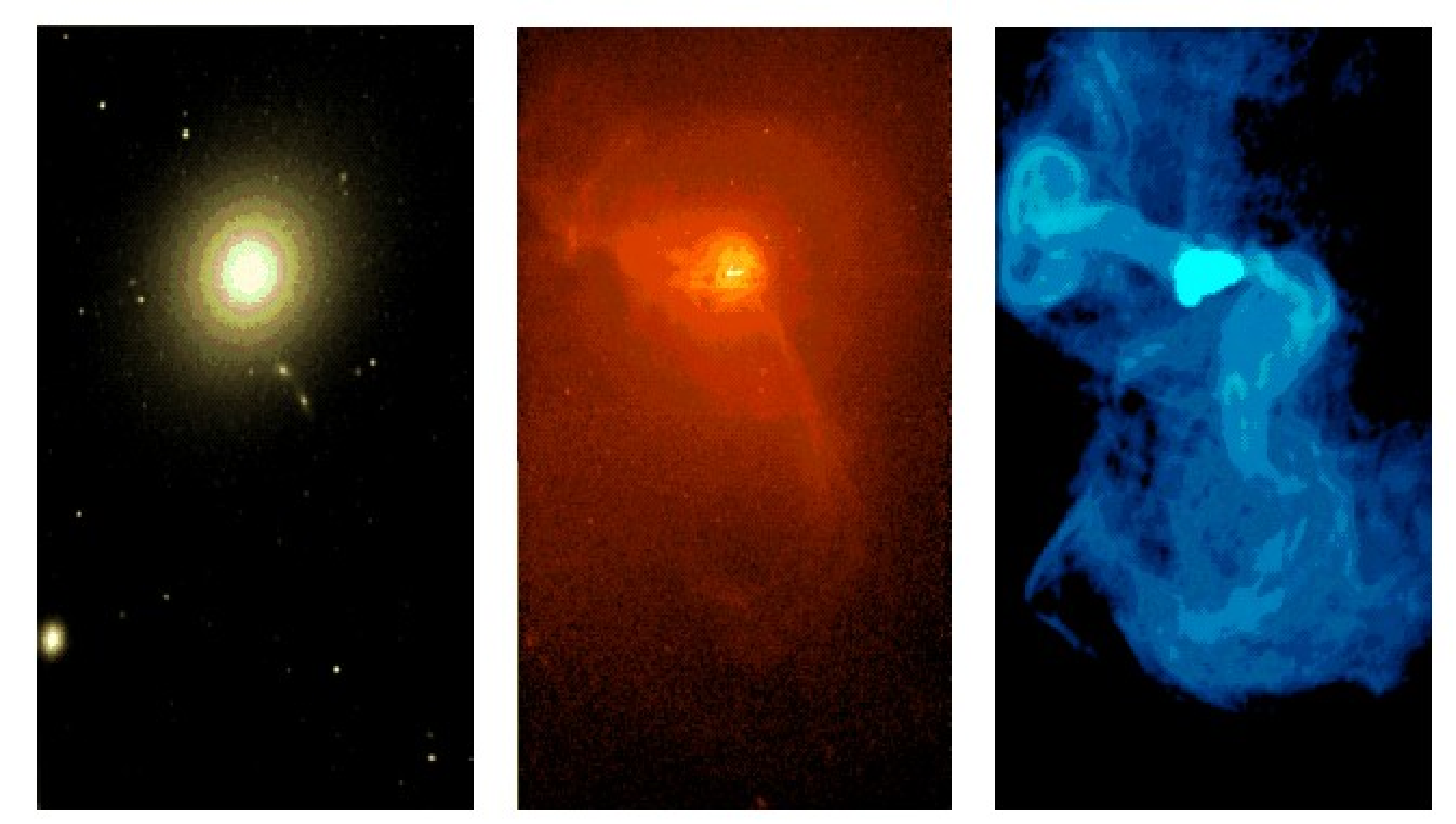
Ellipticals cont.

- 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.

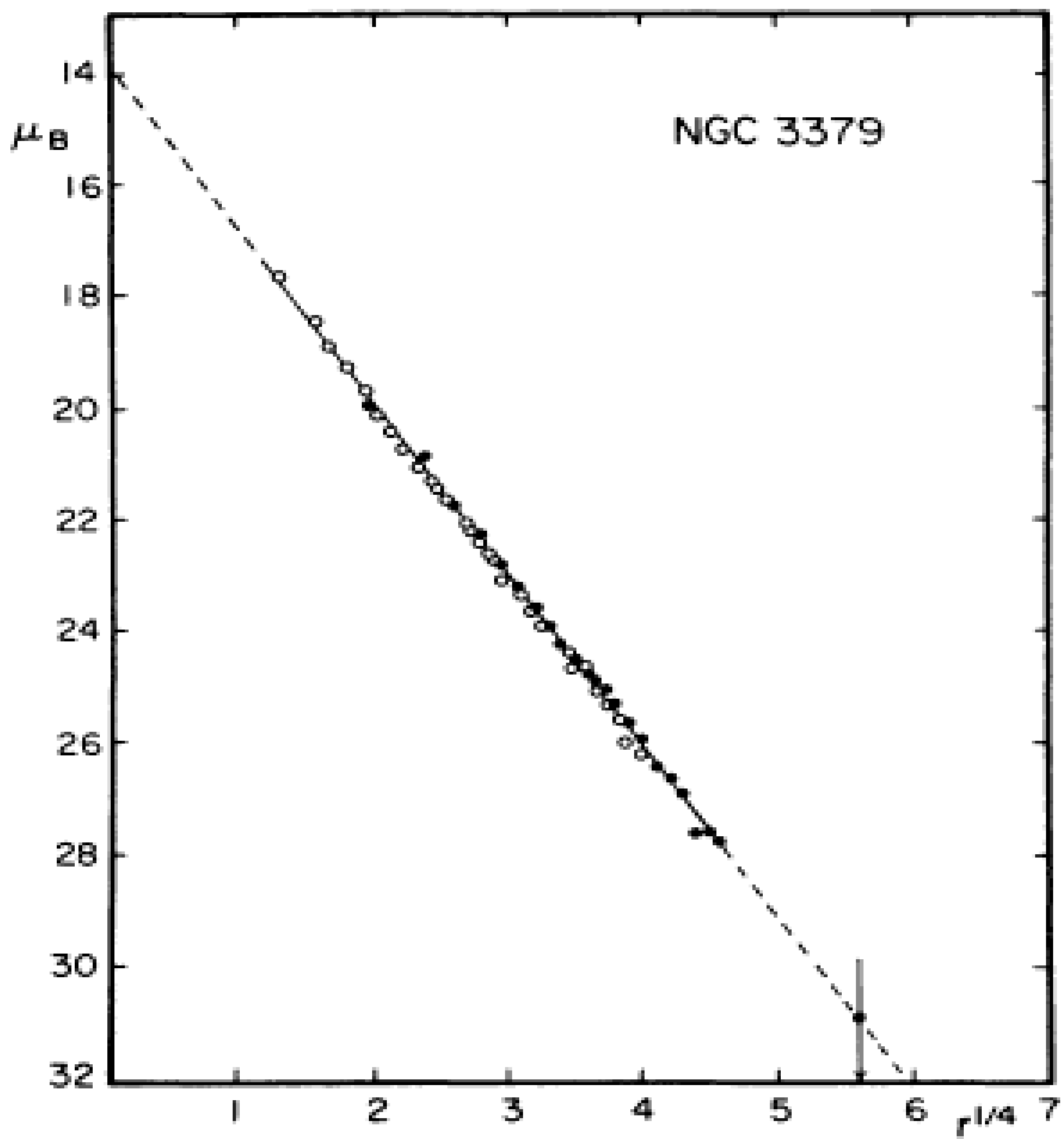
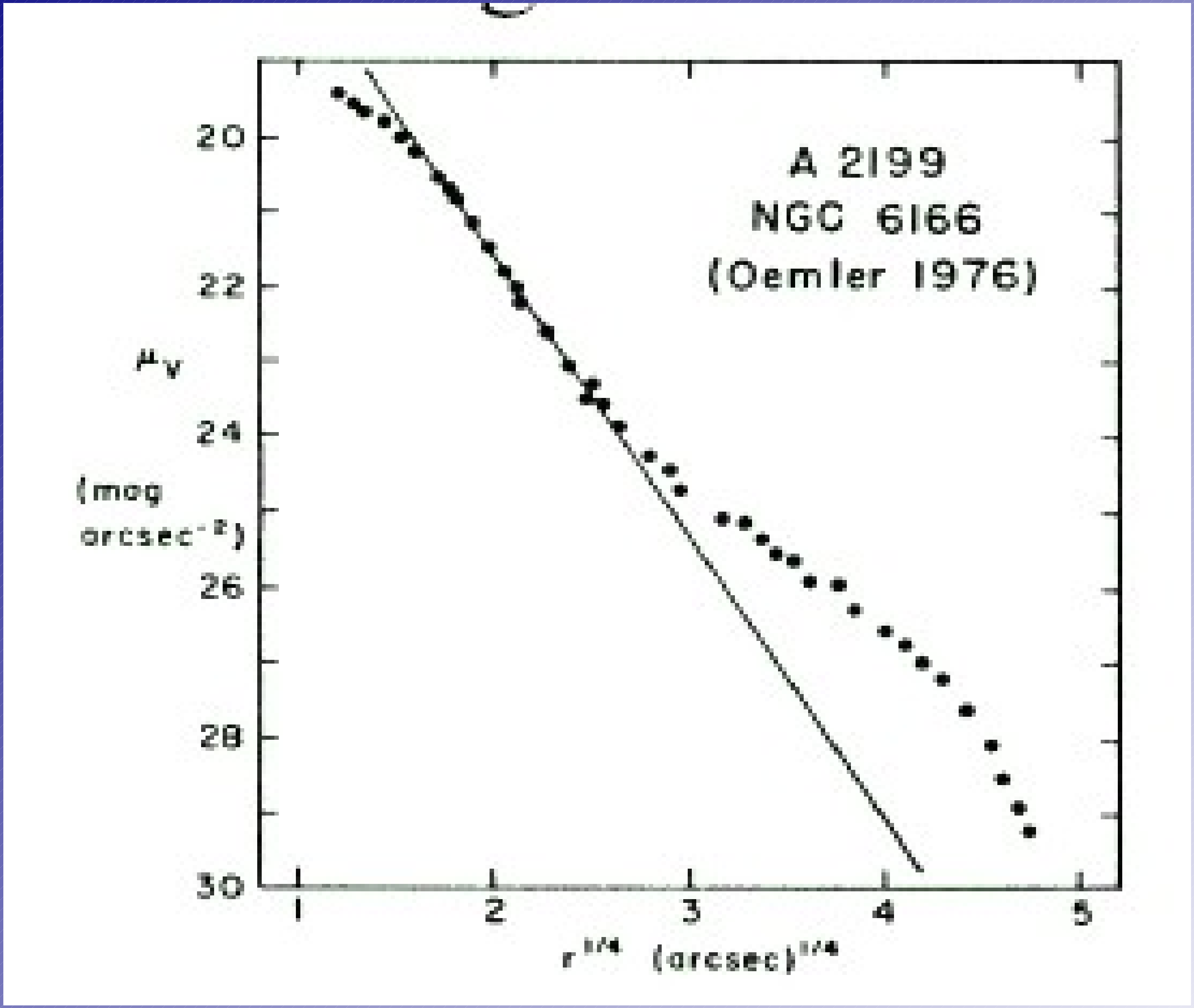
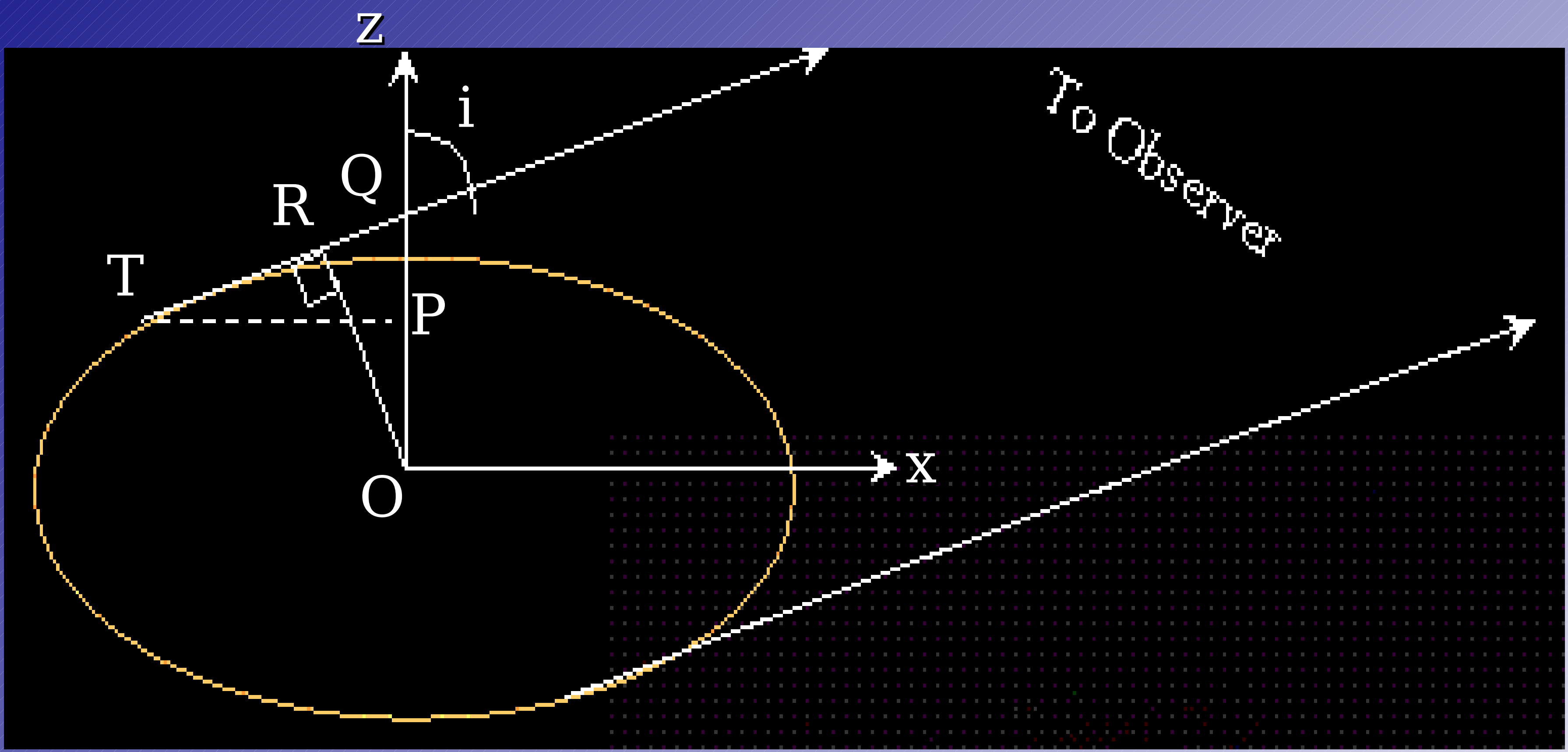


FIG. 2.—Mean E-W luminosity profile of NGC 3379 derived from McDonald photoelectric data. ●, Pe 4 data with 90 cm reflector; ○, Pe 1 data (M + P) with 2 m reflector. Note close agreement with $r^{1/4}$ law.



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)$^{1/4}$



If elliptical galaxies are oblate spheroids then

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

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

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

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

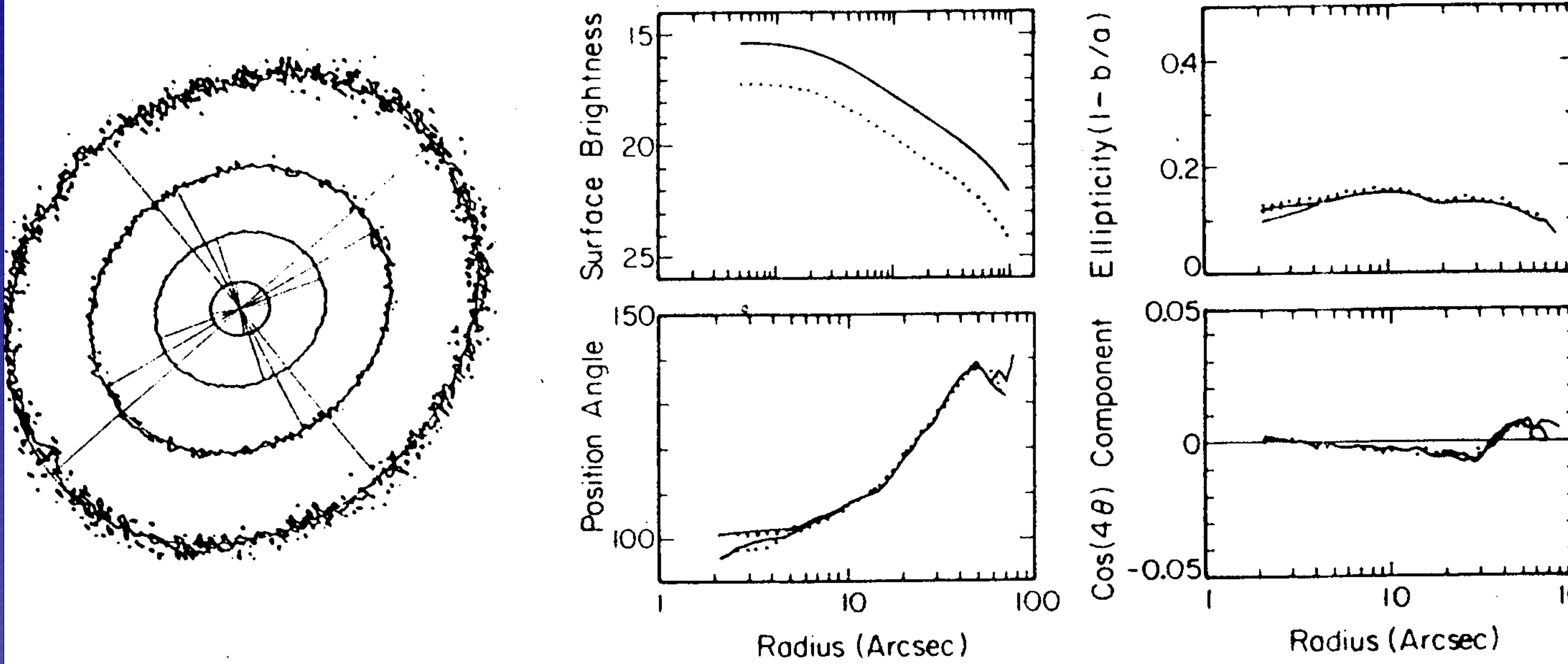
For very flattened systems, B<<A the distribution is almost uniform

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?

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 he minor axes overlaid. The four right hand panels give the surface brightness, he 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 he B band.*

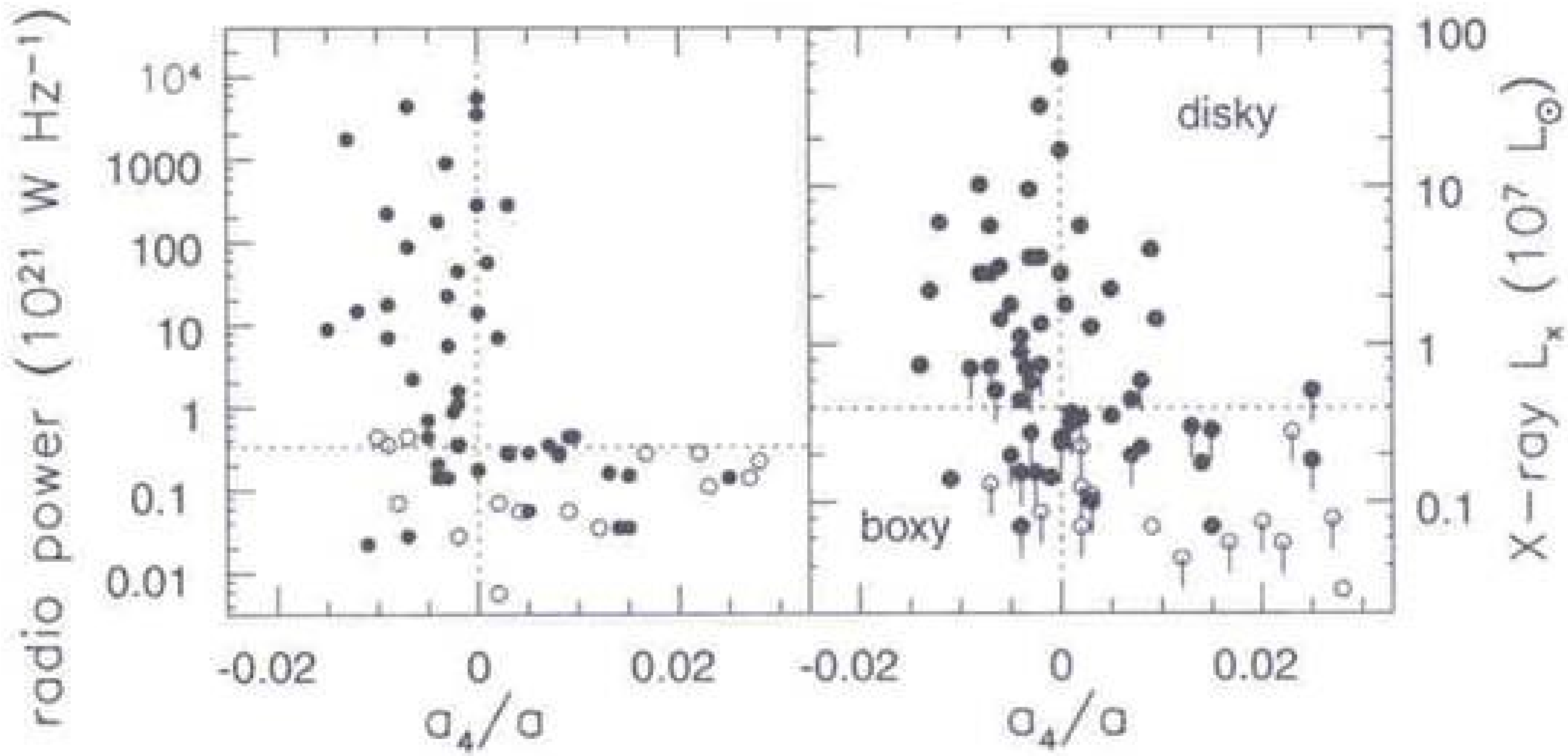
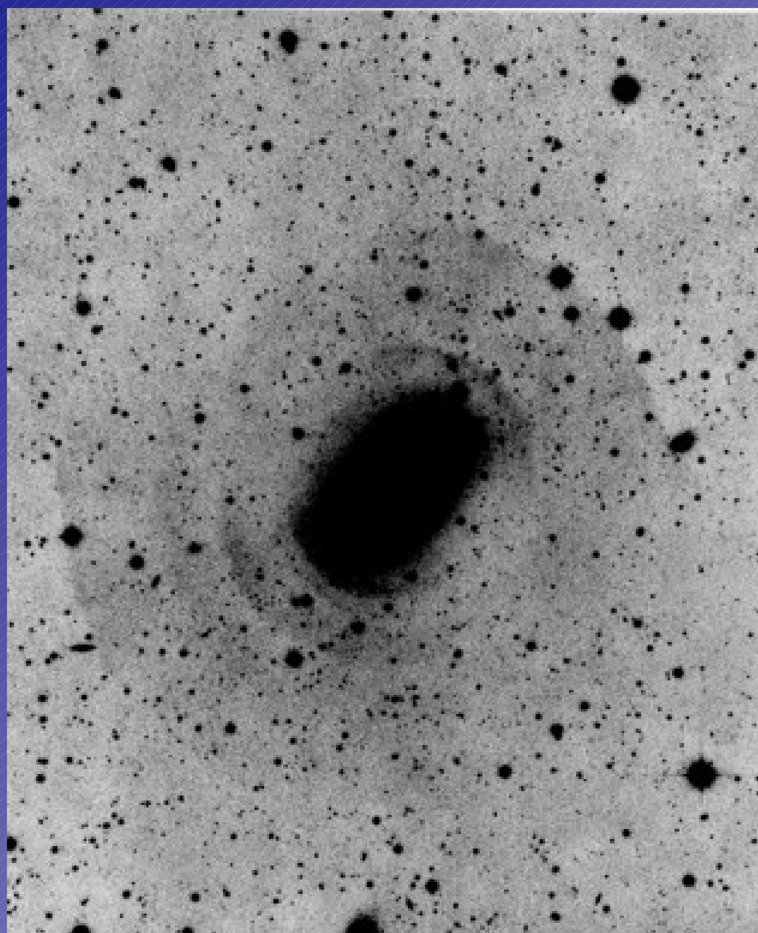


Figure 6.11 Radio and X-ray power of elliptical galaxies. Boxy galaxies, with $a_4 < 0$, tend to be strong sources; disky ellipticals, with $a_4 > 0$, are usually weak. Filled circles show bright objects, with $M_B < -19.5$; open circles are dimmer galaxies. Points with downward-extending bars show upper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

Shell Galaxies



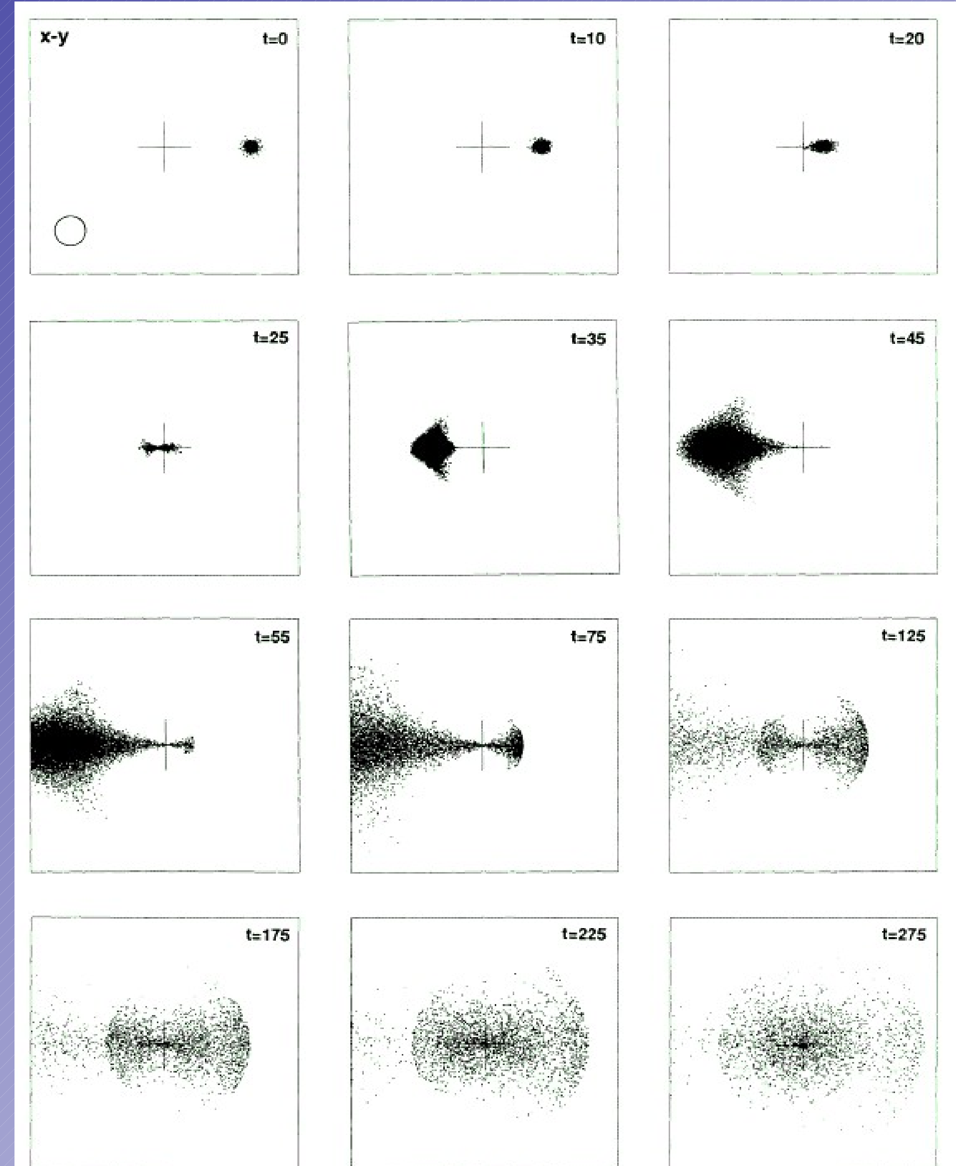


Figure 1. A radial encounter between a spherical Plummer primary and a spherical companion. The companion mass was 0.01 and its half-mass radius was 0.2 (both 1 for primary). The circle in the first frame indicates a spherical primary was used and the cross is at the center-of-mass.

- 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

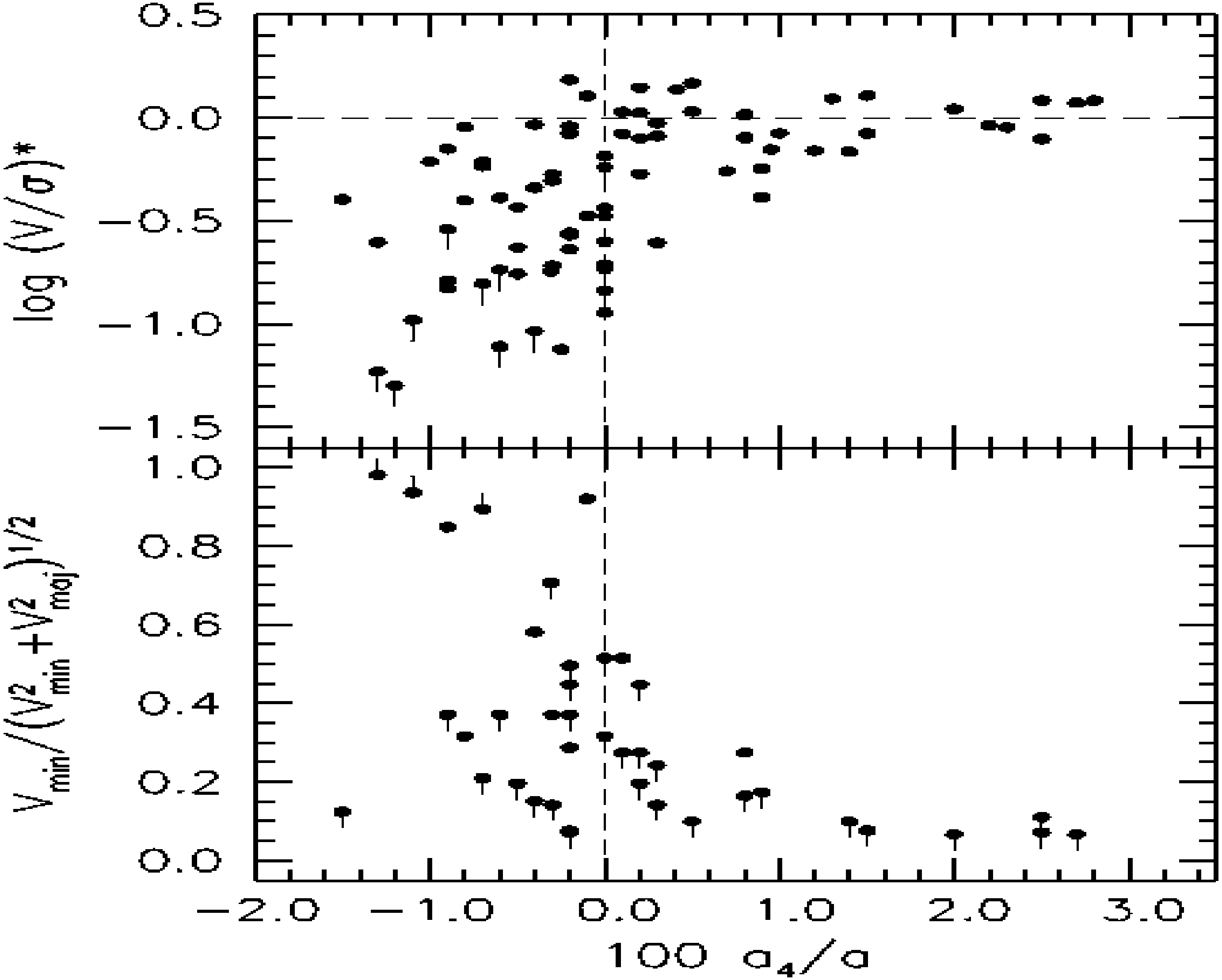
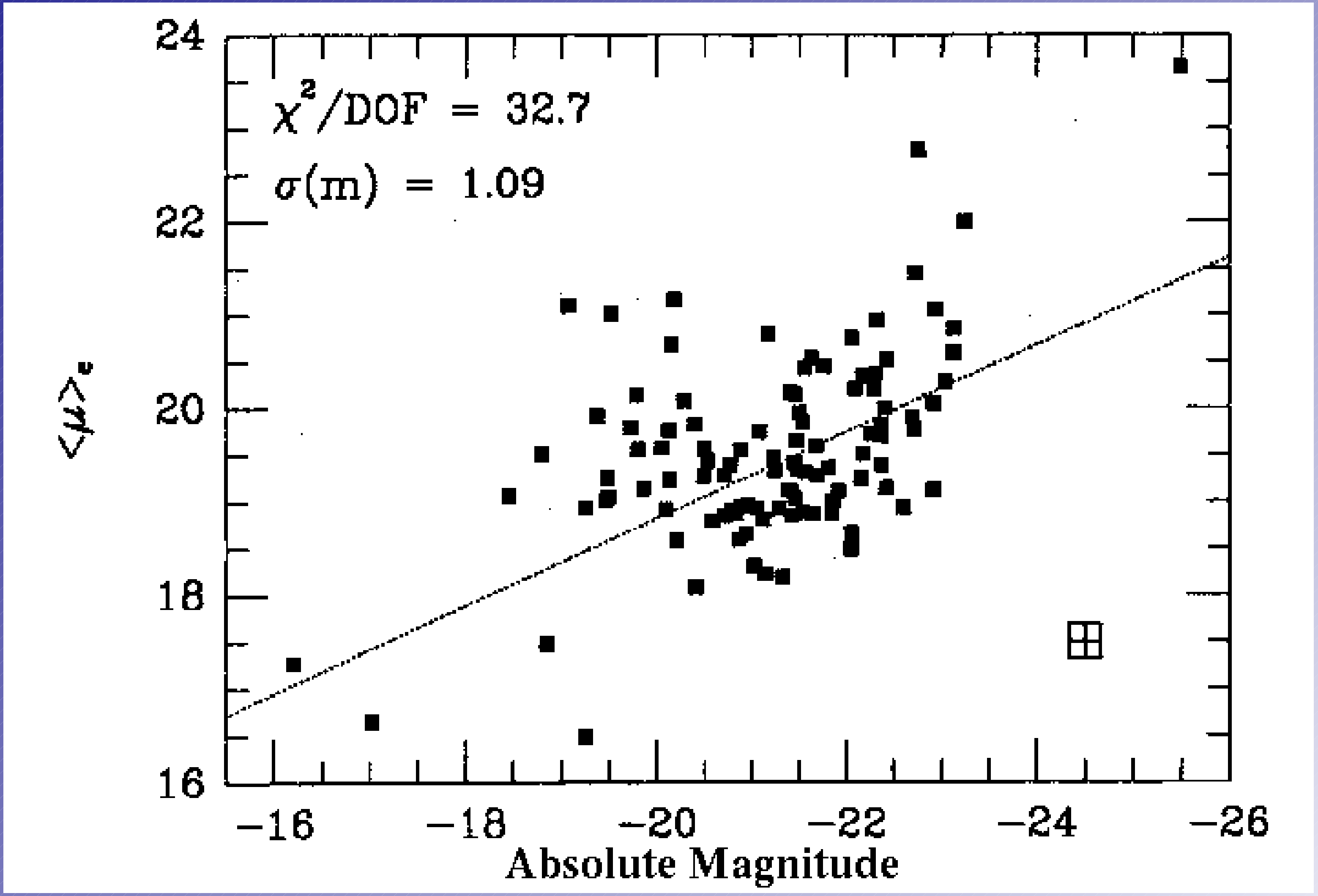


FIG. 2.—Correlations with isophote shape of parameters that are diagnostic of velocity anisotropy. Here $100\,a_4/a$ is the percent inward or outward perturbation of isophote radii along the major axis; negative values imply boxy isophotes; positive values imply disky isophotes. The upper panel shows 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.

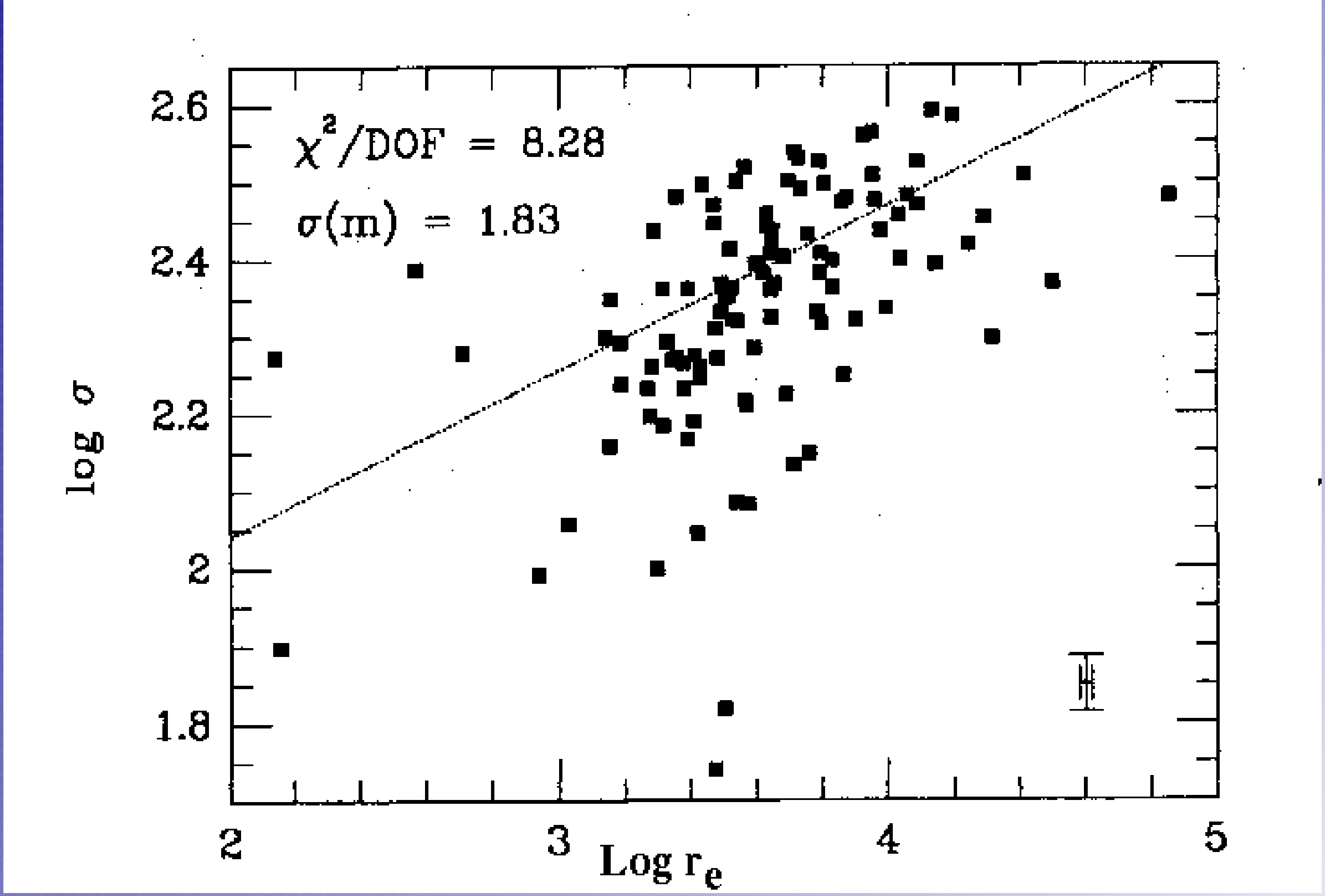
Elliptical Isophotes

Characteristic	Boxy isophotes	Disky isophotes
Support	Mainly pressure	More rotational support
M/L ratio	Generally high with a wide range	Generally lower with a narrower range
Radio Luminosity	Brighter	Fainter
X-ray Luminosity	Brighter with a diffuse halo and discrete sources	Fainter with discrete sources dominate
Core	Frequent counter-rotating cores	Rarely have counter-rotating cores
Shape	Triaxial	Spheroidal

Surface Brightness vs Luminosity



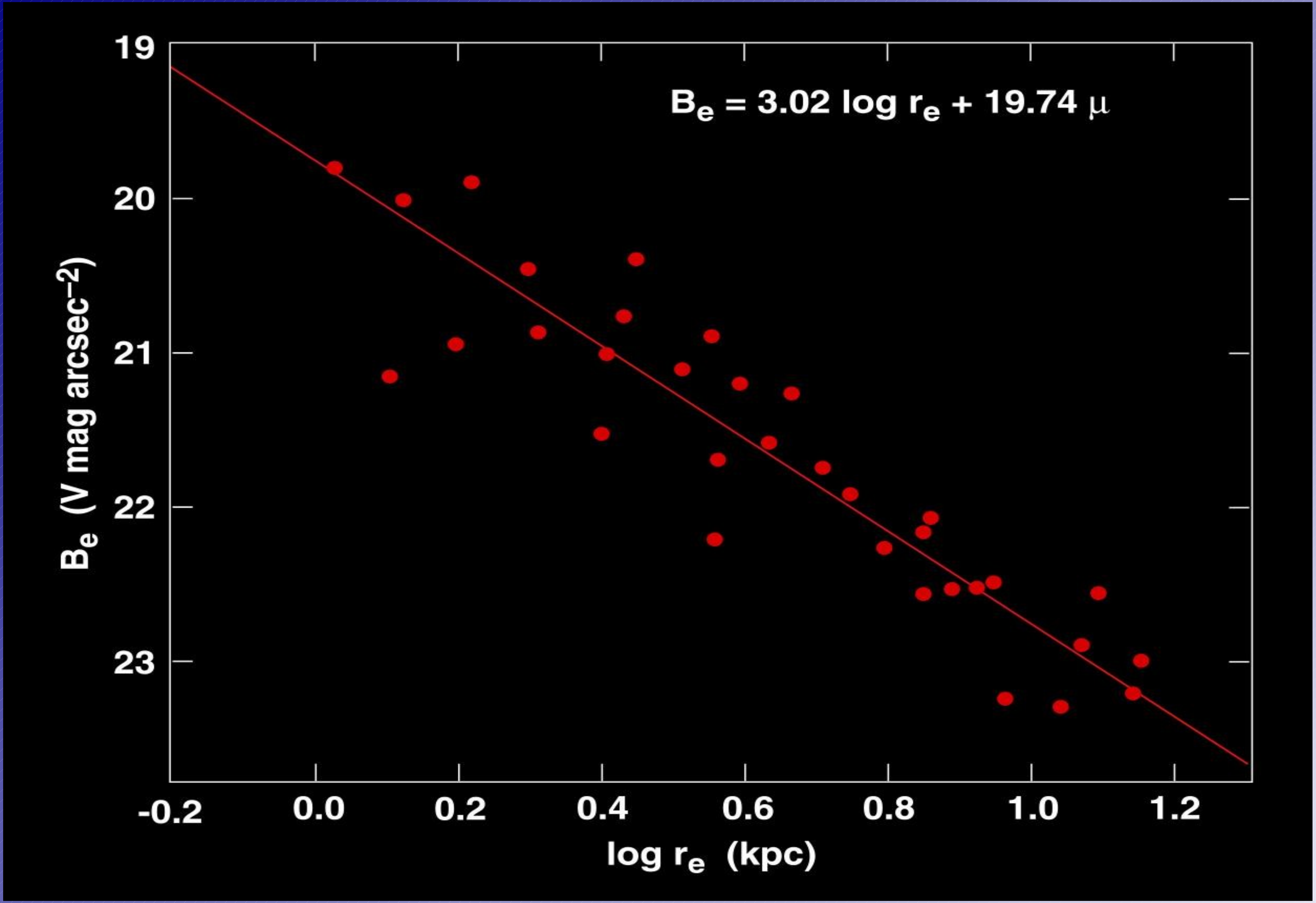
σ_r vs R_e



- 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:
    $\Sigma_{B,e} = 3.02 \log r_e + 19.74$
  - 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)

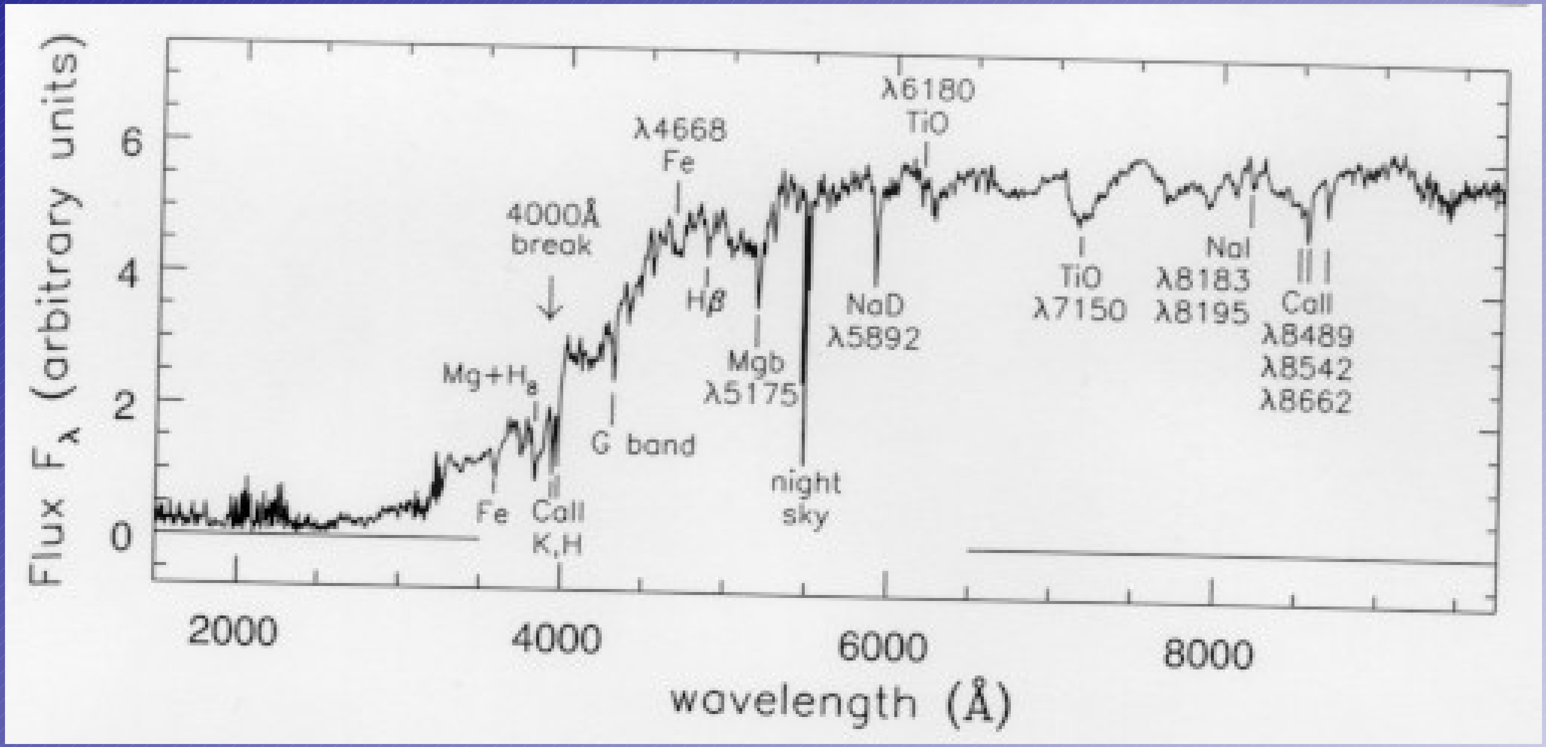


Kormendy (1977) relation

What do the cores of ellipticals look like?

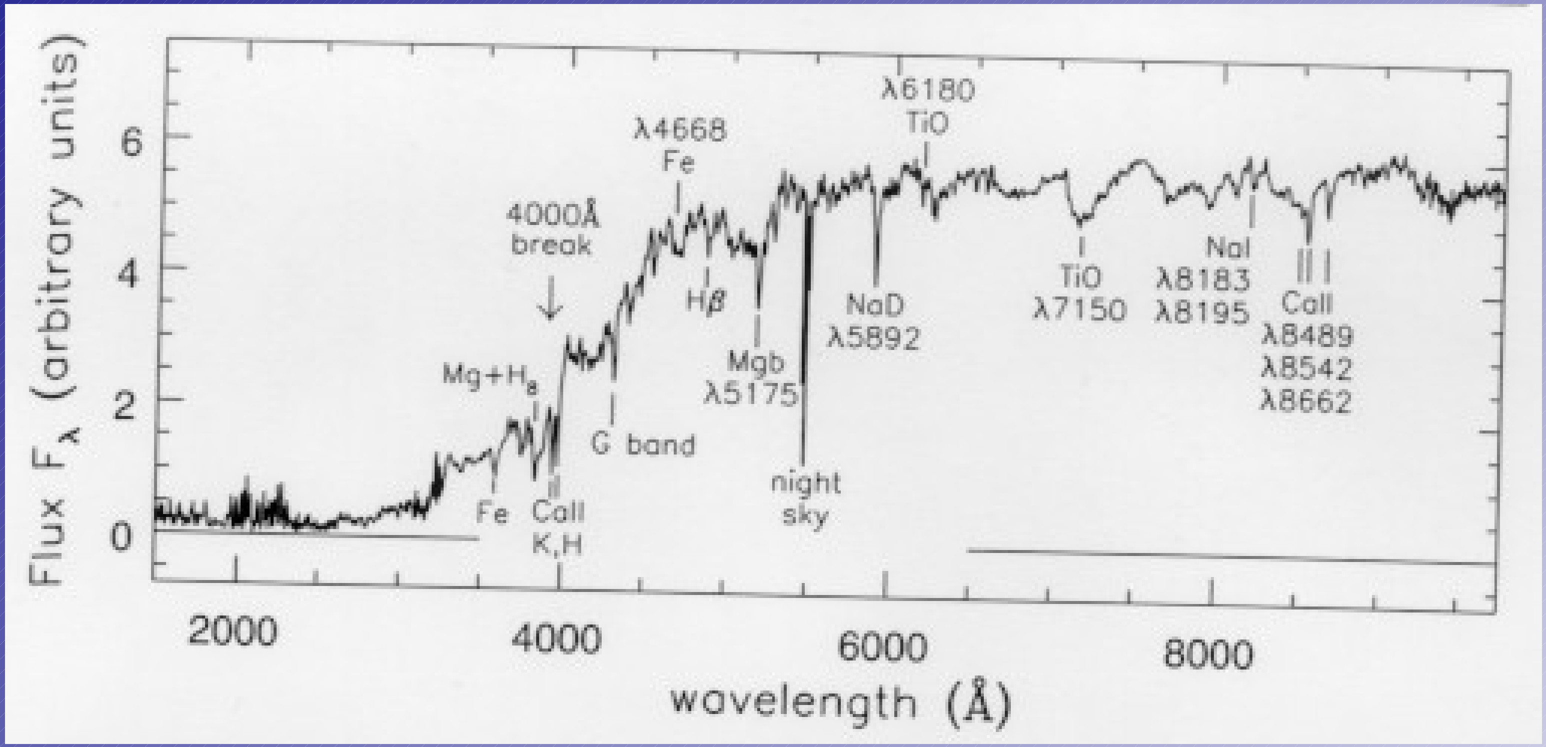
- The core of ellipticals is very hard to study because of atmospheric effects
- Not a problem with HST
  - Luminous ellipticals have power law cores
  - Moderate and dwarf ellipticals have central cusps

Elliptical Spectrum



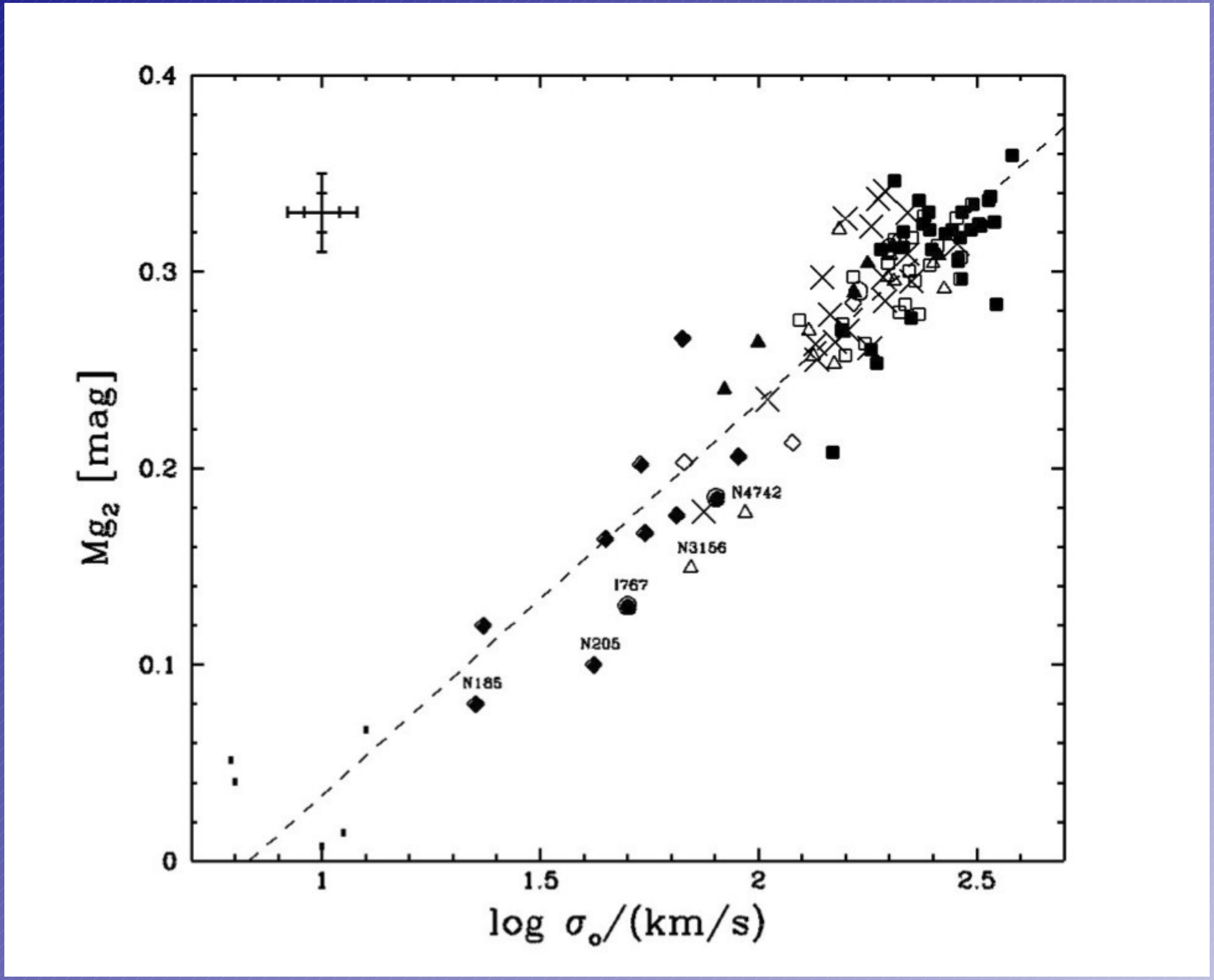
Note the lack of emission lines! The strong absorption lines are from metals. Metallicity in ellipticals are close to solar metallicity.

Elliptical Spectrum



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

Mg_2 vs σ_0



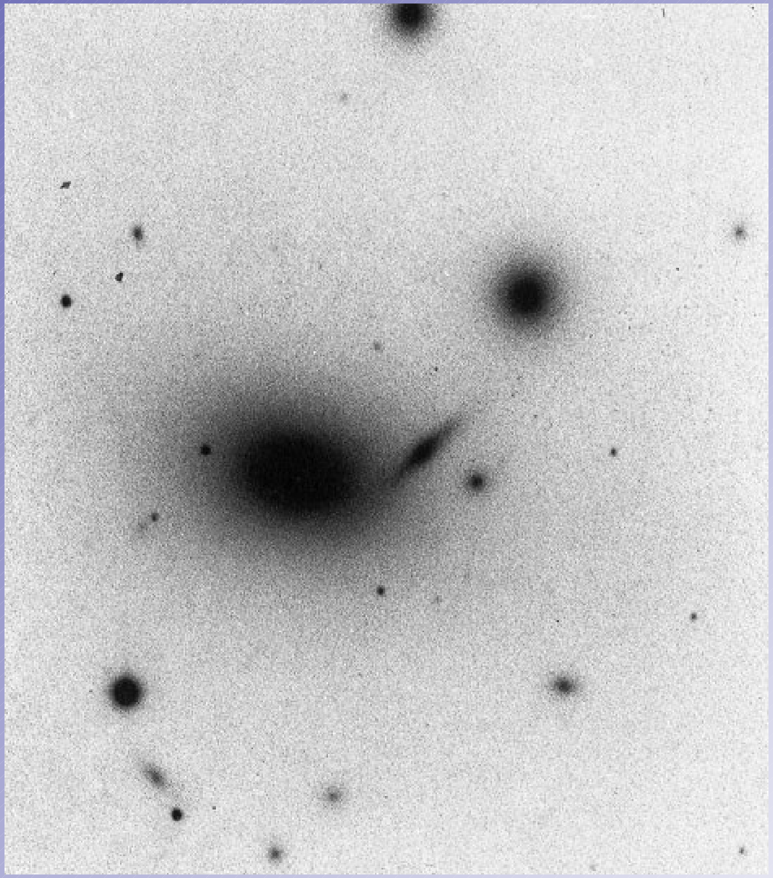
Bender IAU Symp 149
Squares – ellipticals
Crosses – S0 bulge
Diamonds – dwarf
Ellipticals
Open squares-
"special" objects

Mg_2 vs σ_0 origin?

- Velocity dispersion is related to the depth of the potential well
    - σ^2 GM/R_e
- Deeper potentials can
    - Hold on to more SNe enriched gas
    - Enriches the gas near the center of the potential
- Results in a higher stellar and gaseous metallicity

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.

- We can roughly segregate E's by luminosity
  - Luminous: $L>L_*$, $M_B < -20$, $L \approx 2x10^{10} L_\odot$,
  - Midsized: $L \sim (0.1\text{-}1.0)L_*$, $M_B < -18$ to -20, $L \approx 3x10^9 L_\odot$,
  - Dwarf: $L<0.1L_*$, $M_B > -18$, $L<3x10^9 L_\odot$,
- 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)
    - $I(r) = I(r_e) \exp\{-7.67 (r/r_e)^{1/4}-1\}$
  - 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

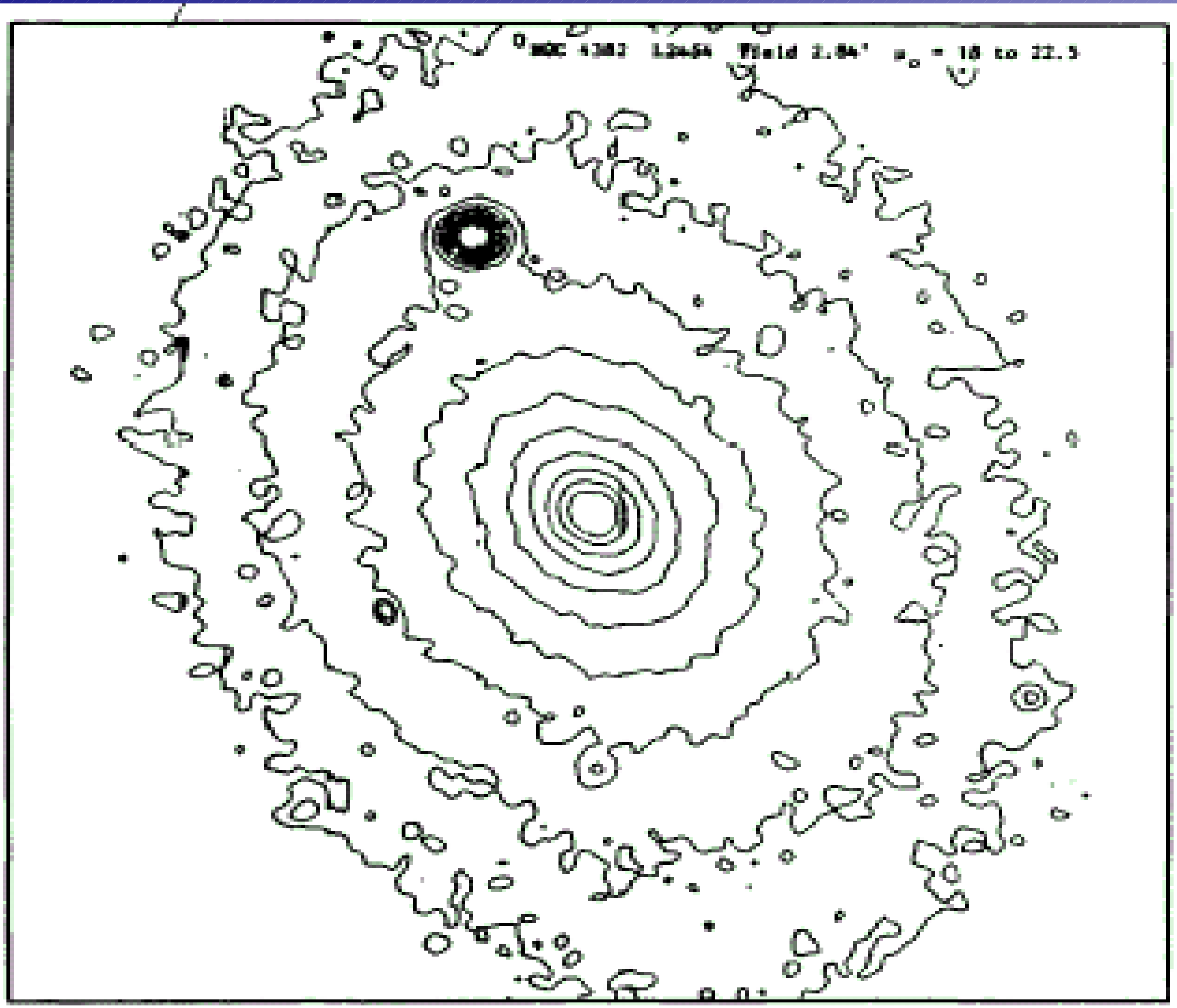


FIGURE 5.5.

Michard 1985

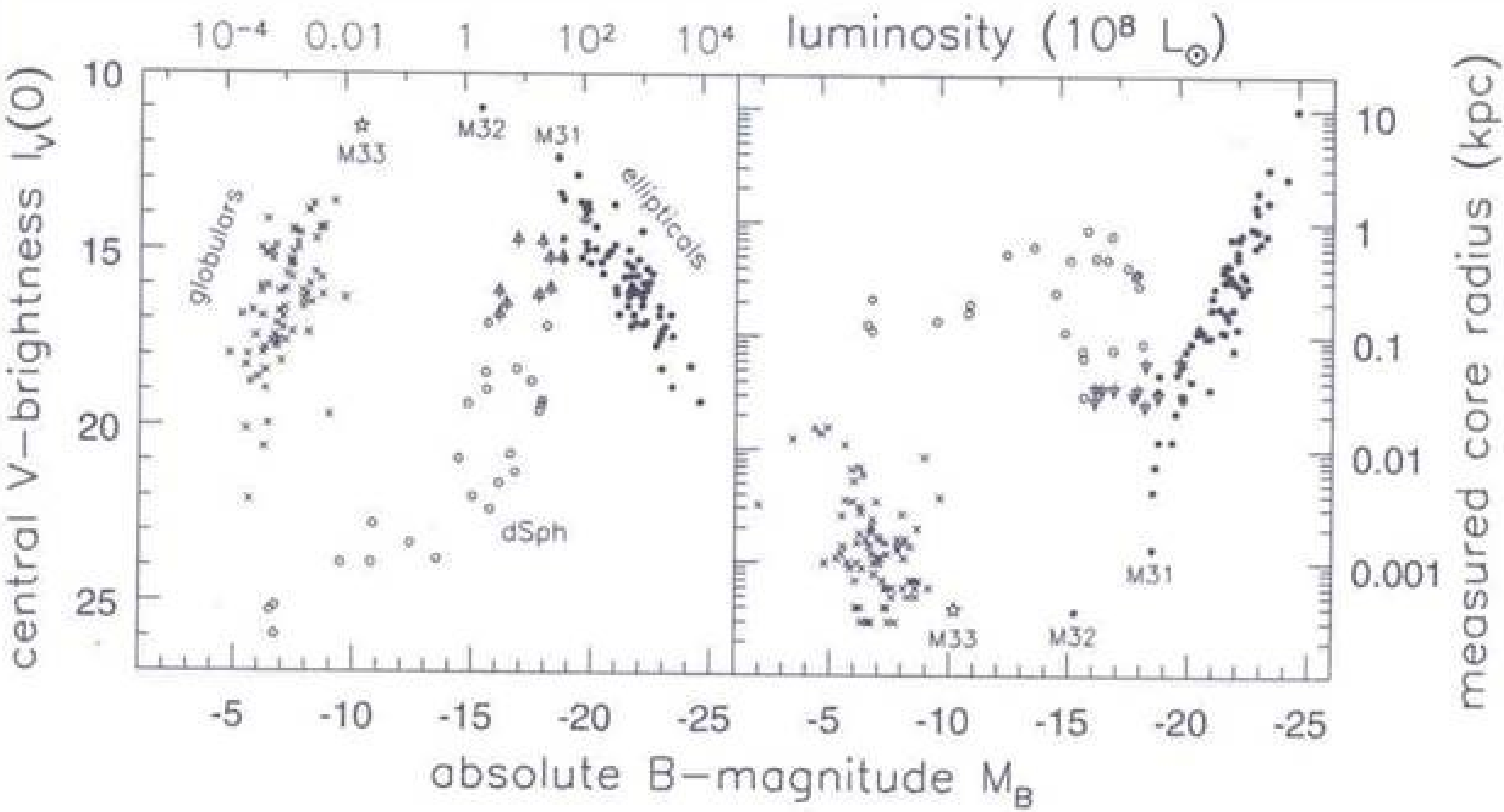


Figure 6.6 Central surface brightness $I_V(0)$ in mag arcsec^{-2} in the V band, and core radius r_c, measured from the ground, plotted against B-band luminosity M_B. Filled circles are elliptical galaxies and bulges of spirals (including the Andromeda galaxy M31); open circles are dwarf spheroidals; 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 q is the ratio of the minor to the major axis then

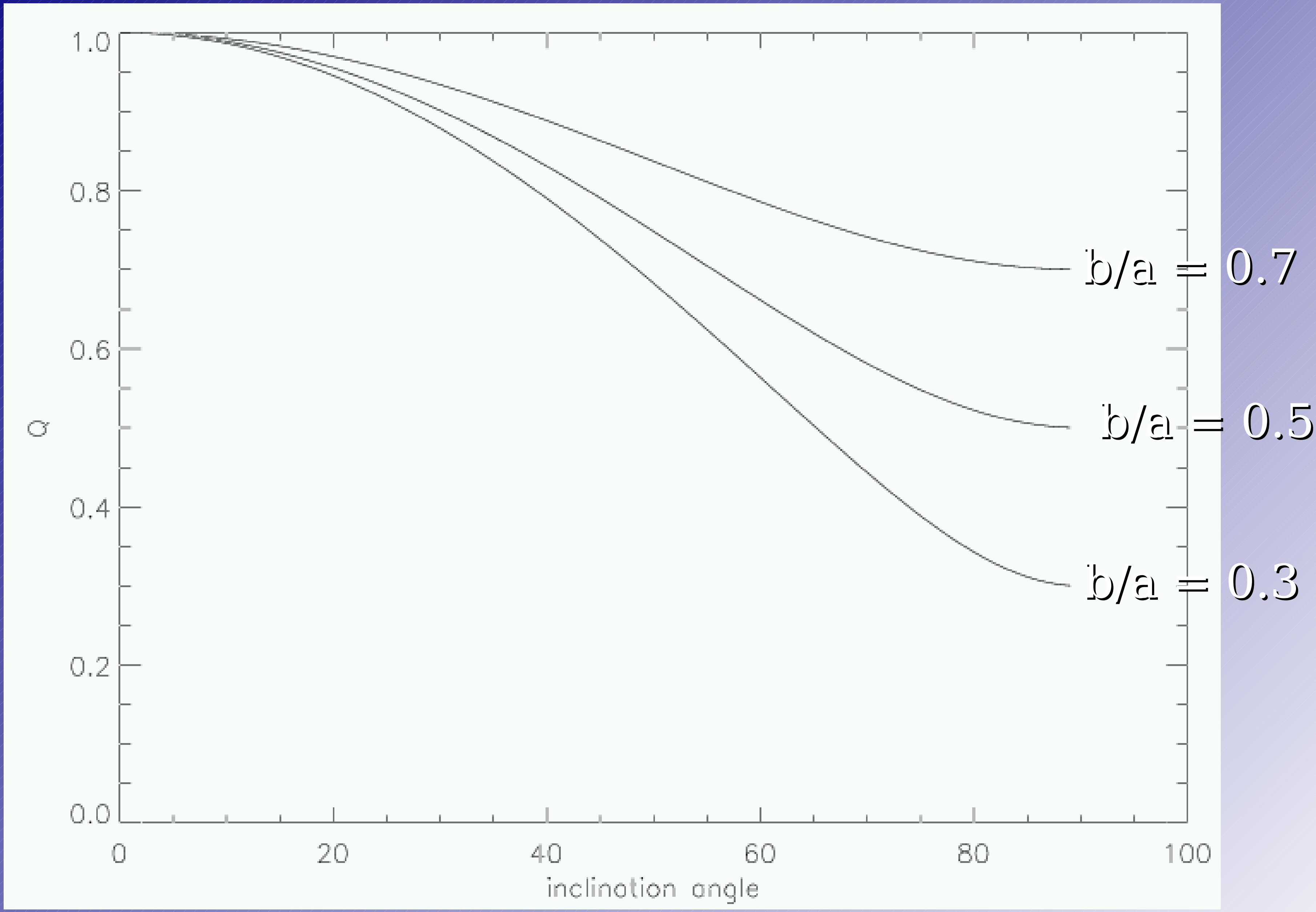
$$q_{obl} = \frac{b}{a} = OQ\,\frac{\sin(i)}{mA} = \frac{B^2 m}{zA}\sin(i) = [\frac{B^2}{A^2} + \cot^2(i)]^{1/2} \sin(i)$$

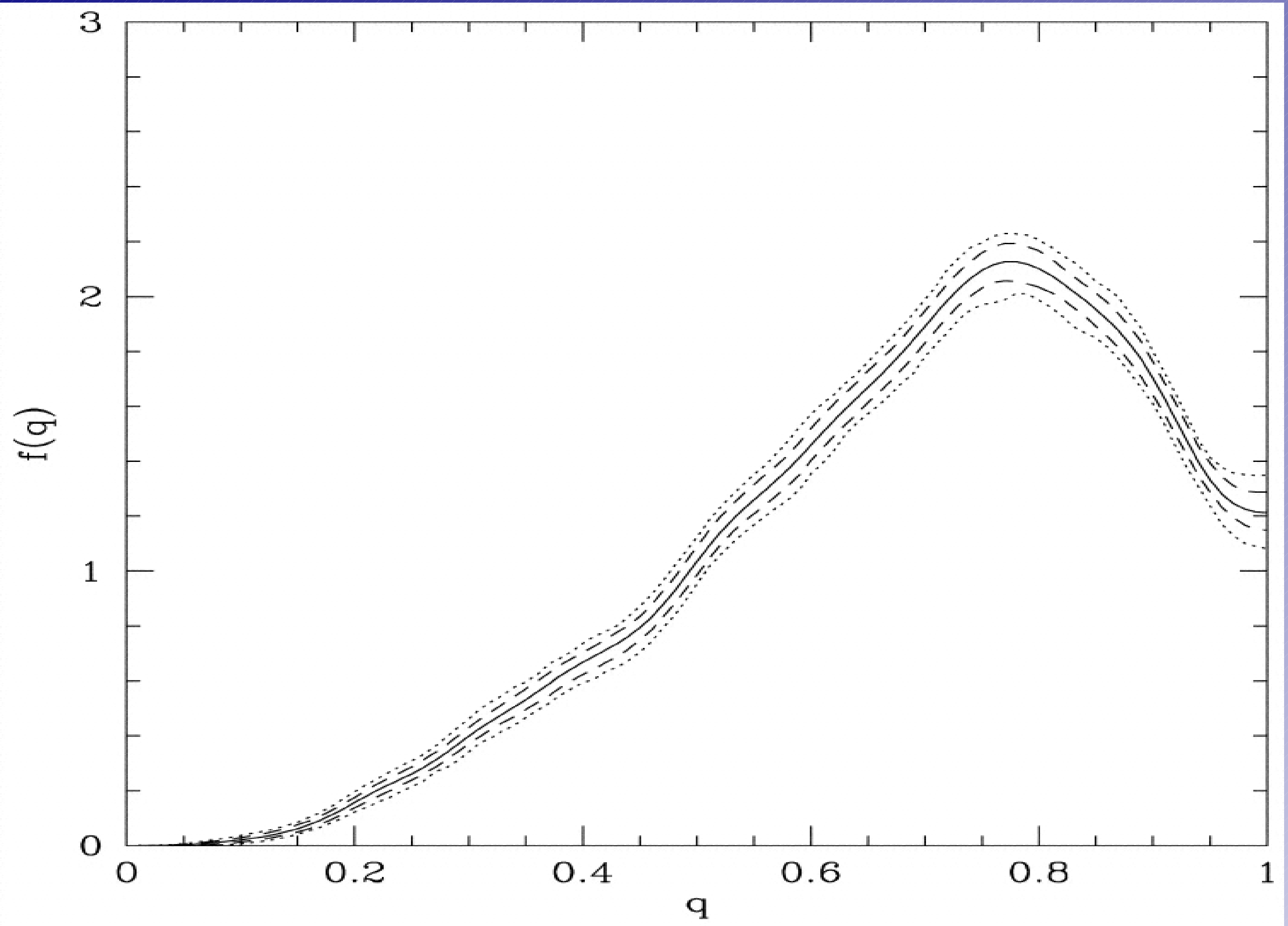
Using our definition of m for the last step. Finally we can rewrite this as

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

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

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


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



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
- Midsized E's have q≈0.75
- Luminous E's have q≈0.85
  - No selection of oblate spheroids can give the observed distribution
  - These galaxies must be triaxial

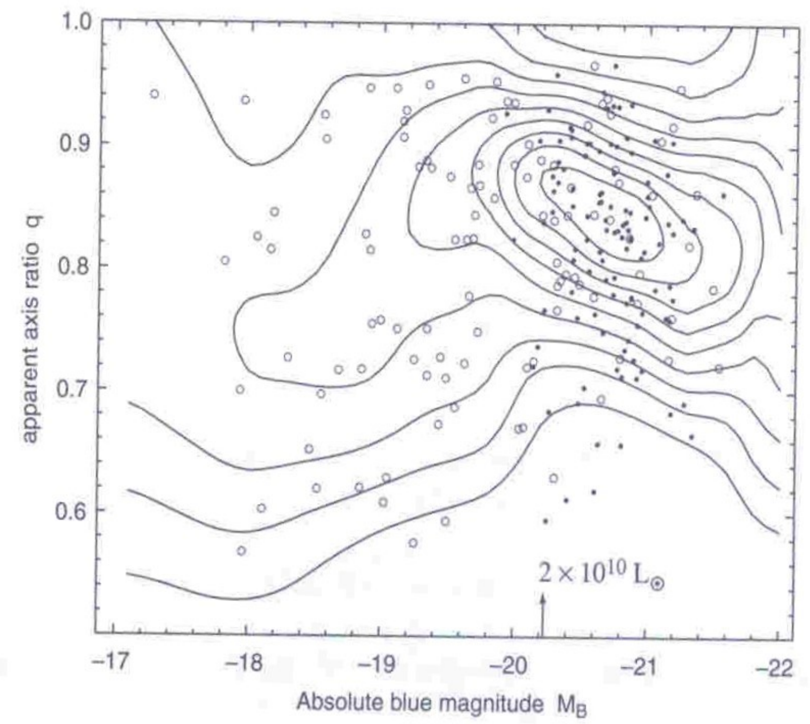


Figure 6.9 Observed axis ratio q and blue absolute magnitude M_B for elliptical galaxies from two different samples, represented by filled and open circles. Bright galaxies (on the right) on average appear rounder. Contours show probability density; the top contour level is 4.5 times higher than at the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

- Deviations from ellipses can be disky or boxy
- Measure difference between observed isophote and fitted ellipse as:
  - $\Delta r(\theta) \quad \sum_{k=3} a_k \cos(k\theta) + b_k \cos(k\theta)$
  - 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)

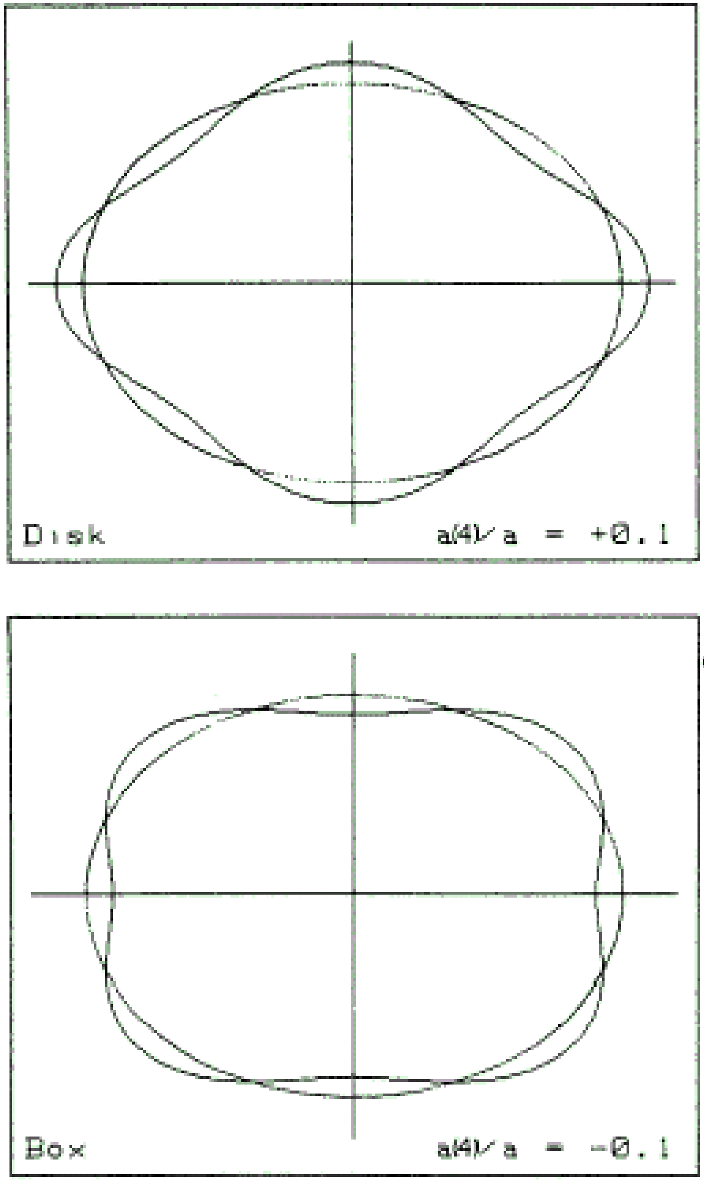


FIGURE 5. — Schematic drawing illustrating isophotes w
$a(4)/a = +0.1$ and $a(4)/a = -0.1$.

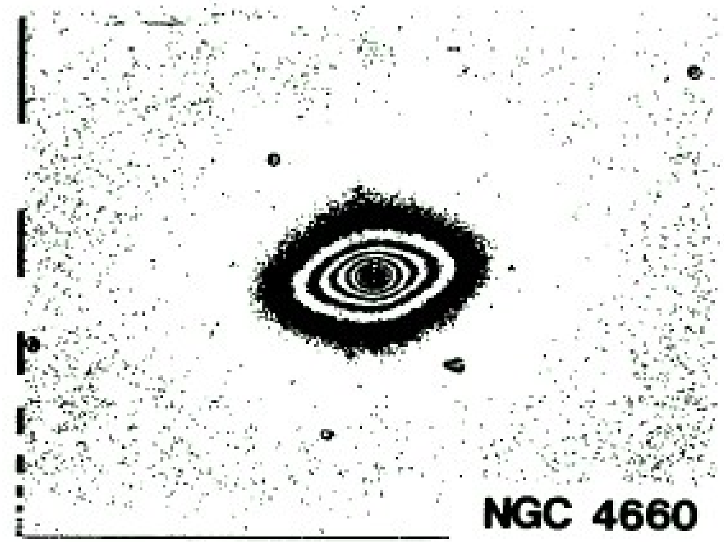


FIGURE 6. — R-image of NGC 4660, an elliptical galaxy with a disk-component in the isophotes ($a(4)/a \sim +0.03$).

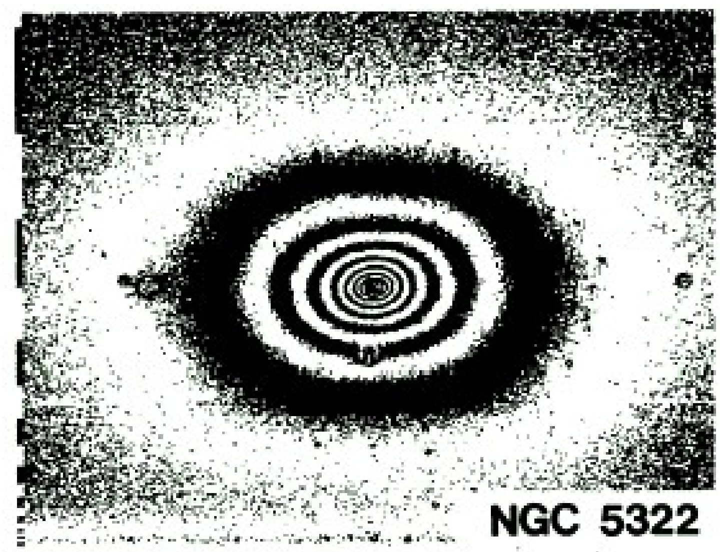
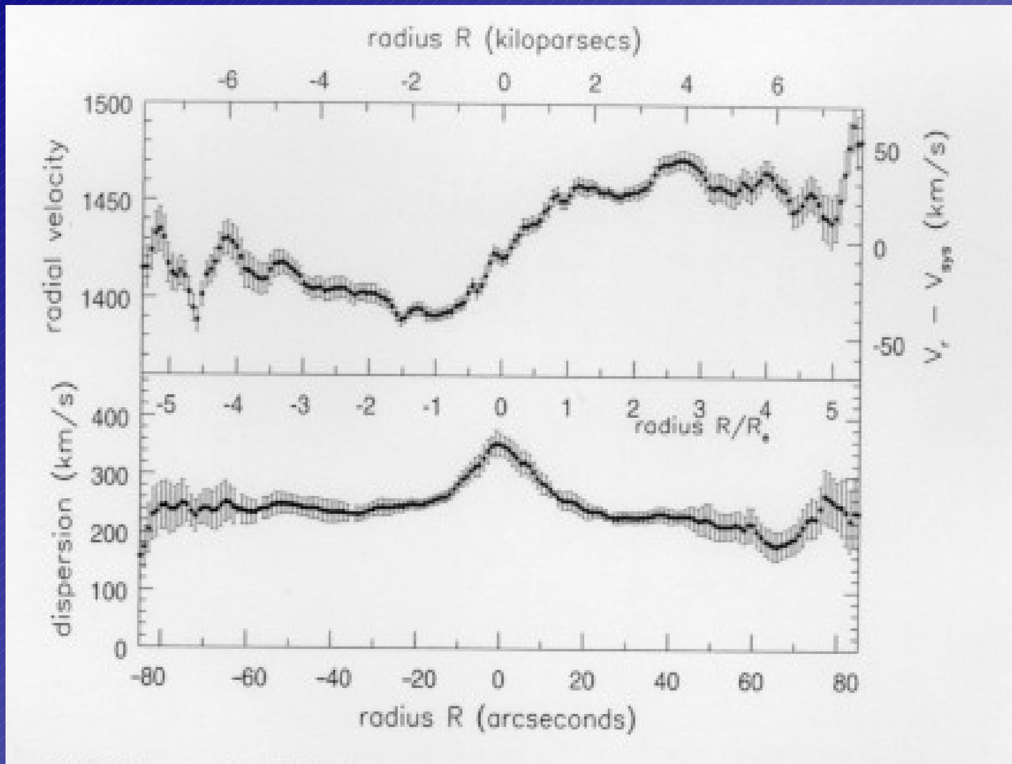
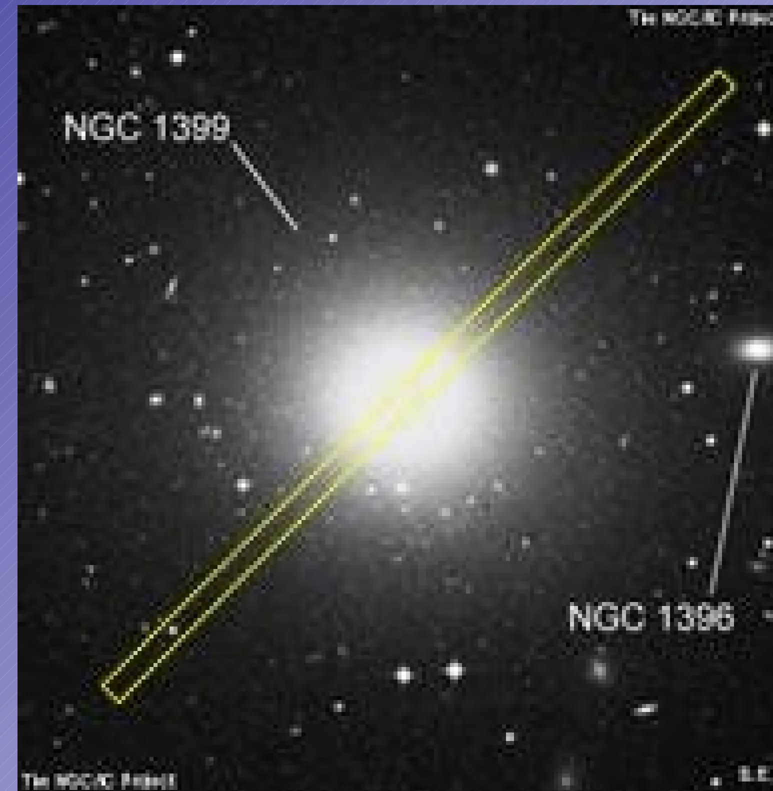


FIGURE 7. — R-image of NGC 5322, an elliptical galaxy with box-shaped isophotes ($a(4)/a \sim -0.01$).

Bender et al. 1988

Some ellipticals are just different





To measure the rotation of elliptical galaxies 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.

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

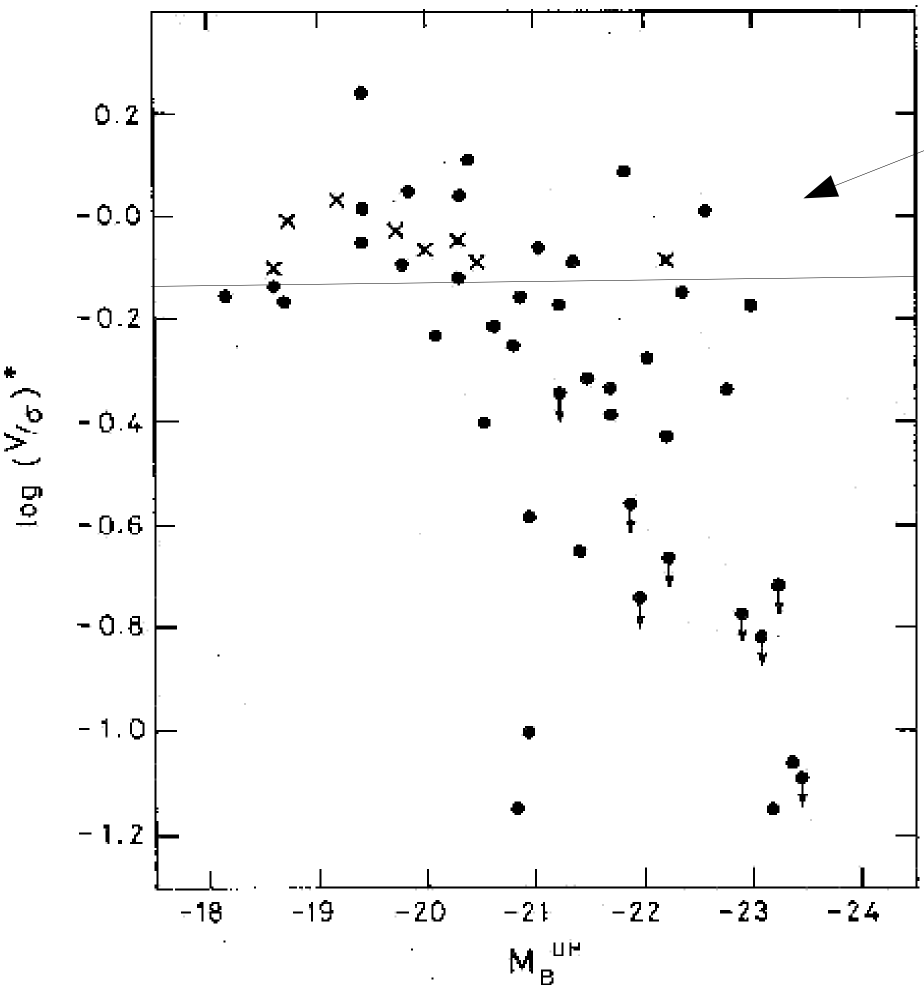


FIG. 4.—Log $(V/\sigma)^*$ against absolute magnitude. Ellipticals are shown as filled circles and the bulges as crosses; $(V/\sigma)^*$ is defined in § IIIb.

Rotationally supported

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

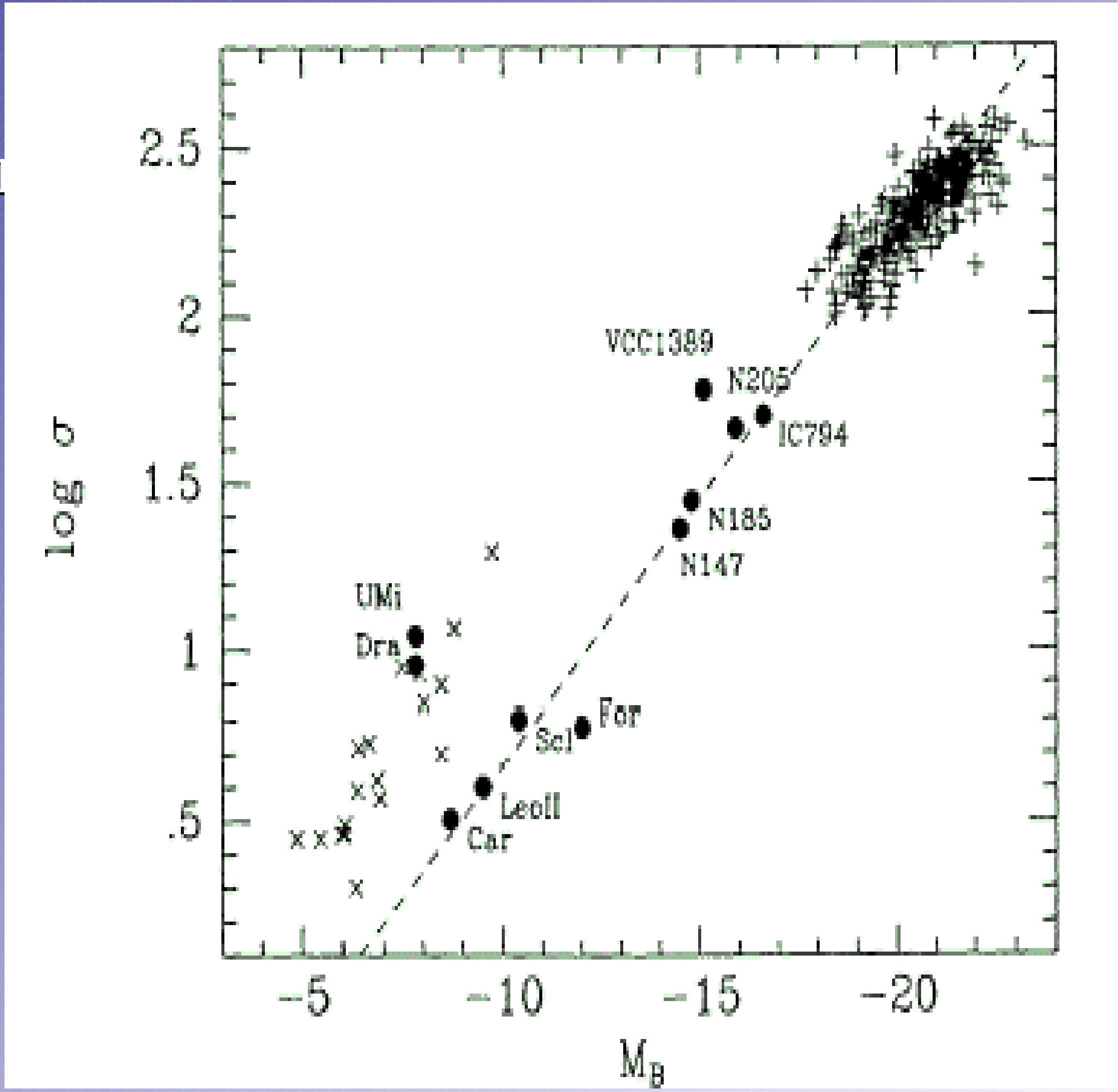
Faber-Jackson Relation

- 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)

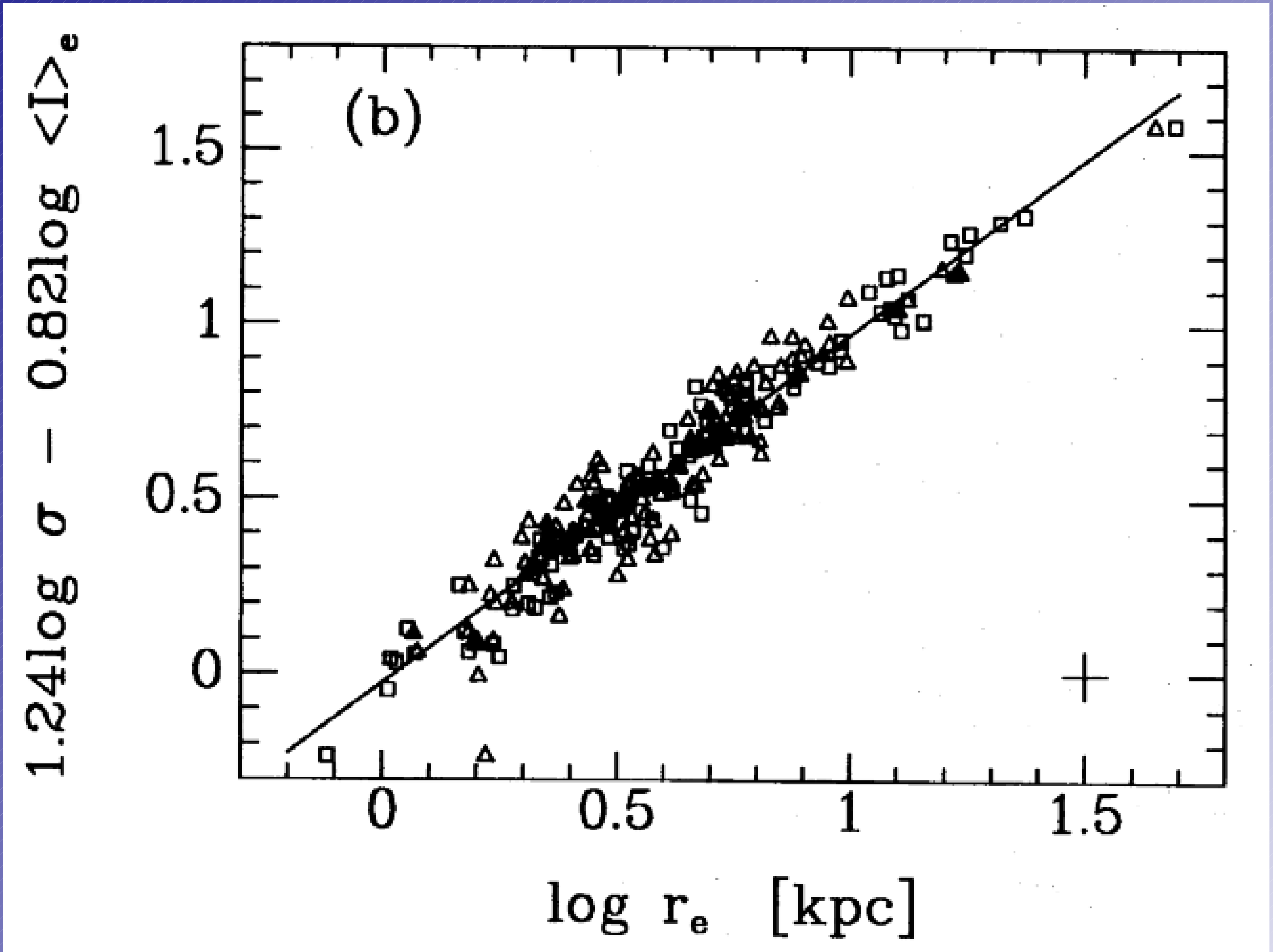
Faber-Jackson relation cont.

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

$$\frac{L_v}{2\mathrm{x}10^{10} L_{sun}} \approx \left(\frac{\sigma}{200\, km\, s^{-1}}\right)^4$$



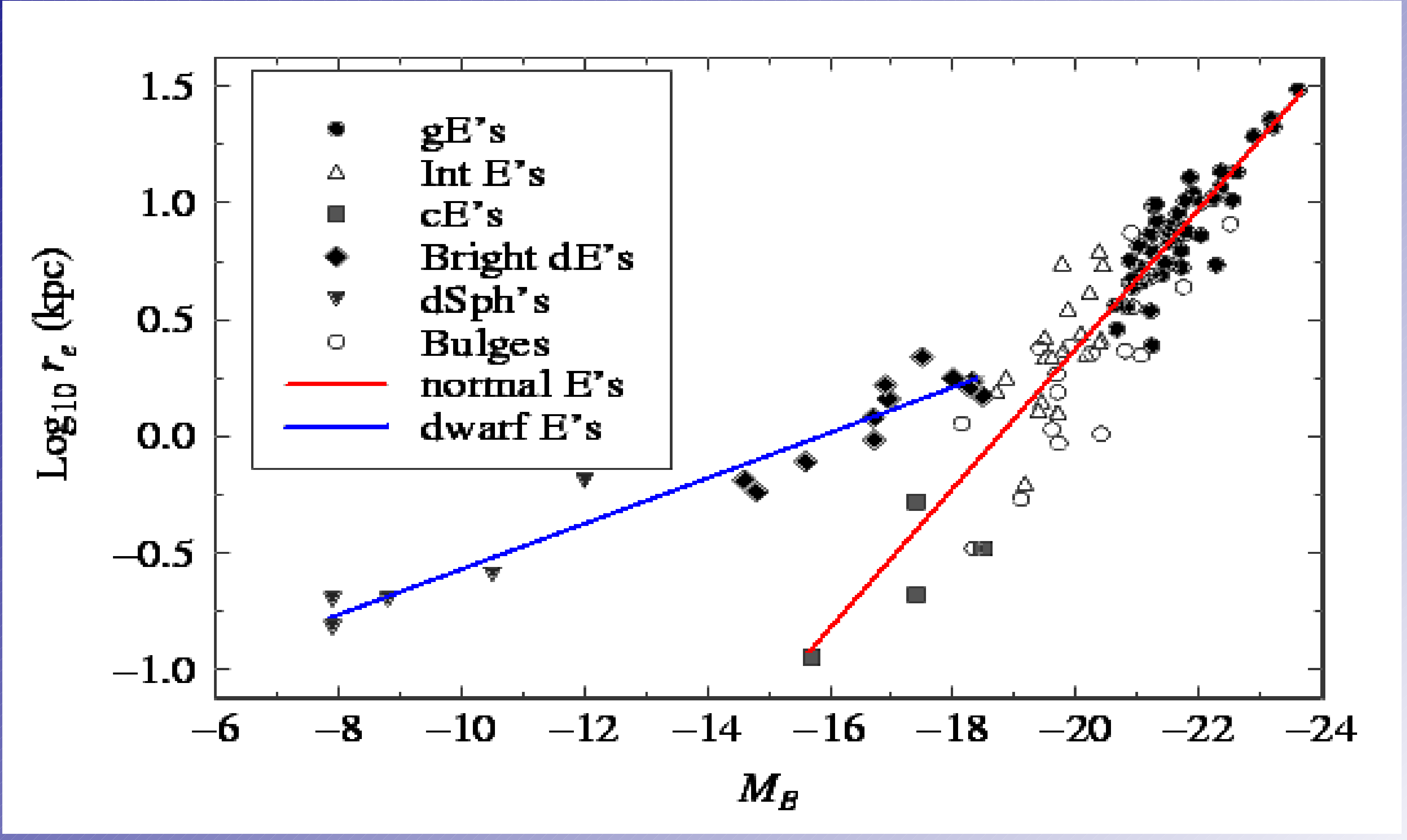
Fundamental Plane



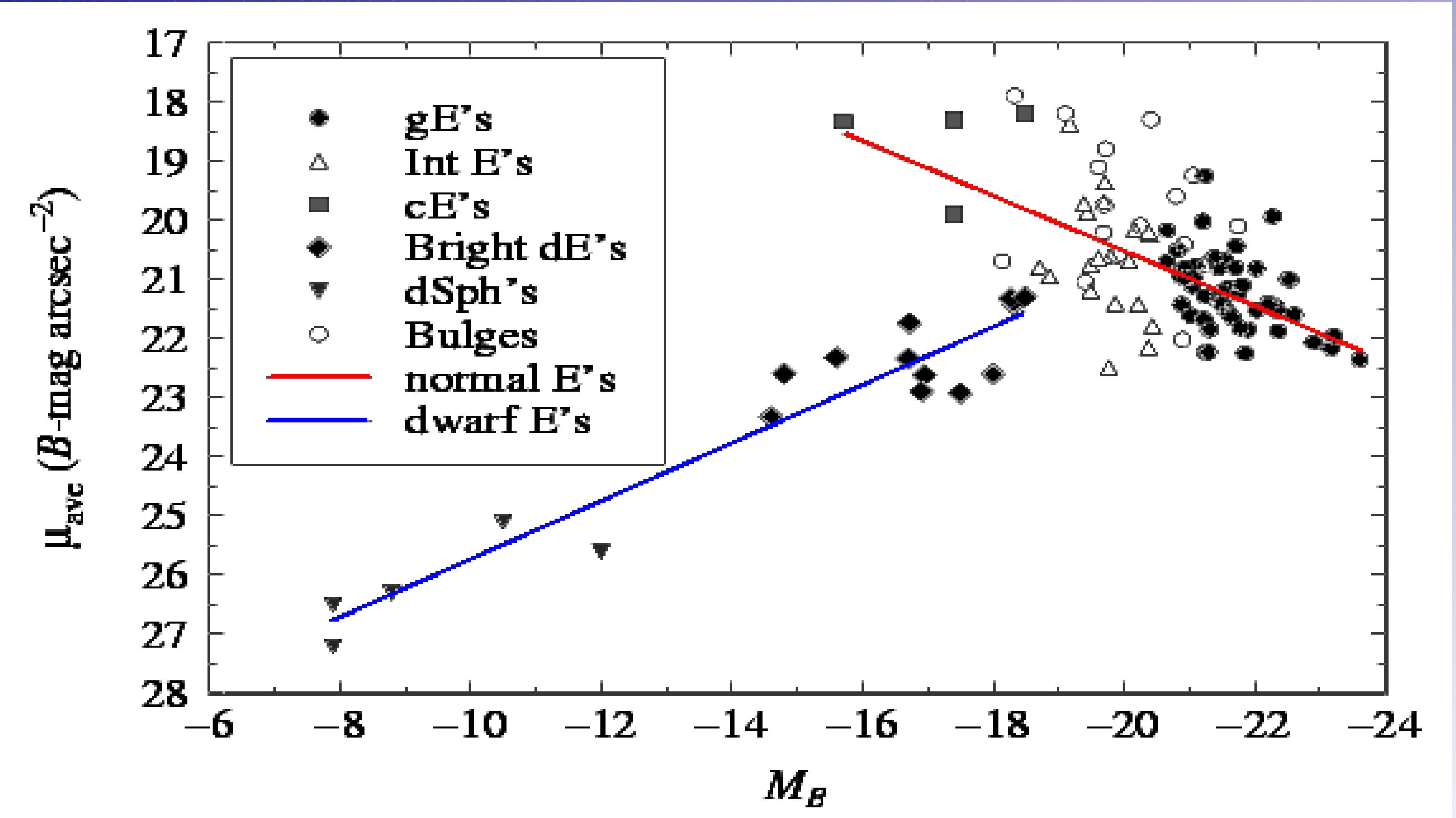
Fundamental Plane

- 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!

Effective radius vs M_B



<Σ> vs M_B



17
18
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23
24
25
26
27
28
μavc (B-mag arcsec−2)
gE's
Int E's
cE's
Bright dE's
dSph's
Bulges
normal E's
dwarf E's
−6
−8
−10
−12
−14
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−18
−20
−22
−24
MB

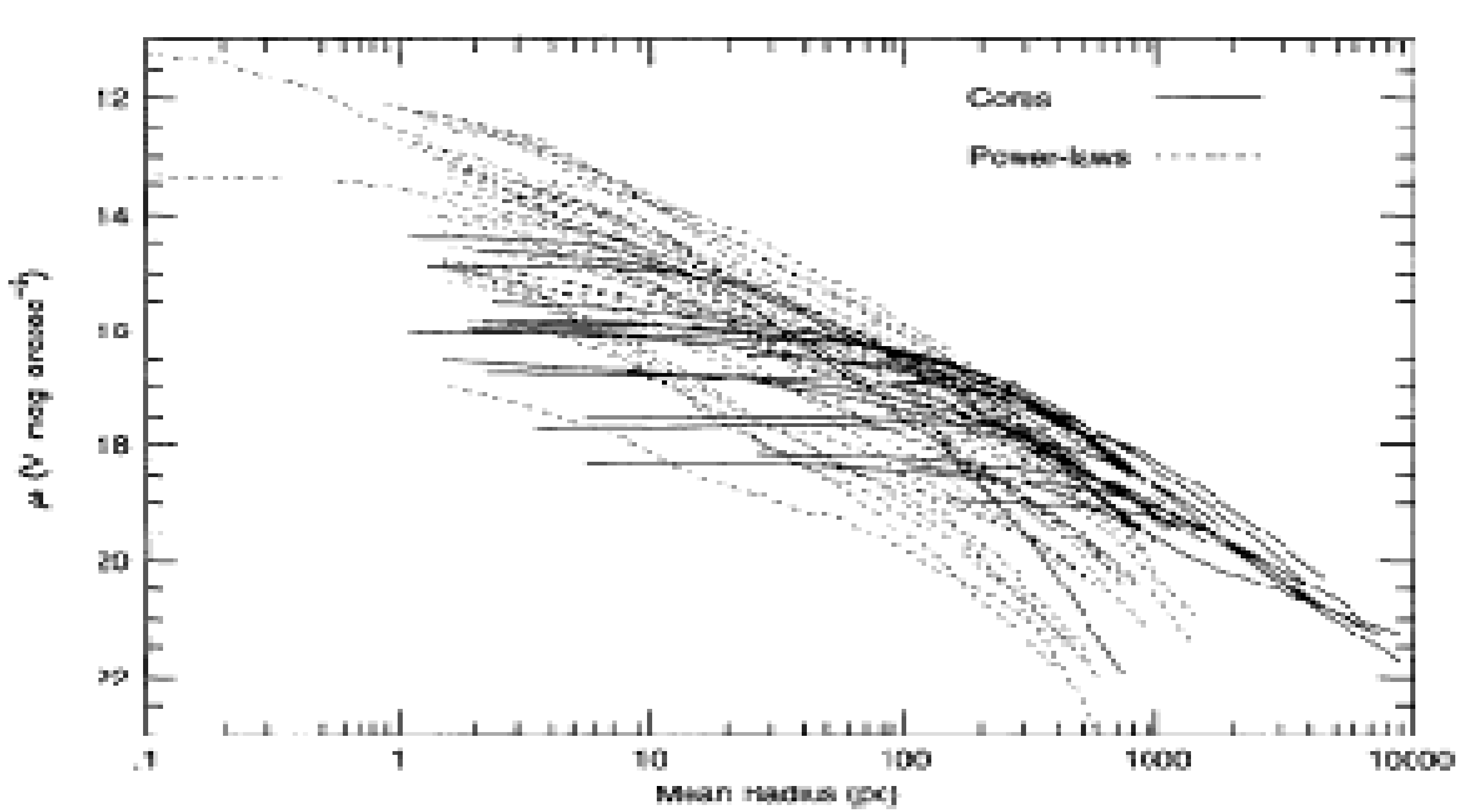


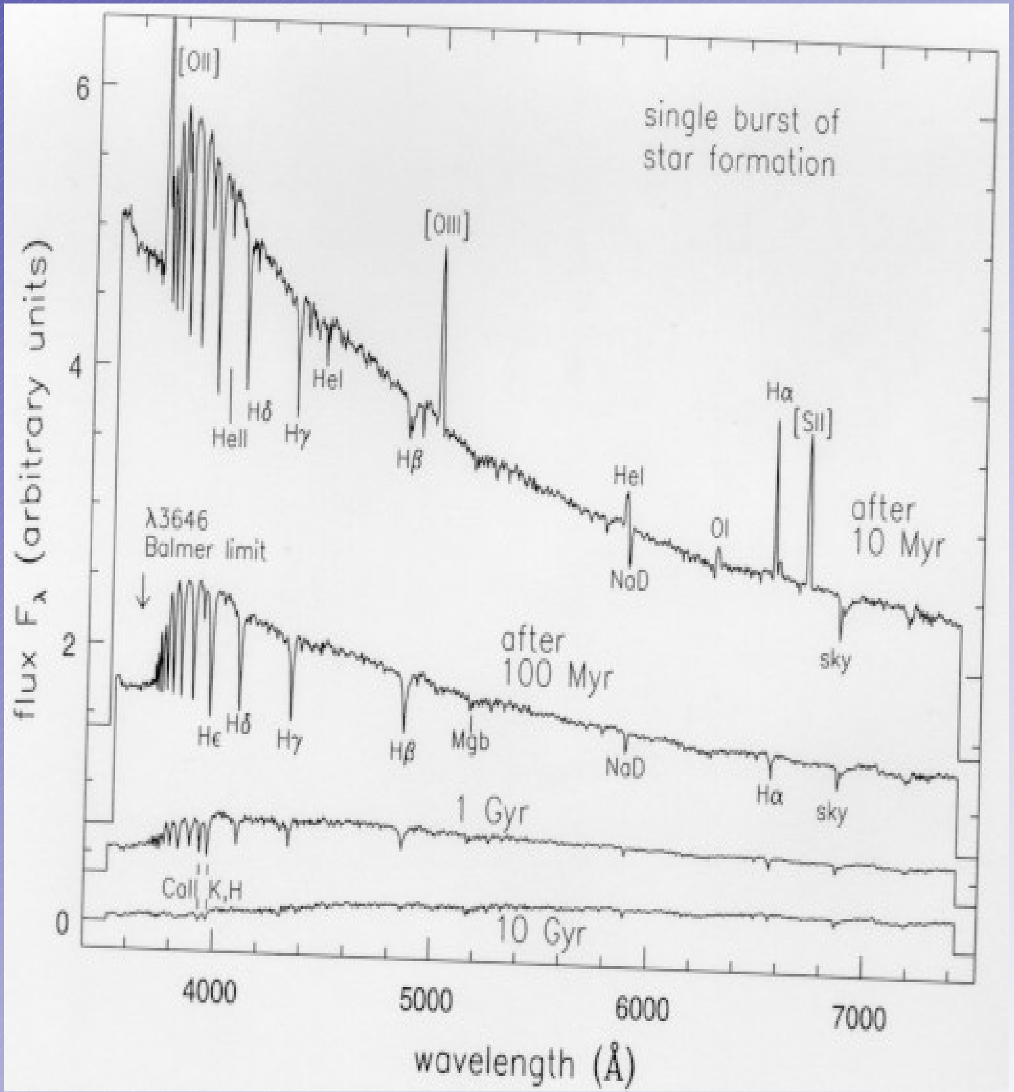
FIG. 1. *V*-band surface-brightness profiles of 55 ellipticals and bulges from *HST*. All were observed in the WFPC1 Planetary Camera through filter F555W and were deconvolved using the Lucy-Richardson algorithm as described in Paper I. Core galaxies (see Sec. 2) are plotted as solid lines, and power-law 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!!

Starburst Spectra

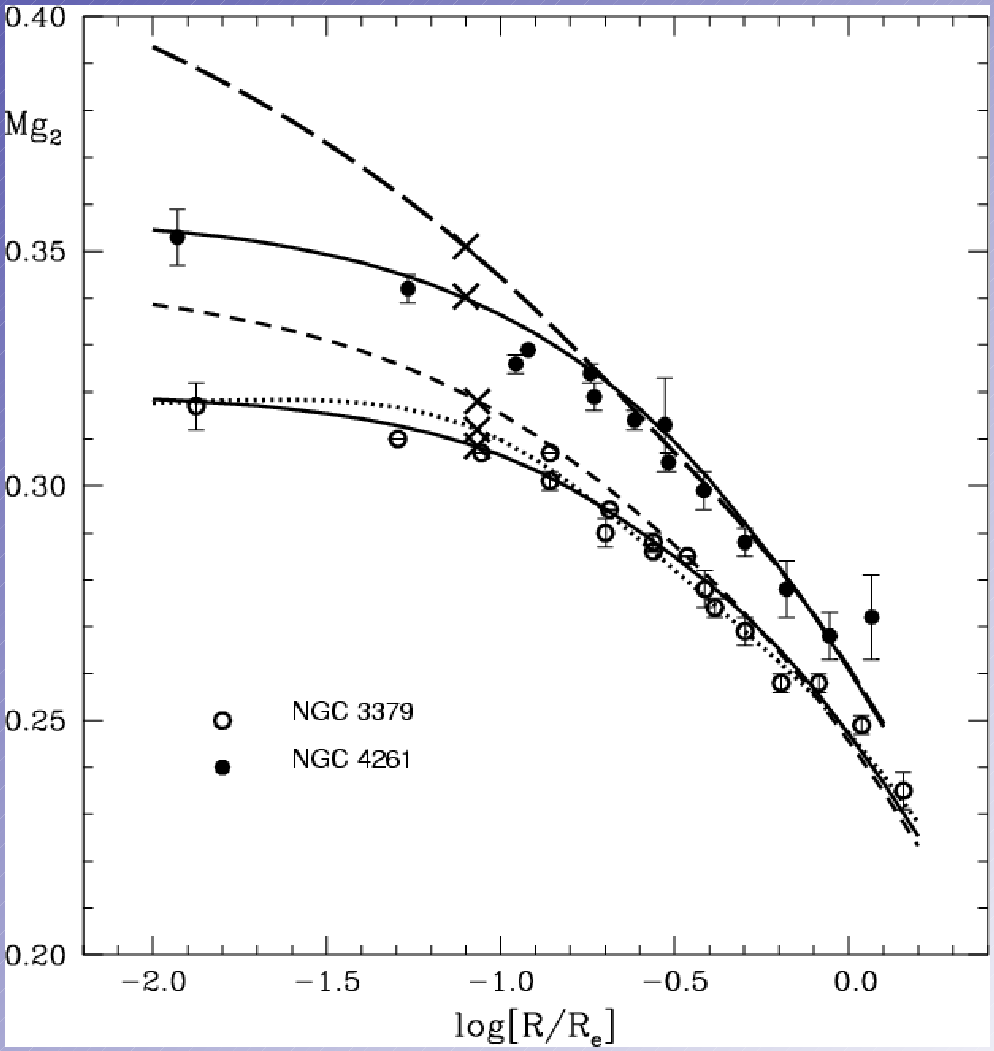
- If smaller ellipticals are younger then they should be bluer
  - A young starburst has a very blue spectrum
  - As the population ages it becomes redder and we see lots of A stars (E+A galaxies)
  - After $2x10^9$ yrs we see a spectrum similar to ellipticals today



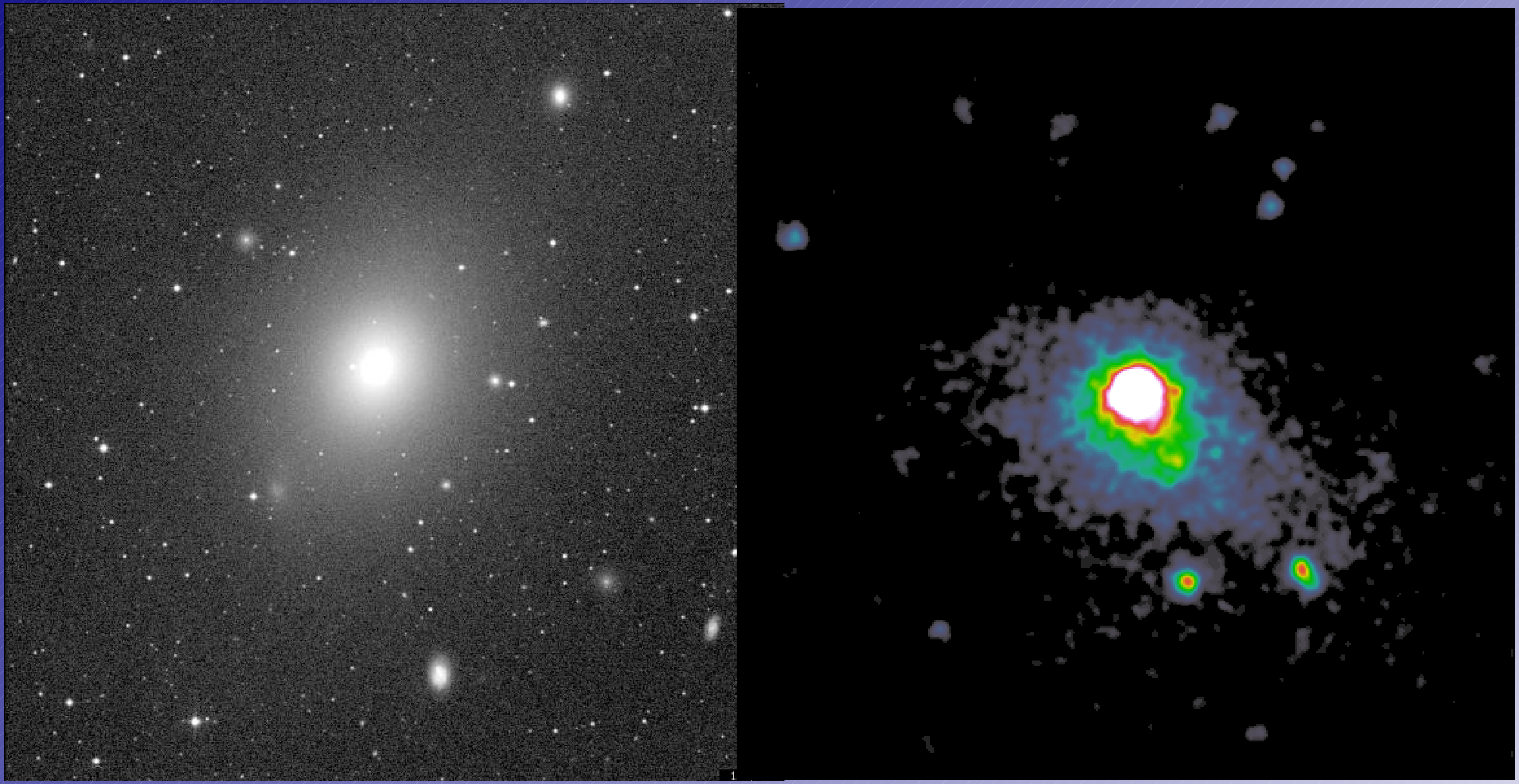
Metallicity

- 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



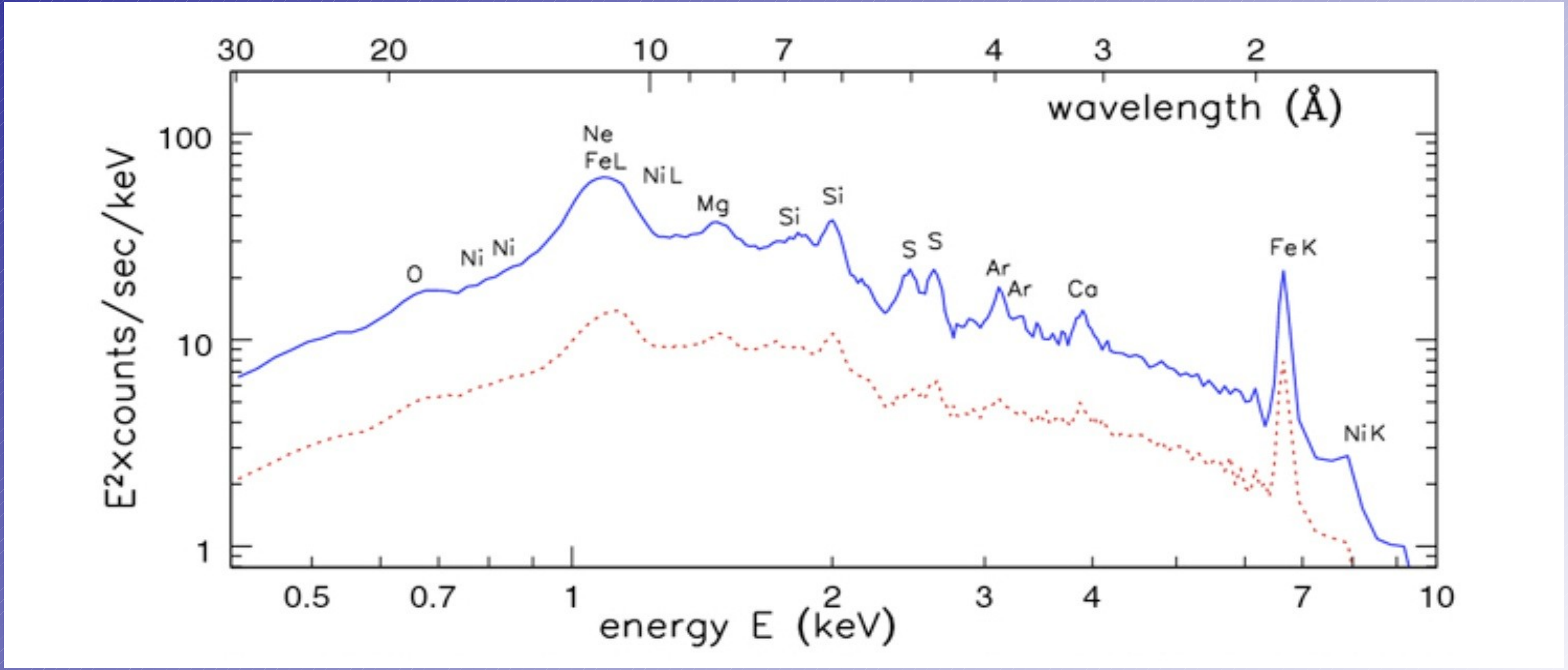
X-ray Halos



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)



X-ray Halos cont.

- Where does the hot gas come from ?
  - Stellar winds from red giants and red supergiants
    - Random velocities $\geq$ 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} $M_\odot$

X-ray Halos cont.

- We see lines from “metals”
  - So at least some of this gas is processed by stars and injected into the ISM via SNe.
  - Typical values are from 0.2 – 0.8 solar
  - SNe produce ejecta enriched 2-5x solar
  - So how do we get gas with less metals?

X-ray Halos cont.

- So how do we get gas with less metals?
  - Dilution
  - Stellar winds
  - Combination

X-ray Halos cont.

- X-ray emission is a major source of cooling the X-ray gas
  - M87 emits ~3x10^{42} erg/s

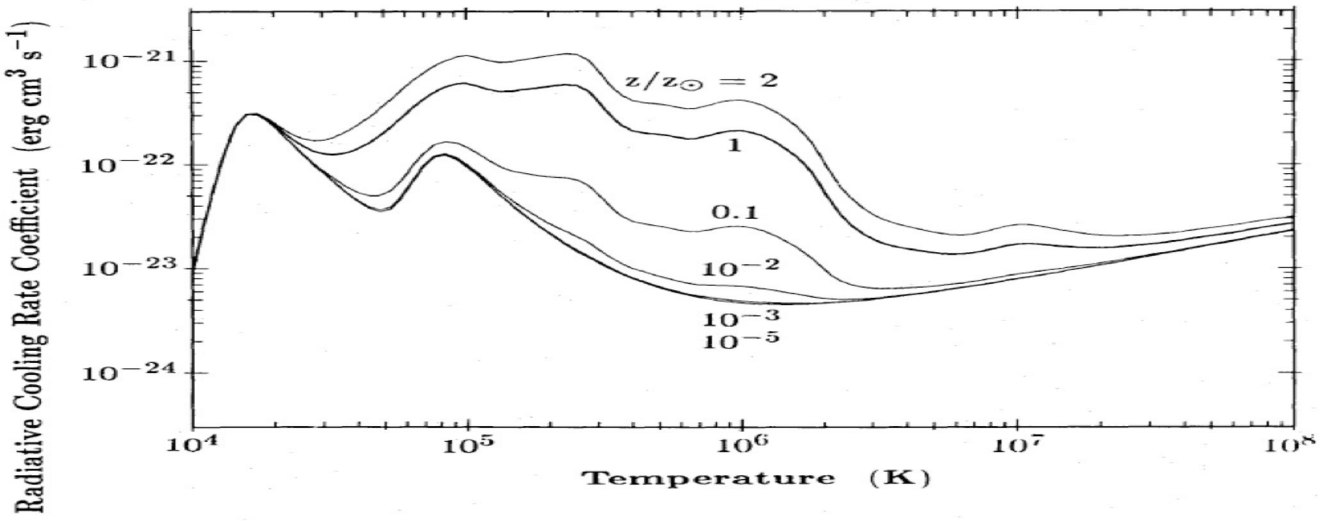


Fig. 1. Total radiative cooling coefficient of optically thin plasma in ionization equilibrium for different metallicities, where the metallicity parameter $Z/Z_\odot$ is normalized to the solar value with solar element abundances as given by Anders and Ebihara (1982) (see text for explanations)

X-ray Halos cont.

- How fast does does the gas cool?

$t_{cool} = kT^{1/2} / 2x10^{-27}\ n_e$

$= 2.2x10^{10}\,yr\ (T/10^8\ K)^{1/2}\ (n_e/10^{-3}\ cm^{-3})^{-1}$

This is larger than the Hubble time so elliptical galaxies will not cool much!

X-ray Halos cont.

- How fast can the gas reach equilibrium?

The timescale for the gas to relax is just

$$t_{relax} = d/c_s$$

The sound speed in a gas is just

$$c_s = (\gamma P/\rho)^{1/2}$$

$$= 6.5\text{x}10^8 \text{ yr } (T/10^8 \text{ K})^{-1/2} (d/\text{Mpc})$$

This is much smaller than the Hubble time so the hot gas is almost always in equilibrium!

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

E2

S0's

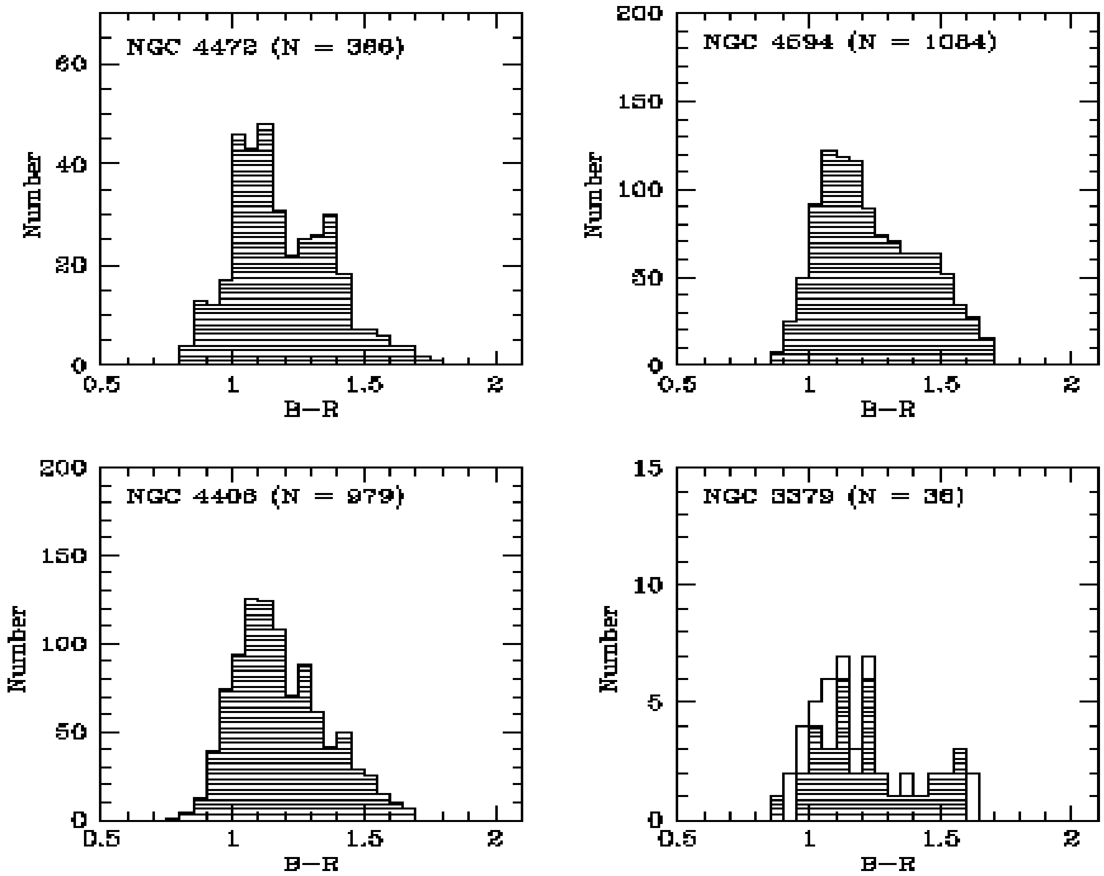


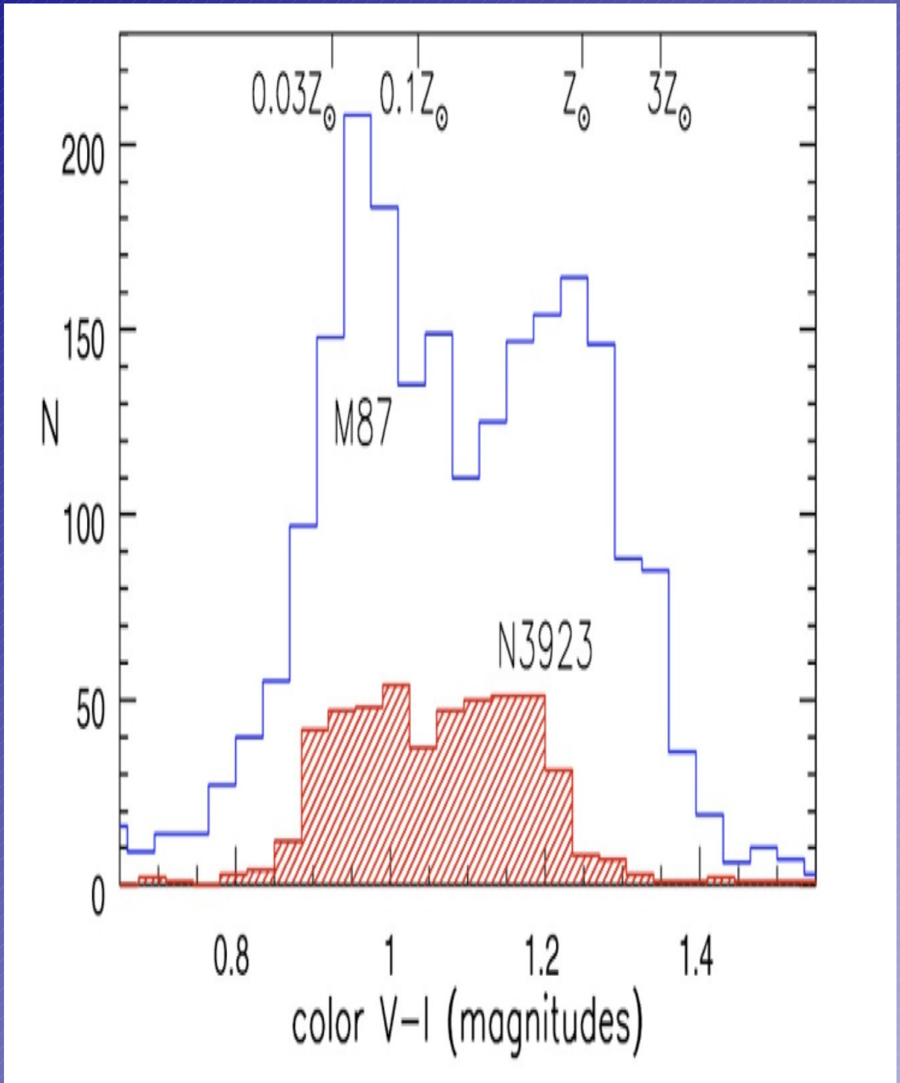
Fig. 9.— $B - R$ distributions for the early-type galaxy sample, including NGC 4473 from Paper I. For NGC 3379, the 36-object sample used to estimate the blue/red GC proportions is shown as a shaded histogram and the 50-object sample used as input to KMM is plotted with a solid line.

E3

E5

Rhode & Zeph (2004)
What does this mean?

Ellipticals & Globular clusters

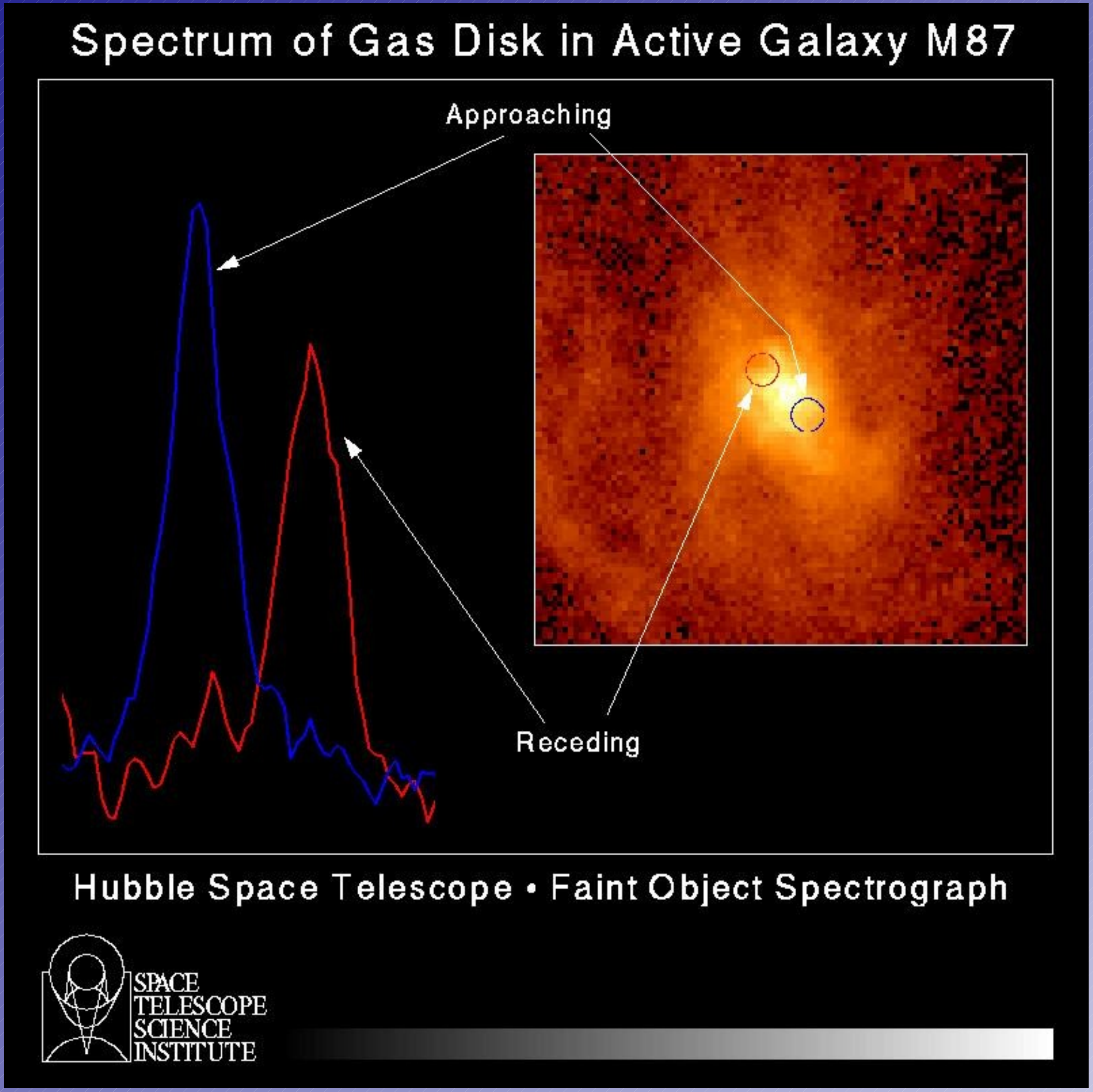


- Generally ellipticals have 2x the globular clusters as spirals
- M87 has about 4x more globulars than N3923

Globular Clusters in Ellipticals cont.

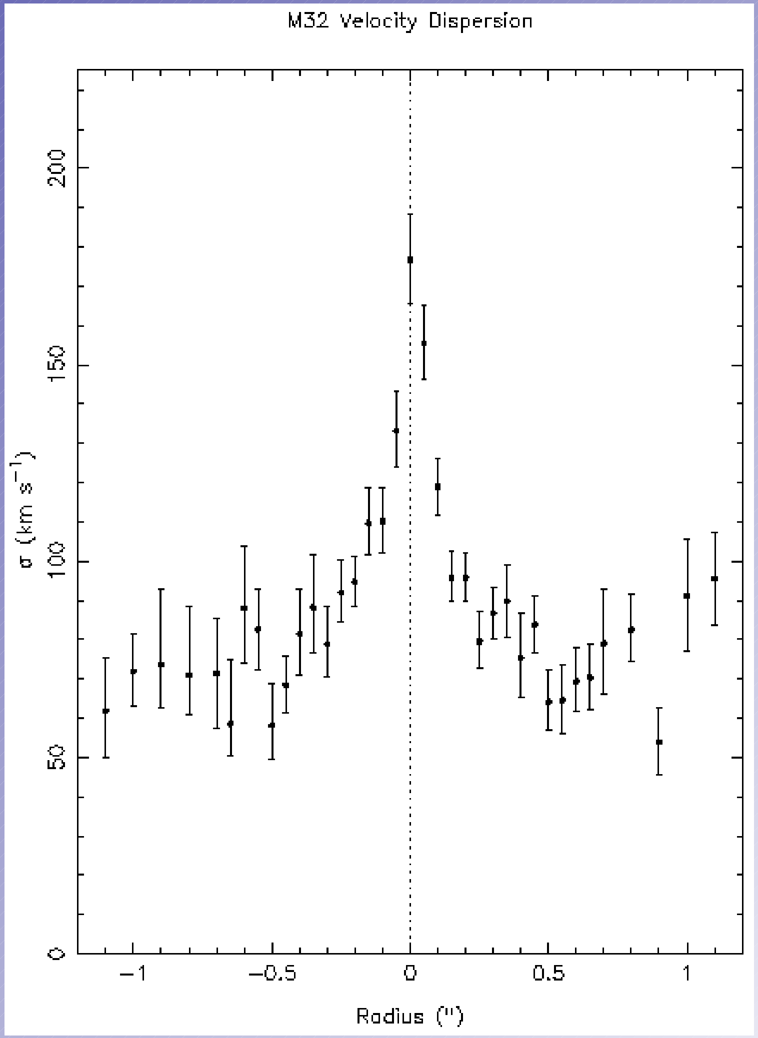
- This could be caused by the
  - Merger of two galaxies – metal poor clusters are old, metal rich clusters formed during merger process
  - Hierarchical formation – Metal poor GC's are form at an early time and the metal rich population builds up during accretion of gas rich spirals

Black Holes in Ellipticals



The first direct detection of gas being drawn into a BH. (Ford et al. 1994)

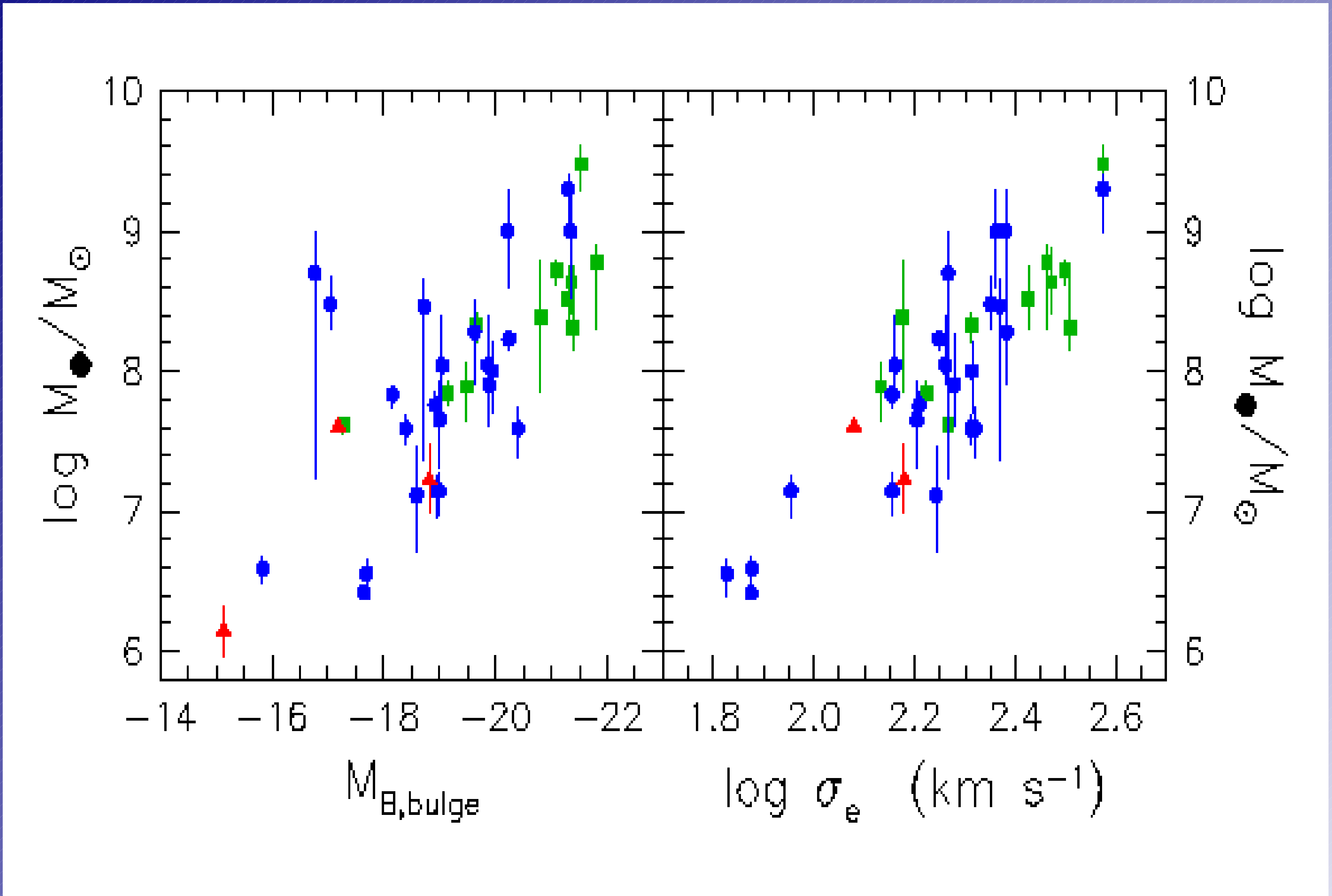
Black Holes in Ellipticals cont.



We can also infer the presence of a BH by looking at the stellar velocity dispersion in the nuclear region (M32).

Black Holes in Ellipticals cont.

- Currently there are at least 40 BH candidates in nearby ellipticals and in the bulges of spirals
- There is a strong correlation between black hole mass and galaxy luminosity and velocity dispersion



Black Hole mass vs bulge mass and σ (Kormendy 2003)

Why is this correlation so good?

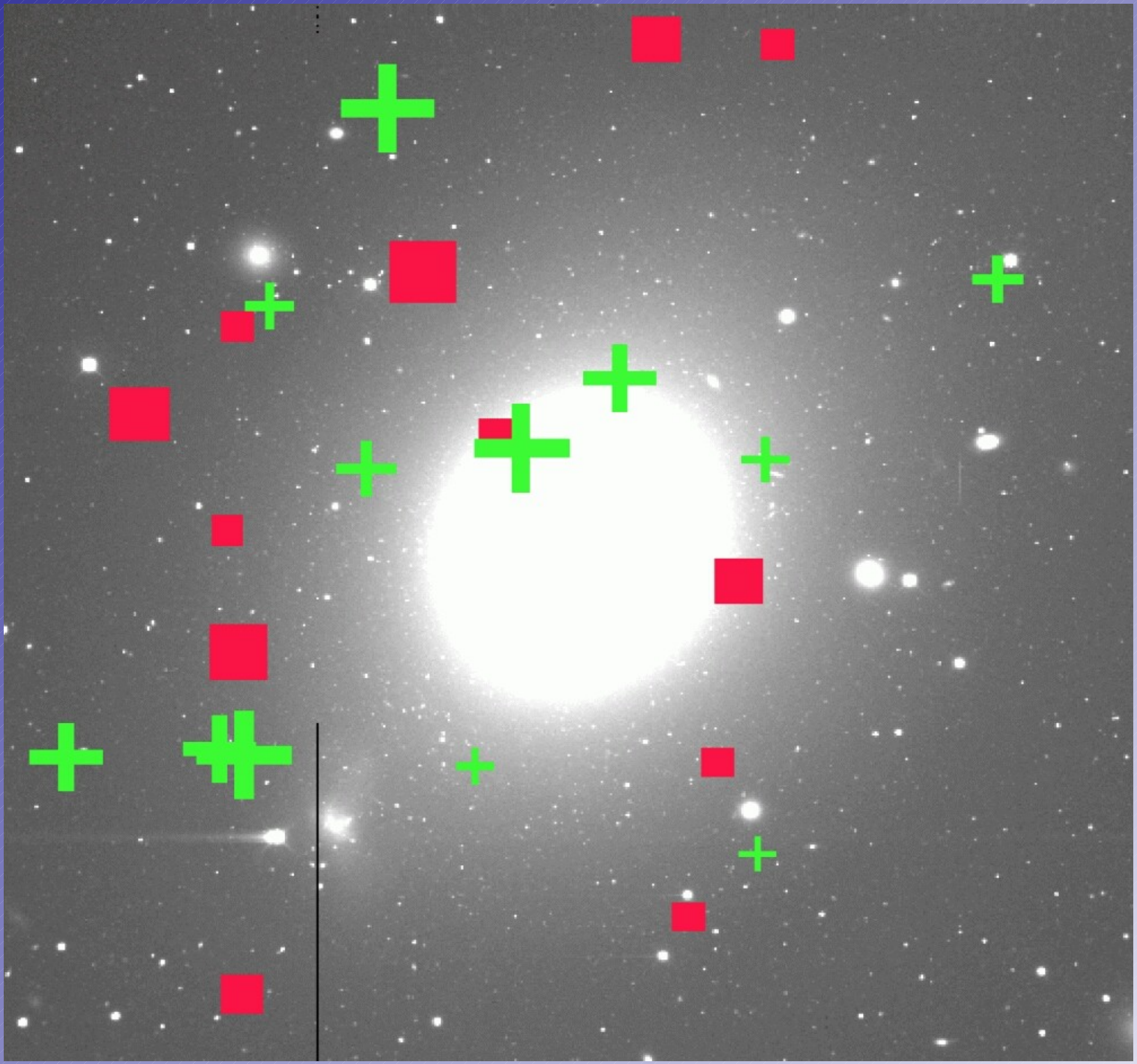
- Observations imply BH mass 'knows' about the formation of bulges and ellipticals
  - All proto-galaxy clumps harbored a BH with the BH mass proportional to the bulge mass and BHs merged as the galaxy formed
  - BH started out small and grew as galaxy formed – e.g., central BH is fed during process of formation
    - Maybe act as the seed for the formation process (implies ->all galaxies have BHs

Dark Matter in Elliptical Galaxies

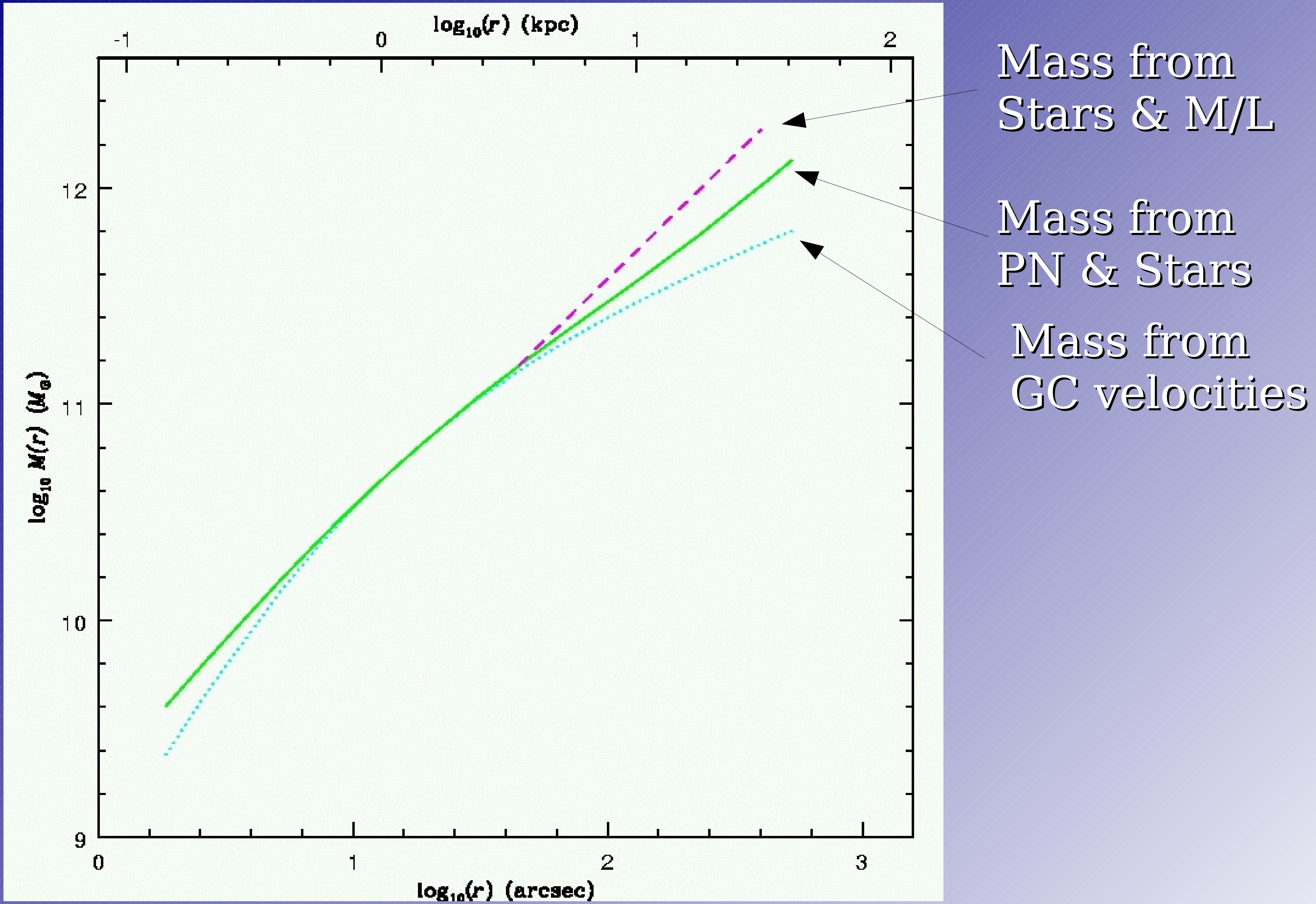
- Looking at just the stars we expect the mass to light ratio of the stellar population to be $M/L_V \sim 3\text{-}5$
- Orbital motions of the stars in the centers of ellipticals imply they are not dark matter dominated
- In the few ellipticals containing cold gas, we can measure the orbit of the gas we find M/L ~ 10 –20
  - But are these galaxies typical of all E's
- Also can use the amount of mass required to retain the hot x-ray gas, find M/L~100 for galaxies with large x-ray halos
  - Mostly Luminous and midsized ellipticals

Dark Matter in Elliptical Galaxies cont.

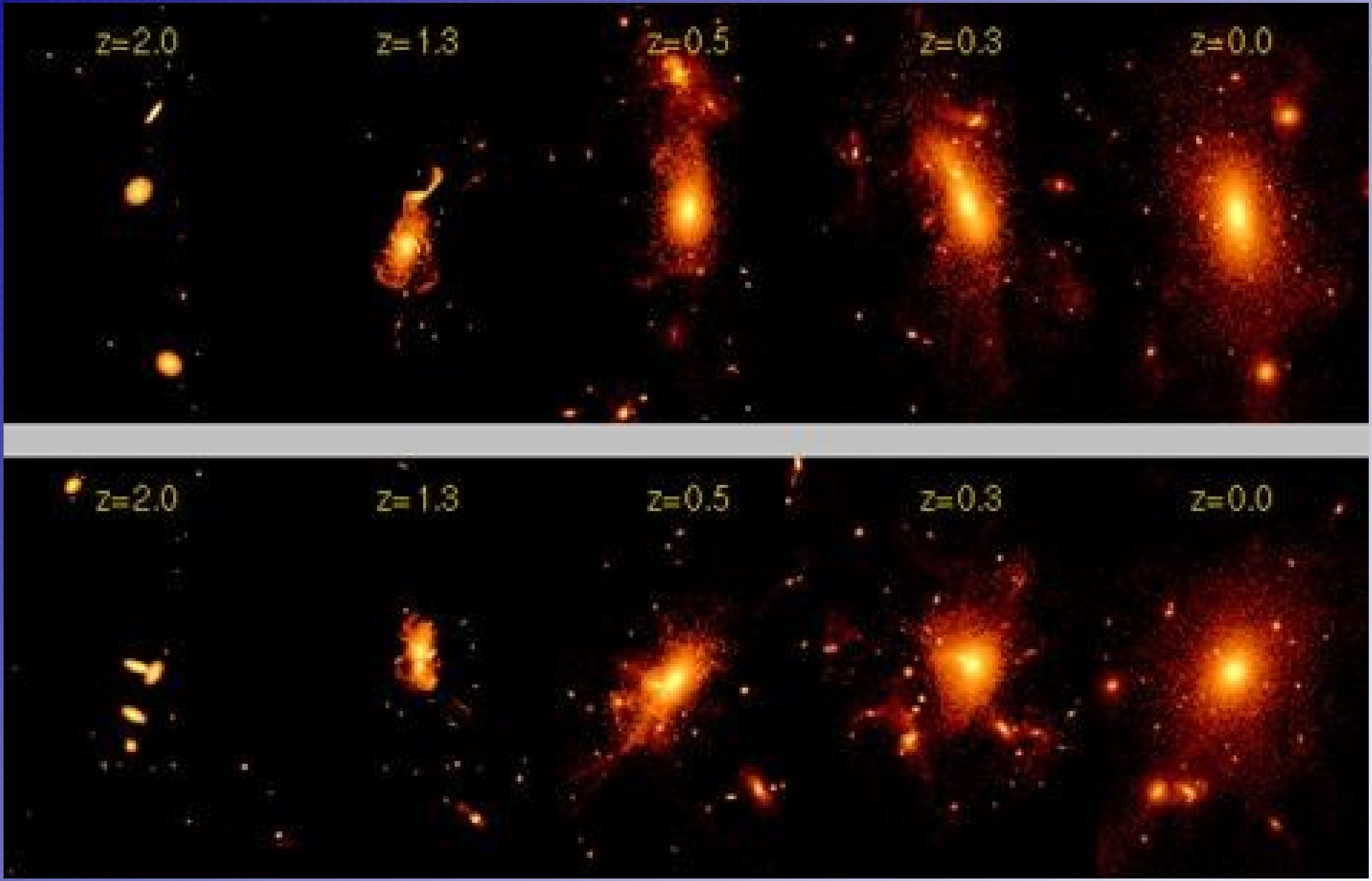
- Are there any other ways to look at velocities?
  - globular clusters and planetary nebulae
  - Recent results of PN dynamics around (a few) elliptical galaxies show NO dark matter, the galaxies are “naked”
  - Recent results of GC dynamics around (a few) elliptical galaxies show large dark halo.



PN velocities in NGC 4472, + is blueshifted, - is redshifted. (Romanowsky 2001)


log10(r) (kpc)
-1
0
1
2
12
11
10
9
0
1
2
3
log10(r) (arcsec)
log10 M(r) (M⊙)
Mass from
Stars & M/L
Mass from
PN & Stars
Mass from
GC velocities

Formation of Ellipticals



Formation of Ellipticals cont.

- Equal mass mergers can account for the massive ellipticals with boxy isophotes and little rotation
- Unequal mass mergers can explain less massive ellipticals with disky isophotes and higher rotation