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Testing BSM Physics with Gravitational Waves

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In this talk, we explore the effect of new Physics in the shape of the Cosmic Gravitational Wave Background (CGWB): a stochastic background of Gravitational Waves (GWs) sourced by the primordial plasma. We argue that the shape of the CGWB is a direct probe for physics at energies much higher than those at the last scattering surface, which bounds electromagnetic astronomy. Due to its characteristic frequency, around 80 GHz, the CGWB is an example of an ultra high frequency source of GWs, which are attracting the attention of a growing community of both theorists and experimentalists [1]. It is becoming increasingly clear that early Universe processes release backgrounds at these high frequencies, and that their potential detection provides a window for the direct study of high energy physics that is not achievable through electromagnetic astronomy or collider physics. We conclude that, if the CGWB is detected at lower frequencies and amplitudes compared to the prediction of the Standard Model, it will hint at extra massive degrees of freedom or hidden sectors which are thermally active after reheating. If it is instead measured at higher values, it will imply a period with $\omega > 1/3$. We argue that for certain scenarios with periods of kination in the early Universe, a significant fraction of the parameter space can be ruled out from dark radiation bounds at BBN. This talk is based on [2].

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[*] Speaker

1. Stochastic backgrounds of Gravitational Waves

Gravitational Waves sourced in the early Universe arrive at Earth forming a superposition of uncorrelated signals. These are better described by stochastic GW backgrounds, which are characterised by the energy density fraction per logarithmic frequency interval [3] and can be computed as

$$h^2\Omega^{(i)}_{\mathrm{GW},0} = \frac{h^2}{\rho_c}\left(\frac{a_{\mathrm{end}}}{a_0}\right)^4 \left.\frac{d\rho^{(i)}_{\mathrm{GW}}}{d\log k}\right|_{\mathrm{end}}, \qquad \rho_{\mathrm{GW}} = \frac{M_p^2}{4}\langle \dot{h}_{jk}\dot{h}_{jk}\rangle\,, \tag{1}$$

where $\rho_c = 3H_0^2M_p^2$ is the critical density, $H_0 = 100\,h\,\mathrm{Km\,sec^{-1}\,Mpc^{-1}}$ ($h \sim 0.7$) is the Hubble constant today, $M_p = 1/\sqrt{8\pi G} \simeq 10^{19}$GeV is the Planck mass and $a(t)$ is the scale factor, which we evaluate today (a_0) and at the end of GW emission (a_{end}). Furthermore, the definition of the GW energy density ρ_{GW} involves an average of the time derivative of metric fluctuations h_{jk} over regions much larger than their wavelength. Here, we are labelling different putative sources of GWs by i, and note that the full GW spectrum is given by the sum over i of these individual contributions.

If sourced at temperatures larger than 1 MeV, any additional contribution ρ_{h} to the energy density of the Universe is strongly constrained by Big Bang Nucleosynthesis (BBN): $\rho_h \lesssim \frac{\pi^2}{30} \times \frac{7}{4}\Delta N_{\mathrm{eff}} T^4_{\mathrm{vis}}$. The latest Planck results [4] constrain $\Delta N_{\mathrm{eff}} \leq 0.30$ at 95% confidence level. As a rule of thumb[1], we will consider the BBN bound to be a constraint on the maximum amplitude of $h^2\Omega_{\mathrm{GW},0} < 10^{-6}$.

2. The CGWB

Let us review the key features of the CGWB. It has been argued [5–7] that thermal quantum field theories source out-of-equilibrium gravitons. The power of emission of such gravitons along the z direction from a plasma with Euclidean stress tensor $T_{\mu\nu} = \sum_i T^{(i)}_{\mu\nu}$, where the sum runs over thermally decoupled sectors, is given by:

$$\frac{d}{dt}\left(\frac{d\rho^{(i)}_{\mathrm{GW}}}{d\log k}\right) = \frac{8k^3}{\pi M_p^2}\int d^4x\, e^{ik(t-z)}\langle T^{(i)}_{12}(0)T^{(i)}_{12}(x)\rangle \tag{2}$$

where the expectation value is computed in the thermal ensemble (see [8]). Without delving into the details, let us simply point out that the presence of the stress tensor implies that the GWs are sourced at any e-fold by the various particles and interactions in the thermal plasma. The computation of this quantity was carried out in [5, 6] to leading-log and full leading order, respectively, for Standard Model (SM) particles and interactions, and this approach was later generalised in [7] to the spectrum of an arbitrary weakly coupled renormalisable gauge theory with couplings to scalars and fermions. We depict the SM result in Fig.1, for distinct initial temperatures. We observe that the SM predicts that the shape of the CGWB features a peak around 80 GHz, with an amplitude that depends in the reheating temperature. Any deviation from such a frequency would thus be an indicator of a deviation from SM Physics in the Early Universe. In this work, we consider two different deviations from SM Physics, both well-motivated in string cosmology (see [9, 10] for recent reviews): hidden sectors and nonstandard cosmologies.

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[1] Strictly speaking, this bound applies to the total energy density integrated over frequencies, but we will see that the spectrum under consideration is dominated by a peak and thus the dominant contribution is of the same order.

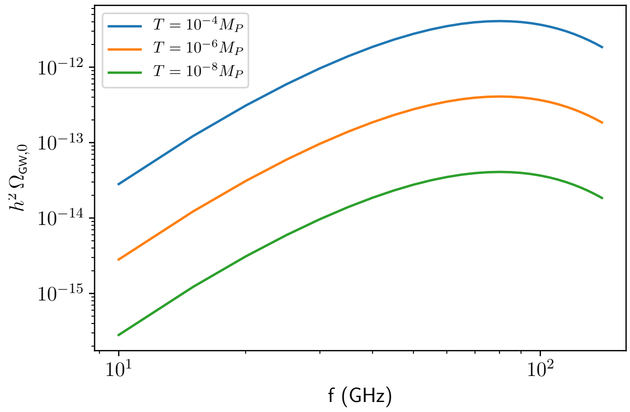

Figure 1: CGWB sourced by the SM for different values of the reheating temperature.

In order to understand how new Physics affects the shape of the CGWB, we may write the following expression for the contribution to the energy density today per e-fold:

$$\frac{d}{d\log a}\left(\frac{d\rho^{(i)}_{\mathrm{GW}}}{d\log k}\right) \sim T_i\,\frac{\rho^{(i)}a(t)^4}{\sqrt{g_{*,tot}}}F(\hat{k})\,. \tag{3}$$

Here, a is the scale factor, k the physical wavenumber of the GW, $g_{*,tot}$ the effective number of massless degrees of freedom and $F(\hat{k}_i)$ a function of $\hat{k}_i \equiv k/T_i$ which encodes the interactions that source GWs.

The main lesson to learn from Eq. (3) is that whenever $\rho^{(i)} \sim a(t)^{-4}$ the contribution to $\rho^{(i)}_{\mathrm{GW},0}$ per e-fold only depends on time through the temperature, and thus the largest contribution to the CGWB arises from the sector dominating the energy density of the Universe right after reheating. The CGWB therefore carries a snapshot of how the Universe looked like at the hot big bang, and it is in this sense that through any deviations from the SM prediction we would be *testing BSM Physics with Gravitational Waves*.

3. New Physics in the CGWB

In this section we will study the effect of new Physics in the CGWB. Even though the ultimate goal would be a direct detection of this background, there are currently no proposals available that can probe amplitudes below the BBN bound in the frequency regime of our interest [1]. However, as we will see, the very existence of the CGWB can be used to assess models of BSM physics, particularly those involving nonstandard cosmologies.

Let us assume the existence of a hidden sector with energy density ρ_{h}, which is thermally decoupled from the visible sector, this being the SM or an extension thereof. A drastic modification from the SM prediction in the CGWB would occur if this hidden sector governed the energy density of the Universe after reheating. Such a scenario is ruled out by BBN unless there is a period in which ρ_{h} redshifts faster than the SM fields. There are two ways in which this can happen, both associated to the existence of new Physics:

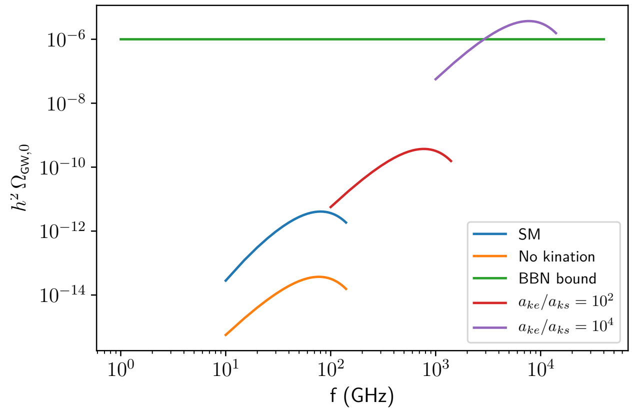

Figure 2: $h^2\Omega_{\rm GW,0}$ sourced by a hidden SU(2) for different e-folds of kination $\omega = 1$. If kination is too long, the BBN bound is violated. The standard scenario with only the SM is illustrated for comparison.

- One way is that the energy density of the visible sector redshifts slower than a^{-4}. This is possible if there are massive fields that, upon annihilation, release their entropy into the SM bath. Even though the shape of the CGWB is modified by such massive fields, the deviation from the SM prediction is rather mild (see [2, 7]).

- More interesting is the opposite case, in which the energy density of the hidden sector redshifts quicker than that of SM fields. This happens if the hidden sector undergoes a period[2] with equation of state $\omega > 1/3$. In such case, for a period with N e-folds, the peak amplitude is boosted to larger values and higher frequencies f_p as:

  $$\Omega_{\rm GW,0}(f_p) = \left(\frac{a_{ke}}{a_{ks}}\right)^{3\omega-1} \tilde{\Omega}_{\rm GW,0}(\tilde{f}_p)\,, \qquad f_p = \left(\frac{a_{ke}}{a_{ks}}\right)^{\frac{3\omega-1}{4}} \tilde{f}_p\,. \tag{4}$$

  where tildes indicate the same quantity in standard cosmology, and a_{ks} and a_{ke} indicate the value of the scale factor at the onset and end of the period with $\omega > 1/3$, respectively. The CGWB for different e-folds for a pure SU(2) hidden sector are depicted in 2.

4. Conclusions

We conclude that the CGWB has the potential to test BSM Physics not only through its direct detection, which is a long-term goal, but also due to a potential contribution to the energy density budget of the Universe. Using the latter approach, we have seen that one can rule out a part of a parameter space involving the initial temperature and the number of e-folds with $\omega > 1/3$, provided there is thermal radiation present before the onset of such epoch. It is worth noting the robustness of the SM prediction, since only very exotic BSM Physics can render a dramatically different shape for the CGWB.

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[2] In this work we remain agnostic about the microscopic origin of this behaviour, but it has been pointed out [11] that a transient kination-like period is to be expected in the context of scalar-tensor theories. Notice that, as discussed in [2] both redshifting and blueshifting of the signal can occur in absence of hidden sectors, but we include this for completeness and because the whole field content of the SM undergoing such a phase seems harder to motivate microscopically.

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