formation & evolution of cosmic superstrings

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outline

- introduction / motivation
- cosmic superstring formation
- differences between cosmic strings and cosmic superstrings
- cosmic string/superstring network evolution
- detection of cosmic superstrings
- conclusions

introduction / motivation

observational data (CMB) strongly support the inflationary paradigm

Spergel (2006)

- despite its success, inflation remains a paradigm in search of a model
- successful inflationary models should be motivated by fundamental physics
- as the cosmological data keep improving impressively fast, it becomes urgent to find an inflationary model with a solid theoretical foundation
- susy guts: end of inflation is accompanied by cosmic string formation

Jeannerot, Rocher, Sakellariadou (2003)

- studies on the probability of the onset of inflation indicate that it should take place in the deep quantum gravity regime

Calzetta, Sakellariadou (1990)

Germani, Nelson, Sakellariadou (2007)

inflation in the process of brane interactions,
within brane cosmology in string theory context

introduction / motivation

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cosmic strings

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Calzetta, Sakellariadou (1990)

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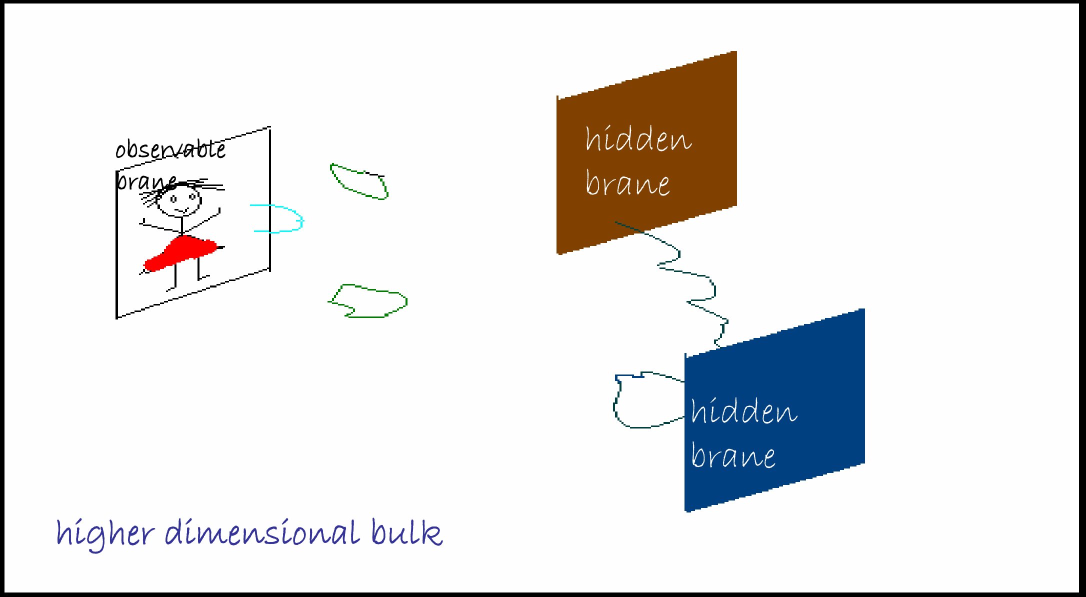
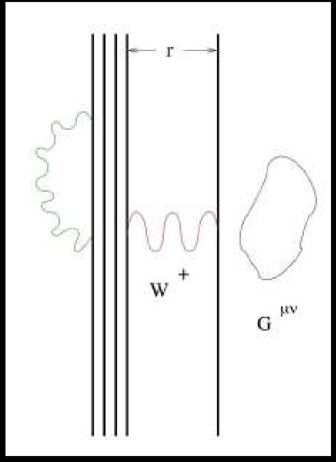
cosmic superstrings

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 world model: realisation of nature in string theory





all standard model particles are open string modes

each end of an open string must end on a brane

⟹ the standard model particles are stuck on a stack of Dp-branes, while the remaining p-3 of the dimensions are wrapping some cycles in the bulk, where closed string modes such as graviton live

cosmological models inspired by string theory:

- compactification to 4 space-time dimensions leads to scalar fields & moduli
- moduli could be the inflaton field, provided they do not roll quickly

runaway moduli would destroy any consistent cosmological model

⇒ **moduli stabilization, e.g. KKLT scenario**

Dasgupta, Rajesh, Sethi (1999)

Giddings, Kachru, Polchinski (2002)

Kachru, Kallosh, Linde, Trivedi (2003)

Kachru, Kallosh, Linde, Malcadena, McAllister, Trivedi (2003)

- brane annihilations allow the survival only of 3-dimensional branes,

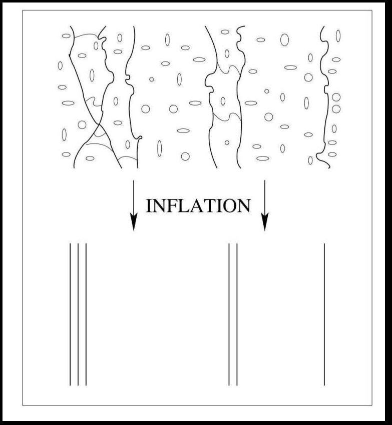
Durrer, Kunz, Sakellariadou (2005)

Nelson, Sakellariadou (2008)

with the production of fundamental (F-strings) & Dirichlet D1-branes (D-strings)

F- and D-strings (**cosmic superstrings**) are of cosmological size and they could play the role of cosmic strings

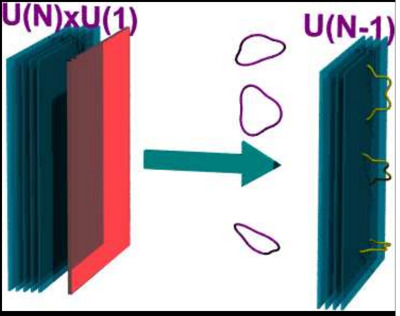
brane inflation



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

$Dp - \bar{D}p$ pair annihilation to form a daughter brane:

- a brane has a $U(1)$ gauge symmetry and the gauge group of the system is $U(1) \times U(1)$
- the 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

$D(p-2)$ -branes are seen as COSMIC SUPERSTRINGS to a 3-dim observer

$D3 - \bar{D}3$ annihilation: vortices are D1-strings

- the other linear combination disappears (only one brane remains) by having its fluxes confined by (confining) fundamental (F) strings

(3+1)-dim universe → either D3-branes or Dp-branes with (p-3)-dim compact

Kibble mechanism in uncompactified dim=3 → $d = 1, 2, 3$ even

$D(p-2)$-branes are seen as COSMIC SUPERSTRINGS to a 3-dim observer

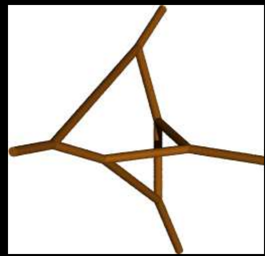
they extend in one large dim, wrapping same compact space as original Dp-branes

$D3 - \bar{D}3$ annihilation: vortices are D1-strings

- the other linear combination $U(1)_+$ disappears (only one brane remains) by having its fluxes confined by confining strings which are thought to be fundamental (F) closed strings

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



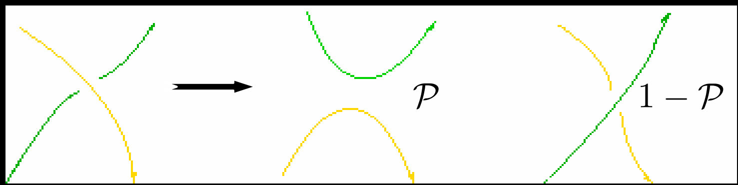
superstring intercommutations form a trilinear vertex

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

$\mathcal{P}_{\text{cosmic strings}} = 1$ $\qquad$ $\mathcal{P}_{\text{cosmic superstrings}} \ll 1$

Jackson, Jones, Polchinski (2004)

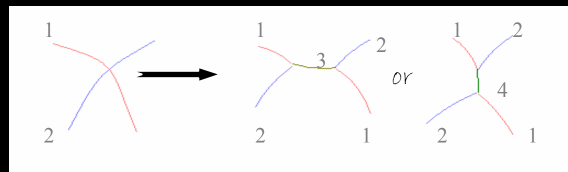


FF-strings: $\mathcal{P} = \mathcal{O}(g_s^2)$ ⟶ $10^{-3} \leq \mathcal{P} \leq 1$

DD-strings: $0.1 \leq \mathcal{P} \leq 1$

FD-strings: $0 \leq \mathcal{P} \leq 1$

- cosmic string networks: (sub-horizon sized) loops and (super-horizon sized) long strings
- **cosmic superstring networks: also junctions at which three string segments meet**



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

these two features are shared with type-I vortices in the Abelian Higgs model, but in constrast with them, superstrings have two integer-valued charges, p and q

Donaire, Rajantie (2006)

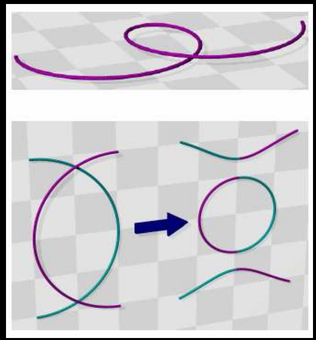
cosmic string evolution

- 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

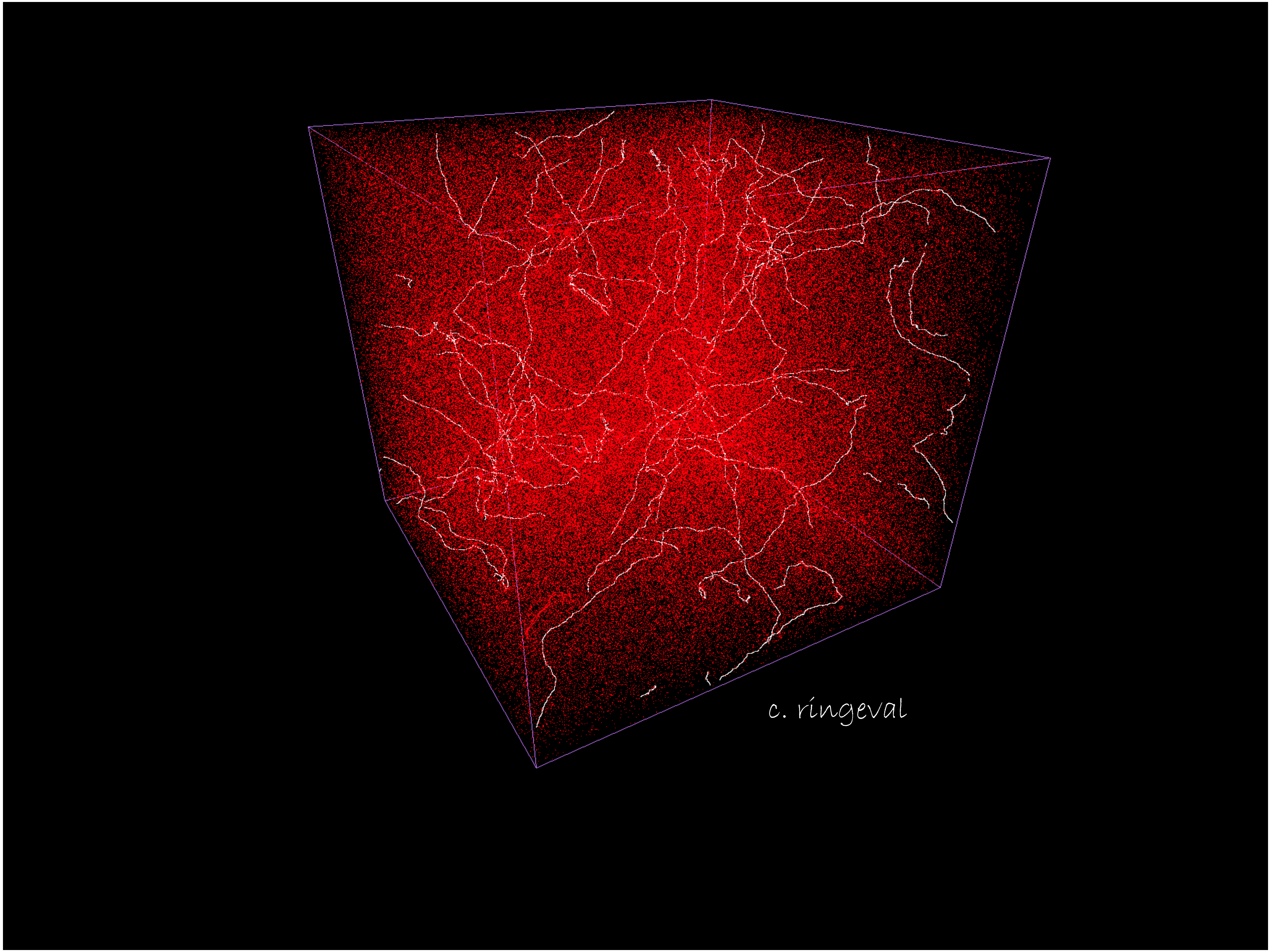
- however, their interactions substantially suppresses the density
- intercommutation of intersecting strings & decay of resulting string loops reduces the density so that it decreases like radiation (matter) during RDE (MDE)
- the network rapidly approaches the scaling solution

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



Bennett, Bouchet (1990)
Sakellariadou, Vilenkin (1990)
Shellard, Allen (1990)

Ringeval, Sakellariadou, Bouchet (2006)
Vanchurin, Olum, Vilenkin (2006)
Martins, Shellard (2006)


c. ringeval

evolution of cosmic superstring networks

aim: build a simple field theory model of bound states, in analogy with the Abelian Higgs model, and study its properties using lattice simulations

characteristics:

- bound states have different tension than single-charge strings

- set long-range interaction of each species of strings individually;

different components of the FD-string are expected to exhibit different types of long-range interactions

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, Sakellariadou, Stoica (2007)

if both species of strings are BPS:

$$S = \int \mathrm{d}^3x\mathrm{d}t \Big[-\frac{1}{4}F^2 - \frac{1}{2}(D_\mu\phi)(D^\mu\phi)^\star - \frac{\lambda_1}{4}(\phi\phi^\star - \eta_1^2)^2$$
$$-\frac{1}{4}H^2 - \frac{1}{2}(D_\mu\chi)(D^\mu\chi)^\star - \frac{\lambda_2}{4}\phi\phi^\star(\chi\chi^\star - \eta_2^2)^2$$

$$D_\mu\phi = \partial_\mu\phi - ie_1A_\mu\phi \qquad D_\mu\chi = \partial_\mu\chi - ie_2C_\mu\chi$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \qquad H_{\mu\nu} = \partial_\mu C_\nu - \partial_\nu C_\mu$$

ϕ the *Higgs* field

χ the *axion* field

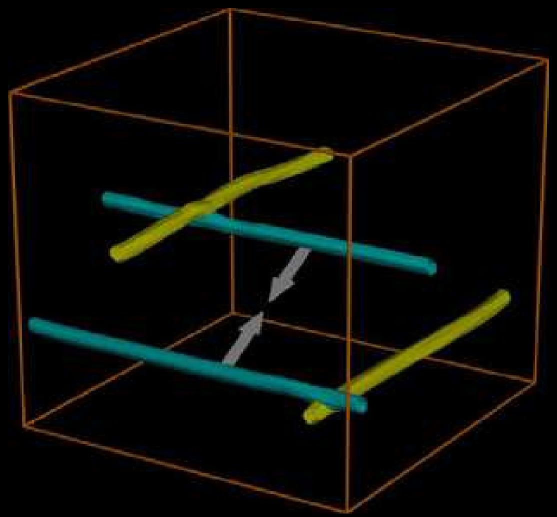
- in the case of a non-BPS species of string: set $e_2 = 0$

Rajantie, Sakellariadou, Stoica (2007)

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

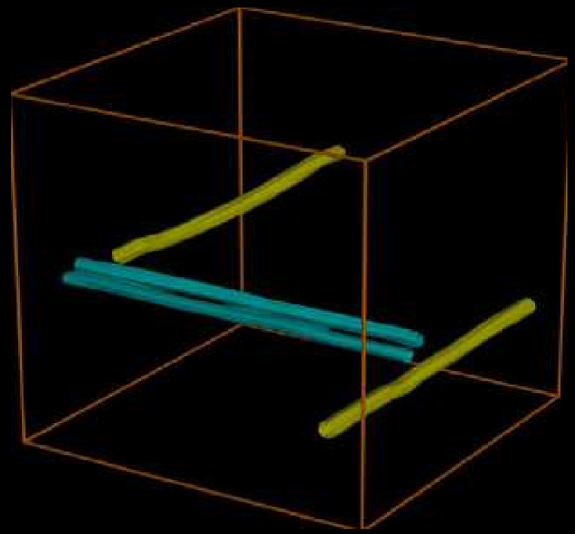
does the formation of bound states can stop the motion of the global strings?



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

these bound states then 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, Sakellariadou, Stoica (2007)

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

use a field theory model to study the effect of junctions in the evolution of a network composed by F, D and FD-strings

- scaling of F,D,FD-strings is robust $\xi = \sqrt{\frac{V}{L}}$ $\xi(\tau) = \gamma\tau$
- there is a supplementary energy loss mechanism, in addition to chopping off loops

new mechanism: **formation of bound states with increasing length**

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

Sakellariadou, Stoica (2008)

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

cosmic 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. in flat space-time:

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

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

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

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

they satisfy: $\int_0^L \mathbf{a}' \mathrm{d}\sigma = \int_0^L \mathbf{b}' \mathrm{d}\sigma = 0$ but otherwise are arbitrary

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

smooth loops will in general have such luminal points: cusps

property of loop solutions: points along the string can reach the velocity of light

non-periodic strings ending on branes

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

$$S = -\mu \int \mathrm{d}\tau \mathrm{d}\sigma \sqrt{-|\gamma_{\alpha\beta} + \lambda F_{\alpha\beta}|}$$

$$\gamma_{\alpha\beta} = g_{\mu\nu} x^{\mu}_{,\alpha} x^{\nu}_{,\beta}$$

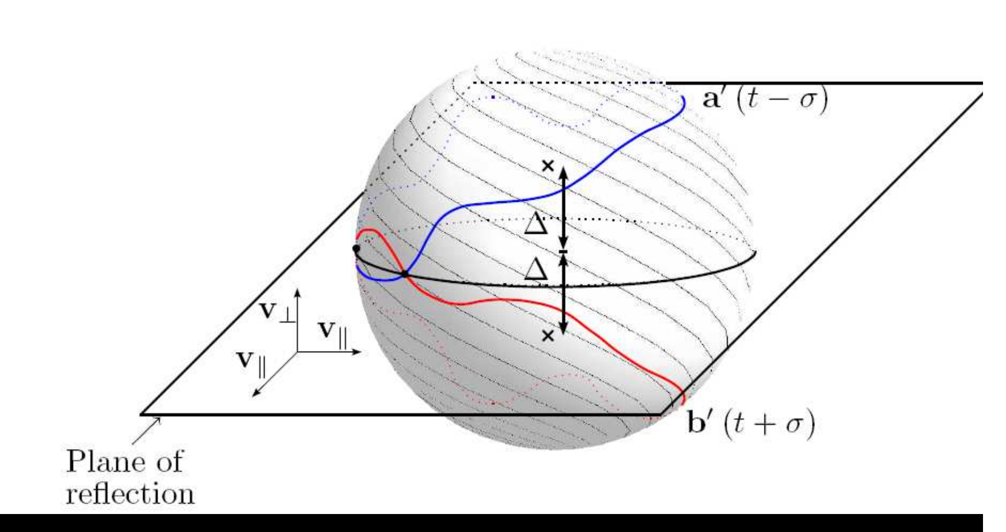
$$\lambda = 2\pi\alpha'$$

$$F_{\alpha\beta} = \partial_\alpha A_\beta - \partial_\beta A_\alpha$$

boundary conditions on $\dot{\mathbf{x}}$ and $\mathbf{x}'$ for Neumann and in Dirichlet directions:

a′ and b′ curves are related by inversion through a surface of identical dimension and orientation to the Dp-branes, that passes through the centre of the unit sphere

a′ , b′ : closed curves on unit sphere, but their centres of mass are not necessarily at centre of unit sphere



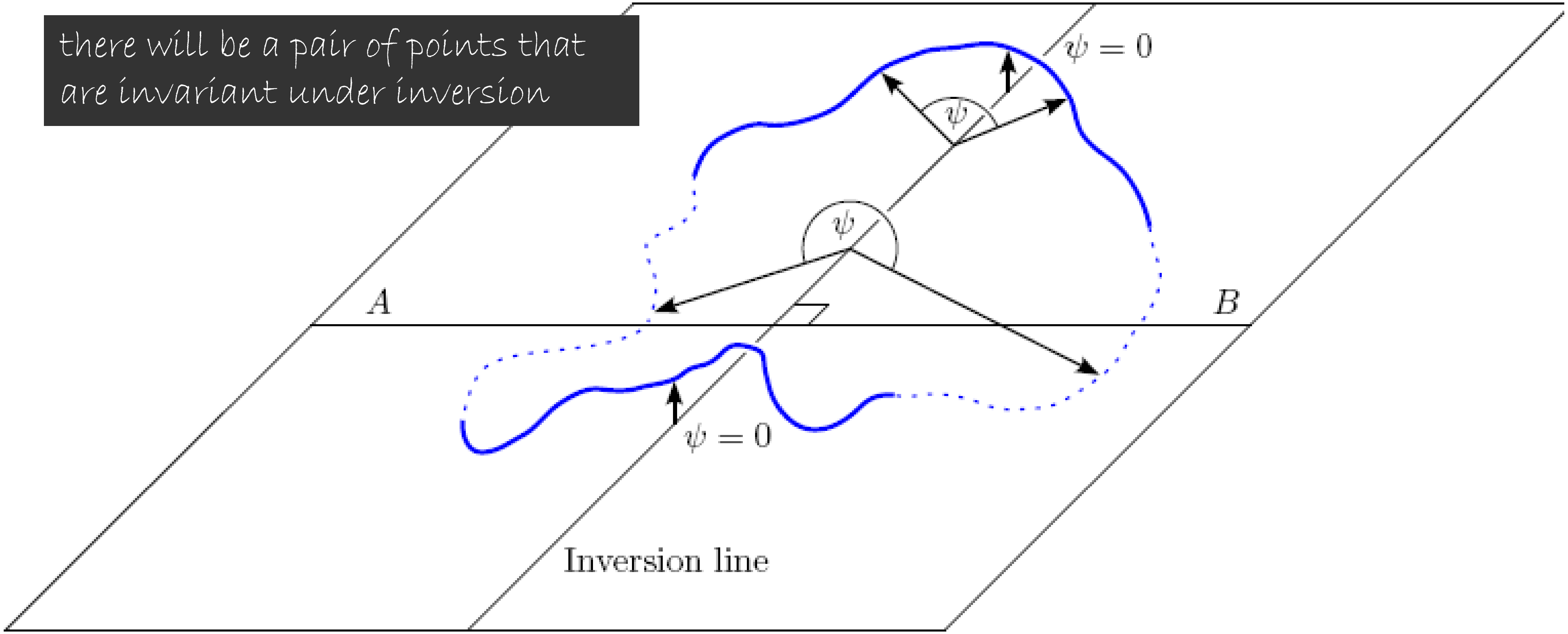
cusps: if and only if a′ and b′ intersect on the unit sphere

p=2: a′ and b′ are reflections of each other across a plane passing through the centre of the unit sphere

D1-branes

a' and b' intersect whenever the line through which they are inverted is enclosed by the closed curves

there will be a pair of points that are invariant under inversion



Davis, Nelson, Rajamanoharan, Sakellariadou (2008)

cusps in a significant fraction of cases provided $|\Delta| \ll L$ inter-brane separation << string length

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, Sakellariadou (2008)

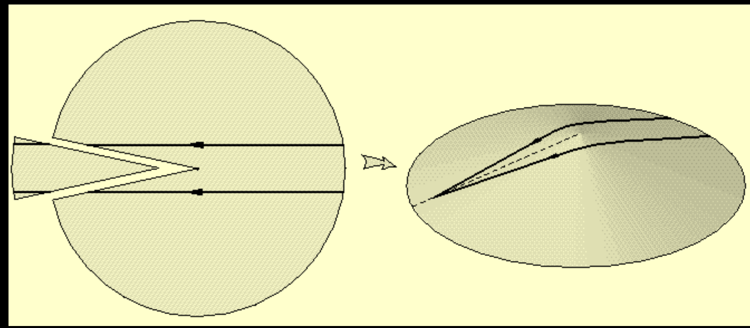
cusps exist in non-periodic strings ending on D-branes

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

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

GW and SM fields + dilaton/RR/moduli/gravitinos/stable SUSY particles can be emitted

gravitational lensing



- deficit angle:
a galaxy behind a long cosmic string will appear as a double undistorted image

Shlaer, Wyman (2005)

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

Dyda, Brandenberger (2007)

- string junctions will effect lensing

Brandenberger, Firouzjahi, Karouby (2007)

micro-lensing

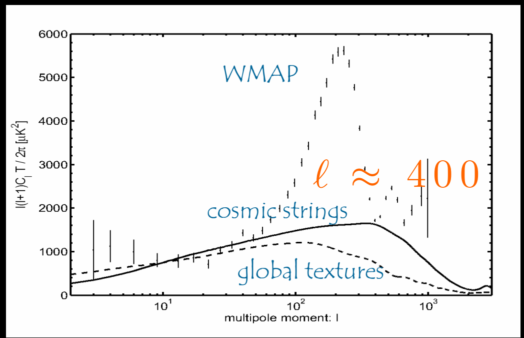
- string loops can lens stars, which shows up as the brightness of a star doubles for a short period of time

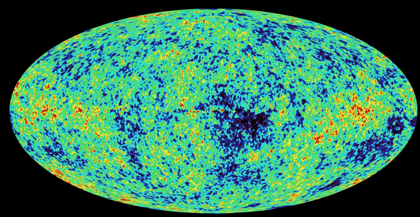
- event rate for micro-lensing of distant quasars by cosmic strings is tiny

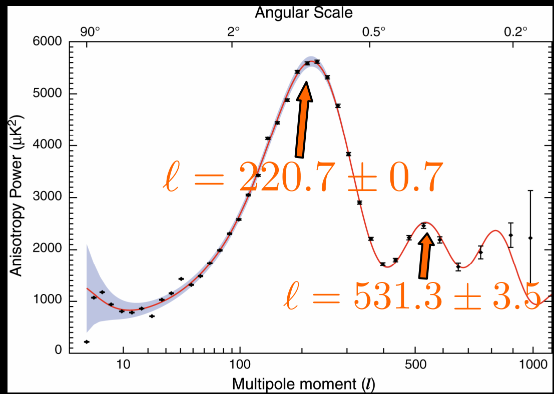
Kuijken, Siemens, Vachaspati (2007)

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

$\Rightarrow$ $G\mu \le 7\times 10^{-7}$

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

at most **10%**

Bouchet, Peter, Riazuelo, Sakellariadou (2000)
Pogosian, Tye, Wassweman, Wyman (2003)
Jeong, Smoot (2005)

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

gravity waves

- a network of strings produces a stochastic background of gravitational waves, within the 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

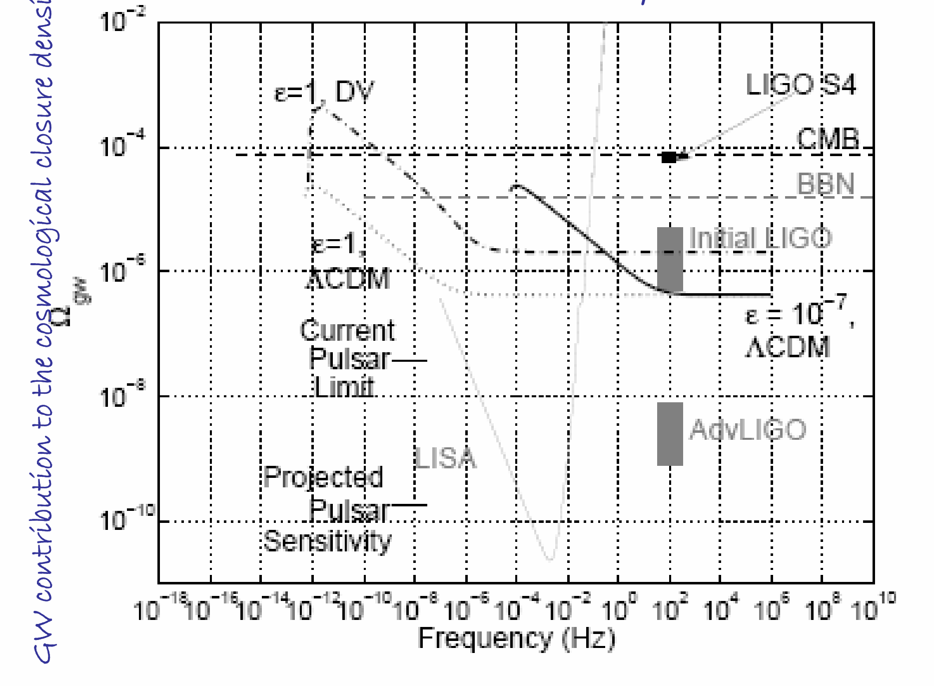
$\Omega_{gw} < 3.9 \times 10^{-8}$
$1/(20yr) - 1/yr$

BBN

$\int \Omega_{gw}(f)d(lnf) < 1.5 \times 10^{-5}$

$z > 5.5 \times 10^9, f > 10^{-10} Hz$

$\mathcal{P} \sim 5 \times 10^{-3}$ $G\mu = 10^{-7}$



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

CMB

$\Omega_{gw}(f)d(lnf) < 7.5 \times 10^{-5}$

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

Siemens, Mandic, Creighton (2007)

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

Sakellariadou (2005)

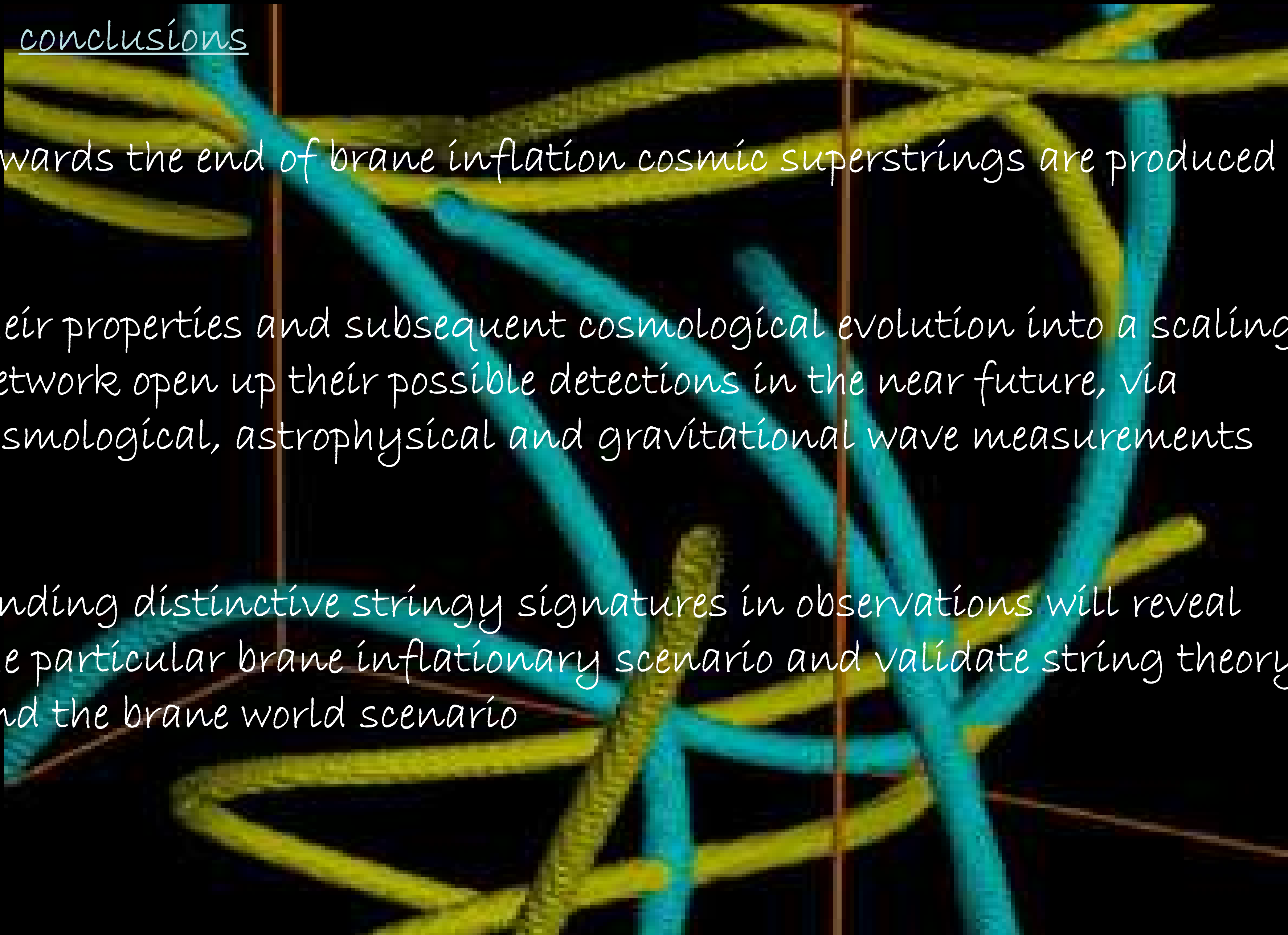
the pulsar limit is the most constraining; BBN & CMB bounds are consistent with, but somewhat weaker

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

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