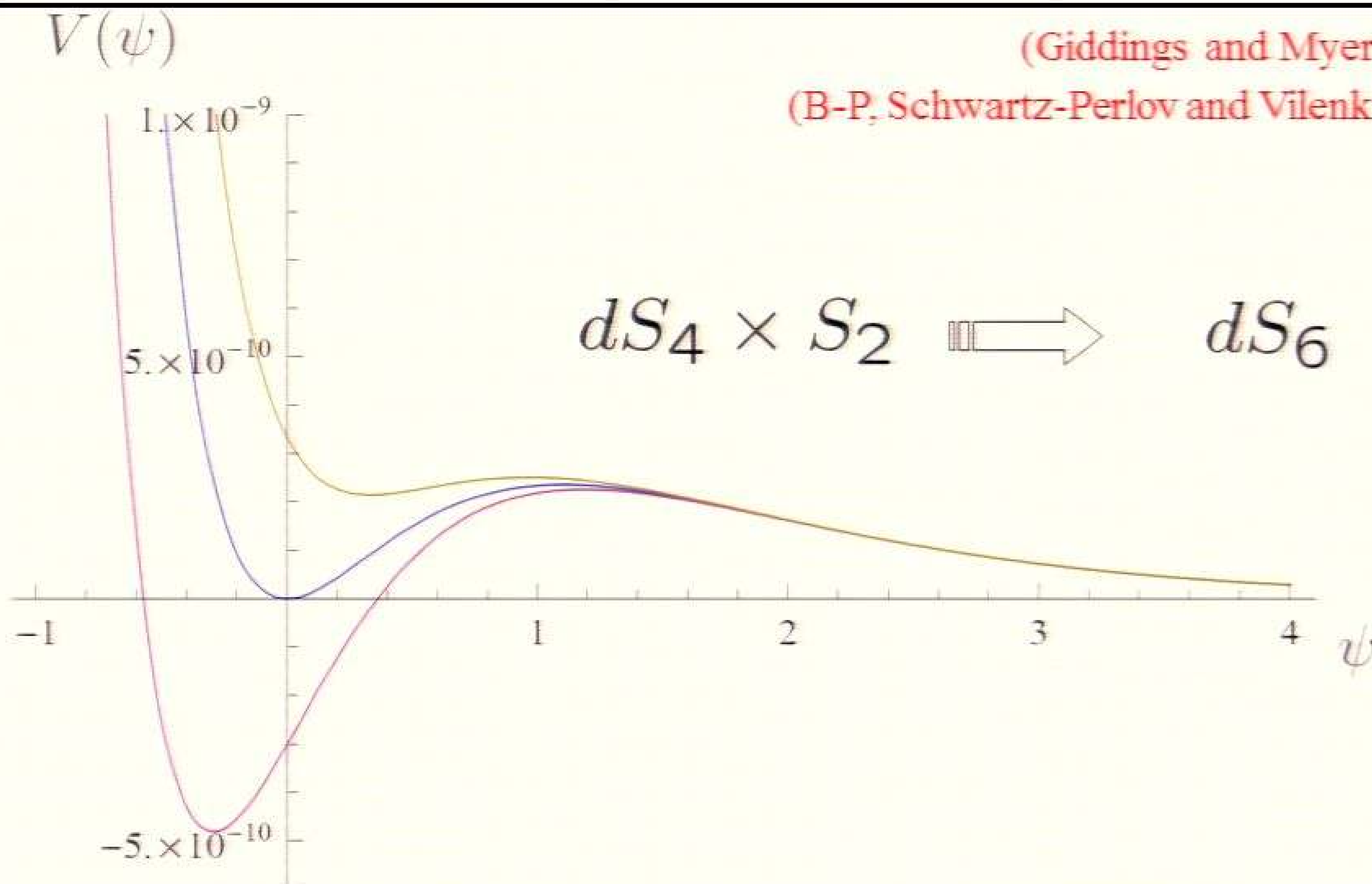
- There is also a dS_6 sector where there is no charge.

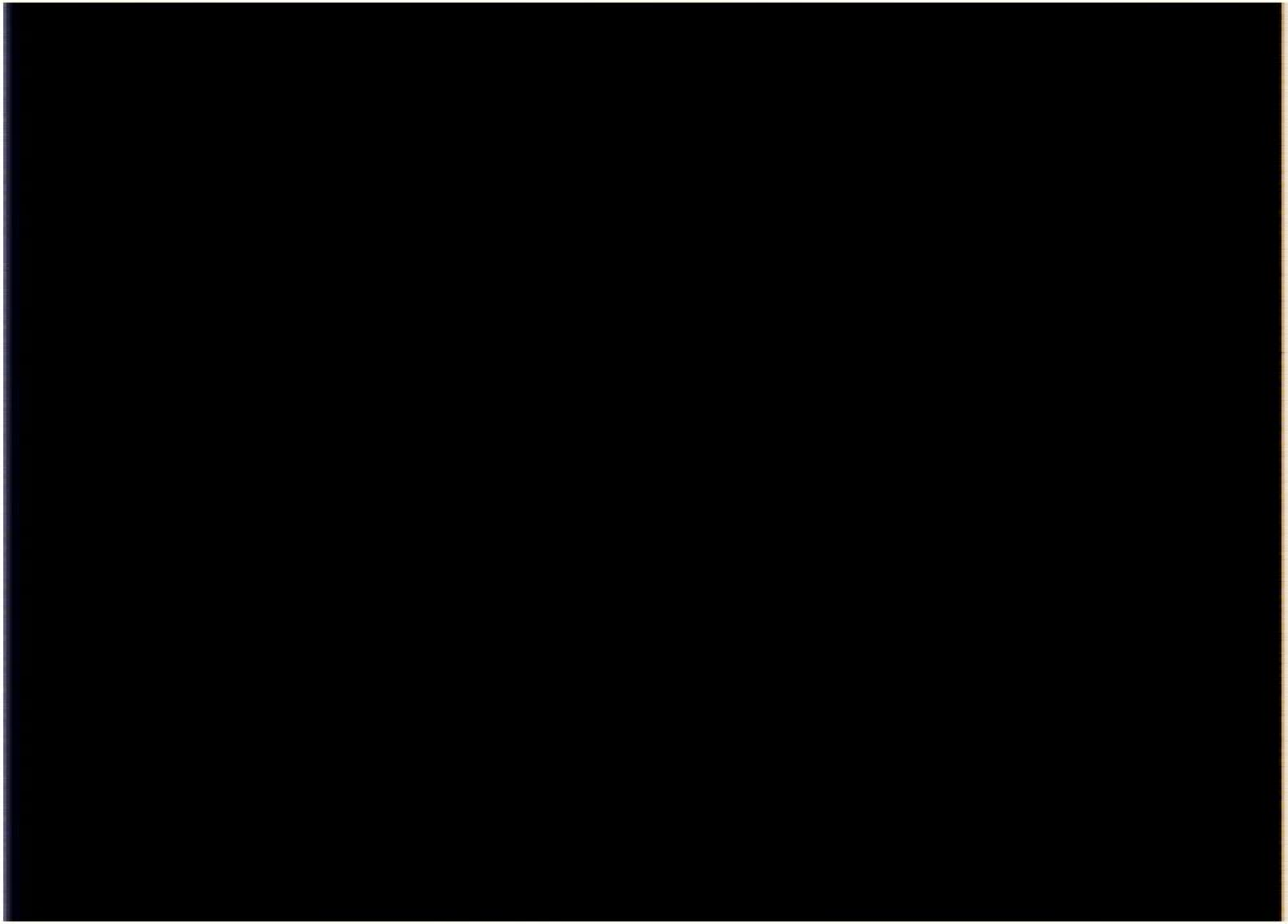
Decompactification

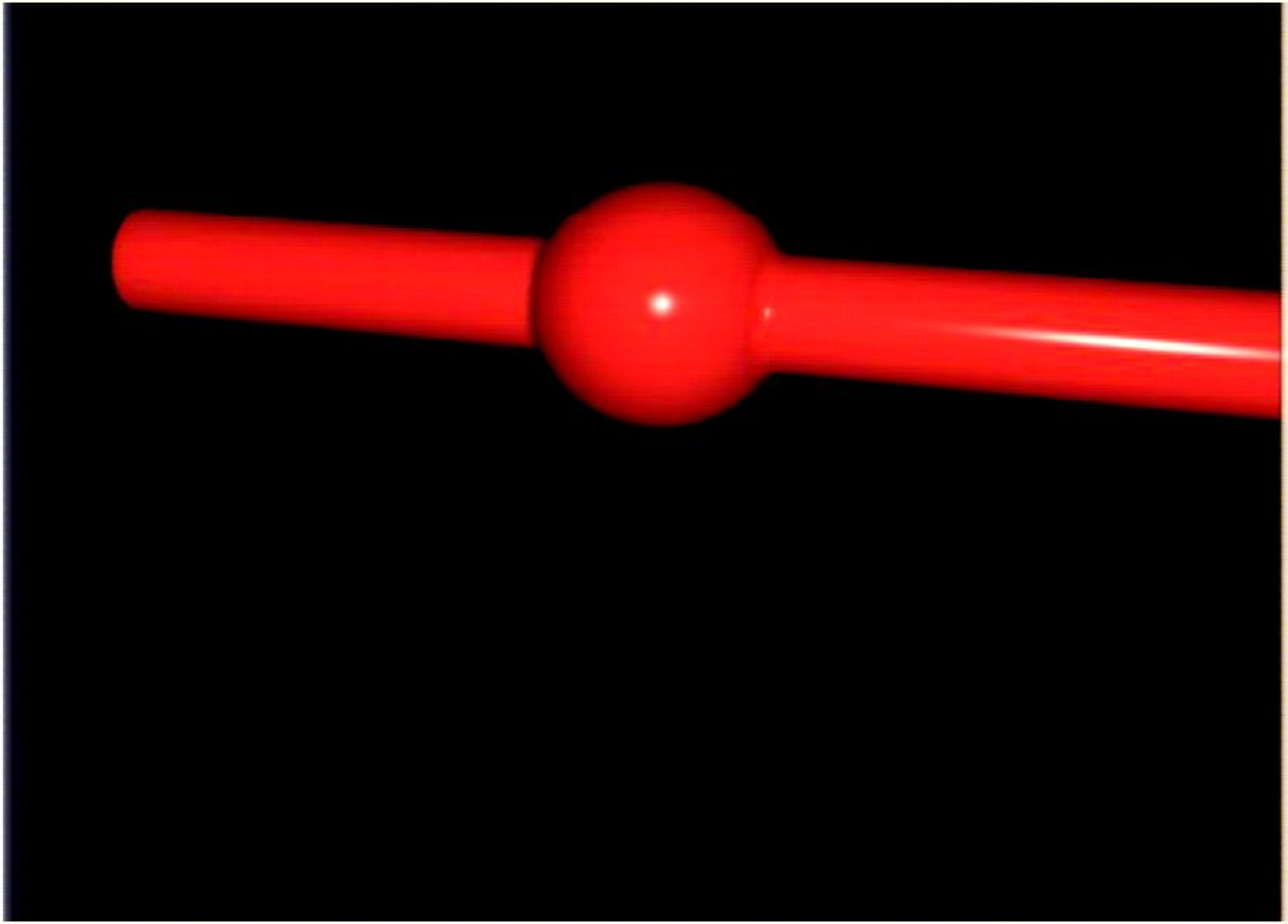
(Linde and Zelnikov, 1988).

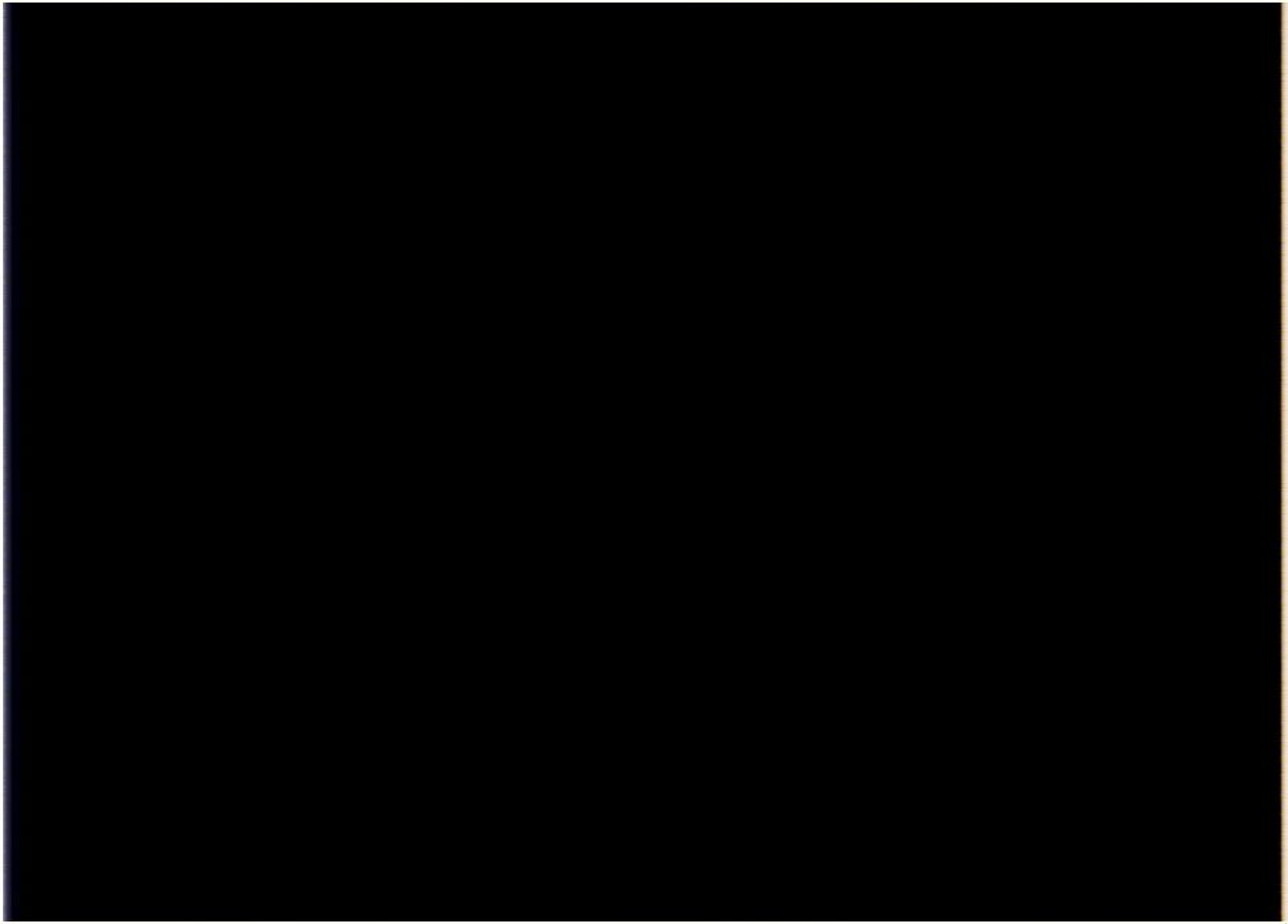
(Giddings and Myers, 2004).

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





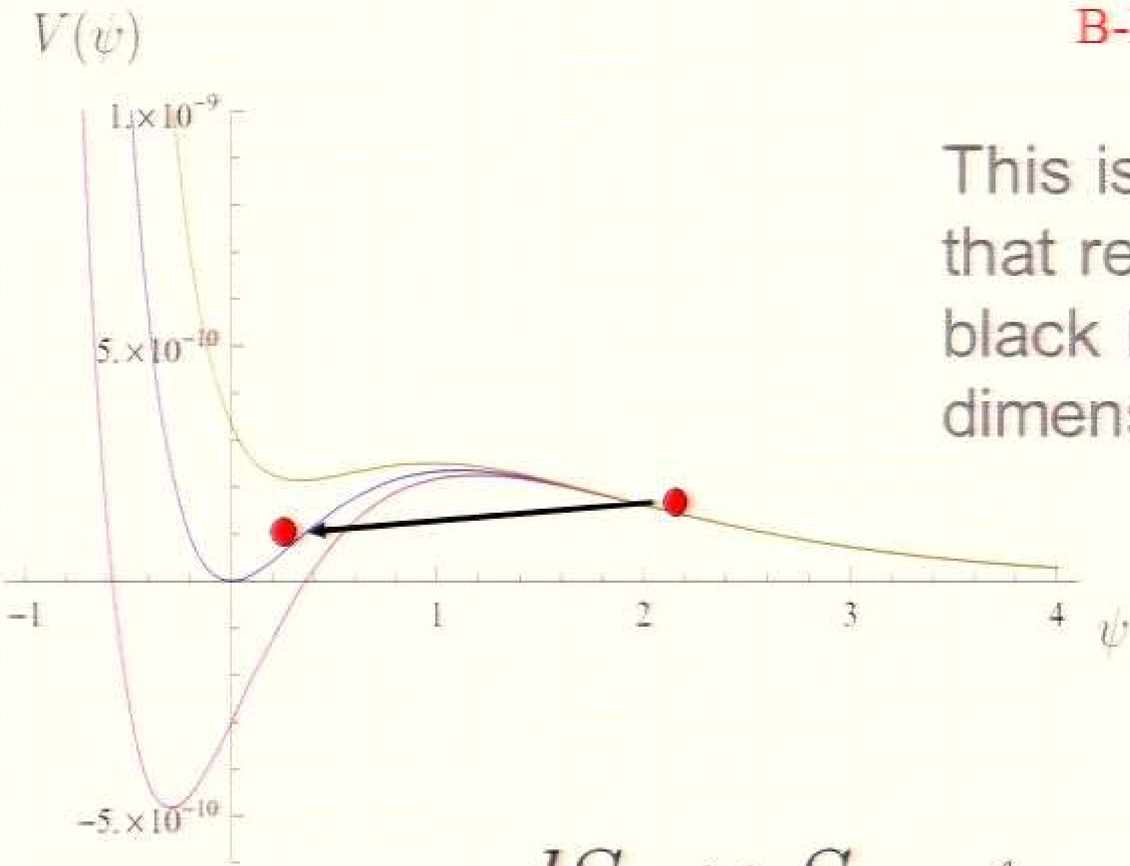




Dynamical compactification

Carroll, Johnson and Randall, (2009).

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



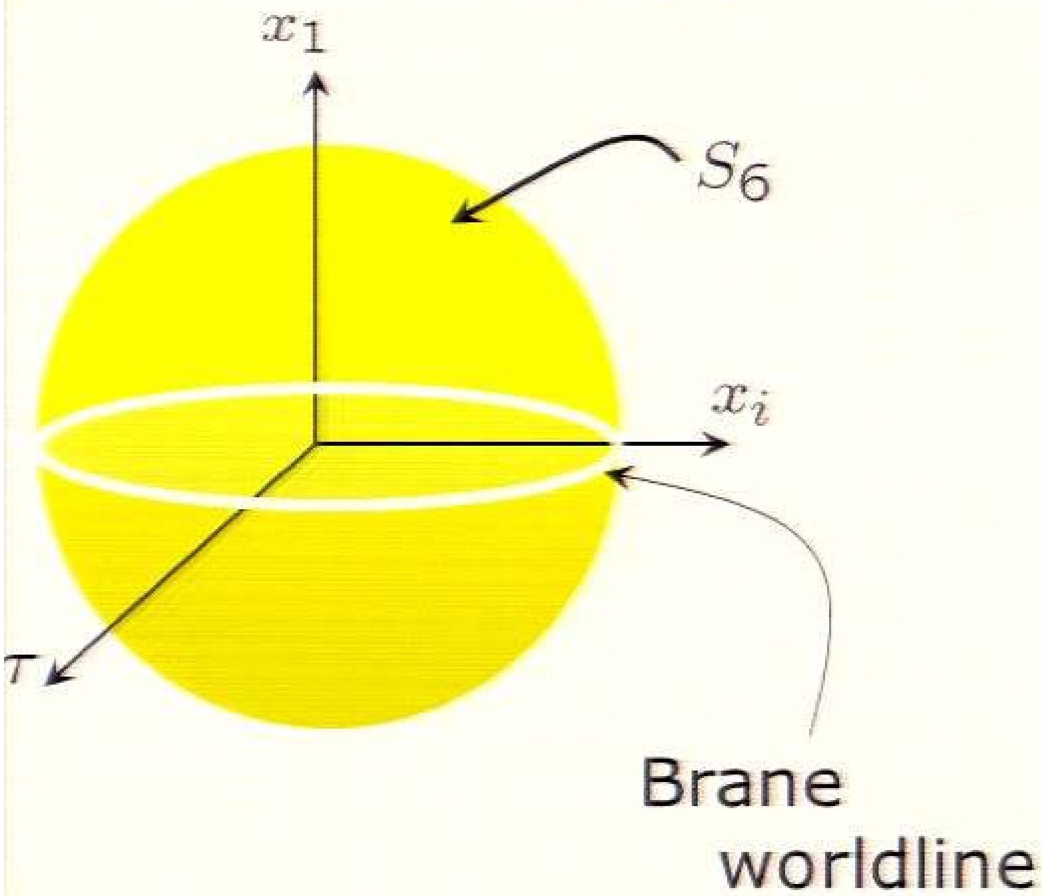
This is another kind of transition that represents the formation of black holes or branes in higher dimensional de Sitter space.

(Lee and Weinberg '87).

$$dS_4 \times S_2 \Longleftarrow dS_6$$

Brane Nucleation in de Sitter

(Basu, Guth and Vilenkin '92).

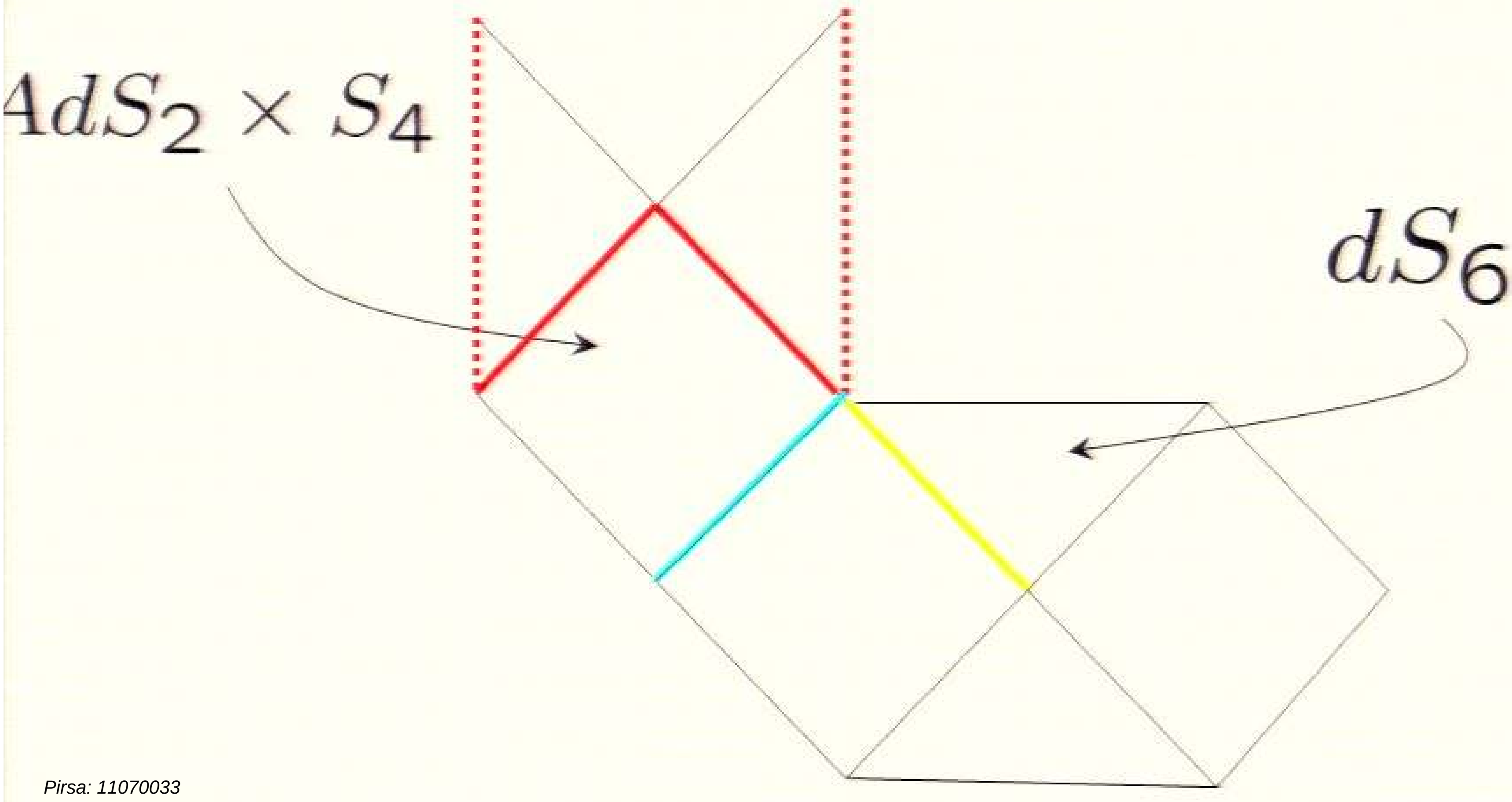


- Solution of the Euclidean equations of motion.
- Disregards backreaction on the geometry.
- In the Lorentzian part objects are stretched by the de Sitter expansion.
- In our case we have 2 types of objects: black holes and magnetic 2-branes.

Black Hole Pair Creation

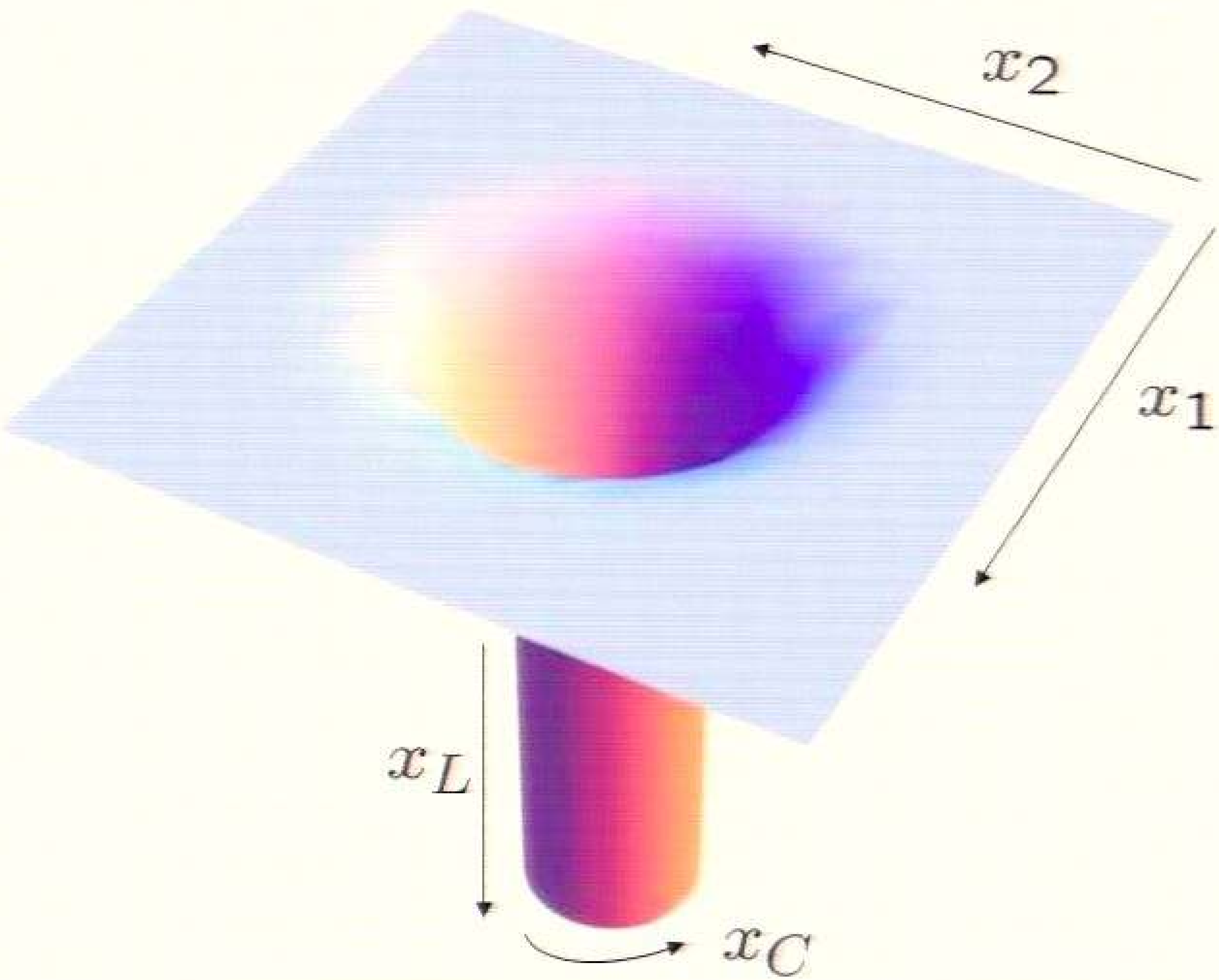
The creation of the pair of electrically charged black holes is a transition of the form:

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:

$$\begin{cases} ds^2 = B(\xi)^2\underbrace{(-dt^2 + \cosh(t)^2 d\tilde{\Omega}_2^2)}_{\text{Inflating 2+1 worldvolume}} + d\xi^2 + r(\xi)^2 d\Omega_2^2 \\ F_{\theta\phi} = \frac{g}{4\pi}\sin\theta \end{cases}$$

$\Longrightarrow$ Magnetically charged

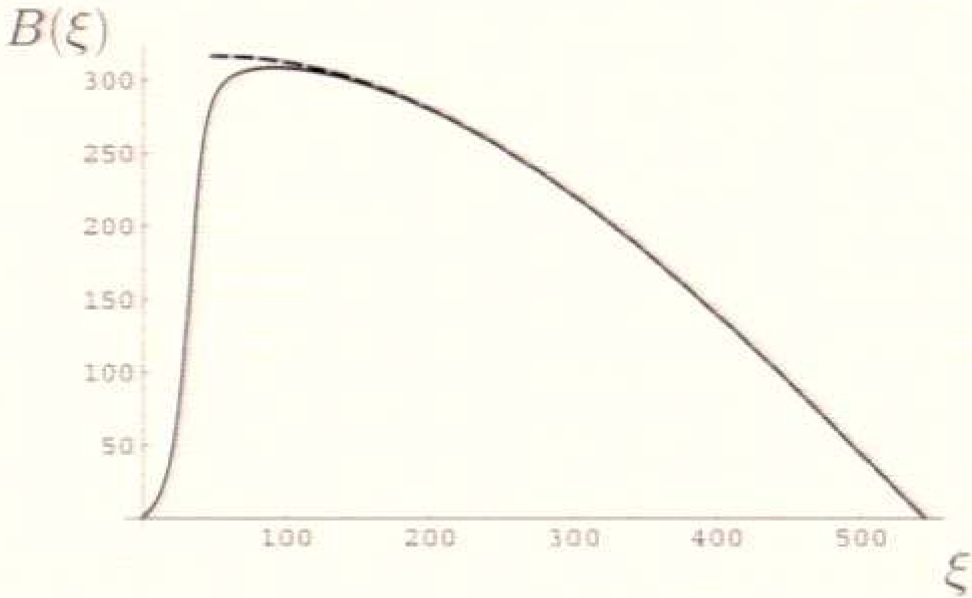
$$\left.\begin{array}{l} B(0) = B(\xi_{max}) = 0 \\ B'(0) = B'(\xi_{max}) = 1 \\ r'(0) = r'(\xi_{max}) = 0 \end{array}\right\}$$

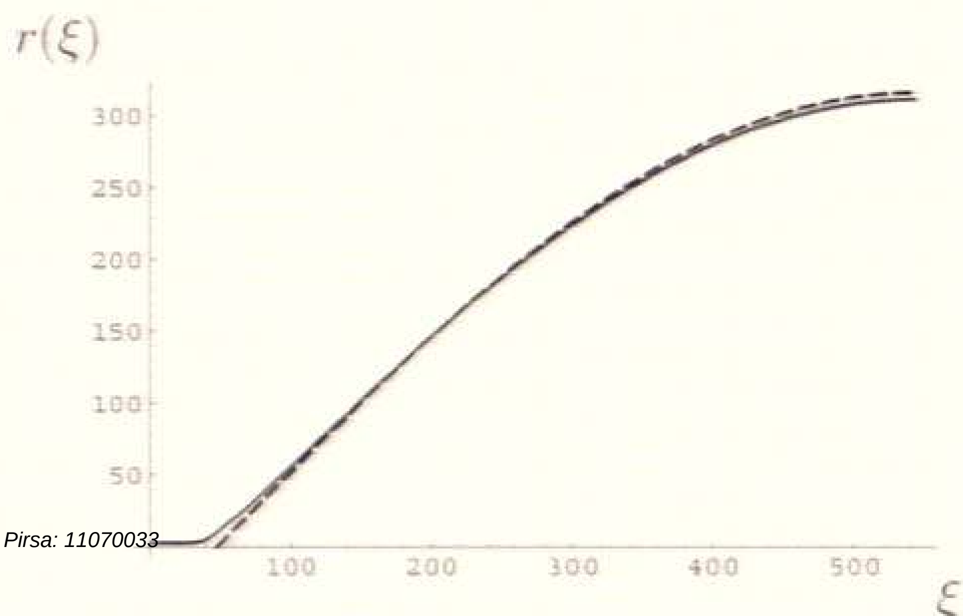
$\Longrightarrow$ Smooth at the horizons

$$\left.\begin{array}{r} r(\xi_{max}) = r_2 \\ r(0) = r_1 \end{array}\right\}$$

$\Longrightarrow$ One should find these values numerically

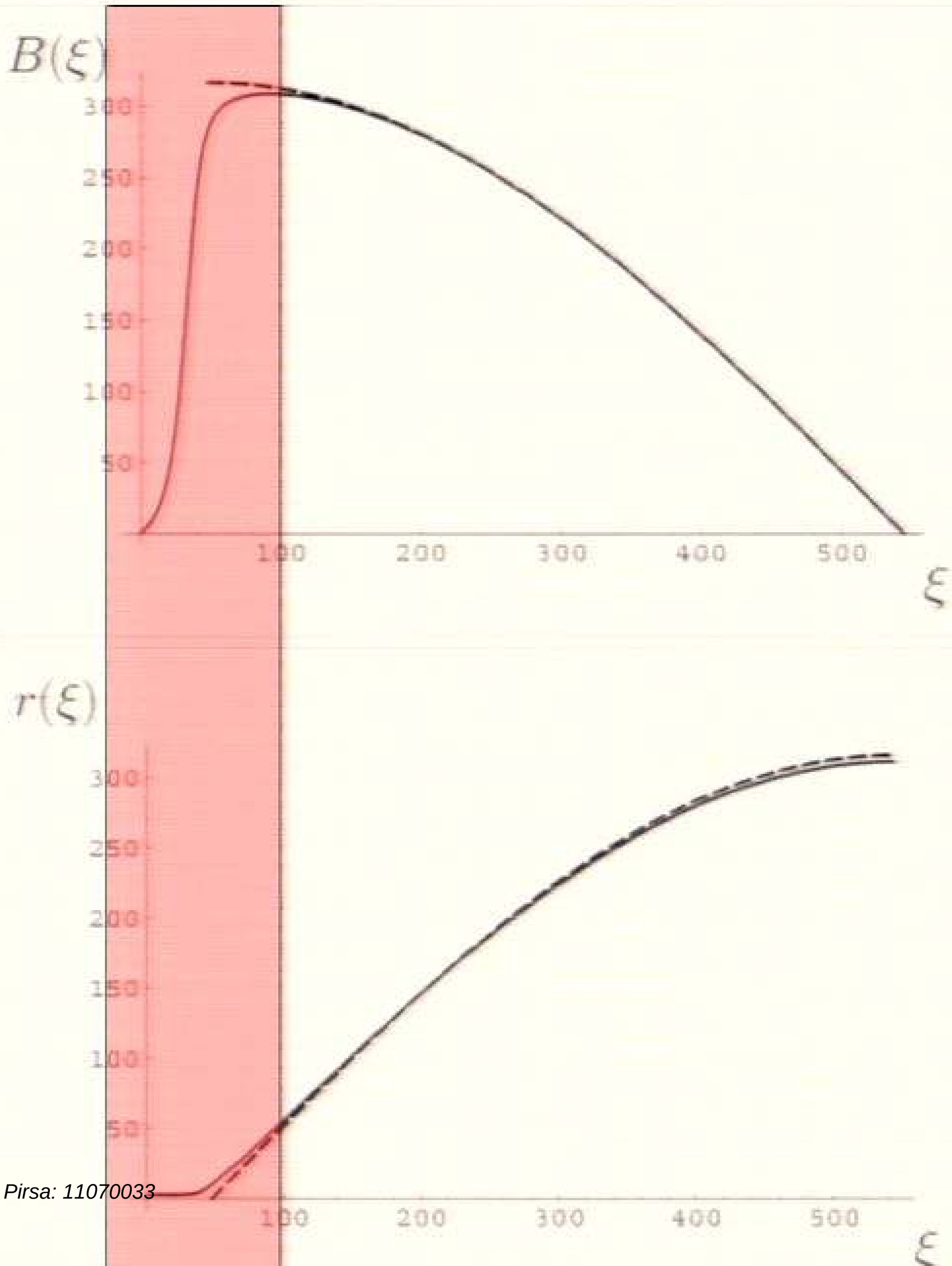
2-brane nucleation





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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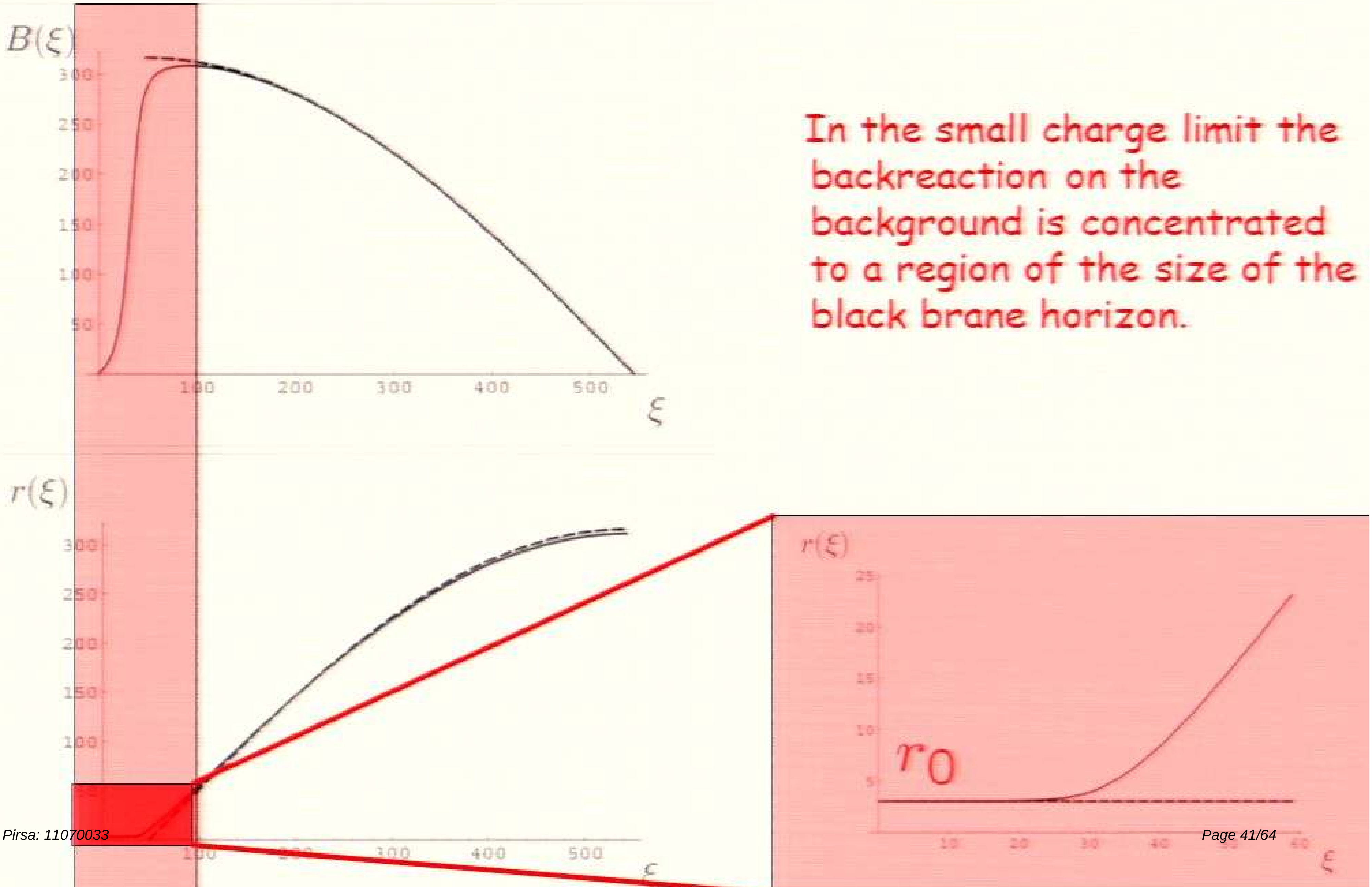
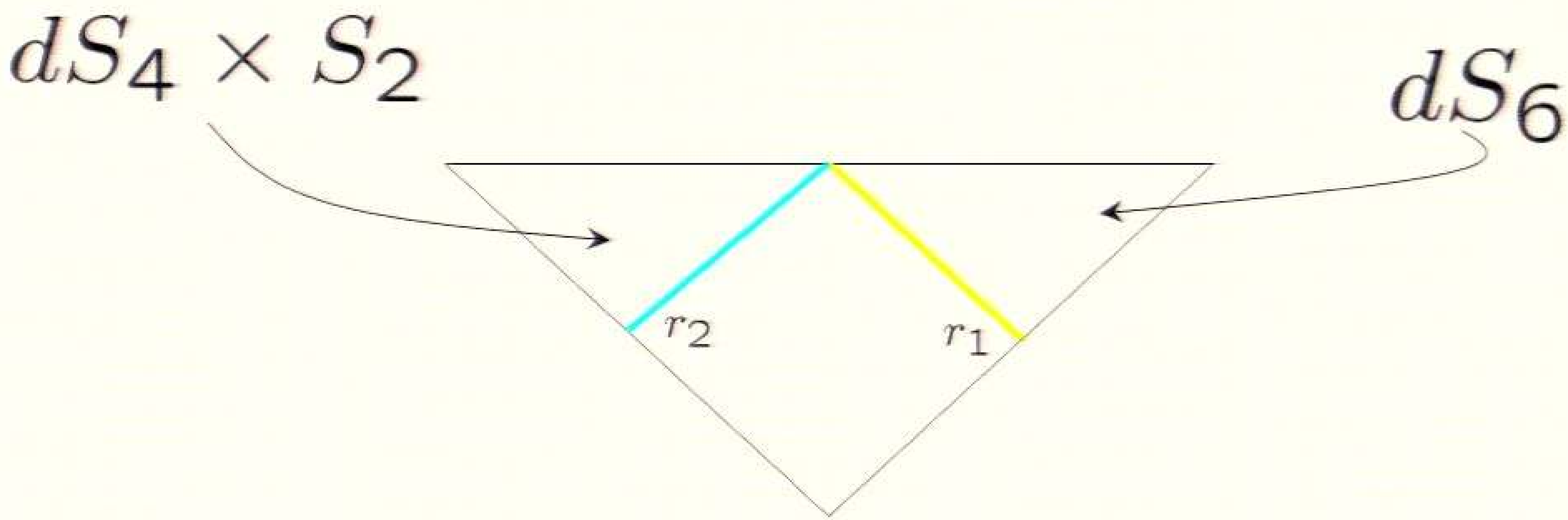


In the small charge limit the backreaction on the background is concentrated to a region of the size of the black brane horizon.

Inflating branes mediate dynamical compactification



Bubbles of Nothing

Witten (82).

Are there are 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 Schwarzchild geometry in 5d we obtain:

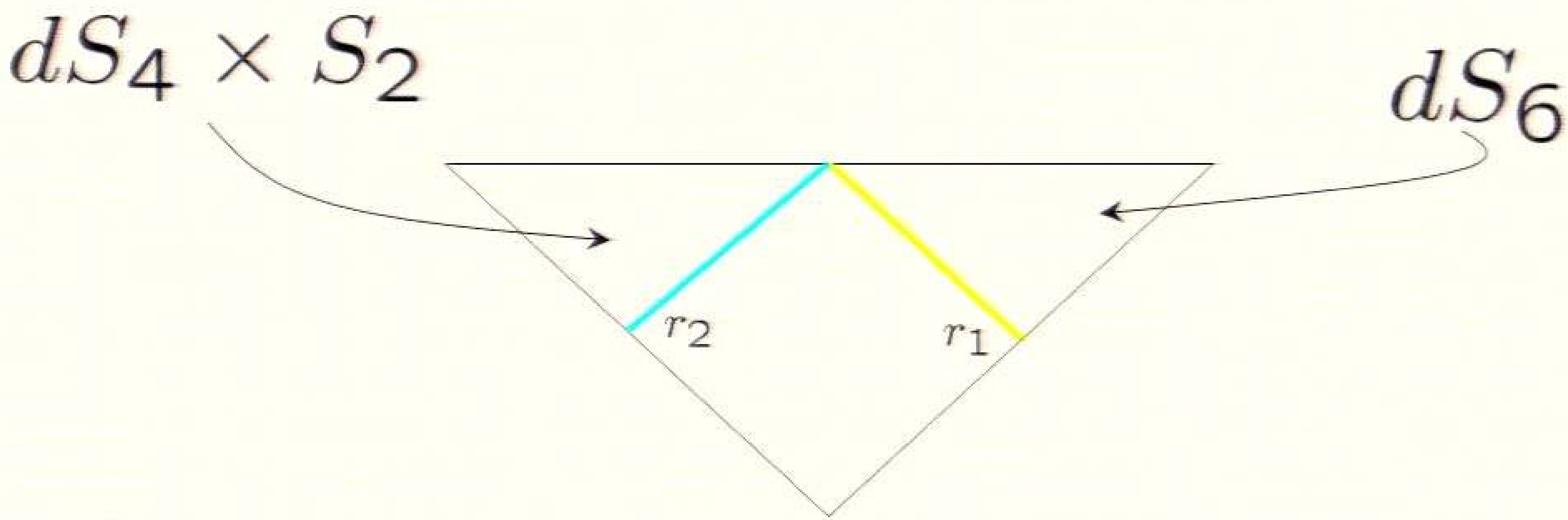
$$y \equiv y + 2\pi$$

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

Cigar geometry

Bubble geometry

Inflating branes mediate dynamical compactification



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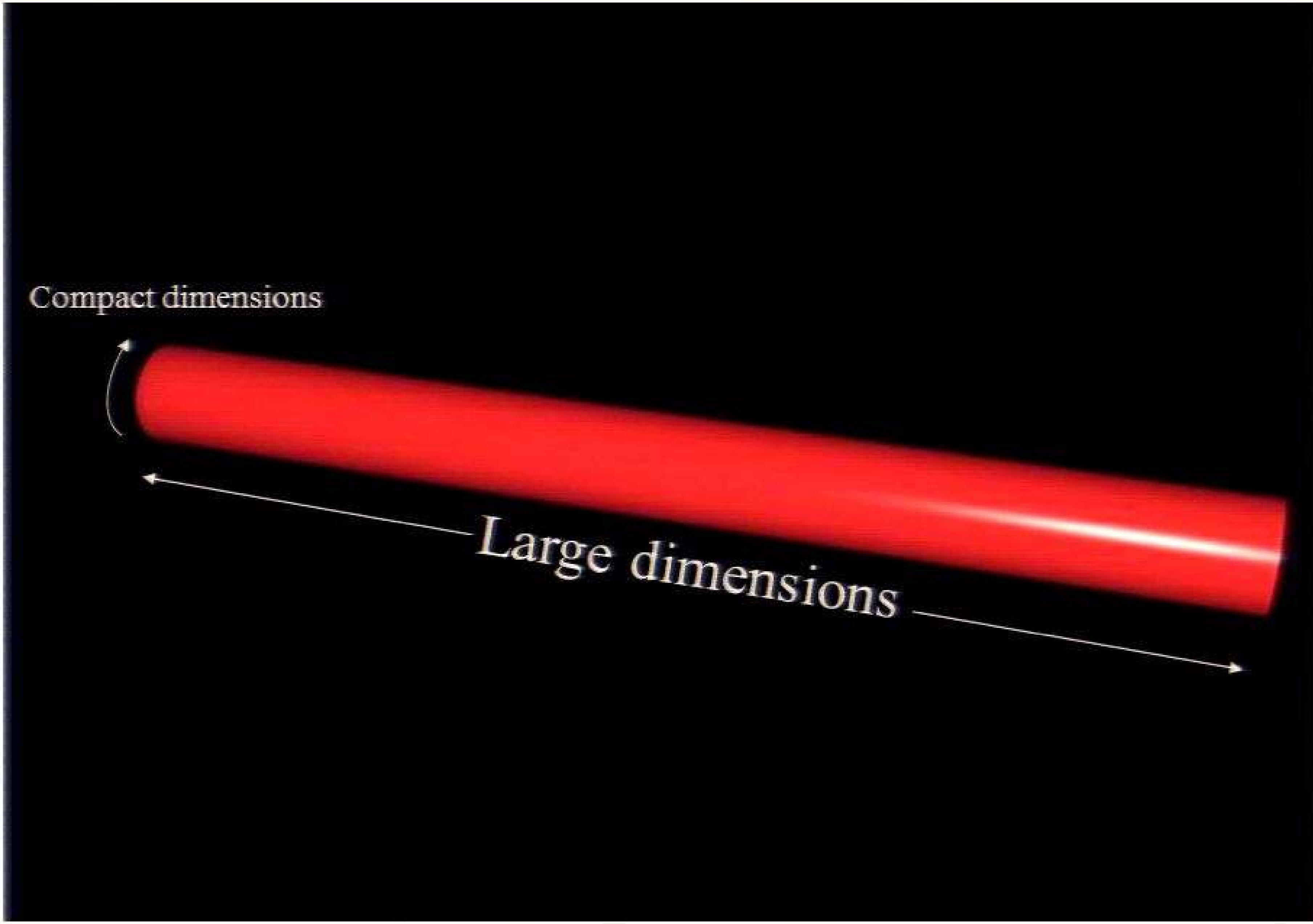
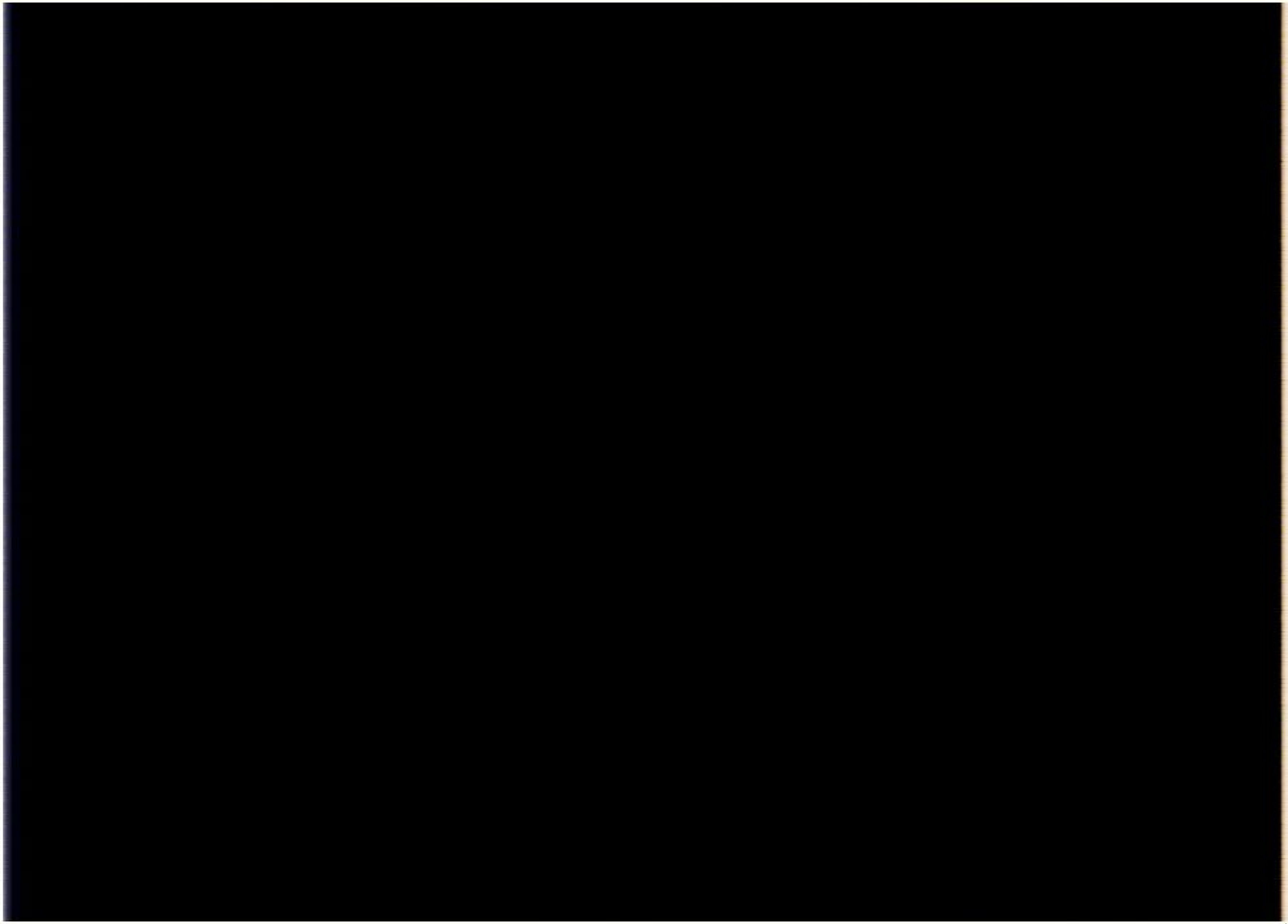
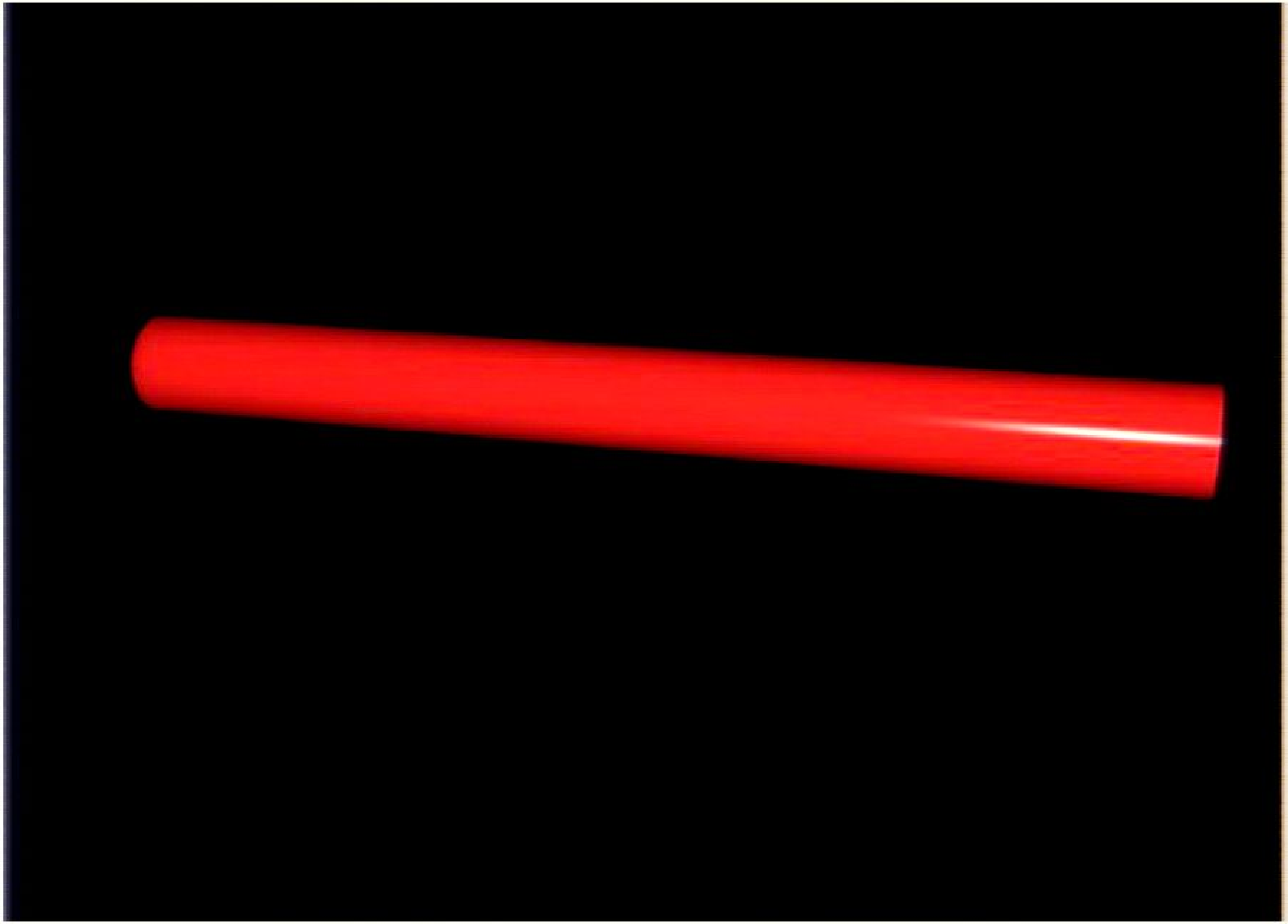
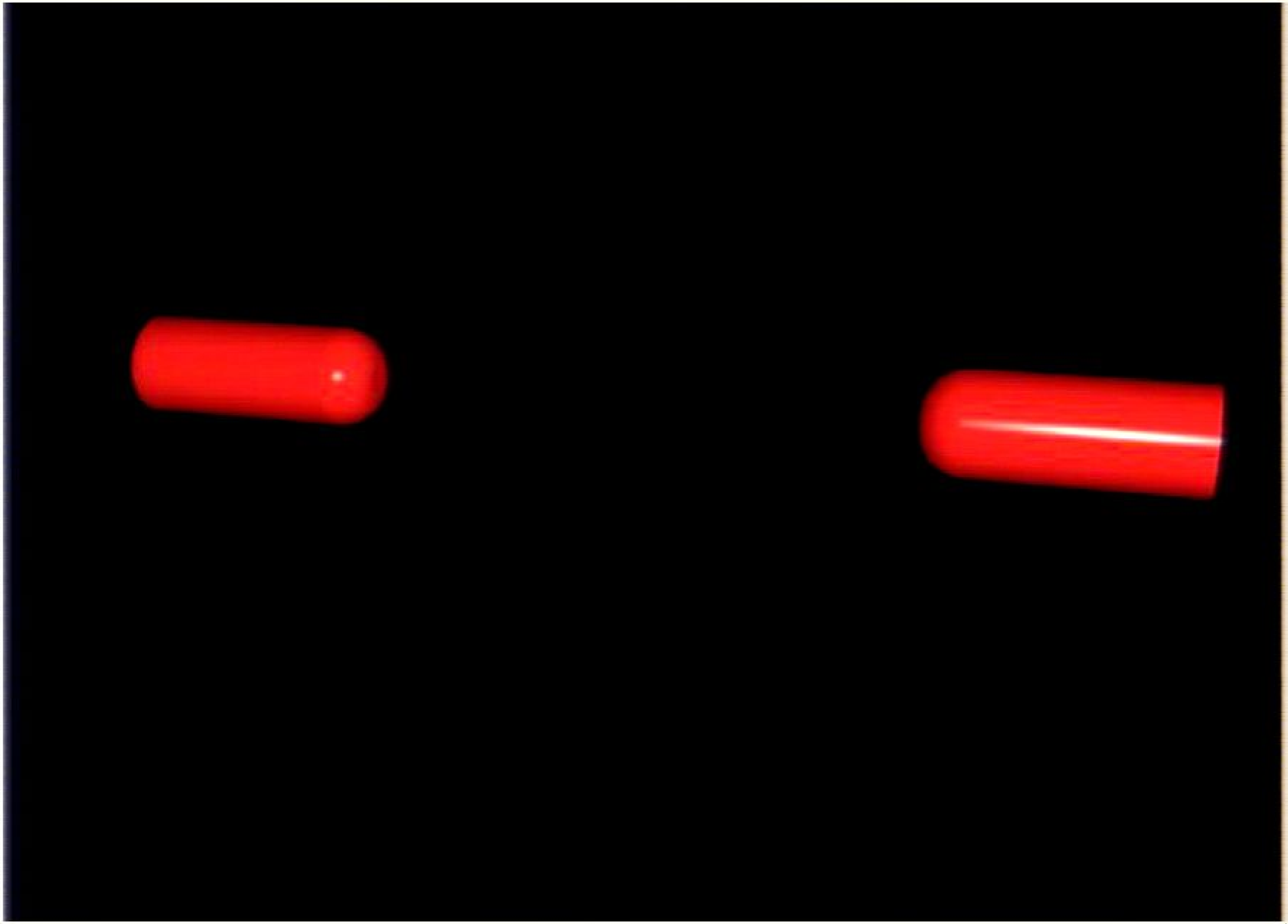
Cigar geometry

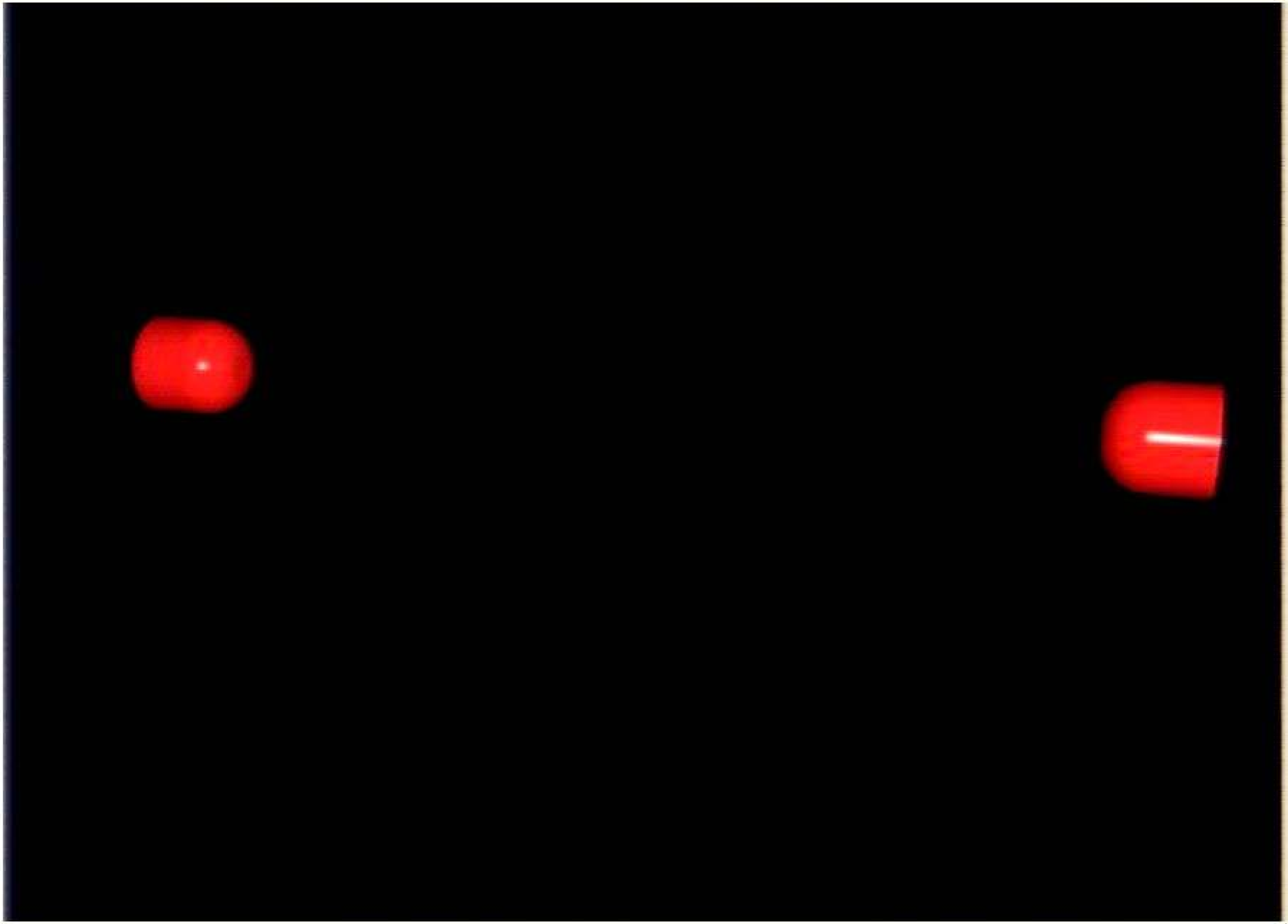
Bubble geometry

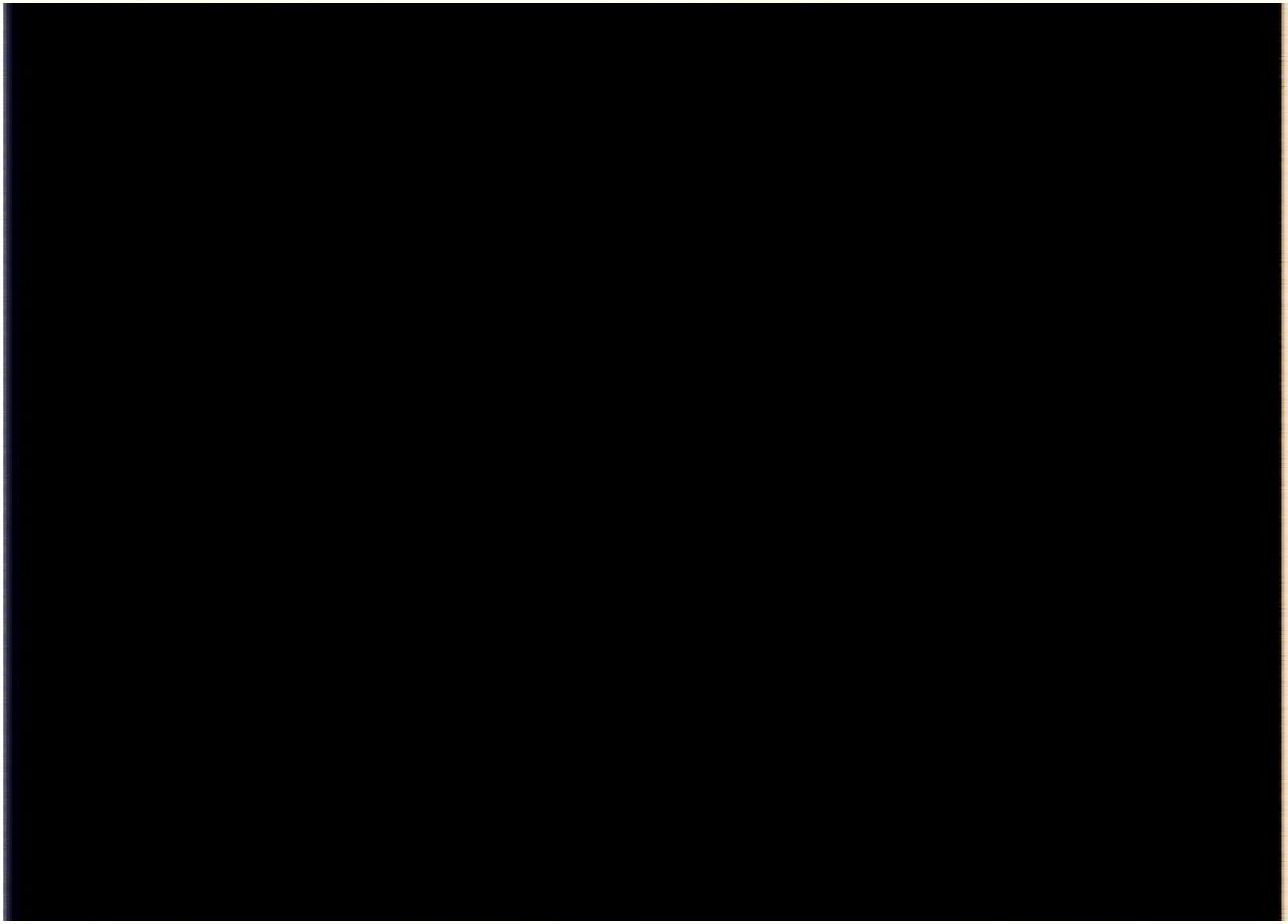

Compact dimensions
Large dimensions











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 ?

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

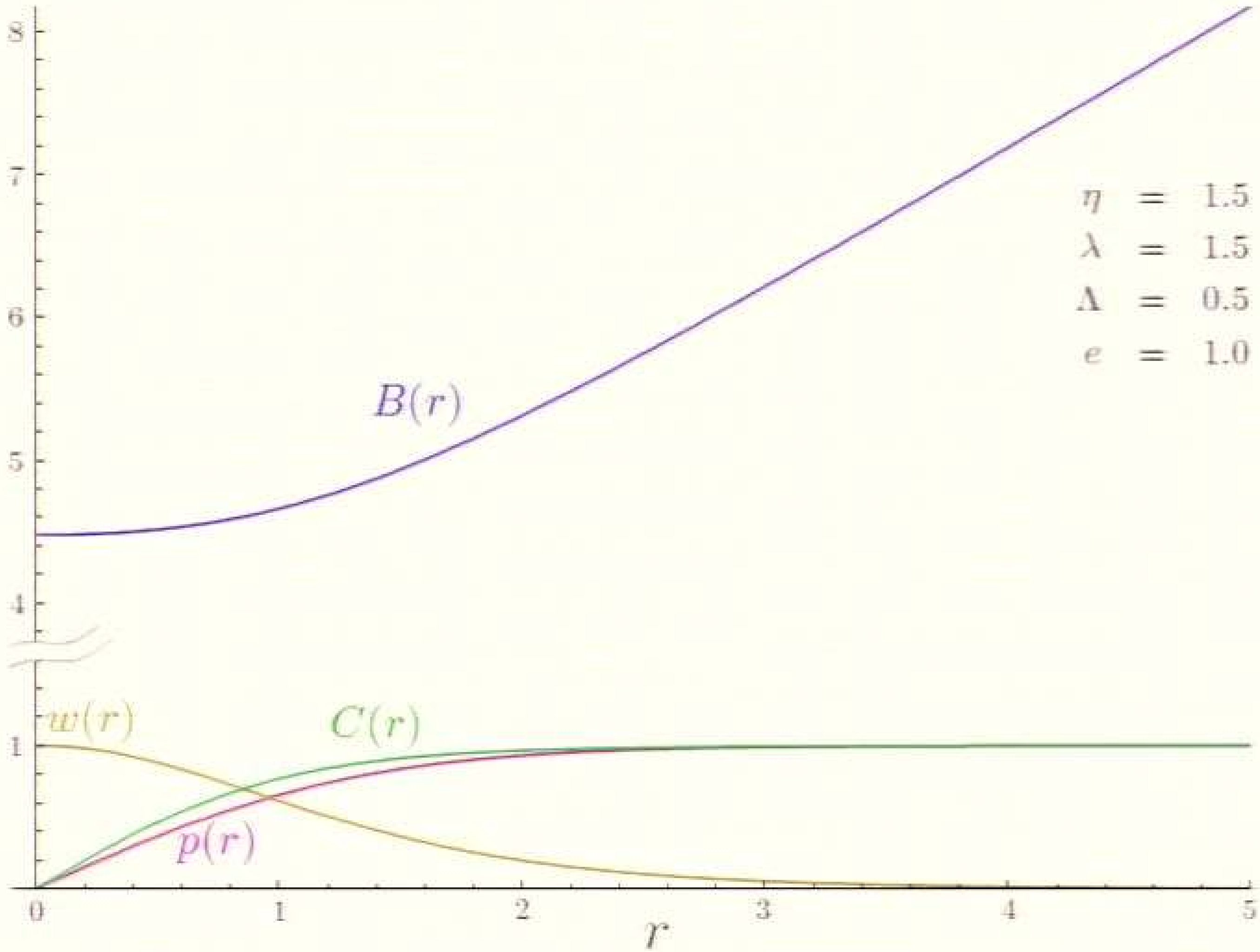
We need to regularize the tip of the cigar geometry so we upgrade our theory to an SU(2) version:

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

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).



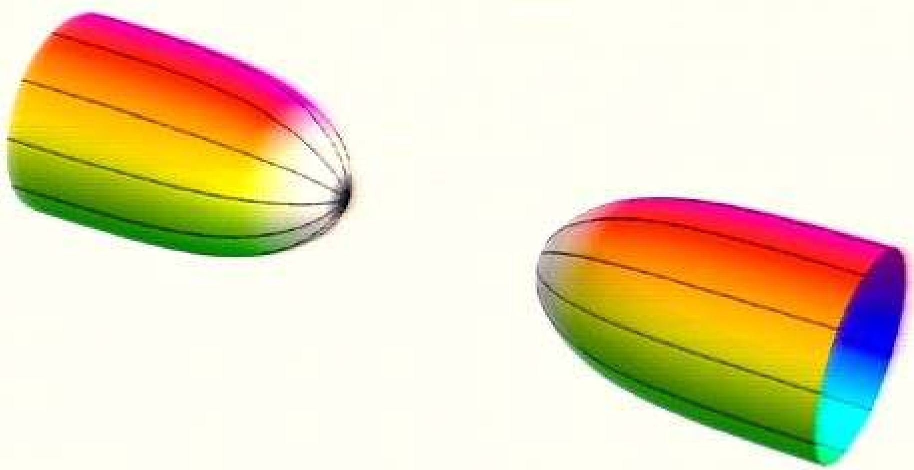
$$ds^2 = B(r)^2(-dt^2 + \cosh(t)^2 d\tilde{\Omega}_2^2) + dr^2 + C(r)^2 d\Omega_2^2$$

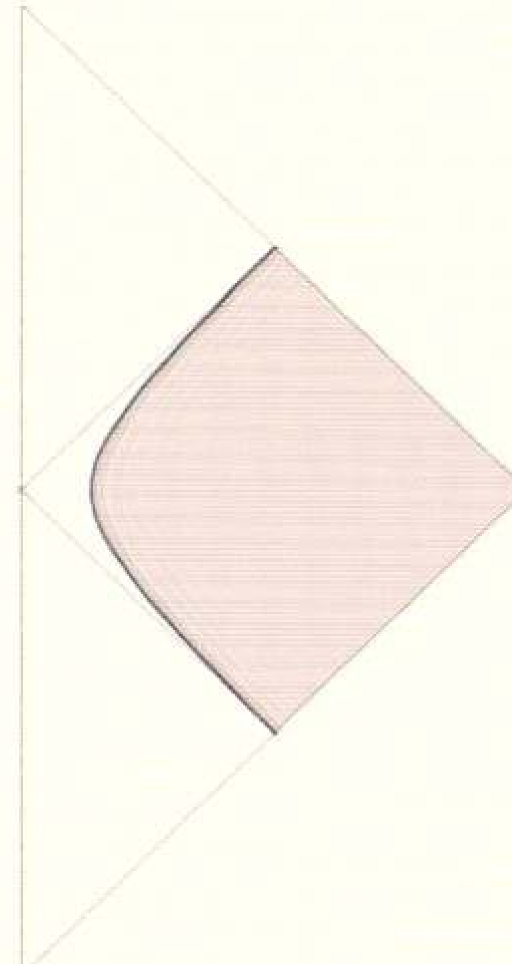
Bubbles of Nothing in Flux Compactifications

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

The solution can be thought of as an inflating brane.

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

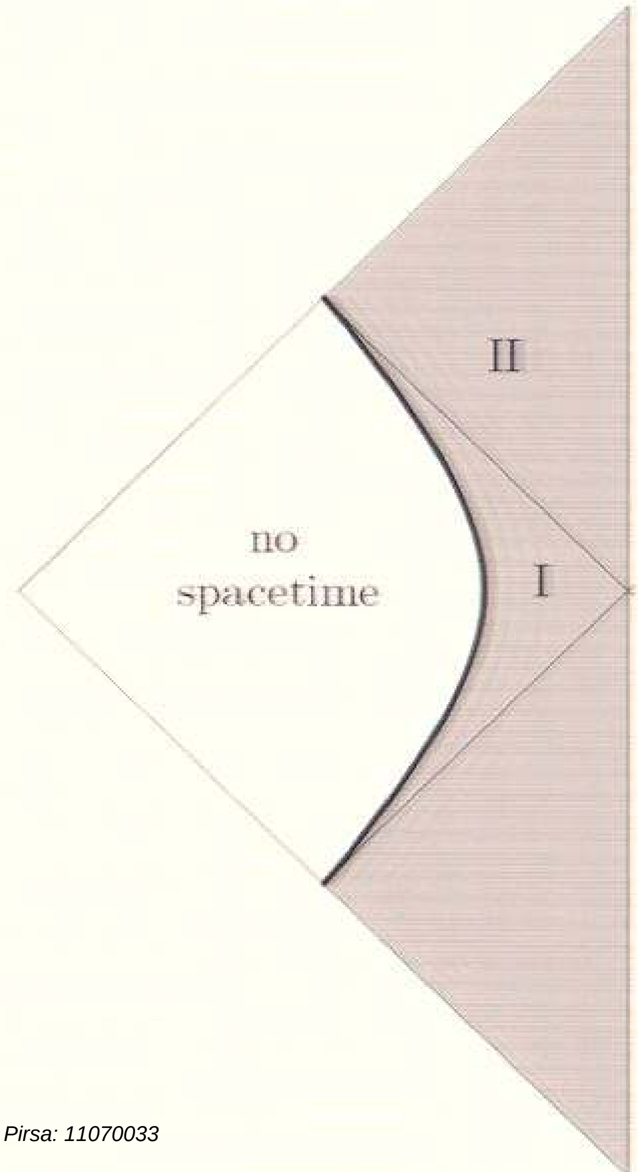




At some point these brane solutions become flat and the decay channel gets suppressed .

Bubbles from Nothing

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

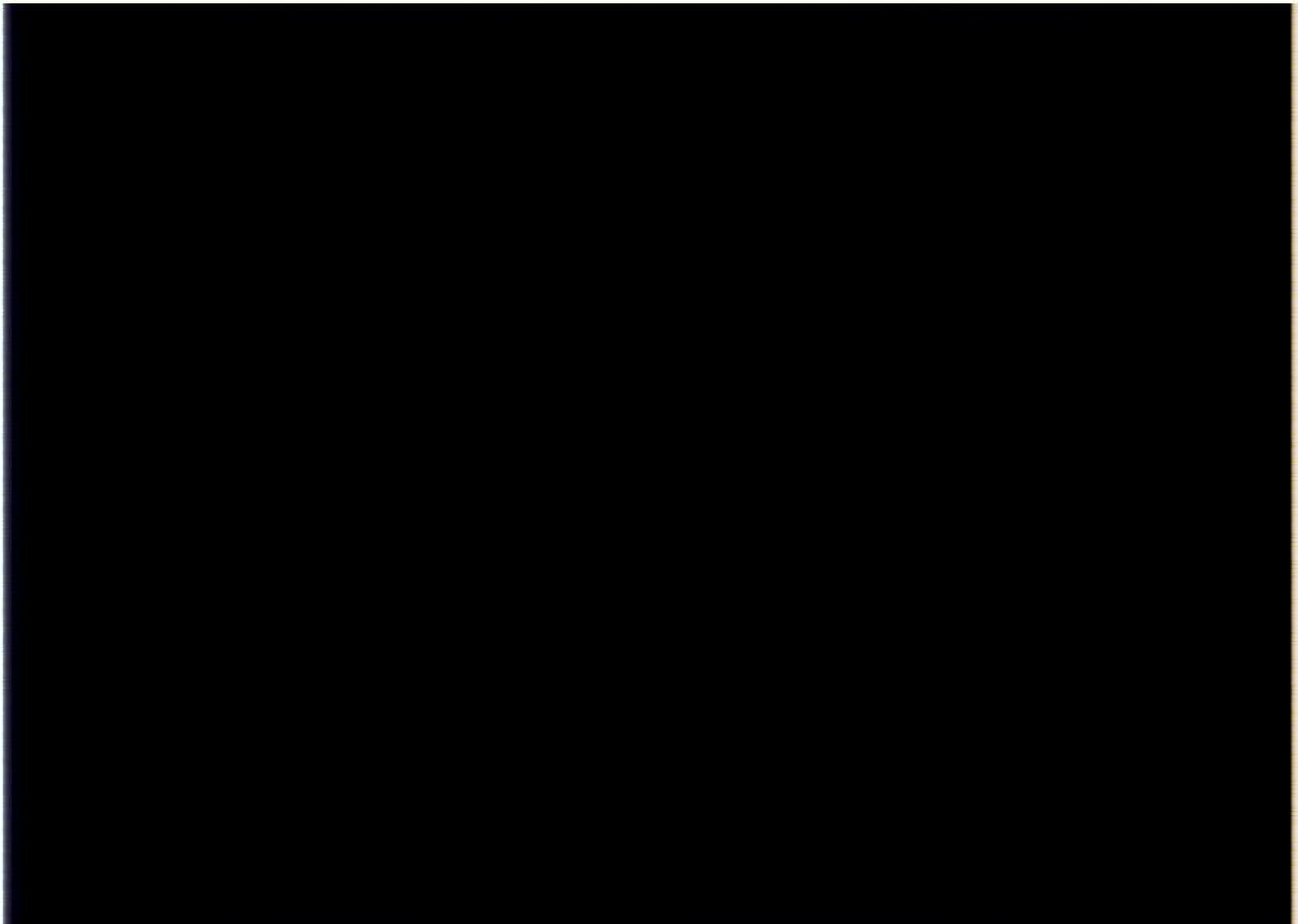


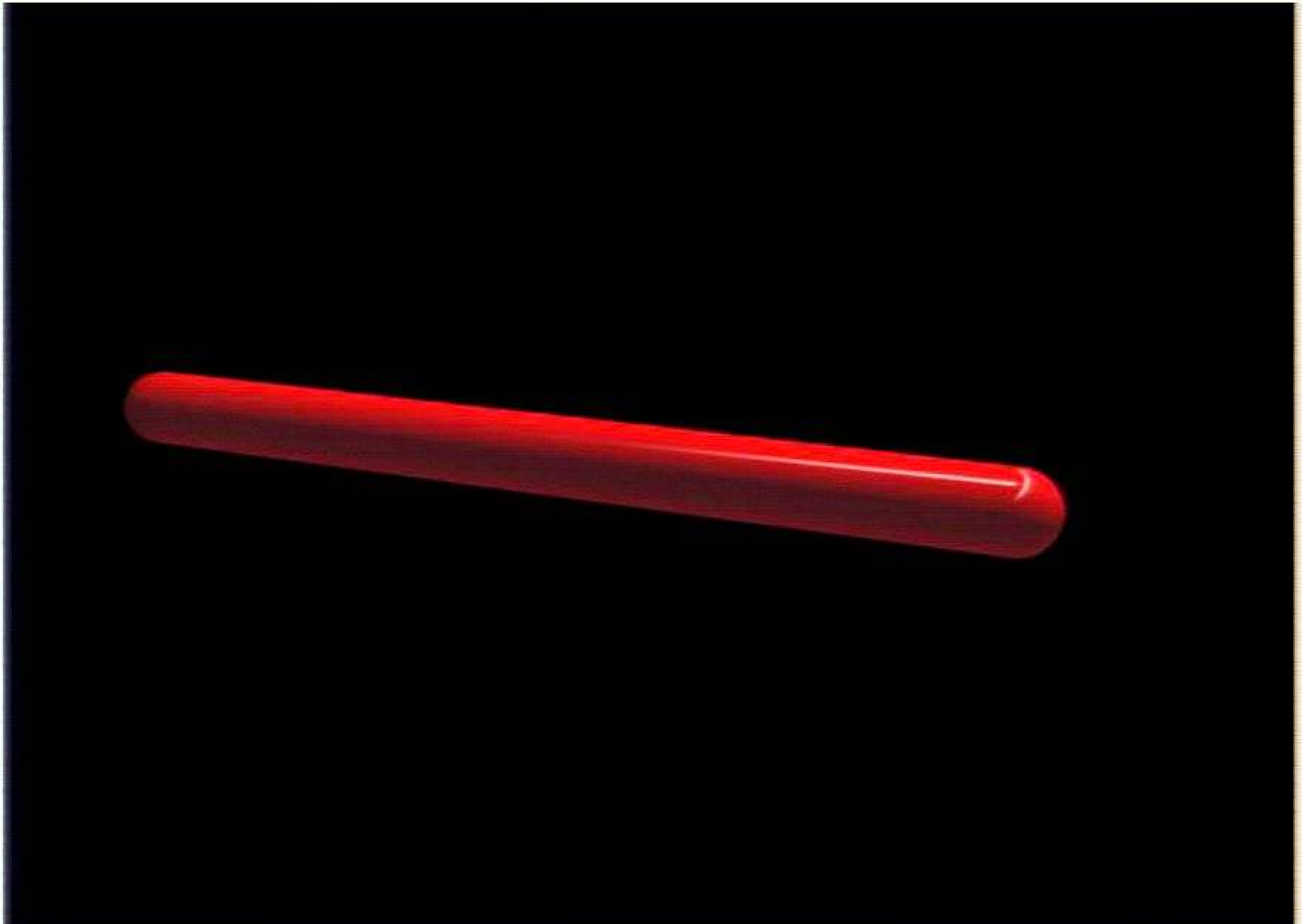
- Taking a different set of parameters allows us to find bubble from nothing geometries.
- Region II describes an open universe similar to the ideas of Hawking and Turok.

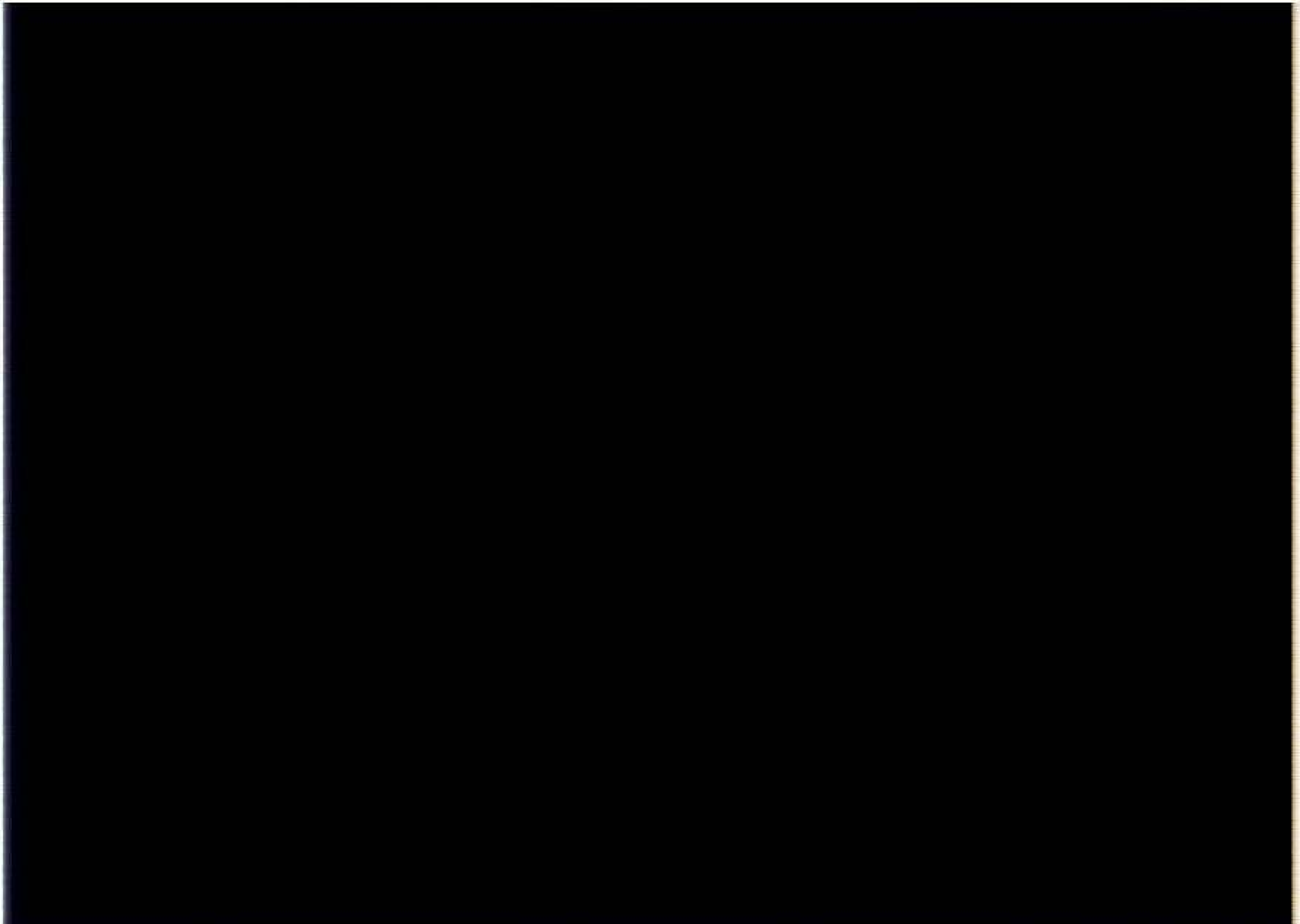
Hawking & Turok (1998).

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

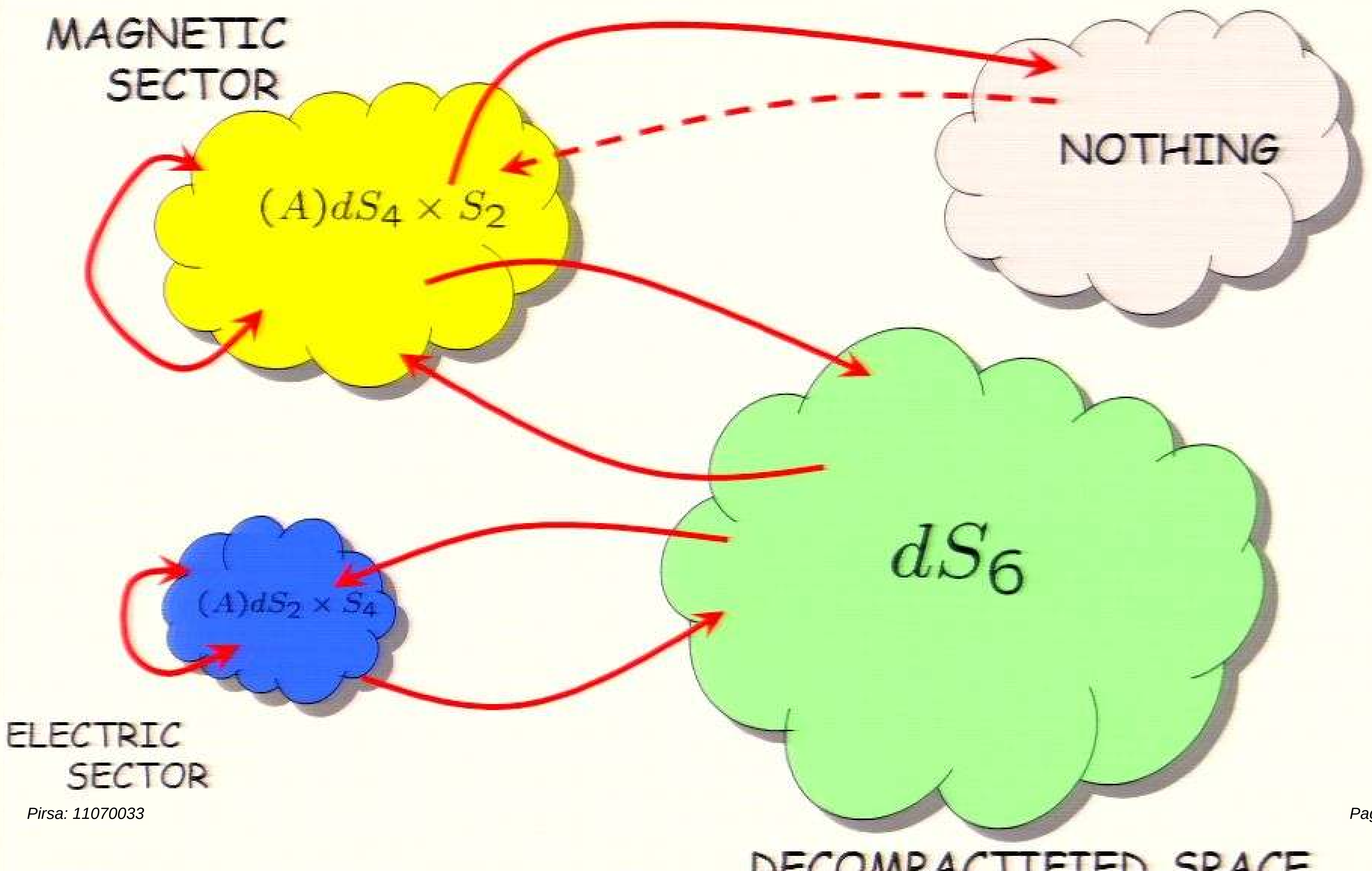
Garriga (1998).







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.

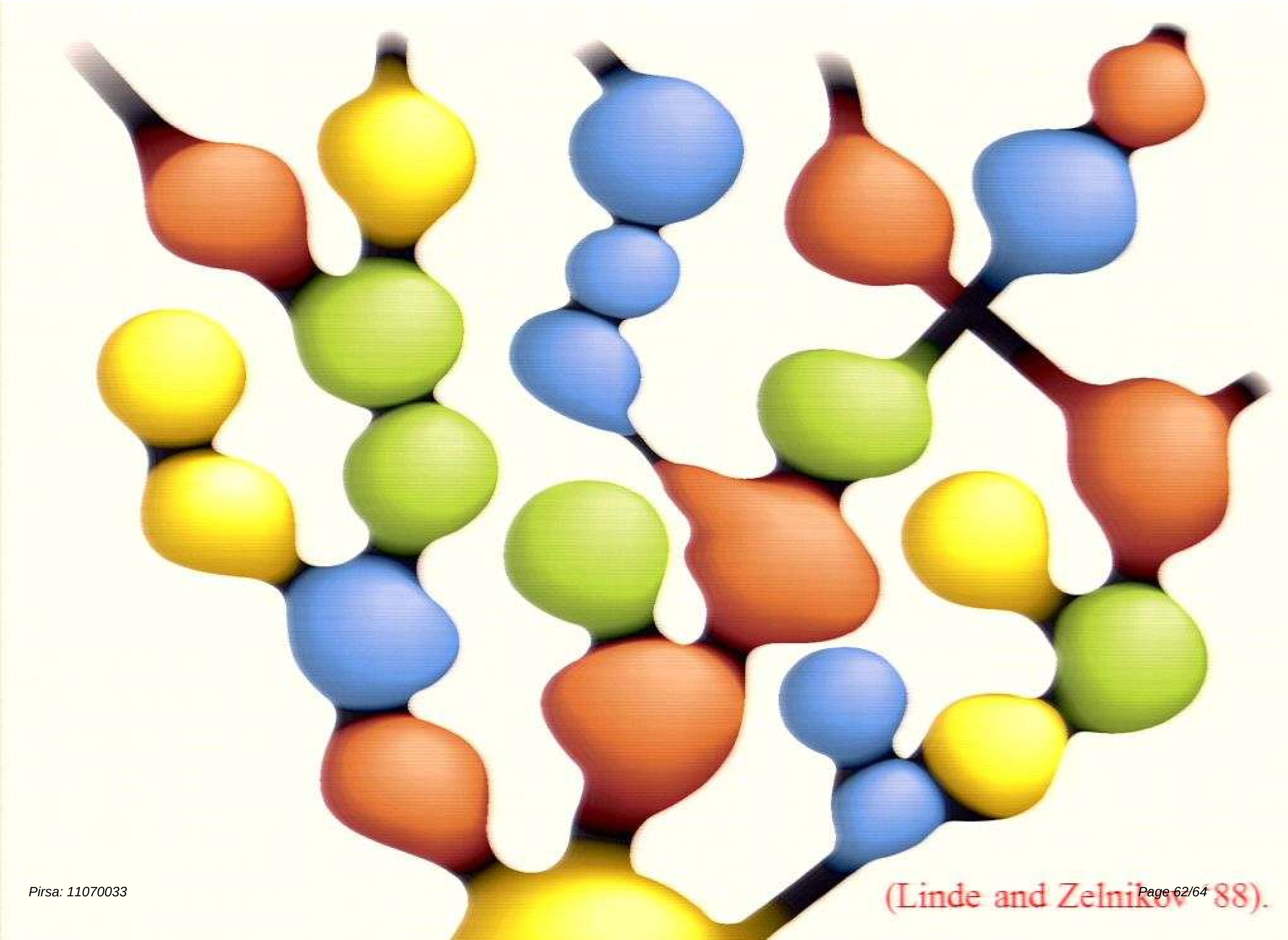
$$Nothing \Longrightarrow dS_4 \times S_2$$

$$(A)dS_2 \times S_4 \Longrightarrow dS_4 \times S_2$$

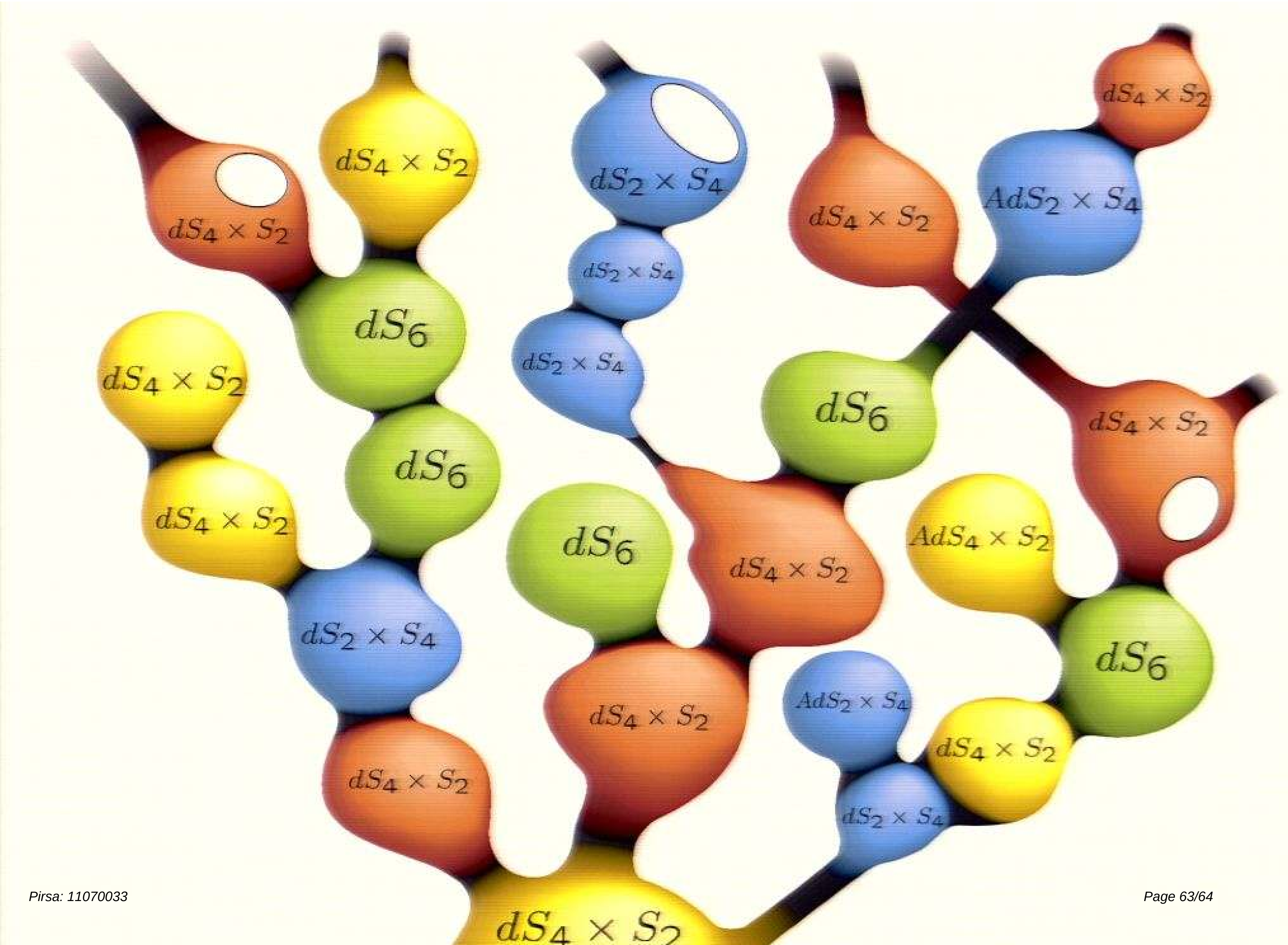
$$dS_4 \times S_2 \Longrightarrow dS_4 \times S_2$$

$$dS_6 \Longrightarrow dS_4 \times S_2$$

What is the BIG PICTURE ?



(Linde and Zelnikov '88).



$dS_4 \times S_2$
$dS_4 \times S_2$
$dS_2 \times S_4$
$dS_4 \times S_2$
$AdS_2 \times S_4$
$dS_4 \times S_2$
$dS_2 \times S_4$
dS_6
$dS_2 \times S_4$
$dS_4 \times S_2$
dS_6
$dS_4 \times S_2$
dS_6
$dS_4 \times S_2$
dS_6
$AdS_4 \times S_2$
$dS_4 \times S_2$
$dS_2 \times S_4$
dS_6
$dS_4 \times S_2$
$AdS_2 \times S_4$
$dS_4 \times S_2$
$dS_4 \times S_2$
$dS_2 \times S_4$
$dS_4 \times S_2$

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