

Constraints on superconducting cosmic strings from the global 21-cm signal before reionization

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Abstract. Electromagnetic radiation from the cusp region of superconducting cosmic strings leads to a radio excess in the photon spectrum in the early universe and can produce a deep absorption feature in the global 21 cm signal before the epoch of reionization. We study the constraints on the parameter space of superconducting strings which can be derived by demanding that the absorption feature is not larger in amplitude than what has recently been reported by the EDGES collaboration. We find a previously unconstrained region of high current, low tension strings would produce too strong of an absorption feature, and are thus ruled out by non-detection.

Keywords: Cosmic strings, domain walls, monopoles, absorption and radiation processes, reionization

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Contents

1	Introduction	1
2	Radio excess and global 21 cm absorption signal	3
3	Radio excess from superconducting cosmic strings	4
4	Conclusions and discussion	7

1 Introduction

There has recently been a lot of work exploring the observational signals of cosmic strings (see e.g. [1] for a review of recent work). Cosmic strings are one-dimensional topological defects which are solutions of the field equations in many theories beyond the Standard Model of particle physics (see e.g. [2–4] for reviews of the physics and cosmology of cosmic strings). If Nature is described by a theory which admits cosmic string solutions, then a network of cosmic strings will form during a phase transition in the early universe and persist until the present time [5, 6]. Strings lead to interesting signatures for a variety of cosmological observations. Not observing these signals will lead to constraints on the parameter space of particle physics models beyond the Standard Model [7].

Most of the recent studies of the cosmological imprints of cosmic strings have been done in the context of strings which only interact gravitationally. In this case, the network of strings is described by a single parameter, the string tension μ (usually expressed in terms of the dimensionless number $G\mu$, where G is Newton’s gravitational constant). However, in many models, strings carry conserved electromagnetic currents, either bosonic or fermionic, and they are hence superconducting [8]. In a theory which has superconducting strings, currents on the string are induced during the phase transition which produces the strings, and during the later evolution of the strings through the plasma of the early universe. Superconducting cosmic strings emit electromagnetic radiation. This radiation is dominated by the cusp region on cosmic string loops, regions which move with a velocity which approaches the speed of light. Cusps are generic features of string loops, with at least one cusp per oscillation period forming on a string loop [25]. The bursts of electromagnetic radiation from strings cusps were studied in [26–28] and [29]. The fact that this emission gives rise to spectral distortions of the CMB was investigated in [30, 31] and [32]. The connection with gamma ray bursts was explored in [33–35], and the connection with fast radio transients in [36–42].¹

Causality implies [5, 6] that at all times after the phase transition during which the strings are formed, there will be at least one “long” string crossing each Hubble patch of space. Here, “long” refers to a string with curvature radius larger than the Hubble radius. Analytical arguments [2–4] indicate that the network of long strings approaches a “scaling” solution, according to which the distribution of strings is statistically the same at all times if lengths are scaled to the Hubble radius. This is confirmed by numerical simulations of the evolution of cosmic string networks [9–16]. The network of long strings maintains its scaling property by losing energy to string loops during long string intersections. Hence, a

¹For earlier work on the connection between superconducting strings and ultra-high energy cosmic rays see [44, 45].

distribution of string loops with a large range of radii R builds up. Analytical arguments (this time not supported by general causality considerations) indicate that the distribution of string loops will also approach a scaling solution. At times later than t_{eq} , the time of equal matter and radiation, the distribution of string loops is given by (see e.g. [17–23])

$$n(R, t) = \nu R^{-5/2} t_{\text{eq}}^{1/2} t^{-2} \text{ for } R_c(t) < R < \alpha t_{\text{eq}}, \quad (1.1)$$

and

$$n(R, t) \sim R^{-2} t^{-2} \text{ for } R > \alpha t_{\text{eq}}, \quad (1.2)$$

where ν is a constant which depends on the number of long string segments crossing a Hubble volume, $R_c(t)$ is a cutoff radius below which loops live less than one Hubble expansion time, and α is a constant indicating at what fraction of the Hubble radius loops are produced.

For non-superconducting strings, the dominant energy loss mechanism of string loops is gravitational radiation. Since string loops have relativistic tension, they oscillate and emit gravitational radiation. The power of gravitational radiation from a string loop is [24]

$$P_{\text{gw}} = \gamma G \mu^2, \quad (1.3)$$

where γ is a constant which, according to numerical simulations of gravitational wave emission [24] is of the order $\gamma \sim 10^2$.

It can be shown that the total power of electromagnetic radiation from cusp regions, averaged over an oscillation period, is [43]

$$P_{\text{em}} = \kappa I \sqrt{\mu}, \quad (1.4)$$

where I is the current on the string and κ is a constant of the order 1. For a fixed value of $G\mu$ there is a critical current I_c above which electromagnetic radiation dominates, and below which gravitational radiation is more important. This critical current is given by

$$I_c = \kappa^{-1} \gamma (G\mu)^{3/2} m_{\text{pl}}, \quad (1.5)$$

where m_{pl} is the Planck mass. If gravitational radiation dominates, then the cutoff radius $R_c(t)$ is given by

$$R_c(t) = \gamma \beta^{-1} G \mu t, \quad (1.6)$$

where β is a constant which gives the mean loop length in terms of the radius (for a circular loop we would have $\beta = 2\pi$), while if electromagnetic radiation dominates we have

$$R_c(t) = \kappa \beta^{-1} I \mu^{-1/2} t. \quad (1.7)$$

There is another energy loss mechanism for string loops: cusp decay [46]. This mechanism is more important than gravitational radiation loss for very low tension strings, and more important than electromagnetic radiation for very small currents. Thus, the mechanism is only important in regions of parameter space where the electromagnetic radiation is small. Hence, in this work we will not consider the cusp decay channels.

The electromagnetic emission is non-thermal and concentrated at low frequencies. We consider the enhanced energy density in electromagnetic radiation for frequencies at and below the frequency of 21 cm radiation. This radio excess leads to a deep absorption signal in the global 21 cm signal before reionization. Such a signal was recently reported by the EDGES experiment [47, 48] with an absorption deeper than predicted by the standard cosmological

paradigm. A radio excess could possibly explain this signal. In an earlier paper [49], we studied the contribution of electromagnetic radiation from cusp decays of non-superconducting strings to the radio excess and found it to be much too small to effect observations. Superconducting strings, on the other hand, produce much more electromagnetic radiation. Here we study the contribution to a possible radio excess which these strings can produce. By demanding that the global absorption is smaller than what has been measured by the EDGES collaboration [47, 48], we can derive constraints on the parameter space of superconducting strings. We find a region of parameter space which is indeed ruled out by observations.

In the following, we will first review how a soft radio photon excess can lead to a large absorption feature in the 21 cm global signal. In section 3, we then compute the radio excess predicted by a network of superconducting cosmic string loops as a function of the cosmic string parameters $G\mu$ and I , determine their fractional contribution to the total radio spectrum of the cosmic microwave background (CMB), and derive the constraints on the parameter space which results from demanding that the induced 21 cm absorption signal is not larger than what has been detected. We discuss our results and compare with previous studies of cosmological constraints on superconducting cosmic strings in the final section.

We work in natural units in which the speed of light, Planck's constant and Boltzmann's constant are set to 1. We work in the context of standard cosmology. The variable t is used for physical time, t_{eq} denotes the time of equal matter and radiation, and t_{rec} is the time of recombination (which is later than the time of equal matter and radiation). The temperature of the radiation gas is denoted by T .

2 Radio excess and global 21 cm absorption signal

One way in which the parameter space of superconducting cosmic strings can be constrained is by the amplitude of the absorption feature in the global 21 cm signal. Observing the universe through the 21 cm window can provide information about the distribution of neutral hydrogen at early times, in particular before and during reionization. CMB photons passing through a cold cloud of neutral hydrogen are absorbed by exciting the hydrogen hyperfine transition (see e.g. [50] for an in-depth review of the physics of 21 cm surveys). In an early paper [51] it was pointed out that the global 21 cm signal can provide a tool to probe for the existence of cosmic string wakes before reionization.

There has recently been a lot of interest in the global 21 cm absorption signal before the epoch of reionization as a consequence of the detection of an unexpectedly large absorption signal by the EDGES collaboration [47, 48]. The detected amplitude of the temperature decrement is at least twice what is expected in standard cosmology. Assuming a mostly neutral IGM, the temperature decrement δT_b is given by the proportionality

$$\delta T_b \propto 1 - \frac{T_\gamma}{T_{\text{spin}}}, \quad (2.1)$$

where T_γ is the effective temperature of the photons at the 21 cm frequency, and T_{spin} is the spin temperature of the hydrogen gas. The effective temperature of the photons, in turn, is given by

$$T_\gamma = T_{\text{CMB}} + T_{21}, \quad (2.2)$$

where T_{CMB} is the overall CMB black body temperature, and T_{21} is the effective temperature due to extra photons at 21 cm frequencies. These effective temperatures are given in terms of

the energy densities of photons in the frequency range of 21 cm. Given a new source of radio photons, the boost in the amplitude of the absorption feature is given by [52] the factor

$$\mathcal{F} \sim 1 + \frac{T_{21}}{T_{CMB}}. \quad (2.3)$$

Following the results reported in [47, 48], there has been a flurry of work proposing ways to explain the extra absorption. A lot of the proposed models have focused on ways to reduce the spin temperature, e.g. by invoking dark matter interactions (see e.g. [53–55] for early work). On the other hand, it was pointed out in [56] that extra 21 cm absorption can also be obtained if there is a new source of radio photons. In fact, an excess of the radio background has been reported by the ARCADE-2 experiment [57]. This serves as an additional piece of motivation, as the existence of cosmic strings (both superconducting and not) would produce an anomalous background.

In this work, we will compute the contribution of superconducting cosmic string loops to the radio photon background and provide bounds on the parameter space of such strings, by demanding that the absorption feature produced by the strings not exceed the amplitude reported in [47, 48].² Note that if the global 21cm signal turns out to be lower than what was reported, our bounds will become stronger.

3 Radio excess from superconducting cosmic strings

In the following, we will compute the energy density in radio photons due to the emission from a network of loops of superconducting cosmic strings. The energy density of photons in the frequency interval $[0, \omega_{21}]$ at time t is

$$\rho^{21}(t) = \int_{t_{\text{rec}}}^t d\tau \frac{d\rho^{21}(\tau)}{d\tau} \left(\frac{\tau}{t}\right)^{8/3}, \quad (3.1)$$

where the first term inside the integral is the energy density in photons inserted per unit time, and the second factor gives the cosmological redshift of the radiation energy density in the matter dominated epoch. The energy density per unit time is given by integrating over all frequencies below the frequency ω_{21} blueshifted to time $\tau < t$

$$\omega_{21}(\tau) = \omega_{21} \left(\frac{t}{\tau}\right)^{2/3}, \quad (3.2)$$

and integrating over the distribution of string loops. This gives

$$\frac{d\rho^{21}(\tau)}{d\tau} = \int_0^{\omega_{21}(\tau)} d\omega \int_{R_c(\tau)}^{\alpha\tau} dR n(R, \tau) \frac{dP}{d\omega}(\omega), \quad (3.3)$$

where the final factor is the power per unit frequency from cosmic string core region emission, and is given by [43]

$$\frac{dP}{d\omega}(\omega) = \kappa I^2 R^{1/3} \omega^{-2/3}. \quad (3.4)$$

²In a recent paper [49] we studied the radio excess produced by the cusp decay of non-superconducting strings, but we found that the predicted radio spectrum is too low in amplitude to yield constraints on the cosmic string parameter space.

The integral over R in (3.3) is dominated by the smallest value of R greater than the cutoff value $R_c(t)$. Let us focus on values of $G\mu$ and I which are sufficiently small such that the value of $R_c(t)$ at the time of reionization is smaller than αt_{eq} . In this case, we can use the expression (1.1) for $n(R, \tau)$. Inserting this and performing the integral over R , we obtain

$$\rho^{21}(t) = 3\tilde{\kappa}\nu I^2 \omega_{21}^{1/3} t_{\text{eq}}^{1/2} t^{-2} \int_{t_{\text{rec}}}^t d\tau R_c(\tau)^{-7/6} \left(\frac{\tau}{t}\right)^{4/9}, \quad (3.5)$$

where $\tilde{\kappa}$ is κ multiplied $\mathcal{O}(1)$ constants.

For currents smaller than the critical current I_c (which is a function of $G\mu$), we insert the value of the cutoff radius given by (1.6) and obtain

$$\rho^{21}(t) = 18\tilde{\kappa}\nu I^2 \omega_{21}^{1/3} t_{\text{eq}}^{1/2} t^{-2} \gamma^{-7/6} \beta^{7/6} (G\mu)^{-7/6} t^{-1/6}. \quad (3.6)$$

Inserting the maximal current for which this expression is valid, namely (1.5), yields

$$\rho^{21}(t) = 18\tilde{\kappa}\kappa^{-2} \nu G^{-1} \omega_{21}^{1/3} t_{\text{eq}}^{1/2} t^{-2} \gamma^{5/6} \beta^{7/6} (G\mu)^{11/6} t^{-1/6}. \quad (3.7)$$

For currents larger than the critical one, we insert the value of the cutoff radius given by (1.7) and obtain

$$\rho^{21}(t) = 18\tilde{\kappa}\kappa^{-7/6} \nu I^{5/6} \omega_{21}^{1/3} t_{\text{eq}}^{1/2} t^{-2} \beta^{7/6} (G\mu)^{7/12} G^{-7/12} t^{-1/6}. \quad (3.8)$$

Inserting the current (1.5), the minimal current for which this computation applies, yields the same result we obtained above, namely (3.7).

We now compare the magnitude of the above radio excess of photons at frequencies smaller than ν_{21} with the CMB black body photons in this frequency range. Since the value ω_{21} is in the low frequency (Rayleigh-Jeans) regime of the black body for the temperature at the time of reionization, the energy density in CMB photons is given by

$$\rho_{\text{CMB}}(t) = \frac{1}{3\pi^2} \omega_{21}^3 T(t). \quad (3.9)$$

To compute the ratio $\mathcal{R} = \rho^{21}(t)/\rho_{\text{CMB}}(t)$ we make use of the Friedmann equation to relate time and temperature. Specifically, we use

$$G^{-1} t^{-2} = 6\pi \left(\frac{t}{t_{\text{eq}}}\right)^{2/3} T^4. \quad (3.10)$$

Inserting the value of I_c into $\rho^{21}(t)$ yields

$$\mathcal{R}(I = I_c) = \mathcal{A} \nu \gamma^{5/6} \beta^{7/6} (G\mu)^{11/6} \left(\frac{t}{t_{\text{eq}}}\right)^{1/18} \left(\frac{T}{\omega_{21}}\right)^{8/3} \left(\frac{m_{\text{pl}}}{T}\right)^{1/3}, \quad (3.11)$$

where \mathcal{A} is a constant of the order 10^3 (assuming that κ is a constant of the order 1), and where we have left the dependence on ν, β and γ explicit. For typical values $\beta = \gamma = \nu = 10$, evaluating the result at the temperature of reionization we obtain

$$\mathcal{R}(I = I_c) \sim 10^{12} (G\mu)_6^{11/6}, \quad (3.12)$$

where $(G\mu)_6$ is the value of $G\mu$ in units of 10^{-6} .

For values of the current larger than I_c we have

$$\mathcal{R}(I) = \left(\frac{I}{I_c}\right)^{5/6} \mathcal{R}(I_c) \quad (I > I_c), \quad (3.13)$$

while for values smaller than I_c we have

$$\mathcal{R}(I) = \left(\frac{I}{I_c}\right)^2 \mathcal{R}(I_c) \quad (I < I_c). \quad (3.14)$$

If the EDGES results are to be explained by excess photons at low frequencies, then the value of \mathcal{R} should be of the order 1 [52]. If we demand that the distribution of superconducting string loops does not produce an absorption feature larger in amplitude than has been observed, the parameter space of strings must be constrained to yield $\mathcal{R} \leq 1$. From (3.12), (3.13) and (3.14) we see that a significant parameter space of high-tension and high-current superconducting cosmic strings is ruled out.

Our results are summarized in figures 1 and 2. In figure 1, our new constraints (the shaded blue region) are shown alongside previously computed constraints (shaded orange region, see [59] and references therein). The region above the brown diagonal line corresponds to the zone in which gravitational wave decay is the primary energy loss mechanism for the strings, and below this line they decay primarily into EM waves. We show that with our analysis, we can rule out a previously allowed region of parameter space by considering the 21 cm photons emitted from superconducting strings between recombination and reionization. We do this by assuming the radiation in 21 cm is not greater than what was detected by the EDGES collaboration ($\mathcal{R} \leq 1$). In figure 2, we show how these constraints can be strengthened in the event that the radiation density in 21 cm produced by strings is 10% or 1% of the EDGES signal.

Assuming standard values of the constants which arise in the cosmic string distribution

$$\begin{aligned} \gamma &= 10 \\ \beta &= 10 \\ \nu &= 10 \end{aligned} \quad (3.15)$$

we find

$$I_c \sim (G\mu)_6^{3/2} 10^{10} \text{ GeV}. \quad (3.16)$$

For $I = I_c$ the constraint $\mathcal{R} < 1$ implies

$$(G\mu) < 10^{-12.5}. \quad (3.17)$$

This limit is marginally stronger than the limit on the string tension from pulsar timing array measurements [58], though previously constrained by BBN considerations and the Parkes Radio Survey. The pulsar timing limit on $G\mu$, however, assumes that the distribution of string loops is determined by energy loss only from gravitational radiation. Since the pulsar timing constraints are dominated by the smallest loops in the scaling distribution, the bounds are much weaker if $I > I_c$. According to the analysis of [59], the pulsar timing constraints essentially disappear for $I > I_c$. Our analysis lets us set an upper bound on the cosmic string current in this regime by requiring $\mathcal{R} < 1$ in (3.13) such that the background radiation density in 21-cm from strings doesn't exceed that of the CMB

$$I < I_c (G\mu)_6^{-11/5} 10^{-72/5} \sim (G\mu)^{-7/10} 10^{-9} \text{ GeV} \quad (I > I_c) \quad (3.18)$$

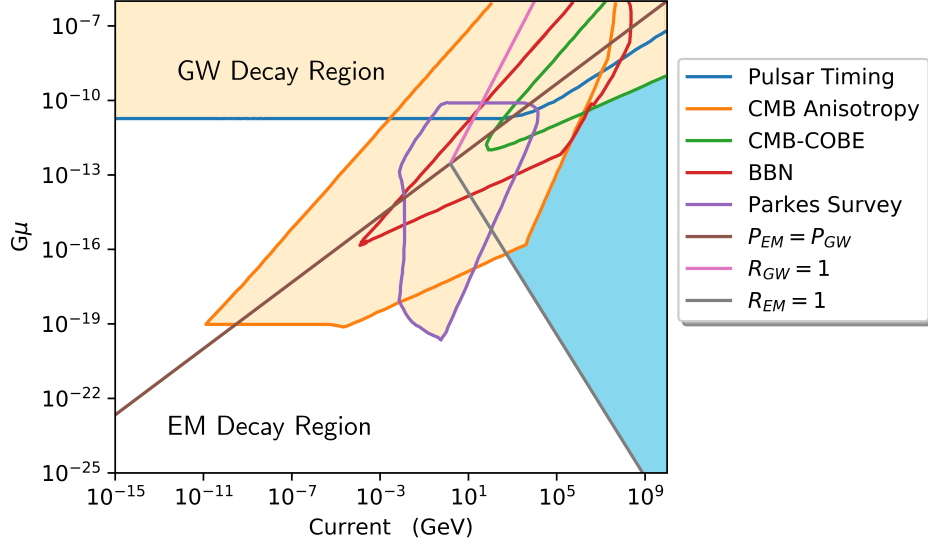


Figure 1. The shaded regions show the parameter space of superconducting cosmic strings which are ruled out. The light orange region corresponds to constraints from previously considered sources (see [59] and references therein for these constraints), whereas the light blue correspond to regions that are now ruled out by our analysis, assuming the global 21 cm absorption signal is not larger than what was reported by the EDGES collaboration. These new regions are bound by the curves along which $\mathcal{R} = 1$ (see the main text for the definition of \mathcal{R}). The vertical axis gives the value of $G\mu$, the horizontal axis is the current. The diagonal brown curve corresponds to the critical current as a function of $G\mu$. Above the curve gravitational radiation is the dominate decay mechanism of the loops. Below it, electromagnetic radiation dominates.

Similarly, we can compute the same constraint for the regime where $I < I_c$ using (3.14)

$$I < I_c (G\mu)_6^{-11/12} 10^{-6} \sim (G\mu)^{7/12} 10^7 \text{ GeV} \quad (I < I_c) \quad (3.19)$$

Though this constraint seems degenerate with other ones compiled by [59].

4 Conclusions and discussion

We have derived constraints on the parameter space of superconducting cosmic strings obtained by demanding that the induced absorption feature in the global 21 cm signal before reionization not exceed the value observed by the EDGES collaboration [47, 48]. Our results are summarized in figure 1. Note that we have implicitly assumed total efficiency in the Lyman alpha coupling of the 21 cm spin temperature to the kinetic temperature of the IGM during the formation of the first stars. If the coupling efficiency was low, then a higher excess radiation would be required to produce a given decrement in the signal, and our bounds on the cosmic string parameter space would weaken.

For values of the string current I smaller than the critical current $I_c(G\mu)$, our constraints are weaker than the ones which follow from pulsar timing array measurements. The pulsar timing constraints come from gravitational radiation emitted by string loops. The effect is dominated by the smallest loops which survive more than one Hubble time. In the region

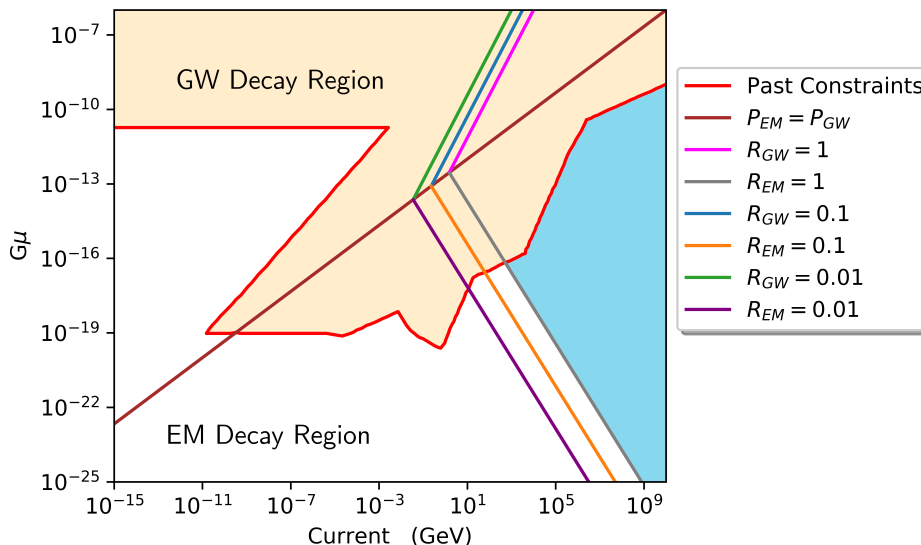


Figure 2. The light orange region bounded by the red curve represents the limiting constraints considered by previous works in [59]. The light blue region bounded by the grey curve corresponds to regions of the superconducting string parameter space that constrained via our analysis by requiring $\mathcal{R} \leq 1$. If the signal from strings is less than 10% of what has been reported, the constrained region extends to the orange line (requiring $\mathcal{R} \leq 0.1$). If it is less than 1%, the region extends even further to the purple line ($\mathcal{R} \leq 0.01$). These new constraints all exist in the region where the decay of loops is dominated by their energy loss into EM radiation. Constraints of this analysis from 21 cm in the gravitational wave regime are plotted here in magenta, blue, and green, but they do not constrain any regions which haven't been constrained previously.

of parameter space where gravitational radiation dominates over electromagnetic radiation, the effective cutoff radius is $\gamma G\mu t$. However, for large currents in which electromagnetic radiation dominates the cutoff radius is larger, and hence the pulsar timing constraints on $G\mu$ are weaker. The analysis of [59] has shown that the pulsar timing constraint essentially disappears for $I > I_c$. In this region, our constraints rule out a large parameter space of strings with large currents.

Before concluding, it is prudent to mention some limitations of our analysis. First, we have remained agnostic to the details of the symmetry breaking scheme that forms these strings. This was done to remain as general as possible, though in doing so we have neglected to describe the best way to generate steady currents on a distribution of loops. The motion of superconducting strings through the universe will naturally produce a range of currents within the loop distribution, as the inhomogeneity of small scale magnetic fields induces different current magnitudes. Future work should consider a distribution of such currents.

As well, it has been shown that the production of low frequency photons off of cosmic string cusps will accelerate particles in the ISM and IGM to very high Lorentz factors [33–35]. This can cause a hydrodynamical flow of gas in the vicinity of a string, which is often terminated by a shock. This shock could lead to a gamma ray burst, of which it is unclear how physics at reionization could be effected. This mechanism is very difficult to track analytically, and so a more numerical approach would be beneficial in elucidating the consequences of this effect.

There have been other constraints on superconducting cosmic strings. For example, the electromagnetic radiation from string loops can locally reionize matter, and thus change the optical depth which has been measured with great accuracy by the recent CMB experiments (see e.g. [60]). The resulting constraints on the parameter space of superconducting strings has been studied in [61] and [59]. In addition, the electromagnetic radiation can lead to CMB spectral distortions, providing still further constraints. Comparing our results of figure 1 with the results of the analysis in [59], which summarizes the constraints mentioned above (see in particular the figure 8 in [59]), we see that our analysis rules out an additional region of parameter space; a region which is particularly interesting for large values of the current.

Non-superconducting cosmic strings can provide nonlinear seeds at high redshifts, which could help explain the abundance of super-massive black holes [62]. They could also play a role in the formation of globular clusters [63, 64]. It would be interesting to study to what extent currents on superconducting strings would change those results.

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