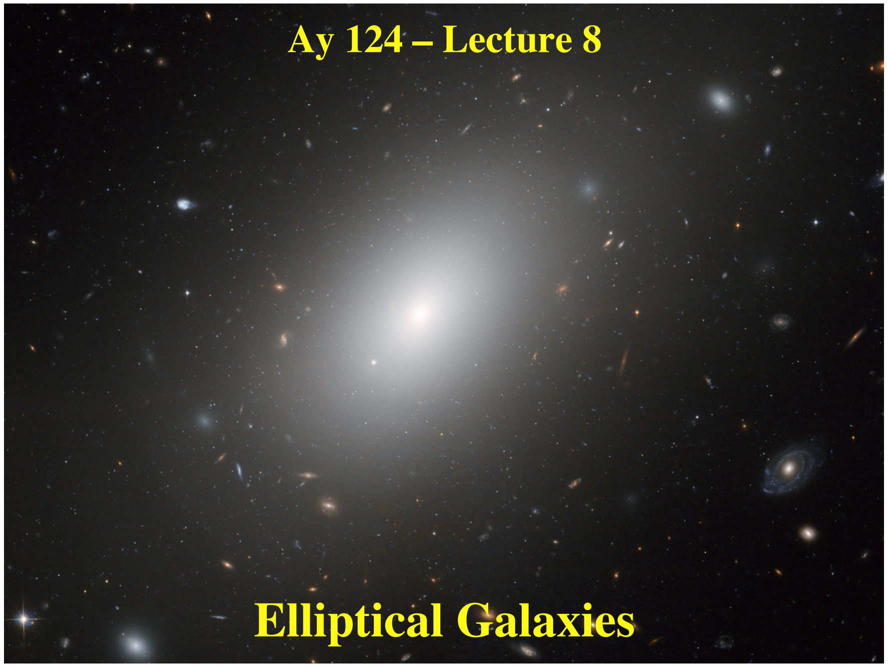
Ay 124 – Lecture 8



Elliptical Galaxies

Elliptical Galaxies

Old view: ellipticals are boring, simple systems

- Ellipticals contain no gas & dust
- Ellipticals are composed of old stars
- Ellipticals formed in a monolithic collapse, which induced violent relaxation of the stars, stars are in an equilibrium state

Modern view:

- Most/all ellipticals have hot x-ray gas, some have dust, even cold gas
- Ellipticals do rotate, but most of the kinetic energy support (and galaxy shapes) come from an anisotropic velocity dispersion
- Some contain decoupled (counter-rotating) cores, or other complex kinematics
- Some have weak stellar disks
- Ellipticals formed by mergers of two spirals, or hierarchical clustering of smaller galaxies

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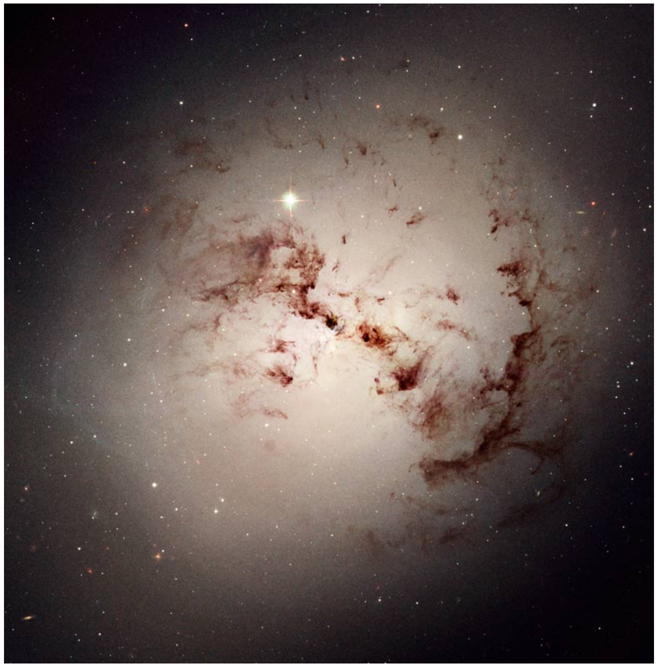
Dust lanes in E galaxy NGC 1316

Dust is surprisingly common in E's

Probably it originates from cannibalized spiral galaxies



Fine Structure in E-Galaxies:

A Signature of Recent Merging

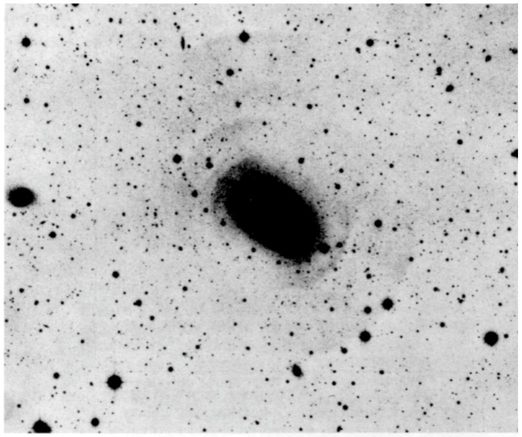


Figure 7-22. The giant elliptical galaxy NGC 3923 is surrounded by faint ripples of brightness. Courtesy of D. F. Malin and the Anglo-Australian Telescope Board.

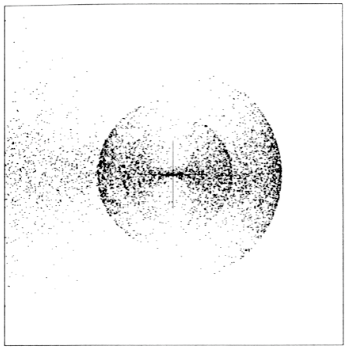
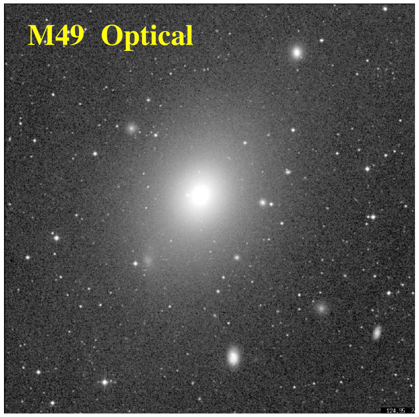
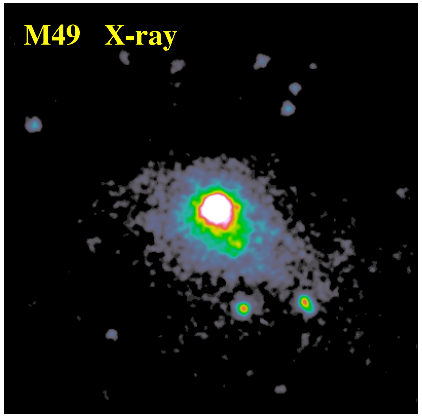


Figure 7-23. Ripples like those shown in Figure 7-22 are formed when a numerical disk galaxy is tidally disrupted by a fixed galaxy-like potential. (See Hernquist & Quinn 1987.)

Hot Gas in Elliptical Galaxies

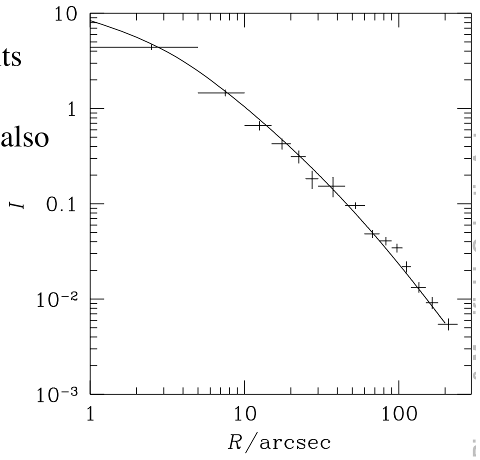




The gas is metal-rich, and thus at least partly a product of stellar evolution
It is at a virial temperature corresponding to the velocity dispersion of stars
Another good probe of dark matter in ellipticals…

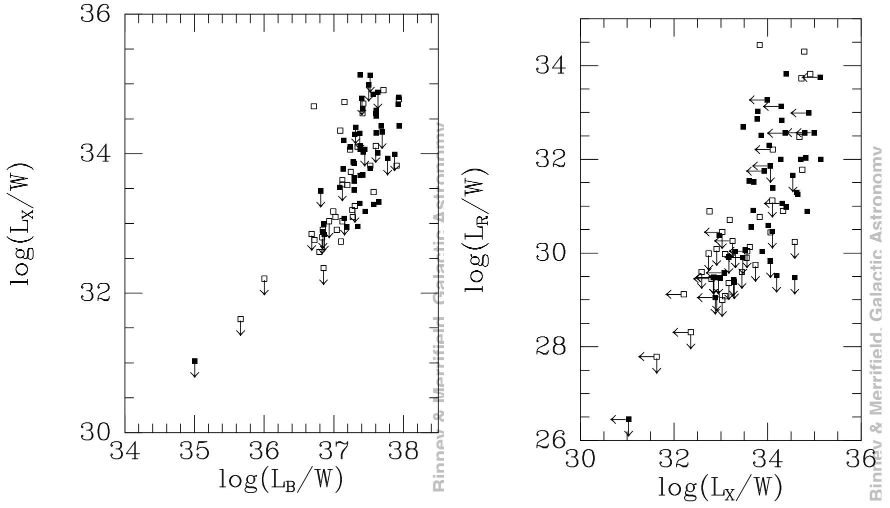
Hot Gas in Ellipticals

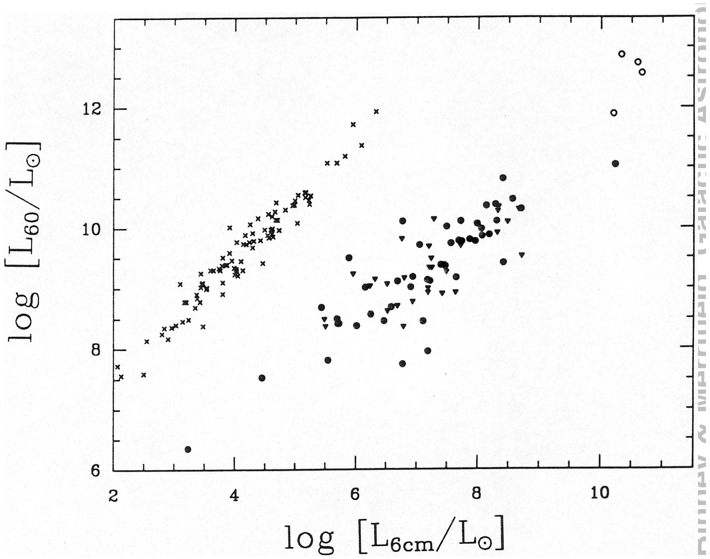
- X-ray emissivity of the gas is proportional to the square of its density
- Stellar populations (binaries) also contribute to the emission
- And so do AGN, if present



X-Raly Luminosity Correlations

Overall correlation: $L_X \sim L_B^{1.8}$





Modeling Elliptical Galaxies

To be completed… I did it the old-fashioned way in class

Testing the Models

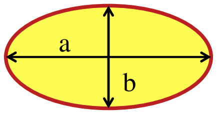
To be completed… I did it the old-fashioned way in class

Elliptical Galaxies

- About 20% of field galaxies are E's, but most E's are in clusters
- There are a number of different subtypes:
  - E's (normal ellipticals)
  - cD's (massive bright ellipticals at the centers of galaxy clusters)
  - dE's (dwarf ellipticals)
  - dSph's (dwarf spheroidals)

  } Not really ellipticals, a different class of objects
- Smooth and almost featureless: no spiral arms or dust lanes. Generally lacking in cool gas, and hence few young blue stars
- Classified by the apparent ellipticity:

$$\varepsilon = 1 - \frac{b}{a}$$

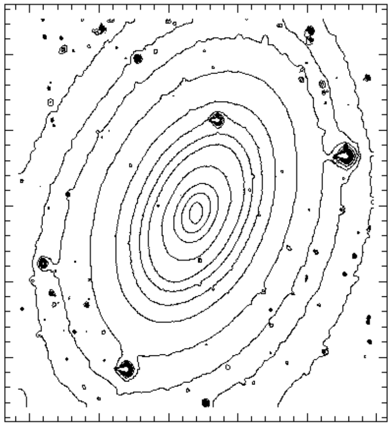


Elliptical galaxies are denoted E*n*, where:

$$\frac{b}{a} = 1 - \frac{n}{10}$$

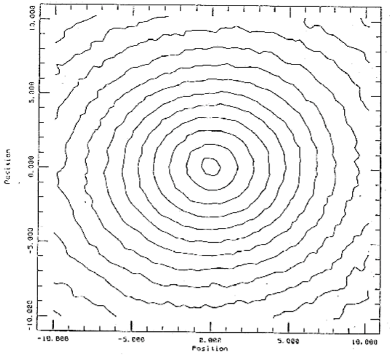
A round elliptical is E0, the most elongated ellipticals are E7

Typical Elliptical Isophotes



NGC 1533

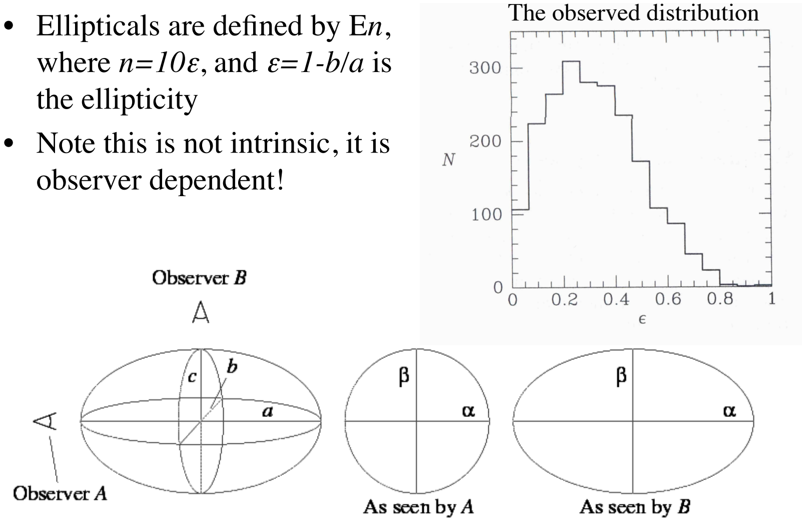
Note the apparent ellipticity gradient



NGC 4689

Shapes of Ellipticals

- Ellipticals are defined by E*n*, where $n=10\varepsilon$, and $\varepsilon=1-b/a$ is the ellipticity
- Note this is not intrinsic, it is observer dependent!



Elliptical Galaxies: Surface Photometry

Surface brightness of elliptical galaxies falls off smoothly with radius. Measured (for example) along the major axis of the galaxy, the profile is normally well represented by the $R^{1/4}$ or de Vaucouleurs law:

$$I(R) = I(0)\ e^{-kR^{1/4}}$$

where k is a constant. This can be rewritten as:

$$I(R) = I_e\ e^{\left\{-7.67\left[(R/R_e)^{0.25}-1\right]\right\}}$$

where R_e is the **effective radius** - the radius of the isophote containing half of the total luminosity. I_e is the surface brightness at the effective radius. Typically, the effective radius of an elliptical galaxy is a few kpc.

De Vaucouleurs' Law

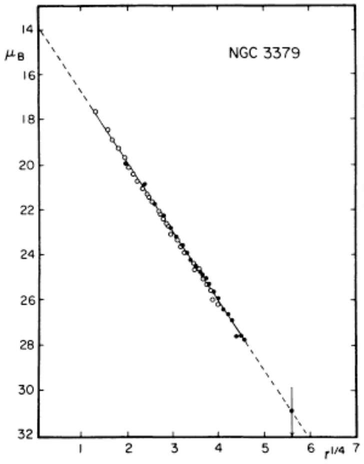
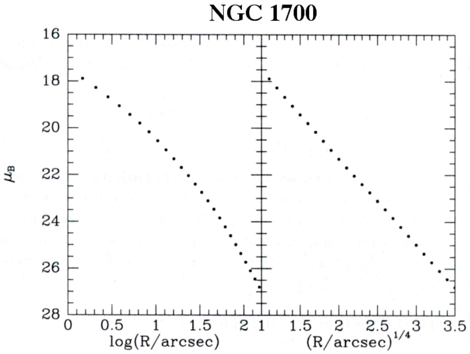


FIG. 2.—Mean E-W luminosity profile of NGC 3379 derived from McDonald photoelectric data. ●, Pe 4 data with 90 cm reflector; ○, Pe 1 data (M + P) with 2 m reflector. Note close agreement with $r^{1/4}$ law.



$R^{1/4}$ profile fits the data very well over some 2 decades in radius

Other Common Profiles

Sersic profile:

$$\Sigma(r) = \Sigma_0 \exp\left\{-b_n\left[(r/r_e)^{1/n}\right]\right\}$$

where $\boldsymbol{\Sigma}$ is the surface brightness in linear units (not magnitudes), $\mathbf{b_n}$ is chosen such that half the luminosity comes from $\boldsymbol{R} < \boldsymbol{R_e}$. This law becomes de Vaucouleurs for $\boldsymbol{n} = 4$, and exponential for $\boldsymbol{n} = 1$.

Hubble's profile:

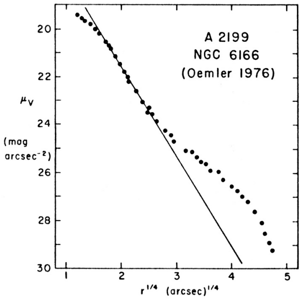
$$\Sigma(r) = \frac{\Sigma_s}{(1+\frac{r}{r_s})^2}$$

with $\boldsymbol{\Sigma}_0$ the central surface brightness, and $\boldsymbol{r}_0$ the "core" radius interior to which the surface brightness profile is approx. constant. Note that the integral under the Hubble profile diverges!

De Vaucouleurs Profile: Deviations

It is remarkable that such simple, 2-parameter profiles, fit the data of many ellipticals rather well. However, when these galaxies are studied in detail it is apparent that there is an individual behavior. It seems that deviations with respect to the de Vaucouleurs profile depend upon the total intrinsic luminosity of the galaxy.

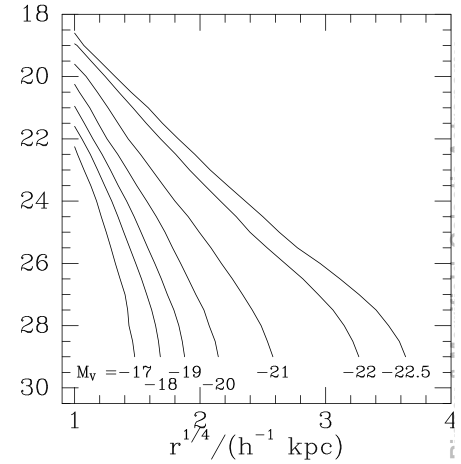
The figure below shows the example of a cD galaxy:

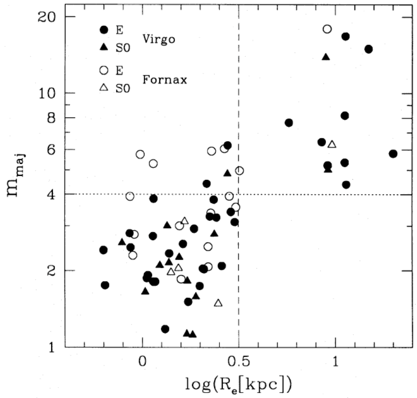


There is an excess of brightness in the outer parts of the galaxy with respect to the standard de Vaucouleurs profile.

In the case of dwarf ellipticals, the deviations occur in the opposite direction.

Larger Ellipticals Have Shallower profiles





Triaxial Ellipsoids

- In general, the 3-D shapes of ellipticals can be triaxial (A,B,C are intrinsic axis radii):
  - Oblate: A = B > C (a flying saucer)
  - Prolate: A > B = C (a cigar)
  - Triaxial A > B > C (a football)
- Studies find that ellipticals are mildly triaxial, with typical axis ratios:

  A:B:C ~ 1 : 0.95 : 0.65 (with some dispersion, ~0.2)
- Triaxiality is supported by observations of isophotal twists in some galaxies (would not see these if galaxies were purely oblate or prolate)
- It is due to the anisotropic velocity dispersions, which stretch the galaxies in proportion along their 3 principal axes

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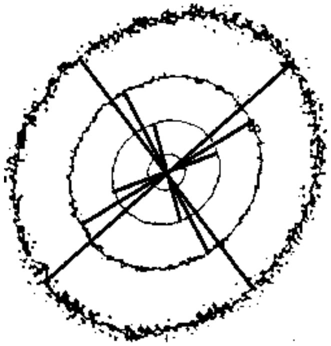
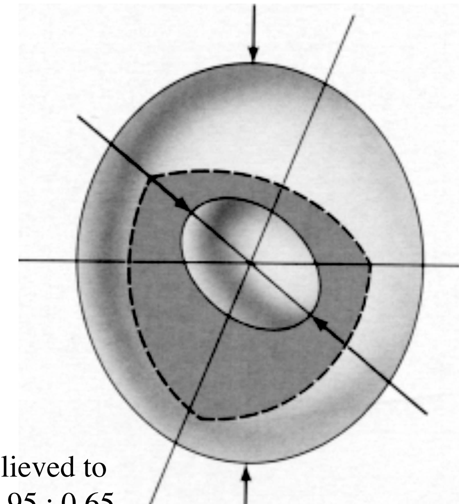
Isophote Twists

Generally interpreted as a consequence of the projected, nested triaxial ellipsoids:



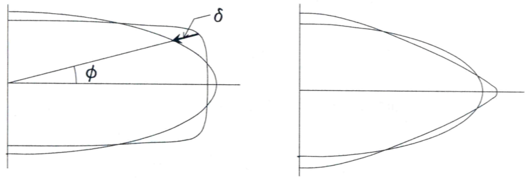


Elipticals as a family are now believed to be mildly triaxial, A:B:C ~ 1 : 0.95 : 0.65

Binney & Merrifield, Galactic Astronomy

Isophotes: Deviations From Ellipses

Isophotes are not perfect ellipses. There may be an excess of light on the major axis (disky), or on the “corners” of the ellipse (boxy):



The ***diskiness/boxiness*** of an isophote is measured by the difference between the real isophote and the best-fit elliptical one:

$$\delta(\phi) = \langle\delta\rangle + \Sigma\, a_n \cos n\phi + \Sigma\, b_n \sin n\phi$$

where the terms with n < 4 all vanish (by construction), and $a_4 > 0$ is a disky E, while $a_4 < 0$ corresponds to a boxy E.

Disky and Boxy Elliptical Isophotes

FIGURE 3. — Distribution of the ellipticity classes for all observed elliptical galaxies.

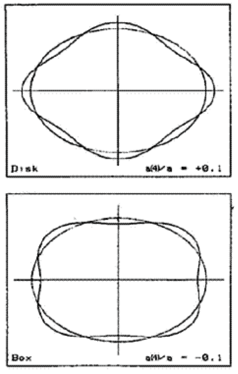


FIGURE 5. — Schematic drawing illustrating isophotes with $a(4)/a = +0.1$ and $a(4)/a = -0.1$.

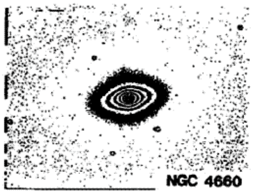


FIGURE 6. — R-image of NGC 4660, an elliptical galaxy with a disk-component in the isophotes ($a(4)/a \sim +0.03$).

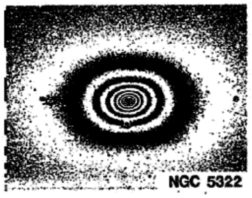


FIGURE 7. — R-image of NGC 5322, an elliptical galaxy with box-shaped isophotes ($a(4)/a \sim -0.01$).

Examples for boxy and disky isophotes from Bender et al. (1988)

Disky and Boxy Ellipticals

- Disky/boxy shapes correlate with various other galaxy parameters:
  - Boxy galaxies more likely to show isophotal twists (and hence be triaxial)
  - Boxy galaxies tend to be more luminous
  - Boxy galaxies have stronger radio and x-ray emission
  - Boxy galaxies are slow rotators, more anisotropic
  - In contrast, disky galaxies are midsized ellipticals, oblate, faster rotators, less luminous in radio and x-ray
- Some believe that more dissipationless mergers lead to more boxy galaxies, whereas any embedded disks imply some dissipative collapse, but the real picture is probably more complicated

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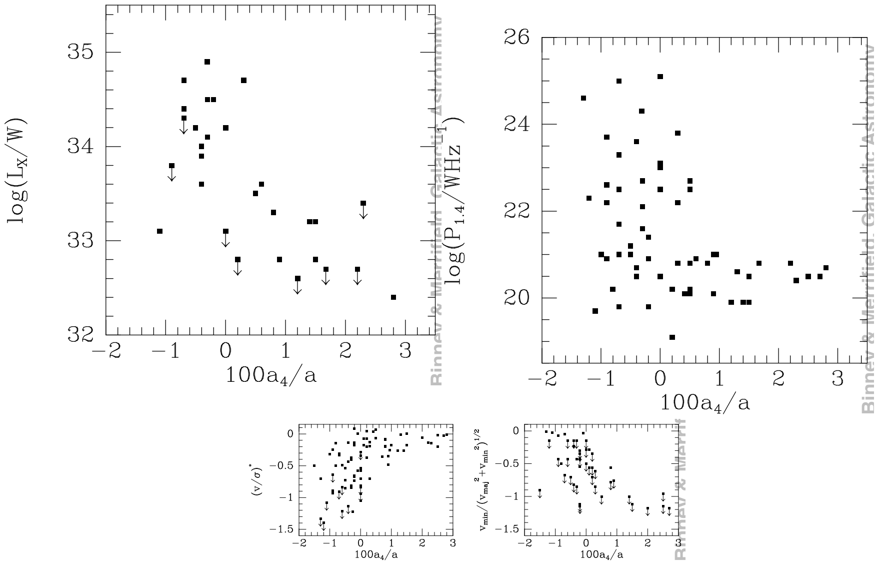
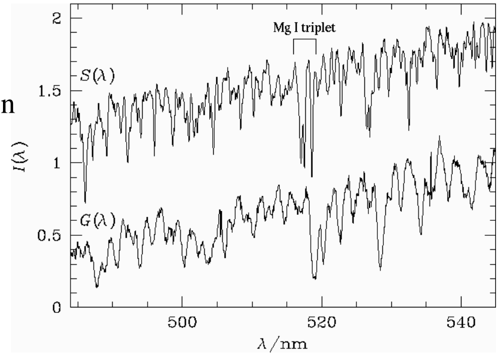


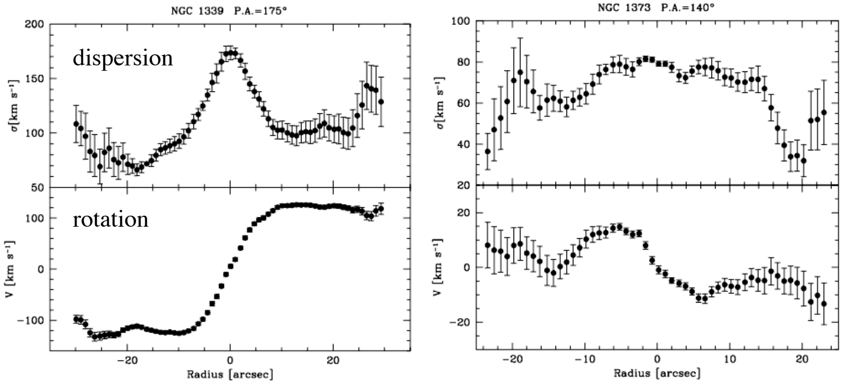
The Kinematics of E-Galaxies

Stars in E galaxies have some ordered motions (e.g., rotation), but most of their kinetic energy is in the form of random motions. Thus, we say that ellipticals are ***pressure-supported systems***

To measure the kinematics within galaxies we use absorption lines. Each star emits a spectrum which is Doppler shifted in wavelength according to its motion. Random distribution of velocities then broadens the spectral lines relative to those of an individual star. Systemic motions (rotation) shift the line centroids.



Kinematical Profiles of E-Galaxies



- Rotation is present, but generally not a dominant component of the kinetic energy
- Velocity dispersion tends to be higher closer to the center

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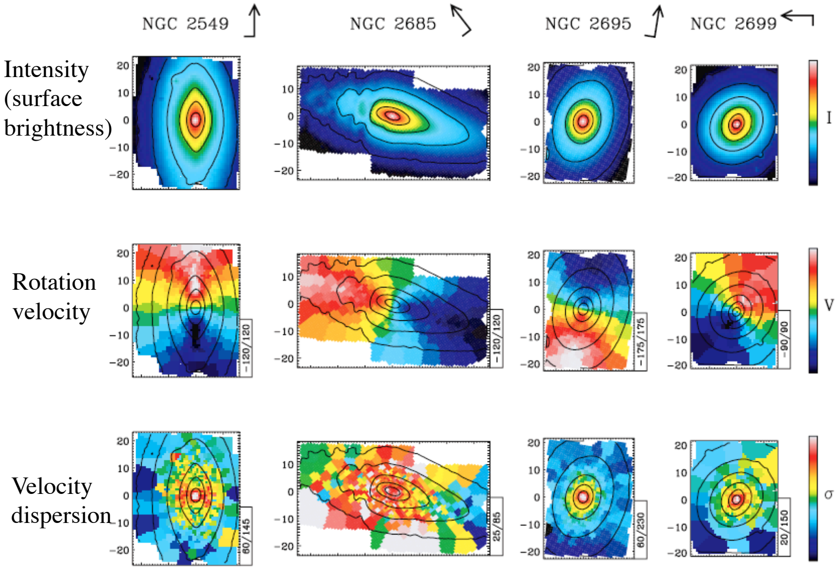
2-Dimensional Kinematics of E-Gal’s



Velocity Anisotropy in Elliptical Galaxies

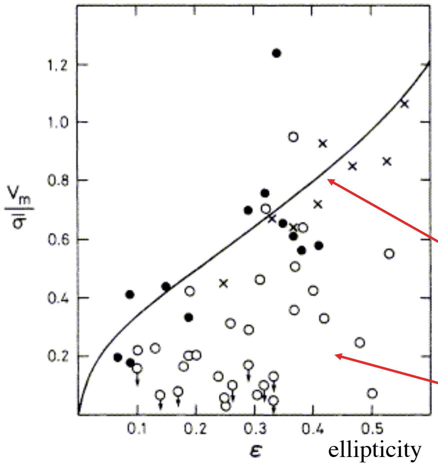


FIG. 3.—The quantity $V_m/\bar{\sigma}$ against ellipticity. Ellipticals with $M_B^{UH} > -20.5$ are shown as filled circles; ellipticals with $M_B^{UH} < -20.5$, as open circles; and the bulges of disk galaxies, as crosses. The solid line shows the $(V/\sigma, \epsilon)$-relation for oblate galaxies with isotropic velocity dispersions (Binney 1978).

The ratio of the maximum rotational velocity V_m and the mean velocity dispersion σ indicates whether the observed shapes of E’s are due to rotation or anisotropic pressure

Galaxies on this line are flattened by rotation

Galaxies below it are flattened by anisotropy

Velocity Anisotropy in Elliptical Galaxies

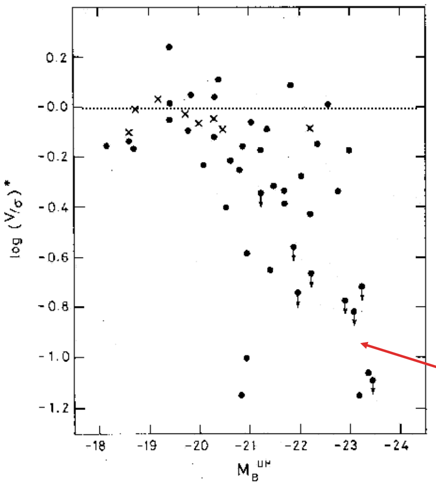


FIG. 4.—Log $(V/\sigma)^*$ against absolute magnitude. Ellipticals are shown as filled circles and the bulges as crosses; $(V/\sigma)^*$ is defined in § IIIb.

Now normalize by the "isotropic rotator" line

Rotational Properties of Elliptical Galaxies:

Anisotropy parameter:

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

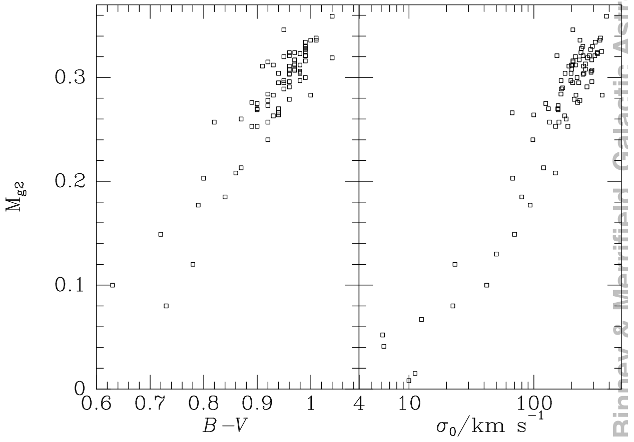
More luminous ellipticals tend to be anisotropic

This can be understood as a consequence of merging

Metallicities and Colors

Higher metallicities give redder colors, due to the line blanketting.

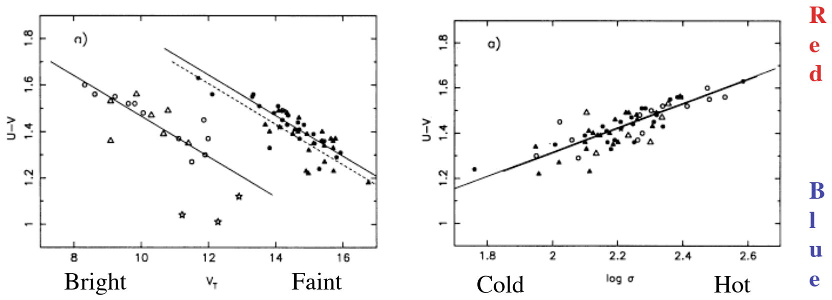
They also correlate with stellar velocity dispersions, implying deeper potential wells



Metallicity-Luminosity Relation

also known as the Color-Magnitude Relation

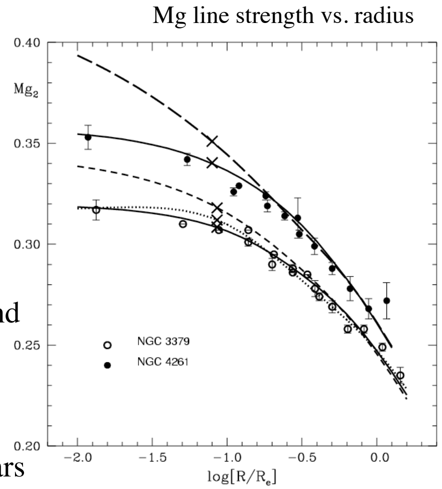
There is a relation between the color (a metallicity indicator) and the total luminosity or velocity dispersion for E galaxies:



Brighter and dynamically hotter galaxies are redder. This could be explained if small E galaxies were younger or more metal-poor than the large ones. More massive galaxies could be more effective in retaining and recycling their supernova ejecta.

Stellar Populations in Ellipticals

- Ellipticals are made mostly from old stars, ages > 1 Gyr and generally ~ 10 Gyr
- They have a broad range of metallicities (which indicate the degree of chemical evolution), up to 10 times Solar!
- More metal rich stars are found closer to the center
- This is observed as line strength gradients, or as color gradients (more metal-rich stars are redder)



The Cores and Nuclei of Ellipticals

Profiles of elliptical galaxies can deviate from the $R^{1/4}$ law at both small and large radii. Close to the center:

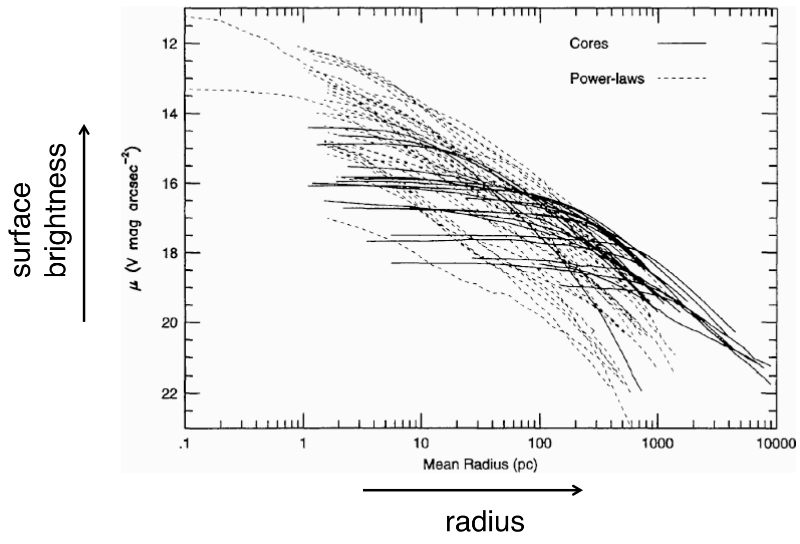
- Some galaxies have **cores** - region where the surface brightness flattens and is ~ constant
- Other galaxies have **cusps** - surface brightness rises steeply as a power-law right to the center

A cuspy galaxy might appear to have a core if the very bright center is blurred out by atmospheric seeing. Thus, HST is essential to studies of galactic nuclei!

It turns out that:

- The most luminous ellipticals have HST-resolved cores
- Low luminosity ellipticals have power law cusps extending inward as far as can be seen

Core Profiles From the HST



Central Surface Brightness Profiles

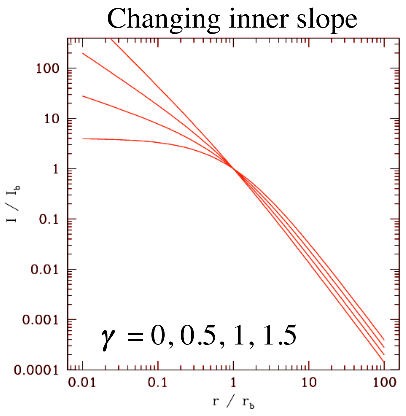
To describe these observations, we can use a new profile suggested by the “Nuker” team:

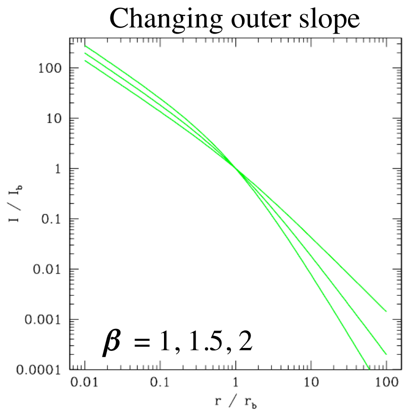
$$I(R) = I_b 2^{(\beta-\gamma)/\alpha}\left(\frac{R}{R_b}\right)^{-\gamma}\left[1+\left(\frac{R}{R_b}\right)^{\alpha}\right]^{(\gamma-\beta)/\alpha}$$

It is a broken power law:

- Slope of $-\gamma$ at small radii
- Slope of $-\beta$ at large radius
- Transition between the two slopes at a break radius R_b, at which point the surface brightness is I_b
- Remaining parameter α controls how sharp the changeover is

The “Nuker” Profile





Massive Black Holes in Galactic Nuclei

- It turns out that they are ***ubiquitous***: nearly every non-dwarf galaxy seems to have one, but only a small fraction are active today; these super-massive black holes (SMBH) are believed to be the central engines of quasars or other AGN
- They are detected through central velocity dispersion or rotation cusps near the center - requiring more mass than can be reasonably provided by stars
- ***Their masses correlate very well with many of their host galaxy properties***, suggesting a co-formation and/or co-evolution of galaxies (or at least their old stellar spheroid components) and the SMBHs they contain
- Understanding of this connection is still not complete, but dissipative mergers can both drive starbursts and fuel/grow SMBHs

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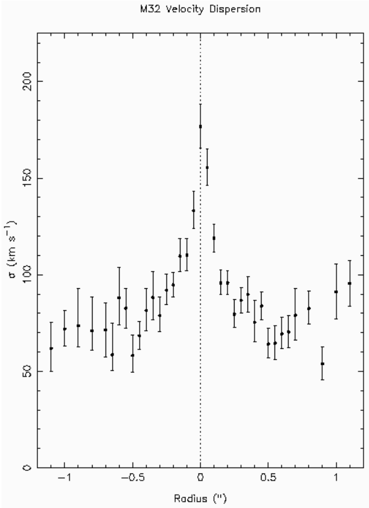
Many (all?) ellipticals (& bulges) have black holes- even compact ones like M32!

Can measure BH masses for galaxies via their velocity dispersion

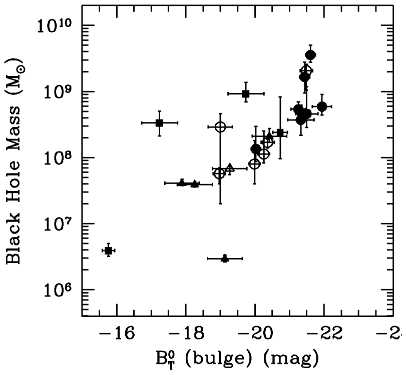


Fundamental Corrrelations Between SMBH Masses and Their Host Galaxy Properties

$$\log \frac{M_{BH}}{M_\odot} = (-0.36 \pm 0.09) B_T^0 + (1.2 \pm 1.9)$$

$$\chi_r^2 = 23$$

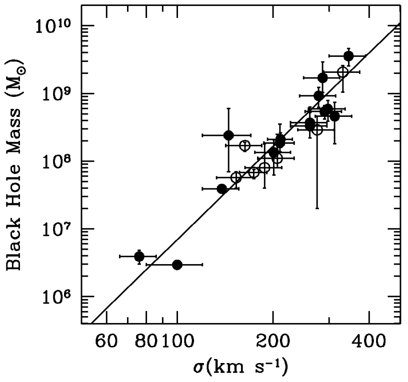
Kormendy & Richstone 1995



$$\frac{M_{BH}}{M_\odot} = (1.7 \pm 0.3) \times 10^8 \left(\frac{\sigma_c}{200 \,\mathrm{km\ s^{-1}}} \right)^{4.6 \pm 0.5}$$

$$\chi_r^2 = 0.72$$

Ferrarese & Merritt 2000; Gebhardt et al. 2000



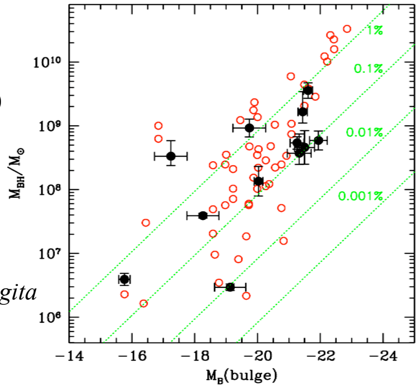
Local SMBH Demographics and Comoving Mass Density

$M_\bullet$ from the $M_\bullet$-σ relation
M_{bulge} from Magorrian et al. (1998)

Mass density in local SMBH:

$\mathbf{x = M_\bullet / M_{bulge} \sim 0.13\%}$

$\rho_{bulge} \sim \mathbf{3.7 \times 10^8\ M_\odot\ Mpc}$ (*Fukugita et al. 1998*)

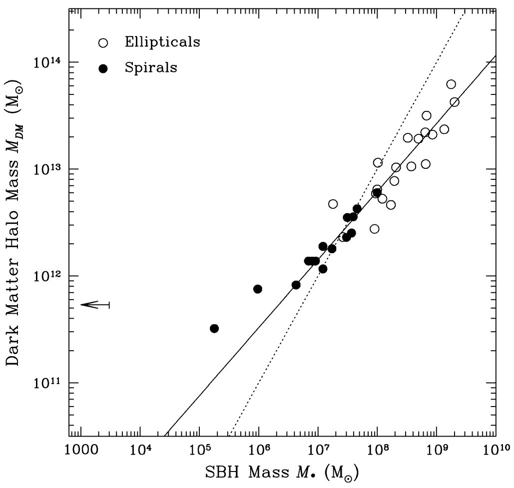


Merritt & Ferrarese 2001

→ $\rho_\bullet \sim \mathbf{4.9 \times 10^5\ M_\odot\ Mpc^{-3}}$

Recall that the normalization of the GLF is $\phi_* \sim 10^{-2}$ Mpc^{-3}, so an average galaxy should contain a ~ **10^7 $M_\odot$** black hole!

An even more fundamental relation?

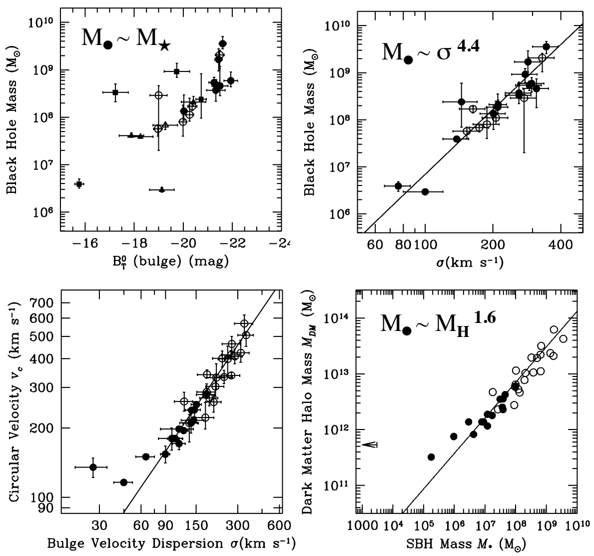


Dark halo mass
vs. SMBH mass

(Ferrarese 2002)

$$\frac{M_\bullet}{10^8\,M_\odot} \sim 0.046\left(\frac{M_{DM}}{10^{12}\,M_\odot}\right)^{1.57}$$

The SMBH - Host Galaxy Correlations



Early-Type Dwarf Galaxies

- Dwarf ellipticals (dE) and dwarf spheroidals (dSph) are a completely different family of objects from normal ellipticals - they are not just small E’s
- In fact, there may be more than one family of gas-poor dwarf galaxies …
- Dwarfs follow completely different correlations from giant galaxies, suggestive of different formative mechanisms
- They are generally dark matter (DM) dominated, especially at the faint end of the sequence
- One possible scenario is that supernova (SN) winds can remove baryons from these low-mass systems, while leaving the DM, while the more massive galaxies retain and recycle their SN ejecta

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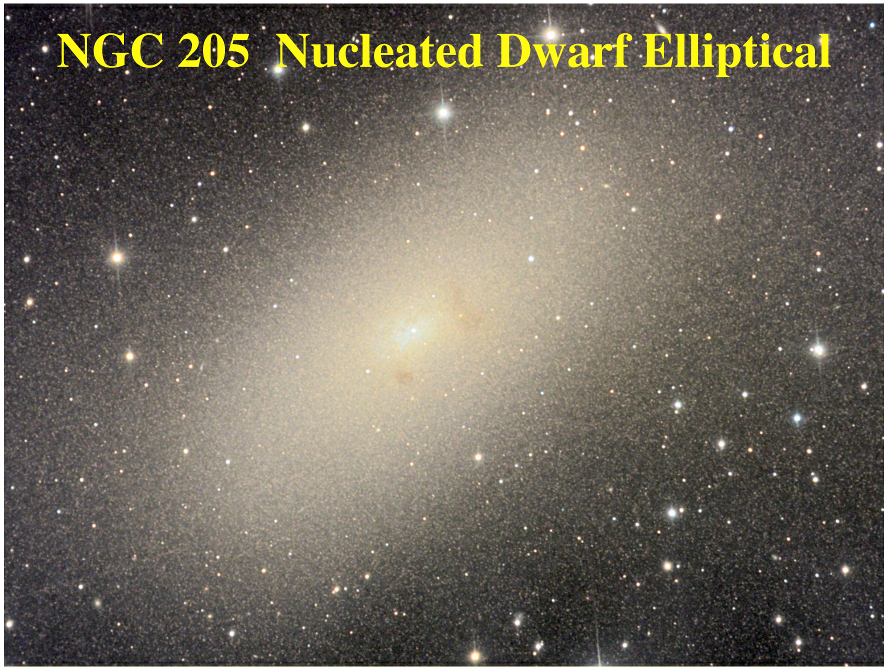
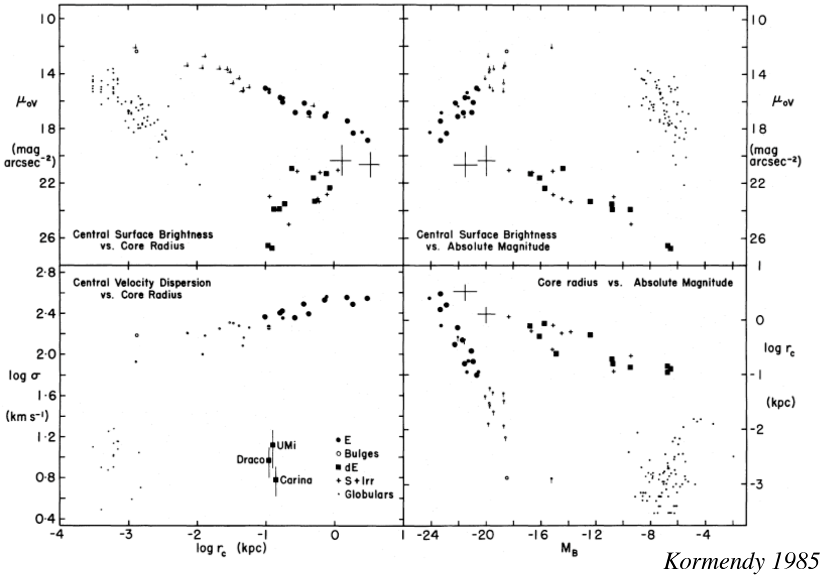
NGC 205 Nucleated Dwarf Elliptical

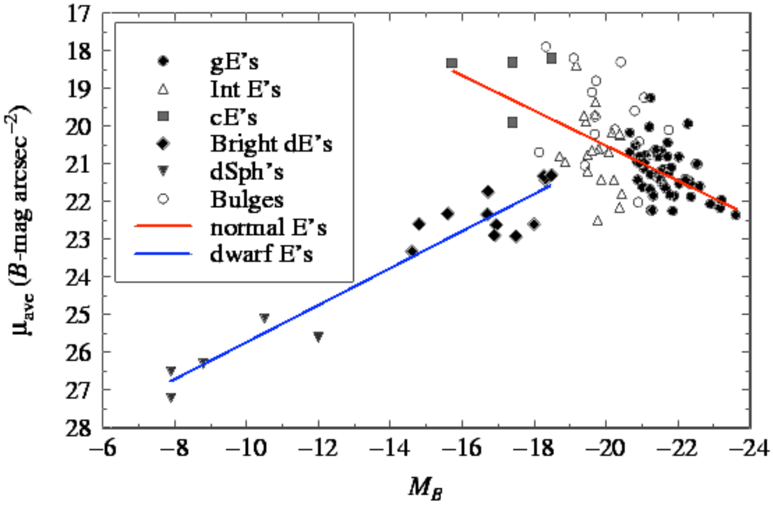


Parameter Correlations



Kormendy 1985

Mean Surface Brightness vs. Absolute Mag.



Mass to Light Ratios