On De Sitter Vacua in Strongly Coupled
Heterotic String Theory

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Abstract

We describe how 4d de Sitter vacua might emerge from 11d heterotic M-theory. Non-perturbative effects and G-fluxes play a crucial role leading to vacua with F-term supersymmetry breaking and a positive energy density. Charged scalar matter fields are no longer massless in these vacua thus solving one of the problems of the heterotic string. Moreover, interesting dark matter candidates appear in a natural way.

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1 Introduction

There is great interest in connecting M-theory to real cosmology. On the one hand, there are no high energy experiments testing M-theory in its generic regime (meaning where all extra dimensions are much smaller than of inverse TeV-scale size) thus rendering cosmology an important ‘experimental’ alternative. On the other hand, one should expect that M-theory in its final formulation will be able to give insight into the origin of inflation and ultimately tell us how to cure the big bang singularity. While the latter problem seems to require first the full microscopic formulation of M-theory for its answer, it seems that the former can already be tackled with current local field theory approximations of M-theory in the form of 11d supergravity.

As a first important step in this direction we have to find robust mechanisms which allow us to obtain 4d de Sitter spacetimes from M-theory. As de Sitter spacetimes with large unsuppressed cosmological constants are relevant during inflation, even the derivation of de Sitter spacetimes without an accompanied solution to the cosmological constant problem will be important (the solution to the cosmological constant problem seems once more to require a much better understanding of the microscopic M-theory and its degrees of freedom which might very well be discrete and finite [1]). In this talk I will focus on heterotic M-theory [2] for two reasons. First, heterotic M-theory includes M-theory in its bulk and is therefore the more general starting point. Second, due to the $E_8$ gauge groups on its 10d boundaries and various phenomenological virtues (see [3] for a review) this theory seems to be ideal to address cosmology with realistic matter and gauge fields.

Let’s consider therefore heterotic M-theory compactified on $CY \times S^1/Z_2$ ($CY =$ Calabi-Yau threefold) from 11d down to 4d. In order to obtain de Sitter vacua we will have to break supersymmetry. Preferentially, this should happen spontaneously through F-term breaking. To this end the inclusion of non-perturbative effects into the dimensionally reduced effective 4d theory will be important. These effects arise either from open membrane instantons (OMI) stretching through the bulk between the two boundaries or from gaugino condensation (GC) on the hidden boundary [4] (in more complicated vacua also M5-instantons wrapping the complete internal CY threefold could be included and might even be required in order to satisfy the anomaly cancelation condition [15]). As these effects lead to boundary-boundary forces (for earlier 11d studies of these see [5]) they are natural candidates for a stabilization of the dilaton which in heterotic M-theory corresponds to the orbifold length $L$. Note that further non-perturbative effects which would be allowed by M-theory, e.g. OMIs wrapping supersymmetric 3-cycles on the internal CY
threefold are not compatible with the supersymmetry preserved by the two boundaries. Therefore since we want to start with a supersymmetric configuration in 11d the first two non-perturbative effects are exhausting and indeed have to be included as they cannot be avoided (as to GC note that in heterotic M-theory the strong coupling of the hidden gauge group is not an option in contrast to the weakly coupled heterotic string).

Stabilizing the orbifold length by means of OMI’s has been considered in [6] for the linearized warped background of [21]. This background solves the 11d gravitino Killing-spinor equation to linear order in a series expansion in the warp-factor and it turns out that in the regime where this approximative background is valid, OMI’s are the most dominant non-perturbative effects [8] while GC is exponentially suppressed against them. It is an important feature of heterotic M-theory that in general it is inconsistent to set all $G$-fluxes to zero. For instance the standard embedding of the spin- into the gauge connection no longer leads to a trivial Bianchi identity. Consequently for an 11d background which preserves 4d, $N = 1$ supersymmetry the $G_{2,2}$ (all indices tangent to the CY) flux component deforms the background such that the CY volume decreases along the orbifold from visible towards hidden boundary (one could also have an increase which however doesn’t seem to be phenomenologically relevant). It turns out that at the level of the effective 4d potential one can stabilize the orbifold modulus $L$ by balancing OMI’s against this non-trivial variation of the background geometry along the orbifold which is generated by the $G_{2,2}$ flux component [6]. However, since the linearized background exhibits a linearly decreasing warp-factor and also CY volume one has to introduce an additional M5 brane (4d spacetime-filling and wrapping an internal holomorphic 2-cycle to preserve supersymmetry) whose additional $G_{2,2}$ flux contribution can be used to prevent the metric and therefore the CY volume from becoming negative. This M5 brane gets then stabilized in the middle of the interval [8].

Unfortunately it turns out that if one wants to study the effective 4d potential for the orbifold length modulus $L$ at values larger than the stabilized critical one, one enters the regime where the metric of the linearized background becomes negative and is therefore no longer Riemannian. To cure this state of affairs one should go to the exact non-linear background which always gives a manifestly positive Riemannian metric and therefore positive CY volume [9, 10]. The linearized background is recovered as the tangent approximation to the exact solution at the location of the visible boundary. One then finds working in the exact background and keeping the parallel M5 brane that by considering OMI’s between the M5 and both boundaries the M5 still gets stabilized at the middle of the orbifold interval. Moreover $L$ can be stabilized again by a balance between a nontriv-
Figure 1: The 4d potential caused by OMI’s in units of the reduced Planck scale as a function of the orbifold length $L = L/l$ where $l = 2\pi^{1/3}l_{11}$ and $l_{11}$ is the 11d Planck length.

The dependence of the geometry on $L$ (due to $G_{2,2}$) and OMI effects (see fig[1]). However, huge CY intersection numbers $d \gtrsim 10^4$ (for the simplest case of a CY with $h^{1,1} = 1$) are required. Moreover, the volume of the OMIs in Planck units, $V_{OM}$, turns out to be smaller than 1 at the location of the critical $L$, thereby unfortunately showing that at the minimum one looses control over the supergravity, not to mention that multiply wrapped instantons are no longer suppressed and would contribute as well.

The attractive features of the $L$ stabilization so far – a positive vacuum energy together with spontaneously broken supersymmetry due to $F$-terms – can however be kept when one works in the exact background and takes into account $GC$ [11]. Let us focus here on the simplest case without additional M5-branes. It is important that in the exact background there is no longer the need to suppress $GC$ against $OMI$ for consistency reasoning of the background. The potential due to OMIs decreases with $L$ while that caused by $GC$ increases which suggests a natural $L$ stabilization mechanism by balancing these two effects against each other (see fig[2]). Indeed by working out the full 4d effective potential it turns out that this gives a very robust mechanism of stabilizing $L$ which is...
Figure 3: The 4d potential which results from OMI and GC in units of the reduced Planck scale as a function of the orbifold length $\mathcal{L}$. The hidden gauge group chosen is $SU(4)$.

equivalent to stabilizing the dilaton (see fig\textsuperscript{3}). Without additional M5-branes the exact background exhibits a naked singularity at a finite $\mathcal{L}_{\text{max}} = 1/G_v$ \cite{10} where $G_v$ measures the visible boundary charge associated to the visible boundary $G_{2,2}$ flux. However, since $G_v \propto \mathcal{V}_v^{-1/3}$ ($\mathcal{V}_v$ being the visible boundary CY-volume) this upper bound on $\mathcal{L}$ is pushed towards infinity in the decompactification limit where $\mathcal{V}_v \to \infty$. It is therefore possible to study this limit and to establish the expected runaway behavior towards a zero energy decompactified flat space. Consequently our local positive energy de Sitter vacua are metastable vacua which will not possess the full maximally de Sitter symmetry. It is therefore likely that their isometry group has finite-dimensional representations, a point recently stressed in \cite{13}.

It is satisfying that the OMI-GC balancing mechanism does not need very high CY-intersection numbers $d$ anymore but works already for $d = 1$. The stabilized critical $\mathcal{L}_0$ scales with $d$ as $\mathcal{L}_0 \propto d^{1/3}$. Moreover, it is essential that now the critical $\mathcal{L}_0$ leads to values of the CY volume and OMI volume which are much bigger than Planck size and therefore show that the vacua lie in a regime where supergravity is under control, meaning that higher order corrections to it are sufficiently suppressed. It turns out that beyond exhibiting a stabilized $\mathcal{L}$, also the $S$ and $T$ axions become fixed and the vacuum expectation value (vev) of the 4d charged matter $C$ fields becomes non-trivial. The vev attained by the $C$’s acquires an exponential suppression factor because the minimization for $C$ requires a balancing between the $C$ vev and the two non-perturbative OMI and GC effects. It is therefore generic that the $C$ vev lies far below the (reduced) Planck scale and can be brought close to the TeV regime. This is interesting as it is one of the problematic features of 4d heterotic string vacua, next to the runaway of the dilaton, to give massless charged scalars after supersymmetry breaking through GC (see however \cite{12} for a generation of such mass terms through higher dimensional operators; combined with an anomalous $U(1)$ these lead to supersymmetry breaking). It would clearly be
interesting to see whether the Cev’s could help breaking the visible GUT groups further down to the standard model. Note that in heterotic M-theory there is no reason to prefer the standard embedding of the spin- into the gauge-connection over any non-standard embedding. One is therefore not restricted to an $E_6$ GUT group but could also aim to obtain $SO(10)$ (which was done in the context of elliptically fibered CY’s e.g. in [15]) or the Pati-Salam group $SU(4)_c \times SU(2)_L \times SU(2)_R$ [16] the two phenomenologically most favored GUT groups [17].

Further moduli like the complex structure moduli and the CY-volume modulus are expected to get stabilized once a Neveu-Schwarz $G_{0,3,1} = H_{0,3}$ flux component is switched on and the respective flux superpotential $W = \int_{CY} H_{0,3} \wedge \Omega$ is added. This type of flux, together with GC and one-loop corrections to the gauge kinetic functions has e.g. been used in [19] in the weakly coupled case for the stabilization of complex structure and Kähler moduli. Note that these ‘one-loop’ corrections appear in heterotic M-theory automatically at ‘tree level’ and are therefore no longer small. Moreover, since the $G_{0,3,1}$ flux component is localized by a delta-function on the boundaries and cannot penetrate the bulk, the situation is indeed very similar to the weakly coupled case. It would of course also be interesting to switch on the $G_{1,2,1} = H_{1,2}$ component leading to non-Kähler manifolds where one would expect a stabilization of the CY-volume modulus at tree level [20]. However, in this case one still has to better understand the moduli structure of these non-Kähler manifolds before one is able to stabilize them.

An interesting property of the resulting de Sitter vacua is the fact that by choosing the hidden gauge group to be of low rank, say $SU(4)$ or $SU(3)$ as opposed to an unbroken $E_8$, one can rather easily bring the supersymmetry breaking scale and gravitino mass close to the relevant TeV scale [11]. In doing so one stabilizes the hidden boundary close to the maximally allowed value $L_{max} = 1/G_v$ which is phenomenologically favored as it leads to the right value for the 4d Newton’s Constant once the Grand Unified gauge coupling and energy scale assume their standard values [21], [10]. Moreover, the hidden matter which arises when we have broken the hidden $E_8$ gauge group down to $SU(4)$ or $SU(3)$ (we take for simplicity simple groups though product groups with low dual Coxeter number would qualify as well) say, represents a natural candidate for dark matter as it couples to the visible matter only (super)gravitationally and can be expected to enjoy similar clustering properties required for dark matter to distinguish it from dark energy. Though the complete vacuum energy turns out to be exponentially suppressed (similar as in warp-geometries [22]) through the non-perturbative geometrical factors, this suppression is unfortunately not big enough to bring it down to a realistic meV vacuum.
energy scale. What one finds instead confirms the general expectation, namely that the vacuum energy turns out to be of the same order as the supersymmetry breaking scale, though smaller by a factor of $\mathcal{O}(10)$. Therefore, in the supergravity approach to de Sitter vacua we still have to live with the cosmological constant problem.

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