Probing Early Universe Cosmology and High Energy Physics Through Space-Borne Interferometers

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Abstract

We discuss the impact of space-borne laser interferometric experiments operating in the low-frequency window ($\sim 1\,\mu$Hz - 1 Hz), with the goal of identifying the fundamental issues that regard the detection of a primordial background of GW predicted by slow-roll inflationary models, corresponding to $h_{100}^2\,\Omega \sim 10^{-16} - 10^{-15}$. We analyse the capabilities of the planned single-instrument LISA mission and the sensitivity improvements that could be achieved by cross-correlating the data streams from a pair of detectors of the LISA-class. We show that the two-detectors configuration is extremely powerful, and leads to the detection of a stochastic background as weak as $h_{100}^2\,\Omega \sim 10^{-14}$. However, such instrumental sensitivity cannot be exploited to achieve a comparable performance for the detection of the primordial component of the background, due to the overwhelming power of the stochastic signal produced by short-period solar-mass binary systems of compact objects, that cannot be resolved as individual sources. We estimate that the primordial background can be detected only if its fractional energy density $h_{100}^2\,\Omega$ is greater than a few times 10^{-12}. The key conclusion of our analysis is that the typical mHz frequency band, regardless of the instrumental noise level, is the wrong observational window to probe slow-roll inflationary models. We discuss possible follow-on missions with optimal sensitivity in the $\sim \mu$Hz-regime and/or in the ~ 0.1Hz-band specifically aimed at gravitational wave cosmology.

1 Introduction

In the time frame 2002-2010 a very wide band of the Gravitational Wave (GW) spectrum will be fully accessible, mainly through large scale laser interferometers. From ground, the world-wide network of km-size interferometers – LIGO, GEO600, VIRGO and TAMA – sensitive in the frequency band $\sim 10\,\mathrm{Hz} - 1\,\mathrm{kHz}$ will start carrying out "science runs" at the beginning of 2002, with the realistic goal of directly detecting GW's. Several instrumental upgrades, starting around 2005, shall drive the sensitivity of the instruments to a GW stochastic background from $h_{100}^2\,\Omega \sim 10^{-6}$ (for the so-called initial generation) to $h_{100}^2\,\Omega \sim 10^{-10}$ (for the so-called advanced configuration), and possibly beyond. In space, ESA and NASA are studying in collaboration the project called LISA (Laser Interferometer Space Antenna), a space-borne 5×10^6-km arms laser interferometer, with the goal of flying the mission by 2010 [1]. This instrument guarantees the detection of GW's at low frequencies ($\sim 10^{-5}\,\mathrm{Hz} - 10^{-2}\,\mathrm{Hz}$).

In this talk we will discuss the role of the experiments in the low-frequency window $\sim 1\,\mu$Hz - 1 Hz, with emphasis on instruments of the LISA-class, to search for a primordial GW background. The main objective is to identify the fundamental issues regarding the achievement of a sensitivity in the range $h_{100}^2\,\Omega \sim 10^{-16} - 10^{-15}$; such target is set by the theoretical prediction of "slow-roll" inflationary models, and could be regarded as the ultimate frontier of GW observational cosmology.

1.1 The stochastic background spectrum

A stochastic GW background is a random process that can be described only in terms of its statistical properties. In the following, we shall assume it to be isotropic, stationary, Gaussian and unpolarised. The energy and spectral content of a stochastic background is described by the dimensionless function

$$\Omega(f) \equiv \frac{1}{\rho_{\mathrm{c}}}\,\frac{d\rho_{\mathrm{gw}}(f)}{d\ln f}\,; \tag{1}$$

ρ_{gw} is the energy density carried by the background radiation, and ρ is the critical energy density

$$\begin{aligned}\rho_{\mathrm{c}} = \frac{3\,H_0^2}{8\pi} \quad &\approx \quad 1.6 \times 10^{-8}\,h_{100}^2\,\mathrm{erg/cm}^3\,,\\ &\approx \quad 1.2 \times 10^{-36}\,h_{100}^2\,\mathrm{sec}^{-2}\,,\end{aligned} \tag{2}$$

where h_{100} is known from observations to be in the range $0.4 \le h_{100} \le 0.85$. $\Omega(f)$ is therefore the ratio of the GW energy density to the critical one per unit logarithmic frequency interval; more properly, one usually refers to $h_{100}^2\Omega(f)$, which is independent of the *unknown* value of the Hubble constant.

It is useful to introduce the *characteristic amplitude* $h_{\mathrm{c}}(f)$ of the GW's background: it is the dimensionless characteristic value of the total GW background-induced fluctuations $h(t)$ at the output of an interferometer per unit logarithmic frequency interval:

$$\langle h^2(t)\rangle = 2\int_0^\infty d(\ln f) h_c^2(f)\,. \tag{3}$$

Here $\langle\rangle$ denotes the expectation value. The spectral density $S(f)$ of the background is related to $h_c(f)$ by

$$h_c^2(f) = 2fS(f)\,, \tag{4}$$

and $\Omega(f)$, $h_c(f)$, and $S(f)$ satisfy the relation

$$\Omega(f) = \frac{2\pi^2}{3H_0^2}\, f^2\, h_c^2(f) = \frac{4\pi^2}{3H_0^2}\, f^3\, S(f)\,. \tag{5}$$

As far as the sources of a stochastic GW background are concerned, they can be divided in two broad classes, based on its origin (for a detailed review see e.g. [2]): (i) the *primordial GW background* (PGB), produced by physical processes in the early Universe, and (ii) the *astrophysically generated GW background* (GGB), generated by the incoherent superposition of gravitational radiation produced, at a much later time in the cosmic history, by a large number of astrophysical sources that cannot be resolved individually.

The emphasis of this talk will be on the detectability of a PGB. There is a number of mechanisms that produce a PGB. In generic inflationary models a GW background is produced as a result of the parametric amplification of quantum metric fluctuations. Other production mechanisms include phase transitions that occur, e.g., when the Universe temperature reaches the QCD and/or the electroweak scale, or topological defects, such as cosmic strings. The detection of a primordial background provides a unique means for exploring very early times in the evolution of the Universe and correspondingly high energies. It would allow us to test *directly* different cosmological models and extract the relevant physical parameters. Since gravitons drop out of thermal equilibrium just below the Planck scale, GW's have not lost memory of the conditions in which they were produced. They still keep in their spectrum, typical frequency and magnitude, information about the very early Universe and the corresponding physics, that cannot be experimentally accessed by any other means.

2 The astrophysically generated stochastic background

The astrophysically generated GW stochastic background (GGB) is due to the incoherent superposition of gravitational radiation emitted by short-period solar-mass binary systems, which cannot be resolved as individual sources; a variety of binary populations contribute to it, but the main contribution, in the mHz region, is due to close white-dwarf binaries (CWDB's): present estimates suggest that it is above the LISA instrumental noise in the frequency region $\approx 10^{-4} - 3\times10^{-3}$ Hz (see Fig. 1). However sizeable effects are also given by W UMa (Ursae Majoris) binary stars, unevolved binaries, cataclysmic binaries, neutron star-neutron star (NS-NS) binary systems, black hole-neutron star (BH-NS) binaries, and possibly BH-BH binary systems.

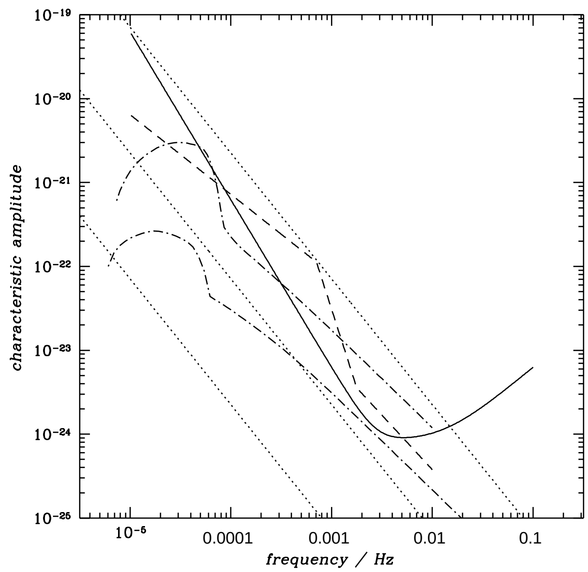

Figure 1: The characteristic amplitude of the LISA noise and several stochastic gravitational wave backgrounds as a function of frequency. The plot shows the rms noise amplitude in one year of observation (solid line) and the characteristic amplitude in a frequency band 1/1 yr of several stochastic signals: backgrounds with flat spectrum $\Omega_{\rm gw} = 10^{-10}$, 10^{-13}, 10^{-16} (dotted-lines, from top to bottom, respectively), the astrophysically generated galactic background (dashed-line), according to [4] and [5], and the (likely optimistic) estimate of the extragalactic contribution due to WD-WD and NS-NS binaries (dotted-dashed lines, from top to bottom, respectively), following [8]).

The GGB is a guaranteed GW source in the low-frequency band and it is likely to overwhelm the PGB, see [4, 5, 6, 7, 8] for a thorough discussion of the astrophysical sources. Radiation from large populations of binary systems is recorded as a stochastic signal at the detector output because there are simply too many free parameters needed to fit the data in order to *resolve* all the binary systems that contribute to the signal. In fact, just Our Galaxy contains $\sim 10^7$ CWDB's; they evolve, due to radiation reaction, over a time scale $\gtrsim 10^7$ years; therefore, during the typical observation time $T \sim 1$ yr, they are seen as highly monochromatic, and, in the band $10^{-4} - 10^{-3}$ Hz, each frequency bin is "contaminated" by roughly 10^3 sources.

Generated backgrounds come into two broad categories: galactic and extra-galactic. Their key distinguishing feature is the degree of isotropy for an observer on board of a LISA-like detector. In fact, the extra-galactic contribution is expected to be isotropic to a rather high degree (the radiation being dominated by binary systems at cosmological distances; for more details see [9]); it is, therefore, impossible to discriminate it from the PGB. On the contrary, the GGB produced by galactic sources is clearly highly anisotropic. In fact, galactic stars are spatially distributed, approximately, according to $\exp(-r/r_0)\,\exp[-(z/z_0)^2]$, where r is the radial distance to the Galactic centre and $r_0 \simeq 5$ kpc; z is the height above the Galactic plane, and the scale height is $z_0 \simeq 5$ kpc for neutron stars binaries and less than 300 pc for other types. Due to the peripheral location of the Solar System, and the change of orientation of the LISA arms during the years-long observation time, galactic generated backgrounds appear as strongly anisotropic [10]. It is also conceivable that the isotropic portion of the galactic contribution does not exceed the total extra-galactic GGB (cfr., however, the optimistic estimate given in [8]).

Several astrophysical uncertainties affect the estimates of the generated background. A careful analysis of the galactic contribution has been performed by P. Bender and collaborators [4, 5], the characteristic amplitude that one infers from the spectral density $S_g(f)$ is given in Fig 1. The extragalactic contribution to the GGB has been estimated in [7], and is likely weaker than the galactic one by a factor $\approx$ 10-to-2, in the relevant frequency band, the main uncertainty coming from the star formation rate at high redshifts [11, 12]. In the following, we will assume that the isotropic portion of $\Omega_g(f)$, the only one that contaminates PGB searches, follows the frequency distribution predicted by Bender and collaborators, but reduced by a factor $\epsilon \leq 1$:

$$\Omega_{g,is} = \epsilon \frac{4\pi^2}{3H_0^2}\, f^3\, S_g(f)\,, \tag{6}$$

and we set as reference value $\epsilon = 0.1$.

3 Cosmological GW background

The major drawback of the presently designed LISA mission is the lack of two instruments with uncorrelated noise; in fact, each pair of the three co-located LISA interferometers share one arm, and therefore common noise. Actually, one can, in principle, extract two data streams with uncorrelated noise at all frequencies [3]. However, since they are equivalent to the outputs of a pair of detectors rotated by 45° one with respect to the other, their cross-correlation is insensitive to a stochastic background. Nonetheless, LISA can play an important role in searching for stochastic backgrounds, as it can possibly achieve a sensitivity $\Omega_{\rm gw} \sim 10^{-10}$ by exploiting some intrinsic properties of the signal and/or a unique feature of the LISA instrumental response.

During the observation time, LISA changes orientation with period 1 yr. A background which is anisotropic produces a periodic modulation in the auto-correlation function that can stand above the noise [10]. One cannot exploit this feature to pick up a primordial signal; indeed, although a dipole anisotropy is always present in the recorded signal due to the motion of our local system (and therefore LISA) with respect to the cosmological rest frame with velocity $v_{\rm prop}/c \simeq 10^{-3}$, an interferometer has a quadrupole antenna pattern, and the SNR produced by the quadrupole component is reduced by a factor $(v_{\rm prop}/c)^2 \sim 10^{-6}$ [18]. On the other hand, the use of the signature due to anisotropies could be successful in detecting the background generated by galactic short-period solar-mass binary systems.

Time delay interferometry with multiple readouts [19] provides a way of suppressing by several orders of magnitude the GW contribution from the LISA output at frequencies below a few mHz, providing a shield to GW radiation. By exploiting this feature, one can calibrate the noise-only response of the instrument, and search for an excess power in the data stream.

LISA can therefore carry out searches for stochastic backgrounds with a single instrument at a very interesting sensitivity level; clearly, more detailed studies regarding the sensitivity that can be realistically achieved are needed; however, LISA is likely to detect the galactic astrophysically generated background, and could set important upper-limits on the primordial contribution, that can rule out existing theoretical predictions. It also provides invaluable information to design future follow-on missions aiming at the detection of the primordial background.

3.1 The sensitivity of two LISA interferometers

In order to reach the sensitivity $\Omega_{\rm gw} \sim 10^{-16}$, two separated interferometers are mandatory. It is important to understand the key issues involved in such experimental configuration, what is within the reach of the technology that will be implemented on LISA, and possible fundamental limitations that might prevent from achieving a detection at the level $\Omega_{\rm gw} \sim 10^{-16}$. Some of these issues have been recently discussed in detail [16], and suggestions have been put forward to introduce minor modifications to the currently envisaged LISA configuration in order to accommodate a pair of independent instruments [17], possibly with the capability of shifting at will the centre of the sensitivity window from $\sim 10^{-3}$ Hz to ~ 0.1 Hz.

It is rather straightforward to derive the sensitivity that the LISA technology allows us to achieve by cross-correlating the outputs of two interferometers [16]. Let us consider two identical LISA instruments, separated by a distance D on the same orbit and with the presently estimated LISA noise spectral density, and determine the minimum value of $h_{100}^2\,\Omega$ that one is able to detect. The answer depends, of course, on the frequency dependence of the true signal $\Omega(f)$. Lacking any solid theoretical prediction, we assume that $\Omega(f)$ is constant over the relevant frequency range. This hypothesis is not unreasonable, because the frequency band over which the SNR builds up is fairly small, due to the noise spectral density $S(f)$ and the overlap reduction function $\gamma(f)$ (for more details see [16]). The minimum detectable value of the energy density content of the GW background is then given by (see e.g. [15])

$$h_{100}^2\,\Omega^{(\rm min)} = \frac{K}{T^{1/2}}\,\frac{\sqrt{50}\pi^2}{3H_0^2}\,\left[\int_0^\infty \frac{\gamma^2(f)}{f^6\,S^2(f)}\right]^{-1/2}\,, \tag{7}$$

where the constant K is related to the false alarm probability and the detection rate associated to the measurement of a background with energy $\Omega^{(\rm min)}$. For a false alarm probability of 5%, and a detection rate of 95%, $K \simeq 3.76$.

Fig. 2 clearly shows that the sensitivity to a generic GW stochastic background is $h_{100}^2\,\Omega_{\rm gw}^{\rm (min)} \gtrsim 5 \times 10^{-14}$, a time of observation $T = 10^7$ sec; this is an extremely remarkable result, especially if we compare it to the sensitivity foreseen for third-generation Earth-based interferometers: $\sim 10^{-11} - 10^{-10}$.

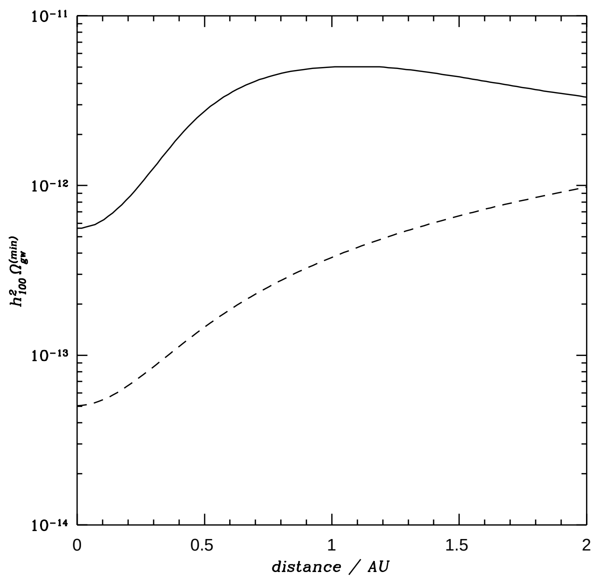

Figure 2: The minimum detectable value of the energy density of a stochastic background characterised by a flat spectrum using cross-correlation experiments between two LISA detectors on the same orbit as a function of the instrument distance D. The plot shows $h_{100}^2\,\Omega_{\rm gw}^{\rm (min)}$ for an integration time $T = 10^7$ sec, and false alarm probability and detection rate 5% and 95%, respectively. The dashed line refers to an experiment limited only by instrumental noise; the solid line also takes into account the isotropic contribution of the astrophysically generated galactic background, according to [4], and [5], which has been set optimistically to 10% of the total. The integration band is in both cases 0.1 mHz - 10 mHz.

However, such remarkable sensitivity cannot be fully exploited to detect a primordial background, due to the presence of a strong astrophysically generated background (see Fig.1). Consider a generic two-component stochastic signal:

$$\Omega(f) = \Omega_p(f) + \Omega_g(f)\,, \tag{8}$$

where $\Omega_p(f)$ and $\Omega_g(f)$ are the primordial and generated contribution, respectively; we assume, for the sake of simplicity, that they share exactly the same statistical properties (they are isotropic, stationary, Gaussian and unpolarised). In order to set up the search for $\Omega_p(f)$, one constructs the optimal filter[1]

$$\tilde{Q}_p = \frac{\gamma(f)\Omega_p(f)}{f^3 R(f)} \tag{9}$$

and correlates it against the data of two instruments. The signal-to-noise ratio at the output of the filtering process is:

$$\mathrm{SNR}^2 = T\left(\frac{3H_0^2}{10\pi^2}\right)^2 \left(\tilde{Q}_p, \tilde{Q}_p\right)\left\{1 + \frac{\left(\tilde{Q}_p, \tilde{Q}_g\right)}{\left(\tilde{Q}_p, \tilde{Q}_p\right)}\right\}^2 , \tag{10}$$

The second term in brackets can be interpreted as the (undesired) residual correlation in the detection filter due to $\Omega_g(f)$, that one cannot eliminate. When it dominates the first one, the component Ω_p cannot be detected, no matter what is the instrumental sensitivity; by constructing a more sensitive detector, therefore lowering the instrument noise, one would simply increase both terms by exactly the same amount, without improving the chances of detection of Ω_p. The same holds for the integration time T: it has no effect at all on the capability of discriminating the two components. Therefore, the minimum detectable value of the primordial contribution $\Omega_p(f)$ is set by the condition:

$$\left(\tilde{Q}_p, \tilde{Q}_p\right) = \left(\tilde{Q}_p, \tilde{Q}_g\right) . \tag{11}$$

Notice that the frequency dependence of the two components is very important: if $\Omega_p(f)$ and $\Omega_g(f)$ follow a similar frequency behaviour, the filter picks up more power from the "spurious" component $\Omega_g(f)$; if they are drastically different, even if $\Omega_g(f)$ dominates $\Omega_p(f)$, one could achieve a detection. The outcome of this analysis is summarised in Fig. 2, where the isotropic component of the generated background is assumed, optimistically, 10% of the total contribution from galactic sources following the estimates given by [4] and [5]: cross-correlations between two separated LISA detectors lead to $h_{100}^2\,\Omega_{\mathrm{gw,p}} \gtrsim 5\times 10^{-13}\,(\epsilon/0.1)(T/10^7 sec)^{-1/2}$; this drastic loss of sensitivity is due to the fact that the generated background is very strong in the mHz band, and have a spectral behaviour that is similar to the one of a primordial signal in the frequency band where most of the SNR is accumulated. The unresolved radiation from binary systems provides therefore a *fundamental sensitivity limit* in searching for the primordial GW background.

3.2 Toward testing slow-roll inflation

The mHz frequency window is therefore unsuitable to reach the ambitious level $h_{100}^2\,\Omega_{\mathrm{gw,p}} \sim 10^{-16}$ predicted by slow roll inflation, due to unresolved short-period

[1] Here $R(f)$ is a function which depends on the noise spectral density, the spectrum and the overlap reduction function, see [15, 16] for more details.

binary systems. Indeed, one needs to design an experiment with optimal sensitivity in a band free from generated backgrounds. The most promising region seems to be $\sim 0.1\,\mathrm{Hz} - 1\,\mathrm{Hz}$, accessible with a space-borne interferometer with arms a factor ~ 100 shorter than LISA's. In fact, the μHz range is likely contaminated by a background generated by massive black hole binaries with energy $\Omega_{\rm gw} \sim 10^{-15}$–$10^{-14}$ [20]; for $10^{-5}\,\mathrm{Hz} \lesssim f \lesssim 10\,\mathrm{mHz}$, as we have argued in the previous section, unevolved binaries and WD-WD binary systems completely swamp the window; above ~ 10 mHz the only residual contribution comes from extra-galactic populations of NS-NS binaries; however, around 0.1 Hz GW's from population of NS-NS binaries are not seen anymore as a stochastic background, but as being produced by individual sources; the frequency band becomes "transparent" to the primordial contribution. It is rather simple to estimate the frequency f_g, at which the transition takes place. In order to do it we use a very simple argument: if the number of independent degrees of freedom of the data set – the number of data points, or, equivalently, the number of frequency bins – is smaller than the total number of independent parameters that describe the radiation, then the superposition of monochromatic GW's must be considered as a stochastic background. If the opposite is true, we have enough information to characterise, at least in principle, each individual source, and the signal is a deterministic one. For the sake of simplicity we assume that each binary system is characterised by one parameter. The critical frequency f_g is, therefore, formally determined by the condition that the (average) number of sources per frequency bin is less than one:

$$\frac{dN(f)}{df}\,\Delta_{\rm b} f = \frac{R}{T}\,\left(\frac{df}{dt}\right)^{-1} \lesssim 1\,; \tag{12}$$

here dN/df is the number of binary sources per unit frequency interval, R the merger rate and df/dt the time derivative of the frequency f

$$\frac{df}{dt} = \frac{96}{5}\pi^{8/3}\mathcal{M}^{5/3}f^{11/3}\,; \tag{13}$$

$\mathcal{M} \equiv (m_1 m_2)^{3/5}/(m_1+m_2)^{1/5}$ is the so-called *chirp mass* (m_1 and m_2 are the masses of the two orbiting stars). The frequency f_g is then easily determined:

$$f_g \simeq \left(\frac{5}{96}\right)^{3/11}\,\pi^{-8/11}\,\mathcal{M}^{-5/11}\,\left(\frac{R}{T}\right)^{3/11}\,. \tag{14}$$

The merger rate of NS-NS binaries is uncertain; current estimates, based both on observational and theoretical grounds, yield a galactic merger rate in the range [13, 14]:

$$R_{\rm NS} \simeq 10^{-5\pm 0.5}\,\mathrm{yr}^{-1}\,. \tag{15}$$

We extrapolate this result to the entire Universe in a rather crude way: we simply multiply the galactic rate by the total number of galaxies N_G. In doing this, we assume that $R_{\rm NS}$ does not vary with the redshift, which is not entirely true. However, even if at high redshift $R_{\rm NS}$ is a factor 10 higher than in Our Galaxy, the very weak dependence of $f_g \propto R^{3/11}$ ensures that this estimate is correct within a factor $\simeq 2$. Assuming that the typical chirp mass of the binaries in the population is $\bar{\mathcal{M}} = 1.2\, M_\odot$, which corresponds to $m_1 = m_2 = 1.4\, M_\odot$, one obtains:

$$f_g \simeq 1.6 \times 10^{-1} \left(\frac{R}{10^6\,\mathrm{yr}^{-1}}\right)^{3/11} \left(\frac{T}{1\,\mathrm{yr}}\right)^{-3/11} \left(\frac{\bar{\mathcal{M}}}{1.2\,M_\odot}\right)^{-5/11} \mathrm{Hz}\,. \tag{16}$$

It is therefore clear that the window $f \gtrsim 0.1$ Hz is free from stochastic backgrounds generated by astrophysical sources, although individual deterministic signals are still present; in principle, one can identify each spectral line at $f \gtrsim 0.1$ Hz and remove it from the data stream to clean the band. How this can be effectively done and what is the SNR that is required to achieve this cleaning is an open question that needs to be addressed carefully; this is a key step in order to reach a noise level that allows to detect a signal with $h_{100}^2\,\Omega_{\mathrm{gw,p}} \sim 10^{-16}$. Clearly the technological challenge is considerable; the main noise sources that would degrade the performance of such a detector are the shot noise, beam pointing fluctuations and accuracy of the phase measurement technique. This imposes stringent requirements on the power and frequency of the laser, as well as on the dimensions of the "optics" and on other aspects of the instrument.

4 Conclusions

In this talk we have discussed the sensitivity of space-borne laser interferometers of the LISA-class, and possible follow-on missions, to a primordial GW background. In order to set a reference frame for this discussion, we have regarded the detection of a GW background produced during the early-Universe consistent with the theoretical prediction of the standard slow-roll inflation. We have considered the operation of two space-detectors, in order to achieve best sensitivity and detection confidence, and we have shown that the LISA technology already ensures the detection of a generic GW stochastic background as weak as $h_{100}^2\,\Omega \sim 10^{-14}$. However, the strong stochastic signal in the mHz band due to short-period solar-mass binary systems that cannot be resolved as individual sources prevents us from detecting a primordial background weaker than $h_{100}^2\,\Omega_p \sim 10^{-12}$. Such astrophysically generated stochastic background represents a fundamental limitation that seems to prevent any experiment in the mHz band to achieve a sensitivity to the primordial background that goes beyond what is already guaranteed by the LISA technology. Dedicated missions with optimal sensitivity in the 0.1 Hz-range or μHz-range appear, at present, the only viable options to search for weaker primordial backgrounds, and our order-of-magnitude analysis of these follow-on experiments suggests that a sensitivity level $h_{100}^2\,\Omega_p \sim 10^{-16}$ is within the capabilities of future dedicated low-frequency detectors.

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