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AGN PHASE: MATCHING NUMERICAL SIMULATIONS TO OBSERVATIONS

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Abstract. We use high resolution cosmological numerical simulation to identify AGNs in field massive galaxies in redshift range z=[0.8, 2.5]. Assuming that their activity is merger driven and that the final product of their accretion is an M-σ SMBH, we calculate expected AGN luminosity at the peak accretion activity. We compare these luminosities to those observed in AGNs of the COSMOS survey and find that most of the observed AGNs have passed their peak activity, accreting at lower Eddington ratios. This explains why a large number of AGNs is observed in red sequence galaxies.

1. INTRODUCTION

SMBH masses correlate with the properties of their host bulges/spheroids (velocity dispersion, mass of the spheroid, total stellar mass, etc). They do not correlate with the mass of dark matter halos in all environments. Halos in, and around dense regions (large groups and galaxy clusters) are subject to stripping of material due to various dynamical processes (tidal stripping, dynamical friction, ram-pressure, etc.). These processes effect both dark and baryon matter. Hence, in dense environments, halo's mass does not correlate with mass of a host galaxy or a central SMBH. However, field halos evolve in relative isolation which in turn establishes relation between their masses and the mass of their stellar component. At the same time, properties of the spheroid are correlated with the SMBH mass. This provides the link between DMH and SMBH and for field halos there exists DMH mass - SMBH mass relation (Kormendy & Ho 2013).

In the most recent study of galaxy - halo relation, Behroozi et al. (2013a) match observed galaxies to simulated halos. They use observed galaxy stellar mass functions, specific star formation rates and cosmic star formation rates to constrain galaxy - halo relation. They present parametrization of this relation for a redshift range $0 < z < 8$ (equations 3 and 4, Behroozi et al. 2013a) together with the intrinsic parameters (section 5 of the same paper). We will address this relation as Behroozi relation from here on.

Haring & Rix (2004) have found that the relation between the mass of the SMBH in nearby galaxies, M_{bh}, and the stellar mass of the surrounding spheroid or bulge, M_{bulge} can be written as:

$$\log M_{BH} = -4.12 + 1.12(\log M_{sph}) \quad (1)$$

It has been established recently that this relation evolves with redshift positively. Merloni et al. (2010) have measured rest-frame K-band luminosity and total stellar mass of the hosts of 89 broad-line AGNs detected in the zCOSMOS survey in the redshift range $1 < z < 2.2$. They found that the local value of SMBH to total host galaxy stellar mass evolves with redshift as $(1+z)^{\gamma}$, where $\gamma = 0.68 \pm 0.12$, From here on we address the evolving SMBH - host galaxy relation as SMBH positive evolution relation:

$$\log M_{BH} = (-4.12 + 1.12(\log M_{*})) \times (1 + z)^{\gamma} \quad (2)$$

Note that Merloni et al. (2010) use total stellar mass instead of the bulge/spheroidal mass in Haring & Rix (2004) relation. This is due to the lack of any imaging information and reliable bulge-to-disk (B/T) decomposition. Bennert et al. (2011) have studied the evolution of this relation for a sample of 11 X-ray selected broad-line AGNs in the redshift range $1 < z < 2$. They have managed to distinguish between M_{*} and M_{sph} by using deep multi-filter HST images. They found that SMBH to total stellar mass of the host evolves with γ coefficient of 1.15 ± 0.15.

In this work we first seed dark matter halos with galaxies using Behroozi relation. Then, we seed galaxies with black holes using SMBH positive evolution relation where we adopt both values for γ (0.68 and 1.15) in two separate models.

2. METHOD

2. 1. COSMOLOGICAL N-BODY SIMULATION

Using GADGET2 (Springel 2005), we performed a high-resolution cosmological N-body simulation within a comoving 130 Mpc^3 section of a ΛCDM Universe (Ω_M=0.25, Ω_Λ=0.75, σ_8=0.8 and h=0.7) from z=599 to z=0. We are using WMAP5 (Komatsu et al. 2009) cosmological parameters in this study, and 2LPT initial conditions. Mass resolution of dark matter particles is 1.14 x 10^9 $M_\odot$.

2. 2. SIMULATIONS AND BLACK HOLE GROWTH WITHOUT A RECIPE

The essence of our method is to calculate the mass accreted by the SMBH in a newly formed halo after every halo merger without using any growth recipes. We do this by subtracting SMBH mass before the merger from the SMBH mass after the merger in the following procedure:

For the identification of dark matter halos and creation of their merger trees, we are using the ROCKSTAR phase space halo finder (Behroozi et al. 2013b). We focus on major mergers with mass ratio of merging dark matter halos of > 0.3. For every major merger we identify three specific moments. z_{init} - redshift when halos touch and when from this point on, smaller halo is inside larger halo at all times. At this moment we use Behroozi relation and SMBH positive evolution relation to obtain SMBH masses in both halos ($M_{BH,1}$ and $M_{BH,2}$) right before halos merge. The SMBH mass before the accretion starts is then $M_{BH,initial} = M_{BH,1} + M_{BH,2}$. z_{AGN} - redshift when smaller halo can not be identified anymore inside the larger one which means that the merger of dark matter halos has finished and merger of their galaxies has started. We assume that this is the moment when the accretion onto the new SMBH starts and enters AGN phase. We follow newly formed halo through snapshots until redshift z=0 or until it merges with another halo. In each of these snapshots we use Behroozi relation and SMBH positive evolution relation to calculate the mass of SMBH hosted by this particular halo. $z_{\rm final}$ is then the redshift when halo is hosting the most massive black hole. In other words, we have traced the final mass of the SMBH ($M_{\rm BH,simulated}$) at the halo center through scaling relations and without using any growth recipes. The mass accreted by the SMBH has to be $M_{\rm BH,accreted}$ = $M_{\rm BH,simulated}$ - $M_{\rm BH,inital}$. We repeat that this method works only for the field halos where clear DMH - galaxy - SMBH relation can be established.

2. 3. OBSERVATIONS AND BLACK HOLE GROWTH WITH A RECIPE

The final goal of this paper is to determine if the Eddington ratios obtained from the observed AGN luminosities and simulated $M_{\rm BH,init}$ can produce $M_{\rm BH,simulated}$ in our simulation.

Bongiorno et al. (2012) have studied $\sim$ 1700 AGNs in COSMOS field obtained by combining X-ray and optical spectroscopic selections. They also study the properties of their hosts including the total stellar mass of galaxies hosting AGNs. As the result they present probability of a galaxy to host an AGN of a given luminosity as a function of stellar mass in three redshift bins: [0.3 - 0.8], [0.8 - 1.5], and [1.5 - 2.5] (Figure 14 in their paper, from here on F14). They group AGNs in four X-ray (2 - 10 KeV) luminosity bins in logarithm space: [42.8 - 43.5], [43.5 - 44.0], [44.0 - 44.5], and [44.5 - 46.0].

We combine black hole growth in our simulation with the observed probability functions for a galaxy to host an AGN in the following procedure.

First we assume that the moment when the accretion onto $M_{\rm BH,init}$ starts is $z_{\rm AGN}$ (the redshift when halo merger has finished and galaxy merger is occurring - AGN phase). The mass of the galaxy where $M_{\rm BH,init}$ is accreting, $M_{*,\rm AGN}$, is calculated from the Behroozi relation directly from the mass of the simulated host halo at $z_{\rm AGN}$.

We are focusing only on SMBH accretion which is activated by galaxy mergers. Merger activated black hole accretion is a characteristic of massive galaxies, log (M_* [$M_\odot$]) > 10.4. In lower mass galaxies SMBHs are more likely to accrete through secular processes related to channeling of the gas through bars or disk instabilities. We also focus only on halos which merge in the field so we exclude halos which are potential hosts to galaxy clusters. Since mass of the halo hosting most massive elliptical galaxy in the field in the simulations is $\sim 2 \times 10^{13} M_\odot$, we only study mergers which produce less massive halos. As additional measure of precaution, we exclude halos which host galaxies more massive than $10^{11.2} M_\odot$. In this manner we obtain a clean sample which matches 10.4 < log (M_* [$M_\odot$]) < 11.2 sample in F14, and we separate $M_{*,\rm AGN}$ into three galaxy-mass bins in logarithm space: [10.4 - 10.7], [10.7 - 10.9], and [10.9 - 11.2].

For every redshift and galaxy-mass bin we calculate the number of simulated galaxies which host AGNs by reading probability values ($P_{\rm AGN}$) directly from F14:

$$N_{\rm AGN,i} = \frac{P_{\rm AGN,i}}{\Sigma P_{\rm AGN,i}} \times N_{*,\rm AGN}, \tag{3}$$

where $P_{\rm AGN,i}$ is the probability function or, in other words, the data points in the

F14, and $N_{*,AGN}$ is number of galaxies in redshift and galaxy-mass bins.

Next we apply Monte Carlo procedure (10,000 realizations) where galaxies in each mass bin and each redshift bin are assigned a luminosity value from the corresponding probability function in F14. As the result, for each $M_{*,AGN}$ we have a set of 10,000 luminosities which we now can use to calculate Eddington ratios for each $M_{BH,init}$. Since these are X-ray luminosities, we use equation (2) in Hopkins et al. (2007) to calculate bolometric luminosities. Eddington ratio is then $\lambda = L_{bol} / L_{Edd}$, where $L_{Edd} = 1.26 \times 10^{38} \times M_{BH,init}$.

Note that we have decided to use $M_{BH,init}$ as a sum of SMBH masses in the merging galaxies at the moment z_{init}. Alternative approach would be to simply calculate SMBH mass at the moment z_{AGN} directly from SMBH positive evolution function. A problem with this approach is accuracy in determining masses of halos and galaxies at the peak of the merger when there is still a lot of unbound material.

For the accretion recipe we assume that $M_{BH,init}$ is accreting for Salpeter time (43 Myr) at the radiative efficiency of e=0.1 and previously calculated Eddington ratios λ. The underlying assumption here is that the observed luminosities are the peak luminosities. In other words, these are the luminosities when accretion onto the black holes is most efficient and where most of the black hole growth occurs. Final black hole mass after accretion at the Eddington ratios which are the result of the observed luminosities is:

$$M_{BH,observed} = M_{BH,inital} \times \exp(\lambda) \tag{4}$$

For each merger we have 10,000 $M_{BH,observed}$ from 10,000 Monte Carlo realizations of probability functions in F14. Now we can compare them to the $M_{BH,simulated}$. If the observed luminosities are peak luminosities when most of the black hole growth occurs, then mass of the grown black hole should match the mass of simulated one. We compare them to see how often observed luminosities can produce simulated SMBH mass and for what values of Eddington ratios.

3. RESULTS AND CONCLUSIONS

Assuming that major mergers are driving AGN activity in massive galaxies, we have selected simulated remnants of halo mergers and matched them to observed samples of AGNs in redshift and galaxy-mass bins in F14. All galaxies in the same mass bin host AGN with the probability defined in F14. They are more likely to host less luminous AGNs or, in other words, there are more galaxies of the same mass hosting lower luminosity AGN than more luminous ones. Galaxies selected in our simulation and separated in mass bins have SMBHs with masses which are not derived from their stellar mass but from the merger history. Masses of these black holes come from merging halos at higher redshifts and also depend on SMBH positive evolution recipes. The initial and final black hole masses are predetermined by the halo mass before and after the merger in our simulation. We accrete onto initial black hole with the Eddington ratios obtained from the luminosity which has a probability defined by F14.

Figure 1 represents mass the growth with positive evolution of γ=0.68 for SMBH in every AGN of a given redshift (rows) and host-galaxy-mass bin (columns), the black lines on the left mark initial black hole masses before the accretion, $M_{BH,initial}$,

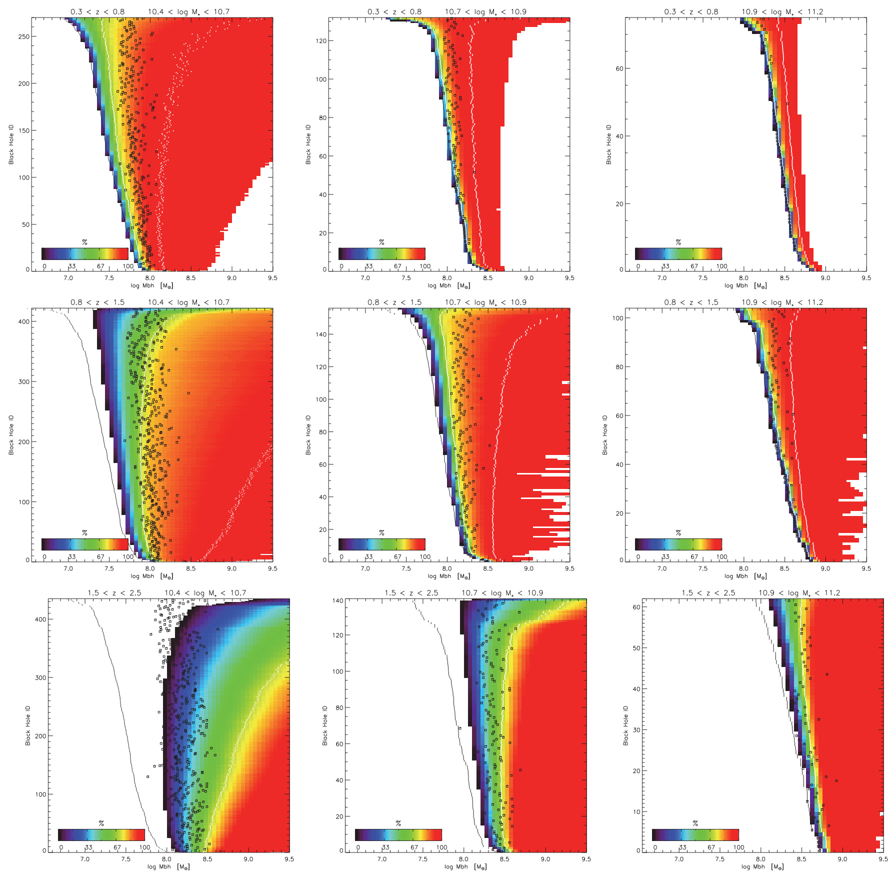

Figure 1: Color represents percentage of Monte Carlo realizations (through the parameter space of luminosities observed for COSMOS AGNs) necessary for simulated black holes (vertical black lines) to accrete accordingly and reach certain mass (X-axis). Squares represent final black hole mass in the simulation and mark the probability for the observed luminosities to grow black holes. Vertical white lines represent 1-σ and 2-σ. Each panel corresponds to the bin for merger redshift and stellar mass of the AGN host. The assumed slope for black hole positive evolution is $\gamma = 0.68$ (Merloni et al 2010).

and squares represent final simulated black hole mass, $M_{BH,simulated}$. Color represents cumulative percentage of Monte Carlo realizations which is sufficient to produce black hole of a particular mass. White lines show 1 - σ and 2 - σ of the distribution. In other words, there are 68.27 % of realizations left of the first white line, and 95.45 % of realizations are left of the second white line. Small percentage of realizations means that it is very likely to reproduce simulated black hole (e.g. mass is easily obtained because it takes just few % of realizations). At the other end, large percentage of realizations means that it is not likely to reproduce simulated black hole (e.g. most of the realizations are left of the square representing final black hole mass). If we assume that 1 - σ marks probable event, then all squares on the left of it represent simulated black holes which can be reproduced by the observed luminosities. For all the squares on the right, observed luminosities can not provide large enough Eddington ratios to produce simulated black holes. If we compare panels in the first column, SMBHs growth in the same galaxy-mass bin, [10.4, 10.7], can not reach simulated mass values at $0.3 < z < 0.8$ for almost all of the black holes. For $0.8 < z < 1.5$, it does for about half of the SMBHs, and for $1.5 < z < 2.5$ almost all of the SMBHs do reach simulated mass. Since our assumption is that we are observing peak AGN luminosities, then conclusion is that at high redshift [1.5, 2.5], almost all of the AGNs we see are observed in the phase of their maximum growth and accretion efficiency corresponding to the starburst "green valley" phase in galaxy evolution. At the other end, for redshift range [0.3, 0.8], almost none of the observed AGNs are in the "green valley" galaxies. These are low Eddington ratio AGNs in "red sequence" galaxies.

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