BLACK HOLE DEMOGRAPHICS

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1 Introduction

It is frequently the case that revolutionary scientific ideas are first proposed and then remain dormant for years, or sometimes decades, before their importance is truly appreciated. Often, the reawakening of interest is driven by new technological developments. Such was, for instance, the case of supermassive black holes (SBHs) in galactic nuclei. By the mid 1960s, just a few years after the discovery of QSOs, it was generally recognized that their energy source must be gravitational in nature. Yet for the following three decades the existence of SBHs was destined to be surrounded by skepticism. By the mid 1990s, a few years after the launch of the Hubble Space Telescope, it was widely accepted. Today, it is generally agreed upon that SBHs play a fundamental role in the formation and evolution of their host galaxies. Freed from the burden of having to demonstrate the very existence of supermassive black holes, we can now begin asking more fundamental questions: how are black holes related to their host galaxies, how did they form, how do they accrete, how do they evolve, and what role do they play in the formation of cosmic structure?

The purpose of this contribution is to review the current status of black hole demographics. I will not address the various techniques that are used to measure black hole masses: excellent discussions can be found in the recent literature (e.g. Kormendy & Richstone 1995; Ho 1999). Neither will I discuss the somewhat tumultuous events that lead to a critical reassessment of the "Magorrian relation" (Magorrian *et al.* 1998) and its analog for local AGNs (Wandel 1999) since a full description of such events can be found elsewhere (Merritt & Ferrarese 2001c). Instead, I will revisit the issue of black hole demographics in light of recent advances in the study of high redshift QSOs (section 2), local AGNs (section 3) and local quiescent galaxies (section 4). I will then outline the prospects for future progress (section 5), and discuss what I believe will be the challenges for the years to come.

2 Black Hole Demographics: High Redshift QSOs

The existence of SBHs in the nuclei of nearby galaxies has gained popular consensus only in recent years. That supermassive black holes must power QSO activity has, however, been widely suspected since the mid 1960s (e.g. Robinson *et al.* 1965). It is therefore not surprising that the first studies of black hole demographics were conducted, over two decades ago, using optical counts of high redshift QSOs. In a seminal paper entitled "Masses of Quasars", Andrzej Soltan (1982) proposed a simple argument: QSO optical number counts yield a QSO luminosity function which can be integrated to give a mean comoving energy density in QSO light. After applying the appropriate bolometric corrections and assuming a reasonable conversion factor of mass into energy, Soltan concluded that the SBHs powering high redshift ($z > 0.3$) QSOs comprise a total mass density of $\sim 5 \times 10^4$ $M_\odot$ Mpc^{-3}, each SBH having a mass of $10^8 - 10^9$ $M_\odot$. Soltan's arguments, which have been employed many times in the following years (Chokshi & Turner 1992; Small & Blandford 1992; Salucci *et al.* 1998), lead to the inescapable conclusion that most, if not all, nearby galaxies must host dormant black holes in their nuclei. This finding has been the main driver for SBH searches in nearby quiescent galaxies and has kindled the interest in the accretion crisis in nearby galactic nuclei (Fabian & Canizares 1988), ultimately leading to the revival of accretion mechanisms with low radiative efficiencies (Rees *et al.* 1982, Narayan & Yi 1995).

Armed with recent measurements of the QSO luminosity function from the 2dF QSO Survey ($0.3 < z < 2.3$, Boyle *et al.* 2000) and the Sloan Digital Sky Survey ($3.0 < z < 5.0$, Fan *et al.* 2001), we are in a position to update Soltan's results. If $\Phi(L, z)$ is the QSO luminosity function, the cumulative mass density in SBHs which power QSO activity can be expressed as:

$$\rho_{QSO}(> M) = \frac{K_{bol}}{\epsilon c^2} \int_0^\infty \int_L^\infty \frac{L' \Phi(L', z)}{H_0(1+z)\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}} \mathrm{d}L' \mathrm{d}z \qquad (1)$$

where the mass accretion rate is simply $= K_{bol} L \epsilon^{-1} c^{-2}$, with K_{bol} the bolometric correction (from Elvis *et al.* 1986), and ϵ the energy conversion coefficient (assumed equal to 0.1). An $\Omega_\Lambda = 0.0$, $\Omega_m = 1.0$, $H_0 = 75$ km s^{-1} Mpc^{-1} cosmology is assumed for consistency in comparing the results with those derived in the following sections. The cumulative mass density due to QSO accretion is shown in Fig. 1. It should be noted that the magnitude limits of the 2dF and Sloan QSO surveys correspond to Eddington limits on the SBHs masses of 4.5×10^7 $M_\odot$ and 7.3×10^8 $M_\odot$ respectively. Cumulative mass densities down to 10^6 $M_\odot$ are calculated on the (unverified) assumption that the QSO luminosity

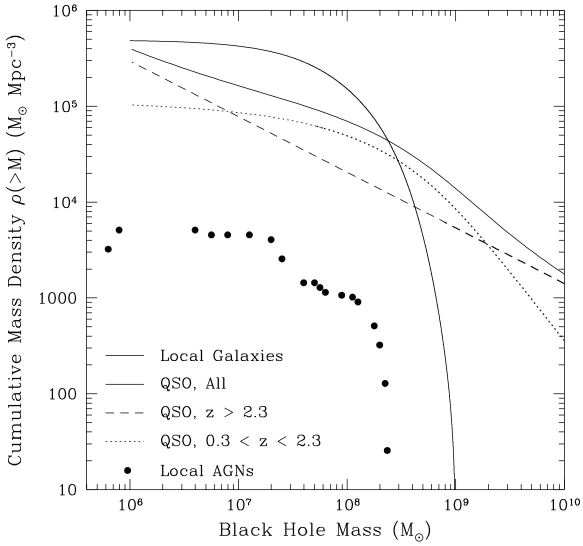


Figure 1: Comparison between the black hole mass function in high redshift QSOs (blue lines - dotted line: 2dF sample; dashed line: SDSS sample; solid line: both samples combined); local AGNs (red) and local quiescent galaxies (black, corresponding to the dotted black line in Fig. 4).

function holds at the corresponding magnitude ($B \sim -19$). Furthermore, the lower redshift limit of integration for the SDSS luminosity function was pushed down to the high redshift boundary of the 2dF survey ($z = 2.3$), although there are no QSO luminosity functions covering the $2.3 < z < 3.0$ range. For masses larger than $10^8\ M_\odot$, the extrapolation from $z = 3$ to $z = 2.3$ of the spatial density (e.g. Fig. 3 of Fan *et al.* 2001) or mass density (Fig. 7 in these proceedings) as a function of redshift from the SDSS joins rather smoothly the curve derived from the 2dF survey, therefore our assumption is likely justified. However, for smaller masses or luminosities, the SDSS mass density, extrapolated to $z \sim 2.3$, overpredicts the QSO mass density (per unit redshift) derived from the 2dF data by an order of magnitude. Thus, it is likely that the linear rise of the SBH cumulative mass density for the high redshift QSOs between 10^8 and $10^6\ M_\odot$ represents an *upper bound* to the real curve, which could have been overestimated by a factor of a few (i.e., up to $\sim$ three).

In short, the cumulative mass density from the optical QSO counts due to accretion onto high redshift QSOs ($0.3 < z < 5.0$) appears to be in the range $(2-4) \times 10^5\ M_\odot$ Mpc^{-3}. Notice that this estimate does not account for the possibility that sizable black holes might have already been in place *before* the optically bright phase of QSOs. Furthermore, I have neglected the contribution to the SBH mass density from the so called "obscured" or "Type II" QSOs, the existence of which is required to explain the observed properties of the X-ray background. In analogy with local Seyfert 1 and Seyfert 2 galaxies, in Type II QSOs molecular material, with column density in the neighborhood of 10^{23} cm^{-2}, completely hides the nucleus from view at optical wavelengths (e.g. Fabian & Iwasawa 1999). The contribution of Type II QSOs could be significant. For instance, Barger *et al.* (2001) calculate lower and upper limits of 6×10^4 and 9×10^5 $M_\odot$ Mpc^{-3} for the mass density in the SBHs which comprise the X-ray background. Gilli, Salvati & Hasinger (2001) find that the spectral shape of the hard ($2-10$ Kev) X-ray background can be best explained if obscured AGNs evolve more rapidly as a function of redshift than do their unobscured counterparts. Their model assumes a ratio between absorbed and unabsorbed AGNs increasing from ~ 4 in the local universe to ~ 10 at $z \sim 1.3$, and remaining constant at higher redshifts. Such a model, if correct, would translate into an increase by nearly a factor of 10 in the SBH cumulative mass density derived above.

3 Black Hole Demographics: Local AGNs

In the supermassive black hole business, the masses which are most challenging to measure are those of the black holes powering local AGNs. Compared to QSOs, lower-luminosity AGNs have a small ratio between nuclear non-thermal and stellar luminosity, making it difficult to assess what fraction of the total luminosity is due to accretion onto the central black hole. Furthermore, the history of past activity is not known, so it is not obvious what fraction of the SBH mass, $M_\bullet$, predated the onset of the present nuclear activity (and the assumption that AGNs radiate at the Eddington limit is not justifiable). In other words, Soltan's arguments, which hold rather nicely for high redshift powerful QSOs, are not applicable to their less flamboyant, nearby cousins.

To make matters worse, the techniques that allow us to detect supermassive black holes in quiescent galaxies are seldom applicable to the hosts of AGNs. In Seyfert 1 galaxies, and in the handful of QSOs for which traditional dynamical studies of the gas or stellar kinematics can be performed, the presence of the bright non-thermal nucleus (e.g. Malkan, Gorjian & Tam 1998) overwhelms the very spectral features which are necessary for dynamical studies. The only Seyfert galaxy in which a SBH has been detected by spatially-resolved kinematics is NGC 4258, which is blessed with the presence of an orderly water maser disk (Watson & Wallin 1994; Greenhill *et al.* 1995;

Miyoshi *et al.* 1995). The radius of influence of the black hole at its center, $\sim 0''.15$, can barely be resolved by the Hubble Space Telescope (HST) but is fully sampled by the VLBA at 22.2 GHz. Unfortunately, water masers are rare (Greenhill *et al.* 2002) and of the handful that are known, only in NGC 4258 are the maser clouds distributed in a simple geometrical configuration that exhibits clear Keplerian motion around the central source (Braatz *et al.* 1996; Greenhill *et al.* 1997, 1996; Greenhill, Moran & Hernquist 1997; Trotter *et al.* 1998). A study of black hole demographics in AGNs must therefore proceed through alternative techniques.

To my knowledge, the only attempt at deriving a mass function for local ($z < 0.1$) AGNs was published by Padovani *et al.* (1990) using the CfA magnitude limited sample of Seyfert 1 galaxies. For each galaxy, the mass of the central SBH was derived from the dynamics of the broad line region (BLR) under the virial approximation, $M_\bullet = v^2 r/G$. The radius r of the BLR was calculated by assuming that the ionization parameter U (or more precisely, its product with the electron density) is known and invariant from object to object. U depends on the inverse square of r, and linearly on the number of ionizing photons; the latter quantity can be derived if the spectral energy distribution of each object is known. As noted by Padovani *et al.* , however, the ionization parameter is likely *not* invariant. More recently, Wandel, Peterson & Malkan (1999) have calibrated the "photoionization method" against the more sophisticated technique which has become known as "reverberation mapping" (Blandford & McKee 1892; Peterson 1993; Netzer & Peterson 1997; Koraktar & Gaskell 1991). The latter method relies on the fact that if the non-thermal nuclear continuum is variable, then the responsivity-weighted radius r of the BLR is measured by the light-travel time delay between emission and continuum variations. As in the case of the photoionization method, the mass of the central black hole follows from the virial approximation, *if* the BLR is gravitationally bound. The latter assumption has now received strong support in a few well-studied cases (Koratkar & Gaskell 1991; Wandel, Peterson & Malkan 1999; Peterson & Wandel 2000, but see also Krolik 2001).

Wandel, Peterson & Malkan (1999) concluded that photoionization techniques and reverberation-mapping estimates of the BLR sizes (or central masses) compare well, but only in a *statistical* sense. In other words, $M_\bullet$ estimates from the two methods can differ by up to an order of magnitude for individual objects, yet there does exist a reasonably good linear correlation between the two quantities when large samples are investigated, which bodes well for the Padovani *et al.* analysis. Eight of the Seyfert 1 galaxies in the Padovani *et al.* sample also have reverberation-mapping masses (Wandel *et al.* 1999; Kaspi *et al.* 2000). For these galaxies, the reverberation masses are a factor 3.6±3.4

larger (in the mean) than the photoionization masses. In Fig. 1, the cumulative mass function in local Seyfert 1 galaxies derived by Padovani *et al.* , once corrected for this factor and scaled to $H_0 = 75$ km s^{-1} Mpc^{-1}, is compared to the mass function in QSO black holes.

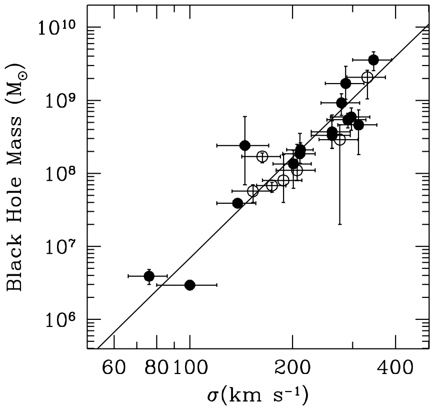
The total density of SBHs in Seyfert 1 galaxies is $\sim$ 5000 $M_\odot$ Mpc^{-3}. Despite the upward revision by a factor $\sim$ eight compared to the original estimate, the main conclusion reached by Padovani *et al.* still holds: "the bulk of the mass related to the accretion processes connected with past QSO activity does not reside in Seyfert 1 nuclei. Instead, the remnants of past activity must be present in a much larger number of galaxies". In the local universe, the ratio of Seyfert 2 to Seyfert 1 galaxies is $\sim$ four (Maiolino & Rieke 1995), while LINERs are a factor of a few more numerous than Seyferts (Vila-Vilaro 2000). Yet even after correcting the mass density given above to include these classes of AGNs, the total cumulative mass density in local AGNs falls a factor of several below that estimated for high redshift QSOs. Thus, in the search for SBHs, powerful QSOs and completely quiescent galaxies appear to be equally promising targets.

4 Black Hole Demographics: Local Quiescent Galaxies

4.1 Supermassive Black Holes and their Host Galaxies

Measuring SBH masses in the nuclei of "normal" nearby galaxies has been a staple of the astronomical literature since the late 1970s. It all started in 1978, when Wallace Sargent and collaborators published an investigation of the nuclear dynamics of the Virgo cluster cD, M87 (Sargent *et al.* 1978), claiming the detection of a five billion solar mass black hole. Other famous detections followed: M32 in the mid '80s (Tonry 1984), M31 a few years later (Kormendy 1988). Each claim, however, seemed to have its detractors, beginning with Binney & Mamon (1982) who dismantled Sargent's M87 black hole detection and alerted the community to the perils of the now familiar "mass-to-light ratio – velocity anisotropy degeneracy".

Important ground-based work on SBHs continued through the '90s (Richstone, Bower & Dressler 1990; Kormendy *et al.* 1996a, 1996b; Magorrian *et al.* 1998), producing a series of tantalizing but frustratingly inconclusive results. Indeed, it was not until the launch of HST that dramatic progress was made. It was HST data that firmly established the existence of a SBH in M87 (Harms *et al.* 1994), thereby ending a two-decade controversy. Since then, SBH masses based on HST/FOS and STIS data have been published for ten additional galaxies (Ferrarese, Ford & Jaffe 1996; Bower *et al.* 1998; van der Marel & van



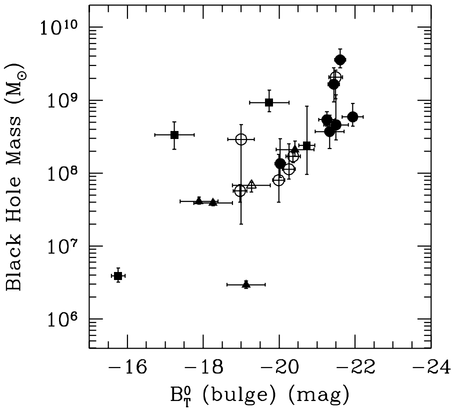


Figure 2: (left) Correlation between central velocity dispersion and black hole mass for all secure SBH detections. Published data are shown as solid symbols, data based on unpublished analyses as open symbols.

Figure 3: (right) Correlation between bulge $B-$band magnitude and black hole mass for the same sample shown in Fig. 2. Elliptical galaxies are shown as circles, lenticulars and compact ellipticals as squares, and spirals as triangles

den Bosch 1998; Ferrarese & Ford 1999; Emsellem *et al.* 1999; Cretton & van den Bosh 1999; Verdoes Kleijn *et al.* 2000; Gebhardt *et al.* 2000; Joseph *et al.* 2001; Barth *et al.* 2001; Sarzi *et al.* 2001).

The success of HST can be ascribed to the fact that its unprecedented spatial resolution (in the optical regime, at least!) makes it possible to resolve, in favorable cases, the region of space within which the SBH's gravitational potential dominates that of the surrounding stars, i.e., the "SBH sphere of influence". This is more crucial than might at first be realized. It has become obvious (Ferrarese & Merritt 2000) that resolving the sphere of influence does not simply aid the SBH detection: it is a *necessary* condition for a detection to be made. Ground-based observations generally lack the spatial resolution necessary to penetrate the SBH sphere of influence, and this condition inevitably leads to spurious detections and overestimated masses (see Merritt & Ferrarese 2001c for a more thorough discussion of this issue). To date, with a few notable exceptions (the Milky Way, Genzel *et al.* 2000, Ghez *et al.* 2000; NGC 4258, Miyoshi *et al.* 1995; NGC 5128, Marconi *et al.* 2001), all firm SBH detections — *detections based on data which resolve the SBH sphere of influence* — are based on HST data (see Table 1 of Merritt & Ferrarese 2001c).

It was by isolating these secure detections that it became possible to unveil the existence of a fundamental, seemingly perfect correlation between black hole mass, $M_\bullet$, and velocity dispersion, σ, of the host bulge (Fig. 2, Ferrarese & Merritt 2000; Gebhardt *et al.* 2000): the relation emerged from what had appeared almost as a scatter plot when the sample was restricted only to galaxies in which the SBH sphere of influence had been resolved (Ferrarese & Merritt 2000; Merritt & Ferrarese 2001b; Merritt & Ferrarese 2001c). A regression analysis, accounting for errors in both coordinates, of all published SBH detections (listed in Table 1 of Merritt & Ferrarese 2001c) gives

$$M_\bullet = (1.66 \pm 0.32) \times 10^8 \; M_\odot \left(\frac{\sigma}{200 \text{ km s}^{-1}}\right)^{4.58 \pm 0.52}. \qquad (2)$$

Including the few preliminary masses based on unpublished analyses produces an indistinguishable slope of 4.64 ± 0.47. The reduced χ^2 of the fit, 0.74, points to a relation with negligible intrinsic scatter, in agreement with the observations made by Ferrarese & Merritt (2000) based on the smaller sample available at the time. Because of its tightness, the $M_\bullet - \sigma$ relation has largely supplanted the well known correlation between $M_\bullet$ and bulge magnitude M_B (Fig. 3; Kormendy & Richstone 1995; Magorrian 1998), and has emerged as the tool of choice in the study of SBH demographics (Merritt & Ferrarese 2001b). Indeed, the tightness of the $M_\bullet - \sigma$ relation is its most puzzling feature, presenting formidable challenges to theoretical models for the formation and evolution of SBHs (e.g Haehnelt & Kauffmann 2000; Kauffmann & Haehnelt 2000; Adams *et al.* 2001; Ciotti & van Albada 2001; Burkert & Silk 2001). Even if one assumes that a tight relation was imprinted at an early stage of galaxy/SBH formation, it is difficult to understand how it could have survived unaltered in the face of mergers. It is especially remarkable that the relation should hold true for galaxies of disparate Hubble types (from SBs to compact ellipticals to cDs) belonging to wildly different environments (from rich clusters to the field), showing perfectly smooth (e.g. NGC 6251) or highly disturbed (e.g. NGC 5128) morphologies. For instance, it has recently been noted (McLure & Dunlop 2001) that the large scatter in the $M_\bullet - M_B$ relation (a reduced χ^2 of 23, Ferrarese & Merritt 2000) can be significantly reduced, but only at the expense of excluding most lenticular and spiral galaxies (and the odd elliptical, cf. Fig. 3). Even the remarkably tight correlation discovered by Graham *et al.* (2001) between $M_\bullet$ and "concentration parameter" C (the fraction of total bulge light contained within a predetermined radius) is marred by the occasional outlier. However, *every* galaxy, even the ones which do not obey the $M_\bullet - M_B$ or $M_\bullet - C$ relations, seems to conform magically to the $M_\bullet - \sigma$ relation.

Because of its tightness, the $M_\bullet - \sigma$ relation provides us with a direct and powerful tool to estimate the mass density of SBHs, $\rho_\bullet$, in the local universe. One approach is to combine the known mass density of spheroids (e.g. Fukugita *et al.* 1998) with the mean ratio between the mass of the SBH and that of the host bulge. Merritt & Ferrarese (2001a) used the $M_\bullet - \sigma$ relation to estimate $M_\bullet$ for a sample of 32 galaxies for which a dynamical measurement of the mass of the hot stellar component was available (from Magorrian *et al.* 1998). For this sample, the frequency function $N[\log(M_\bullet/M_{\rm bulge})]$ is well approximated by a Gaussian with $\langle\log(M_\bullet/M_{\rm bulge})\rangle \sim -2.90$ and standard deviation ~ 0.45. This implies $M_\bullet/M_{\rm bulge} \sim 1.3\times10^{-3}$ or, when combined with the mass density in local spheroids from Fukugita *et al.* (1998), $\rho_\bullet \sim 5 \times 10^5$. This estimate is a factor of five smaller than obtained by Magorrian *et al.* (1998) using what we now believe to be inflated values for the masses of the central black holes in many galaxies.

Here I will present an independent derivation of $\rho_\bullet$ which, while not directly leading to $\langle M_\bullet/M_{\rm bulge}\rangle$, has the advantage of producing an analytical representation of the cumulative SBH mass density as a function of $M_\bullet$. The idea is simple: if $M_\bullet$ correlates with the luminosity of the host bulge, the SBH mass density can be calculated once the luminosity function of bulges is known. Black hole masses are related to bulge luminosity directly through the $M_\bullet - M_B$ relation, a representation of which is given by Ferrarese & Merritt (2000) as $\log M_\bullet = -0.36 M_B + 1.2$. Unfortunately, the large scatter of the $M_\bullet - M_B$ relation (Fig. 3), combined with the small number of galaxies on which it is based, makes it impossible to establish whether elliptical and spiral galaxies follow a similar relation. Indeed, the observations of McLure & Dunlop (2001) cast doubts on whether spirals and lenticulars follow an $M_\bullet - M_B$ relation at all. This is unfortunate since the galaxy luminosity function does show a dependence on morphology (e.g., Marzke *et al.* 1998), and it is therefore desirable to conduct the analysis independently for different Hubble types. An alternative approach is to derive a relation between $M_\bullet$ and bulge luminosity by combining the $M_\bullet - \sigma$ relation (which, given the present sample, seems independent of the morphology of the host galaxy) with the Faber-Jackson relation for ellipticals and its equivalent for spiral bulges. The drawback here is that the Faber-Jackson relation has large scatter and is ill defined, especially for bulges.

The luminosity function for spheroids can be derived from the luminosity function of galaxies, generally represented as a Schechter function, once a ratio between total and bulge luminosity (which depends on the Hubble type of the galaxy considered) is assumed. The latter is adopted from Table 1 of Fukugita *et al.* (1998). Here, I will use the galaxy luminosity function derived by Marzke *et al.* (1998) from the Second Southern Sky Redshift Survey (SSRS2), corrected to $H_0 = 75$ km s^{-1} Mpc^{-1} and an Einstein-de Sitter universe. Marzke *et al.* derived luminosity functions separately for E/S0s and spirals, in a photometric band B_{SSRS2}. This band is similar to the Johnson's B-band, where representations of both the $M_\bullet - M_B$ relation and the Faber-Jackson relation exist: $B_{SSRS2} = B + 0.26$ (Alonso *et al.* 1993). A Schechter luminosity function,

$$\Phi(L)\mathrm{d}L = \Phi_0 \left(\frac{L}{L_*}\right)^\alpha e^{-L/L_*} \frac{\mathrm{d}L}{L_*}, \tag{3}$$

is then easily transformed into a SBH mass density if $L = A{M_\bullet}^k$,

$$\Psi(M_\bullet)\mathrm{d}M_\bullet = \Psi_0 \left(\frac{M_\bullet}{M_*}\right)^{k(\alpha+1)-1} e^{-(M_\bullet/M_*)^k} \frac{\mathrm{d}M_\bullet}{M_*}, \tag{4}$$

where $\Psi_0 = k\Phi_0$, $M_* = (\beta L_* 10^{0.4\times0.26}/A)^{1/k}$, and $\beta \equiv L/L_{bulge} = 0.23$ for spirals and 0.76 for E/S0 galaxies. β is the sum of the ratios between bulge to total B-band luminosity for different Hubble types, each weighted by the fraction of the mean luminosity density contributed by each type (from Fukugita *et al.* 1998).

Fig. 4 shows the cumulative SBH mass function separately for the E/S0 and spiral populations, derived from the $M_\bullet - M_B$ relation (from Ferrarese & Merritt 2000, dotted lines) and the $M_\bullet - \sigma$ relation (from this paper) combined with the Faber-Jackson relations for ellipticals and spirals (from Kormendy & Illingworth 1983, corrected to $H_0 = 75$ km s^{-1} Mpc^{-1}). While the two distributions differ in the details, there is little difference in the total mass density, which falls in the range $(4-5)\times10^5$ $M_\odot$ Mpc^3. This is in excellent agreement with the estimate of Merritt & Ferrarese (2001a).

Table 1 summarizes the mass density estimates for SBHs discussed in the preceeding three sections. While a detailed comparison of the distribution of masses remains to be carried out (for instance, Fig. 1 suggests a larger fraction of very massive black holes, $M > 10^9$, in high redshift QSOs than have been found in local galaxies), the overall picture is one of agreement: local studies seem to have recovered the overall mass density inferred from high redshift QSOs. It appears that supermassive black holes are a fundamental component of every large galaxy.

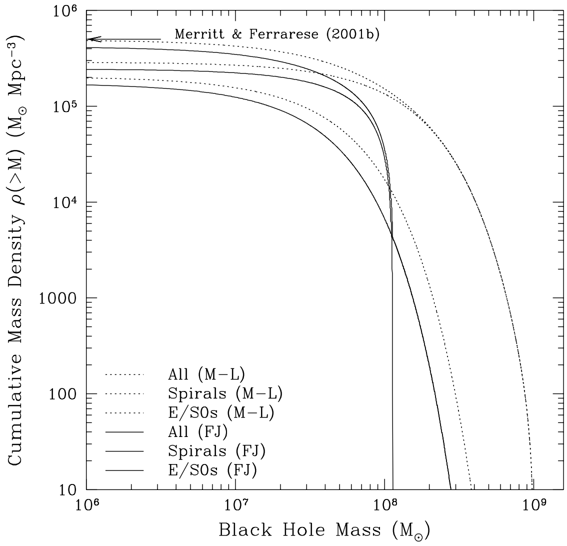


Figure 4: The mass function in local black holes for spirals (blue), E/S0 (red) and a complete sample of galaxies (black). Dotted lines are derived from the $M_\bullet - M_B$ relation, solid lines from the $M_\bullet - \sigma$ combined with the Faber-Jackson relation (as described in the text).

Summary of Mass Densities in Supermassive Black Holes

Method	$\rho_\bullet$ (10^5 $M_\odot$ Mpc^{-3})
QSO optical counts, $0.3 < z < 5.0$	$2 - 4$
AGN X-ray counts, $z > 0.3$	$0.6 - 9$
Spectral fit to the X-ray background, z unknown	$2 - 30$
Local AGNs, $z < 0.1$	$0.05 - 0.6$
Local Quiescent Galaxies, $z < 0.0003$	$4 - 5$

5 Moving Forward: Open Issues

5.1 What More Can Be Learned about the $M_\bullet - \sigma$ Relation?

With so much progress in the past few years, it is only natural to be optimistic about what the near future might bring. Indeed, a considerable amount of effort will be devoted to the study of supermassive black holes in nearby galaxies, with HST remaining the instrument of choice for the investigation. Roughly 130 galaxies have, or will be, observed with HST/STIS within the next year. While only a fraction of these observations are likely to lead to secure SBH detections (Merritt & Ferrarese 2001c), these results are highly anticipated, and will help to better define the slope and scatter of the $M_\bullet - \sigma$ relation.

Nevertheless, one important section of parameter space will remain unexplored. Now that the existence of SBHs is as well established as that of the galaxies in which they reside, the most pressing need has become, in my opinion, an exploration of the low mass end of the $M_\bullet - \sigma$ relation. However, the vast majority of the galaxies in the HST pipeline are expected to host SBHs with $M_\bullet \sim 10^8 M_\odot$, a range already well-sampled by the current data. None of the ongoing programs is likely to measure a SBH of $M_\bullet < 10^7\ M_\odot$ (Merritt & Ferrarese 2001c).

This is unfortunate since determining how far the $M_\bullet - \sigma$ relation extends is key for discriminating between different scenarios for the formation of SBHs. The smallest nuclear SBHs whose masses have been established dynamically are in the Milky Way (Genzel *et al.* 2000) and M32 (Joseph *et al.* 2001), both with $M_\bullet \approx 3 \times 10^6 M_\odot$ (Fig. 2). Evidence for black holes with $10^3 < M_\bullet < 10^6$ $M_\odot$ (dubbed "intermediate" mass black holes, or IBHs) is so far circumstantial, the most likely candidates being the super-luminous *off-nuclear* X-ray sources (ULXs) detected by Chandra in a number of starburst galaxies (Fabbiano *et al.* 2001; Matsumoto *et al.* 2001).

The link between IBHs and SBHs is unclear. If Chandra's off-nuclear ULXs are indeed IBHs, they could sink slowly to the galaxy center through dynamical friction and provide the seeds for nuclear SBHs (Ebisuzaki *et al.* 2001). Or the latter might be born *in situ*, through collapse of a protogalactic cloud, possibly before the onset of star formation in the bulge (Loeb 1993; Silk & Rees 1998; Haehnelt, Natarajan & Rees 1997). Deciding between these and competing formation scenarios will undoubtedly keep theorists busy for many years. However, different theories would almost certainly make different predictions about the form of the $M_\bullet - \sigma$ relation, and this is the most promising route for distinguishing between them. For instance, *in situ* formation in nuclei is unlikely to result in black holes less massive than $\sim 10^6 M_\odot$ (e.g Haehnelt, Natarajan & Rees 1998), while accumulation of IBHs would probably not result in as tight a correlation between $M_\bullet$ and σ unless some additional feedback mechanism were invoked (e.g. Burkert & Silk 2001). But little progress is likely to be made until we know whether IBHs are present in galaxy nuclei and if so, where they lie relative to the $M_\bullet - \sigma$ relation defined by SBHs. Therefore, exploring the $M_\bullet - \sigma$ relation in the $M < 10^6\ M_\odot$ range will be an important challenge in the years to come.

A first step in this direction has been taken recently with the derivation of an upper limit, of a few thousand solar masses, for the putative black hole inhabiting the nucleus of the nearby spiral M33 (Merritt, Ferrarese & Joseph 2001; Gebhardt *et al.* 2001; Valluri *et al.* 2002). As small as this upper limit might seem, it is still consistent with the $M_\bullet - \sigma$ relation as characterized in this paper, when extrapolated (by three orders of magnitude!) to the thousand solar mass range. Unfortunately, until the next technological leap, there is little hope of significantly tightening this upper limit: at the distance of M33, the black hole's sphere of influence is well below (by at least an order of magnitude) the resolution capabilities of HST. Indeed, with one notable exception, there are *no* galaxies expected to contain a black hole below the 10^6 $M_\odot$ mark that are close enough, and have high enough central surface brightness, to allow HST to measure $M_\bullet$. The one exception, the Local Group spheroidal galaxy NGC 205, is scheduled to be observed by HST as part of program 9448 (P.I. L. Ferrarese). NGC 205 is expected to host a $\sim 7.5 \times 10^5$ $M_\odot$ black hole; at a distance of 740 kpc, a black hole as small as 6×10^5 $M_\odot$ can be detected. Even so, it seems inevitable that, to fully characterize the low mass range of the $M_\bullet - \sigma$ relation, we must look beyond HST.

In my opinion, the answer is reverberation mapping. Although the obvious drawback is that it is only applicable to the 1% of galaxies with Type 1 AGNs, reverberation mapping is intrinsically unbiased with respect to black hole mass, provided the galaxies can be monitored with the appropriate time resolution. Furthermore, reverberation mapping can probe galaxies at high redshifts and with a wide range of nuclear activity, opening an avenue for the exploration of possible dependences of the $M_\bullet - \sigma$ relation on cosmic time and activity level.

The stage is being set to embark upon this new endeavor. In the past few years, the reliability of reverberation-mapping masses has been called into question on both observational (e.g. Ho 1999; Richstone *et al.* 1998) and theoretical (Krolik 2001) grounds. However, on the observational side, the doubts appear to be dissipating. The observation that SBHs in AGNs appeared to be undermassive, by a factor ~ 50, compared to SBHs in quiescent galaxies (Wandel 1999), was apparently the result of two erroneous assumptions: the overestimate (by a factor $\sim$ six) of SBH masses in quiescent galaxies derived from the $M_\bullet - M_B$ relation of Magorrian *et al.* (1998); and an overestimate of the AGN host bulge magnitudes (by up to ~ 3.5 mag) adopted by Wandel (McLure & Dunlop 2000; Merritt & Ferrarese 2001c; Wandel 2002). Indeed, Merritt & Ferrarese (2001c) conclude that the ratio of SBH to bulge mass in Seyfert, QSO and quiescent galaxy samples are all consistent: $\langle M_\bullet/M_{\rm bulge}\rangle = 0.09\%$ (QSOs) and 0.12% (Seyferts), $\langle M_\bullet/M_{\rm bulge}\rangle = 0.13\%$ for quiescent galaxies.

On the theoretical side, Krolik (2001) argues that the unknown BLR geometry, radial emissivity distribution, and angular radiation pattern of the line emission, coupled with the often less than optimal temporal sampling of the data, can lead to systematic errors in the reverberation masses of a factor $\sim$ three or more. While there is little doubt that Krolik's objections are all well-justified, my collaborators and I have taken an observational approach to this issue. Since there are no independent measurements of $M_\bullet$ for any of the reverberation-mapped AGNs, we have opted for an indirect comparison by placing these galaxies onto the $M_\bullet - \sigma$ plane. Initial results (Ferrarese *et al.* 2001) suggest that the AGN sample follows the same $M_\bullet - \sigma$ relation as the quiescent galaxies on which the relation is defined. More secure conclusions should be reached within the next year, once the AGN sample is doubled (Pogge *et al.* 2002). At the moment, the evidence suggests that reverberation mapping works, in spite of the theoretically motivated concerns.

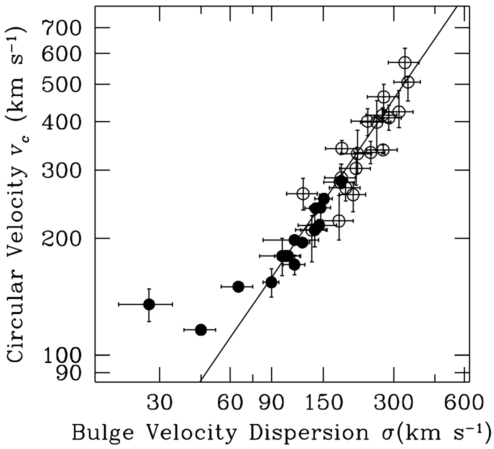
5.2 Beyond the $M_\bullet - \sigma$ Relation: Exploring the Dark Side of Galaxies

The $M_\bullet - \sigma$ relation probes a direct connection between SBHs and galactic bulges. The velocity dispersion, σ, is measured within a region which, though large compared to the black hole sphere of influence, is at least an order of magnitude smaller than the optical radius of the galaxy, and is likely dominated by luminous matter (Faber & Gallagher 1979). Therefore, σ is unable to tell us about the connection between SBHs and other fundamental baryonic structures, such as the galactic disk or halo, while the link to the dark matter (DM) component also remains utterly unexplored.

That this issue has not yet been addressed is somewhat surprising, since it is not the mass of the bulge but rather, the *total mass* of the galaxy (or of the DM halo), which is the key ingredient of most theoretical models proposed for the formation of SBHs (Adams, Graff & Richstone 2000; Monaco *et al.* 2000; Haehnelt, Natarajan & Rees 1998; Silk & Rees 1998; Haehnelt & Kauffmann 2000; Cattaneo, Haehnelt & Rees 1999; Loeb & Rasio 1994). Once the models predict a correlation with total mass (or DM halo mass), the correlation with bulge mass is implicit because, in standard CDM scenarios, the bulge mass is loosely determined by the halo properties (e.g. van den Bosch 2000; Haehnelt, Natarajan & Rees 1998; Zhang & Wyse 2000).

It is natural to ask whether the $M_\bullet - \sigma$ relation might just be the by-product of an even more fundamental relation between $M_\bullet$ and the total gravitational mass of the galaxy. As it turns out, such a fundamental relation is likely to exist (Ferrarese 2002). Fig. 5 demonstrates the existence of a tight correlation between the bulge velocity dispersion (the same quantity used in defining the $M_\bullet - \sigma$ relation, typically measured within an aperture of size $R \lesssim 0.5$ kpc) and the circular velocity v_c, measured at radii $R \sim 20 - 80$ kpc, for a sample of 16 spiral galaxies. A regression analysis, accounting for errors in both variables, gives

$$\log v_c = (0.88 \pm 0.17) \log \sigma + (0.47 \pm 0.35) \qquad (5)$$



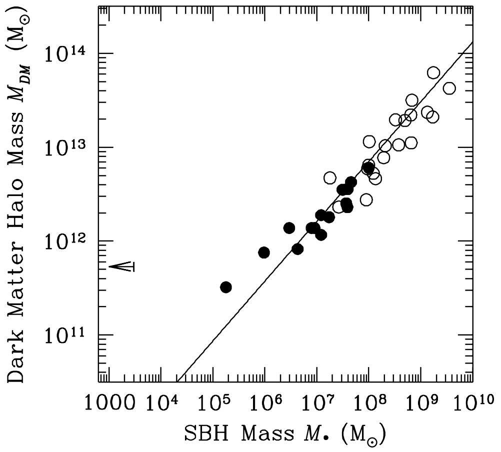


Figure 5: (left) Correlation between the rotational velocity and bulge velocity dispersion for a sample of 16 spiral galaxies (solid circles) and 21 ellipticals (open circles; plot adapted from Ferrarese 2002).

Figure 6: (right) Same as Fig. 5, but with v_c and σ converted to halo mass and black hole mass respectively (see text for further details). The upper limit on the SBH mass in M33 (Merritt *et al.* 2001) is shown by the arrow.

with a reduced χ^2 of 0.64.

For spiral galaxies, v_c is measured directly from HI or optical rotation curves. In elliptical galaxies, v_c can be derived from dynamical models of the observed stellar absorption line profiles, velocity dispersion and surface brightness profiles. Fig. 5 shows that the spirals naturally blend with a sample of 21 elliptical galaxies (from Kronawitter et al. 2000) in the $v_c - \sigma$ plane; both samples obey the relation given in equation (5).

The implications of equation (5) are exciting. The circular velocity v_c is a measure of gravitational mass through the virial theorem, and can be related to the DM halo mass (Navarro & Steinmetz 2000; Bullock et al. 2001). Keeping in mind that, as discussed in section 5.1, the $M_\bullet - \sigma$ relation is not well defined below $10^7\ M_\odot$, and not defined at all below $10^6\ M_\odot$, the $v_c - \sigma$ relation can be translated into a relation between the mass of the central black hole (related to σ through equation 2) and that of the DM halo (Fig. 6):

$$\frac{M_\bullet}{10^8\ M_\odot} \sim 0.046 \left(\frac{M_{DM}}{10^{12}\ M_\odot}\right)^{1.6} \tag{6}$$

(Ferrarese 2002). The existence of this relation seems to conflict with recent claims that SBHs do not relate to any other galactic structure but the bulge

(Richstone 1998; Kormendy & Gebhardt 2001; Gebhardt *et al.* 2001).

The relation between $M_\bullet$ and M_{DM} is non-linear, with the ratio $M_\bullet/M_{DM}$ decreasing from 6×10^{-5} for $M_{DM} \sim 10^{14}$ $M_\odot$, to 5×10^{-6} for $M_{DM} \sim 10^{12}$ $M_\odot$. Haehnelt, Natarajan & Rees (1998) advocated a nonlinear relation between SBH and DM halo mass in order to reproduce the luminosity function of QSOs, noting that a linear relation would translate into too low a value for the QSO duty cycle, $t_{QSO} \sim 3 \times 10^5$ yr. Increasing the QSOs lifetime to values more in line with current observational constraints (e.g. Martini & Weinberg 2001) produces an increasingly steeper relation between $M_\bullet$ and M_{DM}. If $t_{QSO} \sim 1.5 \times 10^7$ yr (equal to the Salpeter time), then the slope of the $M_\bullet - M_{DM}$ relation must be increased to ~ 2 to provide a reasonable fit to the QSO luminosity function. The empirical correlation shown in Fig. 6 seems to support such claims. Furthermore, Fig. 6 indicates that the tendency of massive halos to become less efficient in forming SBH as M_{DM} decreases, is even more pronounced for halos with $M_{DM} < 10^{12}$ $M_\odot$, and breaks down completely in the case of M33. Such halos might indeed be *unable* to form SBH, as proposed on theoretical grounds by Haehnelt, Natarajan & Rees (1998) and Silk & Rees (1998).

5.3 Additional Clues to SBH and Galaxy Formation and Further Challenges

I conclude this review with some general comments about the early stages of galaxy and black hole formation. The $M_\bullet - \sigma$ relation (and, even more so, the $M_\bullet - M_{DM}$ relation) implies a causal connection between the evolution of black holes and their host galaxies. But what came first: the stars or the black holes? And was the $M_\bullet - \sigma$ relation imprinted during the early stages of galaxy formation? The answer to the latter question is generally assumed to be affirmative, but in fact we have no direct proof of it. The most distant galaxy in the $M_\bullet - \sigma$ plot (NGC 6251, Ferrarese & Ford 1999) is at ~ 100 Mpc. Studies of reverberation-mapped galaxies (Ferrarese *et al.* 2001, Pogge *et al.* 2002) have reached two times farther, and it might be technically possible to push the envelope up to $z \sim 1$. It seems unlikely that we will ever be able to build an $M_\bullet - \sigma$ relation at the redshift corresponding to the optically bright phase of the QSOs ($z \sim 2-3$), let alone at redshifts at which the first protogalactic fragments are believed to have formed, $z > 5$. Present day dwarf galaxies might very well be relics from such an era (Mateo 1998; Carraro *et al.* 2001); however, detecting SBHs in these systems requires a spatial resolution well beyond the capabilities of present instrumentation. In fact, the $M_\bullet - \sigma$ relation is defined primarily by bright giant ellipticals which are likely to have an extensive history of merging. In other words, we have no direct information

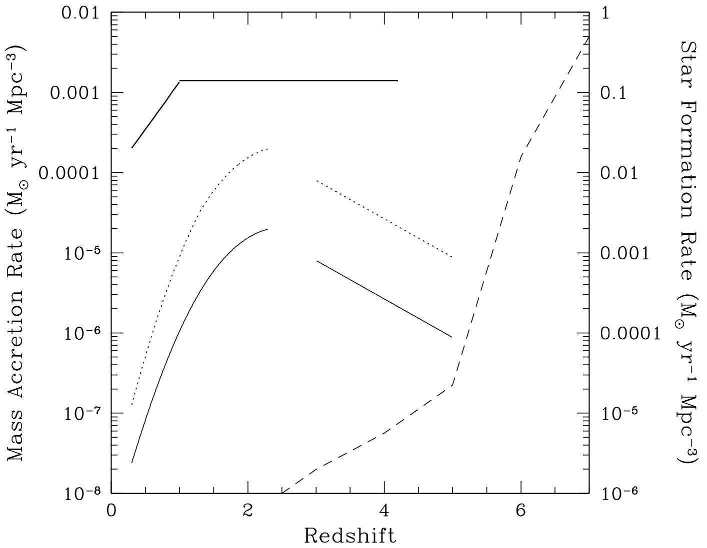


Figure 7: The mass accretion rate onto supermassive black holes with $M_\bullet > 7 \times 10^8\ M_\odot$ (thin solid line, units shown on the left axis), compared to the star formation rate from Steidel *et al.* 1999 (thick solid line, units on the right axis) and the epoch of formation of the DM halos which host such SBHs according to Fig. 5 and 7 (dashed line, from Gottlöber, Klypin & Kravtsov 2001). Eighty percent of the halos which (presumably) host QSO engines are capable of forming stars at redshifts $z > 5$. The dotted line shows the mass accretion rate onto high redshift QSOs corrected for the contribution of obscured objects, as in Gilli *et al.* 2001.

about the "primordial" connection between supermassive black holes and their hosts: what we see is the result of gigayears of evolution.

A scenario in which galaxy formation precedes the formation of supermassive black holes seems to fit more naturally within the current paradigm of hierarchical structure formation (e.g. Miralda-Escude & Rees 1997). For instance, star formation can proceed in halos with virial temperature as low as 10^4 K, which can form at redshifts $z > 10$ (e.g. Ostriker & Gnedin 1996). Subsequent stellar evolution in these systems would produce enough energy through stellar winds or supernovae explosions to expel most of the remaining gas from the shallow potential wells (Couchman & Rees 1986; Dekel & Silk 1986), likely inhibiting the formation of supermassive black holes. Deeper potential wells, which are more conducive to SBH formation (e.g. Haehnelt, Natarajan & Rees 1998) would only form at later times. Studies of elemental abundances in high redshift ($z > 3$) QSOs support this view: most of the metal enrichment and star formation seem to have taken place at least 1 Gyr before the luminous phase of the QSO (Hamann & Ferlan 1999 and references therein; Dietrich, *et al.* 2001).

Fig. 7 shows a comparison between the mass accretion rate onto optically luminous QSOs with $M_\bullet > 7\times10^8$ (corresponding to the magnitude limit of the SDSS QSO Survey for objects radiating at the Eddington limit), and the star formation rate from Steidel *et al.* 1999 (see also Abraham *et al.* 1999; Cowie *et al.* 1997). Similarities between the two curves, which have been noted many times (e.g. Boyle & Terlevich 1998) are diminished by these recent results, even after the QSO results are corrected for the possible contamination of obscured objects (Barger *et al.* 2001; Gilli *et al.* 2001; Salucci *et al.* 1998). If anything, Fig. 7 supports the conclusion that star formation was well underway by the time the QSOs started shining.

The connection between QSO activity and merging rate is also not readily apparent: observations show that the merging rate depends on redshift as $(1+z)^\alpha$ with $\alpha = 2-4$ (Le Fevre *et al.* 1999; Burkey *et al.* 1994; Carlberg *et al.* 1994; Yee & Ellingson 1995; Abraham 1999). Even in the $z < 2.3$ range, where both curves decline, the number of mergers declines by at most a factor 30, while the comoving density of QSO declines by three orders of magnitude. Perhaps more telling is the comparison with the merging history of DM halos and the ensuing formation of galaxies. Fig. 7 also shows the distribution of formation redshifts for present day halos with virial velocities > 300 km s^{-1} taken from the N-body simulation of Gottlöber, Klypin & Kravtsov (2001). According to Figures 5 and 6, these are the halos associated with the black holes sampled by the SDSS, also shown in Fig. 7. Virtually all such halos are able to host a luminous galaxy (a condition reached when the halo progenitor first reaches a virial velocity > 50 km s^{-1}) before a redshift ~ 2.5, i.e. before the optically bright phase of the QSOs.

In the midst of all this, one thing is certain: SHBs can no longer be studied in isolation. Understanding how they form, and how they shape their surroundings, requires a good deal more information from seemingly unrelated fields than could have been anticipated just a few years ago.

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