Cosmic string loops as the seeds of super-massive black holes

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Abstract. Recent discoveries of super-massive black holes at high redshifts indicate a possible tension with the standard ΛCDM paradigm of early universe cosmology which has difficulties in explaining the origin of the required nonlinear compact seeds which trigger the formation of these super-massive black holes. Here we show that cosmic string loops which result from a scaling solution of strings formed during a phase transition in the very early universe lead to an additional source of compact seeds. The number density of string-induced seeds dominates at high redshifts and can help trigger the formation of the observed super-massive black holes.

Keywords: Cosmic strings, domain walls, monopoles, massive black holes

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1 Introduction

Super-massive black holes (SMBH) are among the most mysterious objects in the Universe. Black holes are called “super-massive” if their mass exceeds $10^6 M_\odot$, where $M_\odot$ denotes the solar mass. It is now believed that each galaxy harbors at least one super-massive black hole. The black hole nature of the massive object at the center of our Milky Way galaxy has now been established without much doubt by the precision observations of stellar orbits about it (see e.g. [1]). The ultra-luminous quasars and active galactic nuclei observed in other galaxies are believed to harbor black holes (see e.g. [2, 3] for recent reviews).

The origin of super-massive black holes is still somewhat of a mystery. It is believed (see [2]) that they result from accretion of gas about massive seed objects. Three candidate seed types are Population III stars with mass in the range $10^2 M_\odot$–$10^3 M_\odot$, dense matter clouds with mass between $10^3 M_\odot$ and $10^6 M_\odot$, or compact objects of mass between $10^2 M_\odot$ and $10^4 M_\odot$ formed by the collision of old stellar clusters.

However, we must now explain the origin of the purported seeds of the super-massive black holes. The recent observations of SMBHs of larger masses and higher redshifts are leading to an increasing tension with the standard paradigm of early universe cosmology according to which the spectrum of primordial cosmological fluctuations is approximately Gaussian with an almost scale-invariant spectrum with a small red tilt. In the context of this model nonlinearities form only at late times and there is not enough time to produce the nonlinear massive seeds which are required to seed SMBHs of mass greater or equal to $10^9 M_\odot$ at redshifts of 6 or higher (of which roughly 40 have been discovered [4–11]). In particular, the recently discovered black hole with mass $1.2 \times 10^{10} M_\odot$ at redshift $z = 6.30$ [12] is hard to explain in the context of the standard paradigm.

Here we discuss the possibility that the compact seeds which are required to be present at high redshifts are provided by cosmic string loops. String loops are nonlinear seed masses which are present at arbitrarily early times and which by gravitational accretion can seed the objects which develop into SMBHs.

In the following we first give a very brief review of the connection between cosmic strings and early universe cosmology. We then compare the number densities of nonlinear seeds in the vanilla $\Lambda$CDM cosmology with what is obtained when allowing for the presence of a scaling distribution of cosmic strings. We find that whereas the probability of finding a seed in the range of Population III stars in the vanilla $\Lambda$CDM model is too low to explain

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the presence of SMBHs of the mass and redshift recently discovered [4–12], the presence of cosmic strings easily solves this problem as long as the mass per unit length $\mu$ of the strings obeys the inequality $G\mu > 10^{-14}$. Here, $G$ is Newton’s gravitational constant and where we are using natural units with $c = 1$. We recover the appropriate powers of $c$ when computing dimensionful observable quantities.

2 Cosmic string review

Cosmic strings are linear topological defects which are predicted in a large class of particle physics models beyond the Standard Model (see [13–15] for reviews on cosmic strings). In particular, cosmic strings are predicted to form after inflation in many inflationary models, both models formulated in the context of superstring theory [16] and in models based on supergravity [17, 18]. As first realized by Kibble [19, 20], causality arguments tell us that if Nature is described by a particle physics model which admits cosmic string solutions, then a network of cosmic strings will inevitably form in the early universe and persist to the present time. The distribution of cosmic strings consists of a network of infinite strings and a set of string loops. Analytical arguments tell us that the distribution of cosmic strings will approach a “scaling distribution” in which $\xi(t)$, the mean curvature radius and separation of the long string network, will be of the order of the Hubble radius $t$. The non-trivial dynamics of the long string segments will lead to continuous loop production, and the distribution of loops will also take on a scaling solution in which the number density $n(R,t)$ of loops per unit radius $R$ is independent of time when $R$ is scaled to the Hubble radius $t$.

We will assume a simplified version of the cosmic string loop scaling distribution according to which all loops formed at time $t$ have the same radius $R_f(t)$,

$$R_f(t) = \frac{\alpha}{\beta^t}, \quad (2.1)$$

where $\beta$ is the mean ratio of circumference to radius of a loop (we will use the value $\beta = 10$), and $\alpha$ is a constant whose value we shall take to be $\alpha \sim 0.1$. Loops are formed continuously in time. Note that whereas the value of $\beta$ has little uncertainty, the value of $\alpha$ depends on details of the implementation of cosmic string evolution simulations, and there is a large range of possible values. We have taken a representative value from the most recent cosmic string evolution simulations.

After formation, the number density of loops redshifts due to the cosmic expansion. Loops also slowly decay by emitting gravitational radiation [27, 28], and this gives an effective lower cutoff for the range of string loop radii at any given time. However, the string loops whose mean separation is comparable in comoving coordinates to the separation $d_{\text{gal}}$ of galaxies have a radius larger than the gravitational radiation cutoff. They are also formed before the time $t_{\text{eq}}$ of equal matter and radiation (the reader is invited the check these statements). For such loops the number density per unit radius is given by

$$n(R,t) = N \alpha^{5/2} \beta^{-5/2} t^{1/2} t_{\text{eq}}^{-2} R^{-5/2}, \quad (2.2)$$

where the number $N$ is determined by the number of long string segments per Hubble volume. Inserting for $t$ the present time $t_0$ gives the comoving number density of these loops.

The trapped energy in cosmic strings leads to unique signals in cosmology. Long string segments produce a conical discontinuity in space which leads to lensing signals in CMB temperature maps [29], and to planar overdensities (called “wakes”) [30–33] in the plane
behind the moving strings which in turn lead to direct B-mode polarization signals [34] and to wedges of extra absorption in 21cm redshift maps [35] (see [36] for an overview of these effects).

String loops, on the other hand, accrete matter in a similar way as a point mass (as long as distances large compared to the loop radius are considered). It was at one point [37–39] postulated that cosmic string loops might be the seeds of galaxies and galaxy clusters, without the need for Gaussian fluctuations such as provided by inflation or its alternatives. However, cosmic strings forming during a phase transition in the early universe produce isocurvature fluctuations and hence do not lead to coherent curvature perturbations on super-Hubble scales, and hence do not generate acoustic oscillations in the angular power spectrum of cosmic microwave anisotropies. The discovery of these oscillations [40] demonstrated that the main source of fluctuations cannot be due to cosmic strings. The most reliable limit on the cosmic string tension in fact comes from detailed analyses of the CMB angular power spectrum and yields [41, 42] (see also [43–51])

\[ G\mu < 1.5 \times 10^{-7} . \] (2.3)

String loops, however, may still play an important role in cosmology. In a recent paper [52] we postulated that string loops may seed globular clusters. Here we will study their role as possible seeds for SMBHs.

In the following we first review the mechanism by which compact seeds can lead to SMBHs. Then we compute the expected distribution of seeds as a function of mass and redshift in the ΛCDM model and show that the number of seeds of mass required to explain the most massive high redshift SMBHs is too low. In the third subsection we then compute the number density of seeds induced by cosmic string loops and show that the string models can easily make up the deficit of seeds for reasonable values of the tension \( \mu \).

3 Analysis

3.1 Eddington accretion

A compact seed evolves into a SMBH by accreting gas at a rate that is proportional to its bolometric luminosity. In this way, an initial seed mass \( M_i \) grows into a final mass \( M_f \) according to the equation

\[ M_f = M_i \exp \left( \frac{1 - \epsilon}{\epsilon} \frac{\Delta t}{t_\ast} \lambda \right) , \] (3.1)

where \( \Delta t \) is the time interval during which accretion takes place, \( t_\ast = 4.5 \times 10^8 \) yrs is the Eddington time, \( \lambda \) is the ratio of the bolometric luminosity to the Eddington luminosity [53], and \( \epsilon \) is the efficiency of radiative emission which typically depends on the black-hole spin, and we shall take \( \epsilon = 0.1 \) (see [54–56]). Expressing time in terms of redshift this equation can be re-written as

\[ M(z_i) = M(z) \exp \left[ - \frac{1 - \epsilon t_0}{\epsilon} \frac{1}{(1 + z)^{3/2}} \left( \frac{1}{(1 + z_i)^{3/2}} \right) \lambda \right] , \] (3.2)

where \( M(z_i) \) is the initial seed mass at redshift \( z_i \) and \( M(z) \) is the mass at the final redshift \( z \).

Figure 1 shows the seed mass \( M(z_i) \) required to form a SMBH at final redshift \( z = 6.3 \) (the redshift of the recently discovered object) and for final SMBH masses of \( M(z) = 1.2 \times 10^{10} M_\odot \) (the estimated mass of the discovered object), \( M(z) = 10^9 M_\odot \) and \( M(z) = 10^8 M_\odot \).
assuming $\lambda = 1$. The horizontal axis is $z_i$ and the vertical axis is the mass. The two dashed horizontal lines at $M = 10^2 M_\odot$ and $M = 10^3 M_\odot$ give the mass range of the postulated Population III star seeds. The graph shows that seeds in this mass range had to have been present at redshift of greater than 40 in order to grow into the recently observed SMBH with mass of $1.2 \times 10^{10} M_\odot$. The seeds for $10^9 M_\odot$ objects needed to have been present in the required number density by redshift of $z = 20$. As we will show in the next subsection, we do not expect the $\Lambda$CDM model to yield any nonlinear objects of the required masses at these high redshifts. The initial redshift at which the larger seed masses postulated for the two other conventional sources of SMBH formation needed to have been present is smaller, but since the mass is larger, this does not necessarily make them easier to produce in the standard paradigm of early universe cosmology, as we will see in the following subsection.

The assumption that $\lambda = 1$ implies that SMBHs accrete mass at the Eddington rate. If the accretion process were sub-Eddington, it would force the seeds to have been present at even higher redshifts and thus increase the tension with $\Lambda$CDM. For simplicity, we consider Eddington accretion as a limiting case, keeping in mind that more massive seeds may be required at even higher redshifts. Obviously, if the accretion were super-Eddington, the tension with the standard cosmological model would be less (see [57]). For studies trying to constrain $\lambda$, see e.g. [58–60].

### 3.2 Density of seeds in the $\Lambda$CDM model

For Gaussian fluctuations, it is exponentially unlikely to obtain a nonlinear fluctuation of mass $m$ if the root mean square value of the dimensionless density power spectrum $\sigma(m)$ is smaller than 1. More precisely, the mass function $n(m, z)$ at redshift $z$ is given by (see e.g. [61])

$$n(m, z)m = \rho m^{-1} \left[ \frac{d \log m}{d \log \nu} \right]^{-1} \nu f(\nu),$$

(3.3)
where $\rho$ is the background density and $\nu$ is the excess over the r.m.s. value required to form a nonlinear object, i.e.
\[ \nu \equiv \left( \frac{\delta_c(z)}{\sigma(m)} \right)^2. \tag{3.4} \]
The number $\delta_c(z)$ and its redshift dependence depend slightly on the background cosmology. For our analysis we will take the value $\delta_c = 1.7$ (independent of redshift) \[61\]. This corresponds to neglecting the effects of dark energy. This is a good approximation for our problem where we are interested in high redshifts where dark energy does not have an important effect. For the function $f(\nu)$ we will use the Press-Schechter \[62\] form
\[ \nu f(\nu) = \left( \frac{\nu}{2} \right)^{1/2} \frac{1}{\sqrt{\pi}} e^{-\nu/2}. \tag{3.5} \]
We are interested in mass ranges for which the corresponding wavelength is smaller than the Hubble radius at $t_{eq}$ and which are hence in the region where the power spectrum increases only logarithmically as $m^{-1}$. Specifically, we make the ansatz
\[ \sigma^2(m) = A \log(m_c/m)(1 + z)^{-2}, \tag{3.6} \]
where the last factor is the linear perturbation theory growth of the amplitude of the power spectrum. If we choose $m_c$ to be the mass scale where $\sigma(m) = 1$ today then we can set $A = 1$.

Inserting (3.6), (3.5), and (3.4) into the expression (3.3) for the mass function, we can determine the mass $M_s(z)$ of seeds which have the comoving separation of galaxies at redshift $z$. This amounts to solving the equation
\[ d_{gal}^3 n(m, z)m = 1 \tag{3.7} \]
for the mass $m$, where $d_{gal}$ is the comoving separation of galaxies. We take $d_{gal} = 1$ Mpc independent of redshift, but a more sophisticated analysis could introduce some redshift dependence, although this may no be well-constrained at high redshifts. We find the following transcendental equation from eq. (3.7),
\[ 1 = d_{gal}^3 \rho \delta_c \left( \frac{1}{2\pi} \right)^{1/2} (z + 1) \frac{1}{\log^{3/2}(m_c/m)} m^{-1} \exp \left[ -\frac{(z + 1)^2 \delta_c^2}{2 \log(m_c/m)} \right]. \tag{3.8} \]
Solving for $m$, the resulting function $M_s(z)$ is plotted in figure 2. Note the exponential decrease of the seed mass at high redshifts. This implies that the Gaussian fluctuations in the standard $\Lambda$CDM model have trouble explaining the origins of the massive compact seeds which are required to explain the formation of the highest redshift and most massive observed SMBHs. At redshifts of 20 and higher, the mass of the predicted seeds with the number density of galaxies is smaller than $10^2 M_\odot$. In the following subsection we find that cosmic string loops can come to the rescue.

### 3.3 Density of seeds induced by cosmic string loops

Here we compute the number density of string-induced compact seeds. In the range of loop radius $R$ which we are interested in the loops are already present at $t_{eq}$. Taking the linear perturbation theory growth in mass, the mass of the nonlinear seed produced by a loop of radius $R$ at redshift $z$ is
\[ M(R, z) = \frac{z_{eq} + 1}{z + 1} \beta \mu R, \tag{3.9} \]
where \( z_{eq} \) is the redshift at \( t_{eq} \). Taking into account the Jacobian of the transformation between \( R \) and \( M \), the resulting seed mass function is

\[
n(M, z) = N \beta^{-1} \alpha^{5/2} \left( \frac{z_{eq} + 1}{z + 1} \right)^{3/2} t_{eq}^{1/2} t_0^{-2} \mu^{3/2} M^{-3/2},
\]

where \( n(M, z) M \) gives the number density in comoving coordinates of seeds with mass in the range \([M, 2M]\).

We can now compute the mass \( M_s(z) \) at redshift \( z \) of seeds with a mean separation of \( d_{\text{gal}} \). This is determined by

\[
n(M_s, z) M_s d_{\text{gal}}^3 = 1,
\]

and yields

\[
M_s(z) = N^{2/3} \beta^{-2/3} \mu^{-1/2} G t_0 \left( \frac{d_{\text{gal}}}{t_0} \right)^2 \left( z_{eq} + 1 \right)^{2/3} z + 1.
\]

The only dimensionful number which enters the above expression is \( t_0/G \simeq 10^{23} M_\odot \).

In figure 3 we plot the mass \( M_s(z_i) \) (vertical axis) of seeds which have the mean comoving separation of galaxies as a function of the initial redshift \( z_i \) (horizontal axis) for four values of the dimensionless string tension \( G\mu \). Comparing with the curves in figure 1, we see that for the values \( G\mu = 10^{-7} \) (which is just below the current upper bound on \( G\mu \) from CMB data), and \( G\mu = 10^{-9.5} \) (for which string loops can explain the origin of globular clusters [52]) the seed masses present in the correct number density exceed at redshifts of 20 or higher the mass of Population III stars, and hence for these values of \( G\mu \) there are more than enough seeds to develop into SMBHs. Demanding that string loops provide the right number density of seeds of mass \( 10^3 M_\odot \) and \( 10^2 M_\odot \) leads to values of \( G\mu \) of \( 10^{-12} \) and \( 10^{-13} \), respectively. The seed masses for these values of \( G\mu \) are also shown in figure 3.

Comparing with the results of figure 1, we see that a seed mass of about \( 10^3 M_\odot \) is required to be present at redshift 40 to explain the recently discovered SMBH. We see that for values of \( G\mu > 10^{-12} \) there will be a sufficient number of such seeds present. The less stringent
requirements of having $10^3 M_\odot$ or $10^2 M_\odot$ seeds present at redshift of 20 (which will explain $10^9 M_\odot$ and $10^8 M_\odot$ SMBH masses at redshifts of about 6) are satisfied if $G\mu > 2 \times 10^{-13}$ and $G\mu > 2 \times 10^{14}$, respectively.

Figure 4 is an overlay of the results of figures 2 and 3, namely the mass of seeds separated by a mean galactic distance, taking into account both seeds formed from Gaussian fluctuations and from string loops. As expected, the string loops dominate at high redshift. The crossover redshift depends on $G\mu$. For the entire range of values of $G\mu$ which are of interest to us ($10^{-13} < G\mu < 10^{-7}$) the string loops dominate the seed distribution at redshifts of 20 and higher.

4 Conclusions

The discovery of super-massive black holes at redshifts greater than $z = 6$ and with masses greater than $10^9 M_\odot$ is challenging to explain in the context of a pure ΛCDM cosmology since the number density of the required seeds is not predicted to be high enough (unless super-Eddington accretion is invoked). In this note we have suggested that cosmic string loops might be the seeds about which super-massive black holes form. Cosmic string loops lead to massive compact objects already at high redshift, and can thus provide the massive seeds at high redshifts which are missing in the vanilla ΛCDM model. We have computed the masses of seeds with the correct number density to explain the origin of one SMBH per galaxy both with and without cosmic strings. We note that the one SMBH per galaxy condition is more stringent then necessary since not all galaxies need to host a SMBH at high $z$ to host one today [63]. Still, we find that even cosmic strings with a tension significantly lower than the current upper bound can provide enough seeds at early times.

We are thus postulating that cosmic string loops can play the role which Population III stars or dense early gas clouds are thought to play in the current SMBH formation scenarios [2]. Cosmic string loops lead to compact nonlinear structures with falling rotation curves.
This makes string loops appealing seed candidates for the formation of SMBH. A possible problem, however, is that the gravitational potential may not be deep enough to allow the cooling and star formation [64] required to obtain the compactness needed to get an actual black hole.

In the absence of knowing the exact mechanism by which the seed object leads to the formation of a SMBH, and without more information about the statistics of SMBH, we cannot give a precise value for the string tension $G\mu$ for which our mechanism works best. At the end of section 3 we have given some representative values. They all lie comfortably below the upper bound from current observations.

We do not claim that our cosmic string loop model is the only way to supplement the standard cosmological paradigm in order to provide a way to obtain large mass high redshift SMBHs. Another example is the recent suggestion [65] that a small fraction of the dark matter is ultra-strongly interacting and can undergo gravothermal collapse at early times, leading to compact seeds.

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Figure 4. Mass $M_s(z_i)$ of seeds from both Gaussian fluctuations and from cosmic string loops. It is evident that the cosmic strings dominate the seed distribution at high redshifts. The units of mass on the vertical axis are in $M_\odot$. 
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