The prevalence of pseudo-bulges in the Auriga simulations

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ABSTRACT

We study the galactic bulges in the Auriga simulations, a suite of thirty cosmological magneto-hydrodynamical zoom-in simulations of late-type galaxies in Milky Way-sized dark matter haloes performed with the moving-mesh code AREPO. We aim to characterize bulge formation mechanisms in this large suite of galaxies simulated at high resolution in a fully cosmological context. The bulges of the Auriga galaxies show a large variety in their shapes, sizes and formation histories. According to observational classification criteria, such as Sérsic index and degree of ordered rotation, the majority of the Auriga bulges can be classified as pseudo-bulges, while some of them can be seen as composite bulges with a classical component; however, none can be classified as a classical bulge. Auriga bulges show mostly an in-situ origin, 21\% of them with a negligible accreted fraction ($f_{\text{acc}} < 0.01$). In general, their in-situ component was centrally formed, with ~ 75\% of the bulges forming most of their stars inside the bulge region at $z = 0$. Part of their in-situ mass growth is rapid and is associated with the effects of mergers, while another part is more secular in origin. In 90\% of the Auriga bulges, the accreted bulge component originates from less than four satellites. We investigate the relation between the accreted stellar haloes and the bulges of the Auriga simulations. The total bulge mass shows no correlation with the accreted stellar halo mass, as in observations. However, the accreted mass of bulges tends to correlate with their respective accreted stellar halo mass.

Key words: galaxies: formation – galaxies: bulges – methods: numerical

1 INTRODUCTION

Milky Way (MW)-mass disc galaxies exhibit a large range of bulge properties and sizes, from prominent (e.g. M31), to almost non-existing bulges (e.g. M101). The diversity in the properties of these galaxies reveals the existence of different formation paths in the context of the current hierarchical galaxy formation paradigm (White & Rees 1978), which are not fully understood. The study of bulges of MW sized galaxies in cosmological simulations is then an important task to try to explain the observed properties of the MW and luminous disc galaxies.

Galactic bulges are broadly classified as classical bulges or pseudo-bulges. Historically, the classical bulges were defined as velocity dispersion dominated components in the center of disc galaxies. These objects have old stellar populations, exhibit a slow degree of rotation and present a spherical or elliptical shape. Yet, many bulges show rotation, younger stellar populations and different features related to a disc-origin, like spiral structure, or nuclear bars. These differences have led to suggestions that such bulges (including bars) should be grouped and termed pseudo-bulges.

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The Auriga simulations consist of a suite of thirty high-resolution cosmological zoom simulations of the formation of galaxies in isolated MW-mass dark matter haloes, denoted throughout this paper by ‘AuN’ with N varying from 1 to 30. The Auriga project was introduced in G2017 and we refer the reader to that paper for a detailed description of these simulations. Here, we briefly describe their main features.

Candidate haloes were selected from a lower resolution dark matter only cosmological simulation from the EAGLE project (Schaye et al. 2015), carried out in a periodic cube of side 100h⁻¹ Mpc. A Λ-CDM cosmology was adopted, with parameters $\Omega_m = 0.307$, $\Omega_b = 0.048$, $\Omega_\Lambda = 0.693$, and Hubble constant $H_0 = 100 \ h \ km \ s^{-1} Mpc^{-1}$, $h = 0.6777$ (Planck Collaboration 2014). Gas was added to the initial conditions and its evolution was followed by solving the equations of ideal magnetohydrodynamics on an unstructured Voronoi mesh. Haloes were selected so that they satisfy: a) a narrow mass range of $1 < M_{200}/10^{12}M_\odot < 2$, comparable to that of the MW and b) an isolation criterion at $z = 0$, placing each Auriga halo more distant than nine times its virial radius from any other halo of mass greater than 3% of its own mass. Each halo was re-simulated at higher resolution with the state-of-the-art N-body and moving mesh magnetohydrodynamics code AREPO (Springel 2010; Pakmor et al. 2016). The typical mass of a dark matter particle is $\sim 3 \times 10^5 \ M_\odot$, and the
baryonic mass resolution is $\sim 5 \times 10^4 \, M_\odot$. The gravitational softening length of the stars and dark matter grows with the scale factor up to a maximum of 369 pc, after which it is kept constant in physical units. This value is large enough to resolve inner galactic regions. As shown by GR2017, decreasing the softening length by a factor of 10 does not affect the overall properties of the resulting galactic models. The softening length of gas cells is scaled by the mean radius of the cell, with a maximum physical softening of 1.85 kpc and is never allowed to drop below the stellar softening length. It is worth noting that, in high density regions, gas cells are allowed to become smaller than the gravitational softening length. This is particularly relevant for this study, where we will be focusing in the very inner regions of each galaxy. However, it is important to keep in mind that our results could be sensitive to the subgrid physic model implemented in Auriga.

The simulations include a comprehensive model for galaxy formation physics which includes relevant baryonic processes, such as primordial and metal-line cooling (Vogelsberger et al. 2013); a sub-grid model for the interstellar medium that utilizes an equation of state representing a two-phase medium in pressure equilibrium (Springel & Hernquist 2003); a model for the star formation and stellar feedback that includes a phenomenological wind model (Marinacci et al. 2014; Grand et al. 2017) and metal enrichment from SNII, SNIa and AGB stars (Vogelsberger et al. 2013); black hole formation and active galactic nucleus feedback (Springel et al. 2005; Marinacci et al. 2014; Grand et al. 2017); a spatially uniform, time-varying UV background after reionization at redshift six (Faucher-Giguère et al. 2009; Vogelsberger et al. 2013) and magnetic fields (Pakmor & Springel 2013; Pakmor et al. 2014). The model was specifically developed for the AREPO code and was calibrated to reproduce several observational results such as the stellar mass to halo mass relation, galaxy luminosity functions and the history of the cosmic star formation rate density.

The Auriga simulations reproduce a wide range of present-day observables, e.g. two-component disc-dominated galaxies with appropriate stellar masses, sizes, rotation curves, star formation rates and metallicities (G2017). The relatively large sample of thirty high-resolution simulations of late-type galaxies is an ideal set of simulations to study bulge formation in MW-sized galaxies and to relate our findings to both the accretion history of these galaxies and their stellar bulge properties. It is worth noting that the above described isolation criterion may bias the number and timing of encounters with satellite galaxies with respect to more dense environments. Late time mergers may be less common on average in the sample used in this paper, with respect to a random sample of Milky Way-sized DM haloes. However, these galaxies have not been specifically chosen to match the MW formation and merger history (as in e.g. Bullock & Johnston 2005) or the Local Group environment (as in the APOSTLE simulations of Sawala et al. 2016). Thus it is unclear how large this effect could be. We defer this analysis to a follow-up project based on the Illustris TNG50 simulations (Gargiulo et al. in prep.).

2.2 Bulge definition

Bulges of galaxies are defined in diverse ways in the literature, both in numerical simulations and observations. Observational studies often consider a spatial definition, selecting a region surrounding the center of the galaxy to some extent (see for example Minniti et al. 2010, for a MW bulge aimed survey). On the other hand, in numerical studies bulges are typically selected kinematically, to minimize the contribution of stars with orbits that are too circular, thus associated with the disc (e.g. Tissera et al. 2012; Guéod et al. 2013). It is also common to limit the spatial extent of the bulge to separate it from the stellar halo component, even though this is not a physical criterion to determine where the bulge ceases to exist and gives place to the so-called inner halo. For example, Cooper et al. (2015) and M2019 choose a spherical region of 5 kpc from the galactic center to mark the frontier between stellar halo and bulge. Other authors choose to avoid this spatial segregation, analyzing the overall “central spheroids” (Tissera et al. 2018).

Here we use a combination of a spatial and a kinematical criteria. We define the bulges of the Auriga simulations as all the stellar particles that fulfill the following two conditions at $z = 0$. First, we consider the particles located inside a sphere of radius $r_{\text{bulge}} = 2R_{\text{eff}}$, where $R_{\text{eff}}$ is the effective radius of the bulge and was derived from a Sérsic profile fitting. The Sérsic profiles are fitted together with an exponential profile (modeling the disc) to the face-on Auriga surface brightness profiles in the V-band derived using a non-linear least-square method. The full process is described in Appendix A.

Second, we exclude stellar particles with pure disc kinematics. For that purpose, we consider only particles with circularities $|\epsilon| \leq 0.7$. The circularity parameter for the stellar particles at $z = 0$ was calculated by G2017. It is defined as $\epsilon = J_z/J(E)$ (Abadi et al. 2003), where $J_z$ is the angular momentum component perpendicular to the disc plane of a star particle and $J(E)$ is the maximum possible angular momentum for the orbital energy, $E$, for the same particle. The median of the mass removed from the region defined as the bulge due to this circularity cut, for all Auriga simulations, is $m_{200,0.7} = 19.19$. Only for Au25 the total mass removed within $2R_{\text{eff}}$ reaches almost 45%. The total mass removed from each galaxy in this bulge defined region due to the circularity cut is listed in Table 1, along with other derived properties of the Auriga bulges. It is important to note that, when comparing with observations, the bulge is defined as closely as possible as it is done in the particular observational analysis. The goal is to make fair comparisons with the observed quantities in each particular case.

3 STRUCTURAL PROPERTIES OF BULGES

In Fig. 1 we show the edge-on projected surface brightness maps in the V-band of the stellar particles that form the bulges. These were obtained by computing the photometry of each stellar particle, which represents a single stellar population, using Bruzual & Charlot (2003) population synthesis models. In the corners of each panel, we show the simulation name, the Sérsic index, and the bulge-to-total stellar mass ratio ($B/T_{\text{sim}}$).
| Bulge | $n$ | $B/T$ |
|-------|-----|-------|
| Au1   | 1.26 | 0.4   |
| Au2   | 1.33 | 0.22  |
| Au3   | 1.34 | 0.17  |
| Au4   | 1.66 | 0.18  |
| Au5   | 0.82 | 0.18  |
| Au6   | 1.68 | 0.24  |
| Au7   | 1.35 | 0.23  |
| Au8   | 1.46 | 0.16  |
| Au9   | 1.25 | 0.34  |
| Au10  | 0.88 | 0.35  |
| Au11  | 1.11 | 0.29  |
| Au12  | 0.6  | 0.15  |
| Au13  | 1.18 | 0.41  |
| Au14  | 1.14 | 0.2   |
| Au15  | 0.64 | 0.15  |
| Au16  | 1.21 | 0.12  |
| Au17  | 0.82 | 0.3   |
| Au18  | 1.01 | 0.25  |
| Au19  | 1.21 | 0.16  |
| Au20  | 1.32 | 0.32  |

**Figure 1.** Projected V-band surface brightness maps of the Auriga bulges shown edge-on at $z = 0$ in a square region of 8 kpcs on each side, centered in the galaxy. Bulges are defined using both a spatial and kinematic criteria (see text for details on the bulge definition in this work). The dashed white circle represents the bulge region within $2R_{\text{eff}}$. Note that surface brightness beyond such circle is shown for all stellar particles, i.e. no kinematical cut. In the upper right corner of each panel the model name is shown. In the upper left corner the Sérsic index and in the lower left corner the bulge-to-total ratio.
The bulges show an interesting diversity in morphology. While some of them show a more rounded or elliptical morphology, there are some clear peanut/boxy (p/b) or X-shaped bulges like Au17, Au18 or Au26. Perhaps the most interesting example is Au18, which shows an X-shape that resembles the morphology of the MW bulge (McWilliam & Zoccali 2010; Nataf et al. 2010). We note here that taking a more restrictive limit in the circularity cut in the definition of galactic bulges (e.g. $|e| \leq 0.6$ instead of $|e| \leq 0.7$) does not significantly affect our results. Disc-like features of bulges are present even with a more stringent circularity threshold. Understanding the origin of this diversity is one of the aims of this study and a series of subsequent papers.

The Sérsic index was extracted from the same profile used to define the effective radius, discussed in the Appendix A. $B/T$ was computed in two different ways. First, we computed $B/T_{\text{sim}}$ as the ratio between the total mass of the stellar particles inside the bulge region as defined in the previous section and the total mass of the stellar particles inside a sphere of $0.1 \times$ the virial radius of the host. In addition, we estimated the $B/T_{\text{v}}$ from the two-component fit described in Appendix A. We integrated the fitted Sérsic function and divided the result by the integral of the sum of the Sérsic function and the exponential function describing the disc. The resulting $B/T$ for all simulations using each method are shown in Table 1. We find that for all of the Auriga bulges $B/T_{\text{sim}} < 0.5$ and most of the Auriga bulges, $B/T_{\text{v}} < 0.5$, which is a common threshold above which the presence of a classical bulge is ensured, in observational studies (Kormendy 2016; Brooks & Christensen 2016). However, in some cases, observed bulges can be classified as classical even if the galaxy shows a low $B/T$ (Fisher & Drory 2011). Au13 and Au26 show values of luminosity-weighted $B/T_{\text{v}} > 0.5$. One of the reasons for this result is that these simulated galaxies experienced high levels of star formation in the last snapshots of the simulation, (See the star formation histories in Fig. 7 and 8 in Sec. 4.2). In the case of Au13, the surface brightness profile shows a prominent bump due to the bar that was extracted during the fitting procedure, but high levels of bar contamination in the light profile remain. Light profile decompositions of barred Auriga galaxies adding a third component for the bar show $B/T$ below 0.5 for Au13 and Au26 (Blazquez-Calero et al., private communication). The effective radii of bulges vary from $R_{\text{eff}} = 0.6kpc$ for Au12, to $R_{\text{eff}} = 2.29kpc$ for Au25. The Sérsic indexes have values between $n = 0.6$ for Au12 and $n = 1.88$ for Au15. A list of bulge parameters presented here can be found in Table 1.

The photometric classification of observed galactic bulges as classical or pseudo-bulges can be difficult. The most straightforward approach is using the Sérsic index, which has been shown to correlate with bulge type. Fisher & Drory (2008) studied the bulges of 79 spiral galaxies observed with the Hubble Space Telescope (HST) spanning a range of morphologies from early-type to late-type. They found a bi-modal distribution of Sérsic index and showed that more than 90% of the bulges that are classified as pseudo-bulges morphologically by visual inspection, have Sérsic indices $n \lesssim 2$. On the other side, classical bulges have commonly Sérsic indices $n > 2$. The dependence of this structural parameter with bulge type was already suggested in previous studies, such as Kormendy & Kennicutt (2004, and references therein). But it was also proven that using the Sérsic index as the only parameter of bulge classification can be too simplistic. Fisher & Drory (2011) used a combination of Sérsic index, morphological classification by visual inspection, and star formation activity to discriminate between bulge types and found that for composite bulges (those which show a distinguishable spheroidal classical component and, at the same time, show pseudo-bulge morphological features such as central spiral patterns, a ring
or bar), the use of structural parameters as Sérsic index are not reliable.

If we only consider the Sérsic index parameter to classify the bulges, we find that all of the Auriga bulges should be classified as pseudo-bulges, i.e. \( n < 2 \). Yet, as previously highlighted (see also Kormendy 2016) a multiparameter classification must be carried out to reduce the error in bulge classification. In the following we analyze the scaling relations, intrinsic shapes and degree of ordered rotation of the Auriga bulges.

### 3.1 Scaling relations

Scaling relations of bulges can be used as a complementary tool to help in the bulge classification. Gadotti (2009) used the relation between effective radius and surface brightness at the effective radius of elliptical galaxies, known as the Kormendy diagram (Kormendy 1977), as another way to determine the bulge type. They assumed that all galaxies outside 1\( r_e \) of the relation followed by elliptical galaxies can be considered pseudo-bulges, but again Fisher & Drory (2011) showed that many pseudo-bulges selected morphologically can lie in the same region than classical bulges on this diagram and that this criterion can not be used in isolation to determine a single bulge type. Yet, pseudobulges and classical bulges do show different behaviours in this diagram when seen as different samples. In Fig. 2 we show scaling relations of the bulges for the Auriga galaxies. In the upper panel, we present the relation between the absolute magnitude in the V-band and the surface brightness at the effective radius and in the bottom panel, we present the relation between absolute magnitude and sersic index. The Auriga bulges are indicated with black diamonds. Observational data from Fisher & Drory (2008) of classical bulges, pseudo-bulges and elliptical galaxies are shown as green circles, red pentagons, and blue triangles, respectively. Average error bars of the observed data are indicated in a lower corner of the panels. To make a fair comparison with observations, in these diagrams all the quantities are derived directly from the 2-component decomposition of the V-band surface brightness profiles (See Appendix A), without applying the kinematic cut previously defined in Sec 2.2. Hence, \( M_V \) and \( \mu_e \) values also include the contribution from particles with circular orbits inside the effective radius. It is expected that classical bulges follow the relation found for ellipticals, but pseudo-bulges usually show a larger scatter in these diagrams. In the Kormendy diagram (upper panel), the Auriga bulges occupy a rather narrow range in effective radii and appear to be systematically larger than the observed pseudo-bulges. While some simulated pseudo-bulges have similar sizes to the observed ones, the high surface brightness objects (\( \mu_e < 17 \) mag arcsec\(^2\)) tend to be larger than observed. In general, we find that the Auriga bulges show a correlation in this diagram, with larger effective radii for smaller surface brightness. However, the slope shown by the Auriga bulges in the \( \log (r_{\text{eff}}) - \mu_{\text{eff}} \) relation is flatter than the slope shown by the observed classical bulges or elliptical galaxies. Observed pseudo-bulges in this diagram show little to no-correlation.

In the middle panel of Fig. 2 we show the \( M_V - \mu_{\text{eff}} \) relation. While elliptical galaxies and classical bulges follow the same trend in this space, i.e. more luminous ellipticals and classical bulges are less centrally concentrated, the bulges of Auriga follow an opposite trend. The observed pseudo-bulges in this panel only show a large scatter. However, the results for the extended sample of galaxies with pseudo-bulges presented in Fisher & Drory (2011) follows qualitatively the same trend seen for the Auriga bulges, i.e. the more luminous the denser, as highlighted by the authors of that work (see their Fig. 8)\(^1\). A group of Auriga bulges (23\% of the total), namely Au10, Au11, Au13, Au14, Au17, Au26, Au28, show to be more luminous than any observed pseudo bulge and present a higher surface brightness than most observed pseudo and classical bulges of this sample. In the bottom panel of Fig. 2, we show the relation between \( M_V \) and sersic index. We can see that the sersic index of observed classical bulges follow broadly the relation found for elliptical galaxies and observed pseudo bulges show a large scatter with no signs of correlation. Although a group of the Auriga bulges show absolute magnitudes that are comparable with those of classical bulges, as already shown in the \( M_V - \mu_{\text{eff}} \) relation, their sersic index and total magnitude are not correlated.

There are two points to take into account in the comparison with these set of observations. i) Fisher & Drory (2008) exclude from the analysis the central regions of the surface brightness profiles when they identify a nuclei and due to resolution limits we cannot identify substructure in the underlying peak of surface brightness produced by the bulge component (See Appendix A). ii) Additionally, extinction by dust is neglected in the simulations. Because of these two caveats, the total magnitudes of the Auriga bulges may be overestimated compared with the observed ones. Besides, this group of galaxies with higher absolute magnitudes in the V-band are all actively forming stars in the last snapshots of the simulation (as can be seen in Fig. 7 and Fig. 8. As discussed in Sec. 5, simulated stellar feedback might not suppress enough star formation in this set of simulations, thus likely generating more massive simulated bulges. It is worth also noting that the observational sample contains the whole range of disc galaxy morphologies and, most likely, a wider range in DM halo masses. Our simulations are restricted to a narrow range of DM haloes \((1 - 2 \times 10^{12} M_\odot)\). Note also that, as shown by Fisher & Drory (2011), a reliable classification of a bulge into either pseudo or classical cannot be done only with the object position in the Kormendy diagram. Instead, all available diagnostics, such as morphology, Sérsic index, and kinematics should be combined when possible.

### 3.2 Intrinsic shapes

Different bulge formation mechanisms are thought to contribute to shape bulges in different ways. Costantin et al. (2018a) stated that the intrinsic shape of bulges provides a complementary classification between classical and pseudo-bulges. Their results are based on a statistical method to derive bulge intrinsic shapes from the observed projected 2D

\(^1\) Results in this paper are not quantitatively compared with observations in Fisher & Drory (2011) because they used images with filters centered 3.6\( \mu \)m from the Spitzer telescope, which are not comparable with the available magnitudes in the Auriga simulations.
shape of galaxies (Méndez-Abreu et al. 2008, 2010; Costantin et al. 2018b). Here we compare the results of our simulations with the conclusions drawn from these observations.

We quantify the intrinsic 3D shapes of bulges by computing the eigenvalues of their mass distribution inertia tensor, adopting the same approach as M2019. We compute the principal axes of the mass distributions in the whole bulge, considering the center of the mass distribution as the most bound DM particle. Fig. 3 shows the c/a vs b/a diagram used by Costantin et al. (2018b) to analyze correlations between the intrinsic shapes and properties of bulges. They defined different regimes in this diagram, which are colour coded and indicated with text in Fig. 3. Auriga bulges occupy two well defined loci. 53% of the Auriga bulges show a very clear prolate shape, while the remaining 47% or have very low inclinations, with respect to the disc plane. They defined different regimes in this diagram, which are colour coded and indicated with text in Fig. 3. Auriga bulges occupy two well defined loci. 53% of the Auriga bulges show a very clear prolate shape, while the remaining 47% or have very low inclinations, with respect to the disc plane. Galaxies with bulges in the prolate regime are barred and the major axis of the mass tensor of bulges is in the direction of the bar major axis.

In the right panels, we show the same diagram, but with symbols colour coded according to the Sérsic index (top) and B/Tsim ratio (bottom). We can see that bulges with higher Sérsic indexes tend to cluster in the spherical regime, with values of 0.8 \( \leq c/a \leq 0.9 \) and 0.9 \( \leq b/a \leq 1 \). Two bulges exhibit values of b/a \( \approx 1 \). The bulges with moderately high Sérsic indexes present more spherical shapes, as found by Costantin et al. (2018b). Bulges with lower Sérsic indexes tend to show more prolate shapes, although a group of them also occupies the spherical regime. This is in disagreement with the results of Costantin et al. (2018b), since they find that the low Sérsic index bulges are more commonly triaxial. Interestingly, none of our bulges show triaxial shapes. In the right bottom panel we see that bulges with larger values of B/Tv are also prone to occupy the prolate regime. This is at odds with the results shown by Costantin et al. (2018b), who found that bulges with larger B/Tv tend to be oblate systems. One possible reason for this discrepancy is that they probe the full range of disc morphologies, ranging from lenticulars to late type spiral galaxies. Here we are narrowing the analysis to disc galaxies in MW-sized haloes, which are expected to have similarities in their formation mechanisms, unlike the broad sample selected in the CALIFA survey. This discrepancy can also arise because Costantin et al. (2018b) define a priori the orientation of the axes in the plane of the observed projected bulge, while we define the major, intermediate and minor axes according to the mass distribution. A detailed analysis of the projected and intrinsic shapes of the bulges in high resolution simulations with a broader range of DM halo masses would be of great interest to constrain the connection between bulge shapes and their formation processes, and to shed light on this apparent discrepancy.

### 3.3 Degree of ordered rotation

The degree of ordered rotation of bulges is a fundamental quantity to discriminate between bulges and pseudo-bulges. The seminal work by Kormendy & Illingworth (1982) showed that bulges present kinematical properties that differentiate them from elliptical galaxies. They used the V\(_{\text{max}}\)/\(\sigma\) diagram (Illingworth 1977), where V\(_{\text{max}}\) is the maximum velocity in the line-of-sight (LOS), typically estimated using long-slit spectroscopy along directions parallel to the galaxy major axis, and \(\sigma\) is the velocity dispersion in the LOS. Classical bulges usually have some degree of ordered rotation and oblate shapes, while elliptical galaxies are supported by velocity dispersion and show anisotropy. When classical bulges coexist in barred disc galaxies, for example, they can acquire angular momentum from the bar (Saha 2015). For its part, pseudo-bulges usually show a higher degree of ordered rotation (Kormendy 1993; Kormendy & Kennicutt 2004) as their formation is linked to the discs and bars.

With the advent of integral-field spectroscopy (IFS) surveys like SAURON (de Zeeuw et al. 2002), ATLAS3D (Cappellari et al. 2011) or MaNGA (Bundy 2015), detailed kinematical structure in galaxies can be analyzed. In this context, Binney (2005) proposed another way for computing...
V/σ that could take into account all the available observed data. Cappellari et al. (2007) used this for the first time, applied to the SAURON survey. We follow also this implementation and compute V/σ as:

\[
\frac{V}{\sigma} = \frac{\langle V^2 \rangle}{\langle \sigma^2 \rangle} = \frac{\sum_{n=1}^{N} F_{n} \langle V^2 \rangle_{n}}{\sum_{n=1}^{N} F_{n} \langle \sigma^2 \rangle_{n}}
\]

where the index n denotes the nth-pixel of 0.2 squared kpc size in the edge-on view of Auriga galaxies inside 1 effective radius, a typical radial extent probed in the observations. For this calculation all stellar particles within one effective radius, including the disc, are taken into account, as done in observations. \(V_n\) and \(\sigma_n\) are the mean velocity in the direction perpendicular to the x-z plane and the velocity dispersion, respectively, on the n-pixel. \(F_n\) is the corresponding total flux. Ellipticity is obtained from the mass tensor analysis explained in Sec. 3.2 as:

\[
(1 - \epsilon^2)^2 = \frac{\langle y^2 \rangle}{\langle x^2 \rangle} = \frac{\sum_{n=1}^{N} F_{n} y_n^2}{\sum_{n=1}^{N} F_{n} x_n^2}
\]

where x, and y are the main axes of the mass tensor of the region inside 1 effective radius.

In Fig. 4 we show the V/σ diagram for the Auriga bulges. They all show strong signatures of rotation in a moderate range of ellipticities. The oblate line is indicated with a red line. This line is approximated as \(\epsilon/(1 - \epsilon)^{1/2}\) and describes oblate spheroids that are isotropic and flattened only by rotation.

Classical bulges in this diagram usually occupy positions near the oblate line or below and pseudo-bulges show usually a higher degree of ordered rotation. To illustrate this we also plot in Fig. 4 observational data from Fabricius et al. (2012). Auriga bulges show a higher degree of ordered rotation than the observed pseudo-bulges with a higher degree of ordered rotation found in Fabricius et al. (2012), reaching values of V/σ > 1.5. It is worth noting that we compute the LOS velocity with galaxies oriented perfectly edge-on. This is not the case for these observations, that were selected with inclinations low enough to classify bulges morphologically and velocities were later corrected for the inclination effect. The rotation degree shown by central regions of the Auriga bulges is a strong indication of the prevalence of pseudo-bulge formation in this sample of simulated galaxies.

4 FORMATION HISTORY OF THE AURIGA BULGES

In this section, we study the main physical mechanisms behind the formation of the bulges in the Auriga simulations. A fundamental step to understand the diversity in their formation history is to characterize the origin of the stellar particles that populate each of them.

4.1 Accreted vs In-Situ components

One possible and common practice to define their origin is to subdivide star particles according to whether they formed in-situ or were accreted into the bulge from satellite galaxies (e.g. Zołotov et al. 2009; Tissera et al. 2012; Pillepich et al. 2015). Studies in the literature have subtle differences in these definitions and some gray areas can arise. For example, stars formed in a starburst during a merger event from gas coming from the satellite have been considered as both an accreted or in-situ origin. Stars formed in tidal tails can cause the same ambiguity too.

Here, we define the accreted component of bulges as the stellar particles born bound to satellites of the host galaxy, that are members of the host bulge at \(z = 0\) (see the definition of Auriga bulges in Sec. 2.2). On the other hand, the in-situ component of the Auriga stellar bulges is defined as all \(z = 0\) bulge stellar particles that were born inside the virial radius of the host galaxy and were not bound to any distinct satellite at the time of formation. This definition includes the star particles formed from the stripped gas accreted during a satellite accretion. In Fig. 5 we show the fractions of bulge stars that belong to the accreted and in-situ components. Inside the bars, we show the fractions in terms of percentages. Au1 and Au11 bars are grey, because we exclude them from the current analysis. The reason for this is that both Au1 and Au11 show an ongoing major accretion event, which makes it difficult to define the different components of these galaxies. Only Au4 shows a considerable accreted bulge fraction of 0.42. In all the other cases, the accreted fractions are below 0.28 and for a few bulges like Au5, Au10, Au17, Au18 and Au22, the percentage of accreted material is less than 1%. Despite the rich merger histories of many of our simulated galaxies (see e.g. M2019), the bulge accreted fractions are generally marginal.

In the left and middle panels of Fig. 6 we show the mass density maps of the in-situ and accreted bulge components of a subsample of Auriga bulges as seen edge-on and face-on, respectively. In the right panels, we show the mass density profiles of both components, normalized to their corresponding maximum value. We choose three examples that depict three different types of behaviour of the accreted and in-situ bulge components. We find that the in-situ components are more centrally concentrated than the accreted counterparts in 14 bulges (~ 50%), as shown for Au3 in the first panel. The second panels show the example of Au6. Here the normalized density for both components is similar.
Table 1. Table of bulge parameters at \( z = 0 \). The columns are 1) Model name; 2) Bulge stellar mass, defined as the sum of all stellar particles inside the bulge region defined in Sec. 2.2; 3) Sérsic Index; 4) Bulge-to-total ratio computed as the ratio between the sum of masses of particles inside bulges as defined in Sec. 2.2 and the sum of the masses of all stellar particles inside \( 0.1 \times R_{\text{vir}} \); 5) Bulge-to-total ratio derived from two-component fits to the surface brightness profile in the V-band; 6) Bulge effective radius; 7) Accreted bulge fraction; 8) Minor-to-major axis ratio \( c/a \); 9) Intermediate-to-major axis ratio \( b/a \); 10) Percentage of in-situ bulge stars formed outside the bulge region; 11) Fraction of in-situ (all) stars younger than 8 Gyr; 12) Fraction of stars inside the bulge region with circularities \( \epsilon > 0.7 \).

| Sim | \( M_{\text{bulge}} \) [\( \text{M}_{\odot} \)] | \( n_v \) | \( B/T_{\text{sim}} \) | \( B/T_v \) | \( f_{\text{acc}} \) | \( c/a \) | \( b/a \) | \( f_{\text{b>2R}} \) [%] | \( f_{<8\text{Gyr}} \) | \( f_{>0.7} \) |
|-----|-----------------|--------|-----------------|-----------------|-----------------|--------|--------|-----------------|-----------------|--------|
| Au1 | 1.01            | 1.26   | 0.37            | 0.24            | 1.24            | –      | 0.73   | 0.77            | –              | 0.25   |
| Au2 | 1.36            | 1.32   | 0.19            | 0.07            | 1.40            | 0.15   | 0.72   | 0.78            | 33.1           | 0.37   |
| Au3 | 1.55            | 1.30   | 0.20            | 0.11            | 1.72            | 0.23   | 0.89   | 0.98            | 17.9           | 0.14   |
| Au4 | 1.53            | 1.65   | 0.21            | 0.12            | 1.62            | 0.42   | 0.92   | 0.99            | 42.9           | 0.95   |
| Au5 | 1.31            | 0.82   | 0.19            | 0.09            | 0.68            | < 0.01 | 0.86   | 0.90            | 42.8           | 0.52   |
| Au6 | 1.00            | 1.68   | 0.21            | 0.11            | 2.13            | 0.14   | 0.81   | 0.94            | 31.5           | 0.38   |
| Au7 | 1.01            | 1.35   | 0.21            | 0.10            | 1.02            | 0.20   | 0.81   | 0.87            | 36.3           | 0.94   |
| Au8 | 0.58            | 1.46   | 0.19            | 0.12            | 2.00            | 0.15   | 0.84   | 0.94            | 40.9           | 0.31   |
| Au9 | 2.01            | 1.25   | 0.33            | 0.18            | 1.02            | 0.03   | 0.68   | 0.70            | 41.2           | 0.46   |
| Au10| 1.97            | 0.88   | 0.33            | 0.25            | 0.67            | < 0.01 | 0.68   | 0.73            | 56.8           | 0.74   |
| Au11| 1.83            | 1.10   | 0.26            | 0.41            | 1.34            | –      | 0.65   | 0.69            | –              | 0.16   |
| Au12| 0.83            | 0.60   | 0.14            | 0.07            | 0.60            | 0.01   | 0.76   | 0.81            | 53.1           | 0.71   |
| Au13| 2.10            | 1.18   | 0.34            | 0.53            | 0.95            | 0.01   | 0.71   | 0.74            | 51.1           | 0.79   |
| Au14| 1.88            | 1.14   | 0.18            | 0.12            | 0.75            | 0.02   | 0.75   | 0.80            | 46.1           | 0.74   |
| Au15| 0.27            | 0.64   | 0.07            | 0.03            | 0.62            | 0.02   | 0.88   | 0.99            | 52.1           | 0.84   |
| Au16| 0.65            | 1.20   | 0.12            | 0.05            | 1.44            | 0.01   | 0.85   | 0.96            | 31.9           | 0.18   |
| Au17| 3.41            | 0.88   | 0.45            | 0.49            | 1.06            | < 0.01 | 0.71   | 0.75            | 51.6           | 0.58   |
| Au18| 1.95            | 1.01   | 0.24            | 0.19            | 0.98            | < 0.01 | 0.78   | 0.81            | 57.4           | 0.52   |
| Au19| 1.07            | 1.94   | 0.20            | 0.13            | 1.39            | 0.22   | 0.90   | 0.99            | 32.5           | 0.74   |
| Au20| 1.35            | 1.85   | 0.28            | 0.13            | 1.51            | 0.18   | 0.72   | 0.77            | 33.0           | 0.52   |
| Au21| 1.03            | 1.08   | 0.13            | 0.13            | 1.08            | 0.10   | 0.82   | 0.91            | 38.2           | 0.74   |
| Au22| 1.90            | 0.81   | 0.31            | 0.20            | 0.72            | < 0.01 | 0.80   | 0.89            | 51.5           | 0.60   |
| Au23| 2.35            | 1.26   | 0.26            | 0.17            | 1.33            | 0.03   | 0.73   | 0.76            | 47.6           | 0.52   |
| Au24| 1.90            | 1.65   | 0.29            | 0.13            | 1.06            | 0.01   | 0.65   | 0.67            | 29.8           | 0.28   |
| Au25| 0.55            | 1.88   | 0.17            | 0.09            | 2.29            | 0.08   | 0.83   | 0.97            | 32.2           | 0.30   |
| Au26| 4.10            | 1.10   | 0.37            | 0.62            | 1.00            | 0.11   | 0.72   | 0.75            | 51.8           | 0.77   |
| Au27| 1.52            | 1.09   | 0.16            | 0.07            | 0.84            | 0.05   | 0.75   | 0.79            | 37.9           | 0.32   |
| Au28| 4.03            | 1.63   | 0.38            | 0.42            | 1.49            | 0.24   | 0.75   | 0.80            | 51.8           | 0.87   |
| Au29| 1.67            | 1.21   | 0.18            | 0.20            | 0.86            | 0.28   | 0.84   | 0.91            | 34.9           | 0.52   |
| Au30| 1.26            | 1.32   | 0.29            | 0.47            | 1.71            | 0.16   | 0.84   | 0.96            | 40.7           | 0.80   |

Figure 5. Fraction of accreted and in-Situ stars in bulges of the Auriga galaxies. Despite the rich merger history of the Auriga galaxies, all its bulges are dominated by in-situ formed stars. The median accreted fraction is \( f_{\text{acc}} = 0.08 \). Moreover, 23% of the simulated galactic bulges show negligible contributions from an accreted component. As indicated in the text Au 1 and Au 11 are excluded from this analysis because of ongoing merger activity.
spherical density distribution of the bulge accreted component follows almost exactly the one shown by in-situ bulge. Simulated bulges that show this behaviour (~ 11% of Auriga bulges) have coincidentally a high fraction of accreted bulge stars. The similarity in the shape of the distribution could be the consequence of the violent relaxation of the stellar particles formed in-situ, together with the accreted particles of a massive satellite. Indeed, the morphology of both components of Au6 shows a striking similarity in the left panels. Interestingly, for 4 out of 28 bulges (~ 14%) the accreted component follows the disc-like shape of their in-situ component when seen edge-on (see Gómez et al. 2017a for a dedicated paper regarding the ex-situ discs in the Auriga simulations), and the bar signature when seen face-on. The case of Au2 shown in the third panel is the clearest example where a bar-like distribution is seen in the accreted component. The remaining bulges (~ 25% of Auriga bulges) have too low accreted fractions to make a meaningful comparison between the spatial distribution of both components, but we note that in all these cases of low accreted bulge mass fractions, the accreted bulge components are also less concentrated than the in-situ components. This result indicates that it is possible for the accreted stellar particle distribution to be reshaped by internal secular processes after being accreted (e.g. Saha et al. 2012). The existence of this phenomenon in real galaxies could help to explain to some extent the apparent underabundance of classical bulges in disc galaxies.

4.2 Formation history of the in-situ component

The simplest question that we can ask about the in-situ population is where and when did it form. We show in Fig. 7 and Fig. 8 the stellar particles formation time (age) distribution, \( t_{\text{form}} \), of the \( z = 0 \) in-situ bulge, as a function of birth radius, \( r_{\text{birth}} \). Here \( r_{\text{birth}} \) is defined as the galactocentric distance of each particle at the nearest snapshot of their formation. The blue dashed line on each panel represents the spatial extent of the bulge region. The percentages of stars formed inside and outside this limit are shown next to left and right of this line, respectively. In all cases, the birth radii distributions show that the star formation is peaked towards the central regions of the galaxy. This is in line with observations using the ALMA telescope that show high levels of star formation in the central regions of disc galaxies at high redshift \( (z \sim 2) \) (Tadaki et al. 2017). We can see that, although star particles are formed predominantly inside the bulge regions defined at \( z = 0 \), there are several galaxies which formed a large fraction of their in-situ bulge outside this region. It is interesting to note the cases of Au10, Au12, Au13, Au15, Au17, Au18, Au22, Au26 and Au 28 which have an extended distribution and a dominant fraction \( \left( f_{\text{form}} > \text{0.50} \right) \) of bulge stars that were formed outside the bulge region.

The bulge formation time distributions on the right axis of Fig. 7 and Fig. 8 show great diversity and, in many cases, a high fraction of intermediate-age and young stars \( (t_{\text{form}} < 8 \text{ Gyr}) \). The fraction of these younger stars in the in-situ bulge, indicated for each simulation in Table 1, range from 0.11 for Au3 up to 0.94 for Au7. We can see star formation histories with peaks at different redshifts. During these peaks of star formation, the birth radii span a large range, sometimes reaching 10 kpc. Typically, these peaks are associated to mergers with satellite galaxies. The most relevant merger events are highlighted with arrows on each panel. The colors of the arrows indicate the total masses of the merging satellites, as indicated in the color bar. We only show mergers with satellites of total masses above \( 10^{10} \text{M}_\odot \) that had occurred in the last 10 Gyrs of the simulation. Interestingly, some of the peaks on the bulge star formation histories are associated with groups of small mergers instead of mergers with large satellites. However, not all peaks are correlated with galaxy mergers. For example Au17 shows several peaks of star formation with no associated merger. In many of those cases, we found that different forms of interactions due to flybys of massive satellites are triggering the star formation in the host galaxy (see e.g. Gómez et al. 2016). During the mergers, the host discs are strongly perturbed and star formation is enhanced. Part of these newly formed stars settle down into the central regions as the system relaxes to an equilibrium. Additionally, a fraction of stars is formed in central starbursts driven by gas funneling in the case the merger is wet (Hopkins et al. 2009; Bustamante et al. 2018). Noticeably, the diversity shown in the star formation histories is shown to be related to the expected diverse merger histories experienced by the galaxies during their evolution in a cosmological scenario.

On the other hand, some of the simulations show extended star formation periods, which are associated with secular evolution processes within the galactic discs. The model Au18 provides a typical example of these processes. Au18 undergoes a merger with a satellite in the period between \( 8 \rightarrow 9 \text{ Gyrs ago} \), which is shown by the arrow and generates a strong \( t_{\text{form}} \) peak in Figure 8. As shown by Grand et al. (2016), who characterized the vertical heating of the Auriga discs as a function of time, Au18 develops a strong bar after this merger event (see their Figure 5). As a result, the star formation rate inside the bulge radius is increased by the funneling of cold gas which loses angular momentum due to the torques exerted by the bar. Studies based on detailed hydrodynamic simulations have shown that the accretion of gas with low angular momentum in the inner galactic region produces off-axis shocks that drive gas into internal nuclear rings where stars are formed (Sanders & Huntley 1976; Kim et al. 2012, 2018). Other galaxies like Au17 and Au22 also show extended periods of star formation inside and outside the bulge region that are a consequence of secular evolution. These bulges develop strong non-axisymmetric instabilities during its evolution. In addition, direct cold gas accretion can also play a role in the enhancement of gas density and subsequent star formation both inside and outside the disc region (e.g. Sales et al. 2012). Au18 shows a significant fraction of bulge stellar particles that formed outside the bulge region after the merger event. These are particles that can be brought to the bulge due to an interplay of processes. It is well known that stars in discs can migrate from the original position where they were born in the galactic disc. Dynamical processes that are responsible for such behaviour are the presence of transient spiral arms, which change the angular momentum of stellar particles near the corotation radius and drive outward and inward streaming motions of these particles, and the resonant coupling between the bars and the spiral patterns. (Sellwood & Binney 2002; Minchev & Famaey 2010; Grand et al. 2012). The same physical process can occur due to a bar, that can exert the loss of angular mo-
momentum to the particles captured in resonances. This way, particles can be caught inside the bulge radius during their orbit in the last snapshot of the simulation. Quantifying the evolution of bulges and the precise relative contributions of each mechanism is beyond the scope of this paper and is postponed to future work. The relative importance of these mechanisms of in-situ bulge growth give place to the scatter that is seen in the Auriga bulges properties, together with the different accretion histories.

4.3 Accreted component: the Bulge-Stellar Halo connection

In this section, we analyze the accreted component of the Auriga bulges, and its connection to the more extended stellar halo. As previously discussed in Section 4.1, the accreted component in all our models is subdominant, with a fractional mass that never surpasses the component in all our models is subdominant, with a fraction of mass that never surpasses the component in all our models.

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Figure 7. Formation times as a function of birth radii of stellar particles inside the bulge region at $z = 0$, for each of the first 14 Auriga simulations. Normalized distributions of birth radii and formation times are shown above the horizontal axis and to the right of the vertical axis, respectively. The vertical blue dashed lines indicate the spatial limit of the bulges at $z = 0$. The values to the left and right of the dashed lines indicate the fraction of in-situ bulge stars formed inside and outside the bulge region, respectively. Mergers times are indicated by arrows that are coloured according to the total mass of the merged satellite, as indicated by the color bar. Only mergers with satellites of total masses above $10^{10} M_\odot$ that had occurred in the last 10 Gyrs of the simulation are shown in this figure.
Figure 8. As in Figure 7 for the rest of the 14 Auriga simulations.
progenitors of the bulge. However, as previously stated, several counterexamples can be found.

Bell et al. (2017) compares the stellar masses of the bulges and halos of nearby MW-mass galaxies (MW-peers); that is galaxies with stellar masses in the range of \(3 - 12 \times 10^{10} M_\odot\). The idea of this work was to study the relation between the formation of bulges and the merger history of galaxies. They found very little correlation between the accreted mass of the stellar haloes and the total mass of the bulges. To make a fair comparison with the observations, we computed the total bulge mass of the Auriga galaxies by multiplying the total stellar mass of the simulations, which measures the degree of linear correlation taking values between 1 and −1. The Pearson coefficient for the simulations in the right panel is close to 0, indicating a null correlation. When using the luminosity weighted bulge masses in the left panel the Pearson coefficient yields 0.2 and for the observed sample, the value is 0.15, larger, but still low. We find a group of galaxies (~16% of Auriga haloes) with low accreted stellar halo mass and a large bulge mass. This population is also present in the observed sample.

To further investigate the origin of the location of the Auriga galaxies in the bulge mass vs. halo mass diagram, in the top panel of Fig. 12 we have color-coded the symbols according to respective accreted bulge mass fraction. In this case we show the bulge masses computed directly from the simulations as in the right panel of Fig. 11, since we cannot compute the accreted fractions of the bulge masses derived from the surface brightness profiles. Interestingly, the five simulations with a high bulge mass and low accreted halo mass (Au9, Au10, Au17, Au18, and Au22 in Fig. 11) all have negligible accreted bulge fractions. This fact alone, however, does not explain the offset from the broad relation followed by the other galaxies, since there are other galaxies with low accreted bulge fractions which do follow the weak trend between total bulge mass and accreted stellar halo mass (as we can see in Fig. 12). However, it is important to notice that these are some of the galaxies with the most massive bulges in our set of simulations.

As previously discussed in Sec. 4.2, Grand et al. (2016) recently characterized the disc vertical heating of the Auriga galaxies, associated with non-axisymmetric disc perturbations and merger events. If we concentrate on the group
Figure 10. Fraction of mass that each progenitor (with stellar mass higher than $10^7\,M_\odot$) contributes to the bulge with respect to accreted bulge mass, as a function of the total stellar mass of the progenitor at the time of accretion into the host galaxy. The colouring of the points represents the fraction that each progenitor contributes to the stellar halo with respect to the total accreted mass in the halo. Green rectangles in the simulation identifier indicate the galaxies with accreted bulge fraction lower than 1%. 

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of bulges with high total bulge mass but negligible accreted bulge fraction, Au17 and Au18 show two of the strongest bars in the whole simulation sample, that are present nearly during the entire evolution of these galaxies (see their Fig. 5). Au9 develops a strong bar from 6 Gyr ago until the present-day. Similar results are found for Au10 and Au22. High total bulge mass and low accreted bulge fraction is also seen in Au13, Au14 and Au23. However, they do follow the broad $M_{\text{bulge}}$ vs $M_{\text{halo}}$ correlation in the diagram more closely, mainly thanks to their larger $M_{\text{halo}}$ mass. We find that these galaxies develop relatively strong non-axisymmetric disc features during their evolution. In addition, they experienced a relatively massive merger, which contributed to the formation of the in-situ bulge through the triggering of central star formation bursts and tidal perturbation of the pre-existing discs (see Fig. 7 and Fig. 8), but mainly increasing the accreted halo mass, $M_{\text{acc}}^{\text{halo}}$. This can be seen in Fig 10.

Based on our results, one can infer that galaxies with low accreted stellar halo and high total bulge mass (Au9, Au10, Au17, Au18 and Au22) have a low bulge accreted mass fraction, and that non-axisymmetric disc perturbations have played a significant role in the build-up of the total bulge mass. Following this, M81 and NGC 4565, highlighted in Fig. 12 with grey triangles, should have a low fractional contribution of an accreted bulge component with respect to the in-situ bulge component and that, probably, they have developed strong non-axisymmetric features, such as bars or transient spiral arms, sometime during their evolution. NGC 4565 was studied recently by Kormendy & Bender (2018) and indeed fit this scenario showing lack of a classical bulge component and the presence of an X-shape central region attributed to a bar. M81, for its part, does not show a visible bar, but it is known for its strong spiral pattern (Kendall et al. 2008). Considering our findings, a possible scenario for the apparent excessive mass of M81’s bulge in relation with its stellar halo mass is that an ancient bar might have developed sometime in this galaxy.

In the bottom panel of Fig. 12 we show the accreted bulge mass as a function of the accreted stellar halo mass, color-coded by the accreted bulge fraction. We can see that the accreted bulge mass correlates with the accreted halo mass. Bulges with high accreted fraction show a tight correlation, close to a 1:1 correlation, whilst bulges with low and negligible accreted fractions show a larger scatter. In order to quantify the difference, we computed the Pearson coefficients obtained for galaxies with accreted bulge fractions $f_{\text{acc}} > 0.05$ and for those with lower accreted bulge fractions separately. The high accreted bulge fraction group shows a Pearson coefficient of 0.76 and the group with low accreted bulge fraction has a Pearson coefficient of 0.42, as indicated in the bottom right corner of the bottom panel.

5 DISCUSSION

Historically, simulations of galaxy formation within a ΛCDM framework suffered the overcooling problem (Balogh et al. 2001). Simulations produced highly concentrated galaxies with bulges that exceeded the observed sizes and bulge-to-total ratios (Christensen et al. 2014). With the implementation of plausible sub-grid physics in hydrodynamical simulations that take into account energetic feedback processes, the excess of concentrated star formation was suppressed (Springel & Hernquist 2003; Ceverino & Klypin 2009), although, sometimes, at the expense of destroying the morphology of the galactic discs (Roskar et al. 2014). In the case of the Auriga galaxies, the stellar feedback produces a moderate thickening of the discs but preserves properties that reproduce several observational trends (G2017). With regard to the bulges, we found that the Auriga galaxies show a systematic excess in the effective radii related to an excess in the total mass of bulges. Because of this excess, 23% of Auriga bulges have surface brightness inside effective radius and total Magnitude with no counterpart in nature. This excess could be related to the implementation of the stellar feedback in the Auriga simulations, which has been shown to produce a milder effect than expected in the quenching of dwarf galaxies (Simpson et al. 2018).

One of the main results of this paper is the predominant in-situ formation of the Auriga bulges. In a recent work, Gargiulo et al. (2017) studied the stellar populations of galactic bulges in MW-like galaxies using a semi-analytic model of galaxy formation (Gargiulo et al. 2015; Cora et al. 2018), coupled to cosmological N-body simulations, and found that on average approximately 16% of the bulge mass has an accreted origin. Other cosmological simulations show similar results. Tissera et al. (2018) show the fraction of accreted mass as a function of galactocentric distances in their Fig. 2, and even though the inner spheroid includes some transitional region to the stellar halo, we can see that the accreted fractions inside 4 kpc are also between 0.02 and 0.15. Guedes et al. (2013) reports an accreted fraction of only 4% in the pseudo-bulge of a MW-like galaxy simulation. Buck et al. (2018a) found a contribution of 2.3% of accreted stars to the bulge components. Ours and previous results suggest that bulges of simulated disc galaxies formed in MW-sized DM haloes in a cosmological context commonly lack a strong accreted component.

When we look exclusively at the accreted stellar particles that are part of bulges at $z = 0$ we found that a low number of satellite galaxies (the most massive progenitors in the history of accretion in general) are responsible for the build-up of the accreted bulge component of galaxies (see Fig. 9 and Fig. 10). This result suggests that many mergers with very small satellites are not centrally responsible for the growth of galactic bulges. A similar result was found for the stellar haloes of the Auriga simulations by M2019. As also noted by M2019, this is in line, for example, with the formation scenario of the stellar halo of M31, for which a single satellite is found to account for the build-up of most of its stellar halo (see also D’Souza & Bell 2018b,a). Following our findings, this single satellite could also be responsible for most of the accreted component of its bulge. Although one might at first think that a halo or accreted component of a bulge built from one or a few progenitors would have relatively homogeneous populations, in fact, the halos built from few massive progenitors have complex star formation histories and gradients inherited from the massive satellite that it accreted (D’Souza & Bell 2018b,a).

Mergers are a natural outcome of the Λ-CDM scenario, in which DM haloes, where galaxies are formed, growth hierarchically from smaller structures. Theoretical predictions of merger rates are in close agreement with estimates
of merger rates using pair fractions. Mundy et al. (2017) used this method to estimate observational merger rates and compared with results using the ILLUSTRIS simulation (Rodriguez-Gomez et al. 2017), and merger rates derived from light cones derived from a semi-analytic model (Henriques et al. 2015), and found a good agreement. The influence of mergers in the formation of bulges is found to be central in many simulations. Major mergers are common at high redshift, but after $z \sim 1$ become rare for galaxies with masses in the range of the MW-mass. Garrison-Kimmel et al. (2018) show using the LATTE simulations (Wetzel et al. 2016), that most of the stars in their simulations are born with disc-like kinematics and that gas rich mergers are one of the main drivers of bulge formation at high redshift.

It is often claimed that the hierarchical paradigm is in tension with the lack of classical bulges in bright disc galaxies like the MW (see, for example Shen et al. 2010; Kormendy et al. 2010; Kormendy 2016). It is important to highlight the fact that most large disc galaxies in the local Universe have pseudo-bulges is not at odds with galaxy formation in a hierarchical context, as can be seen in the results of our study. Results presented in this work show that mergers funnel gas into the central parts of the galaxy forming bulges that do not necessarily show a dominant dispersion dominated component that resembles a mini-elliptical galaxy at present, as indicated by the properties of the surface brightness profile at $z=0$, such as the Sérsic index (see Table 1), its shape (see Fig. 3) and the degree of ordered rotation (see Fig. 4). Even though most of the Auriga simulations present rich merger histories and some of the simulated bulges have large accreted fractions (for example Au4), we found, applying criteria based on those used in observations that the majority of bulges in our sample can be classified as pseudo-bulges.

Bulges formed by mergers can change their shape during their evolution. It is possible that the formation of a bar on top of a small classical bulge formed at high redshift can dynamically affect the non-rotating component, making it indistinguishable from a pseudo-bulge at $z=0$, as is demonstrated by simulations (Saha et al. 2012; Saha 2015) and as can be seen clearly in the case of Au2 in Fig. 6. Moreover, mergers or interactions with satellite galaxies can play an important role in the formation of pseudo-bulges, by instigating the formation of bars in globally unstable systems (Byrd et al. 1986; Noguchi 1987; Romano-Díaz et al. 2008). We see this occurring in some Auriga galaxies, see e.g. the case of the formation of the bulge in Au18 which was discussed in Sec. 4.2. In that case, a strong bar is developed after a major merger. Because of this, we stress that studying the formation of the innermost regions of galaxies, where bulges arise, without a hydrodynamical cosmological framework could lead to oversimplified scenarios of the bulge formation in the cases when the accreted component of the galaxy is significant.

As stated before in Sec. 2, the question of environment could play a role here. Although the accretion histories were not explicitly constrained, and a good diversity of accretion histories is available, the Auriga simulations were run adopting an isolation criterion for the host DM halos. MW-analogs in denser environments might suffer later and more numerous accretion events on average and, therefore, contain central regions with a higher degree of random motions. Bars can be destroyed by these interactions, limiting important channels of mass formation via secular processes described in Sec. 4.2.
Figure 12. Total bulge stellar mass (top) and accreted bulge stellar mass (bottom) as a function of accreted stellar halo mass. Points are coloured according to the accreted fraction of stars of each bulge. Grey points with errorbars are observed data from Bell et al. (2017) and the grey dashed line indicates a 1:1 correlation for reference. The group of high total bulge mass, mentioned in Fig. 11, presents marginal accreted bulge fractions. Galaxies with higher accreted bulge fractions show a tight correlation in the bottom panel. Pearson coefficients are shown for galaxies with high and low accreted bulge fraction ($f_{\text{acc, bulge}} > 0.05$ and $f_{\text{acc, bulge}} < 0.05$) respectively.

6 SUMMARY AND CONCLUSIONS

We have analysed the properties and the origin of galactic bulges in 30 cosmological magneto-hydrodynamical simulations of disc galaxies in MW-sized DM haloes. The Auriga simulations have a baryonic resolution of $\sim 5 \times 10^5 M_{\odot}$, and represent one of the largest samples of cosmological collisional simulations at this level of resolution to date. We found a great diversity of bulges in a narrow range of DM halo masses. This diversity is similar to that observed and should be regarded as a good asset to learn about the formation history of the MW and MW-analogs, such as M31, NGC 4565 and NGC 5746 (Kormendy & Bender 2018; Bell et al. 2017). We list here our main results.

- Galactic bulges in the Auriga simulations have considerable diversity in general properties such as morphology, surface brightness, and shape. However, compared with the sample of disc galaxies in the local Universe of Fisher & Drory (2008), the Auriga bulges occupy a rather narrow range in size in the Kormendy diagram. They show a systematic excess in effective radii compared with the observed sample at high surface brightness.
- All bulges in the Auriga galaxies have properties that would define them photometrically as pseudo-bulges. Sérsic indices derived from surface brightness profiles are found to be all $n < 2$ and their behaviour in the $M_v - \mu_e$ diagrams is closer to that observed for pseudo-bulges. Although, 23\% of bulges have higher surface brightness than any observed bulge and are more luminous than observed pseudo-bulges.
- Auriga bulges occupy two marked loci in a diagram that relates the axis ratios of their mass distributions. One group shows marked prolate intrinsic shapes due to the presence of a bar, while the other has close to spherical mass distributions. We found that the more nearly to spherical group has lower $B/T_{\text{sim}}$ ratios and higher Sérsic indices. Prolate bulges develop in barred galaxies and are in general more massive and have lower Sérsic indices.
- Auriga bulges show a high degree of ordered rotation and low ellipticities in the $V/\sigma - \epsilon$ diagram, well above the region occupied by observed classical bulges.
- Auriga bulges are formed predominantly in-situ (see Fig. 5). The largest accreted bulge fraction reaches $f_{\text{acc}} = 0.42$, and only 21\% of bulges have accreted fractions higher than $f_{\text{acc}} = 0.2$. 21\% of bulges have negligible accreted fractions (less than $f_{\text{acc}} = 0.01$).
- The spatial distributions of the accreted and in-situ bulge components show different behaviours. 50\% of the Auriga bulges possess a less concentrated accreted component compared to the in-situ component, whereas 11\% of bulges show that these components have a similar normalised spherical density distribution. Interestingly, 14\% of bulges show accreted components that follow the shape of the bar seen in the corresponding in-situ components. The remaining bulges have too low or negligible accreted fractions to make a meaningful comparison.
- Analysis of the in-situ component of bulges show that bulge stellar particles form predominantly in the central regions of the galaxy, although a low fraction of the sample show approximately equal parts formed outside and inside $2\sigma_{\text{eff}}$ at $z = 0$. Some of them that happen to develop a strong bar during the evolution form more stars outside the bulge radius than inside. This underscores the significance of secular evolution to the growth of bulges in these galaxies. Mergers are also responsible to the in-situ star formation inside the bulge. In situ star formation histories of the Auriga bulges show peaks when a single or several minor mergers occur between snapshots. The strength of these peaks correlates broadly with the mass of the satellites. The star formation history of the in-situ bulge component shows greater diversity, due to the contribution of different mechanisms to in-situ bulge growth and the inherent diversity of merger histories.
- The accreted components of bulges in the Auriga simulations are dominated by a single accretion in 80\% of the cases. Most of the remainder of the mass originates from the next few most massive accretions, which happen to be the more massive satellites that were accreted by the galaxies, in most cases. In addition, the same satellites typically contributed more to the build-up of the corresponding stellar halo. Accretion of stars by a large number of mergers with very small satellites is therefore not a favoured mechanism of the accreted bulge growth in MW-sized galaxies in our models. However, as mentioned before, minor mergers play an important role in the in-situ star formation inside the bulge.
• Total bulge mass and accreted stellar halo mass show little correlation as noted in observations. Those galaxies with a low accreted bulge fraction show no correlation between stellar halo mass and total bulge mass, but a group of them that develop strong bars during its evolution, occupy a well defined region in the bulge mass vs. accreted stellar halo mass diagram. This result can help to constrain the origin of bulge stars in observed galaxies according to the position in this diagram. Accreted bulge mass and accreted stellar halo mass are correlated. Galaxies with higher accreted bulge fraction show lower dispersion than galaxies with low accreted bulge fraction in this relation.

This is the first paper in a series studying the formation of bulges in MW-sized DM haloes. An even larger sample of high resolution simulations spanning a broader range in DM halo masses is necessary to understand the transition in the formation of pseudo-bulges and classical bulges in disc galaxies.

APPENDIX A: TWO-COMPONENT DECOMPOSITION OF SURFACE BRIGHTNESS PROFILES

Here we show the two-component decomposition of surface brightness profiles of the Auriga simulations. Surface brightness profiles were computed with the simulations as seen face-on, in concentric annuli of 500 pc wide, centered in the coordinate origin, defined as the most bound dark matter particle of each simulation. We use a non-linear least-square method to fit the sum of an exponential profile and a S´ersic model (Sersic 1968) which in terms of intensity reads:

\[
I(r) = I_e \exp \left[ -b_n \left( r/r_{eff} \right)^{1/n} - 1 \right] + I_0 \exp \left[ -r/R_{scale} \right] , \quad (A1)
\]

where \( r_{eff} \) is the effective radius that encloses half of the total light of the S´ersic model, \( I_e \) is the intensity of the bulge component at \( r_{eff} \), \( n \) is the S´ersic index, \( b_n \) is the central intensity of the disc component, and \( R_{scale} \) is the disc scale radius. \( b_n \) is such that \( \Gamma(2n) = 2\Gamma(2n,b_n) \), where \( \Gamma \) is the complete gamma function. The intensity is later converted into surface brightness to perform the fit. The fit of the surface brightness profile is limited to the optical radius as in G2017, who performed a similar fit to the mass density profile, following Marinacci et al. (2014). The fitting procedure was performed following Fisher & Drory (2008). In their work, surface brightness excesses due to features like bars, lenses, rings, and bright spiral structures are not taken into account in the fitting procedure. The central nuclei is also excluded from their fits. In the following, we exclude from our analysis the points in the surface brightness profile where the bar and other features, like spiral arms and rings are conspicuous. These surface brightness excesses are considered deviations from the smooth surface brightness profile assumed by our model (Eq. A). However, we do not exclude the central nuclei because the resolution of the simulations does not allow us to separate this component from the underlying peak of surface brightness. Thus, the total magnitudes of the Auriga bulges may be overestimated compared with the observed ones. In Fig. A1 we show the surface brightness profiles of the Auriga simulations. The data used in the fit are shown with black filled circles and those excluded from the analysis with black empty circles. The fitted function is shown with a black line and the corresponding S´ersic and exponential profiles are shown with dotted and dashed lines, respectively.

In order to study the robustness of this method, we compare in Fig. A3 the S´ersic index and \( r_{eff} \) obtained when excluding points in the fitting procedure and those obtained using all the available points. We found that effective radii present small differences when using different fitting procedures, showing lower values, in general, when deviations from the smooth model are included in the fitting of the surface brightness profiles. S´ersic indexes also present differences when adopting different methods to fit the surface brightness profiles, but none of them is larger than \( n=2 \) and none of the conclusions drawn in this work are affected by the fitting method used.

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