Mem. S.A.It. Vol. 77, 678

Memorie della

A close look to quasar-triggered galaxy winds

Is the black hole–bulge relation self-regulated?

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Abstract. We discuss the role of feedback from AGNs on the formation of spheroidal galaxies. The energy released by an accreting Black Hole (BH) may be injected into the ISM through blast waves arising directly from the central engine, radiation pressure or radiative heating. A scenario is described in which radiative heating perturbs the methabolism of a star-forming spheroid, leading to a critical stage where SNe form a cold expanding shell, pushed out of the galaxy by radiation pressure from the AGN. This mechanism can regulate the BH–bulge relation to the observed value. However, this relation may be simply imprinted by the mechanism responsible for the nearly complete loss of angular momentum of the gas that accretes onto the BH. Using a novel model of galaxy formation that includes AGNs, we show that models without self-regulation have problems in reproducing the correct slope of the AGN luminosity function, while models with winds give a much better fit; however, all these models are almost indistingishable as far as their predicted BH–bulge relation is concerned. Finally, we show that the downsizing of the faint AGNs is most likely due to kinetic feedback in star-forming bulges.

Key words. Galaxy: formation – Quasar: formation – Galaxy: winds

1. Introduction

AGN feedback is now considered as a fundamental process for the formation of galaxies. In particular, the correlation between the mass of the super-massive BHs, remnants of the past quasar epoch, and that of their host spheroids (ellipticals and spiral bulges) has often been proposed to be caused by self-regulated feedback by an accreting BH, experienced at the formation epoch of the host itself (see, e.g., Ciotti & Ostriker 1997; Silk & Rees 1998; Haehnelt, Natarajan & Rees 1998; Fabian 1999; Granato et al. 2001, 2004; Murray, Quataert & Thompson 2005; Sazonov et al. 2005; Lapi, Cavaliere & Menci 2005; King 2005). However, many authors have modeled the joint AGN/galaxy formation, reproducing the BH–bulge correlation by assuming a relation between star formation in the host and accretion onto BHs (see i.e. Kauffmann & Haehnelt 2000; Cavaliere & Vittorini 2002; Mahmood, Devriendt & Silk 2004; Bromley, Somerville & Fabian 2004; Bower et al. 2005). In other words, the BH–bulge relation could be due either to the self-limiting action of a wind or to the mechanism responsible for the nearly

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complete loss of angular momentum of the accreting gas. In this paper we will try to clarify this point, following closely the recent paper by Monaco & Fontanot (2005).

Star formation in galaxies and BH accretion show some analogies. In both cases a necessary but not sufficient condition to trigger these processes is the presence of cold and dense gas within a galaxy. Then this gas needs either to gather into massive clouds (say, molecular clouds) or to lose its angular momentum. After this, star formation or accretion can take place, and the resulting energy feeds back on the collapsing/accreting matter, thus regulating the process. So, while feedback is a fundamental step in the process, the real bottleneck of the process is either the formation of star-forming (molecular) clouds or the loss of angular momentum. These processes must be properly taken into account.

Regarding AGNs, many pieces of evidence highlight the need for feedback. The "anti-hierarchical" behaviour, also called "downsizing", of the AGN population (Hasinger et al. 2005; see also Merloni 2004, Marconi et al. 2004), strengthened by the observed dearth of faint AGNs in the GOODS fields (Cristiani et al. 2004; Fontanot et al. 2006a), points to an early assembly of the most massive BHs and a correspondingly later assembly of smaller BHs, at variance with the hierarchical trend of DM halos. A similar trend is suggested to be present in elliptical galaxies (Treu et al. 2005). The hierarchical order can be reverted by feedback (see, e.g., Granato et al. 2001, 2004; Bower et al. 2006); however, whether this feedback has a stellar or AGN origin is not easy to understand. In particular, reverting the hierarchical order requires on the one hand to delay the formation of small objects, and on the other hand to prevent the large objects formed at early time to continue accreting matter for a Hubble time.

2. Injection mechanisms

The AGN releases a huge amount of energy, roughly two orders of magnitude larger than that required to unbind a typical bulge, but most of it comes out in the form of radiation or in highly collimated jets. Whether this energy can be injected into the ISM so as to trigger a massive galactic wind, able to wipe out the galaxy, is still debated (see Begelman 2004 for a review). A first possibility, discussed in length by King, Cavaliere and De Zotti in this conference, is related to injection of kinetic energy directly from the central engine of the AGN. Such events are observed in BAL quasars, which are very common at high redshift; however, the effect of such winds on the ISM depends on the poorly known covering factor and geometry of the wind, and on the amount of mass of the ejecta. These quantities are still uncertain, so while such winds are perfectly plausible, it is useful at the moment to keep an open mind and consider other possibilities.

The jets emitted by slowly accreting BHs (in units of the Eddington accretion) are another very important mechanism, but due to the high level of collimation their direct effect is irrelevant for the galaxy (actually, the longly known alignment effect of star formation and jets in radio galaxies tells us that jets stimulate star formation more than quenching it). On the other hand, these are the most promising candidates to quench the cooling flows in galaxy clusters, and, as pointed out by Frenk in this conference, this quenching is fundamental to keep the most massive galaxies old. So, jet feedback from AGNs is probably very important to solve half of the downsizing problem, that of preventing the most massive galaxies to continue to form stars at late times.

Radiation arising from the accreting BH exherts pressure on the ISM, and can cause runaway radiative heating of the cold phase to a temperature of the order of the inverse-Compton temperature of the quasars, $\sim 10^7$ K (Begelman, McKee & Shields 1983). Radiation pressure alone can lead to a complete removal of ISM only when it amounts to no more than 5-10 % of the bulge mass (Murray, Quataert & Thompson 2004), while radiative heating alone can wipe out the cold phase of an elliptical when the gas amounts to a few % of the mass (Sazonov et al. 2005). On this basis, it is fair to conclude that a shining quasar does influence the galaxy only in a marginal (though important) way.

3. A possible interplay with SNe

Monaco & Fontanot (2005) proposed a mixed scenario where SNe and the AGN cooperate to produce a massive wind able to self-regulate galaxies and BHs. They started by asking what is the effect of a shining AGN on the methabolism of a star-forming spheroid. Using the model of Monaco (2004) as a starting point, they noticed that the inverse-Compton temperature of a quasar is similar to the temperature of the hot phase predicted to be present in a star-forming thick structure. Indeed, multiple SN explosions associated with a single star-forming cloud give rise to a single super-bubble; in thin systems like spiral discs the super-bubbles manage to blow out of the galaxy, but in thicker or denser systems this is not the case, and the efficiency of injection of (thermal and kinetic) energy into the ISM is very high. The resulting ISM is then highly pressurized and the hot phase is very hot ($T \sim 10^7$ K). In this case super-bubbles are typically pressure-confined by the hot phase before the blast can cool and form a Pressure-Driven Snowplough (PDS; Ostriker & McKee 1988; Monaco 2004).

A shining quasar adds to the system an evaporative mass flow which moves mass from the cold to the hot phase. When this mass flow becomes significant with respect to the star-formation rate, the hot phase becomes denser, and the blasts can get to the PDS regime. The snowploughs then compress the hot gas and collapse it back to the cold phase; the system tries to get back to the original configuration. This leads to a drop in thermal pressure, so that the blasts become pressure-confined at larger radii. In typical situations this leads to a percolation of these cold shells, and thus to the formation of a super-super-bubble, or, in other words, to a galaxy-wide cold super-shell.

This cold and thick shell is then pushed by radiation pressure. Its opacity will be initially high, due to the (possibly) large mass involved and to the likely presence of dust, which in this conditions is dynamically coupled to the gas (Begelman 2004). The efficiency of energy injection is then simply $\sim v/c$, where v is the speed of the outwardly moving shell. Its initial velocity is estimated to be of order ~ 200 km s^{-1}, which is the final speed of PDS's at the percolation time. As shown in Monaco & Fontanot (2005), such a shell is accelerated by radiation, but the work done on it is roughly equal to the gravitational energy it gains, so the velocity remains roughly constant. Eventually, the column density and the opacity of such a shell will decrease up to a point that radiation pressure is be negligible. This will take place typically when the gas is already out of the galaxy; however, an ejection of this gas out of its DM halo is extremely unlikely, as the gas should snowplough all the hot halo gas in a condition where radiation pressure is not efficient any more. For a blast velocity of ~ 200 km s^{-1}, the hot halo phase would immediately pressure-confine the blast.

During the ejection of the shell, radiative heating is irrelevant due to the high pressure of the PDS (radiative heating is relevant only when radiation pressure is much higher than the ISM pressure). The drop in pressure consequent to the stalling of the blast would make radiative heating efficient again, so that this gas would be quickly heated up. Such a shell would then be difficult to observe: it would obscure both the quasar and the galaxy during the ejection (an efficient radiation pressure implies a high opacity), then it would be visible as a slow warm absorber, with a systemic velocity of ~ 200 km s^{-1}, during the evaporation phase. It would be not easy to distinguish this component from all the complex structure of absorption lines associated with a typical quasar, though the mass associated with the object would be much larger.

Considering a bulge with mass $M_{\rm bul}$, normalized to 10^{11} M$_\odot$, harbouring a BH accreting at a rate $\dot{M}_{\rm BH}$, normalized to 4 M$_\odot$ yr^{-1} (the Eddington accretion rate of a 1.6×10^8 M$_\odot$ BH typically hosted in the 10^{11} M$_\odot$ bulge), the maximum amount of mass that radiation pressure can eject, quantified as a fraction f_s of the total bulge mass, is estimated as:

$$f_s = 0.21 \left(\frac{\dot{M}_{\rm BH}}{4\ {\rm M}_\odot\,{\rm yr}^{-1}} \right)^{1.5} \left(\frac{M_B}{10^{11}\ {\rm M}_\odot} \right)^{-1.65} \qquad (1)$$

Then, this mechanism is able to self-regulate the BH–bulge system by hampering BH accretion when it overshoots the local BH–bulge relation.

Another important consequence of this wind model is connected to the fact that the wind is generated throughout the galaxy (or at least in its inner regions). In this case a fraction of the matter is expected to be collapsed to the centre by the same blasts that created the outward-moving shell. This would give rise to a wind-stimulated episode of quasar shining. This would then be the main visible phase of the quasar, as it would presubably reach its peak luminosity when the shell has already been destroyed. A more precise assessment of this point is very difficult because the three timescales of ejection of the shell, loss of angular momentum of the gas and accretion timescale are all very similar.

It is then fair to distinguish between the "dry wind" scenario, where the kinetic energy coming from the AGN drives a massive removal of ISM, and this "accreting wind" scenario, where the wind, triggered throughout the galaxy, stimulates a further accretion episode. Whether such an indirect and complicated mechanism is really in place is not easy to assess, and there is no reason to conclude that such a mechanism represents a part of reality. However, the idea that quasar shining perturbs significantly the methabolism of the ISM is worth pursuing, and the generation of a galaxy-wide super-shell comes from the Monaco (2004) model very naturally, without any tuning of parameters.

4. Self-regulated BH–bulge relation?

As mentioned in the Introduction, the BH–bulge relation can be generated either by imposing a correlation between star formation (in bulges) and loss of angular momentum, or by letting the BH–bulge system to self-regulate. However, within the context of a galaxy formation model, the amount of gas available to the BH must be specified; in most cases (see the references in the Introduction) the accretion rate is related to the star-formation rate, so that the BH–bulge relation is imprinted by the (unknow) mechanism responsible for the loss of angular momentum. In other words, there is no real need of self-regulation to justify the BH–bulge relation.

This of course does not imply that no self-regulation is in place. Monaco & Fontanot (2005) proposed to connect self-regulation to the amount of mass available for accretion: whenever this is higher than that required to reproduce the BH–bulge relation at $z = 0$, self-regulation can limit the BH mass to the required value.

We have included BH accretion into a complete model for galaxy formation, quickly described in Monaco & Fontanot (2005); this model will be presented very soon (Monaco, Fontanot & Taffoni 2006). We show here some new results (Fontanot et al. 2006b, in preparation) that highlight a possible role of quasar-triggered winds.

The free parameters of the model are set by requiring good fits for the galaxy population; in particular, this model is able to reproduce correctly the early assembly and late passive evolution of the most massive galaxies. With the standard set of parameters, that include no quasar-triggered winds and then no self-regulation of the BH-bulge systems, we find it impossible to fit the observed quasar LFs. This is shown in figure 1, where we compare models and data in terms of hard X-ray LFs (Ueda et al. 2003); the black line, representing the model with no quasar-triggered winds, is too steep. This model is however able to reproduce the $z = 0$ BH–bulge relation, which shows that this relation is not a very strong constraint after all. The only way to obtain reasonable fits is by increasing the number of degrees of freedom, i.e. by allowing for quasar-triggered winds and self-regulation. This is done at the cost of not having a unique solution; in fact, we identify two possible solutions, one with "dry winds", the other with "accreting winds". The predicted evolution of the number density of

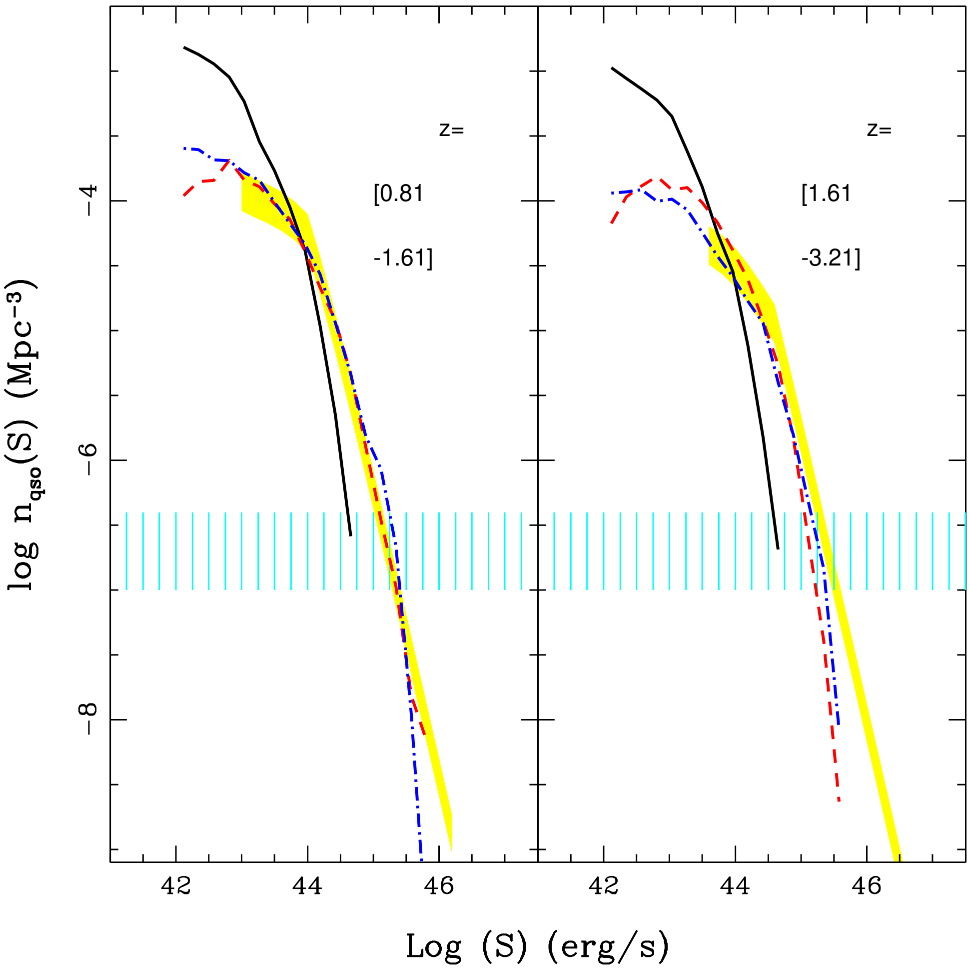

Fig. 1. Predicted AGN LF in the hard-X band (2-10 keV), compared with the analytic fit of Ueda et al. (2003) (yellow region). The redshift range is indicated in the panels. Continuous black lines correspond to the model without quasar-triggered winds, red dashed and blue dot-dashed lines correspond respectively to the model with dry and accreting winds. The hashed area highlights the region where the statistics of the model is poor. The low-redshift LFs are not shown because they are very sensitive to the uncertain quenching of the cooling flow; see Fontanot et al. (2006b) for details.

AGNs is presented in figure 2, where it is evident that the downsizing of the AGN population is reproduced.

4.1. Stellar kinetic feedback causes downsizing

We show here that the origin of the downsizing of AGNs in our model is mostly due to kinetic feedback in star-forming bulges. To remove gas from a galaxy with stellar feedback there are two main ways, namely to heat the gas

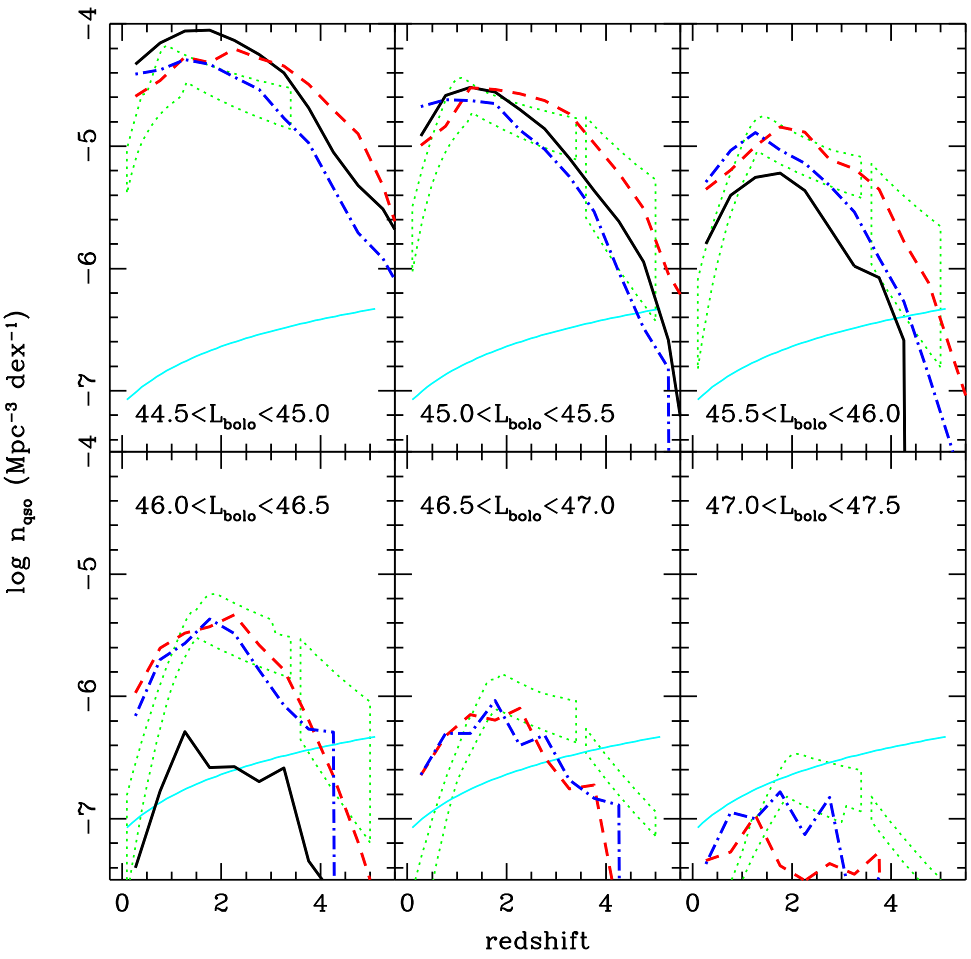

Fig. 2. Predicted number density, as a function of redshift, of AGNs in bins of bolometric luminosity. The region allowed by data (based on Cristiani et al. 2004; Ueda et al. 2005; La Franca et al. 2005) is highlighted by green dots. Lines refers to models as in figure 1. The cyan line marks the regions where the statistics of the model is poor.

(thermal feedback) or to accelerate it (kinetic feedback). In the model of Monaco (2004) for a star-forming ISM, gas is heated by SNe to a temperature ranging from 10^6 K, typical in spiral discs, to 10^7 K, typical in thick systems like star-forming bulges. This gas can easily escape the galaxy, with the exception of the most massive bulges. This leads to hot wind rates that are very similar to the star formation rate. On the other hand, the momentum given by SNe to the ISM can accelerate clouds to high velocities. This does not take place in discs, where the velocity dispersion of clouds regulates to ~ 6 km s^{-1}, but can happen in thick star-forming systems, where the super-bubbles cannot blow out of the system and so the kinetic energy injected into the ISM is much higher. If the energy injection rate from SNe is equated to the loss rate by the decay of turbulence (whose timescale is very similar to the crossing time),

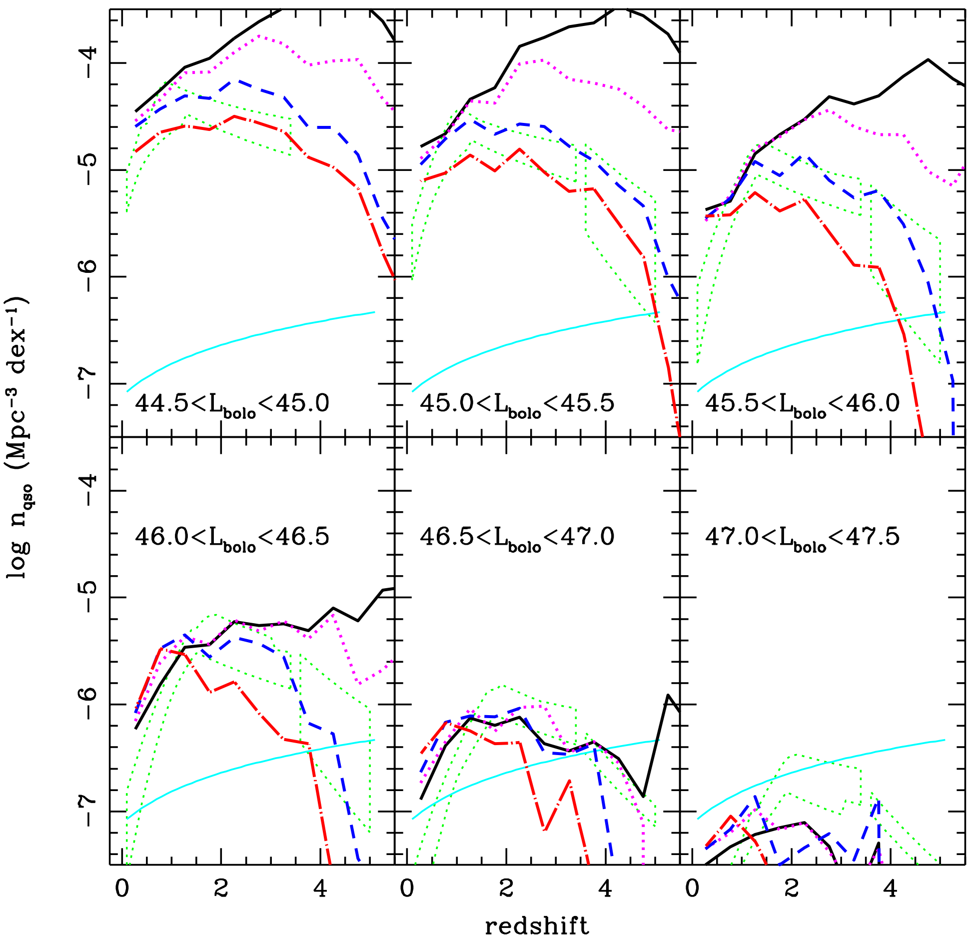

Fig. 3. As in figure 2, for models with dry winds and σ_0 = 0, 40, 80 and 120 km s^{-1}.

it is very easy to obtain that the velocity dispersion of clouds $\sigma_{\rm cold}$ scales with the star-formation time-scale $t_\star$ as:

$$\sigma_{\rm cold} = \sigma_0 t_\star^{-1/3} \quad (2)$$

where $t_\star$ is given in Gyr and σ_0 in km s^{-1}. This mechanism is very effective in removing mass from small star-forming bulges. In figure 3 we show the results of the dry wind model as a function of σ_0; kinetic feedback is able to delay the peak of activity of faint AGNs, while bright quasars remain mostly unaffected.

5. Conclusions

Star-forming galaxies at high redshift harbour shining AGNs, and the energy emitted by them can indeed affect the evolution of the galaxy; however, how this happens is still very unclear. We have mentioned many plausible ways in which some of the AGN energy could be injected into the ISM; as typical cases, the energy could come directly from the AGN in form of a powerful blast, or could be generated throughout the galaxy, say by SNe, then pushed away by radiation pressure. In the first case star formation and accretion would be quenched, in the second case a secondary accreetion event would be induced. In all cases, the efficiency of energy injection is unlikely to be higher than 0.5 %.

The BH–bulge relation is found to be not a very strong constraint for the joint formation of bulges and BHs. Indeed, this relation may be determined either by the mechanism responsible for the nearly complete loss of angular momentum required by the gas to accrete onto the BH, or by a self regulation of the bulge-BH system. To clarify this point we have shown results based on the novel galaxy formation model of Monaco et al. (2006), where a model with no winds is unable to fit the hard-X LF of AGNs, while models with dry or accreting winds are more successfull. However, all the models reproduce the BH–bulge relation in a similar way.

Finally, the most promising mechanisms to achieve the downsizing of AGNs are found to be from the one hand the quenching of late cooling flows by AGN jets, able to avoid the late accretion of mass by massive bulges/BHs, on the other hand the stellar kinetic feedback that takes place in star-forming bulges, able to delay the assembly of small bulges at high redshift.

Acknowledgements. I thanks my collaborators Fabio Fontanot, Stefano Cristiani, Laura Silva, Eros Vanzella, Mario Nonino and Paolo Tozzi for their help.

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