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REVIEW ARTICLE

String theory as a theory of quantum gravity: a status report

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Abstract We review the status of string theory as a quantum theory of gravity. Our emphasis is on outstanding questions and remaining challenges rather then on well-established results and successes.

Keywords String theory · Quantum gravity · Black holes · AdS/CFT · Background independence · String cosmology

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1 Introduction

Any theory of quantum gravity has to be able to address those fundamental questions of gravity for which a purely classical description appears to be incomplete or

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invalid, and for which a perturbative description is almost certainly inadequate. Foremost among them are questions regarding the physics of black holes and cosmological singularities. The occurrence of Newton's and Planck's constants in the expression of the black hole entropy clearly shows that it can only be explained by a quantum theory of gravity. The entropy, being proportional to the area of the horizon rather than to the enclosed volume, is not an extensive quantity. This indicates that the nature of the degrees of freedom of a quantum theory of gravity are quite different from those of a local quantum field theory. The microscopic description of the black hole entropy, the issue of information loss in black hole radiation, etc. are challenging questions for any quantum theory of gravity. The problems related to cosmological singularities are of a different kind. In the very early universe, i.e. at very high energies, it is believed that gravity becomes as strong as the other three forces and a unified theory of all four interactions is needed. Furthermore, at very high energy densities, according to classical general relativity, space-time collapses into black holes. The notions of classical geometry then presumably become inappropriate and have to replaced by a suitable 'quantum geometry'.

In this short note, we will attempt to summarise what string theory, considered as a general framework for a consistent theory of quantum gravity (rather than as a specific unified theory of the other interactions) has to say about these and related issues, focusing not so much on the success stories (which undoubtedly exist), but rather on what we consider to be currently unsatisfactory or open issues. Alternative views on several of the issues discussed here can be found in other contributions to these proceedings.

According to the format of this contribution we will, where available, only cite reviews; references to the original articles can be found there. General references, for background on string theory and for detailed discussion of many of the topics discussed in this survey, are the recent string theory textbooks [1–3].

2 The past: string theory and perturbative quantum gravity

There are basically two approaches to formulate a quantum theory of gravity. The first treats gravity as a fundamental interaction which it attempts to quantise. In the second approach gravity is not fundamental but an emergent phenomenon.

String theory falls into the second category. It has the gratifying feature that not only gravity but also the gauge interactions which are mediated by a spin one gauge boson are emergent. String theory thus provides a unifying framework of all elementary particles and their interactions: it inevitably and automatically includes gravity (in the form of a massless traceless symmetric second-rank tensor excitation of the closed string, identified with the graviton) in addition to gauge forces which arise from massless excitation of the open or closed string (depending on the perturbative formulation of the theory).

The identification of the massless excitation of the closed string with the graviton is, however, rather indirect: correlation functions of vertex operators (there is one for each excitation of the string) computed in the two-dimensional conformal field theory on the world-sheet are interpreted as S-matrix elements of an effective field theory which describes the dynamics of the excitation modes of the string. The effective field theory is determined by the requirement that when expanded around Minkowski space its on-shell S-matrix elements coincide with the string theory correlation functions. One finds that this effective field theory is precisely the Einstein–Hilbert action plus *computable* higher derivative corrections when expanded about a flat background space-time. The corrections are of two types: there are stringy corrections which are organized in powers of $\alpha' R$ where R is the curvature of space-time and there are quantum corrections which are organized in powers of the string coupling constant g_s.[1] Newton's constant is related to g_s, which in turn arises as the expectation value of a massless scalar field in the theory, the dilaton.

This exemplifies a general feature of string theory: coupling constants of the low-energy effective field theory are determined by vacuum expectation values of various fields; in addition to the dilaton there are moduli fields which parametrize marginal perturbation of the conformal field theory. As such they have a flat potential. The degeneracy can be lifted by considering backgrounds where in addition to a metric also various RR fields are switched on (flux compactifications, for a review see [4]). This generates a potential for the dilaton and the moduli.[2]

An alternative way to discover gravity in string theory is to couple the world-sheet theory to an external space-time metric and to demand conformal invariance. The condition for the vanishing of the beta-function for the metric, which plays the role of (an infinite set of) coupling constants, is the same as the equations of motion for the metric derived from the effective action. Higher derivative terms arise from higher orders in the computation of the beta-functions.[3]

In this way string theory provides a (presumably order by order finite) consistent perturbative description of quantum gravity, avoiding the perturbative non-renormalisability of the field theory approach. Since theories with such properties do not grow on trees, from the point of view of desiring to find a theory of quantum gravity one is then led to accept the additional structures introduced by string theory (among them extra dimensions, infinite towers of massive fields, and supersymmetry) even though it is not completely clear at this stage if or why they are required for a consistent theory of quantum gravity per se.

Regarding these additional structures, it is worth keeping in mind the following two facts. Firstly, while superficially string theory may appear to provide a somewhat uneconomical description of quantum gravity, since it typically comes with a lot of

[1] Here one should keep in mind that the S-matrix element calculations are done in a free CFT which corresponds to a string propagating in D-dimensional Minkowski space and the graviton being a fluctuation around this background. Quantum consistency then requires $D = 10$. Other backgrounds, such as Calabi–Yau compactifications or $\mathrm{AdS}_5 \times S^5$ together with a self-dual five-form field strength, are also known to be exact perturbative ground states of string theory, i.e. solutions to the beta function equations to all order in α'. Most known backgrounds, however, only solve the equations of motion to lowest order in α' and therefore receive stringy corrections. The quantization of strings in backgrounds other than Minkowski space-time is, with very few exceptions, an open problem.

[2] Flux compactifications are also the basis of the so-called landscape of string vacua, which we will not discuss here.

[3] The limitation of this approach is that it is not possibly to include all the possible massless background fields, notably the fields in the Ramond–Ramond sector of the RNS formulation of the superstring. In the pure spinor formulation of string theory this problem is solved; for a review see [5].

additional baggage, from another point of view string theory is extremely economical since it reduces all the arbitrary field theory interaction vertices to a single simple open or closed string interaction, namely the splitting or joining of strings. Moreover, it is precisely the infinite tower of massive fields (or the extended nature of the string) that is responsible for the good UV behaviour of the theory.

Secondly, as far as the issue of "extra dimensions" is concerned, one should bear in mind that this is just a simple geometric way of describing certain conformal field theories with a given central charge (which is fixed by the requirement of conformal invariance of the world-sheet theory). For example, the statement that "the space-time dimension is $D = 10$" is only correct if one requires that the corresponding CFT has a geometric interpretation with a large volume limit. But neither is this required by string theory (there are CFTs, leading to so-called non-critical strings, which have no higher-dimensional interpretation and others with no geometric interpretation in terms of space-time dimensions at all—these CFT's are usually not weakly coupled and thus harder to study), nor is it necessary in order to eventually find three macroscopically large spatial dimensions. In fact, the right question to ask seems to be why there are four large dimensions rather than none.

3 The present: non-perturbative string theory and gravity

While the above discussion shows that a theory of quantum gravity based on string theory will automatically have the correct low-energy limit (this may be much less manifest in other approaches), an obvious and serious shortcoming is that it is inherently perturbative (in an expansion in Newton's or the string coupling constant) and limited to a set of rules for computing on-shell scattering amplitudes in an on-shell background. If one wants to study situations where one expects quantum gravitational effects to become relevant (black holes, big bang), or if one wants to address conceptual issues of quantum gravity, this is a double handicap: quantities can only be computed as formal power series in the string coupling, and one has to fix an on-shell background in advance.

It is thus fortunate that in recent years some progress has been made in understanding certain non-perturbative aspects of string theory. This is most notably due to the realisation that there are non-perturbative effects in closed string theory, due to so-called D-branes, that allow for a controlled perturbative description in terms of open string subsectors of the closed string theory. One of the most intriguing aspects of modern string theory, arising form these new non-perturbative methods, is the way information about space-time geometry can be encoded in gauge theory terms and vice versa. This gauge theory/geometry correspondence exhibited by string theory clearly hints at a fascinating deeper structure underlying, and novel ways of thinking about, string theory and quantum gravity.

These new developments have also provided various powerful new tools, frequently in the guise of weak coupling/strong coupling dualities, and most prominently in the form of the Matrix theory proposal and the AdS/CFT correspondence, and have also led to a much improved understanding, e.g. of black hole microstates and black hole entropy (as well as to deep insights into strongly coupled gauge theories, which is not our subject of concern here). These subjects have been extensively reviewed in the literature (see, e.g. [6–11]), and have also been discussed at this meeting [12], and therefore below we will limit ourselves to some brief comments.

3.1 The AdS/CFT correspondence

One of the most profound developments of the past 10 years is the AdS/CFT correspondence or gauge/gravity duality. It is a very powerful and concrete realization of the holographic principle. The duality relates string theory on asymptotically AdS backgrounds to a certain quantum field theory on the conformal boundary of space-time. It thus provides an alternative view of quantum field theories in the form of a higher-dimensional gravity theory and, vice versa, of quantum gravity and string theory, in the guise of a conformal field theory. It offers a new possibility to formulate string theory at a fundamental level and has repercussions for particle and nuclear physics and, optimistically, even for condensed matter systems and hydrodynamics (e.g. turbulence).

Crucial elements of this correspondence are a mapping between bulk (AdS, gravitational) fields or string states and boundary (CFT, gauge theory) operators, e.g. between the boundary energy momentum tensor and the bulk graviton, and the interpretation of the bulk radial direction in terms of a renormalisation group or energy scale of the boundary gauge theory. This provides the first potentially complete and non-perturbative description of quantum gravity within string theory (in a background-independent way but subject to certain boundary conditions), remarkably expressed in conventional gauge theory terms via a kind of holographic correspondence.

Much of the activity has been to test this conjecture, to explore and extend its validity and to use the duality to make predictions about the field theory. This is possible in a regime of parameter space where the string theory is well approximated by classical supergravity. Conversely one can as well use it to define quantum string theory on asymptotically AdS space-times. If one accepts this correspondence (in view of the overwhelming evidence in favour of it, this appears to be a sane position to take), then in principle the dual CFT or gauge theory should contain all the information about, say, dynamical processes in the bulk like the formation, collision and evaporation of black holes. In practice, however, any process localised in the bulk space-time will be encoded in a complicated, and presumably rather non-local, way in the boundary theory, and this code has not yet been completely deciphered. Thus, even though a lot has been understood, much more work is required to learn what AdS/CFT teaches us about the riddles of quantum gravity; cf. [12] for further discussion.

3.2 Black hole microstates and black hole entropy

One of the early impressive applications of the improved understanding of non-perturbative properties of string theory is undoubtedly the successful counting of black hole (D-brane) microstates leading to the known Bekenstein–Hawking area-formula for black hole entropy, including the correct prefactor. String corrections, which in the effective supergravity action are due to higher derivative corrections via the Wald entropy formula, are also correctly reproduced. These successes are for the moment limited to extremal (and near extremal) black holes and they cannot be easily extended to Schwarzschild black holes as they rely on supersymmetry and the BPS property of the contributing microscopic brane configurations. This property allows the extrapolation from zero gravitational coupling where the back reaction of the branes on the geometry can be neglected to finite coupling where the back-reacted geometry is that of a black hole. The expectation, expressed in the introduction, that the degrees of freedom of a theory quantum gravity are not those of a local quantum field theory, is indeed realized in string theory.

Black hole entropy and, more generally, the notion of a black hole as a thermodynamical system which radiates as a black body at the Bekenstein–Hawking temperature, leads to the information paradox. The microscopic information about the star which has collapsed to a black hole cannot be retrieved from thermal radiation. This seemingly renders the process of black hole formation and its subsequent evaporation non-unitary. If true this would violate one of the fundamental principles of quantum mechanics. The AdS/CFT correspondence, which relates gravity to unitary (conformal) field theories, seems to imply that the black hole evaporation is a unitary process after all. While this is a compelling argument its proof would require a precise map between all details of black hole physics and the dual CFT, e.g. maximally supersymmetric Yang-Mills theory in four dimensions. The status of this proposal is reviewed in [12]

The conjectured fuzzball proposal [13,14] offers another resolution of the information paradox. It relates the brane configurations which account for the BH entropy to an ensemble of geometries, none of which has a horizon. It is a consequence of a thermodynamic averaging of the geometries which all have the same asymptotics and charges. If true, this proposal resolves the black hole information paradox in the way that no information ever gets hidden behind a horizon [15]. Everything that falls into the 'black hole' will eventually reappear and the whole process is unitary. The challenge is the construction of sufficiently many metrics (or more general string theory states) with the same global charges and asymptotic symmetries. At the moment it is still an open question whether this can be done, but preliminary results seem to indicate that this is indeed possible [16]. Support for the fuzz-ball proposal also comes from the AdS/CFT correspondence. Of course it is still a long shot until one can decide the issue for Schwarzschild or Kerr black holes, those which appear to be present in the universe.

4 The future: technical problems and conceptual challenges

A crucial issue in any approach to quantum gravity is the question what is the appropriate notion of quantum geometry that replaces the classical space-time geometry at very short distances or high energies. This is also related to the notoriously thorny issue of what qualifies as a (classical or) quantum observable in a generally covariant theory. Moreover, some form of manifest background independence seems to be a desirable feature of any theory of quantum gravity. When addressing these issues, also (and perhaps in particular) when assessing the relative merits of different approaches to quantum gravity, one should take care not to impose one's own prejudices about what quantum geometry may look like or how background independence should be realised, but one should rather see what a candidate theory has to say about these matters.

Since accounting for black hole entropy and, more generally, understanding the presumably holographic nature of quantum gravity are cornerstones of research in quantum gravity, the accomplishments within string theory described above are undoubtedly encouraging, representing significant progress in the quest for a theory of quantum gravity.

Nevertheless, the current status of string theory as a theory of quantum gravity is still somewhat unsatisfactory. While various perturbative and non-perturbative dualities have certainly enhanced the range of quantities which can be computed, and have provided new insights into string theory, there still remain a number of basic open conceptual and technical issues.

Concretely, in string theory, what currently still appears to be missing, at a conceptual and fundamental level, is a good understanding of what are the fundamental symmmetries underlying string theory. This is related to questions such as "what is the appropriate string theory counterpart of general covariance?","what is string geometry?", and "how can one make background independence more manifest?". Furthermore, at a technical level, by and large currently available string theory technology seems to be not well suited to study time-dependent backgrounds, in particular cosmological singularities.

4.1 String geometry and background independence

While the issue of quantum geometry will arise in one form or another in any approach to quantum gravity, compared to approaches to quantum gravity which focus on quantising four-dimensional Einstein gravity, string theory faces additional challenges.

First of all, as mentioned before, string theory backgrounds need not necessarily have a classical geometric interpretation at all. Thus space-time geometry, and with it space-time diffeomorphism invariance, should be considered to be an emergent semi-classical phenomenon in string theory (see, e.g. [17] for a review of this issue and [18] for an alternative perspective), and a suitably general notion of string geometry will necessarily have to take this into account.

Secondly, even when one is in a situation where one can speak of geometric string backgrounds, already at a perturbative level string geometry can differ from classical geometry. This highlights the distinction between background geometry and observed geometry. Background geometries are classical data, used to define the world-sheet conformal field theory. Observed geometry, on the other hand, is the geometry one infers by probing space with strings or branes. A simple illustration is provided by strings in Minkowski space-time, which does not have a minimal length. The shortest length resolved by scattering strings, however, is the string length $\sqrt{\alpha'}$. There is thus a qualitative difference between the classical background used to define the world-sheet theory and the geometry 'seen' by strings. As another example, strings on time-like orbifold singularities provide an example of the phenomenon that string theory can smooth out classical (i.e. point-particle) singularities.[4] The reason why string theory is able to smooth out time-like singularities is that it contains additional degrees of freedom as compared to general relativity. But one can also probe the same geometry using other objects. For example, D-particles resolve a different minimal length, the eleven-dimensional Planck length, which is related to the string scale via the vacuum expectation value of the dilaton. This illustrates the high redundancy in the description of observable quantities. What is needed is a disentanglement between observables and gauge symmetries.

Thirdly, various perturbative and non-perturbative duality symmetries imply a huge redundancy between consistent string backgrounds. General duality transformations mix stringy corrections which are controlled by the sigma-model coupling α' and quantum corrections, which are controlled by the string coupling constant g_s. A prominent and mathematically well-understood special class of duality transformations, which is completely perturbative in the string coupling g_s, but fully non-perturbative in the sigma-model coupling α', is T-duality, which mixes gravitational with other degrees of freedom.[5] While this appears to be a deep observation, what is lacking so far is an understanding of the basic geometry and symmetry principles underlying string theory, together with a sufficiently abstract and general concept of 'state' which would allow one to understand why these apparently different space-times (amended with other background fields) represent the same state.

It has been conjectured that hyperbolic Kac–Moody algebras play a rôle in the description of the symmetries of string theory or, more generally, of M-theory which is, at the moment merely a name for the unknown non-perturbative theory behind string theory. These still poorly understood algebras make their appearance in the dimensional reduction of 11-dimensional supergravity to zero space-dimensions. The latter being the low-energy effective action of M-theory, this naturally leads to the proposal. These and other ideas about the relevance of hyperbolic Kac-Moody algebras for string- and M-theory are explored in [19,20].

So far, Calabi–Yau compactifications, in particular in the context of topological string theory (see [21] for a recent review), have been the major playground for exploring 'string geometry'. Topological string theory is rich enough to address issues such as background independence, quantum space-time structure (space-time foam) and the search for a non-perturbative formulation. Much more work is, however, required before one can address these questions in the full theory.

All this will clearly also have implications for the issue of background independence. String theory is background independent, in the sense that different on-shell

[4] Similar methods have also been used to establish the existence of smooth topology-changing transitions in string theory, processes that are necessarily singular in classical general relativity which is the low-energy and long-wave-length limit of string theory. Cosmological singularities, such as the Big Bang, are a different story and they still pose a problem for string theory.

[5] In the context of mirror symmetry it leads to identifications between space-time geometries with different topologies, e.g. Calabi–Yau manifolds with opposite Euler numbers; it also relates type II string theory on certain Calabi–Yau manifolds to the heterotic string on $K3 \times T^2$ together with a gauge bundle on $K3$.

backgrounds are different solutions of one underlying theory.[6] However, background independence is not manifest as one needs to fix a reference background, or equivalently, a world-sheet conformal field theory before being able to deform it. Therefore in this perturbative description of string theory and background independence there is always a cut between the space-time geometry (plus other background fields) and the dynamics of the background. Such a background dependent realisation of background independence is clearly clumsy and unsatisfactory.

Non-perturbative formulations of string theory have provided new insight into this issue. In particular, the AdS/CFT correspondence provides one with a novel holographic realisation of background independence. Indeed, not only are the boundary degrees of freedom manifestly invariant under bulk diffeomorphisms, there is also (contrary to a frequently raised criticism) no bulk background AdS metric. What is fixed are only asymptotically AdS boundary conditions, and within this superselection sector of string theory the AdS/CFT correspondence is manifestly background independent. For a detailed recent discussion of these issues see [22]. One of the lessons here is that background independence may emerge and be realised in unexpected ways. It remains to be understood what form it takes in other sectors (e.g. asymptotically flat) or formulations (e.g. matrix theory) of the theory.

4.2 Time-dependent string backgrounds and string cosmology

An important topic which any fundamental theory of gravity eventually has to address is that of the evolution of the universe. This entails numerous challenges at vastly different energy scales, such as the big-bang singularity, inflation, the late-time acceleration of the universe, etc. The latter two of these occur at energy scales that may not require a full-fledged theory of quantum gravity, and might be addressed at the level of low-energy effective supergravity with the incorporation of string inspired effects, such as higher derivative corrections, D-branes, etc. (see, e.g. the review [23]). On the other hand, questions related to the fate of cosmological singularities will involve Planck scale physics and can be regarded as a litmus test for the success of a theory of quantum gravity.

Another big challenge is the cosmological constant problem both in the form ‘why is it not huge?’ and in its relation to late-time acceleration. A priori it is not clear where an answer to this riddle should be sought.[7] Also, the cosmological constant problem may not be fundamentally a problem of quantum gravity per se, but rather that of finding a realistic description of the universe we live in. Some kind of anthropic selection could be at work here. Flux compactifications, which give rise to the string

[6] Formally this is clear from the fact that deformations of on-shell backgrounds correspond to marginal deformations of the world-sheet action, which in turn are equivalent to inserting the vertex operator for a coherent string state into correlators. In this spirit, the ‘10^{500}’ valleys of the string landscape are not, as sometimes incorrectly alleged, 10^{500} different theories: there is just one theory with a very large number of *perturbatively* stable vacua.

[7] For instance, it might just say that one is simply not assessing correctly the effect of zero-point energies or vacuum fluctuations on gravity [24].

landscape, combined with the eternal inflationary scenario provide a framework in which anthropic arguments cannot be dismissed a priori, whether one likes it or not.

The issue of cosmological singularities, on the other hand, seems to be immune to the quagmire of anthropic reasoning. Unfortunately, however, little is known about string theory in non-trivial time-dependent (and possibly singular) space-time backgrounds like those describing cosmological singularities. In fact, this time-dependence gives rise to rather basic problems, related, e.g. to the absence of a light-cone gauge and no-ghost theorems, the limited validity of a Euclidean formulation, and the questionable usefulness of the standard on-shell S-matrix formulation of string theory in a cosmological setting, where one is not primarily interested in asymptotic scattering states.

Moreover, many results of string theory rely on supersymmetry. Backgrounds where supersymmetry is completely broken generically suffer from perturbative and non-perturbative instabilities. While some progress in dealing with unstable (tachyonic) backgrounds has been made within string field theory, much more work is required to gain a better understanding of the fate of these backgrounds. The relevance of these considerations for string cosmology is that time-dependent string-theory backgrounds, i.e. backgrounds without time-like Killing vectors, typically have no Killing spinors, i.e. are not supersymmetric.[8]

Broadly speaking, there are three main approaches to string cosmology, based on the low-energy effective action, the world-sheet description, and non-perturbative formulations of string theory, respectively.

The first approach, which is extensively reviewed in [25], is based on the low-energy effective action of string theory, i.e. supergravity augmented by higher derivative corrections, which are computable within perturbative string theory, and which become important in the early universe where space-time curvature is comparable to $(\alpha')^{-1}$. Other string effects, such as T-duality in the form of scale-factor duality, are also taken into account. This approach leads, e.g. to the pre-big bang scenario and to the Brandenberger–Vafa string gas cosmology scenario.[9] Other string inspired cosmological models include D-brane inflation and the ekpyrotic universe. None of these models are completely satisfactory yet, also because they are not formulated within the full (UV complete) string theory, while essential ingredients they are based on are best motivated by string theory.

The second approach relies on the world-sheet description of string theory with time-dependent background geometries. From the world-sheet perspective one is then faced with the problem of CFTs with non-compact target space. Very little is known about these interesting theories, the Liouville theory being a notable exception. Instead of aiming directly for a (semi-) realistic cosmological scenario, in order to gain some insight into the problems that arise when formulating string theory in time-dependent backgrounds and/or in the presence of space-like singularities, one can also study

[8] A small exception to this rule is provided, e.g. by singular pp-wave backgrounds which ride a fine (null) line between time-dependence and supersymmetry.

[9] In this model, the initial Big Bang singularity disappears by virtue of the scale-factor T-duality, and moreover the model potentially provides a dynamical mechanism that generates three (rather than none) large spatial dimensions. Recent developments along these lines are reviewed in [26].

simplified toy-models of such singularities. One particular avenue of research in this direction is the investigation of time-dependent orbifolds (reviewed in [27]). This has led to a number of interesting results, but also to a renewed appreciation of how difficult it is to avoid strong coupling problems even in what may initially look like a weakly coupled situation.

Insight into non-perturbative aspects of string theory has also been applied to studying string theory in singular time-dependent backgrounds; [28,29] are two overviews. For example, within the AdS/CFT correspondence it should be possible to address dynamical questions regarding, e.g. gravitational collapse and cosmology. A concrete proposal for the quantum resolution of a cosmological singularity via AdS/CFT, representative of the state-of-the-art, and also giving a good idea of the complexity of the subject and the issues involved, is the model studied in [30]. There the dual description of an AdS spacelike "big crunch" singularity involves field theories with scalar potentials unbounded from below, and the challenge is then to make sense of and understand quantum field theories of this type.

Instead of the AdS/CFT correspondence, one can imagine using non-perturbative matrix theory formulations of M-theory or string theory to address the fate of singularities. For example, explicit matrix string descriptions of certain string backgrounds with strong string coupling null singularities are known [31,29,32]. The central observation of [31] is that the dual matrix string gauge theory description of string theory in such backgrounds is well-defined and weakly coupled close to the singularity. In this regime the non-Abelian nature of the matrix-string coordinates cannot be neglected and one thus tentatively arrives at a picture where space-time geometry becomes non-commutative near a singularity. This enhancement of the number of degrees of freedom near the singularity is also seen in other situations, as in the case of orbifold singularities mentioned before, and may hold the clue to how string theory resolves singularities in more generality. One of the shortcomings of this approach is that it is so far limited to the study of certain null singularities, which certainly do not capture all the essential ingredients of spacelike cosmological singularities.

Finally, attempts to use string field theory for cosmology have been few; see however [33].

In spite of this and related progress it is probably fair to say that the non-perturbative or holographic description of string theory near cosmological singularities is not yet particularly well understood.

5 Conclusions

String theory is a very promising (and fertile) framework for a consistent theory of quantum gravity. However, we still appear to be at a rather preliminary stage of our understanding of this theory. In particular a non-perturbative formulation of the theory and uncovering its symmetries are important open issues. Matrix models and AdS/CFT correspondence mark recent success on the former issue, while hyperbolic Kac–Moody algebras might be the right language for the latter. Thus, far-reaching statements on either side of the string theory debate, proclaiming either the imminent demise of string theory or the ultimate unavoidability (and virtue) of the anthropic/multiverse scenario, appear to be pre- (and im-) mature, and should not distract one from trying to better understand profound quantum gravitational issues to which string theory presumably holds the clue.

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