MASSIVE NEUTRINOS PROMOTE THE SIZE GROWTH OF EARLY-TYPE GALAXIES

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ABSTRACT
The effect of massive neutrinos on the evolution of early-type galaxies in size and stellar mass is explored by tracing the merging history of galaxy progenitors with the help of robust semi-analytic prescriptions. We show that the presence of massive neutrinos plays a role in enhancing the mean merger rate per halo as well as the merger-driven increment in halo mass, the high-\(z\) progenitors of a massive descendant galactic halo evolve more rapidly in mass-normalized size for a\(\Lambda\)CDM (\(\Lambda\) cold dark matter + massive neutrinos) model than for the \(\Lambda\)CDM (A cold dark matter) case. We provide a physical reason for why the halo mass growth rate and the merger rate are higher in a\(\Lambda\)CDM cosmology and conclude that if the presence and the role of massive neutrinos are properly taken into account, then it may explain the anomalous compactness of the high-\(z\) massive ETGs compared with local giant ellipticals with similar stellar masses.

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

1. INTRODUCTION

It has recently been discovered that quiescent early-type galaxies (ETGs) at high redshifts (\(z \geq 1\)) are smaller in size (\(R_e\)) by a factor of 3–5 compared with local giant ellipticals of similar stellar masses (\(M_*\)) (Daddi et al. 2005; Trujillo et al. 2006; van Dokkum et al. 2008), which implies that the high-\(z\) massive ETGs must have evolved very strongly in size but not in stellar masses. In the beginning, it was suspected that the stellar masses of the high-\(z\) ETGs from the photometric data were overestimated. But the subsequent spectroscopic estimates of their dynamical masses disproved this suspicion, confirming the rapid size growth of the high-\(z\) massive ETGs (van de Sande et al. 2011). It has been a puzzling mystery what mechanism drove such strong size evolution of the ETGs without triggering their star formation activity.

Fan et al. (2008, 2010) proposed a scenario where the compact sizes of the high-\(z\) massive ETGs can be attributed to the active galactic nucleus feedback effect from blowing off the baryonic gas out of the halo potential wells. The merit of this scenario was that it could naturally explain why the compact ETGs were observed at high redshifts \(z > 1\) when the quasars were most energetic. However, Ragone-Figueroa & Granato (2011) cast doubt on this scenario based on the argument that it is difficult to understand in this scenario why the most compact high-\(z\) ETGs are the quiescent ones possessing old stellar populations.

An alternative popular scenario was that the progenitors of the present local giant ellipticals underwent very frequent dry mergers through which they grew rapidly in size but only mildly in stellar mass (Hopkins et al. 2009; Khochfar & Silk 2006; Nipoti et al. 2003, 2009a, 2009b; Oser et al. 2012; van der Wel et al. 2009). At first glance, this scenario seems quite plausible, fitting well into the standard theory of hierarchical structure formation based on the \(\Lambda\)CDM (\(\Lambda\) + cold dark matter) cosmology. But recently Nipoti et al. (2012) have revealed that this scenario in fact challenges the standard model rather than supports it since even the maximum merger-driven size growth predicted by the \(\Lambda\)CDM cosmology is not fast enough to catch up with the observational trend (see also Cimatti et al. 2012), unless the key cosmological parameters deviate substantially from the WMAP7 values (Komatsu et al. 2011).

We note, however, that when Nipoti et al. (2012) calculated the maximum merger-driven size growth consistent with the \(\Lambda\)CDM cosmology merger rate, they missed the one crucial point that the real structure formation in the universe may not proceed in a perfectly hierarchical way due to the presence of a small amount of hot dark matter (DM) components—massive neutrinos. Since it was found and confirmed that the neutrinos are not massless (Ahmad et al. 2001; Arnett & Rosner 1987; Cleveland et al. 1998; Fogli et al. 2006; Fukuda et al. 1998; Maltoni et al. 2004), plenty of theoretical works have been devoted to investigating what effect the massive neutrinos would have on the formation and evolution of the cosmic structures and how significant the effect would be (for a recent review, see Lesgourges & Pastor 2006).

It is now understood that on the time-dependent scales where the massive neutrinos become non-relativistic, the high velocity dispersion of massive neutrinos would dump out the DM halo potential wells, resulting in the suppression of the formation of DM halos (Abazajian et al. 2005; Agarwal & Feldman 2011; Arhipova et al. 2002; Bird et al. 2012; Ichiki & Takada 2012; Lesgourges et al. 2009; Mantz et al. 2010; Marulli et al. 2011; Saito et al. 2008, 2009). The recent works of Song & Lee (2011, 2012) also suggested that the effect of massive neutrinos should also bring about a non-negligible change in the mean merging rate of DM halos. Assuming a strong dependence of the size growth of the observed ETGs on the merging rate of their underlying DM halos, it is logically expected that the ETG compactness would also be affected by the presence of massive neutrinos.

Here we claim that the presence of massive neutrinos (\(\nu\)) could significantly promote the size growth of the massive ETGs, explaining the observed anomalous compactness of massive ETGs at high redshifts. To prove our claim, we trace backward the progenitor evolution of a massive descendant galactic halo, just as Nipoti et al. (2012) did, but taking into account the effect of massive neutrinos. The organization of this paper is as follows. In Section 2, we provide a brief review of the model constructed by Nipoti et al. (2012) for the size and stellar mass evolution of the ETGs. In Section 3, we present a new model for the size and stellar mass evolution of the ETGs for a\(\Lambda\)CDM (\(\Lambda\) mixed dark matter which represents CDM + \(\nu\))
cosmology and explain how the observed compactness of the massive high-z ETGs can be explained away by taking into account the presence of massive neutrinos. In Section 4, we summarize our result and discuss its caveat and cosmological implication as well.

2. MODEL OF THE ETG PROGENITOR

EVALUATION: A REVIEW

Nipoti et al. (2012, hereafter N12) envisaged a simple picture where a dissipationless dry merger (which maximizes the size growth of the progenitor galaxies) occurs between a main galaxy of mass \(M_{\text{main}}(z)\) and a satellite galaxy of mass \(M_{\text{sat}}(z)\) to form a merged galaxy of mass \(M_b(z)\) at redshift \(z\), which represents a progenitor of a descendant galaxy of mass \(M_h(z_0)\) observed at a given redshift \(z_0 < z\). Then, they modeled the merger-driven evolution of the size and stellar mass of the progenitor galaxy as

\[
\frac{d^2 M_{\star}}{dz d\xi} = \frac{dM_{\star}}{dM_h} \left( \frac{d^2 M_h}{dz d\xi} \right)_{\text{merg}},
\]

\[
\frac{d^2 \ln R_e}{dz d\xi} = \frac{d \ln R_e}{d \ln M_*} \frac{1}{d \ln M_h} \frac{d^2 M_h}{dz d\xi} \left( \frac{d^2 M_h}{dz d\xi} \right)_{\text{merg}},
\]

where \(\xi \equiv M_{\text{sat}}/M_{\text{main}}\) and the subscript “merg” on the right-hand side means the change caused by the halo merging events, not by the smooth accretion of matter. Here the progenitor size \(R_e\) represents the effective radius that encloses half the progenitor stellar mass.

To evaluate Equations (1) and (2), N12 prescribed the three ingredients: (1) the evolution of halo mass \(d^2 M_h/(dz d\xi)\); (2) the stellar-to-halo mass relation (SHMR) \(dM_\star/dM_h\); (3) the stellar mass to size relation \(dM_\star/dR_e\). The first ingredient \(d^2 M_h/(dz d\xi)\) was prescribed as

\[
\left( \frac{d^2 M_h}{dz d\xi} \right)_{\text{merg}} = \frac{\xi M_h(z)}{1 + \xi} \frac{d^2 N_{\text{merg}}}{dz d\xi} (M_h, z, \xi),
\]

where \(\xi M_b(z)/(1 + \xi)\) is the amount of mass that a progenitor gathers during a merging event (i.e., the merger-driven increment in halo mass) that occurs in a redshift interval of \([z, z + dz]\) with satellite-to-main mass ratio \(\xi\), while \(d^2 N_{\text{merg}}/(dz d\xi)\) represents the mean number of such merging events per a merged halo of mass \(M_h(z)\) (i.e., mean merger rate per halo). From now on, we denote the mean merger rate per halo by \(B(M_h, z, \xi)\).

The tricky part in evaluating Equation (3) is the quantity \(M_h(z)\) in the right-hand side, which represents the halo accretion history, i.e., the total halo mass of a progenitor at \(z\), which grows not only through merging between the main and satellite galaxies but also through dissipationless accretion of matter. Thus, the functional form of \(M_h(z)\) has to be first determined for the evaluation of Equation (3) rather than regarding it as an integration variable. N12 used the fitting formula for \(B\) and \(M_h(z)\) derived numerically by Fakhouri & Ma (2008, hereafter FM08) from the Millennium Simulations for a ΛCDM cosmology (Springel et al. 2005).

As for the prescription of the second ingredient \(dM_\star/dM_h\), admitting that no standard model has yet to be established for the SHMR, N12 considered three different SHMRs provided by Behroozi et al. (2010, B10 hereafter), Leauthaud et al. (2012, L12 hereafter), and Wake et al. (2011, W11 hereafter), respectively. These three SHMRs were all obtained by matching various physical and statistical properties of the galactic halos from the high-resolution simulations to those of the observed galaxies. The difference among the three SHMRs comes from the different redshift ranges to which the matching between the numerical and observational results was applied. In the current work, we consider only the first two SHMRs (B10 and L12), excluding the last one (W11) which is only valid for a relatively narrow redshift range.

The B10 and the L12 SHMRs have the following same functional form in the redshift range \(1 \leq z \leq 2\):

\[
\log M_h(M_\star) = \log M_1 + q \log \left( \frac{M_\star}{M_\star,0} \right) + \frac{q(a)(M_\star/M_\star,0)^p - 1}{1 + (M_\star/M_\star,0)^\gamma} \frac{1}{2}.
\]

Here the values of the five model parameters, \(M_1, M_\star,0, q, p, \) and \(\gamma\), vary with the scale factor \(a\) as

\[
\log M_1(a) = M_{1,0} + M_{1,a}(a - 1),
\]

\[
\log M_{\star,0}(a) = M_{\star,0,0} + M_{\star,0,a}(a - 1),
\]

\[
q(a) = q_0 + q_a(a - 1),
\]

\[
p(a) = p_0 + p_a(a - 1),
\]

\[
\gamma(a) = \gamma_0 + \gamma_a(a - 1).
\]

At \(z \geq 1\), \(M_{\star,0}\) becomes time dependent as

\[
\log M_\star(0) = M_{\star,0,0} + M_{\star,0,a}(a - 1) + M_{\star,0,a}(a - 0.5)^2.
\]

The best-fit values of these model parameters are provided in Table 2 in B10 and Table 5 in L12, respectively. Although the original best-fit parameters of the L12 SHMR are valid only at \(z \leq 1\), Nipoti et al. (2012) extrapolated the validity of the L12 SHMR to higher redshifts of \(z > 1\) and redetermined the best-fit parameters.

The third ingredient, the size-to-stellar mass relation \(dR_e/dM_\star\), was prescribed as

\[
\frac{d \ln R_e}{d \ln M_*} = \left[ 2 - \frac{\ln(1 + 1.4 \xi)}{\ln(1 + \xi)} \right],
\]

which is a first-order approximation obtained under the following simplified assumptions on the merging process (Naab et al. 2009; Oser et al. 2012): the merging halos have spheroidal shapes; the satellites follow parabolic orbits; there is no energy loss during the dissipationless dry merging events. By plugging the prescribed three ingredients into Equations (1) and (2) and integrating them over \(\xi\) and \(z\), N12 have finally made the quantitative predictions of the standard ΛCDM cosmology for the merger-driven evolution of the size and stellar mass of the progenitors \(R_e(z)\) and \(M_\star(z)\) of a given descendant halo at \(z_0 < z\). By plotting the locations of the high-z progenitors at \(z \geq 2\) in the \(R_e(z) - M_\star(z)\) plane and comparing them with the local relations (see Figure 10 in N12), they clearly demonstrated that the
sizes of the high-\(z\) progenitors in the \(\Lambda\)CDM universe are much larger than the observed ones.

Estimating the uncertainties in \(R_e(z)\) and \(M_e(z)\) due to the simplified assumptions that they made to prescribe \(dR_e/dM_\ast\) and \(dM_e/dM_\ast\), \textit{N12} showed that the most severe uncertainties come from the SHMRs and that the disagreement between the \(\Lambda\)CDM prediction and the observational result is robust against the SHMR uncertainties. In other words, it was confirmed that although several simplified assumptions were made in their determination of the size and stellar mass evolution of the progenitor galaxies, the large discrepancy between the \(\Lambda\)CDM prediction and the observational result is not due to the inaccurate modeling of \(dR_e/dM_\ast\) and \(dM_e/dM_\ast\).

In the follow-up work, Cimatti et al. (2012) quantified the compactness of a progenitor galaxy as the mass-normalized size of \(R_eM_\ast^{0.55}\) with \(M_\ast \equiv M_\ast/(10^{11} M_\odot)\), and modeled the evolution of the progenitor compactness as a power-law scaling with redshift: \(R_eM_\ast^{0.55} \propto (1 + z)^\beta\), given that the effective sizes of the observed galaxies scale as a power law of their stellar masses, \(R_e \propto M_\ast^{0.55}\) (see also Newman et al. 2012 and references therein). Cimatti et al. (2012) determined the best-fit slope to be \(\beta \approx -0.6\) for the ETGs in the redshift range of \(0 \leq z \leq 2\) and to be \(\beta \approx -1\) for the ETGs at \(0 < z < 2.6\), confirming the rapid evolution of the ETG compactness at high redshifts.

3. EFFECT OF MASSIVE NEUTRINOS ON THE ETG PROGENITOR EVOLUTION

In this section, we investigate how the presence of massive neutrinos affects the compactness evolution of the massive ETGs, applying the \textit{N12} model to the case of a \(\Lambda\)MDM cosmology. Basically, we compute Equations (1) and (2) in a similar manner but with a modified prescription for the first ingredient, \(d^2M_\ast/dzd\xi\), by incorporating the presence of massive neutrinos into the picture. First of all, we would like to determine the mean merger rate per halo \(\bar{\nu}\) and the halo accretion history \(\dot{M}_\ast(z)\) for the \(\Lambda\)MDM case. Of course, the most accurate way to determine these quantities would be to run repeatedly high-resolution \(N\)-body simulations for \(\Lambda\)MDM models with various different values of the neutrino mass \(\sum m_\nu\), and then to determine the empirical fitting formula for \(\bar{\nu}(z)\) and \(\dot{M}_\ast(z)\) as a function of \(\sum m_\nu\) by analyzing the \(N\)-body results. Since such simulations are not available at the moment, we utilize the less accurate but practical semi-analytic formula for \(\bar{\nu}\) and \(\dot{M}_\ast\) derived from previous works.

Zhang et al. (2008) analytically derived the following formula for the mean merger rate per halo by incorporating the ellipsoidal collapse dynamics into the extended Press–Schechter (EPS) theory (Press & Schechter 1974; Lacey & Cole 1993):

\[
\bar{\nu}(M_\ast,z,\xi) = \bar{\nu}_{\text{sph}}(M_\ast,z,\xi) \times A_0 \exp \left\{ -A_1\frac{\delta_i}{2} \right\} \times \left[ 1 + A_2\delta_i^{3/2} \left[ 1 + \frac{A_1\delta_i^{1/2}}{T(3/2)} \right] \right],
\]

where \(A_0 = 0.866(1 - 0.133\nu_0^{-0.615})\), \(A_1 = 0.308\nu_0^{-0.115}\), \(A_2 = 0.0373\nu_0^{-0.115}\), \(\nu_0 = \omega^2(z)/S(M_\ast)\), and \(\delta_i = \Delta S_i/S(M_\ast)\). Here, \(\bar{\nu}_{\text{sph}}\) represents the original EPS model based on the spherical collapse dynamics (Lacey & Cole 1993):

\[
\bar{\nu}_{\text{sph}}(M_\ast,z,\xi) = \frac{d\delta_i(z)}{dz} \frac{M_\ast^2}{(1 + \xi)^2} \frac{dS(M_\ast)}{dM_\ast} \frac{1}{\Delta S_i(2\pi\Delta S_i)^{1/2}}.
\]

where \(\delta_i(z) = \delta_c/D(z)\), \(\delta_c = 1.68\), \(D(z)\) is the linear growth factor, \(\Delta S_i \equiv S(M_i) - S(M_\ast)\), and \(S(M) \equiv \sigma^2(M)\) is the variance of the linear density field smoothed on the mass scale of \(M\). The quantity \(M_i\) in Equation (12) represents the mass of a merging halo which could be either a main or a satellite. Zhang et al. (2008) showed that Equation (12) significantly improves its spherical counterpart, Equation (13), agreeing much better with the \(N\)-body results.

We adopt this ellipsoidal EPS model to evaluate the mean merging rate per halo \(\bar{\nu}\) for a \(\Lambda\)MDM cosmology whose linear density power spectrum is characterized by the neutrino mass fraction, \(f_\nu = \Omega_\nu/\Omega_m\) (where \(\Omega_m\) and \(\Omega_\nu\) are the matter and the massive neutrino density parameter, respectively). Extrapolating the validity of the ellipsoidal EPS model to \(\Lambda\)MDM cosmology may be justified by the results of Marulli et al. (2011), which showed that the PS-like approaches are valid for the evaluation of the halo mass function even for \(\Lambda\)MDM cosmologies. For the \(\Lambda\)MDM linear density power spectrum and growth factor, we utilize the analytic formula given by Eisenstein & Hu (1999). To normalize the \(\Lambda\)MDM linear power spectrum, we make its amplitude satisfy \(\sigma_8 = 0.8\) for the case of \(f_\nu = 0\) (i.e., without massive neutrinos), which is equivalent to the large-scale normalization. The other key cosmological parameters are set at the WMAP7 values (Komatsu et al. 2011).

Figure 1 shows the mean merger rate per halo as a function of \(\xi\) for three different cases of \(f_\nu\) with \(M_\ast(0) = 10^{13} M_\odot\) (which corresponds to \(M_\ast(0) \approx 10^{11} h^{-1} M_\odot\)). As can be seen, the larger the neutrino mass fraction is, the higher the mean merging rate per halo is. For the case of \(f_\nu = 0.05\) (which corresponds to the WMAP7 upper limit of \(\sum m_\nu < 0.58\) eV with effective number of massive neutrino \(N_{\text{eff}} = 4.34\)), the overall merger rate per halo increases by a factor of three relative to the case of \(f_\nu = 0\). It is worth mentioning here that the redshift \(z_0\) at which the descendant galactic halo is observed is set at the present epoch, i.e., \(z_0 = 0\), unlike \(z_0 = 1\) in the original \textit{N12} model, as we are interested in the full progenitor history from the high redshifts to the present epoch rather than focusing on explaining the high-\(z\) phenomena.
As for the mass accretion history for a ΛCDM universe, we use the analytic formula proposed by Zhao et al. (2009). Noting the existence of a simple expression for the mass accretion rate as a function of halo mass, redshift, and cosmological parameters, Zhao et al. (2009) developed a theoretical model for the mass accretion history which has the following universal form:

$$\frac{d \log \sigma(M)}{d \log \delta_c(z)} = \frac{\omega(z, M) - p(z, z_0, M_h(z_0))}{5.85}.$$  \hspace{1cm} (14)

Here,

$$\omega(z, M) = \frac{\delta_c(z)}{\sigma(M) 10^{d \log \sigma/d \log M}},$$ \hspace{1cm} (15)

$$p(z, z_0, M_h) = p(z, z_0, M_h(z_0))\times \text{Max} \left[ 0, 1 - \frac{\log \delta_c(z) - \log \delta_c(z_0)}{0.272/\omega(z_0, M_h(z_0))} \right],$$ \hspace{1cm} (16)

$$p(z_0, M_h(z_0)) = \frac{1}{1 + [\omega(z_0, M_h(z_0))/4]^6} \frac{\omega[z_0, M_h(z_0)]}{2}.$$ \hspace{1cm} (17)

Note that in Equation (14), $1/\sigma(M)$ is used as a mass-like variable and $1/\delta_c(z)$ is used as a time-like variable.

Since Zhao et al. (2009) showed that Equations (14)–(17) work on a wide mass range at various redshifts for several different cosmological models, the applicability of Equations (14)–(17) to ΛCDM cosmology is expected. By expressing Equation (14) in terms of mass and redshift according to the chain rule as

$$\frac{d M_h}{dz} = \frac{d M_h}{d \log \sigma(M_h)} \frac{d \log \delta_c(z)}{dz} \frac{d \log \sigma(M_h)}{d \log \delta_c(z)},$$ \hspace{1cm} (18)

and integrating Equation (18) over $z$, we finally determine the halo mass accretion history $M_h(z)$ for a ΛCDM universe. Figure 2 shows the evolution of $M_h(z)$ and $M_\star(z)$ via dry mergers with $\xi \geq \xi_{\text{min}} = 0.03$ for three different cases of $f_\nu$, in the left and right panels, respectively. The mass of a descendant halo at the present epoch is set at $M_h(z_0) = 10^{12} M_\odot$ (corresponding to $M_\star \approx 10^{11} M_\odot$) for all three cases. Here, we follow the evolution up to redshift $z \approx 1.5$ since the formation epoch of a descendant halo with mass $M_h(z_0) = 10^{13} M_\odot$ is approximately $z = 1.5$. As can be seen, both $M_h$ and $M_\star$ evolve more rapidly for the case with a higher value of $f_\nu$, and the differences among the three cases of $f_\nu$ in $M_h$ and $M_\star$ become larger at higher redshifts. This result indicates that the high-$z$ progenitor galaxies of a descendant halo with the same mass accrete a larger amount of DM and stellar masses via dry mergers in a ΛCDM universe than in the ΛCDM case.

The physical reason why the halo mass growth rate and the merger rate are higher in a ΛCDM cosmology may be related to the later formation epochs of dark halos (e.g., Song & Lee 2011). The dark halos tend to form later in a ΛCDM universe than in the ΛCDM universe since the small-scale powers are reduced due to the free streaming effect of massive neutrinos. In a ΛCDM universe the small galactic halos form much earlier than the larger halos and thus the interval between the formation epochs of small galactic halos and larger halos is long. However, in a ΛCDM universe the formations of dark halos (small and large halos alike) are delayed and thus the interval between the formation epochs of small and large halos is much shorter than in the ΛCDM case. In other words, the small halos need to merge faster into the larger halos in a ΛCDM universe.

Now that we have determined the mean merger rate per halo and the mass accretion history for the ΛCDM case, we plug them into Equation (3) to prescribe the first ingredient of our model. Regarding the second and third ingredients (i.e., $d R_c/dM_\star$ and $d M_\star/dM_h$), we use the same prescriptions, i.e., Equations (4)–(11), of the original N12 model under the assumption that these relations are still valid for the ΛCDM case. It is worth discussing, however, whether or not this assumption is reasonable here. As mentioned in Section 2, the SHMRs were all determined by matching the observational data to the numerical results by applying several different techniques such as abundance matching, gravitational lensing, and so on, some of which are not based on ΛCDM models. Therefore, even though the SHMRs that N12 adopted were obtained for the ΛCDM case, we expect it to work for the ΛCDM case. Regarding the size-to-stellar mass relation, Equation (11), it is a local relation obtained by applying the first-order galactic dynamics which is independent of the background cosmology as long as the gravity is well described by Newtonian dynamics. Therefore, it should also be valid for the ΛCDM case.

Plugging the prescribed ingredients into Equations (1) and (2), we finally calculate the size and stellar mass evolution of the progenitor galaxies of a descendant halo observed at the present epoch in a ΛCDM universe and then determine the compactness of the progenitor galaxies at each redshift as $R_c M_\star^{-0.35}$. Figure 3 shows how the compactness of the progenitor galaxies of a descendant halo observed at $z = 0$ evolves in a ΛCDM universe. The left and right panels correspond to the cases of $M_h(0) = 10^{13} h^{-1} M_\odot$ and $M_h(0) = 5 \times 10^{12} h^{-1} M_\odot$, respectively. In each panel, the solid, dashed, and dot-dashed lines correspond to the cases of $f_\nu = 0$, 0.02, and 0.05, respectively. As can be seen, the high-$z$ progenitors become more compact for the higher-$f_\nu$ case, which confirms that the presence of massive neutrinos plays a role in promoting the size growth of the massive ETGs at high redshifts. Furthermore, this effect of massive neutrinos on the size evolution is stronger for the case that $M_h(0)$ has a higher value, which is consistent with the observational result that the most compact high-$z$ ETGs are usually the most massive ones (Cimatti et al. 2012; Daddi et al. 2005; Nipoti et al. 2012; Trujillo et al. 2006; van Dokkum et al. 2008).

The results shown in Figure 3 have been obtained by using the B10 SHMR. To examine whether or not the use of a different
SHMR will change the trend, we repeat the calculation of the compactness evolution, but using the L12 SHMR. The top panel of Figure 4 shows the compactness evolution obtained by using the L12 SHMR as the thick solid and dashed lines for the cases of \( f_\nu = 0 \) and \( f_\nu = 0.05 \), respectively. The results shown in the left panel of Figure 3 (only for the two cases of \( f_\nu = 0 \) and \( f_\nu = 0.05 \)) are also plotted as thin lines for comparison. Since the L12 SHMR was originally obtained for the galaxies at \( z \leq 1 \), we show the results only at \( z \leq 1 \). The bottom panel of Figure 4 shows the fractional difference between the two SHMR cases. As one can see, the use of a different SHMR does not destroy the trend that the progenitor compactness evolves faster for a higher \( f_\nu \) case, which indicates that our result is qualitatively robust against the uncertainties of SHMR. However, it also has to be noted that using a different SHMR yields quantitatively a different compactness evolution of the progenitors, and thus it will be important to refine the SHMR as accurately as possible.

We have so far studied theoretically the progenitor evolution of one single descendant halo existing at \( z = 0 \). The observed ETGs shown in Cimatti et al. (2012) must correspond not only to the progenitors of one single descendant halo existing at \( z = 0 \) but also to the progenitors of different descendants existing at different redshifts. Therefore, to make a comparison with the observational results, it is necessary to model theoretically the progenitor evolutions of different descendant halos existing at different redshifts for each case of \( f_\nu \). We consider only those progenitors whose distribution in the \( M_*, \zeta \) plane are similar to the observed ETGs shown in Figure 2 of Cimatti et al. (2012), having stellar masses in the range of \( 10^{10.5} \leq M_*/M_\odot \leq 10^{12} \) at redshifts of \( 0 \leq z \leq 2.5 \). It amounts to considering those halos as representative descendants whose total mass lies between \( 5 \times 10^{12} \) \( M_\odot \) and \( 2 \times 10^{13} \) \( M_\odot \).

Approximating the compactness evolution of the theoretically modeled progenitors as the scaling relation of \( R_e M_1^{0.55} = (1 + z)^\beta \), we determine the best-fit value of \( \beta \) with the help of the \( \chi^2 \) minimization method for each case of \( f_\nu \). Figure 5 shows the best-fit scaling relations (solid line) and compare them with the average compactness evolution of the modeled progenitor galaxies (dots) for three different cases of \( f_\nu \). As can be seen, the absolute value of \( \beta \) increases from 0.89 to 1.02 as \( f_\nu \) increases from 0 to 0.05. According to Cimatti et al. (2012), the absolute value of \( \beta \) obtained from the observed ETGs at redshifts of \( 0 \leq z \leq 2.5 \) is close to unity. At face value, it suggests that the observational result is consistent with the theoretically estimated value of \( \beta \) for the AMDM model with \( f_\nu = 0.05 \).

4. DISCUSSION AND CONCLUSION

We have shown that the presence of massive neutrinos plays a role in enhancing the mean merging rate per halo as well as the merger-driven increment in halo mass on the massive galaxy scale, and thus that the ETG compactness evolves much more rapidly in a ΛCDM universe. It is worth discussing here whether the AMDM prediction of the higher merging rate per halo is consistent with the observational indication. N12 mentioned that since the inferred merging rate from the observations of binary galaxy systems is even lower than the ΛCDM prediction, enhancing the merging rate should not be the key to explaining away the anomalous compactness of the high-\( \zeta \) ETGs. However, very recently, Jian et al. (2012) have demonstrated that the merging rate inferred from the observed galaxy pairs might be severely contaminated by the spurious projection effect.

However, our current model is only a reasonable approximation based on several simplified assumptions to the true effect of massive neutrinos on the ETG evolution. It will definitely be necessary to improve and refine our model by incorporating more realistic assumptions and adopting more accurate prescriptions. In the first place, it will be essential to determine more accurately the mean merger rate per halo by using high-resolution N-body simulations for a ΛCDM universe. Although the ellipsoidal EPS model that we have used to calculate the mean merger rate per halo is a significantly improved version of the original spherical EPS model, it still suffers from maximum 20% errors when compared with the N-body results (Zhang et al. 2008). The size-to-stellar mass relation also has to be improved by accounting for the following realistic aspects of the true merging process of progenitor galaxies: (1) the occurrence of dissipational wet mergers, (2) the time lapse between the moment of halo merging and that of galaxy merging, and (3) the presence of disk-shaped progenitors. High-resolution gas simulations with massive
neutrinos included will be required to address these complicated issues.

Another thing that may deserve discussing is the question of whether or not the ΛCDM model is the only solution to the anomalous strong size growth of the high-z massive ETGs. One might think that different cosmologies such as models with primordial non-Gaussianity, dynamic dark energy, or modified gravity might also affect the mean merger rate per halo, thus influencing the size growth of the massive high-z ETGs. Examining if any other cosmological models could be also a solution, however, will require much more work, totally renewing all prescriptions, since in these models the extended EPS formalism is no longer valid, the gravitational dynamics changes, and the SHMR could be also quite different.

Our final conclusion is that the tension of the standard structure formation scenario with the observed anomalous compactness of the massive high-z ETGs can be greatly alleviated without changing the key cosmological parameters from the WMAP7 values if the presence and effect of massive neutrinos are properly taken into account.

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Figure 5. Average compactness of the progenitor galaxies (dots) with stellar masses in the range of $10^{10.5} < M_*/M_\odot < 10^{12}$ for three different cases of $f_\nu$. The average is taken over the progenitor histories of representative descendant halos whose progenitors have the same stellar mass distributions in the redshift range of $0 \leq z \leq 2.5$ as the observational results shown in Figure 2 of Cimatti et al. (2012). In each panel, the solid line corresponds to the best-fit scaling relation of $R_c/M_{15}^{0.5} = (1 + z)^\beta$.

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