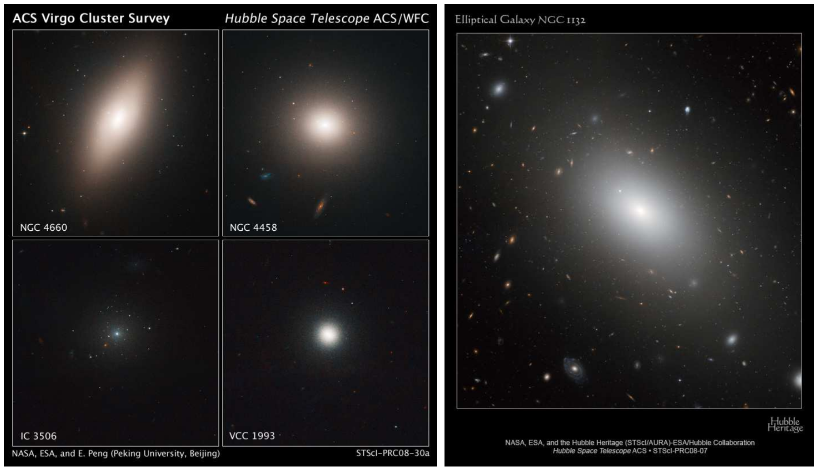
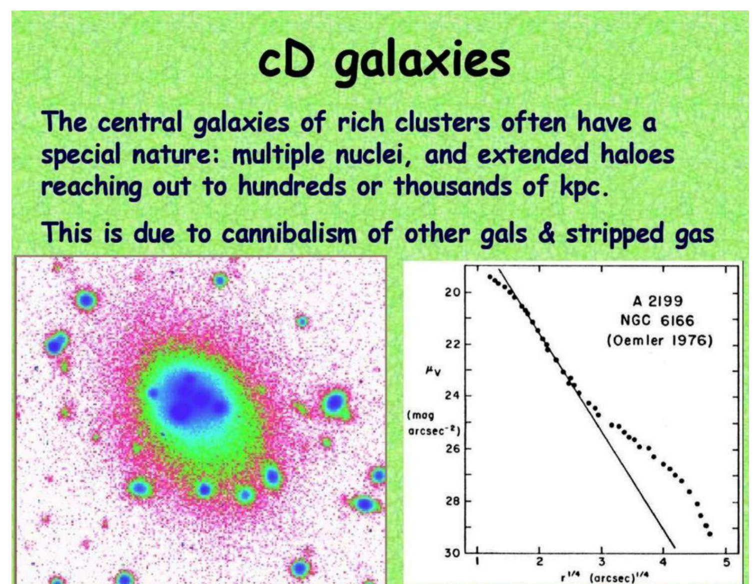


Rough subdivision

- *Normal ellipticals.* Giant ellipticals (gE's), intermediate luminosity (E's), and compact ellipticals (cE's), covering a range of luminosities from $M_B \sim -23^m$ to $M_B \sim -15^m$.
- *Dwarf ellipticals* (dE's). These differ from the cE's in that they have a significantly smaller surface brightness and a lower metallicity.
- *cD galaxies.* Extremely luminous (up to $M_B \sim -25^m$) and large (up to $\sim$1 Mpc) galaxies near centers of rich clusters of galaxies.
- *Blue compact dwarf galaxies* (BCD's). BCD's are clearly bluer ($B - V \approx 0.0 - 0.3$) and contain an appreciable amount of gas in comparison with other E's.
- *Dwarf spheroidals* (dSph's). Low luminosity and surface brightness (they have been observed down to $M_B \sim -8^m$).

Characteristic values for E's (Schneider 2006).

Type	M_B	M($M_\odot$)	D_{25} (kpc)	M/L_B
cD	-22^m to -25^m	$10^{13} - 10^{14}$	300-1000	>100
E	–15 to –23	$10^8 - 10^{13}$	1-200	10–100
dE	–13 to –19	$10^7 - 10^9$	1-10	1–10
BCD	–14 to –17	$\sim 10^9$	< 3	0.1–10
dSph	–8 to –15	$10^7 - 10^8$	0.1–0.5	5–100



Can we learn something about the true distribution of ellipticities from the distribution of observed apparent ellipticities?

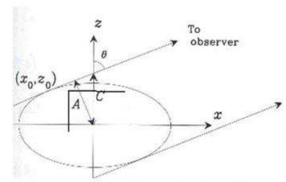
Let's assume that an elliptical galaxy is an oblate spheroid.
The density $\rho(x)$ can be expressed as $\rho(m^2)$, where:

$$m^2 = \frac{x^2 + y^2}{\alpha^2} + \frac{z^2}{\beta^2}$$

And $\alpha > \beta > 0$. The contours of constant density are ellipsoids of m^2 = constant. Note that when $\alpha < \beta$, the galaxy is prolate.

An observer looking down the z-axis will see an E0 galaxy, while when viewed at an angle, the system will look elliptical, with axis ratio $q_0 = b/a$.

How is q_0 related to α and β ?



The observed axis ratio is $q_0 = A/(m\,\alpha)$.

The line of sight intersects the ellipsoid at (x_0, z_0) at the constant-density surface m.

The segment $A = C \sin\theta$, while $C = z_0 - x_0/\tan\theta$; and $\tan\theta = dx/dz$.

Differentiating $d(m^2 = x^2/\alpha^2 + z^2/\beta^2) = 0$, we find $\tan\theta = -z_0/x_0\, \alpha^2/\beta^2$.

Replacing, $C = m^2 \beta^2 / z_0$. Finally $q_0 = m\,\beta^2 / (\alpha\, z_0) \sin\theta$, or

$$q_0^2 = \cos^2\theta + (\beta/\alpha)^2 \sin^2\theta$$

This implies that the apparent axis ratio is always larger than the true axis ratio, a galaxy never appears more flattened than it actually is.

We can use the previous relation to find the distribution of apparent ellipticities produced by a random distribution of oblate/prolate ellipsoids.

If the ellipsoids are randomly oriented with respect of the line-of-sight, then of the N(q) dq galaxies, a fraction $\sin\theta\, d\theta$ will have their axes oriented between θ and $\theta + d\theta$.

So the probability, $P(q_0|q)\, dq_0$, to observe a galaxy with true axis ratio q to have apparent axis ratio between q_0 and $q_0 + dq_0$ is:

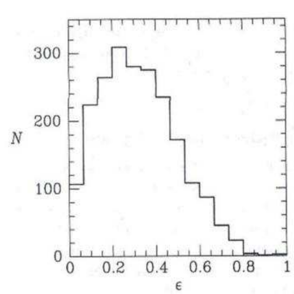
$$P(q_0|q)\, dq_0 = \sin\theta\, d\theta = \sin\theta\; dq_0 / \,|\, dq_0/d\theta \,|.$$

If there are $f(q_0)dq_0$ galaxies with observed axis ratios in $(q_0, q_0 + dq_0)$, this should be equal to $N(q)\, dq\, P(q_0|q)\, dq_0$.

We have then that

$$f(q_0) = \int N(q)\, dq\, P(q_0\,|\,q) = q_0 \int \frac{N(q)\, dq}{\sqrt{1 - q^2}\,\sqrt{q_0^{\,2} - q^2}}$$

This is an integral equation for N(q), which can in principle be solved from the observed distribution of ellipticities.



This is the observed distribution of apparent ellipticities, for 2135 E galaxies

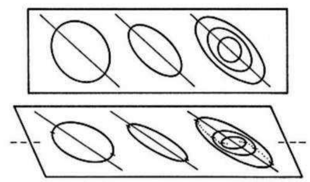
Conclusion: It is not possible to reproduce the observed distribution if all galaxies are either prolate or oblate axisymmetrical ellipsoids.

Some results:

- The apparent shapes of small E are more elongated than for large E
- On average, galaxies with M > -20, have $q_0 \sim 0.75$. If they are oblate, this would correspond to $0.55 < q < 0.7$
- Very luminous E, with M < -20, have on average $q_0 \sim 0.85$. But since there are so few that are spherical on the sky, it is very likely that most of these are actually triaxial.

Isophote twisting

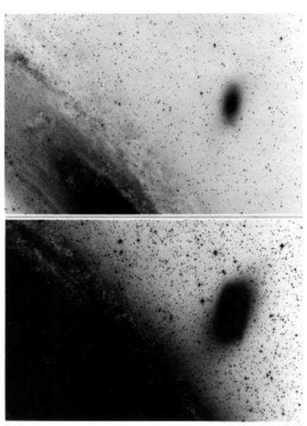
In a triaxial case, the orientation in the sky of the projected ellipses will not only depend upon the orientation of the body, but also upon the body's axis ratio. This is best seen in the projection of the following 2-D figure:



Since the ellipticity changes with radius, even if the major axis of all the ellipses have the same orientation, they appear as if they were rotated in the projected image. This is called ***isophote twisting***.

Unfortunately it is impossible, from an observation of a twisted set of isophotes, to conclude whether there is a real twist, or whether the object is triaxial.

Here is an example of twisted isophotes in a satellite galaxy of Andromeda (M31).

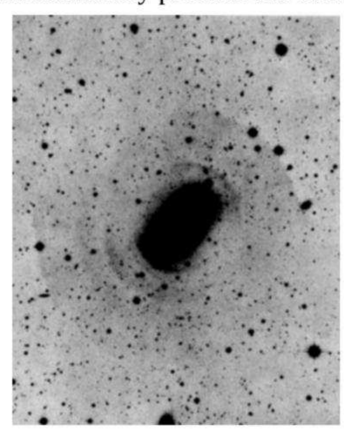


The first, shallower, exposure shows the brightest part of the galaxy. The second, deeper, exposure shows the weaker more extended emission. A twist between both images of the same galaxy are apparent (the orientation in the sky is the same in both figures).

Boxy galaxies are more likely to show isophote twists, more luminous in general, and probably triaxial.
Disky E are midsize, more often oblate, and faster rotators.
Some people have suggested disky E can be considered an intermediate class between the big boxy ones and the S0s.

Fine structures

About 10 to 20% of the elliptical galaxies seem to contain sharp steps in their luminosity profiles. An example is the elliptical NGC 3923:

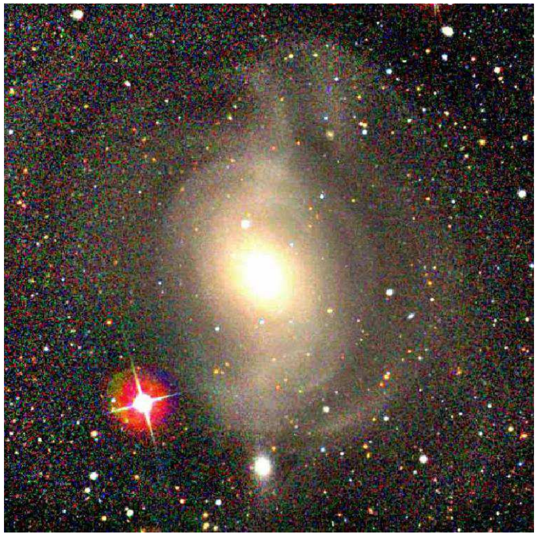


These features are called ***ripples and shells.***

Ripples and shells have also been detected in S0 and Sa galaxies. Since in early-type galaxies they are detected because of the smooth profile of the underlying galaxy, it is not clear whether this is an universal phenomenon also present in later-type galaxies but difficult to detect there.

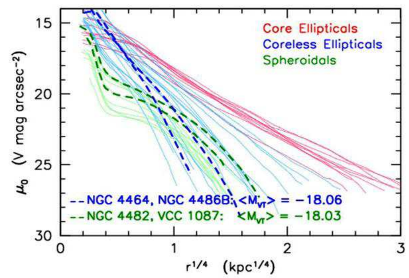
Elliptical galaxies
Shapes of elliptical galaxies

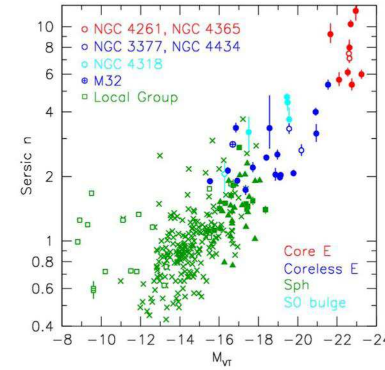
Fine structures: Virgo E/S0 galaxy NGC 4382



Elliptical galaxies
Photometric profiles

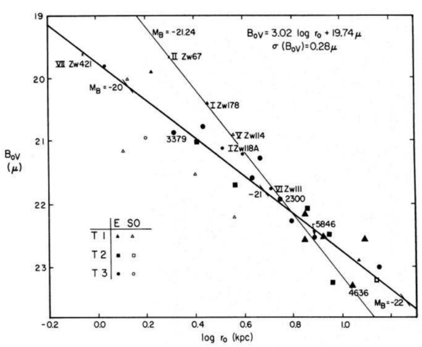
Kormendy et al. (2008):





Elliptical galaxies
Kormendy relation

Kormendy (1977) demonstrated that a correlation exists berween r_e and μ_e in the sense that larger galaxieshave fainter effective surface brightnesses.



Thick solid line –

$\mu_e = A \lg r_e + \mathrm{const},\ A \approx 3$

(Kormendy relation).

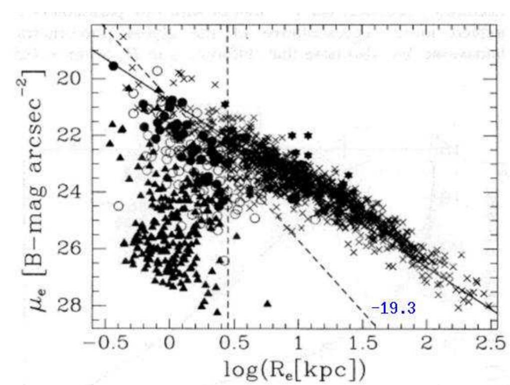
Thin solid line – a line of constant luminosity:

$M_{Vauc} = \mu_e - 5 \lg r_e - 39.96$,

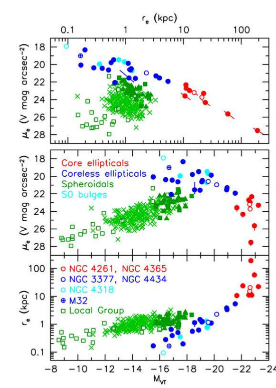
so

$\mu_e \propto 5 \lg r_e$.

Elliptical galaxies
Kormendy relation



Capaccioli et al. (1992)

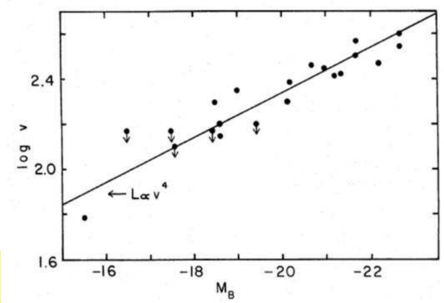


Kormendy et al. (2008)

Applications of the KR: surface brightness evolution,
Tolmen's test for expansion.

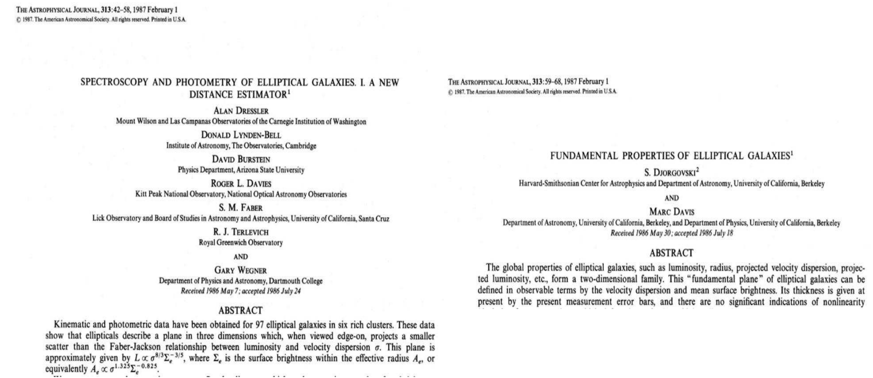
A relation for elliptical galaxies, analogous to the TFR, was found by Sandra Faber and Roger Jackson (1976). They discovered that the velocity dispersion in the center of ellipticals, σ_0, scales with luminosity,

$$L \propto \sigma_0^B, \quad \text{where } B \approx 4.$$



The dispersion of ellipticals about this relation is larger than that of spirals about the TFR.
The FJR can be used to estimate a galaxy's distance from its measured velocity dispersion.

The fundamental plane (FP) is a relation that combines surface photometry with spectroscopy. The FP was discovered independently and simultaneously by Djorgovski & Davis (1987) and Dressler et al. (1987).



The Astrophysical Journal, 313:42–58, 1987 February 1

SPECTROSCOPY AND PHOTOMETRY OF ELLIPTICAL GALAXIES. I. A NEW DISTANCE ESTIMATOR[1]

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Received 1986 May 7; accepted 1986 July 24

ABSTRACT

Kinematic and photometric data have been obtained for 97 elliptical galaxies in six rich clusters. These data show that ellipticals describe a plane in three dimensions which, when viewed edge-on, projects a smaller scatter than the Faber-Jackson relationship between luminosity and velocity dispersion σ. This plane is approximately given by $L \propto \sigma^{8/3}\Sigma_e^{-3/5}$, where Σ_e is the surface brightness within the effective radius A_e, or equivalently $A_e \propto \sigma^{1.325}\Sigma_e^{-0.825}$.

The Astrophysical Journal, 313:59–68, 1987 February 1

FUNDAMENTAL PROPERTIES OF ELLIPTICAL GALAXIES[1]

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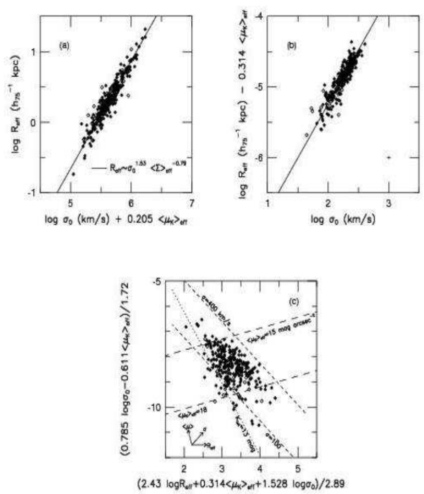
Received 1986 May 30; accepted 1986 July 18

ABSTRACT

The global properties of elliptical galaxies, such as luminosity, radius, projected velocity dispersion, projected luminosity, etc., form a two-dimensional family. This "fundamental plane" of elliptical galaxies can be defined in observable terms by the velocity dispersion and mean surface brightness. Its thickness is given at present by the present measurement error bars, and there are no significant indications of nonlinearity

The FP is a relation between r_e, σ, and μ_e and is linear in logarithmic space. Since $L \propto I_e r_e^2$, the FP can also be expressed as a relation between L, σ, and μ_e or between r_e, σ, and L.



Pahre et al. (1998) – 301 galaxy, K band.

Standard presentation of the FP is

$$\lg r_e = \alpha \lg \sigma_0 + \beta \lg \langle I \rangle_e + \mathrm{const}$$

or

$$r_e \propto \sigma_0^\alpha \langle I \rangle_e^\beta .$$

$\alpha \approx 1.3$ in the B, $\alpha \approx 1.7$ in the K passband;
$\beta \approx -0.8$.

The Kormendy ($\mu_e - r_e$) and the Faber–Jackson ($L - \sigma$) relations are diferent projections of the FP.

Applications: galaxy distances, evolution of E.

Observational data on the FP coefficients

	$A \pm \Delta A$	$B \pm \Delta B$	Band
Dressler et al. (1987)	1.33 ± 0.05	-0.83 ± 0.03	B
Djorgovski and Davis (1987)	1.39 ± 0.14	-0.90 ± 0.09	B
Lucey et al. (1991)	1.27 ± 0.07	-0.78 ± 0.09	V
Guzmán et al. (1993)	1.14 ± 0.07	-0.79 ± 0.07	V
Pahre et al. (1995)	1.44 ± 0.04	-0.79 ± 0.03	K'
Jørgensen et al. (1996)	1.24 ± 0.07	-0.82 ± 0.02	r
Hudson et al. (1997)	1.38 ± 0.04	-0.82 ± 0.03	R
Scodeggio et al. (1997)	1.25 ± 0.02	-0.80 ± 0.02	I
Scodeggio (1997)	1.55 ± 0.05	-0.80 ± 0.02	I
Pahre and Djorgovski (1997)	1.66 ± 0.09	-0.75 ± 0.06	K'
Pahre et al. (1998b)	1.53 ± 0.08	-0.80 ± 0.02	K
Kelson et al. (2000)	1.31 ± 0.13	-0.86 ± 0.10	V
Gibbons et al. (2001)	1.37 ± 0.04	-0.82 ± 0.01	R
Bernardi et al. (2003b)	1.49 ± 0.05	-0.75 ± 0.01	r

Bender et al. (1992) introduced a new orthogonal coordinate system for the FP known as the κ-space, defined by the following independent variables:

$$\kappa_1 = (\log\ \sigma_0^2 + \log\ r_e)/\sqrt{2} \sim \log\ M\ ;$$
$$\kappa_2 = (\log\ \sigma_0^2 + 2\log\ \langle I\rangle_e - \log\ r_e)/\sqrt{6} \sim \log\ \left(\frac{M}{L}\langle I\rangle_e{}^3\right)\ ;$$
$$\kappa_3 = (\log\ \sigma_0^2 - \log\ \langle I\rangle_e - \log\ r_e)/\sqrt{3} \sim \log\ \frac{M}{L}\ ;$$

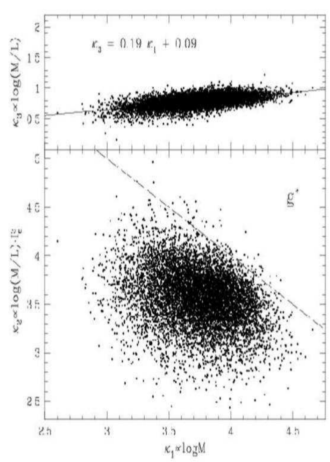
which relate to galaxian total mass, M, average effective surface brightness, $\langle I\rangle_e$, and mass-to-light ratio, M/L, respectively.

Such parametrization is useful for a number of reasons:

(1) κ-variables are expressed only in terms of observables,

(2) the $\kappa_1 - \kappa_3$ plane represents an edge-on view of the FP and provides a direct view of the tilt,

(3) the $\kappa_1 - \kappa_2$ plane almost represents a face-on view of the FP.



$\sim$ 9000 galaxies from the SDSS, g^* band.

Simple interpretation of the FP

For a bound system

$$\frac{GM}{\langle R\rangle} = k_E \frac{\langle V^2\rangle}{2},$$

where $k_E = 2$ for a virialized system.
We relate the observable quantities r_e, σ_0 and $\langle I\rangle_e$ to the physical quantities through

$$r_e = k_R\langle R\rangle, \quad \sigma_0^2 = k_V\langle V^2\rangle, \quad L = k_L\langle I\rangle_e r_e^2.$$

The parameters k_R, k_V, and k_L reflect the density structure, kinematical structure, and luminosity structure of the given galaxy. If these parameters are constant, the galaxies constitute a *homologous* family.

Therefore, assuming $k_E = 2$ we obtain

$$r_e = k_S\,(\mathrm{M}/L)^{-1}\,\sigma_0^2\,\langle I\rangle_e^{-1},$$

where M/L – global mass-to-luminosity ratio and
$k_S = (Gk_R k_V k_L)^{-1}$.
For homology k_S will be constant. (Homology means that structure of small and big galaxies is the same.)

When this relation is compared to the observed FP,

$$r_e \propto \sigma_0^{1.4}\,\langle I\rangle_e^{-0.8},$$

it is seen that the coefficients of the FP are not 2 and -1 as expected from homology and constant mass-to-light ratios. The product $k_S\,(\mathrm{M}/L)^{-1}$ cannot be constant, but has to be a function of σ_0 and $\langle I\rangle_e$.

A non-constant $k_S\,(\mathrm{M}/L)^{-1}$ product can be explained by
a systematic deviation from homology (k_S varies), or
a systematic variations of the M/L ratios,
or both.

The interpretation of the FP is still a matter of debate. There are some evidences in favour of M/L variations (M/$L \propto L^{0.2-0.3}$) and of non-homology (e.g. $n \propto L$).

Dressler et al. (1987) have defined a readily measured photometric parameter that has a tight correlation with σ_0 by virtue of the FP. This parameter, D_n, is the diameter within which the mean surface brightness is $I_n = 20.75$ in the B band.

If we assume that all ellipticals half a self-similar brightness profile, $I(r) = I_e\,f(r/r_e)$, with $f(1) = 1$, then the mean surface brightness I_n can be written as

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

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

For a de Vaucouleurs profile we have approximately $f(x) \propto x^{-\alpha}$ with $\alpha \approx 1.2$ in the relevant range of radius. Using this approximation to evaluate the integral, we obtain

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

Replacing r_e by the FP and taking into account that $\langle I\rangle_e \propto I_e$, we finally find

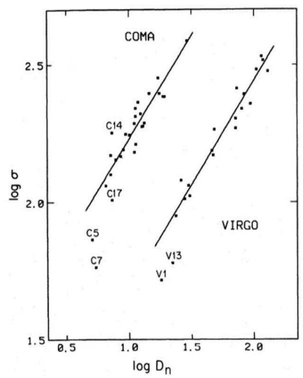
$$D_n \propto \sigma_0^{1.4}\,I_e^{0.05}.$$

This implies that D_n is nearly independent of I_e and only depends on σ_0. The $D_n - \sigma$ relation describes the properties of ellipticals considerably better than the FJR and, in contrast to the FP, it is relation between only two observables.

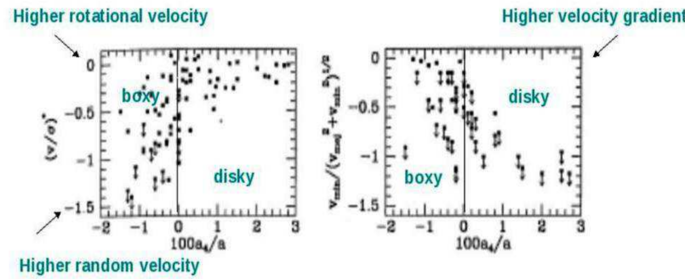
Empirically, ellipticals follow the normalized $D_n - \sigma$ relation

$$\frac{D_n}{\mathrm{kpc}} = 2.05\,(\frac{\sigma_0}{100\,\mathrm{km/s}})^{1.33},$$

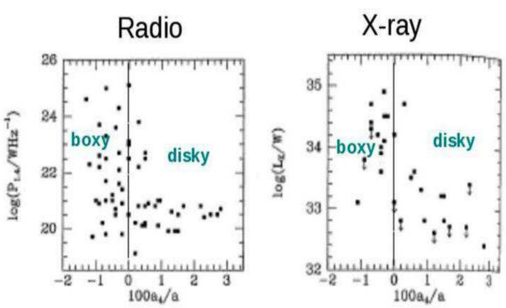
and they scatter around this relation with a relative width of about 15% (Dressler et al. 1987).



- Boxy galaxies are triaxial systems with little net rotation
- Exchange of angular mtm between stars and ISM gas
- No centrifugal "barrier" and thus gas reaches the nucleus easier than in disky, slightly rotating galaxy.

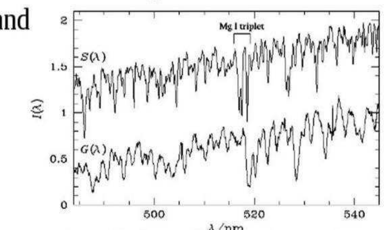


V = rotational velocity
σ = velocity dispersion (random velocities)



- More radio and x-ray emission found among E's with boxy isophotes (from hot gas, fueling AGN?)
- Merrifield (2004) - found E's with active nuclei to be less rotationally supported, while E's with inactive nuclei span a range of rotational support.

It is not possible to see individual stars in galaxies beyond 10-20 Mpc. Hence the stellar populations characteristics of E galaxies must be derived from the integrated colors and spectra. Spectra of an E galaxy resembles that of a K giant star.

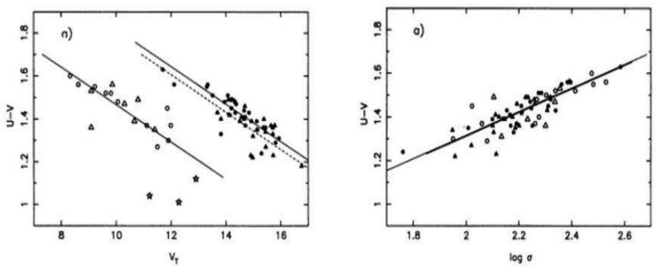


E galaxies appear generally red:

- very few stars made in the last 1-2 Gyr (recall that after 1 Gyr, only stars with masses < 2 Msun survive)
- The stars in the centres of E are very metal-rich, similar to the Sun

This would seem to suggest that E galaxies are very old, however, metallicity can also mimic age effects. Recall that metal-poor stars are generally bluer, for the same age.

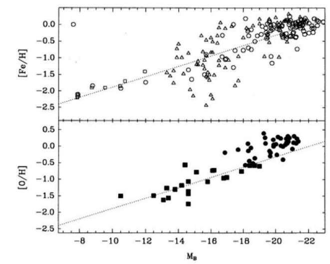
There is a relation between the color, and total luminosity for E galaxies.



These plots show, for galaxies in the Coma and Virgo cluster, that
- Brighter galaxies are redder
- Fainter systems are bluer

This could be explained if small E galaxies were younger or more metal-poor than the large bright ones.

Zaritsky et al. (1994):
ellipticals – open circles



Dressler et al. (1987)