From First Galaxies to QSOs
Feeding the baby monsters

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Abstract. We present a physical model for the coevolution of massive spheroidal galaxies and active nuclei at their centers. Supernova heating is increasingly effective in slowing down the star formation and in driving gas outflows in smaller and smaller dark matter halos. Thus the more massive protogalaxies virializing at early times are the sites of faster star formation. The correspondingly higher radiation drag causes a faster angular momentum loss by the gas and induces a larger accretion rate onto the central black hole. In turn, the kinetic energy of the outflows powered by the active nuclei can unbind the residual gas in a time shorter for larger halos. The model accounts for a broad variety of dynamical, photometric and metallicity properties of early-type galaxies, for the $M_{\text{BH}} - \sigma$ relation and for the local supermassive black-hole mass function.

1 Introduction

There is growing evidence that massive galaxies at high redshifts are far more numerous than predicted by standard semi-analytic models [4,26,8,32,15,34]. Also, the $[\alpha/Fe]$-magnitude relation points towards a higher abundance of $\alpha$-elements for more luminous/massive galaxies, indicating that the time for type Ia SNe to enrich the ISM must have been shorter for the more massive systems [22]. Extremely massive black holes (BH), with $\log (M_{\text{BH}}/M_\odot) > 8-9$, must also have formed very quickly at early cosmic times to power highly luminous quasars at redshift of up to $> 6$ [11].

As stressed by [17,18,32], in the framework of the hierarchical clustering paradigm there are enough massive dark halos to accommodate the observed high redshift galaxies. The problem is to find a mechanism explaining the faster and more efficient star-formation in more massive galactic halos.

The tight relationship between dynamic and photometric properties of galactic bulges and the masses of BHs at their centers [12,16,23,33,21] indicate that a key ingredient in this context is likely to be the mutual feedback from star formation and the growing active nucleus. Indeed the close interplay of the two components has a crucial role in the Anti-hierarchical Baryon Collapse (ABC) model by Granato et al. [17,18], that appears to overcome the main shortcomings of current semi-analytic models. In the following we briefly describe this model and summarize some of its predictions.
The ABC model applies to massive spheroidal galaxies and galactic bulges (halo mass \( \log(M_{\text{halo}}/M_\odot) > 11.4 \)), virializing at \( z \geq 1.5 \). In practice, it is assumed that massive halos virializing in this redshift range end up as spheroidal galaxies, while those virializing at later times host disks or irregular galaxies. The virialization rate of these objects is given by the positive term of the derivative of the Press & Schechter [25] mass function, while the negative part (corresponding to their disappearance due to merging) is negligible. Numerical simulations [35,36] have shown that the build-up of DM halos consists of an early phase of fast accretion, during which there is a rapid increase of the specific binding energy and of the central potential well, and of a late phase of slow accretion with no significant change of the binding energy and of the circular velocity.

The diffuse gas within the DM well, shock heated to the virial temperature of the halo, falls into the star forming regions at a rate ruled by the cooling and dynamic timescales. The cooled gas feels the feedback from SNe and from the central AGN which heat and possibly expel the gas from the potential well. In small halos a few SNe are sufficient to quench the star formation, while in the big ones nothing prevents a huge starburst (1000 \( M_\odot/yr \) over 0.5 Gyr). Furthermore, the radiation drag damps down the angular momentum of the cool gas [20], letting it inflow into a reservoir around the central super-massive BH (SMBH). Viscous drag then causes the gas to flow from the reservoir into the SMBH, increasing its mass and powering the nuclear activity until its feedback is strong enough to unbind the residual ISM, thus stopping the star formation and letting the active nucleus shine unobscured. The time required to sweep out the ISM decreases with increasing halo mass, thus accounting for the \([\alpha/F_{\text{Fe}}]\)-magnitude relation. An almost passive evolution of the stellar population, with a dormant SMBH, follows.

As shown by [18], the ABC model, coupled with the spectro-photometric code GRASIL by Silva et al. [29], accounts for a broad variety of data, including the SCUBA counts at 850 \( \mu m \) (which are strongly under-predicted by the other semi-analytic models), the corresponding preliminary redshift distribution, and the local K-band luminosity function of massive spheroidal galaxies. In Fig. 1 we compare the model predictions with the distribution of stellar masses in galaxies up to \( z \simeq 2 \) determined by [14]. At \( z \sim 3 \) the model predicts a comoving number density of galaxies with masses \( M_{\text{star}} \geq 10^{11}M_\odot \) of \( n \sim 10^{-4}/\text{Mpc}^3 \) in excellent agreement with the estimate by [32] (Fig. 2).

For a given cosmology, a halo of mass \( M_{\text{halo}} \) virializing at \( z_{\text{vir}} \) can be characterized by its circular velocity, \( V_{\text{halo}} \). Thus, the velocity functions of halos virializing at any given redshift, predicted by the standard hierarchical clustering model for galaxy formation, can be straightforwardly computed from their mass function. Integrating over redshift, for \( z_{\text{vir}} \geq 1.5 \), the local velocity function of spheroids can be obtained. Adopting a constant ratio of the velocity
Fig. 1. Stellar mass functions of galaxies in the ranges $1. \leq z < 1.5$ (upper panel) and $1.5 \leq z < 2$ (lower panel) derived by [14] (different symbols correspond to different methods to estimate the stellar mass), compared with theoretical predictions (dot-dashed line: ABC model; dashed and thick solid lines: [30,31]; short dashed line: [6]).

Fig. 2. Comoving number densities of galaxies with baryonic masses $\geq 10^{11} M_\odot$ as a function of redshift. The triangle and open rectangles show densities of massive stellar systems at $z=0$ [7] and $z \sim 1$ [10]. The circle with upward arrow is the lower limit by [32]. The solid curves show the predictions of [19] (upper) and [2]; the dashed curves show the number densities of halos with available baryonic masses $\geq 10^{11} M_\odot$ for the values of $\Omega_b$ adopted by [19] (upper) and [2]. The line with stars is the ABC model prediction. Adapted from [32].
Fig. 3. Local velocity dispersion function derived from the SDSS data [28,27] compared with that predicted by the ABC model.

Fig. 4. Faber-Jackson relation predicted by the ABC model for various virialization redshifts compared with data by [3]. Just above the x-axis are the normalized distributions of velocity dispersions of galaxies in 4 absolute magnitude bins 0.5 mag wide, centered at $M_r^* = -20.2, -21, -22,$ and $-23$ (from left to right), as predicted by the ABC model. The FWHMs of the distributions are remarkably close to the observed values (FWHM $\sim 0.09$, see [3]).

dispersion at $r_e/8$, $\sigma_r$, to $V_{halo}$, $\sigma/V_{halo} = 0.55$, consistent with the results by [13], Cirasuolo et al. [5] have found a very good match to the velocity dispersion function (Fig. 3) of early-type galaxies and bulges derived by [28,27] using SDSS data [3]. Furthermore, [5] have shown that the relationship between the luminosity of spheroids and their velocity dispersion, predicted by the ABC model, fits the Faber-Jackson relation for NVSS galaxies [3] (Fig. 4); the observed distribution of velocity dispersions at given luminosity is accounted for by the range of virialization redshifts.
In the ABC model, the final (i.e. present day) mass of SMBHs in galaxy centers is also a function of $M_{\text{halo}}$ and $z_{\text{vir}}$ only. In Fig. 5 the predicted local supermassive BH mass function is compared with the recent estimate by [27]. As shown by [18,5] the model also gives a good fit of the $M_{\text{BH}} - \sigma$ relation.

4 Summary and conclusions

The spheroid-SMBH coevolution model described here is based on the idea of *Anti-hierarchical growth* of the baryonic component in DM halos. The heating from SNe is increasingly effective in slowing down the star formation and driving gas outflows in shallower potential wells. As a consequence, the star formation is faster within the most massive halos. A higher star formation implies a higher radiation drag, a faster SMBH fuelling and growth, and therefore a stronger AGN kinetic output ($\propto M_{\text{BH}}^{3/2}$, see [24]) causing an earlier sweeping out of the ISM. Thus the duration of the starburst and of the SMBH growth is shorter for more massive halos ($\leq 1$ Gyr for $M_{\text{halo}} \geq 10^{12} M_\odot$ and $3 \leq z_{\text{vir}} \leq 6$).

During the intense starburst and SMBH growth phase the spheroid is heavily dust obscured (SCUBA phase); the model indeed fits the SCUBA counts and the (albeit limited) data on the redshift distribution. We attribute the relatively high hard X-ray emission recently detected from SCUBA galaxies by [1] ($L_X \sim 10^{43} - 10^{44}$ erg/s) as associated to the growing phase of the central SMBH.

When the AGN reaches its maximum power, the ISM is blown away and the AGN shines unobscured (QSO phase). The gas surrounding powerful high-$z$ QSOs is therefore expected to exhibit at least solar abundances and $\alpha$-enhancement, as indeed found by [9].

Afterwards the spheroids evolve passively (ERO phase). The model reproduces the mass and redshift distributions of sources detected by deep K-band surveys, which proved to be extremely challenging for all the other semi-analytical
models, as well as the dynamical/photometric properties of spheroidal galaxies in the SDSS survey [3].

Finally, the model accounts for the local SMBH mass function for $M_{BH} > 10^7 M_\odot$, and for the $M_{BH}-\sigma$ relation. It predicts a steepening at $\sigma \leq 150$ km/s as the SMBH growth is hindered by the combined effect of SNe heating and decreased radiation drag.

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