Kinematics and stellar populations of dwarf elliptical galaxies

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Chapter 3

Kinematics of dwarf elliptical galaxies in the Fornax cluster


In preparation to be submitted
abstract

We present stellar kinematics of a sample of ten dEs, located in the Fornax cluster. The sample covers a large spatial area in the cluster and was observed with the VIMOS IFU at the VLT. We analyse the kinematics and present velocity and velocity dispersion maps, and analyse the rotational support with the use of the specific stellar angular momentum parameter $\lambda_R$. We compare results with some data taken with the SAMI IFU instrument and also compare properties with more massive ETGs and place our sample on the fundamental plane (FP). We notice a range in rotational velocities and also different kinematic signatures which include KDCs, offsets between the kinematic and photometric major axis, a prolate rotator, and also disc- and bar structures. We also notice a small offset on the FP compared to massive ETGs which could be described by different $M/L$ caused by different SFHs in dEs. Investigation into these properties suggest that late-type progenitors of dEs could be shaped during encounters in groups before entering a more dense cluster environment, where the environment is responsible for the final transformation and quenching of star formation.

3.1 Introduction

Detailed studies of Local Group dwarf elliptical galaxies were conducted in the past (e.g., NGC 185 and NGC 147: Geha et al. 2010, M32: Peletier 1993; Rose 1994; del Burgo et al. 2001; Worthey 2004; Monachesi et al. 2012; Zielensiewski et al. 2015 and NGC205: Carter & Sadler 1990; Peletier 1993), however observations of dwarfs outside the Local Group have been limited in the past by instrumental constraints due to their low surface brightness. In the last two decades progress has been made from only having integrated measurements of a few distant dEs (Peterson & Caldwell 1993) to having the capability of obtaining deep spatially resolved data to probe the internal kinematics of these systems (De Rijcke et al. 2001; Pedraz et al. 2002; Geha, Guhathakurta & van der Marel 2003; van Zee, Skillman & Haynes 2004; de Rijcke et al. 2005; Toloba et al. 2009, 2011, 2014b; Koleva et al. 2009a). With this improvement, also provided by the use of IFU, for example with the SAURON, VIMOS, MUSE and SAMI instruments, progress has been made in more detailed and larger spatial coverage studies (i.e., Ryś, Falcón-Barroso & van de Ven 2013; Ryś, van de Ven & Falcón-Barroso 2014; Ryś et al. 2015; Guérou et al. 2015; Mentz et al. 2016) of dwarfs outside the local Group. However with still relatively low spectral resolution and also with integration times up to 5 hours per galaxy, people have not yet been able to measure accurate velocity dispersions below 50 $\text{km s}^{-1}$ outside the Local Group.

The physical appearance or structural properties of these galaxies, observed mostly in clusters, lead to questions regarding our, still incomplete, theoretical
understanding on the different scenarios and processes involved in the formation of these systems.

### 3.1.1 Formation scenarios

The low mass nature of dwarfs, residing in galaxy clusters, makes this class of galaxy especially useful in studying the effect of the cluster environment on galaxy formation. This is mainly due to their shallow potential well which causes increased susceptibility to structural changes by interacting galaxies or tidal heating (i.e., harassment; Moore et al. 1996) and/or the interaction with the intra-cluster medium (i.e., ram-pressure stripping; Gunn & Gott 1972; Lin & Faber 1983). These two processes are currently seen as the most favourable transformational mechanisms, although the contribution of each mechanism is still uncertain. (Lisker, 2009; Lisker et al., 2013).

To understand which of these phenomena has been effective in transforming objects to become dEs, one needs more observable parameters, apart from imaging, in particular rotational support. Even though dEs might photometrically appear very similar, a wide range in rotational support is observed (van Zee, Skillman & Haynes, 2004). Studies on dEs in the Virgo and Fornax clusters have shown galaxies with disc-like rotation and rotational flattening as well as others without any detectable rotation (Geha, Guhathakurta & van der Marel, 2003; Ryš et al., 2015). The amount of rotational support can be used as a strong constraint in formation models due to the expectation for dEs to mostly retain the kinematic properties of their progenitors (Geha, Guhathakurta & van der Marel, 2003). In the last two decades, imaging studies have also revealed more complex structures in dEs such as nuclear disks, bars, and spiral structures (e.g., Jerjen, Kalnajs & Binggeli 2000; Barazza, Binggeli & Jerjen 2002; Geha, Guhathakurta & van der Marel 2003; Graham & Guzmán 2003; De Rijcke et al. 2003a; Lisker, Grebel & Binggeli 2006; Janz et al. 2014), where this may also point to a formation scenario favouring dEs to be transformed late-type galaxies. Other possible scenarios to produce typical properties of dEs include transformations of gas-rich irregular galaxies (Irrs) in burst-like star formation episodes (Davies & Phillipps 1988) leading eventually to dEs from the faded blue compact dwarf galaxies as intermediate step (Lisker, 2009), (see also Toloba et al. 2009, 2014b).

On the contrary, the formation processes in massive ETGs are known to involve hierarchical merging events with a large percentage of their stellar mass accreted from satellite systems (Duc et al., 2011; Khochfar et al., 2011). However, massive ellipticals, like their dwarf counterparts also show a wide range in rotational support. From the ATLAS3D survey, it was shown by Khochfar et al. (2011) that massive slow rotators amount to ~ 20% of the ETG population with different growth histories to that of fast rotating ETGs. They show that the differences in the assembly history between the fast and slow rotators can be linked to the number of major mergers experienced by their progenitors.
However, it is thought that dEs get destroyed in mergers, therefore a different way has to be found to lower their angular momentum. Similarly to dwarfs, the progenitors of these massive ETGs and their interactions play an important role in the kinematic build-up, where the observations of KDCs in both dwarfs and giants could prove to be an important clue in their formation histories.

Another important difference between massive ETGs and dwarfs lies in their stellar populations. Apart from longslit studies by Koleva et al. (2009a); Paudel, Lisker & Kuntschner (2011), not many spatially-resolved stellar population analyses have been done on dEs using IFU data (see Guérou et al. (2015); Ryš et al. (2015); Mentz et al. (2016); Sybilska et al. (2017)). These studies mostly show a wide range in stellar populations, including more recent star formation episodes. In a sample of massive ETGs, La Barbera et al. (2012) showed conclusively that the metallicity is decreasing with increasing radial distance from the centre and also a trend that the centres are generally younger. Although dEs were previously only seen as lower mass elliptical galaxies, more indications are found that they could be identified as a different class with different formation histories.

In order to explain the observations and to improve on formation models of dEs, we need to study them in larger numbers and by using deeper observations. With deep IFU observations, reaching higher S/N ratios and a broader spatial coverage, we can explore in greater detail the stellar kinematics, the stellar population build-up and the observed SFHs, which are all important factors to constrain formation models.

In this chapter we present the kinematical properties of our sample of dEs in the Fornax cluster while we discuss the stellar populations of the same sample in Chapter 4. In order to find clues to the formation mechanisms involved, attention is also directed towards the similarities to dEs in other clusters as well as possible relations when comparing them to other well studied galaxy classes like massive ellipticals.

This chapter is organised as follows. In Section 2 we give an overview on the data in terms of the sample, observations and data reduction. In Section 3, a kinematic comparison is made to dEs from the literature and to data from a SAMI IFU survey with two galaxies in common to our sample. Our kinematical results will be presented in Section 4, which will be followed by a discussion and conclusions in Section 5.

3.2 Data

3.2.1 Sample

Our sample consist of 10 dEs located in the Fornax cluster. These galaxies were chosen as part of a magnitude limited sample of 20 dEs ($M_B > -18$), Table 3.1) for which optical HST imaging is also available from the ACSFCS survey.
3.2. Data (Jordán et al., 2007). The sample of 10 galaxies was observed with the VIMOS IFU instrument (Le Fèvre et al. 2003) mounted on the VLT UT3. In Figure 3.1 we show a spatial distribution of the observed sample (VIMOS I) together with the 10 unobserved dwarf galaxies (VIMOS II) the central massive elliptical galaxy in the Fornax cluster (NGC 1399) and (NGC 1396) presented in Chapter 2.
<table>
<thead>
<tr>
<th>Object</th>
<th>RA</th>
<th>DEC</th>
<th>Type</th>
<th>Integration Time (h)</th>
<th>$M_B$</th>
<th>$D_{25}$ (arcmin)</th>
<th>$R_e$ (arcsec)</th>
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</thead>
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<td>FCC 143</td>
<td>03 34 59.06</td>
<td>-35 10 09.90</td>
<td>E3</td>
<td>1.9</td>
<td>-17.21</td>
<td>0.106</td>
<td>11.8</td>
</tr>
<tr>
<td>FCC 148</td>
<td>03 35 16.79</td>
<td>-35 15 55.95</td>
<td>S0(cross)</td>
<td>1.4</td>
<td>-17.91</td>
<td>0.135</td>
<td>26.9</td>
</tr>
<tr>
<td>FCC 152</td>
<td>03 35 33.09</td>
<td>-32 27 44.79</td>
<td>S0/a pec</td>
<td>2.5</td>
<td>-17.41</td>
<td>0.129</td>
<td>21.4*</td>
</tr>
<tr>
<td>FCC 190</td>
<td>03 37 08.86</td>
<td>-35 11 37.54</td>
<td>SB0</td>
<td>1.4</td>
<td>-18.01</td>
<td>0.118</td>
<td>16.3</td>
</tr>
<tr>
<td>FCC 249</td>
<td>03 40 41.92</td>
<td>-37 30 33.30</td>
<td>E0</td>
<td>1.4</td>
<td>-17.91</td>
<td>0.106</td>
<td>13.8</td>
</tr>
<tr>
<td>FCC 255</td>
<td>03 41 03.40</td>
<td>-33 46 38.42</td>
<td>S0$_1$(6),N</td>
<td>1.4</td>
<td>-17.81</td>
<td>0.122</td>
<td>13.8*</td>
</tr>
<tr>
<td>FCC 277</td>
<td>03 42 22.60</td>
<td>-35 09 10.22</td>
<td>E5(boxy)</td>
<td>1.4</td>
<td>-17.71</td>
<td>0.121</td>
<td>10.1*</td>
</tr>
<tr>
<td>FCC 301</td>
<td>03 45 03.49</td>
<td>-35 58 16.95</td>
<td>E4</td>
<td>1.4</td>
<td>-17.31</td>
<td>0.098</td>
<td>12.4</td>
</tr>
<tr>
<td>FCC 43</td>
<td>03 26 02.30</td>
<td>-32 53 36.80</td>
<td>dS0$_{1/2}$(5),N</td>
<td>1.9</td>
<td>-18.01</td>
<td>0.121</td>
<td>21.0</td>
</tr>
<tr>
<td>FCC 55</td>
<td>03 27 17.90</td>
<td>-34 31 29.17</td>
<td>S0(9),N</td>
<td>1.4</td>
<td>-17.61</td>
<td>0.109</td>
<td>7.9</td>
</tr>
</tbody>
</table>

References: (1), (2), (3), (4) Ferguson (1989); (6) $m_B$ from Ferguson (1989) converted to $M_B$ with $m-M=31.51$ from Blakeslee et al. (2009), (7), (8) Venhola et al. (2017), *: Hamraz et al. (2017) in prep
3.2. Observations

The 10 dEs of this study were observed in 2014 between 18 October and 16 November using the VLT UT3 8.2 m telescope at the ESO Cerro Paranal site. Observations were made with the VIMOS HR-blue grism, with a spatial sampling of 0.66 arcsec per fibre resulting in a $27 \times 27$ arcsec square field of view (FOV). The wavelength coverage in this mode is 3700 Å – 5520 Å, with a pixel size of 0.71 Å in the wavelength direction. Each galaxy was observed with 3 observational blocks consisting of two science exposures with dithering and one sky exposure. The total on-target exposure time per galaxy was 1.4 h with additional 10 min off-target sky exposures. Sky conditions varied over the ten observing nights between photometric conditions to thin cirrus coverage with average seeing conditions of $\sim 1.5$ arcsec (FWHM). Standard calibration frames which includes bias frames, flat fields, and arc-lamps were also observed during each of the nights.

3.2.3 Data reduction

Data reduction was done using a combination of tasks from p3d (a tool for fibre-fed integral field spectrographs by Sandin et al. (2010)) and the IRAF software package. The bias correction, spectrum tracing and flat field corrections were done using p3d. A master bias frame was created by adding all bias frames taken on each observing night. A flat field correction frame was obtained for each science exposure using the same instrumental configuration, which was then also used to trace the spectra on the science exposure. The wavelength calibration was done manually, using tasks from the IRAF longslit package. For each galaxy, these steps were performed on each VIMOS detector quadrants separately, with the propagation of error frames, before using the $p3d_{\text{cvmos\_combine}}$ and $p3d_{\text{rss2cube}}$ tasks to respectively combine the four quadrants and write the resulting file from the 2D RSS format to a data cube for further processing.

Due to the fact that the detector sensitivity varies between the four VIMOS detectors as also explained in more detail by Lagerholm et al. (2012), each quadrant was normalised with the assumption that the correction to the quadrant is independent of the wavelength. A multiplicative normalisation constant was therefore computed for each quadrant of the data cube, after all preprocessing steps, by using the boundary region between two adjacent quadrants. The normalisation was then applied to each quadrant of the cube across the entire wavelength range. Although the extraction of kinematics and the measurement of line-strength indices is not affected by the differences in throughput between the four detectors (Lagerholm et al. 2012), we were compelled to apply the normalisation because of our binning methods which may extend over quadrant boundaries. We used the Voronoi binning method by Cappellari & Copin (2003) and also radial binning scheme to increase the (S/N) of the data.
Figure 3.1 – Map of the Fornax cluster indicating the spatial distribution of the magnitude limited sample of dEs in red and green. The current sample is indicated by filled green circles (VIMOS I) while the unobserved dEs are indicated in red filled circles (VIMOS II). The central massive elliptical galaxy NGC 1399 and the dwarf galaxy NGC 1396 (Mentz et al. 2016, see also Chapter 2) are indicated with black and blue filled circles, respectively. The virial radius (∼4 degrees) of the Fornax cluster is indicated by the solid black line (Drinkwater et al., 2001).
3.2.4 Kinematic maps

In this section we present a selection of some of the most interesting kinematic maps. Most galaxies show some rotation, and a featureless velocity dispersion map. However, some objects show interesting kinematical features, including very prominent KDCs and more obscure structures which causes an imprint on the velocity dispersion profile.

**FCC 190** (Figure 3.2, top panel) is a fairly round SB0 galaxy showing indication of rotation around the optical major axis. This galaxy also shows a velocity dispersion profile with a sharp decrease towards the central regions which is also seen clearly in the SAMI data of this galaxy. This agrees with results from Turner et al. (2012) showing signs of a nuclear disk, where we also measure an offset of \( \sim 10 \) degrees between the kinematic and photometric major axis.

**FCC 249** (Figure 3.2, bottom panel) is a E0 galaxy which contains a very prominent KDC. This is in agreement with Turner et al. (2012) who indicated that, when fitted with a single-Sérsic, a peanut shaped residual in the photometry is left in the centre of the galaxy. This system is also a fast rotator (FR) (Figure 3.7) with a noticeable decrease in velocity dispersion in the central regions, which is also in agreement with a central disk structure.

**FCC 277** (Figure 3.3, top panel) is a nucleated galaxy (Turner et al. 2012) also classified by Ferguson (1989) as a E5 (boxy) type. We notice a decrease in velocity dispersion for a small region inside a radius of 2 arcsec. This galaxy displays a high rotational velocity around the kinematical minor axis, which shows a small displacement from the photometric minor axis by \( \sim 7 \) degrees.

**FCC 301** (Figure 3.3, bottom panel) is a flattened system which is also host to a very prominent KDC. The velocity dispersion profile is rather flat with no noticeable gradient towards the central region. We also see no offset between the photometric and kinematical major axis. This galaxy is also fitted by Turner et al. (2012) with a double-Sérsic profile showing a significant contribution of a nuclear component.

3.3 Measurements

When extracting stellar velocity dispersion measurements, it should be noted that the instrumental resolution \( (\sigma_{\text{inst}}) \) is a limiting factor in obtaining an accurate velocity dispersion of these systems. This is due to the fact that the velocity dispersion values of the dEs under study are in most cases less than the \( (\sigma_{\text{inst}}) \) of the VIMOS instrument \( (R=1440; \sim 88 \text{ km s}^{-1}; \) see also Lagos et al. 2016). This makes the task of extracting credible kinematics particularly challenging for dwarf galaxies. In order to improve on the accurate recovery of velocity dispersion values for dwarf galaxies, binning of the data to a high S/N is of great importance as is also discussed in detail in e.g., Toloba et al. (2011);
Figure 3.2 – Kinematic maps of FCC 190 (top panel) and FCC 249 (bottom panel), showing an indication of a central disk structure for FCC190 and a prominent KDC for FCC 249. Both galaxies show a relatively high degree of rotation, and are classified as FRs, according to the criterium indicated in Figure 3.7.
3.3. Measurements

Figure 3.3 – Kinematic maps of FCC 277 (top panel) and FCC 301 (bottom panel), showing a high degree of rotation in FCC 277 together with a central decrease in velocity dispersion and a clear KDC in FCC 301.
Ryš, Falcón-Barroso & van de Ven (2013). They suggest to have a S/N ratio in excess of 20.

Due to the small FOV of the VIMOS instrument compared to other IFU instruments like SAURON and MUSE, with which it is possible to go out to radii of more than 1 $R_e$, we opted for a radial binning scheme in addition to the Voronoi binning used to create 2D maps. Our radial binning consists of two regions per galaxy, where a central spectrum is extracted from a region inside $R_e/8$ and the second spectrum from a region between $R_e/8$ and $R_e/4$. For the two radial bins extracted from all galaxies we obtained a minimum S/N of $\sim 32$ for the lowest surface-brightness systems. In Table 3.2 we present the tabulated kinematical data of our sample of 10 galaxies together with projected distance from the central galaxy NGC 1399.

Using the pPXF software from Cappellari & Emsellem (2004), we measured the velocity and velocity dispersion of the stellar absorption lines from the extracted Voronoi- and radially binned spectra. This is done by fitting a linear combinations of stellar templates to the galaxy spectrum, which is logarithmically rebinned in wavelength. As templates for the fitting we used high resolution (FWHM $\sim 0.5\text{Å}$) spectra from a selection of 205 stars of spectral types B, A, F, G, K, and M, from the ELODIE library, from which the best-fitting combination is obtained.

### 3.3.1 Comparison with literature

Not many velocity dispersion measurements exist in the literature for these systems and large differences are also reported in some studies using long-slit data. We therefore show a comparison of available average values with our measurements in Figure 3.4. $\sigma_{R_e/8}$ and $\sigma_{R_e/4}$ values are indicated in blue and red, respectively. Green boxes show the average values for all galaxies that were obtained from Kuntschner (2000); Bernardi et al. (2002); Wegner et al. (2003); Vanderbeke et al. (2011) as compiled in the Hyperleda data archive (Makarov et al. 2014).
3.3. Measurements

Figure 3.4 – Stellar velocity dispersion comparison to values obtained from the literature. Values extracted from the regions inside $\sigma_{R_e/8}$ and $\sigma_{R_e/4}$ are indicated in blue and red, respectively. Green boxes indicate the values obtained from the literature, as compiled in the Hyperleda data archive (Makarov et al., 2014).
Table 3.2

<table>
<thead>
<tr>
<th>Object</th>
<th>$V_{\text{sys}}$ (km s$^{-1}$)</th>
<th>$V_{\text{rot}}$ (km s$^{-1}$)</th>
<th>$\sigma_{R_e}/8$ (km s$^{-1}$)</th>
<th>$\sigma_{R_e}/4$ (km s$^{-1}$)</th>
<th>Projected Distance from NGC 1399 (arcmin)</th>
<th>Kin PA (°)</th>
<th>Phot PA (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC 143</td>
<td>1348.1</td>
<td>14.8</td>
<td>74.80 ± 1.99</td>
<td>70.10 ± 2.79</td>
<td>45.97</td>
<td>135</td>
<td>120</td>
</tr>
<tr>
<td>FCC 148</td>
<td>736.6</td>
<td>41.4</td>
<td>52.90 ± 3.31</td>
<td>48.30 ± 6.23</td>
<td>40.73</td>
<td>95</td>
<td>89</td>
</tr>
<tr>
<td>FCC 152</td>
<td>338.9</td>
<td>36.6</td>
<td>48.30 ± 4.99</td>
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<td>182.81</td>
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<td>58</td>
</tr>
<tr>
<td>FCC 190</td>
<td>1765.6</td>
<td>39.8</td>
<td>57.50 ± 5.03</td>
<td>75.00 ± 5.49</td>
<td>22.40</td>
<td>37</td>
<td>28</td>
</tr>
<tr>
<td>FCC 249</td>
<td>1555.3</td>
<td>42.4</td>
<td>109.40 ± 1.56</td>
<td>113.30 ± 2.60</td>
<td>12.47</td>
<td>55</td>
<td>153</td>
</tr>
<tr>
<td>FCC 255</td>
<td>1311.7</td>
<td>48.3</td>
<td>43.00 ± 5.95</td>
<td>48.60 ± 10.89</td>
<td>105.20</td>
<td>173</td>
<td>171</td>
</tr>
<tr>
<td>FCC 277</td>
<td>1625.0</td>
<td>55.7</td>
<td>67.90 ± 2.90</td>
<td>77.30 ± 2.50</td>
<td>50.89</td>
<td>121</td>
<td>114</td>
</tr>
<tr>
<td>FCC 301</td>
<td>1015.0</td>
<td>44.5</td>
<td>53.30 ± 3.68</td>
<td>52.30 ± 3.15</td>
<td>85.91</td>
<td>154</td>
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</tr>
<tr>
<td>FCC 43</td>
<td>1322.6</td>
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<td>...</td>
</tr>
<tr>
<td>FCC 55</td>
<td>1259.3</td>
<td>43.6</td>
<td>51.30 ± 2.64</td>
<td>47.80 ± 3.27</td>
<td>148.18</td>
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<td>31</td>
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</tbody>
</table>

(6): The NASA/IPAC Extragalactic Database (NED).
3.3.2 Comparison with SAMI data

The Sydney-AAO Multi object Integral-field spectrograph (SAMI; Konstantopoulos et al. 2013) is a instrument that makes use of 13 fused hexabundles, containing 61 fibres, to provide a square degree FOV. The FOV of each hexabundle is \( \sim 15 \) arcsec (radius 7 arcsec) which covers most Fornax dEs to a radius up to 0.3 \( R_e \).

From a sample of \( \sim 50 \) dwarfs observed in the SAMI Fornax cluster survey (PI: N. Scott), we compare kinematics of NGC 143 (Figure 3.5) and NGC 190 (Figure 3.6) in common to our sample and the SAMI Fornax cluster survey. Although the SAMI FOV is smaller, the S/N ratio is very high, which means that we have a very good and deep central coverage to compare with.

In terms of the measured range and profile of the velocity dispersion we find a remarkably good agreement between the two data sets. Due to the higher S/N ratio of the SAMI data, we are able to detect some features in the velocity dispersion maps from the SAMI data of FCC 143 which is not as clear in the VIMOS data. This feature likely correspond to a bar structure which is also visible in a residual image from the FDS data (Figure 3.9; (Venhola et al., 2017)).

3.4 Results

3.4.1 Rotational support

Galaxies are generally supported by rotation (rotational supported) and by pressure through random stellar motion. Disc galaxies are generally rotationally supported, while massive ETGs are mostly pressure supported systems, see e.g., (Emsellem et al., 2007, 2011). The most massive giant ellipticals tend to consist of slow rotators, which are generally the most massive galaxies, which barely rotate, except maybe in the centre. However, almost 80% of giant ellipticals consists of FRs, objects for which the flattening is consistent with their rotational support. It seems that dEs, on average, are less rotationally supported than giant ellipticals. The problem, however, is that there are not many dEs with high quality kinematic measurements. This work is meant to alleviate this problem.

In order to compare properties, of our sample, to dEs from the literature, we used the binned spectra from the Voronoi binned data in order to obtain more spatial information. From velocity \( (V) \) and velocity dispersion \( (\sigma) \) measurements on the extracted spectra, we computed the parameter \( \lambda_R \), defined by Emsellem et al. (2007), (Equation. 3.1).

\[
\lambda_R = \frac{\sum_{i=1}^{N} F_i R_i |V_i|}{\sum_{i=1}^{N} F_i R_i \sqrt{V_i^2 + \sigma_i^2}}
\]  

(3.1)

This parameter serves as indicator of the specific stellar angular momentum, a generalisation of the \( v/\sigma \) parameter, which was used before the advent of
Figure 3.5 – Top panels: Maps of intensity, velocity, and velocity dispersion created from SAMI data of FCC 143. The maps were rotated to coincide with the relative position angle of the VIMOS data. Bottom panel: Maps of intensity, velocity, and velocity dispersion created from VIMOS data of FCC 143.
Figure 3.6 – Top panel: Maps of intensity, velocity, and velocity dispersion created from SAMI data of FCC 190. The maps were rotated to coincide with the relative position angle of the VIMOS data. Bottom panel: Maps of intensity, velocity, and velocity dispersion created from VIMOS data of FCC 190.
74 Chapter 3. Kinematics of dwarf elliptical galaxies in the Fornax cluster

Figure 3.7 – Left: Light weighted specific stellar angular momentum, measured inside \( R_e/4 \), \( \lambda_R \) as function of ellipticity for our sample of Fornax dwarfs and the ATLAS3D project (Emsellem et al., 2011). The solid curve \((0.31 \times \sqrt{\epsilon})\), as defined by Emsellem et al. (2011), indicates the distinction between slow and fast rotating galaxies dominated by pressure- and rotational support, respectively. Note that the specific angular momentum for FCC 55 was calculated inside \( R_e/2 \). Right: Cumulative \( \lambda_R \) profiles as function of radial distance.

2D spectroscopy. In Figure 3.7a we show a comparison of 7 of the galaxies in our sample with 260 ETGs from the ATLAS3D galaxy sample as function of ellipticity. Three galaxies were omitted due to large uncertainty in the \( \sigma \) measurement because it is probably too small to be measured at this resolution. Here it should be noted that our \( \lambda_R \) measurements are obtained from the region inside \( R_e/4 \) compared to other results obtained within half an effective radius. With the shallow gradient seen in the cumulative angular momentum profiles of our sample and the Virgo dwarfs, also with a similar mass range as in Ryš, van de Ven & Falcón-Barroso (2014); Toloba et al. (2014b), we expect a reasonable comparison, for most dwarfs, to values obtained at half an \( R_e \).

3.4.2 Kinematic scaling relations

The FP is used to relate kinematic scaling relations and specific properties of ETGs. These properties include stellar velocity dispersion, galaxy size and luminosity which were initially used in specific scaling relations with the main goal of obtaining distance estimates. With this relation we can obtain valuable insight into formation mechanisms in ETGs due to the fact that these related properties evolve differently with different formation mechanism at play (Cappellari, 2015).

In Figure 3.10 we place our sample of 10 Fornax dwarfs on the FP with the Virgo sample of dwarfs from Toloba et al. (2012) and also indicate the FP relation from more massive ETGs from Falcón-Barroso et al. (2011b). In order to make the comparison with \( V \)-band data from the literature, we first corrected the apparent magnitudes to absolute scale with a distance modulus for the Fornax cluster of 31.51 (Blakeslee et al. 2009) and then transformed
3.4. Results

Figure 3.8 – Rotational support as function of projected cluster-centric distance. The dashed line indicates the weighted $\chi^2$ fit to the data which takes the uncertainties of $\lambda_R$ into account.

Figure 3.9 – Residual images from the FDS (Fornax deep survey) of FCC 143 (left) and FCC 190 (right), showing inner structures left, in the photometry, after being fitted by the Galphot routine (Venhola et al., 2017). FCC 143 shows an indication of a bar with a spiral structure, while we notice the presence of a nuclear disk in FCC 190, which is also evident from the central decrease in the velocity dispersion profile.
Figure 3.10 – Edge-on view of the FP relation for our sample of dEs (red dots) together with a sample of dEs from the Virgo cluster (blue crosses) Toloba et al. (2012). Also shown is the relation for massive ETGs by Falcón-Barroso et al. (2011b) as the red solid line with the 1σ scatter as dashed lines in green. Upper-limits for FCC 152 and FCC 255 are indicated by red and black lines, respectively.

our B-band magnitudes to V-band using an average $B - V = 0.8$ (Bassino et al., 2003). The mean surface-brightness within an elliptical effective radius was calculated for each galaxy using Equation 3.2, where half of the flux was measured inside an ellipse with semi-major axis $R_{SMA}$. The relation between $R_{SMA}$ and the effective radius, $R_e$, is defined to be $R_{SMA} = R_e/\sqrt{1-\epsilon}$ as also used in Toloba et al. (2012) for comparison.

$$<\mu> = m_v + 2.5 \times \log(2) + 2.5 \times \log[\pi \times R_{SMA}^2 \times (1 - \epsilon)]$$ (3.2)

For FCC 152 and FCC 255 with central velocity dispersion values below 50 km s$^{-1}$, where the measurement of the velocity dispersion is not possible due to the low VIMOS instrumental resolution, we calculated an upper limit on the FP with the use of a fixed velocity dispersion of 55 km s$^{-1}$. In Figure 3.10, these upper limits for FCC 152 and FCC 255 are indicated by red and black lines, respectively.
3.5 Discussion and conclusions

Although small, this sample can still be used with other observations to test possible formation scenarios based on cases from individual galaxies. By looking from a kinematics point of view, we observe a variety of interesting aspects amongst these 10 galaxies which includes two KDCs, offsets between kinematic and photometric major axis, and a galaxy showing indications of prolate rotation. In this section we will discuss the variety of kinematic results obtained from the current sample and the link to possible formation scenarios by focusing on KDCs, rotational support, and scaling relations.

3.5.1 KDCs

KDCs or central disks in massive ETGs are known to form as a result of merger events, accretion of gas or flyby encounters (Balcells & Quinn, 1990; Weil & Hernquist, 1993; González-García, Aguerri & Balcells, 2005). The first evidence that KDCs are also found in dEs, was presented by De Rijcke et al. (2004) in which they review possible formation scenarios of KDCs (see also Toloba et al. (2014b)). The two scenarios they investigated included mergers and tidal harassment. The latter scenario proved to be more relevant due to slow encounters in which energy and angular momentum can be transferred. Previous studies have also shown that mergers amongst dwarfs in clusters are not very likely to occur and the energy available during fast encounters of dwarf galaxies in cluster prevents larger perturbations to occur (Binney & Tremaine, 1987; Boselli & Gavazzi, 2006; Toloba et al., 2014b). As most cluster environments are known to be of higher density and contain a low amount of cold gas to accrete, these kinematic structures are most likely formed in less dense environments, as found in groups, which later falls into a cluster (Lisker et al., 2013).

In our sample of 10 dEs, we find two KDCs (FCC 249 and FCC 301), where the region around the core is kinematically distinct from the rest of the galaxy, showing a much faster rotating disc structure. In the case of FCC 249 we also see a decrease in the velocity dispersion in the centre of the galaxy due to less random stellar motions, which is also to be expected from the presence of a central disc structure.

These two galaxies are located in the same projected region, with FCC 249 at a farther projected distance from the cluster centre. As opposed to FCC 249, the KDC in FCC 301 is not as localised to the central region of the galaxy, but more extended along the major axis direction. Due to the harsh conditions in the cluster environment and fading stellar populations over time, KDCs are not expected to survive for a long time (McDermid et al., 2006). In light of this, the possibility exists that these two dwarfs could be on an in-falling trajectory into the cluster, experiencing more dynamical friction, and therefore increasing the energy in random stellar motions in the existing KDC. This could then lead to a more extended KDC as seen in the case of FCC 301.
The statistical significance of finding two KDCs in a sample of 10 galaxies is a relatively high occurrence compared to two KDCs from a sample of 39 dEs that have been found in the Virgo cluster by Toloba et al. (2014b). However, it should also be noted that the environment could play an important role and it might also be easier to detect KDCs from high spatial resolution IFU data as compared to long-slit data as used by Toloba et al. (2014b). In similar studies of low mass ETGs the fraction of KDCs varies between $\sim 5$ and $8\%$, where the KDC fraction in large E/S0 galaxies from the volume complete ATLAS$^3D$ sample amounts to $8.1 \pm 1.8\%$ (Krajnović et al., 2011).

### 3.5.2 Rotational support

As with more massive ETGs, dwarfs also show a range in rotational support (van Zee, Skillman & Haynes, 2004; Janz et al., 2014; Toloba et al., 2014b; Ryš, van de Ven & Falcón-Barroso, 2014). We computed the specific stellar angular momentum ($\lambda_R$) and made a comparison to $\lambda_R$ values from 260 ETGs obtained from the ATLAS$^3D$ survey as shown in Figure 3.8. Even though the $\lambda_R$ parameter for our sample was measured within $R_e/4$ for each galaxy, compared to $R_e/2$ for the ATLAS$^3D$ data, and the fact that the mass range between the two samples is different, we still see that the majority of ETGs have a higher angular momentum compared to our dE sample. This was also shown to be true for the Virgo dEs from Toloba et al. (2014b); Ryš, van de Ven & Falcón-Barroso (2014). However, there also exists a large number of SR ETGs and Toloba et al. (2014b) proposed that the formation mechanism for SR galaxies could be different for different mass ranges.

In the progenitor scenario, we know from the comparison to the CALIFA sample (see Ryš, van de Ven & Falcón-Barroso 2014) that possible late-type progenitors of dEs need to lose a considerable amount of angular momentum in the transformation process to account for the rotational support that we observe in dEs today. The question still exists on the efficiency of a transformation mechanism to remove angular momentum from galaxies falling into a cluster environment. The fact that ram-pressure stripping does not affect the stars as much as the gas when a galaxy encounters a denser cluster environment (Kenney, van Gorkom & Vollmer 2004), together with the suggestion from simulations that longer time-scales are needed for galaxies to be kinematically heated when passing through a cluster (Smith et al. 2015a) suggests that the transformation mechanism at play in reducing the angular momentum should have had an earlier onset in groups.

The rotational support of Virgo dEs as function of projected cluster-centric distance was also reported by Ryš, van de Ven & Falcón-Barroso (2014); Toloba et al. (2014b), where a slight general increase in the number of rotational supported dEs towards the outskirts of the Virgo cluster was found. Although small, we do find a similar trend in $\lambda_R$ in our sample as shown in Figure 3.8,
which indicates the effect of the cluster environment on the kinematical heating of in-falling dwarfs.

### 3.5.3 Scaling relations

We compare our sample of dEs to massive ETGs from Falcón-Barroso et al. (2011b) on the FP plane (Figure 3.10). We notice an offset between our sample and the SAURON ETGs from Falcón-Barroso et al. (2011b). This offset between lower mass systems and ETGs seen on the FP has previously been indicated on different samples by de Rijcke et al. (2005) and Toloba et al. (2012). de Rijcke et al. (2005) argued that different star formation histories can lead to this offset observed from the plane occupied by ETGs. This is due to the earlier star formation taking place after dissipative merger events while the progenitors are still interacting in groups rather than clusters. The offset of \( \sim 0.2 \) in magnitude that we obtain from the FP indicates to a brightening of \( 0.2/0.34 \sim 0.6 \) magnitudes. If we compare two different populations, one aged 3 Gyr with a metallicity of \( Z = 0.004 \) dex and the other with an age of 13 Gyr and metallicity of \( Z = 0.02 \) dex, we obtain a \( V \)-band magnitude difference of \( 7.01 - 5.78 = 1.23 \) mag. This presents the likelihood that this offset is accounted for by the different SFHs in dEs compared to that of giant elliptical galaxies.

With more insight into the rotational support of dEs, peculiar kinematical structures like KDCs, and star formation episodes that affect the appearance of these systems in different scaling relations, we begin to form a picture of a general formation scenario where late-type galaxy mergers take place in groups of galaxies. These groups then combine in a hierarchical fashion to build up the clusters we observe today. Angular momentum of progenitors can be lowered more easily in groups due to the higher likelihood of slow encounters (Binney & Tremaine 1987; Boselli & Gavazzi 2006; Toloba et al. 2014b) after which ram pressure stripping can act upon entry into the cluster environment to remove gas and strangulate the galaxy (Toloba et al., 2014b).

From this kinematic analysis we can conclude that this sample of Fornax dEs also show distinctive differences to that of more massive ETGs. This stems from the fact that we notice the offset in the FP relation as also noted by de Rijcke et al. (2005) and Toloba et al. (2012), which could be caused by a lower surface brightness in combination with a larger effective radius relative to more massive ETGs. This could then also be linked to a different formation process, where the onset of star formation takes place while the progenitors of dEs are still interacting in less dense environments (de Rijcke et al., 2005).

We find two KDCs in the sample of 10 dEs, which could indicate to a formation scenario taking place outside the current cluster environment. The lower density environment are better suited for timely and lower velocity encounters between the progenitor galaxies.

We also show that the rotational support observed in this sample is of a similar scale to other dwarfs in the Virgo cluster and also in general less than
Figure 3.11 – pPXF fits to radially binned spectra inside a radius of $R_e/8$ and $R_e/4$. The galaxy spectrum is shown in black with the fit over-plotted in purple.

that of ETGs. As in previous studies on Virgo dEs by Ryš, van de Ven & Falcón-Barroso (2014); Toloba et al. (2014b), we also notice a slight trend in rotational support as a function of projected cluster-centric distance, which is an indication of the environmental effect that these galaxies experience as they enter the cluster.

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3.4 Appendix

3.5 Notes on individual galaxies

We briefly describe the remaining six dEs below:
Figure 3.12 – Figure 3.11. Continued.

Figure 3.13 – Figure 3.11. Continued.
**FCC 143** is a slow rotating galaxy with a relatively steep gradient in the velocity dispersion profile, showing a prominent peak in the centre as also seen in the comparison with SAMI data obtained for this galaxy. Even though no central disk or bar structure is seen from Hubble ACS data from Turner et al. (2012), we measure an offset of \( \sim 25 \) degrees between the kinematic and photometric major axis (Figure 3.17).

**FCC 148** is a flattened S0 dwarf showing also a reasonable amount of rotation. According to the rotational support from the computed \( \lambda_R \) parameter, it is classified as a slow rotator (Figure 3.7). However, the calculated error due to uncertainty in the velocity dispersion of this galaxy is also relatively large. According to Turner et al. (2012), this galaxy hosts a complex central structure, which is evident from a double Sérsic fit with a strong nuclear component.

**FCC 152** shows a fairly extended nuclear region with emission, indicating ongoing or recent star formation. It shows a flat velocity dispersion profile with a small peak in the centre. A fair amount of rotation is also visible around the optical minor axis.

**FCC 255** is a flattened galaxy very similar in appearance to FCC 55. It is nucleated (Turner et al. 2012) and shows a similar amount of rotation around the optical minor axis, where it is also well aligned with the kinematical minor axis.

**FCC 43** is classified as a dS0\(_{1/2}(5)\) galaxy (Ferguson 1989) located at a large projected distance of 217.6 arcmin from the centre of the cluster. The measured velocity dispersion profile is relatively flat over the radial distance of \( R_e/4 \). Previously velocity dispersion measurements were only obtained from long-slit data (Peterson & Caldwell 1993; Wegner et al. 2003; de Rijcke et al. 2005) which also show a wide range in values.

**FCC 55** Classified as type S0(9).N, FCC55 is a flattened and nucleated galaxy with a maximum rotational velocity of \( 43.6 \pm 1.6 \) km s\(^{-1}\). This galaxy also shows a relatively flat velocity dispersion profile with no indication of a dispersion increase in the centre.
Figure 3.14 - Flux, stellar velocity, and velocity dispersion maps of our sample of 10 dEs in the Fornax cluster.
Figure 3.15 – Figure 3.14. Continued.
3.5. Discussion and conclusions

Figure 3.16 – Figure 3.14. Continued.
Figure 3.17 - Kinemetry obtained for all galaxies in the current sample by using the package Kinemetry by Krajnović et al. (2006). The PA is indicated for each galaxy by the solid red line (see Kinematic PA in Table 3.2).