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Why are AGN found in High Mass Galaxies?

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ABSTRACT
We use semi-analytic models implemented in the *Millennium Simulation* to analyze the merging histories of dark matter haloes and of the galaxies that reside in them. We assume that supermassive black holes only exist in galaxies that have experienced at least one major merger. Only a few percent of galaxies with stellar masses less than $M_* < 10^{10} M_\odot$ are predicted to have experienced a major merger and to contain a black hole. The fraction of galaxies with black holes increases very steeply at larger stellar masses. This agrees well with the observed strong mass dependence of the fraction of nearby galaxies that contain either low-luminosity (LINER-type) or higher-luminosity (Seyfert or composite-type) AGN. We then investigate when the major mergers that first create the black holes are predicted to occur. High mass galaxies are predicted to have formed their black holes at very early epochs. The majority of low mass galaxies never experience a major merger and hence do not contain a black hole, but a significant fraction of the supermassive black holes that do exist in low mass galaxies are predicted to have formed recently.

Key words: galaxies: interactions – galaxies: haloes – galaxies: nuclei

1 INTRODUCTION

By studying active galactic nuclei (AGN), we learn about the physical mechanisms that trigger accretion onto the central supermassive black holes of galaxies. When a black hole accretes, it increases in mass. By studying populations of AGN at low and at high redshifts, we hope to infer the history of how black holes build up their mass.

It has been established that supermassive black holes most occur in galaxies with bulges (Kormendy & Richstone 1995), and that the mass of the black hole correlates with the luminosity and the stellar velocity dispersion of the host bulge (Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000). This indicates that the formation of galaxies and supermassive black holes are likely to be closely linked. In the local Universe, the fraction of bulge-dominated galaxies hosting AGN decreases at lower stellar masses (Ho et al. 1997; Kauffmann et al. 2003). In order to form a black hole, it is necessary for gas to lose angular momentum and sink to the centre of the galaxy (Haehnelt & Rees 1993; Volonteri et al. 2003). The gravitational torques that operate during galaxy-galaxy mergers are known to be a very effective mechanism for concentrating gas at the centers of galaxies (Mihos & Hernquist 1996). Models for AGN evolution have often assumed that black holes are formed and fuelled, and AGN activity is triggered during major mergers of galaxies (Kauffmann & Haehnelt 2000; Wyithe & Loeb 2003; Croton et al. 2006).

At low and moderate redshifts, there is no conclusive observational evidence that mergers play a significant role in triggering AGN activity in galaxies. In the local Universe, Li et al. (2006) have shown that narrow line AGN do not have more close companions than matched samples of inactive galaxies. Even at intermediate redshifts (z $\sim 0.4-1.3$), moderate luminosity AGN hosts do not have morphologies indicative of an ongoing merger or interaction (Hasan 2007). The conclusion seems to be that although major mergers may be responsible for AGN activity in some galaxies, other fueling mechanisms are likely to be most important in the low redshift Universe. It has also been established that high mass black holes have largely stopped growing at early cosmic epochs, whereas low mass black holes are still accreting at significant rates today (Heckman et al. 2004). X-ray observations show that very high-luminosity AGN activity peaked at early cosmic epochs ($z \sim 2$), while low-luminosity AGN activity peaks at lower redshifts (Steffen et al. 2003; Barger et al. 2005; Hasinger et al. 2005).

It has been postulated that this so-called “anti-hierarchical” growth of supermassive black holes can be explained if there are two modes of accretion onto black holes that have very different efficiencies (Merloni 2004; Mueller & Hasinger 2007). The early formation formation of “new” black holes may result in very luminous quasar-like events. To form a supermassive black hole, a more violent

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process such as a major merger may be required to funnel a large amount of gas into the central region of the galaxy. Subsequent accretion of gas onto already existing black holes may be an inefficient process and produce lower luminosity AGN (Haehnelt & Rees 1993; Duschl & Strittmatter 2002). The history of accretion after the black hole is formed may not necessarily be tightly linked to the dynamical history of the galaxy, but may be controlled by the accretion and feedback processes occurring in the vicinity of the black hole itself.

In this work, we use the combination of the *Millennium Simulation* and semi-analytic models of galaxy formation to study the fraction of galaxies that have undergone major mergers as a function of mass and cosmic epoch. We investigate whether this can be related to the demographics of black holes in the local Universe and to the apparent disappearance of the most luminous quasar activity in massive galaxies at late times.

In Sec. 2, we briefly introduce the simulation we use and explain how galaxy mergers are tracked in the simulation. In Sec. 3, we show that if we assume that black holes only form when galaxies undergo major merging events, then most present-day low mass galaxies are predicted not not to contain black holes and hence will not host AGN. In Sec. 4, we use the simulations to predict when galaxies of different masses have underdone their first major merger. Conclusions and discussions are presented in the final section.

2 SIMULATION AND MERGER TREES

The *Millennium Simulation*(Springel et al. 2005) is used in this work to study the merging histories of dark matter haloes. The merging histories of galaxies can be inferred when the simulation is combined with semi-analytic models that follow gas cooling, star formation, supernova and AGN feedback and other physical processes that regulate how the baryons condense into galaxies.

The *Millennium Simulation* follows $N = 2160^3$ particles of mass $8.6\times10^8\,h^{-1}\mathrm{M}_\odot$ from redshift $z = 127$ to the present day, within a comoving box of $500\,h^{-1}$Mpc on a side. The cosmological parameters values in the simulation are consistent with the determinations from a combined analysis of the 2dFGRS(Colless et al. 2001) and first year WMAP data (Spergel et al. 2003). A flat ΛCDM cosmology is assumed with $\Omega_\mathrm{m} = 0.25$, $\Omega_\mathrm{b} = 0.045$, $h = 0.73$, $\Omega_\Lambda = 0.75$, $n = 1$, and $\sigma_8 = 0.9$.

Full particle data are stored at 64 output times. For each output, haloes are identified using a friends-of-friends (FOF) group-finder. Substructures (or subhaloes) within a FOF halo are located using the SUBFIND algorithm of Springel et al. (2001). The self-bound part of the FOF group itself also appear in the substructure list. This main subhalo typically contains 90 percent of the mass of the FOF group. After finding all substructures in all the output snapshots, subhalo merging trees are built that describe in detail how these systems merge and grow as the universe evolves. Since structures merge hierarchically in CDM universes, for any given subhalo, there can be several progenitors, but in general each subhalo only has one descendant. Merger trees are thus constructed by defining a unique descendant for each subhalo. We refer below *halo* to the main substructure that can represent the FOF halo, while *subhalo* refers to substructure other than the main one. Halo merger happens when two FOF group merge into one group and one of the haloes becomes a subhalo of the larger structure.

The substructure merger trees form the basic input to the semi-analytic model used to associate galaxies with haloes/subhaloes (De Lucia & Blaizot 2007). The semi-analytic galaxy catalogue we are using in this study is publicly available. A description of the publicly available catalogues, and a link to the database can be found at the webpage: http://www.mpa-garching.mpg.de/millennium/. Once a halo appears in the simulation, a (central) galaxy begins to form within it. The central galaxy is located at the position of the most bound particle of the halo. As the simulation evolves, the halo may merge with a larger structure and become a subhalo. The central galaxy then becomes a satellite galaxy in the larger structure. The galaxy's position and velocity are specified by the position and velocity of the most bound particle of its host halo/subhalo. Even if the subhalo hosting the galaxy is tidally disrupted, the position and velocity of the galaxy is still traced through this most bound particle. Galaxies thus only disappear from the simulation if they merge with another galaxy. The time taken for a galaxy without subhalo to merge with the central object is given by the time taken for dynamical friction to erode its orbit, causing it to spiral into the centre and merge. This is calculated using the standard Chandrasekhar formula. All the information about the formation and merging history of galaxies is stored.

By analyzing these halo and galaxy merger trees, we are able to track when two haloes merge together and whether the galaxies within them also merge into a single object by the present day. In this study, we focus on mergers between satellite and central galaxies, and exclude mergers between two satellites. These events are rare (Springel et al. 2001) and neglecting them should not affect our conclusions about the incidence and fueling of black holes in galaxies.

3 HALO AND GALAXY MERGERS

In this study, we assume that black holes form when a galaxy undergoes a major merging event. Galaxies that have never experienced a major merger do not have a black hole. We define major mergers as events in which the mass ratio of the two progenitors is greater than 0.3. For halo merger, the mass ratio is the virial mass ratio of two progenitor haloes. For galaxy merger, it is the stellar mass ratio of two progenitor galaxies. When we track mergers in the simulation, we include major mergers that occur in all branches of the tree, not just the "main branch".

Since galaxies reside in dark matter haloes and are able to merge only once their host haloes have coalesced, we begin by analyzing the merging histories of the dark matter haloes themselves. In the left panel of Fig. 1, we plot the average number of major mergers a present day dark matter halo has experienced over its lifetime as a function of halo mass. Note that in this analysis we track mergers down to an effective resolution limit of 20 particles, which corresponds to a halo of mass $1.7\times10^{10}h^{-1}M_\odot$. We see that the number of major mergers (above the resolution limit) experienced by a halo is a strongly increasing function of mass; haloes with present-

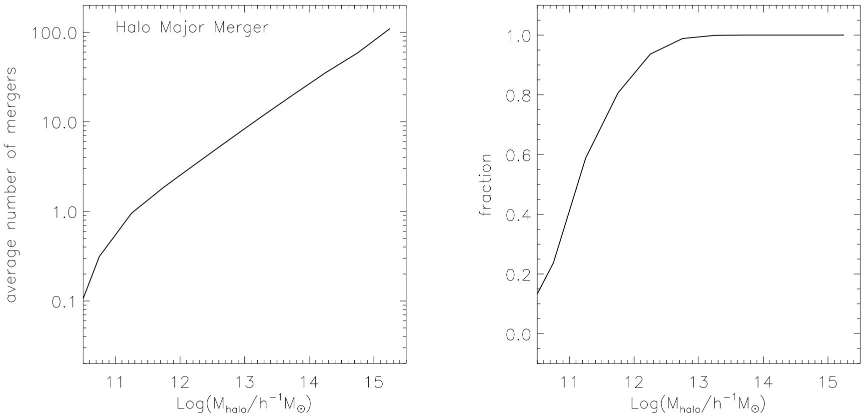

Figure 1. Left panel: the average number of major mergers that a dark matter halo of given mass has experienced over its lifetime. Right panel: the fraction of haloes of given mass that have had at least one major merger.

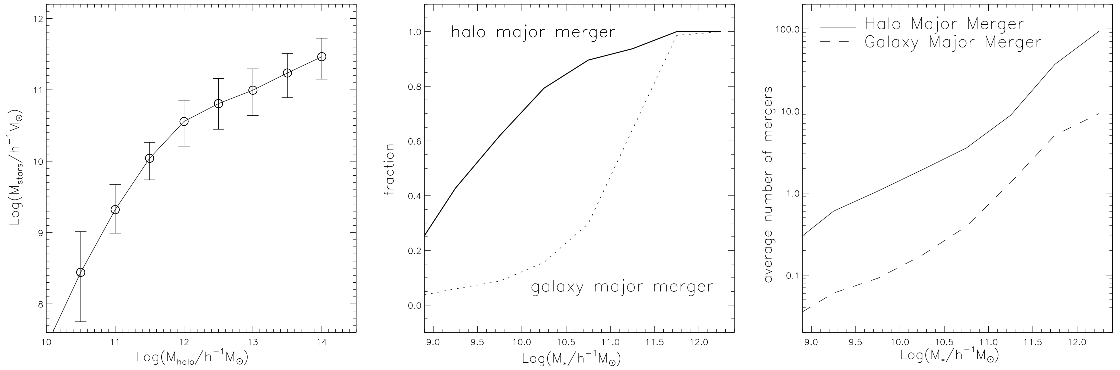

Figure 2. Left panel: The relation between the stellar mass of the central galaxy and the the mass of its host dark matter halo as predicted by the semi-analytic models of De Lucia & Blaizot (2007). The error bars indicate the 95 percentile range in stellar mass at a given value of M_{halo} . Middle panel: The solid line shows the fraction of dark matter haloes that have experienced at least one major merger as a function of the stellar mass of the central galaxy. The dotted line shows the fraction of central galaxies of given mass that have had at least one major merger. Right panel: The solid line shows the average number of major mergers experienced by a dark matter halo as a function of the stellar mass of its central galaxy. The dashed line shows the average number of major mergers experienced by the central galaxy itself.

day masses of $10^{12} M_{\odot}$ have typically experienced only one one major merger, whereas the progenitors of present-day haloes with masses of $10^{15} M_{\odot}$ have merged with each other close to 100 times.

In the right panel, we show the fraction of haloes that have had at least one major merger during their lifetime, as a function of halo mass. The fraction of haloes that have had major mergers also increases rapidly with halo mass. Almost all haloes more massive than $10^{13} h^{-1} M_{\odot}$ have had at least one major merger and this fraction drops to around 20 % for haloes with masses of around $10^{11} h^{-1} M_{\odot}$.

We now investigate the fraction of *galaxies* that have had major mergers. The results are shown as a dotted line in the middle panel of Fig. 2. Rather than rising steeply as a function of mass, the galaxy major merger fraction remains close to zero up to a stellar mass of $10^{10.5} M_{\odot}$ and then rises sharply. This is somewhat surprising in view of the behaviour of the same quantity for dark matter haloes, plotted in the right-hand panel of Fig. 1. For reference, we have plotted the relation between the stellar mass of a central galaxy and the mass of its host halo in the left panel of Fig. 2, as predicted by the semi-analytic models we use in this study (De Lucia & Blaizot 2007). This mean relation can be used to transform between central galaxy mass and halo mass in an approximate way (this conversion neglects scatter between the two quantities and the fact that some galaxies are actually satellite systems). If the fraction of galaxies with major mergers followed the relation derived for their host haloes, this would yield the solid curve in the middle panel of Fig. 2. Why are the merging histories of galaxies and their host haloes so different?

Once two dark matter haloes merge, the galaxies inside them will merge together over a timescale that is determined by dynamical friction. Upon investigation, we find that nearly all galaxies that have experienced major mergers are located in dark matter haloes that have also experienced a major merger. There are almost no galaxy major mergers that have occurred in a halo that has only experi-

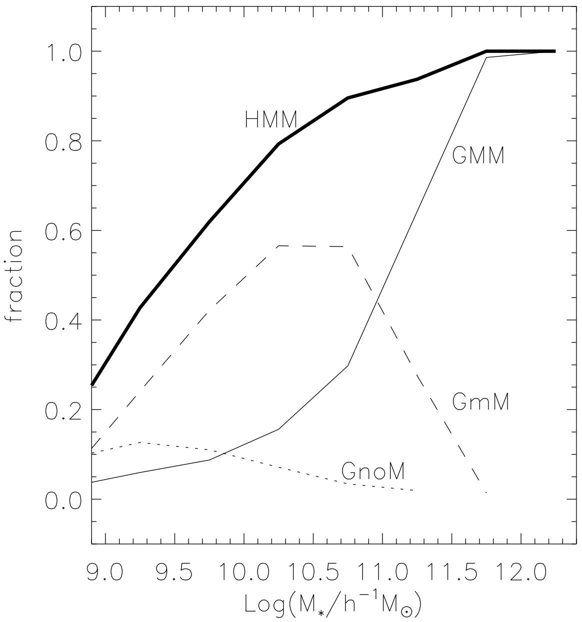

Figure 3. The thick solid line (HMM) shows the fraction of central galaxies whose progenitor haloes have had at least one major merger. The other lines split this sample of central galaxies according to the history of the central galaxy itself. The dotted line (GnoM) shows the contribution from central galaxies that have not experienced a mergers of any kind. The dashed line (GmM) shows the contribution from central galaxies that have experienced only minor mergers. The thin solid line (GMM) shows the contribution from central galaxies that have experienced major majors.

enced a minor merger (~ 0.15 percent). However, the converse is not true; *we find that a substantial fraction of halo major mergers give rise to galaxy minor mergers.* This is illustrated in the right-hand panel of Fig. 2. The solid line shows the number of major mergers experienced by the progenitor *haloes* of a present-day central galaxy as a function of its mass. The dashed line shows the number of major mergers experienced by their progenitor *galaxies*. As can be seen, the number of major mergers experienced by the progenitor galaxies is an order of magnitude smaller. Notice that the number of galaxy mergers is less than 1 for galaxies up to $\sim 10^{11} h^{-1} M_{\odot}$, and increase steeply for massive galaxies. This is in nice agreement with what is shown in Fig.9 of De Lucia et al. (2006), which shows the number of effective progenitors as a function of the stellar mass for elliptical galaxies.

In Fig. 3, we again plot the fraction of central galaxies of a given mass whose progenitor haloes have had a major mergers (thick solid line). The thin solid line shows the fraction whose progenitor *galaxies* have had a major merger. The dashed line shows the fraction of such galaxies that have had minor mergers and the dotted line is the fraction that have had no merger of any kind. The main conclusion that can be gleaned from this plot is that the reason why the thick solid and thin solid curves differ in shape, is because at lower stellar masses, major mergers between the progenitor haloes often correspond to minor mergers between the progenitor galaxies.

How can we understand this? During the period of time between the merger of the two haloes and the merger of the galaxies within them, the stellar mass of the smaller "satellite" galaxy remains about the same because ongoing star formation is quenched when the gas surrounding the galaxy is shock–heated and no longer cools onto the satellite. The central galaxy, however, will continue to increase in mass as a result of cooling and star formation. The stellar mass ratio of two galaxies therefore becomes smaller as a function of time.

This is illustrated in Fig. 4. For every merging event that occurs over the history of a galaxy, we record stellar mass ratio information at the time when the progenitor haloes merge and at the time when the galaxies themselves merge together. For simplicity, we keep information for one randomly chosen merging event in the history of each galaxy. In the left panel of Fig. 4, we plot the average time that elapses between the time when the two haloes merged and the time when the galaxies themselves merged. Results are shown as a function of galaxy stellar mass and the the error bars indicate 68 percentile range in the distribution of delay times. As can be seen, the typical delay time is around 2 Gyr, but individual time delays can range between 1 and 5 Gyr. The delay times are typically shorter for the progenitors of more massive galaxies.

In the right panel of Fig. 4, we plot the average stellar mass ratios of the galaxies at the time when their haloes merge (solid curve) and at the time when the two galaxies themselves merge (dashed line). Notice that the stellar mass ratio can sometimes be larger than 1; this happens when the galaxy inside the smaller halo is more massive than the galaxy in the larger halo. As we expect, the mass ratio of galaxies at the time when the galaxies merge is smaller than that it is at the time when the haloes merge. This effect is somewhat larger for the mergers that give rise to the most massive galaxies at the present day.

3.1 Comparison with Observations

In this section we have seen that the fraction of galaxies that have experienced one or more major merging events is predicted to very close to zero at stellar masses less than $\sim 10^{10} M_{\odot}$, but a very steeply rising fraction of stellar mass for $M_* > 10^{10} M_{\odot}$. We now compare this prediction with the fraction of Sloan Digital Sky Survey galaxies that contain an AGN. We restrict the SDSS sample to redshifts $z < 0.06$ so that we are still able to detect AGN with weak line emission (LINERs). As shown by Kauffmann et al. (2003), weak-lined AGN become progressively more difficult to identify at higher redshifts using SDSS spectra. This is because these spectra are obtained through 3 arcsecond diameter fibre apertures and the contribution from the stellar population of the host galaxy becomes increasingly dominant in more distant galaxies.

The results of the comparison are shown in Fig. 5. The black curve shows the fraction of galaxies in the Millennium Simulation of given stellar mass that have had at least one major merger. The red histogram shows the fraction of galaxies in the SDSS survey that are classified as AGN. As can be seen, both fractions rise steeply from values close to

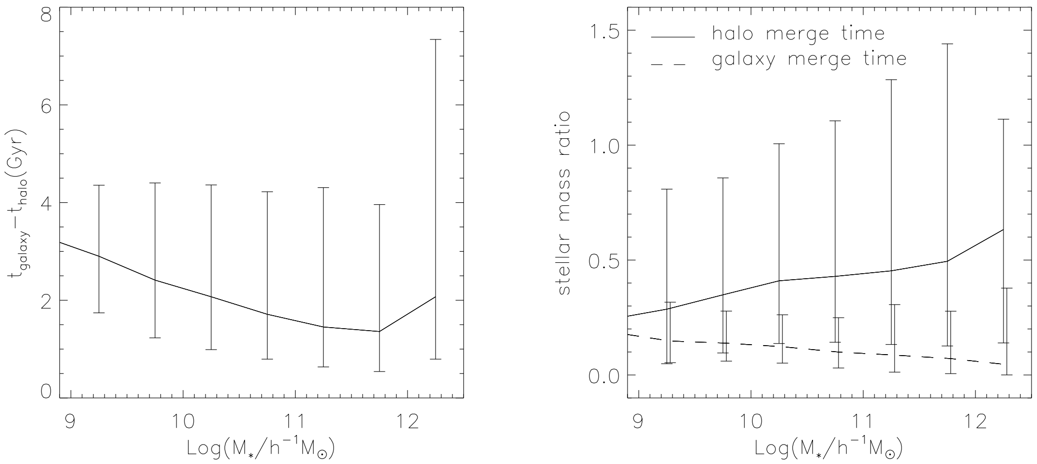

Figure 4. Some characteristics of the merging events with the highest stellar mass ratios that take place during the history of a galaxy: Left: the average time delay between the time that the progenitor haloes merge and the time that the central galaxies merge. Right: the stellar mass ratio of the galaxies at the time that the haloes merge (solid line) and at the time when the central galaxies merge (dashed line). All results are plotted as a function of the stellar mass of the central galaxy and error bars show the 68 percentile dispersion around the mean value.

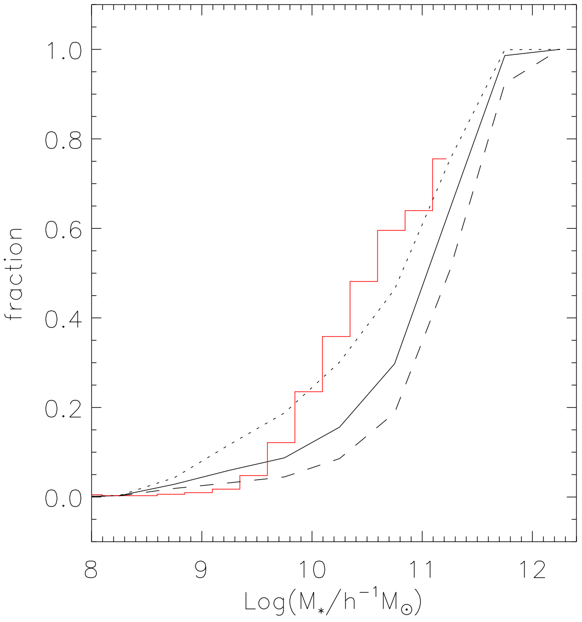

Figure 5. The solid curve shows the fraction of galaxies of given stellar mass that are predicted to have experienced at least one major merger. The red histogram shows the fraction of SDSS galaxies with $z < 0.06$ that are classified as AGN. The dotted and dashed lines show the results from simulation when the mass ratio threshold for defining major merger is changed to 0.2 and 0.4.

zero at $M_* < 10^{10}h^{-1}M_\odot$ to nearly unity at stellar masses greater than $10^{11}h^{-1}M_\odot$. In Fig. 5, the dotted and dashed lines show the results from simulation when the mass ratio threshold for defining major merger is changed to 0.2 and 0.4. Compared with the solid line where we use 0.3 as the mass ratio threshold to define a major merger, the increasing trends are about the same for different thresholds in the range from 0.2 to 0.4.

4 FIRST BLACK HOLES

In this section, we analyze when the first major merger that produces the black hole in the galaxy is predicted to occur. In Fig. 6, we plot the distribution of the times of the first major merging events for galaxies with different present-day stellar masses. The vertical dashed lines indicate the median values of the distributions. The dotted bar in each panel indicates the fraction of galaxies in each stellar mass bin that have not experienced a major merger and are hence not included in the distribution of merging times.

As can be seen, massive galaxies experience their first major merging event at earlier epochs than less massive galaxies. Almost no new black holes form in massive galaxies at the present day. The distribution of black hole formation times in low mass galaxies is much flatter. If the bulk of the black hole mass is built up in a short period following the first major merger, this would explain why present-day massive black holes have stopped growing, while low mass black holes are still growing at a significant rate (Heckman et al. 2004).

We now assume that the black holes formed from the first major mergers of galaxies can shine and be observed for 10^7 years. By counting the numbers of such events at different redshifts, we can compute the evolution in the number density of newly formed black holes. The result is plotted as diamonds in Fig. 7. The comoving number density of such events peaks at redshift of z $\sim 2-3$, consistent with the observed peak in the number density of bright quasars (Richards et al. 2006). The decrease in the number density of newly formed black holes to high redshifts is less pro-

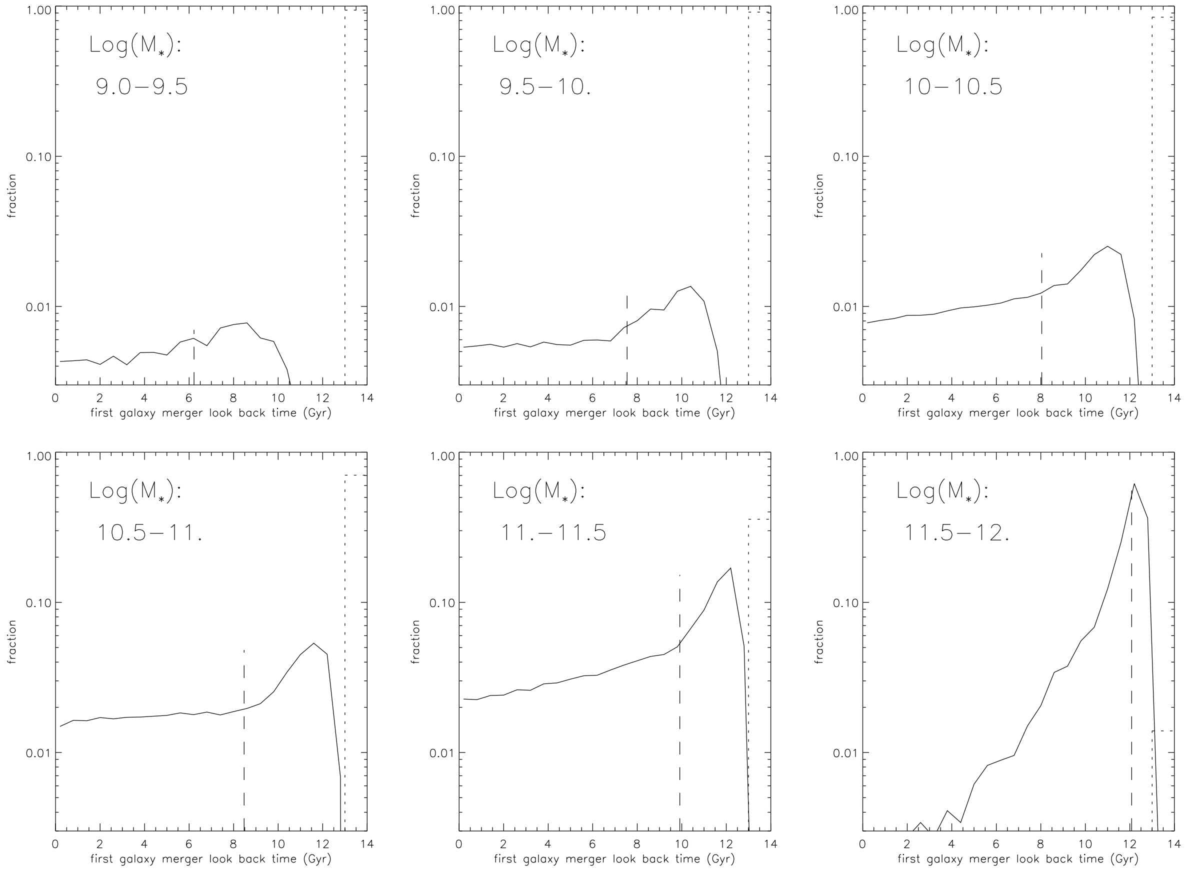

Figure 6. Distribution of time when a galaxy experiences its first major merger for galaxies in different stellar mass bins (solid lines). Galaxy stellar mass is plotted in units of $h^{-1}M_{\odot}$. The vertical dashed lines show the median value of the distributions. In each panel, the dotted bar shows the fraction of galaxies that have never experienced a major merger.

nounced than that found by Fan et al. (2001), who show that the luminous quasar density decreases by a factor of ~ 6 from redshift 3.5 to 5. Note that we have not attempted to model the predicted luminosity of the quasars in this work, so a direct comparison with the observations is not possible. As we have discussed, it is well possible that processes other than mergers contribute to the low-luminosity quasar population.

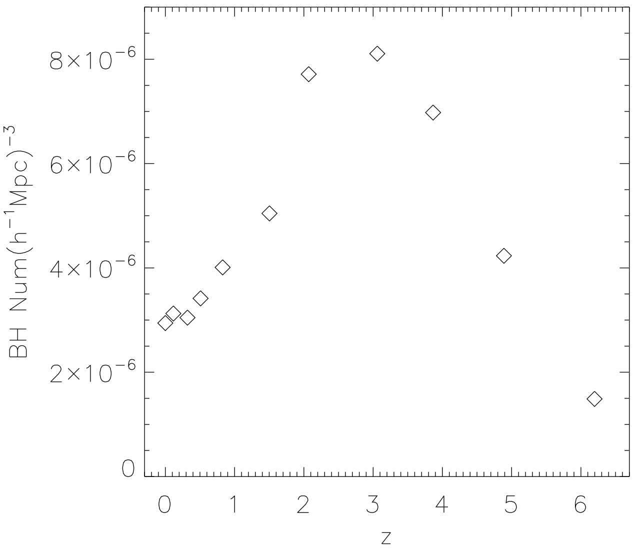

Figure 7. The number density of galaxies experiencing their first major merger (diamonds) is plotted as a function of redshift. Each merger is assumed to be visible for 10^7 years.

5 CONCLUSIONS

We analyze the merger histories of dark matter haloes and galaxies in the *Millennium Simulation* and use our results to try to understand the demographics of black holes in nearby galaxies. Black holes are assumed to form only if a major merger occurs. Although a significant fraction of low mass ($< 10^{10}M_{\odot}$) galaxies have experienced minor mergers, less than a few percent are predicted to have experienced a major merger. If our assumption that a major merger is required in order to form a black hole is correct, the majority of low mass galaxies are predicted not to contain black holes at the present day. This is one possible explanation of the observed lack of AGN in low mass galaxies (Ho et al. 1997; Kauffmann et al. 2003).

We also investigate when galaxies of different stellar masses are predicted to have formed their first black holes. High mass galaxies form their first black holes at very early epochs. The distribution of formation times is almost flat as a function of lookback time for low mass galaxies. This means that if a low mass galaxy has a black hole, there is a significant probability that it formed in the last few Gigyears. We also compute the number density of newly formed black holes as a function of redshift. We find that the peak number density occurs at $z \sim 2-3$, in good agreement with the observed peak in the quasar space density. More detailed predictions for how AGN of different luminosities are expected to evolve requires a more detailed physical model for how the black holes accrete gas over the history of the Universe. In addition, in certain wavebands AGN activity might be obscured by gas and dust surrounding black hole (Hopkins et al. 2006). More detailed consideration of these issues will form the basis for future work.

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