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MAJOR GALAXY MERGERS ONLY TRIGGER THE MOST LUMINOUS ACTIVE GALACTIC NUCLEI

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ABSTRACT

Using multiwavelength surveys of active galactic nuclei (AGNs) across a wide range of bolometric luminosities ($10^{43} < L_{\rm bol}$ (erg s^{-1}) $< 5 \times 10^{46}$) and redshifts ($0 < z < 3$), we find a strong, redshift-independent correlation between the AGN luminosity and the fraction of host galaxies undergoing a major merger. That is, only the most luminous AGN phases are connected to major mergers, while less luminous AGNs appear to be driven by secular processes. Combining this trend with AGN luminosity functions to assess the overall cosmic growth of black holes, we find that ~50% by mass is associated with major mergers, while only 10% of AGNs by number, the most luminous, are connected to these violent events. Our results suggest that to reach the highest AGN luminosities—where the most massive black holes accreted the bulk of their mass—a major merger appears to be required. The luminosity dependence of the fraction of AGNs triggered by major mergers can successfully explain why the observed scatter in the M–σ relation for elliptical galaxies is significantly lower than in spirals. The lack of a significant redshift dependence of the $L_{\rm bol}$–$f_{\rm merger}$ relation suggests that downsizing, i.e., the general decline in AGN and star formation activity with decreasing redshift, is driven by a decline in the frequency of major mergers combined with a decrease in the availability of gas at lower redshifts.

Key words: galaxies: active – galaxies: interactions – galaxies: Seyfert – X-rays: diffuse background – X-rays: galaxies

Online-only material: color figures

1. INTRODUCTION

Theoretical models have shown that the energy output from a growing supermassive black hole can play a fundamental role in the star formation history (Silk & Rees 1998; King 2003). While it is clear now that most galaxies contain a supermassive black hole in their center, in only relatively few cases is this black hole actively growing. This indicates that black hole growth is most likely episodic, with each luminous event lasting $\sim 10^7$–10^8 yr (Di Matteo et al. 2005). Hence, an obvious question is, what triggers these black hole growth episodes?

Major galaxy mergers provide a good explanation, since as simulations show, they are very efficient in driving gas to the galaxy center (Barnes & Hernquist 1991), where it can be used as fuel for both intense circumnuclear star formation and black hole growth. Indeed, a clear link between quasar (high-luminosity active galactic nuclei (AGNs)) activity and galaxy mergers has been seen in intensely star-forming galaxies like ultraluminous infrared galaxies and in some luminous quasars (e.g., Sanders et al. 1988). In contrast, many AGNs are clearly not in mergers or especially rich environments (De Robertis et al. 1998). Instead, minor interactions (Moore et al. 1996), instabilities driven by galaxy bars (Kormendy & Kennicutt 2004), and other internal galaxy processes might be responsible for these lower activity levels. Understanding the role of mergers is further complicated by the difficulty of detecting merger signatures at high redshifts.

In order to reconcile these potentially contradictory observations, it has been suggested that the AGN triggering mechanism is a function of luminosity and/or redshift (Finn et al. 2001 and others). More recently, Hopkins & Hernquist (2009a) used five indirect tests to conclude that the triggering mechanism is strongly luminosity-dependent and more weakly redshift-dependent, so that only the most luminous sources, which are preferentially found at $z > 2$, are triggered by major mergers. Thanks to results from large AGN surveys, which now include heavily obscured IR-selected sources, and recent deep high-resolution observations carried out with the *Hubble* WFC3 detector, it is now possible to obtain reliable morphological information even for high-z, low-luminosity sources. In this Letter we determine directly whether accreting black holes over a broad luminosity range are hosted by galaxies undergoing a major merger. We use visual inspection to find tidal tails, prominent clumps of dust and/or star formation, or other indicators of recent major mergers that would suggest they could act as triggers for the black hole growth episode. Our sample covers over three decades in luminosity and redshifts $z \sim 0$–3 and thus removes the usual luminosity–redshift degeneracy in flux-limited samples. Where needed, we assume a ΛCDM cosmology with $h_0 = 0.7$, $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$.

2. ANALYSIS OF ARCHIVAL OBSERVATIONS

To measure the fraction of AGNs hosted by a galaxy undergoing a major merger as a function of luminosity and redshift, we compiled information from AGN samples selected from X-ray, infrared, and spectroscopic surveys. X-ray surveys currently provide the most complete and cleanest AGN samples (Brandt & Hasinger 2005); the deepest X-ray surveys performed with *Chandra* and *XMM* are sensitive up to column densities of $N_{\rm H} \sim 10^{23}$ (e.g., Treister et al. 2004), i.e.,

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Table 1
Properties of AGN Surveys Studied in This Work

Survey	Morphological Classification	Sources	Redshift	Luminosity (10^{44} $L_{\rm bol}$ erg s^{-1})	Merger Fraction	Symbol
Veron-Cetty & Veron (1991)	Bahcall et al. (1997)	20	$z < 0.3$	33–300	65%	Black triangle
Glikman et al. (2007)	Urrutia et al. (2008)	13	$0.4 < z < 1$	42–500	85%	Black square
Kauffmann et al. (2003)	Koss et al. (2010)	72	$z < 0.05$	0.03–3	4%	Black circle
Georgakakis et al. (2009)	Georgakakis et al. (2009)	80	$0.5 < z < 1.3$	0.1–20	20%	Blue pentagon
Tueller et al. (2010)	Koss et al. (2010)	72	$z < 0.05$	1–10	25%	Blue circle
Hasinger et al. (2007)	Cisternas et al. (2011)	140	$0.3 < z < 1$	2–20	15%	Blue square
Luo et al. (2008)	Schawinski et al. (2011)	23	$1.5 < z < 3$	0.1–20	9%	Blue cross
Xue et al. (2011)	Kocevski et al. (2012)	72	$1.5 < z < 2.5$	0.1–20	16.7%	Blue triangle
Frayer et al. (2009)	Kartaltepe et al. (2010)	354	$0.1 < z < 2$	1–300	5%–60%	Red triangles
Treister et al. (2009a)	Schawinski et al. (2012)	28	$z \sim 2$	$\sim$10	25%	Red square

heavily obscured, nearly Compton thick, sources. In order to properly sample the luminosity–redshift plane we follow the so-called wedding cake scheme, which combines wide, shallow surveys that sample the rare and/or high-luminosity sources, with deep, narrow-field imaging that reaches high-redshift and/or low-luminosity AGNs. Specifically, in this work we compile results from the $z \simeq 0$ measurements of *Swift*/BAT-detected AGNs (Koss et al. 2010), moderate luminosity AGNs at $z \sim 1$ in the COSMOS (Cisternas et al. 2011), AEGIS, and GOODS (Georgakakis et al. 2009) fields, and moderate luminosity AGNs at $z \sim 2$ in the CDF-S/CANDELS field (Schawinski et al. 2011; Kocevski et al. 2012). Despite the range of flux limits, this collective X-ray sample still shows the strong correlation between luminosity and redshift expected from flux-limited surveys. As a consequence, it becomes difficult to disentangle the possible effects of luminosity and redshift on the fraction of AGNs triggered by galaxy mergers.

To widen the coverage of the luminosity–redshift plane and to increase the completeness of our sample by reaching more heavily obscured sources, we incorporate AGN candidates selected from infrared observations. In particular, we incorporate the IR-selected AGNs at observed-frame 24 μm (Schawinski et al. 2012) and 70 μm (Kartaltepe et al. 2010) in the CDF-S and COSMOS fields, respectively. Finally, we complement these samples with AGNs selected from the Sloan Digital Sky Survey survey based on their narrow high-ionization emission lines (Kauffmann et al. 2003), as reported by Koss et al. (2010), and the high-luminosity optical and near-IR quasars studied by Bahcall et al. (1997) and Urrutia et al. (2008), respectively. The samples used in this work are described in Table 1.

The goal is to determine the physical mechanism(s) that provoked the AGN activity identified in these surveys. We separate sources into those that present evidence of external interactions (e.g., galaxy mergers) and those in which no signs of interactions are visible, based on the morphology of the AGN host galaxy. We expect that AGNs triggered by external interactions will present distorted morphologies, obvious signs of interactions, and/or close neighbors. Morphologies of AGN host galaxies have been estimated before using automatic classifications (e.g., Grogin et al. 2005), and two-dimensional surface brightness fitting (Sánchez et al. 2004). However, as shown by simulations, using model-independent parameters such as the CAS (concentration–asymmetry–clumpiness) and the Gini coefficient in many cases can fail to identify major mergers (Lotz et al. 2008), while surface brightness fitting typically involves assumptions of asymmetry that often break down in the case of major mergers, and additionally requires careful separation of nuclear light from host galaxy when used with AGNs (Simmons & Urry 2008; Koss et al. 2011). Hence, visual classification is still the most reliable option to determine if a galaxy is experiencing a major merger (Darg et al. 2010). Therefore, we focus here on surveys with visual merger classifications. For each survey we used the original classifications given by the authors, which in most cases were determined by several independent visual inspections. We do not find evidence for significant differences in the classification criteria from survey to survey.

The fraction of AGNs linked to galaxy mergers in these samples has been computed by dividing the number of AGNs in which the host galaxy has been classified as an ongoing merger or as having major disturbances by the total number of AGNs. Figure 1 shows the fraction of AGNs showing mergers as a function of bolometric luminosity, which increases rapidly, from $\sim$4% at 10^{43} erg s^{-1} to $\sim$90% at 10^{46} erg s^{-1}. We parameterize this dependence as a linear relation of the fraction of AGNs showing mergers with luminosity,

$$\mathrm{frac}(L) = \frac{\log(L_{\rm bol}) - 43.2}{4.5}, \tag{1}$$

or as a power law,

$$\mathrm{frac}(L) = \left(\frac{L_{\rm bol}}{3 \times 10^{46}\,\mathrm{erg\,s^{-1}}}\right)^{0.4}. \tag{2}$$

Both of these parameterizations, which provide good fits to the observed data, are shown in Figure 1. In order to assess the significance of this dependence, we compute the Pearson correlation coefficient for frac(L) and log$L$, finding a high value of $\sim$0.9, which indicates that a statistically strong linear correlation exist between these two quantities. This correlation is also observed in individual samples, such as the infrared-selected sources in the COSMOS field (Kartaltepe et al. 2010), confirming that this correlation is not due to differences in classification schemes among different samples. We also test for possible correlations with other parameters. Interestingly, we do not find a significant correlation between redshift and the fraction of AGNs in major mergers (Pearson correlation coefficient of $\sim$0.2), as is apparent in the right-hand panel of Figure 1. Nor do we find a significant correlation between luminosity and redshift (Pearson coefficient $\sim$0.3), indicating that we are properly sampling the luminosity–redshift plane and thus high-luminosity sources are not preferentially at high redshifts. Our results suggest that while high-luminosity AGNs triggered by major mergers are more common at high redshifts because of the increase of merger rate with redshift (e.g., Kartaltepe et al. 2007), this is not the dominant effect in determining the AGN triggering mechanism.

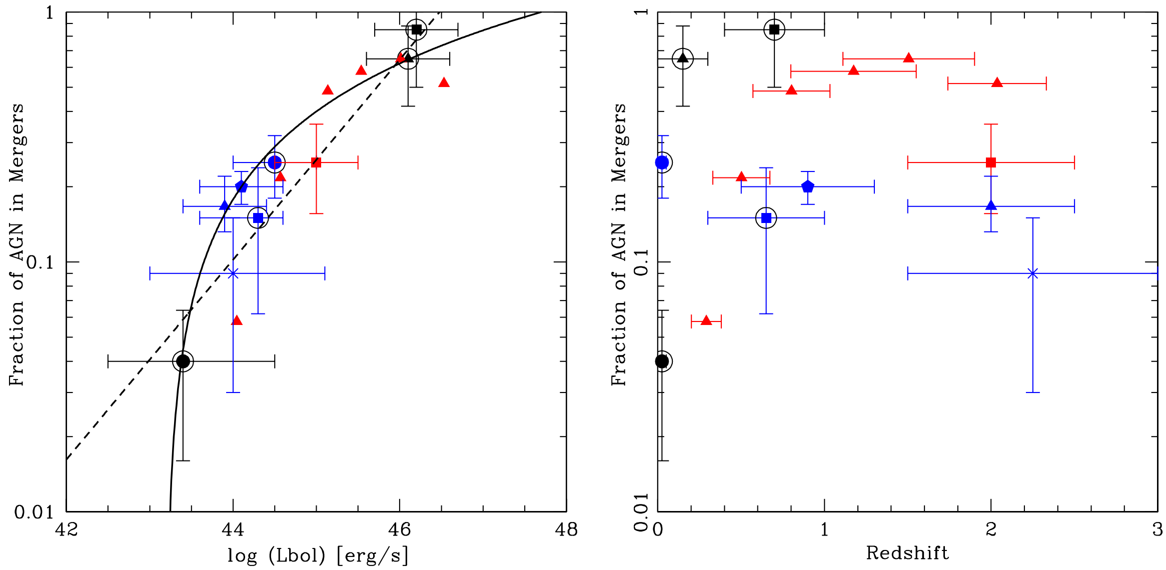

Figure 1. Left panel: fraction of AGNs showing mergers as a function of the AGN bolometric luminosity. Colors indicate the AGN selection method (red: infrared, blue: X-rays, black: optical). Symbols used for each survey are presented in Table 1. Encircled symbols show samples at $z < 1$. Solid line shows a fit to the data assuming a linear dependence of the fraction on $\log(L_{\rm bol})$, while the dashed line assumes a power-law dependence. Right panel: fraction of AGNs showing mergers as a function of redshift. There is a clear luminosity dependence, but no redshift dependence, suggesting that redshift is a second-order effect in determining the dominant AGN triggering mechanism.

(A color version of this figure is available in the online journal.)

It seems unlikely that major mergers do not trigger AGN activity, and that it is instead caused by something else. Specifically, it was observed that the merger rate increases not only with redshift as reported above but also with galaxy mass (e.g., Hopkins et al. 2010). In contrast, the distribution of AGN luminosities is independent of stellar mass (Aird et al. 2012). Hence, we conclude that the observed increase in the fraction of AGNs showing mergers with luminosity is directly linked to the triggering mechanism rather than to the galaxy mass. Furthermore, despite the fact that galaxy mergers are known to increase with redshift, our results indicate that AGN bolometric luminosity (and thus accretion rate) is the largest factor. Establishing the possible presence of other evolutionary effects in the AGN triggering mechanism would require, in addition, measuring the fraction of AGNs in mergers relative to the total merger population, which is beyond the scope of the present work.

3. CONTRIBUTION OF BLACK HOLE GROWTH TO THE EXTRAGALACTIC X-RAY AND UV LIGHT

We combine the observational results reported here with existing AGN luminosity functions in order to establish the importance of galaxy mergers in the growth of supermassive black holes in terms of the total accreted mass. In order to do this, we incorporate the linear parameterization of the luminosity dependence of the dominant AGN triggering mechanism (Equation (1)) into the X-ray luminosity function and evolution of Aird et al. (2010), combined with the distribution of obscuration and evolution of heavily obscured sources of Treister et al. (2009b, 2010). While the original work of Treister et al. (2009b) was based on the X-ray luminosity function of Ueda et al. (2003), only small differences are found if the luminosity function of Aird et al. (2010) is used instead.

The spectral shape and intensity of the extragalactic X-ray light (also known as the X-ray background) can tell us about the average properties of the AGN population. Using the models of Treister et al. (2009b) with the AGN luminosity function of

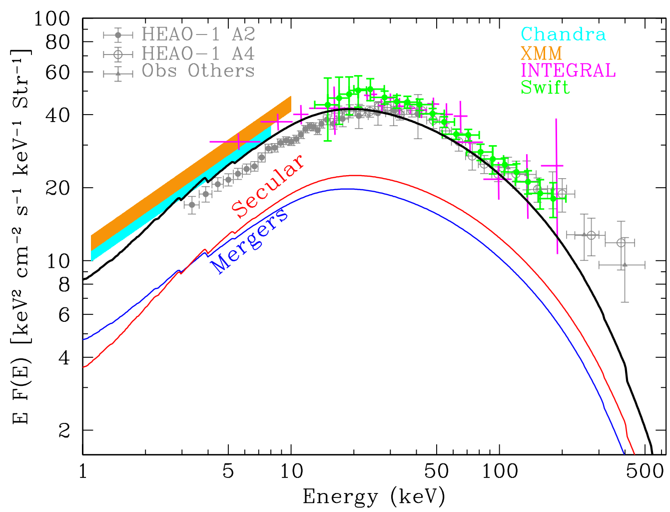

Figure 2. Spectral energy distribution of the extragalactic X-ray "background" (which is actually the sum of AGN emission), as a function of observed-frame energy. Observational data points are summarized by Treister et al. (2009b). Merger-triggered AGNs (blue line) contribute roughly equal amounts of light as black hole growth (red line). Most of the X-ray background emission comes from $z < 1$ (Treister et al. 2009b), hence the relative importance of secularly triggered AGNs. The extragalactic background light from higher redshift AGNs peaks in the optical/UV and is dominated by luminous, merger-triggered AGNs. The spectral shapes of the merger and secular contributions are slightly different since the fraction of obscured sources is a function of luminosity.

(A color version of this figure is available in the online journal.)

Aird et al. (2010) and the luminosity dependence of the fraction of AGNs triggered by major mergers, we can estimate their contribution to the background radiation in X-rays. In Figure 2 we show separately the contributions to the X-ray background from AGNs triggered by secular processes and major mergers, which contribute nearly equally to the X-ray background. This is because most of the X-ray background comes from $z < 1$ sources (e.g., Treister et al. 2009b), where AGN activity

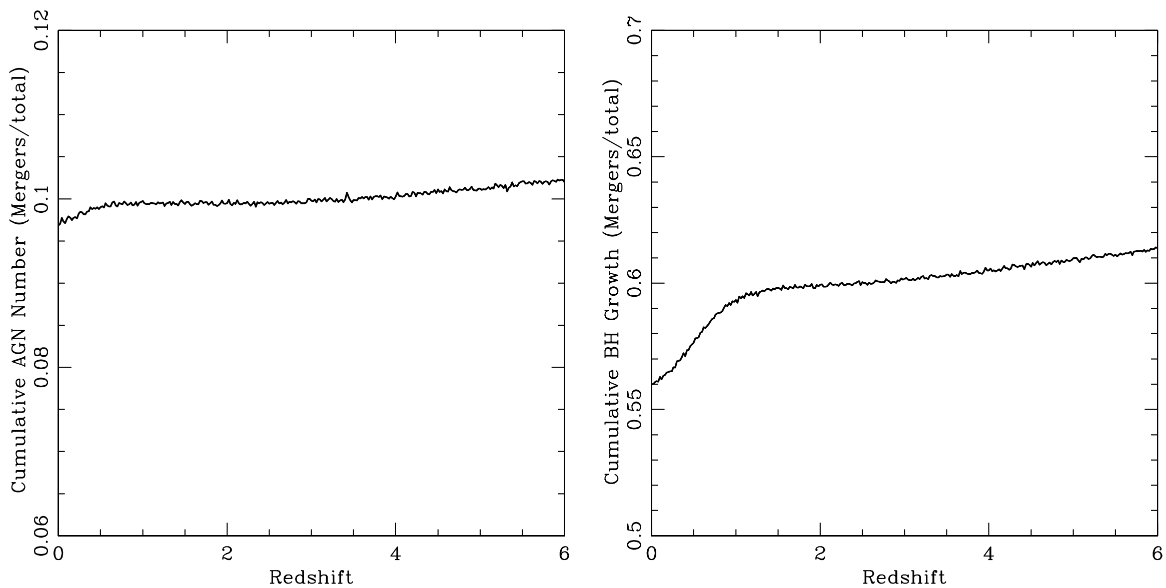

Figure 3. Left panel: cumulative number of merger-triggered AGNs relative to the total number of AGNs as a function of redshift. While secular-triggered AGNs vastly outnumber those triggered by major mergers, by about a factor of $\sim$10, the latter are on average significantly more luminous, thus explaining why they constitute $\sim$60% of black hole accretion. Right panel: cumulative fraction of black hole accreted mass in AGNs triggered by mergers as a function of redshift, assuming a constant efficiency for converting mass to light. Black hole accretion is dominated by merger-triggered AGNs at all redshifts but especially at $z > 1$. At $z \sim 1$, the much lower gas and merger fractions lead to a dominance of secular processes in AGN accretion.

due to secular processes is relatively more important. This is particularly true at $E > 10$ keV, where AGN emission is roughly unaffected by obscuration. Because of the luminosity dependence of the fraction of obscured AGNs (e.g., Ueda et al. 2003), AGNs triggered by secular processes are relatively more obscured than those attributed to major galaxy mergers, which explains the different spectral shapes in Figure 2 and the fact that AGNs triggered by mergers are more important at $E < 5$ keV. We note that a population of high-luminosity heavily obscured quasars likely associated with major mergers have been reported by Treister et al. (2010) and others. These sources are mostly found at $z \sim 2$ and show evidence of very high, Compton thick, levels of obscuration. Hence, these sources do not contribute significantly to the X-ray background radiation at any energy.

At UV wavelengths, the picture is quite complementary. The moderate luminosity AGNs ($L_X \sim 10^{43-44}$ erg s^{-1} or $L_{\rm bol} \sim 10^{44-45}$ erg s^{-1}) tend to be obscured but Compton thin, so while bright in X-rays their rest-frame optical and UV light is completely absorbed. Meanwhile, high-luminosity AGNs tend to have strong UV emission, so they make up most of the extragalactic UV light; most are found at $z \sim 2$ and are likely linked to the later stages of a major galaxy merger.

4. IMPLICATIONS FOR BLACK HOLE GROWTH

In Figure 3 we show, as a function of redshift, the amount of black hole growth and number of AGNs triggered by major galaxy mergers relative to those associated with secular processes. As can be seen and was previously reported (e.g., Treister et al. 2010), black hole growth occurs mostly in accretion episodes triggered by major galaxy mergers, although secular processes are still important. This is particularly true at $z \gtrsim 2$, where there is $\sim$60% more black hole growth in merger-triggered AGNs than in those growing via secular processes. At lower redshifts, there are relatively fewer galaxy mergers and so secular processes become slightly more important. Furthermore, at lower redshifts dry mergers become more common than gas-rich major mergers (Kauffmann & Haehnelt 2000). Since the availability of gas is a critical factor in determining the black hole accretion rate, this further explains why major mergers are relatively more important at high redshifts. It is interesting to note that the diminishing role of mergers coincides with the decline in the space density of black hole growth and with the observed decline in the cosmic star formation rate (Dahlen et al. 2007), i.e., cosmic downsizing. Integrated over the whole cosmic history, to $z = 0$, 56% of the total black hole growth can be attributed to major galaxy mergers.

In terms of numbers, the population is strongly dominated by secularly triggered AGNs. Indeed, as can be seen in Figure 3, $\sim$90% of AGNs at all redshifts are associated with secular processes. This explains the conclusions of previous studies, mostly based on X-ray surveys (e.g., Cisternas et al. 2011; Schawinski et al. 2011; Kocevski et al. 2012) of moderate luminosity AGNs, which found that normal disk-dominated galaxies constitute the majority of the AGN host galaxies. So, we conclude that while most AGNs are triggered by secular processes, most of the black hole growth, particularly at high redshifts, can be attributed to intense accretion episodes linked to major galaxy mergers.

This calculation adopts the simplifying assumption that the accretion efficiency, average Eddington ratios, and AGN duty cycle are constant and the same for secular and merger-triggered AGNs. While this is obviously an idealized approach, it is justified by the good agreement between model results and observations of the integrated black hole mass function at $z = 0$ (Treister et al. 2009b). Recently, Draper & Ballantyne (2012) reported a more sophisticated simulation, in which they assumed a distribution of Eddington ratios (and in general AGN light curves) for secular and merger-triggered AGNs. Qualitatively, however, the results are very similar and consistent.

While it is clear that at the major galaxy mergers are responsible for the highest luminosity events, it is expected that these AGNs while eventually fade to lower luminosities. According to model AGN light curves (e.g., Hopkins & Hernquist 2009b), the nuclear luminosity can decrease by $\sim$4 orders of magnitude in $\sim 10^8$ yr. This is much shorter than the typical duration of the merger sequence, $\sim 10^9$ yr (Di Matteo et al. 2005). Hence, it is unlikely that sources classified as secularly triggered correspond to merger-triggered AGNs in which the merger signatures are lost. Furthermore, and as shown by, e.g., Simmons et al. (2011), most low-luminosity AGNs show significant disks, and thus they probably did not experience a relatively recent major merger.

Our results so far refer only to the integrated black hole growth. Assuming that the Eddington ratio does not depend strongly on black hole mass (Woo & Urry 2002), it is clear that the most massive black holes are gaining most of their mass in episodes triggered by major mergers at relatively high redshifts, $z \gtrsim 1.5$. Smaller black holes are either growing slowly at all redshifts in episodes not related to major mergers or are experiencing their first significant growth episodes at relatively low redshifts $z < 1$. Once massive black holes have acquired most of their mass, they can continue growing in low-luminosity systems at low Eddington rates which are most likely triggered by secular processes (Simmons et al. 2011). This is consistent with the general downsizing paradigm, in the sense that the biggest black holes grow faster and are the first ones to accrete most of their mass, while lower mass black holes are formed later (e.g., Ueda et al. 2003). We also note that there will be a decline, with decreasing redshift, in the effectiveness of major mergers at triggering black hole growth, as the gas supply is used up and dry mergers begin to predominate.

These results can also help explain the observed scatter in the M–σ and M–L relations. Theoretically, it is expected that black hole growth triggered by major galaxy mergers leads to a tighter M–σ relation compared to growth due to stochastic processes (Hopkins & Hernquist 2009a). This is because the former affects both black hole growth and bulge formation simultaneously. Indeed, the scatter of the M–σ relation for elliptical galaxies is observed to be significantly lower than for spiral galaxies (Gültekin et al. 2009). It is possible that the scatter depends more on black hole mass than host galaxy type, since ellipticals host more massive black holes than spirals (e.g., Gültekin et al. 2009), but this is also consistent with the expectations from major mergers, which should produce the largest growth spurts.

In summary, we report a strong observational correlation between the AGN bolometric luminosity and the fraction of AGNs hosted by galaxies undergoing major mergers. In contrast, we find no significant evidence for a correlation between this fraction and redshift. This strongly suggests that at all redshifts, vigorous accretion episodes are directly linked to major galaxy mergers, while less significant nuclear activity is most likely triggered by secular processes. Hence, just having galaxies with large amounts of gas and dust is not enough to trigger intense black hole growth, and to reach the highest black hole masses requires at least one quasar episode ignited by a galaxy merger. These happen preferentially at high redshift, providing a natural explanation for the downsizing of black hole growth and star formation. We conclude that the triggering mechanism is the most relevant factor in determining the AGN luminosity and hence the black hole accretion rate. By incorporating this luminosity dependence into AGN population synthesis models we find that merger-triggered AGNs and those triggered by secular processes contribute roughly equally to the extragalactic X-ray background emission. While $\sim$90% of the AGNs by number are triggered by secular processes, $\sim$50%–60% of the total black hole growth is due to nuclear activity ignited by major galaxy mergers.

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