Title: Brane interactions: the origin of space-time dimensionality and the physics of cosmic superstrings

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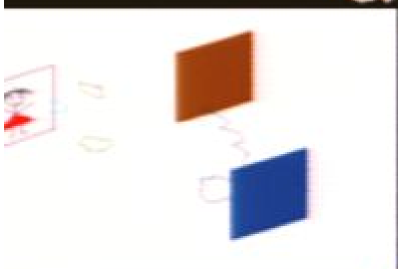
Abstract: Collisions and subsequent decays of higher dimensional branes leave behind three-dimensional branes, one of which could play the role of our universe. This process also leads to the production of one-dimensional branes, D-strings, and fundamental ones (F-strings), known as cosmic superstrings. In the first part of this talk, I will discuss the mechanism we have proposed in order to explain the origin of the space-time dimensionality, while in the second part I will review formation and dynamics of cosmic superstrings.

brane interactions:

the origin of space-time dimensionality

and

the physics of cosmic superstrings



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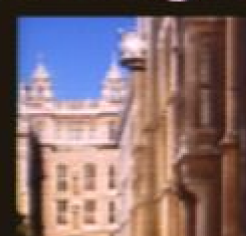

perimeter institute

30 september 2009

outline

- space-time dimensionality
  - kaluza-klein approach (*string gas scenario*)
  - brane-world scenario (*brane interactions*)
- cosmic superstrings
  - formation (*brane inflation*)
  - dynamics
  - cosmological consequences
- conclusions

space-time dimensionality

motivation

space-time dimensionality remains an open question

$d-1$: number of spatial dimensions

$d-1 \geq 3$: weak form of the anthropic principle

but why $d-1$ is not higher than 3 ?

framework

string theory

10-dim superstring theory

9-dim spatial torus, the tenth dimension being time

how the 10 dimensions from string theory can be reduced to the 4 dimensions of the observed space-time ?

kaluza-klein approach

brane-world approach

- kaluza-klein approach

6 extra dimensions are rolled up in a Calabi-Yau manifold with a size given by the string scale $\sqrt{\alpha'}$

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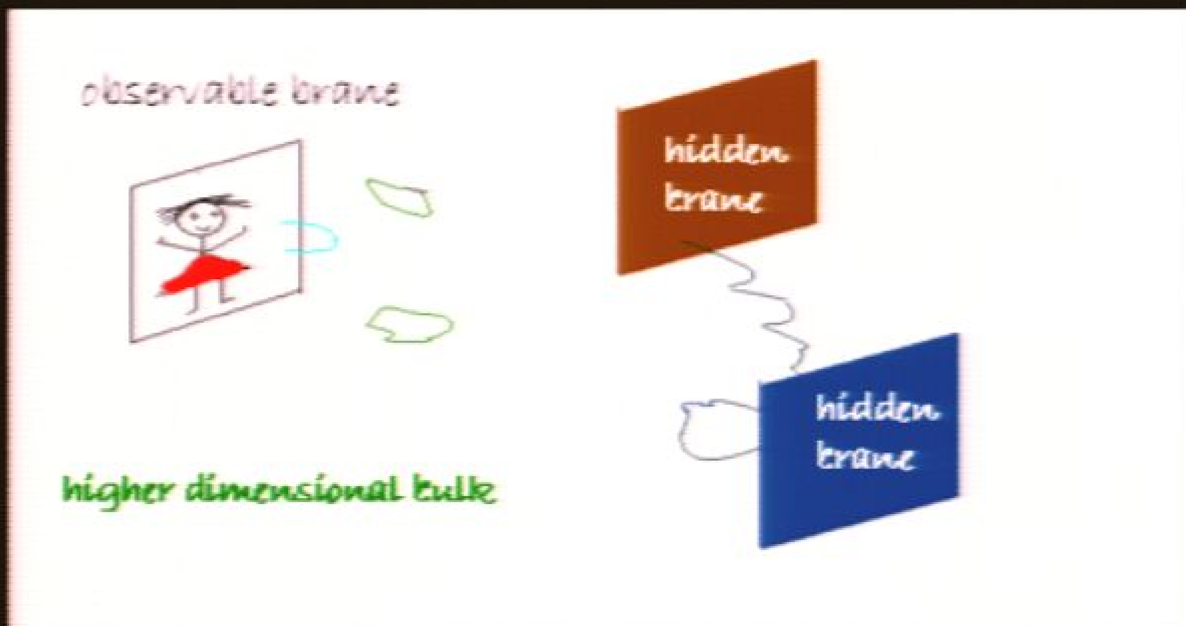
- brane-world approach



open strings (including matter and gauge fields) are attached to branes

closed strings (including gravity & the dilaton) propagate in the bulk

- kaluza-klein approach:

T-duality:

coupling constant invariant up to radius-dependent rescaling

holds at each order of perturbation theory

target-space duality $R \rightarrow \alpha'/R$

it relates string theories compactified on large and small tori by interchanging winding and kaluza-klein states

applications of the $R \to \alpha'/R$ symmetry in cosmology

brandenberger – vafa scenario: *string gas cosmology*

brandenberger & vafa, NPB **316** (1989) 391

- distance has different interpretation in the two dual regimes:

large radius: position coordinate is the conjugate variable to momentum, $p = n/R$ as usual

- distances smaller than the self-dual radius: use the dual coordinate, i.e. the conjugate variable to winding $W = mR$

- mass-shell condition:

$$M^2 = \frac{n^2}{R^2} + \frac{w^2 R^2}{\alpha'^2} + \frac{2}{\alpha'}(N_\mathrm{L} + N_\mathrm{R} - 2)$$

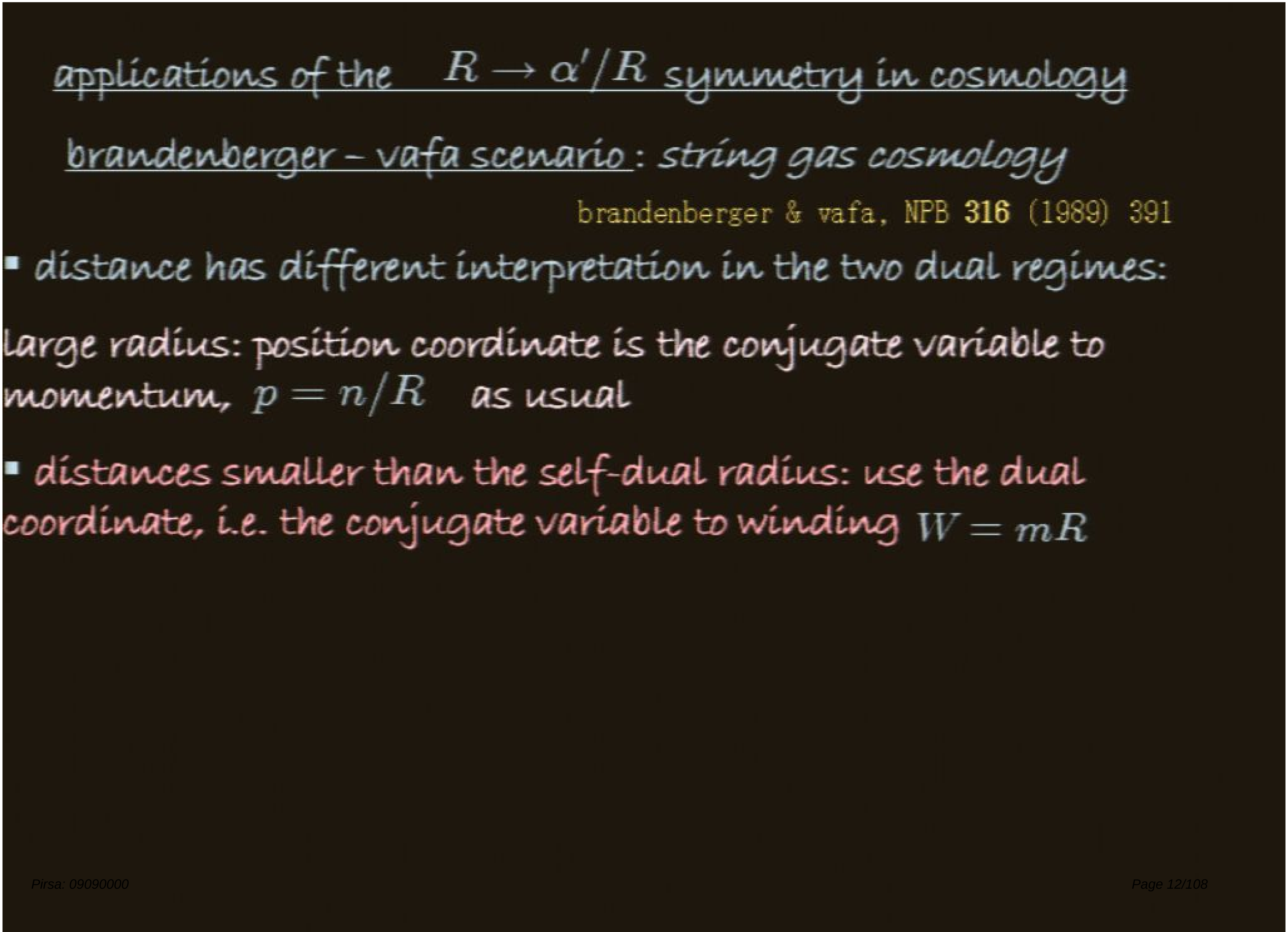
n, w: momentum/winding charge associated with the extra dimensions

$N_\mathrm{L}, N_\mathrm{R}$: left and right oscillator numbers

spectrum remains invariant under simultaneous exchange:

$R \to R' = \frac{\alpha'}{R}$ and $n \leftrightarrow w$

- scattering amplitudes for dual processes are equal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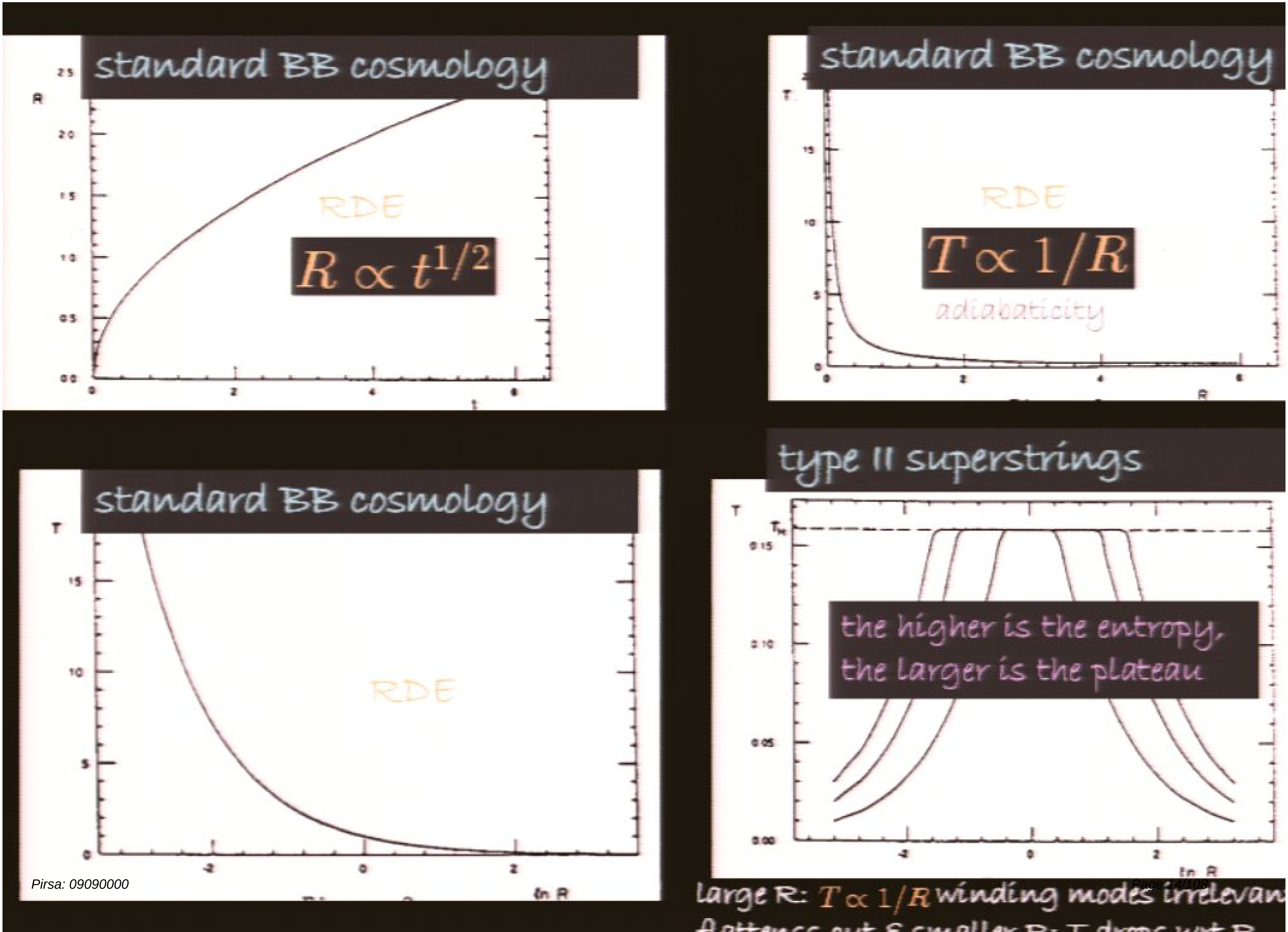
⟹

- there is a minimum distance in string theory
- under the hypothesis that the universe is a product of circles, then the initial singularity is eliminated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RDE
R ∝ t^{1/2}
R
t
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T ∝ 1/R
adiabaticity
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type II superstrings
the higher is the entropy,
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large R: T ∝ 1/R winding modes irrelevan

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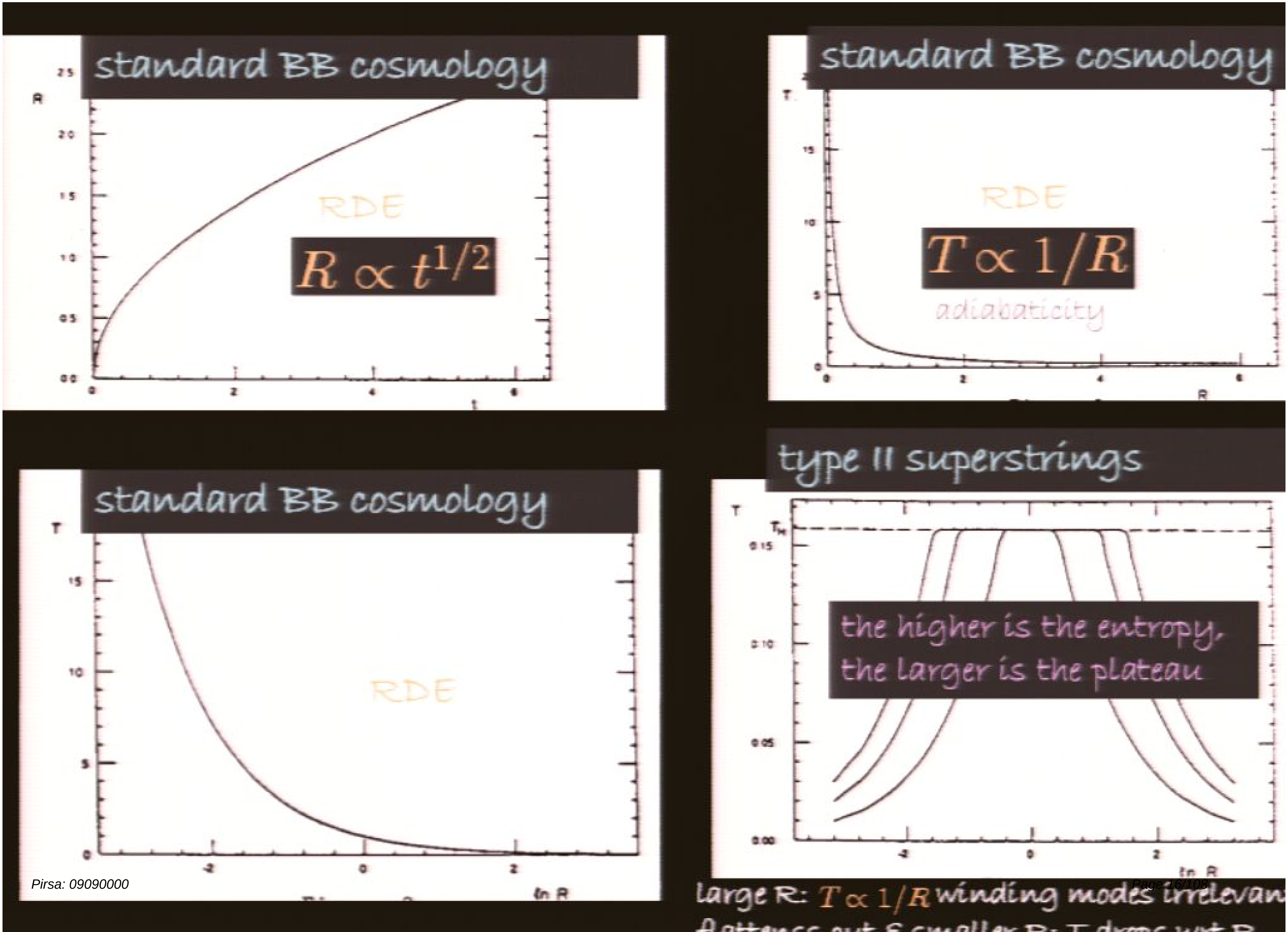
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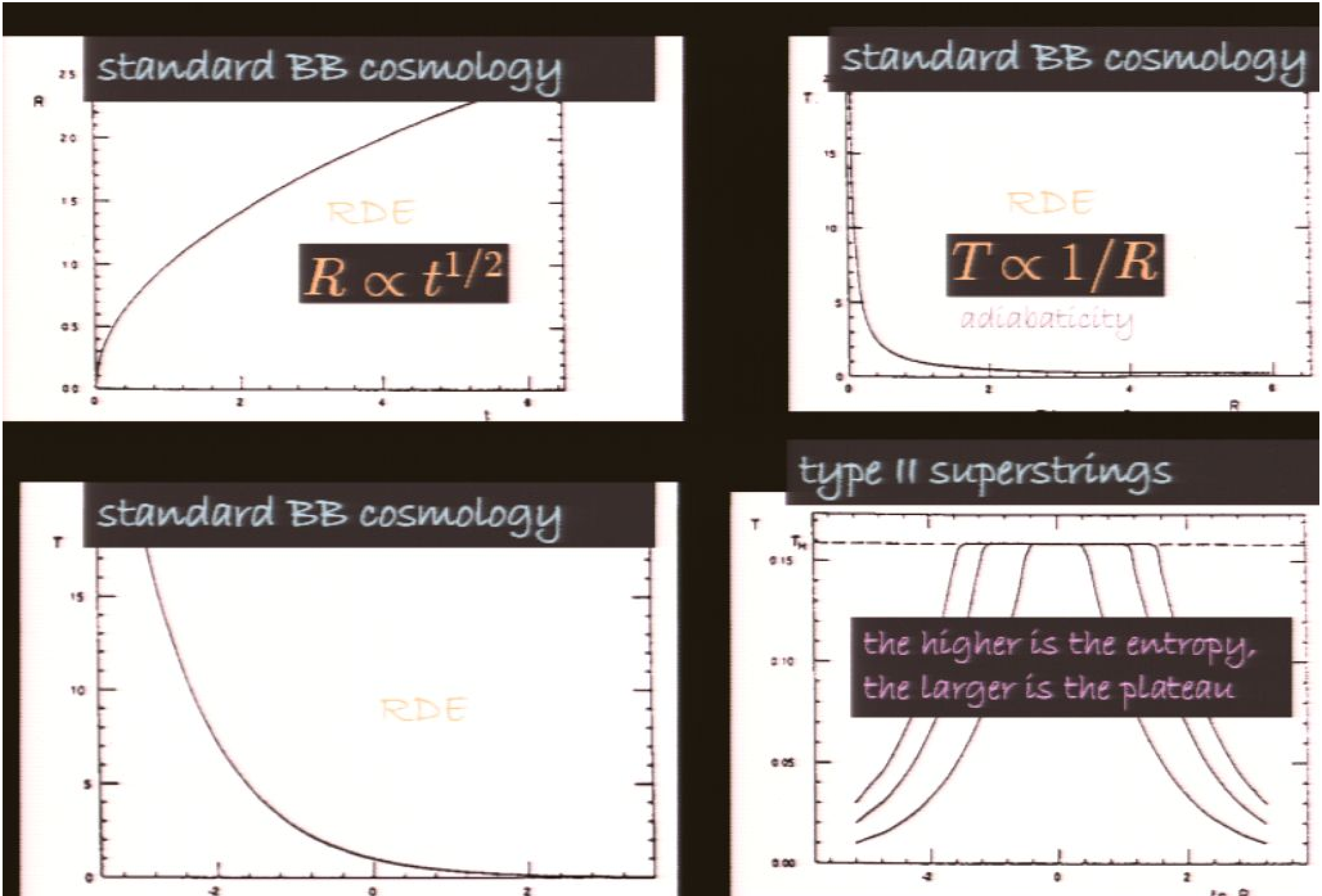


large R: $T \propto 1/R$ winding modes irrelevan explanation for the dimensionality of our universe

universe starts with all spatial dim of string size

winding modes prevent corresponding dim from expanding

but, winding modes in general annihilate with anti-winding ones

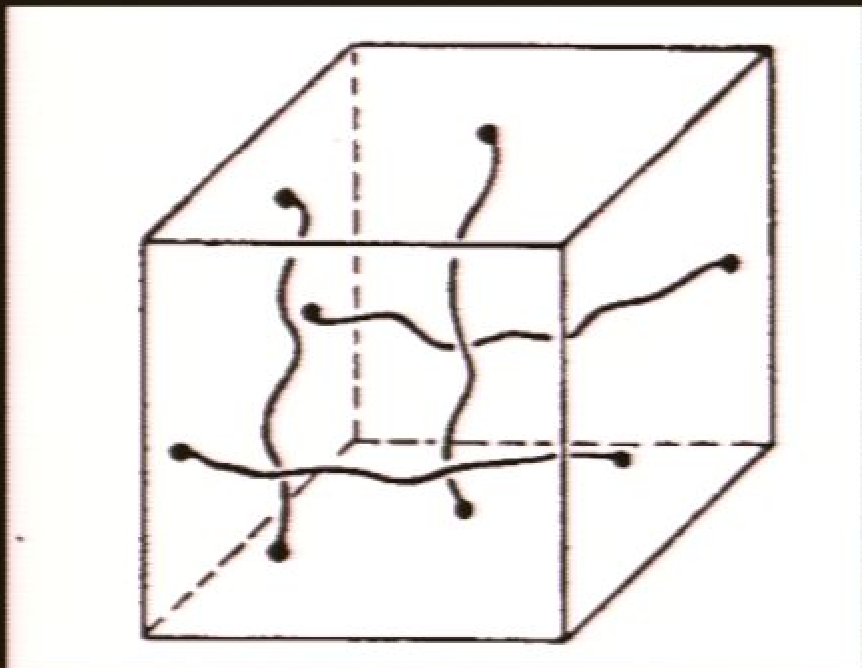
in 10 dim, a winding string will miss the anti-winding one

nly in a 4-dim hypersurface the worldsheets of winding and anti-
inding modes can overlap, leading to annihilation and expansion
f 3 spatial dim

→ winding modes prevent 6 of the dim from expanding
nd leave only 3 dim to expand

brandenberger & vafa, NPB **316** (1989) 391

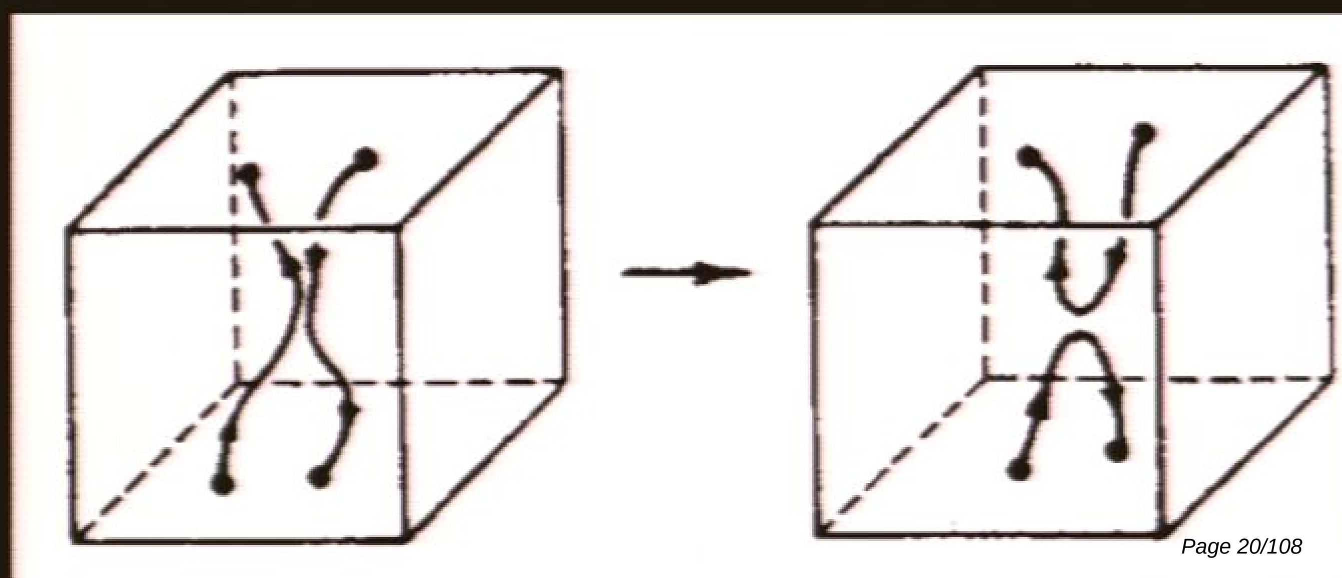
m.s., NPB **468** (1996) 319



winding strings

(periodic boundary conditions)

unwinding of 2 opposite wound strings



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in addition:

- scale invariant spectrum of adiabatic perturbations

  nayeri, brandenberger & Vafa (2005)

- entropy & horizon problems solved without inflation

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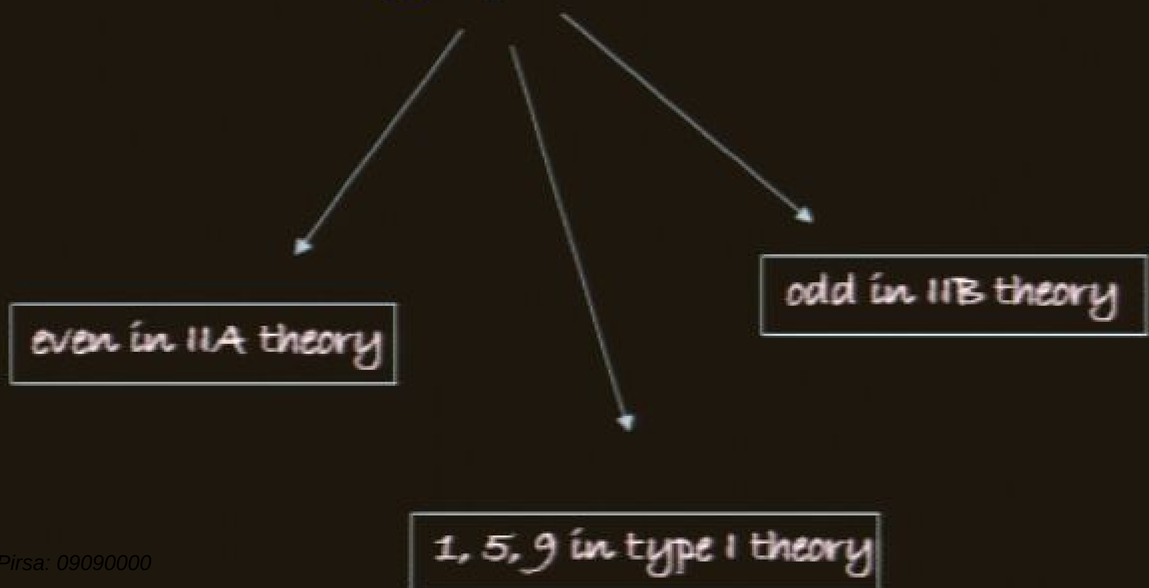
but

- homogeneous fields
- adiabatic approximation
- weak coupling
- toroidal spatial dimensions
- interactions viewed as intersections (classical argument)

- braneworld approach

start with space filled with $\mathrm{D}p$- branes and $\bar{\mathrm{D}}p$-anti-branes of all possible dimensions p

what is the outcome of intersections between $\mathrm{D}p$-branes of various dimensionality p , embedded in a d-dim toroidal bulk ?



note: do not consider a heterotic type theory

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type II string theories:

type IIB: BPS D-branes of odd dim of tangential spatial directions

invariant under half of space-time of supersymmetric transformations

charged under a (p+1)-form gauge field

non-BPS D-branes of even dim

type IIA: BPS D-branes of even dim

non-BPS D-branes of odd dim

type IIB/IIA string theory: non-BPS D-branes are unstable due to
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sen, JHEP **9812** (1988) 021

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even in IIA theory

odd in IIB theory

1, 5, 9 in type I theory

note: do not consider a heterotic type theory type II string theories:

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assume that branes at macroscopic distances do not interact

brane intersection probability is a question of dimensionality assume that branes at macroscopic distances do not interact ⟹

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condition for generic intersection of two Dp-branes embedded in a d-dim space-time (bulk):

two Dp-branes intersect at all times on an intersection-manifold of dim: $2p - d + 1$

$$2p + 1 \geq d - 1$$

two Dp -branes eventually intersect at some time in a point

otherwise, the two Dp-branes will generically never intersect

durrer, kunz & m.s., PLB **614** (2005) 125

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d=10: two Dp -branes will never intersect if $p \leq 3$ but they will eventually collide provided $p \geq 4$

durrer, kunz & m.s., PLB **614** (2005) 125

intersecting branes are unstable and eventually evaporate

⇒ left with D3-branes (and any permitted lower-dim branes, D1-branes in IIB string theory)

D-strings

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1st hypothesis:

9 bulk coordinates compactified on a torus

closed branes not winding around torus, shrink and disappear emitting gravity waves (evaporation)

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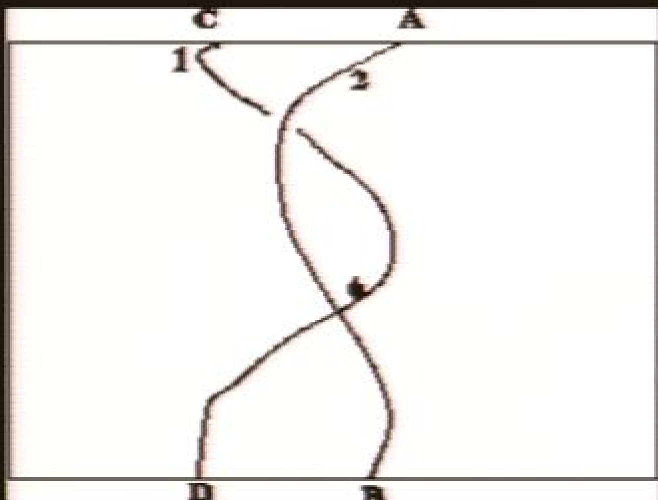
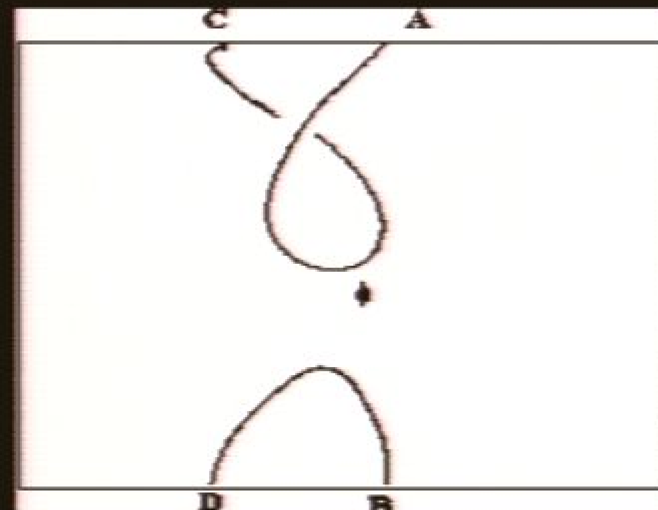
2nd hypothesis:

if a Dp -brane interscets with another Dp-brane on a hypersurface of dim $p-1$, the branes reconnect → winding number is reduced until they do not wind anymore and evaporate





for intersecting D-strings at an angle ϕ there is a tachyon mode which represents instability to reconnection

Dp -branes which intersect in $p-1$ directions can be reduced to this case by applying T-duality in the $p-1$ common directions

m.s., NPB **468** (1996) 319

m.s., JCAP **004** (2005) 003

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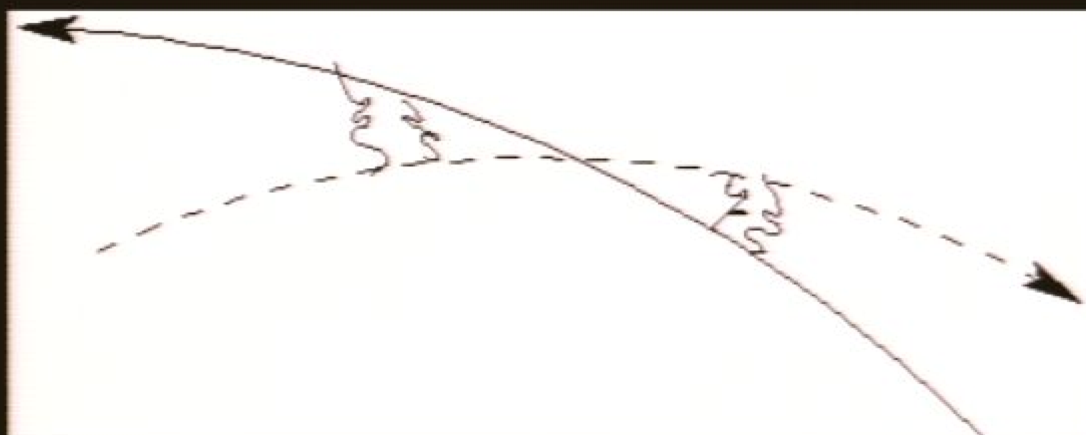
3rd hypothesis:

if two Dp-branes intersect on manifold of dim lower than $p-1$, the open strings which switch between branes lead to alignment/anti-alignment of the directions with smallest respective open angle

finally, intersection manifold has dim $p-1$ and branes can reconnect and separate again



crucial assumption for the validity of our scenario

study interaction potential, obtained by the scattering amplitude of open strings ending on branes

4^{th} hypothesis:

[total winding number of all branes of a given dim vanishes]

not very important

if not satisfied, a few larger dim branes may remain

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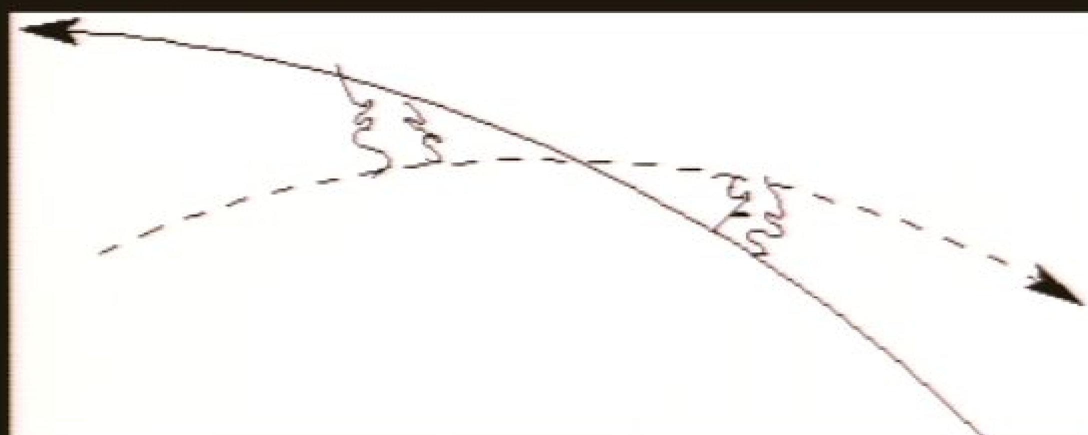

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scenario:

10-dim type IIB supersymmetric string theory

spatial dim of the bulk: $d-1=9$

possible dim of Dp-branes is: $p=1,3,5,7,9$

initial state: bulk is filled with a *gas* of all allowed Dp-branes

assuming the 4 hypotheses, only D3- and D1-branes survive

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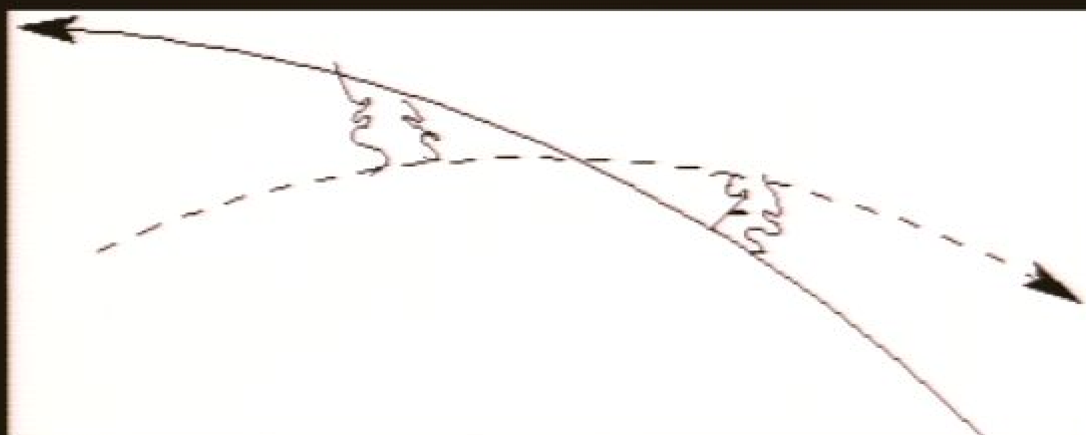

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- D9-branes fill entire space (bulk):
  they overlap, immediately reconnect and evaporate
- two D7-branes always intersect on manifold of dim 5:
  must align along 1 direction to reconnect and unwind
- two D5-branes always intersect on a manifold of dim 1:
  must align 3 directions before they can reconnect

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D9-branes evaporate first, then the D7- and the D5-branes last

at the end: D3- & D1-branes and closed string modes in the bulk

bound state decay

Dq-brane collides with Dp-brane ($q<p$) and dissolves into it;
its degrees of freedom becoming gauge (magnetic) fields

Dp-brane with world-volume gauge fields

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non-BPS Dp-brane with nonzero world volume electromagnetic fields decays into a D(p-1)-brane with the electromagnetic fields conserved and localised on the brane

gauge fields are localised perpendicular to tachyon direction

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presence of dissolved brane does not affect decay mechanism

bound state of D(p-1) and Dq-brane

condition for intersection between a Dp-brane and a Dq-brane:

$$p + q + 1 \geq d - 1$$

collision between a Dp-brane and a Dq-brane, with $p \geq q$

d=10

$p = 9$	$q = 1, 3, 5, 7, 9$
$p = 7$	$q = 1, 3, 5, 7$
$p = 5$	$q = 3, 5$

$D^{\star}p$ is either a Dp-brane or a bound $D(p,q)$-brane

- collision between a $D^{\star}p$-brane and a $D^{\star}q$-brane results to a (different) $D^{\star}p$-brane
- collision between a $D^{\star}p$-brane and an anti-$\bar{D}^{\star}p$-brane results in a non BPS $D^{\star}(p-2)$-brane
- a non BPS $D^{\star}p$-brane will decay into a $D^{\star}(p-1)$-brane

<u>note</u>: it is only collisions between similar dim branes, or their self decay due to being nonBPS, that results in lower dim branes

end of a complicated decay chain: a $D^{\star}5$-brane colliding with an anti-$\bar{D}^{\star}5$-brane forms a $D3$-brane, which possible had previously been absorbed by one of the $D5$-branes

nelson & m.s., PLB **674** (2009) 210

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nelson & m.s., PLB **674** (2009) 210

note

- $D3$ -branes do not, generically collide with lower dim branes
- still possible that bound states $D(3,q)$-branes (q<3) form

if a bound $D(5,q)$-brane collides with anti $\bar{D}5$ -brane ⟶

$D(3,q)$ -brane

process allowing for embedded lower dim branes to be present in our universe as relics of earlier, higher dim collisions

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if a bound $D(5,q)$-brane c… $\bar{D}5$ -brane →

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IIB string theory: only D3, and possibly D1-branes, would be created from the decay of higher dim branes

proce… embedded lower dim branes to be present
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cosmic superstrings

otivation

ne inflationary paradigm provides a causal explanation for the
rimordial fluctuations with the correct features as measured in CMB

espite its successes, inflation has many shortcomings

parameters of inflation need (too) often to be fine-tuned
inflation is still a paradigm in search of a model
inflation must prove itself generic

calzetta & **m. s.** (1992, 1993)
gibbons & turok (2006)
germani, nelson & **m. s.** PRD **76** (2007) 043529

n addition, there are questions that inflation does not address:

what preceded inflation? --- the singularity is not resolved

trans-Planckian problem

cosmic superstrings

otivation

ne inflationary paradigm provides a causal explanation for the rimordial fluctuations with the correct features as measured in CMB

espite its successes, inflation has many shortcomings

parameters of inflation need (too) often to be fine-tuned
inflation is still a paradigm in search of a model
inflation must prove itself generic

calzetta & **m. s.** (1992, 1993)
gibbons & turok (2006)
germani, nelson & **m. s.** PRD **76** (2007) 043529

n addition, there are questions that inflation does not address:

what preceded inflation? --- the singularity is not resolved

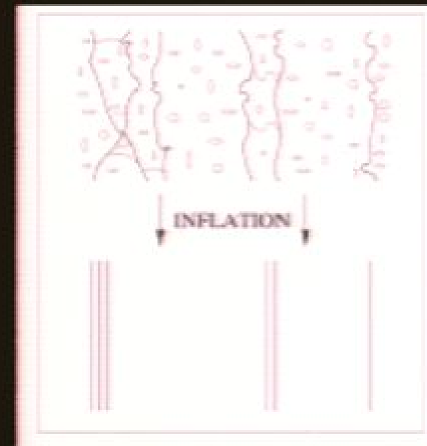
trans-Planckian problem

if string theory is the theory of everything, one should be able to find a natural inflationary scenario within string theory

⇓

- one will be able to identify the inflaton and its properties
- cosmological measurements will help to determine the precise stringy description of our universe

brane inflation

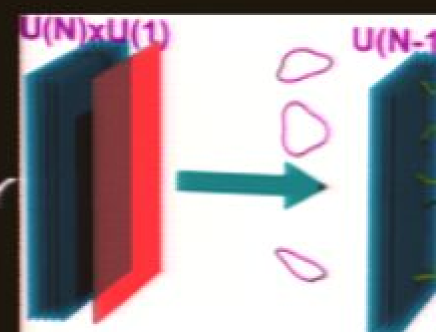


end inflation via brane--anti-brane annihilation

when inter-brane separation decreases below a critical value, the tachyon field (open string stretching between brane--anti-brane) develops an instability, and the rolling of the tachyon field signals the decay of the brane--anti-brane pair

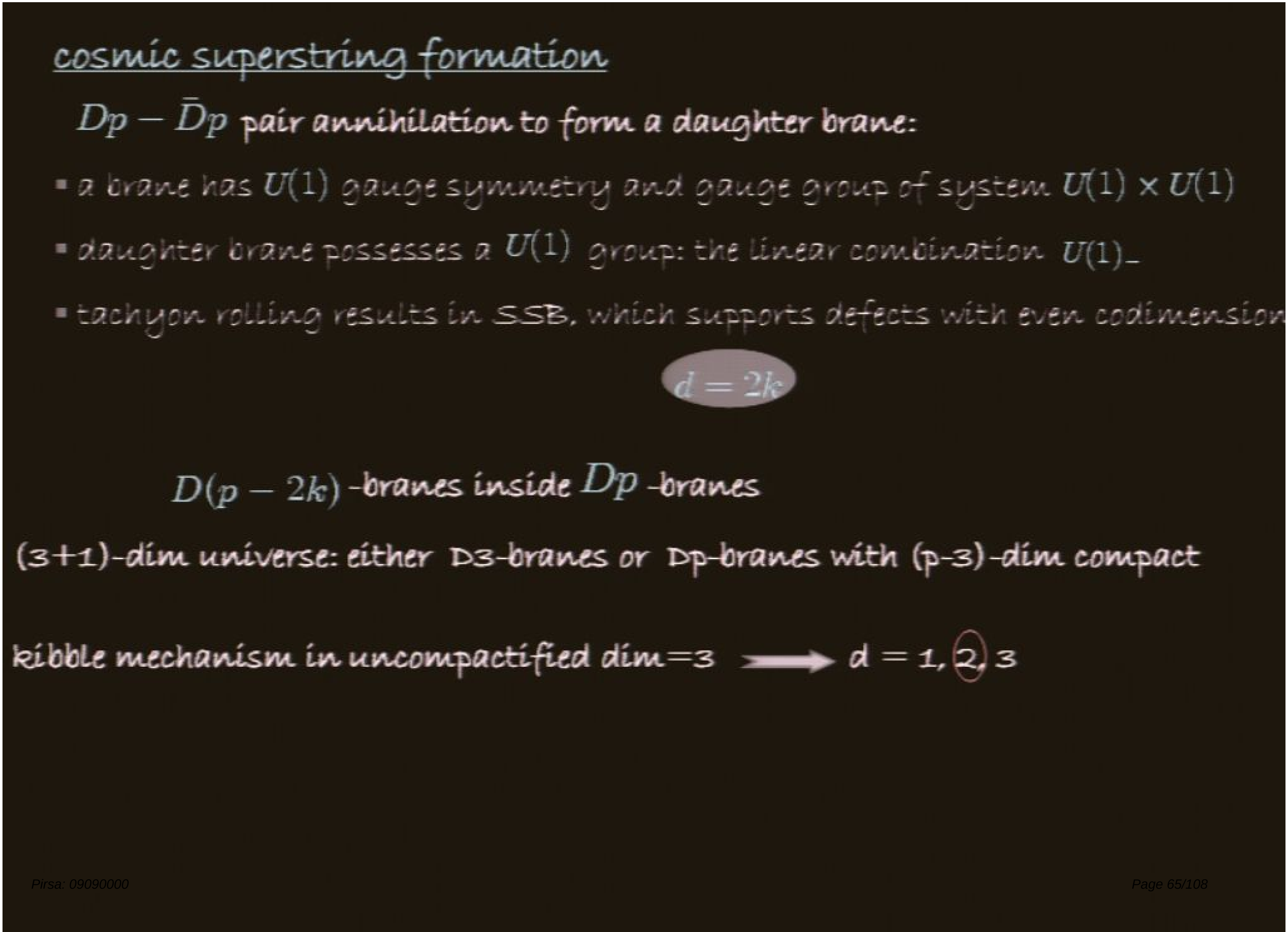
tachyon field: complex field with a non-trivial vacuum manifold

⟶ formation of stable vortex configurations



these vortices are lower-dim branes, which would appear as cosmic strings to a 4-dim observer

cosmic superstring formation



cosmic superstring formation
$Dp - \bar{D}p$ pair annihilation to form a daughter brane:
▪ a brane has $U(1)$ gauge symmetry and gauge group of system $U(1) \times U(1)$
▪ daughter brane possesses a $U(1)$ group: the linear combination $U(1)_-$
▪ tachyon rolling results in SSB, which supports defects with even codimension
$d = 2k$
$D(p-2k)$ -branes inside Dp -branes
(3+1)-dim universe: either D3-branes or Dp-branes with (p-3)-dim compact
kibble mechanism in uncompactified dim=3 → $d = 1, 2, 3$

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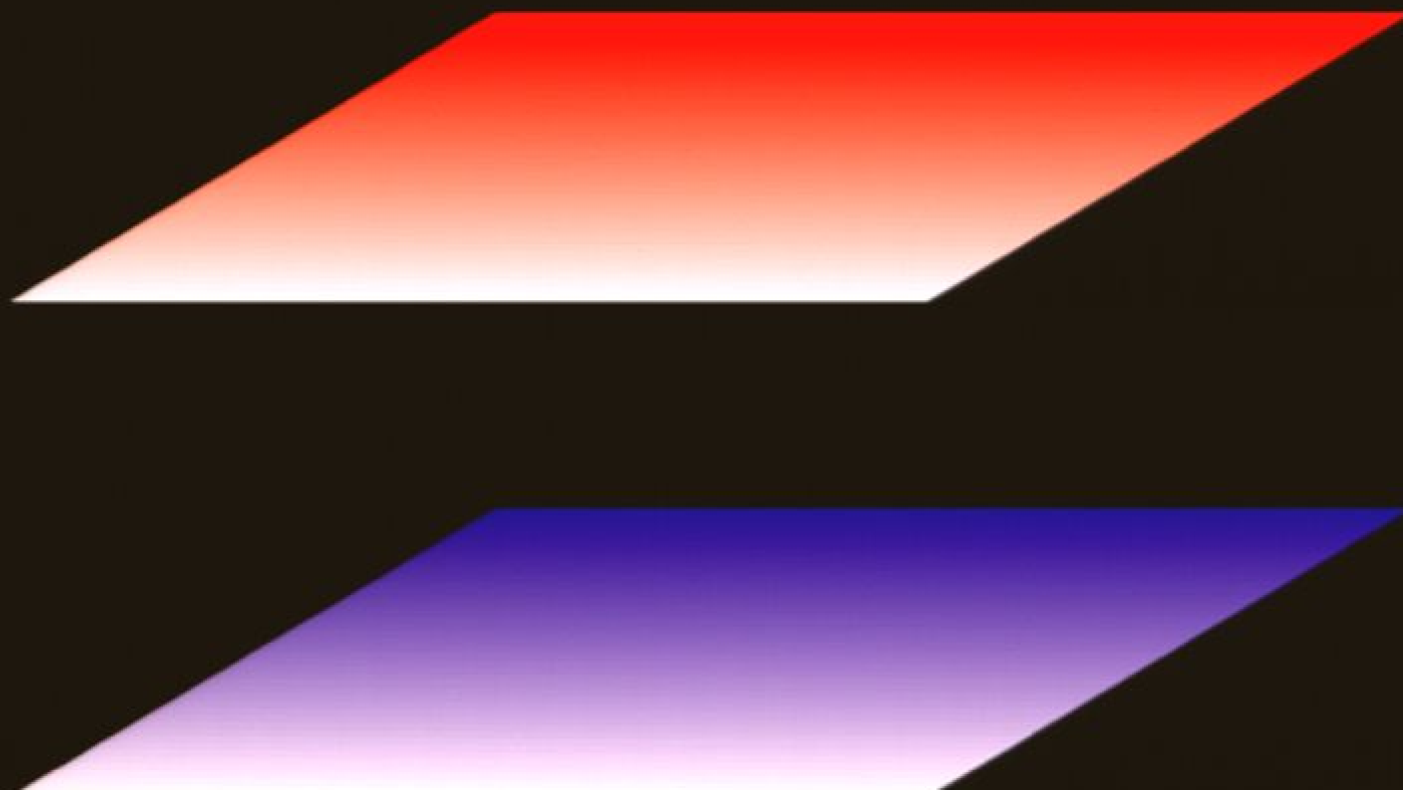
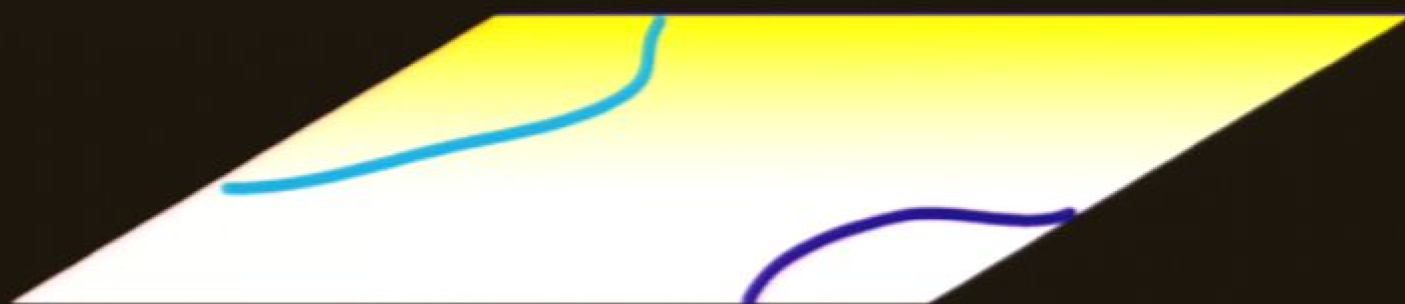
extra brane/anti-brane pairs in the early universe



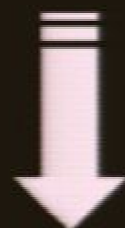
branes/anti-branes come together and annihilate...



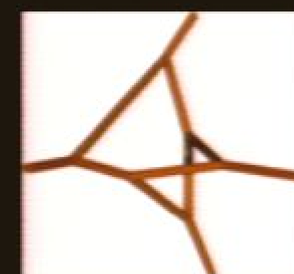
... producing topological defects such as cosmic strings that then evolve

Fundamental (F) strings and 1-dim Dirichlet branes (D-strings) are generically produced at the end of brane inflation

collisions of F-strings & D-strings produce FD bound states



superstring intercommutations form a trilinear vertex



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does a cosmic superstring network reach scaling, or does it freeze leading to predictions inconsistent with our observed universe?

differences between cosmic strings (type II Nielsen-Olesen vortices in the Abelian Higgs model) and cosmic superstrings

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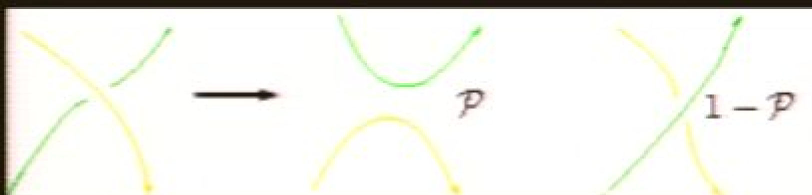
jackson, jones & polchinski, JHEP **0510** (2005) 013



FF-strings: $\mathcal{P} = \mathcal{O}(g_s^2) \longrightarrow 10^{-3} \leq \mathcal{P} \leq 1$

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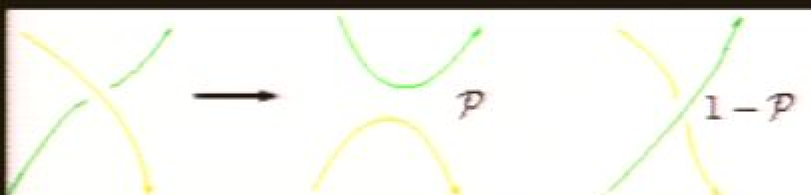

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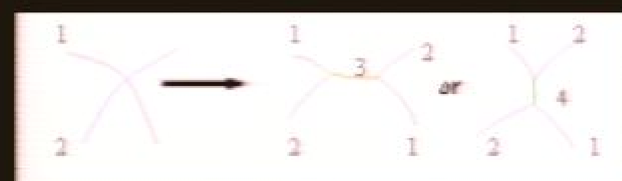
- cosmic superstring networks: also junctions at which three string segments meet



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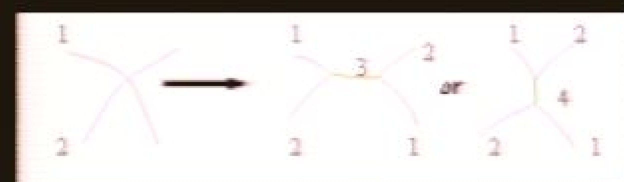


- all strings in an ordinary string network have the same tension, whereas there is a whole range of tensions for cosmic superstrings

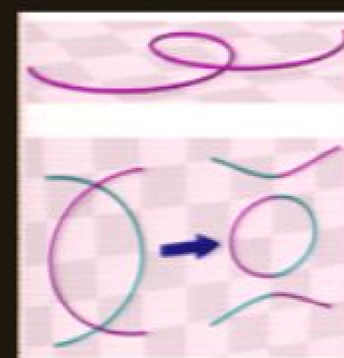
cosmic string evolution

- cosmic strings stretching across the horizon: the energy density scales like $1/a^2$
- cosmic string loops: the energy density (as for monopoles) scales like $1/a^3$

→ naively, the cosmic string density is a problem

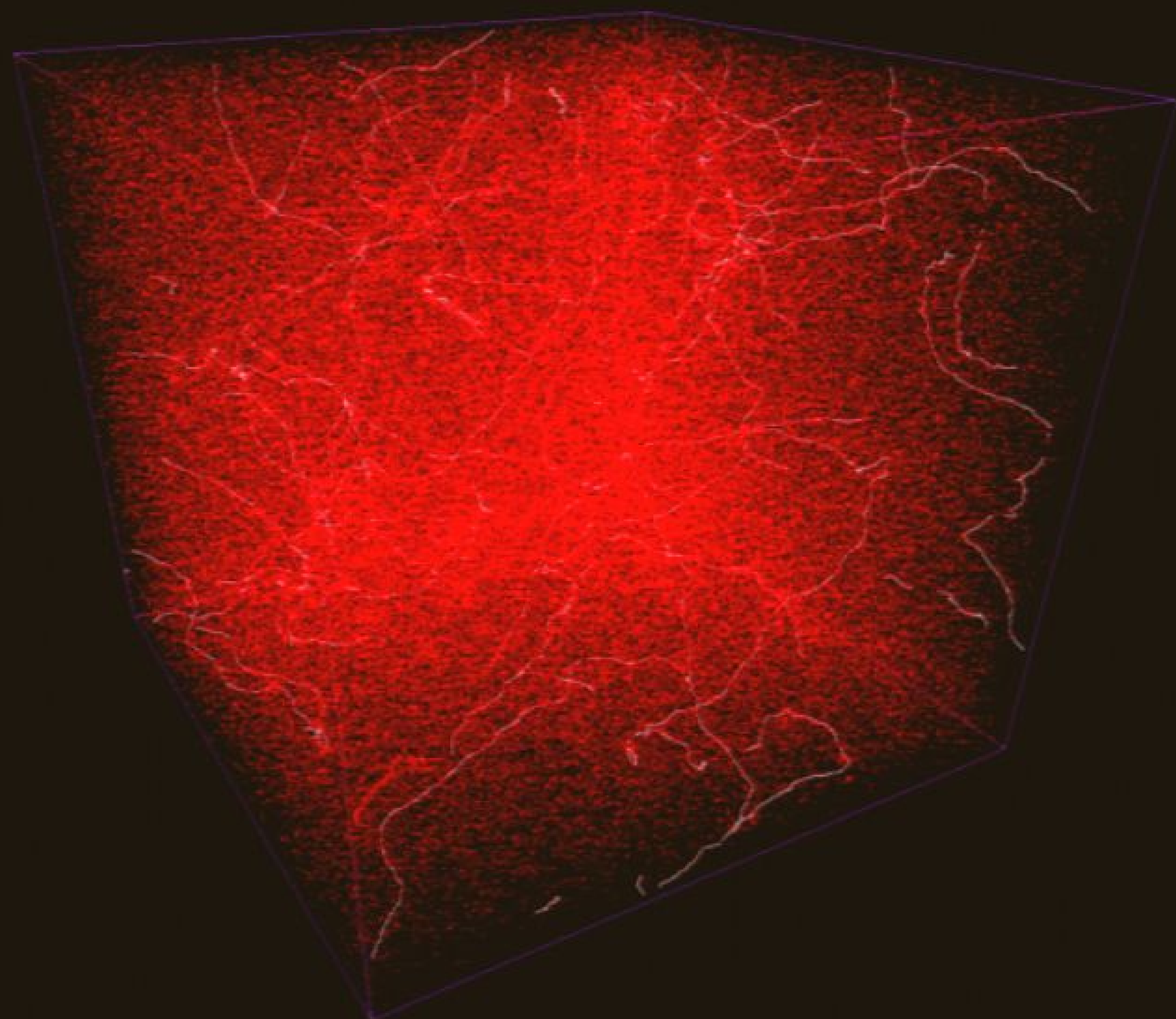
- however, their interactions substantially suppresses the density
- intercommutation of intersecting strings & decay of resulting string loops reduces the density so that it decreases like radiation (matter) during RDE (MDE)
- the network rapidly approaches the scaling solution

→ physics is dictated by the single parameter $G\mu$



bennett, bouchet (1990)
m.s., vilenkin (1990)
shellard, allen (1990)

ringeval, m.s., bouchet (2007)
vanchurin, olum, vilenkin (2007)
martins, shellard (2007)



ringeval, m.s., bouchet JCAP **0702** (2007) 023

evolution of cosmic superstring networks

aim: build simple field theory model of bound states, in analogy with Abelian Higgs model, and study it with lattice simulations

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characteristics:

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the model

rajantie, m.s. & stoica, JCAP 0711 (2007) 021

the model

- two different species of cosmic strings:

  include two sets of fields of the Abelian Higgs model

- formation of bound states:

  introduce a coupling of the scalar fields via a potential

- one non-BPS species of strings (such strings have long range interactions):

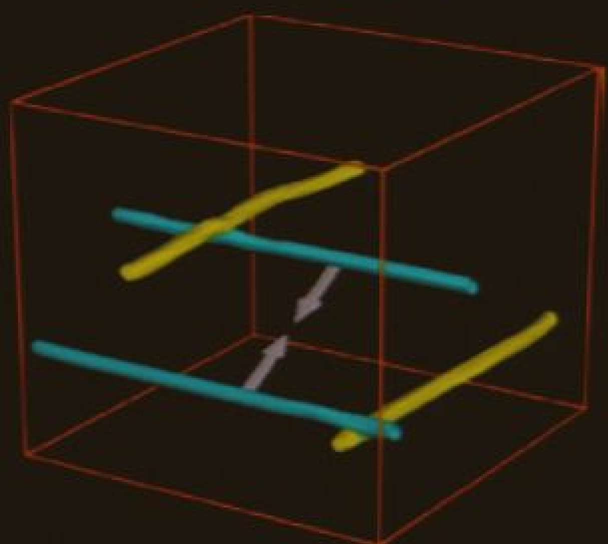
  consider the second type of string to be the topological defect of a scalar field with a global U(1) symmetry

rajantie, m.s. & stoica, JCAP 0711 (2007) 021

there is only one pair of local and one pair of global strings

attractive interactions between global strings result in their motion towards the local ones

does the formation of bound states can stop the motion of the global strings?



global strings move towards local ones and cross them, forming bound states

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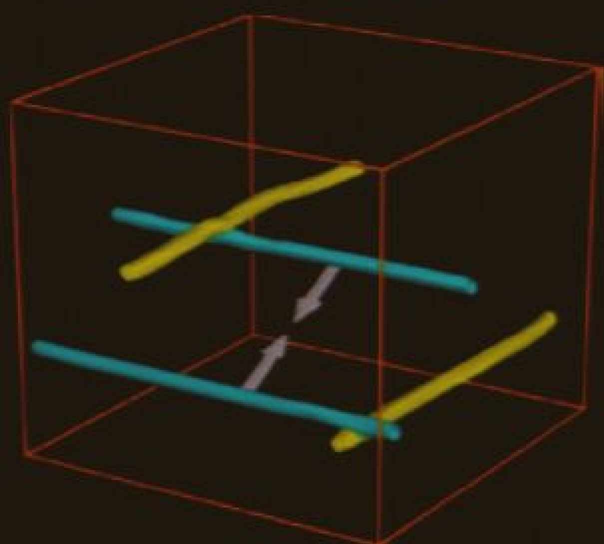

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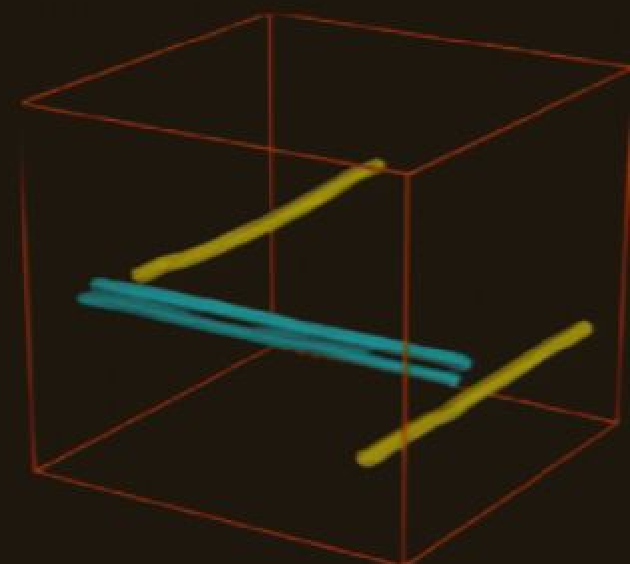
bound states split as the global strings continue to move towards each other

finally they collide and annihilate



bound states do not survive the long-range interactions of global strings

rajantie, m.s. & stoica, JCAP 0711 (2007) 021

does the existence of bound states prevent a cosmic superstring network from reaching a scaling solution?

field theory model to study effect of junctions in the evolution of network composed by cosmic superstrings with bound states

m.s. & stoica, JCAP 0808 (2008) 038

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field theory model to study effect of junctions in the evolution of network composed by cosmic superstrings with bound states

$$\xi = \sqrt{\frac{V}{L}} \qquad \xi(\tau) = \gamma\tau$$

- scaling is robust
- supplementary energy loss mechanism, in addition to loops

<u>new mechanism</u>: formation of bound states with increasing length

> overall network does not freeze because the string length of the unbound states decreases faster

m.s. & stoica, JCAP 0808 (2008) 038

cosmic superstring detection

cosmic superstrings interact with SM particles via gravity

→ detection involves gravitational interactions of cosmic superstrings

- gravity waves
- RR/dilaton emission
- gravitational lensing
- micro-lensing
- CMB anisotropies

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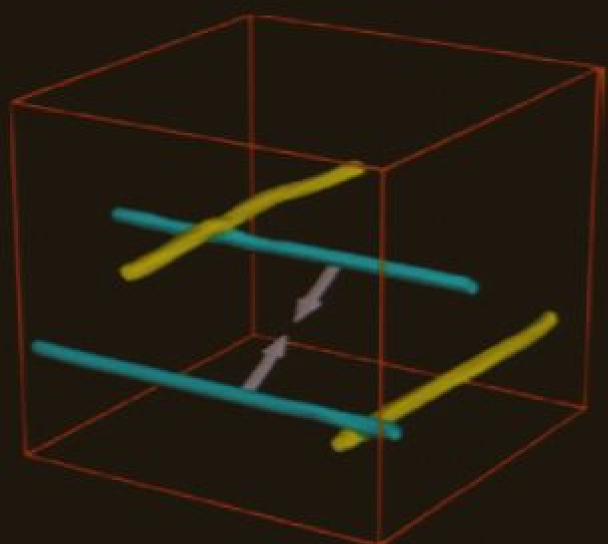

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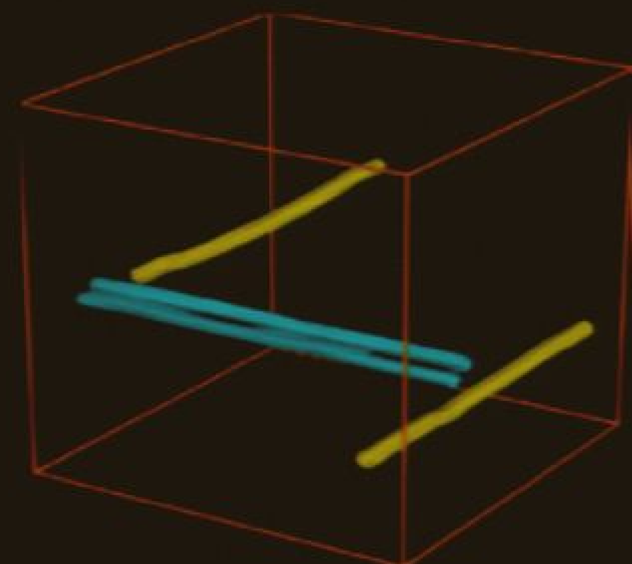

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Microsoft PowerPoint - [PI-branes]

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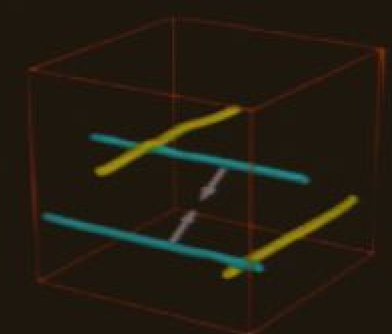

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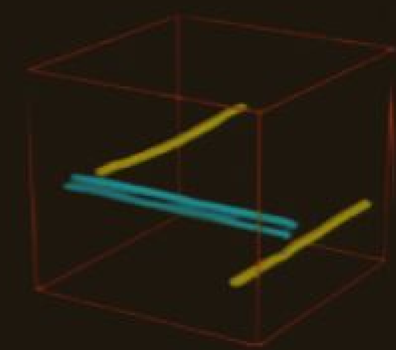

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Cliquez pour ajouter des commentaires

Diapositive 44 sur 55 | Modèle par défaut | Anglais (Royaume-Uni) if both species of strings are BPS:

$$S = \int d^3x\, dt \Big[-\tfrac{1}{4}F^2 - \tfrac{1}{2}(D_\mu\phi)(D^\mu\phi)^* - \tfrac{\lambda_1}{4}(\phi\phi^* - \eta_1^2)^2$$
$$-\tfrac{1}{4}H^2 - \tfrac{1}{2}(D_\mu\chi)(D^\mu\chi)^* - \tfrac{\lambda_2}{4}\phi\phi^*(\chi\chi^* - \eta_2^2)^2$$

$$D_\mu\phi = \partial_\mu\phi - ie_1A_\mu\phi \qquad D_\mu\chi = \partial_\mu\chi - ie_2C_\mu\chi$$
$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \qquad H_{\mu\nu} = \partial_\mu C_\nu - \partial_\nu C_\mu$$

ϕ the Higgs field $\qquad$ χ the axion field

- in the case of a non-BPS species of string: set $e_2 = 0$

raiantie. m.s. & stoica. JCAP 0711 (2007) 021 *does the existence of bound states prevent a cosmic superstring network from reaching a scaling solution?*

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osmic strings in flat space-time

$\mathbf{x}(\sigma, t)$

constraint equations and string e.o.m.:

$$\dot{\mathbf{x}} \cdot \mathbf{x}' = 0$$
$$\dot{\mathbf{x}}^2 + \mathbf{x}'^2 = 1$$
$$\ddot{\mathbf{x}} - \mathbf{x}'' = 0$$

general solution to string e.o.m. :

$$\mathbf{x} = \frac{1}{2}\left[\mathbf{a}(\sigma - t) + \mathbf{b}(\sigma + t)\right]$$

$$\mathbf{a}'^2 = \mathbf{b}'^2 = 1$$

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$$\dot{\mathbf{x}}^2(\sigma, t) = \tfrac{1}{4}[\mathbf{a}'(\sigma - t) - \mathbf{b}'(\sigma + t)]^2$$

$\mathbf{a}'(\sigma)$ and $-\mathbf{b}'(\sigma)$ describe arbitrary closed curves on unit sphere

if the two curves intersect then: $\dot{\mathbf{x}}^2(\sigma, t) = 1$

smooth loops will in general have such luminal points: cusps

non-periodic strings ending on branes

a DBI string ending on two stationary and parallel Dp-branes

non-periodic strings ending on branes

a DBI string ending on two stationary and parallel Dp-branes

boundary conditions on $\dot{\mathbf{x}}$ and $\mathbf{x}'$ for Neumann/Dirichlet directions:
a′ & b′ curves related by inversion through surface of identical dim and orientation to Dp-branes, passing through centre of unit sphere

cusps: if and only if a′ and b′ intersect on the unit sphere

genericity of cusps on non-periodic strings ending on branes

- cusps are generic features of an F-string ending on two parallel D-strings

- an F-string stretched between 2 three-string junctions behaves as an F-string between 2 D1-branes (to order g_s)

⇒ a pair of three-string junctions would have cusps

davis, nelson, rajamanoharan & m.s., JCAP 0811 (2008) 022

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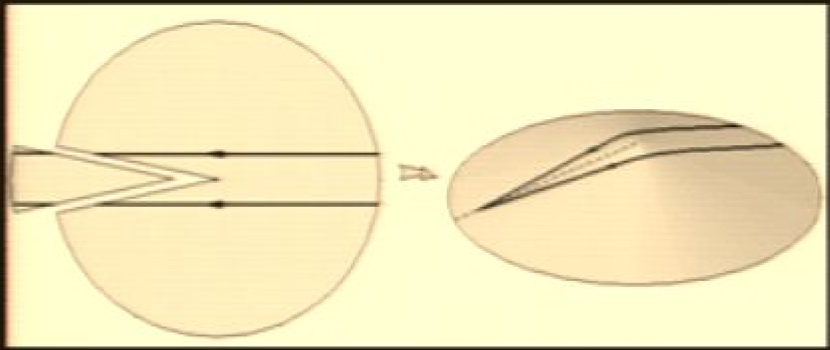
davis, nelson, rajamanoharan & m.s., JCAP 0811 (2008) 022

cusps exist in non-periodic strings ending on D-branes

under S-duality the role of F and D strings is reversed:

cusps exist on light D-strings ending on three-string junctions

gravitational lensing



- deficit angle:

galaxy behind long string will appear as double undistorted image

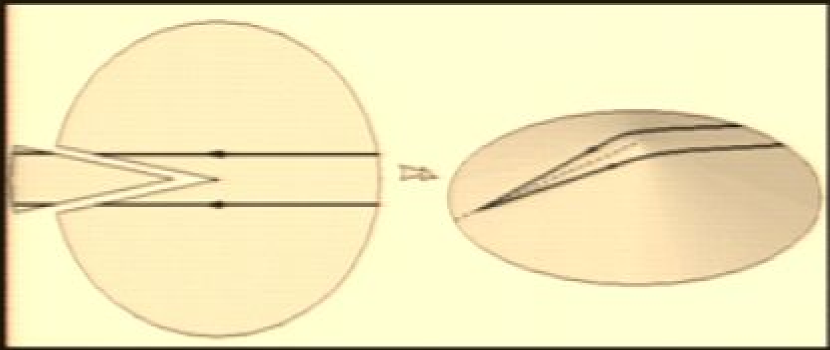
shlaer & wyman (2005)

- wiggly strings lead to local gravitational attractive force towards strings
  → elliptical distortion of background galaxies

dyda & brandenberger (2007)

- string junctions will effect lensing

brandenberger, firouzjahi & karouby (2007) gravitational lensing



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micro-lensing

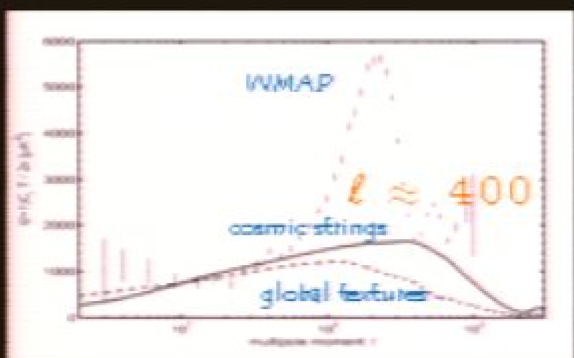
- string loops can lens stars, which shows up as the brightness of a star doubles
for a short period of time

- event rate for micro-lensing of distant quasars by cosmic strings is tiny

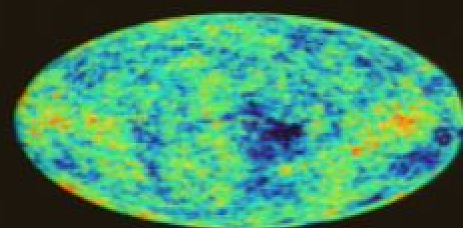
kuijken, siemens & vachaspati (2007)

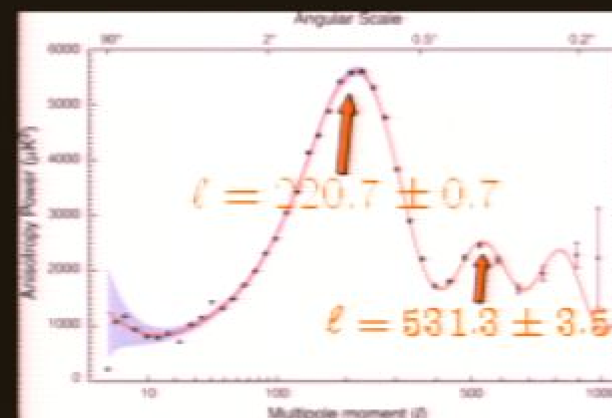
CMB anisotropies

$$\langle \frac{\Delta T}{T_0}(\hat{n}_1)\frac{\Delta T}{T_0}(\hat{n}_2)\rangle = \frac{1}{4\pi}\sum_\ell (2\ell+1)C_\ell P_\ell(\hat{n}_1\cdot\hat{n}_2)\ \mathcal{W}_\ell^2$$



bevis, hindmarsh, kunz, urrestilla (2006)





hinshaw et al (2006)

- WMAP data constrain the contribution from cosmic strings to be at most

→ $G\mu \leq 7 \times 10^{-7}$

$$C_\ell = \alpha C_\ell^{\rm infl} + (1-\alpha)C_\ell^{\rm CS}$$

at most **10%**

bouchet, peter, riazuelo, **m. s.** (2000)
pogosian, tye, wassweman, wyman (2003)
jeong, smoot (2005)

- B-mode polarisation signal from strings is expected to be much stronger than that in pure inflationary scenario

gravity waves

- network of strings produces a stochastic background of gravitational waves, within sensitivity frequency range of Advanced LIGO / VIRGO and LISA
- such stochastic GW also influences the very precise pulsar timing measurements

$$\Omega_{gw}(f) = (f/\rho_c)d\rho_{gw}/df$$

damour & vilenkin (2005)
siemens et al (2006)

LIGO S4

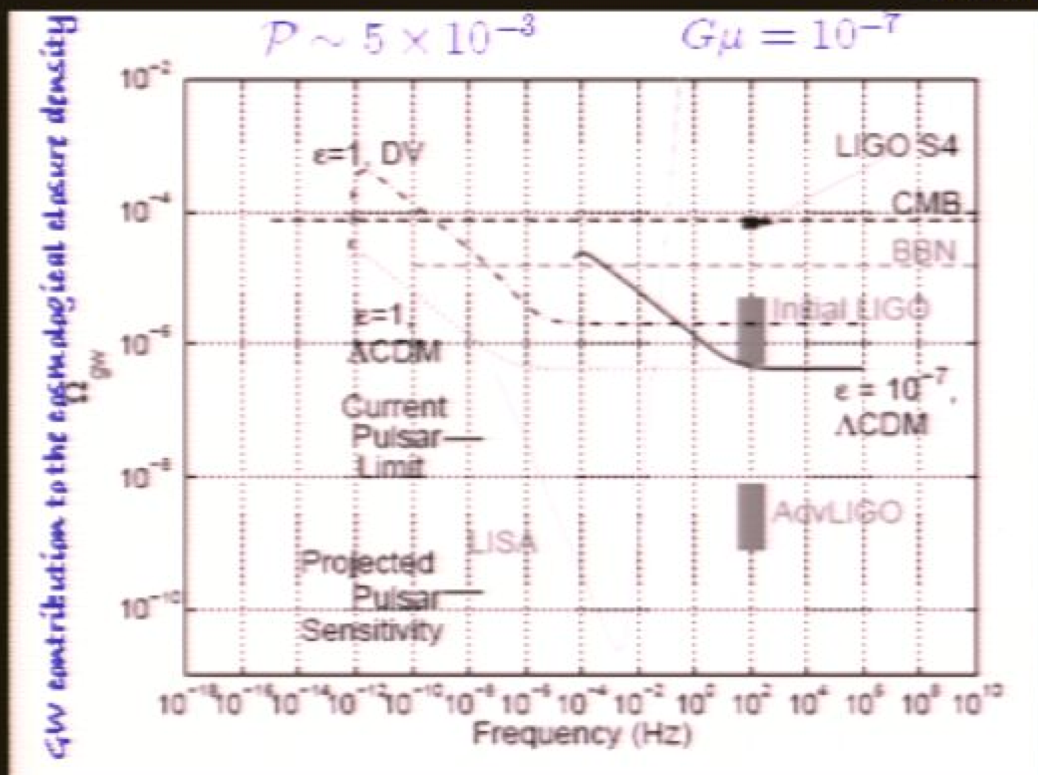
$\Omega_{gw} < 6.5 \times 10^{-5}$
$51 - 150\, Hz$

pulsar

$\Omega_{gw} < 3.9 \times 10^{-8}$
$1/(20yr) - 1/yr$

BBN

$_{gw}(f)d(ln f) < 1.5 \times 10^{-5}$
$5.5 \times 10^9, f > 10^{-10} Hz$



loops are formed with length $l \sim \epsilon\Gamma G\mu$

CMB

$\Omega_{gw}(f)d(ln f) < 7.5 \times 10^{-}$

$z > 5.5 \times 1100, f > 10^{-15} H$

siemens, mandic & greighton (2007)

cosmic superstrings are more accessible because the spectrum amplitude is inversely proportional to $\mathcal{P}$ through its dependence on the loop density

damour & vilenkin (2005)
siemens et al (2006)
m. s. JCAP **0504** (2005) 003

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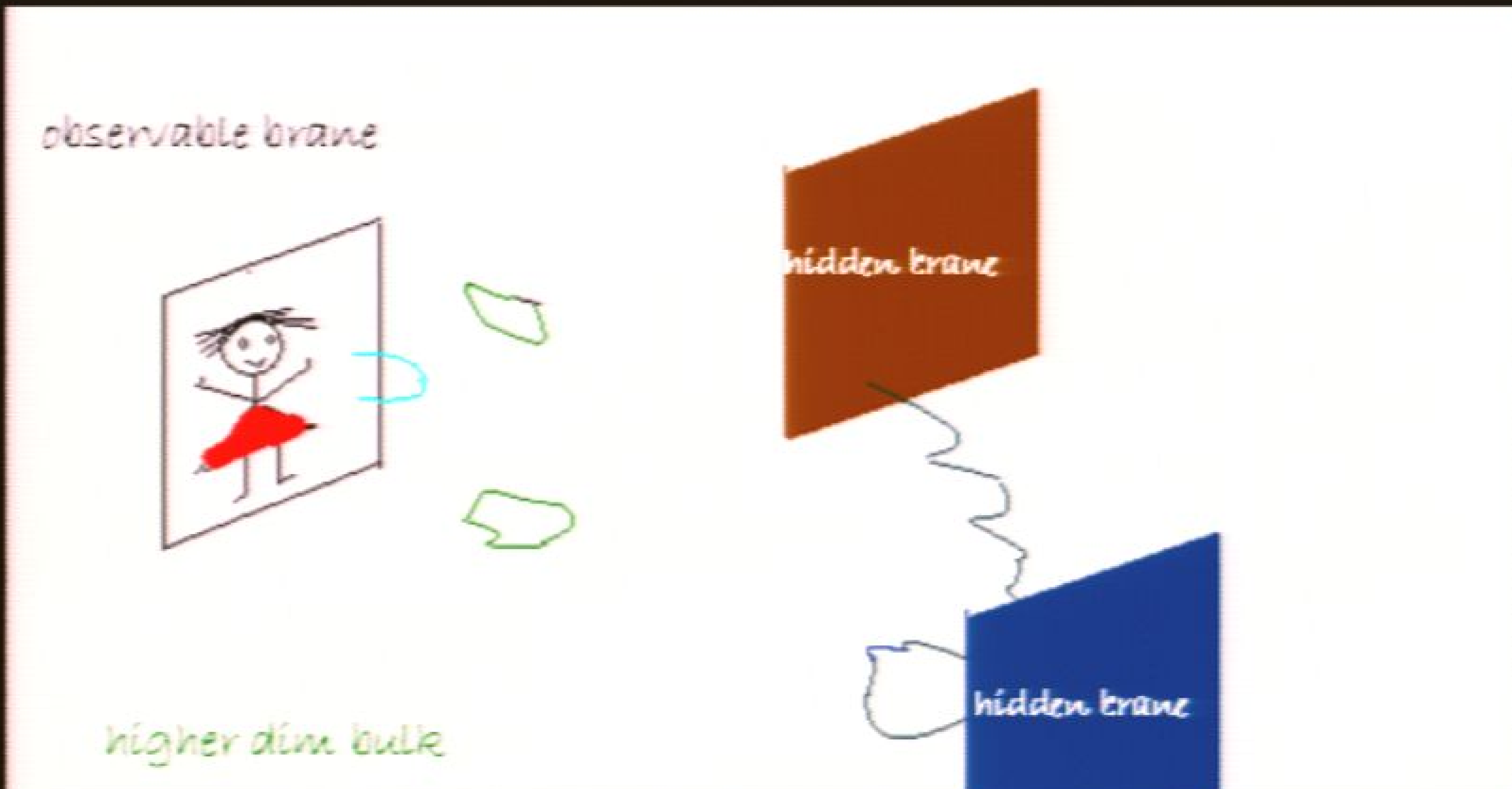
the bound rules out cosmic superstring models with $G\mu \geq 10^{-12}$ when $\mathcal{P} \sim 10^{-3}$
even for $\mathcal{P} \sim 10^{-1}$ superstring tensions with $G\mu \geq 10^{-10}$ are ruled out

field theoretic strings and superstrings with $\mathcal{P} \sim 1$ are ruled our for $G\mu \geq 10^{-8}$

siemens, mandic & creighton (2007)

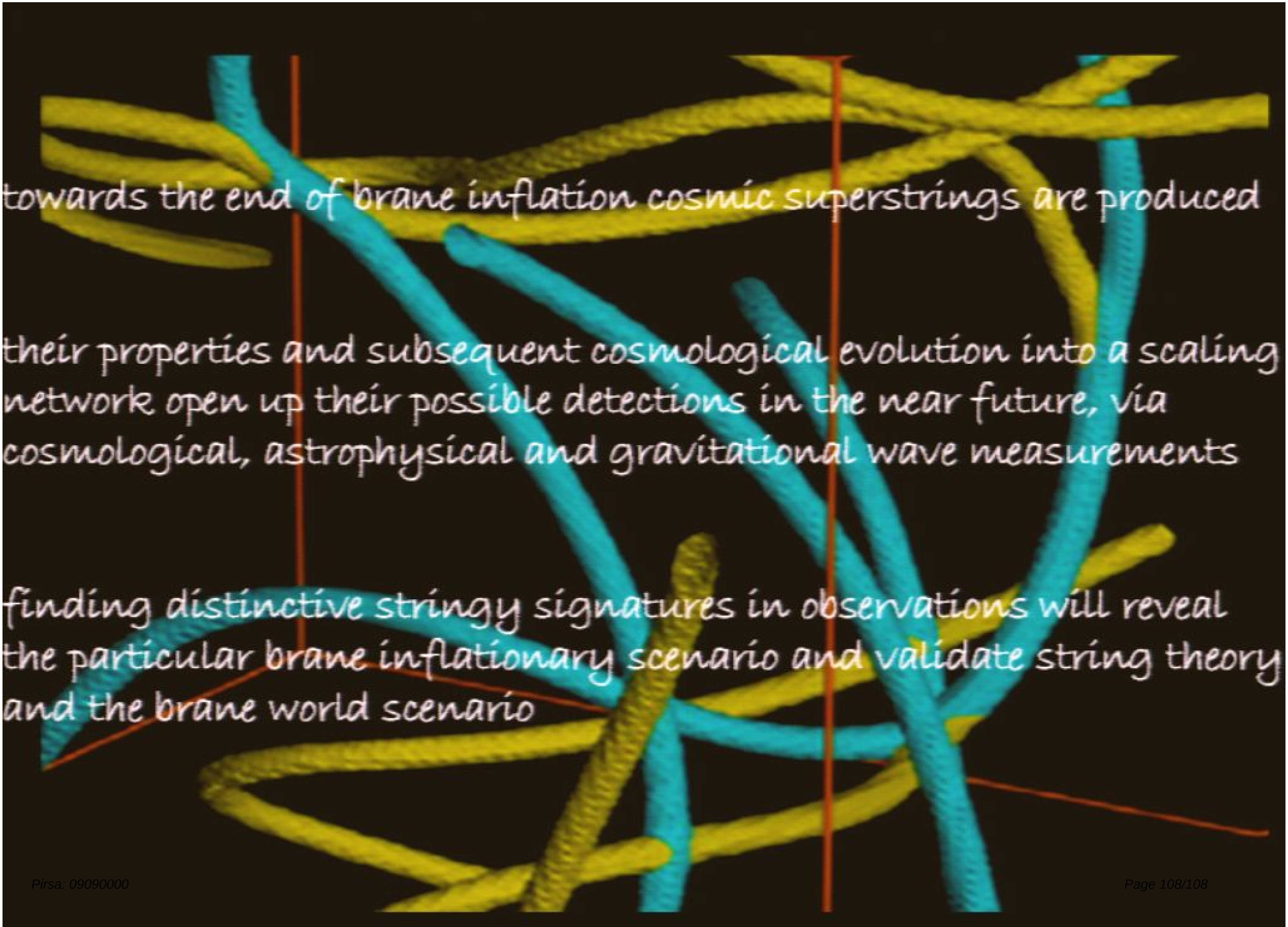
conclusions



collisions and subsequent decays of higher dim branes leave behind 3dim branes/antibranes, one of which could play the role of our universe

few 1dim branes/antibranes may also be formed

brane collisons may also lead to bound states of branes, allowing 1dim branes captured within the 3dim ones


towards the end of brane inflation cosmic superstrings are produced
their properties and subsequent cosmological evolution into a scaling network open up their possible detections in the near future, via cosmological, astrophysical and gravitational wave measurements
finding distinctive stringy signatures in observations will reveal the particular brane inflationary scenario and validate string theory and the brane world scenario