Mem. S.A.It. Vol. 79, 1310

Memorie della

Cosmological evolution of supermassive black holes and AGN: a synthesis model for accretion and feedback

A. Merloni[1,2]

[1] Excellence Cluster Universe, Boltzmannstr. 2, 85748, Garching, Germany
[2] Max Planck Institute für Extraterrestrische Physik, Giessenbachstr., 85741, Garching, Germany, e-mail: am@mpe.mpg.de

Abstract. The growth of supermassive black holes (SMBH) through accretion is accompanied by the release of enormous amounts of energy which can either be radiated away, as happens in quasars, advected into the black hole, or disposed of in kinetic form through powerful jets, as is observed, for example, in radio galaxies. Here, I will present new constraints on the evolution of the SMBH mass function and Eddington ratio distribution, obtained from a study of AGN luminosity functions aimed at accounting for both radiative and kinetic energy output of AGN in a systematic way. First, I discuss how a refined Soltan argument leads to joint constraints on the mass-weighted average spin of SMBH and of the total mass density of high redshift ($z \sim 5$) and "wandering" black holes. Then, I will show how to describe the "downsizing" trend observed in the AGN population in terms of cosmological evolution of physical quantities (black hole mass, accretion rate, radiative and kinetic energy output). Finally, the redshift evolution of the AGN kinetic feedback will be briefly discussed and compared with the radiative output of the evolving SMBH population, thus providing a robust physical framework for phenomenological models of AGN feedback within structure formation.

Key words. accretion, accretion discs - black hole physics - galaxies: active - galaxies: evolution - quasars: general

1. Introduction

Black holes in the local universe come into two main families according to their size, as recognized by the strongly bi-modal distribution of the local black hole mass function (see Fig. 1). While the height, width and exact mass scale of the stellar mass peak should be understood as a by-product of stellar (and binary) evolution, and of the physical processes that make supernovae and gamma-ray bursts explode, the supermassive black holes one is the outcome of the cosmological growth of structures and of the evolution of accretion in the nuclei of galaxies, likely modulated by the mergers these nuclear black holes will experience as a result of the hierarchical galaxy-galaxy coalescences.

In the recent literature, it has become customary to introduce the works on cosmological aspects of AGN astrophysics by referring to the strong role they most likely play in the galaxy

Send offprint requests to: A. Merloni

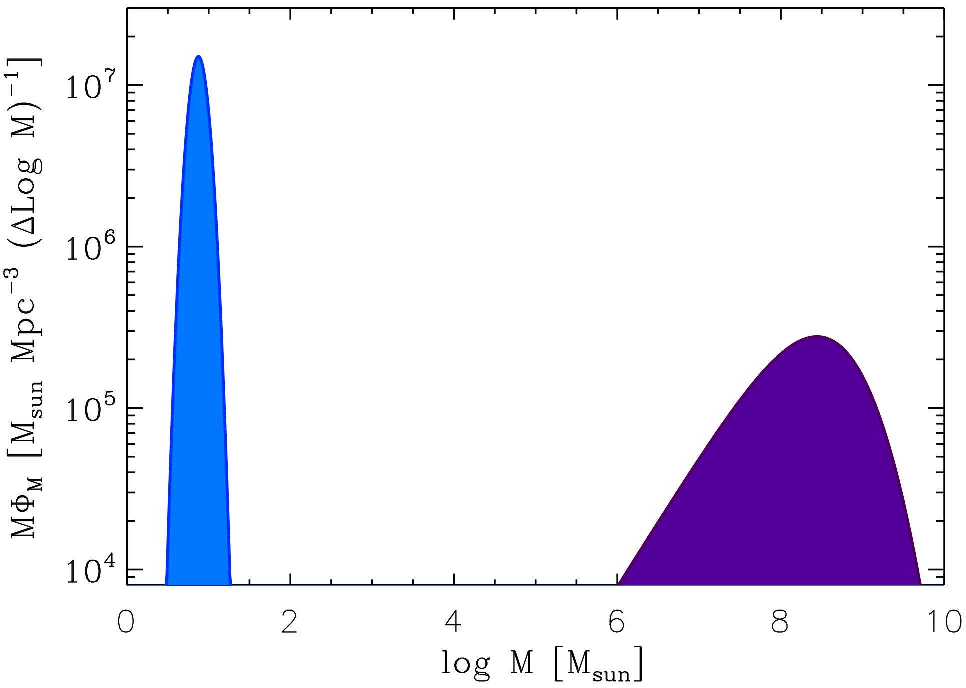

Fig. 1. The local black hole mass function, plotted as $M \times \phi_M$, in order to highlight the location and height of the two main peaks. The stellar mass black holes peak has been drawn assuming a log-normal distribution with mean mass equal to 5 solar masses, width of 0.1 dex and a normalization yielding a density of about $1.1 \times 10^7\ M_\odot\ \mathrm{Mpc}^{-3}$ (Fukugita & Peebles 2004). The supermassive black hole peak, instead, contribute to an overall density of about $1.1 \times 10^7\ M_\odot\ \mathrm{Mpc}^{-3}$ (Merloni & Heinz 2008)

formation process throughout cosmic history. Indeed, a new paradigm has emerged, according to which the feedback energy released by growing supermassive black holes (i.e. AGN) limits the stellar mass growth of their host galaxies in a fundamental, generic, but yet not fully understood fashion.

The strongest observational evidence for such a schematic picture emerged in the last decade. The search for the local QSO relics via the study of their dynamical influence on the surrounding stars and gas carried out since the launch of the *Hubble Space Telescope* (see e.g. Richstone et al. 1998; Ferrarese et al. 2008, and references therein) led ultimately to the discovery of tight scaling relations between SMBH masses and properties of the host galaxies' bulges (Gebhardt et al. 2000; Ferrarese & Merritt 2000; Tremaine et al. 2002; Marconi & Hunt 2003), clearly pointing to an early co-eval stage of SMBH and galaxy growth. A second piece of evidence comes from X-ray observations of galaxy clusters, showing that black holes are able to deposit large amounts of energy into their environment in response to radiative losses of the cluster gas. From studies of the cavities, bubbles and weak shocks generated by the radio emitting jets in the intra-cluster medium (ICM) it appears that AGN are energetically able to balance radiative losses from the ICM in the majority of cases (see Bîrzan et al. 2008, and references therein).

Nevertheless, the physics of AGN heating in galaxy cluster is still not well established, neither have the local scaling relations proved themselves capable to uniquely determine the physical nature of the SMBH-galaxy coupling.

As a consequence, a large number of feedback models have so far been proposed which can reasonably well reproduce these relations. From the observational point of view, the crucial test for most models will be a direct comparison with the high-redshift evolution of the scaling relations.

There is, however, another benchmark, based on existing data, all models have to be tested upon: the evolution of the SMBH mass function and of the predicted energy output (either in radiative or kinetic form) needed to offset gas cooling and star formation in galaxies.

Here I present our recent attempt to reconstruct the history of SMBH accretion in order to follow closely the evolution of the black hole mass function, as needed in order to test various models for SMBH cosmological growth as well as those for the black hole-galaxy co-evolution. Similar to the case of X-ray background synthesis models, where accurate determinations of the XRB intensity and spectral shape, coupled with the resolution of this radiation into individual sources, allow very sensitive tests of how the AGN luminosity and obscuration evolve with redshift, we have argued that accurate determinations of the local SMBH mass density and of the AGN (bolometric) luminosity functions, coupled with accretion models that specify how the observed AGN radiation translates into a black hole growth rate, allow sensitive tests of how the SMBH population (its mass function) evolves with redshift. By analogy, we have named this exercises 'AGN synthesis modelling' (Merloni & Heinz 2008). In performing it, we have taken advantage of the fact that the cosmological evolution of SMBH is markedly simpler than that of their host galaxies, as individual black hole masses can only grow with time, and SMBH do not transform into something else as they grow. Moreover, by identifying active AGN phases with phases of black holes growth, we can follow the evolution of the population by solving a simple continuity equation, where the mass function of SMBH at any given time can be used to predict that at any other time, provided the distribution of accretion rates as a function of black hole mass is known (see § 2).

In order to carry out our calculation, we assumed that black holes accrete in just three distinct physical states, or "modes": a radiatively inefficient, kinetically dominated mode at low Eddington ratios (LK, the so-called "radio mode" of the recent literature), and two modes at high Eddington ratios: a purely radiative one (radio quiet, HR), and a kinetic (radio loud, HK) mode, with the former outnumbering the latter by about a factor of 10. Such a classification is based on our current knowledge of state transitions in stellar mass black hole X-ray binaries as well as on a substantial body of works on scaling relations in nearby SMBH. It allows a relatively simple mapping of the observed luminosities (radio cores, X-ray and/or bolometric) into the physical quantities related to any growing black hole: its accretion rate and the released kinetic power.

In this work I will focus on just a few specific aspects of the derived SMBH evolution, in particular on the redshift evolution of the mass function and Eddington ratio distribution, on the constrains we put on the mass-weighted average spin of the SMBH population, and on the kinetic energy output of growing black holes. A more detailed discussion of the methodology, as well as a wider exploration of our results can be found in Merloni & Heinz (2008).

All results will be shown accounting for the intrinsic uncertainties of the adopted luminosity functions. We estimated that these uncertainties can be evaluated by comparing different analytic parametrization of the same data sets; specifically, we adopted the LDDE and MPLE parametrization for the hard X-ray luminosity function of Silverman et al. (2008), and two alternative parametrizations for the flat-spectrum radio luminosity function of Dunlop & Peacock (1990) and De Zotti et al. (2005).

2. The evolution of SMBH Eddington ratio

We studied the evolution of SMBH mass function through a continuity equation that can be written as:

$$\frac{\partial\psi(M,t)}{\partial t} + \frac{\partial}{\partial M}\left(\psi(M,t)\langle\dot{M}(M,t)\rangle\right) = 0 \qquad (1)$$

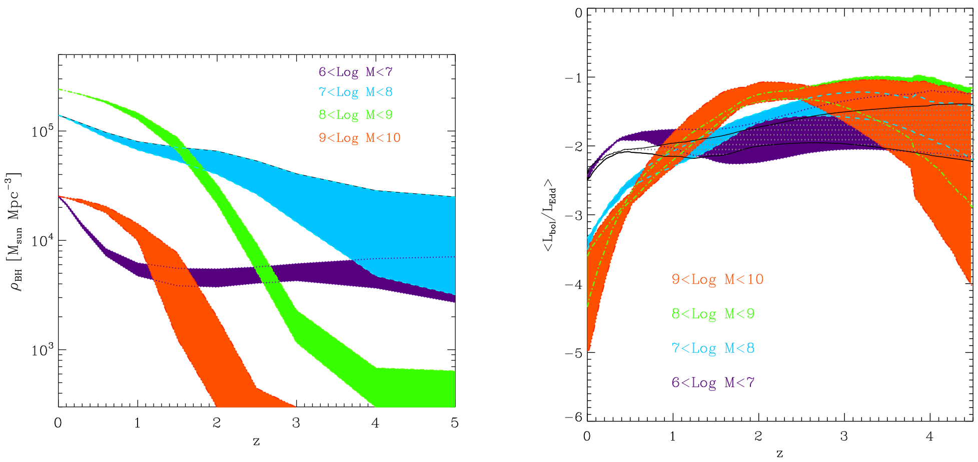

Fig. 2. Redshift evolution of the SMBH mass density (left) and average Eddington ratio (right), calculated for different BH mass bins (in solar mass units). In the right hand plot, black lines and grey shaded area represent the overall (mass-wighted) average Eddington ratio.

where M is the black hole mass, $\mu = Log\, M$, $\dot{\mu} = Log\, \dot{M}$, $\psi(M, t)$ is the SMBH mass function at time t, and $\langle \dot{M}(M, t) \rangle$ is the average accretion rate of SMBH of mass M at time t, and can be defined through a "fueling" function, $F(\dot{\mu}, \mu, t)$, describing the distribution of accretion rates for objects of mass M at time t: $\langle \dot{M}(M, z) \rangle = \int \dot{M} F(\dot{\mu}, \mu, z)\, \mathrm{d}\dot{\mu}$.

Such a fueling function is not a priori known, but can be derived inverting the integral equation that relates the luminosity function of the population in question with its mass function:

$$\phi(\ell, t) = \int F(\dot{\mu}, \mu, t) \psi(\mu, t)\, \mathrm{d}\mu \qquad (2)$$

where I have called $\ell = Log\, L_{\rm bol}$.

Thus, we have integrated eq (1) starting from $z = 0$, where we have simultaneous knowledge of both mass, $\psi(M)$, and luminosity, $\phi(\ell)$, functions, evolving the SMBH mass function backwards in time, up to where reliable estimates of the (hard X-ray selected) AGN luminosity functions are available. The adopted hard X-ray luminosity function (Silverman et al. 2008) is supplemented with luminosity-dependent bolometric corrections (Marconi et al. 2004) and absorbing column density distributions consistent with the X-ray background constraints (as well as the sources number counts, and many others), following the most recent XRB synthesis model (see Gilli et al. 2007, for details).

In Figure 2, I show the evolution of the black hole mass density (left hand side) and of the mass-weighted average Eddington ratio, $\lambda \equiv L_{\rm bol}/L_{\rm Edd}$ (right hand side), both computed for four different black hole mass bins (in solar mass units).

Between redshift zero and one, it is evident how small mass object have a higher Eddington ratio, and increase their total density much more rapidly than their high-mass counterpart, an effect of the well known phenomenon called "AGN downsizing" (Heckman et al. 2004). This trend seems however inverted at higher redshift, when the largest black holes are assembled; a more precise assessment of this phenomenon will require better statistics on the high redshift AGN luminosity functions.

3. Constraints on the average black hole spin

One of the most far-reaching conclusions of the analysis presented in Merloni and Heinz

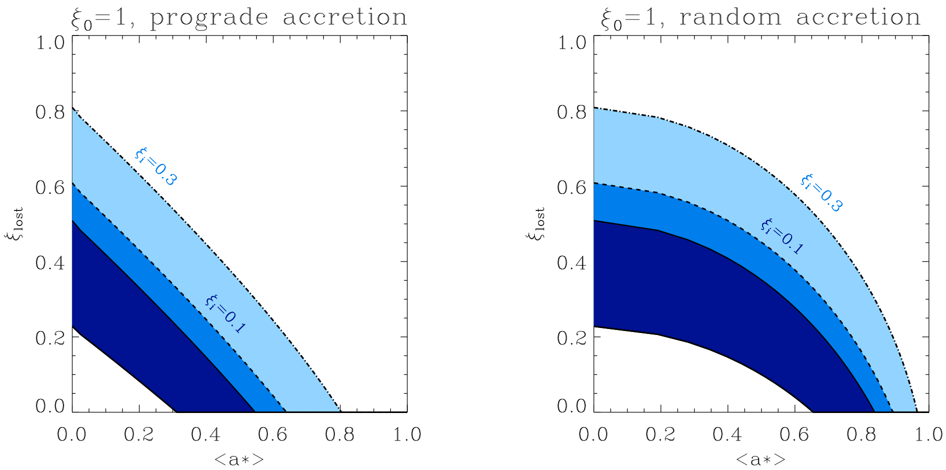

Fig. 3. Constraints on the mass-weighted average spin of SMBH and on the fraction of "wandering" black hole mass density $\xi_{\rm lost}$. The dark blue contours between solid lines correspond to the case of negligible black hole mass density at $z = 5$ ($\xi_i = 0$), progressively lighter blue areas represent the case of larger and larger values of ξ_i. The left hand side shows the calculation assuming accretion onto SMBH proceed always in prograde fashion; the right hand side shows the opposite extreme of purely random accretion. These two extreme cases encompass all possible cosmological solutions.

(2008) was the necessity of a broad distribution of Eddington ratio for SMBH of various masses and redshift, in order to reconcile the observed evolution of the AGN luminosity functions with that of the mass function itself. Consequently, there are always black holes of any mass accreting in different "modes" at any time, and this bears some consequences on the final estimates of the average efficiencies.

In fact, in our three-mode scheme for black hole accretion, the radiative efficiency, $\epsilon_{\rm rad}$, is not necessarily equal to the accretion efficiency, η. The latter represents the maximal amount of potential energy that can be extracted, per unit rest mass energy, from matter accreting onto the black hole. This quantity, $\eta(a)$, depends on the inner boundary condition of the accretion flow only, and, in the classical no-torque inner boundary, is a function of BH spin, a, only, ranging from $\eta(a = 0) \simeq 0.057$ for Schwarzschild (non-spinning) black holes to $\eta(a = 1) \simeq 0.42$ for maximally rotating Kerr black holes.

On the other hand, the radiative efficiency, $\epsilon_{\rm rad} \equiv L_{\rm bol}/\dot{M}c^2$ depends both on the accretion efficiency (i.e. on the inner boundary condition of the accretion flow) and on the nature of the accretion flow itself. Based on our current knowledge of the physical properties of low and high luminosity AGN (and stellar mass black holes), in Merloni & Heinz (2008) we have adopted the following parametrization:

$$\epsilon_{\rm rad} \equiv \eta f(\dot{m}) = \eta \times \begin{cases} 1, & \dot{m} \geq \dot{m}_{\rm cr} \\ (\dot{m}/\dot{m}_{\rm cr}), & \dot{m} < \dot{m}_{\rm cr} \end{cases} \quad (3)$$

where $\dot{m}_{\rm cr} = \lambda_{\rm cr}$ is the critical Eddington-scaled accretion rate above which the disc becomes radiatively efficient, assumed, in our computation, to be at the universal value of 0.03.

In Merloni & Heinz (2008) we have shown how using standard Soltan (1982) type of arguments, i.e. comparing the local mass density to the integrated mass growth in AGN phases, very tight constraints can be put on the average radiative efficiency of the accretion process:

$$\frac{0.065}{\xi_0(1+\xi_{\rm lost})} \lesssim \epsilon_{\rm rad} \lesssim \frac{0.070}{\xi_0(1-\xi_i+\xi_{\rm lost})}, \quad (4)$$

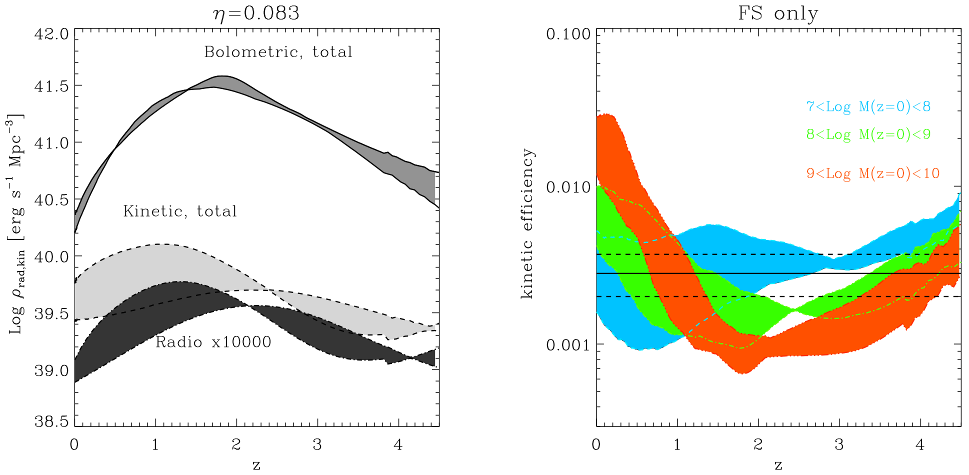

Fig. 4. Left: the AGN kinetic energy density output as a function of redshift, (light grey area between dashed lines) compared to the (bolometric) radiation energy density output (grey area between solid lines) and the radiation energy density in the radio band (5 GHz; dark grey area between dot-dashed lines). Right: Redshift evolution of the kinetic efficiency. SMBH of different masses at $z = 0$ are here plotted separately, with a color coding analogous to that of Fig. 2; the horizontal black solid lines mark the mass weighted average values for the kinetic efficiencies, with the dashed lines representing the uncertainties from the particular choice of radio and X-ray luminosity functions (see Merloni and Heinz 2008 for more details).

where ξ_0 is the local mass density in units of $4.3 \times 10^5 M_\odot$ Mpc^{-3}, while ξ_i and $\xi_{\rm lost}$ are the mass density of $z \sim 5$ and "wandering" SMBH, respectively (also in units of the local mass density).

In order to translate our constrains on the radiative efficiency onto a constrain on the average black hole spin, however, we need to carefully consider the distribution of angular momentum of the matter accreting onto the black holes. As discussed in King et al. (2008), the most important factor is the amount of mass that can be accreted "coherently", i.e. keeping the same large scale angular momentum. If this is larger than a few per cent of the black hole's mass, the black hole will be always spun up, and most of the SMBH mass is accreted from a prograde disk. If, on the other hand, accretion proceeds via small, independent (randomly oriented) sub-units, prograde and retrograde accretion events are almost equally probable (King et al. 2008), and we should use a "symmetrized" relation between black hole spin and accretion efficiency: $\eta_\pm(a) = (1/2)[\eta(a) + \eta(-a)]$. Most likely, the true average relation between spin and efficiency will lie somewhere in between these two extreme cases, depending on the detail of the SMBH fueling mechanism at various redshifts.

Figure 3 shows the constraints derived in the $\xi_{\rm lost}$, $\langle a* \rangle$ plane, where $\langle a* \rangle$ is the mass weighted average spin parameter of the SMBH calculated inverting either the classical GR $\eta(a)$ relation (Shapiro (2005); left panel, prograde accretion only) and its symmetrized version (right panel, random accretion), and taking into account the assumed relationship of eq. (3) between η and $\epsilon_{\rm rad}$.

It is interesting to note that both the amount (numbers and masses) of black holes effectively ejected from galactic nuclei due to gravitational wave recoil after a merger and the average radiative efficiency of accreting black holes depend on the spin distribution of evolving SMBH (see e.g. Berti & Volonteri 2008). Thus, the plots of Fig. 3 couple implicitly the spin distribution of accreting black holes (through $\xi_{\rm lost}$ and $\epsilon_{\rm rad}$) and the properties of the seed black hole population, whose density must be reflected in the $z \sim 5$ mass density ξ_i.

4. The kinetic energy density output of SMBH

Finally, I discuss here briefly the consequences of our synthetic picture of AGN evolution for the issue of AGN feedback in the form of kinetic energy associated to radio jets.

In order to do that, we start from the recently found correlation between kinetic power and radio core luminosity of AGN jets (Merloni & Heinz 2007), and use the flat spectrum radio luminosity function evolution (Dunlop & Peacock 1990; De Zotti et al. 2005) to derive the evolution of the kinetic luminosity function of AGN. The effects of beaming have been taken into account statistically, both in the core-kinetic luminosity relation (Merloni & Heinz 2007) and in the evolving flat spectrum radio luminosity functions (Merloni & Heinz 2008).

By integrating over the kinetic luminosity functions, we get an estimate of the AGN kinetic energy density output as a function of redshift, as shown in the left hand panel of Fig. 4, where a comparison is made with the (bolometric) radiation energy density output and the radiation energy density in the radio band (5 GHz). The most notable feature of this plot is the markedly different redshift evolution of the radiative and kinetic power output, with the latter showing a much smaller amount of evolution between $z = 0$ and $z = 1$. This is due essentially to the increasing number of SMBH accreting at low Eddington ratios in the so-called "low-kinetic" (LK) mode, where a substantial fraction of the gravitational energy of the accreted mass is converted into jet kinetic power. Such a weak redshift dependence, already suggested by Merloni (2004), is in fact necessary in order to reproduce the high-end of the galaxy mass function in semi-analytic models of structure formation that invoke AGN feedback (Croton et al. 2006; Bower et al. 2006).

Let us now examine the kinetic energy production efficiency of growing black holes. We first compute the total integrated (mass weighted) average kinetic efficiency as[1]:

$$\langle \epsilon_{\rm kin} \rangle \equiv \frac{\int_0^{z_i} \rho_{\rm kin}(z) dz}{\int_0^{z_i} c^2 \Psi_{\dot{M}}(z) dz} \simeq (2.8 \pm 0.8) \times 10^{-3} \quad (5)$$

where $\Psi_{\dot{M}}(z)$ is the total black hole accretion rate density at redshift z. Combining the results discussed in section 2 on the average radiative efficiency with those shown in eq. (5) we conclude that SMBH, during their growth from $z \sim 5$ till now, convert about 25 (down to 15 if hidden cores are considered) times more rest mass energy into radiation than into kinetic power, with the exact number depending on the poorly known details of the intrinsic jet cores luminosity function, as well as on our assumptions about the beaming corrections to be made. Similar, but complementary studies of the AGN kinetic luminosity function evolution based instead on *steep* spectrum sources has been recently carried out (Körding et al. 2008; Shankar et al. 2008). Reassuringly, the results of both these works are in reasonable agreement with those I presented here.

We can also compute directly the kinetic efficiency as a function of redshift and SMBH mass *today*, which I show in the right hand panel of Fig. 4, with the horizontal solid lines showing the mass weighted average from eq. (5). The various curves describe the main properties of kinetic feedback as we observe it. For each of the chosen mass ranges, the kinetic efficiency has a minimum when black holes of that mass experience their fastest growth: this is a different way of restating the conclusion that most of the growth of a SMBH happens during radiatively efficient phases of accretion. However, when the mass increases, SMBH are more and more likely to enter the LK mode,

[1] For the sake of simplicity, I discuss here only the case in which we derive the intrinsic radio core luminosity function from the flat spectrum sources only; an upper limit to the contribution from hidden cores in steep spectrum radio sources have been considered in Merloni and Heinz (2008), yielding a final upper limit for the kinetic efficiency about a factor of 2 higher

which increases their kinetic efficiency. More massive holes today, have entered this phase earlier, and by $z = 0$ they have reached the highest kinetic efficiency of a few $\times 10^{-2}$. This is a natural consequence of the observed anti-hierarchical growth of the SMBH population, and of the chosen physical model for the accretion mode of low-Eddington ratio objects.

5. Conclusions

I have outlined some recent results of our work aimed at pinning down as accurately as possible the cosmological evolution of active galactic nuclei and of the associated growth of the supermassive black holes population.

In particular, I have focused here on the global (integrated) constraints on the mass-weighted average spin of SMBH, and I have discussed in some details the specific ways in which these are tighten to the very interesting open issues regarding the population of high-redshift SMBH and that of black holes ejected from galactic nuclei due to gravitational wave recoil in merger events.

I have also discussed a few generic properties of the kinetic energy output of growing black holes, emphasizing the importance of a late phase of low-luminosity, jet-dominated accretion onto the most massive objects.

The richness of details we have been able to unveil demonstrates that times are ripe for comprehensive unified approaches to the multi-wavelength AGN phenomenology. At the same time, our results should serve as a stimulus for semi-analytic and numerical modelers of structure formation in the Universe to consider more detailed physical models for the evolution of the black hole population.

Acknowledgements. I would like to thank warmly Sebastian Heinz for the fruitful collaboration over the last few years, and the organizers of the meeting ”The central Kiloparsec: Active Galactic Nuclei and their Hosts” for the hospitality and the stimulating meeting they have made possible.

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