ARTICLE IN PRESS
COMREN:3373

C. R. Physique ••• (••••) •••–•••

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Testing quantum gravity with cosmology

String cosmology and the landscape

Le paysage des vides et la Cosmologie de la Théorie des Cordes

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ARTICLE INFO

Article history:
Available online xxxx

Keywords:
String theory
Vacuum landscape
Multiverse
De Sitter solutions

Mots-clés :
Théorie des Cordes
Paysage des vides
Multivers
Solutions de Sitter

ABSTRACT

String Theory is believed to have a landscape of 10^{500} vacua with properties that resemble those of our Universe. The existence of these vacua can be combined with anthropic reasoning to explain some of the hardest problems in cosmology and high-energy physics: the cosmological constant problem, the hierarchy problem, and the un-natural almost-flatness of the inflationary potential. We will explain the construction of these vacua, focusing on the challenges of obtaining vacua with a positive cosmological constant.

RÉSUMÉ

Il est généralement accepté que la théorie des cordes contient un paysage de 10^{500} solutions de vide avec des propriétés qui ressemblent à celles de notre Univers. L'existence de ces vides peut être utilisée dans un raisonnement anthropique pour expliquer certains des problèmes les plus ardus en cosmologie et en physique des hautes énergies : ceux de la constante cosmologique, de la hiérarchie et de la platitude du potentiel inflationnaire. Nous expliquerons la construction de ces vides, en insistant sur les défis posés par la construction des vides avec une constante cosmologique positive.

1. Introduction

String Theory is the most promising candidate for a theory that unifies all the forces that exist in nature, and could therefore provide a framework from which one may hope to derive all the observed physical laws. However, String Theory lives in ten dimensions, and to obtain real-world physics one needs to compactify it on certain six-dimensional compact spaces whose size is much smaller than any scale accessible to observations. These compactifications on Calabi–Yau manifolds, give a very elegant way to obtain each and every kind of fundamental particle and interaction observed in nature, as coming from purely geometric data in the compactification manifold.

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http://dx.doi.org/10.1016/j.crhy.2017.04.001

Unfortunately, string theory compactifications also produce unwanted interactions and fields, such as massless scalars (moduli). Such fields have not been observed in the real world, and the bounds on their existence, coming from experiments that fail to detect a fifth force, are quite robust. As such, the first step one has to take in trying to create a viable model for string theory cosmology is to find a mechanism to "fix the moduli", by uplifting the masses of all these scalar fields. For a long time it was believed that once such a mechanism will be found, there will be very few compactifications left, and the physics of one of these compactifications will give exactly the same particle spectra and couplings as those observed in the Standard Model or supersymmetric extensions thereof; this would have yielded a Theory of Everything, that would have explained all observed physics. However, life turned out no to be so simple.

String Theory compactifications have two kinds of moduli: complex structure moduli and Kähler moduli. They can be though intuitively as coming from twisting the angles in the compactification manifold, and respectively from changing its overall volume or the volumes of the even cycles. The only known perturbative mechanism to fix the moduli is to add background p-form fluxes (which are ten-dimensional generalizations of electro-magnetic flux) which wrap p-cycles of the compactification manifold. When fluxes are turned on, the geometry back-reacts and is no longer Ricci-flat, and much of the intricate Calabi–Yau structure is lost, together with the predictability of the model.

One of the authors and Polchinski [1], followed by Giddings, Kachru and Polchinski [2], have found that there exists a particular combination of three-form fluxes in type IIB string theory such that its back-reaction on the geometry still allows for a Calabi–Yau manifold, yet fixing (giving a fixed vacuum expectation value to) half of the moduli of the compactification – the complex structure ones. Given the extensive existing algebraic geometric techniques to construct and deal with Calabi–Yau manifolds, these kind of "flux compactifications" have been amongst the most studied. The next step is to fix the other half of the moduli, the Kähler ones, and this has been done by Kachru, Kallosh, Linde and Trivedi (KKLT) [3] by using certain non-perturbative quantum corrections to the action [4].

However, there is still a hurdle to be overcome: all the solutions obtained in this way have a negative cosmological constant (and are therefore Anti de Sitter, or AdS), and as such have nothing to do with our Universe, which has a positive cosmological constant. One therefore needs to find mechanisms to uplift the value of the cosmological constant, which has proven challenging. These mechanisms, together with other ways to construct deSitter solutions with fixed moduli without using the strategy outlined here will be further discussed in the next section.

The fixing of the moduli of these compactifications introduces another ingredient in the discussion: the Landscape, or the Multiverse. Since there exist a large (perhaps infinite) number of Calabi–Yau manifolds, and a huge number of possibilities of putting flux on them, it has been argued that there exist in the order of 10^{500} "flux compactifications" of String Theory to four-dimensions. The resulting four-dimensional vacua have all possible physical laws with all possible constants, and this has led to a radically new view of physics in which one argues that the constants in the physical laws that we measure in our Universe do not come from an underlying unified theory, but are environmental (anthropic) variables that are determined by where we are in this Multiverse.

This kind of anthropic arguments, claiming that the exact values of the constants in the physical laws governing our universe are not determined by a fundamental theory, but are simply explained by the existence of a very large number of universes (a Multiverse) and by requiring that the universe in which we live allows life to exist, have been around for more than 50 years. However, before flux compactifications and the KKLT construction of deSitter space came along, these arguments were not very popular in the scientific community. And there is good reason for that: throughout all its history, fundamental physics has progressed by finding simpler and simpler models that are deeper and deeper at the root of the observed reality, and the Standard Model is a shining example of the success of such an approach. Furthermore, as explained above, String Theory, which unifies Gravity and Quantum Mechanics and has no dimensionless free parameters, has been long expected to fill in the shoes of a Theory of Everything, thus fulfilling the reductionist paradigm that has been driving fundamental physics from its very beginning. The Anthropic/Multiverse paradigm, on the other hand, states that the constants in the physical laws in our Universe are environmental variables that depend on where we are in the Multiverse, and therefore one should abandon any hope of ever finding a Theory of Everything that predicts all these constants from first principles.

Thus, at this point we have two competing paradigms, which we can call the *Theory of Everything* paradigm and the *Anthropic/Multiverse* paradigm. Of course these paradigms are not specific to String Theory, and any theory that claims to describe nature is bound to fall into one of them. However, what it is so far specific to String Theory is the possibility to try to address the discrepancy between these two approaches by using controlled calculations. Besides the science, there are also philosophical debates on whether the Anthropic paradigm has any predictability, or whether the "Theory of Everything" quest stems from an inaccurate understanding of how science works. A beautiful review is given in [5,6]. However, it is hard for theoretical physicists to deny that the Anthropic/Multiverse paradigm offers a quick and easy way to account for three recent experimental results that at this point seem hard to address within the "Theory of Everything" paradigm.

The first is the cosmological constant, which is 120 orders of magnitude smaller than predicted by particle physics and thus is a strong contender for winning the prize for *the worst theoretical prediction in the history of physics*. Even by invoking supersymmetry, the number of orders of magnitude of the discrepancy only gets cut in half, so this problem plagues any theory that claims to contend in the *Theory of Everything* competition. Incidentally, if the cosmological constant had been exactly zero, one could have tried searching for an underlying symmetry that would have explained its vanishing. But no such principle can predict a finite value that is yet a hundred orders of magnitude smaller than expected. In the Anthropic/Multiverse paradigm, this problem is easily solved if the number of deSitter universes with stabilized moduli is

Please cite this article in press as: I. Bena, M. Graña, String cosmology and the landscape, C. R. Physique (2017), http://dx.doi.org/10.1016/j.crhy.2017.04.001