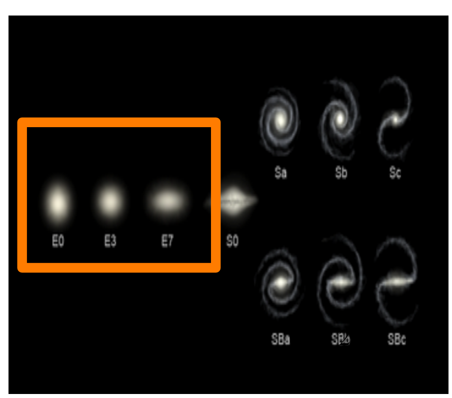
The project: **Due Dec 4**

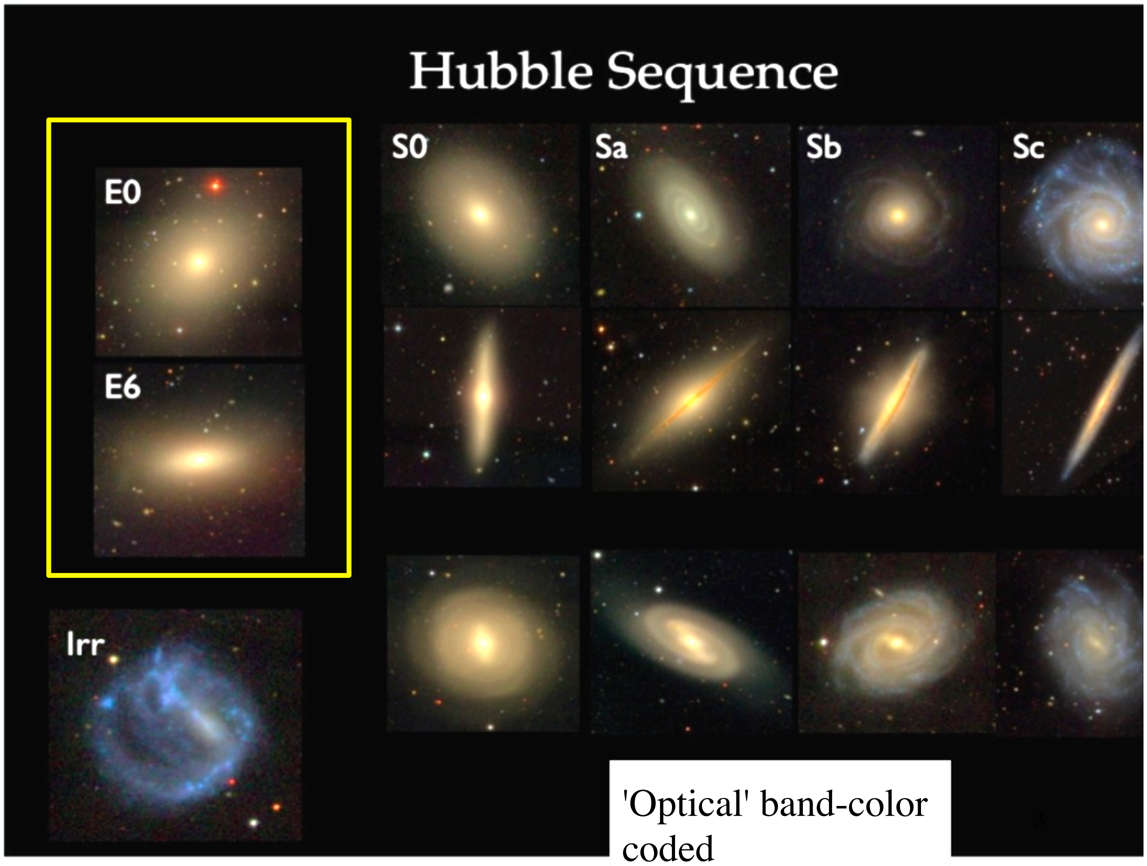
- I expect ~10-15 pages double spaced (250 words/page) with references from material you used (I do not expect 'densely' cited but a sufficient number).
- It must be in a subject related to the class- either an enhancement of something I covered or something new which I did not cover but you find interesting.
- You can use figures if you wish (please cite where they came from) but not so many figures that the text is severely reduced
- Do not copy, things should be in your own words.
- Graded on clarity, understanding, knowledge of material, relationship to class.
  - Imagine you are trying to explain something to another 400 level student (e.g. Scientific American+ level).

I need your topics VERY SOON

Spheroidal (Elliptical) Galaxies – Read **S+G ch 6**

- Visual Impression: smooth, roundish- *deceptively* simple appearing-
- Collisionless systems
- While visually 'similar' detailed analysis of spheroids shows 3 categories-smooth transition as a function of mass
  - Massive/luminous systems: little rotation or cool gas, flat central brightness distribution (*cores*), triaxial; lots of hot x-ray emitting gas, stars very old, lots of globular clusters, solar metallicity or higher **Low central surface brightness**
  - Intermediate mass/luminosity systems:
    power law central brightness distribution
    little cold gas; as mass drops effective rotation increases, oblate, 'disky'
  - Dwarf ellipticals: no rotation, exponential surface brightness (will not cover)

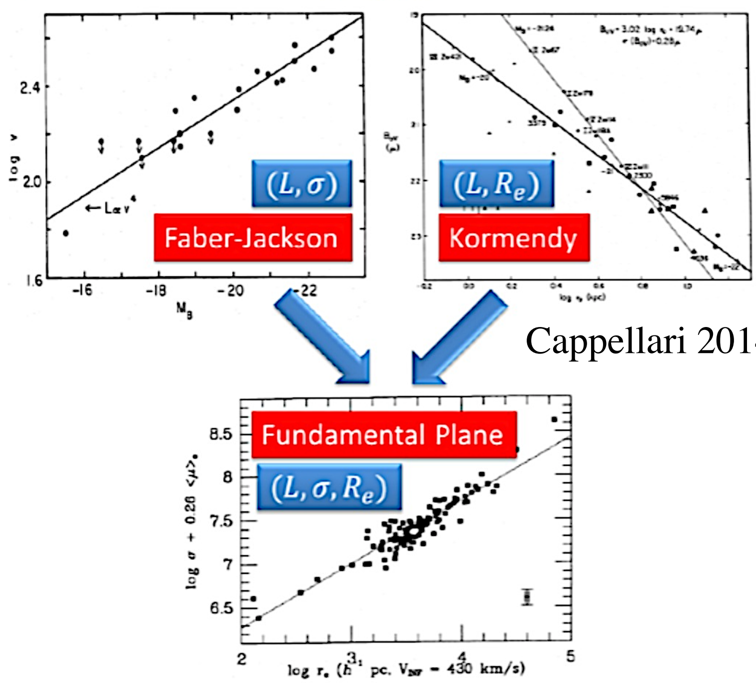




Spheroidal (Elliptical) Galaxies S+G ch 6

At $M>10^9 M_\odot$ general properties **fall on the 'fundamental plane'** which includes **velocity dispersion, size , luminosity surface brightness** (and some other properties like metallicity)

- Spiral galaxies bulges, while visually similar are physically different in many ways from E galaxies



Cappellari 2014

Figure 1. Classic scaling relations. The Faber-Jackson and the Kormendy relations are two special projection of a more fundamental one, aptly named the Fundamental Plane. The three figures are taken from Faber & Jackson (1976), Kormendy (1977) and Djorgovski & Davis (1987) respectively.

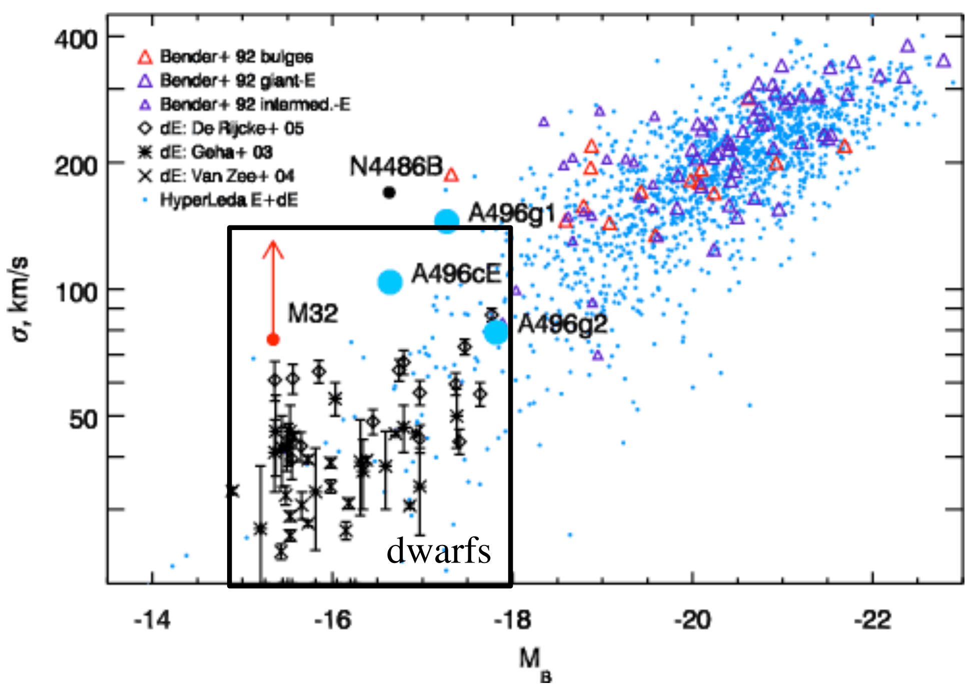
Fundamental Plane

- The Fundamental Plane (FP) describes the relation between the stellar mass, size, and velocity dispersion of elliptical galaxies;
  - the Faber-Jackson relation (FJR) is its projection onto {mass, velocity} space
  - the Kormendy relation is the projection into {surface brightness/ scale} length space
  - Other physical parameters are also correlated

Since the internal motions of galaxies are set primarily by their dark matter mass, these relationships provide key insight into the connection between galaxies and their host haloes.

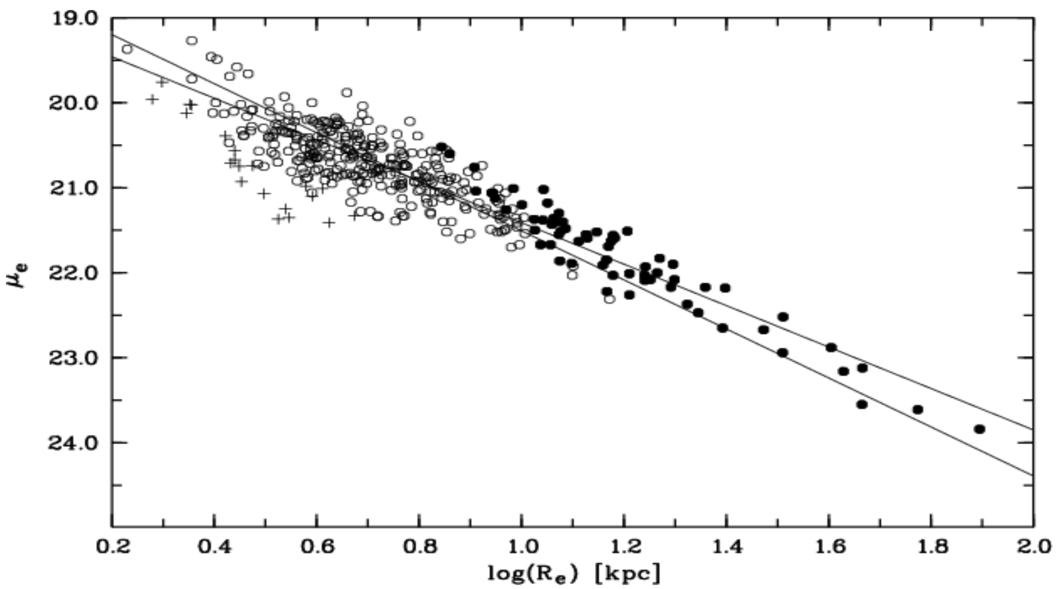
Faber Jackson Relation

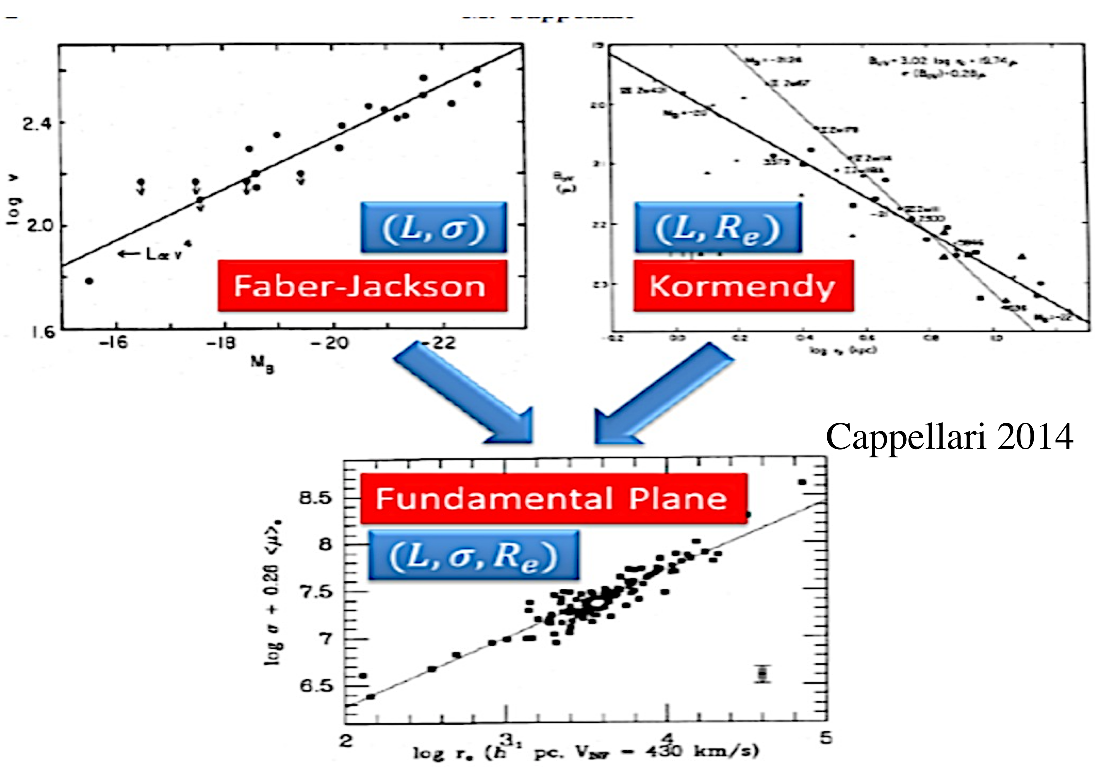
- Like the Tully-Fisher relation, but for ellipticals
- Strong correlation of magnitude with velocity dispersion



Kormendy Relation

- Strong anti-correlation of scale length (R_e) and surface brightness at R_e





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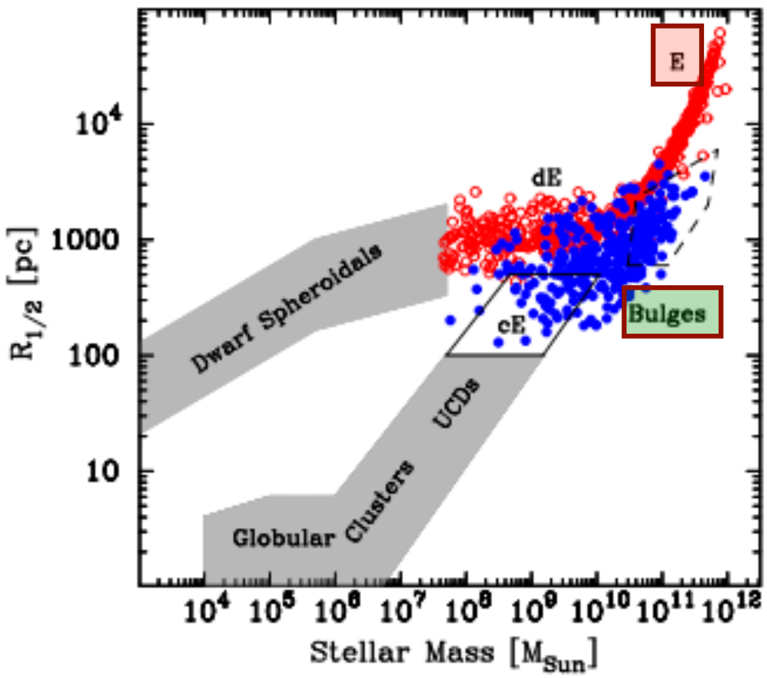
- Comparison of half light size $R_{1/2}$ to mass for the range of spheroidal systems
- Notice that properties bulges of spirals and ellipticals overlap, but at the high mass end there are no bulges.
- Remember $R_{1/2}$ from the Sersic model for the surface brightness distribution

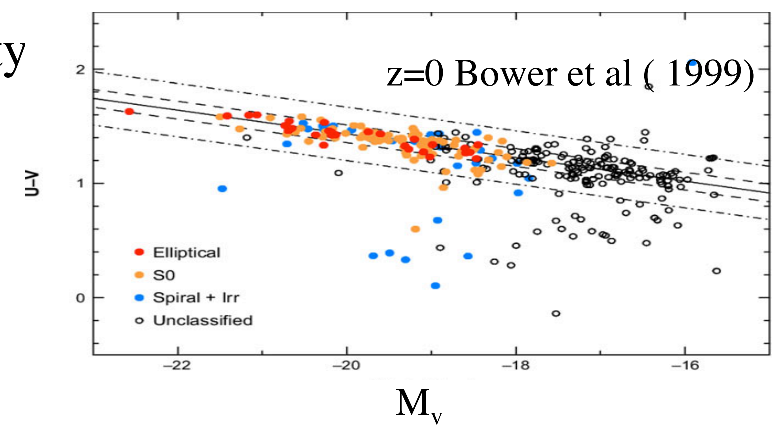
see for more details astr553/Topic07/Lecture_7.html

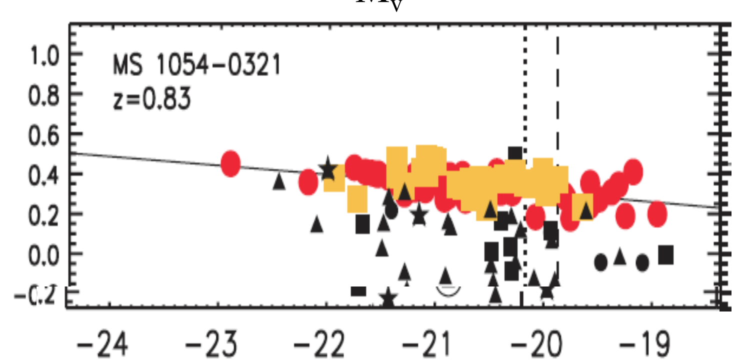


Graham 2012

Color-Luminosity

- there is a strong relation between the colors and luminosities of ellipticals
- This relation is so good it can be used to identify clusters of galaxies at high z via the 'red sequence'
- the correlation is due primarily to a trend of metallicity with luminosity.
- Small scatter argues for high z formation over a small δz

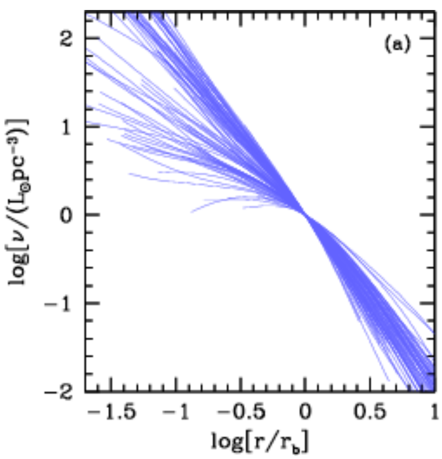


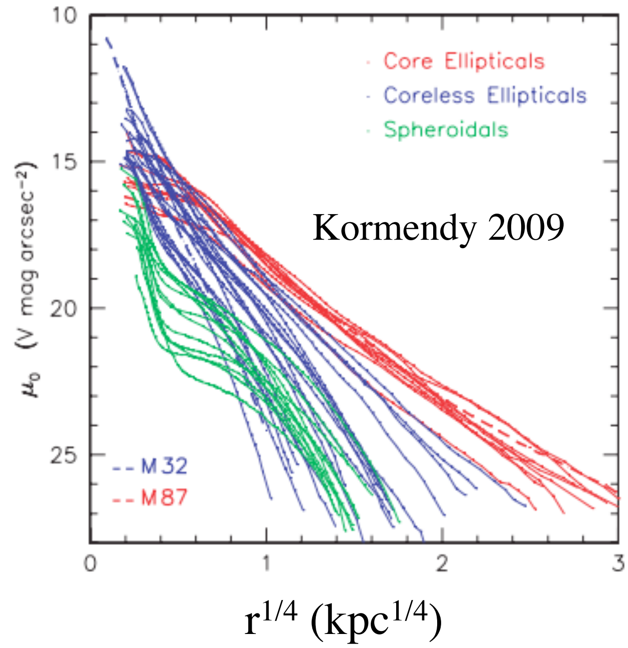


Renzini 2006 ARA&A- Stellar population diagnostics of elliptical galaxy formation

Wide Range of Size But Homologous

- the family of spheroids can usually be well fit by the Sersic model, but there are some deviations in the centers (cores and cusps)

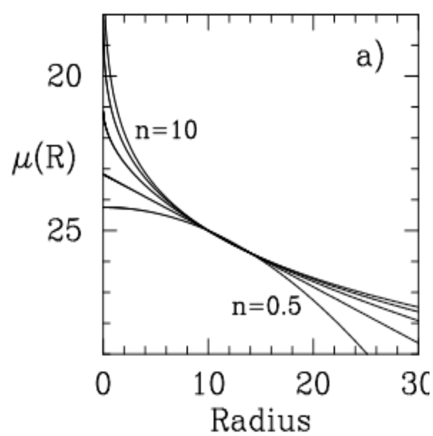


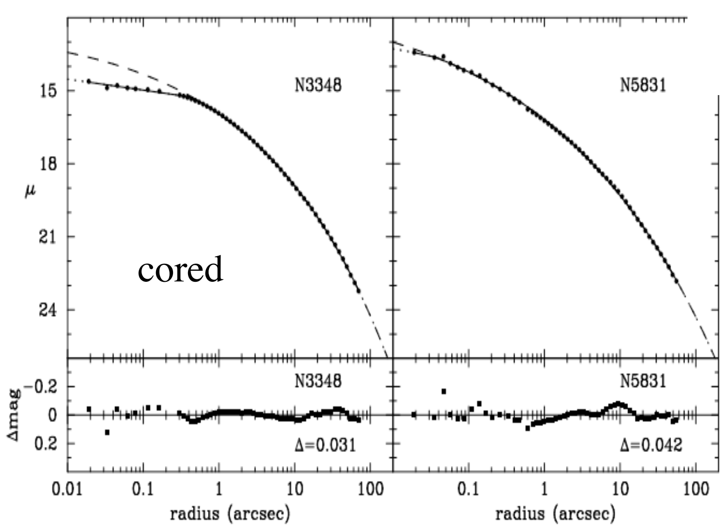


More luminous galaxies tend to have cores, less luminous roughly power law shape in central regions

Fit of Sersic Profile

- Sersic profile for values of n=0.5, 1, 2, 4, 10
- Fit of Sersic profile to 2 elliptical galaxies
- (figures from Graham 2012)



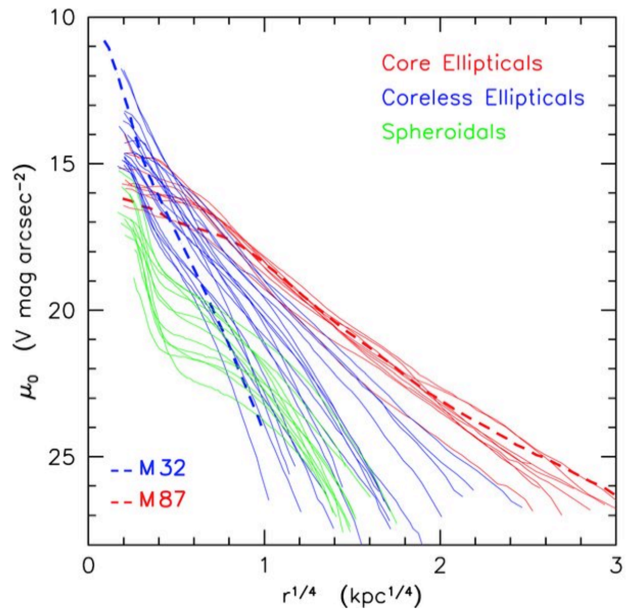


For n=4 (the deV model the total luminosity (S+G problem 6.1) is $7.22pR_e^2 I(R_e)$ and half the light comes from within R_e

Surface Brightness Distribution of E Galaxies

why is a core a big deal?

- a core is a flattening of the surface brightness profile towards the center
- however theoretical Cold dark matter profiles do not have a core.



Why Interesting

- The surface brightness profiles are a hint to the formation process
- hierarchical clustering implies that different galaxies are the products of different merger histories in which different progenitor morphologies and encounter geometries produced a variety of results.
- It is remarkable that the remnants of such varied mergers shows so much regularity (Kormendy 2009)
- At a given mass, smaller galaxies are redder in colour, have lower fractions of molecular gas, and are more rotationally dominated more massive systems are typically old, metal rich and α enhanced

There are several simple types of mergers

- wet (lots of cold gas)- e.g. spiral x spiral
- dry (little cold gas)- elliptical x elliptical
- wet/dry – intermediate amount of gas spiral x elliptical
- wide range of mass (dwarf into normal)

The "Complete" List of Parameters- Kormendy and Bender

- The physically important distinctions between the two varieties of ellipticals
- Giant ellipticals (M_V<-21.5)

(1) **have cores**, i. e., central missing light with respect to and inward extrapolation of the outer Sersic profile;

(2) **rotate slowly, rotation is unimportant dynamically**

(3) are moderately anisotropic and triaxial;

(4)low ellipticity

(5) have boxy-distorted isophotes;

(6) have Sersic (function outer profiles with n ≥ 4;

(7) mostly are made of **very old stars that are enhanced in α elements;**

(8) often contain strong radio sources,

(9) have lots of diffuse X-ray-emitting gas, more of it in bigger Es.

Normal and dwarf true ellipticals (M_V>-21.5)

(1) *coreless* and have central extra light with respect to an inward extrapolation of the outer Sersic profile (power law profile)

(2) **rotate rapidly**, rotation is dynamically important to their structure

(3) are nearly isotropic and oblate spheroidal,

(4) are flatter than giant ellipticals (ellipticity ~0.3);

(5) have disky-distorted isophotes;

(6) have Sersic function outer profiles with n < 4;

(7) are made of younger (but still old) stars with only modest or no α element enhancement;

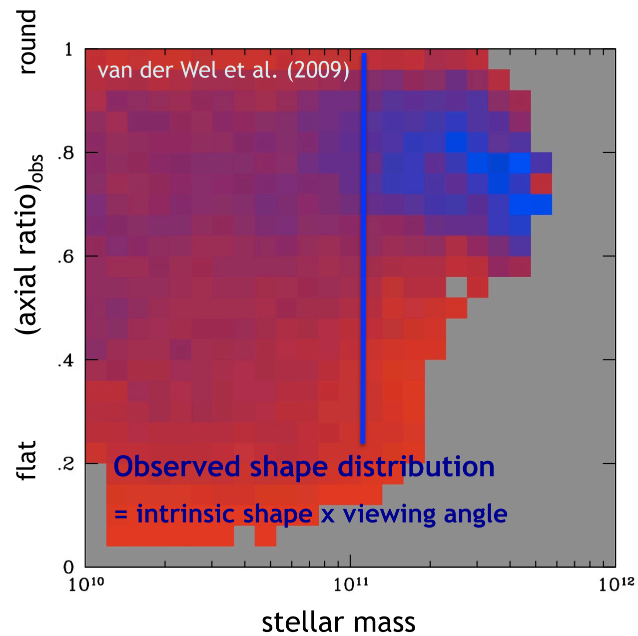
(8) **rarely contain strong radio sources, and**

(9) weak X-ray emission from hot gas

The shapes of Early-Type Galaxies

SDSS study of shape distribution of 'passive' (=early type=E) galaxies:(van der Wel 2009)

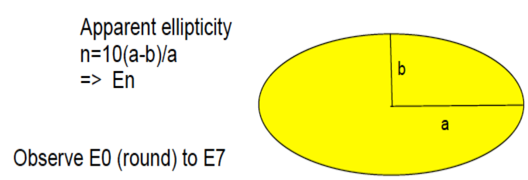
At $M<10^{11}M_{sun}$ there is a wide range of axial ratios (disks/highly flattened systems)
At high mass systems more uniform



Ellipticals −Shape S&G 6.1.1

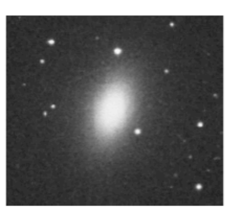
- What does 'roundish' mean
  - Oblate, prolate, triaxial

  Old ideas: "Images have complete rotational symmetry – figures of revolution with two equal principal axes. The third, the axis of rotation, is smaller than the other two." (Sandage) i.e. oblate spheroids, rotating about axis of symmetry



SURFACE PHOTOMETRY AND THE STRUCTURE OF ELLIPTICAL GALAXIES
John Kormendy,S. Djorgovski
Annu. Rev. Astron. Astrophys. 1989. 27: 235-277

M87 (E0)

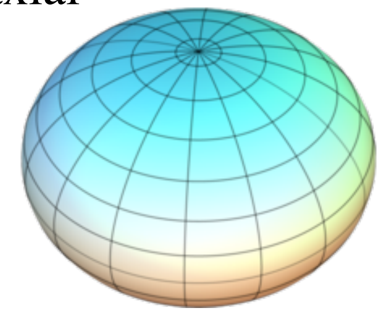


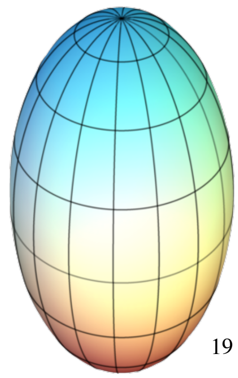
M59 (E5)

E7

Oblate, Prolate Triaxial

- Oblate: rotationally symmetric ellipsoid having a polar axis shorter than the diameter of the equatorial diameters-formed by rotating an ellipse about its minor axis
- Prolate a rotationally symmetric ellipsoid spheroid in which the polar axis is greater than the equatorial diameter.





Ellipticals -Shape

- Shape alone cannot tell us what is going on
- Triaxial ellipsoids:
  – $[x^2/a^2]+[y^2/b]^2+[z^2/c^2]=1$
- From morphology alone can't tell if elliptical galaxies are

1. spherical a=b=c
2. prolate a>b=c (rugby ball)
3. oblate a=b>c (smartie)
4. triaxial a>b>c

Projection Effects

- Please follow the discussion on pages 250-252

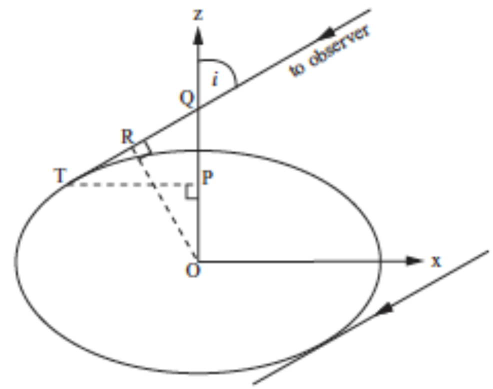
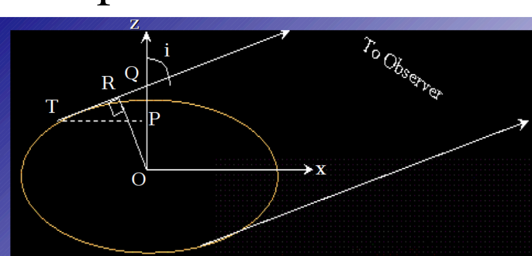


Fig. 6.8. Viewing angles for an oblate galaxy.

Ellipticals Shape

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

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



If elliptical galaxies are oblate spheroids then

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

Distribution of B/A eq 6.11

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

Triaxiality $m = x^2 + y^2/p^2 + z^2/q^2$

D.Davis

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

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

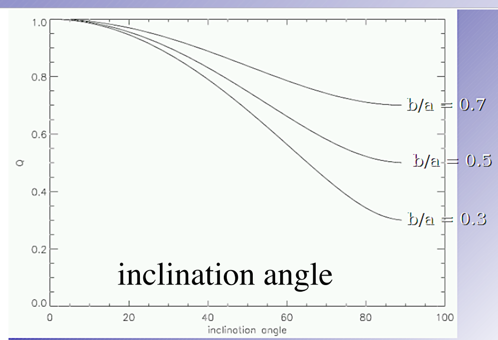
Using our definition of m for the last step. Finally we can rewrite this as

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

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

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

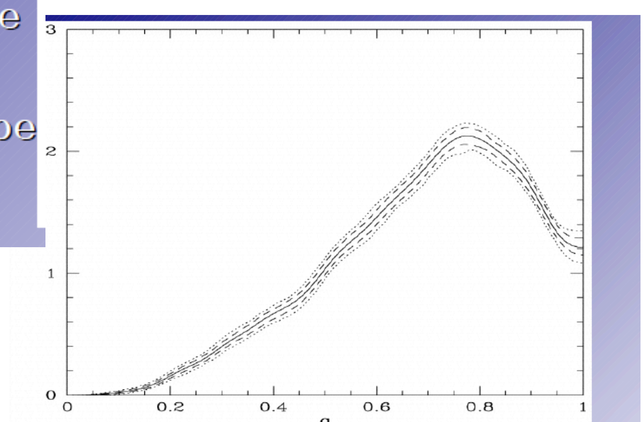
q



Ellipticals are Triaxial

- No selection of oblate spheroids can give the observed distribution
- These galaxies must be triaxial

Shape could also be due to rotation around z axis.



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

Statistics of Shapes

- While the ellipticity of any individual galaxy depends on unknown viewing angle as well as intrinsic shape, information on the intrinsic shapes of E galaxies can be derived from a statistical analysis of the distribution of ellipticity (ε) for a large sample.
- Models based on oblate shapes predict that large samples of randomly-oriented ellipticals should include a substantial number of galaxies with nearly circular isophotes ($\varepsilon \sim 0$).
- In fact, round galaxies are relatively rare, this suggests that most elliptical galaxies are not oblate spheroids
- Also many galaxies show isophotal twists-evidence for triaxiality

Density Profile

- I(R) is the projected luminosity surface brightness, j(r) is the 3-D luminosity density (circular images- if image is elliptical no general solution)

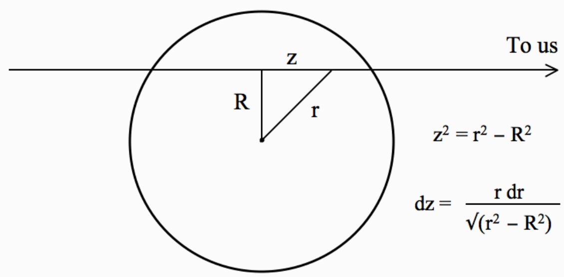
$j(r)=-1/\pi\int_R^{\infty} dI/dR/\mathrm{sqrt}(R^2-r^2)$

this is an <u>Abel integral</u> which has only a few analytic solutions

Simple power law models $I(R)=r^{-\alpha}$

then $j(r)=r^{-\alpha-1}$

$$I(R) = \int_{-\infty}^{\infty} j(r)\, dz = 2\int_R^{\infty} \frac{j(r)\, r\, dr}{\sqrt{(r^2-R^2)}}$$



While the Sersic model is a better fit to the surface brightness profiles it is not analytically invertible to density

-often use a generalized King profile with surface brightness $I(r)=I(0)(1+(r/r_c)^2)^{-5/2}$ which gives a density law $\rho(r)=\rho(0)(1+(r/r_c)^2)^{-3/2}$ where $r_c=3\sigma/\mathrm{sqrt}(4\pi G\rho_c)$; σ is the velocity dispersion