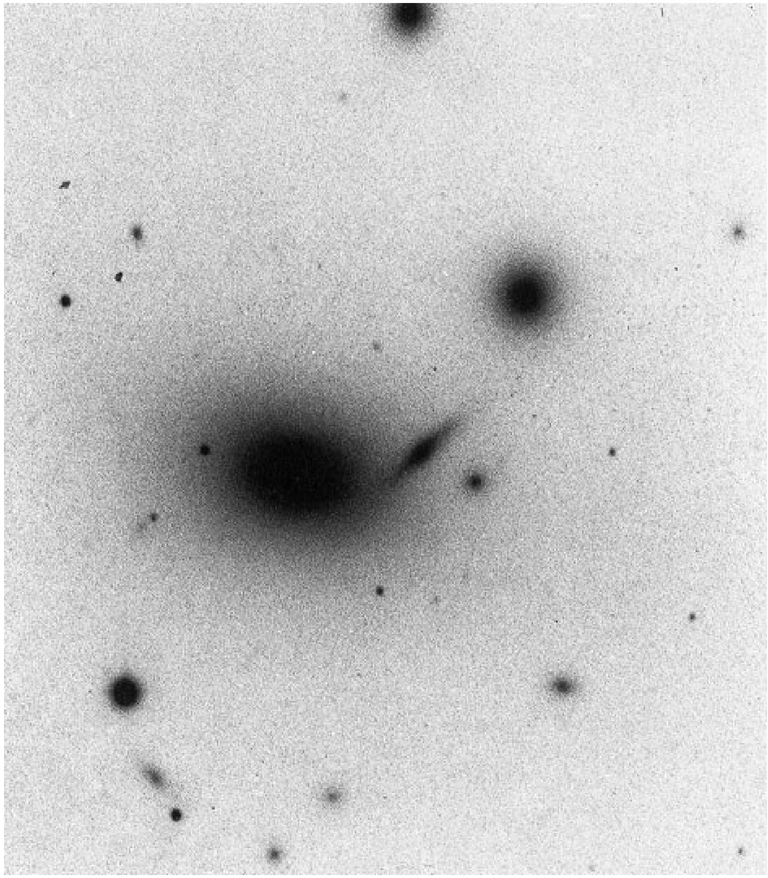
Elliptical Galaxies

NGC 4552 (E0)



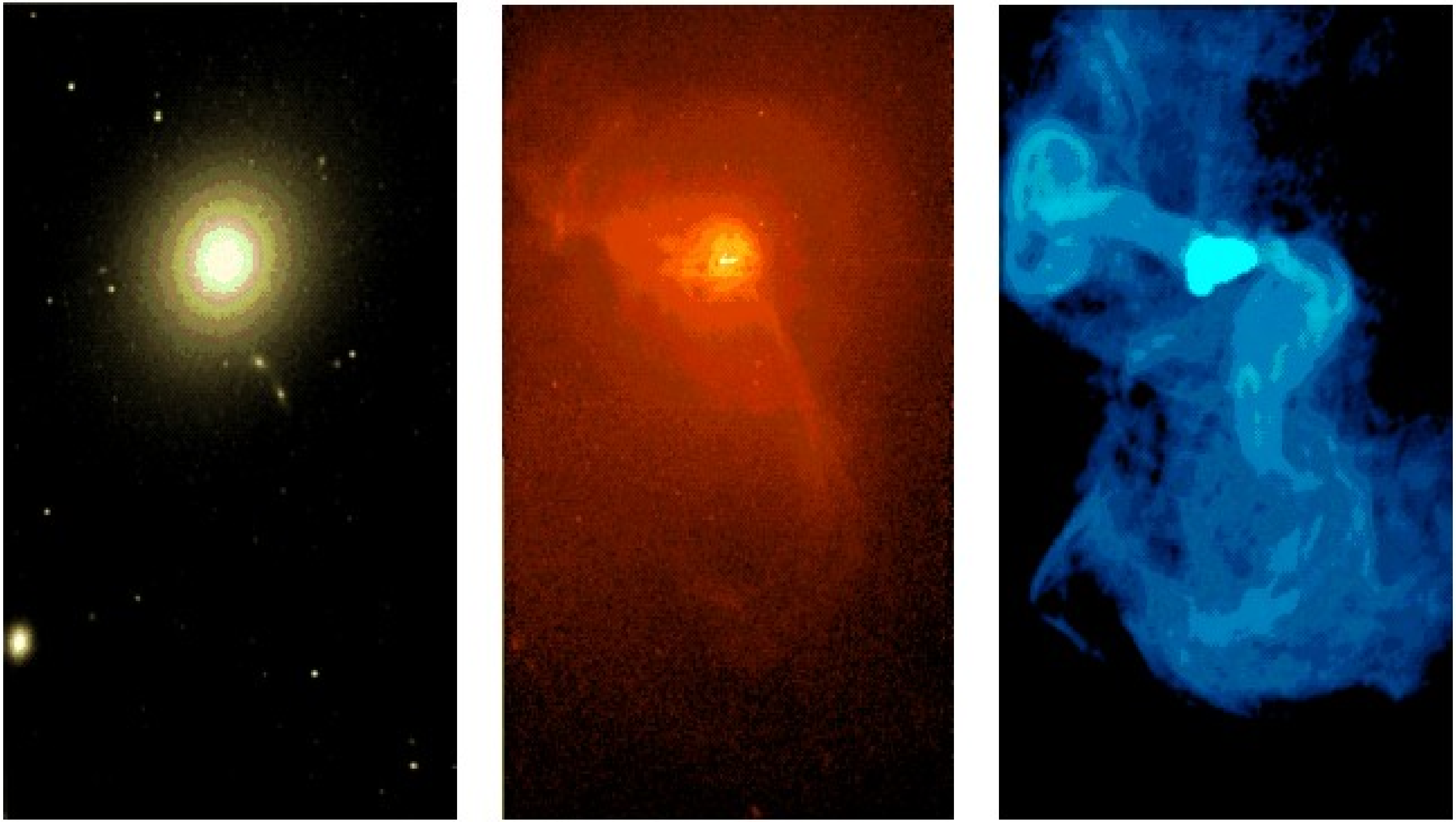
NGC 4889 (E4)

Ellipticals cont.

- Traditional view
  - Ellipticals are simple and dull systems
    - Little or no gas or dusk
    - Old stars
    - Form in a single collapse much like the GC simulation (violent relaxation)
    - Currently in equilibrium

Ellipticals cont.

- Modern view
  - Ellipticals can be complex systems
    - X-ray gas and dust lanes
    - Some have young stars
      - Often in a dynamically distinct disk
    - Some ellipticals have significant rotation
    - Formation is a more complex process, merger of two spirals? Hierarchical accretion of smaller ellipticals? Both?



M87 in the optical X-ray and radio and at the same scale.

Ellipticals cont.

- We can roughly segregate E's by luminosity
  - Luminous: $L>L_*$, $M_B < -20$, $L \approx 2x10^{10} L_\odot$,
  - Mid-sized: $L \sim (0.1-1.0) L_*$, $M_B < -18$ to -20, $L \approx 3x10^{9} L_\odot$,
  - Dwarf: $L<0.1 L_*$, $M_B > -18$, $L<3x10^{9} L_\odot$,
- Unlike disk galaxies once you have measured the luminosity of an elliptical you can predict the other properties very accurately!

Ellipticals cont.

- Luminosity profiles (1D):
  - Sersic profile: $I(r) = I(r_e) \exp\{-b(r/r_e)^{1/n} - 1\}$
  - r_e = effective radius which includes half the light (this defines the constant b), and $I(r_e)$ is the surface brightness at r_e
  - Typical elliptical galaxies have n=4, or follow an $r^{1/4}$-law or “de Vaucouleurs’ law” (de Vaucouleurs1948)
    - $I(r) = I(r_e) \exp\{-7.67\ (r/r_e)^{1/4} - 1\}$

Ellipticals cont.

- The de Vaucouleurs' law
  - provides good description for surface brightness of mid to bright ellipticals outside the center
  - cD galaxies have an "outer envelope" of extended light
- Ellipticals show 2D symmetry
  - Some have weak ripples, shells, other fine structure (remnants of mergers?)
  - Also boxy and/or disky isophotes

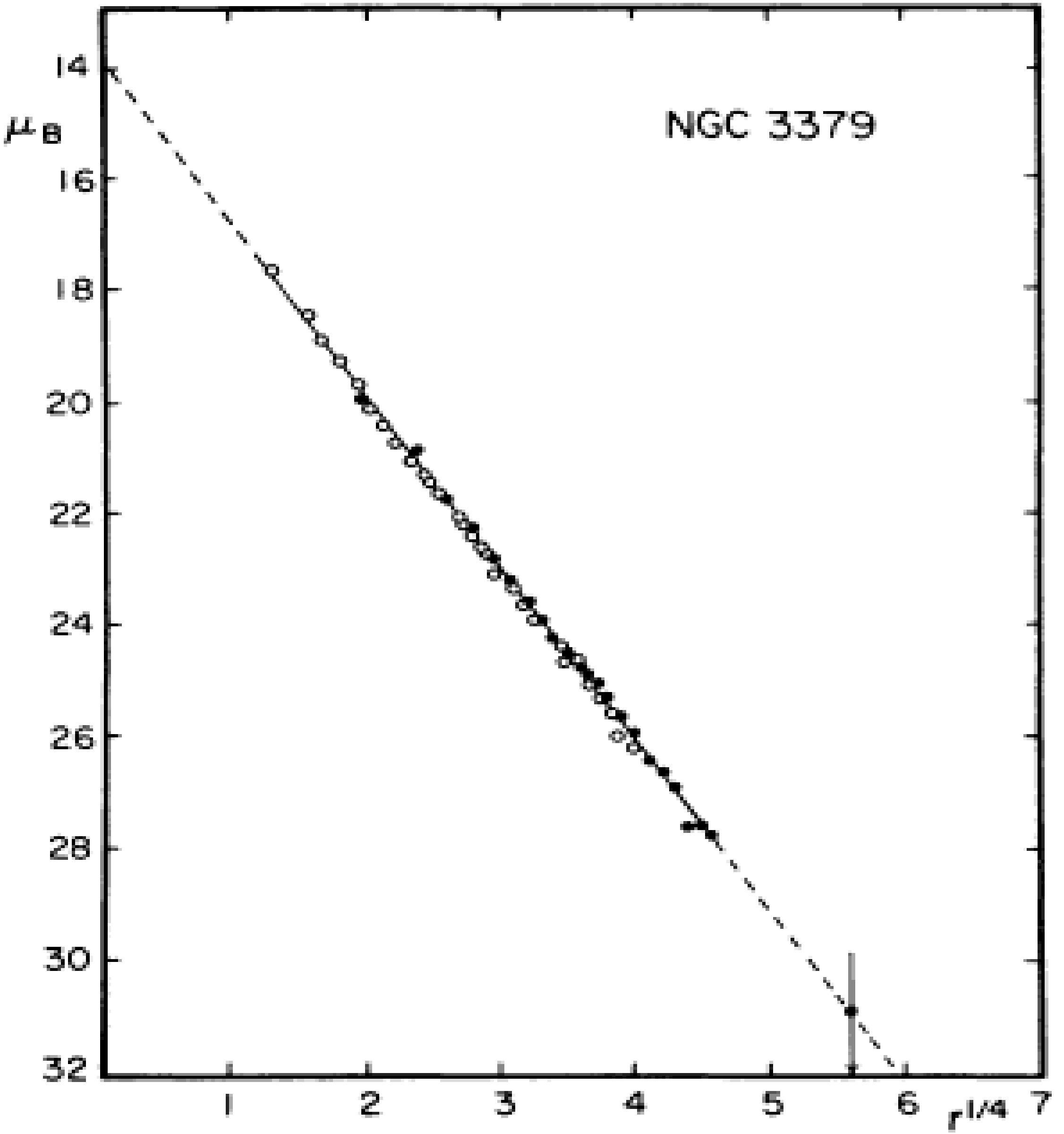
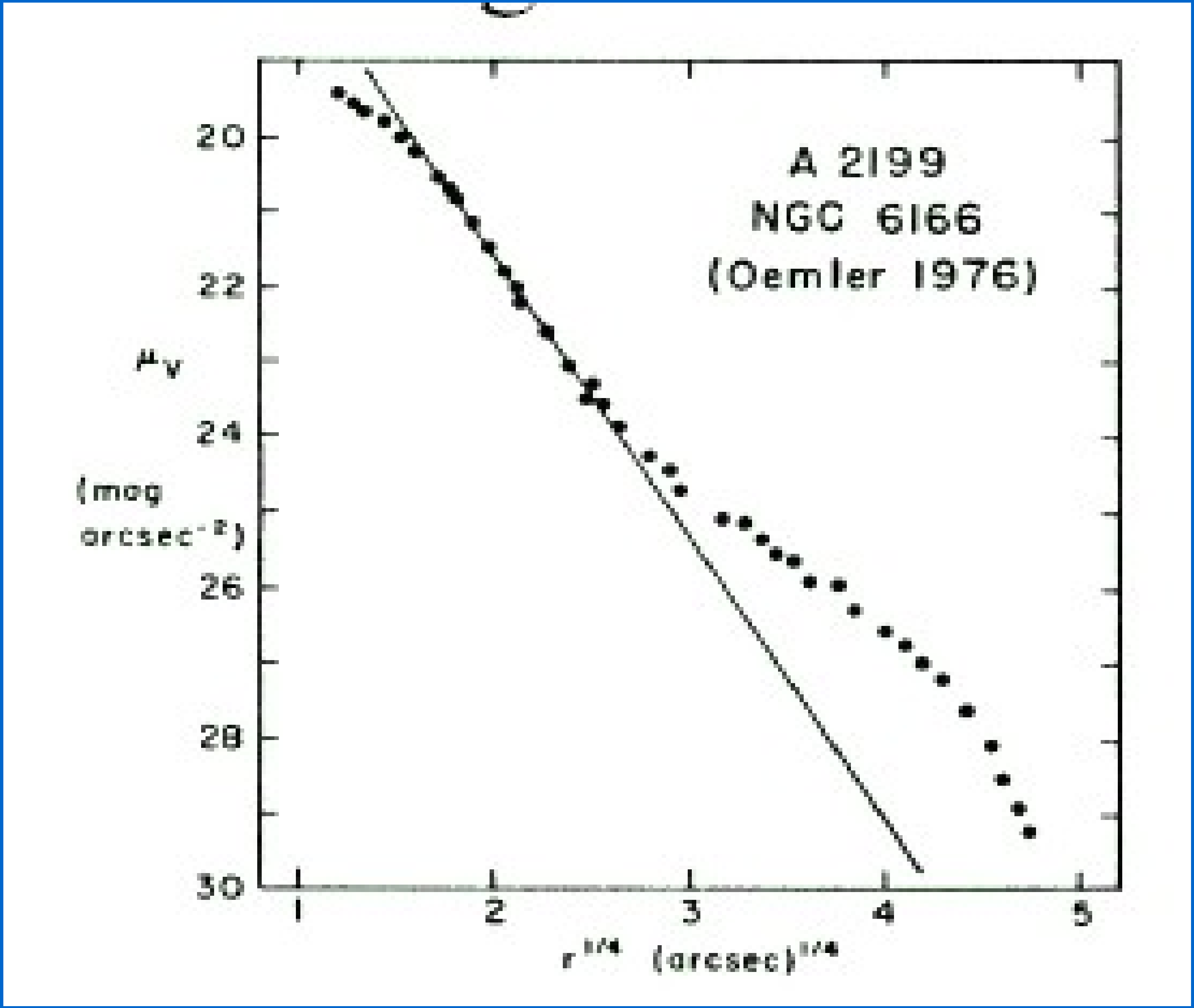


FIG. 2.—Mean E-W luminosity profile of NGC 3379 derived from McDonald photoelectric data. ●, Pe 4 data with 90 cm reflector; ○, Pe 1 data (M + P) with 2 m reflector. Note close agreement with $r^{1/4}$ law.


A 2199
NGC 6166
(Oemler 1976)
μ_V
(mag arcsec^{-2})
20
22
24
26
28
30
1
2
3
4
5
$r^{1/4}$ (arcsec)$^{1/4}$

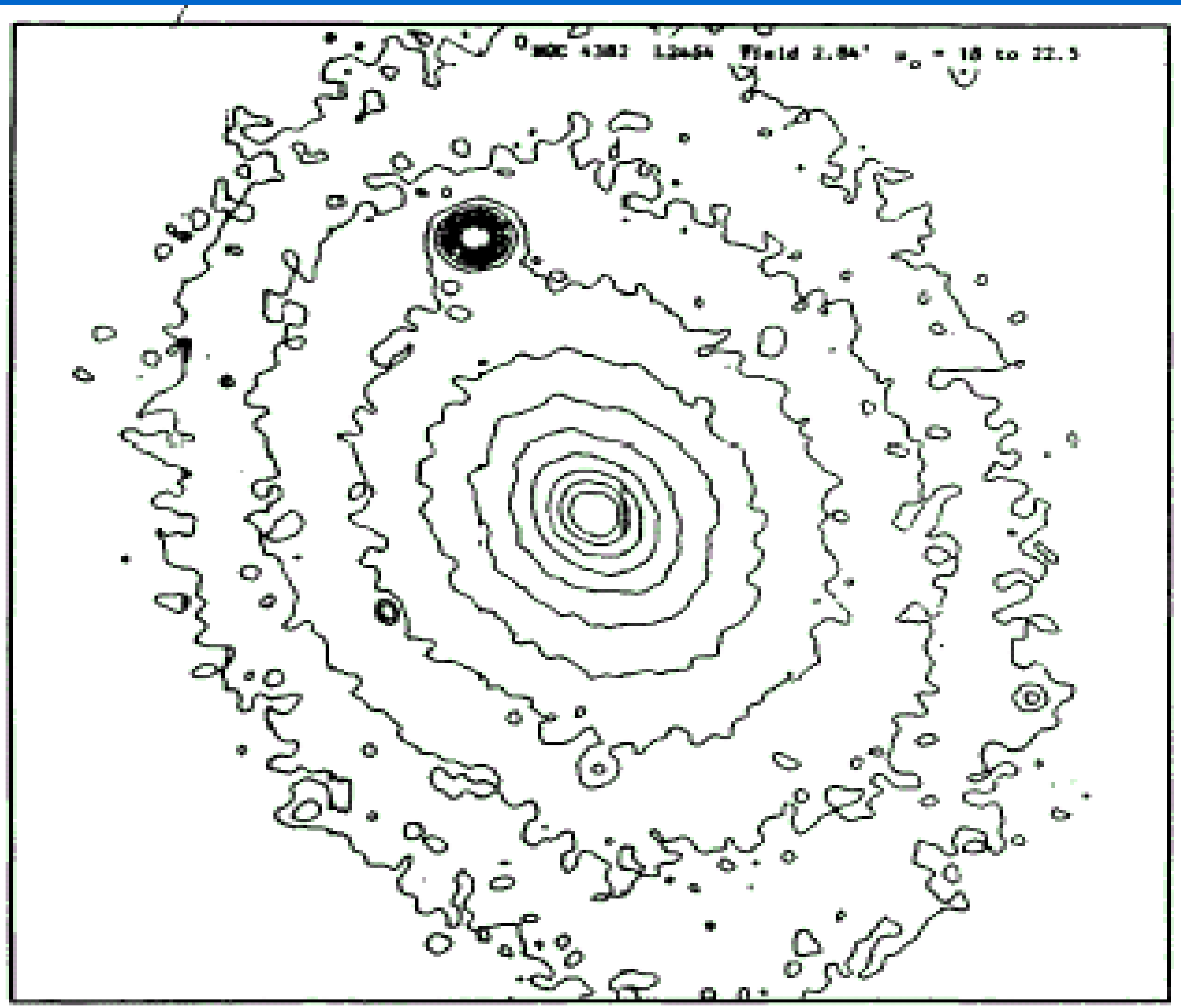


FIGURE 5.5.

Michard 1985

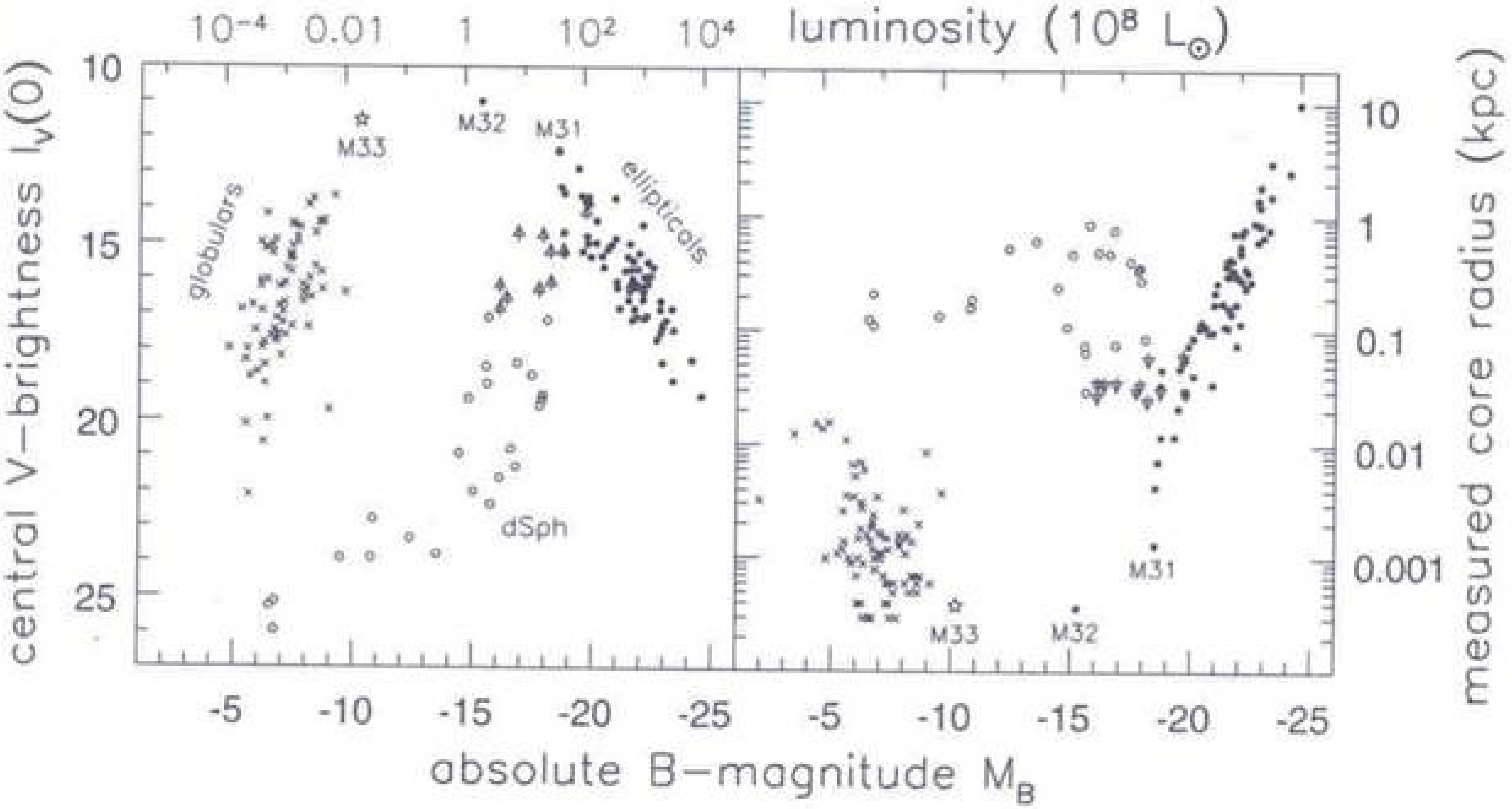
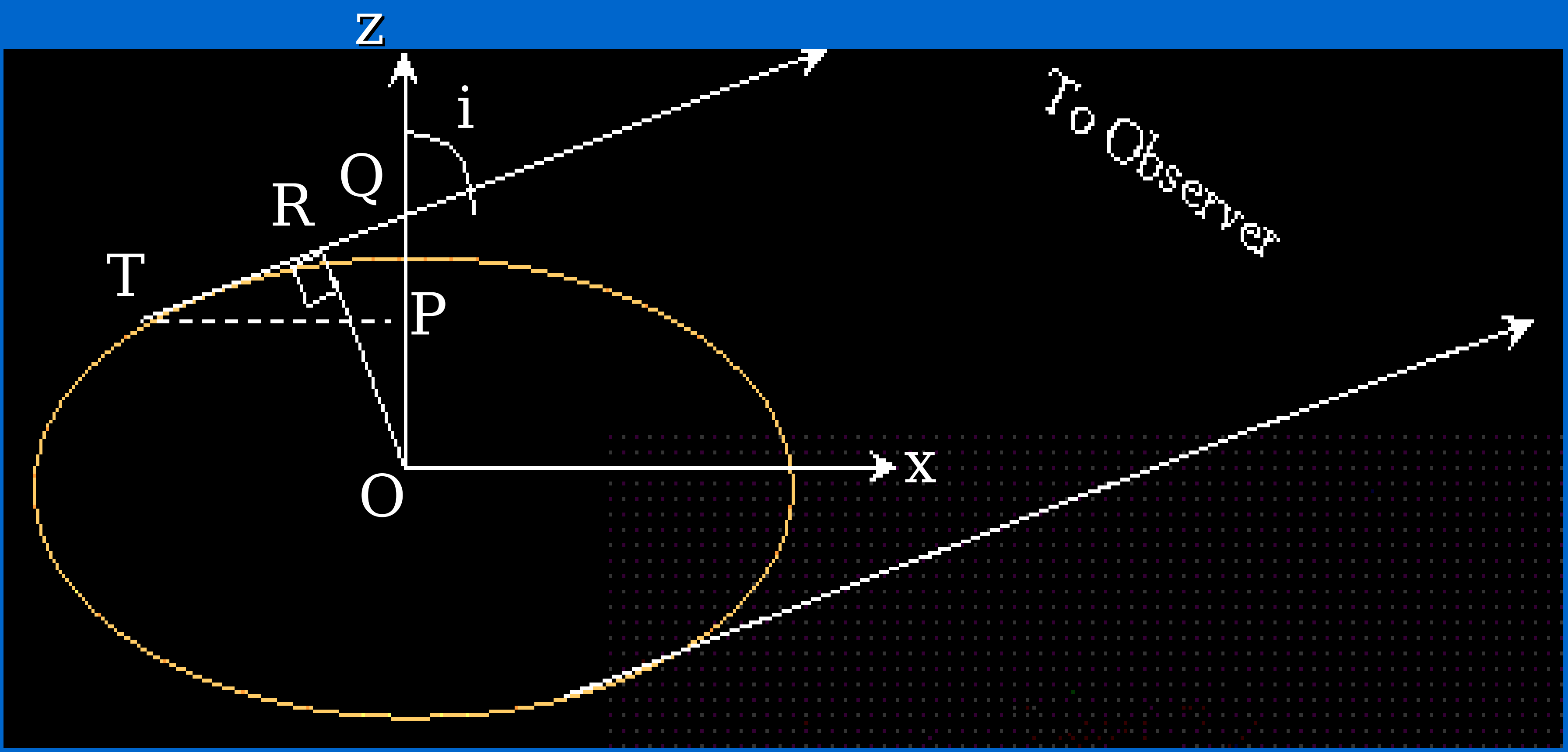


Figure 6.6 Central surface brightness $I_V(0)$ in mag arcsec^{-2} in the V band, and core radius r_c, measured from the ground, plotted against B-band luminosity M_B. Filled circles are elliptical galaxies and bulges of spirals (including the Andromeda galaxy M31); open circles are dwarf spheroidals; crosses are globular clusters; the star is the nucleus of Sc galaxy M33. Arrows show ellipticals in the Virgo cluster; here, seeing may cause us to measure too low a central brightness, and too large a core – J. Kormendy.



If elliptical galaxies are oblate spheriods then

$$\rho(\boldsymbol{x}) = \rho(m^2)\ where\ m^2 = \frac{x^2+y^2}{A^2} + \frac{z^2}{B^2}$$ with $A \geq B > 0$

So an observer looking along the z axis would see an E0 (round) galaxy, when viewed at an angle you would see an elliptical shape with apparent axis ratio q = b/a. Looking at the tangent point to the elliptical surface (T) the coordinates of this point are

$$\tan i = \frac{dx}{dz} = -\left(\frac{z}{x}\right)\left(\frac{A^2}{B^2}\right)$$

The elliptical image of this surface has a semi-major axis of a = mA and the semi-minor axis b is OR and this is also OQ sin(i). So from the equations above we can write

$$OQ = OP + PQ = z + (-x)\cot(i) = \frac{B^2 m^2}{z};$$

If q is the ratio of the minor to the major axis then

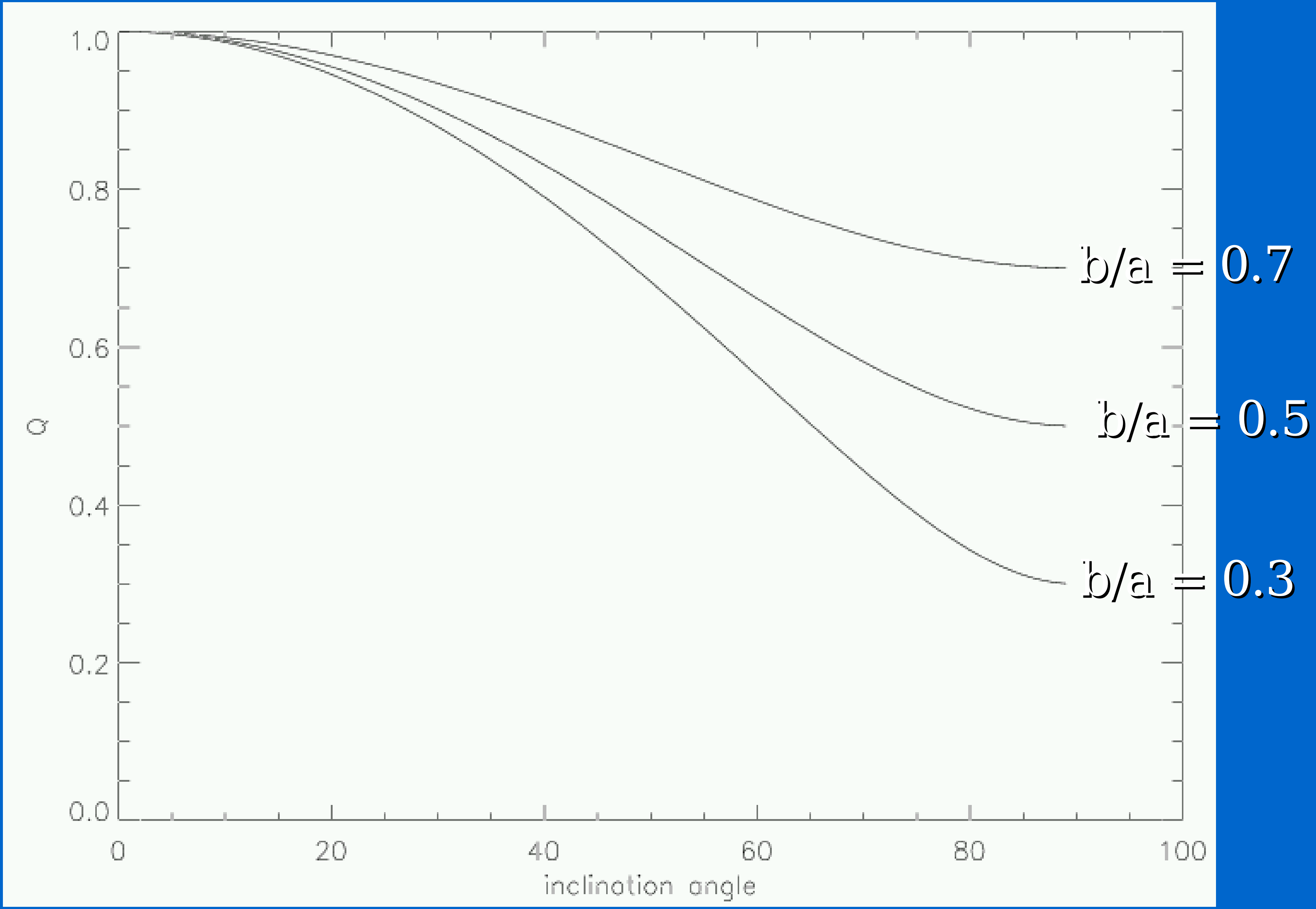
$$q_{obl} = \frac{b}{a} = OQ\,\frac{\sin(i)}{m\,A} = \frac{B^2\,m}{z\,A}\sin(i) = \left[\frac{B^2}{A^2} + \cot^2(i)\right]^{1/2}\sin(i)$$

Using our definition of m for the last step. Finally we can rewrite this as

$$q_{obl}^2 = (b/a)^2 = (B/A)^2\sin^2(i) + \cos^2(i)$$

For an oblate spheroid we can do all this again and get

$$q_{prol}^2 = (b/a)^2 = \left[(B/A)^2\sin^2(i) + \cos^2(i)\right]^{-1}$$


b/a = 0.7
b/a = 0.5
b/a = 0.3
Q
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
inclination angle

Distribution of B/A

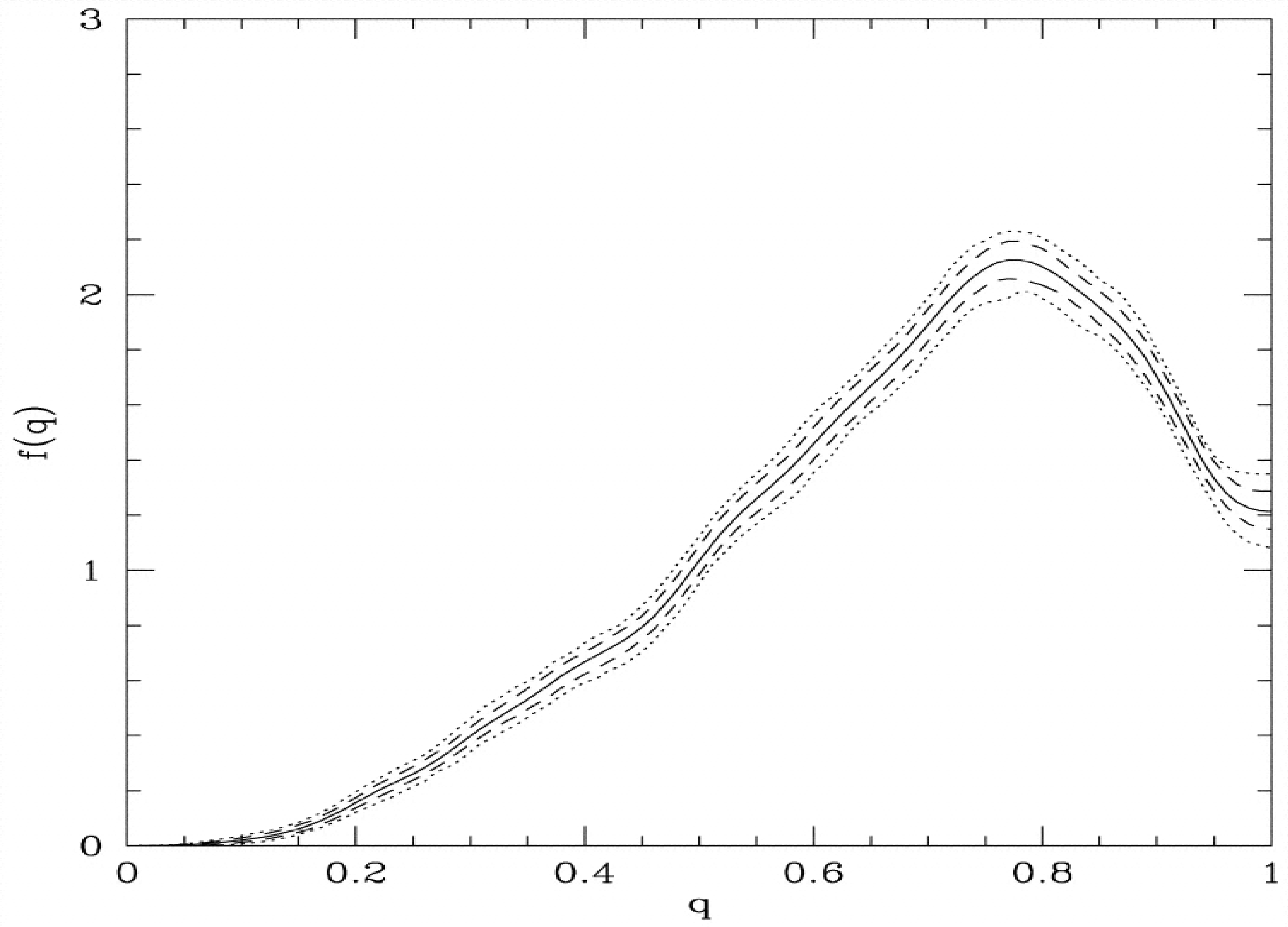
Looking from a random direction what fraction of galaxies do we see between i and i+Δi? It's just sin(i) Δi
So if all galaxies have an axial ratio of B/A then the fraction with apparent ratios between q and q + Δq is

$$f_{obl}(q)\Delta q = \frac{\sin(i)\Delta q}{dq/di} = \frac{q\Delta q}{\sqrt{1-(B/A)^2}\sqrt{q^2-(B/A)^2}}$$

For very flattened systems, B<<A the distribution is almost uniform

Distribution of B/A cont.

- The disks of spiral and S0 galaxies the apparent shapes with $q \approx 0.2$ are found with equal probability.
  - So we conclude that in general their disks have $B/A \leq 0.2$
  - We see very few spirals with $q \leq 0.1$ which means that very few spirals have $B/A \approx 0.1$
- No ellipticals flatter than E7 ($q=0.3$)
  - Dynamically unstable?



Axial ratios for galaxies fit with de Vaucouleurs profiles (Khairul Alam & Ryden 2002).

Distribution of B/A cont.

- Small E's are more elongated that more luminous E's
- Mid-sized E's have q≈0.7
- Luminous E's have q≈0.8
    - No selection of oblate spheroids can give the observed distribution
    - These galaxies must be triaxial

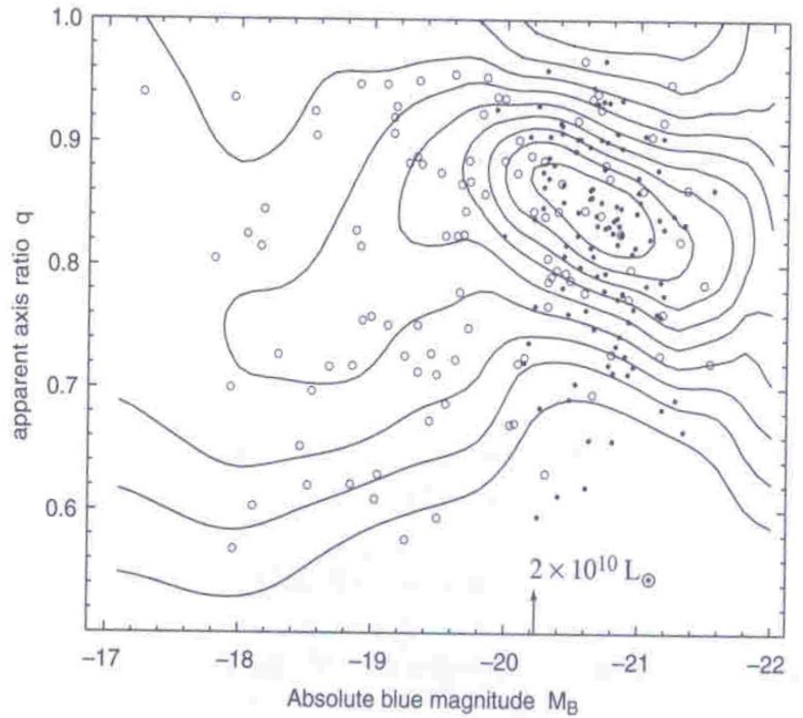
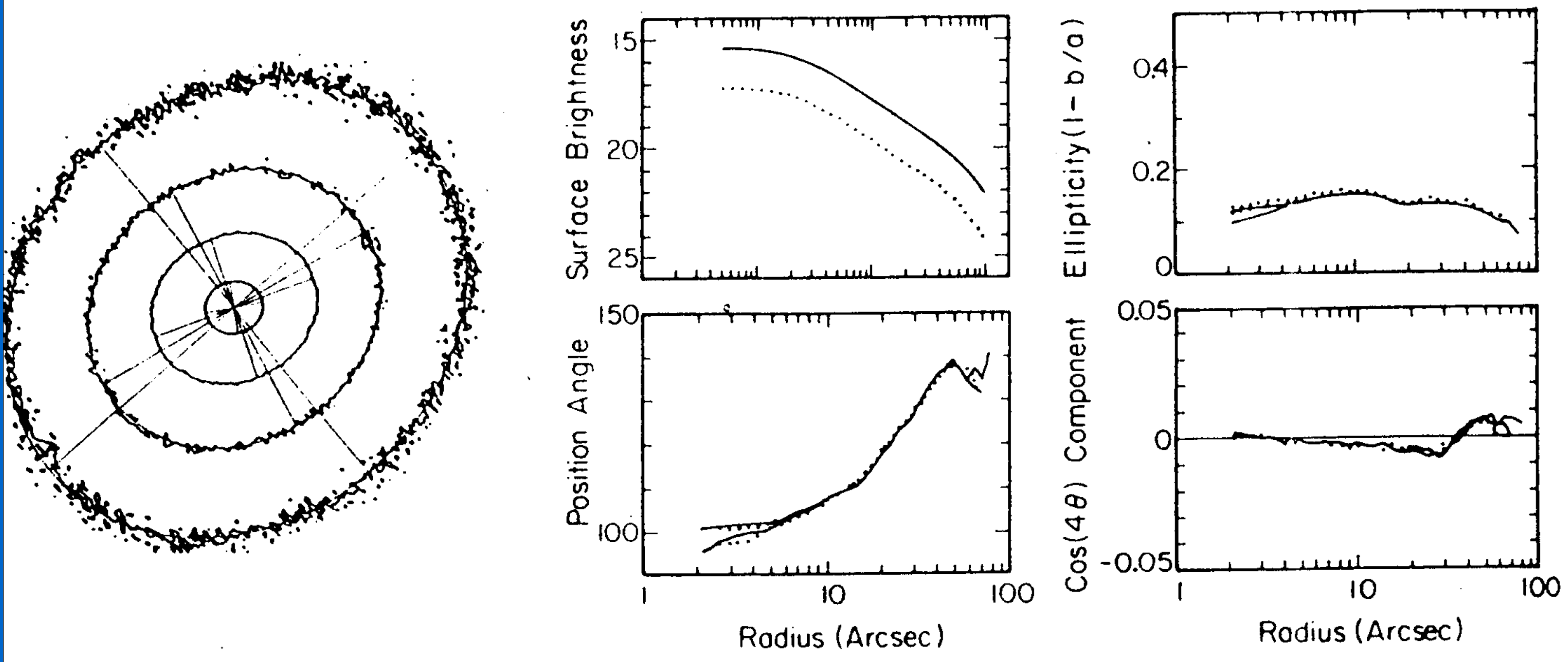


Figure 6.9 Observed axis ratio q and blue absolute magnitude M_B for elliptical galaxies from two different samples, represented by filled and open circles. Bright galaxies (on the right) on average appear rounder. Contours show probability density; the top contour level is 4.5 times higher than at the lowest, with others equally spaced – B. Tremblay & D. Merritt, AJ 111, 2243; 1996.

Isophotal Shapes

- While elliptical galaxy isophotes are close to ellipses small deviations do occur
- We see
  - Twisting isophotes
  - Disky isophotes
  - Boxy isophotes



igure 1: *Surface brightness distribution of the elliptical galaxy NGC 1549, taken* *rom Jedrzejewski (1987). The left panel gives a contour map with the major and* *ıe minor axes overlaid. The four right hand panels give the surface brightness,* *ıe ellipticity* ϵ*, the position angle PA, and the* $\cos 4\theta$ *variation of the surface* *rightness along the best fitting elliptic isophote, all as a function of radius. The* *olid lines show the measurements in the R band, while the dotted lines refer to* *ıe B band.*

- Deviations from ellipses can be disky or boxy
- Measure difference between observed isophote and fitted ellipse as:
  - $\Delta r(\theta) \approx \sum_{k\geq 3} a_k \cos(k\theta) + b_k \cos(k\theta)$
  - θ = angle around ellipse, $\Delta r(\theta)$ is distance between fitted ellipse and observed isophote
  - a_3 and b_3 describe “egg-shaped” ellipses, generally small, b4 is also usually small
  - $a_4 > 0$, isophote is disky (extra light along the axis)
  - $a_4 < 0$ isophote is boxy (extra light at the corners)

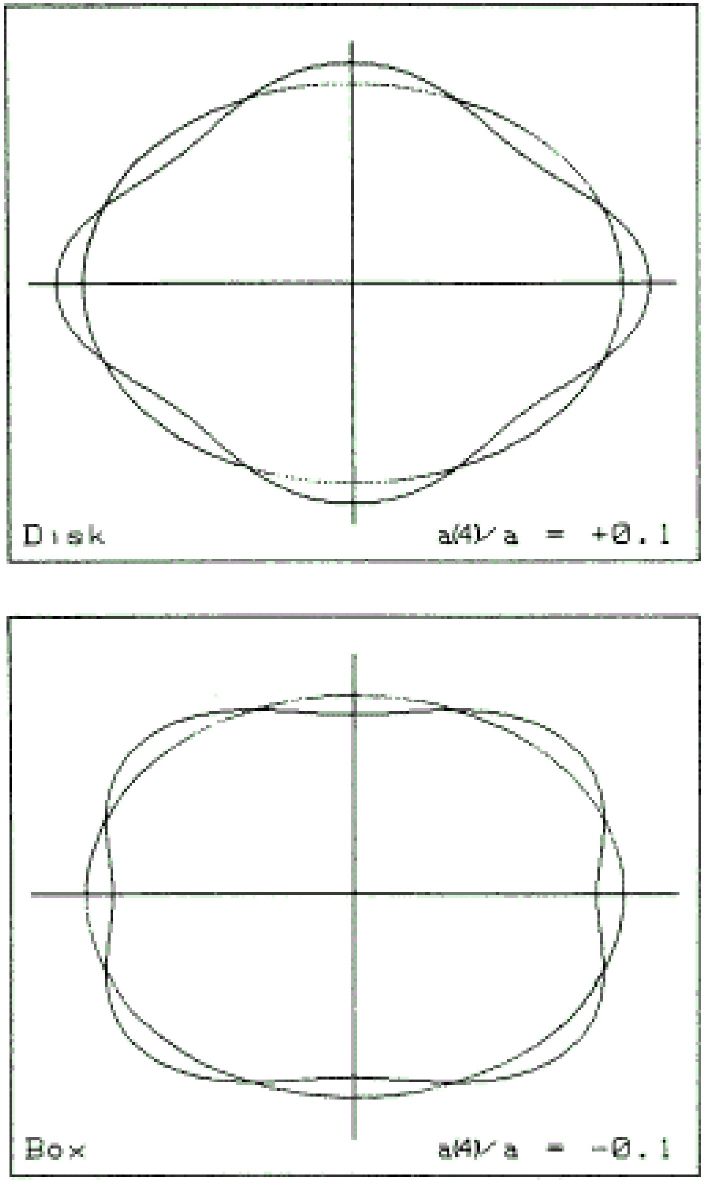


FIGURE 5. — Schematic drawing illustrating isophotes w
$a(4)/a = +0.1$ and $a(4)/a = -0.1$.

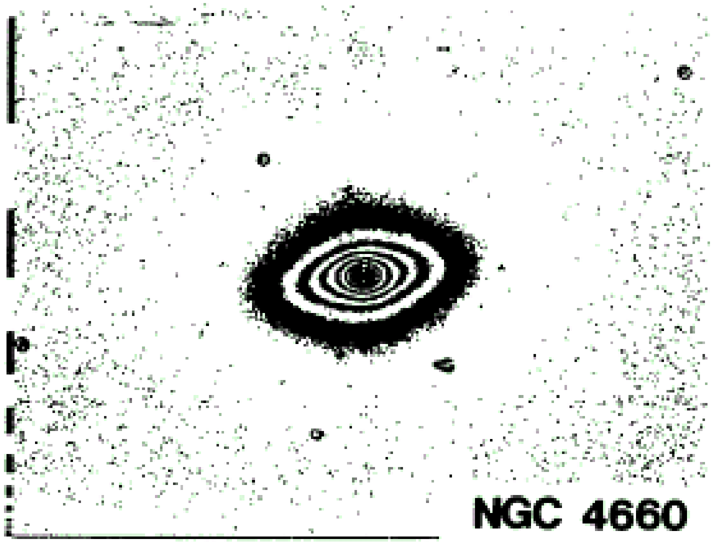


FIGURE 6. — R-image of NGC 4660, an elliptical galaxy with a disk-component in the isophotes ($a(4)/a \sim +0.03$).

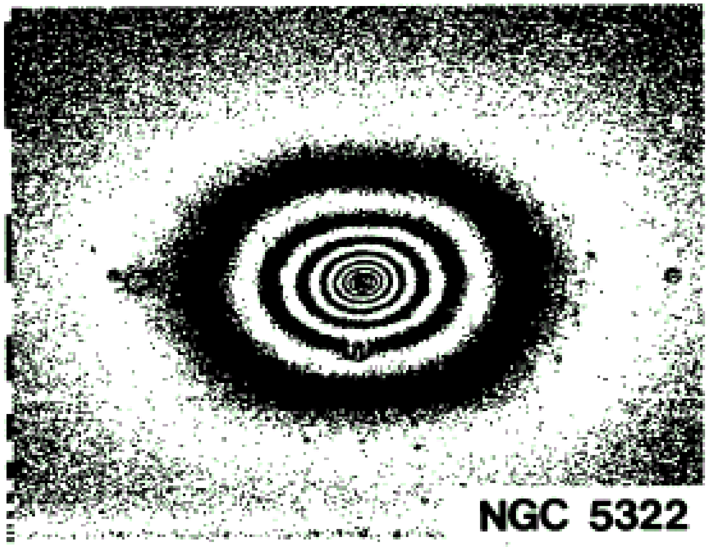


FIGURE 7. — R-image of NGC 5322, an elliptical galaxy with box-shaped isophotes ($a(4)/a \sim -0.01$).

Bender et al. 1988

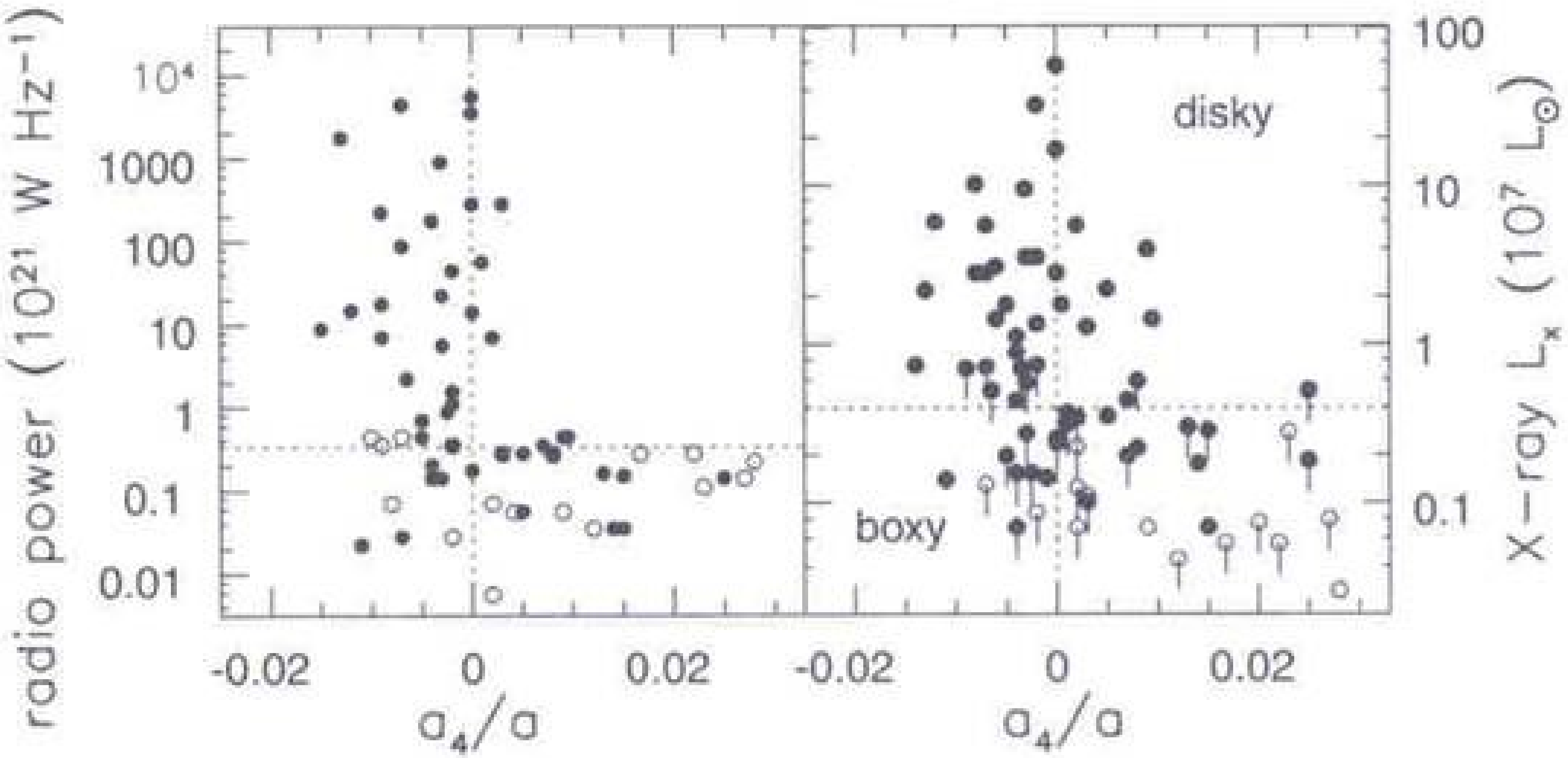
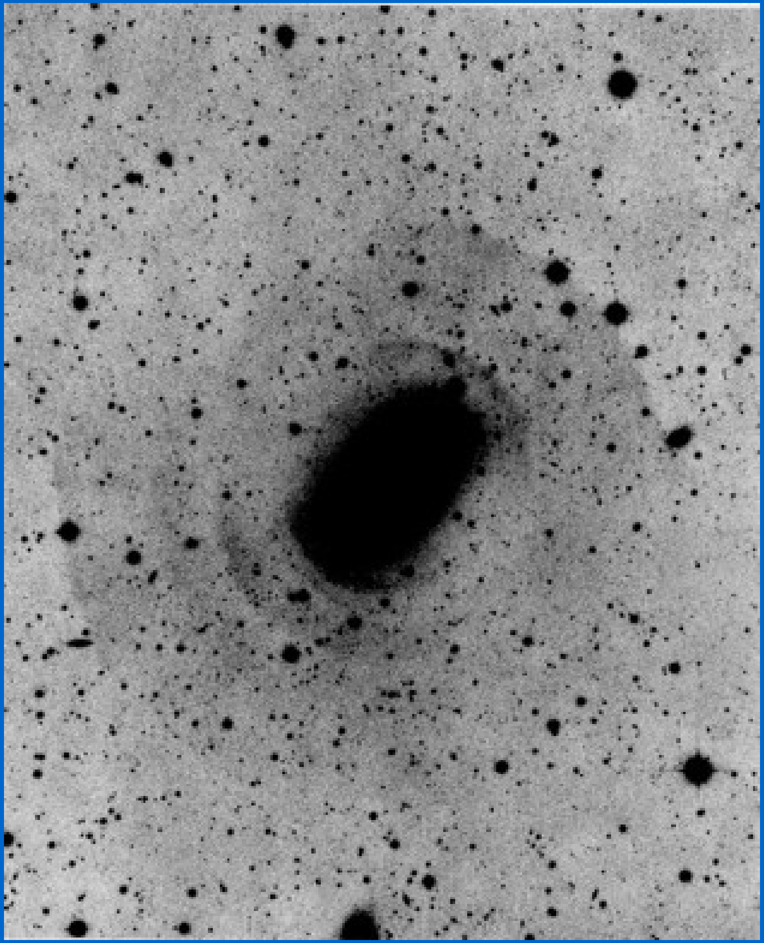


Figure 6.11 Radio and X-ray power of elliptical galaxies. Boxy galaxies, with $a_4 < 0$, tend to be strong sources; disky ellipticals, with $a_4 > 0$, are usually weak. Filled circles show bright objects, with $M_B < -19.5$; open circles are dimmer galaxies. Points with downward-extending bars show upper limits on the X-ray emission; luminosities are calculated for $H_0 = 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ – R. Bender.

Shell Galaxies



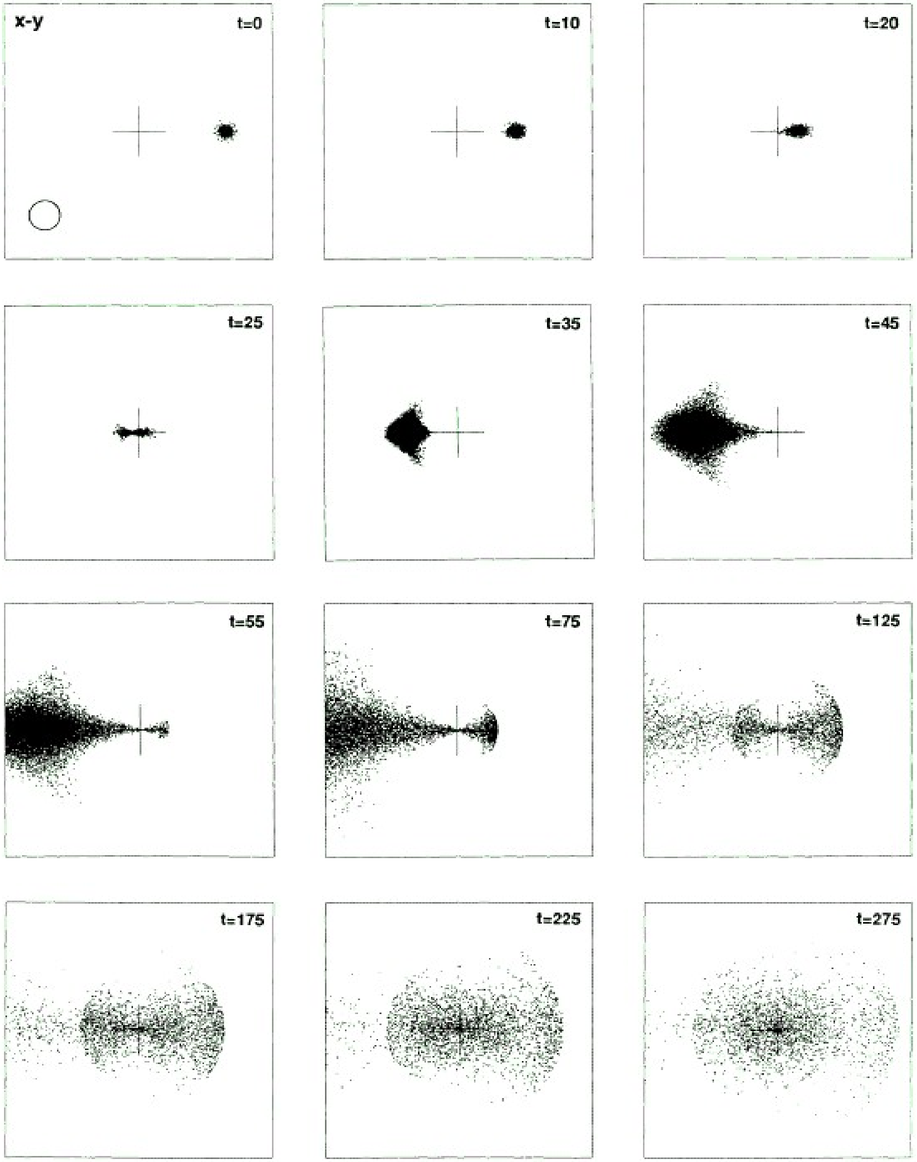
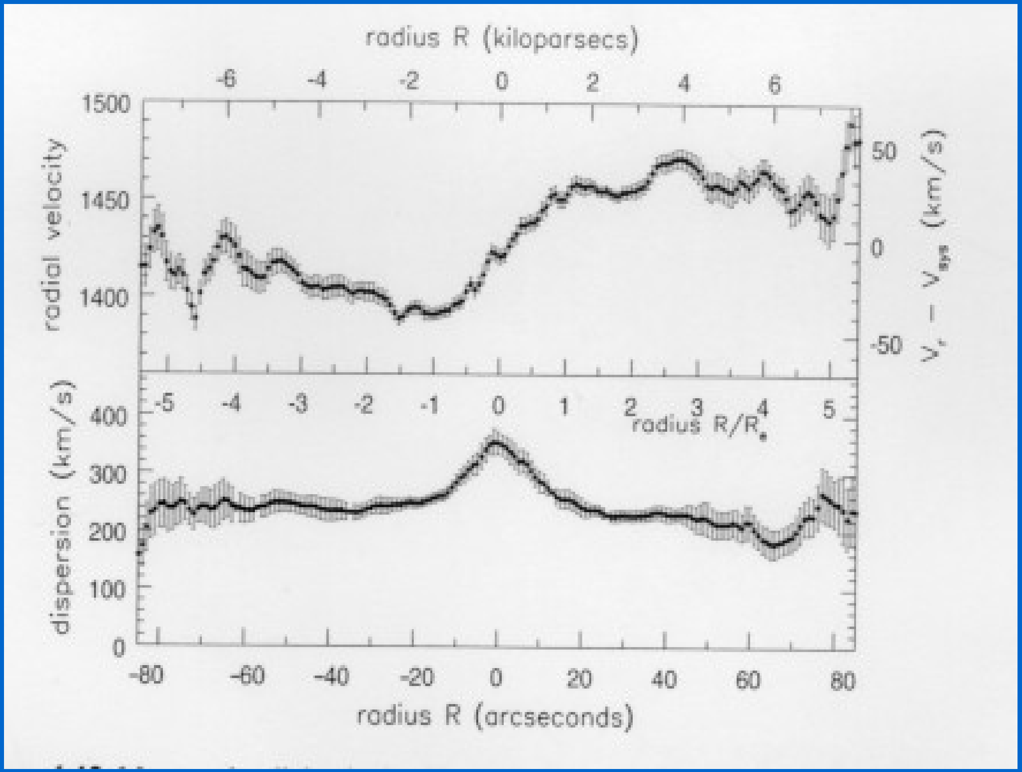
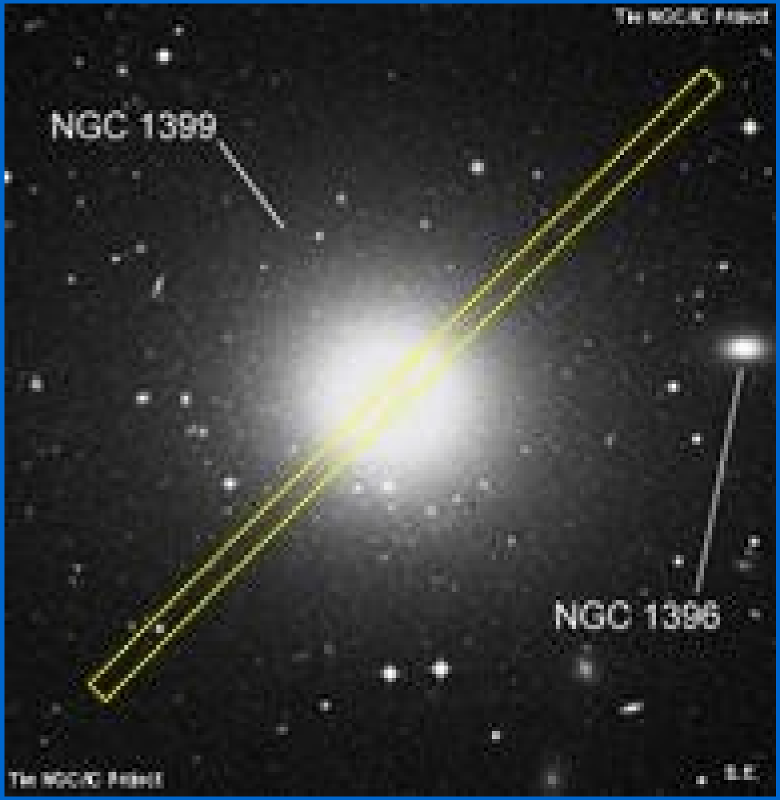


Figure 1. A radial encounter between a spherical Plummer primary and a spherical companion. The companion mass was 0.01 and its half-mass radius was 0.2 (both 1 for primary). The circle in the first frame indicates a spherical primary was used and the cross is at the center-of-mass.

Some ellipticals are just different





To measure the rotation of elliptical galaxies we cannot use HI or emission lines. So we place a long slit spectrograph (same as for spirals) and measure the absorption lines in the stellar spectra.

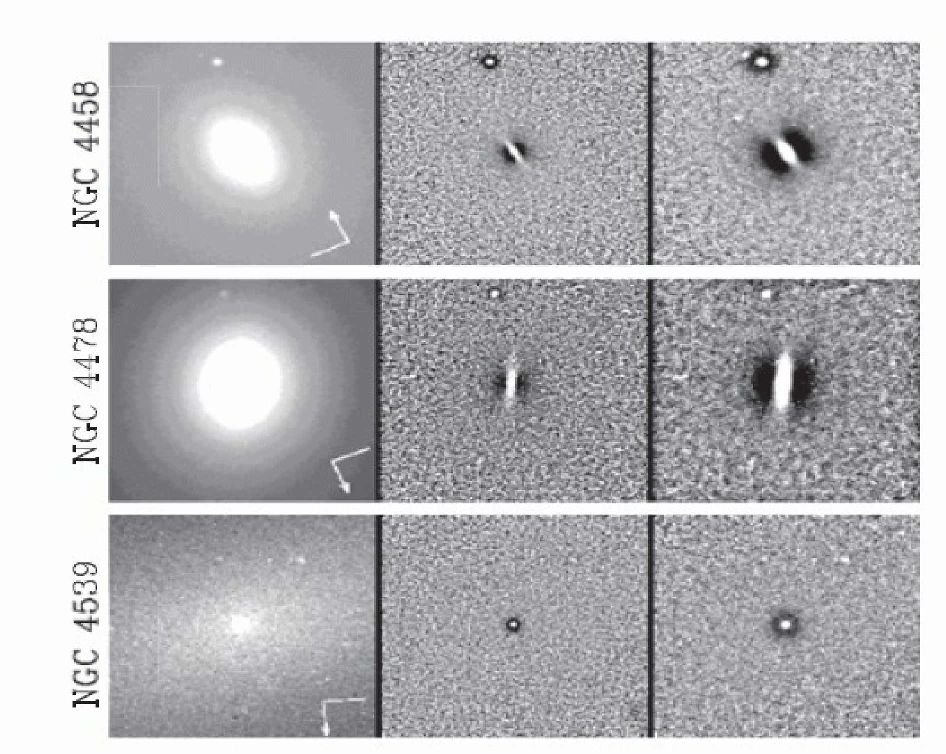
- The rotational velocity for NGC 1399
  - $\Delta v \sim$ 100 km/s
  - σ_r is between 250 – 400 km/s
  - So $V_{max}/\sigma_r < 1$
    - Spirals have $V_{max} \approx 10\sigma_r$
  - So ellipticals are “slow” rotators

Kinematics of Ellipticals

- V_{rot}/σ correlates with luminosity
  - Lower luminosity ellipticals have higher V_{rot}/σ , rotationally supported
  - Higher luminosity ellipticals have lower V_{rot}/σ -- pressure supported
- V_{rot}/σ correlates with boxy/diskiness
  - Disky ellipticals have higher V_{rot}/σ -- rotationally supported
  - Boxy ellipticals have lower V_{rot}/σ -- pressure supported

Kinematics of Ellipticals cont.

- Rotation implies that ellipticals are not relaxed systems
  - Some have kinematically decoupled cores, or rotation along their minor axis (implies triaxiality)



V_{rot}/σ vs Luminosity

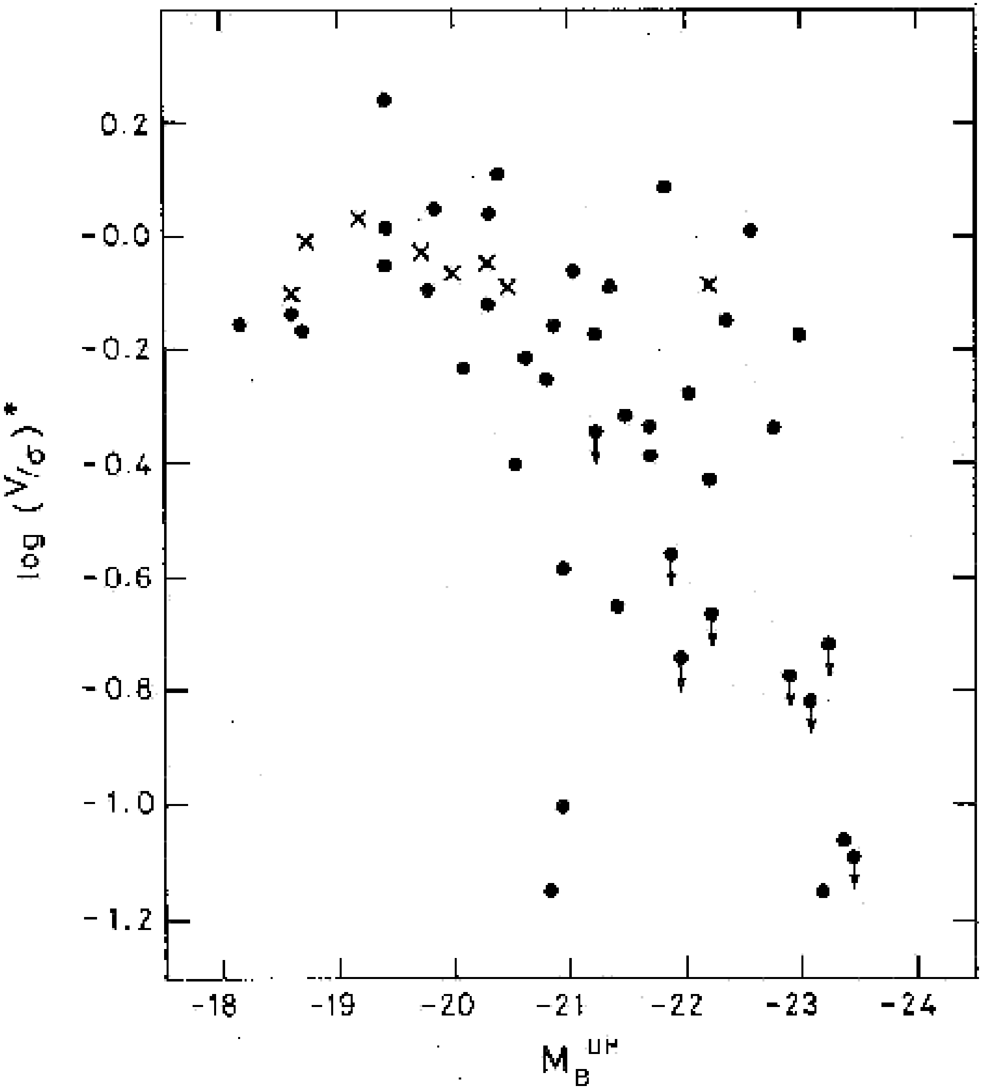


FIG. 4.—Log $(V/\sigma)^*$ against absolute magnitude. Ellipticals are shown as filled circles and the bulges as crosses; $(V/\sigma)^*$ is defined in § III*b*.

Rotational Properties of Elliptical Galaxies:

Anisotropy parameter:

$$\left(\frac{v}{\sigma}\right)^* \equiv \frac{v/\sigma}{\sqrt{\frac{1-b/a}{b/a}}} = \frac{(v/\sigma)_{\text{observed}}}{(v/\sigma)_{\text{rot. flattened}}}$$

see: Davies et al. (1983)
ApJ, **266**, 41

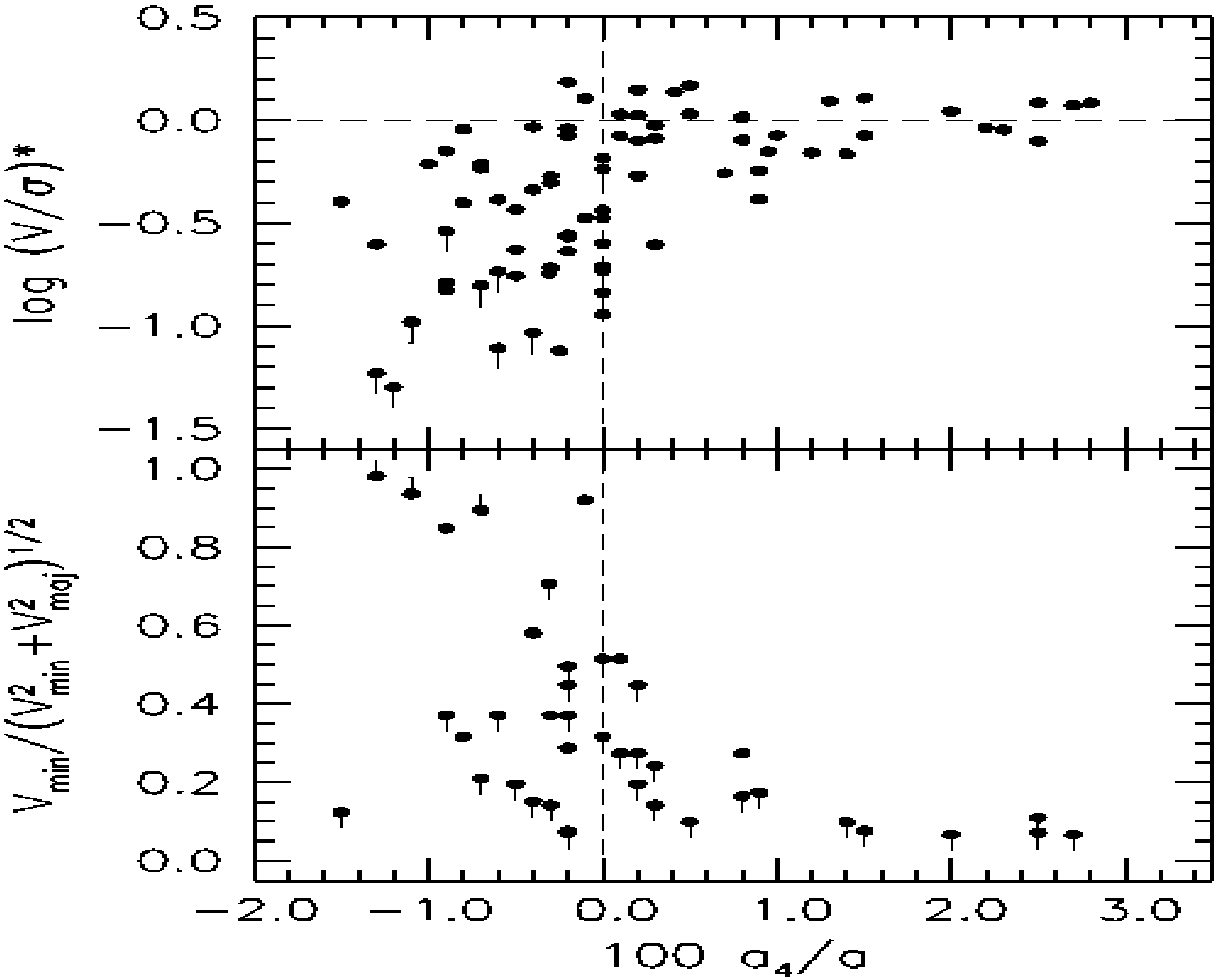


FIG. 2.—Correlations with isophote shape of parameters that are diagnostic of velocity anisotropy. Here 100 a_4/a is the percent inward or outward perturbation of isophote radii along the major axis; negative values imply boxy isophotes; positive values imply disky isophotes. The upper panel shows the rotation parameter $(V/\sigma)^*$ (from Bender 1988, with a_4/a values from B+89 and with $(V/\sigma)^*$ values added from Davies *et al.* 1983). The lower panel shows maximum minor-axis rotation velocities normalized by total rotation velocity.

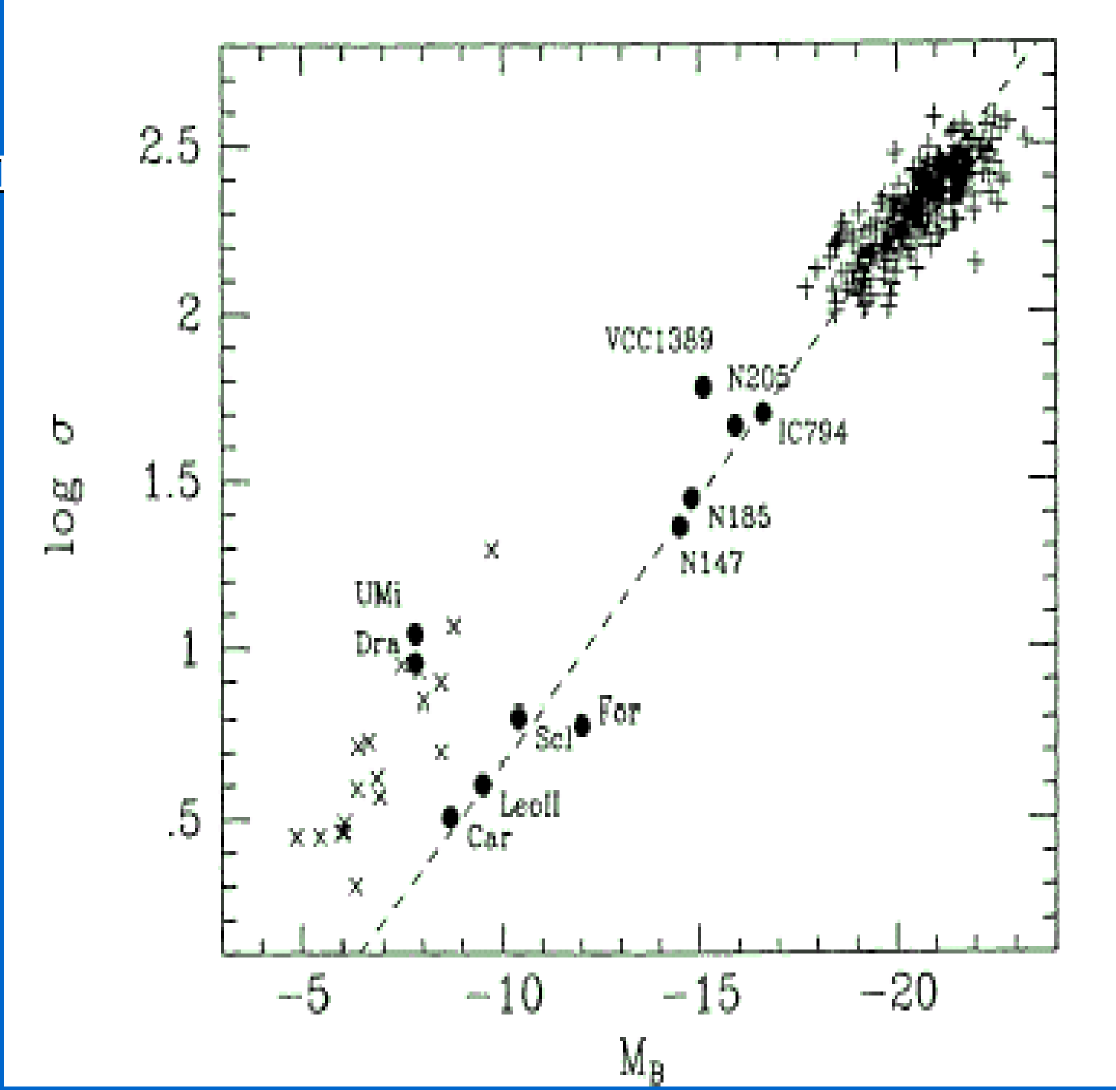
Faber-Jackson Relation

- Faber & Jackson(1976) found that:
  - Roughly, L $\propto \sigma^4$
    - More luminous galaxies have deeper potentials
  - Can show that this follows from the Virial Theorem (just like Tully-Fisher relation)

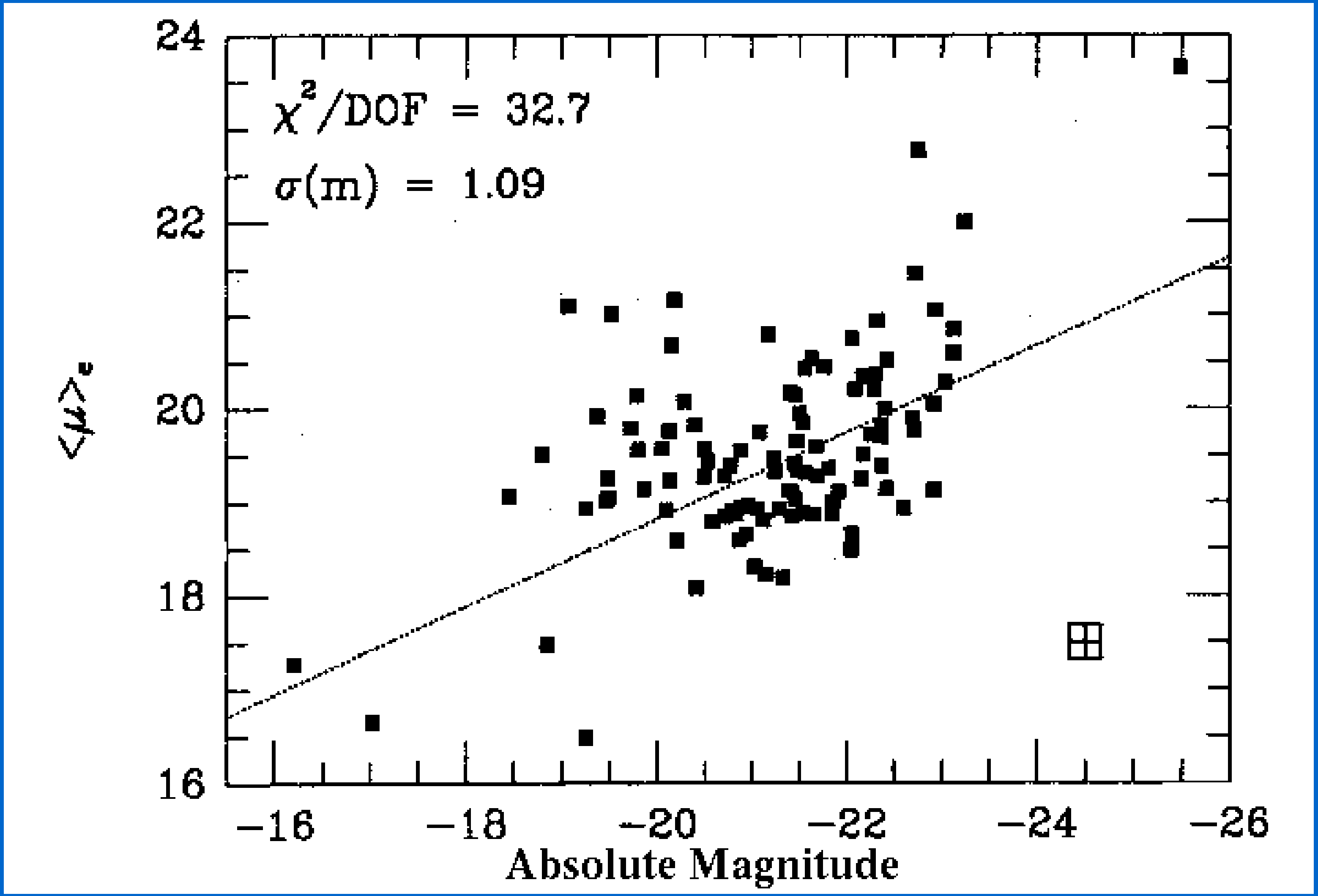
Faber-Jackson relation cont.

- This is similar to the Tully-Fisher relation fo Spirals
- Used to measure distance from σ
- Problem:
  - E's have very extended halos so getting the total luminosity is tricky

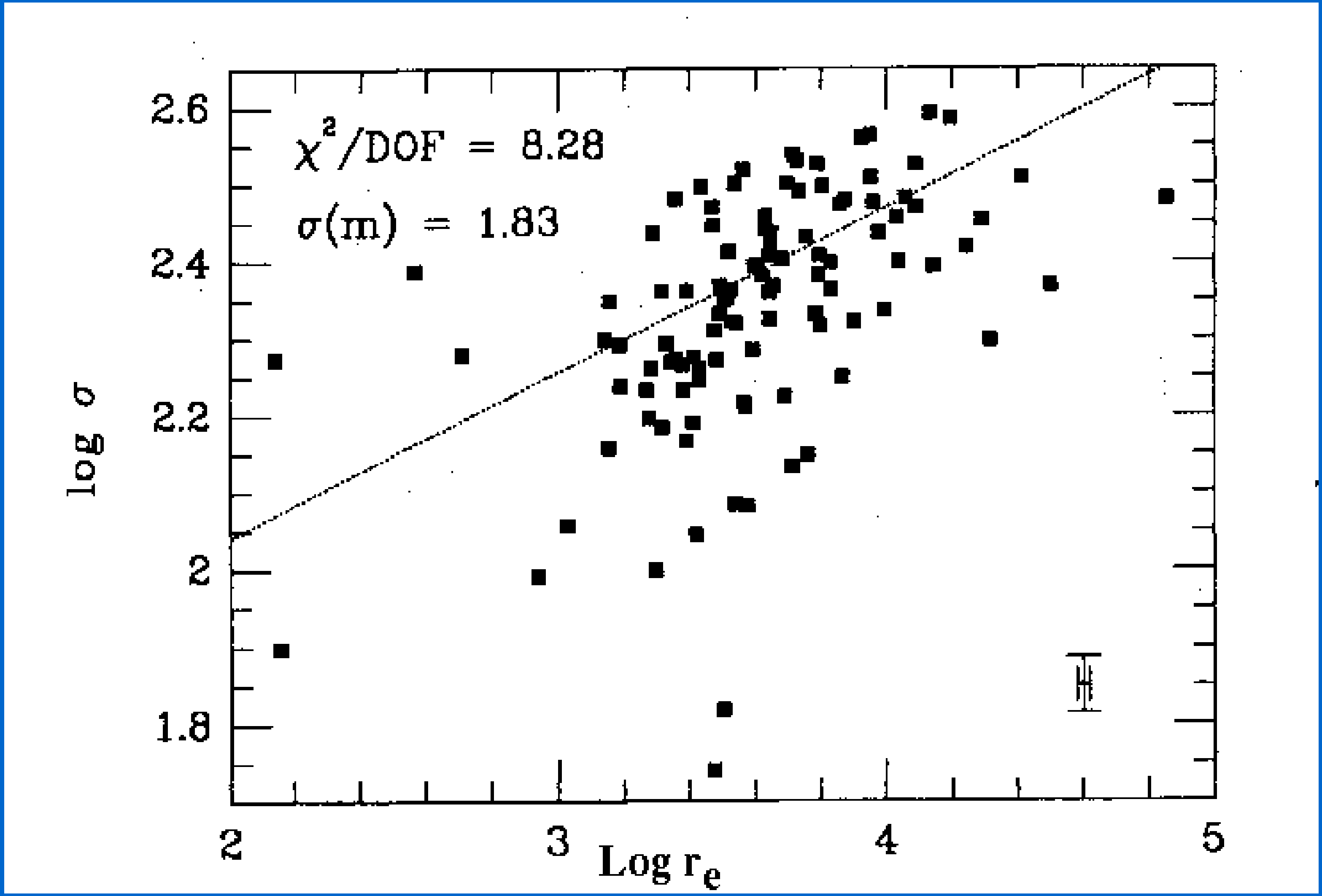
$$\frac{L_v}{2x10^{10} L_{sun}} \approx \left(\frac{\sigma}{200 k\,m\,s^{-1}}\right)^4$$



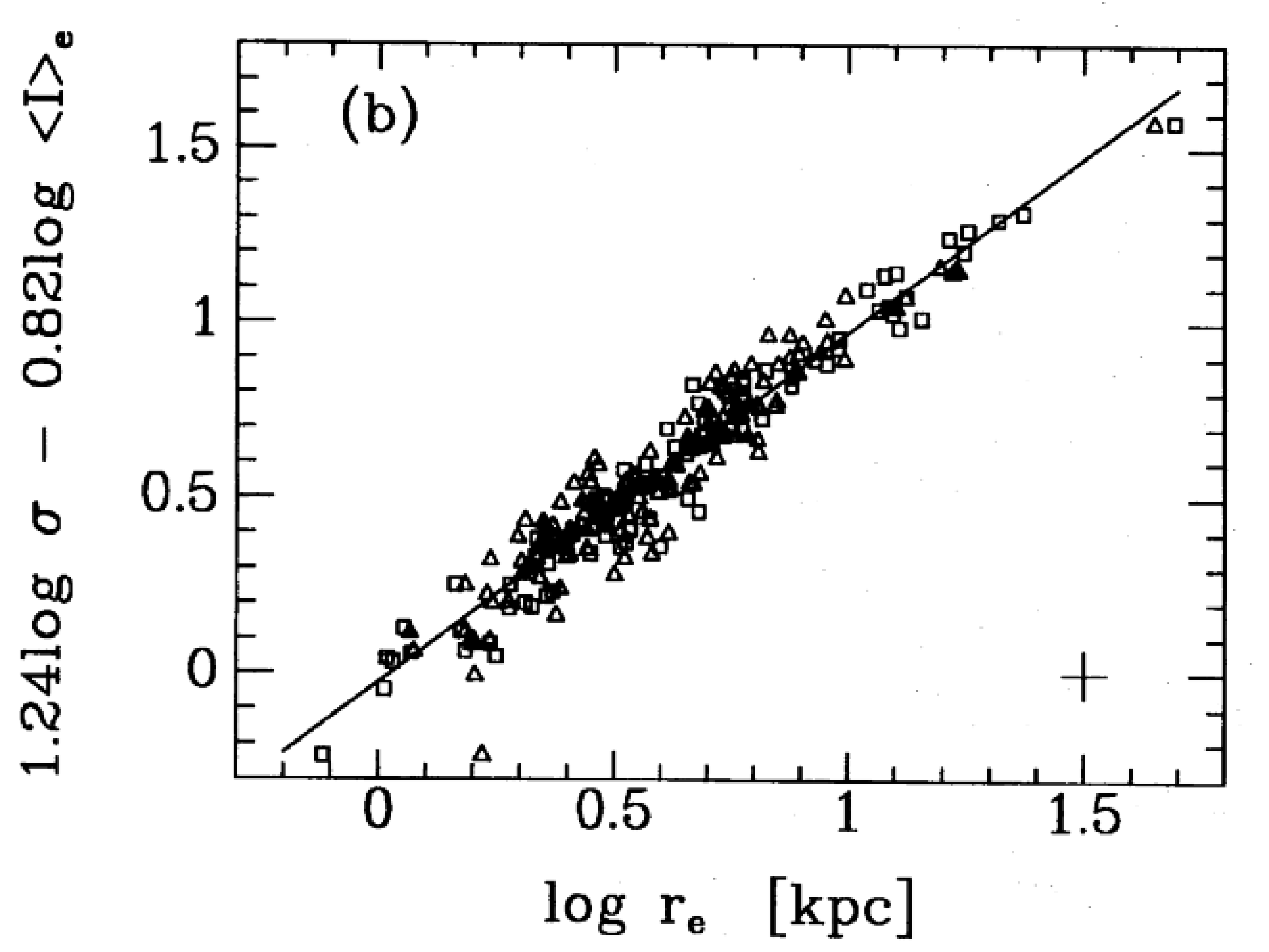
Surface Brightness vs Luminosity



σ_r vs R_e



Fundamental Plane



Fundamental Plane

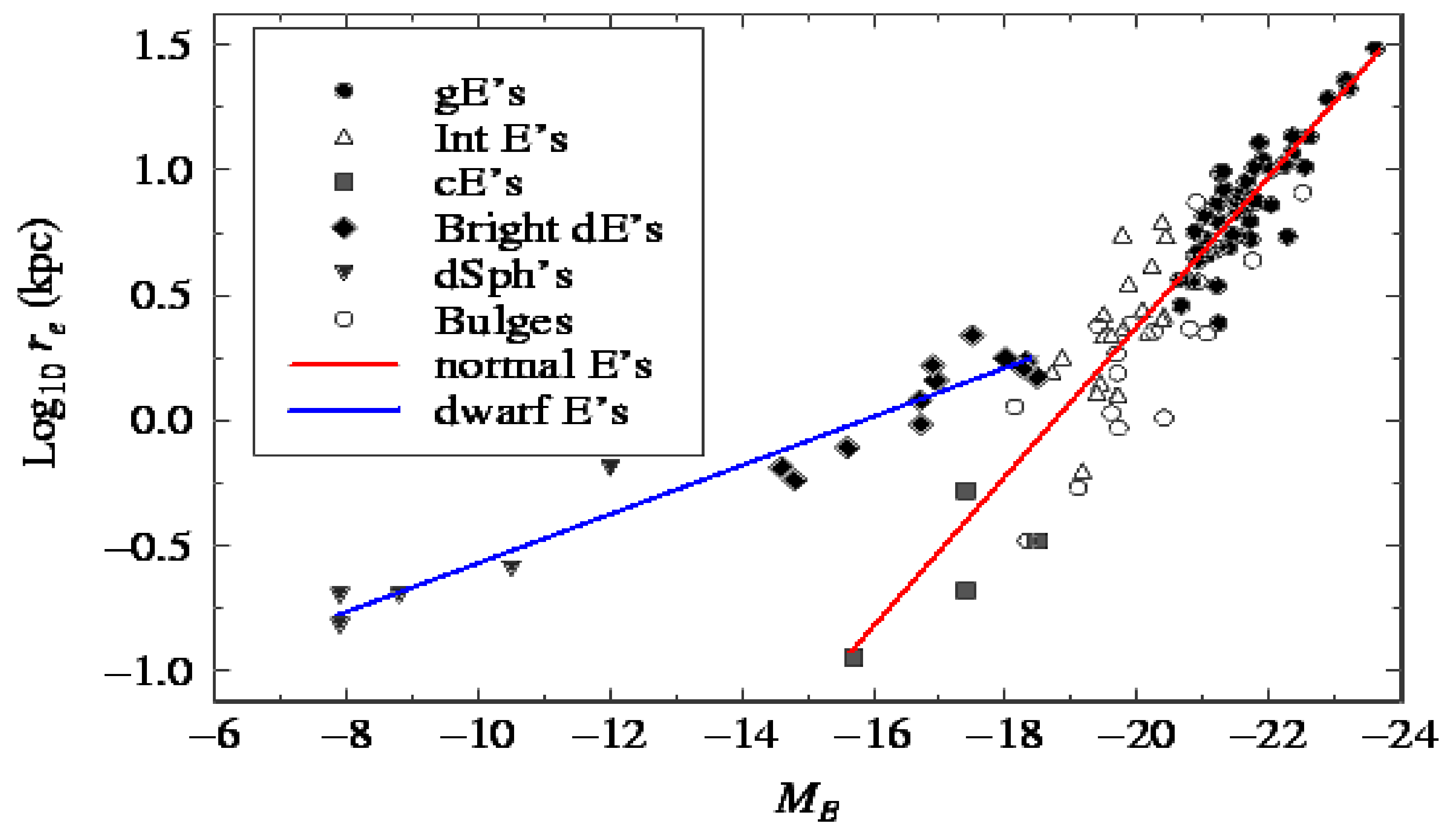
- Observers found that if you plotted
  - R_e
  - $I(R_e)$ and the
  - central σ
- These quantities define a plane – the "Fundamental Plane"
- $R_e \propto \sigma^{1.24}\ I_e^{-0.82}$
- This, like the Tully-Fisher relationship, reflects some fundamental physics for formation of ellipticals!

- In general, ellipticals --
  - Are supported by pressure (slow rotation), stellar motions are mostly random
  - Very little/no disk component
  - Very little/no star formation
  - Very little/no cold (e.g., HI) gas, but contains hot, X-ray gas
  - Almost exclusively found in high density environments (groups and clusters)
  - Populate a fundamental plane in luminosity-surface brightness-central velocity dispersion

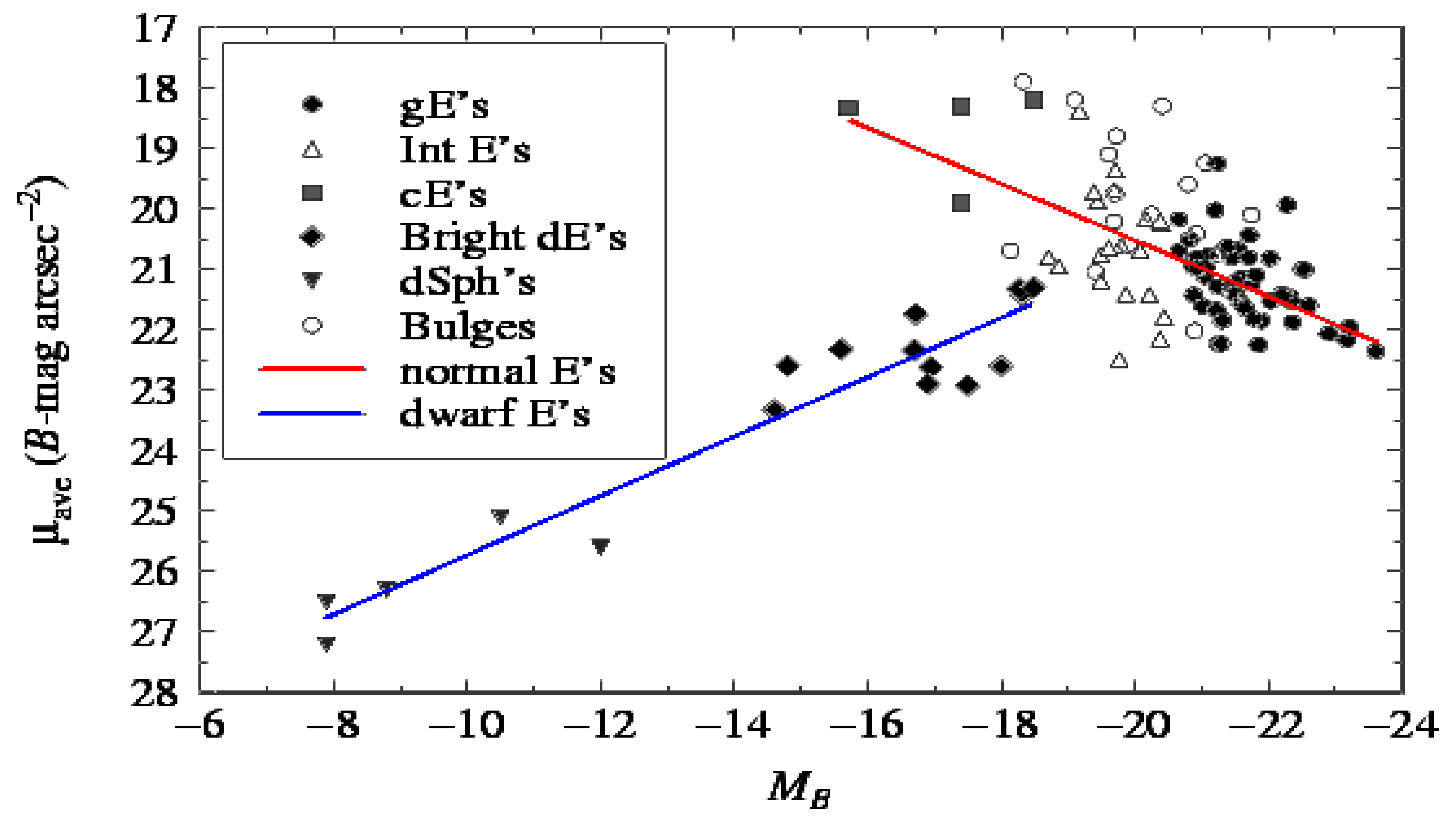
Elliptical Properties

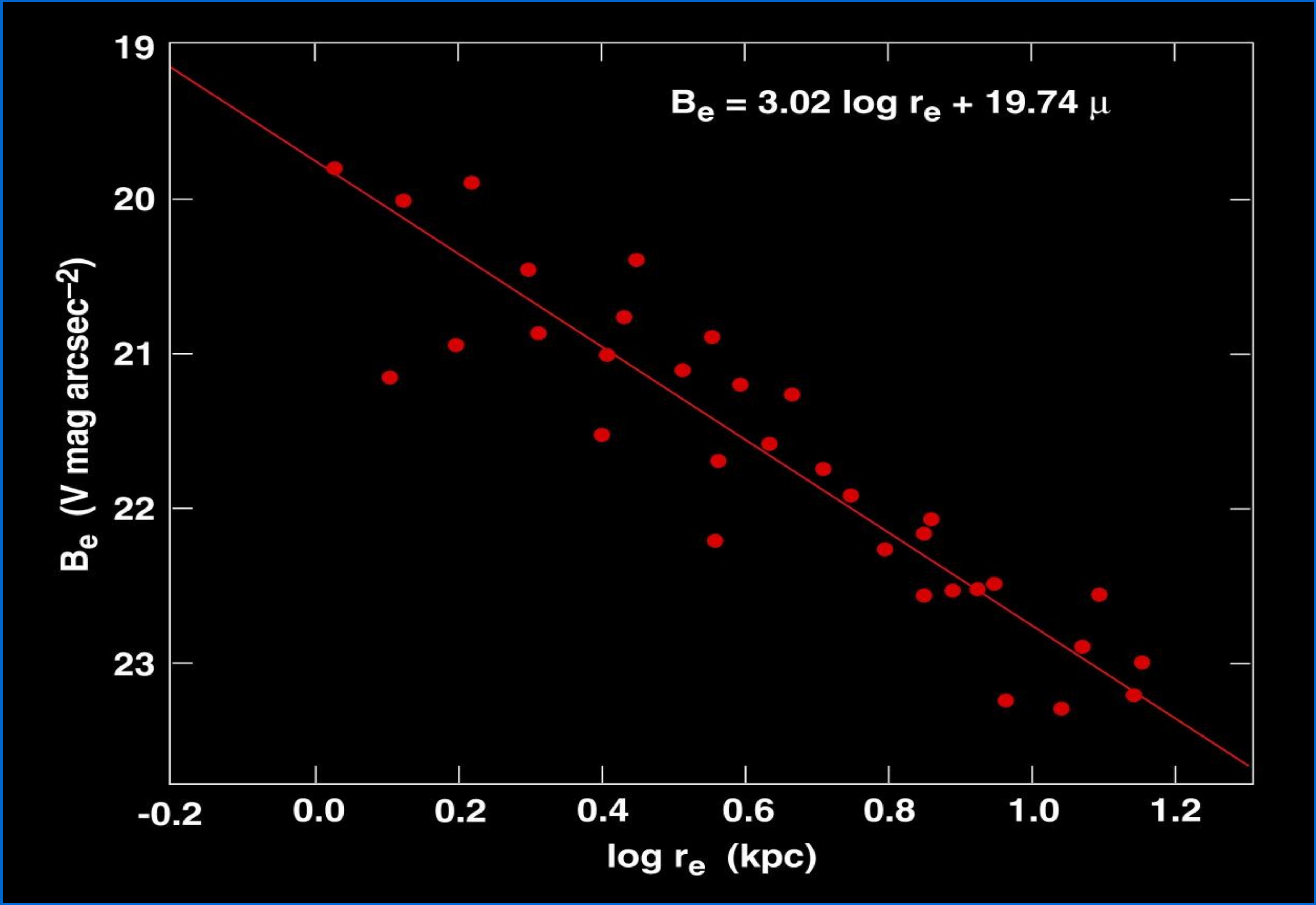
- There are other correlations
  - Brighter ellipticals are bigger
  - Brighter ellipticals have lower average surface brightness
  - Can put these two together and form the Kormendy relation – larger galaxies have lower surface brightnesses: $\mu_{B,e} = 3.02 \log r_e + 19.74$
  - Brighter ellipticals have lower central surface brightness
  - Brighter ellipticals have larger core radii -- the core radius is the radius where the SB drops to ½ that of the central SB, I(r=0)

Effective radius vs M_B



$<\Sigma>$ vs M_B

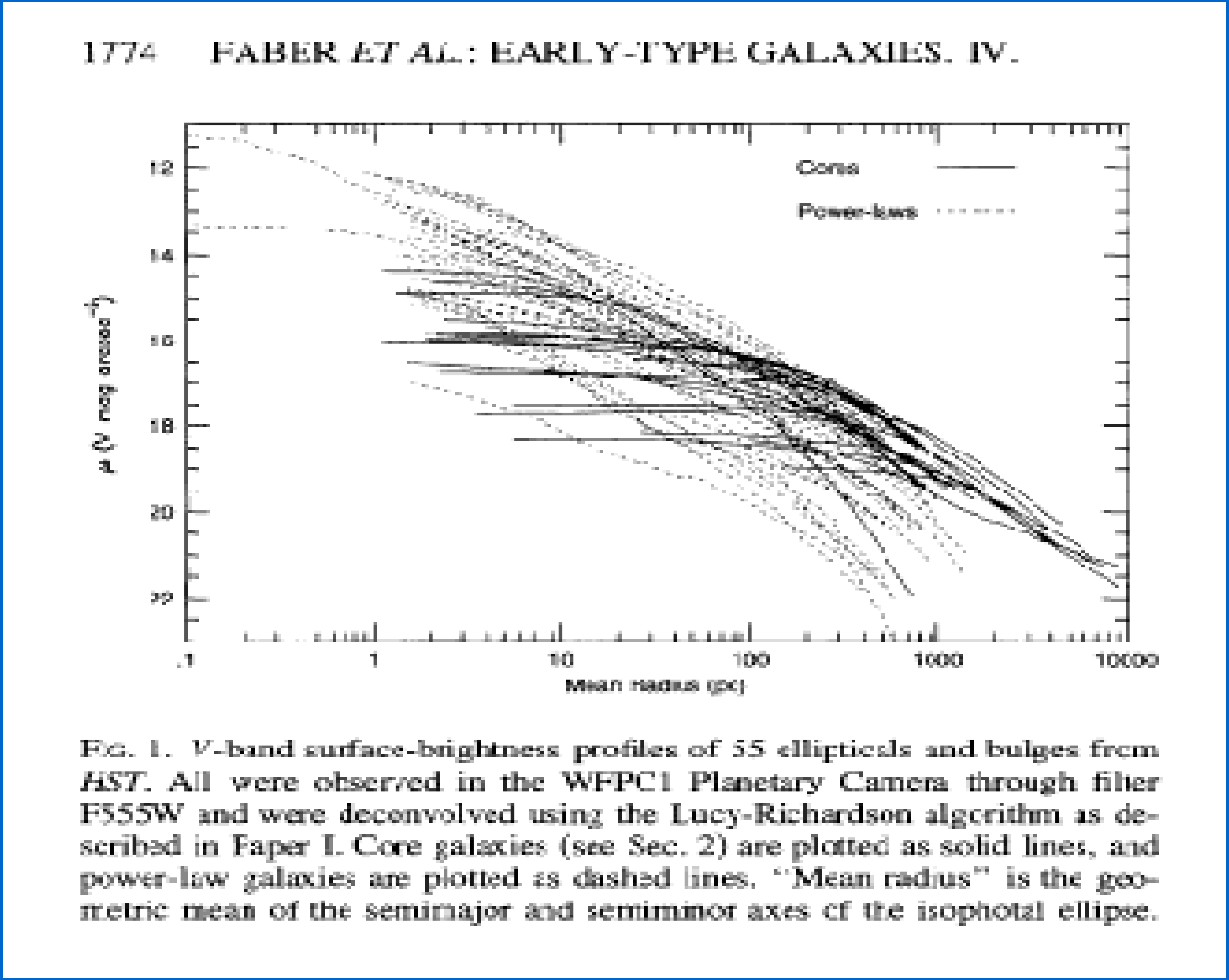

17
18
19
20
21
22
23
24
25
26
27
28
−6
−8
−10
−12
−14
−16
−18
−20
−22
−24
μ_{avc} (B-mag arcsec^{-2})
M_B
● gE's
△ Int E's
■ cE's
◆ Bright dE's
▼ dSph's
○ Bulges
normal E's
dwarf E's



Kormendy (1977) relation

What do the cores of ellipticals look like?

- The core of ellipticals is very hard to study because of atmospheric effects
- Not a problem with HST
  - Luminous ellipticals have power law cores
  - Moderate and dwarf ellipticals have central cusps



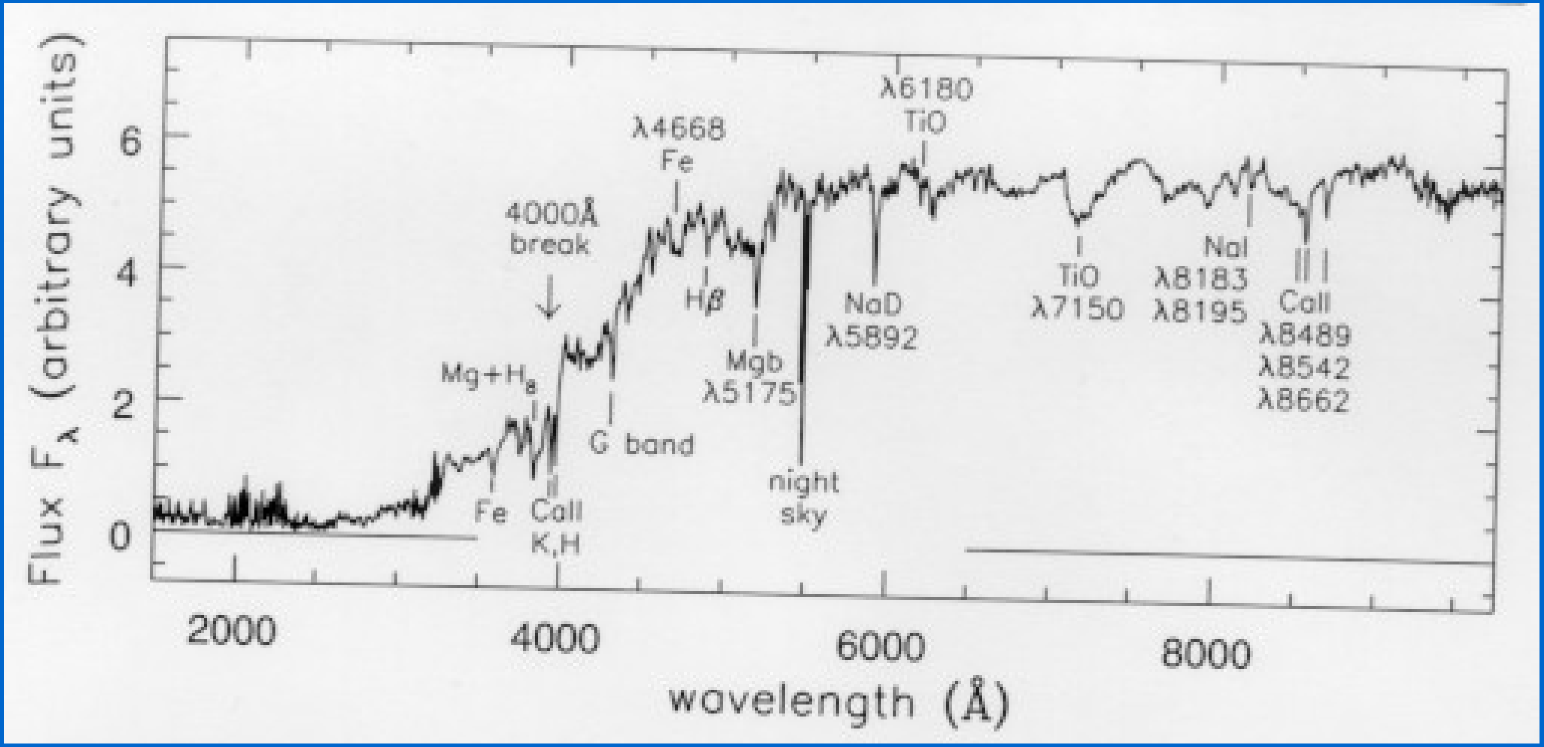
1774 FABER *ET AL.*: EARLY-TYPE GALAXIES. IV.

FIG. 1. *V*-band surface-brightness profiles of 55 ellipticals and bulges from *HST*. All were observed in the WFPC1 Planetary Camera through filter F555W and were deconvolved using the Lucy-Richardson algorithm as described in Paper I. Core galaxies (see Sec. 2) are plotted as solid lines, and power-law galaxies are plotted as dashed lines. "Mean radius" is the geometric mean of the semimajor and semiminor axes of the isophotal ellipse.

Stellar Populations

- Ellipticals are full of old, red stars
- Ellipticals follow a color-magnitude relation such that more luminous galaxies are redder
  - Is this due to age or metallicity?
- This is known as the age/metallicity degeneracy!!

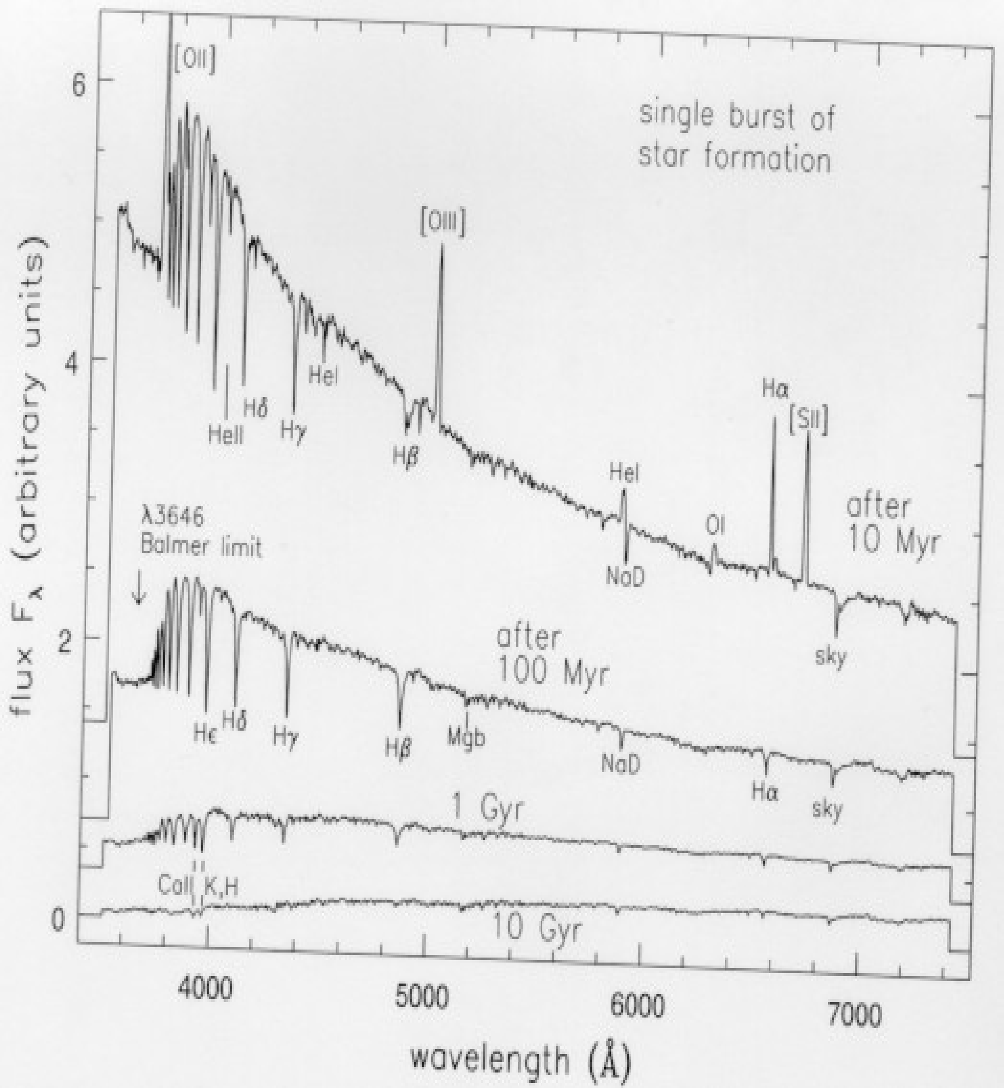
Elliptical Spectrum



Note the lack of emission lines! The strong absorption lines are from metals. Metallicity in ellipticals are close to solar metalicity.

Starburst Spectra

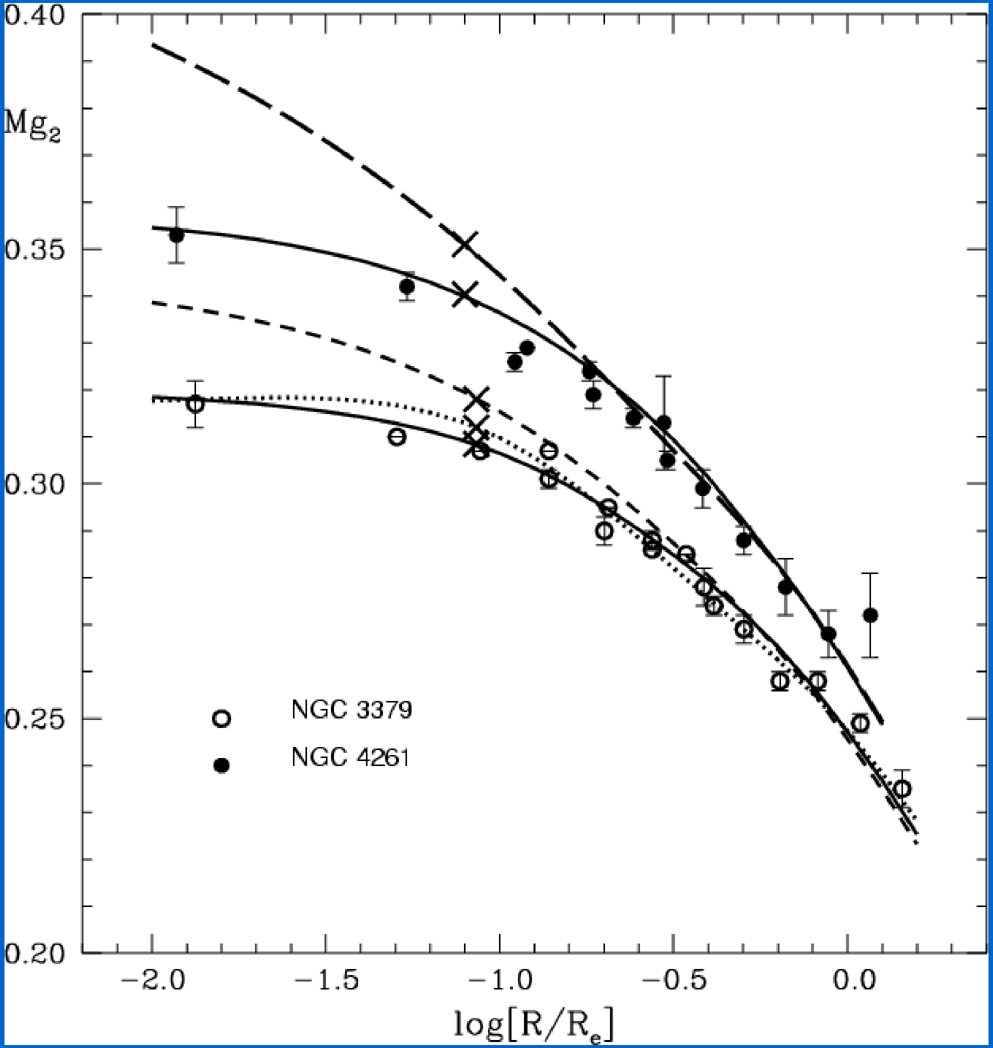
- If smaller ellipticals are younger then they should be bluer
  - A young starburst has a very blue spectrum
  - As the population ages it becomes redder and we see lots of A stars (E+A galaxies)
  - After 2×10^9 yrs we see a spectrum similar to ellipticals today



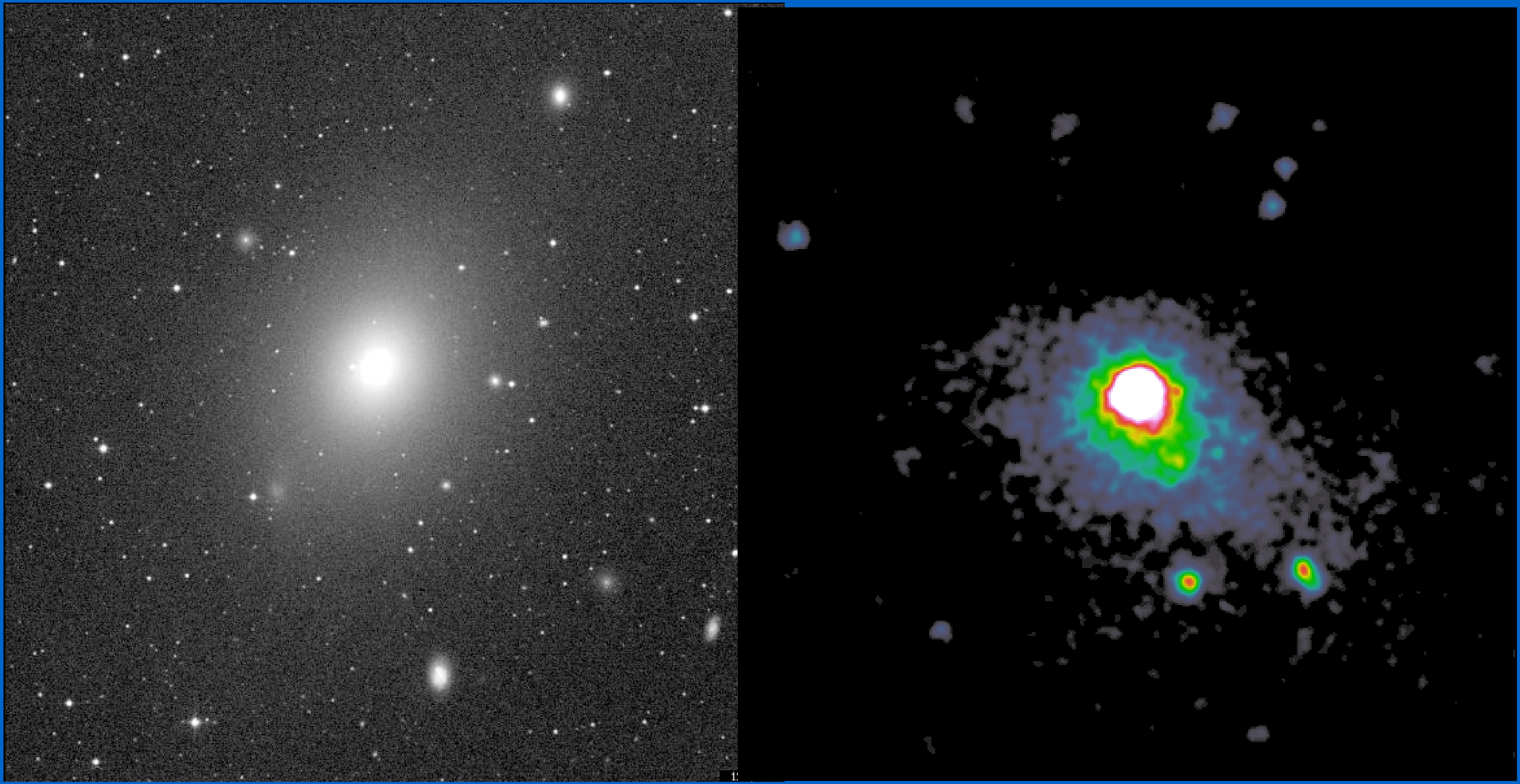
Metallicity

- Can also be a metallicity effect
  - Lower metallicity
  - Less absorption in the blue part of the spectrum
  - Bluer galaxy
- Why would smaller galaxies have less metals
  - Less luminosity --> less mass
  - SNe explosions --> high speed gas
  - So less massive galaxies are less effective at retaining metal rich gas
  - This would lead to a trend that smaller ellipticals would be bluer!

Abundance Gradients



X-ray Halos



Optical and X-ray images of M49

X-ray Halos cont.

- Where does the hot gas come from
  - We know that it is metal rich (Z~0.5 solar)
  - Stellar winds from red giants and red supergiants
    - Random velocities ≥ 350 km/s and we know that $(1/2)m\sigma^2 \sim 3/2\ kT$
    - So when the stellar winds collide it heats the gas to $> 10^6$ K
- The mass of hot gas can be from $10^8 - 10^{11}\ M_\odot$

Globular Clusters in Ellipticals

- Ellipticals are surrounded by a halo of globular clusters (~ 2x the number of a spiral with similar luminosity)
- Colors of globular clusters show a bimodal distribution in ellipticals
- This is probably due to metallicity, so there is a population of metal poor and a population of metal rich GCs

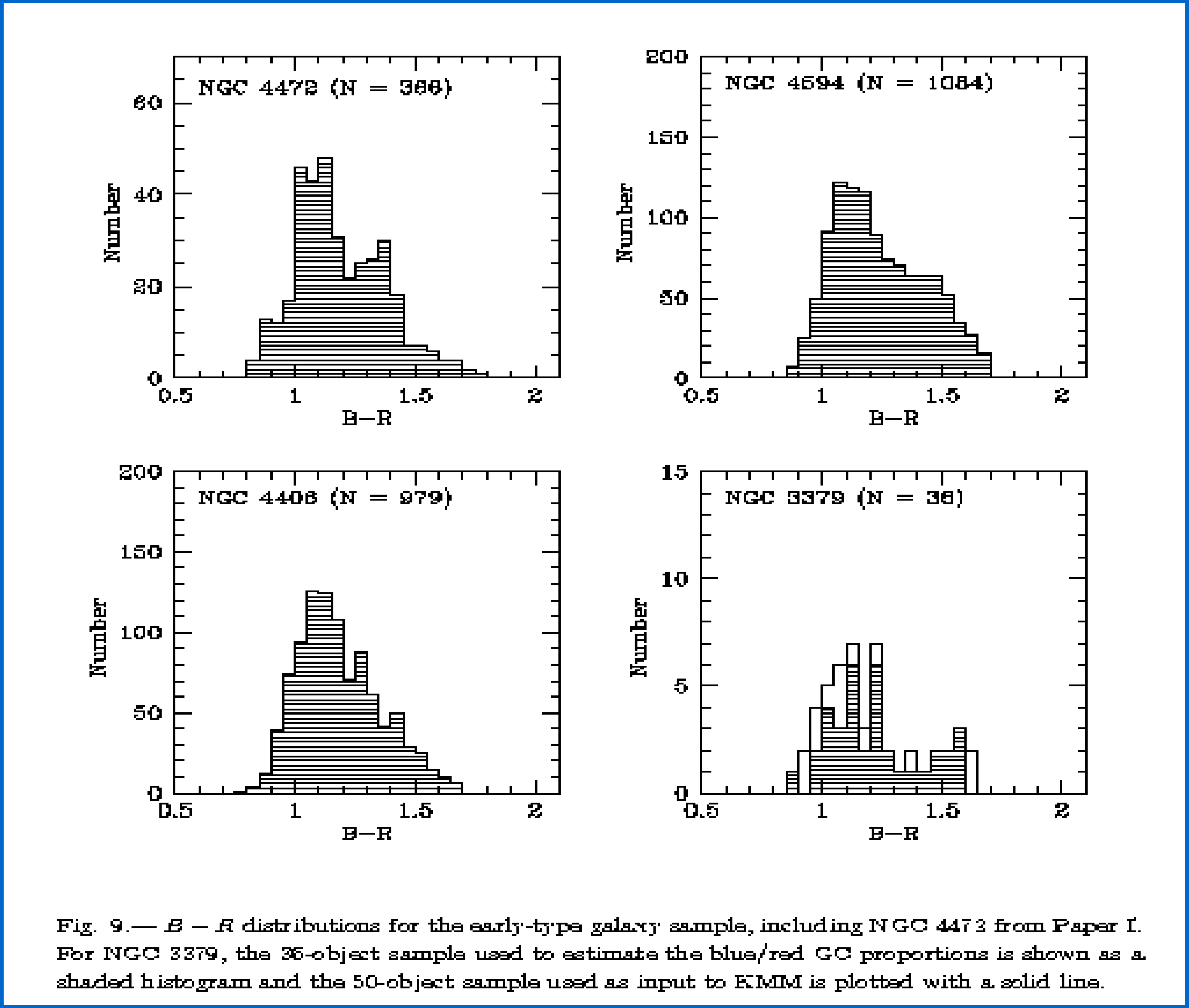


Fig. 9.— $B - R$ distributions for the early-type galaxy sample, including NGC 4473 from Paper I. For NGC 3379, the 36-object sample used to estimate the blue/red GC proportions is shown as a shaded histogram and the 50-object sample used as input to KMM is plotted with a solid line.

E2

S0's

E3

E5

Rhode & Zeph (2004)
What does this mean?

Globular Clusters in Ellipticals cont.

- This could be caused by the
  - Merger of two galaxies – metal poor clusters are old, metal rich clusters formed during merger process
  - Hierarchical formation – Metal poor GC's are form at an early time and the metal rich population builds up during accretion of gas rich spirals