Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **453,** 4112–4120 (2015) doi:10.1093/mnras/stv1930

Interpreting the possible break in the black hole–bulge mass relation

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Accepted 2015 August 18. Received 2015 August 13; in original form 2015 July 8

ABSTRACT

Recent inspections of local available data suggest that the almost linear relation between the stellar mass of spheroids ($M_{\rm sph}$) and the mass of the super massive black holes (BHs), residing at their centres, shows a break below $M_{\rm sph} \sim 10^{10}\,{\rm M}_{\odot}$, with a steeper, about quadratic relation at smaller masses. We investigate the physical mechanisms responsible for the change in slope of this relation, by comparing data with the results of the semi-analytic model of galaxy formation MORGANA, which already predicted such a break in its original formulation. We find that the change of slope is mostly induced by effective stellar feedback in star-forming bulges. The shape of the relation is instead quite insensitive to other physical mechanisms connected to BH accretion such as disc instabilities, galaxy mergers, active galactic nucleus (AGN) feedback, or even the exact modelling of accretion on to the BH, direct or through a reservoir of low angular momentum gas. Our results support a scenario where most stars form in the disc component of galaxies and are carried to bulges through mergers and disc instabilities, while accretion on to BHs is connected to star formation in the spheroidal component. Therefore, a model of stellar feedback that produces stronger outflows in star-forming bulges than in discs will naturally produce a break in the scaling relation. Our results point to a form of co-evolution especially at lower masses, below the putative break, mainly driven by stellar feedback rather than AGN feedback.

Key words: galaxies: active – galaxies: bulges – galaxies: evolution.

1 INTRODUCTION

Since 1998, observations have shown the existence of more or less tight correlations between the mass of the supermassive black holes (BHs), hosted at the centre of local galaxies, and several properties of their spheroidal component like luminosity (e.g. Magorrian et al. 1998; Marconi & Hunt 2003; Läsker et al. 2014), stellar mass (e.g. Häring & Rix 2004; Sani et al. 2011), central velocity dispersion (e.g. Merritt & Ferrarese 2001; Tremaine et al. 2002; Shankar 2009) or radial concentrate of stars (e.g. Graham et al. 2001; Savorgnan et al. 2013).

The discovery of these scaling relations has been the starting point for a re-evaluation of the role of accretion of gas into BHs and their energetic feedback due to active galactic nucleus (AGN) activity, in the context of galaxy evolution. Starting from this evidence, a number of theoretical studies (see e.g. Kauffmann & Haehnelt 2000; Monaco, Salucci & Danese 2000; Granato et al. 2004; Hopkins et al. 2006; Fontanot et al. 2006; Fanidakis et al. 2012; Hirschmann et al. 2012; Menci et al. 2014) have investigated the physical mechanisms responsible for these tight relations. Most of these studies have been developed in the framework of 'co-evolution' of BH growth and host galaxies, where either the modulation of accretion or AGN feedback is responsible for the correlations. Other authors (e.g. Peng 2007; Jahnke & Macciò 2011) have instead pointed out that a linear relation between bulge and BH masses is not necessarily a sign of co-evolution, but is also comparable with a simple 'cohabitation' model where correlations are mainly driven by galaxy mergers, via the central limit theorem.

In the last years, new observations have revisited and sometimes modified these scaling relations. In particular, recent updates have been published pointing to higher normalizations in the BH mass–bulge stellar mass (e.g. Graham 2012; Kormendy & Ho 2013) and BH mass–central velocity dispersion relations (e.g. Graham 2015). This in turn could imply significantly larger total mass densities for the supermassive BHs in the local Universe (e.g. Novak 2013; Shankar 2013; Comastri et al. 2015). These revisions are due to a number of improvements both in the observational data, thanks to adaptive optics and integral-field spectroscopy, and in the modelling of star kinematics. Bulge masses are intrinsically more difficult to determine, with respect to other bulge properties like luminosity or velocity dispersion, due to the uncertainties in mass-to-light

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ratio (which stem from the uncertainties in the initial stellar mass function, the modelling of stellar evolution and the age–metallicity degeneracy). A breakthrough in this respect came from the study of galaxy kinematics in SAURON[1] and ATLAS-3D surveys (Cappellari et al. 2006, 2013), which provided calibrated relations between mass-to-light ratios and, e.g. velocity dispersion for a representative sample of local galaxies. All these developments led to a significant recalibration of the overall $M_{\rm BH}/M_{\rm sph}$ ratio, from ~0.1 per cent (e.g. Sani et al. 2011) to 0.49 per cent (e.g. Graham & Scott 2013).

Moreover, some evidence has also been accumulating suggesting a scenario where different galaxy populations may follow individual (and different) relations. For example, pseudo-bulges, usually defined as spheroids characterized by disc-like exponential profiles and/or rotational kinematics, were reported to systematically lie below the main relation defined by classical bulges and ellipticals (see e.g. the discussion in Graham 2008; Hu 2008; Shankar et al. 2012; Kormendy & Ho 2013), but recent studies do not confirm these findings (Savorgnan et al. in preparation). The power-law, almost linear relation (in logarithmic space) between BH mass and either bulge stellar mass or central velocity dispersion, has been often used as a constraint for models of the joint evolution of galaxies and AGNs. Indeed, although theoretical models may trace different evolutionary paths for different galaxy populations (see e.g. Lamastra et al. 2010), they typically predict a local $M_{\rm bh}$–$M_{\rm sph}$ relation compatible with a single power-law down to small mass scales that are barely probed by observations (e.g. Marulli et al. 2008; Menci et al. 2008; Fanidakis et al. 2012; Hirschmann et al. 2012). A remarkable exception is provided by the MOdel for Rise of GAlaxies aNd AGNs (MORGANA; Monaco, Fontanot & Taffoni 2007), and presented in Fontanot et al. (2006). In that paper, the predicted $M_{\rm bh}$–$M_{\rm sph}$ relation had a change of slope at $M_{\rm BH} \sim 10^8$ M$_{\odot}$, with a steeper relation at smaller masses. This break had no observational support, but was not incompatible with the sparse data available at that time.

In what follows, whenever we refer to the *black hole–bulge relation* ($M_{\rm bh}$–$M_{\rm sph}$ relation), we will specifically focus on the relation between BH mass ($M_{\rm BH}$) and the stellar mass of the spheroidal/bulge component of the host galaxy ($M_{\rm sph}$).

The overall shape of the $M_{\rm bh}$–$M_{\rm sph}$ relation over a wide range in $M_{\rm sph}$ has been recently revised by Graham & Scott (2015), who studied the $M_{\rm bh}$–$M_{\rm sph}$ relation using data from Scott, Graham & Schombert (2013), and included AGN data for which $M_{\rm sph}$ had been derived for the first time. These authors found that the relation is linear for BH masses above $M_{\rm BH} \gtrsim 2 \times 10^8$ M$_{\odot}$, while it significantly steepens towards a quadratic relation below this threshold. They argued that previous studies missed the 'break' in the $M_{\rm bh}$–$M_{\rm sph}$ relation due to an insufficient sampling at the low-mass end, mainly below $M_{\rm BH} \lesssim 10^7$ M$_{\odot}$. It must be however stressed that consensus on the statistical relevance of the break in $M_{\rm bh}$–$M_{\rm sph}$ relation has still to be reached. Graham & Scott (2015) further revealed that the most massive galaxies defining the linear part of the $M_{\rm bh}$–$M_{\rm sph}$ relation are mostly described by a core-Sérsic stellar profile, i.e. a profile with a deficit of light in central regions with respect to the extrapolation of their outer profile, while the less massive ones are better defined by a single Sérsic profile.

The existence of a quadratic, if not steeper, $M_{\rm bh}$–$M_{\rm sph}$ relation has key implications for the modelling of the joint evolution of BHs and their host galaxies. In particular, it implies that the $M_{\rm BH}/M_{\rm sph}$ ratio is not constant, but it rather depends on the final amount of stellar mass in the host galaxy, and/or its morphological type. Graham & Scott (2015) proposed a physical interpretation of their results suggesting that the initial dissipative processes controlled by the gas-rich, initial phases of galaxy–BH formation, establish a quadratic relation. Later, mostly dry (gas-poor) mergers are responsible for the gradual build-up of the flatter, linear portion of the $M_{\rm bh}$–$M_{\rm sph}$ relation.

The aim of this work is to use MORGANA to deepen our understanding of the origin and evolution of the correlation between BHs and their hosts, by searching for the key physical processes that have an effective impact in shaping the $M_{\rm bh}$–$M_{\rm sph}$ relation and its proposed break. More specifically, we will explore the impact of key physical mechanisms (like disc instabilities, galaxy mergers and stellar/AGN feedback) on the observables of interest. MORGANA relies on quite general assumptions on how galaxy formation takes place inside dark matter haloes, and as such it is representative of the whole class of semi-analytic models (SAMs) of galaxy formation and evolution (see e.g. Fontanot et al. 2009, 2012; Knebe et al. 2015, for comparison with other models in the literature).

In the following, we recalibrate the MORGANA model to reproduce the most recent determinations of the local $M_{\rm bh}$–$M_{\rm sph}$ relation and BH mass function, together with the AGN luminosity function along the cosmic history. We confirm the predicted break in the $M_{\rm bh}$–$M_{\rm sph}$ relation, and check that it is compatible with the determinations of Graham (2012) and Scott et al. (2013). We investigate the origin of the break, and identify stellar feedback in star-forming bulges as the mechanism responsible for it. This points towards a co-evolution scenario in which stellar feedback shapes the low-mass $M_{\rm bh}$–$M_{\rm sph}$ relation in a way that is incompatible with a mere cohabitation scenario.

The structure of this paper is as follows. We first summarize the key aspects of the AGN modelling in MORGANA in Section 2, and detail the different model variants considered in this work in Section 3. We then compare in Section 4 model predictions with both the Scott et al. (2013) data on the $M_{\rm bh}$–$M_{\rm sph}$ relation, and other physically linked observational constraints such as the bolometric AGN luminosity function (LF) and the local BH mass function. We then discuss the relative contribution of the different physical mechanism included in our modelling, and present our conclusions in Section 5.

2 SEMI-ANALYTIC MODEL

MORGANA, first presented in Monaco et al. (2007) and further updated in Lo Faro et al. (2009), relies on simplified modelling of those physical processes that are believed to take place inside dark matter haloes and drive the formation of galaxies. These can be broadly divided into gravitational processes, such as stellar stripping, secular evolution, galaxy interactions and mergers, and hydrodynamical/thermal processes, such as gas cooling, star formation, BH accretion, stellar and AGN feedback. The main strength of the semi-analytic approach is the extensive use of approximate prescriptions, based on theoretical, numerical, or observational results, to follow complex physical processes in a simplified way.

We refer the reader to the original papers and to our comparison work (e.g. Fontanot et al. 2009, 2013; De Lucia et al. 2010, 2011) for a complete overview of the model; in the next section, we will mainly focus on a single aspect of MORGANA, namely the modelling of BH accretion and AGN feedback (see Monaco & Fontanot 2005; Fontanot et al. 2006, for a complete overview of this approach).

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2.1 BH accretion

The model for accretion of gas on to the BH follows Granato et al. (2004), and starts from the assumption that the main bottleneck is given by the loss of angular momentum, necessary for the gas to flow on to a putative accretion disc. As soon as a galaxy is formed, the model assumes that it contains a seed BH of 10^3 $M_\odot$. The first step in the loss of angular momentum is connected to the same processes (mergers, disc instabilities) that bring gas to the spheroidal component; this assumption links BH growth with bulge formation events in the history of the model galaxy. Further loss is triggered by other physical processes (i.e. turbulence, magnetic fields or radiation drag) that are related to star formation in the bulge (Umemura 2001). This results in the building up of a reservoir of low angular momentum gas with mass $M_{\rm RS}$. Its evolution is regulated by growth and loss rates ($\dot{M}^+_{\rm RS}$ and $\dot{M}^-_{\rm RS}$, respectively). The growth rate is taken to be proportional to some power of the bulge star formation rate ($\phi_{\rm B}$):

$$\dot{M}^+_{\rm RS} = f_{\rm BH}\phi_{\rm B}\left(\frac{\phi_{\rm B}}{100\,{\rm M}_\odot\,{\rm yr}^{-1}}\right)^{\alpha-1}, \qquad (1)$$

where $\alpha = 1$ refers to the Umemura (2001) relation used in Granato et al. (2004), while $\alpha = 2$ corresponds to a model where the loss of angular momentum is due by cloud encounters (Cattaneo et al. 2005). $f_{\rm BH}$ is a free parameter, whose value affects the normalization of the final $M_{\rm bh}$–$M_{\rm sph}$ relation, as it regulates the total amount of cold gas flowing into the reservoir during galaxy evolution. The gas in the reservoir then accretes on to the BH at a rate regulated by the viscosity of the accretion disc (Granato et al. 2004):

$$\dot{M}^-_{\rm RS} = \dot{M}_{\rm BH} = 0.001\frac{\sigma_B^3}{G}\left(\frac{M_{\rm RS}}{M_{\rm BH}}\right)^{3/2}\left(1+\frac{M_{\rm BH}}{M_{\rm RS}}\right)^{1/2}, \qquad (2)$$

where $\sigma_{\rm B}$ is the 1D velocity dispersion of the bulge and $M_{\rm BH}$ is the BH mass. This term is also capped at the Eddington limit.

A key role in the feeding of the central BH is played by the actual amount of cold gas available in the spheroidal component as a consequence of bulge formation events. A comprehensive discussion of the relative importance of the different physical mechanisms responsible for the building up of spheroidal components in galaxies has been presented in De Lucia et al. (2011).

Here we simply recall that in MORGANA galaxy mergers are distinguished in major (baryonic merger ratio larger than 0.3) and minor mergers. In the former case, the whole stellar and gaseous contents of both colliding galaxies are transferred to the spheroidal remnant, while in the latter the total baryonic mass of the satellite is given to the bulge of the central galaxy.

Secular evolution is an additional mechanism responsible for transporting material to the centre of galaxies. In MORGANA, we use the standard Efstathiou, Lake & Negroponte (1982) criterion to define the stability of disc structures against self-gravity. However, whenever a disc is found to be unstable, no consensus has been reached yet on how to model the resulting instability. Different SAMs have made different choices, from moving just enough material to restore stability (e.g. Guo et al. 2011; Hirschmann et al. 2012), to completely destroying the unstable disc (e.g. Bower et al. 2006; Fanidakis et al. 2012). Menci et al. (2014) used an updated version of a model by Hopkins & Quataert (2011), calibrated on results from numerical simulations. In all cases, whenever an unstable disc contains cold gas, a fraction of it will be made available to accrete on to the BH, powering an AGN. In MORGANA, we assume that, when the instability criterion is met, a fixed fraction ($f_{\rm DI} = 0.5$) of the baryonic mass of an unstable disc goes into the bulge component. Cold gas flowing into the bulge can then accrete on to the BH as described above. In what follows we will discuss the impact of varying $f_{\rm DI}$ on our final results.

2.2 AGN-triggered winds

AGN activity can inject a relevant amount of energy into the interstellar medium, favouring the triggering of a massive galactic wind that halts the star formation episode ultimately responsible for BH accretion. In the AGN feedback model included in MORGANA, the onset of such dramatic events is supposed to be due to the interplay between stellar and AGN feedback, as described in Monaco & Fontanot (2005). The triggering of a massive wind capable of removing all cold gas from the host bulge is subject to three conditions. The first condition is motivated by the theoretical expectation that AGN radiation is able to evaporate some 50 $M_\odot$ of cold gas for each $M_\odot$ of accreted mass. Whenever the evaporation rate overtakes the star formation rate, the interstellar medium is expected to thicken and cause the percolation of all supernovae remnants into a galaxy-wide superbubble, that can be accelerated by radiation pressure from the AGN. The second condition requires that energy needed to sweep out all the interstellar medium of the host bulge is not greater than the available energy from the AGN. The third condition is that the BH is accreting in a radiatively efficient way, i.e. more than 1 per cent of its Eddington limit.

In Fontanot et al. (2006), we showed that AGN-triggered winds are a key ingredient to reproduce the evolution of the AGN LF and the space density of bright quasars in MORGANA: therefore, in this paper we will consider models including this mechanism. In particular, we will refer to the MORGANA version labelled ‘dry winds’, which implies using a high value of $f_{\rm BH}$ with winds actually limiting the BH masses. It is worth noting that AGN-triggered winds are not necessary to reproduce the $M_{\rm bh}$–$M_{\rm sph}$ relation in MORGANA. In a model without winds, however, the $M_{\rm bh}$–$M_{\rm sph}$ relation is mainly determined by the mechanism that regulates the accretion on to the BH, rather than by feedback-based self-regulation. We refer the reader to Fontanot et al. (2006) for more details, here we just stress that, within MORGANA, the AGN-triggered winds have a limited impact on the shape of the $M_{\rm bh}$–$M_{\rm sph}$ relation (their fig. 6), although they can affect its redshift evolution (their fig. 10).

2.3 Role of stellar feedback

The stellar feedback prescriptions included in MORGANA follow the results from the analytic model of Monaco (2004), which postulates different regimes according to the density and vertical scalelength of the galactic system and distinguishes ‘thin’ systems (i.e. discs) from ‘thick’ systems (i.e. bulges and spheroids). In Fontanot et al. (2006), we showed that stellar feedback has an overall modest impact on the evolution of the AGN population, with the relevant exception of *kinetic* feedback in thick systems.

Kinetic stellar feedback is modelled by estimating the level of turbulence in a star-forming bulge, quantified as the gas velocity dispersion $\sigma_{\rm cg}$, due to the injection of kinetic energy from supernovae and the dissipation of turbulence on a sound crossing time-scale. It is easy to show that this quantity scales with the gas consumption time-scale of gas $t_\star$ to the power $-1/3$, so the velocity dispersion of gas in star-forming bulges can be modelled as follows:

$$\sigma_{\rm cg} = \zeta_0\left(\frac{t_\star}{1\ {\rm Gyr}}\right)^{-1/3}\ {\rm km\,s^{-1}}, \qquad (3)$$

Table 1. AGN feedback parameters for the main runs discussed in this work.

Model	$f_{\rm DI}$	ζ_0 (km s^{-1})	$f_{\rm BH}$
Reference	0.5	30	0.05
Low-DI	0.0	20	0.02
High-DI	1.0	20	0.003

where the parameter[2] ζ_0 regulates the efficiency at which supernovae drive turbulence. Assuming that cold gas clouds have a Maxwellian distribution of velocities, cold gas is then ejected into the halo at a rate proportional to the probability that the velocity of a cloud overtakes the escape velocity from the bulge. So, the combination of a significant ζ_0 and a lower $t_\star$ leads to high values of $\sigma_{\rm cg}$ in bulges, driving massive outflows in small bulges.

In thin systems, where supernova energy can be easily blown out of the system, the value of ζ_0 is expected to be smaller. In Fontanot et al. (2006) we showed that kinetic feedback mechanism in star-forming bulges is a viable mechanism to explain the downsizing behaviour of the AGN population, as high velocity dispersions of cold gas lead to massive removal of cold gas and to the suppression of low-luminosity AGN at moderate-to-high redshifts.

3 RUNS

The reference AGN feedback model by Fontanot et al. (2006) adopted here has two main parameters that regulate the accretion rate of the cold gas reservoir around the BH, namely ζ_0, which regulates the amount of stellar kinetic feedback, and $f_{\rm BH}$ which tunes the normalization of the $M_{\rm bh}$–$M_{\rm sph}$ relation. In addition, the overall radiative efficiency η, which is the emitted luminosity in units of the rest-mass energy, must be recalibrated when using a higher normalization for the $M_{\rm bh}$–$M_{\rm sph}$ relation. This quantity is in fact broadly proportional to the ratio between the integrated emissivity of AGN over time and luminosity and the local mass density of BHs (Soltan 1982). We thus decrease it from the original value of $\eta = 0.1$ adopted by Fontanot et al. (2006) to $\eta = 0.06$ (see Shankar, Weinberg & Miralda-Escudé 2013b), and keep it always fixed to this value in what follows.

All the runs presented in this work have been performed on the same cubic box (100 Mpc side) obtained using the code PINOCCHIO (Monaco et al. 2002, 2013) with $N = 1000^3$ particles and assuming a 2006 concordance cosmology with parameters $\Omega_0 = 0.24$, $\Omega_\Lambda = 0.76$, $h = 0.72$, $\sigma_8 = 0.8$, $n_{\rm sp} = 0.96$.

As the original MORGANA runs were calibrated against the observed $M_{\rm bh}$–$M_{\rm sph}$ relation from Marconi & Hunt (2003), we have recalibrated the model to fit the relation proposed by Graham & Scott (2015) (*reference* run), and to reproduce the evolution of the AGN LF. Regarding the $M_{\rm bh}$–$M_{\rm sph}$ relation, we decided to calibrate our models to reproduce the most reliable BH mass estimates, in the bulge mass range of $M_\star > 10^{11}$ M$_\odot$. The best-fitting parameter values are reported in Table 1. Models tend to have marginally steeper slopes in the high-mass end of the $M_{\rm bh}$–$M_{\rm sph}$ relation, so in general the relation is underestimated at the bending point. It would be easy to absorb this discrepancy using a different calibration choice; however, we consider this conservative choice sufficient for the scope of this paper.

We then define some model variants to explore the sensitivity of our results to model assumptions. We first explore the impact of our choice for the modelling of bar instabilities, by defining two additional runs. In the first one, we switch off disc instabilities ($f_{\rm DI} = 0$, *no-DI* run), while in the other, we assume that the unstable disc is completely destroyed and the disc instability results into a purely elliptical galaxy ($f_{\rm DI} = 1$ *high-DI* run). These runs have also been recalibrated to fit the Graham & Scott (2015) $M_{\rm bh}$–$M_{\rm sph}$ relation. Best-fitting values for the relevant parameters have been collected in Table 1.

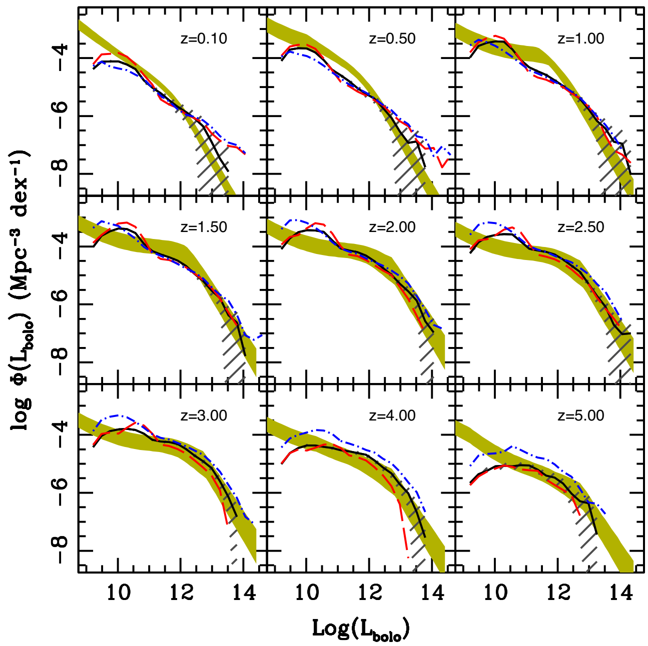

Figure 1. Redshift evolution for the AGN bolometric LF. Yellow areas represent an estimate for the bolometric LF, obtained from the hard X-ray LF (Ueda et al. 2014). Black solid, dashed red and dot–dashed blue lines refer to the predictions of the reference, low-DI and high-DI runs respectively. Hatched areas show the 1σ variance associated with model predictions for the reference model.

The AGN bolometric LF used for calibration is reported in Fig. 1. Here the reference run is shown as a black solid line, while dashed red and dot–dashed blue lines refer to the no-DI and high-DI runs, respectively. The observational estimate of the bolometric LF (yellow area) is obtained from the hard X-ray LF from Ueda et al. (2014, yellow shaded area), using both the Marconi et al. (2004) bolometric correction and an estimate for the fraction of Compton-thick objects by Ueda et al. (2014). All three runs broadly reproduce the evolution of the bolometric AGN LF over wide ranges of redshifts and luminosities, although the high-DI model tends to overproduce AGNs, especially faint ones, at high redshift. It is worth noting that the new calibrations assume relatively low values for ζ_0 with respect to those quoted in Fontanot et al. (2006). This implies that the impact of this parameter to regulate the downsizing behaviour of the AGN population is reduced and also runs with $\zeta_0 = 0$ (see below) provide fair agreement with the data.

For each of the three disc instability options we perform additional MORGANA runs by switching off the stellar kinetic feedback ($\zeta_0 = 0$). These model variants have *not* been recalibrated with respect to the parameters used in the $\zeta_0 > 0$ runs. A further test has been performed by running the model without using the cold, low angular momentum gas reservoir, i.e. assuming that a (Eddington-limited) fraction $\dot{M}^+_{\rm RS}$ of the cold gas in the bulge is directly accreted by the BH. Finally, we have studied the role played by galaxy mergers on the $M_{\rm bh}$–$M_{\rm sph}$ relation.

[2] This parameter was named σ_0 in Fontanot et al. (2006).

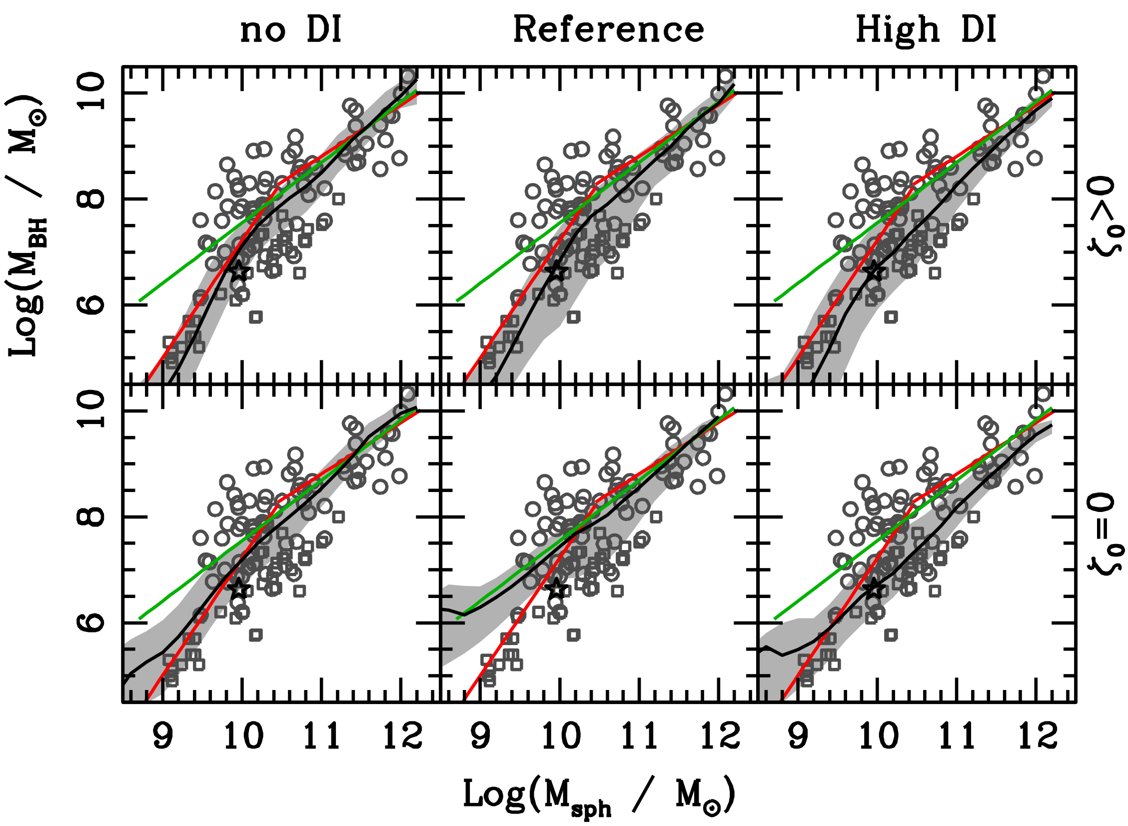

Figure 2. $M_{\rm bh}$–$M_{\rm sph}$ relation at $z = 0$, for different models considered in this work. Red lines correspond to the best fits to the observations as in Scott et al. (2013), while the green line refers to the best fit as in Kormendy & Ho (2013); open circles and squares show data from Scott et al. (2013) and Graham & Scott (2015), respectively. Solid black lines show the median relation for model galaxies, while the grey area represents the 16 and 84 per cent percentiles.

In MORGANA, the merger times for satellite galaxies[3] ($t_{\rm mrg}$) are computed using an updated version of the fitting formulae provided by Taffoni et al. (2003). As shown in De Lucia et al. (2010), over the relevant range of mass ratios, these $t_{\rm mrg}$ are typically shorter than those estimated from other authors, using different and more recent numerical simulations. We then present two model variants obtained using different $t_{\rm mrg}$ definitions, namely the fitting formulae proposed by Boylan-Kolchin, Ma & Quataert (2008, 'longer $t_{\rm mrg}$') and the more extreme case of instantaneous mergers ($t_{\rm mrg} = 0$). Also in these three additional versions we kept the other parameters as in the $\zeta_0 > 0$ runs.

It is also worth stressing that in all the models discussed in this work we do change only the subset of parameters directly connected to AGN modelling, while keeping all other parameters to the values defined in Lo Faro et al. (2009), with the exception of the recomputation of the size of starbursts.[4]

[3] Galaxy merger times are computed whenever a galaxy becomes a satellite, following the merger of its parent DM halo with a larger one.

[4] The computation of gas consumption time-scale $t_\star$, based on the Kennicutt (1998) relation and thus on gas surface density, requires knowledge of the size of the star-forming region. This quantity was set equal to the bulge size in the original MORGANA, while in Lo Faro et al. (2009) a more refined modelling was adopted, based on the idea that the level of turbulence should equate the velocity given by the bulge rotation curve computed at the starburst size. None the less, this change caused a drastic steepening of the $M_{\rm bh}$–$M_{\rm sph}$ relation, so we switched it off to achieve a good modelling of AGNs. The impact on other observables is modest, and can be absorbed by suitable retuning of other parameters.

This implies that, in general, the agreement of model predictions with the calibration set (i.e. local stellar mass function, cosmic star formation rates and morphological mix) may not necessarily be optimal. We, however, explicitly tested that the deviations from the reference models for non-AGN galaxy properties are small. For instance, stellar mass functions are relatively weakly affected by the exact AGN modelling adopted, once the model is calibrated to reproduce the $M_{\rm bh}$–$M_{\rm sph}$ relation and the AGN LF, while the morphological mix is more sensitive to the ζ_0 parameter and to disc instabilities. We checked that our reference run produces a plausible morphological mix.

4 RESULTS

The $z = 0$ $M_{\rm bh}$–$M_{\rm sph}$ relation for the runs defined in the previous section is shown in Fig. 2. In all panels, the black solid line is the median relation for the model galaxy sample, while the grey area represents the 16 and 84 per cent percentiles of the distribution. The central panel in the upper row displays the $M_{\rm bh}$–$M_{\rm sph}$ relation in our reference run, compared to the observational relations proposed by Kormendy & Ho (2013, green solid line) and Graham & Scott (2015, red solid line). A steepening of the $M_{\rm bh}$–$M_{\rm sph}$ relation is evident for $M_\star \lesssim 10^{10}$ M$_\odot$ galaxies, resulting in a break of the relation similar to the results of Graham & Scott (2015) (red lines represent their best fit to power-law-Sérsic and core-Sérsic samples). Moreover, the scatter in the model is broadly compatible with that in the data. The Scott et al. (2013) data points suggest a larger scatter than the predicted one. Note, however, that our model does not include observational errors on BH and stellar masses. Also, the intrinsic scatter reported

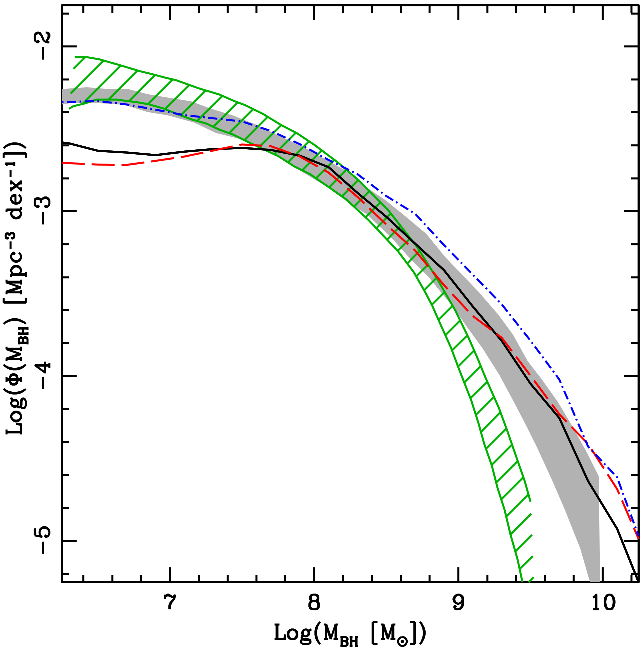

Figure 3. BH mass function at $z = 0$. Data from Shankar (2013, grey area) and Shankar (2009, green hatched area). Line types and colours as in Fig. 1.

by Kormendy & Ho (2013) for the subsample inclusive of only the most accurate BH mass estimates, amounts to ∼0.3 dex, even smaller than what predicted by our models for the total sample.

We now discuss the implications for the $M_{\rm bh}$–$M_{\rm sph}$ relation when varying one or more of the input assumptions in our reference model. We first consider the effect of changing our modelling for disc instabilities (Fig. 2, upper row). We remind that the no-DI and high-DI runs require recalibration of the ζ_0 and $f_{\rm BH}$ parameters to reproduce the observed $M_{\rm bh}$–$M_{\rm sph}$ relation, due to the different predicted amounts of cold gas available for BH accretion and AGN feedback in the models. For all the runs we find a clear break in the $M_{\rm bh}$–$M_{\rm sph}$ relation, thus concluding that its presence does not depend on the exact modelling of disc instabilities. The scatter, compared to the reference run, decreases in the no-DI case, but remains constant in the other case. This is at variance with the results presented, i.e. by Menci et al. (2014). We will deepen into this point in Section 5.

We then turn to the predicted BH mass function (BHMF, Fig. 3), and compare it with the empirical estimates by Shankar (2013), based on the convolution between the galaxy velocity dispersion function from Bernardi et al. (2010), and the BH mass–velocity dispersion relation by McConnell & Ma (2013), which is the most appropriate for our renormalized high BH–stellar mass relation. For completeness, we also report the estimates by Shankar (2009), which were anyway based on previous (lower) normalization of the BH scaling relations. All our runs show a reasonable agreement with the most recent estimate at the high-mass end. At low BH masses the models with no or moderate DI tend to underpredict the mass function, which was anyway estimated assuming a strictly linear power-law scaling relations. The model with strong DI provides a better fit, at the cost of an overprediction at large masses.[5] We caution that the comparison with the local BH mass functions is simply provided as a broad consistency check. As discussed by several authors (see e.g. Tundo et al. 2007; Shankar et al. 2012), these estimates are still affected by systematics on the exact normalization of the input scaling relations and on the actual contributions of low-mass black holes, which can be connected either to possible breaks or other deviations (e.g. those proposed for the ‘pseudo’-bulge population) from the scaling relations defined by more massive black holes.

The results shown in Figs 1 and 3 confirm our previous conclusion that models with different strength of disc instability provide very similar descriptions of the evolution of the AGN population.

We then use our additional model variants to understand which physical mechanism implemented in MORGANA is the main driver for the break in the theoretical $M_{\rm bh}$–$M_{\rm sph}$ relation. In the lower row of Fig. 2, we show MORGANA runs where we switched off kinetic stellar feedback in bulges (i.e. $\zeta_0 = 0$). All the resulting relations are power laws over the whole $M_{\rm sph}$ range, and follow a relation with a slope compatible to, or slightly steeper than, the Kormendy & Ho (2013) best-fitting relation (green line), with no apparent bend at the low-mass end. We thus conclude that the treatment of stellar feedback is mainly responsible for the different behaviours at the high- and low-mass end of the $M_{\rm bh}$–$M_{\rm sph}$ relation.

This is confirmed in Fig. 4, where we report the $M_{\rm bh}$–$M_{\rm sph}$ relation predicted by the variants of the reference model without the reservoir of low angular momentum gas, and with varied merging times. We recall that these additional variants do use the same calibration as the reference run, so the normalization of the $M_{\rm bh}$–$M_{\rm sph}$ relation is not guaranteed to be reproduced. All relations show the same steepening at low masses. Moreover, the typical $M_{\rm sph}$ mass scale corresponding to the resulting break does not change among the various runs (with a possible exception of the zero merger time run), confirming that stellar feedback is setting the mass scale of the change of slope. Changing the merger time-scale in MORGANA has only a limited effect on the shape and normalization of the $M_{\rm bh}$–$M_{\rm sph}$ relation, and we checked that this is independent of the assumed disc instability model.

We finally address the redshift evolution of the $M_{\rm bh}$–$M_{\rm sph}$ relation. We checked that all models predict the $M_{\rm bh}$–$M_{\rm sph}$ relation to be already in place at high redshift, with almost no evolution in the shape with respect to the local relation. It is worth stressing that the actual detectability of a ‘bended’ relation at higher redshifts is related to the abundance of the massive galaxy population.

We find some evolution in the normalization of the $M_{\rm bh}$–$M_{\rm sph}$ relation. We quantify this evolutionary trend by means of the $\Gamma(z)$ parameter, defined as

$$\Gamma(z) = \sum_{M_{\rm sph}} \frac{M_{\rm BH}(z)}{M_{\rm BH}(z=0)}(M_{\rm sph}). \tag{4}$$

In Fig. 5 we show the average evolution of Γ, computed with $M_{\rm sph} > 10^9\,{\rm M}_\odot$ model galaxies, using the corresponding median relations shown in Fig. 2 as $z = 0$ reference. The evolution up to $z = 2$ is similar for all models, but disc instabilities lead to a flattening of Γ at high redshift.

5 DISCUSSION AND CONCLUSIONS

Recent re-calibrations of the locally measured $M_{\rm bh}$–$M_{\rm sph}$ relation suggest its normalization to be a factor of ∼2 higher than

[5] This trend cannot be predicted by the results of Fig. 2, because it is driven by the larger mass in bulges that is obtained in this model. A full recalibration of the model, including also galaxy observables, may absorb this difference, although such a strong role of disc instabilities may easily result in an overproduction of bulges.

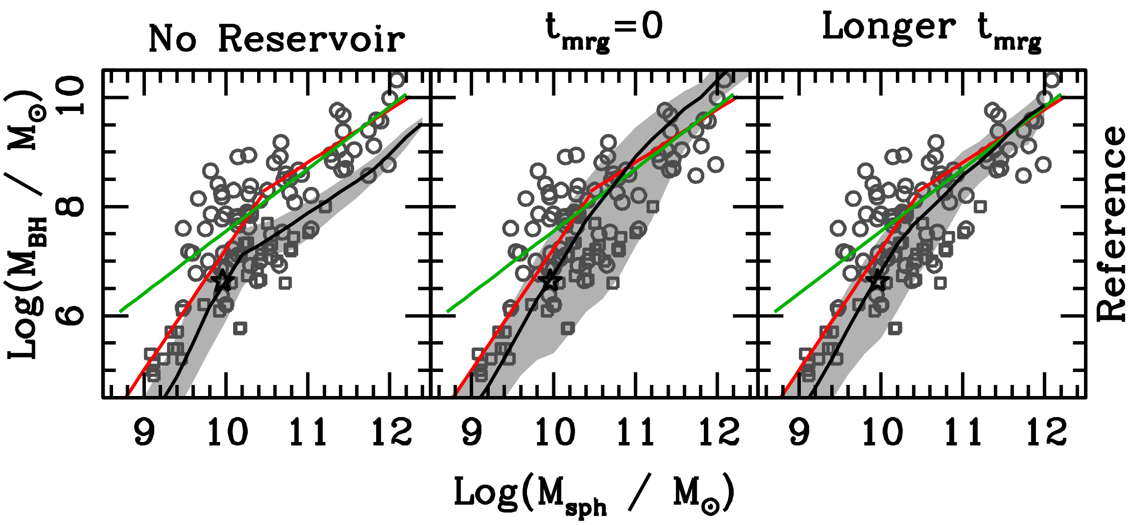

Figure 4. M_{bh}–M_{sph} relation at $z = 0$, for different models considered in this work. Lines, colours and shading as in Fig. 2.

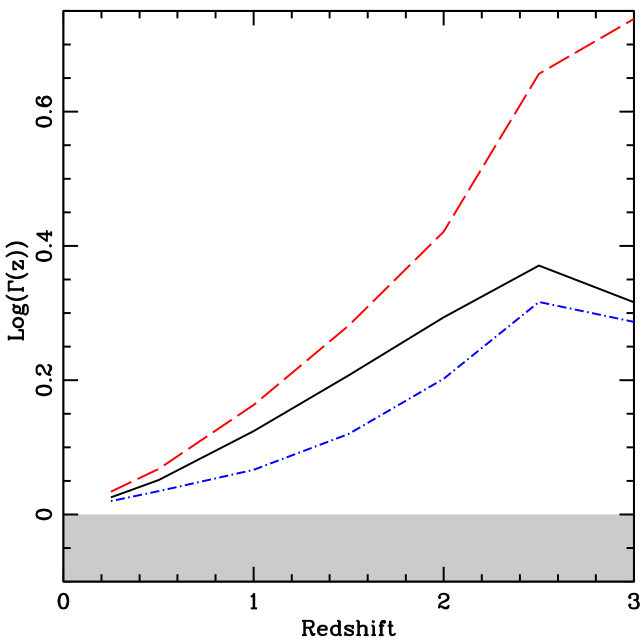

Figure 5. Redshift evolution of the overall M_{bh}–M_{sph} relation. Line types and colours as in Fig. 1. See text for more details on the definition of the Γ parameter.

previously inferred (e.g. Graham & Scott 2013; Kormendy & Ho 2013). Some authors (Scott et al. 2013; Graham & Scott 2015) have found a strong, quadratic steepening of the M_{bh}–M_{sph} relation below $M_{BH} \lesssim 2 \times 10^8$ M$_\odot$. The MORGANA model made a prediction of such a steepening at low masses in 2006 (Fontanot et al. 2006). While consensus on this break in the relation is still to be achieved, in this paper we have further investigated the possible physical causes of such a steepening. To this aim, after recalibrating the predicted M_{bh}–M_{sph} relation to take account of the higher normalization, we explored the impact of varying the strength of the disc instabilities, galaxy mergers and stellar feedback in star-forming spheroids.

We explicitly tested that the strength of the disc instability, i.e. the amount of baryonic material transferred from the unstable disc to the central spheroidal component, does not affect the shape of the M_{bh}–M_{sph} relation, although it may change its normalization. We also showed that neither the assumed modelling of a gas reservoir around the BH, nor the timing of galaxy mergers has a relevant effect on the shape of the M_{bh}–M_{sph} relation in MORGANA, while they have an influence on its normalization and scatter.

In more detail, we find that the scatter in the M_{bh}–M_{sph} relation, as predicted by MORGANA, does not depend on the modelling of disc instabilities, i.e. on the relative importance of this physical mechanism in feeding the central BH. This result may be reconciled with the results from other SAMs (see e.g Menci et al. 2014), by considering the role of the gas reservoir in our model. As a matter of fact, comparing the runs assuming direct (Eddington-limited) accretion on to the central BH, i.e. switching off the modelling of the gas reservoir, we confirm a decrease (of a factor of about 1.5) in the scatter at the high-mass end of the relation moving from the reference to the high-DI runs. This is compatible with the idea that the delayed accretion from the reservoir (with respect to the time when cold gas loses most of its angular momentum) adds another time-scale to the mechanism of BH accretion that couples to disc instabilities. This additional time-scale dominates the scatter in the M_{bh}–M_{sph} relation.

The physical process responsible for the break in the M_{bh}–M_{sph} relation in MORGANA is stellar feedback in star-forming bulges. Its role can be illustrated as follows. Both bulges and BHs acquire stars from merging and local star formation/accretion. While most stars are found in bulges at $z = 0$ (see e.g. Gadotti 2009), star formation mostly takes place in the disc components of galaxies, with a minor contribution from starbursts. This is true in MORGANA (Monaco et al. 2007), but observations suggest a similar trend at $z \sim 2$, with normal star-forming galaxies being predominantly rotating discs (Förster Schreiber et al. 2006) and starbursts lying above the main sequence of star-forming galaxies, contributing only ~10 per cent to the total SFR density (Daddi et al. 2010; Rodighiero et al. 2011; Sargent et al. 2012). As a consequence, most stars in bulges were formed in discs and were carried into the spheroidal component by mergers and disc instabilities. Conversely, most mass in the BHs is brought by accretion and not by mergers (e.g. Salucci et al. 1999; Marconi & Hunt 2003). As long as BH accretion is related to star formation in bulges, a selective suppression of this star formation in small bulges will decrease small BH masses but will not influence much the stellar mass of bulges.

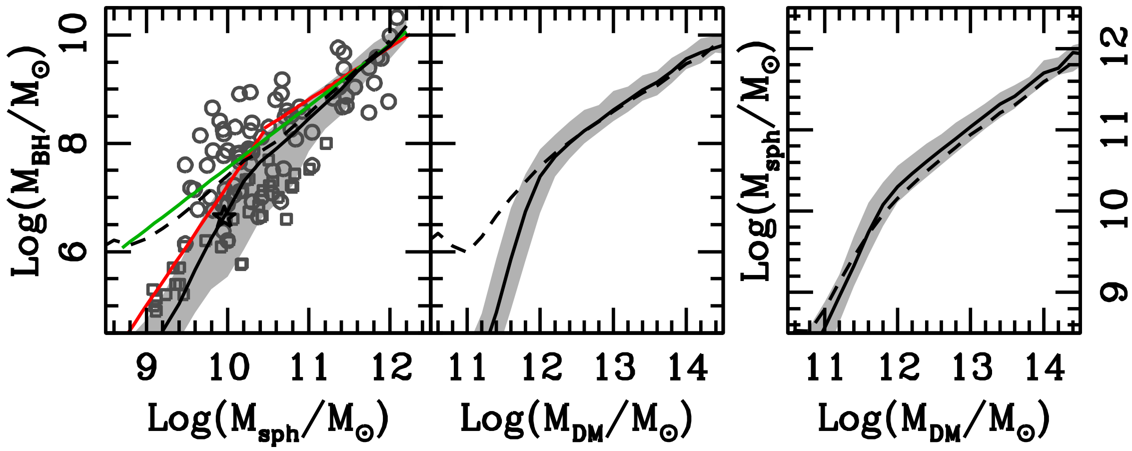

Figure 6. Additional black hole–spheroid scaling relations for at $z = 0$, for the different models considered in this work. Left-hand panel: $M_{\rm bh}$–$M_{\rm sph}$ relation (data as in Fig. 2). Middle panel: $M_{\rm BH}$–$M_{\rm DM}$ relation. Right-hand panel: $M_{\rm sph}$–$M_{\rm DM}$ relation. In all panels, solid lines refer to the median relations in reference model (shaded areas representing the 5 and 95 per cent percentiles), while the dashed line to the corresponding $\zeta_0 = 0$ runs.

This interpretation of the break $M_{\rm bh}$–$M_{\rm sph}$ relation differs from the Graham & Scott (2015), and we propose it as an alternative explanation of the steepening of the $M_{\rm bh}$–$M_{\rm sph}$ relation at small masses. In particular, our model does not produce two clearly different regimes as a function of $M_{\rm sph}$. Star formation,[6] BH accretion and mergers (both dry and wet) happen at all mass scales, although the relative importance of each physical process depends on the total mass of the host galaxy (De Lucia et al. 2011; Shankar et al. 2013a). We also showed that the shape of the $M_{\rm bh}$–$M_{\rm sph}$ relation depends weakly on the choice of merger time-scales. In particular, a significant shortening of the merger time-scales (i.e. assuming instantaneous galaxy mergers) increases the mass of the most massive BHs by a factor of up to ∼2 and changes the position of the break, but the overall $M_{\rm bh}$–$M_{\rm sph}$ relation still shows a bend at the low-mass end.

We also stress that the stellar feedback mechanism we propose is an example of a possible self-regulation of BHs and bulges, where effective stellar feedback leads to starvation of small BHs. In this sense, a steepening of the $M_{\rm bh}$–$M_{\rm sph}$ relation can be seen as an argument in favour of the 'co-evolution' scenario as opposed to the 'cohabitation' one, where a linear relation driven by mergers is the most natural expectation. This self-regulation is not due to AGN feedback, although, as commented in Section 2, the final BH mass is self-regulated by AGN feedback. Indeed, of the three models presented in the original Fontanot et al. (2006) paper, two were based on a self-regulation of BH masses due to AGN feedback, but all three showed a break in the $M_{\rm bh}$–$M_{\rm sph}$ relation.

Previous work already showed that non-trivial AGN feedback schemes, whose efficiency varies as a function of halo mass, can create a break in scaling relations, including the $M_{\rm bh}$–$M_{\rm sph}$ relation (Cirasuolo et al. 2005; Shankar et al. 2006), though possibly milder than the one emphasized by Graham & Scott (2015).

It is at this point natural to ask whether a break in the BH–stellar mass relation corresponds to a break in other scaling relations, especially between $M_{\rm BH}$ and velocity dispersion σ, usually measured to be even tighter. Graham & Scott (2015) have shown that no apparent break is evident in their data when plotting BH mass versus velocity dispersion, while the supernova feedback model implemented by Cirasuolo et al. (2005) predicted a clear break also in this relation. An estimate of the central velocity dispersions of bulges from MORGANA would require to make several additional assumptions on the exact light and mass profiles of the stellar, gas and dark matter components. Instead, we choose to consider the predicted relation between $M_{\rm BH}$ and halo mass $M_{\rm DM}$: this is shown in Fig. 6, where the left-hand panel is a replication of the reference model relation in Fig. 2 (continuous line) and, overplotted, the median relation for the model with $\zeta_0 = 0$ (dashed line). The other two panels of this figure show the relation between BH mass and halo mass (middle), and between halo mass and stellar mass of the spheroidal component (right). A break in the $M_{\rm BH}$–$M_{\rm DM}$ relation is evident in our reference model, while it is nearly absent in the model without kinetic feedback (dashed lines). It is interesting to notice that the shape of the $M_{\rm sph}$–$M_{\rm DM}$ relation is almost unaffected by this mechanisms, confirming that this modelling of feedback in star-forming bulges affects BH masses much more than the spheroidal component of the galaxy.

It is worth stressing that it is not straightforward to infer conclusions on the shape of the $M_{\rm BH}$–σ relation from the results shown in Fig. 6. While we expect $M_{\rm DM}$ to correlate with virial velocity, the relation between the latter quantity and velocity dispersion is still uncertain for large galaxy samples. Several groups (see e.g. Ferrarese & Merritt 2000; Baes et al. 2003) suggested that σ correlates with the circular velocity as measured at the outermost radii, while other authors (Ho 2007) showed that such a correlation has a significant scatter and varies systematically as a function of galaxy properties. Therefore, any further conclusion on the $M_{\rm BH}$–σ relation critically depends on the assumed relation between velocity dispersion and circular velocity, e.g. if we assume a linear correlation, we then expect a break also in this relation.

Of course, our modelling of stellar and AGN feedback still represents an idealized approach and we argue that observations of spatially resolved galaxies (e.g. CALIFA,[7] Sánchez et al. 2012) will provide a better comprehension of the interplay between these two fundamental physical mechanisms.

[6] In detail, star formation is still appreciable for massive galaxies in MORGANA, due to the inefficient quenching of cooling flow in massive haloes for an AGN modelling, which does not include hot gas accretion (Fontanot et al. 2007).

[7] Calar Alto Legacy Integral Field Area Survey

ACKNOWLEDGEMENTS

We thank Alister Graham, Alessandro Marconi and Giulia Savorgnan for interesting discussions and useful suggestions. FF acknowledges financial support from the grants PRIN INAF 2010 'From the dawn of galaxy formation' and PRIN MIUR 2012 'The Intergalactic Medium as a probe of the growth of cosmic structures'. PM acknowledges support from PRIN INAF 2014 'Glittering kaleidoscopes in the sky: the multifaceted nature and role of Galaxy Clusters'.

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