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Signatures of string landscape from inflation

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Open inflation is a cosmological scenario in which the universe is a vacuum bubble nucleated from false vacuum decay and a period of inflationary expansion followed in the nucleated bubble. This scenario is currently receiving renewed interest in the context of the string theory landscape. Since there are a large number of metastable de Sitter vacua in the string landscape, tunneling from one vacuum to another occurs frequently through the bubble nucleation and open inflation is naturally realized. We argue that though the universe appears to be very flat, a small deviation of Ω_0 from unity can make the effect of tensor-type perturbations on the large angle CMB anisotropy significant. Thus we are already testing the string landscape against observations.

Keywords: *string landscape, false vacuum decay, open inflation.*

1 Introduction

Open inflation is attracting a renewed interest in the context of the string theory landscape [1–4]. Since there are a large number of metastable de Sitter vacua in the string landscape, tunneling transitions between metastable vacua through the bubble nucleation occur frequently, and one of those transitions from a high energy false vacuum to a lower energy vacuum might have lead to our universe. If we assume our universe has been born out of bubble nucleation, then our universe must have gone through an era of inflation after that transition. Since the geometry inside the bubble is a spatially homogeneous and isotropic universe with negative spatial curvature, that is, an open universe, this gives a natural realization of open inflation [5–7].

Although the deviation of Ω_0 from unity is small by the observational bound [8], we argue that the effect of this small deviation on the large angle CMB anisotropies can be significant for tensor-type perturbation in open inflation scenario [9].

We consider the situation in which there is a large hierarchy between the energy scale of the quantum tunneling and that of the slow-roll inflation in the nucleated bubble. If the potential just after tunneling is steep enough, a rapid-roll phase appears before the slow-roll inflation. Then the power spectrum is basically determined by the Hubble rate during the slow-roll inflation. Nevertheless, depending on the model parameters, the power spectrum can keep the memory of the previous high energy density false vacuum in the infrared region, and this effect can affect the large angular components of CMB significantly. In other words, though the deivation of Ω_0 is small, say $1-\Omega_0 = 10^{-2} \sim 10^{-3}$, there are models in which this small deviation is large enough to produce measurable effects.

2 Open inflation

We consider false vacuum decay in a system consisting of a minimally coupled scalar field, ϕ with Einstein gravity. The action is given by

$$S = \int \sqrt{-g} d^4x \left[\frac{1}{2\kappa} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right] , \qquad (1)$$

where $\kappa = 8\pi G_N$, or the inverse of the Planck mass squared; $\kappa = M_{pl}^{-2}$. An $O(4)$-symmetric bubble nucleation is described by the Euclidean solution (instanton) [10, 11]. The metric is given by

$$ds^2 = a_{\rm E}^2 \left(d\eta_{\rm E}^2 + d\chi_{\rm E}^2 + \sin^2 \chi_{\rm E} d\Omega^2 \right) , \qquad (2)$$

and the background scalar field is denoted by $\phi = \phi(\eta_{\rm E})$. The Euclidean equations are given by

$$\left(\frac{a'_{\rm E}}{a_{\rm E}} \right)^2 - 1 = \frac{\kappa}{3} \left(\frac{1}{2} \phi'^2 - V(\phi) a_{\rm E}^2 \right) , \qquad (3)$$

$$a_{\rm E} \left(\frac{\dot a_{\rm E}}{a_{\rm E}} \right)^{\cdot} + 1 = -\frac{\kappa}{2} \phi'^2 , \qquad (4)$$

$$\ddot\phi + 2 \frac{\dot a_{\rm E}}{a_{\rm E}} \dot\phi - V'(\phi) a_{\rm E}^2 = 0 , \qquad (5)$$

where the prime represents differentiation with respect to $\eta_{\rm E}$.

The background geometry and the field configuration in the Lorentzian regime are obtained by the analytic continuation of the instanton. The coordinates in the Lorentzian regime are given by

$$\eta_{\rm E} = \eta_{\rm C} = -\eta_{\rm R} - \frac{\pi}{2} i = \eta_{\rm L} + \frac{\pi}{2} i , \qquad (6)$$

$$\chi_{\rm E} = -i\chi_{\rm C} + \frac{\pi}{2} = -i\chi_{\rm R} = -i\chi_{\rm L} , \qquad (7)$$

$$a_{\rm E} = a_{\rm C} = i a_{\rm R} = i a_{\rm L} . \qquad (8)$$

The Penrose diagram for this open universe is presented in Fig. 1.

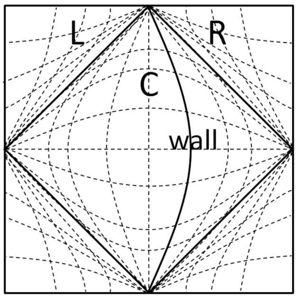

Figure 1: The Penrose diagram of a universe with bubble nucleation. The region R is an open universe inside the bubble, which corresponds to our universe.

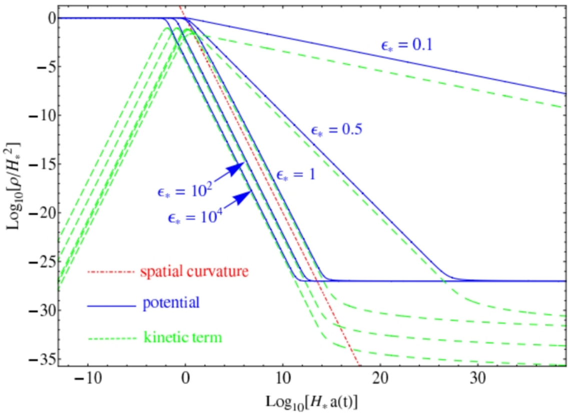

Figure 2: The evolution inside the bubble for an exponential type potential model.

After tunneling, the scalar field starts to roll down the potential. If the vacuum energy of the false vacuum is high, as expected in the string theory landscape, there will be a phase during which the scalar field rolls down rapidly. This rapid roll phase will end when the energy scale becomes sufficiently low and a slow-roll phase commences which should last just about 50 to 60 e-folds, to make our universe slightly open, $1-\Omega_0 = 10^{-2} \sim 10^{-3}$.

To study the field dynamics inside the bubble, it is useful to recall the identity,

$$\frac{d\ln\rho_\phi}{d\ln a_{\mathrm{R}}} = -3\left(1+w_\phi\right), \tag{9}$$

where $\rho_\phi = \dot\phi^2/2+V$, $p_\phi = \dot\phi^2/2-V$ and $w_\phi \equiv p_\phi/\rho_\phi$. The asymptotic boundary conditions at the nucleation point are given by

$$a_{\mathrm{R}}(t) = t\,, \quad \dot\phi(t) = -\frac{V'(\phi_*)}{4}t\,. \tag{10}$$

Thus, we have

$$1+w_\phi = \mathcal{O}\left(\frac{\dot\phi^2}{V}\right) = \mathcal{O}\left(\epsilon_* H_*^2 t^2\right). \tag{11}$$

where we have introduced the 'slow-roll parameter,'

$$\epsilon \equiv \frac{1}{2\kappa}\left(\frac{V'}{V}\right)^2, \tag{12}$$

and $\epsilon_* = \epsilon(\phi_*)$ and $H_*^2 \equiv \kappa V(\phi_*)/3$.

As an example, the evolution of various quantities inside the bubble for a potential of the form,

$$\frac{\kappa}{3}V(\phi) = \left(H_*^2 - H_{\mathrm{R}}^2\right)\exp\left[\sqrt{2\kappa\epsilon_*}\,(\phi-\phi_*)\right] + H_{\mathrm{R}}^2\,, \tag{13}$$

where $H_* \gg H_R$, is shown in Fig. 2, where the constant term H_{R}^2 is added to realize slow-roll inflation after the rapid-roll phase. Namely, $\epsilon(\phi) \sim \epsilon_*$ for $\phi \gg \phi_*$ and $\epsilon(\phi) \ll \epsilon_*$ for $\phi \ll \phi_*$.

As seen from this figure, during the rapid-roll phase there is a tracking behavior for $\epsilon_* \gtrsim 1$. In particular, for $\epsilon_* = O(1)$, the scalar field energy dominates over the curvature term during the rapid-roll phase. As discussed later, this makes all the perturbations existed at the time of nucleation to be effectively frozon until the subsequent slow-roll phase. In short, the memory of the previous false vacuum remains in the spectrum of perturbations inside the bubble if $\epsilon_* = O(1)$.

3 Tensor spectrum in the landscape

The tensor spectrum in the bubble universe may be calculated following the method developed in [12, 13]. The important point is that it reflects both the properties of the tunneling and the evolution inside the bubble. More specifically there are effects from the fluctuations of the bubble wall and the evolution during the rapid-roll phase inside the bubble.

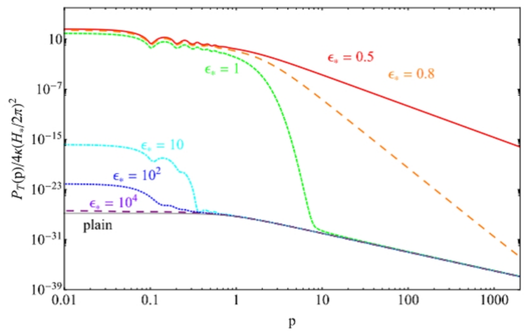

Figure 3: The tensor-type power spectrum for the exponential-type potential, Eq. (13). For comparison, we also plot the plain de Sitter vacuum spectrum by the thin gray line.

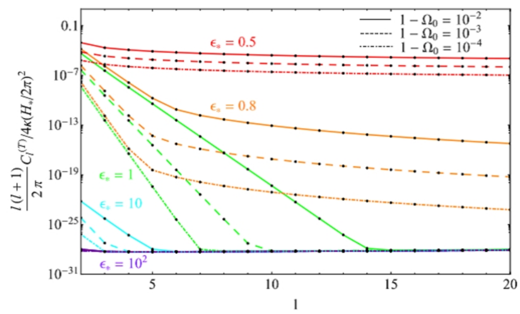

Figure 4: The CMB angular power spectrum from the tensor type perturbations for the exponential-type potential, Eq. (13).

The effect of the bubble wall fluctuations was discussed more than a decade ago [14], where it was found that the infrared part of the spectrum is dominated by the wall fluctuations if the wall is sufficiently soft, that is, if the wall tension is small, $\Delta s = \kappa S_1/2H_* \ll 1$, where S_1 is the wall tension. In other words, models that would yield too soft tension of the wall are already excluded from the current observational data.

Here we focus on the effect of the evolution inside the bubble. The resulting spectrum for the potential (13) is shown in Fig. 3. The solid curves are, from top to bottom, the spectrum with $\epsilon_* = 0.5$, 0.8, 1, 10, 10^2 and 10^4. The contribution from the wall fluctuation mode is assumed to be negligible. As seen from this figure, it is clear that the infrared part of the spectrum is enhanced substantially for $\epsilon_* = O(1)$. This means that the memory of the large vacuum fluctuations associated with the high vacuum energy right after the tunneling is preserved if $\epsilon_* = O(1)$ and can affect the observable part of the spectrum unless $1-\Omega_0$ is extremely small.

4 CMB temperature anisotropy

We translate the spectrum for tensor-type perturbation obtained in the preceding subsection into CMB temperature anisotropies, following the method given in Ref. [14]. The large-angle CMB temperature anisotropies due to tensor-type perturbation can be simply evaluated by the Sachs-Wolfe formula [15],

$$\frac{\Delta T}{T}(\hat{\boldsymbol{n}}) = -\frac{1}{2}\int_{\eta_{\rm LSS}}^{\eta_0} d\eta\, \delta g'_{ij}\left(\eta, x^i(\eta)\right)\hat{n}^i\hat{n}^j\,, \qquad (14)$$

where η_0 and $\eta_{\rm LSS}$, respectively, denote the conformal time at the present epoch and that at the last scattering surface, $\hat{n}^i$ is the unit vector along the observer's line-of-sight and $x^i(\eta) = (\eta_0 - \eta)\,\hat{n}^i$ represents the photon trajectory.

The CMB multipole moments for the tensor type perturbations for the exponential-type potential (13) are shown in Fig. 4. The parameters are $\epsilon_* = 0.5$, 0.8, 1, 10 and 10^2. Again for simplicity, the effect of the wall fluctuations is neglected. We see that the tensor CMB angular power spectrum for small ℓ behaves like $(1-\Omega_0)^\ell$, while it agrees with the scale invariant inflationary tensor spectrum for large ℓ. Comparing it with the amplitude of the tensor perturbation for the standard slow-roll inflation, there is significant enhancement for small ℓ if $\epsilon_* \sim 1$. Hence, we conclude that, if ϵ is of order unity right after tunneling, the rapid roll phase affects the CMB spectrum at low ℓ significantly.

5 Summary

We studied an open inflation in the context of the string theory landscape. We assumed that our universe is an open universe with a moderately small $1-\Omega_0$, born as a bubble nucleated through false vacuum decay. We then discussed that the infrared part of the tensor perturbation can contain the memory of the string landscape, and hence can constrain the landscape considerabley. In fact, we argued that the current observational data already constain the string theory landscape, and near-future data may be able to make yet more strong statements on the string theory landscape. Apparently this is a very exciting topic which should be studied further.

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СИГНАТУРА ЛАНДШАФТА В ТЕОРИИ СТРУН ИЗ ИНФЛЯЦИОННОГО ПЕРИОДА

Открытая инфляция является космологическим сценарием, в котором Вселенная представляет собой вакуумный пузырь, порождаемый распадом фальшивого вакуума и затем периода инфляционного расширения в этом пузыре. Этот сценарий в настоящее время привлекает повышенный интерес в контексте ландшафта теории струн. Поскольку существует большое количество метастабильных вакуумов де Ситтера в струнном ландшафте, часто туннелирование из одного вакуума в другой происходит через зарождение пузыря и, естественным образом, реализуется открытая инфляция. В работе приводятся доводы в пользу того, что, хотя Вселенная и представляется плоской, малое отклонение Ω_0 от единицы может породить возмущения тензорного типа на большой угол анизотропии КМФ. Так в настоящий момент производится тестирование струнного ландшафта с наблюдательными данными.

Ключевые слова: *струнный ландшафт, распад ложного вакуума, открытая инфляция.*

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