Tunneling in models of Flux Vacua

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Outline of the talk

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

A higher dimensional Universe

- Many models of fundamental physics invoke the existence of extra dimensions.

- The idea that our universe is higher dimensional is a very old one.

Kaluza (1921)

Klein (1926)

$$S_5 = \frac{M_5^3}{2} \int d^5x \sqrt{-g_5}\; R_5$$

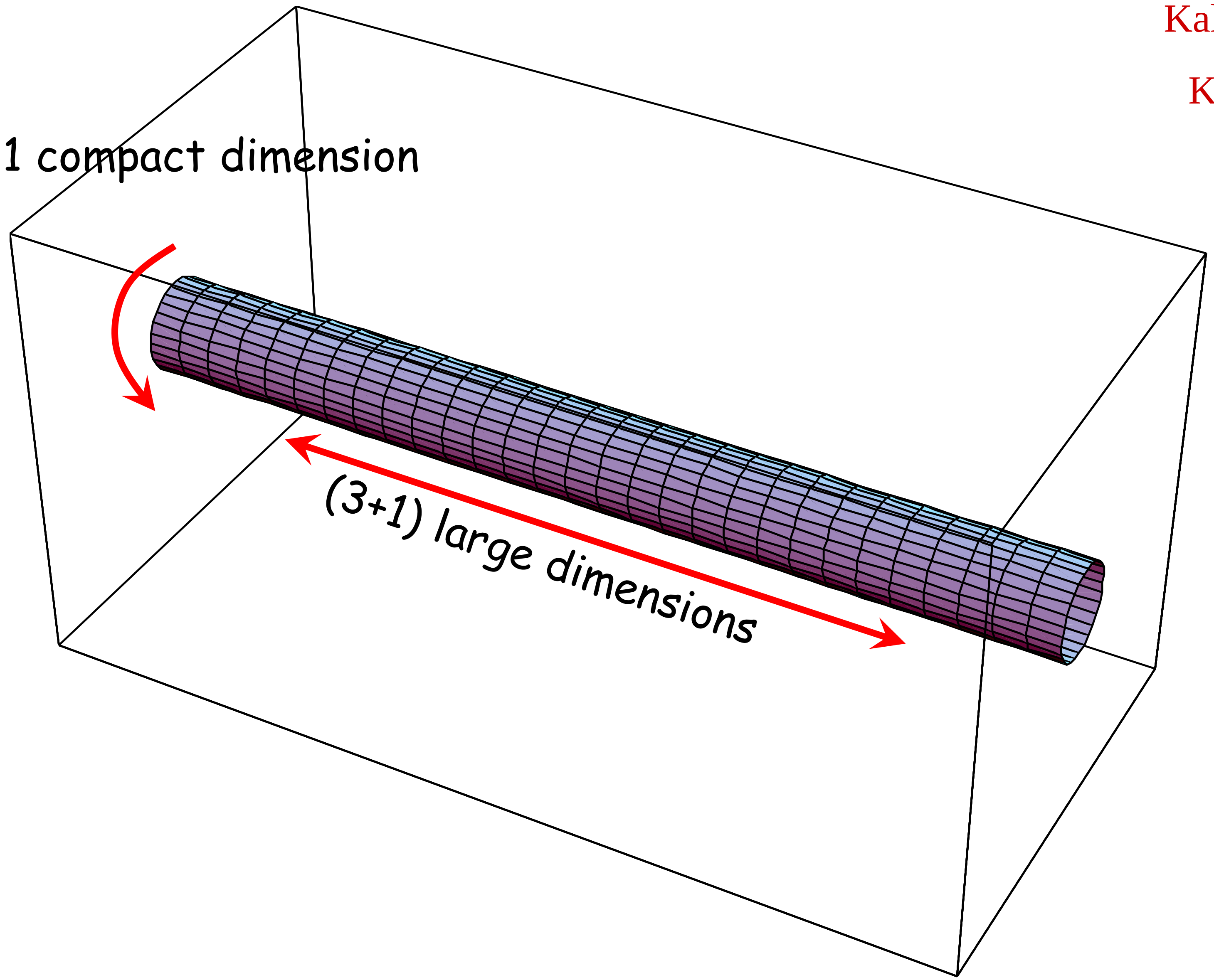
- At low energies we should recover a 4d picture.

- We need to compactify this theory to 4d!

Kaluza-Klein idea $0 < y < L$

Kaluza (1921)

Klein (1926)



Kaluza-Klein idea

- The low energy effective action becomes,

$$S_4 = \int d^4x\sqrt{-g_4}\,\left(\frac{1}{2}M_P^2 R_4 - \frac{1}{2}\partial_\mu\psi\partial^\mu\psi - \frac{e^{\sqrt{3}\psi}}{4}F_{\mu\nu}F^{\mu\nu}\right) + \ldots$$

- All other modes have masses higher than the scale of the compact dimension.

$$\phi_{KK}(x^\mu, y) = \sum_{n=0}^{\infty} \phi_n(x^\mu) e^{i2\pi y/L}$$

$$m_{\phi_n} \sim \frac{n}{L}$$

Kaluza-Klein idea

- The low energy effective action becomes,

$$S_4 = \int d^4x\sqrt{-g_4}\ \left(\frac{1}{2}M_P^2 R_4 - \frac{1}{2}\partial_\mu\psi\partial^\mu\psi\right)$$

- But, this is still a problematic action:

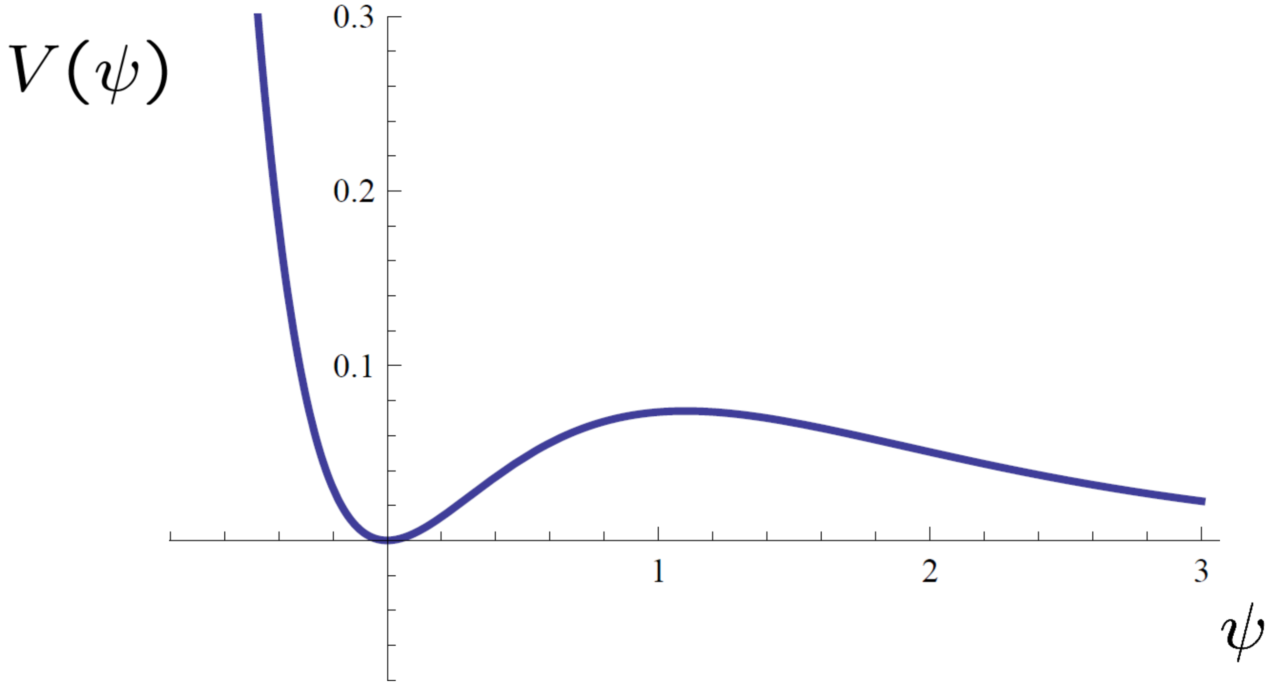
  - We have not observed any massless scalar field.

  - What about cosmology in this model?

Kaluza-Klein Compactification

- We need to find a compactification method that allows us to fix the size of the extra dimension.

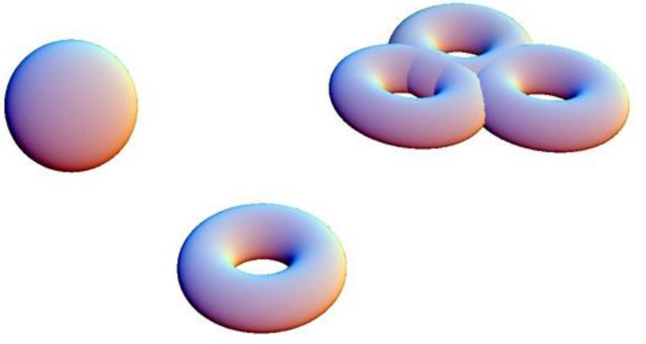
$$S_4 = \int d^4x\sqrt{-g_4}\ \left(\frac{1}{2}M_P^2 R_4 - \frac{1}{2}\partial_\mu\psi\partial^\mu\psi - V(\psi)\right)$$



String Theory Compactification

- Things are now more complicated since we need to hide a 6d manifold !

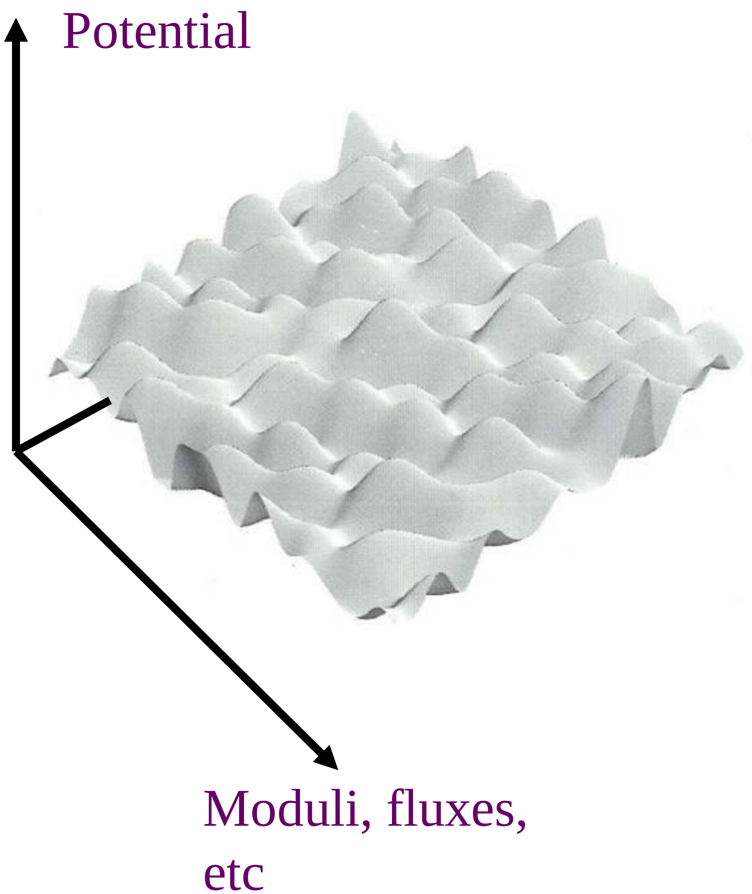
- Many different manifolds to choose from.



- We need to fix all these degrees of freedom.

String Theory Compactification

- New models of String Theory have been recently explored that allow us to fix all the moduli.

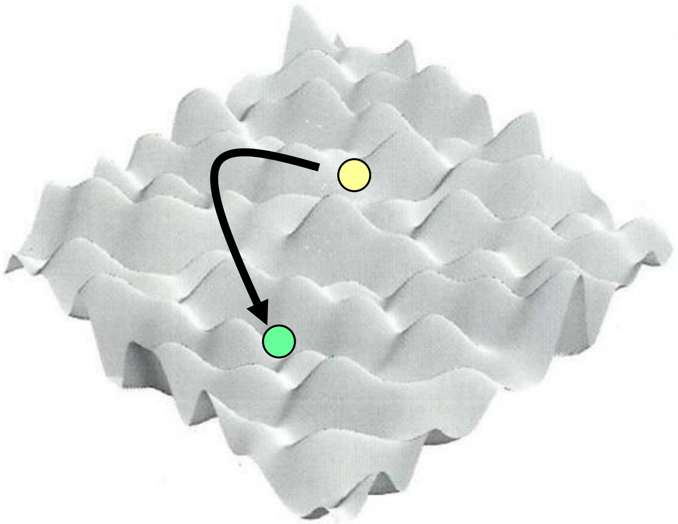


- These models have led us to a complicated 4d effective potential with many metastable minima.

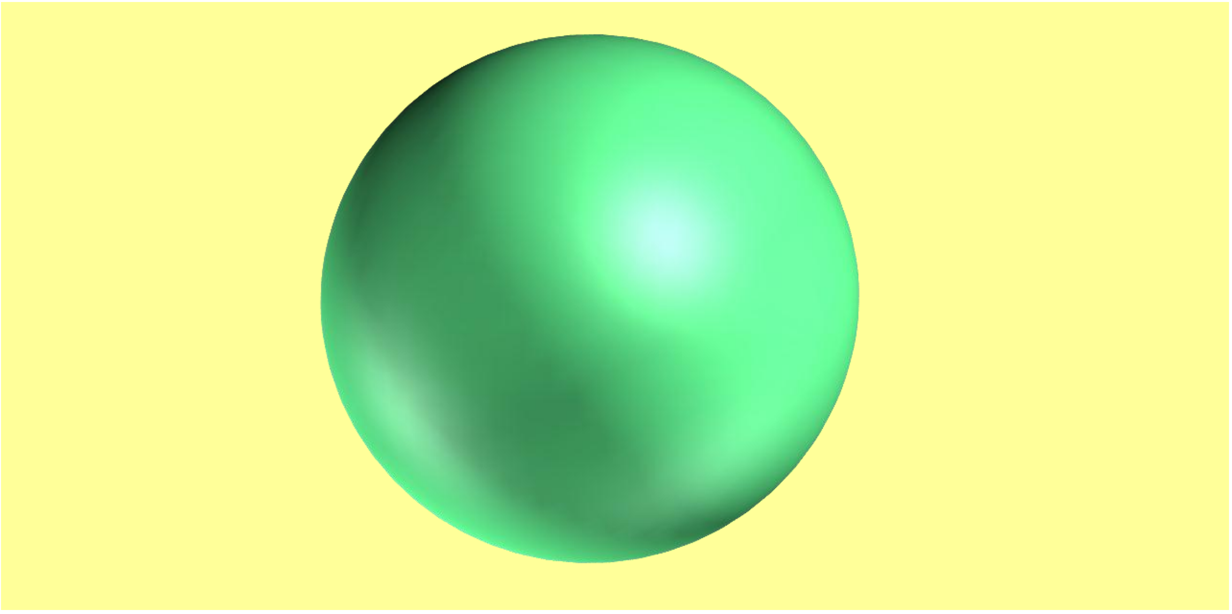
- This has been described in the literature as the String Landscape.

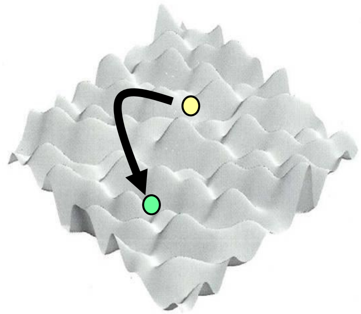
Bubble Universe

Coleman (1977)



- Similarly to what happens in quantum mechanics there will be tunneling transitions.
- These transitions between different vacua are mediated by bubble nucleations.

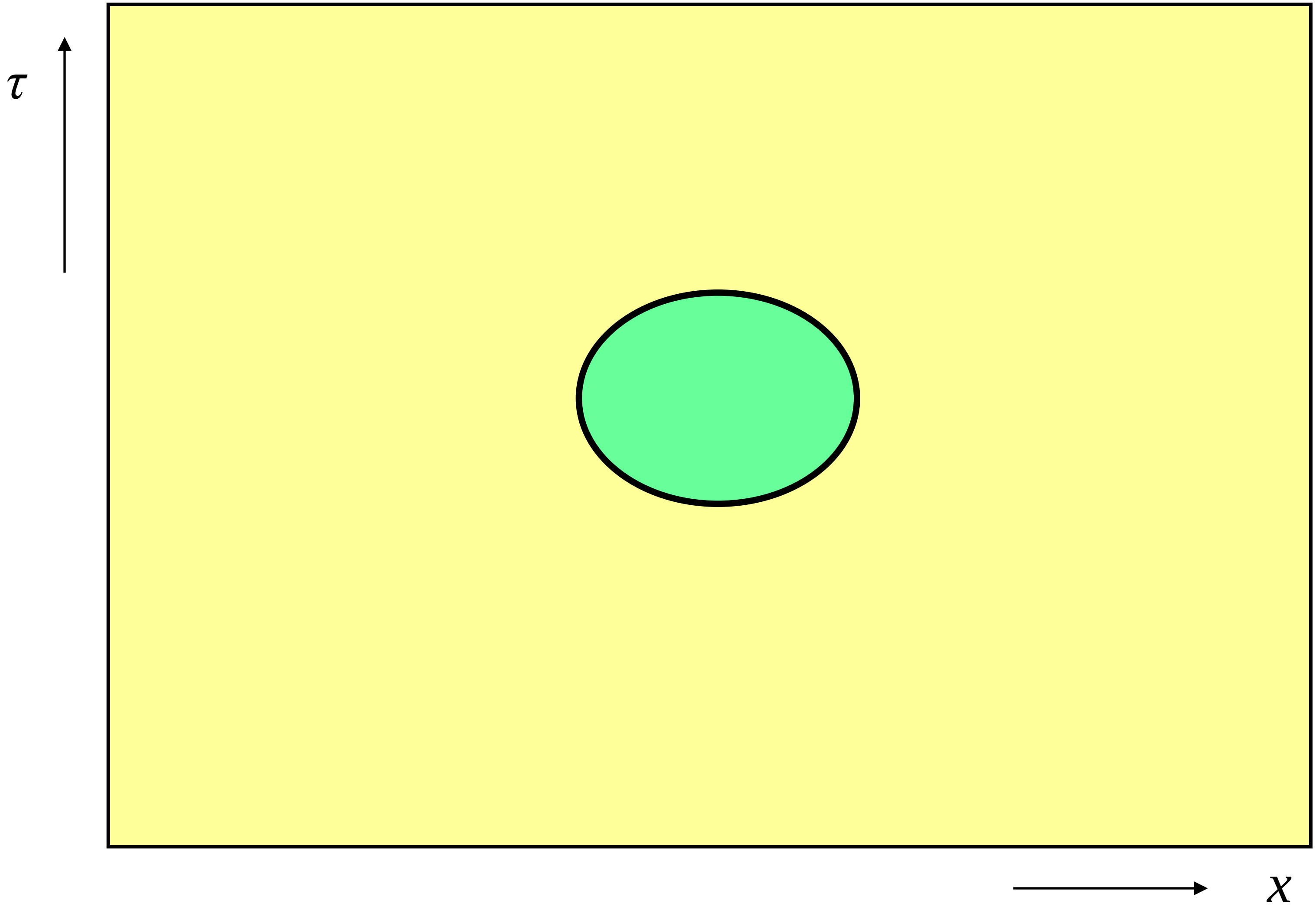




Bubble Universe

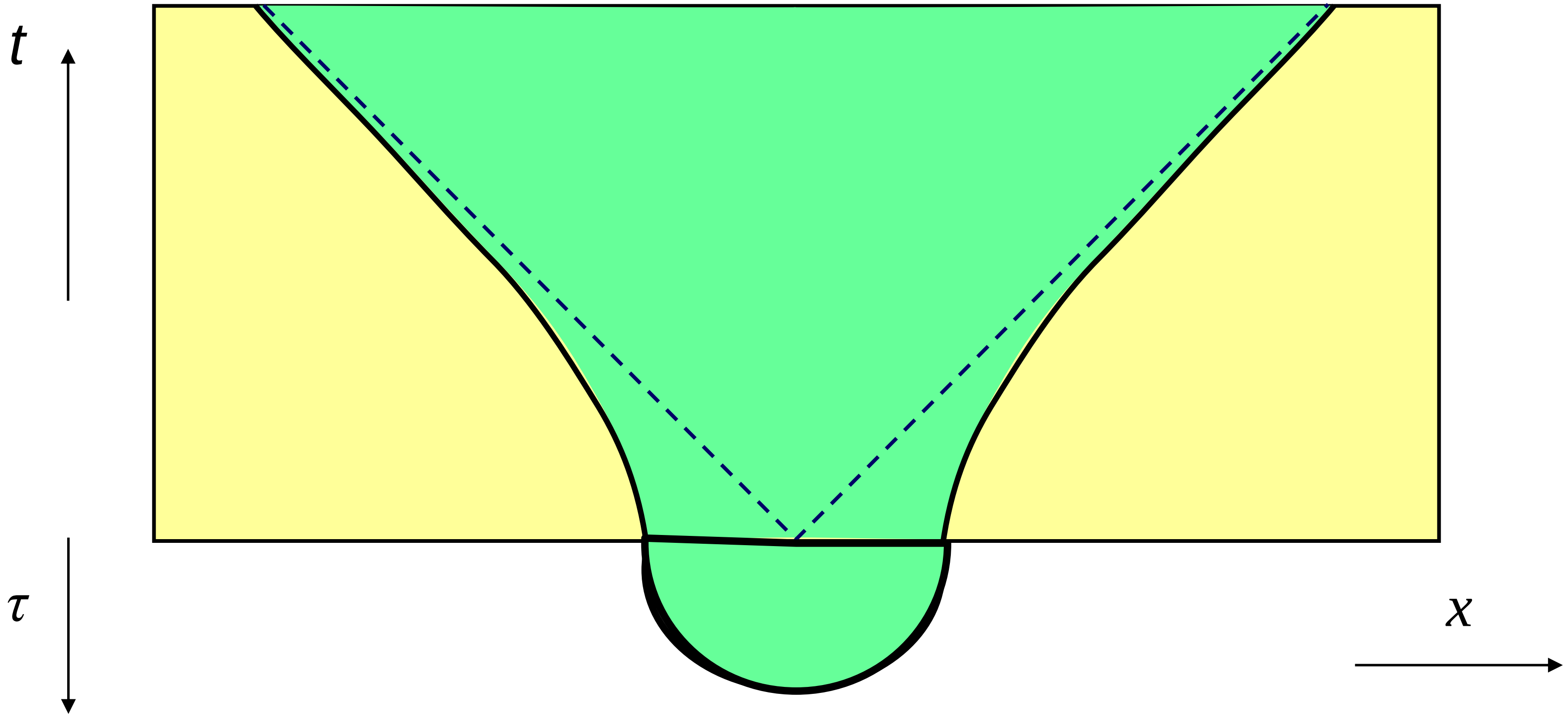
Coleman (1977)

These transitions are mediated by the most symmetric instanton.



Bubble Universe

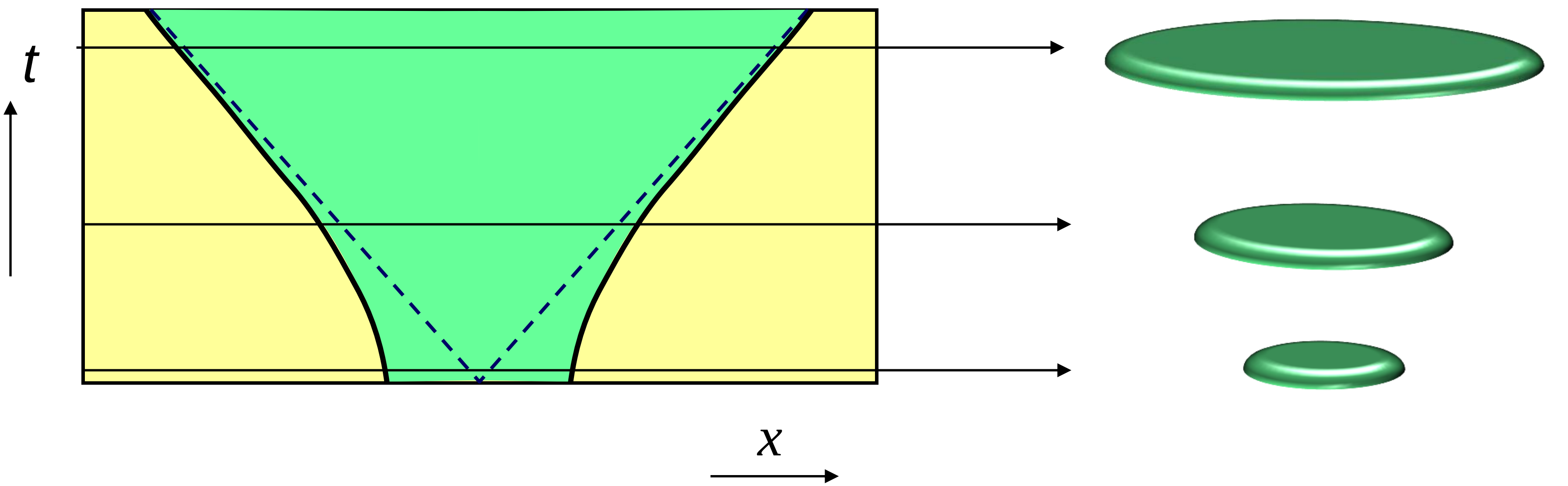
Coleman & de Luccia (1980)



- Analytically continuing to Lorentzian time we get a rapidly accelerating bubble.

Spacetime of a Bubble Universe

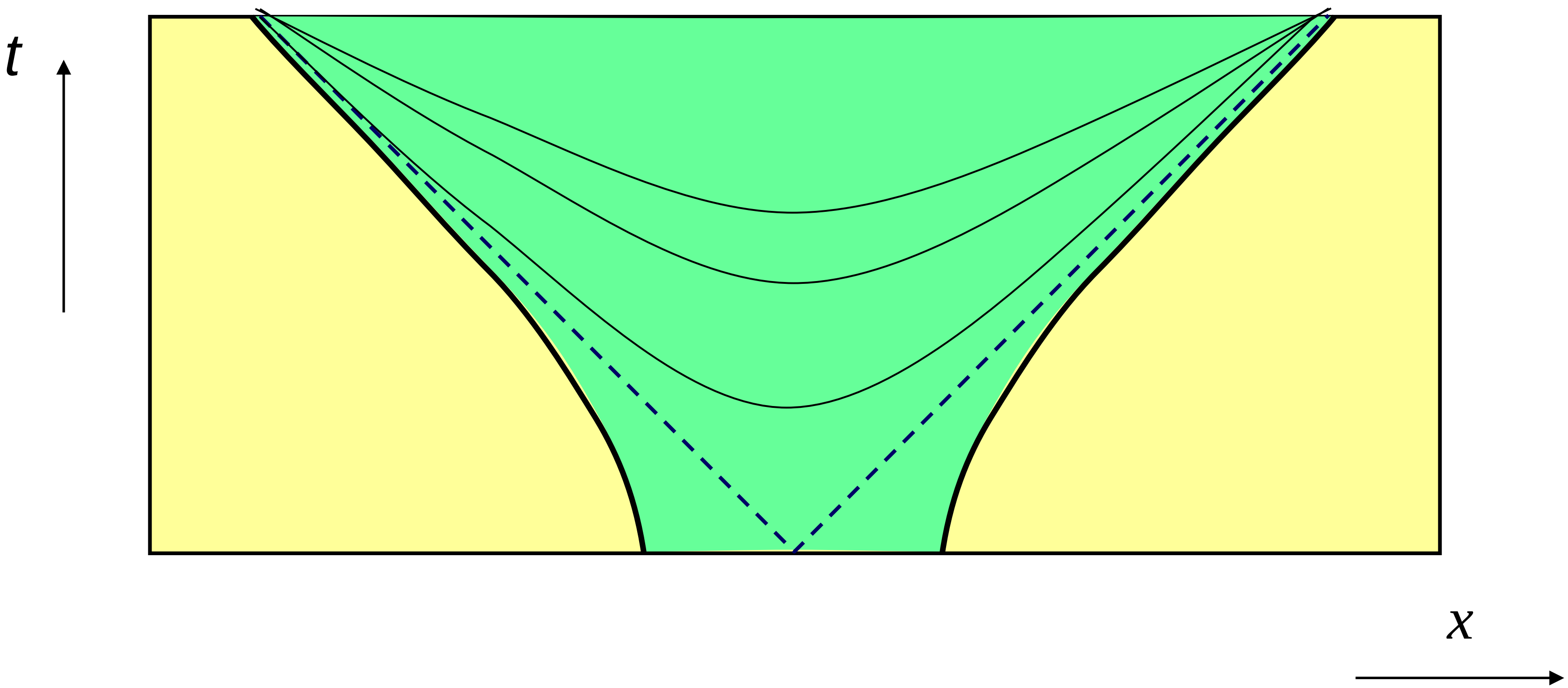
- The interior of the bubble is an infinite open universe.
- How does a finite bubble become an infinite universe?



- The symmetry of the instanton solution specifies the future evolution of the bubble.

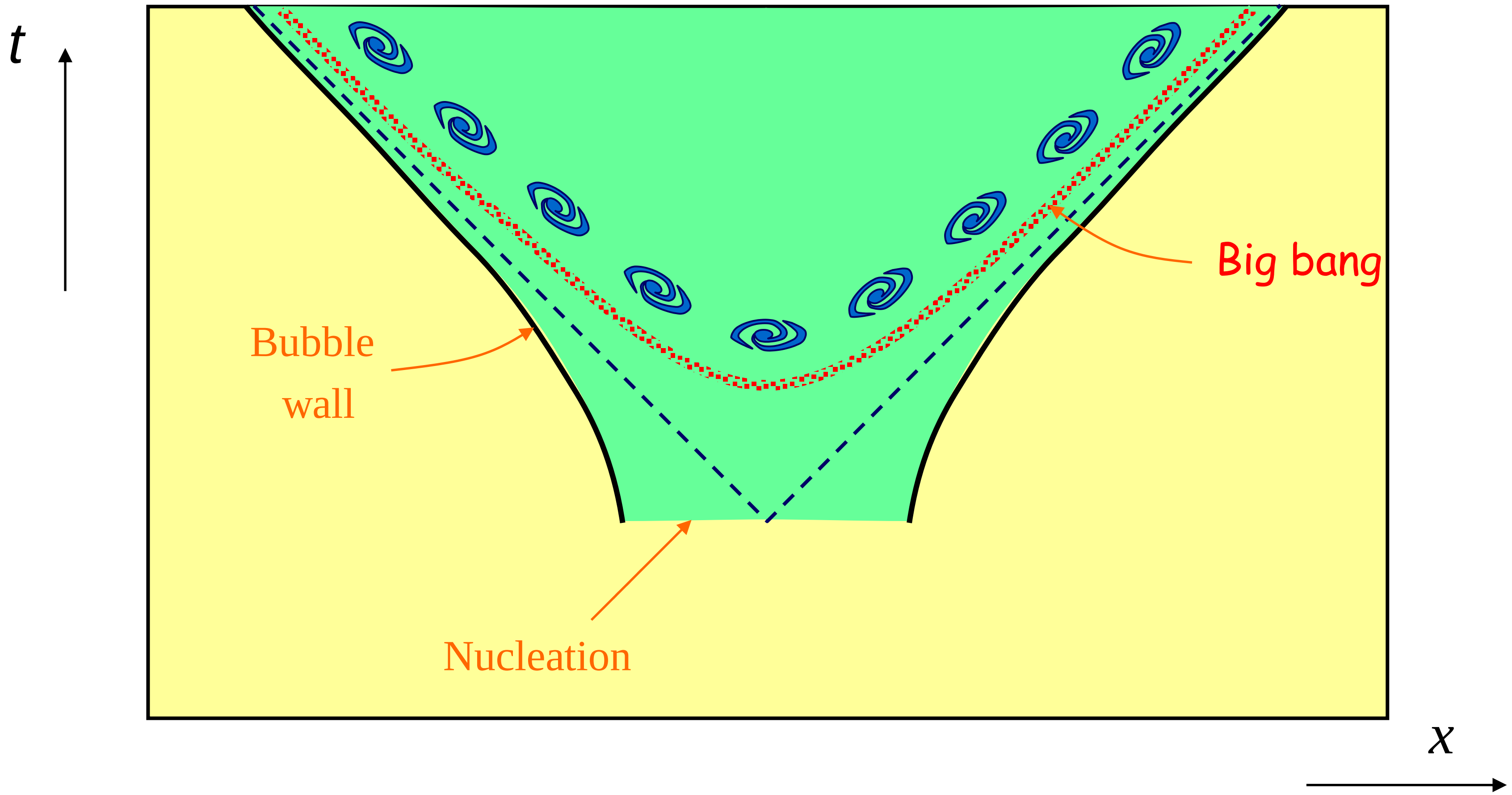
Spacetime of a Bubble Universe

- The surfaces of constant energy describe an open universe.

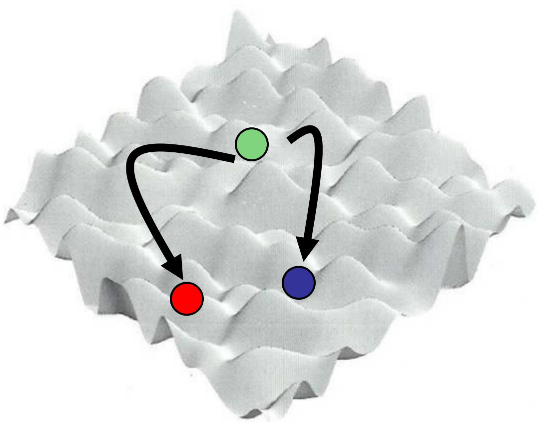


$$ds^2 = -dT^2 + a(T)^2(d\xi^2 + \sinh^2(\xi)d\Omega_2^2)$$

Spacetime of a Bubble Universe



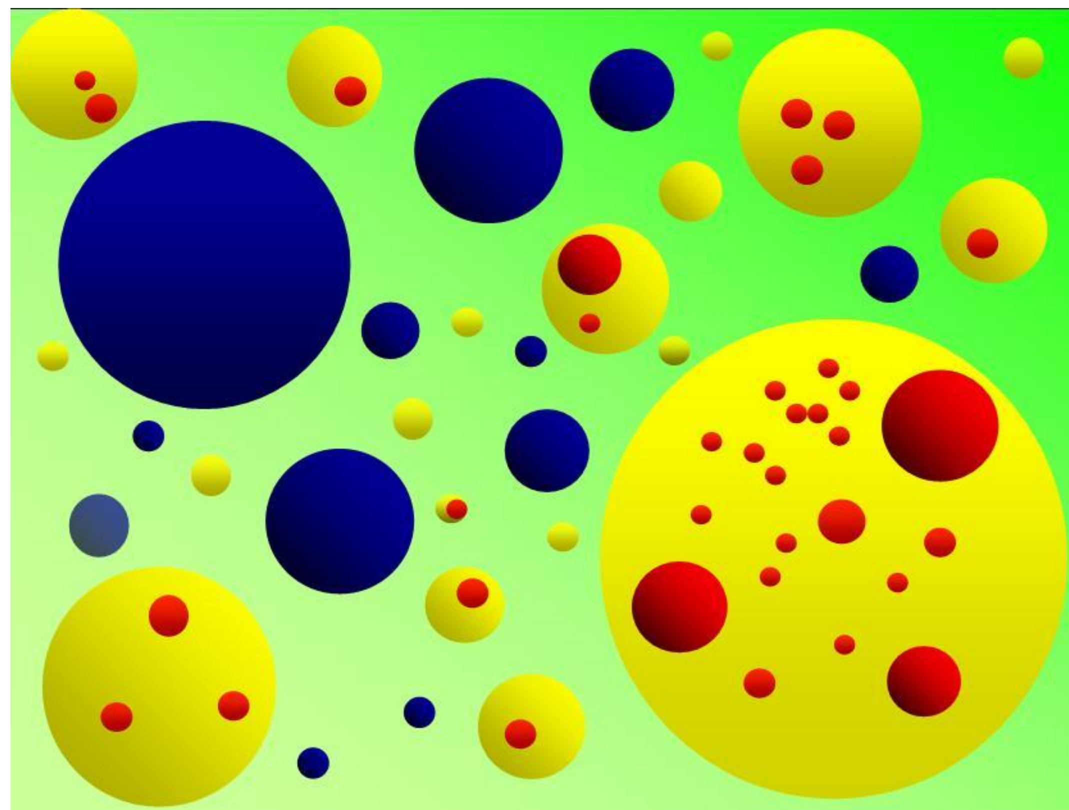
4d String Theory Multiverse



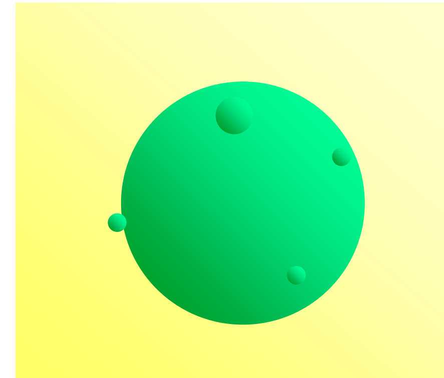
Transitions between different vacua occur via bubble nucleations.

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

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



Observational Signatures



- There are several ways we can try to look for signatures of this model:
  - Our bubble is created in this way as an open universe.
  - Collisions between the bubbles may leave an imprint on the cosmic microwave background.

Is there any other possible observational signatures specific in models of flux compactifications ?

The 6d Flux Compactification

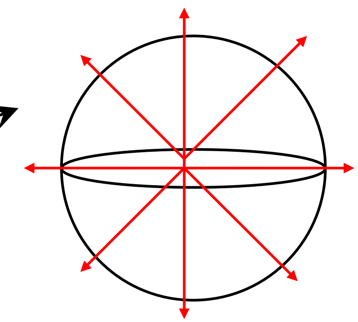
(Freund and Rubin, ‘80).
(Randjbar-Daemi et al., ‘83).

- 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:

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

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:

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

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

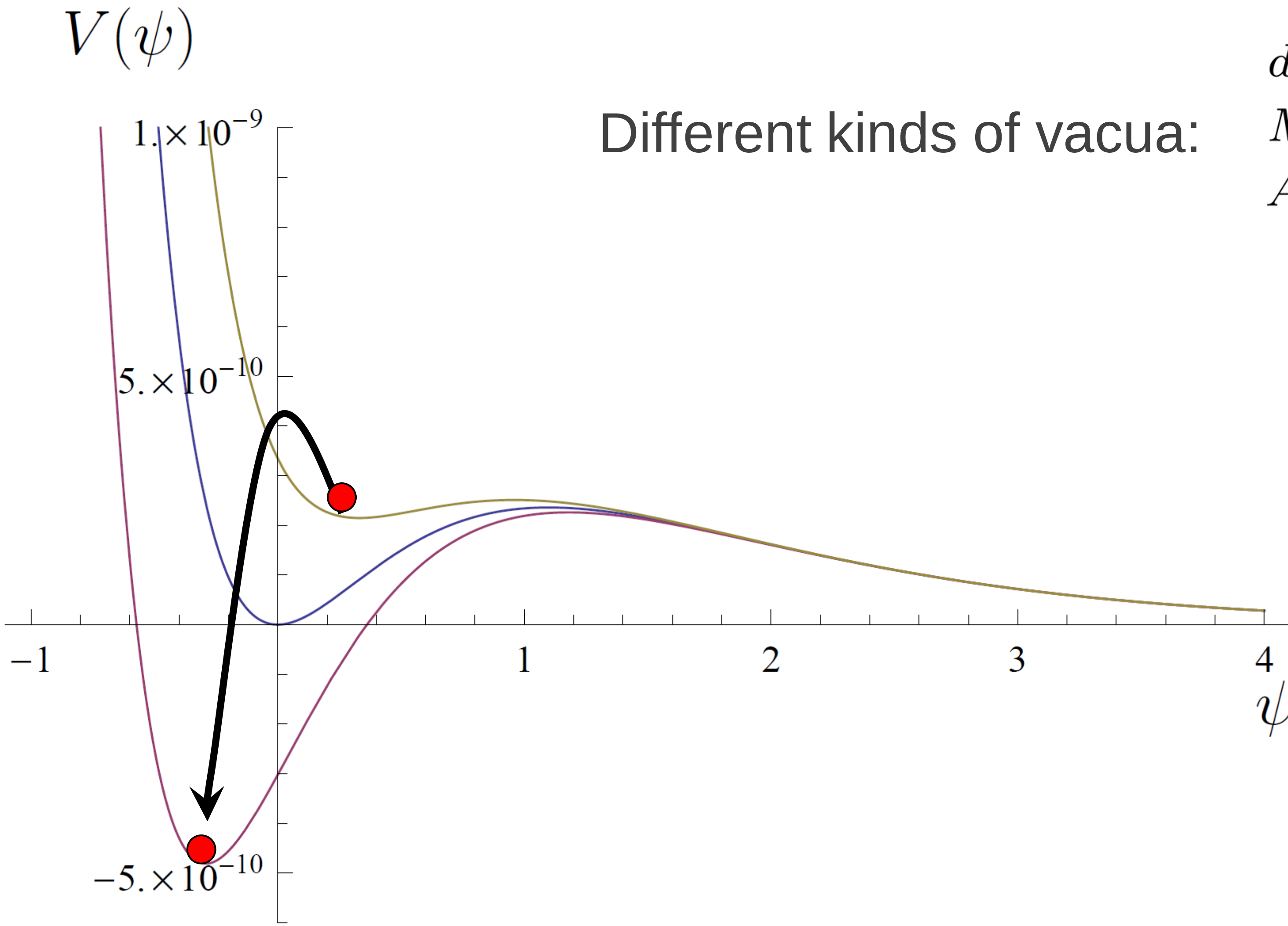
Flux contribution

Curvature of internal space

6d CC contribution

The 6d Flux Compactification

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



Different kinds of vacua:

$dS_4 \times S_2$

$M_4 \times S_2$

$AdS_4 \times S_2$

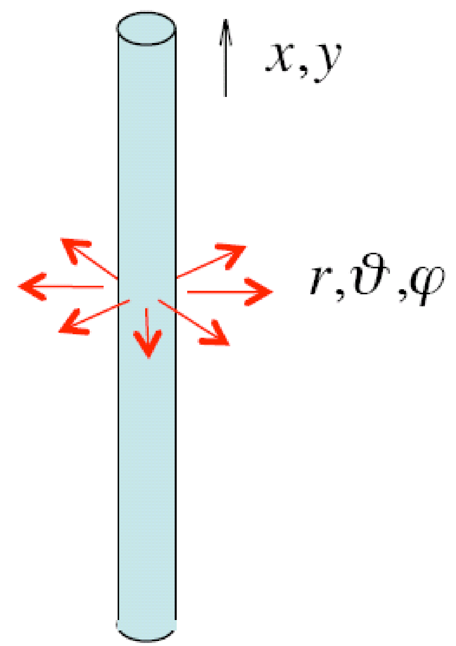
Magnetically Charged Branes

(Gibbons, Horowitz and Townsend '95).

(Gregory, '96).

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

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



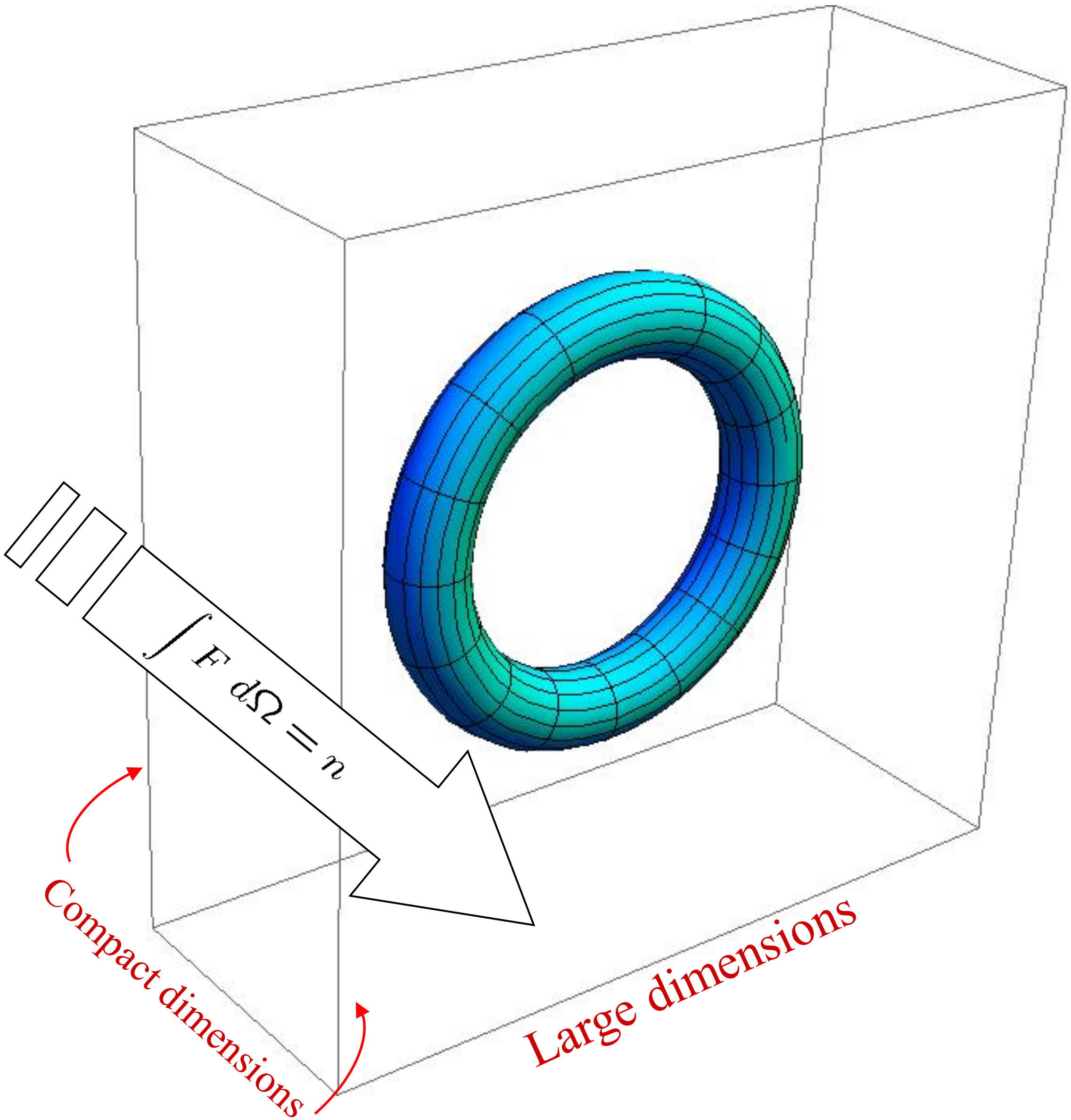
Magnetically charged

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

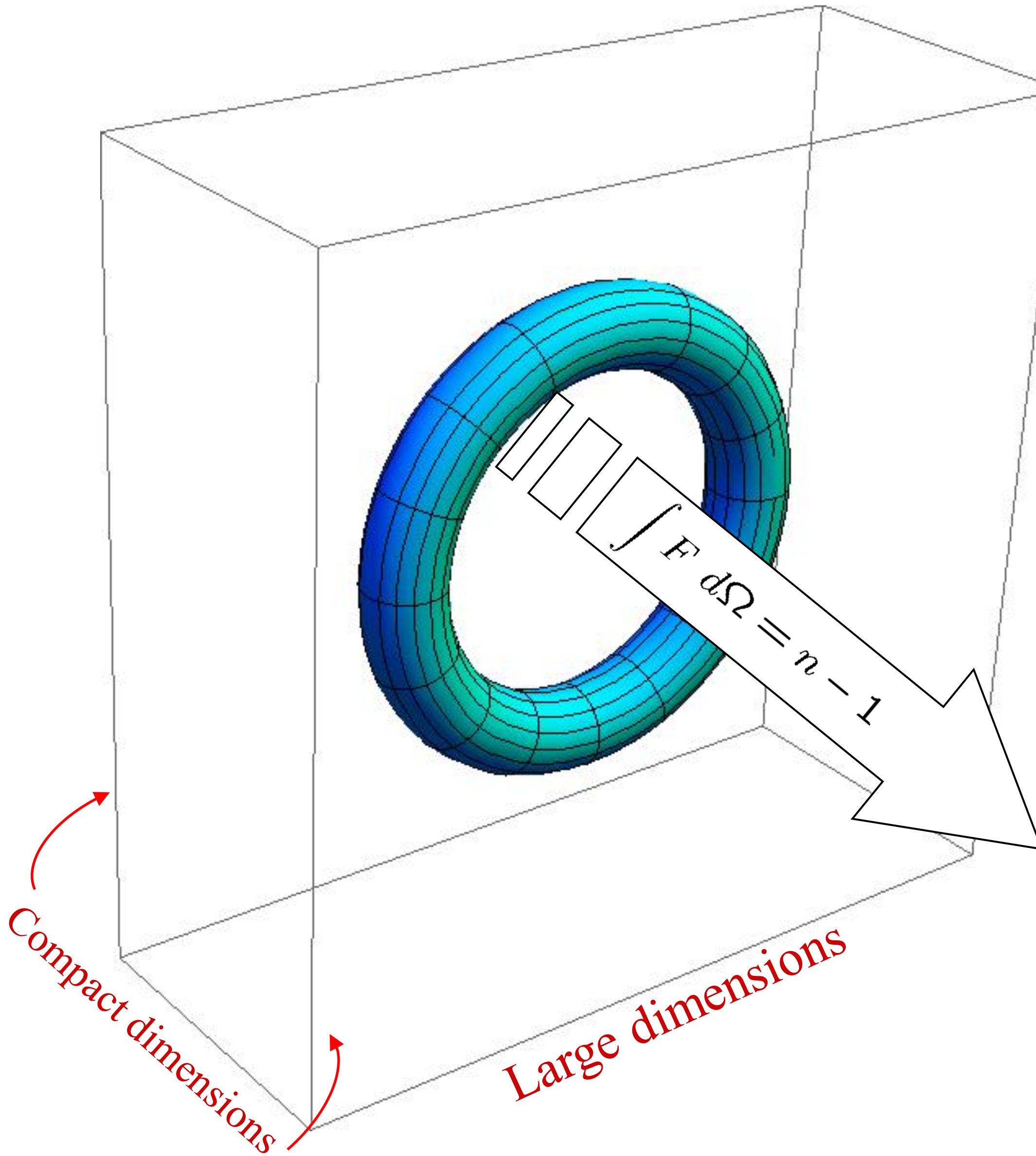
- In the extremal case we have,

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

Flux Tunneling



Flux Tunneling

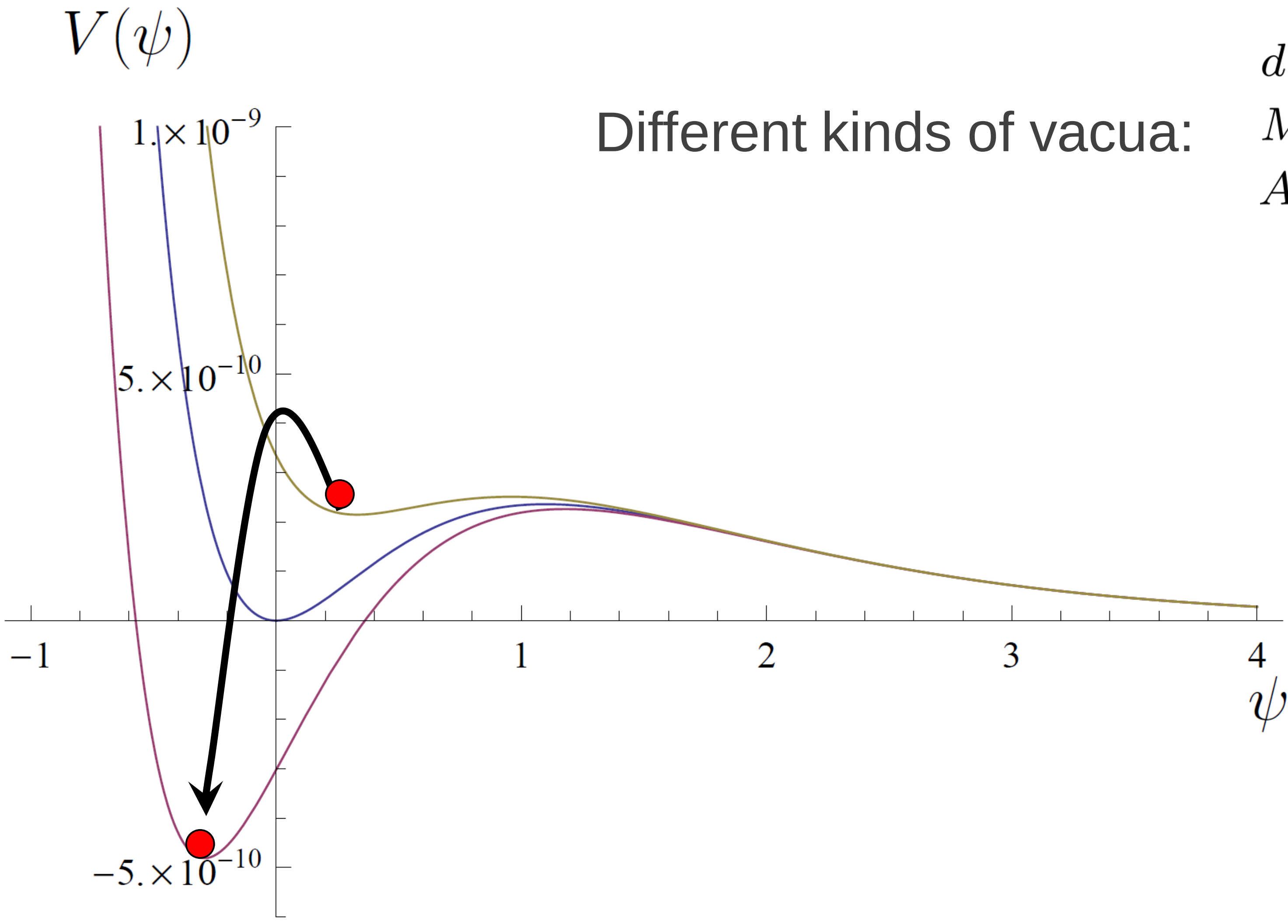


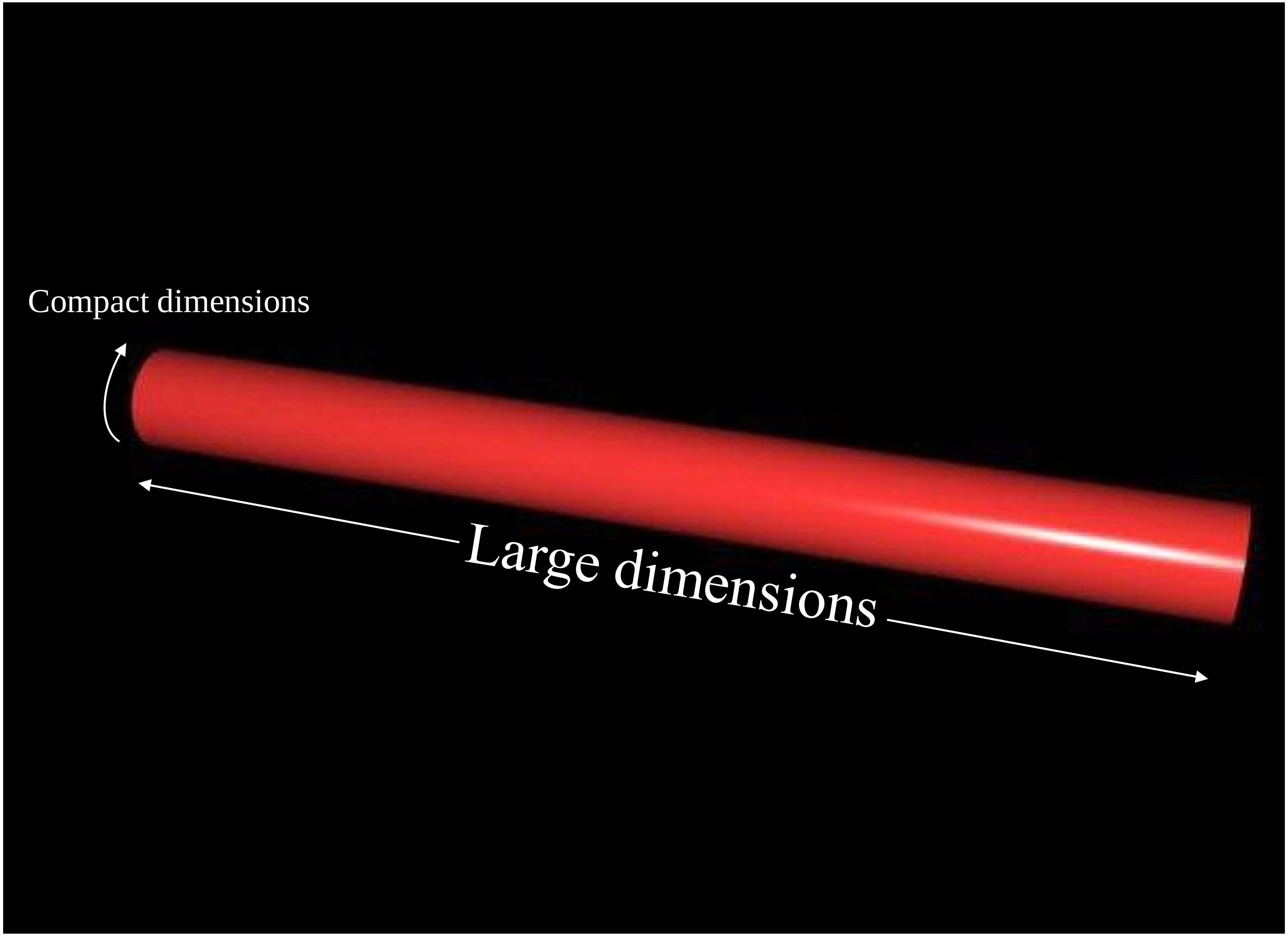
The 6d Flux Compactification

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

Different kinds of vacua:

$dS_4 \times S_2$
$M_4 \times S_2$
$AdS_4 \times S_2$




Compact dimensions
Large dimensions

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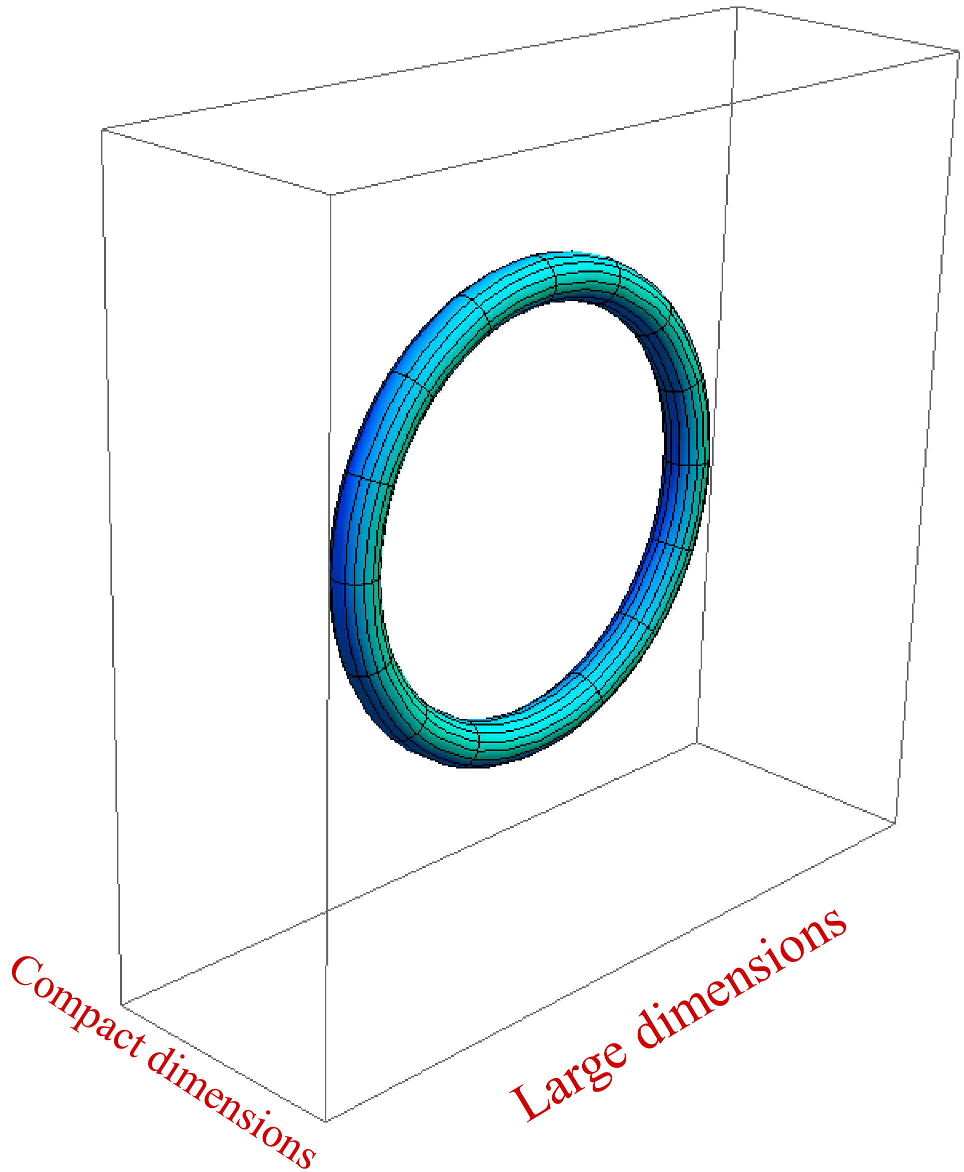
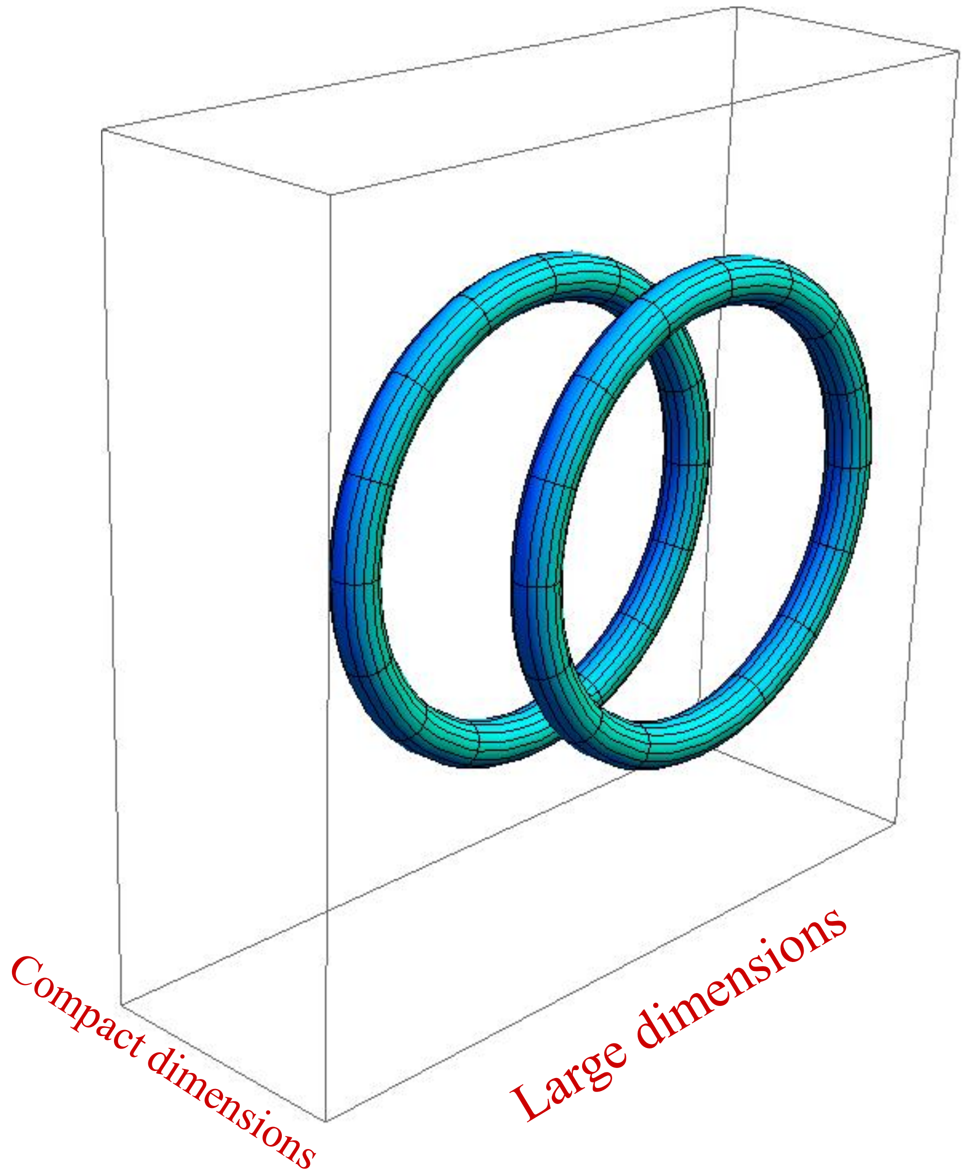
Bubble Ring Collisions



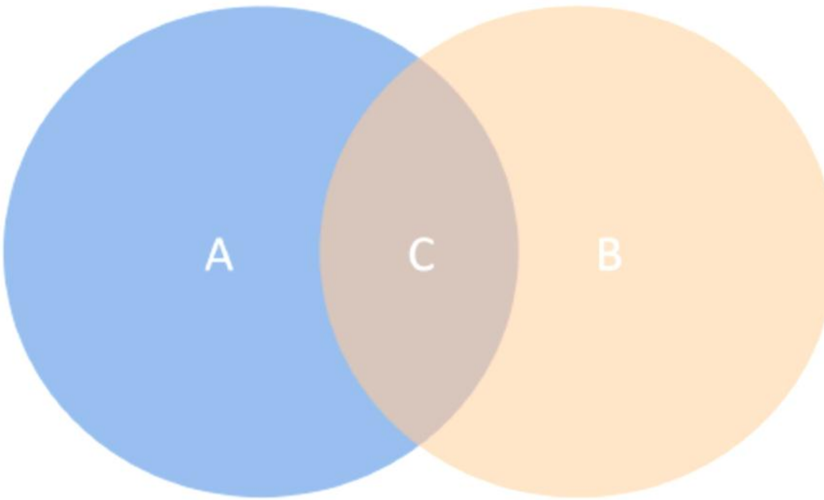
Bubble Ring Collisions



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

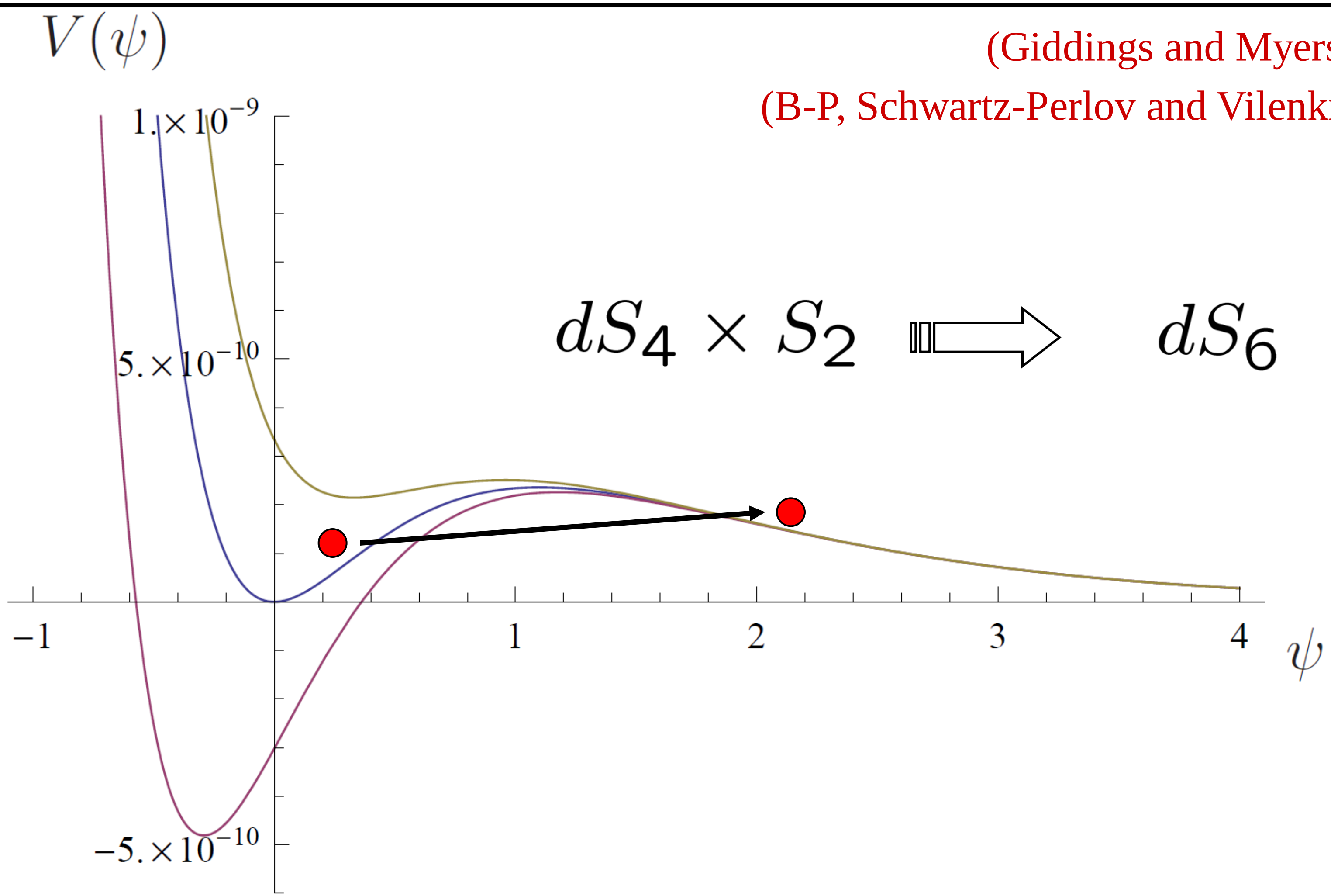
- There is also a dS_6 sector where there is no charge.

Decompactification

(Linde and Zelnikov, 1988).

(Giddings and Myers, 2004).

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



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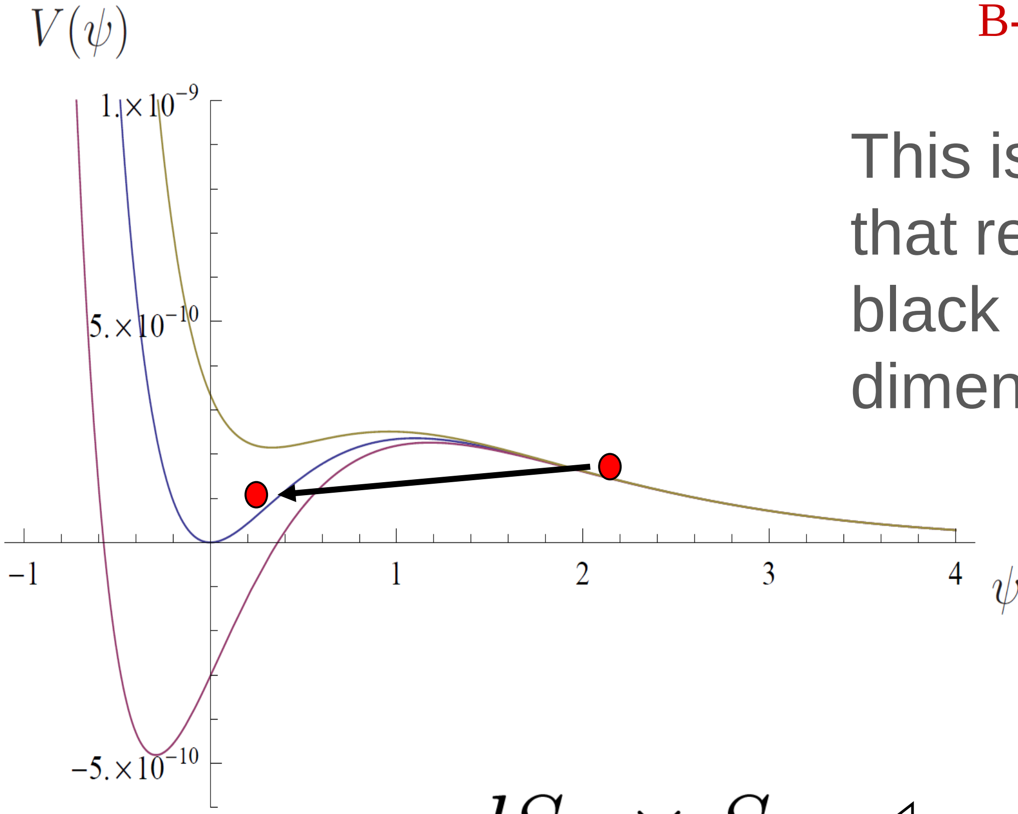
Dynamical compactification

Carroll, Johnson and Randall, (2009).

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



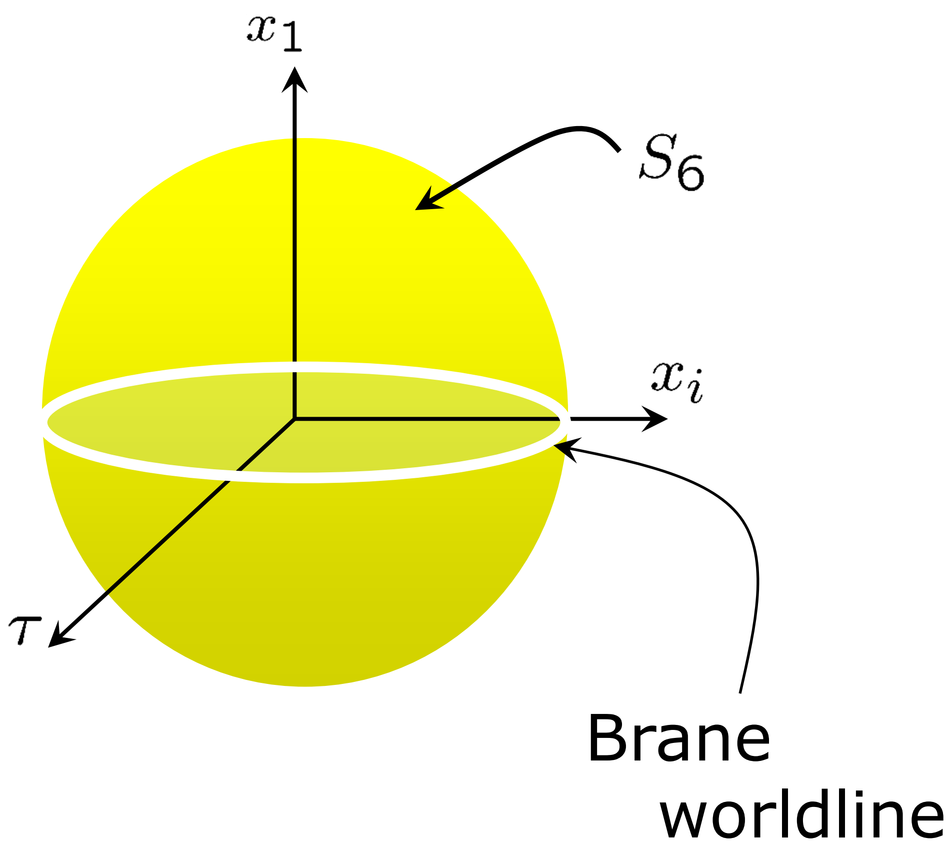
This is another kind of transition that represents the formation of black holes or branes in higher dimensional de Sitter space.

(Lee and Weinberg '87).

$$dS_4 \times S_2 \Longleftarrow dS_6$$

Brane Nucleation in de Sitter

(Basu, Guth and Vilenkin '92).

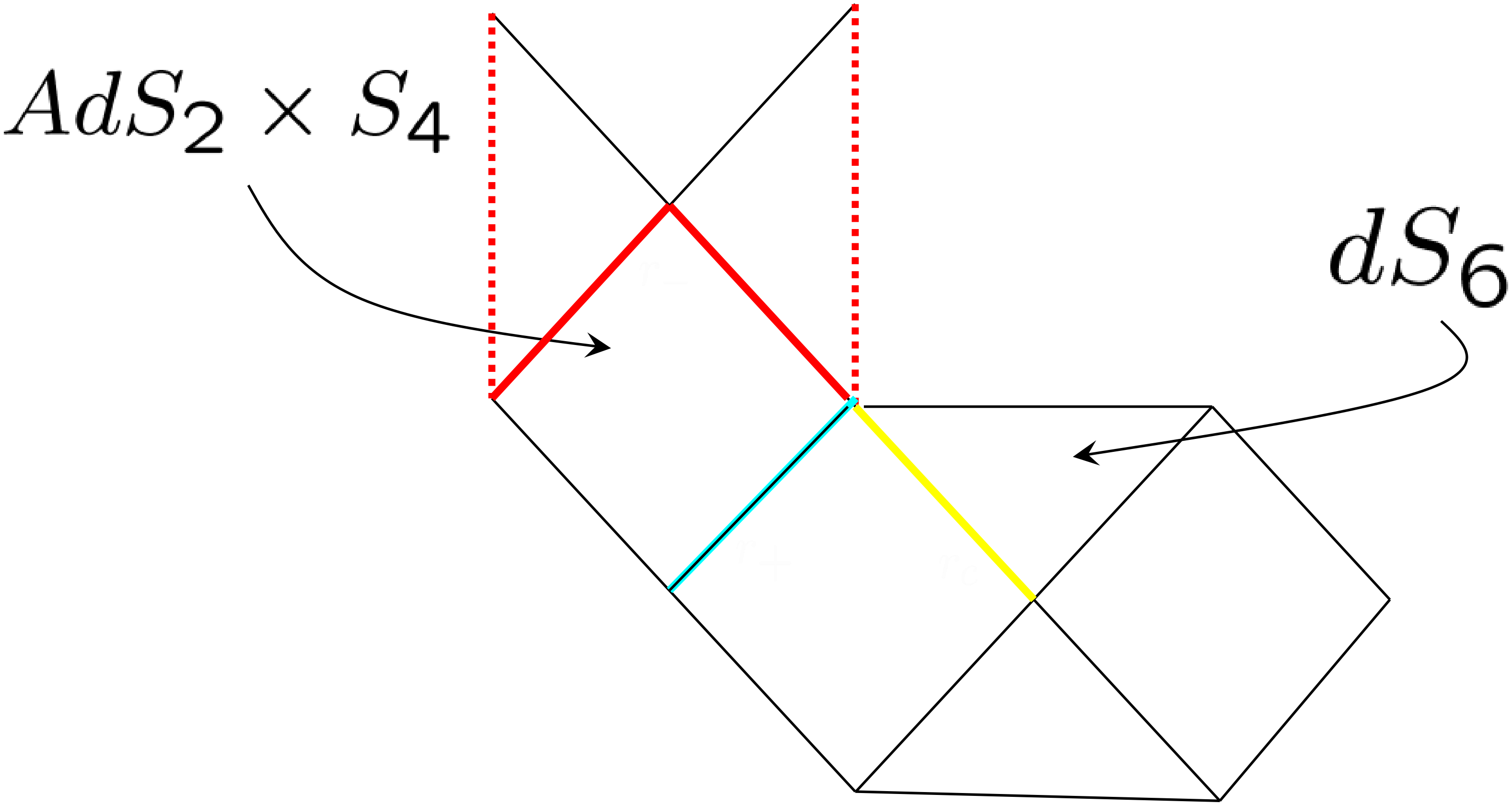


- Solution of the Euclidean equations of motion.
- Disregards backreaction on the geometry.
- In the Lorentzian part objects are stretched by the de Sitter expansion.
- In our case we have 2 types of objects: black holes and magnetic 2-branes.

Black Hole Pair Creation

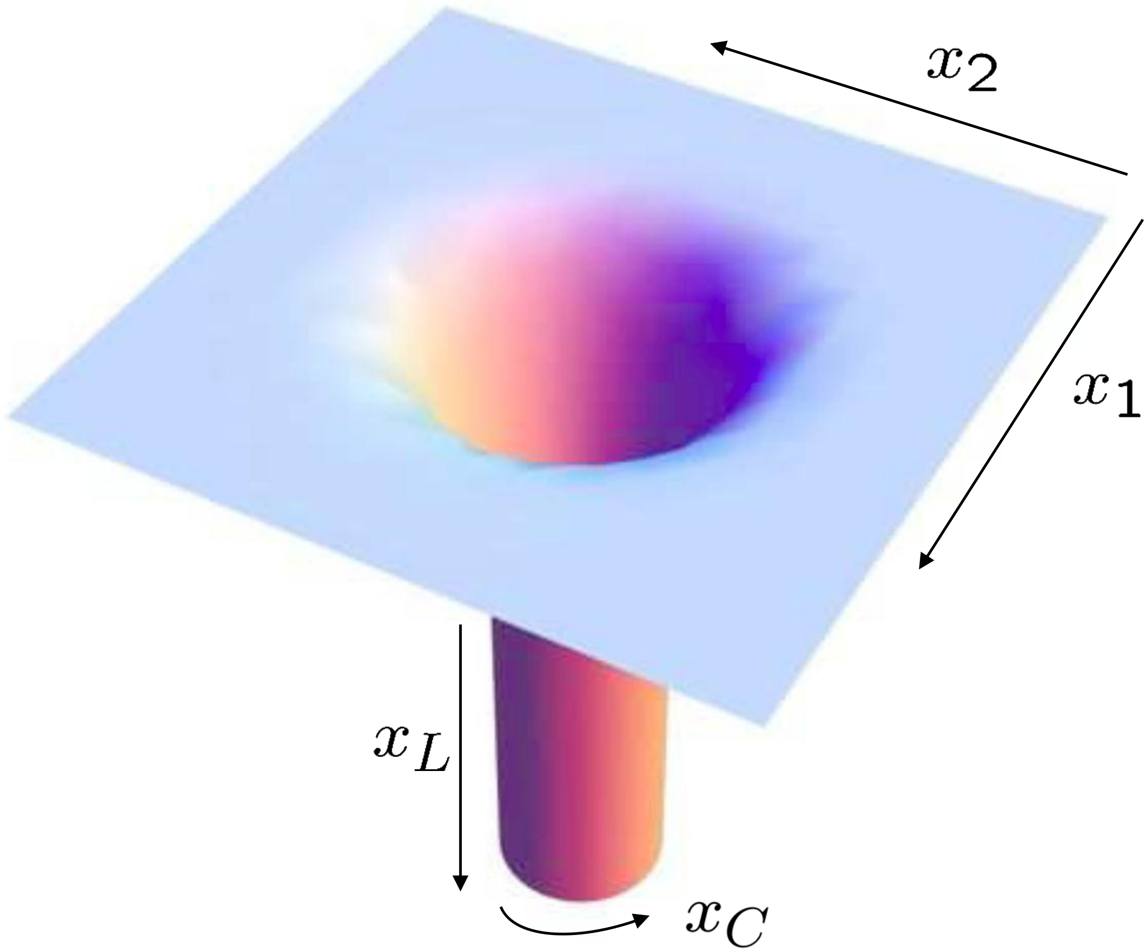
- The creation of the pair of electrically charged black holes is a transition of the form:

Mellor and Moss, ’89 ; 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

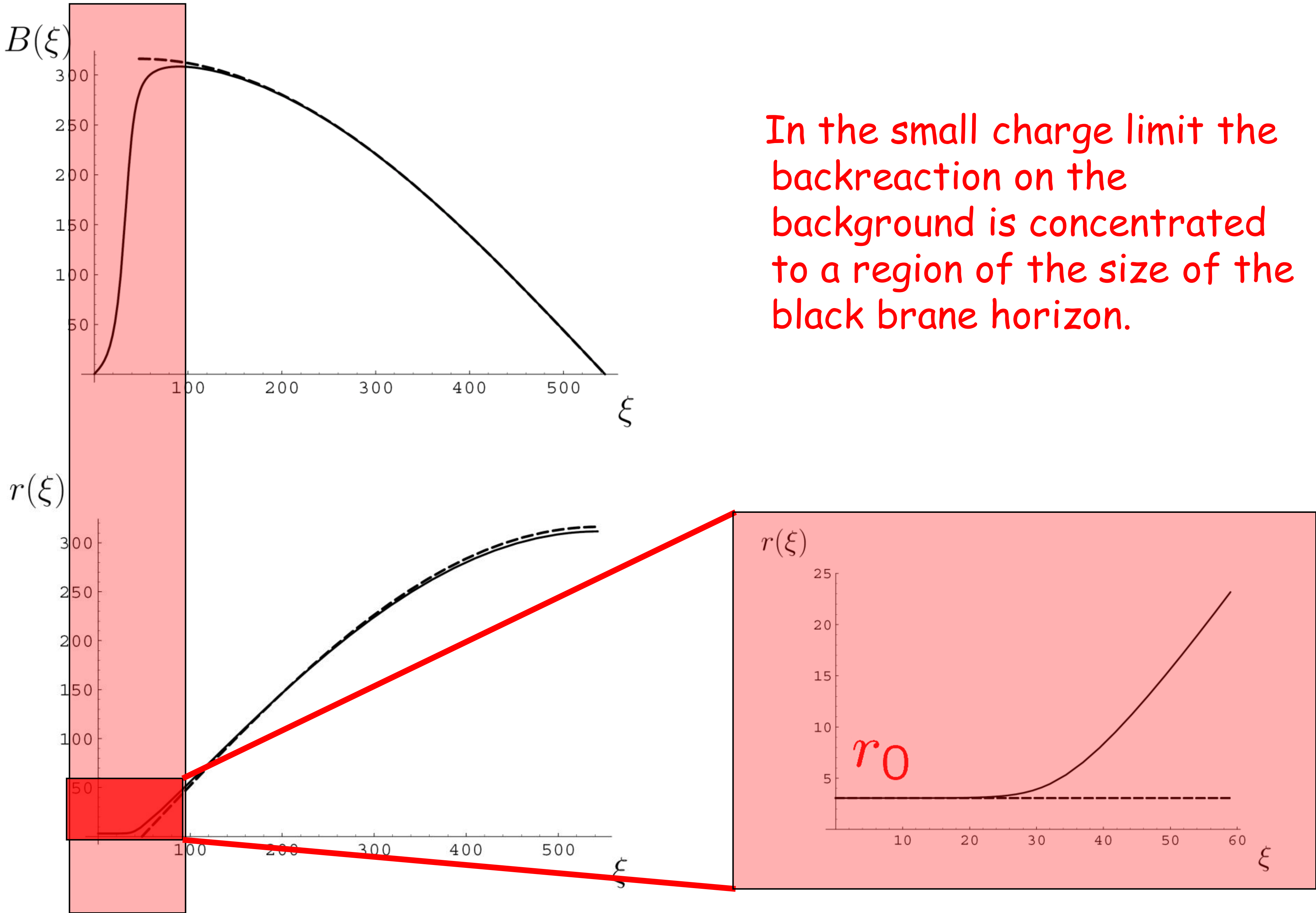
$$\left.\begin{array}{l} B(0) = B(\xi_{max}) = 0 \\ B'(0) = B'(\xi_{max}) = 1 \\ r'(0) = r'(\xi_{max}) = 0 \end{array}\right\}$$

$\Longrightarrow$ Smooth at the horizons

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

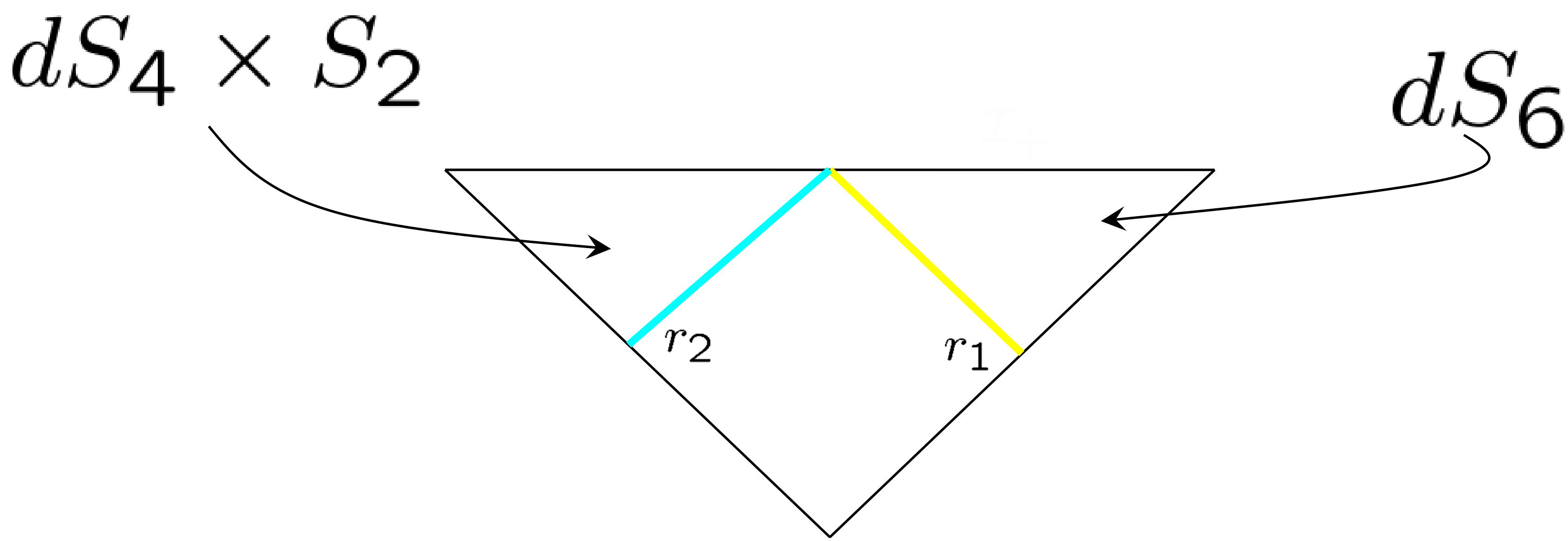
$\Longrightarrow$ One should find these values numerically

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.

Inflating branes mediate dynamical compactification



Bubbles of Nothing

Witten (82).

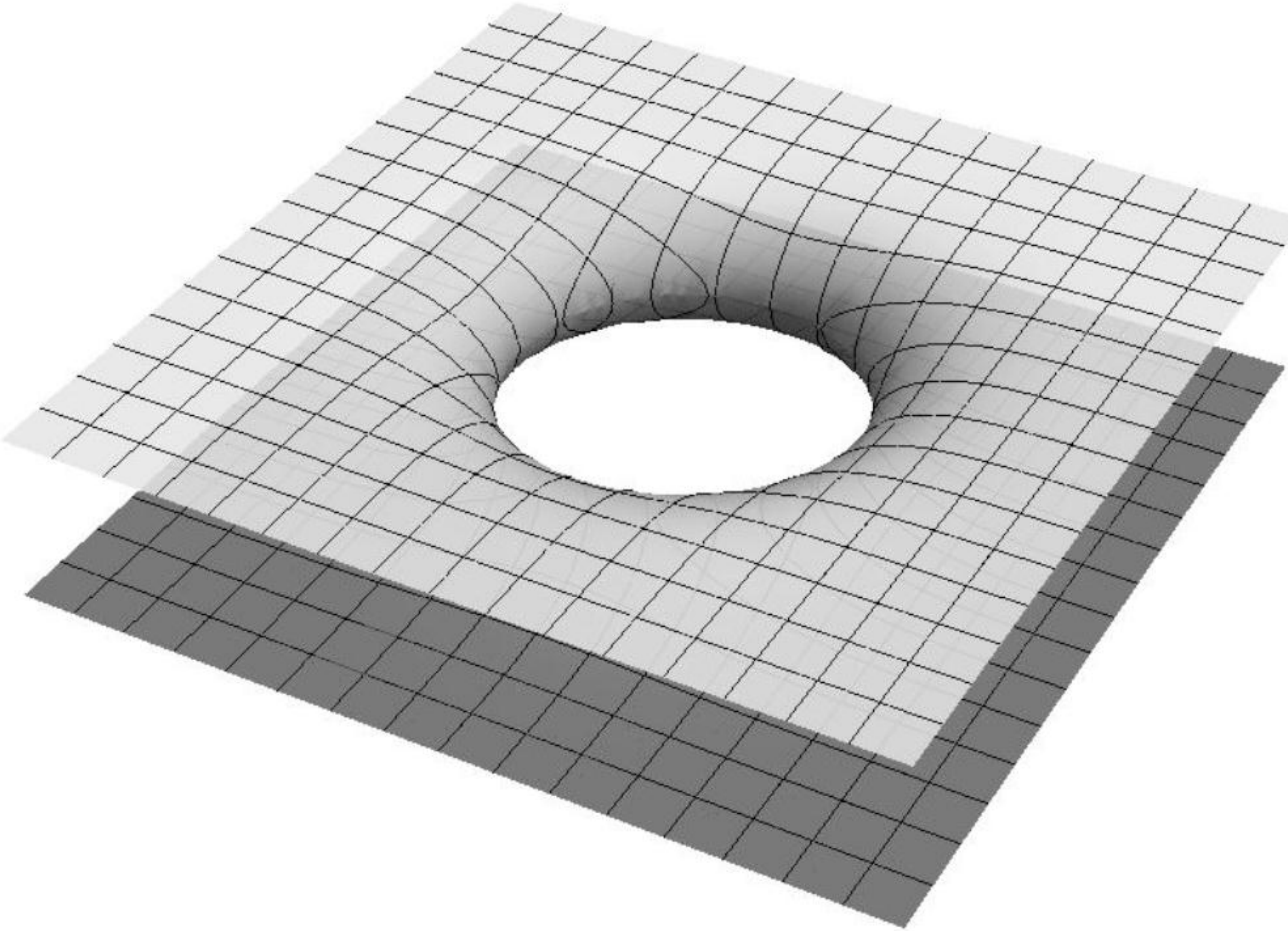
- Are there are other decay channels for compactification models ?

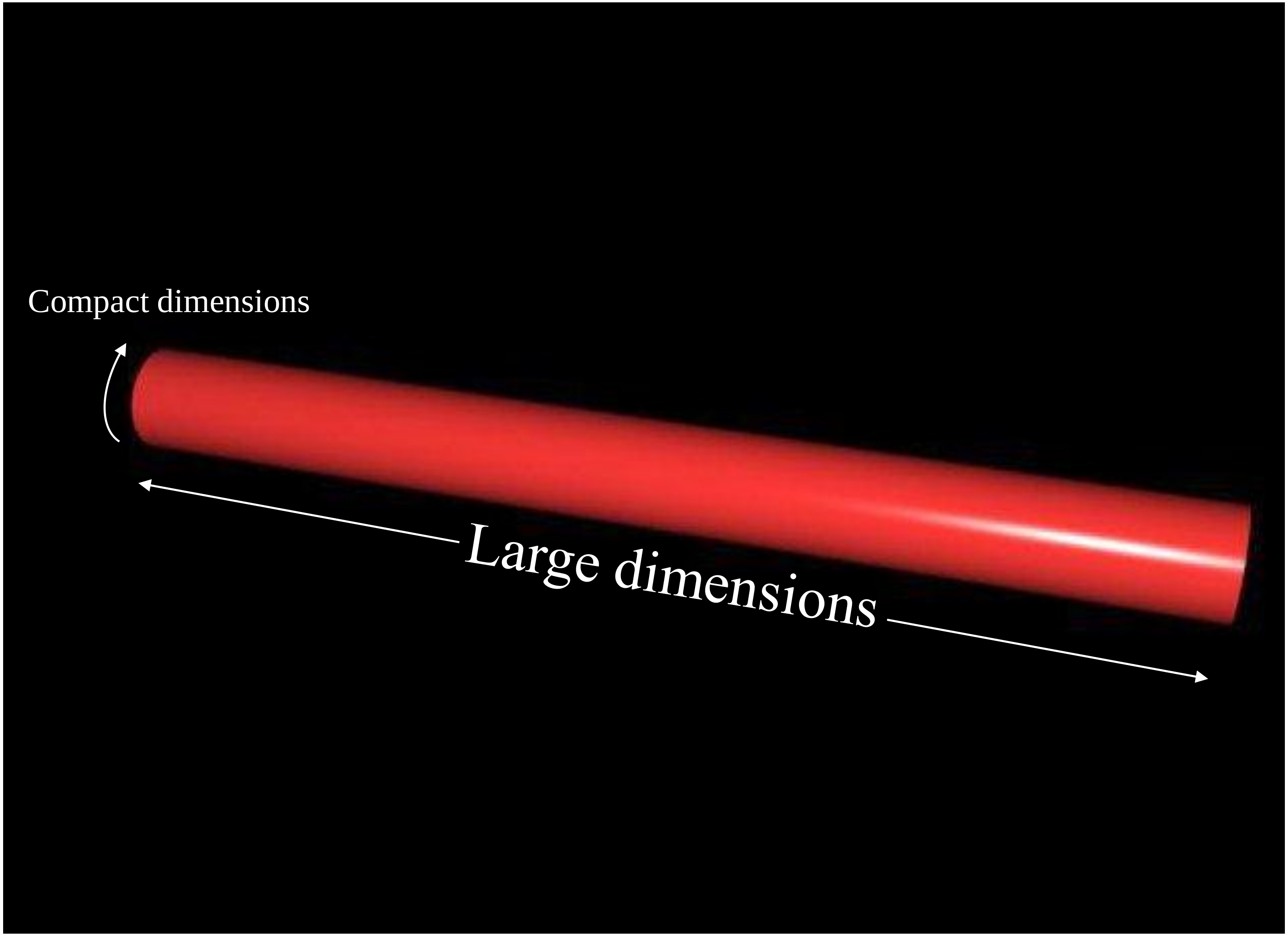
- 5d Kaluza-Klein model is non-perturbative stable and can decay into a bubble of nothing geometry.

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

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

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




Compact dimensions
Large dimensions

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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 ?

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

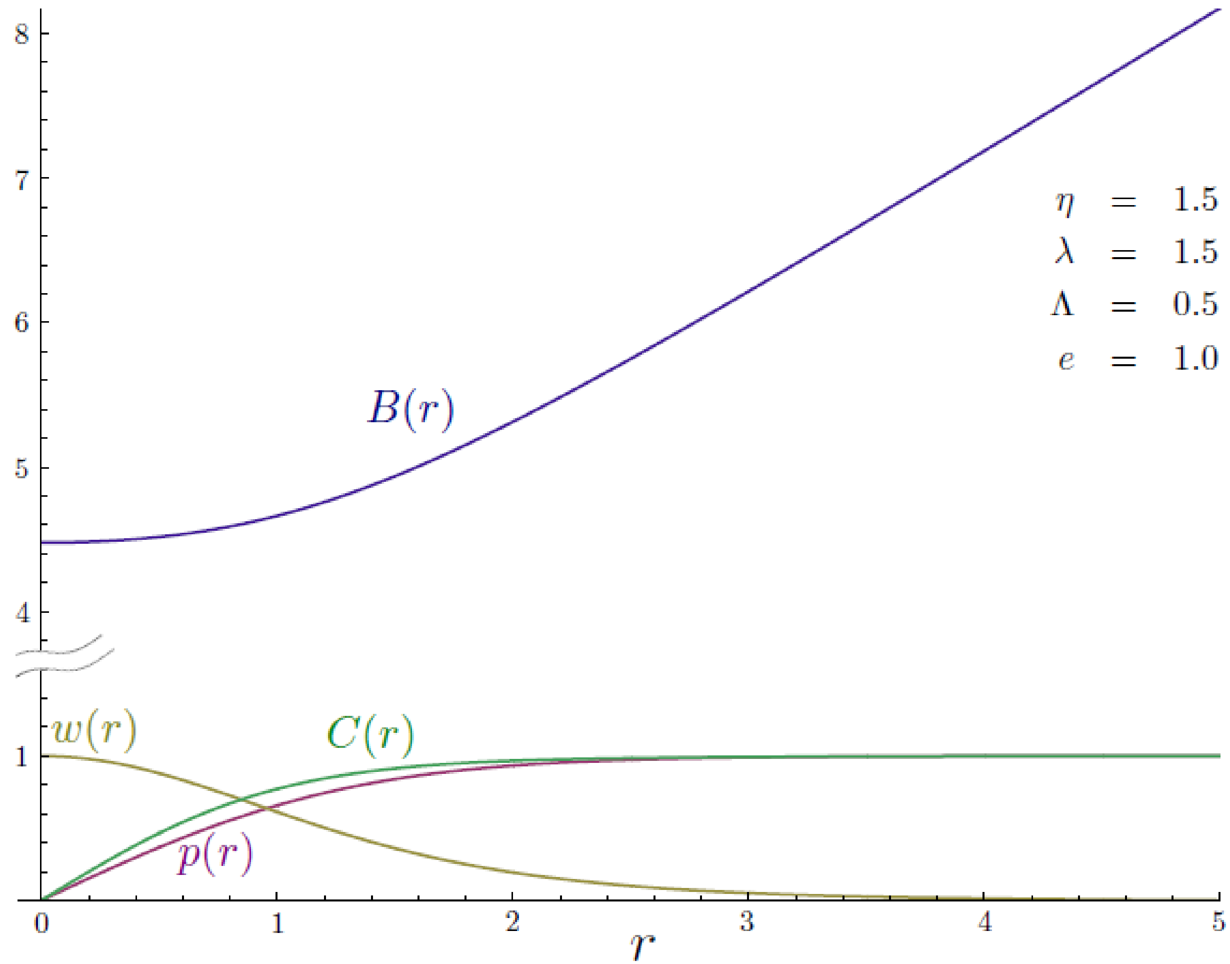
- We need to regularize the tip of the cigar geometry so we upgrade our theory to an SU(2) version:

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

- 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).



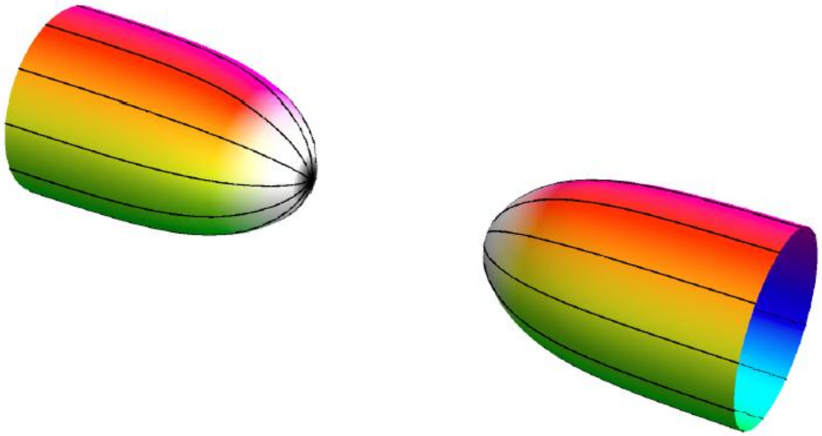
$$ds^2 = B(r)^2(-dt^2 + \cosh(t)^2 d\tilde{\Omega}_2^2) + dr^2 + C(r)^2 d\Omega_2^2$$

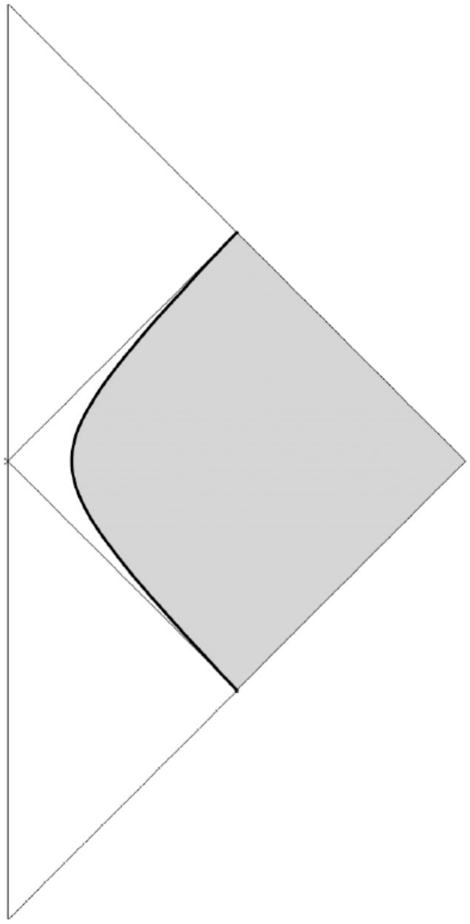
Bubbles of Nothing in Flux Compactifications

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

- The solution can be thought of as an inflating brane.

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

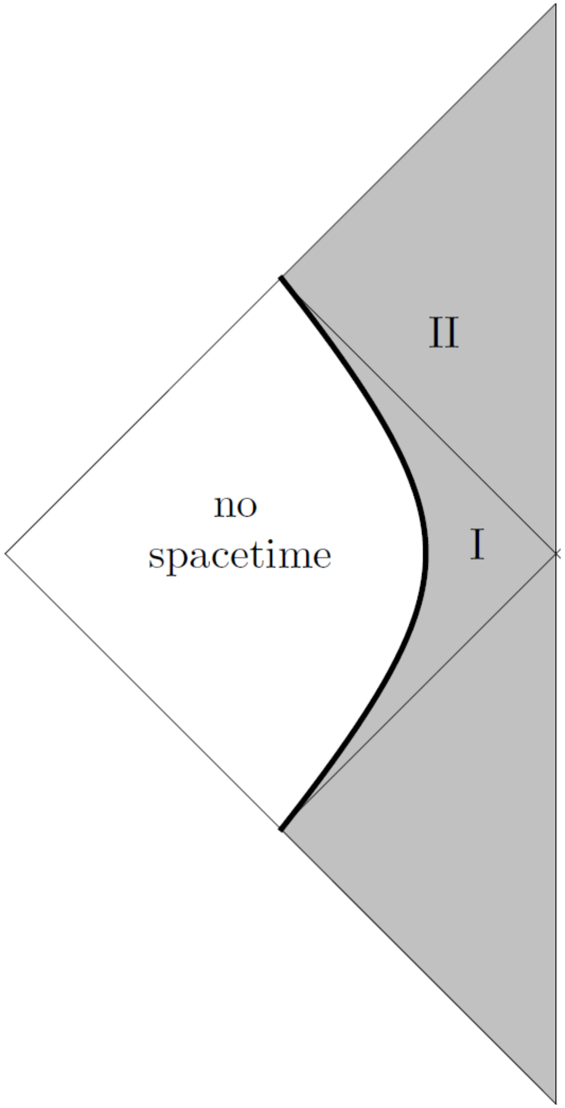




- At some point these brane solutions become flat and the decay channel gets suppressed .

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).

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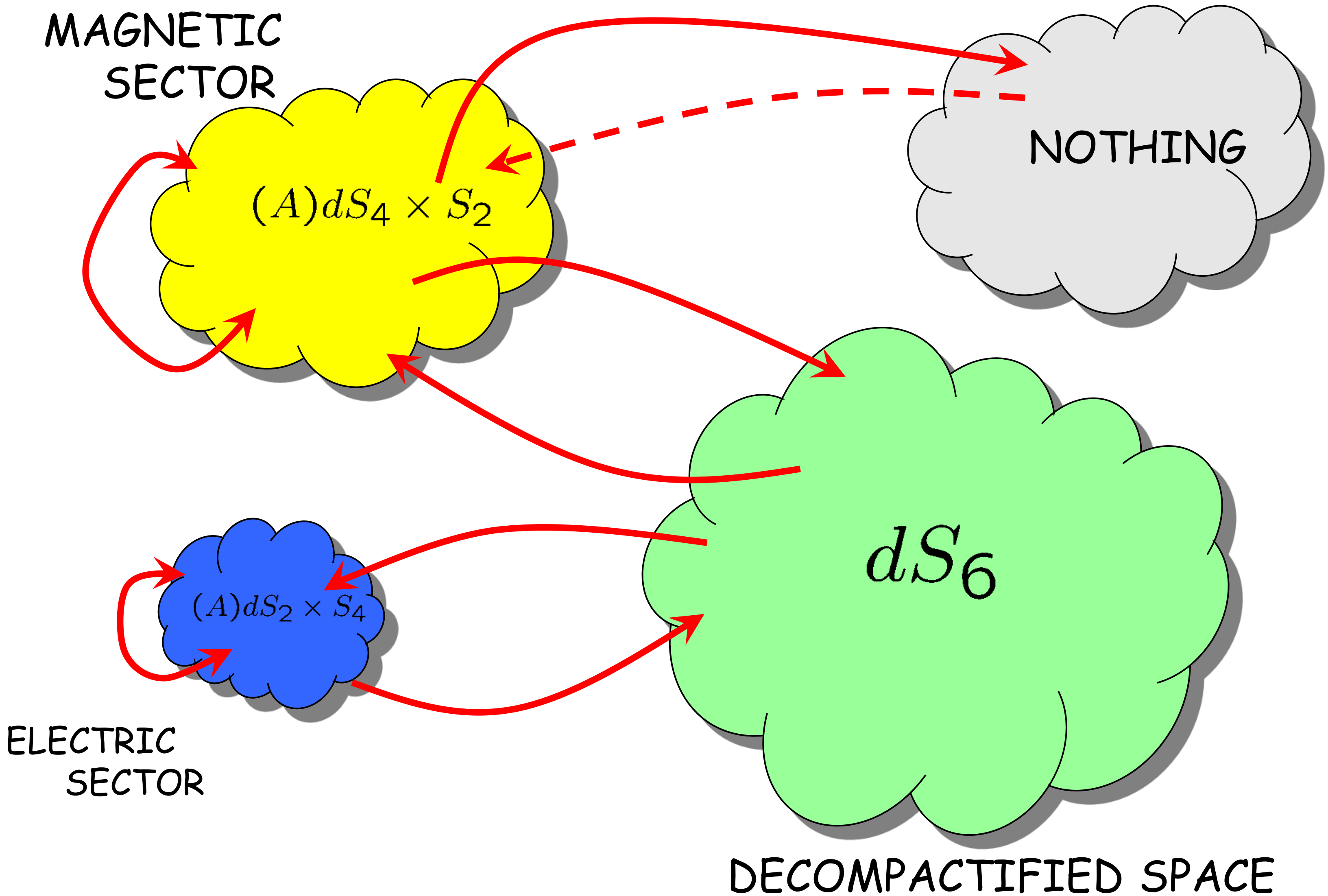
Transdimensional Tunneling



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.

$$Nothing \Longrightarrow dS_4 \times S_2$$

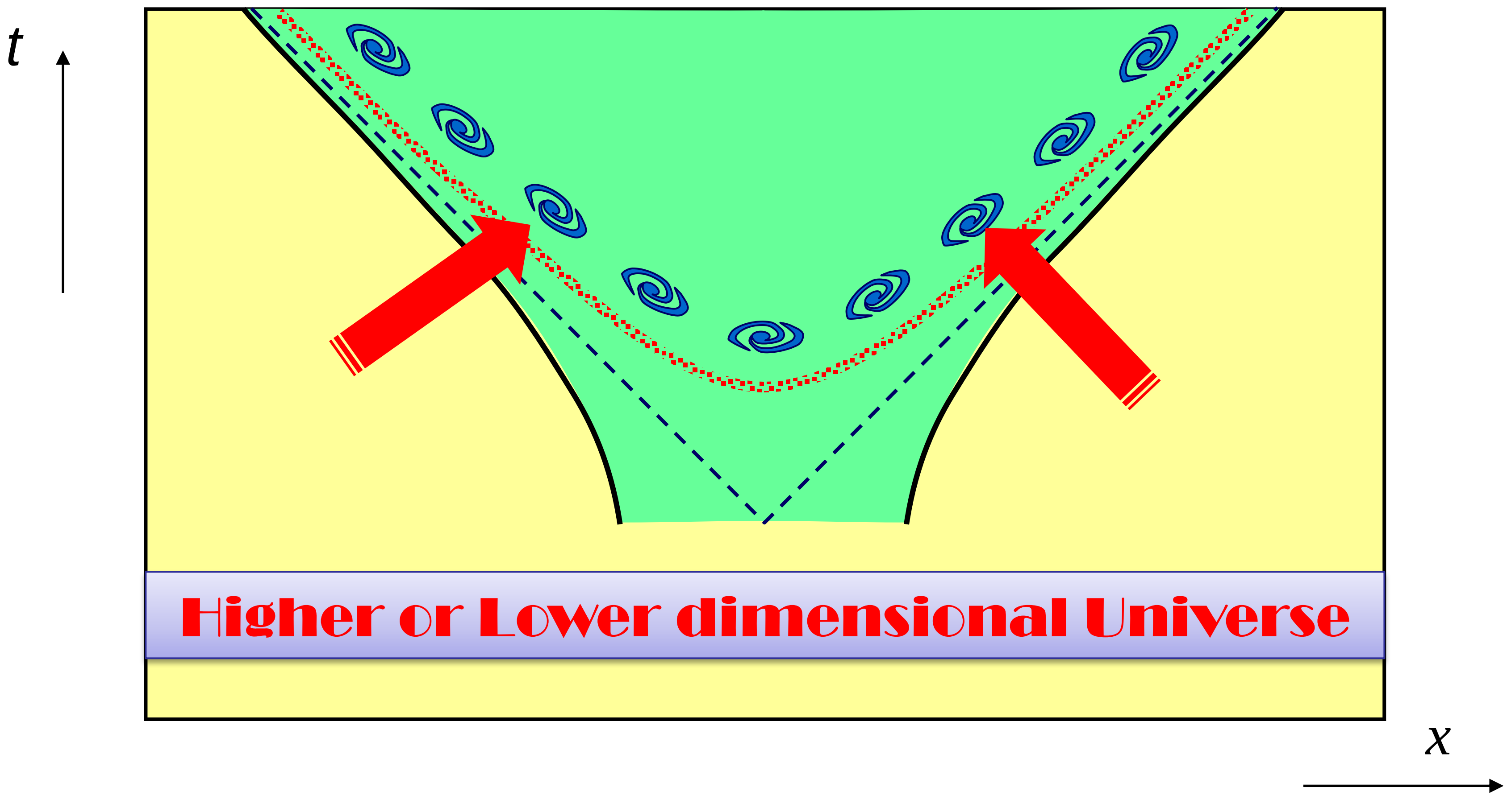
$$(A)dS_2 \times S_4 \Longrightarrow dS_4 \times S_2$$

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

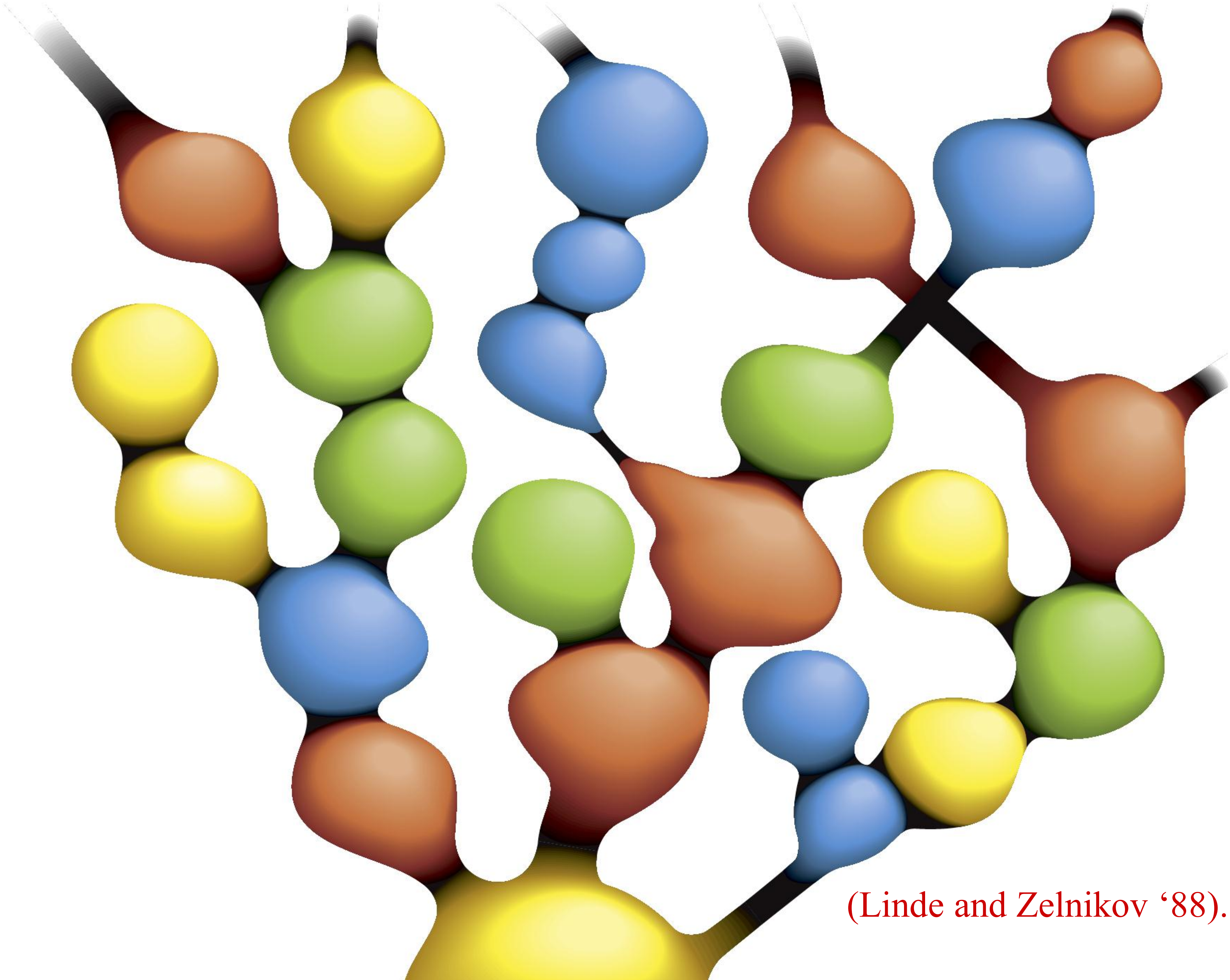
$$dS_6 \Longrightarrow dS_4 \times S_2$$

Spacetime of a Transdimensional Bubble Universe

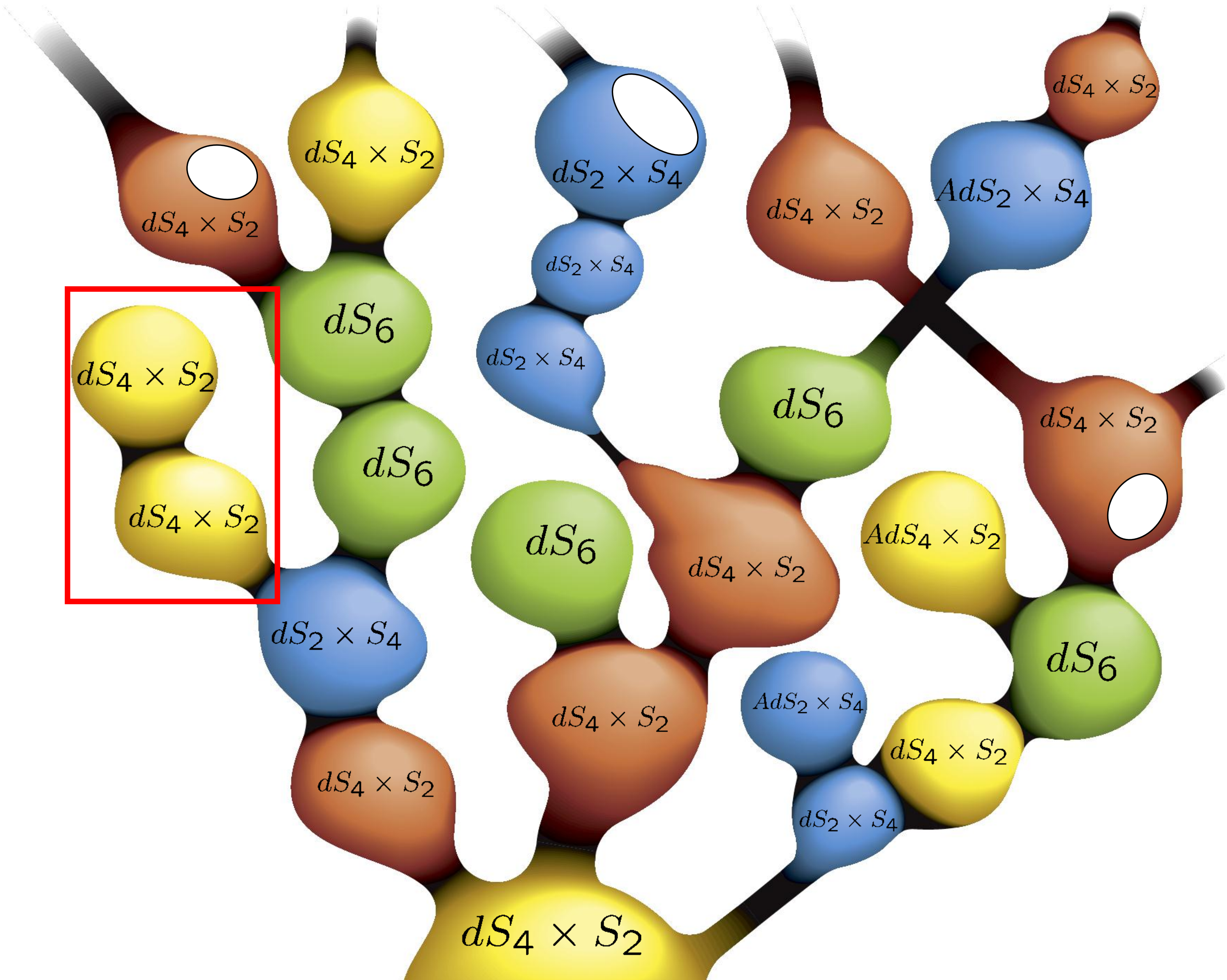
Work in progress…



What is the BIG PICTURE ?



(Linde and Zelnikov ‘88).



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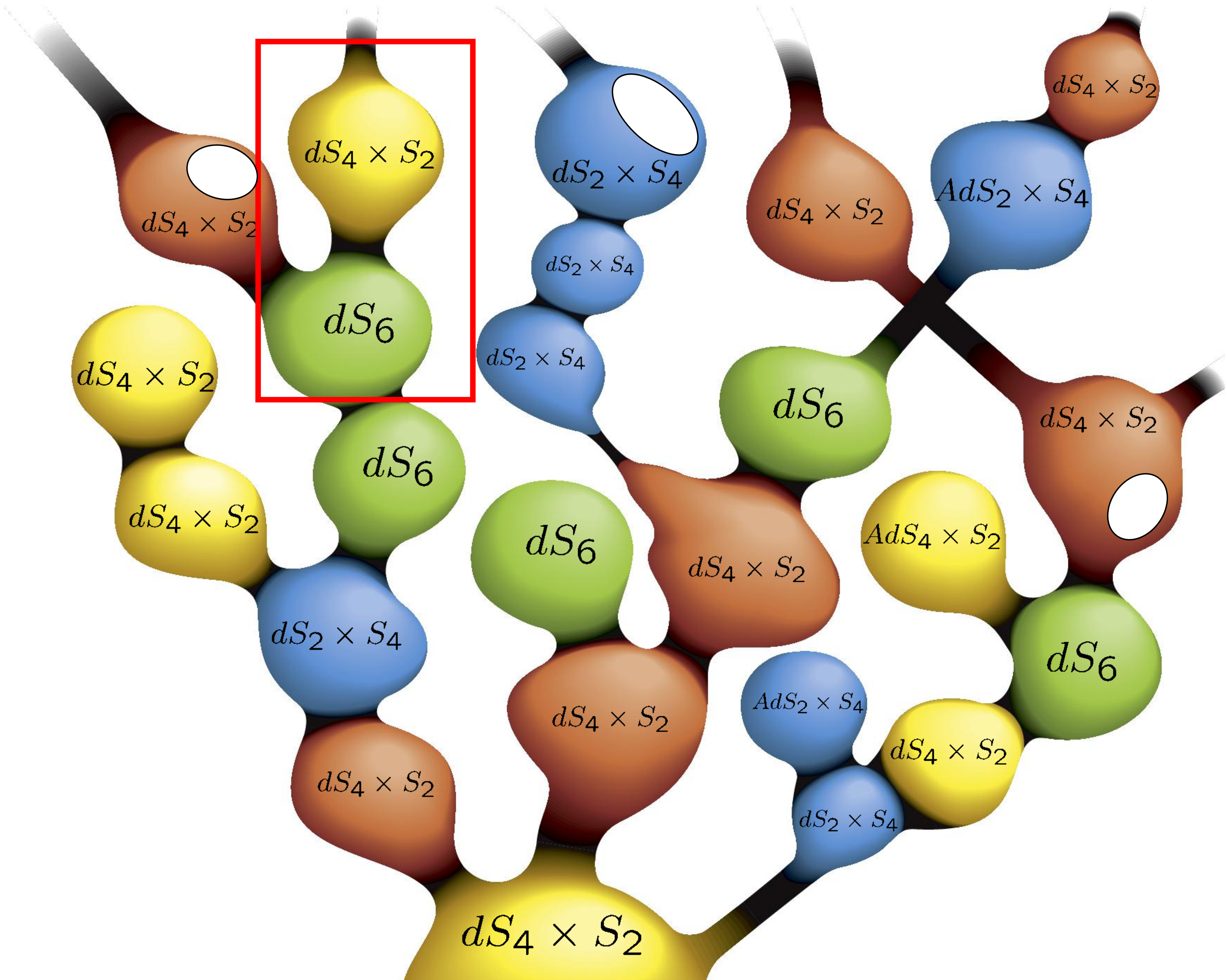

$dS_4 \times S_2$
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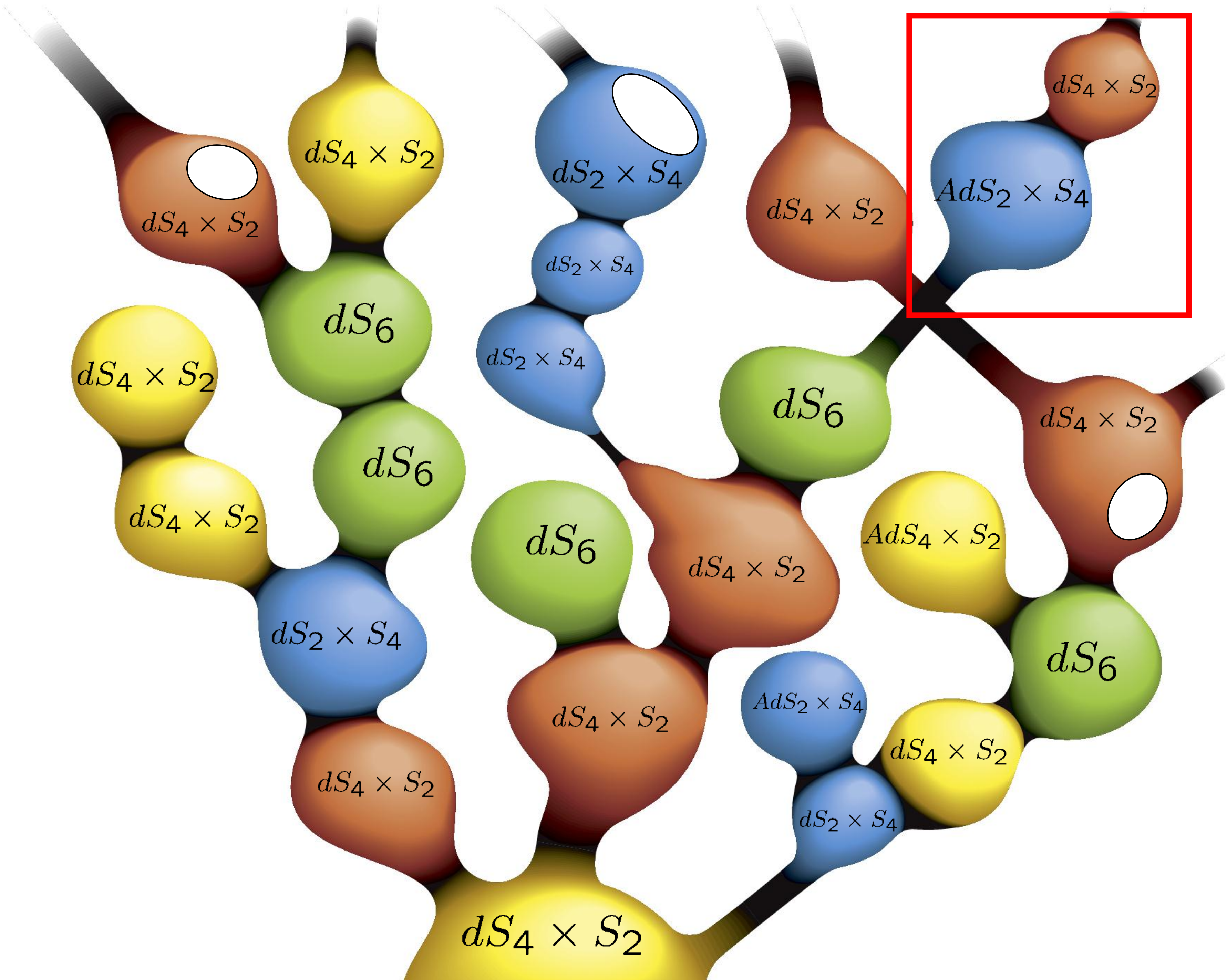
$AdS_2 \times S_4$
$dS_4 \times S_2$
$dS_2 \times S_4$
dS_6
$AdS_4 \times S_2$

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