Title: Early stages of the universe: brane gas-driven bulk dynamics

Date: May 30, 2006 11:00 AM

URL: http://pirsa.org/06050025

Abstract: We propose a new brane world scenario. In our model, the Universe starts as a small bulk filled with a dense gas of branes. The bulk is bounded by two orbifold fixed planes. An initial stage of isotropic expansion ends once a weak potential between the orbifold fixed planes begins to dominate, leading to contraction of the extra spatial dimensions. Depending on the form of the potential, one may obtain either a non-inflationary scenario which solves the entropy and horizon problem, or an improved brane-antibrane inflation model.

Early Stages of the Universe: Brane Gas-Driven Bulk Dynamics

Natalia Shuhmaher (McGill)

Based on:

JHEP **0601**, 074 (2006)

PRL **96**, 161301 (2006)

by Robert Brandenberger, N.S.

Outline

- Overview
- The Model
- An Alternative to Inflation
- Emerging Brane Inflation Models
- Conclusions

Overview

Motivation

Extra Dimensions:

- predicted by String Theory - often treated as static

  Exceptions e.g.
  - SGC
  - brane inflation models
  - Ekpyrotic scenario

Can dynamics explain early stages of the Universe?

New Approach:

bulk dynamics driven by a gas of p-branes

Basic Idea

FRW Cosmology in extra dimensions with new ingredients:

- branes
- orbifold fixed planes

In our scenario:

- Topology distinguishes 3 'our' dimensions
- Difference in topology $\Longrightarrow$ difference in evolution

Starting point: a dense gas of branes

Preview of Results

We present two brane world scenarios:

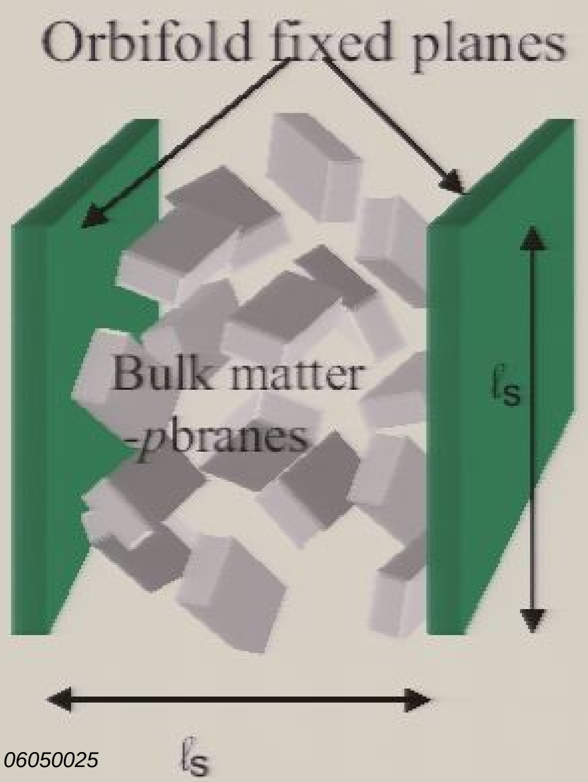
- one which solves non-inflationary entropy and horizon problems
- second which naturally provides initial conditions for brane inflation models

The Model

Setup

Assumptions:

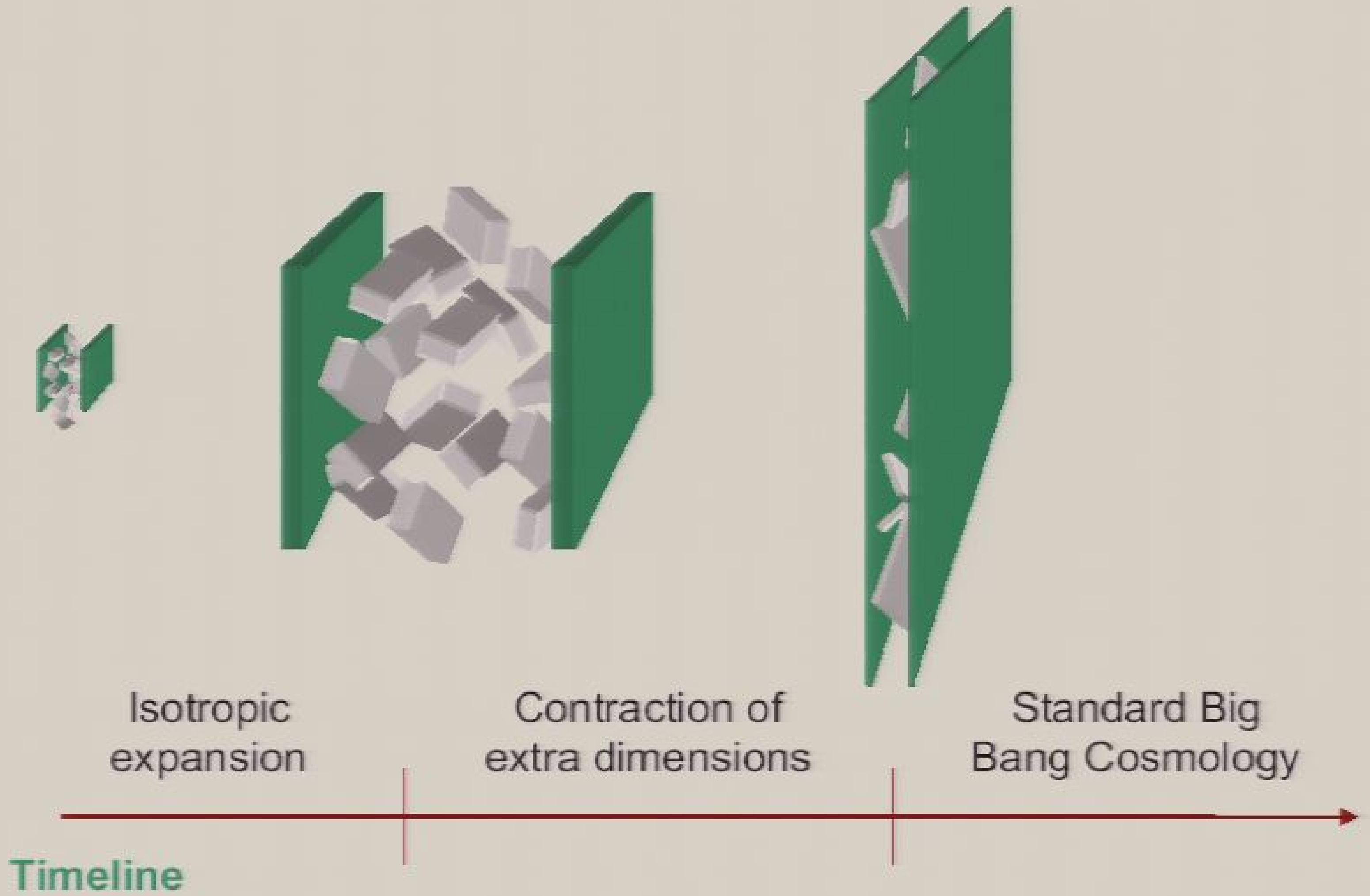
- $\mathcal{M} = \mathcal{R} \times T^3 \times T^d/Z_2$ (d - # of extra dimensions)
- Total Energy $= l^{-1}$ & $\rho_i = l^{-d-4}$ ($l \sim l_s$)



Standard Initial Conditions:

- Universe starts
  - Small
  - Dense
- Unique scale
- An isotropic brane gas

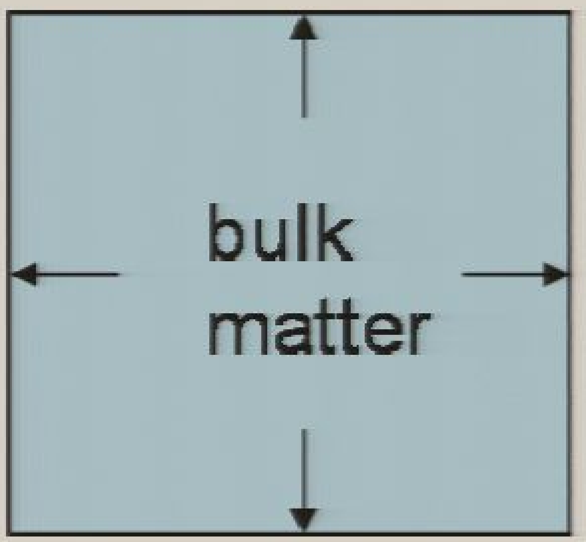
Overall Dynamics



Phase of Expansion

Metric: $ds^2 = dt^2 - a(t)^2 d\mathbf{x}^2 - b(t)^2 d\mathbf{y}^2$

Isotropy: $a(t) = b(t)$



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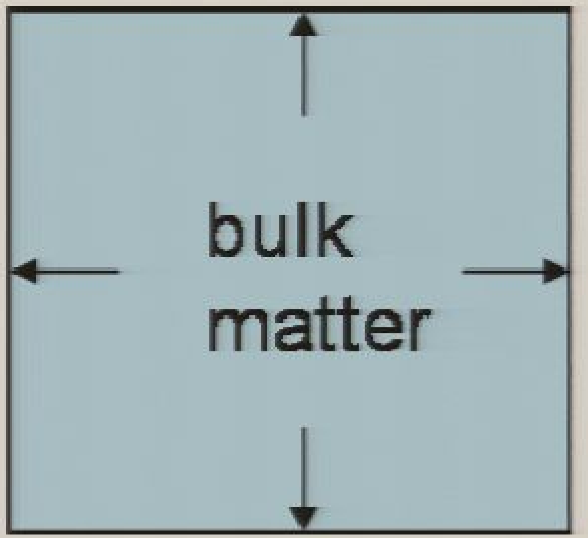

Expansion governed by

$$\frac{\ddot{a}}{a} + (2+d)(\frac{\dot{a}}{a})^2 = \frac{8\pi G}{3+d-1}[\rho - P]$$

Equation of state

$$P = w\rho$$

Leads to

$$a(t) = b(t) \sim t^\alpha \, ; \, \alpha = \frac{2}{(3+d)(1+w)}$$

p-Branes

- 3-brane: $T^{\mu}_{\nu} = (\rho, -\rho, -\rho, -\rho, 0, ...)$
- 5-brane: $T^{\mu}_{\nu} = (\rho, -\rho, -\rho, -\rho, -\rho, -\rho, 0, ...)$
- Perfect fluid approximation for the brane gas

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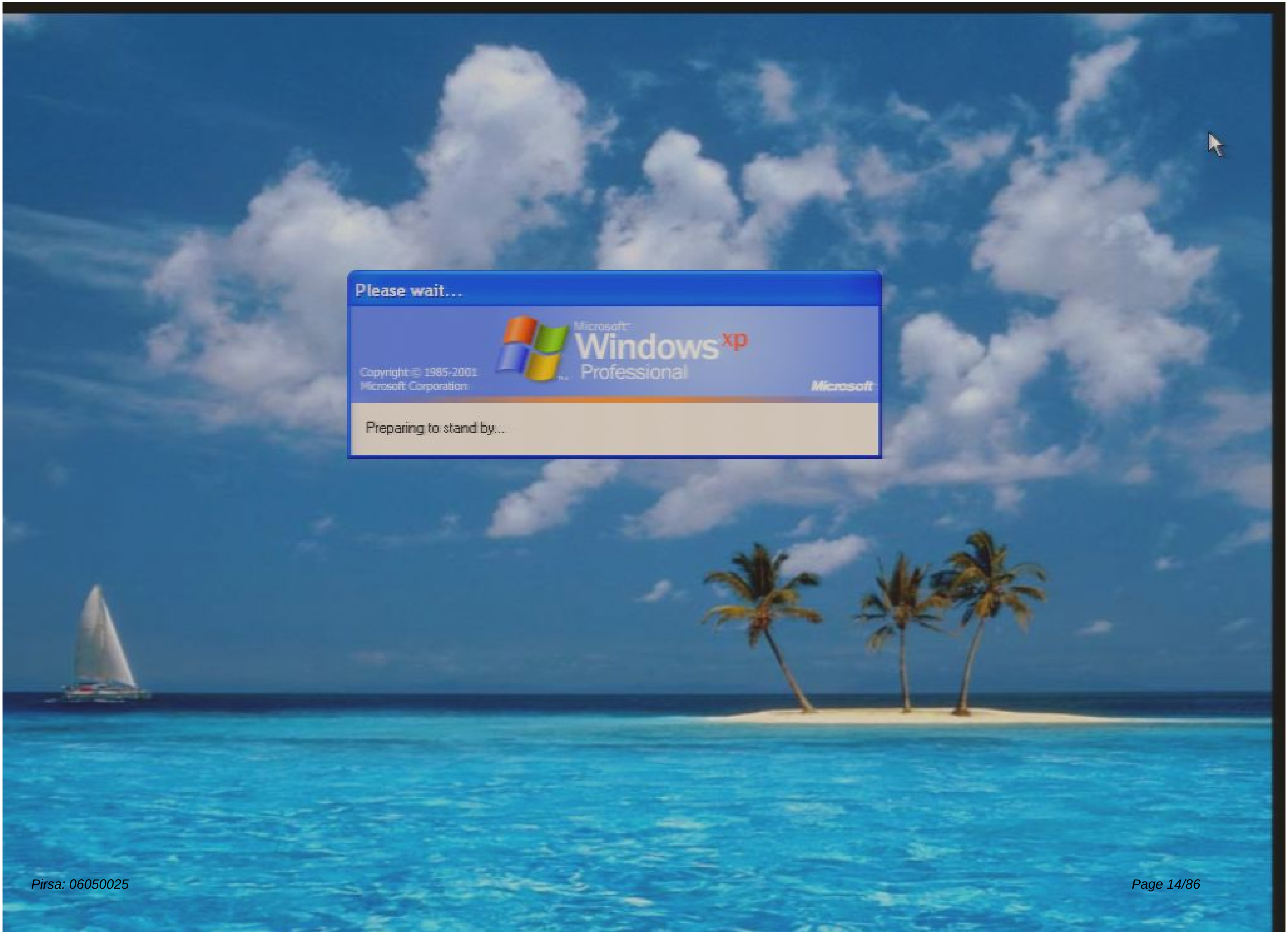
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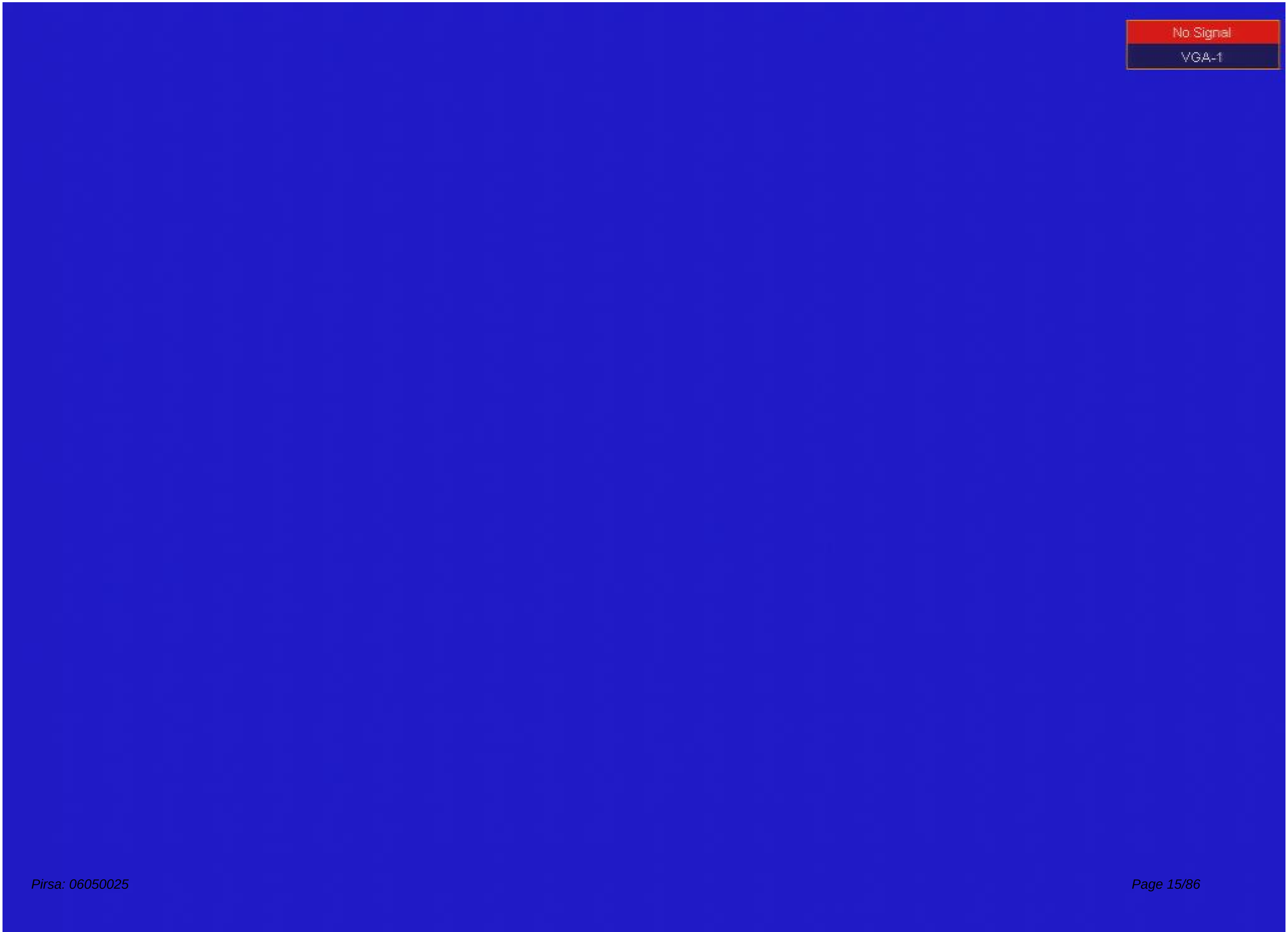
No Signal
VGA-1

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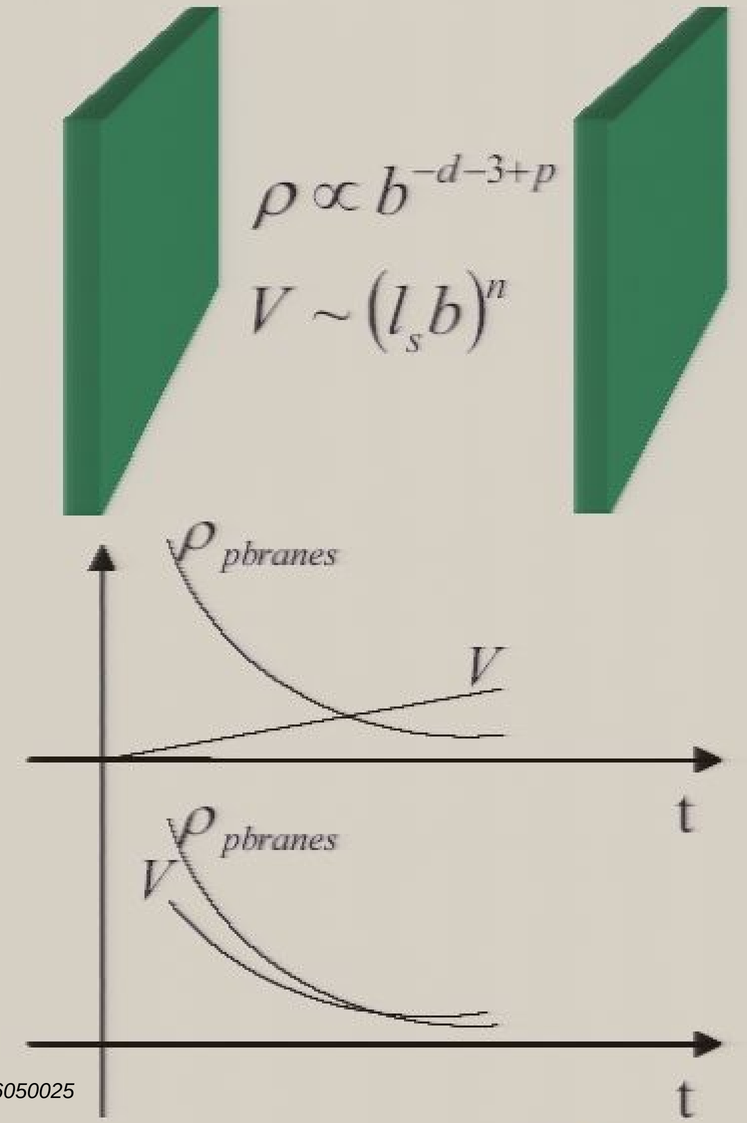
From Expansion to Contraction



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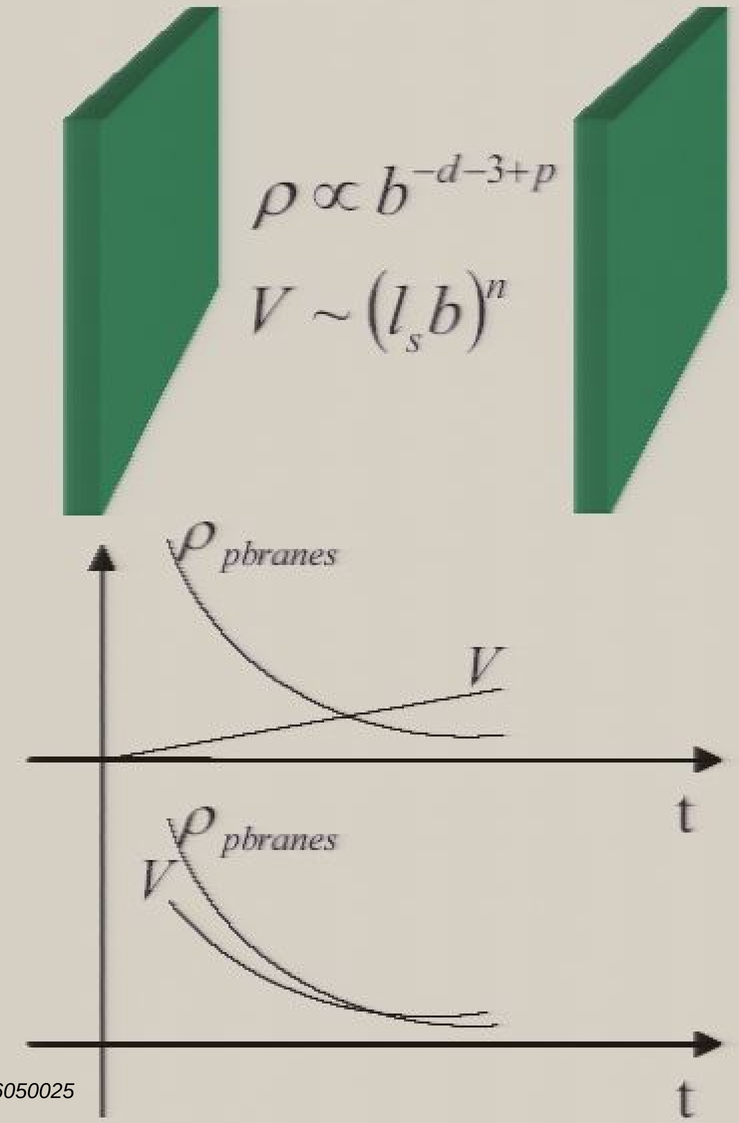

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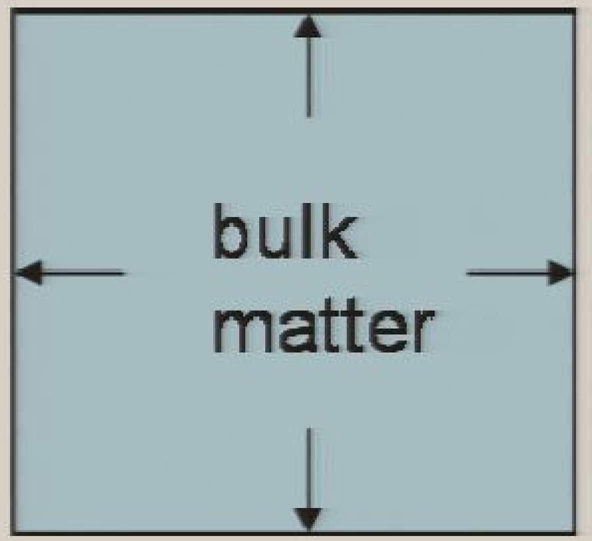

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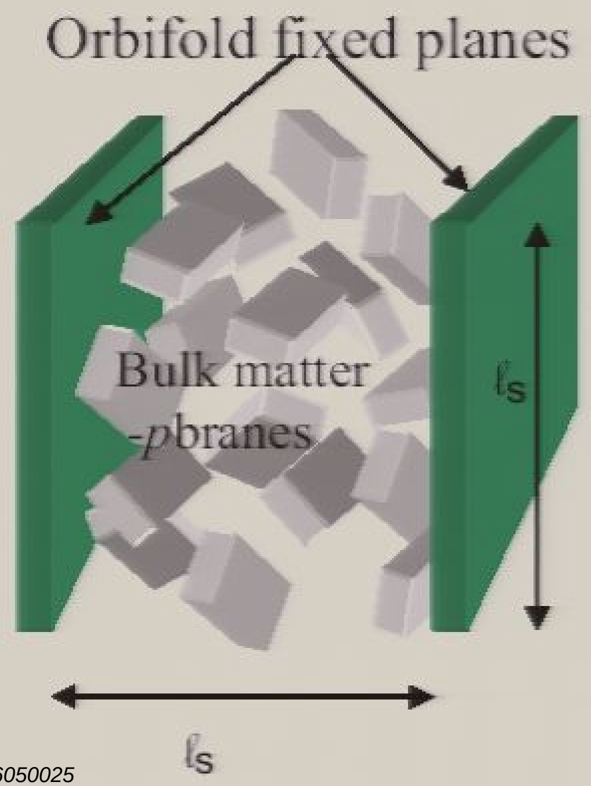

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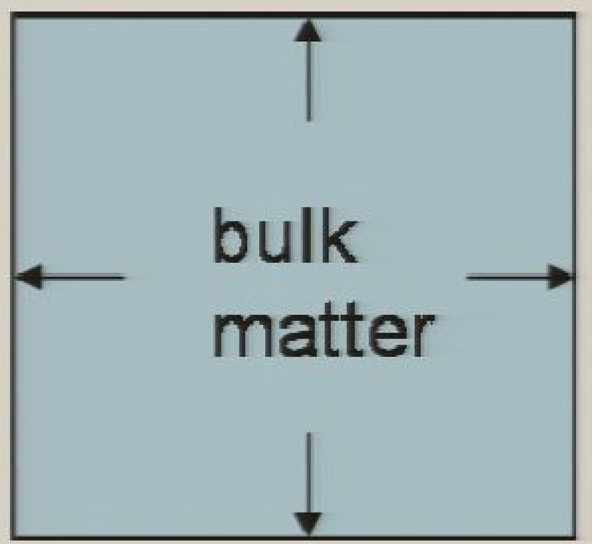

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Examples from String Theory:

- Type IIB superstring theory - $d = 6\,, p = 3 \Rightarrow a(t) = t^{1/3}$
- Heterotic string theory - $d = 6\,, p = 5 \Rightarrow a(t) = t^{1/2}$
- M-theory - $d = 7\,, p = 5 \Rightarrow a(t) = t^{2/5}$

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Conclusion: The expansion phase is non-inflationary

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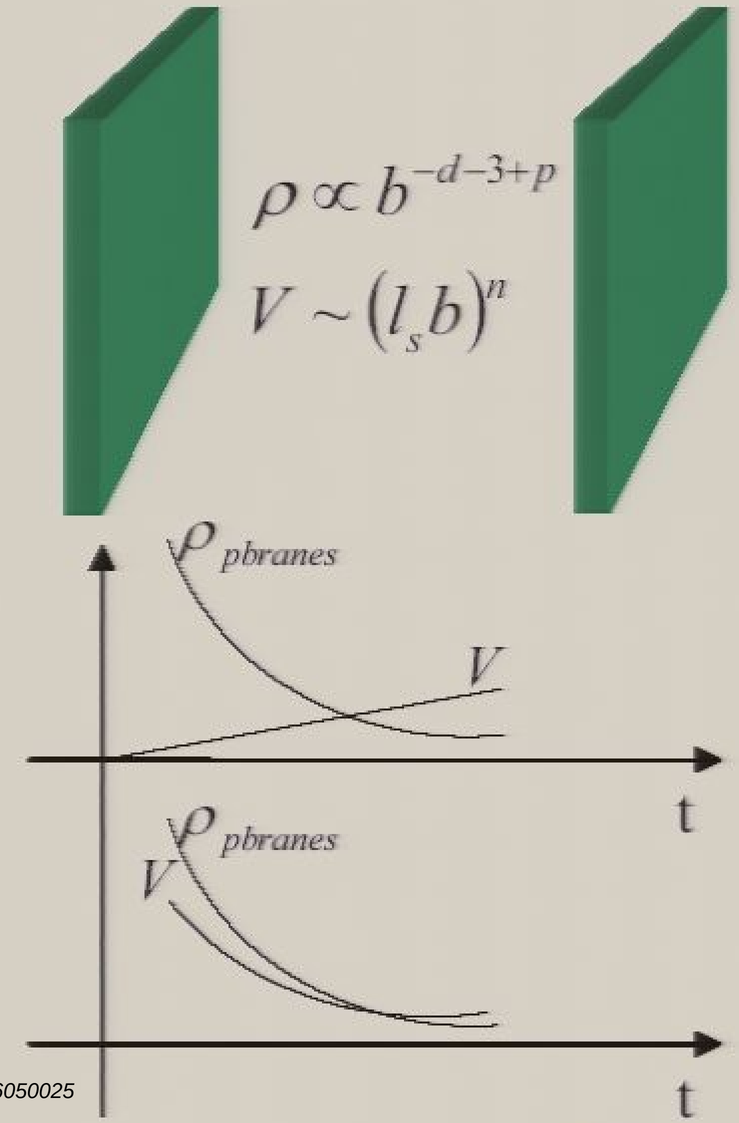


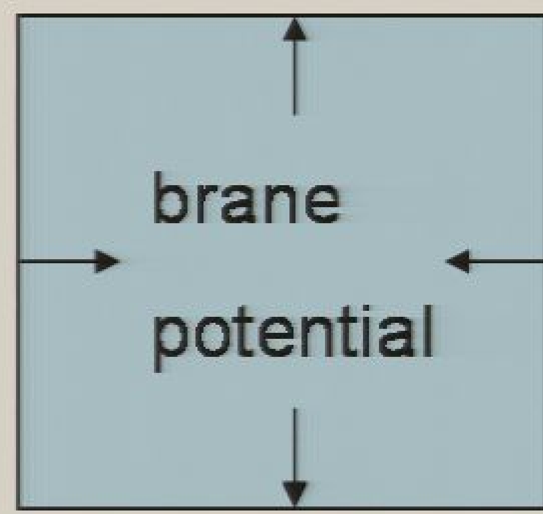
$$\rho \propto b^{-d-3+p}$$

$$V \sim (l_s b)^n$$

Brane potential dominates

when $V = \rho$

leading to contraction of extra dimensions



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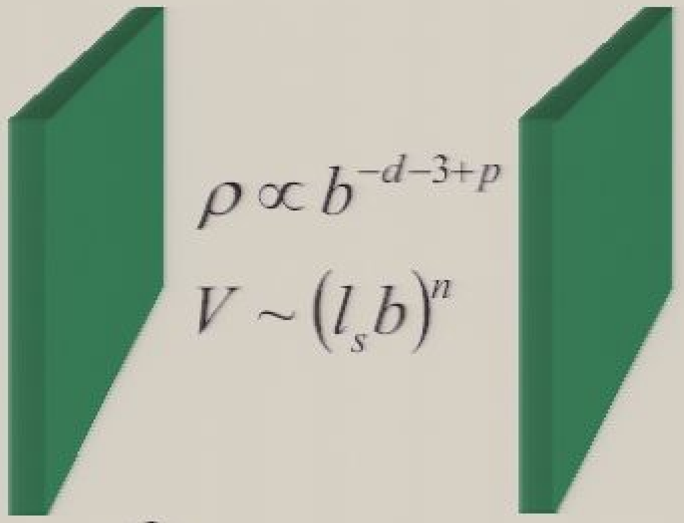

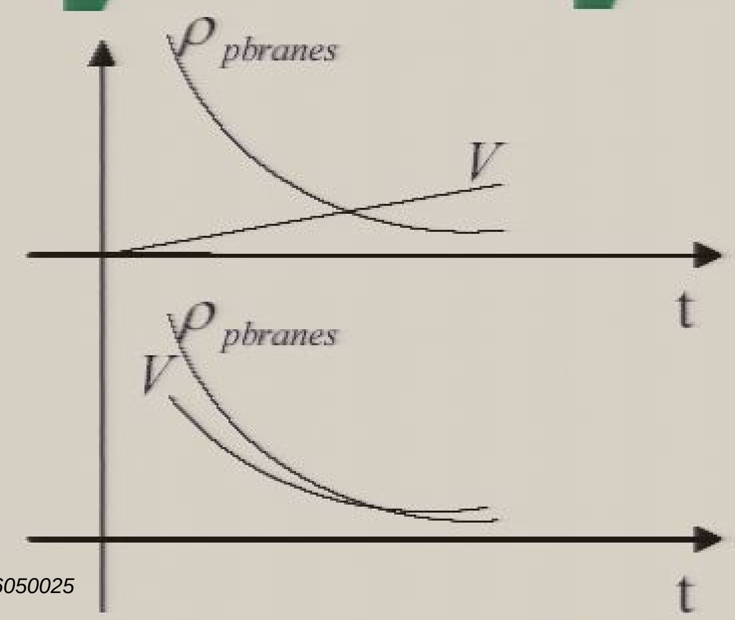

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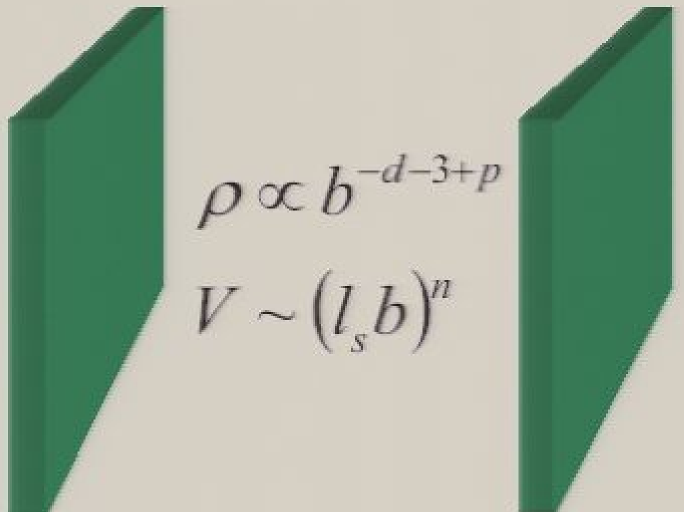

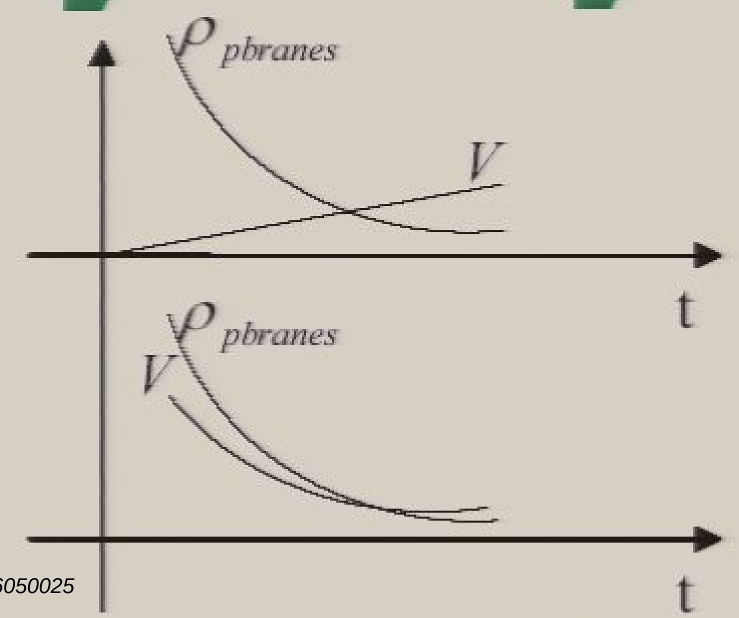

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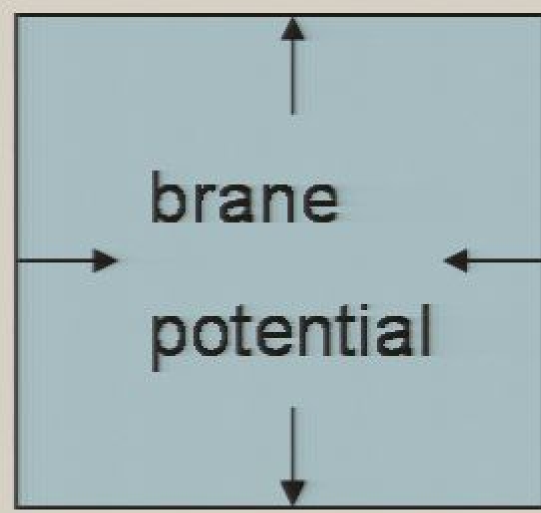

Phase of Contraction

Potential between fixed planes plays a crucial role

- a confining potential $\Rightarrow$
  an alternative to inflation
- a decaying potential $\Rightarrow$
  dynamically emerging initial conditions for brane inflation models

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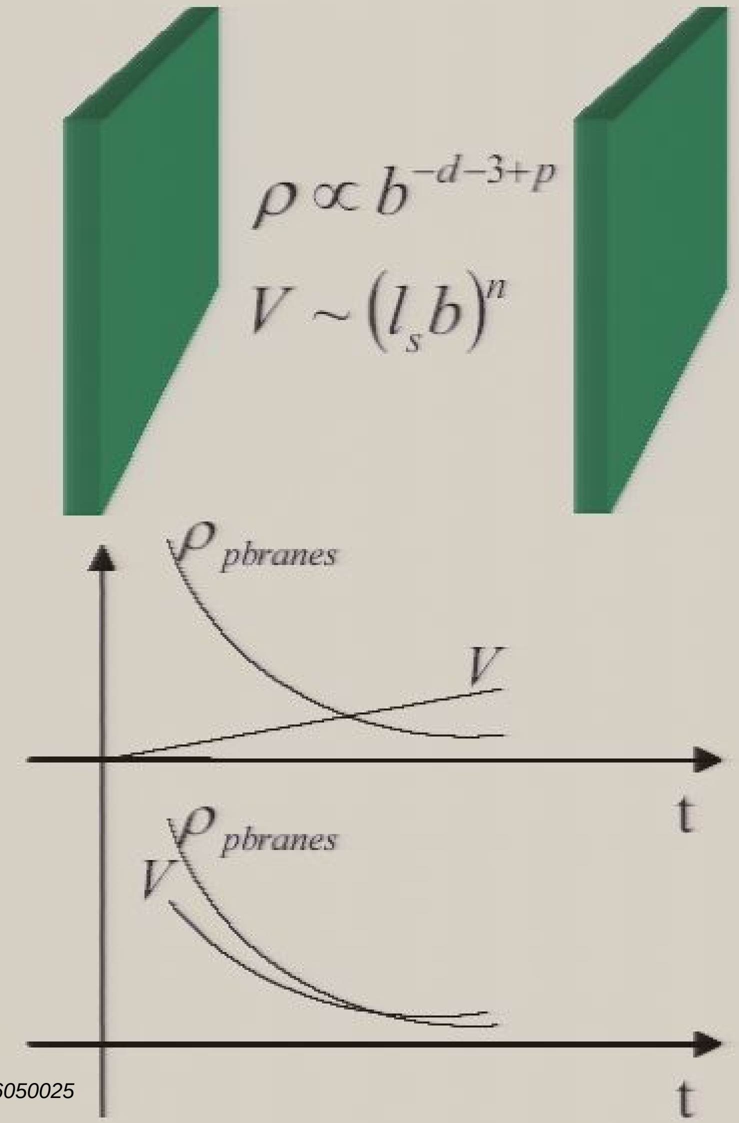

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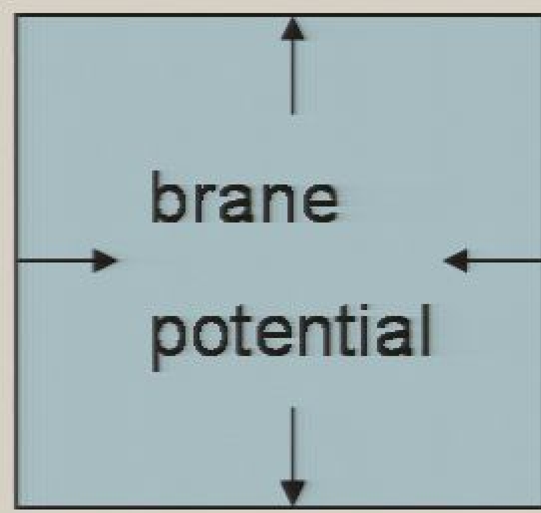

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An Alternative to Inflation

Motivation II

Inflation explains :

- flatness, **horizon**, **entropy**
- scale invariance of density perturbations

Conceptual problems:

- initial condition problem
- singularity

We address

horizon and **entropy** problems
starting with **standard initial conditions**

Note: this is the first time
entropy problem is addressed outside inflationary scenarios

Entropy Problem

Assuming adiabatic expansion

Entropy per co-moving volume which corresponds to H_0^{-1}:

$$
\begin{aligned}
S_U &= \# H_0^{-3} T_0^3 = 10^{90} \\
&\approx (1mm)^3 T_{pl}^3
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Entropy problem = Hierarchy problem: $\rho = m_{pl}^4$

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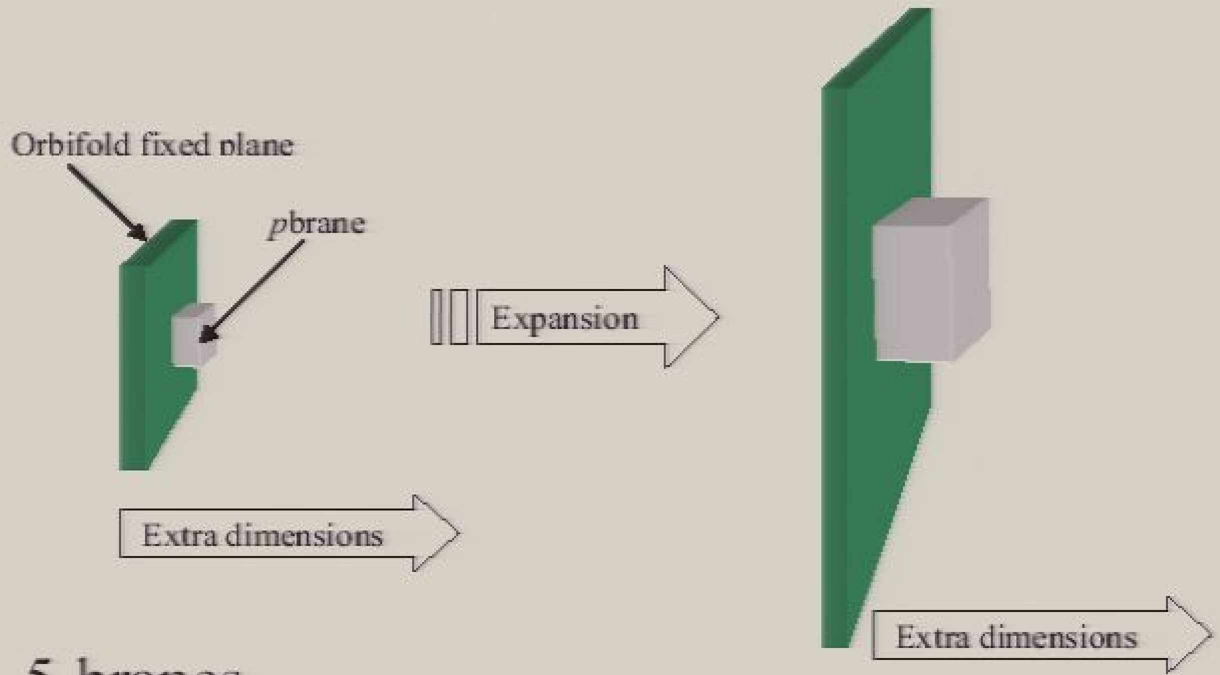
Standard Solution:

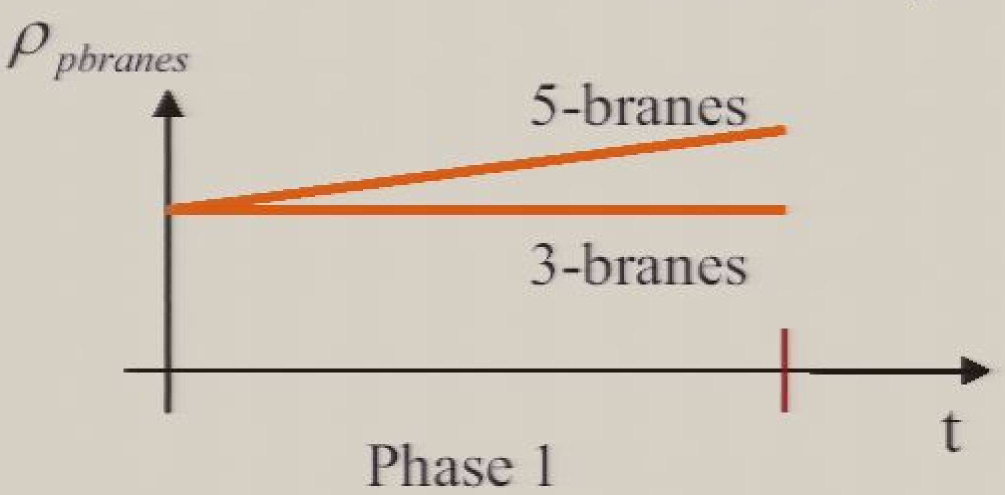
- Amplification of energy during early phase
- Non-adiabatic phase transition converting energy to radiation

Unusual technic: Energy amplified in codimension ≥ 3 branes

$\Longrightarrow$ no accelerated expansion

Projected Energy Density - Phase 1





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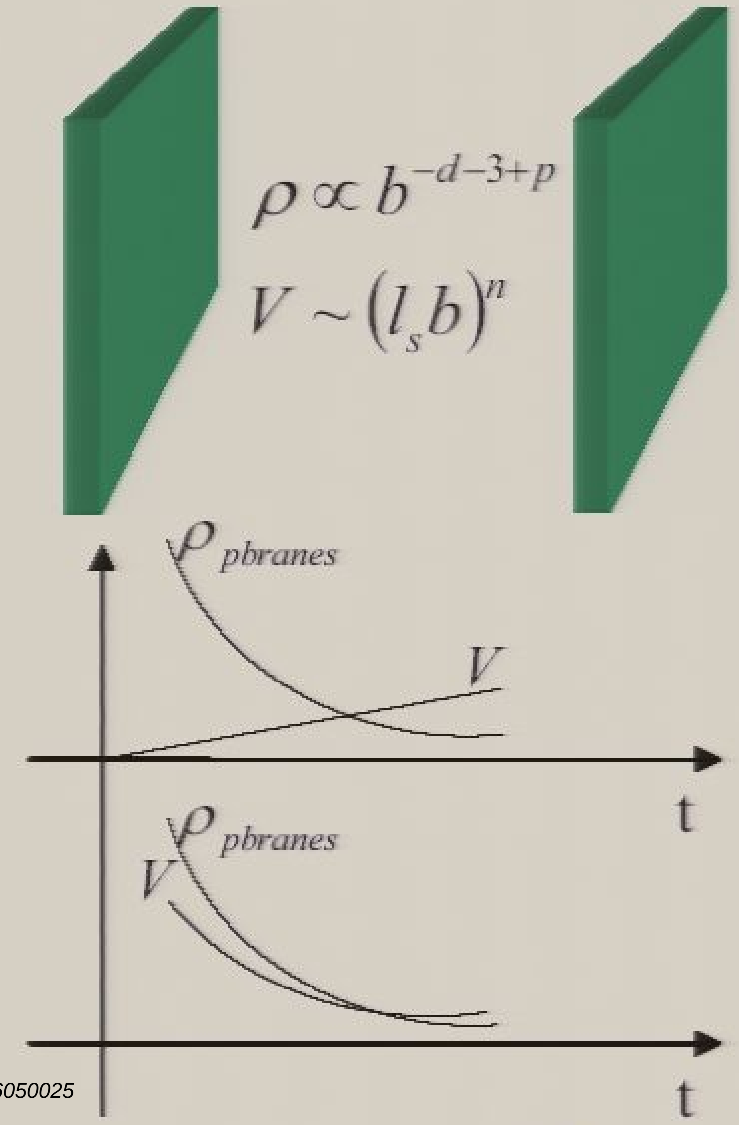

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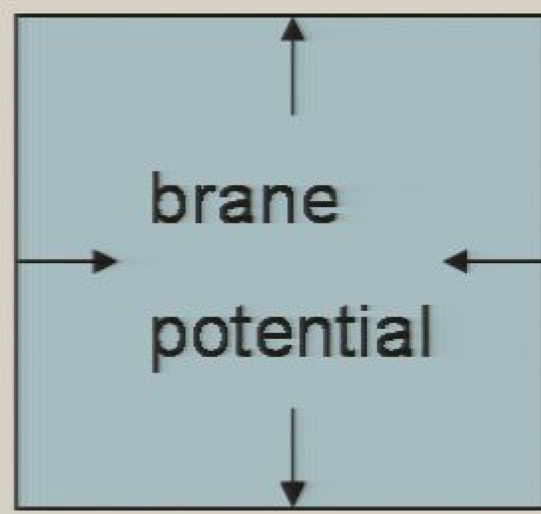

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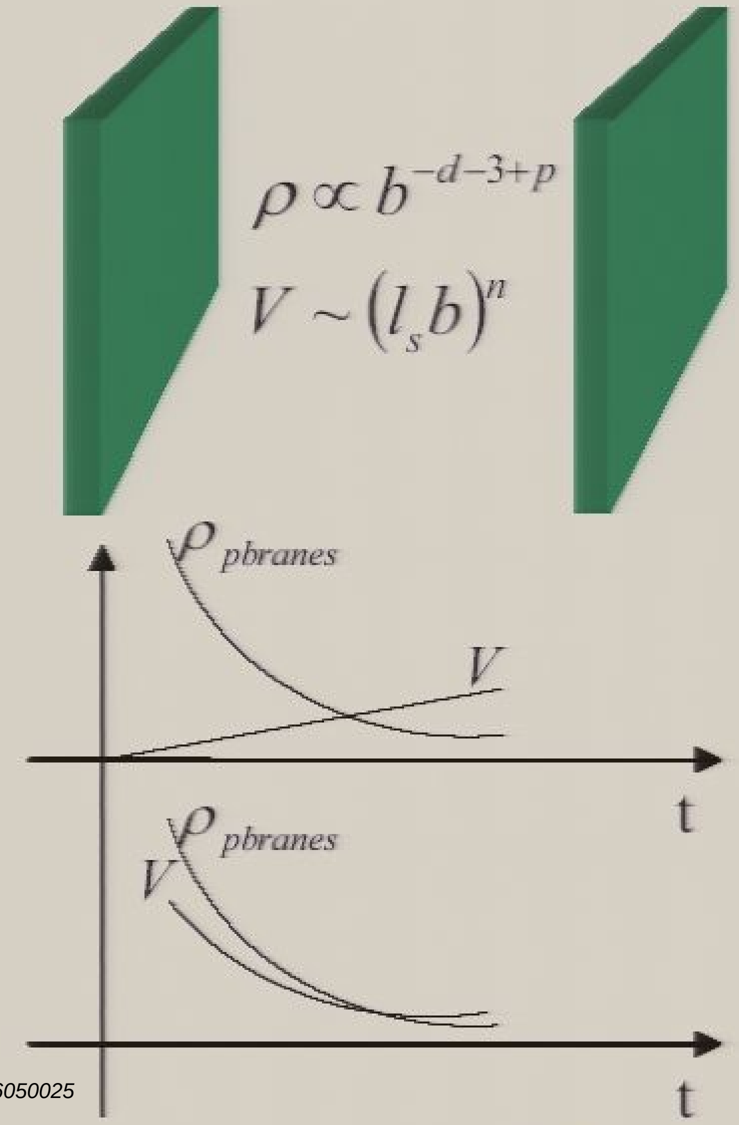

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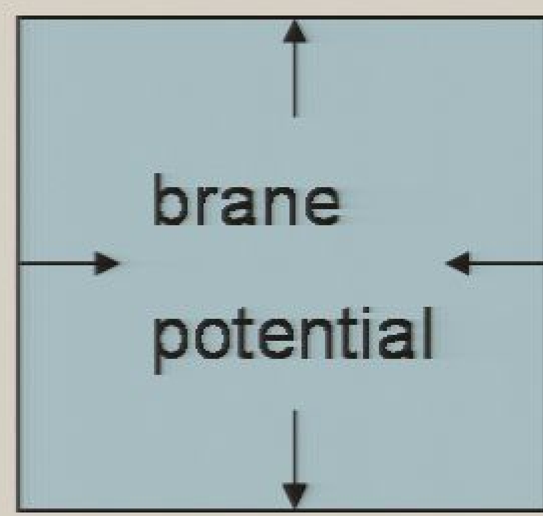

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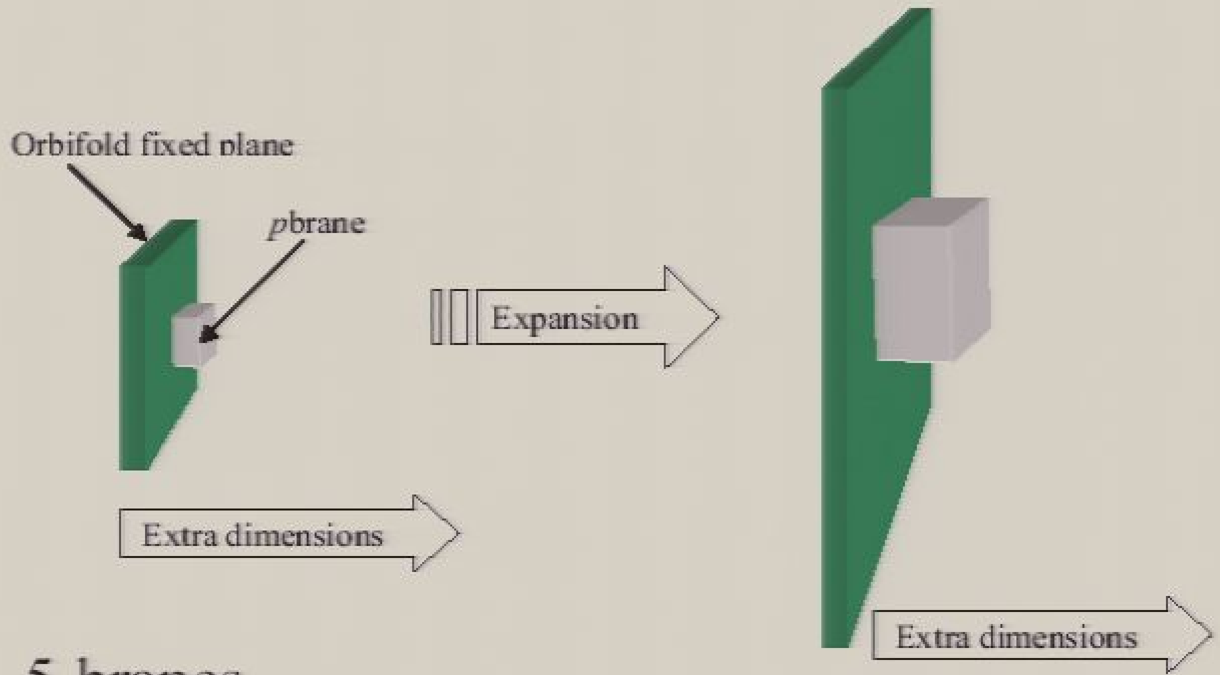
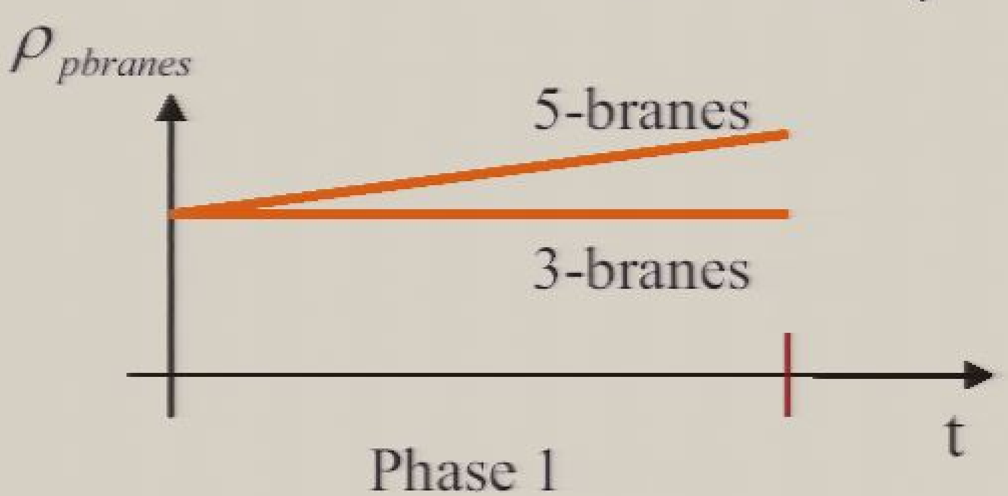
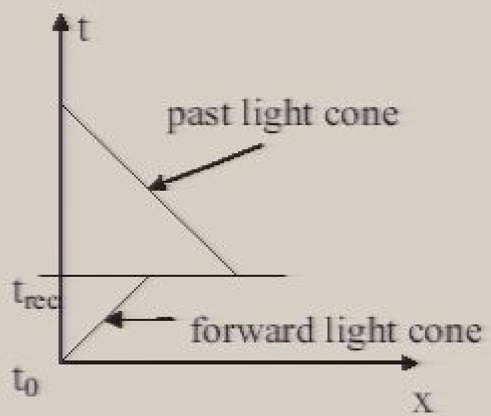


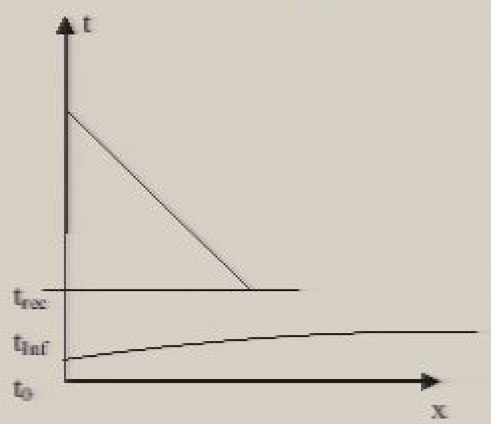


Horizon Problem

Standard Cosmology



Inflation



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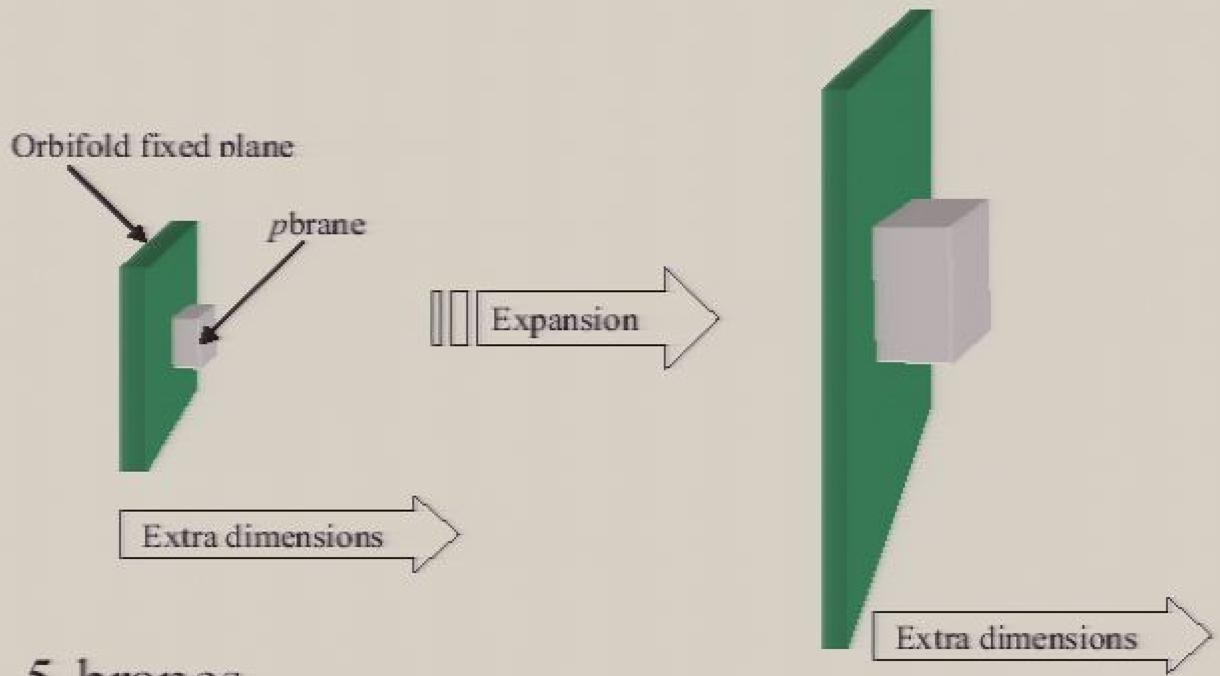

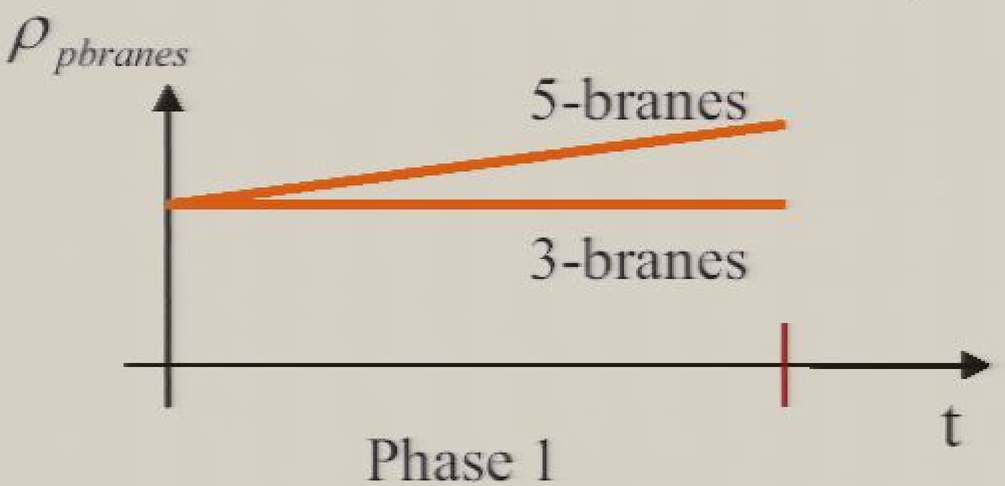

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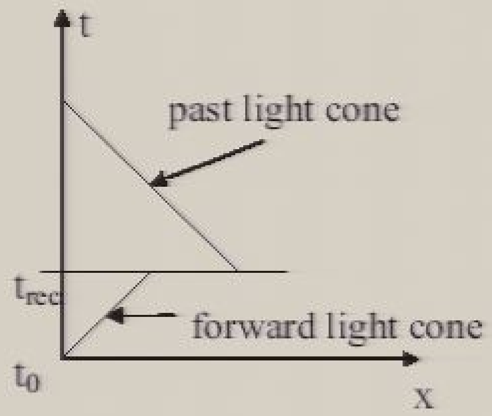

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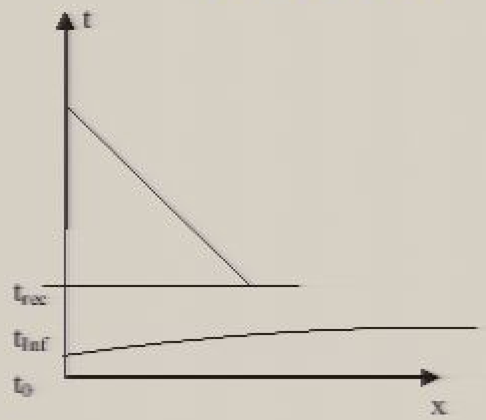

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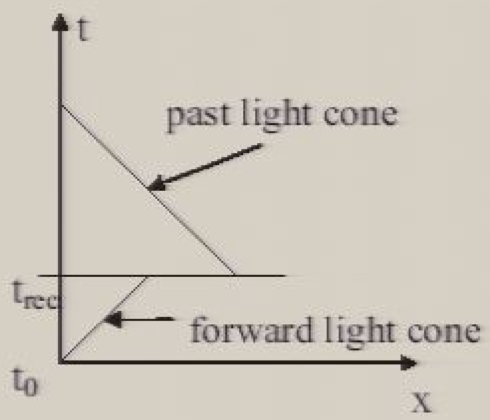

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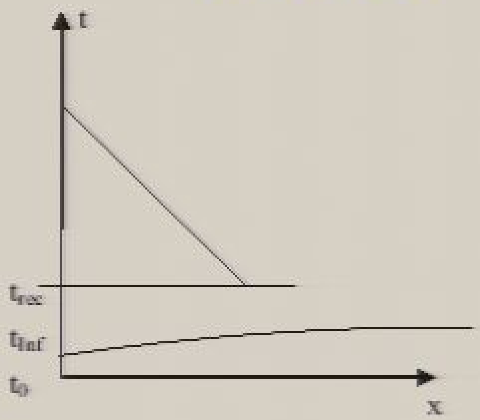
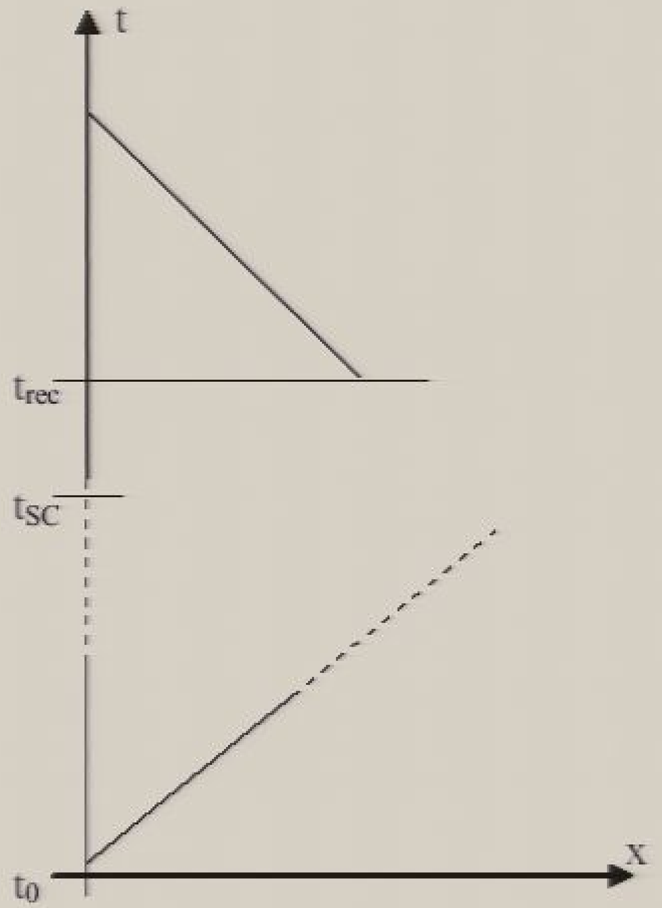


Our Scenario



Effective Field Theory Approach

Canonically normalized scalar field φ:

$$\varphi = \sqrt{\frac{d(d+2)}{2}}\, m_{pl} \log(b)$$

Effective 4d potential:

$$V_{eff}(\varphi) = g_s^2 l_s^d b(\varphi)^{-d} V(b(\varphi))$$

Example

Consider inter-brane potential

$$V(l_s b) = \mu (l_s b)^n \implies V_{eff}(\varphi) \propto e^{\alpha\varphi/m_{pl}}$$

For $\alpha \gtrsim 1$ the evolution of $a(t)$ is non-inflationary.

Size problem:

$$l_s \sim 10^{-17}\text{GeV}^{-1} \rightarrow H(\text{today})^{-1} = 10^{42}\text{GeV}^{-1}$$

During standard cosmology | During earlier phases

$a(t)$ increases by $T_{rh}/T_{today} \approx 10^{29}$ $\Rightarrow$ 10^{30}

Energy scale of the potential $\mu \equiv \Lambda^{d+n+4}$

should satisfy

$$\Lambda \sim l_s^{-1} 10^{-30\frac{d-p+3+n}{d+4+n}} \sim \text{electroweak scale}$$

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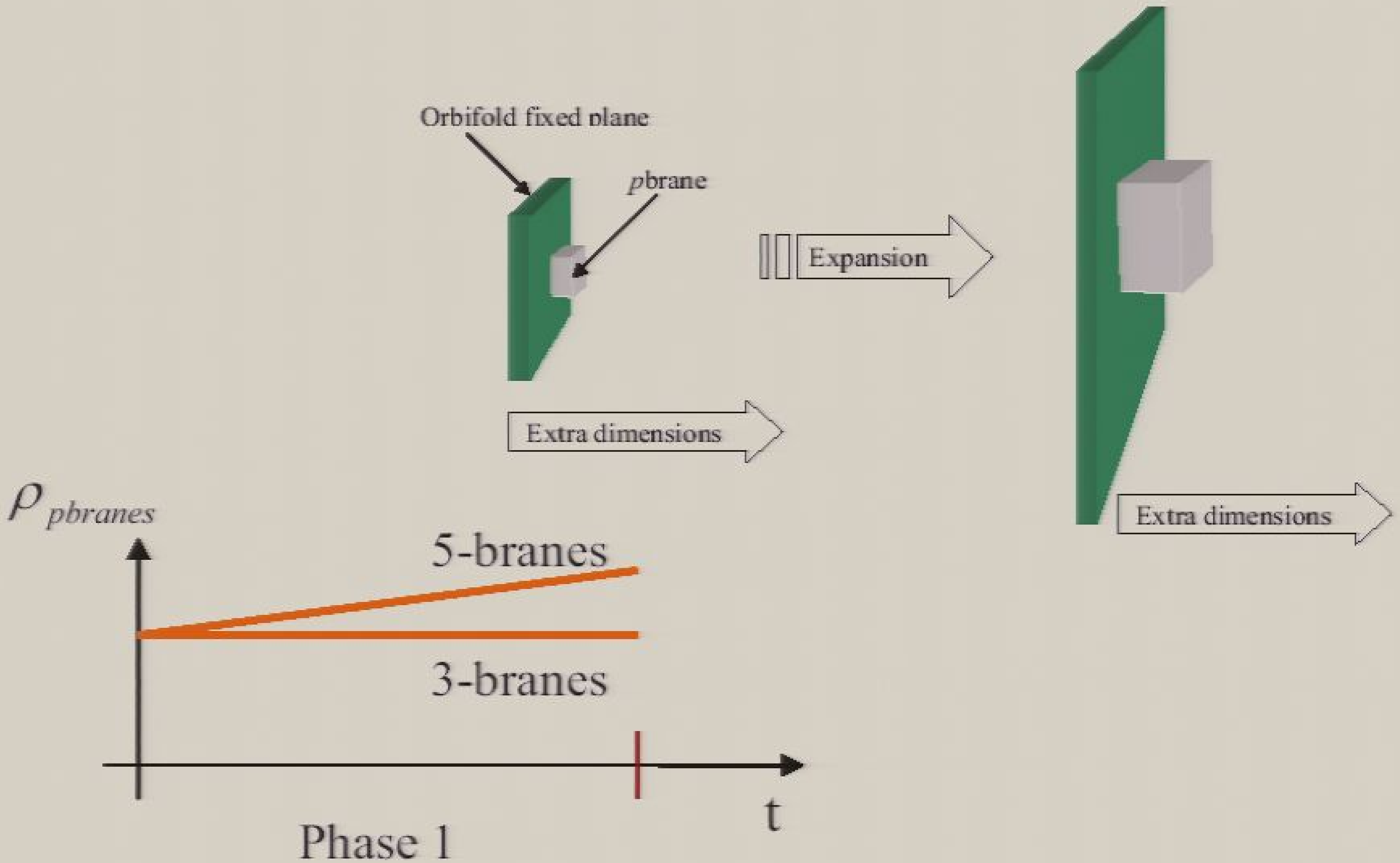

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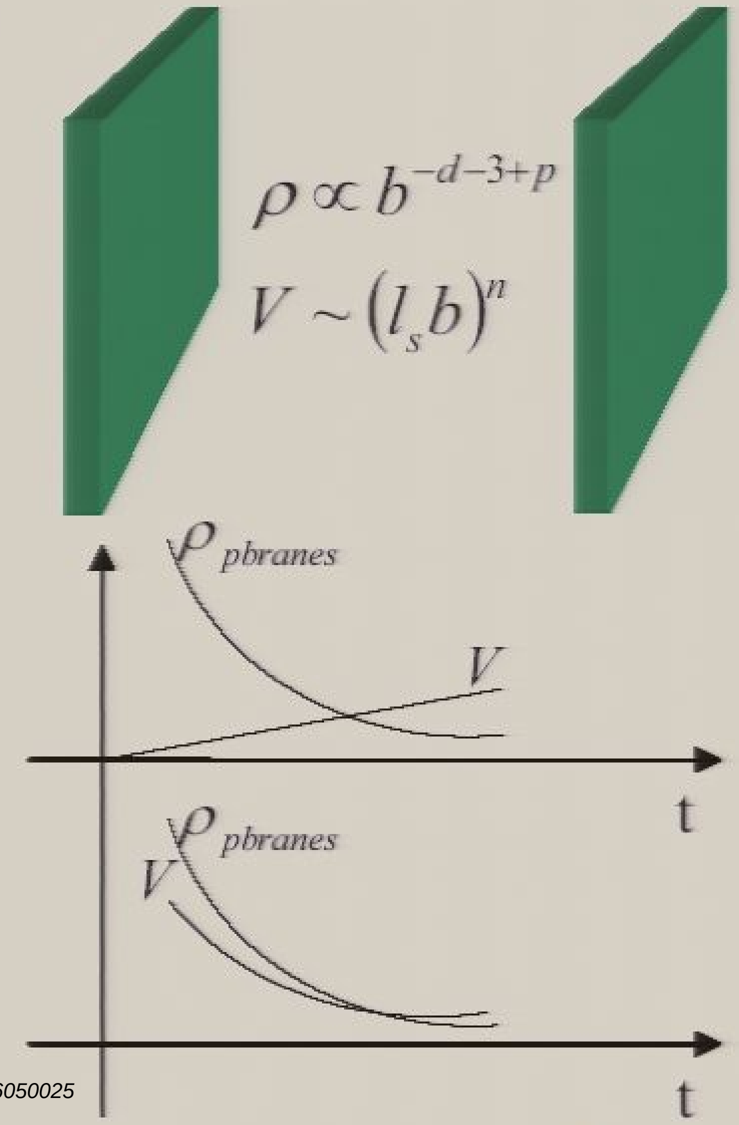

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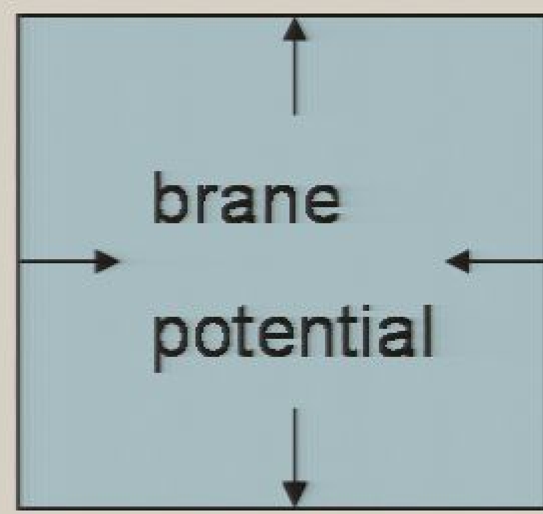

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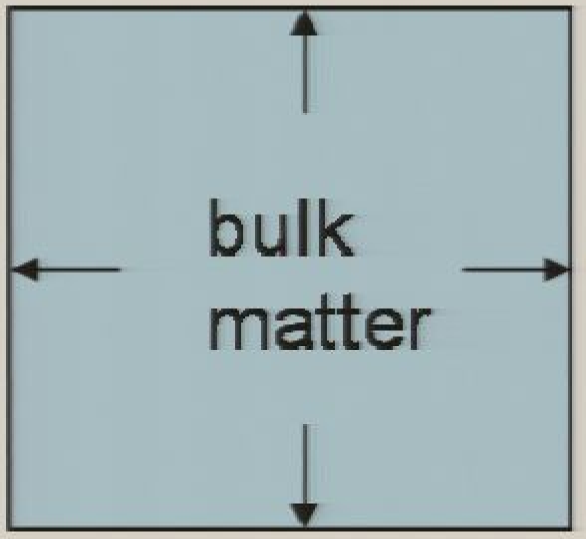

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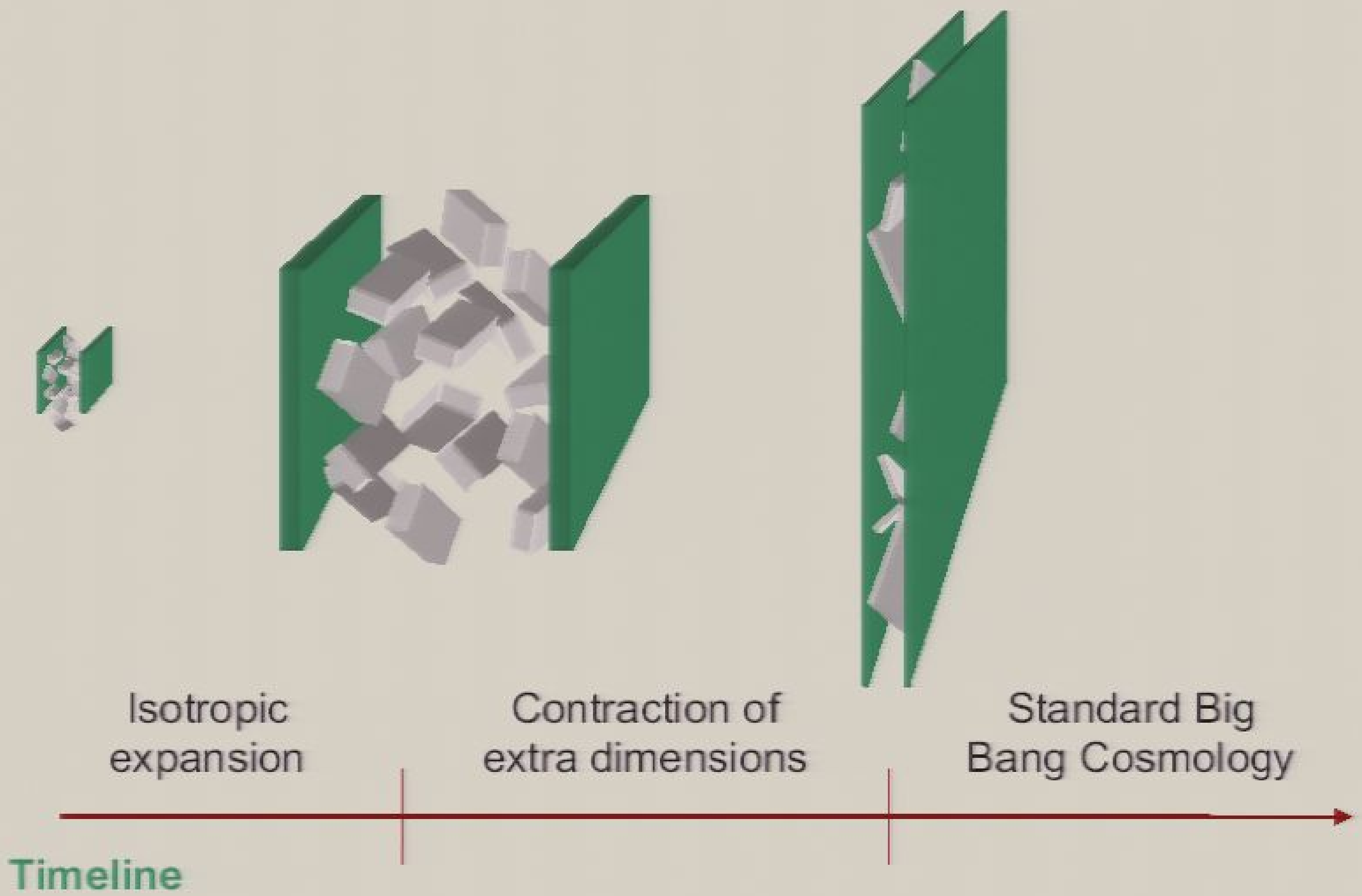

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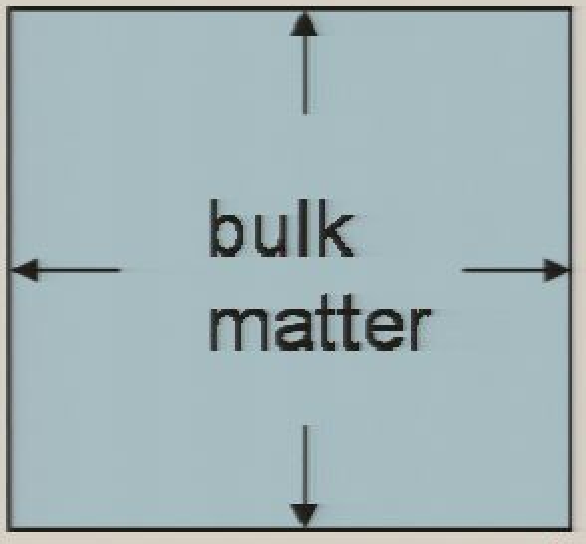
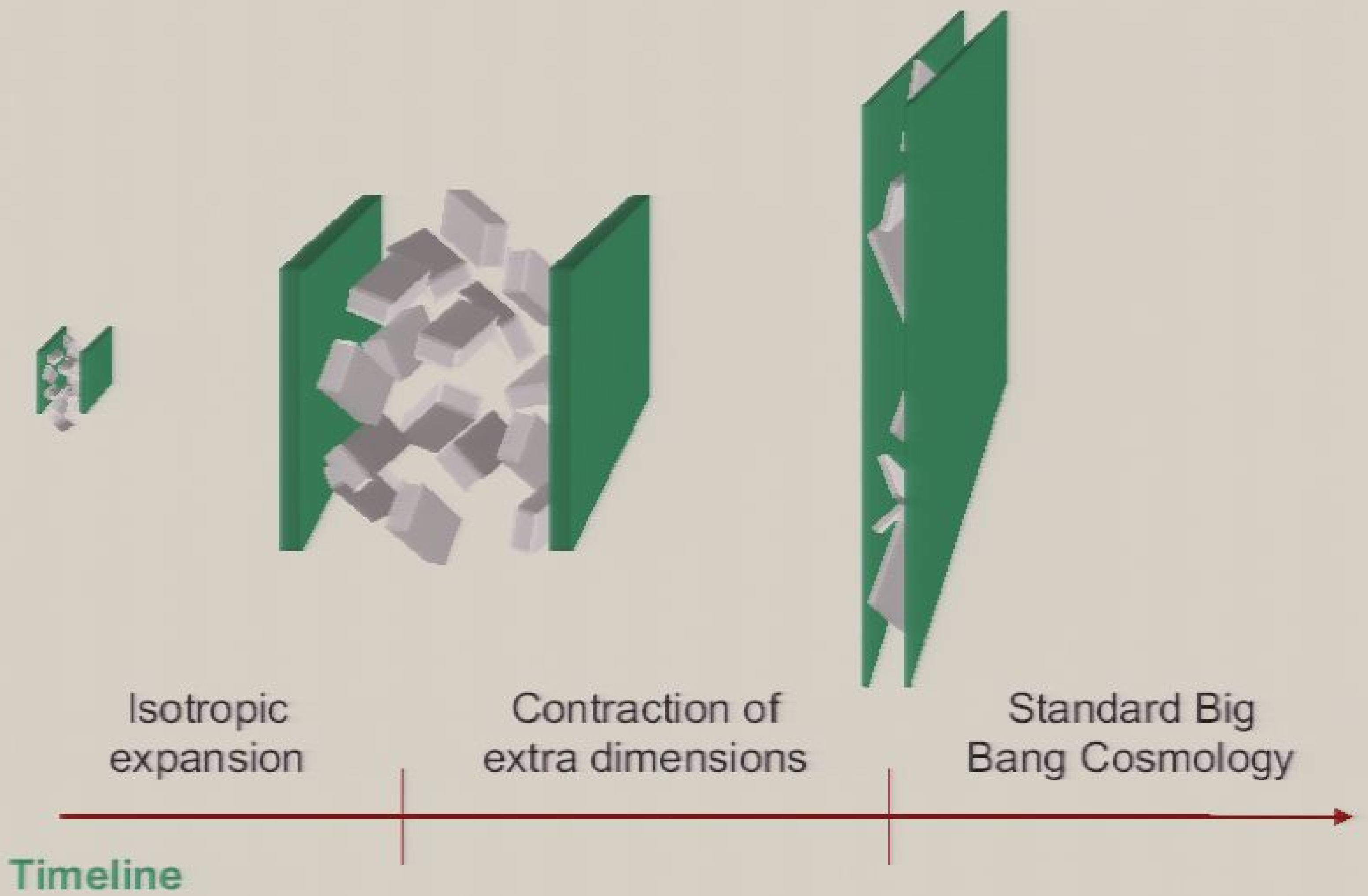


Timeline

Overall Dynamics



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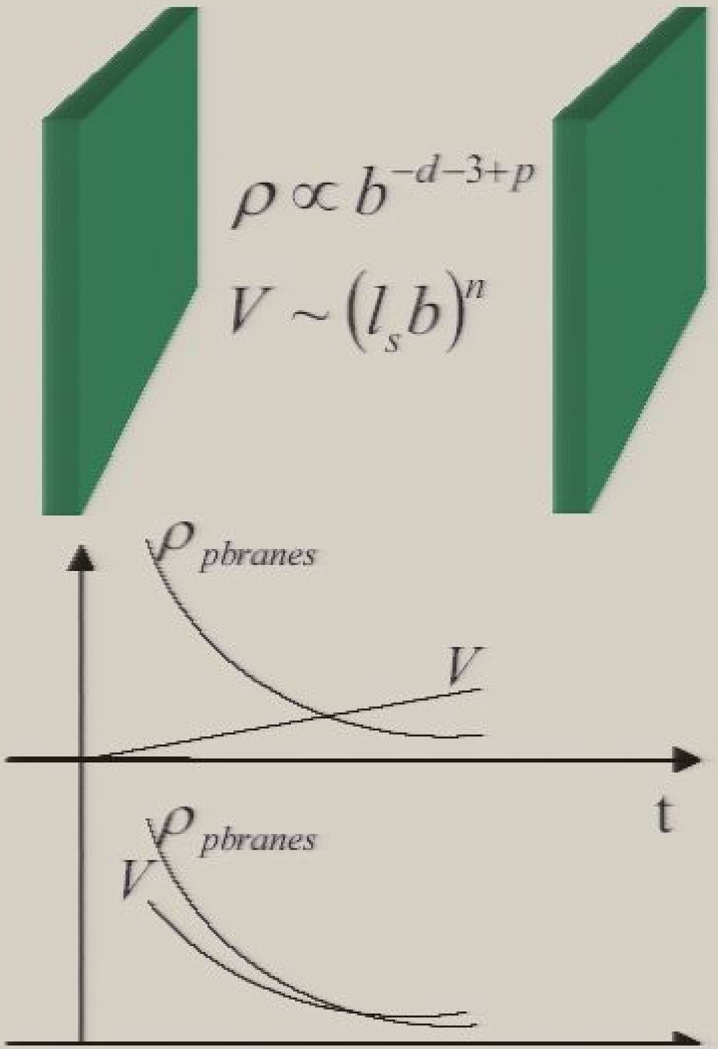
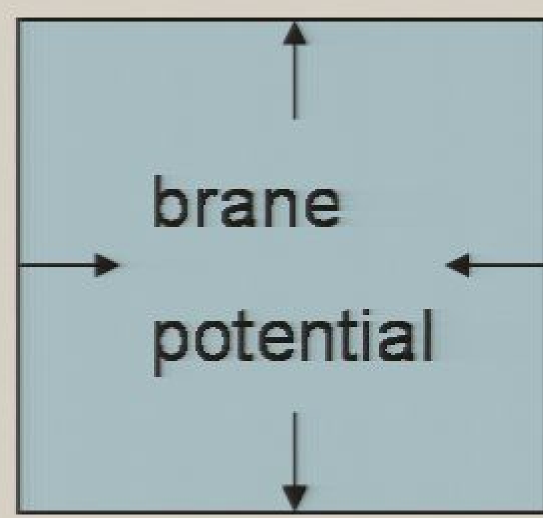


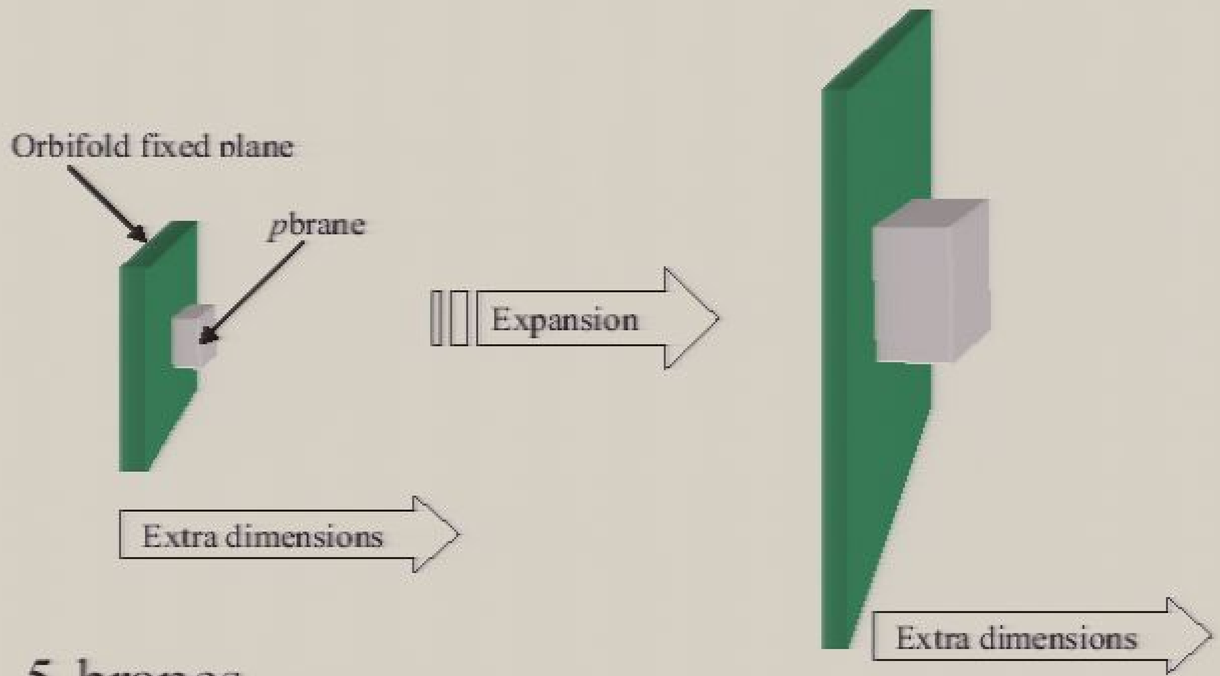
Brane potential dominates

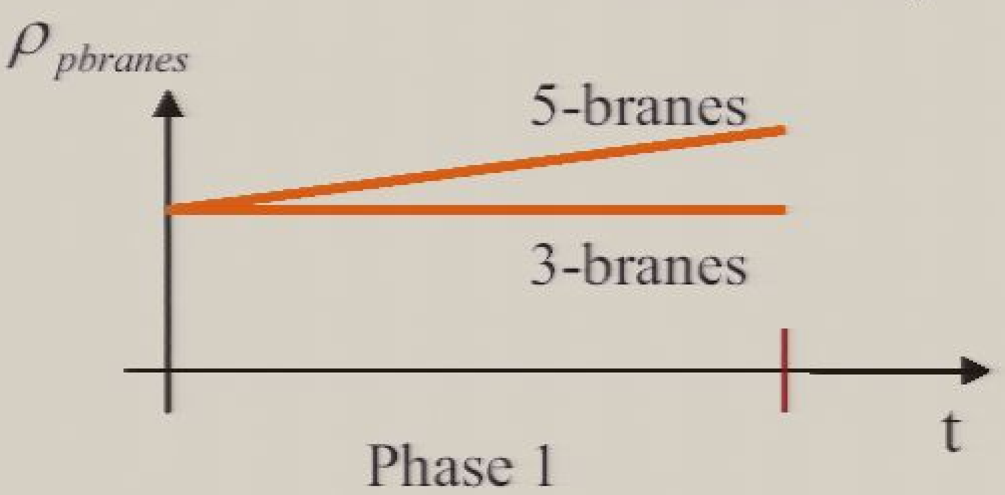
when $V = \rho$

leading to contraction of extra dimensions



Projected Energy Density - Phase 1





Example

Consider inter-brane potential

$$V(l_s b) = \mu(l_s b)^n \implies V_{eff}(\varphi) \propto e^{\alpha\varphi/m_{pl}}$$

For $\alpha \gtrsim 1$ the evolution of $a(t)$ is non-inflationary.

Size problem:

$$l_s \sim 10^{-17}\text{GeV}^{-1} \rightarrow H(\text{today})^{-1} = 10^{42}\text{GeV}^{-1}$$

	During standard cosmology		During earlier phases
$a(t)$ increases by	$T_{rh}/T_{today} \approx 10^{29}$	$\Rightarrow$	10^{30}

Energy scale of the potential $\mu \equiv \Lambda^{d+n+4}$

should satisfy

$$\Lambda \sim l_s^{-1} 10^{-30\frac{d-p+3+n}{d+4+n}} \sim \text{electroweak scale}$$

Effective Field Theory Approach

Canonically normalized scalar field φ:

$$\varphi = \sqrt{\frac{d(d+2)}{2}} m_{pl} \log(b)$$

Effective 4d potential:

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Entropy Problem

Assuming adiabatic expansion

Entropy per co-moving volume which corresponds to H_0^{-1}:

$$S_U = \# H_0^{-3} T_0^3 = 10^{90}$$
$$\approx (1mm)^3 T_{pl}^3$$

Entropy problem = Hierarchy problem: $\rho = m_{pl}^4$

corresponds to Universe of mm size

not m_{pl}^{-1} size

Standard Solution:

- Amplification of energy during early phase
- Non-adiabatic phase transition converting energy to radiation

Unusual technic: Energy amplified in codimension ≥ 3 branes

$\Longrightarrow$ no accelerated expansion

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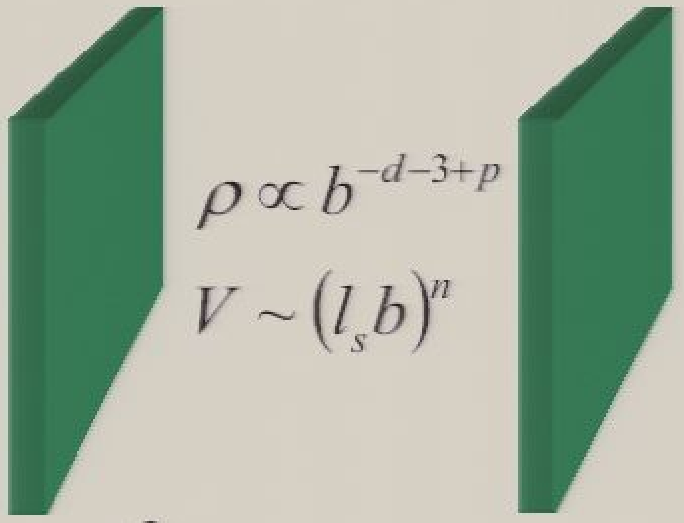
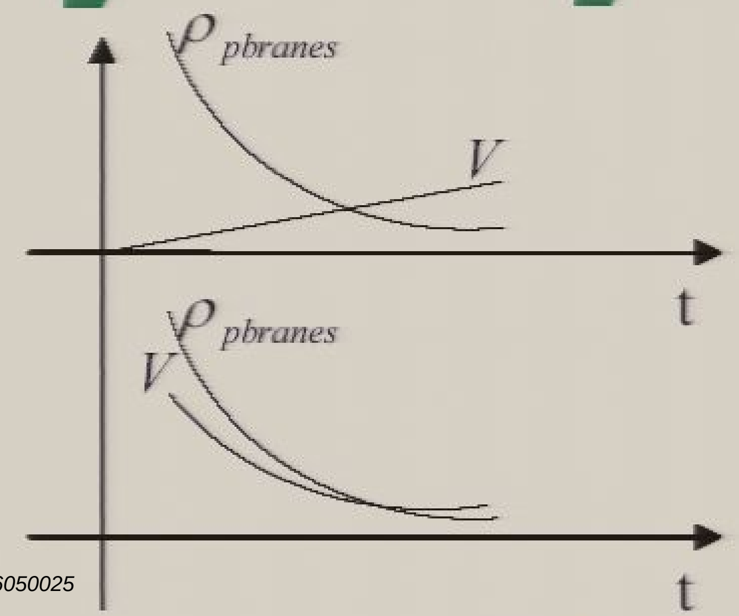


$$\rho \propto b^{-d-3+p}$$

$$V \sim (l_s b)^n$$



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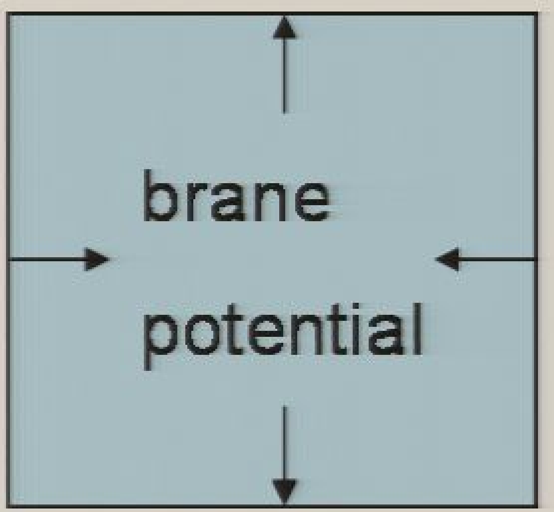
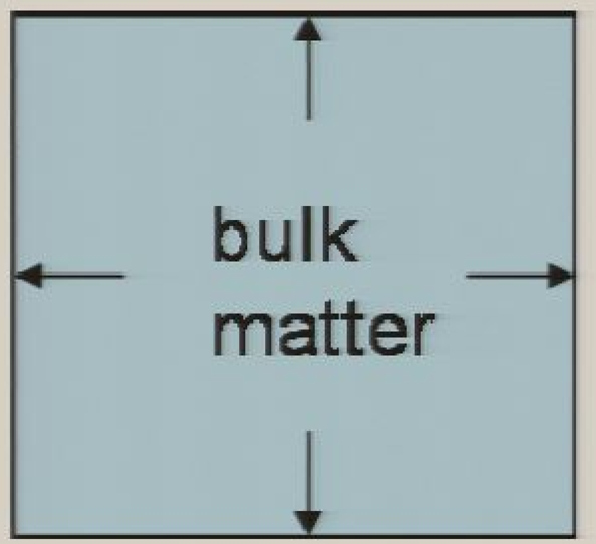


Phase of Expansion

Metric: $ds^2 = dt^2 - a(t)^2 d\mathbf{x}^2 - b(t)^2 d\mathbf{y}^2$

Isotropy: $a(t) = b(t)$



Expansion governed by

$$\frac{\ddot{a}}{a} + (2+d)\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3+d-1}[\rho - P]$$

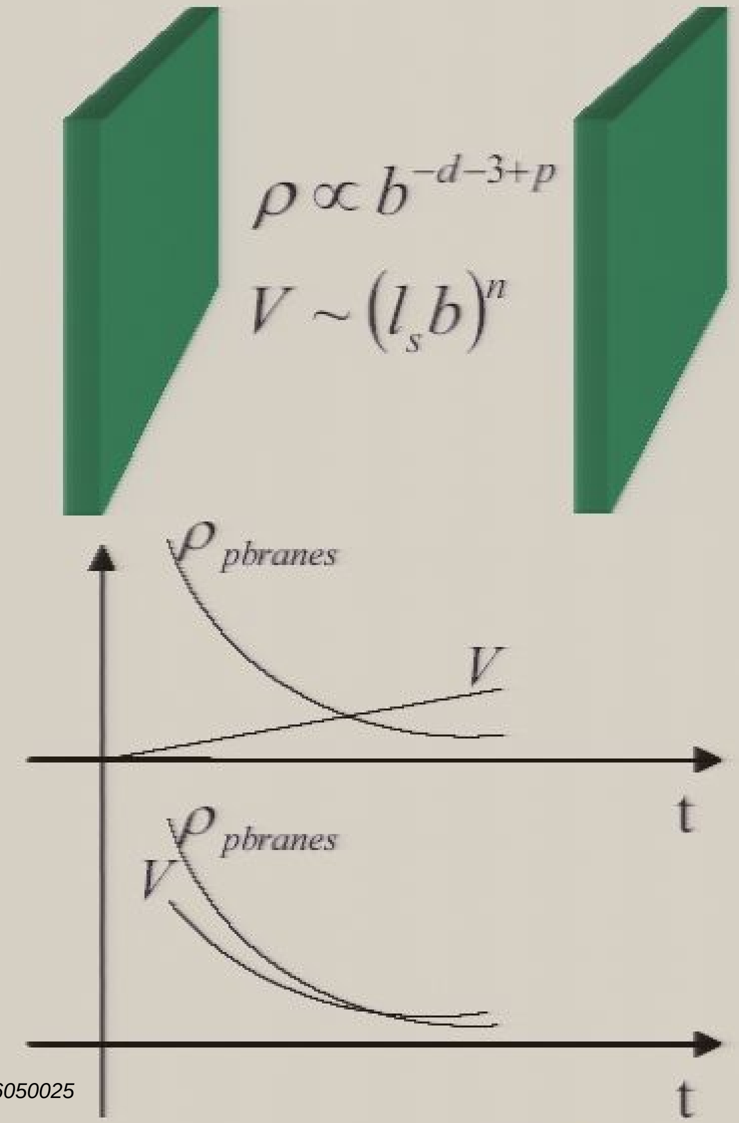
Equation of state

$$P = w\rho$$

Leads to

$$a(t) = b(t) \sim t^{\alpha}\,;\ \alpha = \frac{2}{(3+d)(1+w)}$$

From Expansion to Contraction



Motivation II

Inflation explains :

- flatness, **horizon**, **entropy**
- scale invariance of density perturbations

Conceptual problems:

- initial condition problem
- singularity

We address

horizon and **entropy** problems
starting with **standard initial conditions**

Note: this is the first time
entropy problem is addressed outside inflationary scenarios

Entropy Problem

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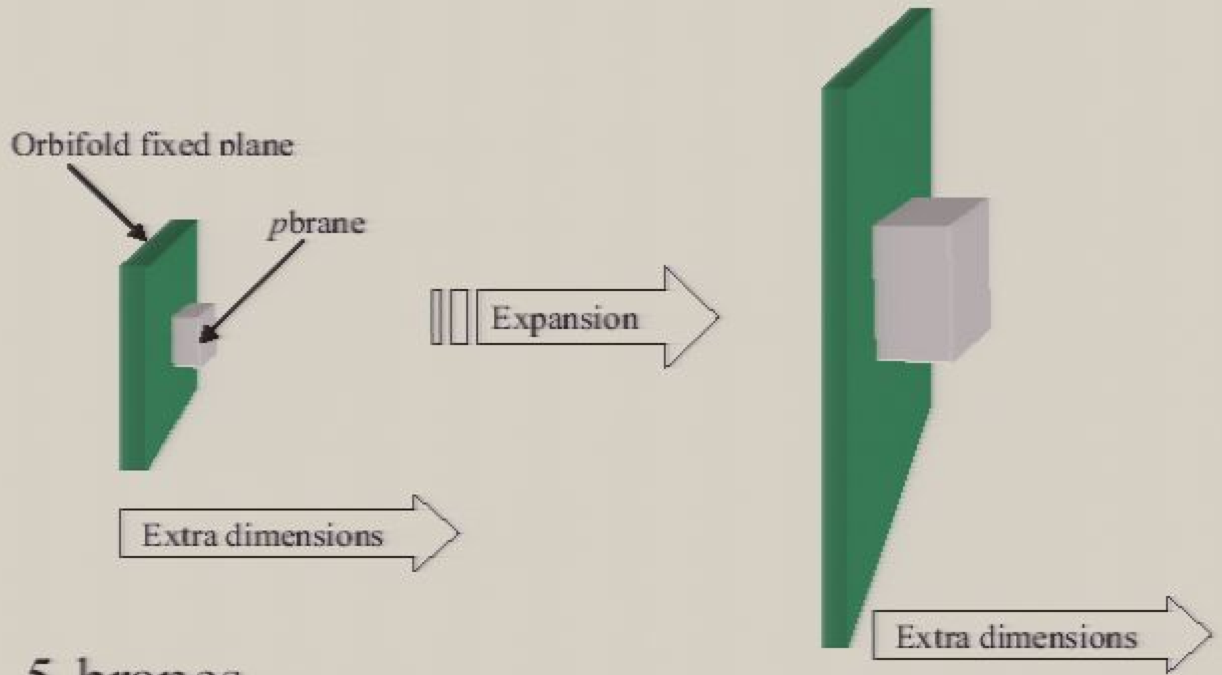

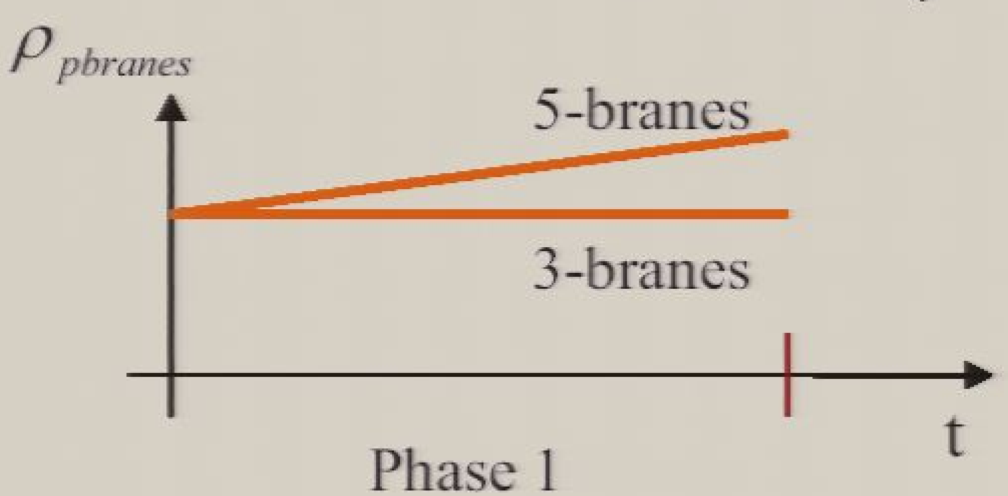

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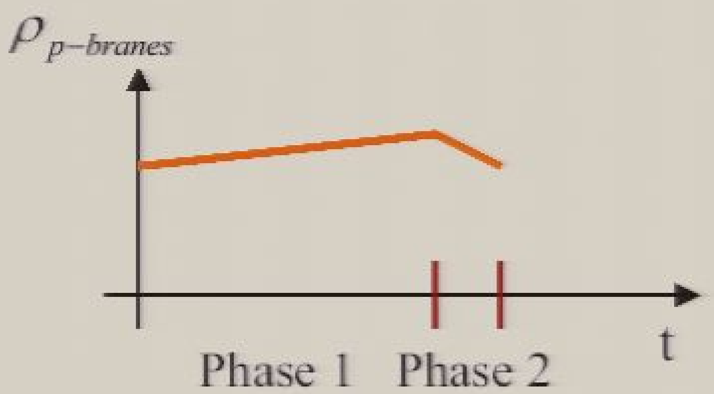
Towards an Alternative

$\Gamma_{p-branes} >> t_{collapce}$

$\Downarrow$



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during the phases of expansion and contraction or before

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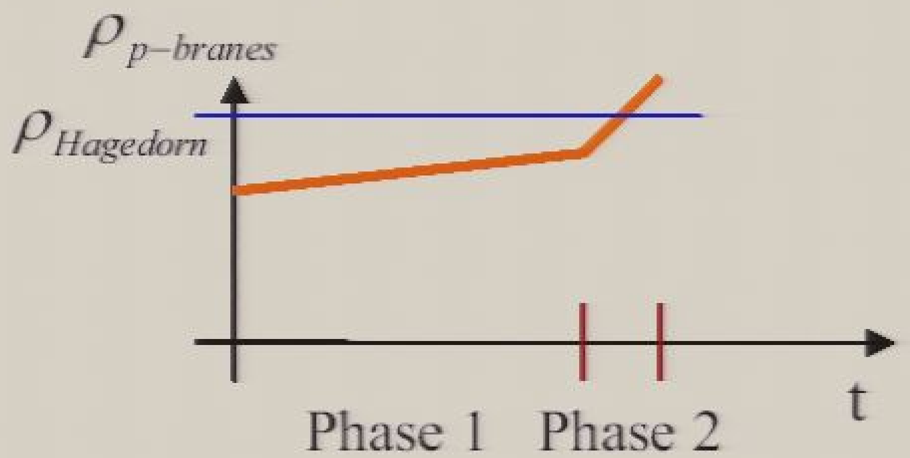

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A. Nayeri, R. H. Brandenberger and C. Vafa, hep-th/0511140.

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- Horizon Problem: long period of dynamics in extra dimensions
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Emerging Brane Inflation Models

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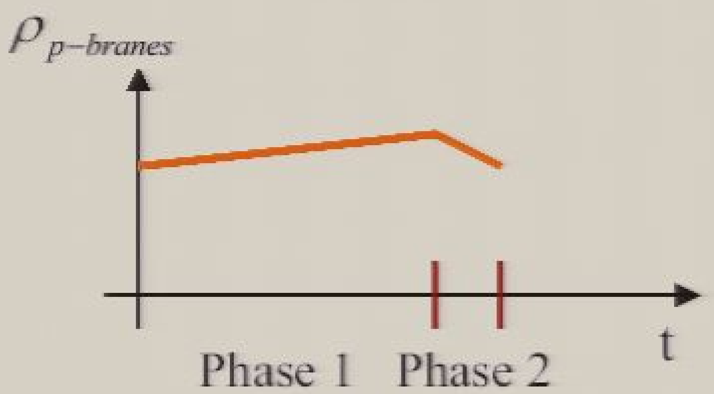

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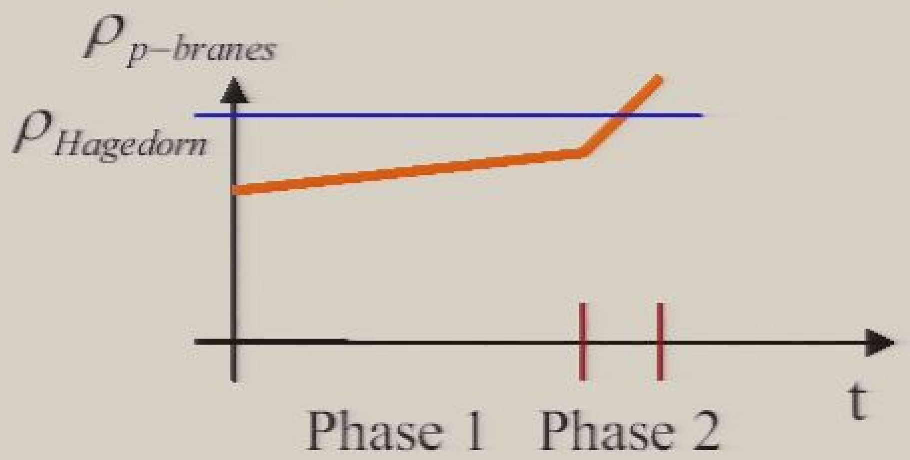

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Emerging Brane Inflation Models

Motivation III

Main Problem:

Brane inflation doesn't occur for generic initial conditions

one needs either

- much weaker couplings than expected from string theory
- large initial separation ($r \gg l_s$)

Conventional approaches: all extra dimensions are static

$\Longrightarrow$ any starting point with $r \gg l_s$ poses hierarchy problem

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Conventional approaches: all extra dimensions are static

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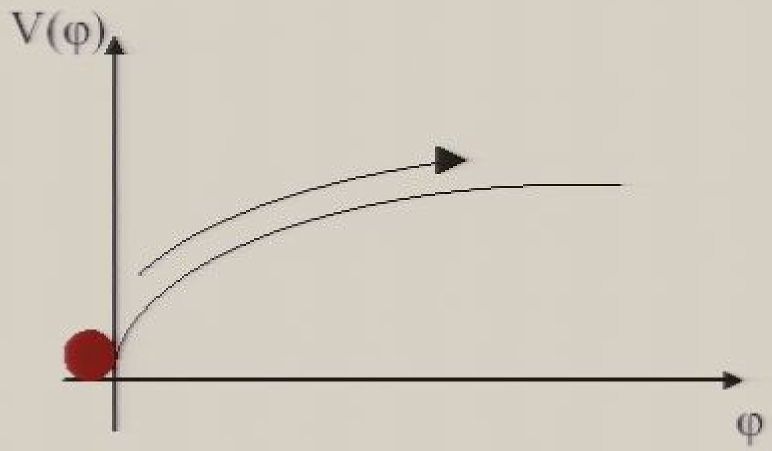
New approach: preceding expansion phase due to gas of p-branes leads to a large separation.

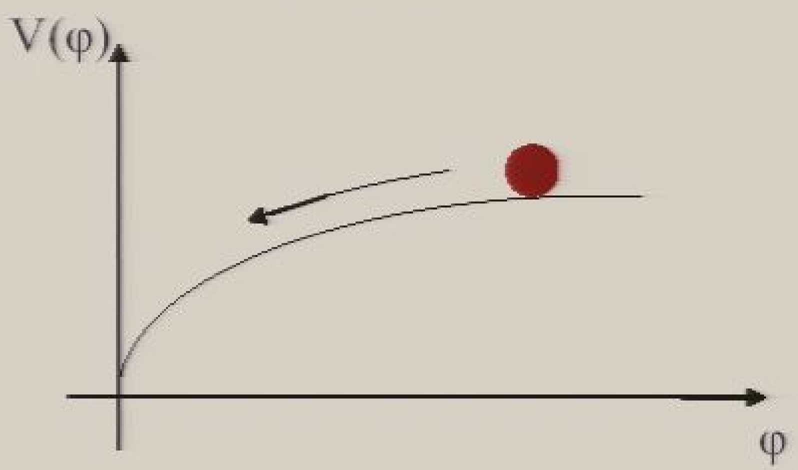
Advantage: Natural starting point

Effective 4d view

Bulk Expansion Phase



Inflation



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Add brane tension

$4d$ potential

$$V(\varphi) = \Lambda^{4+d-n} l_s^{d-n} - \Lambda^{4+d-n} l_s^{d-n} e^{-\alpha \frac{\varphi}{m_{pl}}}$$

If

$$\varphi \gg m_p/\alpha \ln(\alpha^2 + 1)$$

then $a(t)$ is accelerating

N e-foldings require

$$l_s \Lambda \lesssim (\alpha^2 N)^{-\frac{d+3-p-n}{(d+n)(d+4-n)}}$$

Allowing

$$\Lambda \sim 0.1\, l_s^{-1}$$

Summary

- Natural starting point
- Emerging large separation for brane inflation models
- Unique scale

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Conclusions

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- Natural starting point for string inspired cosmology
- Bulk expansion governed by p-branes provides
  - A venue towards an alternative to inflation
  - Emerging brane inflation models
- Details of the inter-brane potential determine the early stages of the universe
- A confining potential $\rightarrow$ a non-inflationary solution of the entropy and horizon problems
- $+$ Correct perturbation (Hagedorn phase ?)
  $\Longrightarrow$ An alternative to inflation ($-$ flatness problem)
- A decaying potential $\rightarrow$ emergent brane-antibrane inflation models.