Physics Letters B ••• (••••) •••–•••

Contents lists available at ScienceDirect

Physics Letters B

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The string soundscape at gravitational wave detectors

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ARTICLE INFO

Article history:
Received 11 December 2017
Received in revised form 7 February 2018
Accepted 11 February 2018
Available online xxxx
Editor: A. Ringwald

Keywords:
Gravitational waves from phase transitions
String phenomenology

ABSTRACT

We argue that gravitational wave signals due to collisions of ultra-relativistic bubble walls may be common in string theory. This occurs due to a process of post-inflationary vacuum decay via quantum tunnelling. Though we study a specific string construction involving warped throats, we argue that our conclusions are more general. Many such transitions could have occurred in the post-inflationary Universe, as a large number of throats with exponentially different mass scales can be present in the string landscape, leading to several signals of widely different frequencies – a *soundscape* connected to the landscape of vacua. Detectors such as aLIGO/VIRGO, LISA, and pulsar timing observations with SKA and EPTA have the sensitivity to detect such signals. A distribution of primordial black holes is also a likely consequence, though reliable estimates of masses and their abundance require dedicated numerical simulations, as do the fine details of the gravitational wave spectrum due to the unusual nature of the transition.

1. Introduction

The recent direct detection of gravitational waves (GWs) [1,2] opens a new mode of physical exploration. Although the potential of GW detectors to study astrophysical objects is well-known [3], their potential for exploring Beyond-the-Standard-Model physics is still in a relative infancy. Prime examples studied so far include the physics of inflation [4–8], the presence of strongly first order thermal phase transitions [9–15], and the possibility of probing the existence of axions [16].

We argue that GW detectors provide a powerful tool to interrogate the nature of short-distance physics, particularly string theory, in a way unrelated to inflation: specifically, GW signals from *post-inflationary* vacuum decay are a natural feature of (at least) the type IIB string landscape. In particular it is well known that type IIB flux compactifications can contain a large number of highly warped throats [17–21], with physics related to that of Randall–Sundrum models [22,23] (see Fig. 1). Importantly for our purposes, a throat can present a metastable vacuum in which supersymmetry (SUSY) is locally broken, along with a locally-SUSY-preserving vacuum [24], to which it eventually decays.

Here we explore early-Universe vacuum decay taking place via zero-temperature quantum nucleation of bubbles of true, locally-SUSY-preserving, vacuum within a given throat, and argue that the resulting ultra-relativistic bubble wall collisions can lead to an *observable* stochastic 'background' of GWs. The peak frequency sensitively depends on the throat characteristics, most of all on the gravitational warp factor $w_{IR} \ll 1$, which sets the relation between the infra-red energy scale of the throat tip and the string scale M_s. Since a large number of throats with exponentially different warp factors can be present in the string landscape [25], GW signals with very different frequencies can be produced – a *soundscape* of possible signals that can be potentially discovered by detectors such as aLIGO [26] and LISA [27], and pulsar timing arrays [28,29]. Larger compactification volumes and smaller w_{IR} both shift the frequency towards smaller values, making pulsar timing optimal for probing large volume and/or strongly warped scenarios.

Ultra-relativistic bubble wall collisions can also produce primordial black holes (pBHs) [30–34]. Both this process and the GW spectrum beyond the frequency peak, are sensitive to the peculiarities of the bubble wall and vacuum decay dynamics applying in our case, which are different from those of both thermal phase transitions and previous studies of inflation-terminating quantum tunnelling vacuum decay. A detailed understanding of both the high-frequency features of the GW signal, and the mass spectrum of pBHs produced, requires dedicated numerical simulations, a study which is beyond the scope of this work. If, however, the

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https://doi.org/10.1016/j.physletb.2018.02.028

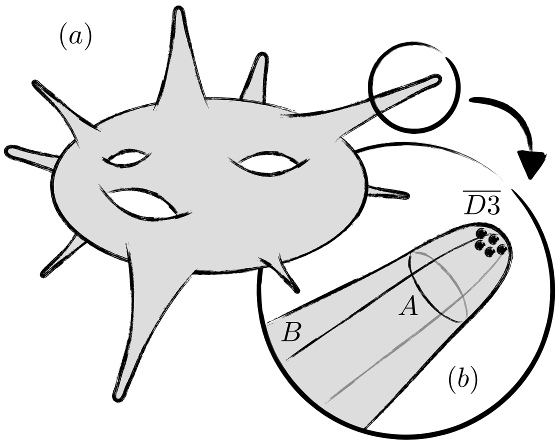

Fig. 1. (a) Cartoon of a type IIB flux compactification with a large number of throats, some of Klebanov–Strassler type [35]. (b) Close-up of a Klebanov–Strassler throat with 3-form flux quanta on the A- and B-cycles. The fluxes lead to a tip warp factor w_{IR}. In the locally SUSY-breaking false vacuum $\overline{D3}$ branes are localized at the tip [24].

production of pBHs is highly efficient, and has a mass distribution extending above $\simeq 10^9$ g, then the maximum amplitude of GWs observable today can be constrained. On the other hand, the possible production of pBHs in those mass ranges where they may account for (part of) the dark matter provides further motivation for detailed studies of the rich physics of the string soundscape.

2. False vacuum decay

2.1. Outline of early universe history

After inflation, the visible sector, i.e. the Standard Model plus other states in significant thermal contact with it, gets reheated to a temperature T_{rh}.[1] On the other hand, hidden sectors such as those living at the end of highly warped throats, may not be equally reheated and, in general, one expects many to be left at temperatures $T \ll T_{rh}$. In the following we take, for simplicity, the throat sector under consideration to be at temperature $T_{th} = 0$, although strictly speaking all required is that T_{th} is much smaller than all mass scales present in the problem. We note that this $T_{th} = 0$ choice is a self-consistent assumption, since the infra-red dynamics of a throat are sufficiently sequestered from the dynamics of the rest of the compactification to ensure that a hot thermal Standard Model sector localized elsewhere in the compactification interacts only feebly with the infra-red degrees of freedom of the throat [36,37].[2]

The relevant throat sector remains in a metastable vacuum so long as $\Gamma/H(T)^4 \ll 1$, where Γ is the decay rate per unit volume, and $H(T)$ is the Hubble rate, dependent on the *visible* sector temperature T. Γ is independent of temperature since $T_{th} = 0$. Only when $\Gamma/H(T)^4 \approx 1$ does the decay occur. Throughout, we assume that the visible sector radiation energy density, $\rho_{rad}(T)$, dominates over the false vacuum energy density, so that a second inflationary phase with potentially disastrous consequences [43,44] never takes place. Thus $\alpha(T) \equiv \rho_{vac}/\rho_{rad}(T) < 1$ for all temperatures of interest, ensuring a radiation dominated Universe.[3]

Both the SM temperature at nucleation, T_n, and the bubble properties, depend on the microphysics of our specific model to which we now turn. Readers primarily interested in the resulting GW phenomenology may jump to the next sub-section.

2.2. Metastable throats

Kachru et al. [24] considered the dynamics of p anti-$D3$ branes ($\overline{D3}$) in a Klebanov–Strassler throat [35]. In this so-called conifold geometry, which is topologically equivalent to $S^3 \times S^2 \times \mathbb{R}$, M units of so-called RR 3-form flux pierce the A-cycle of the conifold, whereas K units of so-called NSNS 3-form flux pierce the dual B-cycle. The A-cycle corresponds to the S^3 of the conifold, and the B-cycle extends into the bulk of the geometry when embedded into a compact manifold, as we illustrate schematically in Fig. 1. These fluxes result in a tip warp factor $w_{IR} \sim \exp(-2\pi K/3Mg_s)$ where g_s is the string coupling [17]. Ignoring back-reaction both local to the throat and arising from other distant parts of the compactification, in [24] it was argued that if the ratio p/M was smaller than a certain critical value $r_c = (\pi - 3 + b_0^4)/(4\pi) \approx 0.08$ then the system features a metastable vacuum in which SUSY is locally broken by the $\overline{D3}$-branes. Decay to the true SUSY-preserving vacuum, with no $\overline{D3}$-branes, $(M-p)$ $D3$-branes, and $(K-1)$ NSNS flux quanta could only take place quantum mechanically, or through a thermal transition.

In the metastable vacuum, the system is not well described in terms of individual $\overline{D3}$ branes, but rather as an NS5 brane (a 5-dimensional object). This NS5 brane has 3 non-compact spatial dimensions, the remaining 2 being wrapped around an S^2 contained in the S^3 of the conifold geometry. The position of this S^2 within the S^3 is described by an angular variable ψ. The state of the system can then be encapsulated by the dynamics of a scalar field ψ, initially in a false vacuum $\psi_{fv} \in [0, \pi/4)$, and whose value in the true vacuum is $\psi_{tv} = \pi$ [24]. The Lagrangian describing this system (setting $M_s \equiv 1/\sqrt{\alpha'} = 1$ and in red-shifted units, so hiding the warp factor w_{IR}) is [24]

$$\mathcal{L} \approx \frac{\mu_3 M}{g_s}\left(-V_2(\psi)\sqrt{1-\partial_\mu\psi\partial^\mu\psi} + \frac{1}{2\pi}(2\psi - \sin 2\psi)\right), \tag{1}$$

where

$$V_2(\psi) = \frac{1}{\pi}\sqrt{b_0^4 \sin^4\psi + (\pi\frac{p}{M} - \psi + \frac{1}{2}\sin 2\psi)^2}, \tag{2}$$

with $\mu_3 = (2\pi)^{-3}$ and $b_0^2 \approx 0.93266$. When $p/M < r_c$ the potential has a local minimum below $\psi = \pi/4$, while for $p/M \geq r_c$ only the minimum at $\psi_{tv} = \pi$ exists. (We refer the reader to [24] for further details.)

Typical values of the flux quanta are $K, M \lesssim \mathcal{O}(10^2)$ [17,46], and a string coupling $g_s \ll 1$ is required for the validity of this effective action, with $g_s \sim \mathcal{O}(10^{-2})$ appropriate to accommodate the correct SM couplings [47]. For illustration, we take $M = 10^2$ and $g_s = 0.03$ in this work. Since we consider different values of the warp factor w_{IR}, this amounts to varying K.

Note that the local non-compact set-up of [24], used in this letter, suffers from back-reaction of $\overline{D3}$-branes on the geometry.

[1] In this work, we assume $T_{rh} \gtrsim 4$ MeV so that Big Bang Nucleosynthesis can proceed undisrupted, although we note that this assumption can be relaxed within more general early Universe histories.

[2] The case $T_{th} \neq 0$ would lead to *thermally assisted* quantum tunnelling decay, or a *purely thermal transition* if T_{th} is high enough, similar to the Randall–Sundrum case [38–42].

[3] A period of matter domination (see [45] for an overview), taking place either during or after the transition, but before the start of Big Bang Nucleosynthesis, is a well motivated possibility, and leads to interesting variant phenomenology.