# **Cosmic Superstrings**

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Cosmic superstrings are expected to be formed at the end of brane inflation, within the context of brane-world cosmological models inspired from string theory. By studying properties of cosmic suprestring networks, and comparing their phenomenological consequences against observational data, we aim at pinning down the successful and natural inflationary model and get an insight into the stringy description of our universe.

Keywords: Cosmic superstrings, F/D strings, (p,q)-bound states, brane inflation

## 1. Introduction

Inflation was proposed (Guth 1981; Linde 1982) in the eighties as a simple and elegant solution to the shortcomings of the hot big bang model. Inflation provides a solution to the flatness and horizon problems within the framework of quantum field theory and general relativity, while it dilutes any undesired relics (e.g., monopoles) from possible extensions of the standard model. Inflation essentially consists of a phase of accelerated expansion which took place at a very high energy scale. Thus, by construction, inflation can liberate the standard model of cosmology (i.e., the hot big bang model) from the requirement of special initial conditions. In addition, amplification of the quantum fluctuations of the inflaton field, which drives inflation, offers a simple mechanism for the origin of the initial density fluctuations, which via gravitational instability could lead to the observed structure formation. The remarkable agreement of the inflationary induced temperature fluctuations in the Cosmic Microwave Background (CMB) radiation with all current measurements is with no doubt an element which strongly supports inflation.

Even though inflation provides a robust field theoretic mechanism which answers the shortcomings of the hot big bang model and is in a surprising agreement with CMB experiments, it still lacks a precise theoretical model. In this sense, inflation still remains a paradigm in search of a model. One should keep in mind that an inflationary model should be considered as successful when not only it fits the data, but in addition it can be accommodated within (or even motivated by) some fundamental theory (e.g., string theory).

In the context of supersymmetric grand unified theories, the most natural inflationary model is that of hybrid inflation (Linde 1994). In this context, a detailed study (Jeannerot, Rocher & Sakellariadou 2003) of all Spontaneously Symmetry Breaking (SSB) schemes which bring — by one or more intermediate steps — the initial symmetric state of the universe, described by a large grand unified theory gauge group, down to a less symmetric state, described by the standard model gauge group, has shown that cosmic strings are generically formed at the end of hybrid inflation (Sakellariadou 2008). Actually, in general such inflationary models require the formation of cosmic strings so that inflation can indeed end (i.e., graceful exit). Thus, cosmic strings have to be considered as a sub-dominant partner of inflation, and contribute (Bouchet *et al.* 2002) to the CMB temperature anisotropies.

Current CMB data impose strong constraints in the maximum allowed contribution of cosmic strings. More precisely, cosmic strings can contribute at most 11% (Bouchet *et al.* 2002; Wyman *et al.* 2005; Bevis *et al.* 2008) to the power spectrum of temperature anisotropies. This upper limit implies a constrain in the string tension and therefore the energy scale of the phase transition accompanied by SSB which left behind cosmic strings as false vacuum remnants. Equivalently, one can impose (Rocher & Sakellariadou 2005a,b, 2006) constraints on the parameter space (couplings and mass scales) of the inflationary model (F-term, D-term or P-term inflation). Cosmic strings formed in this way are sometimes referred to as F-term or D-term strings, if produced at then end of F- or D-term hybrid inflation, respectively<sup>†</sup>.

Inflation must also prove itself generic, in the sense that the onset of inflation must be independent of initial conditions. The first studies (Piran 1986; Goldwirth 1991; Calzetta & Sakellariadou 1992, 1993) addressing the onset of inflation were inconclusive, in the sense that no robust conclusions could be drawn as a quantum theory of gravity was missing. More recently, it has been shown (Germani, Nelson & Sakellariadou 2007) that successful single-field inflation with a polynomial potential is highly improbable within the semi-classical regime of loop quantum cosmology<sup>‡</sup>. Inflation must be addressed in full quantum gravity, or in a string theory context.

It is at present widely believed that string theory is the fundamental theory of all matter and forces, including a consistent quantum gravity sector. If this is the case, then there must exist a natural inflationary scenario within string theory. Such an approach will allow the identification of the inflaton and the determination of its properties, while at the same time cosmological measurements will provide insight into the stringy description of our universe. Since the *discovery* of Dirichlet (D) branes, a natural realisation of our universe in string theory is the brane-world scenario. In this context, a simple, realistic and well-motivated inflationary model is brane inflation, where inflation takes place while two branes move towards each other, and their annihilation releases the brane tension energy that heats up the universe to start the hot big bang era. Typically, strings of all sizes and types may be produced during the collision. Large Fundamental (F) strings and/or D1-branes (D-strings) that survive the cosmological evolution become cosmic superstrings. By observing strings in the sky, we will be able to test, for the first (and maybe only) time, string theory.

Cosmic strings and superstrings — thought for a long time completely disconnected — seem to be closely related, while inflation and topological defects considered for many years either as incompatible or as competing aspects of modern cosmology — must re-conciliate.

In what follows, I will highlight the most important properties of cosmic superstrings. I will first describe briefly the formation of cosmic superstrings at the end of

<sup>&</sup>lt;sup>†</sup> One should not *identify* them with the Fundamental (F) strings or the one-dimensional Dirichlet branes (D-strings), respectively.

<sup>&</sup>lt;sup>‡</sup> The probability to have an inflationary era with sufficient number of e-folds, is exponentially suppressed (Gibbons & Turok 2006) in the context of standard general relativity.

brane inflation. I will then discuss the differences between cosmic superstrings and their solitonic analogues, which arise in gauge theories. After a short review of the evolution of Goto-Nambu cosmic strings, I will summarise the current *understanding* of the evolution of cosmic superstring networks. This issue is far from being resolved. The characteristics of the superstring network are strongly dependent on the specific brane inflationary model, while a realistic modelling through numerical simulations is particularly complex. Finally, I will discuss the observational signatures of cosmic strings/superstrings. This is a very promising area of research, since it may give us the (*unique*) way of testing string theory as a realistic theory of nature. There is a large number of open directions which need to be thoroughly investigated and I will briefly mention them.

One should keep in mind that we are working in the context of type II string theory.

## 2. Cosmic superstring formation

The possible astrophysical rôle of fundamental strings has been advocated already more than twenty years ago. More precisely, it has been proposed (Witten 1985), that superstrings of the O(32) and  $E_8 \times E_8$  string theories are likely to generate string-like stable vortex lines and flux tubes. However, in the context of perturbative string theory, the high tension (close to the Planck scale) of fundamental strings ruled them out (Witten 1985) as potential cosmic string candidates, for the following three reasons. Firstly, such heavy strings would produce CMB inhomogeneities far larger than the ones which have been measured. Secondly, such high tension strings could not have been produced after inflation, since the scale of their tension is higher than the upper bound on the energy scale of the inflationary vacuum. However, any topological defects produced before inflation would have been diluted. Indeed, one of the reasons for which inflation was suggested is to dilute unwanted *beasts* of the zoo of topological defects; historically, inflation was introduced to dilute monopoles. Thirdly, some instabilities were identified, implying that such strings would not be able to survive on cosmologically interested time-scales.

This picture has changed in the framework of brane-world cosmology, which offers an elegant realisation of nature within string theory. Within the brane-world picture, all standard model particles are open string modes. Each end of an open string lies on a brane, implying that all 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. Closed string modes (e.g., dilaton, graviton) live in the high-dimensional bulk. Since gravity has been probed only down to scales of about 0.1mm, the dimensions of the bulk can be much larger than the string scale. In the brane-world context, the extra dimensions can even be infinite, if the geometry is non-trivial and they are warped. As a result of brane interactions, higher dimensional Dp-branes unwind and evaporate so that we are left with D3-branes embedded in a (9+1)-dimensional bulk. One of these D3-branes could play the rôle of our universe (Durrer, Kunz & Sakellariadou 2005). Cosmic superstrings are also left behind.

Inflation can be easily accommodated in a string theory motivated cosmological model. String theory *lives* in a high-dimensional space, so compactification down to four space-time dimensions introduces many gravitationally-coupled scalar fields – moduli – from the point of view of the four-dimensional theory. One of these fields

could play the rôle of the inflaton, provided it does not roll quickly. Runaway or light moduli are extremely problematic in cosmology, so any realistic model should incorporate a mechanism for moduli stabilisation. Indeed, a number of different approaches have been followed (Giddings, Kachru & Polchinski 2002; Kachru *et al.* 2003; Kachru *et al.* 2003) and various successful inflationary models have been proposed within brane-world cosmology.

A correct brane inflation scenario will offer us valuable information on the early stages of our universe, as well as to the particular compactification in string theory. String inflation models can be classified according to the origin of the inflaton field. If the inflaton is a scalar field arising from open strings ending of a D*p*-brane (*p* stands for the dimensionality of the Dirichlet brane), then these open string models are called *D*-brane (or just brane) inflation models. If the inflaton field is a moduli (the most promising closed string modes), then these closed string models are called moduli or modular inflation.

Brane annihilations can also provide a natural mechanism for ending inflation. To illustrate the formation of cosmic superstrings at the end of brane inflation, let us consider a Dp-Dp brane-anti-brane pair annihilation to form a D(p-2)brane. Each parent brane has a U(1) gauge symmetry and the gauge group of the pair is  $U(1) \times U(1)$ . The daughter brane possesses a U(1) gauge group, which is a linear combination,  $U(1)_{-}$ , of the original two U(1)'s. The branes move towards each other and as their inter-brane separation decreases below a critical value, the tachyon field, which is an open string mode stretched between the two branes, develops an instability. The tachyon couples to the combination  $U(1)_{-}$ . The rolling of the tachyon field leads to the decay of the *parent* branes. Tachyon rolling leads to spontaneously symmetry breaking, which supports defects with even co-dimension. So, brane annihilation leads to vortices, D-strings; they are cosmologically produced via the Kibble mechanism. The other linear combination,  $U(1)_+$  disappears, since only one brane remains after the brane collision. The  $U(1)_+$  combination is thought to disappear by having its fluxes confined by fundamental closed strings. Such strings are of cosmological size and they could play the rôle of cosmic strings (Sarangi & Tye 2002; Jones, Stoica & Tye 2003; Dvali & Vilenkin 2004); they are referred to in the literature as cosmic superstrings (Polchinski 2005).

Cosmic strings were found to be generically formed at the end of inflation within supersymmetric grand unified theories. Likewise, cosmic superstrings are found to be generically produced towards the end of brane inflation. The undesired, and cosmologically catastrophic domain walls and monopole-like defects are not produced within the type of string theory we are considering; in type IIB string theory even dimensionality branes do not exist.

## 3. Differences between cosmic strings and cosmic superstrings

Solitonic cosmic strings are classical objects, which have been traditionally assumed to share the characteristics of type-II Abrikosov-Nielsen-Olesen (ANO) vortices (Abrikosov 1957; Nielsen & Olesen 1973) in the Abelian Higgs model. Cosmic superstrings, despite the fact that they are cosmologically extended, they are quantum objects. One thus expects differences in their properties, leading to a different behaviour, and thus to distinct observational signatures.

Over distances that are large compared to the width of the string, but small compared to the horizon size, solitonic cosmic strings can be considered as onedimensional objects and their motion can be well-described by the Nambu-Goto action. However, this action cannot be used to describe what happens when two strings intercommute; a study which necessitates full field theory. When two strings of the same type collide, they may either pass simply through one another, or they may reconnect (intercommute). A necessary, but not sufficient, condition for string reconnection is that the initial and final configurations be kinematically allowed in the infinitely thing string approximation. Such a classical string solution for reconnection has been shown to exist (Bettencourt & Kibble 1994), but the precise outcome of the string intersection depends on the internal structure of strings. Numerical simulations (and analytical estimates) of type-II (and weakly type-I) strings in the Abelian Higgs model suggest that the probability that a pair of strings will reconnect, after they intersect, is close to unity (Shellard 1987: Laguna & Matzner 1990). The results are based on lattice simulations of the corresponding classical field configurations in the Abelian Higgs model; the internal structure of strings is highly non-linear, and thus difficult to treat via analytical means. The only exception for which string reconnection probability was found to be different than one is the case of ANO strings with ultra-high collision speeds, in which case they just pass through each other. In particular, for near-perpendicular collisions the threshold speeds were found (Achúcarro & de Putter 2006) to be bounded above by  $\sim 0.97c$  for type I and  $\sim 0.90c$  for type II strings.

The reconnection probability for cosmic superstrings is smaller (often much smaller) than unity. The corresponding intercommutation probabilities are calculated in string perturbation theory. The result depends on the type of strings and on the details of compactification. For fundamental strings, reconnection is a quantum process and takes place with a probability of order  $g_s^2$  (where  $g_s$  denotes the string tension). It can thus be much less than one, leading to an increased density of strings (Sakellariadou 2005), implying an enhancement of various observational signatures. The reconnection probability is a function of the relative angle and velocity during the collision. One may think that strings can miss each other, as a result of their motion in the compact space. Depending on the supersymmetric compactification, strings can wander over the compact dimensions, thus missing each other, effectively decreasing their reconnection probability. However, it was found (Jackson, Jones & Polchinski 2005) that in realistic compactification schemes, strings are always confined by a potential in the compact dimensions. The value of  $g_s$  and the scale of the confining potential will determine the reconnection probability. Even though these are not known, for a large number of models it wass found (Jackson, Jones & Polchinski 2005) that the reconnection probability for F-F collisions lies in the range between  $10^{-3}$  and 1. The case of D-D collisions is more complicated; for the same models the reconnection probability is anything between 0.1 to 1. Finally, the reconnection probability for F-D collisions can vary from 0 to 1.

Brane collisions lead not only to the formation of F- and D-strings, they also produce bound states, (p, q)-strings, which are composites of p F-strings and q Dstrings (Copeland, Meyers & Polchinski 2004; Leblond and Tye 2004). The presence of stable bound states implies the existence of junctions, where two different types of string meet at a point and form a bound state leading away from that point. Thus, when cosmic superstrings of different types collide, they can not intercommute, instead they exchange partners and form a junction at which three string segments. This is just a consequence of charge conservation at the junction of colliding (p,q)-strings. For p = np' and q = nq', the (p,q) string is neutrally stable to splitting into n bound (p',q') strings. The angles at which strings pointing into a vertex meet, is fixed by the requirement that there be no force on the vertex.

The formation of three-string junctions (Y-junctions) and kinematic constraints for their collisions have been investigated analytically (Copeland, Kibble & Steer 2006, 2007; Copeland *et al.* 2007), under the assumption that each string evolves according to the Nambu-Goto action. Whether these results hold for cosmic superstrings, which carry fluxes of a gauge field and are therefore described instead by the Dirac-Born-Infeld (DBI) action, remains to be shown.

The tension of solitonic strings is set from the energy scale of the phase transition followed by a spontaneously broken symmetry which left behind these defects as false vacuum remnants. Cosmic superstrings span a whole range of tensions, set from the particular brane inflation model. The tension of F-strings in 10 dimensions is  $\mu_{\rm F} = 1/(2\pi\alpha')$ , and the tension of D-strings is  $\mu_{\rm D} = 1/(2\pi\alpha' g_{\rm s})$ , where  $g_{\rm s}$  stands for the string coupling. In 10 flat dimensions, supersymmetry dictates that the tension of the (p, q) bound states reads (Schwarz 1995)

$$\mu_{(p,q)} = \mu_{\rm F} \sqrt{p^2 + q^2/g_{\rm s}^2} . \qquad (3.1)$$

Individually, the F- and D-strings are  $\frac{1}{2}$ -BPS (Bogomol'nyi-Prasad-Sommerfield) objects, which however break a different half of the supersymmetry each. Equation (3.1) represents the BPS bound for an object carrying the charges of p F-strings and q D-strings. In IIB string theory, our universe can be described as a brane-world scenario with flux compactification. In this context, the standard model particles are light open string modes in a warped throat of the Calabi-Yau manifold. The string tension for strings at the bottom of a throat is different from the (simple) expression given in Eq. (3.1). The formula for tension depends on the choice of flux compactification. For example, for the Klebanov-Strassler throat (Klebanov & Strassler 2000), inside which the geometry is a shrinking  $S^2$  fibered over a  $S^3$ , the tension of the bound state of p F-strings and that of q D-strings reads (Herzog & Klebanov 2002; Hartnoll & Portugues 2004; Gubser, Herzog & Klebanov 2004)

$$\mu_{\rm F_1} \simeq \frac{h_{\rm A}^2}{2\pi\alpha'} \sin\left(\frac{\pi p}{M}\right) \text{ and } \mu_{\rm D_1} \simeq \frac{h_{\rm A}^2}{2\pi\alpha'} \frac{q}{g_{\rm s}},$$
(3.2)

respectively, where p, q are integers,  $h_A$  is the warp factor at the bottom of the throat, b = 0.93 is a number of the order of unity, and M denotes the number of fractional D3-branes. The tension formula for the (p, q)-bound states reads (Firouz-jahi, Leblond & Tye 2006)

$$\mu_{p,q} \simeq \frac{h_{\rm A}^2}{2\pi\alpha'} \sqrt{\frac{q^2}{g_{\rm s}^2} + \left(\frac{bM}{\pi}\right)^2 \sin^2\left(\frac{\pi p}{M}\right)} \ . \tag{3.3}$$

For  $M \to \infty$  and  $b = h_A = 1$ , Eq. (3.3) reduces to Eq. (3.1).

Type-I vortices in the Abelian Higgs model can also have three-vertex junctions and a range of tensions (Donaire & Rajantie 2006), in this way they have more similarities with cosmic superstrings. However, cosmic superstrings are the only ones to have the integer-valued charges p and q. Thus, cosmic superstrings can, at least in principle, be distinguished from gauge theory strings.

## 4. Evolution of cosmic string/superstring networks

Let me first summarise our understanding of the evolution of cosmic string networks (Sakellariadou 2007). Knowing the differences between cosmic strings and cosmic superstrings, it is at least in principle *easy* to identify possible deviations between the evolution of the two networks.

The first studies of the evolution of a cosmic string network were analytical. They have shown (Kibble 1985) the existence of *scaling*, where at least the basic properties of the string network can be characterised by a single length scale, roughly the persistence length or the inter-string distance  $\xi$  which grows with the horizon. This is a key property for cosmic strings since it renders them cosmologically acceptable; a crucial difference between cosmic strings and monopoles or domain walls. The scaling solution was supported by subsequent numerical work (Albrecht & Turok 1985, 1989). However, further investigation revealed dynamical processes, including loop production, at scales much smaller than  $\xi$  (Bennett & Bouchet 1989; Sakellariadou & Vilenkin 1990).

The energy density of super-horizon (*infinite*, or long) strings in the scaling regime is given (in the radiation-dominated era) by

$$\rho_{\rm long} = \kappa \mu t^{-2} , \qquad (4.1)$$

where  $\kappa$  is a numerical coefficient ( $\kappa = 20 \pm 10$ ). The sub-horizon loops, their size distribution, and the mechanism of their formation remained for years the least understood parts of the string evolution. Assuming that the super-horizon strings are characterised by a single length scale  $\xi(t)$ , one gets

$$\xi(t) = \left(\frac{\rho_{\text{long}}}{\mu}\right)^{-1/2} = \kappa^{-1/2}t \ . \tag{4.2}$$

The typical distance between the nearest string segments and the typical curvature radius of the strings are both of the order of  $\xi$ .

Early numerical simulations have shown that indeed the typical curvature radius of long strings and the characteristic distance between the strings are both comparable to the evolution time t. Clearly, these results agree with the picture of the scale-invariant evolution of the string network and with the one-scale hypothesis. However, the numerical simulations have also shown (Bennett & Bouchet 1988; Sakellariadou & Vilenkin 1990) that small-scale processes (such as the production of small sub-horizon loops) play an essential rôle in the energy balance of long strings. The existence of an important small-scale (*wiggliness*) superimposed on the superhorizon strings was also evident by analysing the string shapes (Sakellariadou & Vilenkin 1990).

In response to these findings, a three-scale model was developed (Austin, Copeland & Kibble 1993) which describes the network in therms of three scales: the energy density scale  $\xi$ , a correlation length  $\bar{\xi}$  along the string, and a scale  $\zeta$  relating to local structure on the string. The small-scale structure (wiggliness), which offers an explanation for the formation of the small sub-horizon sized loops, is basically developed through intersections of long string segments. It seemed likely from the three-scale model that  $\xi$  and  $\bar{\xi}$  would scale, with  $\zeta$  growing slowly, if at all, until gravitational radiation became important when  $\zeta/\xi \approx 10^{-4}$  (Sakellariadou 1990; Hindmarsh 1990). According to the three-scale model, the small length scale may reach scaling only if one considers the gravitational back reaction effect. Aspects of the three-scale model have been checked (Vincent, Hindmarsh & Sakellariadou 1997) evolving a cosmic string network is Minkowski space-time. These string simulations found that loops are produced with tiny sizes, which led the authors to suggest that the dominant mode of energy loss of a cosmic string network is particle production and not gravitational radiation as the loops collapse almost immediately.

Recently, numerical simulations of cosmic string evolution in a Friedmann-Lemaître-Robertson-Walker universe, found evidence (Ringeval, Sakellariadou & Bouchet 2007) of a scaling regime for the cosmic string loops in the radiation- and matter-dominated eras down to the hundredth of the horizon time. It is important to note that the scaling was found without considering any gravitational back reaction effect; it was just the result of string intercommutations. The scaling regime of string loops appears after a transient relaxation era, driven by a transient overproduction of string loops with length close to the initial correlation length of the string network. Calculating the amount of energy momentum tensor lost from the string network, it was found (Ringeval, Sakellariadou & Bouchet 2007) that a few percents of the total string energy density disappear during a very brief process of formation of numerically unresolved loops, which takes place during the very first time-steps of the string evolution. Subsequently, two other studies supported these findings (Vanchurin, Olum & Vilenkin 2006; Martins & Shellard 2006). More recently, analytical studies (Polchinski & Rocha 2006, 2007; Bubath, Polchinski & Rocha 2007) confirmed the numerical results of Ringeval et al. (Ringeval, Sakellariadou & Bouchet 2007).

The evolution of cosmic superstrings is clearly a more involved problem. Cosmic superstring networks have not only sub-horizon loops and super-horizon strings, they also have Y-junctions. This complicates a lot the study of their evolution. In addition, one must consider a multi-tension spectrum and reconnection probabilities which can be much lower that unity. Certainly, computers are at present much more efficient than in the eighties and nineties when we performed the first numerical experiments with solitonic cosmic strings, and we obviously gained a lot of experience from those studies. Nevertheless, one must keep in mind that evolution of cosmic strings has been almost exclusively studied in the (simple) case of the infinitely thin approximation. So, even for the case of solitonic strings, the problem is so complex that all numerical experiments have been performed for the simplest (and probably, less realistic) models.

The evolution of a cosmic superstring network has very important consequences for the validity of the brane inflation model employed. The existence of Y-junctions may prevent a scaling solution. If such a network freezes, it may lead to undesirable cosmological consequences. A number of numerical experiments have addressed (Sakellariadou 2005; Avgoustidis & Shellard 2005, 2006, 2007; Copeland & Saffin 2005; Saffin 2005; Hindmarsh & Saffin 2006; Rajantie, Sakellariadou & Stoica 2007; Urrestilla & Vilenkin 2007) this issue, each of them at a different level of approximation. I will briefly describe the approach and findings of one of these numerical approaches (Rajantie, Sakellariadou & Stoica 2007), which I consider more realistic than others. The aim of that study was to build a simple field theory model of (p, q)bound states, in analogy with the Abelian Higgs model used to investigate the properties of solitonic cosmic string networks, and to study the overall characteristics of the network using lattice simulations.

The (p,q) string network was modelled (Rajantie, Sakellariadou & Stoica 2007) using two sets of Abelian Higgs fields. Two models were investigated, one in which both species of string have only short-range interactions and another one in which one species of string features long-range interactions. More precisely, we modelled the network with no long-range interactions using two sets of fields, complex scalars coupled to gauge fields, with a potential chosen such that the two types of strings will form bound states. This way junctions of 3 strings with different tension was successfully modelled. In order to introduce long-range interactions we considered a network in which one of the scalars forms global strings. This is important if the strings are of a non-BPS species. For example, for cosmic superstrings at the bottom of a Klebanov-Strassler throat the F-string is not BPS while the D- string is. Thus, the different components of the (p,q) state are expected to exhibit different types of long-range interactions. The evolution of the string networks suggested that the long-range interactions have a much more important rôle in the network evolution than the formation of bound states. In the local-global networks the bound states tend to split as a result of the long-range interactions, resulting in two networks that evolve almost independently. The formation of short-lived bound states and their subsequent splitting only increases the small-scale wiggliness of the local strings. In the case of a local-local network, the absence of long-range interactions allows the bound states to be much longer-lived and significantly influences the evolution of the string network (Rajantie, Sakellariadou & Stoica 2007).

Even though preliminary studies indicate that the presence of junctions is not itself inconsistent with scaling, this issue is far from being resolved. Numerical experiments may support a scaling solution, but this does not necessarily imply that realistic cosmic superstring networks formed at the end of a successful and natural brane inflationary era will reach scaling. Modelling a (p,q) network is indeed a challenging task, and further investigations are necessary before this very important issue gets satisfactory answered.

#### 5. Observational consequences

Since cosmic superstrings interact with the standard model particles via gravity, their detection involves gravitational interactions. By comparing the predictions of cosmic superstring models against recent astrophysical data, one should in principle be able to constrain the free parameters of the specific model. However, since the particular brane inflationary scenario remains unknown, the tensions of superstrings will be only loosely constrained.

I will briefly discuss the various observational signatures of cosmic strings which have been studied in the (simple) case of the Abelian Higgs model and relate them to those of cosmic superstrings. One should keep in mind that all observational consequences of solitonic strings have been studied in the (simple) case of the Abelian Higgs model. Even though curvature corrections have been investigated (Gregory, Haws & Garfinkle 1990; Letelier 1990; Barrabès, Boisseau, & Sakellariadou 1994), observational consequences of strings have been only studied under the zero thickness assumption. The case of superconduncting strings has been quite always neglected in the studies of the observational signatures of cosmic strings. Under these assumptions, cosmic strings can be well-described by the Goto-Nambu action. In addition, the reconnection probability has been always considered as exactly equal to unity. Finally, solitonic strings have been always considered as having winding number equal to unity, thus junctions are not formed.

Certainly, given the complexity of strings evolution (non-linear process) it is very difficult to go beyond this simple context in which solitonic strings have been studied. Nevertheless, one should be very careful when one deduces the observational consequences of strings; at least the quantitative discussion will be invalid for more general string configurations.

The complexity of cosmic superstrings and the uncertainty of the physical context (compactification, brane inflation model) of their formation renders any discussion on their observational consequences even more uncertain.

Cosmic strings perturb the space-time around them so that a conical spacetime is generated, leading to a unique gravitational lensing signature through the appearance of undistorted double images. The finding of even a single such gravitational lensing event would be seen as a convincing evidence for the existence of cosmic strings. In the case of strings with junctions, the Y-shaped junctions give rise to lensing events that are qualitatively distinct from the case of conventional strings can produce (Shlear & Wyman 2005; Brandenberger, Firouzjahi & Karouby 2007). Idientifying such a triple imaging event in the sky, would provide a smoking gun for the existence of a string network with non-trivial interactions. Certainly, to generalise this study in the case of cosmic superstrings may not be straightforward.

Micro-lensing is very useful in detecting lensing when the image splitting is too small to resolve with astronomical measurements. Gravitational micro-lensing of distant quasars by solitonic cosmic strings has been recently investigated (Kuijken, Siemens & Vachaspati 2007). The analysis seems to indicate rather pessimistic results for the detectability of such micro-lensing events generated by cosmic strings. These studies have not been extended for strings with non-trivial interactions.

Cosmic strings can also lead to weak gravitational lensing. A recent study (Dyda & Brandenberger 2007) on gauge cosmic strings has shown that if such strings have a small-scale structure leading to a local gravitational attractive force towards them, then an elliptical distortion of the shape of background galaxies in the direction corresponding to the projection of the string onto the sky may be expected. Weak lensing has not been investigated in the case of cosmic superstrings (neither in the simpler case of strings with Y-junctions).

The CMB temperature anisotropies offer a powerful test for theoretical models aiming at describing the early universe. The characteristics of the CMB multipole moments can be used to discriminate among theoretical models and to constrain the parameters space. According to our present understanding, the CMB temperature anisotropies originate mainly from the amplification of quantum fluctuations at the end of inflation, with a small contribution from the cosmic (super)string network. Given the small size of the observed CMB temperature anisotropies, the perturbations may be treated linearly. Thus, any coupling between perturbations induced by inflation and those seeded by cosmic strings can be neglected. Using the latest WMAP data and Big Bang Nucleosynthesis (BBN) data, fractional contribution from cosmic strings to the temperature power spectrum at the multipole moment  $\ell = 10$  is at most 0.11 (Bevis *et al.* 2008). In other words, if the normalisation of the string component has been set to match the data at multipole  $\ell = 10$ , the string contribution cannot exceed 11%. This translates in the upper limit on the dimensionless parameter  $G\mu$  (G is the gravitational constant and  $\mu$  the string tension) given by (Bevis *et al.* 2008)  $G\mu < 0.7 \times 10^{-6}$ . This limit was derived for classical Abelian Higgs strings with equal vector and scalar particle masses; it is not expected to be valid for other types of strings.

The polarisation of the CMB photons can give further information and constraints on the cosmological rôle of cosmic strings. The B-mode polarisation spectrum provides an important window on cosmic strings, since the corresponding contribution from inflation is rather weak. Scalar modes may contribute to the B-mode only via the gravitational lensing of the E-mode signal, with a second inflationary contribution arising from the sub-dominant tensor modes. It is thus conceivable that the large vector contributions from cosmic strings enable the detection of their imprint through future B-mode measurements. In this way current views on natural inflationary models may challenge the conventional thought that a detection of B-mode polarisation in the CMB will show the existence of gravity waves in the early universe and determine the energy scale of inflation. To distinguish the cosmic string from the inflationary gravity wave signal one should go to rather high energy resolution, since the signal from cosmic strings seem to be dominant at  $\ell \sim 1000$ , while the gravity wave signal from inflation peaks at  $\ell \sim 100$  (Seljak & Slosar 2006). The prediction of a large cosmic string contribution to the B-mode polarisation power spectrum has been confirmed even for small string contributions to the CMB. More precisely, it has been argued (Bevis *et al.* 2007) that data from future ground-based polarisation detectors may bound the dimensionless string parameter to  $G\mu < 0.12 \times 10^{-6}$ .

Cosmic strings can also become apparent through their contribution in the small-angle CMB temperature anisotropies. More precisely, at high multipoles  $\ell$  (small angular resolution), the mean angular power spectrum of string-induced CMB temperature anisotropies can be described (Fraisse *et al.* 2007) by  $\ell^{-\alpha}$ , with  $\alpha \sim 0.889$ . Thus, a non-vanishing string contribution to the overall CMB temperature anisotropies may dominate at high multipoles  $\ell$  (small angular scales). In an arc-minute resolution experiment, strings may be observable for  $G\mu$  down to  $2 \times 10^{-7}$  (Fraisse *et al.* 2007).

Cosmic strings should also induce deviations from Gaussianity. On large angular scales such deviations are washed out due to the low string contribution, however on small angular scales, optimal non-Gaussian, string-devoted statistical estimators may impose severe constraints on a possible cosmic string contribution to the CMB temperature anisotropies.

One should keep in mind that all string-induced CMB temperature anisotropies were performed for Abelian strings in the zero thickness limit with reconnection probability equal to unity and winding number equal to one. Even though in any model where fluctuations are constantly induced by sources (seeds), having a nonlinear evolution, the perfect coherence which characterises the inflationary induced spectrum of perturbations gets destroyed (Durrer *et al.* 1997; Durrer & Sakellariadou 1997), there is still no reason to expect that quantitatively the results found for conventional cosmic strings models will hold in more general cases.

Cosmic strings are expected to produce a stochastic background of Gravity Waves (GW), which can be estimated by the incoherent superposition of GW bursts at the cusps and kinks of a network of oscillating string loops. This stochastic GW background, may be detectable by pulsar timing observations. Gravity waves bursts emitted from cusps of oscillating string loops, may be detected by the LIGO/VIRGO and LISA interferometers. For conventional cosmic strings it has been argued (Damour & Vilenkin 2000, 2001) that even if only 10% of all string loops have cusps, the GW bursts might be detectable by the planned GW detectors LIGO/VIRGO and LISA for string tensions as small as  $G\mu \sim 10^{-13}$ . The result depends on the number of cusps which is still not well-known.

Some preliminary studies of gravity wave emission from cosmic superstring networks have been recently performed (Damour & Vilenkin 2005). The only difference which has been considered for those investigations is the reconnection probability. These studies seem to indicate (Damour & Vilenkin 2005) that the smaller reconnection probability will enhance the observational signature of cosmic superstrings. Analysing the BBN, CMB and pulsar timing bounds, it seems that the BBN and CMB bounds are consistent with, but somewhat weaker than, the pulsar bound. It is argued (Siemens *et al.* 2006a,b) that considering string networks with small reconnection probabilities,  $\mathcal{P}$ , strings with  $G\mu \geq 10^{-12}$  are ruled out when  $\mathcal{P} \sim 10^{-3}$ . Increasing the reconnection probability, strings with  $G\mu \geq 10^{-10}$  are ruled out, while the bound becomes  $G\mu \geq 10^{-8}$  for  $\mathcal{P} \sim 1$ . These results depend on the evolution of the string network, the number of cusps/kinks, as well as the reconnection probability. Since only the reconnection probability has been taken into account, it is rather immature to claim that these bounds correspond to realistic cosmic superstring networks. Further investigations are necessary.

The energy scale of cosmic strings/superstrings can be also constrained from the emission of moduli. Preliminary studies have been done (Damour & Vilenkin 1997; Sakellariadou 2005; Babichev, & Kachelriess 2005; Davis, Binetruy & Davis 2005; Firouzjahi 2007), however further studies with more realistic cosmic superstring networks are required.

#### 6. Conclusions

For a number of years, inflation and topological defects have been considered either as two incompatible or as two competing aspects of modern cosmology. Historically, one of the reasons for which inflation was proposed is to rescue the standard hot big bang model from the monopole problem. However, such a mechanism could also dilute cosmic strings unless they were produced at the end or after inflation. Later on, inflation and topological defects competed as the two alternative mechanisms generating the density perturbations which led to the observed large-scale structure and the anisotropies in the CMB. The plethora of data on the CMB have revealed an early universe in striking agreement with the basic predictions of inflation, while there is a clear inconsistency between predictions from topological defect models and CMB data. This indicates a clear preference for inflation. However, despite its success inflation still lacks a precise theoretical model.

In the context of a brane-world cosmological scenario within string theory, brane inflation can be easily accommodated. Brane inflation takes place while two branes move towards each other, and their annihilation releases the brane tension energy that heats up the universe to start the radiation-dominated era of the hot big bang model. Typically, strings of all sizes and types may be produced during the collision. Large fundamental strings and/or D1-branes that survive the cosmological evolution become cosmic superstrings. The study of cosmic superstrings and their observational signatures will give us an understanding of the early stages of our universe and it will provide information in identifying the details of the string theory model which has relevance with our universe. Thus, the issue of cosmic suprestrings is gaining a lot of interest from the scientific community. Numerical experiments of cosmic superstring networks and analytical studies are trying to unravel the properties and characteristics of such networks. The problem is quite complex and our intuition from the (better known) conventional solitonic strings described by the Goto-Nambu action, may turn out to be misleading. Many open questions are currently under investigation and we expect to have soon a better understanding of their properties and their observational signatures which will allow us to detect them.

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