**MERGING RATES OF THE FIRST OBJECTS AND FORMATION OF THE FIRST MINI-FILAMENTS IN MODELS WITH MASSIVE NEUTRINOS**

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**ABSTRACT**

We study the effect of massive neutrinos on the formation and evolution of the first filaments containing the first star-forming halos of mass $M \sim 10^6 M_\odot$ at $z \sim 20$. With the help of the extended Press–Schecter formalism, we evaluate analytically the merging rates of the first star-forming halos into zero-dimensional larger halos and one-dimensional first filaments. It is shown that as the neutrino mass fraction $f_\nu$ increases, the halo-to-filament merging rate increases while the halo-to-halo merging decreases sharply. For $f_\nu \ll 0.04$, the halo-to-filament merging rate is negligibly low at all filament mass scales, while for $f_\nu \geq 0.07$ it exceeds 0.1 at the characteristic filament mass scale of $\sim 10^9 M_\odot$. The distribution of the redshifts at which the first filaments ultimately collapse along their longest axes is derived and found to have a sharp maximum at $z \sim 8$. We also investigate the formation and evolution of second-generation filaments which contain the first galaxies of mass $10^9 M_\odot$ at $z = 8$. A similar trend is found: for $f_\nu \geq 0.07$ the rate of clustering of the first galaxies into second-generation filaments exceeds 0.3 at the characteristic mass scale of $\sim 10^{11} M_\odot$. The longest-axis collapse of these second-generation filaments is found to occur at $z \sim 3$. The implications of our results on the formation of massive high-$z$ galaxies and the early metal enrichment of the intergalactic medium by supernova-driven outflows, and the possibility of constraining the neutrino mass from the mass distribution of the high-$z$ central black holes, are discussed.

**Key words:** cosmology: theory – large-scale structure of universe

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1. INTRODUCTION

In 1970, Zel’dovich suggested that the large-scale structure of the universe such as sheets and filaments forms through the anisotropic collapse of large-scale density fluctuations along the principal axes of gravitational tidal fields (Zel’dovich 1970). Although his original model assumed a hot dark matter cosmology, this picture can be easily accommodated even by the currently popular Λ-dominated cold dark matter (ΛCDM) cosmology (Bond et al. 1996). The dark matter halos that first condense out on the smallest scales merge anisotropically along the principal axes of the tidal fields into larger and larger structures. The inherent anisotropic nature of the gravitational merging process leads to the formation of filament-like and sheet-like structures, as envisaged by Zel’dovich’s model. The nonlinear evolution of the tidal shear fields sharpens the anisotropic interconnection of the large-scale structure (which is often called the cosmic web), developing a hierarchical system where small filaments are threaded with the larger parent filaments (e.g., Springel et al. 2005). To understand the formation and evolution of the large-scale structure, an important question to answer is how frequently the halos merge into filaments and under what circumstances the halo-to-filament merging event occurs efficiently.

Lacey & Cole (1993, 1994), for the first time, evaluated analytically the merging rates of bound halos by extending the original Press–Schecter formalism (Press & Schechter 1974). Their analytic work was later refined and complemented by numerical calculation of merger trees from N-body simulations (Somerville et al. 2000). Recently, Fakhouri & Ma (2008) constructed merger trees from the large Millennium Run halo catalogs (Springel et al. 2005) and found that the mean merging rate per halo can be well modeled by a nearly universal fitting formula. In addition, Fakhouri & Ma (2008) showed that the prediction of the extended Press–Schecter formalism for the halo merging rates disagrees with the numerical results from the Millennium Run halo catalog by up to a factor of a few.

The halo-to-halo merging rates were originally derived under the assumption that the merging events occur in a hierarchical way. If the matter content of the universe were composed purely of CDM particles, then the structure formation would proceed in a strictly hierarchical way. However, if non-CDM particles (either warm or hot) coexisted with CDM particles, the pure hierarchy in the build-up of the large-scale structure would break down at some level, depending on the particles’ mass fraction (Yoshida et al. 2003). Although current observations put a tight constraint on the amount of possible non-CDM particles, they have not been completely excluded. In fact, the existence of non-CDM particles has been suggested as one possible solution to alleviate the apparent mismatches between observations and the predictions of ΛCDM cosmology on subgalactic scales (see Boyanovsky et al. 2008; Kuzio de Naray et al. 2010; de Vega & Sanchez 2010 for a recent discussion).

Among the various candidates for the non-CDM particles, massive neutrinos have so far attracted the most serious attention. Ever since it was discovered that at least one flavor of neutrino must be massive and that the neutrino masses would be best constrained from the astronomical data (see Lesgourgues & Pastor 2006 for a review), a flurry of research has been conducted to quantify the effect of massive neutrinos on the formation and evolution of the large-scale structure (e.g., Bond et al. 1980; Doroshkevich et al. 1981; Hu 1998; Hu & Eisenstein 1998; Valdarnini et al. 1998; Eisenstein & Hu 1999; Lewis & Challinor 2002; Seljak et al. 2006; Tegmark et al. 2006; Saito et al. 2009; Shoji & Komatsu 2010). In previous studies of structure formation in a ΛCDM (Λ+CDM+massive neutrinos)
universe, the main focus has been the suppression of the small-scale powers in the density power spectrum due to massive neutrino free streaming and its effect on the structure formation.

Since the massive neutrinos would decrease the merging rates of the small-scale halos due to their free streaming, one might naively think that the formation of large-scale structures would be deferred in a AMDM universe. The recent discovery of high-$z$ quasars at $z \geq 6$ (Fan et al. 2001, 2004, 2006; Fan 2003; Jiang et al. 2009; Willott et al. 2009, 2010) has suggested that the first galaxies of mass $\geq 10^8 M_{\odot}$ must have formed at redshifts $z \geq 8$. At first glance the existence of such massive first galaxies at such early epochs might appear difficult to reconcile with a AMDM model. Even in a ΛCDM cosmology, it is not so easy to explain the existence of the high-$z$ quasars since this requires very high merging/accretion rates in the early universe.

However, what has not been noted in previous works is that the presence of massive neutrinos may actually open a new channel for rapid structure formation. Since the massive neutrinos would behave as effective warm dark matter particles, they would fasten the collapse of matter along the major axes of the gravitational tidal fields on large scales. In other words, while the free streaming of massive neutrinos slows down the formation of zero-dimensional bound halos on small scales, it speeds up the formation of one-dimensional filaments on larger scales. The filaments are the most optimal environments for the rapid accretion of gas and matter. Furthermore, when the filaments collapse along their longest axes, they would provoke the violent merging of the constituent halos.

Here, assuming a AMDM universe, we study how the first filaments form through clustering of the first star-forming halos and how they evolve after the longest-axis collapse. The ideal approach for the study of the first filaments would be to use high-resolution $N$-body simulations for a AMDM universe. But it is still a daunting task to implement the dynamics of massive neutrinos into current $N$-body simulations. Instead, we choose an analytic approach based on the extended Press–Schechter formalism (Press & Schechter 1974; Lacey & Cole 1993) for this study. Throughout this paper, we assume flat AMDM models where the neutrinos have mass and three species, $N_{\nu} = 3$. The key cosmological parameters are set at $\Omega_m = 0.266$, $\Omega_{\Lambda} = 0.734$, $\Omega_b = 0.0449$, $\sigma_8 = 0.801$ (for the ΛCDM part), $h = 0.710$, and $n_s = 0.963$, to be consistent with WMAP7 results (Komatsu et al. 2011).

The outline of this paper is as follows. In Section 2, we derive analytically the merging rates of the first star-forming halos into the first filaments and determine their characteristic mass scales. In Section 3.1, we evaluate the epochs of the longest-axis collapse of the first filaments and the merging rates of the first galaxies into second-generation filaments and determine their characteristic mass scales. In Section 4, we explore the possibility of constraining the neutrino mass from the observable mass distribution of high-$z$ supermassive black holes. In Section 5, the results are summarized and a final conclusion is drawn.

2. FORMATION OF THE FIRST FILAMENTS

Recent observations indicate that the first galaxies must have formed in halos of mass $10^8 - 10^9 M_{\odot}$ at redshifts $z \approx 9 - 10$ (e.g., Willott et al. 2009, 2010). What has been inferred from current high-resolution hydrodynamic simulations is that these first galaxies may have formed through rapid merging of the first star-forming mini-halos of mass $10^8 M_{\odot}$ at $z \geq 20$ (Bromm et al. 2009 and references therein). In this section, we investigate how the presence of massive neutrinos would change the evolution channel of the first star-forming halos.

2.1. Variation of Halo-to-halo Merging Rate with Neutrino Mass

In the extended Press–Schechter theory developed by Lacey & Cole (1993, 1994), the key quantity is the conditional probability, $f(M', z'|M, z)$, that a halo of mass $M$ existing at a given redshift $z$ will merge to form a more massive halo of mass $M' (> M)$ at some lower redshift $z' (< z)$. Adopting the spherical collapse condition that a halo of mass $M$ forms at $z$ when its linear density contrast $\delta$ on the mass scale $M$ reaches a redshift-dependent threshold $\delta_c / D(z)$ where $\delta_c \approx 1.68$ and $D(z)$ is the linear growth factor, Lacey & Cole (1993) equated this key conditional probability to the differential fraction of the volume in the linear density field occupied by regions satisfying $\delta' \geq \delta_c / D(z')$ on the mass scale $M'$ at $z'$ provided that it also satisfies the condition $\delta = \delta_c / D(z)$ on the mass scale $M$ at an earlier epoch $z$.

This key conditional probability $f(M', z'|M, z) dM'$ can now be written as

$$f(S', \omega'|S, \omega) dS' = 2 \frac{d}{dS'} \int_{\omega'}^{\infty} p(\delta_M' \geq \omega'|\delta_M = \omega) d\delta_M' dS'$$

$$= \frac{1}{\sqrt{2\pi}} \int_{S'(S - S')} S' \left( \frac{\omega'(\omega - \omega')}{\omega} \right)$$

$$\times \exp \left[ -\frac{(\omega' - \omega)}{2} \right] dS',$$  \tag{1}

where $f(M', z'|M, z) dM' = f(S', \omega'|S, \omega) dS'$ with $S' \equiv \sigma^2(M')$, $\omega' \equiv \delta_c(z')$, and $S' \equiv \sigma^2(M')$, and $\omega' \equiv \delta_c(z')$. Here $\sigma(M)$ and $\sigma(M')$ are the rms fluctuation of the linear density field smoothed on the mass scale $M$ and $M'$, respectively. Normalization of $\sigma$ is done for the AMDM linear power spectrum to be identical to the ΛCDM linear power spectrum at large scale. Here, of course, with the normalized ΛCDM linear power spectrum, the value of $\sigma$ at $8 h^{-1} \text{Mpc}$ is that of $\sigma_8$ given by WMAP7.

Using Equation (1), Lacey & Cole (1993) calculated the (instantaneous) merging rate of a dark halo with mass $M$ at a given redshift $z$ into a larger halo with mass $M'$ by taking the derivative of $f(S', \omega'|S, \omega)$ with respect to $z'$:

$$\frac{d^2 p(M \to M'|z)}{d\ln M dz} = - \frac{dS'}{d\ln M} \frac{d\omega'}{dz'} \frac{d}{dz'} f(S', \omega'|S, \omega)|_{z'=z}$$

$$= - \frac{\Delta M}{M^2} \bar{\rho} P_L(k) \frac{d\omega}{dz} \frac{1}{\sqrt{2\pi}} \left[ \frac{S}{S'(S - S')} \right]^{3/2}$$

$$\times \exp \left[ -\frac{\omega^2}{2} \left( \frac{1}{S'} - \frac{1}{S} \right) \right],$$  \tag{2}

where $\Delta M \equiv M' - M$ and $P_L(k)$ is the linear density power spectrum for a AMDM cosmology. We use the analytic approximation given by Hu & Eisenstein (1998) for the evaluation of $P_L(k)$.

With the help of the above analytic prescriptions, we determine the effect of massive neutrinos on the merging rate
of the first star-forming mini-halos of mass $M = 10^6 \, M_\odot$ at redshift $z = 20$ for five different values of the neutrino mass fraction: $f_\nu = 0.13, 0.10, 0.07, 0.04,$ and 0.0 (solid, dotted, dashed, dot-dashed, and dot-dot-dashed, respectively).

Adopting this condition for the formation of filaments, we modify the Lacey–Cole formalism to determine the halo-to-filament merging rates. In this modified formalism, the key quantity is the conditional probability, $f(M'\to M, z)$, that a halo of mass $M$ observed at $z$ will merge into a filament of mass $M'$ at redshift $z'$. We equate this conditional probability to the differential volume fraction occupied by the regions satisfying the filament-formation condition, $\lambda_1' > \lambda_2' > \lambda_3'/D(z')$, $\lambda_2' < \lambda_1'/D(z)$ on the mass scale $M'$ at redshift $z'$ provided that the linear density contrast of the same regions, $\delta$, on the smaller mass scale $M$ at an earlier epoch $z$ satisfies the spherical collapse condition $\delta = \delta_c/D(z)$. Here $\delta$ equals the sum of the three eigenvalues of the deformation tensor smoothed on the mass scale $M$.

Now, this key conditional probability can be expressed as

$$f(S', \eta'|S, \omega) \, dS' = \frac{2}{dS} \frac{d}{d\omega} p(\lambda_1', \lambda_2', \lambda_3'|\omega) \, dS',$$

Equation (4), with $\eta' \equiv \lambda_c/D(z')$. To evaluate $f(S', \eta'|S, \omega) \, dS'$ in Equation (4), we require the joint conditional probability distribution $p(\lambda_1, \lambda_2, \lambda_3|\delta)$, which has been already derived by Lee (2006) from the original work of Doroshkevich (1970) as

$$p(\lambda_1', \lambda_2', \lambda_3'|\delta) = \frac{p(\lambda_1', \lambda_2', \lambda_3', \delta)}{p(\delta)} = \frac{3375}{8\sqrt{5\pi}} \frac{\sigma}{\sigma_d \sigma_f} \frac{\sigma'}{\sigma'} \left( I_1' - I_2' \right) \left( I_2' - I_3' \right) \left( I_3' - I_1' \right),$$

where $\sigma \equiv \sigma(M), \sigma' \equiv \sigma(M'), \sigma_d \equiv \sqrt{\sigma^2 - \sigma'^2}, I_1' \equiv \lambda_1' + \lambda_2' + \lambda_3', I_2' \equiv \lambda_1' \lambda_2' + \lambda_2' \lambda_3' + \lambda_3' \lambda_1'$.

It is now straightforward to calculate the (instantaneous) merging rate of the first star-forming halos of mass $M = 10^6 \, M_\odot$ at $z = 20$ into the early mini-filaments of mass $M'$ as

$$\frac{d^2 P(M \to M'|z)}{dz'^2} \, dS' = -\frac{\Delta M}{M'^2} \frac{d}{dz'} f(S', \eta'|S, \omega) \bigg|_{z' = z_2}.$$
To prevent mathematical divergence, the mass of a final halo is set at $0.99 M_F$.

3. EVOLUTION OF THE FIRST FILAMENTS

3.1. Longest-axis Collapse of the First Filaments

In the previous section, it was shown that the first star-forming mini-halos would merge rapidly into the first filament of characteristic mass $\sim 10^9 M_\odot$ in the presence of massive neutrinos. As the universe evolved, these first filaments would ultimately collapse along their longest axes, which are in the direction of the minor principal axes of the local tidal field. To determine the distribution of the redshift $z_f$ when the first filaments collapse along their longest axes, we calculate the conditional probability density that a region satisfying the filament-formation condition $(\lambda_1 \geq \eta, \lambda_3 = \eta, \lambda_3 < \eta)$ at $z = 20$ on the mass scale $M_F$ will meet the halo-formation condition $(\delta = \omega)$ at the same mass scale $1$ but at some lower redshift, $z_f < 20$:

$$p(\delta' = \omega' | \lambda_1 \geq \eta, \lambda_2 = \eta, \lambda_3 < \eta) = \frac{\int_{-\infty}^{\eta} d\lambda_3 \int_{-\infty}^{\infty} d\lambda_1 p(\delta' = \omega', \lambda_1, \lambda_2 = \eta, \lambda_3)}{\int_{-\infty}^{\infty} d\lambda_3 \int_{-\infty}^{\infty} d\lambda_1 p(\lambda_1, \lambda_2 = \eta, \lambda_3)},$$

(7)

where $\delta'$ is the linear density contrast on the mass scale $M_F$ at $z_f$, $\lambda_1$, $\lambda_2$, $\lambda_3$ are the three eigenvalues of the deformation tensor smoothed on the mass scale of $M_F$ at $z = 20$, $\omega' \equiv \delta' / D(z_f)$ and $\eta \equiv \lambda_3 / D(z)$. Using the joint probability density distribution of $p(\delta', \lambda_1, \lambda_2, \lambda_3)$ derived by Doroshkevich (1970) and Lee (2006), it is also straightforward to evaluate Equation (7).

Figure 3 plots this distribution $p(z_f)$ of the epochs of the longest-axis collapse of the first filaments for five different values of $f_\nu$. As can be seen, $p(z_f)$ has a maximum value at $z_f = 8-9$ for all five cases, which implies that the first filaments retain their structures for a long period from $z = 20$ to $z = 8-9$ without collapsing into zero-dimensional halos. As $f_\nu$ increases, however, the distribution $p(z_f)$ becomes narrower and its peak position moves slightly to a lower value of $z_f$. That is, the massive neutrinos play the role of delaying the longest-axis collapse of the first filaments.

3.2. Formation and Evolution of Second-generation Filaments

Since we find that the halo-to-filament merging rates increase with neutrino mass fraction, we would like to discover how the presence of massive neutrinos alters the merging rates of the first galaxies. It is naturally expected that some fraction of the first galaxies would also merge first in the filaments (called second-generation filaments). We can ask: what are the characteristic masses of the second-generation filaments, and when would they undergo the longest-axis collapse? To answer this question, we recalculate everything through Equations (1)–(7), but for the first galactic halos of mass $10^9 M_\odot$ at $z = 8$.

Figure 4 plots the halo-to-halo and halo-to-filament merging rates of the first galactic halos of mass $10^9 M_\odot$ at $z = 8$ as thin and thick lines, respectively. A similar trend to that shown in Figure 1 is found for the first galactic halos. As the neutrino mass fraction increases, the halo-to-halo merging rate decreases while the halo-to-filament merging rate increases. A comparison of Figures 1 and 4 also reveals that the halo-to-filament merging rates increase with redshift and with halo mass. For $f_\nu \geq 0.04$, the halos-in-filaments would be at an equilibrium.
the merging rate of the first galaxies into second-generation filaments exceeds 0.1 at all mass scales. The characteristic mass of the second-generation filaments is found to lie in the range $10^{11} < M/M_\odot < 10^{12}$.

Figure 5 plots the distribution of the redshifts at which the second-generation filaments of mass $10^{11} M_\odot$ formed at $z = 8$ experience the longest-axis collapse. A similar trend to that shown in Figure 3 is also found: $p(z_f)$ has a maximum value at $z_f = 3–4$ for all five cases, which implies that the second-generation filaments last from $z = 8$ to $z = 3–4$ without collapsing into zero-dimensional halos. The increase of $f_v$ results in a narrowing of the shape of $p(z_f)$ and a slight shift to the low-$z$ section. Note that these second-generation filaments correspond to filaments hosting galactic halos and are expected to be interconnected to larger-scale parent filaments of mass $\geq 10^{13}–10^{14} M_\odot$ (e.g., Springel et al. 2005). The massive galaxies formed through the longest-axis collapse of the second-generation filaments would grow through the anisotropic accretion of matter and gas along the larger-scale parent filaments in the cosmic web.

4. CONSTRAINING THE NEUTRINO MASS WITH FILAMENT ABUNDANCE

Once the first filaments form through the merging of the first star-forming halos at $z \lesssim 20$, the first stars comprising the first filaments would grow more rapidly as the accretion of matter and gas occur more efficiently along the bridges of the first filaments (Park & Lee 2009). When the latter collapse along their longest axes at $z \sim 8$, strong collisions between stars and gas particles in the filaments would result in seeding the supermassive black holes in the massive first galaxies that are believed to power ultraluminous high-$z$ quasars (Willott et al. 2010). In this scenario, the high-end slope of the mass distribution of the supermassive black holes inferred from the observable luminosity function of the ultraluminous high-$z$ quasars would reflect the mass distribution of the first filaments. Since this mass distribution depends sensitively on the mass of massive neutrinos, it might be possible to constrain the neutrino mass by comparing the mass distribution of the first filaments with that of the high-$z$ supermassive black holes.

The mass distribution function of the first filaments ($dN_f/dM$) at the epoch of longest-axis collapse ($z_f$) can be derived by employing the Press–Schechter approach (Press & Schechter 1974):

$$
\frac{dN_f(M, z_f)}{dM} = \frac{\bar{\rho}}{M} \left| \frac{d}{dM} F(M, z_f) \right|,
$$

where $\bar{\rho}$ is the mean mass density. Here, $F(M, z_f)$ represents the volume fraction occupied by the first filaments of mass larger than $M$ at $z_f$. Following the Press–Schechter approach, this volume fraction can be expressed as

$$
F(M, z_f) = A \frac{\rho_{0}}{M} \left| \frac{d}{dM} F(M, z_f) \right| ,
$$

where $A$ is the normalization factor, and $\lambda_{c}$ is the value of the $\lambda_{2}$ at the epoch of the longest-axis collapse. Since the first filaments formed at the threshold of $\lambda_{c} = 0.3$, the value of $\lambda_{2}$ increases gradually till they eventually collapse along their longest axes. It has been found that at the epoch of the longest-axis collapse, $\lambda_{2}$ reaches the critical value of $\lambda_{c} = 1.0$.

Using the joint distribution of $p(\lambda_{1}, \lambda_{2}, \lambda_{3})$ derived by Doroshkevich (1970), it is straightforward to evaluate Equation (8). Figure 6 plots the mass distribution of the first filaments in logarithmic scales at the epoch of the longest-axis collapse for five different values of the neutrino mass fraction, $f_{\nu}$. As we have already shown in Section 2 that the longest-axis collapse of the first filaments occurs around $z = 8$, we set $z_f$ at 8 for the evaluation of Equation (8). As can be seen, in the high-mass section ($M \geq 10^{9} h^{-1} M_\odot$), the abundance of first filaments decreases sharply with $M$ for all cases. The rate of decrease of the mass function of the first filaments, however, depends sensitively on the value of $f_{\nu}$: the larger the value of $f_{\nu}$, the more rapidly the mass function drops in the high-mass section.

To examine quantitatively how the rate of the decrease of the mass function of the first filaments in the high-mass section changes with $f_{\nu}$, we approximate it as a power law $M^{\alpha}$ and determine the value of the high-end slope, $\alpha$, in the mass range $10^{9} \lesssim M/(h^{-1} M_\odot) \lesssim 10^{12}$. Figure 7 plots the high-end slope, $\alpha$, of the mass distribution of the first filaments versus the neutrino mass fraction, $f_{\nu}$, as a solid line. As can be seen, the absolute value of the high-end slope of the mass function of the first filaments increases sharply as $f_{\nu}$ increases. This result suggests that the value of $f_{\nu}$ could be constrained by using the high-end slope of the mass function of the first filaments. In
practice, of course, it is not possible to measure this directly. As mentioned above, however, we can infer it from the observable high-\(z\) black hole mass function, under the assumption that the longest-axis collapse of the first filaments with mass larger than the characteristic mass \(\left(10^9 h^{-1} M_\odot\right)\) would result in the first galaxies hosting the supermassive black holes that power ultraluminous high-\(z\) quasars.

Now, we would like to compare the high-end slope of this theoretically derived mass distribution of the first filaments with that of the observationally obtained mass function of the massive galaxies hosting the high-\(z\) supermassive black holes. Very recently, Willott et al. (2010) derived the black hole mass function at \(z \approx 6\) from the observed luminosity function of the ultraluminous high-\(z\) quasars (see Figure 8 in Willott et al. 2010). Converting the mass of the high-\(z\) supermassive black holes into the total mass of their host galaxies through the following relation given by Bandara et al. (2009), \(\log(M_{\text{gal}}/M_\odot) = (8.18 \pm 0.11) + (1.55 \pm 0.31) \times \log(M_{\text{tot}}/M_\odot) - 13.0\), we find the best-fit high-end slope is in the range \(-6 \leq \alpha \leq -4.3\), plotted as two dashed lines in Figure 7. Comparing this range of \(\alpha\) against the theoretical curve plotted in Figure 7, it is found that the neutrino mass fraction is constrained as \(0.09 \leq f_\nu \leq 0.13\) which corresponds to a neutrino mass range of \(0.375 \leq m_\nu/(eV) \leq 0.542\).

5. DISCUSSION AND CONCLUSIONS

Starting with the first star-forming halos of mass \(10^6 M_\odot\) at \(z = 20\), we have shown analytically that the presence of massive neutrinos opens a new channel for the rapid formation of massive structures by speeding up the halo-to-filament merging process. Once the first filaments of mass \(\leq 10^9 M_\odot\) form through the clustering of some of the first star-forming halos at \(z \geq 9\), matter and gas would accrete more efficiently along the first filaments, resulting in the rapid growth of the constituent halos in the first filaments. As the universe evolves and the tidal forces increase, the first filaments would undergo ultimate collapse into zero-dimensional halos (corresponding to the first massive galaxies) in directions parallel to the minor principal axes of the local tidal field.

What has been found here is that the longest-axis collapses of the first filaments end up forming the first massive galaxies of mass \(\leq 10^9 M_\odot\) at \(z \geq 8\). These longest-axis collapses would accompany violent mergers among the constituent halos, which in turn would trigger vigorous star formation and feed the central black holes in the resulting first galaxies. Our result suggests that ultraluminous high-\(z\) quasars detected at \(z \geq 6\) might correspond to the first massive galaxies formed through the longest-axis collapses of the first filaments.

It has been also found that second-generation filaments of mass \(10^8 M_\odot\) form through the clustering of some of the first galaxies of mass \(10^9 M_\odot\) at \(z \sim 8\). The first galaxies in the second-generation filaments would evolve rapidly through the filamentary accretion of matter and gas (Park & Lee 2009). When the second-generation filaments collapse along their longest axes, they would also induce violent mergers among the constituent galaxies, which would lead to the formation of massive galaxies of mass larger than \(10^{11} M_\odot\) with high star formation rates and large central black holes at redshifts as high as \(z = 3\).

We test the possibility of constraining the neutrino mass, \(m_\nu\), from the mass function of the high-\(z\) supermassive black holes that power the ultraluminous high-\(z\) quasars, under the assumption that the longest-axis collapses of the first filaments would seed the supermassive black holes. Comparing the high-end slope of the theoretically derived mass function of the first filaments at the epoch of their longest-axis collapse with that of the observed mass function of the massive first galaxies inferred from the luminosity function of the ultraluminous high-\(z\) quasars, we find that the neutrino mass is constrained to be \(0.375 \leq (m_\nu/eV) \leq 0.542\).

However, this is still only a feasibility study. More comprehensive work should be done to place a robust constraint on \(m_\nu\) from observational data. First of all, more refined theoretical models for the halo-to-filament merging rates and the abundance of first filaments should be constructed than the crude approximations based on the extended Press–Schechter formalism, since this formalism has been shown to fail in accurately predicting the merging rates and abundance of bound halos (Fakhouri & Ma 2008). Second, the observational results from the luminosity function of the ultraluminous high-\(z\) quasars still suffer from small-number statistics and thus more quasar data are required. Third, we use the relation given by Bandara et al. (2009) to convert black hole mass into halo mass. However, this relation was obtained from black holes detected at \(z \leq 4\), and thus it may not be applicable to higher-\(z\) black holes. A more accurate relation between high-\(z\) black hole mass and host halo mass should be found.

Our results also hint that the massive neutrinos may have something to do with the early metal enrichment of the intergalactic medium (IGM). Madau et al. (2001) showed that the early outflows driven by supernovae (SNe) ejecta from the galaxies of mass \(\geq 10^8 M_\odot\) at \(z \sim 9\) would enrich the IGM with the products of stellar nucleosynthesis provided that those galaxies possess relatively high star formation efficiencies. It is interesting to note that the halo mass and epoch required for SN-driven outflows are more or less coincident with our estimates for galactic halos formed through longest-axis collapse of the first filaments in a AMDM model. Assuming that the longest-axis collapse of the first filaments triggers star formation rapidly in the first massive galaxies in a AMDM model, their star formation efficiency may be as high as required for early metal enrichment by SN-driven outflows. Furthermore, given our speculation that the longest-axis collapse of the first filaments would feed supermassive black holes, anisotropic outflows from the
active galactic nuclei powered by the supermassive black holes of the first massive galaxies might also contribute to the early metal enrichment of the IGM (e.g., Germain et al. 2009; Barai et al. 2011). It will be intriguing to explore how this enrichment depends on neutrino mass. Our future work is in this direction.

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