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New limits on cosmic strings from gravitational wave observation

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ABSTRACT

We combine new analysis of the stochastic gravitational wave background to be expected from cosmic strings with the latest pulsar timing array (PTA) limits to give an upper bound on the energy scale of the possible cosmic string network, $G\mu < 1.5 \times 10^{-11}$ at the 95% confidence level. We also show bounds from LIGO and to be expected from LISA and BBO.

Current estimates for the gravitational wave background from supermassive black hole binaries are at the level where a PTA detection is expected. But if PTAs do observe a background soon, it will be difficult in the short term to distinguish black holes from cosmic strings as the source, because the spectral indices from the two sources happen to be quite similar.

If PTAs do not observe a background, then the limits on $G\mu$ will improve somewhat, but a string network with $G\mu$ substantially below 10^{-11} will produce gravitational waves primarily at frequencies too high for PTA observation, so significant further progress will depend on intermediate-frequency observatories such as LISA, DECIGO and BBO.

1. Introduction

Our universe may contain a network of cosmic strings arising as topological defects in unified field theories or as fundamental strings (or 1-dimensional D-branes) in string theory [1–3]. If so, the best hope for detecting this network is the observation of gravitational waves from oscillating string loops. Correspondingly, the strongest limits on such a network arise from non-observation of such gravitational waves.

Gravitation wave observations may detect a cosmic string network either through bursts of radiation emitted at cusps or through the stochastic background composed of radiation from all loops existing through cosmic history. Bursts were discussed in Refs. [4–7]; here we will concentrate on the stochastic background.

Current work [8] has advanced our understanding of the expected gravitational wave background spectrum, taking into account all known effects, except that Ref. [8] approximated gravitational back reaction as a smoothing process (implemented by convolving the string shape with a Lorentzian) instead of calculating the exact back-reaction effect on each loop. It is thus appropriate to update existing observational bounds [9–15] on cosmic string network properties.

Cosmic strings are classified by their tension or energy per unit length μ. The gravitational effects of strings depend on the product $G\mu$, where G is Newton's constant. We will work in units where $c = 1$, so $G\mu$ is a dimensionless number. Early models of strings considered $G\mu \sim 10^{-6}$, which is what one might expect for symmetry breaking at the grand unification scale. At such values, strings could be the cause of structure formation, but they were ruled out long ago as a primary source of large scale structure perturbations in the universe by cosmic microwave background (CMB) observations. Current limits from CMB observations give $G\mu \lesssim 10^{-7}$ [16], but pulsar timing observations give a much stronger limit, as we will discuss.

We consider here the usual model of local strings, with no couplings to any light particle except the graviton. At any given time the cosmic string "network" consists of infinite strings and a distribution of loops of various sizes. Loops are formed by reconnection of long strings with themselves. They oscillate relativistically and eventually lose their energy to gravitational radiation.

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In a uniform cosmological epoch, e.g., the radiation era between the time of electron–positron recombination and matter–radiation equality, long strings form a scaling network, in which the energy density of strings maintains a fixed ratio to the critical density by redshifting as matter in the matter era or radiation in the radiation era. This is possible because the excess energy which would otherwise accumulate is transferred into the production of loops.

The loop population is diluted like matter, even in the radiation era. As a result, radiation-era loops are greatly enhanced over long strings. With current bounds on $G\mu$, relic loops from the radiation era always dominate over loops produced more recently. The effect on the gravitational wave background of loops formed in the matter era is negligible.

To compute the stochastic background, we integrate the emission of gravitational waves at each redshift z, transferred to the present, accounting for redshifting of the waves and dilution of the energy in the subsequent cosmological evolution. The background thus depends, in general, on the distribution of loop sizes, the cosmological evolution, and the power emitted by each loop at each frequency. However, for a scaling distribution of loops in a uniform radiation era, there is a coincidence of power-law dependence among these ingredients, which leads to a flat spectrum in $\Omega_{\rm gw}$ with amplitude that depends on the number density of loops and the total gravitational power of a loop, $\Gamma G\mu^2$, but not on the shape of the emission spectrum [17]. For more detail see Ref. [8].

The high frequency background today consists almost entirely of gravitational waves emitted in the radiation era and thus participates in this flat spectrum. However, there is an important correction because at early times the number of relativistic degrees of freedom was changing, mainly at the times of the quark–hadron transition and electron–positron annihilation. These changes in the cosmological kinematics lead to a decline in the spectrum towards higher frequencies.

At lower frequencies, the spectrum is increasingly dominated by gravitational waves emitted in the matter era (from relic radiation-era loops). Again the different kinematics lead to an enhancement in the background. At still lower frequencies, the background spectrum falls rapidly, because there are few loops large enough to emit such long waves.

Here we use the results of Ref. [8], which extracted loops from simulations, smoothed them to model the change of shape due to gravitational back reaction, computed the gravitational power from each loop and propagated the resulting gravitational waves to find the present-day stochastic background. Many of these details make only a small difference to the gravitational spectrum, but there are a few points that must be handled correctly. Most importantly, it is not correct to compute the loop density by applying energy conservation to the long string network, because the great majority of the energy appears as the kinetic energy of small, rapidly moving loops, which contribute little to the gravitational spectrum [15]. For more information, see Ref. [8].

Early simulations [18,19] found the dominant loop size at the resolution of the simulations, giving rise to the idea that all important loops were at small scales limited only by gravitational back reaction on long strings. In such models, loops last for only about one Hubble time, and the gravitational wave background is reduced. But recent simulations [20–25], with much greater reach, found loop production at scales related to the horizon size at the time of production, so it does not seem that the "small loop" models are still relevant to gravitation wave calculations.

2. Results

Figs. 1 and 2 show the cosmic string gravitational-wave spectra for cosmic string tensions in the range of $G\mu = 10^{-23}$ to 10^{-9}, along with a sample of current and future gravitational wave experiments. We show the current upper limit spectra for the LIGO O1 run [26], advanced LIGO (aLIGO) at design sensitivity assuming 1 year of integration, and the best PTA limit (from the Parkes PTA [27]) along with the spectrum produced by supermassive binary black holes (SMBBH) with characteristic amplitude 10^{-15}, which is the largest currently allowed by that limit [27]. We include curves for LISA [28] and BBO [29,30] assuming 5 years of observation.

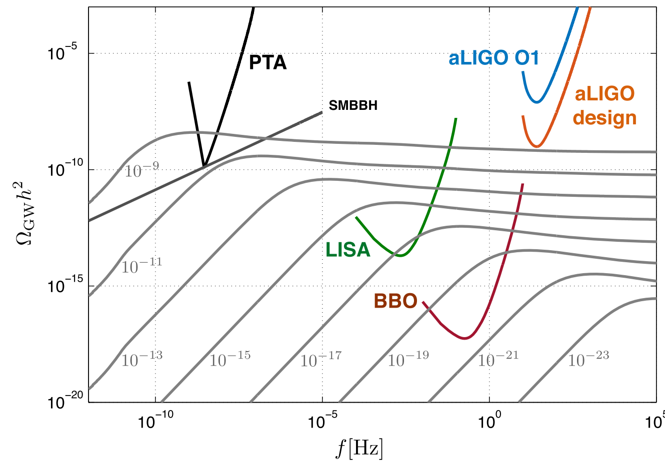

Fig. 1. Stochastic gravitational wave backgrounds compared with present and future experiments. The gray curves labeled with $G\mu$ values show the background from cosmic strings with the indicated energy scales. The straight black line is the largest allowable background from SMBBH. The remaining curves show the sensitivities of the various instruments.

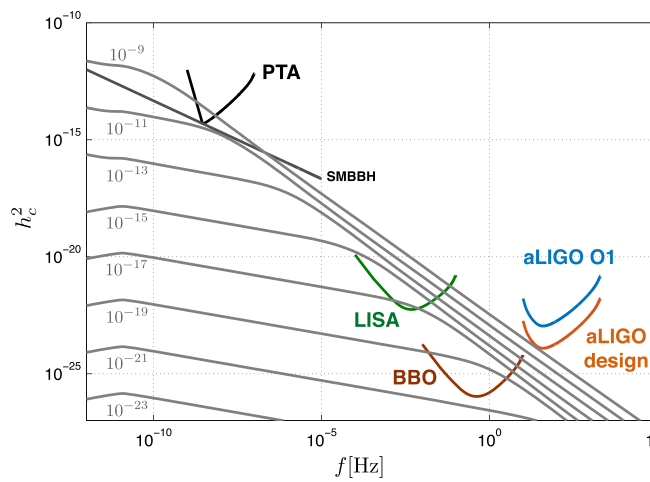

Fig. 2. As in Fig. 1 but for characteristic strain h_c (not including the solid angle and polarization sensitivity factor ($\sqrt{5}$ for LIGO or VIRGO) conventionally used by interferometers).

The instrumental curves are in the "power-law integrated" form [31], and were calculated using the publicly available codes used in Ref. [31]. In the case of LIGO and PTAs, this means that any power-law spectrum tangent to the instrumental curve has been ruled out at the 95% confidence level. For future experiments, the instrument will be able to exclude such spectra at 95% confidence level 95% of the time, if there is no signal. Either a Bayesian or a frequentist analysis can be used to derive these curves, with little difference in the result.

With current limits on $G\mu$, the peak of the background is close to the nHz frequencies to which pulsar timing arrays are most sensitive. However, if $G\mu$ is significantly below these lim-

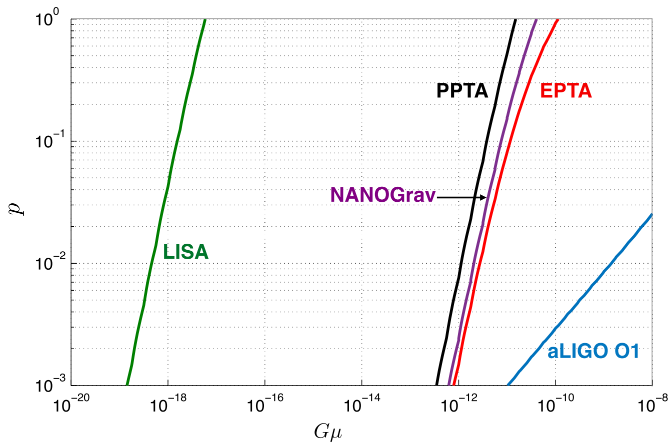

Fig. 3. Excluded regions in the $G\mu$–p plane from present and potential future observations, by the instruments labeled. The excluded area is to the right of each curve.

its, PTA frequencies will lie on the falling edge of the spectrum at low frequencies, and discovery or further constraint will become more difficult. At that point, other instruments such as LISA, (B-)DECIGO [32], and BBO will have much greater ability to study cosmic string gravitational wave backgrounds.

LIGO frequencies are to the right of the peak and suffer from the decrease due to changes in the number of degrees of freedom at early times, and the sensitivity of LIGO to measure Ω is significantly worse than PTAs. Thus LIGO is not expected to be competitive for this purpose. The proposed Einstein Telescope [33] would operate at frequencies generally similar to LIGO with about 100 times the sensitivity in $\Omega_{\rm gw}$. From Fig. 1, we see that this gives only slightly more reach for cosmic string backgrounds than current PTAs, and is not competitive with LISA.

Fig. 3 shows current 95% confidence limits on $G\mu$ from present and future experiments (in the absence of a detection). These constraints are derived as follows. LIGO [26] gives a constraint on the energy density of a flat spectrum of gravitational waves, $\Omega < 1.7 \times 10^{-7}$ in the frequency band 20–86 Hz. Since the cosmic string spectrum is close to flat in this band, this constraint can be used directly. Pulsar timing experiments report constraints on $\Omega_{\rm gw}$ at a specific frequency, the one in which the observations are most sensitive. This constraint applies not only to a flat spectrum but also to a wide range of power laws, and the effects of the period of observation are taken into account as in Ref. [31]. The 95% confidence limits are $\Omega h^2 < 1.2 \times 10^{-9}$ at frequency 5×10^{-9} Hz for the EPTA [34], $\Omega h^2 < 4.2 \times 10^{-10}$ at frequency 3.3×10^{-9} Hz for NANOGrav [35], and $\Omega h^2 < 10^{-10}$ at frequency 2.8×10^{-9} Hz for the PPTA [27,36]. We then simply find the $G\mu$ at which each constraint is saturated. For LISA we find the $G\mu$ that would lead to a 95% chance of detection in 5 years of observation, using the techniques and publicly available codes used in [31], applied to the predicted cosmic string background spectra.

In Fig. 3 we have plotted the limits on $G\mu$ against possible intercommutation probability p, using the conventional assumption that $p < 1$ simply increases the network density and thus the gravitational wave background by factor $1/p$. However, we note that while long string reconnection is the same in a denser network with lower p, loop production depends on strings reconnecting with themselves, which is not affected by the overall density. Thus we feel that the nature of low-p networks may not be well understood.

Among present experiments, the strongest limit comes from the Parkes PTA [27,36], which gives $G\mu < 1.5 \times 10^{-11}$ for $p = 1$. NANOGrav results give of $G\mu < 4.0 \times 10^{-11}$ [35], while EPTA [34] gives $G\mu < 1.1 \times 10^{-10}$. LISA could in principle set a limit of 5.8×10^{-18}, but here we have not considered effect of foregrounds and other backgrounds.

These limits apply to string networks that lose their energy primarily by gravitational waves. Global strings would evade it, as would strings that couple directly to some moduli field or the Higgs [37–39] or have other mechanisms for emitting energy into massless particles.[1]

3. Discussion

Strings were first proposed as an explanation for structure formation, with symmetry breaking at the grand unification scale giving $G\mu \sim 10^{-6}$ [45,46]. Such models were ruled out in the late 1990s by the acoustic peaks in the CMB power spectrum [47–49]. In the two decades since then, gravitational wave background limits have lowered the maximum possible $G\mu$ by five orders of magnitude to 1.5×10^{-11}. At this level and below, we will not see any effects in the CMB, nor will we discover strings by gravitational lensing (except perhaps microlensing in certain models [50]). Other possible gravitational effects of strings [51–53] will also be significantly limited by this bound.

Usual models of the evolution of black holes from merging galaxies predict that an SMBBH background should already have been observed [27]. Thus it seems likely that such a background, if nothing else, will soon be detected. If and when a gravitational wave background is observed, it will be important to distinguish cosmic strings from SMBBH as the source. Since both give Gaussian backgrounds,[2] the only distinguishing feature is the spectrum. For black holes, $\Omega \sim f^{2/3}$ up to a cutoff. For cosmic strings, the spectrum is more complicated, with a rising power $\Omega \sim f^{3/2}$, then a peak, followed by a small decline and then a plateau. At the current limit, $G\mu \sim 1.5 \times 10^{-11}$, PTA frequencies lie just to the left of the peak, and unfortunately the spectral index there is quite close to the $f^{2/3}$ of black hole binaries, as shown in Fig. 1. Thus if a signal is detected at about this level, it will be difficult to attribute it definitively to black holes or strings. On the other hand, even a small increase in PTA sensitivity without detection will break this degeneracy by further limiting the maximum $G\mu$, and so pushing the peak to higher frequencies. Then PTA frequencies will lie in the $f^{3/2}$ region of the cosmic string spectrum. In any event, LISA or (B-)DECIGO will make this distinction very clearly.

The limit on $G\mu$ given here is about 10^5 below what one would expect for strings at the grand unification (GUT) scale, and thus the non-observation of strings constrains GUT model building. Jeannerot, Rocher, and Sakellariadou [62] examined a wide range of SUSY GUT models with hybrid inflation [63–65] and found that all gave rise to cosmic strings at the inflationary scale. If this is near the GUT scale, the models are ruled out. If the inflationary scale is low enough, the resulting strings could obey the PTA bounds, and the model is admissible, but then the inflationary tensor-to-scalar ratio r (proportional to η^4 and thus $(G\mu)^2$) is so small that relic gravitational waves from inflation would not be detectable by any foreseeable experiment.

[1] Refs. [40–42] simulated cosmic string networks in lattice field theory for the Abelian Higgs model and found energy going almost entirely into the high-mass particles of the string fields. However, it is very hard to see how such results could be applicable to a realistic situation where there is a vast difference between the cosmological and string scales, which suppresses any massive radiation from the strings (see for example Refs. [43,44]).

[2] We may be able to distinguish a cosmic string background from one produced by SMBBHs via anisotropy measurements [54–61]; further work is needed to establish whether this is a viable possibility.

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The data from Ref. [8], used to make the cosmic string curves in Fig. 1, are available at http://cosmos.phy.tufts.edu/cosmic-string-spectra/.

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