Cosmic Superstrings

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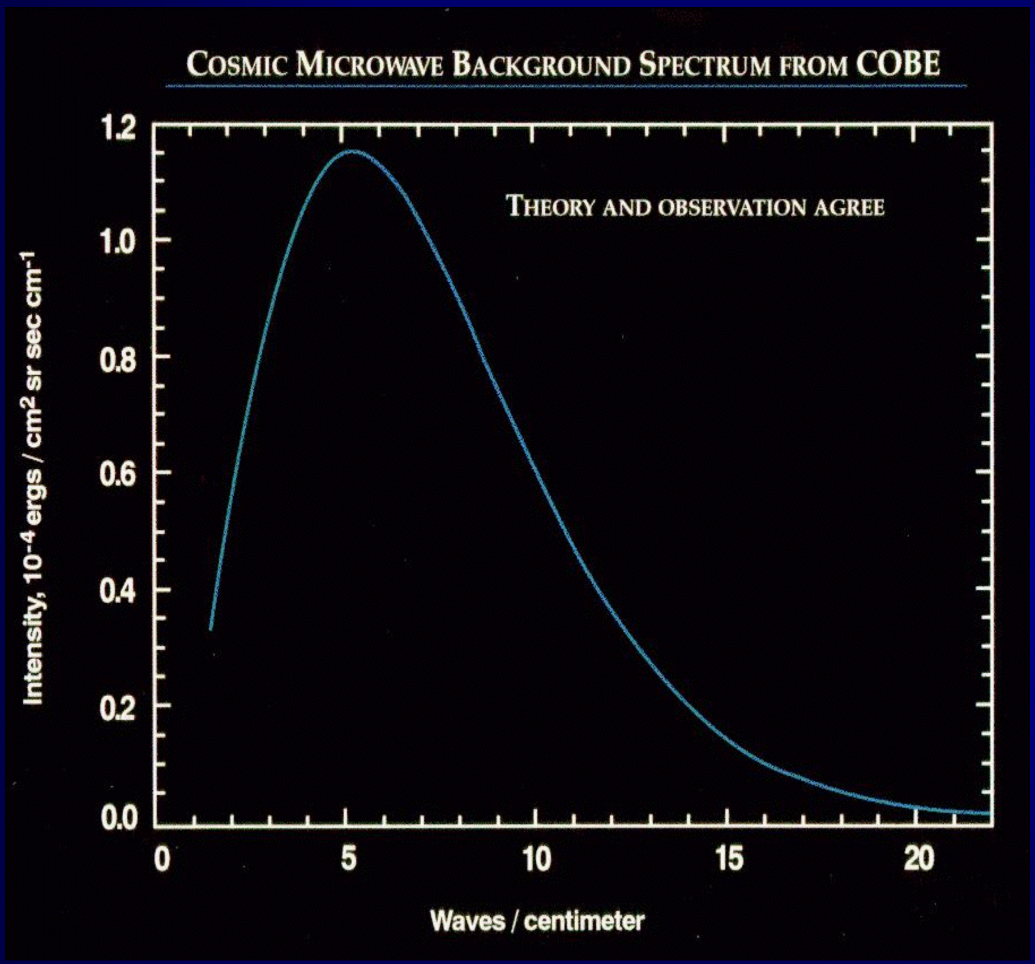
Outline

- Summary of the constraints on topological defects
- Elements on Inflation
- Motivation
- Cosmic superstring formation
- Evolution of cosmic superstring networks
- Observational consequences
- Open questions
- Conclusions

Summary of the constraints on topological defects

The Universe is homogeneous and isotropic on large scales

CMB radiation : Perfect black body spectrum of cosmic photons



$$T_\gamma = 2.728 \pm 0.004\mathrm{K}$$

Gamov (1946)

Penzias & Wilson (1965)

The CMB photons have not only a very thermal spectrum, but they are also distributed very isotropically.

COBE DMR (1992)

Isotropy of 3K CMB:

a relic of the plasma of baryons, electrons and radiation at times before protons and electrons combined to hydrogen.

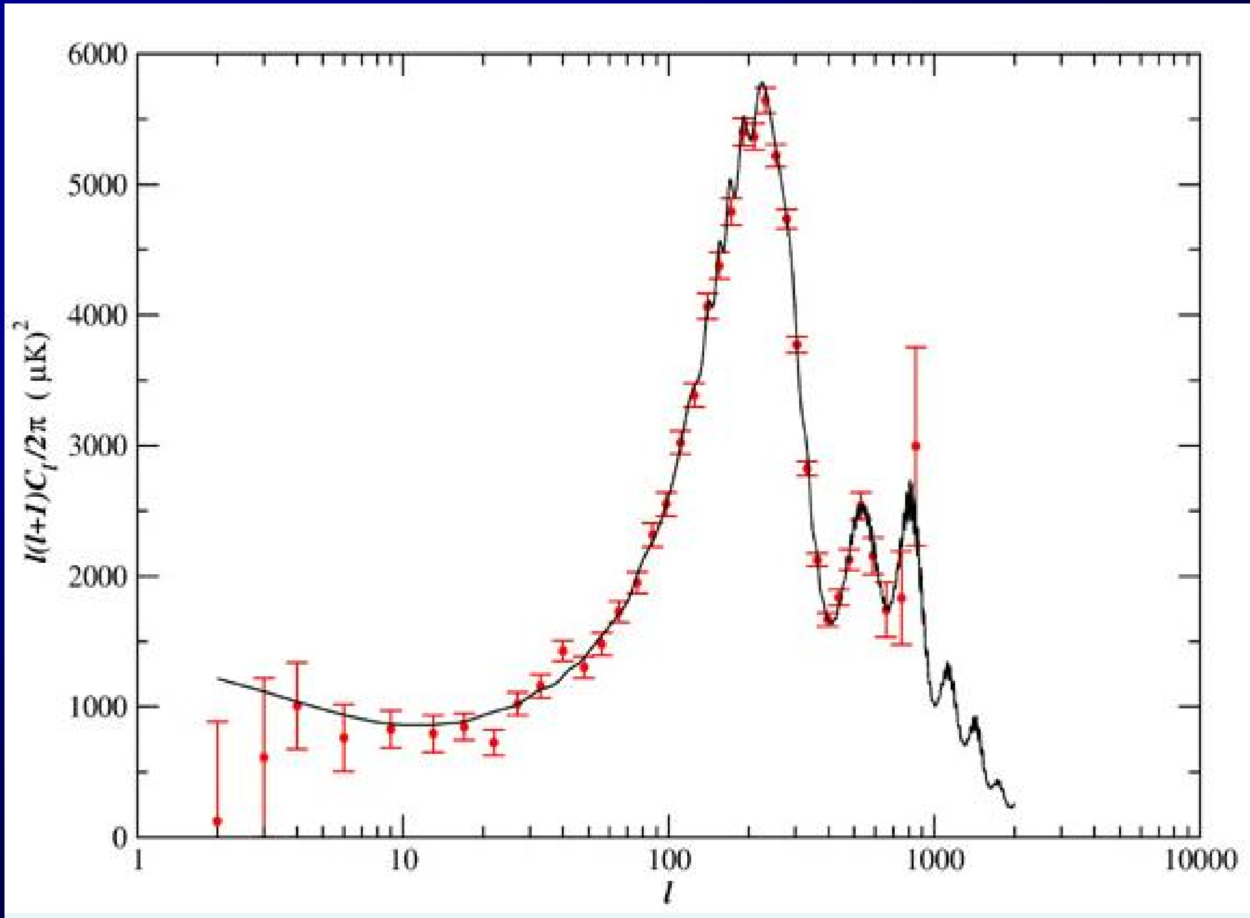
WMAP:

The CMB has distinct peaks in its temperature angular power spectrum

1st peak at $\ell = 220.1 \pm 0.8$ with amplitude $74.7 \pm 0.5\mu\mathrm{K}$

2nd peak at $\ell = 546 \pm 10$ with amplitude $48.8 \pm 0.9\mu\mathrm{K}$ Hinshaw et al (2003)

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



Theoretical models of structure formation:

Within the theory of gravitational instability, initial density perturbations can be either

- induced by quantum fluctuations of a scalar field at the end of an inflationary era,

or

- they can be triggered by seeds, as for example a class of topological defects, which could have formed during phase transitions, followed by SSB, in the early universe.

Topological defects

Consider SSB: $\mathrm{G} \longrightarrow \mathrm{H}$, with $\mathrm{H} \subset \mathrm{G}$

Defect formation during SSB depends on the homotopy groups $\pi_k(G/H)$ of the vacuum maniford $\mathcal{M} = G/H$

If $\pi_k(G/H) \neq I$ then $(2-k)-$ dim defects appear

Gauge defects

Monopoles $(k=2)$ or domain walls $(k=0)$ are ruled out (incompatible with our universe, except if inflation took place after their formation)

Textures are irrelevant $(k=3)$ (their relative contribution to the energy density of the universe decreases rapidly with time)

Turok (1989)

Cosmic strings ! $(k=1)$

Global defects

Global defects: The first peak is shifted to $l \sim 350$ with an amplitude ~1.5 times higher than the Sachs-Wolfe plateau.

Durrer, Gangui & Sakellariadou, PRL **76** (1996) 579

Local Cosmic Strings: Predictions range from an almost flat spectrum to a single wide bump at $l \sim 500$ with extremely rapidly decaying tail.

Allen et al (1997) ; Contaldi, Hindmarsh & Magueijo (1999)

Topological defects: non-Gaussian statistics for the CMB.

Inflation: if the quantum fluctuations of the inflaton field are in the vacuum state, then the statistics of the CMB is Gaussian.

IF you introduce a built-in characteristic scale, the four-point correlation function does NOT satisfy Gaussian statistics, but the signal is undetectable (|S/N|~ 4/10000).

Martin, Riazuelo & Sakellariadou, PRD **61** (2000) 083518; Gangui, Martin & Sakellariadou, PRD **66** (2002) 083502

Topological defects are ruled out as the unique source of the CMB temperature anisotropies.

Questions

Are topological defects completely ruled out ?

Can we have mixed models ?

How generic is defects formation ?

Which are the implications for GUTs ?

Which model of inflation ?

. . .

- Within SUSY GUTs, cosmic strings are generically formed at the end of standard hybrid inflation.

$$G_{GUT} \rightarrow H \rightarrow \ldots \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times Z_2$$

Jeannerot, Rocher & Sakellariadou PRD **68** (2003) 103514

- Cosmic strings contribute up to ~10% to the CMB measurements.

Bouchet, Riazuelo, Peter & Sakellariadou PRD**65** (2001) 021301

Pogosian, Wyman, Wasserman, astro-ph/0403268

- Cosmic strings at the GUT scale are consistent with CMB data.

Rocher & Sakellariadou, hep-ph/0406120 (2004)

- Cosmology sets constraints on the free parameters (mass scales and couplings) of the SUSY/SUGRA models.

Rocher & Sakellariadou, hep-ph/0412143

Four pillars of the standard Hot Big Bang model

- Expansion of the Universe
- Origin of the Cosmic Background Radiation
- Synthesis of light elements
- Formation of galaxies and large-scale structure

But ...

Shortcomings of the standard Hot Big Bang Model

- Flatness problem
- Horizon problem
- Density fluctuations
- Exotic relics
- Cosmological constant
- Singularity problem

Solution ???

Inflation

Guth (1981)

Era of repulsive gravity $\ddot{a} > 0 \longleftrightarrow 3p < -\rho$

The fluid dominating the matter content of the Universe must have $p < 0$

During inflation the energy density and pressure are dominated by a scalar field with:

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi) \qquad p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

If $V(\phi) \gg \dot{\phi}^2$ one obtains $p \simeq -\rho \rightarrow \rho < 0$

Energy conservation: $\dot{\rho} + 3\frac{\dot{a}}{a}(\rho + p) = 0 \rightarrow \rho$ is constant

$\rightarrow H_{\rm infl}$ is constant and $a(t) \propto \exp(H_{\rm infl} t)$

The evolution of the inflaton field ϕ is: $\boxed{\ddot{\phi} + 3H\dot{\phi} = -\frac{\mathrm{d}V}{\mathrm{d}\phi}}$

Inflation

But ...

It is difficult to implement inflation in High Energy Physics (the inflaton potential coupling constant must be low in order to reproduce the CMB data).

...

Only certain special initial conditions eventually lead to successful inflationary cosmologies. These initial conditions may be the likely out-come of quantum events before the inflationary era (?).

Calzetta & Sakellariadou, PRD **45** (1992) 2802

Calzetta & Sakellariadou, PRD **47** (1993) 3184

Which kind of inflationary scenario should one prefer?

Cosmic Superstrings: Motivation

Extra dimensions

Which is the origin of the inflaton and its potential ?

Superstring theory → Brane world scenario

SM of strong & EW interactions are open string (brane) modes, while the graviton & radions are closed string (bulk) modes.

Light scalar modes :

- ~~bulk modes like radions (sizes/shape of compactified dimensions) and the dilaton (coupling)~~ Gravitational strength couplings, which is too weak for reheating.
- brane positions (or relative brane positions)
- ~~tachyonic modes~~ They roll down the potential too fast for inflation.

Brane inflation scenario : the inflaton is an open string mode , identified with the inter-brane separation & the inflaton potential emerges from exchange of closed string modes between branes.

Dvali & Tye, hep-ph/9812483

End of brane inflation : As branes come closer due to an attractive potential, open string modes stretching between branes contribute strongly to the inflaton potential. At a critical distance $\sim M_{\rm s}^{-1}$ open string modes become tachyonic, slow-roll breaks and inflation ends.

Inter-brane interactions

Brane-antibrane collision : not very likely (too steep potential to give slow roll)

probability to have sufficient inflation $\boxed{\mathcal{P} \sim (3\%)^{d_\perp}}$ $d_\perp$:# of large extra dim

Jones, Stoica & Tye, hep-th/0203163

There are at least 3 solutions:

- Inflation between branes in a warped throat

  (the warp factor can flatten the potential)

- D-term inflation

  (the inflaton gets a mass only through loop effects, so $\eta = M_{\rm Pl}^2 \frac{V''}{V} \ll 1$)

  e.g., D3/D7 inflationary scenario

- Brane collision at angles

  the inter-brane potential depends on the angle (~θ^3)

T-duality

$\boxed{\mathcal{P}(\theta) \propto \theta^{-d_\perp}}$ $\Longrightarrow$ for $\theta \leq 1/10:$ $\boxed{\mathcal{P}(\theta) \simeq 1}$

Jones, Stoica & Tye, hep-th/0203163

Buchan, Shlaer, Stoica & Tye, hep-th/0311207

Formation

Tachyonic instability $\longleftrightarrow$ Symmetry breaking patterns

Vacuum manifold $\mathcal{M}$ is isomorphic to $U(N)$

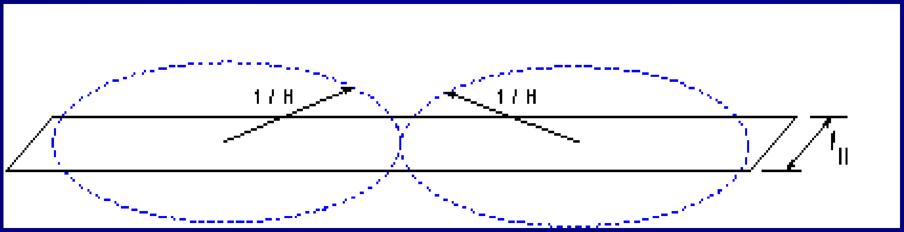
$$\pi_i(U(N)) = Z \quad \text{if} \quad i = 2k-1$$

when $i < 2N$

$\Rightarrow$ Codimension of defects: $d = 2k$

$\boxed{D(p-2k) \text{ -branes inside } Dp\text{-branes}}$

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



Kibble mechanism is uncompactified dim=3 $\Rightarrow$ $d = \cancel{1}, 2, \cancel{3}$ even

Sarangi & Tye, hep-th/0204074

$\boxed{D(p-2)\text{-branes are seen as COSMIC SUPERSTRINGS for a 3dim observer.}}$

They extend in one large dim and are wrapped on the same small dim

Remark:

The size of the compact dimensions is orders of magnitude smaller than the Hubble distance at inflation $\Longrightarrow$ there are no causally disconnected regions along the compact dimensions $\Longrightarrow$ the production of monopole-like and domain wall-like defects is suppressed.

Superstring density:

About one superstring per Hubble volume ?

Not really…

o 1 defect per Hubble volume is only a lower bound via causality

o The effective FT which describes the dynamics of the tachyon has an unusual causal structure and Kibble mechanism may not apply.

Using Shen's effective FT description:

Due to the suppression of gradient energy in the tachyon action, defects form with a correlation length proportional to $M_{\rm str}^{-1}$ rather than H^{-1} .

Barnaby, Berndsen, Cline & Stoica, hep-th/0412095

Tachyon potential: $V(T) = \tau_p \ \exp(-T^2/b^2)$

τ_p is the $Dp-$brane tension and b determines the tachyon mass $M_T = \sqrt{2}\, b^{-1}$

Once the field starts rolling, it continues rolling towards $T = \pm\infty$

The gradient force is insufficient to stop or reverse the rolling.

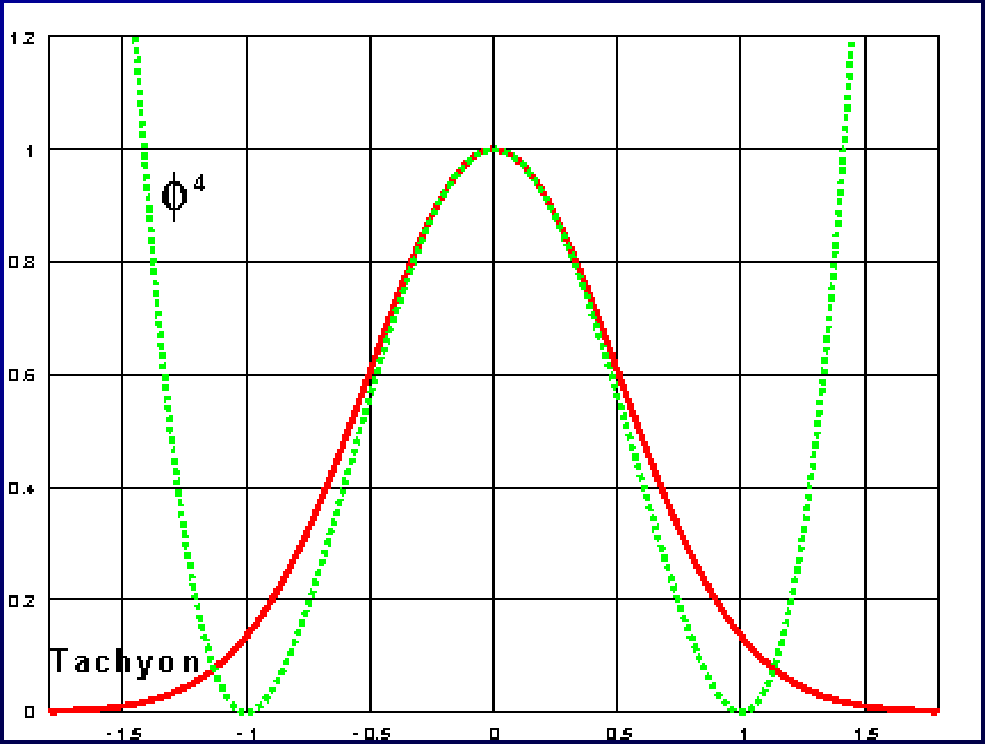
The Hubble damping plays no role in determining final string density.

ϕ^4 potential:

$$\frac{\lambda}{4}(|\phi|^2 - \sigma^2)^2$$

Oscillations of the field can restore symmetry and wipe out defects.

The string density depends on how fast oscillations are damped, either through Hubble expansion, or through coupling of $|\phi|$ with other fields.

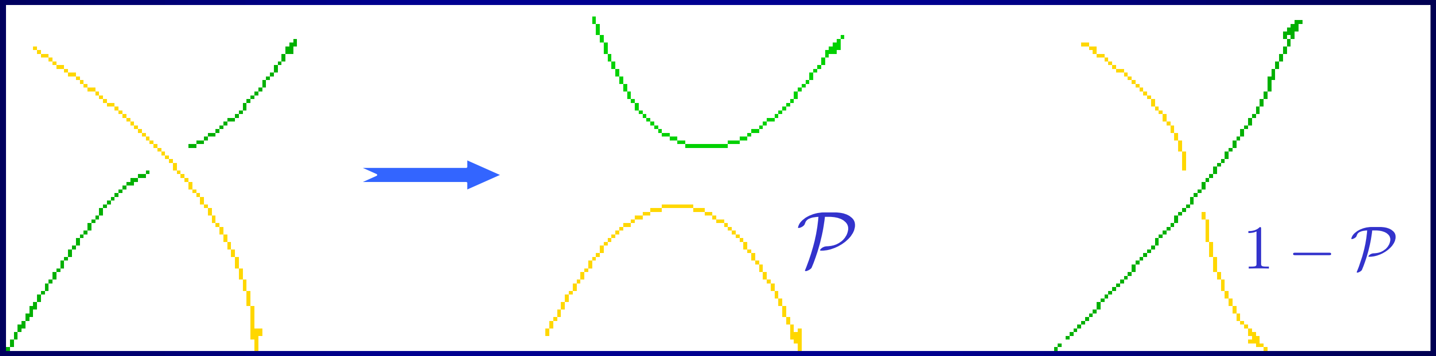


Evolution

Brane annihilation $\longrightarrow$ independent stochastic networks of Dirichlet (D) and fundamental (F) strings.

String/Superstring collisions

$\mathcal{P}$: reconnection probability



- Gauge theory solitons: $\mathcal{P}=1$ exactly
- FF-strings: $\mathcal{P}=\mathcal{O}(g_s^2) \longrightarrow 10^{-3} \leq \mathcal{P} \leq 1$
- DD-strings: $0.1 \leq \mathcal{P} \leq 1$ $\qquad \mu_{\rm D} = \mu_{\rm F}/g_{\rm S}$
- FD-strings: $0 \leq \mathcal{P} \leq 1$

Jackson, Jones & Polchinski , hep-th/0405229

[collisions between pairs of superstrings in string perturbation theory]

Evolution of cosmic superstrings networks as a function of $\mathcal{P}$:

Numerical study

Sakellariadou & Vilenkin, PRD**42** (1990) 349
Sakellariadou, hep-th/0410234

Initial string configuration:

- Monte Carlo algorithm — Vachaspati & Vilenkin, PRD**30** (1984) 2036
- Long winding strings and a loop gas — Sakellariadou, NPB**468** (1996) 319

Evolution: Discretise the Nambu eqs of motion in Minkowski space

The long strings are characterised by a single length scale:

$$\boxed{\xi(t) = \left(\frac{\rho_{\mathrm{l}}}{\mu}\right)^{-1/2}}$$

ρ_{l} energy density of long strings

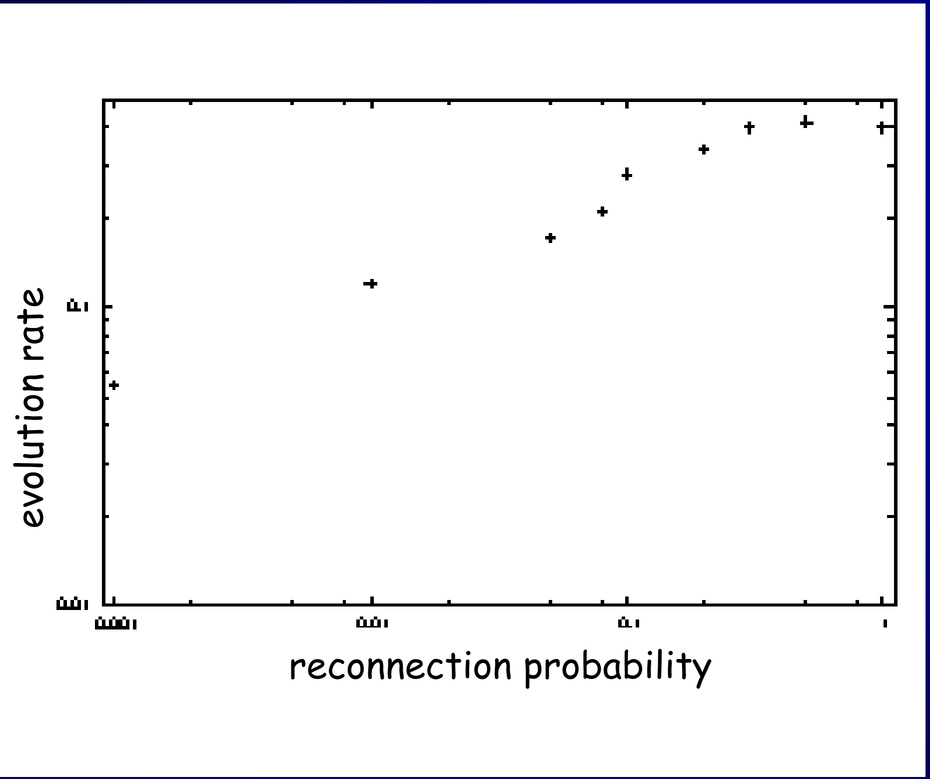
μ linear lass density = string tension

Typical distance between nearest string segments and typical curvature of strings are both of the order of ξ .

Evolution of characteristic length ξ as a function of evolution time t:

$$\boxed{\xi \propto \zeta t}$$

The slope ζ depends on the reconnection probability $\mathcal{P}$ and on the energy cutt-off.



For $\mathcal{P} \in [10^{-3}, 0.3]$ a good fitting is:

$$\boxed{\zeta \propto \sqrt{\mathcal{P}} \quad \Rightarrow \quad \xi(t) \propto \sqrt{\mathcal{P}}\, t}$$

Sakellariadou, hep-th/0410234

[Disagreement with

Dvali & Vilenkin, JCAP**0403** (2004) 010

and Jones, Stoica & Tye PLB**563** (2003) 6]

A long string of length l moving with velocity u in a box of size D, it sweeps out a surface $lu(\Delta t)/D^2$ in a unit time interval Δt .

$$l = D \equiv L$$

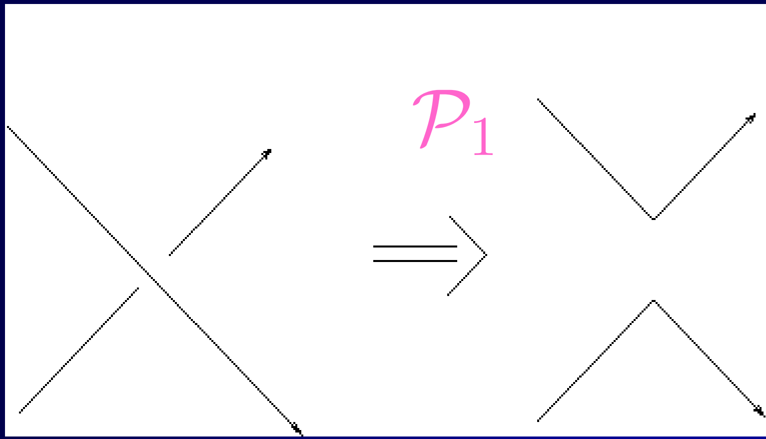
The number of collisions per unit time interval Δt between two long strings is $(u/L)N$; N is the number of long strings is the volume.

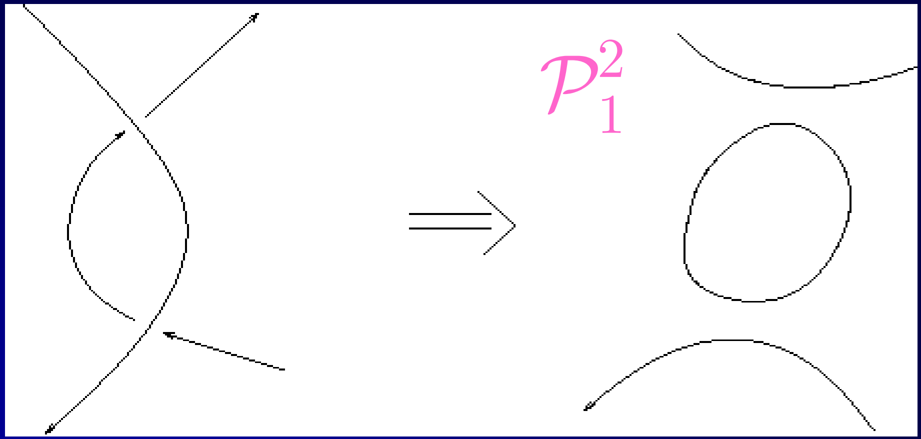
⇒ The number of intercommutations for relativistic strings per unit time and per unit volume is: $\mathcal{P}N(1/L)(1/L^3)$

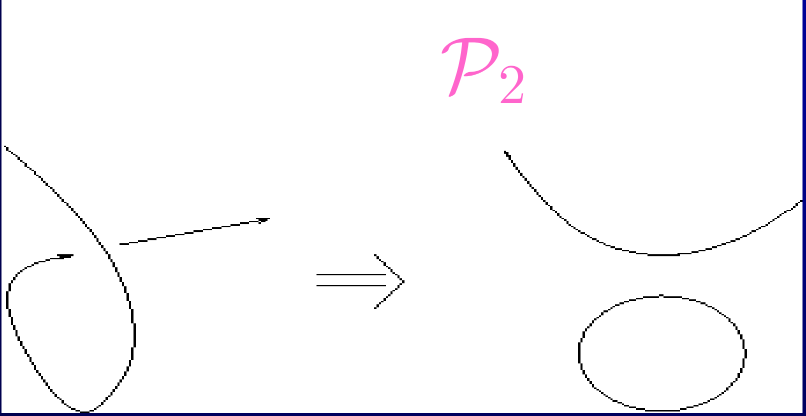
$\mathcal{P}$: Intercommutation probability per string intersection

but intersections between two long strings do not, in principle, chop off loops !

<u>String intersections:</u>







Efficient way of forming loops and dissipating energy

Two components characterise the network:

- A few long strings with a scale-invariant evolution;

the curvature radius of long strings and the typical separation between two long strings are both comparable to the horizon size $\boxed{\xi(t) \simeq \sqrt{\mathcal{P}}t}$

- A large number of small closed loops with sizes $\ll t$

asymptotic energy density of long strings: $\rho_{\rm l} = \frac{\mu}{\mathcal{P}t^2}$

The effect of extra dim is to increase the energy density of strings (but the enhancement is less than what it was originally believed)

RDE: $$\boxed{\frac{\rho_{\rm strings}}{\rho_{\rm total}} = \frac{32\pi}{3}\,\frac{G\mu}{\mathcal{P}}}$$

The role of velocities in the extra dimensions:

- Gauge theory solitons: $u^2 \leq \frac{1}{2}$ (for expanding universe)
- Cosmic superstrings: $u_e^2 + u_c^2 \leq \frac{1}{2}$

u_e : rms peculiar velocities in the 3 expanding directions

u_c : rms peculiar velocities in (D-3) compact directions

u_e^2: redshifted due to expansion

u_c^2: very weakly damped

If the strings are created with significant velocities in the extra dimensions, these will survive for a long time and will act to slow down string motion in the tree infinite dimensions.

Dangerous possibility: velocities in the extra dim accumulate and dominate while string motion in the three infinite dim comes to an halt and superstrings are no longer able to intercommute.

Augoustidis & Shellard, hep-ph/0410349

The role of extra dim on the shape of superstrings

The metric $$\boxed{ds^2 = dt^2 - a(t)[dx^i_{\rm e}]^2 - b(t)[dx^j_{\rm c}]^2}$$

$$i = 1, 2, 3 \quad ; \quad j = 4, 5, ..., D$$

is not in general isotropic $\Rightarrow$ the Brownian initial structure of the superstrings is not preserved by the evolution.

Augoustidis & Shellard, hep-ph/0410349

Unless:

- isotropic expansion corresponding to a generalised (D+1)-dim FLRW
- the formation of the string network is localised on an isotropic slice (e.g. brane inflation)

Focus on the isotropic case.

The role of extra dim on the loop production parameter $\tilde{c}$

- 3-dim: a string segment of size L travels a distance L before encountering another segment and interacting with it in a volume L^{-3}

$f(l/L)$: probability to produce a loop of length $(l, l+dl)$

Energy loss due to loop production

$$\boxed{\dot{\rho}_{\rm loops} = -\frac{u\rho}{L}\int_0^\infty \frac{dl}{L} f(l/L) \equiv -\frac{\tilde{c}u\rho}{L}}$$

Augoustidis & Shellard, hep-ph/0410349

- $D > 3$: string segments do not interact after moving distance L .

Energy loss due to loop production

$$\boxed{\dot{\rho}_{\rm loops} = \frac{\tilde{c}u\rho}{L}\left(\frac{\delta}{L}\right)^{D-3}}$$

δ capture radius (thickness)

Is there scaling?

Scaling regime: the characteristic length stays constant relative to horizon $\xi \sim d_{\rm H} \sim t$ (cosmic strings)

But …

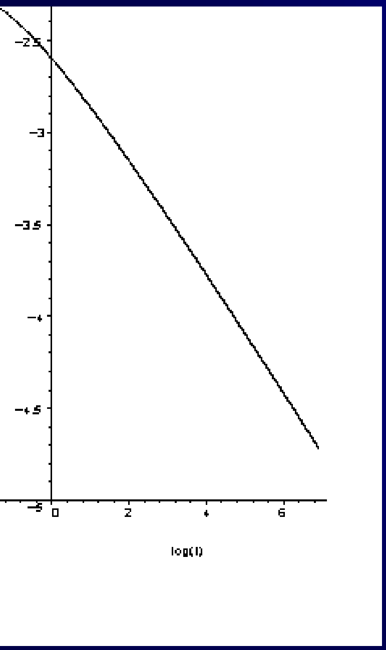
Higher dim space : $\boxed{D > 3}$

- $\rho \propto 1/\xi^{D-1}$

The energy density decreases faster (more expanding dim)

- The loop production parameter is much smaller

(it is harder two strings to find each other and intercommute)



Hint that ζ decreases with time meaning that there is no scaling and the superstrings will dominate the universe.

Augoustidis & Shellard, hep-ph/0410349

Observational consequences

Oscillating strings loose energy by emitting graviton, dilaton and Ramond-Rammond fields.

- Gravity waves:

Smaller $\mathcal{P}$ increases GW amplitude of bursts emitted by cusps of strings in LIGO/VIRGO frequency band.

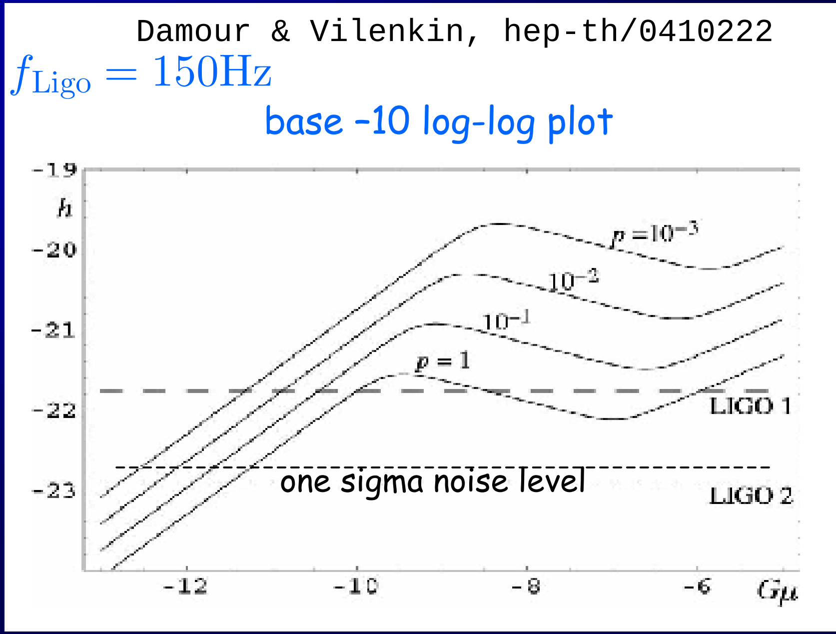
For a given $G\mu$: for $\mathcal{P} \sim 10^{-3}$

we gain an order of magnitude in

the GW amplitude h of bursts emitted

by string cusps

Damour & Vilenkin, hep-th/0410222



- Dilaton field:

String theory predicts the existence of light gauge-neutral scalar fields with gravitational-strength couplings to ordinary matter.

Oscillating loops of cosmic strings will copiously emit dilatons.

Damour & Vilenkin, gr-qc/9610005

Put constraints on the energy scale of strings from the observational bounds on dilaton decay.

For a dilaton mass $m_\phi \sim 1\mathrm{TeV}$ and lifetime $10^7 s \leq \tau_\phi \leq t_{\rm dec}$

$$\Longrightarrow \boxed{G\mu \leq \mathcal{P}^{-2/3}\ 10^{-16} \Rightarrow T_{\rm c} \leq \mathcal{P}^{-1/3}\ 10^{11}\mathrm{GeV}}$$

Sakellariadou, hep-th/0410234

Open questions

- Is there scaling ?
- Is gravitational radiation an efficient mechanism to damp small scale wiggles?

Vincent, Hindmarsh & Sakellariadou, PRD**56** (1997) 637

Vincent, Antunes & Hindmarsh, PRL**80** (1998) 2277

- Which is the average number of cusps per loop oscillation?
- Are the cosmic superstrings superconducting?
- Which are the observational signatures in angular spectrum of CMB anisotropies and in gravitational lensing?
- What about FD networks?

...

Conclusions

In string theory there are fundamental (F) strings and
D-branes of all dim

In models with large compact dim, the string tension
is anything between the Planck scale and the weak scale

→ F-strings of macroscopic length are not ruled out.

Dp-brane collision leads to the formation of D-strings, which
are D(p-2) branes wrapping the (p-3)dim compactified space.

F- and D-strings share some common features with gauge
theory soliton strings but they also differ in some aspects

→ Cosmic superstrings might be distinguishable.