Elliptical Galaxies: kinematics

To make a quantitative analysis of the shifts and broadening of the absorption lines in a galaxy spectrum, we define the line-of-sight velocity distribution (LOSVD),
$F(V_{los})$,
such that the fraction of the stars contributing to the spectrum which have line-of-sight velocities between **V_{los}** and **$V_{los} + dV_{los}$** is given by
$F(v_{los})dv_{los}$.
At any given spectral velocity **u** in the galaxy's spectrum, we will observe the light from individual stars that was emitted at many different spectral velocities; for a star moving with a line-of-sight velocity Vlos, this light will have originated at a spectral velocity of
$u - V_{los}$, and been Doppler shifted to **u**. If we assume for the moment that all of the stars have intrinsically identical spectra, **S(u)**, then the intensity received at spectral velocity **u** from a star with line-of-sight velocity **V_{los}** is
$S(u - V_{los})$. Summing over all stars we obtain the spectrum G(u):

$$G(u) \propto \int \mathrm{d}v_{\mathrm{los}} F(v_{\mathrm{los}}) S(u - v_{\mathrm{los}}).$$

$$\overline{v}_{\mathrm{los}} = \int \mathrm{d}v_{\mathrm{los}} v_{\mathrm{los}} F(v_{\mathrm{los}}),$$

$$\sigma^2_{\mathrm{los}} = \int \mathrm{d}v_{\mathrm{los}} \left(v_{\mathrm{los}} - \overline{v}_{\mathrm{los}}\right)^2 F(v_{\mathrm{los}}).$$

LOSVD is approximated as gaussian with small deviations.
Only the k=3 (skewness) and k=4 (kurtosis) are used

$$F_{\mathrm{TGH}}(v_{\mathrm{los}}) \propto \mathrm{e}^{-\frac{1}{2}w^2}\left[1 + \sum_{k=3}^{n} h_k H_k(w)\right],$$

where $w \equiv (v_{\mathrm{los}} - \overline{v})/\sigma$ with $\overline{v}$ and σ free parameters. In equation (11.12), the h_k are constant coefficients and $H_k(w)$ is a Gauss-Hermite function,

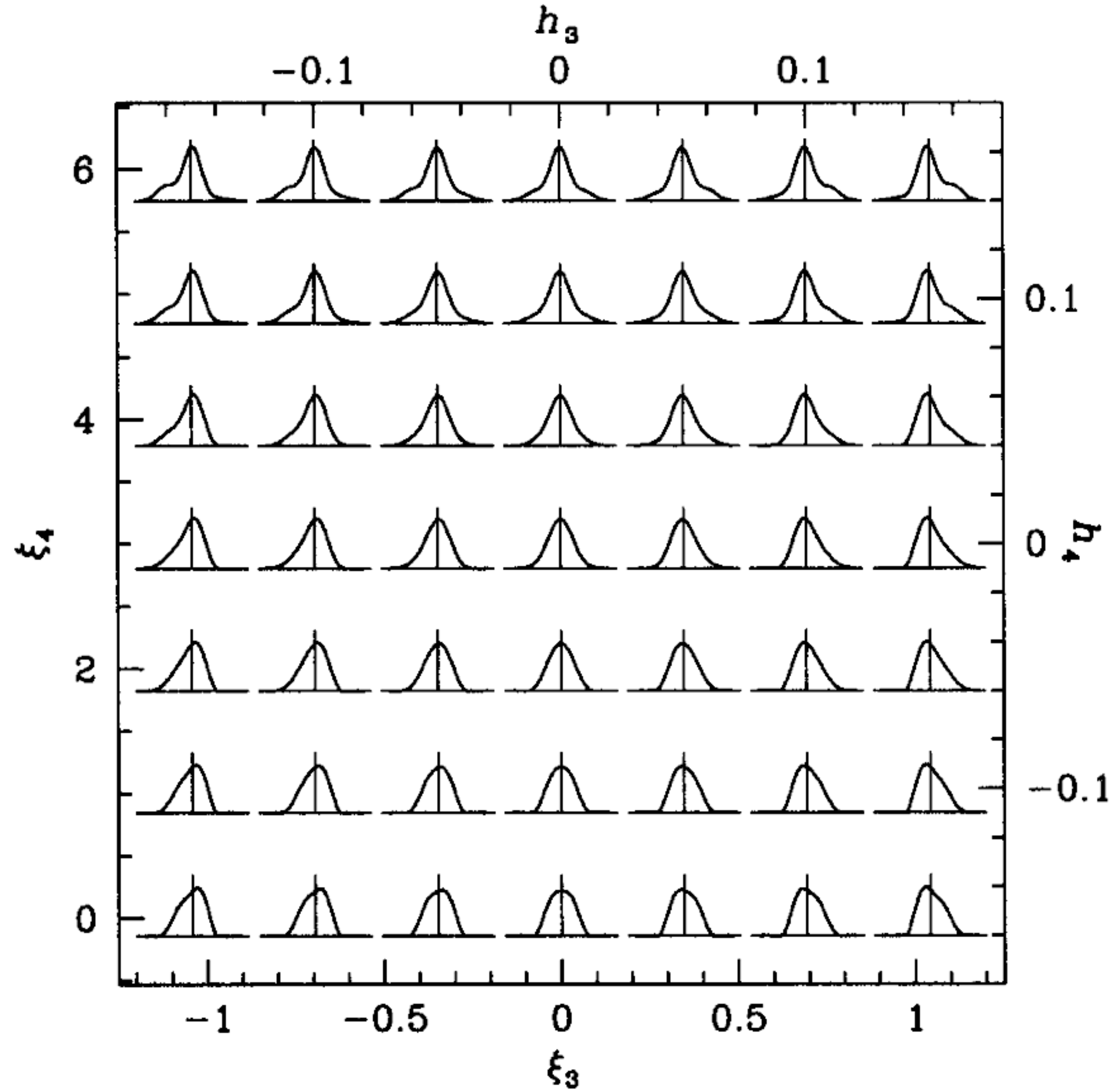
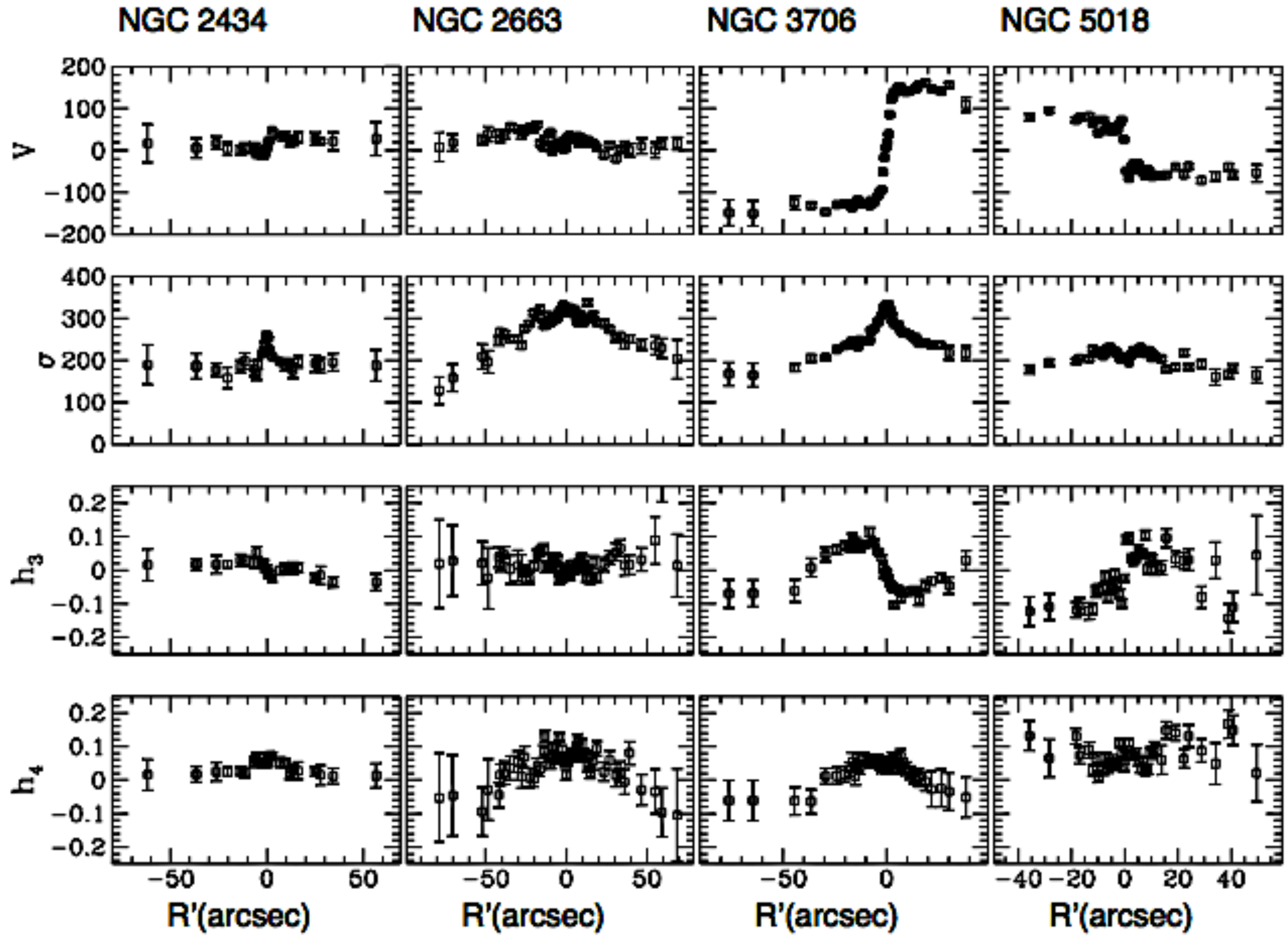


Figure 11.5 Montage showing how a velocity distribution typically changes depending on its shape parameters ξ_3 and ξ_4. The central distribution is a pure Gaussian ($\xi_3 = 0$, $\xi_4 = 3$). All distributions have identical values for the Gauss-Hermite parameters $\overline{v}_{\rm los}$ (marked as the y-axis for each LOSVD) and $\sigma_{\rm los}$. The right-hand and top axes are marked with the approximately corresponding values of the quantities h_3 and h_4 that are defined by equation (11.12).

Major-axis kinematics of four giant ellipticals



Galaxy	$R_e('')$	ϵ	α	β	$b('')$
NGC 2434	24	0.08	-1.9	-0.52	13
NGC 2663	50	0.30	-1.6	-0.55	10
NGC 3706	27	0.35	-2.3	-0.53	31
NGC 5018	22	0.30	-2.1	-0.90	31

[a]Listed are: the effective radius R_e (Lauberts & Valentijn 1989), the average ellipticity ϵ outside $R_e/2$ (CDa,b), and the model parameters α, β, and b of equation (1). Mean errors on the best fit parameters are $\Delta\alpha = \pm 0.1$, $\Delta\beta = \pm 0.05$, and $\Delta b = \pm 5''$.

$$\rho_L(R, z) = \rho_0 \left(\frac{m}{b}\right)^{\alpha} \left(1 + \frac{m^2}{b^2}\right)^{\beta}, \qquad m^2 = R^2 + z^2/q^2. \tag{1}$$

Results: steep profiles for mass in the central region

Analytics: Jeans equation

$$\frac{d\rho\sigma^2}{\rho dr} + \frac{2\beta\sigma^2}{r} = -g(r),$$

σ^2 = radial velocity dispersion

$\beta(r)$= velocity anisotropy

$$\beta(r) = 1 - \sigma_\perp^2/2\sigma^2$$

ρ = (number)density of tracer population (=satellites)

$g(r)$= force of gravity

$$\sigma^2(r) = e^{-F}\int_r^\infty g(r)e^F dr,$$

$$\alpha \equiv d\ln\rho/d\ln r$$

$$F(r) = \int^r \frac{2\beta + \alpha}{r} dr$$

How to use the velocity data: recovering mass profile in M87 (McLaughlin 1999)

Data: velocity dispersion profile and the surface brightness profile

Assume that the system is stationary and spherically symmetric. Constant mass-to-light ratio. Assume a parametric model for dark matter. β_{gal} is the velocity anisotropy

Jeans equation for radial velocity dispersion

$$n_{\rm gal}\sigma_r^2(r) = \exp\left(-\int \frac{2\beta_{\rm gal}}{r}\,dr\right) \times \left[\int_r^\infty n_{\rm gal}\frac{GM_{\rm tot}}{x^2}\exp\left(\int \frac{2\beta_{\rm gal}}{x}\,dx\right)dx\right], \qquad (2)$$

$$N_{\rm gal}\sigma_p^2(R) = 2\int_R^\infty n_{\rm gal}\sigma_r^2(r)\left(1-\beta_{\rm gal}\frac{R^2}{r^2}\right)\frac{r\,dr}{\sqrt{r^2-R^2}}, \qquad (3)$$

LOS velocity dispersion in the model

with $N_{\rm gal}(R) = 2\int_R^\infty n_{\rm gal}(r^2 - R^2)^{-1/2}\,r\,dr$.

M87: Virgo Cluster

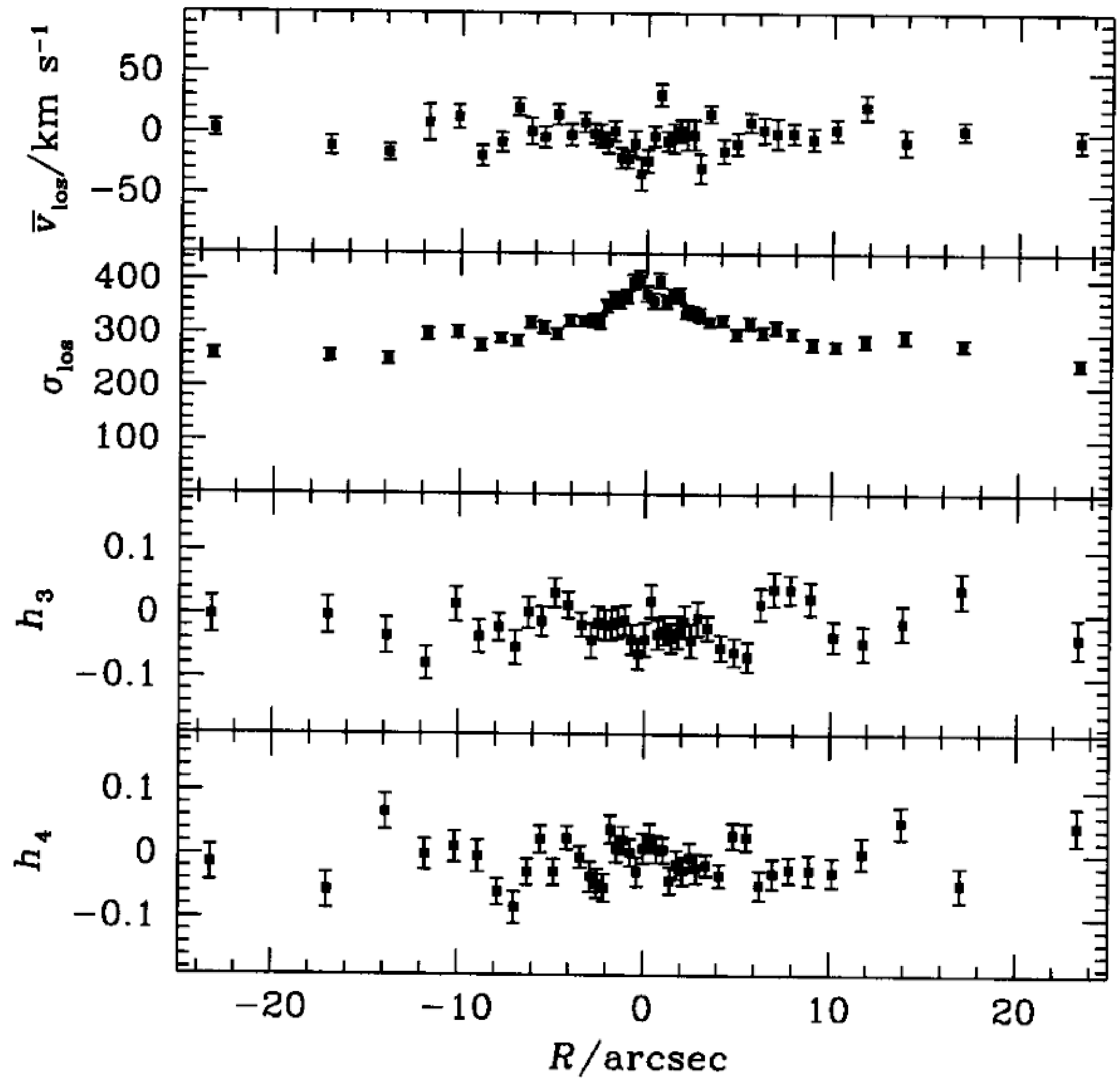


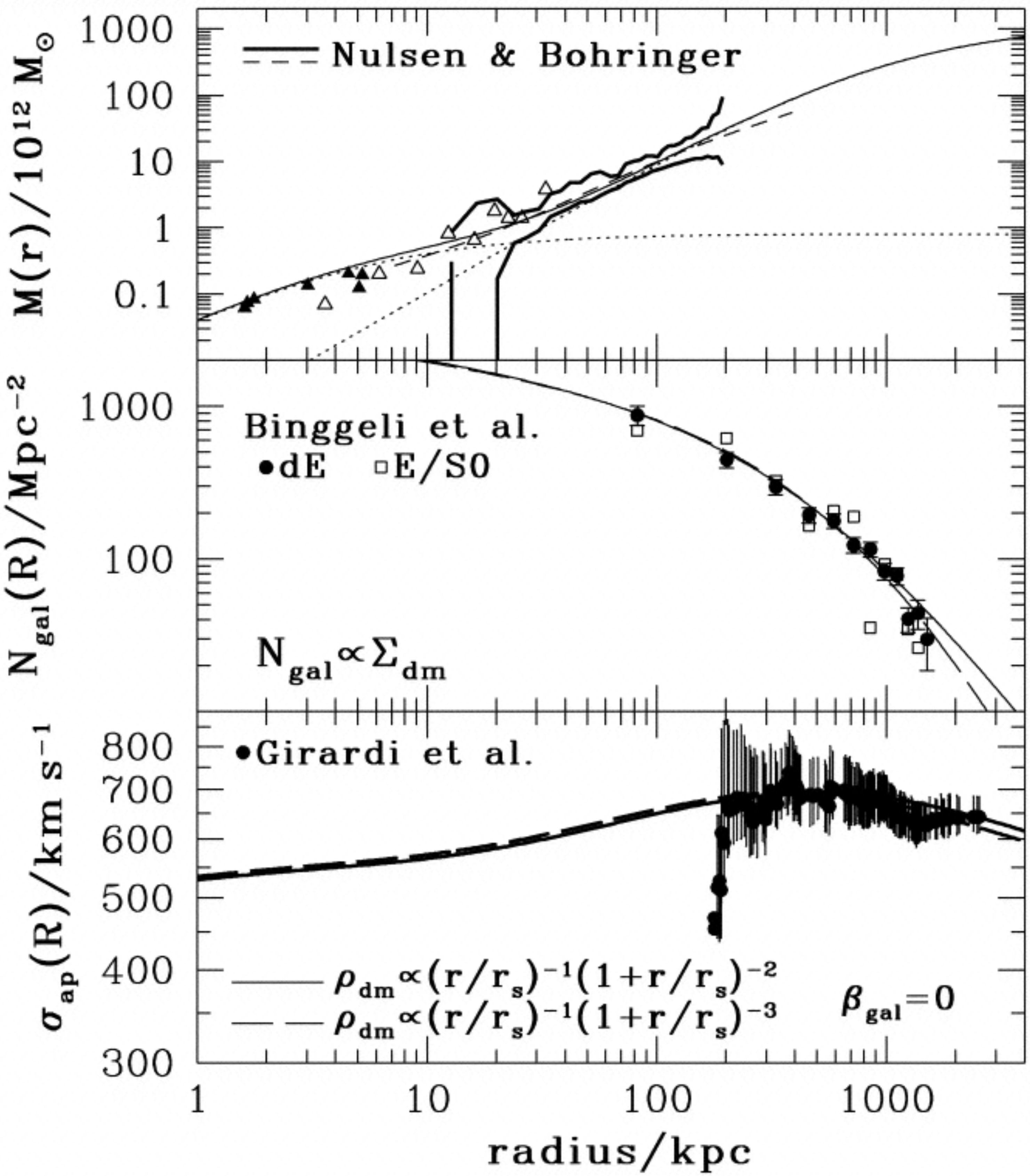
Figure 11.12 The variation in properties of the LOSVD derived by applying the truncated Gauss-Hermite algorithm (§11.1.2) to spectra obtained close to the center of M87. [From the data published in van der Marel (1994)]

M87

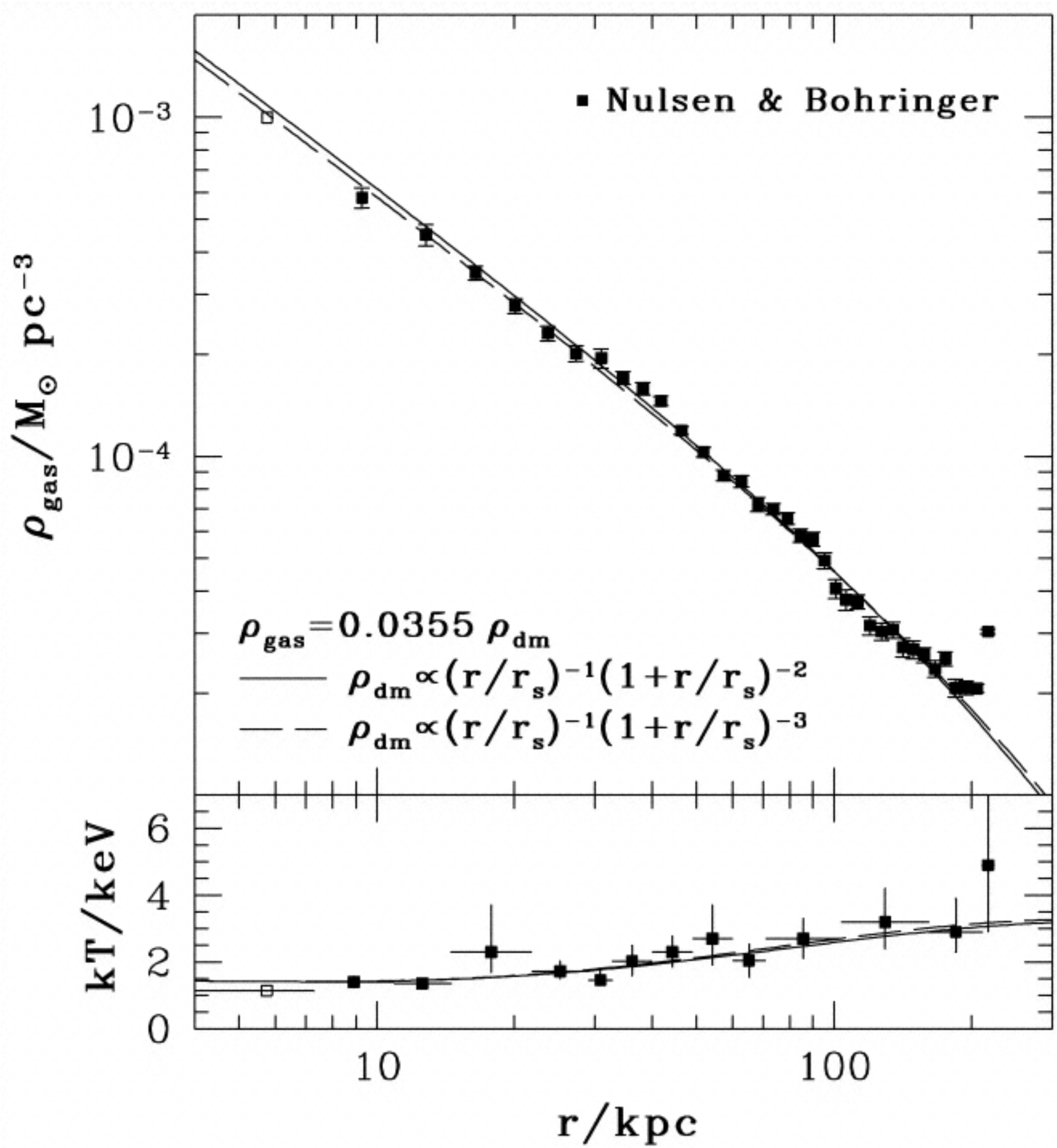
$$M_{\rm tot}(r \lesssim 30 \text{ kpc}) = (1.6^{+0.3}_{-0.7}) \times 10^{12}\ M_\odot,$$

$$M_{\rm tot}(r \lesssim 150 \text{ kpc}) = (1.9 \pm 0.8) \times 10^{13}\ M_\odot,$$

$$\sigma_{\rm ap}(R \leq 2 \text{ Mpc}) = 640^{+85}_{-65} \text{ km s}^{-1},$$

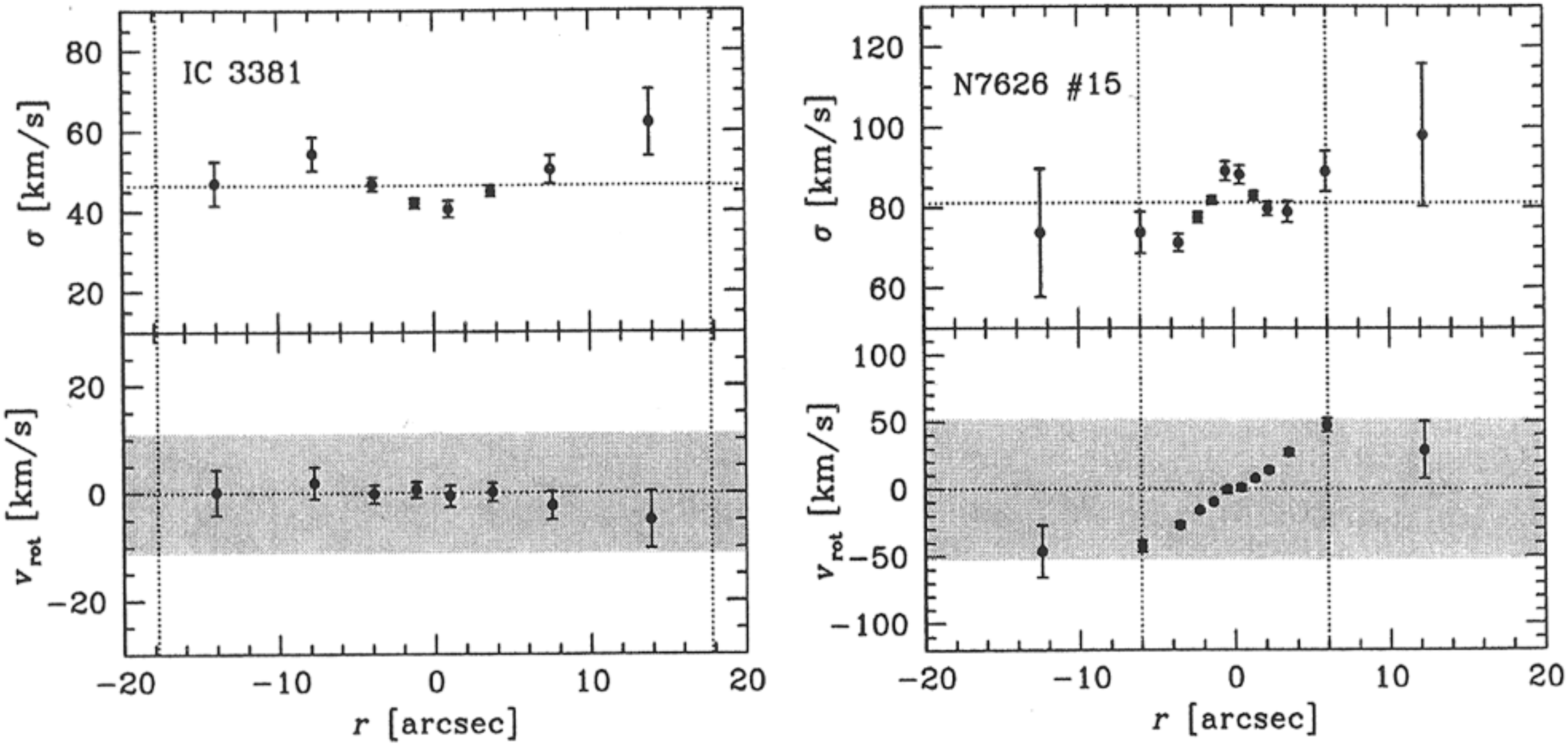


Comparison of dark matter and intracluster gas density and temperature profiles. Assume gas follows DM. Nulsen&Bohringer are results from X-ray measurements



2002 astro-ph/0210474

E So



in Virgo

Figure 1. Velocity dispersion and velocity as functions of radius. The grey shaded area indicates the maximum amount of rotation for which the object is still anisotropic, hence $(v/\sigma)^* = \frac{v_{\rm rot}/\bar{\sigma}}{\sqrt{\epsilon/(1-\epsilon)}} \approx 0.7$.

Correlation: shape and rotation

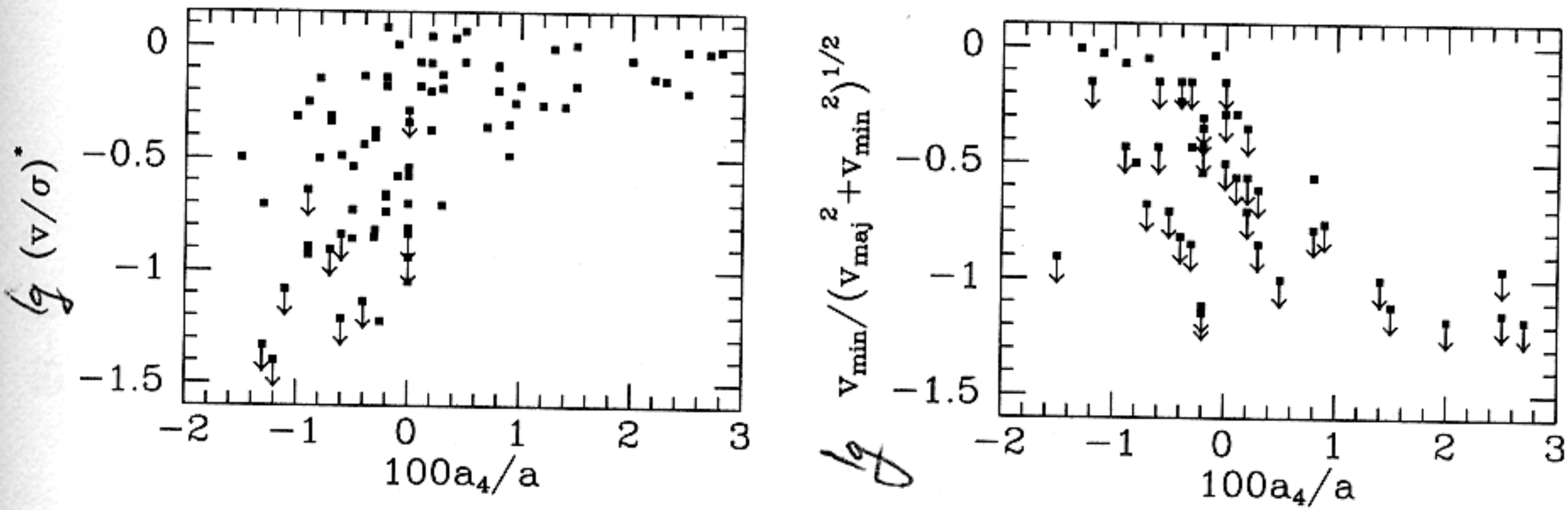


Figure 4.39 Boxy galaxies frequently rotate very slowly, and then about an axis other than the apparent minor axis. The left panel shows that the indicative rotation rate $(v/\sigma)^*$ [equation (11.14)] is invariably of order unity for disky galaxies but sometimes very small for boxy galaxies. The right-hand panel shows that boxy galaxies frequently show a non-negligible velocity gradient along their minor axes. [From data kindly provided by R. Bender]

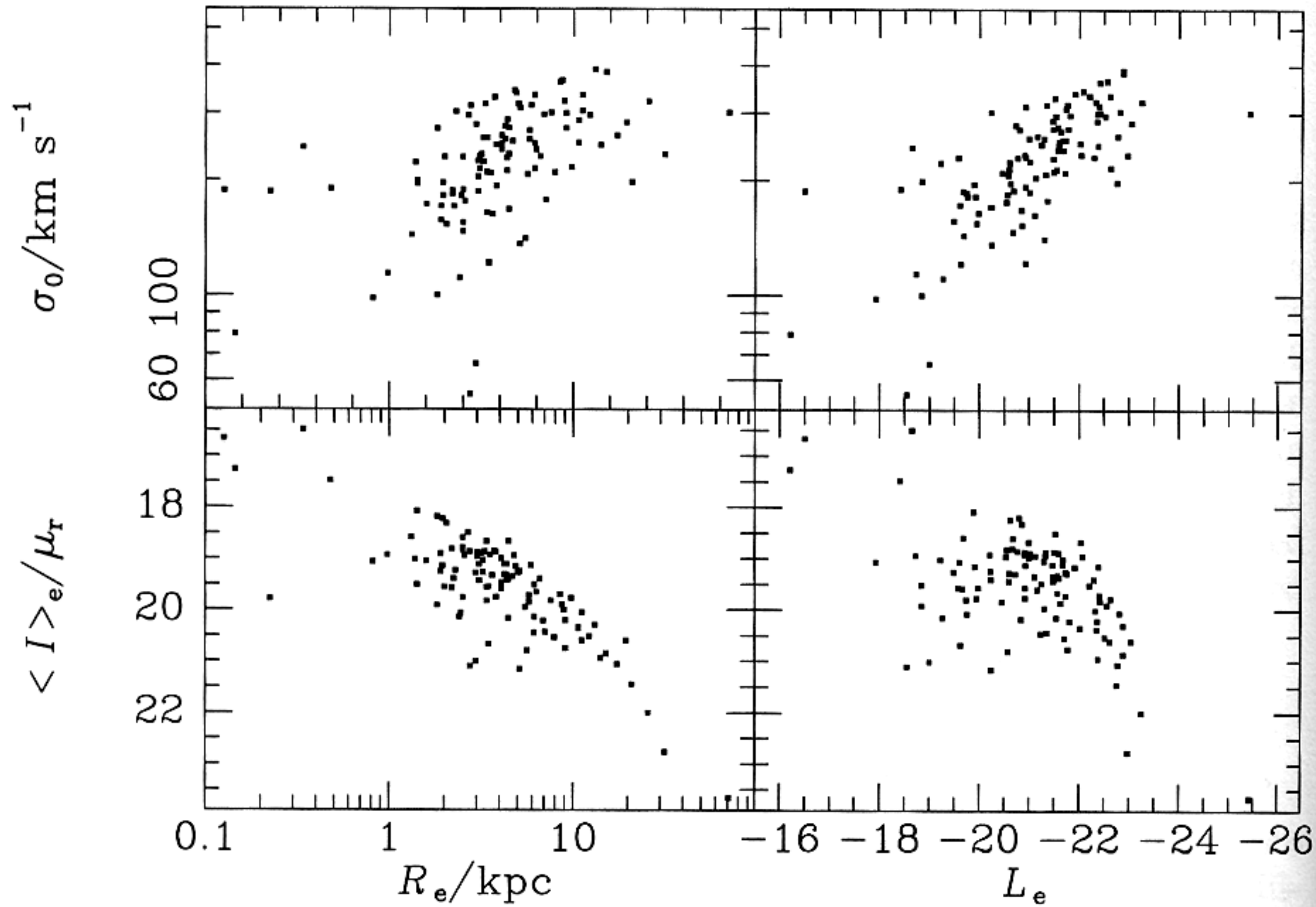
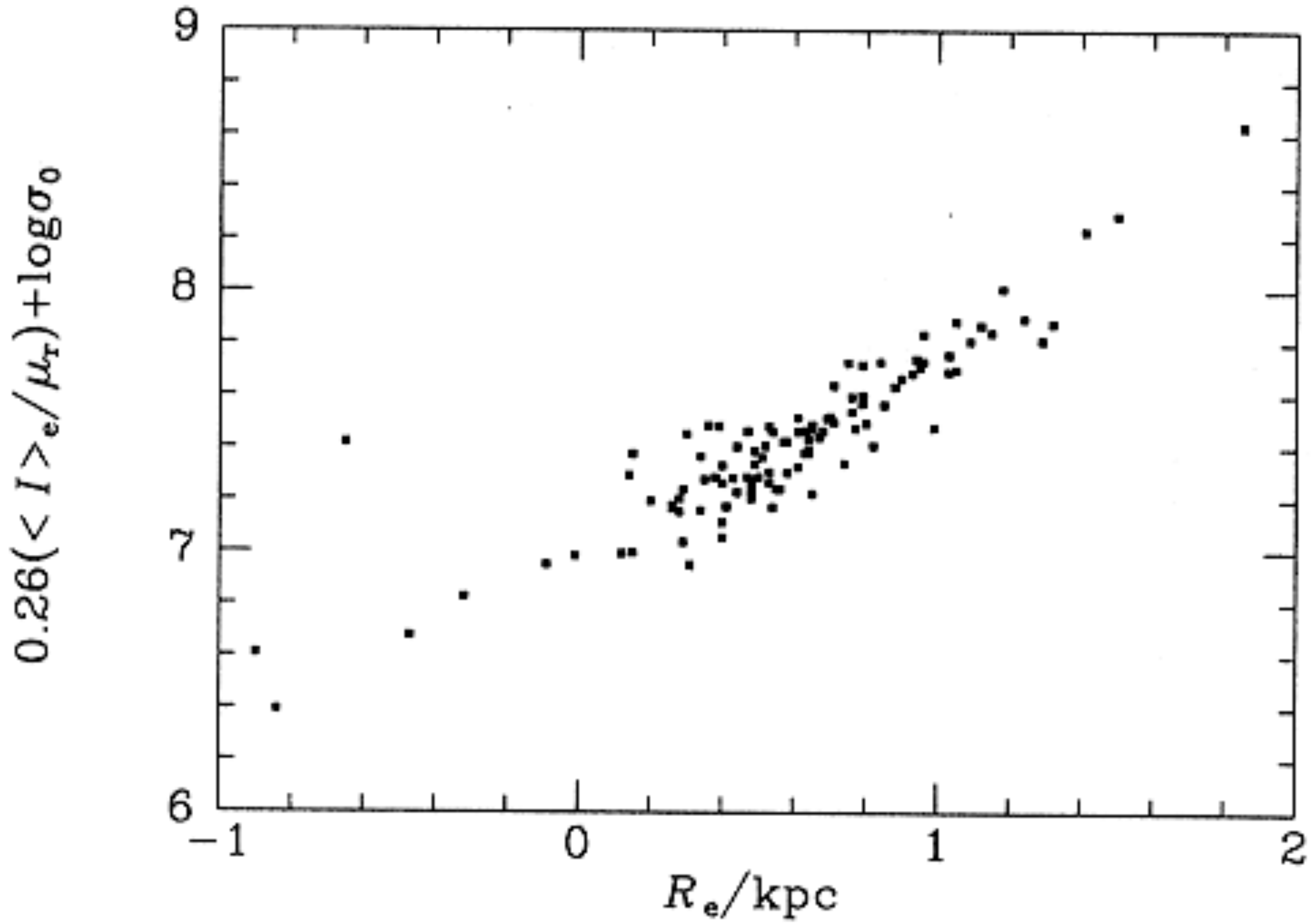


Figure 4.43 Correlations between four shape-independent parameters of elliptical galaxies. The parameters are the effective radius R_e, the mean surface brightness within R_e, $\langle I \rangle_e$, the central velocity dispersion σ_0 and L_e, the luminosity in Djorgovski's G band interior to R_e. The luminosity and the surface brightness are expressed in magnitudes and in magnitudes per square arcsecond, respectively. [From data published in Djorgovski & Davis (1987)]



Fundamental Plane

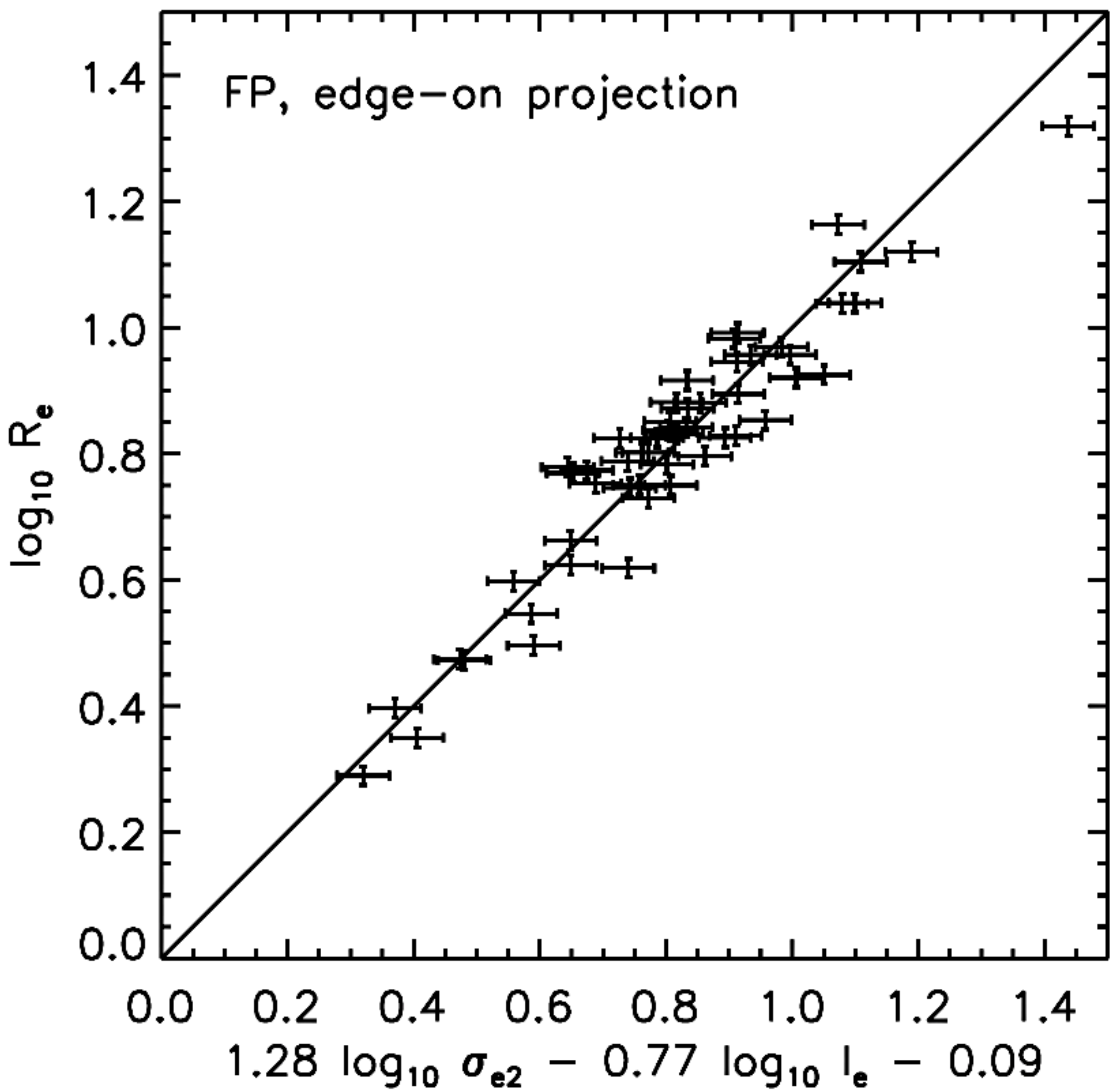
$$\log R_{\rm e} = 0.36(\langle I\rangle_{\rm e}/\mu_B) + 1.4\log\sigma_0$$

More recent results

The Astrophysical Journal, 684:248–259, 2008 September 1

THE SLOAN LENS ACS SURVEY. VII. ELLIPTICAL GALAXY SCALING LAWS FROM DIRECT OBSERVATIONAL MASS MEASUREMENTS[1]

Adam S. Bolton,[2,3] Tommaso Treu,[4,5] Léon V. E. Koopmans,[6] Raphaël Gavazzi,[4,7] Leonidas A. Moustakas,[8] Scott Burles,[9] David J. Schlegel,[10] and Randall Wayth[3]



Units are 100 km s^{-1} for σ_{e2}, $10^9 L_{V,\odot}$ kpc^{-2} for I_e, $10^9\ M_\odot$ kpc^{-2} for Σ_{e2}, and kpc for R_e.

Dn - sigma relation

$$I_n = \frac{2\pi I_e \int_0^{D_n/2} \mathrm{d}R\, R f(R/R_e)}{\frac{1}{4}\pi D_n^2}$$

$$= 8 I_e \left(\frac{R_e}{D_n}\right)^2 \int_0^{D_n/2R_e} \mathrm{d}x\, x f(x).$$

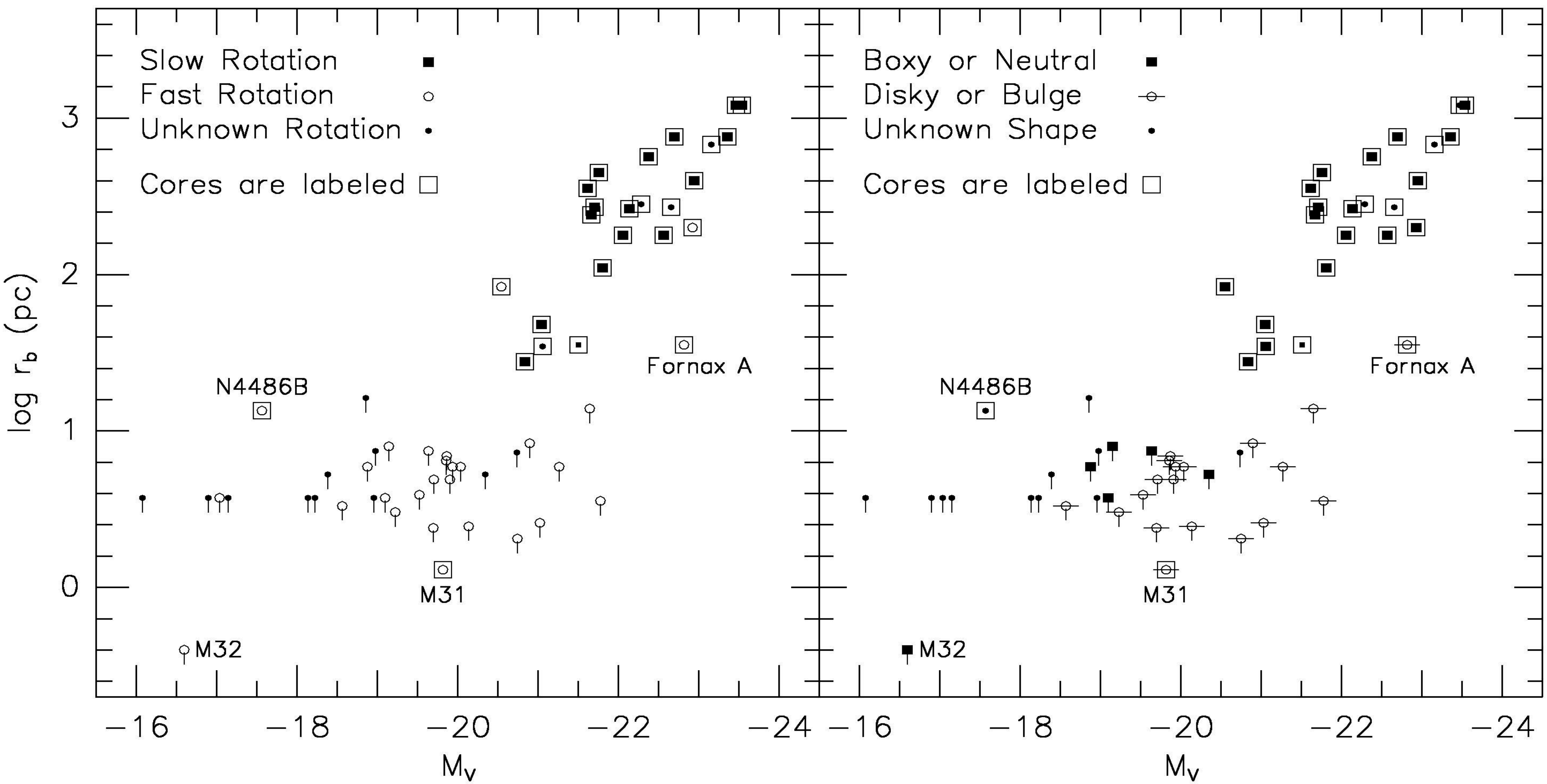
Dn is the diameter within which the mean surface brightness is I_n =20.75

evaluate the integral:

$$D_n \propto R_e I_e^{1/\alpha} \sim R_e I_e^{0.8}.$$

use fundamental plane to remove Re. Dn only weakly depends on I_e:

$$\frac{D_n}{\mathrm{kpc}} = 2.05 \left(\frac{\sigma}{100\,\mathrm{km\,s^{-1}}}\right)^{1.33}$$



Slow Rotation
Fast Rotation
Unknown Rotation
Cores are labeled
N4486B
Fornax A
M31
M32
Boxy or Neutral
Disky or Bulge
Unknown Shape
Cores are labeled
N4486B
Fornax A
M31
M32
log r_b (pc)
M_V
M_V
3
2
1
0
−16
−18
−20
−22
−24

$(V/\sigma, \varepsilon)$ diagram

Rotational velocity:

$$\left(\frac{V}{\sigma}\right)_{\mathrm{e}}^{2} \equiv \frac{\langle V^2 \rangle}{\langle \sigma^2 \rangle} = \frac{\sum_{n=1}^{N} F_n V_n^2}{\sum_{n=1}^{N} F_n \sigma_n^2}$$

F_n is the flux

V_n and σ_n are mean velocity and velocity disper

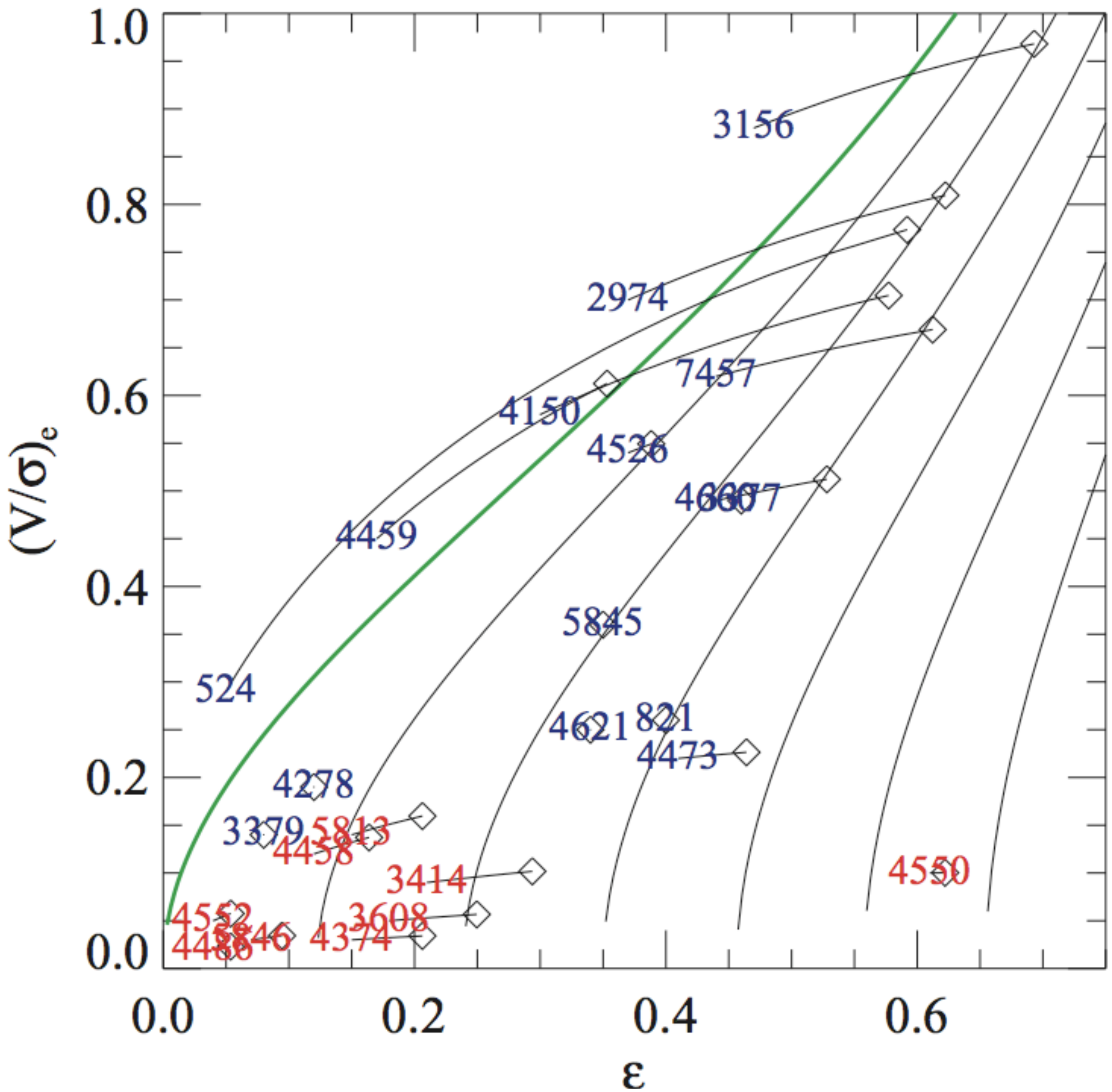
Elliliptcity:

$$(1-\varepsilon)^2 = q^2 = \frac{\langle y^2 \rangle}{\langle x^2 \rangle} = \frac{\sum_{n=1}^{N} F_n y_n^2}{\sum_{n=1}^{N} F_n x_n^2}$$

(x, y) coordinates are centred on the galaxy nucleus

Cappellari et al Mon. Not. R. Astron. Soc. **379,** 418–444 (2007)

Figure 3. (V/σ, ε) diagram for our modelling subsample of 24 galaxies. The red and blue labels refer to the NGC number of the slow and fast rotators, respectively, and show the measured values of the luminosity-weighted ellipticity ε and V/σ. The solid lines, starting from each object, show the effect of correcting the observed values of each galaxy to an edge-on view (diamonds).



The grid of solid curves shows the location on this diagram of edge-on oblate galaxies with different anisotropy $\delta = 0, 0.1, \ldots, 0.6$ (edge-on isotropic models $\delta = 0$ are shown with the thick green line).

δ = velocity anisotropy of random motions

Mon. Not. R. Astron. Soc. **379,** 418–444 (2007)

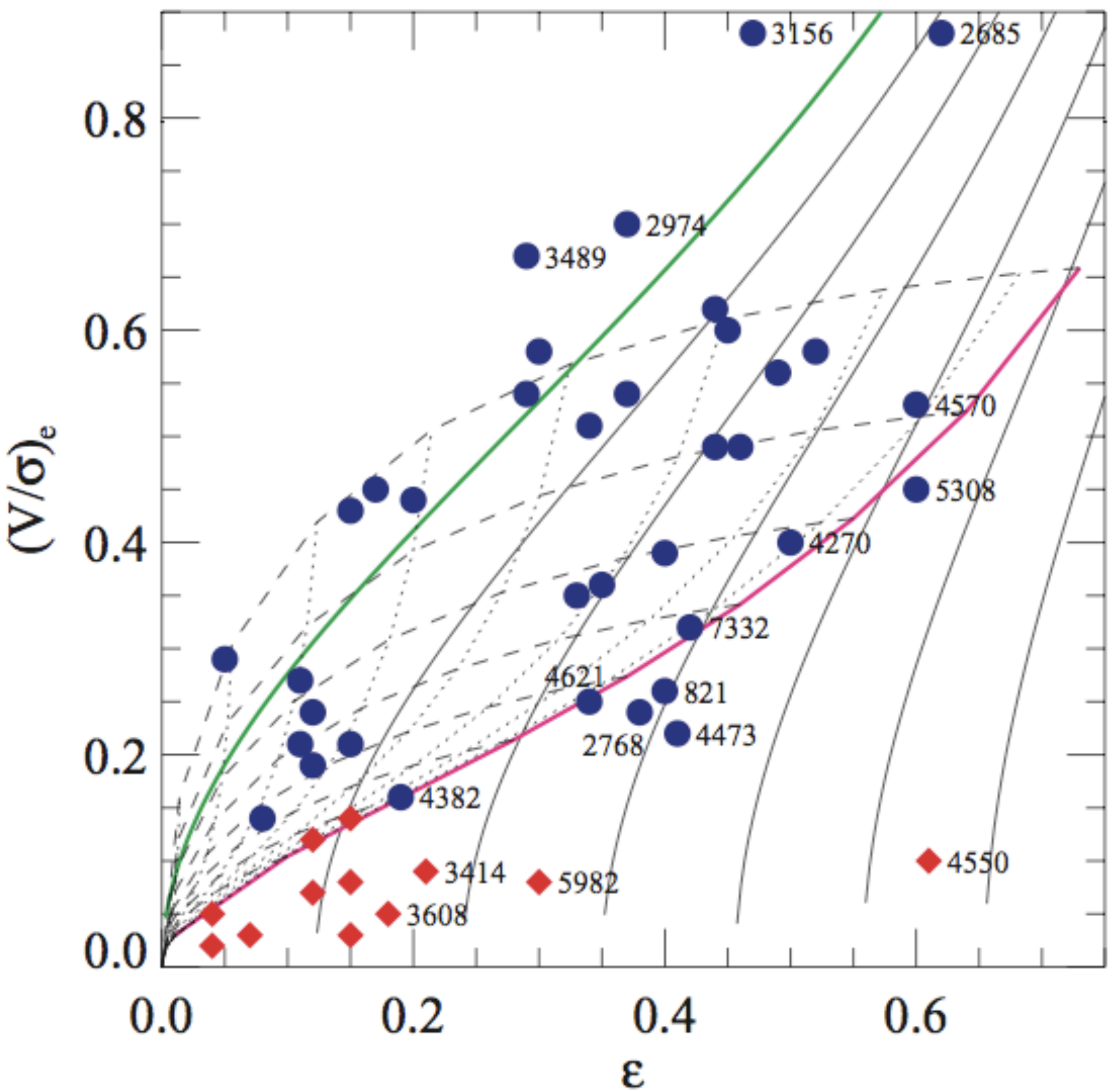


Figure 9. $(V/\sigma, \varepsilon)$ diagram for the 48 galaxies in the SAURON representative sample. The red diamonds and the blue circles refer to the slow and fast rotators, respectively (Table 1). The magenta line corresponds to the relation $\delta = 0.7\,\varepsilon_{\rm intr}$ for edge-on galaxies. The dotted lines show the location of galaxies, originally on the magenta line, when the inclination is varied. Different lines are separated by steps of 10° in the inclination. The dashed lines are equally spaced in the intrinsic ellipticity.

The slow rotators are more common among the most massive systems and are generally classified as E from photometry alone. Those in our sample tend to be fairly round ($\varepsilon \lesssim 0.3$), but can have significant kinematical misalignments, indicating that as a class they are moderately triaxial, and span a range of anisotropies ($\delta \lesssim 0.3$). The fast rotators are generally fainter and are classified as either E or S0. They can appear quite flattened ($\varepsilon \lesssim 0.7$), do not show significant kinematical misalignments (unless barred or interacting), indicating they are nearly axisymmetric and span an even larger range of anisotropies ($\delta \lesssim 0.5$).

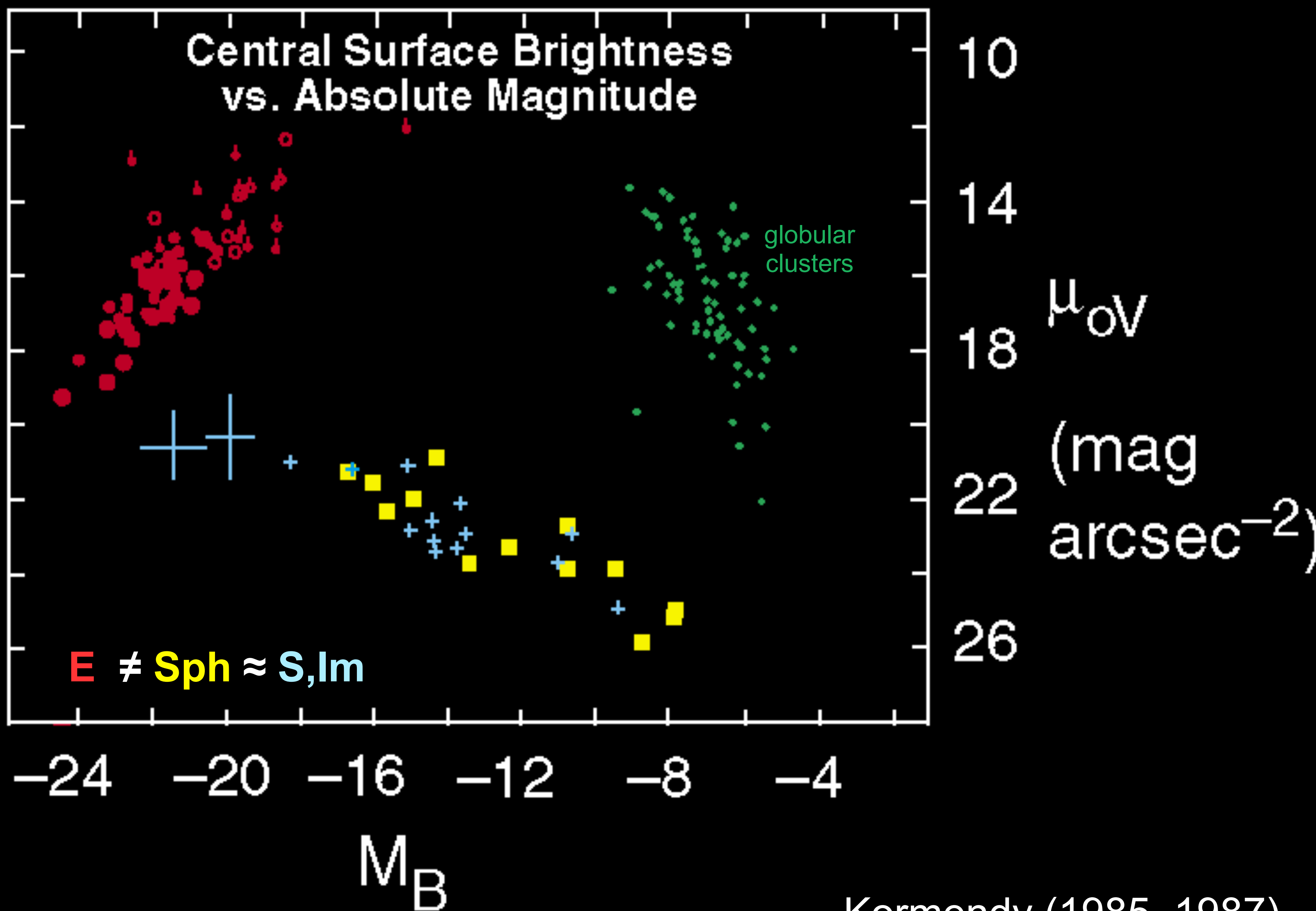
Types of Ellipticals

Normal and low luminosity Es
- rotate rapidly,
- are nearly isotropic oblate spheroids,
- are substantially flattened (E3.5),
- are coreless
- have disky-distorted isophotes.

Giant ellipticals
- are essentially non-rotating,
- are anisotropic and triaxial,
- are less flattened (E2.5),
- have cuspy cores,
- have boxy-distorted isophotes.

Dwarf spheroids are special
- low-surface brightness,
- do not respect the fundamental plane,
- slow rotators for their ellipticity

Core "fundamental plane" correlations define what it means to be an elliptical galaxy.



Kormendy (1985, 1987)