Vertical structure of galaxy disks

We can measure vertical structure of disks by looking at precisely edge-on spirals e.g. van der Kruit & Searle 1981, A&A 95, 105

\[ p(z) = p_0 \text{ sech}^2 \left( \frac{z}{z_0} \right) \]

(cylindrical coords \( R, \phi, z \))

\[ \text{sech} z = \left( \frac{e^z + e^{-z}}{2} \right) \]

- For large \( z \) this is exponential, with scale height \( h_z = \frac{z_0}{2} \) i.e. \( p(z) = e^{-z/h_z} \)

- Disks fit well by \( \text{sech}^2 \) function, with \( z_0 \sim 700 \text{ pc} \) \( (h_z = 350 \text{ pc}) \)

- Scale height \( z_0 \) constant with \( R \)

so \( p(R, z) = p_0 e^{-R/h_R} e^{-z/h_z} \) \( \text{(large \( z \))} \)

or \( p_0 e^{-R/h_R} \text{ sech}^2 \left( \frac{z}{z_0} \right) \) \( \text{(all \( z \))} \)
- disks show a radial cutoff at 4-5 scale lengths

Q. Why was this visible in vdK & Searle's data but not Boroson's?

- face on
  - edge on
Fig. 1a–c. Contour diagrams showing the isophotes in the maps of NGC 5907. a The UG-plate after star-removal (see Paper I) and smoothing to 5'' resolution. The contour interval is 0.5 starting at a faintest level of 24.7 mag arc s^{-2}. The distance between tickmarks around the border is 150''. b The J-plate after star-removal. The faintest contour is at a level of 26.4 mag arc s^{-2}. c Superposition of the two F-plates after star-removal. The faintest contour is at a level of 25.7 mag arc s^{-2}.

Fig. 2. Comparison of the model and observed z- and R-profiles for NGC 5907, obtained after rectangle smoothing and averaging over four quadrants. The rectangles measure 57.5 x 57.03 parallel and perpendicular to the major axis on the sky. The data-points include those from all three colours arbitrarily shifted so as to give general agreement. The dashed line in the parallel profile at the right indicates the infinite disk ($R_{\text{max}} = \infty$).
Fig. 10. Isohote map of the surface brightness distribution in NGC 4565 after removal of 53 field stars near the galaxy. A similar map before star removal appears as Fig. 6b in van der Kruit (1979). The data are based on two IIIa-J+Wratten 2 C exposures with the Palomar 122-cm Schmidt telescope. Further as in Fig. 1.

Fig. 11. The same as Fig. 4 for NGC 4565. The smoothing rectangles now measure 46''0 x 5''03 and the position angle is 135°. The z-profiles are shifted into coincidence at z = 30''2, but only those with a distance from the rotation axis R > 200'' are used.
~1995 CCD data of NGC 4565

Distance from major axis (kpc)

R mag/sq arcsec

Minor axis

±4 kpc

±8 kpc

Bulge

Thick + thin disk model

Thin disk model
Fig. 7. Variation in the thickness of the H I layer with radius. Squares were obtained by averaging in azimuth. Crosses were derived from tangent point data.
Fig. 7. The complete set of model and observed $z$-profiles after rectangle smoothing for NGC 5907
Thickness of disks determined by interplay between kinetic energy of stars (described by velocity dispersion $\sqrt{\langle v^2 \rangle}$) and gravitational potential in self-gravitating disk.

In galaxies with large bulges, evidence for a second, thicker, fainter component with e-folding $h_z \sim 1$ kpc.

Thick disks are important because they are likely to contain the oldest disk stars, and so give a fossil record of early disk evolution.
Bulges & Ellipticals after SAURON

Recall that a galaxy needs to be close to edge-on before we can be sure that the central luminous component is vertically extended (bulges out)

So some 'bulges' in galaxies may be complete monomers, actually simply flattened inner disks

The SAURON project studied a sample of nearby galaxies:

48 E or S0
24 Sa
even 18 Sb–Sd spirals

Most of the really important results have come from the detailed kinematical maps of the E and S0 galaxies, not from later types. Why?
Figure 1. SAURON stellar velocity fields for our 48 E and S0 galaxies (see Paper III), the global outer photometric axis being horizontal. Colour cuts were tuned for each individual galaxy as to properly emphasize the observed velocity structures. A representative isophote is overplotted in each thumbnail as a black solid line, and the centre is marked with a cross. Galaxies are ordered by increasing value of $ARe$ (from left to right-hand side, top to bottom; see Section 3). Slow rotators are galaxies on the first two rows. NGC numbers and Hubble types are provided in the lower-right and upper-right corners of each panel, respectively. Tick marks correspond to 10 arcsec.
NGC2273 (UGC03546)

α = 06h 45m 38s  δ = 60° 54' 13"

$M_B = -20.21$  \( \varepsilon = 0.25 \)

Field galaxy

Figure 6 – continued
Figure 5 – continued
→ Bars have complex kinematics, found more in later type spirals
→ dust obscures & confuses for actual spirals.
   S0s tend to have less

→ SAURON's spectral resolution is 120 km/s.
   So it's better matched to massive galaxies
   with high velocity dispersion

It's likely that we can apply what we learn
from S0s to spirals, at least early type (S0, Sb)

What have we learned?

(i) Morphology can be misleading; fast and
    slow rotators don't split neatly into S0s & Es

(ii) Boxy-diskky classifications (quantitative
     morphology) work a bit better, but
     are not wonderful.
Figure 1. SAURON stellar velocity fields for our 48 E and S0 galaxies (see Paper III), the global outer photometric axis being horizontal. Colour cuts were tuned for each individual galaxy to properly emphasize the observed velocity structures. A representative isophote is overplotted in each thumbnail as a black solid line, and the centre is marked with a cross. Galaxies are ordered by increasing value of $A_R$, (from left to right-hand side, top to bottom; see Section 3). Slow rotators are galaxies on the first two rows. NGC numbers and Hubble types are provided in the lower-right and upper-right corners of each panel, respectively. Tick marks correspond to 10 arcsec.
Early-type galaxies (E, S0, Sa) can be best classified into slow & fast rotators.

The parameter $I_e$ is a better spatial average of $V/2$, which is dominated by very central regions.

- Old idea (Davies et al #1983)
  - luminous ellipticals ($M_B < 20.5$) are non-rotating.
    - If they are flattened, it is via velocity anisotropy.
  - low-luminosity ellipticals & galaxy disks have rotational support, & flattened via rotation.

- post-SAURON (2007)
  - Slow rotators tend to be mildly triaxial but fairly round.
  - correlations with luminosity are there, but weaker.
may be influenced by the presence of a central mass concentration or velocity anisotropy, and we therefore consider $\sigma$ to be a more representative dispersion. As expected, $\sigma$ is usually smaller than $\sigma_{\text{eff}}$, but only in a few cases does the difference exceed 20%.

Estimates of the effective radii, $r_\text{e}$, for the ellipticals are given in arc seconds in column (5) of Table 3. The values of the $r_\text{e}$ for the majority of galaxies in the sample were calculated from the effective diameters, $A_\text{e}$, in the RC2, which were determined from multiaperature photometry or detailed photographic photometry. For seven galaxies, $A_\text{e}$ was not given, and so we have taken $r_\text{e} = D_{\text{eff}}$, where $D_{\text{eff}}$ is the diameter at the $B = 25$ mag arc sec$^{-2}$ isophote. A comparison of the two estimates of the $r_\text{e}$ for the majority of galaxies in our sample shows that this procedure leads to no systematic bias and an rms scatter of only 17%.

For comparison with theoretical models, it is preferable to have measurements of ellipticity and kinematics in the same part of a galaxy. Ellipticities at the appropriate radii are available for only 16 of the galaxies in our sample from the studies of King (1978) and Leach (1981). We have compared their ellipticities at $r_\text{e}$ with those at $D_{\text{eff}}$ ($\sim 3 r_\text{e}$) from the RC2 and find no systematic difference. Except when noted, the ellipticities given in column (4) of Table 3 are those from the RC2 or are averages of the RC2 values and the Leach and King values at $r_\text{e}$. In individual cases, these estimates may not reflect the ellipticity in the central regions of a galaxy, but they should be appropriate for the sample as a whole.

To estimate absolute magnitudes, we have assigned the galaxies to groups and have used the mean velocity of each group as a distance indicator. The name of the group and the adopted group velocity are given in columns (2) and (3) of Table 3. Group membership was determined from de Vaucouleurs (1975), from our inspection of the Palomar and ESO sky surveys, and from recession velocities in the lists of Tonry and Davis (1981a, b), Rood (1981), Sandage and Visvanathan (1978), Sandage (1978), and the RC2. Apparent magnitudes, on the $B_T$ system, were taken from the RC2. One set of absolute magnitudes, $M_V^\text{obs}$, given in column (10) of Table 3, was derived assuming a uniform Hubble flow with $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$. Another set of magnitudes, $M_V^\text{eff}$, given in column (11), was derived using a model of the Virgo-centric flow, equation (2) in Schechter (1980) with $\gamma = 2$, and an infall velocity of 500 km s$^{-1}$. The distance modulus and center of the Virgo Cluster were taken to be 30.98 (Mould, Aaronson, and Huchra 1980) and $a(1950) = 12^h27^m6, b(1950) = 12^\circ56'$. In this case, the far-field Hubble constant is $H_0 = 84$ km s$^{-1}$ Mpc$^{-1}$. Entries marked with plus signs have triple-valued distances on the infall model, and only the intermediate solutions are tabulated. An extinction correction of 0.13 (csc $b - 1$) and a $K$-correction of 5.32 have been applied to both sets of magnitudes.

b) Relation between Rotation and Luminosity

In Figure 3 we have plotted $V/m$ against ellipticity. The filled circles show ellipticals fainter than $M_V^\text{obs} = -20.5$ and the open circles show the brighter galaxies. It is clear that the faint ellipticals rotate more rapidly than most of the bright ellipticals. Also shown in this diagram is the relationship derived from the tensor virial theorem under the assumption that ellipticals are oblate spheroids of constant ellipticity with isotropic velocity distributions (Binney 1978). The predicted ratio, $(V/m)_0$, follows if the rotation curve and dispersion profiles are

$$
\frac{V}{m} = \frac{\sigma}{0.66}
$$

FIG. 2.—Velocity dispersions from this paper plotted against those of Tonry and Davis (1981a, b) and Tonry (1981).

FIG. 3.—The quantity $V/m$ against ellipticity. Ellipticals with $M_V^\text{obs} > -20.5$ are shown as filled circles; ellipticals with $M_V^\text{obs} < -20.5$, as open circles; and the bulges of disk galaxies, as crosses. The solid line shows the $(V/m, e)$-relation for oblate galaxies with isotropic velocity dispersions (Binney 1978).
shows that slow rotators are not velocity scaled-down versions of fast rotators. The small number of galaxies in our sample, as well as our biased representation of the galaxy luminosity function, reminds us that a larger and complete sample is required to reveal the true $\lambda_{R_e}$ distribution in early-type galaxies.

We therefore first briefly discuss here the results obtained so far, this time including 18 additional early-type galaxies (‘specials’) observed with SAURON within the course of other specific projects. For these additional targets, we had to retrieve the main photometric parameters (e.g. $R_e$, $e$, $a_4/a$) from the literature (e.g. Bender et al. 1988; Faber et al. 1997), the kinematic measurements ($\sigma_0$, $\lambda_{R_e}$) being derived from the available SAURON data as for the 48 E/S0 galaxies of the main sample (only 12 galaxies out of the 18 specials have available $a_4$ measurements). Adding these 18 galaxies does not change the overall distribution of fast and slow rotators in a $\lambda_{R_e}$ versus $e$ diagram, as shown in Fig. 9. The fraction of slow rotators (17 out of 66) is still $\sim 25$ per cent. We also confirm that most slow rotators have relatively small ellipticities ($e < 0.3$), in contrast with fast rotators which span a wide range of flattening. The most remarkable fact lies in the confirmation that within these 18 extra targets, there are five slow rotators (NGC4168, 4406, 4472, 4261 and 4365), and they all contain large (kpc) scale KDCs. Similarly, in Fig. 10 we confirm the lack of a global significant correlation between $\lambda_{R_e}$ and $a_4/a$ as shown in Fig. 6. Again, about two-thirds of the slow rotators are boxy (five out of 17 are discy and one has $a_4/a = 0$), and very discy galaxies tend to be fast rotators with high $\lambda_{R_e}$ values. However, $a_4/a$ is clearly not a good proxy for angular momentum. We then show in Fig. 11 the relation between $\lambda_{R_e}$ and $M_{vir}$ with an additional 17 ‘specials’ (excluding the compact galaxy NGC 221 [M 32] which would stretch the plot unnecessarily). Most slow rotators are massive galaxies with $M_{vir} > 10^{11} M_\odot$, with still only two exceptions (NGC 4550 and 4458), reinforcing the results from Fig. 11. The trend for more massive galaxies to have lower $\lambda_{R_e}$ values is still observed, with an overlap of fast and slow rotators in the range $10^{11}-10^{12} M_\odot$. The fast rotator NGC 2320 seems to have a rather large $\lambda_{R_e}$ for its virial mass (being in fact the most massive galaxy out of the 66). NGC 2320 is the most distant galaxy of this set (with $D \sim 83$ Mpc), and has a rather unusual molecular gas content for an early-type galaxy: it exhibits an asymmetric molecular gas disc with a mass of about $4 \times 10^9 M_\odot$, interpreted as a sign of recent accretion or dynamical perturbation (Young 2005).

In Fig. 11, we also show the ‘cusp/core’ classification as in Section 4.3. Most fast rotators are still galaxies with cusps, and most slow rotators are core galaxies. Conversely, massive galaxies tend to have cores, and smaller ones tend to exhibit cuspy central luminosity profiles: in fact, all galaxies with $M_{vir} > 10^{11.5} M_\odot$ have cores. There is a transition region, in the range $10^{11}-10^{11.5} M_\odot$ where we find both cusp and core galaxies. More interestingly, all core galaxies still have $\lambda_{R_e} < 0.3$. However, a galaxy like NGC 524 is almost certainly very inclined (see Paper IV), its corresponding ‘edge-on’ $\lambda_{R_e}$ value being then much larger than 0.75. It would thus be interesting to understand if an edge-on version of NGC 524 would still have a core-like central luminosity profile. We also observe a few galaxies with cusps and rather low $\lambda_{R_e}$ values (NGC 5831) which cannot be reconciled with inclined fast rotators. We may therefore only discriminate cusp and core galaxies combining both their mass and their $\lambda_{R_e}$ values: massive galaxies ($M_{vir} > 10^{11.5} M_\odot$) with $\lambda_{R_e} < 0.3$ are indeed all core galaxies, while smaller galaxies ($M_{vir} < 10^{11} M_\odot$) with $\lambda_{R_e} > 0.3$ seem to all be galaxies with

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**Figure 9.** Left-hand panel: $\lambda_{R_e}$ versus the ellipticity $e$ including the additional 18 E and S0 galaxies observed with SAURON (labelled with NGC numbers). Symbols and the dashed line are as in Fig. 5. Right-hand panel: histogram of $\lambda_{R_e}$ values including the 18 ‘specials’.

**Figure 10.** $\lambda_{R_e}$ versus $a_4$ for the 48 E/S0 of the SAURON sample and an additional 12 galaxies for which we have available $a_4$ values. Symbols for slow and fast rotators are as in Fig. 6.

**Figure 11.** $\lambda_{R_e}$ versus the virial mass $M_{vir}$ for the 48 E/S0 of the SAURON sample plus an additional 17 ‘specials’ (we do not include the fast rotator NGC 221 – M 32 – in this plot considering its very low mass). The top panel shows histograms of $M_{vir}$ (in log, with steps of 0.5) for both slow (red) and fast rotators (blue). Colours in both panels for slow and fast rotators are as in Fig. 6. NGC numbers are indicated for all specials. Symbols for galaxies with cores and cusps are as in the left-hand panel of Fig. 7.
rotation ($V$) dominates, with $V^2 + \sigma^2$ being a reasonable proxy for mass (see Appendix A). The use of higher-order moments of either $V$ or the spatial weighting $R$ would make this parameter more strongly dependent on the aperture and presence of noise in the data. $\lambda_R$ obviously depends on the spatial extent over which the sums in equation (6) are achieved. In practice, we measure $\lambda_R(R_m)$ within regions defined by the photometric best-fitting ellipses, where $R_m$ is the mean radius of that ellipse $\left(a\sqrt{1 - \epsilon}, \text{with } a \text{ its semimajor axis and } \epsilon \text{ its ellipticity}\right)$, the area $A_{\text{ellipse}}$ of the corresponding aperture being thus $\pi R_m^2$, the area of a circle with a radius of $R_m$. When our SAURON kinematic measurements do not fully sample the defined ellipse, we instead set the radius $R_m = \sqrt{A_S}/\pi$ as that of a circular aperture with the same area $A_S$ on the sky actually covered by the SAURON data inside that aperture (see Paper IV). For a specific galaxy, we measure $\lambda_R(R_m)$ up to the radius for which we reach a maximum difference of 15 per cent between $A_S$ and $A_{\text{ellipse}}$: this guarantees that the SAURON kinematic data still properly fill up the elliptic aperture defined by the photometry.

### 3.2 Rotators and $\lambda_R$

Values of $\lambda_R$, $\lambda_R$ within $R_0$ or the largest radius allowed by our SAURON data, whichever is smaller, are provided in Table 1 for the 48 E/S0 galaxies. As expected, NGC 3379 and 5813, which have similar $V/\sigma$ values (see Fig. 1 and Section 3.1) but qualitatively different velocity structures, are now qualitatively distinguished with $\lambda_R$, values of 0.14 and 0.06, respectively. This difference is significant because the formal uncertainty in the derivation of $\lambda_R$, due to the presence of noise in the data is almost always negligible, and anyway smaller than 0.02 for galaxies such as NGC 3379 and 5813 (Appendix B): this can be understood because $\lambda_R$, includes averages over a large area. There is, however, a systematic (positive) bias which obviously increases as the velocity amplitudes in the galaxy decrease, and can reach up to about 0.03 in the measurement of $\lambda_R$. This bias is therefore dominant for the three galaxies with very low $\lambda_R$ (< 0.03), the mean stellar velocities being in fact consistent with zero values everywhere in the field of view.

As we go from galaxies with low to high $\lambda_R$, values, the overall velocity amplitude naturally tends to increase. More importantly, there seems to be a qualitative change in the observed stellar velocity structures. This is already illustrated in Fig. 1, where the 48 SAURON stellar velocity fields are ordered, from left to right, top to bottom, by increasing value of $\lambda_R$. Rotators with $\lambda_R < 0.1$ exhibit low stellar mean velocities at large radii, with very perturbed stellar kinematics and large-scale KDCs (this point will be further examined in Section 4.4).

This qualitative change is nicely illustrated in Fig. 2 where we show the radial $\lambda_R$ profiles. Galaxies with $\lambda_R$, below and above 0.1 exhibit qualitatively very different $\lambda_R$ profiles: the former have either decreasing or nearly flat (and small amplitude) $\lambda_R$ profiles, while the latter preferentially exhibit significantly increasing $\lambda_R$ radial profiles. Observed $\lambda_R$ gradients are therefore negative or rather small within $1R_e$ for galaxies with $\lambda_R < 0.1$, and we will label them as ‘slow rotators’. This contrasts with the significantly rising $\lambda_R$ profiles for galaxies with $\lambda_R > 0.1$, which all exhibit clear large-scale and relatively regular rotation patterns, and which we label, by opposition, as ‘fast rotators’: the fact that this class includes both mild and very fast rotators is discussed in Section 3.4.

As mentioned, Table 1 includes $\lambda_R$, values derived using the SAURON two-dimensional kinematic maps available and a default equivalent aperture of $1R_e$. This aperture is in fact covered by the SAURON datacubes for 17 galaxies out of the 48 in the SAURON E/S0 sample (see Paper IV), with two galaxies being mapped only to $\sim 0.3R_e$ (NGC 4486 and 5846). Galaxies with the narrowest relative spatial coverage (with the largest $R_e$: NGC 4486, 5846) are among the slowest rotators of our sample: these two galaxies are in fact known not to exhibit any significant rotation within $1R_e$ (see Sembach & Tonry 1996), even though NGC 4486 (M 87) is in fact flattened at very large radii (see Kissler-Patig & Gebhardt 1998, and references therein). This implies that only a few galaxies near the $\lambda_R = 0.1$ threshold (NGC 5982, 4550, 4278) could cross that threshold if we were to have a complete coverage up to $1R_e$.

This is also illustrated in Fig. 3 which shows that histograms of $\lambda_R$, for radii of $1R_e$ and $R_e/2$ (or restricted to the equivalent effective aperture of the SAURON field of view, whichever is smaller) have the same fraction of slow and fast rotators. The overall distribution of $\lambda_R$ values is similar for $R_e$ and $R_e/2$, although $\lambda_R$ tends to increase significantly from $R_e/2$ to $R_e$ for fast rotators (see also the solid straight lines in Fig. 5), an obvious implication of the observed rising $\lambda_R$ profiles in Fig. 2. There are 36 fast rotators and 12 slow rotators with $\lambda_R < 0.1$, which all exhibit clear large-scale and relatively regular rotation patterns, and which we label, by opposition, as ‘fast rotators’: the fact that this class includes both mild and very fast rotators is discussed in Section 3.4.

As mentioned, Table 1 includes $\lambda_R$, values derived using the SAURON two-dimensional kinematic maps available and a default equivalent aperture of $1R_e$. This aperture is in fact covered by the SAURON datacubes for 17 galaxies out of the 48 in the SAURON...
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Figure 7. \( \lambda_R \) versus absolute magnitude \( M_B \) (left-hand panel) and virial mass \( M_{\text{vir}} \) (right-hand panel) for the 48 E and SO of the SAURON sample. In the left-hand panel, symbols correspond to the cusp slope classification (Faber et al. 1997; Ravindranath et al. 2001; Rest et al. 2001; Lauer et al. 2005) with power laws as triangles, cores as squares, NGC 821 which is an 'intermediate' object as a circle, and crosses indicating galaxies for which there is no published classification. In the right-hand panel, symbols for slow and fast rotators are as in Fig. 5, and NGC numbers for a few galaxies are indicated.

are in fact at the limit of being CLVs (NGC 4621 and 7332) with a maximum velocity for their inner component around 20 km s\(^{-1}\) at the SAURON resolution. The latter two galaxies as well as the CLVs have in fact all been shown to harbour small counter-rotating stellar systems (Wernli, Emsellem & Copin 2002; Falcón-Barroso et al. 2004; McDermid et al. 2006, hereafter Paper VIII): it is the lower spatial resolution of the SAURON data which produces the low central velocity gradient. If we therefore count CLVs as galaxies with KDCs, this would result in a total of 14 KDC (29 per cent) early-type objects. Among the KDCs, five galaxies (NGC 3414, 3608, 4458, 5813 and 5831) have outer LV components. KMs are observed in 12 galaxies (25 per cent), and six galaxies have individual kinematic components which have KTs (two of them also having KM). Considering the difficulty of detecting these structures at certain viewing angles or low spatial resolution, the number of such detected velocity structures is a lower limit.

In Fig. 8, we show the \((\lambda_R, \epsilon)\) diagram (as in Fig. 5), now with the characteristic velocity structures detected via kinemetry. The three slowest rotators are obviously tagged as low-velocity (LV) systems. As mentioned above, these three galaxies are giant (bright and massive) roundish Es with \( M_B \) \(<\) -21. Apart from these three and the atypical case of NGC 4550, all other slow rotators harbour KDCs, the central kinematic component having a typical size of 1 kpc or larger (see Paper VIII). This contrasts with KDCs and CLVs in fast rotators (NGC 3032, 4150, 7332, 7457), where the size of the central (counter-rotating) stellar component is only a few arcsec in radius, corresponding to significantly less than 500 pc (Paper VIII).

A number of fast rotators show KM and twists (KT), most of these being relatively small in contrast with the ones found in slow rotators (see Section 3.3). The four fastest rotators with a KT, KM or KDC, namely NGC 1023, 3377, 7332 and 7457, are all barred galaxies. Most of the galaxies with multicomponents but no specific velocity structures are among the fastest rotators. This result may be partly understood if these objects tend to be close to edge-on, which renders the detection of such velocity structures harder, but the detection of MCs easier.

5 DISCUSSION

The fast rotators are mostly discy galaxies exhibiting MCs in their stellar velocity fields. Contrarily to slow rotators, the main stellar kinematic axis in fast rotators is relatively well aligned with the photometric major axis, except for one galaxy (NGC 474) known to harbour irregular shells. This result together with the fact that the \( \lambda_R \) profiles are qualitatively different for slow and fast rotators clearly
Boxy-disky classification (quantitative morphology) shows only weak correlation with $\lambda_0$ (angular momentum within $R_e$).

Fast rotators (plus occasional slow rotators which have 2 counter-rotating disks) contain components with a range of thickness: the amount of rotational vs pressure support varies.

Athanassoula describes both boxy-peanut bulges (which need to be seen close to edge-on to be identified) and ‘disky’ bulges, and comments that face-on galaxy bulges may not be vertically extended at all. What would we expect to see kinematically for these two classes?
clearly not a good proxy for rotation or angular momentum. This seems partly in contradiction with the claim by KB96 that rotation is dynamically less important in boxy than in discy early-type galaxies. The latter result probably originated from the combination of two observed facts: first boxy galaxies are on average less flattened (extremely flattened galaxies are very discy), and secondly other slow rotators tend to be bright but are spread over a wide range among the brightest galaxies in our sample with absolute magnitude going from the relatively faint NGC 4458 to the total luminosity of early-type galaxies, bright members tending to be core galaxies, and lower luminosity ones to have power-law profiles (Faber et al. 1997). All galaxies with \( \lambda_{\alpha} > 0.3 \) have indeed \( M_{\text{vir}} > -20.7 \) and conversely none has \( M_{\text{vir}} > 10^{11.5} \) \( M_{\odot} \). This is, however, not a one-to-one correspondence since we find both power-law in slow rotators (NGC 3414 and 5813) and core-like fast rotator (e.g. NGC 524). There is also a domain in mass and luminosity where both cusp and cores are found, namely for \( M_{\text{vir}} \) between \( 10^{11} \) and \( 10^{11.5} \) \( M_{\odot} \), or correspondingly for \( M_{\text{vir}} \) from \(-19.5 \) to \(-20.5 \). Another interesting result is found when examining the larger-scale luminosity profiles of galaxies in our sample via the representation by a Sersic law. Besides the atypical case of NGC 4550, all slow rotators have Sersic index \( n > 4 \); again, this is expected since galaxies with larger Sersic shape index tend to be brighter (Caon, Capaccioli & D’Onofrio 1993; Graham & Guzmán 2003). Finally, galaxies with the lowest Sersic \( n \) values are also among the fastest rotators. A more detailed account regarding these issues will be provided in Fal
cin-Barroso et al. (in preparation).

4.3 Luminosity and mass

In the left-hand panel of Fig. 7, we show the distribution of \( \lambda_{\alpha} \) as a function of absolute magnitude \( M_B \) for the 48 SAURON E/S0 galaxies. The three slowest rotators (NGC 4486, 4374, 5846) are among the brightest galaxies in our sample with \( M_B < -21 \) mag. Other slow rotators tend to be bright but are spread over a wide range of absolute magnitude going from the relatively faint NGC 4458 to brighter objects such as NGC 5813. The bright and faint end of slow rotators can be distinguished by the shapes of their isophotes: slow rotators brighter than \( M_B < -20 \) mag all exhibit mildly boxy isophotes (negative \( a_{\alpha}/a \) with amplitude less than 1 per cent) while the four discy slow rotators are all fainter than \( M_B > -20 \) mag, following the known correlation between the isophote shapes and the total luminosity of early-type galaxies (Bender, Burstein & Faber 1992). Most fast rotators are fainter than \( M_B > -20.5 \) mag.

Going from total luminosity to mass, we have estimated the latter by approximating it with the virial mass \( M_{\text{vir}} \) derived from the best-fitting relation obtained in Paper IV, namely \( M_{\text{vir}} \sim 5.0 \times 10^{10} \) \( G/\sigma_v^2 \), where \( \sigma_v \) is the luminosity-weighted second velocity moment within \( 1 R_e \) (see Paper IV for details). The calculation of \( M_{\text{vir}} \) from observables depends on the distance of the object, which we obtained from different sources for the galaxies in our sample (in order of priority, from Tonry et al. 2001; Tully 1988, and from the LEDA data base assuming a Hubble flow with \( H = 75 \) \( \text{km s}^{-1} \text{Mpc}^{-1} \)). A trend of \( \lambda_{\alpha} \), tending to be lower for more massive galaxies clearly emerges if we now use this estimate of the virial mass \( M_{\text{vir}} \) (right-hand panel of Fig. 7), as expected from the one observed with absolute magnitude \( M_B \) (left-hand panel of Fig. 7). The three slowest rotators are in the high range of \( M_{\text{vir}} \) with values above \( 10^{11.5} \) \( M_{\odot} \). There is a clear overlap in mass between fast and slow rotators for \( M_{\text{vir}} \) between \( 10^{11} \) and \( 10^{11.5} \) \( M_{\odot} \). However, all slow rotators, besides NGC 4458 and 4550, have \( M_{\text{vir}} > 10^{11} \) \( M_{\odot} \), whereas most fast rotators have \( M_{\text{vir}} < 10^{11} \) \( M_{\odot} \). Lower masses being reached as the value of \( \lambda_{\alpha} \) increases. It is worth pointing out that the absolute magnitude in the K band, \( M_K \), very nicely correlates with \( M_{\text{vir}} \) (significantly better than with \( M_B \)), so that the trend observed between \( \lambda_{\alpha} \) and \( M_{\text{vir}} \) is also observed if we were to examine the relation between \( \lambda_{\alpha} \) and \( M_K \).

Out of the 48 SAURON galaxies, 33 have published cusp slope classification, distinguishing ‘core’ and ‘power-law’ galaxies (Faber et al. 1997; Ravindranath et al. 2001; Rest et al. 2001; Lauer et al. 2005). As illustrated in the left-hand panel of Fig. 7, we find that most slow rotators are core galaxies, and most fast rotators are power-law galaxies (note that NGC 821 has an \( \lambda_{\alpha} \sim 0.25 \) and is specified as an ‘intermediate’ object between a core and power law in Lauer et al. 2005). There are yet no core galaxies with \( \lambda_{\alpha} > 0.3 \), although the inclined galaxy NGC 524 (see Paper IV) would have a very high \( \lambda_{\alpha} \) value if seen edge-on. These results are expected as there is a known trend between the central luminosity gradient and the total luminosity of early-type galaxies, bright members tending to be core galaxies, and lower luminosity ones to have power-law profiles (Faber et al. 1997). All galaxies with \( \lambda_{\alpha} > 0.3 \) have indeed \( M_{\text{vir}} > -20.7 \) and conversely none has \( M_{\text{vir}} > 10^{11.5} \) \( M_{\odot} \). This is, however, not a one-to-one correspondence since we find both power law in slow rotators (NGC 3414 and 5813) and core-like fast rotator (e.g. NGC 524). There is also a domain in mass and luminosity where both cusp and cores are found, namely for \( M_{\text{vir}} \) between \( 10^{11} \) and \( 10^{11.5} \) \( M_{\odot} \), or correspondingly for \( M_{\text{vir}} \) from \(-19.5 \) to \(-20.5 \). Another interesting result is found when examining the larger-scale luminosity profiles of galaxies in our sample via the representation by a Sersic law. Besides the atypical case of NGC 4550, all slow rotators have Sersic index \( n > 4 \); again, this is expected since galaxies with larger Sersic shape index tend to be brighter (Caon, Capaccioli & D’Onofrio 1993; Graham & Guzmán 2003). Finally, galaxies with the lowest Sersic \( n \) values are also among the fastest rotators. A more detailed account regarding these issues will be provided in Fal
cin-Barroso et al. (in preparation).

4.4 Kinemetric groups

We now turn to the kinemetric profiles (see Section 2.4) of the 48 SAURON galaxies, which allow us to determine the number of observed kinematic components and their individual characteristics. We thus make use of the average photometric and kinematic position angles and axis ratio (\( \text{PA}_{\text{phot}} \) and \( \text{PA}_{\text{kio}}, q \) and \( q_{\text{kio}} \)), and the average and maximum of the velocity amplitude \( k_1 \).

The kinemetric groups of the observed 48 SAURON velocity maps, defined in Section 2.4, are provided in Table 1. Out of 48 galaxies in this sample, 33 (69 per cent) exhibit MC, including 10 KDCs (21 per cent) and four objects with CLVs (namely NGC 3032, 4150, 4382 and 7457). Two more galaxies with KDCs
Figure 5. Integral space at a given energy for the solution of the Schwarzschild models for the galaxies NGC 4473, 4550, 4660 and 4486. Each panel plots the meridional plane $(R, z)$ with the location (white dots) where orbits are started with $v_R = v_z = 0$ at the given energy. For nearly edge-on galaxies, the white dots also correspond to the position of the orbital cusps, where every orbit gives its strongest contribution to the observables on the sky plane. The energy was chosen as that of a circular orbit with radial velocity $V_R = 32$ arcsec, which is about the size of the observed SAURON field (red rectangle). The coloured contours show the fraction of mass assigned to different orbits at that energy, where bright colours correspond to high-mass fractions. Orbits at negative and positive $R$ starting conditions correspond to prograde and retrograde, respectively. Orbits with high angular momentum are found in the bottom right and bottom left corner, respectively, on the plots. Orbits near the symmetry axis (green line) have low angular momentum. Orbits near the equatorial plane ($z = 0$) are intrinsically flat (see fig. 6 of Paper IV for a detailed explanation of this diagram).

processes (e.g. Shapiro, Gerssen & van der Marel 2003). In some cases, the disc-like components may happen to counter-rotate, or two discs may be present, in which case tangential anisotropy dominates the observed anisotropy.

Interestingly, the disc-like components, which tend to characterize the fast rotators, not only seem to be distinct in integral space, but also differ in terms of their stellar population. As shown in fig. 11 of Kuntschner et al. (2006, hereafter Paper VI), all the fast rotators are characterized by an Mgb line-strength distribution which is flatter than the isophotes. The fact that a flat Mgb is seen in all the flat galaxies suggests that perhaps all the fast rotators contain this metallicity-enhanced disc-like component, which is only visible in the flattest objects because they are closer to edge on. This result is reminiscent of the finding by Lauer et al. (2005) that all flat cuspy galaxies show a disc. This metallicity enhancement indicates that additional star formation activity happened in the disc and, not surprisingly, implies that gas dissipation was involved in the formation of these flat structures. The radial anisotropy, however, shows that heating was significant after the disc formation, as otherwise the stars in the flat components would still move on orbits that are closer to circular.

4.6 Relation of anisotropy with other global observables

In Fig. 6, we show the correlation between the anisotropy and the galaxy velocity dispersion $\sigma_0$ within the effective radius, taken from Paper IV. There is a trend for the most massive galaxies to have a smaller anisotropy within one $R_e$, with the exception of the special case NGC 4458 (see also Paper IV, Section 5.1). In this diagram, we use the parameter $\beta$ to characterize the anisotropy. This parameter is measured in the galaxy meridional plane so it describes the orbital distribution in a way that is not affected by the direction of rotation of the stars in the galaxy. The $\beta$ parameter measures the same anisotropy, for example, in two galaxies that formed with the same physical process, but in which one galaxy experienced a merger in a prograde direction and the other in a retrograde direction.

A general trend is found between anisotropy and the intrinsic galaxy ellipticity (Fig. 7). The best-fitting relation to this rather scattered distribution of points, using a robust bisector algorithm, has the form

$$\beta = (0.6 \pm 0.1) \epsilon_{\text{intr}}.$$  \hspace{1cm} (19)

Given that the errors on both $\beta$ and $\epsilon_{\text{intr}}$ are model dependent and difficult to estimate, we adopted constant errors on both variables. The quoted error on the slope was determined by enforcing the condition $\chi^2 = v$, where $v$ is the number of degrees of freedom of the fit.