Tracing the cosmological assembly of stars and supermassive black holes in galaxies

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ABSTRACT
We examine possible phenomenological constraints for the joint evolution of supermassive black holes (SMBH) and their host spheroids. We compare all the available observational data on the redshift evolution of the total stellar mass and star formation rate density in the Universe with the mass and accretion rate density evolution of supermassive black holes, estimated from the hard X-ray selected luminosity function of quasars and active galactic nuclei (AGN) for a given radiative efficiency, $\epsilon$. We assume that the ratio of the stellar mass in spheroids to the black hole mass density evolves as $(1+z)^{-\alpha}$, while the ratio of the stellar mass in disks + irregulars to that in spheroids evolves as $(1+z)^{-\beta}$, and we derive constraints on $\alpha$, $\beta$ and $\epsilon$. We find that $\alpha > 0$ at the more than 4-sigma level, implying a larger black hole mass at higher redshift for a given spheroid stellar mass. The favored values for $\beta$ are typically negative, suggesting that the fraction of stellar mass in spheroids decreases with increasing redshift. This is consistent with recent determinations that show that the mass density at high redshift is dominated by galaxies with irregular morphology. In agreement with earlier work, we constrain $\epsilon$ to be between 0.04 and 0.11, depending on the exact value of the local SMBH mass density, but almost independently of $\alpha$ and $\beta$.

Key words: black hole physics – galaxies: active – galaxies: evolution – galaxies: nuclei – galaxies: stellar content – quasars: general – cosmology: miscellaneous

1 INTRODUCTION
Recent work has shown that supermassive black holes (SMBH) are ubiquitous in the centers of nearby galaxies. The observational evidence indicates that the mass of the central black hole is correlated with spheroid luminosity and mass (e.g., Kormendy and Richstone 1995; Magorrian et al. 1998) and also with the velocity dispersion of the spheroid (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002), suggesting that the process that leads to the formation of galactic spheroids must be intimately linked to the growth of the central SMBH. In addition, studies of active galactic nuclei (AGN) hosts in the local universe with the Sloan Digital Sky Survey (SDSS) have also shown that AGN activity is closely related to star formation in local galaxies (Kauffmann et al. 2003; Heckman et al. 2004). From a theoretical perspective, several groups have attempted to investigate the link between the cosmological evolution of QSOs and formation history of galaxies within the context of semi-analytic and numerical models of galaxy formation and evolution (e.g., Monaco et al. 2000; Kauffmann & Haehnelt 2000; Wyithe & Loeb 2003; Di Matteo et al. 2003; Granato et al. 2004; Haiman, Ciotti & Ostriker 2004).

In this paper we make a phenomenological investigation of the link between the growth of black holes and the buildup of their spheroidal hosts over time. Specifically, we compare the evolution of the black hole mass density, $\rho_{BH}$, to that of the observed mass density of stars in galaxies, $\rho_*$, and derive constraints on their co-evolution.

To derive $\rho_{BH}$ as a function of redshift, we use the recently determined mass density of local black holes (Yu & Tremaine 2002; Aller & Richstone 2002; Marconi et al. 2003; Shankar et al. 2004), and evolve it back to $z \sim 3$ using the observed AGN X-ray luminosity functions (see also Merloni 2004 and references therein). The black hole assembly history gathered in such a way assumes that the majority of black hole growth is due to mass accretion and hence is a function of the efficiency associated with mass to (radiative) energy conversion. This provides directly the evolution of mass accretion rate density as well, given by $\dot{\rho}_{BH} \equiv \Psi_{BH}$.

To constrain the build-up of stars in the Universe we use the independent measurements of the total star formation rate density ($\Psi_*$) and the total stellar mass density ($\rho_*$) evolution. Because current observations indicate that the black hole mass in galaxies is related to the spheroidal component, we will split up the observed $\rho_*$ into two terms. We will hereafter refer to the mass density of stars in spheroids and disks + irregulars as $\rho_{sph}$ and $\rho_{disk+irr}$, respectively. In addition to counting the mass contribution from pure spheroid, disk, and irregular galaxies, these terms also include masses in the spheroid and disk components of individual galaxies. Estimates of the ratio of $\rho_{disk+irr}$ to $\rho_{sph}$ at $z = 0$ differ by more than a factor of 5, ranging from 0.2-0.3 (Salucci & Persic 1999; Fukugita, Hogan & Peebles 1998; Fukugita & Peebles 2004) to 1.0-1.2 (Schechter & Dressler 1987; Benson et al. 2002). The redshift evolution of
this ratio should depend not only on the rate of star formation in galaxies of different morphologies at different epochs, but also on the role of mergers, interactions, and secular instabilities in determining galaxy morphology. Both from the theoretical and observational point of view, such an evolution has been so far very hard to quantify (see e.g. Baugh, Cole & Frenk 1996; van den Bosch 1998; Brinchmann & Ellis 2000; Conselice et al. 2004; Combes 2004).

The rest of the paper is organized as follows. In Section 2 we briefly summarize and describe recent measurements of \( \rho_* \) and \( \Psi_* \) as functions of redshift. In Section 3 we derive the black hole mass density evolution using the X-ray luminosity function and the local black hole mass function. Under the assumption that \( \rho_{\text{ph}}(z) \propto \rho_{\text{BH}}(z)(1+z)^{-3} \) and that, at the same time, \( \rho_{\text{disk+irr}}/\rho_{\text{ph}} \) evolves as \( (1+z)^{-3} \), we then compare the history of black hole and total stellar mass assembly in the Universe and derive our global constraints on \( \alpha, \beta \), and \( \beta \) (Section 4). Finally, in Section 5 we summarize and discuss our results and explore their implications.

Throughout this paper, we adopt a background cosmological model in accordance with the Wilkinson Microwave Anisotropy Probe (WMAP) experiment. The model has zero spatial curvature, a cosmological constant, \( \Omega_m = 0.71 \) a Hubble constant \( H_0 = 72 \text{ km s}^{-1} \), dominated by cold dark matter with \( \Omega_m = 0.29 \) and \( \Omega_b = 0.047 \) (Spergel et al. 2003).

### 2 THE STELLAR MASS DENSITY EVOLUTION

In this work we make use of all available measurements of the stellar mass and star formation rate densities from the literature. The stellar mass density, \( \rho_* \), has been measured in the redshift range from \( z = 0 \) to \( z \sim 3 \) from surveys that select galaxies by rest-frame optical or Near Infrared (NIR) light and, in general, estimate the stellar masses and mass-to-light ratios of individual galaxies by fitting spectral synthesis models to optical/NIR spectral energy distributions (see e.g. Brinchmann & Ellis 2000; Cole et al. 2001; Dickinson et al. 2003; Fontana et al. 2003; Drory et al. 2004). One exception is Rudnick et al. (2003) who have determined the evolution in \( \rho_* \), from the change in the luminosity density and the mass-to-light ratio, the latter being determined by using simple models to interpret the cosmically averaged rest-frame optical colors. Although cosmic variance is a dominant source of error for all but the local values, all support a scenario in which \( \rho_* \) at \( z \sim 3 \) was a factor of \( \sim 7-20 \) times lower when it was today and that roughly 50% of the current stellar mass was assembled by \( z = 1-1.5 \).

The measurements of \( \rho_* \) as a function of redshift also match well with the independently measured integrated global star formation rate density (SFR). The SFR measurements are usually obtained from e.g., optical emission line measurements, MIR dust luminosities, sub-mm observations, or observations of the rest-frame ultraviolet light. These typically show a rapid rise of the SFR(z) out to \( z \lesssim 1.5 \) where it peaks, followed by a roughly constant level out to at least \( z \sim 4 \) (see caption of Figure [I] for detailed references).

For the most part, not enough information exists to empirically divide \( \rho_* \) and the SFR into different morphological components. However, when comparing these data with \( \rho_{\text{BH}} \) (see below), it is necessary to take into account the fact that local black hole masses only correlate with the properties of their spheroidal hosts. We account for this by defining a parameter \( \lambda(z) \) as the ratio of the mass in disks + irregulars to that in spheroids, in the following way:

\[ \rho_*(z) = \rho_{\text{ph}}(z) + \rho_{\text{disk+irr}}(z) = \rho_{\text{ph}}(z)(1 + \lambda(z)). \]  

We then assume that \( \lambda(z) \) evolves simply according to \( \lambda(z) = \lambda_0(1+z)^{-\beta} \), where \( \lambda_0 \) is the value of the disk to spheroid ratio in the local universe.

### 3 THE BLACK HOLE MASS DENSITY EVOLUTION

Under the standard assumption that black holes grow mainly by accretion, the cosmic evolution of the SMBH accretion rate and its associated mass density can be calculated from the luminosity function of AGN \( \phi(L_{\text{bol}}, z) = \frac{dN}{dL_{\text{bol}}} \), where \( L_{\text{bol}} = \epsilon M_c^2 \) is the bolometric luminosity produced by a SMBH accreting at a rate of \( M \) with a radiative efficiency \( \epsilon \). In practice, the accreting black hole population is always selected through observations in specific wavebands. Crucial is therefore the knowledge of two factors: the completeness of any specific AGN survey, and the bolometric correction needed in order to estimate \( L_{\text{bol}} \) from the observed luminosity in any specific band.

In recent years, enormous progress has been made in understanding both of the above issues. Here we refer to the discussion of Marconi et al. (2004), who carry out a detailed comparison between optically selected QSOs from the 2dF survey (Boyle et al. 2000), soft X-ray (0.5-2 keV) selected AGN (Miyaji, Hasinger and Schmidt 2000), and hard X-ray (2-10 keV) selected ones (Ueda et al. 2003), and work out the respective bolometric corrections.

The general picture that emerges is that the 2-10 keV AGN luminosity function probes by far the largest fraction of the whole AGN population. This is primarily due to the fact that hard X-rays are less affected by obscuration than either soft X-rays or optical light (Marconi et al. 2004). It has also been shown that most of the obscured sources, which are the major contributor to the X-ray background light, (see e.g. Hasinger 2003, and references therein; Fiore 2003) have typically lower luminosity and lie at a lower redshift than the the optically selected QSOs. Therefore, the growth of SMBH (and of their associated spheroidal hosts) at \( z < 1 \) is best estimated by studying the evolution of the hard X-ray emitting AGN. At higher redshifts, optical and hard X-ray selection give consistent results (see e.g. Hasinger 2003).

In the following we will indeed assume that the absorption corrected hard X-ray luminosity function of AGN best describes the evolution of the entire accreting black holes population between \( z = 0 \) and \( z \sim 3 \). For the sake of simplicity, we will adopt for our calculations the luminosity dependent density evolution (LDDE) parameterization of the (intrinsically) 2-10 keV luminosity function described by Ueda et al. (2003).

The redshift evolution of the SMBH accretion rate density can then be easily calculated as follows:

\[ \Psi_{\text{BH}}(z) = \int_0^\infty \frac{(1-\epsilon)L_{\text{bol}}(L_X)}{c^2} \phi(L_X, z) dL_X, \]  

where \( L_X \) is the X-ray luminosity in the rest-frame 2-10 keV band, and the bolometric correction function \( L_{\text{bol}}(L_X) \) is given by eq. (21) of Marconi et al. (2004), that also takes into account the observed dependence of the optical-to-X-ray ratio \( \alpha_{\text{opt}} \) on luminosity (Vignali, Brandt & Schneider 2003). This in turn yields for the SMBH mass density:

\[ ^{1} \text{Since the stellar mass budget at low redshift is overwhelmingly dominated by spheroids and disks, } \rho_{\text{disk+irr}}(z = 0) \approx \rho_{\text{disk}}(z = 0). \text{ At high redshift, where irregulars contribute more to the stellar mass density, e.g. Brinchmann & Ellis (2000), } \rho_{\text{disk+irr}} \approx \rho_{\text{disk}} + \rho_{\text{irregular}}. \]
\[
\frac{\rho_{\text{BH}}(z)}{\rho_{\text{BH,0}}} = 1 - \int_0^z \frac{\Psi_{\text{BH}}(z')}{{\dot{\rho}}_{\text{BH,0}}} \frac{dz'}{dz}.
\]  

For any given \(\phi(L_X, z)\) and bolometric correction, the exact shapes of \(\rho_{\text{BH}}(z)\) and \(\Psi_{\text{BH}}\) then depend only on two numbers: the local black holes mass density \(\rho_{\text{BH,0}}\) and the (average) radiative efficiency \(\epsilon\).

## 4 THE JOINT EVOLUTION OF THE STELLAR AND BLACK HOLE MASS DENSITIES

Given the derived \(\rho_{\text{BH}}(z)\) above, we now want to investigate how the buildup of spheroidal mass in galaxies is related to the build up of black hole mass over time. We make the simple hypothesis that the redshift evolution of the spheroid and SMBH mass densities are related by the expression:

\[
\rho_{\text{ sph}}(z) = A_0 \rho_{\text{BH}}(z)(1 + z)^{-\alpha},
\]

where \(A_0\) is defined by:

\[
A_0 = \frac{\rho_{\text{BH,0}}}{\rho_{\text{BH,0}} - \rho_{\text{BH,0}}(1 + \lambda_0)}.
\]

For all reasonable values of \(\rho_{\text{BH,0}}, \rho_{\text{BH,0}}\), and \(\lambda_0, A_0\), is consistent with the expectation from the \(M_{\text{BH}} - M_{\text{ sph}}\) relation in the local universe (Merritt & Ferrarese 2001; Mc Lure & Dunlop 2002; Marconi & Hunt 2003; Haring & Rix 2004). Then, from eqs. 14 and 15 we obtain the desired relation between total stellar and black holes mass densities:

\[
\rho_*(z) = A_0 \rho_{\text{BH}}(z)(1 + z)^{-\alpha}[1 + \lambda_0(1 + z)^{-\beta}].
\]

Finally, the total star formation rate \(\dot{\Psi}_*\) as a function of redshift is given by:

\[
d\dot{\rho}_*(z)/dt = \dot{\Psi}_*(z) - \int_{z_1}^z \dot{\Psi}_s(z') \frac{d\mu(t)}{dt} \frac{dz'}{dz} dz',
\]

where \(\mu(t) = (1 + \lambda_0)/(1 + \lambda(t))\). With such a prescription, the fractional mass loss after 13 Gyr amounts to about 30%.

We perform a simultaneous fit to the observed stellar mass density and SFR points, assuming the functional forms of 14 and 15 above and calculating the black hole mass density evolution according to eqs. 16 and 17. We vary \(\alpha, \beta, \epsilon\) and \(\epsilon\) over the range [0, 1.5], [-2, 1], and [0.02, 0.3] respectively. In Figure 1 we show the observational data for both \(\dot{\Psi}_*(z)\) and \(\dot{\Psi}_s(z)\), together with the best fit curves, in this case calculated assuming \(\lambda_0 = 0.3\) and \(\rho_{\text{BH,0}} = 4.2 \times 10^5 M_\odot\, Mpc^{-3}\) (Marconi et al. 2004). The shaded areas represent the 1-sigma range of models allowed from the joint fitting of both datasets. It is important to note that, for different possible choices of the local values of \(\rho_{\text{BH,0}}\) and \(\lambda_0\) (see below), our best fits for \(\rho_*\) and \(\Psi_*\) are almost unchanged and always statistically acceptable, with \(\chi^2\) values typically ranging from 40 to 45, for

\[2\text{ An analogous term for }\rho_{\text{BH}}\text{, due to the ejection of SMBHs from galaxy halos after a merger event, is much more difficult to estimate (see e.g. Volonteri, Haardt & Madau (2003)) and is neglected here.}
55 degrees of freedom. Nonetheless, it is apparent from Fig. 4 that the best fit solution for $\rho_*$ systematically overpredicts the observed points in the redshift range $1.5 \lesssim z \lesssim 2$, where, however, cosmic variance plays a large role and the $\rho_*$ measurements are quite uncertain.

Also shown in Fig. 4 are the relative contributions to the total stellar mass density of $\rho_{\text{BH},0}$ and $\rho_{\text{disk},0}$. It should be stressed that such a decomposition is strongly dependent on $\lambda_0$. The relative growth in spheroids and disks + irregulars relative to their respective local values is in fact well represented by these curves, as it mainly depends on the value of $\beta$, but their absolute growth, and hence the total mass density in disks + irregulars relative to that in spheroids at any $z$, is highly dependent on the adopted value of $\lambda_0$. For example, if $\lambda_0 = 1.0$, the dashed and dotted lines in Fig. 4 will be moved vertically to attain the same value at $z = 0$.

In Figure 4 we show the results as probability contours in the 2-D parameter space ($\epsilon, \alpha$), obtained by marginalizing the total probability distribution over $\beta$, assuming a flat prior on its distribution, to be conservative. The results are shown for two possible values of the parameter $\lambda_0$ (0.3 and 1). As it is well known, a constraint on the average radiative efficiency of accreting SMBH can be obtained by comparing the total mass of the relic population in the phase (here assumed to be given by the HXLF of AGN), the total star formation rate density with eqn. 6, and fitting the low redshift points (see below) with this simple expression we obtain the relation $\alpha + \beta \lambda_0/(1 + \lambda_0)$, and fitting the low redshift points (see below) with this simple expression we obtain the relation $\alpha + \beta \lambda_0/(1 + \lambda_0)\approx 0.3$, which indeed determines the approximate direction along which the best fit parameters $\alpha$ and $\beta$ are allowed to move.

As it is expected, the lower the value of $\lambda_0$, the less constrained will the parameter $\beta$ be. A constant $\lambda(z)$ ($\beta = 0$) is allowed at the 3-sigma level only if $\lambda_0 < 0.3$, but the best fit value always correspond to a negative $\beta$, i.e. to an increase of the disk/irregulars stellar mass fraction with respect to the spheroid one with increasing redshift.

To further test the sensitivity of our constraints on $\alpha$, $\beta$ and $\epsilon$ we have also performed a fit restricted to the redshift interval $0 \leq z \leq 1$, where the observational data points are more numerous and have smaller error bars. In doing this, we have found that while the constraints on $\alpha$ and $\beta$ remain virtually unchanged, those on the radiative efficiency are much looser. In particular, for high values of the local SMBH mass density, we find that the radiative efficiency is constrained, at the 3-sigma level, between $0.04 < \epsilon < 0.11$. On the other hand, if the local SMBH mass density is as high as $\rho_{\text{BH},0} = 4.2 \times 10^5 M_\odot$ Mpc$^{-3}$, as suggested by Marconi et al. (2004), the radiative efficiency is allowed to take lower values and is constrained, at the 3-sigma level between $0.05 \lesssim \epsilon \lesssim 0.07$, as shown by the leftmost (a) contours. In fact, the range of allowed radiative efficiencies would have been larger than those shown in Fig. 4 had we also considered the uncertainties on the measures of the local black hole mass density$^3$. It is clear that there is almost complete degeneracy between $\epsilon$ and $\rho_{\text{BH},0}$, once the luminosity function of AGN is fixed. Efficiencies lower than 0.04 are excluded at the more than 4-sigma level, whatever the prior on the local SMBH mass density, provided that it is not higher than $6.5 \times 10^5 M_\odot$ Mpc$^{-3}$. This is naturally included, as black holes accreting with $\epsilon < 0.04$ build up, in the redshift interval between $z = 0$ and $z = 3$, a mass larger than this value.

Figure 5 shows the probability contours in the 2-D parameter space ($\beta, \alpha$), obtained by marginalizing the total probability distribution over $\epsilon$, assuming a flat prior on its distribution, once again calculated for two different values of $\lambda_0$. We note here that the constraints on these two parameters are almost independent of the adopted value for $\rho_{\text{BH},0}$. The two sets of contours in figure 5 can be understood as follows. At low redshifts, $\Psi_{\text{BH}} \ll 1$, and $\rho_{\text{BH}} \sim \text{const}$. Therefore, from eq. 4, we see that the observed decline of the total stellar mass density, and the corresponding increase of the star formation rate density, will be driven by the term $(1 + z)^{-\alpha}[1 + \lambda_0(1 + z)^{-\beta}]$. For low values of $z$, this term can be approximated by $(1 + z)^{-\gamma}$, with $\gamma = \alpha + \beta \lambda_0/(1 + \lambda_0)$, and fitting the low redshift points (see below) with this simple expression we obtain the relation $\alpha + \beta \lambda_0/(1 + \lambda_0)\approx 0.3$, which indeed determines the approximate direction along which the best fit parameters $\alpha$ and $\beta$ are allowed to move.

3 We note here that the main difference between the two values of $\rho_{\text{BH},0}$ comes from a higher normalization of the $M_\sigma$ relation by a factor 1.6 adopted by Marconi et al. (2004). It is beyond the scope of this letter to discuss thoroughly the reason of this discrepancy. The reader is referred to Yu and Tremaine (2002) and to Marconi et al. (2004) for such a discussion.

![Figure 2](image-url)
Tracing the cosmological assembly of stars and SMBH

Figure 3. The contours show the 1, 2 and 3 sigma confidence levels for the parameters $\alpha$ and $\beta$ obtained by simultaneously fitting the redshift evolution of the stellar mass density and of the star formation rate density with eqns. (6) and (7), respectively, and then marginalizing over the radiative efficiency of black holes, $\epsilon$, assuming a flat prior on its probability distribution between 0.02 < $\epsilon$ < 0.4. Solid contours correspond to the case in which we fix the local ratio of disk + irregular to spheroid stellar mass density to $\lambda_{0} = 0.3$, dashed contours correspond to the case of $\lambda_{0} = 1$. The two parameters are degenerate along the line $\alpha + \lambda_{0}\beta/(1 + \lambda_{0}) \approx 0.3$ (see text for details).

In summary, irrespective of all the uncertainties in the determination of $\lambda_{0}$ and in the high redshift stellar mass and star formation rate points, the data do indeed put some constraints on the redshift evolution of $\rho_{BH}/\rho_{sph}$. In particular, a constant ratio, $\alpha = 0$ is excluded at a more than 4-sigma confidence level, implying that the black hole to spheroid mass density ratio must have been larger in the past.

5 DISCUSSION

It is well known that both AGN activity and SFR decline at low redshift. Moreover, the correlation observed locally between supermassive black hole masses and global properties of their host spheroids are suggestive of a fundamental link between the formation and evolution of black holes and galaxies.

In this letter we have attempted to constrain phenomenologically the joint evolution of supermassive black holes, their host spheroids and the total stellar mass density in the universe.

We have assumed that the black hole mass density evolution is due to accretion only and that it can therefore be reliably reconstructed from the local black hole mass density and from the redshift evolution of the hard X-ray luminosity function of AGN/QSO, with the (average) radiative efficiency of accretion, $\epsilon$ as the only free parameter. We have then examined the relation between $\rho_{BH}$ and $\rho_{sph}$, assuming that the ratio of these two densities simply evolves as $(1 + z)^{-\alpha}$. Finally, we have considered the simple case in which the ratio of the stellar mass density in disk components + irregular galaxies to that of the spheroid component of galaxies evolves as $\lambda(z) \propto (1 + z)^{-\beta}$. By fitting simultaneously all the available observational data on the total stellar mass density and star formation rate density as a function of redshift, we have obtained a set of constraints on the three model parameters ($\epsilon$, $\alpha$, $\beta$), which themselves depend on the local values of $\rho_{BH}$ and $\lambda$.

We have shown that the constraint we obtain on the radiative efficiency of accretion crucially depends on the adopted value for the local black hole mass density, but not on $\alpha$ or $\beta$.

More importantly, we have shown that BH accretion does not exactly track either the spheroid nor the total star assembly (i.e. both $\alpha$ and $\gamma = \alpha + \lambda_{0}\beta/(1 + \lambda_{0})$ are larger than zero). This is the most important result of our study: irrespective of the exact mass budget in spheroids and disks + irregulars, the ratio of the total or spheroid stellar to black hole mass density was lower at higher redshift. The simultaneous fit we obtain for both $\rho_{sph}$ and $\Psi_{stellar}$ also indicates that the black hole growth rate is suppressed with respect to the total SFR at $z < 2$, as it can be seen in Figure 4 (as also shown in the cosmological simulations of Di Matteo et al. 2003).

Our findings have a direct observable consequences for the expected redshift evolution of the $M_{BH} - M_{sph}$ relationship: $\alpha > 0$ implies a larger black hole mass for a given host spheroid mass at higher redshift.

We can also compare our results with recent semi-analytical work that tries to incorporate SMBH growth and feedback into a galaxy evolution scenario. The simplest way to relate black hole mass and global galactic properties is via an energy argument, as discussed, for example, in Wyithe and Loeb (2003): a SMBH will stop growing as soon as the energy provided by accretion onto it at a fraction $\eta$ of the Eddington rate for a time $t_{Q}$ will equal the binding energy of the gas in the DM halo: $M_{BH}L_{eddy,\epsilon}t_{Q} = 2\Omega_{b}\Omega_{m}M_{halo}v_{c}^{2}$. Here, the black hole mass is in solar units, $L_{eddy,\epsilon}$ is the Eddington rate of a one solar mass black hole, $F_{Q}$ is a coupling coefficient that can be determined from the normalization of the $M_{BH} - \sigma$ relation, $\Omega_{m}$ and $\Omega_{b}$ are the matter and baryon densities, respectively, and $M_{halo}$, $v_{c}$ are the mass and circular velocity of a DM halo. Most of the feedback models in the recent literature (Kauffmann and Haenelt 2000; Cavaliere & Vittorini 2002; Menci et al. 2003; Wyithe and Loeb 2003; Granato et al. 2004) assume (sometimes implicitly) a linear proportionality between the quasar lifetime and the dynamical time of the dark matter halo in which it is embedded: $t_{Q} = t_{dyneq} \propto \xi(z)^{-1/2}(1 + z)^{-3/2}$, where $\xi(z)$ is a weak function of $z$ and depends on the cosmological parameters only (see e.g.; Barkana and Loeb 2001 for more details). Indeed, Wyithe and Loeb (2003) have shown that, if the QSO lifetime is equal to the dynamical time of a DM halo, then the $M_{BH} - \sigma$ relation does not change with redshift, while the ratio of the black hole to (spheroid) stellar mass density should evolve as $\rho_{sph}/\rho_{BH} \propto [\xi(z)]^{-1/2}(1 + z)^{-3/2} \sim (1 + z)^{-1.15}$, where the final approximation is valid for $0 < z < 2$. Comparing this with the constraints on $\alpha$ we have obtained in section 4 we see that, although marginally consistent with these simple semi-analytical schemes, and only for the high $\lambda_{0}$ case, the data clearly suggest a slower evolution for the spheroid to black hole mass ratio than that predicted by just assuming a constant $M_{BH} - \sigma$ relation at all $z$. Therefore, this would imply that the normalization of the $M_{BH} - \sigma$ relation should evolve with redshift. A caveat is however in place here, as of course $\eta$ and $F_{Q}$ in prescriptions such as those of Wyithe and Loeb (2003) may not be constant, but vary as a function of black hole mass, or mass accretion and as function of redshift (e.g.; Merloni 2004). Observational tests of the $M_{BH} - \sigma$ and $M_{BH} - M_{sph}$ relations at higher redshift (see e.g. Shields et al. 2003) will be crucial to our understanding of the interplay between black holes and their host galaxies.
Finally, our results suggest that the fraction of $r_s$, locked up into the non-spheroidal components of galaxies and in irregular galaxies should increase with increasing redshift. This result is consistent with Brinchmann & Ellis (2001) that show that the mass density in irregulars increases rapidly out to $z \sim 1$.

If we relax the assumption that black hole mass and spheroid mass densities are related at all redshifts, then $\rho_{sph}$ and $\rho_{disk+irr}$ in eq. (1) would simply correspond to the stellar mass that ends up in spheroids and disks, respectively, at $z = 0$, where we know that black hole mass and spheroid mass are related. Under this assumption, negative values of $\beta$ would imply that the stars in local spheroids were formed at a later time than the stars in present day disks. This would directly contradict the relative observed ages of disks and spheroids. On the other hand, no such contradiction occurs when using our adopted assumption, i.e. that there is a $M_{BH} - M_{sph}$ relation at all redshifts and that $\rho_{sph}$ and $\rho_{disk+irr}$ correspond, at any given redshift, to the mass in spheroids and disks + irregulars respectively. This further supports the idea that the dynamical events that lead to the assembly of spheroid stellar mass (mergers, secular instabilities, gas accretion, etc.) are directly linked to the major accretion events onto the SMBH.

The upcoming results from projects such as the GEMS (Galaxy Evolution from Morphological Studies; see Rix et al. 2004) survey, that will provide morphologies and structural parameters for nearly 10,000 galaxies at $0.2 \leq z \leq 1.1$ and their respective contributions to the mass density, will surely improve our understanding of this issue, and will possibly help us to better understand how the simultaneous evolution of black holes, spheroids, and disks in galaxies proceed.

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