Singular compactifications and cosmology*†

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Abstract

We summarize our recent results of studying five-dimensional Kasner cosmologies in a time-dependent Calabi-Yau compactification of M-theory undergoing a topological flop transition. The dynamics of the additional states, which become massless at the transition point and give rise to a scalar potential, helps to stabilize the moduli and triggers short periods of accelerated cosmological expansion.

During the last year a lot of effort has been made to explain the astronomical evidence for an inflationary epoch of the early universe and the current modest accelerated expansion by invoking a scalar potential derived from string or M-theory compactifications. So far two mechanisms leading to potentials viable to describe accelerated cosmological expansion have been explored [1]: (i) compactifications on hyperbolic spaces [2] and (ii) compactifications with fluxes [3]. Our recent work [4, 5] gives the first example of (iii) compactification on a singular internal manifold.

In the case of smooth compactifications one usually has a moduli space of vacua corresponding to the deformations of the internal manifold X and the background fields. For theories with eight or less supercharges this moduli space includes special points where X degenerates, rendering the corresponding low energy effective action (LEEA) discontinuous or singular. However, within the full string or M-theory these singularities are believed to be artifacts, which result from ignoring some relevant modes of the theory, namely the winding states of strings or branes around the cycles of X. Singularities of X arise when such cycles are contracted to zero volume,

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thereby introducing additional massless states. Incorporating these states leads to a smooth *gauged* supergravity action which entails a scalar potential.

In Calabi-Yau (CY) compactifications of M-theory undergoing a topological flop transition these additional states ('transition states') are given by N charged hypermultiplets which become massless at the transition locus. There are two ways to include the effect of these extra states in the LEEA. The usual LEEA is obtained by dimensional reduction on the smooth CY and contains only states which are generically massless. The flop manifests itself in a discontinuous change of the vector multiplet couplings at the transition locus. We call this description the 'Out-picture' since the extra states are left out. On the contrary, the 'In-picture' is obtained by including the transition states as dynamical fields in the Lagrangian.

In [4] we constructed an In-picture LEEA for a generic M-theory flop by combining knowledge about the general $\mathcal{N} = 2, D = 5$ gauged supergravity action with information about the extra massless states.[1] While the vector multiplet sector could be treated exactly we used a toy model based on the quaternion-Kähler manifolds $\frac{U(1+N,2)}{U(1+N)\times U(2)}$ to describe the hypermultiplet sector. In order to find the gauging describing the flop we worked out the metrics, the Killing vectors, and the moment maps of these spaces. This data enabled us to construct a unique LEEA which has all the properties to model a flop: the extra hypermultiplets acquire a mass away from the transition locus while the universal hypermultiplet remains massless.

In [5] we considered an explicit model for a CY compactification undergoing a flop with $N = 1$ and investigated the effect of the transition states on five-dimensional Kasner cosmologies,[2]

$$ds^2 = -d\tau^2 + e^{2\alpha(\tau)} d\vec{x}^2 + e^{2\beta(\tau)} dy^2 \ . \tag{1}$$

Comparing the cosmological solutions of the Out- and the In-picture, we found that the inclusion of the dynamical transition states has drastic consequences for moduli stabilization and accelerated expansion.

As soon as we allow all light states to be excited the scalar fields no longer show the usual run-away behavior but are attracted to the flop region where they oscillate around the transition locus. Thus the "almost singular" manifolds close to the flop are dynamically preferred. This is somewhat surprising, because the potential has still many unlifted flat directions meaning there is no energy barrier which prevents the system from running away.

[1] This strategy was first applied in [6] in the case of $SU(2)$ enhancement.

[2] This setup was previously considered in [7], but there the hypermultiplet manifold was taken to be hyper-Kähler which is not consistent with local supersymmetry.

Hence this effect cannot be predicted by just analyzing the critical points of the superpotential. The following thermodynamic analogy helps to explain the situation. Generically the available energy of the system is distributed equally among all the light modes ("thermalization"). Thus near the flop line the additional degrees of freedom get their natural share of it. Once this has happened, it becomes very unlikely that the system "finds" the flat directions and "escapes" from the flop region. Our numerical solutions confirm this picture: irrespective of the initial conditions the system finally settles down in a state where all the fields either approach finite values or oscillate around the transition region with comparable and small amplitudes. From time to time one sees "fluctuations from equilibrium", i.e., some mode picks up a bigger share of the energy for a while, but the system eventually thermalizes again. In an ideal scenario of moduli stabilization, however, one would like to have a damped system so that the moduli converge to fixed point values.

The second important aspect is that the scalar potential of the In-picture induces short periods of accelerated expansion in the three-space. Yet the net effect of the accelerating periods on cosmic expansion is not very significant. Again, this feature can be understood qualitatively in terms of the properties of the scalar potential. The point is that the potential is only flat along the unlifted directions while along the non-flat ones it is too steep to support sustained accelerated expansion. Transient periods of acceleration occur when the scalar fields pass through their collective turning point, where running "uphill" the potential turns into running "downhill" and the potential energy momentarily dominates over the kinetic energy.[3] To get a considerable amount of inflation via a slow-roll mechanism, one would need to lift some of the flat directions gently without making them too steep.

In summary we see that the dynamics of the transition states is interesting and relevant, and can be part of the solution of the problems of moduli stabilization and inflation. One direction for further investigations is to consider more general gaugings of our five-dimensional model. Once gaugings leading to interesting cosmological solutions are found, one should clarify whether these can be derived from string or M-theory where they correspond to adding fluxes or branes. Another direction is to extend our construction to other topological transitions. In particular it would be interesting to study the effect of transition states on four-dimensional cosmologies arising, e.g., from type II compactifications on singular CY manifolds. It is

[3]This behavior is also common to the models of hyperbolic and flux compactifications, where likewise the acceleration is not pronounced enough for primordial inflation.

conceivable that a realistic cosmology derived from sting or M-theory will have to include both the effects of fluxes and branes, and the possibility of internal manifolds becoming singular.

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