Barred Galaxies in the Illustris-1 and TNG100 Simulations: A Comparison Study

Ze-Bang Zhou1, Weishan Zhu1, Yang Wang1, and Long-Long Feng1,2

1 School of Physics and Astronomy, Sun Yat-Sen University, Zhuhai campus, No. 2, Daxue Road Zhuhai, Guangdong, 519082, People’s Republic of China; zhuwshan5@mail.sysu.edu.cn
2 Purple Mountain Observatory, CAS, No.10 Yuanhua Road, Qixia District, Nanjing 210033, People’s Republic of China

Received 2019 December 17; revised 2020 April 23; accepted 2020 April 23; published 2020 June 1

Abstract

We carry out a comparison study on the bar structure in the Illustris-1 and TNG100 simulations. At $z = 0$, 8.9% of 1232 disk galaxies with stellar masses $>10^{10.5} M_\odot$ in Illustris-1 are barred, while the numbers are 55% of 1269 in TNG100. The bar fraction as a function of stellar mass in TNG100 agrees well with the survey $S^4G$. The median redshifts of bar formation are $\sim$0.4–0.5 and $\sim$0.25 in TNG100 and Illustris-1, respectively. Bar fraction generally increases with stellar mass and decreases with gas fraction in both simulations. For galaxies with bars at $z = 0$, their bar formation time is generally anti-correlated with their gas fraction at high redshift. When the bars were formed, the disk gas fractions were mostly lower than 0.4. The much higher bar fraction in TNG100 probably benefits from the much lower gas fractions in massive disk galaxies since $z \sim 3$, which may result from the combination of more effective stellar and AGN feedback. The latter may be the primary factor at $z < 2$. Meanwhile, in both simulations, barred galaxies have higher star formation rates before bar formation and have stronger AGN feedback, at all times, than unbarred galaxies. The properties of dark matter halos hosting massive disk galaxies are similar between the two simulations and should have a minor effect on the frequencies of different bars. For individual galaxies under similar halo environments across the two simulations, different baryonic physics can lead to striking discrepancies in morphology. The morphologies of individual galaxies are subject to the combined effects of environment and internal baryonic physics and are often not predictable.

Unified Astronomy Thesaurus concepts: Galaxy structure (622); Galaxy evolution (594); Galaxy dark matter halos (1880); Hydrodynamical simulations (767); Barred spiral galaxies (136)

1. Introduction

Stellar bars are present in the inner regions of many disk galaxies in the local and high-redshift universe. The reported frequency of bars declines from 30% to 70% at $z = 0$ to $\sim$10%–20% at $z = 0.8$ in different observational studies (e.g., Barazza et al. 2008; Sheth et al. 2008; Aguerri et al. 2009; Nair & Abraham 2010; Masters et al. 2011; Melvin et al. 2014; Buta et al. 2015; Díaz-García et al. 2016; Simmons et al. 2017; Willett et al. 2017). Many of these observations suggest that massive and gas-poor disk galaxies are more likely to host bars than low-mass and gas-rich galaxies (e.g., Masters et al. 2011; Cheung et al. 2013), while some studies indicate the opposite trend (e.g., Barazza et al. 2008; Nair & Abraham 2010) or argue that there is no difference (Erwin 2018). The bar plays an important role in driving the secular evolution of disk galaxies by redistributing the gas, stars, and even dark matter, as well as altering the angular momentum associated with these components (see Kormendy 2013, for a review). For instance, bars could induce gas flow into the galaxy central region and contribute to the formation of pseudo-bulges and bulges. On the other hand, the origin, growth, and destruction of bars is a key piece of the galaxy evolution puzzle, and many details remain unclear. Answering this issue is crucial to explaining the presence or absence of bars in disk galaxies with different properties.

Bar formation can be triggered either by internal secular evolution or by external processes, including merge and tidal effects of nearby galaxies. Early theoretical and N-body simulation studies suggested that massive cold stellar disks are highly vulnerable to instability, and bars can grow quickly in these stellar disks (e.g., Ostriker & Peebles 1973; Toomre 1977, 1981). However, this scenario is unable to account for the origin of bars in realistic galaxies, because these studies did not account for several factors, such as dark matter halos, gas component, baryonic physics including cooling, star formation, and feedback, and the impact of external processes (Athanassoula et al. 2013; Kormendy 2013).

Later, idealized simulations including halos, gas component, and gas physics showed that bar formation may be a gradual process, and both dark matter halos and gas play important roles (e.g., Berentzen et al. 1998; Debattista & Sellwood 2000; Athanassoula & Misiriotis 2002; Athanassoula 2002, 2003; Berentzen et al. 2004; Berentzen et al. 2007; Villa-Vargas et al. 2010; Athanassoula et al. 2013; Seo et al. 2019). Athanassoula (2002) demonstrated that a halo would first delay bar formation but would then be capable of strengthening the bar during secular evolution by absorbing the angular momentum of the stars. The strength of the bars in the simulated isolated galaxies was found to correlate with the amount of angular momentum absorbed by the halos, and it depends on the halo central concentration (Athanassoula & Misiriotis 2002; Athanassoula 2003). Many simulations showed that gas would obstruct the growth of the bar by giving angular momentum to the bar. Consequently, bars will form much later and are much weaker in gas-rich disk galaxies (e.g., Berentzen et al. 2004; Bournaud et al. 2005; Berentzen et al. 2007; Athanassoula et al. 2013).

These idealized simulations, however, usually study the formation and evolution of bars in isolated disk galaxies. Those disk galaxies were set up at the beginning of the simulations by assuming various models, but they do not result from self-consistent evolution. In addition, the effect of tidal force, if included, was modeled in simplified ways. To overcome these two limitations, several works have investigated the origin and development of bars in more realistic environments using...
cosmological zoom-in simulations (e.g., Kraljic et al. 2012; Scannapieco & Athanassoula 2012; Goz et al. 2015; Bonoli et al. 2016; Zana et al. 2018). These simulations show that bars can emerge naturally in the concord $\Lambda$CDM cosmology, and most of the bars became easily observable only after $z \sim 0.4–0.5$.

In addition, the roles of baryon physics, such as gas content, star formation, and feedback from supernovae and supermassive black holes (SMBH) in the evolution of the bars are explored in the literature. Based on the cosmological zoom-in simulations Eris and ErisBH, Bonoli et al. (2016) show that the AGN feedback in ErisBH can lower the gas content and star formation in the central region of disk galaxy, which results in a smaller bulge and larger disk, and the formation of a bar. Zana et al. (2019) further show that different implementation of sub-grid physics can lead to bars with very different properties in the simulations ErisBH and Eris2k. They find that stronger effective stellar feedback can remove low angular momentum gas more efficiently and help to develop a stronger and longer bar in Eris2k. However, the impact of the difference on AGN feedback is not presented in their work. Meanwhile, whether the bar would induce quenching or enhance star formation in the inner regions of disks (e.g., Lin et al. 2017; Spinoso et al. 2017; Kim et al. 2017; Newhann et al. 2020) and whether it would enhance black hole activity or not are still controversial topics in different works (e.g., Alonso et al. 2013; Cisternas et al. 2013).

Recently, galaxy formation and evolution in cosmic volume, up to a cubic of 100 Mpc, and high resolution, down to 0.1–1 kpc, have been studied in state-of-the-art cosmological hydrodynamical simulations such as Illustris-1, EAGLE, and IllustrisTNG (Vogelsberger et al. 2014; Schaye et al. 2015; Nelson et al. 2019). The properties of bars in the disk galaxies in these simulations, including their frequency, origin, and correlation with gas fraction and stellar mass, have been examined (Algorry et al. 2017; Peschken & Łokas 2019). Algorry et al. (2017) found that 20% of the disk galaxies in EAGLE have strong bars, and another 20% have weak bars, resulting in a total bar frequency that is consistent with the observation. They also found that the bar strength is correlated with the stellar mass, and stronger bars tend to be located in less gas-rich systems. Similar trends are found in Illustris-1. In contrast, the bar fraction in Illustris-1 is much lower, $\sim 21\%$, and increases slightly with increasing redshift, which is in contradiction to the observed trend (Peschken & Łokas 2019).

These discrepancies over the bar fraction between simulations may be partially attributed to different baryon physics, such as the feedback from star formation and AGNs. As the Illustris-1 and TNG simulations share the same initial conditions, it would be worthwhile to carry out a comparison study on barred galaxies in them. Such a comparison study would determine the impact of baryon physics on the formation and evolution of bars. Note that, during the preparation of this work, Rosas-Guevara et al. (2020) published their analysis on the bar fraction in the TNG100 simulations, which is 40% in the stellar mass range $M_*$ = 10$^{10.4–11.0}$ $M_\odot$ and is much higher than the fraction in the Illustris-1 simulation reported by Peschken & Łokas (2019). Moreover, Rosas-Guevara et al. (2020) show that the star formation and black hole activity in barred galaxies are stronger than those in unbarred galaxies, using TNG100.

This paper is organized as follows. We introduce the simulations and galaxy samples in Section 2. The overall features of barred galaxies, such as the bar fractions and their origins in the two simulations, are shown in Section 3. We explore properties such as gas fraction, star formation, black hole feedback, and the mass and shape of host dark matter halos during the evolution of bars in Section 4. A comparison of the bar properties between matched galaxy pairs in the Illustris and TNG100 simulations is presented in Section 5. We summarize our findings, compare them with previous works, and discuss the results in Section 6.

2. Simulations and Galaxy Samples

2.1. The Illustris-1 and TNG100 Simulations

In this paper, we make use of publicly released data from the Illustris-1 and TNG100 simulations. These two simulations use the same initial conditions, except for some adjustments in TNG100 for updated cosmology. There are some differences in the cosmological parameters and baryon physics between these two simulations.

The Illustris project (Vogelsberger et al. 2014) is a set of large hybrid $N$-body/hydrodynamic simulations of galaxy formation, using the moving-mesh code AREPO (Springel 2010). The cosmological parameters of the Illustris simulations are set to the latest Wilkinson Microwave Anisotropy Probe (WMAP9) measurements: $\Omega_m = \Omega_{dm} + \Omega_b = 0.2726$, $\Omega_{\Lambda} = 0.7274$, $\Omega_k = 0.0456$, $\sigma_8 = 0.809$, $n_s = 0.963$, and $H_0 = 100$ km s$^{-1}$Mpc$^{-1}$ with $h = 0.704$ (Hinshaw et al. 2013). The IllustrisTNG project (Nelson et al. 2019) is the successor of the original Illustris project. It updates galaxy formation models, which include new physics and numerical improvements, as well as refinements to the original Illustris simulations. The IllustrisTNG simulations are normalized by the recent Planck constraints: $\Omega_m = 0.3089$, $\Omega_b = 0.0486$, $\Omega_{\Lambda} = 0.6911$, $\sigma_8 = 0.8159$, $n_s = 0.9667$, and $h = 0.6774$ (Ade et al. 2016).

The Illustris-1 and TNG100 simulations have the same box size ($75h^{-1}$Mpc$^3$), and both use $2 \times 1820^3$ dark matter and gas particles. The masses of each dark matter and gas particle are $6.3 \times 10^8 M_\odot$ and $1.6 \times 10^9 M_\odot$ in Illustris-1, and $6.3 \times 10^9 M_\odot$ and $1.4 \times 10^9 M_\odot$ in TNG100, respectively. Both simulations have evolved from redshift $z = 127$ to the present time $z = 0$. The Illustris-1 simulation outputs 134 snapshots, while TNG100 has 100 snapshots.

The differences of baryonic physics between IllustrisTNG and the original Illustris have been described in detail in Weinberger et al. (2017) and Pillepich et al. (2018b). In addition to some key numerical improvements, the major updates in recipes of galaxy physics include three aspects: the evolution and feedback of supermassive black holes, galactic winds driven by star formation, and stellar evolution. In IllustrisTNG, the seed mass of the SMBHs is increased by a factor of eight, and the thermal “bubble” model in Illustris is replaced by a kinetic model when the accretion rate is low. A model of isotropic galactic winds with a velocity floor is implemented in TNG, instead of the “bipolar” winds model without a velocity floor in Illustris. In addition, the velocity of the galactic winds in TNG is assumed to be redshift dependent.

In the TNG models, the impacts of AGN feedback and galactic winds on star formation, black hole growth, and other galaxy properties have been studied in Pillepich et al. (2018b).
In these projects, “galaxy” is identified as the stellar component in a subhalo, and a dark matter halo is named “Halo”.

We basically follow the same schemes as in Peschken & Lokas (2019) to identify barred galaxies in simulation samples. In order to study the bars, one should first locate the disk galaxies. Peschken & Lokas (2019) use two parameters provided by the simulations to specify disk galaxies, i.e., the stellar circularities $\epsilon$, and the flatness of galaxies. We first set the position of the most bounded stellar particle in a galaxy as its center and then take the plane perpendicular to the angular momentum vector of stellar component as the galaxy plane. Stellar particles belonging to galaxy disk are expected to have a circularity parameter $\epsilon$ close to 1. The Illustris and Illustris-TNG projects provide the fractional mass of stellar component with $\epsilon > 0.7$, i.e., $f(\epsilon > 0.7)$ for each galaxy, which was first given by Genel et al. (2015) as a measure of the fraction of stellar mass in the disk component. If more than 20% of a galaxy’s stellar mass has $\epsilon > 0.7$, i.e., $f(\epsilon > 0.7) > 0.2$, which means this galaxy has more than 20% of its stellar mass behaving kinematically as a disk component, this galaxy would be taken as a disk galaxy candidate. Then, we use the three eigenvalues of the stellar mass tensor $M_1$, $M_2$, and $M_3$ to calculate the flatness of disk galaxy candidates, which is defined by $M_3/\sqrt{M_1M_2}$, ($M_1 < M_2 < M_3$). Finally, a disk galaxy candidate will be confirmed as a disk galaxy if its flatness is smaller than 0.7.

Using this method, we find 2658 disk galaxies with stellar masses above $10^{10.25}M_\odot$ and 1269 disk galaxies with more than 40,000 stellar particles ($M_* > 10^{10.5}M_\odot$) in the TNG100 samples at redshift $z = 0$. In Illustris-1, we find 1232 disk galaxies with over 40,000 stellar particles. Further, we use the $A_2$ parameter (Athanassoula et al. 2013) to identify whether these disk galaxies have bars or not. $A_2$ is defined by the following two Fourier components (Athanassoula et al. 2013):

$$a_m(R) = \sum_i^N M_i \cos(m\phi_i)$$

$$b_m(R) = \sum_i^N M_i \sin(m\phi_i),$$

where $N_R$ is the number of star particles within a given cylindrical radius $R$, $M_i$ is the $i$th star particle’s mass, and $\phi_i$ is its azimuthal angle. $A_2(R)$ is a function of cylindrical radius $R$, defined as

$$A_2(R) = \frac{\sqrt{a_0^2 + b_0^2}}{a_0}.\tag{3}$$

We measure the bar strength by the maximum value of $A_2(R)$, i.e., $A_{2,max}$. We calculate the $A_{2,max}$ parameter over all disk galaxies and place a threshold value of 0.15 for the $A_{2,max}$ parameter to preliminarily determine whether a galaxy is barred or not. Next, we inspect the stellar surface density maps of galaxies with $A_{2,max} > 0.15$ by eye to confirm that this non-axisymmetric feature is indeed due to a bar. For these candidate galaxies, we visualize their morphological features and exclude those that actually exhibit no bar structure but have chaotic and distorted structures. This inspection procedure is somewhat crude, but the final estimated bar fraction is consistent with previous works on bars of these two simulations (Peschken & Lokas 2019; Rosas-Guevara et al. 2020). We define disk
galaxies with $A_{2,\text{max}} > 0.15$ but that visually do not look like barred galaxies. There are 21 and 70 false-positive cases in Illustris-1 and TNG100, respectively, and they are not included in our barred galaxy sample. Finally, we identify 110 and 871 barred galaxies in Illustris-1 and TNG100, respectively at $z = 0$. We display images of two examples of barred galaxies from each simulation in Figure 1. The top and bottom panels show galaxies with stellar masses of $M_*= 10^{11.5}M_\odot$ and $M_*= 10^{10.8-10.9}M_\odot$, respectively. In both simulations, the bar features are manifest for galaxies with stellar masses around $10^{11}M_\odot$ and are still visible with stellar mass $\sim 10^{10.8-10.9}M_\odot$. Figure 2 shows four samples of disk galaxies with $A_{2,\text{max}} > 0.15$ but without bar structure, i.e., false-positive samples. Their non-axisymmetry is mainly caused by complex substructures or arms. As mentioned above, these false-positive samples are not identified as barred galaxies.

### 3. Bars in Disk Galaxies

#### 3.1. Bar Fraction

We measure the overall bar fraction of disk galaxies as a function of stellar mass $M_*$ at redshift $z = 0$ in the TNG100 and Illustris-1 simulations, respectively, and plot the results in Figure 3. In Illustris-1, the bar fraction increases gradually from $\sim 0\%$ in the stellar mass bin $M_*= 10^{10.50-10.58}M_\odot$ to $\sim 10\%$ in the bin $M_*= 10^{11.00-11.08}M_\odot$ and then grows rapidly to $\sim 30\% - 40\%$ for galaxies more massive than $M_*= 10^{11.25}M_\odot$. The bar fraction in Illustris-1 identified by our procedures is basically in agreement with that of Peschken & Lokas (2019); although, there are some slight differences in some mass bins. These differences may result from the fact that Peschken & Lokas (2019) recomputed the stellar masses of some interacting galaxies, but we use the original estimations of stellar masses provided by the Illustris-1 project.
The bar fraction in TNG100 is much higher than that in Illustris-1 in the stellar mass range from $\sim 10^{10.5}$ to $\sim 10^{11.25}M_\odot$. It increases rapidly from $\sim 0\%$ in the bin $M_*= 10^{10.25-10.33}M_\odot$ to $\sim 30\%$ in the bin $M_*= 10^{10.80-10.90}M_\odot$ and then to $\sim 50\%$ for galaxies in the mass range $M_*= 10^{10.66-11.25}M_\odot$. For galaxies more massive than $M_*= 10^{11.25}M_\odot$, the bar fraction has a significant scatter because of the very limited number of very massive disk samples. Different feedback models are expected to be responsible for the discrepancy in the bar fraction between the two simulations. The properties of gas content, stellar component, SMBH, and halo are influenced by the feedback models and should have significant effects on bar formation (Bonoli et al. 2016; Zana et al. 2019). We will investigate these properties and their relations with bar formation in the next section.

Unless specified otherwise, in the following comparison study, we will only include disk galaxies containing more than 40,000 stellar particles, i.e., $M_*> 10^{10.50}M_\odot$ so as to obtain reliable results. Disk galaxies with and without bars will be named as “barred” and “unbarred”, respectively. The same threshold has been applied in Peschken & Lokas (2019). Above this mass threshold, there are 1269 disk galaxies, of which 698 galaxies are identified as barred in TNG100. The median stellar mass of these 698 barred galaxies is $M_*= 10^{10.38}M_\odot$. In Illustris-1, there are 1232 disk galaxies more massive than $M_*= 10^{11.00}M_\odot$.
10^{10.50} \text{M}_\odot$, of which 110 galaxies are barred, and the median stellar mass of the barred galaxies is $M_\text{b} = 10^{11.20} \text{M}_\odot$. In contrast, Rosas-Guevara et al. (2020) identified 270 disk galaxies at $z = 0$ within the range $M_\text{b} = 10^{10.4} - 11.0 \text{M}_\odot$, and 107 of them are barred in TNG100. They used the kinematic bulge-to-disk composition algorithm and additional limitation on the stellar disk/bulge-to-total mass ratio to identify bars. In Peschken & Łokas (2019), very few bars are found in low-mass galaxies ($3.3 \times 10^{10} \text{M}_\odot < M_\text{b} < 8.3 \times 10^{10} \text{M}_\odot$), and also, 109 out of 509 disk galaxies that are more massive than $8.3 \times 10^{10} \text{M}_\odot$ are found to be barred at $z = 0$ in Illustris-1.

We also track disk galaxies at different redshifts and calculate the corresponding bar fractions. Some of the disks at $z = 0$ might not be disks at high redshifts, and some disk galaxies at high redshifts may evolve into non-disk galaxies at $z = 0$. Figure 4 shows that in Illustris-1, the fraction of disk galaxies having $A_2^{\text{max}} > 0.15$ increases with redshift, which agrees with Peschken & Łokas (2019) but is inconsistent with many other observations (e.g., Sheth et al. 2008; Melvin et al. 2014). Peschken & Łokas (2019) argued that the observed trend showing that the bar fraction decreases with increasing redshift holds for low-mass galaxies, but for massive galaxies, the bar fraction is roughly constant or even increases with redshift. Nevertheless, the bottom panel of Figure 4 shows that TNG100 has a roughly constant fraction of $A_2^{\text{max}} > 0.15$ at different epochs, partly alleviating this conflict. Moreover, the bar fractions of disk galaxies that are more massive than $M_\text{b} = 10^{10.83} \text{M}_\odot$, i.e., the mass threshold of the default sample in Peschken & Łokas (2019), evolve slowly with redshift in TNG100. The bar fractions of massive disk galaxies at $z = 0$ decrease slightly in comparison with high redshifts.

### 3.2. Formation Time and Origin of Bars

To determine the formation time of bars in our samples, we track the evolution history of barred galaxies to identify the formation redshift of bars, denoted as $z_{\text{bar}}$. For each barred disk galaxy at $z = 0$, we calculate the value of its $A_2^{\text{max}}$ at different redshifts. The solid lines in Figure 5 show the evolution of $A_2^{\text{max}}$ for two sample galaxies. Then, we determine $z_{\text{bar}}$ of each barred galaxy by the following procedure. First, we determine the redshift at which one galaxy’s $A_2^{\text{max}}$ is above 0.15 for the first time while evolving from high to low redshifts; if $A_2^{\text{max}}$ stays above 0.15 thereafter, then this redshift will be marked as a candidate of $z_{\text{bar}}$ for this galaxy. Otherwise, we will keep searching whenever $A_2^{\text{max}}$ crosses above the threshold of 0.15 toward lower redshifts, until we find the candidate of $z_{\text{bar}}$. Second, this candidate will be defined as this galaxy’s $z_{\text{bar}}$ if it satisfies the following condition:

$$\frac{|A_2^{\text{max}}(z) - A_2^{\text{max}}(z + \Delta z)|}{A_2^{\text{max}}(z)} < 0.4 \tag{4}$$

where $\Delta z$ is the redshift gap between the snapshot corresponding to the candidate redshift and its previous snapshot at a higher redshift. Equation (4) is applied to ensure that the bar is stable and avoids violent fluctuations. A similar measure is adopted in Rosas-Guevara et al. (2020). If the candidate redshift does not meet the condition of Equation (4), we will track toward lower redshifts to find the next candidate and check whether it fulfills Equation (4) or not. The procedure is repeated until $z_{\text{bar}}$ of this galaxy is found. We perform this kind of search for all of the barred galaxies at $z = 0$ to determine their $z_{\text{bar}}$. The vertical red dashed-dotted lines marked in Figure 5 indicate the detected bar formation time of two example galaxies.

Figure 6 shows the redshift distribution of the bar formation. We find a median value of $z_{\text{bar}}$ of $\sim 0.4-0.5$ in TNG100 and $\sim 0.25$ in Illustris-1. Peschken & Łokas (2019) and Rosas-Guevara et al. (2020) used a few different ways to determine the formation time of galaxy bars, which is about $z = 0.5$ in TNG100 and $z = 0.3$ in Illustris-1. Our results are in agreement with theirs. Note that our sample size is larger than that in Rosas-Guevara et al. (2020) due to a wider mass range and different sample-selecting method. Figure 6 also shows the distribution of time when disk galaxies had accumulated 50%
of their stellar mass at $z=0$. Generally, barred galaxies reach this milestone at higher redshifts than unbarred galaxies. For most barred galaxies, the bar structures emerge after most of the stars have been formed or assembled. In Figure 6, we have assigned galaxies with a bar/galaxy formation redshift equal to or higher than $z=2$ to the bin of $z=2$, resulting in a peak at $z=2$.

There are generally three types of processes that can drive the formation of galaxy bars, i.e., galaxy merger, flyby interaction, and secular evolution. To determine the roles of these processes, we checked the barred disk galaxies visually, probing their images to see if there was a merger or flyby when the bar was newly formed. More specifically, we determine the origin of the galaxy bar by first checking the halo’s merger history around $z_{\text{bar}}$, i.e., within the nearest two time snapshots before and after $z_{\text{bar}}$. If there was a merger event that occurred around $z_{\text{bar}}$, this bar is then defined to be associated with a merger. Otherwise, we inspect the three orthographic views of the distribution of the stellar particles within a radius 50 times greater than a single barred galaxy’s half-stellar radius, $r_{50}$, in the same time ranges. If many other galaxy particles are located within the sphere of radius $50r_{50}$ around a barred galaxy, and this bar galaxy also exhibits features of interaction, i.e., a disturbed stellar distribution, we define this bar to be associated with a flyby event. The rest of the galaxy bars are classified as “secular evolution.”

Table 1 lists the frequency of each process in the two simulations. In Illustris-1, 48.2% and 40.9% of the bars are associated with merge and flyby events, respectively, and the remaining 10.9% of bars result from secular evolution. These fractions basically agree with those found by Peschken & Lokas (2019), despite the slight crudeness of our procedure. In TNG100, the fractions of merge, flyby, and secular events are 57.3%, 17.0%, and 25.7%, respectively. We further explore the origin of bars in disk galaxies that are more/less massive than $M_*$ = $10^{10.83}M_\odot$, i.e., 100,000 stellar particles, in TNG100. The corresponding frequencies are 54.6%, 15.1%, and 30.3% for relatively massive disk galaxies. Thus, these frequencies depend weakly on galaxy stellar mass in TNG100. The fraction of bars due to secular evolution in TNG100 is roughly triple that in Illustris-1, but the fraction of flyby-related bars decreases by a factor of $\sim 2.4$.

### 4. Impact of Gas Fraction, Star Formation, Black Holes, and Dark Matter Halos

Previous studies using idealized simulations and cosmological hydrodynamical simulations found that the gas component, star formation, feedback from supernovae and AGNs, and properties of dark matter halos play important roles in bar formation and evolution. Meanwhile, the star formation history and growth of supermassive black holes should be different between Illustris-1 and TNG100 due to the implemented different models, which would influence the bar formation in disk galaxies. We examine these factors in this section.
First, we explore the dependence of bar fraction on the gas content in disk galaxies. We measure the gas fraction within twice of the stellar half-mass radius $r_{50}$ as $f_{\text{gas}}(2r_{50}) = \frac{M_{\text{gas}}(<2r_{50}) + M_{\text{star}}(<2r_{50})}{M_{\text{star}}}$, where $M_{\text{gas}}(2r_{50})$ and $M_{\text{gas}}(2r_{50})$ are the mass of gas and star particles within this region, respectively. The top left panel in Figure 7 presents the bar fraction as a function of the gas fraction of disk galaxies at redshift $z = 0$ in the two simulations, while the top middle panel plots the number of galaxies in different bins of gas fraction. Figure 7 indicates that the bar fraction generally increases as the gas fraction decreases. Namely, bars prefer to appear in gas-poor galaxies. The bar fraction grows especially rapidly when $f_{\text{gas}}(z = 0)$ falls below 0.25–0.30. This trend holds for both simulations and is consistent with the analysis of Illustris-1 in Peschken & Łokas (2019) and that of TNG100 in Rosas-Guevara et al. (2020). Note that the definition of the gas fraction in Rossas-Guevara et al. (2020) is somewhat different from that in our work. This result has been actually inferred from the idealized simulations showing that a higher gas fraction will hinder the presence of bars (e.g., Athanassoula et al. 2013). On the other hand, we should be cautious when comparing our results with those of Athanassoula et al. (2013), as the value of their gas fraction was intentionally placed in the initial conditions of their isolated simulations, rather than occurring as a naturally evolved result.

The distribution of bar frequency over gas fraction in TNG100 differs from that in Illustris-1 in two aspects. First, the top middle panel of Figure 7 shows that the gas fraction of disk galaxies in TNG100 is generally lower than that of disk galaxies in Illustris-1 at redshift $z = 0$. About ~67% of the disk galaxies have a gas fraction lower than 0.054 at $z = 0$ in TNG100. In contrast, only ~25% of the disk galaxies in Illustris-1 have $f_{\text{gas}} < 0.054$. This feature is consistent with the statistics on gas fraction reported in Kauffmann et al. (2019). Given the trend mentioned above, the much lower gas fraction in TNG100 than Illustris-1 could be responsible for the higher bar fraction in TNG100. Second, we see that even in the same gas fraction bin, the bar fraction of disk galaxies in TNG100 is much higher than in Illustris-1. This suggests that, in addition to gas fraction, there are some other factors that could promote the bar formation in TNG100.

As shown in Figure 3, the bar fractions as a function of stellar mass are different in the two simulations: TNG100 has much higher fractions than Illustris-1 in the stellar mass range $\sim 10^{10.5} - 11.2 M_\odot$. This difference may be related to the distribution of the gas fraction in different mass bins. The top right panel of Figure 7 shows the median gas fraction as a function of stellar mass in the two simulations, respectively. In Illustris-1, the median gas fraction decreases gradually from ~40% at $M_\star = 10^{10.5} M_\odot$ to ~10% at $M_\star = 10^{11.1} M_\odot$ and drops below ~10% for $M_\star > 10^{11.1} M_\odot$, which is the reverse of the change in bar fraction. In TNG100, the median gas fraction is lower than 10% in all of the mass bins, with relatively higher fractions at the high-mass end and larger scatters at the low-mass end. The difference of bar fraction in different mass bins between the two simulations is consistent with the effect of gas fraction on bar presence. As Figure 3 includes galaxies with $10^{10.2} M_\odot < M_\star < 10^{10.5} M_\odot$, we also show their median gas fractions in the top right panel of Figure 7. In Illustris-1, the gas fraction in systems less massive than $10^{10.5} M_\odot$ also decreases

4.1. Gas Fraction

First, we explore the dependence of bar fraction on the gas content in disk galaxies. We measure the gas fraction within twice of the stellar half-mass radius $r_{50}$ as $f_{\text{gas}}(2r_{50}) = \frac{M_{\text{gas}}(<2r_{50}) + M_{\text{star}}(<2r_{50})}{M_{\text{star}}}$, where $M_{\text{gas}}(2r_{50})$ and $M_{\text{gas}}(2r_{50})$ are the mass of gas and star particles within this region, respectively. The top left panel in Figure 7 presents the bar fraction as a function of the gas fraction of disk galaxies at redshift $z = 0$ in the two simulations, while the top middle panel plots the number of galaxies in different bins of gas fraction. Figure 7 indicates that the bar fraction generally increases as the gas fraction decreases. Namely, bars prefer to appear in gas-poor galaxies. The bar fraction grows especially rapidly when $f_{\text{gas}}(z = 0)$ falls below 0.25–0.30. This trend holds for both simulations and is consistent with the analysis of Illustris-1 in Peschken & Łokas (2019) and that of TNG100 in Rosas-Guevara et al. (2020). Note that the definition of the gas fraction in Rosas-Guevara et al. (2020) is somewhat different from that in our work. This result has been actually inferred from the idealized simulations showing that a higher gas fraction will hinder the presence of bars (e.g., Athanassoula et al. 2013). On the other hand, we should be cautious when comparing our results with those of Athanassoula et al. (2013), as the value of their gas fraction was intentionally placed in the initial conditions of their isolated simulations, rather than occurring as a naturally evolved result.

The distribution of bar frequency over gas fraction in TNG100 differs from that in Illustris-1 in two aspects. First, the top middle panel of Figure 7 shows that the gas fraction of disk galaxies in TNG100 is generally lower than that of disk galaxies in Illustris-1 at redshift $z = 0$. About ~67% of the disk galaxies have a gas fraction lower than 0.054 at $z = 0$ in TNG100. In contrast, only ~25% of the disk galaxies in Illustris-1 have $f_{\text{gas}} < 0.054$. This feature is consistent with the statistics on gas fraction reported in Kauffmann et al. (2019). Given the trend mentioned above, the much lower gas fraction in TNG100 than Illustris-1 could be responsible for the higher bar fraction in TNG100. Second, we see that even in the same gas fraction bin, the bar fraction of disk galaxies in TNG100 is much higher than in Illustris-1. This suggests that, in addition to gas fraction, there are some other factors that could promote the bar formation in TNG100.

As shown in Figure 3, the bar fractions as a function of stellar mass are different in the two simulations: TNG100 has much higher fractions than Illustris-1 in the stellar mass range $\sim 10^{10.5} - 11.2 M_\odot$. This difference may be related to the distribution of the gas fraction in different mass bins. The top right panel of Figure 7 shows the median gas fraction as a function of stellar mass in the two simulations, respectively. In Illustris-1, the median gas fraction decreases gradually from ~40% at $M_\star = 10^{10.5} M_\odot$ to ~10% at $M_\star = 10^{11.1} M_\odot$ and drops below ~10% for $M_\star > 10^{11.1} M_\odot$, which is the reverse of the change in bar fraction. In TNG100, the median gas fraction is lower than 10% in all of the mass bins, with relatively higher fractions at the high-mass end and larger scatters at the low-mass end. The difference of bar fraction in different mass bins between the two simulations is consistent with the effect of gas fraction on bar presence. As Figure 3 includes galaxies with $10^{10.2} M_\odot < M_\star < 10^{10.5} M_\odot$, we also show their median gas fractions in the top right panel of Figure 7. In Illustris-1, the gas fraction in systems less massive than $10^{10.5} M_\odot$ also decreases
with increasing stellar mass, which is in agreement with the trend at $M_\ast > 10^{10.5}M_\odot$. A similar trend is observed at the low-mass end of TNG100 but with larger scatters. As bars are located in the central region of galaxies, their formation and evolution may also correlate with the gas fraction in the inner-most regions of galaxies. We measure the gas fraction within $r_{50}$, $f_{\text{gas}}(r_{50})$ and show the dependence of bar fraction and stellar mass on it, as well as the distribution of galaxies in the bottom panels of Figure 7. Bars are found in galaxies with $f_{\text{gas}}(r_{50}) < 0.3$, and the bar fraction decreases with increasing $f_{\text{gas}}(r_{50})$. Gas fractions within $r_{50}$ are lower than $f_{\text{gas}}(2r_{50})$ in both simulations, but the drop in TNG100 is more significant, which can be displayed by the scatter plot of $f_{\text{gas}}(2r_{50})$ against $f_{\text{gas}}(r_{50})$ in Figure 8. This feature is likely caused by the more effective feedback from star formation and AGN accretion in the TNG simulations (Pillepich et al. 2018b; Weinberger et al. 2018), which would expel gas more efficiently from the central region. Meanwhile, being more gas-poor in the central region could make the disk galaxies in TNG more favorable for forming bars.

In Figure 9, we plot the bar fraction and gas fraction as functions of the total baryonic mass, i.e., sum of gases and stars, and of the total mass of the baryonic and dark matter, within $2r_{50}$ at $z = 0$, respectively. The trends are generally similar to the functions of stellar mass shown in Figure 7. Galaxies with baryonic (total) mass less than $\sim 10^{10.3}(10^{12.4})M_\odot$ in Illustris-1 have much higher gas fractions and lower bar fractions than those in TNG100. However, the gas fraction in Illustris-1 increases with increasing baryonic (total) mass at $M_{\text{baryon}} < 10^{11.0}M_\odot (M_{\text{total}} < 10^{12.0}M_\odot)$. This pattern is mainly due to the fact that we have designated a threshold of stellar mass for sample selection. The bins of galaxies with small baryonic/total mass would be biased by galaxies with low gas fractions. To demonstrate that, Figure 9 gives the results of two different thresholds of stellar mass. For instance, when the threshold decreases from $M_\ast > 10^{10.5}M_\odot$ to $M_\ast > 10^{10.25}M_\odot$, the median gas fraction of galaxies in the range $10^{10.5}M_\odot < M_{\text{baryon}} < 10^{11.2}M_\odot$ is enhanced. This is because a lower threshold would include many gas-rich galaxies with stellar masses of $10^{10.25}M_\odot < M_\ast < 10^{10.5}M_\odot$ in the sample.

To further probe the impact of gas on bar formation, we trace the evolution of the gas fraction in disk galaxies toward high redshifts. For galaxies that developed bars at $z = 0$, Figure 10 shows the bar formation redshift against their gas fraction $f_{\text{gas}}(2r_{50})$ at $z = 2$, since that is when most of the bars appear. We can see that galaxies with a relatively higher $f_{\text{gas}}(2r_{50})$ at $z = 2$ will form a bar at relatively lower redshifts, and vice versa. For those galaxies with $f_{\text{gas}}(2r_{50}) > 0.5$ at $z = 2$,
the median redshift of the bar formation is lower than 0.4 and depends weakly on the gas fraction in both simulations, shown in the middle panel. But the median redshift of the bar fraction increases from $z \sim 0.4-0.5$ for $0.3 < f_{\text{gas}}(2r_{50}) < 0.4$ to $z \sim 0.75-0.80$ for $0.0 < f_{\text{gas}}(2r_{50}) < 0.1$ at $z = 2$. This trend agrees with Athanassoula et al. (2013). We also measure the gas fraction of barred galaxies at their bar formation redshifts and present the results in the bottom plot of Figure 10. For most of the barred galaxies, the gas fractions $f_{\text{gas}}(2r_{50})$ were lower than 0.4 at the epoch when their bars could be identified by our algorithm. This feature would be helpful in explaining the enhanced bar fractions in galaxies with $f_{\text{gas}}(2r_{50}) < 0.3-0.4$ at $z = 0$, as shown in Figure 7.

The top panel of Figure 11 shows the evolutionary history of the median gas fraction for disk galaxies in TNG100 and Illustris-1. The solid (dashed–dotted) lines indicate galaxies that have (do not have) a bar at $z = 0$. The upper and lower bars represent the 25th and 75th percentiles in each bin for each category. The red and orange colors represent galaxy samples in TNG100. The blue and cyan colors represent samples in Illustris-1. Bottom panel: the ratio of the median gas fraction of galaxies in four categories over that of TNG100 barred galaxies' data.
fraction of TNG100 barred galaxies is small, resulting in fluctuations in the ratio plot.

4.2. Star Formation

An important physical process related to the gas component is star formation. Also, feedback from massive stars and supernovae can affect the distribution of gas and stars and influence bar formation. Previous studies have investigated the link between star formation activity and bar formation. However, whether bars can suppress or enhance star formation activity is still a controversial issue. Nevertheless, it has been shown that more effective stellar feedback can aid in building stronger and longer bars (e.g., Zana et al. 2019). We now explore the star formation activity in our samples. Figure 12 presents the evolution of the SFR in the simulated disk galaxies with $M_*>10^{10.5}M_\odot$ at $z=0$. In both simulations, SFR generally increases from $z=3.0$ to $z\sim1.5$ and then declines as redshift decreases, where barred galaxies fall faster than unbarred galaxies. The SFRs of the barred and unbarred galaxies in Illustris-1 are generally higher than their counterparts in TNG100. The barred galaxies in Illustris-1 have much higher SFRs than the other three categories at $z\geq0.5$, which may be because the barred galaxies in Illustris-1 are more massive, as shown in Figure 3. The SFRs of the barred galaxies in TNG100 are higher than those of the unbarred galaxies in Illustris-1 before $z=1.5$, but the situation has reversed since then. Above $z\sim0.3$–0.5, the star formation rates of the barred galaxies are higher than those of the unbarred galaxies in both simulations. The situation is reversed below $z\sim0.3$–0.5, which is close to the median redshift of bar formation. Rosas-Guevara et al. (2020) reported similar results for the TNG100 disk galaxies in the stellar mass range $10^{10.4}$–$11M_\odot$, and they argue that the presence of the bars can promote quenching in the galaxy central region.

The middle panel of Figure 12 shows the evolution of specific star formation rate (sSFR) in the disk galaxy samples. At redshifts higher than 0.7, the sSFRs are almost the same for all subsamples. After $z=0.7$, when most of the bars began to appear, the sSFR in the barred galaxies drops more rapidly than in the unbarred galaxies. At redshifts lower than 0.5, the unbarred and barred galaxies in Illustris-1 have the highest and lowest median sSFRs, respectively. Multiple factors may account for the drop of sSFR in the barred galaxies after bar formation. The formation of bars could stabilize the gas disk and inhibit star formation, as suggested by Khoperskov et al. (2018). Alternatively, it is also likely that the progenitors of barred galaxies, which have higher star formation rates than unbarred galaxies, have consumed more gas before the bar formation (Kim et al. 2017). A detail investigation is needed to justify this issue, which, however, is outside of the scope of this work.

The bottom panel of Figure 12 shows the depletion time of gas, which is denoted as $\tau_g=M_{gas}/SFR$ and is the inverse to the star formation efficiency (SFE) of disk galaxies. Barred galaxies have shorter gas depletion times, i.e., higher SFEs, than unbarred galaxies at $z>0.2$ in TNG100 and at $z>0.5$ in Illustris-1. At $z\lesssim1.5$–2.0, the star formation efficiency of galaxies in TNG100 is lower than that in Illustris-1. At $z>2.0$, the SFE in TNG100 is moderately higher than Illustris-1. For these massive disk galaxies with $M_*>10^{10.5}M_\odot$ at $z=0$, the suppression of star formation in TNG100 is probably more efficient than in Illustris-1 at $z\lesssim2$ but less efficient at $z>2$. 

Figure 12. The top, middle, and bottom panels show the evolution of the median star formation rate, specific star formation rate, and gas depletion time in disk galaxies, respectively. The meaning of the lines and bars is the same as in Figure 11.
TNG100 is higher than that in Illustris-1 within the range $z < 1.5$. Before that, the black holes in the Illustris-1 barred galaxies were more massive. For TNG100, the black hole masses in the barred galaxies are slightly higher than those of the unbarred ones at $z < 0.7$, and this mass gap is moderate at higher redshifts. The median SMBH mass in the barred galaxies has been much higher than that of the unbarred galaxies since $z = 3.0$ in the Illustris-1 simulation.

The bottom panel of Figure 13 presents the mass accretion rate of SMBHs in disk galaxies. In the redshift range $0.5 < z < 2.5$, the TNG100 barred galaxies have the highest median accretion rate, followed by the TNG100 unbarred galaxies, the Illustris-1 barred galaxies, and the Illustris-1 unbarred galaxies in decreasing order. At lower redshifts, i.e., $z < 0.5$, the median accretion rates in the TNG100 barred and unbarred galaxies become comparable, declining sharply with time, and are lower than those in the Illustris-1 barred galaxies.

The methodologies for AGN feedback in the two simulations are different in several aspects (Weinberger et al. 2017). To further explore the differences of AGN feedback in galaxies, we track the energy released by SMBH accretion in the two simulations. The bottom panel in Figure 14 gives the rate of thermal energy injected by SMBHs, $\dot{E}_{\text{BH,thermal}}$. At $z > 2.0$, there is more thermal energy injected into the gas component in Illustris-1 than that in TNG100, and the situation is reversed at $z < 2.0$. In TNG100, $\dot{E}_{\text{BH,thermal}}$ in the barred galaxies is slightly higher than that in the unbarred galaxies at $z > 0.5$, i.e., the median redshift of bar formation. The median $\dot{E}_{\text{BH,thermal}}$ in the Illustris-1 barred galaxies is lower than that in the TNG barred galaxies by a factor of $\sim 40\% - 100\%$ but is higher than the Illustris-1 unbarred galaxies by a factor of $3 - 4$ at $z < 2$. Weinberger et al. (2018) illustrate that a large amount of the thermal AGN feedback energy would be radiated away immediately by dense star-forming gas around SMBHs. Only the remaining amount of injected thermal energy would actually regulate the gas component.

In the TNG simulations, the AGN feedback is partially injected into the gas via the kinetic mode, which has not been implemented in Illustris-1. The top panel in Figure 14 shows the rate of kinetic energy released by black holes, denoted as $\dot{E}_{\text{BH,kin}}$, in TNG100. $\dot{E}_{\text{BH,kin}}$ has been increasing rapidly since $z \sim 1.5$. The median rate grows from $\sim 10^{37}\text{erg s}^{-1}$ at $z = 1.5$ to $\sim 10^{42}\text{erg s}^{-1}$ at $z = 0$. The median rate in the barred galaxies is higher than in the unbarred galaxies by $\sim 70\%$ at $z > 0.2$. Combining the thermal and kinetic channels, massive disk galaxies in TNG100 experience stronger AGN feedback than in Illustris-1 at $z \lesssim 2$. The evolution of AGN feedback energy in the two simulations is coincident with the evolution of star formation rate and efficiency presented in the last subsection. At $z \lesssim 2$, the SFRs and SFEs in the TNG100 samples drop more rapidly than those in Illustris-1. This coincidence agrees with the results of TNG300 in Weinberger et al. (2018). Note that our galaxy samples have $M_\odot > 10^{10.5}M_\odot$ at $z = 0$. For galaxies with similar masses in the TNG300 simulation, Weinberger et al. (2018) found that their star formation rates have been significantly reduced since $z \sim 2$, when the kinetic AGN feedback became the dominant feedback energy channel.

4.3. Growth of Supermassive Black Holes and Feedback

In the previous subsections, we concluded that gas fraction is strongly correlated with the development of bars. In addition to stellar processes, i.e., star formation and feedback, the growth of supermassive black holes and AGN feedback may also play an important role in regulating the gas component and influencing the growth of bars. We trace the evolution of black hole mass in each disk galaxy with $M_\bullet > 10^{10.5}M_\odot$. Figure 13 shows that the barred galaxies in the two simulations have had similar black hole masses since $z < 1.5$. Before that, the black holes in the Illustris-1 barred galaxies were more massive. For TNG100, the black hole masses in the barred galaxies are slightly higher than those of the unbarred ones at $z < 0.7$, and this mass gap is moderate at higher redshifts. The median SMBH mass in the barred galaxies has been much higher than that of the unbarred galaxies since $z = 3.0$ in the Illustris-1 simulation.

In the TNG simulations, the AGN feedback is partially injected into the gas via the kinetic mode, which has not been implemented in Illustris-1. The top panel in Figure 14 shows the rate of kinetic energy released by black holes, denoted as $\dot{E}_{\text{BH,kin}}$, in TNG100. $\dot{E}_{\text{BH,kin}}$ has been increasing rapidly since $z \sim 1.5$. The median rate grows from $\sim 10^{37}\text{erg s}^{-1}$ at $z = 1.5$ to $\sim 10^{42}\text{erg s}^{-1}$ at $z = 0$. The median rate in the barred galaxies is higher than in the unbarred galaxies by $\sim 70\%$ at $z > 0.2$. Combining the thermal and kinetic channels, massive disk galaxies in TNG100 experience stronger AGN feedback than in Illustris-1 at $z \lesssim 2$. The evolution of AGN feedback energy in the two simulations is coincident with the evolution of star formation rate and efficiency presented in the last subsection. At $z \lesssim 2$, the SFRs and SFEs in the TNG100 samples drop more rapidly than those in Illustris-1. This coincidence agrees with the results of TNG300 in Weinberger et al. (2018). Note that our galaxy samples have $M_\odot > 10^{10.5}M_\odot$ at $z = 0$. For galaxies with similar masses in the TNG300 simulation, Weinberger et al. (2018) found that their star formation rates have been significantly reduced since $z \sim 2$, when the kinetic AGN feedback became the dominant feedback energy channel.
One particularly important question is that how star formation, stellar feedback, black hole growth, and AGN feedback have influenced bar formation and led to the different properties of the bars in these two simulations. These influences may have been exerted via many different avenues. One aspect that is closely related to our investigation is the disk gas fraction. More specifically, lowering the gas fraction in disks, either by more effective expulsion with stronger feedback or more consumption by a relatively higher star formation rate, or by both, could create more favorable conditions for bar formation. As for the TNG100 and Illustris-1 simulations we are concerned with here, the relatively higher star formation efficiency and, hence, more effective stellar feedback at \( z > 2 \) in TNG100 may result in proto-disks with lower gas fraction than those in Illustris-1 at high \( z \), as shown in Figure 11. Then, at \( z \leq 2 \), the stronger AGN feedback (Figure 14), in combination with stellar feedback, helps the massive disk galaxies in TNG100 to drop their gas fractions more rapidly than the disk galaxies in Illustris-1.

AGN feedback may have served as the primary factor driving the gas fraction of galaxies in TNG100 to decline more rapidly at \( z < 2 \). We illustrate this point by Figure 15. From \( z = 3 \) to \( z = 0 \), the median gas fraction drops by factors of 3, 20, 25, and 160 for Illustris-1 unbarred, Illustris-1 barred, TNG100 unbarred, and TNG100 barred disk galaxies with \( \epsilon = 0 \) and stellar masses of \( 10^{10.5} - 10^{10.9} M_\odot \), respectively. The fastest decline happens at \( z < 2 \), when the SFRs and SFEs in TNG100 are lower than those in Illustris-1, as shown in the left and middle panels. But the AGN feedback energy rate in TNG100 is higher than in Illustris-1, as is presented in the right panels. Only the thermal feedback energy is shown in this plot; however, we remind the reader that TNG100 also implements kinetic AGN feedback and that Illustris-1 does not. For more massive galaxies with stellar masses of \( 10^{11.0} - 10^{11.9} M_\odot \), the decline rates of the gas fractions in the two simulations are much closer; although, the differences in SFR and SFE between the two simulations are comparable to the differences in less massive galaxies. The differences in AGN feedback energy rate, however, are narrowed down with respect to the galaxies with lower stellar masses. In addition, as SMBHs sit at the center of galaxies, their feedback could have a relatively more significant effect on the gas fraction of the central region and could partly contribute to the relation between \( f_{\text{gas}}(2 + r_{50}) \) and \( f_{\text{gas}}(r_{50}) \), as shown in Figure 8.

4.4. Properties of Host Dark Matter Halos

Isolated simulations show that the properties of dark matter halos have important effects on bar formation (e.g., Athanassoula & Misiriotis 2002; Athanassoula 2003). Here, we investigate the connection between halo properties and the presence and strength of the bars in our samples, focusing on the halo mass, concentration, and triaxiality of sub-halos. The top panel in Figure 16 traces the mass evolution of dark matter sub-halos. The masses of the sub-halos hosting the Illustris-1 unbarred galaxies and all of the TNG100 disk galaxies are similar. Host sub-halos of the barred galaxies in Illustris-1 are about two to three times more massive than other sub-halos hosting disk galaxies in the two simulations. This feature should result from the bars in Illustris-1 appearing in more massive galaxies, as suggested by Figure 3. In TNG100, the sub-halos of the barred galaxies are slightly more massive than those of the unbarred galaxies. The bottom panel in Figure 16 shows the masses of the host halos within \( R_{200} \), exhibiting a similar trend as the masses of the sub-halos, but the gap between the barred galaxies in Illustris-1 and in other samples is narrowed. At \( z = 0 \), the median halo mass within \( R_{200} \) is about \( 2 - 5 \times 10^{12} M_\odot \).

The top panel of Figure 17 presents the concentration parameter, \( c \), of the halos hosting disk galaxies in the two simulations. Except for the barred galaxies in Illustris-1, the median values of \( c \) for the dark matter halos are similar in both simulations. The barred galaxies in Illustris-1 have relatively lower values of \( c \) than others. This feature is also related to the halo mass. For each simulation, we divide the disk galaxies into two categories via a stellar mass threshold of \( 10^{11.0} M_\odot \). We show the concentration parameters of these two categories in the bottom panel of Figure 17. The concentration of halos hosting barred galaxies in Illustris-1 is close to that of halos hosting galaxies with stellar mass \( M_* > 10^{11.0} M_\odot \) in both simulations. For galaxies with the same stellar mass, the concentration of host halos is very similar between Illustris-1
and TNG100, and also in barred and unbarred galaxies. Therefore, halo concentration should have a negligible effect on the discrepancy of the bar frequency between the two simulations.

Figure 18 shows the evolution of the halo axial ratio in disk galaxies in the both simulations. Generally, all host halos in our disk galaxy sample have a considerably round shape at high redshifts. The axial ratios \( c/a \) and \( b/a \) are larger than 0.86 and 0.92, respectively, at \( z = 2 \) for most of the halos. All of the halos have been getting gradually rounder with decreasing redshift. There are barely any differences between the barred and unbarred galaxies in Illustris-1, except for slight scatters in the barred samples, which should be caused by the limited number of samples. Overall, the halos in TNG100 show stronger triaxiality than those in Illustris-1. Furthermore, the halos of the unbarred galaxies in TNG100 show slightly stronger triaxiality than those of the barred galaxies. Overall, halo shape should have a minor effect on the discrepancy of the bar frequency between TNG100 and Illustris-1.

5. Evolution of Bars in Matched Halos

The results described above give the statistical views of the bars in the TNG100 and Illustris-1 simulations, including the differences between the two simulations and related physical factors. Since the initial conditions are basically the same, this allows us to compare galaxies evolved from similar initial conditions and environments in the two simulations. This section examines the differences in the bar structure and related physical factors between the galaxies hosted by analog subhalos in the two simulations.

5.1. Halo Match Algorithm and Matched Galaxy Pairs

We apply the Lagrangian-region matching algorithm proposed by Lovell et al. (2014) to identify pairs of galaxies hosted by analog sub-halos across the two simulations. This algorithm first finds candidates of subhalo pairs by comparing their positions and then traces their particles back to the initial conditions to determine whether overlapping Lagrangian regions are matched or not. The initial density distribution and gravitational potentials of halo particles are used as key indicators in this algorithm.

We select all disk galaxies with more than 40,000 stellar particles from one simulation and try to match their counterparts in the other simulation. For disk galaxies with \( M_* > 10^{10.5} \) in TNG100, 813 out of 1269 are found to have counterparts in Illustris-1. Meanwhile, 748 out of 1232 disk galaxies with \( M_* > 10^{10.5} \) in Illustris-1 have analogs in TNG100. A total of 1079 matched pairs of galaxies is compiled by cross-checking. The morphology correlations of these galaxy pairs in the two simulations are listed in Table 2. We can see that most of the matched galaxy pairs have different morphological types at \( z = 0 \). Only a fraction of about 21% of the matched pairs have the same morphology. Moreover, for 331/813 of the disk galaxies in TNG100, their counterparts in Illustris-1 are non-disk galaxies. The corresponding fraction is 266/748 for the Illustris-1 disk galaxies. This result suggests that for an individual galaxy hosted in a similar halo environment, the differences in baryonic physics can lead to a significant discrepancy in galaxy properties. In the literature, differences in stellar and AGN feedback models and in the initial conditions have been found to lead to notable differences in the properties of simulated galaxies (e.g., Genel et al. 2019; Keller et al. 2019 and references therein).
5.2. Comparison of Analog Disk Galaxies

Next, we analyze the properties of galaxy pairs that are disk galaxies in both of the simulations, focusing on gas fraction, star formation rate, and SMBHs. We carry out controlled comparisons by dividing these pairs into four categories marked as bar–bar, bar–unbar, unbar–bar, and unbar–unbar. The tag before and after the dash in each category name indicates the morphologies in TNG100 and Illustris-1, respectively. The evolutions of the gas fraction, star formation rate, and SMBH mass accretion rate are shown in Figure 19. The SMBH mass accretion rate is used here to approximately indicate the strength of the AGN feedback. Illustris-1 includes thermal AGN feedback only, but TNG100 has implemented both kinetic and thermal AGN feedback, and the feedback energies injected by these two channels cannot be simply added together. As was shown in Section 4.3, the SMBH mass accretion rate can roughly characterize the relative strengths of AGN feedback. On the other hand, we should keep in mind that the kinetic AGN feedback energy may dominate in the massive disk galaxies of TNG100 at low $z$ (Weinberger et al. 2018).

Overall, the discrepancies in the gas fraction, star formation rate, and black hole mass accretion rate between galaxies in TNG100 and Illustris-1 are similar in the four categories. Namely, the galaxies in TNG100 basically have lower gas fractions, star formation rates, and higher black hole mass accretion rates at $z < 2.0$ in each category, except for the black hole mass accretion rates of the barred galaxies in Illustris-1, which are able to match or exceed their counterparts in TNG100 at redshift $z < 0.5$. Both the star formation and SMBH activity in Illustris-1 unbarred galaxies are relatively weak. These differences are consistent with the overall systematic differences shown in Section 4. We draw particular attention to the bar (TNG100)–unbar (Illustris-1) category, which has 243 pairs of galaxies and has contributed significantly to the discrepancy of the bar frequency between the two simulations. The star formation rates of the galaxies in this category compiled from both simulations are comparable at $z \geq 0.5$ and are relatively inefficient, while the growth of SMBH and AGN feedback in the TNG100 samples has been much stronger since $z = 2$. Hence, AGN feedback is likely a real game changer in this category.

Figure 16. Top panel: the median dark matter mass of the subhalo. Bottom panel: the median total mass within $R_{200}$ of the host halo, including dark matter, stellar, and gas.

Figure 17. Top panel: the median concentration parameter, $c$, of dark matter halo hosting disk galaxies in both simulations. The meaning of the bars is the same as in Figure 11. Bottom panel: the yellow and cyan lines indicate the concentration parameter of halos hosting disk galaxies with $M_\star < 10^{11} M_\odot$ and $M_\star < 10^{10.5} M_\odot$, respectively. The blue line is the concentration parameter of $z = 0$ barred galaxies in Illustris-1. The solid lines represent Illustris-1 halos, and the dashed lines represent TNG100 halos.
Illustris-1 at high redshifts and has been suppressed more effectively since \( z = 2 \). Coincidentally, the gas fraction in TNG100 decreases more significantly, and the black hole mass accretion rates in all of the TNG disk galaxies become relatively higher at \( z \lesssim 2 \). The bar–unbar category is a good example of these differences.

The similarities between each category on the divergence of the galaxy properties across the two simulations also suggest that the morphologies of individual galaxies are a result of the combination of environment and internal multiple baryonic physics and are often not predictable. The higher bar fraction in the TNG100 disk galaxies benefits from more favorable conditions for bar growth, such as the lower gas fraction in the disks, which may result from the combination of enhanced star formation and stellar feedback efficiency at high redshifts, as well as stronger AGN feedback at \( z < 2 \).

### 6. Summary and Discussions

In this work, we have carried out a comparison study on the bar structure in the simulations Illustris-1 and TNG100. Based on methods described in the literature, we identify 1269 and 1232 disk galaxies with stellar masses more massive than \( 10^{10.5} M_\odot \) in TNG100 and Illustris-1, respectively. By examining the bar structures in these galaxies, we find a much higher bar fraction in TNG100, and we further study the correlation between the bar structures and galaxy properties including the gas component, star formation, AGN feedback, and dark matter halo. We attempt to understand the underlying baryonic physics that may have led to the different bar frequencies in the two simulations. We summarize our major findings as follows:

1. At redshift \( z = 0 \), the overall bar fractions are 55% and 8.9% for galaxies with stellar mass \( M_* > 10^{10.5} M_\odot \) in TNG100 and Illustris-1, respectively, i.e., 698 and 110 barred galaxies. In TNG100, the bar fraction grows from \( \sim 30\% \) at \( M_* = 10^{10.5} M_\odot \) to \( \sim 50\% \) at \( M_* = 10^{10.75} M_\odot \) and stays flat to around \( M_* = 10^{11.2} M_\odot \). In the stellar mass range \( M_* = 10^{10.66 - 11.25} M_\odot \), the bar fraction in TNG100 agrees well with the results of local survey \( S^4G \) (Díaz-García et al. 2016). In Illustris-1, the bar fraction grows from \( \sim 0\% \) at \( M_* = 10^{10.5} M_\odot \) to \( \sim 10\% \) at \( M_* = 10^{11.9} M_\odot \) and then to \( \sim 30\% - 40\% \) for \( M_* > 10^{11.5} M_\odot \). In Illustris-1, 48.2%, 40.9%, and 10.9% of the bars are associated with mergers, flybys, and secular evolution, respectively. The corresponding fractions in TNG100 are 57.3%, 17.0%, and 25.7%, respectively. The median redshifts of bar formation are \( z \sim 0.4 - 0.5 \) in TNG100 and \( z \sim 0.25 \) in Illustris-1.

2. In both simulations, bars form much more easily in galaxies with less gas in the disk. Namely, the bar fraction increases as the gas fraction decreases. At \( z = 0 \), the disk galaxies in TNG100 generally have much lower gas fractions than those in Illustris-1. This systematic discrepancy can be traced back to redshifts as high as \( z \sim 3 \). Moreover, if \( z = 0 \) barred galaxy has a higher gas fraction at high redshifts, it will tend to form bars later, which holds for both simulations. For most of the barred galaxies, their disk gas fractions were lower than 0.4 at the time their bars were just formed.

3. The star formation efficiency in TNG100 disk galaxies is higher than that in Illustris-1 at \( z > 1.5 - 2.0 \), but the
situation is reversed thereafter. The thermal AGN feedback energy injected into disk galaxies in TNG100 is lower than in Illustris-1 at $z > 2$, however, becomes higher at $z \lesssim 2$, when the gas fraction in TNG100 disk galaxies drops more significantly than that in Illustris-1 disk galaxies. In addition, the kinetic feedback in TNG100 increases rapidly at $z < 1.5$, which is not implemented in Illustris-1. In each of the two simulations, barred galaxies have relatively higher star formation rates and efficiencies than unbarred galaxies before the median redshift of bar formation. Once bars have formed, however, the star formation rates and efficiencies in barred galaxies decline more significantly. Also, the AGN feedback in the barred galaxies is enhanced with respect to the unbarred galaxies in both simulations.

4. By and large, the properties of halos hosting disk galaxies are found to be comparable in the two simulations and have little contribution to the discrepancy of bar frequency. The masses of host dark matter halos of barred galaxies in TNG100 are similar to those of the unbarred galaxies in TNG100 and Illustris-1, but they are less massive than those of the barred galaxies in Illustris-1. This is mainly because that the latter have higher stellar masses. There is little difference between the two simulations on the concentration of halos hosting disk galaxies. All of these halos in the two simulations are significantly rounder. There is only a slight difference in halo shape between the two simulations, and between the barred and unbarred galaxies.

5. A large fraction of the galaxy pairs that are hosted by analog halos, i.e., that have similar initial conditions and evolution environments, across the two simulations can have strikingly different morphologies at $z = 0$. The morphologies of individual galaxies are subject to the combined effects of environment and internal baryonic physics and are often not predictable. Based on the morphological types in TNG100 and Illustris-1, the matched galaxy pairs are divided into four sub categories: bar–bar, bar–unbar, unbar–bar, and unbar–unbar. We find that the differences in star formation rate and AGN feedback between samples in each category are similar to the overall difference between TNG100 and Illustris-1. The bar (TNG100)–unbar (Illustris-1) category, which contributes significantly to the discrepancy in the bar fraction, shows a clear difference in AGN feedback between the two simulations.

Our results concerning the bar structure in TNG100 and Illustris-1, including the bar fraction and formation times, agree with those of the previous investigations reported in Peschken & Lokas (2019) and Rosas-Guevara et al. (2020). We have a larger sample size than Rosas-Guevara et al. (2020), as we studied samples over a wider range of stellar masses within galaxies and used a different sample selection method. The star formation rate in barred galaxies is found to decline more significantly than that in unbarred galaxies after bar formation, which also agrees with Rosas-Guevara et al. (2020) and previous observational studies (e.g., Gavazzi et al. 2015). However, this should not be taken as direct evidence of bar quenching, considering that the star formation rate in barred galaxies is higher than in unbarred galaxies before bar formation. The trend that bars are more common in more massive and gas-poor galaxies is consistent with the findings of Peschken & Lokas (2019) and Rosas-Guevara et al. (2020). Furthermore, our result that a high gas fraction will suppress the growth of the bar agrees well with the results of idealized isolated simulations (e.g., Berentzen et al. 2004; Bournaud et al. 2005; Berentzen et al. 2007; Athanassoula et al. 2013).

The trend that massive and gas-poor disk galaxies are more favorable hosts for bars is in line with findings of many observations (e.g., Masters et al. 2011; Cheung et al. 2013; Gavazzi et al. 2015; Cervantes Sodi 2017; Newham et al. 2020). However, we note that there is a divergence of interpretations on this point between different observations. Some studies imply the opposite picture (e.g., Barazza et al. 2008; Nair & Abraham 2010). More recently, Erwin (2018) reported that the bar frequency peaks at $M_\star = 10^{9.7} M_\odot$ and shows barely any dependence on gas content, using samples of
the Spitzer Survey of Stellar Structure in Galaxies. On the other hand, other factors, including halo properties, seem to have minor contributions to the discrepancy in the overall bar fraction of the two simulations. This is because these factors are statistically similar for disk galaxies with similar stellar masses across the two simulations. This is not surprising, since the initial conditions are quite similar in these two simulations.

However, this result does not indicate that halos are not important for bar growth in individual galaxies.

Our investigation indicates that the much higher bar fraction in the TNG100 simulation probably arises from the joint effects of multiple physics that more heavily favor bar formation. One factor, in particular, could be the lower gas fraction in massive disk galaxies, which may result from the more effective stellar
and AGN feedback in TNG. Massive disk galaxies in TNG100 have relatively higher star formation efficiencies at $z > 2$, which could lead to lower gas fractions than those in Illustris-1 at $z = 2$–3. At $z \lesssim 2$, stronger AGN feedback through both thermal and kinetic channels, in combination with stellar feedback, will help the gas fractions of the TNG100 disk galaxies fall below 0.4 more rapidly than their counterparts in Illustris-1. At $z \lesssim 2$, AGN feedback is probably the primary factor that causes the gas fraction of massive disk galaxies in TNG100 to decrease dramatically, given the evolution history of star formation efficiency and AGN feedback energy in disk galaxies with stellar masses more massive than $10^{10.5} M_\odot$ in these two simulations. Actually, Weinberger et al. (2018) show that, for galaxies with $z = 0$ and stellar mass $M_\ast > 10^{10.5} M_\odot$ in TNG300, whenever the AGN feedback (especially in the kinetic channel) became a dominant feedback channel at redshift $z \sim 2$, the star formation rate in those galaxies was suppressed significantly.

In addition to lowering the gas fraction, the more effective stellar and AGN feedback models in TNG100 may also help increase the bar fraction by other means, such as changing the galaxy size, the bulge-to-disk ratio, and the angular momentum of the gas and stellar particles, which make the disk galaxies in TNG100 more favorable for bar growth. A careful investigation of the stellar properties and dynamical evolution of the bars in the two simulations, as has been done for previous isolated and cosmologically zoomed-in simulations (e.g., Athanassoula & Misiriotis 2002; Bonoli et al. 2016; Zana et al. 2019), is urged to be conducted in the future to obtain a more direct view of the roles of stellar and AGN feedback on bar structure in simulations of galaxy formation within a cosmic volume.

Last but not least, our work indicates that the bar frequency in TNG100 agrees well with the observational result obtained from the Spitzer Survey of Stellar Structure in Galaxies. The TNG models have made a substantial improvement upon Illustris-1, and our work offers a complement to the literature, showing that the TNG models can overcome the main shortcomings of Illustris-1 that are in conflict with observations (e.g., Pillepich et al. 2018b; Nelson et al. 2019). On the other hand, both Illustris-1 and TNG100 reproduce the $M_{\text{BH}} - M_\ast$ correlation, but it is tighter than the observations, especially in TNG100. This is because the simulated galaxies host overly massive black holes (Li et al. 2019). This needs further improvement and may change the bar fraction somewhat. Meanwhile, we note that the bar fraction in the EAGLE simulation also agrees with the observations (Algory et al. 2017); and yet, EAGLE adopts quite a different model of stellar and AGN feedback compared to the TNG model. For instance, stellar and AGN feedback are injected only in thermal channels in EAGLE (Schaye et al. 2015). Consequently, we still need to be very cautious about the agreement of the bar fractions between the simulations and observations. More reliable results from observations are expected to significantly aid in the proper interpretation and application of the simulations results, ensuring that sub-grid physics are implemented appropriately in different simulations and converge with each other.

We would like to thank the anonymous referee for the helpful comments and suggestions, which greatly improved the manuscript. This work is supported by the Key Program of the National Natural Science Foundation of China (NSFC) through grant No. 11733010. W.S.Z. is supported by NSFC grant No. 11673077. W.Y. is supported by NSFC grant No. 11803095 and the Fundamental Research Funds for the Central Universities. F.L.L. is supported by NSFC grant No. 11851301.

References

Ade, P. A. R., Aghanim, N., Arnaud, M., et al. 2016, A&A, 594, A13
Aguerri, J. A., Méndez-Abreu, J., & Corsini, E. M. 2009, A&A, 495, 491
Agnoli, D. G., Navarro, J. F., Abadi, M. G., et al. 2017, MNRAS, 469, 1054
Alonso, M. S., Coldwell, G., & Lambas, D. G. 2013, A&A, 549, A141
Athanassoula, E. 2002, ApJL, 569, L83
Athanassoula, E. 2003, MNRAS, 341, 1179
Athanassoula, E., Machado, R. E. G., & Rodionov, S. A. 2013, MNRAS, 429, 1949
Athanassoula, E., & Misiriotis, A. 2002, MNRAS, 330, 2603
Bournaud, F., Combes, F., & Semelin, B. 2005, MNRAS, 364, L18
Bournaud, F., Combes, F., & Semelin, B. 2005, MNRAS, 364, L18
Buta, R. J., Sheth, K., Athanassoula, E., et al. 2015, ApJS, 217, 32
Cervantes Sodi, B. 2017, APL, 835, 80
Cheung, E., Athanassoula, E., Masters, K. L., et al. 2013, ApJ, 779, 162
Cisternas, M., Gadotti, D. A., Knapen, J. H., et al. 2011, ApJ, 776, 50
Debattista, V. P., & Sellwood, J. A. 2000, ApJ, 543, 704
Díaz-García, S., Salo, H., Laurikainen, E., & Herrera-Endoqui, M. 2016, A&A, 587, A160
Erwin, P. 2018, MNRAS, 474, 5372
Gavazzi, G., Consolandi, G., Dotti, M., et al. 2015, A&A, 580, A116
Genel, S., Bryan, G. L., Springel, V., et al. 2019, ApJ, 871, 21
Genel, S., Fall, S. M., Hernquist, L., et al. 2015, ApJL, 804, L40
Goz, D., Monaco, P., Murante, G., & Curir, A. 2015, MNRAS, 447, 1774
Hinshaw, G., Larson, D., Komatsu, E., et al. 2013, ApJS, 208, 19
Kaufmann, G., Nelson, D., Borthakur, S., et al. 2019, MNRAS, 486, 4686
Keller, B. W., Wadsley, J. W., Wang, L., & Kruijssen, J. M. D. 2019, MNRAS, 482, 2244
Khoperskov, S., Haywood, M., Di Matteo, P., Lehner, M. D., & Combes, F. 2018, A&A, 609, A60
Kim, E., Hwang, H. S., Chung, H., et al. 2017, ApJ, 845, 93
Kormendy, J. 2013, in Secular Evolution in Disk Galaxies, ed. J. Falcón-Barroso & J. H. Knapen (Cambridge: Cambridge Univ. Press), 1
Kraljic, K., Bournaud, F., & Martig, M. 2012, ApJ, 757, 60
Li, Y., Habouzit, M., Genel, S., et al. 2019, arXiv:1910.00017
Lin, L., Li, C., He, Y., Xiao, T., & Wang, E. 2017, ApJ, 838, 105
Lovell, M. R., Frenk, C. S., Eke, V. R., et al. 2014, MNRAS, 439, 300
Masters, K. L., Nichol, R. C., Hoyle, B., et al. 2011, MNRAS, 411, 2026
Melvin, T., Masters, K., Lintott, C., et al. 2014, MNRAS, 438, 2882
Nair, P. B., & Abraham, R. G. 2010, ApJS, 186, 427
Nelson, D., Pillepich, A., Springel, V., et al. 2018, MNRAS, 475, 624
Nelson, D., Springel, V., Pillepich, A., et al. 2019, ComAC, 6, 2
Newmann, L., Hess, K. M., Masters, K. L., et al. 2020, MNRAS, 492, 4697
Ostriker, J. P., & Peebles, P. J. E. 1973, ApJ, 186, 467
Peschken, N., & Lokas, E. L. 2019, MNRAS, 483, 2721
Pillepich, A., Nelson, D., & Hernquist, L. 2018a, ApJL, 855, 684
Pillepich, A., Springel, V., Nelson, D., et al. 2018b, MNRAS, 473, 4077
Rosa-Guevara, Y., Bonoli, S., Dotti, M., et al. 2020, MNRAS, 491, 2547
Scannapieco, C., & Athanassoula, E. 2012, MNRAS, 425, L10
Schaye, J., Crain, R. A., Bower, R. G., et al. 2015, MNRAS, 444, 521
Seo, W.-Y., Kim, W.-T., Kwak, S., et al. 2019, ApJ, 872, 5
Sheth, K., Elmegreen, D. M., Elmegreen, B. G., et al. 2008, ApJ, 675, 1141
Simmons, B. D., Lintott, C., Willett, K. W., et al. 2017, MNRAS, 464, 4420
Spinoglio, D., Bonoli, S., Dotti, M., et al. 2017, MNRAS, 465, 3729
Springel, V. 2010, MNRAS, 401, 791
Springel, V., White, S. D. M., Tormen, G., & Kauffmann, G. 2001, MNRAS, 328, 726
Toomre, A. 1977, ARA&A, 15, 437
Toomre, A. 1981, in Proc. ASI A82-11951 02-90, The Structure and Evolution of Normal Galaxies (Cambridge: Cambridge Univ. Press), 111
Villa-Vargas, J., Shlosman, I., & Heller, C. 2010, ApJ, 719, 1470
Vogelsberger, M., Genel, S., Springel, V., et al. 2014, MNRAS, 444, 1518
Weinberger, R., Springel, V., Hernquist, L., et al. 2017, MNRAS, 465, 3291
Weinberger, R., Springel, V., Pakmor, R., et al. 2018, MNRAS, 479, 4056
Willett, K. W., Galloway, M. A., Bamford, S. P., et al. 2017, MNRAS, 464, 4176
Zana, T., Capelo, P. R., Dotti, M., et al. 2019, MNRAS, 488, 1864
Zana, T., Dotti, M., Capelo, P. R., et al. 2018, MNRAS, 473, 2608