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Testing String Cosmology with Gravity Wave Detectors

M. Gasperini
Dipartimento di Fisica Teorica, Università di Torino,
Via P. Giuria 1, 10125 Turin, Italy
and
Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Turin, Italy

Abstract

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TESTING STRING COSMOLOGY WITH GRAVITY WAVE DETECTORS

MAURIZIO GASPERINI

Dipartimento di Fisica Teorica, Università di Torino,
Via P. Giuria 1, 10125, Turin, Italy
and *Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Turin, Italy*

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1. Introduction

The amplification of the quantum fluctuation of the vacuum, and the generation of primordial perturbation spectra, is one of the most celebrated aspects of the standard inflationary scenario[1]. In particular, the amplification of the transverse and trace-free part of the metric fluctuations (which are decoupled from the sources, in the linear approximation), leads to the formation of a primordial gravity wave background that may survive, nearly unchanged, down to the present time[2]. Such background is characterized by three main properties:

- it is stochastic, because of its quantum origin;
- the present fluctuation amplitude, for each Fourier mode, is directly related to the curvature scale of the Universe at the time of first horizon crossing of that mode;
- the spectral distribution of the amplitude is determined by the kinematic behavior of the scale factor at the horizon crossing epoch.

It is thus obvious that a cosmic background of relic gravity waves retains the imprint of the primordial dynamics, and may provide direct information on the very early history of our Universe[3].

Unfortunately, however, the relic background expected in the frequency band of the present interferometric and resonant-mass detectors, according to the standard inflationary scenario, is by far too low to be detected[4], both in first and second generation experiments. The reason for this disappointing conclusion is that the background, characterized by a flat or decreasing spectrum, is strongly constrained by the large scale anisotropy observed by COBE at the present horizon scale[5], $\Delta T/T \sim 10^{-5}$. The energy density Ω_G of the graviton background, in critical units, is thus bounded at high frequency by the condition[6]:

$$\Omega_G \lesssim \Omega_{CMB} \left(\frac{\Delta T}{T}\right)^2_{COBE} \sim 10^{-14}, \qquad \omega \gtrsim 10^{-16}\ \mathrm{Hz}. \tag{1.1}$$

where Ω_{CMB} is the present fraction of critical energy density in the form of Cosmic Microwave Background (CMB) radiation. The above bound is saturated by a flat, Harrison-Zeldovich spectral distribution (assuming that the spectrum is normalized at the horizon scale by the COBE data), while decreasing spectra always lead to a lower Ω_G. For comparison, the maximal sensitivity to a stochastic background[7] expected in the context of the Advanced LIGO project is only $\Omega_G \sim 10^{-10}$, at a frequency $\nu \sim 10^2$ Hertz.

The situation is instead more rosy for the pre-big bang models[8] formulated in the context of string cosmology. In that case, the spectral energy density of the background tends to grow very fast with frequency, and it is thus too low, at the COBE scale, to be constrained by the observed CMB anisotropy[8,9] (the constraint from pulsar timing data[10], $\Omega_G \lesssim 10^{-8}$ at a frequency $\nu \sim 10^{-8}$ Hz, can also be easily satisfied). At high frequency, the maximal intensity of the background is simply controlled by the fundamental ratio between string (M_s) and Planck (M_P) mass, which sets the natural value of the final inflation scale, and which is expected[11] to be a number in the range $0.3 - 0.03$. One thus obtain the bound[12,13]

$$\Omega_G \lesssim \Omega_{CMB} \left(\frac{M_s}{M_P}\right)^2 \lesssim 10^{-5}, \tag{1.2}$$

which corresponds to a possible enhancement of nine orders of magnitude, at high frequency, with respect to the peak intensity (1.1) typical of the standard inflationary scenario.

The amplification of the vacuum fluctuations, however, is not the only mechanism leading to the formation of a primordial gravity wave background. There are processes, in the context of the standard inflationary models, producing backgrounds which are mainly localized at high frequency, and which may thus evade the constraint (1.1). Three possible backgrounds, in particular, should be mentioned. The background due to gravitational radiation from cosmic strings[14] and other topological defects[15], the background due to bubble collision at the end of a first order phase transition[16], in extended inflation models, and the background produced by parametric resonance effects[17], during the so-called "preheating" phase.

A global view of these possible primordial relic backgrounds, in the frequency range $\omega > 1$ Hz, is qualitatively sketched in Fig. 1, where I have plotted the present value of the spectral energy density (in critical units) of the background:

$$\Omega_G(\omega, t_0) = \frac{\omega}{\rho_c(t_0)} \frac{d\rho_G(\omega, t_0)}{d\omega}, \qquad \rho_c(t_0) = \frac{3M_p^2 H_0^2}{8\pi},$$
$$H_0 = h_{100} \times (100\ \mathrm{km\ sec^{-1} Mpc^{-1}}). \tag{1.3}$$

The bold solid line of Fig. 1 define the allowed region for a background produced through the parametric amplification of the vacuum fluctuations, in string cosmology (upper lines) and in standard inflationary cosmology (lower lines). The dashed lines represent possible spectra for backgrounds obtained from topological defects, phase transitions and resonant inflaton oscillations. In the first case the plotted spectrum refers to the maximal allowed background associated to graviton radiation from cosmic strings[14]. In the other two cases the spectrum is strongly dependent on the final reheating temperature, T_r. The example of phase transitions illustrated in Fig. 1 refers to $T_r \sim 10^8 - 10^9$ GeV, but higher backgrounds are possible[16] for higher values of T_r.

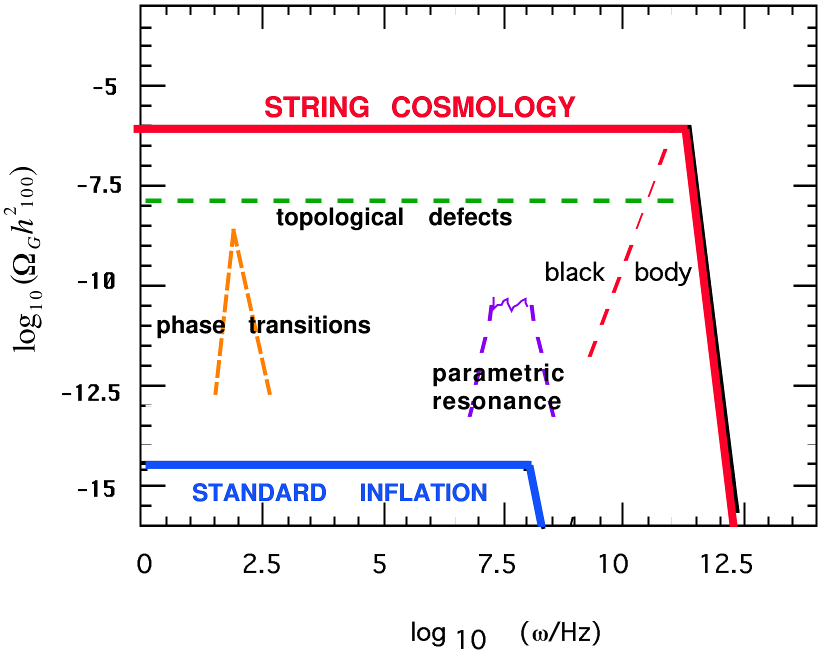

Figure 1: *Possible gravity wave backgrounds of cosmological origin (dashed lines), in the frequency range $\omega > 1$ Hz. The bold solid lines define the allowed region for a background obtained from the quantum fluctuations of the metric, in string cosmology (upper lines) and in standard inflationary cosmology (lower lines).*

Also shown in Fig. 1 is a thermal black-body spectrum corresponding to a temperature $T_0 \sim 1^0 K$. In the standard scenario a thermal gravity wave background might originate at the Planck scale, when the temperature is high enough to maintain gravitons in thermal equilibrium. However, such a background should be strongly diluted (with respect to the present CMB radiation) by the action of the subsequent inflationary phase, occurring at curvature scales lower than Planckian. As a consequence, the surviving spectrum should correspond today to an effective temperature so depressed to be practically invisible. In string cosmology, on the contrary, a graviton background with the typical low-frequency slope of a black-body spectrum, $\Omega_G \sim \omega^3$, is possibly generated by the sudden transition from an initial dilaton-driven phase to the standard radiation-dominated era[8,12]. Modulo logarithmic corrections, such a spectrum may simulate a relic thermal background of Planckian origin[18,19], with a typical effective temperature which is just of the same order as that of the thermal spectrum shown in Fig. 1.

The rest of this paper will be devoted to explain, and discuss, the big difference between the two allowed regions relative to a vacuum fluctuation spectrum. Before starting the discussion, however, it may be be appropriate to recall that at present the best experimental upper bound on a possible stochastic background, in the frequency range of Fig. 1, is provided by the cross-correlation of the two resonant-mass detectors NAUTILUS and EXPLORER. The most recent data imply[20]

$$\Omega_G h_{100} \lesssim 60, \qquad\qquad \nu \simeq 907 \text{ Hz}. \tag{1.4}$$

improving by about an order of magnitude the previous upper limit[21] obtained with EXPLORER. A much better sensitivity, $\Omega_G h_{100} \sim 10^{-3} - 10^{-5}$, is expected to be reached in the near future by the cross-correlation of NAUTILUS, EXPLORER and AURIGA[21,22], and by the first operating version[7,23] of LIGO and VIRGO, in the frequency bands $\nu \sim 10^3$ Hz and $\nu \sim 10^2$ Hz, respectively. Similar sensitivities are expected from the cross-correlation of a bar and an interferometer[24]. These sensitivities are still outside, but not so far off, the upper border of the allowed region in Fig. 1. To get inside we have to wait, for instance, for the cross-correlation of two spherical resonant-mass detectors[22,25], with expected sensitivity $\Omega_G \sim 10^{-7}$ around $\nu \sim 10^3$ Hz, or for the advanced version of the interferometric detectors[7,23], with expected sensitivity $\Omega_G \sim 10^{-10}$ around $\nu \sim 10^2$ Hz. In both cases the detectors will cross the border of the allowed region, and will explore, for the first time, the parameter space of string cosmology and of Planck scale physics.

2. Properties of the string cosmology background

In string cosmology, like in the standard inflationary scenario, the generation of a gravity wave background from the ground state configuration is due to a process of parametric amplification of the metric fluctuations, under the action of the cosmological gravitational field playing the role of the external "pumping" force[2]. The basic difference from the standard scenario arises from an enhancement of this amplification process in the high frequency sector. This enhancement can be ascribed to three independent mechanisms:

- the growth of the curvature during the phase of accelerated evolution, and the consequent growth with frequency of the perturbation spectrum;

- the possible growth in time of the comoving amplitude of perturbations even outside the horizon, instead of its "freezing" typical of standard inflation;
- the additional amplification due to the higher-derivative terms that must be added to the effective action when the curvature becomes large in string units.

The first two effects are a consequence of the special kinematic of the phase of accelerated pre-big bang evolution, characterized by shrinking event horizons[8]. During such a phase the scale factor can be parametrized, in conformal time η and in the Einstein frame, as

$$a(\eta) = (-\eta)^{\alpha}, \qquad \eta < 0, \qquad \alpha \geq -1. \tag{2.1}$$

The tensor perturbation equation[2], for the Fourier component of each polarization mode of comoving amplitude h_k,

$$\psi_k'' + \left(k^2 - \frac{a''}{a}\right)\psi_k = 0, \qquad \psi_k = a h_k, \tag{2.2}$$

outside the horizon ($|k\eta| \rightarrow 0$) has the general asymptotic solution:

$$h_k = A_k + B_k\,|\eta|^{1-2\alpha}, \qquad \eta \rightarrow 0_- \tag{2.3}$$

(A_k, B_k are integration constant, and the prime denotes differentiation with respect to η). For the metric (2.1) we may thus distinguish two possibilities.

If $\alpha < 1/2$, h_k tends to stay constant outside the horizon. By normalizing the canonical variable ψ_k to a vacuum fluctuation spectrum, at the time of horizon crossing $|\eta| = k^{-1}$, we obtain asymptotically $\psi_k \sim (a/a_{hc})k^{-1/2}$, with consequent spectral amplitude $k^{3/2}|h_k| \sim |a\eta|^{-1}_{hc} \sim |H|_{hc}$, where $H = \dot{a}/a = a'/a^2$ (a dot denotes differentiation with respect to the cosmic time t, defined by $dt = a d\eta$). This amplitude grows with k because higher frequency modes cross the horizon later in time, and then at higher values of $|H|$, since $|H|$ is growing for the metric (2.1).

If $\alpha > 1/2$ there is an additional growth in time of h_k itself outside the horizon, according to the asymptotic solution (2.3). This second effect is usually excluded in the standard inflationary models, characterized by $\alpha < 0$. In string cosmology this effect is due to the accelerated growth of the dilaton[9,26], which accompanies the growth of the curvature scale, and which transforms the scale factor kinematic of the Einstein frame (where the dilaton is decoupled from tensor perturbations) into a fast, accelerated contraction[8], with $\alpha > 0$. In the limiting case $\alpha = 1/2$, corresponding to the simplest low-energy gravi-dilaton model, the growth in time of h_k is simply logarithmic[18], $h_k \sim \ln|k\eta|$, and can be neglected for an order of magnitude estimate of the spectrum.

A third, additional contribution to the amplification is due to the fact that, because of the growth of the curvature during the pre-big bang phase, the late-time evolution of perturbations takes place in the high-curvature regime. In this regime, the higher derivative corrections predicted by string theory may become important, and should be included into the effective action. To the first non-leading order of the so-called α' expansion, where $\alpha' = \lambda_s^2$ is the basic string length parameter, the corrected action can be written as[27]

$$S = -\frac{1}{2\lambda_s^{d-1}} \int d^{d+1}x\sqrt{|g|}e^{-\phi}\left[R + (\nabla\phi)^2 - \frac{k\alpha'}{4}\left(R_{GB}^2 - (\nabla\phi)^4\right)\right], \qquad (2.4)$$

where we have used a convenient field-redefinition that introduces the Gauss-Bonnet invariant R_{GB}, thus eliminating higher-than-second derivatives from the equations of motion. Such higher-curvature corrections are important because they tend to stop the growth of the curvature and of the dilaton[28], driving the Universe to a phase with $H =$ const, $\dot{\phi} =$ const.

The perturbation of the action (2.4) around a homogeneous and isotropic background solution, $a(\eta), \phi(\eta)$, leads to a generalized tensor perturbation equation[29]:

$$\psi_k'' + \left[k^2 - \frac{z''}{z} + \frac{k^2}{z^2}(y^2 - z^2)\right]\psi_k = 0, \quad \psi_k = zh_k,$$
$$z^2(\eta) = e^{-\phi}\left(a^2 - \alpha'\frac{a'}{a}\phi'\right), \quad y^2(\eta) = e^{-\phi}\left[a^2 + \alpha'\left(\phi'^2 - \phi'' + \frac{a'}{a}\phi'\right)\right] \qquad (2.5)$$

(here a is the metric scale factor in the frame of the action (2.4)). This equation includes the high-curvature corrections to first order in α', and reduces to the low-energy equation in the limit $\alpha' \to 0$.

The results of a numerical integration of eq. (2.5) are illustrated in Fig. 2, where we show the evolution in cosmic time of the comoving perturbation amplitude $|h_k|$, computed with and without the α' corrections[29]. In both cases the amplitude is oscillating inside the horizon, and frozen outside the horizon. When the α' corrections are included, however, the final asymptotic amplitude is enhanced with respect to the amplitude obtained, for the *same* mode and in the *same* background, without the α' corrections.

This enhancement is the same for all modes, and thus does not affect the gravity wave spectrum computed with the low-energy perturbation equation (2.2). The effect of the high-curvature corrections amounts to an overall rescaling, by a numerical factor of the order of unity, of the total energy density of the background, and may thus be neglected for an order of magnitude estimate of graviton production.

By using eqs. (2.2) and (2.5) we can now predict some general property of the gravity wave background expected in the context of the pre-big bang scenario. Such predictions are to a large extent model-independent, provided we accept that the Universe becomes radiation-dominated soon after the end of the high-curvature string phase.

At low energy, i.e. for modes crossing the the horizon when the α' corrections are still negligible, the slope of the spectrum can be computed exactly, and for the

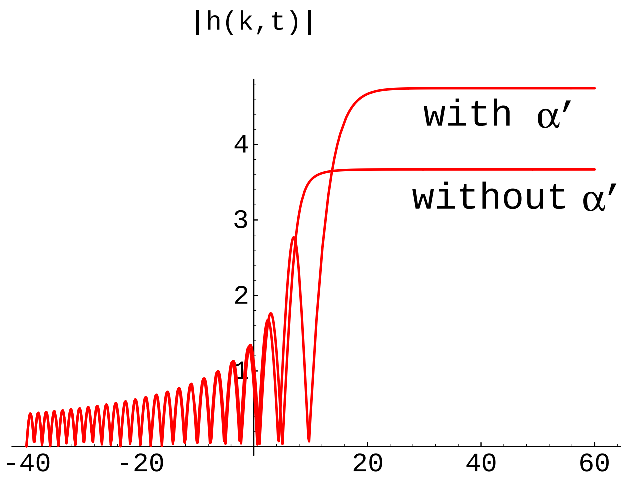

Figure 2: *Time-evolution of the comoving amplitude $|h_k(t)|$, according to a numerical integration of eq. (2.5) with and without the high-curvature corrections.*

metric (2.1) with $\alpha = 1/2$ we find the nearly thermal behavior[8,18]

$$\Omega_G(\omega) \propto \left(\frac{\omega}{\omega_s}\right)^3 \ln\left(\frac{\omega}{\omega_s}\right), \qquad \omega < \omega_s. \tag{2.6}$$

Here ω_s is the frequency scale at which high-curvature string effects may become important. At high frequency the slope is model-dependent, but in general flatter than cubic[12,13,30] because the high-derivative[28] and loop[31] corrections tend to stop the growth of the curvature and of the dilaton kinetic energy, and thus tend to depress the slope of the metric perturbation spectrum.

The maximal amplified frequency ω_1, i.e. the frequency corresponding to the production of one graviton per polarization and per unit phase space volume, can also be computed in a model-independent way, an can be conveniently related to the present CMB temperature T_0 as follows[13]:

$$\omega_1(t_0) \simeq T_0 \left(\frac{M_s}{M_P}\right)^{1/2} \left(\frac{10^3}{n_r}\right)^{1/12} (1-\delta S)^{1/3}, \quad T_0 \simeq 3.6 \times 10^{11}\mathrm{Hz} \tag{2.7}$$

Here $n_r \simeq 10^3$ is the total number of thermal degrees of freedom in equilibrium at the beginning of the radiation era, and δS is the fraction of present thermal entropy density due to all reheating processes occurring well below the end of the string phase. The occurrence of such processes would imply that the radiation which becomes dominant at the end of the string phase is only a fraction of the CMB radiation that we observe today, and this would dilute the energy density of the gravity wave background with respect to the present CMB energy density.

The peak intensity of the background, in this context, has to be of the same order as the end-point energy density[13],

$$\Omega_G(\omega_1, t_0) = \frac{\omega_1^4(t_0)}{\pi^2 \rho_c(t_0)} \simeq 7 \times 10^{-5} h_{100}^{-2} \left(\frac{M_s}{M_P}\right)^2 \left(\frac{10^3}{n_r}\right)^{1/3} (1-\delta S)^{4/3}. \tag{2.8}$$

As a consequence, for $\omega < \omega_1$, the spectrum may be decreasing or at most flat, leading to the allowed region illustrated in Fig. 1 (where we have assumed $n_r = 10^3$).

The allowed region can be obviously extended also at frequencies $\omega < 1$ Hz. At lower frequencies, however, the upper border of the region has to be slightly decreasing, in order to satisfy the constraint coming from primordial nucleosynthesis[32], which implies that the total integrated energy density of the background cannot exceed, roughly, that of one massless degree of freedom in thermal equilibrium. More precisely, nucleosynthesis implies the bound[13]

$$h_{100}^2 \int \Omega_G(\omega, t_0) d \ln \omega \lesssim 0.5 \times 10^{-5}. \tag{2.9}$$

This bound is compatible with, but almost completely saturated (depending on M_s/M_P) by the peak intensity (2.8). So, a strictly flat maximal spectral density cannot be extended to arbitrarily low frequencies ($\ll 1$ Hz) without conflicting with the bound (2.9). At very low frequencies there are, in addition, stronger phenomenological constraints from pulsar-timing data[10] and COBE data[5], as discussed in the previous Section.

3. Testing string cosmology models

In the context of the pre-big bang scenario, any relic graviton spectrum $\Omega_G(\omega)$ which reaches the end point with a slope not larger than cubic (in the low frequency sector) is in principle allowed, like the spectra represented by the bold solid lines of Fig. 3. Notice that above the maximal frequency ω_1 the graviton production is exponentially suppressed[33], and the spectrum must decrease with the typical high frequency behavior of a Planckian distribution.

For any given value of n_r and δS there is a residual uncertainty on the values ω_1 and $\Omega_G(\omega_1)$, according to eqs. (2.7) and (2.8), corresponding to the present theoretical uncertainty on the values of the fundamental string theory parameter $M_s = \lambda_s^{-1}$. This uncertainty is represented by the shaded boxes of Fig. 3, where we have chosen, for illustrative purpose, $n_r = 10^3$ and

$$0.01 \lesssim \left(\frac{M_s}{M_P}\right) \lesssim 0.1. \tag{3.1}$$

To the left of the end point the spectrum can be at most flat, for the simplest class of models considered in the previous section. In the absence of significant reheating at scales much lower than the end of the string phase, the maximal intensity of the gravity wave background is thus expected within the dashed lines, in the band labeled $\delta S = 0$.

Also plotted in Fig. 3 is the corresponding band for the case that 99 per cent of the present large scale entropy is due to some low-energy process occurring well below the string scale. Even in that case, the expected peak intensity stays well above the full line labeled "de Sitter", and corresponding to the most optimistic predictions of the standard inflationary scenario.

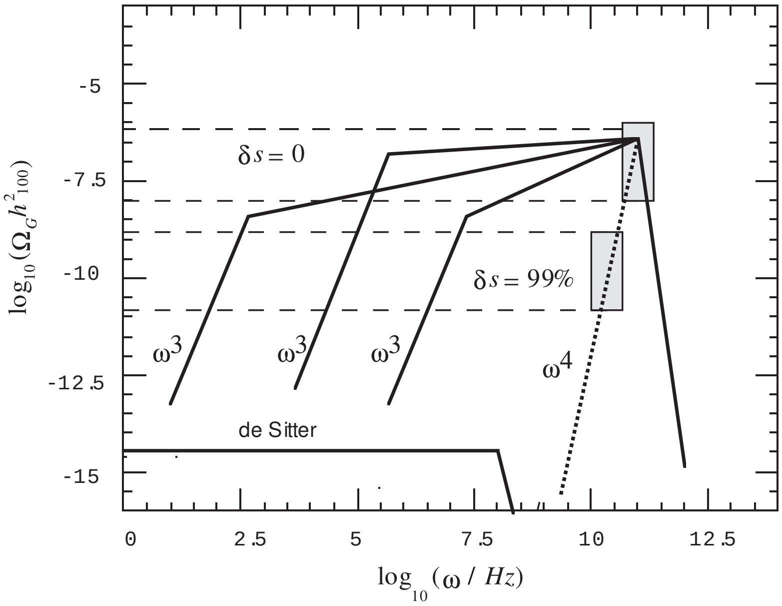

Figure 3: *Possible allowed spectra for a typical class of string cosmology models.*

Entering the region where we may expect a signal thus require a minimal sensitivity[12,13]

$$\Omega_G h_{100} \lesssim 10^{-6}, \tag{3.2}$$

or, in terms of the strain density $S_h(\nu)$,

$$S_h^{1/2}(\nu) \lesssim 3 \times 10^{-26} \left(\frac{\mathrm{kHz}}{\nu}\right)^{3/2} \mathrm{Hz}^{-1/2}, \qquad S_h(\nu) = \frac{3H_0^2}{4\pi^2\nu^3}\Omega_G(\nu). \tag{3.3}$$

Any detector able to reach this limit will be already in a position to receive a signal from the cosmic graviton background or, in case of a negative result, to constrain the parameter space of the string cosmology models[12,19]. In particular, any measure inside the allowed region will provide significant information on the possible value of the frequency ω_s which marks the end of the low-energy branch of the spectrum (2.6), and on the corresponding value of the dilaton ϕ_s and of the string coupling $g_s^2 = \exp(\phi_s)$.

The importance of determining the coordinates (ω_s and $\Omega_G(\omega_s)$) of this break point of the spectrum, signalling the beginning of the high-curvature regime, is self-evident. From its position in the plane of Fig. 3 we could immediately deduce the duration in time ($\sim \omega_s/\omega_1$), and the rate of growth of the curvature in Planck units ($\sim \Omega_s/\Omega_1$), for the "stringy" regime. This would impose important constraints on other phenomenological aspects of the pre-big bang scenario indirectly related to graviton production (such as the production of seeds for the cosmic magnetic fields[34]), as discussed elsewhere[19,35].

Also, suppose to detect the high frequency part of the graviton spectrum, namely a signal which grows with frequency, $\Omega_G \sim \omega^\gamma$, with a positive slope $\gamma < 3$, as illustrated in Fig. 3. The intercept of that spectrum (extrapolated up to the GHz range) with the "one-graviton" line $\Omega_G \sim \omega_1^4$ (the dotted line of Fig. 3), would give a first *experimental* indication of the value of the fundamental ratio M_s/M_P.

Of course, the situation is not so simple. The possibility of detecting a signal inside the allowed region depends on the shape of the spectrum, and the shape, unlike the allowed region, is strongly model-dependent. A detailed discussion of this point is outside the scope of this paper; it will be enough to recall, in this context, that there are two main classes of models which we may call[35] "minimal" and "non-minimal", characterized by a different evolution in time of the curvature scale and of the string coupling e^ϕ. In the minimal case the beginning of the radiation era coincides with the end of the high-curvature string phase, in the non-minimal case the coupling is still small at the end of the string phase, and the radiation era begins much later.

The main difference between the two cases is that in the second case the effective potential which amplifies tensor perturbation, according to eqs. (2.2), (2.5), is non-monotonic, and the highest frequency modes may reenter the horizon before the beginning of the radiation era. This modifies the slope of the spectrum in the high-frequency sector, with the possible appearance of a negative power. The gravity wave spectrum may thus become non-monotonic[35], and the peak may not coincide any longer with the end point (see also [36] for a different possibility of non-monotonic spectrum).

These are good news from an experimental point of view, because they make more probable a large detectable signal at frequencies lower than the GHz band. However, they also provide a warning against a too naive interpretation of possible future experimental data, because of the complexity of the parameter space of the string cosmology models.

4. Conclusion

Summarizing the results reported here, my conclusion is very simple: there is no compelling reason (at present, and to the best of my knowledge) to exclude the presence of a stochastic graviton background of primordial origin, with an energy density as high as

$$\Omega_g(\omega) \sim 10^{-6} h_{100}^{-2}, \qquad 1 \text{ Hz} \lesssim \omega \lesssim 100 \text{ GHz}. \tag{4.1}$$

Future gravity wave detectors, able to reach this sensitivity level, will directly test string theory and Planck scale physics.

As a final remark, I would like to answer a question that Guido Pizzella asked me last year at CERN, during the First Meeting on *"Detection of high-frequency gravitational waves"*. The question was: "How sound is the prediction of such a high graviton background"?

It is difficult to answer, and probably I am not the right person to answer this question, but I would like to suggest an analogy. It seems to me that we are in a situation similar, in some respect, to the situation of many years ago in cosmology, when we had to compare the steady-state model, and the hot-big bang model. One of the main differences between the two models was just the background of thermal radiation. Now, how sound was the prediction of the thermal black body spectrum, before the experimental discovery[37] of Penzias and Wilson?

Difficult to say. The present situation seems to be similar. There are standard inflationary models that predict a low background of cosmic gravitons, at high frequency, and there are other models, based on string theory, that predict a much higher background. How sound are such predictions?

In my opinion, the experimentalist should tell us how sound are the predictions, and not the converse. The answer should come, and may come (in a not so far future), from experiments. Whatever the final result may be, the experimental search for a cosmic graviton background will become as important, for cosmology, as the study of the electromagnetic CMB radiation. Even more important, in some sense, because the thermal photons are relic radiation from the big bang, while the cosmic graviton of a background like that of eq. (4.1) would be relic radiation from a much earlier pre-big bang phase, preceding the hot, standard regime.

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