Curvatons in Warped Throats

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Abstract

We present a curvaton model from type IIB string theory compactified on a warped throat with approximate isometries. Considering an (anti-)D3-brane sitting at the throat tip as a prototype standard model brane, we show that the brane's position in the isometry directions can play the role of curvatons. The basic picture is that the fluctuations of the (anti-)D3-brane in the angular isometry directions during inflation eventually turns into the primordial curvature perturbations, and subsequently the brane's oscillation excites other open string modes on the brane and reheat the universe. We find in the explicit case of the KS throat that a wide range of parameters allows a consistent curvaton scenario. It is also shown that the oscillations of branes at throat tips are capable of producing large non-Gaussianity, either through curvature or isocurvature perturbations. Since such setups naturally arise in warped (multi-)throat compactifications and are constrained by observational data, the model can provide tests for compactification scenarios. This work gives an explicit example of string theory providing light fields for generating curvature perturbations. Such mechanisms free the inflaton from being responsible for the perturbations, thus open up new possibilities for inflation models. The discussions in this paper are based on [1].

1 Introduction

An important feature of string cosmology is its high sensitivity to the physics of string compactification. This imposes stringent restrictions on string inflationary models, and it is nontrivial whether the inflaton can generate the primordial curvature perturbations. However, one can expect some field(s) other than the inflaton to have generated the curvature perturbations, as in the case of the curvaton scenario [2–5]. In this paper, we present a simple curvaton model from string theory compactified on a warped throat with approximate isometries. A good example of such throats is the deformed conifold [6] in type IIB string theory, where it has been shown that fluxes and nonperturbative effects can stabilize all its moduli [7, 8]. Considering an (anti-)D3-brane sitting at the throat tip as a prototype standard model brane, we show that the brane's position in the isometry directions can play the role of the curvaton. The basic picture is that the fluctuations of the (anti-)D3-brane in the angular isometry directions during inflation eventually turns into the primordial curvature perturbations, and subsequently the brane's oscillation excites other open string modes on the brane and reheat our universe. We find in the explicit case of the Klebanov-Strassler (KS) throat [6] that a wide range of parameters allows a consistent curvaton scenario. The discussions in this paper are based on [1].

2 Effective Action

Let us consider the six-dimensional internal space to be compactified to a (conformally) Calabi-Yau (CY) space which includes warped deformed conifold throat regions, whose leading order background geometry takes the following form,

$$ds^2 = h(r)^2 g^{(4)}_{\mu\nu} dx^\mu dx^\nu + h(r)^{-2} \left(dr^2 + r^2 g^{(5)}_{mn} d\theta^m d\theta^n \right), \tag{1}$$

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where r is the radial coordinate which decreases as one approaches the tip of the throat, and θ^m are the five-dimensional angular coordinates. $h(r)$ is the warp factor, which is to leading order independent of the angular coordinates.

Assuming that we are living on an $\overline{\text{D3}}$-brane sitting at the tip of the conifold throat, the angular position of the $\overline{\text{D3}}$ in the isometry directions plays the role of curvatons. However, since the throat is glued to the bulk CY which in general do not preserve such isometries, the throat isometries are broken. Also, nonperturbative effects that stabilize the Kähler moduli confine the $\overline{\text{D3}}$ to certain loci on the tip. The warping of the throat suppresses all such effects at the tip, and consequently the angular position of the $\overline{\text{D3}}$ receives small mass and couplings to other open string modes on the brane. As a consequence, one can obtain the curvaton action from the DBI and CS terms of a probe $\overline{\text{D3}}$-brane inside a GKP[7]-type warped throat,

$$\frac{\mathcal{L}}{\sqrt{-g^{(4)}}} \simeq -(\partial\sigma)^2 + \bar{\psi} i \not{D} \psi - (m_{\text{bulk}}^2 + m_{\text{np}}^2)\sigma^2 + \frac{g_s M^{1/2} \alpha'^{3/2}}{h_0^3} \frac{m_{\text{bulk}}^2 m_{\text{np}}^2}{m_{\text{bulk}}^2 + m_{\text{np}}^2} \sigma \bar{\psi} i \not{D} \psi, \tag{2}$$

where g_s is the string coupling, α' is the string scale, M is the R-R flux number of the throat, and h_0 is the warp factor at the throat tip. Here we have focused on the flattest angular direction θ (among the three angular directions of the S^3 tip), and assumed that the $\overline{\text{D3}}$ is stabilized in the other directions. The curvaton σ is obtained by canonically normalizing this direction,

$$\sigma \equiv \sqrt{T_3} r_0 \theta, \tag{3}$$

where r_0 is the IR cutoff of the deformed conifold and $T_3 \sim 1/(g_s \alpha'^2)$ is the D3 ($\overline{\text{D3}}$) tension. Also, ψ is the world-volume fermion, into which the angular degrees of freedom (i.e. the curvaton) decay first. (We assume that (some of) the world-volume fermions are significantly lighter than the curvaton.)[3] We have dropped numerical factors and will carry out order-of-magnitude estimations in this paper.

The masses arising from bulk and nonperturbative effects are defined as follows, respectively,

$$m_{\text{bulk}}^2 \equiv \frac{h_0^{\Delta}}{r_0^2} \sim \frac{h_0^{\Delta-2}}{g_s M \alpha'}, \qquad m_{\text{np}}^2 \equiv \frac{h_0^{\lambda-2}}{g_s M \alpha'}, \tag{4}$$

The symbols Δ and λ respectively denote how much the bulk and nonperturbative effects are suppressed in terms of the warp factor. By comparing Δ and λ, one can measure the relative strength of the bulk and nonperturbative effects at the throat tip, e.g., $\Delta \sim 5.3$ for a KS throat [9], and $\lambda \sim 5.5$ for simple cases of the Kuperstein embedding of wrapped D7-branes [10]. The point we would like to emphasize is that various effects with different angular dependence misalign the (local) minima of the potential and interaction terms, hence providing decay channels to the curvaton.

Since the field range of σ is restricted by the radius of the S^3 tip, one statistically expects that the field value of the curvaton during inflation is

$$\sigma_* \sim \frac{h_0 M^{1/2}}{\alpha'^{1/2}}. \tag{5}$$

3 Cosmological Perturbations

Equipped with the information on the angular position of the $\overline{\text{D3}}$-brane discussed in the previous section, let us look into the parameter space and show that the angular oscillation of the $\overline{\text{D3}}$ at the throat tip actually plays the role of the curvaton. We assume that the SM particles are realized on the curvaton $\overline{\text{D3}}$-brane. How the SM particles are realized on the world-volume of the D-brane is out of the scope of this paper, though one naively expects that the interactions among the open string modes on the brane is suppressed by the local string scale. The decay rate from the curvaton to the world-volume fermions is further suppressed by the warp factor. Therefore, after the curvaton decay into world-volume fermions,

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[3] One can check that the decay of the curvaton into world-volume fermions induced by the three-point term in (2) is the most important interaction. The curvaton also interacts with world-volume gauge fields, gravitons, and Kaluza-Klein modes in the throat, but those interactions have no major effect on the curvaton dynamics, perturbatively nor through parametric resonance.

we can expect the fermions to soon decay into or thermalize with the SM particles (or particles that eventually turn into SM particles). For the cosmic inflation, we do not specify its details. However, we assume that the inflaton energy is transferred to radiation right after the end of inflation. In cases where the curvaton dominates the universe before it decays, the reheating of the universe is sourced by the decay of the curvaton. On the other hand, if the curvaton is subdominant at decay, then reheating should rely on the remnants of inflation. We require the curvaton to decay before BBN, but if one also wants to incorporate baryogenesis, then the decay time should be corrected according to the baryogenesis scenario.

In addition to such cosmological requirements, several microscopic constraints need to be satisfied. In order to trust our action (2), the curvaton brane has to be moving nonrelativistically. Furthermore, the Hubble parameter during inflation should be smaller than the local string scale of the throat to avoid stringy corrections to the throat. For the same reason, the curvaton's oscillation energy also should be smaller than the local string scale.

We illustrate the parameter space on the Δ-λ plane in Figure 1. The remaining four parameters (i.e. g_s, M, h_0, and the length scale of the internal bulk $L/\alpha'^{1/2}$) are fixed to the values explained in the caption. One sees that as Δ or λ increase, i.e. the bulk or nonperturbative effects weaken, the decay rate of the curvaton is suppressed and the curvaton comes closer to dominating the universe before decay. The figure clearly shows that when either the bulk or nonperturbative effect is absent, i.e. Δ or $\lambda \to \infty$, the curvaton cannot decay, and one crosses the orange line which is the BBN constraint. As we take different values for the four parameters g_s, M, $L/\alpha'^{1/2}$, and h_0, the consistent region (the yellow region in the figure) deforms and shifts in the Δ-λ plane. Though we have shown only a single example, one can check that consistent curvaton scenarios are allowed for broad ranges of the parameters.

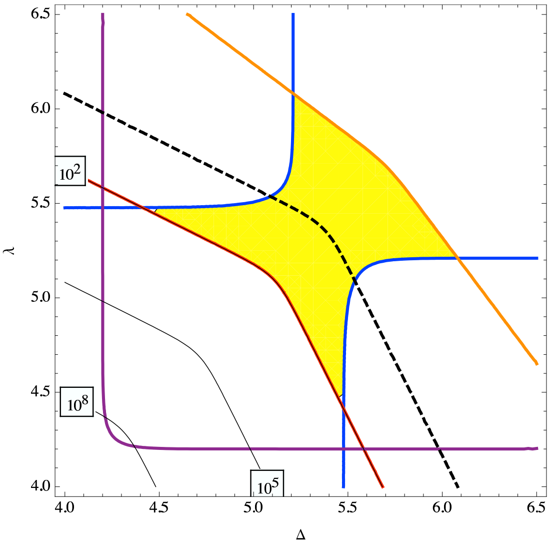

Figure 1: The consistency conditions for the curvaton scenario on the Δ-λ plane, where the other parameters are set to $g_s = 0.1$, $M = 300$, $L/\alpha'^{1/2} = 3$, $h_0 = 10^{-5}$ (hence $N \sim 50000$, $K \sim 200$, $M_{\rm Pl}\alpha'^{1/2} \sim 300$). The lines denote where each condition is saturated, blue: masslessness of the curvaton, orange: decay before BBN, red: $f_{\rm NL} \lesssim 100$, purple: curvaton oscillation energy bound. The yellow region satisfies all four conditions. (In this case, these four conditions include other cosmological and microscopic requirements.) On the right (left) side of the dashed line, the curvaton dominates (subdominates) the universe at the decay epoch. The produced non-Gaussianities are also shown as contour lines for $f_{\rm NL}$. Here the inflation scale can be estimated from $H_{\rm inf}/M_{\rm Pl} \sim 10^{-11} f_{\rm NL}$.

4 Conclusions

We have proposed a model for generating the primordial perturbations and reheating our universe from angular oscillations of D-branes at the tip of throats. The geometrical features of throats – warping and (approximate) isometries – yielded curvaton scenarios. We have also seen that effects that break the force-free condition of the D-brane in the isometry directions, such as the isometry breaking bulk effects and moduli stabilizing nonperturbative effects played an important role in our model. Depending on the (un)balance between the various features of the background geometry, the curvaton model shows different behaviours, e.g., the curvaton may contribute mainly to non-Gaussianity, or survive until now and contribute to dark matter, generating non-Gaussian isocurvature perturbations. These cases of interest are further studied in [1], where it is shown that each scenario can be realized in a wide range of parameter space. In other words, our model may be considered as generally arising from compactification scenarios containing warped throats with isometries. Therefore, it may serve as a test for discussing the validness of (multi-)throat compactification scenarios. The curvaton model is capable of producing large non-Gaussianity, and upcoming CMB experiments are expected to allow us to give more rigorous arguments.

One of the general lessons of our work is that in string theory, one finds it quite natural to consider fields other than the inflaton for generating the primordial perturbations. Such light fields can be realized in string theory, thus giving rise to mechanisms which may have seemed too intricate from the phenomenological point of view. It is fair to say that top-down approaches to inflationary cosmology can provide us with rich ideas beyond the standard slow-roll inflation pictures.

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References

[1] T. Kobayashi and S. Mukohyama, JCAP **0907**, 032 (2009) [arXiv:0905.2835 [hep-th]].

[2] A. D. Linde and V. F. Mukhanov, Phys. Rev. D **56**, 535 (1997) [arXiv:astro-ph/9610219].

[3] K. Enqvist and M. S. Sloth, Nucl. Phys. B **626**, 395 (2002) [arXiv:hep-ph/0109214].

[4] D. H. Lyth and D. Wands, Phys. Lett. B **524**, 5 (2002) [arXiv:hep-ph/0110002].

[5] T. Moroi and T. Takahashi, Phys. Lett. B **522**, 215 (2001) [Erratum-ibid. B **539**, 303 (2002)] [arXiv:hep-ph/0110096].

[6] I. R. Klebanov and M. J. Strassler, JHEP **0008**, 052 (2000) [arXiv:hep-th/0007191].

[7] S. B. Giddings, S. Kachru and J. Polchinski, Phys. Rev. D **66**, 106006 (2002) [arXiv:hep-th/0105097].

[8] S. Kachru, R. Kallosh, A. D. Linde and S. P. Trivedi, Phys. Rev. D **68**, 046005 (2003) [arXiv:hep-th/0301240].

[9] O. Aharony, Y. E. Antebi and M. Berkooz, Phys. Rev. D **72**, 106009 (2005) [arXiv:hep-th/0508080].

[10] O. DeWolfe, L. McAllister, G. Shiu and B. Underwood, JHEP **0709**, 121 (2007) [arXiv:hep-th/0703088].