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Local supermassive black holes and relics of Active Galactic Nuclei

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Abstract. We show that local supermassive black holes (BH) detected in nearby galactic nuclei were grown during bright AGN phases. We compare the mass function of BHs in the local universe with that expected from AGN relics, which are BHs grown entirely with mass accretion during AGN phases. The local BH mass function (BHMF) is estimated by applying the well-known correlations between BH mass, bulge luminosity and stellar velocity dispersion to galaxy luminosity and velocity functions. The density of BHs in the local universe is $\rho_{\rm BH} = 4.6^{+1.9}_{-1.4}\, h_{0.7}^2 \times 10^5$ M$_\odot$ Mpc^{-3}. The relic BHMF is derived from the continuity equation with the only assumption that AGN activity is due to accretion onto massive BHs and that merging is not important. We find that the relic BHMF at $z = 0$ is generated mainly at $z < 3$. Moreover, the BH growth is anti-hierarchical in the sense that smaller BHs ($M_{\rm BH} < 10^7 M_\odot$) grow at lower redshifts ($z < 1$) with respect to more massive ones ($z \sim 1 - 3$). Unlike previous work, we find that the BHMF of AGN relics is perfectly consistent with the local BHMF indicating the local BHs were mainly grown during AGN activity. This agreement is obtained while satisfying, at the same time, the constraints imposed by the X-ray background. The comparison with the local BHMF also suggests that the merging process is not important in shaping the relic BHMF, at least at low redshifts ($z < 3$). Our analysis thus suggests the following scenario: local BHs grew during AGN phases in which accreting matter was converted into radiation with efficiencies $\varepsilon \sim 0.1$ and emitted close to the Eddington luminosity. The average total lifetime of these active phases ranges from $\simeq 3 - 7 \times 10^8$ yr for $M_{\rm BH} < 10^7 M_\odot$ to $\simeq 1.5 \times 10^8$ yr for $M_{\rm BH} > 10^9 M_\odot$. The results obtained here with the most recent AGN luminosity functions and XRB models are nonetheless perfectly consistent with the results of Marconi et al. (2004).

Key words. black hole physics - galaxies: active - galaxies: evolution - galaxies: nuclei - quasars: general

1. Introduction

One of the key questions of current astrophysical research is how galaxies formed and

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evolved. The most popular galaxy formation scenario is the so-called hierarchical model in which galaxies are assembled through repeated merging events of smaller "building blocks". In this scenario, a late final assembly (no earlier than $z \sim 1$) is expected for the most massive galaxies (see De Zotti, Frenk, Menci, these proceedings). The hierarchical model is appealing because galaxy formation can be inserted into a more general framework for structure formation, the ΛCDM cosmological model. However, hierarchical models are facing severe problems since in their simplest formulations they are unable to account for the presence of a substantial population of massive ellipticals found at $z \sim 1-2$ which require a formation epoch of $z \sim 2{-}3$ (e.g. Cimatti, these proceedings). Galaxy formation thus appears to be anti-hierarchical with the most massive galaxies forming at earlier times than smaller ones. Observations indicate that either hierarchical models are wrong or missing important physics.

Important elements in the process of galaxy evolution are certainly the supermassive black holes (BH) present in galactic nuclei. Supermassive black holes with masses in the $10^6 - 10^{10}$ $M_\odot$ range are now believed to be hosted in most, if not all, nearby galaxy nuclei (e.g. Ferrarese & Ford 2005). The striking correlations between BH mass and host galaxy structural parameters like bulge luminosity/mass (Kormendy & Richstone, 1995; Marconi & Hunt, 2003) and stellar velocity dispersion (Ferrarese & Merritt, 2000; Gebhardt et al., 2000) indicate that the process of BH growth is intimately linked with the evolution of the host galaxy.

Active Galactic Nuclei are the most likely responsibles for the existence of supermassive BHs in nearby galaxy nuclei. According to the current paradigm AGNs are powered by mass accretion onto a massive BH and, in combination with the observed evolution of AGN, it follows that many (if not all) nearby galaxies should host a BH in their nuclei as relic of past AGN activity. If local supermassive BHs are the relics of AGNs, then the key to understand the tight link between BH and host galaxy must be related to AGN activity. Is the physics at the base of the link among AGN, Black Holes and Galaxies the key to solve the apparent anti-hierarchical behaviour of galaxy formation?

Thus, an important open question is whether local BHs are only relics of AGN activity (i.e. grown entirely with mass accretion during AGN phases) or if other processes, such as merging, play an important role. This can be answered by comparing the mass density of local BHs with that expected from AGN relics (e.g. Soltan 1982; Fabian 1999; Elvis et al. 2002) and by comparing the local BH Mass Function with the mass function of relic BHs (e.g. Marconi & Salvati 2002; Yu & Tremaine 2002; Ferrarese 2002; Marconi et al. 2004; Merloni 2004; Shankar et al. 2004). Yu & Tremaine (2002) and Ferrarese (2002) found a discrepancy in the BHMF at high masses ($M_{\rm BH} > 10^8$ $M_\odot$): more AGN relics are expected than those estimated from the local BHMF. This discrepancy can be reconciled by assuming accretion efficiencies larger than the canonically adopted value of $\varepsilon = 0.1$, i.e. $\varepsilon > 0.2$. A refinement of the analysis by Yu & Tremaine (2002) is also presented in Yu & Lu (2004) who find $\varepsilon > 0.1$. High efficiencies are also required from the comparison of $\rho_{\rm BH}$ derived from the X-ray Background (XRB) and from local BHs Elvis et al. (2002). Such high efficiencies, if confirmed, would imply that most, if not all BHs, should be rapidly rotating (for comparison with theoretical expectations see, e.g., Volonteri et al. 2005).

In this paper we investigate the possibility that massive black holes in nearby galaxies are relics of AGN activity by comparing the local BHMF with that of AGN relics. The only assumption is that AGN activity is caused by mass accretion onto the central BH. The work is described in detail in Marconi et al. (2004) and here we focus on a few among the more critical and important issues, presenting an updated analysis which takes into account the newest AGN luminosity functions and X-ray background synthesis models. Similar analyses, reaching conclusions analogous to ours, are presented in Merloni (2004) and Shankar et al. (2004).

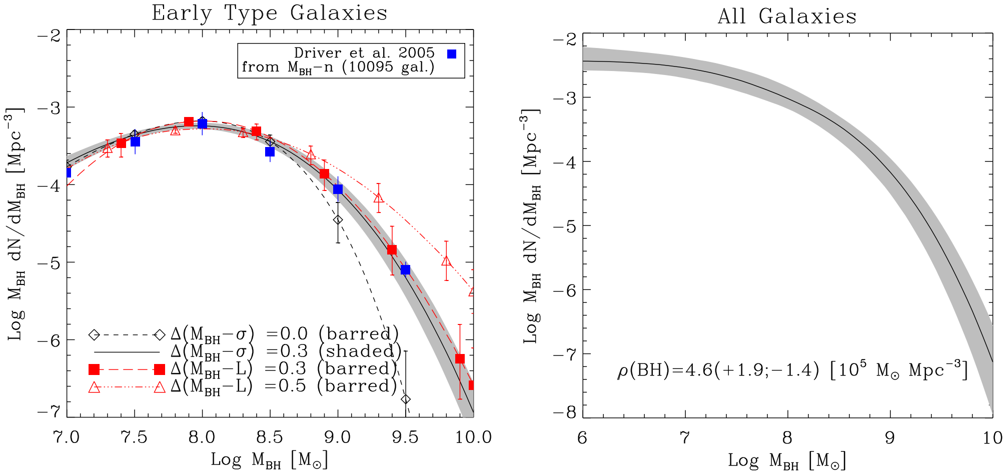

Fig. 1. (a) Local BHMF for early type galaxies based on the SDSS sample of Bernardi et al. (2003). The shaded area and error bars ("barred") indicate 1σ uncertainties. The Δ indicate the assumed intrinsic dispersions of the $M_{\rm BH}$-$\sigma_\star$ or $M_{\rm BH}$-$L_{\rm bul}$ relations. The big squares with errorbars represent the BHMF estimate by Driver et al. (2005). (b) Best estimate of the local BHMF (solid line) with 1σ uncertainties (shaded area).

2. The Mass Function of Local Black Holes

The mass function of local BHs can be estimated by simply convolving the existing galaxy luminosity [$\phi(L)$] or velocity functions [$\phi(\sigma)$] with the $M_{\rm BH}$-$L_{\rm bul}$ and $M_{\rm BH}$-$\sigma_\star$ relations respectively. One should apply corrections to convert from total to bulge luminosity in the first case and should take into account the intrinsic dispersion (if any) of the $M_{\rm BH}$-host galaxy relations.

In Fig. 1a we first check the consistency of the $M_{\rm BH}$–host-galaxy relations by applying $M_{\rm BH}$-$L_{\rm bul}$ and $M_{\rm BH}$-$\sigma_\star$ relations to galaxy luminosity and velocity functions of the same sample of early type galaxies (Bernardi et al., 2003; Sheth et al., 2003). The derived BHMFs are the same within the uncertainties -estimated with many Montecarlo realizations of the BHMF- provided that $M_{\rm BH}$-$L_{\rm bul}$ and $M_{\rm BH}$-$\sigma_\star$ share the same intrinsic dispersion. As shown in the figure, very different BHMFs are derived when $M_{\rm BH}$-$L_{\rm bul}$ has dispersion 0.5 in $\log M_{\rm BH}$ at given $L_{\rm bul}$ while $M_{\rm BH}$-$\sigma_\star$ has 0 intrinsic dispersion (e.g. Yu & Tremaine 2002). This confirms the completely independent result by Marconi & Hunt (2003) that all correlations $M_{\rm BH}$– host-galaxy-properties are equally good, i.e. they have similar intrinsic dispersion. In Fig. 1b we plot the estimate of the local BH mass function obtained considering galaxies of all morphological types. The density in local BHs is $\rho_{\rm BH} = 4.6(-1.4;+1.9)(h/0.7)^2 \times 10^5\ {\rm M}_\odot\,{\rm Mpc}^{-3}$. We have used the galaxy luminosity functions by Kochanek et al. (2001),Nakamura et al. (2003), Marzke et al. (1994) and the galaxy velocity function by Sheth et al. (2003).

Our estimate of the local BH density is a factor ~ 1.8 larger than the estimate by Yu & Tremaine (2002). $\rho_{\rm BH}$ is increased by $\sim 30\%$ when taking into account an intrinsic dispersion for $M_{\rm BH}$-$L_{\rm bul}$ and $M_{\rm BH}$-$\sigma_\star$ (0.3 in $\log M_{\rm BH}$ at constant $\sigma_\star$ or $L_{\rm bul}$). $\rho_{\rm BH}$ is also increased by $\sim 50\%$ because we have used the zero points of the $M_{\rm BH}$-$L_{\rm bul}$ and $M_{\rm BH}$-$\sigma_\star$ correlations determined by Marconi & Hunt (2003). These are a factor 1.5 larger than those used by Yu & Tremaine (2002) (see also Tremaine et al. 2002) because they were determined by considering only secure BH detections, where the

BH sphere of influence is resolved by the observations. Fig. 8 of Gebhardt et al. (2003) show that measurements obtained with data either resolving or not resolving the BH sphere of influence provide similar $M_{\rm BH}$ values, albeit with much larger errorbars in the latter case. However, from the same figure it can be evinced that on average BH measurements where the sphere of influence is not resolved are underestimated by a factor $\sim$ 2, and this fully accounts for the larger zero points found by Marconi & Hunt (2003). Apart from the larger zero points, by excluding the non-secure BH detections Marconi & Hunt (2003) find that $M_{\rm BH}$-$\sigma_\star$ and $M_{\rm BH}$-$L_{\rm bul}$ have the same dispersion which, as we have just shown, is independently confirmed by the requirement of obtaining the same BHMF from $M_{\rm BH}$-$\sigma_\star$ and $M_{\rm BH}$-$L_{\rm bul}$ applied to $\phi(\sigma)$ and $\phi(L)$, respectively.

In Fig. 1a we also compare our BHMF for Early Type galaxies with an independent estimate by Driver et al. (2005) who determine the BHMF by applying the $M_{\rm BH}$-n correlation (n is the Sersic index; Graham et al. 2003) to a sample of $\sim$ 10000 galaxies. Our BHMF and the one by Driver et al. (2005) are in excellent agreement both in shape and normalization.

3. The Mass Function of AGN Relics

The Mass Function of AGN relics $N(M,t)$ is estimated with the continuity equation which, with the assumption that AGNs are powered by mass accretion onto a massive BH and that we can neglect merging of BHs, relates the relic BHMF, $N(M,t)$, to the AGN luminosity function (LF), $\phi(L,t)$ (Small & Blandford 1992; see Marconi et al. 2004 for more details). The efficiency of mass-to-energy conversion is ε and the BH is emitting at a fraction λ of the Eddington luminosity ($\lambda = L/L_{\rm Edd}$).

Two are the critical points here: $\phi(L,t)$ is the luminosity function of *all* AGNs and L is the *bolometric* luminosity from *accretion*. AGN surveys are usually performed in a given spectral band b with well defined selection criteria and flux limits thus the derived luminosity function describes a subset of all AGNs at a given luminosity L_b. One must then convert from L_b to L and correct for the missing AGNs.

L must be the AGN 'bolometric' luminosity from accretion and must not include reprocessed radiation like the infrared emission from the obscuring torus. Otherwise it would not be possible to derive the BH Mass of an AGN with luminosity L through ε and λ. The quasar bolometric corrections by Elvis et al. (1994) include the IR emission and are not applicable here. Therefore to obtain L from L_b we derive new luminosity-dependent bolometric corrections which do not take into account IR re-radiation (see Marconi et al. 2004 for more details) and which are a factor $\sim$ 30% lower than those by Elvis et al. (1994).

To take into account the whole AGN population we consider AGN LFs in the X-ray band: the soft X-ray luminosity function by Hasinger et al. (2005) and the hard X-ray luminosity functions by Ueda et al. (2003) and La Franca et al. (2005). The AGNs which are not included in the soft and hard X-rays surveys are mainly the absorbed (N(H)$>10^{21}$ cm^{-2}) and Compton-thick ones (N(H)$>10^{24}$ cm^{-2}), respectively. Their fraction is not a free parameter but can be derived from X-ray background (XRB) synthesis models (see, e.g., Gilli et al. 2001 for a description). By comparing the observed XRB spectrum with the model one obtained using a given X-ray luminosity function it is possible to estimate the fraction of "missing" AGNs. In this paper we consider the three most recent X-ray LFs Ueda et al. (2003); La Franca et al. (2005); Hasinger et al. (2005) and the corresponding XRB models which have been derived with them. Using the soft X-ray luminosity function by Hasinger et al. (2005), Gilli, Comastri & Hasinger (2006, in preparation) perform a detailed XRB synthesis model which not only reproduces the XRB spectrum but also the soft and hard X-ray source counts. They consider two possibilities, which are also adopted here: in model 1 (M1) they assume constant absorbed/unabsorbed ratio, (absorbed have N(H)$>10^{21}$ cm^{2}) while in their model 2 (M2) R depends on the soft X-ray luminosity.

With the above assumptions it is possible to transform soft and hard X-ray luminosities to bolometric ones and to correct AGN

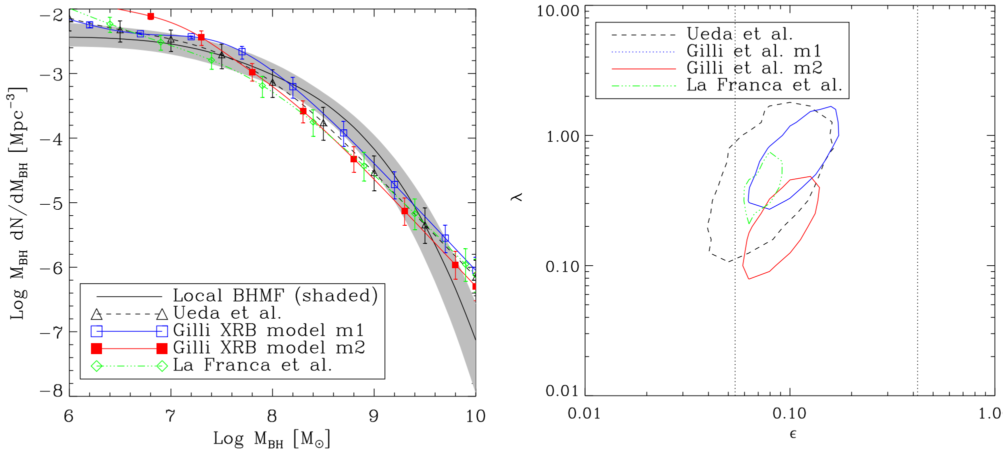

Fig. 2. (a) Best estimate of the local BHMF (solid line with shaded area, see Fig. 1b) compared with the BHMF of AGN relics obtained using the luminosity function by Ueda et al. (2003); Hasinger et al. (2005), and La Franca et al. (2005) corrected for the missing Compton-thick AGNs using X-ray Background synthesis models as described in the text. (b) Locus where ε and λ provide the best match between local and relic BHMFs. The contours indicate an average deviation of 1σ between the Local and Relic BHMFs. The dotted lines represent the theoretical efficiencies around a Schwarzschild ($\varepsilon \sim 0.06$) and a maximally rotating Kerr BH ($\varepsilon \sim 0.4$).

LFs for the missing sources in order to derive $\phi(L,t)$. Further assuming that at $z = 3$ all BHs are active (this initial condition does not affect the final results), we can estimate the relic BHMF (with $\varepsilon = 0.1$ and $\lambda = 1$) and compare it with the local BHMF (Fig. 2a). The local BHMF and the relic BHMF are in good agreement within the uncertainties, regardless of the adopted luminosity function. This comparison also shows that it is unlikely that merging can play a major role in shaping the BHMF for $z < 3$. The relic BHMF presented in Fig. 2a is not the one providing the best match with the local BHMF but is the one computed with the "standard" $\varepsilon = 0.1$ and $\lambda = 1$ values.

In our analysis, the local BHMF and the XRB are produced by the same sources. The disagreement found by Elvis et al. (2002) between the density of local massive BHs and that inferred from the X-ray background light can be reconciled noting that the average redshift of the sources making the XRB is not $\langle z\rangle \simeq 2$ but $\langle z\rangle \simeq 1$, as shown by the redshift evolution of the LFs. It is worth stressing the importance of the XRB constraint which removes one free parameter in this analysis, the fraction of obscured AGNs. The results by Marconi et al. (2004), which used only the Ueda et al. (2003) LF are confirmed even with the adoption of different luminosity functions.

4. Accretion efficiency and $L/L_{\rm Edd}$

Accretion efficiency ε and Eddington ratio λ are the only free parameters in the relic BHMF and Fig. 2b shows the locus where they provide the best match between the relic and local BHMFs. The contours show the loci where the average deviation between the BHMFs is less than 1σ according to the adopted LF. Outside the agreement between the BHMFs is poor. The dotted lines marks the ε values for a non-rotating Schwarzschild BH and a maximally rotating Kerr BH. All AGN luminosity functions and XRB models provide consistent allowed values for ε and λ which, conservatively, are in the range $\varepsilon = 0.04 - 0.16$ and $\lambda = 0.1 - 1.7$. We remark that ε and λ are as-

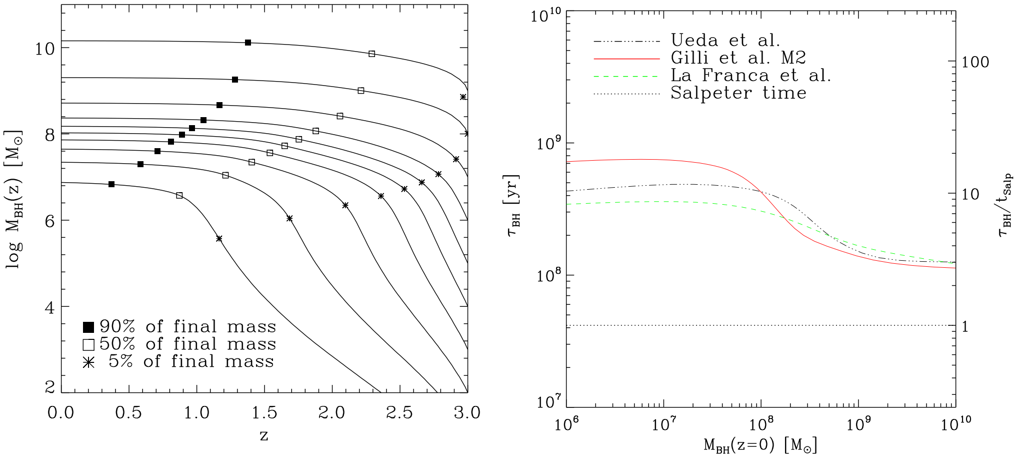

Fig. 3. (a) Average growth history of BHs obtained using the Hasinger et al. (2005) AGN LF and Gilli et al. (2006) model 2. The symbols indicate the points when a BH reaches a given fraction of its final mass. (b) Average mean lifetimes of active BHs as a function of their mass at $z = 0$ for different adopted AGN LF.

sumed constants for all luminosities and at all redshifts.

The discrepancy at high BH masses, i.e. more AGN relics than local BHs, found by Yu & Tremaine (2002) and Ferrarese (2002) is thus removed without requiring large accretion efficiencies because of (i) the use of the zero points of Marconi & Hunt (2003), (ii) the non-zero intrinsic dispersion of the $M_{\rm BH}$-$\sigma_\star$ and $M_{\rm BH}$-$L_{\rm bul}$ relations, and (iii) the smaller bolometric corrections adopted. Most important for matching the shapes of the BH mass functions at high masses are (ii) and (iii) while (i) has more impact on the derived accretion efficiency. While (ii) and (iii) are generally accepted, (i) is more controversial because the definition of 'secure' BH mass measurement varies from author to author. However, even using the same zero points as Yu & Tremaine (2002) to estimate the local BHMF we obtain $\varepsilon = 0.05-0.2$ and $\lambda = 0.15-2.5$, i.e. efficiency is still $\varepsilon < 0.2$. It is worth noticing that the average limits on $L/L_{\rm Edd}$ that we find are perfectly in agreement with the average values estimated by McLure & Dunlop (2004) on a large sample of SDSS quasars (see their Fig. 2).

5. Anti-hierarchical BH growth and AGN lifetimes

Fig. 3a shows the average growth history of BHs with different starting masses at $z = 3$ obtained using the Hasinger et al. (2005) AGN LF and Gilli et al. (2006) model 2. Symbols mark the point when a BH reaches a given fraction of its final mass. At $z < 3$, all BHs gain at least 95% of their final mass but BHs which are now more massive than 10^8 $M_\odot$ grew earlier and gained 50% of their final mass by $z \sim 2$. Conversely, smaller BHs grow at lower redshifts ($z < 1$). This anti-hierarchical growth of BHs is a consequence of the redshift evolution of the Hasinger et al. (2005) luminosity function. The same anti-hierarchical growth is also found using the Ueda et al. (2003) and La Franca et al. (2005) AGN luminosity functions.

Fig. 3b shows the average total lifetimes of active BHs, i.e. the time required for the BH growth since $z = 3$, obtained with different AGN LF in the reference case with $\varepsilon = 0.1$, $\lambda = 1$ (see Marconi et al. 2004 for more details). Local high mass BHs ($M_{\rm BH} > 10^9$ $M_\odot$) have been active, on average, $\simeq 1.5\times10^8$ yr. On the contrary, the assembly of lower mass BHs has required active phases lasting at least twice that much ($\simeq 3 - 7 \times 10^8$ yr).

Overall, the plots in Fig. 3 indicate that larger BHs ($M_{\rm BH} > 10^9$ M$_\odot$) are already in place at earlier times with respect to smaller ones which take a longer time to grow. This anti-hierarchical behaviour, similar to the one found for massive galaxies, originates from the feedback of the AGN on the host galaxy (see, e.g., Granato et al. 2004; Menci et al. 2004). Smaller BHs form in shallower potential wells with respect to more massive ones and are thus more subject to feedback from star formation (e.g. supernovae explosions) and from the AGN itself. Conversely, the most massive BHs form in deep potential wells where feedback effects are much less important. The feedback from the AGN and from star formation is the critical ingredient to understand also the anti-hierarchical behaviour of massive galaxies. Recent models including a proper treatment of feedback represent a step forward in understanding the formation of massive galaxies at high redshift and are able to explain at the same time $M_{\rm BH}$-galaxy correlations and, partially, the presence of massive galaxies at high redshift (Granato et al., 2004; Menci et al., 2004).

6. Conclusions

We have quantified the importance of mass accretion during AGN phases in the growth of supermassive black holes (BH) by comparing the mass function of black holes in the local universe with that expected from AGN relics, which are black holes grown entirely during AGN phases.

The local BH mass function (BHMF) has been estimated by applying the well-known correlations between BH mass, bulge luminosity and stellar velocity dispersion to galaxy luminosity and velocity functions. We have found that different BH-galaxy correlations provide the same BHMF only if they have the same intrinsic dispersion, confirming the findings of Marconi & Hunt (2003). The density of supermassive black holes in the local universe is $\rho_{\rm BH} = 4.6^{+1.9}_{-1.4}\, h^2_{0.7} \times 10^5$ M$_\odot$ Mpc^{-3}.

The relic BHMF is derived from the continuity equation with the only assumption that AGN activity is due to accretion onto massive BHs and that merging is not important. We find that the relic BHMF at $z = 0$ is generated mainly at $z < 3$ where the major part of BHs growth takes place. The relic BHMF at $z = 0$ is very little dependent on its value at $z = 3$ since the main growth of BHs took place at $z < 3$. Moreover, the BH growth is anti-hierarchical in the sense that smaller BHs ($M_{BH} < 10^7 M_\odot$) grow at lower redshifts ($z < 1$) with respect to more massive ones ($z \sim 1 - 3$).

We find that the BHMF of AGN relics is perfectly consistent with the local BHMF indicating that local black holes were mainly grown during AGN activity. This agreement is obtained while satisfying, at the same time, the constraints imposed from the X-ray background both in terms of BH mass density and fraction of obscured AGN's. The reasons for the solution of the discrepancy at high masses found by other authors are the following:

- we have taken into account the intrinsic dispersion of the $M_{\rm BH}$-$\sigma_\star$ and $M_{\rm BH}$-$L_{\rm bul}$ correlations in the determination of the local BHMF;
- we have adopted the coefficients of the $M_{\rm BH}$-$\sigma_\star$ and $M_{\rm BH}$-$L_{\rm bul}$ (K band) correlations derived by Marconi & Hunt (2003) after considering only 'secure' BH masses;
- we have derived improved bolometric corrections which do not take into account reprocessed IR emission in the estimate of the bolometric luminosity.

The comparison between the local and relic BHMF's also suggests that the merging process at low redshifts ($z < 3$) is not important in shaping the relic BHMF, and allows us to estimate the average radiative efficiency (ε), the ratio between emitted and Eddington luminosity (λ) and the average lifetime of active BHs.

Our analysis thus suggests the following scenario: local black holes grew during AGN phases in which accreting matter was converted into radiation with efficiencies $\varepsilon \sim 0.1$ and emitted close to the Eddington luminosity. The average total lifetime of these active phases ranges from $\simeq 3 - 7 \times 10^8$ yr for $M_{BH} <$

$10^7 M_\odot$ to $\simeq 1.5\times10^8$ yr for $M_{BH} > 10^9 M_\odot$. The results obtained here with the most recent AGN luminosity functions and XRB models are perfectly consistent with the results of Marconi et al. (2004).

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