

Testing string theory by probing the pre-bangian Universe

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Abstract. After recalling why superstring theory suggests a new cosmological principle of “asymptotic past triviality”, I will argue that classical (quantum) gravitational instabilities can inflate (warm up) an asymptotic-past-trivial Universe. I will then discuss how near-future observations could provide a window through which we can probe the pre-bangian Universe and thus test string theory both at short and at large distances.

INTRODUCTION

Earlier at this Conference, the pre-big bang (PBB) scenario was quickly dismissed as being: i) misguided; ii) fine-tuned; iii) non-predictive. It so happens that this talk was prepared precisely in such a way as to answer those three “allegations” in the order: i) by arguing that superstring theory’s short and large-distance properties strongly motivate the PBB scenario; ii) by showing that inflation follows, without fine-tuning, from generic initial conditions of the PBB type; iii) by claiming that the PBB model is so predictive that, at least in its minimal form, it may soon be ruled out experimentally. These three topics will be dealt with in the following three sections. The last one will present some conclusions.

SUPERSTRING-BASED MOTIVATIONS

Short-distance inspiration

Since the classical (Nambu-Goto) action of a string is proportional to the area

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A of the surface it sweeps, its quantization must introduce a quantum of length λ_s through:

$$S/\hbar = A/\lambda_s^2 . \quad (1)$$

By replacing Planck's constant in quantum string theory [1], λ_s plays the role of a minimal observable length, an ultraviolet cut-off. Physical quantities are expected to be bound by appropriate powers of it, e.g.

$$H^2 \sim R \sim G\rho < \lambda_s^{-2} , \quad k_B T/\hbar < c\lambda_s^{-1} , \quad R_{comp} > \lambda_s . \quad (2)$$

In other words, in quantum string theory (QST), relativistic quantum mechanics should solve the singularity problems in much the same way as non-relativistic quantum mechanics solved the singularity problem of the hydrogen atom by putting the electron and the proton a finite distance apart. Also, QST gives us a framework where we can ask daring questions such as: What was there before the big bang?

Large-distance inspiration

Even at large distance (low-energy, small curvatures), superstring theory does not automatically give Einstein's general relativity. Rather, it leads to a scalar-tensor theory. The new scalar particle/field ϕ , the so-called dilaton, is unavoidable in string theory; it gets reinterpreted as the radius of a new dimension of space in so-called M-theory [2]. The dilaton is massless to all orders in perturbation theory, i.e. as long as supersymmetry remains unbroken. Is the dilaton a problem or an opportunity? Possibly both: while we can try to avoid its potential dangers, we may use some of its properties to our advantage ... Let me discuss how.

In string theory, ϕ controls the strength of all forces, gravitational and gauge alike. One finds, typically:

$$l_P^2/\lambda_s^2 \sim \alpha_{gauge} \sim e^\phi , \quad (3)$$

expressing the basic unification of all forces in string theory. Note that, in our conventions, the weak-coupling region corresponds to $\phi \ll -1$. In order not to contradict precision tests of the equivalence principle and of the constancy of the gauge and gravitational couplings in the recent past, we require [3] the dilaton to have a mass and to be frozen at the bottom of its own potential *today*. This does not exclude, however, the possibility of the dilaton having evolved cosmologically (after all, the metric did!) within the weak-coupling region, where it was practically massless. The amazing (yet simple) observation [4] is that, by so doing, the dilaton may have inflated the Universe!

A simplified argument, which, although not completely accurate, captures the essential physical point, consists in writing the ($k = 0$) Friedmann equation, $3H^2 =$

$8\pi G\rho$, and in noticing that a growing dilaton (meaning through (3) a growing G) can drive the growth of H even if the energy density of standard matter decreases in an expanding Universe. This new kind of inflation (characterized by growing H and ϕ) has been termed dilaton-driven inflation (DDI). The basic idea of pre-big bang cosmology [4–6] is thus clear: the dilaton started at very large negative values (where it is massless), grew according to its field equations while inflating the Universe, and finally settled, sometime in our recent past, at its present value ($\phi = \phi_0$) corresponding to the minimum of its potential.

DDI is not just possible. It exists as a class of cosmological solutions thanks to the duality symmetries of string cosmology. Under a prototype example of these symmetries, the so-called scale-factor duality [4], an FRW cosmology evolving (at lowest order in derivatives) from a singularity in the past, is mapped into a DDI cosmology going towards a singularity in the future. Of course, the lowest-order approximation breaks down *before* either singularity is reached. A (stringy) moment away from their respective singularities, these two branches should join smoothly to give a single non-singular cosmology (the so-called graceful exit). Since the DDI phase is characterized by growing coupling and curvature, it must itself have originated from a regime in which both quantities were very small. We take this as the main lesson/hint to be learned from low-energy string theory and raise it to the level of a new cosmological principle [7].

Asymptotic Past Triviality

The concept of asymptotic past triviality (APT) is quite similar to that of “asymptotic flatness”, familiar from general relativity. The main differences consist in making only assumptions concerning the asymptotic past (rather than future or space-like infinity) and in the additional presence of the dilaton. It seems physically (and philosophically) satisfactory to identify the beginning with simplicity (see e.g. entropy-related arguments concerning the arrow of time). What could be simpler than a trivial, empty and flat Universe? Nothing of course! The problem is that such a Universe, besides being uninteresting, is also non-generic. By contrast, asymptotically flat/trivial Universes are initially simple, yet generic (i.e. not fine-tuned) in the precise mathematical sense that they involve the right number of “integration constants” to describe a general solution. We will ask whether these APT initial data will evolve as to generate a physically interesting big bang-like state at some later time, and argue that it is precisely what should be expected, owing to well-known classical and quantum gravitational instabilities.

INFLATION AS GRAVITATIONAL COLLAPSE

The assumption of APT entitles us to treat the early history of the Universe through the classical field equations of the low-energy (because of the small cur-

vature), tree-level (because of the weak coupling), effective action of string theory. Even then, the problem of determining the properties of a generic solution to the field equations is a formidable one. Very luckily, however, through a field redefinition, we are able to map our problem into one that has been much investigated, both analytically and numerically, in the literature: that of the gravitational collapse of a massless scalar field. Such a system has been considered by many authors, in particular by Christodoulou [8], precisely in the regime of interest to us. In line with the APT postulate, one assumes, in the analogue gravitational collapse problem, very “weak” initial data with the aim of finding under which conditions gravitational collapse later occurs. Gravitational collapse means that the metric (and the volume of 3-space) shrinks to zero at a space-like singularity. However, typically, the dilaton blows up at that same singularity. By undoing the field redefinition one can show that gravitational collapse becomes DDI in the original string-cosmology problem.

How generically does gravitational collapse take place? The singularity theorems by Hawking and Penrose [9] state that, under some general assumptions, singularities are inescapable in GR. All but one of those assumptions are automatically satisfied in the case at hand. Only the existence of a closed trapped surface needs to be imposed. Rigorous results [8] show that this condition cannot be waived: sufficiently weak initial data do not lead to closed trapped surfaces, to collapse, or to singularities. Sufficiently strong initial data do. But where is the borderline? This is not known in general, but precise criteria do exist for particularly symmetric space-times, e.g. for those endowed with spherical symmetry. However, no matter what the general collapse/singularity criterion will eventually turn out to be, we do know that: i) it cannot depend on an over-all additive constant in ϕ ; ii) it cannot depend on an over-all multiplicative factor in $g_{\mu\nu}$. This is a simple consequence of the invariance of the effective equations describing the system in this regime under shifts of the dilaton and rescaling of the metric.

We conclude that, generically, some regions of space will undergo gravitational collapse, will form horizons and singularities therein, but nothing, at the level of our approximations, will be able to fix either the size of the horizon or the value of ϕ at the onset of collapse. When this is translated into the original cosmological problem, one is describing, in the region of space-time within the horizon, a period of DDI in which both the initial value of the Hubble parameter and that of ϕ are left arbitrary. These two initial parameters determine the range of validity of our description, since both curvature and coupling increase during DDI and, therefore, the low-energy and/or tree-level description is bound to break down at some point. The smaller the initial Hubble parameter (i.e. the larger the initial horizon size) and the initial coupling, the longer we can follow DDI through the effective equations and the larger the number of reliable e-folds that we gain.

This does answer, in my opinion, the objections raised recently [10] to the PBB scenario according to which it is fine-tuned. The situation here actually resem-

bles that of chaotic inflation [11]. Given some generic (though APT) initial data, we should ask which is the distribution of sizes of the collapsing regions and of couplings therein. Then, only the “tails” of these distributions, i.e. those corresponding to sufficiently large, and sufficiently weakly coupled regions, will produce Universes like ours, the rest will not. A basic difference between the large numbers needed in (non-inflationary) FRW cosmology and the large numbers needed in PBB cosmology should be stressed. In the former, the ratio of two classical scales, i.e. of total curvature to its spatial component, which is expected to be $O(1)$, has to be taken as large as 10^{60} . In the latter, the above ratio is initially $O(1)$ in the collapsing/inflating region, and ends up being very large in that region thanks to DDI. However, the common order of magnitude of these two classical quantities is a free parameter, and is taken to be much larger than a (classically irrelevant) quantum scale.

In conclusion, we may summarize recent progress on the problem of initial conditions by saying that [7]: **Dilaton-driven inflation in string cosmology is as generic as gravitational collapse in general relativity.**

OBSERVABLE RELICS AND HEATING THE PRE-BANG UNIVERSE

PBB relics

Since there are already several review papers on this subject (e.g. [12]), I will limit myself to a short summary:

- For gravitational waves and dilatons, one obtains quite steep spectra [13] and thus small contributions at large scales. The reverse is also true: at short scales, the expected yield in a stochastic background of gravitational waves is much larger than in standard inflationary cosmology, where one expects $\Omega_{GW} < 10^{-14}$. Values of Ω_{GW} in the range of 10^{-6} – 10^{-7} are possible in some regions of parameter space, which, according to some estimates of sensitivities [14], could be inside detection capabilities in the near future.
- Vacuum fluctuations of gauge bosons are not amplification in standard cosmology, since a conformally flat metric (of the type forced upon by inflation) decouples from the electromagnetic (EM) field precisely in $D = 3 + 1$ dimensions. As a very general remark, the only background field that can, through its cosmological variation, amplify EM (more generally gauge-field) quantum fluctuations is the effective gauge coupling itself. By its very nature, in the pre-big bang scenario the effective gauge coupling inflates together with space during the PBB phase. It is thus automatic that any efficient PBB inflation

brings together a huge variation of the effective gauge coupling and thus a very large amplification of the primordial EM fluctuations [15–17]. This can possibly provide the long-sought origin for the primordial seeds of the observed galactic magnetic fields. Notice, however, that, unlike GW, EM perturbations interact considerably with the hot plasma of the early (post-big bang) Universe. Thus, converting the primordial seeds into those that may have existed at the proto-galaxy formation epoch is by no means a trivial exercise. Work is in progress to try to adapt existing codes [18] to the evolution of our primordial seeds.

- Fluctuations of the so-called universal axion of string theory, i.e. of the supersymmetric partner of the dilaton, can be large even at large scales [19]. Also, unlike the GW spectrum, that of axions is very sensitive to the cosmological behaviour of internal dimensions during the DDI epoch. On one side, this makes the model less predictive. On the other, it tells us that axions represent a window over the multidimensional cosmology expected generically from string theories, which must live in more than four dimensions. Curiously enough, the axion spectrum becomes exactly HZ (i.e. scale-invariant) when all the nine spatial dimensions of superstring theory evolve in a rather symmetric way [16]. In situations near this particularly symmetric one, axions are able to provide a new mechanism [20] for generating large-scale CMB anisotropy and LSS. This model, being of the isocurvature type, bears some resemblance to the one recently advocated by Peebles [21] and, like his, is expected to contain some calculable amount of non-Gaussianity, as well as some characteristic acoustic peak structure.
- Many other perturbations, which arise in generic compactifications of superstrings, have also been studied, and lead to interesting spectra. For lack of time, I will refer to the existing literature [16,17].

Heat and entropy as a quantum gravitational instability

Before closing this section, I wish to recall how one sees the very origin of the hot big bang from a cold start in the PBB scenario. One can easily estimate the total energy stored in the quantum fluctuations, which were amplified by the pre-big bang backgrounds. The result is, roughly, $\rho_{quantum} \sim N_{eff} H_{max}^4$, where N_{eff} is the effective number of species that are amplified and H_{max} is the maximal curvature scale reached. We expect $H_{max} \sim M_s = \lambda_s^{-1}$, and we know that, in heterotic string theory, N_{eff} is in the hundreds. It is tempting to assume [16] that, precisely when the dilaton reaches a value such that $\rho_{quantum}$ is critical, the Universe will enter the radiation-dominated phase. This constraint gives, typically, $e^{\phi_{exit}} \sim 1/N_{eff}$, i.e. a value for the dilaton close to its present value [16]. The entropy density σ in these

quantum fluctuations can also be estimated by using some general results [22]. One finds:

$$\sigma \sim N_{eff} H_{max}^3 . \quad (4)$$

It is easy to check that, at the assumed time of exit, this entropy saturates a recently proposed bound [23], which also turns out to be a physically acceptable value for the entropy of the Universe just after the big bang: a large entropy ($\sim 10^{90}$) on the one hand, a small entropy for the total mass and size of the observable Universe on the other. Thus, PBB cosmology neatly explains why the Universe, at the big bang, *looks* so fine-tuned, and provides for it a natural arrow of time [23].

CONCLUSIONS

- Pre-big bang cosmology is a “top-down” rather than a “bottom-up” approach to cosmology. This should not be forgotten when testing its predictions.
- It does not need to invent an inflaton, or to fine-tune its potential: inflation is “natural” thanks to the duality symmetries of string cosmology and to its relation to gravitational collapse.
- The problem of initial conditions “decouples” from the singularity problem; it is classical, scale-free, and unambiguously defined. Issues of fine-tuning can be addressed and, I believe, answered.
- PBB cosmology is a tight, highly constrained scenario. As such, it makes a number of predictions:
 - the tensor contribution to $\Delta T/T$ should be very small;
 - some non-Gaussianity in $\Delta T/T$ correlations is expected, and calculable.
 - the axion-seed mechanism should lead to a characteristic acoustic-peak structure, which is being calculated;
 - it should be possible to convert the predicted seed magnetic fields into observables by using some reliable code for their late evolution;
 - a characteristic spectrum of stochastic gravitational waves is expected to surround us, and could be large enough to be measurable within a decade or so.

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