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Cosmic superstrings in large volume compactifications

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We summarise recent proposals for embedding the physics of cosmic strings and superstrings into concrete models in string compactifications. Such embeddings feature epochs of moduli-mediated matter domination which alter the resulting gravitational wave spectrum at frequencies that can be computed from the properties of the network. Further, we study the effects of a varying tension, which in string theory would be mediated by dynamical moduli. The resulting spectral index is computed as a function of the equation of state of the background and the rate of variation of the tension, showing that large spectral indices occur when the tension decreases. We then study two scenarios: first, a simple scenario where the modulus decays gravitationally predicts a feature in the LISA band when the PTA signal is used as a benchmark. Another scenario with string-motivated potentials and moduli stabilisation provides a simple example of large boosts in the spectrum at high frequencies. This work is a contribution to the proceedings of the third general meeting of the COST Action CA21106 (Cosmic WISPers) and is based on [1, 2].

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1. Introduction

Cosmic strings are one of the few examples of possibly stable remnants of physics at very high energies that could be present today. The way this happens is that a network of superhorizon cosmic strings reaches a so-called scaling regime which ensures that their energy density remains a constant fraction of the energy density of the Universe. This fraction is characterised by the dimensionless number $G\mu$, where G is Newton's constant and μ is the tension of the string. A small tension (in Planck units) therefore allows the network to remain a very subdominant fraction of the energy density of the Universe, avoiding in particular stringent CMB bounds [3].

In order to maintain the scaling regime, the network must have a mechanism for energy loss that balances the otherwise dangerously slow $\rho \sim 1/a(t)^2$ redshift of its energy density. This happens via emission of gravitational waves (GW) and presumably other massless modes, depending on the microphysics of the strings. Scaling is preserved if the network loses a constant fraction of its energy density into GWs at every e-fold, and so the resulting GW spectrum today features large contributions from all times. Furthermore, it can be argued that the largest contribution to a given frequency bin is sourced at a computable time, with high frequencies corresponding to early times. If a deviation from radiation domination occurs in the early Universe, the resulting GW spectrum redshifts in a different way than the background during this period, giving rise to a spectral index in the spectrum that carries information about the equation of state of the background: if present, cosmic strings could provide us with information about times much earlier than Big Bang Nucleosynthesis, the currently earliest time to which we have experimental access.

This motivates us to study what can be expected from UV completions of current theories at high energies. String theory backgrounds very generically feature light scalar fields with gravitational couplings and whose expectation values set fundamental constants. These can naturally be dynamical in the early Universe and alter the equation of state of the background, or induce variations in the dimensionless quantity $G\mu$. Both of these effects can give rise to modifications in the GW spectrum, and in [2] we study two well-motivated scenarios featuring this behaviour, which we summarise in the present talk. The main results are shown in Fig. 1 which show the gravitational wave spectrum $\Omega_{\mathrm{GW}}(f)$. Deviations from the standard flat plateau are due to periods of matter domination and varying tension. We describe and justify these periods in what follows.

2. String theory and the first half of the Universe

So far we have discussed the physics of cosmic string networks and argued that they can be described by the dimensionless number $G\mu$.[1] String theory famously has no free parameters and all quantities are determined dynamically in a given vacuum. A key challenge in this determination is the issue of moduli fixing: the tree-level higher dimensional equations of motion that describe string theory at energies smaller than the string scale are degenerate. A subspace of the space of solutions is spanned by continuous deformations of a given solution, like the volume of the extra dimensions. In the effectively 4-dimensional description, these degeneracies manifest themselves

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[1] A further parameter P must be introduced in order to correctly describe the dynamics of cosmic superstrings as discussed later.

as scalar fields with no potential at tree level, with their expectation value setting quantities like the lower-dimensional Planck scale.

Massless scalar fields are problematic for many phenomenological reasons, the simplest being that they would mediate fifth forces which are constrained experimentally. These fields are however never massless in realistic setups: classical sources of energy and quantum corrections generically lift these directions in backgrounds with a sufficiently large amount of supersymmetry breaking. The lessons to learn here then is that realistic string theory backgrounds robustly feature light scalar fields whose dynamics determine low energy quantities like gauge couplings or energy scales in Planck units. Further, they induce correlations between scales that seem surprising from a low-energy point of view (e.g. between the supersymmetry breaking scale and the mass of the volume modulus in a given background). This will be important in Fig. 1a where fixing $G\mu$ also fixes the frequency at which the tilt in the spectrum occurs, which turns out to be the LISA band for the well motivated value $G\mu = 10^{-12}$.

The present discussion then motivates explaining hierarchies via moduli dynamics. If cosmic superstrings[2] are actually present in the Universe then observational bounds restrict $G\mu < 10^{-11}$,[3] a hierarchy that ought to be explained dynamically. Interestingly, a class of string theory models naturally feature such hierarchies: the Large Volume Scenario (LVS) [5] and variants thereof. In these scenarios the volume mode $\mathcal{V}$ is stabilised at exponentially large values (in string units), inducing hierarchies of the form:

$$M_P \gg m_s \sim M_P/\mathcal{V}^{1/2} \gg m_\phi \sim M_P/\mathcal{V}^{3/2} \tag{1}$$

where M_P is the Planck scale, $m_s \sim \mu^{1/2}$ is the string scale and m_ϕ is the mass of the volume mode, and $\mathcal{V} \sim 10^{10}$ reasonable values. The volume mode couples to all sources of energy and so, being a light field, it is expected to be displaced from its minimum in the early Universe. In what follows we will discuss the dynamics of this field and its implications for the GW spectrum from cosmic superstrings in two scenarios within the LVS:

- Gravitational decay. An unavoidable coupling of the volume mode is gravitational. If no stronger couplings can arise, its vacuum misalignment induces a period of early matter domination which ends via its decay, with a rate given by

$$\Gamma_{\text{grav}} = \frac{1}{48\pi}\frac{m_\phi^3}{M_P^2}\,. \tag{2}$$

- Short Volume Lifetime LVS (SVL-LVS). The gravitational decay of the volume mode actually gives rise to dark radiation issues which we ignore in the present discussion. Concrete solutions have been proposed in this context and in this scenario we follow [6]. The main result for our purposes is a faster decay rate given by:

$$\Gamma_{\text{SVL}} = \frac{\mathcal{V}^2}{16\pi}\frac{m_\phi^3}{M_P^2}\,. \tag{3}$$

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[2] Broadly defined as highly excited effective strings, which could be F-strings, (p,q) strings or wrapped D- or NS5-branes. The discussion does not make a difference between these as all that is required is the low-energy dynamics of these objects, which is described by the Nambu-Goto action.

[3] This bound arises from Pulsar Timing Arrays [4] and is subject to uncertainties in the emision of GWs by the network. More robust are CMB bounds [3] restricting $G\mu \lesssim 10^{-8}$.

The period of matter domination can be much shorter in this case and so signals from earlier times can be large. Fig. (1b) shows the signal that arises if the volume modulus undergoes a period of kination before settling in its minimum.

3. Vanilla LVS: PTAs and LISA

Something that is particularly interesting about the previous discussion is that, in order not to spoil Big Bang Nucleosynthesis (BBN), the mass of the volume mode is constrained to be $m_\phi > 30$ TeV if it decays gravitationally. This in turn bounds $\mathcal{V} \lesssim 10^{10}$ and so an interesting region for cosmic superstrings to exist is $G\mu \sim 10^{-12}$. Pulsar Timing Arrays have reported [7] hints for a GW background at nHz frequencies which could be explained by cosmic strings with $P \ll 1$ [8, 9]. [4] In what follows we will take $G\mu = 2 \cdot 10^{-12}$, $P = 4 \cdot 10^{-3}$ as a benchmark [8] and discuss further aspects of the signal that arise when embedded in the UV completion of section 2.

Let us now give a short description of how the GW spectrum from a cosmic string network is computed. Once two pieces of string find each other they exchange partners with probability P. This number is typically one in field theory but suppressed by the string coupling $g_s^2 \ll 1$ for superstrings. When intercommutation happens, subhorizon loops are formed that then decay into GW radiation. It is these GWs that form the background whose spectrum we wish to compute. The master formula is

$$\Omega_{\rm GW}(f) = \frac{f}{\rho_c} \int_{t_0}^{t_i} dt \left(\frac{a(t)}{a_0}\right)^4 \frac{dE_{\rm GW}}{dt} \frac{dn(f,t)}{df} \, . \tag{4}$$

which takes some number of loops dn/df which at a time t source GWs with frequency today in the range $(f, f+df)$, with an emission power $dE/dt \sim G\mu^2$ per loop (distributed throughout frequencies in the loop vibrational modes, see the references for details), and redshifts the resulting energy density to today. (ρ_c is the energy density of the universe today, t_0.)

At this point we need information about the distribution of string loops. This is a matter of heated debate in the literature to which we have nothing new to add. In what follows we simply follow the class of models called “Model 1” in [11] which take the production distribution of loops to be monochromatic with initial lengths $\ell_i = \alpha t_i = \alpha_L L$.[5] Further, due to scaling, the number of loops of such length produced between $(t_i, t_i + dt_i)$ is $\sim 1/t_i^4$. The loops redshift like matter until they source GWs in the relevant frequency bin at a time t. One relates this time to a given frequency by solving the evolution equation for the loop length (obtained from an integral of the worldsheet equations of motion supplemented by a term which takes decay into GWs into account) with initial conditions as above.

The period of early matter domination induces a dip in the spectral index at a frequency f_Γ which can be computed in terms of the parameters of the problem:

$$f_\Gamma = 8.6 \times 10^{-4}\ \text{Hz}\ \times \left(\frac{0.1}{\alpha P^\chi} \times \frac{2\times 10^{-12}}{G\mu}\right)^{1/2} \times \left(\frac{m_\Phi}{30\ \text{TeV}}\right)^{3/2} , \tag{5}$$

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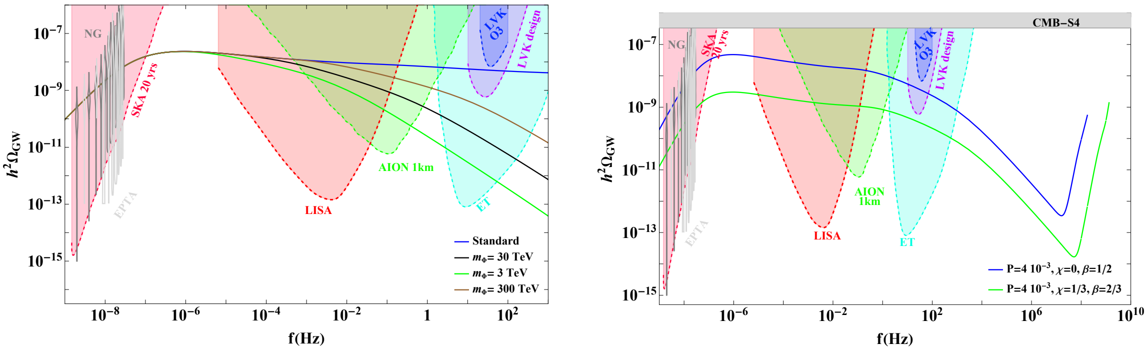
[4] A more conservative explanation is supermassive black hole mergers. Recent discussions [4, 10] compare these and other candidates and conclude that cosmic superstrings provide a good fit to the data.

[5] We thus have $\alpha = \alpha_L \xi$, with ξ defined as L/t, where L is the correlation length of the network. During scaling, ξ is a number whose value depends on the equation of state of the background and the intercommutation probability. For ease of comparison with the literature we take $\alpha \to \alpha P^\chi$ to parametrise the induced P-dependence on the initial length - see Ref. [2] for details.



(a) GW spectrum in the first scenario. Sensible values of m_ϕ give rise to a dip in the spectrum computed as in Eq. (5).

(b) GW spectrum in the second scenario. The period of varying tension induces a large boost at high frequencies with a spectral index computed as in Eq. (6).

Figure 1: GW spectra in the two scenarios discussed in Ref. [2]. The values $G\mu = 2 \cdot 10^{-12}$ and $P = 4 \cdot 10^{-3}$ are chosen following [8]. Embedding into UV complete scenarios gives rise to features in the spectrum.

which for our benchmark values is constrained to lie within the LISA band![6] If cosmic superstrings actually explain the PTA signal as in [8], the small value of $G\mu$ suggests an UV completion as a LVS. The simplest models feature a scalar mode that decays gravitationally and induces a feature in the LISA band.

4. SVL-LVS and varying tension

For our next study we consider a system accommodating high-scale inflation and a low $G\mu$ dynamically. That is, we assume that the inflationary dynamics results in a network of cosmic strings and the canonically normalised volume mode ϕ dominating the energy density of the Universe ρ, and an exponential potential $V = \exp(-\lambda\phi/M_P)$. ($\lambda = 4\sqrt{2/3}$ in the plots, see Ref. [2]). The field undergoes a period of kination until some seed radiation overtakes the energy density of the Universe. Then, a scaling regime where the energy density of the field tracks that of radiation is achieved, and eventually the field reaches its minimum, giving rise to a period of early matter domination until it decays, generating standard reheating after a timescale set by the rate (3).

An important assumption required for the computation of the GW spectrum is that the network still reaches a scaling regime when the tension varies. We gave arguments in support of this in previous work [1]. The logic is to take averages of the worldsheet equations of motion (with a possibly time-dependent tension) and supplement them with a term that captures energy loss by the network, a generalisation of the well known Velocity One Scale model [12]. One of the main results of [1] is that scaling solutions are attractors of the dynamics (provided the strings do not percolate [13]), still featuring the relation $\rho_s \sim G\mu(t)\rho$. It would be interesting to corroborate these results with simulations.

Having justified the existence of a scaling regime, we can now compute the GW spectrum. The resulting spectrum in this case is qualitatively different, because the GW emission power (set

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[6] In LVS, m_ϕ is given by three microscopic quantities: $\mathcal{V}$, g_s and W_0. Fixing $G\mu$ and P fixes $\mathcal{V}$ and g_s. W_0 cannot be too large for consistency of the effective description or, for fixed $\mathcal{V}$ and g_s, too small since it would spoil BBN.

by $G\mu^2$) varies with time. The fractional energy density of the background into GWs per efold is now time-dependent and larger at early times, and so we expect a boost in the spectrum at high frequencies. The details of the computation of this GW spectrum can be found in [2]. The punchline is that within a range of frequencies the spectrum can be described by a power-law with

$$h^2\Omega_{\rm GW} = h^2\Omega_{{\rm GW},\Delta}\left(\frac{f}{f_\Delta}\right)^A \,, \qquad A = 2\left(1 + \frac{n\,p-2}{n-2}\right) \,. \tag{6}$$

for some computable $\Omega_{{\rm GW},\Delta}$ and f_Δ, and a background satisfying $H = 2/(n\,t)$ and $G\mu \sim t^{-p}$. Figure 1b shows the GW spectrum computed in a cosmology with volume modulus kination ($p = 1$ and $n = 6$) and a SVL-LVS decay rate. The resulting spectral index at high frequency is read off from $h^2\Omega_{\rm GW} \sim f^4$, providing a much larger boost than at constant tension (for which during kination one finds $h^2\Omega_{\rm GW} \sim f$).

5. Conclusions

Cosmic strings are exciting possibilities for high energy physics whose GW imprint will be tested in the near future (again with the caveat that some of our assumptions are standard in the literature but remain under debate). If detected, their spectrum will become an unvaluable window to pre-BBN physics. Further, UV complete scenarios make concrete predictions that relate the characteristics of the network to other observable quantities, such as the frequency at which a dip in the spectrum appears, as in Fig. 1a and Eq. (5).

Let us speculate with the case of a detection of the LISA dip. This feature can be reproduced by any scenario featuring a period of early matter domination and so such a detection would not be enough to claim victory for the LVS in string theory.[7] However, when understood within string theory, it would give us a hint of the size of the extra dimensions, which would inform about other low-energy quantities, like the supersymmetry breaking scale in the Standard Model sector. Such correlations between low-energy quantities which seem *ad hoc* from the field theory perspective are the best candidates for eventually testing string theory.

Another exciting possibility inspired by string theory is the existence of periods of varying tension, which induce large boosts in the spectrum at high frequencies, with computable spectral indices, as in Eq. (6), that cannot be reproduced by scenarios with constant tension. Work that explores further well-motivated time-dependences of the tension in string theory is on its way (see also [14, 15]). It would also be very interesting to perform simulations of the physics of cosmic strings with time dependent tension.

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[7] Similarly a non-detection would not be evidence against string theory: the scenario assumes non-necessary features in string constructions. These include the production and stability of cosmic superstrings and the simplest features of the LVS, which in particular neglect possible effects due to realistic Standard Model model building. It is hard to make fully model-independent predictions within string theory inasmuch as it is hard to make them within quantum field theory - and we do not yet know which string theory model (vacuum) describes our Universe, if any.

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