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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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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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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 parametrically larger than 10^{120}, by arguing à la Weinberg [7] that any universe with a much larger cosmological constant expands too fast for stars to form, and hence cannot be inhabited by intelligent beings. And 10^{500} clearly fits the bill.

The second is the hierarchy problem: the 24 orders of magnitude between the electroweak energy scale and the gravity scale. Unlike the cosmological constant problem, for which we lack a non-Multiverse theoretical explanation, supersymmetry provides a beautiful solution to the hierarchy problem: the contribution from bosons and fermions cancel in quantum corrections to the Higgs mass that would otherwise drive it to the Planck scale. However, experimental results are not so hot on this solution: the Higgs boson is the only discovery at LHC so far, and furthermore the experimental phase space available for supersymmetric extensions of the standard model has been drastically shrunk, with no sign of new physics. If supersymmetry is not discovered, or otherwise pushed into a corner of parameter space where it no longer gives a viable solution to the hierarchy problem, the only competitor left is the multiverse/anthropic explanation.

The third experimental result comes from the cosmic microwave background measurements. Models of cosmological inflation require considerable fine-tuning when trying to achieve the almost flatness of the inflationary potential, as well as to meet the upper bound from *Planck* 2015 results on tensor-to-scalar ratio in the spectrum of perturbations. Constructing such flat potentials from a fundamental theory without fine-tuning has been impossible in the more than 35 years, since inflation has been around [8,9], and the multiverse paradigm provides a framework where this fine-tuning does not require an explanation. Among the 10^{500} vacua, there are clearly some with an extremely flat inflationary potential, and one can always cook up an anthropic argument that without a lot of e-folds of inflation the universe would be a much more bumpy place, and intelligent life much more unlikely to develop.

Hence, anthropic/multiverse arguments give a quick and easy path to solve some of the most thorny problems plaguing theoretical physics. Of course, one can always argue that the quick and easy path is not necessarily the correct one, and point out to countless historical examples where invoking that anthropic arguments would have prevented the discovery of important physics and would have stunted or retarded the development of science. However, the cornerstone of the Multiverse paradigm and the reason why so many scientists have accepted it is the existence in String Theory of a very large number of deSitter vacua that resemble our Universe. There are only two ways out of this paradigm: either to shatter this cornerstone by somehow invalidating all the deSitter constructions, or otherwise to just find the right compactification to yield a Theory of Everything that reproduces all the Standard Model particles and couplings, the inflationary potential, and the cosmological constant at the same time.

Before delving into the intricate details of the landscape constructions, it is essential to re-emphasize that the conflict between the *Theory of Everything* paradigm and the *Landscape* paradigm is intrinsic to any theory that claims to make a precise cosmological prediction from first principles, though it may be less visible or less clearly brought to light than in String Theory. Indeed, in the absence of a Landscape/Anthropic argument, it is clear that any solution to the cosmological constant problem will involve physical ingredients that are not only unknown, but are of a nature that is fundamentally different from anything we are familiar with. Once this solution will be discovered, it is obvious that these ingredients, which involve unknown physics that stretches over 120 orders of magnitude, will drastically modify *all* the cosmological predictions that one makes in any fundamental theory. Hence, in the absence of a solution to the cosmological constant problem, none of these predictions has any theoretical self-consistency. The only way a theoretical prediction can be robust is if the solution to the cosmological constant problem does not invalidate it. And since so far the only solution to the cosmological constant that uses known physical ingredients is through the landscape of flux compactifications, the choice is quite grim. One can either:

1) make cosmological predictions in various string models, and rely on the anthropic/landscape solution to the cosmological constant problem to argue that these predictions are robust;

2) try to construct landscapes of deSitter vacua in one's favorite theory, and argue that the mechanisms that give rise to this landscape do not invalidate whatever cosmological predictions one makes;

3) make cosmological predictions without providing a solution to the cosmological constant problem. But since this solution would involve nontrivial unknown physics that stretches over 120 orders of magnitude and that furthermore cannot fit in the "effective theory" framework, none of these predictions is robust.

2. The de Sitter landscape

The landscape of deSitter vacua of String Theory is built out of solutions found using effective theories in four space-time dimensions. These theories are obtained from a dimensional reduction of ten-dimensional supergravity (the low-energy limit of string theory) in some particular six-dimensional internal curled-up small space. There are two general approaches to obtain deSitter solutions: one can try to directly construct classical non-supersymmetric deSitter solutions, or one can build supersymmetric flux compactifications with all the moduli stabilized, and then to uplift the negative cosmological constant of the resulting universes to a positive one.

2.1. Direct constructions

There are many no-go theorems (see for example [10], or for more recent work [11]) against finding de Sitter vacua in ten-dimensional supergravity in the absence of certain ingredients (Orientifold p-plane sources for a given dimensionality p, parallel sources, smeared sources, negative curvature of the internal manifold, etc.), but this possibility is not completely ruled out. Furthermore, de Sitter vacua have been found in the context of four-dimensional gauged supergravities that could a priori come from string theory without quantum corrections. However, no stable de Sitter vacuum with a known string theory embedding has been found yet. To be more precise, it was shown that metastable de Sitter vacua can only arise in maximal and half-maximal supergravities ($\mathcal{N} = 8$ and $\mathcal{N} = 4$ in four dimensions) in a very constrained region of parameter space [12], and moreover all the explicit de Sitter vacua found within this region turned out to be unstable. In supergravities with less supersymmetry ($\mathcal{N} = 2$ and $\mathcal{N} = 1$), which are far less rigid, some de Sitter solutions have been found, which have so far proven to be stable [13]. However, they generically require gauging a non-compact group, which puts their string theory origin in doubt. These cannot correspond to a traditional compactification, but could come from a so-called "non-geometric" compactification, which will be further discussed below.

An alternative and very powerful approach to analyze the existence of de Sitter vacua is the conformal field theory (CFT) of the string world-sheet. This CFT takes into account all α' corrections and therefore can describe high-curvature regimes as well. Using CFT techniques and very simple symmetry arguments, it has recently been shown that there are no de Sitter vacua in heterotic string theory [14].

2.1.1. Non-geometric backgrounds

Non-geometric backgrounds are string theory solutions that have no description in terms of a conventional six-dimensional geometry. Typical examples are asymmetric orbifolds: backgrounds where the left- and right-moving parts of the string spectrum are quotiented out by a different discrete symmetry of the internal space, and thus each sector "sees" a different geometry. The set of geometric compactifications has measure zero in the space of possible solutions, and thus one might expect that the string landscape should actually be mostly populated by non-geometric backgrounds, and the only reason people have focused much more on geometric backgrounds is because they are technically more controlled.

There has been a considerable amount of activity on non-geometric backgrounds, but we are still missing the answer to some key questions. In particular, to what extent a low-energy effective theory can be derived in these backgrounds where one cannot invoke typical geometric concepts such as "large volume" to construct a perturbative parameter. Furthermore, the non-geometric fluxes seem to evade all no-go theorems for de Sitter vacua: the only de Sitter solutions found at tree level whose stability has not been disproven so far, require them. Given the genericity of non-geometric backgrounds, it would not be surprising if the String Theory de Sitter landscape is then actually made mostly of non-geometric backgrounds; unfortunately, our current understanding and technical control of these backgrounds is still too poor to believe in the consistency of any part of this landscape.

2.2. Constructions with an uplifted cosmological constant

The common ingredient in the deSitter constructions that require uplifting is to consider non-perturbative corrections to the four-dimensional $\mathcal{N} = 1$ effective action resulting from compactifying type-IIB string theory on a Calabi–Yau manifold in the presence of three-form fluxes à la [1]. The effective four-dimensional theory is completely determined by three functions: the gauge kinetic function, the Kähler potential that governs the kinetic terms of the chiral fields and the superpotential that gives rise to the potential. Both the Kähler potential and the superpotential receive quantum corrections, the former perturbative as well as non-perturbative, while the latter is only corrected non-perturbatively. Fluxes give rise to a tree-level superpotential that fixes or "stabilizes" the moduli corresponding to the sizes of three-cycles (called complex structure moduli). This can be understood since the fluxes have support on three cycles of the compactification manifold, and the interplay of their electromagnetic repulsion and gravitational attraction gives a preferred size for them. On the contrary, the "Kähler moduli", corresponding to the sizes of even cycles (such as the six-dimensional overall volume) are not fixed by the three-form fluxes. As shown by Kallosh, Kachru, Linde and Trivedi (KKLT) [3], non-perturbative corrections to the superpotential can do this job. These corrections come either from Euclidean D3-brane instantons wrapped on a four-cycle of the internal manifold, or from (field-theoretic) gaugino condensation on D7-branes extending in space-time and wrapping also a four cycle. The combination of these non-perturbative contributions to the superpotential, together with the perturbative contribution coming from the fluxes, allows fixing all the geometric data of the compactification. However, the vacua obtained by this procedure are AdS, and one has to add other ingredients to uplift the cosmological constant of these compactifications and obtain de Sitter solutions.

There three most common ways to uplift the cosmological constant while keeping all the physics under control: using antibranes, correction to the Kähler potential and T-branes, and we will review them in turn. One can also try to uplift the cosmological constant using the non-geometric constructions described above, but their computational consistency is much more feeble than for the other methods.

2.2.1. Antibranes

The most generic known mechanism for uplifting the cosmological constant is to place D3-branes (solitonic objects in string theory extended in the four-dimensional space-time) whose charge is opposite to that carried by the fluxes (and therefore called "antibranes"), in regions of the compactification manifold that have a large warp factor (also known as throats). In the probe limit, where the back-reaction of the branes on the geometry is ignored, these configurations were shown to be metastable [15]. However, starting from [16], there has been an intensive research programme to compute the back-reaction of the antibranes on the geometry and to understand whether this metastability is just an artifact of the probe approximation (as it happened for example in [17]) or is a generic feature of antibranes. The first important result coming out of this research line has been that antibranes have a singularity, which is visible both when considering the first-order backreaction of the probe [16] and the full backreaction [18], and irrespective of whether the antibranes are smeared or localized [19]. Since in any self-respecting theory solutions containing singularities should be discarded, unless one finds a mechanism to resolve them, and since String Theory has a glorious history of resolving singularities to reveal new physics [20–22], one can ask whether this singularity is really pathological or rather signifies a deeper feature with the underlying physics.

There have been several investigations on this issue, involving highly nontrivial calculations which a priori could have inclined the balance in either direction, or could have given a result that strongly depended on the intricate details of the construction. However, all the calculations so far have yielded strong results against the singularity: the singularity cannot be cloaked by turning on a black-hole horizon [23,24], which is one of the generic singularity-acceptance principles of string theory [25]. Moreover, the singularity of smeared antibranes cannot be resolved by brane polarization [26], and a detailed study of the singularity of localized antibranes reveals the existence of a brane–brane-repelling tachyonic mode that renders the solution unstable [27], explicitly contradicting a large amount of previous intuition-based arguments that antibranes are mutually attracting and their spectrum is gapped.

The ultimate fate of this instability is still unknown, but its understanding is crucial for determining whether the uplifting mechanism works at all: if the endpoint of this instability is the one where the antibranes are infinitely separated from each other, or have annihilated against the flux, or produce the collapse of the geometry, then the effective theory does not capture the actual physics, and de Sitter local minima constructed in the effective theory are not solutions to String Theory.

This work on antibranes has recently triggered renewed interest in the physics of antibranes, including a paper by Michel, Mintum, Polchinski, Puhm and Saad proposing a brane-effective action for describing the physics of antibranes in the weak coupling regime [28] opposite to that of [18,26,27], and several recent papers by Kallosh and collaborators [29,30], which propose an alternative scenario that goes around the instability of antibranes found above: an anti-D3-brane placed on top of an orientifold plane.[1] However, a detailed exploration of the brane effective action [31] in the only regime of parameters where a precise calculation can be done has revealed that the effective action describing antibranes still has a brane–brane-repelling tachyon.

2.2.2. *Kähler uplifting*

In the so-called *large volume scenarios* [32], one considers a correction to the Kähler potential of the effective four-dimensional theory that is perturbative in the string length parameter α', and this correction gives rise to a potential with non-supersymmetric AdS minima where the overall volume of the compactification manifold is fixed at an exponentially large value. The exponentially large volume is such that higher-order α' corrections can a priori be ignored. Furthermore, the perturbatively-corrected effective four-dimensional action allows also for de Sitter vacua, if the parameters entering the corrections are sufficiently fine tuned with respect to the tree-level contribution to the potential coming from the fluxes [33]. The name Kähler uplifting comes from the fact that it is the perturbative correction to the Kähler potential the new ingredient that gives potentials with local minima of positive value. The Kähler uplifting scenario has, on the one hand, the advantage of not introducing exotic objects. On the other hand, it is far less generic than the other mechanisms described below, and involves a considerable amount of fine-tuning of the (mostly unknown) quantum corrections.

The string theory origin of α' corrections are higher-derivative terms in the ten-dimensional supergravity action. These give rise to a perturbative series of corrections to the Kähler potential of the four-dimensional effective theory, out of which only one contribution in the leading order terms is known and used in the large-volume scenario and its Kähler uplifted vacua. Such correction has been computed a long time ago [34] since it is the only one “inherited” from a higher supersymmetric ($\mathcal{N} = 2$) theory, and is parameterized by a topological number of the internal manifold. However, one expects to have plenty of other corrections at the same order in α', which are genuinely $\mathcal{N} = 1$, and which are generally hard to compute. One such correction has recently been found [35] and depends on more refined topological data counting intersection numbers. More corrections are expected to arise at the same order in perturbation theory, and can potentially destroy the uplifting mechanism. Furthermore, in the Kähler uplifted de Sitter vacua, the volume is not exponentially large, and therefore one cannot safely ignore higher-order corrections.

2.2.3. *T-branes*

A mechanism to obtain de Sitter vacua in four-dimensional $\mathcal{N} = 1$ supergravities involve F-terms from hidden-sector matter fields which D-term stabilization renders non-zero in the presence of a Fayet–Iliopoulos term. Very recently, a proposal for a string theory origin of the hidden sector in terms of the so-called T-branes [36] has been put forward [37]. The understanding of T-branes is still in its infancy, we only know how to describe them in a weakly coupled region in terms of vacuum configurations of branes with world-volume fluxes and non-commuting vacuum expectation value for the world-volume scalars. However, in order for T-branes to provide the uplifting mechanism, one needs to be precisely in the

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[1] Since the antibrane is stuck at the orientifolds plane, it does not suffer from the instability of [27]. However, it is very unclear whether the resulting configuration can give rise to stable de Sitter solutions: the stability problem may turn out to be more severe than for antibranes away from orientifold planes: the combination of an antibrane and an orientifold plane has a non-zero charge yet zero mass. Such an object is not expected to be stable.

opposite regime, that of strong coupling. Recently, it has been shown that in this regime of parameters, the T-branes are nothing but ordinary D7 branes with Abelian worldvolume fields, and that all the T-brane data is encoded in the shape of these D7 branes [38]. This indicates that there is nothing more one can do with T-branes than with Abelian D7 branes, and hence the backreaction of T-branes will be hunted by the same problems as antibranes. Thus one cannot invoke T-branes to magically solve all the problems arising when constructing de Sitter string compactifications.

2.3. Stability issues

As we have seen, obtaining deSitter vacua in String Theory is no easy task. However, besides their construction, there is still the issue of their stability. Since de Sitter solutions are non-supersymmetric, their stability is by no means guaranteed, and when it happens it is rather the exception than the rule. Some instabilities are easy to see, such as those that arise in universal sectors, namely in scalars that appear in any gauged supergravity coming from a string compactification. These are the dilaton, the overall volume, or the Goldstino direction in solutions where supersymmetry is spontaneously broken. If these sectors pass the stability tests, there is still a large room where instabilities can hide. In particular, most hidden instabilities arise when considering fields outside of the truncation performed to find the effective action. Indeed, when obtaining the four-dimensional low-energy description of the dynamics, one is led to truncate the fields of ten-dimensional supergravity to a subset of modes. The truncation is called consistent if these modes form a closed set, in the sense that if only these are given a vacuum expectation value in the solution to the truncated action, the others can be consistently turned off (or in other words, a solution to the truncated action is also a solution to the equations of motion coming from the full non-truncated theory).

However, the consistency of the truncation does not guarantee stability: even if a solution is stable within the truncation, it can be unstable outside the truncation: a small perturbation along a mode not seen in the truncated action triggers a decay of the solution. All the $\mathcal{N} = 4$ de Sitter vacua found that seemed stable at first, were finally shown to have this kind of instabilities. For anti-D3 branes, the direction of instability found in [27,31] is a combination of an angular direction on the sphere at the bottom of the throat and the radial direction away from the bottom. Since in string theory there are plenty of modes, the stability test is a much harder one.

Even in the enormous landscape of Anti de Sitter solutions, a quick inspection outside of the truncation can give huge surprises: using the weak gravity conjecture [39], it has been argued very recently that all non-supersymmetric Anti de Sitter vacua are in the swampland [40] (the space of consistent-looking semiclassical effective theories which are actually inconsistent), with instabilities coming from an interplay between closed and open string sectors.

3. Conclusions

String Cosmology is a challenging, exciting and fast-moving area of research. It suffers though from a tension between the necessity of novel ingredients to bring the field in line with observations, and the requirement to stay within the framework of a consistent quantum theory of gravity. The string theory landscape is, in a way, a result of this tension. Further exploration needs to be done to determine how much of the landscape, if any, is made of honest-to-goodness string theory solutions, thus resolving the question of their consistency. If most of the candidate vacua do not survive consistency and stability checks, the landscape would be drastically trimmed; this in turn would greatly weaken the *Anthropic/Multiverse* paradigm in favor of the *Theory of Everything* paradigm, and reinforce the quest for predictability in String Theory.

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