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STRINGS, COSMOLOGY, ... AND A PARTICLE*)

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Abstract

After recalling a few basic concepts from cosmology and string theory, I will stress the crucial role played in the latter by the so-called dilaton, an ubiquitous scalar particle/field. The symmetries of string cosmology, largely due to the dilaton, are then described and invoked to motivate and construct an appealing, natural alternative to traditional inflation. In such a dilaton-driven inflation the Universe has evolved from an initial weak-coupling, weak-curvature state to its present era through a high curvature - but non-singular - quantum stringy epoch. Observable consequences of the new scenario are discussed together with possible theoretical and phenomenological problems.

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ABSTRACT

After recalling a few basic concepts from cosmology and string theory, I will stress the crucial role played in the latter by the so-called dilaton, an ubiquitous scalar particle/field. The symmetries of string cosmology, largely due to the dilaton, are then described and invoked to motivate and construct an appealing, natural alternative to traditional inflation. In such a dilaton-driven inflation the Universe has evolved from an initial weak-coupling, weak-curvature state to its present era through a high curvature - but non-singular - quantum stringy epoch. Observable consequences of the new scenario are discussed together with possible theoretical and phenomenological problems.

1. Introduction

In this talk I will try to summarize the work done by our group over the last three years on attempting to construct a stringy alternative to the standard inflationary scenario.

The main distinctive feature of our version of string-inspired inflation will reside in the crucial role played in it by the so-called dilaton field. The possibility of dilaton-driven inflation –even in the absence of a dilaton potential– follows from the unconventional coefficient (and sign) of its kinetic term in the effective action, which, in turn, is dictated by a new, stringy symmetry: scale-factor-duality.

The outline of the talk is as follows: I will start with a kinematical "appetizer", contrasting how non-inflationary, standard inflationary and string cosmology differ w.r.t. the so-called horizon problem. Next, in order to motivate the string-inspired scenario, I will digress a moment to recall some basic facts in string theory. I will then put forward the basic idea underlying our approach, adding some non-technical details in a kind of picture-book style. We shall then discuss how the scenario is able to make quantitative predictions, which might become testable in the near future, and conclude by recalling the main unsolved theoretical and phenomenological problems.

Before proceeding I would like to acknowledge with deep gratitude the help and encouragement of my collaborators in this project, i.e. Ram Brustein (CERN), Maurizio Gasperini (Turin), Jnan Maharana (Bhubaneswar), Kris Meissner (Trieste), Norma Sanchez (Paris), Nguyen Suan Han (Hanoi), as well as my Ph.D. students Massimo Giovannini and Roberto Ricci. I would also like to mention that somewhat different lines in string cosmology have been followed recently by A. Tseytlin and C. Vafa, and that some pioneering (pre-dilaton) work on the subject is due to E. Alvarez, Y. Leblanc and to R. Brandenberger and C. Vafa.

2. Three scenarios for the very early Universe

It is well known [1] that the Standard Cosmological Model (SCM) works well at "late" times, its most striking successes being perhaps the red shift, the cosmic microwave background, and primordial nucleosynthesis.

By contrast, the physics of the very early Universe is still clouded with mystery. Three possible scenarios are illustrated in Fig. 1, where is plotted, against cosmic time, a representative scale of the cosmological evolution, such as the Hubble parameter

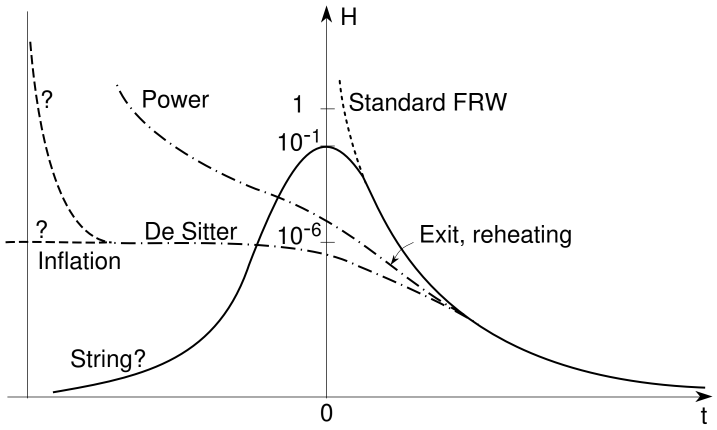

Figure 1: Three scenarios (H as a function of t) for the very early Universe.

$$H(t) \equiv \frac{\dot{a}(t)}{a(t)} , \tag{1}$$

with $a(t)$ the scale factor of a homogeneous Friedman–Robertson–Walker (FRW) Universe, hereafter assumed to be spatially flat ($k = 0$). By definition, the three scenarios converge as we go forward in time. They diverge from one another, however, as we go backward in time. While in the standard, non-inflationary, FRW scenario H keeps increasing until it reaches a singularity at $t = 0$ (the Big Bang), in de Sitter-type inflation H flattens off and stays essentially constant at a value H_1 for a long time (more than $60 H_1^{-1}$). What happens in that scenario at even earlier times is unclear. In models of inflation based on a phase transition [2], inflation is preceded by another radiation-dominated FRW era, while in chaotic inflation [3] this is not necessary. Inflation is generically defined as a period of accelerated expansion, $\ddot{a} > 0$. This is the necessary and sufficient mathematical requirement needed to solve the kinematical problems (horizon, flatness) posed by pre-inflationary cosmology. Since

$$\frac{\ddot{a}}{a} = \dot{H} + H^2 \ , \tag{2}$$

$\dot{H} = 0$ gives inflation. It is also possible, however, to have inflation while $\dot{H} < 0$ (provided $H^2 + \dot{H} > 0$). This is the so-called power inflation, also shown in Fig. 1, which will be considered here as a variant of de Sitter inflation. We will argue below that string cosmology suggests a third type of inflation, the so-called super (or pole) inflation [4] in which, actually, $\dot{H} > 0$. In other words, we will claim that the symmetries of string cosmology speak for an almost bell-shaped curve for $H(t)$ as a function of cosmic time (see Fig. 1 again). Note that, in all three scenarios, $H > 0$ at all t, hence that we are not considering oscillatory Universes here.

The main kinematical point to be stressed is that the above scenarios differ quite substantially w.r.t. the horizon problem. Indeed, as illustrated in Fig. 2:

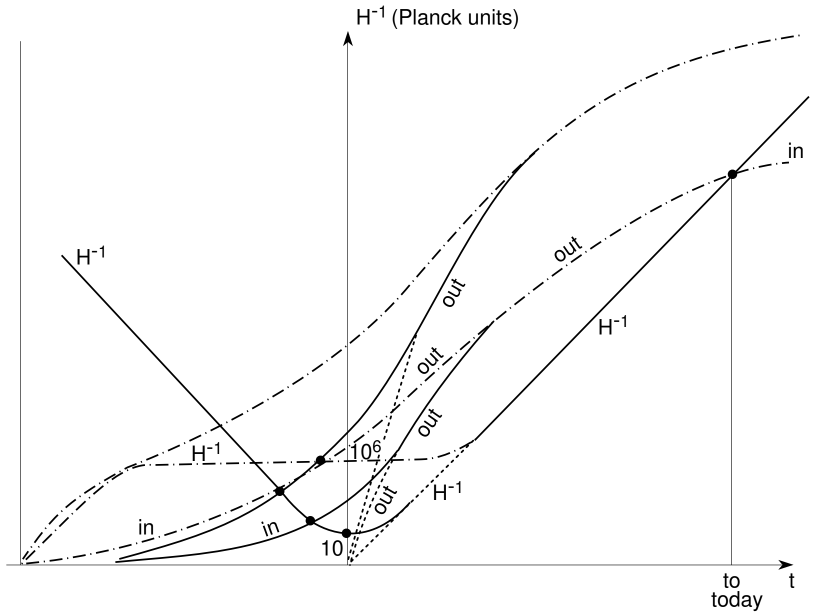

Figure 2: Horizon crossing in the three scenarios.

a) In the standard FRW scenario every scale crosses the horizon only once, leading to the horizon-homogeneity problem of standard cosmology.

b) In de Sitter (or power) inflation only short enough scales cross the horizon twice. A long enough inflationary era is needed for our present horizon scale to have been within the horizon during the inflationary epoch.

c) In the string-inspired scenario all scales cross the horizon twice and they have been already in causal contact during inflation.

The second important kinematical observation (also shown in Fig. 2) is that, obviously, different scales cross the horizon at $H = H_1$ in de Sitter-type inflation, while in power (resp. super) inflation larger scales cross the horizon at larger (resp. smaller) values of H. As discussed in Section VI, this fact will have interesting physical consequences.

In order to substantiate the claim that string theory suggests the third scenario, I will have to digress and recall a few basic facts in Quantum String Theory.

3. Basic Facts in Quantum String Theory (QST)

I am listing below a few basic properties of strings, emphasizing those that are most relevant for our subsequent discussion. These are:

1. Unlike classical strings, which do not contain a characteristic scale, quantum strings contain a fundamental length scale λ_s, which shows up almost everywhere. It represents:

a) Planck's constant (in appropriate units of energy) [5].

b) The ultraviolet (UV) cut-off, which is roughly equivalent to a lattice cut-off of spacing λ_s. It is indeed amazing that two concepts [a) and b)], which are conceptually distinct and are unrelated in conventional QFT, become one and the same thing in QST [5].

c) The scale of tree-level masses that are either zero or $O(\lambda_s^{-1})$. Incidentally, it is quantization that allows strings with non-zero angular momentum to be massless [6], classically $M^2 > const. \times J$. This is obviously a crucial property of QST, without which it could not pretend to be a candidate theory of all known interactions.

d) A minimal size, $\Delta x > \lambda_s$. This is, of course, related to point b) and is a consequence of the uncertainty principle (cf. Δx for harmonic oscillator).

e) The entropy per unit length is $O(\lambda_s^{-1})$. This is what leads to a Hagedorn temperature in string theory [7], $T_{Hag} = 0(\lambda_s^{-1})$.

2. The absence of free parameters ($c = \lambda_s = 1$ defines units of length and of time intervals), which are replaced by expectation values of fields [6]. Basically, some huge (and still largely unknown) symmetries should fix the tree-level "Lagrangian", while UV finiteness [point 1b)] preserves full predictive power at loop level. Note again here the contrast with QFT, where, even if the bare couplings were fixed, the need to renormalize the theory at loop level would make the renormalized constants finite but uncalculable.

3. The effective interactions of the massless fields at $E \ll \lambda_s^{-1}$ is a classical, gauge-plus-gravity field theory. It is described by an effective action [8,9] of the (schematic) type:

$$\Gamma_{eff} = \frac{1}{2}\int d^4x\sqrt{-g}\; e^{-\phi}\left[\lambda_s^{-2}(\mathcal{R} + \partial_\mu\phi\partial^\mu\phi) + F_{\mu\nu}^2 + \bar{\psi}\not{D}\psi + higher\ derivatives\right] + \left[higher\ orders\ in\ e^{\phi}\right] \quad (3)$$

While the higher orders in e^{ϕ} have a QFT analogue (they are the equivalent of loop corrections), the higher derivative terms are genuine string-size effects, typically of order $\lambda_s^2 \cdot \partial^2$.

4. As indicated in (3), QST has (actually needs!) a new particle/field, the so-called dilaton ϕ, a scalar, massless particle (at tree level). It appears in Γ_{eff} as a Jordan–Brans–Dicke [10] (JBD) scalar with a negative "small" ω_{BD} parameter, $\omega_{BD} = -1$.

5. The dilaton's VEV provides [9,11] a unified value for:

a) The gauge coupling(s) at $E = O(\lambda_s^{-1})$.

b) The gravitational coupling in string units.

c) Yukawa couplings, etc., at the string scale.

In formulae:

$$\ell_p^2 \equiv 8\pi G_N\hbar = e^{\phi}\lambda_s^2\ ,$$
$$\alpha_{GUT}(\lambda_s^{-1}) \simeq \frac{e^{\phi}}{4\pi} \quad (4)$$

implying (from $\alpha_{GUT} \approx 1/20$) that the string-length parameter λ_s will be about 10^{-32}cm. Note, however, that, in a cosmological context in which ϕ evolves in time, the above formulae can only be taken to give the present values of α and ℓ_p/λ_s. In the scenario we will advocate, both quantities should have been much smaller than today in the very early Universe!

6. Dilaton couplings at large distance are essentially known [12] and can be summarized in the following effective Lagrangian (taking loop effects into account)

$$\mathcal{L}_{eff} = \sum_i g_{\phi A_i A_i}\phi A_i^2$$

$$g_{\phi A_i A_i} \;=\; \sqrt{4\pi G} m_i^2 Z_\phi^{-1/2} \left(\frac{\partial}{\partial\phi} ln \frac{m_i^2}{M_P^2}\right)\Big|_{\phi=\langle\phi\rangle} \quad . \tag{5}$$

Here $\sqrt{4\pi G} m_i^2$ is the same strength as for (static) gravity, the correction $Z_\phi^{1/2}$ is $1 + O(\alpha_{GUT})$, while the last factor is computable if e^ϕ is reasonably small. One finds [12] that the dilaton coupling to nuclear matter (QCD confinement mass) is about 80 times larger than gravity. Furthermore, since the coupling to electromagnetic mass or to leptons is expected to be substantially different (probably smaller), one predicts a composition-dependent "5th force" of strength larger than gravity. Tests of the equivalence principle down to ranges of $10^{-1} \div 1$ cm [13] thus put bounds [12,14] on the dilaton mass, i.e.,

$$M_\phi > 10^{-4}\ eV \ . \tag{6}$$

Recently, Damour and Polyakov [15] made a daring proposal, which, at least in my own interpretation of it, decouples the dilaton from matter by having the dilaton's VEV coincide with a stationary point of α_{GUT}, M_P and m_i

$$\frac{\partial}{\partial\phi} \left(\alpha_{GUT}, M_P, m_i\right)|_{\phi=\langle\phi\rangle} = 0 \ . \tag{7}$$

Such a condition is not satisfied at perturbative values of ϕ [see (4)] but could perhaps be true at strong string coupling ($e^\phi/4\pi \gtrsim 1$) even if that corresponds to a reasonably small α_{GUT}.

7. Details about the dilaton potential are unknown, but we are not completely ignorant about its form. In particular:

a) On <u>theoretical</u> grounds, in critical superstring theory, the dilaton potential has to go to zero as $\phi \to -\infty$ (weak coupling) as a double exponential:

$$V(\phi) \sim exp\left(-c^2 exp(-\phi)\right) = exp\left(-\frac{c^2}{4\pi\alpha_{GUT}}\right) \ , \tag{8}$$

with c^2 a positive (but model-dependent) constant.

b) On <u>physical</u> grounds it should have a non-trivial minimum at its present value ($-1 < \langle\phi\rangle = \phi_0 < 0$) with (an effectively) vanishing cosmological constant, $V(\langle\phi\rangle) = 0$.

A typical potential satisfying a) and b) is shown in Fig. 3. The dotted lines at $\phi > 0$ represent our ignorance about strongly coupled string theory. Fortunately, the details of what happens in that region will not be very relevant for our subsequent discussion.

Note that string theory gives naturally one of the dreams of inflationary cosmologists, a flat, very flat indeed, potential. Unfortunately, however, there is no potential energy there! How can one then play the inflationary game? This is the subject of our next section.

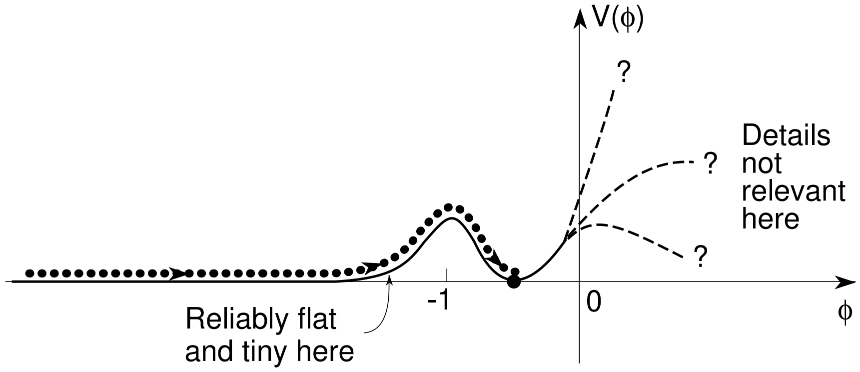

Figure 3: A possible dilaton potential and inflation being driven by a rolling-up dilaton.

4. The Basic Idea/Postulate of String Cosmology

In conventional de Sitter-type inflation, a long epoch is needed during which the energy–momentum tensor is dominated by potential (vacuum) energy:

$$\rho = -p = V(\sigma) \sim constant$$
$$a(t) = exp(Ht) \ , \quad H^2 = \frac{8\pi G}{3} V \ , \tag{9}$$

where σ is the so-called inflaton field. As stated in Section II, something like $\int_{infl.} Hdt \gtrsim 60$ is needed in order to solve the horizon-flatness problems. It is the (false) vacuum energy that drives the inflationary expansion while the inflaton slowly rolls down.

Playing such a game in string theory meets with several problems [16]. Besides, if $H \sim$ constant, it is well known (see below) that $H < 10^{-5} M_P$ in order that fluctuations on the CMB temperature $\Delta T/T$ remain at the 10^{-5} level. In this case, $H \ll \lambda_s^{-1} \approx 10^{-1} M_P$ and it is difficult to imagine that any rôle can be played by genuine string physics.

We are thus led to conceive a totally different mechanism for inflation in string theory [17], whereby the Universe inflates at zero potential energy simply as a result of the rolling up of ϕ from the trivial vacuum at $\phi = -\infty$ (or some $\phi_{in} \ll -1$) to the physical vacuum of Fig. 3. Still in Fig. 3 we indicate by large dots the dilaton's path as it climbs a potential well and finds its way to the present vacuum. In this scenario the growth of coupling entails with it the (inflationary) growth of the Universe. But how can inflation occur while $V = 0$? And how can the dilaton climb over mountains in V and then settle down to $\langle \phi \rangle$?

The answer is that behaviours that look very unnatural in ordinary Einstein–Friedman cosmology become completely natural in string cosmology. The reason is a new, stringy symmetry [17–19], known as Scale Factor Duality (SFD). In its simplest form, SFD tells us that, given a standard FRW cosmology such as

$$\left\{ \begin{array}{ll} a(t) \sim t^{1/2} \ , & \phi = const. \\ \frac{p}{\rho} = \frac{1}{3} \ , & \rho \sim a^{-4} \end{array} \right. , \tag{10}$$

one can construct a new cosmological solution (of string <u>not</u> of Einstein cosmology) given by

$$\left\{ \begin{array}{lll} \tilde{a}(t) = a^{-1}(-t) \ , & i.e. & \tilde{a} \sim (-t)^{-1/2} \\ \tilde{\phi}(t) = \phi(-t) - 2d \ln a(-t) \ , & i.e. & \tilde{\phi} \sim -3 \ln(-t) \\ \frac{\tilde{p}}{\tilde{\rho}} = -\frac{p}{\rho} = -\frac{1}{3} \ , & \tilde{\rho} \sim a^{-2} & \end{array} \right. \tag{11}$$

Note that, necessarily, under $a \rightarrow \tilde{a}$ a cosmology with $H > 0, \dot{H} < 0$ (typical FRW with $p > 0$) gives a new cosmology with $\tilde{H} > 0, \dot{\tilde{H}} > 0$, i.e. of the (super) inflationary type. Also, a constant ϕ goes into a growing $\tilde{\phi}$, which starts very large and negative at large negative t. Finally, note the flip of sign in the equation of state of matter. This is in perfect agreement with the properties of classical string motions in cosmology [20], the place where SFD was first observed [17]. SFD is actually a subgroup of a larger $O(d, d)$ symmetry [21] on which I cannot digress here.

5. The Scenario in more detail

Let us indeed assume that the Universe starts in (or very near) its perturbative vacuum:

$$e^{\phi} \ll 1 \ , \quad H \ll \lambda_s^{-1} \ , \tag{12}$$

and at low temperature and entropy. Such a vacuum looks unstable since the equations of string cosmology yield (in $d = 3$ for simplicity)

$$\left\{ \begin{array}{c} \dot{\phi} = 3H \pm \sqrt{3H^2 + V + e^{\phi}\rho} \\ \dot{H} = \pm H\sqrt{3H^2 + V + e^{\phi}\rho} - \frac{1}{2}V' + \frac{1}{2}e^{\phi}p \\ \dot{\rho} + 3H(\rho + p) = 0 \ . \end{array} \right. \tag{13}$$

Choosing the (+) sign in (13) [the (−) and (+) signs are related by SFD], we see that not much can stop ϕ and H from growing faster and faster. A small potential bump (as in Fig. 3) -or some non vanishing ρ and p from a fluid- cannot help much in slowing down the process. Thus we get an irresistible inflationary evolution that, in the absence of higher-curvature (derivative) effects, can only lead to a singularity (a big bang!)

Here comes the crucial postulate of string cosmology. As $H, \dot{\phi}$ become $O(\lambda_s^{-1})$, higher-order effects should intervene to stop their faster and faster growth and prevent the singularity from occurring. What should happen instead is that a "branch change" occurs [i.e. one switches from (+) to (−) signs in (13)] around the maximal scale of H. We may call the instant of branch change the stringy big bang and refer to the phase before it as the pre-big bang epoch in string cosmology. It is easy to see that, if the $(-)$ sign is taken in (13), the dilaton starts behaving normally and is attracted by the minimum of V. Assuming $V(\phi_0) = V'(\phi_0) = 0$, one ends up, eventually, with the standard radiation-dominated Universe if $p \to \rho/3$.

Branch changes are not as unusual and unfamiliar as it may look at first sight. Even uniform accelerated motions go through them ($\dot{x} = \pm\sqrt{2gx}$ needs a branch change at $x = 0$!) and, indeed, branch changes in string cosmology have been seen and studied [18]. The problem found in Ref. [18] is that, unless the change occurs at the string scale, it is not stable, i.e. a second branch change takes place later, bringing us back to the inflationary branch (exit problem in string cosmology!). Similar exit problems were found to occur in generic JBD theories [22] and also after inclusion of spatial curvature and/or antisymmetric-tensor contributions [23].

It thus looks that confirmation (or refusal) of our basic postulate can only come from the fully fledged incarnation of string theory. It is still conceivable, however, that the branch change will occur at weak coupling (i.e. with $e^{\phi} \ll 1$), in which case the problem can be studied in the context of tree-level conformal invariance.

While no realistic case has been found yet, it is encouraging that there are examples [24] of exact, non-singular conformal string theories where duality-related low-curvature solutions go into one another (in real cosmic time) through a very stringy era for which no conventional space-time description can be used. Such a phenomenon is certainly related to the much discussed phenomenon of topology change in string theory [25], the main difference being that branch changes should occur in real time cosmic.

If an example of the same sort –i.e. connecting our duality-related epochs– could be found, the appealing picture of Fig. 4 would become an actual possibility. In the next section, we will assume the existence of such a possibility and examine its observable consequences.

6. Observable Consequences

We shall discuss below three possible physical consequences of our string-inspired cosmology in order of decreasing reliability:

a) The most solid prediction of our scenario is that of a cosmic background of gravitational waves or, if one prefers to use a particle physics language, of gravitons. The mechanism that generates gravitons during a cosmological evolution is by now well understood and studied especially in the context of de Sitter inflation [26]. Basically, some primordial quantum flucutations of the tensor part of the metric undergo an amplification during inflation (a kind of anti-tunnelling) and become classical, stochastic gravitational waves. Since quantum mechan-

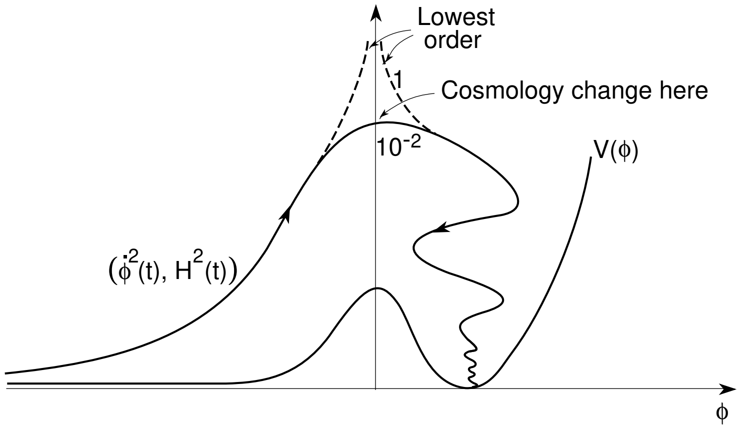

Figure 4: Parametric plot of the entire history.

ics specifies completely the magnitude of the primordial fluctuations, the final normalization is also known for any given cosmological evolution. What distinguishes gravitational waves from other perturbations (e.g. from electromagnetic waves/photons) is that they decouple from everything else just after the big bang and should have survived until today without any distorsion other than the overall redshift.

The power(energy) contained in these waves today can be computed as a function of frequency ω:

$$\begin{aligned}
\Omega_g &= \rho_c^{-1}\frac{d\rho_{gr}}{d\ln\omega} \simeq \frac{H_1^2}{M_p^2}\Omega_\gamma(t_0)\left(\frac{\omega}{\omega_1}\right)^{\alpha} \quad , \ \omega_1 > \omega > \omega_2 \\
\Omega_g &= (same)\times\left(\frac{\omega}{\omega_2}\right)^{-2} \quad , \ \omega < \omega_2 \\
\Omega_g &\sim exp(-\omega/\omega_1) \ \ , \ \omega > \omega_1 \quad .
\end{aligned} \tag{14}$$

Here $H_1 \approx 0(\lambda_s^{-1})$ is the maximal scale reached at the end of inflation just before the start of the radiation-dominated era (the transition is assumed to be a sudden one for simplicity); $\Omega_\gamma \equiv \rho_\gamma/\rho_c \sim 10^{-4}$ is the critical density of radiation today; ω_1 is the maximal frequency which gets amplified: it was equal to H_1 at $t \sim 0$ and it is now redshifted to $\omega_1 \simeq 10^{11}\sqrt{\frac{H_1}{M_P}}$ Hz; $\Omega_2 \sim 10^{-16}$Hz is the largest frequency that undergoes a second amplification during the radiation/matter transition. Finally, the index α is related to the details of the cosmological inflationary evolution. For de Sitter-type inflation α is very small, i.e. one has the celebrated Harrison–Zeldovich scale-invariant spectrum. For power inflation α tends to be negative, i.e. spectra tend to emphasize long wavelengths. Finally, for superinflationary scenarios of the type we described earlier, α is positive, possibly in the vicinity of 3.

The simplest way to explain this trend is by relating the size of the perturbation on a given scale to the value H_{HC}/M_P of H/M_P at the time at which that scale crosses the horizon [28]. As is evident from Fig. 2, this favours large ω in the string-inspired scenario. Since $H_1 < M_P$, there is no problem with overclosing the Universe with gravitons if $\alpha > 0$ (for $\alpha < 0$ this can be a problem). On the other hand, gravitational waves on the surface of last scattering (i.e. before the Universe became transparent to photons at recombination time) produces a $\Delta T/T|_{CMB}$ of order H_{HC}/M_P. Since the scales at which COBE measures $\Delta T/T$ are very large ($0(10^{-18}\mathrm{Hz})$), flat or decreasing spectra ($\alpha \leq 0$) lead to strong constraints on $H_1 (H_1 < 10^{-5} M_P$ for de Sitter and even less for power inflation). By contrast, increasing spectra ($\alpha > 0$) are comfortable, even too comfortable with COBE in the sense that they tend to contribute very little to $\Delta T/T|_{COBE}$ since fluctuations are already $\leq O(1)$ at the maximal amplified frequency ω_1.

The gravitational-wave yield instead could be non-negligible at the scales of $10^2 - 10^3$ Hz at which LIGO or VIRGO have their maximal sensitivity [30]. LIGO claims a possible sensitivity to $\Omega_{gr} \sim 10^{-11}$ at $\sim 10^2$ Hz (for two years of running and stochastic sources) which is close to our prediction if $\alpha \sim 1$ and H_1 is close to M_P. If, instead, we adjust α so that, for $H_1 \sim M_P/10$, we also go through COBE's $\Delta T/T$, the prediction for gravitational waves at 10^2 Hz corresponds to $\Omega_{gr} \sim 10^{-6}$ and could swamp the signals from discrete sources of gravitational waves.

Finally, I should point out that gravitons can convert into real photons in galactic magnetic fields [31] (via a $\gamma\gamma^* g$ vertex!) and that, again, the yields could be interesting. This could also represent a further source of inhomogeneity in the CMB [31].

b) In analogy to gravitational waves scalar metric and energy density perturbations can also be predicted to occur and to give effects on $\Delta T/T$ similar to those of the gravitons. However, a peculiarity of our scenario is that scalar perturbations are coupled to dilaton perturbations, i.e. to dilaton production. This has been studied in some details recently [32] and the resulting spectra turned out to be qualitatively similar to those of the gravitons. On this basis bounds can be put on the dilaton mass on top of those already implied by tests of the equivalence principle (Section 3). It is thus possible to determine the allowed windows and to examine the possibility that dilatons of a few eV mass might constitute a component of (cold) dark matter.

c) It does look, finally, that there is also a natural way to produce all sorts of species of massless particles in string cosmology. Unlike what happens in ordinary cosmology, where scale-invariance prevents photon production from conformally flat (3+1-dimensional) backgrounds, in string cosmology the dilaton evolution can yield photons and, more generally, any kind of gauge particles.

Computation of the rates is still underway, but it does look as though, again, the spectra favour the largest frequencies, which thus dominate the integrated energy density. The above observation allows speculations on the possible revival, in our framework, of a rather old idea [see, e.g.[33]] according to which the big bang itself could produce, via a quantum effect, enough radiation to sustain the subsequent radiation-dominated era. In our context we expect, roughly, an energy density in the i^{th} species at the end of the pre-big bang given by

$$\rho_i \sim c_i H_1^4 \ , \quad c_i \simeq \frac{1}{16\pi^2}$$
$$\Omega_i = \frac{\rho_i}{\rho_c} \sim 0.1 c_i \ e^{(\phi_{end} - \phi_0)} \tag{15}$$

If, as we argued, $\phi_{end} <$ (or $\ll$) ϕ_0, $\sum_i \Omega_i$ will be typically $\ll 1$, justifying the neglect of back reaction. However, in our scenario, ϕ keeps growing after the big bang to land eventually at ϕ_0. At this point it is conceivable that

$$\sum_i \Omega_i \sim 10^{-3} N_{eff} \sim O(1) \ , \tag{16}$$

since the number of gauge particles in (heterotic) string theory is $O(10^3)$! If some kind of picture such as this would hold, the transition from pre-big bang inflation to a post-big bang decelerated expansion would lead to a huge reheating, to large entropy production [34] and, finally, to a theory of what went into the primordial soup from where usual standard cosmology starts.

7. Conclusions

The game is still wide open and one should not draw premature conclusions. I will instead summarize the main points of this talk:

a) A symmetry of string cosmology, SFD, calls for the existence of the dilaton and fixes its couplings, making it a sort of JBD scalar with $\omega_{BD} = -1$.

b) Most likely the dilaton mass has to exceed $10^{-4} eV$ in order not to have a conflict with present tests of the equivalence principle.

c) At large negative ϕ the dilaton potential is expected to be practically zero.

d) SFD implies the existence of solutions to the string cosmology equations which, by simply being dual to ordinary FRW solutions, necessarily exhibit a (super) inflationary behaviour. In these solutions inflation occurs while ϕ, the effective coupling grows, and the potential is negligible. It is $\dot{\phi}$ that drives inflation.

e) <u>If</u> string theory is able to tame the indefinite growth of H and $\dot{\phi}$ as soon as they reach the string scale, <u>if</u> at that point a "branch change" occurs to the duality-related solution and <u>if</u>, finally, the dilaton potential has a nice-looking non-perturbative minimum, then there can be both a long inflation and a graceful exit from it into the radiation-dominated era.

f) The picture makes definite predictions on the spectrum of gravitational waves (gravitons), of dilatons, and of density perturbations produced during its inflationary era. A generic feature of these spectra is that they emphasize the higher frequencies (blue spectra) since shorter wave-lengths crossed the horizon at larger values of H/M_P during inflation.

g) There is no problem of overclosing the Universe even if string-size curvature scales are reached at the end of inflation. There is no problem either with too large CMB fluctuations; quite the opposite, in our scenario there do not seem to be enough fluctuations at the scales measured by COBE.

h) On the contrary, there might be a reasonable power in gravitational waves at the scales at which LIGO and VIRGO have their best sensitivity.

i) Finally, the scenario seems to possess a built-in mechanism for producing, via the amplification of quantum fluctuations, a primordial soup of particles, which are light (massless) during inflation, increase their masses as the coupling grows into the non-perturbative region and, finally, may give rise, through their decay, to the hot Universe that the Standard Cosmological Model of the "late" Universe badly needs as its initial state.

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