The SAMI Galaxy Survey: revising the fraction of slow rotators in IFS galaxy surveys

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ABSTRACT
The fraction of galaxies supported by internal rotation compared to galaxies stabilized by internal pressure provides a strong constraint on galaxy formation models. In integral field spectroscopy surveys, this fraction is biased because survey instruments typically only trace the inner parts of the most massive galaxies. We present aperture corrections for the two most widely used stellar kinematic quantities $V/\sigma$ and $\lambda_R$ (spin parameter proxy). Our demonstration involves integral field data from the SAMI (Sydney-AAO Multi-object Integral-field spectrograph) Galaxy Survey and the ATLAS$^{3D}$ survey. We find a tight relation for both $V/\sigma$ and $\lambda_R$ when measured in different apertures that can be used as a linear transformation as a function of radius, i.e. a first-order aperture correction. In degraded seeing, however, the aperture corrections are more significant as the steeper inner profile is more strongly affected by the point spread function than the outskirts. We find that $V/\sigma$ and $\lambda_R$ radial growth curves are well approximated by second-order polynomials. By only fitting the inner profile ($0.5R_e$), we successfully recover the profile out to one $R_e$ if a constraint between the linear and quadratic parameter in the fit is applied. However, the aperture corrections for $V/\sigma$ and $\lambda_R$ derived by extrapolating the profiles perform as well as applying a first-order correction. With our aperture-corrected $\lambda_R$ measurements, we find that the fraction of slow rotating galaxies increases with stellar mass. For galaxies with $\log M_* / M_\odot > 11$, the fraction of slow rotators is $35.9 \pm 4.3$ per cent, but is underestimated if galaxies without coverage beyond one $R_e$ are not included in the sample ($24.2 \pm 5.3$ per cent). With measurements out to the largest aperture radius, the slow rotator fraction is similar as compared to using aperture-corrected values ($38.3 \pm 4.4$ per cent). Thus, aperture effects can significantly bias stellar kinematic integral field spectrograph studies, but this bias can now be removed with the method outlined here.

Key words: galaxies: evolution – galaxies: formation – galaxies: kinematics and dynamics – galaxies: stellar content – galaxies: structure – cosmology: observations.

1 INTRODUCTION
Dynamical studies of stars in galaxies are key to understanding their individual formation history (e.g. de Zeeuw & Franx 1991; Cappellari 2016). Stellar absorption line spectroscopy revealed for the first time that certain galaxies are rotating (Slipher 1914; Pease 1916), well before the discovery was made in our own Galaxy (Oort 1927). Later studies confirmed that most disc galaxies show rotation (see e.g. van der Kruit & Allen 1978). Kinematic observations using long-slit spectroscopy of elliptical galaxies discovered that luminous ellipticals rotate slowly (Illingworth 1977; Binney 1978; Bertola, Zeilinger & Rubin 1989), bulges of spiral

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galaxies show rapid rotation (Illingworth & Schechter 1982; Kormendy & Illingworth 1982; McElroy 1983; Whitmore, Rubin & Ford 1984; Fillmore, Boroson & Dressler 1986) and that intrinsically faint ellipticals rotate as rapidly as bulges (Davies et al. 1983).

The introduction of the SAURON integral field spectographograph (IFS; Bacon et al. 2001), and the subsequent SAURON (de Zeeuw et al. 2002) and ATLAS SDP survey (Cappellari et al. 2011), led to a more quantified classification of rotation by using two-dimensional (2D) measurements of \( V/\sigma \), the flux-weighted ratio between the projected velocity and velocity dispersion, and the spin parameter proxy \( \lambda_R \) (Cappellari et al. 2007; Emsellem et al. 2007). Galaxies with \( \lambda_R > 0.31 \sqrt{\epsilon} \) were classified as fast rotators, and galaxies below this limit as slow rotators (Emsellem et al. 2011). The fast/slow rotator separation was motivated by a classification based on kinematic features of the velocity field (Krajnovič et al. 2011). The ATLAS SDP results indicate that galaxies with regular rotation fields are almost always fast rotators, but non-regular rotators either showed no indication of rotation, revealed signs of kinematically decoupled cores or counter-rotating discs.

Kinematic classifications of galaxies, however, are sensitive to the aperture in which \( V/\sigma \) or \( \lambda_R \) are measured. Due to the limited angular size of IFS, almost all surveys have observed a fraction of galaxies where the aperture does not extend to one effective radius (\( R_e \): 57 per cent of galaxies in the ATLAS SDP survey (Emsellem et al. 2011), 10 per cent in the CALIFA survey (Falcón-Barroso et al. 2017) and 24 per cent in the SAMI (Sydney-AAO Multi-object Integral-field spectographograph) Galaxy Survey (van de Sande et al. 2017). As \( \lambda_R \) growth curves are typically steeply increasing within one \( R_e \) (Emsellem et al. 2011; Fogarty et al. 2014; Foster et al. 2016; van de Sande et al. 2017; Veale et al. 2017b), with the exception of kinematically decoupled cores or counter-rotating discs (Emsellem et al. 2011), this implies that the fast/slow classification becomes more uncertain if a mix of projected apertures are used.\(^1\)

One solution is to implement different selection criteria depending on the aperture (e.g. Fogarty et al. 2014; Brough et al. 2017). Another solution is to aperture correct \( V/\sigma \) and \( \lambda_R \) to one \( R_e \), similar to methods applied to velocity dispersions, where aperture correction has been measured and applied to low- and high-redshift galaxies for more than two decades (Jorgensen, Franx & Kjaergaard 1995; Cappellari et al. 2006; van de Sande et al. 2013; Falcón-Barroso et al. 2017).

In order to estimate aperture corrections for \( V/\sigma \) and \( \lambda_R \), we require 2D stellar kinematic measurements with sufficient sampling within \( R_e \). A wealth of such stellar kinematic data is becoming available from large multi-object IFS surveys such as the SAMI Galaxy Survey (\( N \sim 3600 \); Croom et al. 2012; Bryant et al. 2015) and the SDSS-IV MaNGA survey (Sloan Digital Sky Survey Data; Mapping Nearby Galaxies at APO; \( N \sim 10000 \); Bundy et al. 2015) and other single-shot IFS surveys, such as the ATLAS SDP survey (\( N = 260 \); Cappellari et al. 2011), the CALIFA survey (\( N \sim 480–600 \); Sánchez et al. 2012) and the MASSIVE survey (\( N \sim 100 \); Ma et al. 2014; Veale et al. 2017b). Given the large spread in aperture size between these IFS surveys, a simple aperture correction method is urgently required to spatially homogenize all samples.

In this paper, we present stellar kinematic aperture corrections for \( V/\sigma \) and \( \lambda_R \) from the SAMI Galaxy Survey and the publicly available data from the ATLAS SDP survey. The paper is organized as follows: Section 2 describes the SAMI Galaxy Survey and ATLAS SDP data, and our method for extracting the stellar kinematics. In Section 3, we explore aperture corrections using a simple method (Section 3.3) and using growth curves (Section 3.4). With the SAMI and ATLAS SDP aperture-corrected data, we study the fraction of fast and slow rotators in Section 4, and summarize and conclude in Section 5. Throughout the paper, we assume a \( \Lambda \) cold dark matter cosmology with \( \Omega_m = 0.3, \Omega_{\Lambda} = 0.7 \) and \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\).

2 DATA

2.1 SAMI galaxy survey

2.1.1 Observations and target selection

SAMI is a multi-object IFS mounted at the prime focus of the 3.9 m Anglo-Australian Telescope (AAT). It employs 13 of the revolutionary imaging fibre bundles, or hexabundles (Bland-Hawthorn et al. 2011; Bryant et al. 2011, 2014; Bryant & Bland-Hawthorn 2012), which are made out of 61 individual fibres with 1.6 arcsec angle on sky. Each hexabundle covers a \( \sim 15 \) arcsec diameter region on the sky, has a maximal filling factor of 75 per cent and is deployable over a 1° diameter field of view. All 819 fibres, including 26 individual sky fibres, are fed into the AAOmega dual-beamed spectrographograph (Saunders et al. 2004; Smith et al. 2004; Sharp et al. 2006).

The SAMI Galaxy Survey (Croom et al. 2012; Bryant et al. 2015) aims to observe 3600 galaxies, covering a broad range in galaxy stellar mass (\( M_* = 10^{9–10^{12}} M_\odot \)) and galaxy environment (field, groups and clusters). The redshift range of the survey, 0.004 \( < z < 0.095 \), results in spatial resolutions of 1.6 kpc per fibre at \( z = 0.05 \). Field and group targets were selected from four volume-limited galaxy samples derived from cuts in stellar mass in the Galaxy and Mass Assembly (GAMA) G09, G12 and G15 regions (Driver et al. 2011). GAMA is a major campaign that compiles a large spectroscopic survey of \( \sim 300 \) 000 galaxies carried out using the AAOmega multi-object spectrographograph on the AAT, with a large multi-wavelength photometric data set. Cluster targets were obtained from eight high-density cluster regions sampled within radius \( R_{200} \) with the same stellar mass limit as for the GAMA fields (Owers et al. 2017).

For the SAMI Galaxy Survey, the 580V and 1000R grating are used in the blue (3750–5750 Å) and red (6300–7400 Å) arm of the spectrograph, respectively. This results in a resolution of \( R_{\text{blue}} \sim 1810 \) at 4800 Å, and \( R_{\text{red}} \sim 4260 \) at 6850 Å (van de Sande et al. 2017). In order to create data cubes with 0.5 arcsec spaxel size, all observations are carried out using a six to seven position dither pattern (Allen et al. 2015; Sharp et al. 2015).

2.1.2 Ancillary data

For galaxies in the GAMA fields, we use the aperture-matched \( g \) and \( i \) photometry from the GAMA catalogue (Hill et al. 2011; Liske et al. 2015), measured from reprocessed SDSS Data Release Seven (York et al. 2000; Kelvin et al. 2012), to derive \( g – i \) colours. For the cluster environment, photometry from the SDSS (York et al. 2000) and VLT Survey Telescope (VST) ATLAS imaging data are used (Shanks et al. 2013; Owers et al. 2017).

Effective radii, ellipticities and positions angles are derived using the Multi-Gaussian Expansion (MGE; Emsellem, Monnet & Bacon 1994; Cappellari 2002) technique and the code from Scott et al. (2009) on imaging from the GAMA–SDSS (Driver et al. 2011), SDSS (York et al. 2000) and VST (Shanks et al. 2013; Owers et al. 2015).

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\(^1\) For example, in Emsellem et al. (2011), \( \lambda_{R_e} \) is quoted and used regardless of the \( R_e \) coverage factor.
et al. 2017). We define $R_e$ as the semi-major axis effective radius, and the ellipticity of the galaxy within one effective radius as $\epsilon$, measured from the best-fitting MGE model. For more details, we refer to D'Eugenio et al. (in preparation).

### 2.1.3 Stellar kinematics

Stellar kinematics are measured from the SAMI data by using the penalized pixel fitting code (PPXF; Cappellari & Emsellem 2004) as described in van de Sande et al. (2017). All 1380 unique galaxy cubes, i.e. not including repeat observations, that make up the SAMI Galaxy Survey internal v0.9.1 data release (from observations up to 2015 December) are fitted with the SAMI stellar kinematic pipeline, assuming a Gaussian line-of-sight velocity distribution (LOSVD), i.e. extracting only the stellar velocity and stellar velocity dispersion.

In summary, we first convolve the red spectra to match the instrumental resolution in the blue. The blue and red spectra are then rebinned on to a logarithmic wavelength scale with constant velocity spacing (57.9 km s$^{-1}$), using the code LOG_REBIN provided with the PPXF package. We use annular binned spectra for deriving local optimal templates from the MILES stellar library (Sánchez-Blázquez et al. 2006), which consists of 985 stars spanning a large range in stellar atmospheric parameters.

After the optimal template is constructed for each annular bin, we run PPXF three times on each galaxy spaxel. One time for getting the uncertainties on the LOSVD parameters, estimating from 150 rebinned on to a logarithmic wavelength scale with constant velocity spacing (3 Å−1), the code LOG_REBIN provided with the PPXF package. We use annular binned spectra for deriving local optimal templates from the MILES stellar library (Sánchez-Blázquez et al. 2006), which consists of 985 stars spanning a large range in stellar atmospheric parameters.

As demonstrated in van de Sande et al. (2017), for the SAMI Galaxy Survey we impose the following quality criteria to the stellar kinematic data: signal-to-noise (S/N) $>$3 Å−1, $\sigma_{\text{obs}}$ $>$ FHWM$_{\text{max}}$/2 $\sim$ 35 km s$^{-1}$, where the FHWM is the full width at half-maximum, $V_{\text{err}}$ $<$ 30 km s$^{-1}$, and $\sigma_{\text{err}}$ $<$ $\sigma_{\text{obs}}$ 0.1 $+$ 25 km s$^{-1}$ ($Q_1$ and $Q_2$ from van de Sande et al. 2017). From a visual inspection of all 1380 SAMI kinematic maps, we flag and exclude 41 galaxies with irregular kinematic maps due to nearby objects or mergers that influence the stellar kinematics of the main object. We furthermore exclude 369 galaxies where $R_e$ $<$ 1.5 arcsec or where either $R_e$ or the radius out to which we can accurately measure the stellar kinematics is less than the half-width at half-maximum of the point spread function (FWHM$_{\text{PSF}}$). This brings the final number of galaxies with usable stellar velocity and stellar velocity dispersion maps to 970.

### 2.2 ATLAS$^{3D}$ survey

The SAURON survey (de Zeeuw et al. 2002) and ATLAS$^{3D}$ survey (Cappellari et al. 2011) have a complete combined sample of 260 early-type galaxies within the local (42 Mpc) volume observed with the SAURON spectrograph (Bacon et al. 2001). For the SAURON survey, a spectral resolution of 4.2 Å FWHM ($\sigma_{\text{inst}}$ = 105 km s$^{-1}$) was adopted, covering the wavelength range 4800–5380 Å, whereas for the ATLAS$^{3D}$ survey, galaxies were observed with a higher resolution of 3.9 Å FWHM ($\sigma_{\text{inst}}$ = 98 km s$^{-1}$). With a pixel scale of 0.7 arcsec, the average spatial resolution is $\sim$0.1 kpc at $\sim$20 Mpc.

The data were Voronoi binned (Cappellari & Copin 2003) with a target S/N of 40. As described in Cappellari et al. (2011), the stellar kinematics were extracted using PPXF with stellar templates from the MILES stellar library (Sánchez-Blázquez et al. 2006).

Here, we use the ATLAS$^{3D}$ survey’s publicly available online data. In particular, we use the unbinned data cubes (V1.0) and the 2D Voronoi binned stellar kinematic maps (Emsellem et al. 2004; Cappellari et al. 2011). Galaxy NGC 0936 is excluded from the sample as no unbinned data are available. We adopt the circularized size measurements from Cappellari et al. (2011), which are corrected to semi-major axis effective radii using the global ellipticities from Krajnović et al. (2011, $R_e = R_{c,e}/\sqrt{1-\epsilon}$). Ellipticities at one effective radius are from Emsellem et al. (2011), and position angles from Krajnović et al. (2011). Furthermore, we calculate stellar masses from the $R$-band luminosity and mass-to-light ratio as presented in Cappellari et al. (2013a,b) and correct these to a Chabrier (2003) initial mass function.

### 3 APERTURE CORRECTIONS FOR V/σ AND $\lambda_R$

In this section, we first discuss why aperture corrections are needed by showing the largest stellar kinematic aperture radius as a function of stellar mass. Next, we explore two different approaches for calculating aperture corrections: corrections from a simple relation between $V/\sigma$, or $\lambda_R$, at different radii, and corrections extrapolated from radial growth curves.

#### 3.1 Largest aperture radius

For each galaxy, we calculate the largest aperture radius out to which the stellar kinematic data meet our quality criteria. This $R_{\text{ap max}}$ is defined as the semi-major axis of an ellipse where at least 85 percent of the spaxels meet our quality control criteria. The axial ratio and position angle of the ellipse are obtained from the MGE fits to the imaging data. For the SAMI Galaxy Survey data, we use the unbinned velocity and velocity dispersion maps as described in Section 2.1.3. For the ATLAS$^{3D}$ data, the unbinned flux maps are combined with the Voronoi binned stellar kinematic data. To translate the Voronoi binned stellar kinematic data back to the unbinned grid, we assign the same velocity and velocity dispersion of a Voronoi bin to all spaxels within the same Voronoi bin. All spaxels that are flagged or impacted by cosmic rays, stars or nearby objects are masked.

Fig. 1 shows the ratio of the largest aperture radius to the effective semi-major radius for galaxies in both samples. In the SAMI sample, 79 per cent (767/970) have $R_{\text{ap max}}/R_e$ $>$ 1, whereas the ATLAS$^{3D}$ sample 46 per cent (118/259) have $R_{\text{ap max}}/R_e$ $>$ 2, and 4 per cent (9/259) have $R_{\text{ap max}}/R_e$ $>$ 4. The distribution in stellar mass (top panel) is similar between the samples, although SAMI has a significantly larger number of galaxies at low stellar mass ($M_*/$10$^{8.5}$ M$_\odot$).

Both samples, however, suffer from the same aperture bias. This is clearly visible from the triangular shaped overall distribution, and from the median $R_{\text{ap max}}/R_e$ in stellar mass bins as indicated by the

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2 http://www-astro.physics.ox.ac.uk/atlas3d/

3 Unbinned stellar kinematic measurements are not available.
For each galaxy, we derive $V_R$ below one aperture. For the SAMI Galaxy Survey data, we use the unbinned flux, velocity and velocity dispersion maps as described in Section 2.1.3. For the ATLAS3D data, the unbinned flux maps are combined with the Voronoi binned stellar kinematic data as described in Section 3.1. We measure $V/\sigma$ and $\lambda_R$ for a large number of elliptical apertures out to $R_e^{\text{max}}$.

From now on, we will require a stricter fill factor of 95 per cent of spaxels within the aperture, as these measurements will be used for deriving aperture corrections. This restricts the analysis to smaller subsamples: $N = 528$ at $R_e/2$, $N = 654$ at $R_e$ and $N = 169$ at $2R_e$ in the SAMI sample, whereas for ATLAS3D we have $N = 233$ at $R_e$, $N = 94$ at $R_e$ and $N = 3$ at $2R_e$. For SAMI data, we typically extract 20 different apertures, and for ATLAS3D data 50 different apertures because of the larger number of spatial resolution elements for each galaxy. Finally, the $V/\sigma$ and $\lambda_R$ radial growth curves are interpolated at fixed apertures ranging from 0.2, 0.3, etc., out to $2.5R_e$ but never beyond $R_e^{\text{max}}$.

In Fig. 2, we show $V/\sigma$ and $\lambda_R$ in three different apertures ($R_e/2$, $R_e$, $2R_e$) for SAMI data (blue circles) and ATLAS3D data (orange diamonds). For SAMI, we find a tight relation between $V/\sigma$ and $\lambda_R$ with little scatter, at every aperture. In the ATLAS3D sample, there appear to be more outliers, which could be due to the higher spatial resolution data in which complex dynamical features are spatially resolved. In our best-fitting relation to the SAMI data, using the IDL function MPFIT (Markwardt 2009), reveals an increasing $\tau$ with low stellar mass ($M_* > 10^{10} M_\odot$), $R_e^{\text{max}}/R_e$ is limited by spectral resolution and S/N. At high stellar mass ($M_* > 10^{11} M_\odot$) $R_e^{\text{max}}/R_e$ is limited by the galaxy mass–size relation, i.e. in redshift-limited surveys such as the SAMI and ATLAS3D survey, massive galaxies typically have larger angular sizes than the hexabundles or IFU.

Our best-fitting relation to the SAMI data, using the idl function MPFIT (Markwardt 2009), reveals an increasing $\kappa$ for increasing apertures: $\kappa = 0.94$, 0.97, 1.00 for $R_e/2$, $R_e$, $2R_e$, respectively. We find a similar trend for $R_e/2$ and $R_e$ in the ATLAS3D data ($\kappa = 1.01$, 1.06, respectively), but there are too few galaxies ($N = 3$) with apertures out to $2R_e$ to obtain an accurate fit. The formal fitting uncertainties on $\kappa$ are small, $\sim 0.001$ for SAMI data, and $\sim 0.0005$ for ATLAS3D, but systematic errors due to spatial resolution and seeing are not included in the fit. Our best-fitting $\kappa$ for the ATLAS3D data out to one $R_e$ is lower as compared to the value given by Emsellem et al. (2011), $\kappa \sim 1.1$, which can be ascribed to our different definition of $\lambda_R$ and a different sample selection.

The best-fitting relation to the ATLAS3D data is always higher as compared to the SAMI data. We investigate if the lower SAMI value could be caused by spatial resolution and seeing in Appendix A, but we find that this has no significant effect on the $\lambda_R - V/\sigma$ relation ($\Delta \lambda_R = -0.02$ with a $\Delta \text{FWHM}_{\text{PSF}} = 0.5 – 3.0$ arcsec seeing). Furthermore, for SAMI data, we find no correlation between the fit residual (data minus best-fitting model) and $R_e/\text{FWHM}_{\text{PSF}}$. However, the fit residual does correlate with S/N and the uncertainty on $V/\sigma$ and $\lambda_R$. When the uncertainties are relatively large, or when the S/N is relatively low, the offset from the best-fitting relation is more negative. $\lambda_R$ is known to be sensitive to measurement uncertainties (Emsellem et al. 2011; Wu et al. 2014; van de Sande et al. 2017), and can be overestimated because the $\lambda_R$ calculation includes $|V|$, which can never be less than zero. As $V/\sigma$ (equation 1) and $\lambda_R$ (equation 2) contain $|V|$ and $V^2$, respectively, both measurements can be biased by measurement uncertainties, which is strongly correlated with S/N. However, $\lambda_R$ is normalized by $V$ and $\sigma$, whereas
V/σ is only normalized by σ. Thus, V/σ will be more biased towards higher values than λR when the S/N is low, which results in a negative offset from the λR–V/σ relation. The median V/σ offset of the SAMI data from the ATLAS3D relation is ~0.04, which is still lower than uncertainties due to the impact of seeing (e.g. van de Sande et al. 2017). Thus, while S/N impacts the V/σ measurements more than λR, it will not change the conclusions of this paper.

We also detect a weak trend with stellar mass, such that low-mass galaxies scatter more below the relation. However, as stellar mass and mean S/N are correlated in SAMI Galaxy Survey data, the trend is more likely to be caused by S/N rather than stellar mass. Another potential bias could arise from using different sources for Figs 2(a)–(c) because only 25 galaxies in the SAMI sample have reliable measurement at all of 0.5RE, 1.0RE and 2.0RE. If we repeat the fit with only those 25 sources with full coverage, we find a small deviation (~0.01) of the best-fitting values as compared to fitting the full sample: κ = 0.93, 0.96, 1.02. For ATLAS3D, there are too few sources (N = 3) to obtain an accurate fit for all three apertures. Given that the offset is significantly smaller than the scatter in the λR–V/σ relation, we conclude that using different sources for different aperture comparisons does not bias our results. Similarly, by refitting a low- (z < 0.05) and high-redshift (z > 0.05) sample, we find no significant (~0.01) deviation from the best-fitting values of the full sample.

Some of the λR and V/σ outliers were highlighted by Emsellem et al. (2007, 2011) to motivate that λR is better than V/σ at discriminating between fast and slow rotators. For galaxies with complex inner kinematic structures, λR appeared more consistent with the overall kinematic properties than V/σ. However, in the SAMI data, such outliers appear to be absent. For relatively small apertures of R_e/2, seeing and spatial resolution of SAMI data could wash out the impact of inner dynamical structures, but for larger apertures of R_e and 2R_e, the tight relation between λR and V/σ persists. Furthermore, the examples used in Emsellem et al. (2007, 2011), namely NGC 5813 and 3379, have limited apertures of R_e and R_e/2, which make it harder to argue that at one R_e, either λR or (V/σ)_e is better at classifying these galaxies as fast or slow rotators. Thus, given the low number of outliers in our SAMI data, we argue that V/σ and λR have the same predictive and classification power when a consistent aperture of one R_e is used in seeing-limited surveys. Though, as the scatter appears to be larger in the ATLAS3D data, λR could still prove to be more useful than V/σ for classifying slow and fast rotators. However, the addition of kinematics (Krajnović et al. 2006, 2011), Jeans anisotropic modelling (Cappellari 2008), radial kinematic information (Foster et al. 2016; Bellstedt et al. 2017) and/or high-order stellar kinematics (Krajnović et al. 2011; van de Sande et al. 2017) could provide significantly more insight in the stellar kinematic properties of galaxies than using V/σ or λR alone.

3.3 Simple aperture corrections

Here, we explore whether a tight relation exists for V/σ and λR, which could be used to correct the aperture-incomplete data. We start by comparing V/σ (Fig. 3a) and λR (Fig. 3b) in two different apertures: R_e/2 and R_e. In the SAMI Galaxy Survey, a total of 381 galaxies simultaneously have reliable R_e/2 and R_e measurements, and 94 galaxies in the ATLAS3D data.

There is a tight linear correlation between (V/σ)_e and (V/σ)_e, whereas λR_e/2 versus λR_e is slightly non-linear and curves downwards towards the one-to-one relation at higher λR_e, most prominently visible in the SAMI data. We model the data by fitting linear relations, which are shown as the solid lines in Figs 3(a) and (b):

\[ (V/σ)_e = C_e(V/σ)_e, \quad (V/σ)_{e/2} = C_{e/2}(V/σ)_{e/2}. \]

\[ λR_e = C_λR_eλR_e/2. \]

For SAMI galaxies, the best-fitting aperture corrections are C_e = 1.64, C_{e/2} = 1.57, whereas for ATLAS3D galaxies, the values are significantly lower: C_e = 1.29, C_{e/2} = 1.26. The vertical root-mean-square (rms) scatter increases for larger values of V/σ and λR and is similar for V/σ and λR: 15.1 per cent versus 15.6 for SAMI data, and 16.4 per cent versus 16.8 per cent for ATLAS3D data. In Fig. 3(b), we see that for λR_e/2 > 0.35 most of the SAMI data are on the right-hand side of the best-fitting relation. We could use an exponential function to fit the relation between λR_e and λR_e/2; however, for the larger aperture λR_e, versus λR_e/2, the curvature changes direction from downwards to upwards. This makes it more complicated to construct an aperture correction using one single function that describes all combinations of radii. Therefore, we...
remove the non-linearity in $\lambda_R$ by replacing $\lambda_R$ with $f_{\lambda_R}$ following Emsellem et al. (2011):

$$f_{\lambda_R} = \frac{\lambda_R}{\sqrt{1 - \lambda_R^2}}.$$  \hspace{1cm} (6)

This equation is based on the relation between $\lambda_R$ and $V/\sigma$ (equation 3). Next, we fit the $f_{\lambda_R}$ versus $f_{\lambda_R}/R$ data with the following linear relation:

$$f_{\lambda_R} = C_{f_{\lambda_R}} f_{\lambda_R}/R.$$  \hspace{1cm} (7)

In Fig. 3(c), we show the relation between $f_{\lambda_R}/R$ and $f_{\lambda_R}$ and the best-fitting relation ($C_{f_{\lambda_R}} = 1.72$ for SAMI, $C_{f_{\lambda_R}} = 1.33$ for ATLAS3D). The non-linearity at high values has now disappeared but the rms scatter from the best-fitting relation is slightly higher as compared to the $\lambda_R - \lambda_R/R$ relation: 16.6 per cent and 19.4 per cent for SAMI and ATLAS3D data, respectively.

However, we find that our best-fitting $C$ values to the ATLAS3D data are significantly higher than the quoted values of $C_{V/\sigma_k} \sim 1.1$ and $C_{f_{\lambda_R}} \sim 1.15$ in Emsellem et al. (2011). We can only recover these values for the ATLAS3D data if all 259 ATLAS3D galaxies are fitted, irrespective of their aperture coverage. As 57 per cent of the sample have aperture radii less than one $R_e$, consequently the relation between $\lambda_R$ and $\lambda_R/R$ will be artificially closer to the one-to-one relation.

In Appendix A, we show that seeing has a significant effect on $C_{V/\sigma_k}$ and $C_{f_{\lambda_R}}$. With increasing seeing, smaller apertures (e.g. $R_{e}/2$) are more severely impacted as compared to larger apertures (e.g. $R_e$) as the strongest gradients in both flux and velocity are in the centre. For seeing with FWHM = 0.5–3.0 arcsec, we find an increase in $C_{V/\sigma_k}$ from 1.24 to 1.50, and for $C_{f_{\lambda_R}}$ from 1.28 to 1.50. The trend is the same as for the SAMI and ATLAS3D data in Fig. 3. However, with the typical seeing for SAMI (2.1 arcsec; Allen et al. 2015), the simulated aperture correction is lower than the observed: $C_{V/\sigma_k}$ = 1.37 versus 1.64, respectively, and $C_{f_{\lambda_R}}$ = 1.45 versus 1.72, respectively. The mismatch could be caused by the selected sample of galaxies used to estimate the impact of seeing, which is relatively small and has a limited range in $V/\sigma$ and $\lambda_R$. A more thorough analysis of the impact of seeing on SAMI measurements is under way, but beyond the scope of this paper.

Thus, while seeing is important, by analysing both the SAMI and ATLAS3D aperture relations, we can now work towards providing simple aperture corrections for seeing-impacted surveys (e.g. SAMI and MaNGA) and for surveys where the impact of seeing is small (e.g. ATLAS3D and CALIFA). We emphasize that the key result from Fig. 3 is that the vertical rms scatter between both $(V/\sigma)_{\lambda_R}$ and $(V/\sigma)_{\lambda_R}/R$ is small: ~0.08. Furthermore, we find no correlations between the residual of the aperture correction relation with stellar mass and effective radius of the galaxy. This suggests that it is possible to apply a simple correction to our $V/\sigma$ and $\lambda_R$ measurements when the size of the aperture is limited over the entire sample.

Next, we fit equations (4) and (7) over a large range of apertures, from 0.3–2.5 $R_{aper}/R_e$ for SAMI galaxies to 0.2–1.5 $R_{aper}/R_e$ for ATLAS3D galaxies. We require a minimum of 10 galaxies to accurately fit the relation. Fig. 4 shows the best-fitting values of $C_{V/\sigma_k}$ and $C_{f_{\lambda_R}}$ as a function of aperture radius, which follows a simple tight power law. For all apertures, the relation for SAMI is steeper than for ATLAS3D, which we show is predominantly due to seeing (see Appendix A). We find that the $(V/\sigma)$ aperture corrections can be derived from

$$C_{V/\sigma_k} = (R_{aper}/R_e)^{-0.64} \text{ [ SAMI ]},$$  \hspace{1cm} (8)

$$C_{V/\sigma_k} = (R_{aper}/R_e)^{-0.36} \text{ [ ATLAS3D ]}.$$  \hspace{1cm} (9)

Similarly for $f_{\lambda_R}$, we find that

$$C_{f_{\lambda_R}} = (R_{aper}/R_e)^{-0.72} \text{ [ SAMI ]},$$  \hspace{1cm} (10)

$$C_{f_{\lambda_R}} = (R_{aper}/R_e)^{-0.42} \text{ [ ATLAS3D ]}.$$  \hspace{1cm} (11)

In summary, from measuring the relation between different apertures for $V/\sigma$ and $f_{\lambda_R}$, we derive a simple relation between the aperture correction $C_{V/\sigma_k}$ and $C_{f_{\lambda_R}}$ and aperture radius $R_{aper}/R_e$ (equations 8–11), which can be used to aperture correct data. We test the accuracy of this method in Section 3.5, and apply it to the full SAMI Galaxy Survey and ATLAS3D survey in Section 4.

### 3.4 Aperture corrections from radial growth curves

In this section, we aim to reduce the scatter in the aperture corrections further, by extrapolating the full measured kinematic radial

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**Figure 3.** $V/\sigma$, $\lambda_R$ and $f_{\lambda_R}$ (corrected $\lambda_R$) measured in different apertures $R_e$ and $R_e/2$. Symbols as in Fig. 2. The median uncertainty is shown in the bottom-right corner. We find a strong linear relation between $(V/\sigma)_{\lambda_R}$ and $(V/\sigma)_{\lambda_R}/R$ in panel (a), and between $f_{\lambda_R}$ and $f_{\lambda_R}/R$ in panel (c), whereas the $\lambda_R$ and $\lambda_R/R$ relation is more curved. The different lines show the best-fitting relation (equations 4 and 7) between the two parameters, which can be used to apply a simple aperture correction. The SAMI data lie above the ATLAS3D data, due to atmospheric seeing effects.
We find that both spaxels to lower the impact of complex inner dynamics (e.g. counter-rotating cores) on the growth curve fits. We indeed find that there is a relation indicated by the solid lines, which can be approximated by equations (8)–(11). These relations can be used as a first-order aperture correction in seeing-limited surveys (e.g. SAMI, MaNGA) and in surveys where the impact of seeing is small (e.g. ATLAS3D and CALIFA).

In Fig. 5, we show three example SAMI galaxies with their growth curves as the black solid line for \( V/\sigma \) (top row) and \( \lambda_R \) (bottom row), and their best-fitting second-order polynomial shown in red. Residuals (data minus best fit) of the full profile fit are shown as red pluses around the zero line. For fitting, we use the IDL function MPFIT (Markwardt 2009). For the SAMI data, we set the minimum radial profile aperture to contain 15 good spaxels due to seeing limitations; for ATLAS 3D, we set the limit to 20 good spaxels to lower the impact of complex inner dynamics (e.g. counter-rotating cores) on the growth curve fits. We find that both \( V/\sigma \) and \( \lambda_R \) are well fitted by second-order polynomials, with less than 1 per cent scatter: \( V/\sigma \) rms = 0.010, \( \lambda_R \) rms = 0.008 for SAMI data (\( N = 629 \)), and \( V/\sigma \) rms = 0.009, \( \lambda_R \) rms = 0.009 for ATLAS 3D data (\( N = 68 \)).

From a visual inspection of the growth curves, it appears that galaxies with low \( V/\sigma \) and \( \lambda_R \) show mostly linear behaviour, whereas galaxies with high \( V/\sigma \) and \( \lambda_R \) follow more quadratic functions. In Fig. 6, we investigate this further by showing the best-fitting linear parameter \( b \) versus the quadratic parameter \( c \) from equations (12) and (13). We indeed find that there is a relation between the two: if the \( V/\sigma \) or \( \lambda_R \) profile is slowly rising (small \( b \)), then the profile is mostly linear (small \( c \)), whereas if the profile is steeply increasing (high \( b \)), the profile is always more curved (lower \( c \)). To approximate the scatter, we fit a quadratic function between \( b \) and \( c \) (solid lines in Fig. 6), and find an rms = 0.046 for \( V/\sigma \) and rms = 0.030 for \( \lambda_R \) in the SAMI data, and an rms = 0.074 for \( V/\sigma \) and rms = 0.058 for \( \lambda_R \) in the ATLAS 3D data.

The relation for ATLAS 3D galaxies lies below the one for SAMI, i.e. ATLAS3D growth curves show a stronger quadratic behaviour as compared to the ones from SAMI. After inspecting several outliers, we find that some of the curvature is caused by a premature radial flattening of the profiles. One explanation is that this could be due to more extensive binning in the outskirts of these ATLAS3D galaxies that could artificially lower \( V/\sigma \) and \( \lambda_R \). When we apply a stricter aperture quality cut to the ATLAS3D data, many of the lower outliers indeed disappear, but the sample size also decreases to \( N \sim 50 \), which makes it harder to quantify the relation. In both the SAMI and ATLAS3D data, there are several galaxies where the profile shows a quadratic upturn (\( c > 0 \)). Nearly all of the ATLAS3D objects with \( c > 0 \) are classified by Krajnović et al. (2011) as non-regular rotators with kinematically distinct cores, double maxima or double \( \sigma \) features. Thus, it is unsurprising that the growth curves for these galaxies deviate from galaxies with regular rotation velocity fields.

Motivated by the tight relation between the linear and quadratic components in the \( V/\sigma \) and \( \lambda_R \) growth curves, we postulate that the inner profile (\( \lesssim R_{2/2} \)) can be used to derive a more accurate aperture correction than the single aperture correction value from Section 3.3. To test this theory, we first fit the inner \( R_{2/2} \) profiles with a second-order polynomial without any constraints, shown in Fig. 5 as the green dashed lines, and extrapolate beyond \( R_{2/2} \). In the fit, we require a minimum of five radial points within \( R_{2/2} \), which significantly lowers the number of galaxies in both samples for which we can test this method: \( N = 141 \) for SAMI, \( N = 44 \) for ATLAS 3D.
Figure 5. Growth curves of $V/\sigma$ and $\lambda_R$ in three example SAMI galaxies. We show the observed data in black, the best-fitting quadratic function to the full profile as the red dashed line, the best-fitting relation to the inner $R_{e}/2$ profile in green and in blue the best-fitting relation to the inner $R_{e}/2$ profile with fitting constraints as described in Section 3.4. Residuals (data − best fit) are shown as the plus symbols. $V/\sigma$ and $\lambda_R$ growth curves are well approximated by second-order polynomials. The constrained fits out to $R_{e}/2$ (blue) show that the inner profile can be extrapolated and used to recover $V/\sigma$ and $\lambda_R$ profiles out to at least one effective radius. We find that in 84 per cent of the cases the fits with constraints (blue) recover the observed value at $R_{e}$ better than the fits without (green).

Figure 6. Best-fitting linear and quadratic parameters of all $V/\sigma$ and $\lambda_R$ profiles. Galaxies from the SAMI Galaxy Survey are shown as blue circles, and ATLAS3D survey data are shown as orange diamonds. The median uncertainty is shown in the top-right corner. There is a tight relation between $b$ and $c$ with little scatter, which suggest that the best-fitting relation between $b$ and $c$ can be used as a constraint when fitting the inner $V/\sigma$ and $\lambda_R$ growth curves.
For all three galaxies in Fig. 5, we obtain a poor match between the extrapolated profile (green) and the observed (black) beyond \( R_{e/3} \). Therefore, to improve the fit, we now add a constraint to the parameter \( c \) in equations (12) and (13) by using the relation as given in Fig. 6. Thus, parameter \( c \) is now coupled to parameter \( b \). In other words, if the profile is slowly increasing (low value of \( b \)), the fit is also forced to be linear (low \( c \)). However, if the profile is steeply increasing (high \( b \)), the fit is now forced to have a more quadratic shape (higher \( c \)). The blue dashed line in Fig. 5 shows the fit to the inner \( R_{e/2} \) growth curves, now including these constraints. There is a clear improvement for two galaxies as compared to fits without a constraint (green), and the extrapolated profile now more closely matches the observed (black) profiles; in general, we find that in 84 per cent (118/141) the fit with constraints recovers the observed value at \( R_e \) better.

In summary, we show that \( V/\sigma \) and \( \lambda_R \) growth curves can be well approximated by a quadratic function, and that there is a tight relation between the linear and quadratic component of each profile. We use the relation between the linear and quadratic component to demonstrate that the outer profile can be extrapolated from the inner profile. This provides an alternative method for calculating aperture-corrected \( V/\sigma_e \) and \( \lambda_{R_e} \) values. In the next section, we test how well this new method works as compared to the more simple aperture correction method derived in Section 3.3.

### 3.5 Comparing methods

In the previous sections, we explored two different methods for calculating aperture-corrected \( V/\sigma \) and \( \lambda_R \) values. Here, we test and compare both methods on SAMI and ATLAS3D data. The test sample is similar to the sample from Section 3.4, where we selected galaxies that have coverage out to at least one \( R_e \), with a minimum of five radial points within \( R_{e/2} \), to extrapolate the profiles.

Our method for comparing the accuracy of the aperture corrections is as follows: first, we extract \( V/\sigma \) and \( \lambda_R \) within \( R_{e/2} \) and \( R_e \) from the observed growth curves. Then \( V/\sigma_{e/2} \) and \( \lambda_{R_{e/2}} \) are used to calculate the aperture-corrected values at one \( R_e \) using the method described in Section 3.3. The results are shown in the top row of Fig. 7, where in panel (a) we compare \( \Delta(V/\sigma)_e = (V/\sigma)_e - (V/\sigma)_e \) observed \( - (V/\sigma)_e \) aperture corrected, as a function of \( (V/\sigma)_e \) observed, and likewise in panel (b) for \( \lambda_{R_e} \). With increasing \( (V/\sigma)_e \) and \( \lambda_{R_e} \), the scatter between the observed and aperture-corrected measurements increases. This is perhaps unsurprising, as we earlier observed that the scatter in Fig. 3 also increases for larger \( V/\sigma \) and \( \lambda_R \). However, the absolute fractional scatter in the data is similar across \( (V/\sigma)_e \) (mean 10.9 per cent for SAMI data) and \( \lambda_{R_e} \) values (10.5 per cent for SAMI data). We find no significant difference between the SAMI and ATLAS3D data, which indicates that the scatter is more likely caused by the intrinsic differences in galaxies, rather than measurement uncertainties.

We note that by applying the wrong aperture correction to the wrong sample, e.g. equation (9) on SAMI data, causes a median offset of \( \Delta(V/\sigma)_e = 0.09 \). Thus, applying the aperture corrections presented here to other survey data could create an artificial offset in \( V/\sigma \) and \( \lambda_R \) if they do not match the instrumental set-up and typical atmospheric conditions of either the SAMI or ATLAS3D survey. For large upcoming surveys such as MaNGA, we would advise following the method outlined here to calibrate the aperture correction relations, if a subset of the data allows for multi-aperture measurements.

Next, we derive the aperture-corrected \( R_e \) values by fitting the inner \( R_{e/2} \) growth curves with constraints as described in Section 3.4 (Figs 7c and d). The trends are similar to the top row, i.e. the scatter in the recovered values increases as a function of \( (V/\sigma)_e \) and \( \lambda_{R_e} \). Disappointingly, we find that the scatter on average is slightly larger for the extrapolated growth curve method as compared to the simple

![Figure 7](https://example.com/figure7.png)
aperture corrections. Similar results are obtained if we restrict the sample to the best-quality data, i.e. most complete spatial sampling and highest S/N; the overall rms scatter is lower, but no significant differences are found between both methods. This suggests that our simple method of calculating aperture corrections works as well as, or even better than compared to, our more complicated growth curve fitting approach.

Overall, in Fig. 7 we find that the mean fractional uncertainty on $V/\sigma$ and $\lambda_R$ at one $R_e$ is 11 per cent when the aperture only extends out to $R_{e/2}$. Thus, applying an aperture correction to $V/\sigma$ and $\lambda_R$ is a significant improvement over using non-aperture-corrected data; if no aperture corrections are applied, $V/\sigma$ and $\lambda_R$ would be underestimated by a factor of 30–60 per cent (Fig. 3).

4 APPLICATION: FRACTION OF SLOW ROTATORS

We started this paper by arguing that aperture effects are important for studying the fraction of galaxies with slow rotation as a function of stellar mass. Here, we investigate if and how the fraction of slow rotators changes if aperture-corrected data are included in this calculation. For the SAMI sample, the number of galaxies increases from $N = 767$ to 920 when we include aperture-corrected measurements; the number of galaxies in the ATLAS3D sample increases from $N = 118$ to 259.

Before we calculate the fraction of slow rotators, in Fig. 8 we first show the impact of the aperture corrections in the $(V/\sigma)_{R_e=\epsilon_e}$ and $\lambda_R=\epsilon_e$ plane for all galaxies where the aperture coverage is insufficient. The solid lines show the total aperture correction from $R_{e/2}$ to $R_e$ as indicated by the filled symbols. For SAMI galaxies where the largest aperture radius is less than $R_e(N = 153)$, the mean aperture correction is $\Delta V/\sigma = 0.087$, or 18 per cent, and $\Delta \lambda_R = 0.062$ or 9 per cent. For ATLAS3D data with $R_{e/2}^{\text{max}} < R_e$ ($N = 140$), the median aperture correction is $\Delta V/\sigma = 0.047$, or 11 per cent, and $\Delta \lambda_R = 0.036$ or 9 per cent.

In Fig. 9, we show the full SAMI Galaxy Survey and ATLAS3D survey sample, with full $R_e$ measurements (open symbols) and aperture-corrected (filled symbols) for $(V/\sigma)_e$ (panel a) and $\lambda_R$ (panel b), versus the ellipticity within one effective radius $\epsilon_e$. We find that a large fraction of galaxies with aperture corrections populate the low-$(V/\sigma)_e$ and low-$\lambda_R$ region, but also at high $(V/\sigma)_e$ (>0.6) and $\lambda_R$ (>0.5). Low $(V/\sigma)_e$–$\lambda_R$ galaxies are likely large massive galaxies with little rotation, whereas the latter are big rotating discs.

We define galaxies as slow rotators by adopting the selection criteria from Cappellari (2016):

$$\lambda_R < 0.08 + \epsilon_e/4 \quad \text{with} \quad \epsilon_e < 0.4.$$  

(14)

For the combined SAMI–ATLAS3D sample, we find that the fraction of slow rotators increases from $7.8 \pm 1.0$ per cent (69/886) to $9.2 \pm 0.9$ per cent (108/1179) when aperture-corrected measurements are combined with the non-aperture-corrected values. Confidence intervals are calculated using the method outlined in Cameron (2011). If we ignore the aperture corrections and use the largest aperture radius $\lambda_R$ measurements, the fraction of slow rotators is slightly overestimated: 9.4±0.9 per cent (111/1179); however, this is not significantly different from using aperture-corrected values.

The reason for the similarity is caused by the fact that the aperture corrections are most significant for large $\lambda_R$ and $V/\sigma$ values, whereas the fast/slow rotation division is around $\lambda_R \sim 0.2$. With aperture corrections included, the fraction of slow rotators is lower in the SAMI Galaxy Survey than in the ATLAS3D survey: 8.6±1.0 per cent (79/920) versus 11.2±2.0 per cent (29/259), respectively.

This is due to the fact that the ATLAS3D survey was selected to only contain early-type galaxies, whereas the SAMI Galaxy Survey sample consists of both early- and late-type galaxies and includes more low-mass galaxies.

Next, we limit the sample to massive galaxies with $\log M_*/M_\odot > 11$. The fraction of slow rotators increases more dramatically when aperture-corrected galaxies are included: from

Figure 8. $(V/\sigma)_e$ and $\lambda_R$, versus ellipticity $\epsilon_e$ for all galaxies where an aperture correction is required ($R_{e/2}^{\text{max}} < R_e$). For SAMI (blue circles) and ATLAS3D (orange diamonds) data, the aperture corrections are shown as the solid lines; the final aperture-corrected value is indicated by the filled symbols. The median uncertainty is shown in the top-left corner. We find that the aperture corrections on average significantly increase $V/\sigma$ (respectively 18 and 11 per cent for SAMI and ATLAS3D) and $\lambda_R$ (respectively 14 and 9 per cent for SAMI and ATLAS3D).
If we ignore the aperture corrections and use the largest aperture radius as a function of stellar mass (Fig. 1), and from the fact that the fraction of slow rotators increases from 24.2 ± 5.3 per cent to 35.9 ± 4.3 per cent when aperture-corrected measurements are combined with the data without aperture corrections.

Thus, these results confirm that aperture corrections are important when calculating the fraction of slow rotating galaxies as a function of stellar mass, but that selection effects (i.e. excluding galaxies with $R_{\text{e}} > \sigma / \lambda$) have a significantly stronger impact on the fraction than aperture corrections. In order to assess how much the fraction could furthermore change due to selection effects, in the middle panel of Fig. 10, we provide the total number of galaxies in the SAMI v0.9.1 sample (grey numbers, top row), as compared to the total number of galaxies with (aperture-corrected) stellar kinematic measurements (blue numbers, middle row). In the most massive bin, we are nearly complete with a success rate of 99 galaxies with stellar kinematic measurements out of 105 galaxies in the parent sample. At lower stellar mass, the incompleteness increases as we no longer reach the S/N requirements to accurately measure the LOSVD parameters. Above a stellar mass of $\log M_*/M_\odot > 10.5$, however, the fraction of slow rotators is not significantly going to change due to selection effects.

5 CONCLUSIONS

In this paper, we present two methods for aperture-correcting 2D stellar kinematic $V/\sigma$ and $\lambda_R$ measurements using integral field spectroscopic data from the SAMI Galaxy Survey and ATLAS$^{3D}$ survey. The necessity for aperture-correcting data is demonstrated by showing that there is a strong bias in the largest kinematic aperture radius as a function of stellar mass (Fig. 1), and from the fact that $V/\sigma$ and $\lambda_R$ increase rapidly out to at least an effective radius ($R_e$).

We measure $V/\sigma$ and $\lambda_R$ for a large number of apertures in the SAMI and ATLAS$^{3D}$ data, and show that there is a tight relation for both $V/\sigma$ and $\lambda_R$ between different apertures (Fig. 3). The coefficient
of the relation between different $V/\sigma$ and $\lambda_R$ apertures follows a simple power law (Fig. 5), which can be used as first-order aperture correction (equations 10 and 11).

Spatial resolution and seeing have a strong impact on the amplitude of the aperture correction (Appendix A). In worsening seeing, the relation between small and large apertures becomes steeper as the inner profile is more strongly affected by the point spread function than the outskirts. However, because we calculate aperture corrections for both SAMI and ATLAS$^{3D}$ data separately, this work provides aperture corrections for all seeing-impacted surveys where the typical seeing is $\sim 2$ arcsec (e.g. SAMI and MaNGA) and for surveys where the impact of seeing is small (e.g. ATLAS$^{3D}$ and CALIFA).

We explore a second method for providing more accurate aperture correction based on fitting $V/\sigma$ and $\lambda_R$ growth curves of individual galaxies. $V/\sigma$ and $\lambda_R$ radial growth curves are well approximated by second-order polynomials out to $1.5R_e$, with little scatter (rms $< 1$ per cent). We show that we can successfully recover the profile out to one $R_e$, from fitting the inner profile ($0.5R_e$), but only if a constraint between the linear and quadratic parameter is applied.

Using data with full $R_e$ coverage, we demonstrate that if the aperture only extends out to $R_{e/2}$, the simple aperture correction method and the radial growth curves can both recover $V/\sigma$ and $\lambda_R$ at one $R_e$ with a mean uncertainty of 11 per cent. However, our simple first-order approach for calculating aperture corrections works slightly better than the more complicated approach of fitting and extrapolating the inner profile. The methods presented here provide a significant improvement over using non-aperture-corrected data, as the mean ratio between $R_{e/2}$ and $R_e$ is a factor of 1.3–1.6 for $V/\sigma$ and $\lambda_R$, which is significantly larger than the mean uncertainty of the aperture corrections.

We investigate the fraction of fast and slow rotating galaxies changes as a function of stellar mass with and without aperture-corrected data. For the SAMI Galaxy Survey and ATLAS$^{3D}$ survey, the fraction of slow versus fast rotating galaxies with $\log M/M_\odot > 11$ changes from $24.2 \pm 5.3$ per cent (16/66) to $35.9 \pm 4.3$ per cent (46/128) when aperture data are included. However, by using measurements out to the largest aperture radius, we find a slow rotator fraction of $38.3 \pm 4.4$ per cent (49/128), similar as compared to using aperture-corrected values. Thus, our works suggest that when the IFS observations do not have coverage out to one $R_e$, it is better to use largest aperture radius measurements of $V/\sigma$ and $\lambda_R$, rather than excluding such galaxies from the sample, if a mass complete sample is required. As recent studies show that mass is the main driver of the kinematic morphology–density relation in clusters (Brough et al. 2017; Veale et al. 2017a), and with cosmological simulations that are beginning to explore the evolution of spin as a function of redshift (Naab et al. 2014; Choi & Yi 2017; Penoyre et al. 2017), this emphasizes the need for using spatially homogeneous, or aperture-corrected measurements when investigating these trends.

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GAMA is a joint European-Australasian project based around a spectroscopic campaign using the Anglo-Australian Telescope. The GAMA input catalogue is based on data taken from the Sloan Digital Sky Survey and the UKIRT Infrared Deep Sky Survey. Complementary imaging of the GAMA regions is being obtained by a number of independent survey programmes including GALEX MIS, VST KiDS, VISTA VIKING, WISE, Herschel-ATLAS, GMRT and ASKAP providing UV-to-radio coverage. GAMA is funded by the STFC (UK), the ARC (Australia), and the participating institutions. The GAMA website is http://www.gama-survey.org/.

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APPENDIX A: EFFECT OF SEEING ON APERTURE CORRECTIONS

In Figs 2 and 3, we found that SAMI and ATLAS3D data show different trends, most likely due to the impact of spatial resolution and seeing. Here, we follow the same approach as outlined in van de Sande et al. (2017) where we use existing ATLAS3D kinematic measurements to study the effect of seeing and measurement uncertainty on SAMI observations. Only galaxies that have full coverage out to at least one effective radius are included. We furthermore only use galaxies where the binned data have been derived from four or less original spaxels, in order to avoid step functions in the velocity and dispersion maps. A total of 23 galaxies meet these selection criteria.
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(a) (b) (c)

Figure A1. Relation between $(V/\sigma)_e$–$\lambda_\text{R,e}$ (a), $(V/\sigma)_{e/2}$–$(V/\sigma)_e$ (b) and $f_{\lambda_{\text{R,e}}}/f_{\lambda_{\text{R,0.5e}}}$ (c) for 23 galaxies from the ATLAS3D ‘re-observed’ with SAMI under different simulated seeing conditions. Different realizations of the seeing are shown by different colours, from 0.5 arcsec in blue to 3.0 arcsec in red. The typical seeing for the SAMI Galaxy Survey is 2.1 arcsec. The different values are the best-fitting relation between the two parameters. The difference between $(V/\sigma)_{e/2}$ and $(V/\sigma)_e$, and $\lambda_{\text{R,e}}/2$ and $\lambda_{\text{R,e}}$, is larger with increasing seeing values.

criteria, which have a broad range in $\lambda_R$ (0.05–0.6) and ellipticity (0.05–0.6; Emsellem et al. 2011).

The details of creating SAMI mock observations are described in van de Sande et al. (2017). In short, we rebin the flux, velocity and velocity dispersion maps to get similar angular size distribution as SAMI galaxies. The effect of seeing is mimicked by constructing three-dimensional flux-weighted LOSVD cubes, which are convolved with a Gaussian with FWHM ranging from 0.5, 1.0, . . . , 3.0 arcsec. For each simulated galaxy, we measure $V/\sigma$ and $\lambda_R$ in different apertures as described in Section 3.2. Figs A1(a)–(c) show the results for $V/\sigma$ and $\lambda_R$ under different simulated seeing conditions. Different colours show different realizations of the seeing, from 0.1 arcsec in blue to 3.0 arcsec in red. We note that typical seeing for the SAMI Galaxy Survey is ~2 arcsec, indicated by the beige data.

We do not find a strong impact of seeing on the relation between $\lambda_R$ and $(V/\sigma)_e$ (Fig. A1a). With increasing seeing (FWHM = 0.5–3.0 arcsec), the relation becomes less steep ($\kappa = 0.98$–0.96). However, the difference due to seeing ($\Delta \kappa = 0.02$) is significantly less than the difference we find between the SAMI and ATLAS3D data ($\Delta \kappa = 0.09$). The effect of seeing is much stronger when we compare $R_{e/2}$ and $R_e$ aperture measurements. For both $V/\sigma$ and $\lambda_R$, the relation becomes steeper with increasing seeing, as the inner $R_{e/2}$ profile is more affected than the outer profile.

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