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ScienceDirect
Nuclear Physics B (Proc. Suppl.) 246–247 (2014) 45–57
NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS
www.elsevier.com/locate/npbps

Searching for Cosmic Strings in New Observational Windows

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Abstract

Cosmic strings are predicted in many models beyond the Standard Model of particle physics. In such models, a network of strings will inevitably be formed in a phase transition in the early universe and will persist to the present time. Strings leave behind distinctive features in cosmology. Searching for these signatures in new observational windows provides a way to constrain particle physics at the high energy scale and is thus complementary to searches for new physics at the low energy end, for example at the LHC. Specifically, I will discuss signatures of cosmic strings in cosmic microwave background polarization maps and in 21cm redshift surveys.

Keywords: Cosmic Strings, CMB Polarization, 21cm Redshift Surveys

1. Introduction

Cosmic strings [1] are linear topological defects which arise in a range of relativistic quantum field theories (for reviews see e.g [2]). Good analogs of cosmic strings are vortex lines in superfluids and superconductors. Line defects in crystals can be viewed as another analog system. Cosmic strings form lines of trapped energy density, and this energy density can curve space-time and have important effects in cosmology [3].

Cosmic strings are predicted to form in many particle physics models beyond the Standard Model. In particular, they are predicted to form at the end of inflation in many inflationary models, e.g. supergravity models [4] and brane inflation models [5]. Cosmic strings may also survive as cosmic superstrings in alternatives to inflation such as "String Gas Cosmology" [6]. The key point for cosmology is that in any field theory model which admits cosmic string solutions, a network of strings inevitably forms at some point during the early universe [7], and it persists to the present time. Hence, the detection of cosmic strings would give us information about particle physics at very high energy scales.

Since cosmic strings are relativistic objects, a straight string is described by one number, namely its mass per unit length μ which also equals its tension, or equivalently by the dimensionless number $G\mu$, where G is Newton's gravitational constant (we are using units in which the speed of light is $c = 1$). In simple quantum field theory models the tension is related to the energy scale η at which the strings are formed via $\mu \sim \eta^2$ (see the following section for a more precise discussion). The cosmological signatures of strings are thus more substantial for larger values of μ which implies larger values of the energy scale η. Hence, searching for cosmological signatures of strings is a tool to probe particle physics beyond the Standard Model at the highest energy scales (as opposed to accelerator experiments like the LHC which probe new physics at the lowest energy scales).

In fact, current limits on cosmic strings already [8] provide a constraint

$$G\mu \; < \; 1.5 \times 10^{-7} \tag{1}$$

which already rules out certain Grand Unified particle physics models with very high scale symmetry breaking. This limit comes from the observational upper bound on the contribution of cosmic strings to the angular power spectrum of cosmic microwave background (CMB) anisotropies obtained by combining the results of the WMAP satellite [9] with those of South Pole

http://dx.doi.org/10.1016/j.nuclphysbps.2013.10.064

Telescope [10] (see also [11] for a comparable limit obtained by combining results from WMAP and from the Atacama Cosmology Telescope [12], and [13] for earlier limits).

Given the constraints on particle physics model which can be derived from current observations, is of great interest to try to improve the observational upper bounds on the cosmic string tension since this will allow us to constrain high energy scale particle physics models more strongly than possible today.

Cosmic strings can also produce many good things for cosmology in addition to contributing to cosmological structure formation. Cosmic strings may play a role in baryogenesis (see e.g. [14]). Certain types of string can also provide a mechanism for the production [15] of seed magnetic fields which are coherent on galactic scales [1] Cusps on cosmic string loops can also yield a contribution to ultra-high-energy cosmic rays [16, 17]. Finally, cosmic string loops may also assist in the assembly of the large mass concentrations required to seed super-massive black holes.

For all of the above reasons it would thus be wonderful to have evidence for the existence of cosmic strings in nature. The search for cosmic strings is therefore of great interest independent of whether the search in fact finds signals of cosmic strings. If it does, then we will have discovered something completely new in the universe. If it does not, then we will have derived tighter constraints on particle physics at very high energy scales.

In this talk I will review recent work on signatures of cosmic strings in new observational windows. Up to the present time, the tightest and most robust constraints on the cosmic string tension have come from analyses of CMB temperature maps. Here, I will focus on the signatures of strings in CMB polarization maps and 21cm redshift surveys, two emerging windows to explore the cosmos.

The main points to take away from this talk are the following. Firstly, cosmic strings lead to nonlinearities already at very high redshifts. Hence, the signatures of cosmic strings are more pronounced at higher than at lower redshifts where they are masked by the nonlinearities produced by the Gaussian density fluctuations which must be present and which dominate the total power spectrum of cosmological perturbations. Secondly, cosmic strings lead to perturbations which are highly non-Gaussian and which predict specific geometrical patterns in position space. By computing a power spectrum information about these patterns are lost. Hence, tighter limits on the cosmic string tension can be obtained if we analyze the data in position space. Thirdly, 21cm redshift surveys appear to be an ideal window to search for cosmic string signatures [18].

The outline of this talk is as follows. We first present a brief review of the basics of cosmic strings. In Section 3 we introduce the two main mechanisms which will play a role in determining the cosmic string signals in observations, namely the Kaiser-Stebbins [19] (see also [20]) lensing effect and the cosmic string wake [21]. We also briefly review the well-known resulting signal of strings in CMB temperature maps. The key sections of this talk are Sections 4 and 5. In the first, we discuss the signal of a long straight cosmic string in CMB polarization maps, and in the second we turn to the signal in 21cm redshift surveys.

2. Cosmic String Review

In a class of relativistic quantum field theories, cosmic strings form after a phase transition in the early universe during which an internal symmetry in field space is spontaneously broken. Let us consider a simple toy model involving a complex scalar field ϕ with potential

$$V(\phi) \;=\; \frac{\lambda}{4}\Big(|\phi|^2 - \eta^2\Big)^2 \tag{2}$$

where η is the vacuum expectation value of the modulus of ϕ and λ is a coupling constant.

To determine whether a particular field theory admits cosmic string solutions or not, the key concept is that of the *vacuum manifold* $\mathcal{M}$, the set of field values which minizes the potential. In the above example $\mathcal{M}$ is homotopically equivalent to the circle S^1.

In thermal equilibrium, the potential obtains finite temperature corrections [22, 23] (see e.g. [24] for a review). Specifically, there is an extra contribution

$$\Delta V_T(\phi) \;\sim\; T^2|\phi|^2\,, \tag{3}$$

where T is the temperature. Hence, there is a critical temperature T_c above which the lowest potential energy state is $\phi = 0$ and the field symmetry (rotation in the complex field plane) is unbroken. Thus, in the early universe the average value of ϕ at each point in space will be $\phi = 0$, but as the universe cools below the temperature T_c this state becomes unstable and at each point in space ϕ will want to roll down the potential to take on a value in $\mathcal{M}$.

The key point is [7] that by causality there can be no correlation between the field values in $\mathcal{M}$ which are

[1]The challenge for particle physics models of magnetogenesis is to obtain the observed coherence length since microphysics typically produces coherence lengths which are much too small.