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The SLUGGS survey: combining stars, globular clusters, and planetary nebulae to understand the assembly history of early-type galaxies from their large radii kinematics

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ABSTRACT

We investigate the kinematic properties of nine nearby early-type galaxies with evidence of a disc-like component. Three of these galaxies are located in the field, five in the group, and only one in the cluster environment. By combining the kinematics of the stars with those of the globular clusters (GCs) and planetary nebulae (PNe), we probe the outer regions of our galaxies out to ~4–6 R_e. Six galaxies have PNe and red GCs that show good kinematic alignment with the stars, whose rotation occurs along the photometric major-axis of the galaxies, suggesting that both the PNe and red GCs are good tracers of the underlying stellar population beyond that traced by the stars. Additionally, the blue GCs also show rotation that is overall consistent with that of the red GCs in these six galaxies. The remaining three galaxies show kinematic twists and misalignment of the PNe and GCs with respect to the underlying stars, suggesting recent galaxy interactions. From the comparison with simulations, we propose that all six aligned galaxies that show similar dispersion-dominated kinematics at large radii (>2–3 R_e) had similar late (z ≤ 1) assembly histories characterized by mini mergers (mass-ratio < 1:10). The different V_rot/σ profiles are then the result of an early (z > 1) minor merger (1:10 < mass-ratio < 1:4) for the four galaxies with peaked and decreasing V_rot/σ profiles and of a late minor merger for the two galaxies with flat V_rot/σ profiles. The three misaligned galaxies likely formed through multiple late minor mergers that enhanced their velocity dispersion at all radii, or a late major merger that spun-up both the GC subpopulations at large radii. Therefore, lenticular galaxies can have complex merger histories that shape their characteristic kinematic profile shapes.

Key words: planetary nebulae: general – galaxies: elliptical and lenticular, cD – galaxies: formation – galaxies: kinematics and dynamics – galaxies: star clusters: general.

1 INTRODUCTION

Early-type galaxies (ETGs; i.e. elliptical and lenticular) are found to be more numerous towards the denser regions of rich galaxy clusters (Dressler 1980), with the fraction of lenticular (S0) galaxies increasing by a factor of 2–3 in such regions between z ≃ 0.5 and the present day at the expenses of spirals (Dressler et al. 1997; Fasano et al. 2000). This suggests that S0 galaxies could be formed from spirals with quenched star formation and faded spiral arms, as a result of cluster-related physical processes, such as ram-pressure stripping, tidal interactions, and starvation, which stripped the gas envelope surrounding the spiral galaxy or suppressed its gas supply from the Intergalactic Medium (IGM; e.g. Gunn & Gott 1972; Larson, Tinsley & Caldwell 1980; Bekki 2009; Bekki & Couch 2011; Merluzzi et al. 2016).

However, all these physical processes require a high-density environment in order to be most effective. The observations of S0s in low-density environments, where the interactions between galaxies are limited or non-existent, require alternative formation pathways. Mergers and accretion events have been shown to be able to produce S0 galaxies (e.g. Bekki 1998; Bournaud, Jog & Combes 2005; Naab et al. 2014; Tapia et al. 2017; Eliche-Moral et al. 2018). Specifically, Bournaud et al. (2005) showed that minor mergers with mass-ratio 1:4.5–1:10 can produce discy ETGs, resembling the kinematics and morphology of S0s, while major mergers with mass-ratio 1:1–1:3 are likely to produce elliptical (E) galaxies with hotter kinematics. However, Tapia et al. (2017) and Eliche-Moral et al. (2018) have shown that a few Gyr after a major merger, many galaxy remnants displayed relaxed morphology and properties typical of S0s, suggesting that major mergers are also a possible S0 formation pathway.

Alternatively, a secular evolution scenario has been proposed for the formation of S0 galaxies, where the spiral galaxy evolves mostly passively, consuming its own in-situ gas through star formation,
and slowly fades due to internal processes and instabilities. This scenario is expected to produce more rotationally supported S0s, as they preserve a higher degree of rotation of their progenitor spiral. Internal processes, such as the collapse of a cold disc that becomes gravitationally unstable at high redshifts, feedback events from active galactic nuclei (AGNs) and quenching of star formation due to the stabilization of the gas disc (i.e. morphological quenching), have been proposed as possible formation pathways for S0 galaxies (Martig et al. 2009; Mishra, Wadadekar & Barway 2018; Saha & Cortesi 2018). Bellstedt et al. (2017) and Rizzo, Fraternali & Iorio (2018) have found S0 galaxies displaying high values of stellar angular momentum, which are more consistent with those of disc galaxies rather than with those of merger remnants.

Finally, an alternative scenario involves the build-up of a disc component around a massive compact quiescent galaxy at high redshift (Damjanov et al. 2014; Dullo & Graham 2013; Graham et al. 2015) from the accretion of a gas-rich dwarf galaxy (Diaz et al. 2018).

Many physical processes have been thus shown to be able to produce S0 galaxies; therefore, a wide range of stellar kinematic and population properties should be expected in S0s formed through these different formation pathways, as well as in the different environments.

Early results from the ATLAS3D survey (Cappellari et al. 2011) classified a sample of 260 nearby ETGs (i.e. S0s and Es) into the two families of fast and slow rotators, based on the stellar kinematics of the central 1 R_e (Emsellem et al. 2011). The fast rotators typically showed regular rotation patterns with aligned kinematic and photometric position angles, while the slow rotators showed more complex velocity fields with misaligned kinematic and photometric position angles and were typically found among the most massive galaxies and in higher density environments. These results suggested a wide range of different processes for the formation of the fast/slowly rotating ETGs (e.g. mergers, interactions, gas stripping, and secular evolution; Krajnović et al. 2011).

Coccato et al. (2020) studied the stellar kinematics out to ~1.5–2 R_e for a sample of 21 S0 galaxies located in field and cluster environments. Their results showed that cluster S0s were more rotationally supported (i.e. high Vrot/σ) and consistent with a faded spiral scenario, while field S0s were more pressure supported (i.e. low Vrot/σ) and consistent with a formation through minor mergers. They also performed a stellar population analysis of such S0s, but they did not find any clear environmental dependence as for the stellar kinematics. However, the subsequent work by Johnston et al. (2020), that specifically focused on the stellar population analysis of 8 of the S0s from Coccato et al. (2020), found that the field S0s had a younger stellar population than the cluster S0s, therefore suggesting a minor merger formation pathway. Similar conclusions to Coccato et al. (2020) were reached by Deeley et al. (2020), who studied the stellar and gas kinematics of a sample of 219 S0 galaxies from the SAMI survey (Croom et al. 2012). Deeley et al. (2020) found that pressure-supported S0s were located in low-density environments (i.e. field and small groups) and had misaligned stellar and gas kinematics, consistent with a minor merger formation scenario. On the other hand, rotationally supported S0s were located in high-density environments and had kinematic properties more similar to spiral galaxies, therefore suggesting a faded spiral formation scenario. Tous, Solanes & Perea (2020) have identified two subpopulations of S0s, one being characterized by S0s with star formation rates similar to those of late-type spirals and the other being characterized by quiescent S0s. They find that the subpopulation of active S0s is slightly less massive with a younger and more metal-poor stellar population than the quiescent S0s, and is pre-dominantly located in low-density regions (Tous et al. 2020), suggesting that the environment has likely played some role in the formation of S0s.

Fraser-McKelvie et al. (2018) suggested that the stellar mass of the galaxies, rather than the environment, is the main discriminator in the formation of S0s from the stellar population analysis of a sample of S0 galaxies in the MaNGA survey (Bundy et al. 2015). Specifically, Fraser-McKelvie et al. (2018) found that more massive S0s had an older and more metal-rich stellar population in the bulge than in the disc, while low-mass S0s had a younger stellar population in the bulge than in the disc, suggesting an inside-out quenching scenario for the more massive S0s and an outside-in quenching scenario for the low-mass S0s. A more recent stellar population analysis of a sample of S0 galaxies in the MaNGA survey has also revealed a bimodal S0 population, with massive S0s (i.e. M_* > 3 × 10^10 M_⊙) having mostly flat metallicity gradients and low-mass S0s having steeper metallicity gradients, while the age gradients show the opposite trend (Dominguez Sánchez et al. 2020). These results suggest that gas-rich mergers are more important in the formation of massive S0s.

The SAGES Legacy Unifying Globulars and GalaxieS (SLUGGS; Brodie et al. 2014) survey was able to obtain extended stellar kinematic measurements out to ~2–4 R_e for a sample of 25 nearby ETGs (including S0s), as well as radial velocities for a large number of globular clusters (GCs; Forbes et al. 2017a). From the stellar kinematics, Arnold et al. (2014) and Foster et al. (2016) found that the kinematic behaviour of the central 1 R_e of ETGs can be quite different from the kinematic behaviour of the outer galaxy regions, with centrally fast rotators often showing decreasing or rapidly increasing rotation at larger radii. Specifically, Arnold et al. (2014) found that many of their ETGs showed evidence of a fast-rotating stellar disc embedded in a more slowly rotating spheroidal component, which is consistent with the model of a two-phase formation scenario (e.g. Oser et al. 2010; Zolotov et al. 2015; Rodriguez-Gomez et al. 2016). According to the two-phase model, massive ETGs formed at early times (i.e. z ≥ 2) with a rapid collapse or wet merger event during which they formed most of their stellar mass; in a compact object known as ‘red-nugget’ (Damjanov et al. 2014; Zolotov et al. 2015), i.e. in-situ formation. At later times (i.e. z ≃ 0), they mostly grew in size through the accretion of low-mass dwarf galaxies deposited on to their outskirts (ex-situ formation). These low-mass mergers are responsible for producing the decreasing rotation in the outer regions of ETGs. However, stellar kinematic studies of different samples of ETGs, extending beyond 2 R_e, found different results from Arnold et al. (2014), with centrally fast rotator galaxies remaining fast-rotating and centrally slow rotator galaxies remaining slow-rotating beyond 1 R_e (Raskuti, Greene & Murphy 2014; Boardman et al. 2017). The differences between these works could be due to differences in the sample selection criteria. For instance, the sample of ETGs from Boardman et al. (2017) contains ETGs with lower stellar masses than the SLUGGS sample, therefore the transition radius (which anticorrelates with the galaxy stellar mass; Pulsoni et al. 2021) in the stellar kinematics of the galaxies from Boardman et al. (2017) could simply be located at larger radii as compared to the SLUGGS galaxies. Nevertheless, all these results suggest the importance of studying the kinematic properties of larger samples of ETGs out to larger radii. This will not only help us to constrain the formation histories of ETGs, but also to understand the kinematic behaviour of the galaxy outskirts with respect to that of the galaxy central regions.

The stellar kinematic results obtained by Arnold et al. (2014) and Foster et al. (2016), as part of SLUGGS, have shown the importance
of studying the kinematic properties of the outer regions of ETGs, i.e. beyond $\sim 2-3 R_e$. In fact, the galaxy outskirts are characterized by longer dynamical time-scales, therefore they better preserve the imprints of the galaxy formation processes in the stellar dynamic and population content. However, the galaxy outskirts are difficult and time-consuming to observe due to their lower surface brightness as compared to the inner regions.

One way to overcome this issue and probe the outskirts of the galaxies is to use discrete kinematic tracers, such as GCs and planetary nebulae (PNe). GCs are observed in all galaxy types and numerous in the most massive ETGs. They are typically found to display a colour bimodality that reflects the two distinct subpopulations of the red, metal-rich and blue, metal-poor GCs, which are expected to trace the kinematic properties of the host ETGs differently (Forbes, Brodie & Grillmair 1997; Strader et al. 2005; Brodie & Strader 2006). Specifically, the red, metal-rich GCs are expected to have formed largely in-situ together with the bulk of the host galaxy stars, while the blue, metal-poor GCs are expected to have formed mostly at early times of the galaxy formation process or subsequently accreted on to the host galaxy from tidally stripped dwarfs during the late evolutionary phase of the galaxy. Therefore, the red, metal-rich GCs should trace the kinematic properties of the stellar population of the bulge and spheroid in massive ETGs, while the blue, metal-poor GCs have typically a more extended spatial distribution than the red GCs and should trace the kinematic properties of the stellar population of the galaxy halo (Forbes et al. 1997; Forbes & Remus 2018).

PNe are a late evolutionary stage of the stars with stellar masses $1 M_\odot < M^* < 8 M_\odot$ and are expected to trace the underlying stellar population in ETGs out to large radii (e.g. Buzzoni, Arnaboldi & Corradi 2006; Romanowsky 2006).

Since GCs are bright star clusters and PNe are strong [O III] emitters, they can be observed out to larger radii (i.e. $\sim 8-10 R_e$) in ETGs, where the stellar component becomes too faint for spectroscopy studies. Some previous works have found that the PNe and GCs are generally good tracers of the kinematics of the underlying stellar population and stellar surface brightness profile for many ETGs (e.g. Coccato et al. 2009; Pota et al. 2013, 2015). Others adopted a novel approach to study the formation histories of S0 galaxies that combined the kinematics of the PNe and GCs with the photometric decomposition (i.e. bulge+disc) of the galaxy in order to associate the PNe and GCs to either the bulge or disc component using a maximum likelihood method (e.g. Cortesi et al. 2011; Forbes et al. 2012; Cortesi et al. 2013b, 2016; Zanatta et al. 2018).

Recent simulations extending out to large galactocentric radii, i.e. $5 R_e$ (Schulze et al. 2020), have shown that different $V_{\text{rot}}/\sigma$ profiles can be the result of merger events that occurred at different redshifts. These merger events are expected to influence not only the kinematics of the stars, but also that of both GC subpopulations depending on the mass-ratio and orbital configuration of the mergers (Bekki et al. 2005; Cavanagh & Bekki 2020). Therefore, in this work, we study the kinematic profiles for a sample of 8 selected S0 and E/S0 galaxies in the SLUGGS survey that are located mainly in low-density environments by combining the stellar with the GC and PNe kinematics in order to reach beyond $\sim 2-3 R_e$, similarly to what has already been done in Dolfi et al. (2020) for the nearest S0 galaxy, NGC 3115. If the PNe and GCs are tracing the kinematics of the underlying stellar population in the galaxies, then we can use them as proxies for the stars to study the galaxy outskirts beyond the radius probed by the stars. From the comparison of the overall $V_{\text{rot}}/\sigma$ kinematic profiles of the galaxies out to large radii, i.e. $\sim 5 R_e$, with the simulations, we can constrain the merger history of our galaxies with the most likely epoch when the merger event occurred that shaped the characteristic $V_{\text{rot}}/\sigma$ profiles of our galaxies.

The structure of the paper is as follows. In Section 2, we describe the selected sample of ETGs with their stellar, GC and PNe kinematic data. In Section 3, we present the kinematic results in the form of 2D kinematic maps and 1D kinematic profiles for all the kinematic tracers of each individual galaxy. In Section 4, we discuss the likely formation histories of our sample of S0 galaxies from the comparison with simulations of galaxy formation. Appendix A (Supporting Information) gives a more detailed description of the kinematic properties of each one of our individual selected ETGs.

2 THE GALAXY SAMPLE

We select a sample of 8 ETGs out of 25 from the SLUGGS survey (Brodie et al. 2014), based on the availability of a sufficient number of both GCs and PNe with measured radial velocities in order to study their kinematic properties. The GC and PNe spectroscopic catalogues come from the SLUGGS (Forbes et al. 2017a) and the extended Planetary Nebula Spectrograph (ePNe; Pulsoni et al. 2018) surveys, respectively. Photometry measurements are available for the GC systems of each one of our selected galaxies and they have been presented in Pota et al. (2013, 2015).

Table 1 shows the list of the 8 selected ETGs with a summary of some of their main characteristics. We also indicate the total number of spectroscopically confirmed GCs and PNe in each galaxy with the adopted colour-split to separate between the red metal-rich and blue metal-poor GC subpopulations, where applicable. The colour-splits to separate between the red and blue GCs were selected after visually inspecting the colour–magnitude diagrams, in the corresponding magnitude bands, of the photometric GC catalogues. We note that the GC colour-splits adopted in this work are consistent with those from Pota et al. (2013, 2015) and Cortesi et al. (2016). NGC 3115 is also included in the list, but its study has been carried out in a separate paper (Dolfi et al. 2020). All selected ETGs have a total number of spectroscopically confirmed GCs or PNe greater than 100 and Fig. 1 shows the measured radial velocities of the GC and PNe systems as a function of the galactocentric radius, $R/R_e$, for each galaxy.

The stellar kinematics for all our galaxies come from ATLAS 3D (Cappellari et al. 2011), MUSE (Guérout et al. 2016) in the case of NGC 3115, and SLUGGS (Arnold et al. 2014; Foster et al. 2016) surveys. The former provides spatially resolved 2D maps of the inner $1 R_e$ of ETGs, while the latter provides discrete stellar kinematic measurements around the galaxies that are obtained using the Stellar Kinematics from Multiple Slits (SKiMS) technique (Proctor et al. 2009; Foster et al. 2009, 2011) and extend further out to $\sim 2-4 R_e$.

We note here that all our selected ETGs, except for NGC 3115 and NGC 5846, show regular rotation in the 2D kinematic maps of their velocity fields within the central $\sim R_e$ and are, thus, classified as fast rotators (Emsellem et al. 2004). NGC 5846 is the only massive ETG in our selected sample classified as slow-rotator within the central $\sim 1 R_e$ from ATLAS 3D (Emsellem et al. 2004). Finally, NGC 3115 was not observed as part of the ATLAS 3D (Cappellari et al. 2011), however the stellar kinematic results from MUSE, extending out to $\sim 3 R_e$, show that NGC 3115 is also a fast rotator S0 galaxy (Guérout et al. 2016).

We note that five out of nine of our selected ETGs in Table 1 are found in groups, while three are found in the field and only one galaxy, NGC 4649, is in a cluster environment. Additionally, we note that only three of the ETGs in Table 1 are classified as pure S0s (i.e. NGC 1023, NGC 3115, and NGC 7457), while the remaining
six ETGs are not classified as E/S0s or Es. However, even though these six ETGs are not classified as pure S0s based on their morphology (see Table 1), they have been all found to show evidence of a disc-like component from early kinematic or photometric studies (see Appendix A in the Supporting Information also for more specific details about the main properties of each individual galaxy in Table 1 with the description of their GC and PNe systems).

3 RESULTS

3.1 2D kinematic maps and 1D kinematic profiles

In this section, we produce the 2D kinematic maps of the GC and PNe tracers, as well as stars, for each galaxy in Table 1. Similarly to Dolfi et al. (2020) and in previous literature works (e.g. Proctor et al. 2009; Foster et al. 2013, 2016; Bellstedt et al. 2017), we use the kriging spatial interpolation technique (Pastorello et al. 2014), which is an inverse-noise-weighted method, to generate the continuous 2D velocity and velocity dispersion maps shown in Fig. 2 and Figs A1–A8 (Supporting Information). We fold the PNe kinematic catalogue only for NGC 4649 prior to producing the 2D maps in order to have full position angle (PA) coverage around the galaxy, as described in Appendix A2.2 (Supporting Information).

To estimate the velocity dispersion of the GC and PNe tracers of each galaxy, we calculate the standard deviation of the tracer velocities from the mean in spatial bins centred at the position of each tracer and containing a chosen number of nearest-neighbour objects. In general, the higher is the number of nearest-neighbour objects, the more accurate the estimate of the velocity dispersion of the GCs and PNe would be in each spatial bin. However, we need to be careful when choosing the number of nearest-neighbour objects so that we do not average together GC and PNe tracers that are located in significantly different spatial regions around the galaxy. For this reason, we use 5 nearest-neighbours for the GCs and 10 nearest-neighbours for the PNe, since the latter have better sampled velocity fields, i.e. higher number of objects in the catalogues. We use 10 nearest-neighbour for the GCs for only NGC 4649 as this galaxy has the largest spectroscopic GC catalogue (see Table 1). This procedure is the same as the one adopted in Dolfi et al. (2020) and it is not necessary for the stellar kinematics for which we have the integrated line-of-sight velocity dispersion.

We calculate the 1D kinematic profiles of all our kinematic data sets, i.e. ATLAS3D and SLUGGS stars, GCs, and PNe (see Section 2) using the kinemetry$^1$ method (Krajnović et al. 2006), which was initially used with 2D spatially resolved stellar kinematic maps of galaxies to recover the best-fitting moments of the Line-Of-Sight-Velocity-Distribution (LOSVD) as a function of the galactocentric radius (e.g. Krajnović et al. 2011). Here, we adopt a similar procedure as in Proctor et al. (2009), Foster et al. (2011, 2016), Bellstedt et al. (2017), and Dolfi et al. (2020) to recover the LOSVD moments for our non-homogeneous and sparse kinematic data sets, i.e. SLUGGS stars, GCs, and PNe. As for the 2D kinematic maps, we use the folded PNe catalogue of NGC 4649 (see Appendix A2.2 in the Supporting Information) to derive its 1D kinematic profiles. Within kinemetry, the computation of the best-fitting moments of the LOSVD is performed at the different galactocentric radii by least-squares minimization of the cosine model function, described in equations 3 and 4 of Dolfi et al. (2020), fitted to the observed kinematic data binned in concentric elliptical annuli. For a more detailed description of how we apply kinemetry to our kinematic data sets see section 6.2 in Dolfi et al. (2020), while for the equations describing in details the chi-squared minimization procedure within kinemetry for recovering the best-fitting LOSVD moments of our kinematic data see Foster et al. (2011, 2016).

As previously done in Dolfi et al. (2020) for NGC 3115, we focus on recovering the first- and second-order moments of the LOSVD (i.e. $V_{\text{rot}}$ and $\sigma$, respectively) for all the kinematic data sets of each one of our galaxies in Table 1 and we fit for both the $PA_{\text{kin}}$ and $q_{\text{kin}}$ parameters, where we find that these can be reliably constrained (i.e. they do not excessively vary as a function of the galactocentric radius within the different elliptical annuli). If this is not the case, then we fix them to the corresponding photometric values, i.e. $PA_{\text{phot}}$ and $q_{\text{phot}} = q_{\text{phot}}$ (see Table 1), of the galaxies for more stable results during the fit. We find this to be mostly the case for $q_{\text{kin}}$, which is generally hard to constrain even in the presence of well-sampled data sets (Foster et al. 2016), and has been, therefore, usually fixed to the photometric value in many previous works (e.g. Foster et al. 2011, 2013, 2016; Bellstedt et al. 2017; Dolfi et al. 2020). Overall, we find that whether we fix or fit for $q_{\text{kin}}$, the shape of the derived rotation velocity and velocity dispersion profiles as a function of the galactocentric radius does not significantly change.

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$^1$http://davor.krajnovic.org/ld/
Figure 1. Phase space diagrams showing the measured radial velocities of the GC and PNe tracers of each galaxy as a function of the galactocentric radius, $R$, divided by the corresponding effective radius of the galaxy, $R_e$ (see Table 1). The red metal-rich and blue metal-poor GC subpopulations are represented as red and blue dots, respectively, for all those galaxies for which we identify a colour bimodality distribution, otherwise the GCs are shown as magenta dots. The PNe are shown as green dots. For NGC 1023, we show the 8 GCs and 20 PNe (orange stars) associated with the companion galaxy, NGC 1023A, that we remove from the final catalogues as described in Appendix A1.1 (Supporting Information).

The 1D kinematic profiles of the distinct tracers (i.e. GCs, PNe and stars) of each galaxy in Table 1 are shown in Fig. 3. Each subfigure of Fig. 3 represents one individual galaxy, with the derived $P_{\text{kin}}$ and $q_{\text{kin}}$ (where fitted), rotation velocity, $V_{\text{rot}}$, velocity dispersion, $\sigma$, and rotation velocity to velocity dispersion, $V_{\text{rot}}/\sigma$, profiles shown from the top to the bottom panel, respectively. The $P_{\text{kin}}$ is always measured from North towards East for consistency with the 2D kinematic maps in Fig. 2 and Figs A1–A8 (Supporting Information).
Figure 2. From top to bottom, 2D velocity (left-hand side) and velocity dispersion (right-hand side) maps of the SLUGGS stars, PNe, red and blue GCs for NGC 1023, shown here as an example (the 2D kinematic maps of the remaining eight galaxies in Table 1 are shown in the Figs A1–A8 in the Supporting Information). North is up, East is left. The small open circles indicate the positions of the tracers, the black solid lines indicate the isovelocity contours and the black dashed lines represent the 1–6 $R_e$ and 10 $R_e$ photometric ellipses, which are inclined by the PA$\text{phot}$ of the galaxy. The PA$\text{phot}$ is measured from North towards East. The 2D maps are normalized with respect to the velocity scale bar on the right of each map.

and with the PA$\text{phot}$ of the galaxy shown in Table 1. The 1$\sigma$ errors of the PA$\text{kin}$ and $q$ profiles are calculated from running kinemetry on 500 bootstrapped samples obtained from sampling with replacement the original kinematic data sets. On the other hand, the 1$\sigma$ errors of the rotation velocity and velocity dispersion profiles are the standard errors of the mean, calculated from the standard deviation of the velocity and velocity dispersion measurements of the data points in each elliptical annuli,$^2$ divided by the square root of

$^2$These are the same concentric elliptical annuli used in the kinemetry algorithm to recover the 1D kinematic profiles at the different galactocentric radii.
Figure 3. 1D kinematic profiles for the ATLAS3D, or MUSE for NGC 3115 (orange line), and SLUGGS (black line) stars, PNe (green line), red and blue GCs (red and blue lines, respectively) and all GCs (magenta line) for those galaxies with no bimodal colour distribution in the GC population (see Table 1). Each column represents one individual galaxy, which are being grouped based on whether they are aligned or misaligned. NGC 3115 is taken from Dolfi et al. (2020). For the aligned galaxies, we also show the smooth $V_{\text{rot}}/\sigma$ profile (cyan line), calculated by averaging the individual $V_{\text{rot}}/\sigma$ profiles of the distinct kinematic tracers in the overlapping radii for each galaxy. For NGC 4649, we only fit for the $\text{PA}_{\text{kin}}$ and we keep $q_{\text{kin}}$ fixed to the photometric value, $q_{\text{phot}}$, of the galaxy (see Table 1) for all our kinematic data sets, while, for NGC 5846, we keep both $\text{PA}_{\text{kin}}$ and $q_{\text{kin}}$ fixed to the photometric values, $\text{PA}_{\text{phot}}$ and $q_{\text{phot}}$, of the galaxy.

3.2 The kinematic behaviour of the galaxies

From the 2D kinematic maps in Fig. 2 and Figs A1–A8 (Supporting Information), and from the 1D kinematic profiles in Fig. 3, we find that six galaxies (i.e. NGC 1023, NGC 2768, NGC 3115, NGC 3377, NGC 4697, and NGC 7457) show good kinematic alignment of the GC subpopulations and PNe with respect to the underlying stars.
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Figure 3. Continued.

 Mis-aligned galaxies

NGC 821

NGC 4649

NGC 5846

Figure 3. Continued.

(hereafter, aligned galaxies). Specifically, four of the galaxies (i.e. NGC 1023, NGC 2768, NGC 3115, NGC 4697 and NGC 7457) have the $P_{\text{Akin}}$ of both the GCs and PNe that are closely aligned with the $P_{\text{Akin}}$ of the underlying stars (that is, in turn, closely aligned with the $P_{\text{Aphot}}$ of the galaxy given in Table 1), as they are consistent within the 1σ errors. Additionally, the $P_{\text{Akin}}$ of both the GCs and PNe in these four galaxies do not show significant scatter around the $P_{\text{Akin}}$ of the underlying stars, but they all display rotation along the photometric major-axis of the galaxy, as it can be seen also from the 2D kinematic maps in Fig. 2 and Figs A1, A3, and A4 in the Supporting Information [and in fig. 6 of Dolfi et al. (2020) for NGC 3115].

An exception is NGC 3377, whose blue GC subpopulation does not show evidence of a significant rotation (see Fig. A2 in the Supporting Information and Fig. 3). Additionally, the PNe of NGC 3377 show a possible twist in the $P_{\text{Akin}}$ between $\sim$ 3–5 $R_e$ and evidence of such a kinematic twist of the PNe was also previously seen by Coccato et al. (2009). However, the PNe show rotation that is closely aligned to that of the underlying stars, as well as red GCs, within the inner $\sim$ 3 $R_e$. At larger radii, we see that the rotation of the PNe is still overall consistent with the photometric major-axis of the galaxy from the 2D kinematic maps. Therefore, we also include NGC 3377 in the group of the aligned galaxies.

On the other hand, the remaining three galaxies show kinematic misalignments of the GC subpopulations and PNe with respect to the underlying stars, i.e. NGC 821 and NGC 4649, or no net rotation, i.e. NGC 5846 (hereafter, misaligned galaxies). Specifically, NGC 4649 shows the largest scatter in the $P_{\text{Akin}}$ of the PNe and blue GC subpopulation with respect to the underlying stars, with clear kinematic twists and minor-axis rotation beyond $\sim$ 2 $R_e$. On the other hand, the red GCs of NGC 4649 have $P_{\text{Akin}}$ that is slightly offset from that of the stars, but it does not show significant variations as a function of the radius (Fig. 3 and Fig. A7 in the Supporting Information). Similarly, in NGC 821, the PNe are rotating more closely aligned to the photometric minor-axis of the galaxy and the GCs are also rotating along a $P_{\text{Akin}}$ that is offset from the photometric major-axis of the galaxy (Fig. A5 in the Supporting Information) and consistent with the large 1σ errors in the 1D kinematic profiles in Fig. 3.

Finally, in NGC 5846, we are not able to reliably recover the $P_{\text{Akin}}$ of the stars, PNe and GC subpopulations. However, from the 2D kinematic maps in Fig. A8 (Supporting Information), we do not see evidence of any ordered rotation around the galaxy and therefore, of any possible kinematic alignment between the distinct tracers. For this reason, we include these three galaxies (i.e. NGC 821, NGC 4649 and NGC 5846) in the group of the misaligned galaxies.

The different kinematic behaviours of the aligned and misaligned galaxies would suggest different formation histories for these two galaxy groups, with the latter being, possibly, the result of more recent interaction and merger events that have perturbed the dynamical equilibrium state of the galaxies. In Table 2, we summarize the kinematic alignment or misalignment of the GC and PNe tracers with respect to the underlying stars (from SLUGGS) and we indicate whether the red and blue GC subpopulations are kinematically aligned for each galaxy, based on the 2D and 1D kinematic results shown in the Figs A1–A8 (Supporting Information) and in Fig. 3, respectively, and described in more detail in Appendix A (Supporting Information) for each individual galaxy.

In Fig. 4, we compare together the 1D kinematic profiles of the stars, PNe and GC subpopulations of the aligned (top) and misaligned (bottom) galaxies, with the aim of identifying common trends in their behaviours. Therefore, in Fig. 4, we show the $V_{\text{rot}}$, $\sigma$ and $V_{\text{rot}}/\sigma$ profiles (from left to right) for the stars (from SLUGGS), PNe, red GCs, blue GCs, and all GCs (if no colour bimodality distribution is observed) from the top to the bottom panels, respectively. We also include NGC 3115 for the comparison with the aligned galaxies, with its kinematic profiles taken from Dolfi et al. (2020). We notice that the $V_{\text{rot}}/\sigma$ profiles of the aligned and misaligned galaxies have
very similar shapes to the corresponding $V_{\text{rot}}$ profiles. Therefore, we focus in this section on describing the common features of the $V_{\text{rot}}/\sigma$ profiles of the different kinematic tracers of the galaxies.

We notice that the velocity dispersion profiles of the aligned and misaligned galaxies in Fig. 4 all show weakly decreasing or overall flat behaviours out to large radii, with the exception of NGC 1023, whose PNe and GC subpopulations are characterized by slightly rising velocity dispersion profiles beyond $\sim 2 R_e$.

For the aligned galaxies in Fig. 4, we notice that their $V_{\text{rot}}/\sigma$ profiles show clearly peaked (NGC 1023, NGC 3115) to flatter (NGC 2768, NGC 3377, NGC 4697) behaviours. NGC 7457 also show a peaked $V_{\text{rot}}/\sigma$ profile, as seen from the GCs at $\sim 2 R_e$, even though both the stars and PNe show rising $V_{\text{rot}}/\sigma$ out to $\sim 2$–$2.5 R_e$. It is worth noticing here that all aligned galaxies have blue GCs that are rotating, with the exception of NGC 3377 that shows very low rotation in its blue GC subpopulation, with $V_{\text{rot}}/\sigma \leq 0.5$ out to large radii. Additionally, while NGC 1023 and NGC 2768 have overall consistent $V_{\text{rot}}/\sigma$ profiles between the red and blue GC subpopulations, the blue GCs of NGC 3115 are characterized by a peak of the $V_{\text{rot}}/\sigma \sim 1.5$ located at larger radii (i.e. $\sim 3 R_e$) than that of the red GCs (i.e. $\sim 1$–$1.5 R_e$).

The misaligned galaxies in Fig. 4 are, instead, characterized by more peculiar $V_{\text{rot}}/\sigma$ profiles. Only NGC 821 shows an overall flatter $V_{\text{rot}}/\sigma$ profile out to large radii, similarly to NGC 2768, NGC 3377 and NGC 4697. However, in NGC 821, the rotation of the PNe and GCs occurs more closely aligned to the photometric minor-axis of the galaxy. On the other hand, NGC 5846 shows spheroid-like kinematics (i.e. $V_{\text{rot}}/\sigma < 0.5$) out to large radii, while NGC 4649 shows the more interesting double-peaked $V_{\text{rot}}/\sigma$ profiles, as seen from the PNe and red GCs (see Appendix A in the Supporting Information) for a more detailed description of the kinematic profiles of these two individual galaxies.

Finally, we look for any mass or environment dependence in the 1D kinematic profiles of our galaxies. Some previous works have found differences in the stellar kinematics of S0 galaxies in different environments, with S0s located in clusters and large groups being more rotationally supported than S0s found in isolation or in small groups (e.g. Deeley et al. 2020; Coccato et al. 2020). This might suggest different formation pathways for cluster and field S0s. However, we do not find any clear dependence on the environment in our kinematic profiles, nor more specifically in the $V_{\text{rot}}/\sigma$ profiles. We argue that this is likely due to the small galaxy sample size that we are using and to the fact that our sample only contains one cluster (i.e. NGC 4649) and three field (i.e. NGC 821, NGC 3115, and NGC 7457) S0s, while the remaining galaxies are located in groups. Therefore, we are missing the high density environments of galaxy clusters.

On the other hand, we do find a dependence of the velocity dispersion profiles on the stellar mass of the galaxies for all our kinematic tracers (i.e. stars, PNe, and GCs), with the more massive galaxies showing higher velocity dispersion profiles than the less massive ones, as expected and also observed in previous works (e.g. Foster et al. 2018). At the same time, we also find a stellar mass dependence of the $V_{\text{rot}}/\sigma$ profiles of the stars, PNe and GC subpopulations, with low-mass galaxies showing higher $V_{\text{rot}}/\sigma$ profiles than more massive ones. This is, again, consistent with the general picture from previous observational results, in which fast rotators are typically found among the population of low-mass galaxies, while slow rotators are found among the class of rounder and more massive galaxies (e.g. Cappellari et al. 2013).

### 4 Discussion

#### 4.1 Do the PNe and GC subpopulations follow the rotation of the stars?

In Fig. 3, we see that the PNe are overall good tracers of the kinematics of the stars in the overlapping radii out to $\sim 2$–$3 R_e$ for the aligned galaxies, suggesting that we can use the PNe as proxies of the dynamics of the stars out to larger radii (e.g. Coccato et al. 2009; Coccato, Arnaboldi & Gerhard 2013; Cortes et al. 2016; Zanatta et al. 2018). We see that the red GCs also show a good agreement with the kinematics of the stars out to similar radii. The blue GCs show overall consistent rotation with that of red GCs within the 1$\sigma$ errors in NGC 1023 and NGC 2768, suggesting that both GC subpopulations are likely tracing the kinematic properties of the same underlying stellar population in these two aligned galaxies. The blue GCs are also rotating in NGC 3115, however their rotation velocity peaks at larger radii (i.e. $\sim 3 R_e$) than that of the red GCs (i.e. $\sim 1$–$2 R_e$), possibly suggesting differences in the formation history of NGC 3115 as compared to NGC 1023 and NGC 2768, e.g. different properties of the merger event, that we discuss in more details in Section 4.2. On the other hand, the blue GCs in NGC 3377 show very little amount of rotation at all radii as compared to the red GCs, suggesting that they are likely tracing the kinematic properties of the underlying stellar population of the galaxy halo, with some blue GCs that may also have an ex-situ origin (e.g. Forbes et al. 1997; Forbes & Remus 2018).

The misaligned galaxies show more interesting kinematic behaviours, as both the PNe and GC subpopulations display minor-axis
Figure 4. 1D kinematic profiles of the aligned (top) and misaligned (bottom) galaxies compared together. The $V_{\text{rot}}$, $\sigma$, and $V_{\text{rot}}/\sigma$ profiles are shown from left to right, respectively, while the kinematic profiles of the stars (from SLUGGS), PNe, red GCs, blue GCs, and all GCs (if no colour bimodality distribution is observed) are shown from the top to the bottom panels, respectively. The kinematic profiles are the same as in Fig. 3, with the addition of NGC 3115 (Dolfi et al. 2020) among the aligned galaxies.
rotation and kinematic twists with respect to the underlying stars (i.e. NGC 821 and NGC 4649). NGC 5846 is also an example of a non-rotating galaxy. These kinematic behaviours suggest a more complex formation histories for the *misaligned* galaxies, with, possibly, recent merger and accretion events.

### 4.2 How did the *aligned* galaxies form?

We have seen that the six *aligned* galaxies show good kinematic alignment of both the PNe and GC tracers with respect to the underlying stars in the overlapping radii. In Fig. 5, we now calculate their $V_{rot}/\sigma$ profiles by averaging the contributions of the individual $V_{rot}/\sigma$ profiles of the distinct kinematic tracers (i.e. stars, PNe, and GCs) of each galaxy in the overlapping radii. The shaded areas represent the $1\sigma$ standard errors of the mean. The inset plot shows the gradients, as adopted in the *Magneticum* simulations by Schulze et al. (2020), to classify their simulated ETGs as flat $V_{rot}/\sigma$ profiles from the increasing ($V_{rot}/\sigma > 0.04$) and peaked ($V_{rot}/\sigma < -0.04$) $V_{rot}/\sigma$ profiles. The ATLAS$^3D$ data are also shown in this plot; however, they typically do not reach beyond $\sim 0.5 R_e$ and, therefore, do not overlap in radius with the other kinematic tracers (with the exception of the MUSE data of NGC 3115).

#### 4.2.1 Galaxies with peaked $V_{rot}/\sigma$ profiles

The four galaxies (i.e. NGC 1023, NGC 3115, NGC 3377, and NGC 7457) with peaked $V_{rot}/\sigma$ profiles should share similar accretion histories in more recent times (i.e. $z \lesssim 1$) according to Schulze et al. (2020), dominated by minor ($1:10 < \text{mass-ratio} < 1:4$) and mini ($\text{mass-ratio} < 1:10$) mergers that enhanced the velocity dispersion of the galaxy outer regions without disrupting its central disc-like kinematics. Some of these *peaked* galaxies may have also experienced a major merger (mass-ratio $> 1:4$), however this is most likely to have occurred at early times, i.e. more than 5 Gyr ago. In any case, Schulze et al. (2020) find that more than half of the population of the *peaked* galaxies (i.e. $\sim 60$ per cent) is likely to have experienced no major mergers in its past evolutionary history.

Using the Illustris TNG100 simulations, Pulsoni et al. (2021) studied the accretion histories of a sample of ETGs in the stellar mass range $10^{10.3} \leq M/\text{M}_\odot \leq 10^{12}$, reaching out to $15 R_e$. They find overall consistent results with those from Schulze et al. (2020), where galaxies with peaked $V_{rot}/\sigma$ profiles have typically lower stellar masses and have evolved mostly passively after having, possibly, experienced a gas-rich major merger at early times (i.e. $z > 1$). Although a significant fraction (i.e. $\sim 60$ per cent) of the galaxies with peaked $V_{rot}/\sigma$ profiles may have not experienced any major merger and have only evolved through the accretion of low-mass galaxies in minor and mini mergers that influenced the outer galaxy regions, the gas-rich nature of these merger events may still play an important role. Indeed, Pulsoni et al. (2021) find that the peak...
of rotation in galaxies with *peak* v_rot/σ profiles becomes less prominent as the fraction of ex-situ stars accreted through major mergers increases. However, the peak in rotation can re-establish itself if new (z ≤ 1) stars are formed within the galaxy from its cold gas, either in-situ or recently accreted through mergers. This is true for both fast and slow rotator galaxies (see their fig. 8).

Finally, even though mini mergers do not largely affect the central peak of rotation of the galaxies with *peak* v_rot/σ profiles, they can increase the stellar rotation of the galaxies at larger radii if high fractions of the stellar mass (i.e. 10–30 per cent) are accreted through this channel (Pulsoni et al. 2021). This mild increase of the stellar v_rot/σ at larger radii could be a consequence of the orbital configuration of the merger, as Karademir et al. (2019) have shown with simulations that mini mergers can increase the size of the host galaxy disc if they occur along the disc plane. Therefore, these mini mergers could produce galaxies with extended stellar discs characterized by, possibly, higher rotation out to larger radii.

NGC 1023 and NGC 3115 are more massive than NGC 3377 and NGC 7457. For this reason, NGC 1023 and NGC 3115 should be more similar to the Class II galaxies of Pulsoni et al. (2021), that are in-situ dominated in the inner regions and ex-situ dominated in the outskirts of the galaxies. On the other hand, NGC 3377 and NGC 7457 should have more similar properties to the Class I galaxies of Pulsoni et al. (2021), that are in-situ dominated at all radii. Therefore, this suggests that NGC 3377 and NGC 7457 have, on average, accreted larger (i.e. up to ∼ 50–60 per cent) gas fractions than NGC 1023 and NGC 3115 (i.e. up to ∼ 30–40 per cent), possibly through an early gas-rich major merger, that contributed to the in-situ star formation of the galaxies. This merger event is expected to have occurred at earlier times, i.e. z ≥ 2, for NGC 3377 and NGC 7457 as compared to NGC 1023 and NGC 3115, i.e. 1 < z < 2, while no major mergers have likely happened in the evolution histories of all four galaxies since z = 1 (Schulze et al. 2020; Pulsoni et al. 2021).

However, NGC 1023, NGC 3115 and NGC 7457 are rotationally supported S0 galaxies, with v_rot/σ > 1 out to ∼ 3 R_e, as seen in Fig. 5. Following Bournaud et al. (2005), a mean v_rot/σ > 1 is more compatible with a minor merger rather than a major one, which would produce hotter disc kinematics with mean v_rot/σ < 1. For this reason, NGC 1023 and NGC 7457 are more consistent with having experienced at most a minor merger with mass-ratio 1:10, due to their high v_rot/σ > 2 (Bournaud et al. 2005). On the other hand, NGC 3115 is more consistent with a minor merger with mass-ratio 1:7 that resulted in its 1 < v_rot/σ < 2 (Bournaud et al. 2005) as seen in Fig. 5. Indeed, for NGC 3115, Dolfs et al. (2020) have proposed a scenario in which the galaxy was originally a spiral that experienced an early (i.e. ∼ 9 Gyr ago) gas-rich minor merger in the mass-ratio range 1:4-1:10, which shaped its current embedded kinematically cold disc. In more recent times, NGC 3115 has evolved mostly passively, exhausting its own gas through in-situ star formation and accreting low-mass dwarf galaxies in mini mergers that produced the spheroid-like kinematics of the outer regions of the galaxy. This formation scenario for NGC 3115 is consistent with the stellar population results from Poci et al. (2019), who found a dominant old (i.e. ∼ 9 Gyr), metal-rich stellar population in the kinematically cold disc component of NGC 3115, therefore ruling out the occurrence of recent major or minor merger events that would likely destroy this disc structure. At the same time, the old and metal-poor stellar population with hotter kinematics found in the stellar halo of NGC 3115 suggests a late accretion of low-mass dwarf galaxies in dry minor and mini mergers on to the outer regions of the galaxy.

For NGC 1023, we propose a similar formation history as for NGC 3115, characterized by an early (i.e. 1 < z < 2) gas-rich minor merger with mass-ratio 1:10. This gas-rich minor merger would be consistent with the high stellar v_rot/σ > 2 of NGC 1023 (see Fig. 3), according to Bournaud et al. (2005), and would shape the embedded kinematically cold disc of NGC 1023, according to Naab et al. (2014). Moreover, NGC 1023 is classified as an SB0 galaxy from previous photometric studies that detected the presence of a barred bulge (Barbon & Capaccioli 1975). From simulations, Cavanagh & Bekki (2020) have shown that bars can be formed from both major and minor mergers and that the orbital configuration of the merger plays a decisive role in determining whether the bar can survive after the merger. Specifically, they found that minor mergers with mass-ratio 1:10 and closely aligned spin angles are most conducive to the bar formation. Therefore, this seems to reinforce our proposed scenario that NGC 1023 formed through an early gas-rich minor merger with mass-ratio 1:10, where the merging galaxies had similar orientations of their spin angles. The v_rot/σ profiles of the red and blue GCs that show little rotation at larger radii (see Fig. 3) would also be more consistent with a minor merger scenario, according to Bekki et al. (2005). Cortesi et al. (2016) have also found that the majority of the red GCs (and a small fraction of the blue GCs) are associated with the disc of NGC 1023 and, therefore, show a similar disc-like kinematics as the stars and PNe. These GCs could have, thus, formed together with the disc of NGC 1023 at early times (i.e. z ∼ 2) and, possibly, at the epoch of the early gas-rich minor merger. At late times, NGC 1023 has likely continued its evolution history through the accretion of dwarf galaxies in mini mergers (Schulze et al. 2020). Indeed, NGC 1023 is currently ongoing an interaction with its companion dwarf galaxy, NGC 1023A, suggesting that NGC 1023 is still experiencing its late mini merger accretion. The HI gas cloud detected around NGC 1023, with its asymmetric spatial distribution (Sancisi et al. 1984; Capaccioli, Lorenz & Afanasjev 1986), could be the result of the gas that was stripped from the dwarf galaxies accreted by NGC 1023 in mini mergers, as previously suggested also by Cortesi et al. (2016).

Finally, Corsini et al. (2016) detected the presence of a nuclear disc in NGC 1023, which is characterized by a younger (∼ 3.4 Gyr) and more metal-rich ([Fe/H] = 0.50 dex) stellar population than the host galaxy bulge, suggesting that it may have formed from pre-processed, metal-enriched gas within NGC 1023. Therefore, the presence of the young nuclear disc would seem to agree with a recent (and, possibly, still ongoing) mini merger accretion in NGC 1023, where the gas stripped from the dwarf galaxies may have been funnelled towards the galaxy central regions, facilitated by the presence of the bar, to form the young and metal-rich nuclear disc of NGC 1023.

Overall, the formation histories of NGC 1023 and NGC 3115 should be very similar, with the main difference being, possibly, in the orbital configuration of the mergers. In Fig. 3, we notice that the blue GCs of NGC 3115 have a v_rot/σ peak located at larger radii (i.e. ∼ 3 R_e) than the red GCs (i.e. ∼ 1 R_e). On the other hand, the red and blue GCs of NGC 1023 have similar v_rot/σ profiles. According to Bekki et al. (2005), minor mergers can produce a rotation velocity difference between the blue and red GCs, as we see for NGC 3115 in Fig. 3. The fact that we do not see this rotation velocity difference in the red and blue GCs of NGC 1023, that also formed through a minor merger of similar mass-ratio, could suggest different orbital configurations of the minor mergers in NGC 1023 and NGC 3115. Alternatively, Karademir et al. (2019) showed that mini mergers occurring along the disc plane of the galaxy can increase the size of the host galaxy disc. Therefore, this could suggest that the mini mergers in NGC 3115 have occurred along the plane of the disc, causing the size of the disc to increase. As a result, we see a more extended disc-like kinematics in NGC 3115 than in NGC 1023. Additional simulations of GC kinematics would be required in order to understand whether
a specific orbital configuration of the minor and mini mergers can, indeed, produce the observed rotation velocity difference in the red and blue GCs of NGC 3115, as compared to NGC 1023.

Similarly to NGC 1023, NGC 7457 should have also formed through a gas-rich minor merger with mass-ratio 1:10, which would be more consistent with its high stellar $V_{\text{rot}/\sigma} > 2$ (see Fig. 3), according to (Bournaud et al. 2005). However, according to Pulsoni et al. (2021), low-mass galaxies, such as NGC 7457, should be in-situ dominated at all radii, with very large gas fractions (i.e. $\sim 50$–$60$ per cent) that were accreted at early times (i.e. $z > 2$) and that contributed to the in-situ star formation of the galaxy until more recently. These galaxies are also expected to have accreted only very few ex-situ stars on to their outskirts from mini mergers. Therefore, this would suggest that the vast majority of the gas fraction in NGC 7457 already belonged to the galaxy (i.e. in-situ origin). From the stellar kinematics, Bellstedt et al. (2017) showed that the high $V_{\text{rot}/\sigma}$ of NGC 7457 was more consistent with that of a disc progenitor galaxy that evolved passively through secular evolution, consuming its own in-situ gas. Zanatta et al. (2018) also found that $\sim 70$ per cent of the GCs of NGC 7457 belong to the disc of the galaxy and closely follow the kinematics of the stars and PNe (as we have also seen in Fig. 3), therefore suggesting mostly an in-situ origin for the GCs of NGC 7457. According to Zanatta et al. (2018), the central $V_{\text{rot}/\sigma}$ profiles are, indeed, decreasing, even weak, is also visible from the $V_{\text{rot}/\sigma}$ profile of the GCs in Zanatta et al. (2018). Finally, NGC 7457 shows the youngest ($\sim 6$ Gyr) stellar population (McDermid et al. 2015; Forbes et al. 2017b), with respect to the other galaxies in our sample, suggesting that the galaxy continued to form new stars from its large in-situ gas reservoir during its passive evolution until more recently. Indeed, according to Pulsoni et al. (2021), Class I galaxies, such as NGC 7457, are characterized by the largest fraction ($\sim 50$ per cent) of in-situ formed stars at $z \leq 1$, with respect to the other classes. Therefore, NGC 7457 seems to be consistent with mostly a secular evolution during which it consumed its own in-situ gas. At late times, NGC 7457 has likely accreted dwarf galaxies in mini mergers that caused the rotation velocity of the GCs to, possibly, decrease beyond $\sim 2R_e$. It would be interesting to extend the stellar and GC kinematics beyond $2R_e$, in order to confirm whether the $V_{\text{rot}/\sigma}$ profiles are, indeed, decreasing, consistent with a spheroid-like kinematics at larger radii produced by the late mini merger accretion.

Similarly to NGC 7457, NGC 3377 should also be mostly in-situ dominated at all radii, with a somewhat larger fractions of ex-situ stars that are accreted through minor and mini mergers (Pulsoni et al. 2021). The stellar $V_{\text{rot}/\sigma} \sim 1$ of NGC 3377 (see Fig. 3) would be consistent with a minor merger with mass-ratio 1:4,5, according to Bournaud et al. (2005). This minor merger was likely gas-rich and occurred early (i.e. $1 < z < 2$), in order to shape the embedded kinematically cold disc of NGC 3377, according to Naab et al. (2014), Schulze et al. (2020). Additionally, the red GCs are following the rotation of the stars (see Fig. 3) in the overlapping radii and they show little rotation at larger radii, which is also consistent with a minor merger scenario (Bekki et al. 2005). However, it is interesting to note that the red GCs in NGC 3377 are not as old as the red GCs in NGC 3115, as found by (Usher et al. 2019). This would suggest a more recent formation for the red GCs of NGC 3377, as compared to the red GCs of NGC 3115, possibly after the epoch of the gas-rich minor merger that produced the host galaxy disc. A fraction of the GCs in NGC 3377 could also have an ex-situ origin. Indeed, the results from Usher et al. (2019) showed that the GCs of NGC 3377 display a wide range of metallicities, including few very young and metal-poor GCs, suggesting the contribution from recently accreted dwarf galaxies. According to Pulsoni et al. (2021) and Schulze et al. (2020), the late (i.e. $z < 1$) evolution history of NGC 3377 is likely dominated by the accretion of dwarf galaxies in mini mergers, which may have contributed to ex-situ stars as well as to ex-situ GCs in the outer regions of the galaxy. Specifically, the blue GCs in NGC 3377 show very little rotation out to large radii, as compared to the other kinematic tracers in NGC 3377 and to the other galaxies in our sample (see Fig. 3), suggesting that some blue GCs have an ex-situ origin.

4.2.2 Galaxies with flat $V_{\text{rot}/\sigma}$ profiles

The two galaxies with flat $V_{\text{rot}/\sigma}$ profiles (i.e. NGC 2768, NGC 4697) should share similar accretion histories according to Schulze et al. (2020) and should be dominated by minor and mini mergers in more recent times (i.e. $z < 1$), similarly to the peaked galaxies. However, galaxies with flat $V_{\text{rot}/\sigma}$ profiles are more likely to have experienced also a late (i.e. $z < 1$) major merger that destroyed the central disc-like kinematics of the galaxy (Schulze et al. 2020). These results are also consistent with those from Pulsoni et al. (2021), who find that the $V_{\text{rot}/\sigma}$ of the galaxies decreases as the ex-situ fraction increases. Therefore, galaxies with flat $V_{\text{rot}/\sigma}$ profiles should have typically higher stellar masses, since they have likely experienced more recent ($z < 1$) and more gas poor mergers that brought in larger fractions of ex-situ stars, without much gas, flattening the central disc-like kinematics of the galaxy (Pulsoni et al. 2021). NGC 2768 and NGC 4697 are also more massive than the four peaked galaxies, therefore they should be characterized by similar in-situ and ex-situ fractions in the inner regions and be ex-situ dominated in the outskirts of the galaxies (i.e. Class III of Pulsoni et al. 2021).

NGC 2768 shows a $V_{\text{rot}/\sigma} \sim 1$ out to large radii from the stars and PNe (see Fig. 3), which would be consistent with a minor merger with mass-ratio 1:4,5, according to Bournaud et al. (2005). However, this merger is likely to have occurred more recently at $z < 1$ (Schulze et al. 2020; Pulsoni et al. 2021) and to be more gas-poor, as compared to the mergers experienced by the peaked galaxies that are typically gas-rich (Pulsoni et al. 2021). Naab et al. (2014) showed that a late ($z < 2$) gas-poor major merger can spin-up the stars in the merger remnant and produce a rising $\lambda_k$ profile, as seen in Fig. 5 of Naab et al. (2014), which resembles the rising stellar $V_{\text{rot}/\sigma}$ profile, shown in Fig. 3. However, a gas poor major merger with mass-ratio $>1$ would produce a galaxy remnant with hotter disc kinematics, i.e. $V_{\text{rot}/\sigma} < 1$ (Bournaud et al. 2005), which would not be entirely consistent with the $V_{\text{rot}/\sigma}$ of NGC 2768. Therefore, we suggest that NGC 2768 likely formed through a late (i.e. $z < 1$) gas-poor minor merger with mass-ratio $\sim 1$:4,5, as was previously suggested by Zanatta et al. (2018). This late gas-poor minor merger was likely responsible for producing the kinematic misalignment between the stars and gas in the centre of the galaxy (Sarzi et al. 2006) and the flat $V_{\text{rot}/\sigma}$ profile of the stars and PNe out to larger radii (see Fig. 5). Additionally, the gas-poor minor merger also likely contributed to a fraction of the ex-situ stars, even though a significant fraction of ex-situ stars (i.e. $\sim 20$ per cent) is expected to come from the mini
mergers that also shaped the late ($z < 1$) evolution history of the galaxy (Pulsoni et al. 2021; Schulze et al. 2020). The kinematics of the red and blue GC subpopulations, which show low $V_{rot}/\sigma \lesssim 1$ out to large radii, is also more consistent with a minor merger scenario (Bekki et al. 2005). Moreover, Forbes et al. (2012) have shown that the red GCs follow the radial density distribution of the bulge PNe and stars and are, therefore, mostly associated with the spheroidal component of the galaxy. This could be consistent with NGC 2768 having undergone a more gas-poor accretion history (Pulsoni et al. 2021) that has produced the spheroid-like kinematics of the GC subpopulations, a fraction of which could likely have an ex-situ origin.

NGC 4697 shows a $V_{rot}/\sigma \sim 0.5$ (see Fig. 5), which would be consistent with a major merger with mass-ratio 1:3, according to Bournaud et al. (2005). However, the GCs show a $V_{rot}/\sigma$ that is decreasing at larger radii and this kinematic behaviour is more consistent with a minor merger (Bekki et al. 2005). Bournaud et al. (2005) showed that multiple minor mergers in the mass-ratio range 1:4.5–1:10 can, ultimately, produce an elliptical galaxy with stellar kinematics and morphology that are similar to those of an elliptical galaxy produced through an individual major merger. Therefore, we suggest that NGC 4697 has likely formed through multiple minor mergers (at least two) in the mass-ratio range 1:4.5–1:10. These minor mergers likely occurred more recently (i.e. $z \lesssim 1$) and were gas-poor, as for NGC 2768, therefore contributing to some fraction of the ex-situ stars at all radii (Pulsoni et al. 2021; Schulze et al. 2020). At late times (i.e. $z \lesssim 1$), NGC 4697 has likely continued its evolution through the accretion of dwarf galaxies in mini mergers that contributed to the remaining fraction of ex-situ stars (Pulsoni et al. 2021; Schulze et al. 2020). An early work has detected the presence of a young (i.e. $\sim 1$ Gyr old) stellar population as well as of low levels of ongoing star formation in the central regions of NGC 4697 (Ford & Bregman 2013). According to Pulsoni et al. (2021), galaxies in Class III, such as NGC 4697, may also have accreted some small gas fractions, i.e. $\sim 30$ per cent, from which new stars can be born. If this gas was funnelled towards the central regions of the galaxy at the time of the minor mergers, then it could have triggered a more recent star formation event that formed the young stars detected by Ford & Bregman (2013) in the galaxy central regions. Alternatively, a more recent star formation event could have been induced from the remaining in-situ gas of NGC 4697 that was funnelled towards the central regions of the galaxy at the epoch of the late gas-poor minor and mini mergers. This young stellar population could, possibly, be associated with the subpopulation of bright PNe that was identified by Sambhus, Gerhard & Méndez (2006), as theoretical studies suggests that such a bright PNe subpopulation in ETGs would require high-mass, young (i.e. $\leq 1$ Gyr old) stars (Kalirai et al. 2008; Ciardullo 2010). Sambhus et al. (2006) showed that the bright PNe subpopulation had an asymmetric distribution and was concentrated near the central regions of the galaxy, but it was not tracing the kinematics of the underlying stars (Sambhus et al. 2006). Therefore, this could be consistent with a scenario in which this small fraction of young stars in the central regions of the galaxy has formed from the gas, of either in-situ or ex-situ origin, that induced a recent star formation event during the late minor and mini merger accretion of NGC 4697.

4.3 How did the misaligned galaxies form?

The three misaligned galaxies show kinematic twists and misalignment of both the PNe and GC subpopulations with respect to the underlying stars. For this reason, they have more peculiar kinematic profiles that cannot be easily linked to one of the three characteristic profile shapes (i.e. peaked, flat, increasing) investigated by Schulze et al. (2020). This suggests, therefore, that these galaxies had a more complex formation history that involved a larger number of recent merger and interaction events.

NGC 821 is an isolated elliptical galaxy that should share a similar accretion history to the Class III galaxies of Pulsoni et al. (2021), characterized by more recent and gas-poor mergers. The stellar $V_{rot}/\sigma \sim 0.5$ would be consistent with a major merger of mass-ratio 1:3 (Bournaud et al. 2005). This gas-poor major merger would have likely occurred more recently, i.e. $z \lesssim 1$, and contributed to the accretion of a fraction of the ex-situ stars (Pulsoni et al. 2021). However, Proctor et al. (2005) found evidence of strong metallicity gradients in NGC 821, with the central regions showing young ($\sim 4$ Gyr old) ages and high ($[\text{Z}/\text{H}] = 0.5$ dex) metallicities. Outside the central 1 $R_e$ of the galaxy, the ages steeply rise to $\sim 12$ Gyr and the metallicities drop to $\sim 1/3$ of the central value. These steep metallicity gradients rule out a recent major merger in the formation history of the galaxy that would produce a mixing of the stellar population and flatter metallicity gradients, as also shown with simulations (Cook et al. 2016). Therefore, it seems more likely that NGC 821 has experienced multiple minor mergers rather than a single major merger. Indeed, Bournaud et al. (2005) showed that multiple minor mergers in the mass-ratio range 1:4.5–1:10 have the same effect of a single major merger, ultimately producing an elliptical galaxy with hotter kinematics. For NGC 821, we, thus, propose that the galaxy formed through multiple gas-poor minor (at least two) mergers in the mass-ratio range 1:4.5–1:10 in more recent times (i.e. $z \lesssim 1$), similarly to NGC 4697. This formation scenario for NGC 821 would be in agreement with the conclusions reached by Proctor et al. (2005), who suggested that the most likely explanation for the central young and metal-rich stellar population in NGC 821 was the accretion of a low-mass galaxy that triggered a centrally concentrated burst of star formation from the in-situ gas of the galaxy. The decreasing $V_{rot}/\sigma$ profile of the GCs (see Fig. 3) also suggests a minor merger scenario that is expected to produce little rotation of the GCs at larger radii (Bekki et al. 2005). Finally, the minor-axis rotation of the PNe at all radii as well as the kinematic misalignment shown by the GCs with respect to the underlying stars (see Fig. 3 and Appendix A6 in the Supporting Information) could, possibly, be a result of the late gas-poor accretion history of NGC 821. Naab et al. (2014) found that late gas-poor major mergers can produce slowly rotating galaxies with kinematic twists and misalignment. In the case of NGC 821, the multiple (and late) gas-poor minor mergers could have had the effect of a gas-poor major merger, producing the minor-axis rotation of the PNe. Coccato et al. (2009) found similar misalignment in the rotation velocity of the PNe with respect to the underlying stars and Pota et al. (2013) found that the blue GCs are rotating along the photometric minor-axis of the galaxy, consistently with the PNe, while some outer red GCs are counter-rotating with respect to the underlying stars. Coccato et al. (2009) suggested that the disagreement between the stars and PNe may be due to a rapid change of the major kinematic axis of rotation of NGC 821 just outside $\sim 1 R_e$, beyond which the stellar kinematics do not reach. It would be interesting to extend the stellar kinematics beyond 1 $R_e$ with new observations in order to confirm whether the major kinematic axis of rotation of the stars changes beyond $\sim 1 R_e$, in agreement with the PNe data.

NGC 4649 is the only cluster galaxy in our sample and the most massive together with NGC 5846. Therefore, NGC 4649 should be ex-situ dominated at all radii (Class IV galaxy; Pulsoni et al. 2021). This galaxy is expected to have had a very gas-poor accretion history,
with only very small fraction of accreted gas (i.e. < 20 per cent), and to have experienced at least one gas-poor major merger in recent times, i.e. \( z < 1 \), that contributed to a large fraction (up to \( \sim 40 \) per cent) of the ex-situ stars (Pulsoni et al. 2021). Naab et al. (2014) found that a late gas-poor major merger can spin-up the stars in the merger remnant, producing a fast rotator galaxy with rising \( \lambda_K \) profile out to \( \sim 2 R_e \), which roughly resembles the rising stellar \( V_{\text{rot/}}/\sigma \) profile out to \( \sim 2 R_e \) of NGC 4649 in Fig. 3. According to Bournaud et al. (2005), a major merger with mass-ratio 1:3 can produce elliptical galaxies with less discy isophotes (low ellipticity) and stellar \( V_{\text{rot/}}/\sigma < 1 \), which would also be consistent with our kinematic results in Fig. 3. Both the red and blue GCs subpopulations show rotation in the inner regions of the galaxy within \( \sim 2 R_e \), consistent with the photometric major-axis of the galaxy. The red GCs also show rotation at larger radii, i.e. beyond \( \sim 4 R_e \), which is overall aligned with the galaxy photometric major-axis (see Fig. 3).

We note here that we do not detect rotation at large radii for the blue GCs, as for the red GCs, from our 1D kinematic profiles in Fig. 3. However, Pota et al. (2015) found that the blue GCs in NGC 4649 also show significant rotation at larger radii, similarly to the red GCs. However, Pota et al. (2015) found that the rotation of the blue GCs increases beyond \( \sim 30 \) kpc. Our 1D kinematic profiles of NGC 4649 in Fig. 3 do not reach beyond \( \sim 35 \) kpc, therefore we are not detecting the rotation of the blue GCs at larger radii. If the blue GCs are also rotating at larger radii as seen by Pota et al. (2015), then a late (i.e. \( z < 1 \)) gas-poor major merger formation scenario would be consistent with the kinematic results shown in Fig. 3. In fact, according to Bekki et al. (2005), a major merger is expected to spin-up both the red and blue GC subpopulations at larger radii, with the blue GCs having larger velocity dispersion than the red GCs, as we have seen in Fig. 3. We notice that the PNe also show a dip in the rotation velocity at \( \sim 2 R_e \), beyond which the rotation increases again but it is more closely aligned to the photometric minor-axis of the galaxy, as was also seen in Pota et al. (2015) and Coccato et al. (2013). The kinematic twist of the PNe could, possibly, also be a result of the late gas-poor major merger (Naab et al. 2014). Forbes et al. (2017a) have found a large number of ultracompact dwarfs (UCDs) that are associated with NGC 4649. Strader, Brodie & Forbes (2004) also identified a very massive UCD in NGC 4649, which is located at \( \sim 2 R_e \) towards south-west, in correspondence of the rotation velocity dip of the PNe and red GCs (see Fig. 3). Therefore, these UCDs could be the remnant nuclei of dwarf galaxies (e.g. Drinkwater et al. 2000) that have been tidally stripped by NGC 4649 during its late (i.e. \( z < 1 \)) gas-poor minor and mini merger accretion events that are expected to contribute in roughly equal amounts to the fraction of the ex-situ stars (Pulsoni et al. 2021). Similarly to NGC 4649, NGC 5846 is also expected to be ex-situ dominated at all radii due to its large stellar mass. Therefore, its accretion history should be characterized by more very gas-poor merger events that happened very recently, i.e. \( z < 1 \). NGC 5846 is a massive slow rotator galaxy with \( V_{\text{rot/}}/\sigma \lesssim 0.2 \) out to large radii, as seen from both the stars and PNe in Fig. 3. According to Naab et al. (2014)’s simulations, the kinematic properties of NGC 5846 would be more consistent with a formation history dominated by late gas-poor minor mergers, as a late gas-poor major merger is, instead, expected to produce a weakly rising stellar rotation out to \( \sim 2 R_e \). Indeed, multiple minor, as well as mini, mergers are expected to, ultimately, produce an elliptical slowly rotating galaxy, with similar properties as if it had undergone one single major merger (Bournaud et al. 2005). Finally, both the red and blue GC subpopulations do not show any strong rotation at large radii, consistent with a minor merger formation pathway (Bekki et al. 2005). We note here that the rotation of the red and blue GCs in the inner regions of the galaxy within \( \sim 2–3 R_e \) in Fig. 3 may not be real but due to the contamination of the GC system of NGC 5846 with outliers from its nearby companion galaxies, e.g. NGC 5846A, as also previously pointed out by Pota et al. (2013). We also mention this issue in the observed rotation of the red and blue GCs in the inner regions of NGC 5846 in Appendix A2.3.1 (Supporting Information). Therefore, we propose that NGC 5846 has likely formed through a series of multiple gas-poor minor mergers in recent times (i.e. \( z < 1 \)), which may have also contributed ex-situ GCs.

**5 SUMMARY AND CONCLUSIONS**

In this work, we have studied the kinematic properties of nine S0 and E/S0 galaxies (including NGC 3115 from Dolfi et al. 2020) by combining the stars from ATLAS3D and SLUGGS with the discrete PNe and GC tracers, in order to probe the outer regions of the galaxies out to \( \sim 4–6 R_e \).

From 2D kinematic maps (see Figs A1–A8 in the Supporting Information) and 1D kinematic profiles (see Fig. 3), we find that:

(i) For NGC 1023, NGC 2768, NGC 3115, NGC 3377, NGC 4697, and NGC 7457 (aligned galaxies), the kinematics of their PNe and GC systems are well aligned with the kinematics of the stars in the overlapping radii. Overall, the rotation is also consistent with the photometric major-axis of the galaxies. This suggests that both the PNe and GC subpopulations are tracing the main underlying stellar population in these six galaxies out to large galactocentric radii.

(ii) For NGC 821, NGC 4649, and NGC 5846 (misaligned galaxies), the kinematics of their PNe and GC systems are not aligned with the kinematics of the stars in the overlapping radii. Specifically, the PNe and GCs show rotation more closely aligned with the photometric minor-axis of the galaxy in NGC 821, while the PNe and blue GCs show a kinematic twist in the major-axis of rotation beyond \( \sim 2 R_e \) in NGC 4649 and, finally, no clear rotation is detected from all kinematic tracers in NGC 5846. This suggests more complex formation histories for these three galaxies that have likely involved more numerous and more recent mergers.

From the comparison with the simulations of Schulze et al. (2020), we suggest that four of the aligned galaxies (i.e. NGC 1023, NGC 3115, NGC 3377, and NGC 7457) show the characteristic peaked \( V_{\text{rot/}}/\sigma \) profile shape, while the remaining two galaxies (i.e. NGC 2768 and NGC 4697) show the characteristic flat \( V_{\text{rot/}}/\sigma \) profile shape. However, in Fig. 5, we see that all six aligned galaxies show similar kinematic behaviours at large radii, i.e. beyond \( \sim 2–3 R_e \), characterized by low \( V_{\text{rot/}}/\sigma \). Therefore, we suggest two main times in the assembly history of the six aligned galaxies. At late (\( z \lesssim 1 \)) times, all six aligned galaxies had similar accretion histories likely characterized by the accretion of dwarf galaxies in mini mergers that enhanced the velocity dispersion of the galaxies in the outer regions (i.e. beyond \( \sim 2–3 R_e \)) without altering their central disc-like kinematics. However, from the differences in the \( V_{\text{rot/}}/\sigma \) profiles of the galaxies in the central regions (i.e. within \( \sim 2–3 R_e \)), we suggest that the two flat galaxies had, possibly, experienced also a late (\( z \lesssim 1 \)), and relatively more gas-poor, minor merger that flattened the \( V_{\text{rot/}}/\sigma \) profile in the central regions of the galaxy (Schulze et al. 2020; Pulsoni et al. 2021). On the other hand, we suggest that the four galaxies with peaked \( V_{\text{rot/}}/\sigma \) profiles had, possibly, experienced an early (\( z > 1 \)) gas-rich minor merger with some larger accreted gas fractions that preserved the amplitude of the \( V_{\text{rot/}}/\sigma \) peak in the central regions of the galaxies (Pulsoni et al. 2021), or had evolved...
mostly passively through secular evolution as it seems to be the case for NGC 7457.

Among the four peaked galaxies, we also note differences in the 1D kinematic profiles of their tracers (see Fig. 3), therefore suggesting differences in their individual assembly histories that in some cases may, possibly, be a result of the specific orbital configuration of the mergers (see Section 4.2.1). Specifically, we suggest that the orbital configuration of the minor and mini merger events may have induced the formation of the bar in NGC 1023, i.e. a minor merger of mass-ratio 1:10 with closely aligned spin angles (Cavanagh & Bekki 2020), as well as the higher rotation velocity amplitude of the blue GCs than the red GCs at \( \sim 3 R_e \) in NGC 3115 (Bekki et al. 2005). In fact, the late accretion of low-mass dwarf galaxies along a preferential direction may have caused the more extended disc-like kinematics in NGC 3115 than in NGC 1023, i.e. mini mergers occurring along the disc plane of the galaxy (Karademir et al. 2019).

However, further simulations of GC kinematics that explore a wider range of parameters in the orbital configuration of the mergers would be required in order to explain these observed differences.

Finally, all three misaligned galaxies had also overall similar assembly histories, characterized by late (i.e. \( z < 1 \)) mergers. These mergers were likely minor and occurred more than once in the case of NGC 821 and NGC 5846, therefore enhancing the velocity dispersion of the kinematic tracers at all radii. On the other hand, NGC 4649 is likely the result of a major merger (i.e. mass-ratio \( > 1:4 \)) that spun-up both the red and blue GC subpopulations at large radii, with minor and mini merger events that contributed to its population of UCDs.

In this work, we find that the formation histories of S0 galaxies in low-density environments can be quite complex with merger events playing a crucial role in shaping the observed distinct velocity dispersion profiles of the different kinematic tracers in our galaxies out to large radii, depending mainly on their time of occurrence, specific orbital configuration and mass-ratio.

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DATA AVAILABILITY

Original Keck data are available from the Keck Observatory Archive (https://www2.keck.hawaii.edu/koa/public/koa.php).

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Assembly history of S0s at large radii

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SUPPORTING INFORMATION

Supplementary data are available at MNRAS online.

Appendix A. Description of the Individual Galaxies.

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