STRINGS, BRANES AND COSMOLOGY: WHAT CAN WE HOPE TO LEARN?

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This article briefly summarizes the motivations for — and recent progress in — searching for cosmological configurations within string theory, with a focus on how much we might reasonably hope to learn about fundamental physics from precision cosmological measurements.

1 Why String Cosmology?

The last few years have seen a number of scientific gatherings which have brought together string theorists and cosmologists in a way which would have been unheard-of only a few years ago, stimulated by a relatively recent convergence of interest between these two fields. This convergence is interesting in its own right, promising as it does to relate the laws of nature at the smallest of distances to the behaviour of the universe as a whole, as seen writ large across the sky by contemporary cosmologists. But the possibility that there should be such a connection also contains within itself a puzzle, to do with why it is possible for these two fields usefully to inform one another at all.

1.1 Why doesn't string theory decouple from cosmology?

What is so puzzling about a connection between string theory and cosmology? The puzzle inherent in this field is intimately tied up with its promise: the potential it holds out for a connection between the workings of nature on the smallest of distance scales and the properties of the universe at large. Such a connection is intrinsically puzzling because of a fundamental property of nature, which might be called the *Principle of Decoupling.*

> *The Principle of Decoupling:* Although the world comes to us in many scales, these scales can each be understood on their own terms since their properties do not depend strongly on all of the details of the physics of other scales.

For example, we know that atoms are built from constituents (electrons and nuclei) which are much smaller than the atoms themselves, and some of these constituents (nuclei) themselves consist of still smaller things like quarks and gluons. But a detailed understanding of atomic properties (*i.e.* the spectra and chemistry of atoms) depends only on gross properties of their constituents (like the nuclear mass and charge). In particular, it does *not* depend on any of the complicated details of how they are constructed from their own constituents. Historically, this is why it was possible to understand atomic physics before having a complete understanding of nuclear physics. Indeed, this property of nature could be argued to be an important part of the reason why Science is possible at all, since it shows why we can hope to understand part of what is going on in nature without having to understand everything at once.

This gives rise to the puzzle: given the decoupling of scales in nature, how can cosmology — the understanding of the properties and behaviour of the largest objects known — possibly depend on the details of string theory — our best candidate for a theory of nature at the very smallest of scales? After all, we don't have meetings at which condensed-matter physicists or atomic physicists expect to learn much that is useful from string theorists. These meetings don't take place because string theory is likely to get right all of the details of atomic and condensed matter physics provided only that it predicts the existence of electrons and nuclei, and it gets right the laws of electromagnetism (as expressed by QED). For this reason there is little to be gained by comparing string predictions with detailed measurements of condensed matter phenomena.

There seem to be three reasons why string theory can usefully inform cosmology, and vice versa.

1. *Access by cosmology to very high energies:* This is the traditional reason for the decades-old development of a fruitful interface between astrophysics and particle physics. Some astronomical systems (like active galactic nuclei or ultra-high-energy cosmic rays) can involve physical processes involving astronomically large energies, whose understanding requires knowing how high-energy elementary particles behave.

   The same can be true for cosmology because we know that the observable early universe is well described by the Hot Big Bang model, but only if special initial conditions (homogeneity, isotropy, flatness, and a spectrum of primordial density fluctuations) are chosen before the earliest epoch (nucleosynthesis) for which we have direct observational evidence. Although nuclear physics seems to suffice for understanding nucleosynthesis, particle physics is required in order to understand the origin of the special initial conditions. In particular, the extremely high energies associated with string theory are very likely to be important if these initial conditions are explained by a very early epoch of inflationary universal expansion.[1]

2. *Dependence on UV-sensitive properties:* Cosmology is unusual because the vast majority of cosmological models rely for their phenomenological success on properties which are notoriously sensitive to microscopic details. For example specific models of Dark Energy [2] or inflation [3,4] often depend on the existence of very shallow scalar potentials which give rise to extremely light scalar masses, $M_\phi \le H$, where H is the Hubble scale at the epoch of interest. But scalar masses are famously difficult to keep from getting large contributions when the short-distance (UV) sector of the theory is integrated out. To take an extreme case, most Dark Energy models require $M_\phi < 10^{-33}$ eV, while it is difficult to make the contribution to M_ϕ due integrating out a particle of mass m smaller than $\delta M_\phi \sim m^2/M_p$, where $M_p = (8\pi G)^{-1/2} \sim 10^{18}$ GeV. This correction is already larger than M_ϕ for $m > 10^{-3}$ eV, and so is many orders of magnitude too large even for the electron, for which $m_e \sim 5 \times 10^5$ eV.

3. *Difficulty of modifying gravity on long distance scales:* Much of the evidence for the existence of exotic matter (like the scalar particles just mentioned) in cosmology is based on inferences which assume General Relativity is the correct theory of gravity. But General Relativity has never been experimentally tested over distances as large as required for cosmological applications, and this observation has led many people to try to avoid the

need for exotic matter by instead appropriately modifying gravity at long distances. Some phenomenological success can be achieved along these lines, provided one is judicious in the modifications which are made.

However, what this line of argument misses is that it is *extremely* difficult to embed any modification of gravity at long distances into any kind of a sensible theory of short-distance physics. This is because we now know that General Relativity is the most general kind of interaction which a massless spin-two particle can have which is consistent with very general principles (like special relativity, stability and unitarity), and as a result we have a very general understanding as to *why* General Relativity provides a good description of gravity.[5,6] So far as is known, it seems very likely that *any* sensible theory of gravity must look in the far infrared (IR) like a combination of scalar fields and gauge fields interacting with General Relativity, and there is no compelling theory which is both consistent with measurements in the solar system and in astrophysics and yet also observably different from gravity at very long distances in a phenomenologically successful way.[7] This indicates that consistency issues at short distances provide an important clue as to what is possible to entertain as a description of nature over long distances.[a]

For the above reasons there is at present an unusual opportunity at the interface between cosmology and microphysics, which provides a real chance for learning something important about nature. The opportunity arises because the very success of cosmological models relies in detail on properties (like shallow scalar potentials) which we know to be extremely sensitive to the details of short-distance physics. Furthermore, it is not generic that these microscopic details provide phenomenologically successful models for cosmology. The condition that a model *both* provide successful phenomenology *and* be sensibly embedded into microscopic physics is very strong, making the finding of examples which do both a worthwhile exercise. Furthermore, as we now argue, there is an opportunity for information to flow in *both* directions, with potential theoretical insights for both string theory and cosmology.

1.2 What is useful for cosmologists

We first ask how short-distance physics can be useful for practical cosmologists interested in understanding observational data. The utility here comes from the observation that cosmological observations (marvellously precise though they are) are likely to remain inadequate into the foreseeable future for unambiguously differentiating amongst the many competing phenomenological cosmological models.[9]

However cosmological observations provide only part of the clues as to what is going one. We must also weed out those models which do not make sense when embedded into more microscopic theories, and it is the interplay between these two kinds of constraints which makes the exercise theoretically constrained. In practice this means ruthlessly rejecting those models of cosmology which predict low-energy ghosts, instabilities or violations of the experimental tests of gravity within the solar system or for binary pulsars. Such a restriction dramatically reduces the number of models which require more detailed scrutiny.

1.3 What is useful for string theorists

The information exchange between string theory and cosmology is likely also to be of use to string theorists, for the following reason. String theory involves an enormous number of degrees

[a]It must be emphasized that because these issues deal with *long-distance* problems, they may be unambiguously addressed using current knowledge — using standard Effective Field Theory techniques [8] — and in particular need not await an eventual 'final' theory of Quantum Gravity, as is sometimes argued.

of freedom and so may be expected to enjoy an equally enormous number of solutions. A precise counting of how many solutions there might be requires an understanding the form of the potential which stabilizes the many fields of the theory, but recent progress [10,11,12] in computing this potential for some types of string vacua indicates there to be more than 10^{100} such vacua. A central question for string theorists is to find which solutions can describe the universe around us, and to understand why the universe should end up being described by these solutions rather than by the many other possible solutions.

Cosmology may help this process in two ways. First, cosmology can help to *find* string vacua with acceptable phenomenology. It can do so because the direct examination of various vacua is impractical, given the likely enormous number of solutions which exist. What can be useful when looking for potentially realistic vacua, however, is the identification of low-energy *modules* which capture one or another of the phenomenologically desirable features required to describe our low-energy world. For instance, these could include modules for ensuring an acceptable particle spectrum; a mechanism for understanding the electroweak hierarchy, and so on. Some of these modules can involve cosmology, such as by demanding the existence of an early inflationary phase; a candidate for dark matter; or an understanding of the observed features of the dark energy density.

The second useful role cosmology might play for string theory is by providing potentially measurable signals for comparison with experiments. Recall that the existence of an enormous number of vacua makes the extraction of a theory's predictions much more complicated, since the properties of each vacuum provide in principle a separate set of predictions for what might be found around us. The most likely way in which such a theory will be tested in practice is through its statements about the *correlations* of the properties to be found about any particular vacuum, along the lines of: "Any vacuum which has property X must also have property Y". For instance, X might be the statement "contains the standard model gauge group, and Y might be "has 3 generations of chiral fermions".

Cosmology can usefully contribute to the kinds of statements, X and Y, since it is plausible that our understanding of why the universe is the way it is now will depend on our understanding of where it has been in its past. For instance X or Y might include "has at least 60 e-foldings of inflation", or "has such-and-such a relic abundance of cosmic strings". In particular, one can hope that the class of string solutions which give a reasonable description of cosmology might also lead to a restricted class of particle physics properties to be compared with laboratory experiments.

2 Branes and naturalness

An important way in which string theory has influenced thinking about more phenomenological issues can be traced to the discovery of branes.[13] This discovery has radically changed the kinds of low-energy implications which the vacua of the theory can have, and this has in turn led to a number of important new insights into the nature of the various 'naturalness' problems which arise within the effective theories relevant for phenomenology.

2.1 Why are branes important?

The main reason why branes have provided new insights into low-energy naturalness problems is because the study of the low-energy properties of vacua containing branes has identified a number of important (and overly restrictive) hidden assumptions which had been hitherto made regarding what is possible for the low-energy limit of a sensible high-energy theory.

The identification of such assumptions is crucial for naturalness problems, because these problems in essence amount to statements like: "a broad class of low-energy theories (obtained by integrating out heavy modes in some fundamental theory) have a generic property X, which is not observed to be true in nature." Property X here might be: "has a Higgs mass similar in size to the Planck mass", or "has a large cosmological constant." It is crucial to know when these unwanted but generic properties depend on hidden assumptions, since these may prove to be unwarranted and so may be the loopholes through which nature evades the problem.

For instance, a very important hidden assumption which the study of branes has identified is the assumption that all interactions 'see' the same number of spacetime dimensions. This assumption is violated, for instance, if particles like photons arise from open strings, which at low energies are localized on the branes on which such strings must end. In this case photons must propagate only within the dimensions spanned by the branes, while gravitons can move throughout the full extra-dimensional environment. Among the suggestive new insights which have emerged in this way are:

1. *A Lower String Scale:* The string scale need not be close to the Planck scale,[14] opening up interesting new possibilities for understanding the electroweak hierarchy with the string scale being associated with the intermediate scale [15] or the TeV scale.[16]

2. *Large Extra Dimensions:* A possibility which is related to (but not identical with) having the string scale at the TeV scale is that extra dimensions can be much larger than had been thought, being potentially as large as micron size.[16]

3. *Decoupling 4D Vacuum Energy from 4D Curvature:* In four dimensions a large vacuum energy is identical with a large cosmological constant, and so also with a large 4D curvature. (This connection underlies the cosmological constant problem since the curvature is observed to be small while the vacuum energy is expected to be large.) Higher-dimensional brane solutions show that this connection need not survive to higher dimensions, where large 4D energies can co-exist with flat 4D geometries.[17,18]

4. *Non-locality:* Locality is normally automatically ensured for effective theories because these theories are defined by integrating out only very heavy states. However since brane constructions can allow extra dimensions to be large compared with particle-physics length scales, the effective theories which result can admit a restricted form of nonlocality. They can do so because the observable particles might now be identified as those living on a collection of branes, rather than simply in terms of a low-energy limit. For instance, interactions which are obtained by integrating out modes which are *not* heavy compared with TeV scales — such as bulk Kaluza Klein (KK) states — can mediate nominally nonlocal correlations into the remaining fields.

These possibilities show why string theory may have the potential to teach us a considerable amount about how to think about any new physics which might be encountered in future observations, even if the string scale should turn out to be much higher than the energies being directly probed in these experiments. The fact that string theory makes it plausible that the particles we observe might be trapped on branes within extra dimensions, and that this possibility changes how we think about general naturalness issues, makes it worthwhile to take the possibility of brane localization very seriously.

3 String Inflation

Inflation is the simplest application of string theory to cosmology to motivate, because it could easily involve energy scales which are so high that they could plausibly directly probe string-related physics. Furthermore, recent precision measurements [19] of the properties of the cosmic microwave background radiation (CMBR) have accumulated impressive evidence supporting the existence of an early inflationary epoch. One of the pleasures of this particular meeting at Moriond was the very recent announcement of the most precise such measurements [20] to date.

Observations of the CMBR are only sensitive to essentially three numbers in any slow-roll inflationary model:[3] the inflationary Hubble scale, $H_{\rm inf}$, and its first and second logarithmic derivatives with respect to the scale factor, evaluated at 'horizon exit' (*i.e.* the moment when observable scales cross the Hubble scale). (It is conventional to describe these latter two derivatives in terms of two small dimensionless slow-roll parameters, ϵ and η.)

In principle these three parameters provide one relationship amongst the four observables defined by the amplitude and spectral tilts of the primordial spectrum of scalar and tensor perturbations to the metric, although the full power of this prediction is difficult to fully exploit until tensor fluctuations are detected. In the meantime, one may instead constrain ϵ and η from measurements of the scalar spectral tilt, n_s, as measured from the fluctuations in the CMBR, and from upper limits on r, defined as the ratio of the amplitude of tensor fluctuations to the amplitude of scalar fluctuations.

At present, current measurements are only now starting to be able to distinguish between the predictions of broad classes of models. Three classes of models which may be distinguished in this way are:[19,20]

1. *Large-Field Models,* for which ϵ and η vary inversely with the value of the inflaton field: $\propto (M_p/\varphi)^p$, for some $p > 0$;

2. *Small-Field Models,* for which ϵ and η are proportional to a positive power of the value of the inflaton field: $\propto (\varphi/M_p)^p$, for some $p > 0$;

3. *Hybrid Models,* for which field evolution at the end of inflation involves at least a two-dimensional field space, and for which the slow-roll parameters depend on parameters in the potential which govern the couplings between these fields.

Varying the various parameters in these models leads to predictions which fill regions of the observable $r - n_s$ plane. In the limit where $H_{\rm inf}$ is essentially constant during horizon exit (*i.e.* $\epsilon, \eta \approx 0$), all slow-roll models approach the scale-invariant point, corresponding to an unobservably small amplitude for tensor modes and a precisely Harrison-Zeldovich (HZ) spectrum: $(r, n_s) = (0, 1)$. But each of the above classes tends to sweep out a different region of predictions within the $r - n_s$ plane, all of which overlap near the scale-invariant HZ point. In particular, the bulk of small-field models (although not all) tend to prefer $n_s < 1$, while the bulk of hybrid models (although not all) prefer $n_s > 1$. What is exciting about the latest CMBR observations [20] is that they are now beginning to exclude the HZ point which is common to all classes of models, and as a result are beginning to provide observationally-justifiable preferences amongst these models.

3.1 Why embed inflation within string theory?

Given the few quantities to which observations are sensitive, the skeptical reader might reasonably wonder whether it is premature to invest considerable effort in finding inflationary evolution within string theory. There are nevertheless several good reasons for doing so. In particular, inflationary models must be embedded into a fundamental theory like string theory in order to understand the following issues:

1. *Naturalness:* Are the choices made in order to obtain acceptable values for $H_{\rm inf}$, ϵ and η inordinately sensitive to short-distance (UV) effects, or must they be finely-tuned in order to achieve sufficient inflation? (And if anthropic arguments are used to explain these tunings,[21] what assigns the probabilities [22] which must be used in order to have an adequate explanation?)

2. *Reheating:* At the end of inflation how does the energy associated with inflation get converted into observable heat (as is required in order to launch the present-day Hot Big Bang epoch)? As anyone who lives in a cold climate knows: a warm house requires *both* an efficient furnace and good insulation. Likewise, for inflation it is not sufficient for there to be a channel for coupling energy between the inflationary and observed sectors, one must also show that too much energy is not lost into any unobserved degrees of freedom. But this question cannot be addressed without a proper theory (like string theory) of what are *all* of the relevant degrees of freedom at inflationary energies.[23]

3. *Initial Conditions:* What justifies the choices which are made for initial conditions *before* inflation? This question can arise because part of the motivation for inflation is to explain the unusual initial conditions of Hot Big Bang cosmology. And inflation can itself require special initial conditions for some kinds of inflationary models (such as for hybrid models, for example). For such models the full microscopic theory is required in order to understand the origin of these initial conditions. Whether initial conditions really are a problem depends on the type of model of interest, since for some cases (like some large-field models) inflation can be an *attractor* solution, inasmuch as it is the endpoint for a broad class of initial conditions. Alternatively, for some cases (like for small field models) one can instead appeal to eternal inflation to explain why the inflating initial conditions might come to dominate the later universe.[24,25,26]

3.2 Why is string inflation so hard to find?

Twenty years of experience has shown that it is quite difficult to embed inflation into string theory in a controllable way. This is somewhat paradoxical given that supersymmetric string vacua provide so many massless scalar fields for which the corresponding scalar potential is completely flat (and so for which $\epsilon = \eta = 0$). The problem arises because a convincing case for a slow roll requires a complete understanding of the potential for these fields even after supersymmetry breaks. In particular one must check that this stabilizing potential does not introduce new, steep, directions into the potential along which the fields will prefer to roll. Although a number of mechanisms were proposed over the years taking advantage of supersymmetric flat potentials,[3] the difficulty in reliably computing supersymmetry-breaking effects, together with cosmological problems with the resulting potentials in the few calculable cases,[27] proved to be an obstacle to further progress.

The introduction of branes proved to be the way forward for string inflation, although the initial brane-brane proposal [28] also relied on supersymmetry for the flatness of its potential (and so suffered from the same calculational difficulties to do with supersymmetry breaking as did earlier ideas). The decisive advantage of branes became apparent only much later, for two reasons. First, it was realized that supersymmetry breaking can become calculable, based on the mutual attraction of a brane-antibrane pair [29,30] or branes at angles, [31] leading to the brane-antibrane mechanism of inflation. With calculability came an explosion of scenarios, including models using $D3$ branes attracted towards $D7$ branes,[32] branes undergoing relativistic motion,[33] intrinsically stringy modes [34], extensions to M-theory vacua [35], assisted inflation using string axions [36] and more — see ref. 3 for more extensive references than are possible here.

The second reason branes proved to be crucial for progess was the insight they provided[10,11] into the stabilization of the many scalar fields of string vacua. Once the simplest vacuum with all moduli stabilized was obtained,[12] its combination with the brane-antibrane inflationary mechanism led to the first inflationary scenario with a plausibly detailed string pedigree.[37,38] Shortly thereafter, variations on this theme also led to the discovery of inflationary scenarios for which it is the modulus describing the size of the extra dimensions (and its axionic superpartner) which is the inflaton.[39] Improved understanding of the potentials which stabilize the moduli of string vacua, has allowed better and better control over the approximations which are required in order to establish inflation, enabling more detailed connections to be made to the properties of explicit string vacua.[40,41]

3.3 How natural is inflation in string theory?

Now that some plausibly stringy inflationary models exist, how fine-tuned do they appear to be? Although it is still a bit early to draw definitive conclusions, since comparatively few corners of field space have been explored to this point, some tentative conclusions can be drawn. For instance, so far all of the proposals but one (including in particular all of the brane-antibrane scenarios) seem to require the same amount of fine-tuning as do their field theoretical counterparts: *i.e.* slow roll inflation requires parameters must be adjusted to within a part in 100 or 1000. In the one example for which inflation seems natural[40] it is a modulus, $X/M_p \sim \ln(L/\ell_s)$, of the extra dimensions which is the inflaton. (Here L is the length of a cycle in the extra dimensions, M_p is the 4D Planck mass and ℓ_s is the string length scale.) It is natural because it takes advantage of a mechanism earlier identified[42] in the field-theoretic limit, wherein the inflaton potential takes the schematic form

$$V(X) = V_0 - A\, X^c \exp[-a\,(X/M_p)^c] + \cdots\,, \tag{1}$$

where V_0, A, a and c are constants, and the ellipses represent terms which become important only as inflation ends. Such a potential has a slow roll provided that $X \gg M_p$, but the point is that this is *generic* to the domain of validity of the effective theory in which this potential appears. It is generic because $X \gg M_p$ corresponds to the condition $L \gg \ell_s$, which is a prerequisite for describing the dynamics of L in an effective field theory. It is clearly of considerable interest to see whether this example is representative, and if so to identify reliably the regions of solution space where inflation occurs so naturally.

3.4 What kind of stringy effects can we hope to measure?

Given that inflation appears to be possible in string theory, and given the wealth and precision of current observations, can we expect there to be any stringy ‘smoking guns’ awaiting us in the sky? Of course, a complete answer to this question must await a proper exploration of the reheating problem in models containing both inflation and a realistic standard model sector, since it is only then that we can see how many stringy remnants might survive into the late-time universe which we can observe. But three kinds of broad conclusions about observable signals can already be drawn.

1. *Remnant Cosmic Strings:* Within the brane-antibrane inflationary mechanism inflation ends when the brane and antibrane annihilate, and although not completely understood, it was recognized from the beginning[29] that this process is likely to generate an extremely rich spectrum of post-inflationary remnants.[b] The key point for observational purposes is that cosmic strings are special amongst these remnants inasmuch as they can plausibly be produced with observable string tensions and residual abundances,[44] although whether they can live long enough to survive to the present epoch is a somewhat model-dependent issue.[45]

[b] For high-dimension branes the cascade of annihilations of these remnants might in some circumstances provide a dynamical explanation for why 3-branes might be more abundant at late times,[29] an idea which when investigated in a fully cosmological context also predicts the same for 7-branes.[43]

2. *Observational Constraints Among Slow-Roll Parameters:* In all of the calculations to date the conclusion that the observed 4 dimensions inflate in a particular string (or string-motivated) model is drawn using a low-energy 4D effective field theory. As such, their direct predictions for the CMBR fall within the category of predictions for 4D slow-roll inflationary models. In particular, brane-antibrane models tend to fall into the category of hybrid inflation models, with the earliest models predicting [38] a 'blue' spectral index $n_s > 1$. (Subsequent more detailed studies have shown this conclusion not to be robust against adjustment of the details of the model, with $n_s < 1$ being possible for some choices of parameters.[46]) By contrast, moduli-driven models, like those of the 'racetrack' type,[39,41] are of the small-field type for which $n_s < 1$ is more robustly preferred. (Indeed the most recent of these [41] obtained $n_s = 0.95$ in what was probably the last theoretical calculation not to be biased by the most recent observations [20] which favour this value.) It is remarkable that the preference of the current data [20] for $n_s < 1$ already differentiates amongst some of these models at a statistically significant level, by differentiating amongst the classes of low-energy inflationary field theories to which they give rise.[47]

   One might hope that string theory might be more predictive than are the low-energy field theories which describe their effects at low energies. For instance, this would occur if it happened that not all of the three-dimensional inflationary parameter space — *i.e.* $H_{\rm inf}$, ϵ and η — of the 4D field theories were generated by varying the underlying parameters of the string models through all of their allowed values. This would be an attractive possibility if it were true, since it might permit a definitive test of string-based inflation by observations. Unfortunately there is as yet no evidence that string models do not explore the entire parameter space of 4D inflationary slow rolls, although admittedly the parameter space of the string-based models has not yet been extensively explored.

3. *Non-Decoupling Effects:* Everything known about string theory is consistent with the dynamics around string vacua being described at low energies by an appropriate effective field theory — although the occasional worry does get raised.[48] This allows a fairly robust analysis of the influence of high-energy states on inflationary predictions for the CMB since it is possible to analyze its effects in the effective field theory limit. And this theory can be taken to be four dimensional provided that the physics of interest around horizon exit is itself four-dimensional. Since the cosmological backgrounds of interest are time-dependent, care must be taken when performing this analysis to keep track the additional conditions which arise in this case for the validity of the effective-field theory description.[8]

   The results of such an analysis are interesting. First, one finds that by far the majority of effective interactions do not perturb the standard slow-roll inflationary predictions for the CMBR, with a vast number of effects first arising at order $(H_{\rm inf}/M)^2$, where M is the relevant string (or KK) scale describing the relevant high-energy physics.[49] This is good news, since it ensures the robustness of the standard predictions to high-energy string details. But there can be exceptions to this statement, of two types.[50] One type involves non-adiabatic time-dependent effects during the e-foldings just before horizon exit. These effects can cause deviations from the predictions of slow-roll inflation because they violate the assumptions on which the slow-roll calculations rely. Their existence is interesting since it motivates a careful search within the observations for deviations from standard slow-roll predictions.[c]

   Alternatively, there can also be static effects [50] which are larger than $O[(H_{\rm inf}/M)^2]$ because they arise with coefficients of order $(v/M)^2$, where $v \gg H_{\rm inf}$ is the scale in the scalar

[c] It should be remarked parenthetically that the expected deviations [50] can be physically distinguished from those predicted by the more speculative 'transplanckian' effects [51] which have been much discussed recently.

potential which gives rise to inflation: $H_{\rm inf} \sim v^2/M_p$. However, most of these $(v/M)^2$ effects arise as modifications of the inflaton potential and so represent a change in the connection between the slow-roll parameters and the underlying string parameters, rather than an observable deviation from the physical predictions of slow-roll inflation themselves.

It is clear that it is still early days for the exploration of the implications of string theory for cosmology in the very early and more recent universe. But the preliminary results are encouraging, and the prospects remain bright for learning something interesting about the physics of very high energies.

And perhaps the string-cosmology connection will prove to be even more interesting once it is understood — such as perhaps providing an alternative to inflation [52], by providing accelerating universes through more exotic kinds of stringy sources [53], or in some other way we do not yet anticipate. Let us hope so!

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