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Warping the Weak Gravity Conjecture

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ABSTRACT

The Weak Gravity Conjecture, if valid, rules out simple models of Natural Inflation by restricting their axion decay constant to be sub-Planckian. We revisit stringy attempts to realise Natural Inflation, with a single open string axionic inflaton from a probe D-brane in a warped throat. We show that warped geometries can allow the requisite super-Planckian axion decay constant to be achieved, within the supergravity approximation and consistently with the Weak Gravity Conjecture. Preliminary estimates of the brane backreaction suggest that the probe approximation may be under control. However, there is a tension between large axion decay constant and high string scale, where the requisite high string scale is difficult to achieve in *all* attempts to realise large field inflation using perturbative string theory. We comment on the Generalized Weak Gravity Conjecture in the light of our results.

1. Introduction

Cosmological inflation stands strong as the leading mechanism to provide the seeds that gave rise to the large structure we observe today in the Universe. Precision observations in the Cosmic Microwave Background provide a window into this very early history of the Universe. The latest results from Planck [1] are in perfect agreement with the simplest inflationary models, driven by the dynamics of a single scalar field rolling down a very flat potential. Current bounds from Planck/BICEP2 on the scalar to tensor ratio in the CMB power spectrum are $r \lesssim 0.12$ (95% CL). Any future detection of tensor modes would have the remarkable implications, via the Lyth relation [2–4], that inflation occurred at scales close to the Planck scale:

$$V_{inf}^{1/4} \approx \left(\frac{r}{0.1}\right)^{1/4} \times 1.8 \times 10^{16}\,\text{GeV} \tag{1}$$

and that the inflaton field had super-Planckian excursions:

$$\frac{\Delta\phi}{M_{Pl}} \gtrsim 0.25 \times \left(\frac{r}{0.01}\right)^{1/2} . \tag{2}$$

"Large field" inflationary models are intriguing not only due to their robust prediction of high scale inflation with observable primordial gravitational waves. They depend sensitively on the degrees of freedom comprising the ultraviolet completion of gravity. In particular, Planck suppressed corrections to the slow-roll inflaton potential typically become large when the inflaton varies over super-Planckian scales. One idea to protect the slow-roll inflaton potential from dangerous quantum corrections is to invoke a shift symmetry in the inflaton field, for instance by identifying the inflaton with a Goldstone boson, the axion. The classical example in this vein is Natural Inflation [5], now tightly constrained by the latest CMB observations.[1] In Natural Inflation, the axion enjoys a continuous shift symmetry within the perturbative approximation. This is broken to a discrete symmetry by non-perturbative effects, which generate a potential of the form:

$$V(\phi) = V_0 \left(1 \pm \cos\left(\frac{\phi}{f}\right)\right) , \tag{3}$$

where f is the axion decay constant. The potential is sufficiently flat for slow-roll inflation provided that $f \gg M_{Pl}$, and as a consequence the axion can undergo super-Planckian field excursions.

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[1] Although massive modes during inflation can change the classic NI predictions by generating a smaller than unity speed of sound bringing the model back to the allowed parameter region, as shown in [6].

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The current bound on the Natural Inflation potential (3), given by PLANCK from the spectral index, n_s, is $f/M_{Pl} \gtrsim 6.8$ (95% CL) [1].

To understand whether or not such ideas are viable requires the embedding of large field models in a theory of quantum gravity. In fact, much interest has recently been generated by the possibility that general features of quantum gravity can constrain inflationary models with observable consequences. The Weak Gravity Conjecture [7] roughly proposes that gravity must be the "weakest force" in a quantum theory of gravity, in order to avoid stable black hole remnants. For example, for a four dimensional theory describing gravity and a $U(1)$ gauge sector with gauge coupling, $\mathbf{g}$, there must exist a state with mass, m, which satisfies $m \lesssim M_{Pl}\,\mathbf{g}$. Moreover, the effective field theory has a new UV cutoff scale, $\Lambda \sim M_{Pl}\,\mathbf{g}$. This conjecture was used [7] to rule out Extra Natural Inflation [8], where the inflaton arises from a Wilson line in a five-dimensional $U(1)$ gauge theory compactified on a circle.

The Weak Gravity Conjecture might also be generalized to D dimensions, p-form Abelian gauge fields, and their p spacetime dimensional charged objects. Then, in a four dimensional gravitational theory with a 0-form axion, there must exist an instanton with action, $S_{cl} \lesssim M_{Pl}/f$, where f is the axion decay constant. Although this conjecture lacks convincing motivation from black hole physics, the same phenomenon was observed in [9] in several diverse string theoretic setups. If valid, it would essentially rule out single field models of inflation with super-Planckian axion decay constants, as instanton corrections would always introduce higher harmonics to the inflation potential:

$$e^{n\frac{M_{Pl}}{f}} e^{in\theta} \,, \tag{4}$$

effectively limiting the axion field range. Analogous arguments considering gravitational instantons in effective field theory lead to similar conclusions [10]. Moreover, the examples studied in [9] demonstrated the difficulty in obtaining axions with large decay constants within the limits of perturbative string theory, and raised the question if this is possible at all.

Recent work has focused on whether these constraints from the Generalized Weak Gravity Conjecture on axion inflation can be evaded, in particular, by introducing multiple axion fields [11–19]. There has also been a large amount of work towards developing string theoretic models of large field inflation with sub-Planckian axion decay constants. These come under two main classes, firstly, stringy mononomial chaotic inflation scenarios where monodromy effects explicitly break the axion shift symmetry [20–28], and secondly, many field models where multiple axions generate an effective decay constant that is super-Planckian [29–34]. Most constructions have used closed string axions in type II string theory.

In this letter, we revisit open string, single field models of axion inflation, in the light of quantum gravity constraints and the Weak Gravity Conjecture discussed above. Open string inflatons include Wilson lines on wrapped Dp-branes and the position moduli of moving Dp-branes. In fact, these scenarios are T-dual to each other. By considering D3-branes moving down a long warped throat, Baumann and McAllister pointed out a rigid, sub-Planckian upper bound on the field range [35,36], and this can indeed be interpreted as a consequence of the Weak Gravity Conjecture. However, single field models have been proposed with moderately super-Planckian decay constants. Wilson lines on wrapped Dp-branes with sub-Planckian decay constants were studied in [37], and with super-Planckian decay constants in [38]. Planckian decay constants from wrapped Dp-branes moving down or around a warped throat were found, respectively, in [39] and [40].

We show that warping and wrapped volumes indeed allow for single field models with super-Planckian axion decay constant consistently with the Weak Gravity Conjecture. The large decay constants are generated within the perturbative limits of the supergravity approximation, and initial estimates support the validity of the probe brane approximation used. Moreover, scalar potentials that break the continuous axion shift symmetry to a discrete one are potentially generated by classical or loop effects [8,40–43]. Therefore, any non-perturbative instanton effects are by construction exponentially suppressed, and would not rule out single field, large field, slow-roll inflation.

Unfortunately, these results do not lead to promising models of large field inflation and observable primordial gravitational waves. This is because in explicit constructions, there is a tension between obtaining large decay constant and high string scale. In fact, as we emphasize, it is always difficult to obtain a sufficiently high string scale within the limits of perturbation theory. This presents an important challenge in building string theoretic models of large field inflation.

The paper is organized as follows. In the next section we introduce inflation from D-branes in warped geometries and fix our conventions. In Section 3 we study scenarios in which the candidate axionic inflaton is a Wilson line on a wrapped D-brane, and in Section 4 we turn to the T-dual picture of the position modulus of a wrapped D-brane. The most attractive scenario studied can be found at the end of this section. Finally, in Section 5 we discuss our results, and the light they shed on the Generalized Weak Gravity Conjecture.

2. Open string inflation

Our starting point is a generic type IIB string warped compactification from ten to four dimensions with metric (in the Einstein frame[2]):

$$ds^2 = h^{-1/2}(r) g_{\mu\nu} dx^\mu dx^\nu + h^{1/2}(r) g_{mn} dx^m dx^n \,, \tag{5}$$

where $\mu, \nu = 0, \ldots 3$, $m, n = 4, \ldots 9$ and $h(r)$ is the warp factor, possibly trivial, depending on a radial-like direction in the internal space. For example, for an $adS_5 \times X_5$ geometry which describes well a generic warped throat generated by branes and fluxes in the mid-throat region, we have:

$$h(r) = L^4/r^4 \quad \text{and} \quad ds_6^2 = g_{mn} dx^m dx^n = dr^2 + r^2 d\Omega_5^2 \,, \tag{6}$$

where L is the adS length scale and $d\Omega_5^2 = \tilde{g}_{ij} d\phi^i d\phi^j$ is the metric on some five-dimensional Einstein–Sasaki space that ensures $\mathcal{N} = 1$ supersymmetry. To construct a smooth, compact internal space out of the adS throat, we take $r_{IR} < r < r_{UV}$, where the adS region is glued to the tip of the throat at the IR cutoff and to a compact Calabi–Yau at the UV cutoff [44].

The four-dimensional Planck mass after compactification takes the form:

$$M_{Pl}^2 = \frac{4\pi \mathcal{V}_6^w}{g_s^2} M_s^2 \quad \text{with} \quad \mathcal{V}_6^w l_s^6 = \int d^6 y \sqrt{\det g_{mn}}\, h \,, \tag{7}$$

where we defined the string scale as $l_s^2 = M_s^{-2} = (2\pi)^2 \alpha'$, $g_s = e^{\varphi_0}$ is the string coupling and $\mathcal{V}_6^w$ is the warped volume of the six-dimensional internal space in string units. For example, assuming most of the volume comes from the middle region of an adS throat generated by N D3-branes at its tip, we have:

$$L^4 = \frac{g_s N}{4 \mathcal{V}_5} l_s^4 \tag{8}$$

[2] Our conventions for going from string to Einstein frame are $G^E_{MN} = e^{\frac{\varphi_0 - \varphi}{2}} G^s_{MN}$, where φ is the dilaton, whose vev $\langle \varphi \rangle = \varphi_0$ defines the string coupling as $g_s = e^{\varphi_0}$. In these conventions the volumes evaluated in the background are frame independent.