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The cosmological co-evolution of supermassive black holes, AGN and galaxies

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Abstract. We model the cosmological co-evolution of galaxies and their central supermassive black holes (BHs) within a semi-analytical framework developed on the outputs of the Millennium Simulation (Croton et al. 2006; De Lucia & Blaizot 2007). In this work, we analyze the model BH scaling relations, fundamental plane and mass function, and compare them with the most recent observational data. Furthermore, we extend the original code developed by Croton et al. (2006) to follow the evolution of the BH mass accretion and its conversion into radiation, and compare the derived AGN bolometric luminosity function with the observed one. We find, for the most part, a very good agreement between predicted and observed BH properties. Moreover, the model is in good agreement with the observed AGN number density in $0 \leq z \leq 5$, provided it is assumed that the cold gas fraction accreted by BHs at high redshifts is larger than at low redshifts (Marulli et al. 2008).

Key words. AGN: general – galaxies: formation – galaxies: active – cosmology: theory – cosmology: observations

1. The model

Our cosmological model for the co-evolution of DM haloes, galaxies and their central BHs consists of three ingredients: i) a numerical N-body simulation, the Millennium Run, to obtain the merger history of the DM haloes and subhaloes within the framework of the ΛCDM model, ii) a set of analytic prescriptions to trace the formation and evolution of galaxies and iii) a set of recipes to follow the BH accretion history and the AGN phenomenon. This model is described in detail in Croton et al. (2006), De Lucia & Blaizot (2007) and Marulli et al. (2008). In the following, we just give a brief description of the assumptions introduced to describe the BH and AGN evolution.

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1.1. Black Holes and Active Galactic Nuclei

1.1.1. Quasar Mode

As it is well established that galaxy major mergers cannot constitute the only trigger to accretion episodes in the local BH population (see e.g. Marulli et al. 2007, and reference therein), we assume that BHs can accrete mass after every galaxy mergers, both through coalescence with another BH and by accreting cold gas, the latter being the dominant accretion mechanism (see e.g. Marulli et al. 2006, and reference therein). For simplicity, the BH coalescence is modelled as a direct sum of the progenitor masses, thus ignoring gravitational wave losses. We assume that the gas mass accreted during a merger is proportional to the total cold gas mass present, but with an efficiency which is lower for smaller mass systems and for unequal mergers. This kind of accretion is also closely associated with starbursts, which occur concurrently. We do not model feedback from the quasar activity, but it can be approximately represented by an enhanced effective feedback efficiency for the supernovae associated with the intense starburst.

The evolution of an active BH is described as a two-stage process of a rapid, Eddington-limited growth up to a peak BH mass, preceded and followed by a much longer quiescent phase with lower Eddington ratios. In this latter phase, the average time spent by AGN per logarithmic luminosity interval can be approximated as in Hopkins et al. (2005).

As discussed in details in Marulli et al. (2008), with the original semi-analytic recipes introduced by Croton et al. (2006) to follow the BH mass accretion, the model underestimates the number density of luminous AGN at high redshifts, independently of the assumptions introduced to describe the accretion efficiency, the Eddington factor, or the BH seed masses. Significant improvement can be obtained by simply assuming an accretion efficiency that increases with the redshift. In the following Section, we will focus on the predictions of this new model, which we called 'best model' in Marulli et al. (2008).

1.1.2. Radio Mode

We assume that, when a static hot halo has formed around a galaxy, a fraction of the hot gas continuously accretes onto the central BH, causing a low-energy 'radio' activity in the galaxy centre. This accretion rate is typically orders-of-magnitude below the Eddington limit, so that the total mass growth of BHs in the radio relative to the quasar mode is negligible. It is also assumed that the radio mode feedback injects energy efficiently into the surrounding medium, which can reduce or even stop the cooling flow in the halo centres. In this scenario, the effectiveness of radio AGN in suppressing cooling flows is greatest at late times and for large values of the BH mass, which is required to successfully reproduce the luminosities, colours and clustering of low-redshift bright galaxies.

2. Models vs. Observations

In this Section, we show the most interesting results about the comparison between our model predictions and several observed statistical properties of BHs and AGN. In all the Figures, black and grey symbols show the observational data, while red and blue ones show the model predictions.

Figure 1 shows the correlation between the masses of the model BHs with six properties of their hosts: the K- and B-band bulge magnitude (M_B and M_K) (Marconi & Hunt 2003), the bulge mass and velocity dispersion (M_{bulge} and σ_c) (Häring & Rix 2004; Ferrarese & Ford 2005), the circular velocity of the galaxy and the virial mass of the DM halo (V_c and M_{DM}) (Ferrarese 2002; Baes et al. 2003; Shankar et al. 2006).

In Figure 2, we compare the BH fundamental plane relation in the redshift range $0.1 \leq z \leq 5$ predicted by our model with that obtained by Hopkins et al. (2007a), using both observational data and the outputs of hydrodynamical simulations of galaxy merger.

In Figure 3, we show the BH mass function predicted by our model with those observed by Shankar et al. (2004) and by Shankar (private communication) at $z \sim 0$. In nei-

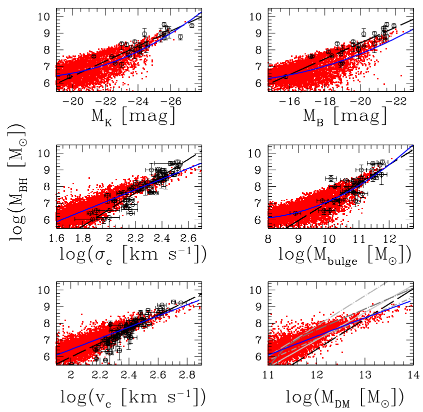

Fig. 1. Scaling relations between the masses of the central BHs in the simulated galaxies with six different properties of their hosts: the K- and B-band bulge magnitude (top left and right panels, respectively), the bulge velocity dispersion and mass (central left and right panels, respectively), the circular velocity of the galaxy (bottom left panel) and the virial mass of the DM halo (bottom right panel). Red and black dots represent model predictions and observations, respectively. Solid blue and dashed black and grey lines show the best fit to the model predictions and to the observational datasets, respectively.

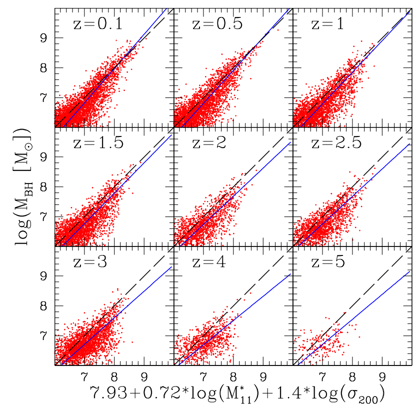

Fig. 2. The BH fundamental plane in the redshift range $0.1 \leq z \leq 5$. The red dots are the model outputs, while the blue solid lines show the best fits to them. The black dashed lines show the predictions of Hopkins et al. (2007a). The galaxy stellar mass, M^*_{11}, is given in units of $10^{11} M_{\odot}$, while the bulge velocity dispersion, σ_{200}, is in units of 200 km s^{-1}.

ther case the BH masses were determined directly: Shankar et al. (2004) derive the BH mass from the observed $M_{BH} - L_{bulge}$ relation, while Shankar (private communication) uses the $M_{BH} - \sigma_c$ relation of Tundo et al. (2007).

Finally, in Figure 4 we compare the AGN bolometric luminosity function predicted by our model with several observed ones in different bands. The bolometric corrections adopted and the datasets considered are the ones discussed in Hopkins et al. (2006).

3. Conclusions

The main results of our analysis are as follows:

(i) The semi-analytic model is able to reproduce the observed BH scaling relations over the whole range of BH masses and galaxy properties probed by observations. The intrinsic scatter in the model is significantly larger than in the data, a mismatch that can be accounted for by adopting the observational selection criteria to obtain a mock BH catalogue with similar characteristics as the observed one.

(ii) We find evidence that a quadratic relationship provides a significantly better fit to some of the model scaling relationships than a linear one, as already noticed by Wyithe (2006).

(iii) Our model also matches the BH fundamental plane relation derived by Hopkins et al. (2007a), and predicts very little evolution of this plane, at least out to $z \sim 3$.

(iv) The model BH mass function is in good agreement with the observed one within the mass range accessible by observations, except on the range $\sim 10^7 - 10^9 M_{\odot}$, in which the number density predicted by the model is smaller than the observed one.

(v) Model predictions for the BH mass function, scaling relations and fundamental

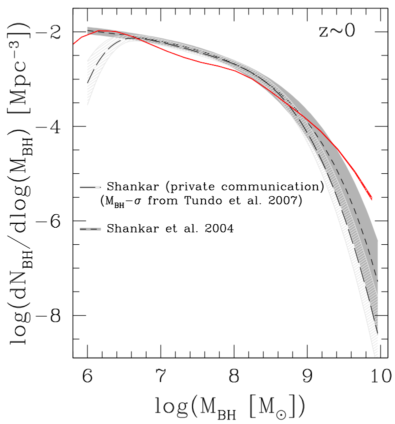

Fig. 3. The model BH mass function (red line) compared with the one observationally derived by Shankar et al. (2004) (dark grey area), and with the new one obtained by Shankar (private communication) (light grey area) using the $M_{\rm BH} - \sigma$ relation by Tundo et al. (2007).

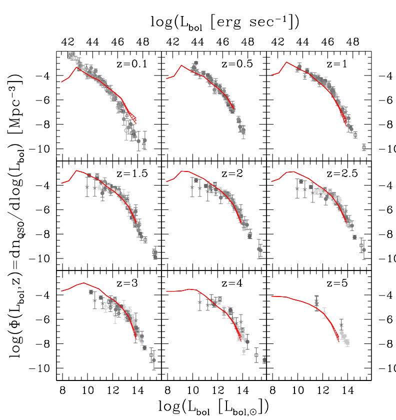

Fig. 4. The model AGN bolometric luminosity functions (red lines) compared with several observed ones (grey dots). The bolometric corrections adopted and the datasets considered are the ones discussed in Hopkins et al. (2006)

plane relation are basically unaffected when using different prescriptions for the AGN lightcurves of individual quasar events.

(vi) The model underestimates the number density of luminous AGN at high redshifts, independently of the lightcurve model adopted. We were not able to eliminate this mismatch by simply modifying the accretion efficiency, the Eddington factor or the BH seed mass (when considered in physically plausible ranges). A simple, *ad hoc* increase of the mass fraction accreted during the *quasar mode* at high redshifts can indeed remedy the problem. However, this solution is not unique as several high-redshift modifications to the original model, like new mechanisms that trigger BH activity in addition to galaxy merging or more efficient gas cooling resulting in a larger reservoir of cold gas, can be advocated to bring the predictions in line with observations. However, it remains to be seen whether any of these alternatives is physically plausible.

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