B polarization of the cosmic microwave background as a tracer of strings

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String models can produce successful inflationary scenarios in the context of brane collisions, and in many of these models cosmic strings may also be produced. In scenarios such as Kachru-Kallosh-Linde-Maldacena-McAllister-Trivedi (KKLMMT) scenario the string contribution is naturally predicted to be well below the inflationary signal for cosmic microwave background (CMB) temperature anisotropies, in agreement with the existing limits. We find that for *B* type polarization of CMB the situation is reversed and the dominant signal comes from vector modes generated by cosmic strings, which exceeds the gravity wave signal from both inflation and strings. The signal can be detected for a broad range of parameter space; future polarization experiments may be able to detect the string signal down to the string tension $G\mu = 10^{-9}$, although foregrounds and lensing are likely to worsen these limits. We argue that the optimal scale to search for the string signature is at $\ell \sim 1000$, but in models with high optical depth the signal from reionization peak at large scales is also significant. The shape of the power spectrum allows one to distinguish the string signature from the gravity waves from inflation, but only with a sufficiently high angular resolution experiment.

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I. INTRODUCTION

Inflation is a theory that predicts the universe has undergone a period of exponential expansion sometime in the early epoch of its history [1–4]. The success of inflation is due to the fact that it solves a number of problems in cosmology, such as flatness and horizon. Even more importantly, it can explain the origin of structure formation in the universe, as quantum fluctuations are stretched to cosmological scales during the exponential expansion [5–9]. Inflation makes a number of potentially observable predictions, such as a nearly scale-invariant shape of the primordial spectrum, adiabatic nature of perturbations, absence of detectable non-Gaussianity, and zero curvature. It has passed all of these observational tests so far and is the leading paradigm for the origin of structure formation in the universe.

One of the most distinguished tests of inflation is its prediction of gravity waves, which are generically produced in all models of inflation and reflect the energy scale of inflation [10]. No gravity waves have been detected so far, but the current limits are weak. This is because the gravity wave signal is expected to contribute only on large angular scales, where cosmic variance limits the precision of their extraction. With cosmic microwave background (CMB) temperature spectrum the limits cannot be improved much better than the existing limits. It is often argued that a smoking gun for their detection is *B* type polarization of CMB, which is not contaminated by scalar perturbations and thus not limited by cosmic variance [11–13]. It is only limited by detector noise and other contaminants such as foregrounds and weak lensing which convert *E* polarization into *B*. The importance of this probe and its promise for a ground breaking discovery has been recognized by the wider community, and there are many ground-based CMB polarization experiments in various stages of planning or building. Moreover, a future satellite mission dedicated to *B* type polarization has been identified as one of the NASA Einstein probes to be built over the next decade, although recent budgetary constraints may delay its implementation.

In contrast to the success of inflation as a phenomenological model, producing inflation from fundamental theories like string theory has been more of a challenge. There has been recent progress on this subject in the context of the brane world scenarios, which suggest that we may be living on a hypersurface embedded in higher dimensions. Brane inflation is a generic outcome of scenarios where branes collide and heat the universe, initiating the hot big bang [14]. Another generic prediction of these models is that cosmic strings are produced during the brane collision [15].

Cosmic strings and other topological defects have long been one of the candidates for the origin of structure formation, but this scenario has been shown to lead to predictions incompatible with observations such as the power spectrum of cosmic microwave background temperature anisotropies [16–18]. In the absence of explicit predictions it seems unnatural to have topological defects play a subdominant, yet non-negligible role, so such models have largely been abandoned. This has changed in the context of string inspired models of brane inflation, some of which naturally explain why cosmic strings have a small contribution to the CMB relative to inflation, therefore accommodating the observational limits. Other more standard models inspired by supersymmetric grand unification theories can also make similar predictions [19,20]. This has led to a significant revival of all aspects of cosmic string scenario, including new theoretical motivations, phenomenological implications, and direct observational searches. While not all string-inspired models of inflation produce significant cosmic strings [21,22], the possibility of having an observable window to the string theory is too important to be ignored.

One of the most fully developed models of string inflation is KKLMMT model, in which $\bar{D}3$ brane is sitting at the bottom of a throat and a $D3$ brane is moving towards it until they collide [23]. Brane inflation in this model leads to an adiabatic spectrum of fluctuations and can satisfy all the observational constraints, provided that the inflationary potential is sufficiently flat, which requires fine-tuning at a few percent level. In the collision, a network of effectively local strings is generated, and these may remain stable due to the warping of the compact dimensions. The tension of these strings is naturally predicted to be small, and their contribution to CMB is well below the current limits [24]. Since cosmic variance limits our ability to distinguish between the two components, it is likely that we cannot detect their signal in CMB temperature anisotropies, unless the level is just below the current limits.

The above arguments suggests that one cannot observe a small signal from cosmic strings in CMB because it is dominated by the scalar perturbations from inflation. However, just as in the case for gravity wave signal from inflation, the situation changes if one considers B type polarization of CMB, which does not receive a contribution from primordial scalar modes apart from what is produced by gravitational lensing [25]. First calculations of CMB polarization in global cosmic strings and other global defects have found that B polarization signal can be significant and is dominated by vector modes [26], but there has been some controversy on the applicability of these results to local strings relevant for the string inspired models considered here [18,27,28]. The purpose of this paper is to explore the predictions of cosmic strings in polarization in the context of string inflation models and to establish prospects for their future detectability. While we work in a specific context of KKLMMT model, our results on the detectability levels in terms of string tension are more general and applicable not only to other string inspired models of inflation, but also to the more standard cosmic strings production scenarios such as those based on (SUSY) GUT scale phase transition [29].

B-mode polarization is also produced by lensing of the E-mode polarization into the B-mode polarization through the effect that is analogous to the Kaiser-Stebbins effect [30]. This has been explored in [31]. Since this is a second order effect, we neglect this contribution here as it is expected to be considerably smaller.

II. MODEL AND ANALYSIS METHOD

In this paper we adopt a simple generalization of KKLMMT scenario considered in [32]. The potential in this model is of the form

$$V = \frac{1}{2}\beta H^2\phi^2 + V_0\left(1 - \frac{A}{\phi^4}\right), \tag{1}$$

where H is the Hubble parameter and ϕ is the scalar field representing the separation between the branes. The second term in Eq. (1) represents the potential of the branes when they are far apart and are driving inflation. The third term represents attractive potential during collision which causes inflation to end at collision. The first term is conformal coupling-like and arises from additional contributions such as from Kähler potential and is spoiling the slow-roll conditions, unless β is sufficiently small, which requires fine-tuning. It also has to be positive to prevent the brane repelling even before the collision takes place. For the observationally relevant range with $0 < \beta < 0.05$ this model gives (approximately), for primordial spectral index: $n_s \sim 0.98 + \beta$, for tensor to scalar ratio: $\log r \sim -8.8 + 60\beta$, and for string tension: $\log G\mu \sim -9.4 + 30\beta$. Gravity wave signal from inflation is extremely small in these models and is not expected to be detected for any relevant value of β. Adopting the existing constraints on the slope of spectral index in the absence of tensors and running, $n_s < 1.03$ (95% C.L.) requires $\beta < 0.05$. However, the latest WMAP constraints from their 3 year analysis are even more stringent, and only a narrow range of parameter space for this model is still allowed [33]. Nevertheless, even if the current model is ruled out we expect that the more generic predictions presented here will survive. Specifically, in this model the predicted string tension $G\mu$ is well below the existing limits from CMB temperature, which are around 2.7×10^{-7} [27,28,34], yet the tension is also larger than 3×10^{-10} for all of the parameter space. An analysis of recent cosmic microwave background data, large scale structure data, supernovae Ia and Lyman-α forest data results in an upper limit of $G\mu < 2.3 \times 10^{-7}$ at 95% confidence limits for a fixed fiducial cosmic string model [35].

To describe the effects of strings on the structure formation one must first solve for their evolution given their initial conditions of a string network. As the universe expands new strings continuously enter the horizon, intersect and develop loops, which then decay away through radiation of gravity waves and possibly other fields. This reconnection probability can be much smaller than 1, which is one of the distinguishing new features of cosmic strings produced by fundamental strings as opposed to those based on field-theory driven symmetry breaking. One expects the string network to achieve scaling both in matter and radiation dominated epochs, so that the network is self-similar relative to the horizon scale. Evolution of this string network is nonlinear and has to be modeled numerically. Since most of the small scale smoothing comes from small loops and wiggles a large dynamic range is required and the convergence of the simulations has been difficult to achieve. Results from recent simulations in an expanding universe suggest that the convergence has finally been achieved, but it is not clear whether the results from different groups are entirely in agreement [36,37]. Generally, while there is considerable uncertainty in the evolution of string network on small scales, the situation is more robust on horizon scales where causality plays an important role [38].

In this work we use the public cosmic string code developed and maintained by L. Pogosian [39], which has been calibrated to reproduce the correlation functions of full-scale simulations. In [39] it was found that the simulations exhibit a significant amount of string wiggliness at the resolution scale. Since small scale simulations are still poorly resolved one parametrizes the uncertainty in the level of wiggliness with a free parameter. Increased wiggliness of the strings can be accounted for by modifying the string energy-momentum tensor [39]. Cosmic string network acts as a continuous source of metric perturbations. To compute their effect on CMB and large scale structure (LSS) one needs to know the unequal-time correlators of energy-momentum tensor. We use Pogosian's code [39] for computing the cosmic string energy-momentum source terms, which are then fed into a Boltzmann code. Pogosian's code uses CMBFAST [40], and we wrote a separate code using CAMB [41] to verify the calculations, which now agree with each other [34]. For the purpose of this paper it is particularly relevant to know the relation between scalar, vector, and tensor sources. All three add incoherently to the CMB temperature perturbations, but only vector and tensor modes contribute to *B* type polarization. Since the perturbations themselves are incoherent they result in a broad peak in CMB power spectrum, contrary to coherent oscillations seen in the data and in theoretical predictions of inflation. As a result, cosmic strings can only contribute up to 10% of the total contribution to CMB on observed scales, and this translates in the upper limit on the dimensionless string tension $G\mu < 2.7 \times 10^{-7}$ [27,28,34]. Anything below this is allowed by the current data, and due to cosmic variance it will be difficult to improve these limits much in the future using CMB temperature information only. However, since *B* polarization only receives contributions from vectors and scalars the cosmic variance problem is alleviated; the main contamination to cosmic string signal comes from gravity waves from inflation and from lensing of *E* polarization.

In this paper we are interested in the regime where the string signal is negligible if the contribution from the inflationary scalar modes is present. Therefore we focus on *BB* power spectrum, and we do not study the lensing of the CMB by the string network itself. If this is not the case, the string network should be much easier to identify via its non-Gaussian nature rather than power spectrum.

Analytical calculations in [38] have shown there exists a relation between scalar, vector, and tensor perturbations on horizon scale, which can be used to predict the corresponding fractions of the three components in the CMB, subject to some important assumptions such as comparable correlation length. This prediction was shown to be reasonably well satisfied in the simulations of global strings [38]. One of the outcomes of these calculations is that vector modes play an important role and may, depending on the model, even be the dominant source of perturbations. In particular, they were shown to dominate over the tensor modes [16,26] in global string simulations. However, it has been often argued that the evolution of local strings may be significantly different from that of global strings, so that insights attained in the global case may not apply to the local case. Therefore a more direct calculation of local strings is needed.

III. RESULTS

Our calculations of CMB predictions using modified Pogosian's code are shown in Fig. 1, assuming $\beta = 0.02$ and smooth strings with no extra small scale wiggliness. In this example we have $r = 10^{-6}$ and $G\mu = 10^{-8}$. In temperature, *E* polarization autospectra, and their cross-correlation the string signal, are orders of magnitude below the scalar contribution from inflation, and for much of the parameter space strings cannot be detected [42].

The situation is reversed for *B* polarization, where there is no primordial scalar contribution from inflation. Moreover, the tensor contribution from inflation is well below the string contribution. This is true for all the values of β in this model. It is interesting to note that over most of the range vector perturbations exceed tensor perturbations from strings, just as it was found for global strings [26]. The exception may be around $\ell \sim 30$–100, where however the signal is weakest compared to the noise. As Fig. 1 shows there are two peaks in the signal, reionization peak for $\ell < 20$–50 and the recombination peak at $\ell \sim 1000$. Reionization peak has the origin in the large quadrupole moment on the scale of horizon due to the free streaming of photons after recombination. Because of reionization these photons are rescattered, and this generates polarization on the angular scale of horizon at that epoch. The reionization peak amplitude strongly depends on the adopted value of optical depth τ and increases by an order of magnitude between $\tau = 0.04$ and $\tau = 0.17$. Recent WMAP results [33] have converged onto $\tau \sim 0.1$, so we adopt this value in our calculations. The main recombination peak is dominated by incoherent contributions generated by cosmic strings during and after recombination. It is much less dependent on reionization optical depth. Overall, we find very similar results to the global string predictions in [16,26], suggesting that there is little qualitative difference between global and local strings in their CMB predictions,

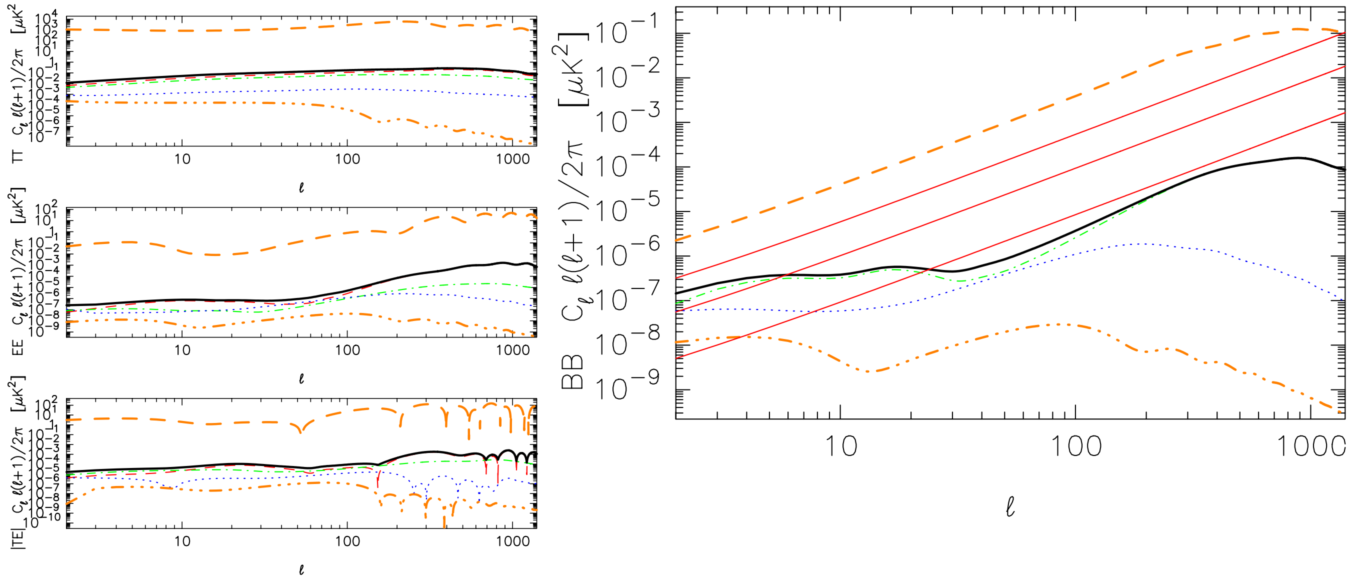

FIG. 1 (color online). This figure shows various CMB temperature and polarization power spectra. The left panel shows TT (top), EE (middle) and the absolute value of the TE (bottom) power spectra, while the larger right-hand side plot shows the same for the BB power spectrum. The thick dashed and dot-dashed lines (orange) correspond to the inflationary contribution for the scalar and tensor modes, respectively; in the BB power spectrum the scalar contribution comes exclusively from lensing of the EE polarization modes by the intervening structure between us and the surface of the last scattering. The thin dashed (red), dot-dashed (green) and dotted (blue) lines show the scalar, vector and tensor contributions to the total string contribution plotted as a thick solid line (black), assuming $G\mu = 10^{-8}$. The red thin straight lines in the BB power spectrum correspond to rough limits on residual noise obtained by cleaning the lensing contamination from E polarization by the quadratic estimator (top) and iterative method (middle), while the bottom is the instrumental noise for a hypothetical future instrument with polarization sensitivity of $\sim 0.25\ \mu$K arcmin and beam size of $2'$.

at least for the smooth string models considered in this example.

At what level can the string signal be detected in CMB? As discussed above, for CMB temperature anisotropy T the cosmic variance prevents detection of the string contribution if the signal is below a few percent of the inflationary signal and if only $\ell < 1000$–2000 information is used. The same conclusion is valid for E polarization and its cross-correlation with T. Thus it is the B polarization autocorrelation that offers the best prospects for a detection given sufficiently high signal-to-noise detector, since it is not contaminated by primary scalar modes. However, even B polarization is contaminated, because gravitational lensing converts some of the scalar E polarization into B [25]. The dashed curve at the top of bottom right panel of Fig. 1 shows this lensing induced B polarization generated from E polarization as computed by CMBFAST [40]. It has roughly a white noise power spectrum up to $\ell \sim 700$, beyond which it gradually flattens and eventually drops.

This lensing induced B polarization can be reduced if one has information on the projected lensing potential, which allows one to delens the CMB [43–45]. This can be achieved using the non-Gaussian correlations in the CMB temperature or polarization [46–48] or from external information obtained from other tracers (e.g. 21 cm fluctuations [49,50]). If one assumes quadratic estimator from [46], then one can reduce the lensing noise in the white noise regime by a factor of 7. Iterative estimator can, in cases of very low detector noise, such as a hypothetical CMBPOL type satellite, give $w_{\rm P,eff}^{-1/2} = 0.8\ \mu$K arcmin for a $2'$ beam, i.e. an improvement of a factor of 40 relative to the no lens noise cleaning [45]. This is still several times above the instrument noise, so lensing noise always dominates. All three noise curves are shown in Fig. 1. We have adopted the white noise approximation for quadratic and iterative lens cleaning, although in practice the situation may be better since the lensing noise itself decreases below the white noise on small scales. On the other hand, it is unclear whether the iterative method can obtain this reduction on small scales in this model, since the method works on the assumption that there is no B signal except that coming from lensing and so it must be generalized to account for the signal from strings.

For a given signal and lensing induced B-mode noise power spectrum the resulting uncertainty on $G\mu$ is:

$$\sigma_{(G\mu)^2}^{-2} = f_{\rm sky}\sum_\ell \frac{2\ell+1}{2} w_{\rm P,eff,\ell}^2 \left(\frac{C_\ell^{BB}}{(G\mu)^2}\right)^2, \qquad (2)$$

where C_ℓ^{BB} is the string power spectrum of B modes as in Fig. 1, and $w_{\rm P,eff,\ell} = C_\ell^{BB}(\text{residual})$ is the inverse noise variance per solid angle per polarization that has units of

TABLE I. This table show the detectability limits for $G\mu$ for various combinations of the optical depth (τ), wiggliness (α), ℓ range and assumed noise.

		$(\sigma_{(G\mu)^2})^{1/2}/10^{-9}$			
		$w_{\rm P,eff}^{-1/2} = 0.8\ \mu$K arcmin		$w_{\rm P,eff}^{-1} = C_{\rm scalar,lensed}(\ell)$	
τ	α	$\ell < 100$	$100 < \ell < 1200$	$\ell < 100$	$100 < \ell < 1200$
0.04	1.0	3.4	1.4	22.9	9.3
0.04	1.9	5.3	1.8	35.9	12.4
0.04	3.0	7.6	2.4	51.6	16.5
0.10	1.0	2.2	1.4	14.0	9.3
0.10	1.9	3.3	1.9	20.6	12.4
0.10	3.0	4.5	2.6	28.6	16.5
0.17	1.0	1.5	1.5	8.9	9.3
0.17	1.9	2.2	2.1	13.0	12.4
0.17	3.0	3.0	2.7	18.2	16.5

$(\mu\text{K arcmin})^2$ and represents the noise from combined instrument noise and lensing residuals that limits the detectability of the signal.

It is worth considering the reionization peak and the main peak separately. The reionization peak depends sensitively on the Thomson scattering optical depth τ due to reionization, which is still somewhat uncertain, while the main peak sensitivity is much weaker. In addition, incomplete sky coverage and foregrounds are particularly worrisome on large scales, so the reionization peak may be more difficult to observe than the recombination peak [51,52]. The results of the calculations for various levels of wiggliness are given in Table I. For reionization peak, using information with $\ell < 100$, we find that the error on $G\mu$ varies between 1.5×10^{-9} for $\tau = 0.17$ and no wiggliness to 7.6×10^{-9} for $\tau = 0.04$ and high wiggliness, assuming noise levels of iterative lens cleaning procedure in a CMBPOL type experiment. In all cases full sky is assumed. In the other extreme we assume full lensing noise with no delensing. In this case we find the limits are between 10^{-8} and 5×10^{-8} on $G\mu$.

For partial-sky coverage, Eq. (2) must be modified to take into account sky cuts; while $\sigma_{(G\mu)^2} \propto f_{\rm sky}^{-1/2}$ for the small scale peak on subdegree scales, the reionization peak present at $\ell < 20$ exhibits a much more complicated dependence on the survey geometry due to cross-leakage of E and B modes induced by, e.g. the Galactic Plane cut [53,54]. In [51] it was argued that the scaling with sky fraction becomes $\sigma_{(G\mu)^2} \propto f_{\rm sky}^{-2}$ for $f_{\rm sky} > 0.7$. This could further weaken the limits from large scales given in Table I. The degradation is worst for models with late reionization because this pushes the B reionization peak to the lower multipoles where sky-cut effects are most severe. In particular, using the analysis in [51] and assuming we can remove dust foregrounds at the 0.01% level of unpolarized emission, we find that $G\mu \sim 10^{-8}$ can be achieved from large scales, but it will be difficult to go below that using reionization peak information alone.

The situation is better for the main recombination peak at $\ell \sim 1000$. We find that we can achieve between $G\mu = 1.4 \times 10^{-9}$ and 2.7×10^{-9} depending on the wiggliness and assuming iterative delensing procedure with high angular resolution and low noise detector like CMBPOL. For the case of no lens cleaning, the numbers vary between 9×10^{-9} and 1.6×10^{-8}. Even in this case the improvements are at least 1 order of magnitude better than the current limits. While the level of polarization foregrounds is poorly known on these scales, galactic emission tends to be smooth and decreases towards smaller angular scales, although this prediction could be modified if there are small scale magnetic fields in our galaxy generating small scale power in synchrotron polarization.

We should warn that there is still considerable uncertainty regarding the predictions of string models and our results on the value of $G\mu$ should be viewed as qualitative. However, both the shape of the power spectrum and string tension normalization appear to be very similar among different groups, suggesting that the remaining uncertainties may not make much of a quantitative difference to the results found here. On the other hand, varying the details of the string network evolution, such as decay rate, intercommutation probability and wiggliness, can change the coherence length and move the peak of the power spectrum in CMB temperature and polarization. It can also change the ratios of scalar to vector to tensor contributions to CMB temperature or polarization.

IV. DISCUSSION

It has long been recognized that gravity waves are a natural outcome of inflation with an amplitude in CMB that may be close to observed limits and may be best observed in CMB B polarization experiments. Recent models of inflation in brane collisions suggest a very similar situation for cosmic strings generated from the brane collisions and a natural outcome of such models may also be CMB polarization at a detectable level in B channel. We find the string signal is dominated by vector modes over tensor modes and, for models analyzed here, both of these exceed the gravity wave signal from inflation.

Thus string inspired models of inflation may challenge the conventional view that a detection of B type polarization in cosmic microwave background (CMB) will demonstrate the existence of gravity waves in the early universe and measure the energy scale of inflation. If only the large scale signal is observed in B polarization then it may be difficult to distinguish between the string and inflation scenarios. This is because there is only a finite number of modes being observed and cosmic variance prevents one from accurately determining the shape of the power spectrum on large scales, and the differences between the two models are small (Fig. 1).

One possible way to distinguish between the two models is the string induced non-Gaussianity. However, at least initially, detections are likely to be of a low signal-to-noise and so extracting information beyond two-point function is going to be difficult. Alternatively, if high angular resolution is available, then separating cosmic string signal from inflationary gravity wave signal should be possible using the power spectrum shape information, since strings predict the signal dominates at $l \sim 1000$, while gravity wave signal from inflation peaks at $l \sim 100$ and decays away on smaller scales. For our most optimistic case we find that string tension down to $G\mu \sim 10^{-9}$ can be detected with B-polarization, 2 orders of magnitude below the current limits. Galactic foregrounds and gravitational lensing may considerably weaken these limits and $G\mu \sim 10^{-8}$ may be a more realistic target. These limits are in the range of current model predictions, although they do not cover the entire range since even lower values of string tension are possible. Nevertheless, searching for this signature provides additional motivation for upcoming CMB polarization experiments, specially on small angular scales, where only the lensing induced B polarization was previously expected to be seen. A search for excess signal on these scales may instead reveal a signature of string physics.

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