Elliptical Galaxies

Virgo Cluster: distance 15Mpc

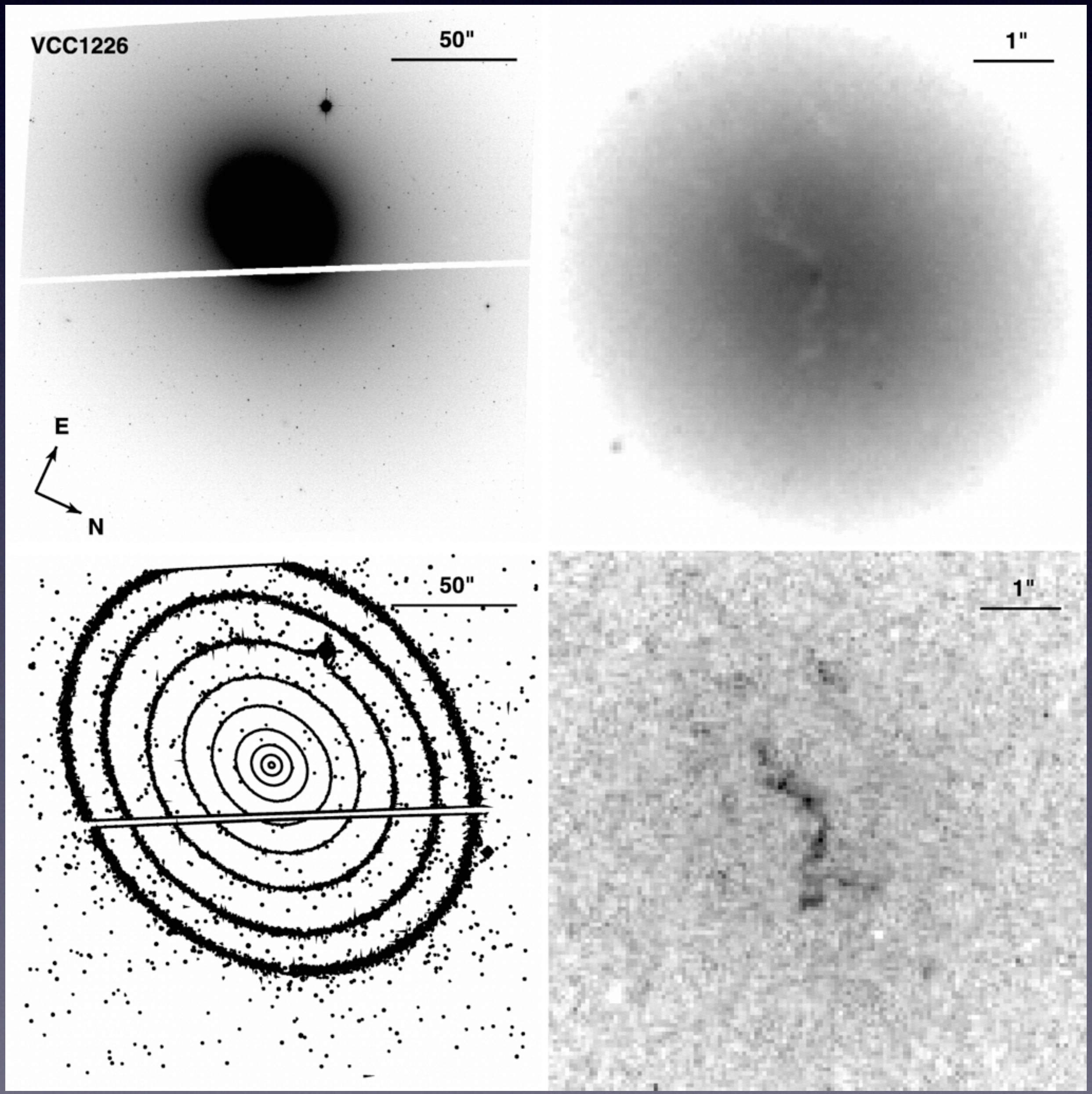
Elliptical Galaxies

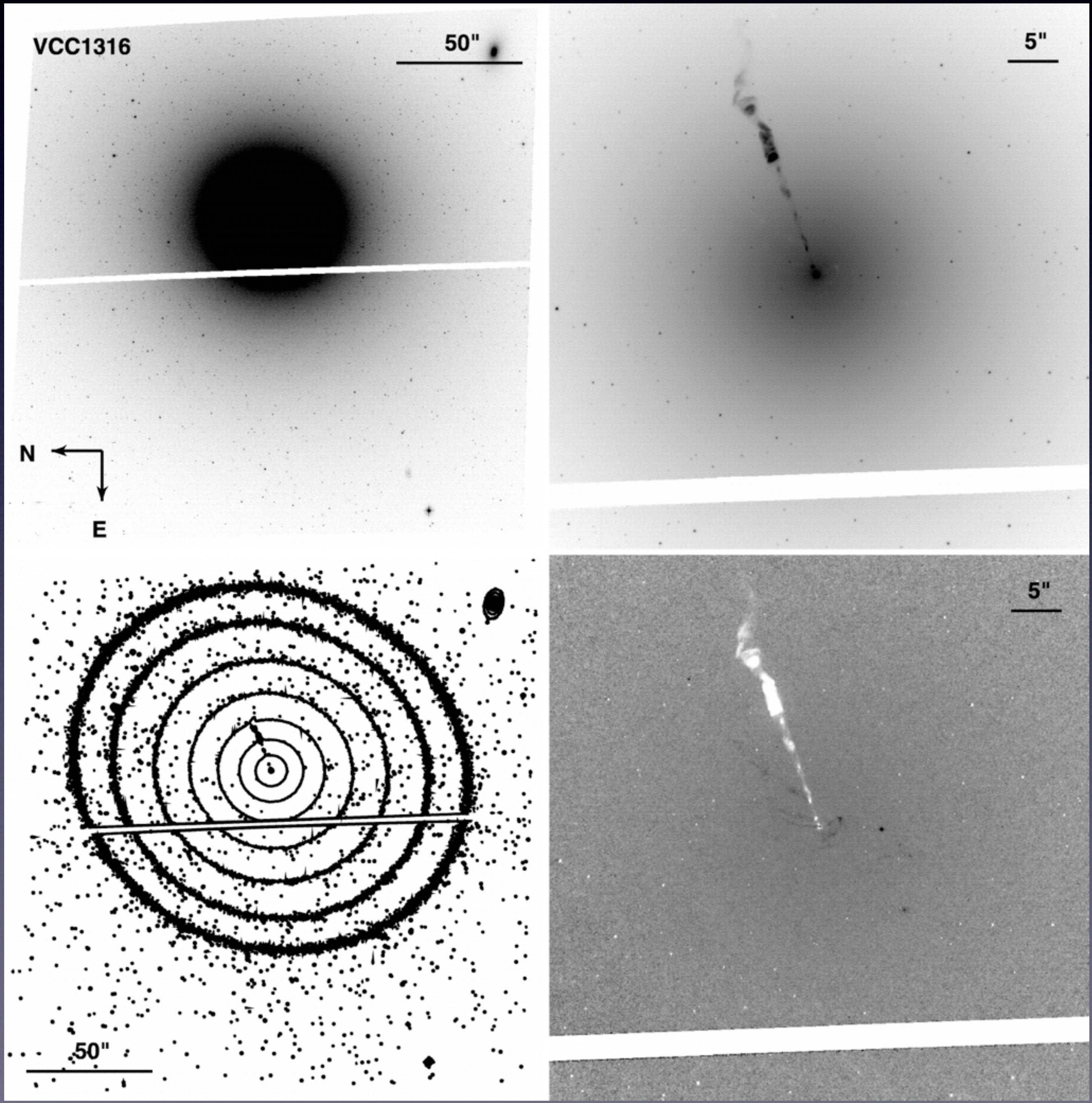
Elliptical galaxies are thought to be the simplest of all types of galaxies. Yet, detailed analysis shows that they are much more complicated that "dead spherish lumps".

Elliptical galaxies are typically found in clusters and groups of galaxies. Still, 10% of all field galaxies are ellipticals; 20% are S0's and the rest is spirals.

Elliptical galaxies dominate the bright end the very dim ends of the luminosity function.

Examples: M49 and M87: Virgo Cluster





Surface brightness profiles

- laws and approximations
- history: old good results
- more recent results: cores, cusps, power-laws and so on

Projected Brightness Profiles of E Galaxies Are Sérsic (1968) Functions

de Vaucouleurs (1948) $r^{1/4}$ law:

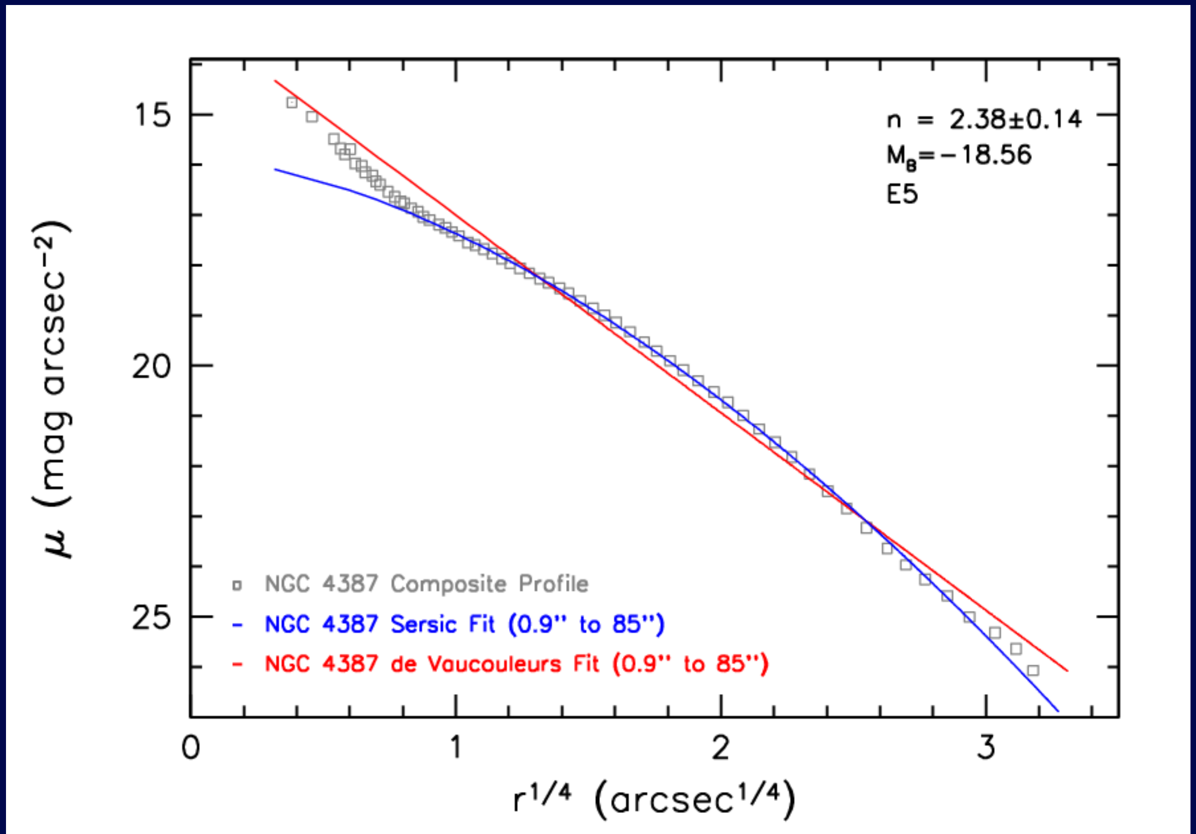
$$\mu_{deV} = \mu_0 \exp\left[-\left(\frac{r}{r_0}\right)^{\frac{1}{4}}\right]$$

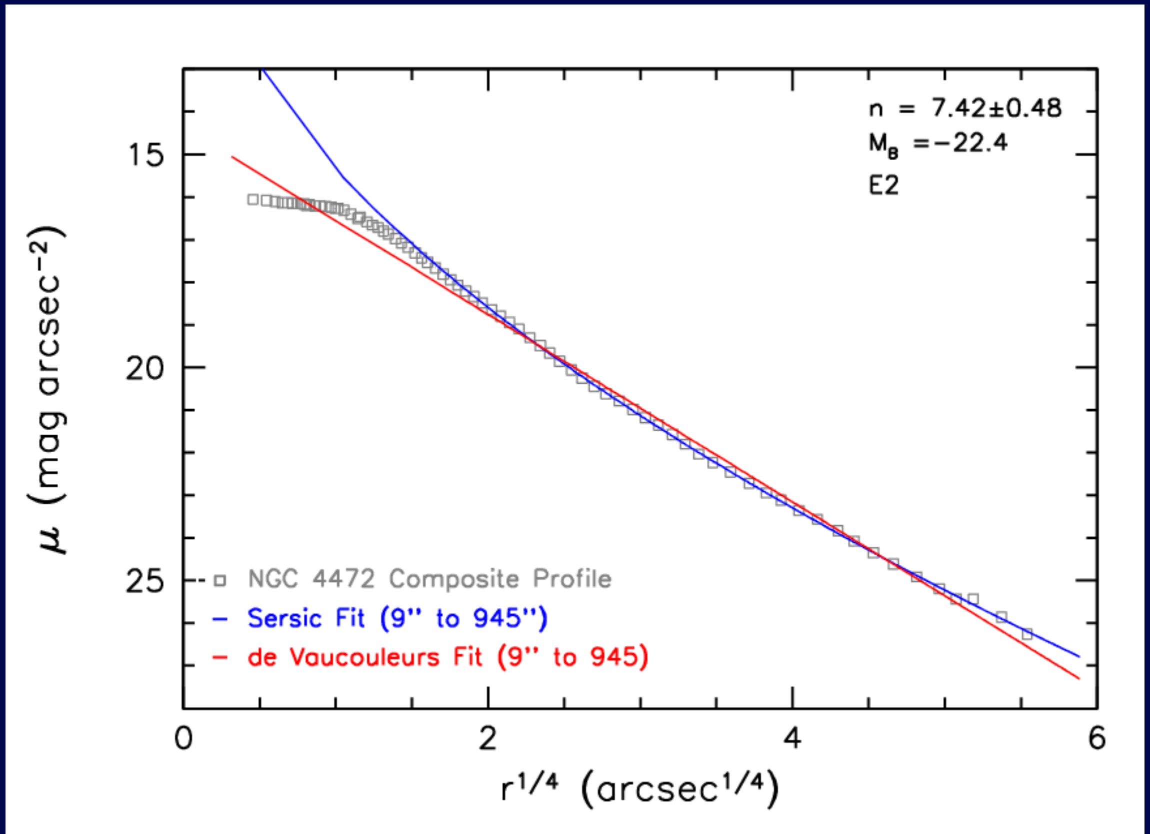
Sérsic (1968) generalization:

$$\mu_{ser} = \mu_0 \exp\left[-\left(\frac{r}{r_0}\right)^{\frac{1}{n}}\right]$$

n = 1 ⇒ exponential (many disks)

n = 4 ⇒ de Vaucouleurs law





Laws and approximations

de Vaucouleurs

$$I(R) = I(0)\exp\left(-kR^{1/4}\right)$$
$$= I_e \exp\left(-7.67\left[\left(\frac{R}{R_e}\right)^{1/4} - 1\right]\right)$$

where Ie is the surface brightness at Re
Re is half-light radius

Hubble law

$$I(R) = I_0\left(1 + \frac{R}{R_H}\right)^{-2}$$

β-model $$\rho = \frac{\rho_0}{\left[1 + \left(\frac{r}{a}\right)^2\right]^{\frac{3\beta}{2}}}$$

Cuspy profiles

NFW

$$\rho = \frac{\rho_0}{x(1+x)^2}, \quad x \equiv \frac{r}{r_s}$$

Hernquist

$$\rho = \frac{\rho_0}{x(1+x)^3}, \quad x \equiv \frac{r}{r_H}$$

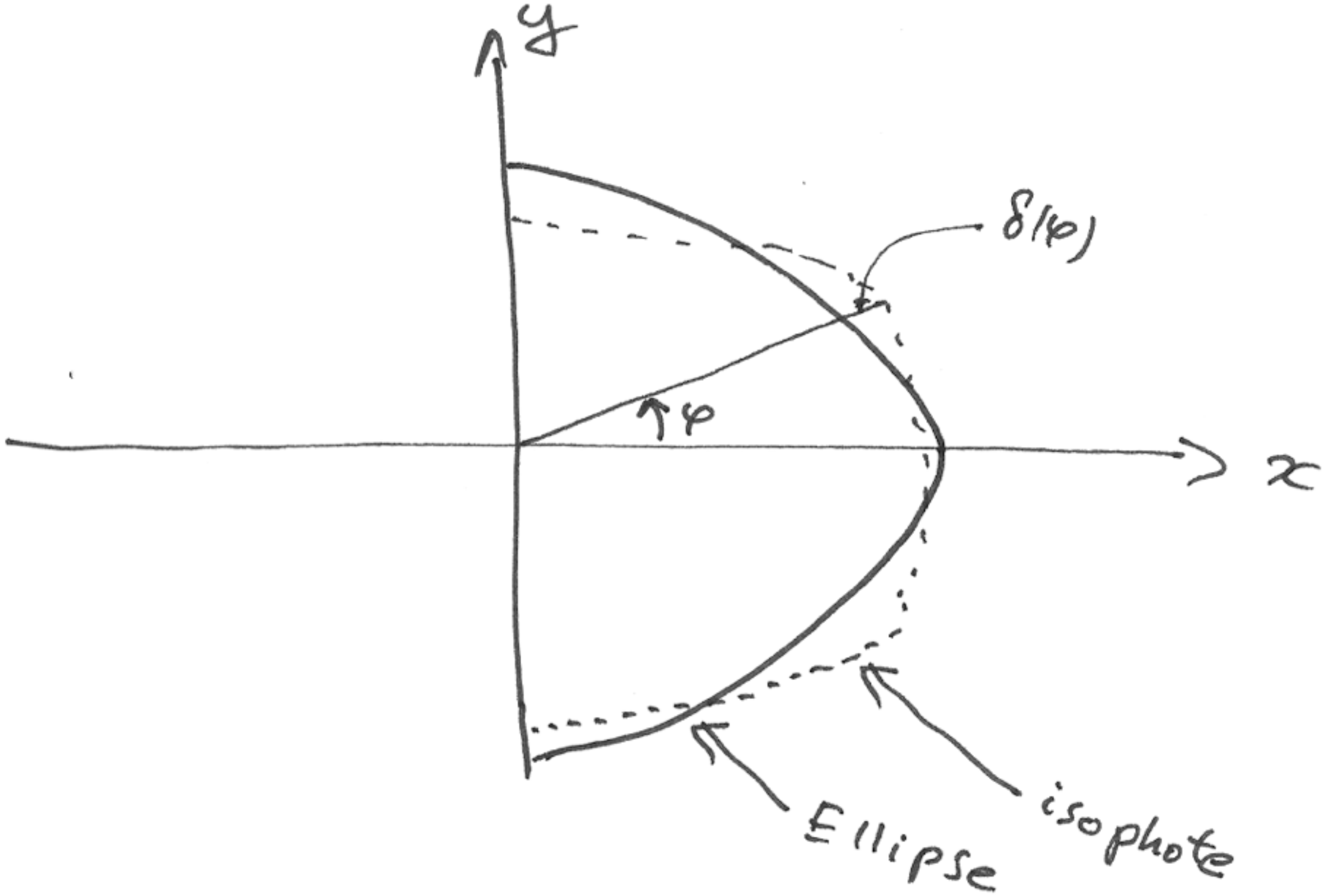
Nuker (for surface)
Kravtsov (3D)

$$\rho = \frac{\rho_0}{\left(\frac{r}{r_0}\right)^{\gamma}\left[1+\left(\frac{r}{r_0}\right)^{\alpha}\right]^{\frac{(\beta-\gamma)}{\alpha}}}$$

Burkert (not cuspy)

$$\rho = \frac{\rho_0}{\left(1+\frac{r}{r_b}\right)\left(1+\left(\frac{r}{r_b}\right)^2\right)}$$

Deviations from ellipticity



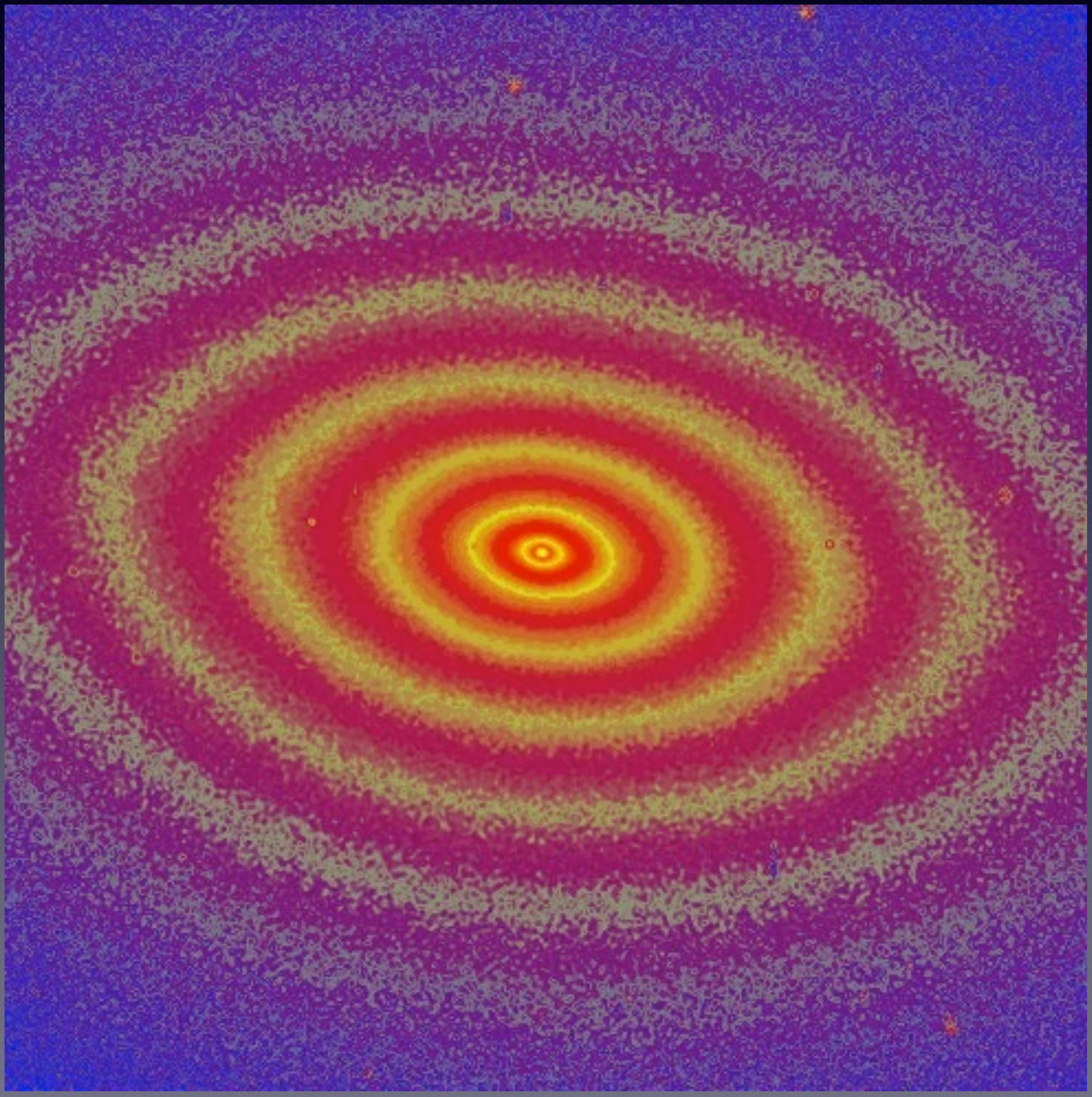
$$\delta(\varphi) = \bar{\delta} + \sum_{n=1}^{\infty} a_n \cos(n\varphi) + \sum_{n=1}^{\infty} b_n \sin(n\varphi)$$

$a_4 > 0 \rightarrow$ "disky" isophotes

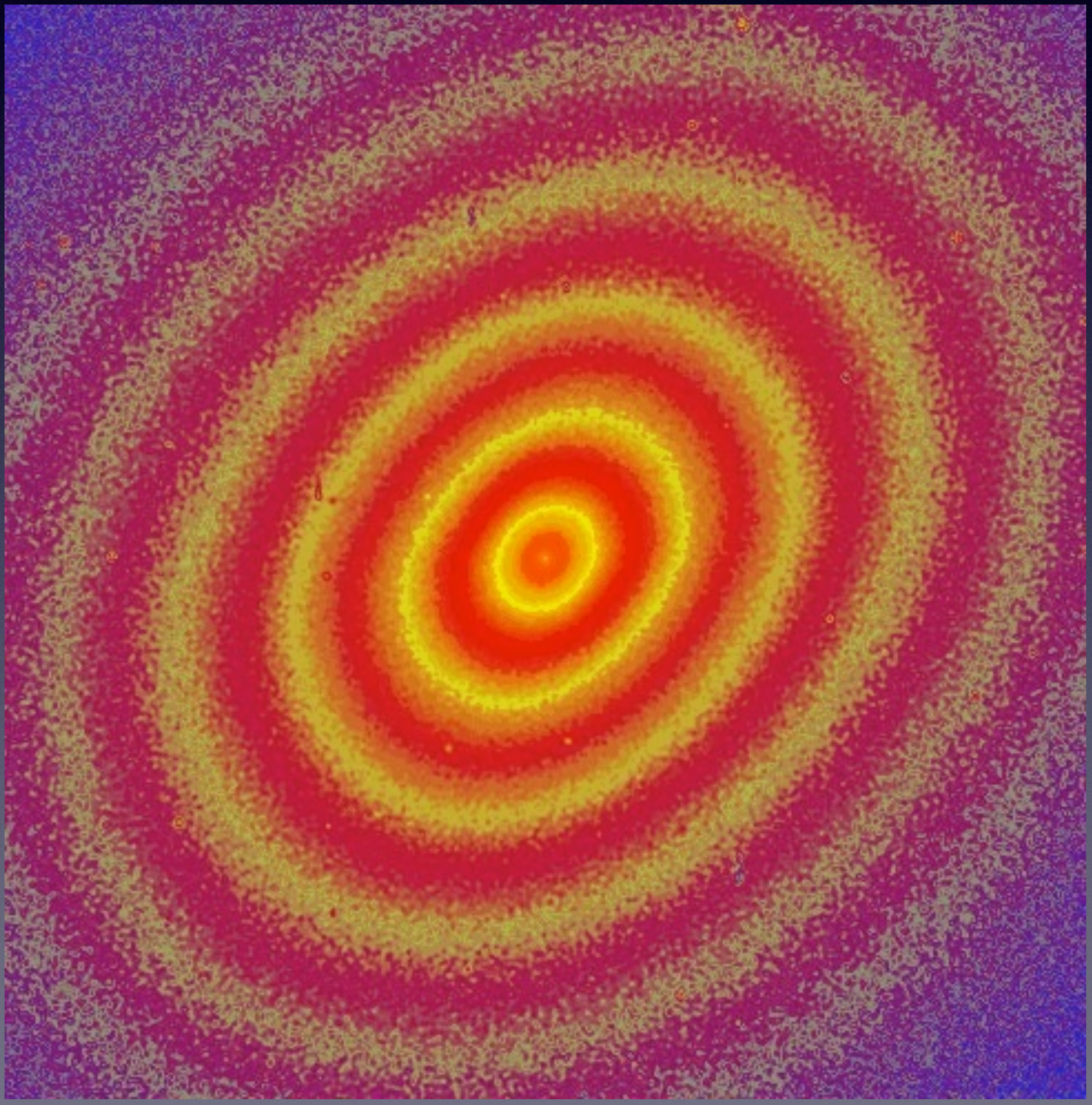
$a_4 < 0 \rightarrow$ "boxy" isophotes

Examples of boxy and disky isophotes

NGC821



NGC2300



Old results

Concentration: log of ratio of outer radius to core radius. E's have very large concentrations

Old results indicated that the surface brightness profiles flatten close to the center (cores). This is now believed to be an effect of insufficient angular resolution.

Note that profiles have different shapes: outer slopes are different for different galaxies.

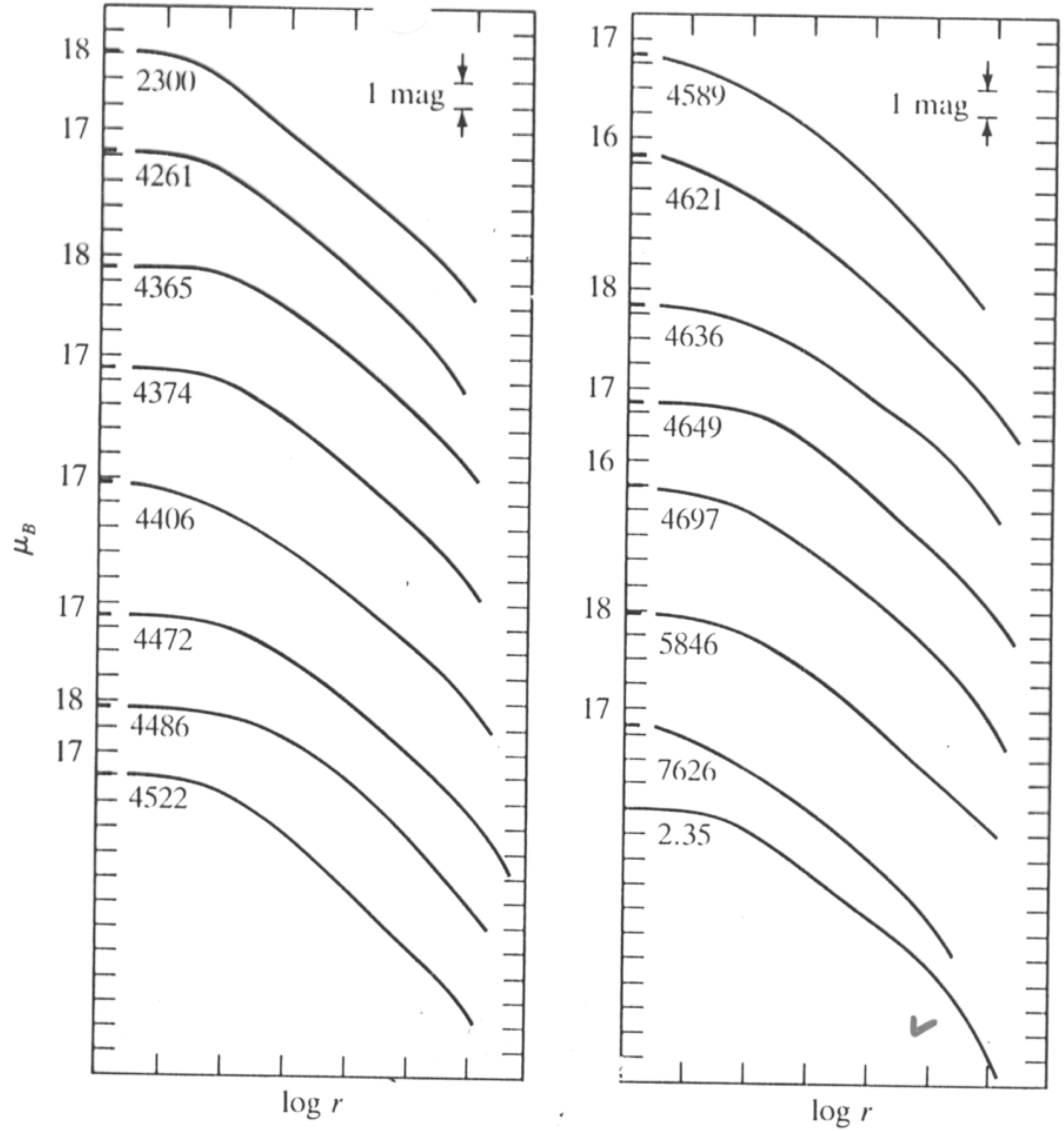


Figure 5-10. Brightness profiles of 15 elliptical galaxies, labeled by their NGC numbers, as measured by King. The curve labeled 2.35 is one of King's theoretical curves with $c = 2.35$. [From (**K2**), by permission. Copyright © 1978 by the American Astronomical Society.]

cD galaxies have very extended profiles

Central galaxies in rich galaxy clusters extend to very large radii. They may account for a large fraction of the total cluster luminosity. Different issues: where is the boundary of cD and where the cD galaxy ends and real cluster starts?

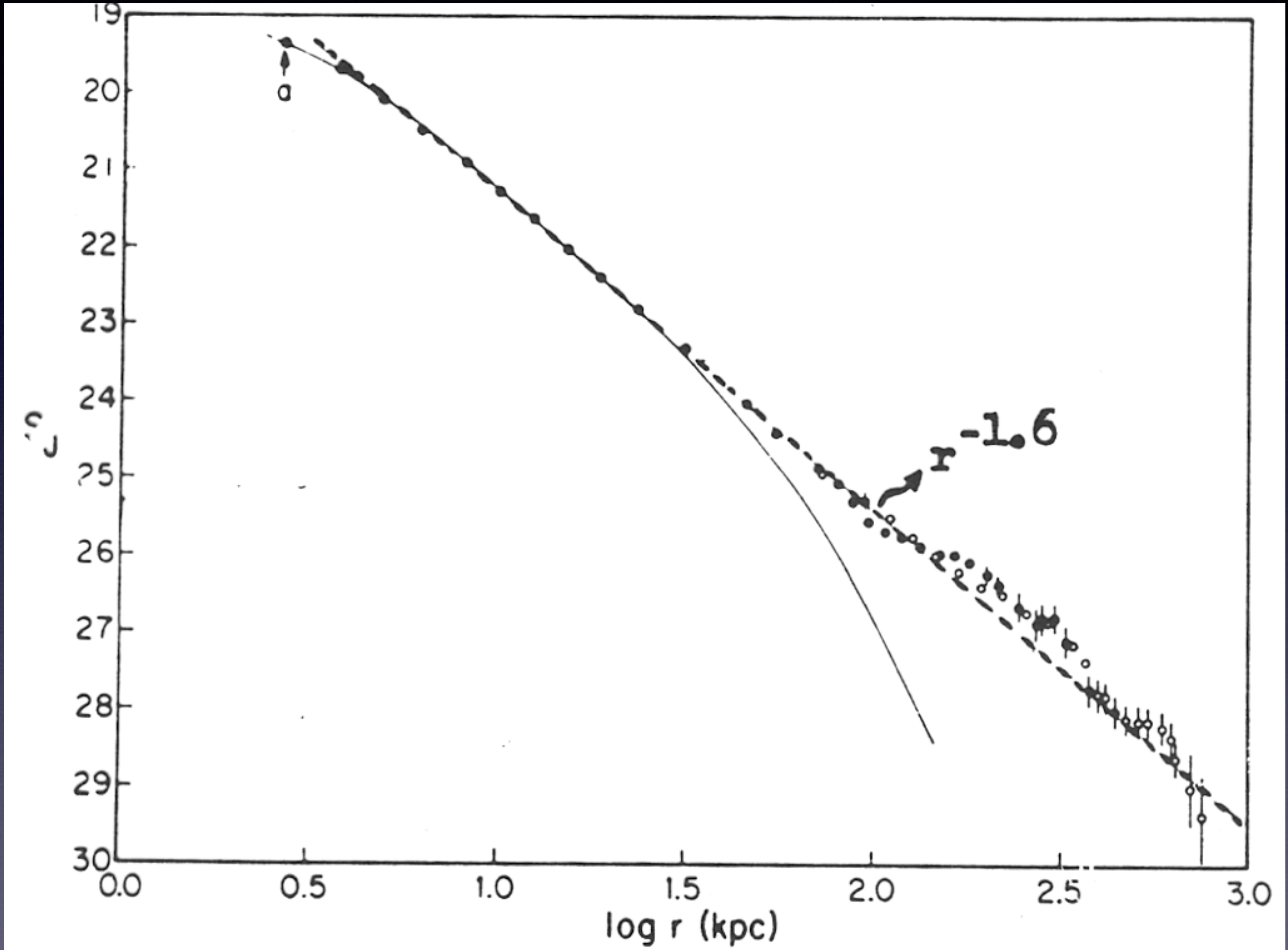
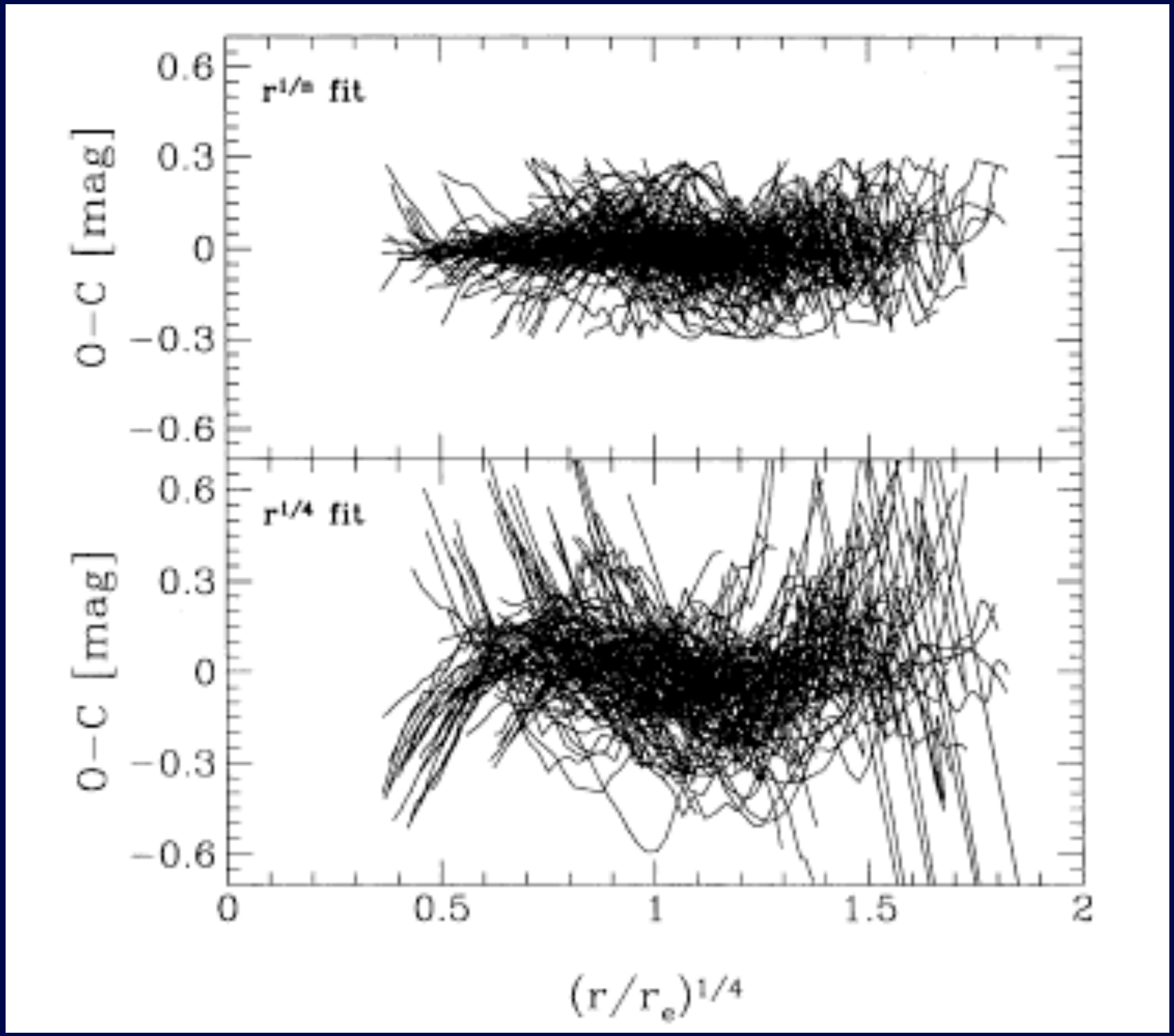
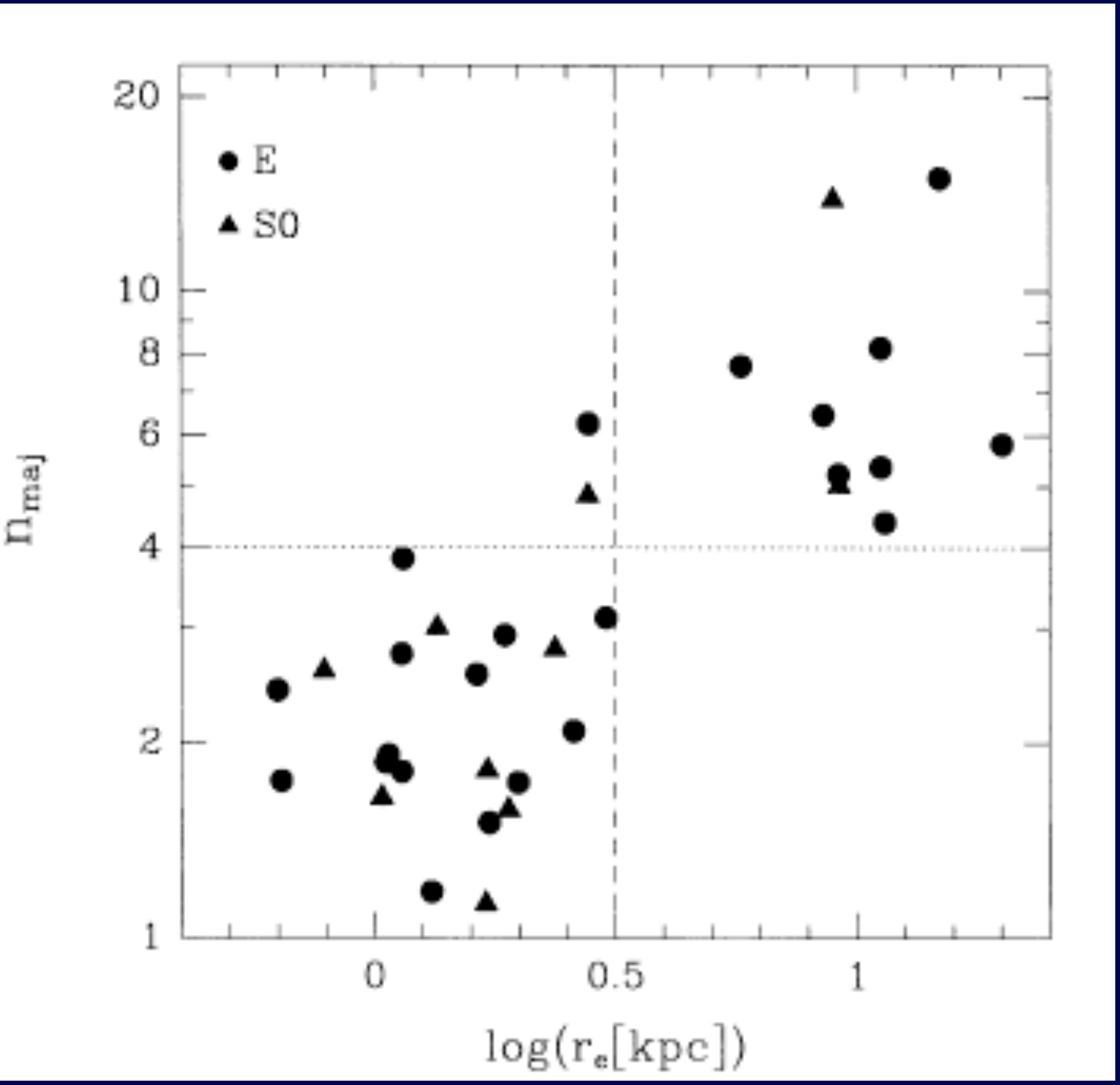


Figure 1 Surface brightness profile of the cD galaxy in A2670 (measured by Oemler 1973a). S_J is in mag (arc sec)$^{-2}$; open circles are green (J) magnitudes and filled circles are red magnitudes shifted by +1.1 mag. The solid line is the profile of a normal elliptical galaxy with a length scale a. The dashed line represents the relation $\sigma(r) \propto r^{-1.6}$ suggested by Equation 4 (Section 3.4).

The Sérsic (1968) Function

Caon et al. (1993) showed that residuals of Sérsic fits are systematically smaller than residuals of $r^{1/4}$-law fits.



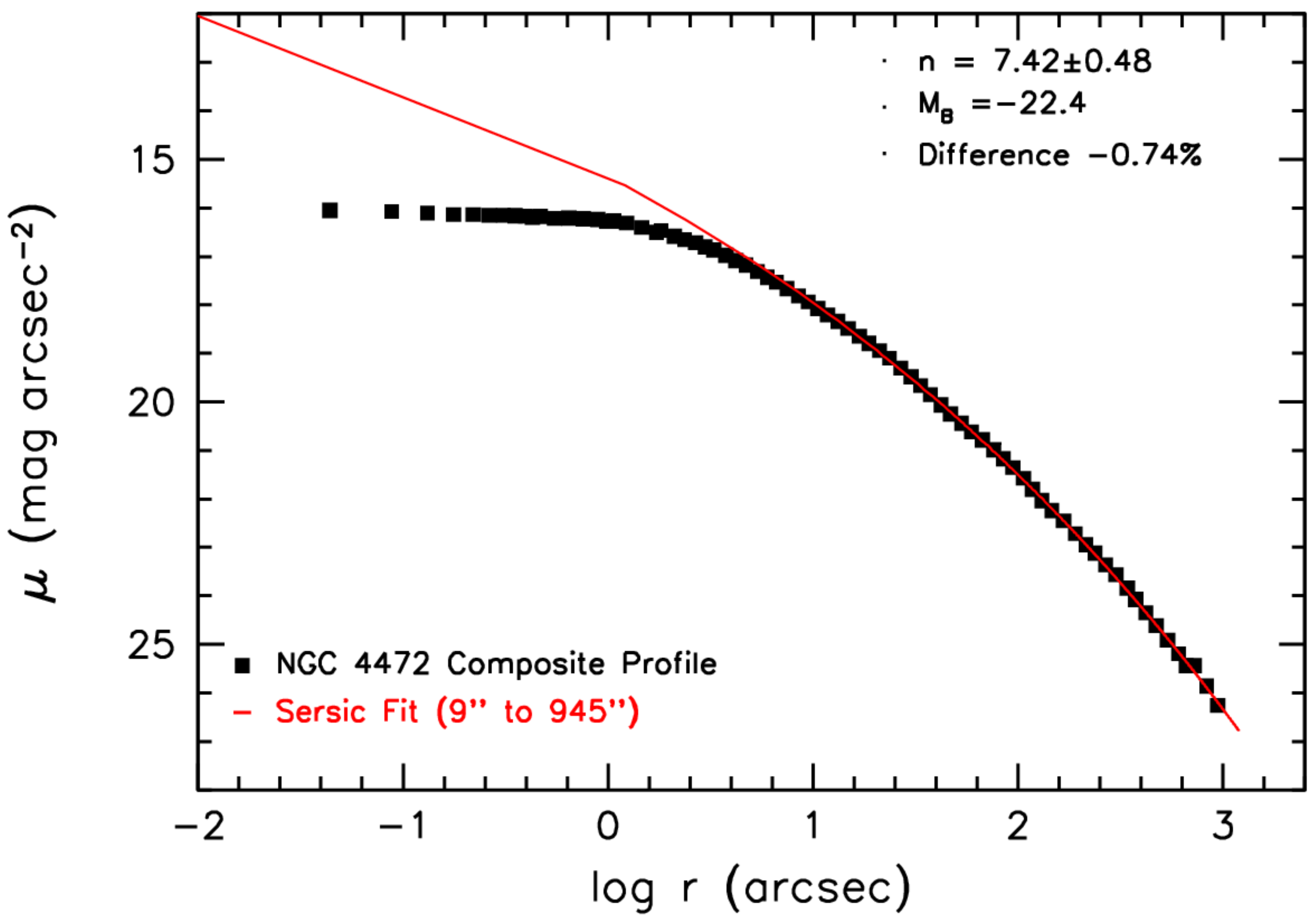


They suggested that the shape parameter n is physically meaningful because it correlates

with effective radius.

Diagnostic Departures From Sérsic Profiles: **Cores**

Near the center, the profiles of many Es *break below the inward extrapolation* of the outer Sérsic profile into a nonisothermal "core" (Kormendy 1977; King 1978; Lauer 1985; Kormendy 1985).

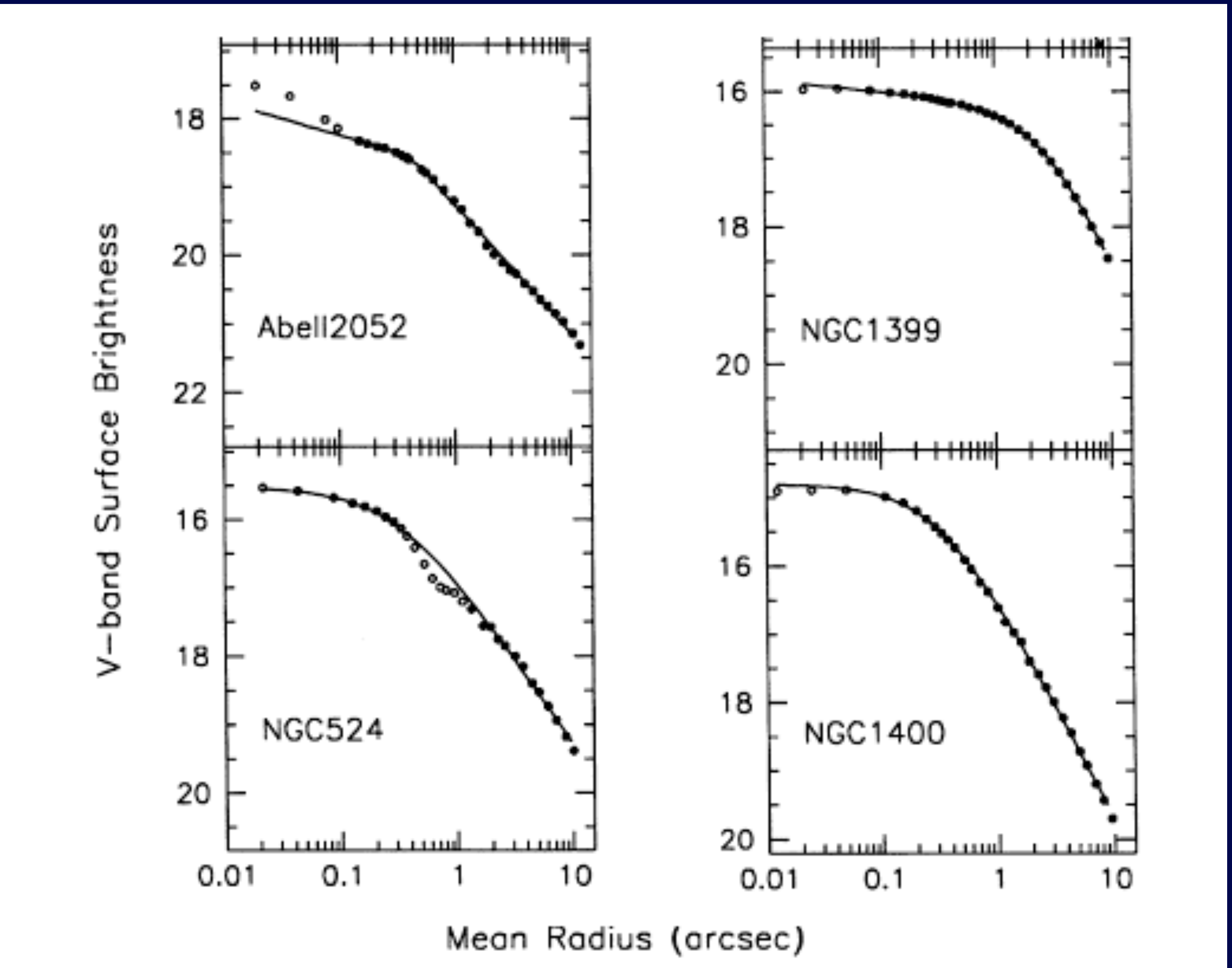


We adopt this definition of cores (e.g., Trujillo et al. 2004, AJ, 127, 1917).

HST Era: “Cuspy cores” are shallow power laws.

Nuker function (Kormendy et nuk. 1994; Lauer et nuk. 1995; Byun et nuk. 1996),

$$I(r) = I_b 2^{(\beta-\gamma)/\alpha} \left(\frac{r_b}{r}\right)^{\gamma} \left[1 + \left(\frac{r}{r_b}\right)^{\alpha}\right]^{(\gamma-\beta)/\alpha} ,$$



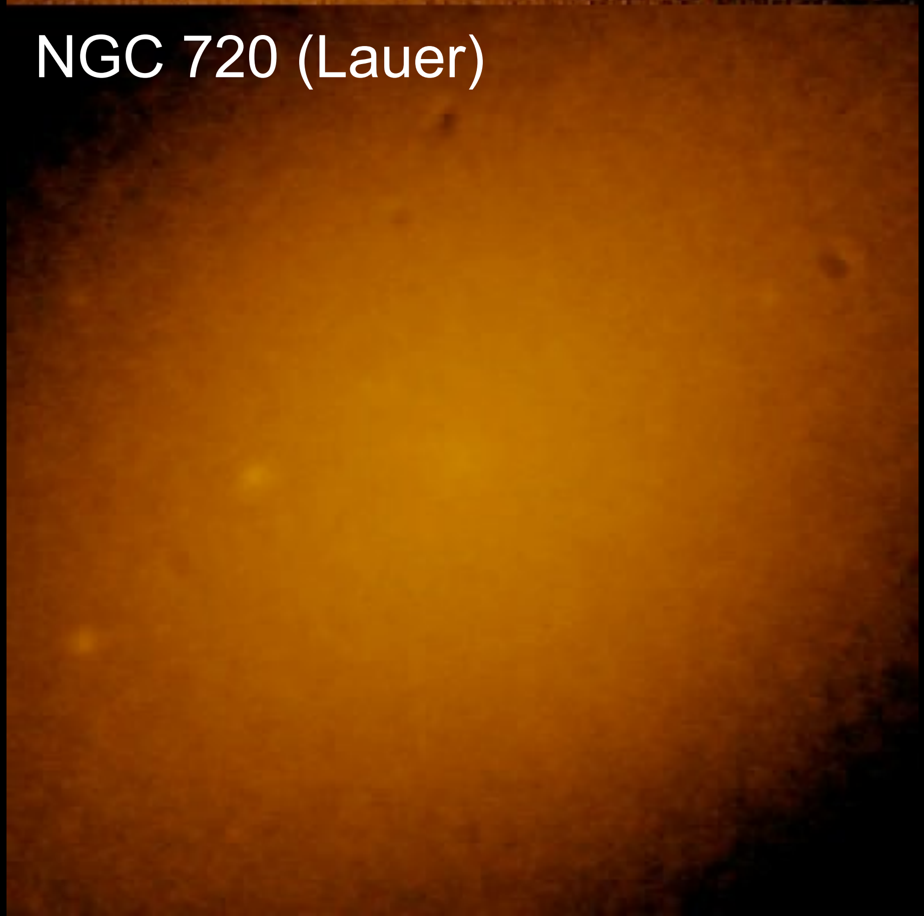
Byun et nuk. (1996)

is a (yet another) empirical, analytic fitting function with

γ = slope of inner power law;
β = slope of outer power law;
α = sharpness of break between them.

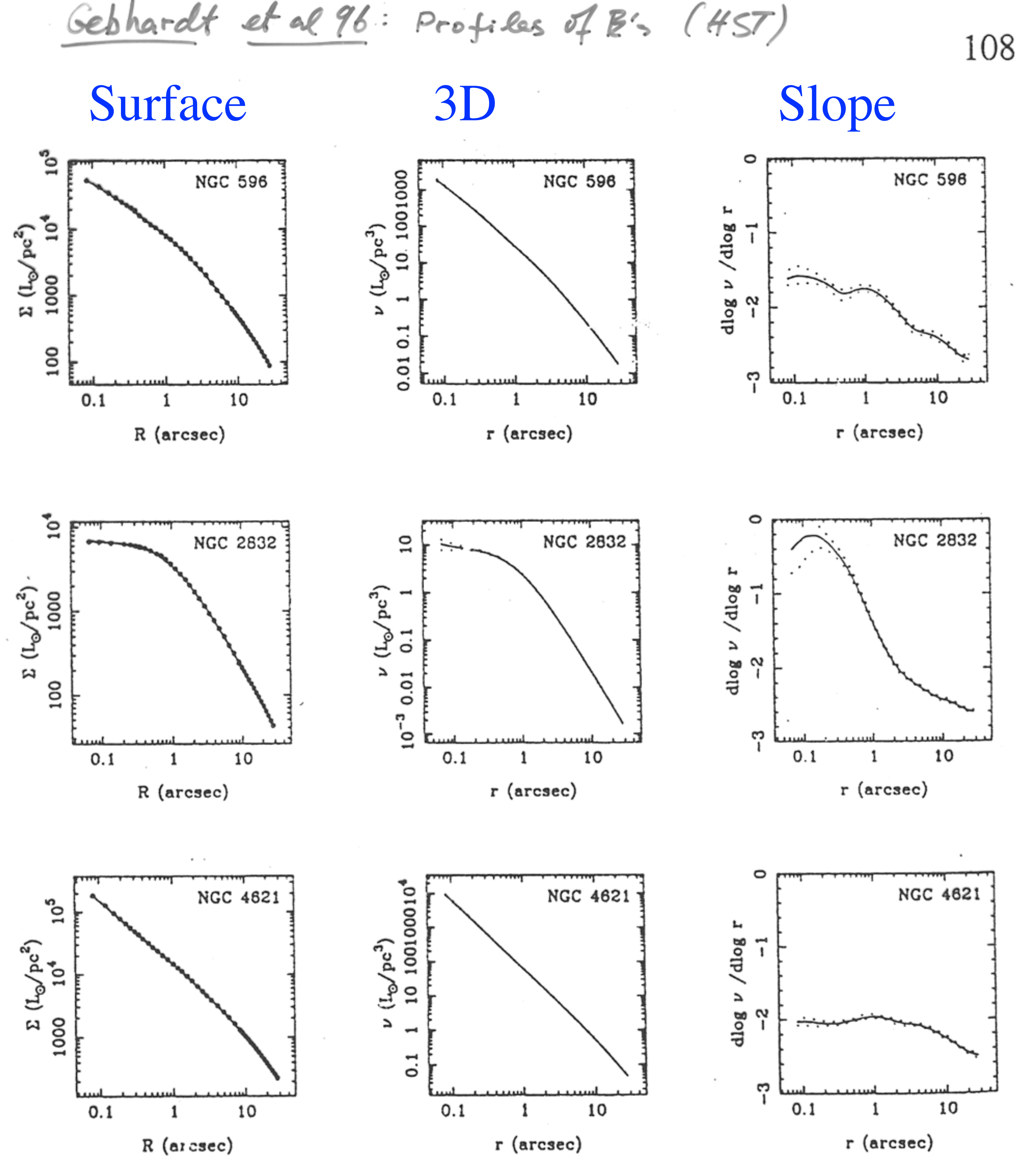
This function fits many Es and bulges over the central 10″.

Dichotomy: Cores vs. No Cores

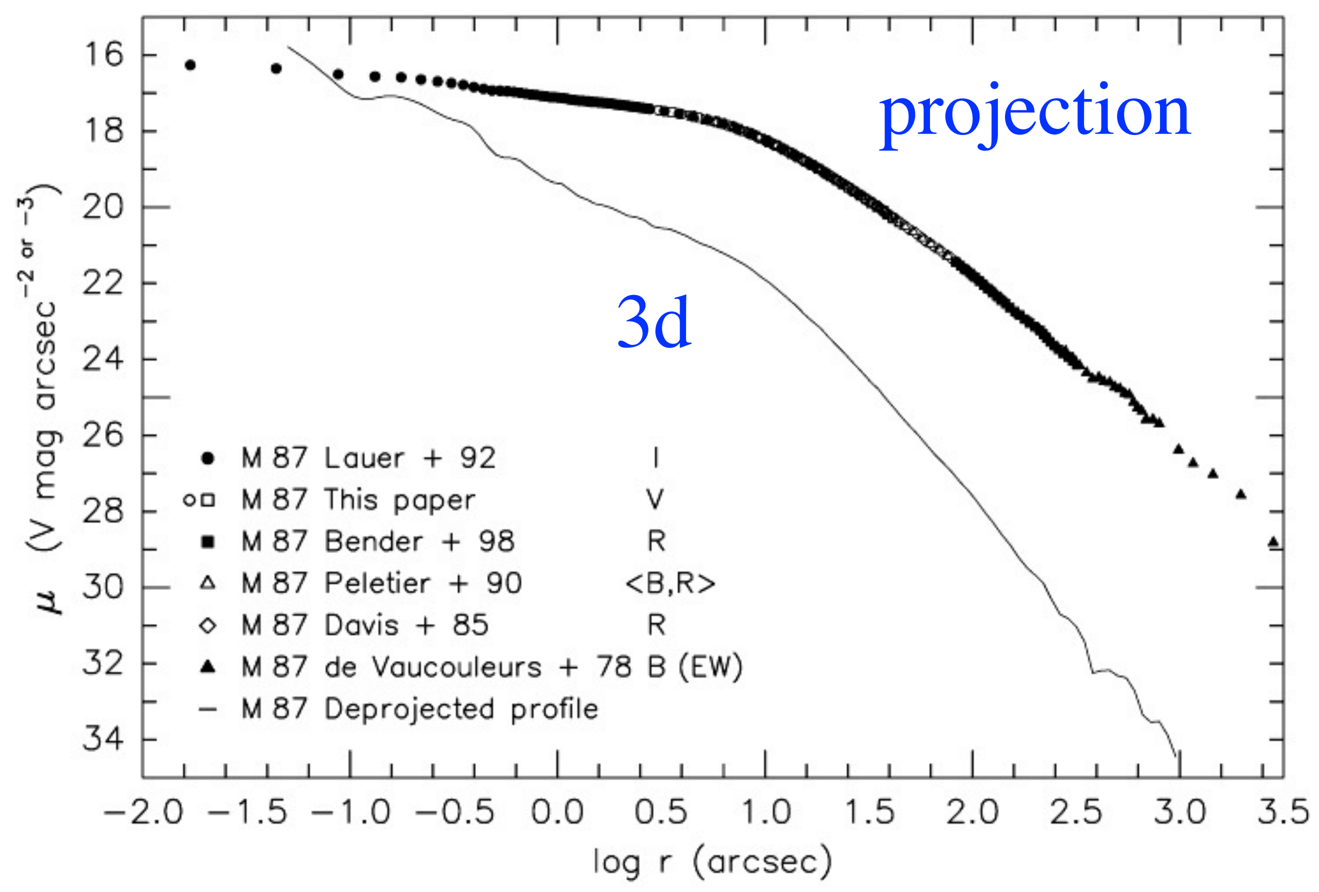


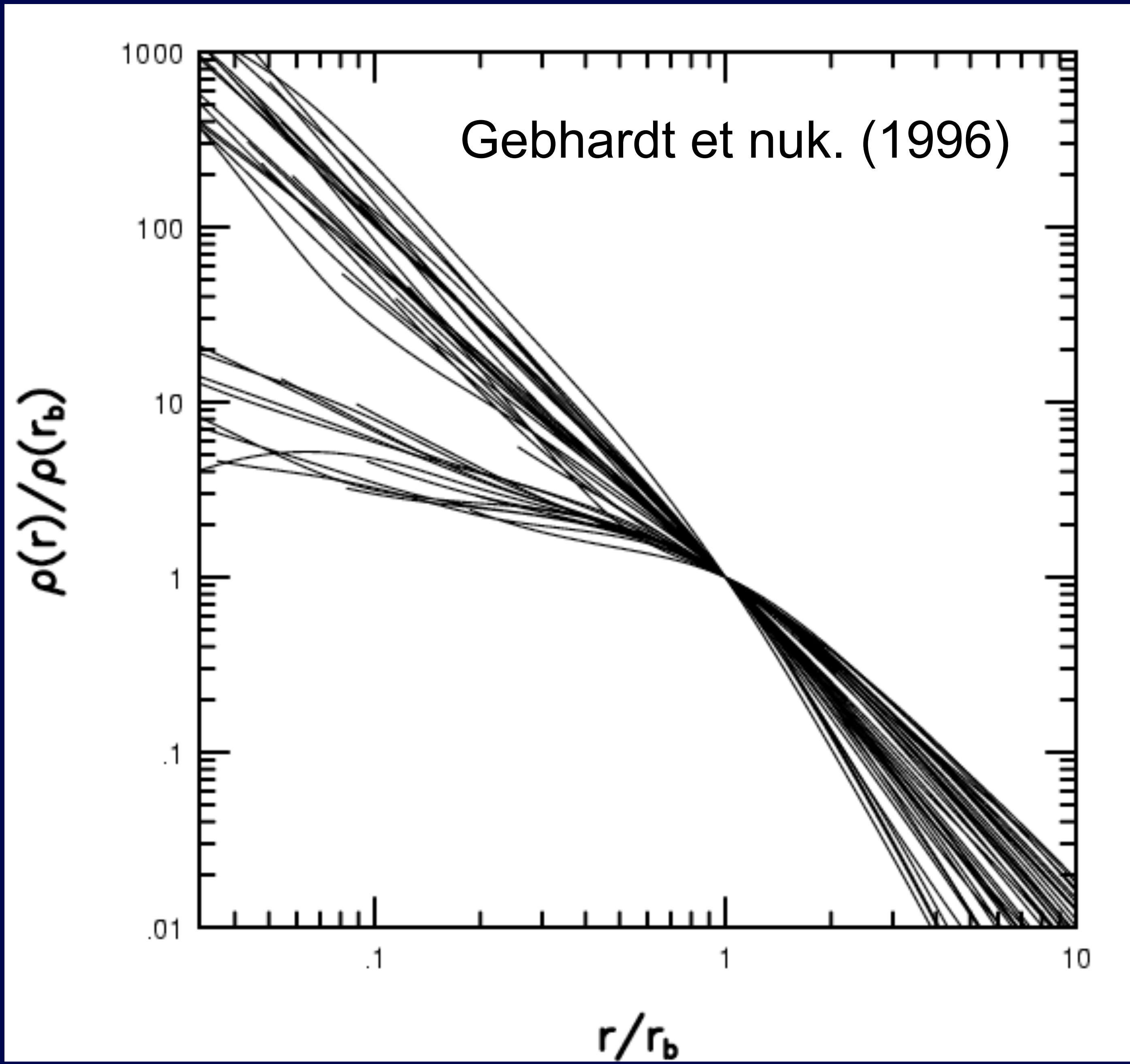
Gebhardt et al 96 (HST): 3D reconstruction.
Note that higher resolution results do not show flat cores.

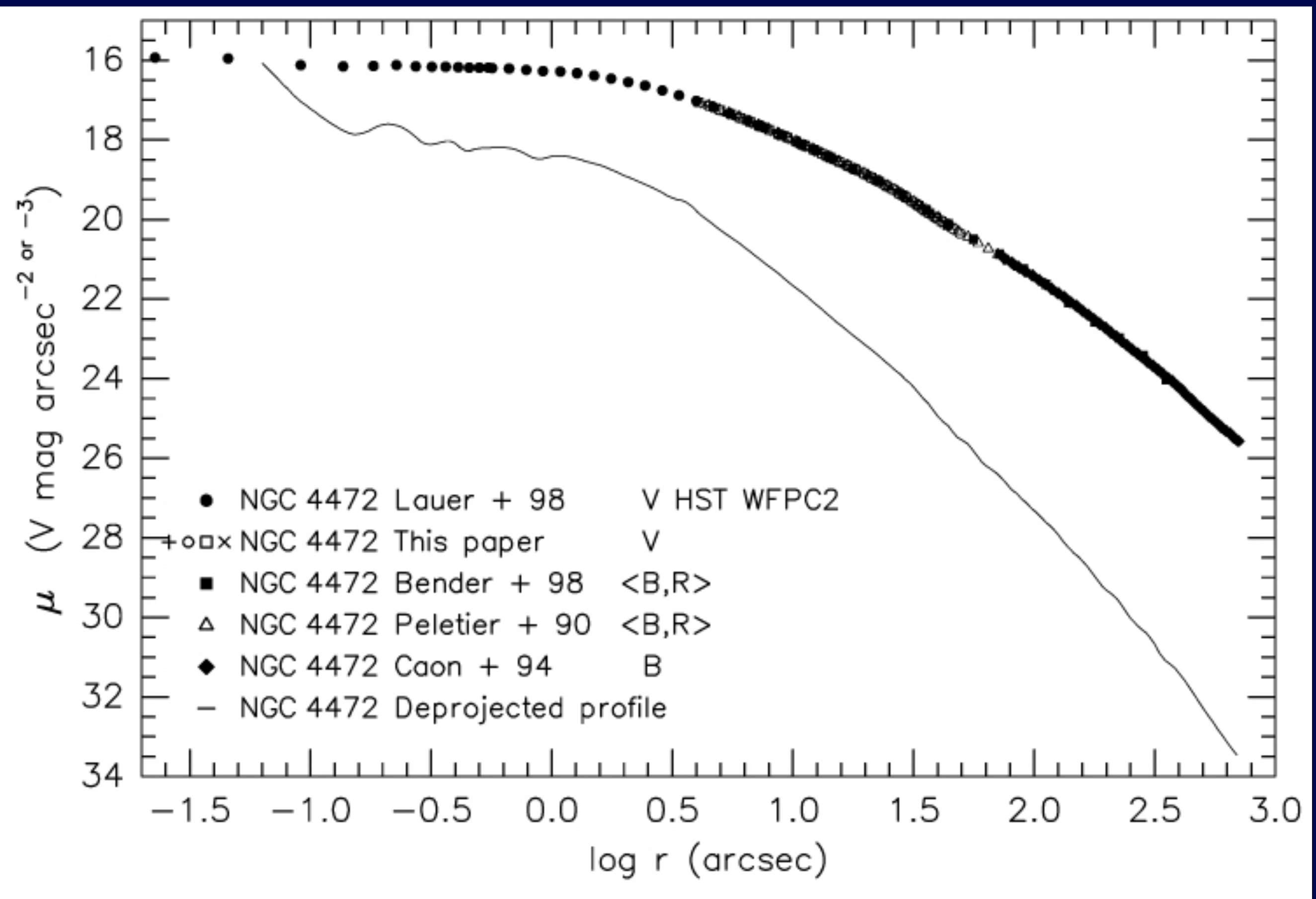
Two types of profiles:
- steep cusps (power-law)
- “cores” -- much flatter



Dichotomy: Cores vs. No Cores







Cores are real breaks
in the volume density profile
(Kormendy 1999).

Surface Photometry of Virgo Cluster Ellipticals

Kormendy et al 2006

Surface brightness profiles for all elliptical galaxies in the Virgo cluster. HST data are combined with new ground-based, wide-field measurements and with published data for each galaxy.

Sources of Published Profiles:

- Lauer et nuk. 1995
- Peletier et al. 1995
- Caon et al. 1990
- Bender et al. 2005
- de Vaucouleurs (various)
- Davies et al. 1985
- Kormendy (various CFHT)
- Lauer 1985
- Dressler 1987

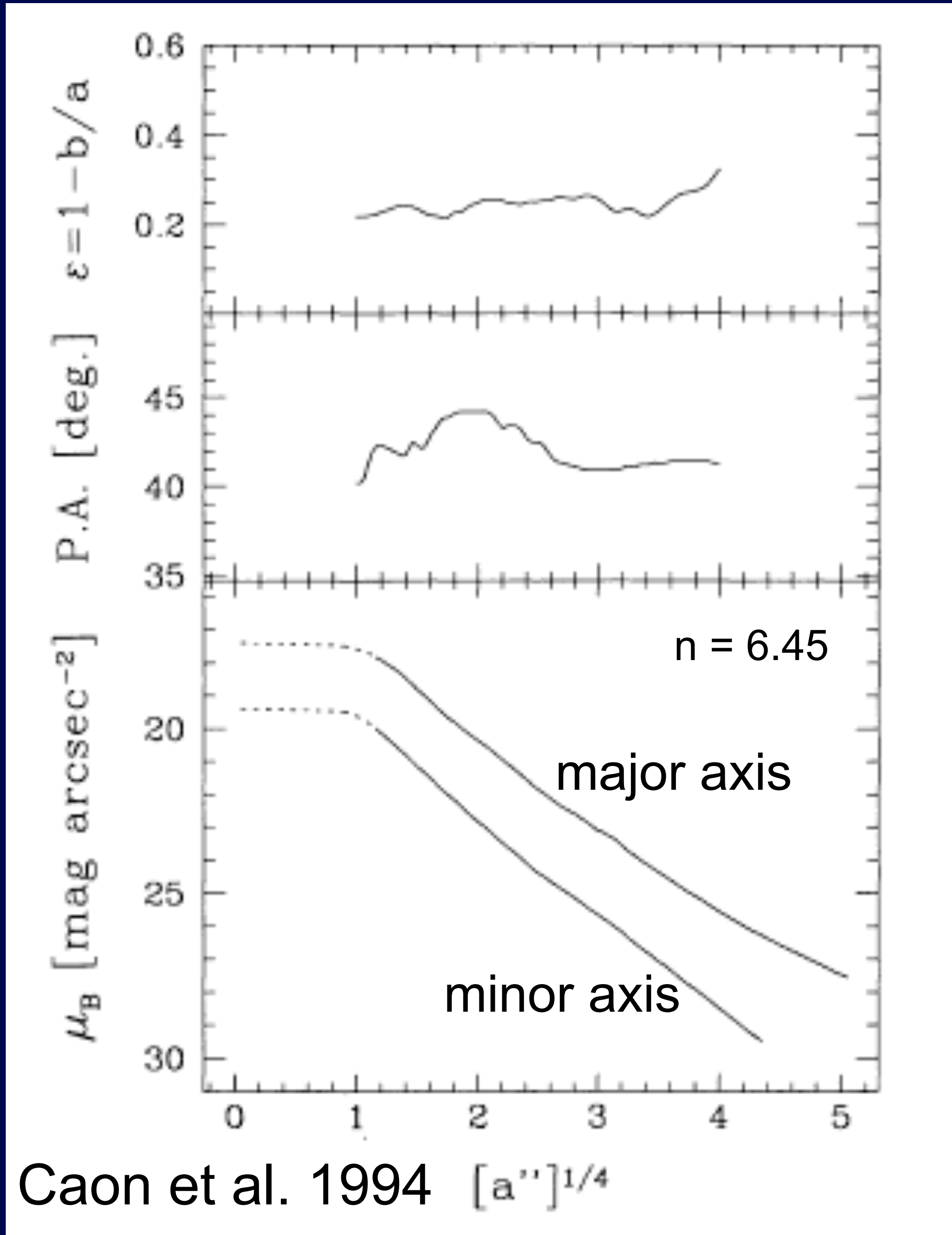
Sources of Measured Profiles:

- McDonald 0.8 m: 1.4″ pixel^{-1} over 46′
- CFHT 12K (Kormendy & Wainscoat): 0.21″ pixel^{-1} over 42′ x 28′
- One AO image from CFHT: 0.035″ pixel^{-1}
- HST ACS Virgo cluster survey (Côté et al.): 0.049″ pixel^{-1} over 3.3′
- SDSS

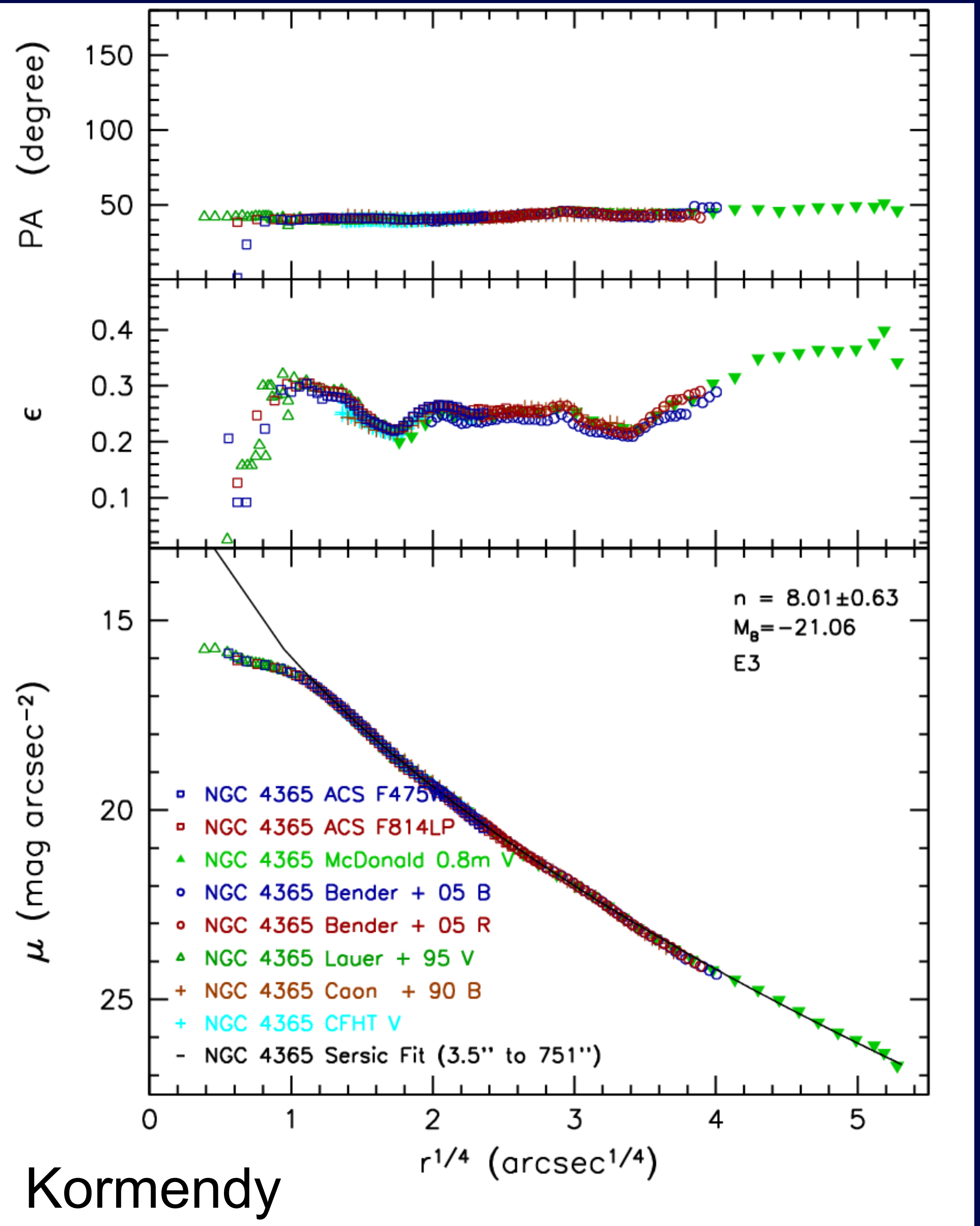
Composite Profiles

We combine multiple data sets for each galaxy to provide large dynamic range :

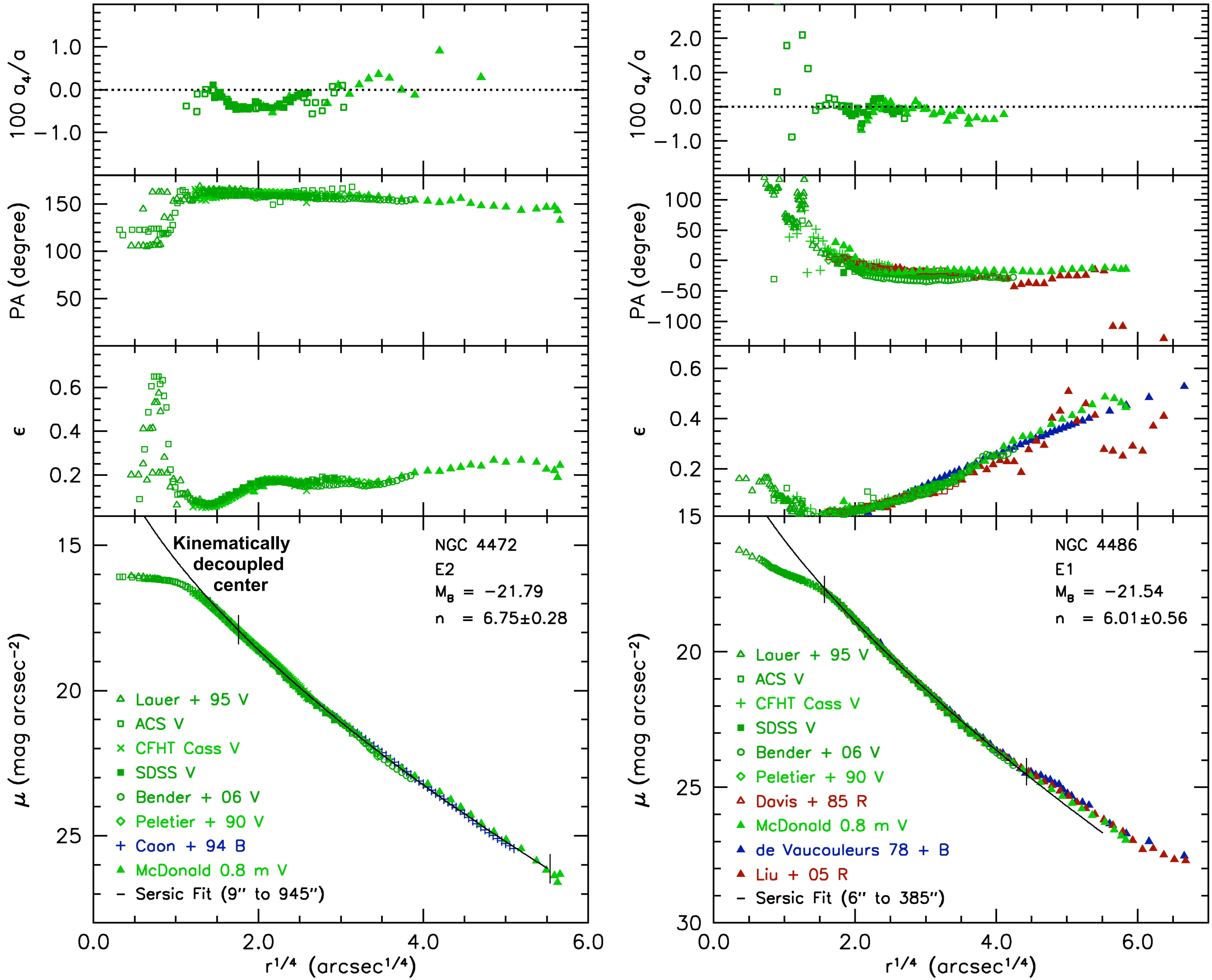
- reduced systematic errors (e. g., sky subtraction)
- more accurate values of μ_e , r_e, n (as shown by tight parameter correlations)
- more reliable detection of diagnostic departures from Sérsic fits



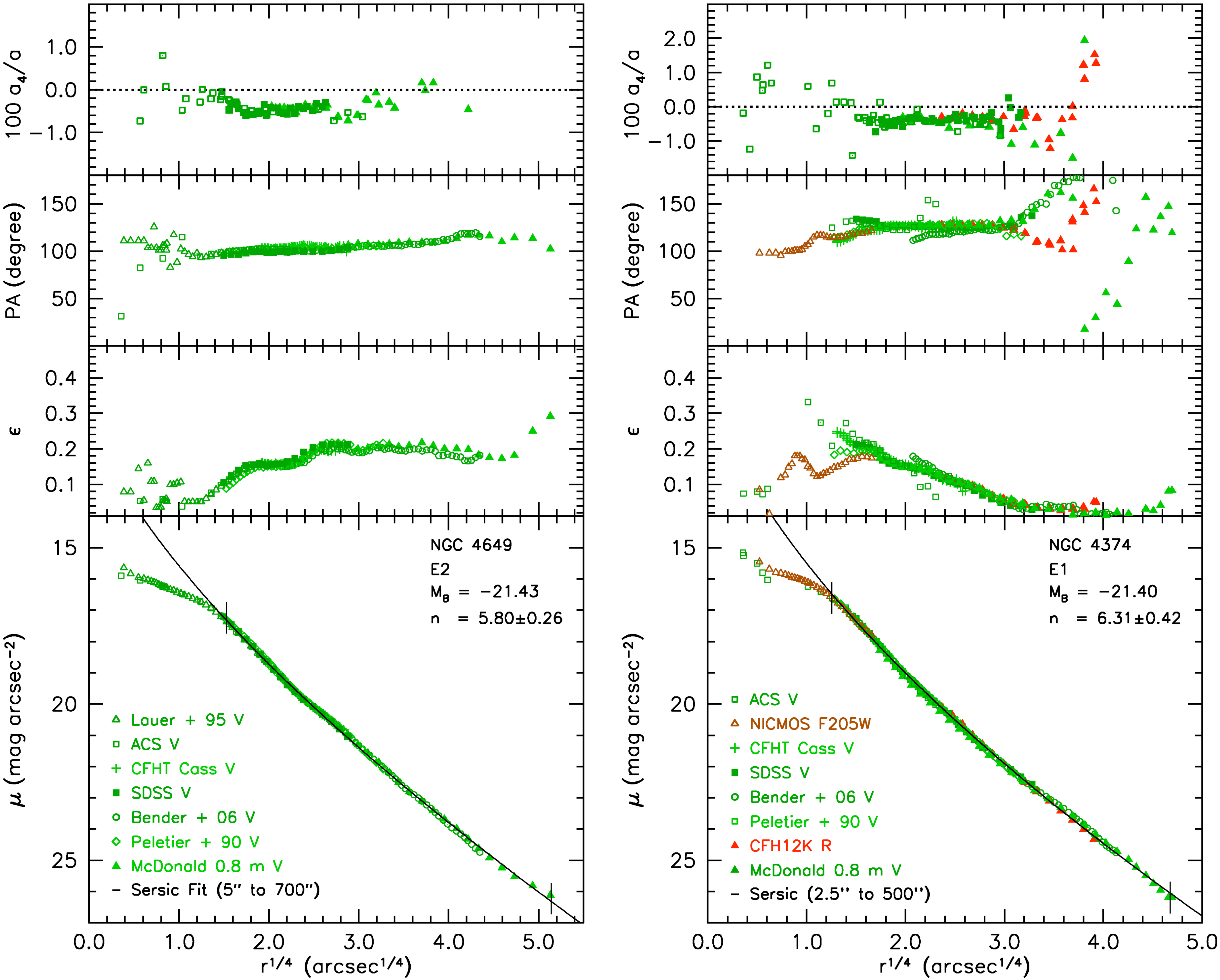
Caon et al. 1994



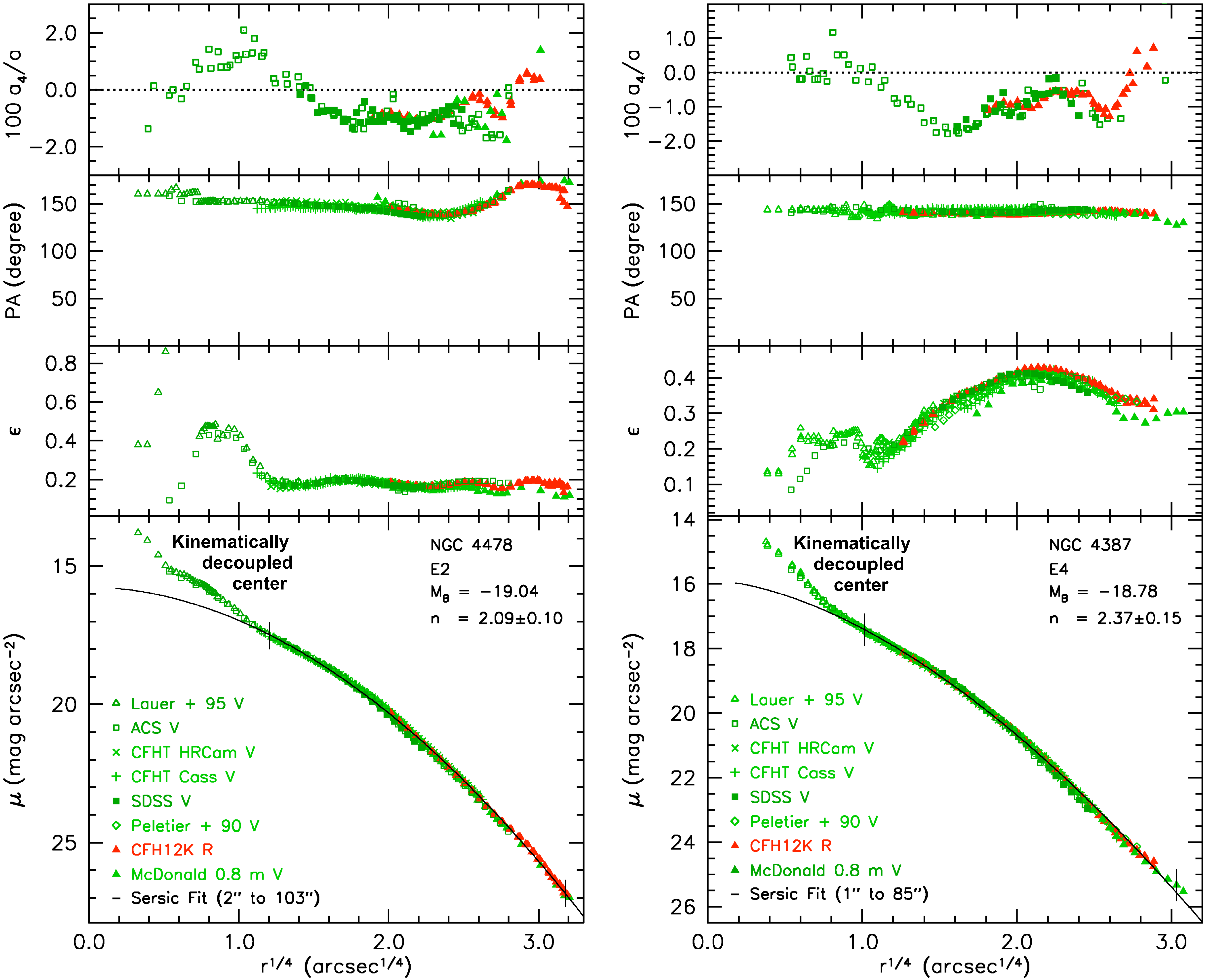
Kormendy



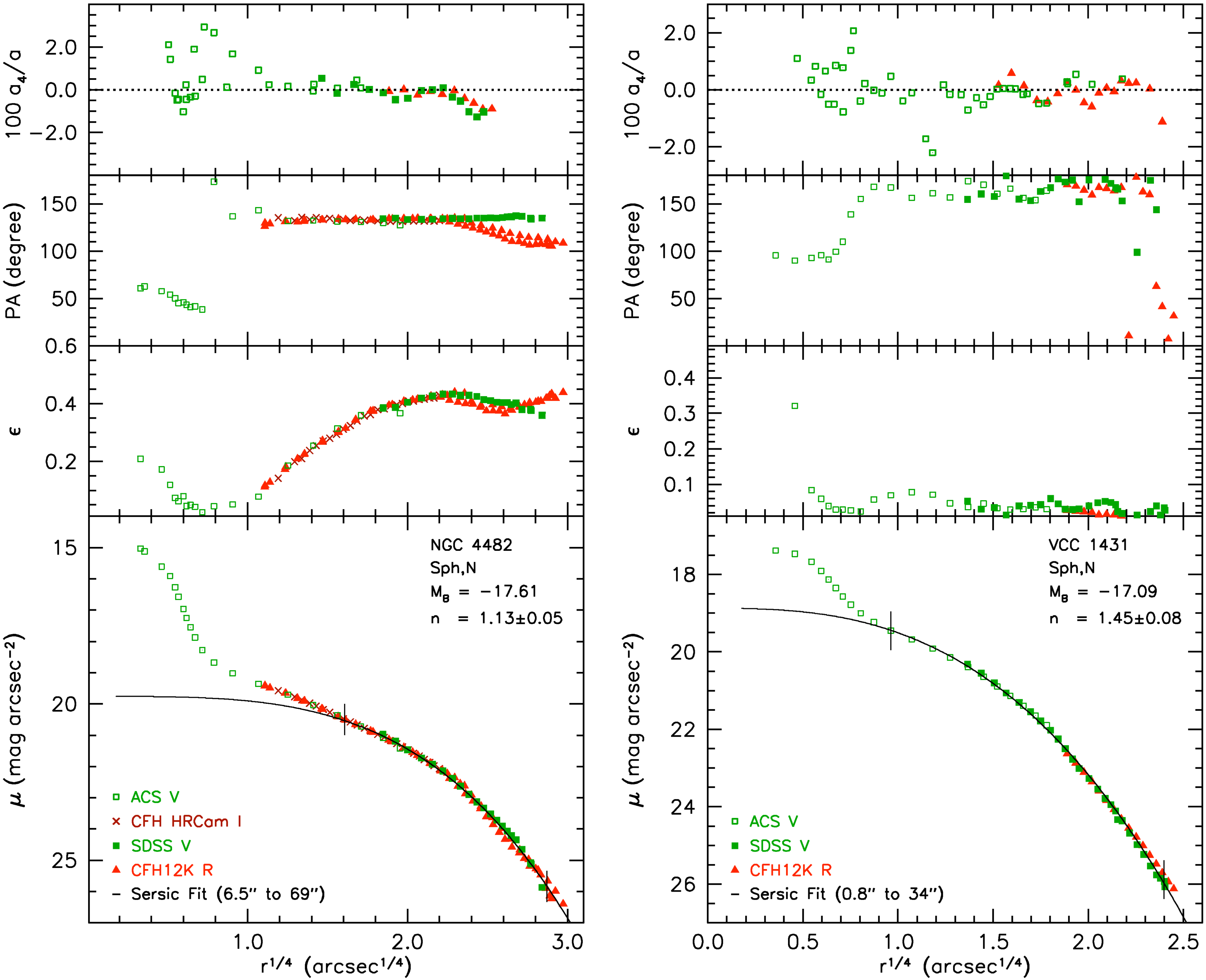
100 a4/a
PA (degree)
ε
μ (mag arcsec−2)
r1/4 (arcsec1/4)
Kinematically decoupled center
NGC 4472
E2
MB = −21.79
n = 6.75±0.28
Lauer + 95 V
ACS V
CFHT Cass V
SDSS V
Bender + 06 V
Peletier + 90 V
Caon + 94 B
McDonald 0.8 m V
Sersic Fit (9″ to 945″)
NGC 4486
E1
MB = −21.54
n = 6.01±0.56
Lauer + 95 V
ACS V
CFHT Cass V
SDSS V
Bender + 06 V
Peletier + 90 V
Davis + 85 R
McDonald 0.8 m V
de Vaucouleurs 78 + B
Liu + 05 R
Sersic Fit (6″ to 385″)



NGC 4649
E2
M_B = −21.43
n = 5.80±0.26
Lauer + 95 V
ACS V
CFHT Cass V
SDSS V
Bender + 06 V
Peletier + 90 V
McDonald 0.8 m V
Sersic Fit (5'' to 700'')
NGC 4374
E1
M_B = −21.40
n = 6.31±0.42
ACS V
NICMOS F205W
CFHT Cass V
SDSS V
Bender + 06 V
Peletier + 90 V
CFH12K R
McDonald 0.8 m V
Sersic (2.5'' to 500'')
100 a_4/a
PA (degree)
ε
μ (mag arcsec^{-2})
$r^{1/4}$ (arcsec$^{1/4}$)

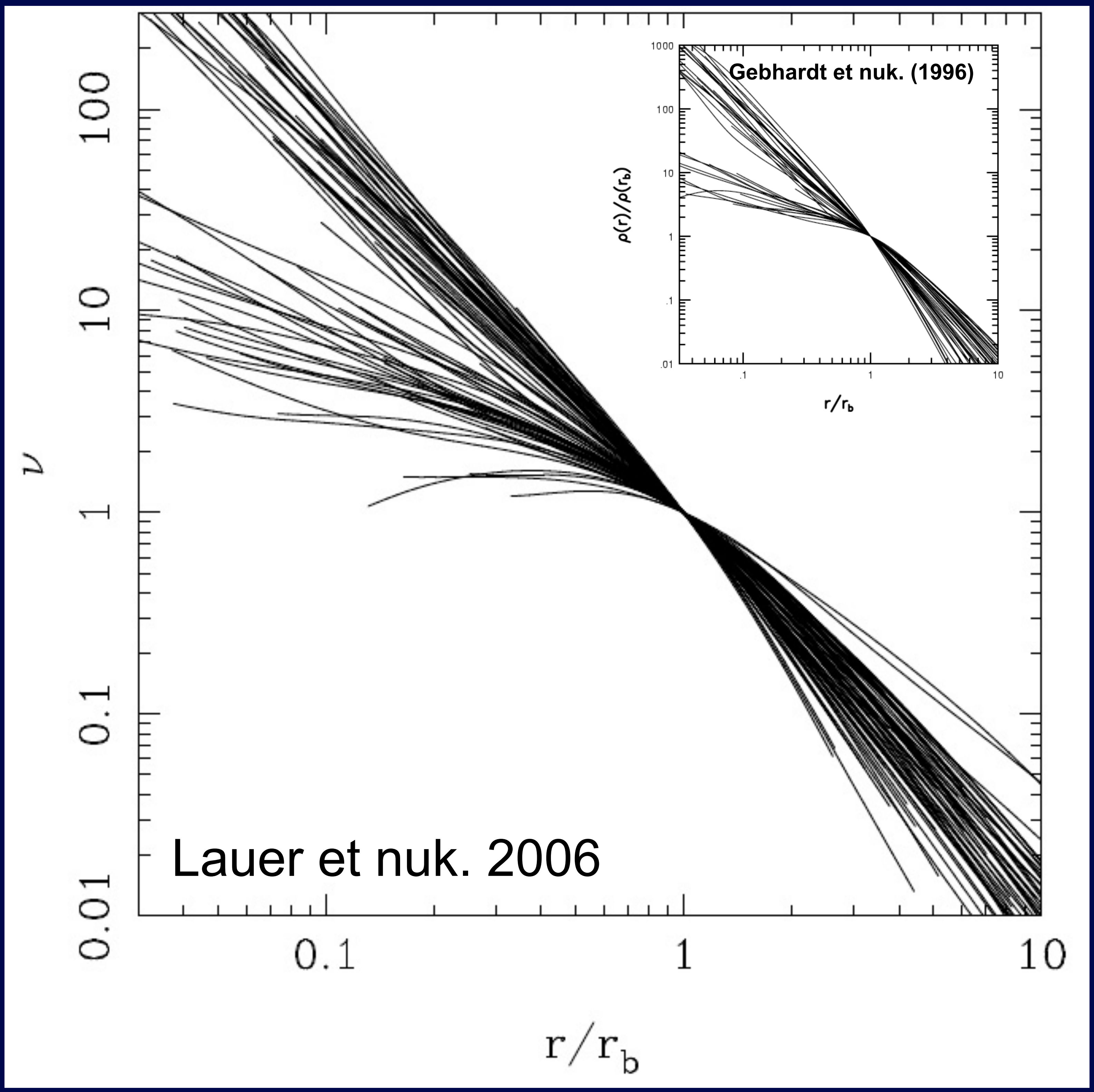


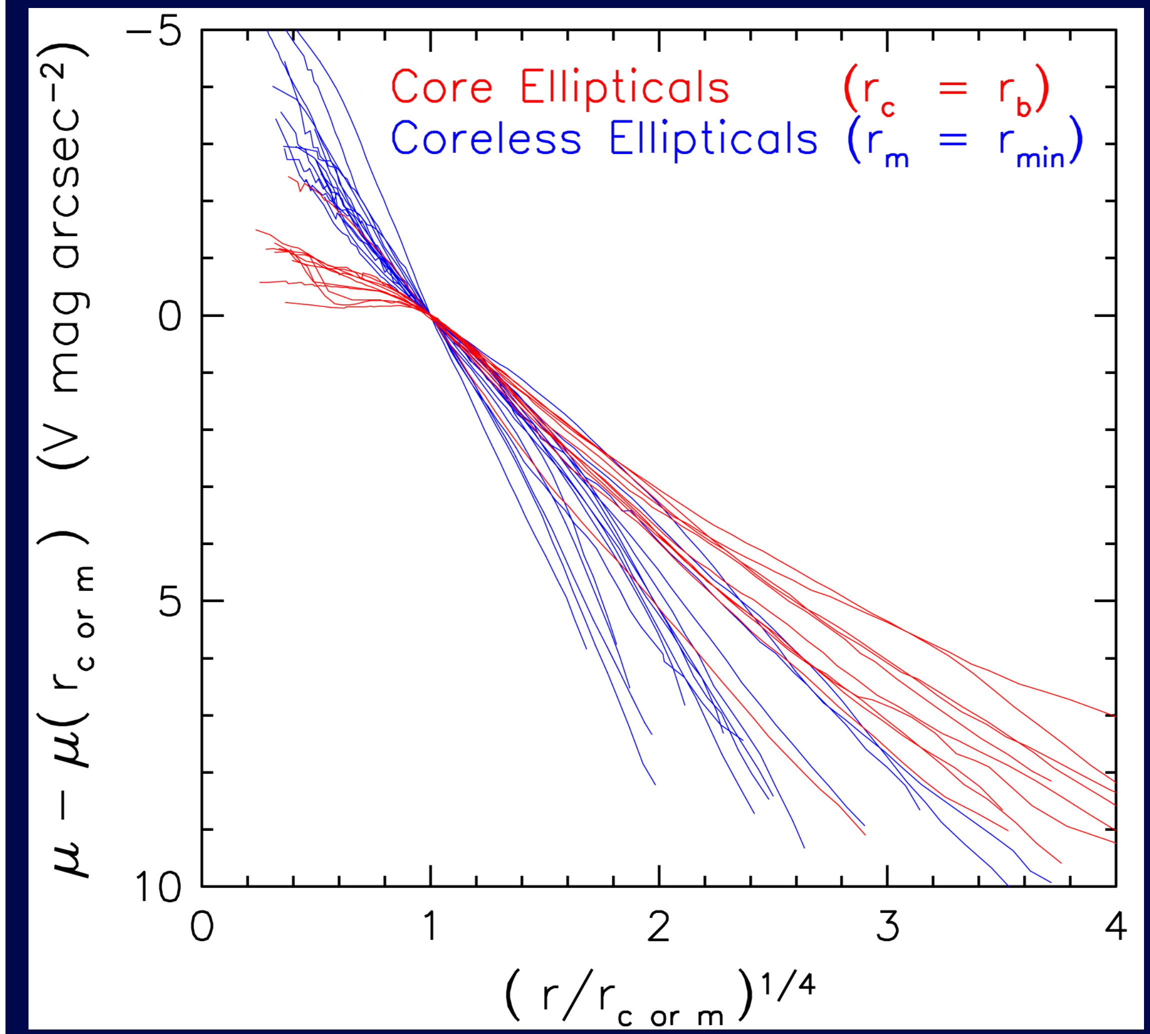
100 a4/a
PA (degree)
ε
μ (mag arcsec−2)
Kinematically decoupled center
NGC 4478
E2
MB = −19.04
n = 2.09±0.10
Lauer + 95 V
ACS V
CFHT HRCam V
CFHT Cass V
SDSS V
Peletier + 90 V
CFH12K R
McDonald 0.8 m V
Sersic Fit (2″ to 103″)
r1/4 (arcsec1/4)
Kinematically decoupled center
NGC 4387
E4
MB = −18.78
n = 2.37±0.15
Lauer + 95 V
ACS V
CFHT HRCam V
CFHT Cass V
SDSS V
Peletier + 90 V
CFH12K R
McDonald 0.8 m V
Sersic Fit (1″ to 85″)
r1/4 (arcsec1/4)


NGC 4482
Sph,N
M_B = −17.61
n = 1.13±0.05
VCC 1431
Sph,N
M_B = −17.09
n = 1.45±0.08
ACS V
CFH HRCam I
SDSS V
CFH12K R
Sersic Fit (6.5″ to 69″)
Sersic Fit (0.8″ to 34″)
100 a_4/a
PA (degree)
ε
μ (mag arcsec⁻²)
$r^{1/4}$ (arcsec$^{1/4}$)

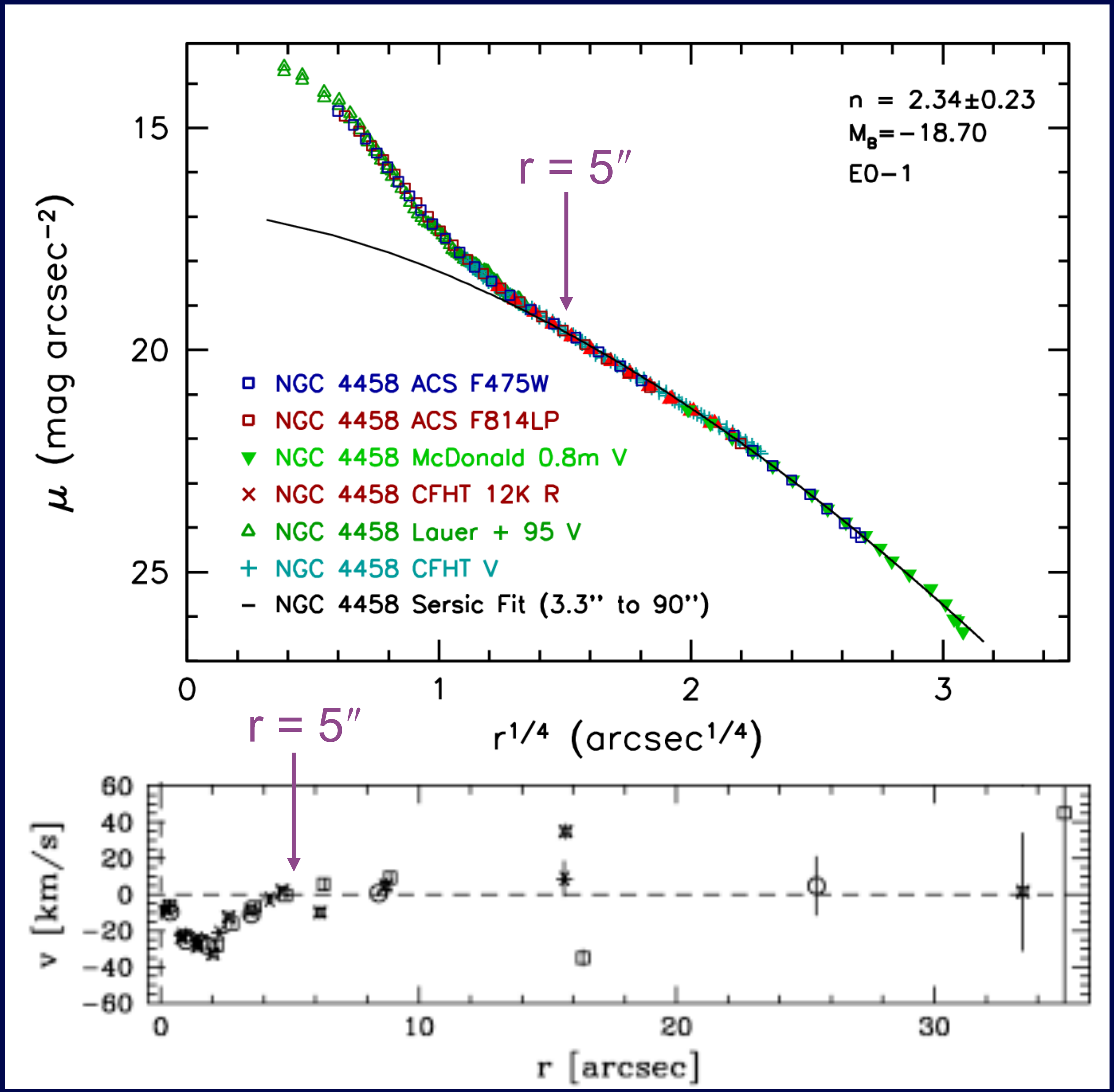
E profiles are bimodal (Gebhardt et nuk. 1996; Lauer et nuk. 2006): either they have cores, or they have “extra light” (Kormendy et al. 2006).

Kormendy et al. 2006





Extra light is often a kinematically decoupled center:

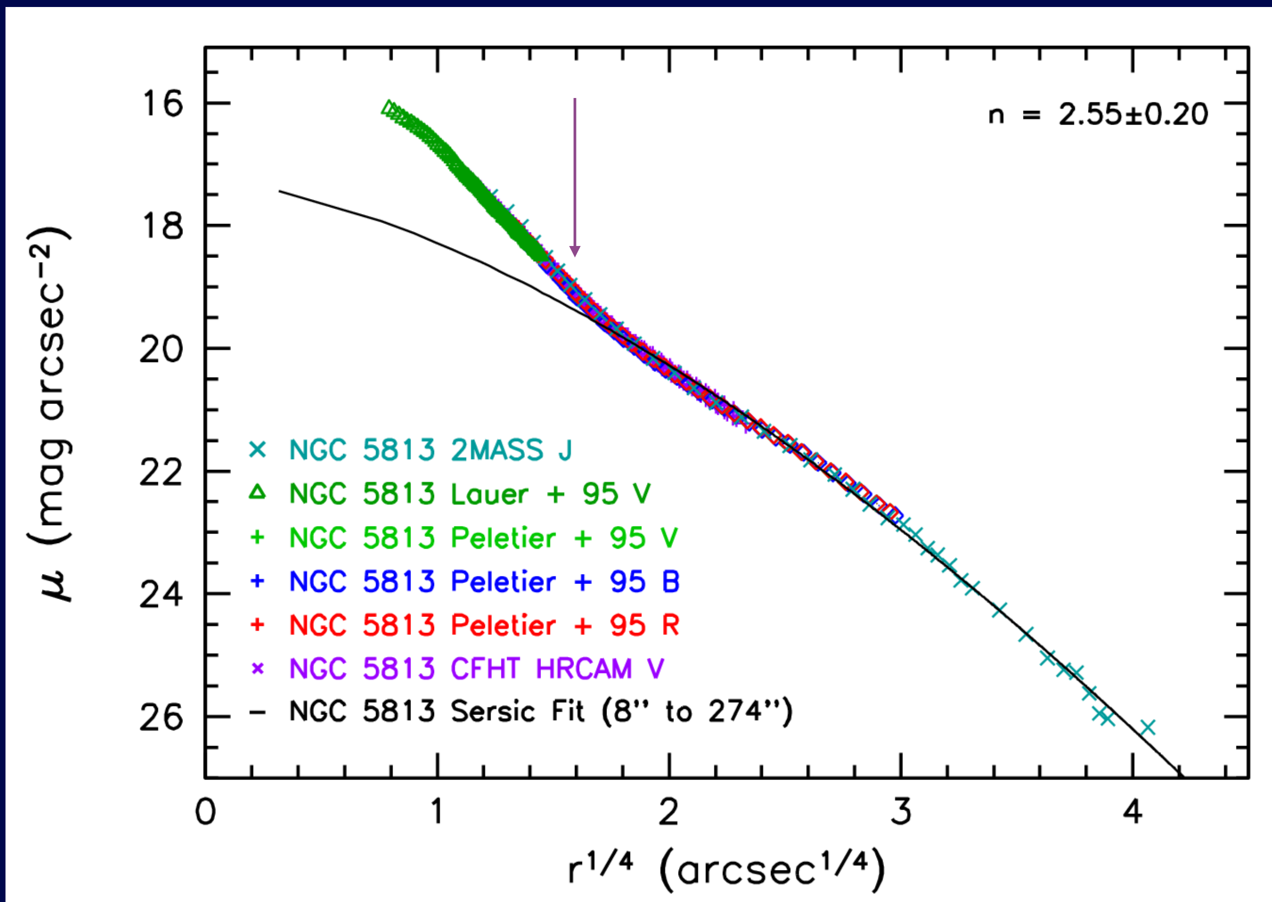


Halliday et al. (2001) : NGC 4458 has a “clear signature of a KDC within r < 5 arcsec.”

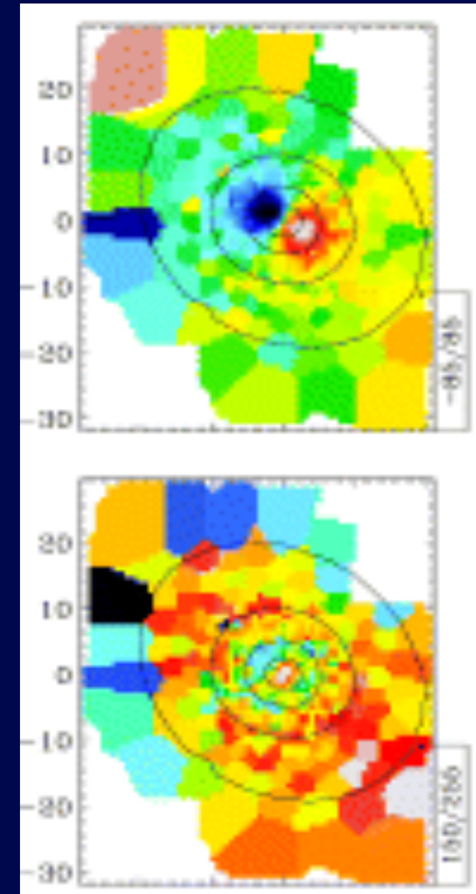
Also in:
NGC 4551
NGC 4478
NGC 4387

This result supports interpretation that the central extra light is a distinct component that originates in an accretion event.

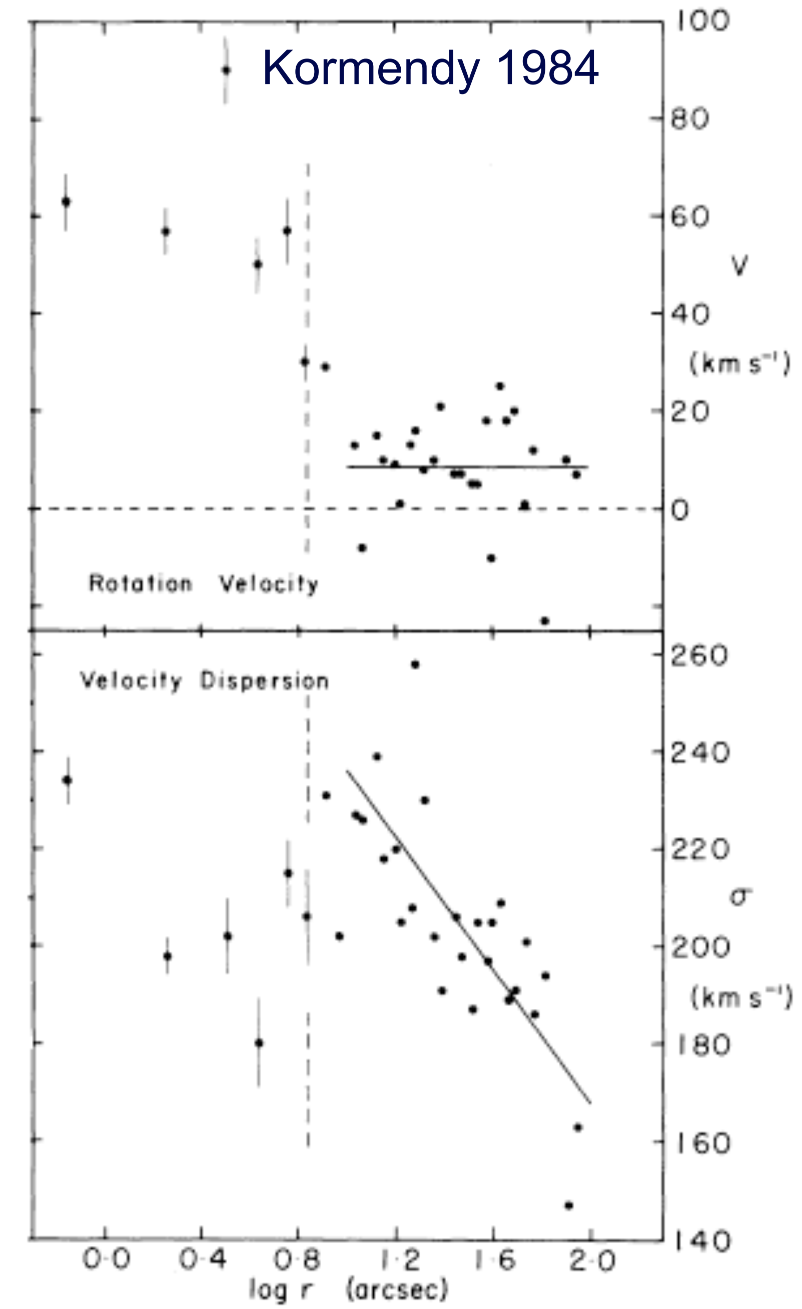
Extra light is often a kinematically decoupled center:



Sauron V,σ fields



Emsellem + (2004)



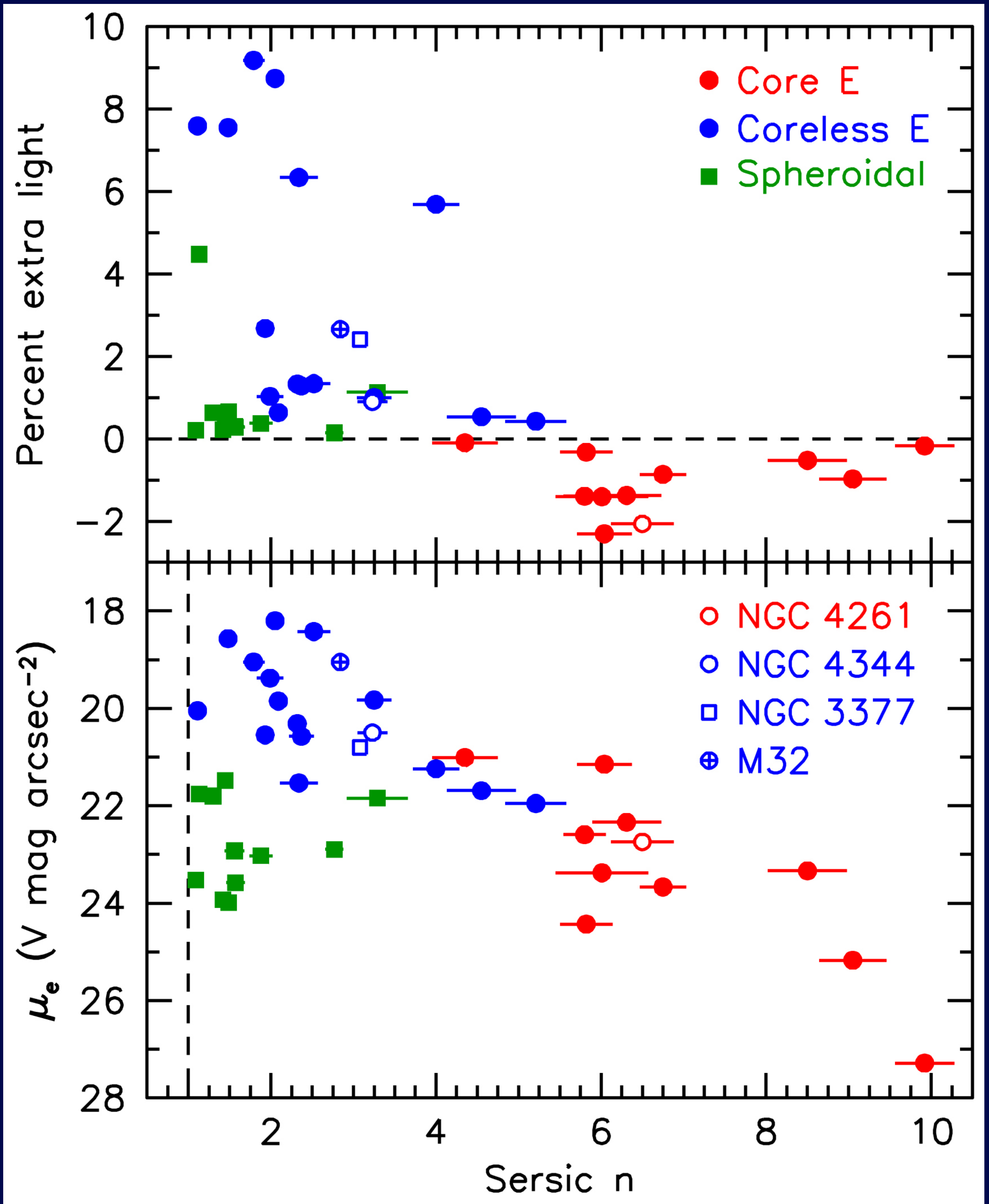
NGC 5813: kinematically decoupled center at $r \le 6 – 9$ arcsec (Efstathiou et al. 1982, Kormendy 1984).

We find extra light at $r \le 8$ arcsec.

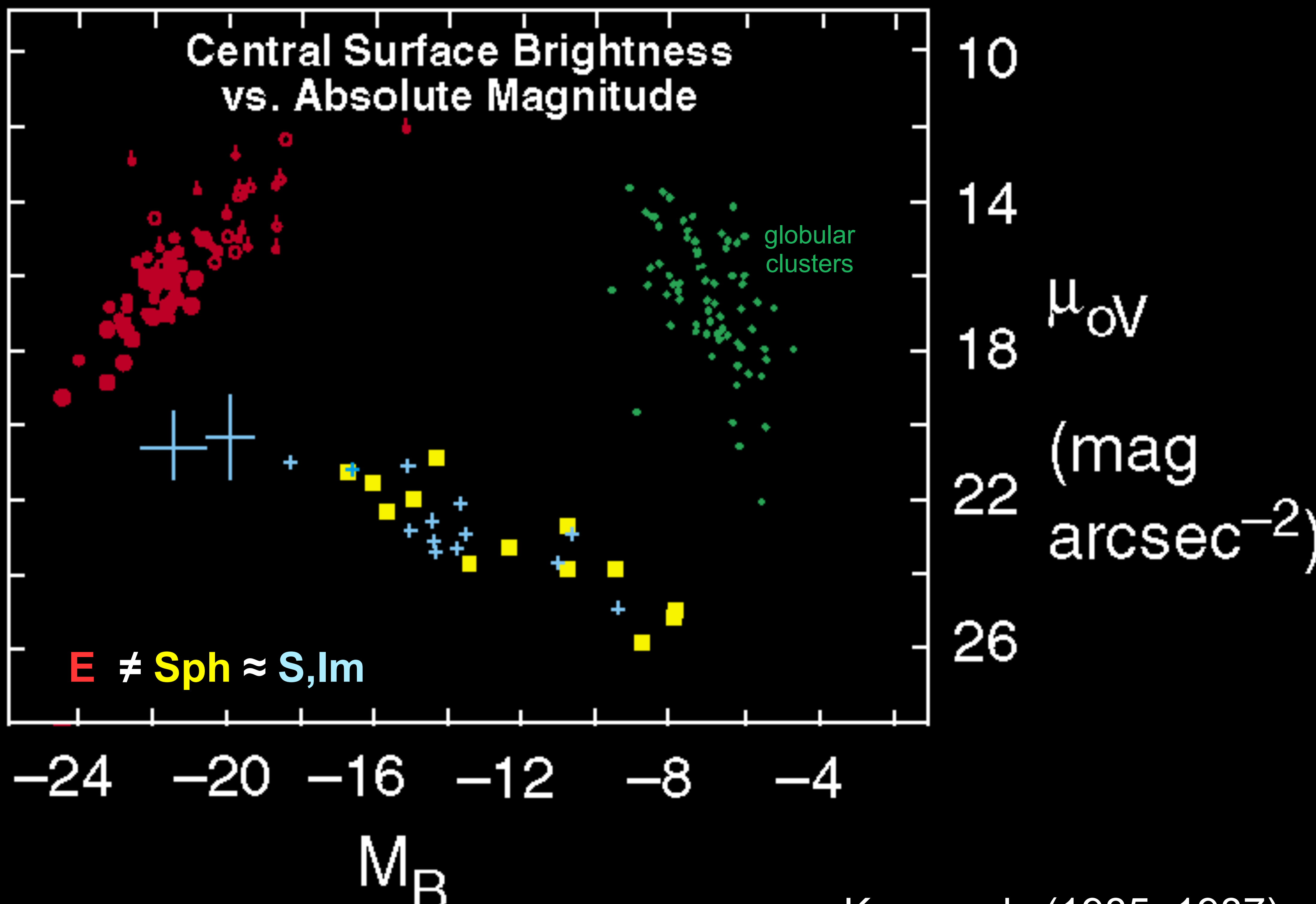
This result supports our interpretation that the central extra light is a distinct component that originates in an accretion event.

Profile Shape (i. e., Sérsic n) Participates in the E Dichotomy

Low-luminosity ellipticals have extra light and n ≤ 4.   Core galaxies have n > 4.



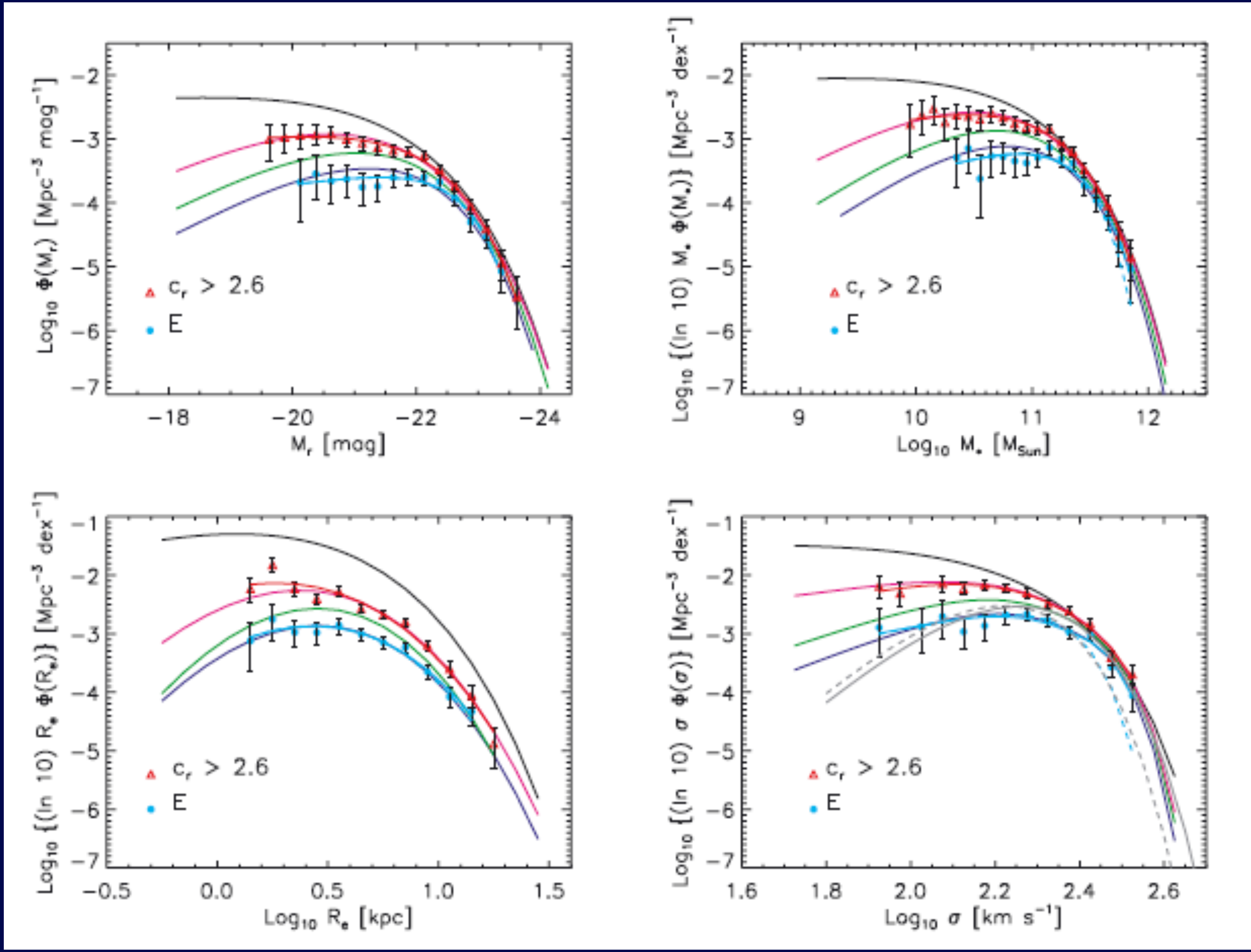
Core “fundamental plane” correlations define what it means to be an elliptical galaxy.



Kormendy (1985, 1987)

SDSS ellipticals

Bernardi et al 2010
Black - all galaxies
Cyan - Elliptical
Cr = concentration index:
ratio of radii containing 90% and 50% of light

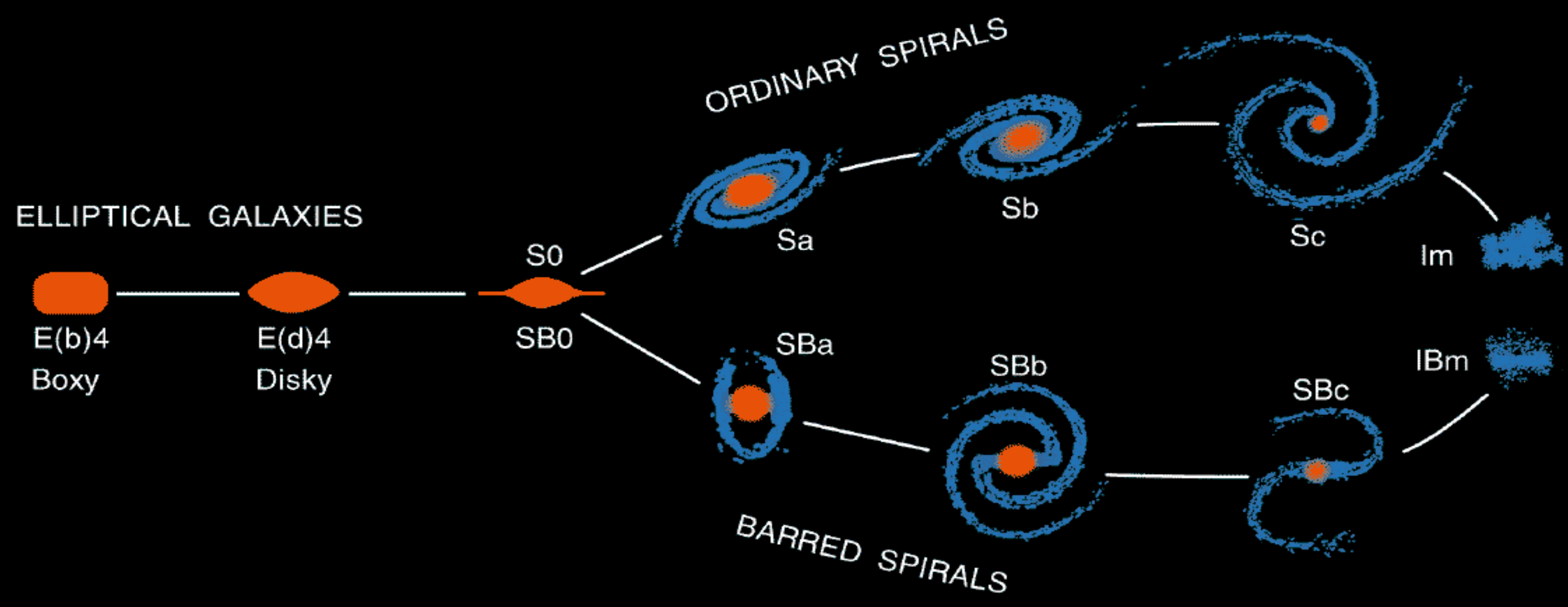


The E Dichotomy: There are two kinds of elliptical galaxies

(Bender 1988; Bender et al. 1989; Kormendy et nuk. 1994; Kormendy & Bender 1996; Gebhardt et nuk. 1996; Tremblay & Merritt 1996; Faber et nuk. 1997)

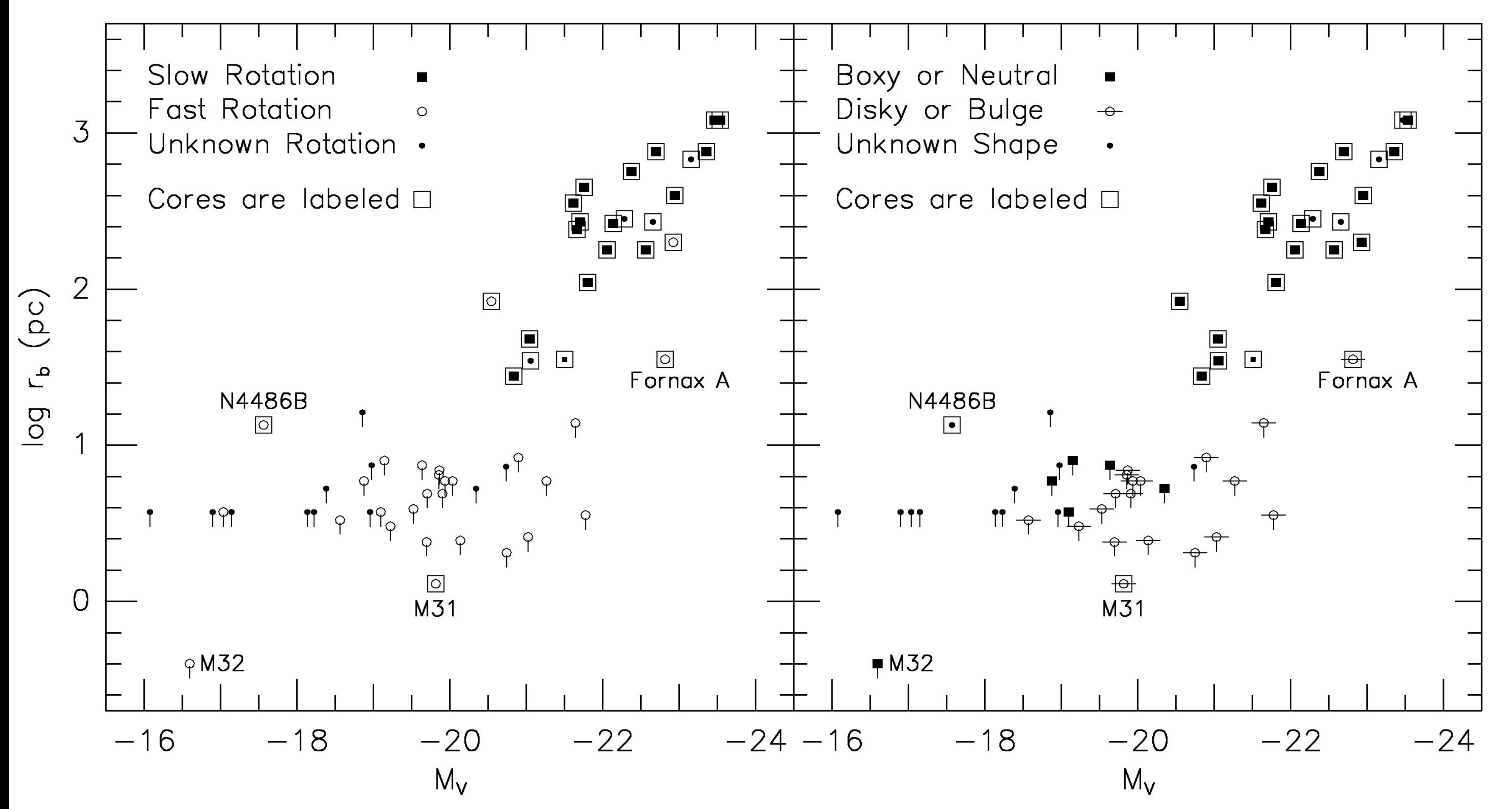
Normal and low luminosity Es
– rotate rapidly,
– are nearly isotropic oblate spheroids,
– are substantially flattened (E3.5),
– are coreless
– have disky-distorted isophotes.

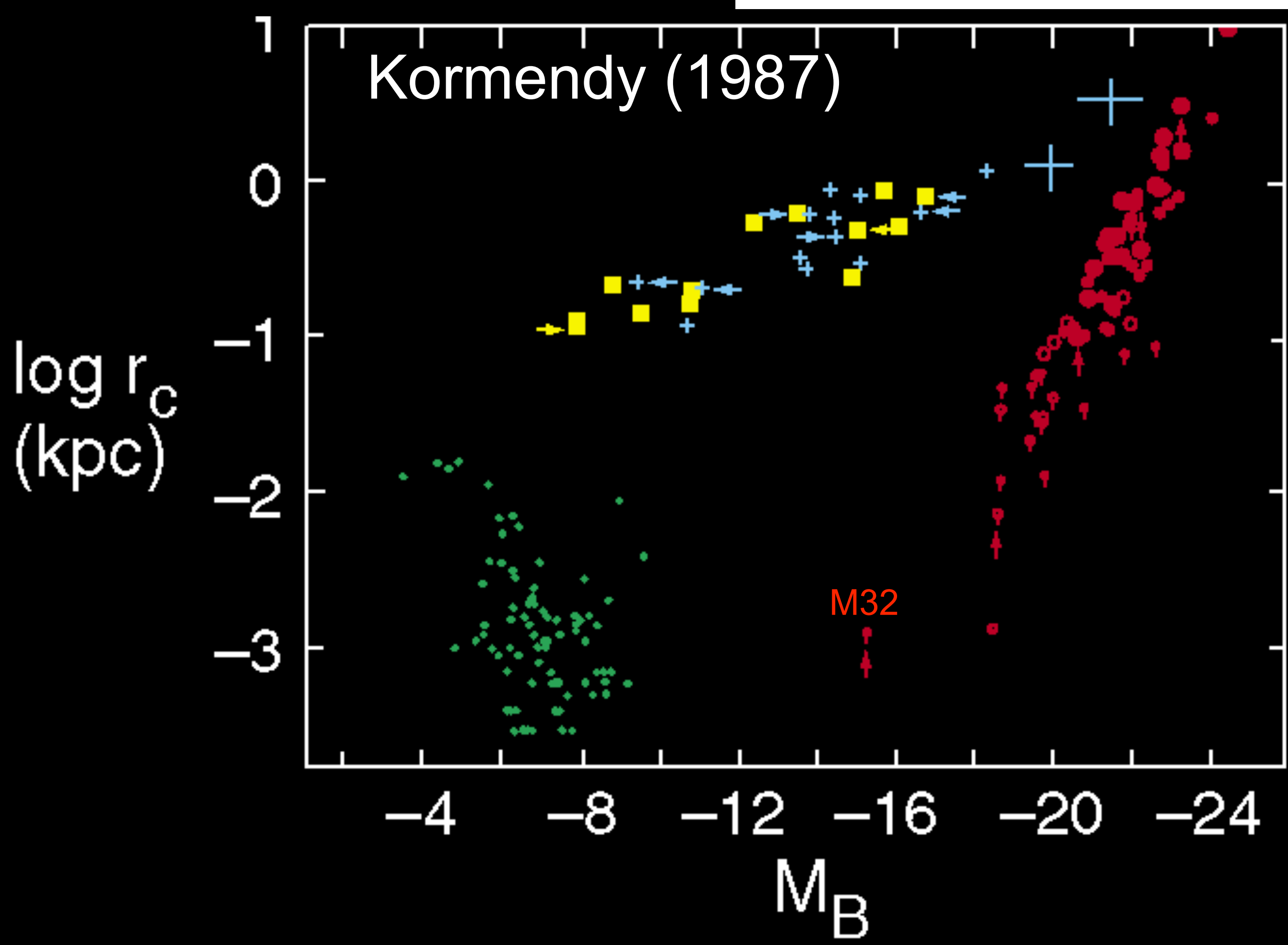
Giant ellipticals
– are essentially non-rotating,
– are anisotropic and triaxial,
– are less flattened (E2.5),
– have cuspy cores,
– have boxy-distorted isophotes.



Kormendy & Bender (1996)

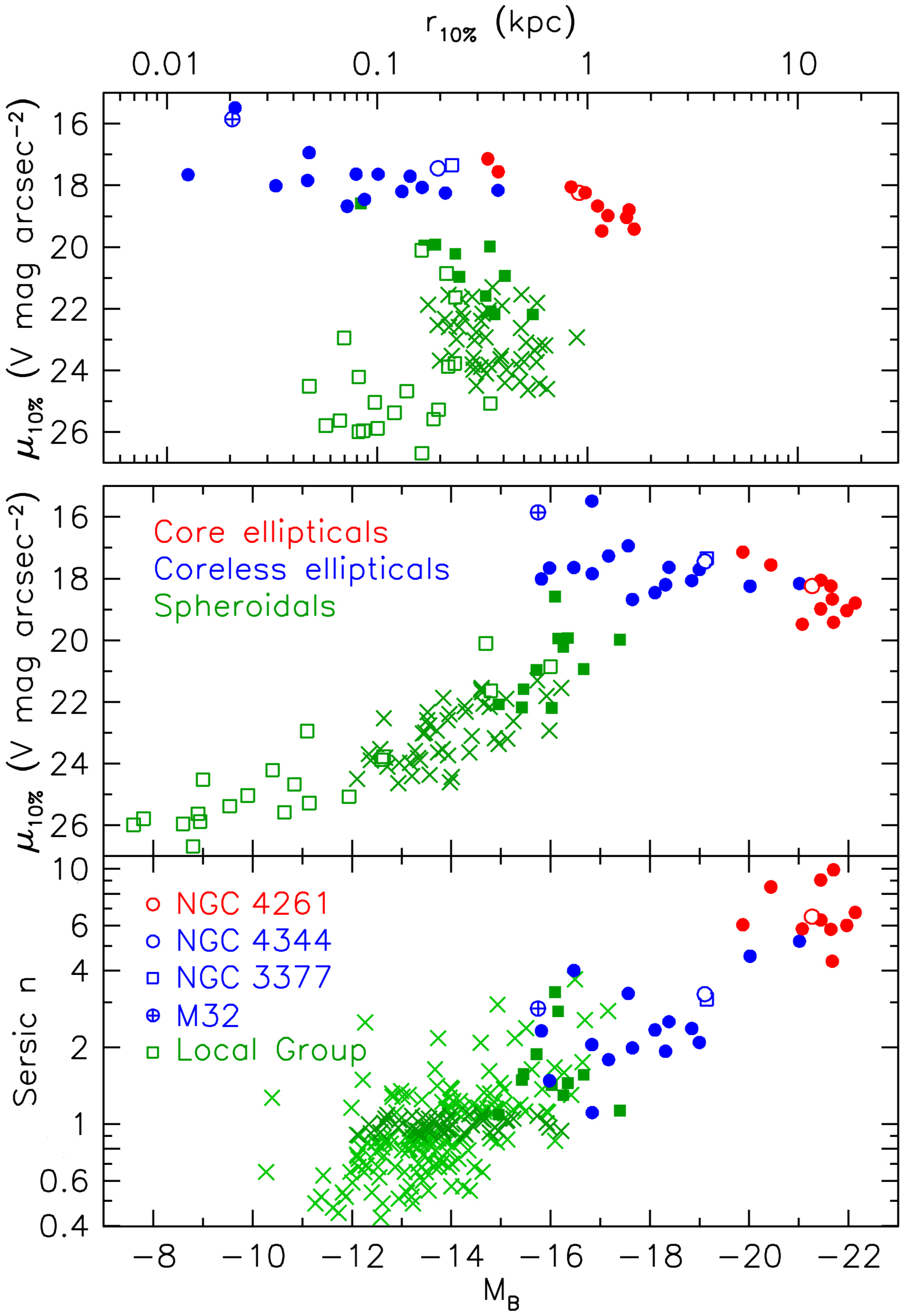
Faber et nuk. (1997);
Kormendy (1999);
also Nieto, Bender, & Surma (1991)





Dichotomy: Cores vs. No Cores

Core galaxies are boxy & slow rotators;
power-law galaxies are disky & fast rotators.



Non-Parametric Version From Virgo Sample (Top 2 Panels)

Here $r_{10\%}$ is the radius that Contains 10% of the light of the galaxy and $\mu_{10\%}$ is the surface brightness at $r_{10\%}$.

Bottom panel: Sérsic n versus absolute magnitude.

Note:
Our Sph galaxies (■) are biased in favor of those that are most like ellipticals.