Co-evolution of galaxies and Active Galactic Nuclei

Gianfranco De Zotti

1. INAF-Osservatorio Astronomico di Padova, Vicolo dell’Osservatorio 5, I-35122 Padova, Italy

Supermassive black holes (SMBHs) have been found to be ubiquitous in the nuclei of early-type galaxies and of bulges of spirals. There are evidences of a tight correlation between the SMBH masses, the velocity dispersions of stars in the spheroidal components galaxies and other galaxy properties. Also the evolution of the luminosity density due to nuclear activity is similar to that due to star formation. All that suggests an evolutionary connection between Active Galactic Nuclei (AGNs) and their host galaxies. After a review of these evidences this lecture discusses how AGNs can affect the host galaxies. Other feedback processes advocated to account for the differences between the halo and the stellar mass functions are also briefly introduced.

1 Introduction

The mutual interactions between super-massive black holes (SMBHs) and host galaxies are a key ingredient to understand the evolution of both source populations. There are now clear evidences that SMBHs and host galaxies evolve in a coordinated way over cosmic history. The understanding of the processes that drive the SMBH-galaxy co-evolution is a central topic in current extragalactic studies.

The starting point was the discovery, via stellar/gas dynamics and photometric observations, that nearby galaxies possessing massive spheroidal components (bulges) host, at their centers, a massive dark object (MDO) endowed with a mass proportional to the mass in old stars or to the K-band luminosity (Kormendy & Richstone, 1995; Magorrian et al., 1998). The MDOs were generally interpreted as the black hole (BH) remnants of a past nuclear activity. Salucci et al. (1999) demonstrated that the mass function of MDOs, derived on the basis of the observed correlation between their masses and the stellar masses in galactic bulges, is consistent with the SMBH mass function derived from the redshift-dependent luminosity function of Active Galactic Nuclei (AGNs), for standard values of the radiative efficiency of BH accretion.

The SMBH interpretation of MDOs was strongly confirmed by the analysis of the orbits for a number of individual stars in the central region of our Galaxy (Ghez et al., 2008; Genzel et al., 2010), ruling out alternative possibilities. A further quite unambiguous evidence of a central SMBH was provided by VLBI measurements at milli-arcsecond (mas) resolution of the $H_2O$ mega-maser at 22 GHz of the galaxy NGC 4258 (Miyoshi et al., 1995).
The luminosity/mass of the stellar component is not the only global property of the local ETGs that correlates with the central BH mass, $M_{BH}$. In fact, a tighter correlation was found between $M_{BH}$ and the stellar velocity dispersion (Ferrarese & Merritt, 2000; Gebhardt et al., 2000). The connection between SMBH mass and galaxy properties, linking scales differing by as much as nine orders of magnitude is likely imprinted by the huge amount of energy released by AGNs, a small fraction of which may come out in a mechanical form (AGN feedback). However, many important details of the processes governing the AGN-galaxy co-evolution are still to be clarified.

In this paper, after a short introduction to AGNs (Sect. 2) I will touch on their demography (Sect. 3). Section 4 deals the main mechanism of SMBH growth: radiative accretion and/or non-radiative processes such as BH mergers? The argument put forward long ago by Soltan (1982) has still an important bearing on this matter. Section 5 is about relationships between galaxy properties and the central SMBH. Section 6 concerns the AGN impact on the host galaxy; the two main mechanisms currently discussed in the literature, energy- and momentum-driven winds, are illustrated. In Section 7 winds powered by AGNs are put in the more general context of feedback processes invoked to account for the different shapes of the mass functions of dark matter halos and of galaxies. Finally, the main conclusions are summarized in Sect. 8.

2 Introduction to AGNs

The AGN (or quasar) discovery dates back to the Schmidt (1963) paper in which the redshift measurement of a bright radio source, 3C 273, was reported: “The stellar object is the nuclear region of a galaxy with a cosmological redshift of 0.158, corresponding to an apparent velocity of 47,400 km/s. The distance would be around 500 megaparsecs, and the diameter of the nuclear region would have to be less than 1 kiloparsec. This nuclear region would be about 100 times brighter than the luminous galaxies which have been identified with radio sources so far...”.

The extreme luminosity of these sources, coming from very compact regions, called for a new energy source. Hoyle & Fowler (1963) were the first to argue that such energy was of gravitational origin. Salpeter (1964) and Zeldovich (1964) showed that accretion into a SMBH can indeed account for the quasar luminosity. The idea was further elaborated by several authors (e.g., Lynden-Bell, 1969, 1978; Lynden-Bell & Rees, 1971) and gained widespread acceptance.

The argument went as follows. The total energy output from a quasar is at least the energy stored in its radio halo ($\approx 10^{54}$ J = $10^{61}$ erg); via $E = mc^2$ this corresponds to $10^7 M_\odot$. Nuclear reactions have at best an efficiency of 0.7% (H burning). So the mass undergoing nuclear reactions capable of powering a quasar is $> 10^9 M_\odot$. Rapid variability implies that a typical quasar is no bigger than a few light-hours. But the gravitational energy of $10^9 M_\odot$ compressed within this size is $10^{55}$ J, i.e. 10 times larger than the fusion energy. In Lynden-Bell’s words: “Evidently, although our aim was to produce a model based on nuclear fuel, we have ended up with a model which has produced more than enough energy by gravitational contraction. The nuclear fuel has ended as an irrelevance.”

Salpeter (1964) considered the radiative efficiency of accretion onto a “Schwarzschild singularity”, showing that it can release an energy of $0.057 c^2$ per unit mass. Bardeen (1970) showed that for a rotating (Kerr) singularity up to nearly 42% of
the accreted rest mass energy is emitted.

3 BH demography

3.1 Why did it take so long to realize the AGN role in galaxy evolution?

Although it was clear from the beginning that quasars are located in the nuclei of galaxies, their presence was considered for decades just as an incidental diversion, an ornament irrelevant for galaxy formation and evolution. There are reasons for that:

- The physical scale of the AGNs is incomparably smaller than that of galaxies: typical radii of the stellar distribution of galaxies are of several kpc, to be compared with the Schwarzschild radius

\[
r_S = \frac{2G M_{\text{BH}}}{c^2} \simeq 9.56 \times 10^{-6} \frac{M_{\text{BH}}}{10^8 M_\odot} \text{ pc},
\]

i.e. \( r_{\text{BH}} \sim 10^{-9} r_{\text{gal}} \).

- The radius of the ”sphere of influence” of the SMBH (the distance at which its potential significantly affects the motion of the stars or of the interstellar medium) is also small:

\[
r_{\text{inf}} = \frac{G M_{\text{BH}}}{\sigma^2} \simeq 11 \frac{M_{\text{BH}}}{10^8 M_\odot} \left( \frac{\sigma_*}{200 \text{ km s}^{-1}} \right)^{-2} \text{ pc},
\]

\( \sigma_* \) being the velocity dispersion of stars in the host galaxies (SMBHs are generally associated to spheroidal components of galaxies, whose stellar dynamics is dominated by random motions, not by rotation). Hence SMBHs have a negligible impact on the global stellar and interstellar medium (ISM) dynamics.

- AGNs and galaxies have very different evolutionary properties. AGNs evolve much faster: they are much rarer than galaxies at low redshifts, where galaxies were most extensively studied, and become much more numerous at \( z \geq 2 \).

Although powerful AGNs are rare locally, the SMBHs powering the quasars at high \( z \) do not disappear. After they stop accreting, they should live essentially forever as dark remnants. So dead quasar engines should hide in many nearby galaxies. This was pointed out early on (Lynden-Bell, 1969; Schmidt, 1978), but a direct test of this idea had to wait for decades.

3.2 How solid is the evidence of SMBHs in galactic nuclei?

The difficulty to reveal inactive SMBHs in galactic nuclei stems from the fact that the SMBH masses required to power the AGNs are a tiny fraction of the stellar mass (let alone the total mass, including dark matter!) of galaxies\(^1\) and therefore their

\(^1\)Estimates of \( M_{\text{BH}}/M_* \) range from \( \simeq 0.1\% \) (Sani et al., 2011) to \( \simeq 0.49\% \) (Kormendy & Ho, 2013).
radius of influence is very small. Even in nearby galaxies the angular scale associated to $r_{\text{inf}}$ is sub-arcsecond:

$$\theta_{\text{inf}} \sim 0.2 \frac{M_{\text{BH}}}{10^8 M_\odot} \left(\frac{\sigma_\star}{200 \text{ km s}^{-1}}\right)^{-2} \left(\frac{D}{10 \text{ Mpc}}\right)^{-1} \text{arcsec},$$

(3)

where $D$ is the distance. Thus dynamical evidence for SMBHs is hard to find.

The first stellar dynamical SMBH detections followed in the mid- to late-1980s, when CCDs became available on spectrographs and required the excellent seeing of observatories like Palomar and Mauna Kea (for reviews see Kormendy & Richstone, 1995; Ferrarese & Ford, 2005). The Hubble Space Telescope (HST), by delivering five-times-better resolution than ground-based optical spectroscopy, made it possible to find SMBHs in many more galaxies. This led to the convincing conclusion that SMBHs are present in essentially every galaxy that has a bulge component.

Because of the smallness of their sphere of influence, resolving it is possible only for relatively nearby, very massive SMBHs. Dynamical estimates based on line widths may not be reliable because of contributions to the mass from other components (dense star clusters, dark matter, ...).

Completely reliable estimates would require resolved proper motions of stars surrounding the SMBH, but so far this could be achieved only for the Milky Way, for which orbits have been determined for about 30 stars within $\lesssim 0.5$ arcsec from the SMBH and distances $\lesssim 0.1$ arcsec at periastron. The SMBH mass can be derived for each of them. However a complete orbit is well measured only for the star S2 which then provides the most accurate determination of the SMBH mass: $M_{\text{BH}} = 4.30 \pm 0.20$ (statistical) $\pm 0.30$ (systematic) $\times 10^6 M_\odot$ (Kormendy & Ho, 2013).

The pericenter radius of S2 is 0.0146 arcsec. At the distance $R_0 = 8.28 \pm 0.15$ (statistical) $\pm 0.29$ (systematic) kpc (Genzel et al., 2010), this angular radius corresponds to $0.00059 \text{ pc}$ or $1,400 r_S$. The mass density within this radius is $\approx 5 \times 10^{15} M_\odot \text{ pc}^{-3}$. The extended mass component within the orbit of S2 (visible stars, stellar remnants and possible diffuse dark matter) contributes less than 4 to 6.6% of this central mass (2 $\sigma$; Gillessen et al., 2009).

Maoz (1998) investigated the dynamical constraints on alternatives to the SMBH interpretation. Can the dark mass density be accounted for not by a point mass but by an ultra-dense cluster of any plausible form of nonluminous objects, such as brown dwarfs or stellar remnants? To answer this question he has investigated the maximum possible lifetime of such dark cluster against the processes of evaporation and physical collisions. It is highly improbable that clusters with a lifetime much shorter than the age of a galaxy ($\sim 10^{10}$ yr, i.e. 10 Gyr) survives till the present epoch. Thus short cluster lifetimes lend strong support to the SMBH interpretation.

The mass and the lower limit to the mass density of the Milky Way central object imply a cluster lifetime of only a few $\times 10^5$ yr, implying that the case for a SMBH is quite strong. The Milky Way situation is however still unique. Maoz (1998) found a cluster lifetime shorter than $\approx 10 \text{ Gyr}$ for only another galaxy, NGC 4258, for which VLBI measurements at mas resolution (i.e. about 100 times better than the HST) of the $H_2O$ mega-maser at 22 GHz from the circum-BH molecular gas disk were available (Miyoshi et al., 1995).

The observations of Miyoshi et al. (1995) established the $H_2O$ mega-masers as one of the most powerful tools for measuring SMBH masses. At the distance of
NGC 4258 1 mas corresponds to 0.035 pc. The masers have almost exactly a Keplerian velocity \( V \propto r^{-1/2} \), as expected in the case of a point source gravitational field. So it is likely that the disk mass is negligible so that the SMBH mass can be straightforwardly derived as \( M_{\text{BH}} = V^2 r / G \).

Useful maser disks are however rare, not least because they must be edge-on, and the orientation of the host galaxy gives no clue about when this is the case. Also in several cases the disk mass was found to be comparable to the SMBH mass, a major complication for SMBH mass measurements. However, progress on this subject has been accelerating in recent years (Kuo et al., 2017a,b; Gao et al., 2017; Henkel et al., 2018).

Information on the immediate environment, within a few gravitational radii, of the SMBH is provided by the asymmetric Kα iron line due to fluorescence (e.g., Fabian, 2013). X-ray observations have shown that AGNs possess a strong, broad Fe Kα line at 6.4 keV (rest-frame). Spectral-timing studies, such as reverberation and broad iron line fitting, of these sources yield coronal sizes, often showing them to be small and in the range of 3 to 10 gravitational radii in size (Fabian et al., 2015). The line then experiences general-relativistic effects, such as strong light bending and large gravitational redshift. If the SMBH is rotating, its angular momentum manifests through the Lense-Thirring precession which occurs only in the innermost part of the accretion disk where the space-time becomes twisted in the same direction that the SMBH is rotating.

The BH spin is measured by the parameter \( a = c J / G M_{\text{BH}}^2 \), \( J \) being the angular momentum. Negative spin values represent retrograde configurations in which the BH spins in the opposite direction to the disk, positive values denote prograde spin configurations, and \( a = 0 \) implies a non-spinning BH. The relativistic effects allow the BH spin to be measured. In particular, the Fe Kα line shape changes, as a function of BH spin; the breadth of the red wing of the line is enhanced as the BH spin increases (Brenneman, 2013).

4 The So\(^\star\)tan argument

A still not completely settled issue is: which is the main mechanism of SMBH growth? Radiative accretion certainly contributes. Actually, most of the accreted material is incorporated by the BH: the standard radiative efficiency adopted by AGN evolutionary models is \( \sim 10\% \), implying that \( \sim 90\% \) of the mass adds to the BH. On the other hand, models of merger-driven galaxy evolution envisage that also the central SMBHs grow by merging. In this case the angular momentum is dissipated by gravitational radiation, i.e. happens without electromagnetic emission. So\(^\star\)tan (1982) pointed out that, if the SMBH growth is mostly due to radiative accretion, the luminosity function of QSOs as a function of redshift traces the accretion history of the SMBHs: for an assumed mass-to-energy conversion efficiency, the luminosity function at any given redshift directly translates into an accreted mass density at that redshift. Integrating such mass density over redshift, gives a present day accreted mass density, which is a lower limit to the present day SMBH mass density since the SMBH mass can have also increased non-radiatively (e.g. via mergers).

Thus a comparison of the accreted mass density with the local SMBH mass density provides considerable insight into the formation and growth of massive SMBHs.
If a BH is accreting at a rate $\dot{M}$, its emitted luminosity is

$$L = \epsilon \dot{M}_{\text{acc}} c^2$$  \hspace{1cm} (4)

where $\epsilon$ is the radiation efficiency, i.e. the fraction of the accreted mass which is converted into radiation and thus escapes the BH.

The growth rate of the BH, $\dot{M}$, is thus given by

$$\dot{M} = (1 - \epsilon) \dot{M}_{\text{acc}}.$$  \hspace{1cm} (5)

Let’s neglect any process which, at time $t$, might ‘create’ or ‘destroy’ a BH with mass $M$. In particular, this means neglecting BH merging. Indeed, the merging process of two BHs, $M_1 + M_2 \rightarrow M_{12}$, means that BHs with $M_1$ and $M_2$ are destroyed while a BH with $M_{12}$ is created. Then, if $\epsilon$ is constant we have:

$$\rho_{\text{BH}} = \frac{1 - \epsilon}{\epsilon c^2} U_T$$  \hspace{1cm} (6)

where $U_T$ is the total comoving energy density from AGNs (not to be confused with the total observed energy density), given by

$$U_T = \int_{0}^{z_s} \frac{dz}{dz} \int_{L_1}^{L_2} L \phi(L, z) dL.$$  \hspace{1cm} (7)

Here $\phi(L, z) dL$ is the bolometric AGN luminosity function. Note the factor $(1 - \epsilon)$ which is needed to account for the part of the accreting matter which is radiated away during the accretion process. If BH mergers, which don’t yield electromagnetic radiation but only gravitational waves, are important, the derived $\rho_{\text{BH}}$ is a lower limit.

Marconi et al. (2004) used luminosity functions in the optical B-band, soft X-ray (0.5–2 keV) and hard X-ray (2–10 keV) band (Ueda et al., 2003) transformed into a bolometric luminosity function using bolometric corrections obtained from template spectral energy distributions (SEDs). In addition, they constrained the redshift-dependent X-ray luminosity function to reproduce the hard X-ray background, which can be considered an integral constraint on the total mass accreted over the cosmic time and locked in SMBHs. They obtained:

$$\rho_{\text{BH}} = (4.7 - 10.6) \frac{(1 - \epsilon)}{9 \epsilon} \times 10^5 \text{ M}_\odot \text{ Mpc}^{-3},$$  \hspace{1cm} (8)

consistent with their own estimate from the local SMBH mass function, $\rho_{\text{BH}} = (3.2 - 6.5) \times 10^5 \text{ M}_\odot \text{ Mpc}^{-3}$, for the ‘canonical’ value $\epsilon = 0.1$.

A similar conclusion was reached by Ueda et al. (2014) using updated X-ray luminosity functions, still constrained to reproduce the X-ray background, and comparing with the local SMBH mass density by Vika et al. (2009), $\rho_{\text{BH}} = (4.9 \pm 0.7) \times 10^5 \text{ M}_\odot \text{ Mpc}^{-3}$, derived from the empirical relation between SMBH mass and host-spheroid luminosity (or mass).

However, recent analyses of SMBH mass measurements and scaling relations concluded that the BH-to-bulge mass ratio shows a mass dependence and varies from 0.1–0.2% at $M_{\text{bulge}} \sim 10^9 \text{ M}_\odot$ to $\sim 0.5\%$ at $M_{\text{bulge}} \sim 10^{11} \text{ M}_\odot$ (Graham & Scott, 2013; Kormendy & Ho, 2013). A similarly large median $M_{\text{BH}}/M_{\text{bulge}}$ ratio for early
type galaxies was found by Savorgnan et al. (2016) who however reported a substantial decrease of the ratio with decreasing stellar mass of the bulges of late-type galaxies.

The revised normalization is a factor of 2 to 5 larger than previous estimates ranging from $\sim 0.10\%$ (Merritt & Ferrarese, 2001; McLure & Dunlop, 2002; Sani et al., 2011) to $\sim 0.23\%$ (Marconi & Hunt, 2003), therefore resulting in an overall increase in the effective ratio, which is dominated by massive bulges.

This would imply either a lower mean radiative efficiency or an important non-radiative (e.g. merging) contribution to the BH growth. Radiatively inefficient processes (i.e. slim accretion disks) have been independently advocated to explain the fast growth of SMBHs in the early Universe (e.g., Madau et al., 2014).

On the other hand, it was pointed out that the bulgeDisk decomposition can lead to a considerable underestimate of the spheroid luminosity and stellar mass, $M_\ast$ (Savorgnan & Graham, 2016) and the selection bias (the AGNs with higher luminosity, i.e., generally, with higher SMBH mass for given stellar mass, are more easily detected) can lead to an overestimate of $M_{BH}$. Both effects lead to an overestimate of the $M_{BH}/M_\ast$ ratio. According to Shankar et al. (2016) the selection bias leads to an overestimate of $M_{BH}$ by at least a factor of 3.

Based on a comprehensive analysis of the co-evolution of galaxies and SMBHs throughout the history of the universe by a statistical approach using the continuity equation and the abundance matching technique, Aversa et al. (2015) found a mean $M_{BH}-M_\ast$ relation systematically lower by a factor of $\sim 2.5$ than that proposed by Kormendy & Ho (2013). The SMBH-to-stellar mass ratio was found to evolve mildly at least up to $z \lesssim 3$, indicating that the SMBH and stellar mass growth occurs in parallel by in situ accretion and star formation processes, with dry mergers playing a marginal role at least for the stellar and SMBH mass ranges for which the observations are more secure.

Although the issue is still debated, there are physical arguments indicating that the AGN radiative efficiency, $\epsilon$, varies with the system age, although how this happens is not yet clear. The global consistency between the SMBH mass density inferred from the So/suppress ltan approach and from the local SMBH mass function constrains predictions on the gravitational wave signals expected from SMBH mergers.

In the case of thin-disk accretion, $\epsilon$ may range from 0.057 for a non-rotating BH to 0.32 for a rotating Kerr BH with spin parameter $a = 0.998$ (Thorne, 1974). During a coherent disk accretion, the SMBH is expected to spin up very rapidly, and correspondingly the efficiency is expected to increase up to $\sim 0.3$. On the other hand, when the mass is flowing towards the SMBH at high rates (super-Eddington accretion), the matter accumulates in the vicinity of the BH and the accretion may happen via the radiatively-inefficient ‘slim-disk’ solution (Abramowicz et al., 1988; Begelman, 2012; Madau et al., 2014; Abramowicz & Straub, 2014; Volonteri et al., 2015) that speeds up the SMBH growth.

This would relieve the challenge set by the existence of billion-solar-mass black holes at the end of the reionization epoch (see, e.g., Haiman, 2013, for a review). The most distant quasar discovered to date, ULAS J1120+0641 at a redshift $z = 7.084$, is believed to host a black hole with a mass of $2.0(+1.5, -0.7) \times 10^9 M_\odot$, only 0.78 Gyr after the big bang (Mortlock et al., 2011). The need of a radiatively inefficient phase is however debated. For example, Trakhtenbrot et al. (2017) argue that “the available luminosities and masses for the highest-redshift quasars can be explained.
self-consistently within the thin, radiatively efficient accretion disk paradigm”.

Trakhtenbrot et al. (2018) have observed with ALMA six luminous quasars at $z \sim 4.8$ finding spectroscopically confirmed companion sub-millimeter galaxies for three of them. The companions are separated by $\sim 14 - 45$ kpc from the quasar, supporting the idea that major mergers may be important drivers for rapid, early BH growth. However, the fact that not all quasar hosts with intense star formation are accompanied by interacting sub-mm galaxies, and their ordered gas kinematics observed by ALMA, suggest that other processes may be fueling these systems. They then conclude that data demonstrate the diversity of host galaxy properties and gas accretion mechanisms associated with early and rapid SMBH growth.

5 Relationships between galaxies and central SMBHs

A tight correlation between $M_{\text{BH}}$ and the galaxy velocity dispersion, $\sigma$, was reported, independently, by Ferrarese & Merritt (2000) and by Gebhardt et al. (2000). Both papers claimed that the scatter was only 0.30 dex over almost 3 orders of magnitude in $M_{\text{BH}}$ and no larger than expected on the basis of measurement errors alone. This suggested that the most fundamental relationship between SMBHs and host galaxies had been found and that it implies a close link between SMBH growth and bulge formation.

Many papers have expanded on this result with bigger samples (for a review, see Kormendy & Ho, 2013). The $M_{\text{BH}}-\sigma$ correlation has been confirmed to be the strongest, with the lowest measured and intrinsic scatter (Saglia et al., 2016). The correlations with the bulge mass, $M_{\text{bulge}}$, is also strong, except for the pseudo-bulge subsample.

Saglia et al. (2016) find, for ellipticals and classical bulges:

$$\log(M_{\text{BH}}/M_{\odot}) = (4.868 \pm 0.32) \log(\sigma/\text{km s}^{-1}) - (2.827 \pm 0.75) \quad (9)$$

$$\log(M_{\text{BH}}/M_{\odot}) = (0.846 \pm 0.064) \log(M_{\text{bulge}}/M_{\odot}) - (0.713 \pm 0.697) \quad (10)$$

Both relationships agree, within the errors, with those derived by Kormendy & Ho (2013); however, while Saglia et al. (2016) find a mean $M_{\text{BH}}/M_{\text{bulge}}$ ratio slowly decreasing with increasing $M_{\text{bulge}}$, Kormendy & Ho (2013) find a slowly increasing trend.

The normalization of the $M_{\text{BH}}-M_{\text{bulge}}$ relation is currently debated. As mentioned above, the main issues are the difficulties of removing the disk component to derive $M_{\text{bulge}}$ and, even more, the bias on $M_{\text{BH}}$ estimates.

An inspection of the Saglia et al. (2016) results shows that:

- “core” elliptical3 have more massive BHs than other classical bulges, at a given

---

3While bulge properties are indistinguishable from those of elliptical galaxies, except that they are embedded in disks, pseudo-bulges have more disk-like properties and are thought to be made by slow (“secular”) evolution internal to isolated galaxy disks.

4Detailed studies of the central regions of early-type galaxies (Ferrarese et al., 1994; Faber et al., 1997) have identified two distinct classes of galaxy centers: “power-law” galaxies, whose central surface brightness shows a steep power-law profile; and “core” galaxies, where the luminosity profile turns over at a fairly sharp “break radius” into a shallower power-law. Ferrarese et al. (1994) and Faber et al. (1997) found evidence that global parameters of early-type galaxies correlated with their nuclear profiles: “core” galaxies tend to have high luminosities, boxy isophotes, and pressure-supported kinematics, while “power-law” galaxies are typically lower-luminosity and often have disky isophotes and rotationally supported kinematics.
Co-evolution of galaxies and Active Galactic Nuclei

\( \sigma \) or bulge mass;

- the smallest intrinsic and measured scatters of the \( M_{BH} - \sigma \) and \( M_{BH} - M_{\text{bulge}} \) relations are measured for the sample of “core” ellipticals;

- “power-law” early-type galaxies and classical bulges follow similar \( M_{BH} - \sigma \) and \( M_{BH} - M_{\text{bulge}} \) relations;

- pseudo-bulges have smaller SMBH masses than the rest of the sample at a given \( \sigma \) or \( M_{\text{bulge}} \);

- disks do not correlate with \( M_{BH} \) and it is unclear whether pseudo-bulges do: SMBH masses do not “know about” galaxy disks [Kormendy et al., 2011].

These relations suggest a tight link between star-formation activity in the spheroidal components of galaxies (not in the disks) and SMBH growth. Such link is strongly confirmed by the striking similarity of the evolution of the SMBH accretion rate and of the star formation rate or of the AGN and galaxy luminosity densities, especially at substantial redshifts where the star formation mostly occurs in the spheroidal components [Shankar et al., 2009; Fiore et al., 2017].

The growth histories of the stellar mass and of the AGN luminosity (hence of SMBH mass) share further similarities. The most massive early-type galaxies form in short (duration \( \lesssim 1 \) Gyr), intense starbursts at high redshift while less massive galaxies have more extended star formation histories that peak later with decreasing mass (e.g., Fig. 9 of Thomas et al., 2010). This “anti-hierarchical” nature (called “downsizing”) is mirrored in the SMBH growth: the most massive SMBHs likely grow in intense quasar phases which peak in the early universe, while less massive SMBHs have more extended, less intense growth histories that peak at lower redshift (e.g., [Ueda et al., 2014]). All that suggests a strong galaxy-AGN co-evolution.

6 AGN impact on galaxy evolution

6.1 AGN-driven winds

As we have seen, the smallness of the radius of influence means that the SMBH’s gravity has a completely negligible effect on its host galaxy. On the other hand, the energy released by the AGN

\[
E_{BH} \simeq \epsilon M c^2 \sim 2 \times 10^{61} \frac{\epsilon M_{BH}}{0.1 \, 10^8 M_\odot} \text{erg}, \tag{11}
\]

where \( \epsilon \) is the mass to radiation conversion efficiency, is far larger than the gas binding energy. Setting \( M_{\text{gas}} = f M_{\text{bulge}} \), with \( f < 1 \), we have

\[
E_{\text{gas}} \sim \frac{3}{2} f M_{\text{bulge}} \sigma^2 \sim 1.2 \times 10^{58} f \frac{M_{\text{bulge}}}{M_{BH}} \frac{M_{BH}}{10^8 M_\odot} \left( \frac{\sigma}{200 \, \text{km/s}} \right)^{-2} \text{erg}, \tag{12}
\]

where \( \sigma \) is the line-of-sight velocity dispersion (the corresponding 3D velocity is \( v = \sqrt{3} \sigma \)). This means that only a few percent of the SMBH energy output may have a strong influence on the gas in the host galaxy, potentially expelling it and, at the same time, limiting the SMBH own growth.
The SMBH energy release can potentially affect its surroundings in two main ways. By far the stronger one (in principle) is through direct radiation. This is particularly effective during heavily dust-obscured phases of AGN evolution \cite{Fabian+2002}.

The second form of coupling the SMBH energy release to a host bulge is mechanical. The huge accretion luminosity of SMBH’s may drive powerful gas flows into the host, impacting into its interstellar medium. A well know form of flow is jets, highly collimated flows driven from the immediate vicinity of the SMBH ("radio-mode" feedback). However to affect most of the bulge requires a way of making the interaction relatively isotropic, perhaps with changes of the jet direction over time. Moreover, radio observations show that the jet energy is dissipated on scales from several kpc to Mpc, i.e. on scales larger than that of a galaxy. Therefore they are more relevant for heating the intergalactic medium (IGM) in galaxy clusters.

A form of mechanical interaction that has automatically the right property are near-isotropic winds carrying large momentum fluxes ("quasar mode" feedback). Such winds are indeed observed in many AGNs, as we will see. \cite{Silk+Rees1998} pointed out that an AGN emitting at close to the Eddington rate could expel gas completely from its host galaxy provided that

$$M_{\text{BH}} > \frac{f \sigma_5 \sigma_T}{4 \pi G^2 m_p c},$$

(13)

where $\sigma_T$, $G$, $m_p$, $c$ and $f$ are the Thomson cross section for electron scattering, the gravitational constant, the proton mass, the speed of light and the gas mass fraction, respectively. The galaxy bulge is assumed to be isothermal with the radius $r$, so that its mass is $M_{\text{bulge}} = 2 \sigma^2 r / G$. The gas mass can be written as $M_{\text{gas}} = f M_{\text{bulge}}$ with $f < 1$. The maximum collapse rate of the gas is $M_{\text{gas}} = M_{\text{gas}} / t_{\text{free-fall}}$ with $t_{\text{free-fall}} = r / \sigma$. The corresponding power is

$$\dot{E}_{\text{gas}} = 1/2 (M_{\text{gas}} / t_{\text{free-fall}}) v^2 = 3 f \sigma^5 / G,$$

(14)

($v = \sqrt{3} \sigma$). The relation $M_{\text{BH}} - \sigma$ then follows equating $\dot{E}_{\text{gas}}$ to the Eddington luminosity

$$L_{\text{Edd}} = \frac{4 \pi G M_{\text{BH}} m_p c}{\sigma_T}.$$

(15)

Plugging in the numbers and considering that only a fraction, $f_{\text{Edd}}$, of the Eddington luminosity can be used to throw the gas out we get:

$$M_{\text{BH}} = \frac{3.6 \times 10^5}{f_{\text{Edd}}} \left( \frac{\sigma}{100 \text{ km/s}} \right)^5 M_{\sun}.$$

(16)

A comparison with the empirical $M_{\text{BH}} - \sigma$ relation shows that $f_{\text{Edd}}$ at the few/several percent level is enough to stop the accretion and to expel the gas from the host galaxy.

Alternatively, we may have momentum or force (instead of energy) balance \cite{Fabian1999,Fabian+2002,King2003,King2005,Murray+2005}. Balancing the outward radiation force with the inward one due to gravity gives

$$\frac{4 \pi G M_{\text{BH}} m_p}{\sigma_T} = \frac{L_{\text{Edd}}}{c} = \frac{G M_{\text{gal}} M_{\text{gas}}}{r^2} = \frac{f G M_{\text{gal}}^2}{r^2} = \frac{f G}{r^2} \left( \frac{2 \sigma^2 r}{G} \right)^2$$

(17)
Co-evolution of galaxies and Active Galactic Nuclei

\[ \frac{4\pi G M_{BH} m_p}{\sigma_T} = \frac{4f}{G}, \quad (18) \]

from which we get

\[ M_{BH} = \frac{f \sigma^4 \sigma_T}{\pi G^2 m_p} = 1.43 \times 10^9 f \left( \frac{\sigma}{100 \text{ km/s}} \right)^4 M_\odot. \quad (19) \]

Thus in the case of momentum-driven flows, the SMBH mass required to stop the accretion is a factor \( \sim c/\sigma \) larger than in the energy-driven case. A comparison with the empirical \( M_{BH} - \sigma \) relation shows that in this case, even the full Eddington luminosity is not enough to unbind the gas unless the gas fraction is small \( (f < 0.1) \) or the AGN has a strongly super-Eddington luminosity. That the full AGN luminosity goes into radiation pressure is expected in the case of “Compton-thick” objects, most of whose radiation is absorbed by the gas.

In the radiation-driven case it is implicitly assumed that the cooling of the SMBH wind is negligible. Under what conditions does this apply? We can crudely model the outflows as quasi-spherical winds from SMBHs accreting at about the Eddington rate

\[ \dot{M}_w \simeq \dot{M}_{Edd} = \frac{L_{Edd}}{c^2} \simeq 0.22 \frac{M_{BH}}{10^8} M_\odot \text{ yr}^{-1}. \quad (20) \]

Winds like this have electron scattering optical depth \( \tau \sim 1 \), measured inward from infinity to a distance of order the Schwarzschild radius \( R_S = 2GM/c^2 \) (King & Pounds, 2015). So on average every photon emitted by the AGN scatters about once before escaping to infinity.

Because electron scattering is front-back symmetric, each photon on average gives up all its momentum to the wind, and so the total (scalar) wind momentum should be of order the photon momentum, or

\[ \dot{M}_w v \sim \frac{L_{Edd}}{c} \simeq \dot{M}_{Edd} \epsilon c, \quad (21) \]

where \( v \) is the wind’s terminal velocity. Since \( \dot{M}_w \simeq \dot{M}_{Edd} \) we get (King & Pounds, 2015):

\[ v \simeq 0.1 \frac{\epsilon}{0.1} c. \quad (22) \]

The instantaneous wind mechanical luminosity is then

\[ L_{BH\text{wind}} = \frac{1}{2} v^2 \dot{M}_w \simeq \frac{1}{2} \frac{v}{c} L_{Edd} \simeq 0.05 \frac{\epsilon}{0.1} L_{Edd}, \quad (23) \]

in good agreement with the earlier estimate for the energy-driven winds.

A self-consistent model is described by (King & Pounds, 2015). The black hole wind is abruptly slowed in an inner (within the SMBH sphere of influence) shock, in which the temperature approaches \( \sim 10^{11} \text{ K} \). The shocked wind gas acts like a piston, sweeping up the host ISM at a contact discontinuity moving ahead of it. Because this swept-up gas moves supersonically into the ambient ISM, it drives an outer (forward) shock into it. The dominant interaction here is the reverse shock slowing the black hole wind, which injects energy into the host ISM. The nature of this shock differs sharply depending on whether some form of cooling (typically
radiation) removes significant energy from the hot shocked gas on a timescale shorter than its flow time.

If the cooling is strong (momentum-driven flow), most of the pre-shock kinetic energy is lost (usually to radiation). As momentum must be conserved, the post-shock gas transmits just its ram pressure to the host ISM. As we have seen, this amounts to transfer of only a fraction $\sim \sigma/c \sim 10^{-3}$ of the mechanical luminosity $L_{\text{BH, wind}} \simeq 0.05 L_{\text{Edd}}$ to the ISM. In other words, for SMBHs close to the $M_{\text{BH}} - \sigma$ relation, in the momentum-driven limit only $\sim 10\%$ of the gas binding energy is injected into the bulge ISM, which is therefore stable.

In the opposite limit in which cooling is negligible, the post-shock gas retains all the mechanical luminosity and expands adiabatically into the ISM. The post-shock gas is now geometrically extended. The mechanical energy, thermalized in the shock and released to the ISM, now equals the gas binding energy. The energy-driven flow is much more violent than the momentum-driven flow and can unbind the bulge.

Note that if the SMBH and galaxy evolve strictly in parallel, preserving the $M_{\text{BH}} - \sigma$ relation, a SMBH in an energy-driven environment is unlikely to reach the observed SMBH masses because it would stop its gas accretion. We will come back to this point in the following.

To sum up, for both momentum- and energy-driven outflows a fast wind (velocity $\sim 0.1c$) impacts the interstellar gas of the host galaxy, producing an inner reverse shock that slows the wind and an outer forward shock that accelerates the swept-up gas. In the momentum-driven case, the shocks are very narrow and rapidly cool to become effectively isothermal; only the ram pressure is communicated to the outflow, leading to very low kinetic energy; $\sim (\sigma/c) L_{\text{Edd}}$. In an energy-driven outflow, the shocked regions are much wider and do not cool; they expand adiabatically, transferring most of the kinetic energy of the wind to the outflow.

### 6.2 Observed wind properties

A recent study of relations between AGN properties, host galaxy properties, and AGN winds has been carried out by Fiore et al. (2017). This paper also contains an exhaustive list of references to observations of massive outflows of ionised, neutral and molecular gas, extended on kpc scales, with velocities of order of 1000 km s$^{-1}$. Three main techniques have been used to detect such outflows (see Fiore et al., 2017, for references): deep optical/near-infrared spectroscopy, mainly from integral field observations; interferometric observations in the (sub)millimetre domain; far-infrared spectroscopy from Herschel. In addition, AGN-driven winds on sub-parsec scales, from the accretion disk scale up to the dusty torus, are now detected routinely up to $z > 2$ as blue-shifted absorption lines in the X-ray spectra of a substantial fraction of AGNs (e.g., Kaastra et al., 2014). The most powerful of these winds have extreme velocities (ultrafast outflows, UFOs, with $v \sim 0.1$–0.3$c$) and are made by highly ionised gas which can be detected only at X-ray energies.

The main conclusions of the Fiore et al. (2017) study are:

- the mass outflow rate is correlated with the AGN bolometric luminosity;
- the fraction of outflowing gas in the ionised phase increases with the bolometric luminosity;
• the wind kinetic energy rate (kinetic power) $\dot{E}_{\text{kin}}$ is correlated with the AGN bolometric luminosity, $L_{\text{bol}}$, for both molecular and ionized outflows: we have $\dot{E}_{\text{kin}} / L_{\text{bol}} \sim 1-10\%$ for molecular winds and $\dot{E}_{\text{kin}} / L_{\text{bol}} \sim 0.1-10\%$ for ionised winds;

• About half X-ray absorbers and broad absorption line (BAL) winds have $\dot{E}_{\text{kin}} / L_{\text{bol}} \sim 0.1-1\%$ with another half having $\dot{E}_{\text{kin}} / L_{\text{bol}} \sim 1-10\%$.

• Most molecular winds and the majority of ionised winds have kinetic power in excess to what would be predicted if they were driven by supernovae, based on the SFRs measured in the AGN host galaxies. The straightforward conclusion is that the most powerful winds are AGN driven.

• The average AGN wind mass-loading factor $\langle \eta \rangle$, is between 0.2 and 0.3 for the full galaxy population while $\langle \eta \rangle \gg 1$ for massive galaxies at $z \lesssim 2$. We may then tentatively conclude that AGN winds are, on average, powerful enough to clean galaxies from their molecular gas (either expelling it from the galaxy or by destroying the molecules) in massive systems only, and at $z \lesssim 2$.

• What happens at $z > 2$ is still unclear.

AGN winds may then be the manifestation of AGN feedback linking nuclear and galactic processes in massive galaxies and accounting for the correlation of SMBH masses and properties of host bulges.

### 6.3 Do SFR and BH accretion rate simply track each other?

A widely cited galaxy-AGN co-evolution model (Hopkins et al., 2008, see, in particular, their Fig. 1) envisage the following scenario for galaxy evolution. Early galaxies have a disk morphology and grow mainly in quiescence until the onset of a major merger. During the early stages of the merger, tidal torques excite some enhanced star formation and SMBH accretion. During the final coalescence of the galaxies, massive inflows of gas trigger strong starbursts. The high gas densities feed a rapid SMBH growth.

In this scenario, star formation and SMBH accretion evolve strictly in parallel. If so we expect a direct proportionality between the corresponding luminosities, i.e., in practice between infrared (IR)$^5$ and X-ray luminosities, $L_X$. In fact, since star formation at substantial redshifts is dust enshrouded, the light emitted by young stars is absorbed by dust and re-emitted at far-IR wavelengths; so $L_{\text{IR}}$ is a measure of the luminosity produced by star formation. In turn, $L_X$ is the best indicator of accretion luminosity.

The connection between star formation and SMBH accretion has been investigated by several authors using samples of far-IR selected galaxies followed up in X-rays and of X-ray/optically selected AGNs followed up in the far-IR band (e.g., Lapi et al., 2014, and references therein). Most recently, Lanzuisi et al. (2017) looked for correlations between the average properties of X-ray detected AGNs and

---

$^4$The mass-loading factor, $\eta$, is the ratio between the mass outflow rate, $\dot{M}_w$, and the SFR: $\eta = \dot{M}_w / \text{SFR}$.

$^5$It has become common practice to define the IR luminosity, $L_{\text{IR}}$, as the integrated emission between 8 and 1000 $\mu$m. In this paper we adopt this convention.
their far-IR detected star forming host galaxies, using a large sample of X-ray and far-IR detected objects in the COSMOS field. The sample covered the redshift range $0.1 < z < 4$ and about 4 orders of magnitude in X-ray and far-IR luminosity, and in stellar mass. They found that $L_X$ and $L_{\text{IR}}$ are significantly correlated. However, splitting the sample into five redshift bins, they found that for every redshift bin both luminosities have a broad distribution, with weak or no signs of a correlation (see their Fig. 4).

Lanzuisi et al. (2017) further investigated, for each redshift bin, the relationships between $L_{\text{IR}}$ and $L_X$ in $L_X$ bins and between $L_X$ and $L_{\text{IR}}$ in $L_{\text{IR}}$ bins (see their Fig. 5). The two relationships can be very different if the link between the two luminosities is complex, as in the case of a weak correlation for the bulk of the population and a strong correlation only for the most extreme objects. This turns out to be case. The average host $L_{\text{IR}}$ has a quite flat distribution in bins of $L_X$ (i.e. the two quantities are weakly, if at all, correlated), while the average $L_X$ somewhat increases in bins of $L_{\text{IR}}$ with logarithmic slope of $\sim 0.7$ in the redshift range $0.4 < z < 1.2$. At higher redshifts the slopes become flatter.

The simplest interpretation of these data goes as follows. At high-$z$ the gas is very abundant in galactic halos and therefore both the star formation and the SMBH accretion can proceed vigorously. However the timescales are widely different. In the case of star formation, the relevant timescale is the minimum between the dynamical time, which is $\sim 0.1$ Gyr for massive galaxies, and the cooling timescale, that can be much longer. Also, since there is an abundant amount of gas available, the star formation can proceed until the gas is swept outside the galaxy by some feedback process (see Sect. 7). As argued by several authors (Granato et al., 2004; Thomas et al., 2010; Lapi et al., 2014) the star formation timescale is likely of at least 0.5–0.7 Gyr for massive spheroidal galaxies and longer for less massive galaxies.

The SMBH accretion timescale is much shorter. During the early evolutionary phases the AGN accretion rate likely occurs at about the Eddington limit:

$$L_{\text{AGN}} = \epsilon c^2 M_{\text{BH}} = \lambda L_{\text{Edd}}$$

(24)

where $\lambda$ is the Eddington ratio and

$$L_{\text{Edd}} = \frac{4 \pi c G M_{\text{BH}} \mu_e}{\sigma_T} = 1.51 \times 10^{38} \frac{M_{\text{BH}}}{M_{\odot}} \text{ erg s}^{-1}$$

(25)

$\mu_e \simeq 1.2 m_p$ being the mass per unit electron and $\sigma_T$ the Thomson cross-section.

If $L_{\text{AGN}} = L_{\text{Edd}}$, i.e. $\lambda = 1$, $M_{\text{BH}}$ grows exponentially:

$$M_{\text{BH}} = M_{\text{seed}} e^{t/\tau_S}$$

(26)

where $\tau_S$ is the Salpeter time

$$\tau_S = \frac{\epsilon c \sigma_T}{4 \pi G \mu_e} = 3.7 \times 10^7 \frac{\epsilon}{0.1} \text{ yr.}$$

(27)

Because of the large difference between the accretion and the star-formation timescale, during the Eddington-limited regime the star-formation and the AGN luminosities cannot be proportional to each other: the AGN luminosity increases exponentially while that due to star formation is approximately constant.
On the other hand, at later times, the accretion is strongly sub-Eddington and
the accretion timescale can match the star-formation timescale, as in the case of
re-activation of star-formation and nuclear activity ("rejuvenation") by interactions
or mergers.

7 Feedback and galaxy evolution

The AGN feedback avoids the formation of too many massive galaxies and the pres-
ence of too many baryons in their galactic halos. In fact, while the mean cosmic
baryon density in units of the critical density is \( \Omega_b = 0.0486 \) (Planck Collaboration XIII,
2016), the baryon density in galaxies is \( \Omega_{b,\text{gal}} \approx 0.00345 \) (Fukugita & Peebles, 2004),
i.e. only \( \sim 7\% \) of baryons are in galaxies. Thus a process capable of sweeping out
more than 90\% of baryons initially present in galactic halos is necessary.

There are however other structural problems that cannot be solved by the AGN
feedback alone. The na"ıve assumption that the stellar mass follows the halo mass
leads also to too many small galaxies (see Fig. 1 of Silk & Mamon, 2012). For halo
masses \( \lesssim 10^{11} M_\odot \) the energy input into the interstellar medium is dominated by
supernovae (Granato et al., 2004) that become the key player in determining the
slope of the low-mass portion of the galaxy stellar mass function as well as the shape
of the Faber-Jackson and of the \( M_{BH} - \sigma \) for less massive bulges.

Why is the energy injection by supernovae insufficient for the most massive galax-
ies? Although the total energy released by supernovae, integrated over the galaxy
lifetime, may be large, the mean power (energy released per unit time) is not enough
to expel the gas from large galaxies. According to Dekel & Silk (1986) supernovae
can cause gas disruption and dispersal in intermediate mass and massive dwarf galax-
ies (halo mass \( \sim 10^8 - 10^{10} M_\odot \)) and can expel the remaining baryons in systems of
halo mass up to \( \sim 10^8 M_\odot \), leaving behind dim dwarf galaxy remnants. According
to Granato et al. (2004), if 5\% of the energy released by supernova explosions goes
into heating of the gas, supernova-driven winds can eject large gas fractions from
halos of up to \( \sim 10^{11} M_\odot \).

In very low-mass halos gas cannot even fall in, because its specific entropy is
too high (Rees, 1986). Only halos of mass \( > 10^5 M_\odot \) can trap baryons that are able to undergo early \( H_2 \) cooling and eventually form stars. Heating by re-ionization
increases this mass limit. The abrupt increase of the sound speed to \( 10 - 20 \text{ kms}^{-1} \) at
\( z \sim 8 \) means that dwarfs of halo mass \( \sim 10^6 - 10^7 M_\odot \), which have not yet collapsed
and fragmented into stars, will be disrupted (Silk & Mamon, 2012).

8 Conclusions

SMBH masses are tightly correlated with properties of the spheroidal component
(classical bulges) of their host galaxies, such as the stellar velocity dispersion (that
shows the tightest correlation), the stellar mass, the luminosity. In contrast, they
do not correlate with disk properties.

Since the spheroidal components of galaxies possess the older stellar populations,
this suggests that the SMBH growth happens in the context of dissipative baryon
collapse at substantial redshifts. The evolution of luminosity densities due to star-
formation in spheroidal galaxies and to AGN activity proceed in parallel, i.e. the
SMBH growth and galaxy build up follow a similar evolution through cosmic history,
Gianfranco De Zotti

with a peak at $z \sim 2 - 3$ and a sharp decline toward the present age.

This implies a mutual relationship between star formation and SMBH accretion rates, which however do not simply track each other. Most growth of large SMBHs happens by radiatively efficient gas accretion (Soltan argument). The energy radiated by a SMBH ($\sim 0.1 M_{\text{BH}} c^2$, assuming a radiative efficiency of 10%) is much larger than the binding energy of its host bulge ($\sim M_{\text{bulge}} \sigma^2$, $\sigma$ being the stellar velocity dispersion). If only $\sim 5\%$ of the AGN energy output couples to gas in the forming galaxy, then all of the gas can be blown. Thus, SMBH growth may be self-limiting, and AGNs may quench star formation.

The substantial stellar masses and star-formation rates of sub-millimeter galaxies (SMGs) and the evidence for subdominant AGN activity and moderate SMBH masses in these objects imply that most of the star formation occurs before the SMBH reach large masses. This is easily understood since the early SMBH growth is Eddington limited.

When the SMBHs reach a critical threshold, their “quasar-mode energy feedback” balances outward radiation or mechanical pressure against gravity. Then the AGNs blow away the interstellar gas, quenching star formation and leaving the galaxies red and dead. AGNs become visible and continue to shine for a few Salpeter times, accreting the “reservoir” (torus) mass. This convincingly solves some problems of galaxy formation, such as expelling a large fraction of initial gas to account for the present day baryon to dark matter ratio in galaxies and preventing excessive star formation (the stellar mass function of galaxies sinks down, at large masses, much faster than the halo mass function).

However, observations of winds capable of removing the interstellar gas from $z > 2$ galaxies are still missing, and a large fraction of massive early type galaxies formed most of their stars at these redshifts. To remove the gas we need a kinetic power of $\sim 5\%$ of the AGN bolometric luminosity, but the scanty observations of high $z$ winds generally indicate lower kinetic powers.

Two kinds of AGN feedback have been considered. Radio-mode feedback (powerful jets of radio sources) is a well known phenomenon but can hardly substantially affect the galaxy evolution: it is very hard to confine well-collimated jets within their galaxies. As Kormendy & Ho (2013) put it: “Firing a rifle in a room does not much heat the air in the room”. It is much more plausible that the jet energy is dissipated by interactions with the intergalactic gas, especially in galaxy clusters.

To efficiently operate on galaxy scales, the feedback must be relatively isotropic (quasar-model feedback). But the physics is not well understood. The correlations between SMBH masses and the galaxy velocity dispersions are consistent with both energy- and momentum-driven feedback. But only energy-driven feedback can efficiently quench star formation.

Outflows with kinetic power sufficient to clean the galaxy of cold gas were found for only a few high-$z$ galaxies. They are more common at $z \lesssim 2$. But most local AGNs accrete at very sub-Eddington rates. Very few galaxies are still growing their SMBHs at a significant level. Rapid SMBH growth by radiatively efficient accretion took place mostly in more massive galaxies that are largely quenched today. That is, the era of SMBH growth by radiatively efficient accretion is now mostly over: co-evolution happened at high $z$. 

66 * PTA Proceedings * February 23, 2018 * vol. 123 pta.edu.pl/proc/2018feb23/123
Acknowledgements. I’m grateful to the organizers of the Third Cosmology School in Cracow for the kind invitation and the extraordinarily warm hospitality. Work supported in part by ASI/INAF agreement n. 2014-024-R.1 for the Planck LFI Activity of Phase E2 and

References

Abramowicz, M. A., Czerny, B., Lasota, J. P., Szuszkiewicz, E., Slim accretion disks, ApJ 332, 646 (1988)

Abramowicz, M. A., Straub, O., Accretion discs, Scholarpedia 9 (2014)

Aversa, R., et al., Black Hole and Galaxy Coevolution from Continuity Equation and Abundance Matching, ApJ 810, 74 (2015), 1507.07318

Bardeen, J. M., Kerr Metric Black Holes, Nature 226, 64 (1970)

Begelman, M. C., Force-feeding Black Holes, ApJ 749, L3 (2012), 1203.1628

Brenneman, L., Measuring the Angular Momentum of Supermassive Black Holes (2013)

Dekel, A., Silk, J., The origin of dwarf galaxies, cold dark matter, and biased galaxy formation, ApJ 303, 39 (1986)

Faber, S. M., et al., The Centers of Early-Type Galaxies with HST. IV. Central Parameter Relations., AJ 114, 1771 (1997), astro-ph/9610055

Fabian, A. C., The obscured growth of massive black holes, MNRAS 308, L39 (1999), astro-ph/9908064

Fabian, A. C., Probing General Relativity with Accreting Black Holes, in C. M. Zhang, T. Belloni, M. Méndez, S. N. Zhang (eds.) Feeding Compact Objects: Accretion on All Scales, IAU Symposium, volume 290, 3–12 (2013), 1211.2146

Fabian, A. C., Wilman, R. J., Crawford, C. S., On the detectability of distant Compton-thick obscured quasars, MNRAS 329, L18 (2002), astro-ph/0111422

Fabian, A. C., et al., Properties of AGN coronae in the NuSTAR era, MNRAS 451, 4375 (2015), 1505.07603

Ferrarese, L., Ford, H., Supermassive Black Holes in Galactic Nuclei: Past, Present and Future Research, Space Sci. Rev. 116, 523 (2005), astro-ph/0411247

Ferrarese, L., Merritt, D., A Fundamental Relation between Supermassive Black Holes and Their Host Galaxies, ApJ 539, L9 (2000), astro-ph/0006053

Ferrarese, L., et al., Hubble Space Telescope photometry of the central regions of Virgo cluster elliptical galaxies. 3: Brightness profiles, AJ 108, 1598 (1994)

Fiore, F., et al., AGN wind scaling relations and the co-evolution of black holes and galaxies, A&A 601, A143 (2017), 1702.04507

Fukugita, M., Peebles, P. J. E., The Cosmic Energy Inventory, ApJ 616, 643 (2004), astro-ph/0406095

Gao, F., et al., The Megamaser Cosmology Project. IX. Black Hole Masses for Three Maser Galaxies, ApJ 834, 52 (2017), 1610.06802

Gebhardt, K., et al., A Relationship between Nuclear Black Hole Mass and Galaxy Velocity Dispersion, ApJ 539, L13 (2000), astro-ph/0006289

Genzel, R., Eisenhauer, F., Gillessen, S., The Galactic Center massive black hole and nuclear star cluster, Reviews of Modern Physics 82, 3121 (2010), 1006.0064

Ghez, A. M., et al., Measuring Distance and Properties of the Milky Way’s Central Supermassive Black Hole with Stellar Orbits, ApJ 689, 1044-1062 (2008), 0808.2870
Gianfranco De Zotti

Gillessen, S., et al., *Monitoring Stellar Orbits Around the Massive Black Hole in the Galactic Center*, ApJ 692, 1075 (2009), [0810.4674](https://arxiv.org/abs/0810.4674)

Graham, A. W., Scott, N., *The M_{BH}-L_{spheroid} Relation at High and Low Masses, the Quadratic Growth of Black Holes, and Intermediate-mass Black Hole Candidates*, ApJ 764, 151 (2013), [1211.3199](https://arxiv.org/abs/1211.3199)

Granato, G. L., et al., *A Physical Model for the Coevolution of QSOs and Their Spheroidal Hosts*, ApJ 600, 580 (2004), [astro-ph/0307202](https://arxiv.org/abs/astro-ph/0307202)

Haiman, Z., *The Formation of the First Massive Black Holes*, in T. Wiklind, B. Mobasher, V. Bromm (eds.) The First Galaxies, Astrophysics and Space Science Library, volume 396, 293 (2013), [1203.6075](https://arxiv.org/abs/1203.6075)

Henkel, C., Greene, J.-E., Kamali, F., *Extragalactic maser surveys*, ArXiv e-prints (2018), [1802.04727](https://arxiv.org/abs/1802.04727)

Hopkins, P. F., Hernquist, L., Cox, T. J., Kereš, D., *A Cosmological Framework for the Co-Evolution of Quasars, Supermassive Black Holes, and Elliptical Galaxies. I. Galaxy Mergers and Quasar Activity*, ApJS 175, 356-389 (2008), [0706.1243](https://arxiv.org/abs/0706.1243)

Hoyle, F., Fowler, W. A., *Nature of Strong Radio Sources*, Nature 197, 533 (1963)

King, A., *The AGN-Starburst Connection, Galactic Superwinds, and M_{BH}-σ*, ApJ 635, L121 (2005), [astro-ph/0511034](https://arxiv.org/abs/astro-ph/0511034)

Kormendy, J., Bender, R., Cornell, M. E., *Supermassive black holes do not correlate with galaxy disks or pseudobulges*, Nature 469, 374 (2011), [1101.3781](https://arxiv.org/abs/1101.3781)

Kormendy, J., Ho, L. C., *Coevolution (Or Not) of Supermassive Black Holes and Host Galaxies*, ARA&A 51, 511 (2013), [1304.7762](https://arxiv.org/abs/1304.7762)

Kormendy, J., Richstone, D., *Inward Bound—The Search For Supermassive Black Holes In Galactic Nuclei*, ARA&A 33, 581 (1995)

Kuo, C. Y., et al., *Enhancing the H2O Megamaser Detection Rate Using Optical and Mid-infrared Photometry*, ArXiv e-prints (2017a), [1712.04204](https://arxiv.org/abs/1712.04204)

Kuo, C.-Y., et al., *On Estimating the Mass of Keplerian Accretion Disks in H2O Maser Galaxies*, ArXiv e-prints (2017b), [1712.09170](https://arxiv.org/abs/1712.09170)

Lanzuisi, G., et al., *Active galactic nuclei vs. host galaxy properties in the COSMOS field*, A&A 602, A123 (2017), [1702.07357](https://arxiv.org/abs/1702.07357)

Lapi, A., et al., *The Coevolution of Supermassive Black Holes and Massive Galaxies at High Redshift*, ApJ 782, 69 (2014), [1312.3751](https://arxiv.org/abs/1312.3751)

Lynden-Bell, D., *Galactic Nuclei as Collapsed Old Quasars*, Nature 223, 690 (1969)

Lynden-Bell, D., *Gravity power*, Phys. Scr 17, 185 (1978)

Lynden-Bell, D., Rees, M. J., *On quasars, dust and the galactic centre*, MNRAS 152, 461 (1971)

Madau, P., Haardt, F., Dotti, M., *Super-critical Growth of Massive Black Holes from Stellar-mass Seeds*, ApJ 784, L38 (2014), [1402.6995](https://arxiv.org/abs/1402.6995)

Magorriian, J., et al., *The Demography of Massive Dark Objects in Galaxy Centers*, AJ 115, 2285 (1998), [astro-ph/9708072](https://arxiv.org/abs/astro-ph/9708072)
Maoz, E., *Dynamical Constraints on Alternatives to Supermassive Black Holes in Galactic Nuclei*, ApJ **494**, L181 (1998), astro-ph/9710309

Marconi, A., Hunt, L. K., *The Relation between Black Hole Mass, Bulge Mass, and Near-Infrared Luminosity*, ApJ **589**, L21 (2003), astro-ph/0304274

Marconi, A., et al., *Local supermassive black holes, relics of active galactic nuclei and the X-ray background*, MNRAS **351**, 169 (2004), astro-ph/0311619

McLure, R. J., Dunlop, J. S., *On the black hole-bulge mass relation in active and inactive galaxies*, MNRAS **331**, 795 (2002), astro-ph/0108417

Merritt, D., Ferrarese, L., *Black hole demographics from the M_H-σ relation*, MNRAS **320**, L30 (2001), astro-ph/0009076

Miyoshi, M., et al., *Evidence for a black hole from high rotation velocities in a sub-parsec region of NGC4258*, Nature **373**, 127 (1995)

Mortlock, D. J., et al., *A luminous quasar at a redshift of z = 7.085*, Nature **474**, 616 (2011), 1106.6088

Murray, N., Quataert, E., Thompson, T. A., *On the Maximum Luminosity of Galaxies and Their Central Black Holes: Feedback from Momentum-driven Winds*, ApJ **618**, 569 (2005), astro-ph/0406070

Planck Collaboration XIII, *Planck 2015 results. XIII. Cosmological parameters*, A&A **594**, A13 (2016), 1502.01589

Rees, M. J., *Lyman absorption lines in quasar spectra - Evidence for gravitationally-confined gas in dark minihaloes*, MNRAS **218**, 25P (1986)

Saglia, R. P., et al., *The SINFONI Black Hole Survey: The Black Hole Fundamental Plane Revisited and the Paths of (Co)evolution of Supermassive Black Holes and Bulges*, ApJ **818**, 47 (2016), 1601.00974

Salpeter, E. E., *Accretion of Interstellar Matter by Massive Objects*, ApJ **140**, 796 (1964)

Salucci, P., Szuszkiewicz, E., Monaco, P., Danese, L., *Mass function of dormant black holes and the evolution of active galactic nuclei*, MNRAS **307**, 637 (1999), astro-ph/9811102

Sani, E., Marconi, A., Hunt, L. K., Risaliti, G., *The Spitzer/IRAC view of black hole-bulge scaling relations*, MNRAS **413**, 1479 (2011), 1012.3073

Savorgnan, G. A. D., Graham, A. W., *Explaining the reportedly overmassive black holes in early-type galaxies with intermediate-scale discs*, MNRAS **457**, 320 (2016), 1511.05654

Savorgnan, G. A. D., Graham, A. W., Marconi, A., Sani, E., *Supermassive Black Holes and Their Host Spheroids. II. The Red and Blue Sequence in the M_{BH}-M_{*,sph} Diagram*, ApJ **817**, 21 (2016), 1511.07437

Schmidt, M., *3C 273 : A Star-Like Object with Large Red-Shift*, Nature **197**, 1040 (1963)

Schmidt, M., *The Local Space Density of Quasars and Active Nuclei*, Phys. Scr **17**, 135 (1978)

Shankar, F., Weinberg, D. H., Mirakda-Escudé, J., *Self-Consistent Models of the AGN and Black Hole Populations: Duty Cycles, Accretion Rates, and the Mean Radiative Efficiency*, ApJ **690**, 20 (2009), 0710.4488

Shankar, F., et al., *Selection bias in dynamically measured supermassive black hole samples: its consequences and the quest for the most fundamental relation*, MNRAS **460**, 3119 (2016), 1603.01276

Silk, J., Mamon, G. A., *The current status of galaxy formation*, Research in Astronomy and Astrophysics **12**, 917 (2012), 1207.3080
Silk, J., Rees, M. J., *Quasars and galaxy formation*, A&A **331**, L1 (1998), astro-ph/9801013

Soltan, A., *Masses of quasars*, MNRAS **200**, 115 (1982)

Thomas, D., et al., *Environment and self-regulation in galaxy formation*, MNRAS **404**, 1775 (2010), 0912.0259

Thorne, K. S., *Disk-Accretion onto a Black Hole. II. Evolution of the Hole*, ApJ **191**, 507 (1974)

Trakhtenbrot, B., Volonteri, M., Natarajan, P., *On the Accretion Rates and Radiative Efficiencies of the Highest-redshift Quasars*, ApJ **836**, L1 (2017), 1611.00772

Trakhtenbrot, B., et al., *Fast-growing SMBHs in Fast-growing Galaxies, at High Redshifts: the Role of Major Mergers as Revealed by ALMA*, ArXiv e-prints (2018), 1801.01508

Ueda, Y., Akiyama, M., Ohta, K., Miyaji, T., *Cosmological Evolution of the Hard X-Ray Active Galactic Nucleus Luminosity Function and the Origin of the Hard X-Ray Background*, ApJ **598**, 886 (2003), astro-ph/0308140

Ueda, Y., et al., *Toward the Standard Population Synthesis Model of the X-Ray Background: Evolution of X-Ray Luminosity and Absorption Functions of Active Galactic Nuclei Including Compton-thick Populations*, ApJ **786**, 104 (2014), 1402.1836

Vika, M., Driver, S. P., Graham, A. W., Liske, J., *The Millennium Galaxy Catalogue: the $M_{bh}$-$L_{spheroid}$ derived supermassive black hole mass function*, MNRAS **400**, 1451 (2009), 0908.2102

Volonteri, M., Silk, J., Dubus, G., *The Case for Supercritical Accretion onto Massive Black Holes at High Redshift*, ApJ **804**, 148 (2015), 1401.3513

Zeldovich, Y. B., *The Fate of a Star and the Evolution of Gravitational Energy Upon Accretion*, Soviet Physics Doklady **9**, 195 (1964)