The connection between mass, environment, and slow rotation in simulated galaxies

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ABSTRACT

Recent observations from integral field spectroscopy (IFS) indicate that the fraction of galaxies that are slow rotators (SRs), \( F_{SR} \), depends primarily on stellar mass, with no significant dependence on environment. We investigate these trends and the formation paths of SRs using the EAGLE and HYDRANGEA hydrodynamical simulations. EAGLE consists of several cosmological boxes of volumes up to \((100 \text{ Mpc})^3\), while HYDRANGEA consists of 24 cosmological simulations of galaxy clusters and their environment. Together they provide a statistically significant sample in the stellar mass range \(10^{9.5} - 10^{12.3} \text{ M}_\odot\), of 16 358 galaxies. We construct IFS-like cubes and measure stellar spin parameters, \( \lambda_R \), and ellipticities, allowing us to classify galaxies into slow/fast rotators as in observations. The simulations display a primary dependence of \( F_{SR} \) on stellar mass, with a weak dependence on environment. At fixed stellar mass, satellite galaxies are more likely to be SRs than centrals. \( F_{SR} \) shows a dependence on halo mass at fixed stellar mass for central galaxies, while no such trend is seen for satellites. We find that \( \approx 70\% \) per cent of SRs at \( z = 0 \) have experienced at least one merger with mass ratio \( \geq 0.1 \), with dry mergers being at least twice more common than wet mergers. Individual dry mergers tend to decrease \( \lambda_R \), while wet mergers mostly increase it. However, 30 per cent of SRs at \( z = 0 \) have not experienced mergers, and those inhabit haloes with median spins twice smaller than the haloes hosting the rest of the SRs. Thus, although the formation paths of SRs can be varied, dry mergers and/or haloes with small spins dominate.

Key words: galaxies: evolution – galaxies: formation – galaxies: kinematics and dynamics – galaxies: structure.

1 INTRODUCTION

Integral field spectroscopy (IFS) is opening a new window for exploring galaxy formation and evolution. Many recent surveys, such as ATLAS3D (Cappellari et al. 2011), Sydney-Australian Astronomical-Telescope Multi-object IFS (SAMI) (Croom et al. 2012; Bryant et al. 2015), Calar Alto Legacy Integral Field Area (Sánchez et al. 2012), MASSIVE (Ma et al. 2014), and Mapping Nearby Galaxies at the Apache Point Observatory (MaNGA) (Bundy et al. 2015) are exploring how the resolved kinematics of the stars and ionized gas relate to global galaxy properties, such as stellar mass, colour, star formation rate (SFR) and environment, among others. The most revolutionizing aspect of these surveys is that due to their significant volumes, they are able to observe many hundreds to many thousands galaxies spanning a very wide dynamic range in mass and environment. This enables the galaxy population to be dissected into many properties, but most significantly into stellar and environment, which are thought to be primary drivers in the evolution of galaxies (e.g. Peng et al. 2010).

One of the most prominent early examples of the success of IFS surveys was the pioneering work of the Spectrographic Area Unit for Research in Optical Nebulae (SAURON) (Bacon et al. 2001) and ATLAS3D (Cappellari et al. 2011) surveys, comprised of 260...
early-type galaxies in total. These surveys showed that the stellar kinematics and distributions of stars are not strongly correlated in early types, and thus that morphology is not necessarily a good indicator of the dynamics of galaxies (Krajnović et al. 2013). Based on these surveys, Elmegreen et al. (2007, 2011) coined the terms slow and fast rotators, and proposed the $\lambda_{20}$ parameter, which measures how rotationally or dispersion-dominated a galaxy is, as a new, improved scheme to classify galaxies. The most significant trend found by Elmegreen et al. (2011) and extended recently to higher stellar masses by Veale et al. (2017b), is that the fraction of slow rotators (SRs) increases steeply with stellar mass and towards denser environments, and that the vast majority of S0 galaxies are fast rotators.

Recent surveys spanning much larger volumes have been able to revisit this issue including the trends with environment. Brough et al. (2017), Veale et al. (2017b), and Greene et al. (2018) using the SAMI, MASSIVE, and MaNGA surveys, respectively, found that the fraction of SRs depends strongly on stellar mass, with a very weak or no dependence on environment once stellar mass is controlled for (see Houghton et al. 2013; D’Eugenio et al. 2013 for earlier studies on cluster regions). They found that the original environmental dependence reported in ATLAS$^{3D}$ (Elmegreen et al. 2011) was fully accounted for by massive galaxies preferentially living in denser environments. Interestingly, the three surveys reached the same conclusion despite the very different environments and mass ranges studied. Brough et al. (2017) focused on cluster galaxies only, while Greene et al. (2018) covered a much wider halo mass range, $M_{\text{halo}} = (10^{12} - 10^{15}) \, M_\odot$. Veale et al. (2017b) on the other hand make no environmental selection, but only study galaxies with stellar masses $\geq 10^{11} \, M_\odot$. Note, however, that Greene et al. (2018) observed a weak trend for satellite galaxies to display a slightly higher frequency of slow rotation than centrals at fixed stellar mass, but this trend is not significant. Thus, the question of whether there is an environmental effect on the incidence of slow rotation or not, and in which regimes it is more likely to be significant, remains unanswered.

The early results from SAURON and ATLAS$^{3D}$ prompted a wealth of simulations and theoretical work. Jesseit et al. (2009), Bois et al. (2011), and Naab et al. (2014), based on simulations of modest numbers of galaxies, found that the formation paths of SRs and fast rotators can be highly varied. Naab et al. (2014) showed that SRs could be formed as a result of wet or dry major mergers, or by dry minor mergers. In case of wet mergers, the remnant can be either a fast rotator or a SR, or even a disc (e.g. Springel 2000; Cox et al. 2006; Robertson et al. 2006; Johansson, Naab & Burkert 2009; Di Matteo et al. 2009; Peirani et al. 2010; Lotz et al. 2010; Naab et al. 2014; Moreno et al. 2015). Sparre & Springel (2017), however, found that galaxy remnants of major mergers can easily evolve into star-forming disc galaxies unless sufficiently strong feedback is present to prevent the disc regrowth. Similarly, Moster et al. (2011) concluded that even a dry merger remnant can become a fast rotator if the surrounding gaseous halo continues to cool down, fuelling the central galaxy and leading to disc regrowth. Naab et al. (2014) and Li et al. (2018) show that the shapes and the velocity anisotropies of galaxies can provide unique clues that may help disentangle the merger history of galaxies.

Although valuable insight can be gained from the idealized and cosmological zoom-in simulations above, they struggle to shed light into the effect of environment and in having an unbiased representation of different formation pathways. The latter comes naturally from large, cosmological hydrodynamical simulations, which have the ability to simultaneously follow the evolution of tens of thousands of galaxies in a very wide range of environments. Recently, there has been a major breakthrough in the capability of cosmological hydrodynamical simulations to produce realistic galaxy populations. This has been achieved thanks to improved subgrid models for unresolved feedback processes, the calibration of subgrid feedback parameters to match key observables, and the ability to run large cosmological volumes with sub-kpc resolution. Examples of these simulations include EAGLE (Schaye et al. 2015), Illustris (Vogelsberger et al. 2014), and its successor Illustris-TNG (Pillepich et al. 2018), and Horizon-AGN (Dubois et al. 2014).

The simulations above reproduce, with various degrees of success, the morphological diversity of galaxies observed in the local Universe, the galaxy colour bimodality, the SFR–stellar mass relation, the stellar mass function, and the cosmic SFR density evolution (e.g. Furlong et al. 2015b; Genel et al. 2014; Trayford et al. 2015, 2016; Snyder et al. 2015; Dubois et al. 2016; Nelson et al. 2018). Recently, Penoyre et al. (2017) analysed the formation path of thousands of elliptical galaxies in Illustris and concluded that major mergers were the most important formation path of SRs. Surprisingly, Penoyre et al. (2017) found no significant difference between the effect of dry versus wet mergers on the spin of galaxies, in contradiction with the work of Naab et al. (2014) on cosmological zooms. Li et al. (2018), also on the Illustris simulation, showed that the orbital parameters of the merger can affect the rotation of the remnant galaxy, with circular orbits preferentially producing fast rotators (see also Lagos et al. 2018).

In this paper, we use the EAGLE and HYDRANGEA simulations with the aim of exploring how the frequency of SRs depend on mass and environment. EAGLE simulated a box of 100cMpc$^3$, while HYDRANGEA is a suite of 24 cosmological zoom-in simulations of galaxy clusters and their environments (Bahré et al. 2017), which is part of the larger Cluster-EAGLE project (Barnes et al. 2017). The latter consists of 30 galaxy clusters (6 more than HYDRANGEA). The advantage of using HYDRANGEA here is that it resolves a larger Lagrangian region of $10^{200}$ for each cluster (as oppose to $5_{200}^{200}$ in Cluster-EAGLE), allowing us to study groups around clusters. Together EAGLE and HYDRANGEA span the halo mass range $10^{12} - 10^{15.3} \, M_\odot$ and provide large statistics. Given this wide dynamic range, we expect our simulations to be able to reveal an environmental dependence of the fraction of SRs if any is present. Our aim is to connect these dependencies with the different formation paths of SRs and to disentangle nurture versus nature in their formation.

EAGLE is an ideal test bed for our analysis, as it has been shown to reproduce the size–stellar mass relation (Furlong et al. 2015a; Katsianis et al. 2017) and the specific angular momentum–stellar mass relation (Lagos et al. 2017; Swinbank et al. 2017) throughout time, both of which reflect the ability of the simulation to reproduce structural and dynamical properties of galaxies. In addition, EAGLE reproduces very well the evolution of SFR properties of galaxies (Furlong et al. 2015b), colours (Trayford et al. 2015), the gas contents of galaxies (Bahé et al. 2016; Lagos et al. 2015, 2016; Crain et al. 2016), and produces both a blue cloud of predominantly discy galaxies, and a red sequence of mostly elliptical galaxies (Correa et al. 2017).

This paper is organized as follows. In Section 2, we briefly describe the EAGLE simulation suite and introduce the IFU-like cubes and the kinematic properties we measure in the simulated galaxies. Section 3 presents an analysis of the kinematic properties of simulated galaxies at $z = 0$ and the dependence on mass, environment, and morphology. Here, we also present a thorough comparison with observations. In Section 4, we study the physical origin of SRs in EAGLE by connecting kinematics with the formation history of galaxies. We present a discussion of our results and our main
Table 1. Features of the EAGLE Ref-L100N1504 and Ref-L050N752 and simulations used in this paper. The rows list: (1) initial particle masses of gas, (2) dark matter, (3) comoving Plummer-equivalent gravitational softening length, and (4) maximum physical gravitational softening length. Units are indicated in each row. EAGLE adopts (3) as the softening length at \( z \geq 2.8 \), and (4) at \( z < 2.8 \). These two simulations have volumes of side \( L = 100 \) and 50 cMpc\(^3\), respectively.

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Gas particle mass</td>
<td>( M_\odot )</td>
<td>( 1.81 \times 10^9 )</td>
</tr>
<tr>
<td>(2) DM particle mass</td>
<td>( M_\odot )</td>
<td>( 9.7 \times 10^6 )</td>
</tr>
<tr>
<td>(3) Softening length</td>
<td>[ckpc]</td>
<td>2.66</td>
</tr>
<tr>
<td>(4) Max. gravitational softening</td>
<td>[pkpc]</td>
<td>0.7</td>
</tr>
</tbody>
</table>

conclusions in Section 5. Finally, Appendix A presents our convergence studies.

2 THE EAGLE SIMULATION

The EAGLE simulation suite (described in detail by Schaye et al. 2015, hereafter S15, and Crain et al. 2015, hereafter C15) consists of a large number of cosmological hydrodynamic simulations with different resolutions, cosmological volumes, and subgrid models, adopting the Planck Collaboration XVI (2014) cosmological parameters. A major aspect of the EAGLE project is the use of state-of-the-art subgrid models, which include: (i) radiative cooling and photoheating (Wiersma, Schaye & Smith 2009a), (ii) star formation (Schaye & Dalla Vecchia 2008), (iii) stellar evolution and chemical enrichment (Wiersma et al. 2009b), (iv) stellar feedback (Dalla Vecchia & Schaye 2012), and (v) black hole (BH) growth and active galactic nucleus (AGN) feedback (Rosas-Guevara et al. 2015). S15 introduced a reference model, within which the parameters of the subgrid models governing energy feedback from stars and accreting BHs were calibrated to ensure a good match to the galaxy stellar mass function and the sizes of present-day disc galaxies. Table 1 summarizes the parameters of the simulation used in this work. Throughout the text, we use pkpc to denote proper kiloparsecs and cMpc to denote comoving megaparsecs.

In addition to the EAGLE suite, we also analyse the HYDRANGEA suite presented in Bahé et al. (2017). This suite consists of 24 cosmological zoom-in simulations of galaxy clusters and their large-scale environments in the halo mass range \( M_\text{halo} = 10^{14} - 10^{15.5} \ M_\odot \), with \( M_\text{200} \) denoting the total mass within a sphere of radius \( r_\text{200} \), within which the average density equals 200 times the critical density. These clusters were simulated with the same EAGLE reference model, but with a higher temperature to which AGN heat nearby gas particles, \( \Delta T_\text{AGN} \), and a higher viscosity parameter, \( C_\text{visc} \), that controls the effect of angular momentum on BH gas accretion. The reference EAGLE model adopted \( \Delta T_\text{AGN} = 10^{5.5} \text{K} \) and \( C_\text{visc} = 2 \pi r \), while HYDRANGEA adopted \( \Delta T_\text{AGN} = 10^{6} \text{K} \) and \( C_\text{visc} = 2 \pi r \times 10^2 \) (this model is referred to as AGNdT9 in S15; see their table 3). S15 compared the stellar mass function and size–mass relation at \( z = 0 \) of these two models (their figs 9 and 11), and showed that they agree to better than 10 per cent and 20 per cent, respectively. The HYDRANGEA outputs were analysed with the same tools employed in EAGLE, and described above. In Appendix A2, we compare the AGNdT9 and reference models on the same box, number of particles, and initial conditions, and show that AGNdT9 tends to produce a very similar number of SRs at \( 10^{10} \ M_\odot \gtrsim M_\text{stars} \gtrsim 10^{11} \ M_\odot \) compared to the reference EAGLE model (\( \approx 9 \) per cent).

Throughout the text, we will refer to ‘central’ and ‘satellite’ galaxies, where the central corresponds to the galaxy hosted by the main subhalo of a friends-of-friends halo, while other subhaloes within the group host satellite galaxies (Qu et al. 2017). Lagos et al. (2017) showed in a study of the specific angular momentum evolution of galaxies in EAGLE that an appropriate stellar mass cut above which galaxies have angular momentum profiles converged is \( M_\text{stars} \gtrsim 5 \times 10^9 \ M_\odot \). Thus, we adopt that threshold in this work (see Appendix A1 for a convergence study). EAGLE and HYDRANGEA have 5587 and 10771 galaxies, respectively, at \( z = 0 \) above this mass threshold, which compose the sample used in this work.

2.1 Kinematic measurements

In this paper, we measure the \( r \)-band luminosity-weighted line-of-sight velocity, velocity dispersion, stellar spin parameter \( \lambda_R \), and ellipticity of all galaxies in EAGLE in the simulations presented in Table 1 and the HYDRANGEA clusters. We describe our procedure below.

We first construct the stellar kinematic maps for each galaxy by projecting them on to a two-dimensional plane. We use two orientations: an edge-on view, in which the stellar spin is oriented along the y-axis of the image, and a random view, in which the line of sight is along the z-axis of the simulated box. We bin this two-dimensional image on to pixels of width \( w \) and construct a \( r \)-band luminosity-weighted velocity distribution for each bin, using the centre of potential of the galaxy as the rest frame. We adopted \( w = 1.5 \) pkpc (approximately twice the softening length of EAGLE; see Table 1). In Appendix A3, we show that the kinematic properties we measure are converged to better than 10 per cent. We only see significant convergence issues if the bin is chosen to be close to the softening length of the simulation or in galaxies of stellar masses \( \approx 5 \times 10^9 \ M_\odot \) when the bin is too similar to their \( r_\text{50} \). The chosen bin of 1.5 pkpc is very similar to the average spatial resolution of SAMI galaxies (1.6 pkpc; van de Sande et al. 2017).

We fit a Gaussian to the \( r \)-band luminosity line-of-sight velocity distribution of each pixel, and define the rotational velocity as the velocity at which the Gaussian peaks, and the velocity dispersion as the square root of the variance. This procedure closely mimics the measurements performed in IFS surveys, such as ATLAS\(^{3D}\) (Cappellari et al. 2011) and SAMI (van de Sande et al. 2017). The result of this procedure is shown in Fig. 1 for four relatively massive galaxies in the Ref-L050N752 simulation, two star forming and two passive, oriented edge-on. For this visualization, we use the KINEMETY package of Krajnović et al. (2006), and for the colour scale of the rotational velocity maps we adopt the range \([- V_{\text{max}}, V_{\text{max}}]\). Here, \( V_{\text{max}} \) is the maximum circular velocity expected for the stellar mass of the galaxy assuming the Tully–Fisher relation measured by Dutton et al. (2011). The purpose of this colour scheme is to make slow rotation visually evident. In general, we find that at fixed stellar mass, passive galaxies tend to be rounder and more slowly rotating than star-forming galaxies. We will come back to this in Section 3.

We construct velocity and luminosity maps, such as those in Fig. 1, for all galaxies in the simulations of Table 1 and in the HYDRANGEA cluster suite at \( z = 0 \). From these maps, we calculate the \( r \)-band luminosity-weighted spin parameter, \( \lambda_R \) at radii \( 0.5, 1, 1.5, 2, 3 \times r_\text{50} \), with \( r_\text{50} \) being the projected half-stellar mass radius. The ellipticities, \( \epsilon \), are calculated in the same apertures from the projected positions of particles following Cappellari et al. (2007).

\[
\epsilon = 1 - \sqrt{b^2/a^2},
\]
Figure 1. Examples of an edge-on view of the $r$-band luminosity (left), rotation (middle), and velocity dispersion (right) fields of four galaxies with $2 \times 10^{10} \, M_\odot < M_{\text{stars}} < 10^{11} \, M_\odot$ at $z = 0$ in the Ref-L050N752 simulation. Axes show distance from galaxy centre in pkpc. The top two galaxies have SFR $> 6 \, M_\odot \, \text{yr}^{-1}$, while the bottom two have SFR $< 0.2 \, M_\odot \, \text{yr}^{-1}$. The colour scales are indicated at the top of each panel, and in the case of the rotational velocity map, we force the range $[-V_{\text{max}}, V_{\text{max}}]$, where $V_{\text{max}}$ is the maximum circular velocity expected for the stellar mass of the galaxy given the Tully–Fisher relation measured by Dutton et al. (2011). The physical scale of the images is shown along the axes and is in pkpc. Circles show 1 and 2 $r_{50}$ of the galaxies, while ellipses are constructed using our ellipticity measurements at 1 and 2 $r_{50}$ (see equation 1). From top to bottom, the values of $\epsilon_{150}$ are 0.6, 0.65, 0.12, and 0.19, respectively.
Connecting kinematics, mass, and environment

where,
\[ a^2 = \frac{x^2 + y^2}{2} + \sqrt{\left(\frac{x^2 - y^2}{2}\right)^2 + xy}, \]
\[ b^2 = \frac{x^2 + y^2}{2} - \sqrt{\left(\frac{x^2 - y^2}{2}\right)^2 + xy}, \]
and,
\[ \chi^2 = \sum_i L_i x_i^2, \quad \tilde{y}^2 = \sum_i L_i y_i^2, \quad \tilde{x}y = \sum_i L_i x_i y_i. \]
Here, \( i \) corresponds to the stellar particles inside the aperture wherein we wish to measure \( \epsilon \). \( \epsilon \) is the \( r \)-band luminosity of the particle, \((x_i, y_i)\) are their \( x \) and \( y \) positions in the projected map. This measurement of \( \epsilon \) is equivalent to diagonalizing the inertia tensor of the galaxy’s luminosity surface density. We also calculate the position angle of the major axis of the galaxy (measured counterclockwise from \( y = 0 \)) as
\[ \theta_{\text{PA}} = \frac{1}{2} \arctan \left( \frac{2xy}{x^2 - y^2} \right). \]
Examples of the values of \( \epsilon \) obtained via this method are shown in Fig. 1. We then calculate \( \lambda_R \) as
\[ \lambda_R = \frac{\sum_i r_i V_i}{\sum_i r_i V_j^2 + \sigma_j^2}, \]
where \( V_i \) and \( \sigma_j \) are the \( r \)-band luminosity-weighted line-of-sight mean and standard deviation velocities in the pixel \( j \) of the velocity maps calculated as described above, and \( r_i \) is the distance from the centre of the galaxy to the pixel (i.e. the circular radius). As in Emsellem et al. (2011), to measure these quantities within \( r \), we include only pixels enclosed by the ellipse of major axis \( r \), ellipticity \( \epsilon \), and position angle \( \theta_{\text{PA}} \).
IFS surveys typically compare \( \epsilon \) and \( \lambda_R \) measured within the same aperture (typically an effective radius; e.g. Emsellem et al. 2011 and van de Sande et al. 2017). We follow this and compare \( \lambda_R \) and \( \epsilon \) measured within \( r_{50} \), and refer to these as \( \lambda_{r_{50}} \) and \( \epsilon_{r_{50}} \), respectively, unless otherwise stated.

2.2 Galaxy mergers

We use the merger trees available in the EAGLE data base (McAlpine et al. 2015) to identify merger galaxies (see Qu et al. 2017 for details on how these trees are constructed). Galaxies that went through mergers have more than one progenitor, and we track the most massive progenitor to compare their kinematic properties with that of the merger remnant. The trees used here connect 29 epochs, with time span between snapshots ranging from \( \approx 0.3 \) to \( \approx 1 \) Gyr. Lagos et al. (2018) showed that these time-scales are appropriate to study the effect of galaxy mergers on the specific angular momentum of galaxies, as mergers roughly take that time to settle.

We split mergers into major and minor mergers. The former are those with a stellar mass ratio between the secondary and the primary galaxies \( \geq 0.3 \), while minor mergers have a mass ratio between 0.1 and 0.3. Lower mass ratios are classified as smooth accretion (Crain et al. 2016). In addition, and following Lagos et al. (2018), we split mergers into gas-rich (wet) and gas-poor (dry) based on the neutral gas (atomic plus molecular) to stellar mass ratio of the merger:
\[ R_{\text{gas,merger}} = \frac{M_{\text{neutral}}^* + M_{\text{neutral}}^p}{M_{\text{stars}}^* + M_{\text{stars}}^p}, \]
where \( M_{\text{neutral}}^* \) and \( M_{\text{neutral}}^p \) are the neutral gas masses of the secondary and primary galaxies, respectively, while \( M_{\text{stars}}^* \) and \( M_{\text{stars}}^p \) are the corresponding stellar masses. Here, we classify mergers with \( R_{\text{gas,merger}} \leq 0.1 \) as dry, and the complement as wet. For dry mergers, the average \( R_{\text{gas,merger}} \) is \( \approx 0.02 \).

We calculate the orbital specific angular momentum of the merger, \( j_{\text{orbital}} \), as \( j_{\text{orbital}} = |\mathbf{r} \times \mathbf{v}| / \mu \), with \( \mathbf{r} \) and \( \mathbf{v} \) being the position and velocity vectors, respectively, of the secondary galaxy in the rest frame of the primary.

Masses are measured within an aperture of 30 pkpc. The fraction of atomic and molecular gas in gas particles are calculated in post-processing following Rahmati et al. (2013) and Lagos et al. (2015).

3 KINEMATIC PROPERTIES OF EAGLE GALAXIES

We visually inspect the kinematic morphology of galaxies in the \( \lambda_{r_{50}}-\epsilon \) plane, which has been proposed by Emsellem et al. (2007) as an effective way of distinguishing slow and fast rotators. Fig. 2 shows the rotational velocity maps of randomly selected galaxies in bins of \( \lambda_{r_{50}} \) and \( \epsilon \). We construct the maps as in Fig. 1. Lines indicate different ways of defining SRs from the literature. There is an evident transition at around \( \lambda_{r_{50}} \approx 0.2 \) below which galaxies appear deficient in rotation. By inspecting the edge-on orientation maps of galaxies that are classified as SRs in EAGLE, we confirm their deficient rotation out to 3 \( r_{50} \). If EAGLE galaxies are a good representation of real ones, this would mean that SRs would be classified as such even if we had kinematics extending out to much larger radii than available (typically kinematics is available only at \( r \approx r_{50} \)). On the other hand, galaxies with \( 0.2 \lesssim \lambda_{r_{50}} \lesssim 0.4 \) reach their expected rotational velocity at 2 – 3 \( r_{50} \), while galaxies with \( \lambda_{r_{50}} \gtrsim 0.4 \) reach it by \( \approx r_{50} \). Fig. 2 indicates that \( \lambda_{r_{50}} \) is a good proxy for the kinematic structure of galaxies, as suggested by Emsellem et al. (2007, 2011).

In Fig. 3, we visually compare the positions of galaxies in the \( \lambda_{r_{50}}-\epsilon \) plane in the Ref-L100N504 and HYDRANGEA simulations with those of the observational surveys ATLAS3D (Emsellem et al. 2011), MASSIVE (Veale et al. 2017a), and SAMI (van de Sande et al. 2017). The former two are volume-limited surveys of early-type galaxies, while SAMI is a stellar mass-selected survey, thus including both late and early types. Since we include all galaxies with \( M_{\text{stars}} \gg 5 \times 10^9 M_\odot \) in the simulations, our results may be more comparable to SAMI. The sizes and colours of the symbols scale with stellar mass, so that the most massive galaxies appear as larger symbols.

SAMI appears to have systematically lower \( \lambda_{r_{50}} \) compared to ATLAS3D, which is not surprising as the measurements are not performed exactly in the same way. In ATLAS3D, Emsellem et al. (2011) adopted the radial distance to the luminosity centre as \( r_i \) in equation (5), while in SAMI, van de Sande et al. (2017) adopted the semi-major axis of the ellipse that goes through the given bin as \( r_i \) in equation (5).

Our calculation of \( \lambda_{r_{50}} \) resembles more closely that in ATLAS3D. In the three surveys, galaxies with \( M_{\text{stars}} \gtrsim 10^{11.5} M_\odot \) (largest symbols in Fig. 3) preferentially have low \( \lambda_{r_{50}} \), and the same is seen to some extent in the HYDRANGEA simulation, but in the Ref-L100N504 simulation few massive galaxies below the observational delimitation of SRs. Compared to MASSIVE (middle panel in Fig. 3), it is apparent that our simulations do not produce the right fraction of SRs at the very massive end. We will come back to this in Section 3.1.
Both simulations lack the very high ellipticity galaxies, $\epsilon_{r50} \gtrsim 0.75$. The latter may be due to the subgrid interstellar medium physics included in the simulations, which prevents very flat Milky Way-like discs from forming. In EAGLE, a global temperature floor, $T_{\text{cos}}(\rho)$, is imposed corresponding to a polytropic equation of state $P_{\text{eos}} \propto \rho^{\gamma_{\text{eos}}}$, normalized to $T_{\text{eos}} = 8000$ K and $n_H = 0.1$ cm$^{-3}$. In addition, a second temperature floor of 8000 K is imposed on gas with $n_H > 10^{-3}$ cm$^{-3}$, preventing the metal-rich gas from cooling below that threshold. This sets a minimum disc height of $\lesssim 1$ kpc, larger than the Milky Way or other grand-design spiral galaxies, which exhibit scale heights typically of $\approx 0.4$ kpc (Kregel, van der Kruit & de Grijs 2002). Thus, it is not surprising that very flat galaxies do not exist in EAGLE or HYDRANGEA. Appendix A1 shows that increasing the resolution by a factor of 8 in mass and 2 in spatial resolution does not significantly change the ellipticity of galaxies, supporting our conclusion. The topic of convergence in the formation of elliptical galaxies is contingent. Bois et al. (2010) performed a resolution study of idealized galaxy mergers and concluded that the product of wet mergers was resolution dependant, and that their role on the formation of SRs may be underestimated in simulations such as EAGLE. However, more recently Sparre & Springel (2016, 2017) showed in cosmological zooms of galaxy mergers that environment and feedback play a decisive role in the fate of the remnant, more so than the resolution. Our resolution tests show no evidence for convergence issues at the stellar masses we are investigating, on average, but we cannot rule out that individual cases may be more affected.

Fig. 4 shows $\lambda_{r50}$ as a function of stellar mass for galaxies in the Ref-L100N1504 and HYDRANGEA simulations at $z = 0$. We use different symbols to show starburst (SB), main-sequence (MS), and passive galaxies. We define the latter in terms of their specific star formation rate, $s\text{SFR} = \text{SFR}/M_{\text{stars}}$, relative to the MS at that stellar mass. We calculate the latter as in Furlong et al. (2015b). In short, the MS is calculated as the median $s\text{SFR}$ of all galaxies that have $s\text{SFR} > 0.01$ Gyr$^{-1}$ in a bin of stellar mass. We refer to this as $\langle s\text{SFR}(M) \rangle$. We then calculate the $s\text{SFR}$ of galaxies relative to the MS, $\delta_{\text{MS}} = \frac{s\text{SFR}}{\langle s\text{SFR}(M) \rangle}$.

SB, MS, and passive galaxies are classified as those with $\delta_{\text{MS}} \geq 4$, $0.1 < \delta_{\text{MS}} < 4$ and $\delta_{\text{MS}} < 0.1$, respectively.
Connecting kinematics, mass, and environment

Figure 3. $\lambda_{r50}$ as a function of $\epsilon_{r50}$ for galaxies in the ATLAS$^{3D}$ (Emsellem et al. 2011; top panel), MASSIVE (Veale et al. 2017a; second panel), and SAMI (van de Sande et al. 2017; third panel) surveys, and for the simulations Ref-L100N1504 (fourth panel), and HYDRANGEA (bottom panel). Galaxies in the two simulations are randomly oriented. Lines show the classification of slow and fast rotators from Emsellem et al. (2007), Emsellem et al. (2011), and Cappellari (2016), as dashed, solid, and dotted lines, respectively. Sizes and colours of the symbols correspond to different stellar masses, as labelled in the top panel.

Figure 4. $\lambda_{r50}$ as a function of stellar mass for galaxies in the Ref-L100N1504 (top panel) and HYDRANGEA (bottom panel) simulations. Lines and error bars show the median and 16th–84th percentile ranges, respectively, for galaxies that are classified as SB, MS or passive (P), as labelled. We define the above samples based on $\delta_{MS}$: $>4$, $0.1-4$, $<0.1$. Only bins with $\geq 5$ objects are shown.

In both simulations passive galaxies tend to have a lower $\lambda_{r50}$ than MS galaxies at fixed stellar mass. SB galaxies have a slightly higher median $\lambda_{r50}$ than MS galaxies but the scatter is much larger. In HYDRANGEA most of the galaxies with $M_{stars} \gtrsim 10^{11.7} M_\odot$ are passive, which is expected given that the environments of these simulations are designed to represent the densest in the Universe. We also see that MS galaxies show a clear peak at $M_{stars} \approx 10^{10.8} M_\odot$ below and above which galaxies display a decrease in $\lambda_{r50}$. This peak is also seen in the FIRE simulations (El-Badry et al. 2018). Passive galaxies also exhibit a peak but only in the HYDRANGEA simulation, which may be due to poor statistics in the passive population in the Ref-L100N1504 simulation below that transition mass.

3.1 The fraction of slow rotators in EAGLE

Due to the availability of large IFS surveys, there has been a lot of recent interest in how the fraction of SRs depends on stellar mass and environment. Veale et al. (2017b), Brough et al. (2017), and Greene et al. (2018) found that the fraction of SRs depends strongly on stellar mass, with a very weak dependence on environment once stellar mass is controlled for. Similar results have been reported from the study of galaxy shapes (Pasquali, van den Bosch & Rix 2007). The complementarity of EAGLE and HYDRANGEA in dynamical mass allows us to explore a very wide range of environments and hence to study this question.

Fig. 5 shows the fraction of SRs, $F_{SR}$, as a function of stellar mass at $z = 0$ in the Ref-L100N1504 and HYDRANGEA simulations, using
the three definitions of SRs shown in Fig. 3. The two simulations agree well at $M_{\text{stars}} \lesssim 10^{10.8} M_{\odot}$ within the uncertainties, but there are some differences worth noting. Both simulations show that there is a clear transition at $M_{\text{stars}} \approx 10^{11} M_{\odot}$ above which $F_{\text{SR}}$ starts to raise quickly, except for the highest mass bin, in which we see a flattening or downturn, depending on the criteria adopted to classify SRs. In the case of the Ref-L100N1504 simulation, this is due to applying a Gaussian error of width 0.05 to the values of $\lambda_R$.

In Fig. 5, we also show a compilation of observations from the SAMI, ATLAS3D, and MASSIVE surveys. Both simulations agree remarkably well with the observations at $M_{\text{stars}} \lesssim 10^{11.2} M_{\odot}$, with some tension arising at $M_{\text{stars}} \gtrsim 10^{11.5} M_{\odot}$. We show below that this is caused by unrealistic properties of our simulated BCGs. In our simulations, $F_{\text{SR}}$ does not rise above $\approx 0.7$ in disagreement with the observations. We show later (Fig. 7) that $F_{\text{SR}}$ at $M_{\text{stars}} \gtrsim 10^{11.2} M_{\odot}$ is very sensitive to environmental effects and a slightly different preference for satellites over central galaxies can significantly skew $F_{\text{SR}}$.

Central galaxies in the HYDRANGEA simulation show a downturn at much larger masses ($\gtrsim 10^{11} M_{\odot}$). Because the HYDRANGEA suite covers large regions around the 24 resimulated clusters (out to $10 r_{50}$), there are in total 34 haloes with those masses in the suite, and thus the same number of BCGs.

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The effect of satellite/central galaxies in the Ref-L100N1504 and HYDRANGEA simulations is shown in Fig. 6. For clarity, we only show the classifications of SRs of Cappellari (2016). Adopting instead the Emsellem et al. (2011) criterion after applying a Gaussian error of width 0.05 to the values of $\lambda_R$.

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Therefore likely that more efficient feedback at high redshift would not only lead to more realistic stellar masses and SFRs of these BCGs, but also increase their SR fraction (see also Barnes et al. 2017).

Fig. 7 also shows that satellite galaxies reach an $F_{\text{SR}} \gtrsim 0.5$ at $M_{\text{stars}} \approx 10^{11.5} M_\odot$ in better agreement with the observations. Since both surveys, ATLAS3D and MASSIVE, are volume-limited, $\approx 42$ per cent of those are satellite galaxies, 24 per cent are brightest group/cluster galaxies, and the rest are field galaxies. Thus, it is not surprising that satellite galaxies better follow the results from MASSIVE. In the Ref-L100N1504 and HYDRANGEA simulations, there is a clear environmental effect that becomes apparent when comparing satellites and centrals at fixed stellar mass (Fig. 6).

Recently, Greene et al. (2018) found differences between satellite/central early-type galaxies in MaNGA of a similar magnitude to the one found in our simulations. Their observations are shown as shaded bands in Fig. 7. Greene et al. found that satellites are $\approx 20$ per cent more likely to be SRs than centrals. They, however, cautioned that due to the different spatial coverage and slightly different stellar mass distribution, this difference between satellites and centrals is not obviously significant. In EAGLE and HYDRANGEA, the $F_{\text{SR}}$ differences between these two populations are present over the entire mass range, albeit with differences been very small at $M_{\text{stars}} < 10^{10.3} M_\odot$. Note, however, that the Greene et al. (2018) SR fraction is generally higher than both the Ref-L100N1504 and HYDRANGEA simulations and the observations from ATLAS3D, SAMI, and MASSIVE.

Greene et al. (2018) measured $\lambda_5$ out to larger radii than ATLAS3D, SAMI, and MASSIVE, and in addition they measured ellipticities from a single Sérsic index fit to their images. Greene et al. (2018) adapted the SR classification criteria of Emsellem et al. (2011) to work with their measurements, and argued that about 10 per cent of their galaxies would change classification from SRs to fast rotator if the measurements were done at $r_{50}$. None the less, the reported $F_{\text{SR}}$ is higher by a factor of $\approx 25$ per cent at least compared to other IFS surveys; hence, there probably are other systematic effects that have not yet been taken into account. Since these authors analysed only early-type galaxies, we also show in Fig. 7 the $F_{\text{SR}}$--$M_{\text{stars}}$ relation for passive galaxies (those with a $\delta$MS $< 0.1$). $F_{\text{SR}}$ is higher for centrals being $\approx$ 2 times larger than for satellites at $M_{\text{stars}} \lesssim 10^{10.7} M_\odot$.

We explore the effect of environment on $F_{\text{SR}}$ further by studying the dependence on halo mass for centrals and satellite galaxies in Fig. 8. Here, we combined the galaxy populations of the Ref-L100N1504 and HYDRANGEA simulations at $z = 0$. The top panel of Fig. 8 shows central galaxies. There is a trend of increasing $F_{\text{SR}}$ with increasing halo mass, at fixed stellar mass. Since stellar and halo mass are well correlated for central galaxies in EAGLE (Schaye et al. 2015; Guo et al. 2015), the overlap in stellar mass between the different halo mass bins is only partial. We quantify the environmental dependence in the stellar mass range where overlap occurs: (i) at $M_{\text{stars}} = 10^{10.1} - 10^{10.8} M_\odot$, centrals hosted by haloes of masses $10^{12.2} - 10^{13.7} M_\odot$ are 2 times more likely to be SRs than centrals in haloes of masses $< 10^{12.2} M_\odot$.

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**Figure 7.** The fraction of SRs obtained by applying the Cappellari (2016) classification to the HYDRANGEA simulations, separating central and satellite galaxies. BCGs are not included in this figure. Dotted lines show all galaxies in the samples, while solid lines show the subsample of galaxies that have an sSFR relative to the MS $\lesssim 0.1$. The observations of Greene et al. (2018) using MaNGA early-type galaxies are shown as lines with shaded regions indicating the 1$\sigma$ scatter.

**Figure 8.** Top panel: $F_{\text{SR}}$ as a function of stellar mass for central galaxies at $z = 0$ in the combined galaxy sample of the Ref-L100N1504 and HYDRANGEA simulations. Here, we only show the SR classification of Cappellari (2016). Central galaxies are shown in four bins of halo mass: $< 10^{12.2} M_\odot$ (solid line), $10^{12.2} - 10^{12.8} M_\odot$ (dotted line), $10^{12.8} - 10^{13} M_\odot$ (dashed line), and $> 10^{13} M_\odot$ (filled circle; as in Fig. 7). Error bars show 1 standard deviation calculated with 10 jackknife resamplings in each stellar mass bin. Observations are shown as symbols, as labelled. Bottom panel: as in the top panel but for satellite galaxies. Here, we adopt halo mass bins of: $10^{12} - 10^{13} M_\odot$ (solid line), $10^{13} - 10^{14} M_\odot$ (dotted line), $10^{14} - 10^{14.3} M_\odot$ (dashed line), and $> 10^{14.3} M_\odot$ (dot–dashed line). There is a weak but significant systematic effect of $F_{\text{SR}}$ increasing with increasing halo mass at fixed stellar mass for central galaxies, with no clear trend in case of satellites.
On the other hand, we predict that the halo mass effect on SRs should be detectable in the population of centrals and passive satellite galaxies, but only if a wide range of halo masses is explored, $10^{13} \mathrm{M}_\odot \lesssim M_{\text{halo}} \lesssim 10^{15} \mathrm{M}_\odot$.

**4 THE PHYSICAL ORIGIN OF SLOW ROTATORS**

In this section, we analyse the physical origin of SRs in two ways. First, we analyse the merger history of galaxies that at $z = 0$ are SRs to establish how correlated their low $\lambda_R$ is with the presence and type of mergers they suffered throughout their lives, if any. Second, we analyse the effect that individual merging events have on $\lambda_R$ and $\epsilon$ by comparing the kinematic properties of the main progenitors and merger remnants. Lagos et al. (2018) analysed the merger history of galaxies in the Ref-L100N1504 simulation, adding information on the cold gas masses of merging galaxies, orientation of mergers, orbital angular momentum, and mass ratios. We use this extended merger catalogue to study the connection between mergers and slow rotation. Thus, here we focus solely on the Ref-L100N1504 simulation. We classify mergers as dry ($R_{\text{gas, merger}} \geq 0.1$), wet ($R_{\text{gas, merger}} > 0.1$), major (secondary to primary stellar mass ratio, $m_2/m_1 \geq 0.3$), and minor ($0.1 < m_2/m_1 < 0.3$; see Section 2.2).

We take all galaxies at $z = 0$ in the Ref-L100N1504 simulation and split them into five samples: (i) galaxies that have not suffered mergers, those that have not suffered major mergers, but have suffered either (ii) dry or (iii) wet minor mergers, and those that have had major mergers either (iv) dry or (v) wet. Galaxies that suffered major mergers could have also suffered minor mergers, but from the samples of minor mergers we remove all galaxies that had at least one major merger. This is done under the premise that major mergers have a more important effect on galaxy properties than minor mergers. This is supported by our previous results (Lagos et al. 2018). Our selection is based on the merger history of galaxies over the last 10 Gyr (i.e. approximately since $z = 2$).

Fig. 10 shows the median $\lambda_{\text{R0}}$ as a function of $M_{\text{stars}}$ and $\epsilon_{\text{R0}}$ for galaxies at $z = 0$ that have $M_{\text{stars}} > 5 \times 10^{10} \mathrm{M}_\odot$, separated in the five samples above, i.e. depending on their merger history. Here, we do not distinguish between recent or far in the past mergers, but simply count their occurrence. We see a clear connection between the incidence of dry mergers (either major or minor) with slow rotation in galaxies with $M_{\text{stars}} > 10^{10} \mathrm{M}_\odot$. On average, galaxies that went through dry major mergers have a lower $\lambda_{\text{R0}}$ than those that went through dry minor mergers. The remnants of wet major mergers also tend to have relatively low $\lambda_{\text{R0}}$, but not enough to place them on the slow rotation class, though $\approx$10 per cent of the wet major merger sample are SRs. Galaxies that had wet minor mergers have slightly larger $\lambda_{\text{R0}}$ at fixed $\epsilon_{\text{R0}}$ than galaxies that have not had mergers, possibly reflecting the fact that the former are on average a lot more gas-rich (average neutral gas to stellar mass ratio of 19 per cent compared to 6 per cent in the latter sample). In Lagos et al. (2017) we showed, also using EAGLE, that continuous gas accretion and star formation efficiently spin-up galaxies because the angular momentum brought by newly accreted gas is expected to grow proportionally with time (Catelan & Theuns 1996). Regardless of this effect, we find that the parameter space of $\lambda_{\text{R0}}$, $0.7$ and $\epsilon \lesssim 0.6$ is almost exclusively occupied by galaxies that have not had any mergers.

The fact that wet minor mergers appear to only slightly affect galaxies agrees with the conclusions of Lagos et al. (2018), in which it was shown that galaxies undergoing wet minor mergers have angular momentum radial profiles similar to galaxies that have
not had mergers. The exception is the very centres of those galaxies, as the remnants of wet minor mergers tend to have slightly more massive bulges (see their fig. 6). Although there is a clear trend between how galaxies populate the $\lambda_{50} - M_{\text{stars}}$ and $\epsilon_{50} - \epsilon_{50}$ planes and their merger history, the scatter is large, suggesting that mergers result in a plethora of remnants with no unique outcome. Our results support the findings of Naab et al. (2014) though with ≈50 times more mergers, which allows us to disentangle preferred formation mechanisms.

To disentangle the formation paths of SRs in EAGLE, we focus on their merger history as a function of stellar mass. The top panel of Fig. 11 shows the fraction of SRs that went through the four merging scenarios described above (wet/dry minor mergers and wet/dry major mergers), as a function of stellar mass at $z = 0$. We also show as black lines the fraction of SRs that had any form of merger with $m/s/m_p \geq 0.1$. We define SRs using the Cappellari (2016) criterion.

At $10^{10} M_\odot \lesssim M_{\text{stars}} \lesssim 3 \times 10^{10} M_\odot$, ≈40 per cent of SRs have not had any mergers. This percentage decreases systematically with
increasing stellar mass, and by $M_{\text{stars}} > 10^{11} M_\odot$, 96 per cent of the SRs had at least one merger during their past 10 Gyr. Among the SRs that had mergers, the most common type of merger is dry major merger, followed by minor mergers and wet major mergers.

In the bottom panel of Fig. 11, we separate centrals and satellites. The prevalence of dry major mergers is more significant in central galaxies. Here, dry major mergers are twice more common in SRs than the other forms of mergers. For satellites, we see that the different types of mergers have a similar incidence and dry minor mergers become more prevalent at $M_{\text{stars}} \gtrsim 10^{10.6} M_\odot$. This shows that the importance of mergers and their type for slow rotation may have an environmental dependence. Nevertheless, there is a clear connection between dry mergers and SRs, but we still need to establish whether there is a causal connection between the two. We come back to this in Section 4.1 where we analyse the effect of individual merger events on $\lambda_{50}$ and $\epsilon_{50}$.

In Fig. 12, we show the history of $\lambda_{50}$ of galaxies that at $z = 0$ are classified as SRs. For the latter, we apply a simple cut of $\lambda_{50} \leq 0.1$ (Emsellem et al. 2007). To make the interpretation easier, we show the history of $\lambda_{50}$ measured after orienting galaxies edge-on (i.e. $\lambda_{50}$ takes its maximum value). We separate SRs that have only had minor mergers (top panel), and that have had major mergers (bottom panel). The latter could also have had minor mergers. In addition to minor and major mergers, we distinguish between different numbers of mergers (either wet or dry), and also show separately the SRs that had dry mergers. Symbols show the median mass-weighted stellar age of the galaxies in the different samples. SRs that have not experienced any minor or major mergers were born with low $\lambda_{50}$ values, and at a lookback time of 8.5 Gyr, which is roughly the median mass-weighted stellar age of all these galaxies, they have $\lambda_{50}$ at least twice smaller than the rest of the galaxies. This is driven by the environments in which these galaxies formed. We come back to this in Section 4.2.

The top panel of Fig. 12 shows that there is a cumulative effect of minor mergers, in which galaxies could have started with a high $\lambda_{50}$ but lost it through successive minor merger events. Note that those SRs that only had one minor merger, started with relatively low $\lambda_{50}$. The subsample of SRs that had at least one dry minor merger shows the most dramatic evolution of $\lambda_{50}$ (i.e. the fastest decrease), again supporting our conclusion that dry mergers are most effective at producing SRs. In the case of galaxies having $\lambda_{50} \gtrsim 3$ minor mergers, a fast decrease of $\lambda_{50}$ is also seen, but this sample includes only 13 galaxies at $z = 0$. Penoyre et al. (2017) recently analysed the Illustris simulation and concluded that they do not see a cumulative effect of minor mergers, in contradiction with the findings of Naab et al. (2014) and our results here. Given how sensitive the outcome of mergers are to their gas fraction (see Section 4.1), one possible explanation to the different findings is that EAGLE produces a different gas fraction evolution of galaxies compared to Illustris, impacting the effect mergers have on galaxies. However, because the nature of these simulations is complex, with many processes acting simultaneously at any one time, it is hard to conclusively say what drives the differences between EAGLE and Illustris.

The bottom panel of Fig. 12 shows that single major mergers generally have a stronger effect than single minor mergers on the history of $\lambda_{50}$. This is clear when comparing the dashed lines between the top and bottom panels of Fig. 12, where galaxies that went through one major merger started with $\lambda_{50} \approx 0.45$, on average, while those that went through one minor merger started with $\lambda_{50} \approx 0.35$, on average. Major mergers also display a cumulative effect, but given how much rarer they are compared to minor mergers (see fig. 2 in Lagos et al. 2018), the significance of this is minimal for the entire galaxy population; i.e. there are only 11 galaxies in the entire simulated volume that had $\geq 2$ major mergers in the last 10 Gyr. When selecting SRs that had at least one dry major merger, we see a much more drastic decrease in $\lambda_{50}$. In Section 4.1, we show that dry mergers are connected with the most significant decrease in $\lambda_{50}$ in individual merger events.

For both minor and major mergers, we see that SRs that went through dry mergers, experience a rapid decrease of $\lambda_{50}$ at lookback times $\lesssim 6$ Gyr. This is due to the dry merger rate increasing rapidly after that epoch towards $z = 0$. On the other hand, the total merger rate decreases smoothly, which explains why the $\lambda_{50}$ evolutionary
tracks of galaxies that suffered one or two mergers display a smoother decrease.

The fact that all the galaxies that at $z = 0$ are SRs display an overall spin-down throughout their lives even in the absence of mergers, is probably connected to the evolution of the local environment in which galaxies and haloes reside. Welker et al. (2015) show that haloes, as they move from high-vorticity regions in the cosmic web towards the filaments and nodes, start to be subject to less and less coherent gas accretion. In the limit of nodes in the cosmic web, accretion happens a lot more isotropically than in the high-vorticity regions or filaments, with several filaments connecting to the node from different directions. High-vorticity regions accrete gas from preferential directions, thus gaining more coherent angular momentum. The overall spin-down we see in massive galaxies and haloes preferential directions, thus gaining more coherent angular momentum. In order to determine the effect that individual mergers have on the rotation of galaxies, we take all the minor and major mergers that have primary galaxies with $M_{\text{stars}} \geq 10^{10} \, M_\odot$ from $z = 0$ to 2, and compute the change in $\lambda_R$ before and after the merger. Note that here we do not distinguish between descendants that are slow/fast rotators, but take all mergers. We then compare $\lambda_R$ between the main progenitor (the most massive) in the last snapshot, the two merging galaxies were identified individually and the merger remnant. The latter corresponds to the first snapshot in which the two galaxies appear merged. Typically, the time-scale between these snapshots is $\approx 0.5$ Gyr. We define

$$\delta \lambda_R = \frac{\lambda_{R,\text{rem}}}{\lambda_{R,\text{prog}}},$$

with $\lambda_{R,\text{rem}}$ and $\lambda_{R,\text{prog}}$ being the remnant’s and main progenitor’s $\lambda_R$, respectively.

Fig. 14 shows $\delta \lambda_{\text{prog}}$ (measured at $r_{50}$) as a function of the cold gas to stellar mass ratio of the merger, $R_{\text{gas, merger}}$ (equation 6). We show minor and major mergers separately. The right-hand panel of Fig. 14 shows the subsample of galaxies with $M_{\text{stars}} \geq 10^{11} \, M_\odot$. There is a positive correlation between $\delta \lambda_{\text{prov}}$ and $R_{\text{gas, merger}}$, but with an offset in normalization in a way that major mergers are 25 per cent more likely to decrease $\lambda_R$ compared to minor mergers. Major mergers also do this to a greater extent than minor mergers, decreasing $\lambda_R$ by 39 per cent compared to 12 per cent in the latter, on average. Galaxy minor (major) mergers with $R_{\text{gas, merger}} \geq 0.5$ (0.8) have a clear preference for increasing $\lambda_R$, while those with $R_{\text{gas, merger}} < 0.1$ have a strong preference for decreasing $\lambda_R$. However, the scatter around the median relation is large, suggesting that the effect of a merger on $\lambda_R$ is not uniquely determined by its mass ratio and gas fraction. Penoyre et al. (2017) found in Illustris that major mergers, regardless of their gas fraction, are connected with the spinning down of galaxies, in contradiction with our findings. This may be due to their major mergers being mostly gas poor (gas-to-stellar mass ratios $\leq 0.1$; see their fig. 13), thus, lacking the very gas-rich major mergers we obtain in EAGLE that spin-up galaxies ($R_{\text{gas, merger}} \geq 0.8$).

Focusing specifically on dry mergers ($R_{\text{gas, merger}} \leq 0.1$), we find that in $\approx 15$ per cent of the major mergers $\lambda_R$ increases, while for minor mergers, this fraction is 25 per cent. Selecting only massive galaxies in EAGLE (right-hand panel in Fig. 14) does not change the correlation between $\delta \lambda_{\text{prov}}$ and $R_{\text{gas, merger}}$ significantly. We analysed $\delta \lambda_{2\text{ini}}$ (measured at $2 \, r_{50}$) and found a very similar relation to that shown in Fig. 14. This suggests that mergers modify $\lambda_R$ in a similar
also studied the effect of alignments of the rotation axis of the merger pair and found no effect on $\lambda_R$ (not shown here).

Li et al. (2018) analysed the effect of the merger orbits on the shape and $\lambda_R$ of merger remnants using the Illustris simulation, and found that circular orbits tend to produce fast rotators, while radial orbits produce SRs. In our calculation, radial orbits correspond to low $j_{\text{orbital}}$, and in agreement with Li et al., we find that the decrease in $\lambda_R$ is the largest in these cases. However, the scatter around the median is very large, and the dependence on $R_{\text{gas,merge}}$ is stronger. This agrees with the conclusion of Lagos et al. (2018), who showed that the gas fraction of the merger is the most fundamental property determining the effect on the angular momentum of the merger remnant in EAGLE, with the mass ratio modulating the strength of the effect.

We find that in the absence of mergers, galaxies display little change in their $\lambda_R, <5\%$. This seems to contradict the result of Choi & Yi (2017), who argued that most of the spin-down of galaxies is driven by environment and not mergers. This could be due to their study being performed exclusively on cluster regions, which represent an upper limit for the effect of environment.

We also studied the effect of mergers on the ellipticity, $e$, of galaxies and found little effect (not shown here). Dry mergers have a tendency to increase $e$, which, combined with the fact that they tend to decrease $\lambda_R$, results in galaxies ending up more comfortably in the SR zone in the $\lambda_R-e$ plane. On the other hand, wet major mergers tend to decrease $e$, thus making galaxies rounder. This is expected since wet mergers tend to increase the central stellar density of galaxies due to efficient gas fuelling to the centre (e.g. Cox et al. 2006; Robertson et al. 2006; Johansson et al. 2009; Peirani et al. 2010; Moreno et al. 2015; Lagos et al. 2018).

4.2 The connection between slow rotators and the halo spin parameters

Fig. 11 showed that about 30 per cent of the slow rotator population in the Ref-L100N1504 have not had any mergers. Fig. 12 showed that these slow rotators also had modest $\lambda_{r50}$ in the past, smaller than the $\lambda_{r50}$ values of the progenitors of slow rotators that experienced mergers. Here, we study the haloes of these galaxies to understand why they are SRs.

We calculate the spin of haloes, $\lambda_{DM}$, as in Mo, Mao & White (1998),

$$\lambda_{DM} = \frac{j_h}{\sqrt{2} G m_{h}^{3/2}} (10 H)^{1/3}$$

where $j_h$ and $M_h$ are the halo specific angular momentum and dark matter $M_{200}$ mass, $^1$ respectively, $G$ is Newton’s gravity constant, and $H$ is the Hubble parameter. We calculate $j_h$ with all the dark matter particles within a halo’s $r_{200}$. We find a positive correlation between the stellar $\lambda_R$ and $\lambda_{DM}$ in central galaxies (Fig. 16), but with significant scatter. Interestingly, this scatter tends to decrease with increasing aperture within which $\lambda_R$ is measured.

We now focus only on SRs to investigate the possible connection with their host halo spin. The top panel of Fig. 17 shows the distribution of halo dark matter spin parameters, $\lambda_{DM}$, of all central galaxies in the Ref-L100N1504 at $z = 0$ that have stellar masses $>10^{10} M_\odot$ (solid line). In the top panel of Fig. 17, we also show central galaxies with $\lambda_{r50} < 0.1$ (dashed line), and the subsamples

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1 Measured with all the dark matter particles within the halo’s $r_{200}$, the radius within which the density is 200 $\rho_{\text{crit}}$, with $\rho_{\text{crit}}$ being the critical density.
of these SRs that have had mergers (dot–dashed line) and had not had minor/major mergers (dashed line) over the last 10 Gyr. SRs that have not had mergers display a $\lambda_{\text{DM}}$ distribution that is significantly shifted compared to the other three samples. Note that the median $\lambda_{\text{DM}}$ of galaxies with $\lambda_{\text{SR}} < 0.1$ that have had mergers is very similar to the overall population of central galaxies. The sample of centrals with $\lambda_{\text{SR}} < 0.1$ has a slightly smaller median, but that is caused by the contribution of centrals with $\lambda_{\text{SR}} < 0.1$ that have not had mergers. The latter is clear when comparing the SRs that have had mergers to the overall galaxy population (dot–dashed and solid lines in the top panel of Fig. 17). The median $\lambda_{\text{DM}}$ of SRs that have not experienced mergers is a factor of $\approx 2$ smaller. This explains why they formed with low $\lambda_{\text{SR}}$ values: they formed and evolved in haloes of low spins. On average, galaxies and their host haloes grow their angular momentum together in a way that resembles weak conservation of angular momentum (Mo et al. 1998; Zavala et al. 2016; Lagos et al. 2017), and so it is expected that low spin haloes preferentially lead to the formation of galaxies with low spins.

The bottom panel of Fig. 17 shows the distribution of spin parameters of the $z = 1$ haloes that contain the progenitors of the SRs at $z = 0$. This shows that the spins of the haloes hosting the SRs that never had mergers were already low 7 Gyr ago, preventing the galaxies from reaching significant $\lambda_R$. Interestingly, we see that on average the haloes hosting these galaxies decrease their $\lambda_{\text{DM}}$ from $\approx 0.025$ to 0.02 from $z = 1$ to 0, which may be the cause for the systematic spinning down displayed by the SRs that never had mergers (solid lines in Fig. 12).

There is an overall weak positive correlation between $\lambda_{\text{SR}}$ and $\lambda_{\text{DM}}$ for central galaxies (Fig. 16). However, when studying the incidence of SRs, a stronger correlation with $\lambda_{\text{DM}}$ emerges. This is investigated in Fig. 18 for central galaxies in the Ref-L100N1504 simulation at $z = 0$ in three bins of stellar mass. The average $F_{\text{SR}}$ of all central galaxies is shown as the solid line, while the subsamples of galaxies that had mergers and those that did not have mergers are shown as dashed and dotted lines, respectively. The stellar mass bins were chosen to have $> 500$ galaxies in each of the three samples above.

The dependence of $F_{\text{SR}}$ on $\lambda_{\text{DM}}$ is close to monotonic with $F_{\text{SR}}$ decreasing with increasing $\lambda_{\text{DM}}$. We find that galaxies that have had mergers at $z < 2$ have a higher $F_{\text{SR}}$ compared to galaxies that have not had mergers at fixed $\lambda_{\text{DM}}$. The correlation is similarly tight for the different samples; i.e. jackknife errors are of a similar magnitude regardless of the merger history of galaxies. The top and middle panels of Fig. 18 shows that galaxies that have not had mergers and are hosted by haloes of low $\lambda_{\text{DM}}$, have an $F_{\text{SR}}$ that is similar or higher than that of the overall galaxy population at that stellar mass. Our results show the importance of the halo spin in determining slow rotation in central galaxies.

5 DISCUSSION AND CONCLUSIONS

Recent observational results from IFS surveys have reached contradictory conclusions regarding the effect of environment on the frequency of SRs. The early work from ATLAS3D (Cappellari et al. 2011) concluded that the fraction of SRs increases steeply with stellar mass and towards denser environments (Emsellem et al. 2011).
for their halo mass and have SFRs that are higher than observations. Continuing star formation is very efficient at spinning up galaxies, resulting in BCGs being mostly fast rotators.

We explored the effect of environment in two ways: by separating centrals and satellites, and by studying the effect of halo mass on the distribution of galaxies in the $F_{SR}$–stellar mass plane. We find that satellite galaxies are $49 \pm 15$ per cent more likely to be SRs than centrals at stellar masses in the range $10^{10.8} - 10^{11.5} M_{\odot}$. At lower masses, we find little differences in the overall populations of satellites and centrals (Fig. 6). However, when focusing on the massive population, we find that centrals of masses $M_{\text{stars}} < 10^{10.5} M_{\odot}$ are twice as likely to be SRs than satellites are (Fig. 7). We interpret this as centrals undergoing quenching and morphological transformation simultaneously, while satellites can quench due to the environment they live in without changing morphology.

We separate satellites and centrals by the halo mass they reside in, and find a significant trend with halo mass for centrals galaxies, where $F_{SR}$ increases with increasing halo mass at fixed stellar mass (top panel of Fig. 8). Satellite galaxies on the other hand show no dependence on halo mass once stellar mass is controlled for (bottom panel Fig. 8). However, the subsample of passive satellites shows a significant trend with halo mass, with $F_{SR}$ increasing with decreasing halo mass at $M_{\text{stars}} < 10^{10.5} M_{\odot}$ (Fig. 9). We speculate that satellite galaxies in low-mass haloes, $M_{\text{halo}} \lesssim 10^{13} M_{\odot}$, require morphological transformation to be quenched, while this is not the case in massive haloes, $M_{\text{halo}} \gtrsim 10^{14} M_{\odot}$. Correa et al. (2017) presented an analysis of the connection between the bulge-to-total stellar mass ratio of EAGLE galaxies with their colours. The authors concluded that satellite galaxies in the red sequence are more morphologically diverse compared to centrals, consistent with satellites quenching without having to transform morphologically.

However, recent surveys that sample much larger numbers of galaxies have concluded that there is only a very weak or no dependence on environment once stellar mass is controlled for (Brough et al. 2017; Veale et al. 2017b; Greene et al. 2018). Here, we used the EAGLE and HYDRANGEA simulations to explore this question and shed light on to the formation mechanisms of SRs.

We took special care in constructing IFS-like cubes for all of our simulated galaxies to measure the relevant quantities, $\lambda_{r50}$ and $\epsilon$, in a way that is more directly comparable to observations. We classify galaxies in EAGLE and HYDRANGEA that have stellar masses $> 5 \times 10^{9} M_{\odot}$ into slow and fast rotators, using several observational criteria. We compare with the observations of Emsellem et al. (2011), Brough et al. (2017), and Veale et al. (2017b) and find that our simulations reproduce the dependence of the fraction of SRs, $F_{SR}$, on stellar mass relatively well. We showed that by applying a small error to our measurements of $\lambda_{r50}$ we recover excellent agreement with the observations at $M_{\text{stars}} \lesssim 10^{11.5} M_{\odot}$ (Fig. 5). At higher masses, we find a low frequency of SRs, $\approx 26$ per cent, while observations point to a much higher fraction $> 50$ per cent (Oliva-Altamirano et al. 2017; Brough et al. 2017). This discrepancy is likely due to BCGs in EAGLE and HYDRANGEA being overly massive for their halo mass and have SFRs that are higher than observations. Continuing star formation is very efficient at spinning up galaxies, resulting in BCGs being mostly fast rotators.

By studying individual merger events, we find that dry major and minor mergers tend to be associated with a net spin-down of galaxies, while wet mergers can spin-up galaxies very efficiently (Fig. 14). We find that mergers have a cumulative effect, and galaxies undergoing successive minor mergers are more likely to spin-down and become SRs. For comparison, galaxies that had $\geq 3$ mergers have an incidence of SRs of 30 per cent, while this fraction decreases to 10 per cent in galaxies that had one merger (not shown here). We also found a secondary effect of the orbital angular momentum on the remnant $\lambda_{r50}$ in case of major mergers, in a way that lower

![Figure 18](https://academic.oup.com/mnras/article-abstract/476/4/4327/4904139)

**Figure 18.** The fraction of central galaxies that are SRs at $z = 0$ (defined as those with $\lambda_{r50} \leq 0.1$) as a function of the halo spin parameter, $\lambda_{DM}$, in three bins of stellar mass of the central galaxy, as labelled in each panel. We show this for three samples: all central galaxies (solid line), and the subsamples that had at least one merger (dashed line) or no mergers (dotted line). Bins are chosen to have $\approx 150$ galaxies. Error bars correspond to 1 standard deviation calculated with 10 jackknife resamplings in individual mass bins. The horizontal and vertical lines show the fraction of SRs for all galaxies at $z = 0$ in the stellar mass bins and their median $\lambda_{DM}$. There is a clear tendency for low $\lambda$ haloes to have a higher fraction of SRs.

Notes: The latter may not hold for low-mass galaxies (here we are only analysing galaxies with stellar masses $> 5 \times 10^{9} M_{\odot}$). These are predictions that should be testable with the full catalogues of MaNGA (Bundy et al. 2015) and SAMI (Bryant et al. 2015) in combination with high-quality group catalogues (Yang et al. 2007; Robotham et al. 2011; Saulder et al. 2016).

We use the extended merger tree information of EAGLE, as described in Qu et al. (2017) and Lagos et al. (2018), to study the formation history of simulated galaxies. We find that there is a strong correlation between slow rotation and the incidence of dry mergers. Most galaxies ($\approx 60$ per cent) that have had at least one dry major merger in the last 10 Gyr reside in the slow rotation region of the $\lambda_{r50}-\epsilon_{r50}$ plane. Less frequent, but none the less common among SRs, are dry minor mergers. Wet major and minor mergers are however more common in fast rotators (see Fig. 10). We find that the region of $\lambda_{r50} \geq 0.7$ and $\epsilon_{r50} \geq 0.6$ is almost exclusively occupied by galaxies that have not had any mergers with mass ratios $\geq 0.1$. Separating centrals and satellites, we find that dry major mergers are twice more common than any other merger with mass ratio $\geq 0.1$ in the population of central SRs, while for satellites dry minor and major mergers are the dominant form of mergers (Fig 11).

By studying individual merger events, we find that dry major and minor mergers tend to be associated with a net spin-down of galaxies, while wet mergers can spin-up galaxies very efficiently (Fig. 14). We find that mergers have a cumulative effect, and galaxies undergoing successive minor mergers are more likely to spin-down and become SRs. For comparison, galaxies that had $\geq 3$ mergers have an incidence of SRs of 30 per cent, while this fraction decreases to 10 per cent in galaxies that had one merger (not shown here). We also found a secondary effect of the orbital angular momentum on the remnant $\lambda_{r50}$ in case of major mergers, in a way that lower
orbital angular momentum leads to a larger decrease in $\lambda_{\text{iso}}$ (Fig. 15). Surprisingly, $\approx 30$ per cent of the SRs in EAGLE have not had mergers with mass ratios $\geq 0.1$. Those galaxies tend to have been born in haloes of low spins (Fig. 17) and we find that they currently reside in haloes with median spin at least twice smaller than the rest of the SRs and the overall galaxy population.

EAGLE shows that although the formation paths of SRs can be varied, as previously pointed out by Naab et al. (2014) using a small sample of 44 simulated galaxies, there are preferred formation mechanisms. Those are dry major mergers in case of central galaxies, dry minor and major mergers in case of satellites, and being formed in haloes of small spins in case of SRs that have not had mergers.

One limitation we found is that the most massive galaxies in EAGLE and HYDRANGEA, $M_{\text{stars}} > 10^{11.8} M_{\odot}$, are preferentially fast rotators, in contradiction with observations. This is connected to them being overly massive for their halo mass and star forming (Bahé et al. 2017; Barnes et al. 2017). All these features are indicative of AGN feedback not being strong enough at the highest masses. In addition, EAGLE lacks the population of very flat galaxies, $\epsilon_{\text{iso}} > 0.75$. This is most likely due to the modelling of the ISM and cooling adopted in EAGLE, as gas is forced to not cool down below $\approx 8000 \, \text{K}$, which corresponds to a Jeans length of $\approx 1 \, \text{kpc}$, much larger than the scale heights of discs in the local Universe (Kregel et al. 2002). This issue could be solved by including the formation of the cold ISM. This, however, does not affect the capability of our simulations to study SRs. Overall, our results show that simulations like EAGLE and HYDRANGEA are extremely powerful as their resolution allows us to look at their internal kinematics, at the same time as having large statistical samples to distinguish preferred formation scenarios.

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APPENDIX A: CONVERGENCE TESTS

A1 Resolution convergence

We present convergence tests for the ellipticity and \( \lambda_{50} \) measurements performed on galaxies with \( M_{\text{star}} \geq 5 \times 10^9 M_\odot \) at \( r_{50} \). The stellar mass limit above was motivated by Lagos et al. (2017) as the stellar mass above which the stellar specific angular momentum of galaxies measured at \( r \geq r_{50} \) converges. For our convergence test, we use the run referred to as Recal-L025N0752 in S15, which corresponds to a volume of length \( L = 25 \) cMpc and with \( 2 \times 752^3 \) particles, and that adopts the same subgrid physics as the reference simulation used in this work (Ref-L100N1504 and Ref-L050N752; see Table 1), but has parameters adjusted to fit the stellar mass function at \( z = 0 \). This is referred to as ‘weak convergence’ test in S15. To allow for a fair comparison, we use the Ref-L025N0376, which has the same resolution, subgrid physics, and parameters as the simulations in Table 1, but with a box of length \( L = 25 \) cMpc.

Fig. A1 shows \( \lambda_{50} \) as a function of ellipticity for galaxies in the Ref-L025N0376 (top panel) and Recal-L025N0752 (bottom panel) simulations that have \( M_{\text{star}} \geq 5 \times 10^9 M_\odot \) at \( z = 0 \). Circles and squares show galaxies seen edge-on and randomly, respectively. The three lines correspond to different classifications of slow rotations, and are as in Fig. 3.
Connecting kinematics, mass, and environment

Figure A2. Top panel: distribution of $\lambda_{r50}$ and $\epsilon_{r50}$ for the galaxies in Fig. A1, adopting random orientations. Solid and dashed lines correspond to the Ref-L025N0376 and Recal-L025N0752 simulations, respectively. Bottom panel: $F_{\text{SR}}$ using the Cappellari (2016) criterion as a function of stellar mass in the Ref-L025N0376 (solid line) and Recal-L025N0752 (dashed line) simulations. Error bars correspond to $1\sigma$ calculated with 10 jackknife resamplings in individual mass bins.

Figure A3. As in Fig. A2, but for the Ref-L050N0752 and the AGNdT9-L050N0752 simulations.

Figure A4. The fractional variation of $\lambda_{r50}$ as a function of $\lambda_{r50}$ using bins of 1 and 2 pkpc, as labelled (see equation (A1) for a definition of the fractional variation). Lines and error bars show the median and 25th–75th percentile ranges. For clarity, error bars are shown only for one mass bin. In this test, we use the Ref-L050N0752 simulation and show galaxies at $z = 0$ in two stellar mass bins, $5 \times 10^9 M_\odot < M_{\text{stars}} < 2 \times 10^{10} M_\odot$ (thin lines) and $M_{\text{stars}} \geq 2 \times 10^{10} M_\odot$ (thick lines).

A3 Convergence of kinematic measurements

To create the $r$-band luminosity-weighted mock IFU-like cubes for each simulated galaxy we bin the two-dimensional projected $r$-band luminosity map as described in Section 2.1. The chosen bin for the analysis of this paper is 1.5 pkpc. Here, we analyse the impact of this bin on $\lambda_{r50}$. For this analysis, we use the Ref-L050N0752 simulation and select all galaxies that have $M_{\text{stars}} \geq 5 \times 10^9 M_\odot$. We recompute all kinematic quantities but this time using bins of 1 and 2 pkpc. We define the fractional variation $\delta x$ of a kinematic quantity $x$ in terms of the value obtained when we adopt a bin of 1.5 pkpc, $\delta x_{(\text{bin})} = \frac{[x_{(\text{bin})} - x_{(1.5 \text{ pkpc})}]}{x_{(1.5 \text{ pkpc})}}$ (A1).

In Fig. A4, we show the impact the adopted bin has on the measurements of $\lambda_{r50}$ in two bins of stellar mass. Adopting a smaller bin, closer to the softening length (see Table 1), drives significant deviations in $\lambda_{r50}$ at low values of $\lambda_{r50}$, while adopting a larger bin does not have much of an impact. This is expected as choosing smaller bins, too close to the resolution limit, imply a much smaller number of particles per bin, which can produce significant errors in the determination of the kinematic parameters. We find that the two bins of stellar mass reach similar results. Our results show that choosing a bin of 1 pkpc is not appropriate for a simulation of the resolution of EAGLE, while choosing 1.5 or 2 pkpc has little impact on the kinematic measurements, implying good convergence. $\lambda_{r50}$ is converged to better than 7 per cent for our adopted bin.

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