EVOLUTION OF GALAXY GROUPS IN THE ILLUSTRIS SIMULATION

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ABSTRACT

We present the first study of the evolution of galaxy groups in the Illustris simulation. We focus on dynamically relaxed and unrelaxed galaxy groups representing dynamically evolved and evolving galaxy systems, respectively. The evolutionary state of a group is probed from its luminosity gap and separation between the brightest group galaxy and the center of mass of the group members. We find that the Illustris simulation overproduces galaxy systems with a large luminosity gap, known as fossil systems, in comparison to observations and the probed semi-analytical predictions. However, this simulation is just as successful as the probed semi-analytic model in recovering the correlation between luminosity gap and offset of the luminosity centroid. We find evolutionary tracks based on luminosity gap that indicate that a group with a large luminosity gap is rooted in one with a small luminosity gap, regardless of the position of the brightest group galaxy within the halo. This simulation helps to explore, for the first time, the black hole mass and its accretion rate in galaxy groups. For a given stellar mass of the brightest group galaxies, the black hole mass is larger in dynamically relaxed groups with a lower rate of mass accretion. We find this to be consistent with the latest observational studies of radio activity in the brightest group galaxies in fossil groups. We also find that the intragalactic medium in dynamically evolved groups is hotter for a given halo mass than that in evolving groups, again consistent with earlier observational studies.

Key words: galaxies: evolution – galaxies: formation – galaxies: general – galaxies: individual (old, young) – galaxies: structure

1. INTRODUCTION

In earlier contributions, we have highlighted the importance of identifying fossils groups or dynamically relaxed groups and clusters (Khosroshahi et al. 2006, 2007, 2014; Gozaliasl et al. 2014; Miraghaei et al. 2014; Raouf et al. 2014; H. G. Khosroshahi et al. 2016, in preparation). Adaptation of these classifications and continued studies enable us (i) to explore whether these systems truly follow a different evolutionary path in their galaxy or halo properties, (ii) to employ these galaxy systems and their statistical properties to identify the best possible model of galaxy formation and evolution, generally implemented in cosmological simulations, and (iii) to better understand the galaxy–halo connection.

Dark matter (DM) simulations have shown that galaxies in compact groups should merge into a single massive galaxy within 1 Gyr (Barnes 1989; Bode et al. 1993). Consequently, an elliptical galaxy is formed, developing a large luminosity gap while the X-ray emitting halo remains unaffected by merging (Ponman et al. 1994). Such groups are known as fossil groups, in which the essential observational tracers have been identified including the luminosity gap between the first and second brightest galaxies in the group and the presence of an extended, i.e., group-scale, X-ray emission with a luminosity of at least $L_{X,BG} \approx 10^{42} h_{50}^{-2}$ erg s$^{-1}$ (Jones et al. 2003). There are several studies in the literature focusing on the detailed characterization and properties of fossil groups based on X-ray and optical observations (Khosroshahi et al. 2004, 2006, 2007; Sun et al. 2004; Ulmer et al. 2005; Miraghaei et al. 2014), cosmological simulations (Yoshioka et al. 2004; Milosavljevic et al. 2006; van den Bosch et al. 2007; Von Benda-Beckmann et al. 2008; Deason et al. 2013), semi-analytical models (SAMs) (Dariush et al. 2007, 2010; Sales et al. 2007; Díaz-Giménez et al. 2008; Raouf et al. 2014), and hydrodynamical simulations (D’Onghia et al. 2005; Cui et al. 2011). The recent study of Khosroshahi et al. (2014) reveals that a diffuse extended X-ray emission beyond the optical size of the brightest group galaxy exists, especially when a large magnitude gap is present.

Khosroshahi et al. (2006) presented evidence that the majority of fossil galaxy groups with the brightest group galaxy (BGG) dominating have non-boxy isophotes that could point to a wet, or gas-rich, nature of galaxy merger in their evolutionary history. Smith et al. (2010) employed a large sample of BGGs observed with the Hubble Space Telescope and found the trend in the luminosity gap (as an indication of the dynamical age of the system) and the isophotal shape of the BGGs to be consistent with the earlier study of Khosroshahi et al. (2006). Furthermore, in comparison with the general population of galaxy groups, Khosroshahi et al. (2007) show that for a given optical luminosity, fossil groups not only contain a hotter intragalactic medium (IGM) for a given halo mass, but also their DM halo is more concentrated, all pointing to their relatively earlier formation epoch. In addition, the study of scaling laws in fossil groups indicates that they mostly follow the trend of galaxy clusters, which is likely to be driven by the dynamically relaxed state of the cluster core. It is worth highlighting an apparent conflict, as Voevodkin et al. (2010) show that there is no noticeable difference between the X-ray luminosity of the fossils and non-fossils for a given optical luminosity. While more recent studies support the latter (Aguerri et al. 2011; Proctor et al. 2011; Harrison et al. 2012; Girardi et al. 2014), the apparent contradiction could, however, originate primarily from the sample selection and be due to the fundamental differences between galaxy groups, which form the basis for Khosroshahi et al. (2007), and the sample of galaxy clusters examined by Santos et al. (2007),
which forms the basis for contrasting studies. In a ΛCDM model galaxy clusters are generally young assemblies of galaxies, while galaxy groups can be old or young depending on whether they survive major mergers during the hierarchical cosmic evolution.

In recent years, cosmological simulations have offered the necessary tools to address open questions regarding the formation and evolution of galaxies. This is generally achieved through SAMs and hydrodynamical models. In the semi-analytic approach the baryonic matter properties are calculated on the basis of an analytical prescription in a post-processing procedure built on the merger tree (Bower et al. 2006; Croton et al. 2006; De Lucia & Blaizot 2007; Guo et al. 2011). In the hydrodynamical approach, baryons directly interact and co-evolve with the DM particles within the cosmological volume. Although the hydrodynamic approach has the upper hand in dealing with baryonic matter that can be directly linked to the gas properties, such as cooling, heating, and feedback processes in and around galaxy halos (Springel et al. 2005; Vogelsberger et al. 2014, and references therein), the semi-analytic approach is less computationally expensive and facilitates the construction of samples of galaxies that are an order of magnitude larger than those allowed by hydrodynamical simulations. Furthermore, the SAMs are more suitable for adding in new physics and assessing its impact.

A number of authors have suggested ways in which, radio-AGN (active galactic nucleus) heating is powerful enough to expel a fraction of baryons from the galaxy groups or clusters (Croton et al. 2006; Bower et al. 2008). Observationally, some studies show that radio-AGN heating could account for the missing baryons in galaxy groups (Oklopič et al. 2010; Giodini et al. 2010). A useful approach for understanding the role of AGN feedback in galaxy evolution is to connect the astrophysical parameters related to the AGN feedback to observable quantities and make predictions that can be verified by existing or future observations.

In a recent study (Raouf et al. 2014), we established a set of four observationally measurable parameters using the semi-analytic models of Guo et al. (2011), based on the Millennium Simulation, which can be used in combination to identify a subset of galaxy groups that are dynamically old, with a very high statistical probability. We argued that a sample of fossil groups selected based on luminosity gap will result in a contaminated sample of old galaxy groups. However, by adding constraints on the offset between the luminosity centroid of the group and the BGG position, we considerably improved the age-dating method for galaxy groups and clusters in comparison to the method based on the luminosity gap alone.

In this study, the main focus is to explore the Illustris simulation in the context of the formation of a luminosity gap and the advantage that this simulation may offer in providing a hydrodynamics-based measure of accretion rate and mass of a supermassive black hole. Thus we prepare an observed sample of galaxy systems using the Sloan Digital Sky Survey (SDSS) data release 10 (Ahn et al. 2014, SDSS-DR10), which covers 14,555 deg2 in imaging data and contains 469,053,874 unique objects for which 3,276,914 spectra were measured. In this study, we use the friends-of-friends (FOF) group/cluster catalog of Tempel et al. (2014) for the redshift range 0.015–0.05 (Figure 1). Morphologically, all BGGs in our sample are elliptical with an absolute r-band magnitude of $M_r(BGG) < -22$ mag and reside in halos with masses (referred to in the catalog as “massNFW”) $> 10^{13}M_\odot$. Groups contain at least four spectroscopic members. With these constraints the observational sample contains 300 galaxy groups/clusters. We estimate the offset ($D_{\text{obj}}$) between the BGG location and the luminosity centroid using the r-band magnitude of the group’s spectroscopic members and their coordinates. The luminosity gap in the r-band is obtained within a radius of 500 kpc/h from the BGG. Figure 1 shows the distribution of absolute magnitude in the r-band versus the redshift for all galaxies (gray points) as well as the selected sample in the SDSS (blue and red points).

**Figure 1.** Distribution of absolute r-band magnitude as a function of redshift based on the SDSS-DR10 group catalog of Tempel et al. (2014). The red triangles show the BGGs belonging to fossil groups ($\Delta M_r > 2$) while blue diamonds show non-fossil ($\Delta M_r < 0.5$) galaxy groups. In addition, the red and blue dots represent the members of fossil and non-fossil galaxy groups, respectively.

2. DATA AND SIMULATIONS

2.1. Observations: SDSS Group Catalogs

We use the legacy archive of the SDSS-III, Data Release 10 (Ahn et al. 2014, SDSS-DR10), which covers 14,555 deg2 in imaging data and contains 469,053,874 unique objects for which 3,276,914 spectra were measured. In this study, we use the friends-of-friends (FOF) group/cluster catalog of Tempel et al. (2014) for the redshift range 0.015–0.05 (Figure 1). Morphologically, all BGGs in our sample are elliptical with an absolute r-band magnitude of $M_r(BGG) < -22$ mag and reside in halos with masses (referred to in the catalog as “massNFW”)$> 10^{13}M_\odot$. Groups contain at least four spectroscopic members. With these constraints the observational sample contains 300 galaxy groups/clusters. We estimate the offset ($D_{\text{obj}}$) between the BGG location and the luminosity centroid using the r-band magnitude of the group’s spectroscopic members and their coordinates. The luminosity gap in the r-band is obtained within a radius of 500 kpc/h from the BGG. Figure 1 shows the distribution of absolute magnitude in the r-band versus the redshift for all galaxies (gray points) as well as the selected sample in the SDSS (blue and red points).

2.2. Simulations: Illustris-1 and Millennium Simulations

We use the public release of the Illustris-1 Simulation (Vogelsberger et al. 2014, hereafter: IS-1)—a series of gravity as well as hydrodynamics realizations of a (106.5 Mpc)3 cosmological volume that contains 18203 gas cells and 18203 DM particles, run with the AREPO code (Springel 2010). The highest-resolution run of the Illustris-1 handles the DM component with a mass resolution of $m_{\text{DM}} = 6.3 \times 10^9M_\odot$. 

![Figure 1](image-url)
and a baryonic component with $m_{\text{baryon}} = 1.6 \times 10^9 M_\odot$ in 136 snapshots from $z = 127$ to $z = 0$ by adopting cosmological parameters consistent with the latest observations from the Wilkinson Microwave Anisotropy Probe (WMAP-9, Hinshaw et al. 2013). Halos, subhalos, and their basic properties have been identified with the FOF and SUBFIND algorithms (Davis et al. 1985; Springel et al. 2001; Dolag et al. 2009) at every stored snapshot. Based on a halo mass limit of $M_{\text{halo}} \geq 10^{13} - 10^{14} M_\odot$ on galaxy systems with a BGG absolute r-band magnitude of $M_r(BGG) < -22$ mag and a multiplicity of at least four members for groups, the number of galaxy groups in the present epoch is reduced to $\sim 190$ systems containing $\sim 15,000$ galaxies. See Nelson et al. (2015) for more a detailed description of the properties of the galaxy group catalog.

In addition, we are using the Millennium Simulation (MS, Springel et al. 2005) combined with the SAM of Guo et al. (2011) (hereafter: MS-Guo+11) to extract galaxy properties. The cosmological model adopted in the Millennium Simulation is consistent with the first data from the Wilkinson Microwave Anisotropy Probe (WMAP-1, Spergel et al. 2003) (note that the value of $\sigma_8$ is assumed to be greater than its present value of 0.82 given by WMAP-9, which does not strongly affect this study). The simulation box $(500 h^{-1} \text{Mpc})^3$ contains 2160$^3$ particles and presents a mass resolution of $8.6 \times 10^8 h^{-1} M_\odot$. The DM merger trees within each simulation snapshot (64 snapshots in total) range approximately logarithmically in time between $z = 127$ and $z = 0$ and are extracted from the simulation using a combination of FOF (Davis et al. 1985) and SUBFIND (Springel et al. 2001) halo-finding algorithms. The gas and stellar components of galaxies in DM halos are constructed semi-analytically, based on laying a series of coupled differential equations on top of the halo merger trees. In this study, we use the SAM of Guo et al. (2011) at the present epoch, which contains $\sim 23,000$ galaxy groups/clusters with at least four members and halo mass above $10^{13} M_\odot$ to $\sim 10^{14} M_\odot$ with BGG absolute r-band magnitude of $M_r(BGG) < -22$ mag and $\sim 2$ million galaxies.

The luminosity centroid for the simulations is defined based on $X_l = \sum X_i L_i / \sum L_i$, where $L_i$ is the luminosity of a galaxy within a group in the r-band and $X_i$ is the projected coordinate of each galaxy within the radius of $r_{200}$. Finally, we use the r-band magnitude of the group members and their coordinates to obtain the luminosity gaps within a radius of 500 kpc/$h$ radius in each simulation.

3. RESULT

3.1. The Luminosity Gap

In previous studies of fossil groups, the luminosity gap between the two most luminous galaxies, located within a given physical radius of the group center (e.g., $0.5 R_{200}$), has been used as a statistical test to probe the accuracy of a number of semi-analytic models of galaxy formation in cosmological simulations (Dariush et al. 2007, 2010; Smith et al. 2010; Gozaliasl et al. 2014a; Raouf et al. 2014). Dariush et al. (2007) used the SAM of Croton et al. (2006) in MS studies to predict that fossil systems could be found in significant numbers (3%–4% of the population) even in quite rich clusters. Other probes have also been proposed, for instance Dariush et al. (2010) introduced $\Delta m_{12} \geq 2.5$, i.e., the luminosity gap between the first and fourth brightest galaxies within $0.5 R_{200}$, as opposed to the conventional $\Delta m_{12} \geq 2.0$. Smith et al. (2010) combined a series of observational data to study the luminosity gap statistics within a radius of $\sim 640$ kpc in a sample of 59 intermediate-mass galaxy clusters. They showed that, based on the luminosity gap parameters, (8 ± 3)% of the sample are fossil systems. Recently, Gozaliasl et al. (2014a) studied the luminosity gap distribution using a large sample of X-ray galaxy groups (129 groups) spanning redshifts $z \leq 1$ in the XMM-LSS X-ray observations and the CFHT follow-up optical observations. They found that (22 ± 6)% of groups at $z \leq 0.6$ are fossils.

All of these studies rule out the possibility that a large luminosity gap has a statistical origin. In this study, we estimate the luminosity gap parameter within a radius of 300 kpc/$h$ for three samples of galaxy groups: SDSS (observational), MS-Guo+11 (simulations; semi-analytic), and IS-1 (simulations; hydrodynamical). In both observation and simulations, the luminosity gap is measured within a projected distance from the most luminous galaxy in the group.

Figure 2 shows the distribution of the luminosity gap for the SDSS groups and the two aforementioned model predictions. The distributions show that the fossil groups, i.e., galaxy groups with a large luminosity gap, are overproduced by the IS-1 in comparison to the observations and semi-analytic model used here. For instance, the fractions of fossil galaxy groups based on the definition of luminosity gap $(\Delta m_{12} \geq 1.7 \text{ mag})$ in IS-1, MS-Guo+11, and SDSS are $\approx 47\%$, $22\%$, and $27\%$, respectively. Moreover, galaxy groups with small magnitude gaps are underproduced in contrast to observation and previous studies (Smith et al. 2010). Note that an upper limit of $\Delta m_{12} = 4$ mag has been adopted based on the redshift completeness in the SDSS galaxies.

As in Smith et al. (2010) and Tavasoli et al. (2011), we present in Figure 3 the distribution of the luminosity gap as a function of the SDSS absolute r-band magnitudes (rest frame; Stoughton 2002) for the group galaxies ranked first and second in the SDSS, MS-Guo+11, and IS-1. The figure suggests that,
in contrast to IS-1, MS-Guo+11 and SDSS follow the same trend.

We note here that there are several adjustments that one could make in order to make SAMs consistent with a set of observational properties of galaxies. For example, although all SAMs based on the Millennium Simulation (e.g., Bower et al. 2006; Croton et al. 2006; De Lucia & Blaizot 2007; Guo et al. 2011) reproduce well the general observed characteristics of galaxies such as luminosity function and color bimodality, which indeed are important factors to properly recover the majority of observed galaxy properties, they do not fully agree on the prediction of observable parameters such as the luminosity gap (e.g., $\Delta m_{12}$ or $\Delta m_{13}$; Dariush et al. 2010). The source of such a discrepancy depends, to some extent, on the ways in which different treatments have been implemented in SAMs to account for the dynamical friction (as well as other physical processes involved) in order to predict the fate of infall galaxies in groups/clusters. Indeed the main reason that the model of Guo et al. (2011) has been adopted for the purpose of the current study is its robustness against the luminosity gap measurements (e.g., Gozaliasl et al. 2014b).

3.2. Magnitude Gap Versus Offset of BGG Centroid

In Raouf et al. (2014), we show that the luminosity gap and the offset between the location of the BGG and the luminosity centroid are useful indicators of the dynamical age or virialization state of galaxy groups. Thus in Figure 4 we show the correlation of the luminosity gap with the inverse of centroid offset ($1/D_{\text{off}}$) for the three group catalogs of SDSS, IS-1, and MS-Guo+11. Data points are color-coded according to the indicators of halo age, i.e., history of mass assembly ($M_{200,z=1}/M_{200,z=0}$) in the case of the simulation and the map of age probability in the 3D parameter space of $\Delta m_{12}$, centroid offset, and $M_*(\text{BGG})$ (associated with a different range of luminosities of group galaxies) as an indicator of the halo dynamical age in the case of the SDSS data, as explained in Raouf et al. (2014).

The gray line in each panel shows the mean of binned data points with the standard deviation errors. Broadly, the three panels in Figure 4 show similar trends in the $\Delta m_{12}-D_{\text{off}}$ relation. In comparison to the observations, the IS-1 appears to perform more successfully in predicting the observed distribution; however, as mentioned before, it significantly overpredicts the fraction of galaxy systems with a large luminosity gap. A possible explanation is the highly enhanced resolution of DM particle mass of IS-1 (by a factor of $\sim 100\times$) compared
to the Millennium DM simulation because this makes the former more robust in handling the dynamics of baryon particles.

### 3.2.1. An Evolutionary Track For Galaxy Groups

As stated above, the luminosity gap and the luminosity offset complement each other in targeting the most evolved galaxy groups. To better understand this we superimpose all panels in Figure 4 on top of each other. This is shown in Figure 5 where data points represent the mean and error bars the standard deviation associated with the SDSS (gray dotted line), IS-1 (gray dotted–dashed line), and MS-Guo+11 (gray dashed line) catalogs. We trace back the evolution of galaxy groups located at the top right of the Figure (red model, i.e., high magnitude gap \( \Delta M_{12} > 2 \) and small centroid offset \( D_{\text{off}} < 50 \text{ kpc} \)) from the present epoch at \( z = 0 \) to the snapshot corresponding to \( z = 0.2 \) in MS-Guo+11. The medians of the evolutionary tracks, color-coded according to the halo dynamical age (similar to the bottom panel of Figure 4), are also shown in Figure 5. Hence the red color indicates a high probability for a group to be old.

Similarly, we trace back the evolution of galaxy groups with large luminosity gaps \( (1 < \Delta M_{12} < 2) \) and a large centroid offset \( (D_{\text{off}} > 300 \text{ kpc}) \) (sky-blue model) between \( z = 0 \) and \( z = 1 \). Galaxy groups of this type also end up originating from a population of young galaxy groups with a small luminosity gap. Likewise, the median of the evolutionary track of sample groups is color-coded (sky-blue to blue) based on the age of halos. As indicated by the color of the track, these galaxy groups are not entirely populated by old groups. The evolutions of the magnitude gap and centroid offset against the redshift in red and sky-blue galaxy models (indices 1 and 2 respectively) are summarized in Table 1.

### 3.3. Black Hole Feedback

In the IS-1, black holes are implemented as sink particles (Bellovary et al. 2010) and thus grow in mass by accreting surrounding gas or through mergers with other black holes and accretion. Accretion by a black hole is described by the Bondi–Hoyle–Lyttleton equation:

\[
\dot{M}_{\text{BH}} = \frac{4\pi\alpha G^2 M_{\text{BH}}^2 \rho}{(c_s^2 + v_{\text{BH}}^2)^{3/2}}
\]

where \( \rho \) and \( c_s \) are the density and sound speed of the surrounding gas, respectively, and \( v_{\text{BH}} \) is the black hole velocity relative to the gas. Also, \( \alpha \) and \( G \) are the stagnation point and the gravitational constants, respectively. In the IS-1, a repositioning scheme is used for black hole sink particles that connects them to the minimum of gravitational potential, in which case the term for relative gas velocity, \( v_{\text{BH}} \), is disregarded in the accretion rate (see also Vogelsberger et al. 2013).

In the IS-1, AGN feedback regulates star formation in the process of galaxy formation through black hole accretion via thermal quasar mode (cold mode), thermal–mechanical radio mode (hot mode), and radiative mode. At a high accretion rate
with respect to the Eddington rate, i.e., cold-mode accretion, the black hole mass grows substantially. In contrast, with a low accretion rate in radio mode, the AGN jets expand hot bubbles in the surrounding halo. An AGN in radiative mode, also known as electromagnetic feedback, impacts the photoionization and photoheating rates, which represent net cooling rates for a short interval of cosmic time. Moreover, this feedback is present only for a black hole that is in the state of highest accretion around the Eddington limit (Sijacki et al. 2007).

In a recent observational study of dynamically relaxed (old) and unrelaxed (young) galaxy groups, we show that relaxed systems are less luminous in radio emissivity than unrelaxed galaxy groups (Miraghaei et al. 2014). In addition Suresh et al. (2015) study the central galaxies of FOF groups, based on hydrodynamical simulation, and show that the environment of central galaxies (e.g., BGGs) is influenced by the AGN feedback. They show that radio-mode feedback, which inflates large hot bubbles, heats the environment of the BGG and reduces the fraction of cold gas available for star formation. Another study, by Genel et al. (2014), shows that AGN radio-mode feedback operates by powerfully ejecting gas in the most massive halos below \( z = 1 \) such that halos are almost devoid of gas, in disagreement with observations. Moreover, Vogelsberger et al. (2013) show that the radio-mode feedback requires more power to suppress efficient cooling in massive halos compared to previous studies.

In Figure 6, we present the distribution of the instantaneous accretion rate \( (dM_{\text{BH}}/dt) \) of all black holes (top panel), the black hole mass (middle panel), and the gas fraction \( f_{\text{gas}} \) in the subhalo of the BGG (bottom panel) as functions of stellar mass for the BGG of old and young halos in the IS-1. As seen in Figure 6, the brightest galaxy in the dynamically relaxed galaxy groups displays a lower accretion rate than the brightest galaxies in dynamically young groups. At the same time the

### Table 1

| Redshift | \( \Delta M_2(1) \) (mag) | \( D_{\text{off}}(1) \) (Mpc) | \( \Delta M_2(2) \) (Mag) | \( D_{\text{off}}(2) \) (Mpc) |
|----------|--------------------------|-----------------------------|--------------------------|-----------------------------|
| 0.98871  | 0.88478                  | 0.13739                     | 0.86139                  | 0.06907                     |
| 0.90546  | 0.81897                  | 0.12588                     | 0.95807                  | 0.05898                     |
| 0.8277   | 0.87772                  | 0.13164                     | 0.9606                   | 0.06625                     |
| 0.75504  | 0.83571                  | 0.13995                     | 0.91877                  | 0.06247                     |
| 0.68711  | 0.82057                  | 0.12339                     | 0.81165                  | 0.05092                     |
| 0.62359  | 0.87549                  | 0.12641                     | 0.94561                  | 0.04388                     |
| 0.56418  | 0.89932                  | 0.12322                     | 0.9324                   | 0.04949                     |
| 0.50859  | 0.90665                  | 0.12058                     | 1.03455                  | 0.04188                     |
| 0.45658  | 0.98908                  | 0.11449                     | 1.0715                   | 0.03431                     |
| 0.4079   | 1.00568                  | 0.12119                     | 1.15871                  | 0.02996                     |
| 0.36234  | 1.07564                  | 0.11808                     | 1.24518                  | 0.0296                      |
| 0.3197   | 1.09738                  | 0.11                        | 1.25695                  | 0.0256                      |
| 0.2798   | 1.11613                  | 0.12398                     | 1.38156                  | 0.02494                     |
| 0.24247  | 1.17151                  | 0.12331                     | 1.58907                  | 0.02589                     |
| 0.20755  | 1.19065                  | 0.14448                     | 1.74282                  | 0.02078                     |
| 0.1749   | 1.24234                  | 0.15149                     | 1.97987                  | 0.01951                     |
| 0.14438  | 1.27901                  | 0.21507                     | 2.12837                  | 0.0189                      |
| 0.11588  | 1.30518                  | 0.40083                     | 2.26004                  | 0.01662                     |
| 0.08929  | 1.35794                  | 0.82458                     | 2.30102                  | 0.01515                     |
| 0.06449  | 1.3548                  | 0.9089                     | 2.34741                  | 0.0124                      |
| 0.0414   | 1.39455                  | 0.93671                     | 2.41839                  | 0.01003                     |
| 0.01993  | 1.4333                  | 0.95849                     | 2.49909                  | 0.00796                     |
| 0.0      | 1.42636                  | 1.00297                     | 2.57957                  | 0.00624                     |

**Note.** Values are shown for two categories of galaxy groups shown in Figure 5: (1) sky blue and (2) red. Column 1: redshift; columns 2, 4: magnitude gap between the two most luminous galaxies in the group; columns 3, 5: physical separation between the BGG and the luminosity centroid of the group, i.e., the centroid offset.
black hole mass in the BGGs dominating the dynamically relaxed groups is larger than that in the BGGs of dynamically unrelaxed or young groups. This means that the history of mass assembly of the group halos has a significant impact on the supermassive black hole of the brightest group galaxy. The BGGs dominating the dynamically old galaxy groups seem to be very efficient in black hole growth by consuming the gas that could have been generally found with a higher density in the early stages of halo formation (as shown in the bottom panel of Figure 6). While this was argued in earlier studies of fossil groups, the Illustris provides the first direct numerical evidence.

Note that we define the relaxed (old) and unrelaxed (young) halos based on the accumulation of >50% and <30% of their final mass at \( z \sim 1 \), respectively. Based on this definition, we find that 33% and 29% out of about 190 halos with mass over \( \sim 10^{13}M_\odot \) within IS-1 fall into the categories of old and young groups, respectively. The remaining halos form an intermediate population.

This is a new finding because the Illustris simulation is the first simulation, on a cosmological scale, that allows us to study the growth of the supermassive black hole in the dominant fossil galaxies and also relative to giant elliptical galaxies with similar masses but in groups with a small luminosity gap. This finding makes a direct connection between the dynamical state and thus the dynamical age of the halo and the growth in black hole mass. Observationally also H. G. Khosroshahi et al. (2016, in preparation) show that there is a relation between the dynamical age of groups and the radio luminosity of BGGs. This is following a study by Miraghaei et al. (2014) based on a smaller sample. A popular argument to support the findings is based on the lack of recent on-going galaxy mergers in dynamically old and fossil groups compared to their rivals, the dynamically young groups, where their brightest group galaxy is expected to be surrounded by other massive galaxies (Khosroshahi et al. 2007; Smith et al. 2010).

### 3.3.1. IGM Temperature

In the IS-1, the gas temperature in each cell is obtained from the internal energy \( u \) and the electron abundance \( x_e \). At first, we estimate the mean molecular weight using the equation

\[
\mu = \frac{4}{1 + 3X_H + 4X_H x_e},
\]

where \( X_H \) is equal to 0.76 and represents the hydrogen mass fraction. Therefore, the temperature of cells in kelvin is estimated from the equation

\[
T = (\gamma - 1) \frac{u}{K_B} (\mu m_p),
\]

where \( \gamma = 5/3 \) is the adiabatic index, and \( m_p \) and \( K_B \) are the proton mass and the Boltzmann constant, respectively.

The top panel in Figure 7 shows the IGM gas temperature as a function of radial distance from the center in units of \( r_{200} \) for dynamically old and young galaxy groups with halo masses over \( 10^{13}M_\odot \) at the present epoch, \( z = 0 \). A comparison of the median temperature profile of old (red solid line) and young (blue dashed line) galaxy groups in IS-1 suggests that the IGM temperature in halos with an earlier formation epoch is systematically higher than that in halos formed recently. In order to see whether such an observed difference is due to a systematic bias in halo mass selection, we present in the lower panel of Figure 7 the mean value of the IGM temperature, estimated within \( r_{200} \), as a function of the halo mass, i.e., the \( M-T \) scaling relation.

From X-ray and optical observations of a sample of galaxy groups, Khosroshahi et al. (2007) show that for the same halo mass, the IGM in fossil groups is hotter than in non-fossil groups. Their sample was constructed from a small sample of fossil groups, e.g., \( \Delta m_{12} \geq 2 \), in which the brightest group galaxy was located at the peak of X-ray emission, suggesting a high degree of dynamical relaxation. Although the scales on which the IGM temperature and mass were measured in the observations with which we are comparing differ from the
scales shown in this study, we find that the results are robust and consistent with the observations. The scaling properties of relaxed and unrelaxed galaxy groups in the Illustris simulation and a comparison with the observations will be presented in a separate study.

In most SAMs, black hole feedback is estimated in a crude way by suppressing the gas cooling provided by the radio mode of AGNs (Croton et al. 2006), then acting to make the stellar mass function closely match the observations. The gas temperature also has to be constant and equal to the virial temperature in all processes, and there are simple assumptions in this that do not let us use the temperature and feedback analysis for an instantaneous estimation. We try to address this issue in a separate study (M. Raouf et al. 2016, in preparation) by using the Semi-Analytic Galaxy Evolution code (Croton et al. 2016), which helps to use the temperature analysis and feedback process in a more physical way to closely match the previous X-ray observations.

4. SUMMARY AND DISCUSSION

In this study we probe the distribution of the luminosity gap in Illustris, a new cosmological simulation, in which the properties of galaxies are dealt with hydrodynamically as opposed to in a more economic, semi-analytic computation (Vogelsberger et al. 2014). We find that galaxy groups with relatively large luminosity gaps are overproduced in Illustris with ≈47% of groups having a large magnitude gap (∆M₁₂) whereas this figure is ≈22% and ≈27% in the semi-analytic model of Guo et al. (2011) and the SDSS-based group catalog of Tempel et al. (2014), respectively. However, we find that the Illustris recovers the observed trend in the plane of the luminosity gap and the offset between location of brightest group galaxy and center of mass of the halo, as two independent indicators of the dynamical state of the halo. We show for the first time the evolutionary track of galaxy groups in the plane of luminosity gap (∆M₁₂) versus BGG offset (Dₜₐₐₜ), indicating that galaxy groups with large luminosity gaps, regardless of the position of the BGG within the group, originate from groups with small luminosity gaps. However, the majority of groups with BGGs at the center of their halos are systems that formed early on.

One could argue that the higher production of systems with a large luminosity gap in Illustris is due to inefficient AGN feedback. Theoretical studies suggest that AGN activity should supply enough energy to prevent gas from being accumulated in the central regions of galaxy clusters and therefore quenching the formation of stars (Tabor & Binney 1993; Ciotti & Ostriker 1997; Silk & Rees 1998). According to SAMs, where the AGN feedback is paired with N-body simulations, most of the current stellar mass in the brightest cluster galaxies is assembled through dry minor mergers, following a phase of quiescent star formation influenced by feedback processes (Bower et al. 2006; Croton et al. 2006; De Lucia & Blaizot 2007; Guo et al. 2011).

Our study of the mass of the central black hole and the amount of mass it accreted, in old and young galaxy groups and for a given stellar mass, shows that the central black hole in the dominant fossil galaxy (BGG) is noticeably more massive than a BGG of similar mass in a non-fossil or a young galaxy group (e.g., Figure 6). Furthermore, the black hole accretion in dominant fossil galaxies occurs, on average, at slower rates than in systems with smaller luminosity gaps (i.e., non-fossil systems). This is consistent with our earlier observational findings in which fossil groups are less luminous in radio emission due to relatively less cold-mode accretion (Miraghaei et al. 2014, 2015).

If galaxies in fossil groups are produced in major, possibly multiple, mergers at high redshifts, their supermassive black holes could well be more massive for the total stellar mass in the galaxies, and as a result of there being no recent major merger or interaction with massive galaxies, the accretion to their central black hole could be occurring more slowly than in galaxies that are subject to stronger interactions with more massive counterparts in groups with smaller luminosity gap (Ellison et al. 2011; Silverman et al. 2011; Lackner et al. 2014; Capelo et al. 2015). This argument is supported by a recent study in which over a dozen fossil groups were studied with a focus on their IGM properties (Bharadwaj et al. 2016).

The Illustris simulation allows us to study the IGM temperature profile for the first time, suggesting that the IGM in dynamically old galaxy systems is hotter than the IGM in dynamically young/evolving halos. This is in agreement with the previous observational study of Khosroshahi et al. (2007) in which a hotter IGM was found to be more likely associated with fossil galaxy groups than with non-fossil groups with the same halo mass.

For this study we have used the Illustris simulation data base which is publicly available at www.illustris-project.org. We gratefully acknowledge Dylan Nelson for facilitating the access to the data. The Millennium database used in this paper and the web application providing online access to them were constructed as part of the activities of the German Astrophysical Virtual Observatory and www.sdss3.org/. SDSS-III is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS-III. The authors thank the anonymous referee for useful comments which helped the improvement of the text. We thank Gary Mamon (IAP) and Joe Silk (IAP) for useful discussions during this study.

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